Friday 13 July 2012
Strong and ElectroWeak Matter, Swansea

Direct and Indirect searches for **Dark Matter**: status and perspectives

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

in collaboration with:
A.Strumia (Pisa)
N.Fornengo (Torino)
M.Tamburini (Pisa)
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (L'Aquila + Saclay + CERN)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

Friday 13 July 2012
Strong and ElectroWeak Matter, Swansea

Direct and Indirect searches for **Dark Matter**: status and perspectives

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

in collaboration with:
A.Strumia (Pisa)
N.Fornengo (Torino)
M.Tamburini (Pisa)
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (L'Aquila + Saclay + CERN)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

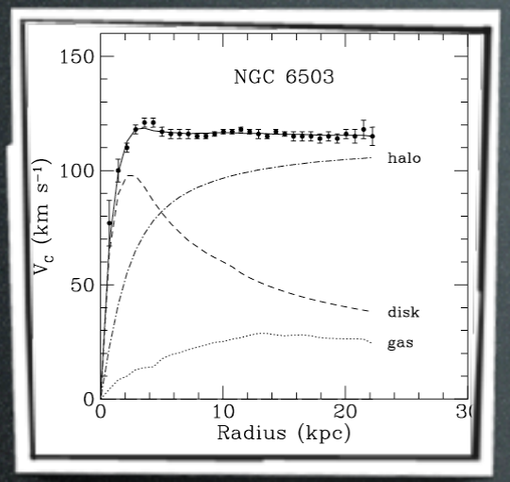
Introduction

Introduction

DM exists

Introduction

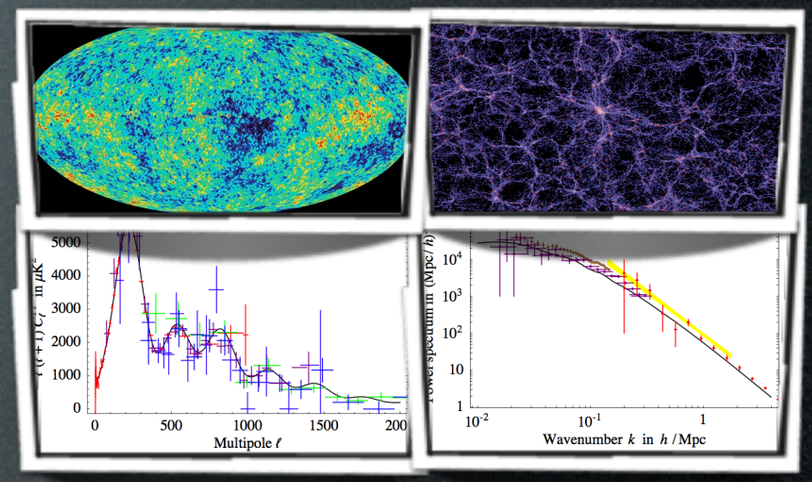
DM exists



galactic rotation curves



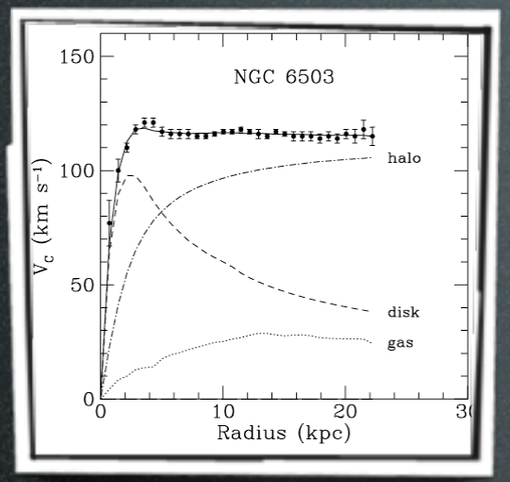
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Introduction

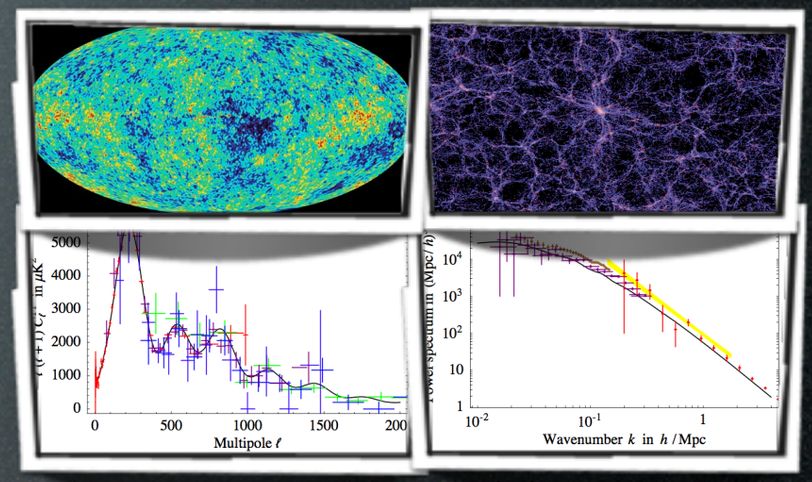
DM exists



galactic rotation curves



weak lensing (e.g. in clusters)

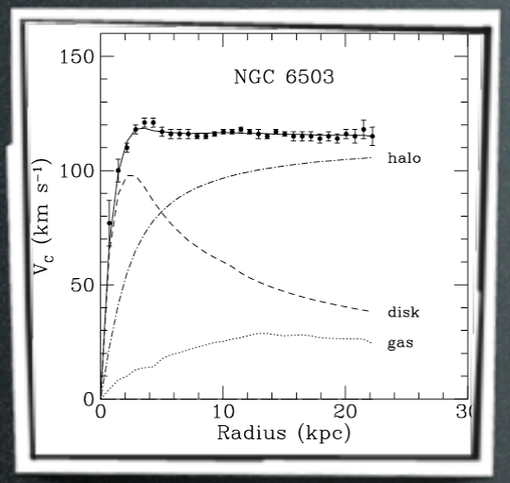


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, feebly interacting particle.

Introduction

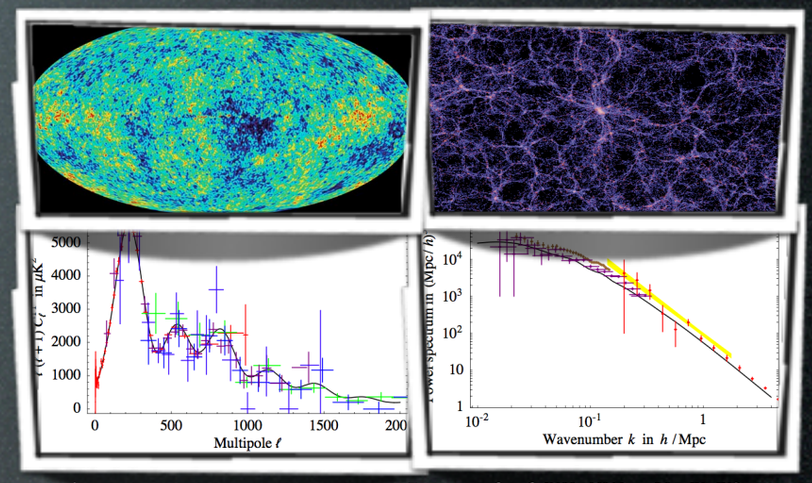
DM exists



galactic rotation curves



weak lensing (e.g. in clusters)

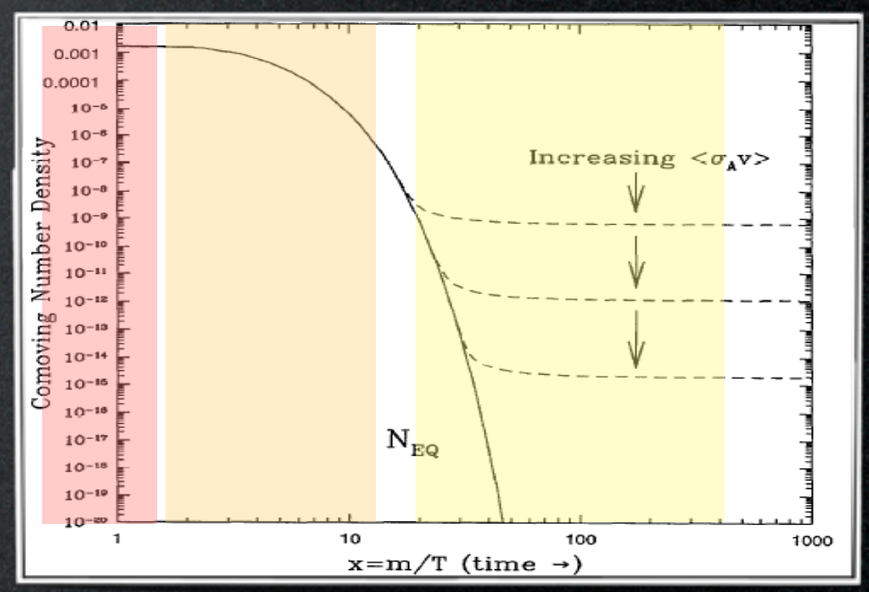


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, feebly interacting particle.

Some of us believe in the WIMP miracle.

- *weak*-scale mass (10 GeV - 1 TeV)
- *weak* interactions $\sigma v = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$
- give automatically correct abundance



DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

OUTLINE

direct detection

basics
constraints
hints
'theory'
tentative conclusion

production at colliders

indirect

basics
constraints
hints
'theory'
tentative conclusion

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

$\bar{p}$ from annihil in galactic halo or center

$\bar{d}$ from annihil in galactic halo or center

GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

DM detection

direct detection

production at colliders

indirect

- γ from annihil in galactic center or halo and from synchrotron emission
  Fermi, HESS, radio telescopes
- e^+ from annihil in galactic halo or center
  PAMELA, ATIC, Fermi
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center
  GAPS
- $\nu, \bar{\nu}$ from annihil in massive bodies
  Icecube, Km3Net

DM detection

direct detection

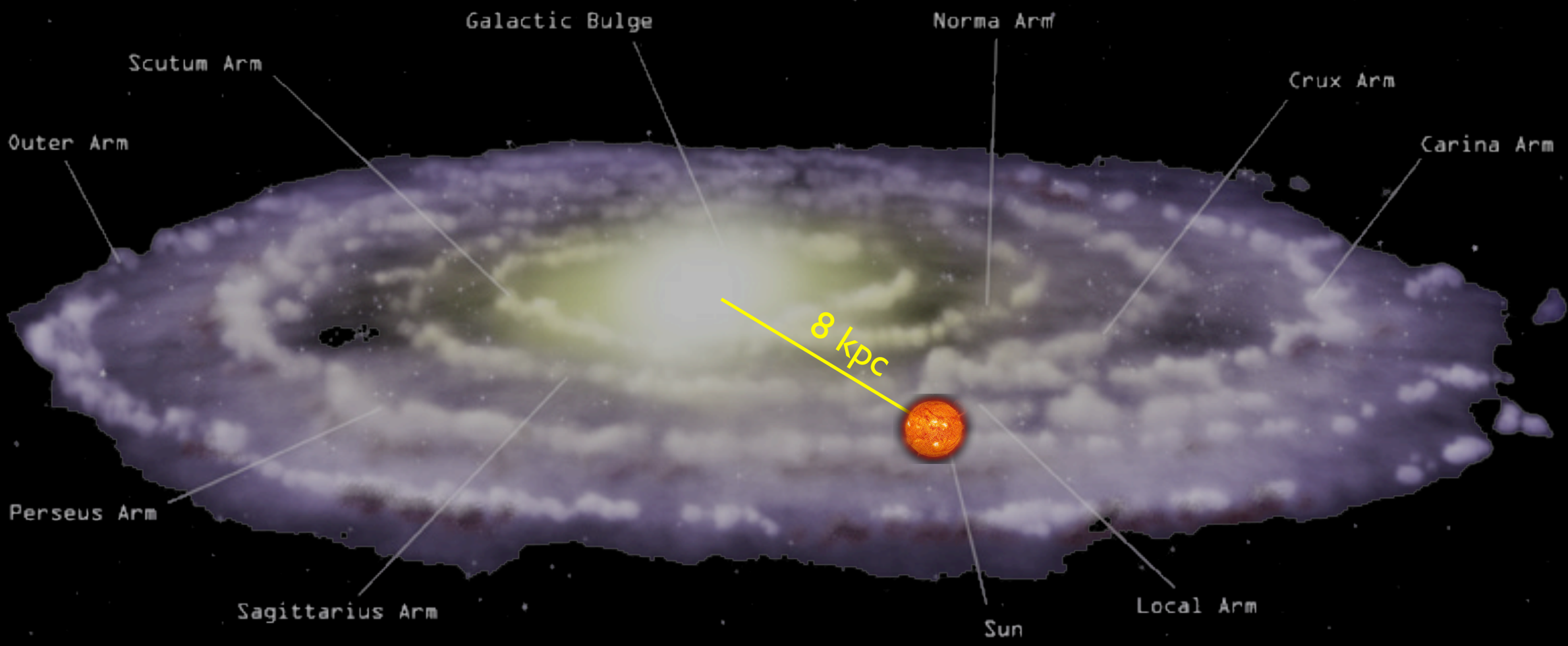
production at colliders

indirect

- γ from annihil in galactic center or halo and from synchrotron emission
  Fermi, HESS, radio telescopes
- e^+ from annihil in galactic halo or center
  PAMELA, ATIC, Fermi
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center
  GAPS
- $\nu, \bar{\nu}$ from annihil in massive bodies
  Icecube, Km3Net

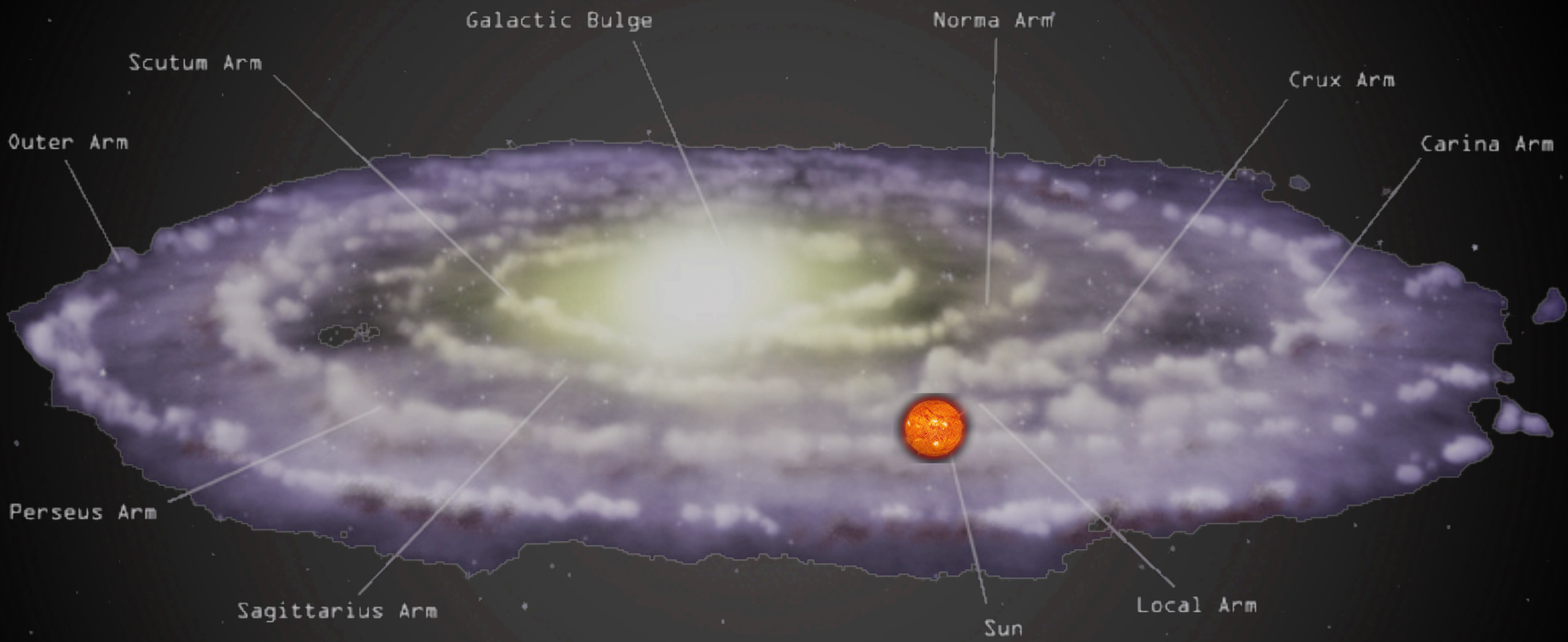
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



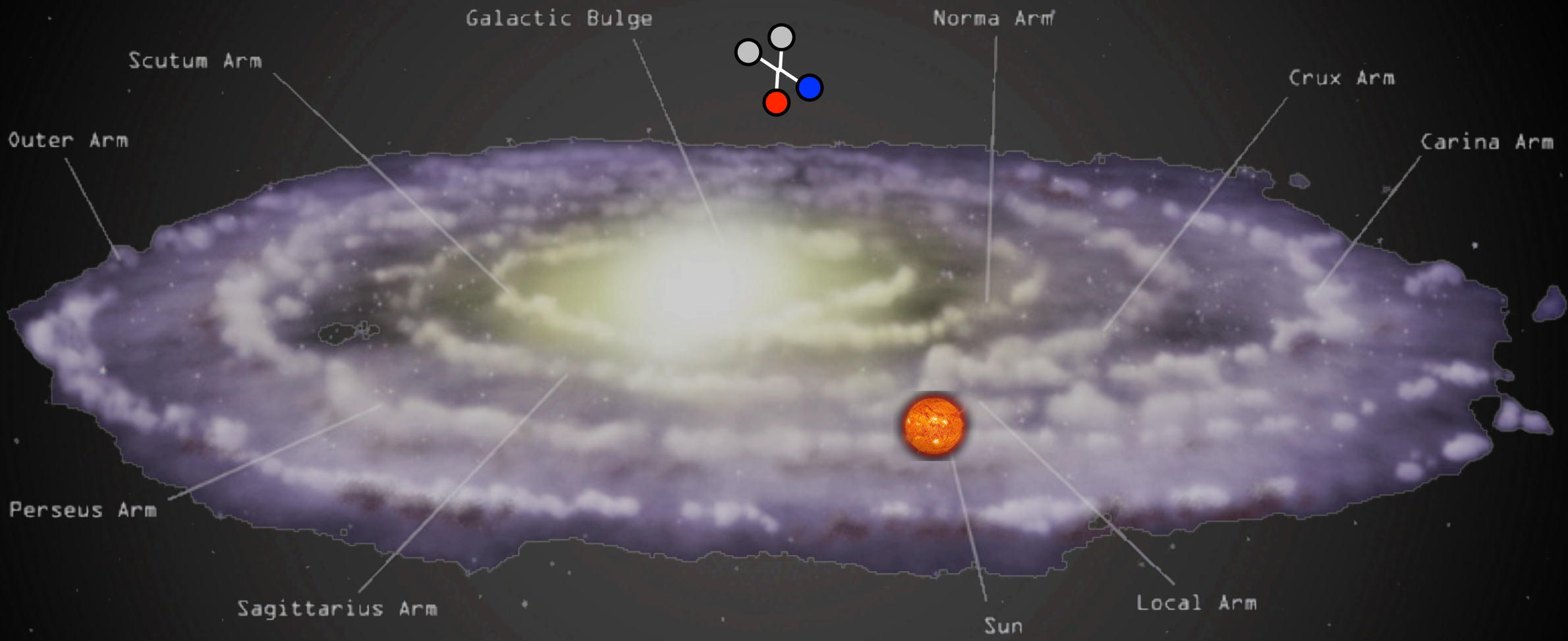
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



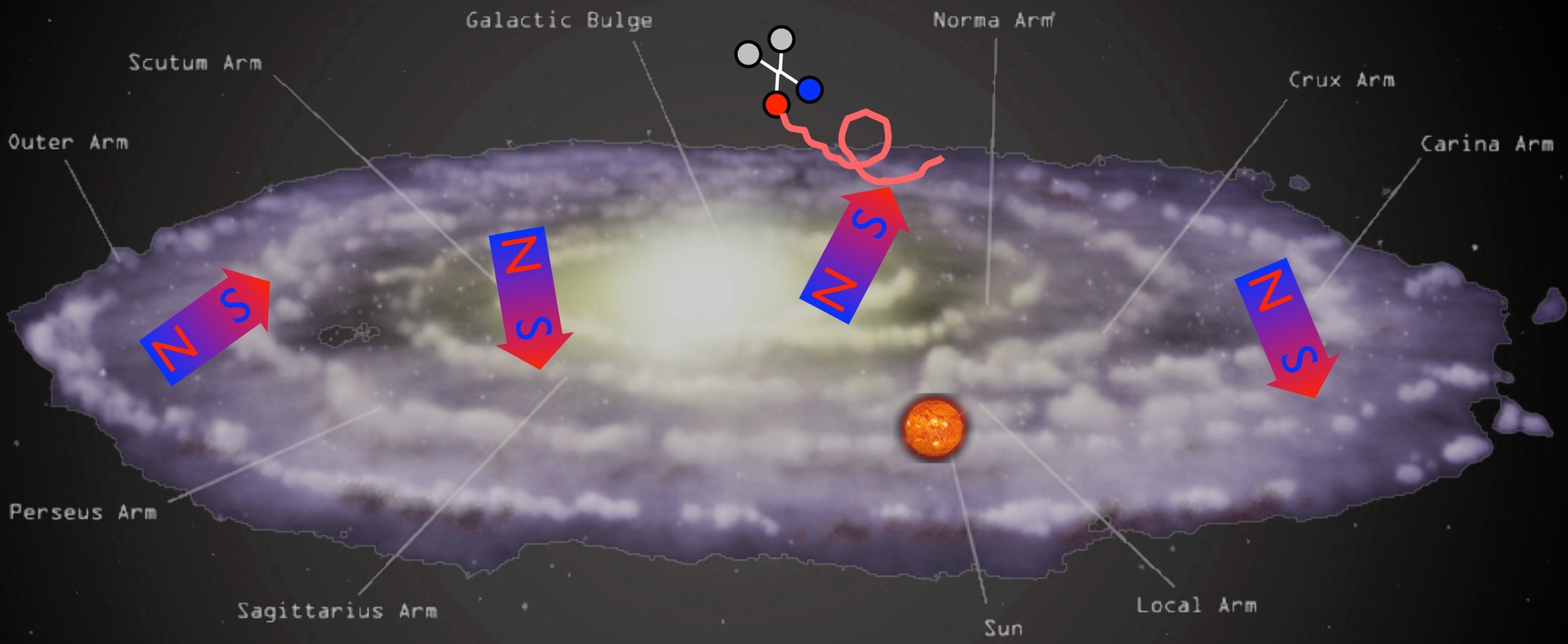
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



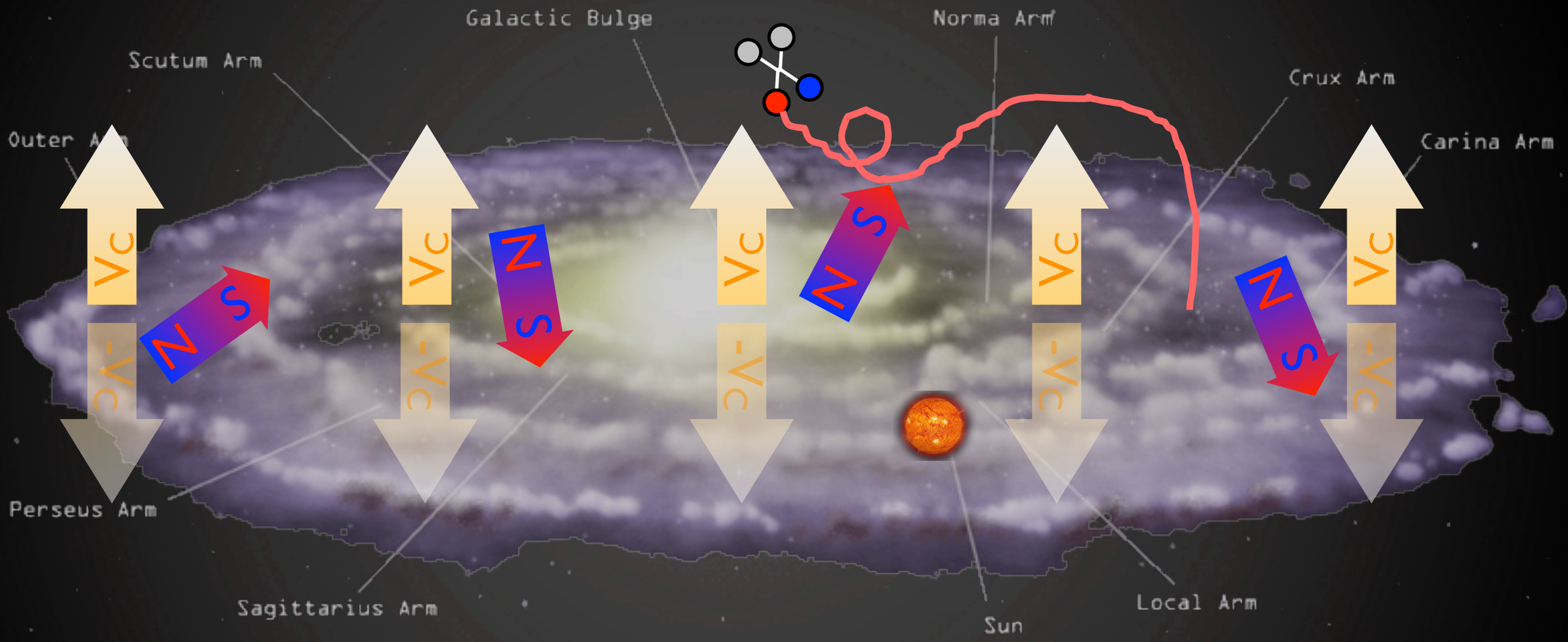
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



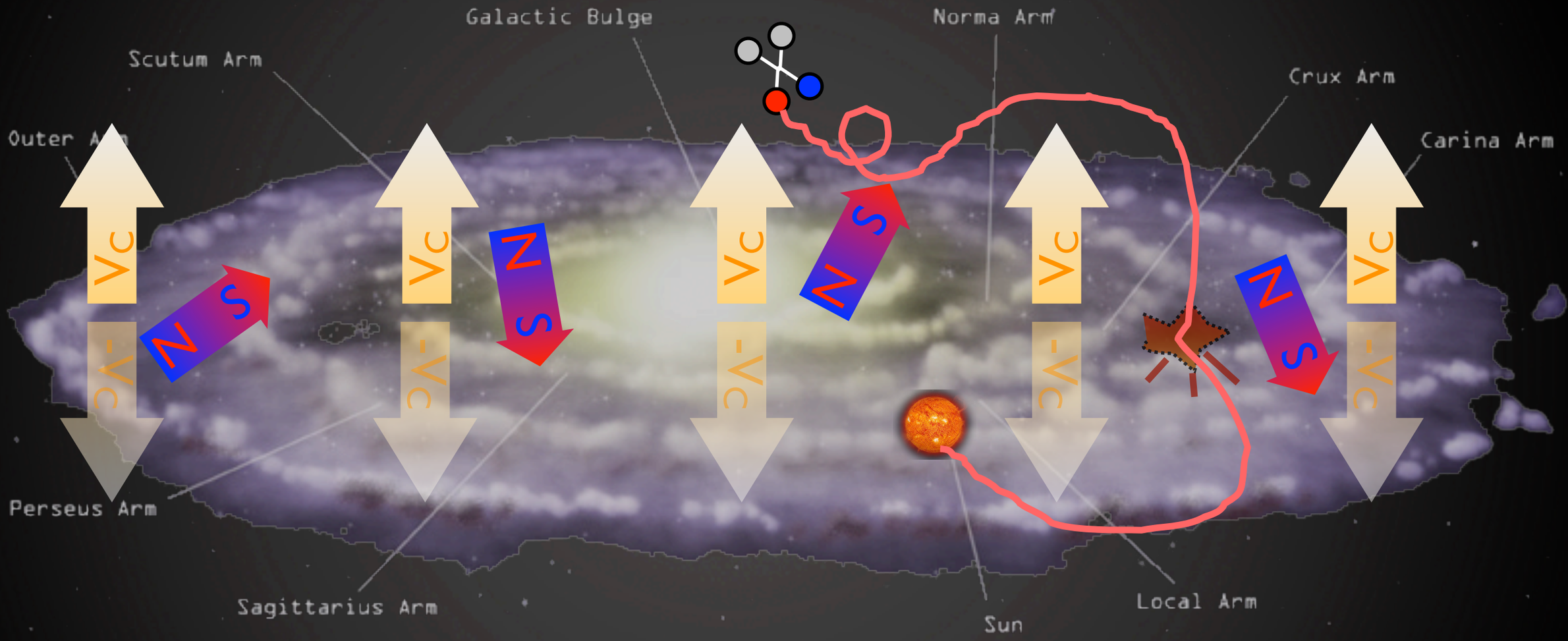
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



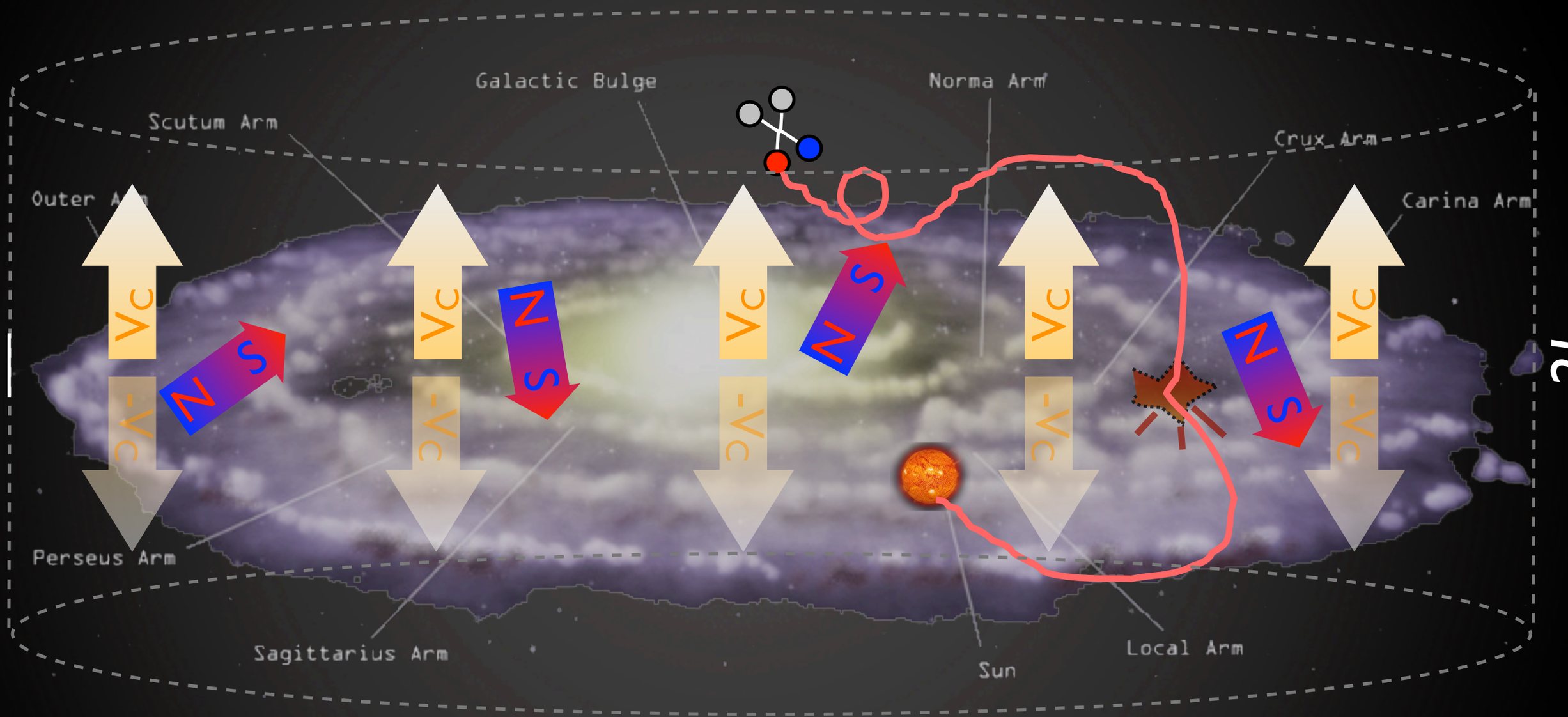
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

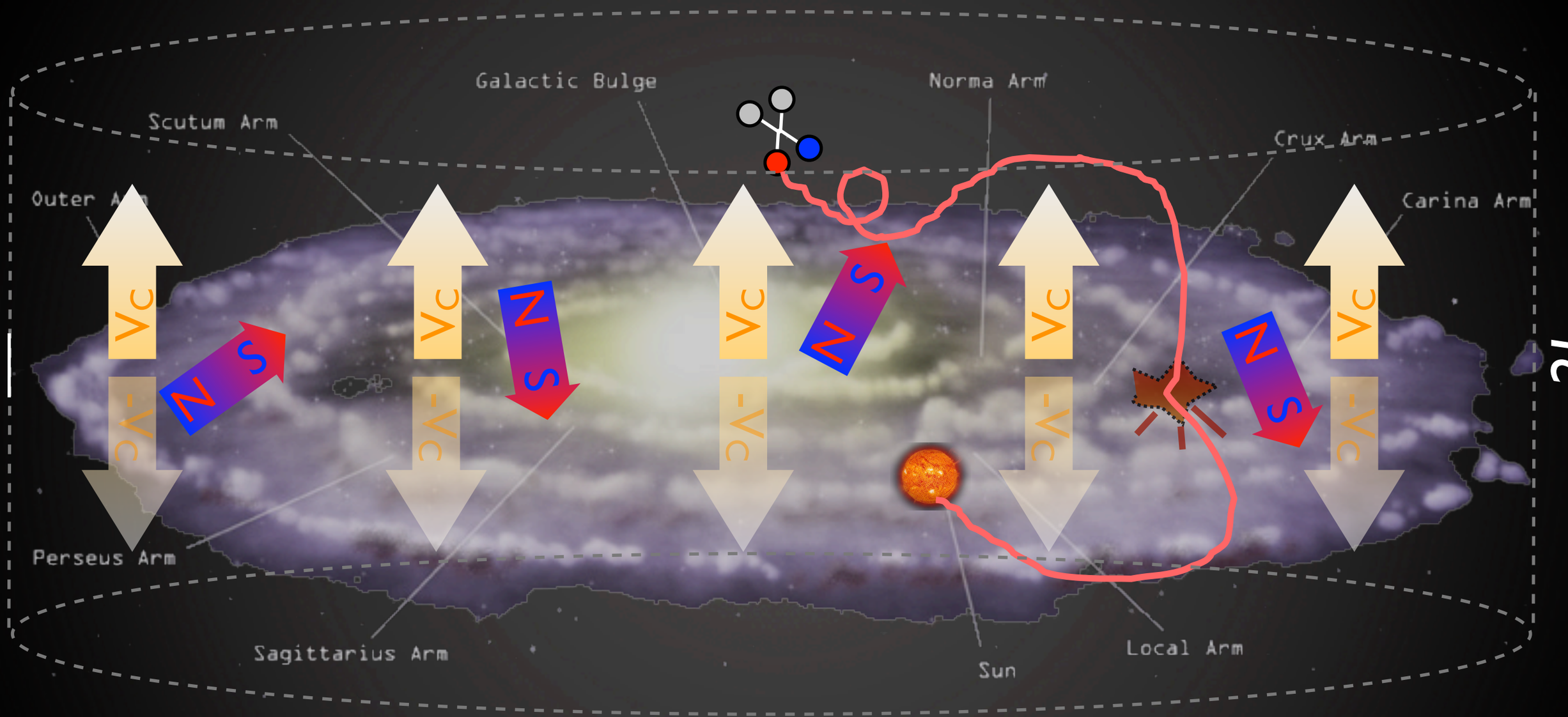
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations

[uncert]

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo

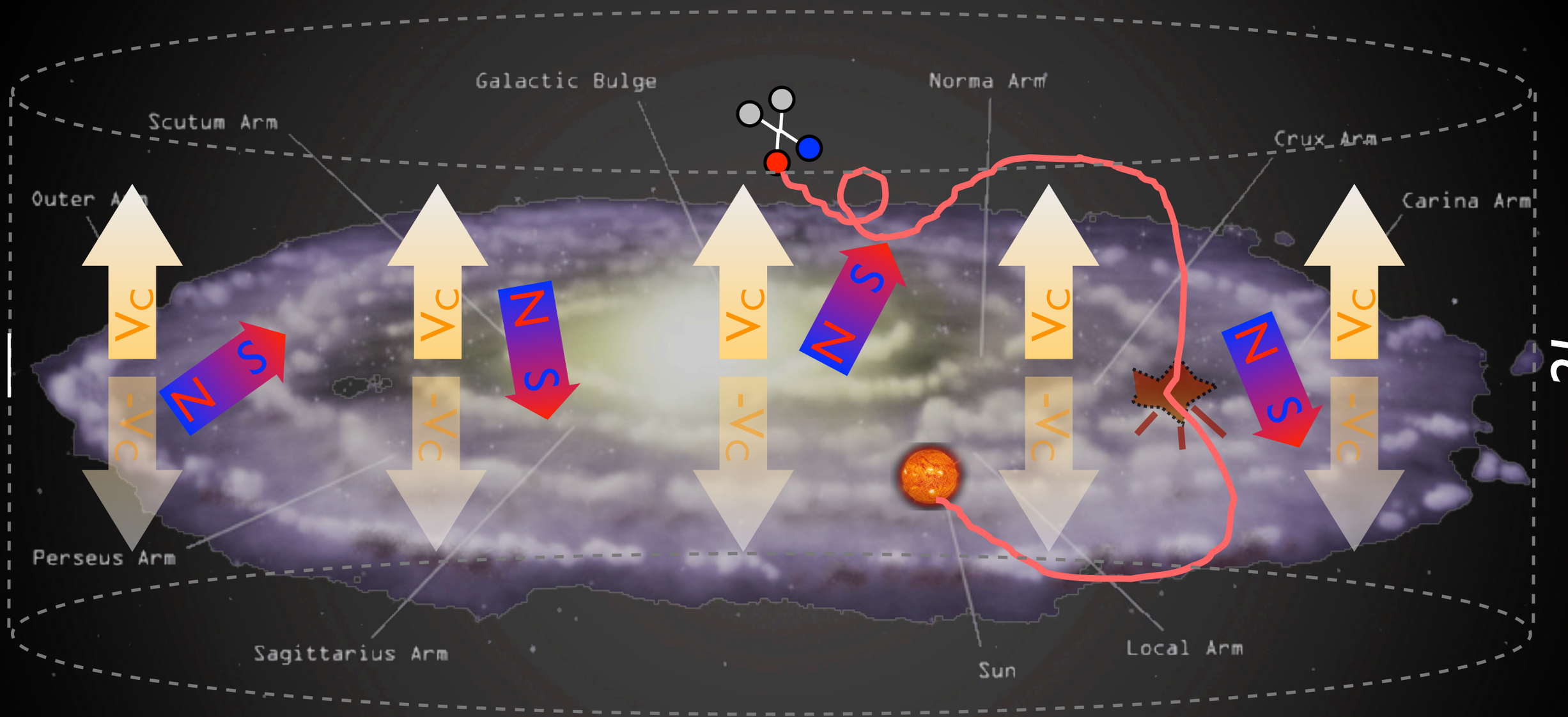


What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo

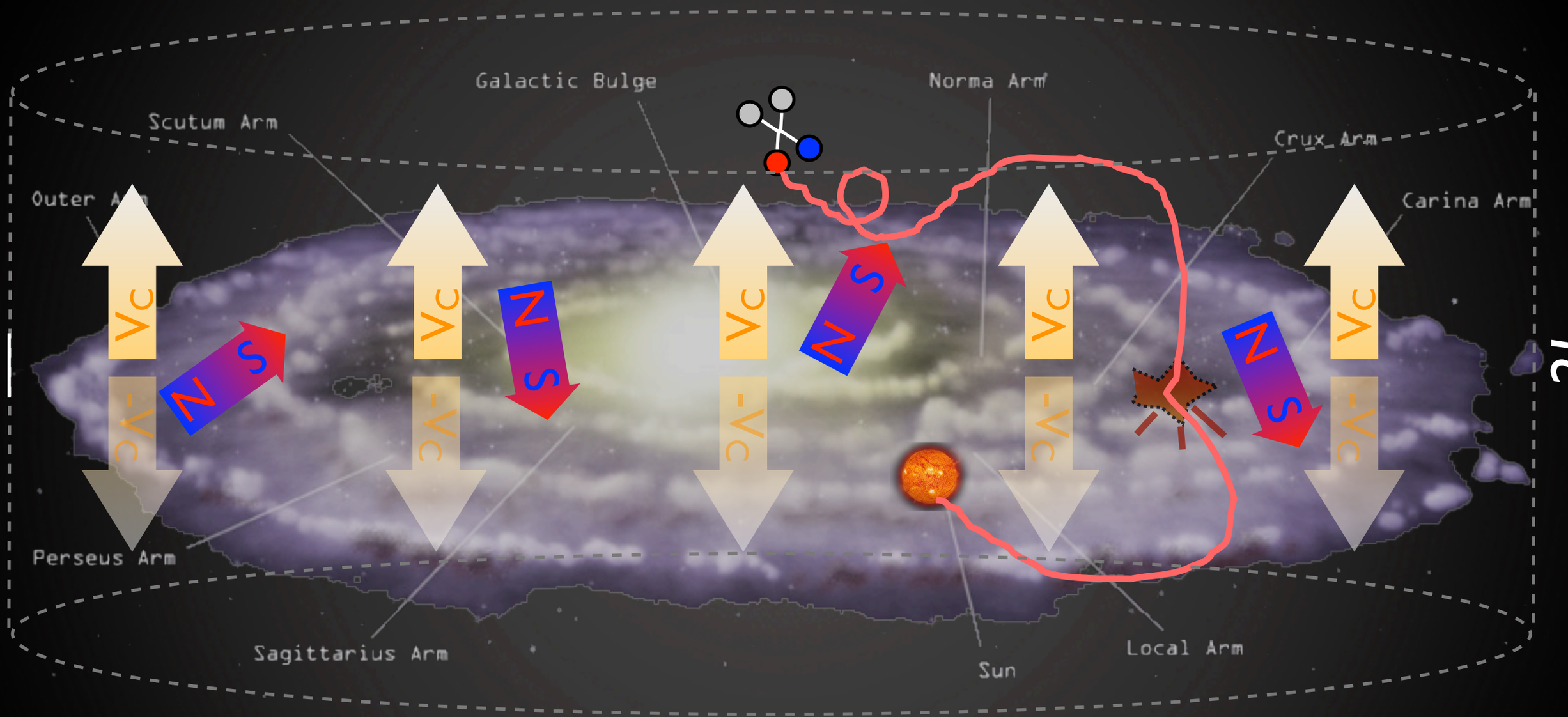


What sets the overall expected flux?

$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



What sets the overall expected flux?

$$\text{flux} \propto \underbrace{n^2}_{\text{astro\&cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

$$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$$

DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

At small r: $\rho(r) \propto 1/r^{\gamma}$

6 profiles:

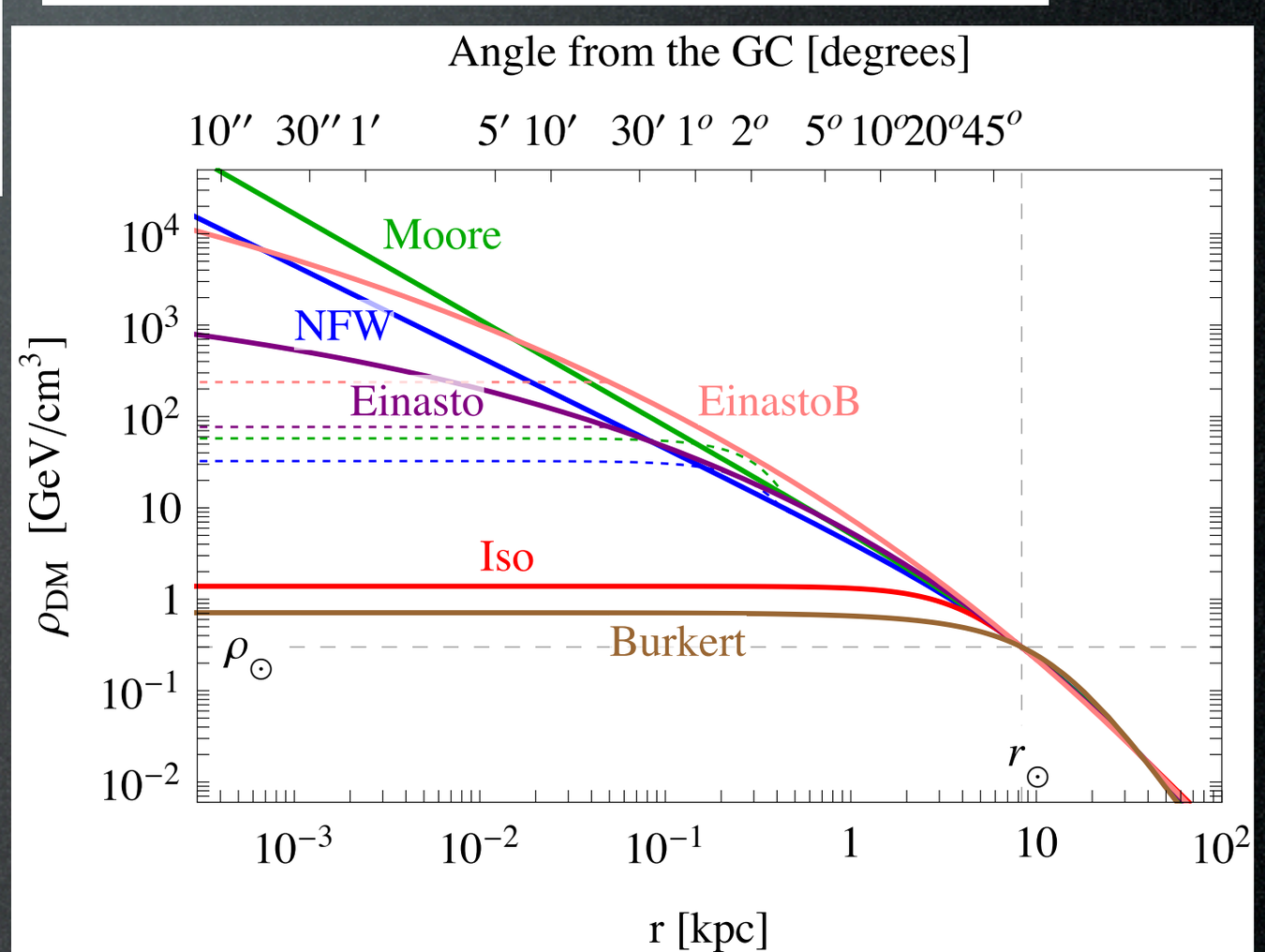
cuspy: **NFW**, **Moore**

mild: **Einasto**

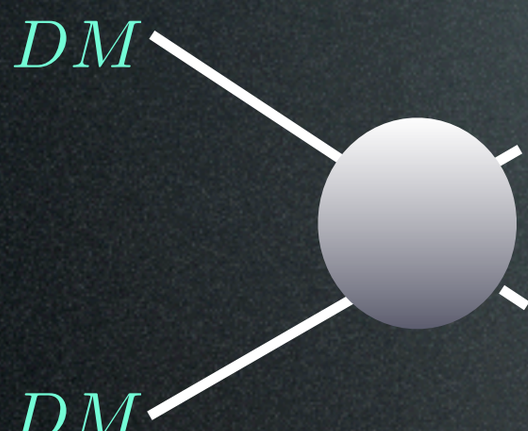
smooth: **isothermal**, **Burkert**

EinastoB = steepened Einasto

(effect of baryons?)



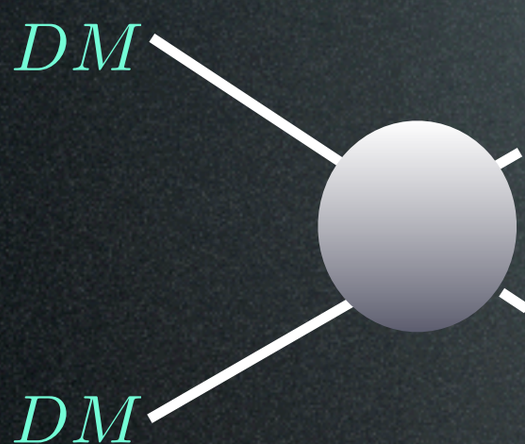
Indirect Detection: basics



$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

Indirect Detection: basics

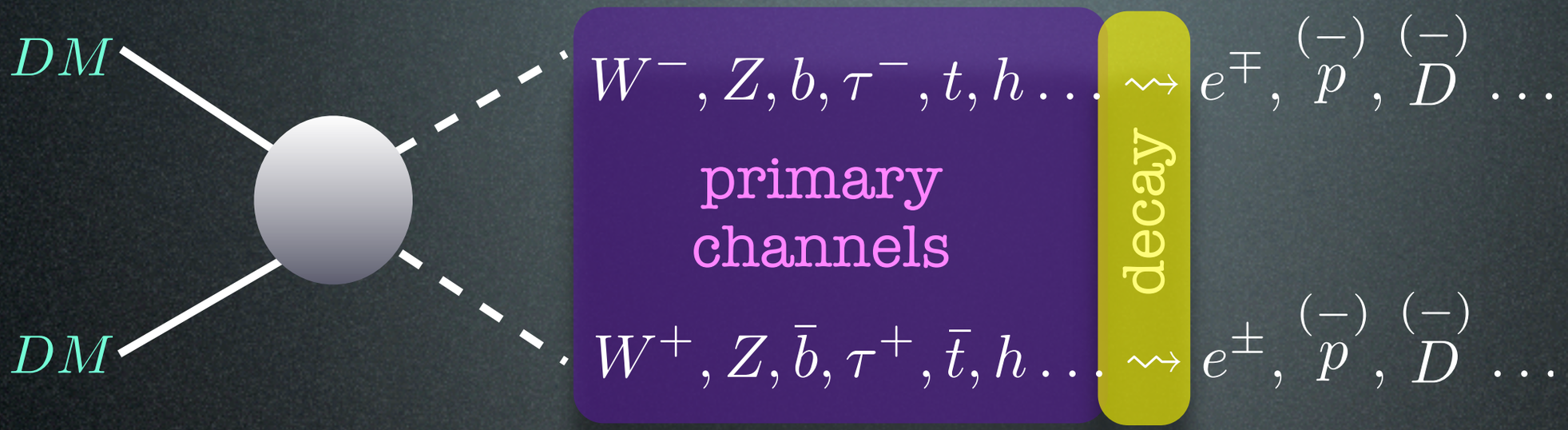


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

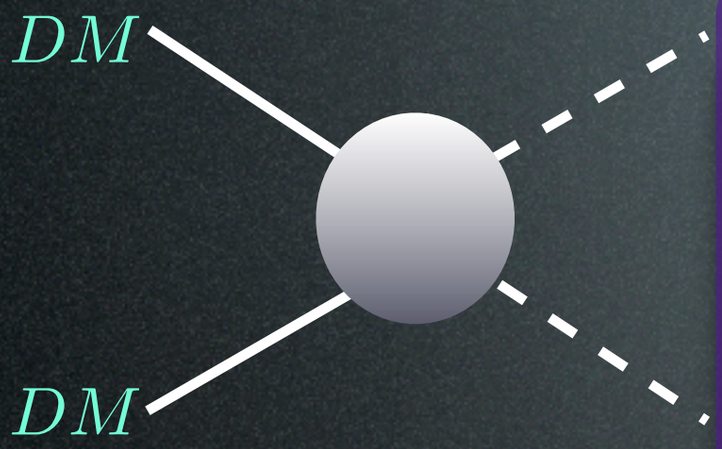
primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

Indirect Detection: basics



Indirect Detection: basics



$W^-, Z, b, \tau^-, t, h \ldots$

primary channels

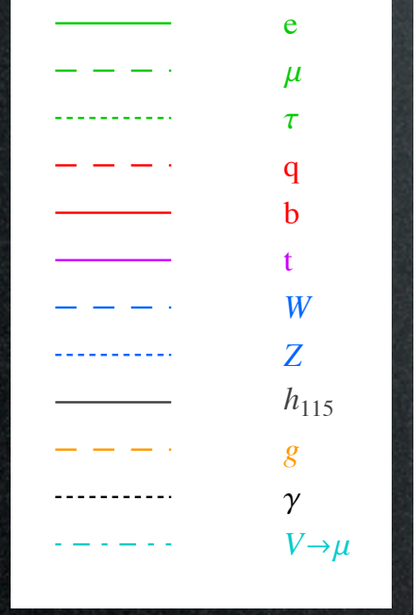
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

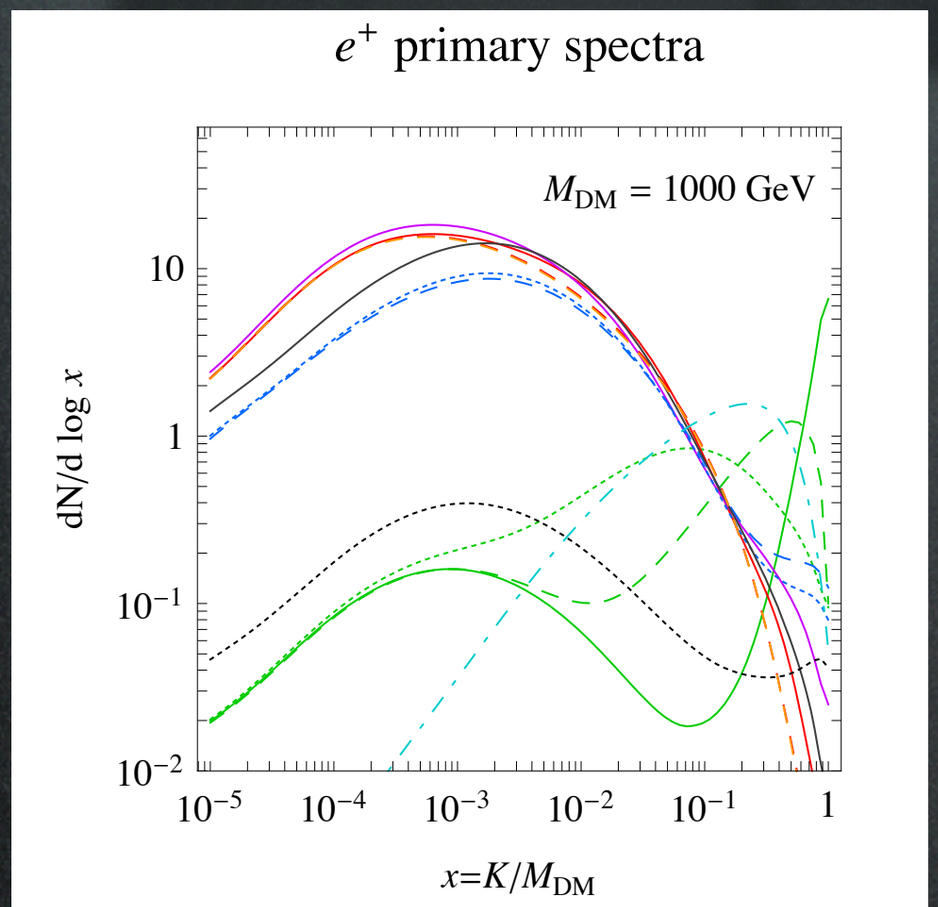
decay

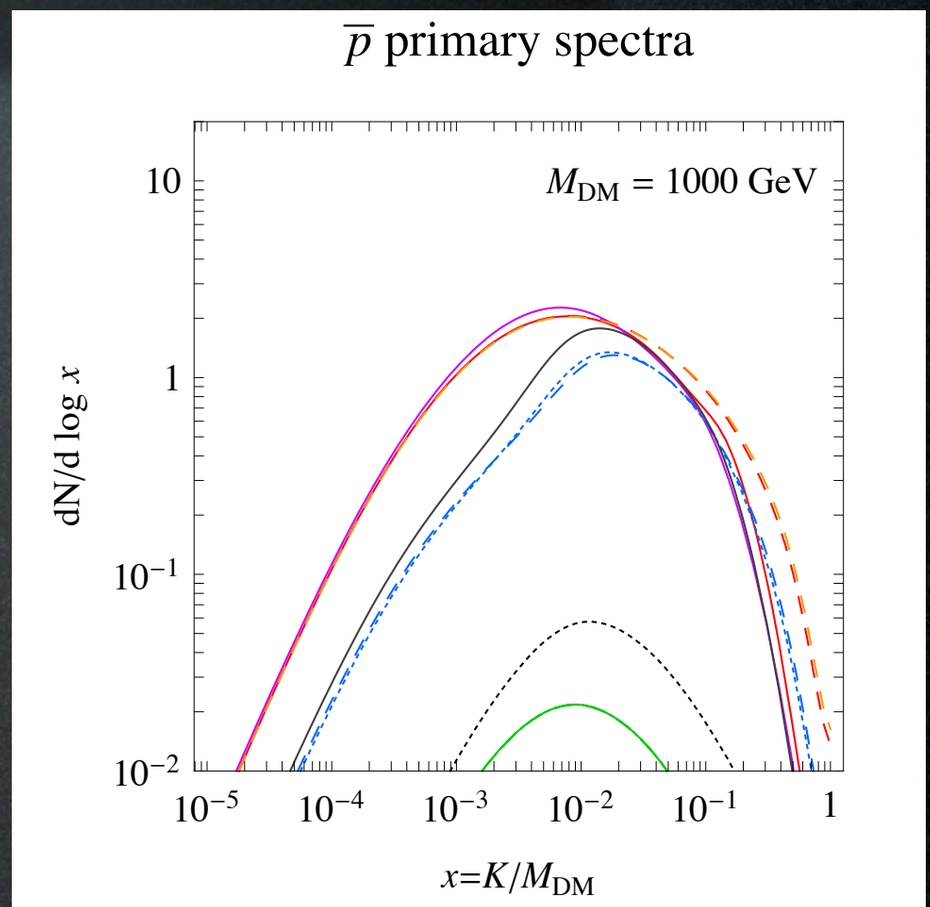
$e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

final products

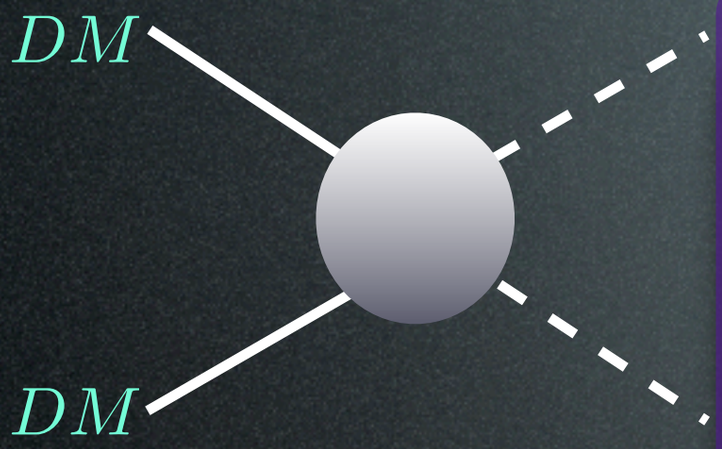
$e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$







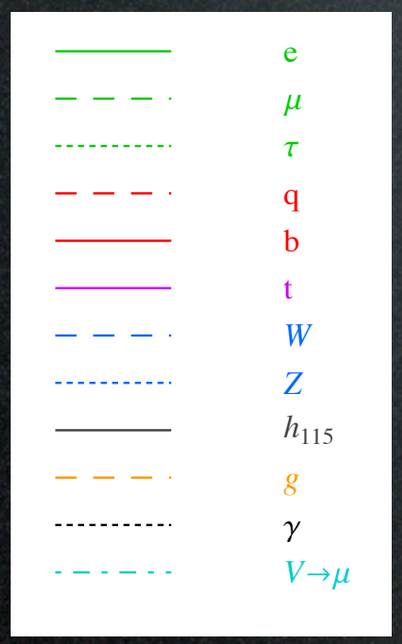
Indirect Detection: basics

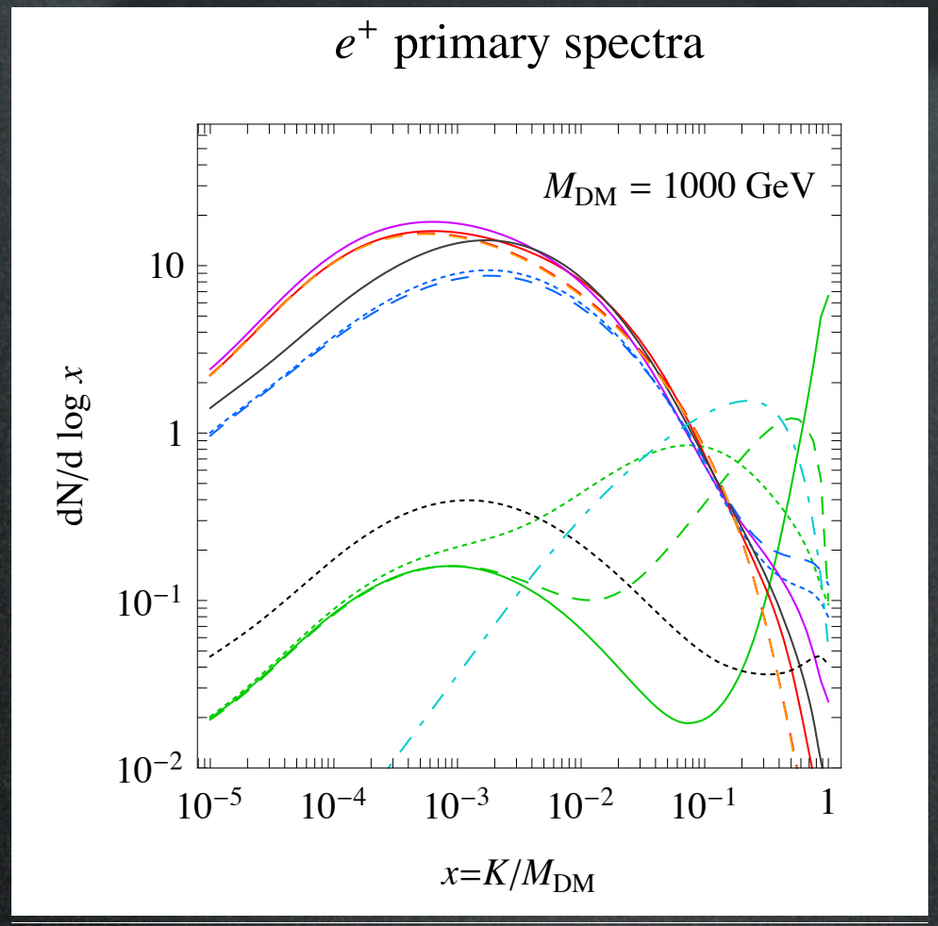


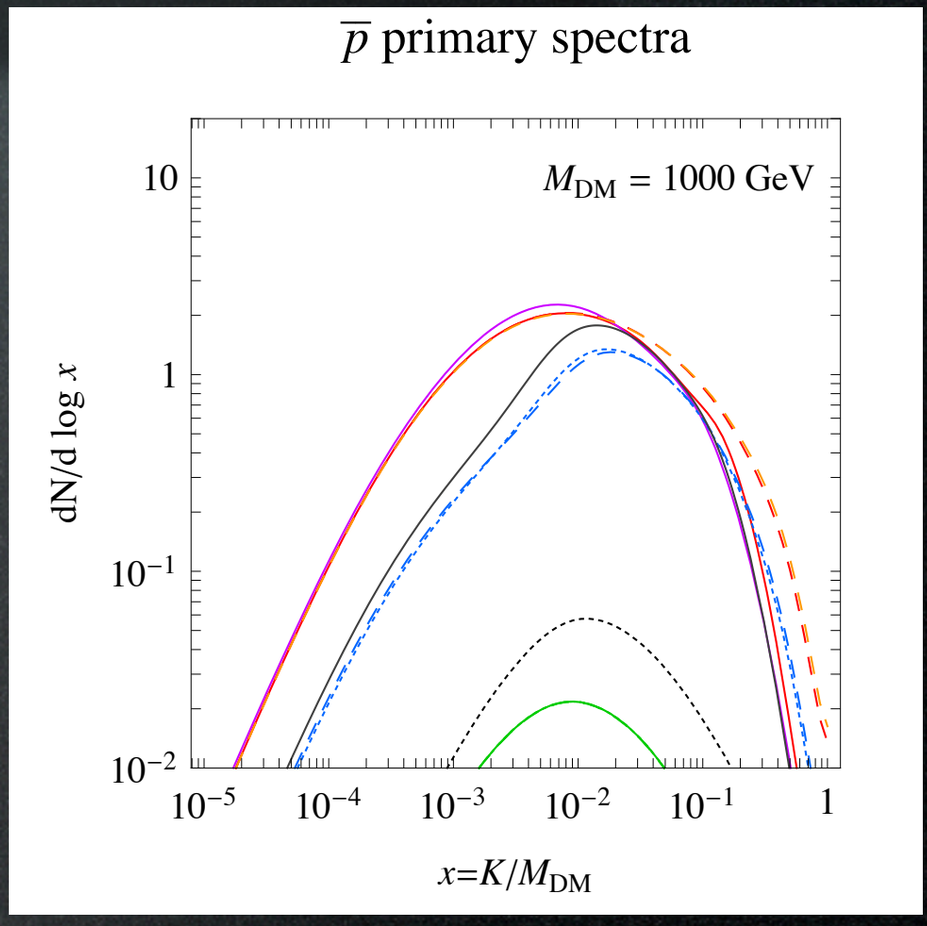
$W^-, Z, b, \tau^-, t, h \ldots$ — primary channels — $W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

decay

$e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ — final products — $e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$





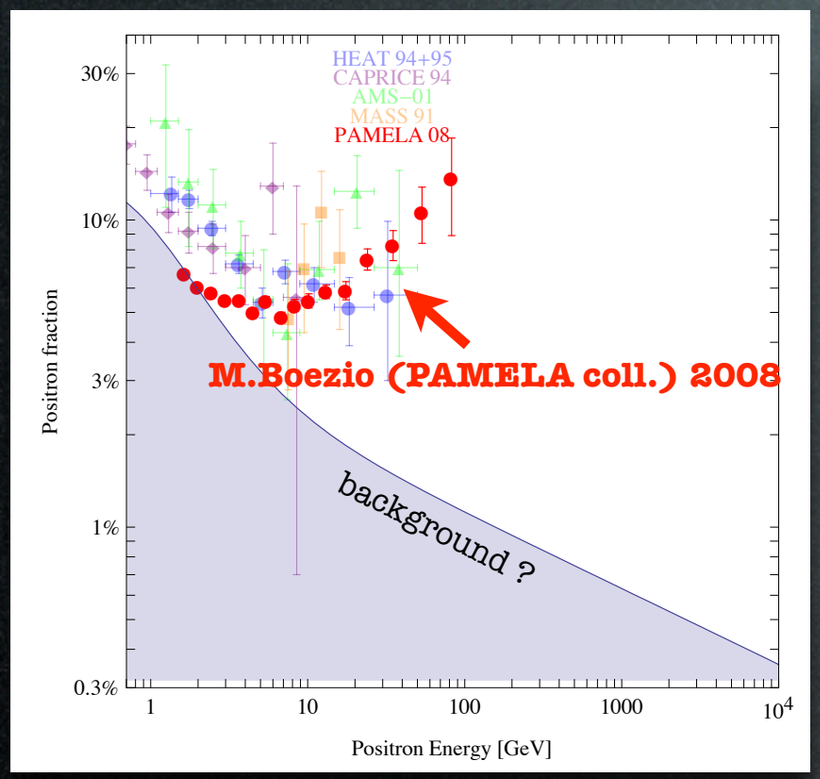


So what are the particle physics parameters?

