16 february 2011
CERN-TH

DM phenomenology: status circa 02.11

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)

Reviews on Dark Matter:

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Introduction

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DM exists

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

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Some of us believe in the WIMP miracle

Introduction

DM exists → *Need a proof?*

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

Some of us believe in the WIMP miracle → *Do you?*

DM detection

direct detection

Dama/Libra, Xenon, CDMS

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

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DM detection

- direct detection
  - Dama/Libra, Xenon, CDMS
- 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
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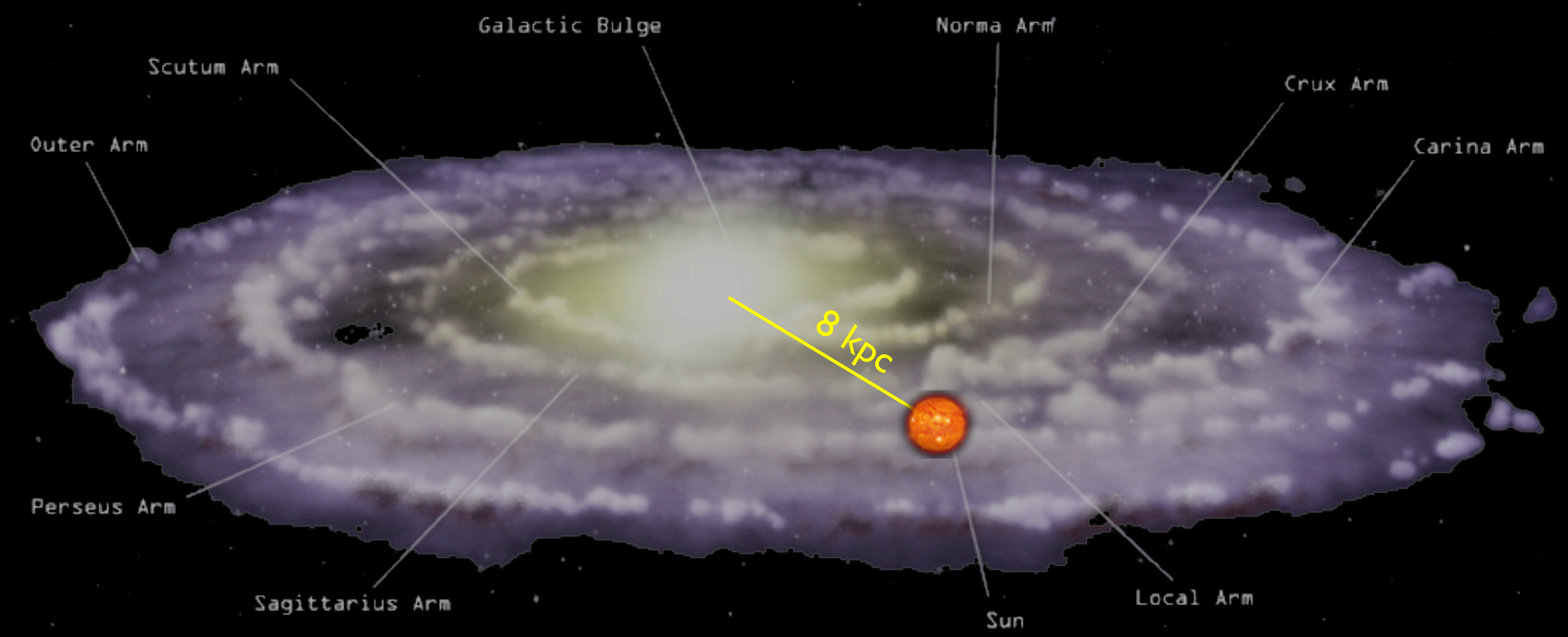
Indirect Detection: basics

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



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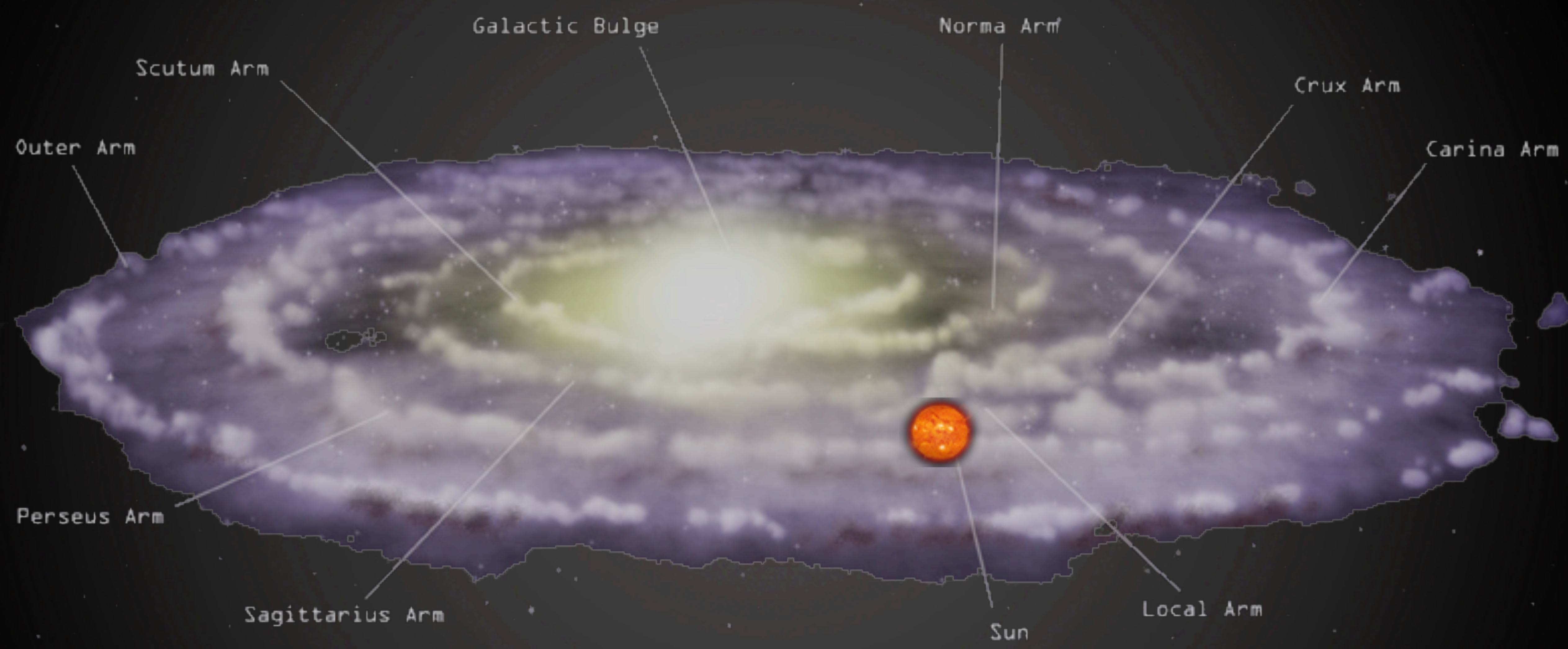

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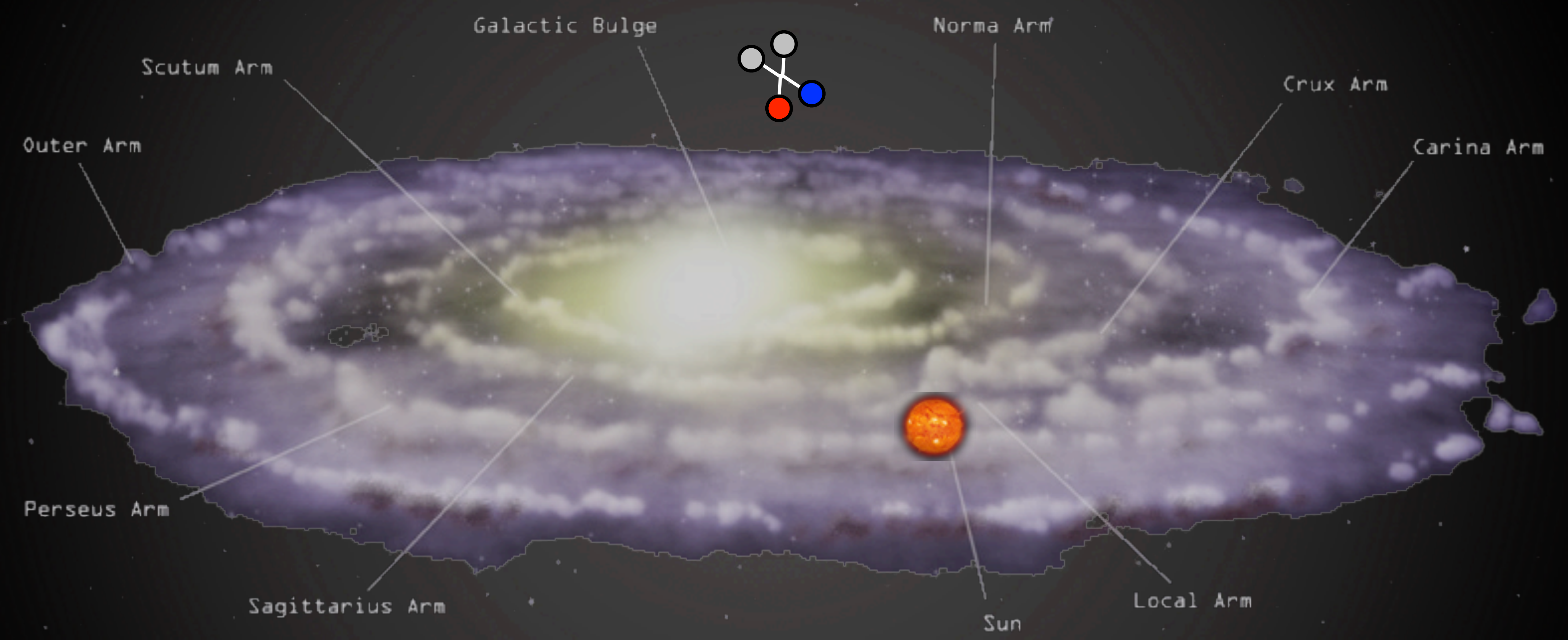

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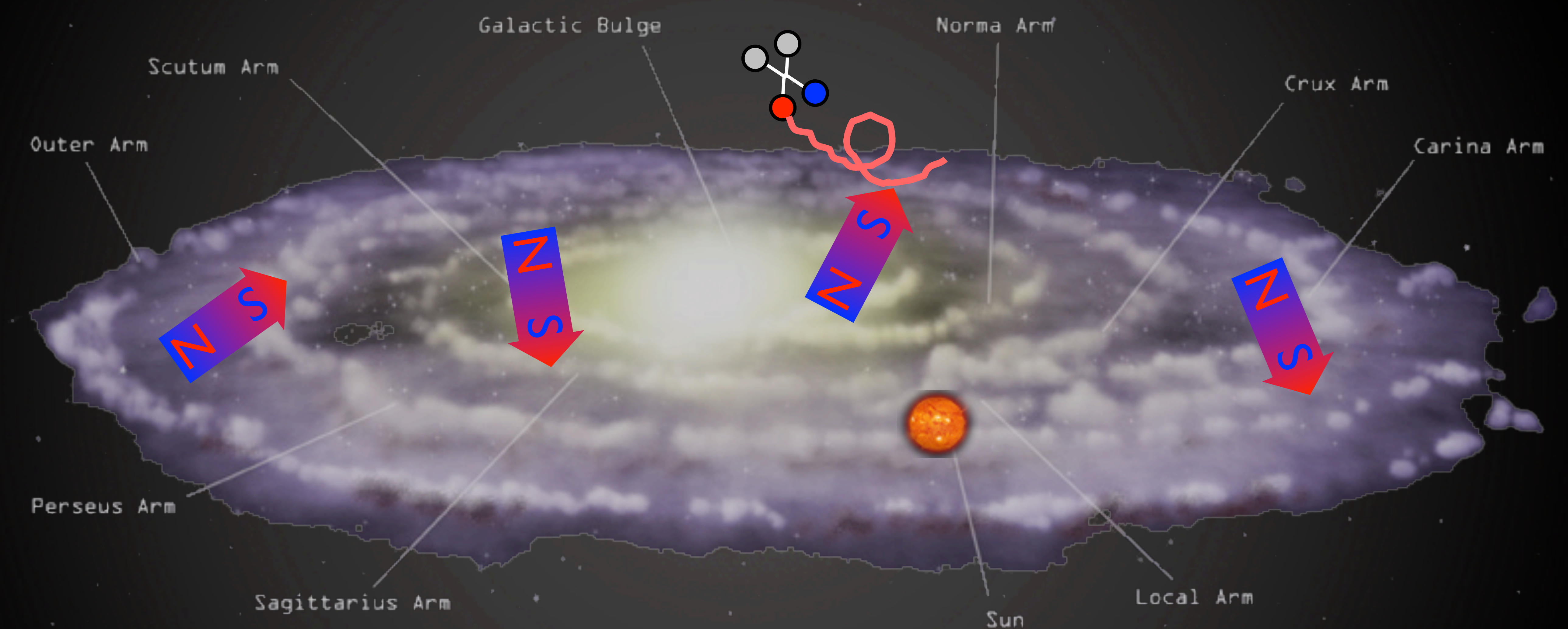
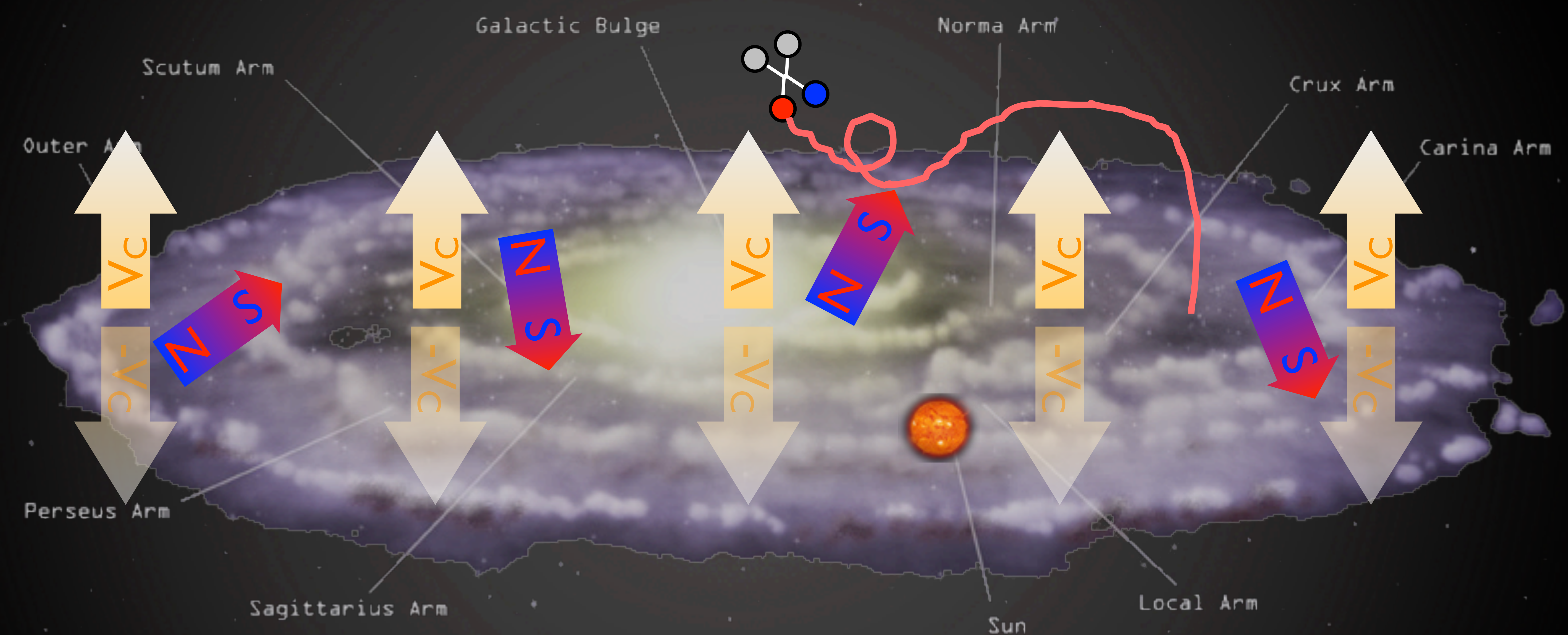


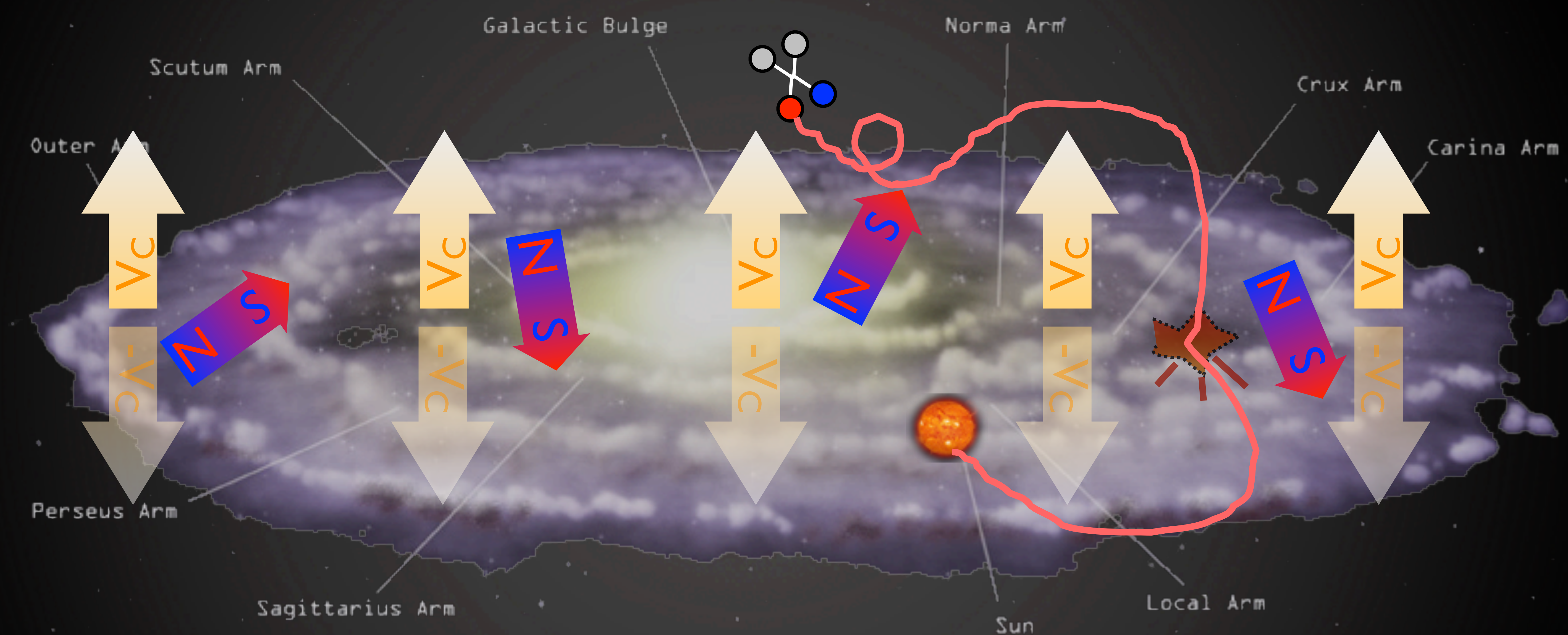
Indirect Detection: basics

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



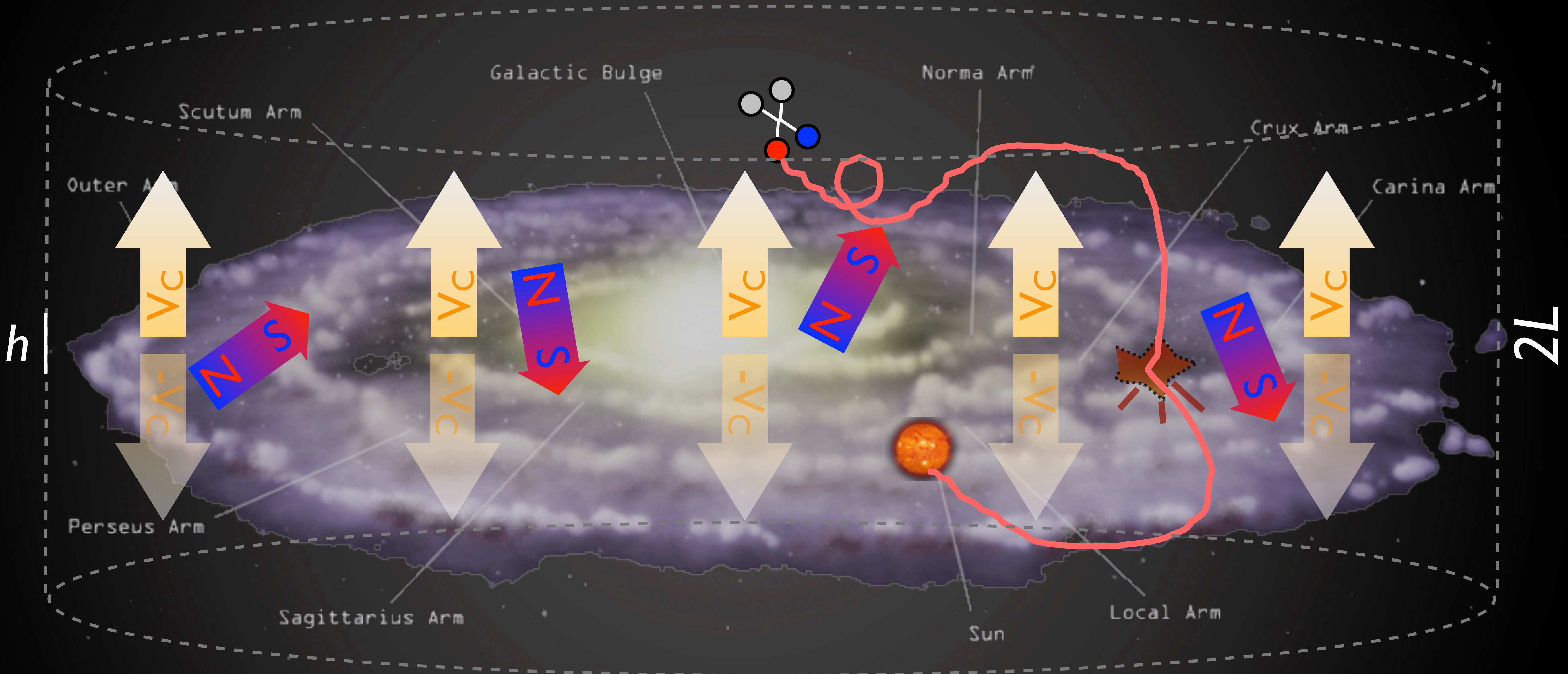
Indirect Detection: basics

$\bar{p}$ 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

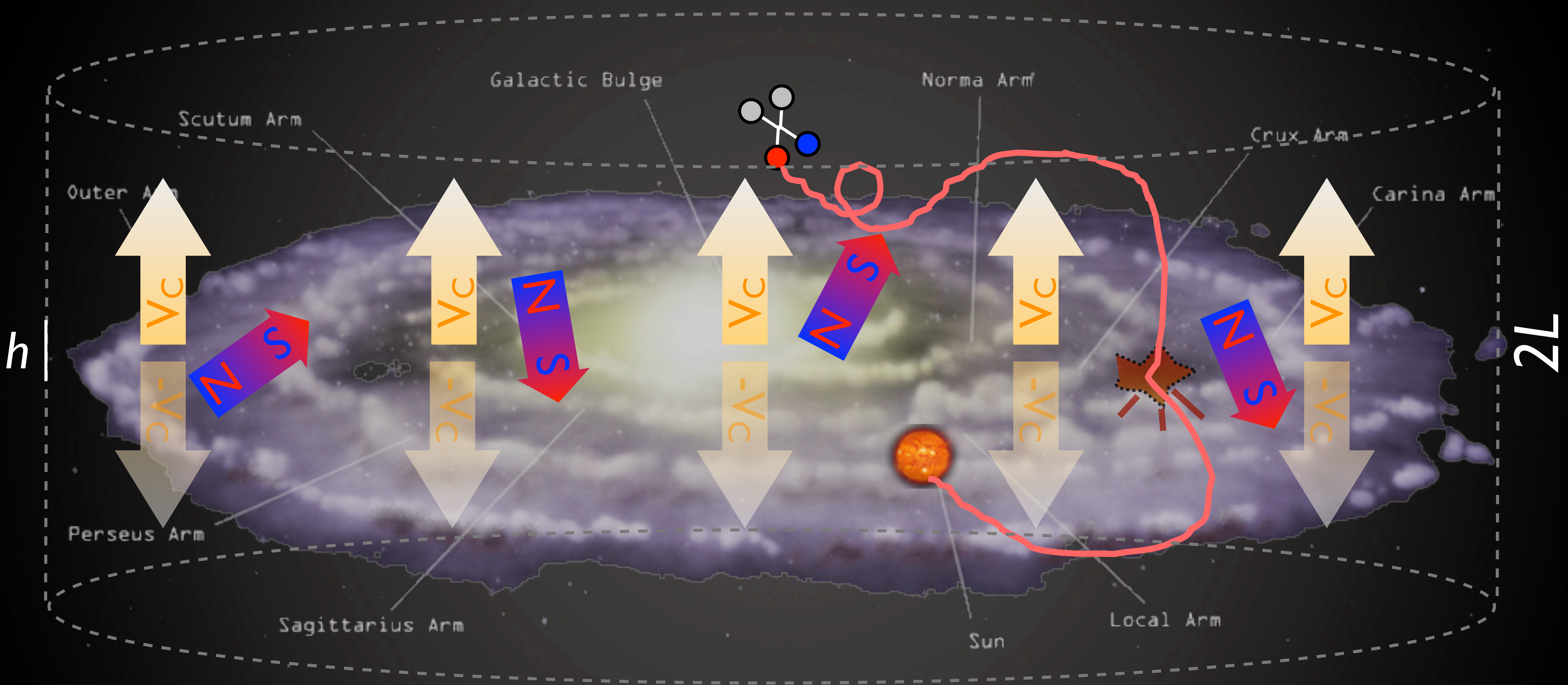
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}(b(E) f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

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

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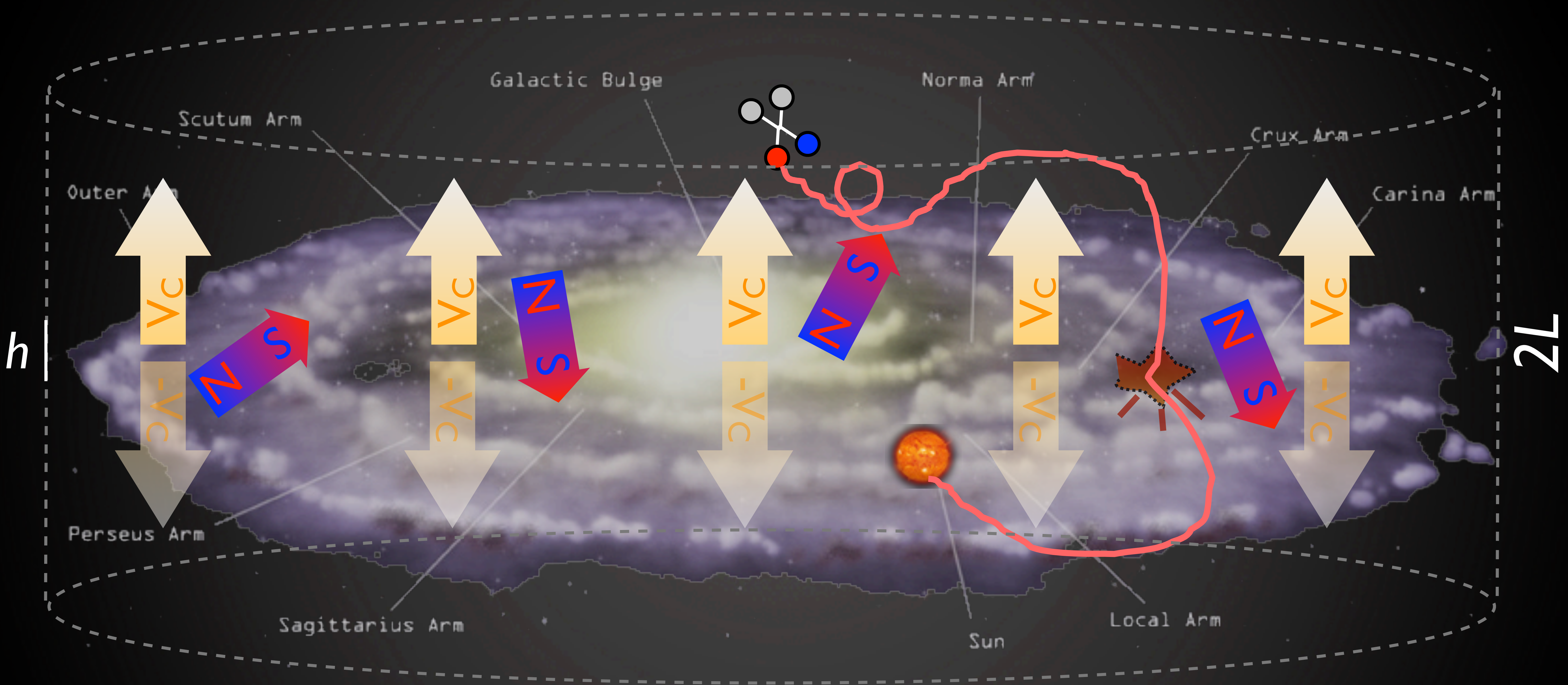

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astro& cosmo

particle

Indirect Detection: basics

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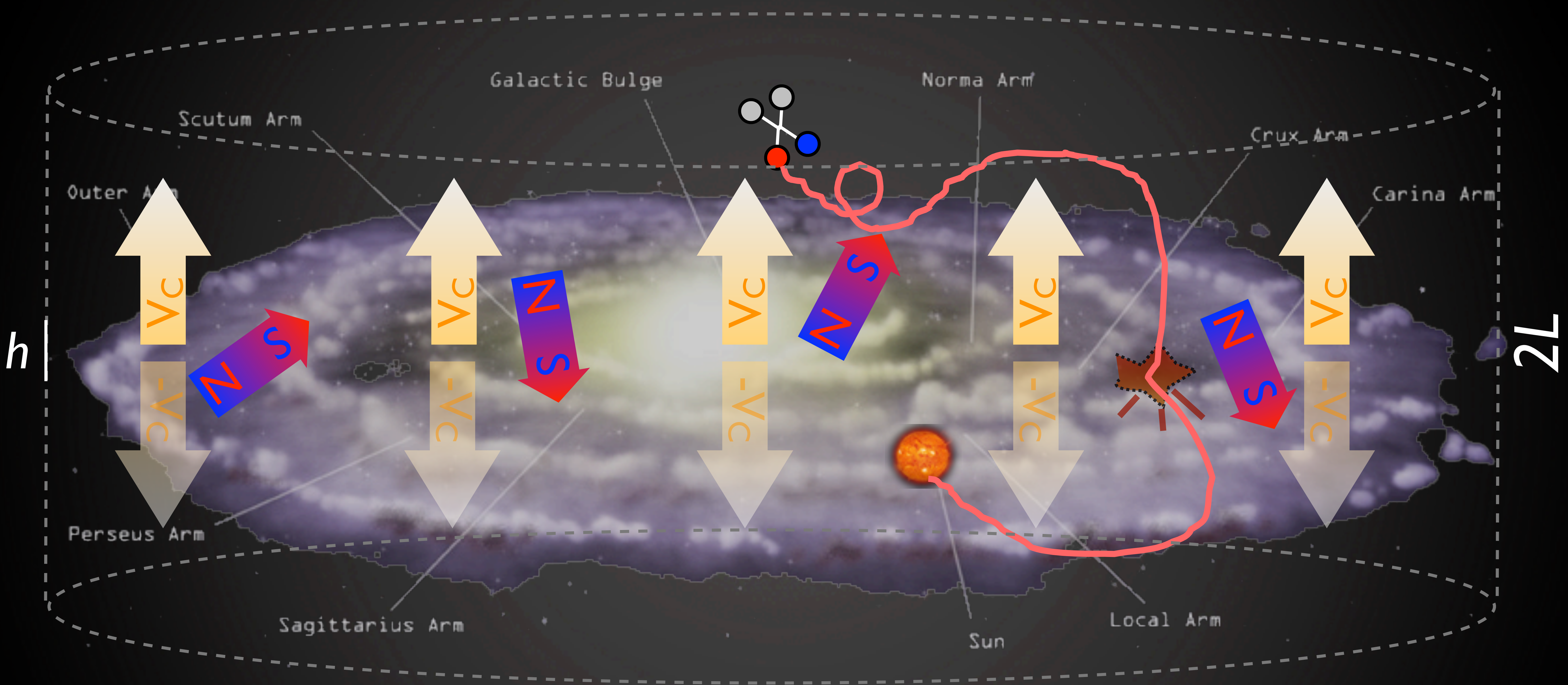

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astro& cosmo

particle

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

DM halo profiles

From N-body numerical simulations:

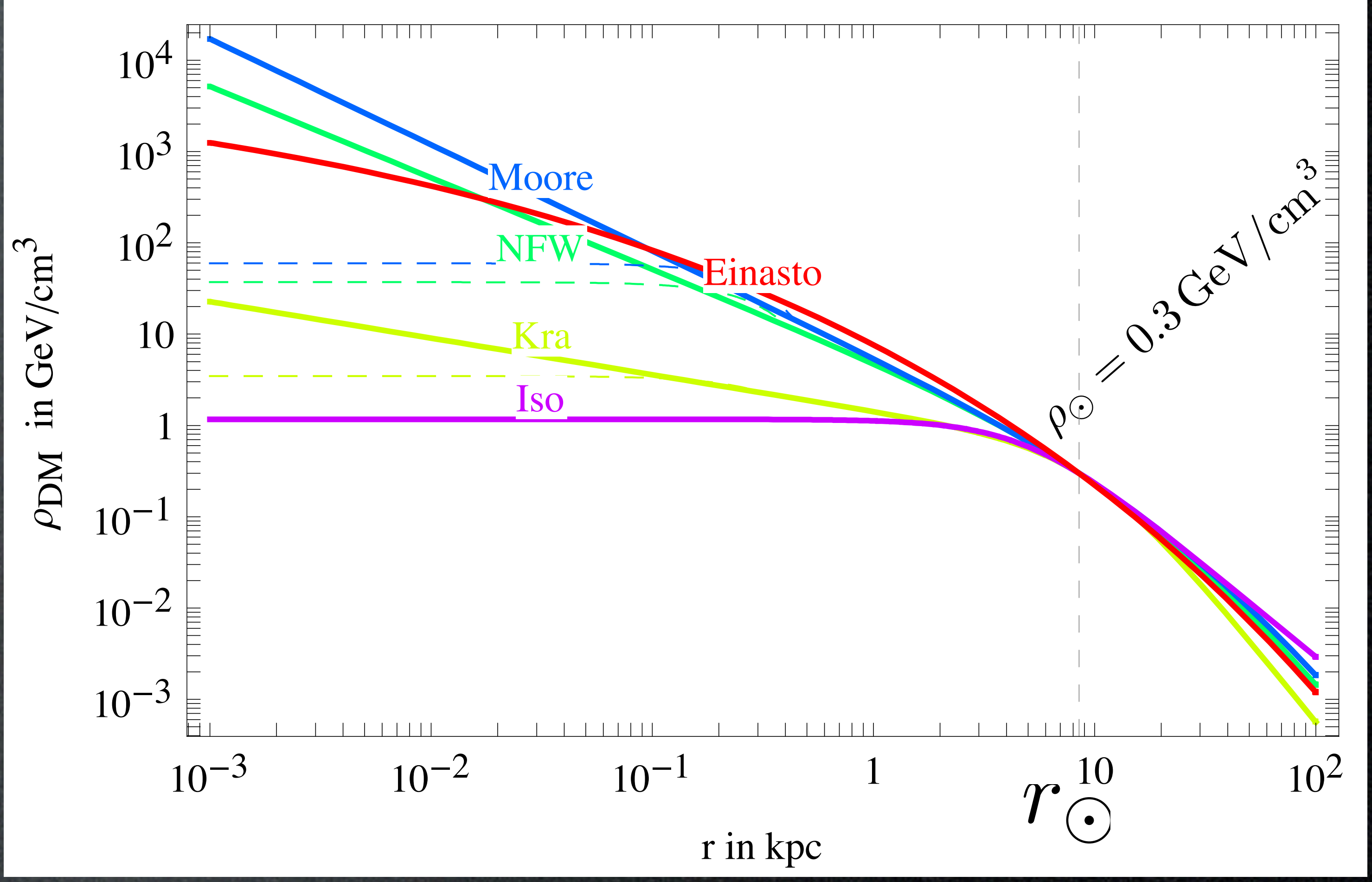
$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

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

$$\rho(r) = \rho_s \cdot \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV}/\text{cm}^3$

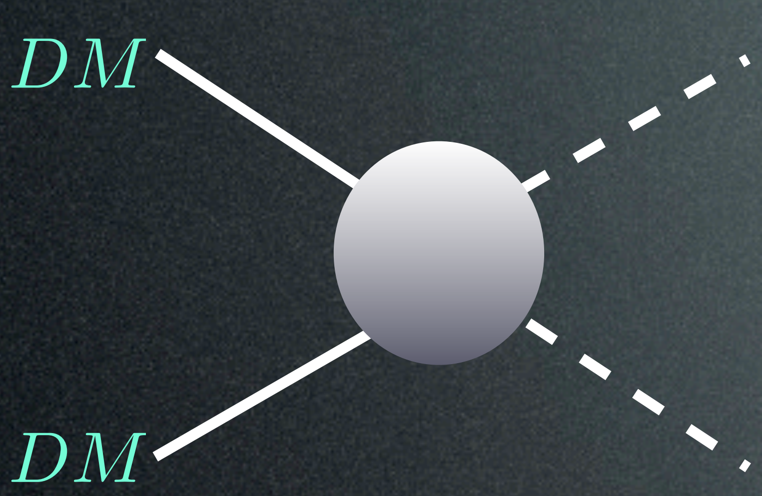


cuspy: NFW, Moore

mild: Einasto

smooth: isothermal

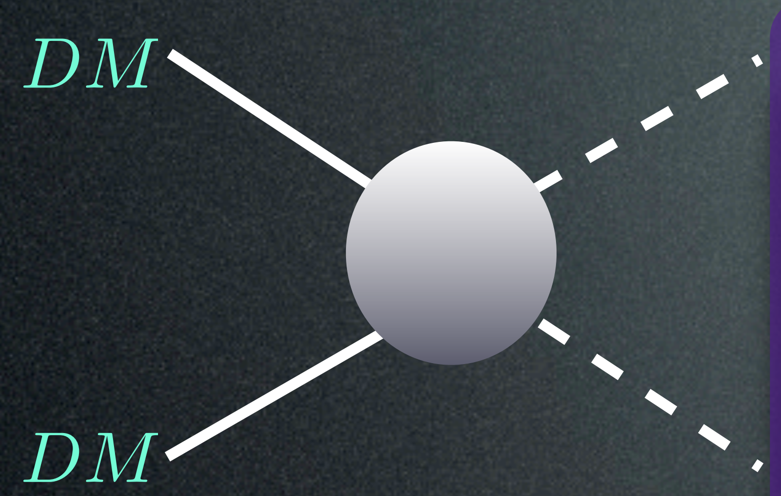
Indirect Detection: basics



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

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

Indirect Detection: basics

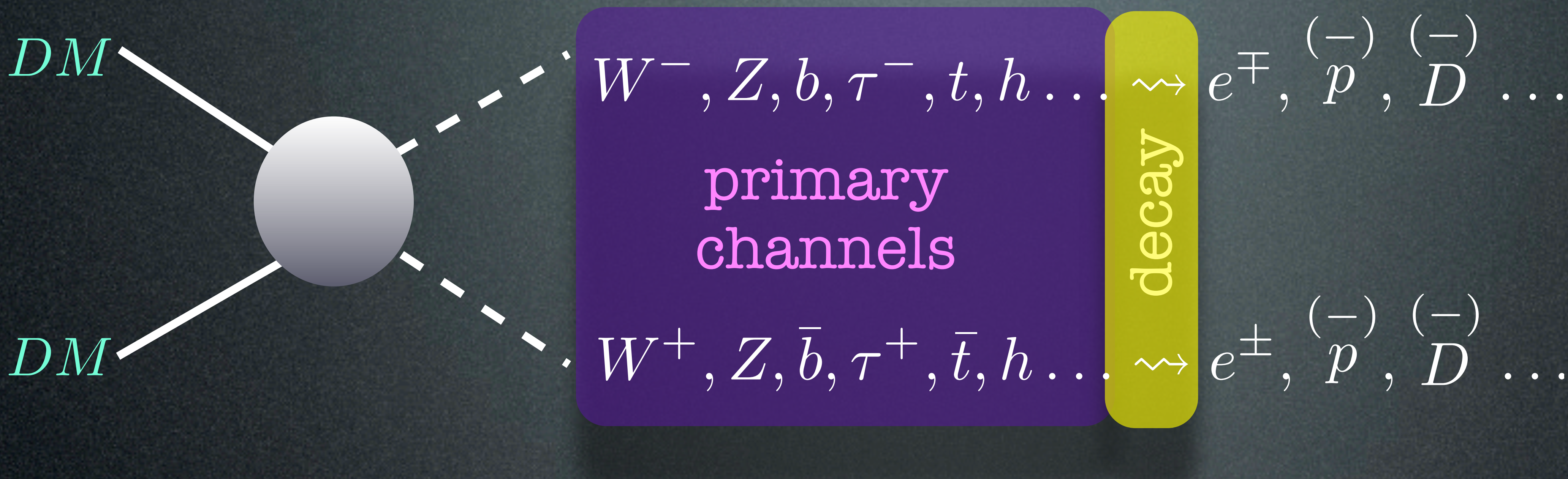


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

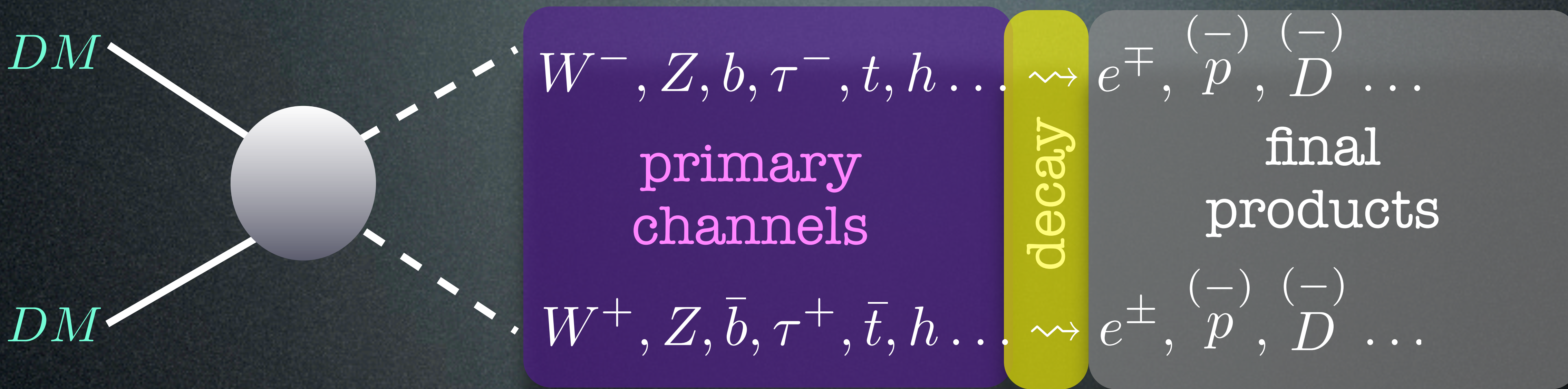
primary channels

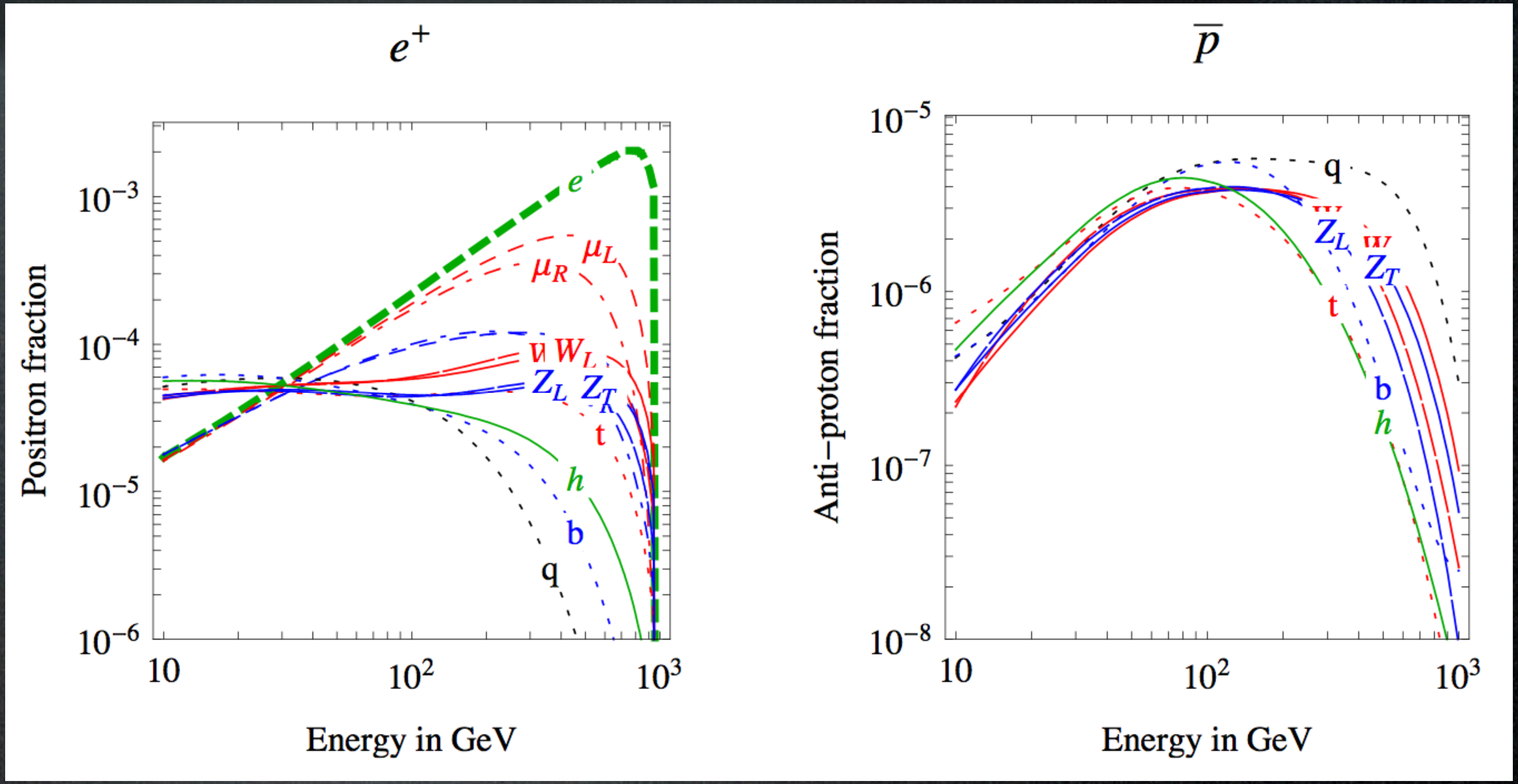
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

Indirect Detection: basics



Indirect Detection: basics





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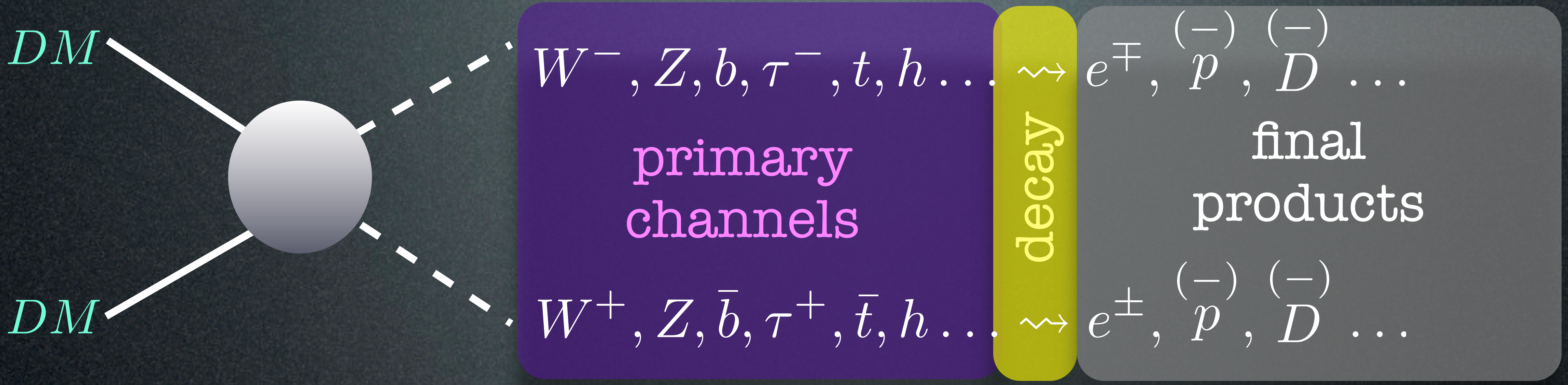
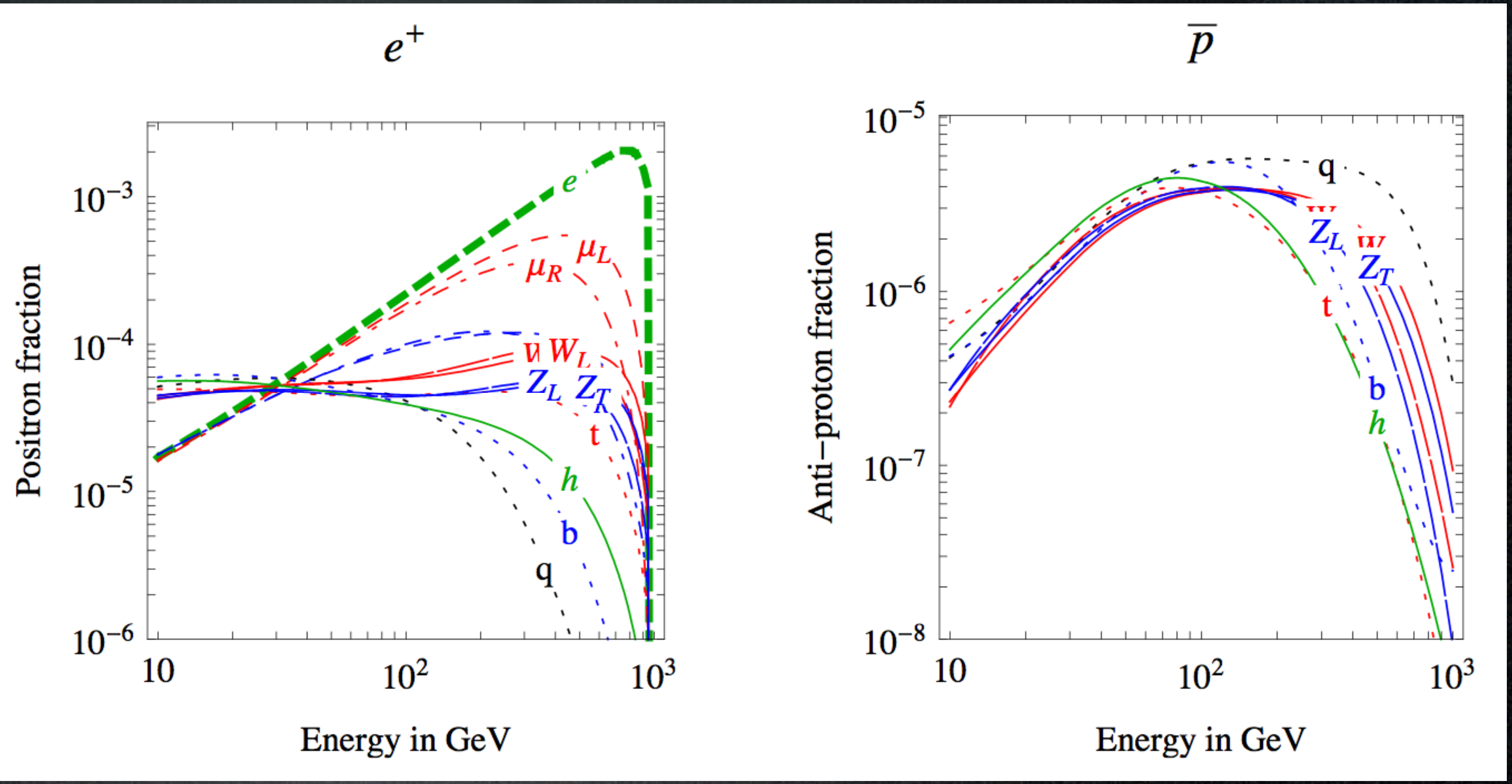


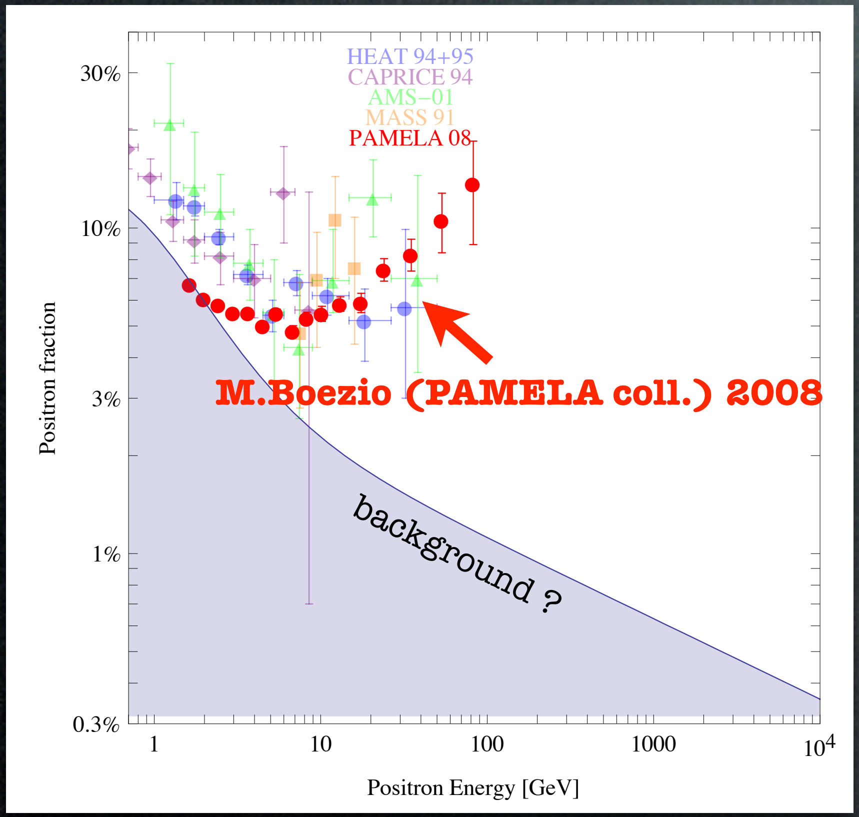


So what are the particle physics parameters?

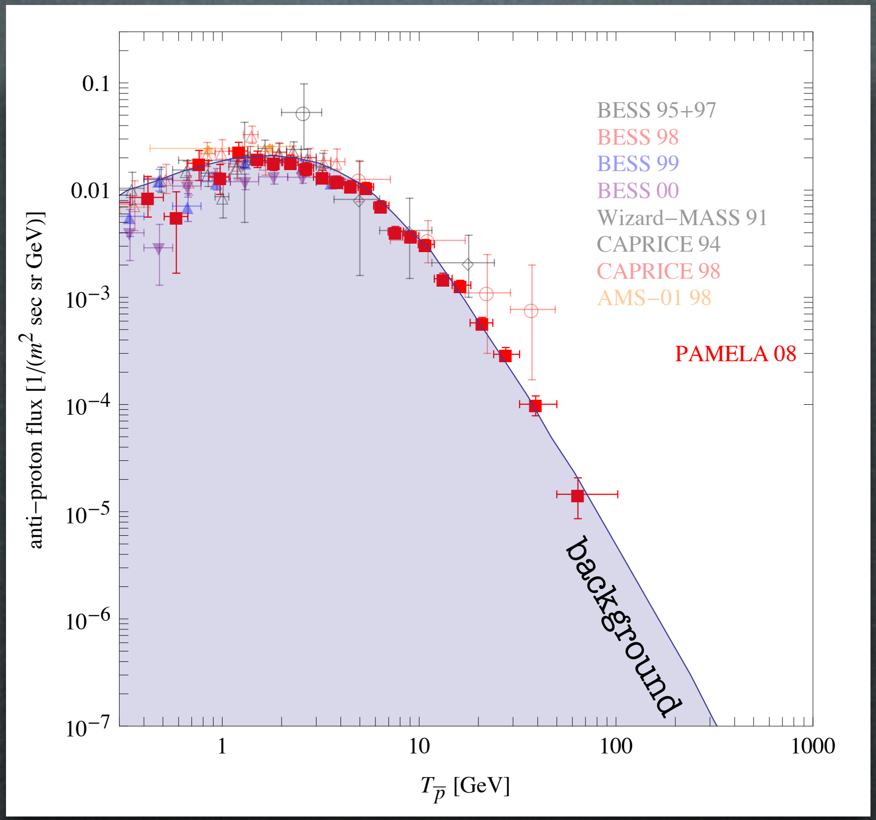
1. Dark Matter mass
2. primary channel(s)

Indirect Detection: **hints**

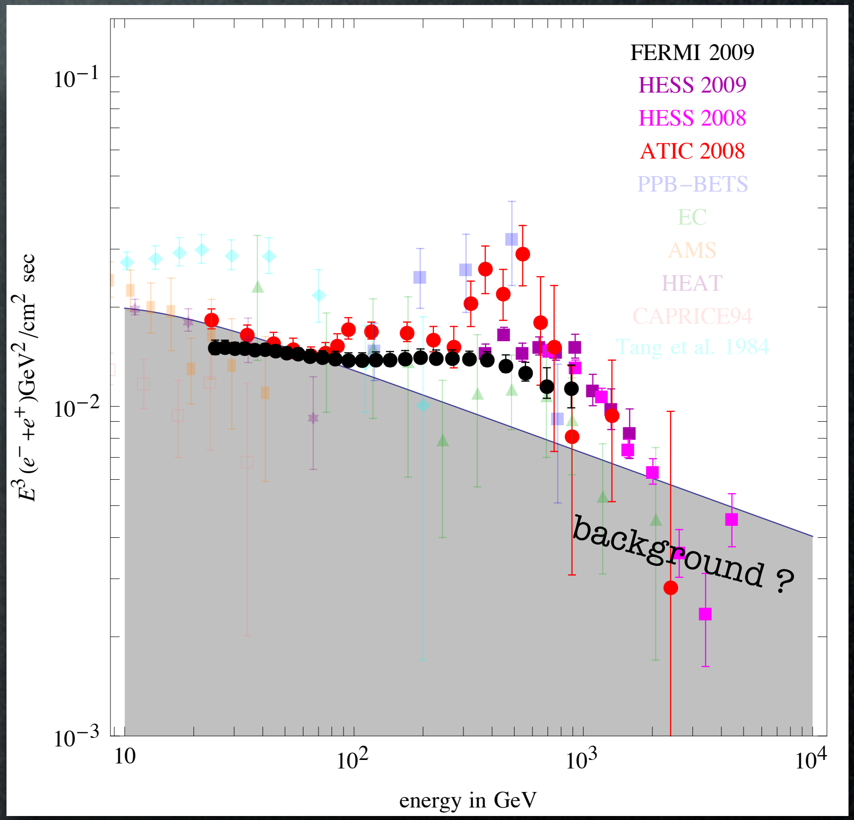
positron fraction



antiprotons



electrons + positrons



Indirect Detection: hints

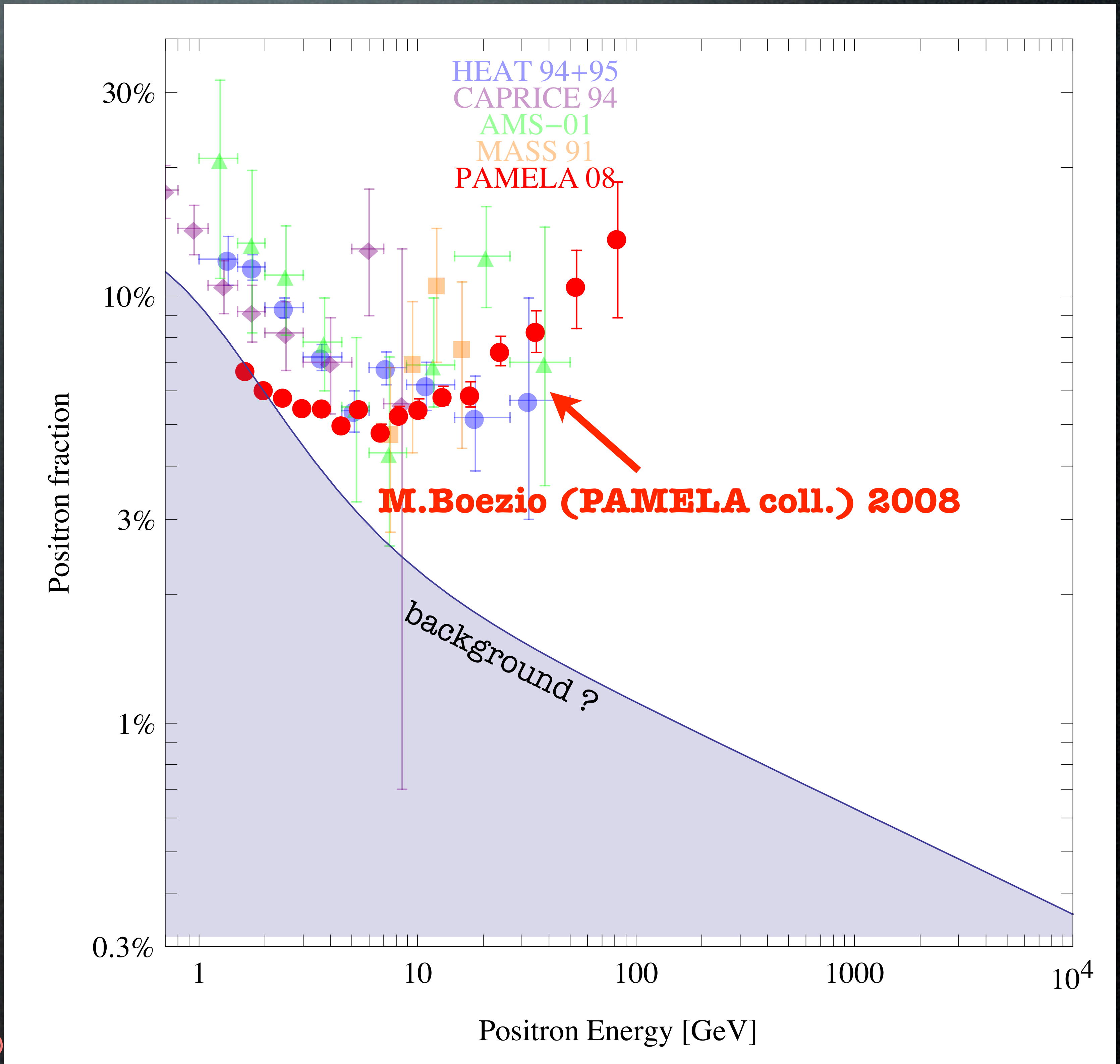
Positrons from PAMELA:

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

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

(9430 e⁺ collected)

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

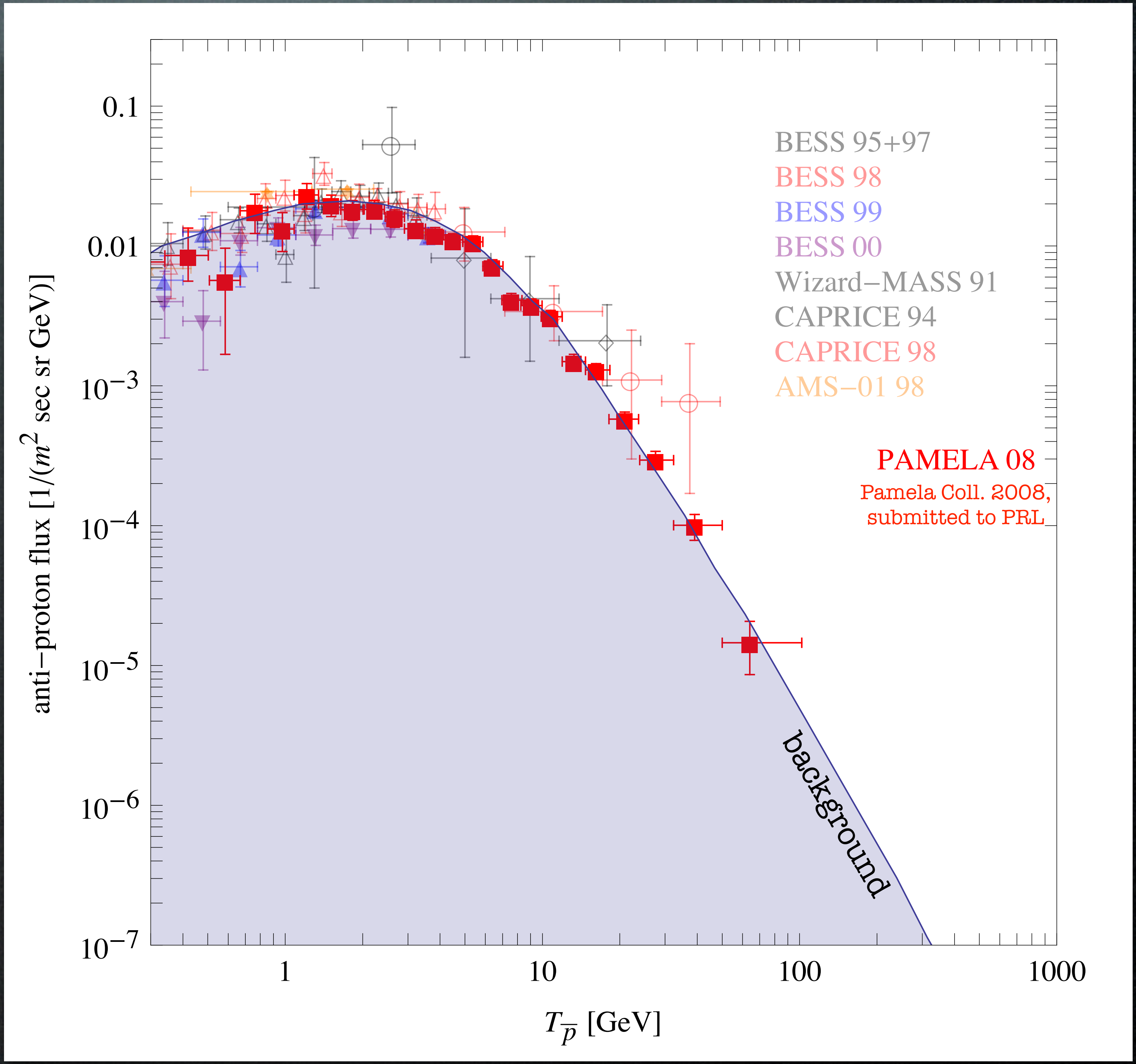


[backgnd]

Indirect Detection: hints

Antiprotons from PAMELA:

- consistent with the background

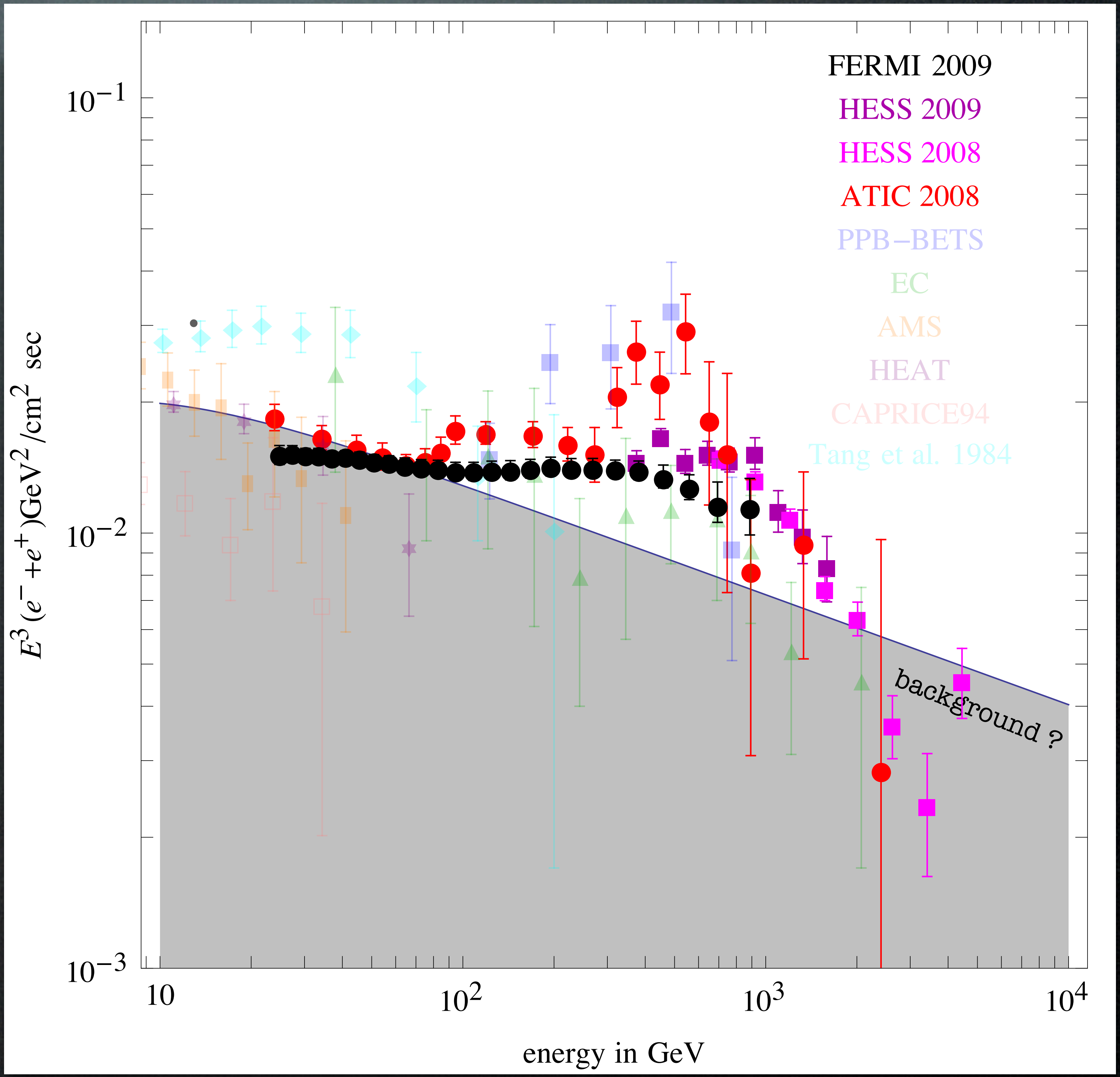


(about 1000 $\bar{p}$ collected)

Indirect Detection: hints

Electrons + positrons adding FERMI and HESS:

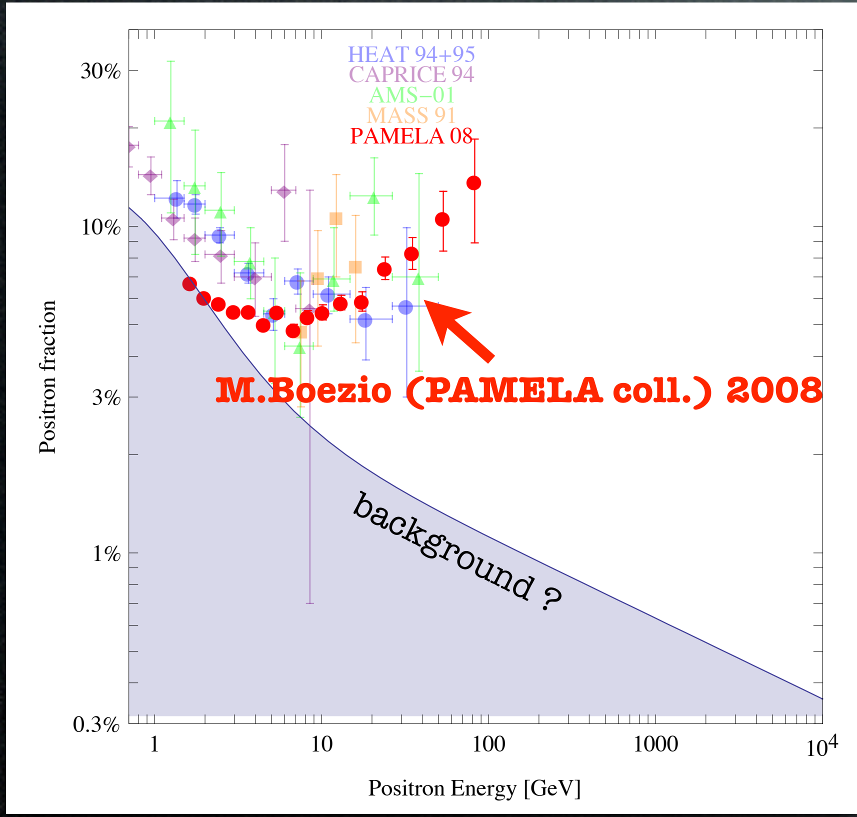
- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?



