

14 November 2011
Bethe Forum, Bonn

Indirect Searches for DM: status circa 11/2011

Marco Cirelli
(CERN-TH & CNRS IPhT Saclay)

Reviews on Dark Matter and DM ID:

Jungman, Kamionkowski, Griest, Phys.Rept. 267, 195-373, 1996

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even worse!

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The current status: a story of:

Hints

Constraints

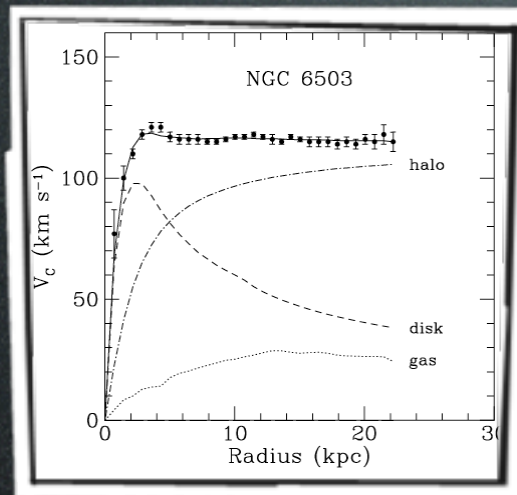
Hopes

Introduction

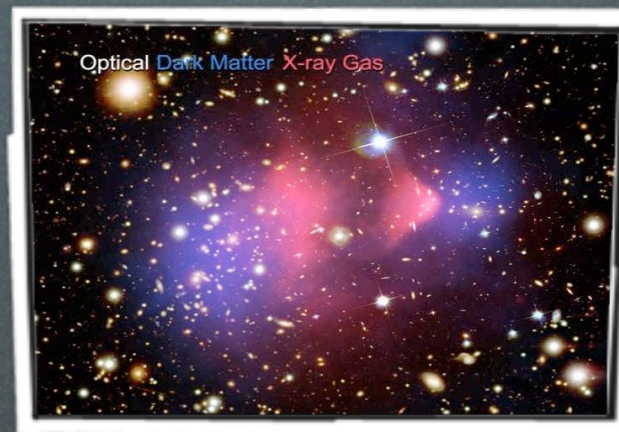
DM exists

Introduction

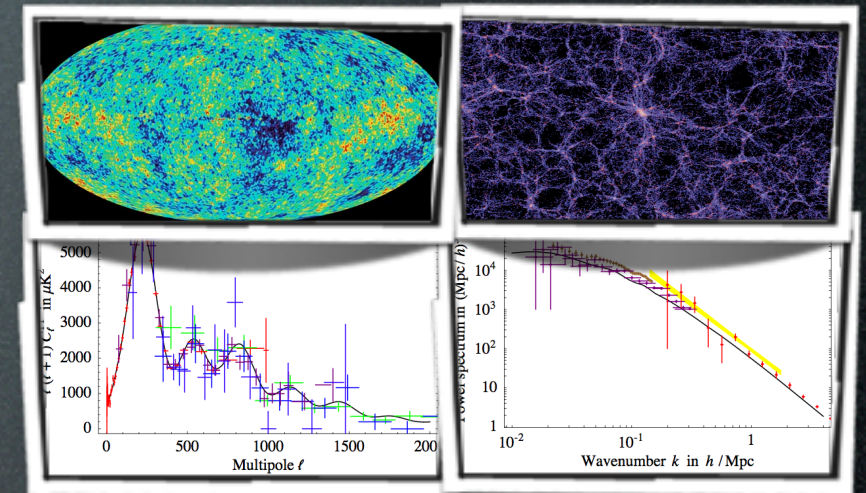
DM exists



galactic rotation curves



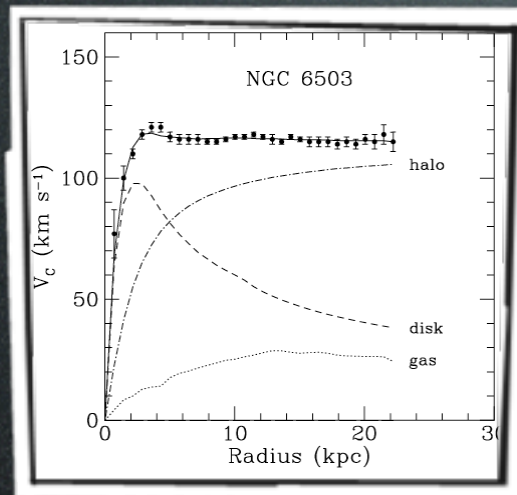
weak lensing (e.g. in clusters)



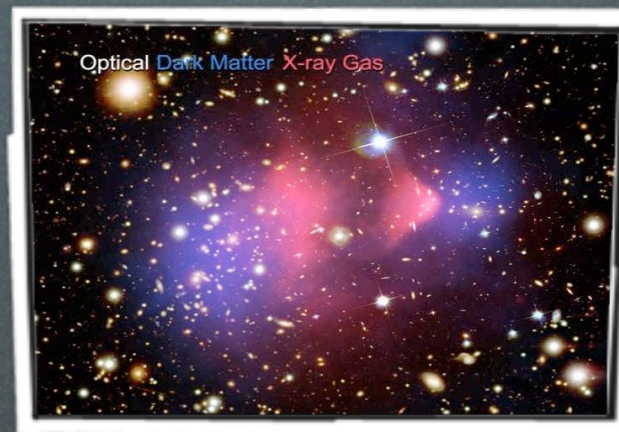
'precision cosmology' (CMB, LSS)

Introduction

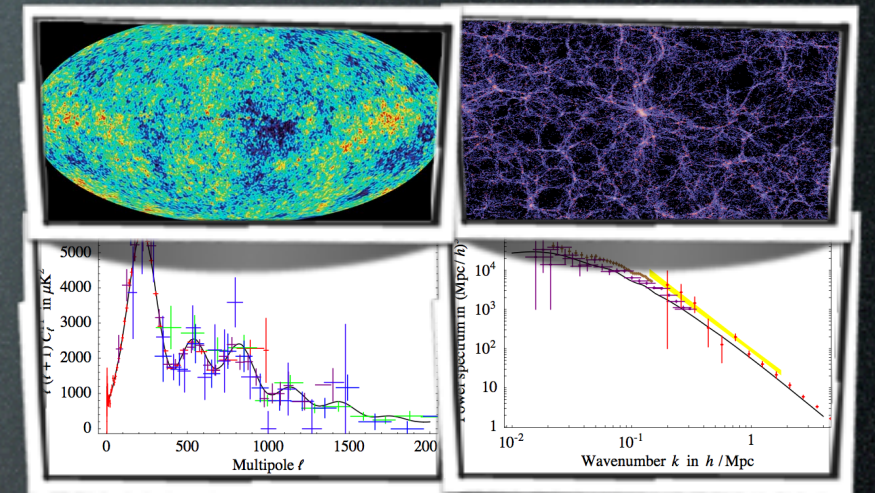
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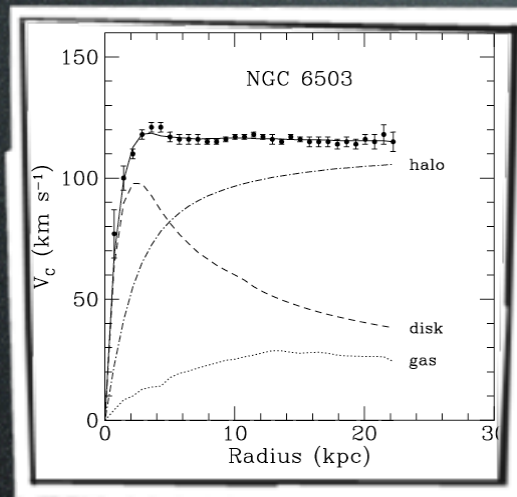


'precision cosmology' (CMB, LSS)

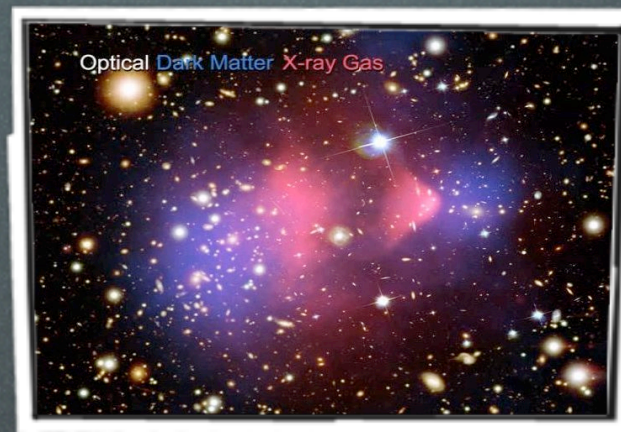
DM is a neutral, very long lived, feebly interacting particle.

Introduction

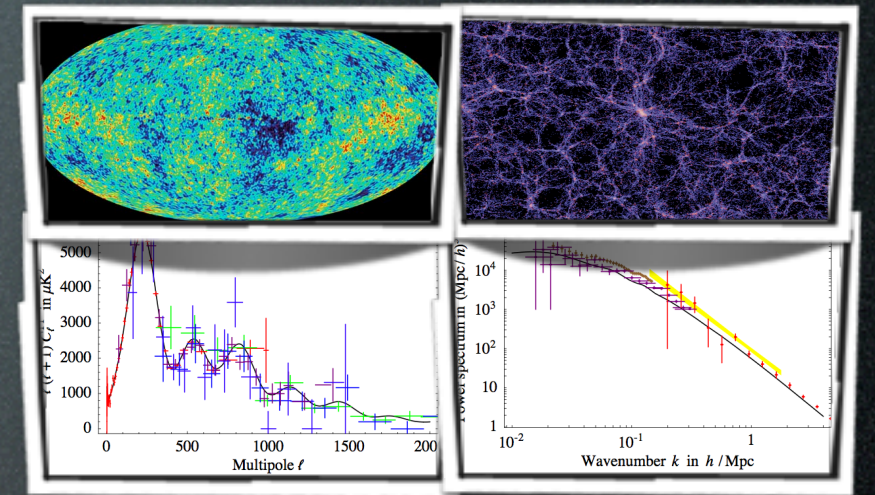
DM **exists**



galactic rotation curves



weak lensing (e.g. in clusters)

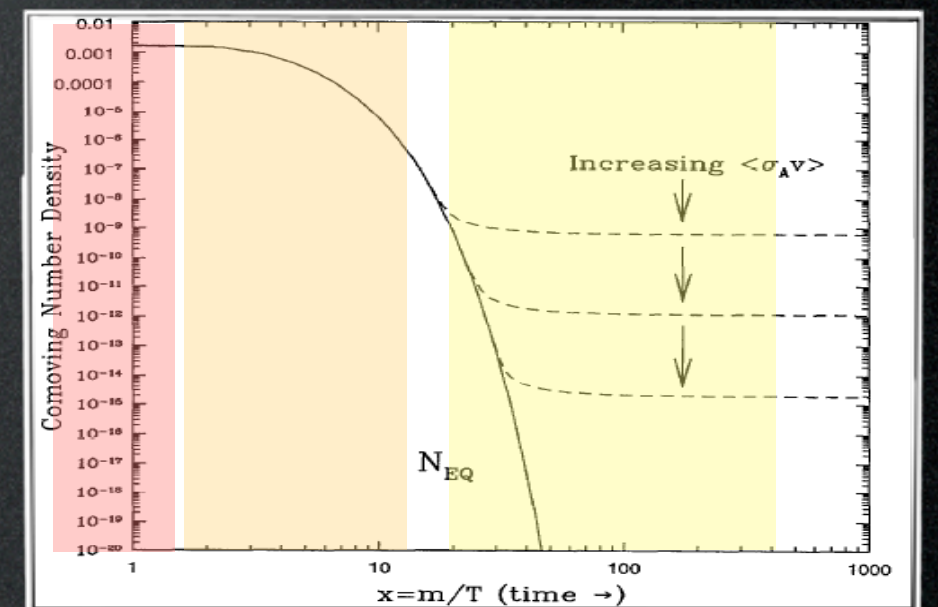


'precision cosmology' (CMB, LSS)

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



DM detection

direct detection

Xenon, CDMS, Edelweiss... (CoGeNT, Dama/Libra...)

production at colliders

LHC

indirect

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

Fermi, ICT, radio telescopes...

e^+ from annihil in galactic halo or center

PAMELA, Fermi, HESS, AMS, balloons...

$\bar{p}$ 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

SK, Icecube, Km3Net

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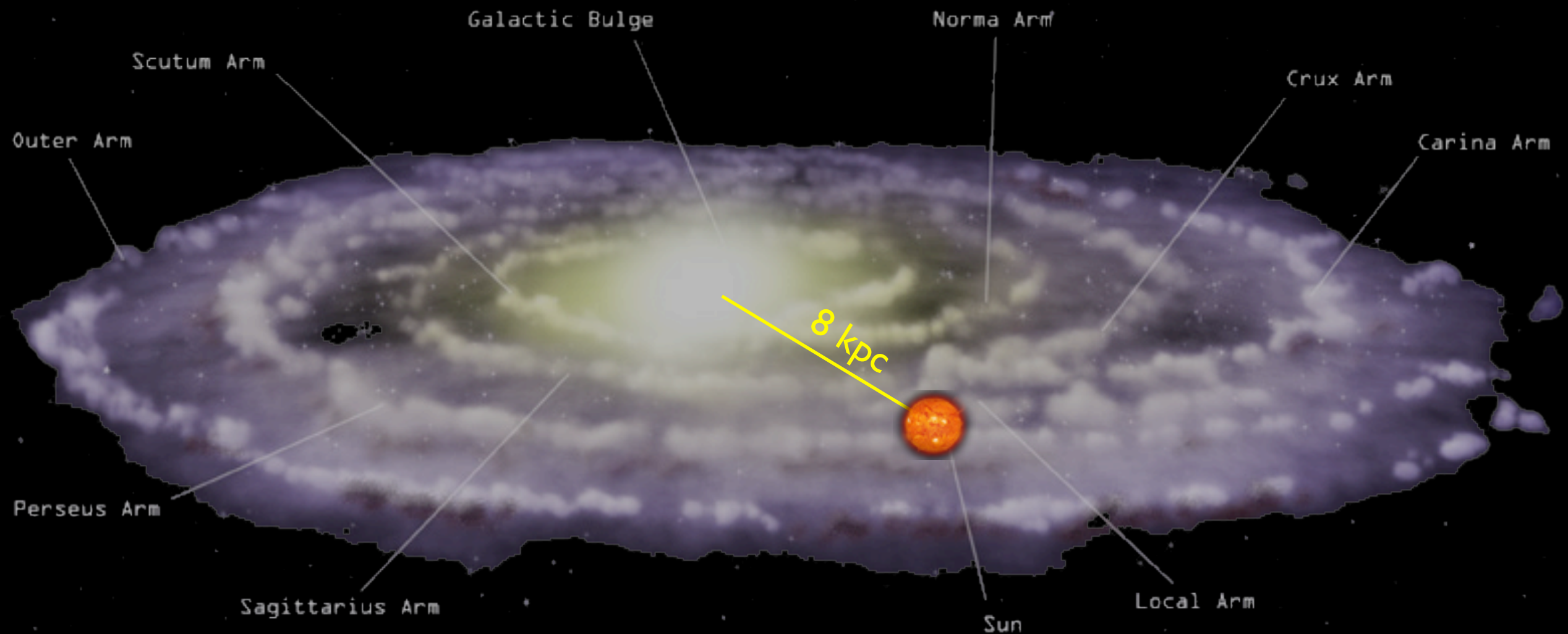
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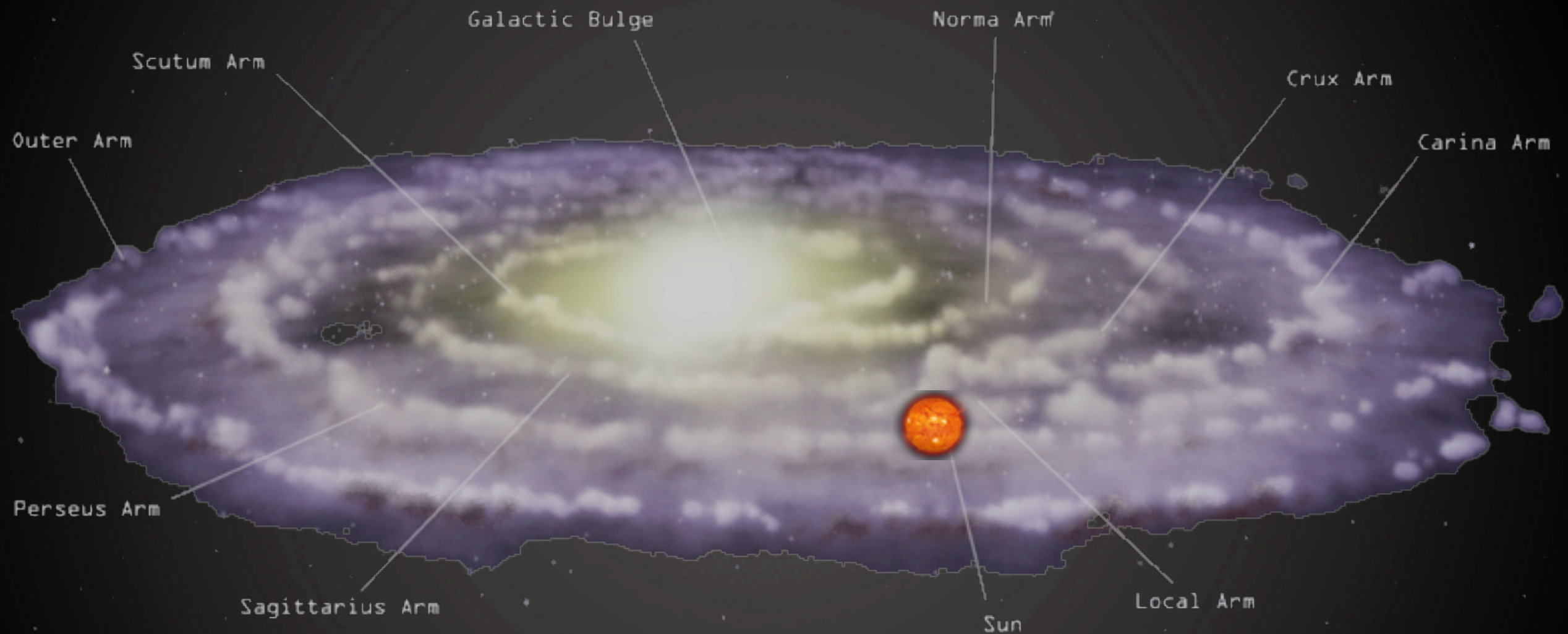
Indirect Detection: basics