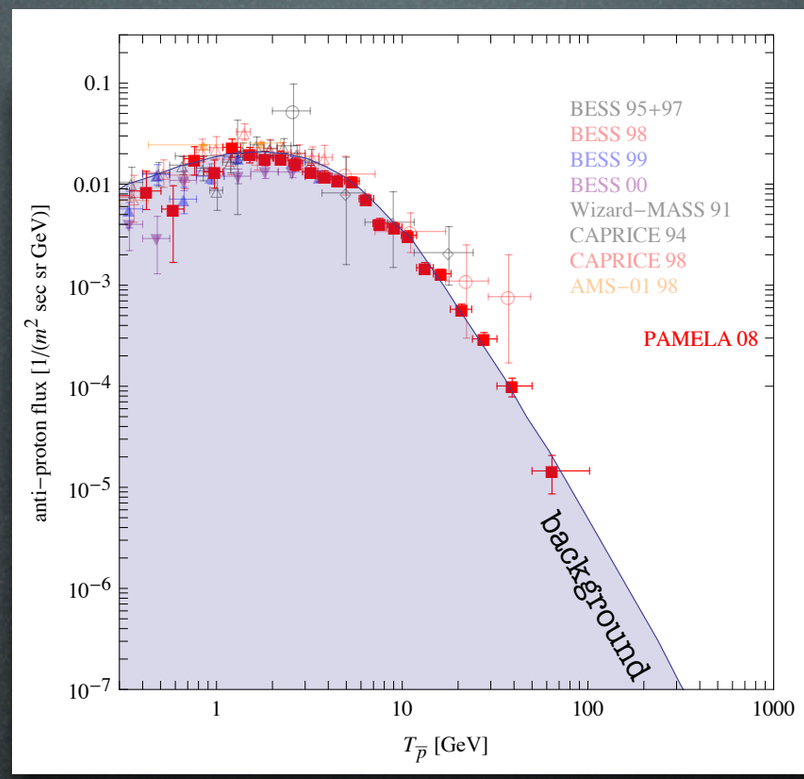
1. Dark Matter mass
2. primary channel(s)

Indirect Detection: **hints**

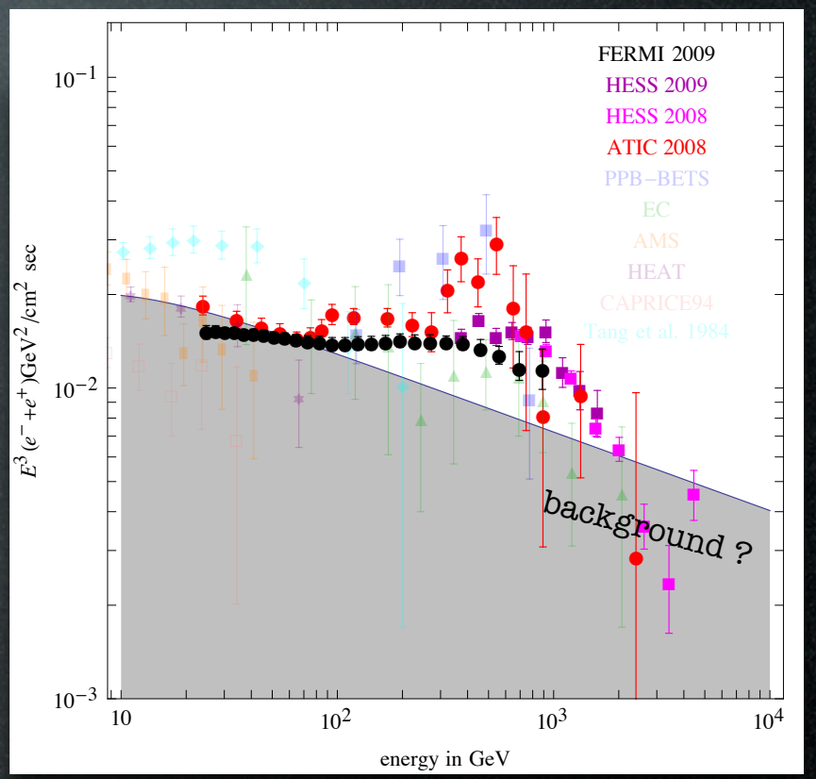
positron fraction



antiprotons



electrons + positrons



Indirect Detection: hints

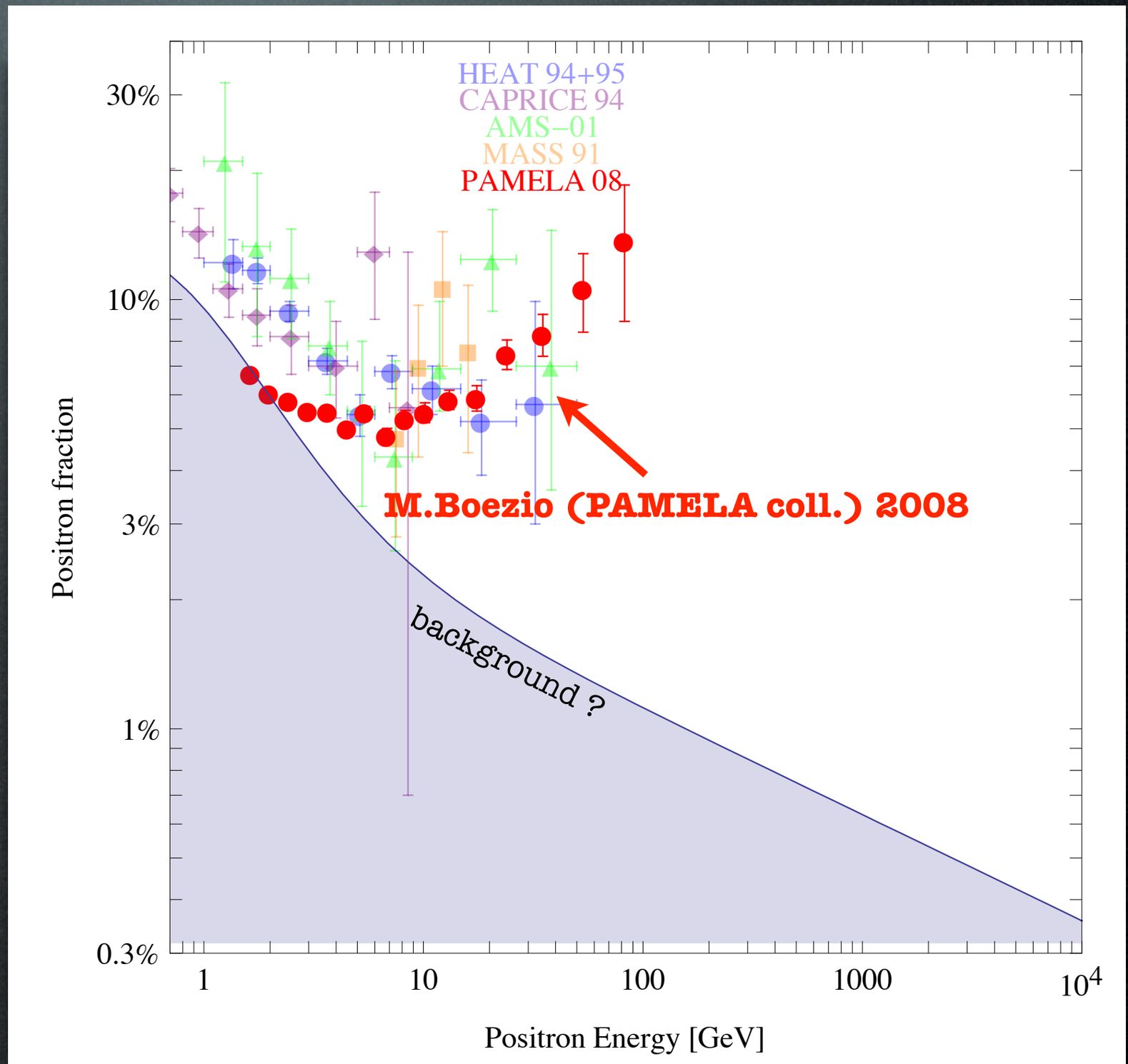
Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\dfrac{e^+}{e^+ + e^-}$

(9430 e^+ initially collected)

(errors statistical only in this plot, that's why larger at high energy)



Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

[backgnd]

Indirect Detection: hints

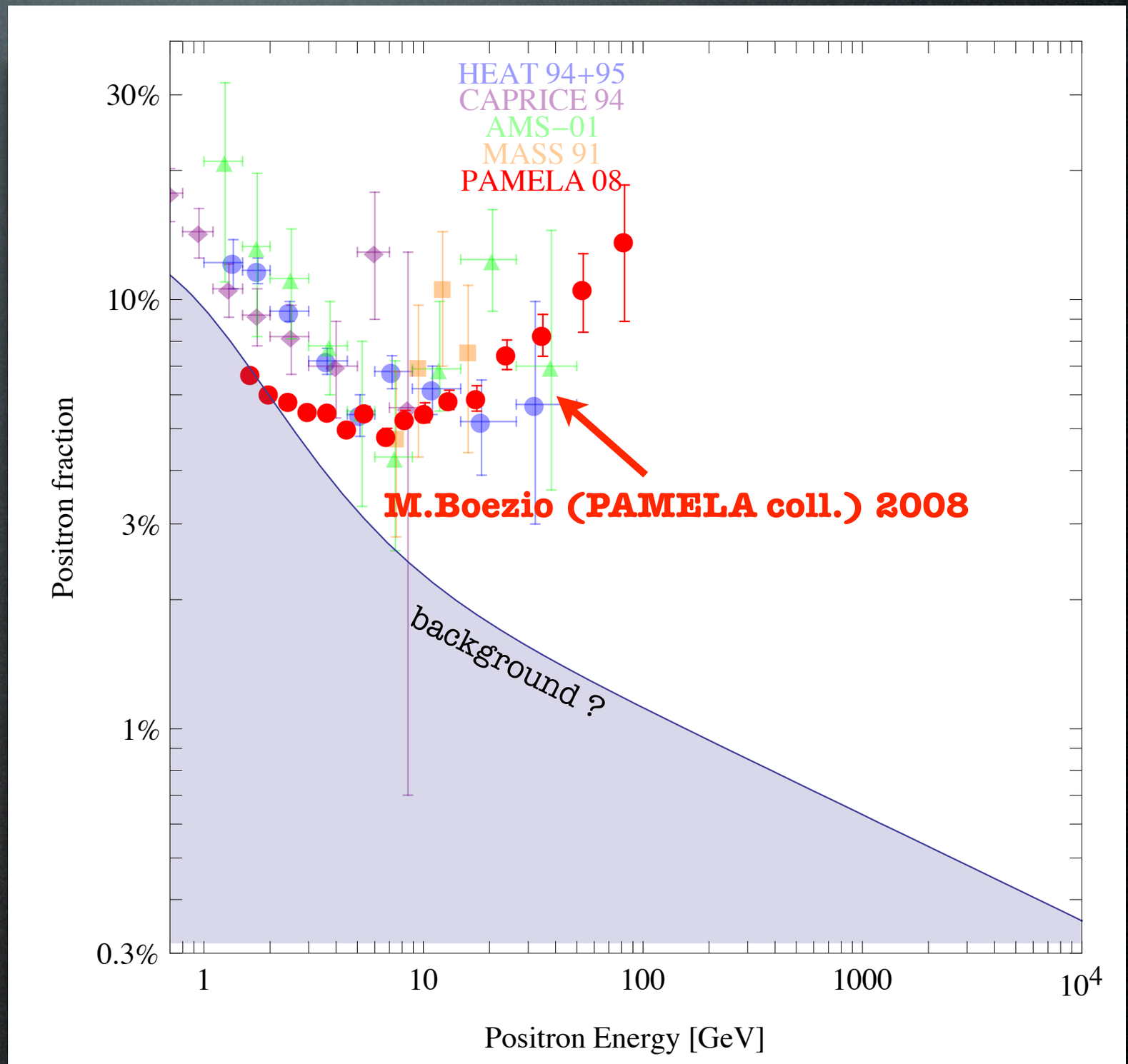
Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\dfrac{e^+}{e^+ + e^-}$

(9430 e^+ initially collected)

(errors statistical only in this plot, that's why larger at high energy)



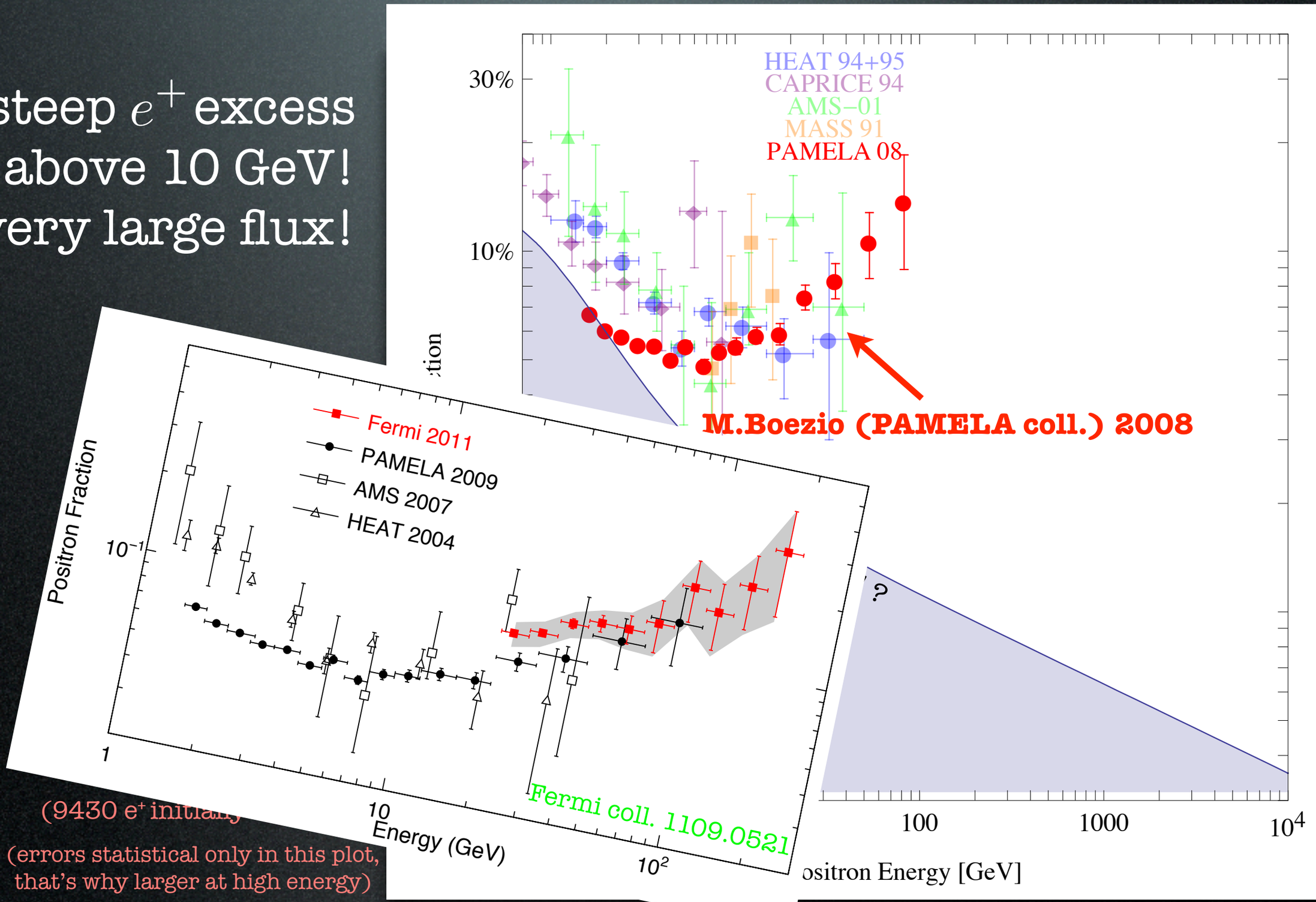
Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

[FERMI method]

Indirect Detection: hints

Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!



(9430 e^+ initial

(errors statistical only in this plot, that's why larger at high energy)

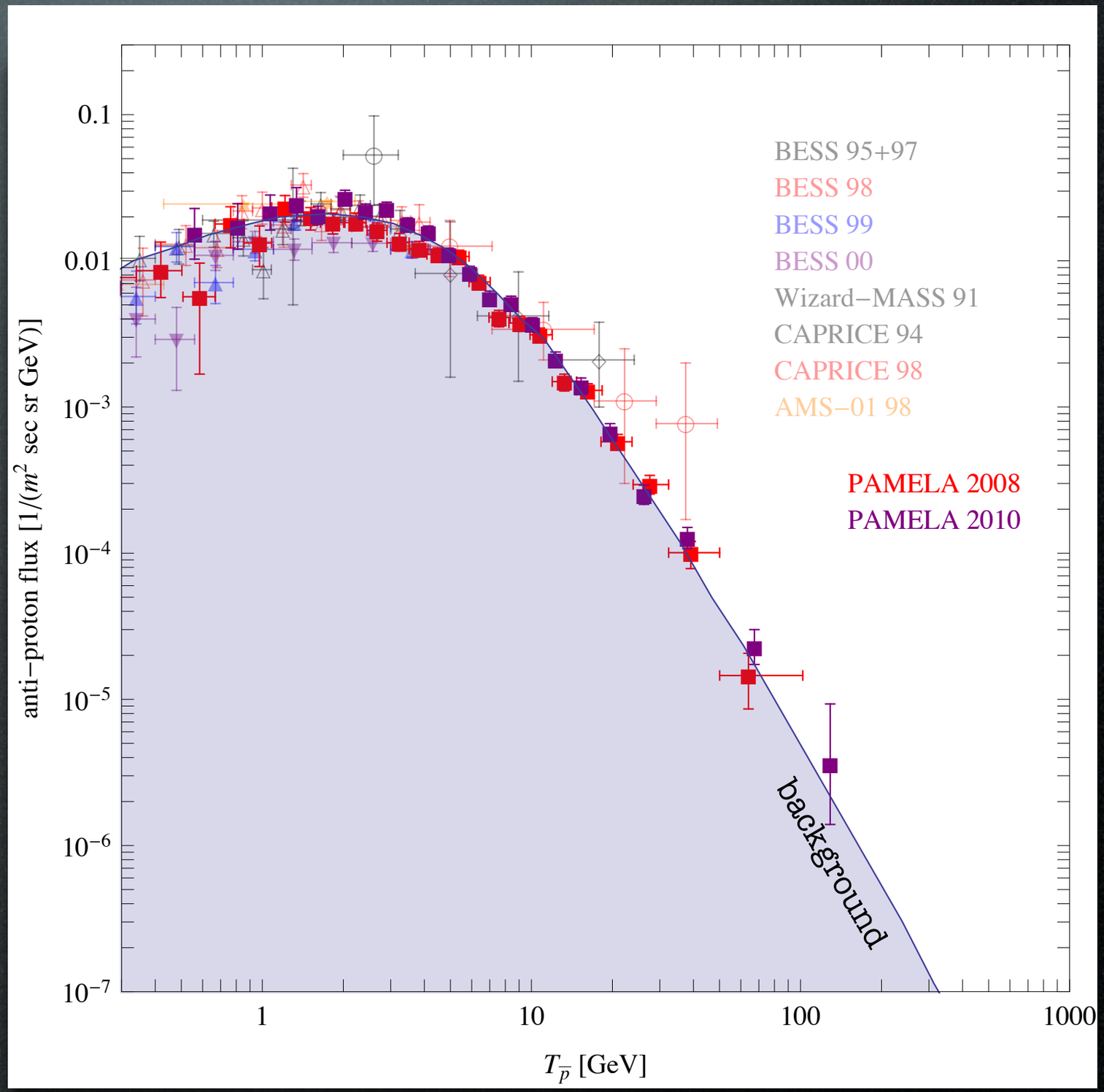
Adriani et al., Nature 458 (2 07; ApP 34 (2010) 1

[FERMI method]

Indirect Detection: hints

Antiprotons from PAMELA:

- consistent with the background



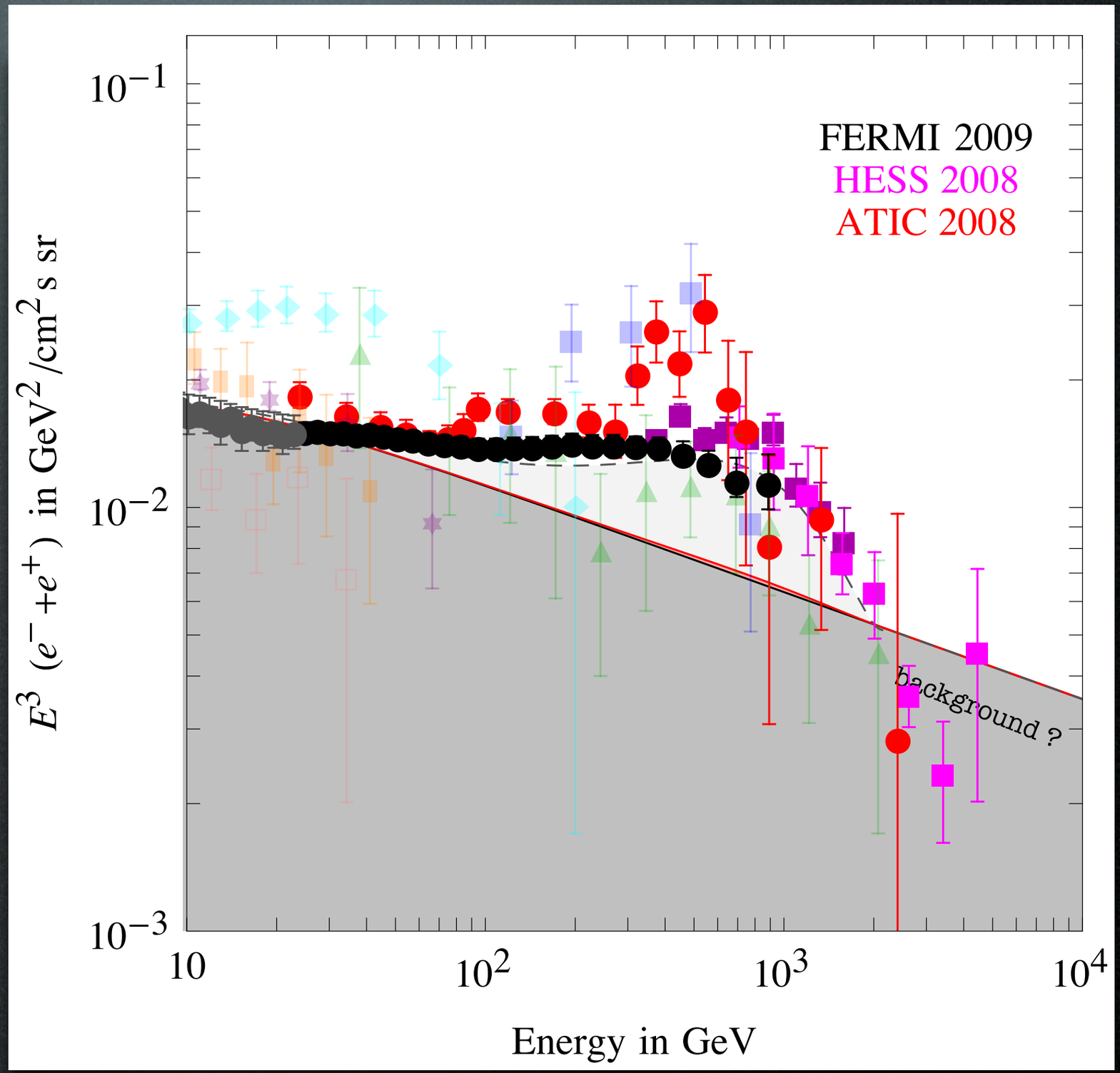
(about 1000 $\bar{p}$ collected initially)

Adriani et al., PRL 105 (2010) 121101, 1007.0821

Indirect Detection: hints

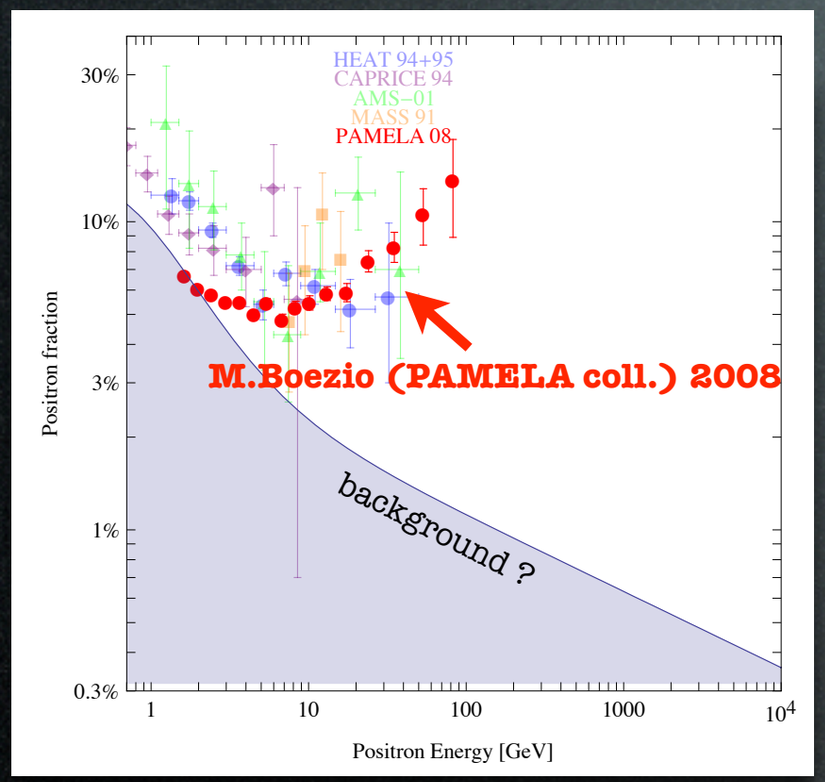
Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?

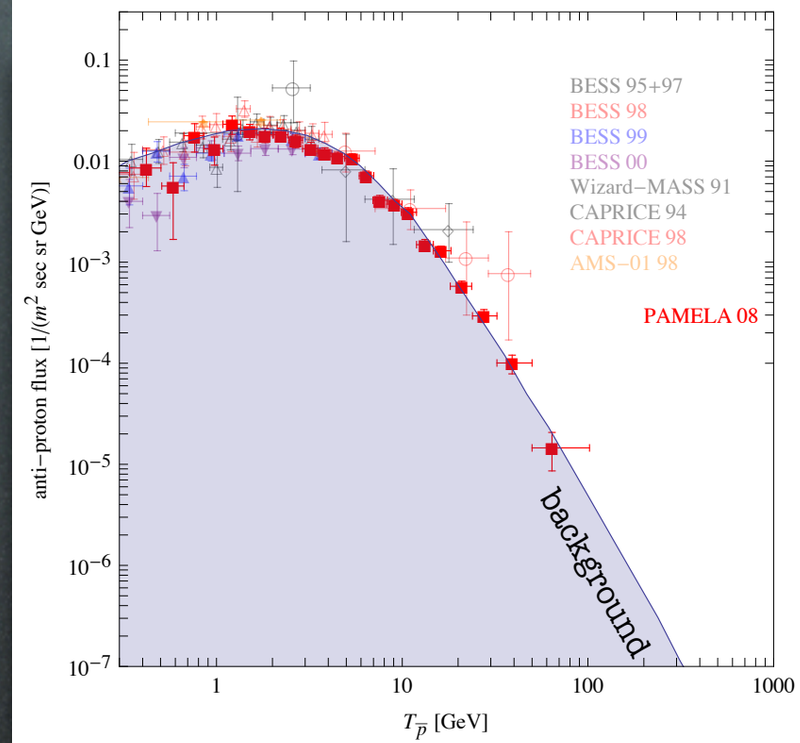


Indirect Detection: hints

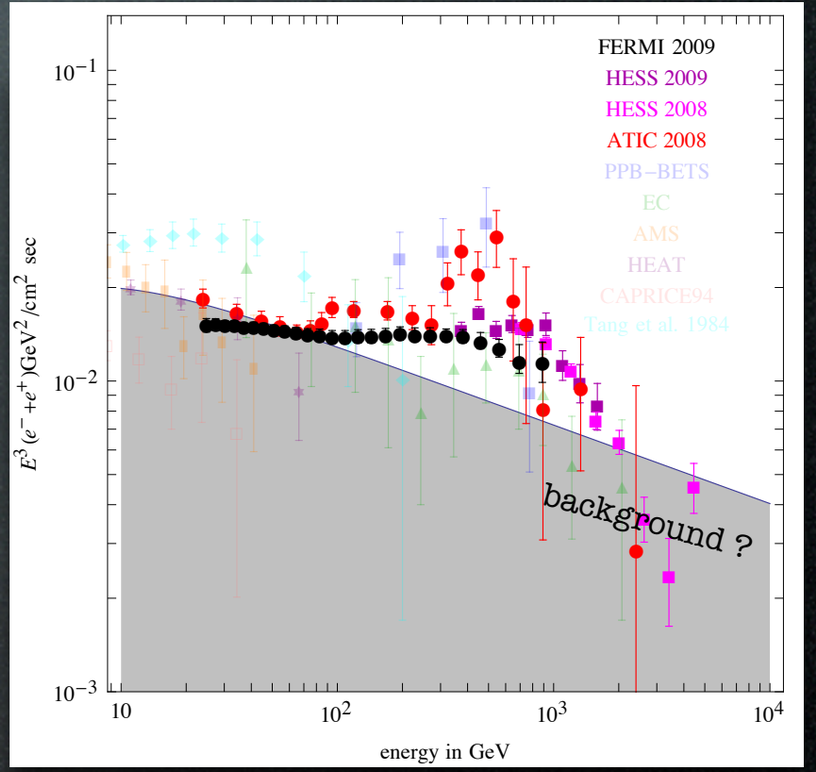
positron fraction



antiprotons



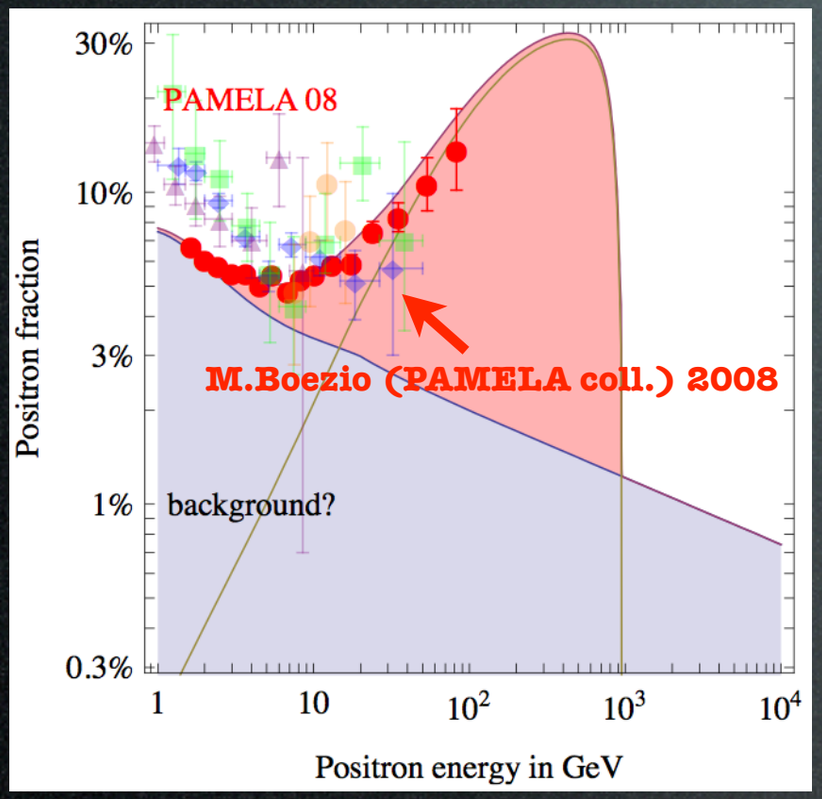
electrons + positrons



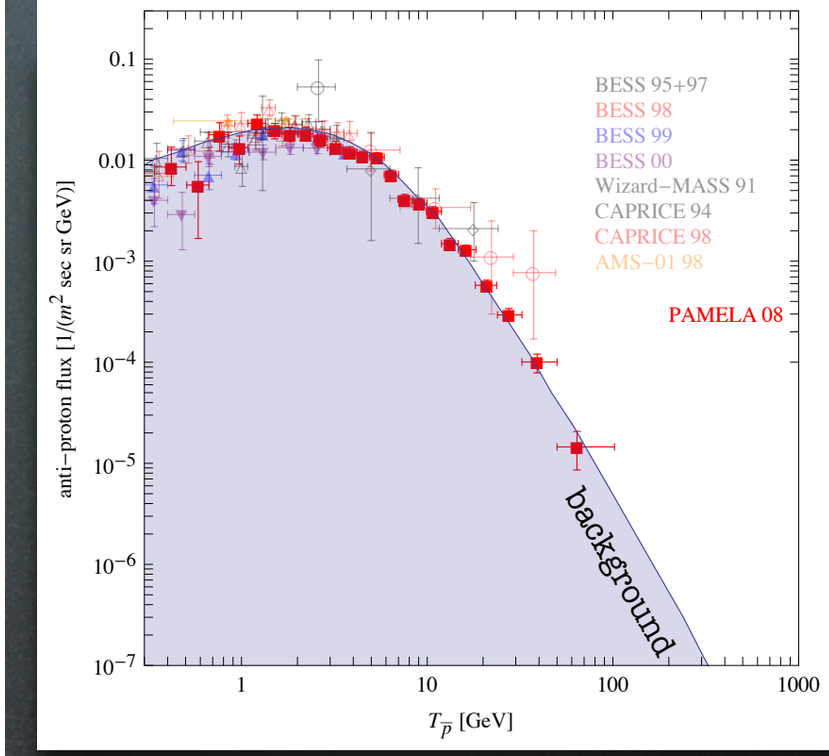
Are these signals of Dark Matter?

Indirect Detection: hints

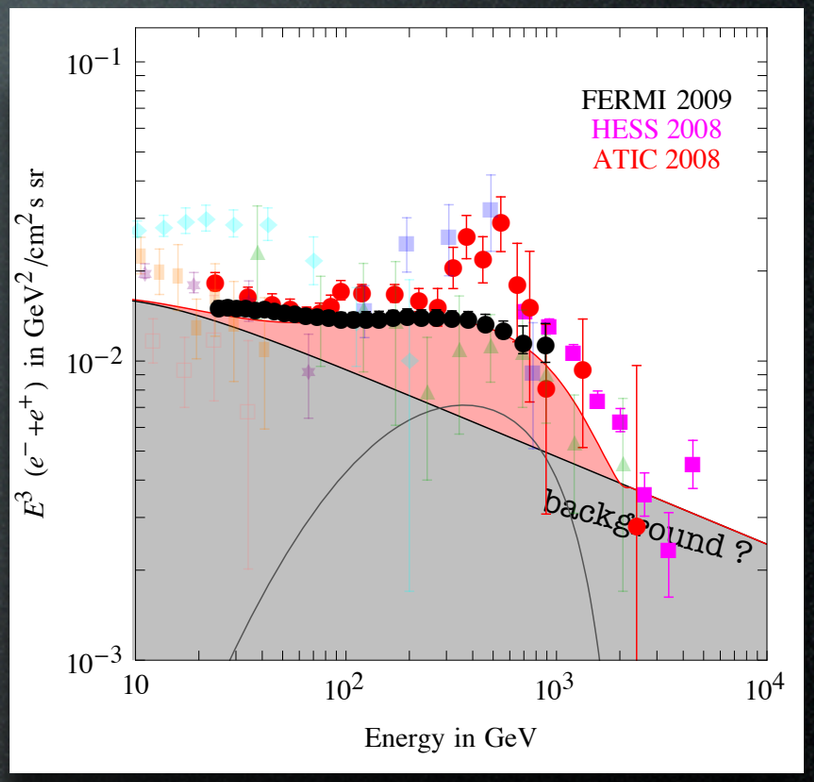
positron fraction



antiprotons



electrons + positrons

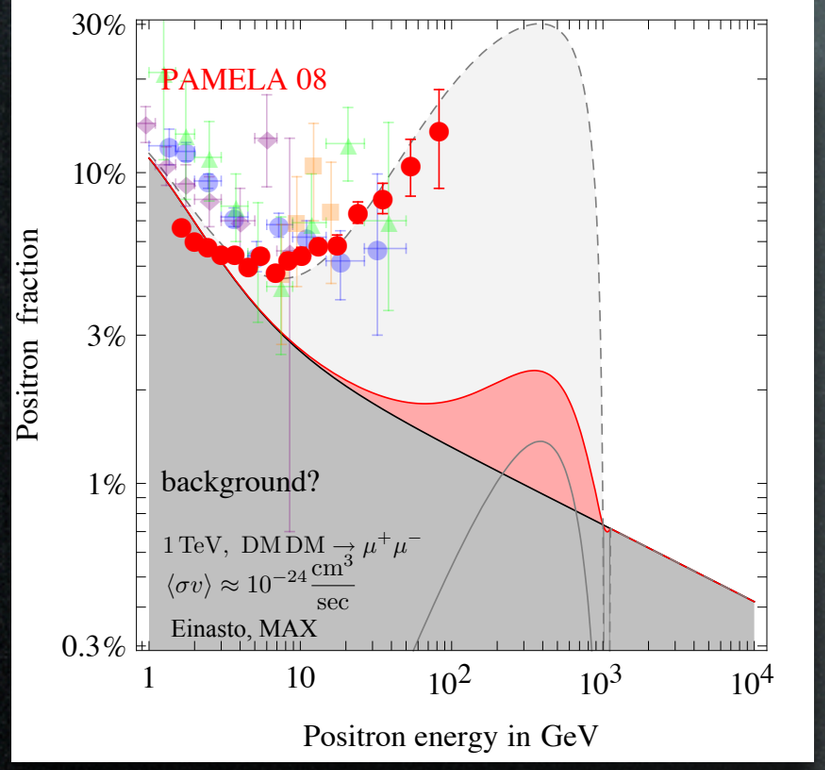


Are these signals of Dark Matter?

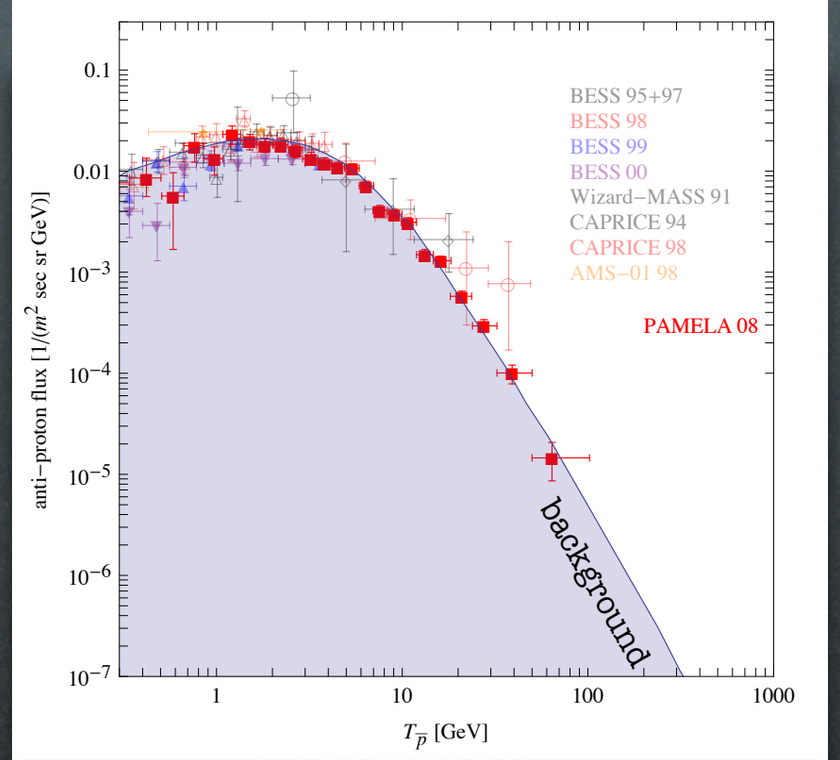
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Indirect Detection: hints

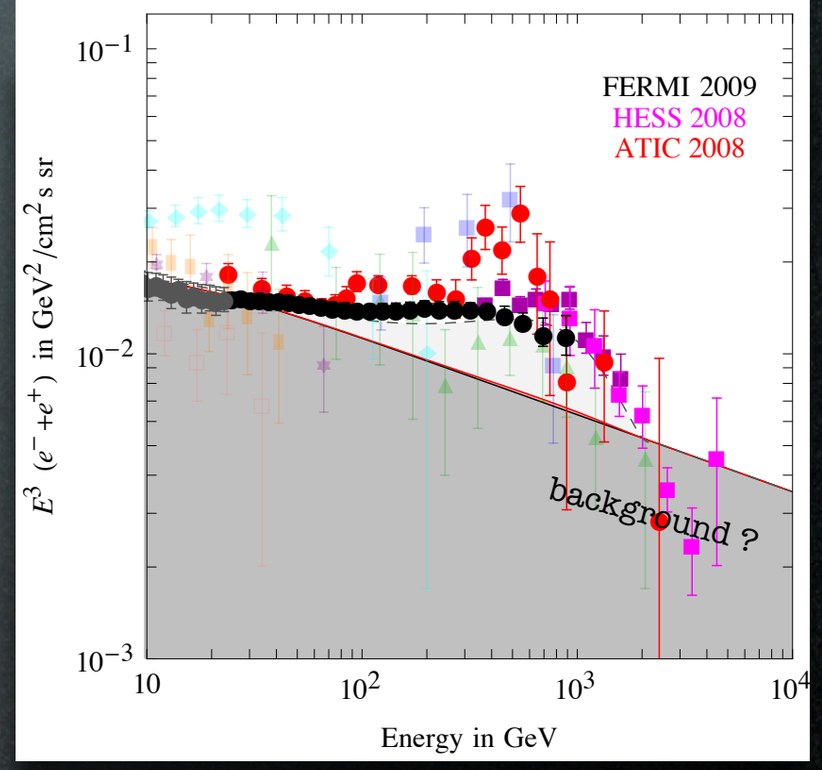
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\text{cm}^3/\text{sec}$

NO: a formidable 'background' for future searches

Indirect Detection: **constraints**

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

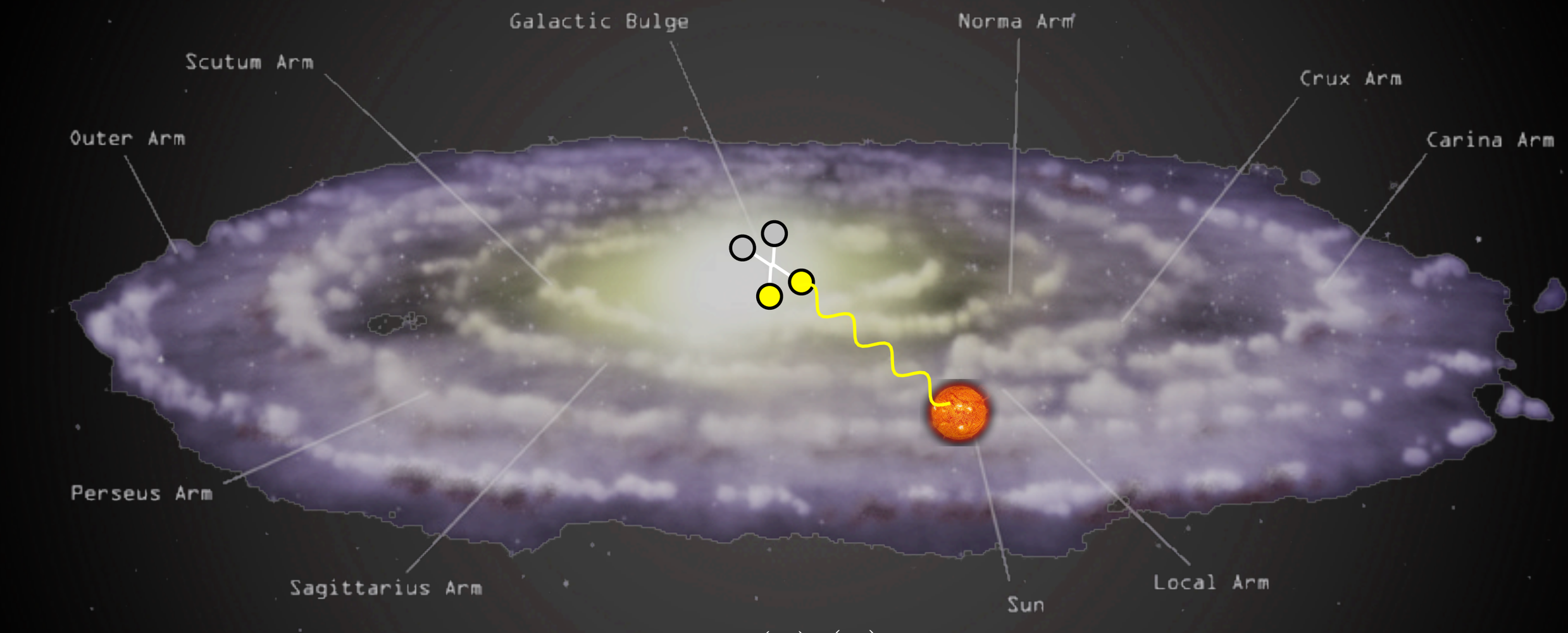
$\bar{p}$ from annihil in galactic halo or center

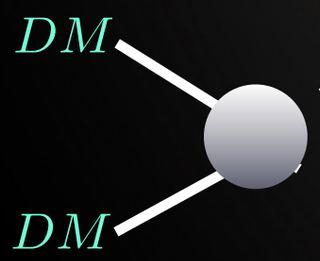
$\bar{d}$ from annihil in galactic halo or center

$\nu, \bar{\nu}$ from annihil in massive bodies

Indirect Detection: constraints

γ from DM annihilations in galactic center



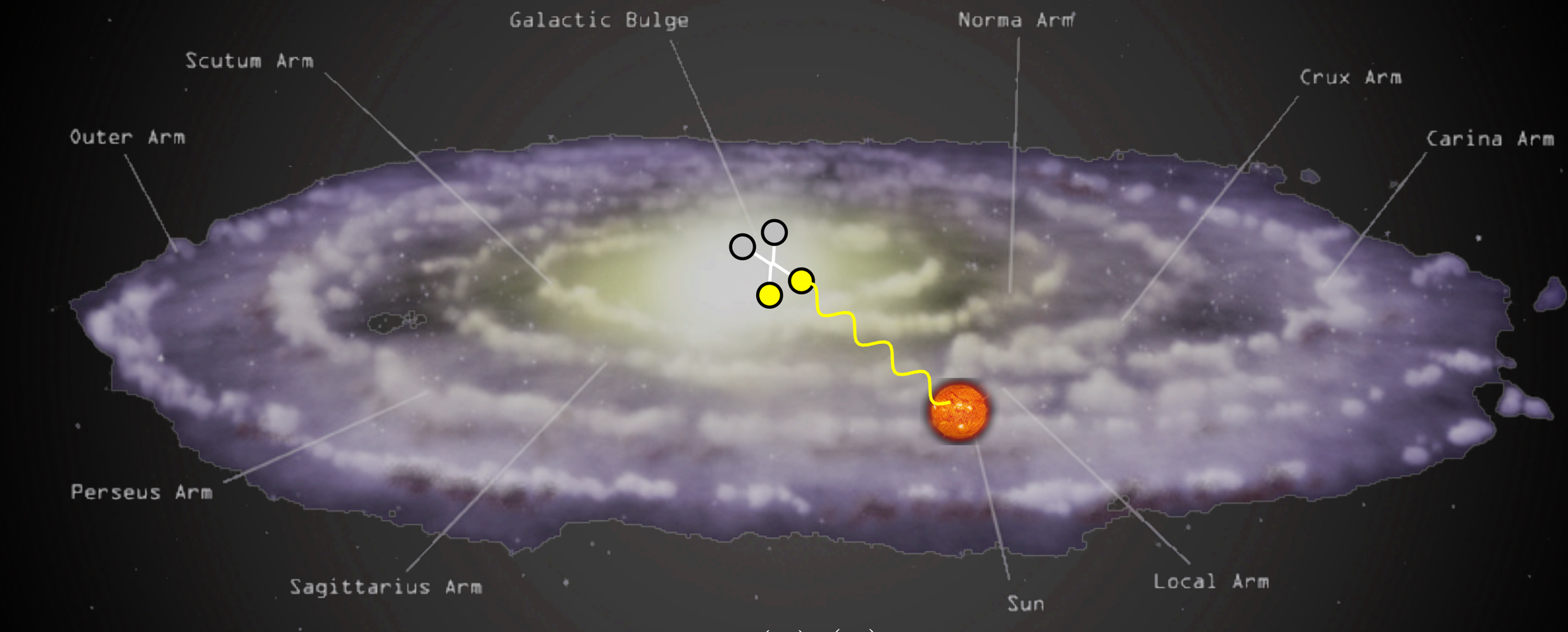


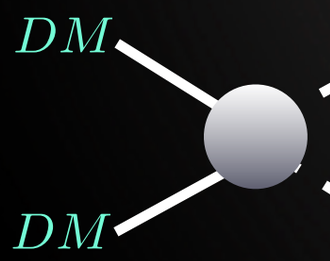
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

Indirect Detection: constraints

a. γ from DM annihilations in galactic center



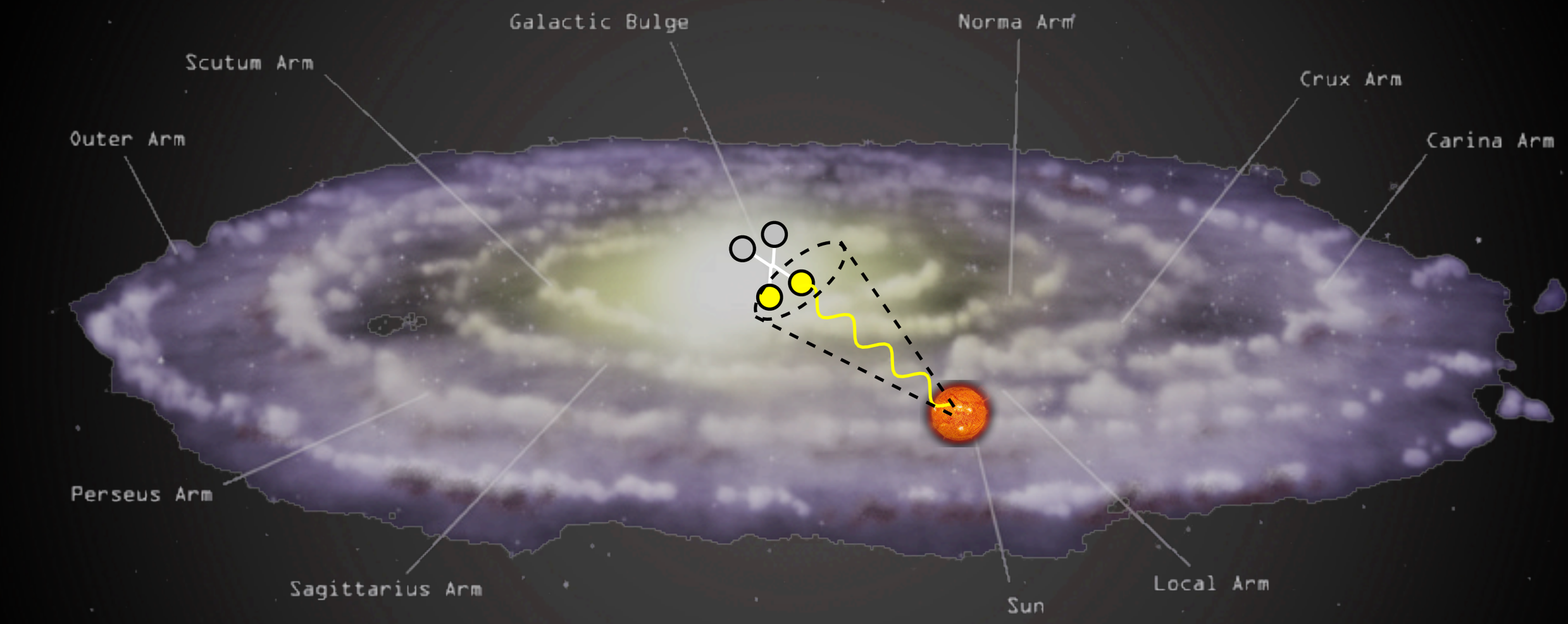


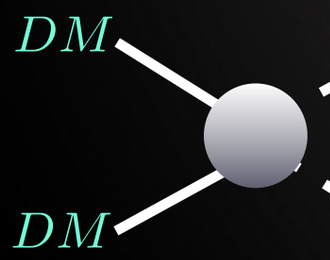
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

Indirect Detection: constraints

a. γ from DM annihilations in galactic center



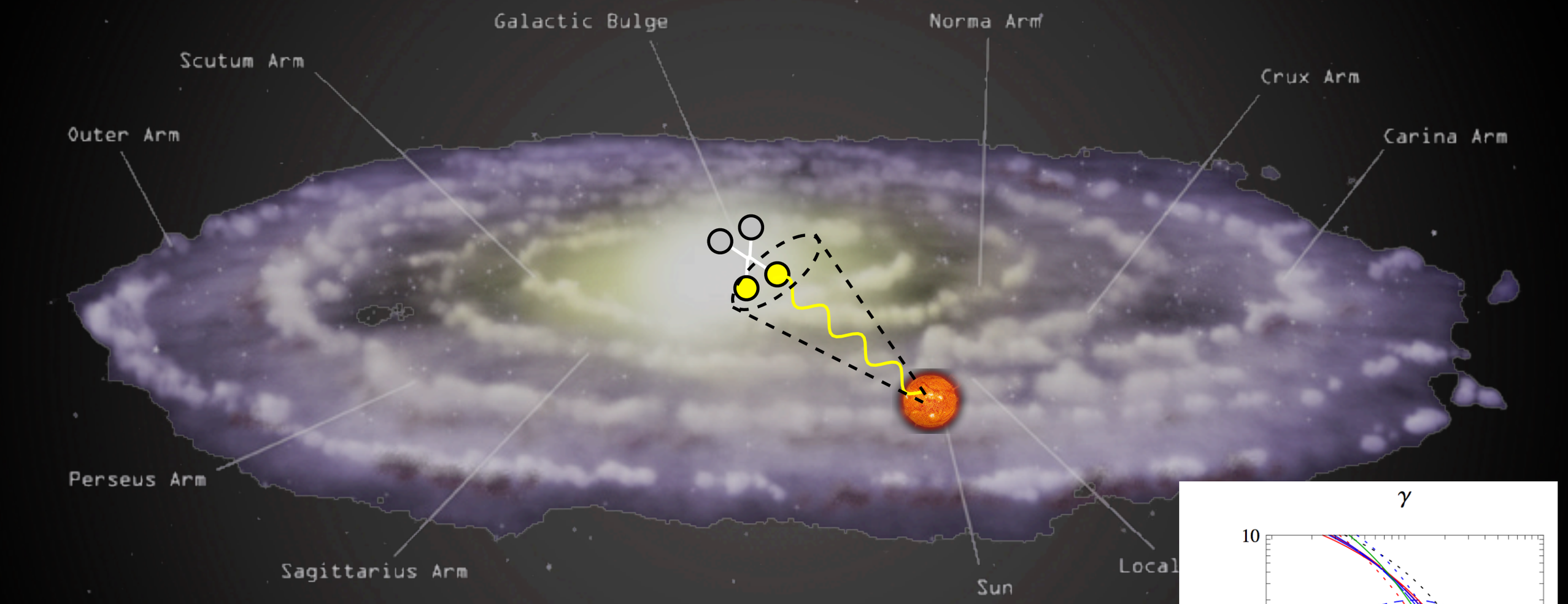


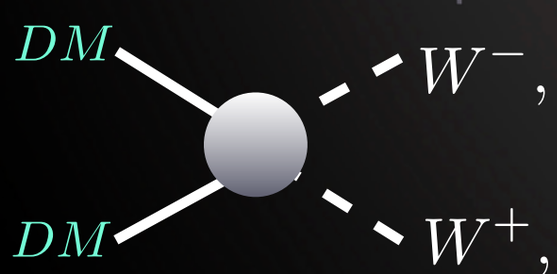
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

Indirect Detection: constraints

a. γ from DM annihilations in galactic center

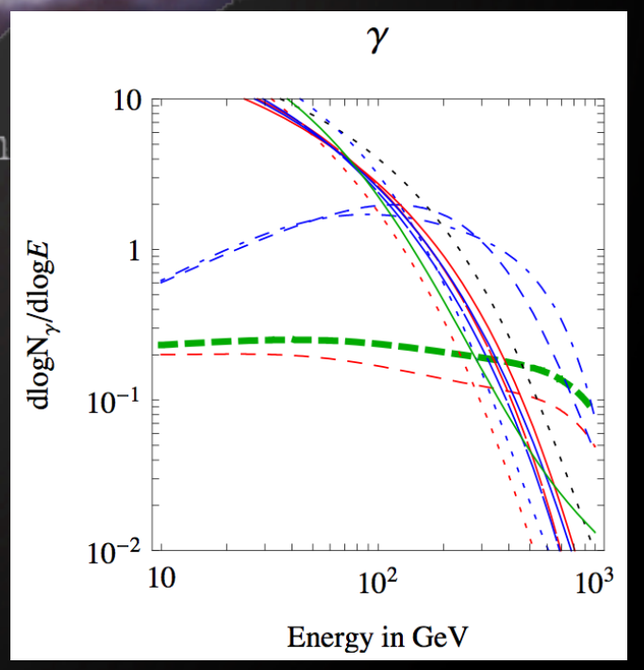




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

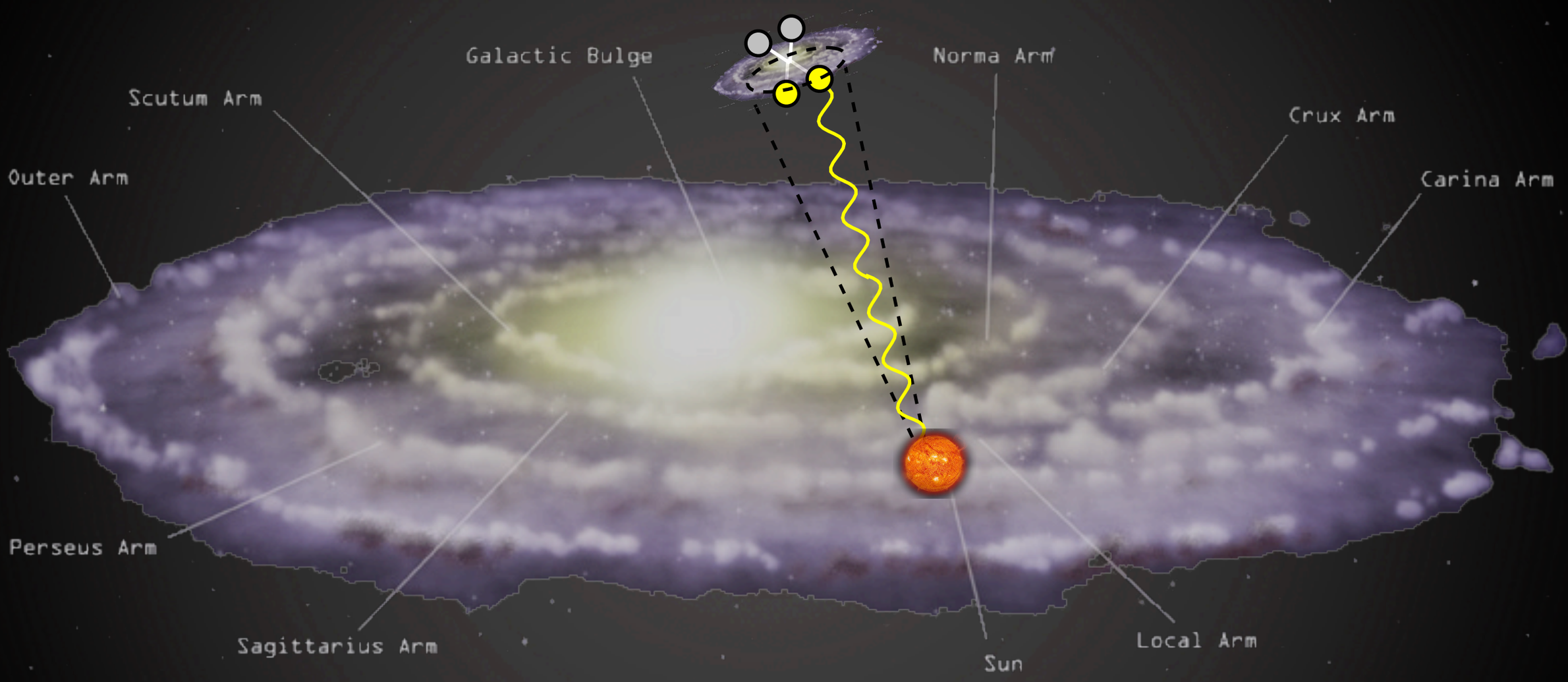
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

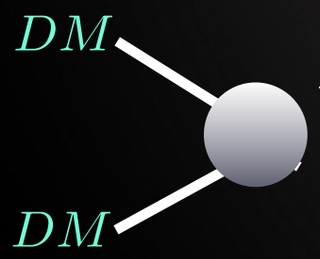
typically sub-TeV energies



Indirect Detection: constraints

b. γ from DM annihilations in Sagittarius Dwarf



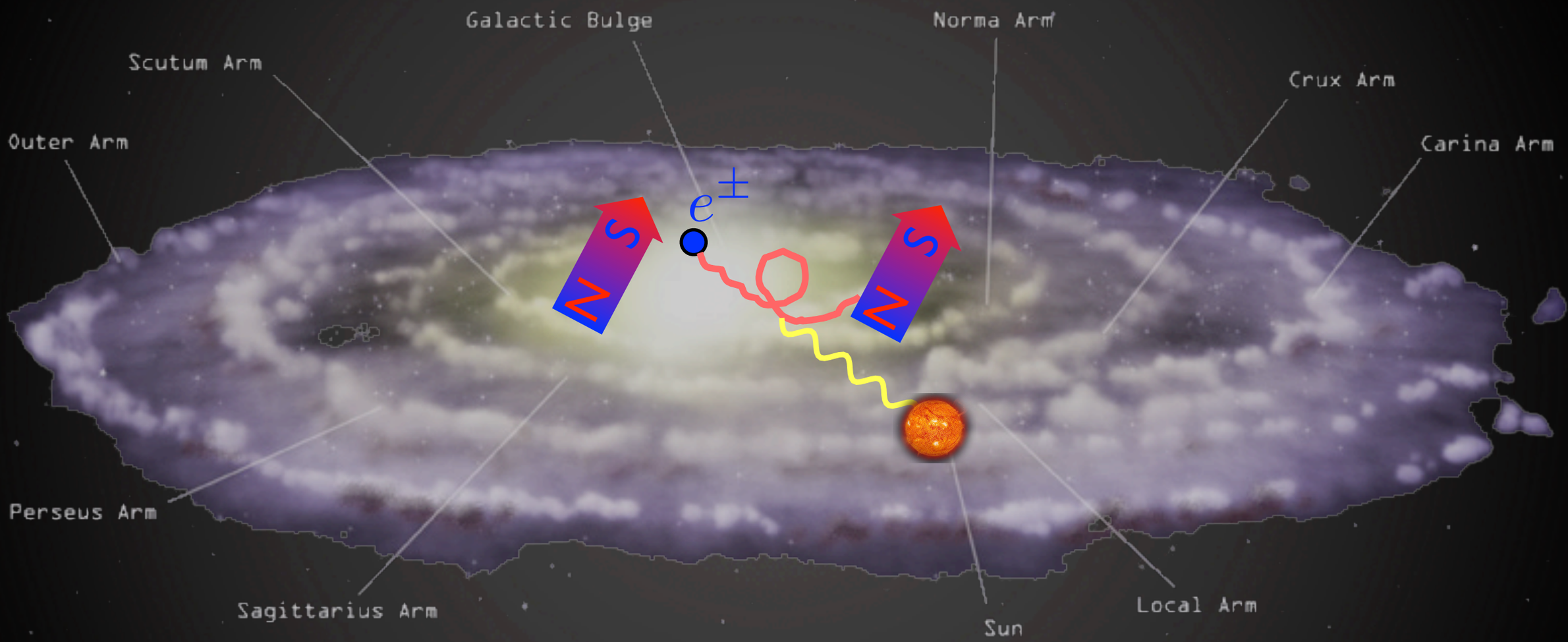


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and} \ \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and} \ \gamma$$