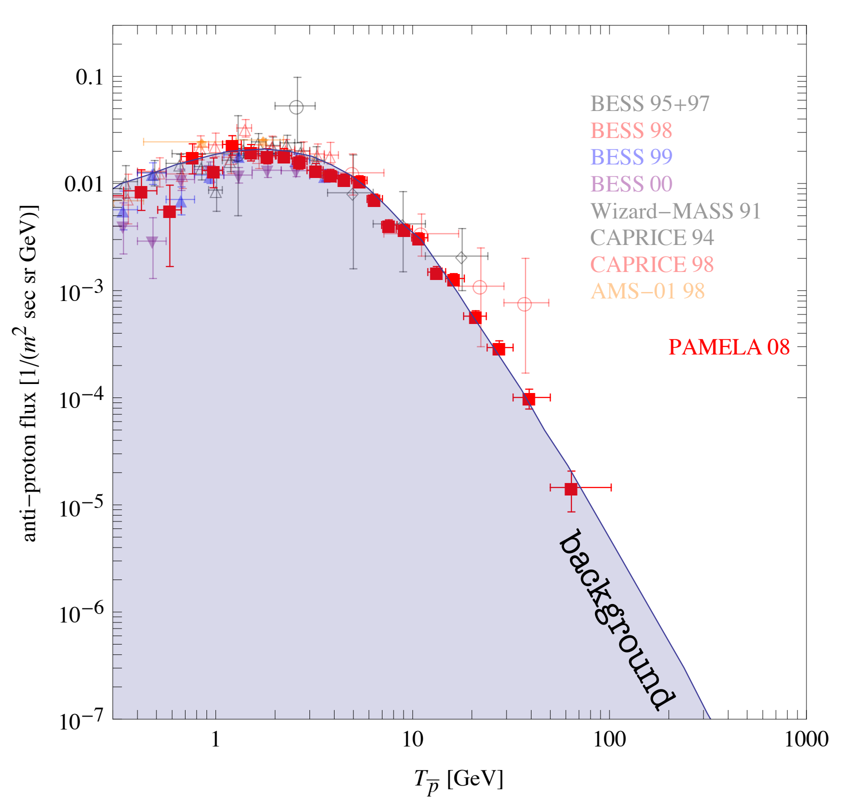
[formerly predicted GLAST sensitivity]

Indirect Detection: hints

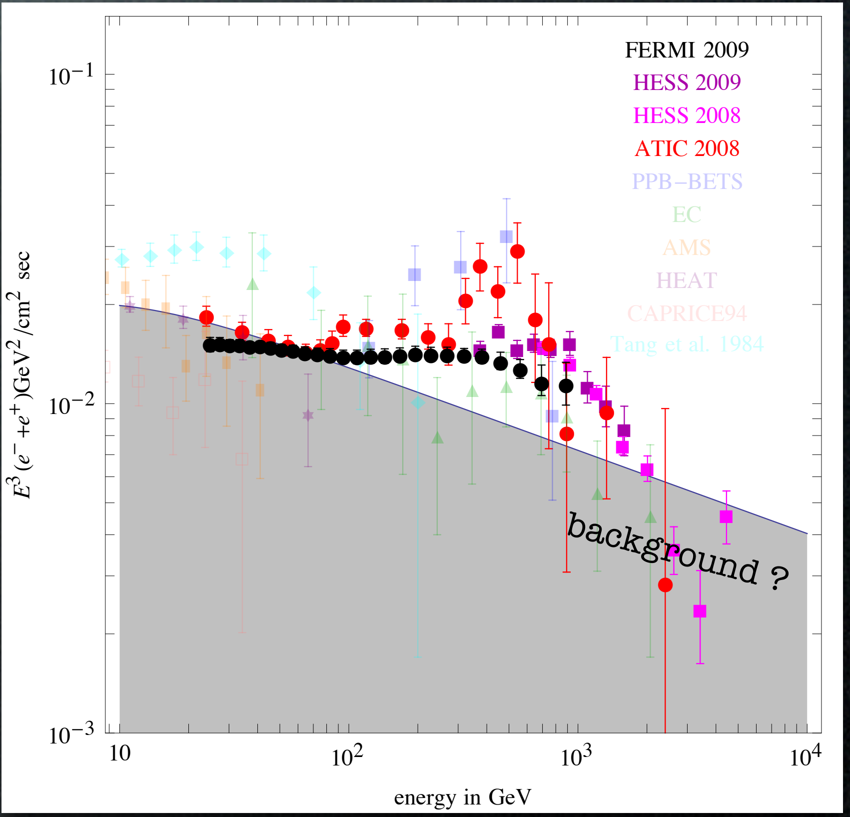
positron fraction



antiprotons



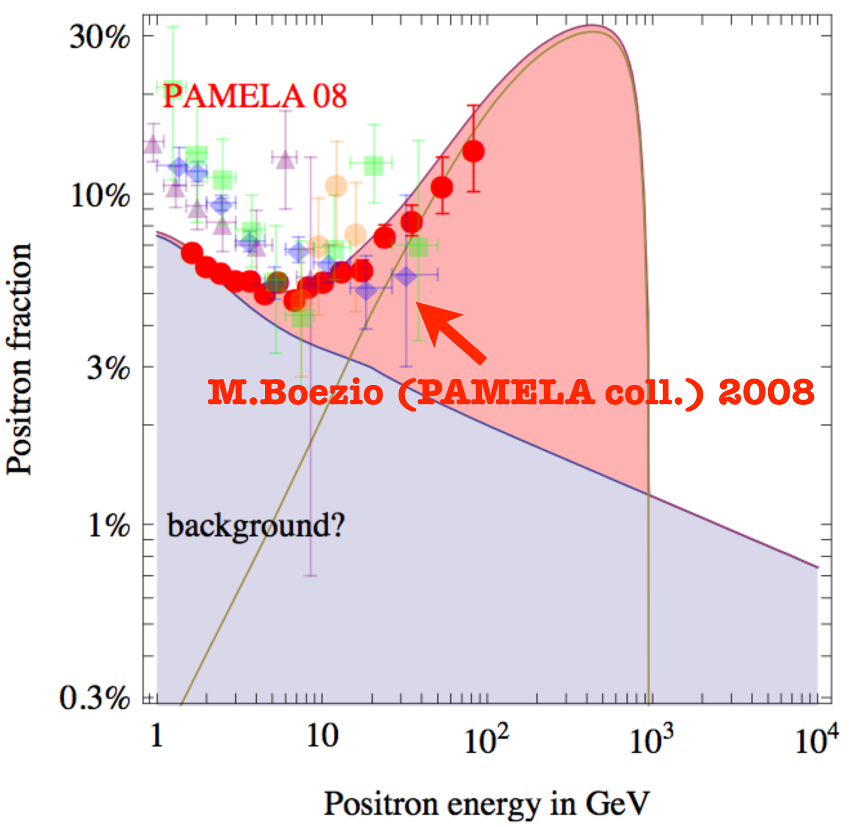
electrons + positrons



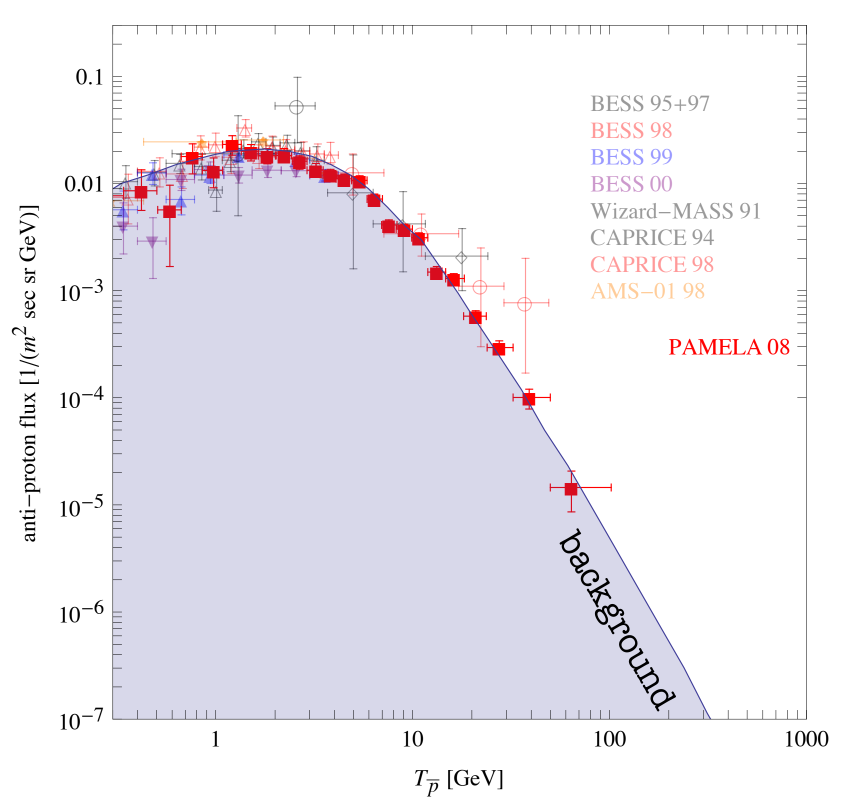
Are these signals of Dark Matter?

Indirect Detection: hints

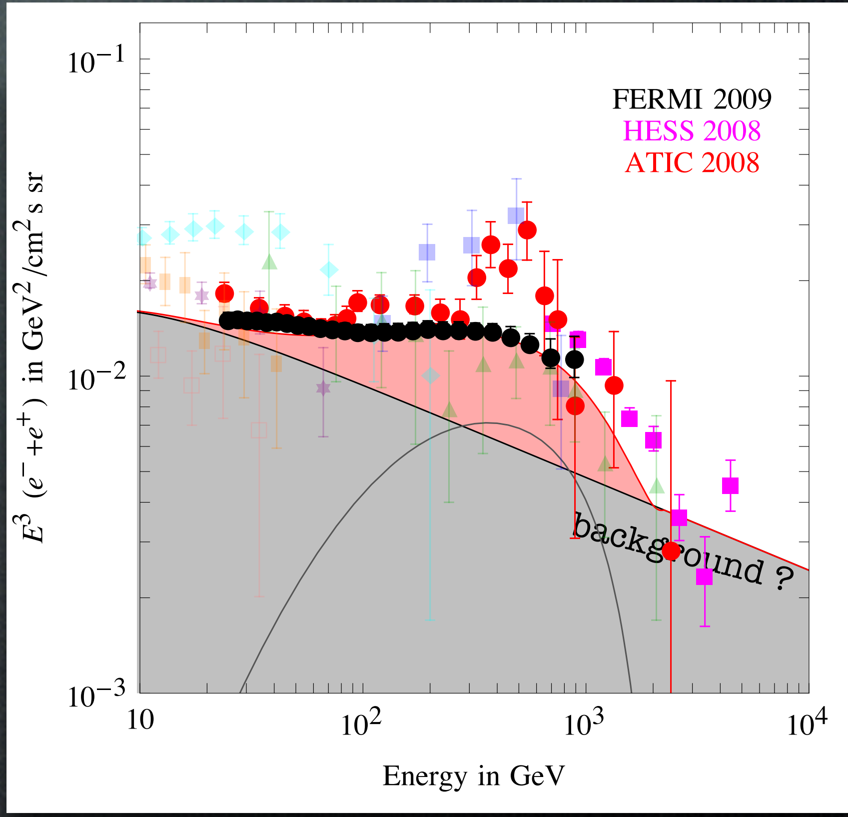
positron fraction



antiprotons



electrons + positrons

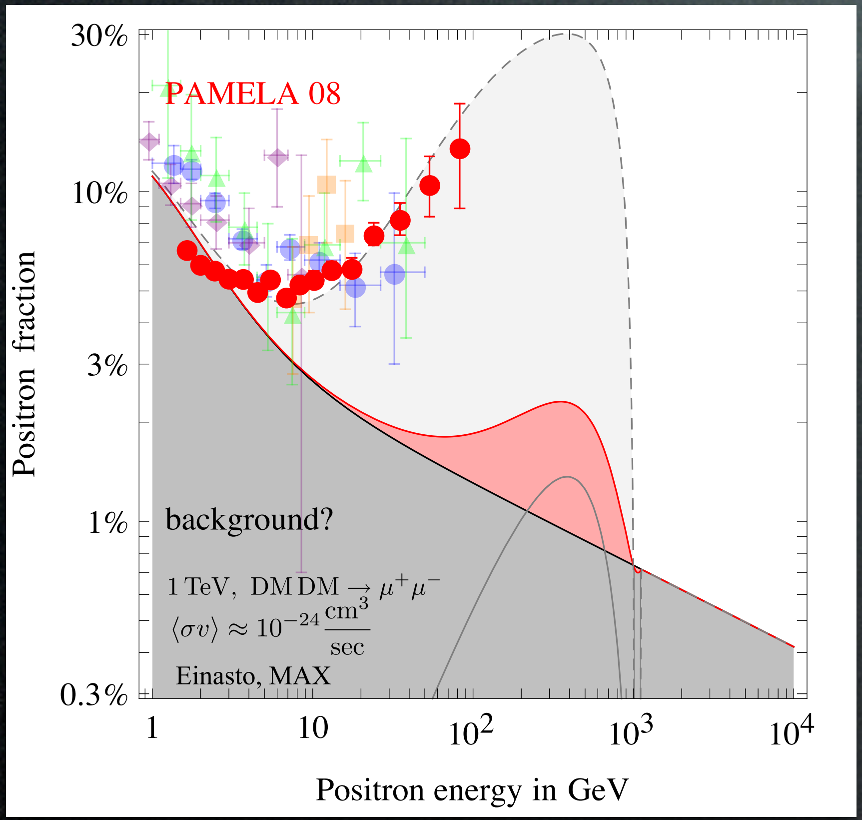


Are these signals of Dark Matter?

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

Indirect Detection: hints

positron fraction



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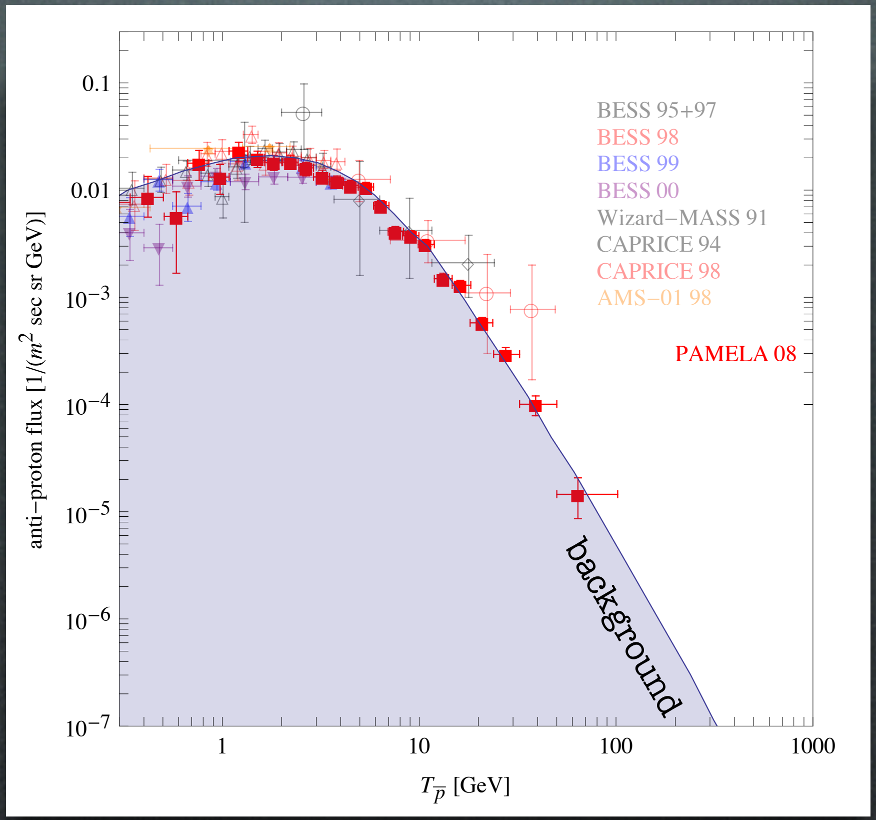
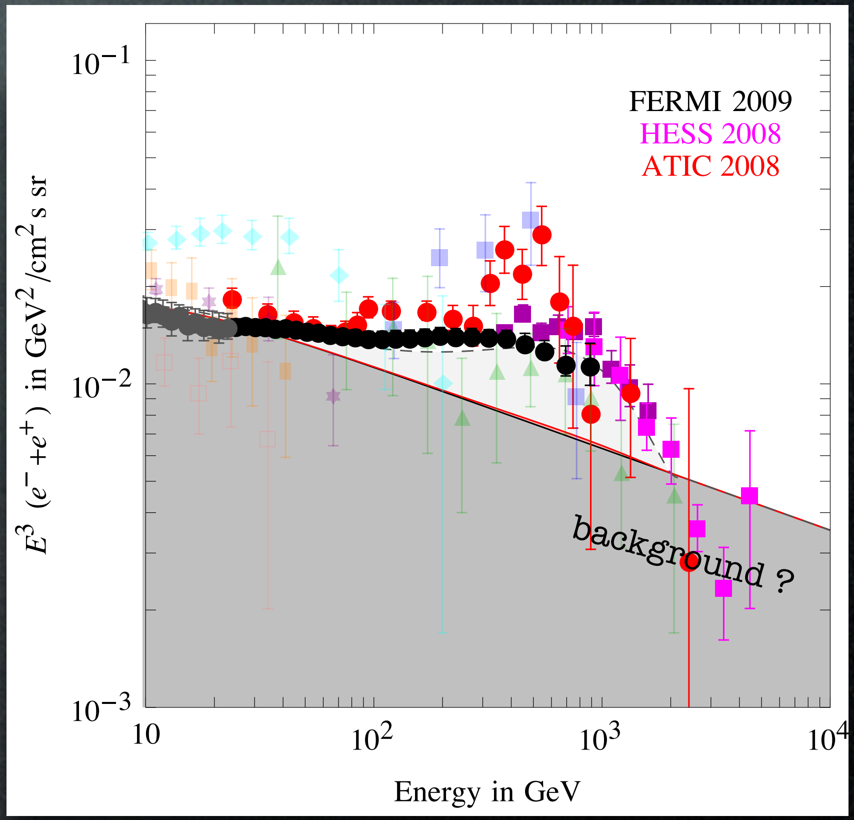


electrons + positrons



Are these signals of Dark Matter?

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

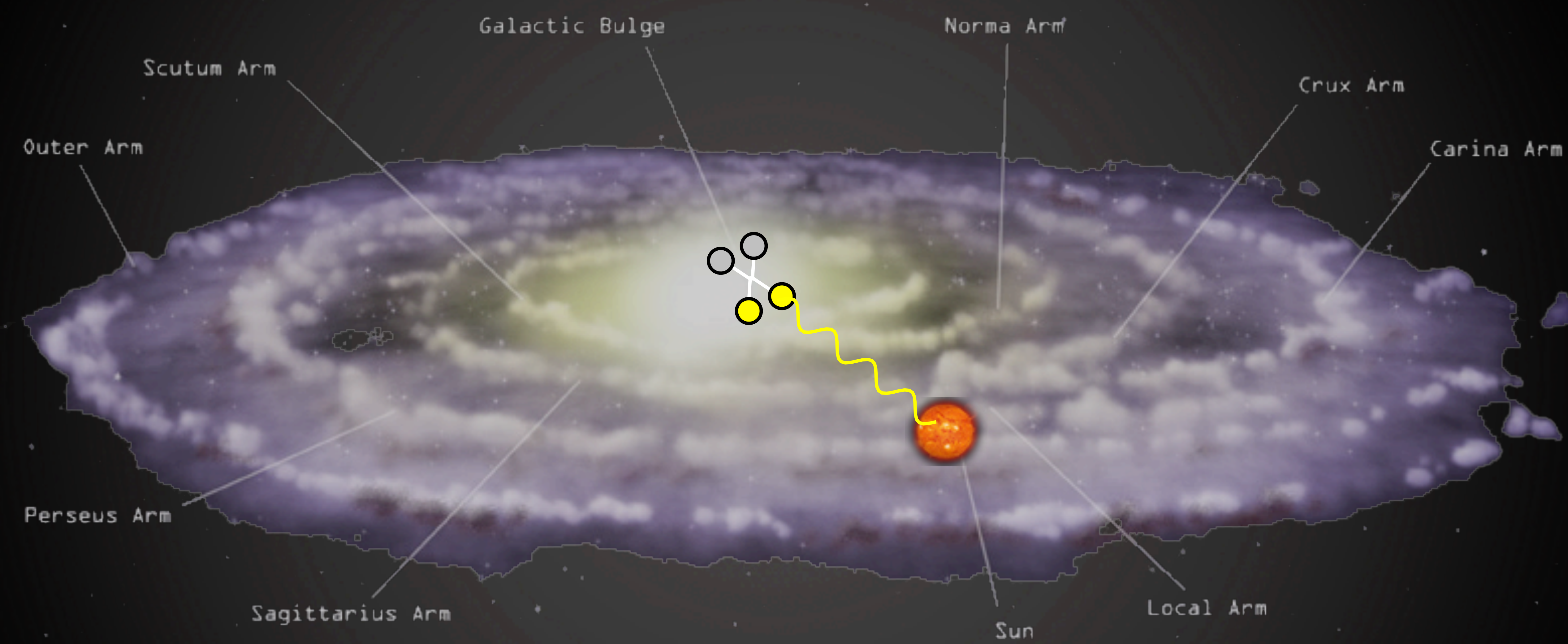
NO: a formidable ‘background’ for future searches

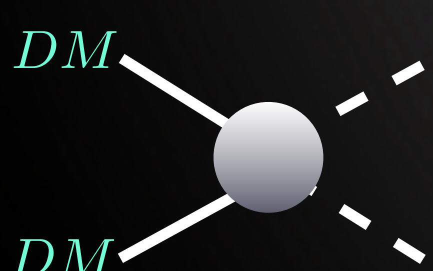
Indirect Detection: **constraints**

- 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



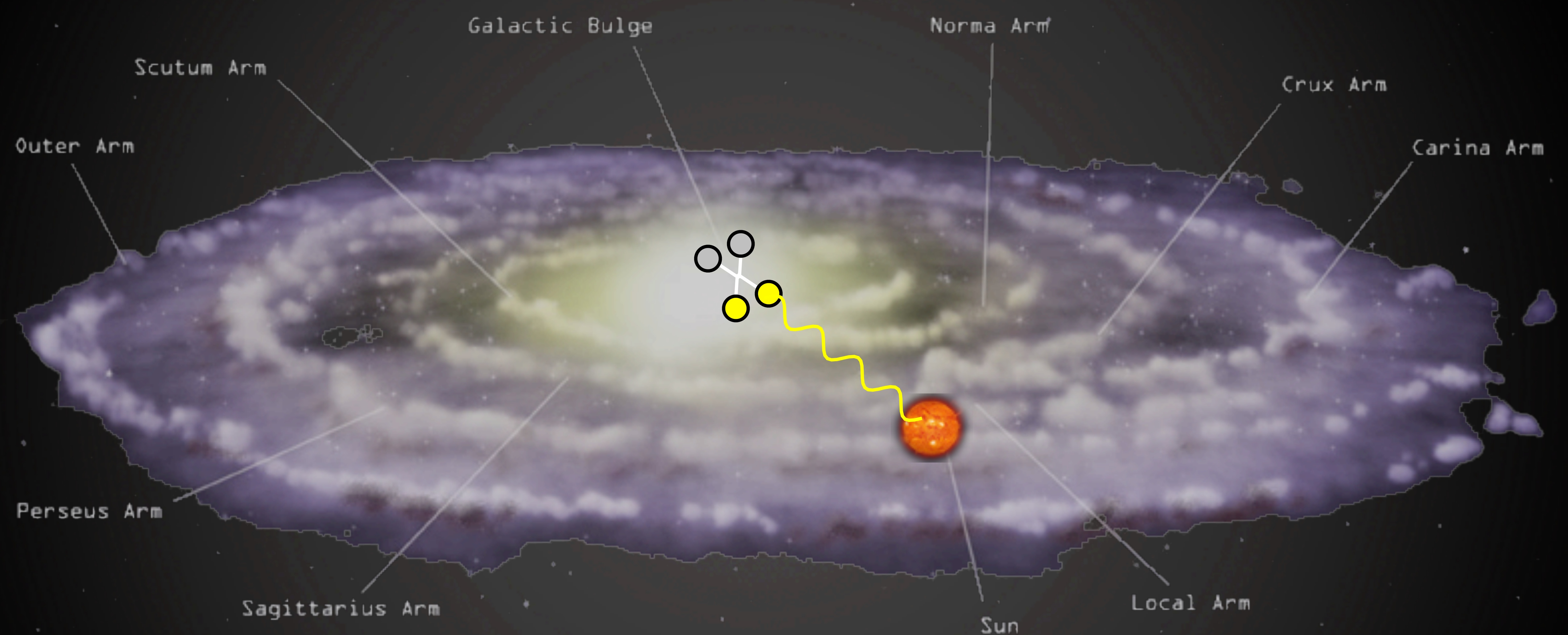


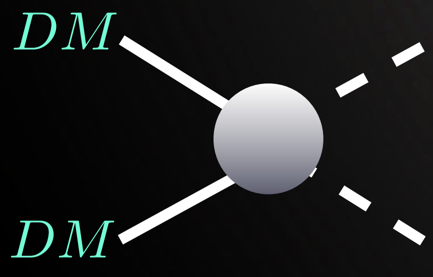
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots \ \text{and}\ \gamma$$

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

Indirect Detection: constraints

a. γ from DM annihilations in galactic center





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

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

Indirect Detection: constraints

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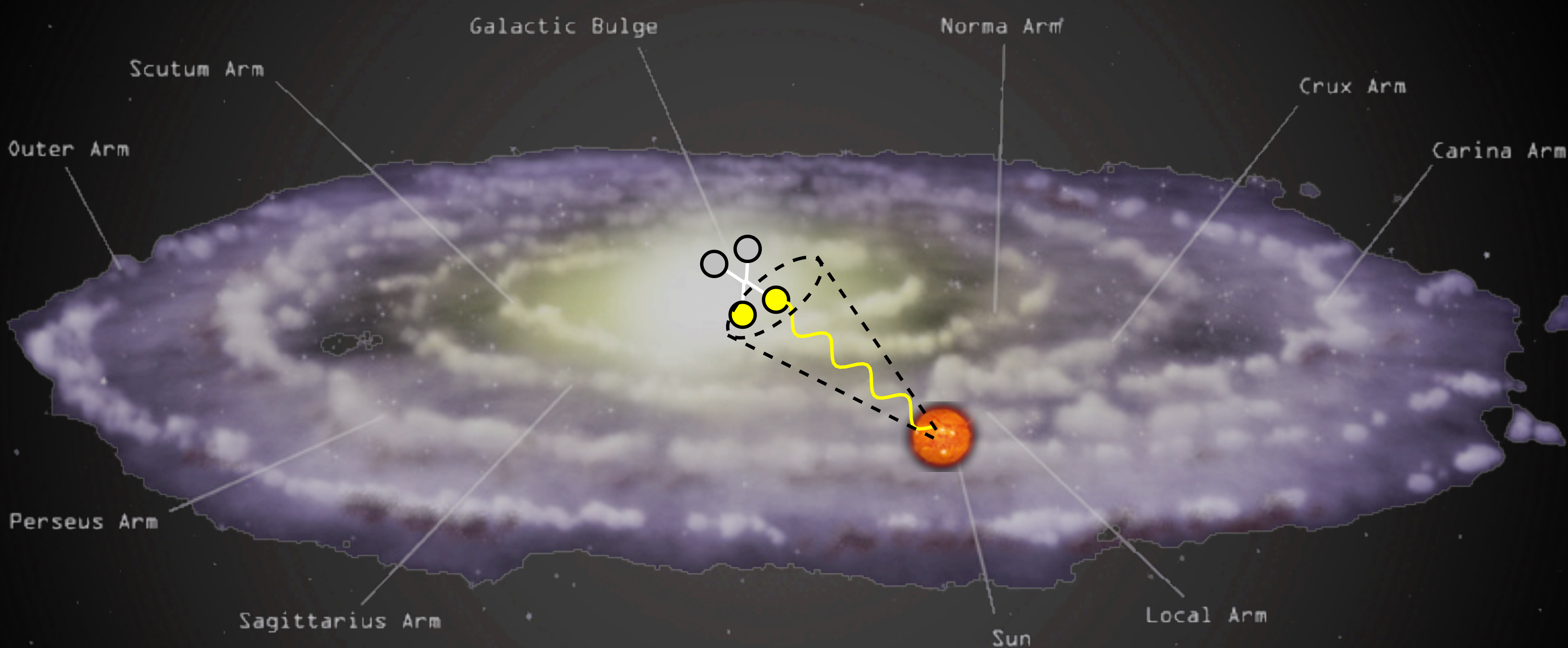

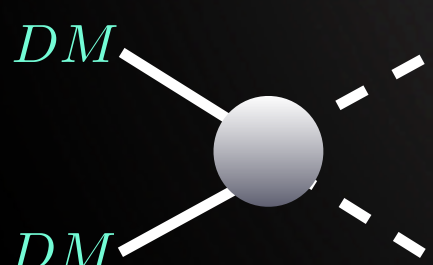

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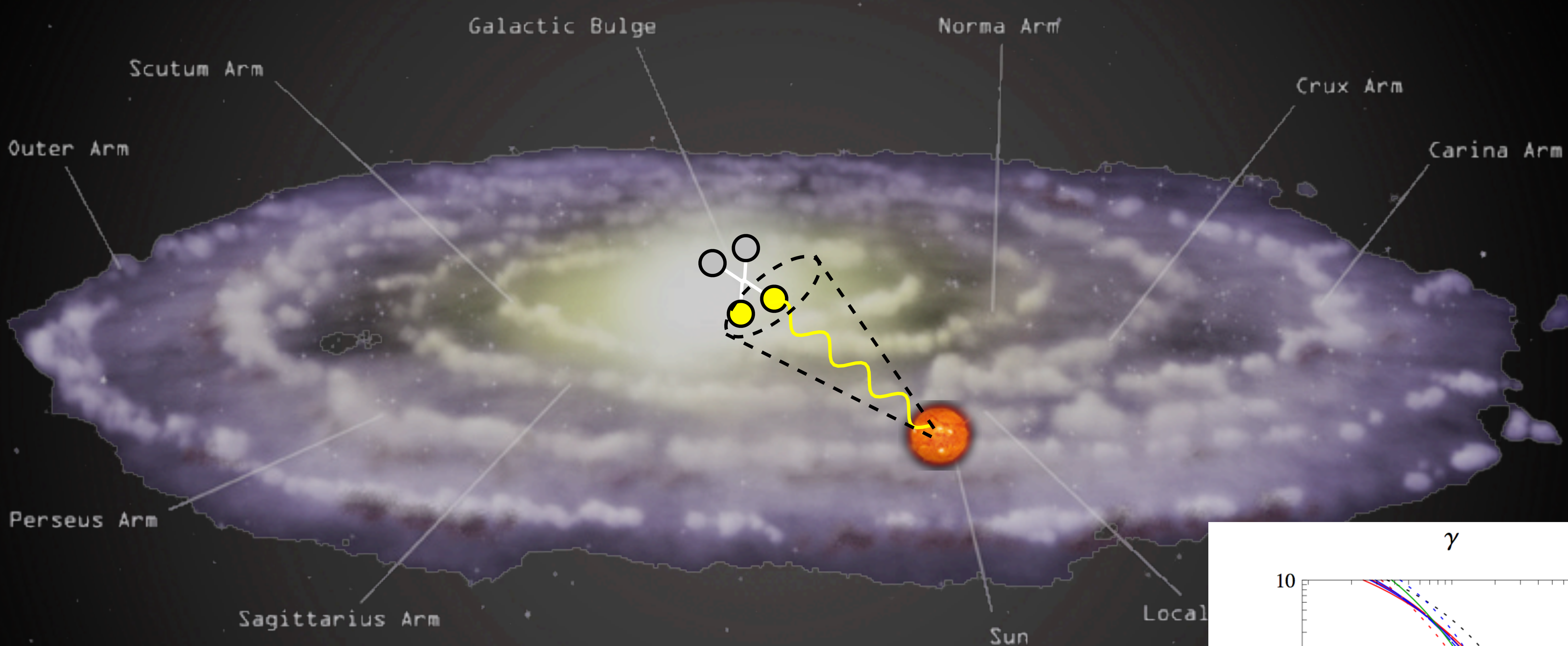
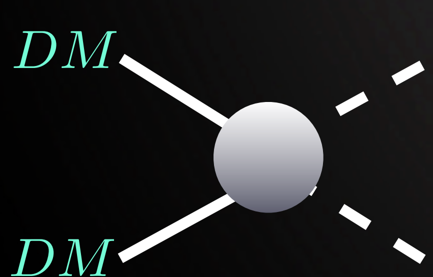
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

Indirect Detection: constraints

a. γ from DM annihilations in galactic center





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

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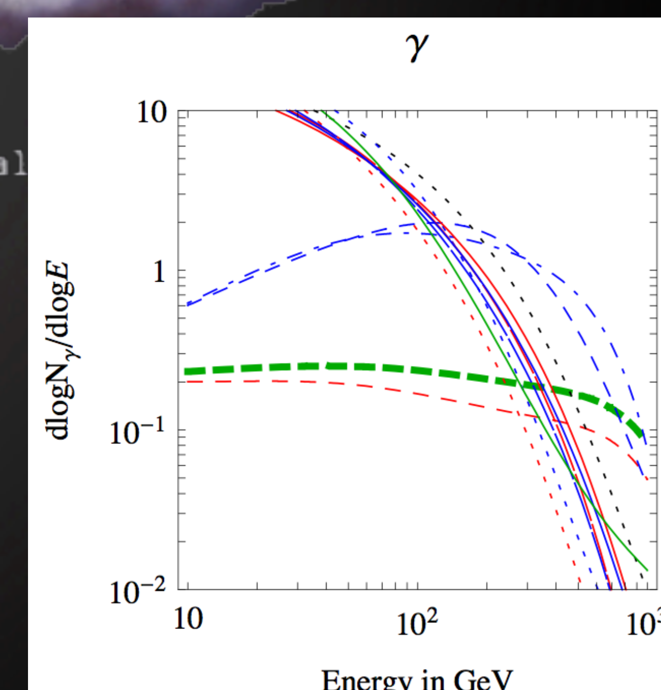
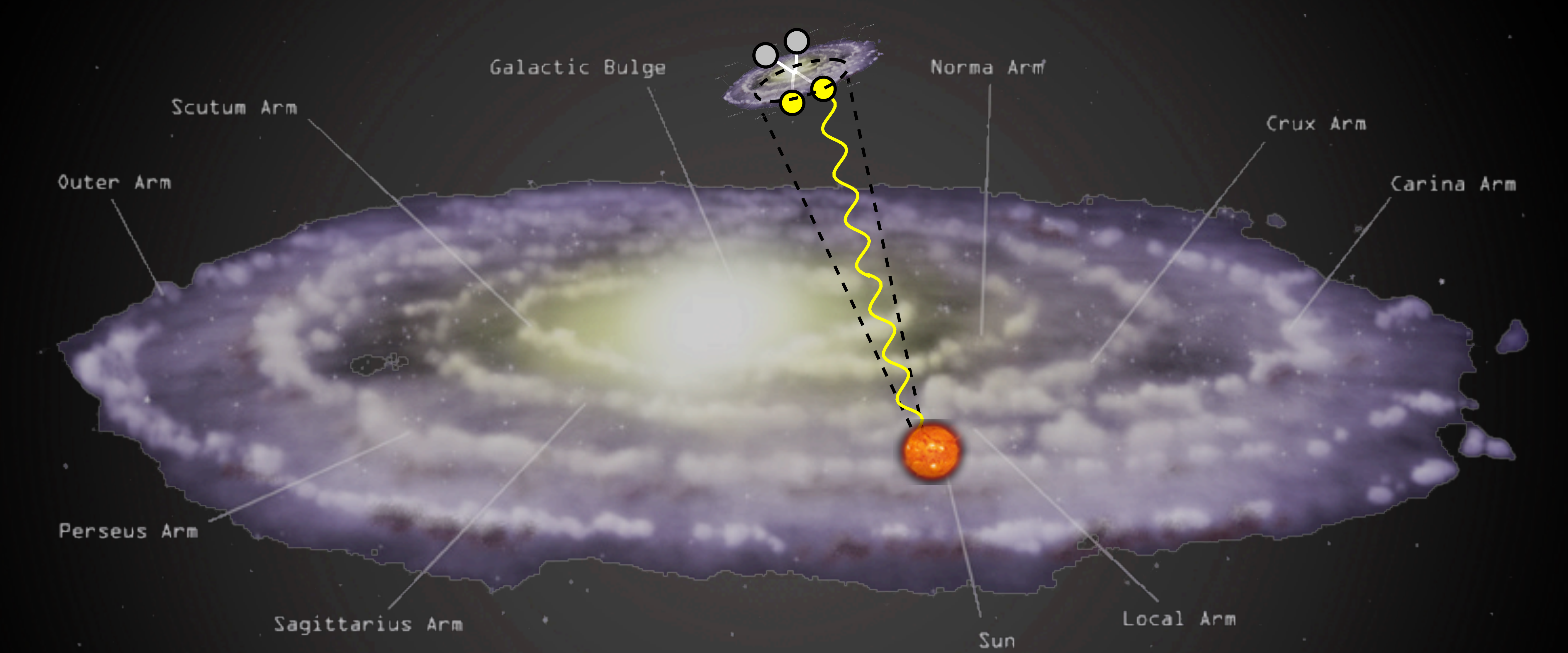
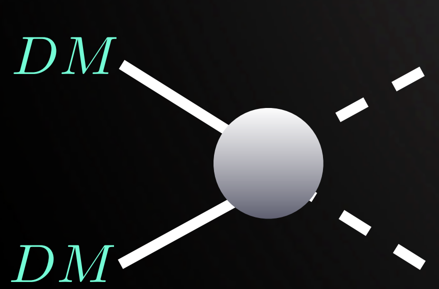


typically sub-TeV energies

Indirect Detection: constraints

b. γ from DM annihilations in Sagittarius Dwarf



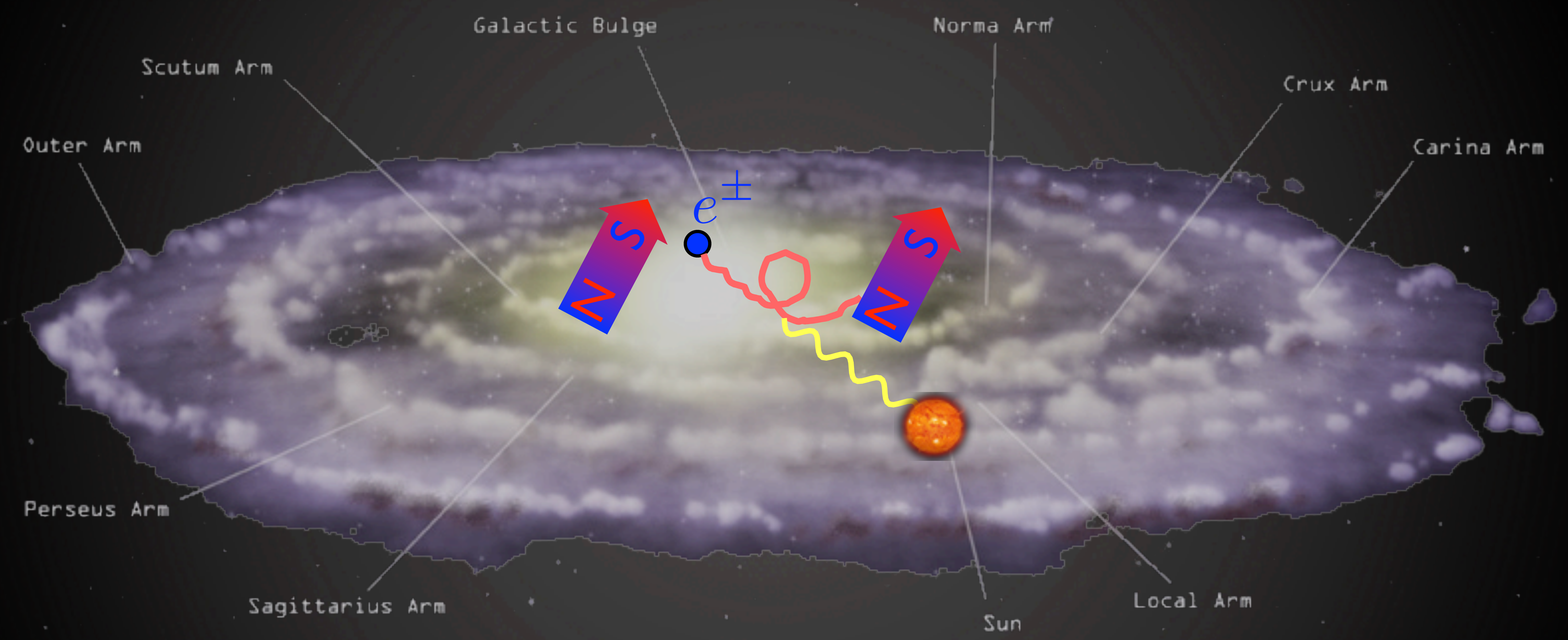


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

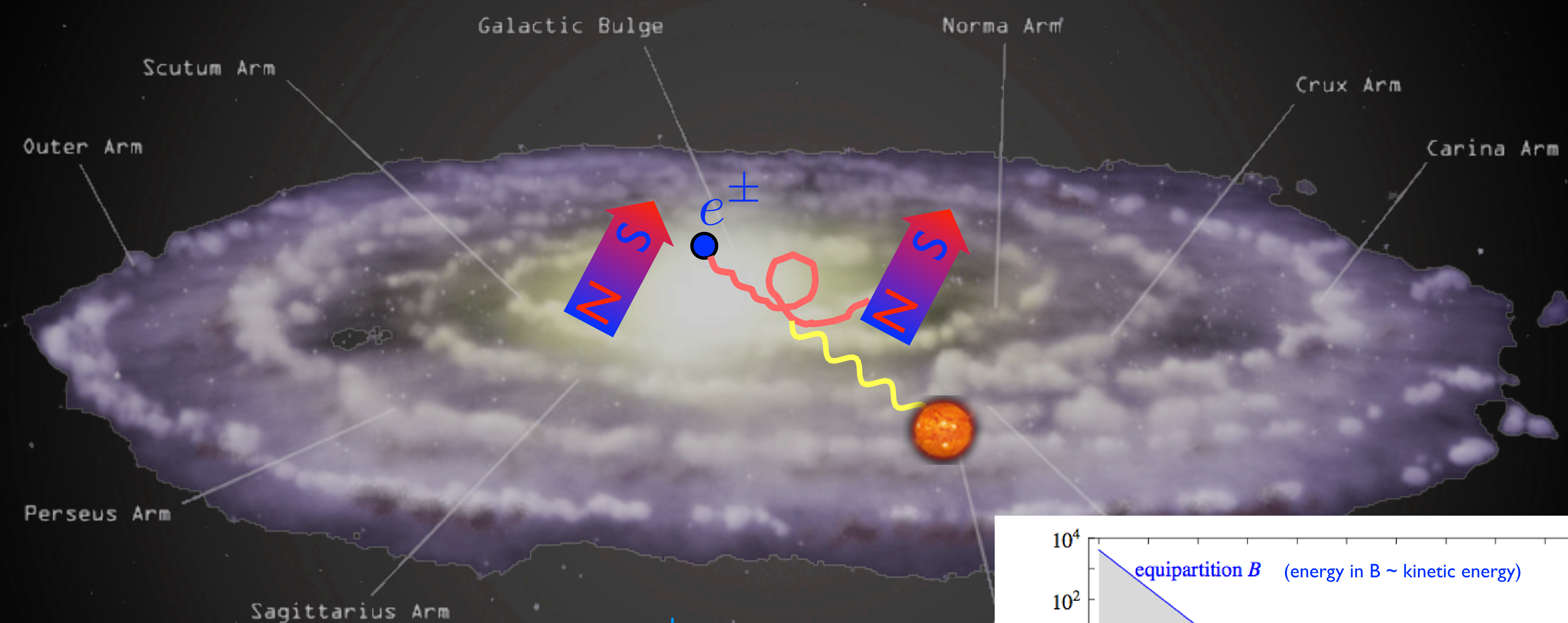
Indirect Detection: constraints

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



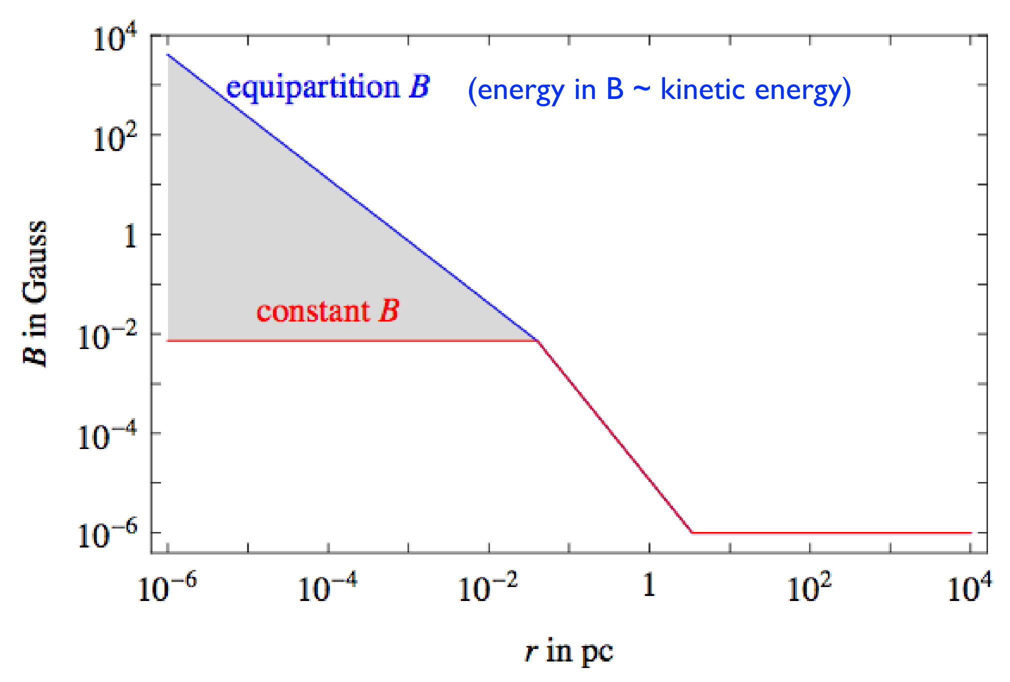
Indirect Detection: constraints

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



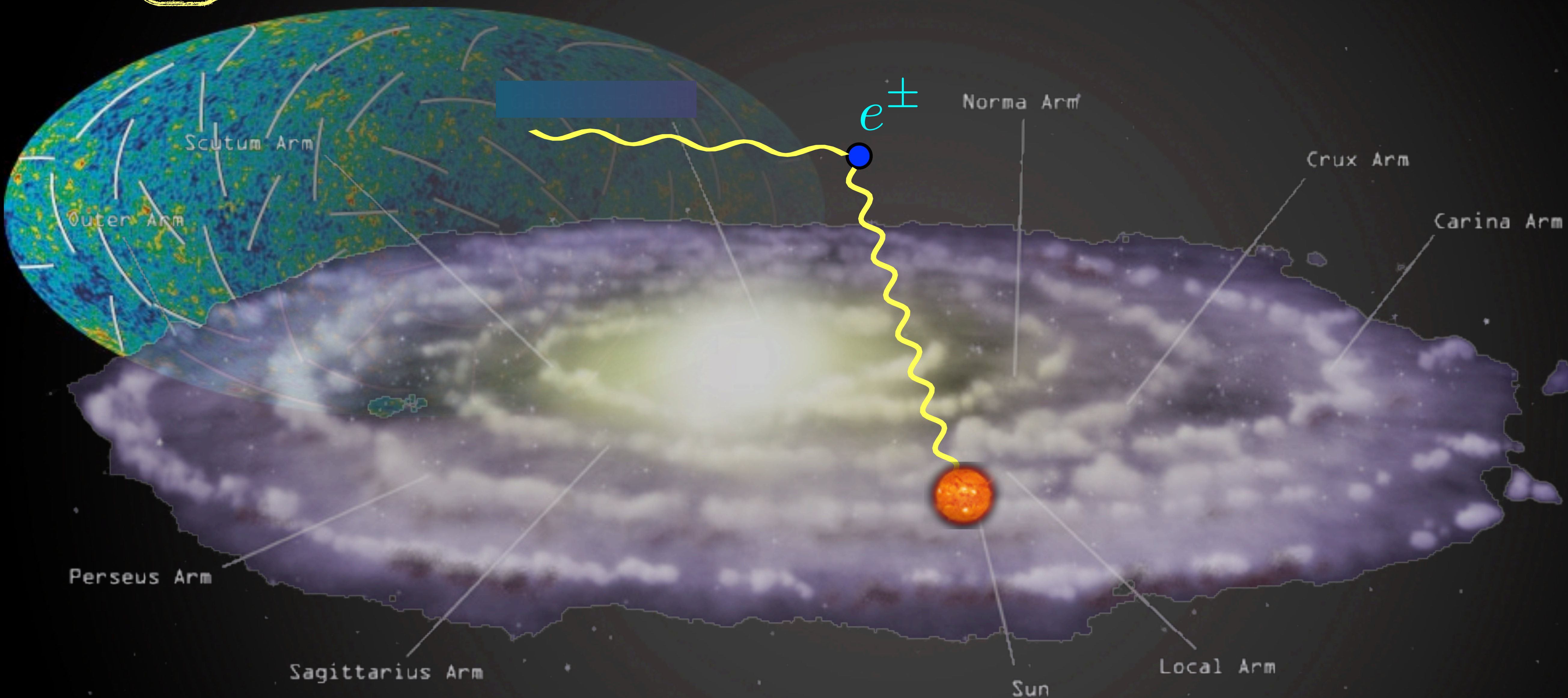
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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



Indirect Detection: constraints

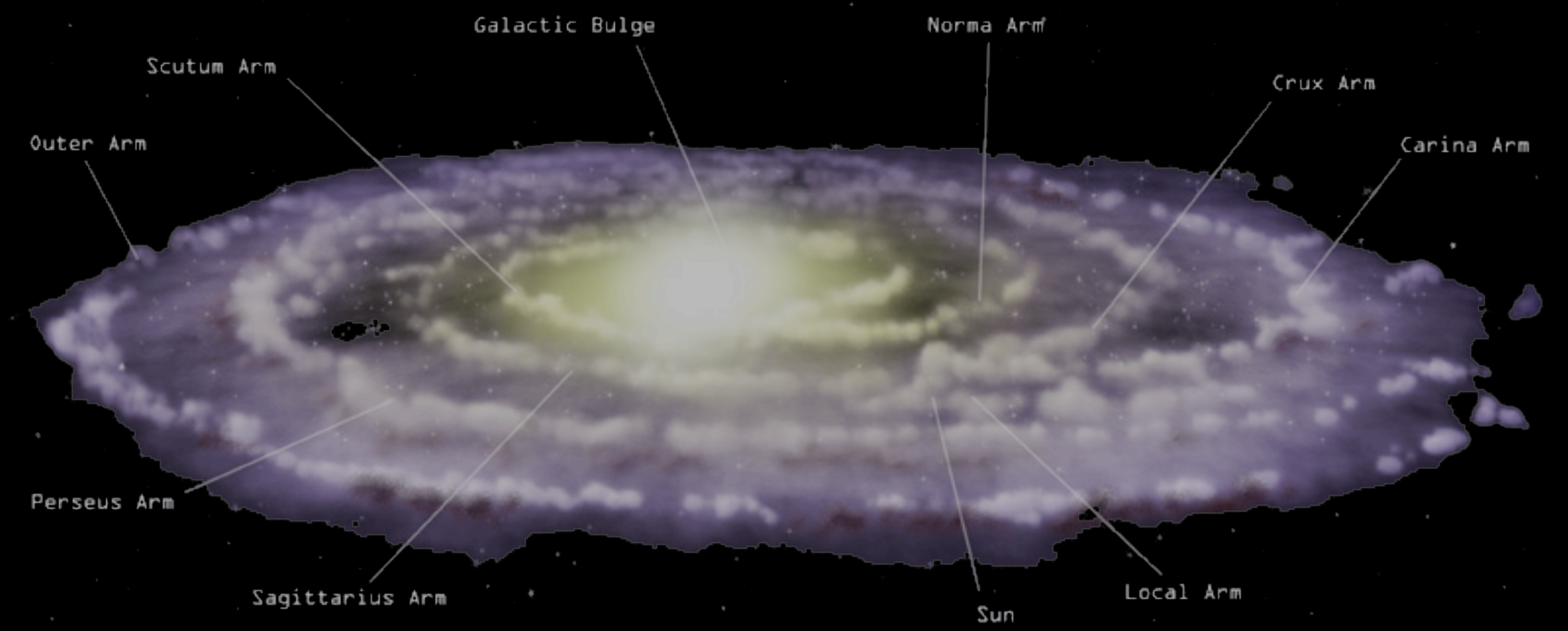
d. γ from Inverse Compton on $e^{\pm}$ in halo