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



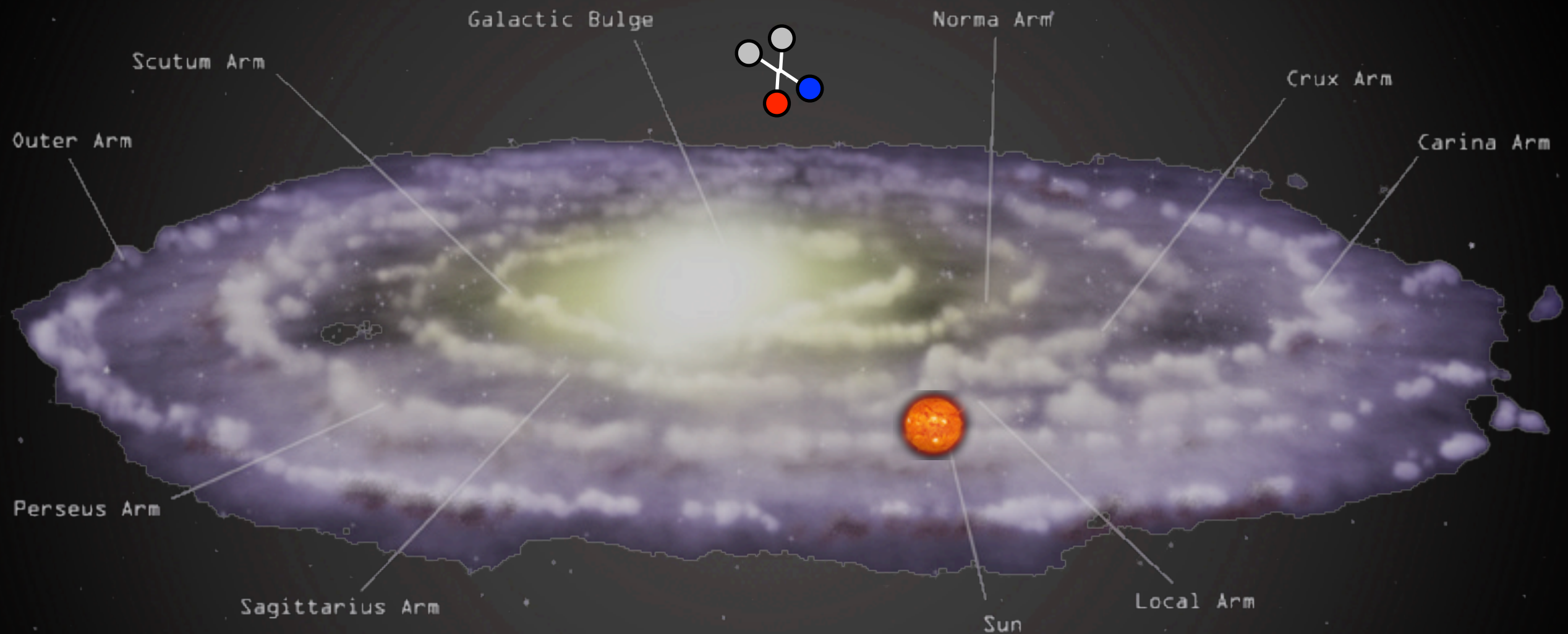
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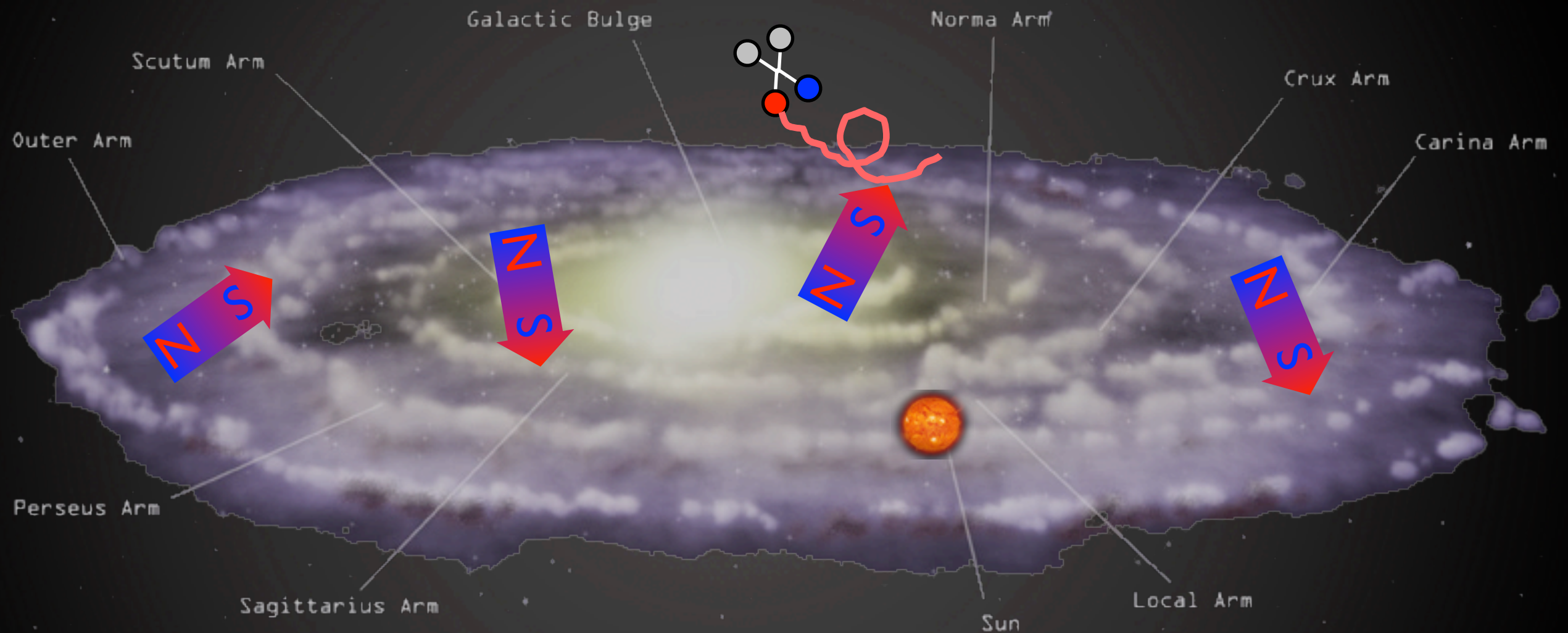
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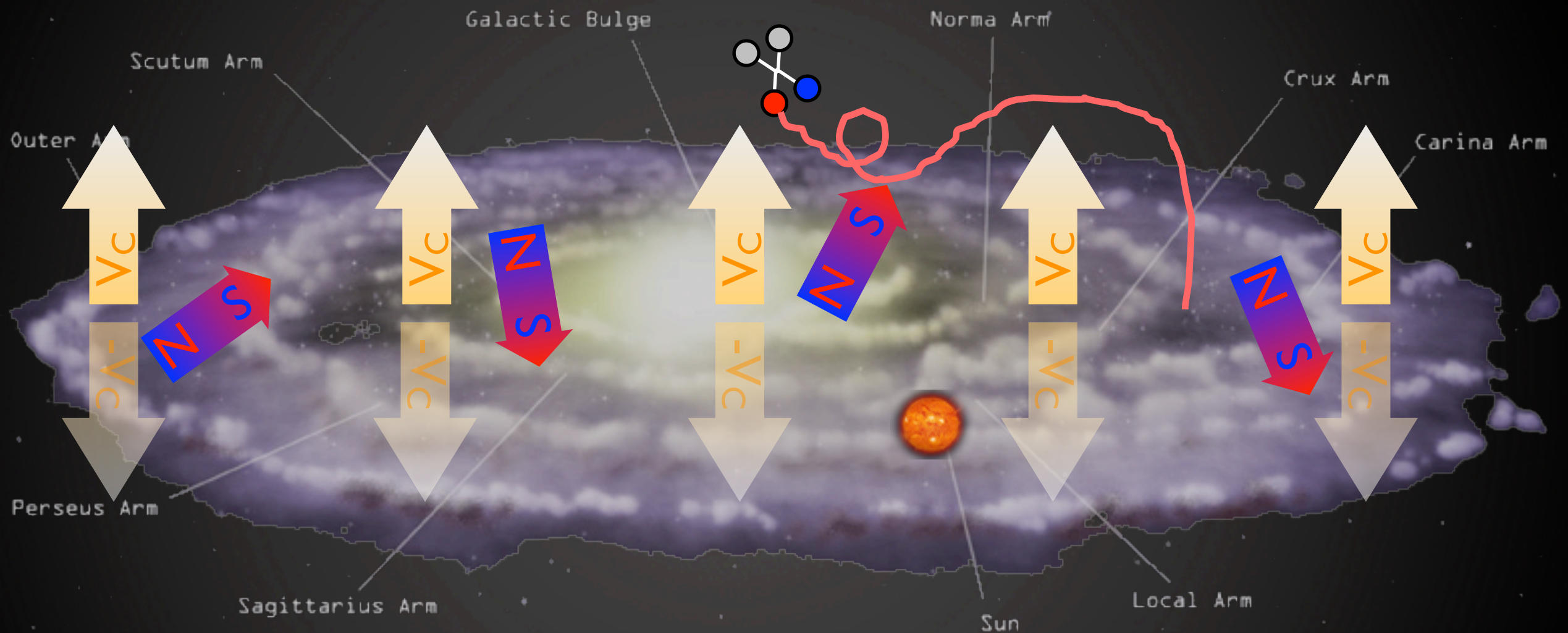
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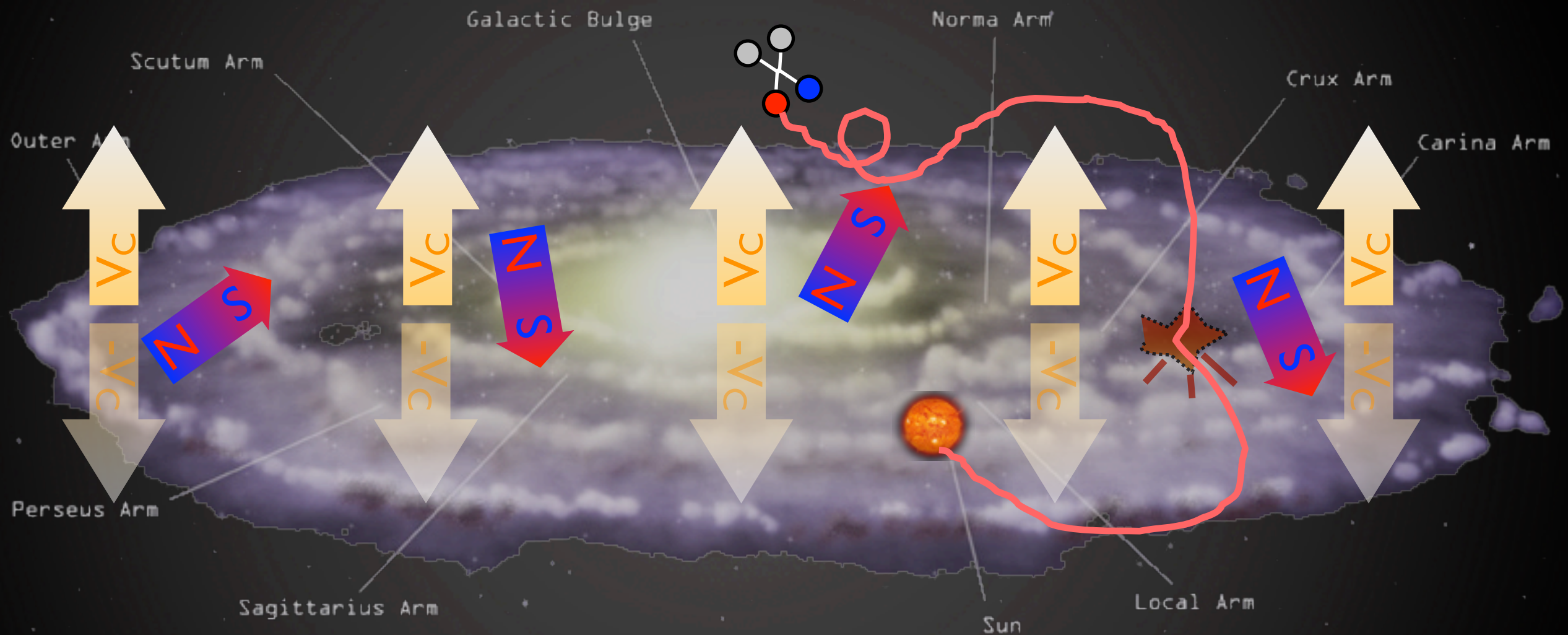
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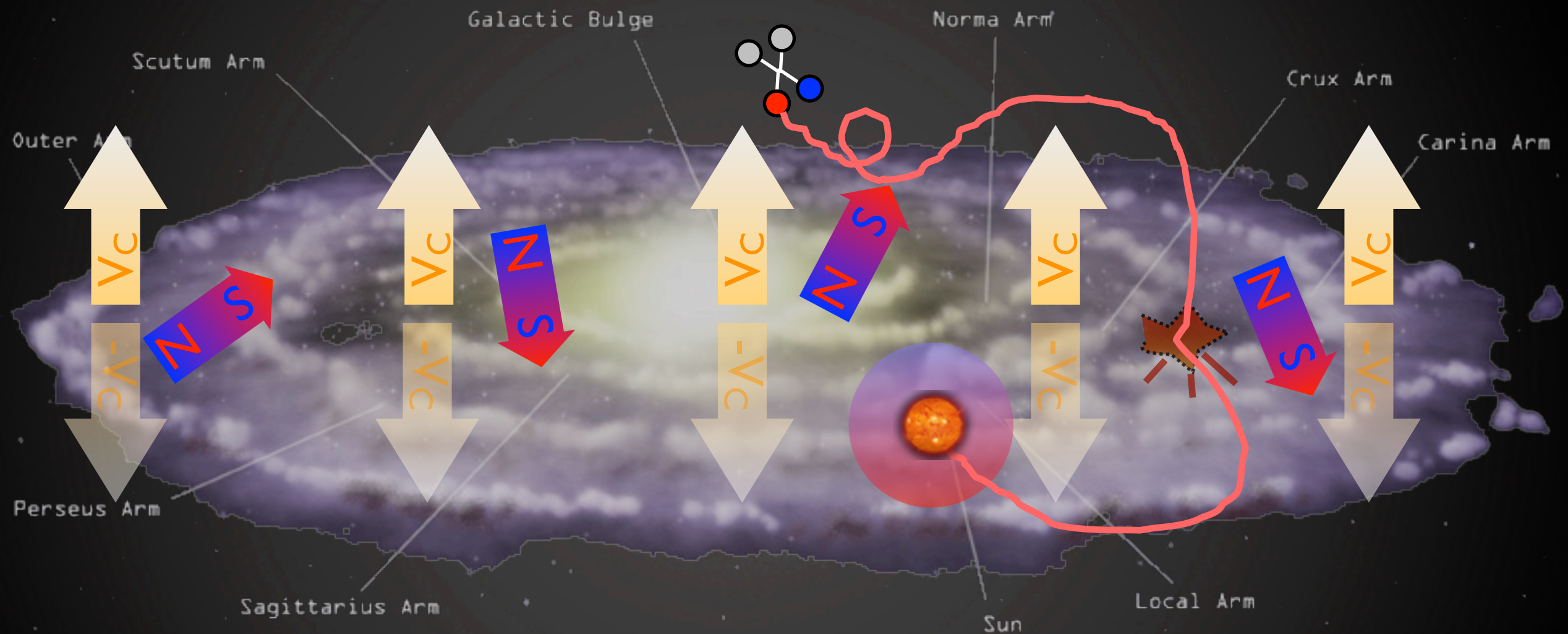
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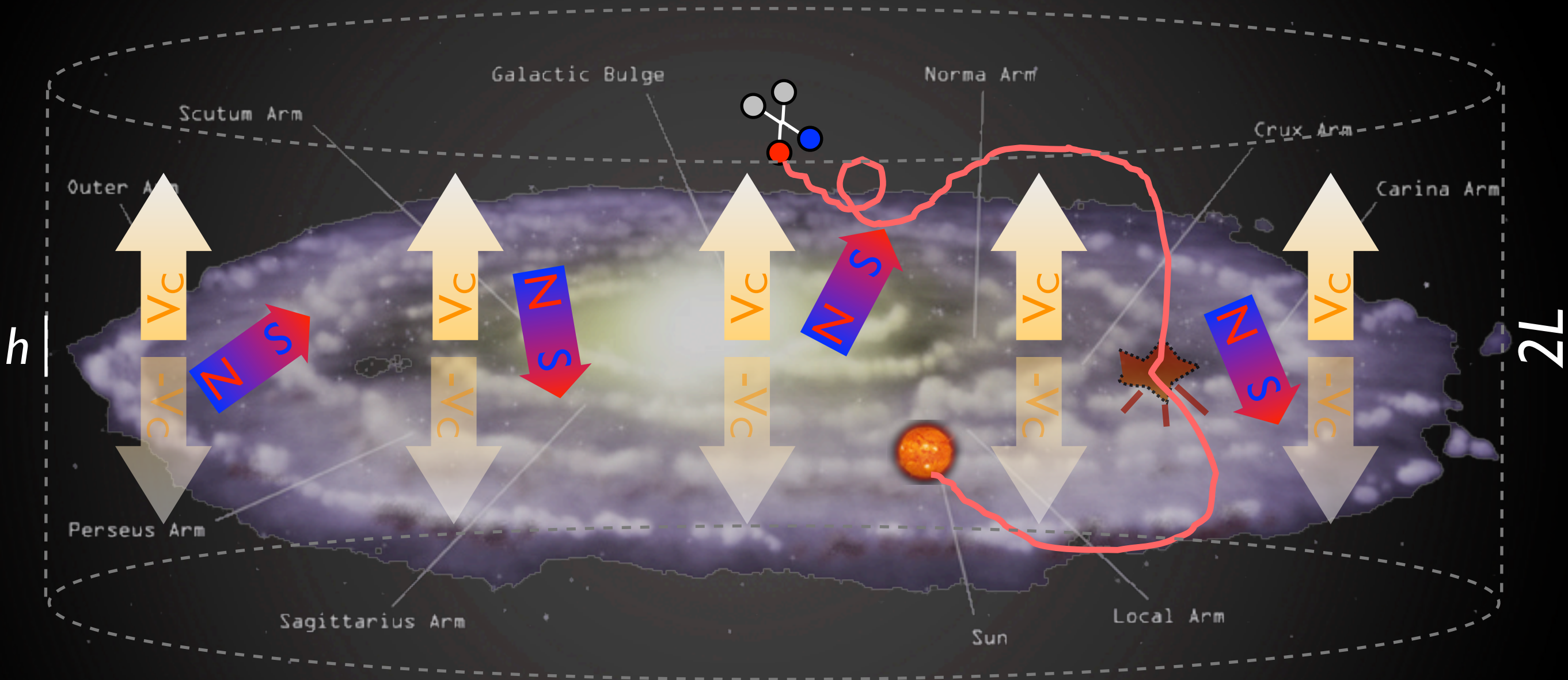
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Indirect Detection: basics

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



spectrum

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

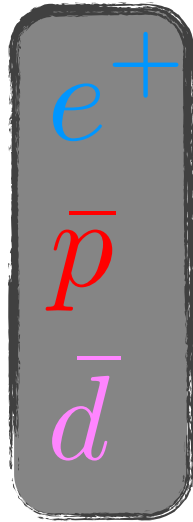
diffusion energy loss convective wind source spallations [uncert]

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

Uncertainties, uncertainties...