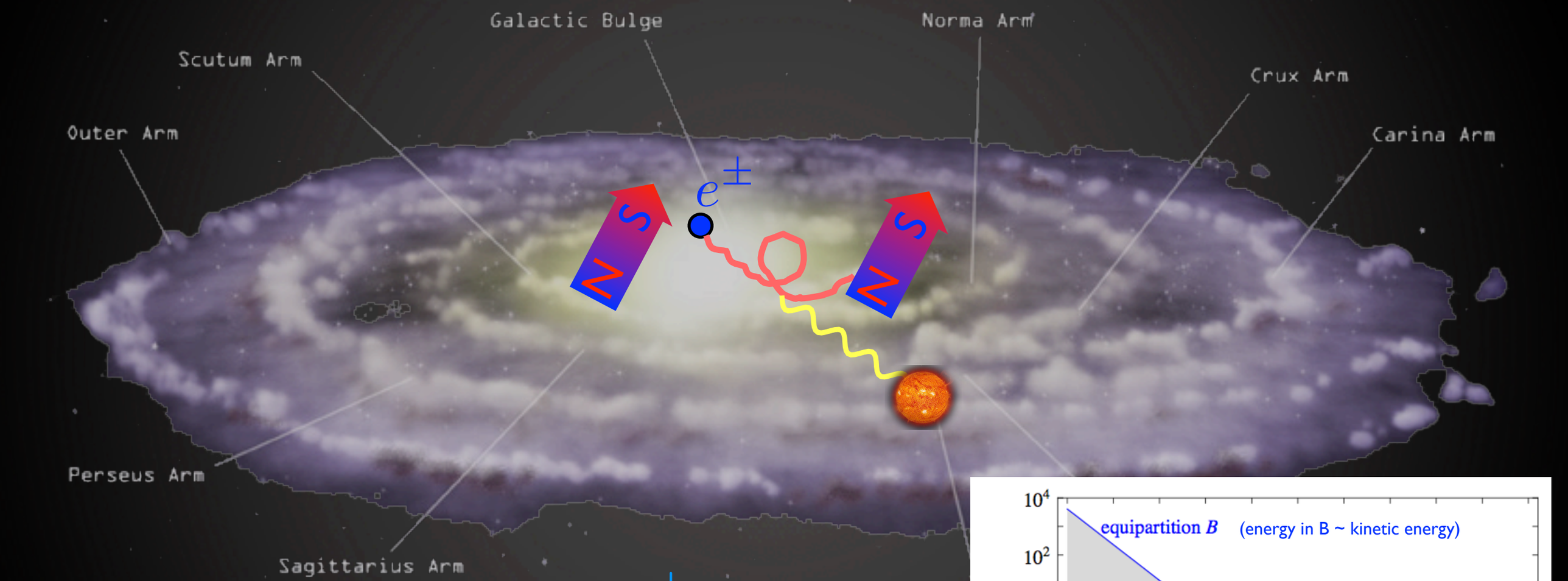
Indirect Detection: constraints

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



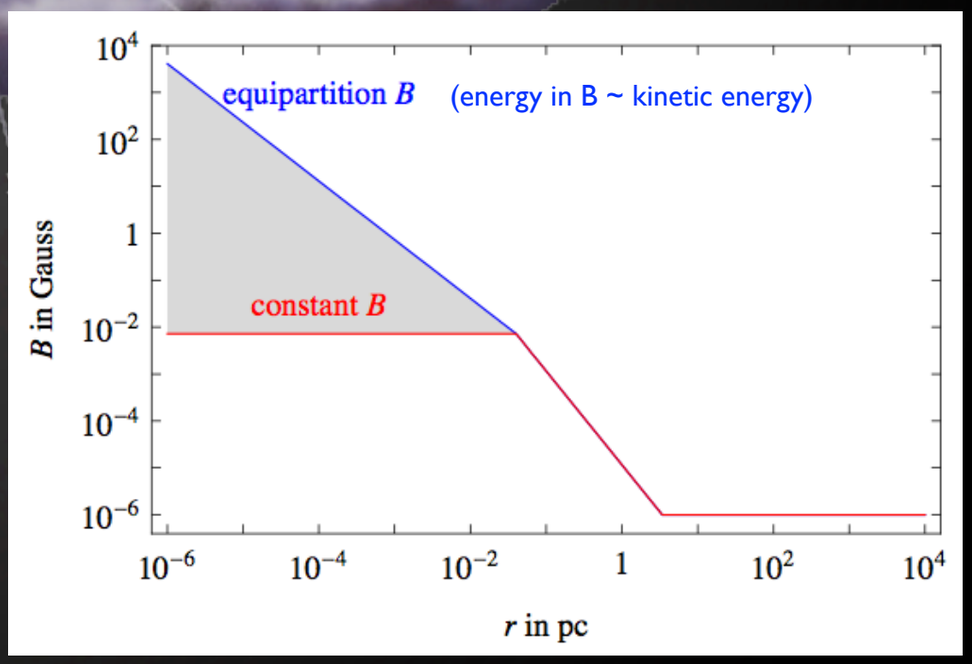
Indirect Detection: constraints

c. radio-waves from synchro radiation of $e^{\pm}$ in GC



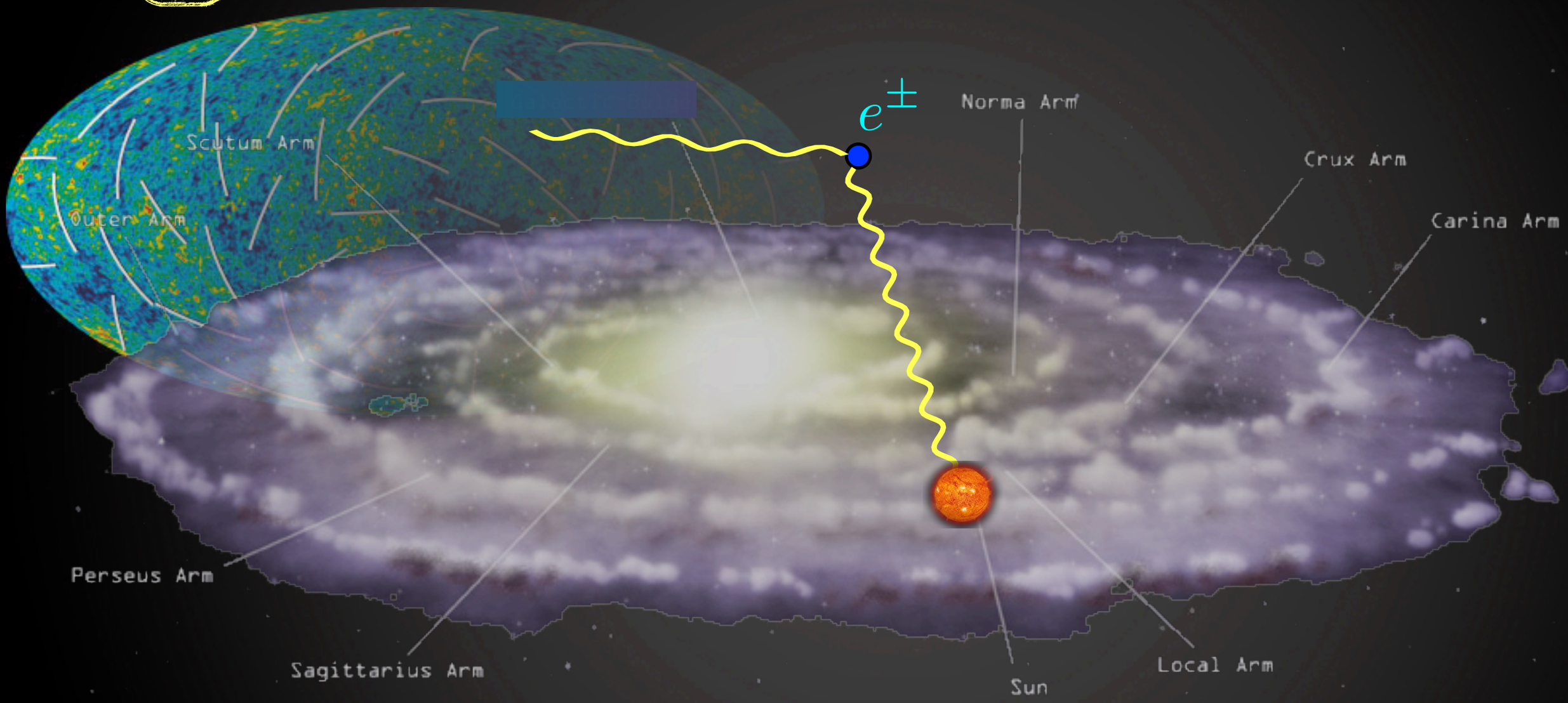
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

(assuming 'scrambled' B; in principle, directionality could focus emission, lift bounds by O(some))



Indirect Detection: constraints

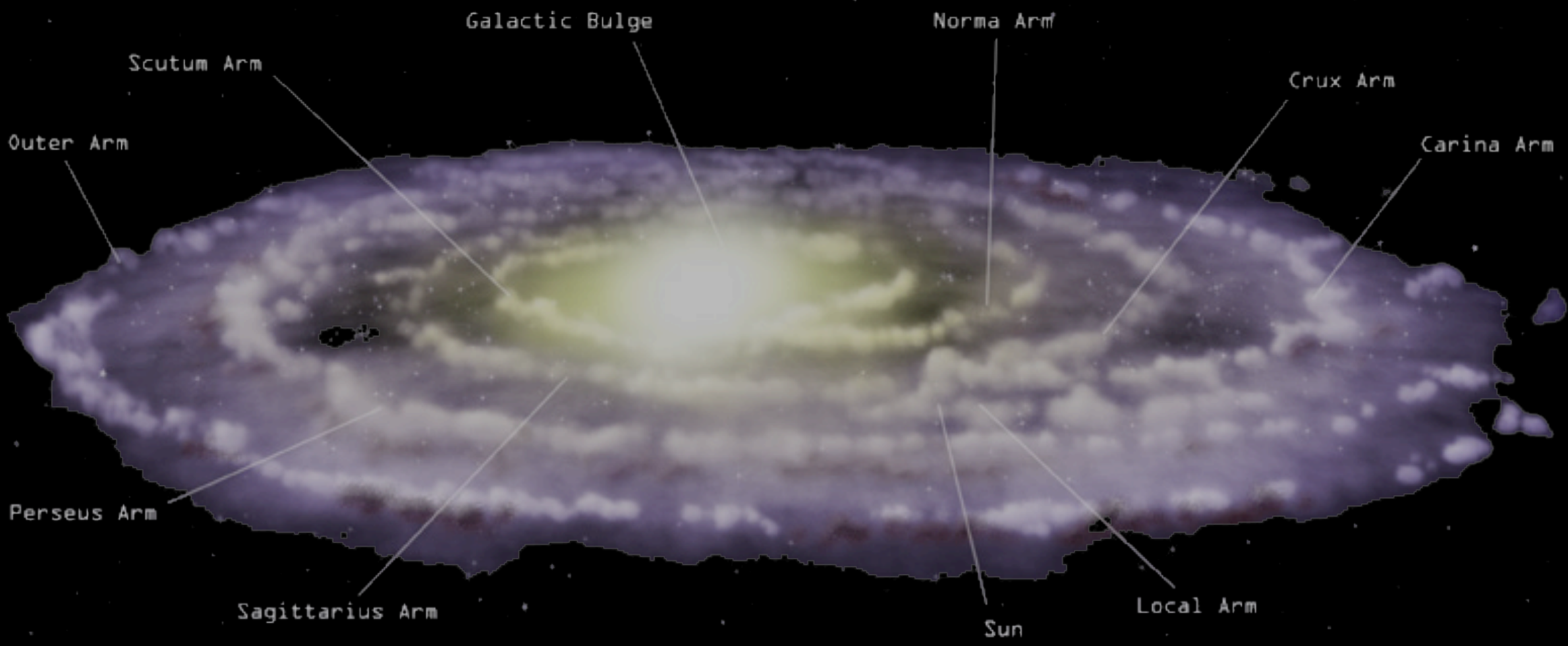
d. γ from Inverse Compton on $e^{\pm}$ in halo



- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

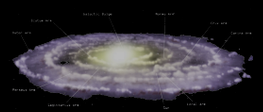
Indirect Detection: constraints

e. γ from outside the Galaxy



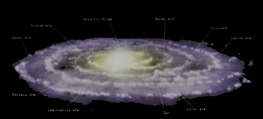
Indirect Detection: constraints

e. γ from outside the Galaxy



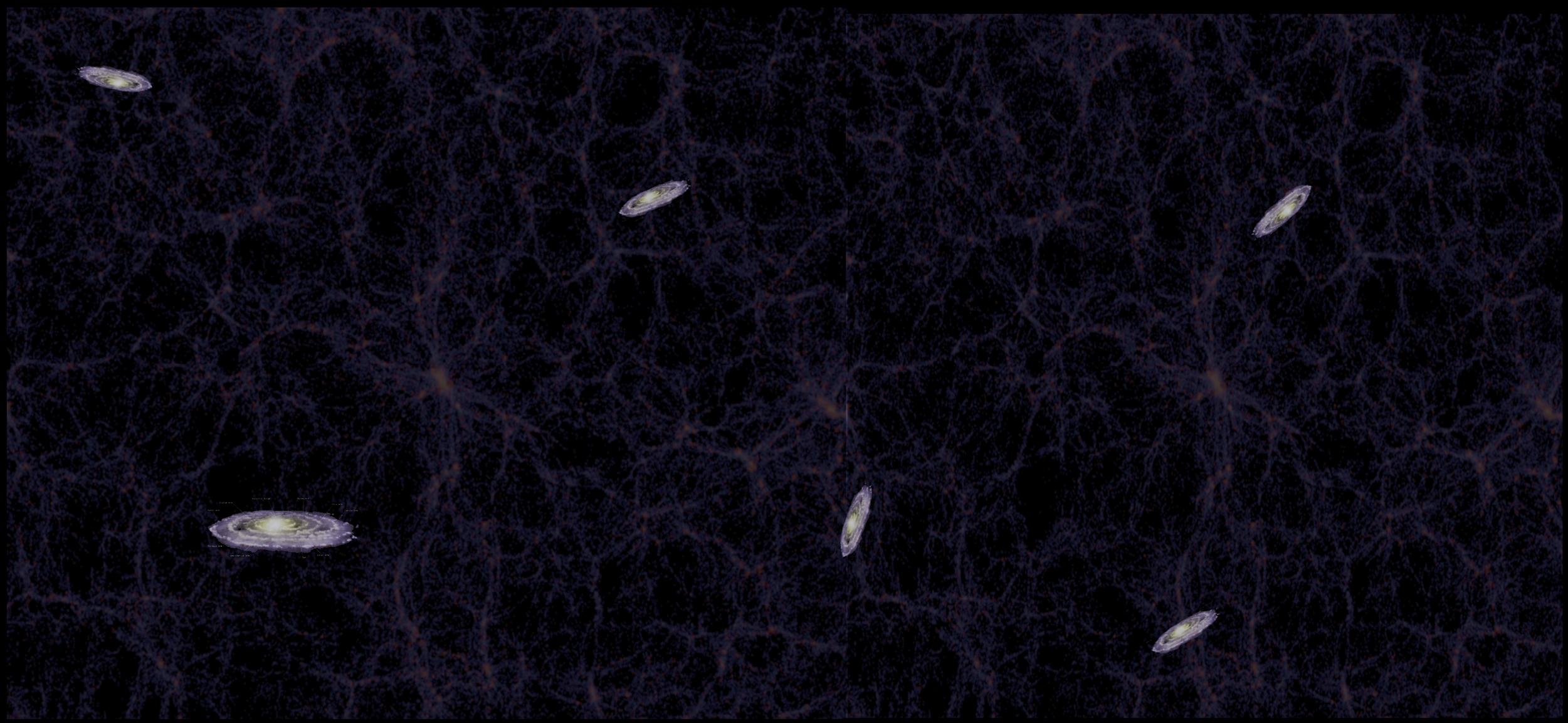
Indirect Detection: constraints

e. γ from outside the Galaxy



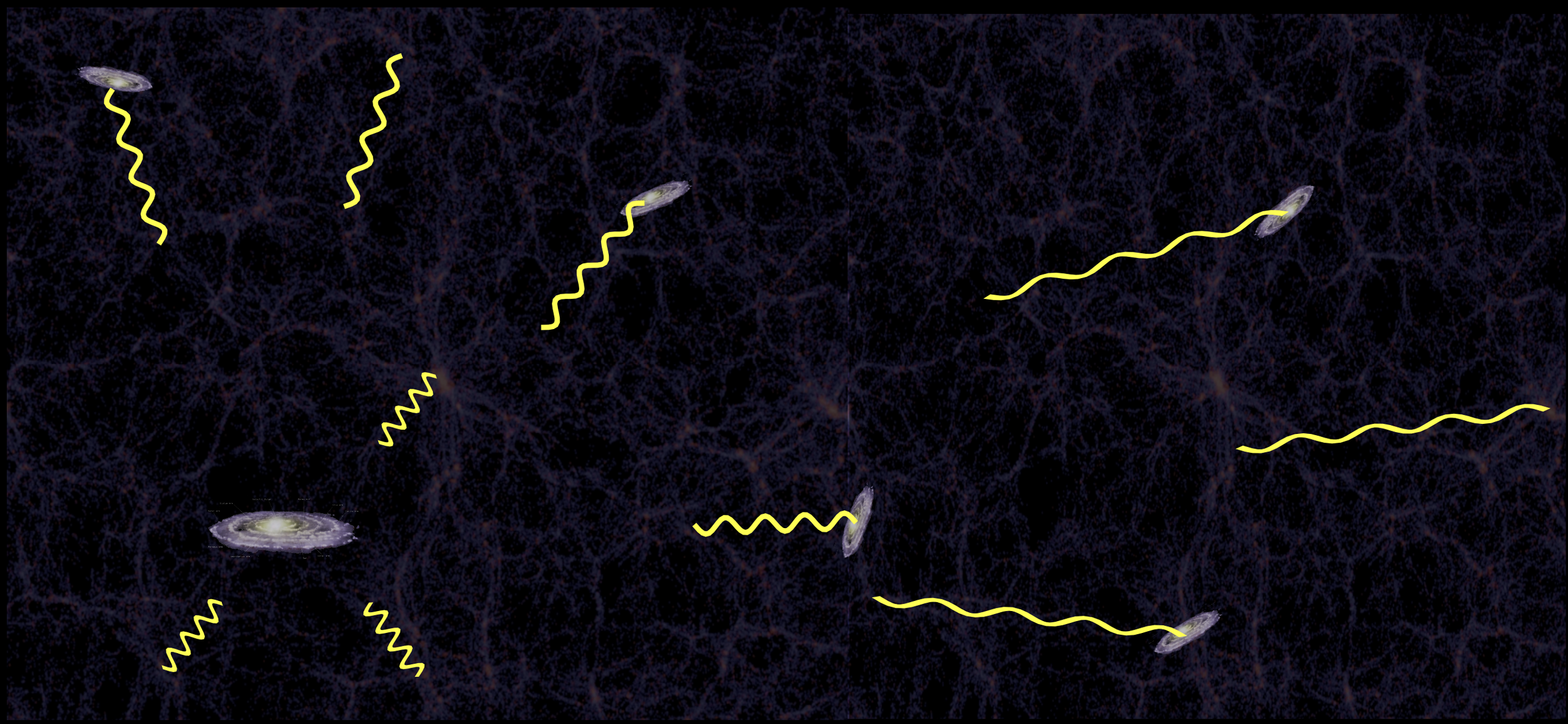
Indirect Detection: constraints

e. γ from outside the Galaxy



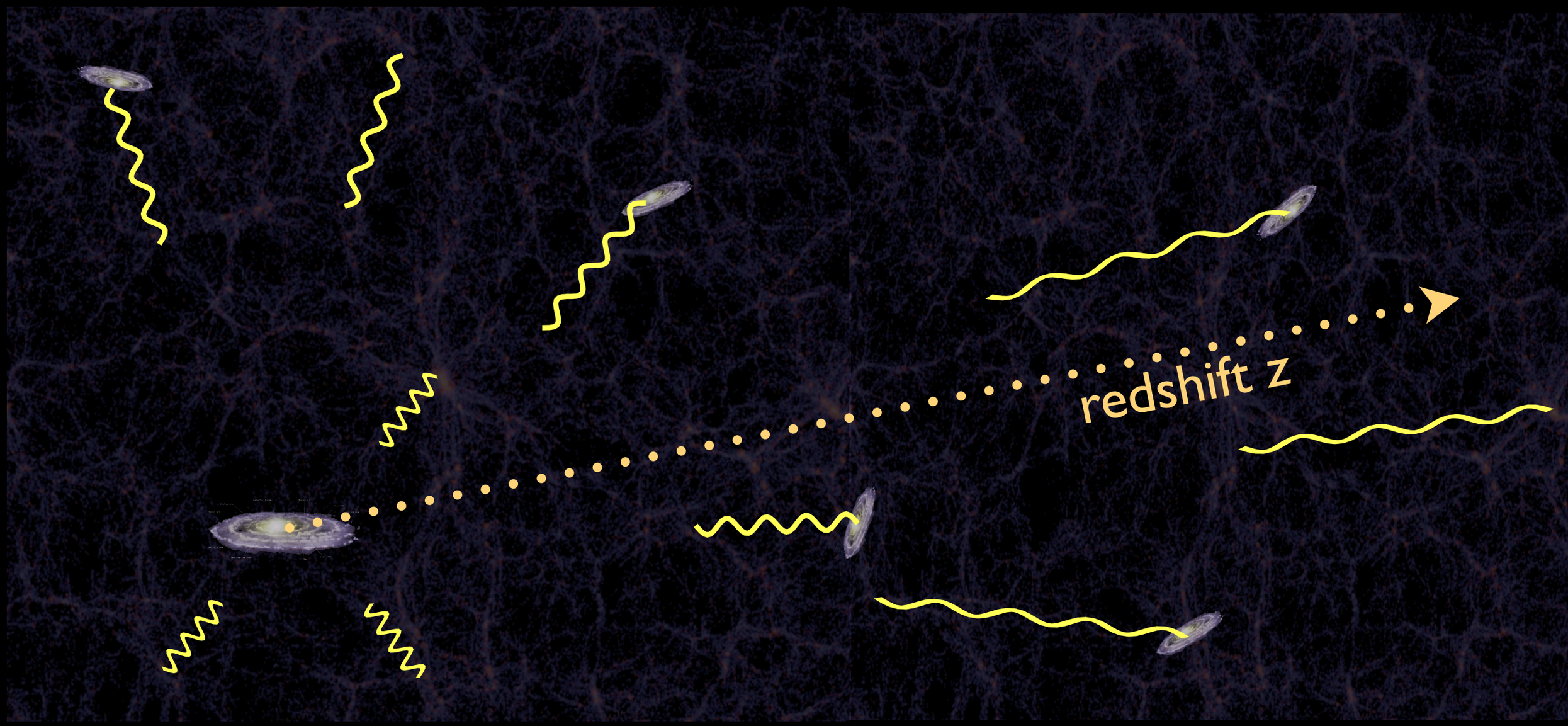
Indirect Detection: constraints

e. γ from outside the Galaxy



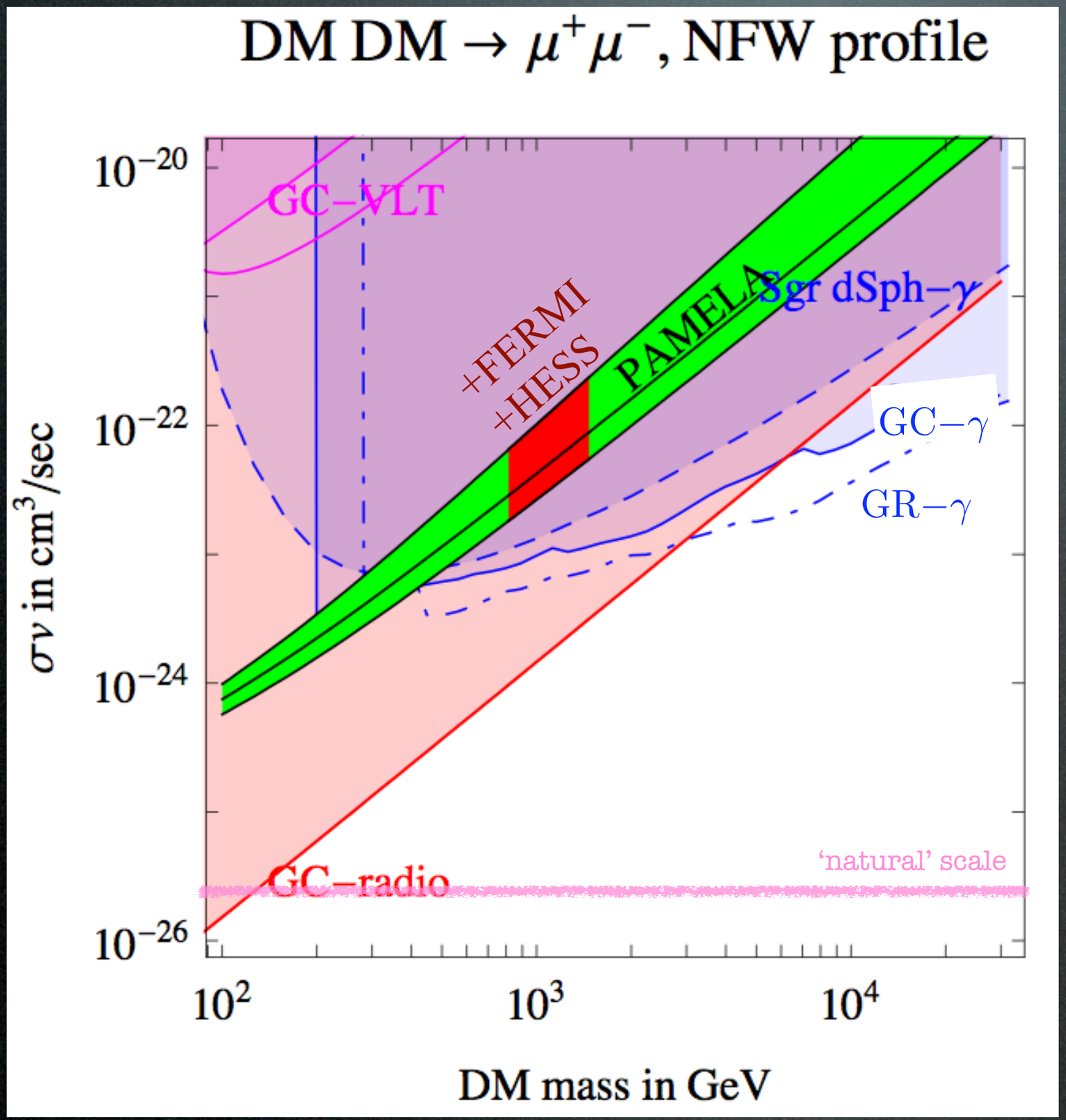
Indirect Detection: constraints

e. γ from outside the Galaxy



- isotropic flux of prompt and ICS gamma rays, integrated over *z* and *r*
- depends strongly on halo formation details and history

Gamma constraints



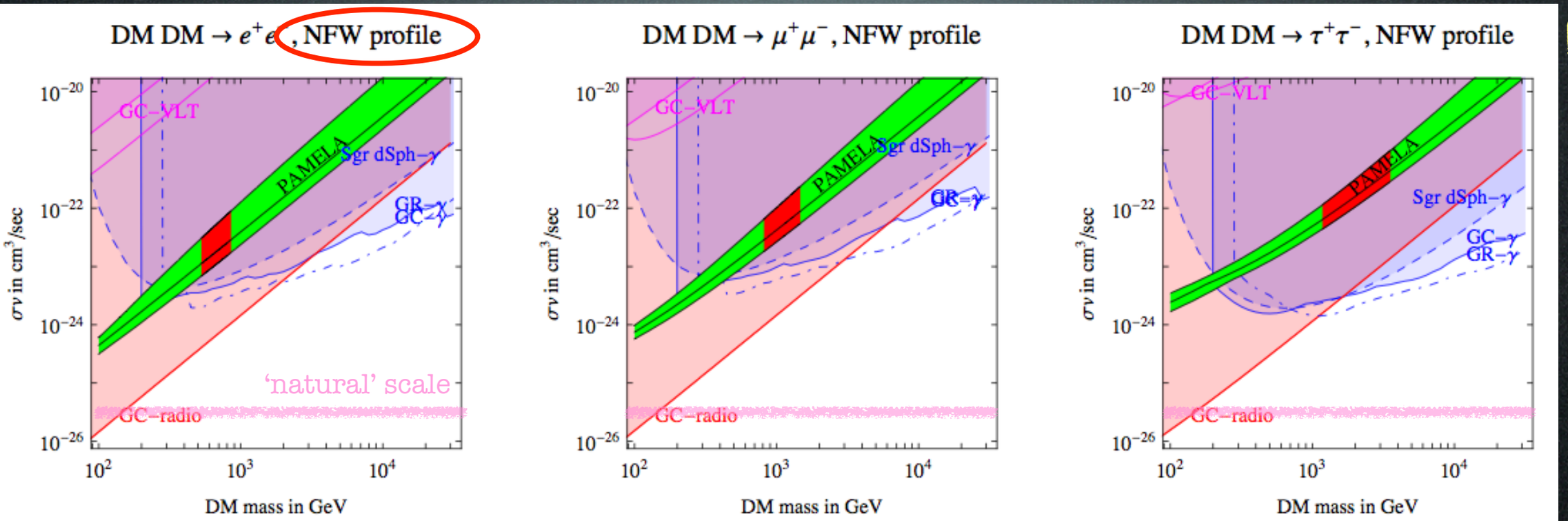
Bertone, Cirelli, Strumia, Taoso 0811.3744

a+b+c.

The PAMELA +FERMI regions are in conflict with gamma constraints, unless...

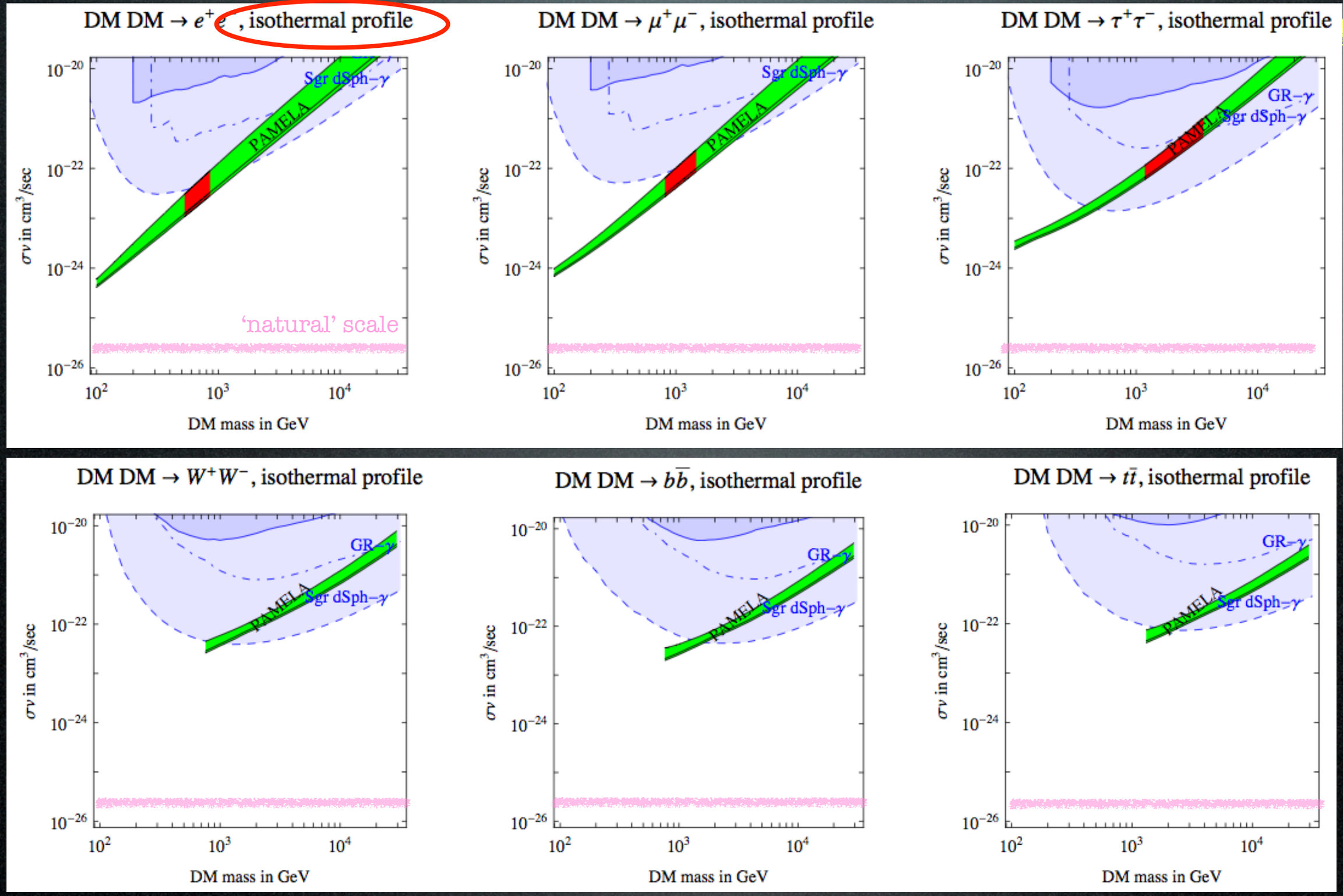
Gamma constraints

a+b+c.



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints



a+b+c.

Bertone, Cirelli, Strumia, Taoso 0811.3744

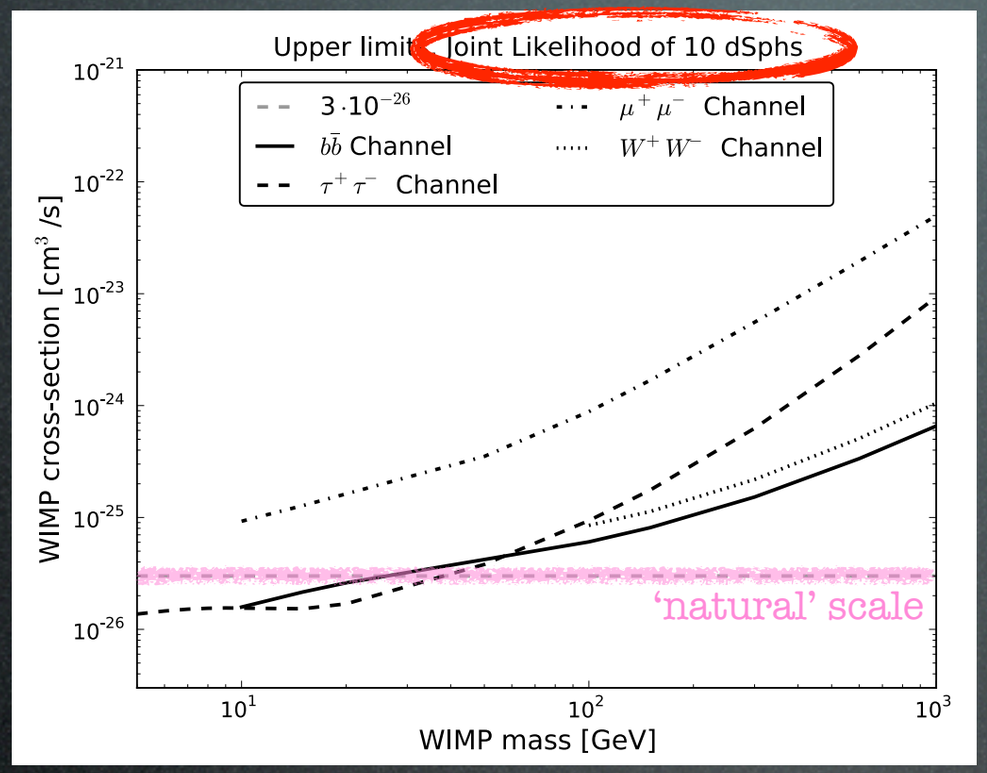
...not-too-steep profile needed.

Gamma constraints

b. γ from DM annihilations in Satellite Galaxies

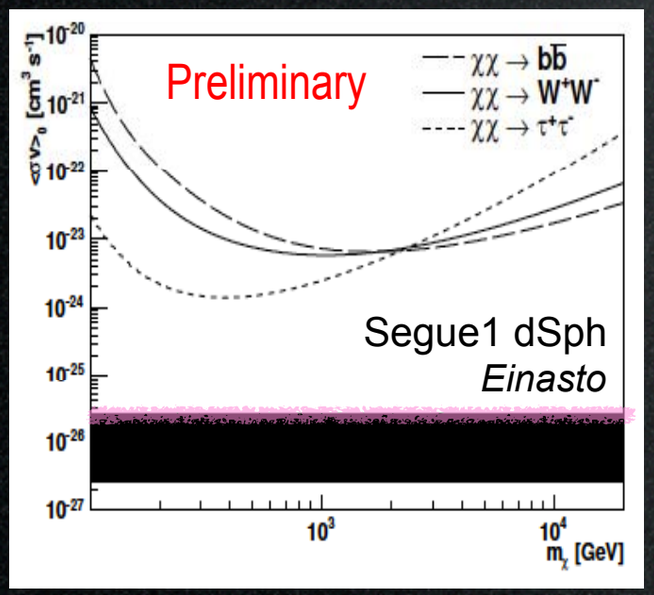
FERMI

FERMI coll., 1108.3546



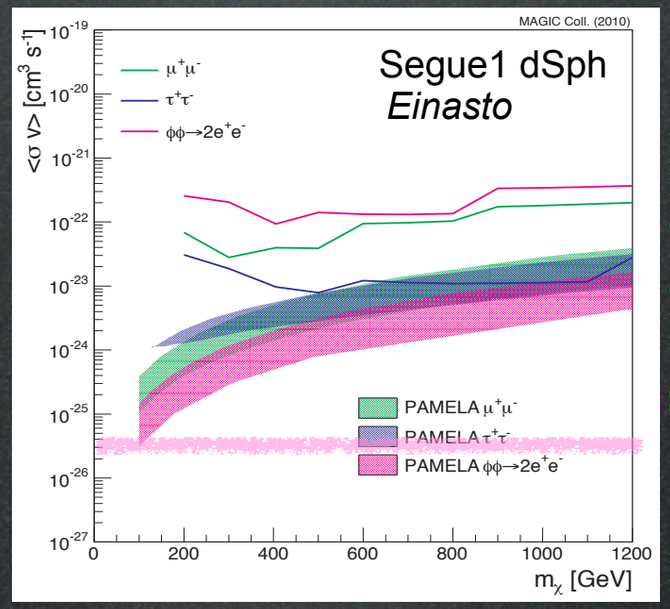
And the winner is...

VERITAS



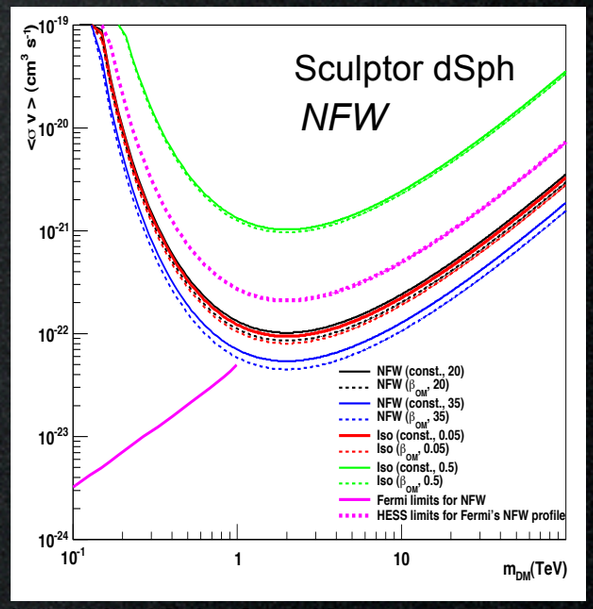
Veritas coll., courtesy of R.Ong

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

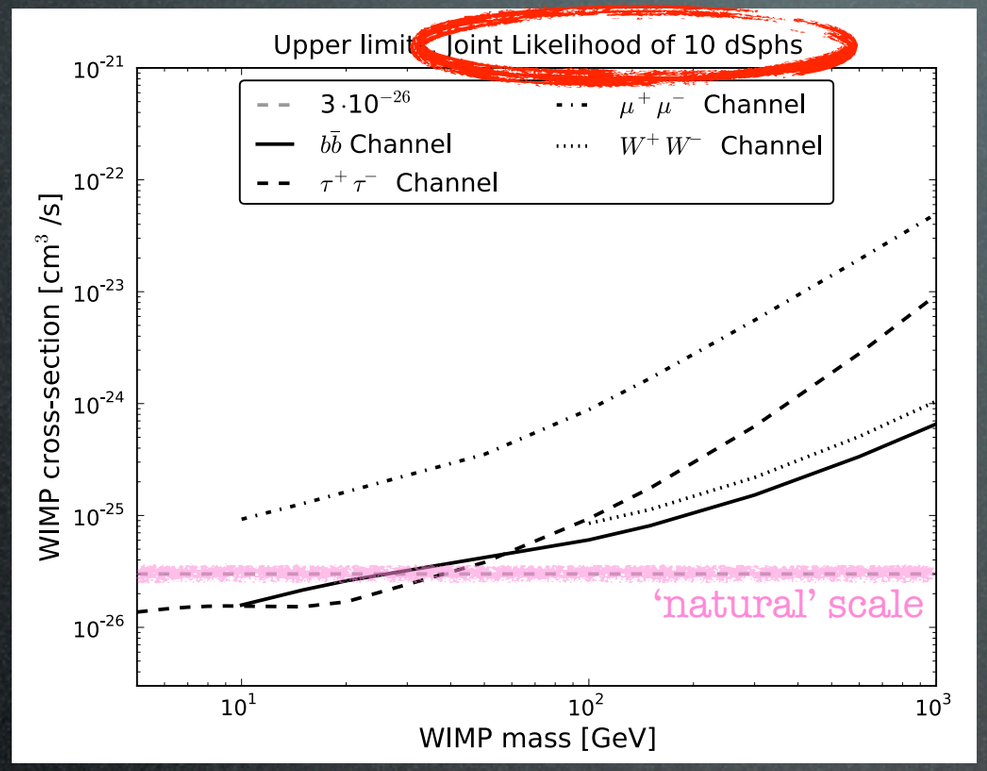
(HESS: Globular Clusters analysis too)

Gamma constraints

b. γ from DM annihilations in Satellite Galaxies

FERMI

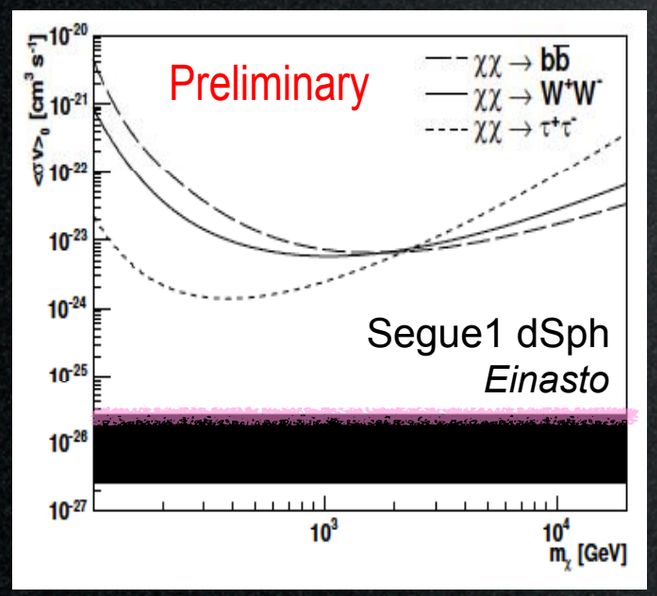
FERMI coll., 1108.3546



And the winner is...
FERMI.
But beware of different profiles, techniques...

see also:
Geringer-Sameth, Koushiappas, 1108.2914
Strigari et al. (0902.4750, 1007.4199...)
Baxter, Dodelson et al.

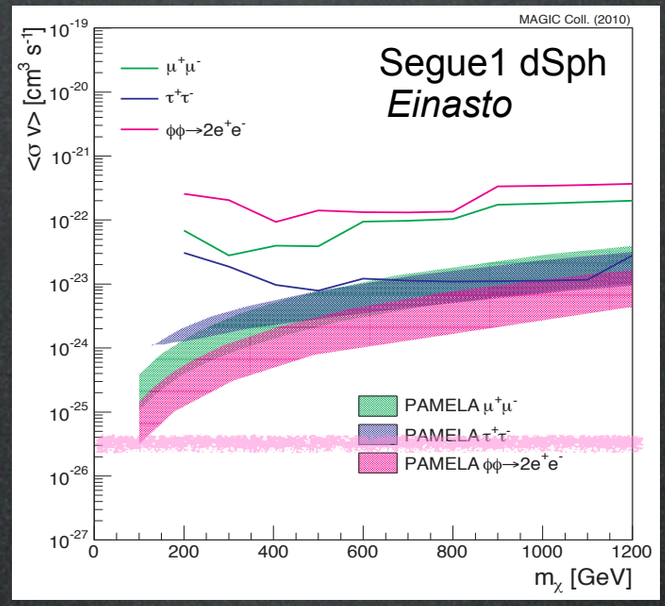
VERITAS



Veritas coll., courtesy of R.Ong

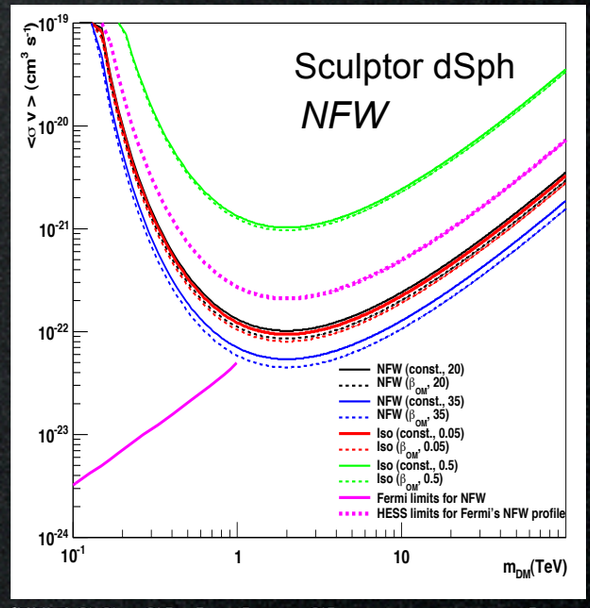
(currently the winner in the '1 dSph' category)

MAGIC



Magic coll., 1103.0477

HESS



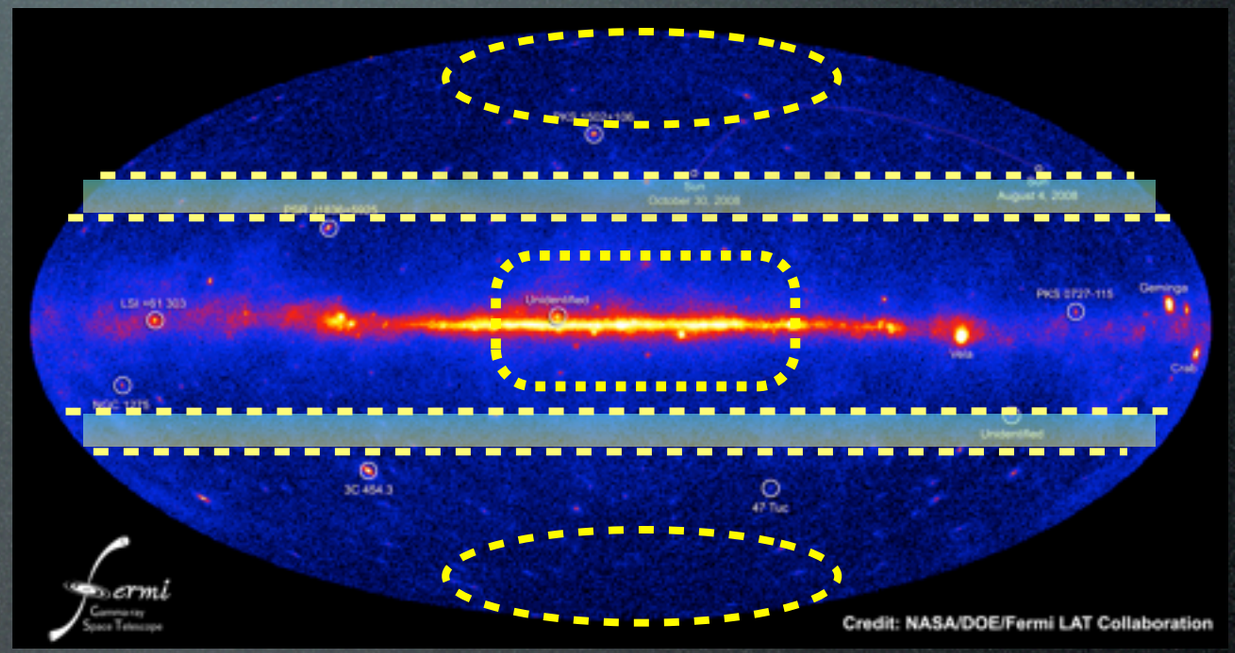
HESS coll., 1012.5602

(HESS: Globular Clusters analysis too)

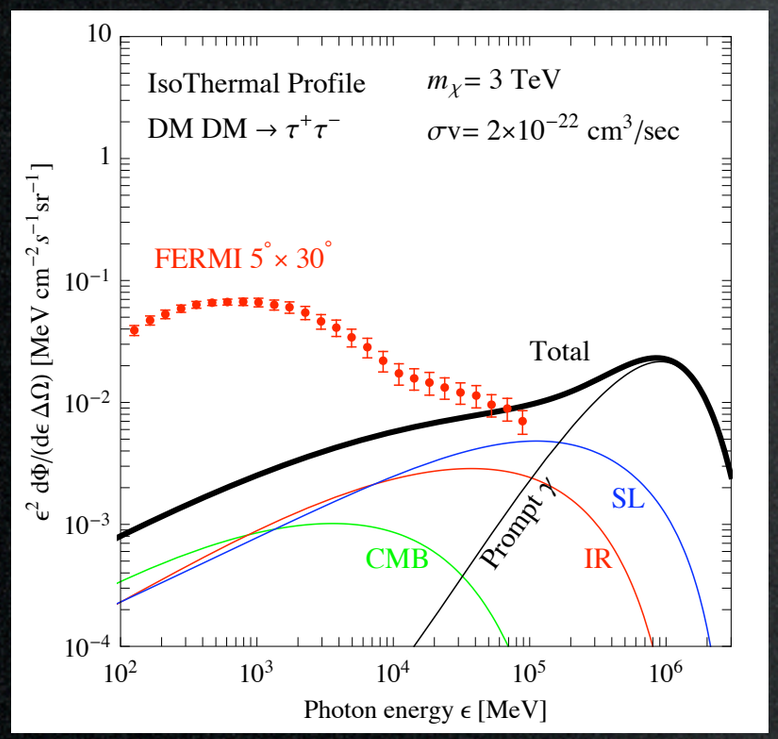
Gamma constraints

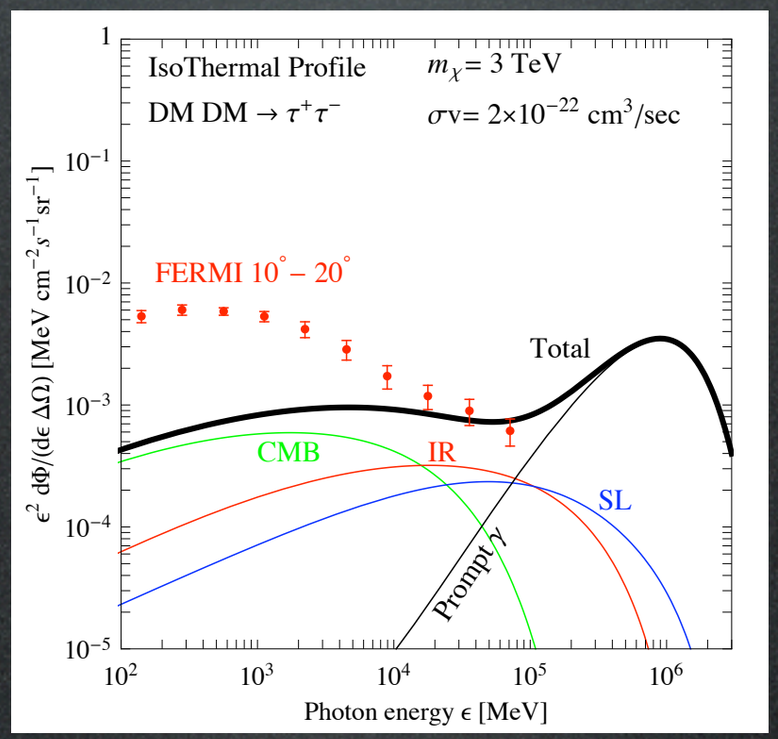
d. γ from Inverse Compton on $e^{\pm}$ in halo

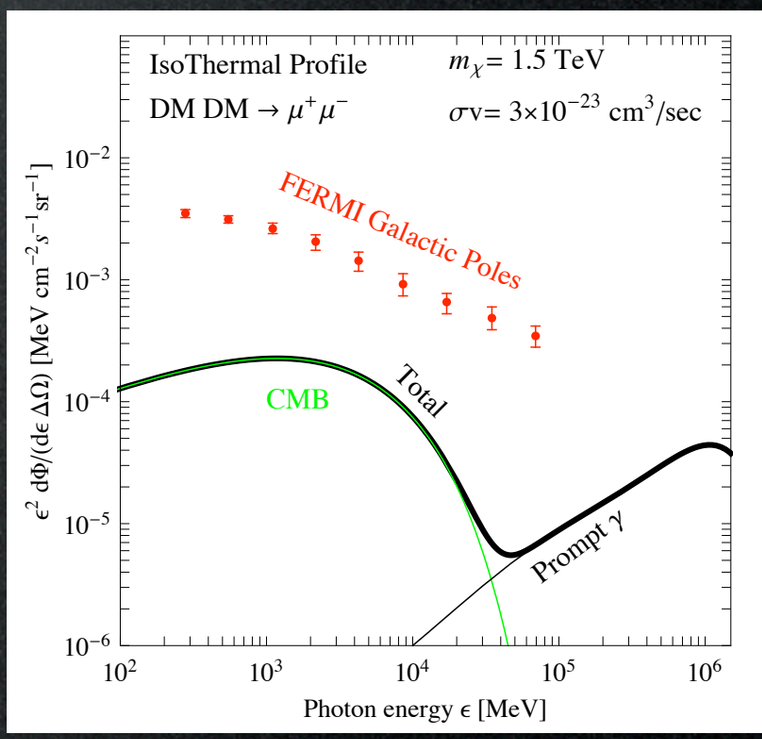
FERMI has measured diffuse γ-ray emission. The DM signal must not excede that.



FERMI coll.





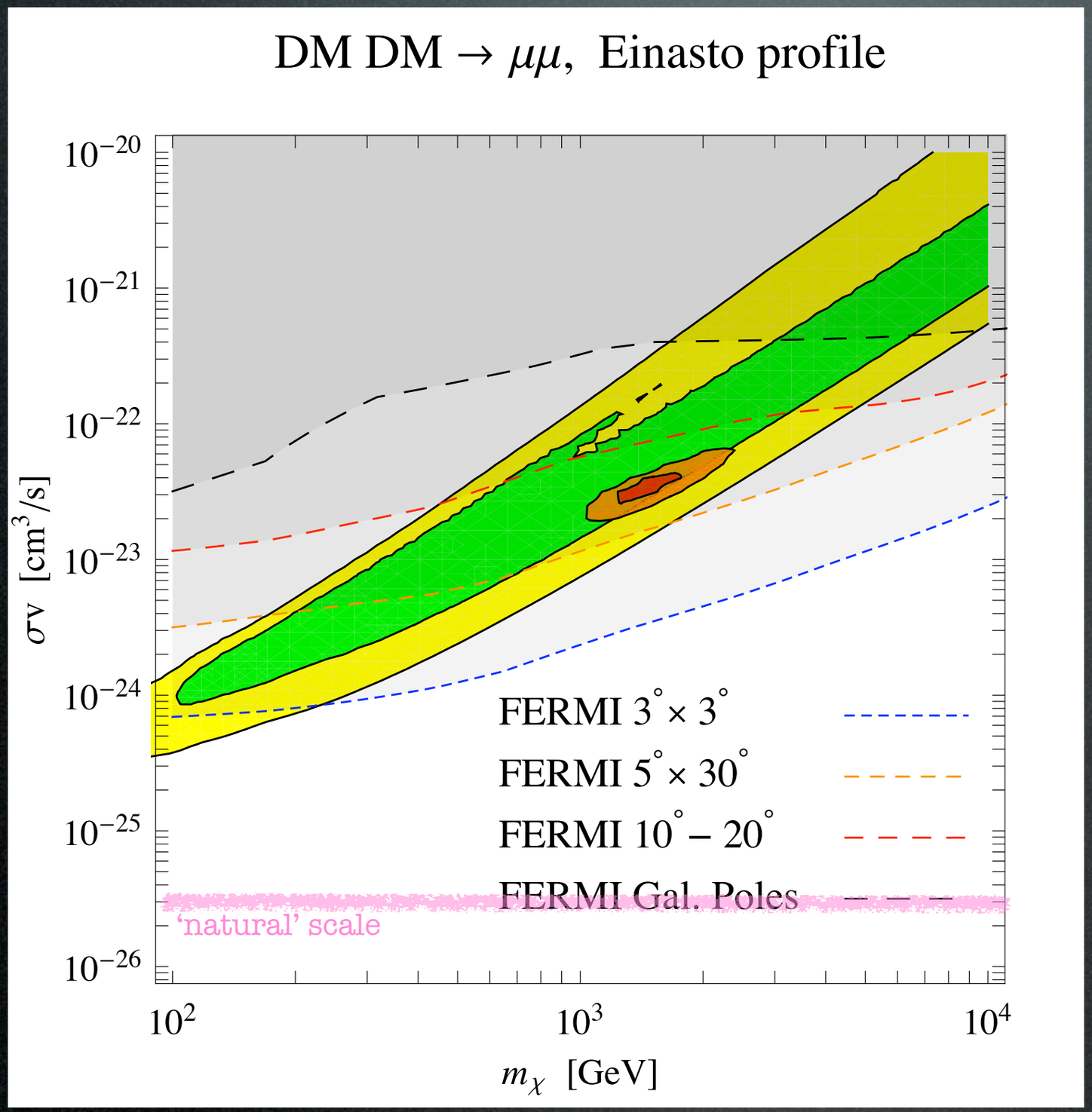


Data: FERMI coll., several talks and papers

Cirelli, Panci, Serpico 0912.0663

Gamma constraints

d. γ from Inverse Compton on $e^{\pm}$ in halo

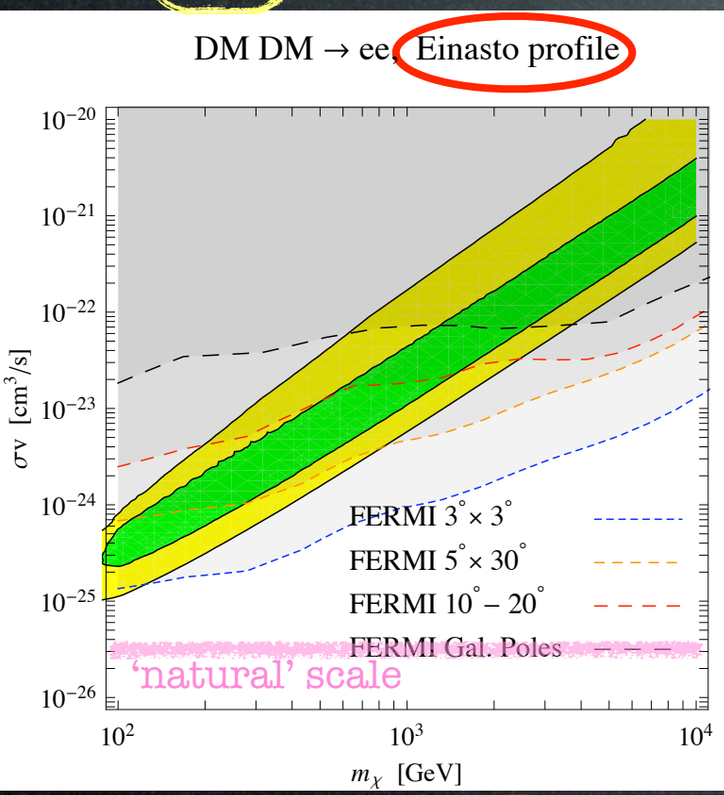


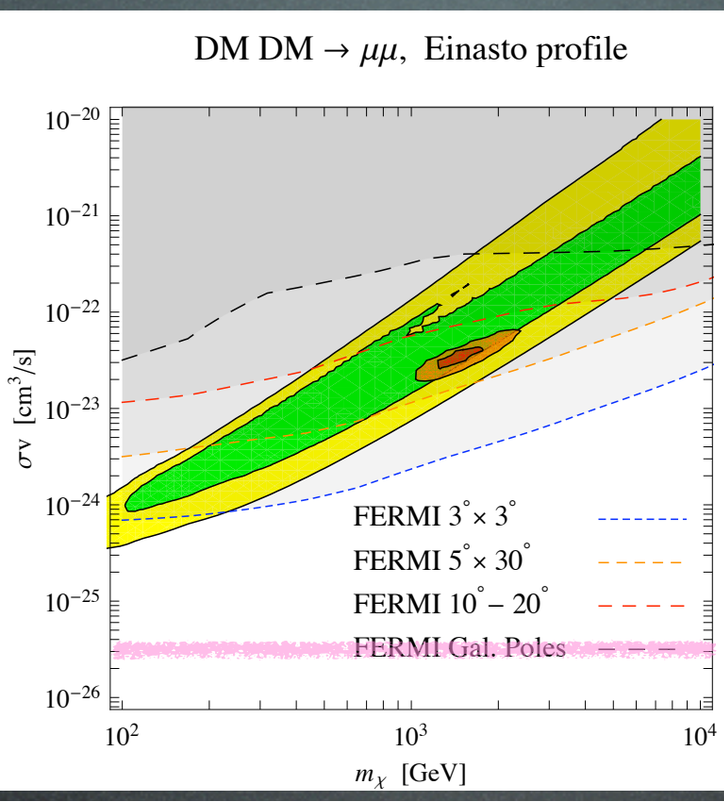
Cirelli, Panci, Serpico 0912.0663

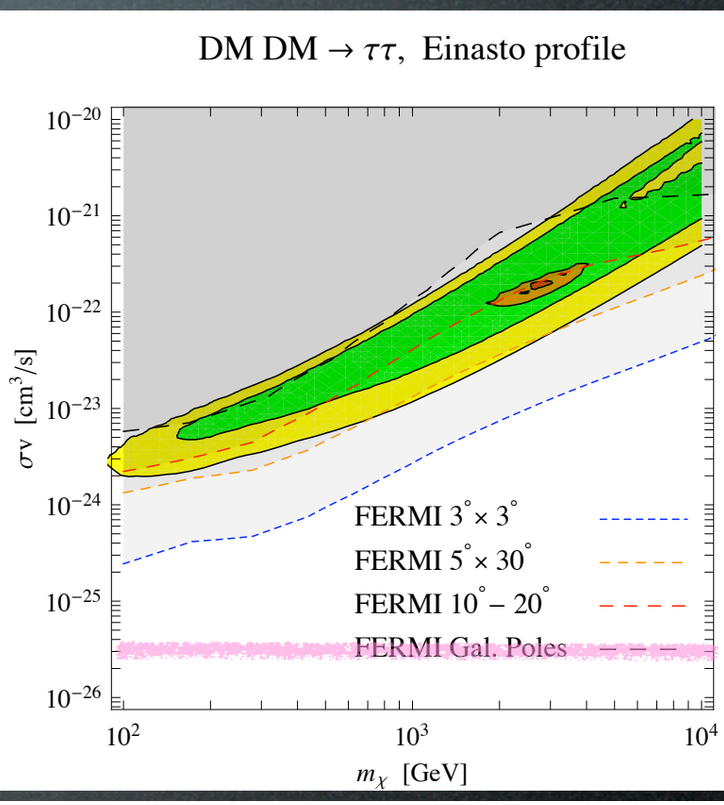
The PAMELA and ATIC regions are in conflict with these gamma constraints, and here...