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

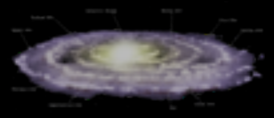
Indirect Detection: constraints

e. γ from outside the Galaxy



Indirect Detection: constraints

e. γ from outside the Galaxy

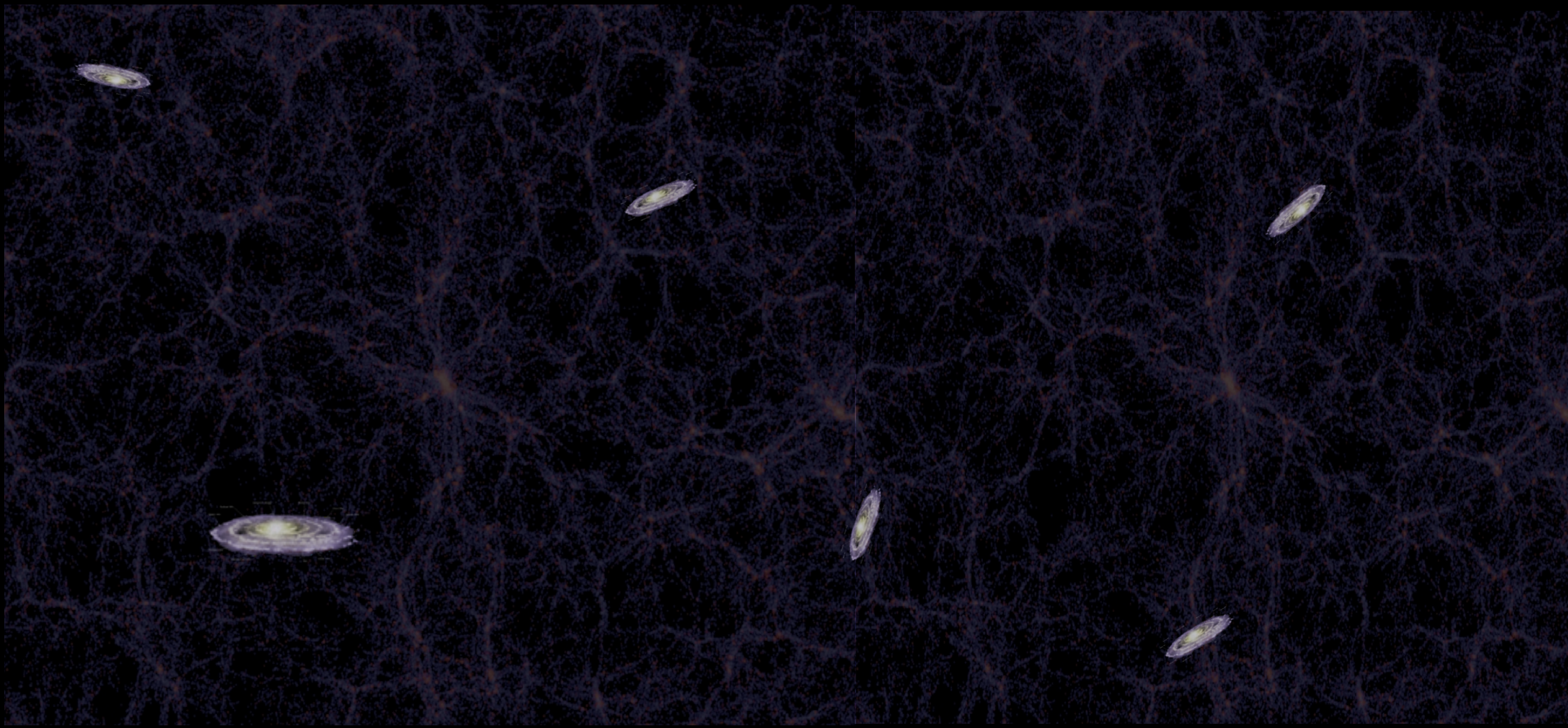


Indirect Detection: constraints

e. γ from outside the Galaxy

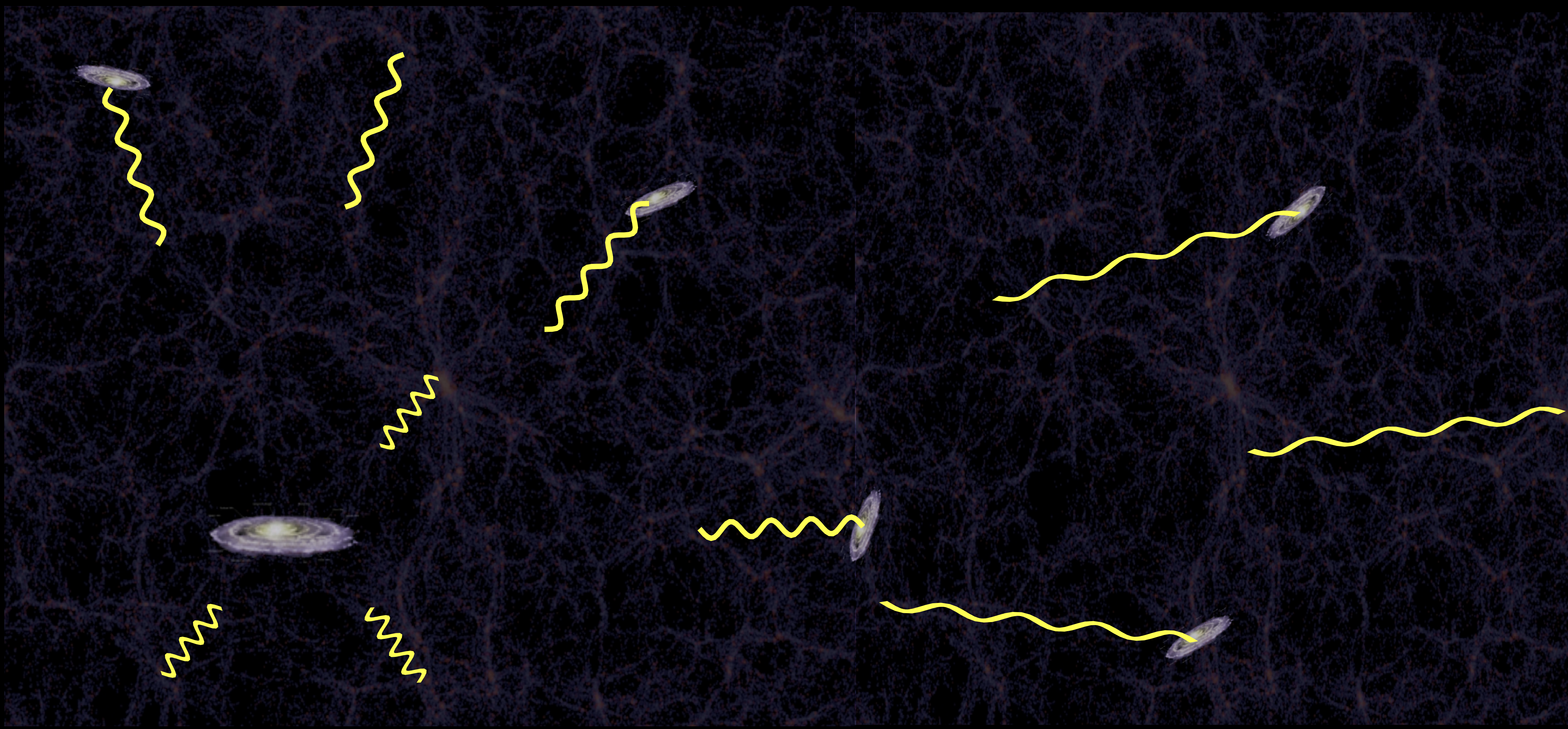
Indirect Detection: constraints

e. γ from outside the Galaxy



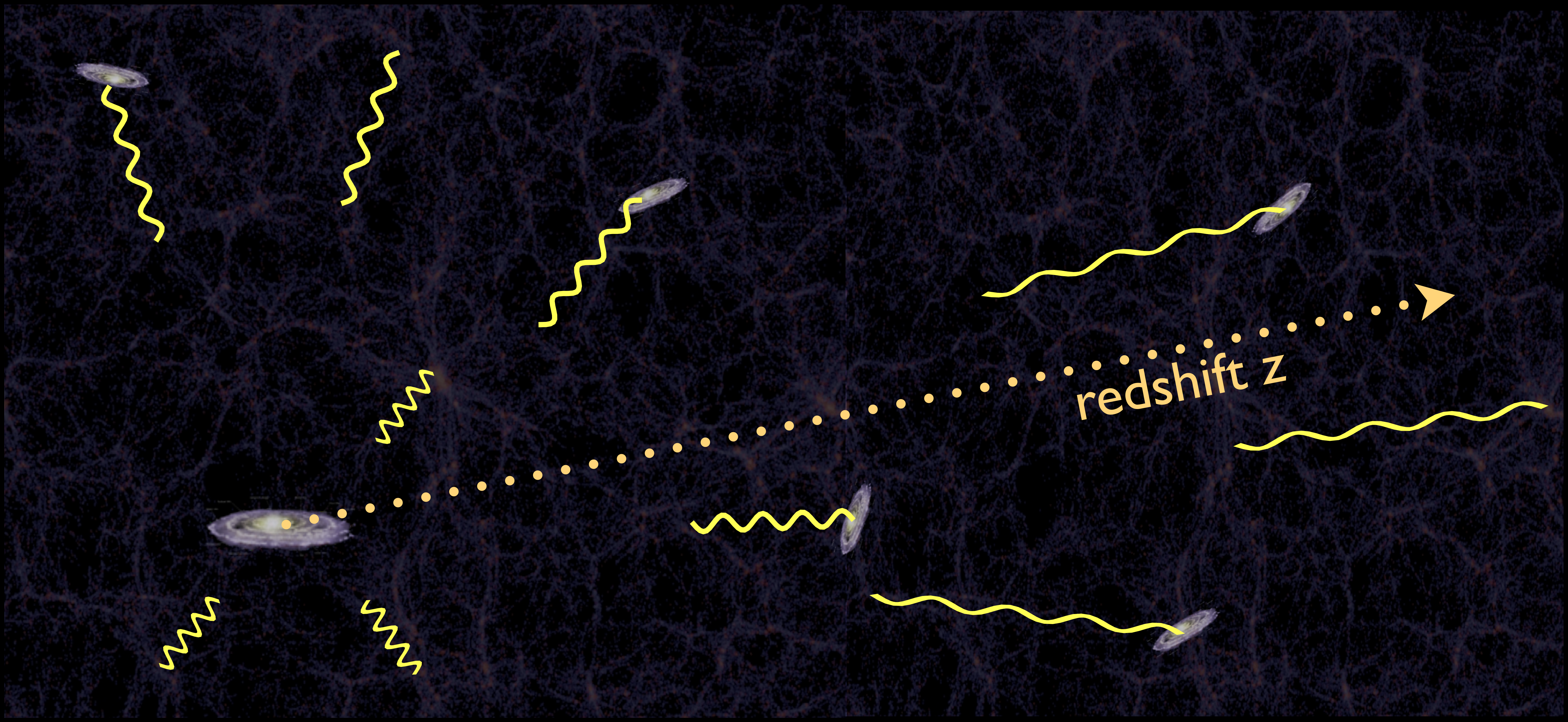
Indirect Detection: constraints

e. γ from outside the Galaxy



Indirect Detection: constraints

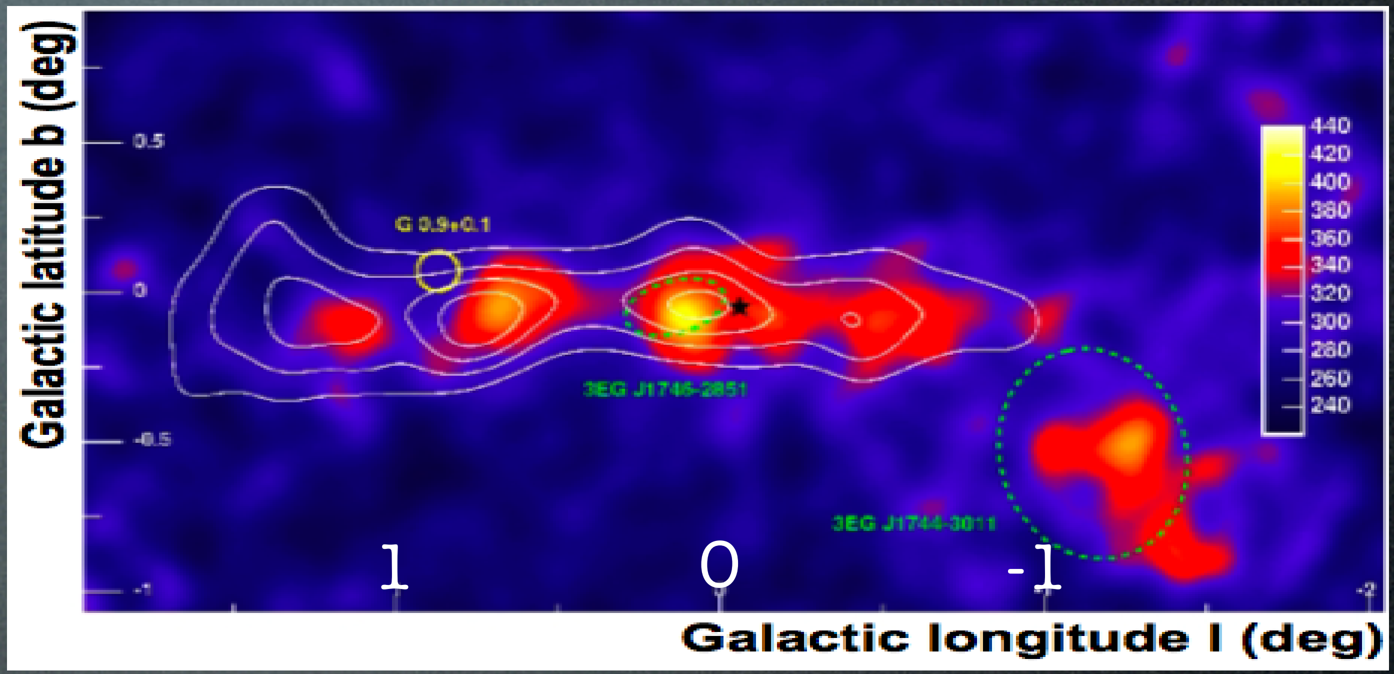
e. γ from outside the Galaxy



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

Gamma constraints

HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.

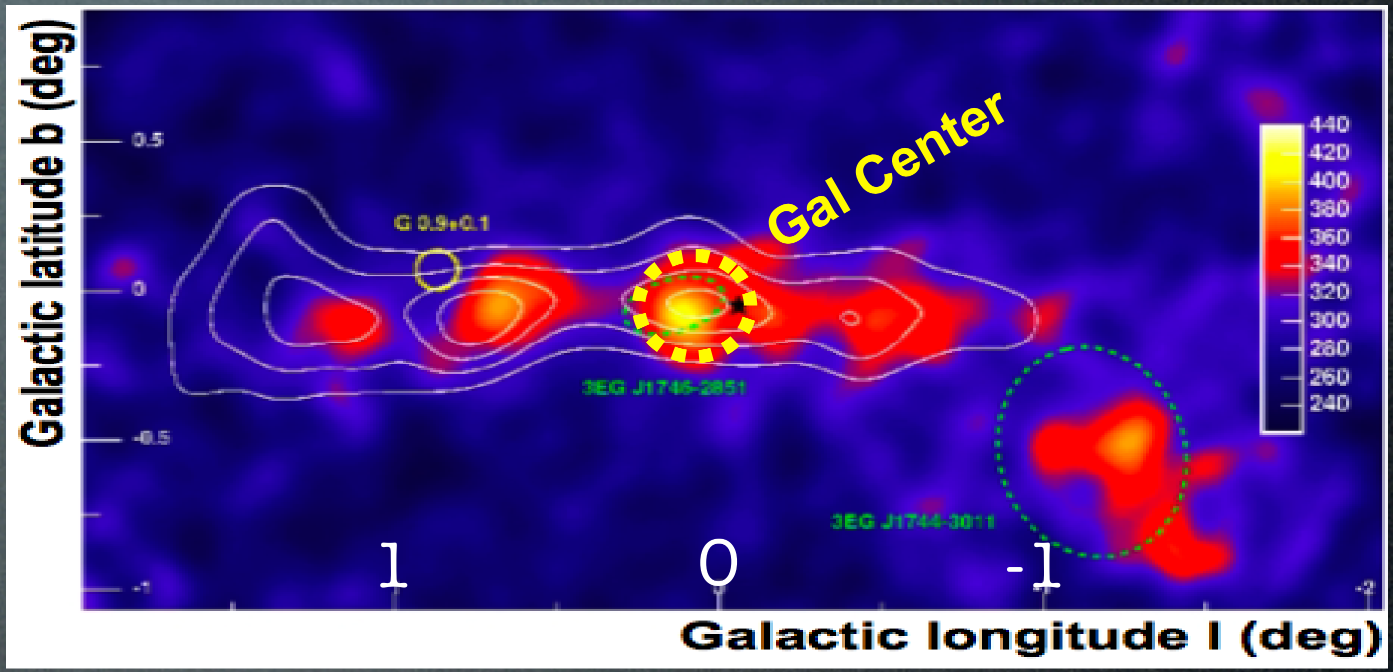


a.

HESS coll.

Gamma constraints

HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.



a.

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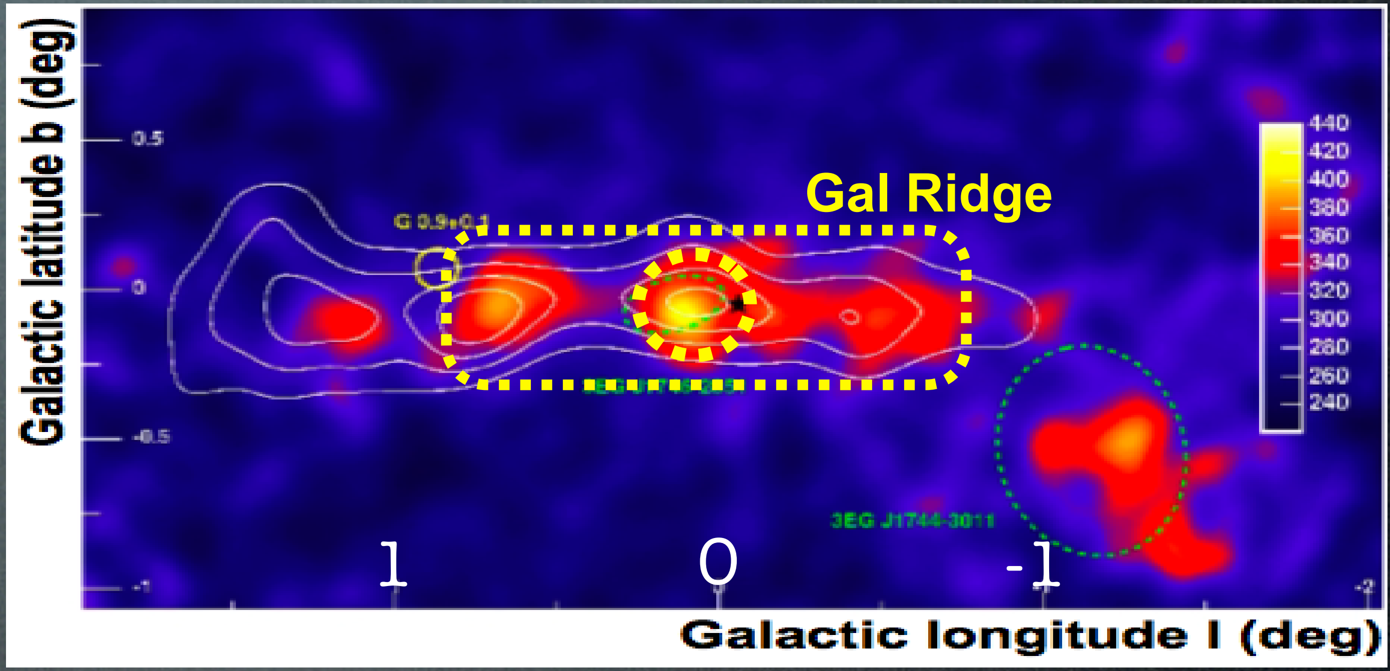

a.

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Gamma constraints

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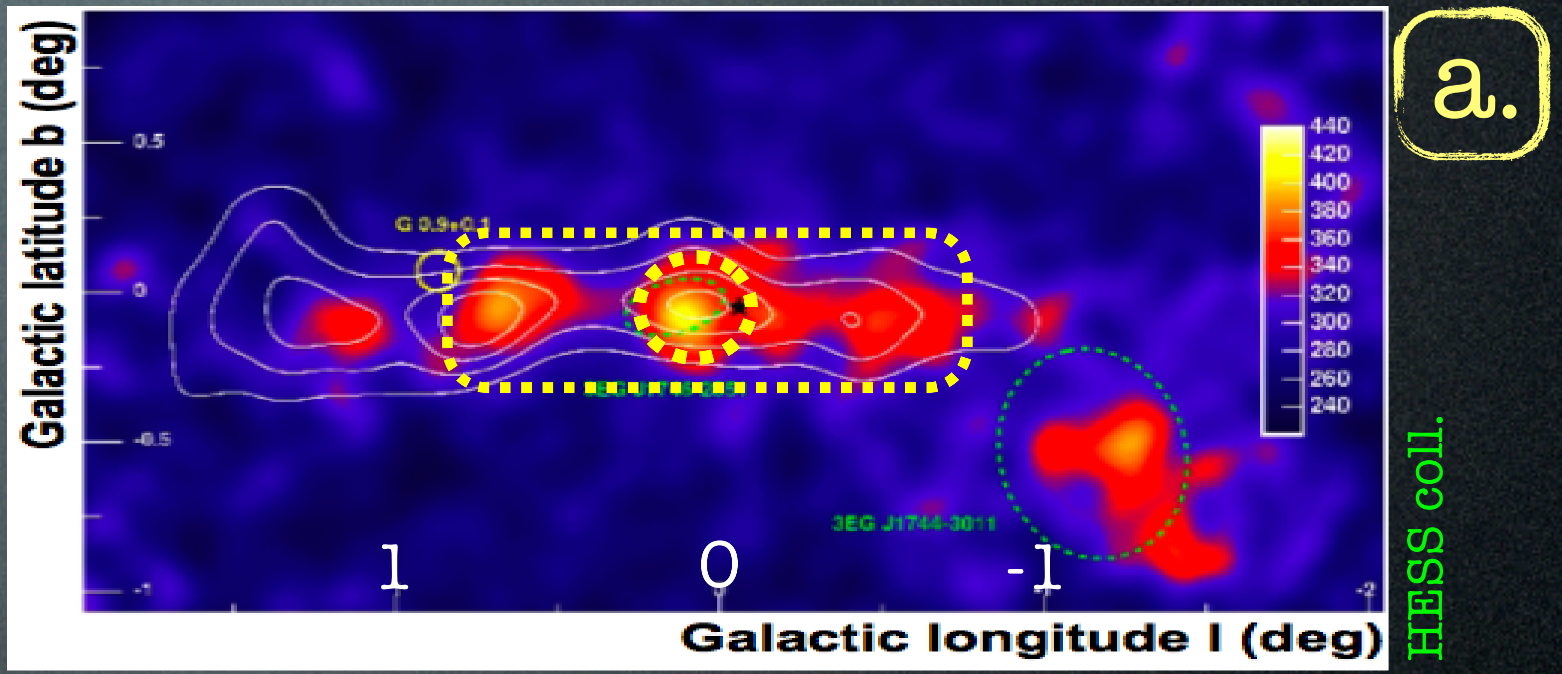

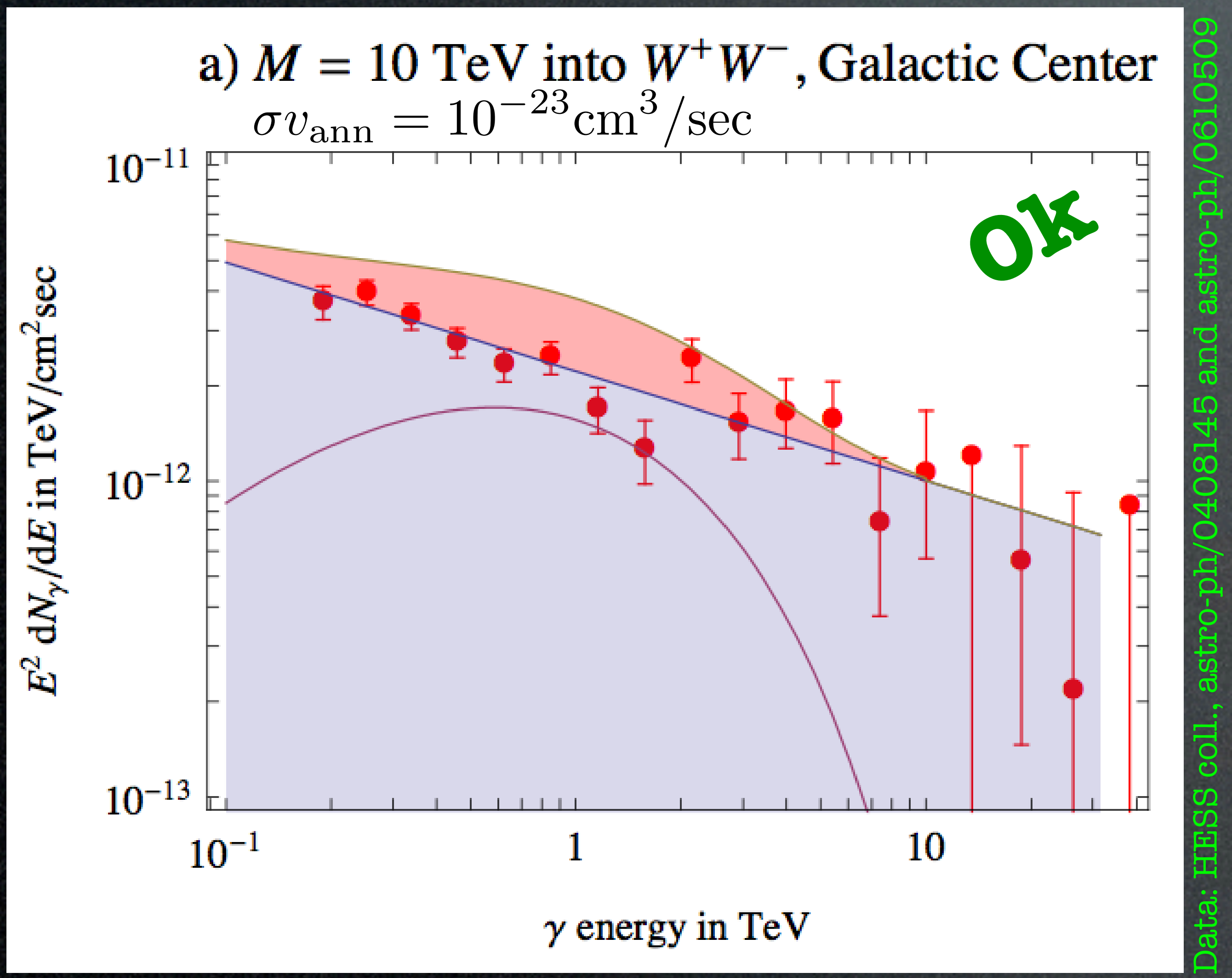

Gamma constraints

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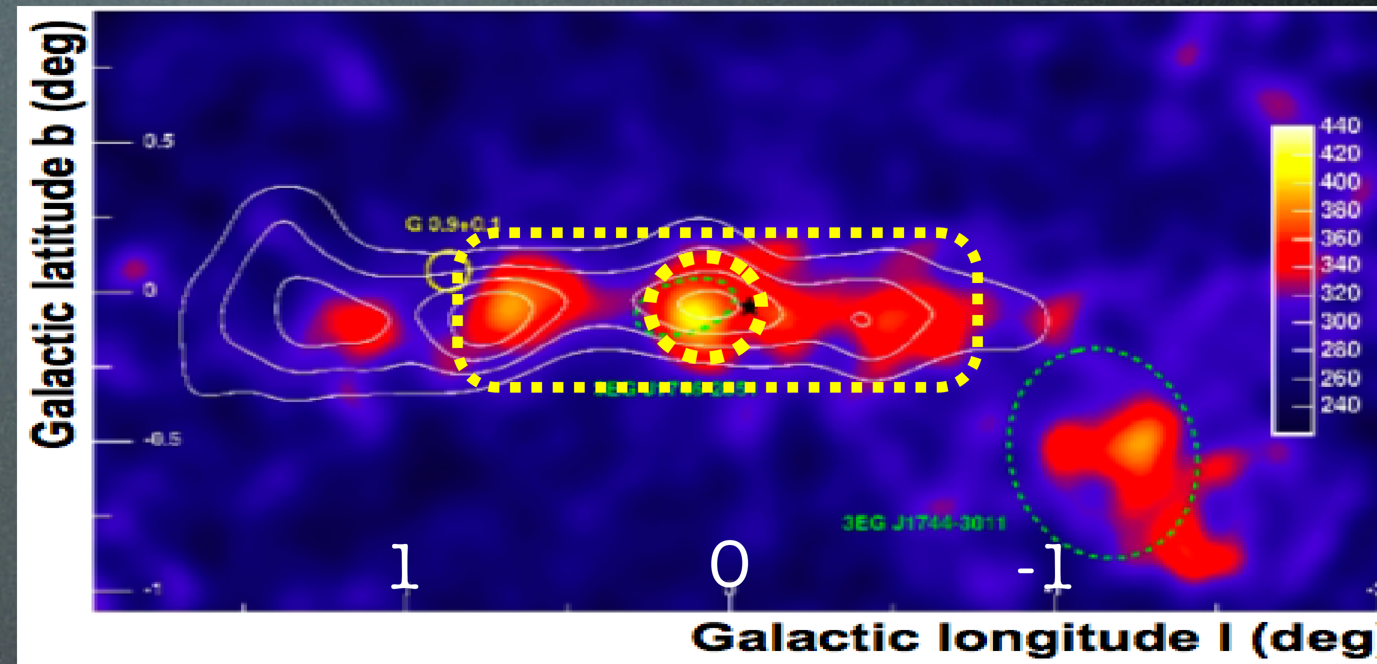
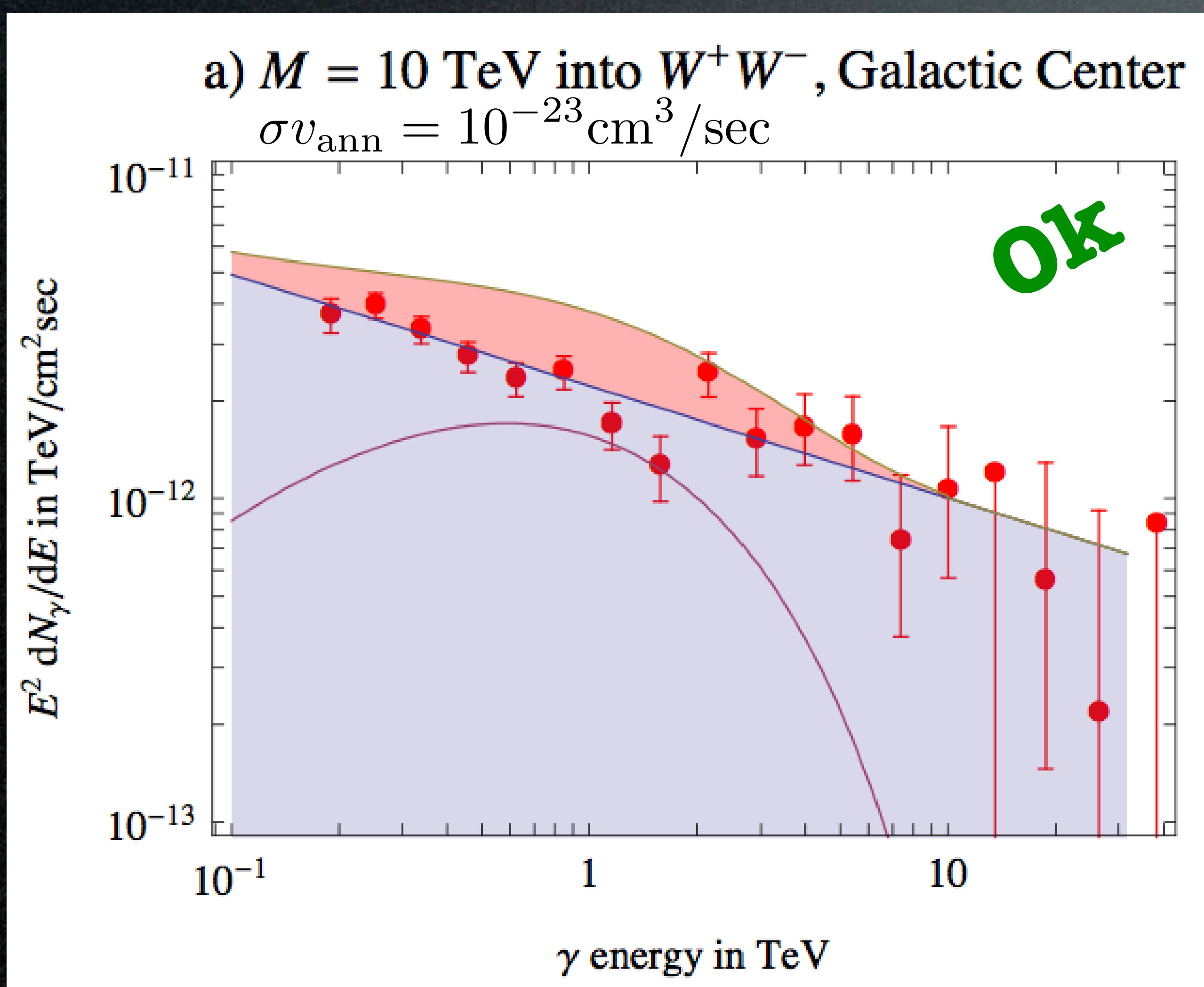
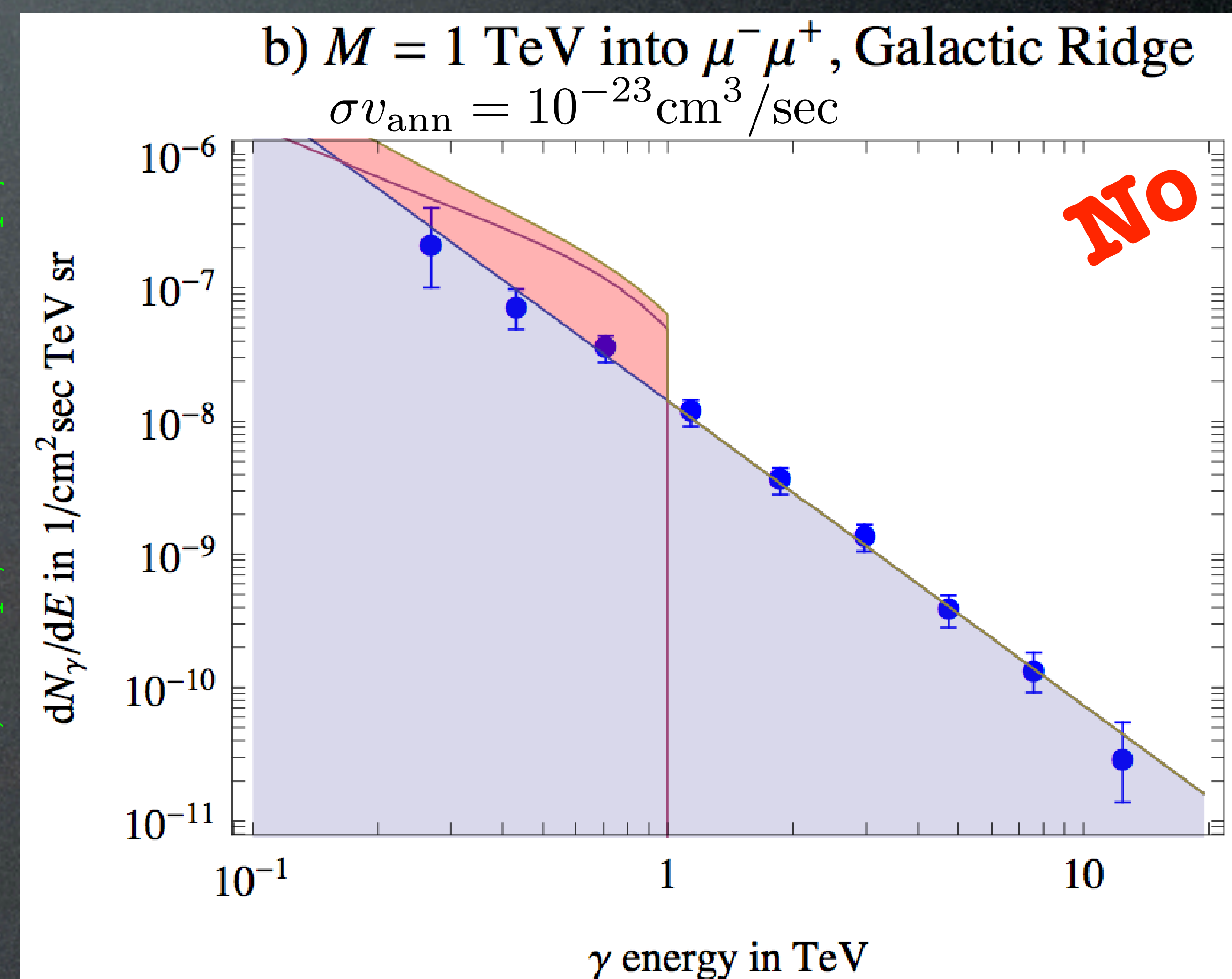


a.

HESS coll.



Data: HESS coll., astro-ph/0408145 and astro-ph/0610509

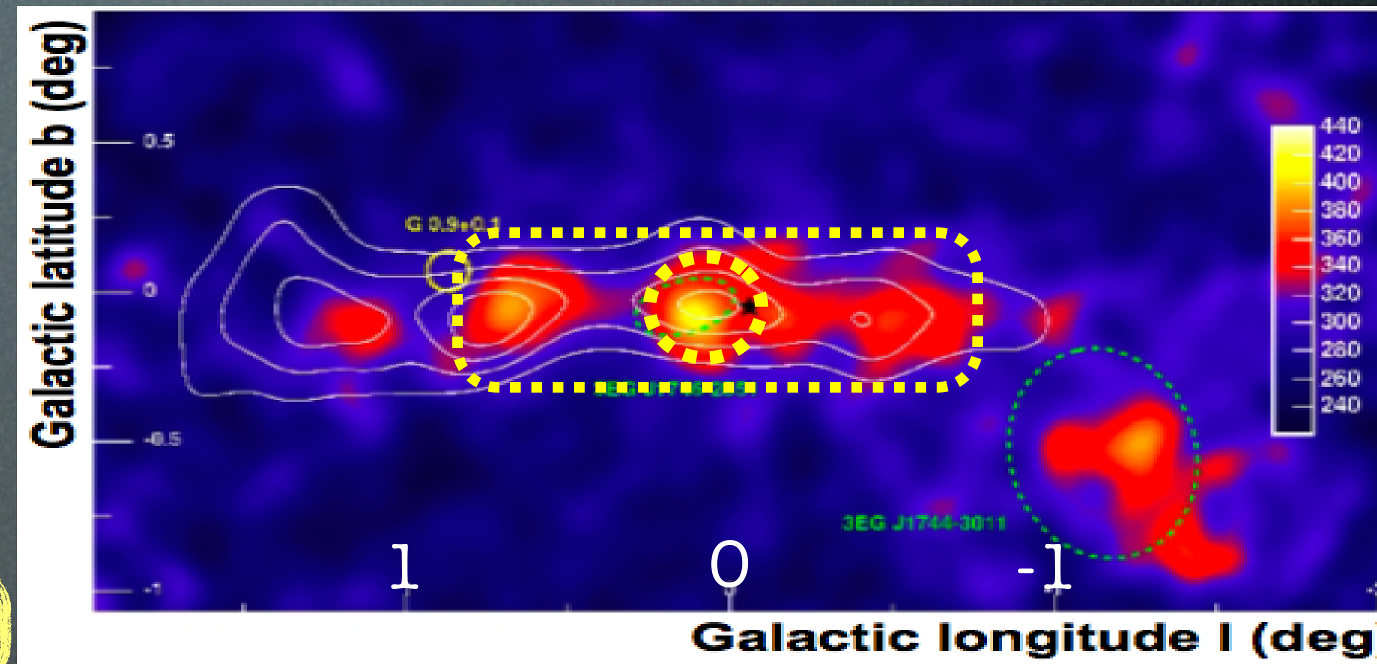


Data: HESS coll., astro-ph/0603021

Gamma constraints

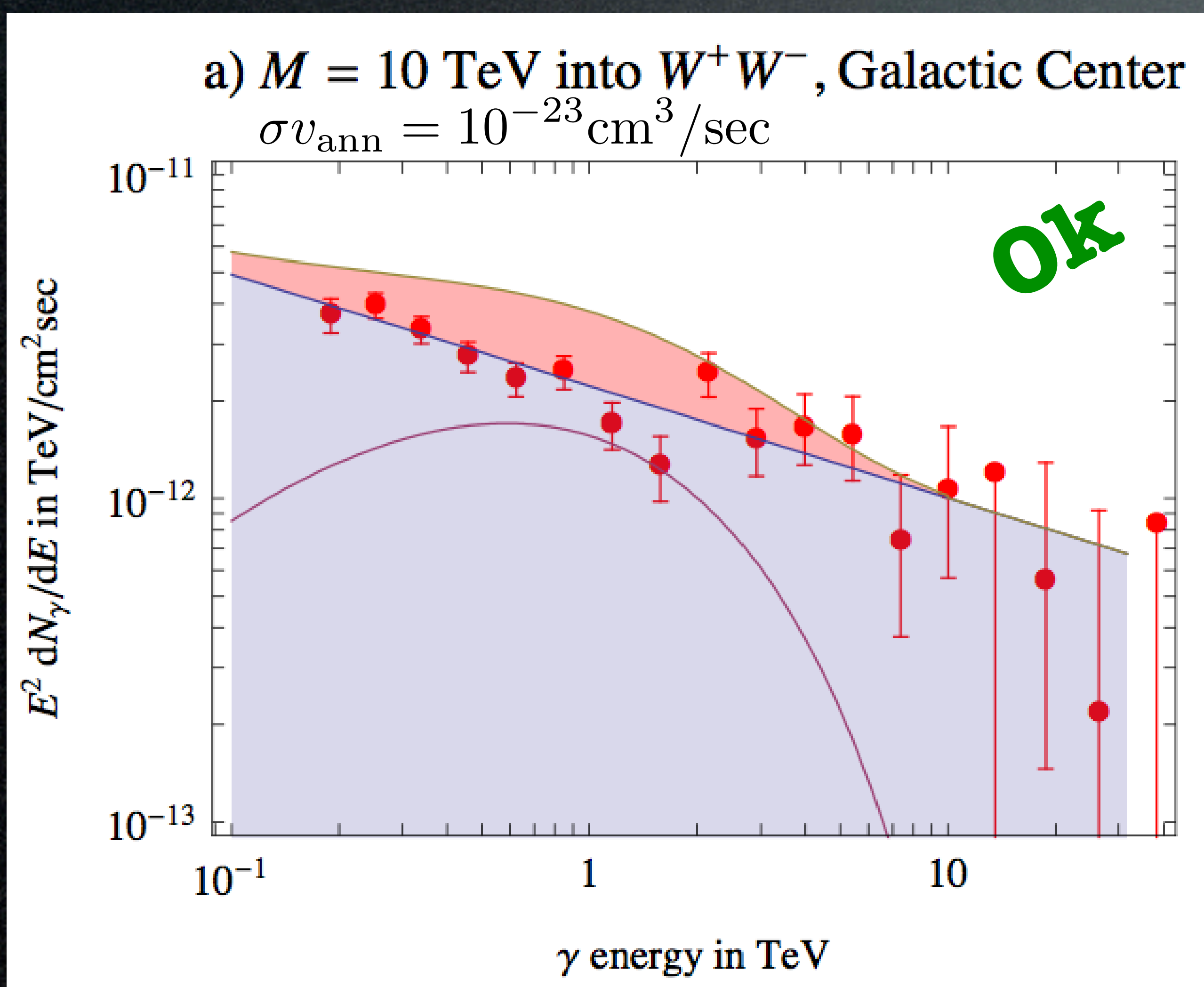
HESS has detected γ-ray emission from Gal Center and Gal Ridge. The DM signal must not excede that.

Moreover: no detection from Sgr dSph => upper bound. b.

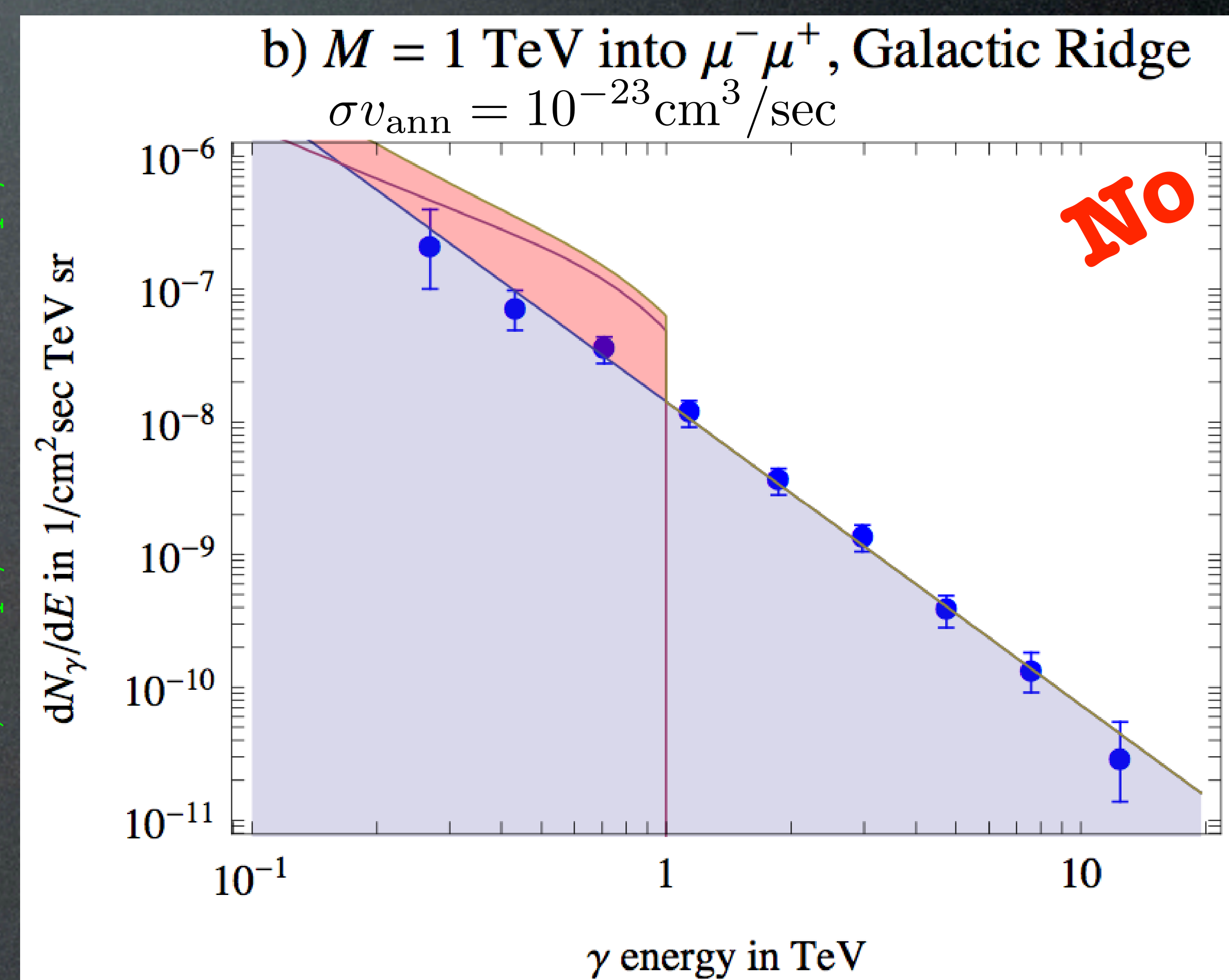


a.

HESS coll.

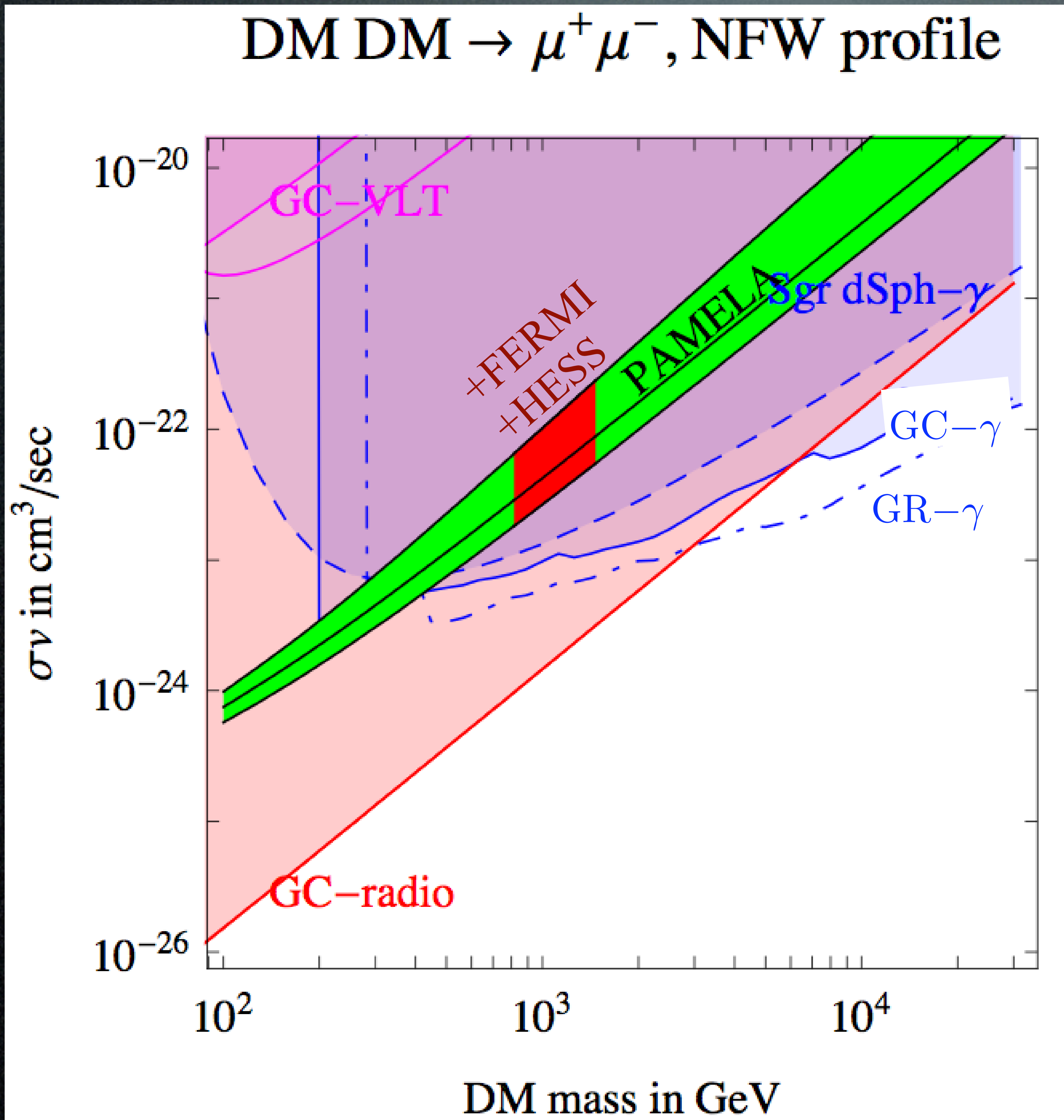


Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



Data: HESS coll., astro-ph/0603021

Gamma constraints



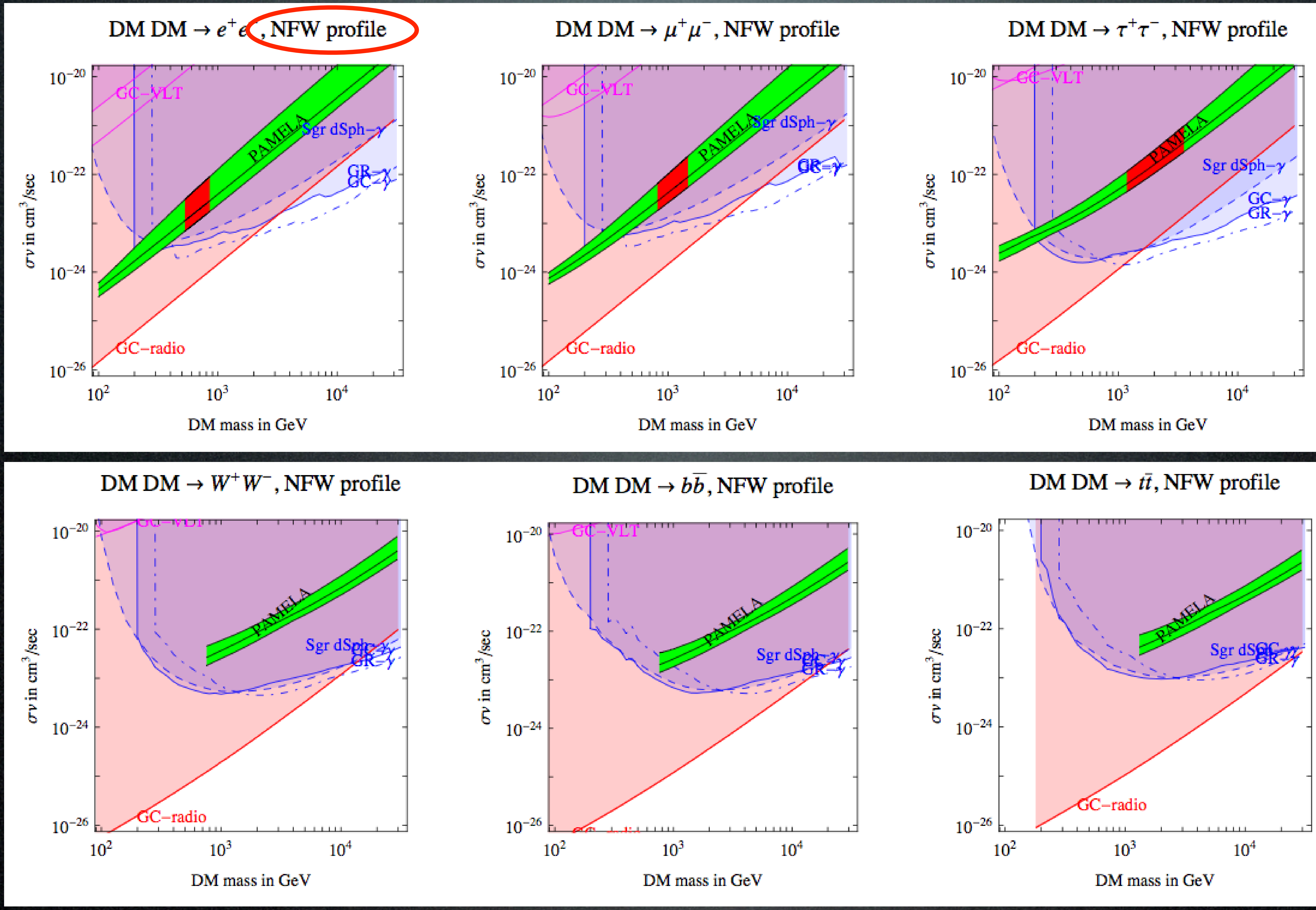
Bertone, Cirelli, Strumia, Taoso 0811.3744

a+b+c.

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

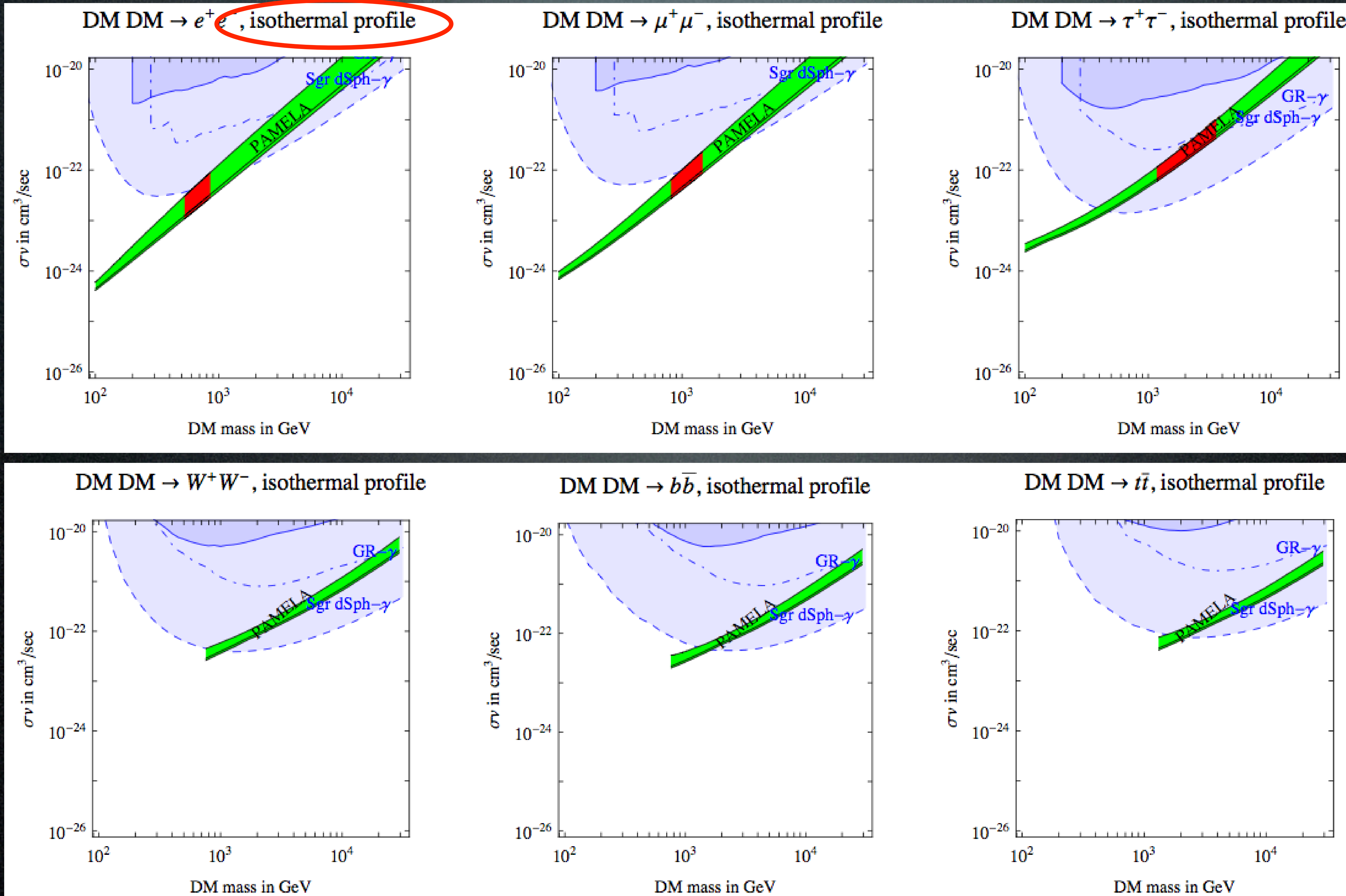
Gamma constraints

a+b+c.



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints



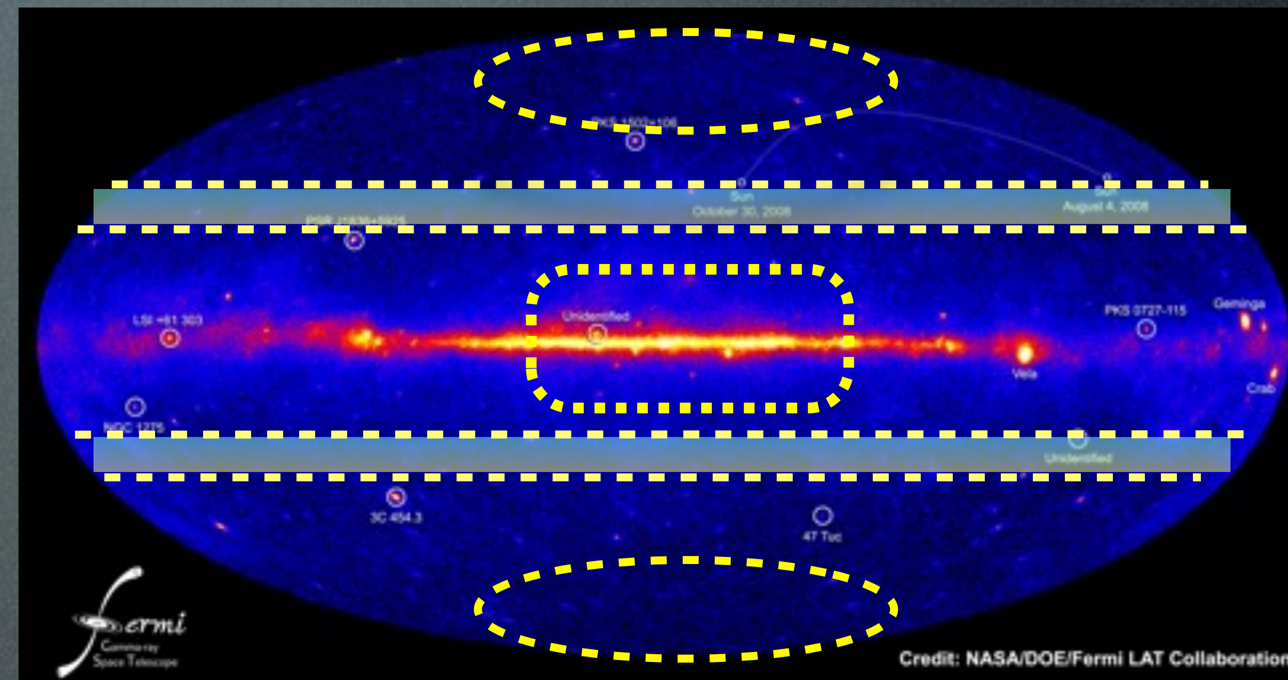
a+b+c.

Bertone, Cirelli, Strumia, Taoso 0811.3744

...not-too-steep profile needed.

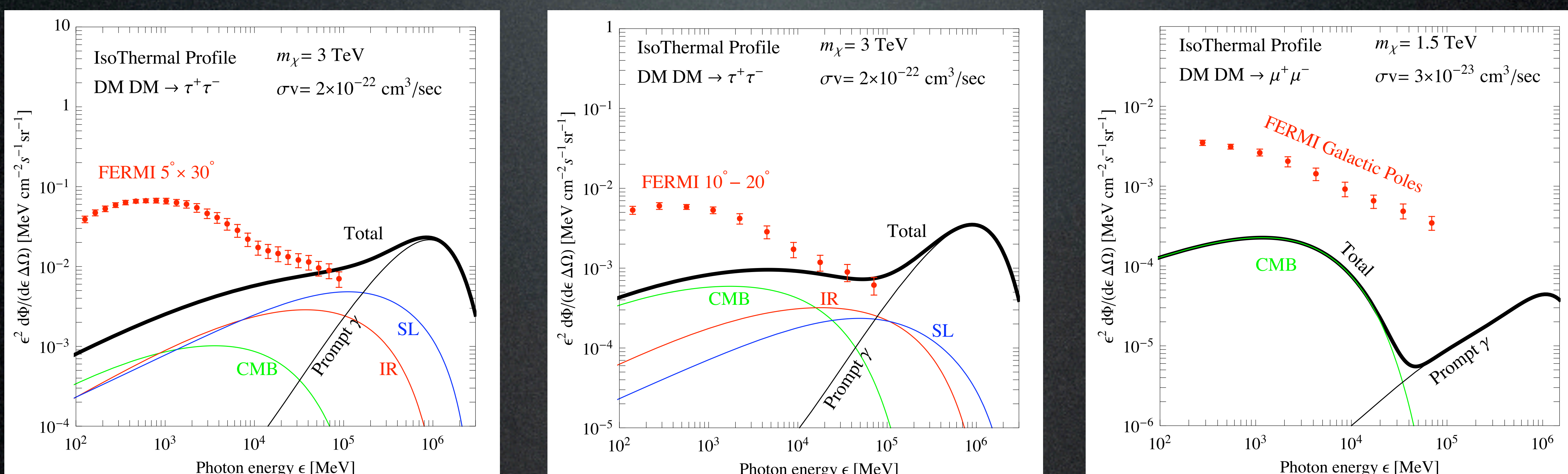
Gamma constraints

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



d.

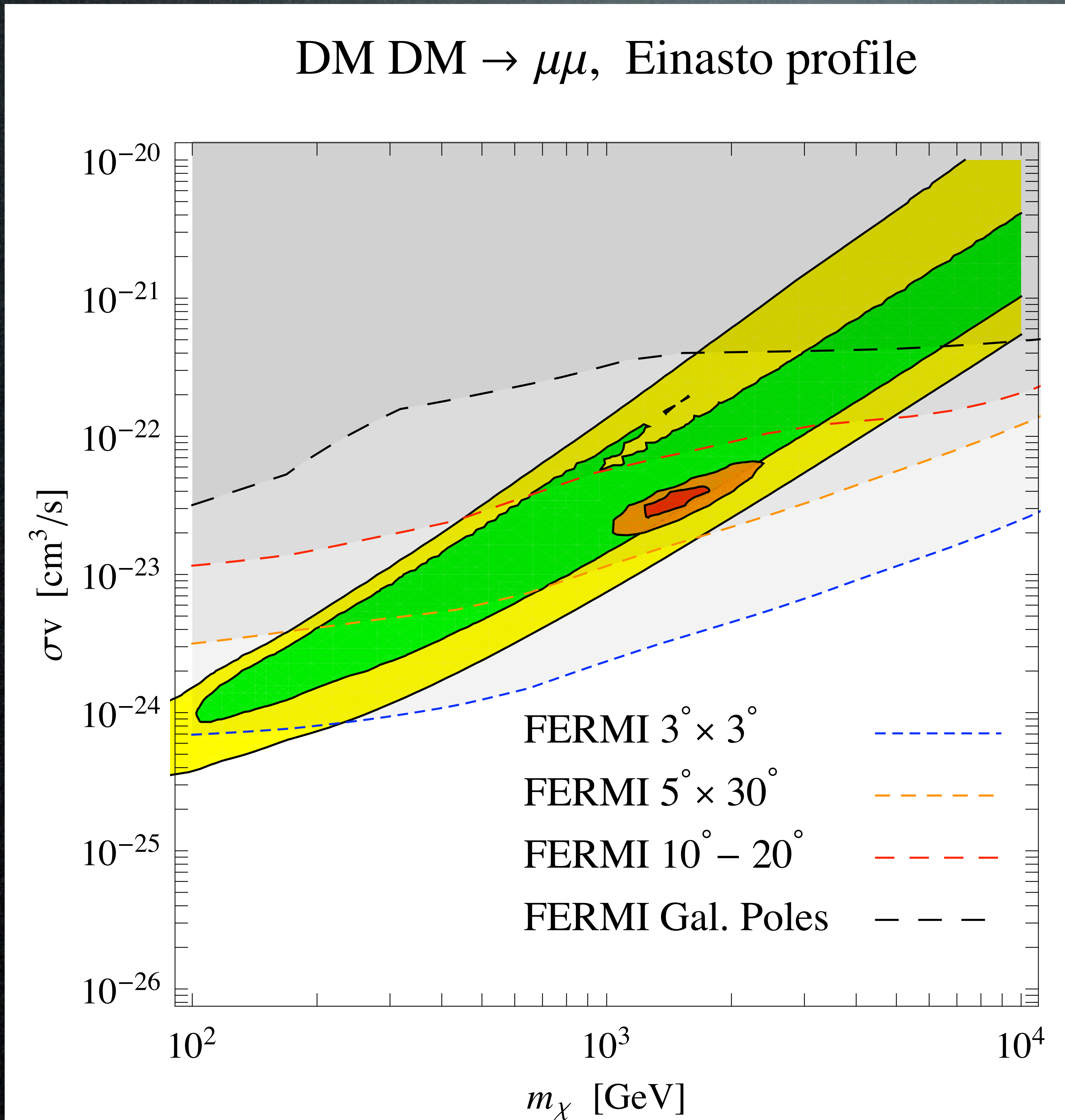
FERMI coll.