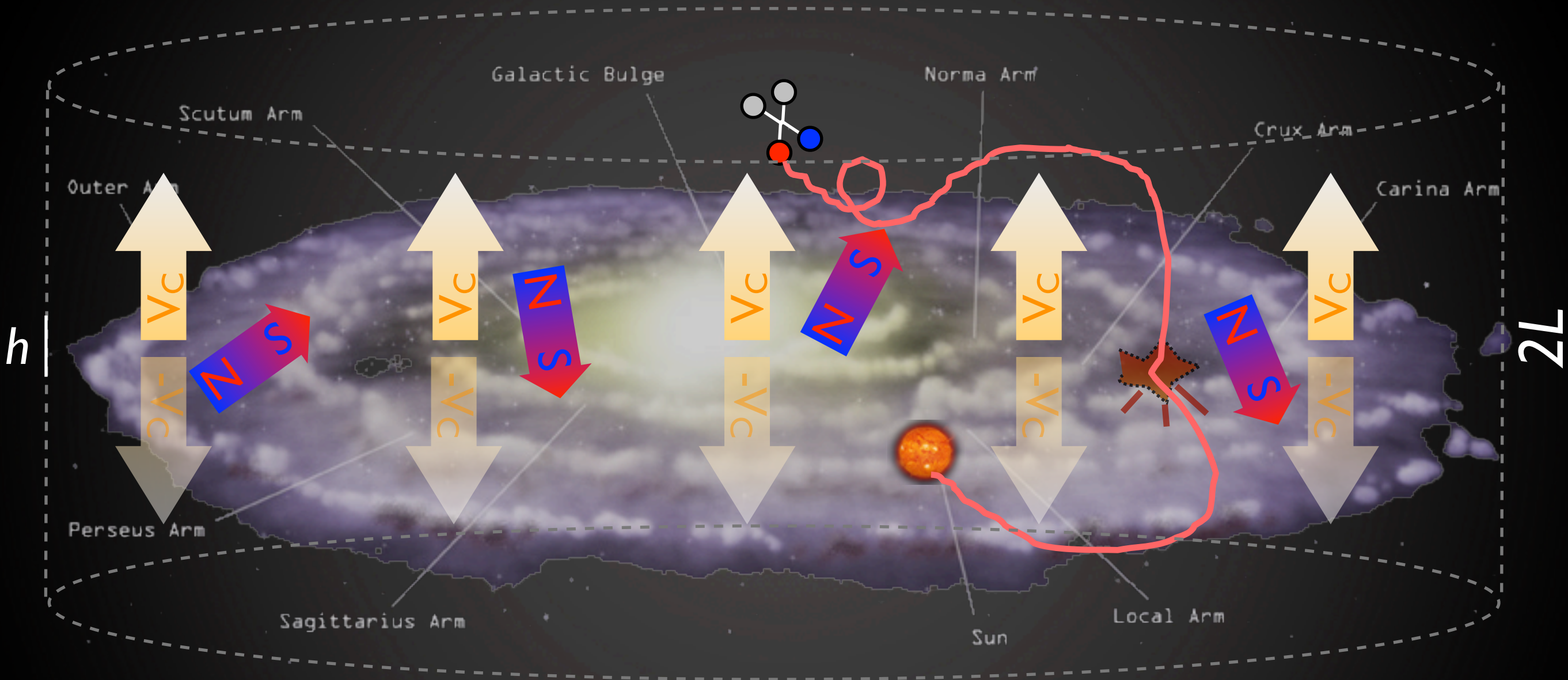
CR propagation

- diffusion
- energy losses
- solar modulation



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

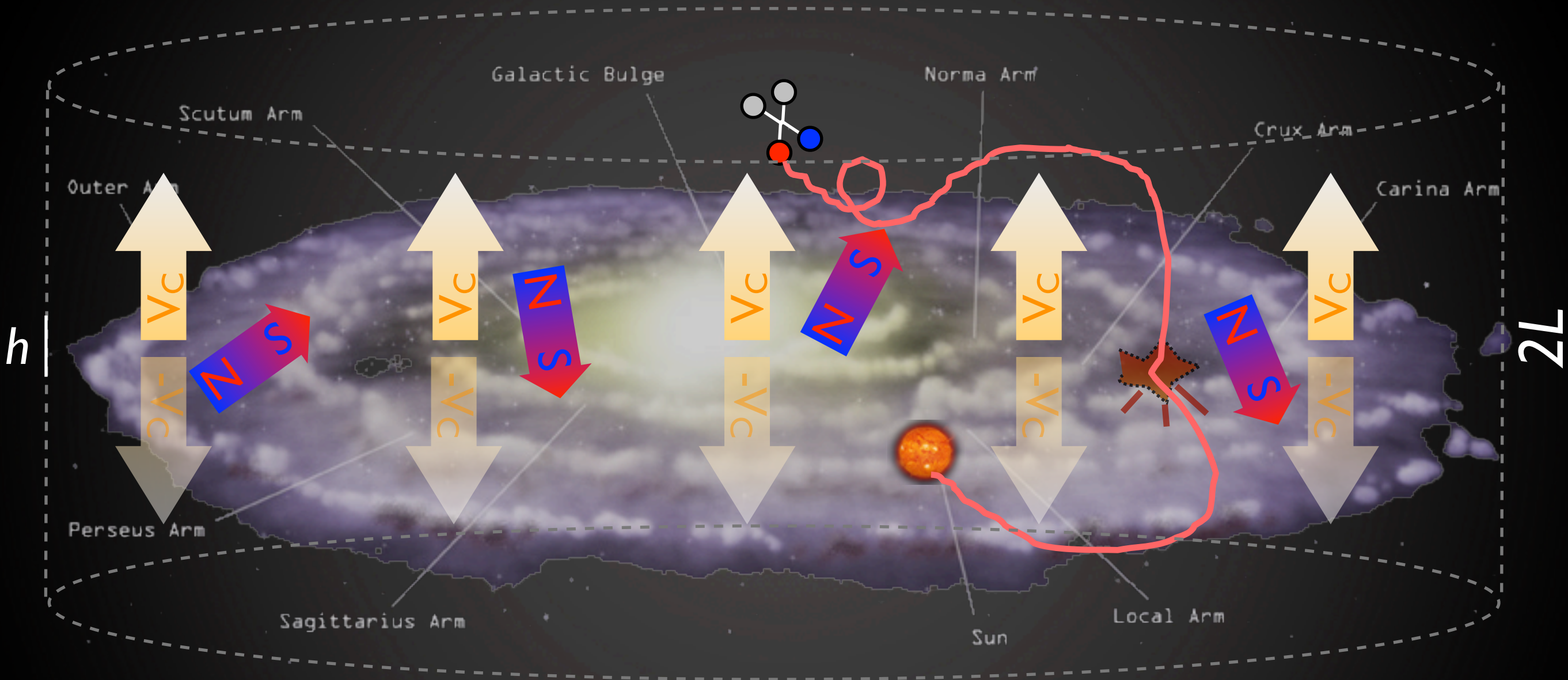


What sets the overall expected flux?

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

Indirect Detection: basics

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



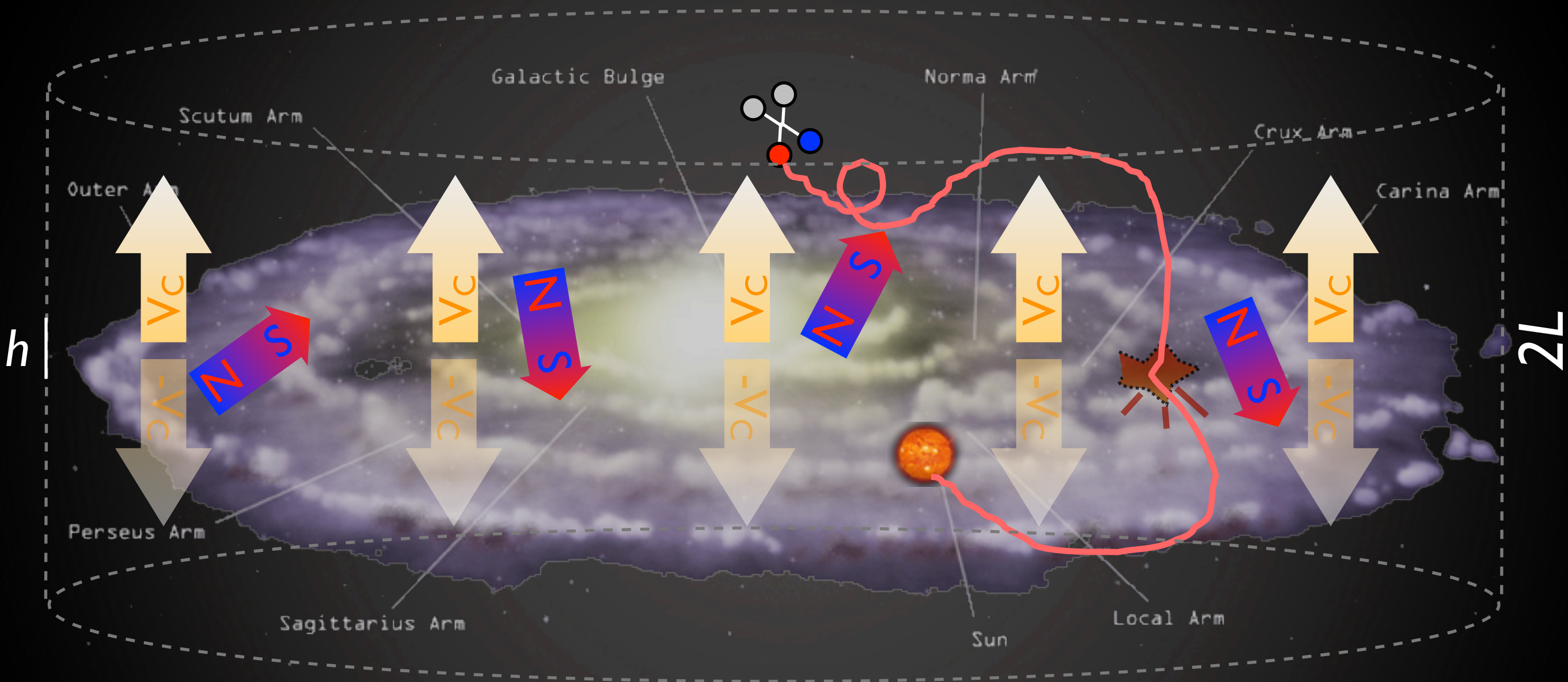
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astro&cosmo particle

Indirect Detection: basics

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



What sets the overall expected flux?

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

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:

$$\begin{aligned} \text{NFW : } \rho_{\text{NFW}}(r) &= \rho_s \frac{r_s}{r} \left(1 + \frac{r}{r_s}\right)^{-2} \\ \text{Einasto : } \rho_{\text{Ein}}(r) &= \rho_s \exp \left\{ -\frac{2}{\alpha} \left[\left(\frac{r}{r_s}\right)^\alpha - 1 \right] \right\} \\ \text{Isothermal : } \rho_{\text{Iso}}(r) &= \frac{\rho_s}{1 + (r/r_s)^2} \\ \text{Burkert : } \rho_{\text{Bur}}(r) &= \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \\ \text{Moore : } \rho_{\text{Moo}}(r) &= \rho_s \left(\frac{r_s}{r}\right)^{1.16} \left(1 + \frac{r}{r_s}\right)^{-1.84} \end{aligned}$$

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

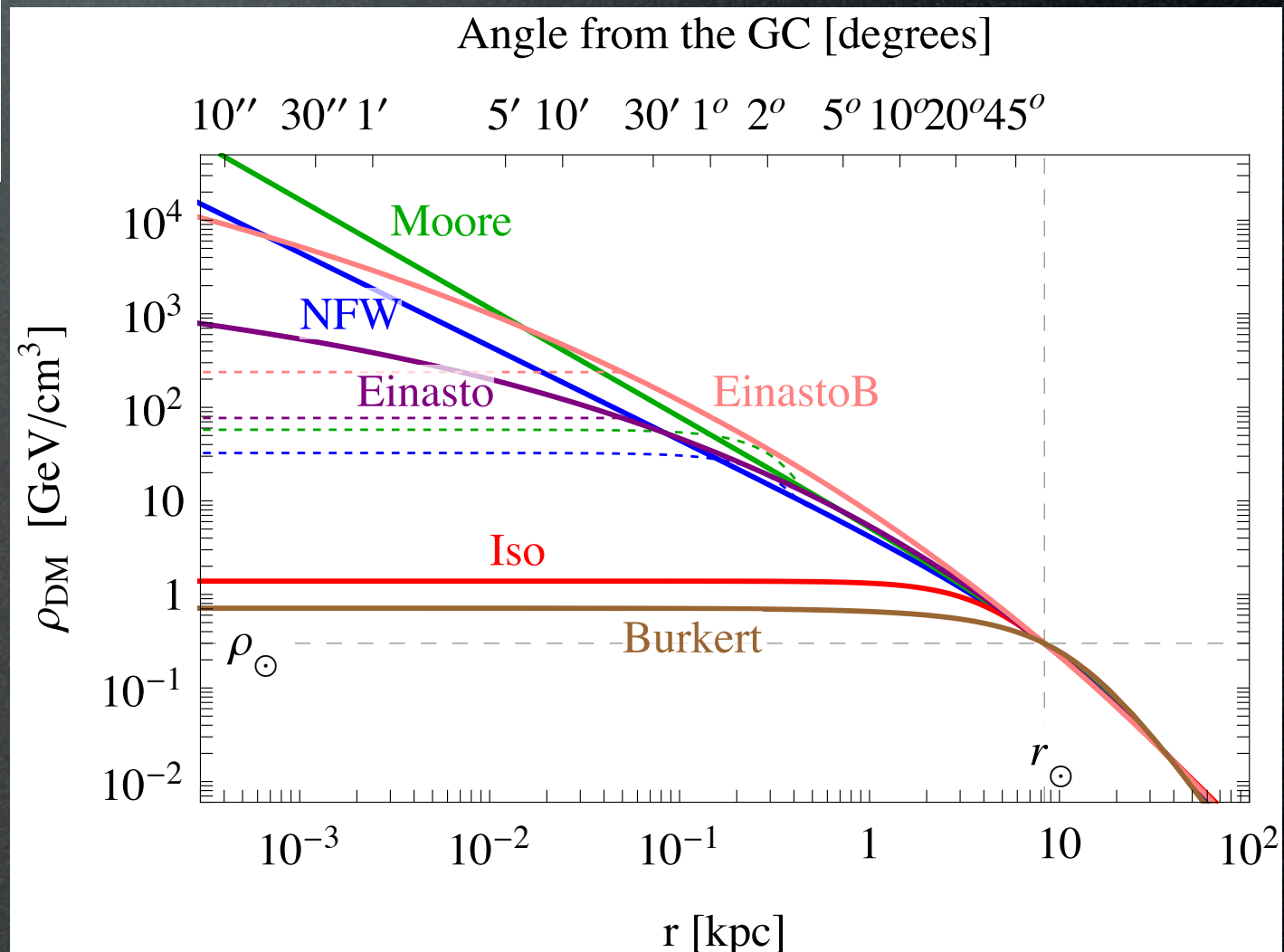
6 profiles:

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

mild: **Einasto**

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

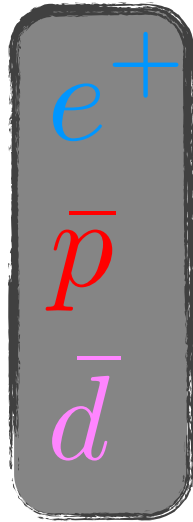
EinastoB = steepened Einasto
(effect of baryons?)



Uncertainties, uncertainties...