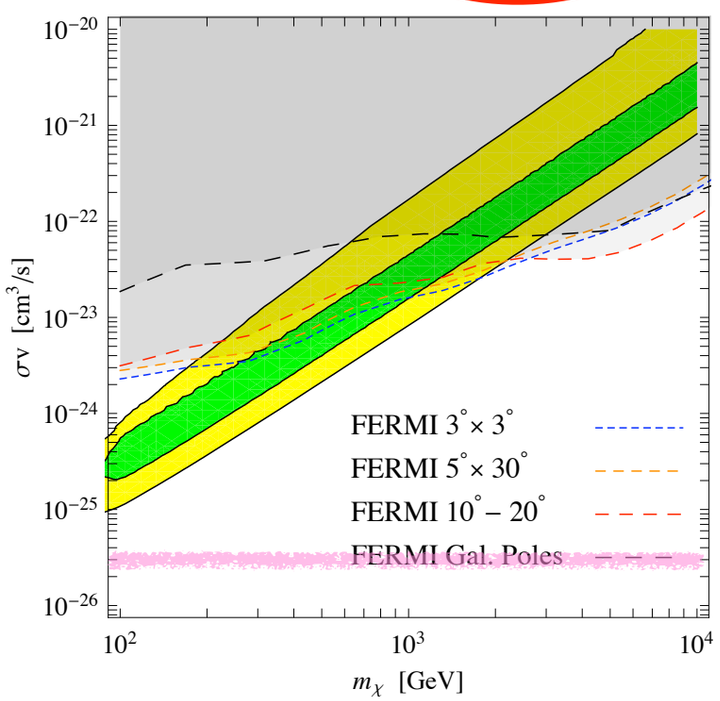
Gamma constraints

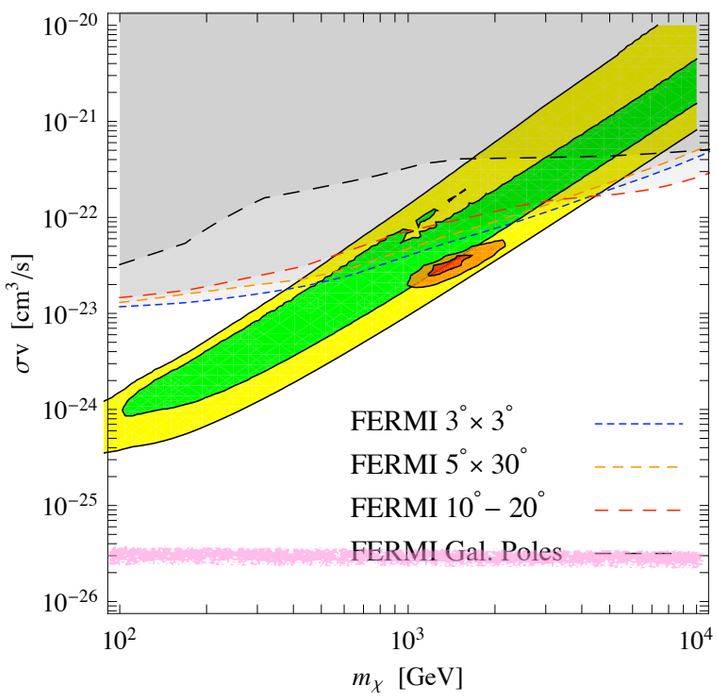
d. γ from Inverse Compton on $e^{\pm}$ in halo

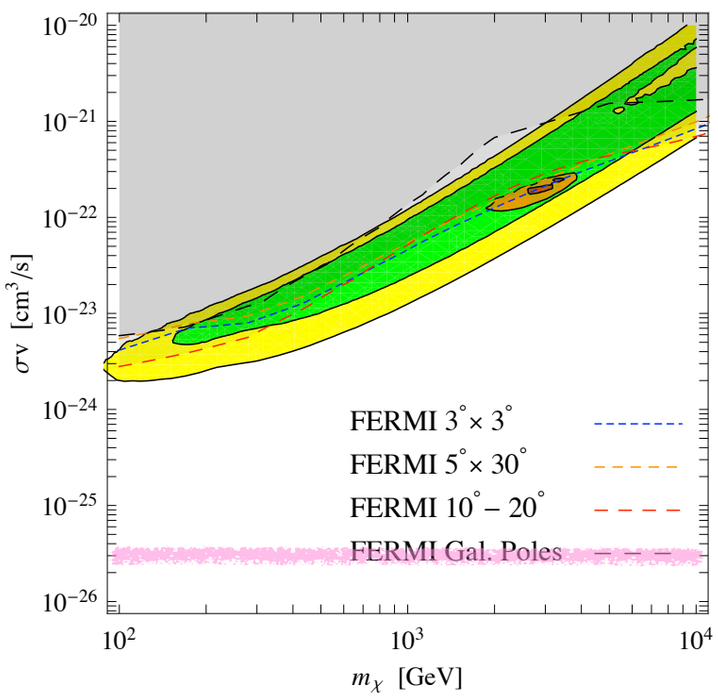












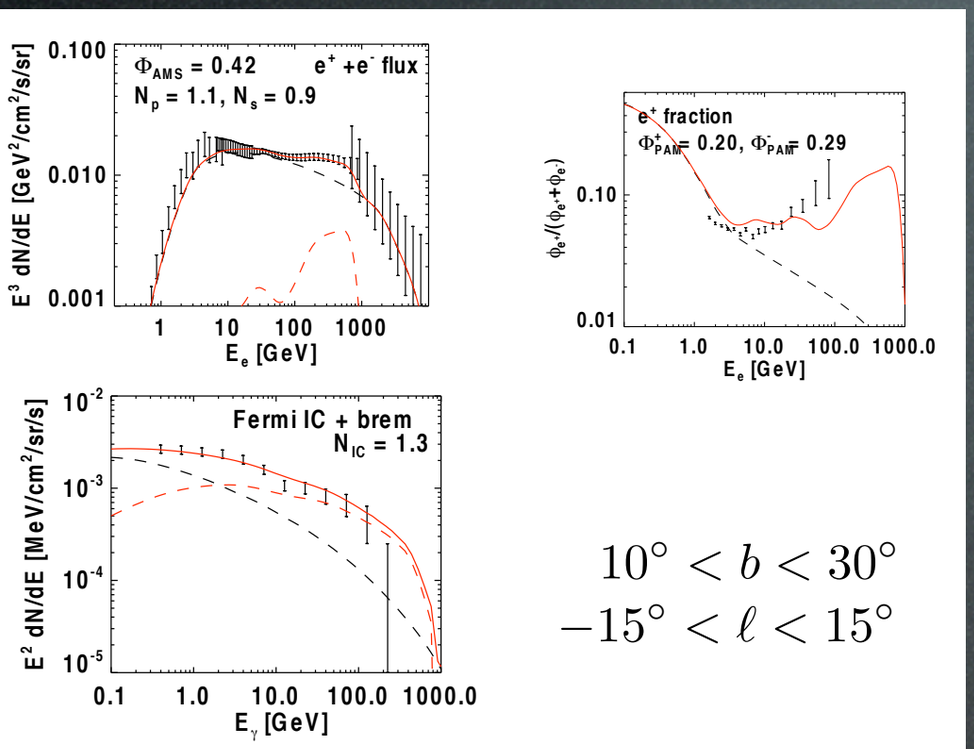
Cirelli, Panci, Serpico 0912.0663

Gamma **hints**?

What if a signal of DM is *already* hidden in Fermi diffuse γ data?

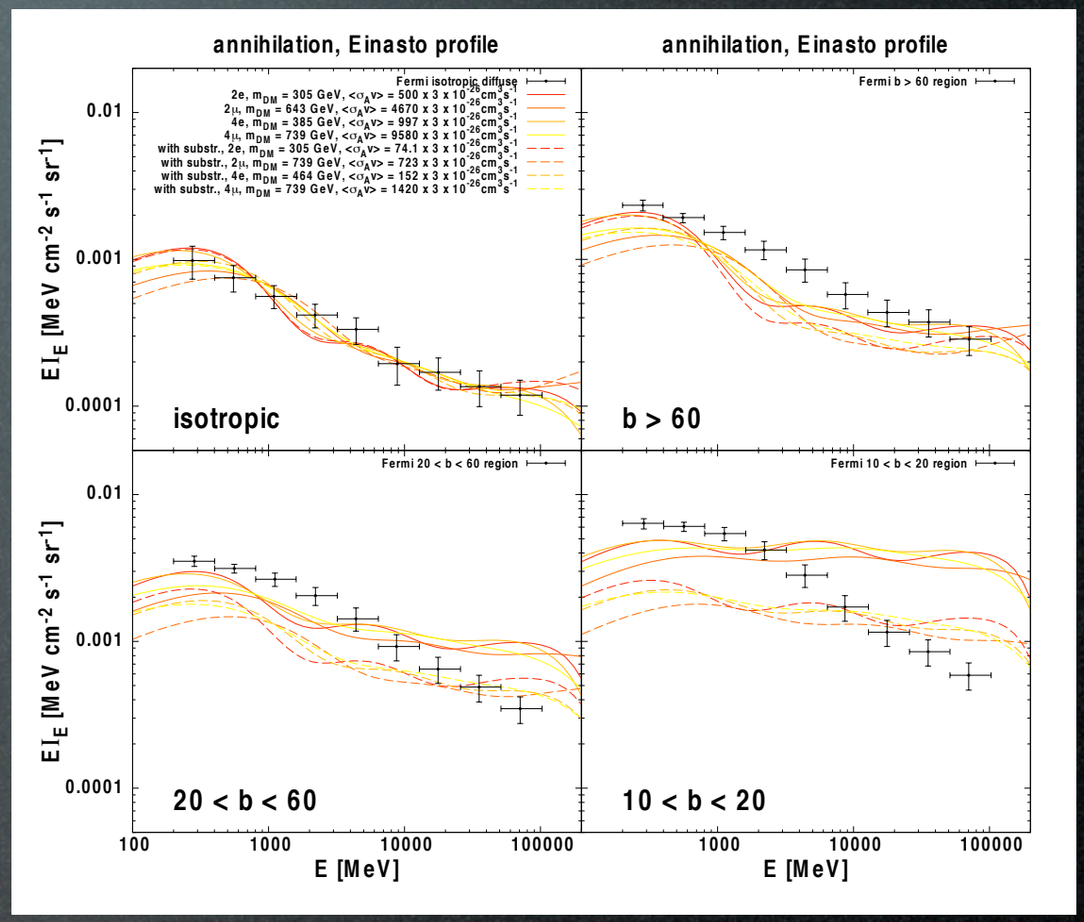
Gamma hints?

What if a signal of DM is *already* hidden in Fermi diffuse γ data?

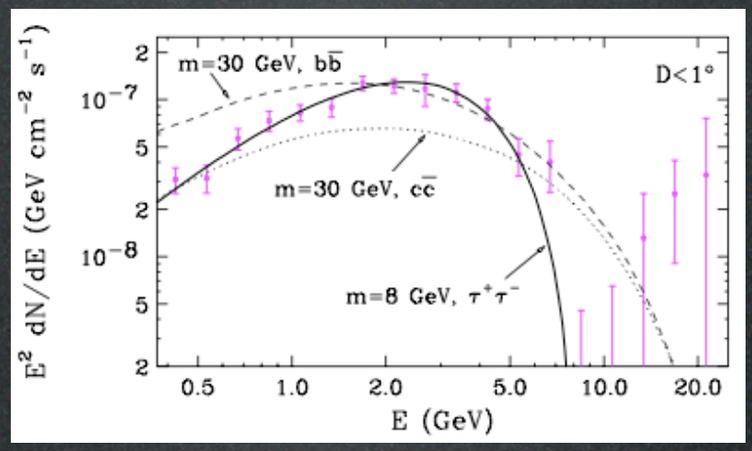


$$10^\circ < b < 30^\circ$$
$$-15^\circ < \ell < 15^\circ$$

Lin, Finkbeiner, Dobler 1004.0989



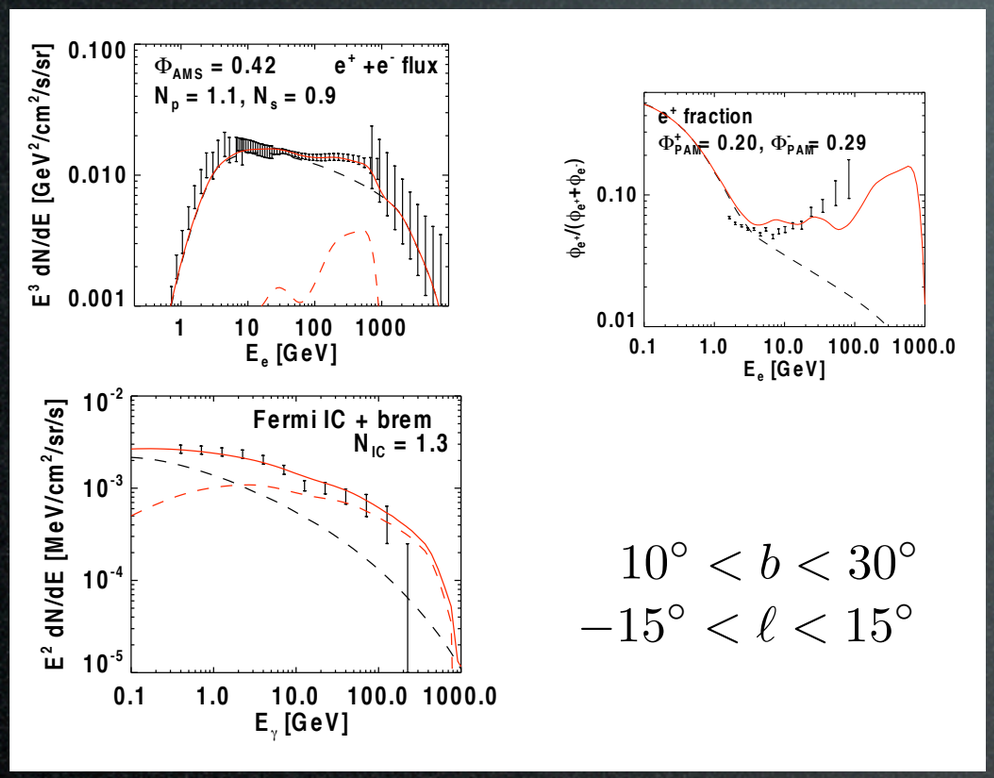
Hutsi, Hektor, Raidal 1004.2036



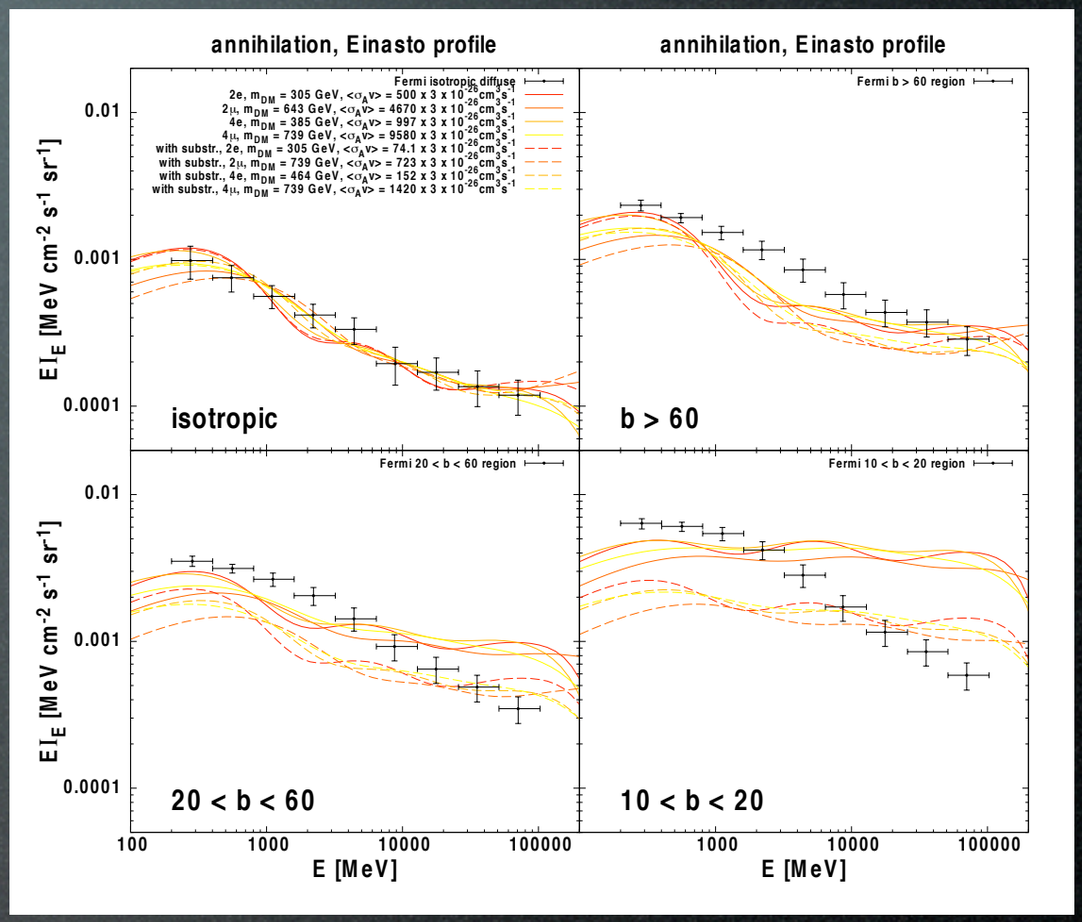
Hooper, Goodenough 1010.2752

Gamma hints?

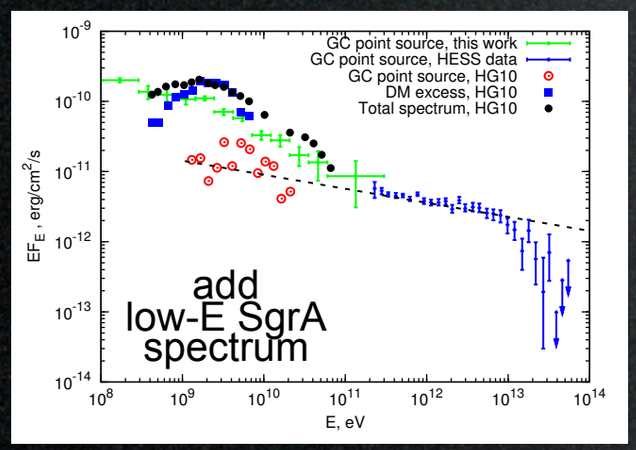
What if a signal of DM is *already* hidden in Fermi diffuse γ data?



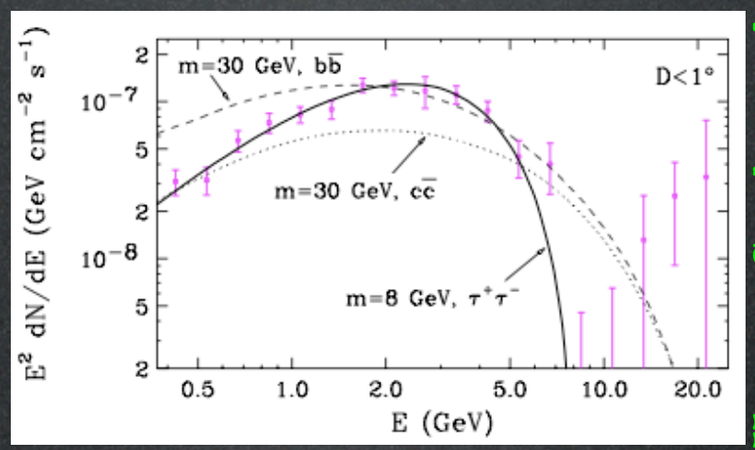
Lin, Finkbeiner, Dobler 1004.0989



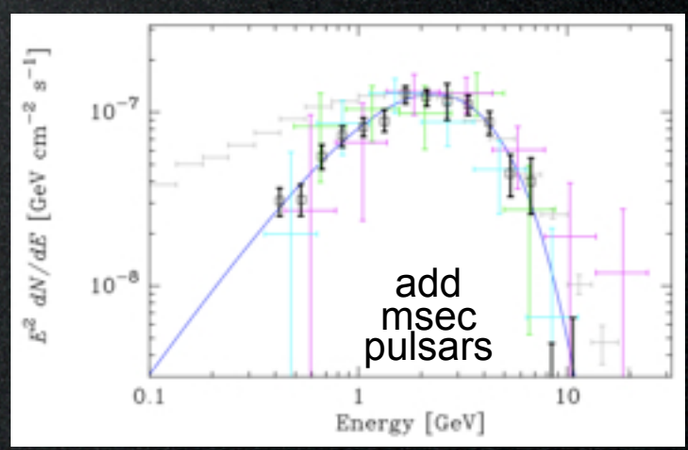
Hutsi, Hektor, Raidal 1004.2036



Boyarsky et al., 1012.5839



Hooper, Goodenough 1010.2752

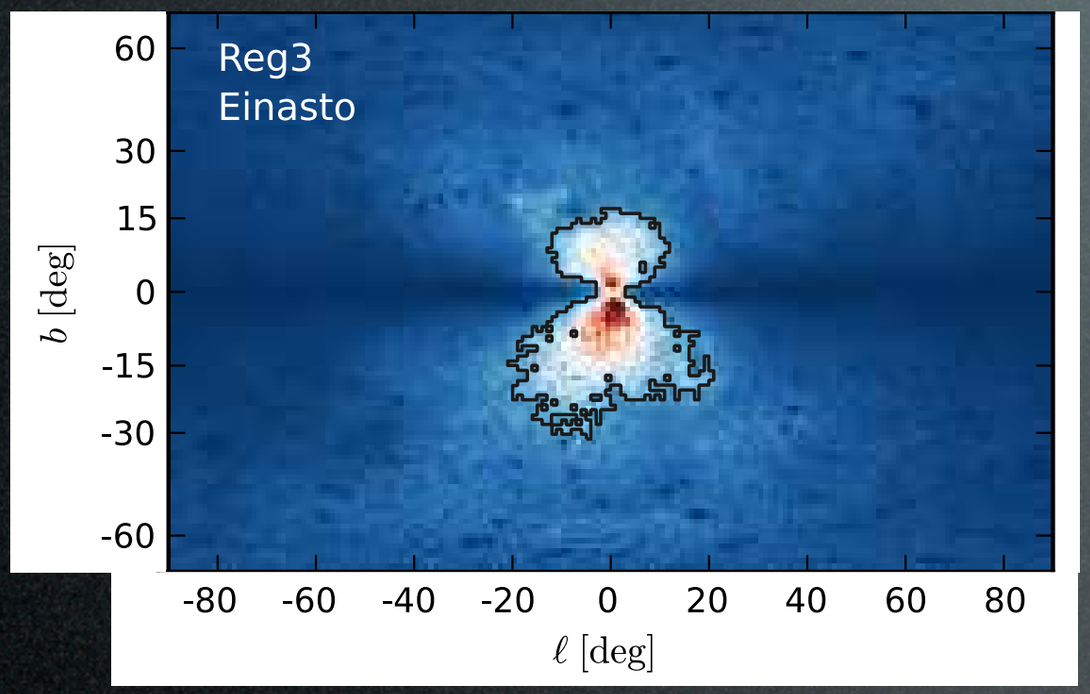


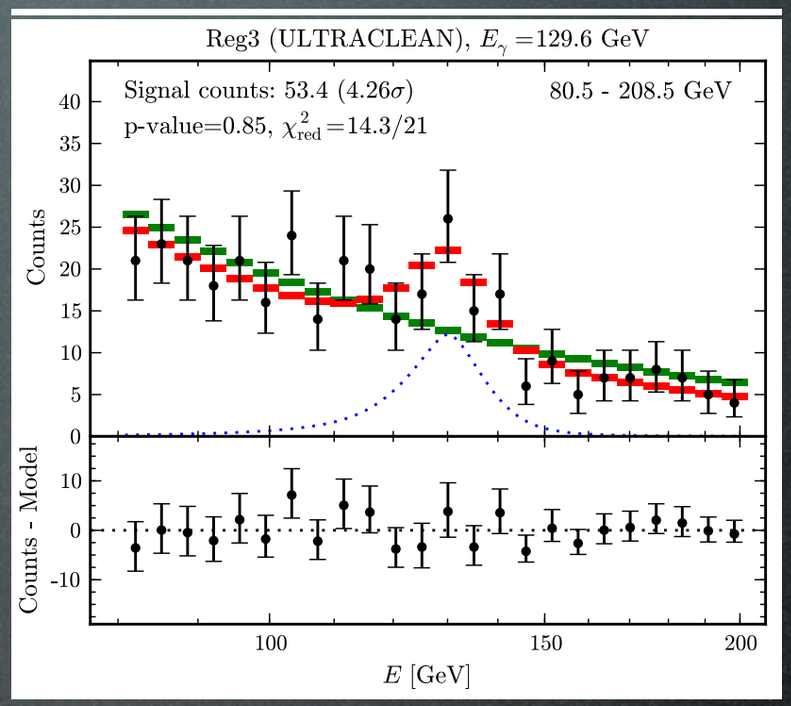
Abazajian 1011.4275

Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

Gamma hints? (cont'd)

What if a signal of DM is *already* hidden in Fermi diffuse γ data?





Ch. Weniger, 1204.2797

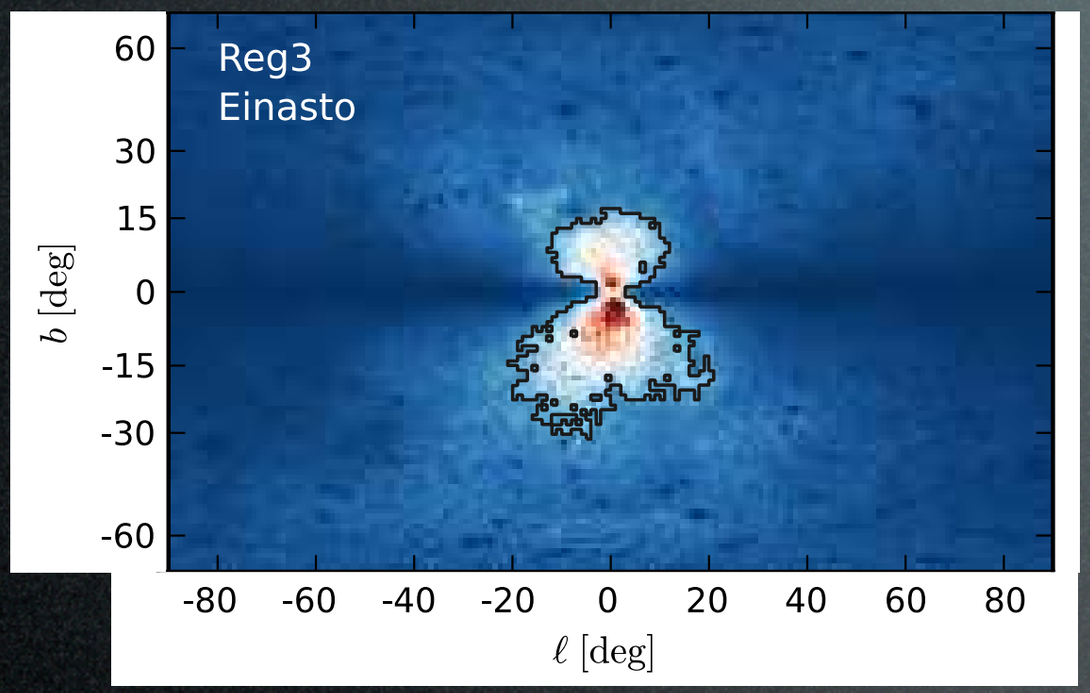
4.6σ (3.3σ with LEE)

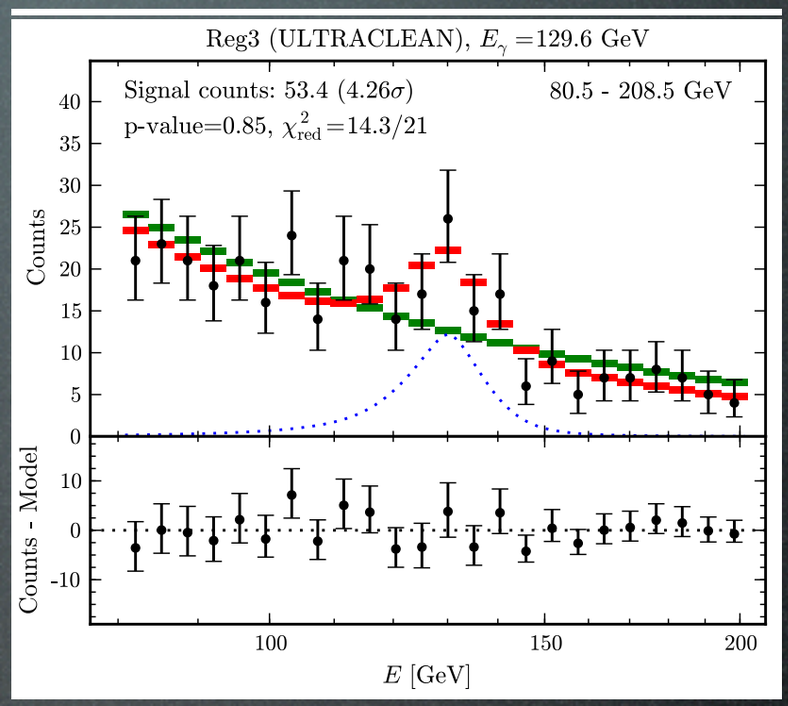
$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3 \cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}$ (large!)

Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

Gamma hints? (cont'd)

What if a signal of DM is *already* hidden in Fermi diffuse γ data?



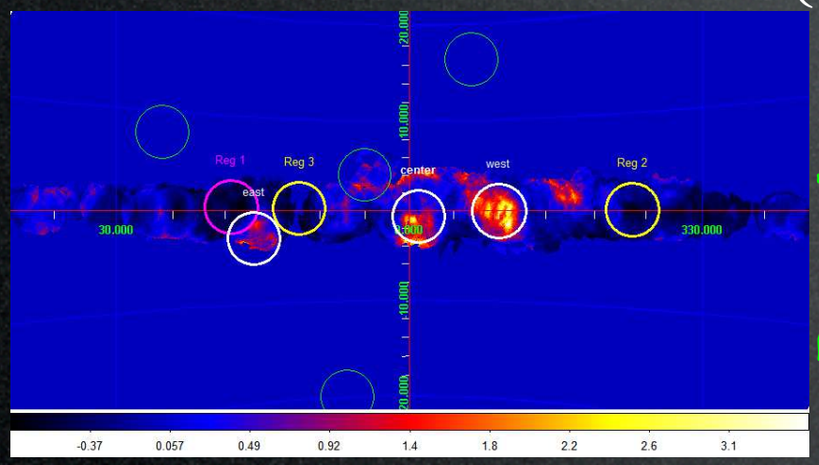


Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

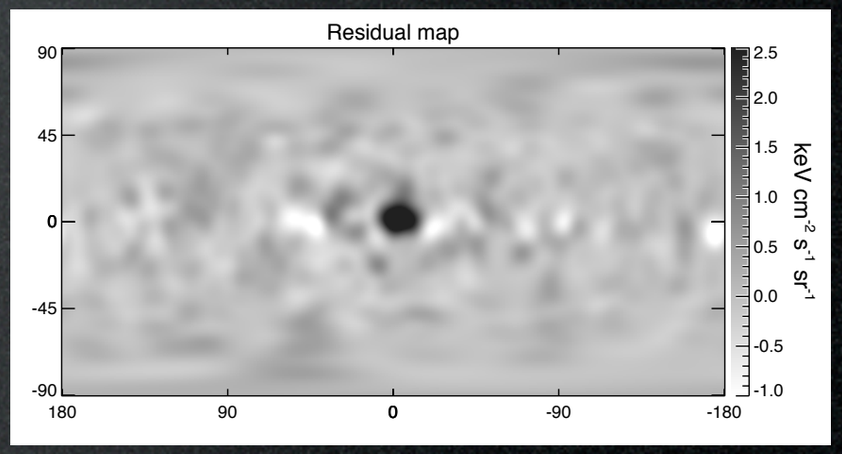
$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}$ (large!)

Similar excesses found elsewhere (fluctuation?)



Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is actually (only) in the GC



Su, Finkbeiner, 1206.1616

Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

Theorist's reaction

Theorist's reaction



Challenges for the 'conventional' DM candidates

Needs:	SuSy DM	KK DM
- TeV or multi-TeV masses	difficult	ok
- no hadronic channels	difficult	difficult
- very large flux	no	ok

for any Majorana DM,
s-wave annihilation cross section

$$\sigma_{\rm ann}(\mathrm{DM}\,\bar{\mathrm{DM}} \to f\bar{f}) \propto \left(\frac{m_f}{M_{\rm DM}}\right)^2$$

Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$ with $\sigma \simeq 10^{-23} \mathrm{cm}^3/\mathrm{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$
+ (Wimponium)		

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

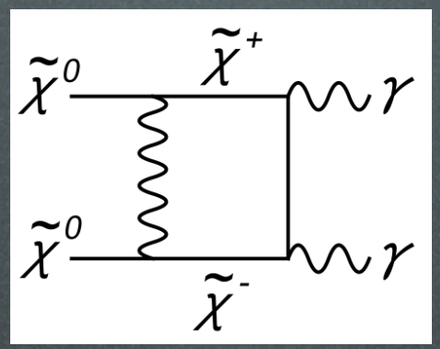
Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

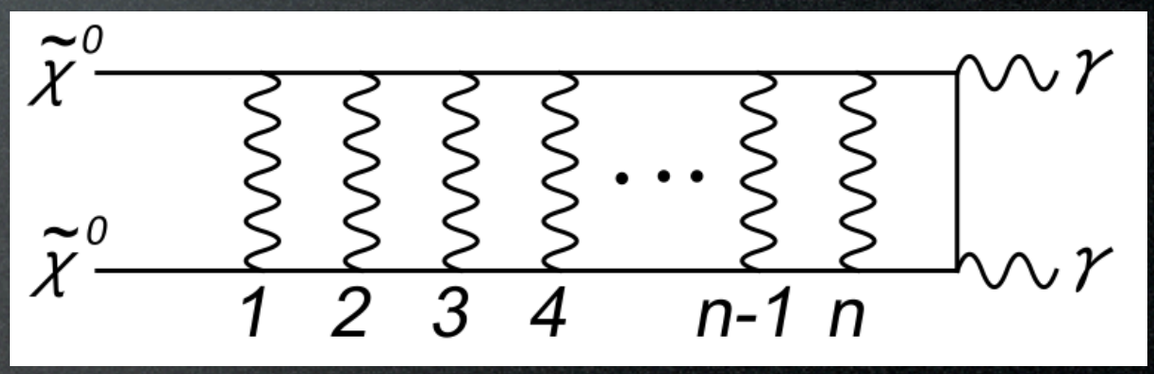
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:

New models with a rich Dark sector

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17}{\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26}{\rm sec}$$

Motivations from theory?

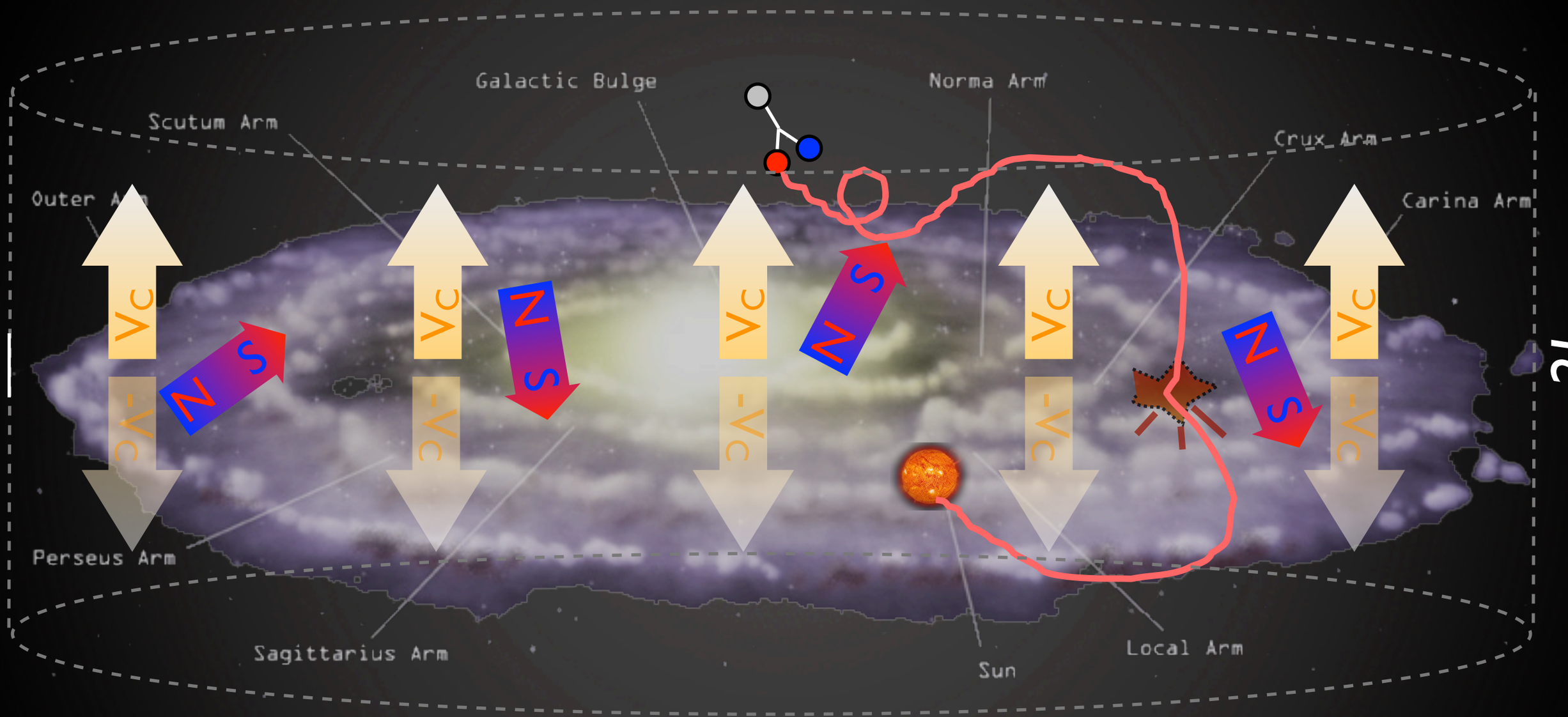
- dim 6 suppressed operator in GUT Arvanitaki, Dimopoulos et al., 2008+09

$$\tau_{\rm DM} \simeq 3 \cdot 10^{27}{\rm sec} \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2 \cdot 10^{16}\,{\rm GeV}}\right)^4$$

- or in TechniColor Nardi, Sannino, Strumia 2008
- gravitino in SuSy with broken R-parity...

Indirect Detection

$\bar{p}$ and e^+ from DM decay in halo



What sets the overall expected flux?

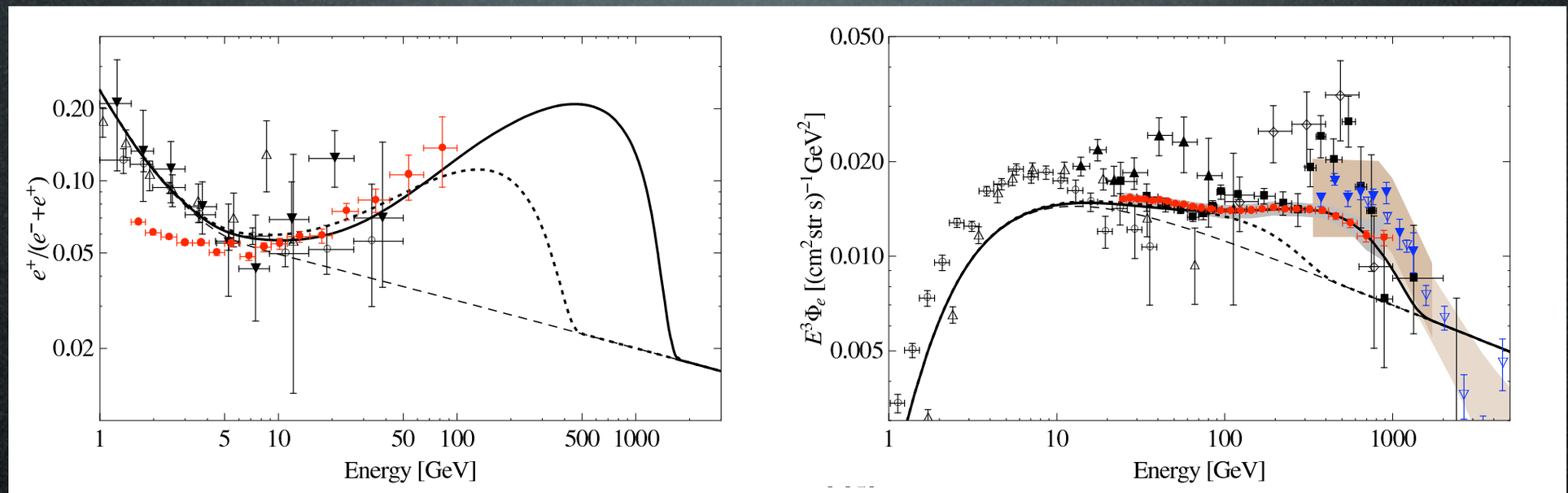
$$\text{flux} \propto n\ \Gamma_{\text{decay}}$$

$$\Gamma^{-1}_{\text{decay}} = \tau_{\text{decay}} \approx 10^{26}\text{sec}$$

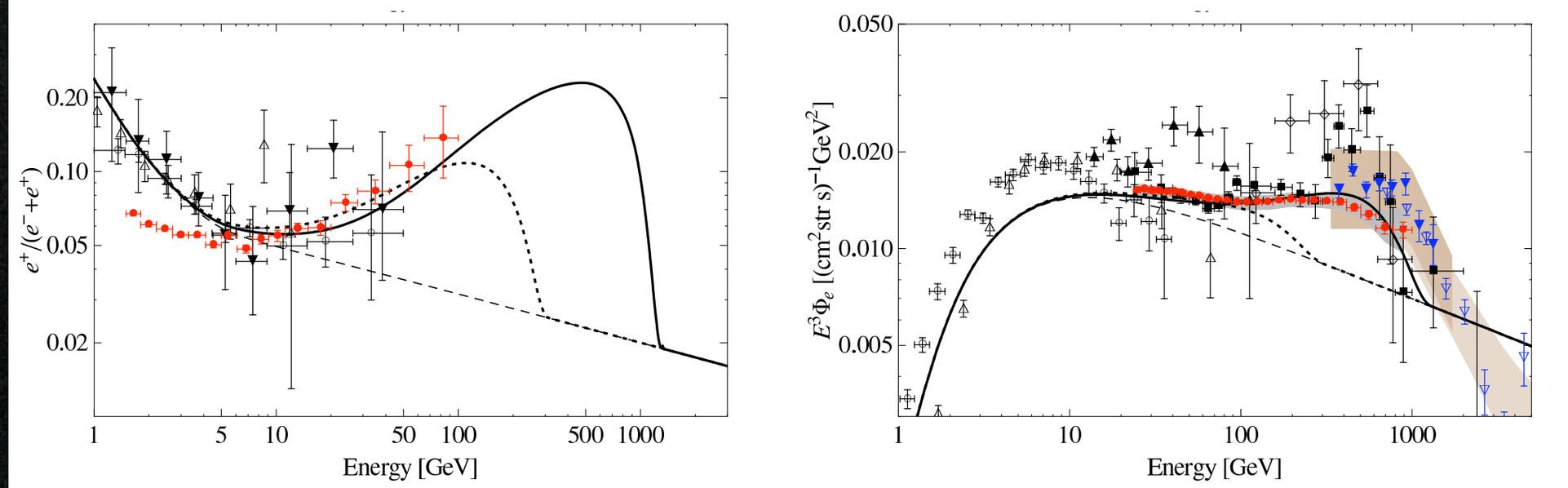
Decaying DM

Which DM spectra can fit the data?

E.g. a fermionic $\mathrm{DM} \to \mu^+\mu^-\nu$ with $M_{\mathrm{DM}} = 3.5\,\mathrm{TeV}$:



E.g. a scalar $\mathrm{DM} \to \mu^+\mu^-$ with $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

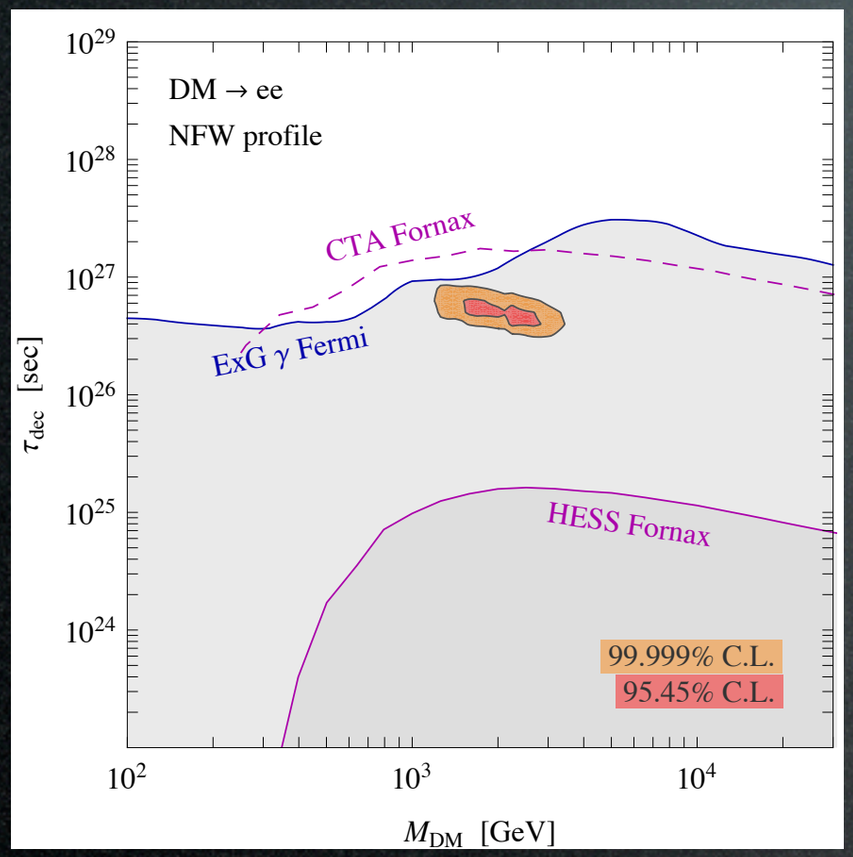


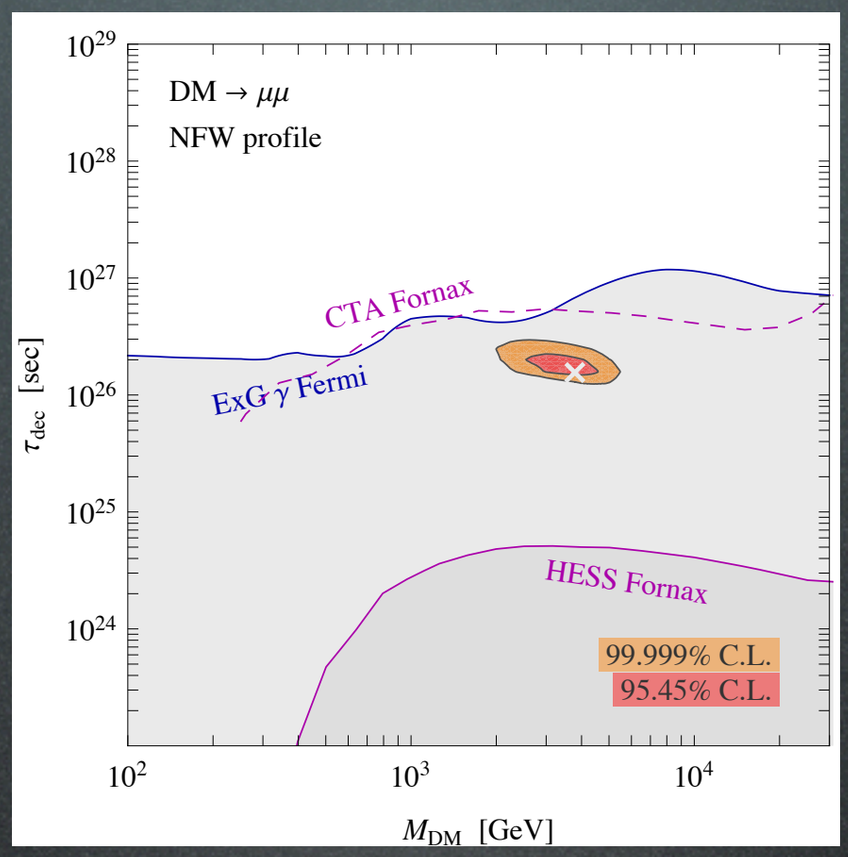
Ibarra, Tran, Weniger 2009

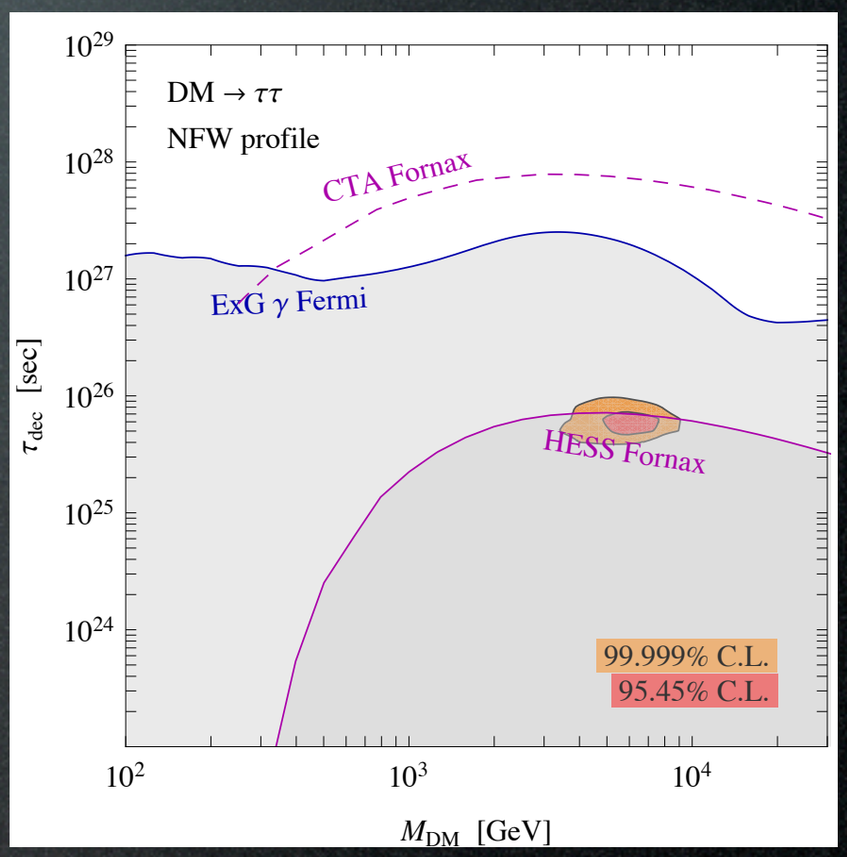
Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)







Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

The PAMELA and FERMI regions are in conflict with these gamma constraints.

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:

New models with a rich Dark sector

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:
  New models with a rich Dark sector
  - TeV mass DM
  - new forces (that Sommerfeld enhance)
  - leptophilic because: - kinematics (light mediator)
    - DM carries lepton #

- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153
A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

The "Theory of DM"

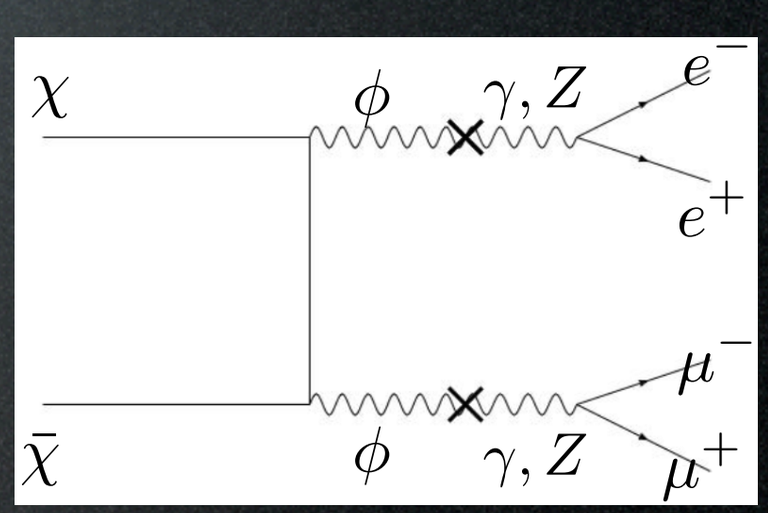
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



The "Theory of DM"

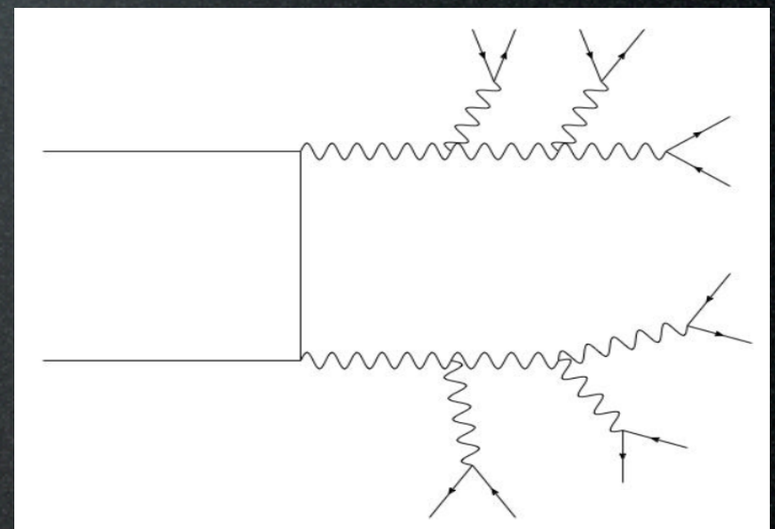
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit

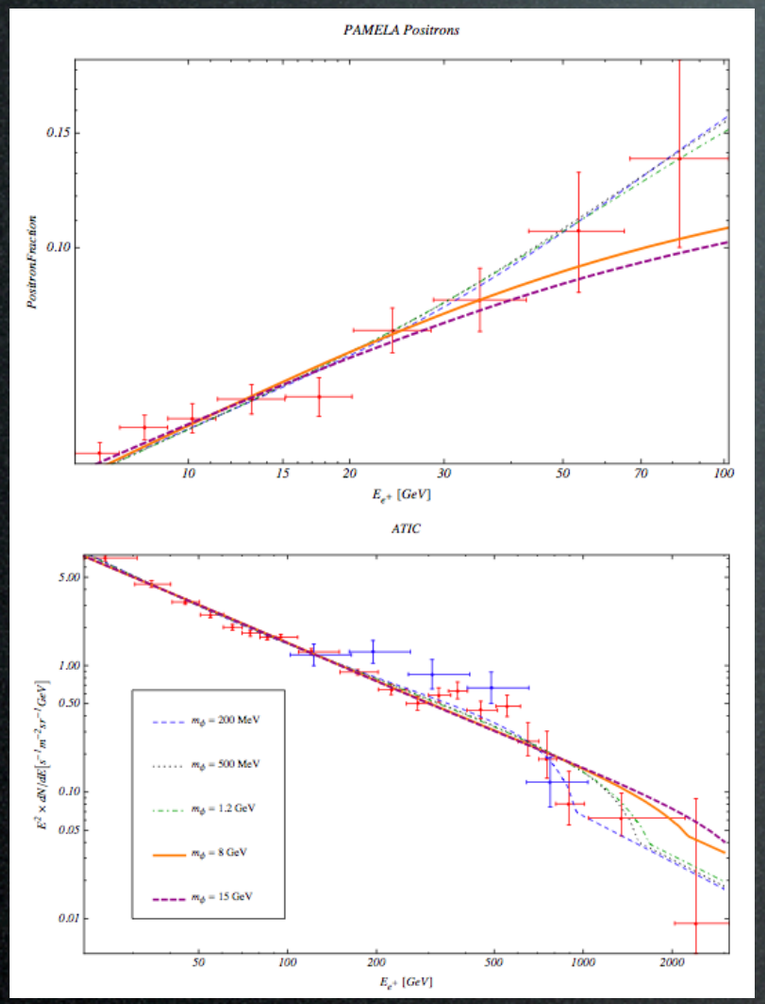


Extras:

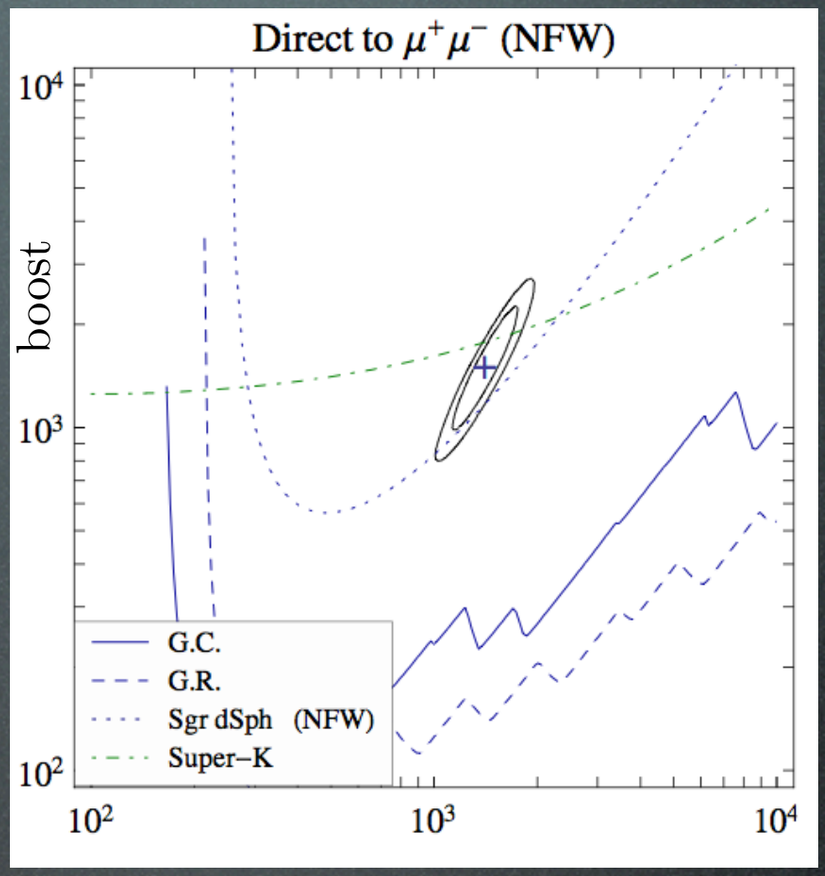
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

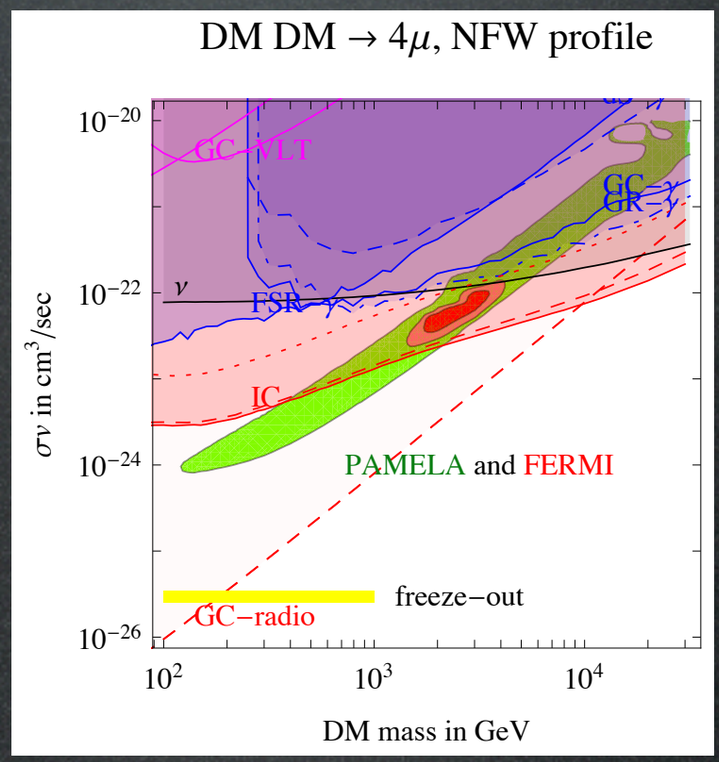
Phenomenology:

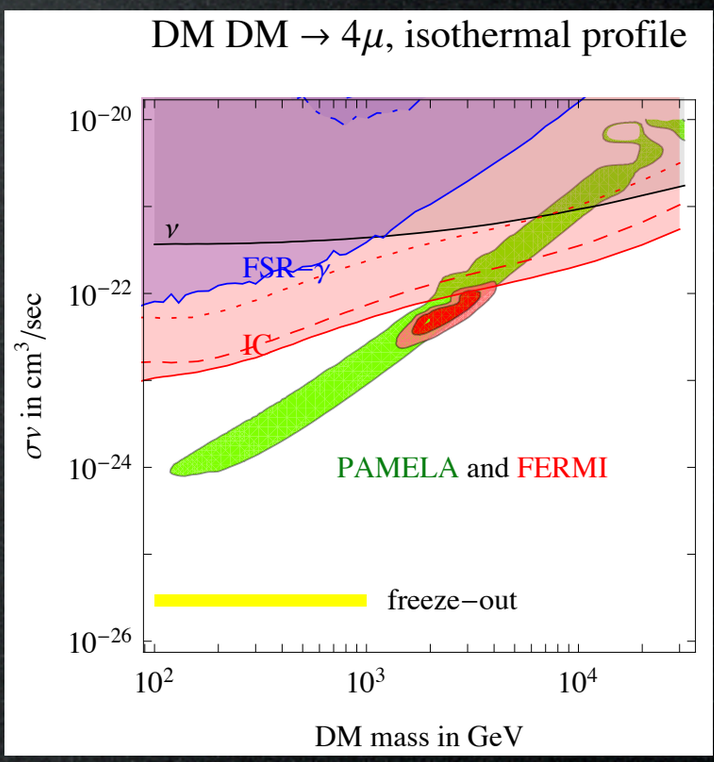


Meade, Papucci, Volanski 0901.2925



Mardon, Nomura, Stolarski, Thaler 0901.2926





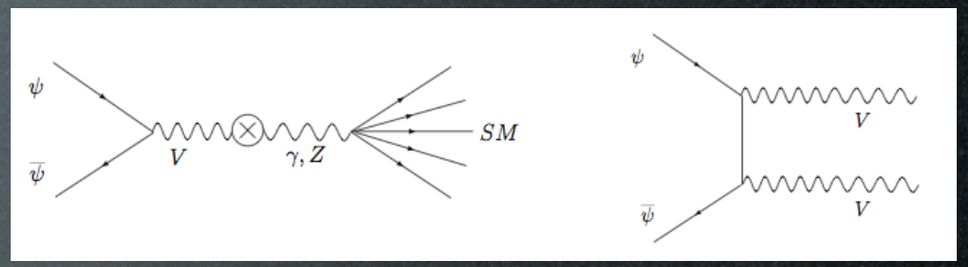
Strumia, Papucci 0912.0742

Variations

(selected)

★ pioneering: Secluded DM, U(1) Stückelberg extension of SM

Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



★ Axion Portal: ϕ is pseudoscalar axion-like

Nomura, Thaler 0810.5397

★ singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

Bai, Han 0811.0387

★ split UED: χ annihilates only to leptons because quarks are on another brane

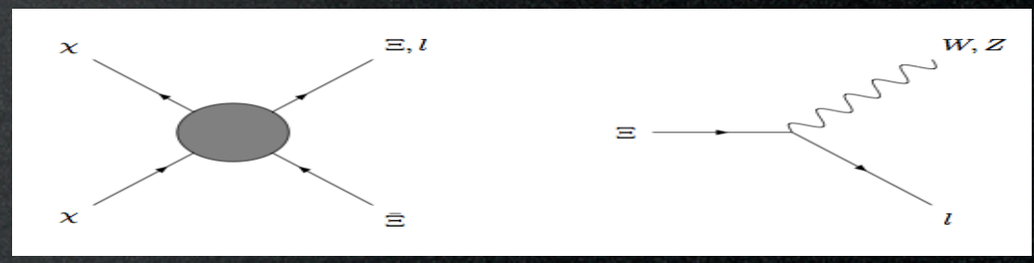
Park, Shu 0901.0720

★ DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson $(m_\phi \sim \text{tens GeV})$

Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399

★ New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim 100\text{s GeV})$

Phalen, Pierce, Weiner 0901.3165



★ .....