Data: FERMI coll., several talks and papers

Cirelli, Panci, Serpico 0912.0663

Inverse Compton γ constraints

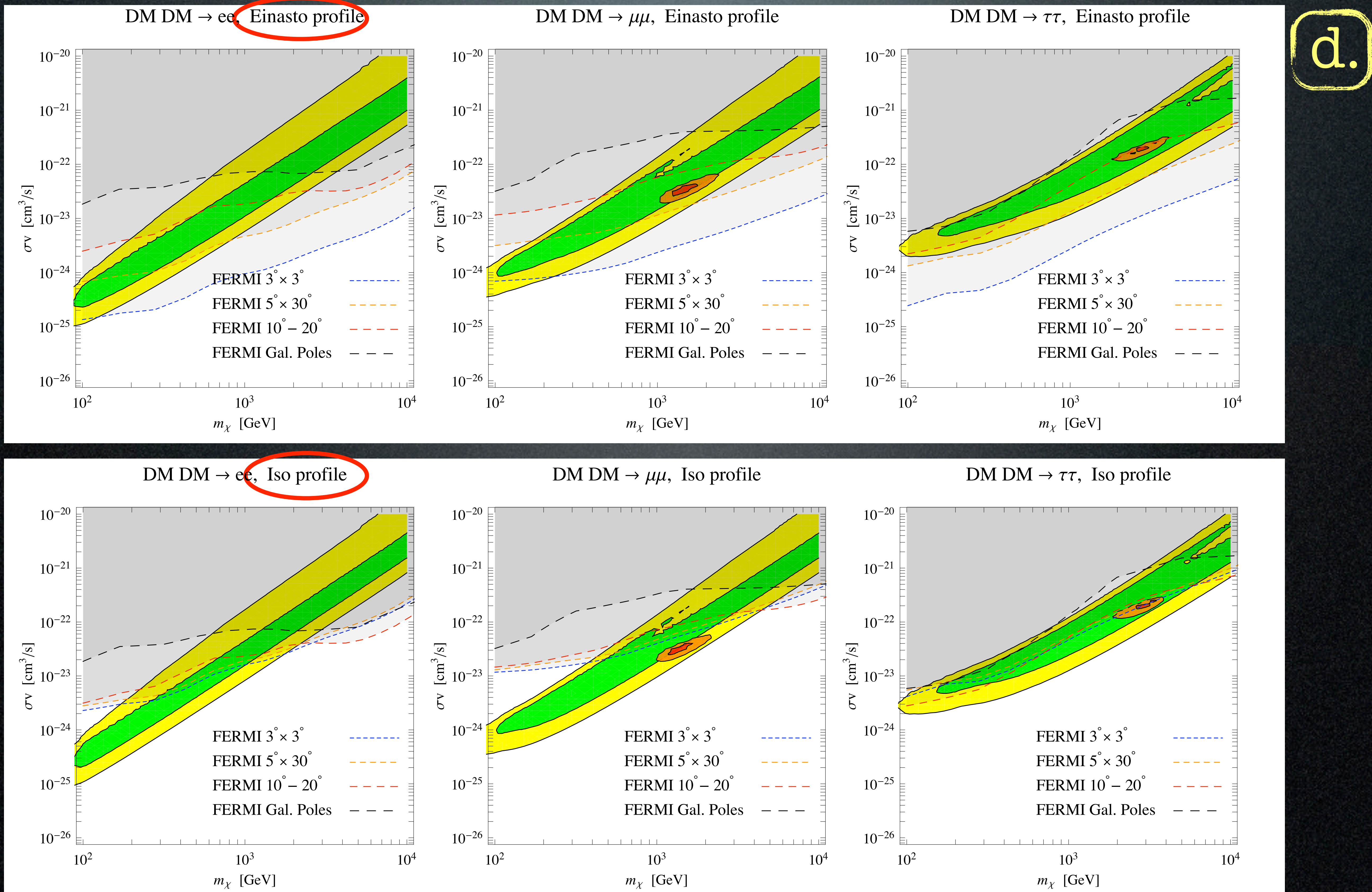


d.

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

Cirelli, Panci, Serpico 0912.0663

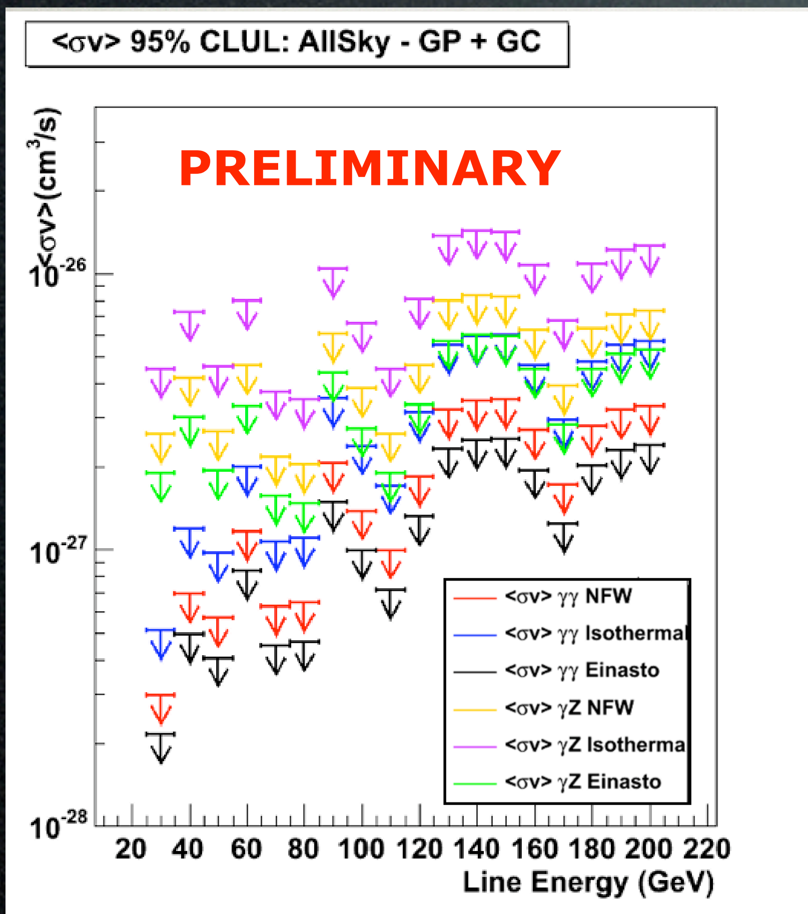
Inverse Compton γ constraints



Cirelli, Panci, Serpico 0912.0663

More FERMI γ constraints

Gamma lines

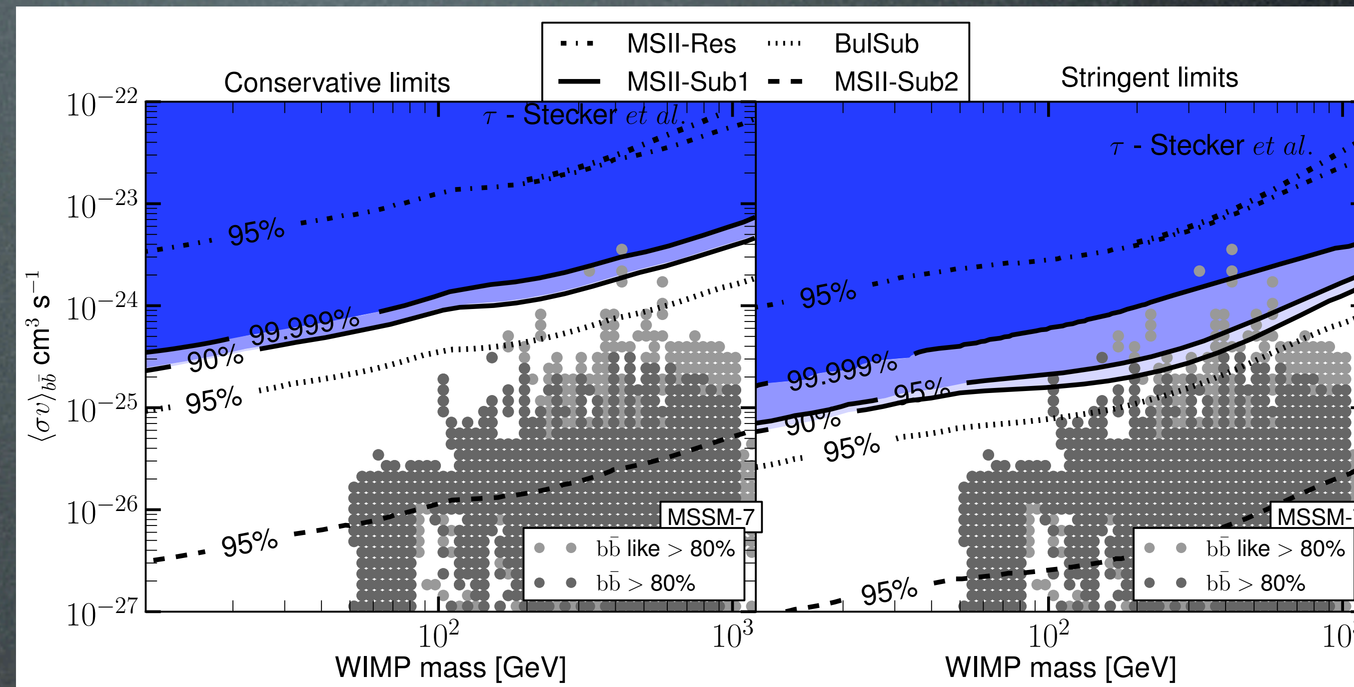


a.

FERMI Coll. 1001.4836

model dependent constraints, can be stringent

Isotropic gamma background

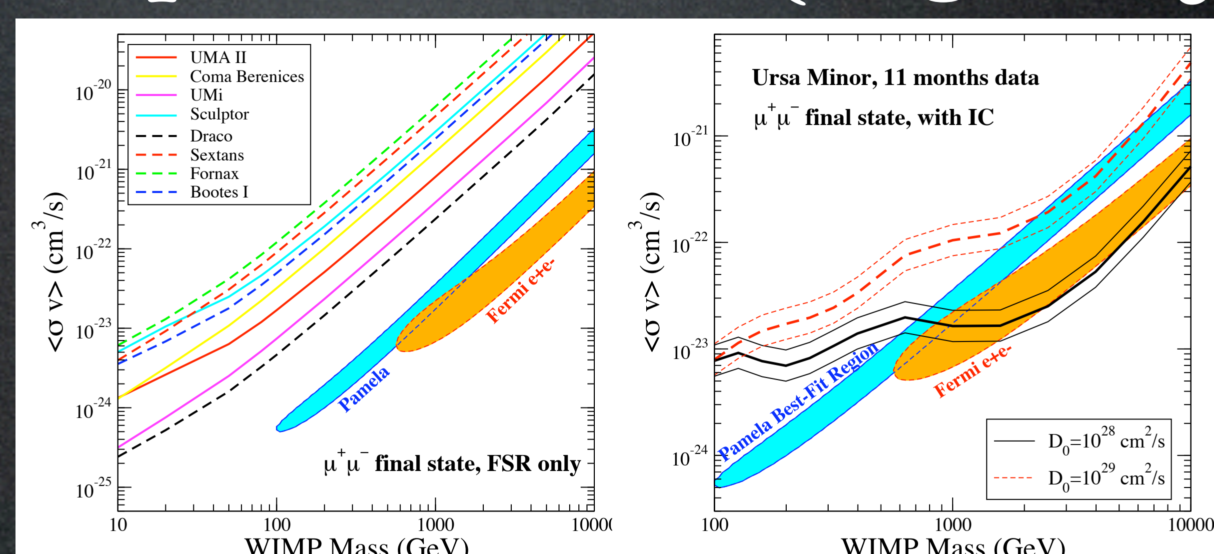


e.

Conrad, Gustafsson, Sellerholm, Zaharijas, FERMI coll. JCAP 04 (2010) 014

bounds are typically very sensitive to assumptions on the cosmological evolution of DM halos

dSph satellites (& galaxy clusters)



Competitive constraints (if ICS included)

b.

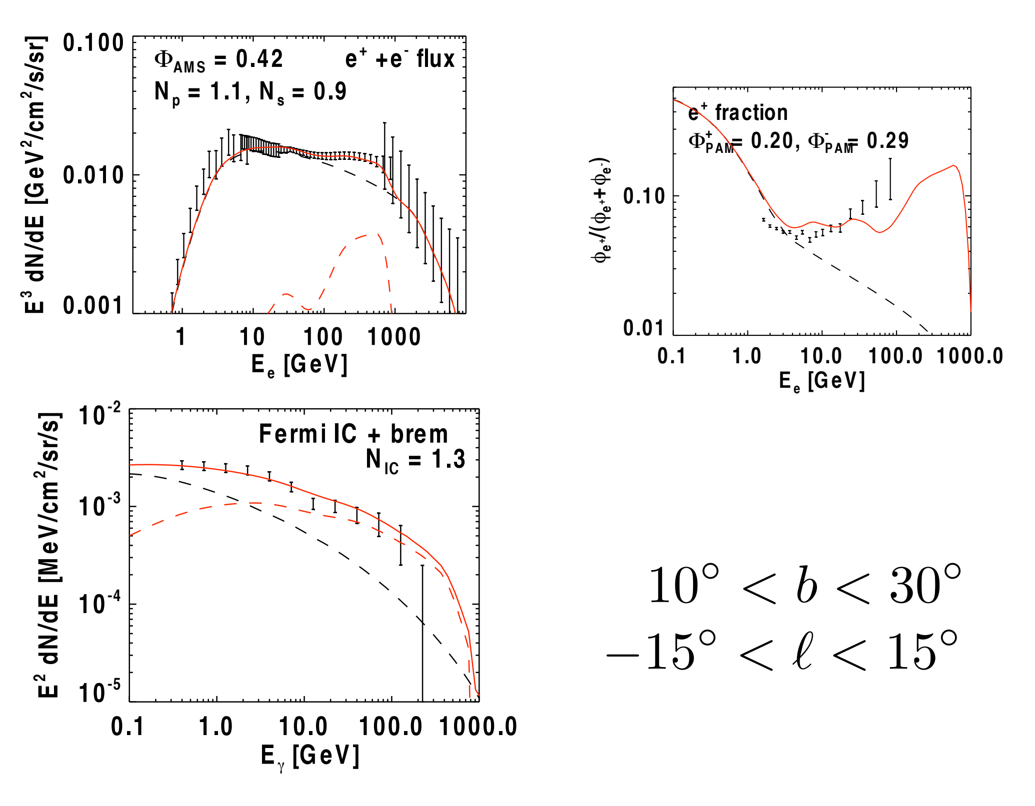
Cohen-Tanugi, Farnier, Jeltema, Nuss, Profumo, 1001.4531

Gamma **hints**?

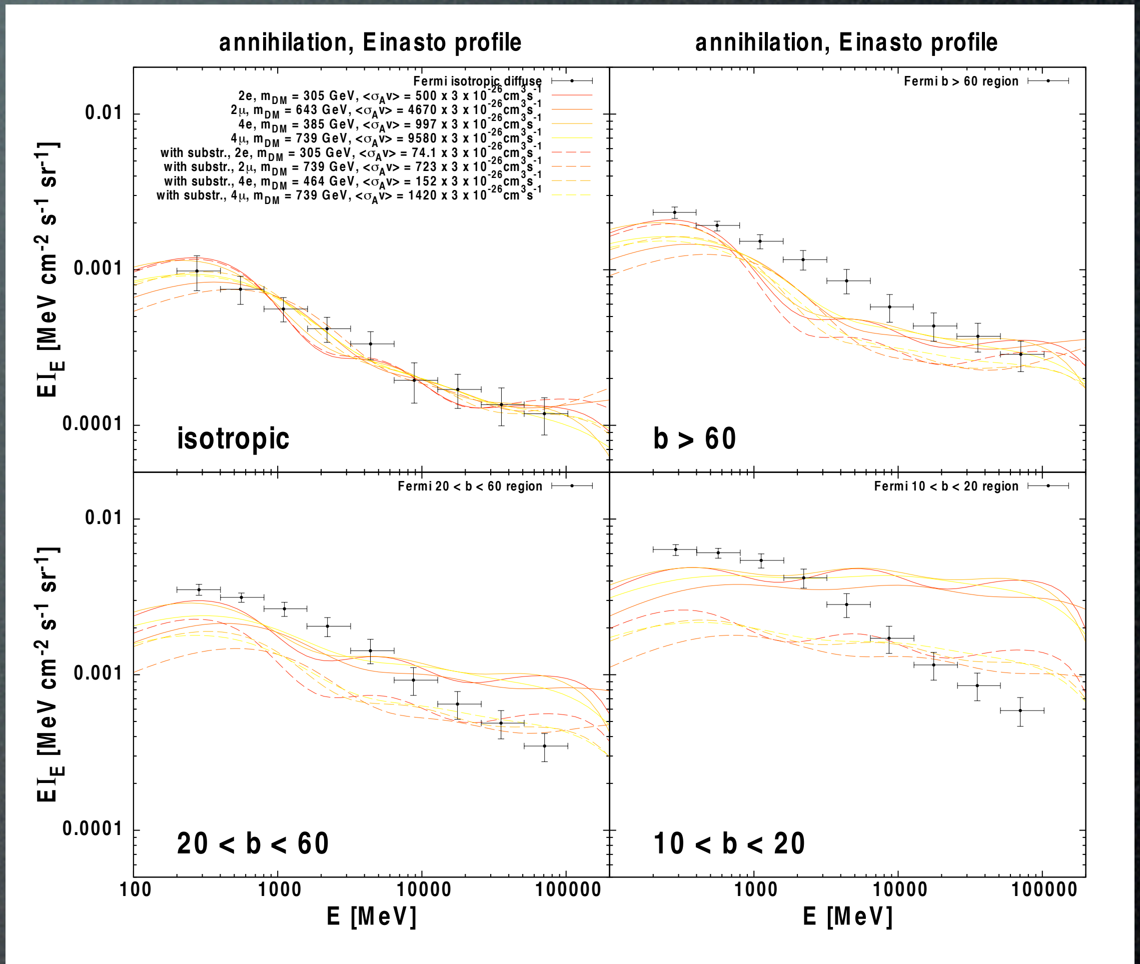
What if a signal of DM is *already* hidden in Fermi diffuse γ data?

Gamma hints?

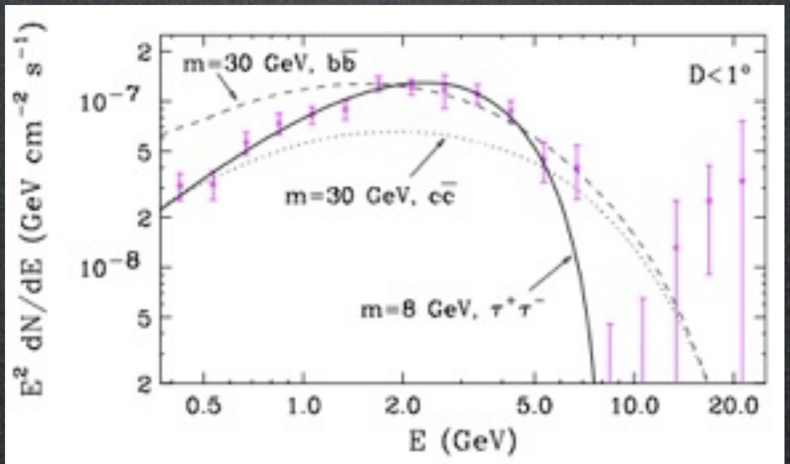
What if a signal of DM is *already* hidden in Fermi diffuse γ data?



Lin, Finkbeiner, Dobler 1004.0989



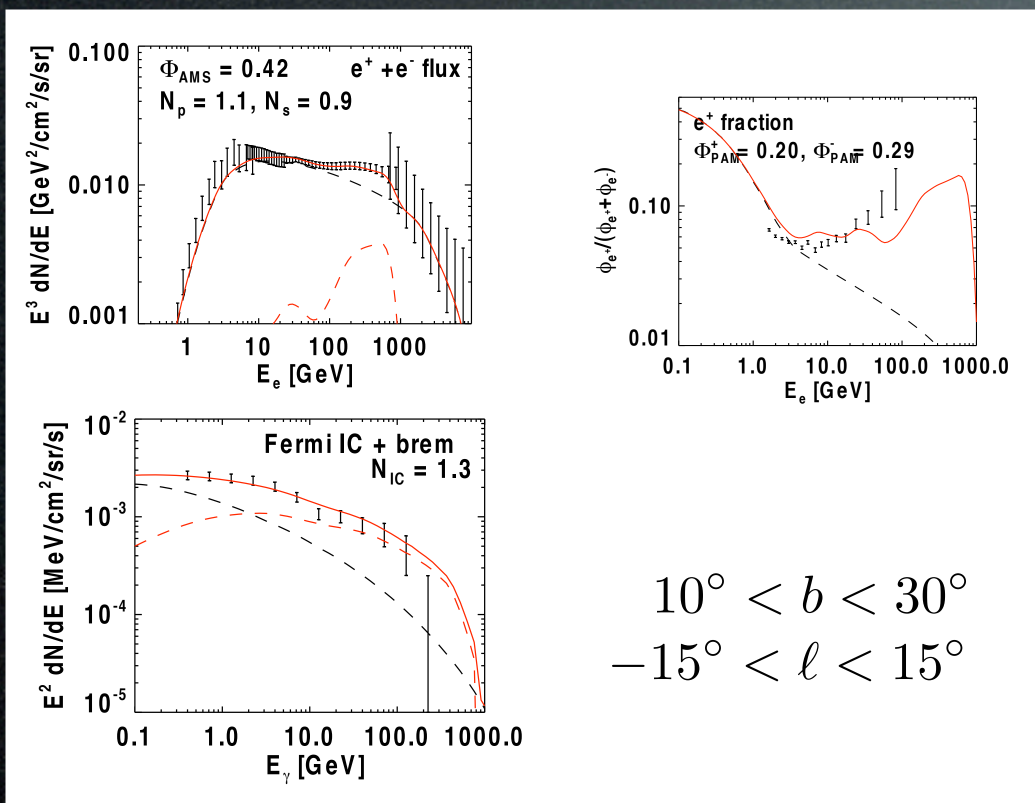
Hutsi, Hektor, Raidal 1004.2036



Hooper, Goodenough 1010.2752

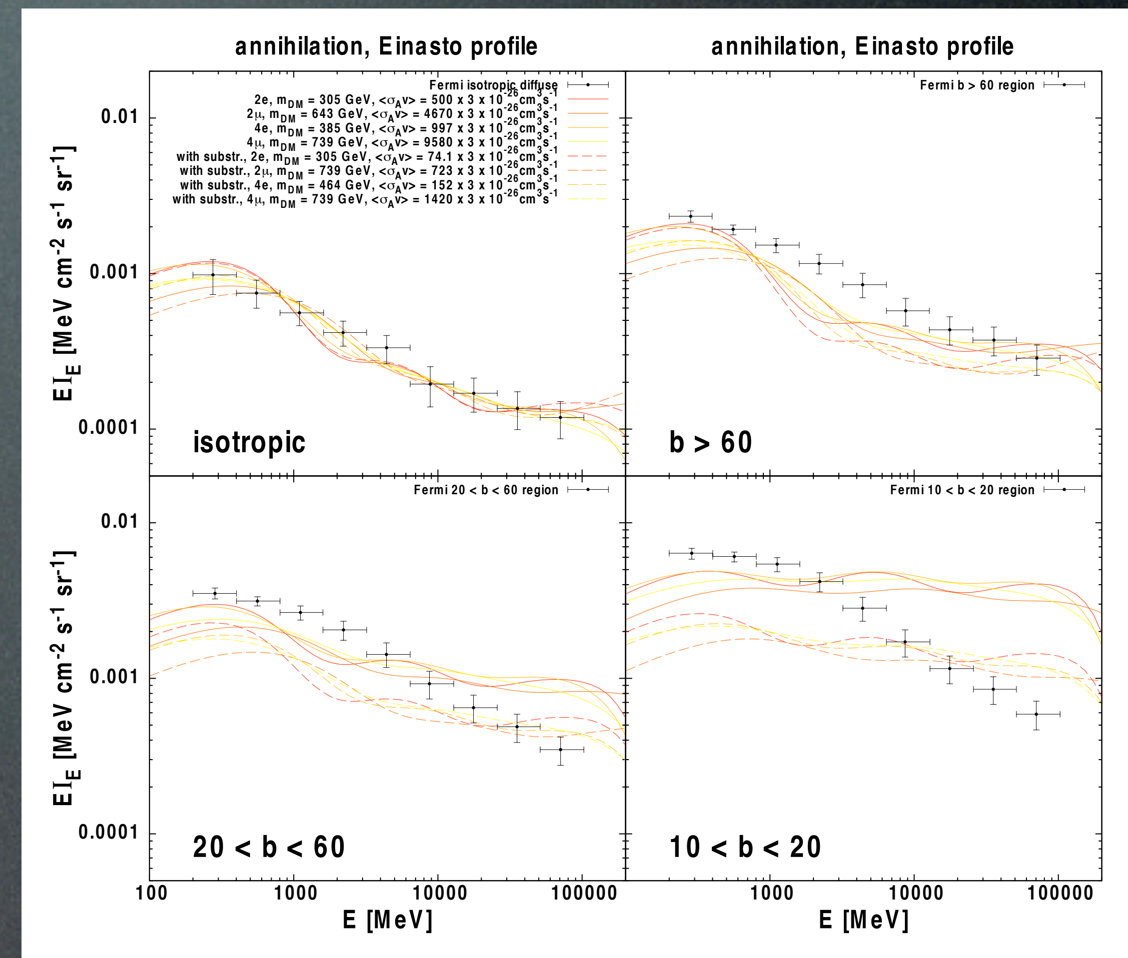
Gamma hints?

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

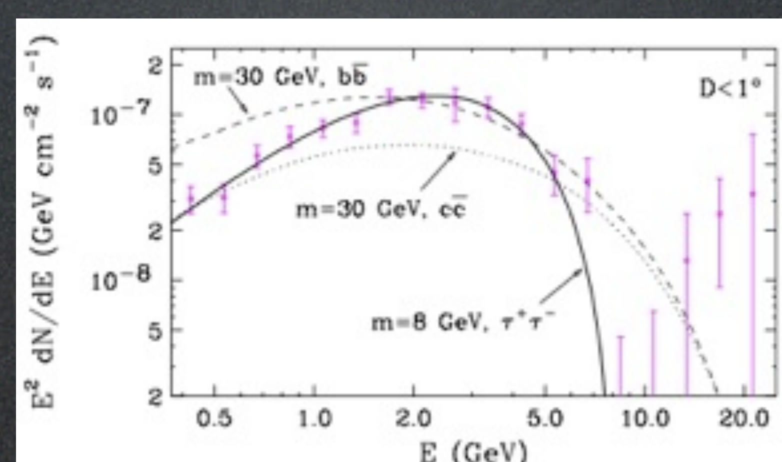


$10^\circ < b < 30^\circ$
$-15^\circ < \ell < 15^\circ$

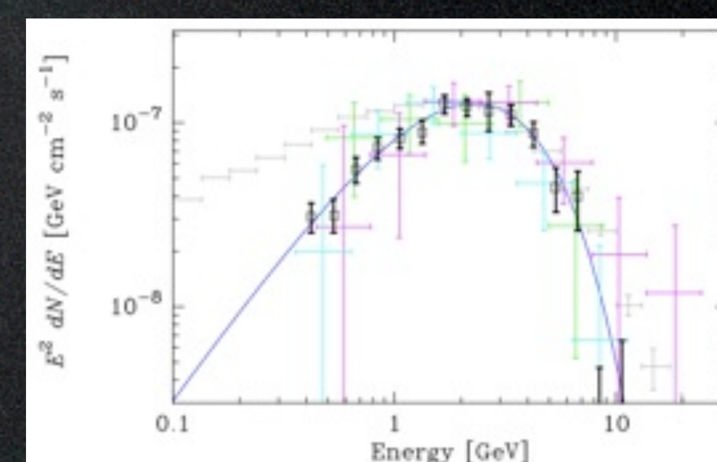
Lin, Finkbeiner, Dobler 1004.0989



Hutsi, Hektor, Raidal 1004.2036



Hooper, Goodenough 1010.2752

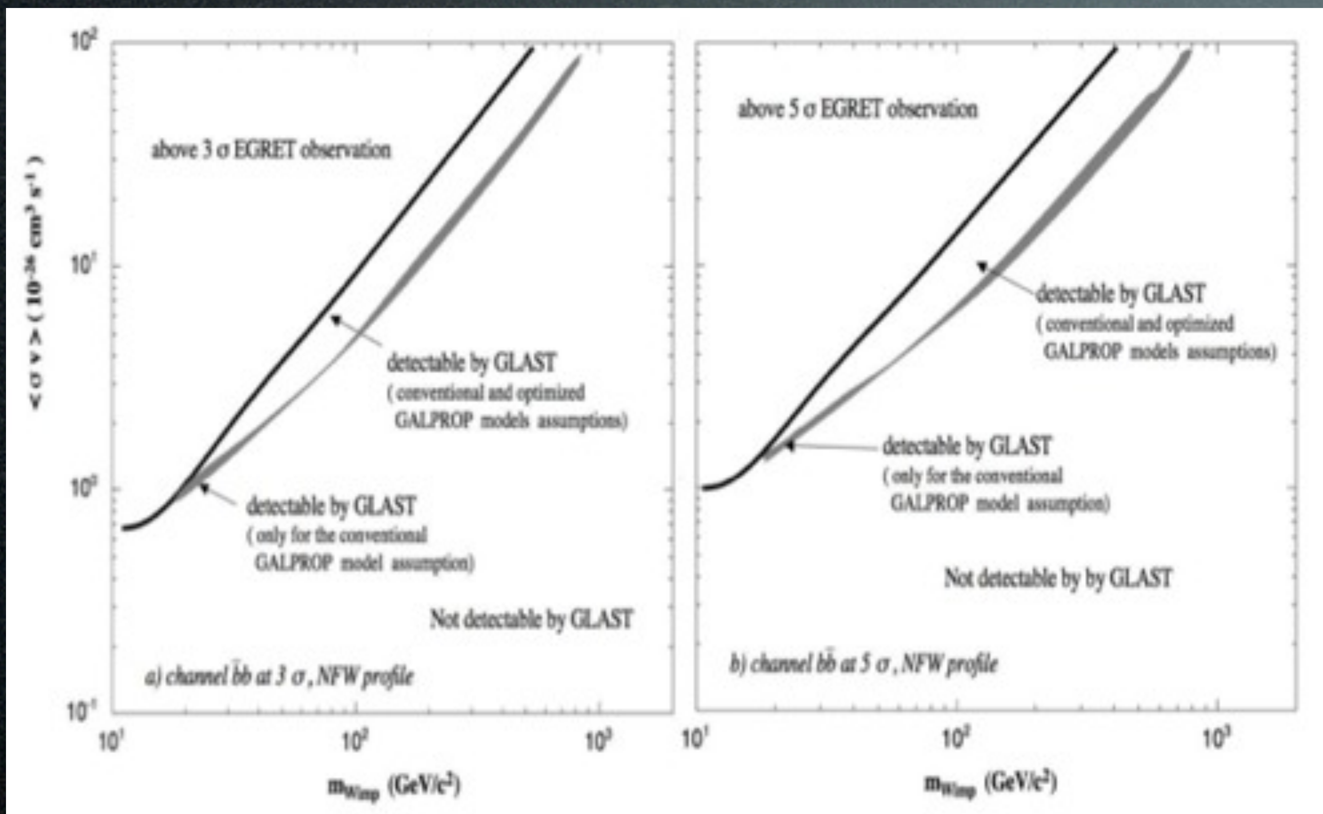


Abazajian 1011.4275

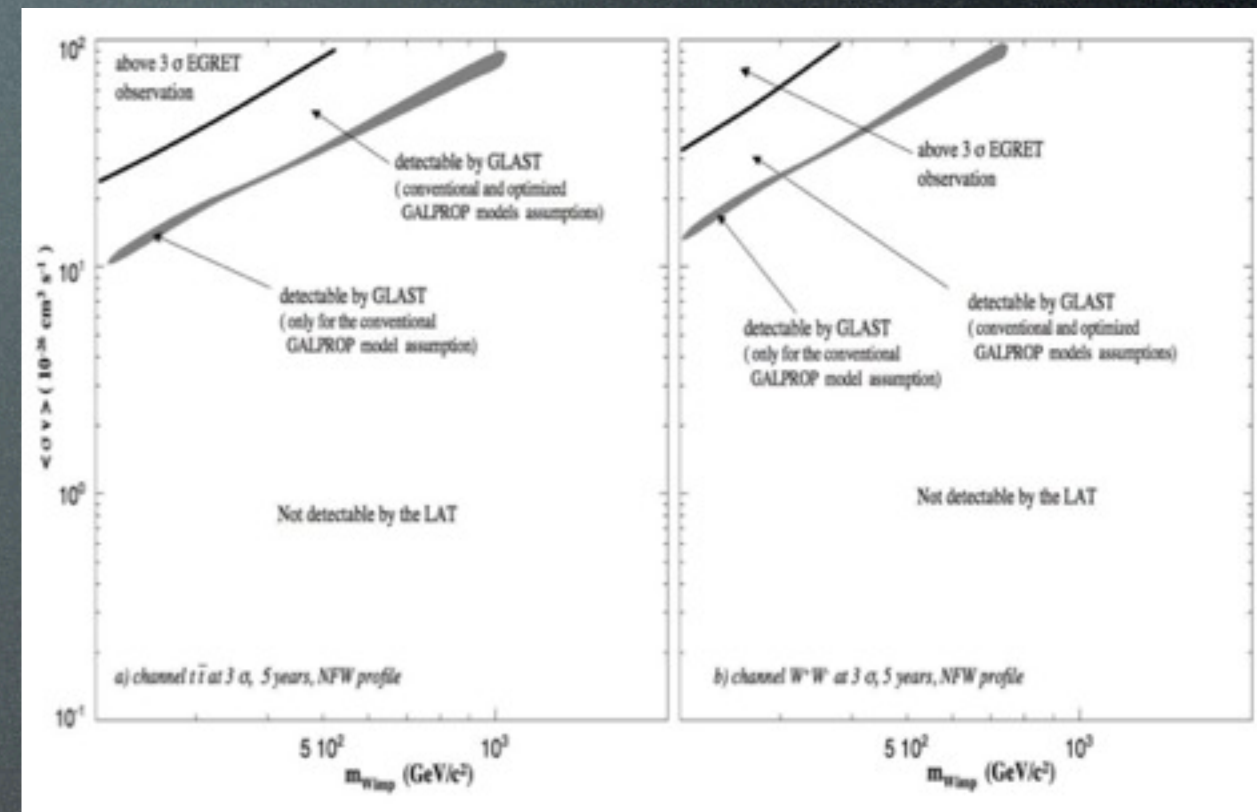
Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

Gamma reach

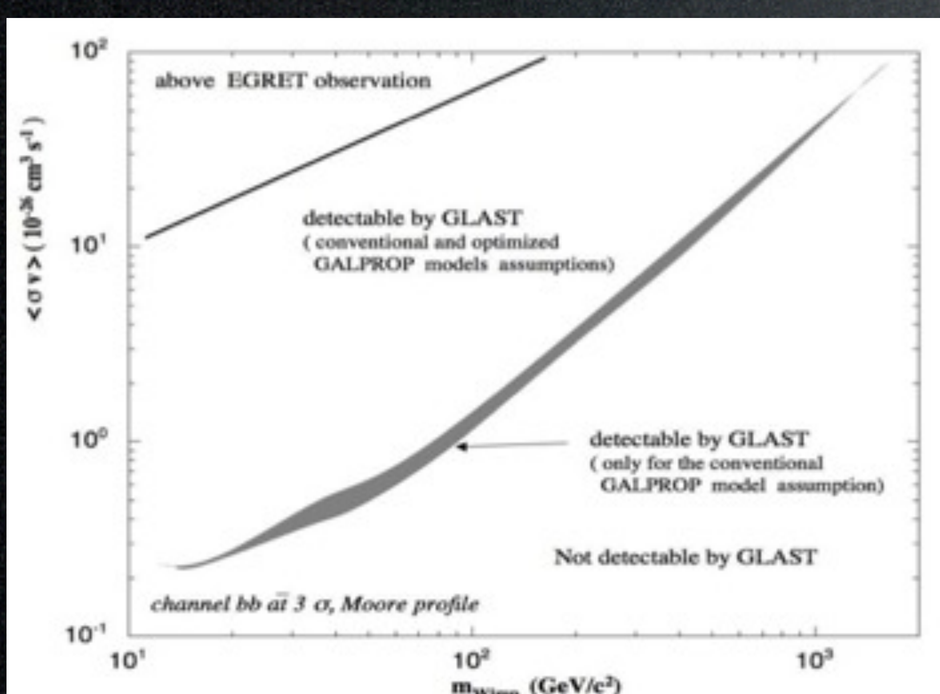
'Fermi pre-launch estimates', Baltz et al., 0806.2911



Diffuse galactic gamma (bb channel)



(tt, WW channel)



Dwarf Satellites

With a bit of luck,
Fermi will see signals.

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

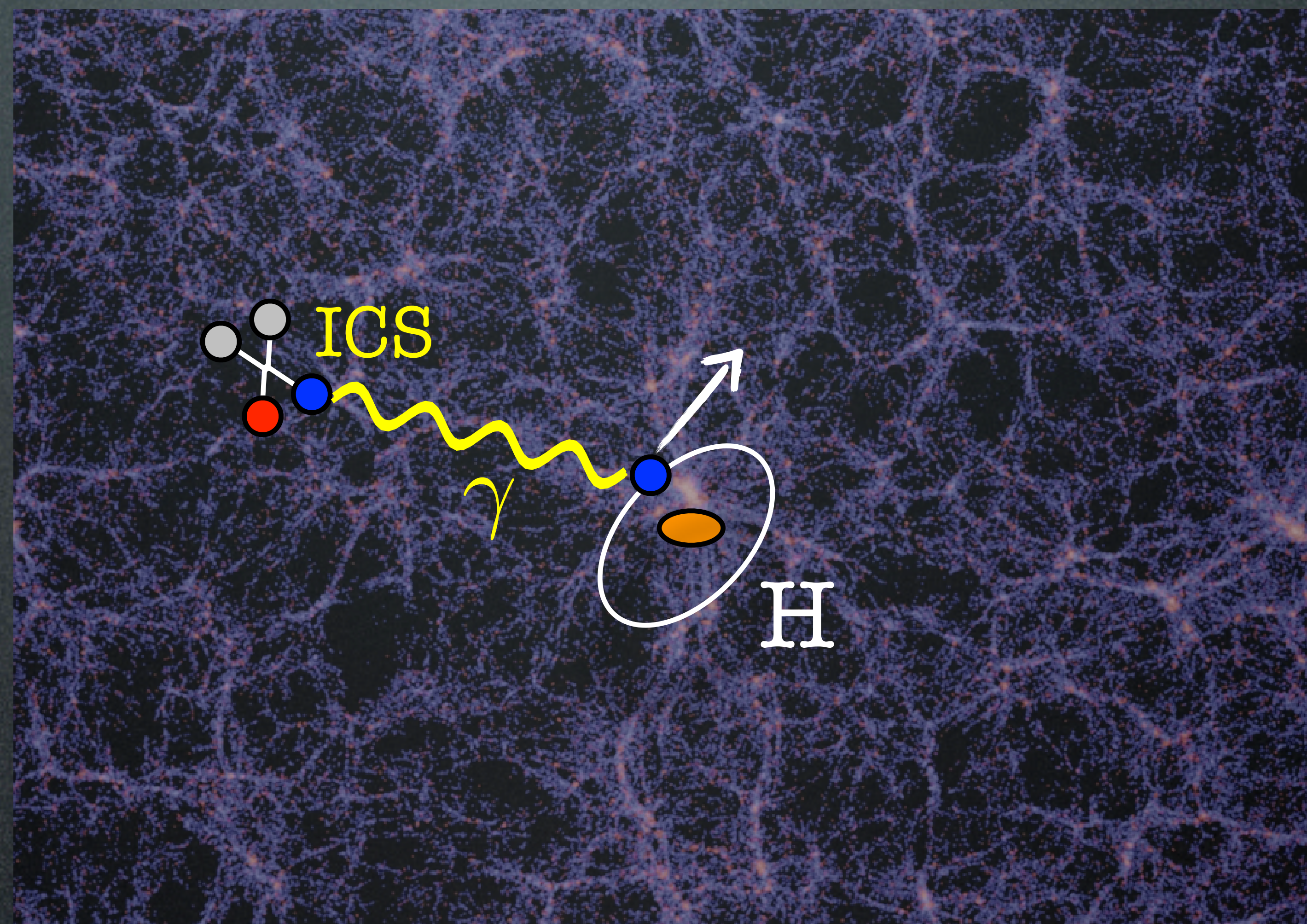
$\bar{D}$ from annihil in galactic halo or center

$\nu, \bar{\nu}$ from annihil in galactic center

bonus track: cosmology

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



$$-n_{\rm A} H_0 \sqrt{\Omega_{\rm M}} (1+z)^{11/2} \frac{dx_{\rm ion}(z)}{dz} = I(z) - R(z).$$

$$I(z) = \int_{e_{\rm i}}^{m_\chi} dE_\gamma \, \frac{dn}{dE_\gamma}(z) \cdot P(E_\gamma, z) \cdot N_{\rm ion}(E_\gamma)$$

$$P(E_\gamma, z) = n_{\rm A}(1+z)^3 \left[1 - x_{\rm ion}(z)\right] \cdot \sigma_{\rm tot}(E_\gamma),$$

$$N_{\rm ion}(E_\gamma) = \eta_{\rm ion}(x_{\rm ion}(z)) \; E_\gamma \left[\frac{n_{\rm H}}{n_{\rm A}} \frac{1}{e_{\rm i,H}} + \frac{n_{\rm He}}{n_{\rm A}} \frac{1}{e_{\rm i,He}}\right] = \eta_{\rm ion}(x_{\rm ion}(z)) \; \frac{E_\gamma}{\rm GeV} \, \mu$$

$$\frac{dn}{dE_\gamma}(z) = \int_\infty^z dz' \, \frac{dt}{dz'} \, \frac{dN}{dE'_\gamma}(z') \, \frac{(1+z)^3}{(1+z')^3} \cdot A(z') \cdot \exp\left[\Upsilon(z, z', E'_\gamma)\right].$$

$$\Upsilon(z, z', E'_\gamma) \simeq -\int_{z'}^{z} dz'' \frac{dt}{dz''} n_{\rm A} (1+z'')^3 \sigma_{\rm tot}(E''_\gamma)$$

$$\frac{dT_{\rm igm}(z)}{dz} = \frac{2\, T_{\rm igm}(z)}{1+z} - \frac{1}{H_0 \sqrt{\Omega_{\rm M}}\,(1+z)^{5/2}} \left(\frac{x_{\rm ion}(z)}{1 + x_{\rm ion}(z) + 0.073} \frac{T_{\rm CMB}(z) - T_{\rm igm}(z)}{t_{\rm c}(z)} + \frac{2\, \eta_{\rm heat}(x_{\rm ion}(z))\, \mathcal{E}(z)}{3\, n_{\rm A}(1+z)^3}\right).$$

$$A(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \rho_{\rm DM,0}^2 (1+z)^6 \left(1 + \mathcal{B}_i(z)\right),$$

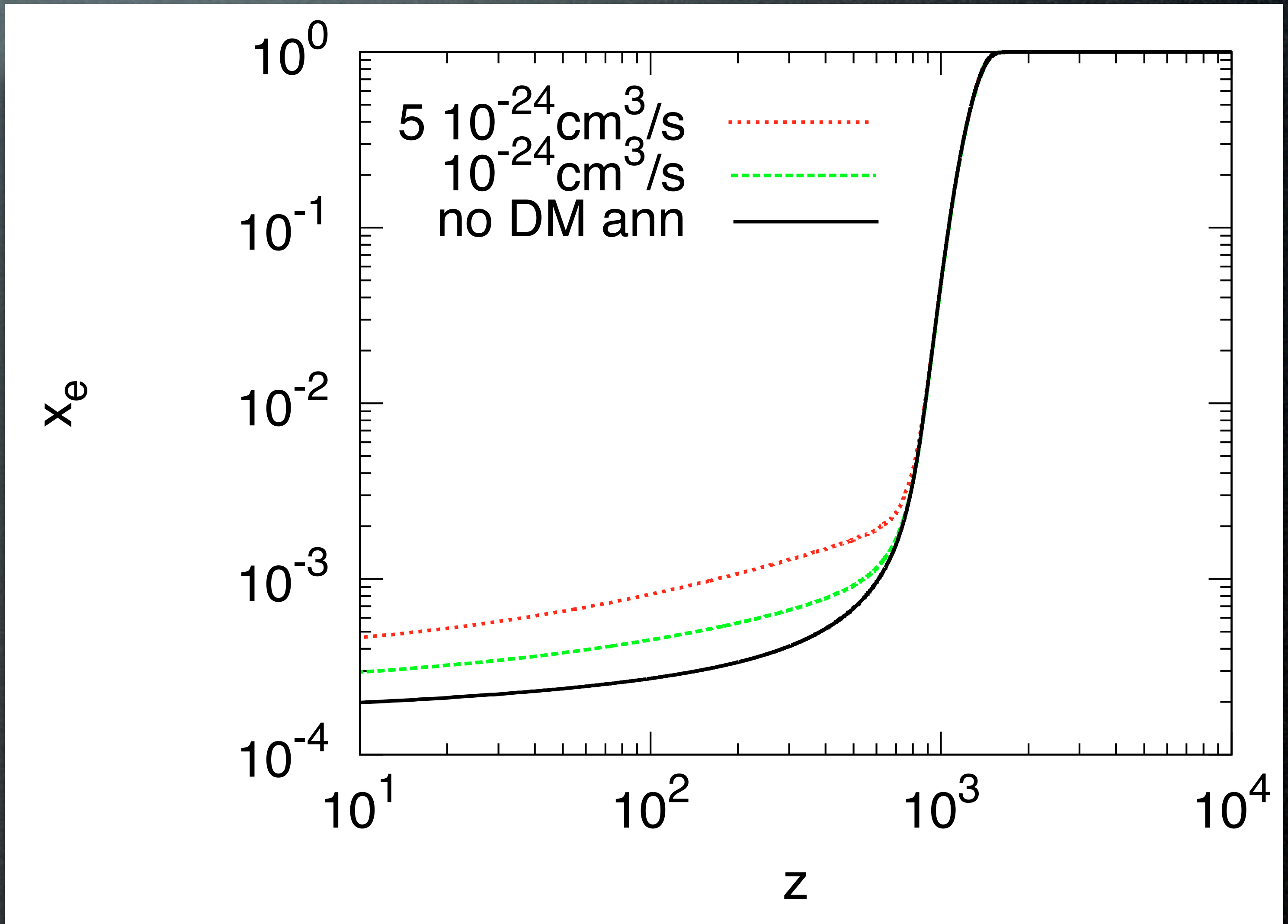
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\, \rho_{\rm c} \Omega_{\rm M}} \int_{M_{\rm min}}^{\infty} dM \, M \frac{dn}{dM}(z, M)\, F_i(M, z),$$

$$\frac{dn}{dM}(M, z) = \sqrt{\frac{\pi}{2}} \frac{\rho_{\rm M}}{M} \, \delta_{\rm c} \, (1+z) \frac{d\sigma(R)}{dM} \frac{1}{\sigma^2(R)} \exp\left(-\frac{\delta_{\rm c}^2 \, (1+z)^2}{2\sigma^2(R)}\right)$$

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

DM particles that fit PAMELA+FERMI+HESS produce free electrons

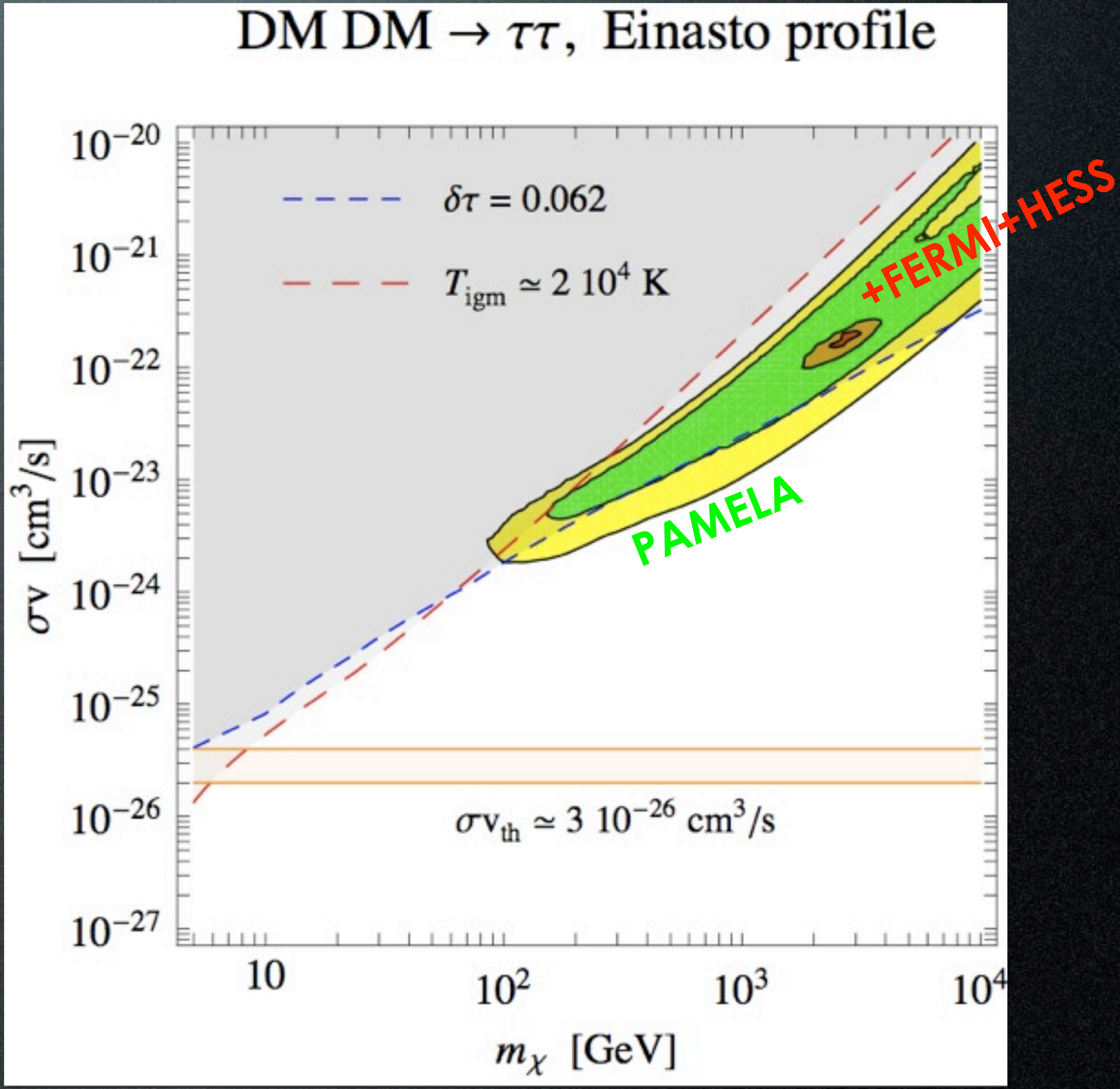


Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

DM particles that fit PAMELA+FERMI+HESS produce too many free electrons: bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)



see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985

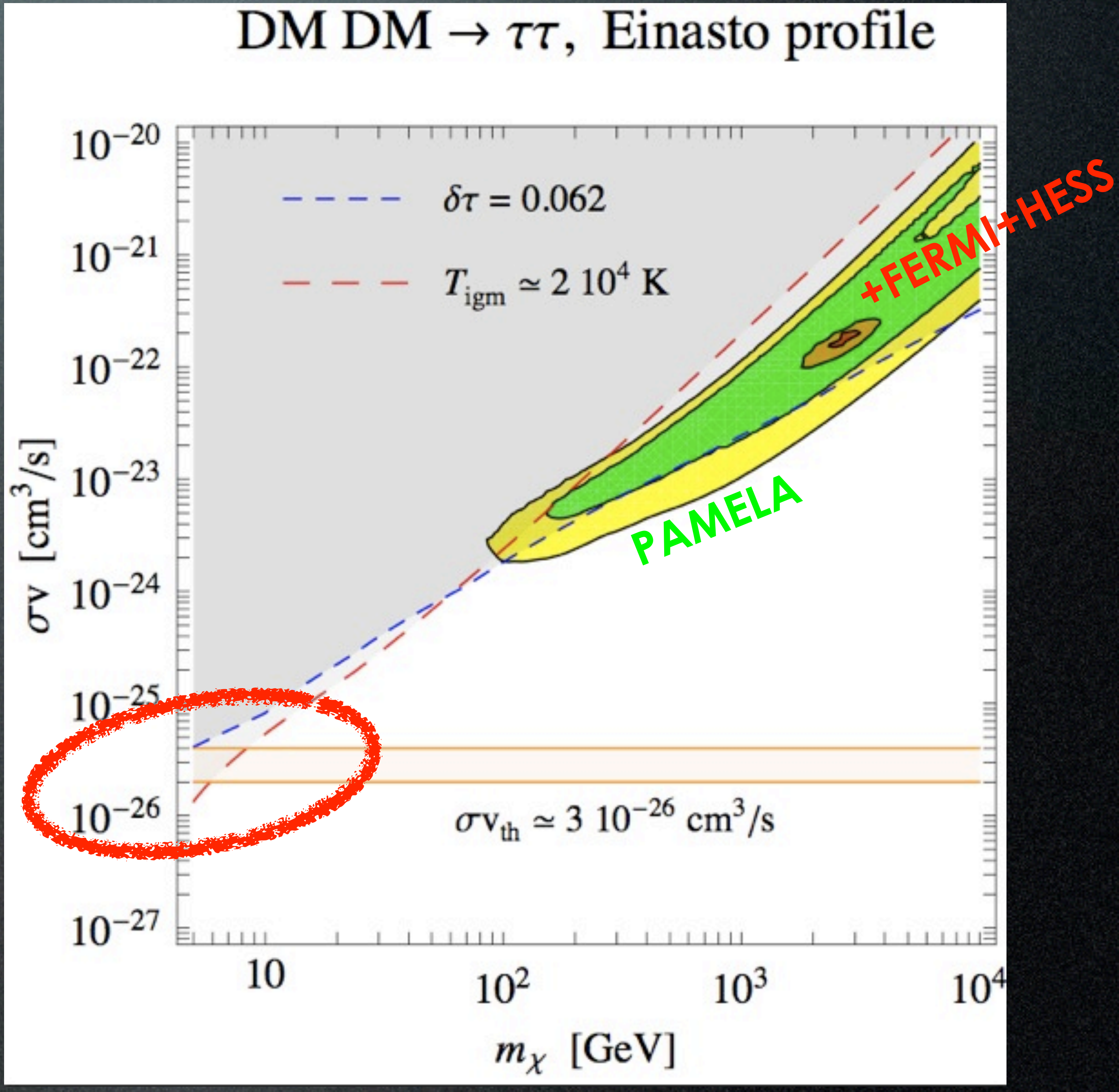
Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

DM particles that fit PAMELA+FERMI+HESS produce too many free electrons: bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)

Starts constraining even thermal DM!



Cirelli, Iocco, Panci, JCAP 0910

OUTLINE

direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

indirect

basics
hints
constraints
'theory'
tentative conclusion

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

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- 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?

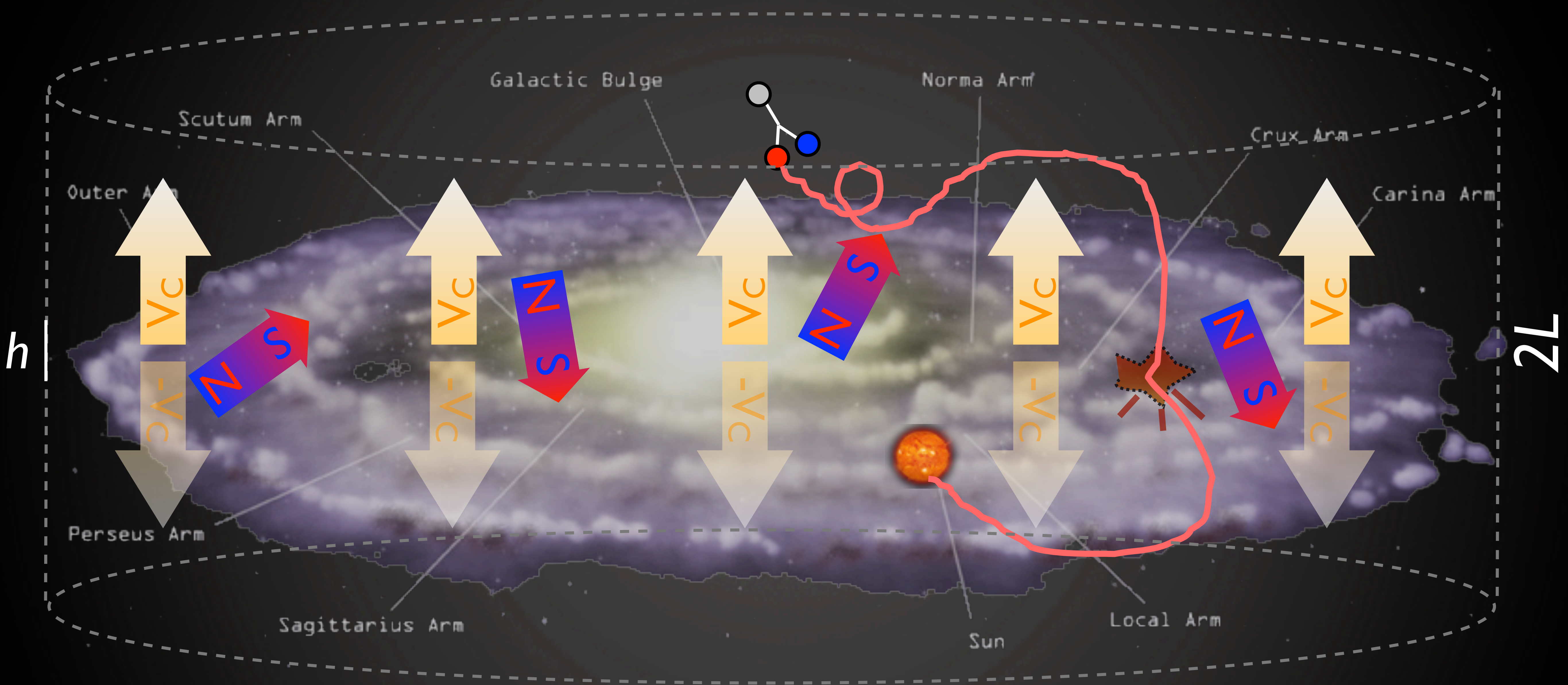
- dim 6 suppressed operator in GUT — Arvanitaki, Dimopoulos et al., 2008+09

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

- 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?