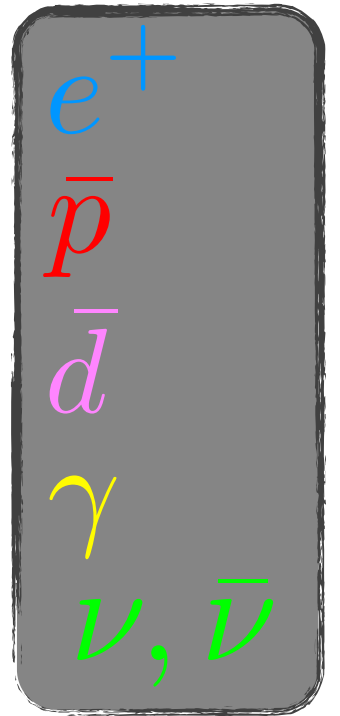
CR propagation

- diffusion
- energy losses
- solar modulation

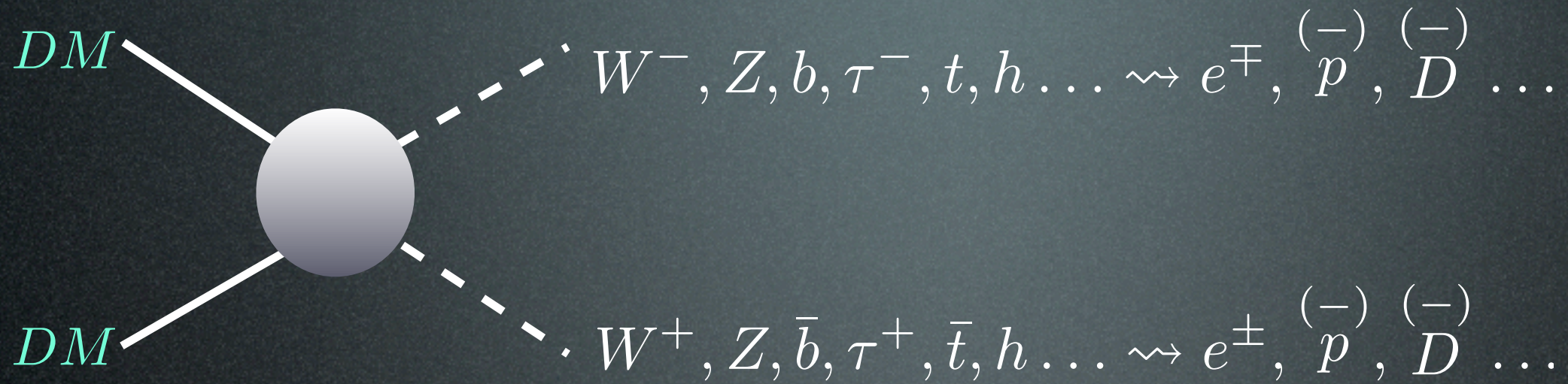


DM distribution in the Galaxy

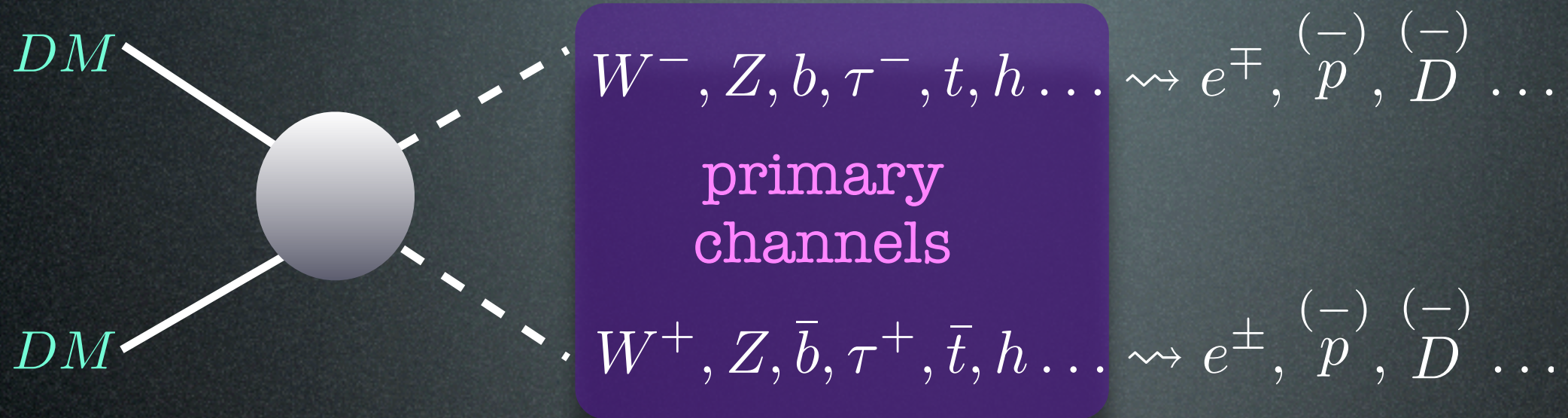
- local DM density
- DM profile
- beware of extrapolations!
- effect of baryons in DM halos
- (velocity distribution)
- (escape velocity)



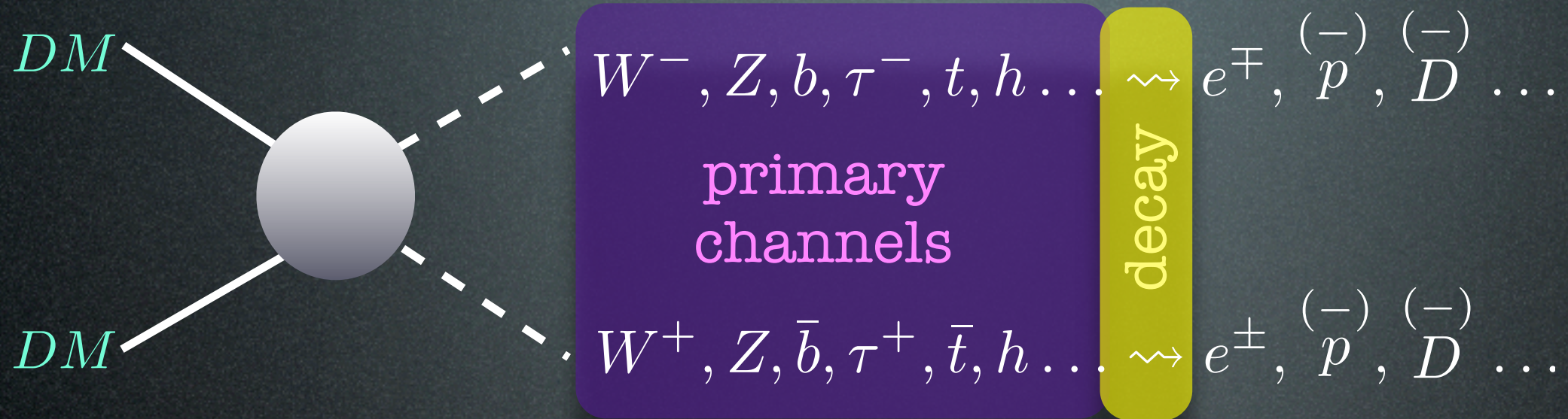
Indirect Detection: basics



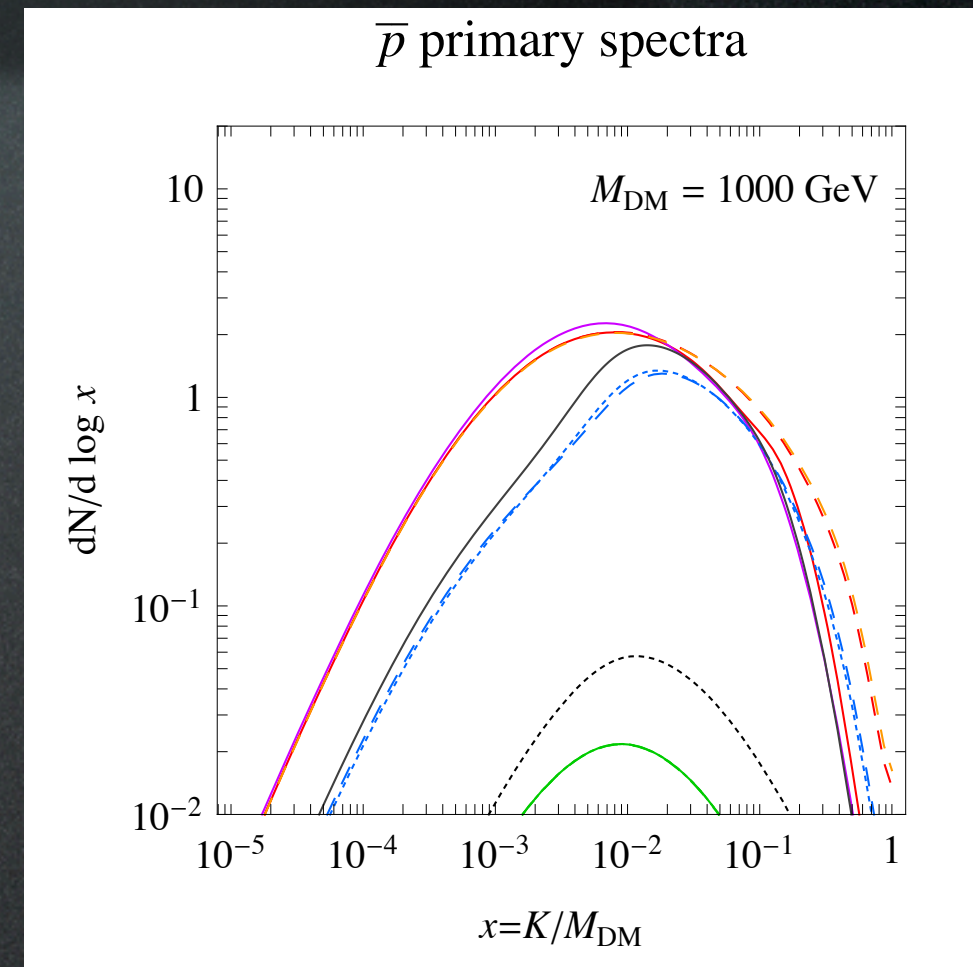
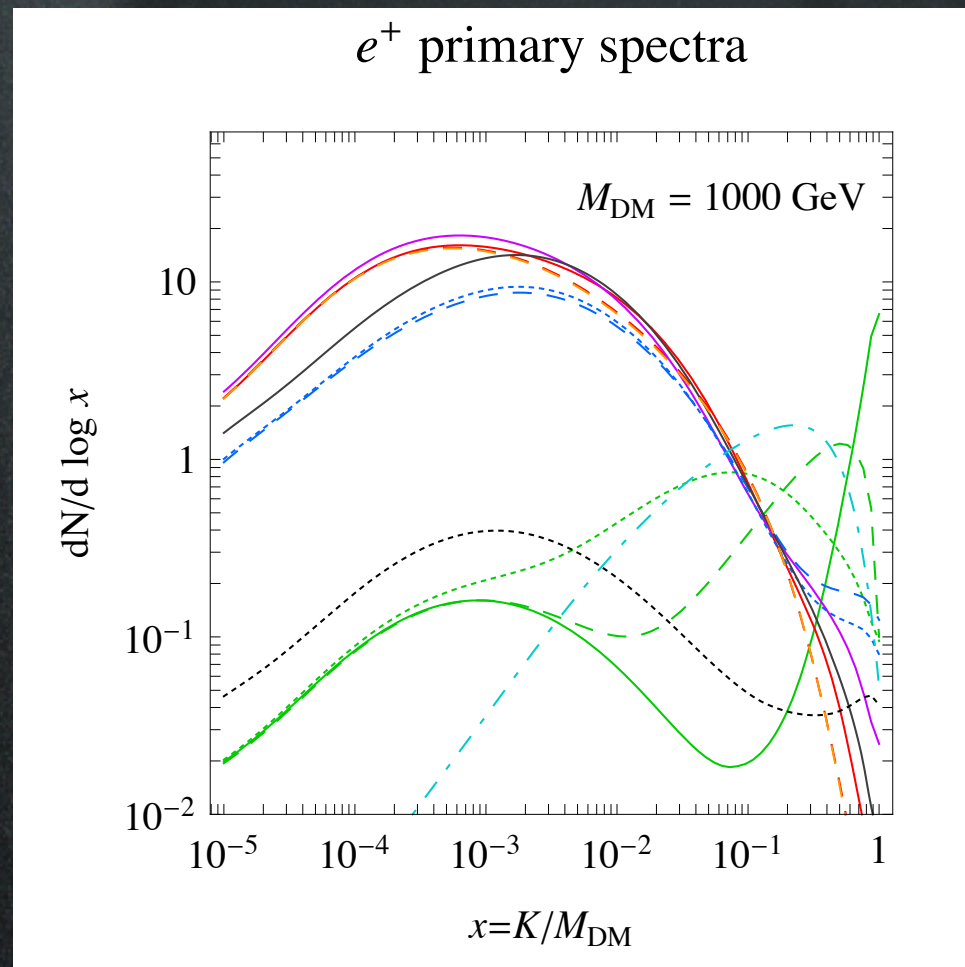
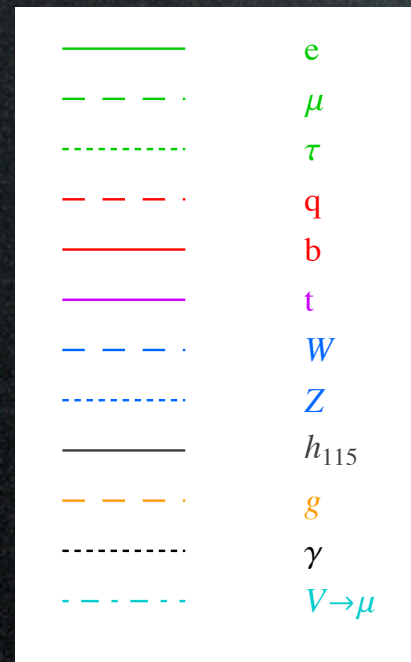
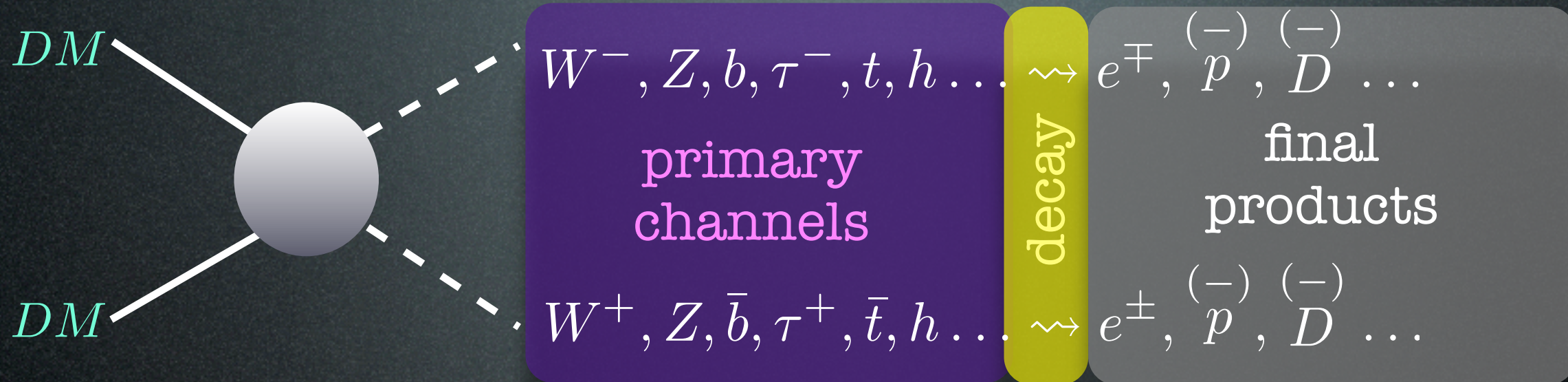
Indirect Detection: basics



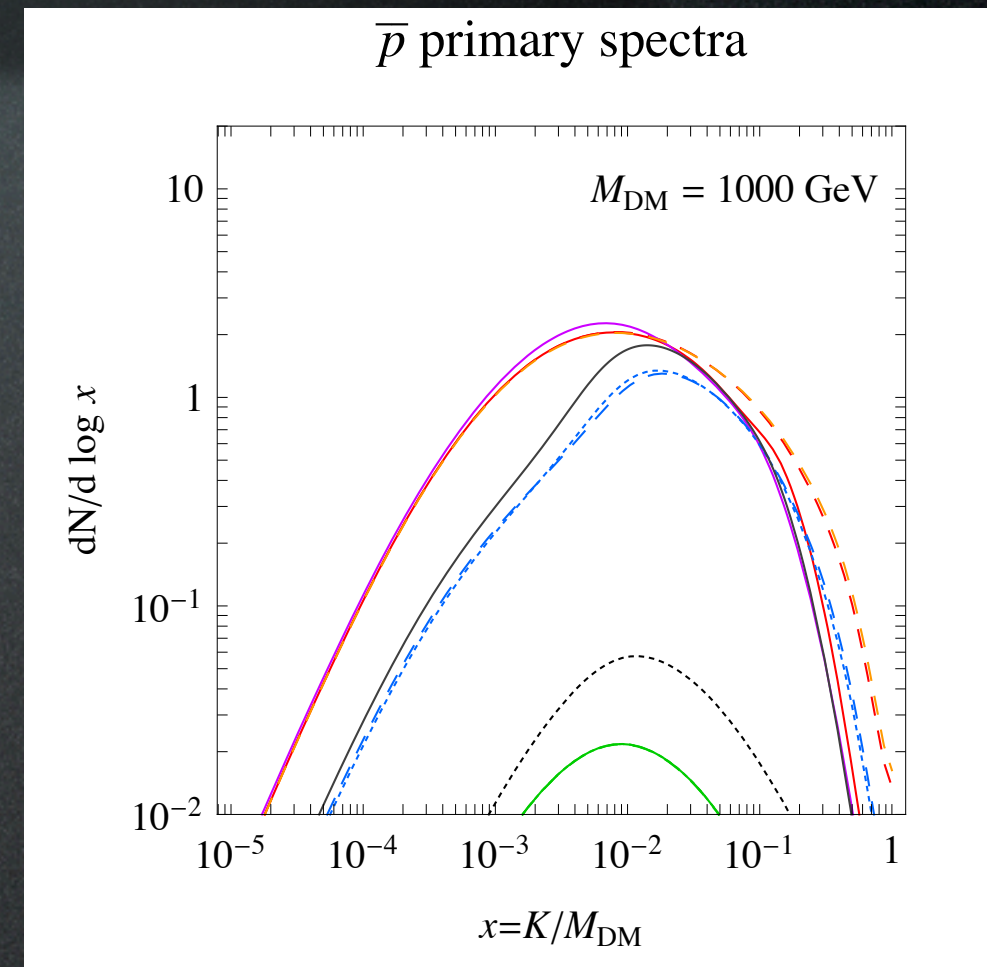
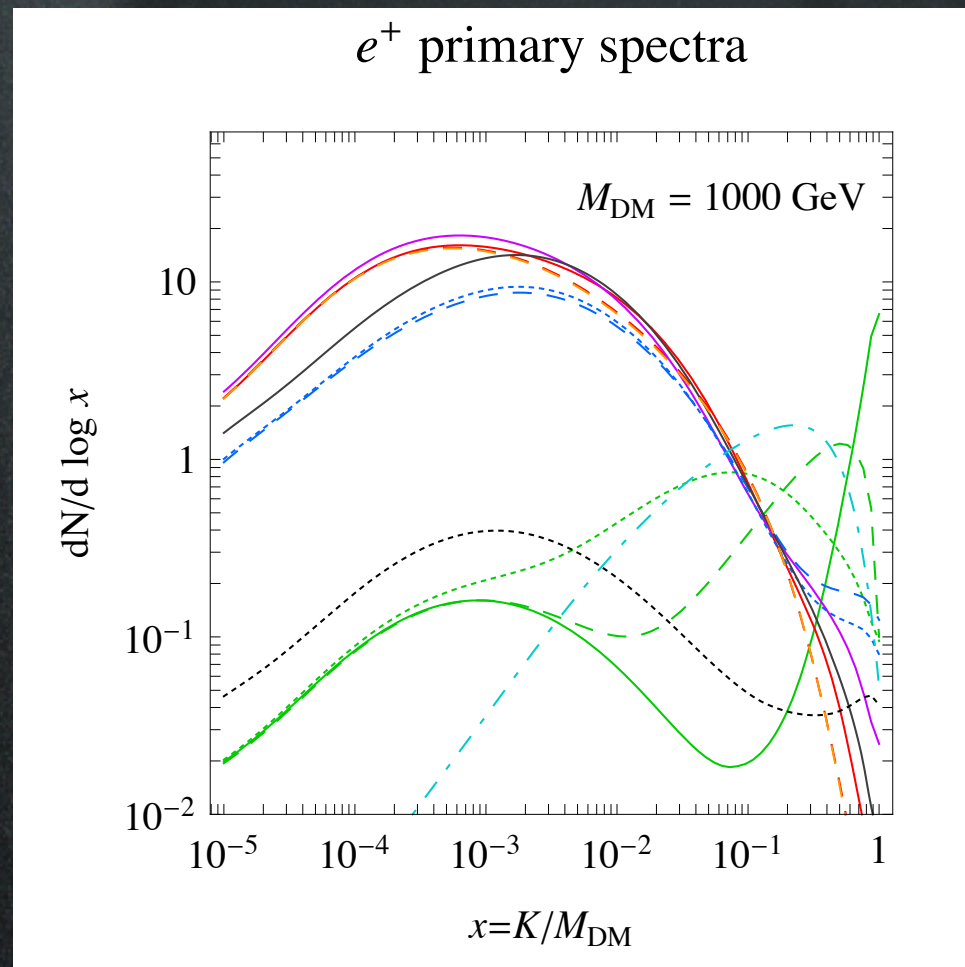
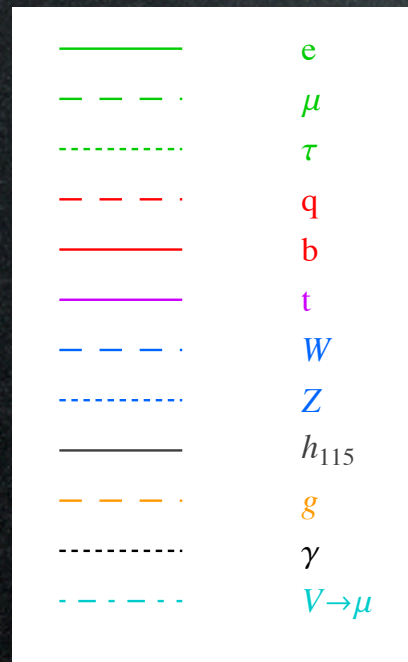
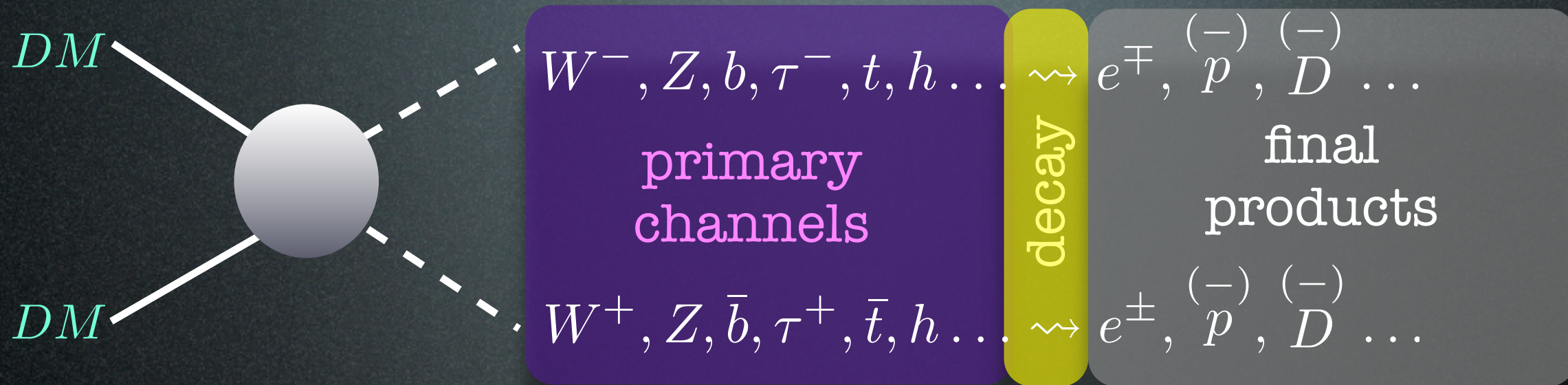
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So what are the particle physics parameters?