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

[jump to end]

Direct Detection: **basics**



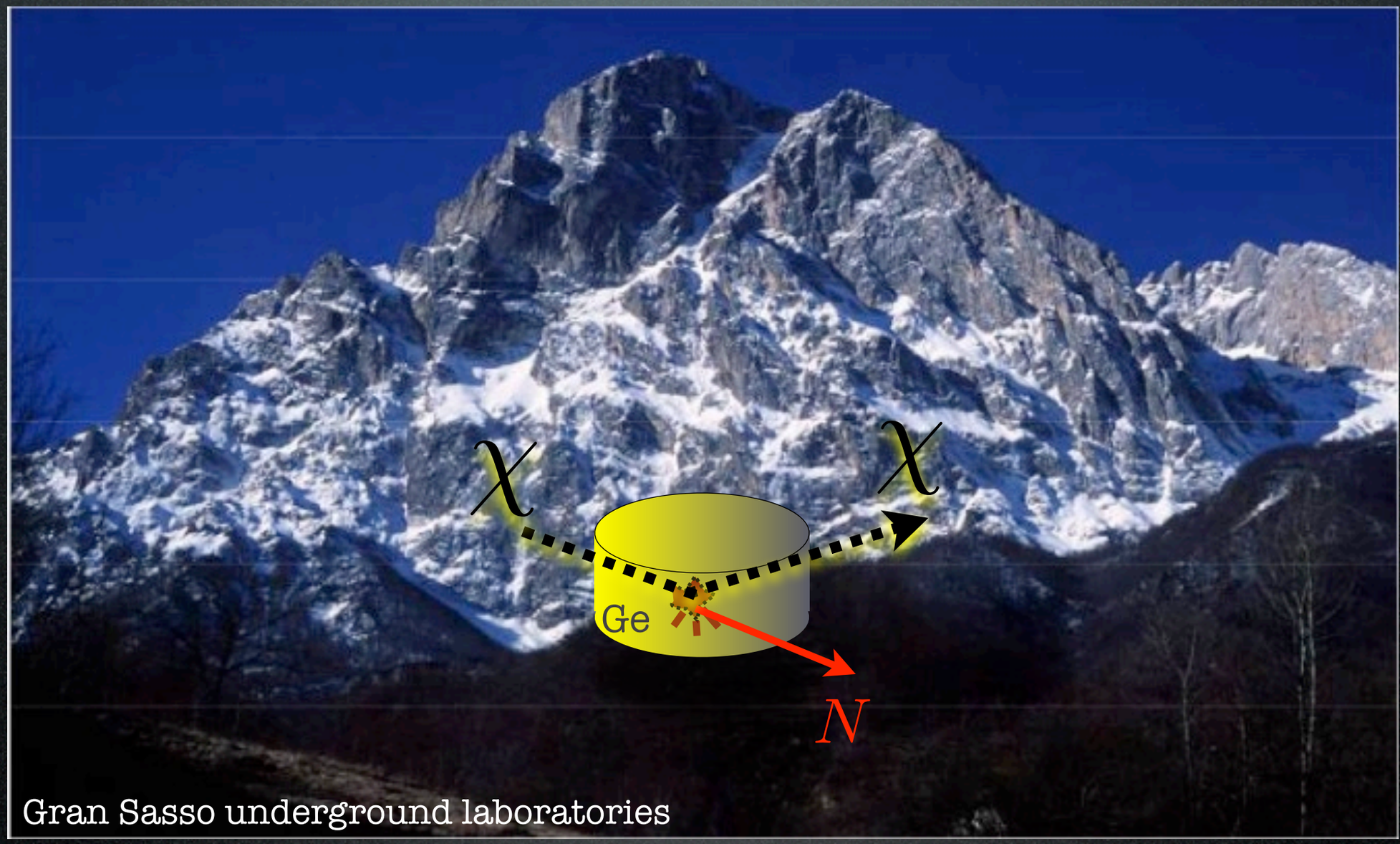
Gran Sasso underground laboratories

Direct Detection: basics



Gran Sasso underground laboratories

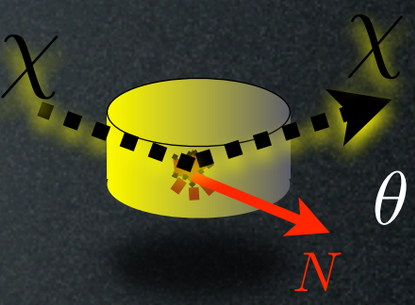
Direct Detection: basics



Gran Sasso underground laboratories

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



$$\mu_\chi = \frac{m_\chi\, m_N}{m_\chi + m_N} \to \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\ \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

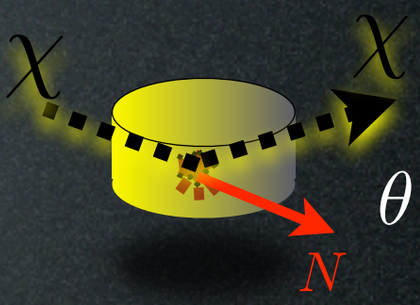
$\sigma \approx \sigma_n^{\rm SI}\, A^4$ × nuclear form factors

number of events

$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



$$\mu_\chi = \frac{m_\chi\, m_N}{m_\chi + m_N} \to \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

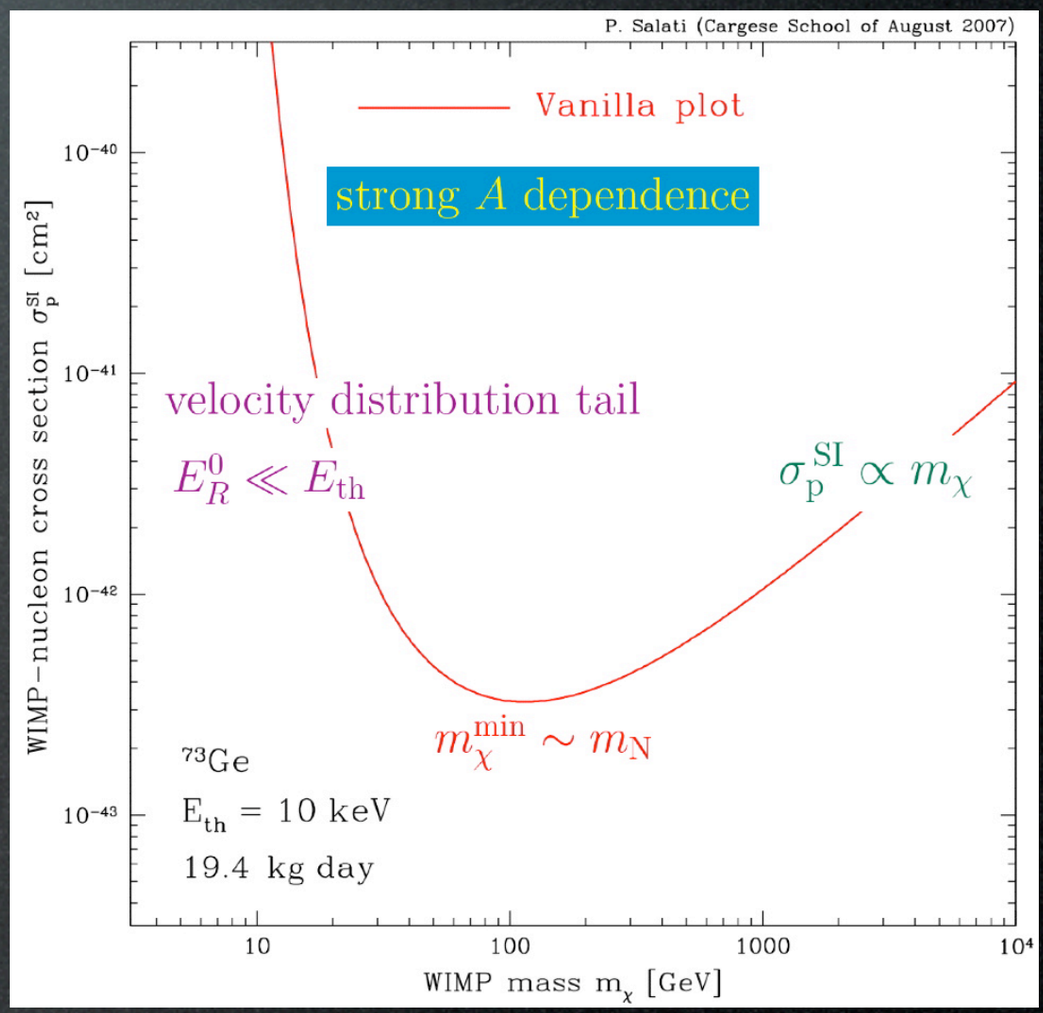
$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\ \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

$$\sigma \approx \sigma_n^{\rm SI} A^4 \times \text{nuclear form factors}$$

number of events

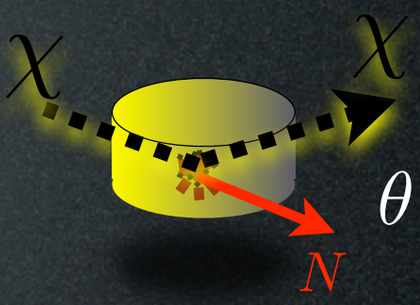
$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$



P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



$$\mu_\chi = \frac{m_\chi\, m_N}{m_\chi + m_N} \to \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

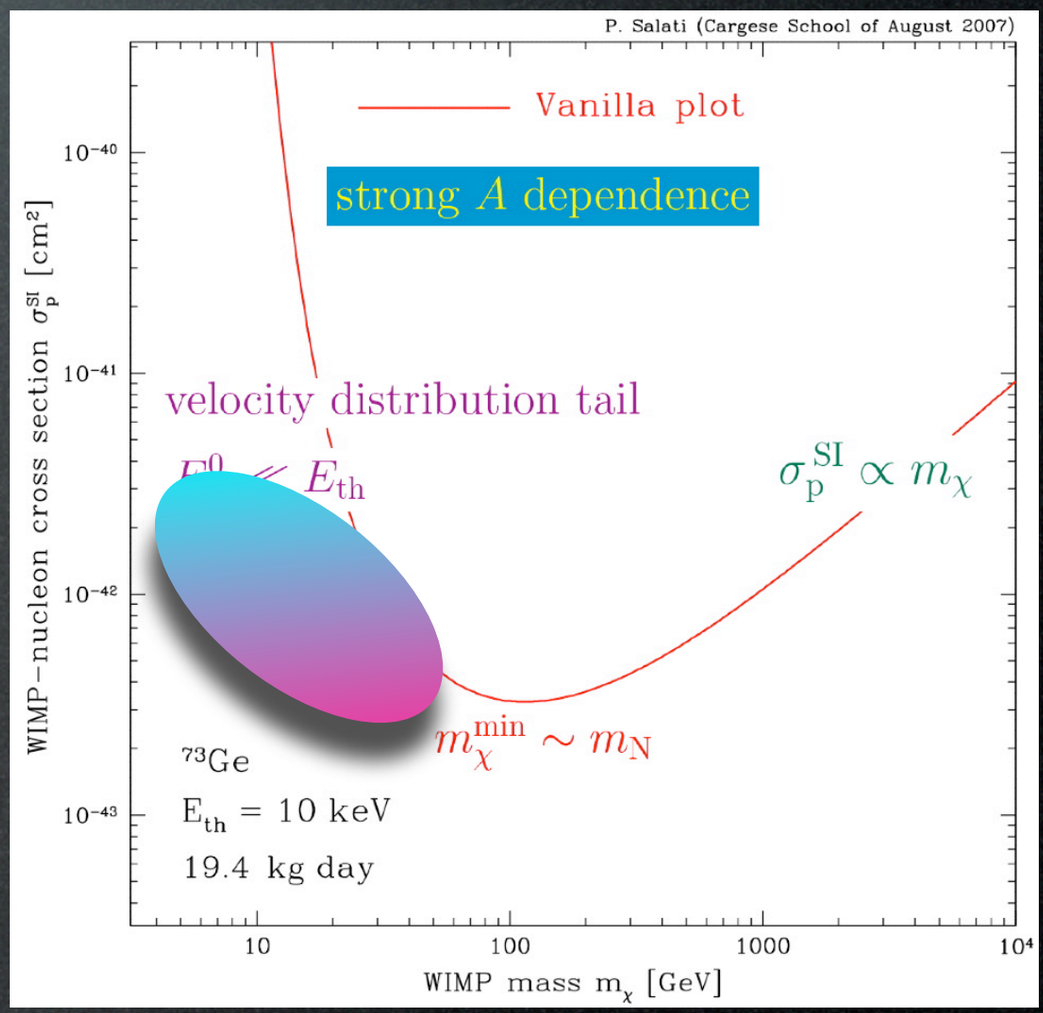
$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\, \mathrm{d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

$$\sigma \approx \sigma_n^{\rm SI} A^4 \times \text{nuclear form factors}$$

number of events

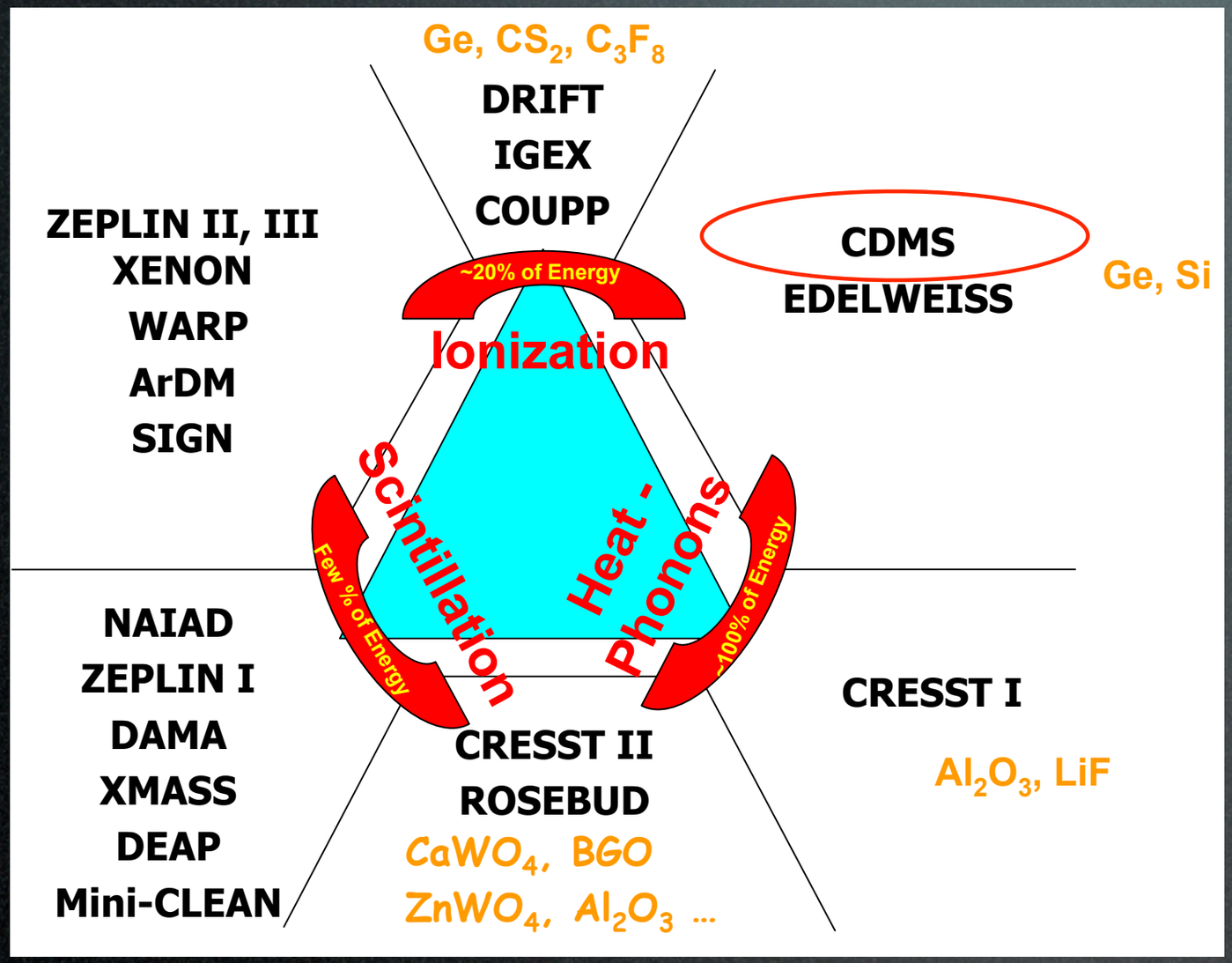
$$N = \mathcal{E}\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$



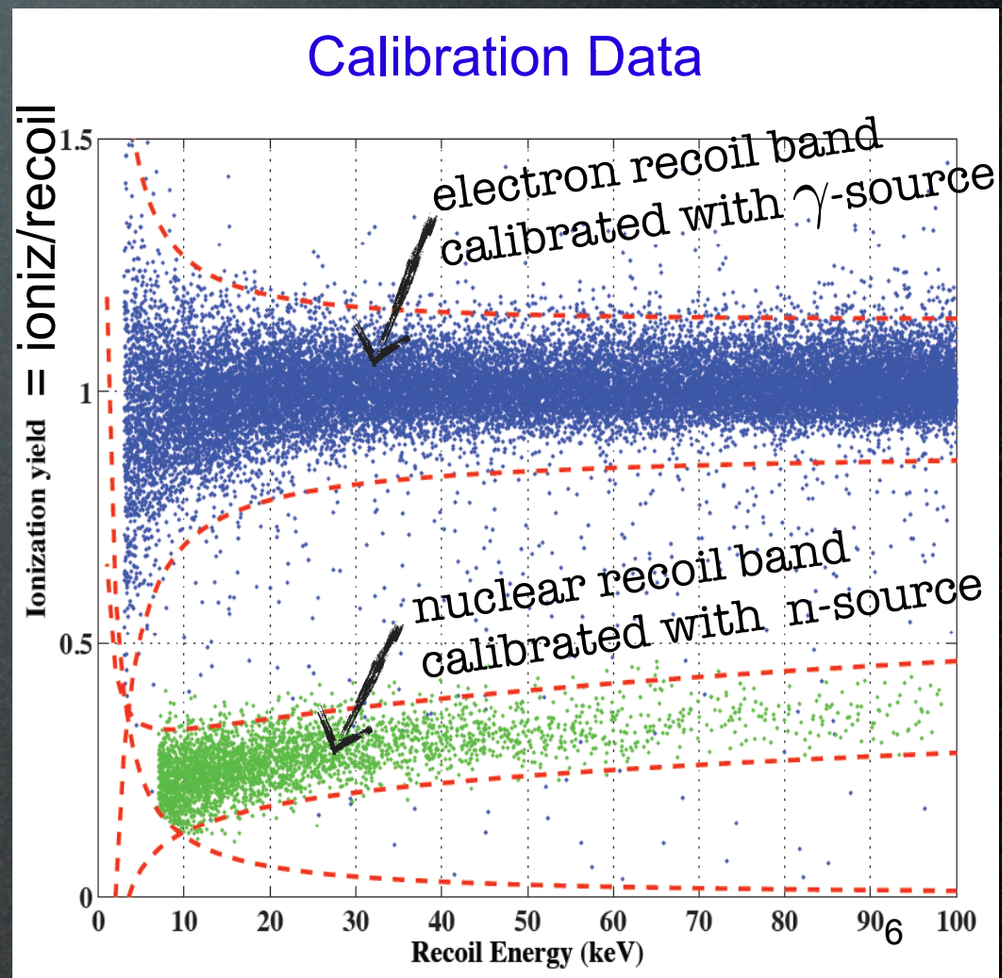
P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

Background rejection



[credit: B.Sadoulet]



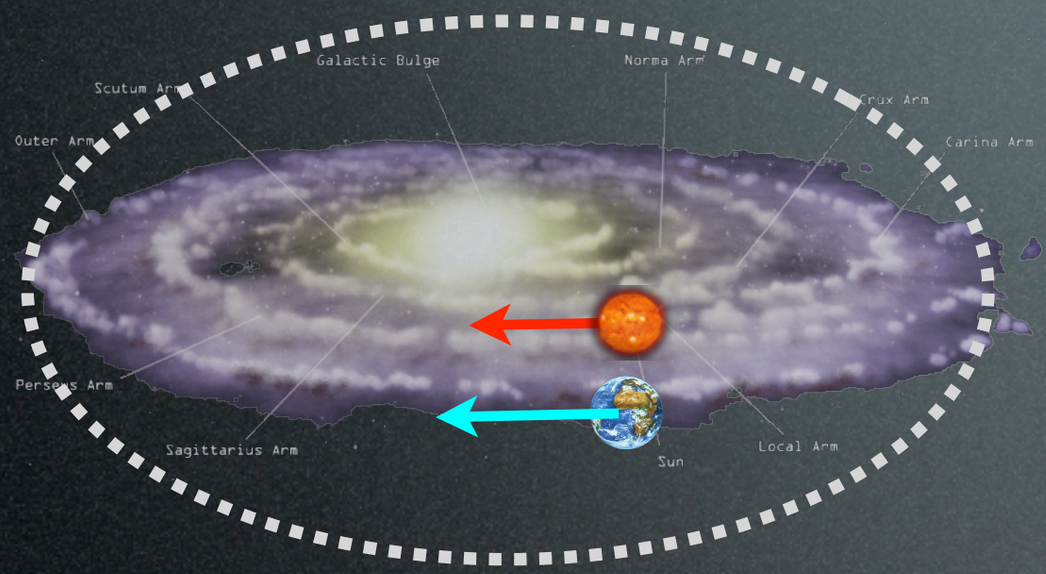
CDMS coll.

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

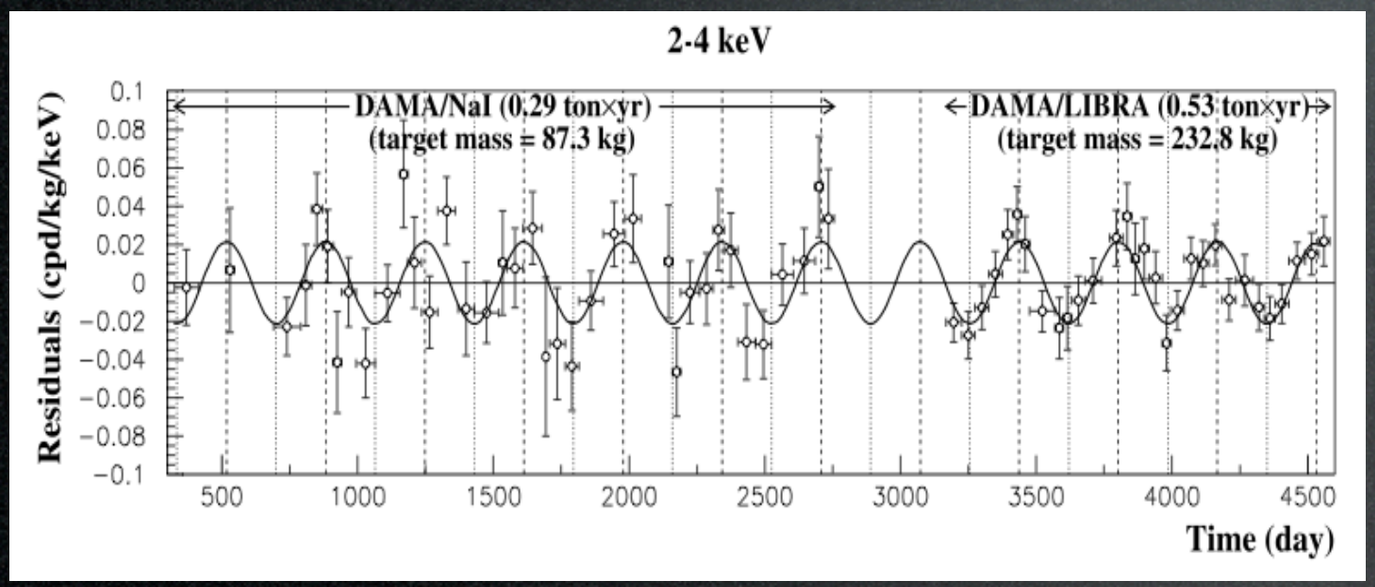
Direct Detection: hints

DAMA/Libra

NaI(Tl)



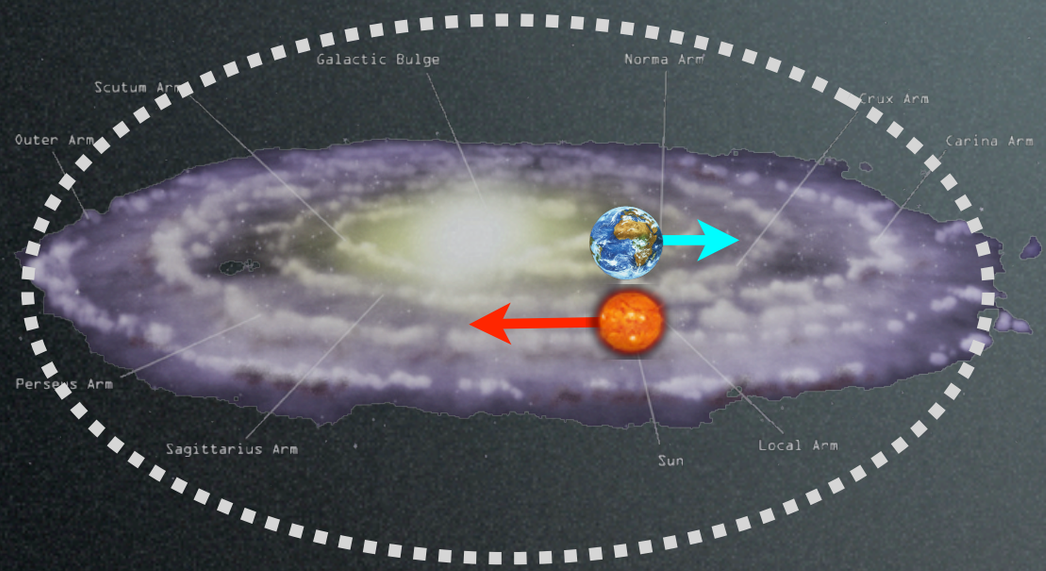
Annual modulation seen (8σ):



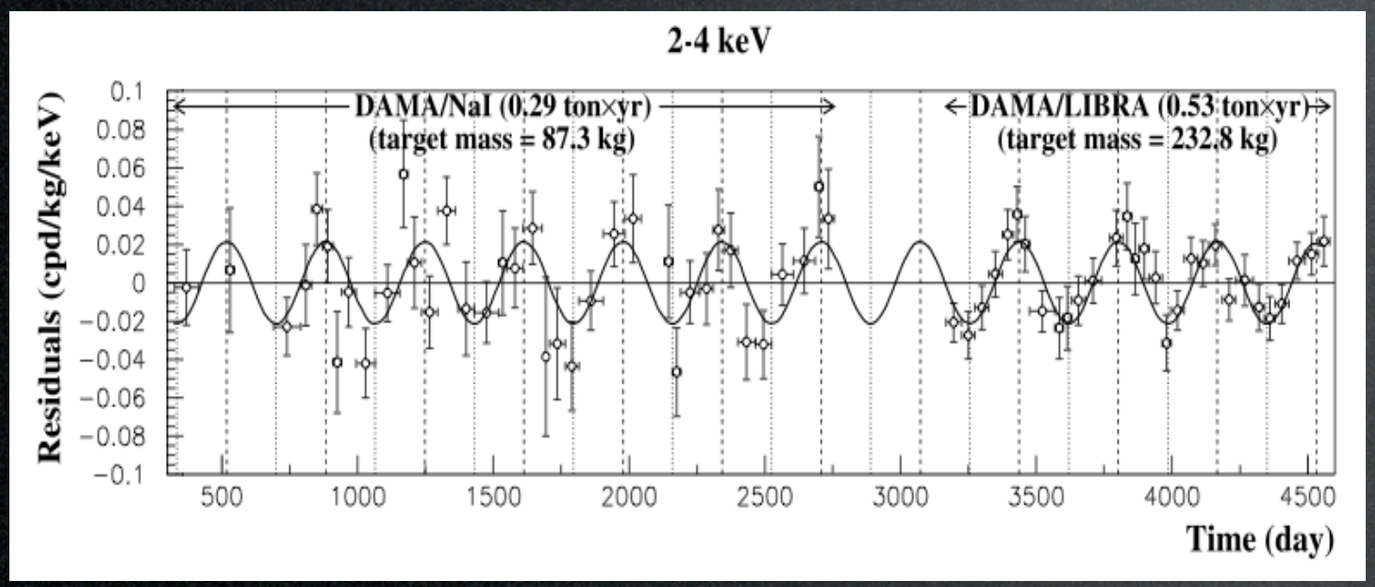
DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



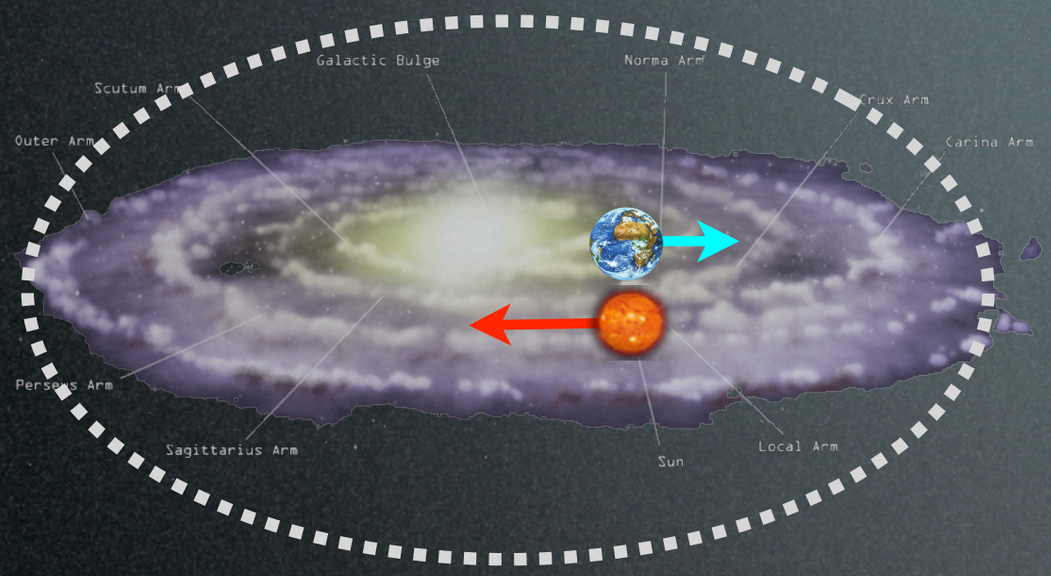
Annual modulation seen (8σ):



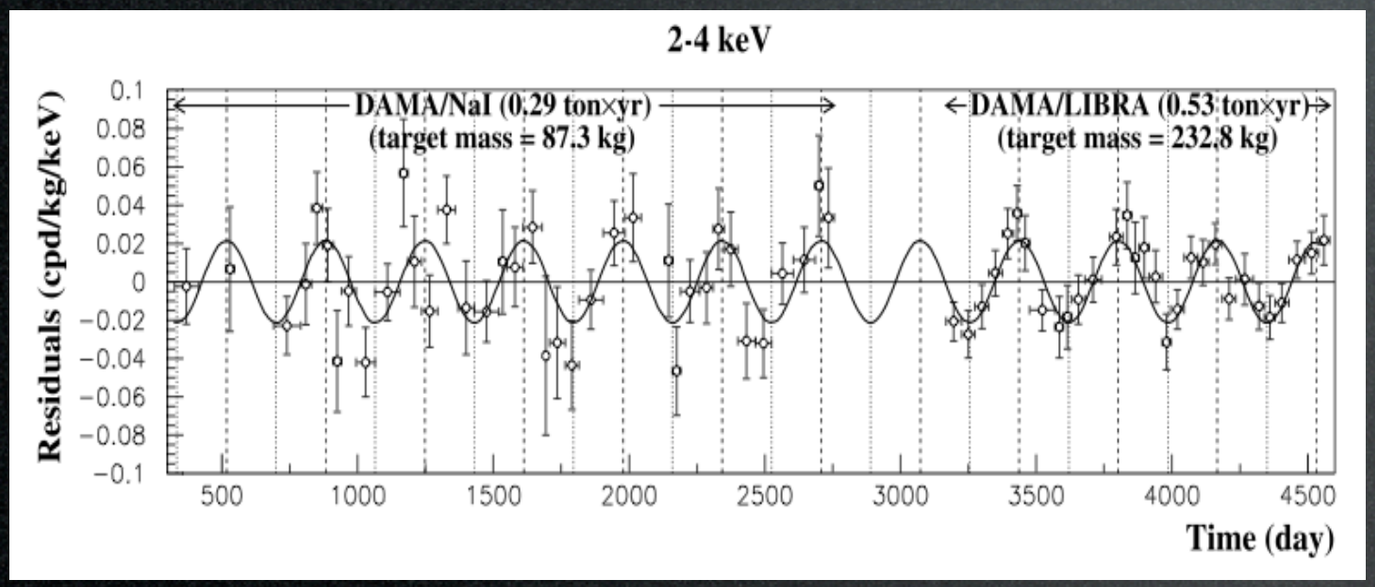
DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):



DAMA Coll., 0804.2741, 2008

An instrumental effect?

Summary of the results obtained in the additional investigations of possible systematics or side reactions
(DAMA/LIBRA - NIMA592(2008)297, EPJC56(2008)333)

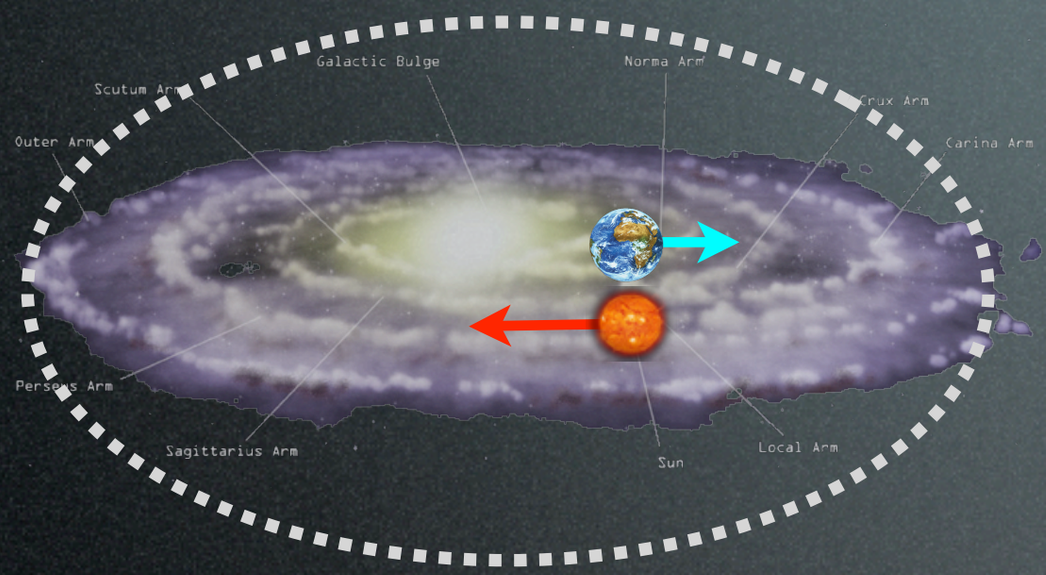
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured by MACRO	**$<3\times10^{-5}$ cpd/kg/keV**

+ even if larger they cannot satisfy all the requirements of annual modulation signature → **Thus, they can not mimic the observed annual modulation effect**

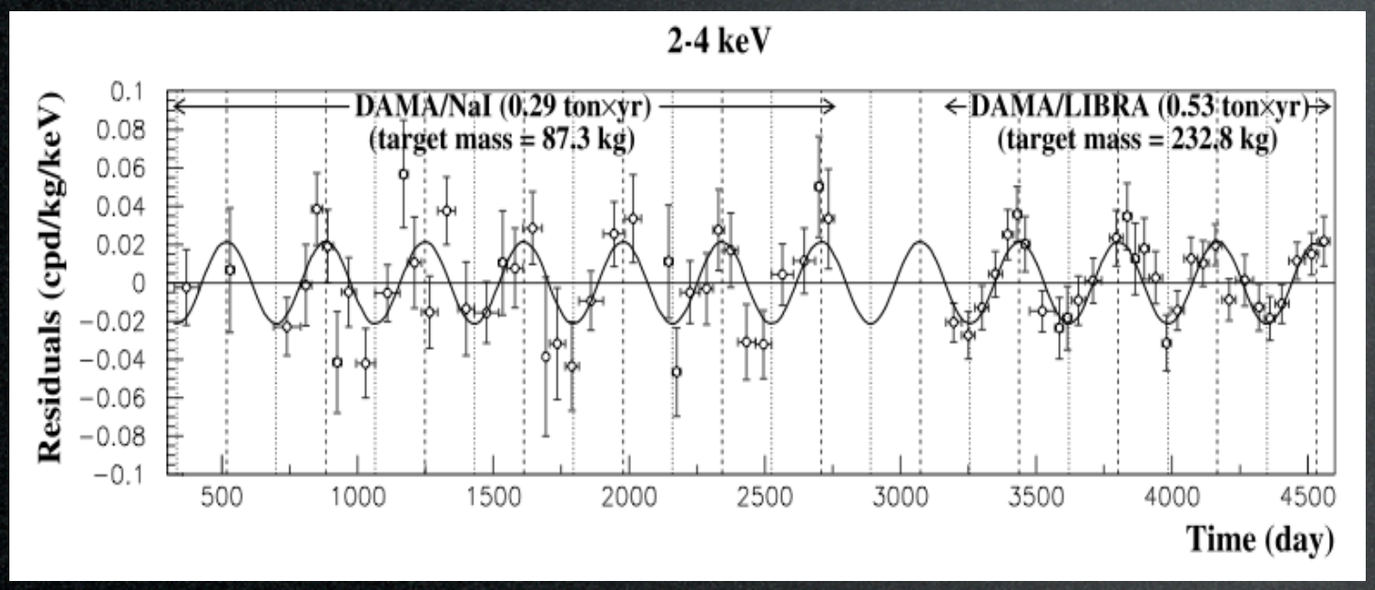
'NO!' e.g. P.Belli, KITP workshop 12.2009

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

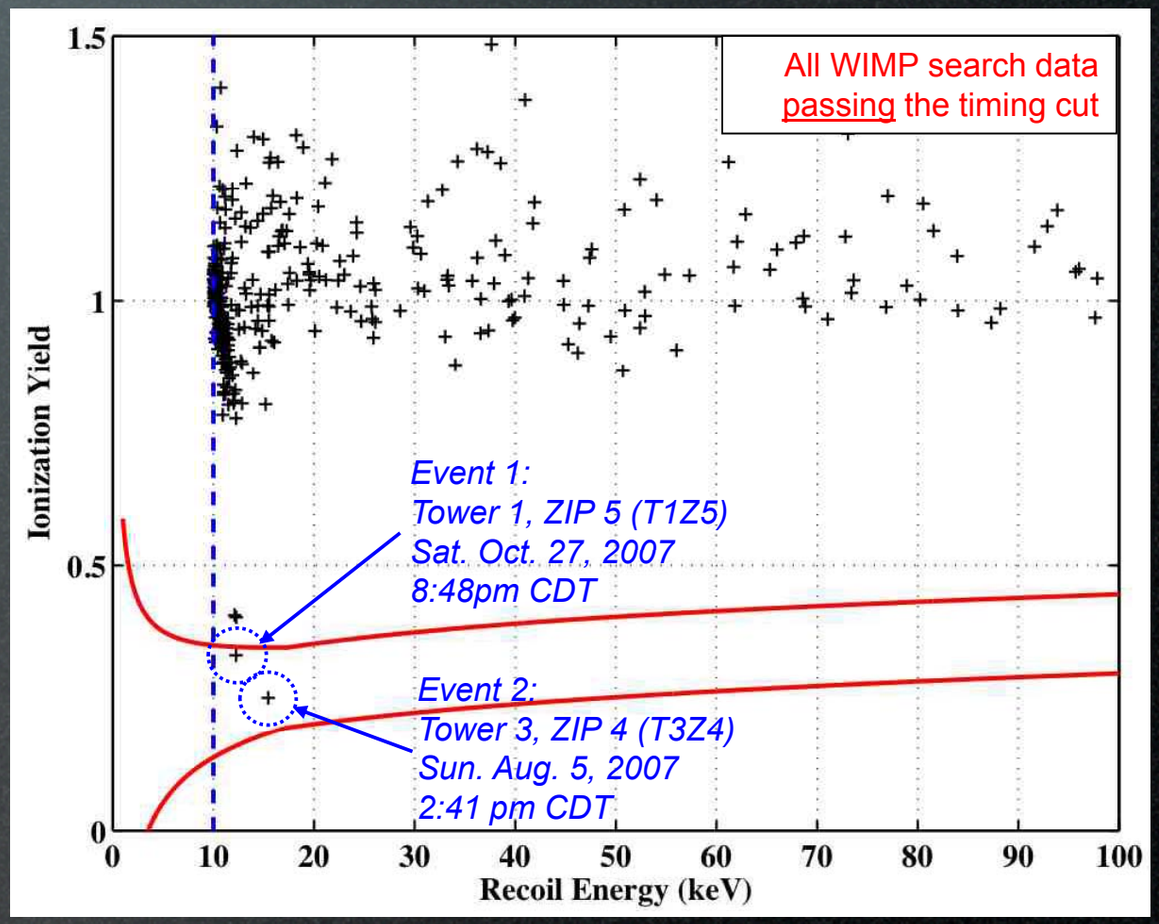


DAMA Coll., 0804.2741, 2008

CDMS

Ge+Si

2 events seen,
with 0.6 exp'd background

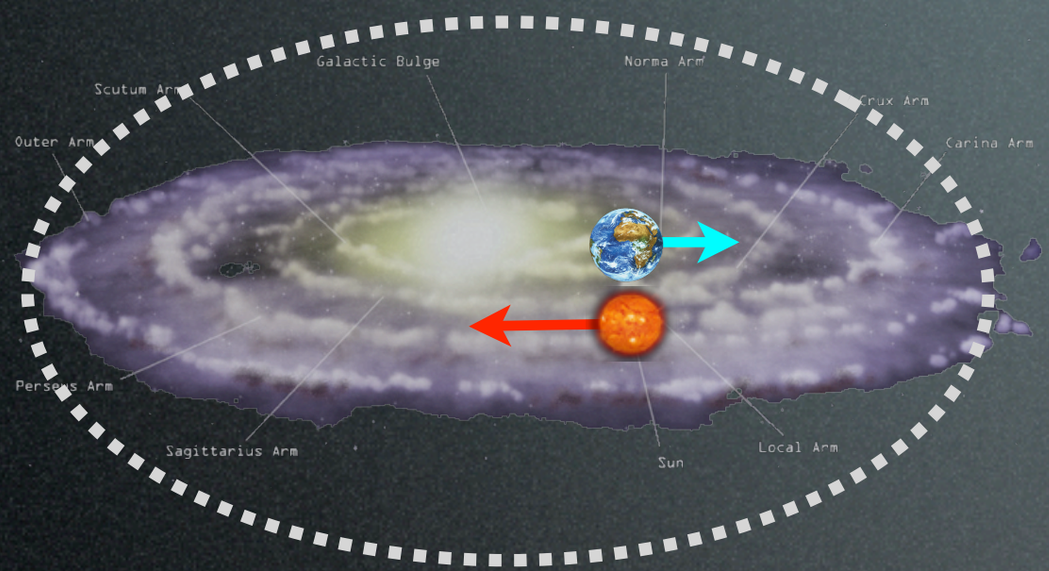


CDMS coll., Science 327 (2010), 0912.3592

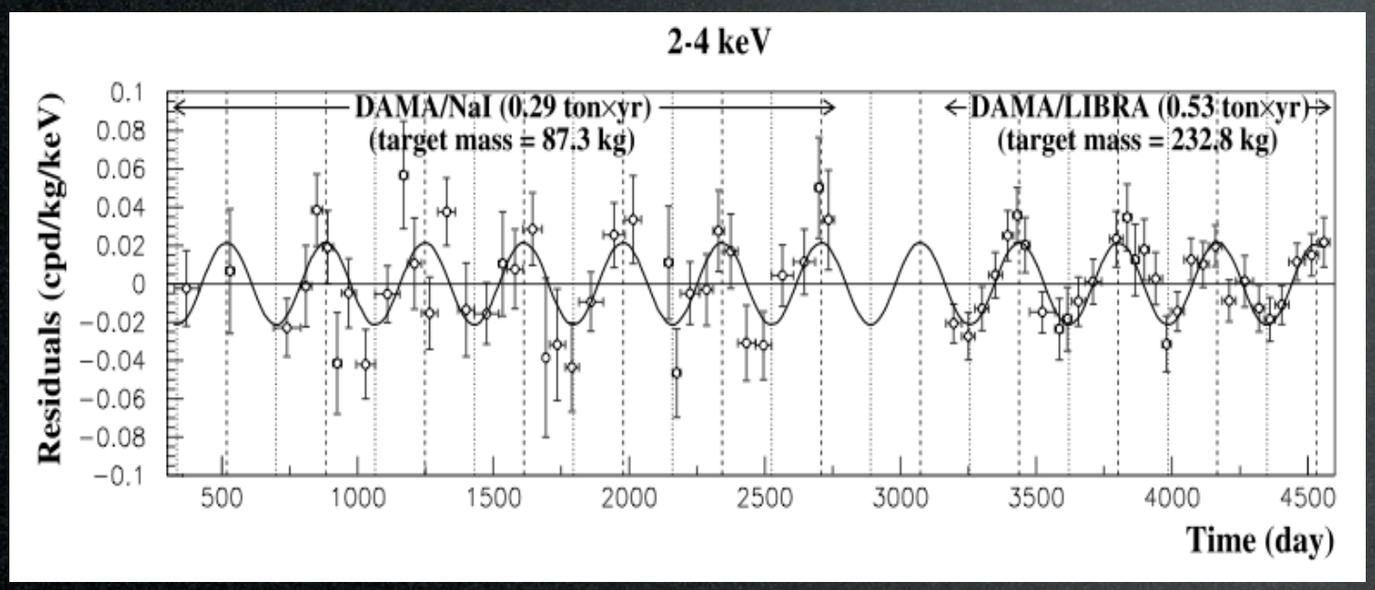
cited 500 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

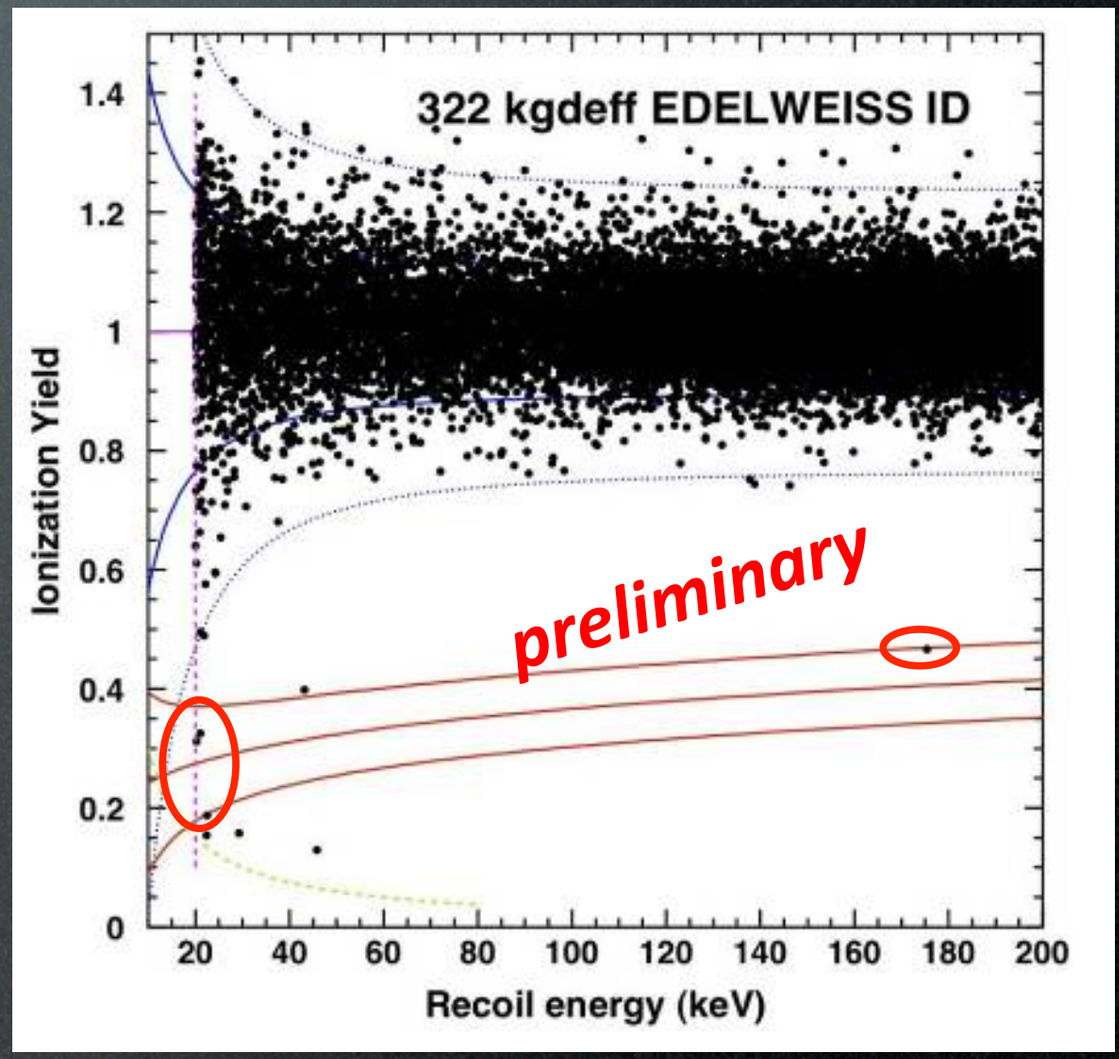


DAMA Coll., 0804.2741, 2008

Edelweiss Ge

3 events seen

'background starts to appear'

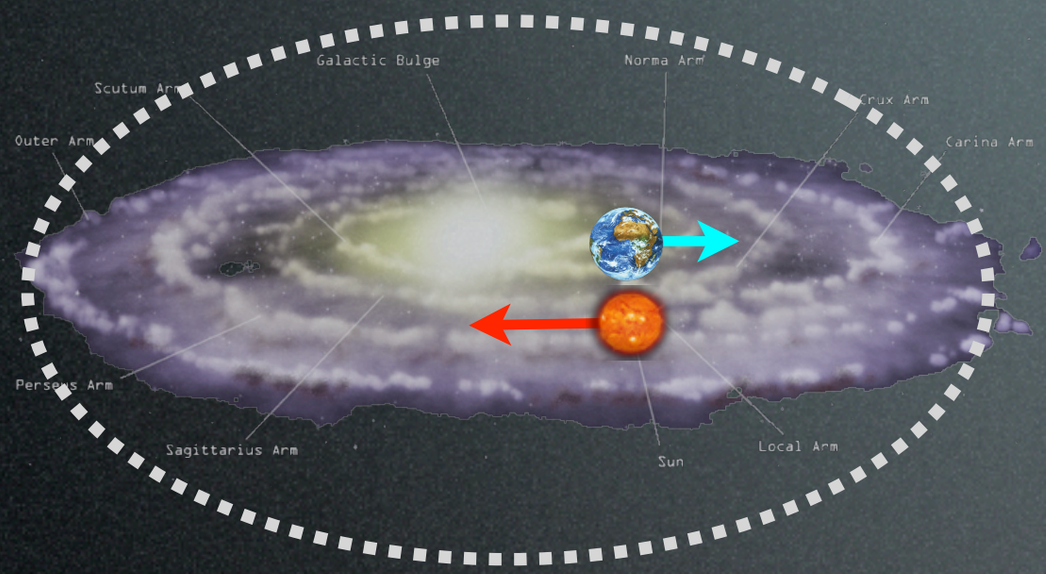


Edelweiss coll, TeVPA 2010 and 1011.2319

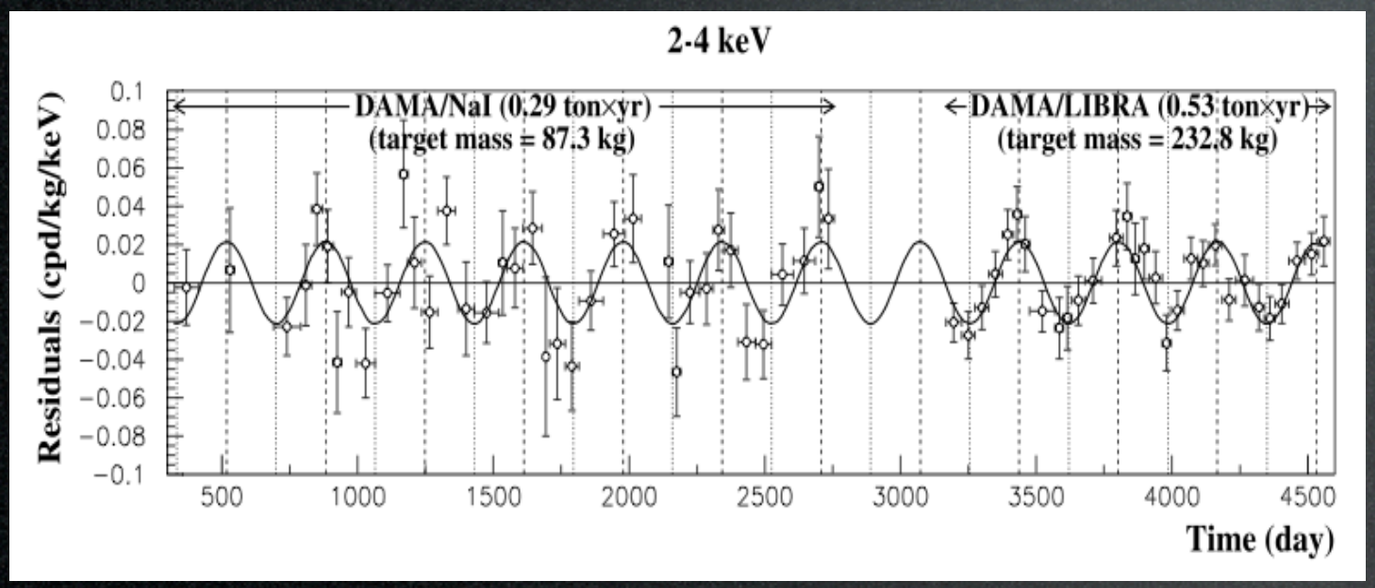
cited 500/10 = 50 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

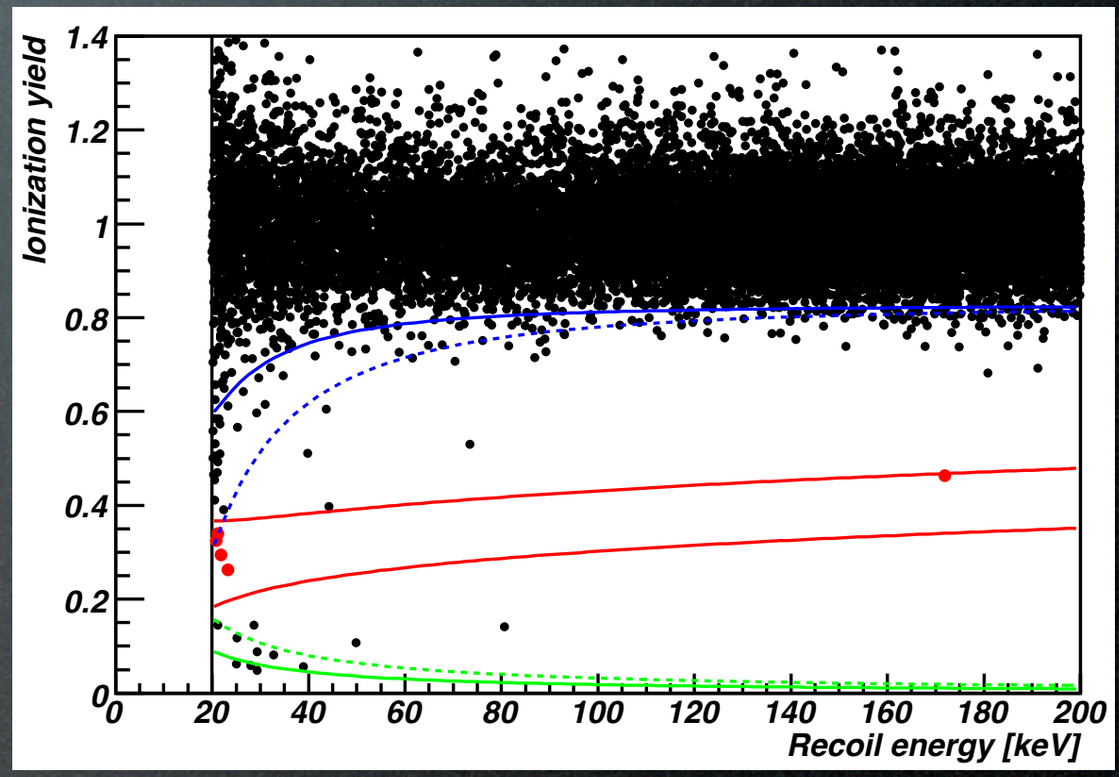


DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

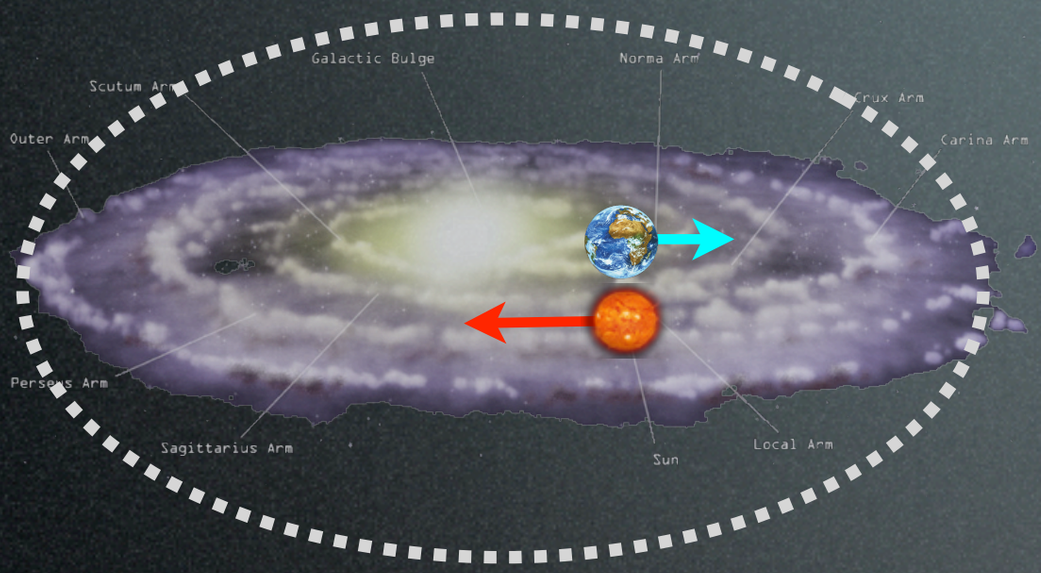
5 events seen,
with 3 exp'd background



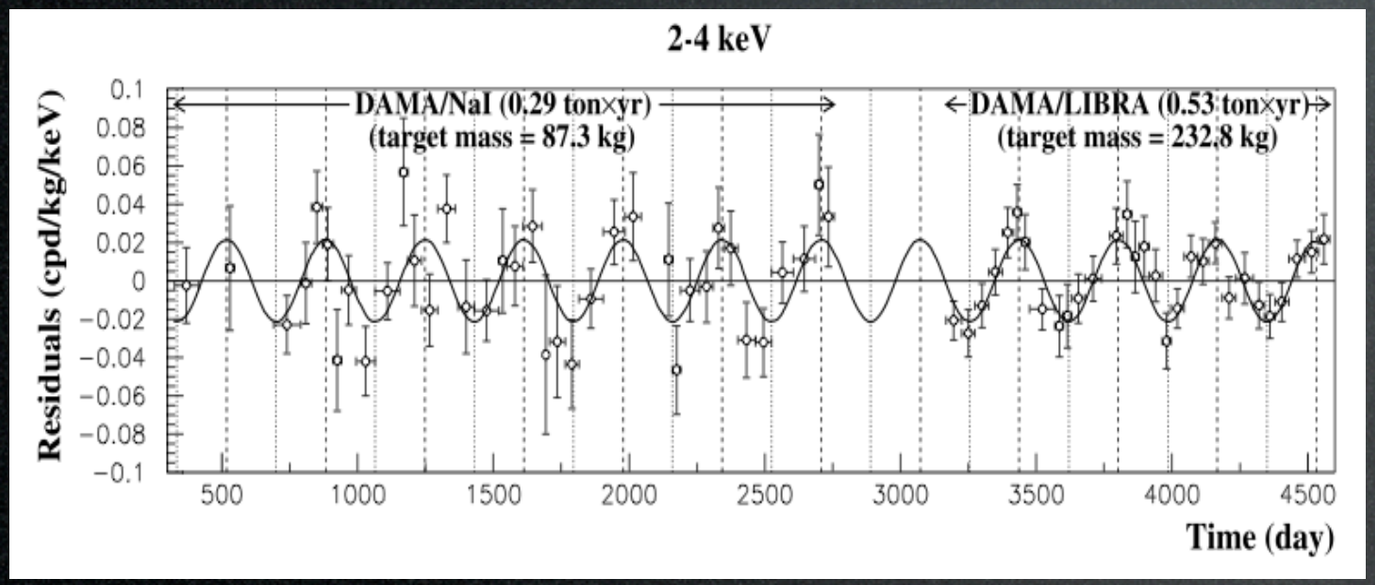
Edelweiss coll, 1103.4070

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

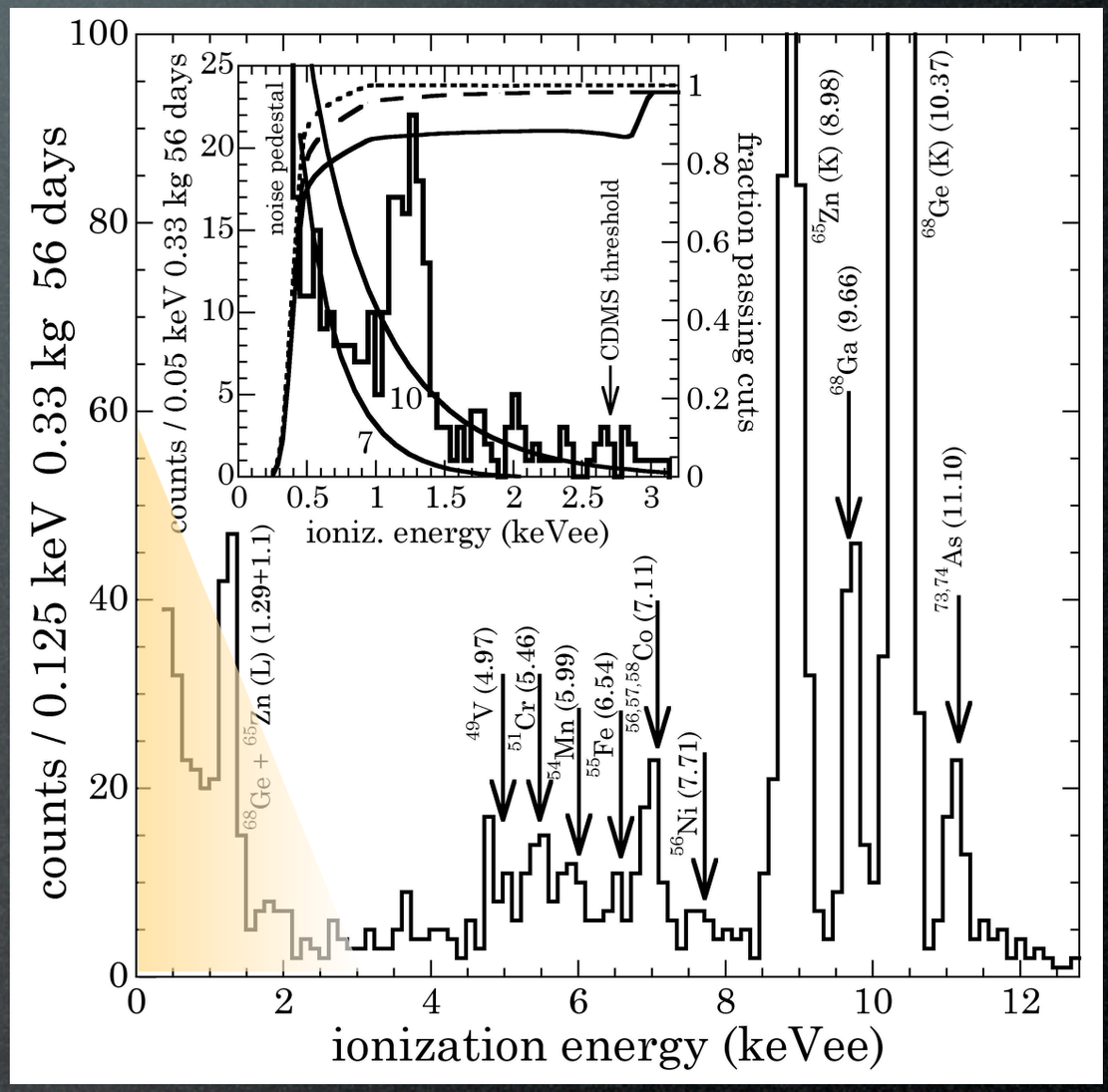


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

'irreducible excess of bulk events below 3 KeVee'

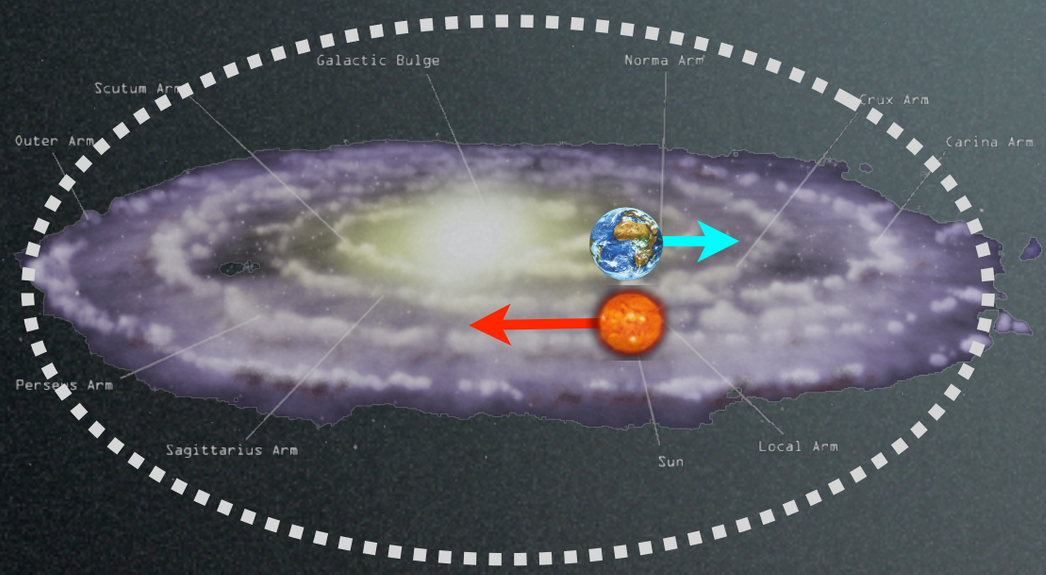


CoGeNT Coll., 1002.4703

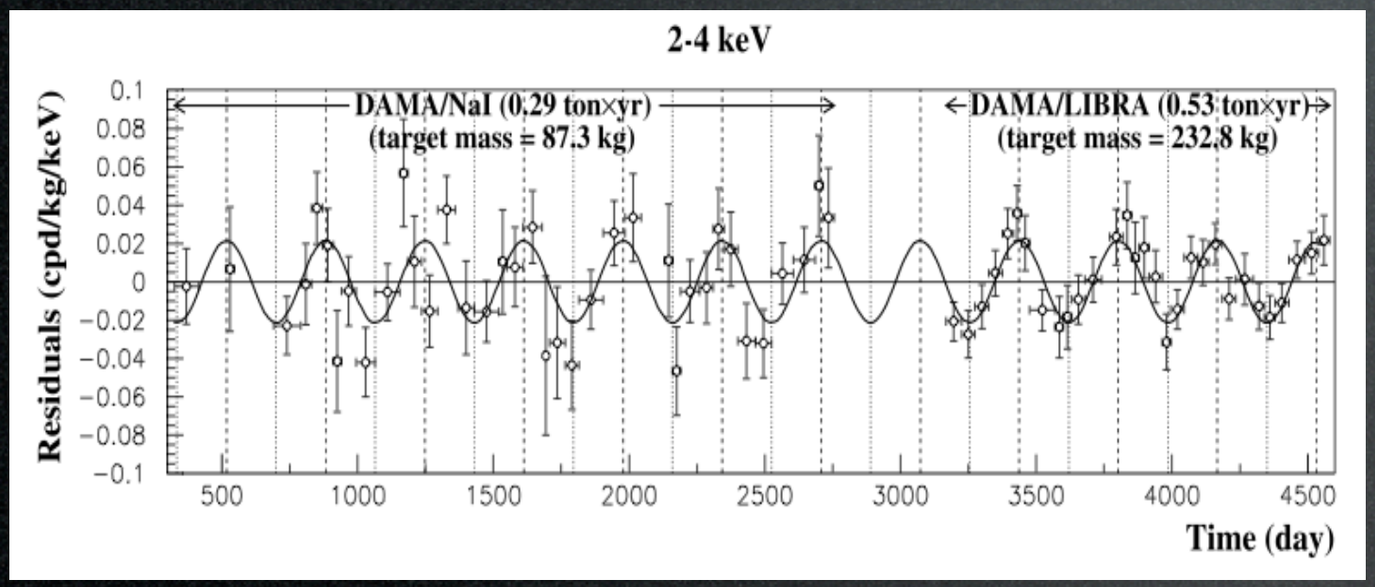
We lack a satisfactorily explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