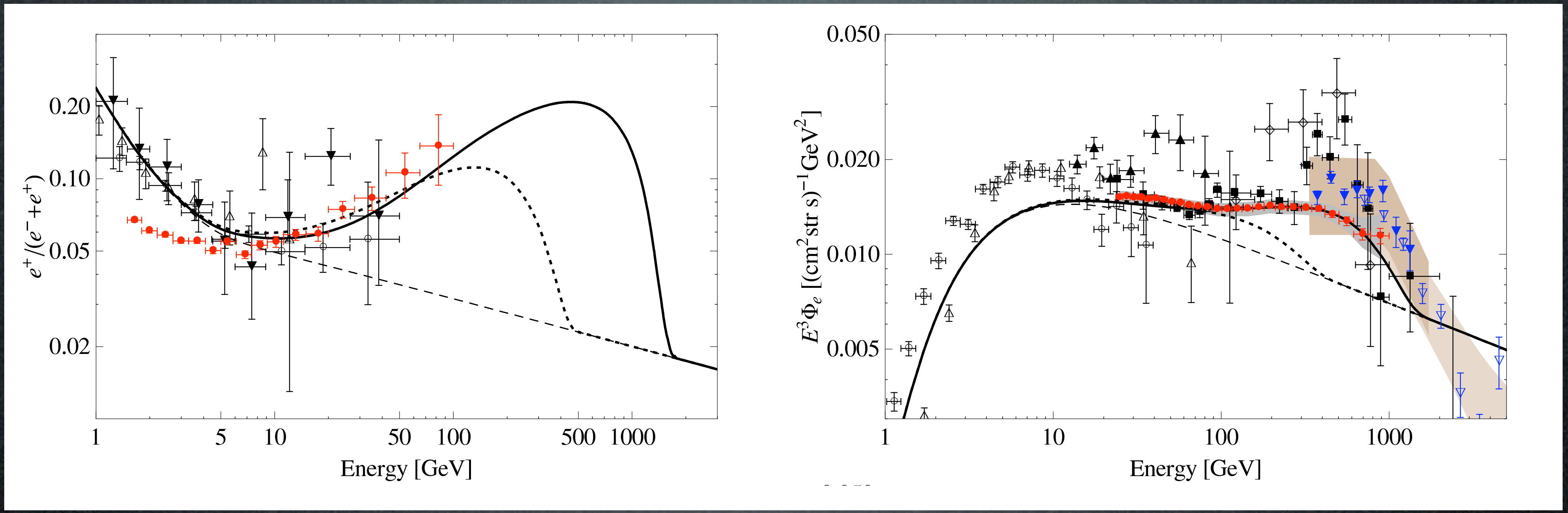
$$\text{flux} \propto n\, \Gamma_{\rm decay}$$

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

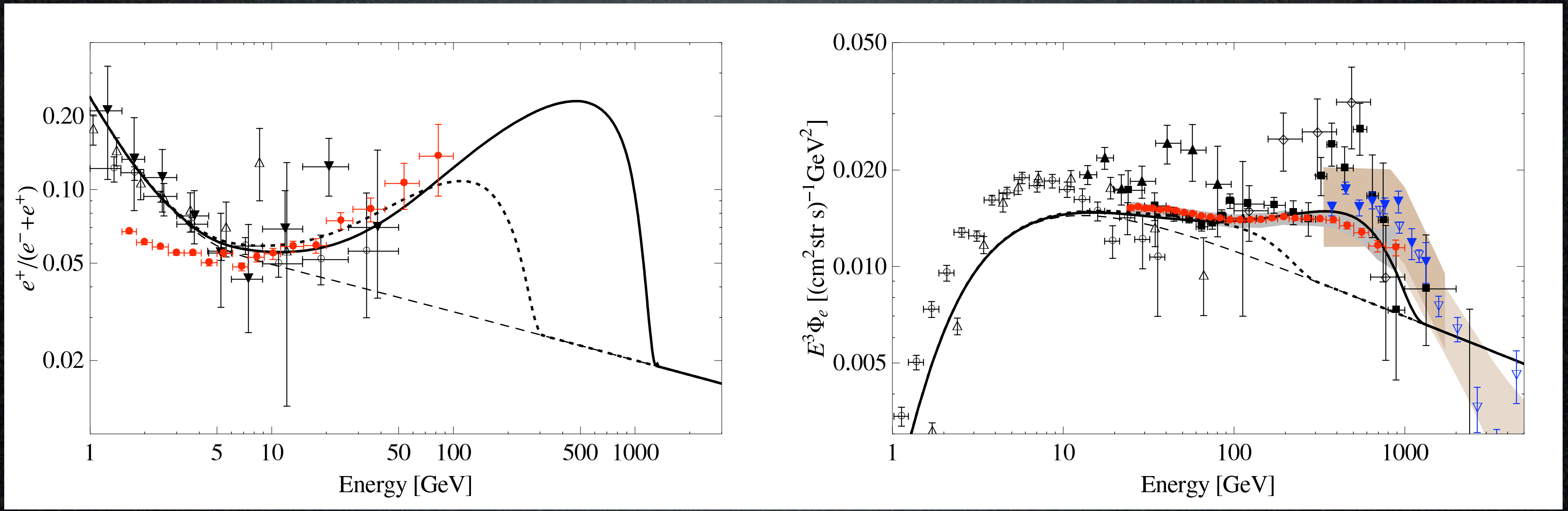
Decaying DM

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 $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

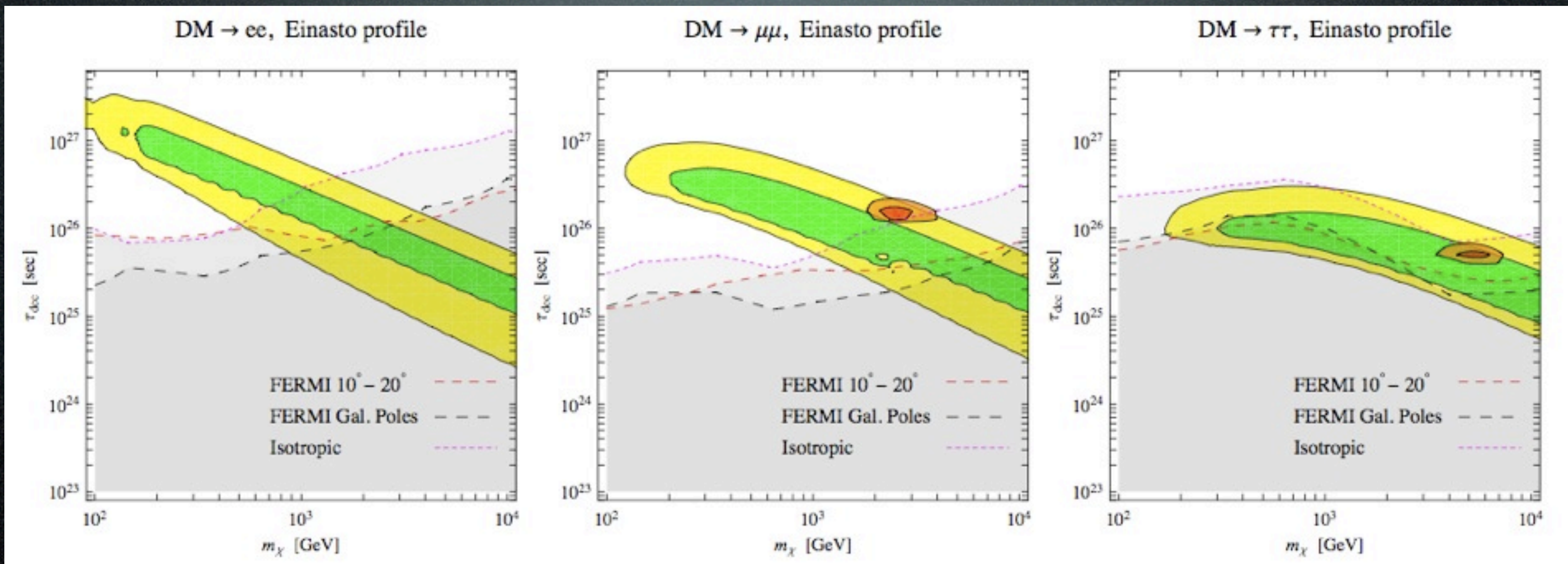


Ibarra, Tran, Weniger 2009

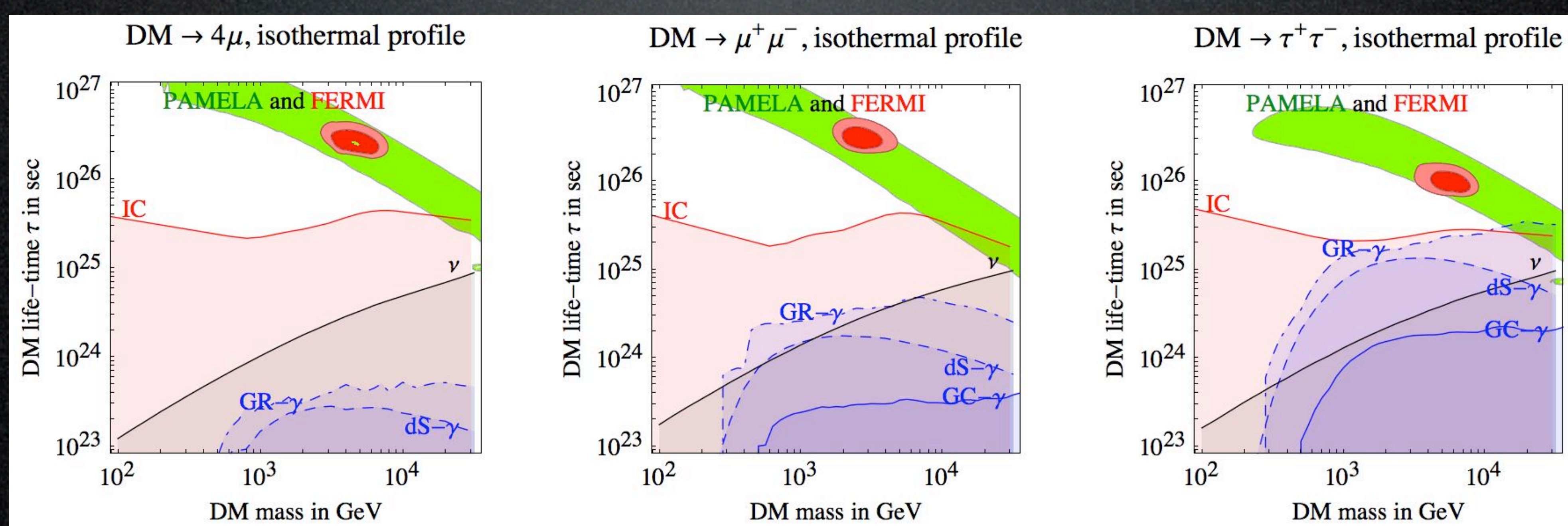
Decaying DM

Beware of gamma ray constraints

(but no radio, neutrino constraints)



Cirelli, Panci, Serpico 0912. 0663



Strumia, Papucci et al. 0905.0480

Model building

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

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

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

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  - TeV mass DM
  - new forces (that Sommerfeld enhance)
  - leptophilic because: - kinematics (light mediator)
    - DM carries lepton #

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The "Theory of DM"

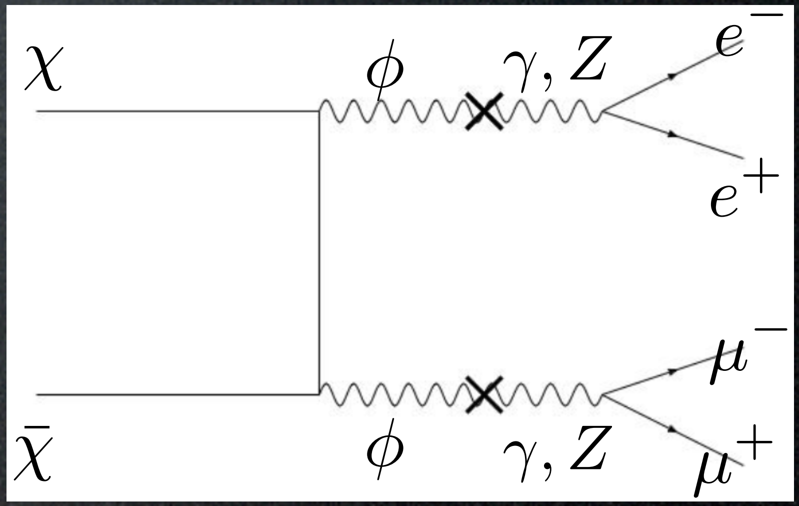
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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



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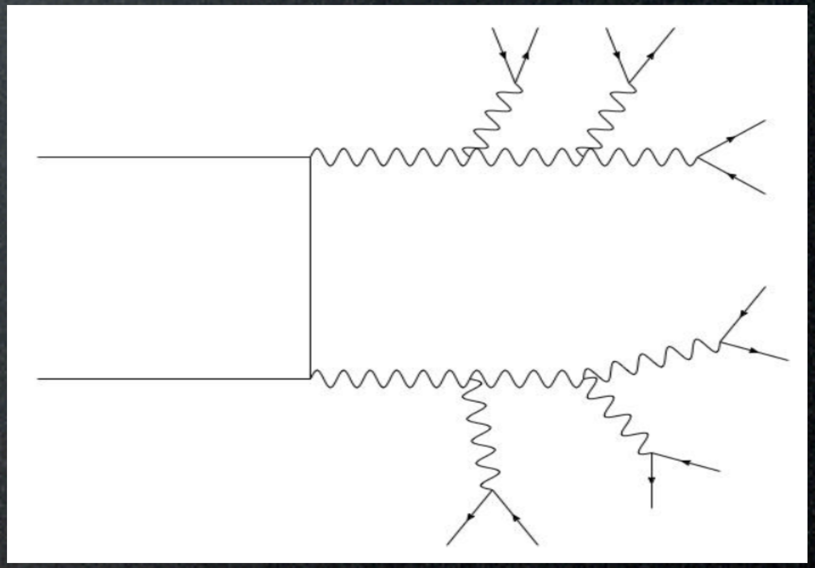
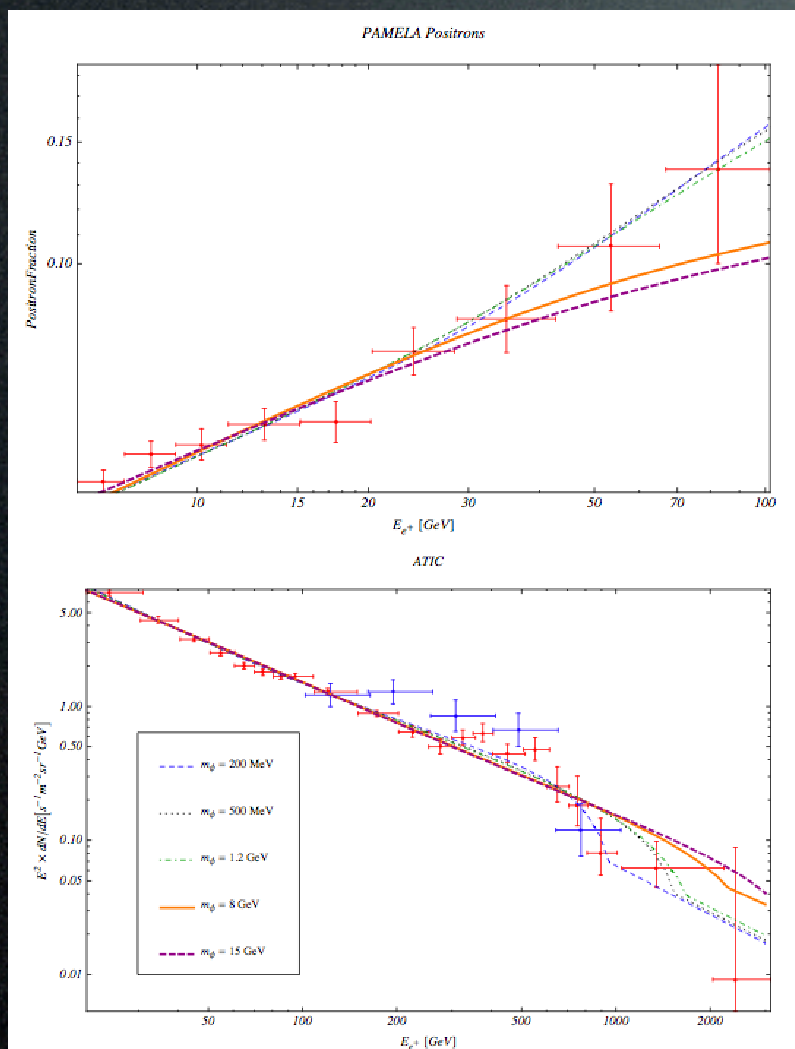


Extras:

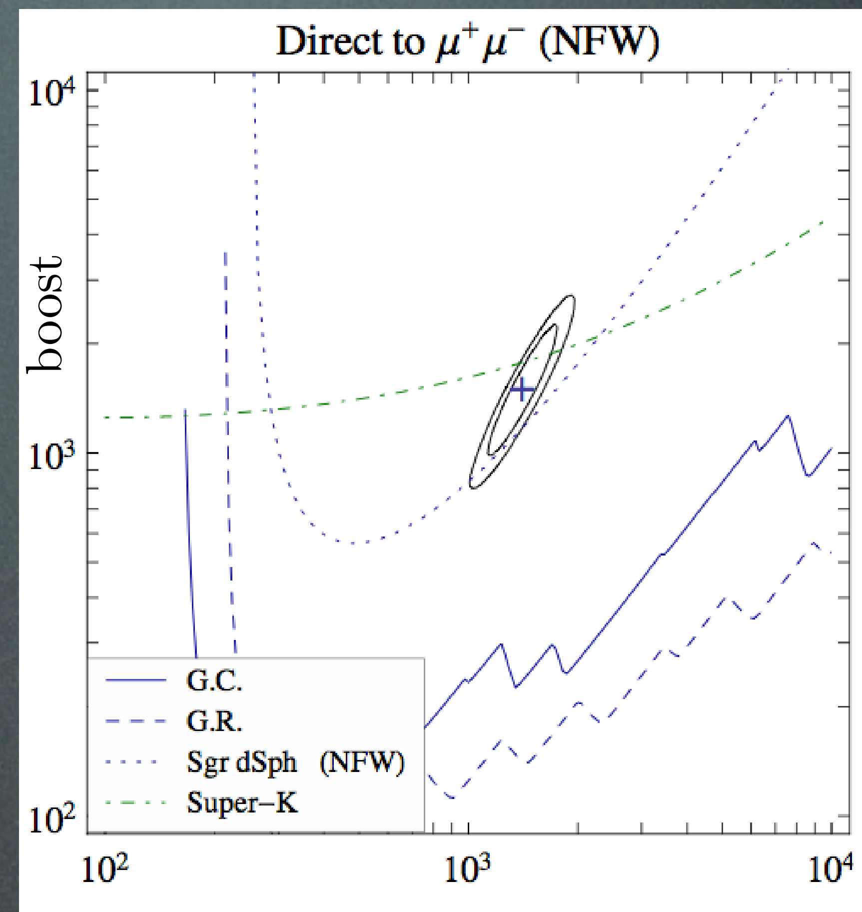
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200\ \mathrm{KeV}$ (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

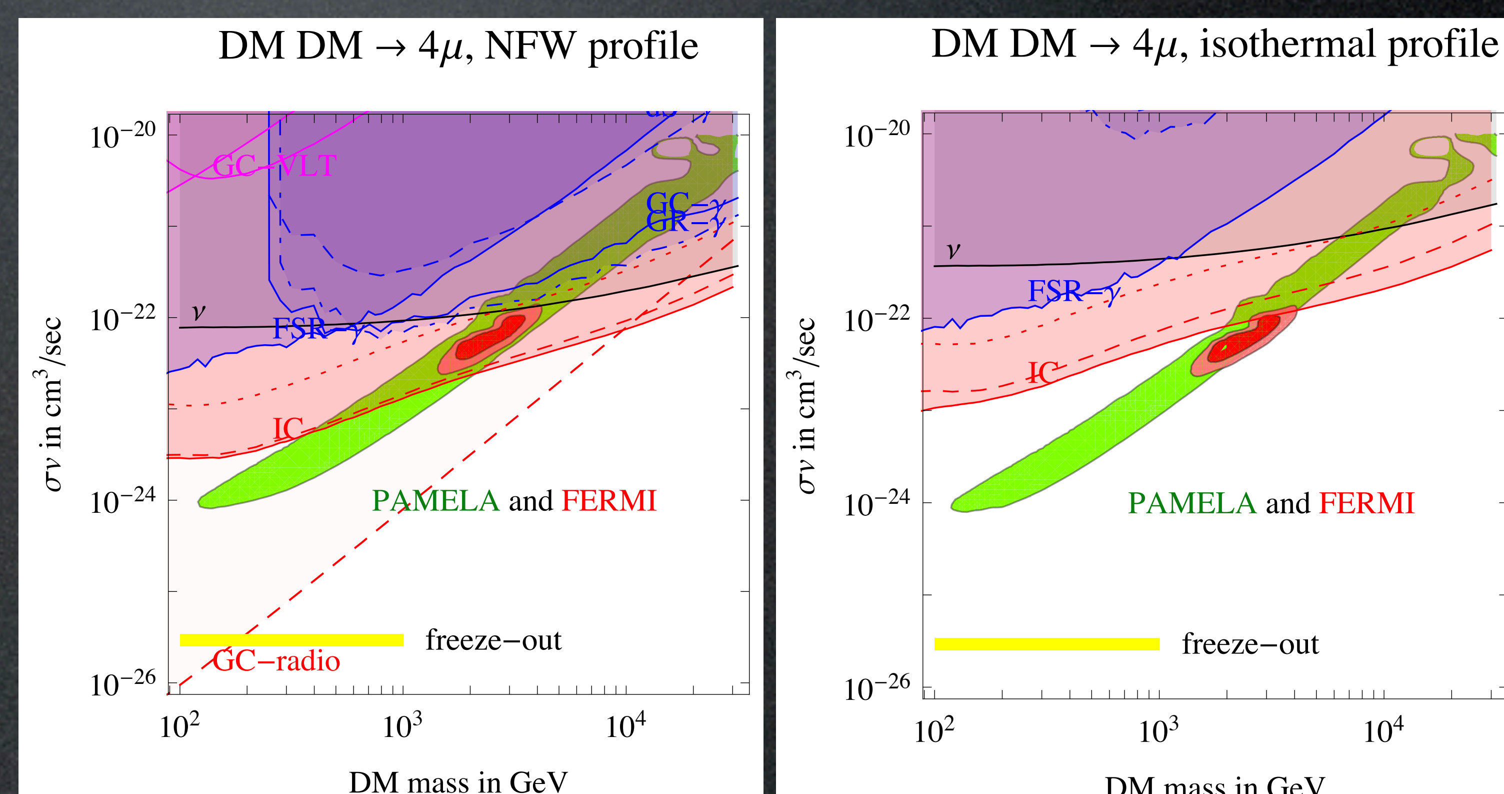
Phenomenology:



Meade, Papucci, Volanski 0901.2925



Mardon, Nomura, Stolarski, Thaler 0901.2926



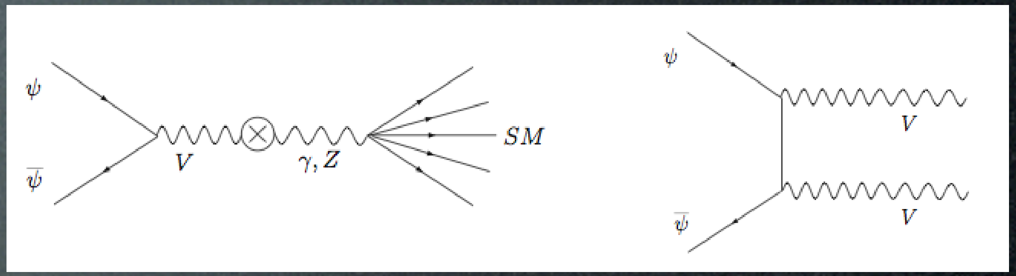
Strumia, Papucci 0912.0742

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

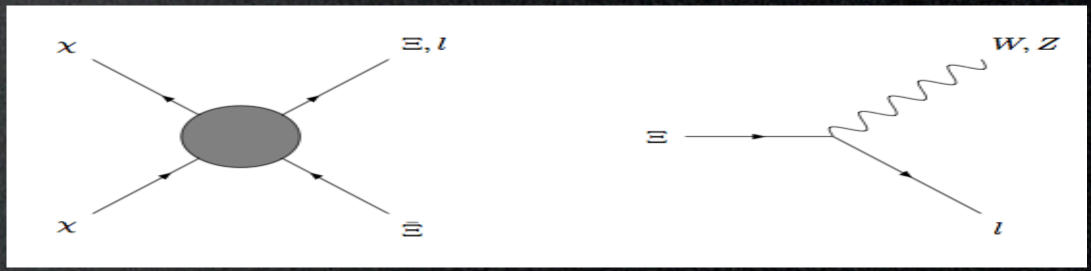
  Park, Shu 0901.0720

- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399 $(m_\phi \sim \text{tens GeV})$

- 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



- ......

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You need a quick **reference** for formulæ and methods
to compute indirect detection signals?

You want to compute all **signatures** of your DM model in
positrons, electrons, neutrinos, gamma rays...
but you don't want to mess around with astrophysics?

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'The Poor Particle Physicist Cookbook
for Dark Matter Indirect Direction'

PPPC 4 DM ID

We provide ingredients and recipes for computing signals of TeV-scale
Dark Matter annihilations and decays in the Galaxy and beyond.

Cirelli, Corcella, Hektor,
Hütsi, Kadastik, Panci,
Raidal, Sala, Strumia

1012.4515 [hep-ph]

www.marcocirelli.net/PPPC4DMID.html

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You want to compute all **signatures** of your DM model in positrons, electrons, neutrinos, gamma rays...
but you don't want to mess around with astrophysics?

Propagation functions for electrons and positrons everywhere in the Galaxy:

Energy loss coefficient function *b[E, r, z]* for electrons and positrons in the Galaxy: *Mathematica* function b.m, refer to the notebook Sample.nb for usage.

Annihilation

Positrons: The file ElectronHaloFunctGalaxyAnn.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy.
The notebook Sample.nb shows how to load and use it.

Decay

Positrons: The file ElectronHaloFunctGalaxyDec.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy
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Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation

Positrons: The file ElectronHaloFunctEarthAnn.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth.
The notebook Sample.nb shows how to load and use it.

Table of fit coefficients for the reduced halo function $I(\lambda)$ (in the approximated formalism - see paper).

Antiprotons: Table of fit coefficients for the propagation function R(T).

Antideuterons: Table of fit coefficients for the propagation function R(T).

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Fluxes of charged cosmic rays at the Earth, after propagation:

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Main added value features:

- ✓ compare different MCs
- ✓ include EW corrections (Ciafaloni, Riotto et al., 1009.0224)
- ✓ improved $e^{\pm}$ propagation
- ✓ improved ICS γ-ray computation

www.marcocirelli.net/PPPC4DMID.html

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direct detection

basics
hints
constraints
'theory'
tentative conclusion

production at colliders

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PAMELA & C. probably was <u>not DM</u>, but it has been fun

OUTLINE

direct detection

- basics
  - hints
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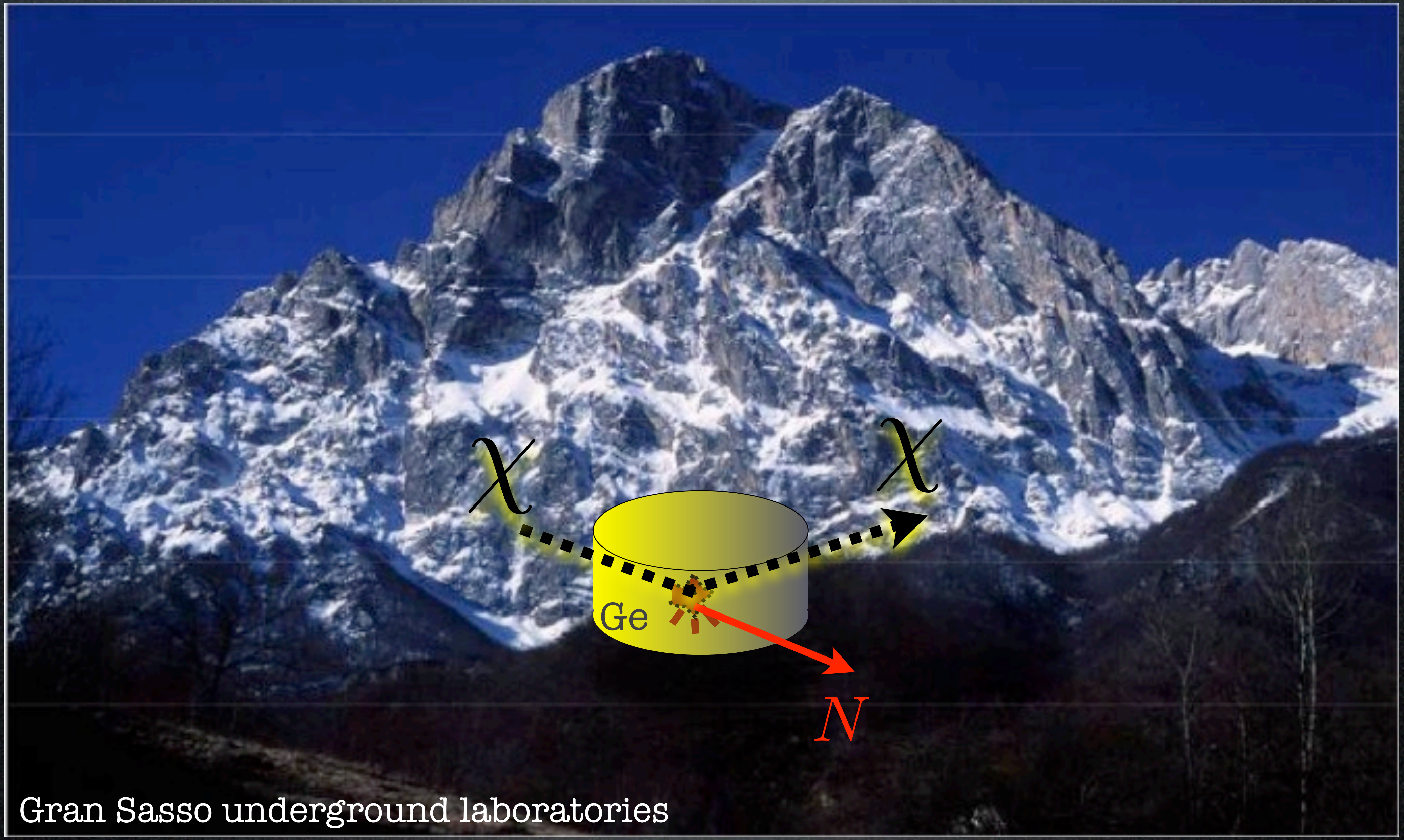
Direct Detection: **basics**

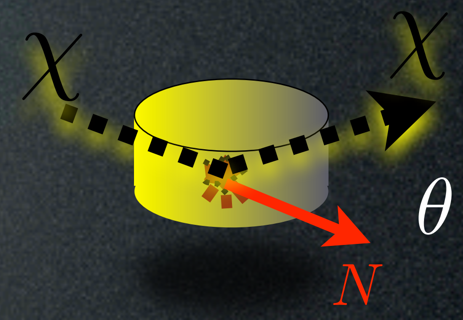
Direct Detection: basics

Direct Detection: basics



Direct Detection: basics

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



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recoil energy spectrum

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

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

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

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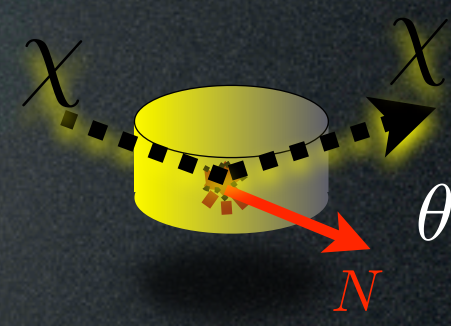

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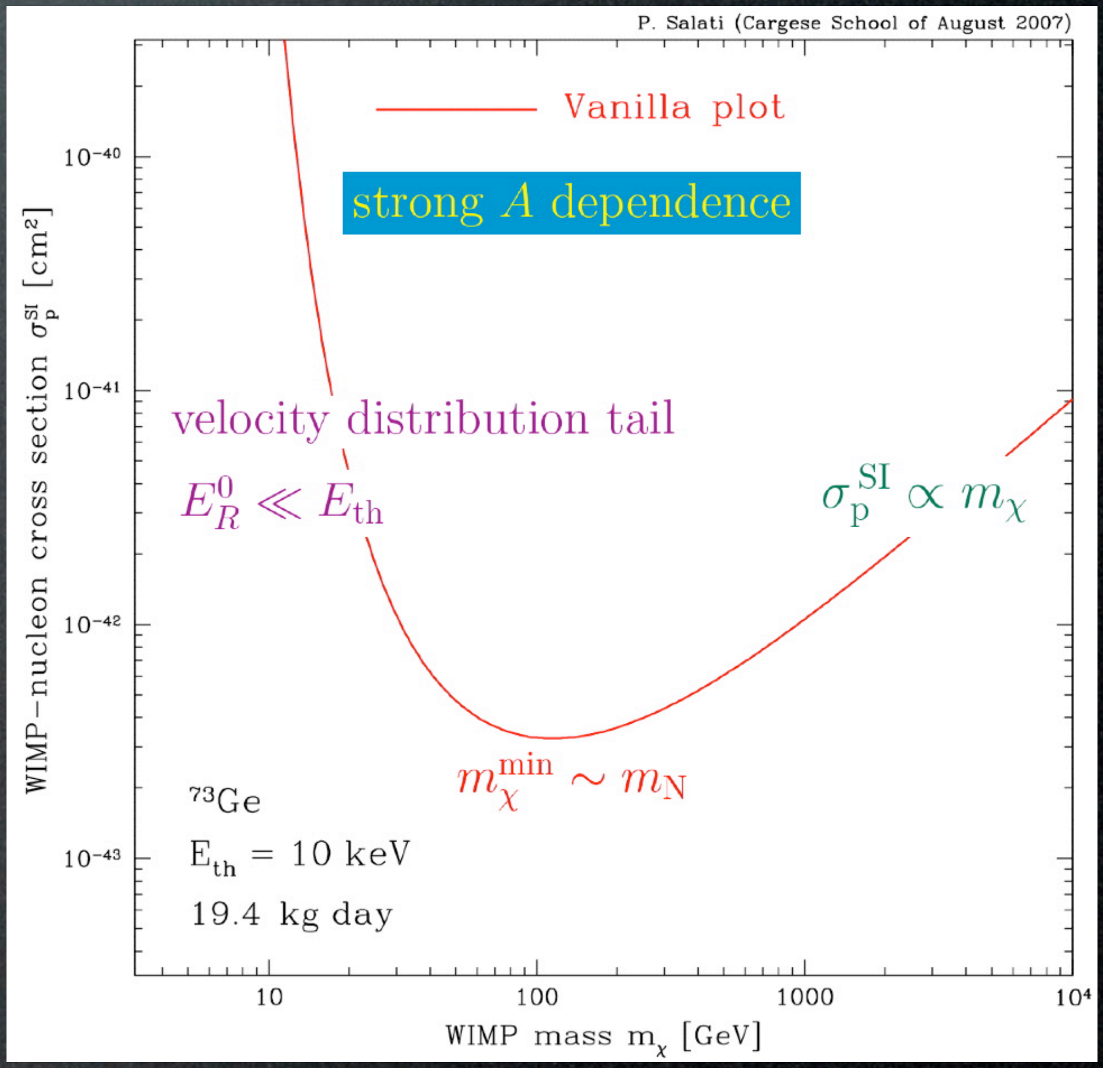

P.Salati, proceedings of Cargèse 2007

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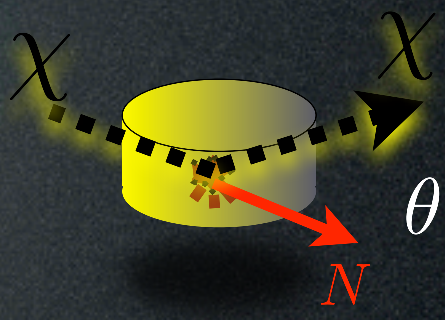

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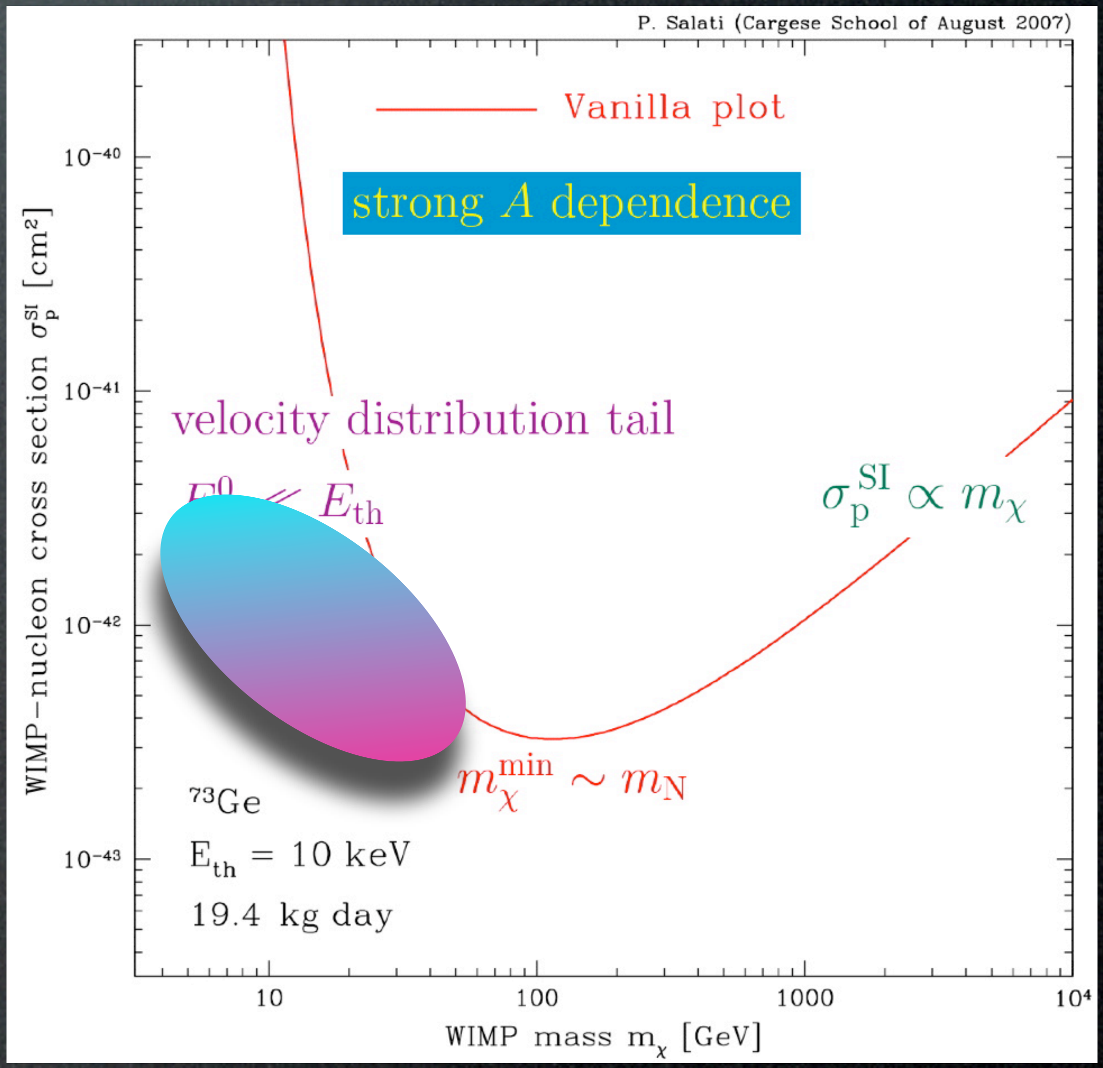
$\sigma \approx \sigma_n^{\rm SI} A^4$ × nuclear form factors

number of events

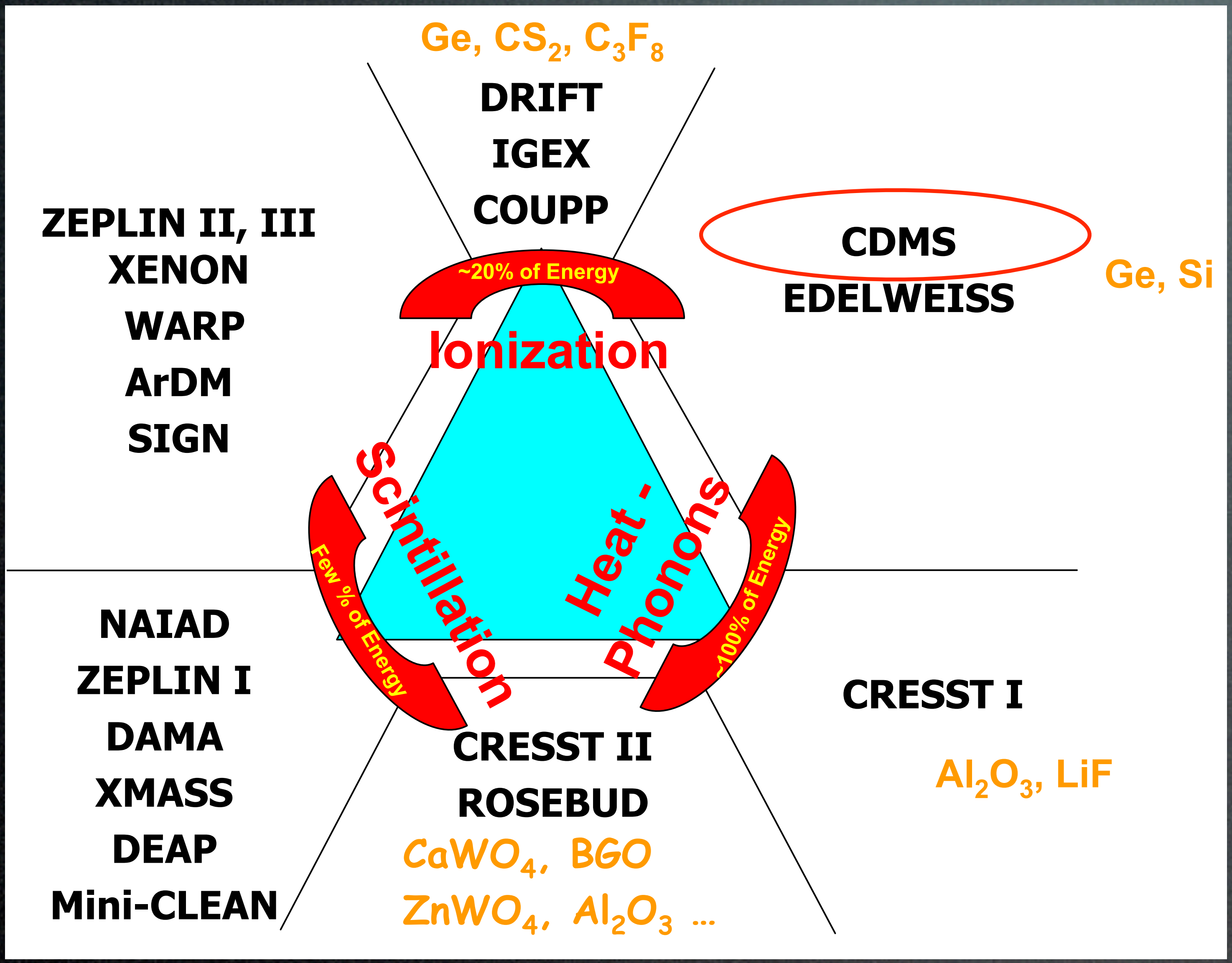
$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\max}} \frac{dR}{dE_R}\, dE_R$$



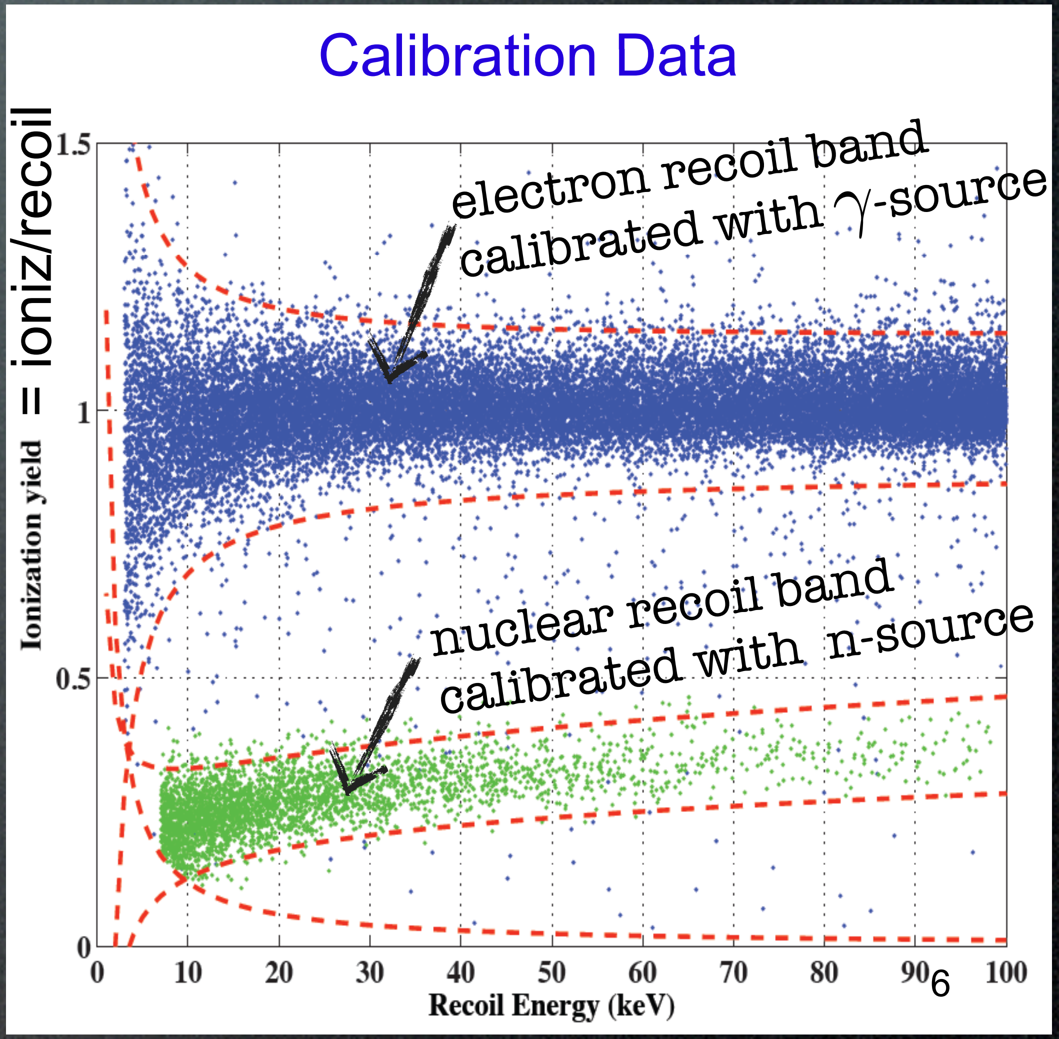
P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

Background rejection



[credit: B.Sadoulet]



CDMS coll.

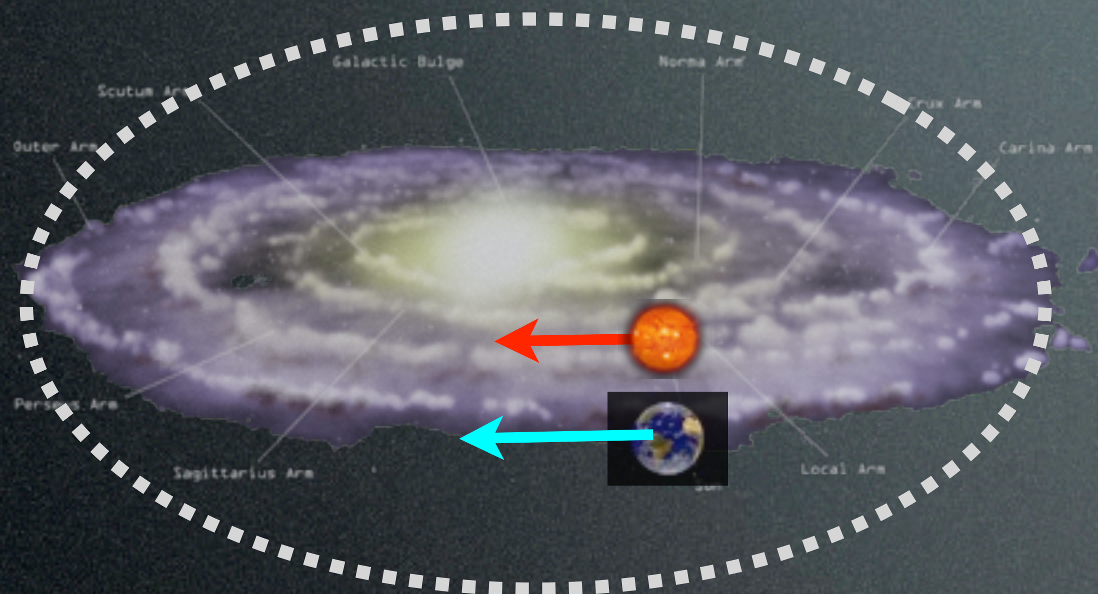
measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

6

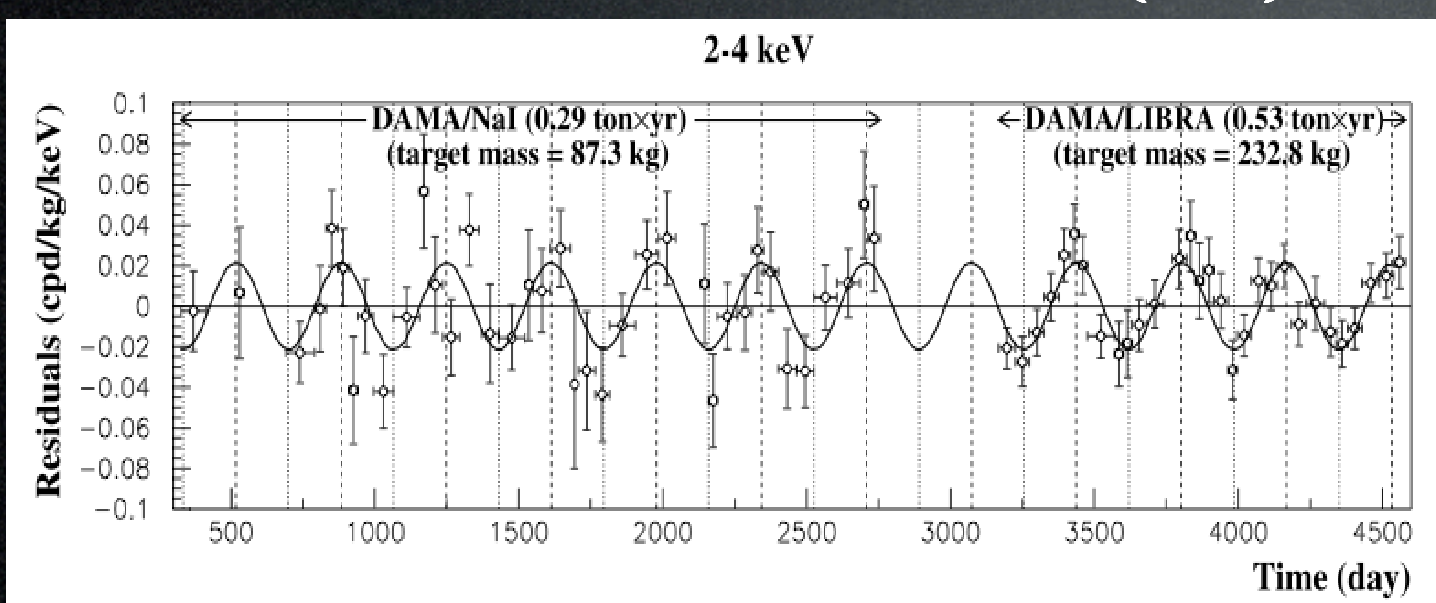
Direct Detection: hints

DAMA/Libra

NaI(Tl)



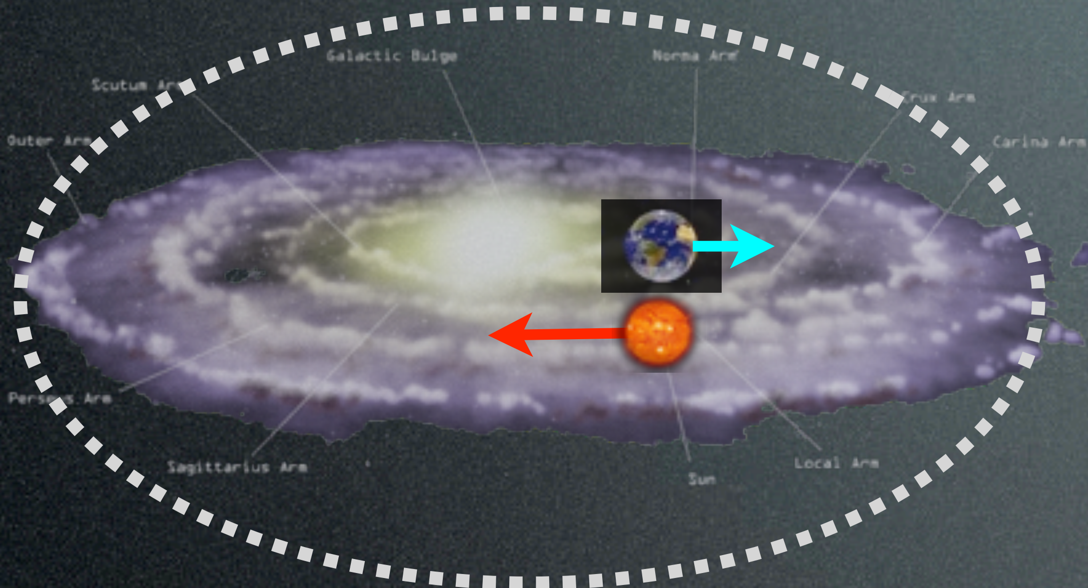
Annual modulation seen (8σ):



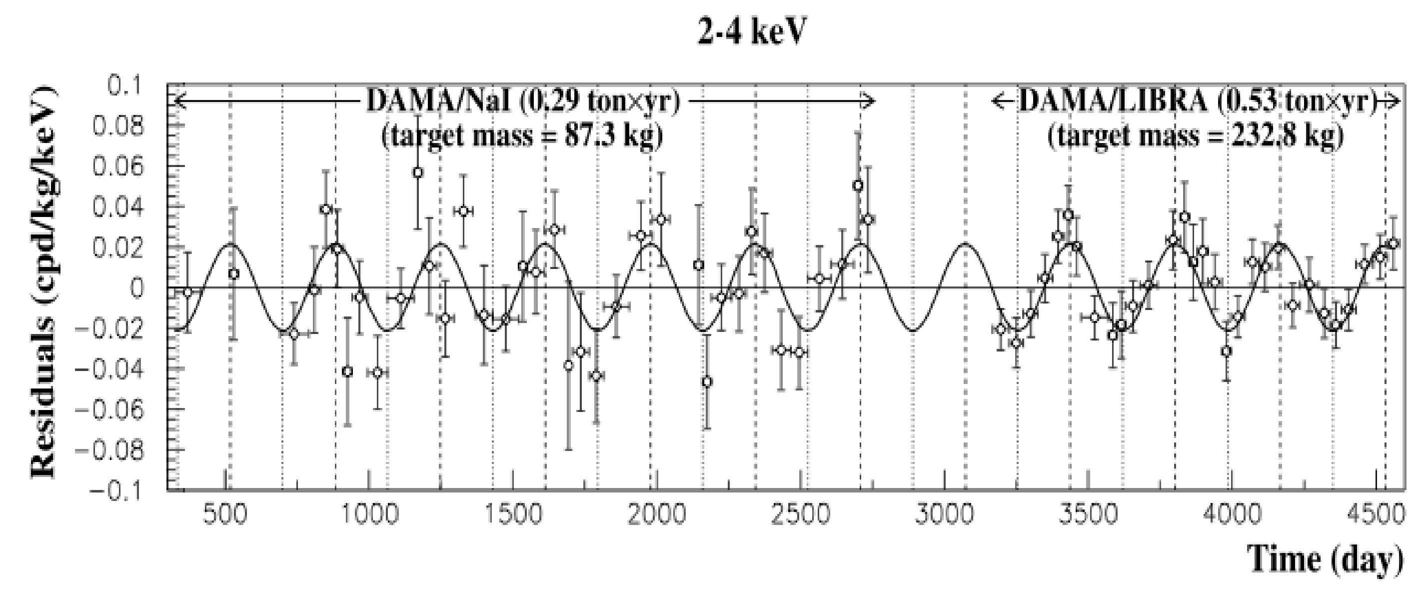
DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



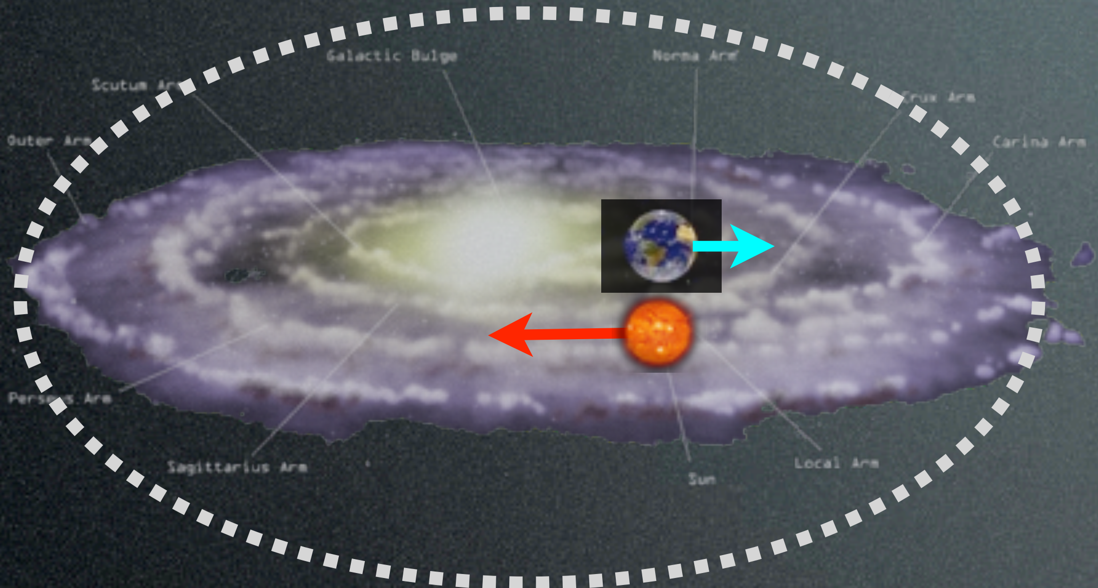
Annual modulation seen (8σ):



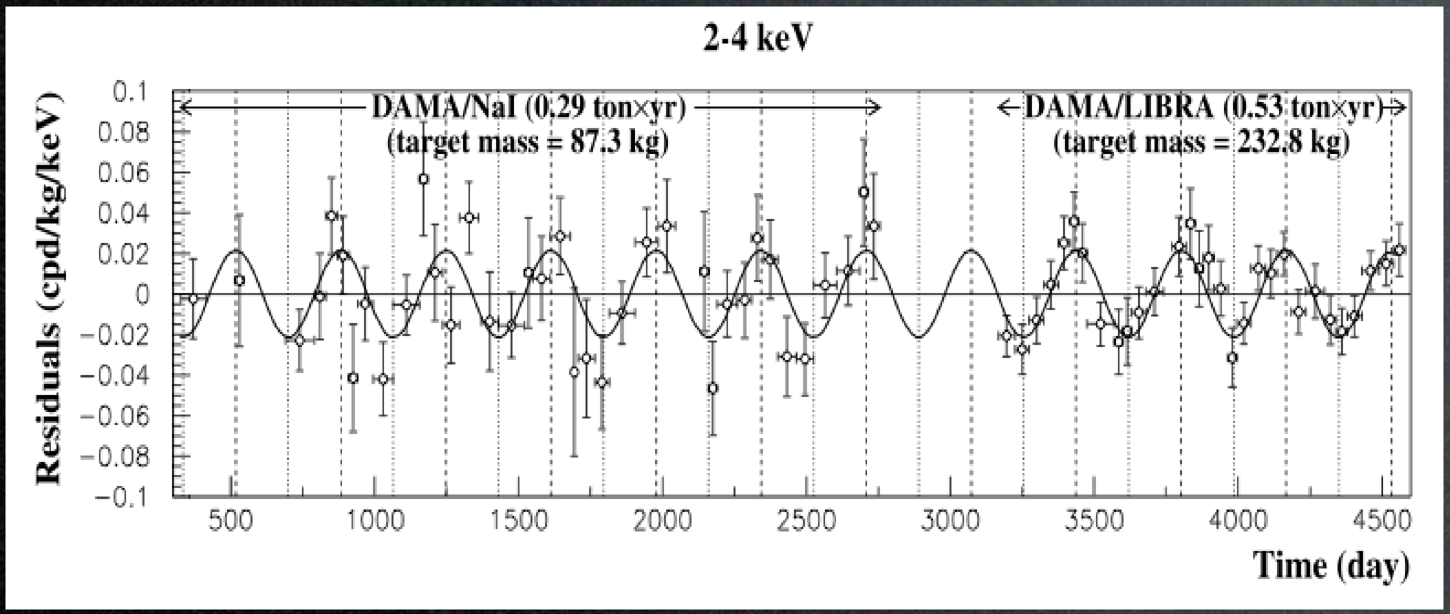
DAMA Coll., 0804.2741, 2008

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)

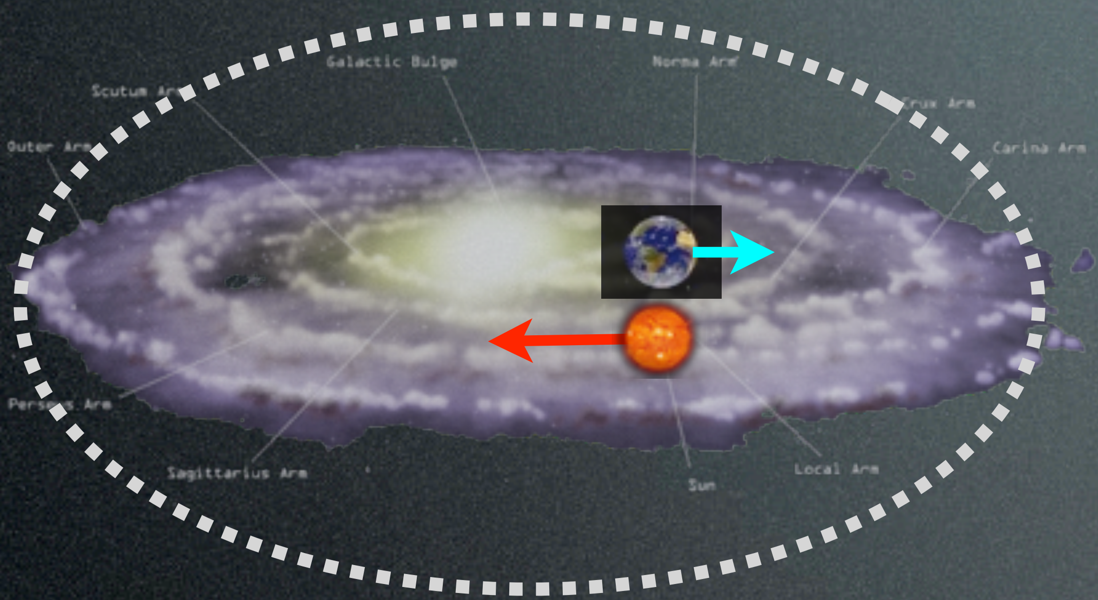
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously 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



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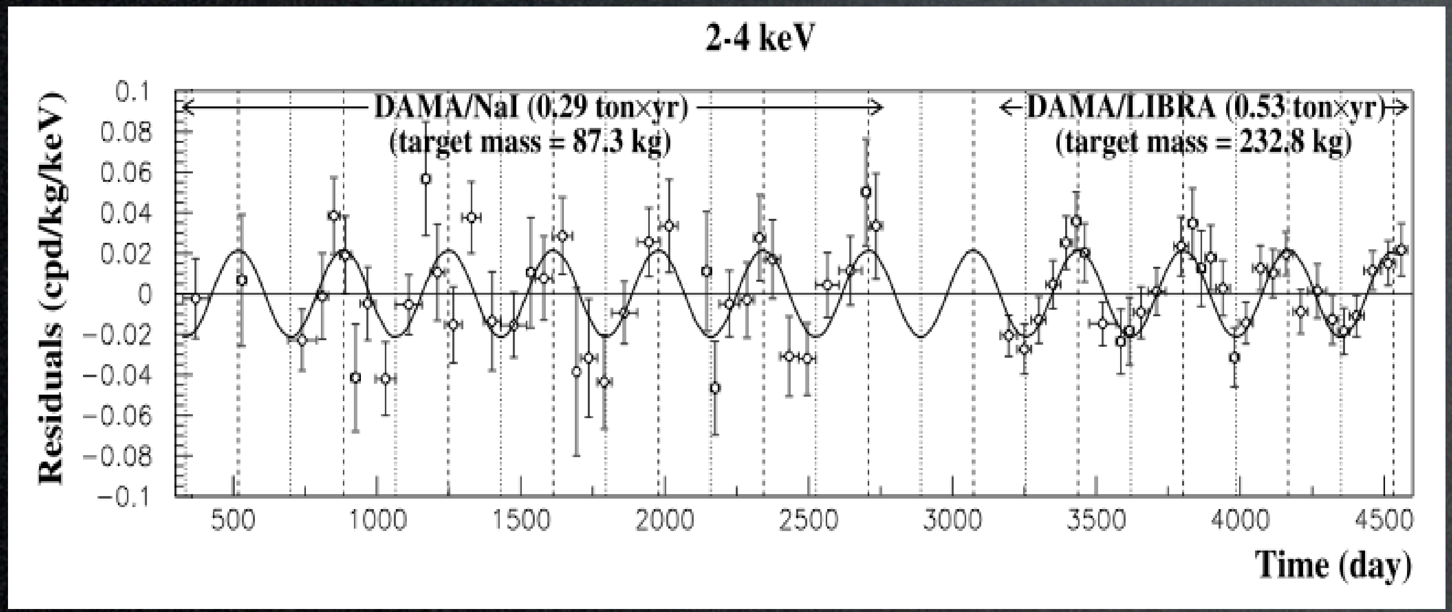


DAMA Coll., 0804.2741, 2008

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

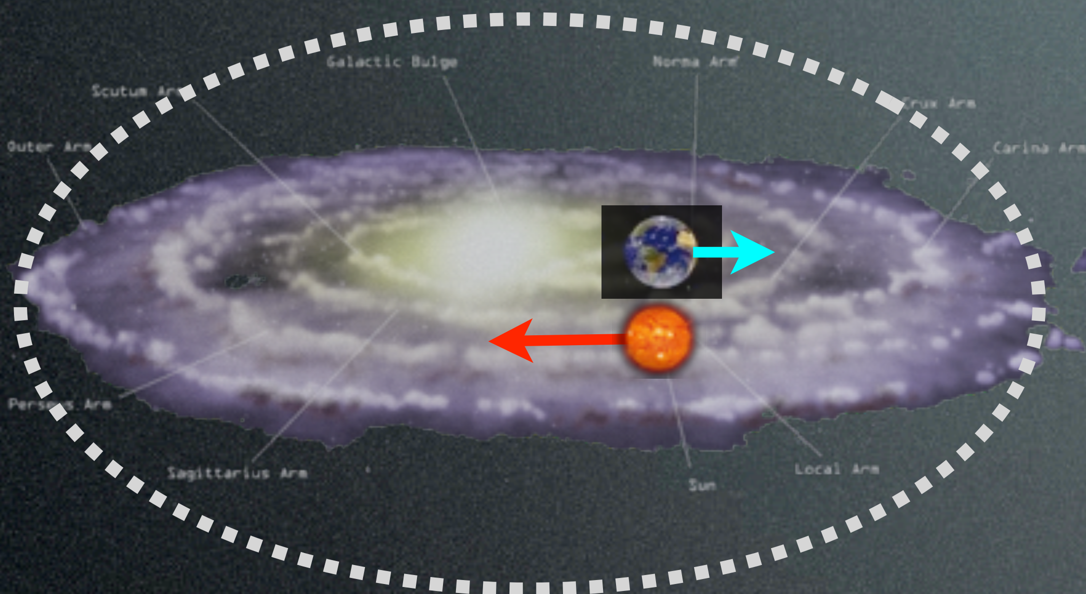
SAINT-GOBAIN

e.g. D.Nygren, 1102.0815

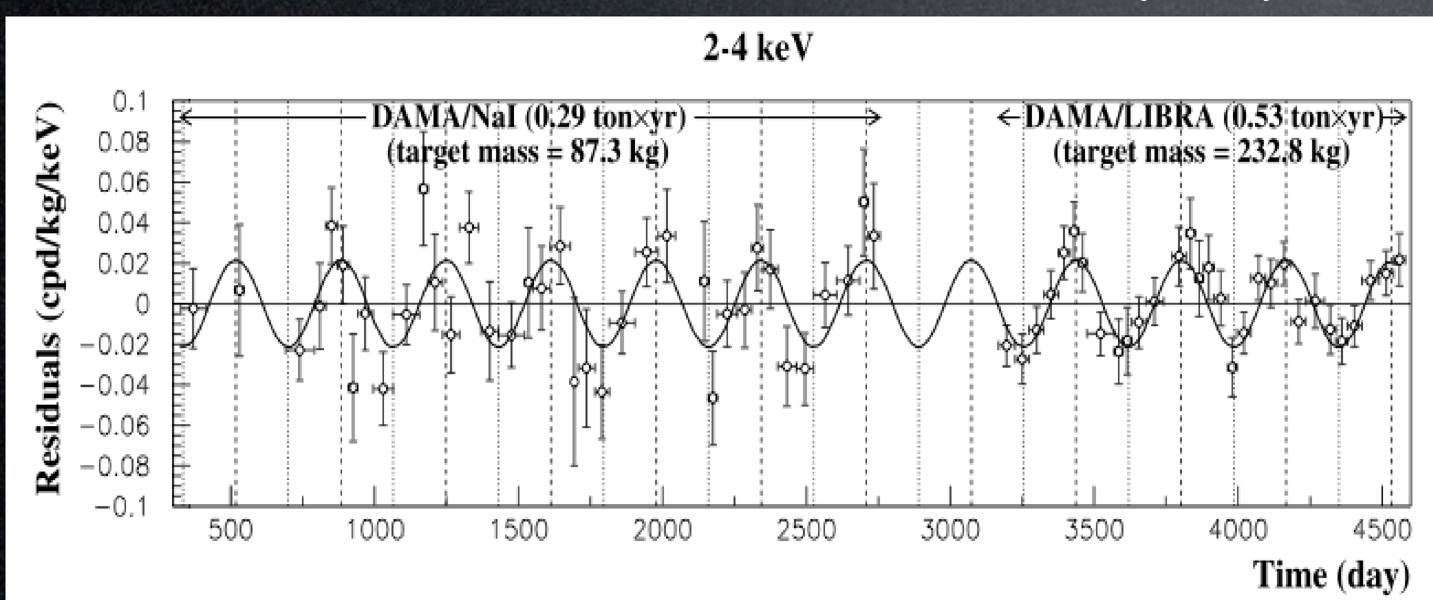
NaI(Tl) crystals might be activated by cosmic muons (modulated!) and release pulses minutes/days later. IceDM will test perhaps.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