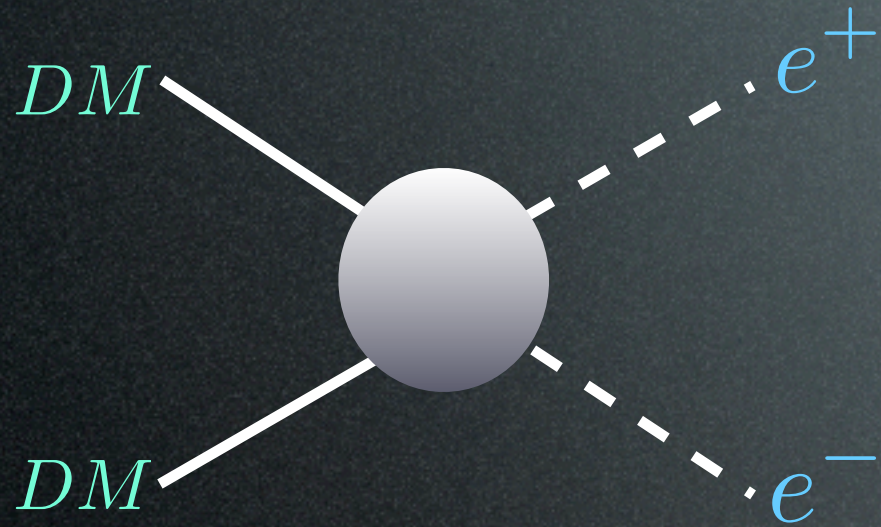
1. Dark Matter mass
2. primary channel(s)

Fluxes at production

ElectroWeak corrections are important!

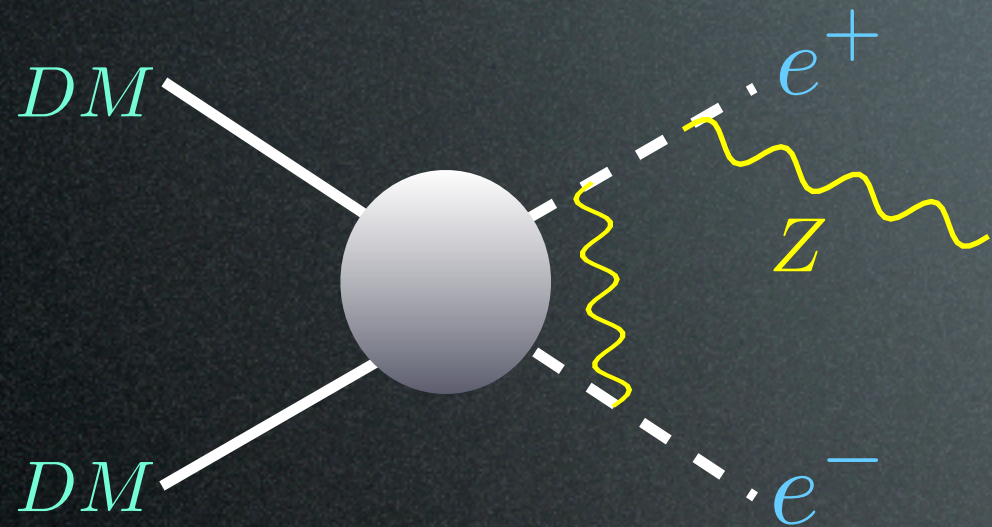
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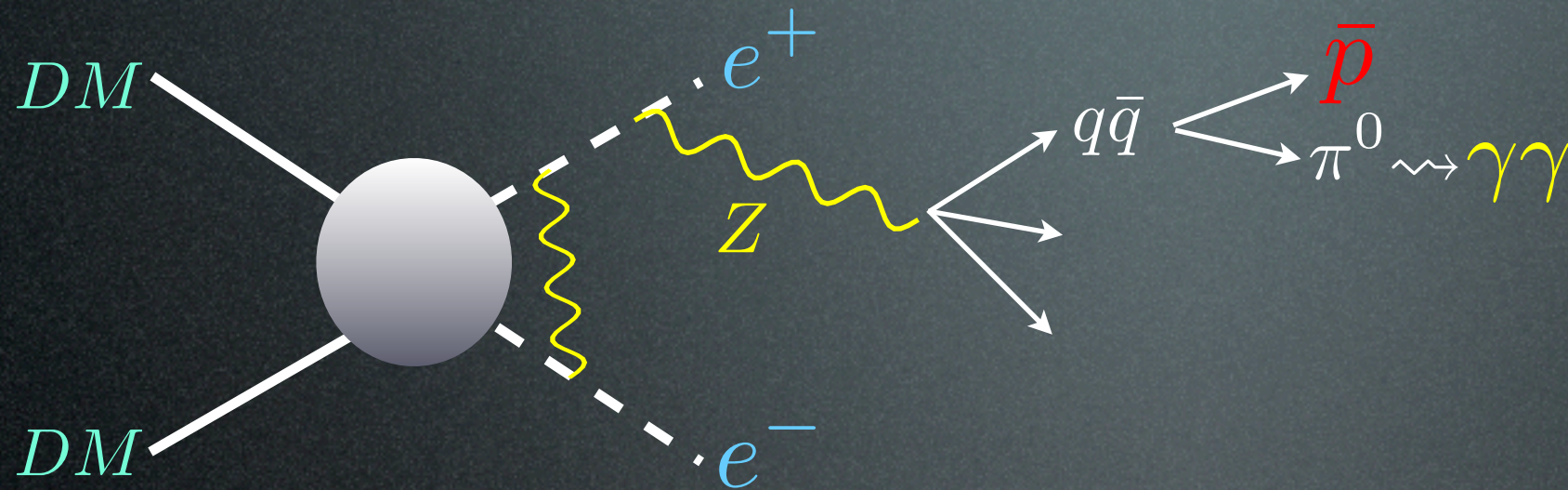
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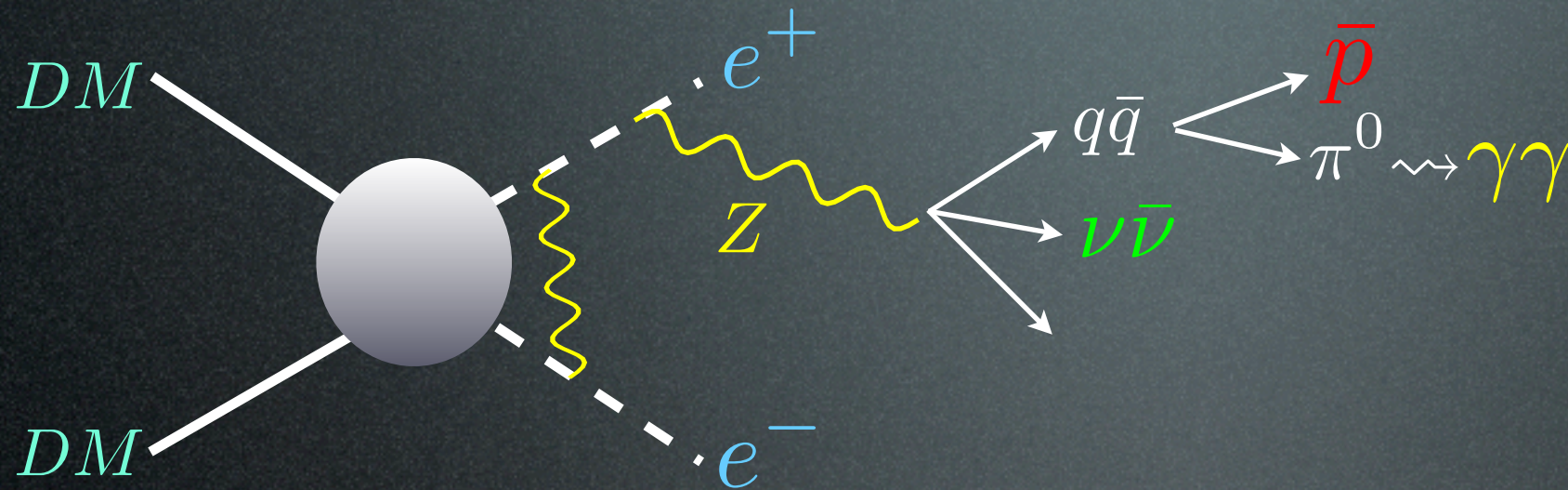
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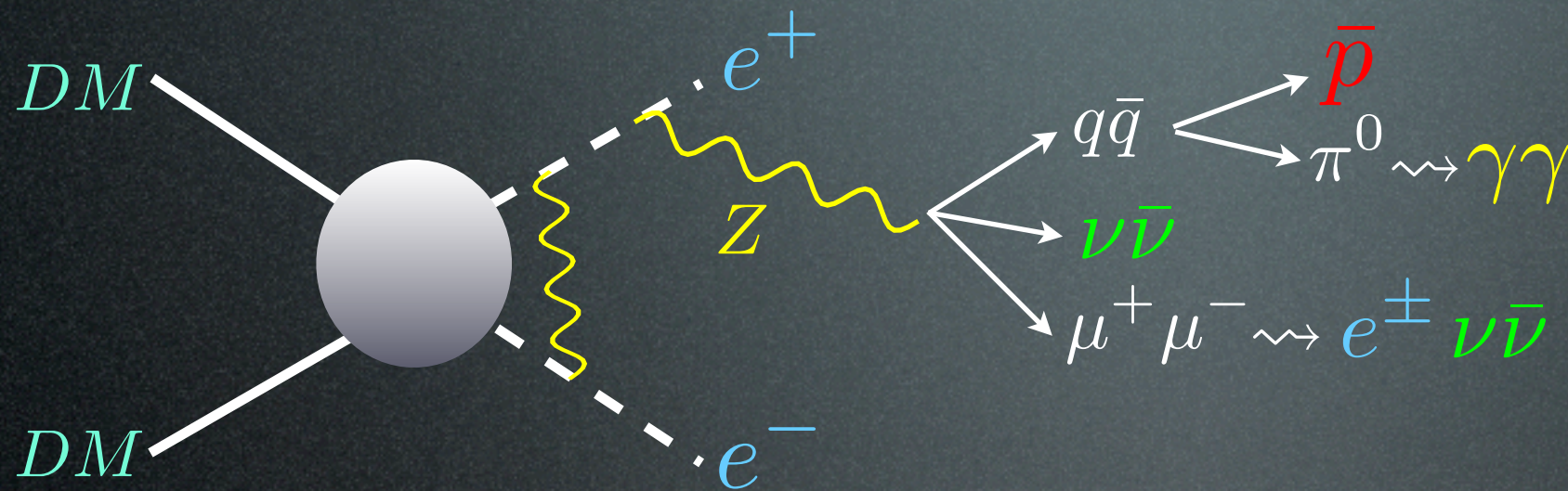
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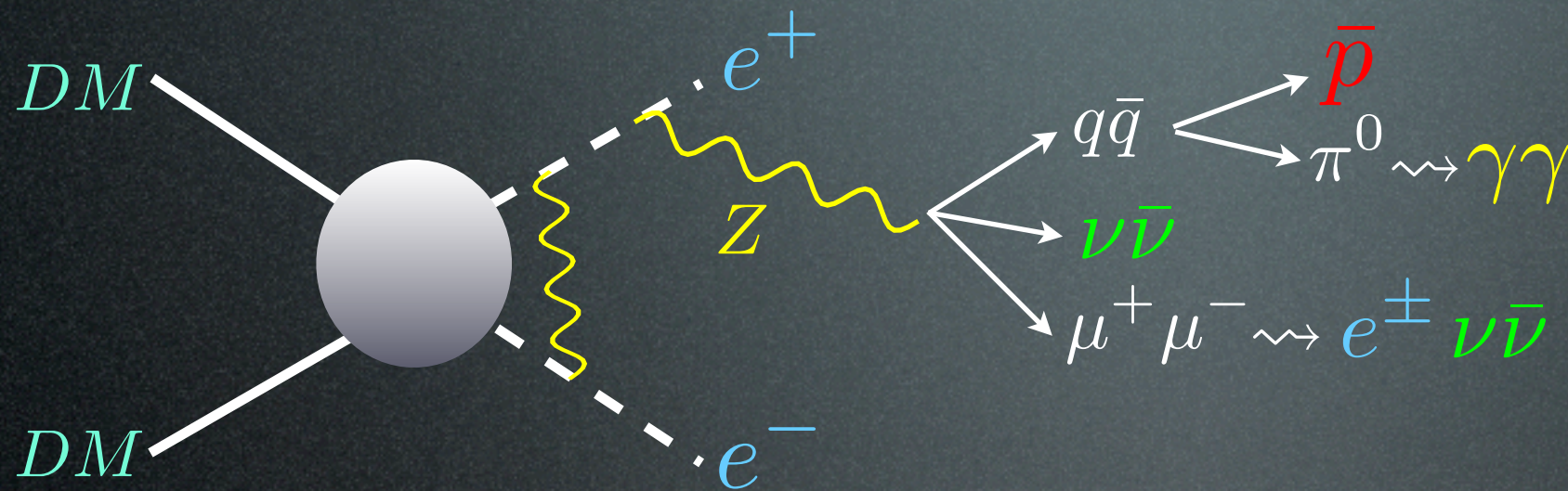
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Fluxes at production

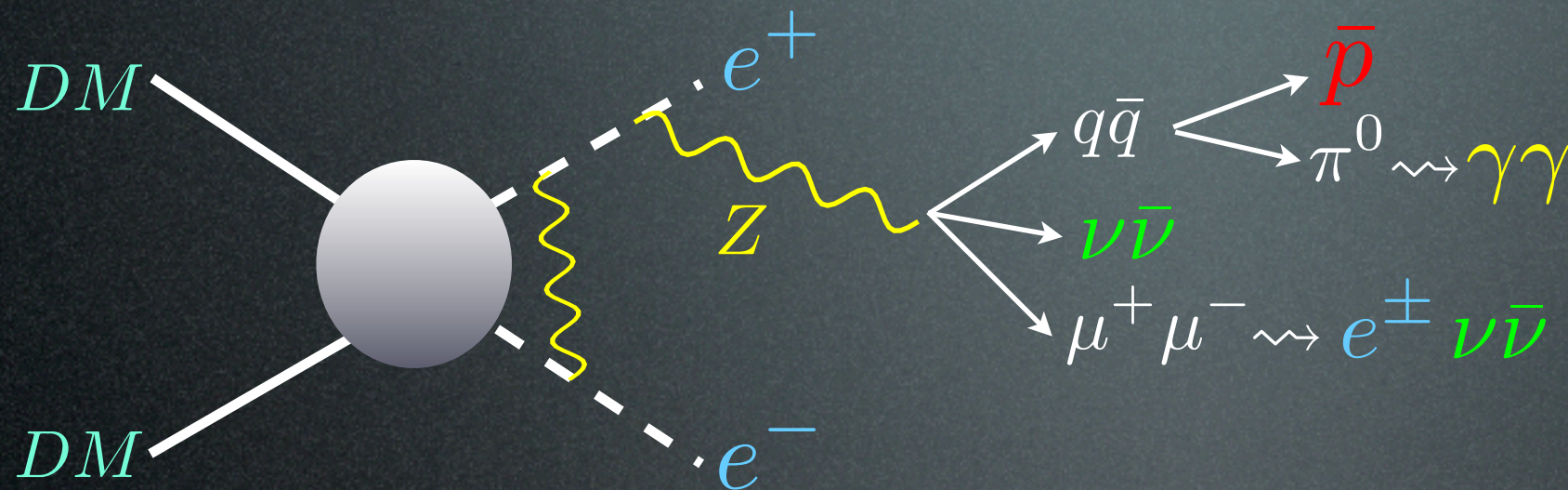
ElectroWeak corrections are important!



$$\frac{\Delta\sigma}{\sigma} \propto \alpha_{\text{weak}} \ln^2 \left(\frac{M_{\text{DM}}^2}{M_Z^2} \right)$$

Fluxes at production

ElectroWeak corrections are important!