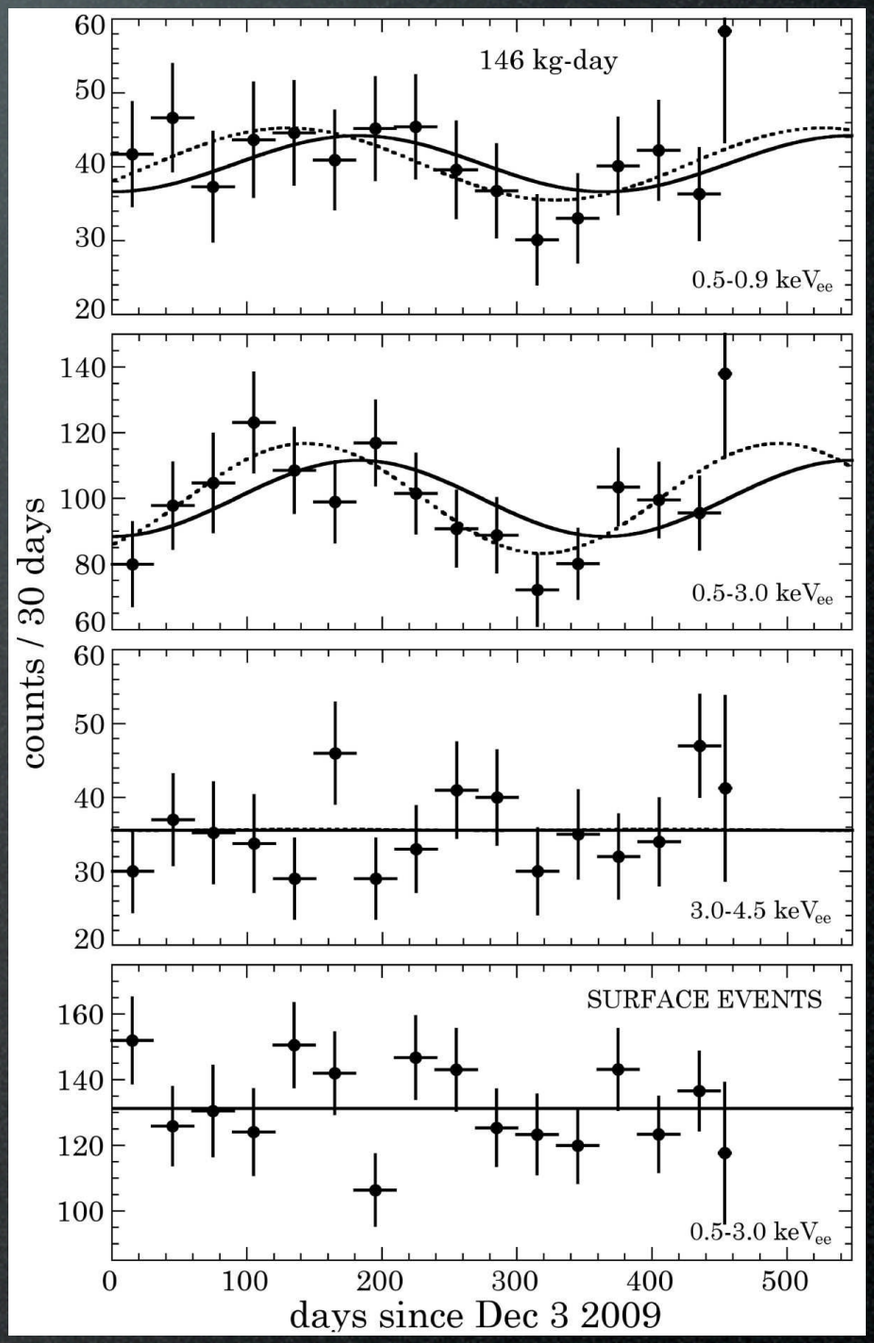


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

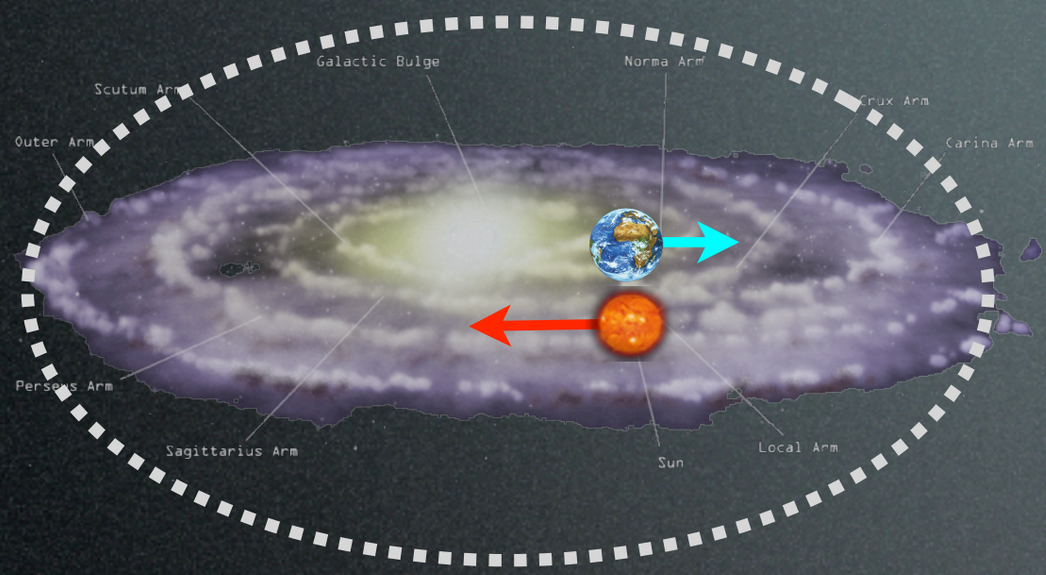
'irreducible excess of bulk events below 3 KeVee'



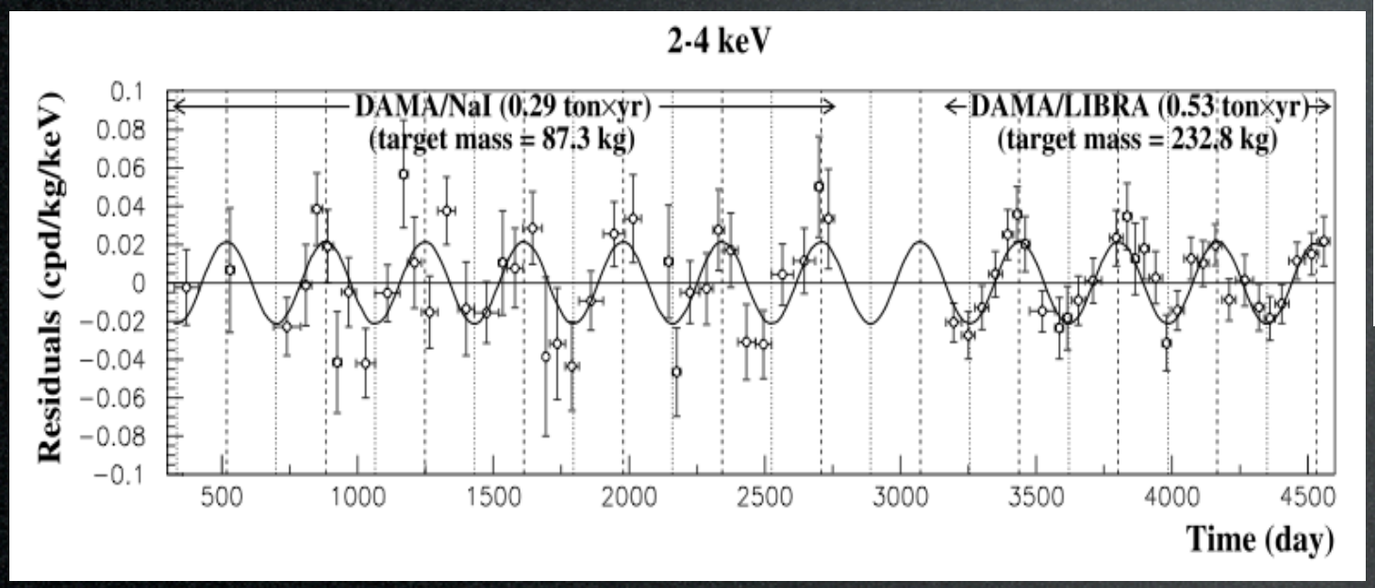
CoGeNT coll., 1106.0650

Direct Detection: hints

DAMA/Libra



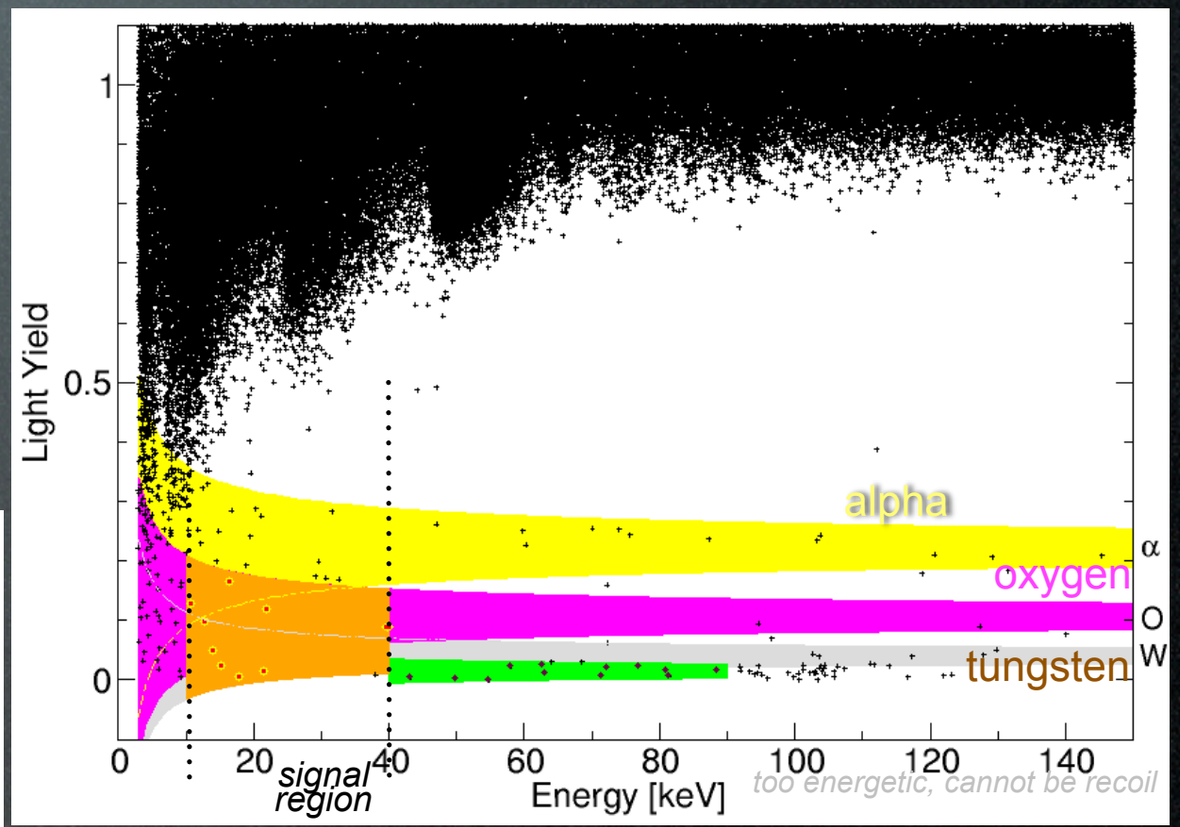
Annual modulation seen (8σ):



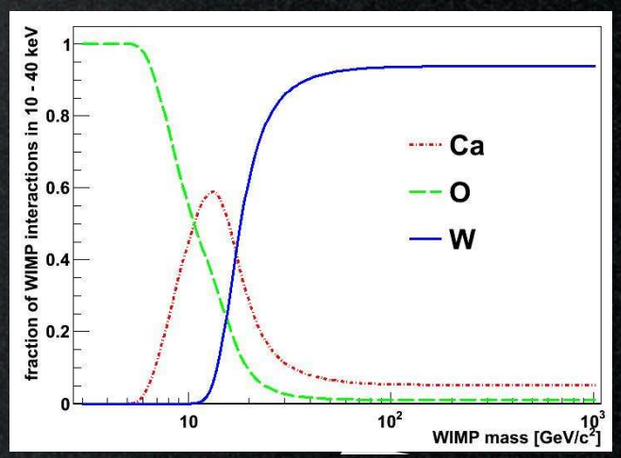
DAMA Coll., 0804.2741, 2008

CRESST-II $CaWO_4$

67 events seen on Oxygen, twice the exp'd background



CRESST-II Coll., 1109.0702



Direct Detection: hints

Plotolympics 2011: fits performed by different groups



Belli+Fornengo+al.,
1106.4667



Farina+Pappadopulo+Strumia+
Volansky, 1107.0715



Arina+Hamann+Wong,
1105.5121



(Kopp+)Schwetz+Zupan,
1106.6241 & 1110.2721



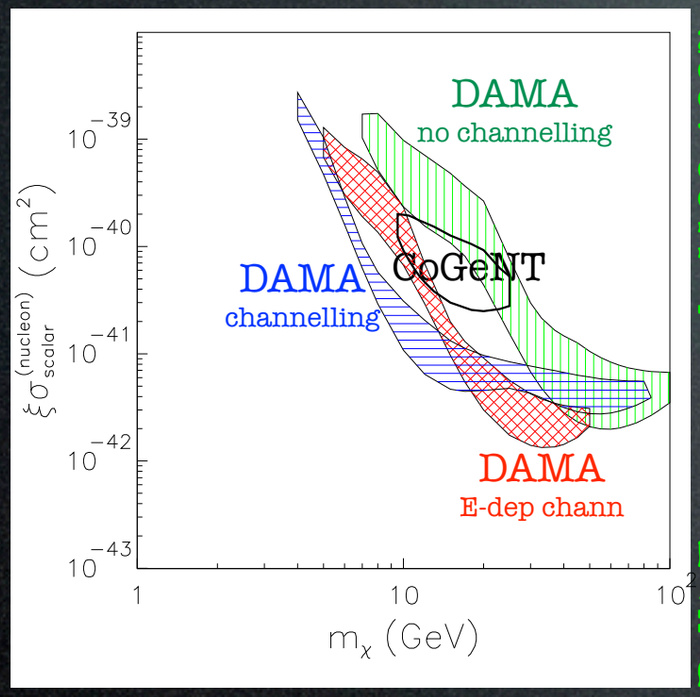
Hooper+Kelso, 1106.1066

Space available
Call 911-drk-mttr
now!

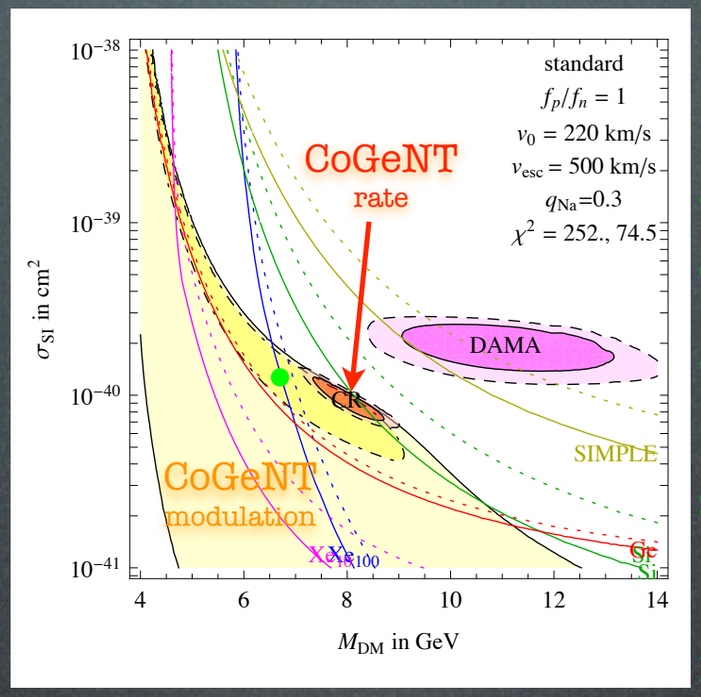
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

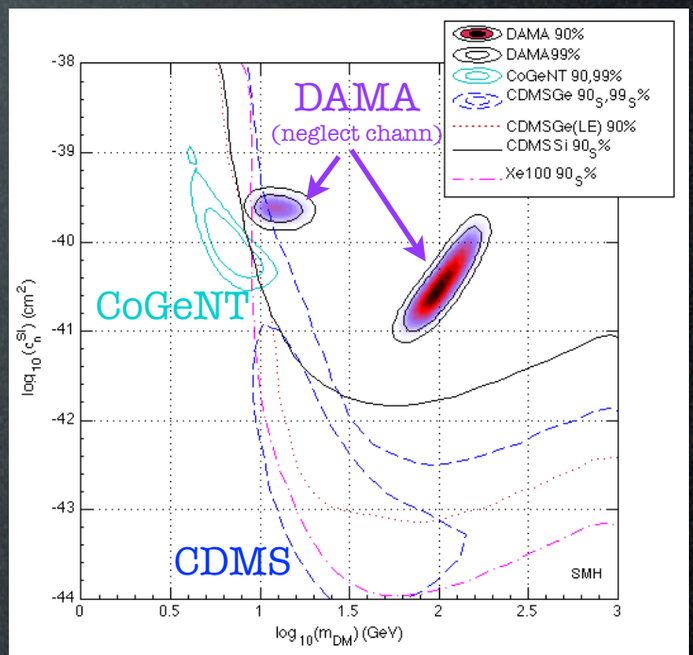
Discipline: Standard Fit: SI, standard halo



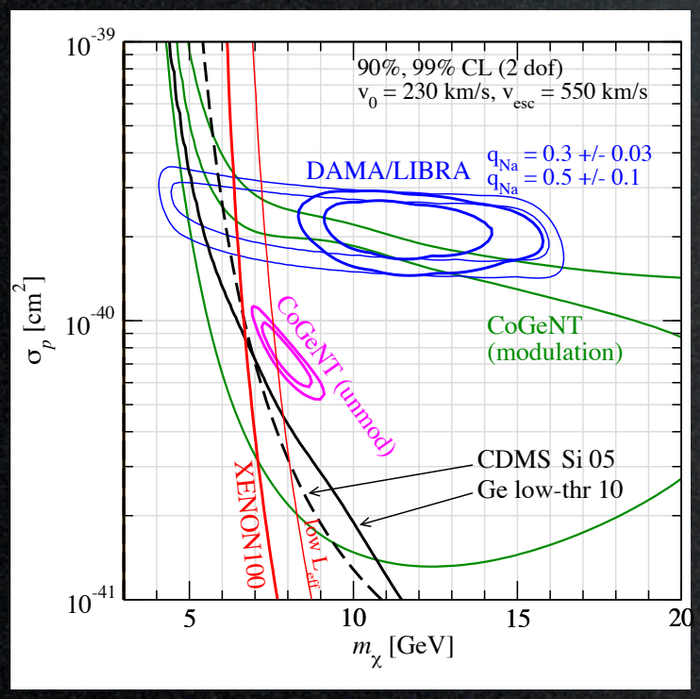
Belli+Fornengo+al., 1106.4667



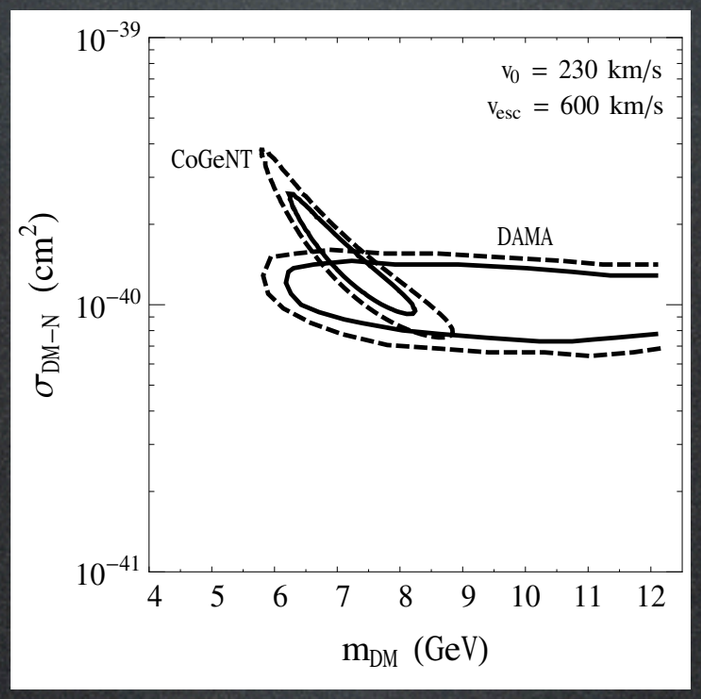
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

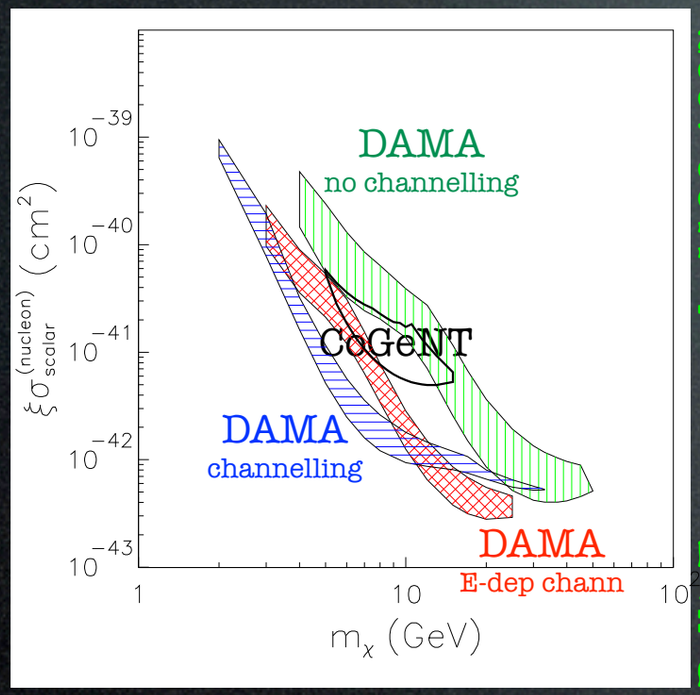
Comments:

- the ballparks agree, but the individual regions differ
  [do not ask me why]
- DAMA and CoGeNT overlap or not???

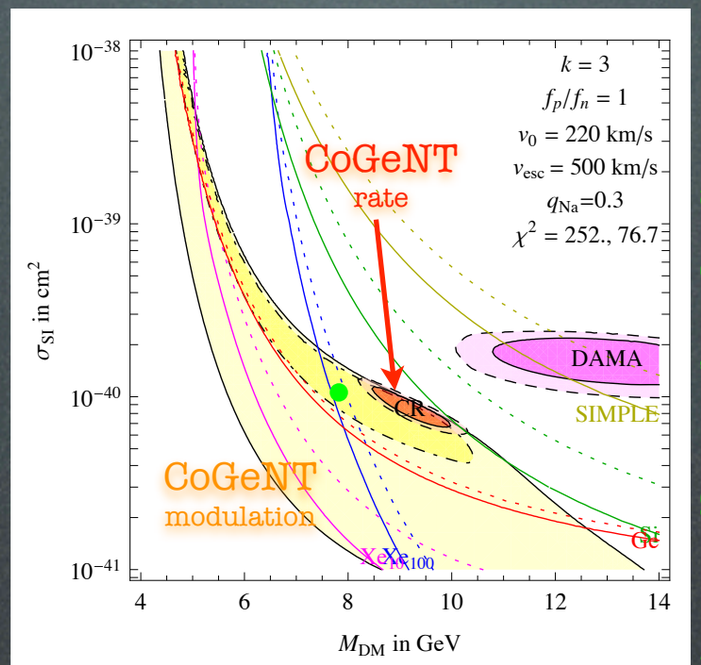
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

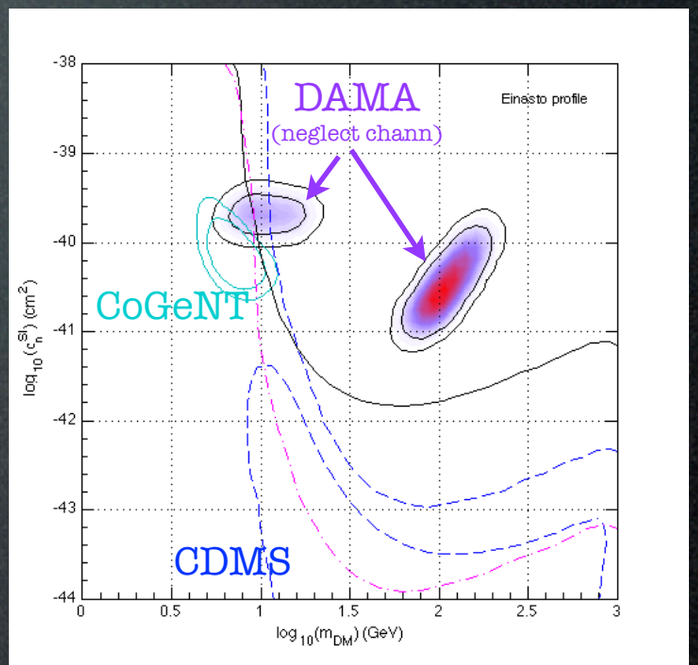
Discipline: Astro Fit: modifying velocity distrib, local density, profile...



Belli+Fornengo+al., 1106.4667



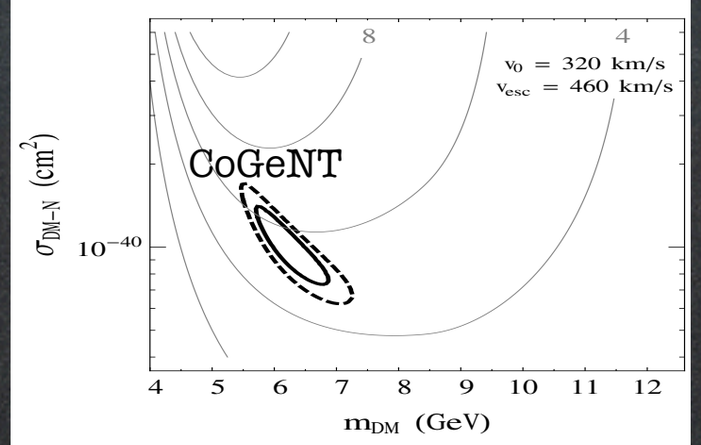
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121

Boycott

(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

Comments:

- not big quantitative change

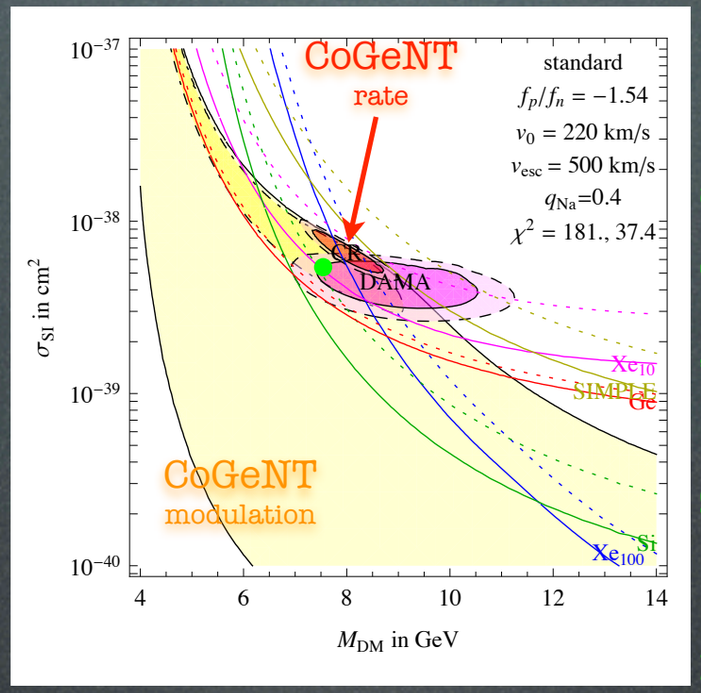
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

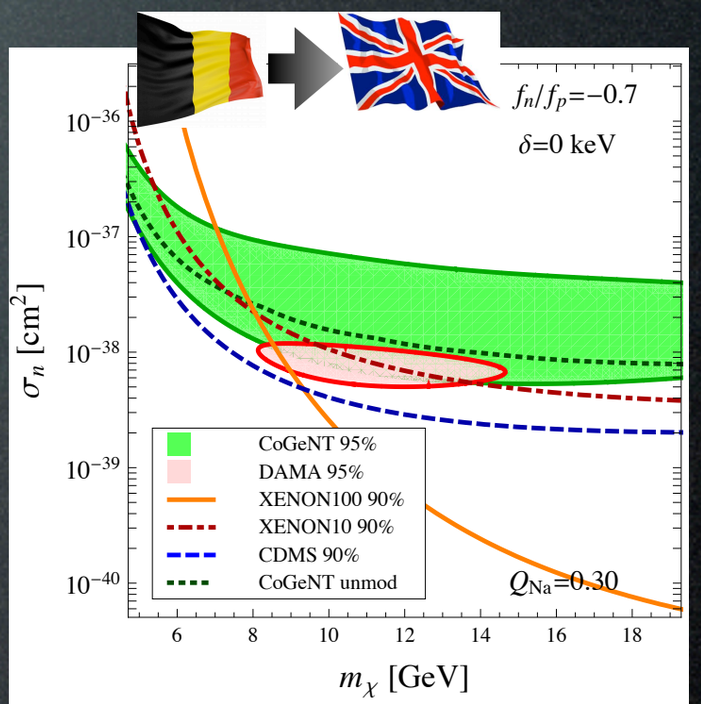
Discipline: Isospin Fit: assuming different coupling to **p** and **n**...

Boycott

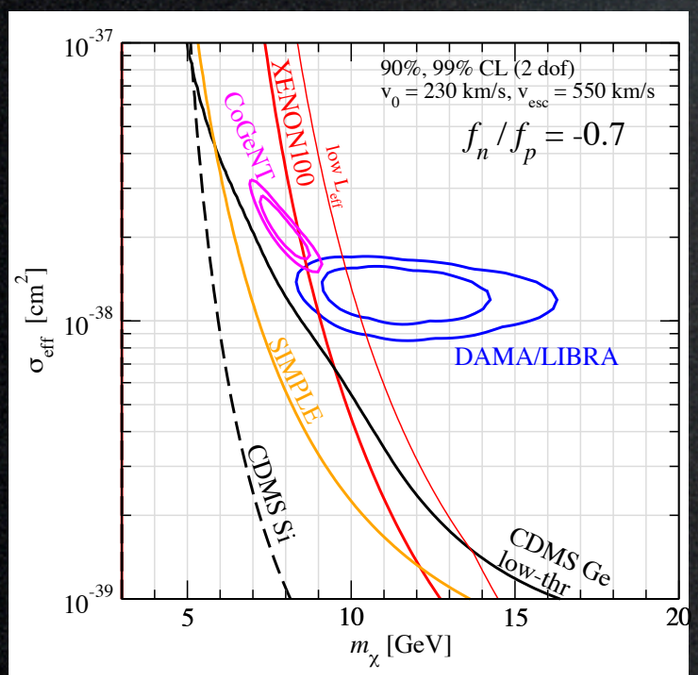
Belli+Bernabei+Formengo+al., 1106.4667



Farina+Pappadopulo+Strumia+Volansky, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

Not qualified

Hooper+Kelso, 1106.1066

Comments:

- those who dared to try find some improvement

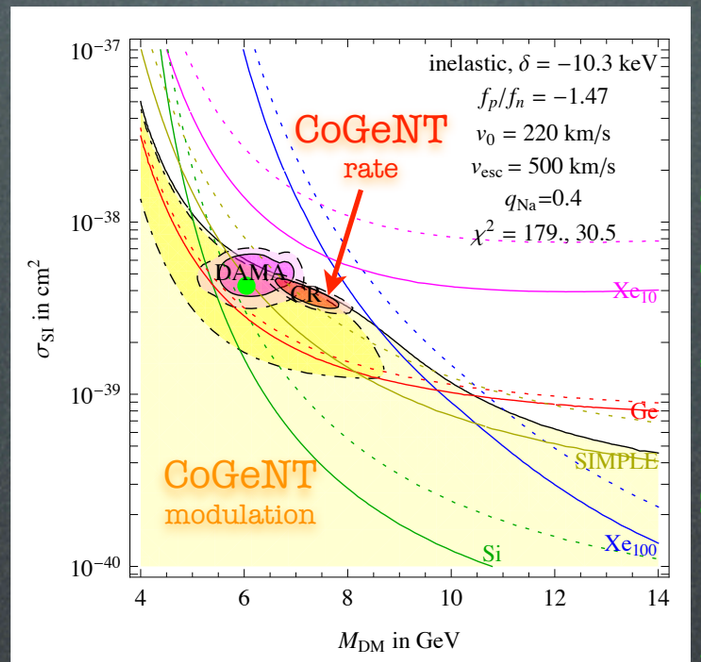
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

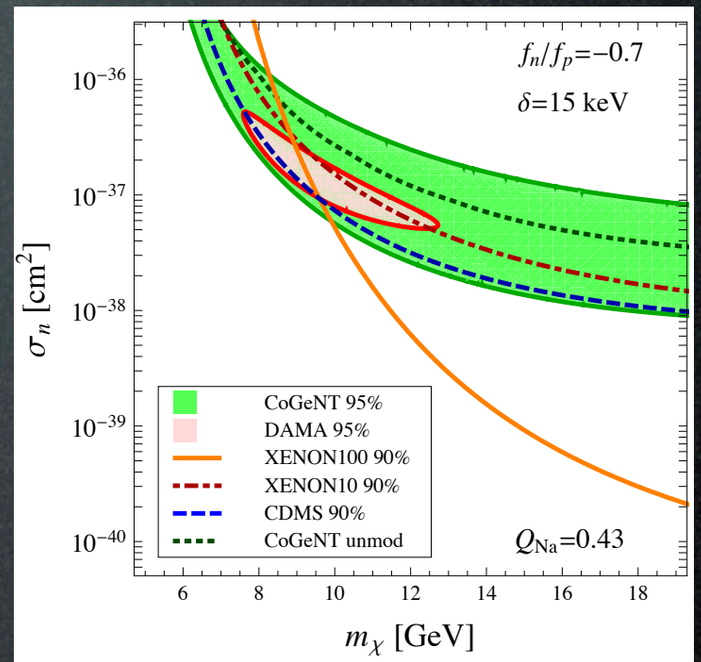
Discipline: Isospin & Inelastic Fit: different coupling + inelastic scatt

Boycott

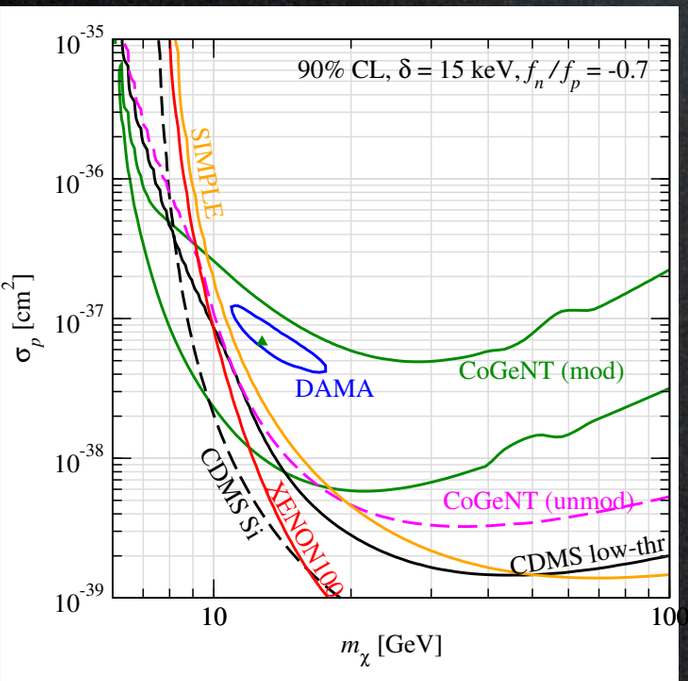
Belli+Bernabei+Cappella+Cerulli+Fornengo+al., 1106.4667



Farina+Pappadopulo+Strumia+Volansky, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

Not qualified

Hooper+Kelso, 1106.1066

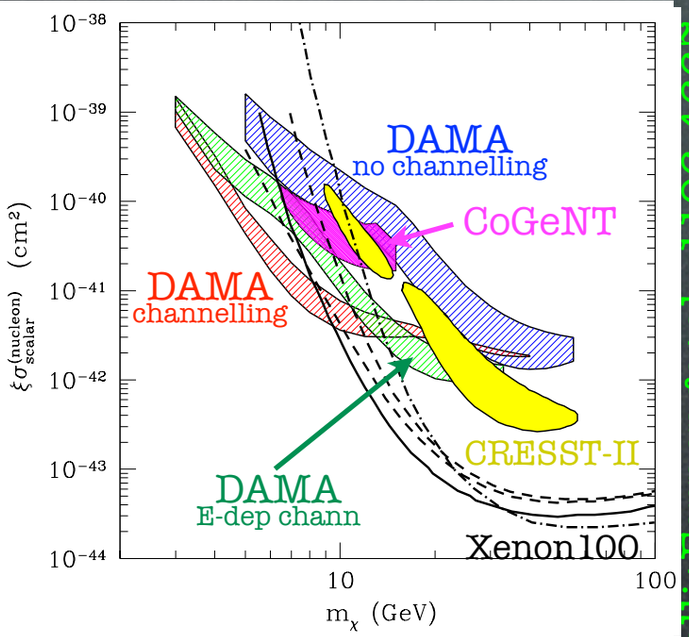
Comments:

- those who dared to try find some **more** improvement

Direct Detection: hints

Plotolympics 2011: fits performed by different groups

Discipline: CRESST-II overtime: add 1109.0702



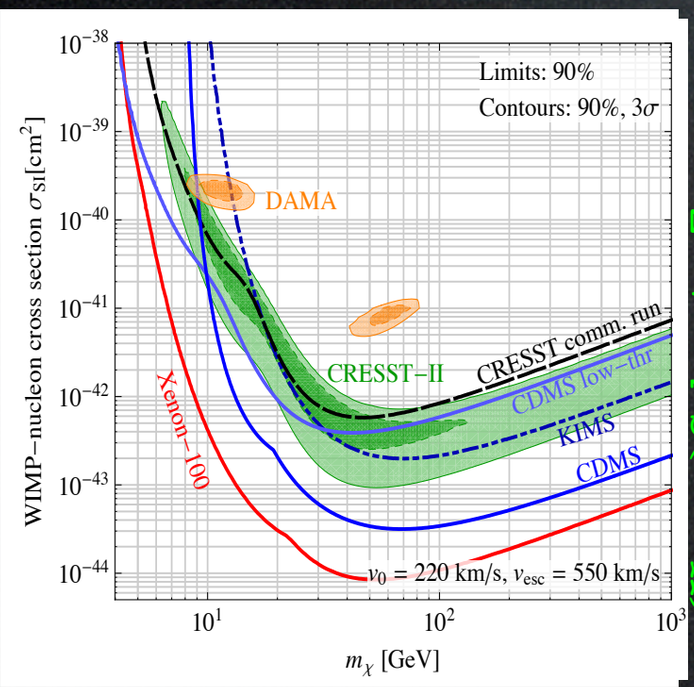
Belli+Fornengo+al., 1106.4667

No show

Farina+Pappadopulo+Strumia+Volansky, 1107.0715

No show

Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

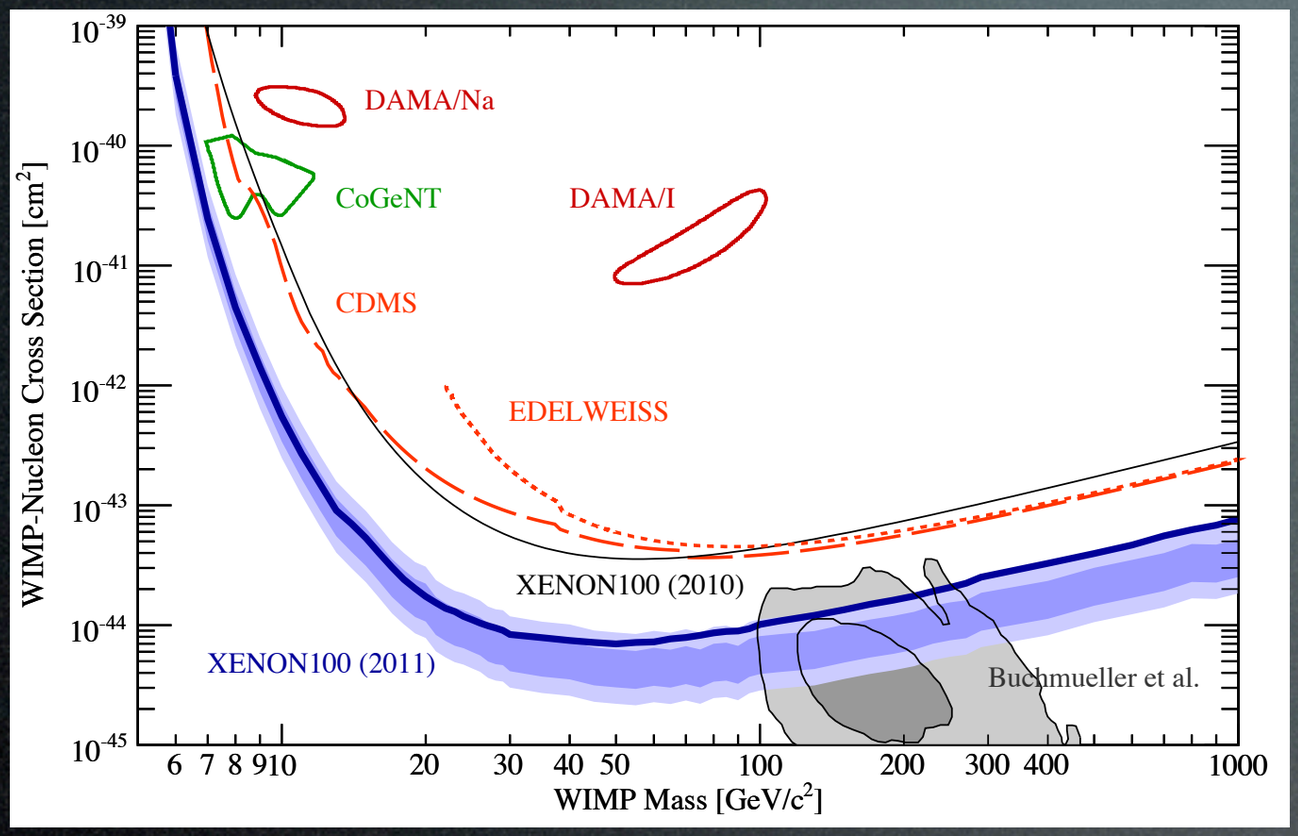
No show

Hooper+Kelso, 1106.1066

Comments:

- does CRESST-II agree or not?

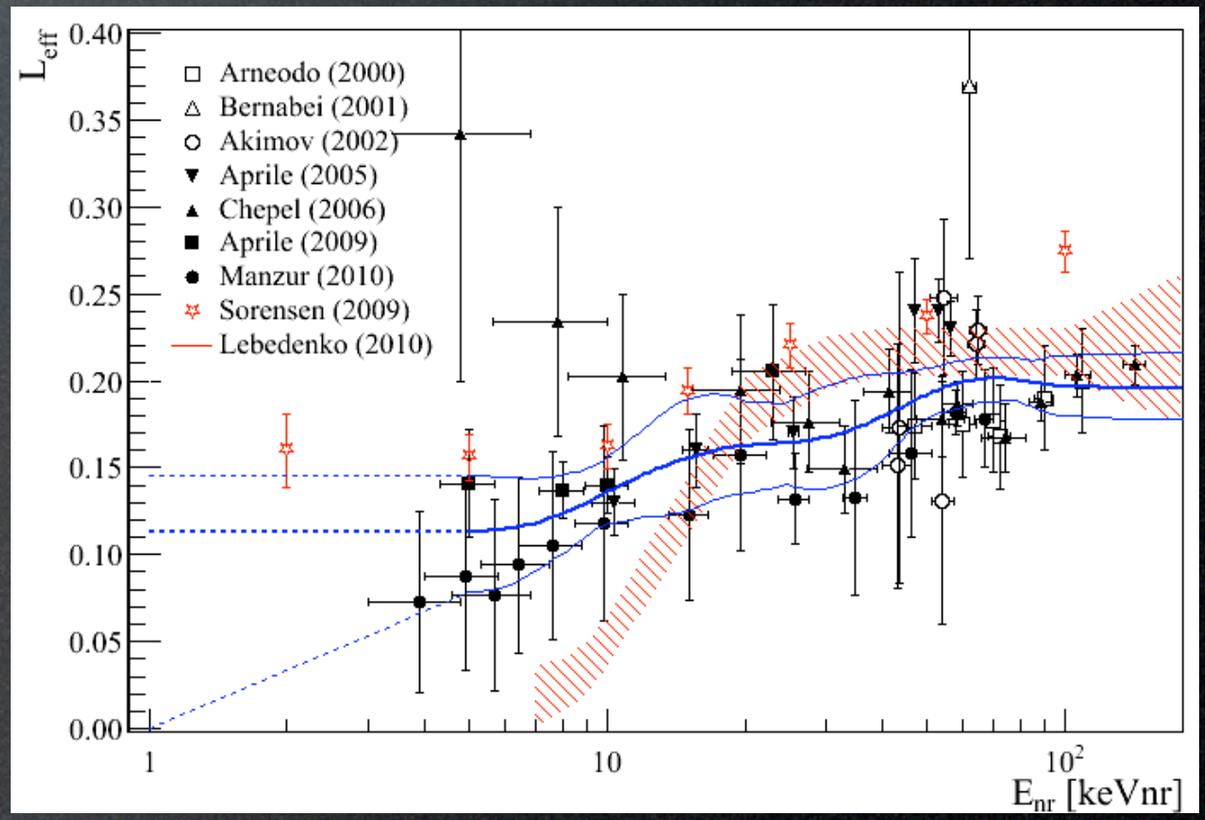
Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1104.2549

100.9 live days
3 events seen
(1.8 exp'd bkgd)

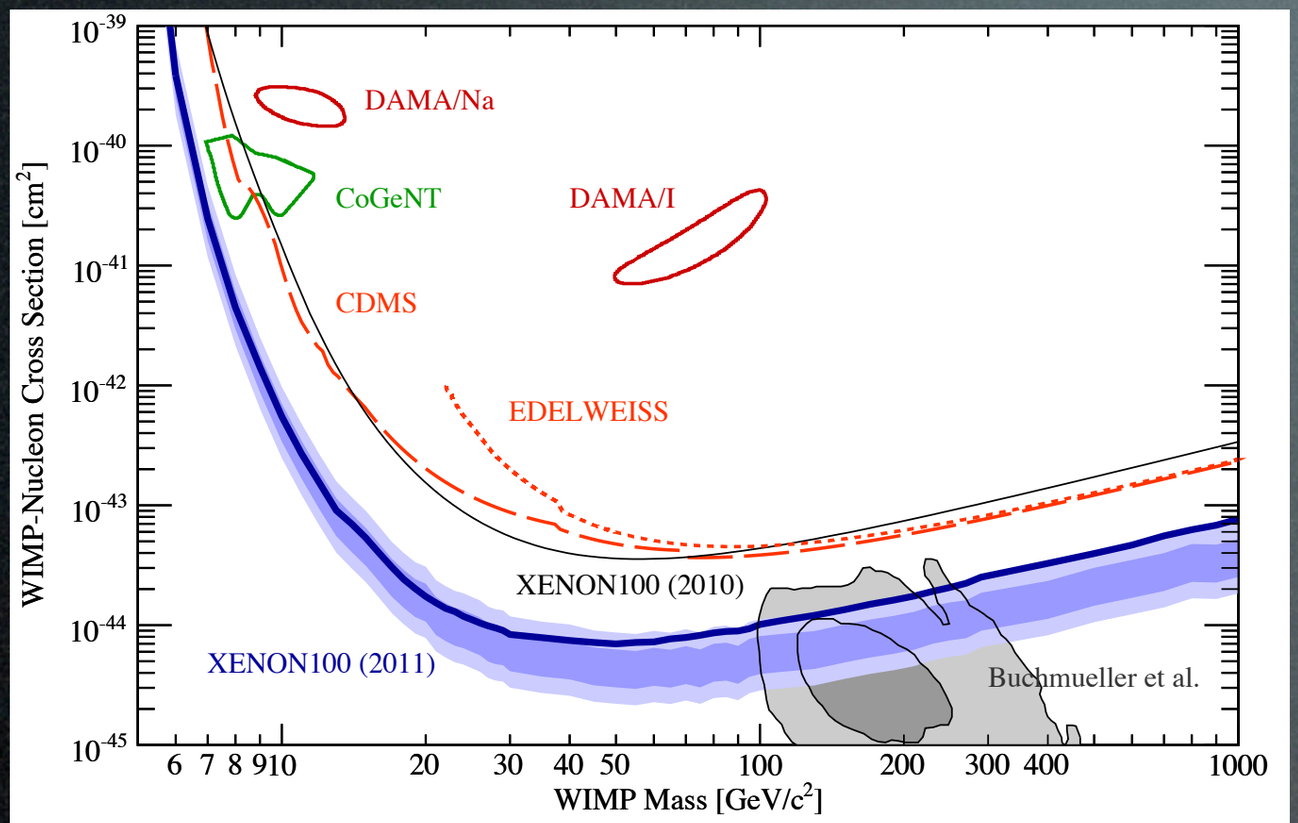
scintillation efficiency in LXe



XENON 100 Coll., 1005.2615

ferocious criticism in
Collar & McKinsey, 1005.0838v1, v2, v3

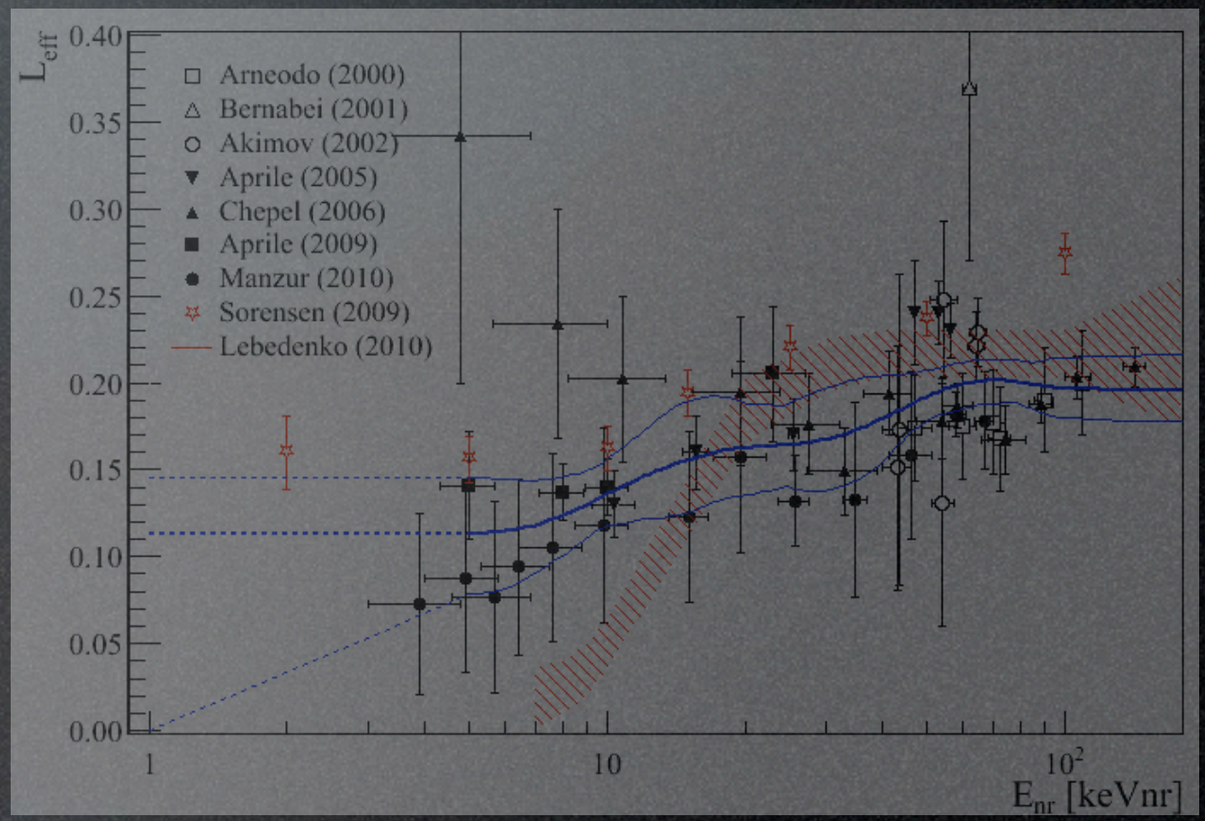
Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1104.2549

100.9 live days
3 events seen
(1.8 exp'd bkgd)

scintillation efficiency in LXe

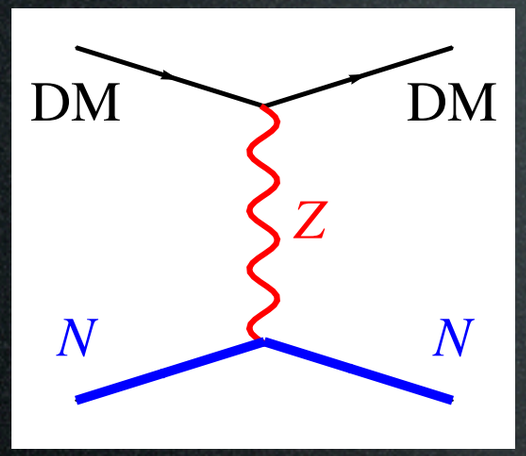


XENON 100 Coll., 1005.2615

ferocious criticism in
Collar & McKinsey, 1005.0838v1, v2, v3

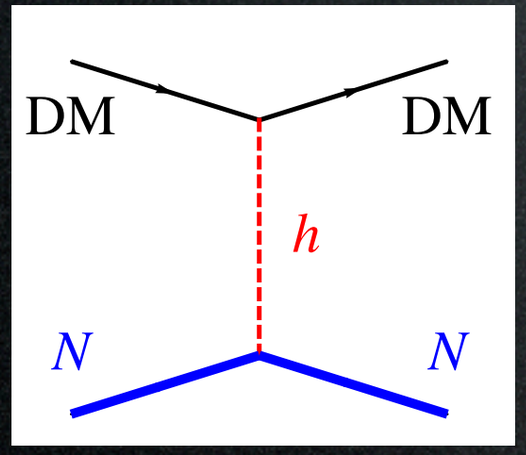
Direct Detection: '**theory**'

SM weak scale SI interactions



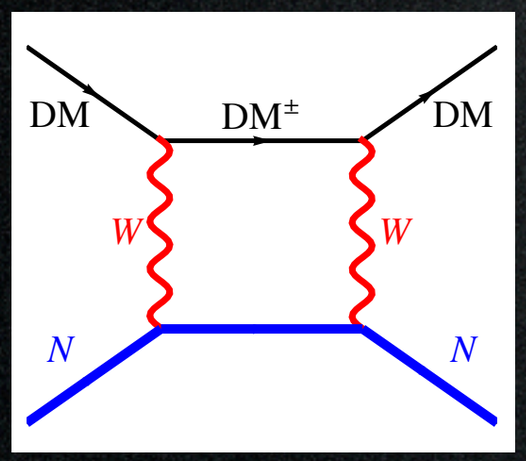
tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$



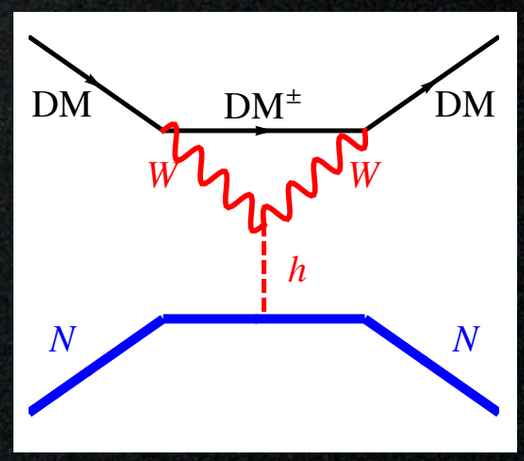
tree level, scalar

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^4}{M_h^6}$$



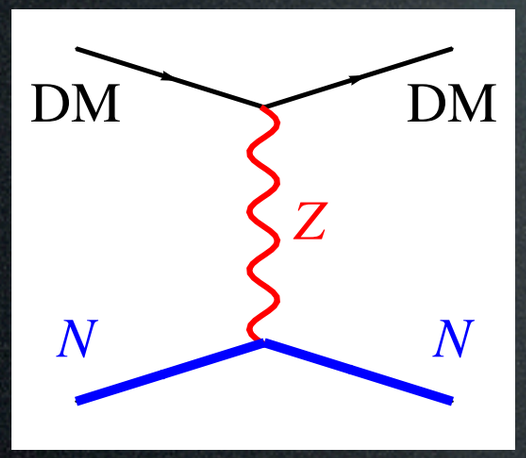
one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4 \ m_N^4}{M_W^6}$$

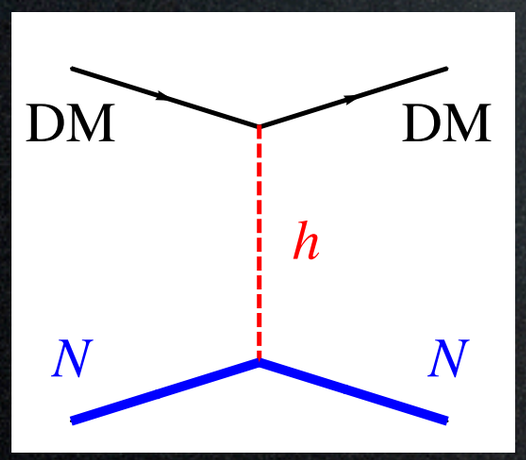


Direct Detection: 'theory'

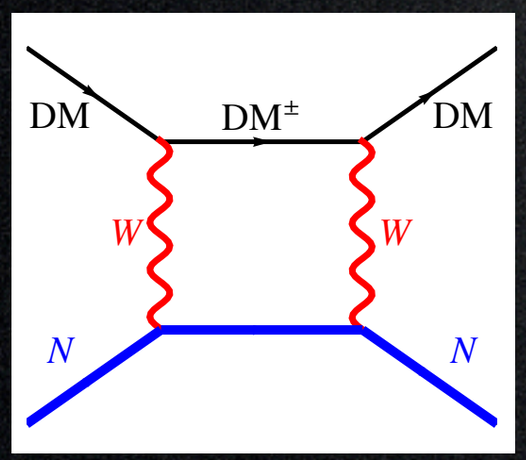
SM weak scale SI interactions



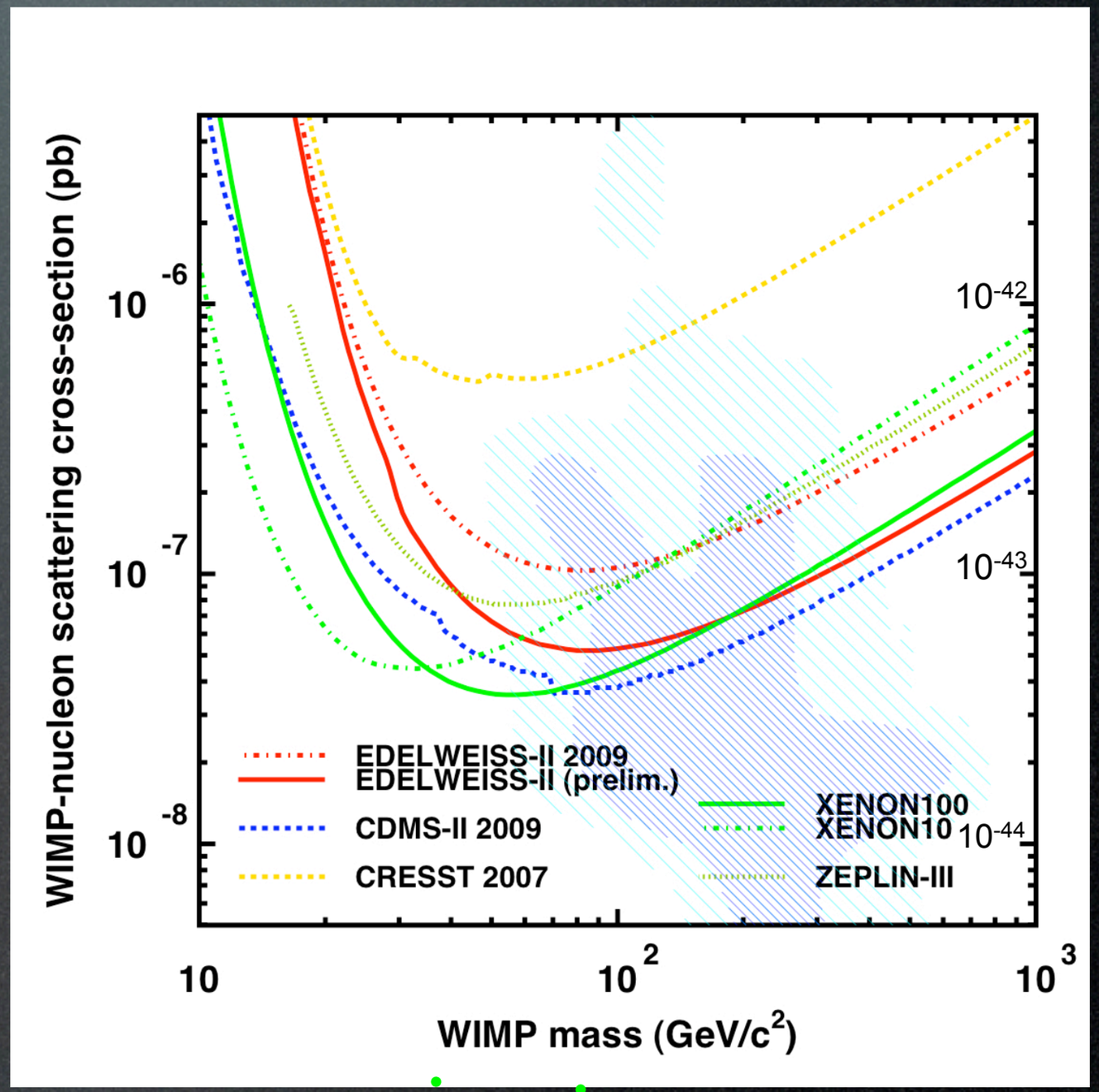
tree level, vector



tree level, scalar

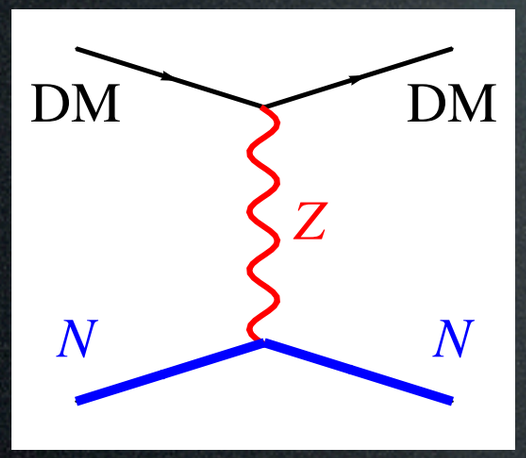


one loop

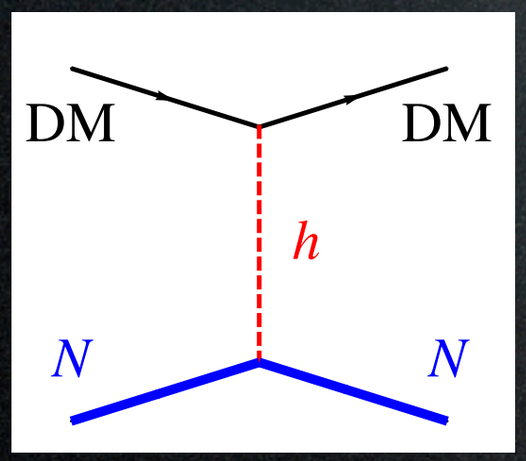


Direct Detection: 'theory'

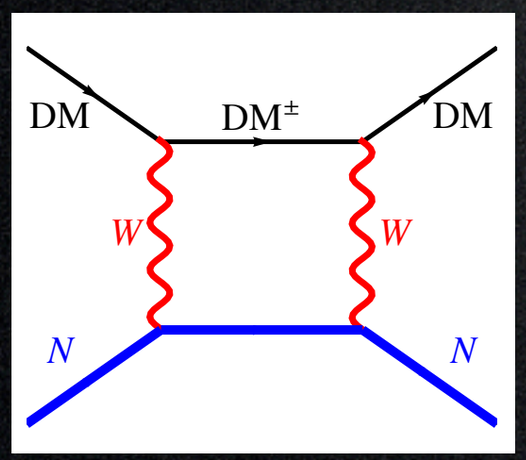
SM weak scale SI interactions



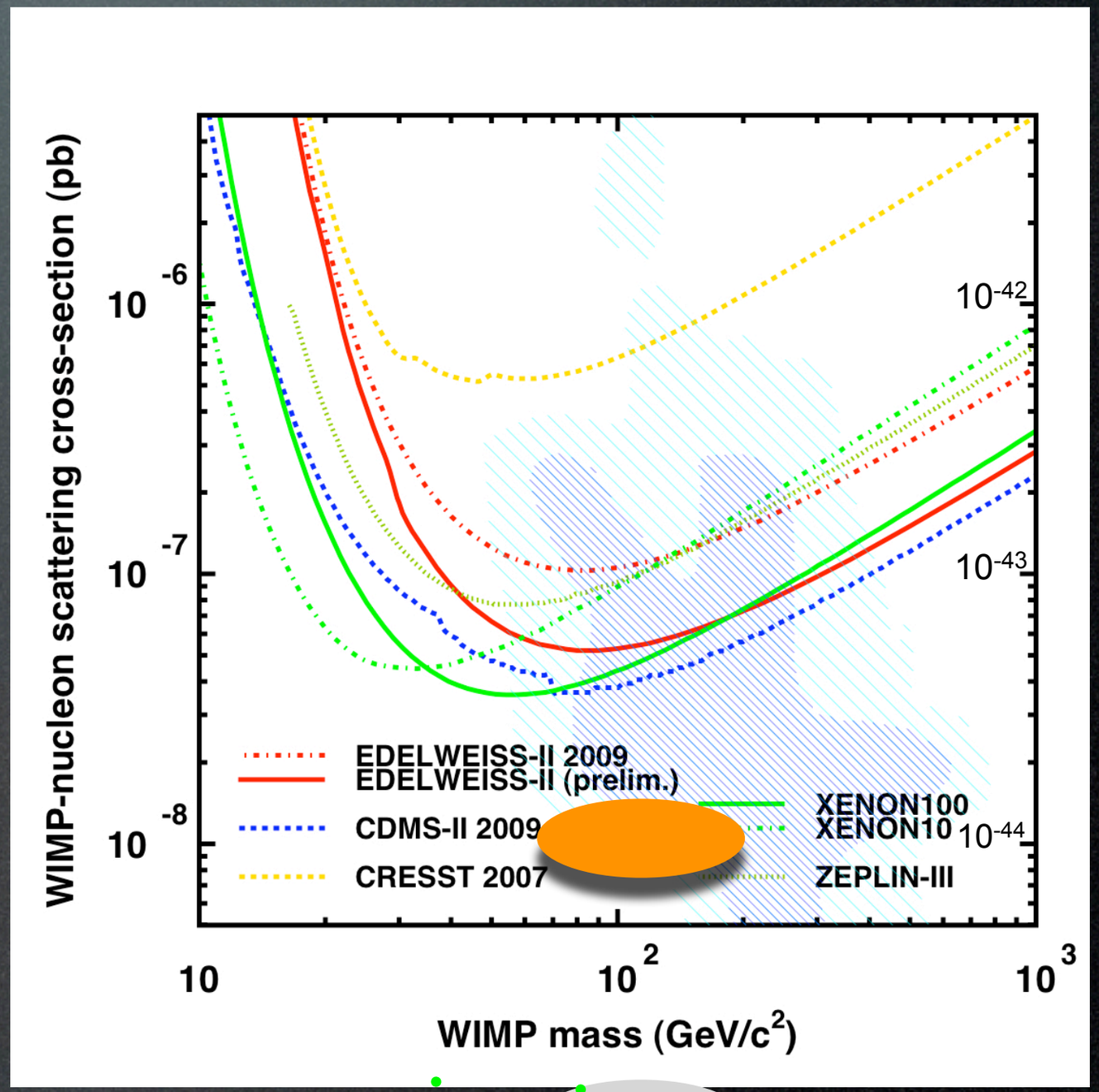
tree level, vector



tree level, scalar

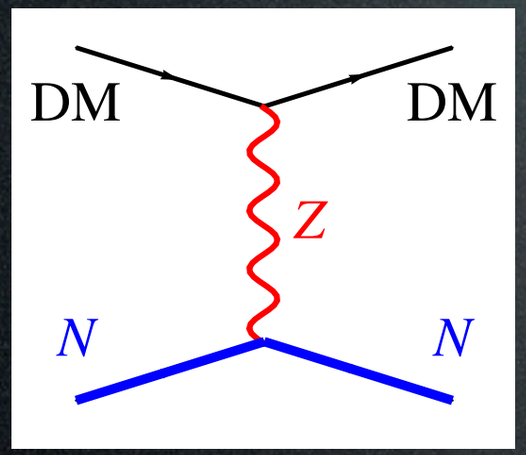


one loop



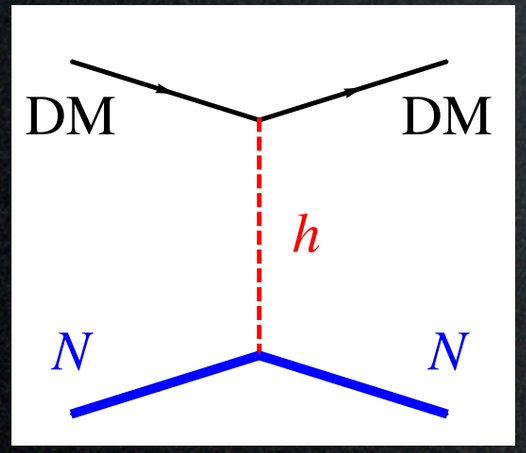
Direct Detection: 'theory'

SM weak scale SI interactions

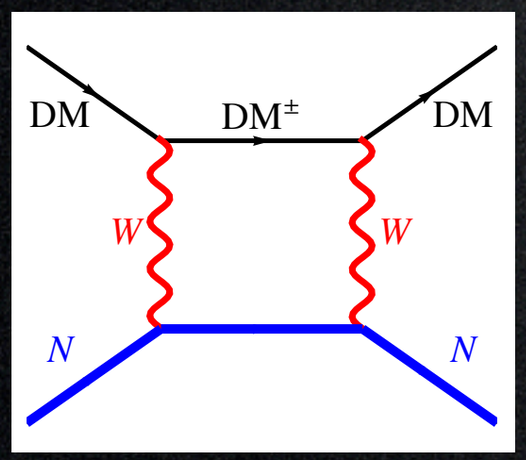


tree level, vector

Still viable under which conditions?