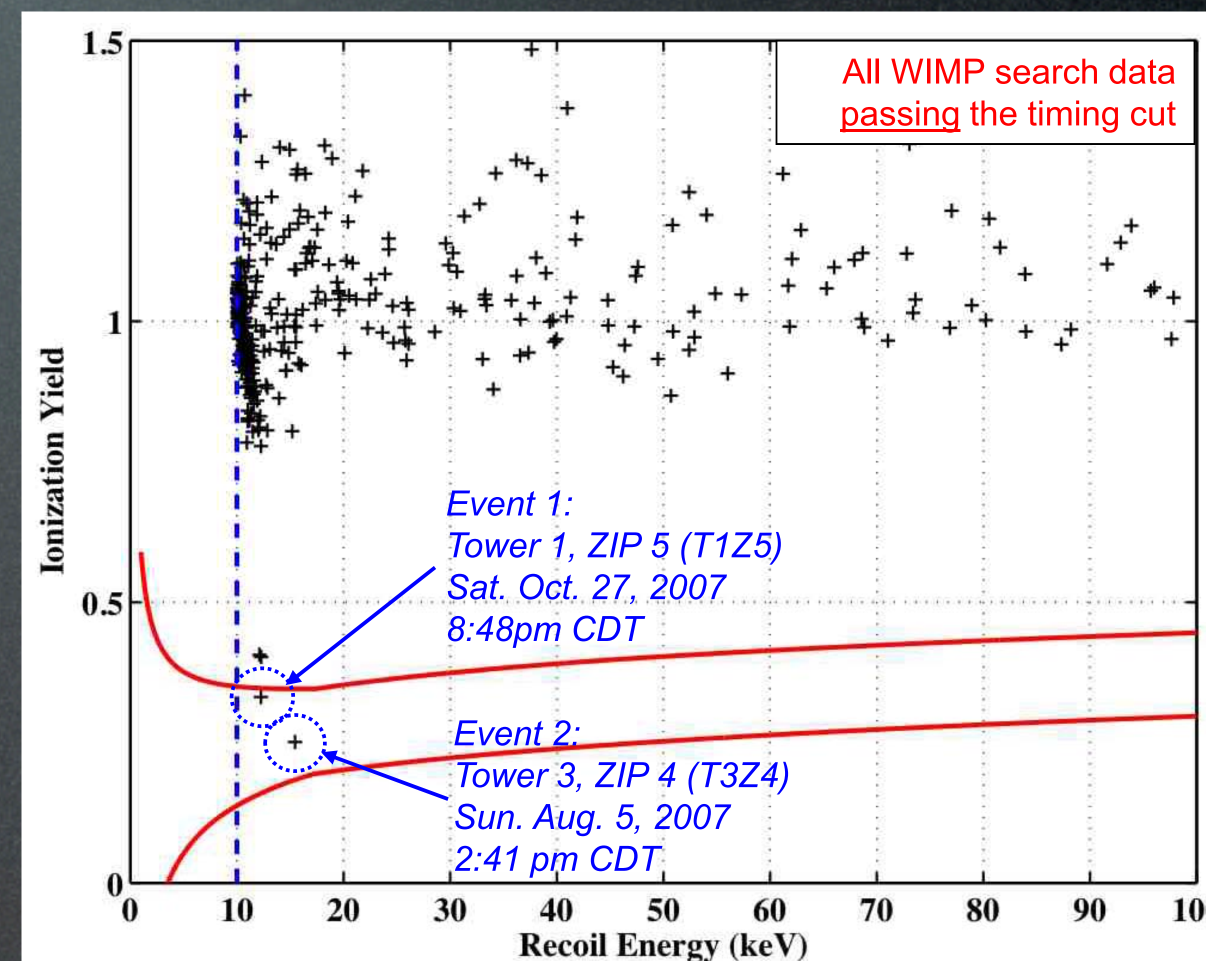


DAMA Coll., 0804.2741, 2008

CDMS

Ge+Si

2 events seen,
with 0.6 exp'd background

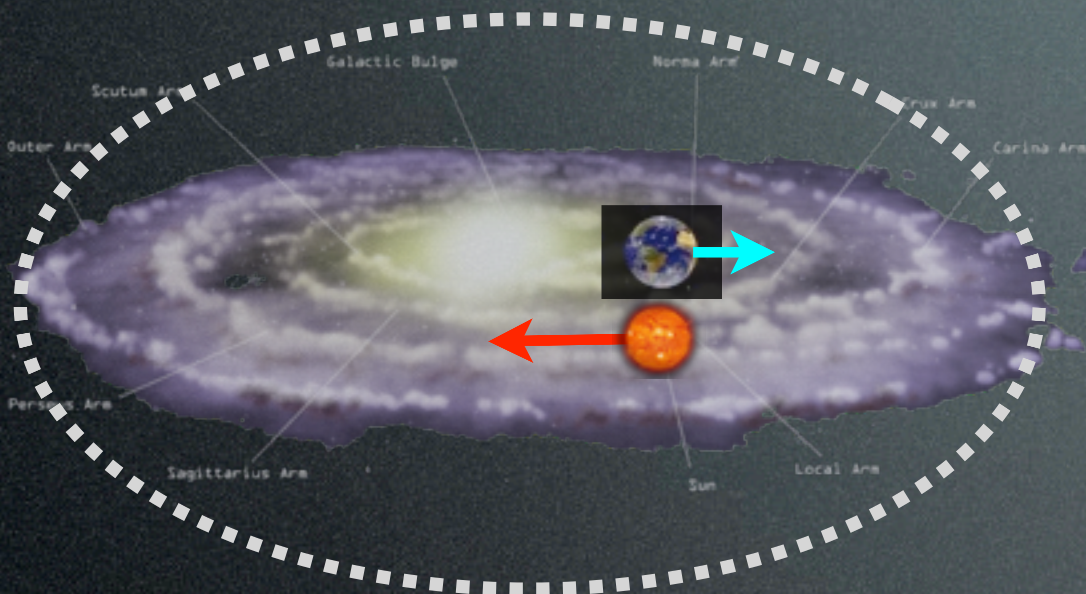


CDMS coll., Science 327 (2010), 0912.3592

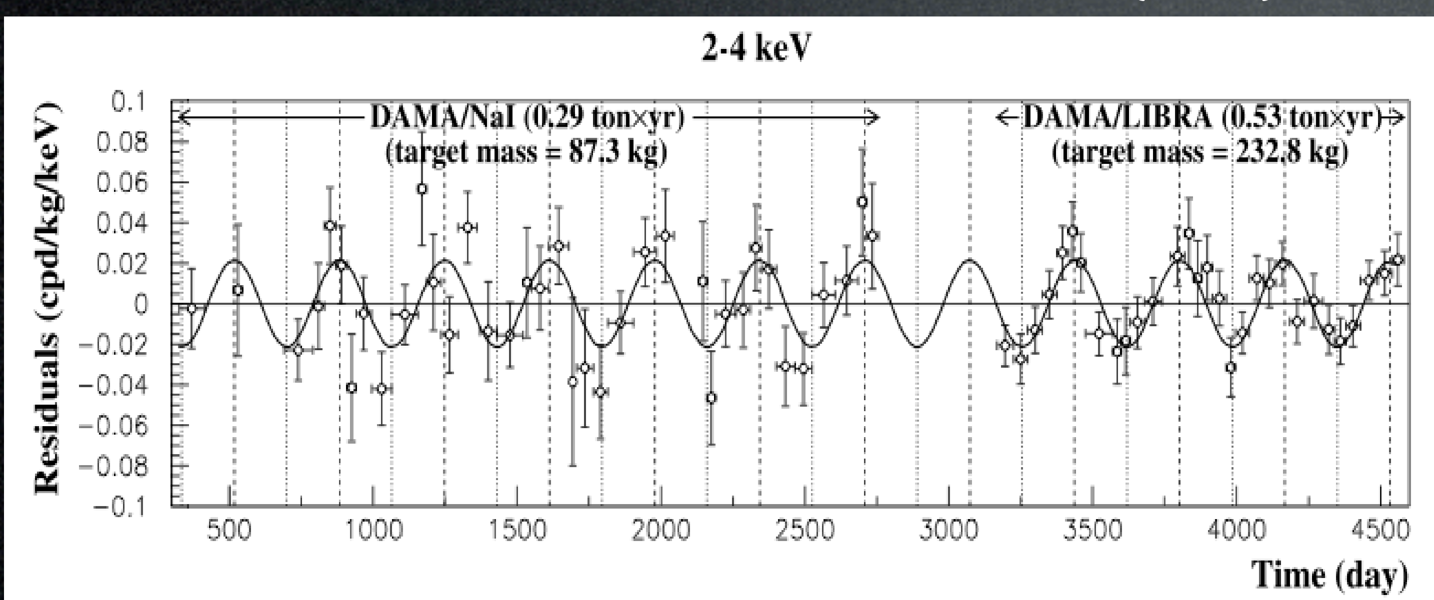
cited 250 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

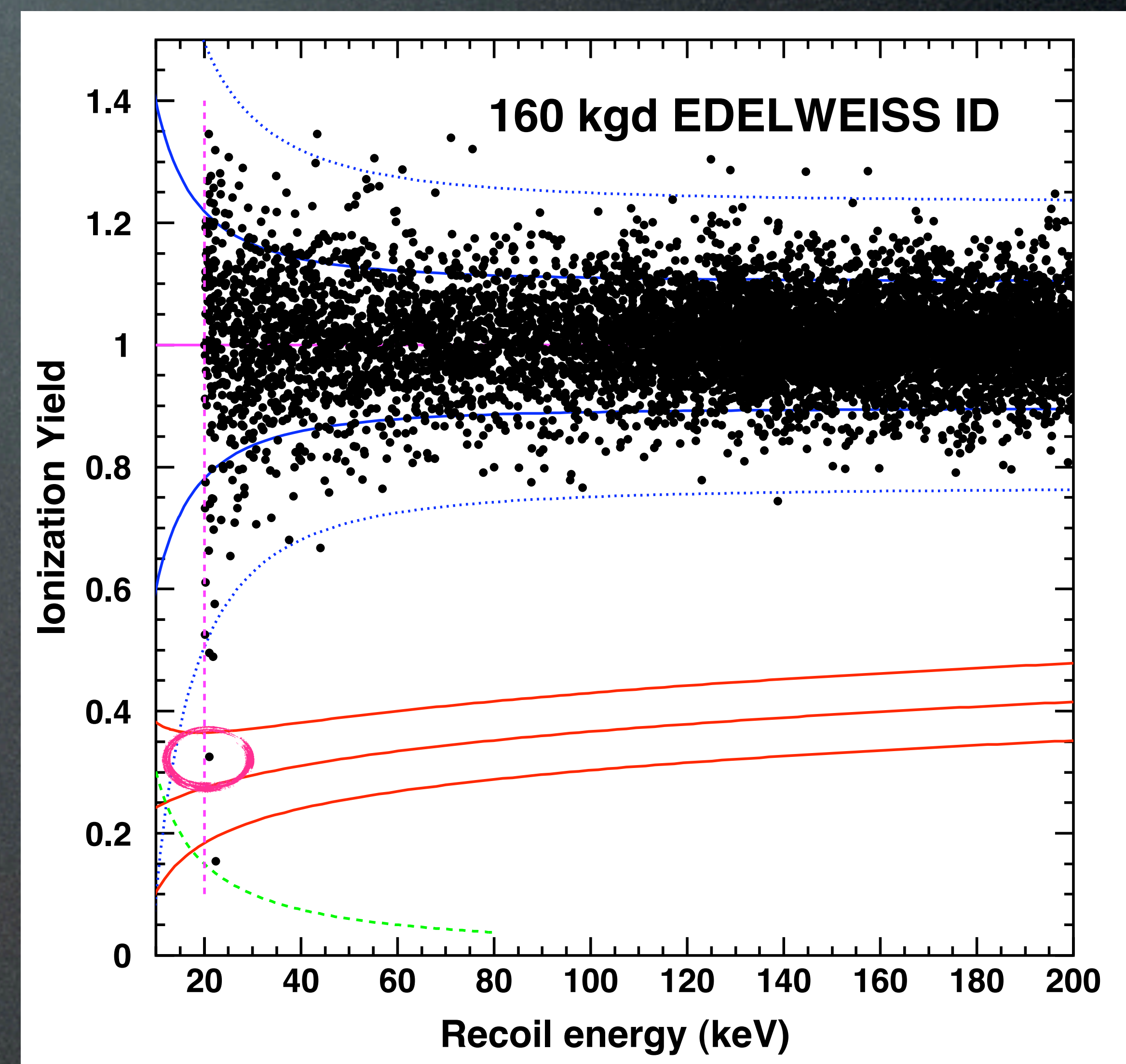


DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

1 event seen,
with 0.24 exp'd background

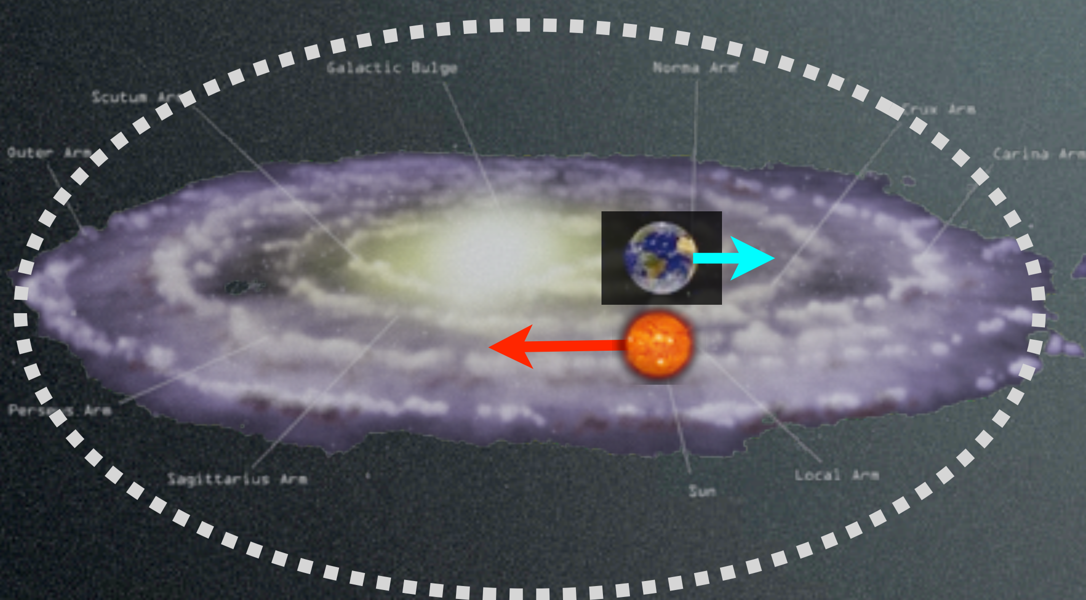


Edelweiss coll. PLB 687 (2010), 0912.0805

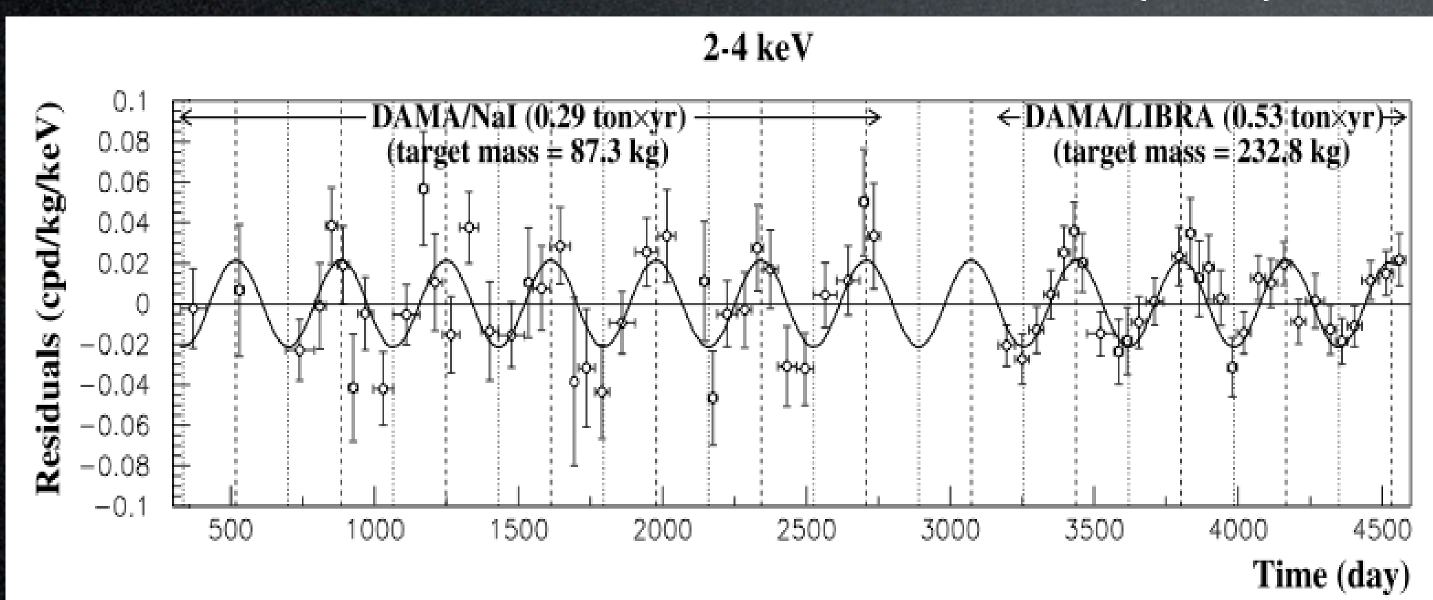
cited 250/10 = 25 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):



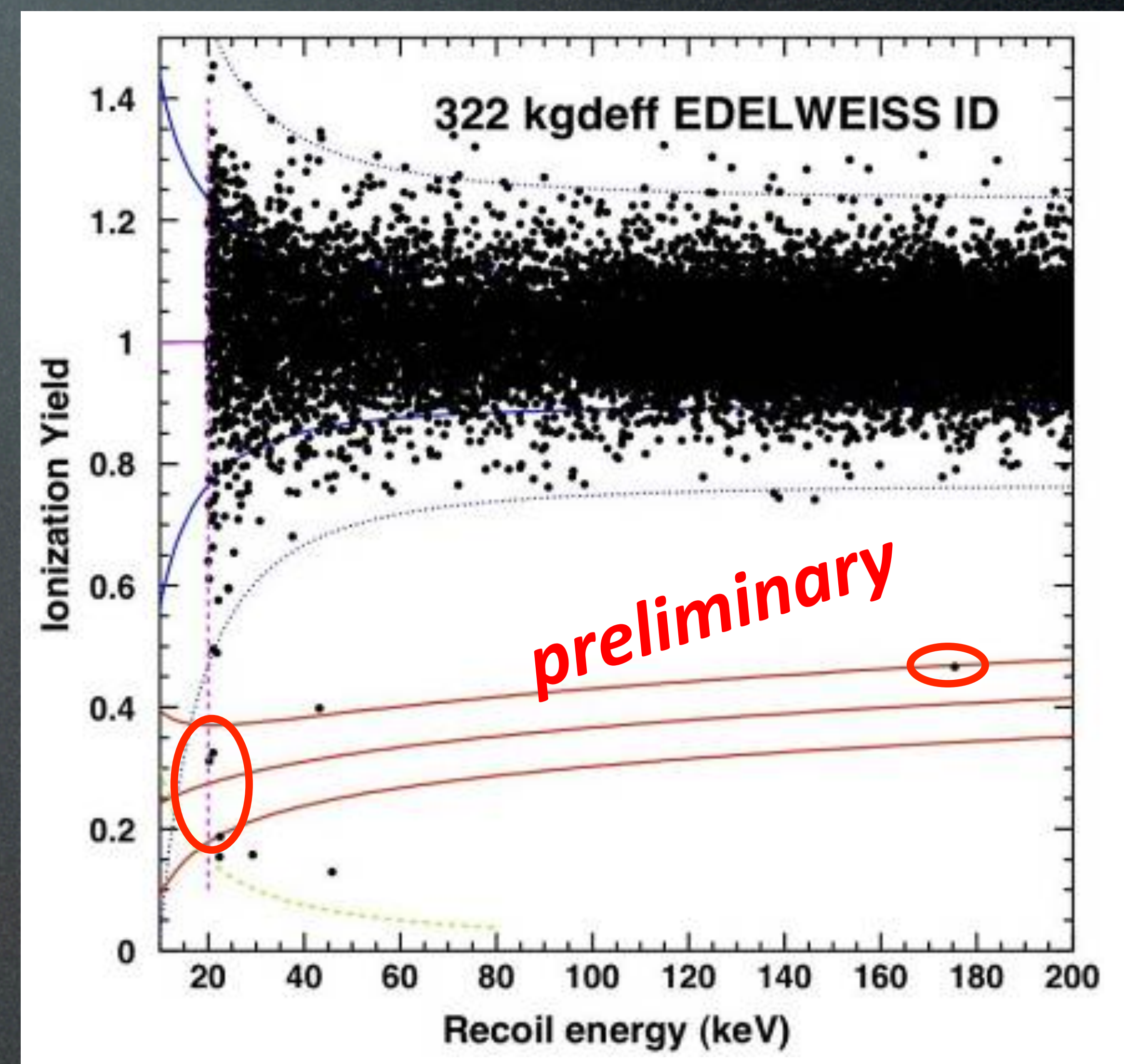
DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

3 events seen

'background starts to appear'

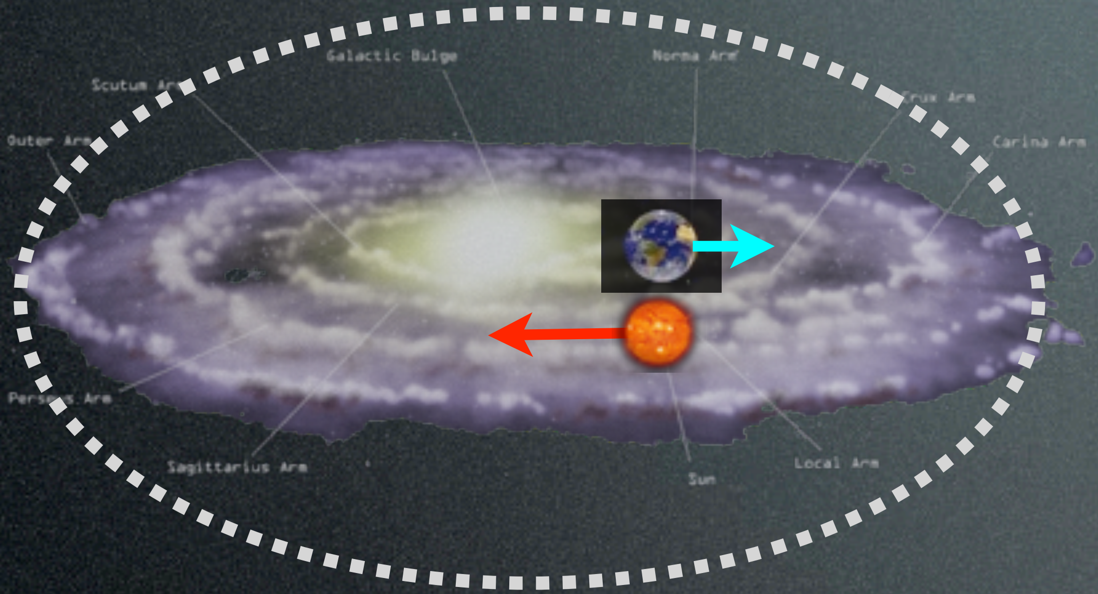


Edelweiss coll, TeVPA 2010

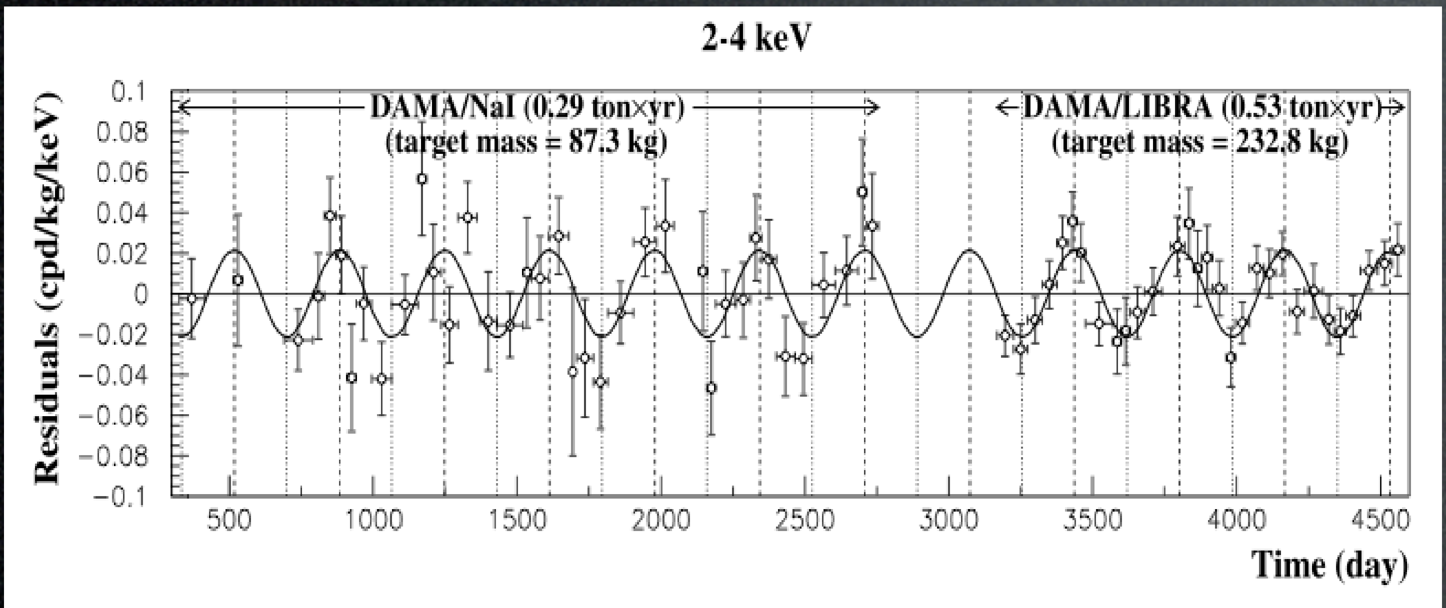
cited 250/10 = 25 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

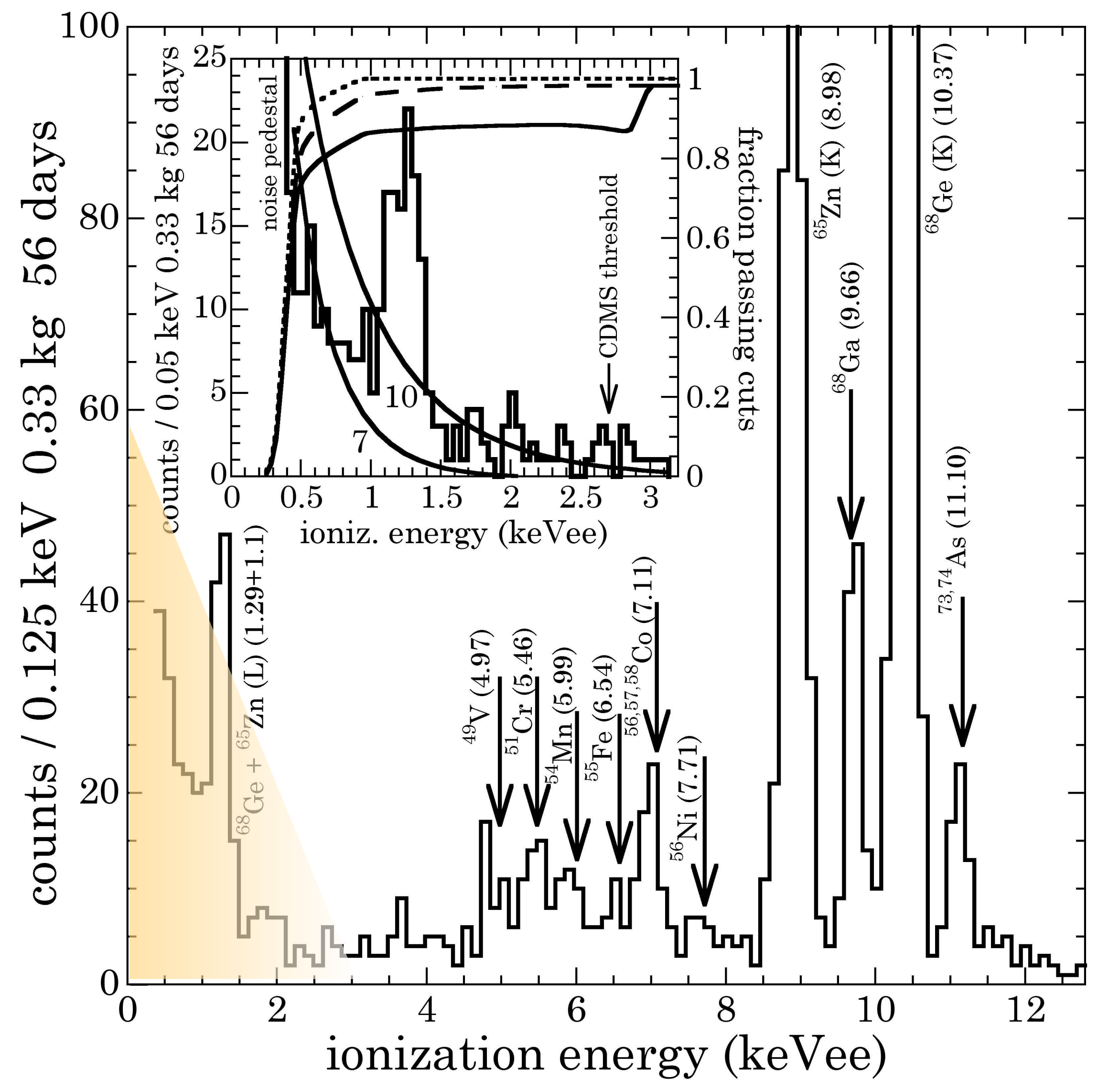


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

'irreducible excess of bulk events below 3 KeVee'

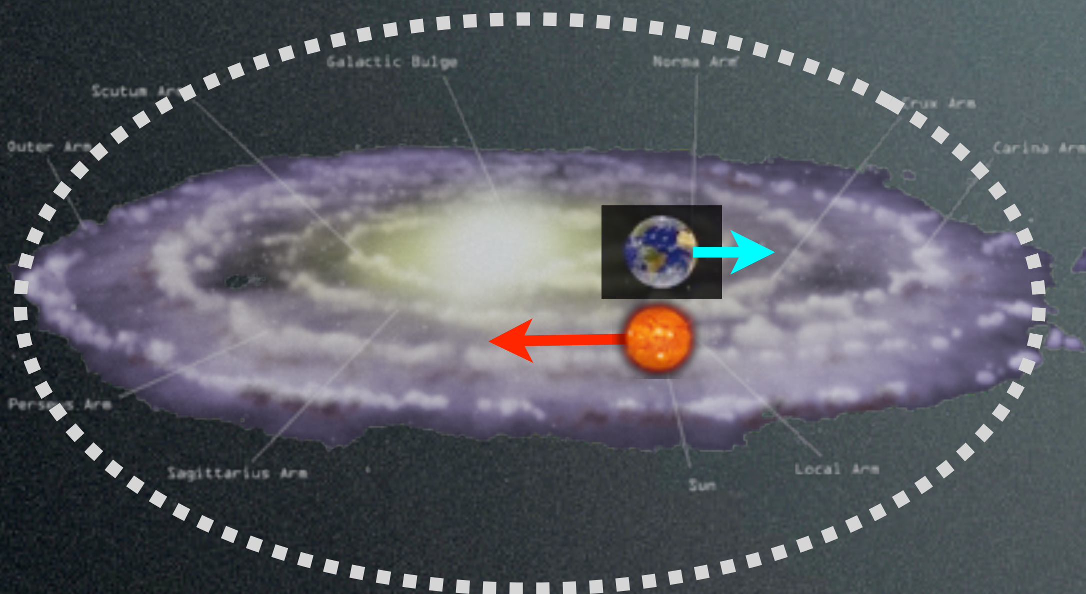


CoGeNT Coll., 1002.4703

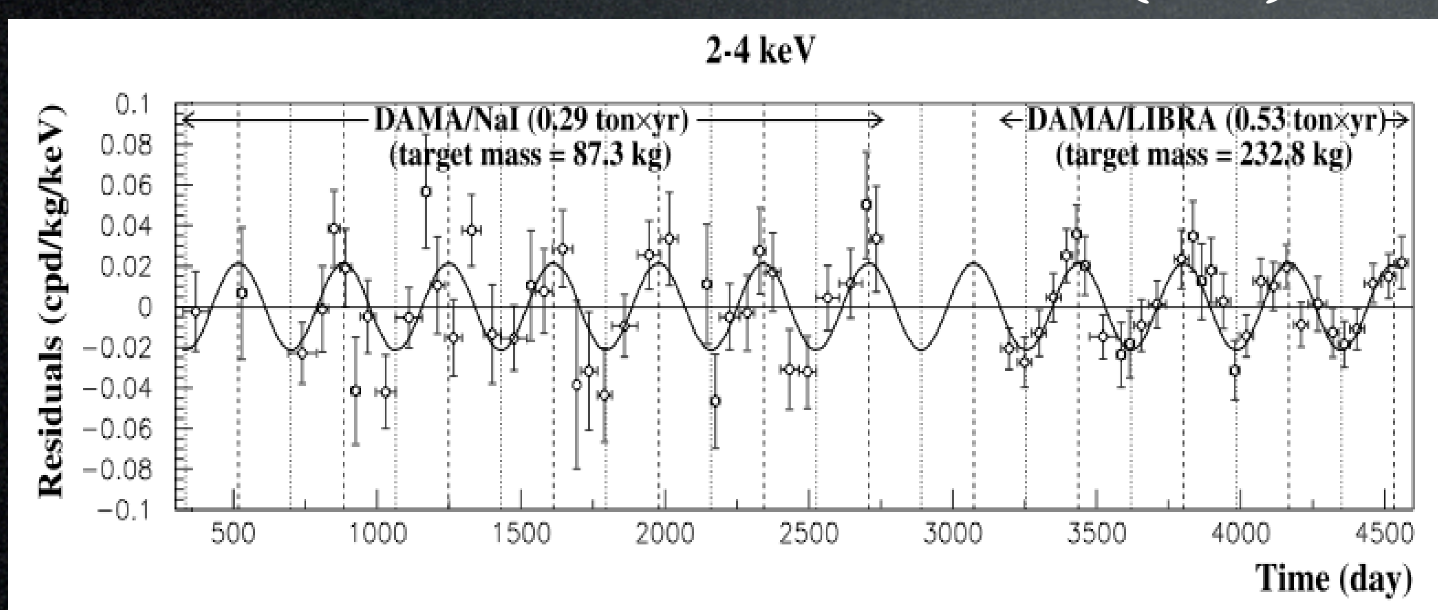
We lack a satisfactorily explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

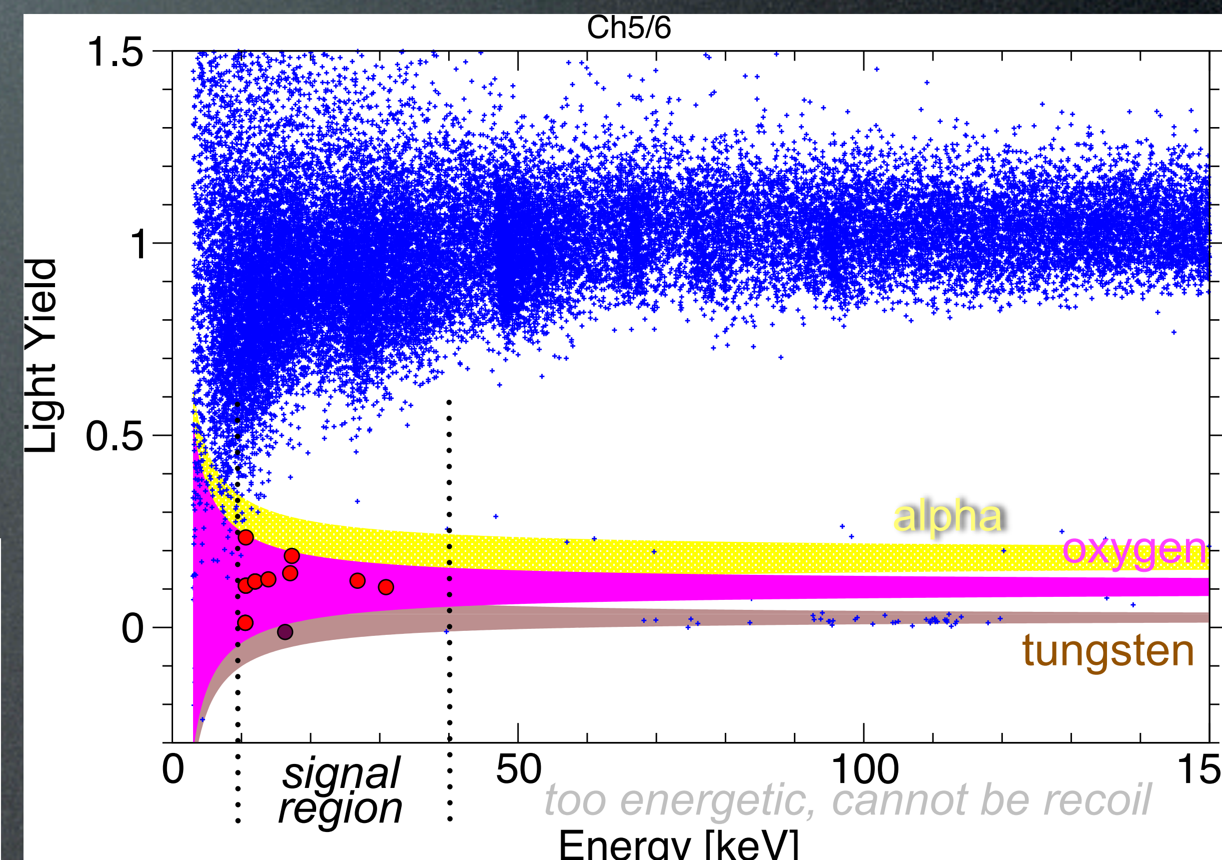


DAMA Coll., 0804.2741, 2008

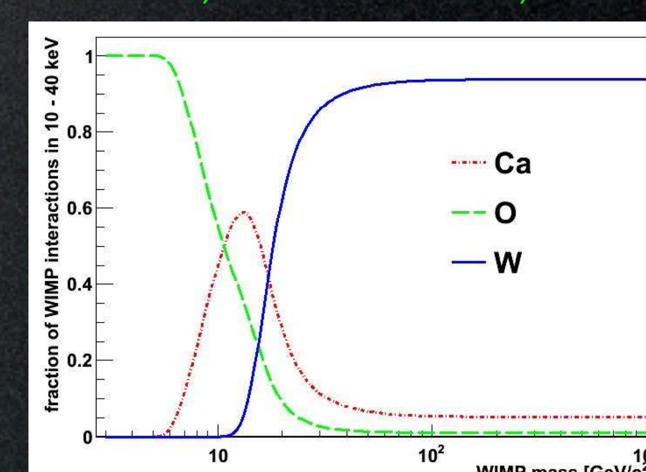
CRESST-II

$CaWO_4$

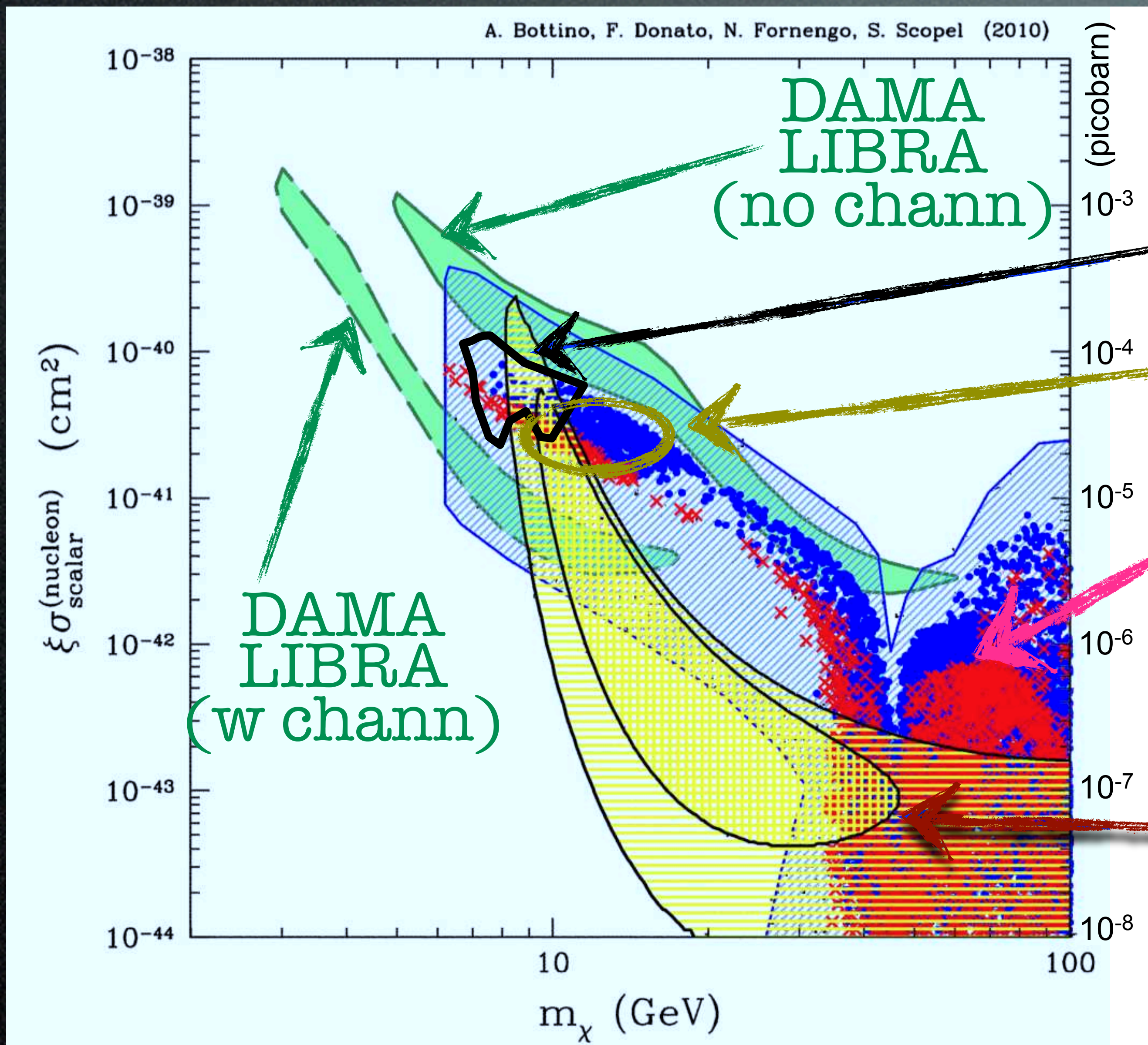
32 events seen on Oxygen, with 8.2 exp'd background



Jochum et al., JPPNP 3369, 15.01.2011



Direct Detection: hints



CoGeNT 2010

CRESST 2011

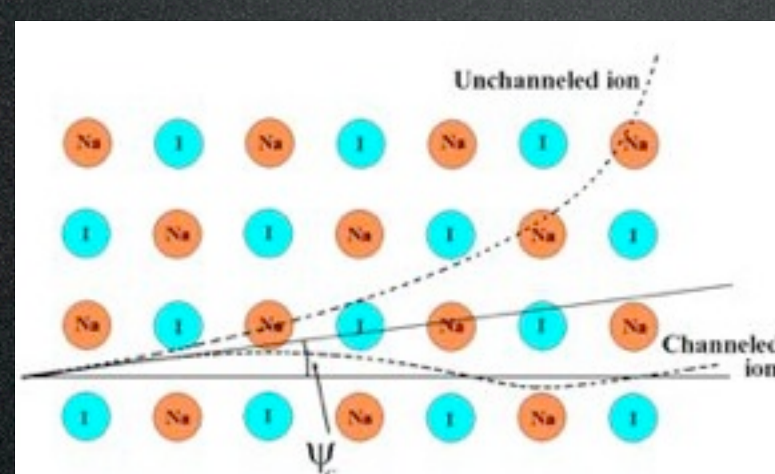
some SuSy theory prediction

CDMS 2009

see also Hooper et al. 1007.1005: DAMA+CoGeNT(& CRESST)

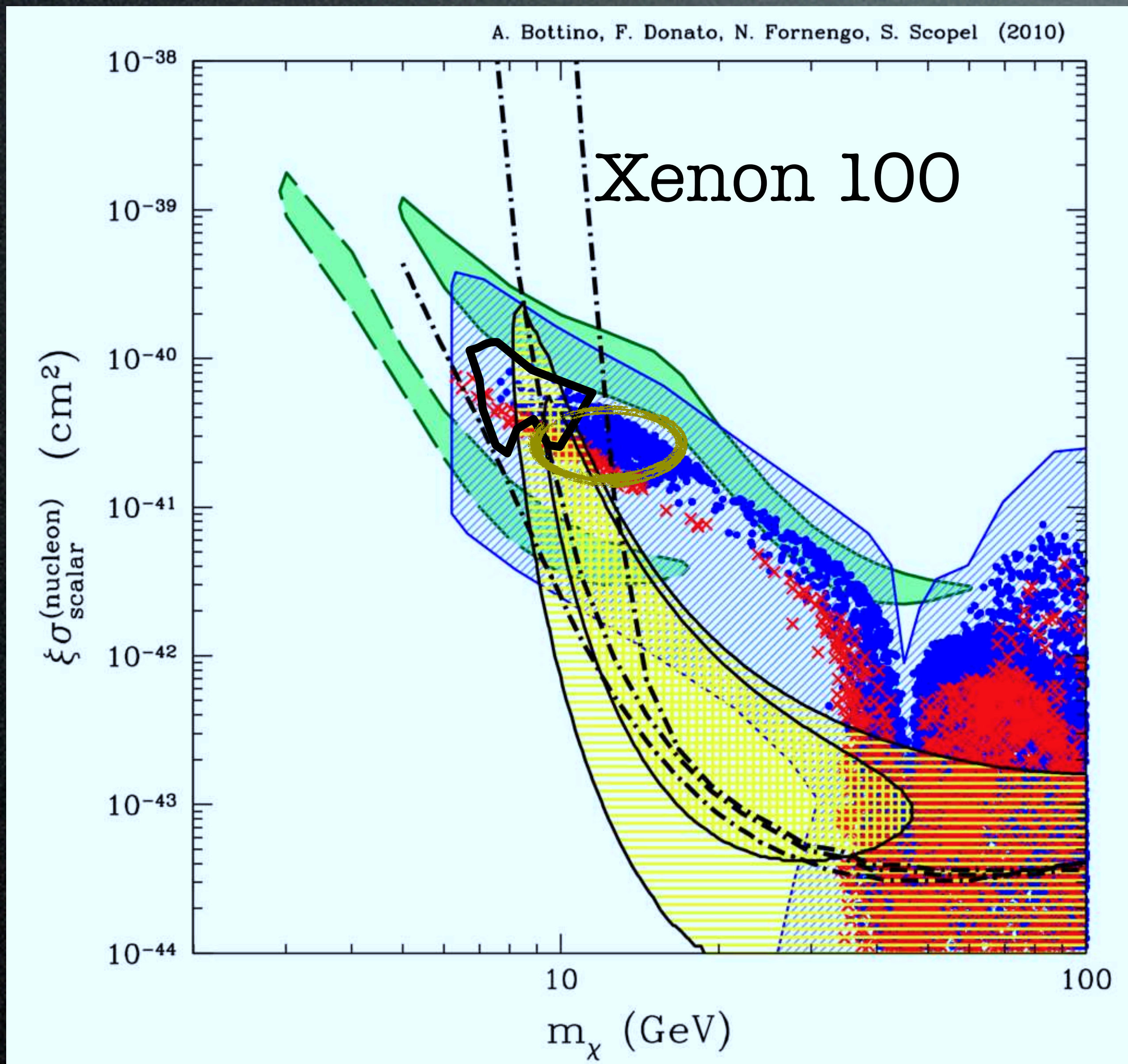
adapted from Bottino et al., 0912.4025

Channelling:



if recoiling nucleus is channelled, 'no' energy lost thermally i.e. more scintillation (higher quenching), smaller reconstructed mass

Direct Detection: **constraints**

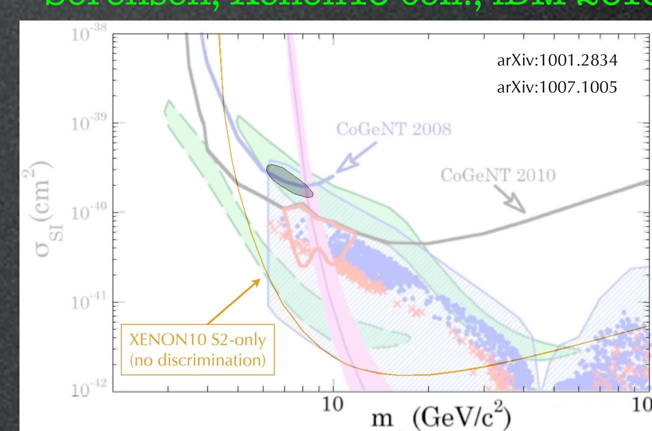


adapted from Bottino et al., 0912.4025

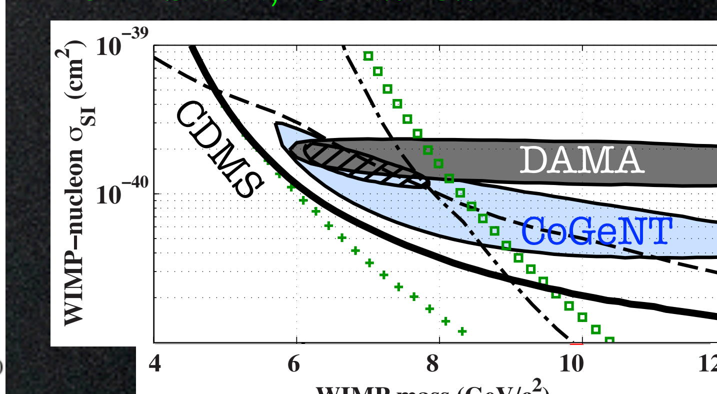
Xenon 100 XENON 100 Coll., 1005.0380

11.17 live days
no events seen

Sorensen, Xenon10 coll., iDM 2010

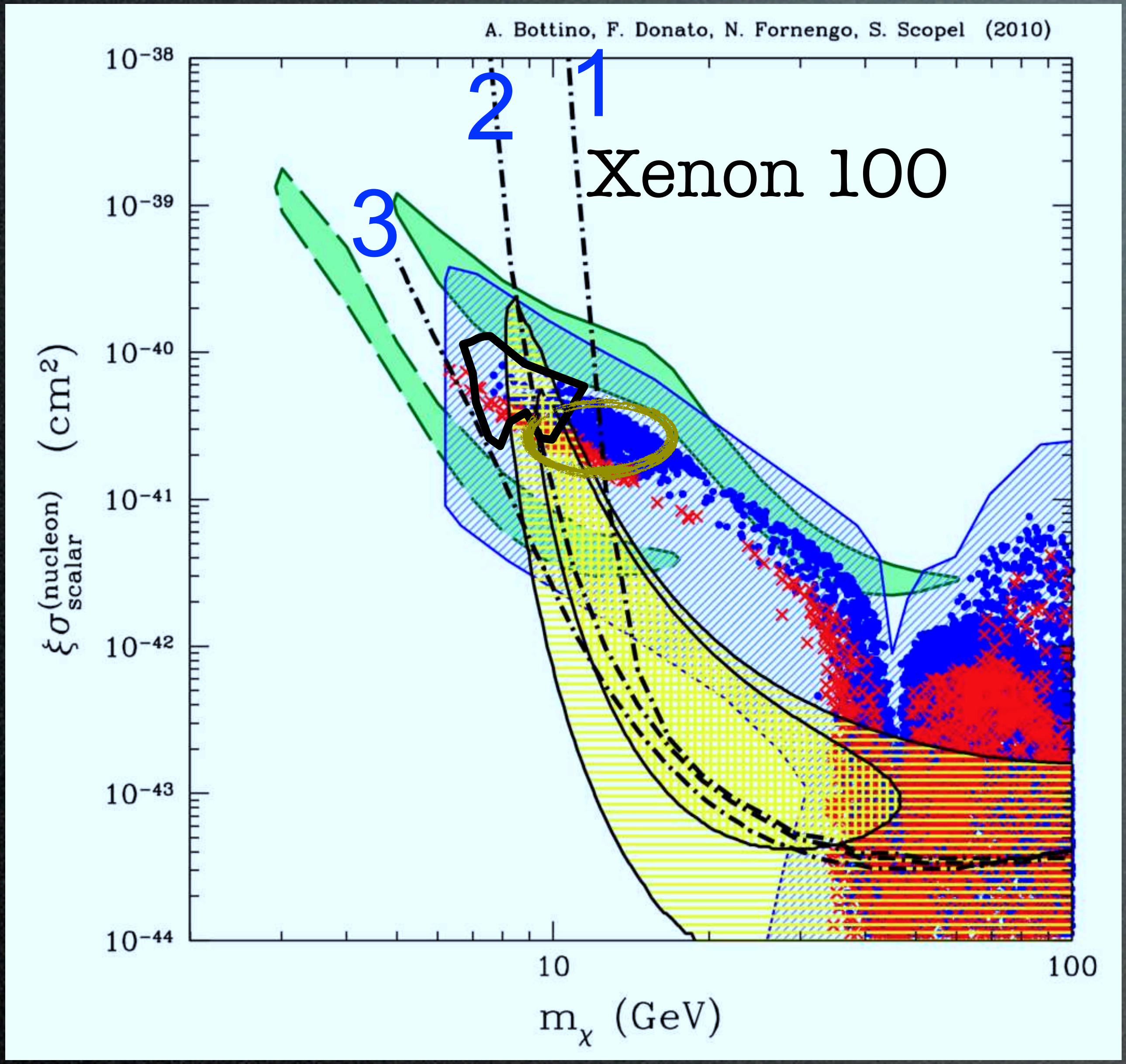


CDMS coll., 1011.2482



Footnote:
Xenon10 & CDMS w/o background discrimination also impose limits

Direct Detection: **constraints**

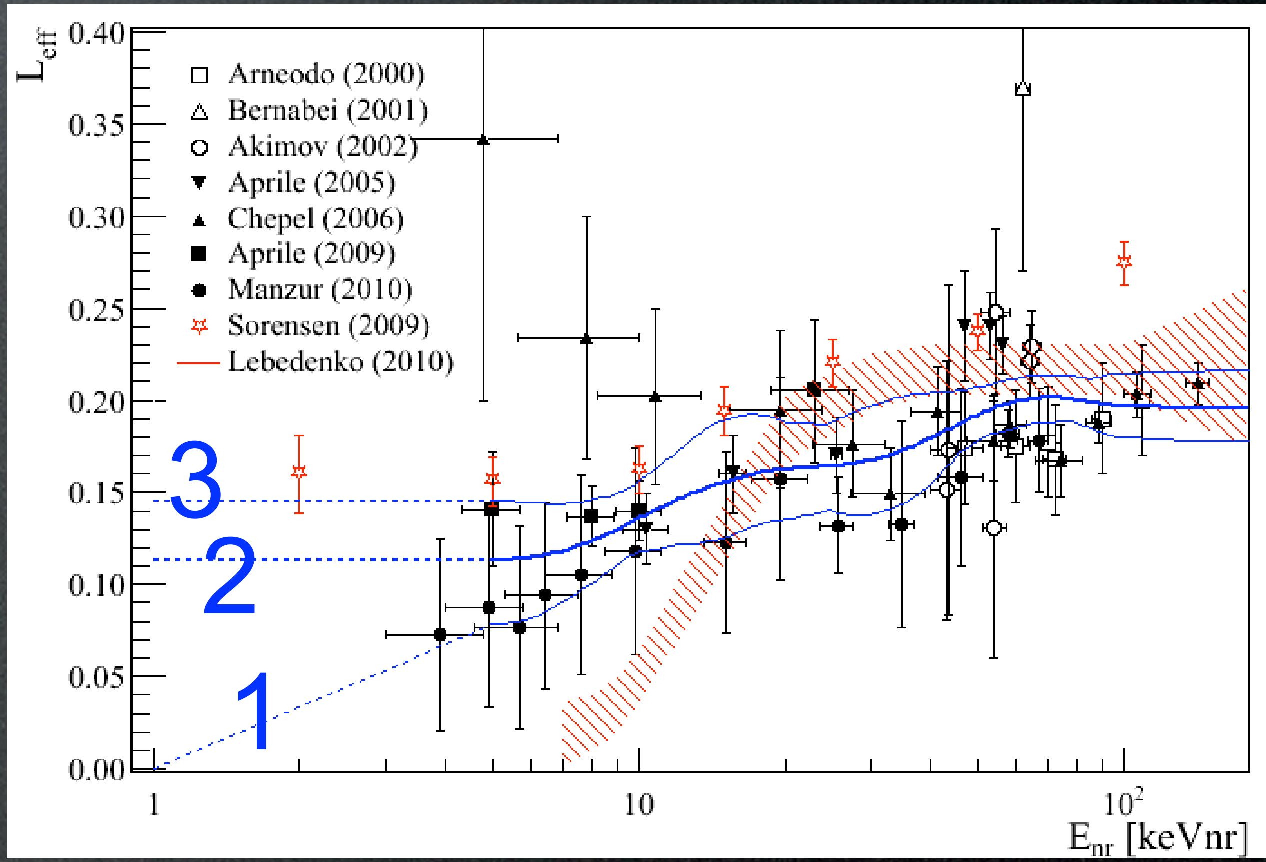


adapted from Bottino et al., 0912.4025

Xenon 100 XENON 100 Coll., 1005.0380

11.17 live days
no events seen

scintillation efficiency in LXe

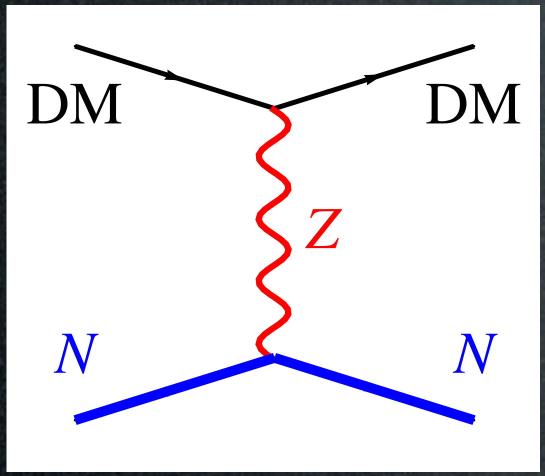


XENON 100 Coll., 1005.2615

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

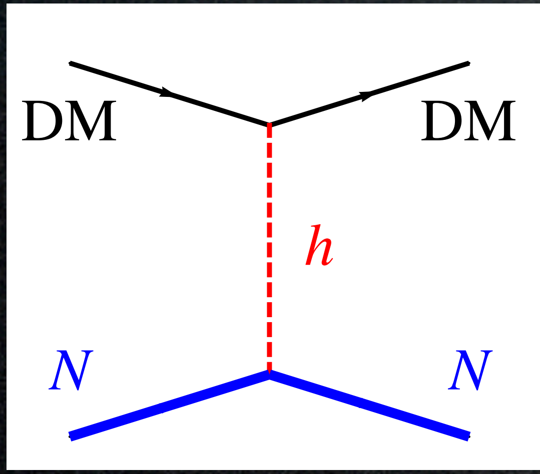
Direct Detection: '**theory**'

SM weak scale SI interactions



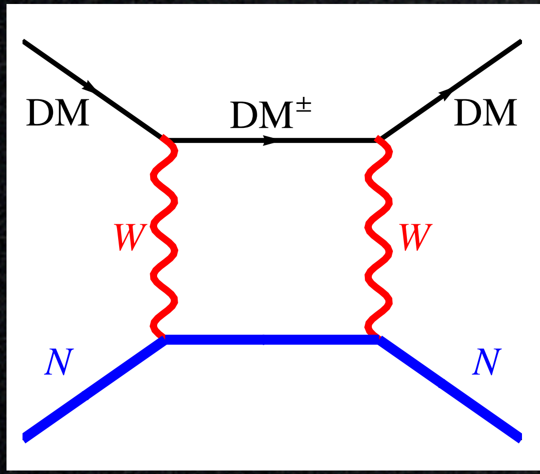
tree level, vector

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



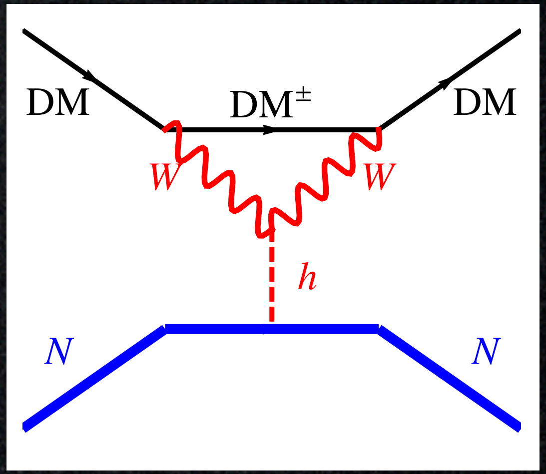
tree level, scalar

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



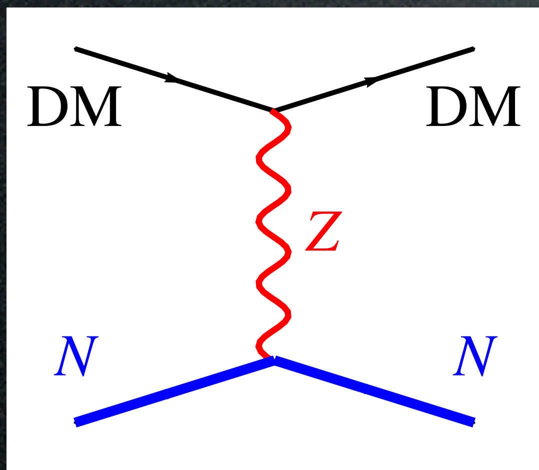
one loop

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

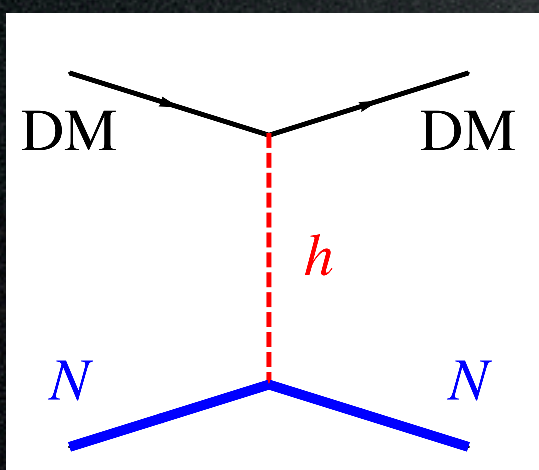


Direct Detection: 'theory'