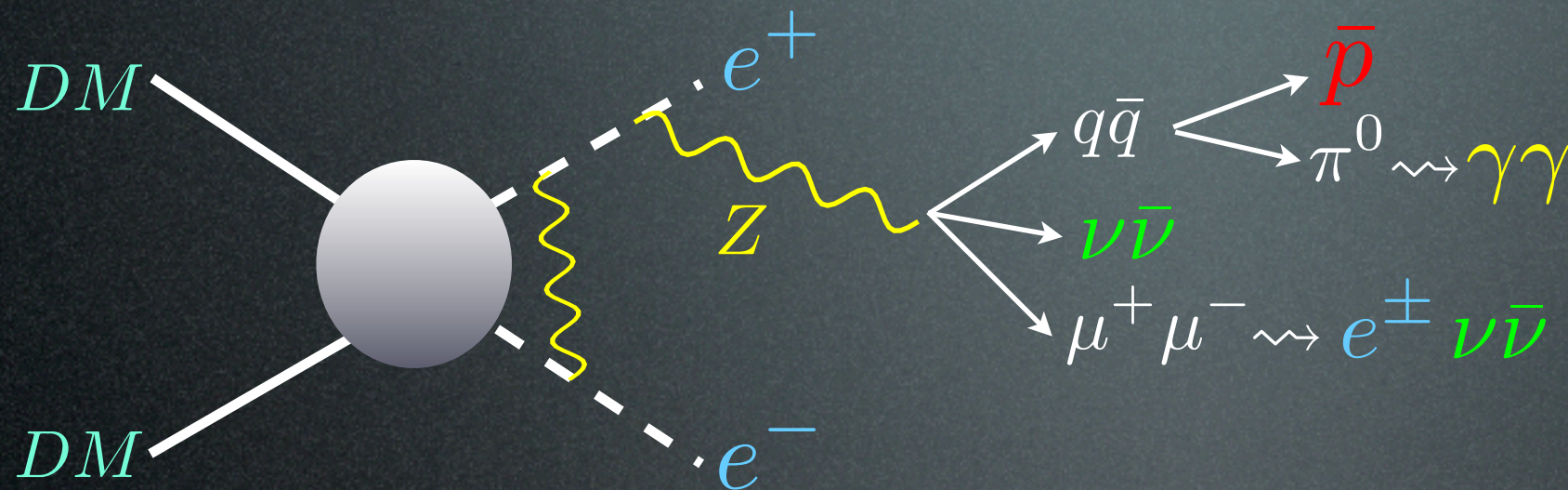


$$\frac{\Delta\sigma}{\sigma} \propto \underbrace{\alpha_{\text{weak}}}_{\sim 0.03} \underbrace{\ln^2\left(\frac{M_{\text{DM}}^2}{M_Z^2}\right)}_{\sim 25}$$

$\sim \text{TeV}$
↓

Fluxes at production

ElectroWeak corrections are important!

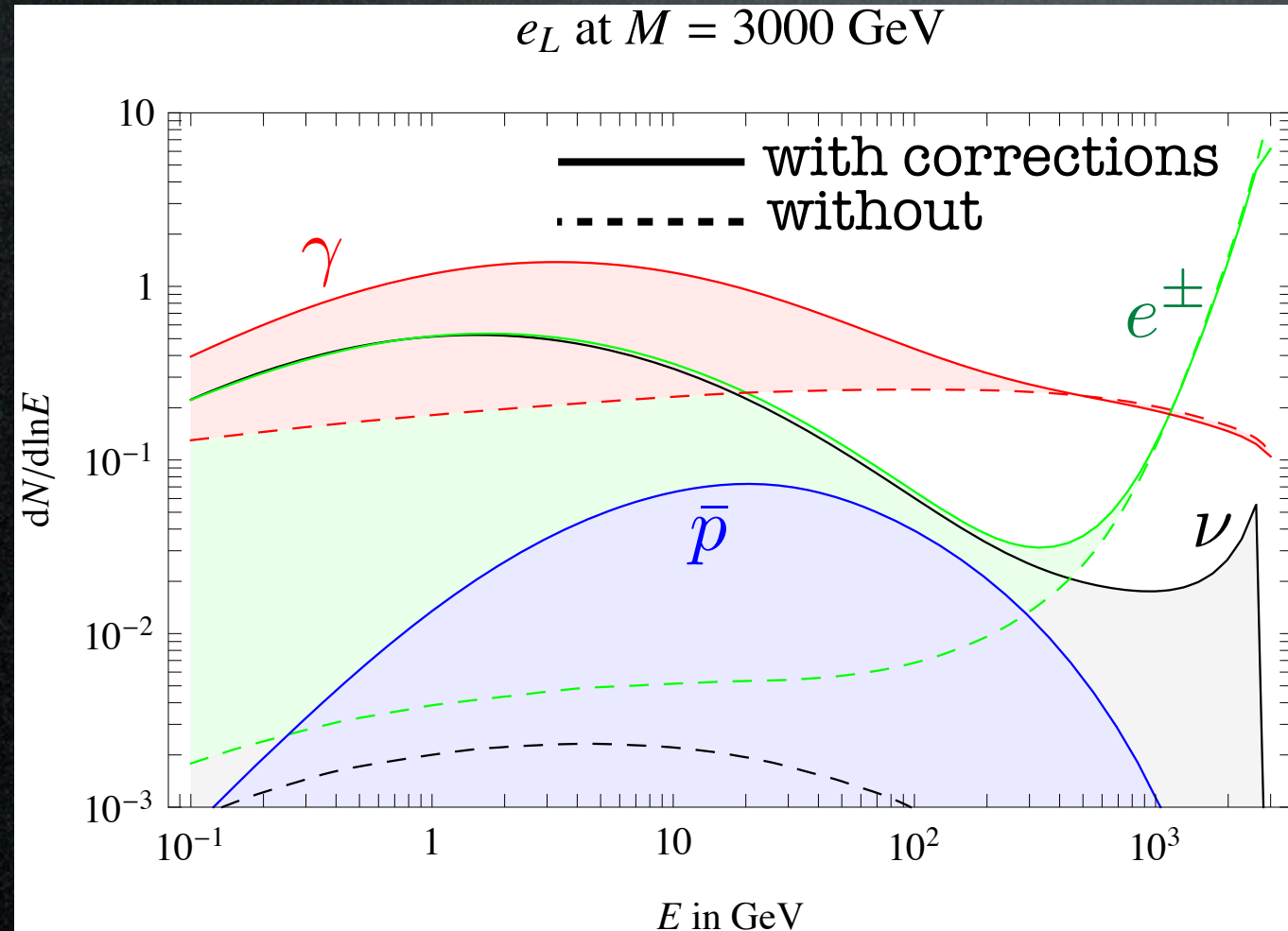
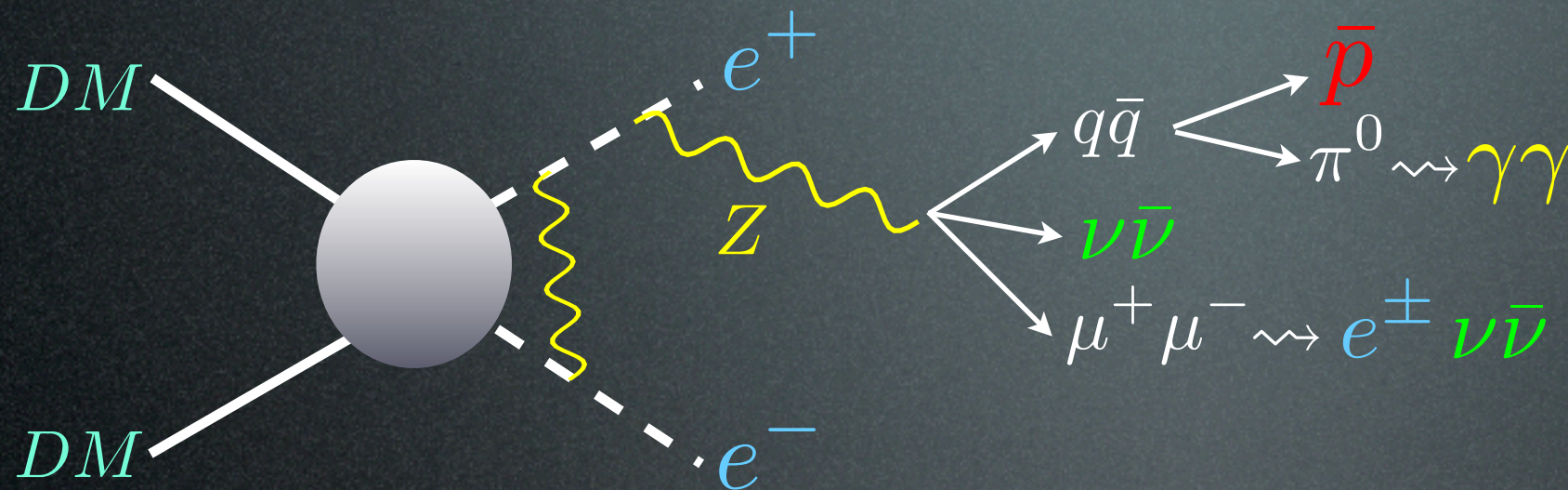


$$\frac{\Delta\sigma}{\sigma} \propto \underbrace{\alpha_{\text{weak}}}_{\sim 0.03} \underbrace{\ln^2\left(\frac{M_{\text{DM}}^2}{M_Z^2}\right)}_{\sim 25} \sim 75\%$$

$\sim \text{TeV}$
↓

Fluxes at production

ElectroWeak corrections are important!

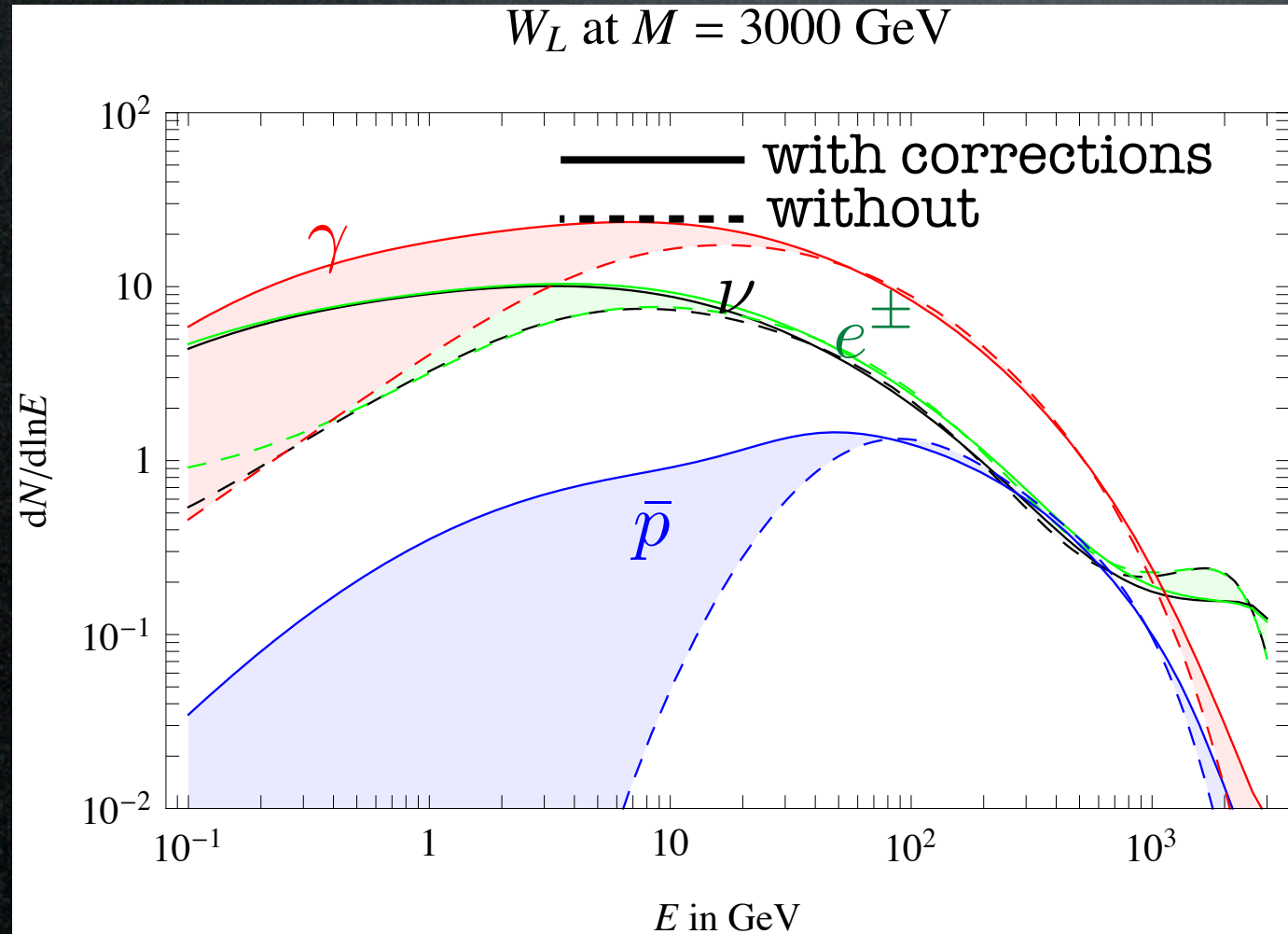
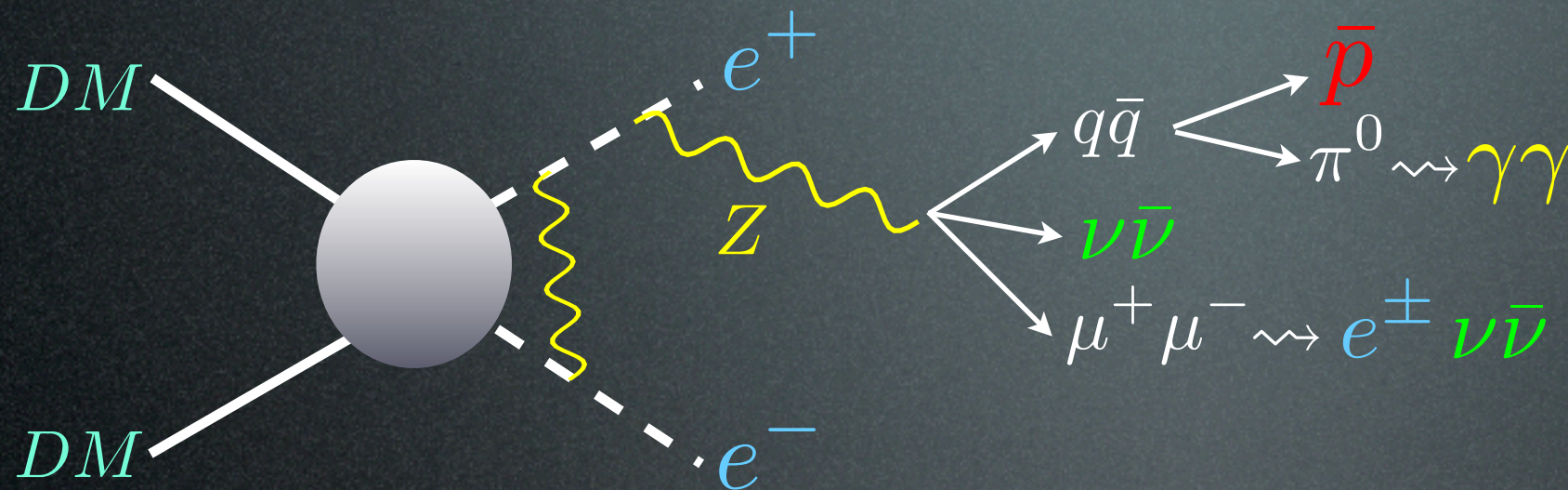


- unexpected species
- different spectra
(especially at low energy, but not only)

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

ElectroWeak corrections are important!



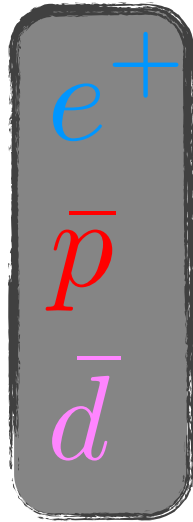
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Uncertainties, uncertainties...

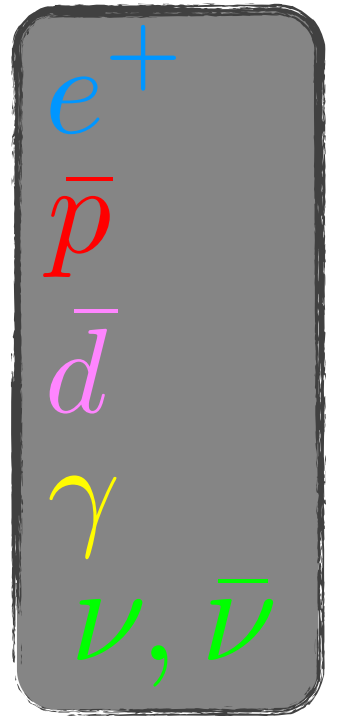
CR propagation

- diffusion
- energy losses
- solar modulation



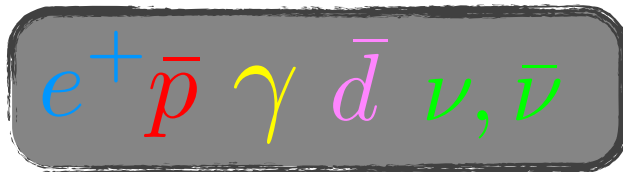
DM distribution in the Galaxy

- local DM density
- DM profile
- beware of extrapolations!
- effect of baryons in DM halos
- (velocity distribution)
- (escape velocity)



Particle Physics uncertainty

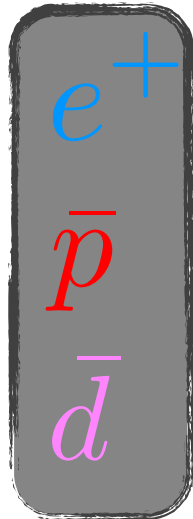
- Pythia at many TeV



Uncertainties, uncertainties...