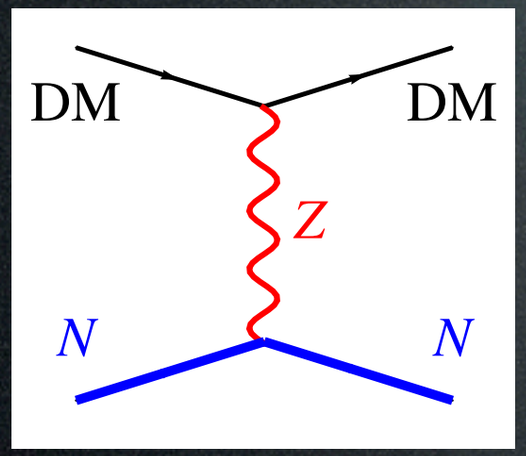
tree level, scalar



one loop

Direct Detection: 'theory'

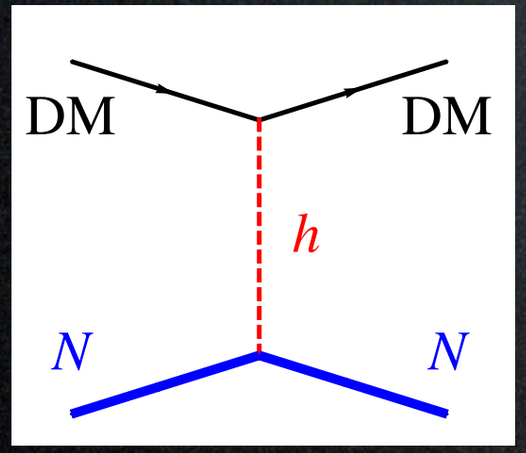
SM weak scale SI interactions



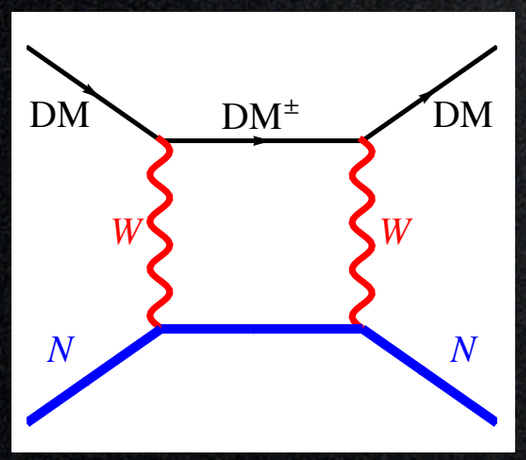
tree level, vector

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



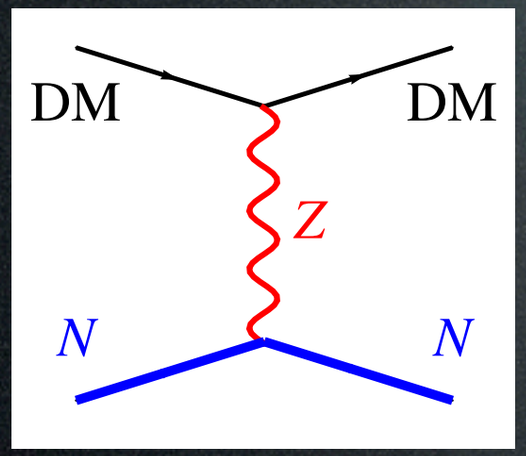
tree level, scalar



one loop

Direct Detection: 'theory'

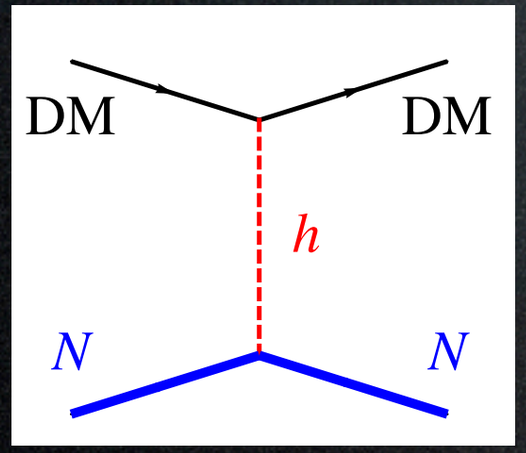
SM weak scale SI interactions



tree level, vector

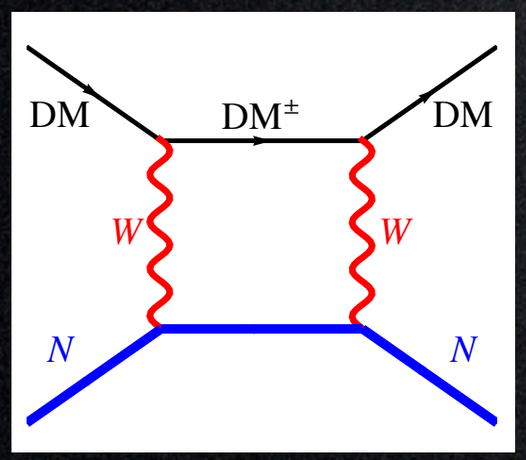
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



tree level, scalar

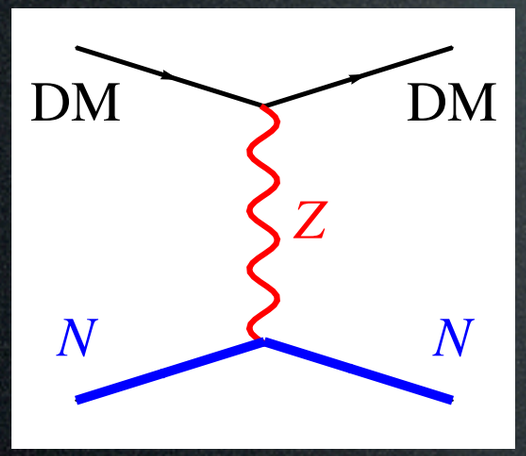
- hypercharge $Y = 0$



one loop

Direct Detection: 'theory'

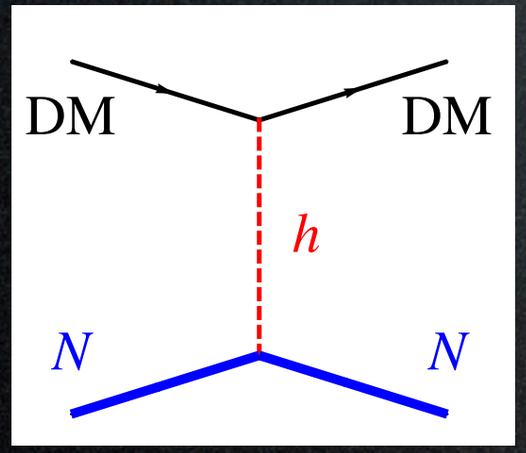
SM weak scale SI interactions



tree level, vector

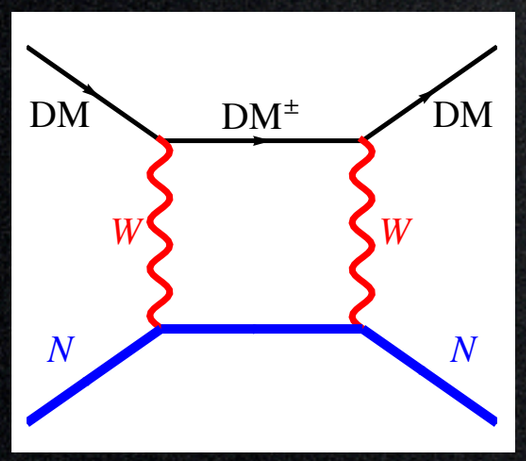
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)

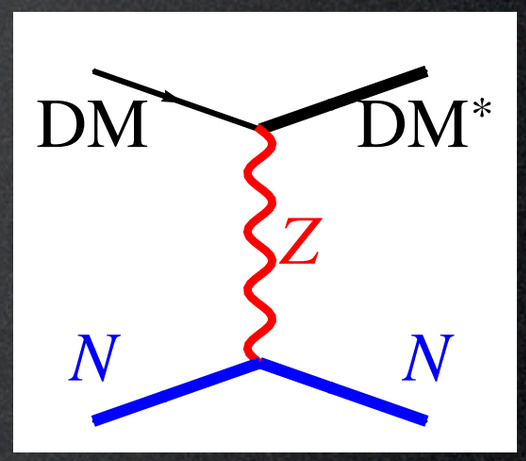


tree level, scalar

- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering



one loop



OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

FERMI
ongoing

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

FERMI
ongoing

AMS2
summer 2012?

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detec

Xenon
any day now

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

FERMI
ongoing

AMS2
summer 2012?

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detec

Xenon
any day now

KIMS
summer 2011

basics
hints
constraints
heory'
ntative conclusion

production at colliders

indirect

FERMI
ongoing

AMS2
summer 2012?

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detec

Xenon
any day now

KIMS
summer 2011

MiMAC

DRIFT

DEAP/

WARP

LUX

XMASS

COUPP

lusion

production at colliders

indirect

FERMI
ongoing

AMS2
summer 2012?

basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

OUTLOOK

direct detec

Xenon
any day now

KIMS
summer 2011

MiMAC

DRIFT

DEAP/

WARP

LUX

XMASS

COUPP

rusion

production at colliders

LHC
> 2012?

indirect

FERMI
ongoing

AMS2
summer 2012?

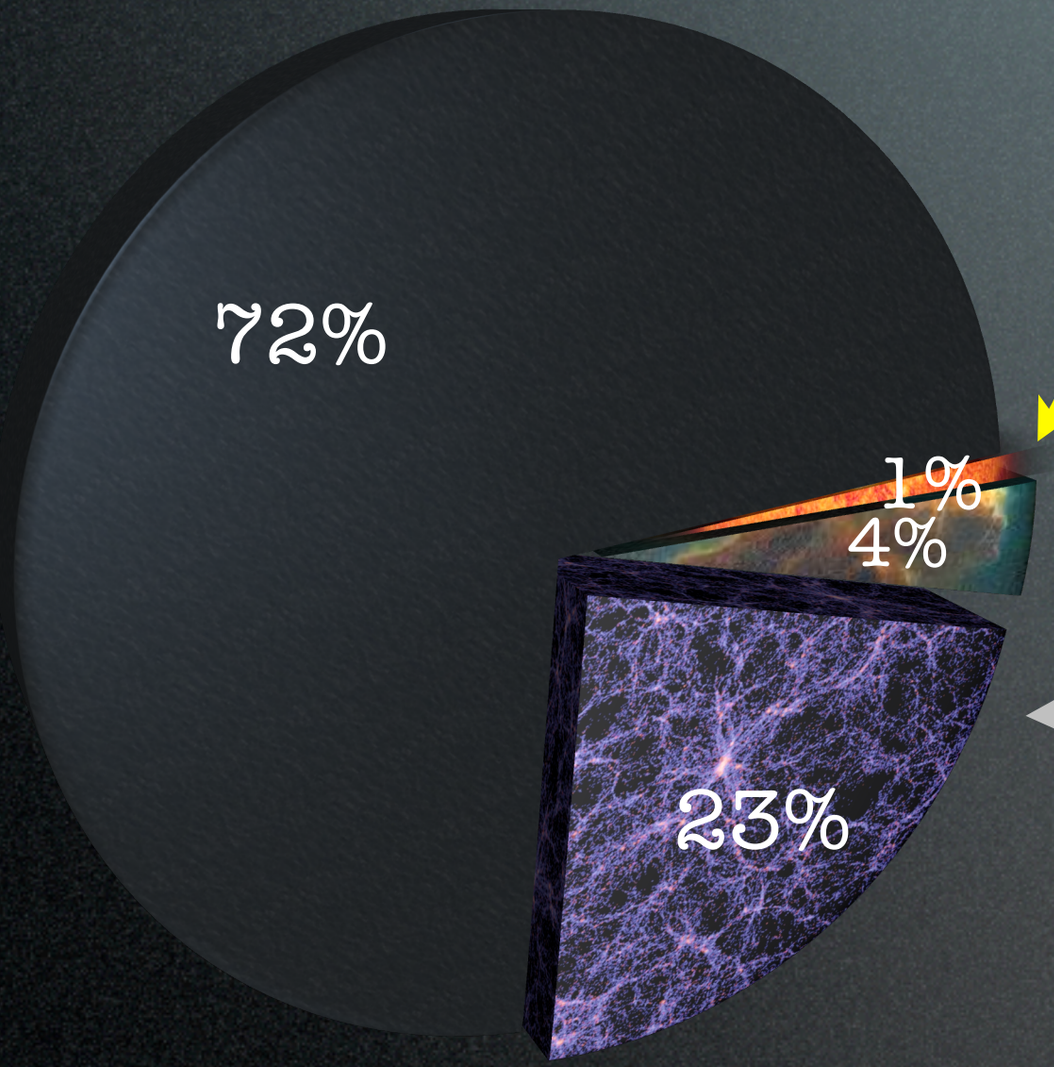
basics
hints
constraints
'theory'
tentative conclusion

PAMELA & C. probably was not DM, but it has been fun
The jury is out. Anyway: the parameter space is infinite!

Back up slides

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.23$

$\Omega_{\rm de} \sim 0.72$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c};\ \text{CMB first peak} \Rightarrow \Omega_{\rm tot} = 1\ (\text{flat});\ \text{HST}\ h = 0.71 \pm 0.07\right)$

what's the difference between DM and DE?

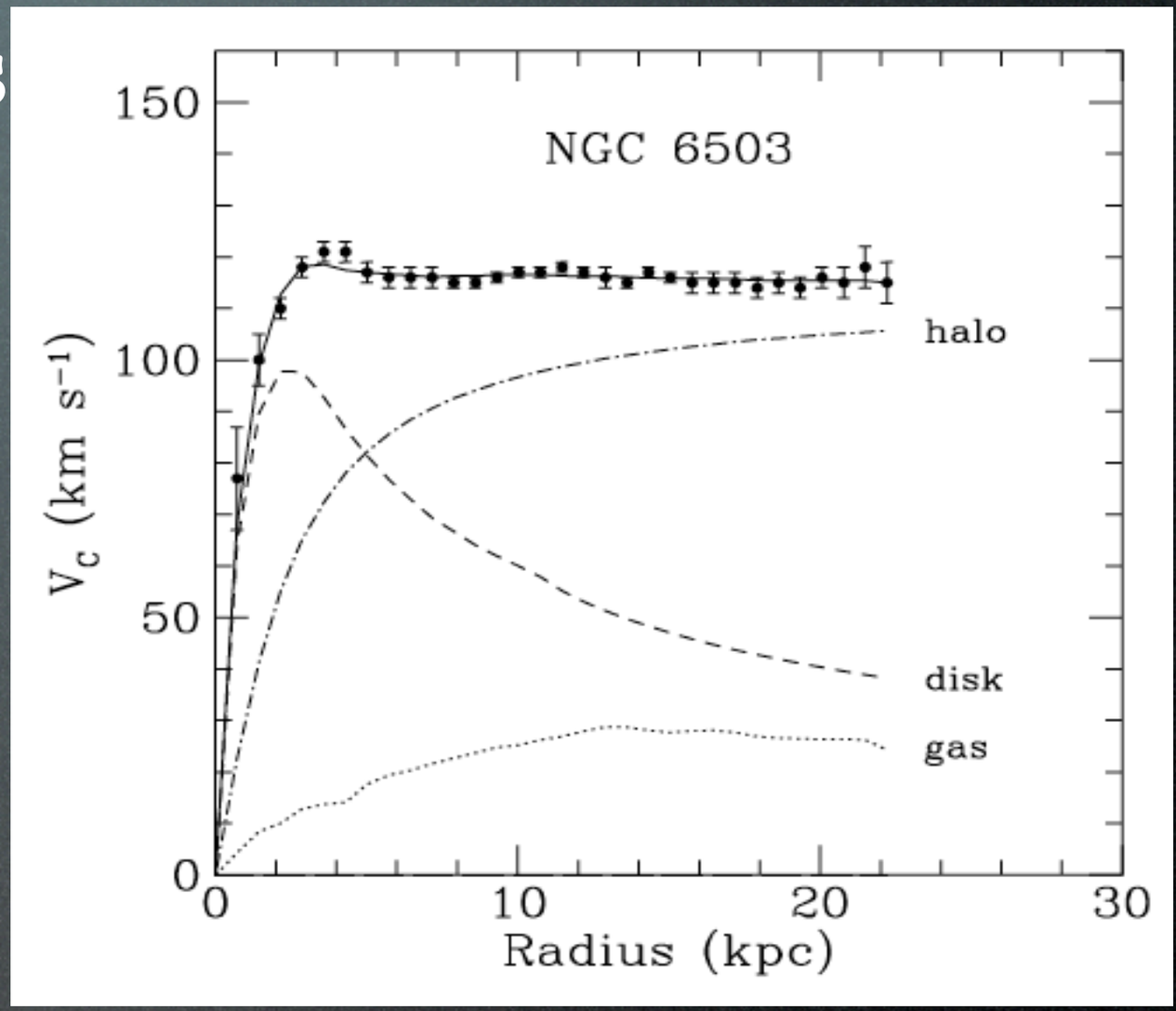
The Evidence for DM

1) galaxy rotation curves

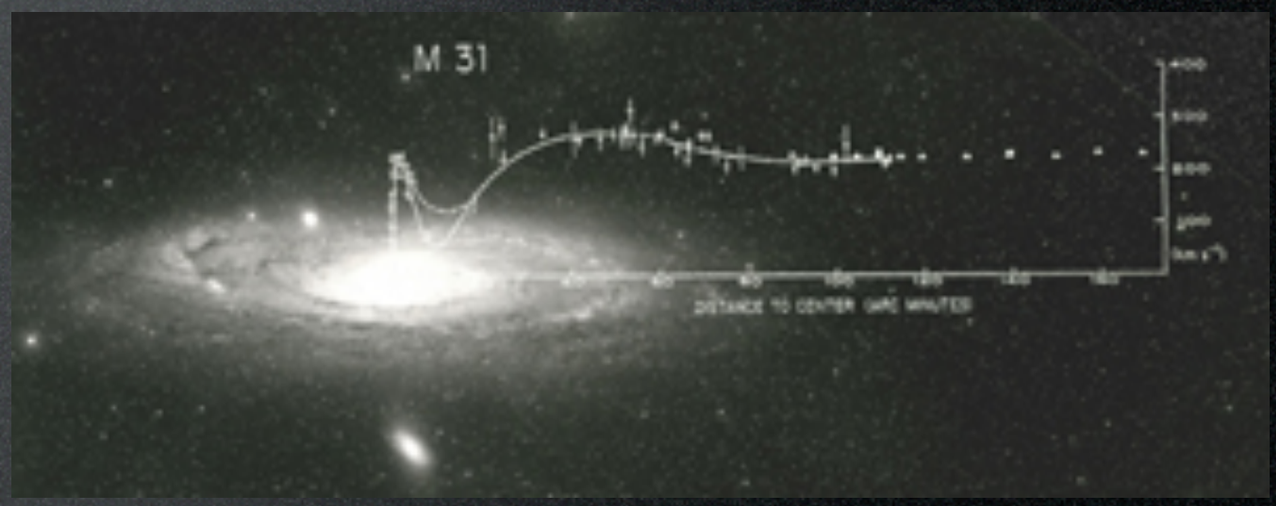
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_{\rm M} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



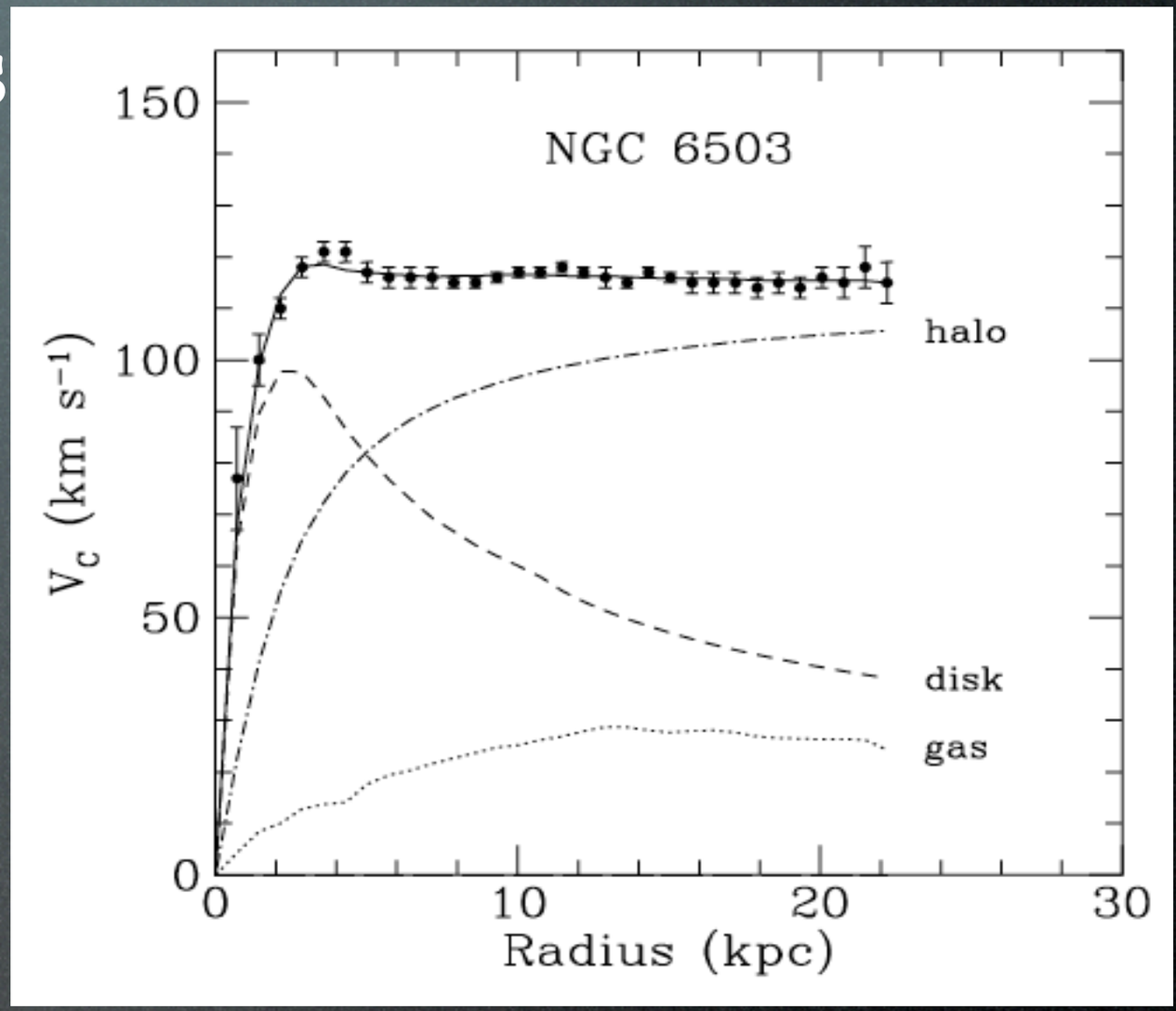
The Evidence for DM

1) galaxy rotation curves

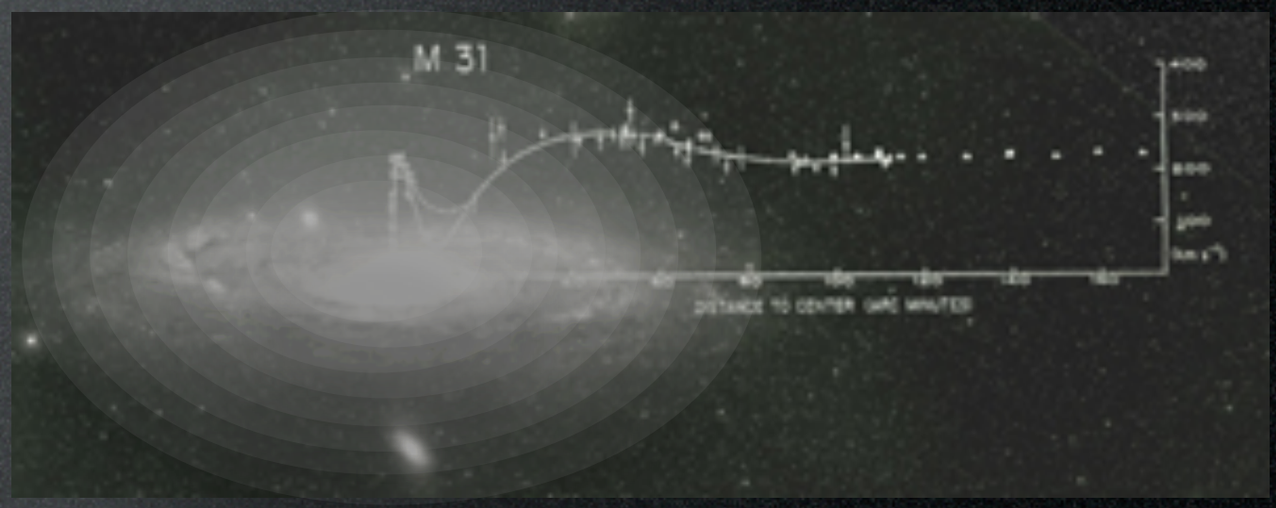
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_{\rm M} \gtrsim 0.1$$

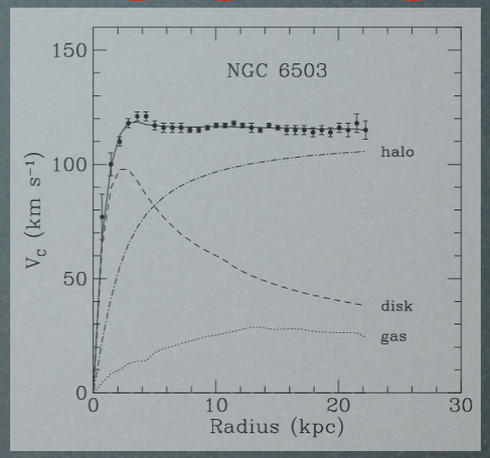


Begeman et al., MNRAS 249 (1991)



The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

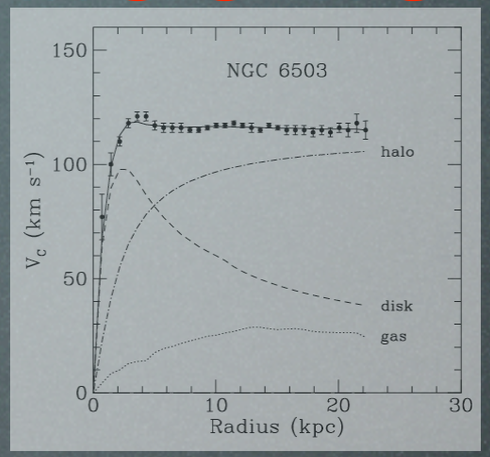
$\Omega_M \sim 0.2 \div 0.4$



"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

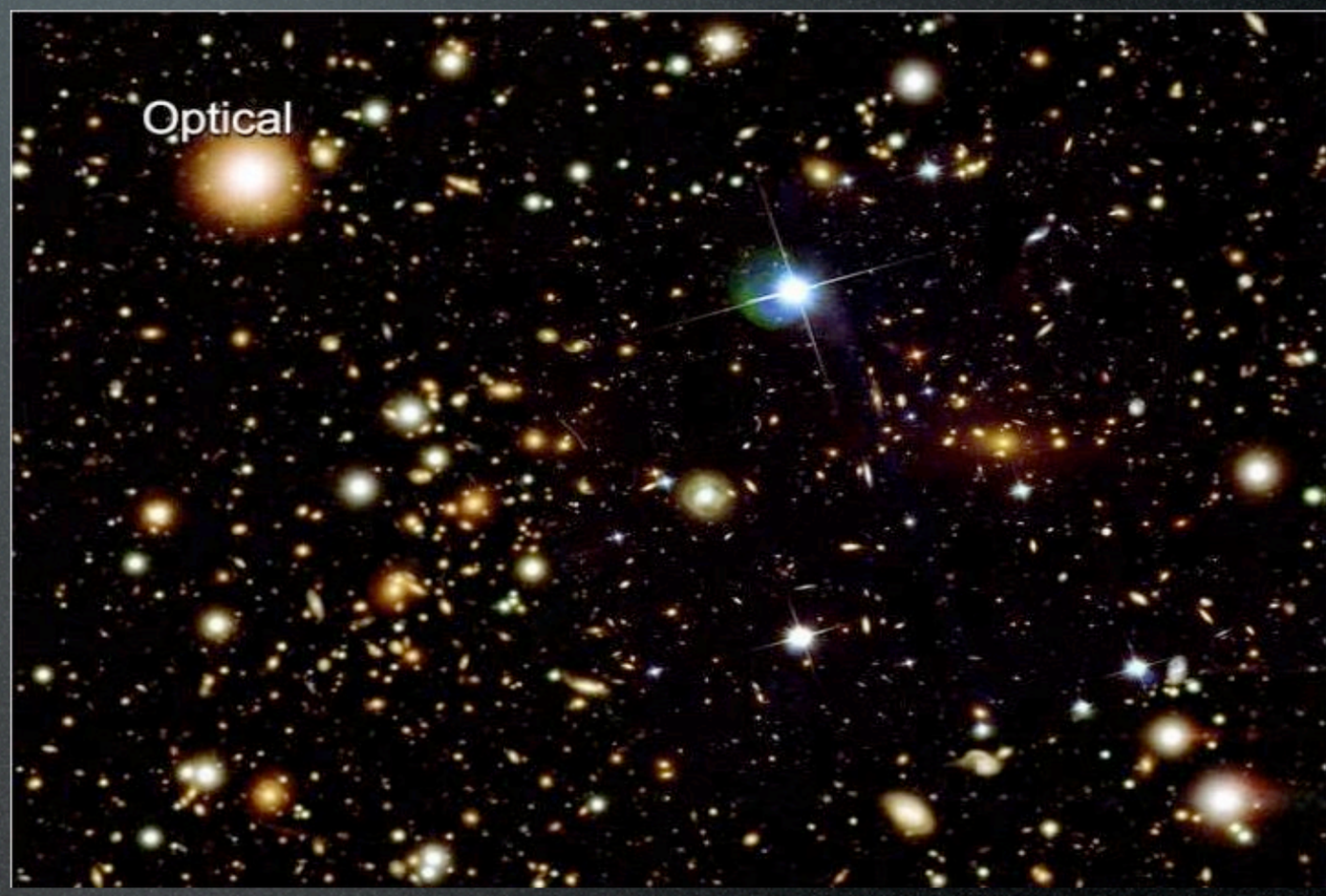
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

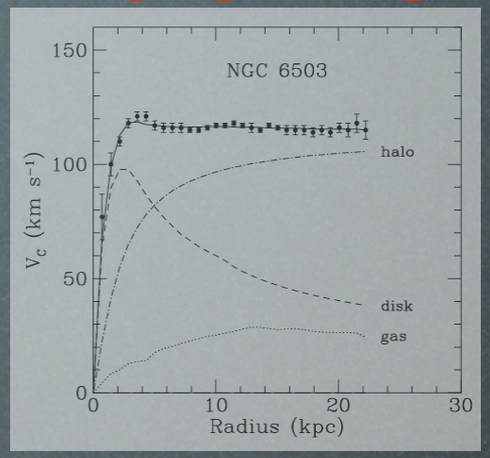


"bullet cluster" - NASA
astro-ph/0608247
[further developments]

$\Omega_M \sim 0.2 \div 0.4$

The Evidence for DM

1) galaxy rotation curves

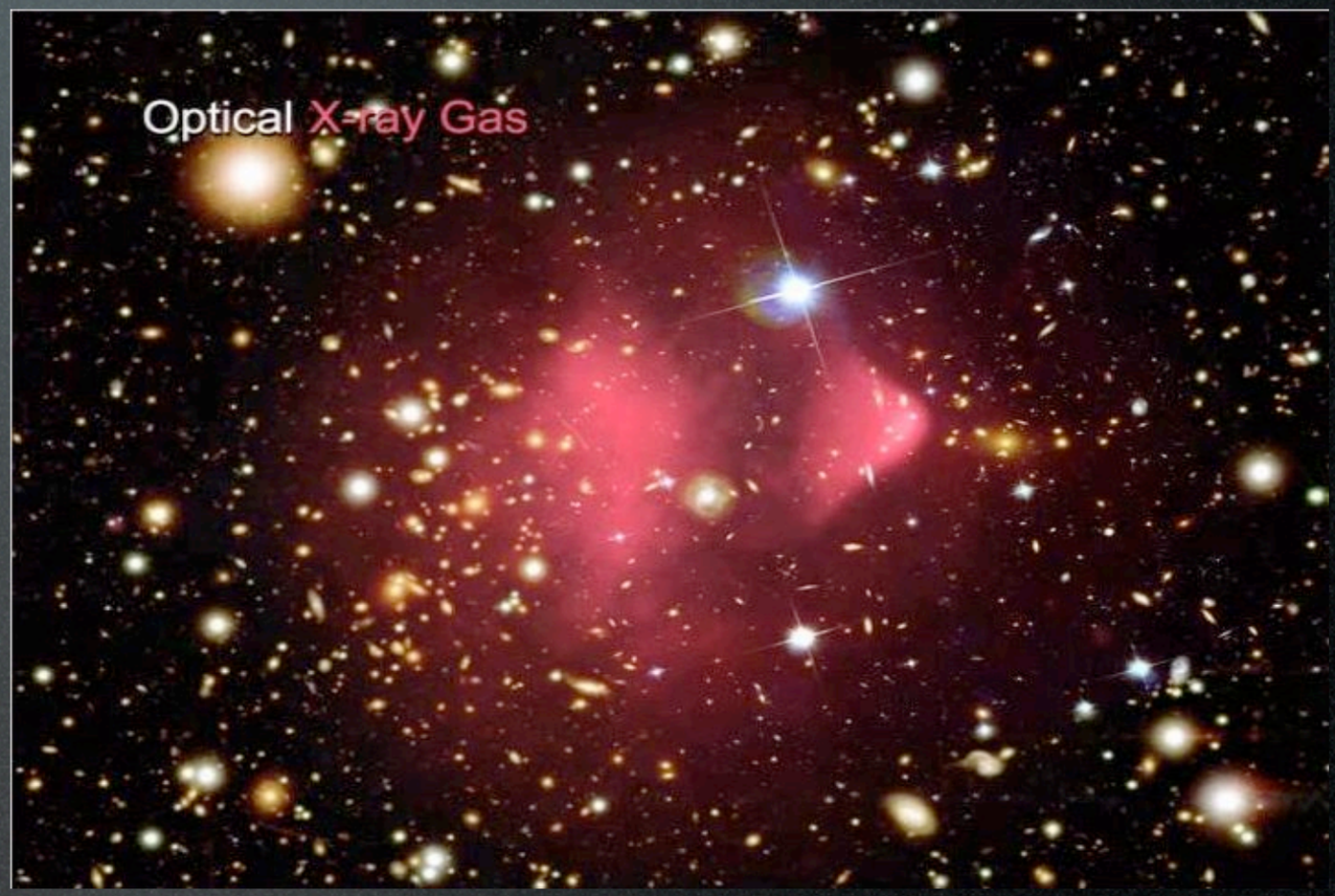


$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

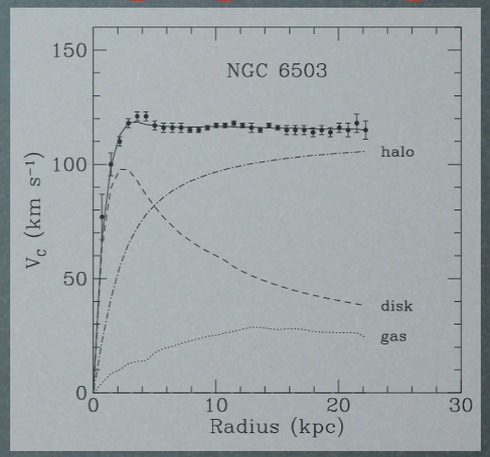
$\Omega_M \sim 0.2 \div 0.4$



"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

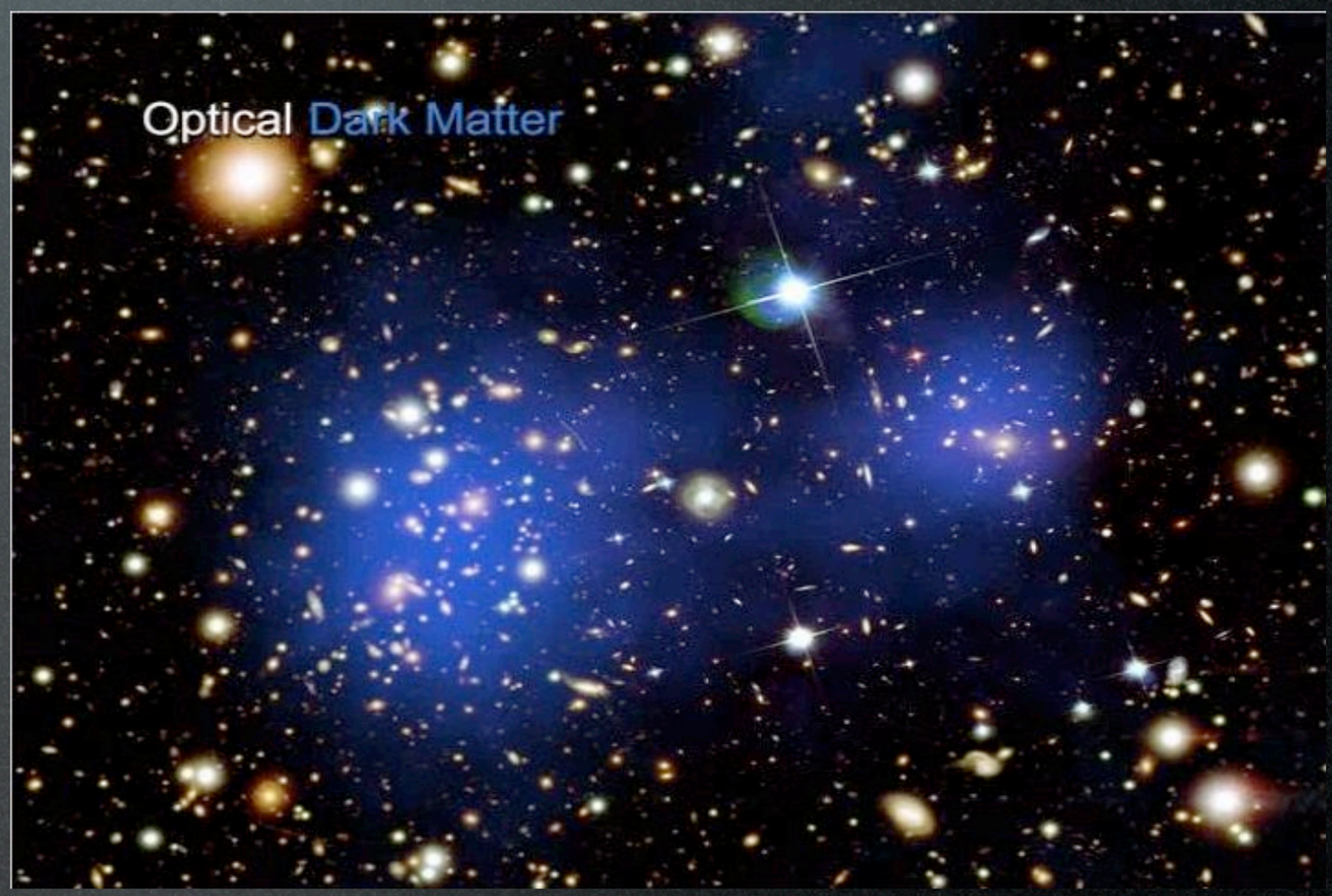
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

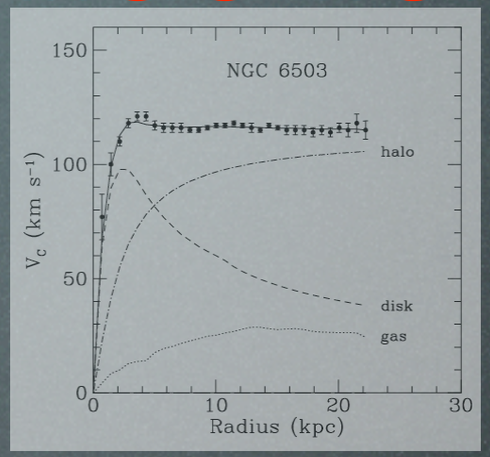


"bullet cluster" - NASA
astro-ph/0608247
[further developments]

$\Omega_M \sim 0.2 \div 0.4$

The Evidence for DM

1) galaxy rotation curves

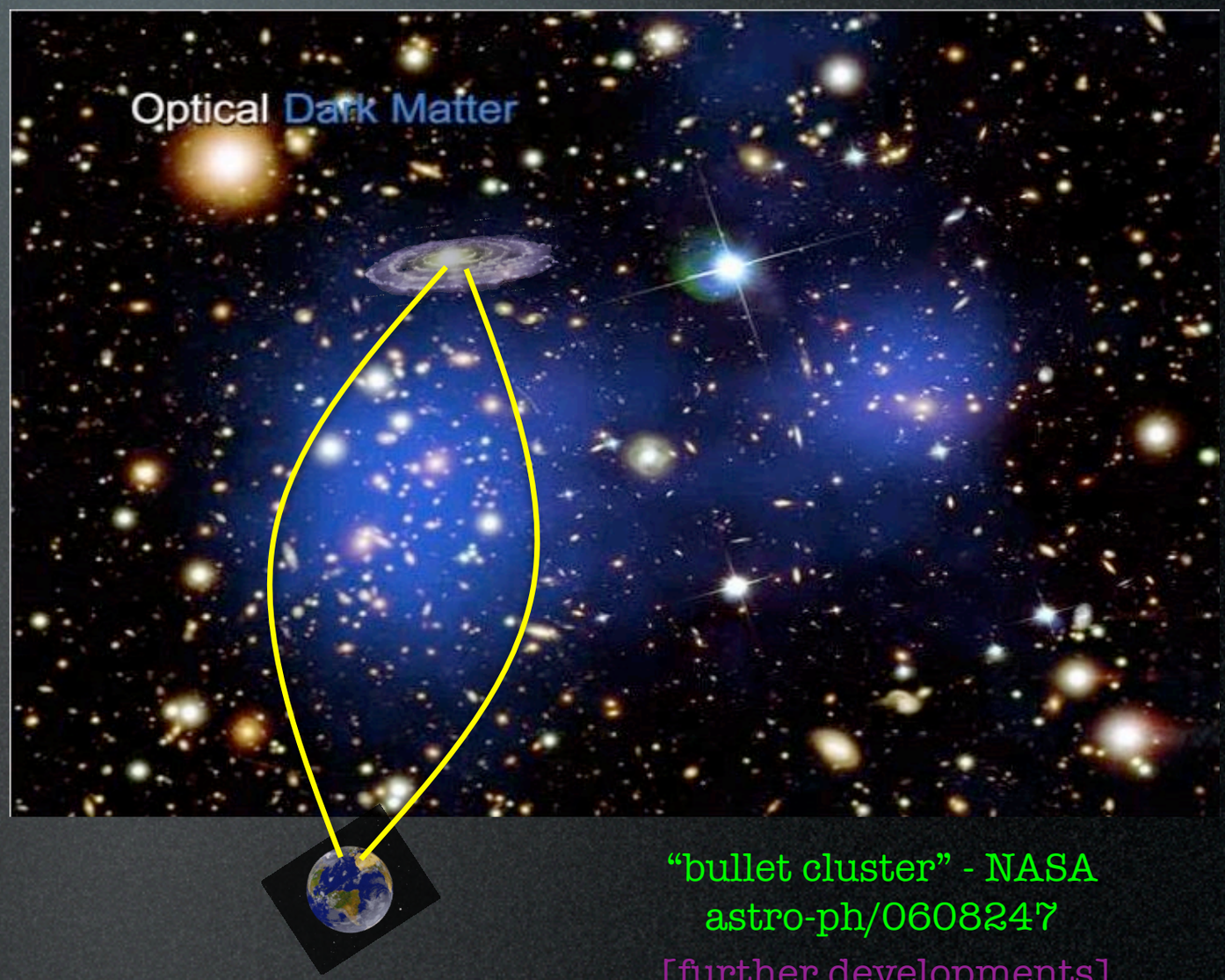


$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

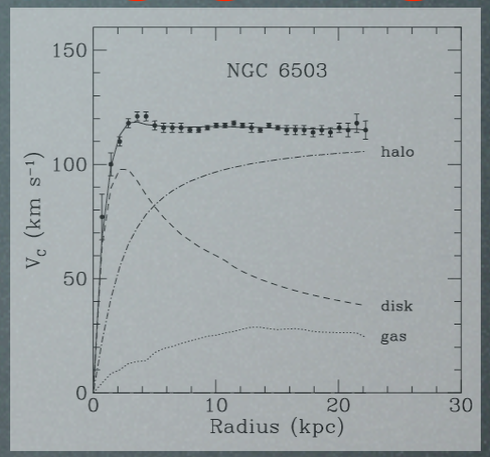
$\Omega_M \sim 0.2 \div 0.4$



"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

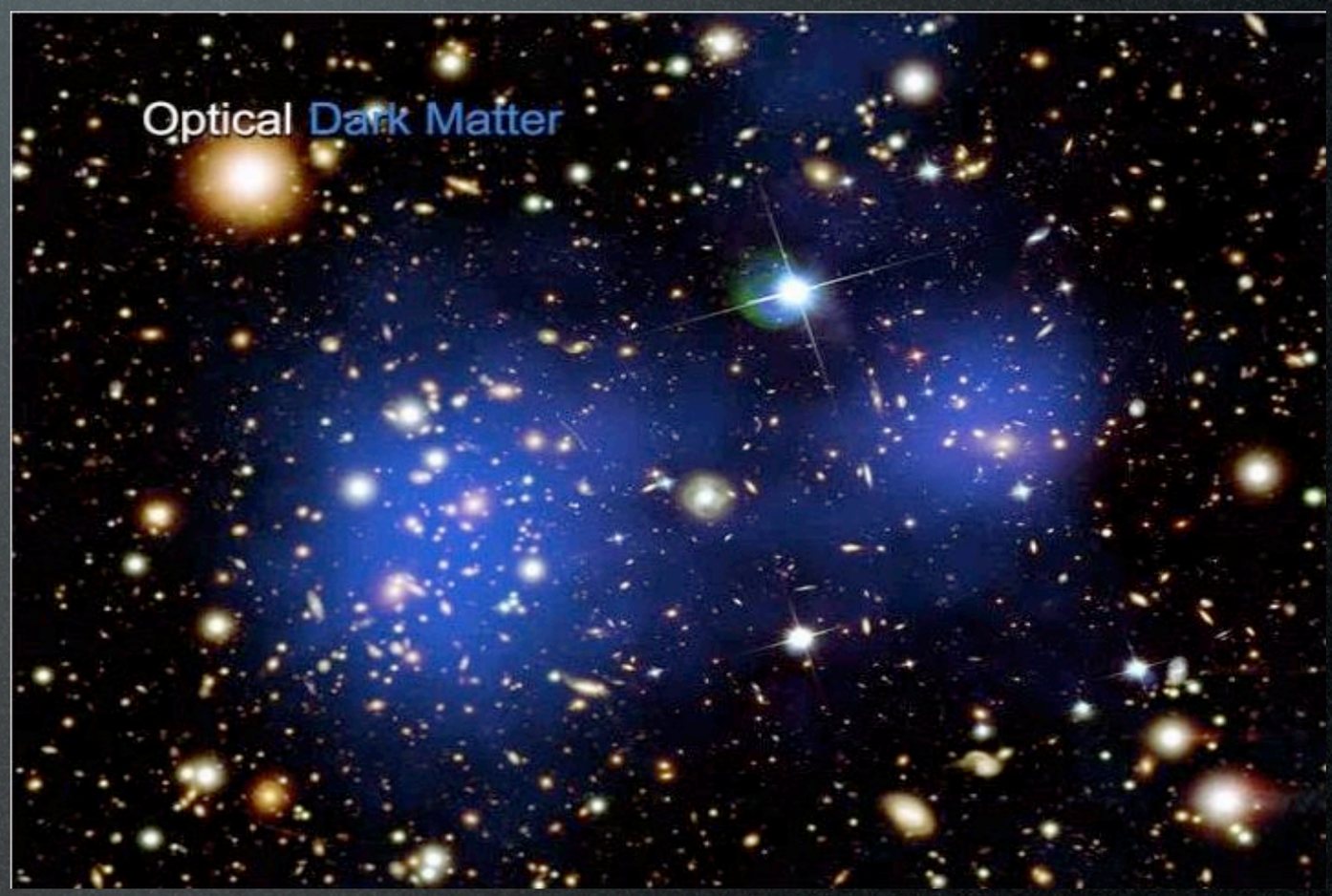
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

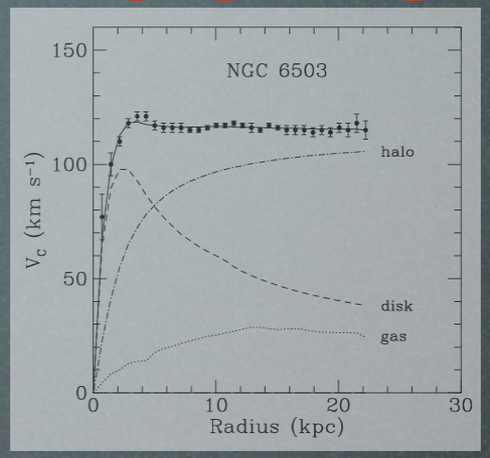


"bullet cluster" - NASA
astro-ph/0608247
[further developments]

$\Omega_M \sim 0.2 \div 0.4$

The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

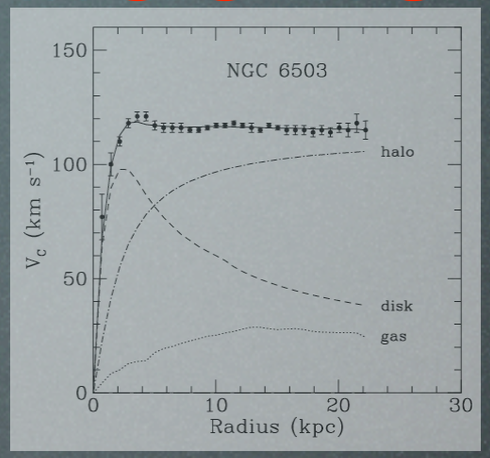
$\Omega_M \sim 0.2 \div 0.4$



"bullet cluster" - NASA
astro-ph/0608247
[further developments]

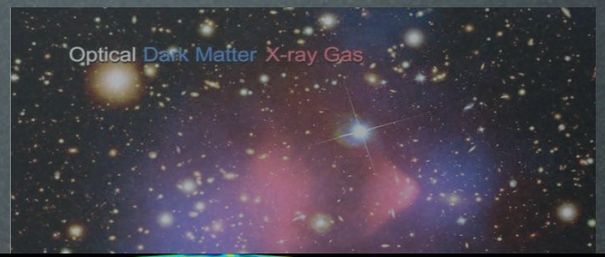
The Evidence for DM

1) galaxy rotation curves



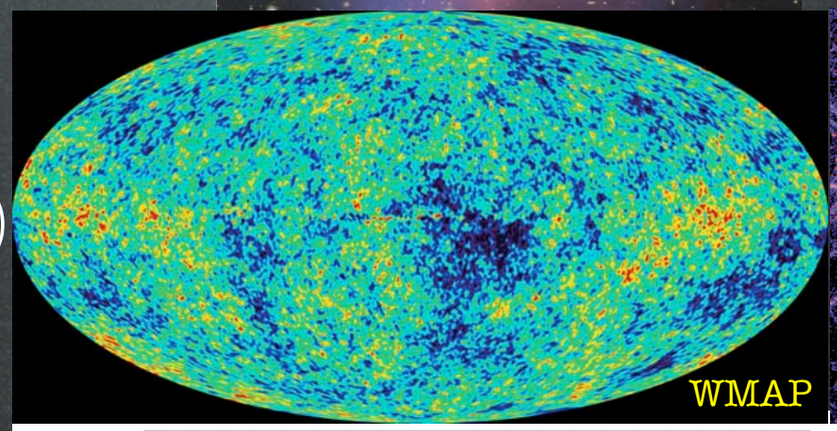
$\Omega_M \gtrsim 0.1$

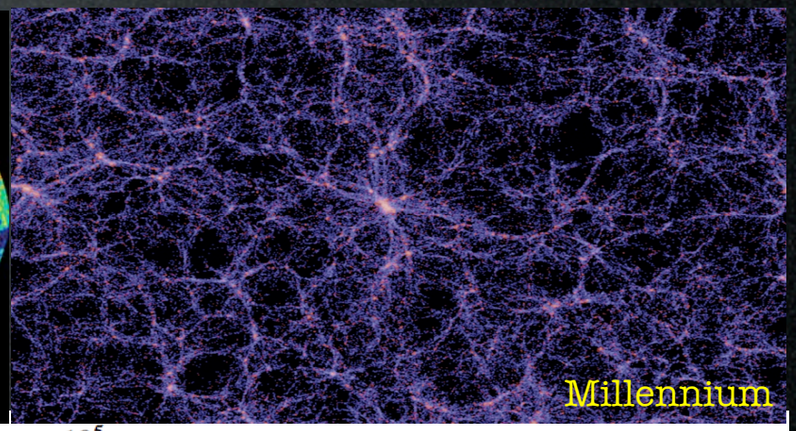
2) clusters of galaxies

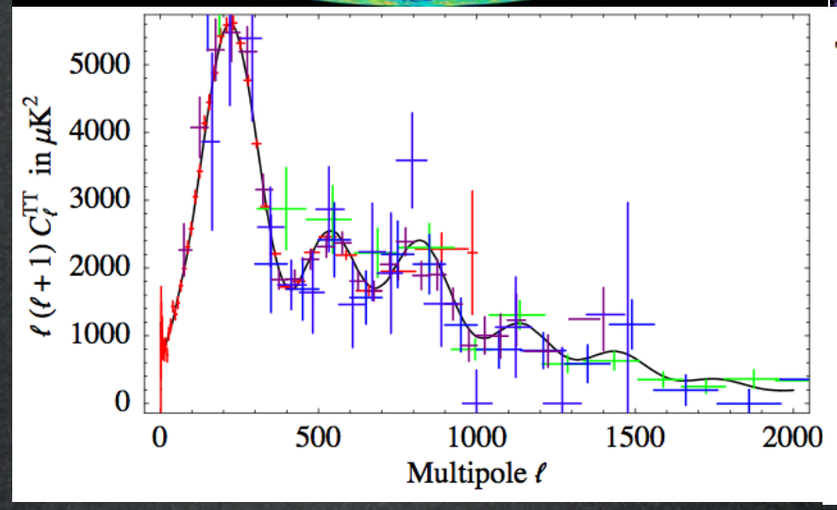


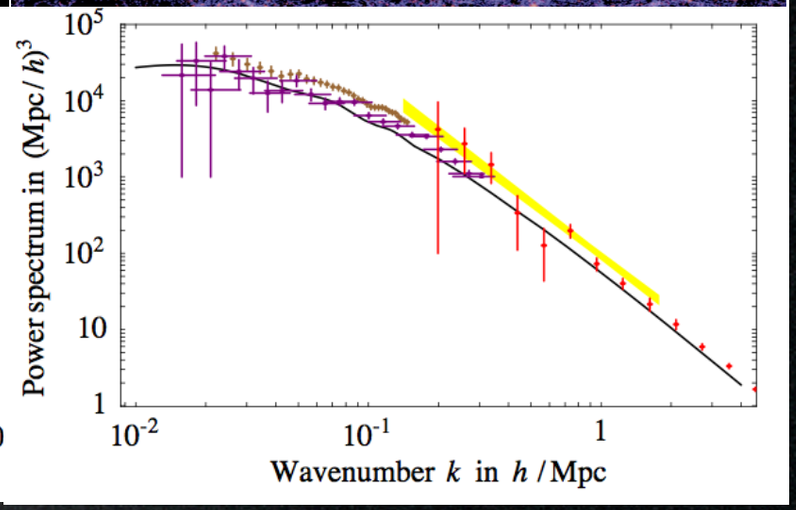
$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)









M.Cirelli and A.Strumia, astro-ph/0607086

DM N-body simulations

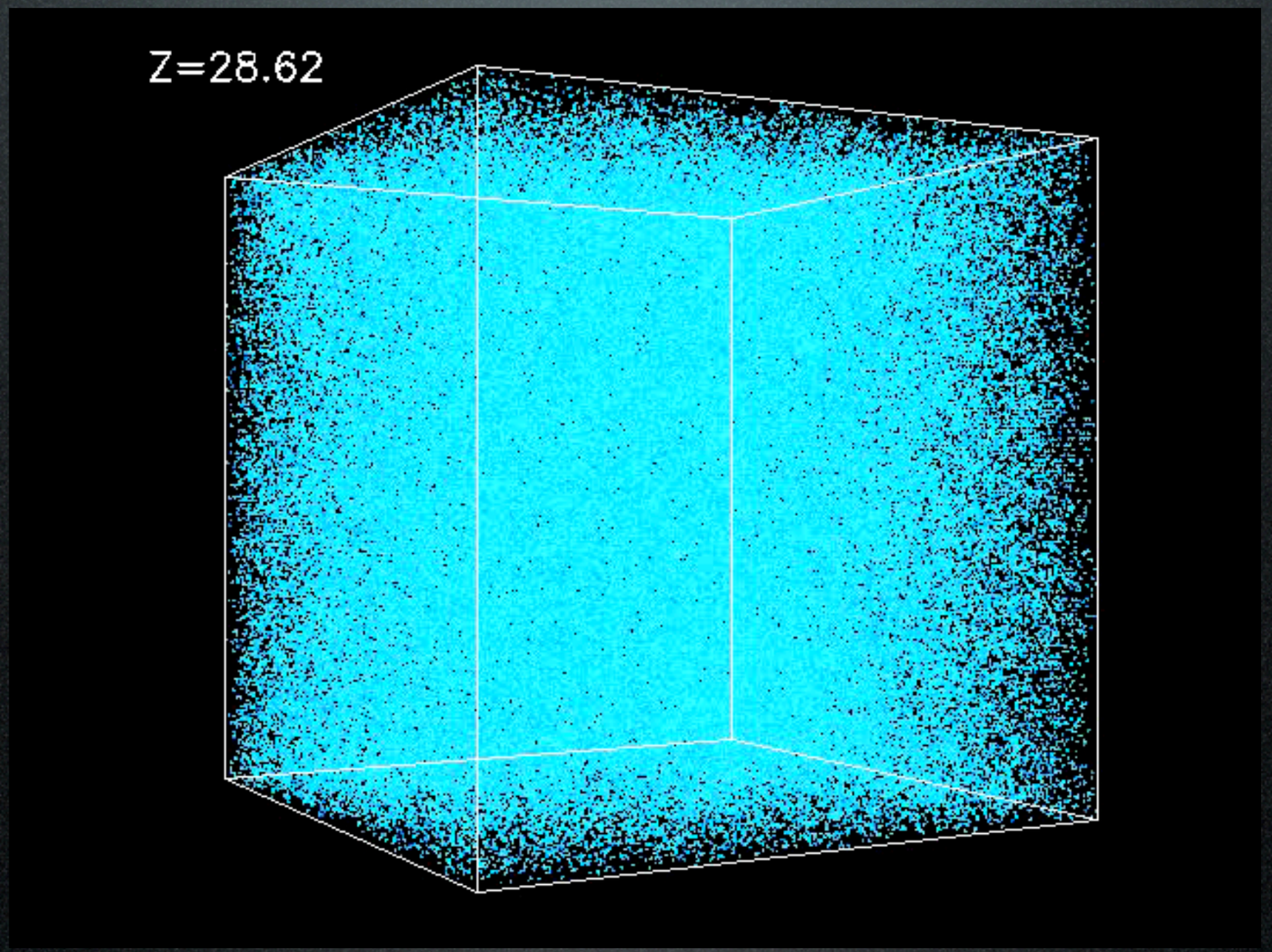
2 10^6 CDM particles, 43 Mpc cubic box

Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box



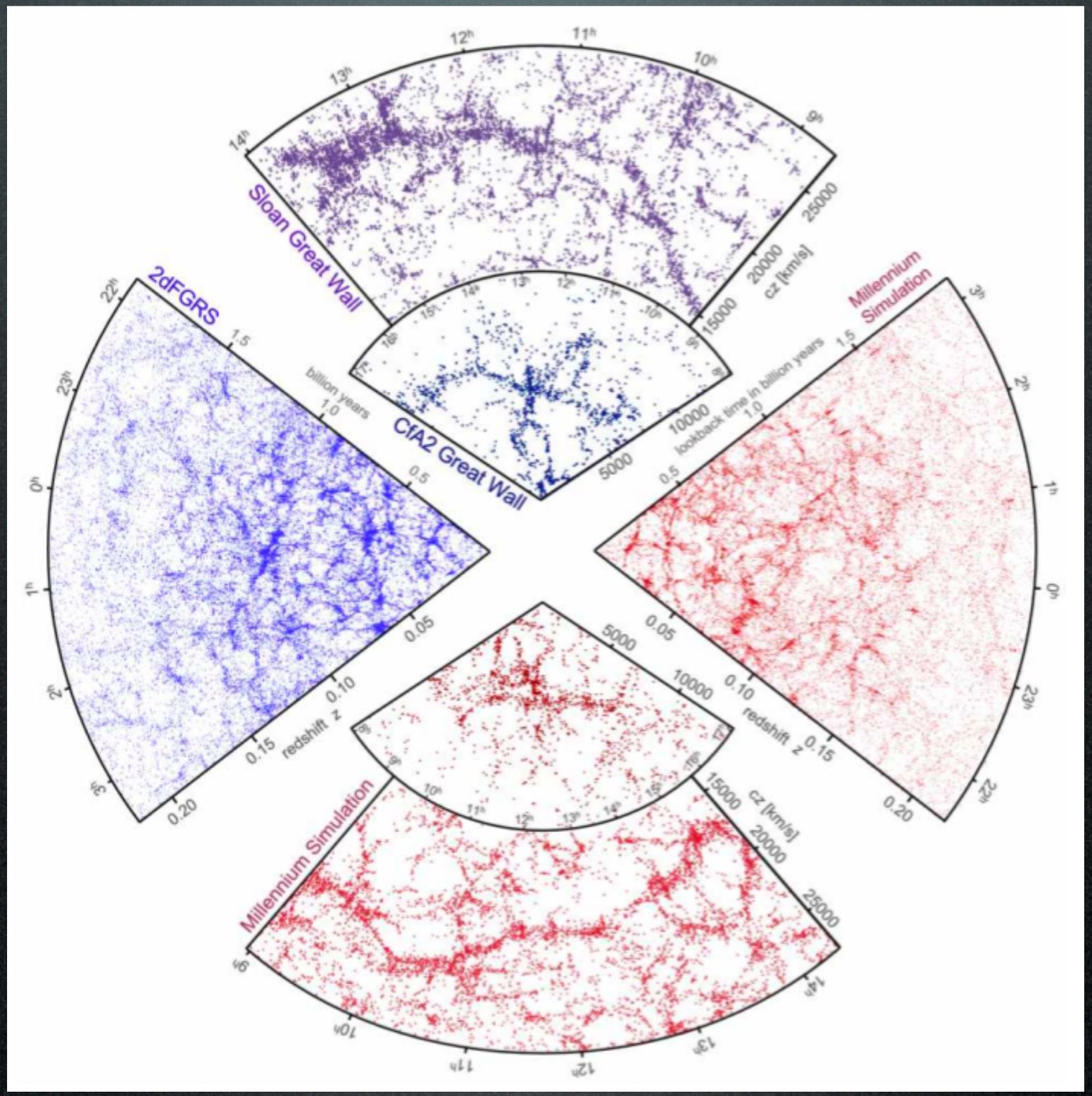
Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies, 2 billion lyr