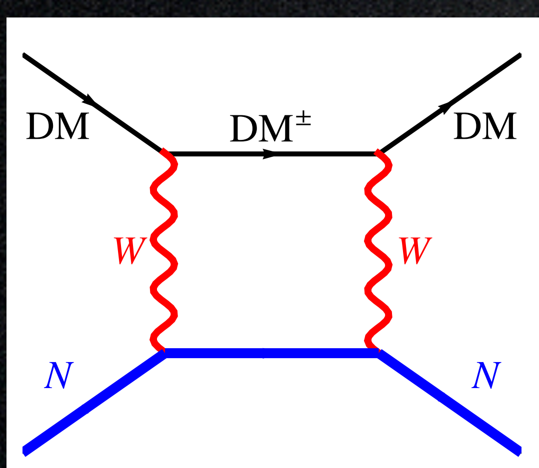
SM weak scale SI interactions



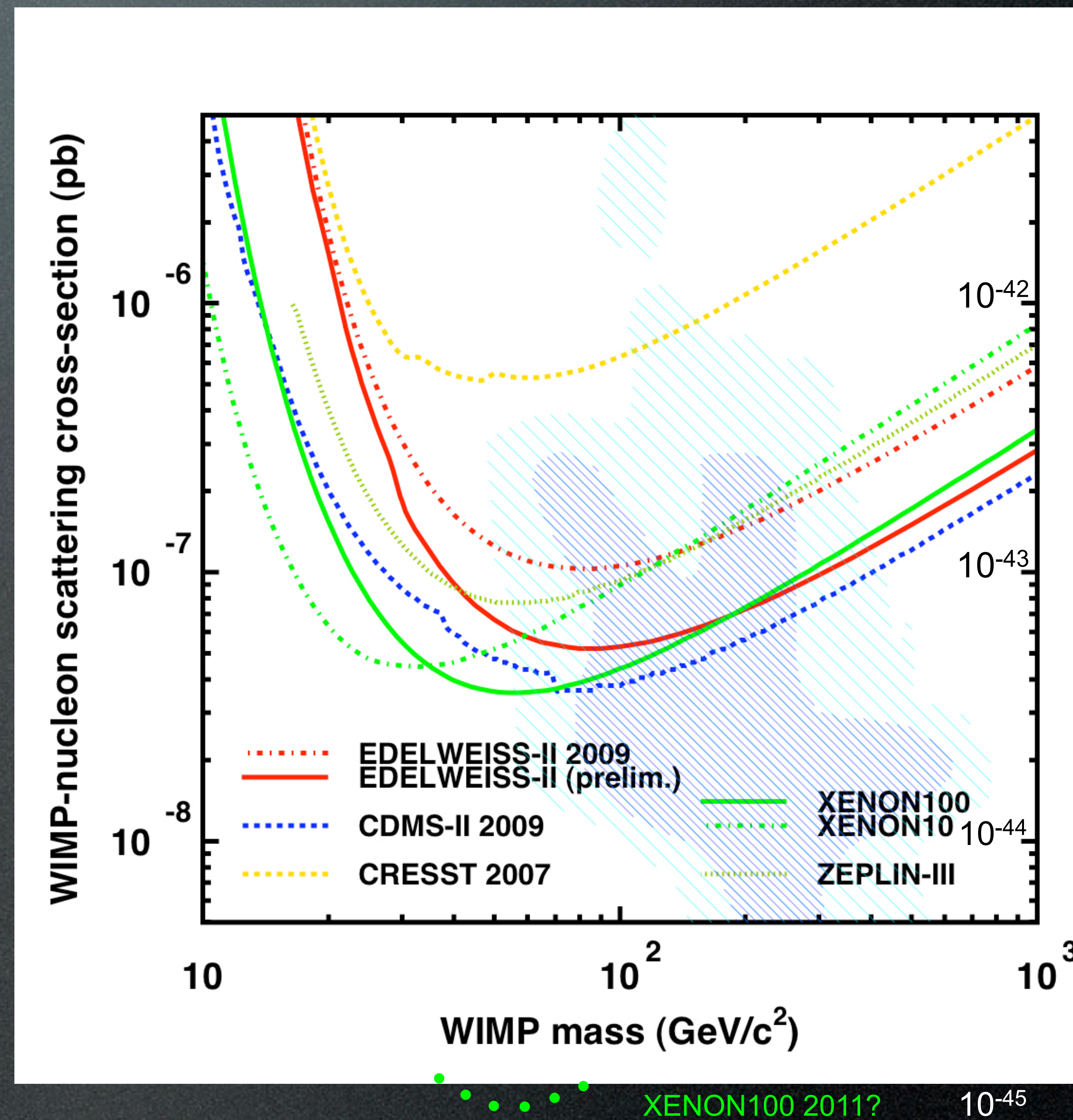
tree level,
vector



tree level,
scalar



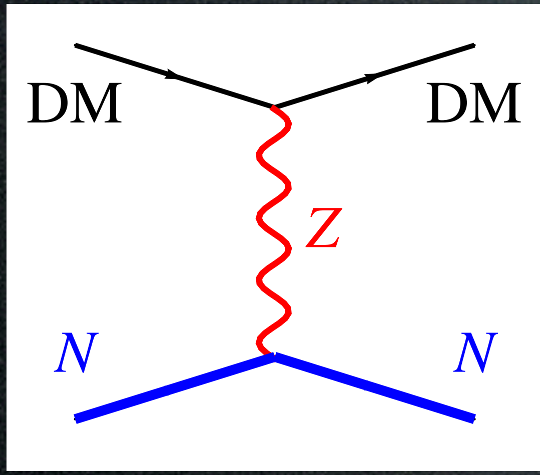
one loop



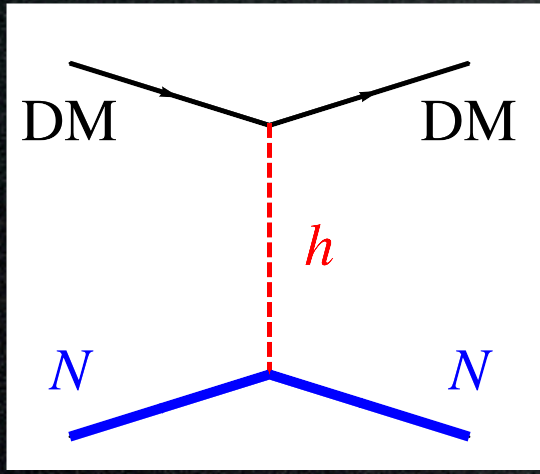
Edelweiss Collaboration (at TeVPA 2010)

Direct Detection: 'theory'

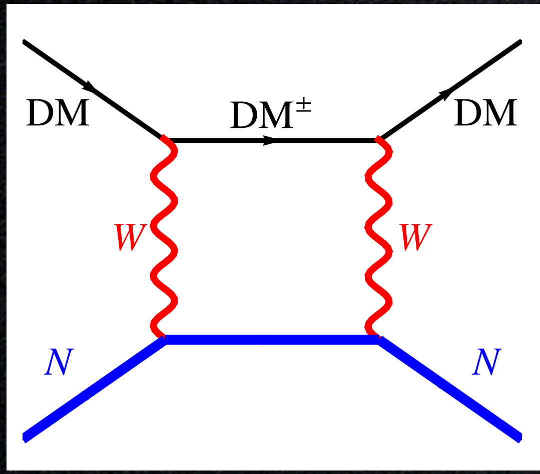
SM weak scale SI interactions



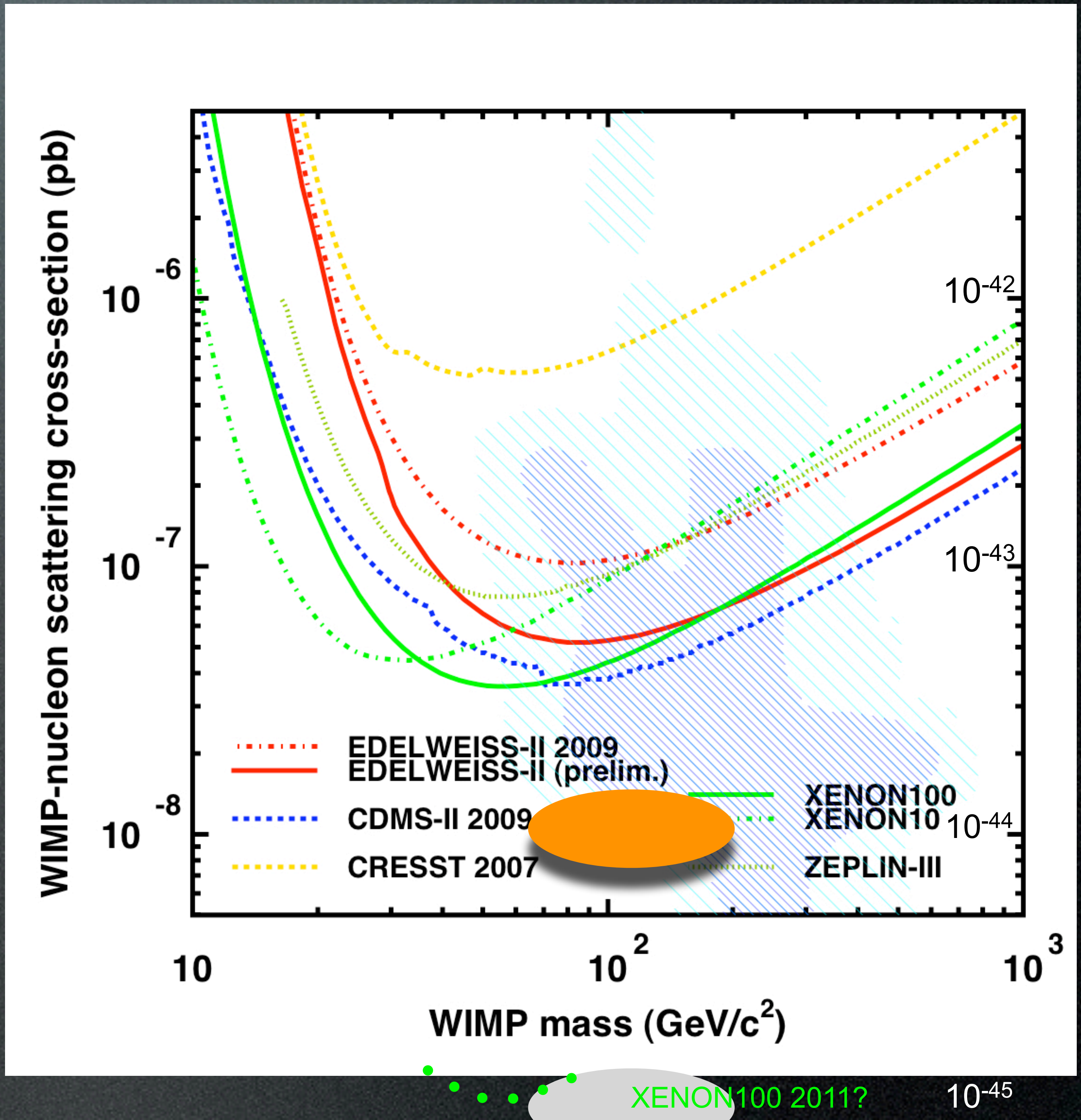
tree level, vector



tree level, scalar



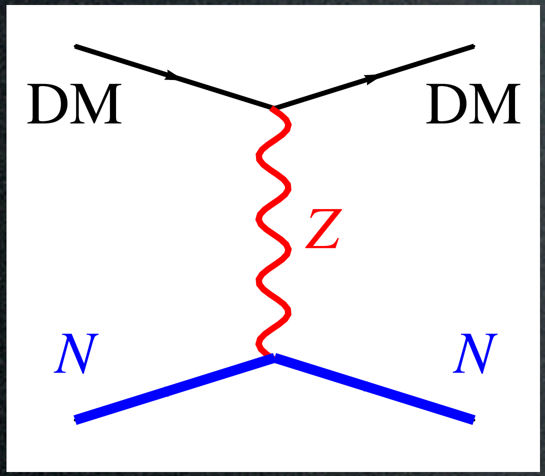
one loop



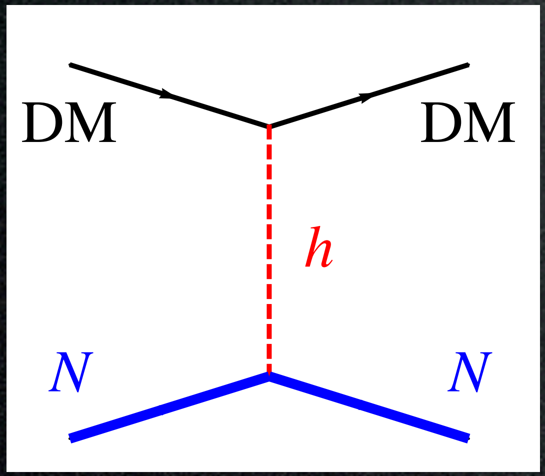
Edelweiss Collaboration (at TeVPA 2010)

Direct Detection: 'theory'

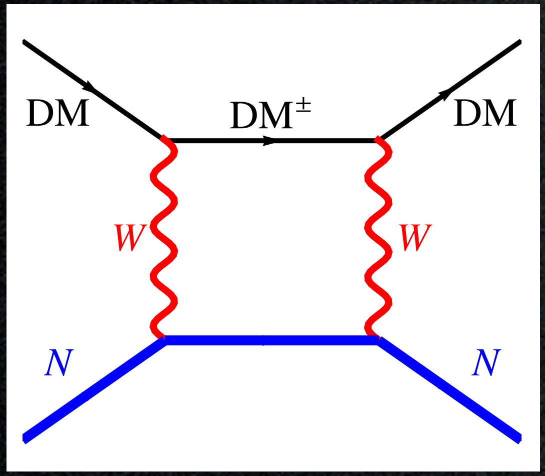
SM weak scale SI interactions



tree level, vector



tree level, scalar

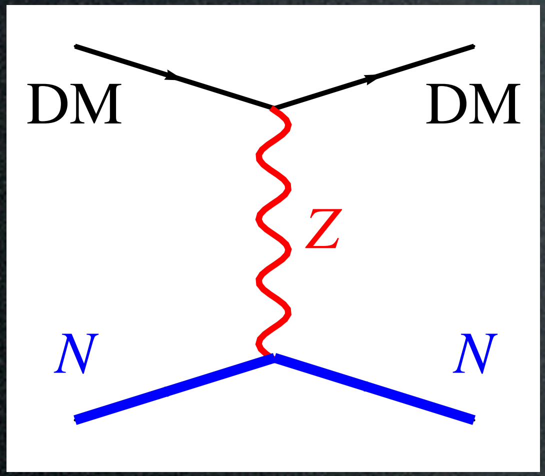


one loop

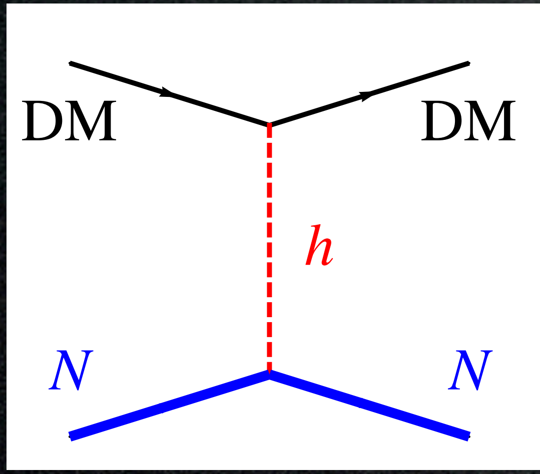
Still viable under which conditions?

Direct Detection: 'theory'

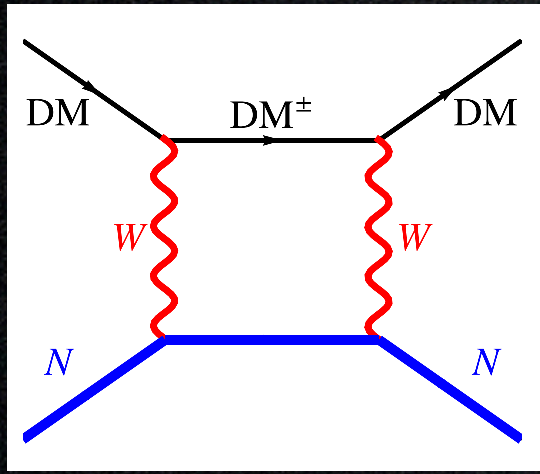
SM weak scale SI interactions



~~tree level, vector~~



tree level, scalar



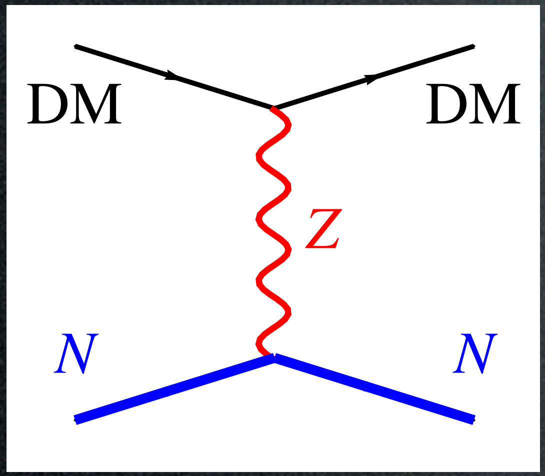
one loop

Still viable under which conditions?

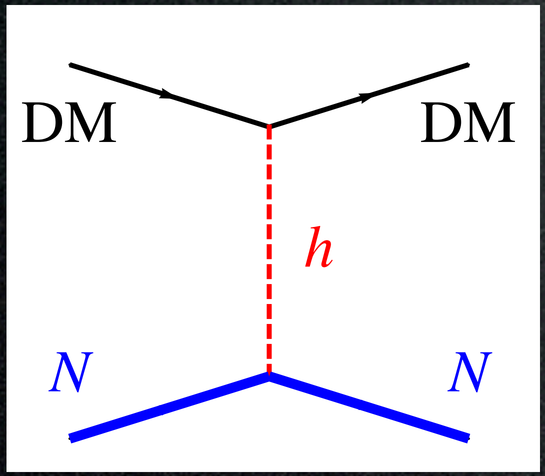
- real particle
  (Majorana fermion, real scalar)

Direct Detection: 'theory'

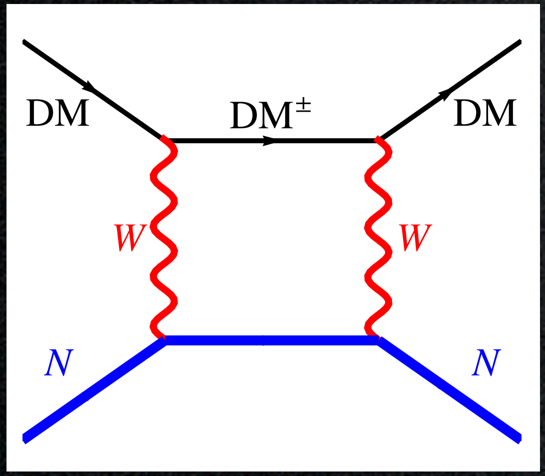
SM weak scale SI interactions



~~tree level, vector~~



~~tree level, scalar~~



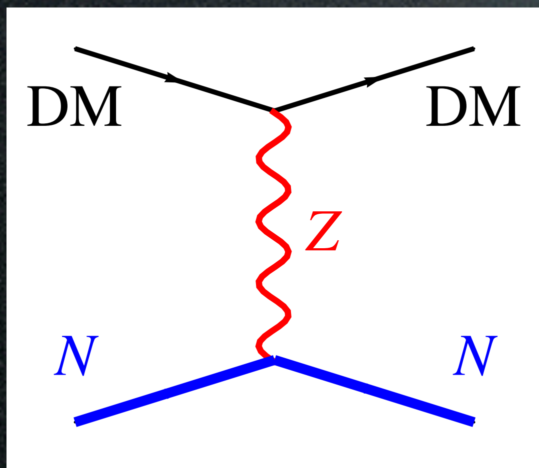
one loop

Still viable under which conditions?

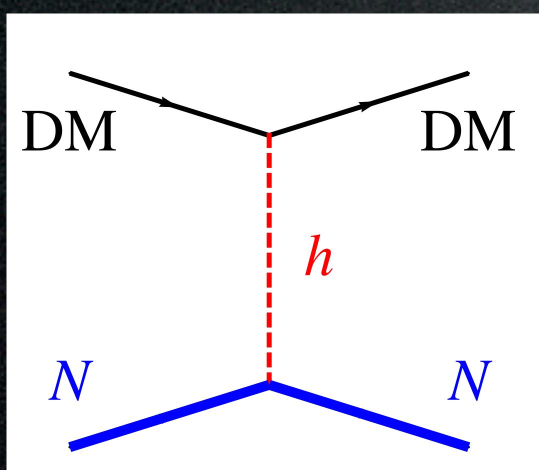
- real particle
  (Majorana fermion, real scalar)
- hypercharge $Y = 0$

Direct Detection: ‘theory’

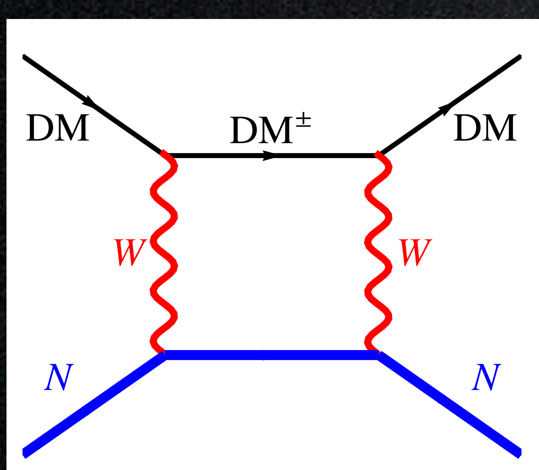
SM weak scale SI interactions



~~tree level, vector~~



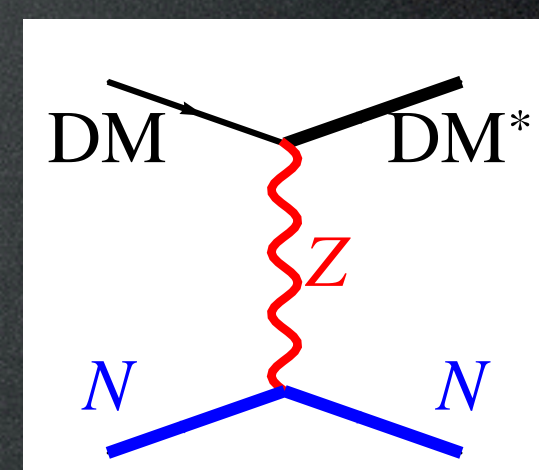
~~tree level, scalar~~



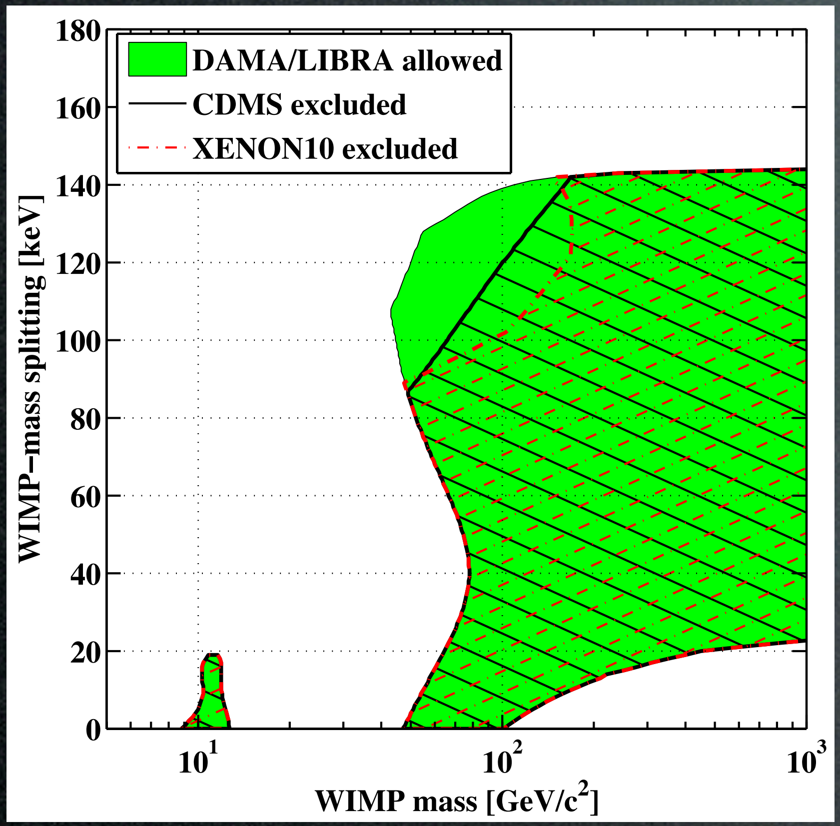
one loop

Still viable under which conditions?

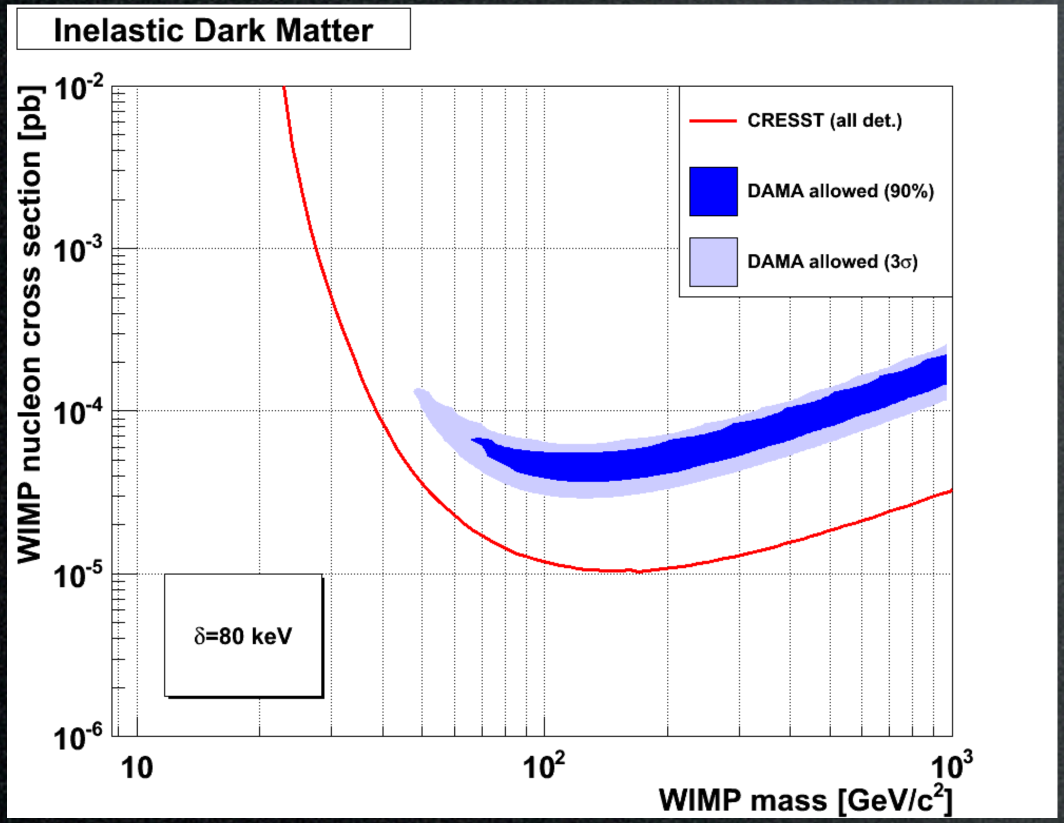
- real particle
  (Majorana fermion, real scalar)
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering

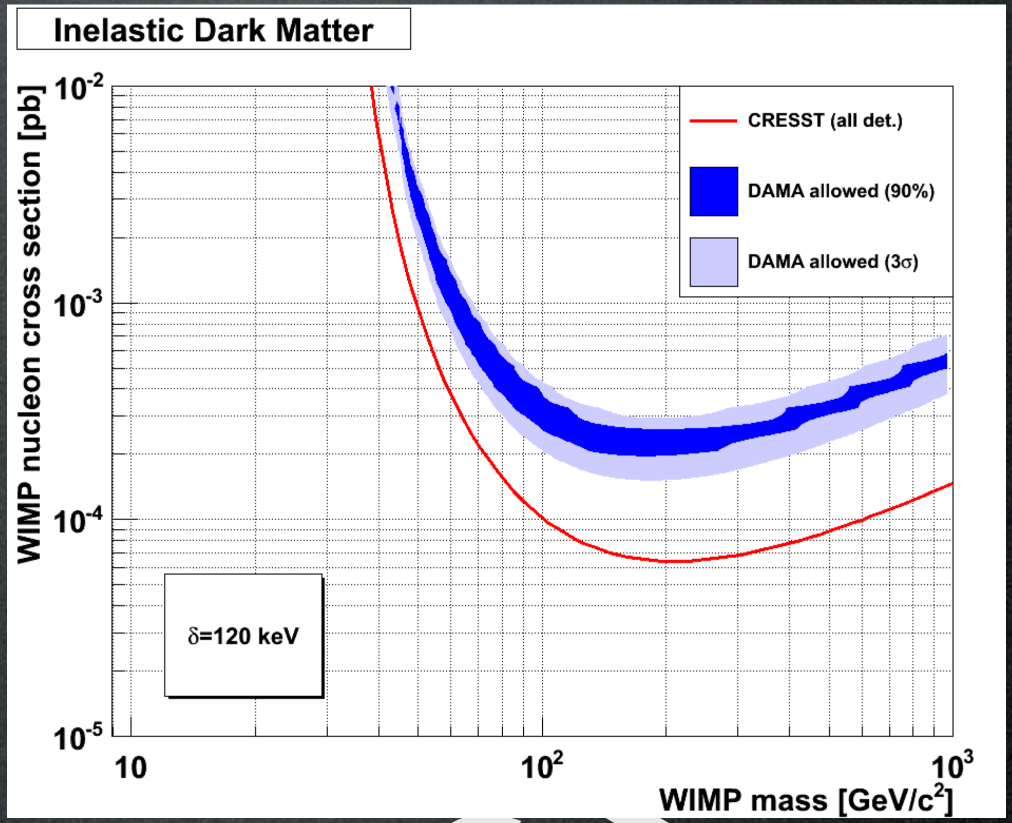


Direct Detection: constraints



CDMS coll., Science 327 (2010), 0912.3592





CRESST, Jochum et al., JPPNP 3369, 15.01.2011

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

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

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- basics
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FERMI *ongoing*

AMS2 *summer 2011*

- basics
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OUTLOOK

direct detec[...]

more
CoGeNT

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KIMS
summer 2011

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Xenon100
summer 2011

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OUTLOOK

MiMAC

DRIFT

DEAP/CLEAN

WARP

LUX

Xenon100
summer 2011

direct detection

CoG

Edelweiss

CDMS
summer 2011

XMASS

COUPP

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WARP
LUX

direct detec...

Xenon100
summer 2011

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...MS
...r 2011
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production at colliders

LHC
> 2012?

indirect

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Back up slides

The cosmic inventory

Most of the Universe is Dark

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

72%

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

-BBN
-CMB

1%
4%

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

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?

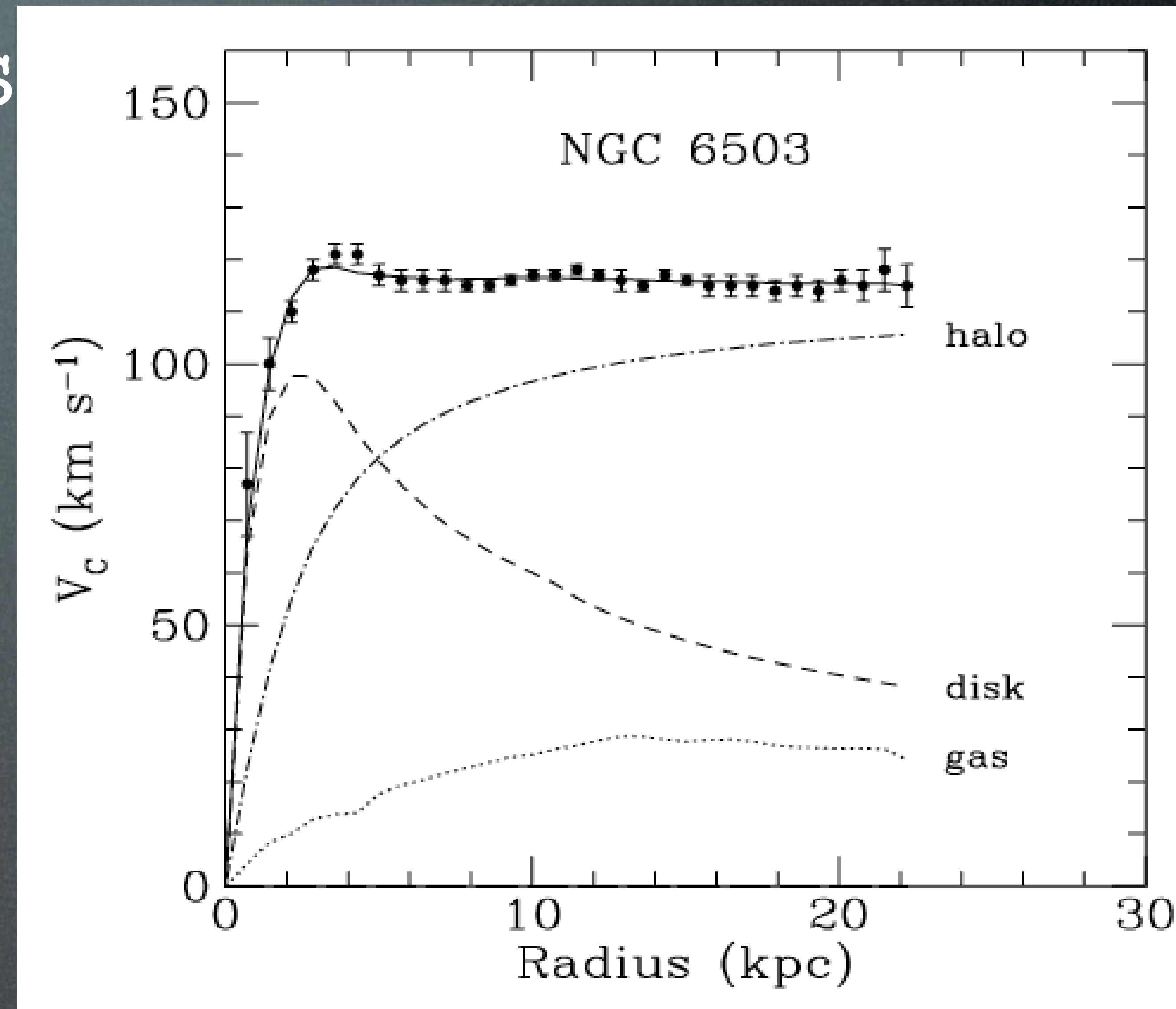
The Evidence for DM

1) galaxy rotation curves

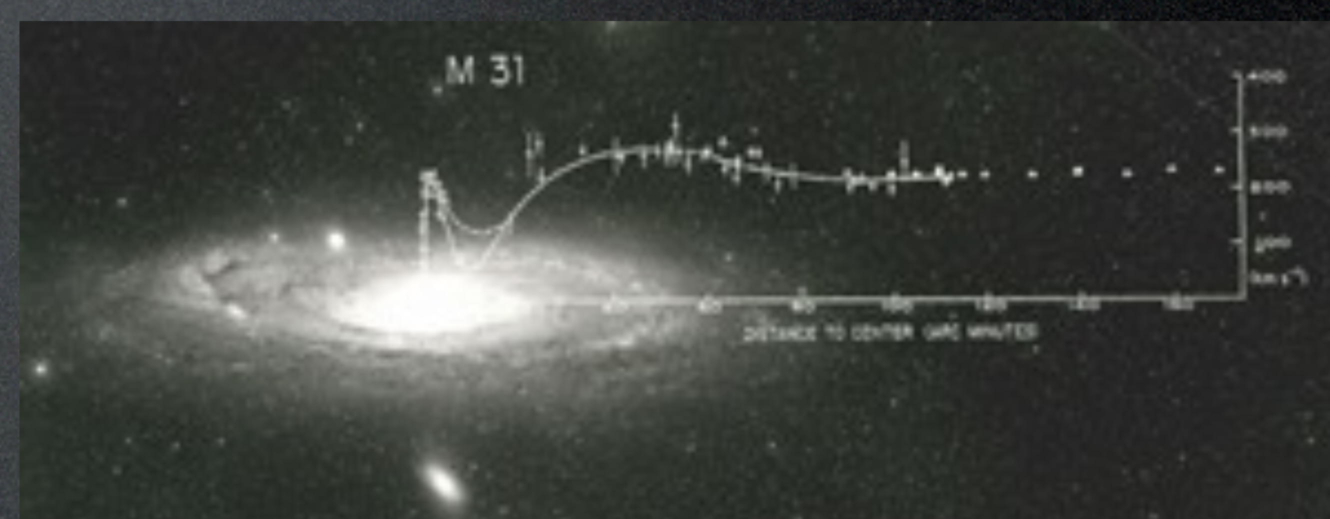
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

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

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



Begeman et al., MNRAS 249 (1991)



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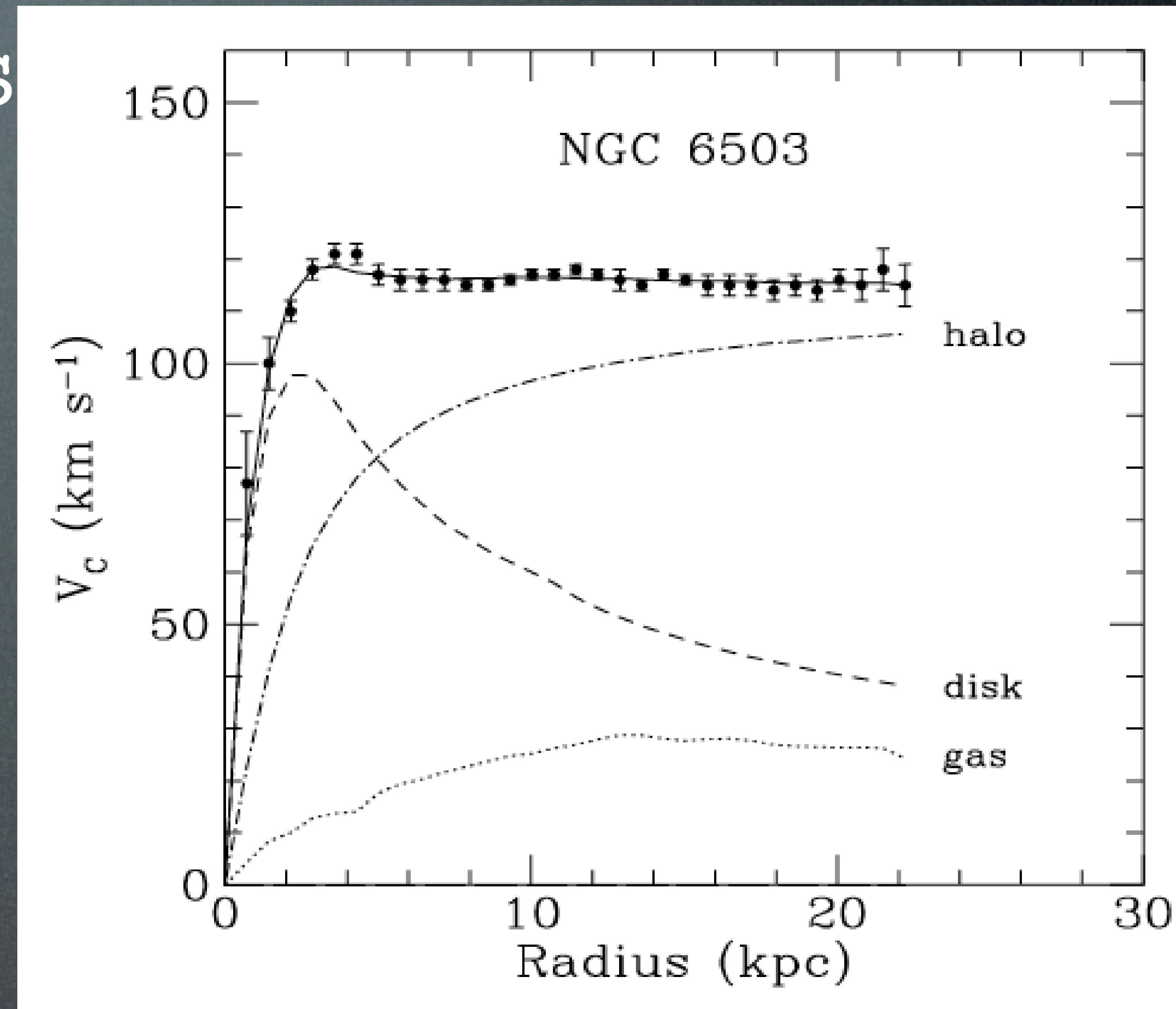

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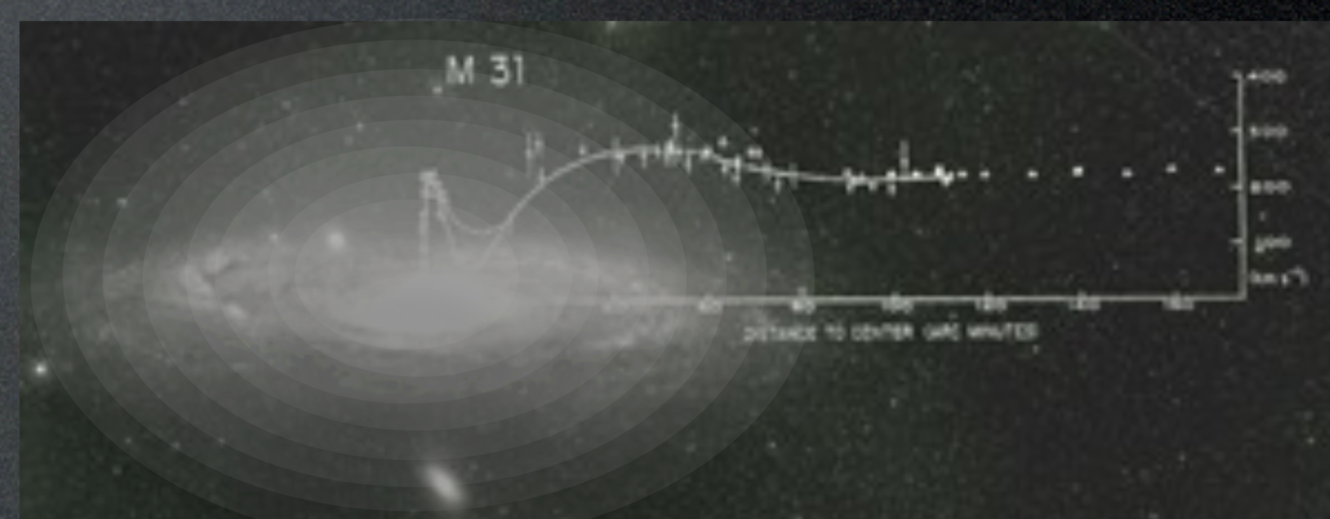

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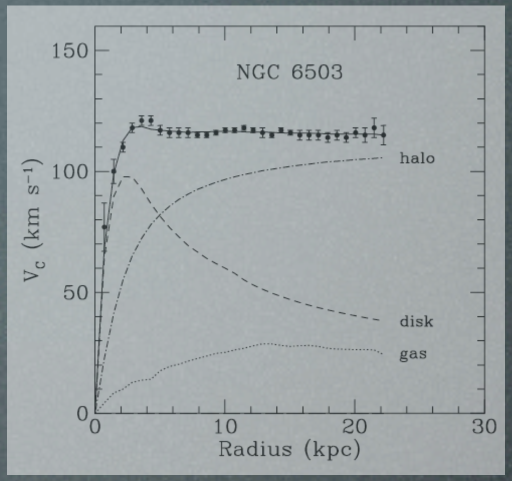

$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

- "rotation curves"
- gravitation lensing

$$\Omega_M \sim 0.2 \div 0.4$$

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

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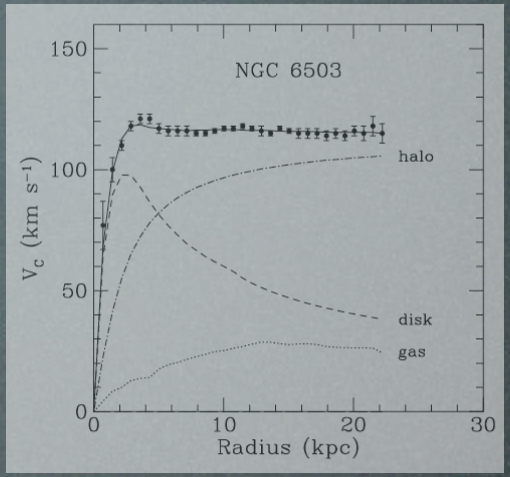

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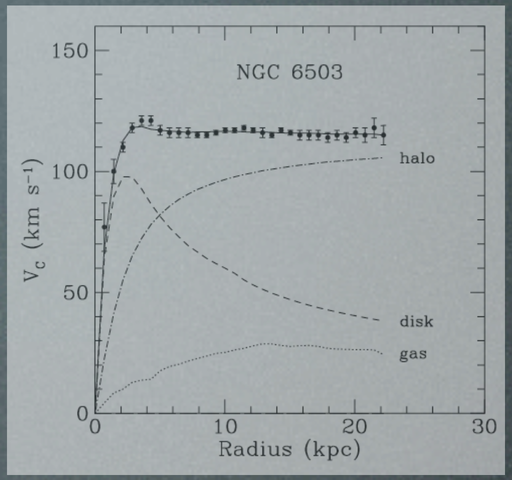

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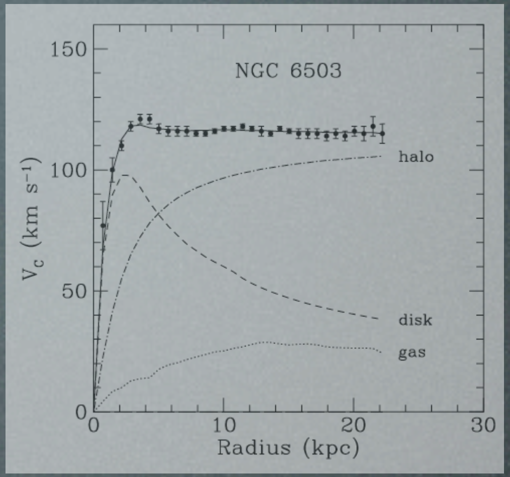

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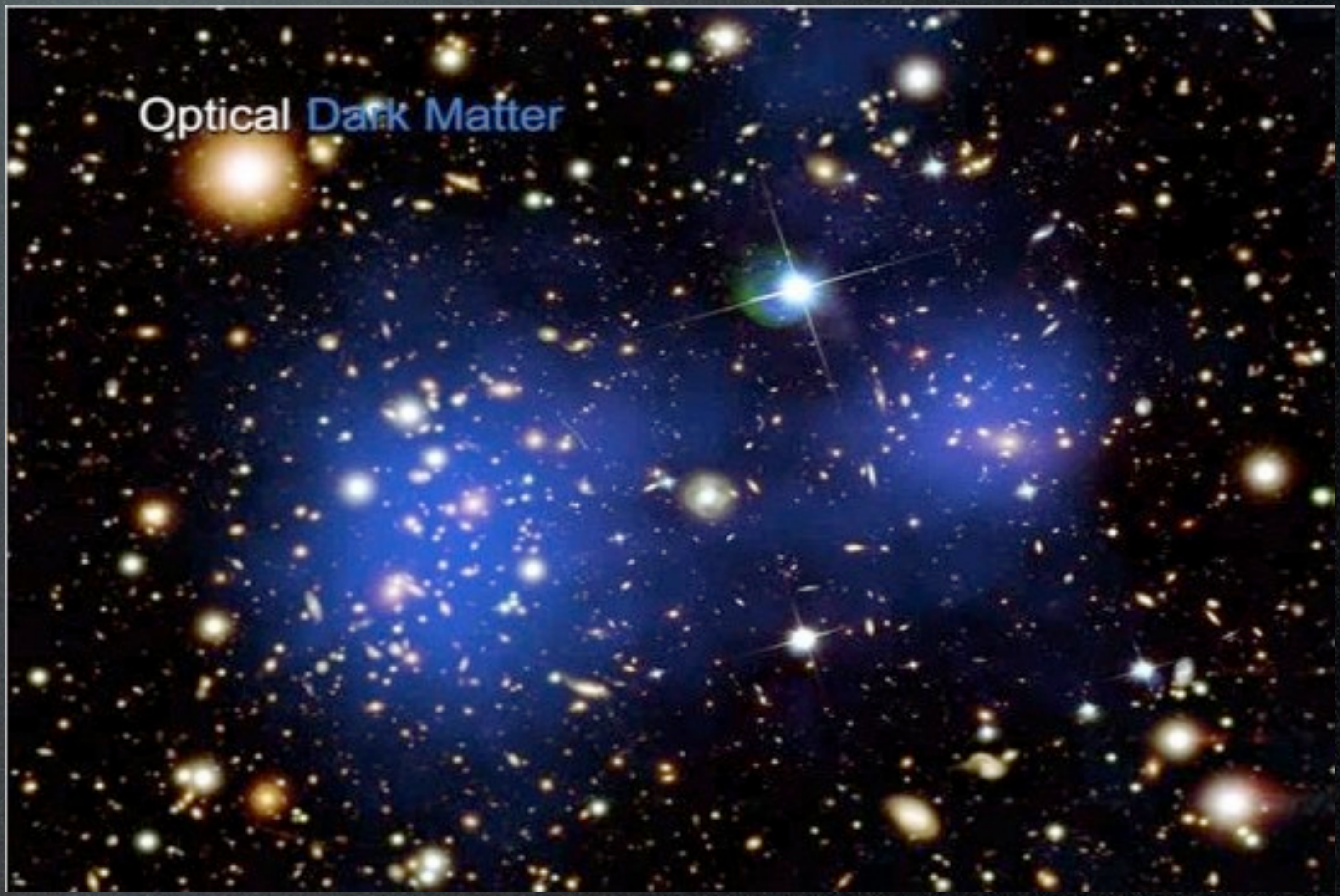

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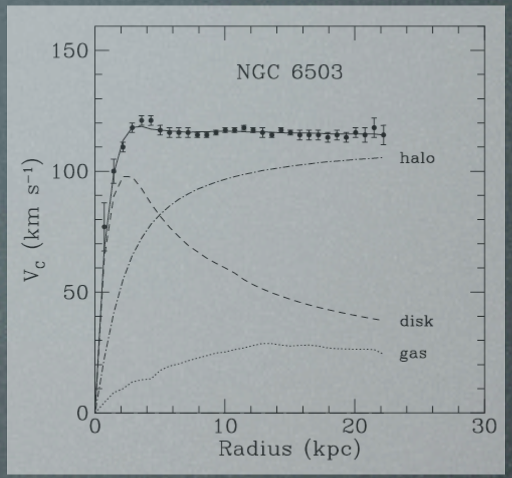

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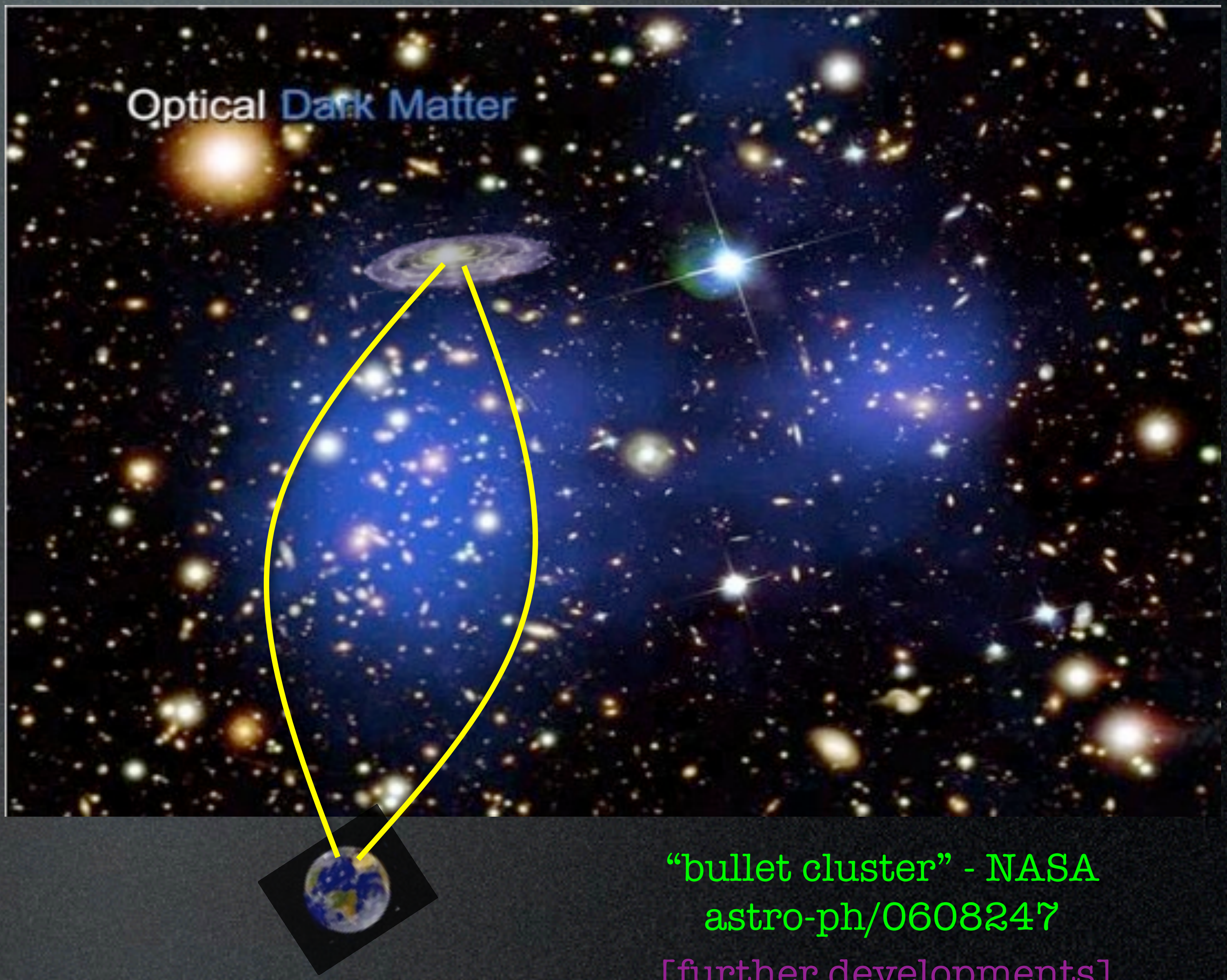

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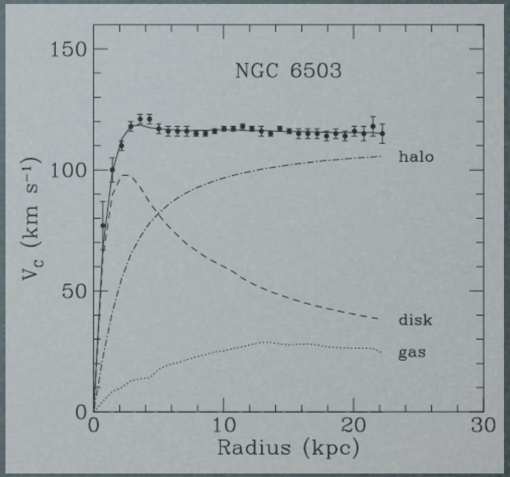

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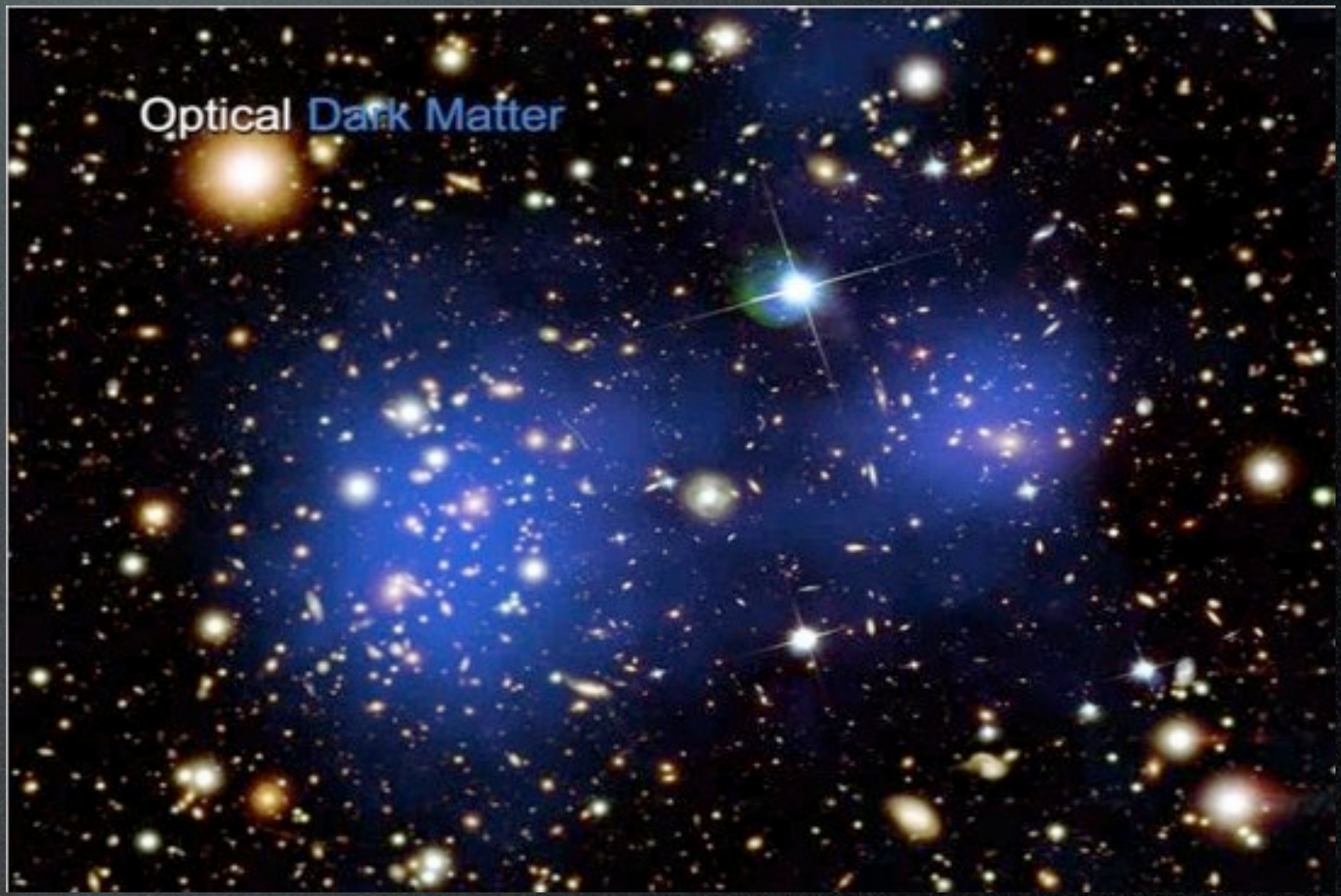

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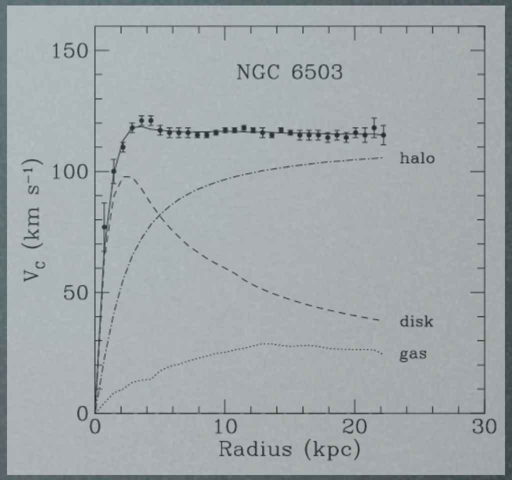

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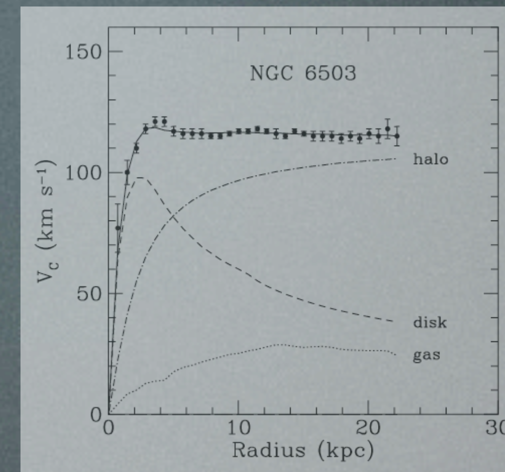

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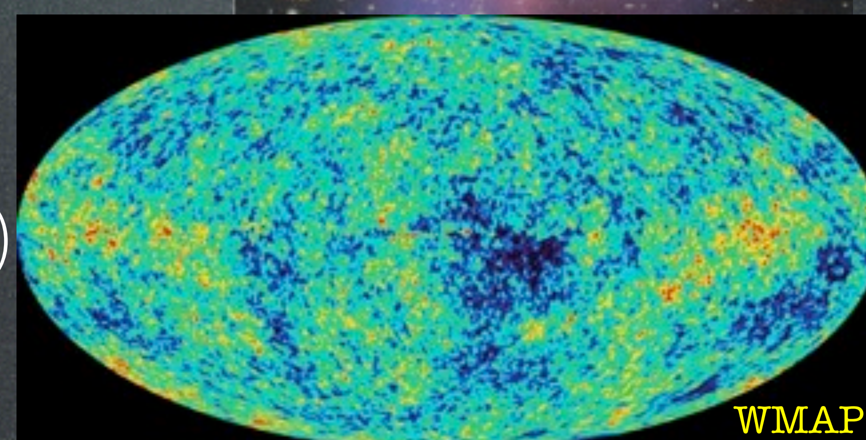

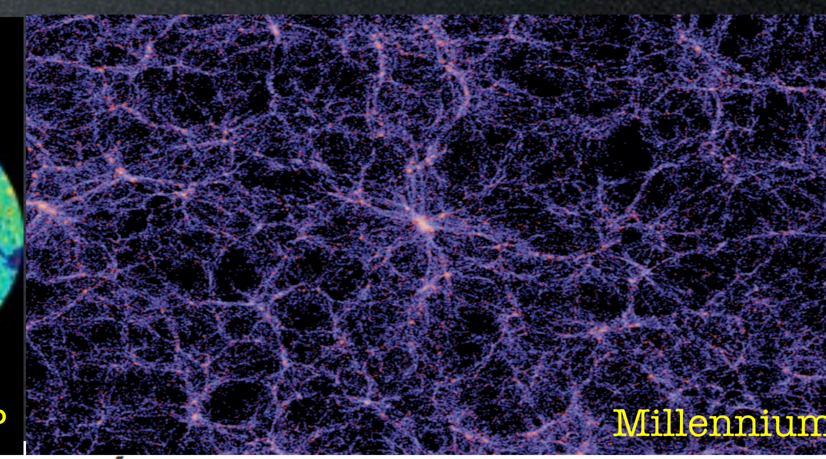

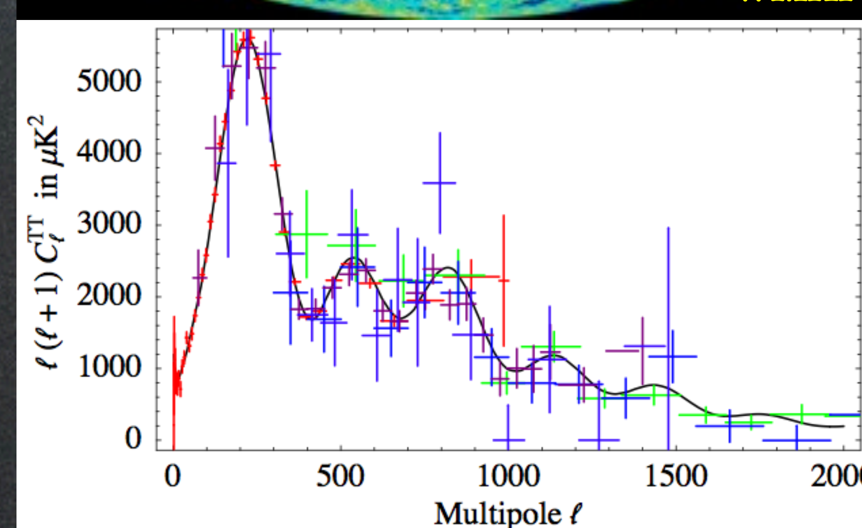

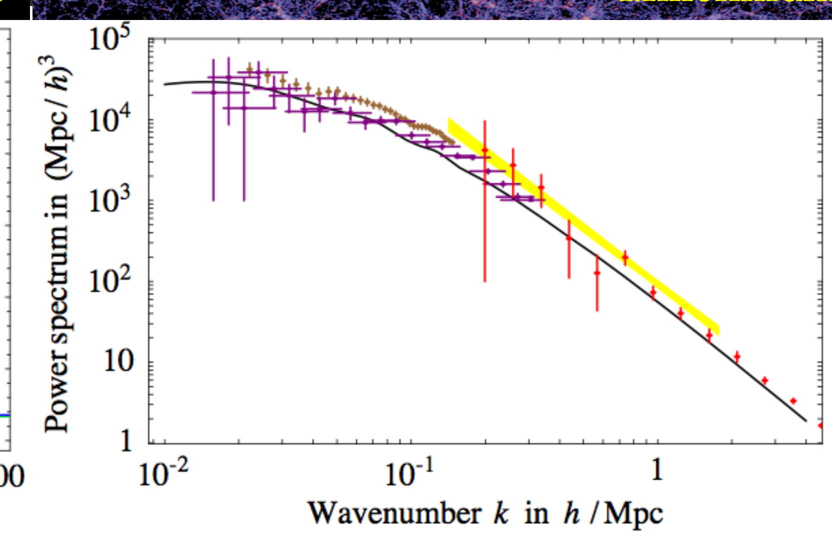

M.Cirelli and A.Strumia, astro-ph/0607086

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

Andrey Kravtsov, cosmicweb.uchicago.edu

[back]

DM N-body simulations

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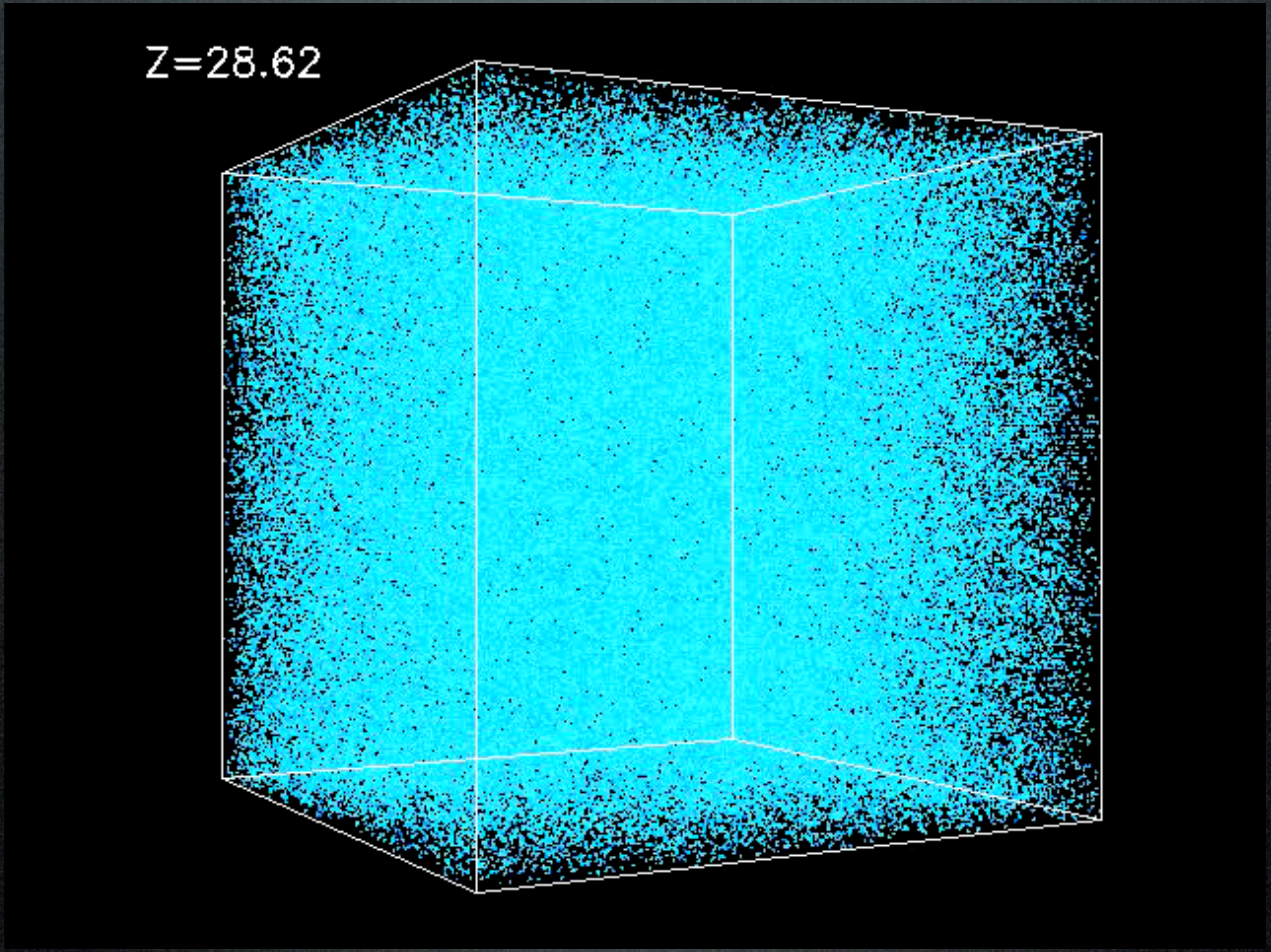

Andrey Kravtsov, cosmicweb.uchicago.edu

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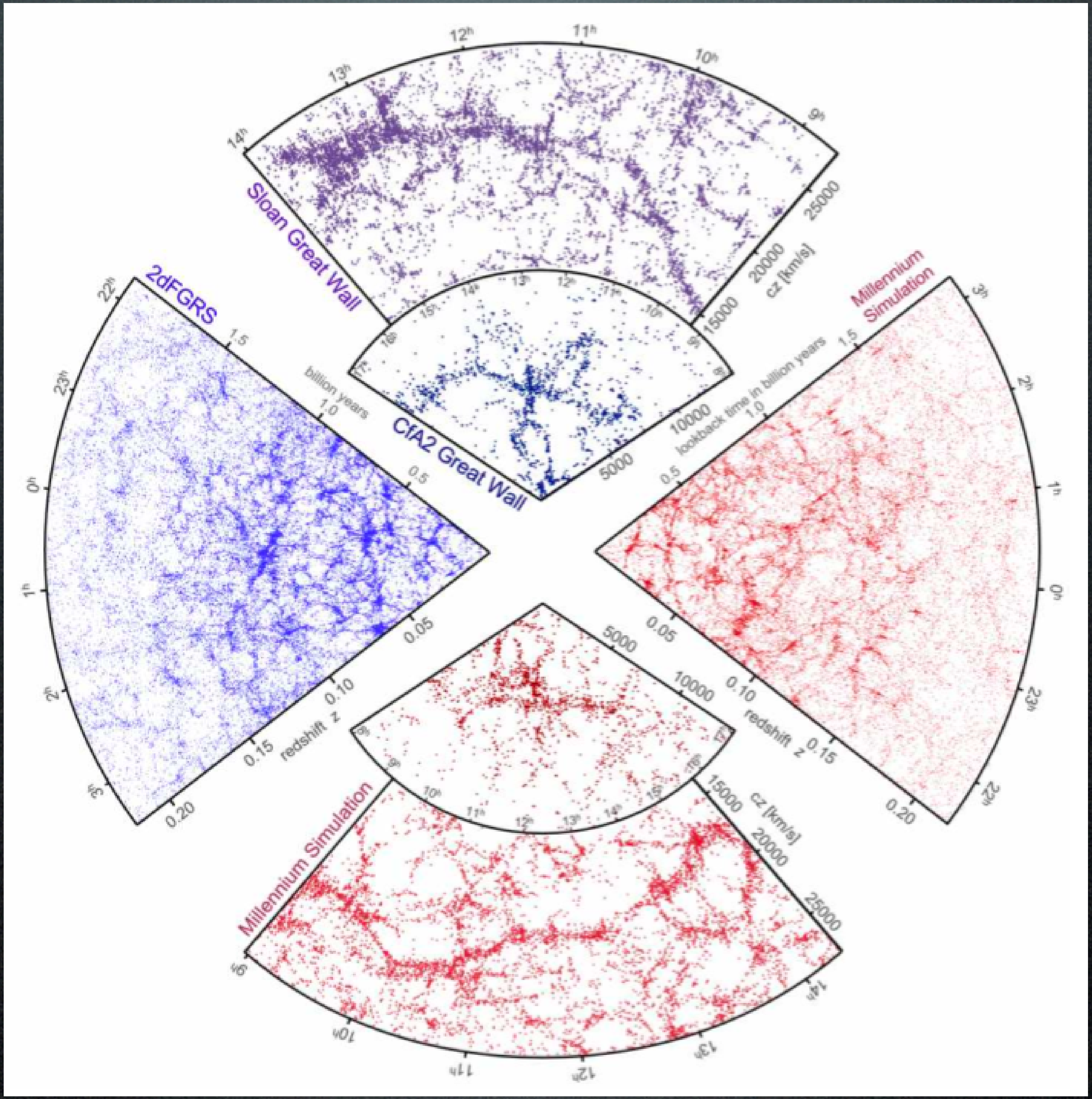
DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr



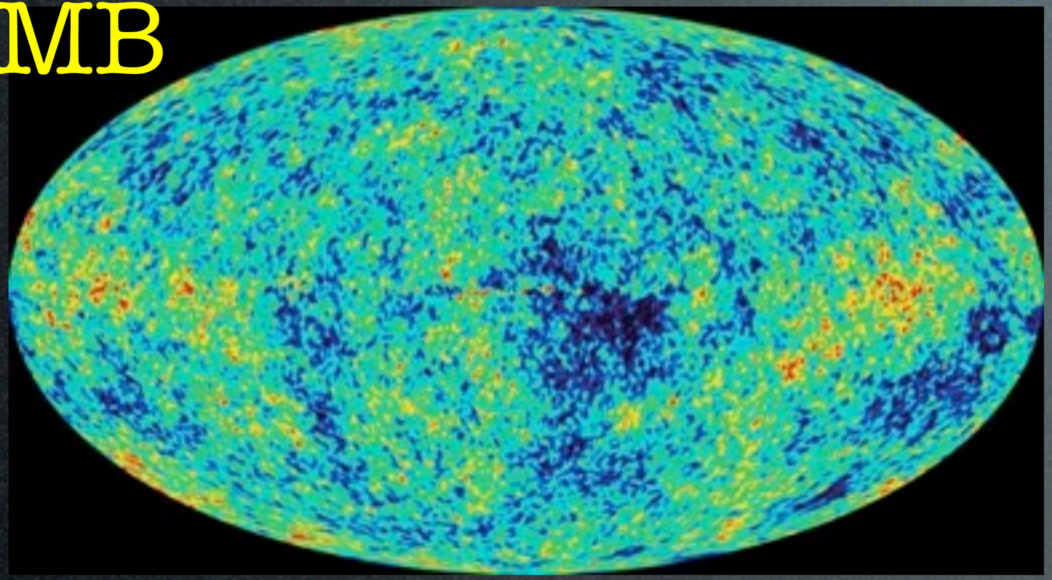
Springel, Frenk, White, Nature 440 (2006)

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

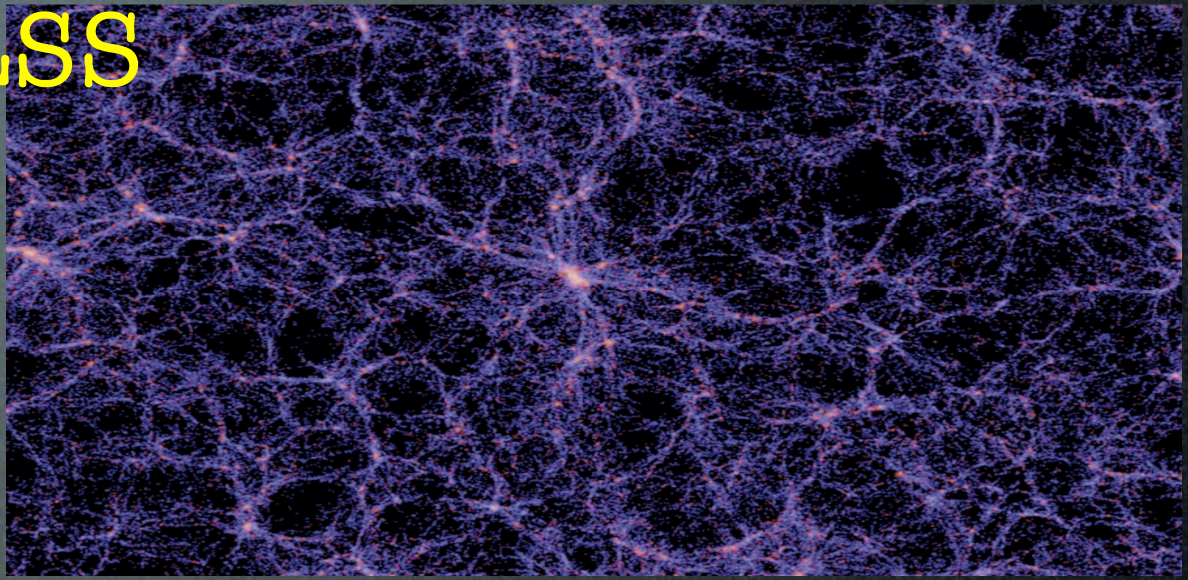
[back]

The Evidence for DM

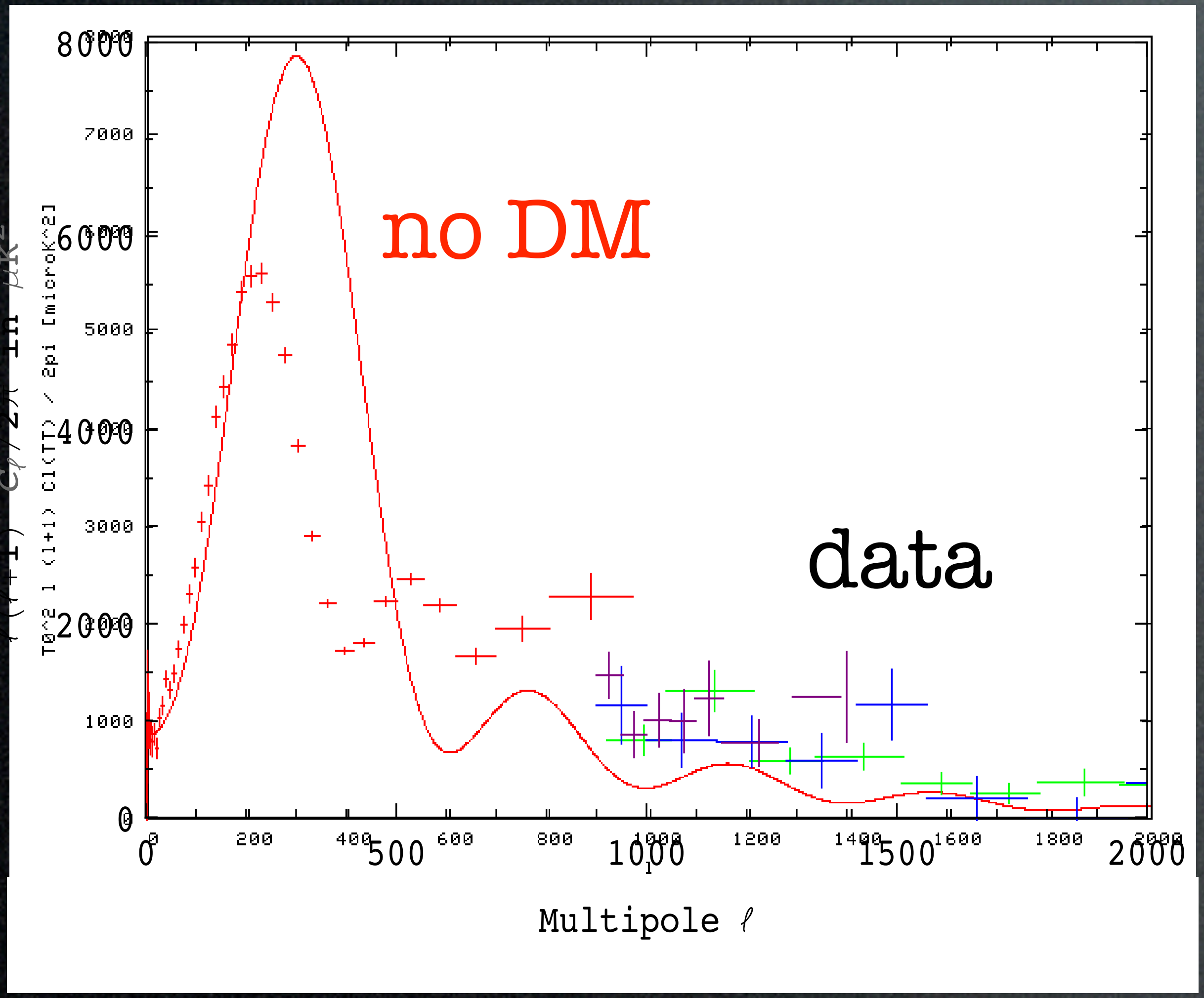
CMB



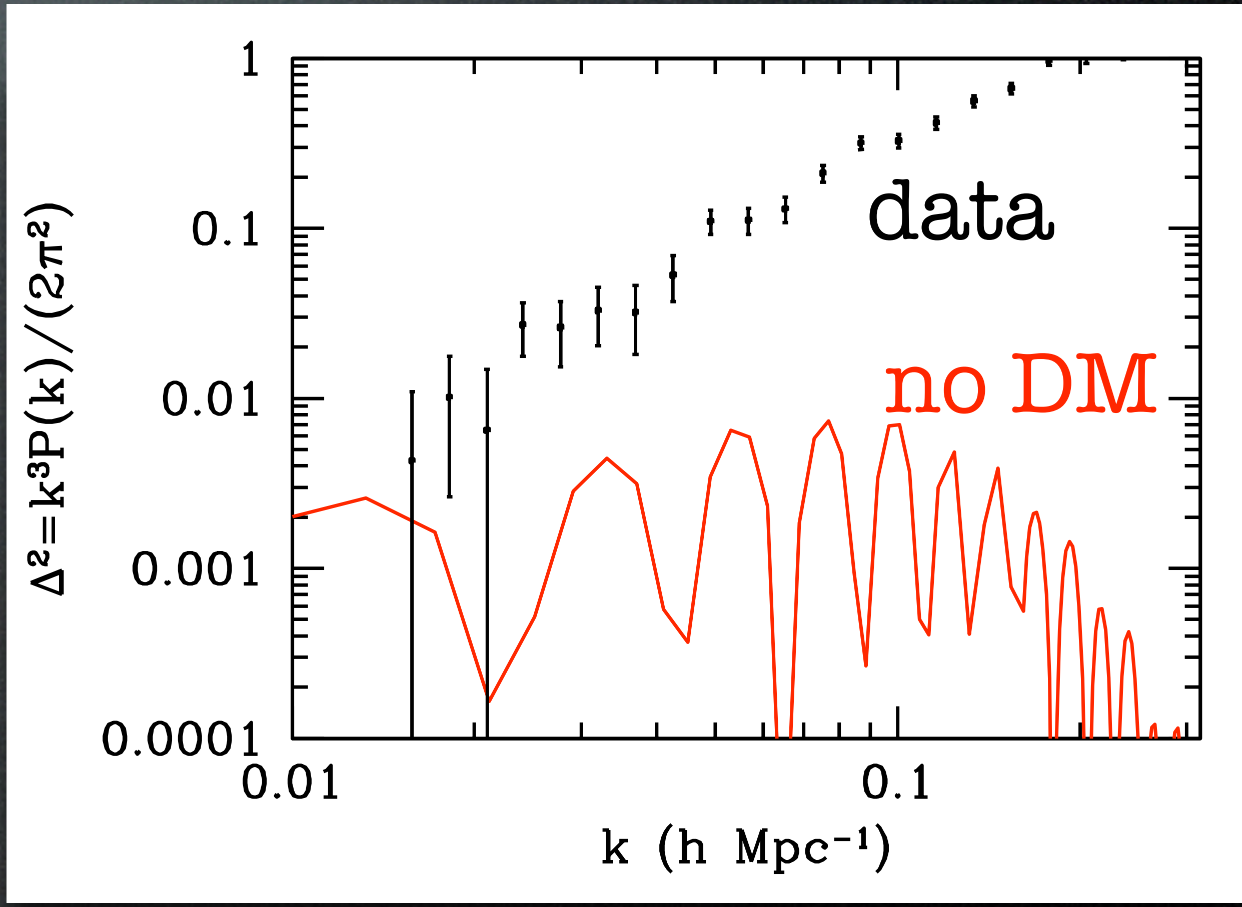
LSS



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



CAMB online



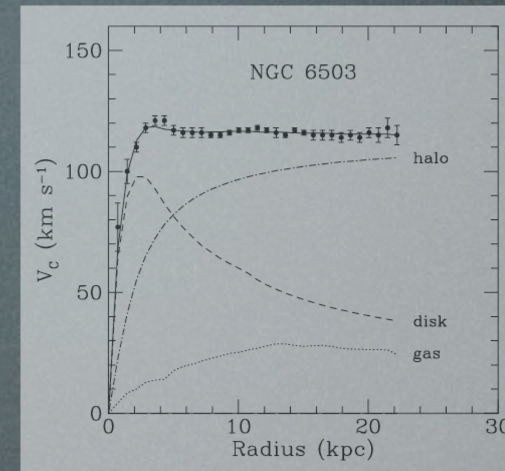
Dodelson, Liguori 2006

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

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

The Evidence for DM

1) galaxy rotation curves

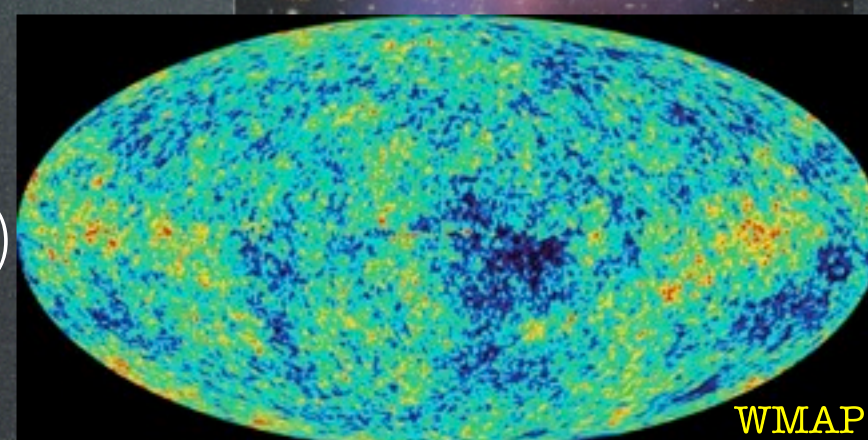


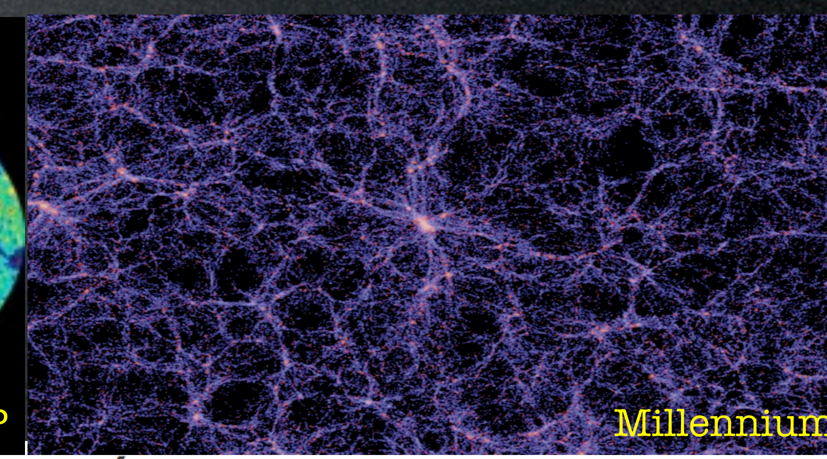
$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

$\Omega_M \sim 0.2 \div 0.4$

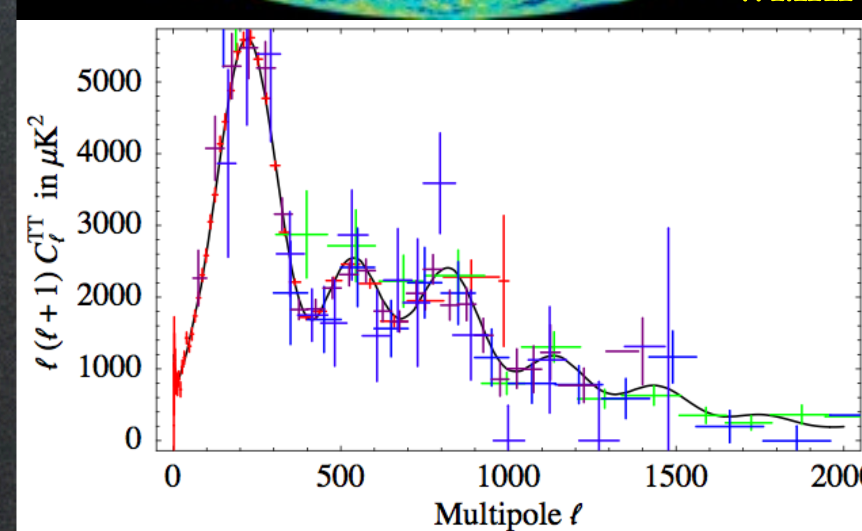
3) CMB+LSS(+SNIa:)

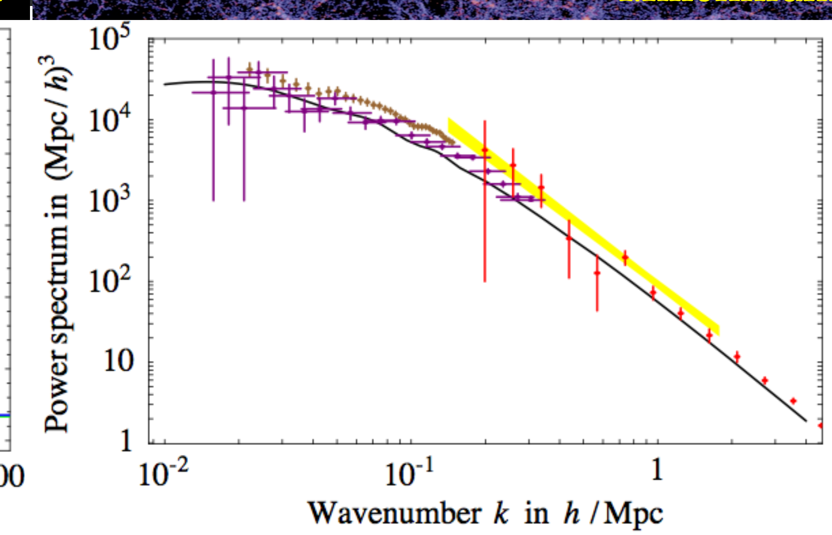




WMAP-3yr Boomerang
ACbar DASI
CBI VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS





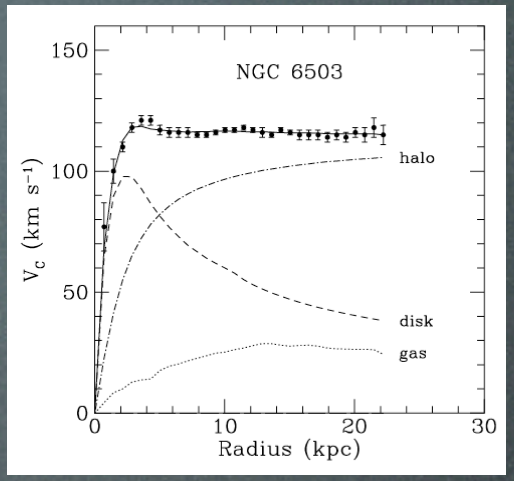
$\Omega_M \approx 0.26 \pm 0.05$

(spectra w/o DM)

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

The Evidence for DM

1) galaxy rotation curves



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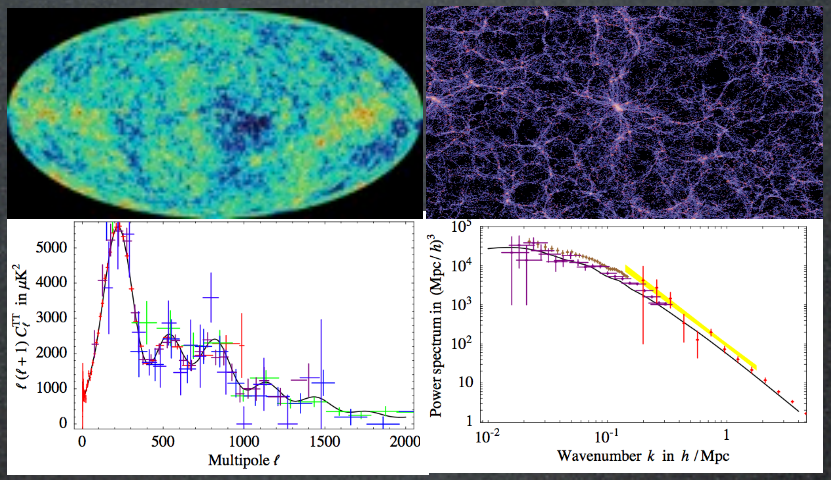

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[back]

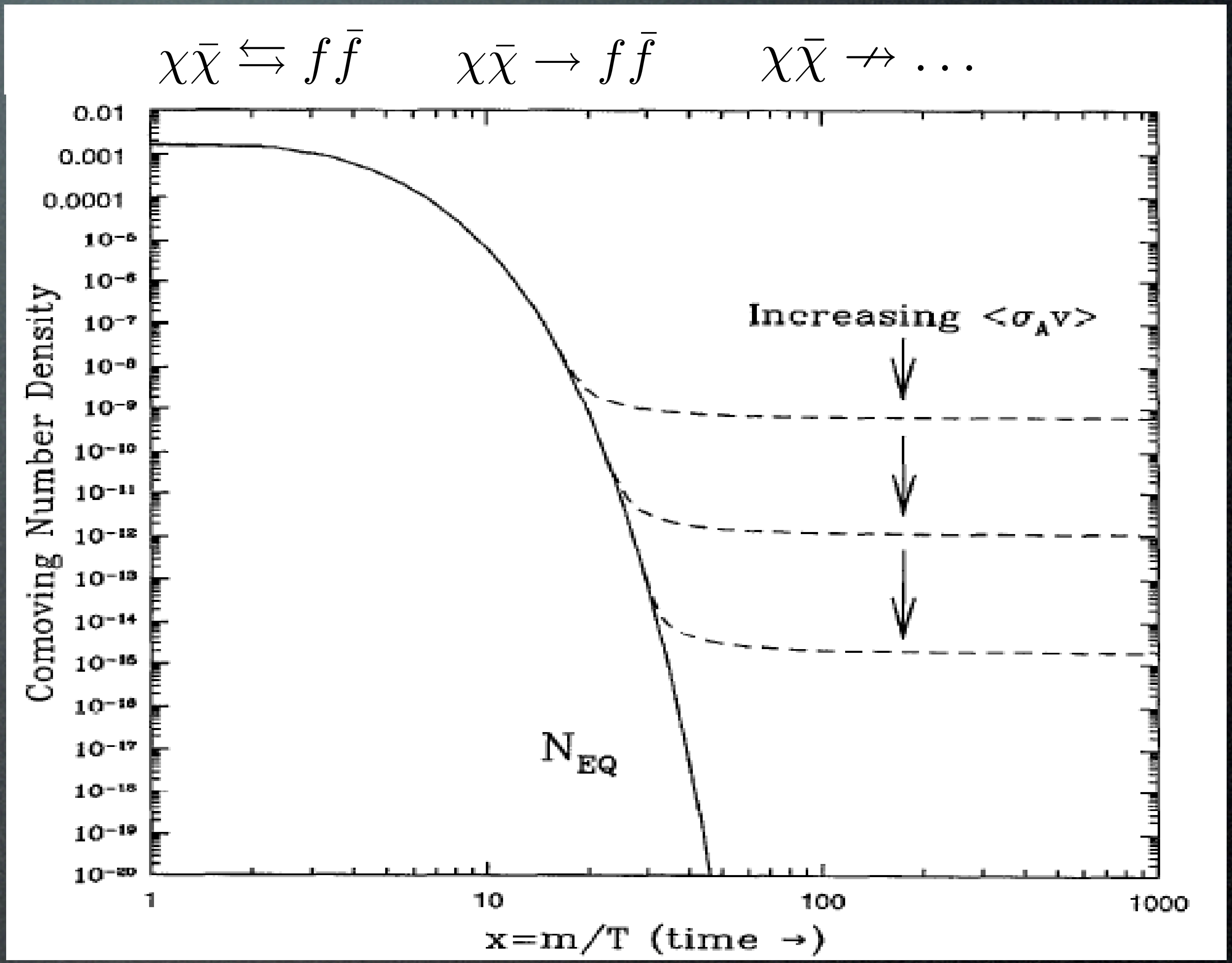
A thermal relic from the Early Universe

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)

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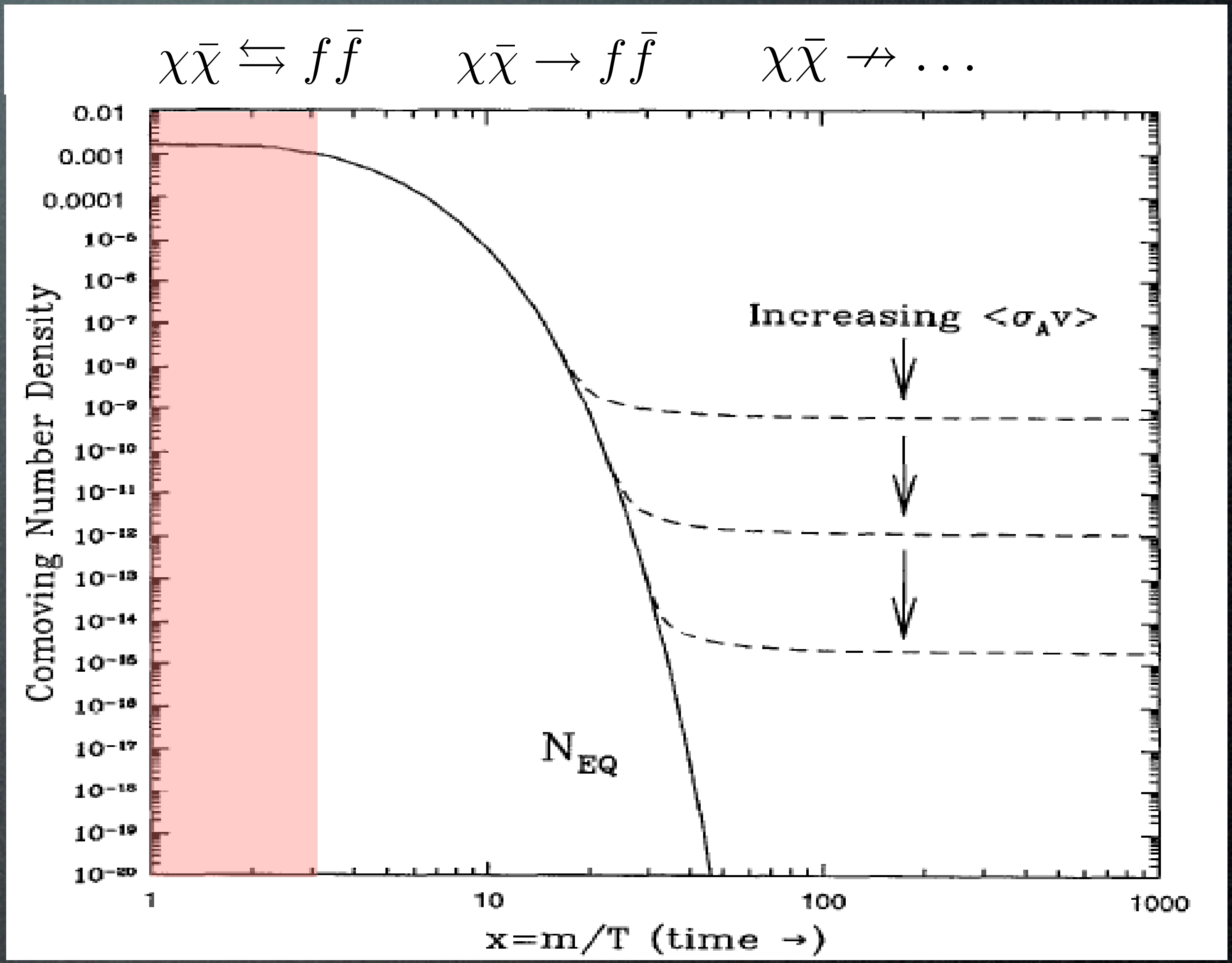

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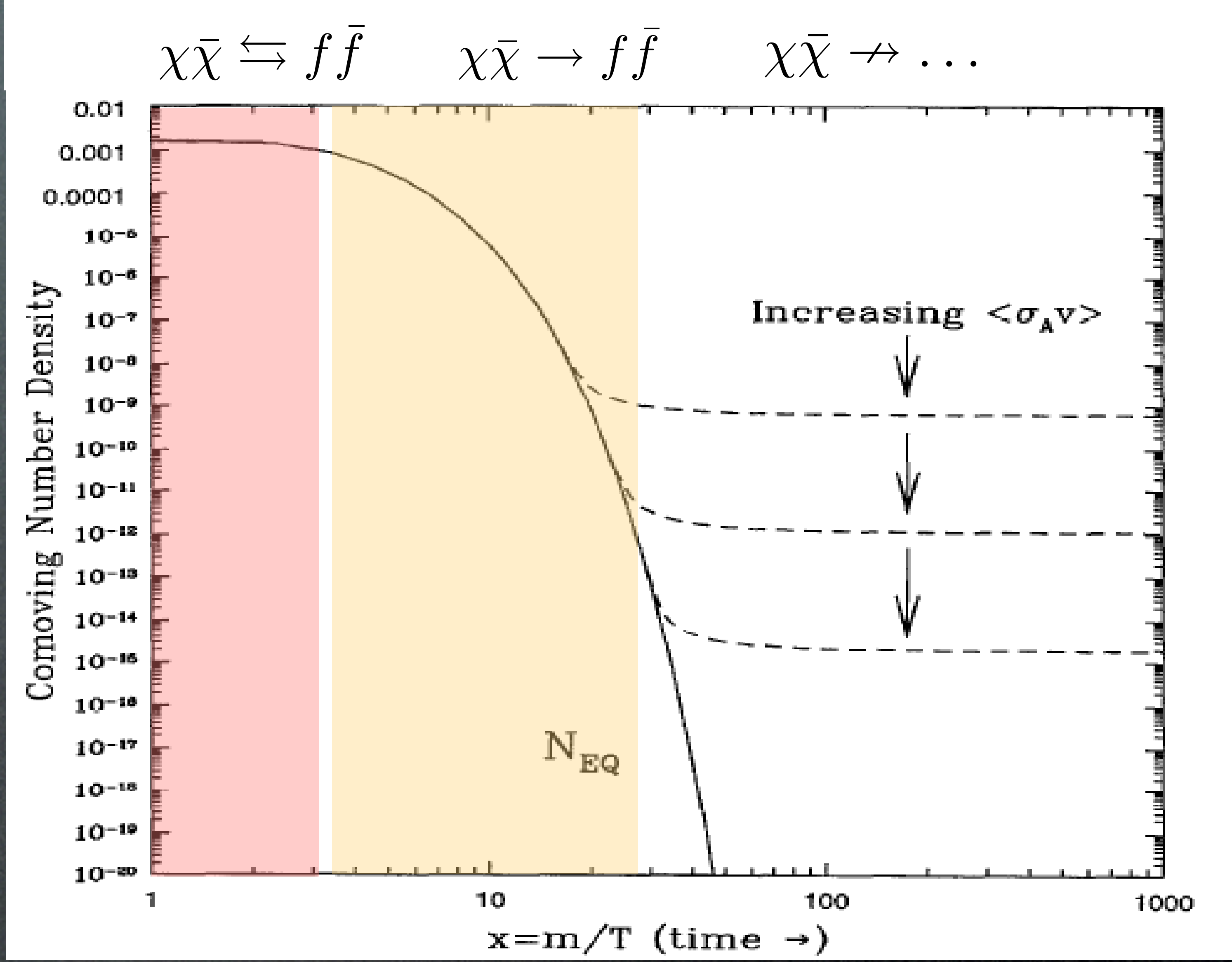

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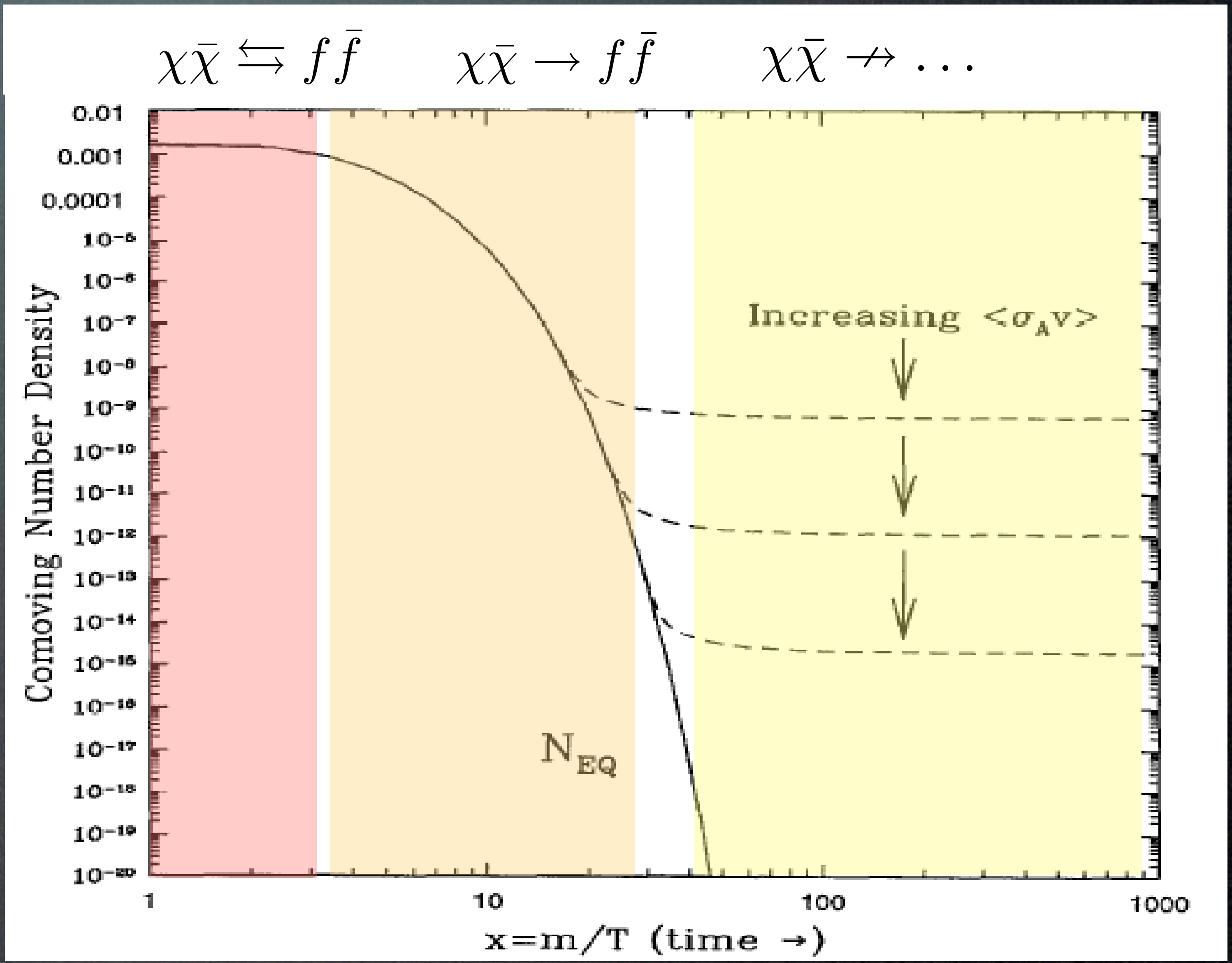


Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

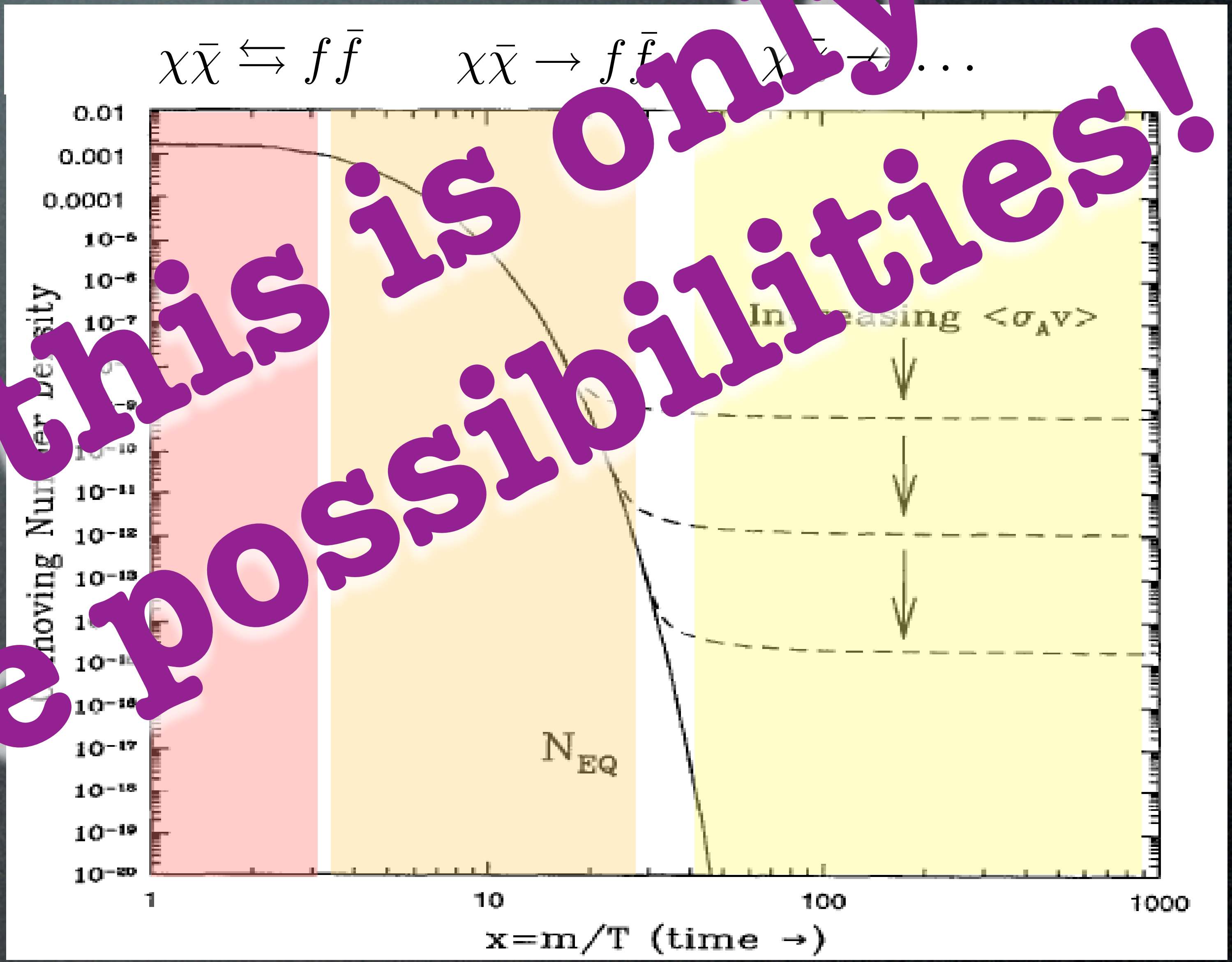
A thermal relic from the Early Universe

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

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)

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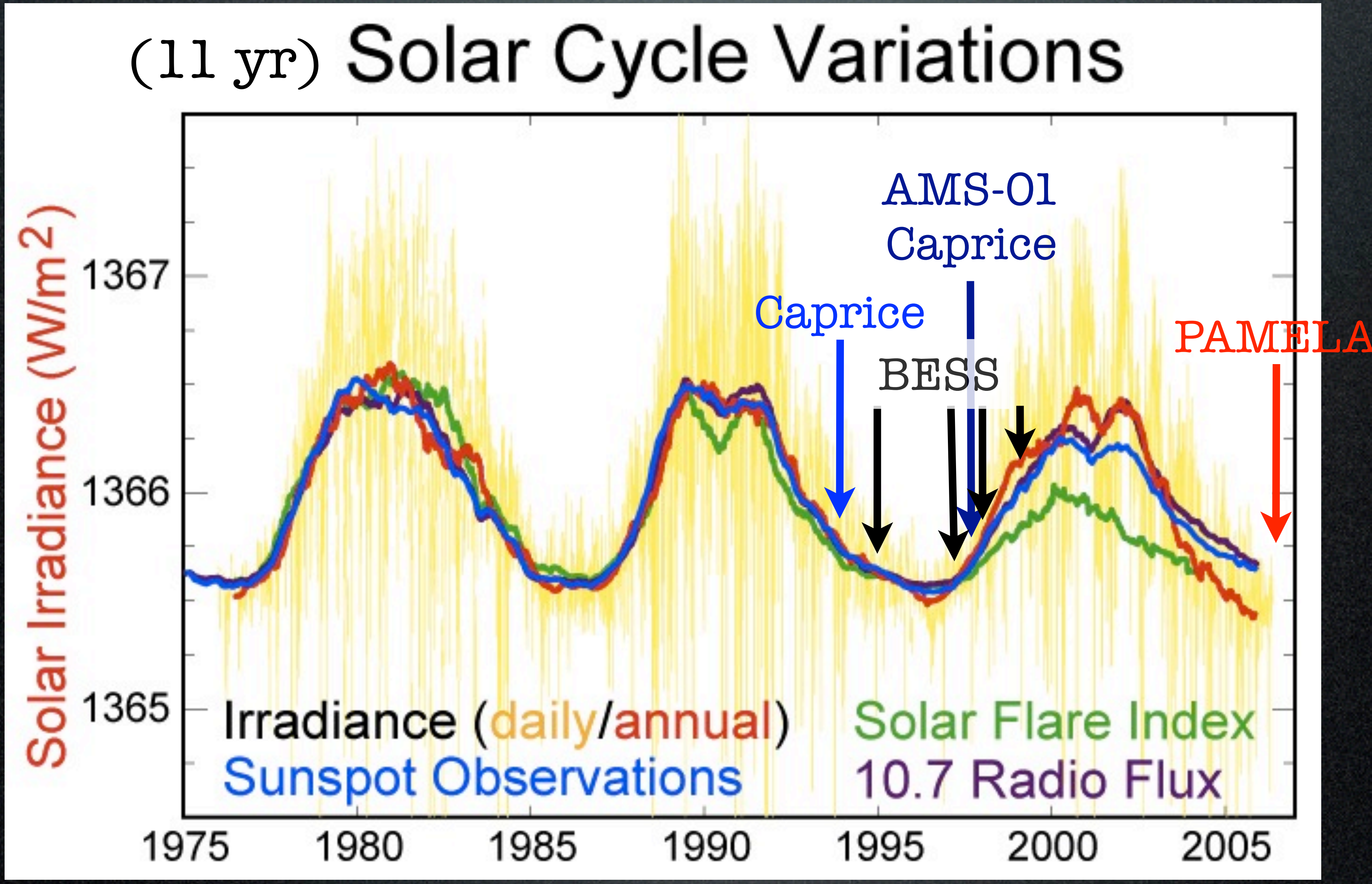
Indirect Detection

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

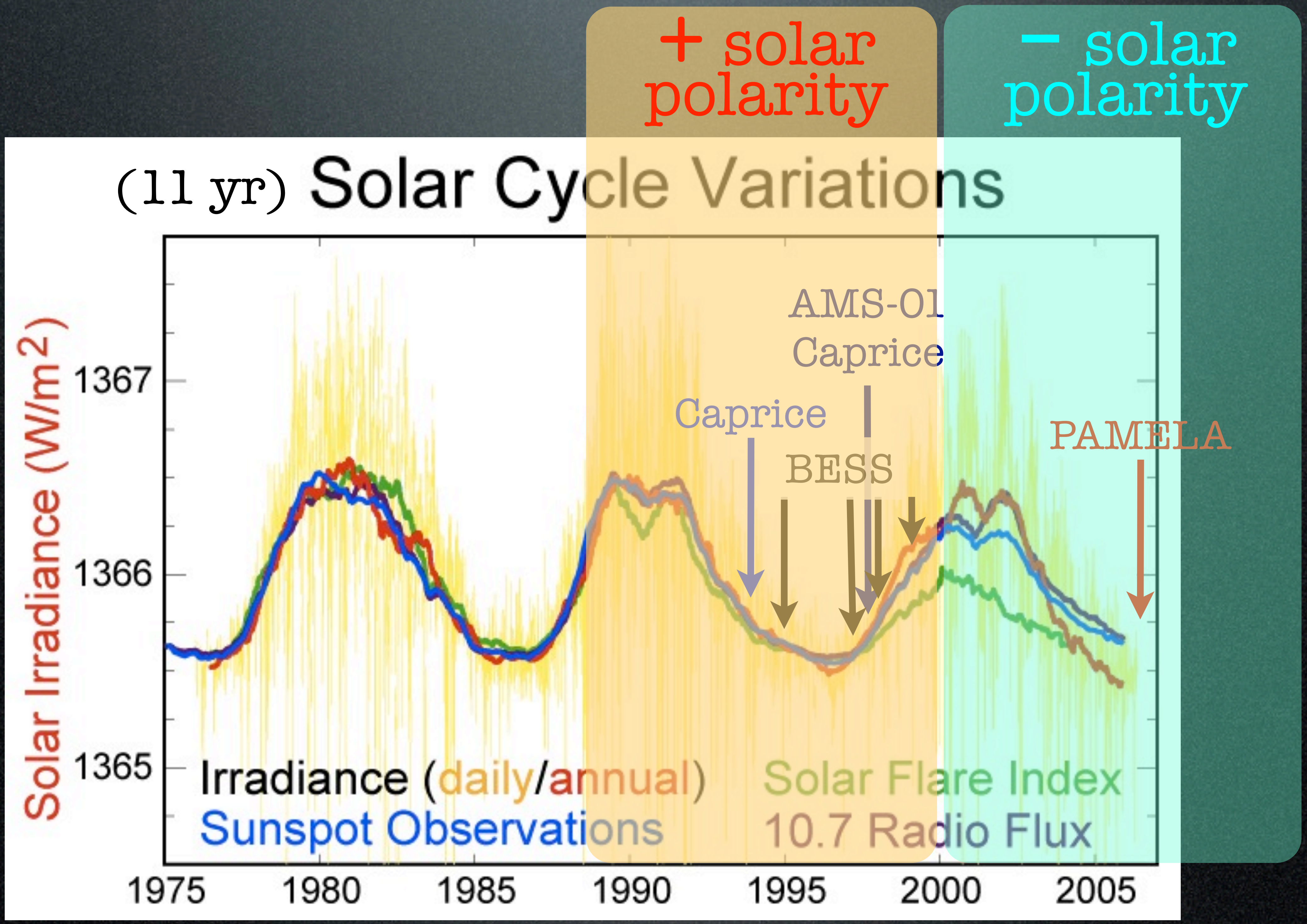


Indirect Detection

Solar polarity Modulation of cosmic rays:

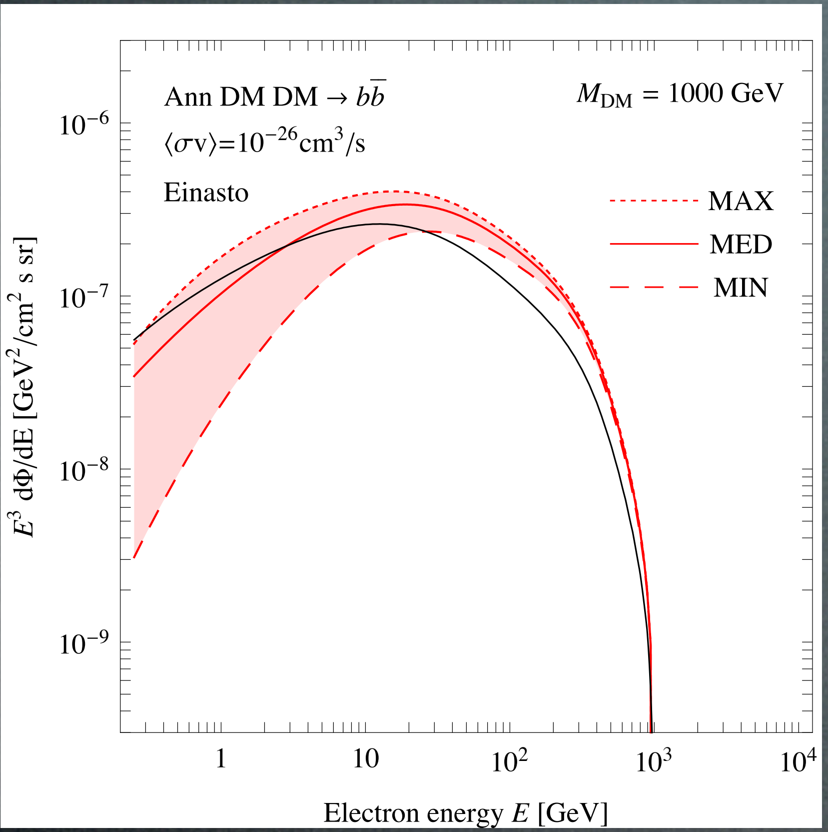
solar magnetic polarity reverses at (the max of) each cycle;
during '– polarity' state, positive particles are more deflected away

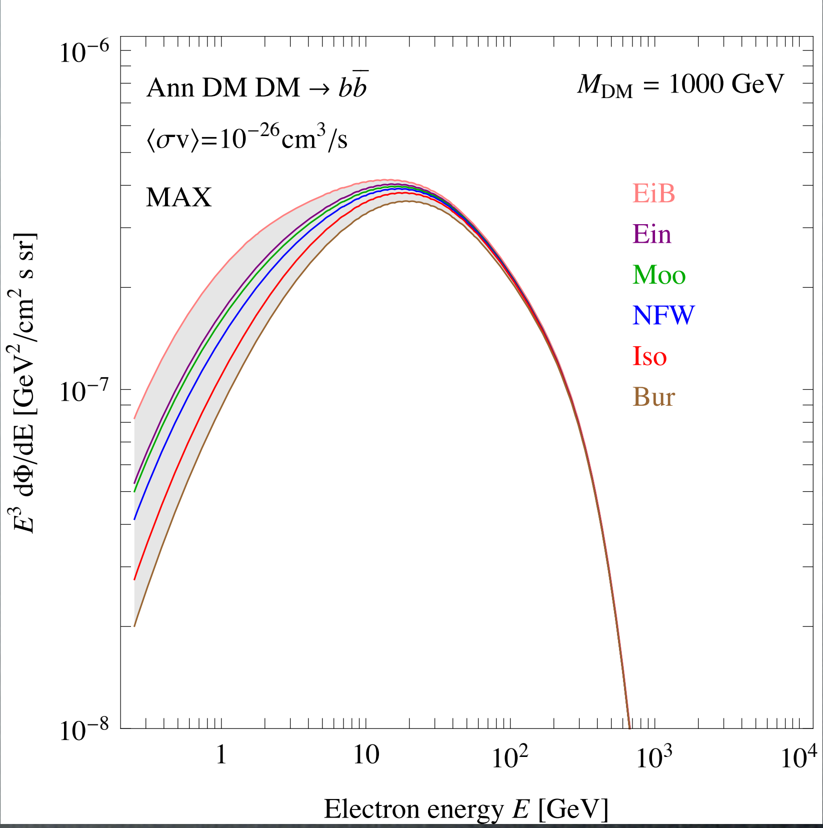
+ = rotation parallel to magnetic field;
- = antiparallel



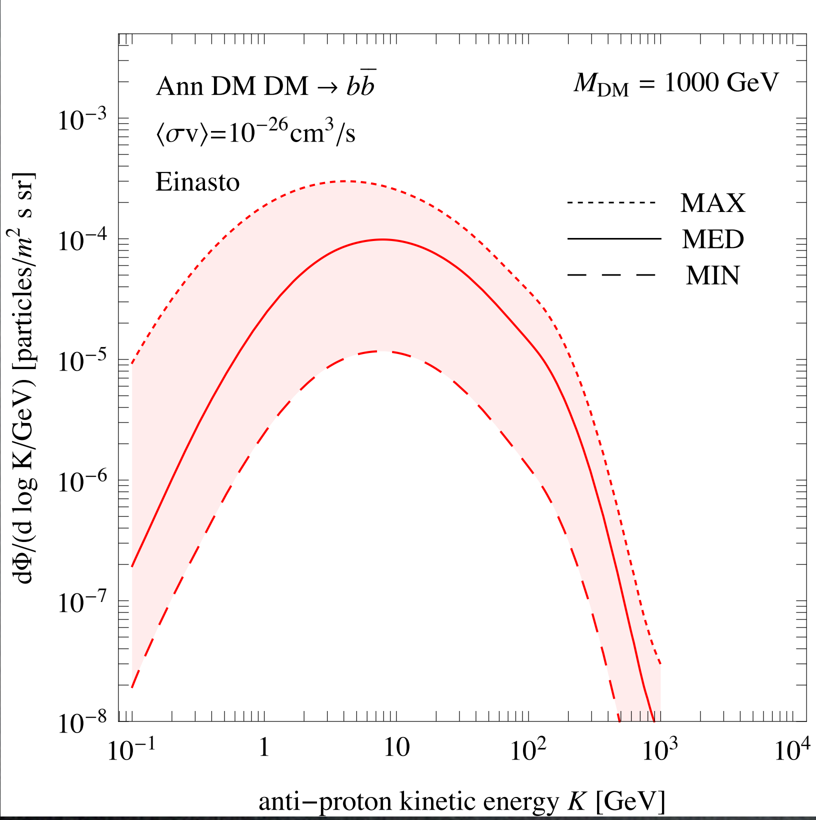
‘Astro’ uncertainties

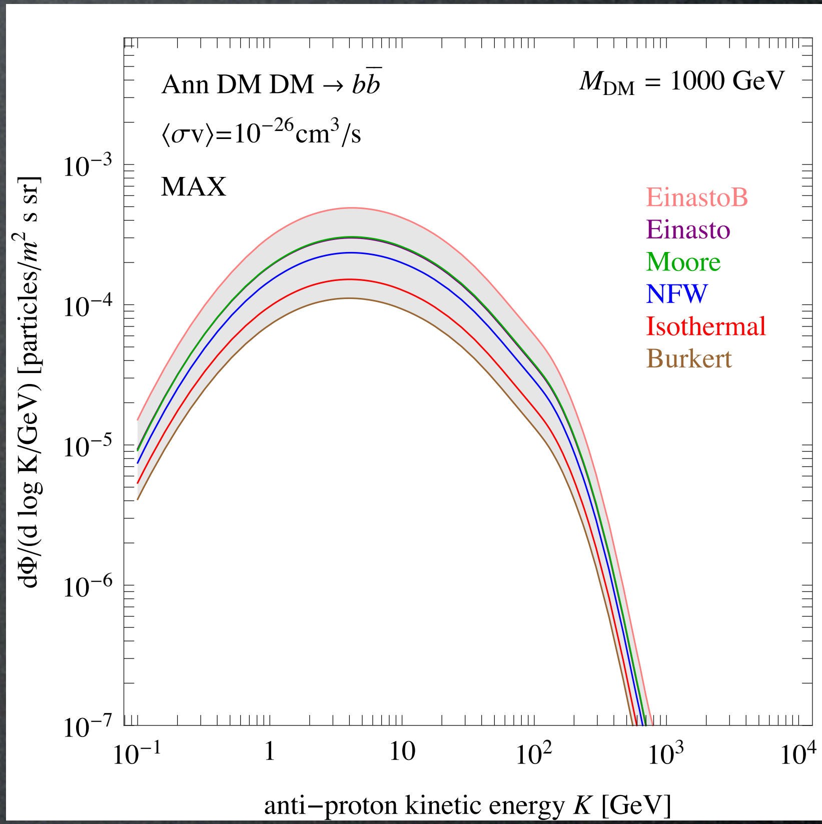
$e^{\pm}$





$\bar{p}$





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Predictions?!?

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Is Dark Matter around the corner?

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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.