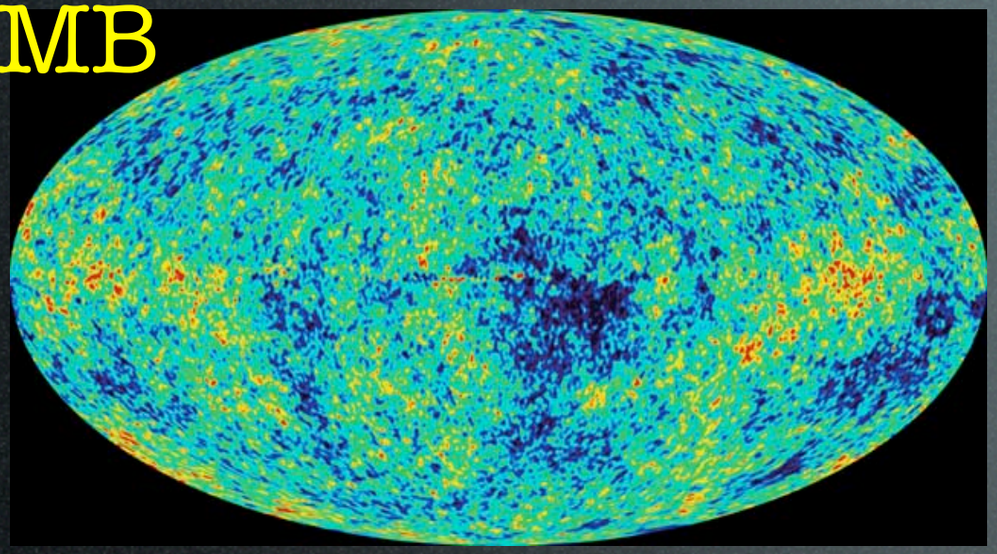
Springel, Frenk, White, Nature 440 (2006)

Millennium: 10^{10} particles, 500 h^{-1} Mpc

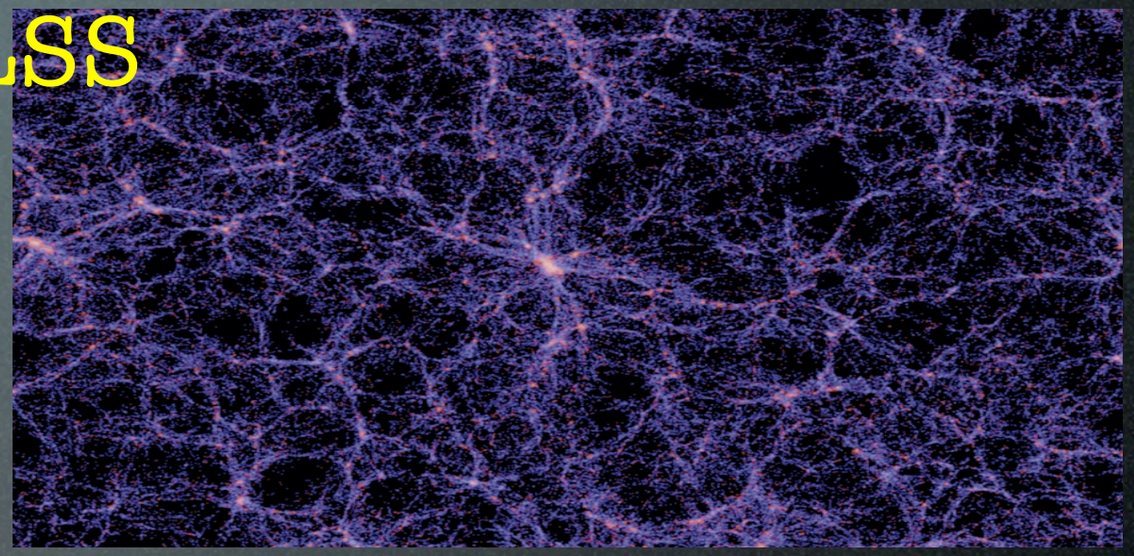
[back]

The Evidence for DM

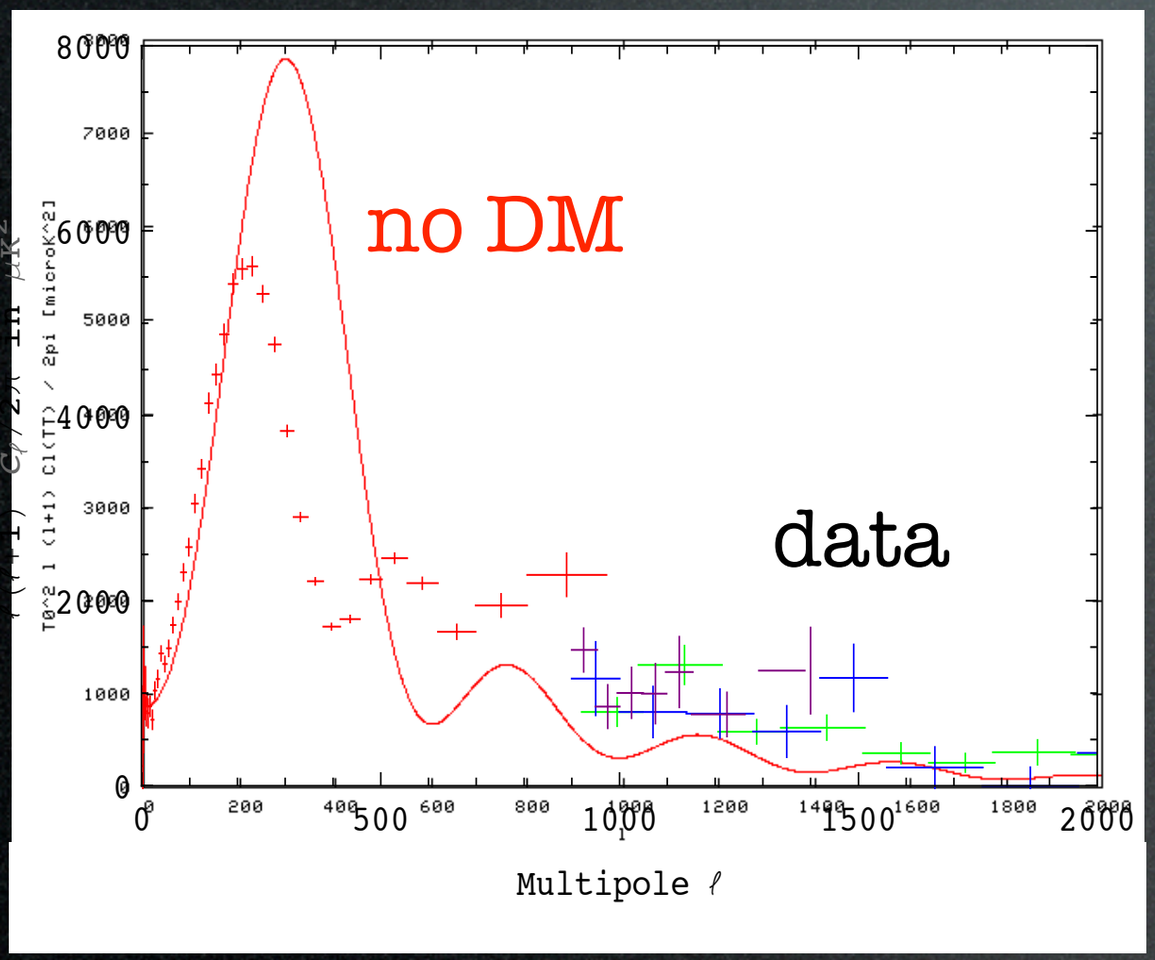
CMB



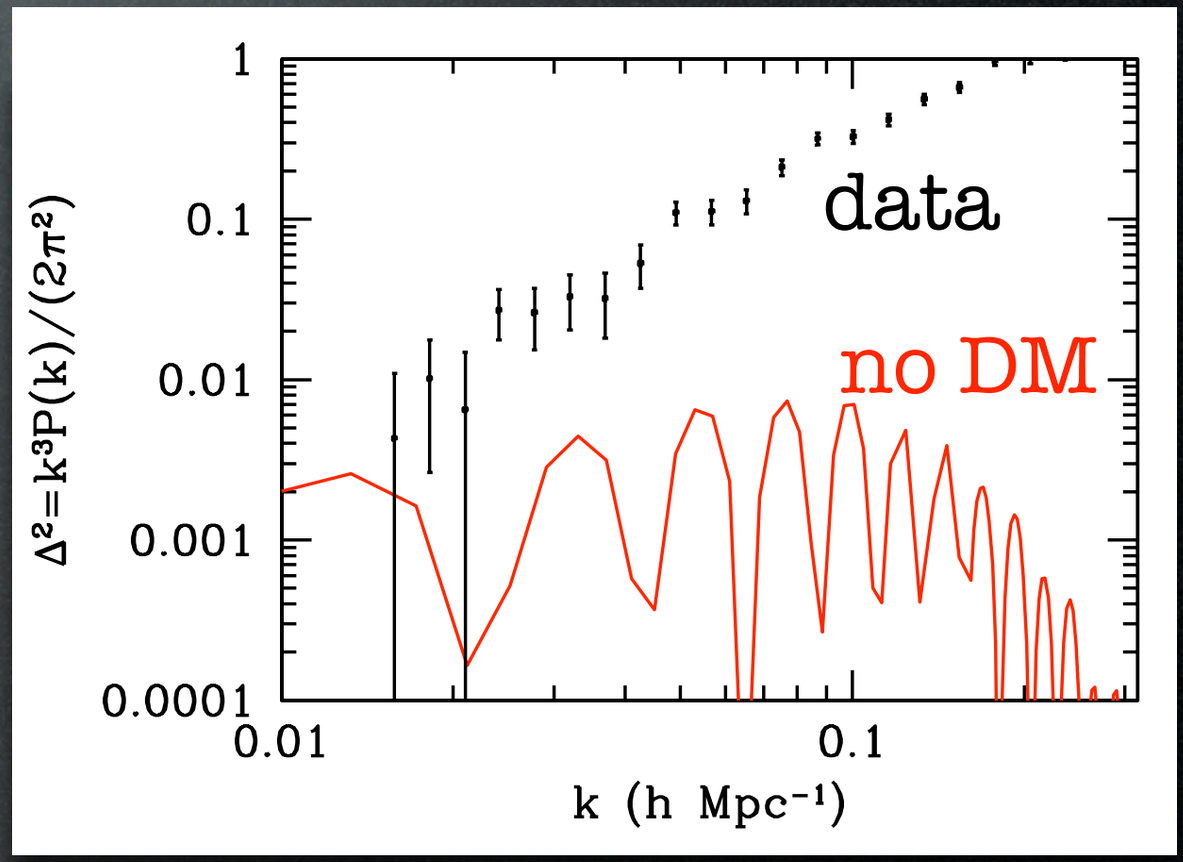
LSS



How would the power spectra be without DM? (and no other extra ingredient)



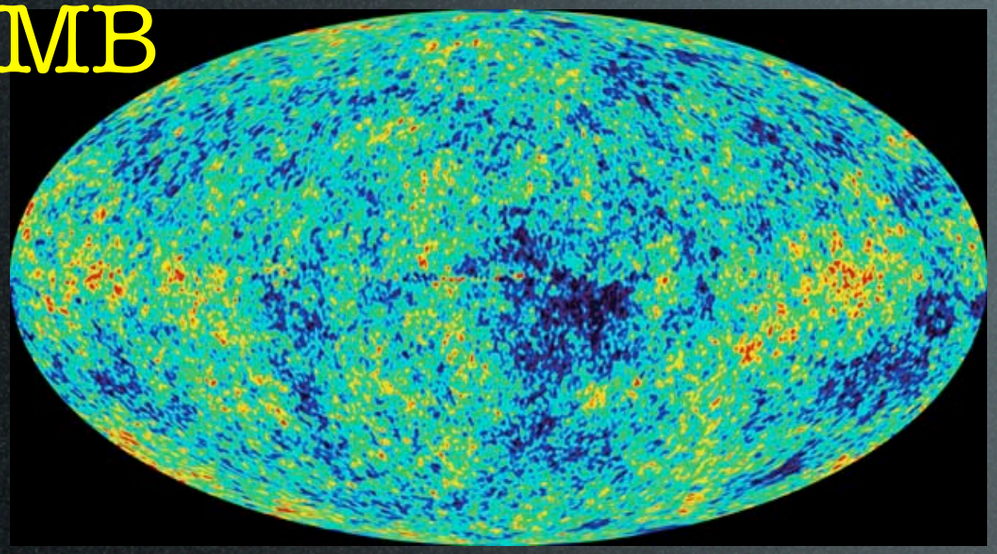
(in particular: no DM => no 3rd peak!)



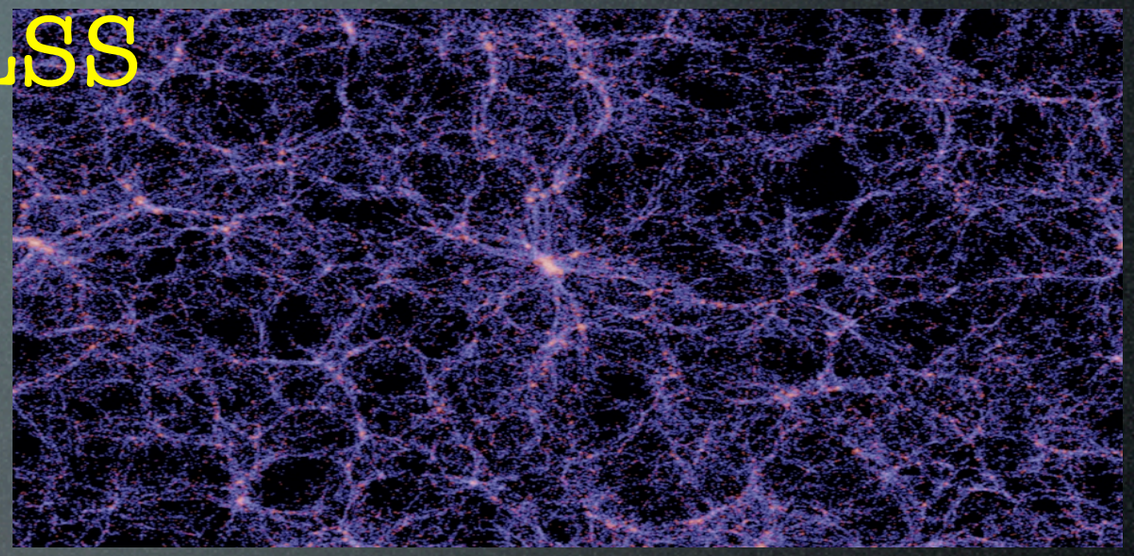
(you need DM to gravitationally "catalyse" structure formation)

The Evidence for DM

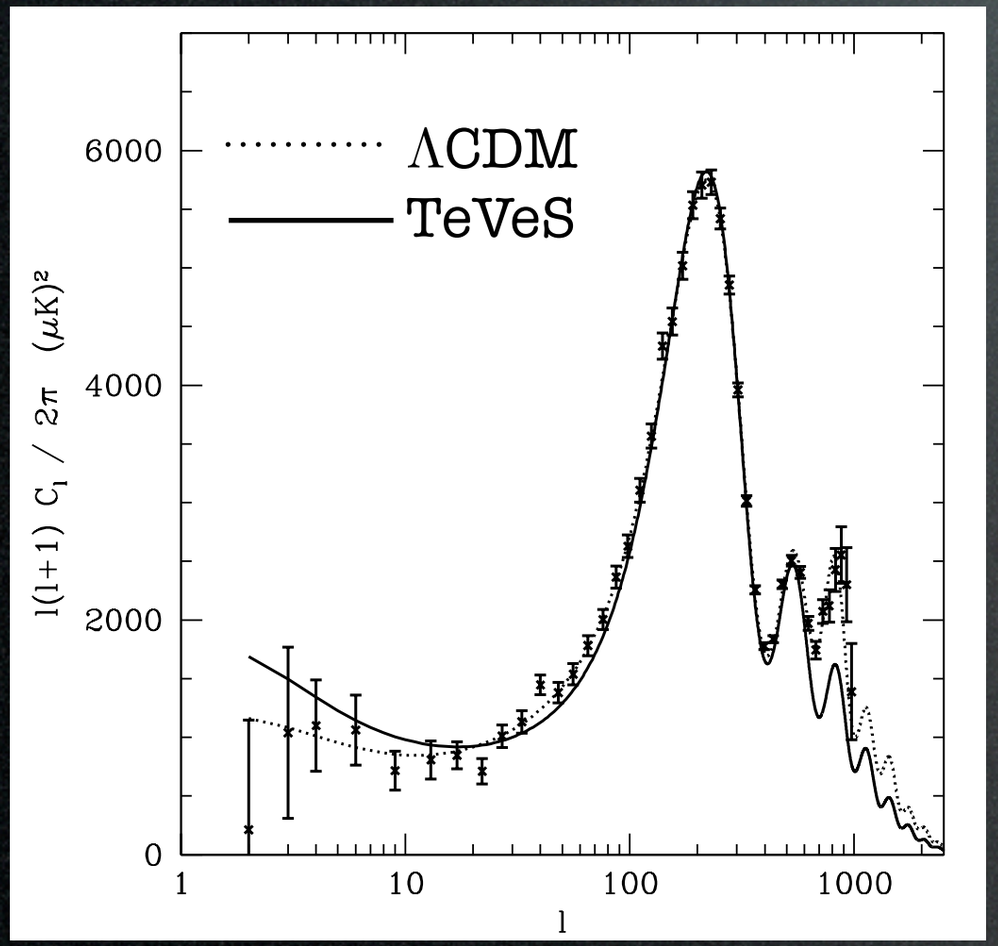
CMB



LSS

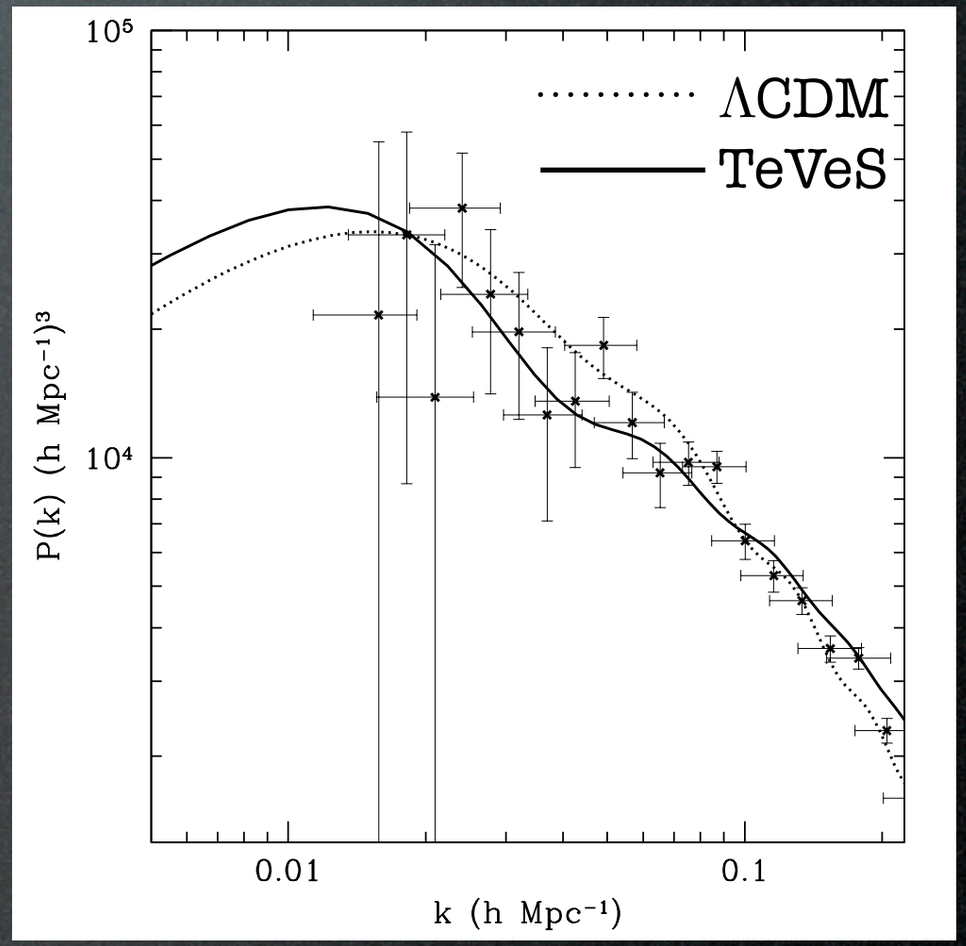


How would the power spectra be in MOND/TeVeS, without DM ?



C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)

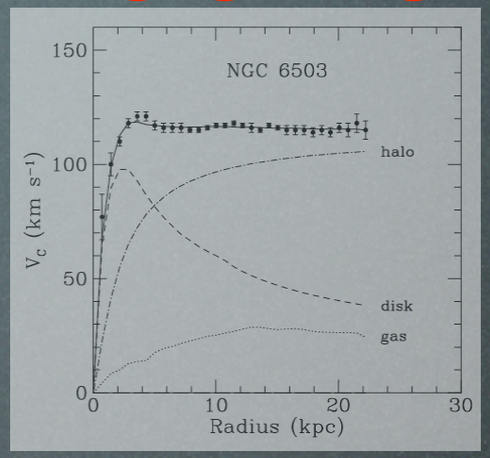


C.Skordis, Review, 0903.3602

(here you can make it)

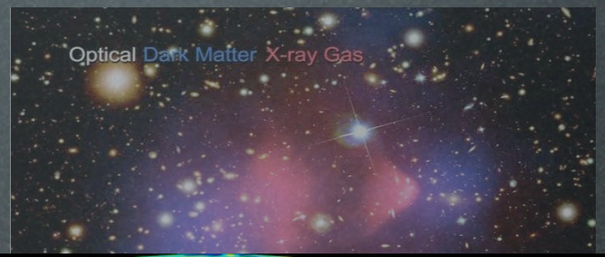
The Evidence for DM

1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

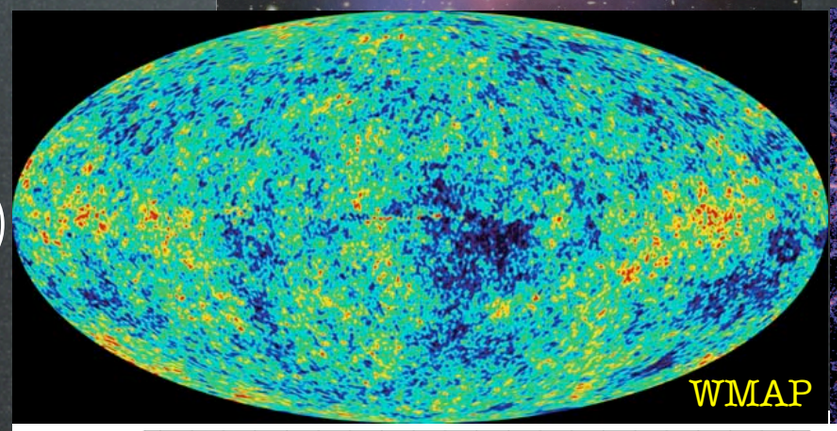


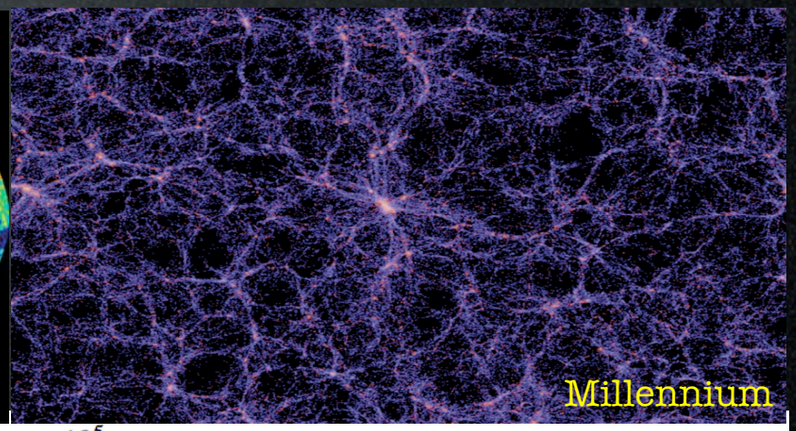
$\Omega_M \sim 0.2 \div 0.4$

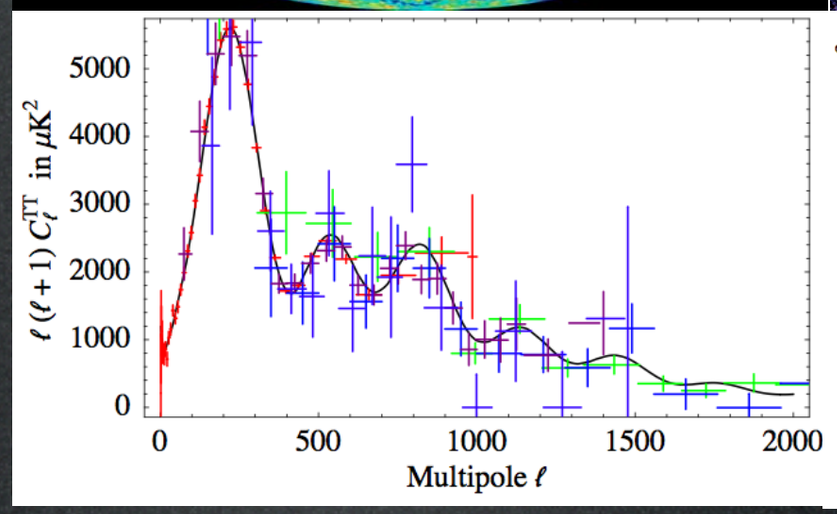
3) CMB+LSS(+SNIa:)

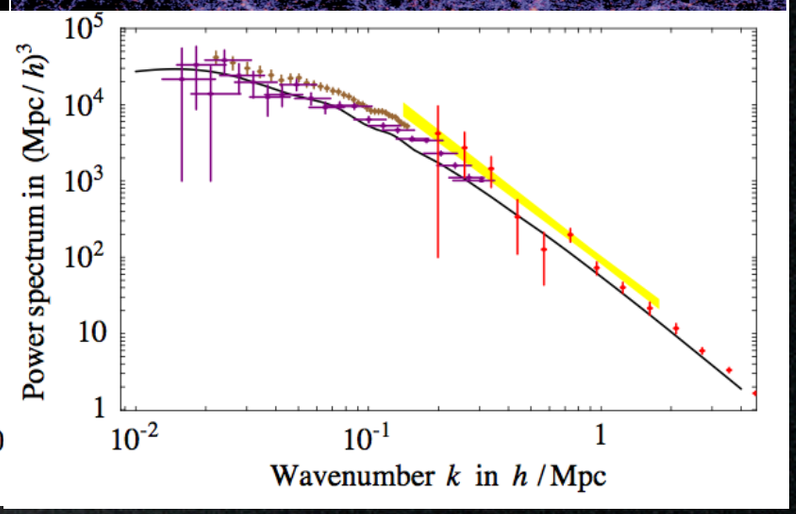
WMAP-3yr Boomerang
ACbar DASI
CBI VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS









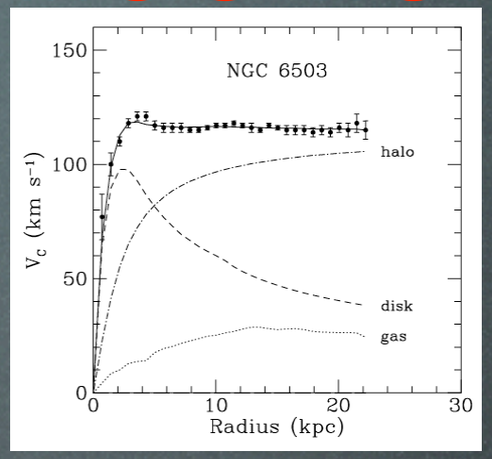
$\Omega_M \approx 0.26 \pm 0.05$

(spectra w/o DM)

M.Cirelli and A.Strumia, astro-ph/0607086

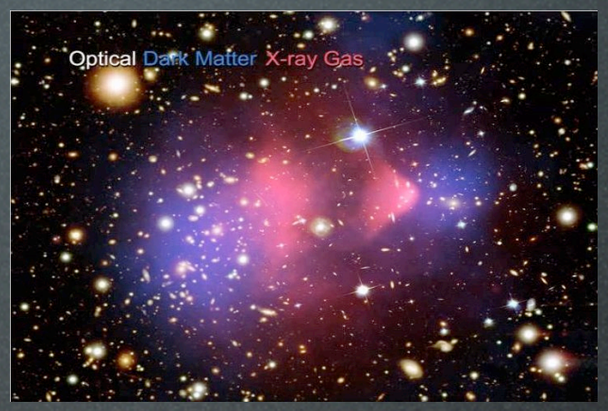
The Evidence for DM

1) galaxy rotation curves



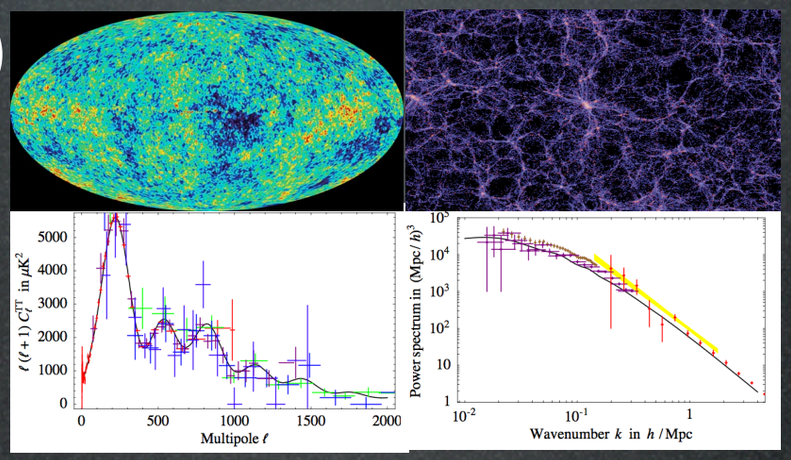
$\Omega_{\rm M} \gtrsim 0.1$

2) clusters of galaxies



$\Omega_{\rm M} \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)



$\Omega_{\rm M} \approx 0.26 \pm 0.05$

[back]

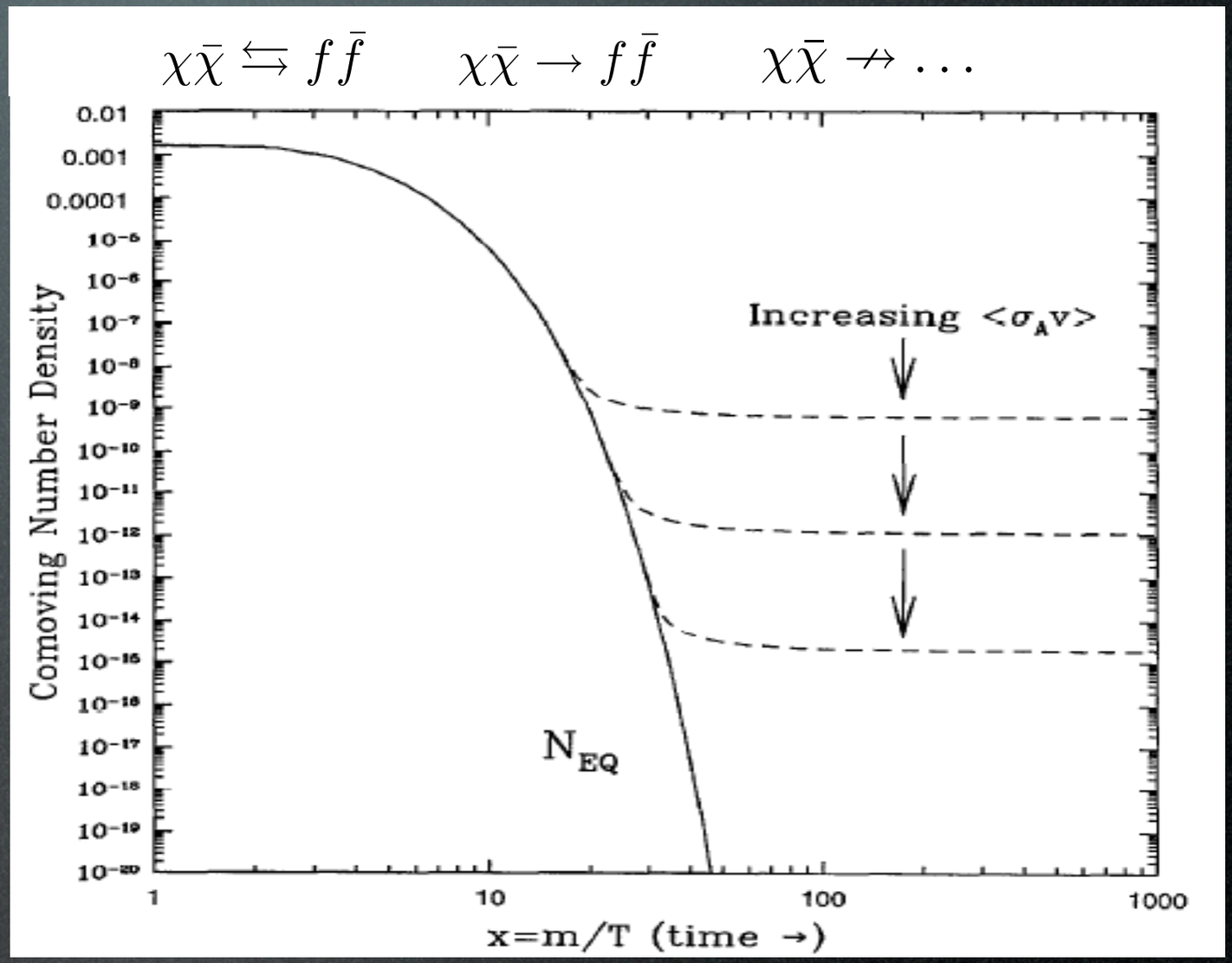
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$\langle\sigma_{\mathrm{ann}}v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

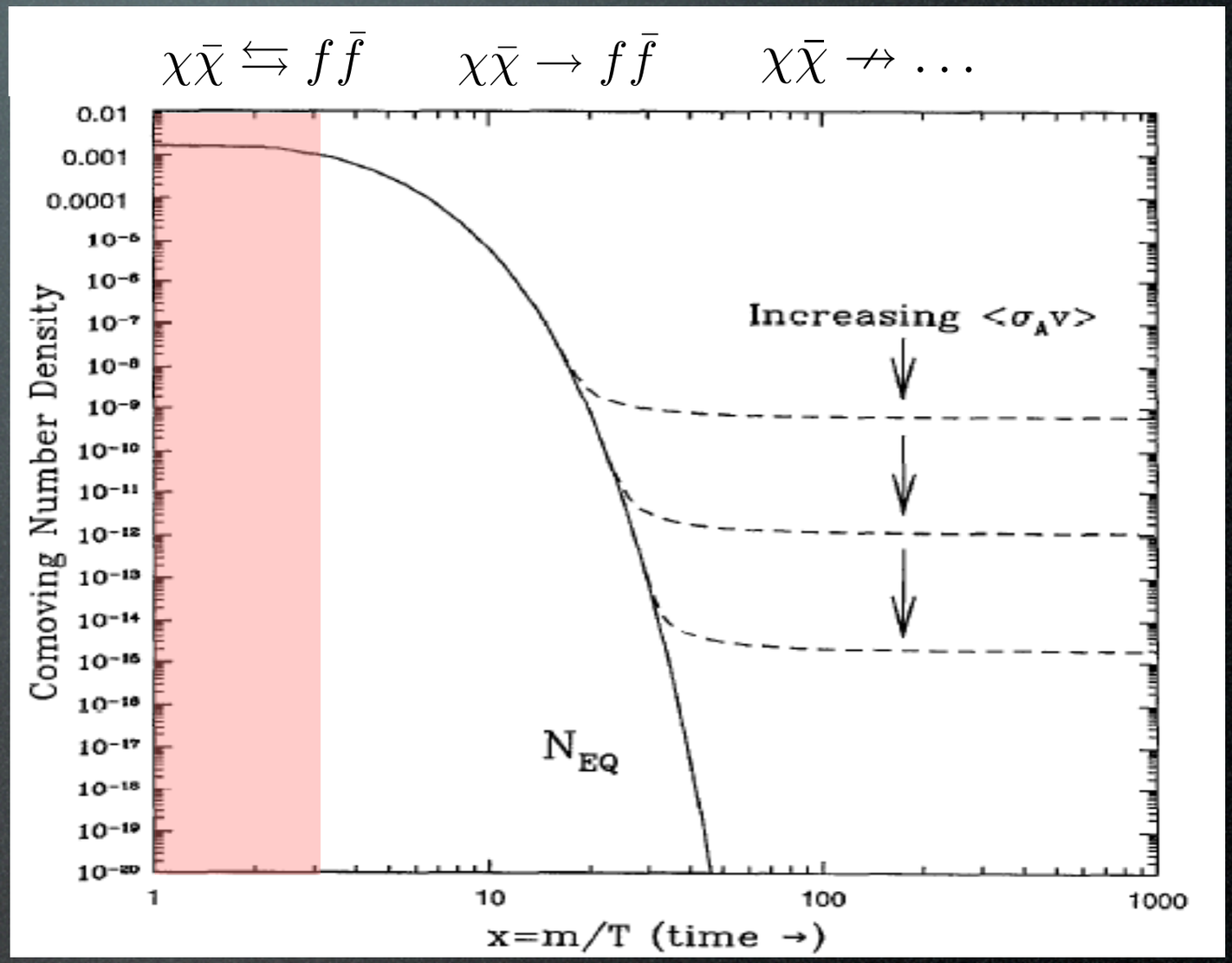
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}}v\rangle = 3\cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

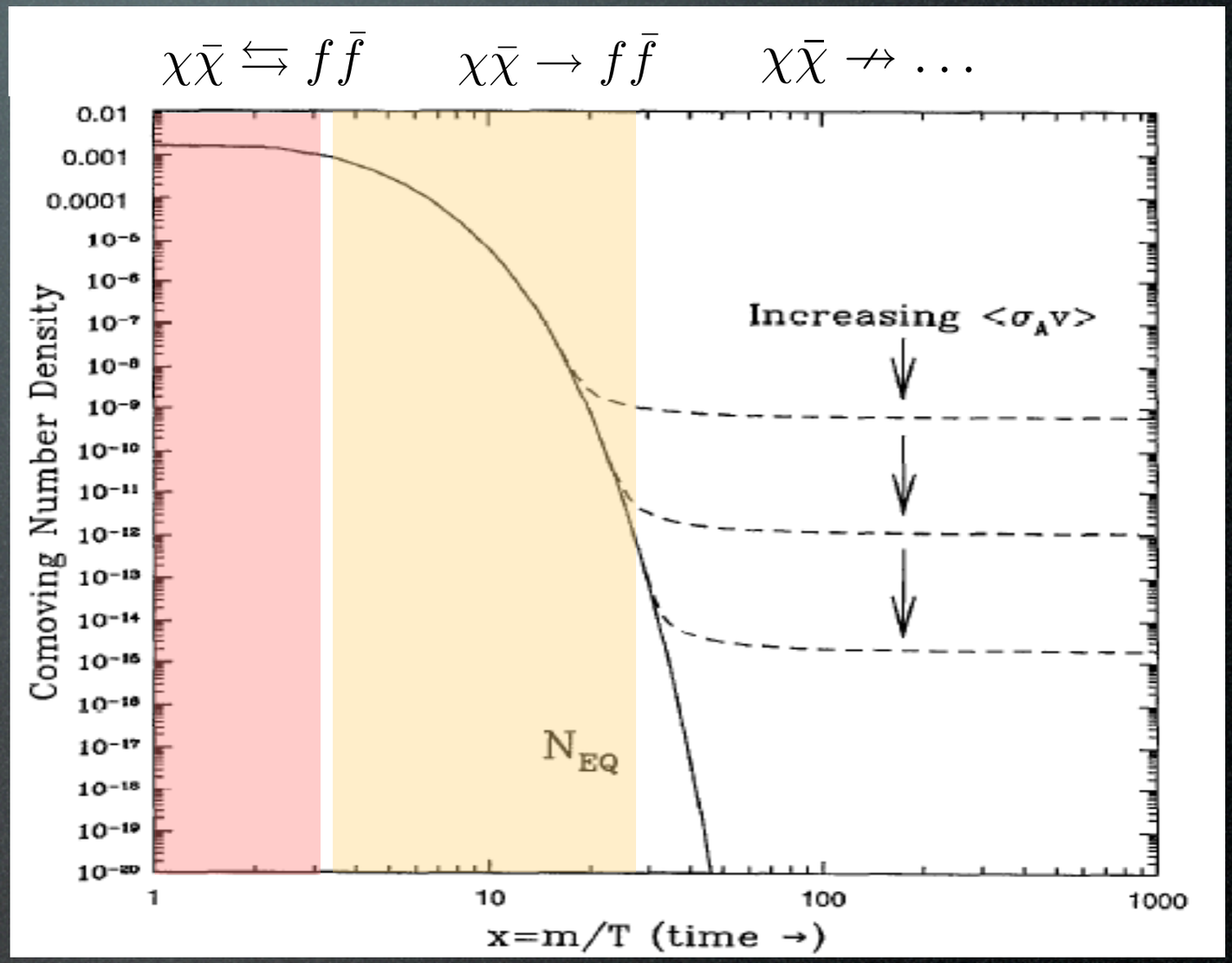
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV^2}} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

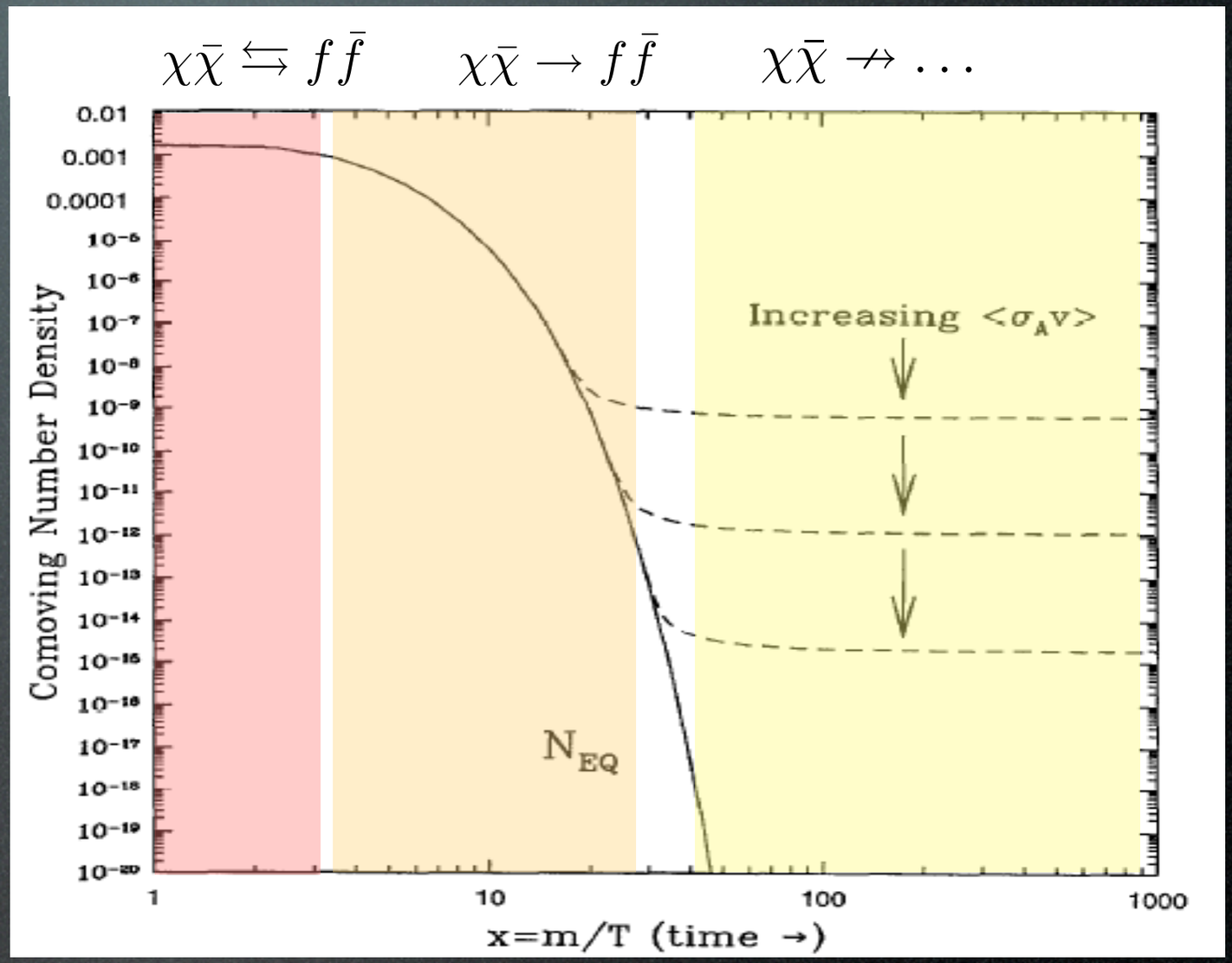
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Kolb,Turner, The Early Universe, 1995

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\,TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

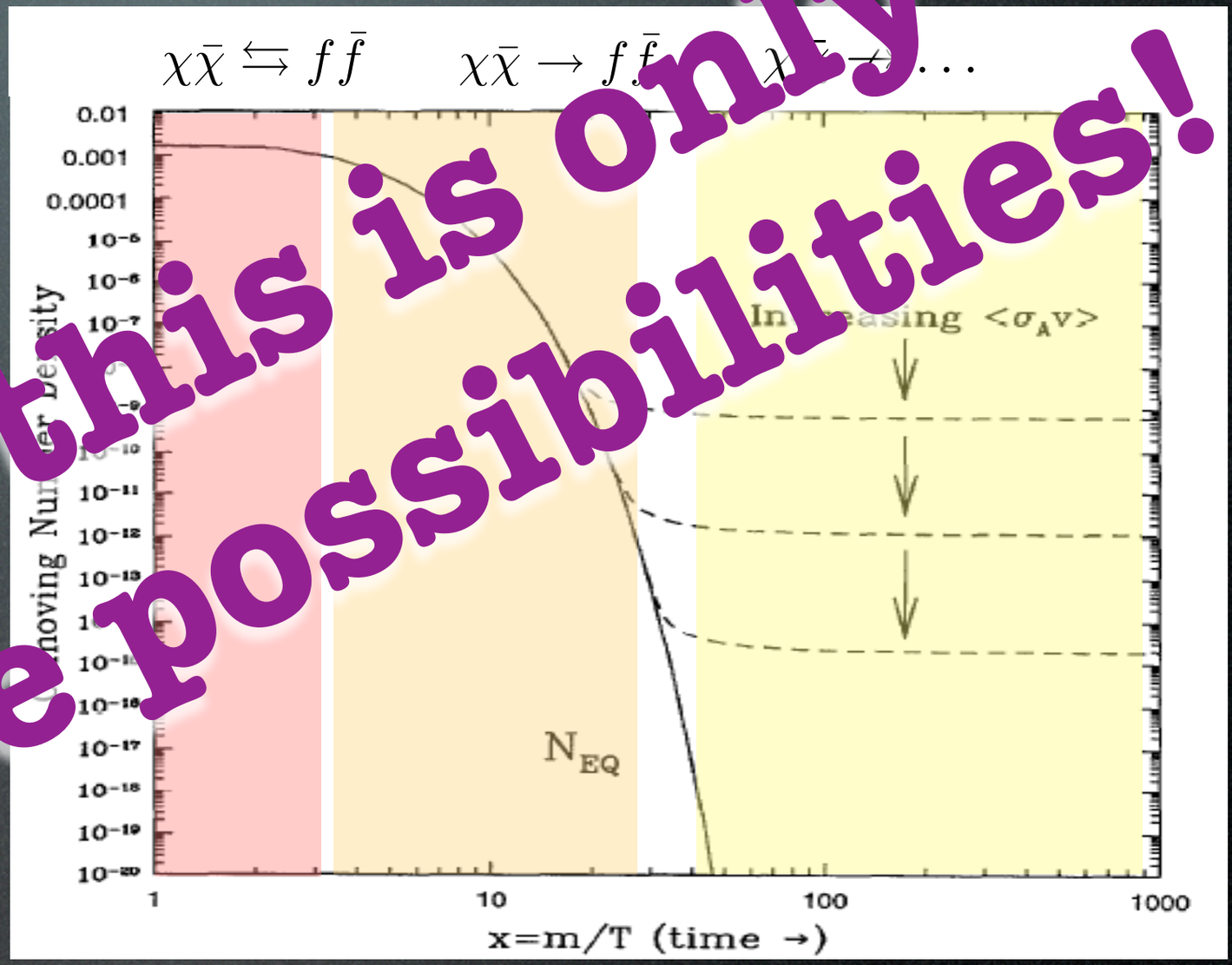
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$



Caveat: this is only one of the possibilities!

Weak cross section:

$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1\,\mathrm{TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$

(WIMP)

[back]

Indirect Detection

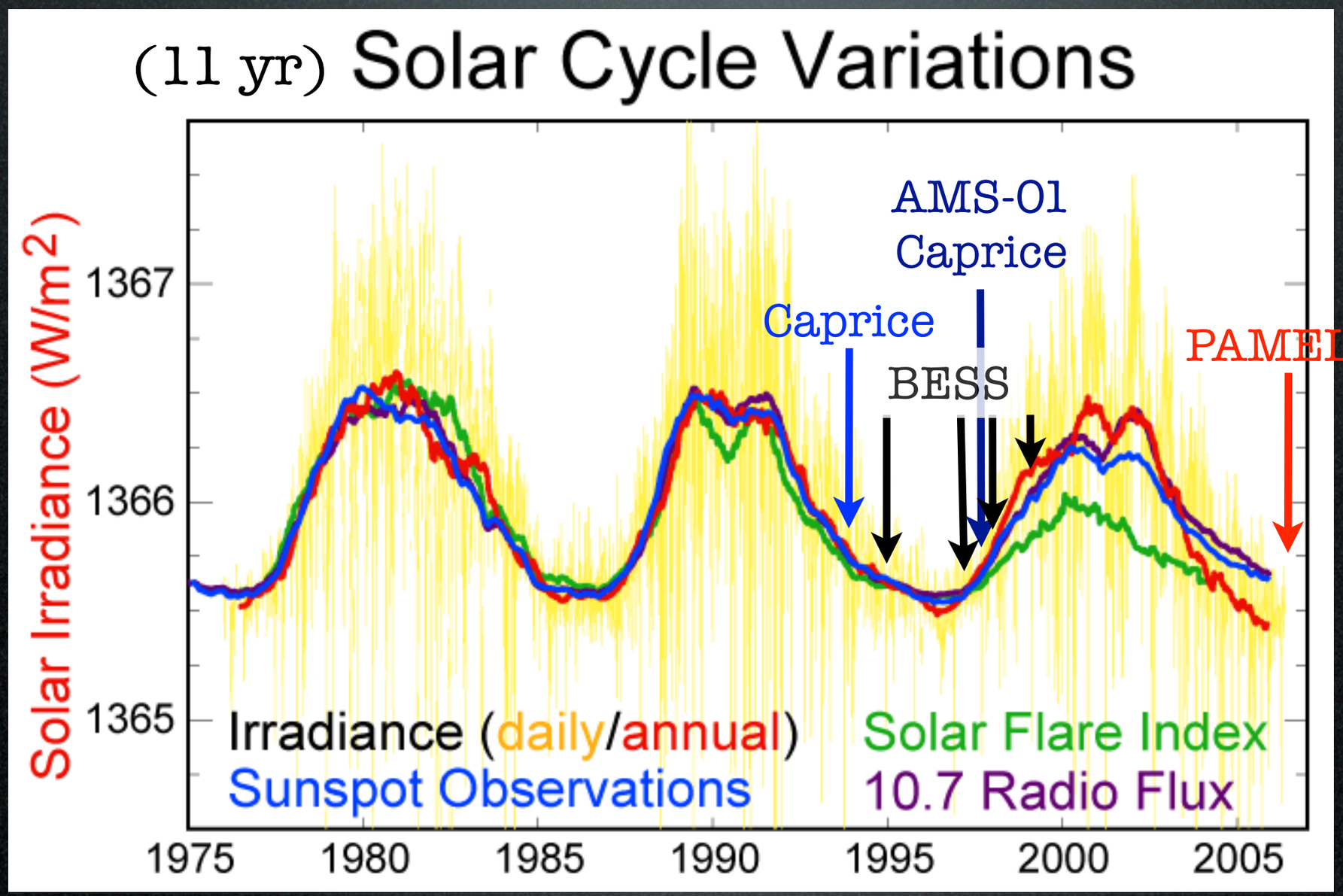
Solar wind Modulation of cosmic rays:

$$\frac{d\Phi_{\bar{p}\oplus}}{dT_\oplus} = \frac{p_\oplus^2}{p^2}\frac{d\Phi_{\bar{p}}}{dT}, \qquad T = T_\oplus + |Ze|\phi_F$$

spectrum at Earth

spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

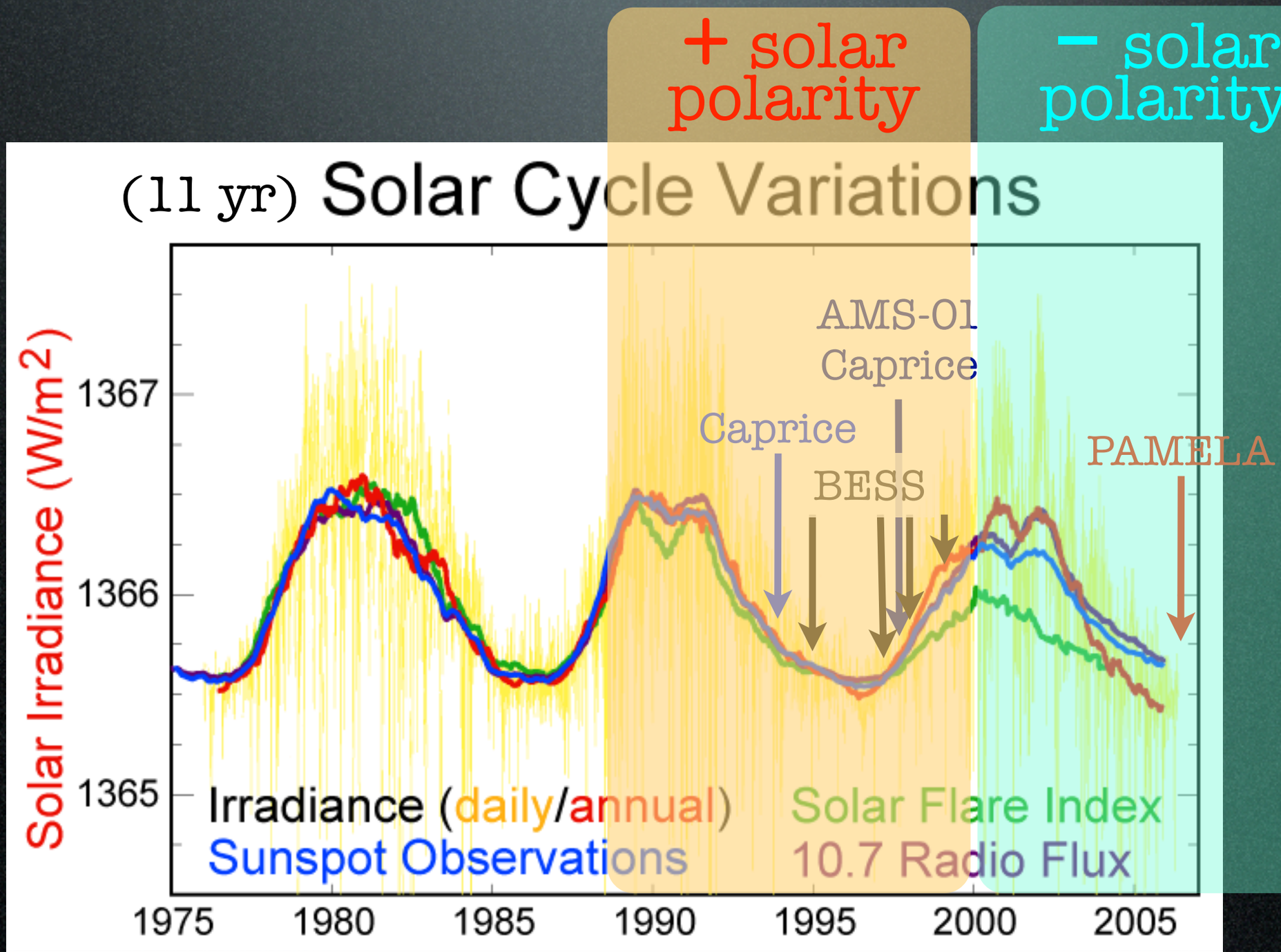


Indirect Detection

Solar polarity Modulation of cosmic rays:

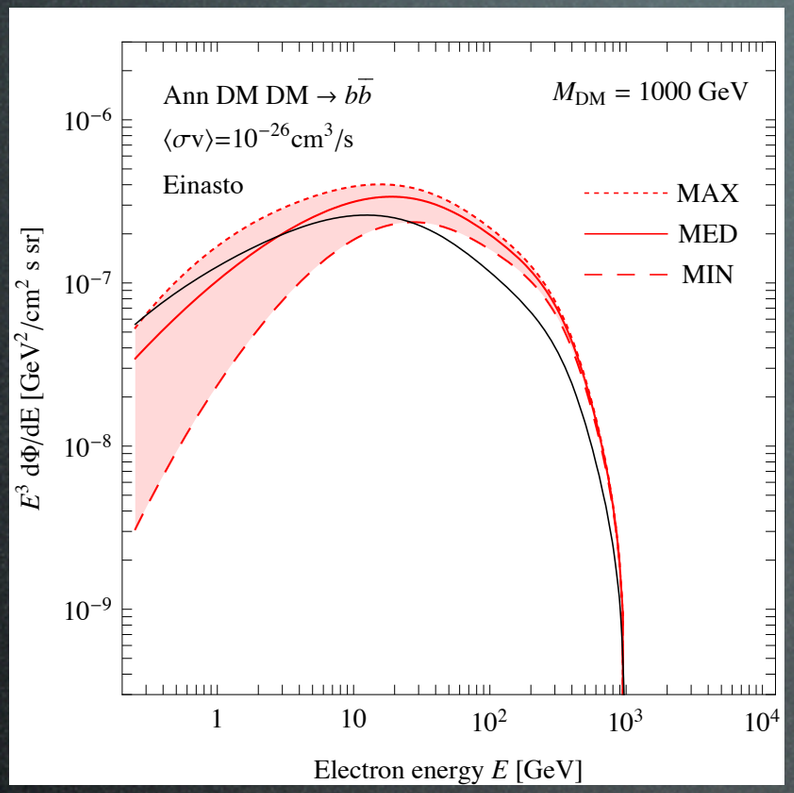
solar magnetic polarity reverses at (the max of) each cycle;
during '– polarity' state, positive particles are more deflected away

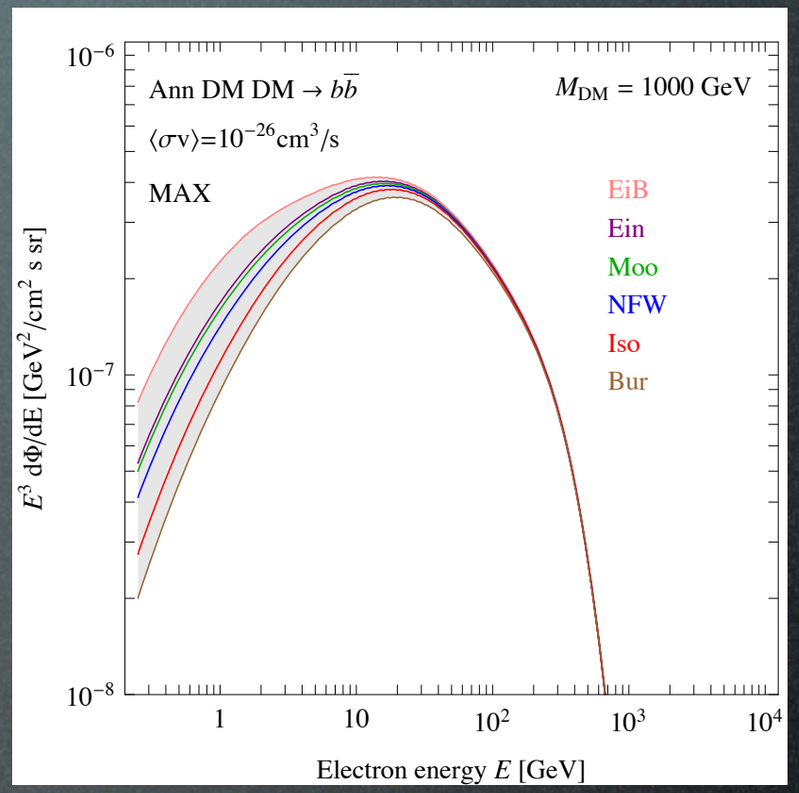
+ = rotation parallel to magnetic field;
- = antiparallel



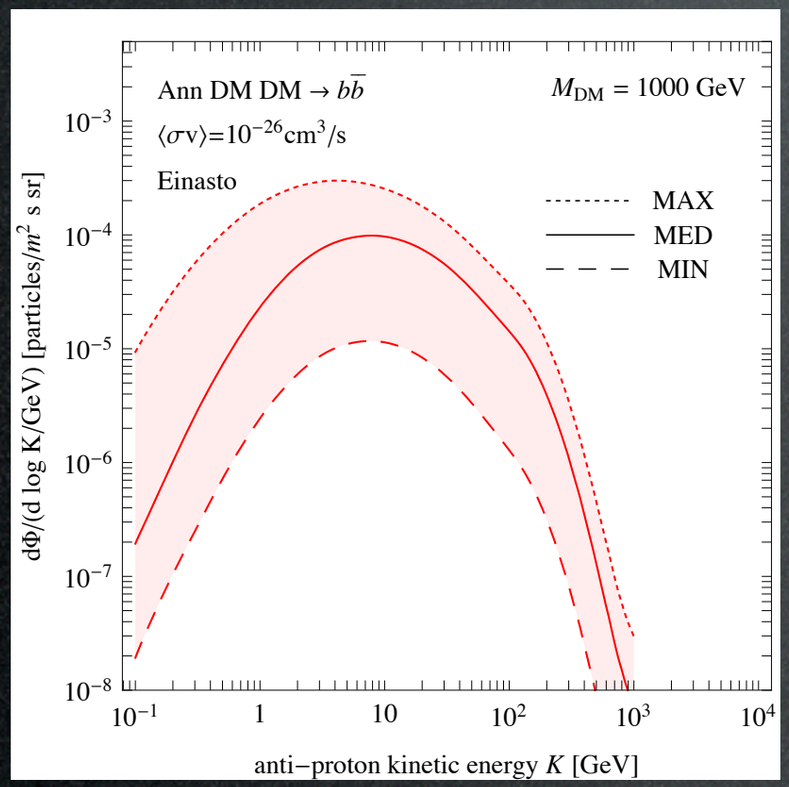
'Astro' uncertainties

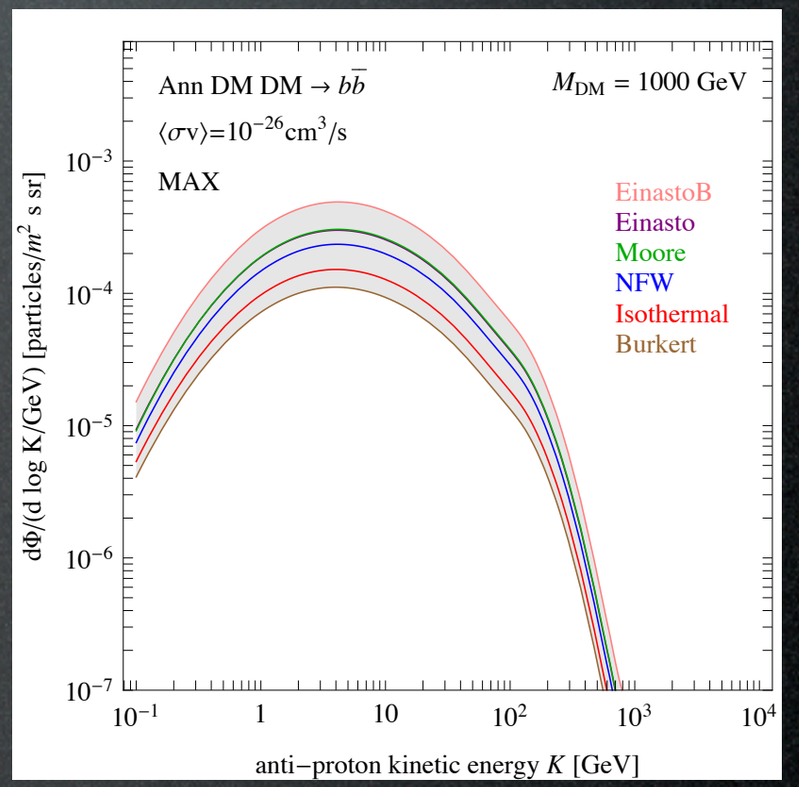
$e^{\pm}$





$\bar{p}$





[back]

Predictions?!?



Predictions?!?



Predictions?!?

Is Dark Matter around the corner?



Predictions?!?

Is Dark Matter around the corner?

Look for model-independent ‘answers’.



Predictions?!?

Is Dark Matter around the corner?

In predictive models, a prediction can be given.
In general, generic statements are difficult.

Direct detection:
- experiments are digging into the relevant parameter space
- but the parameter space is huge

Indirect detection:
- need to understand ‘background’ astrophysics
- new DM models open new avenues with promising signals
- very promising if (Sommerfeld?) enhancement is at play

Predictions?!?

Is Dark Matter around the corner?

Maybe.