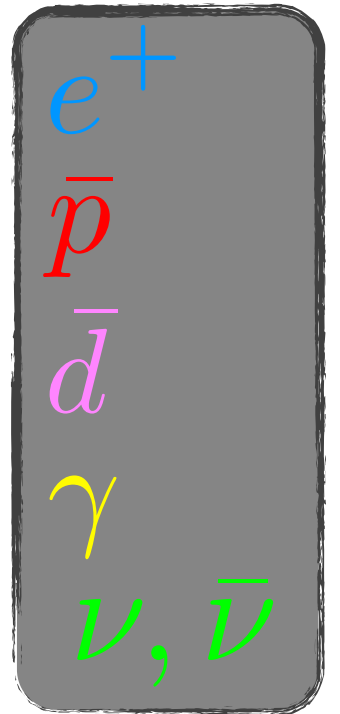
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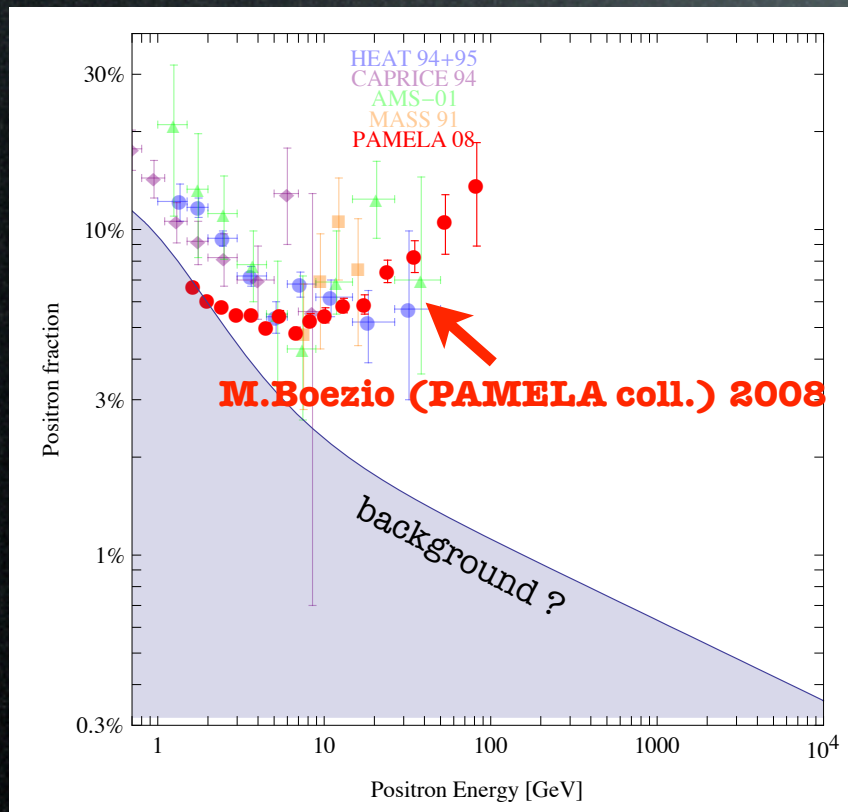
Particle Physics uncertainty

- Pythia at many TeV
- higher order corrections

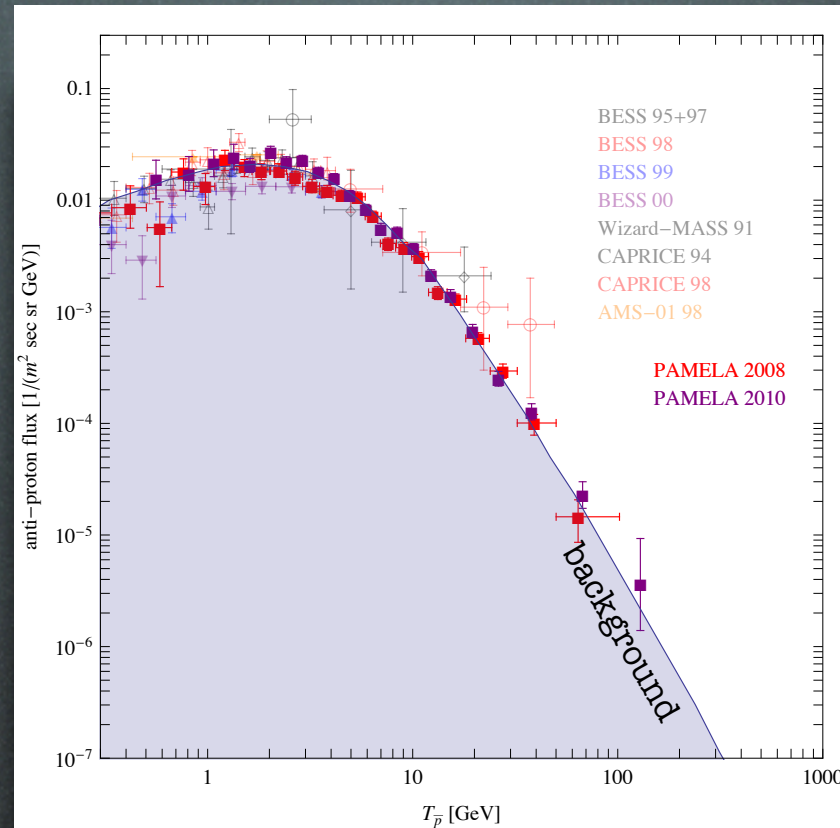


Indirect Detection: hints

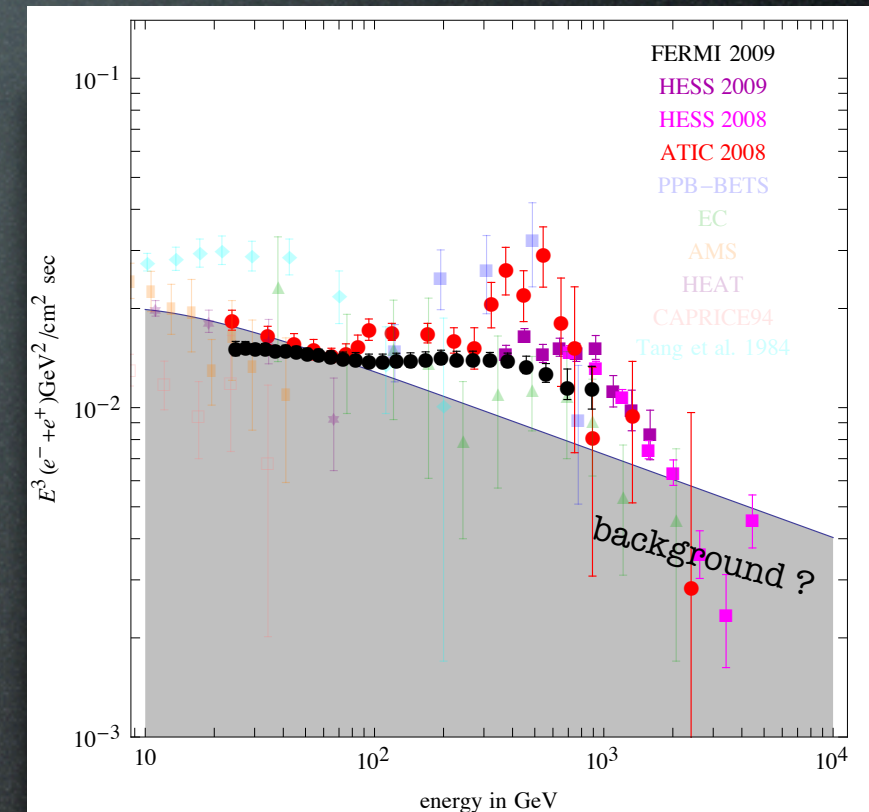
positron fraction



antiprotons



electrons + positrons



Indirect Detection: hints

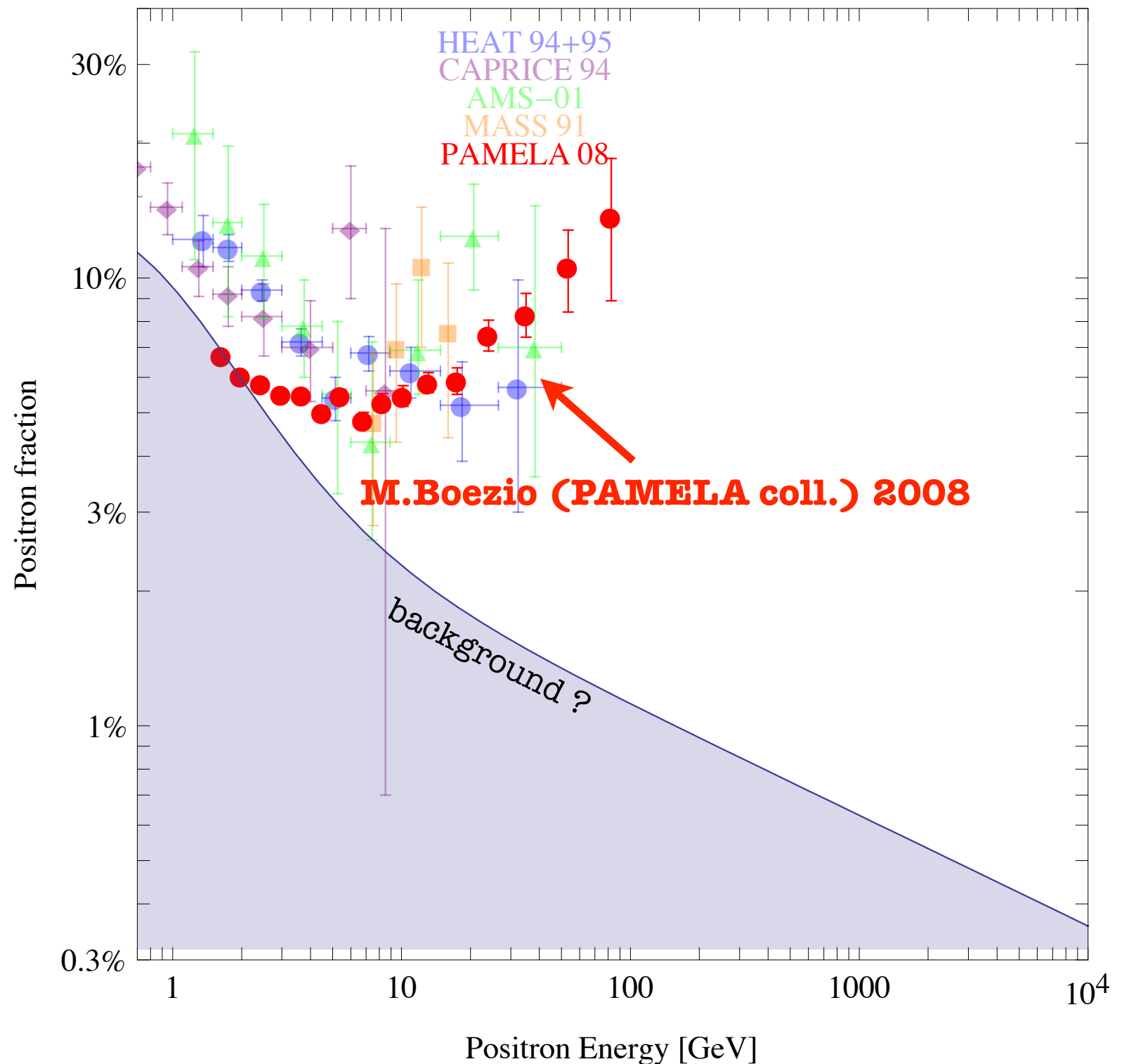
Positrons from PAMELA:

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

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

(9430 e^+ initially collected)

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



Indirect Detection: hints

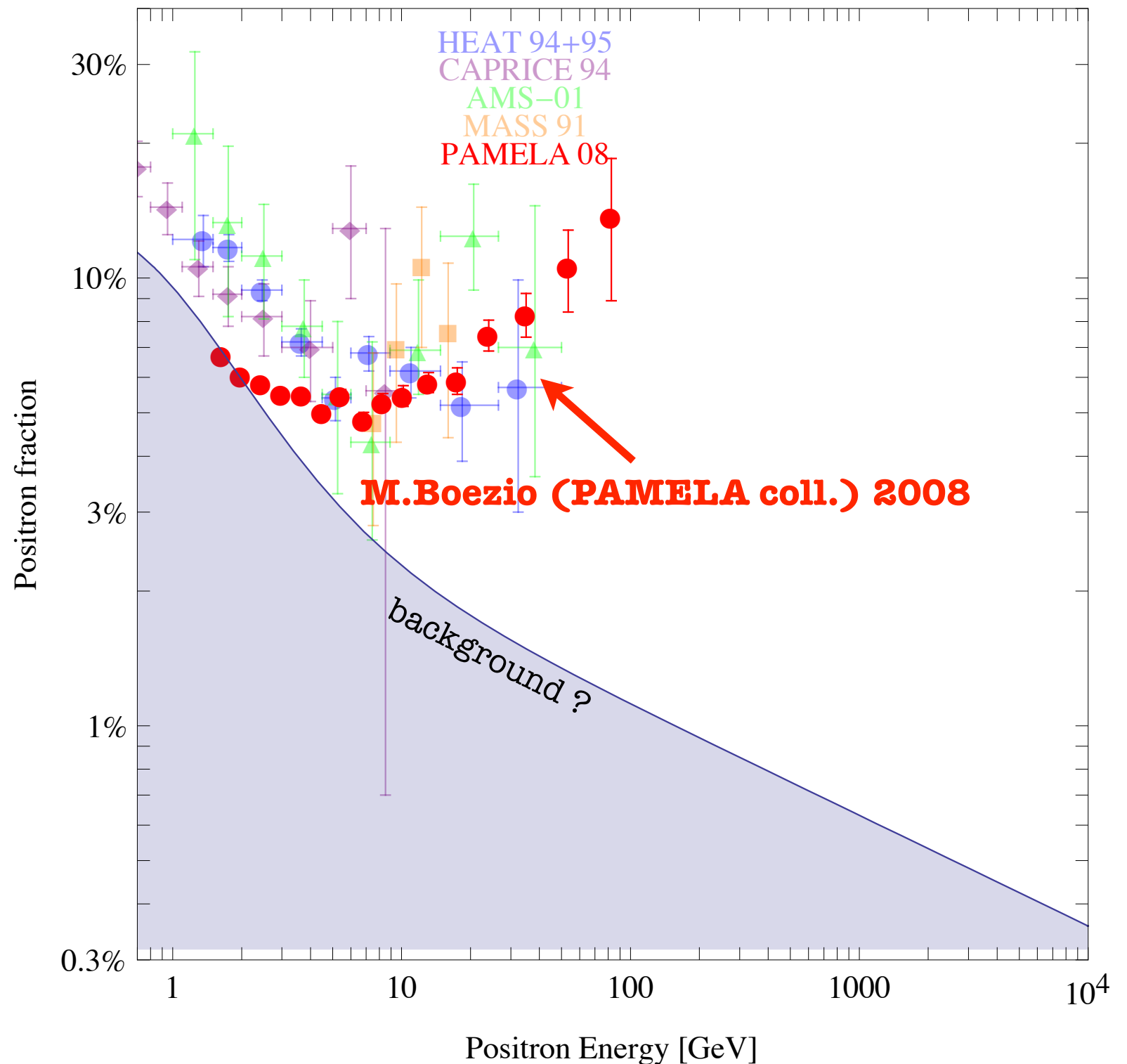
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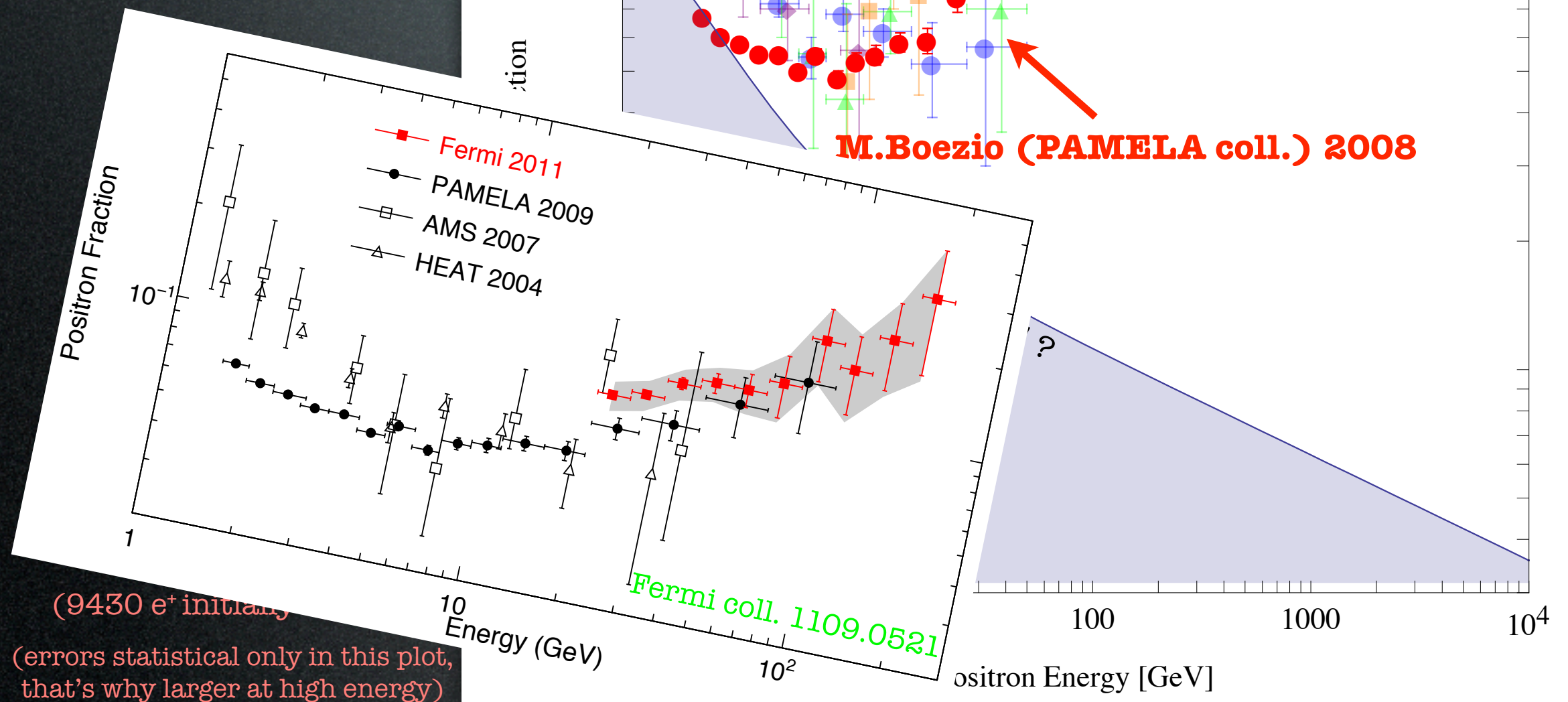
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Indirect Detection: hints

Positrons from PAMELA:

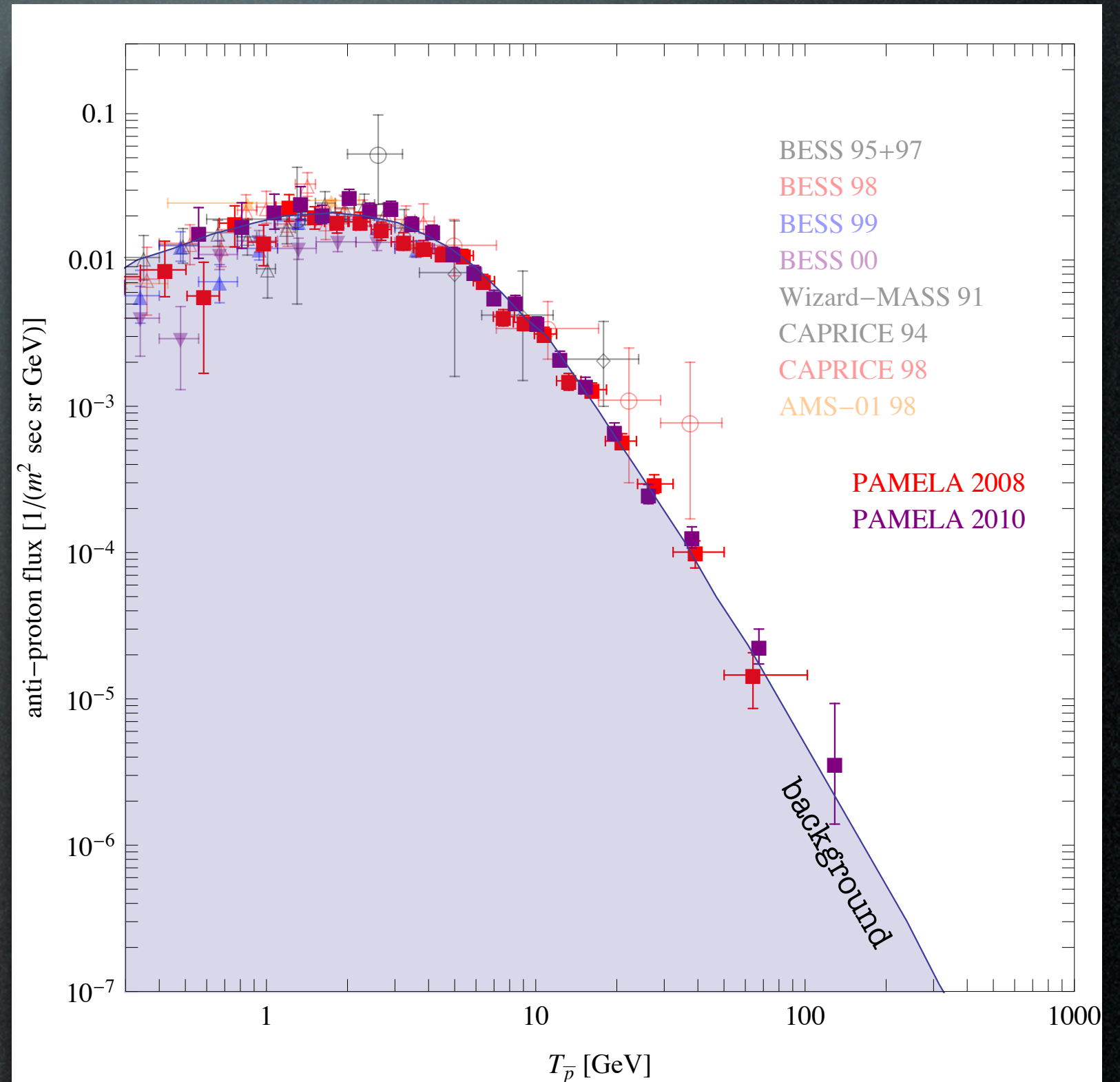
- steep e^+ excess above 10 GeV!
- very large flux!



Indirect Detection: hints

Antiprotons from PAMELA:

- consistent with
the background

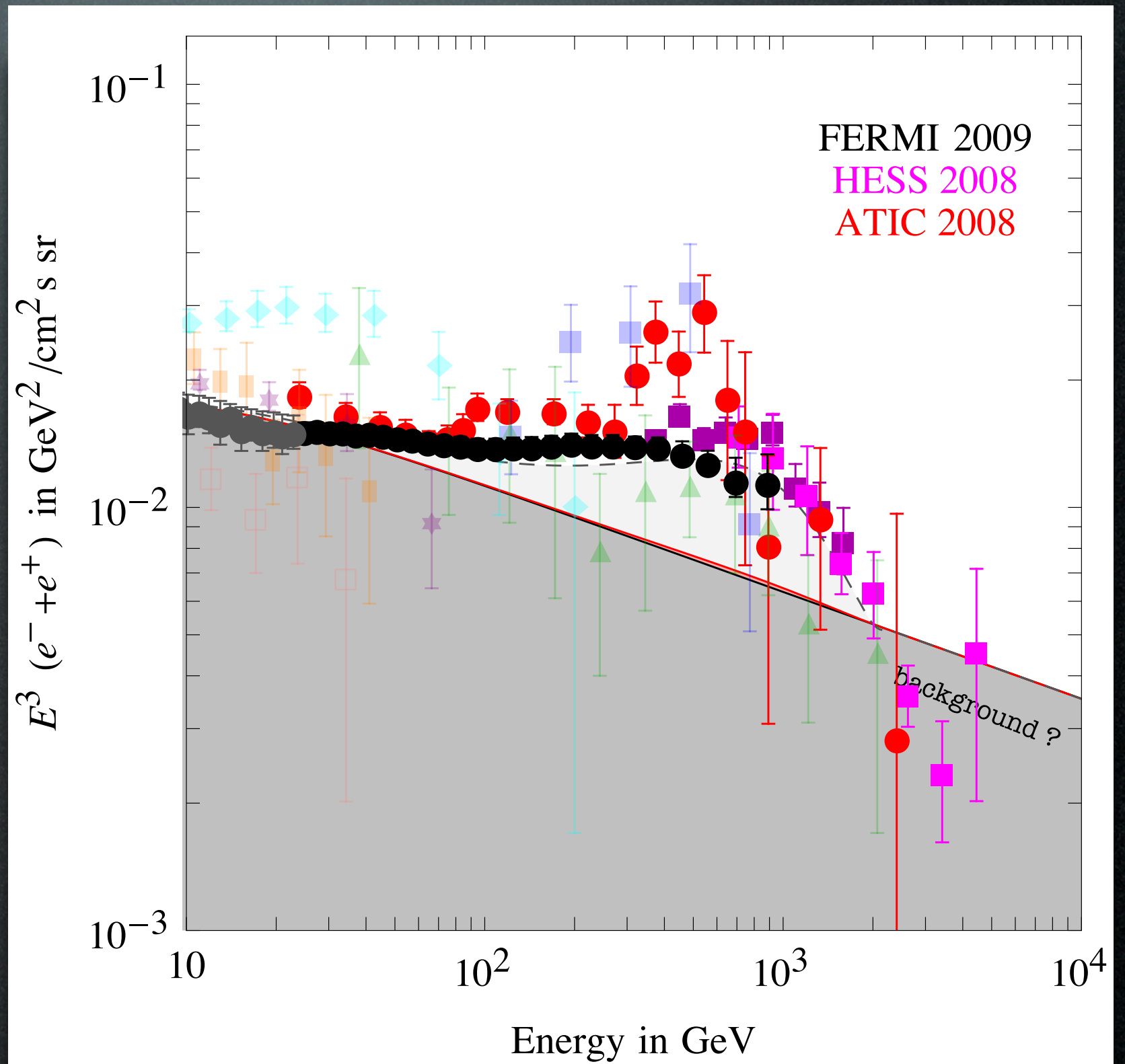


(about 1000 $\bar{p}$ collected
initially)

Indirect Detection: hints

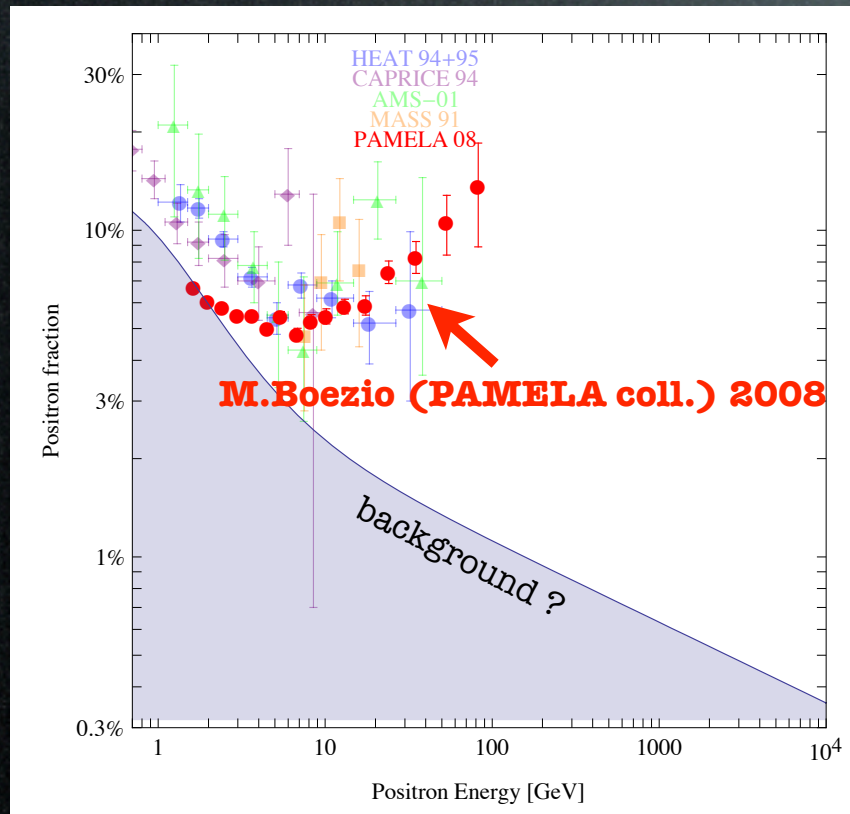
Electrons + positrons adding FERMI and HESS:

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

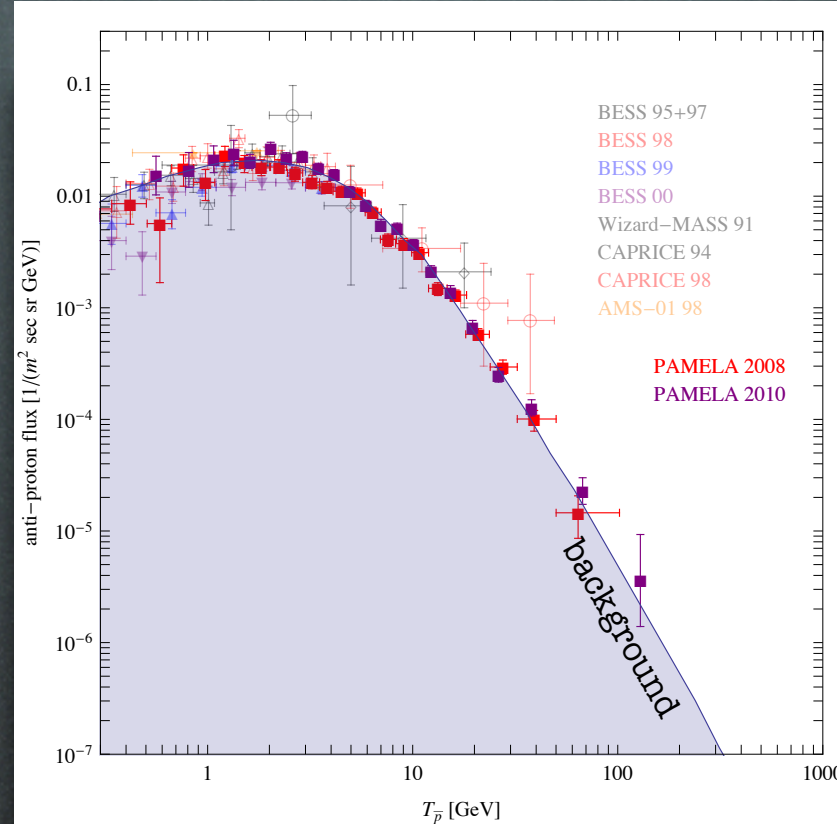


Indirect Detection: hints

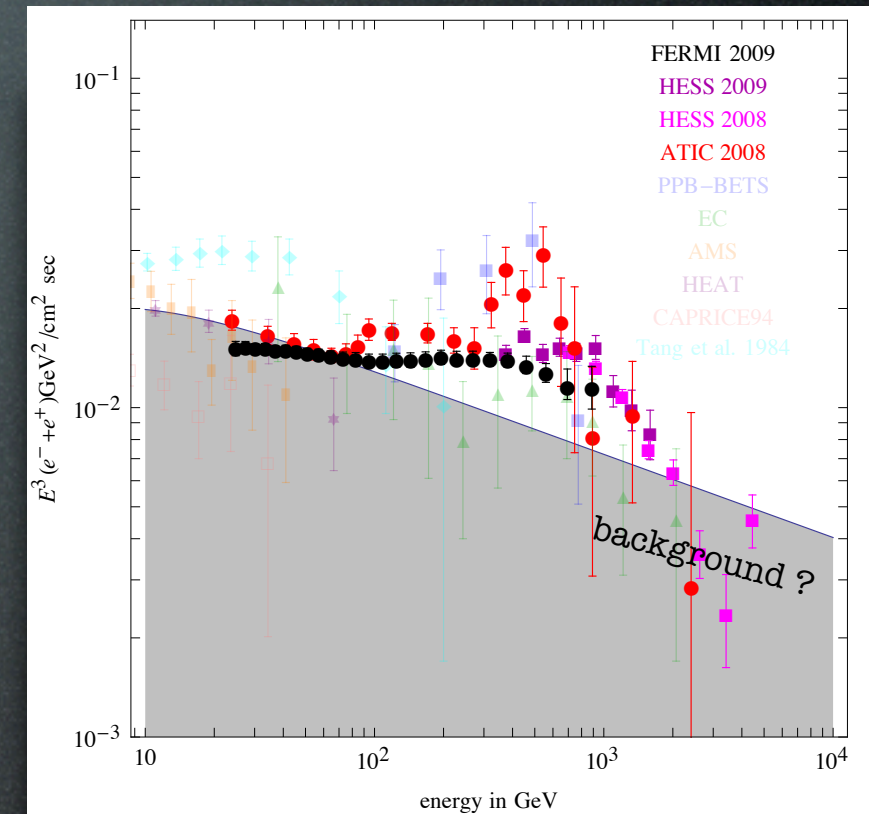
positron fraction



antiprotons



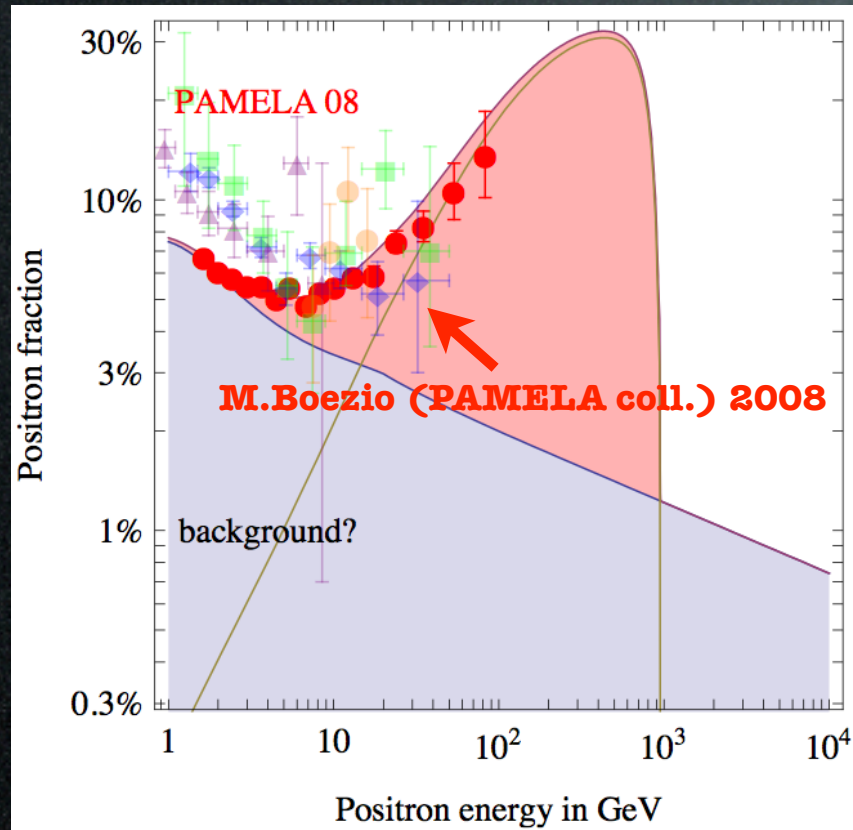
electrons + positrons



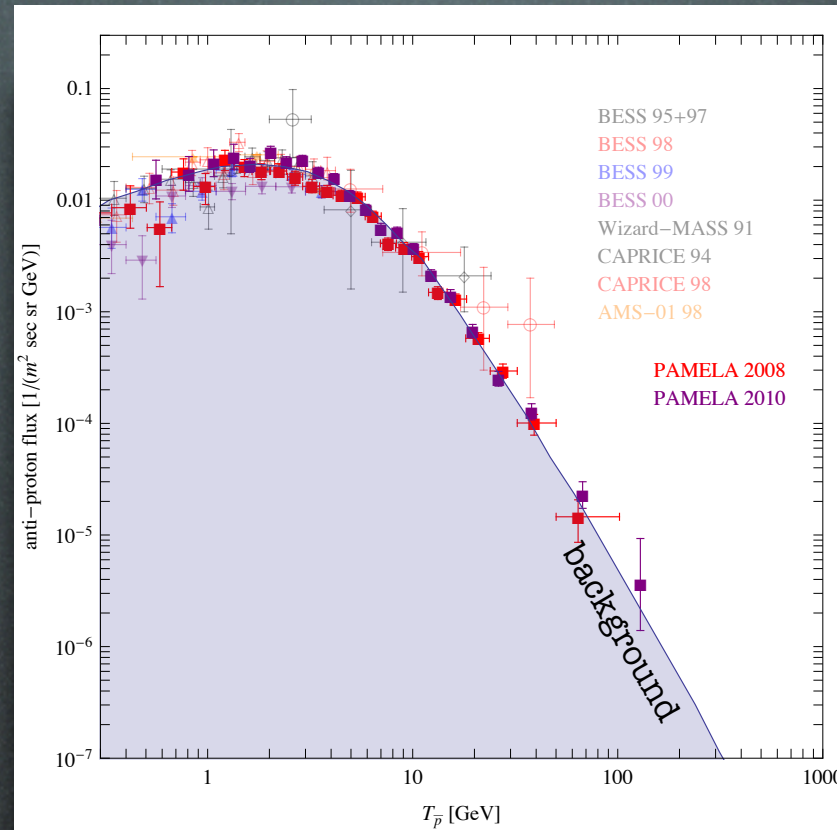
Are these signals of Dark Matter?

Indirect Detection: hints

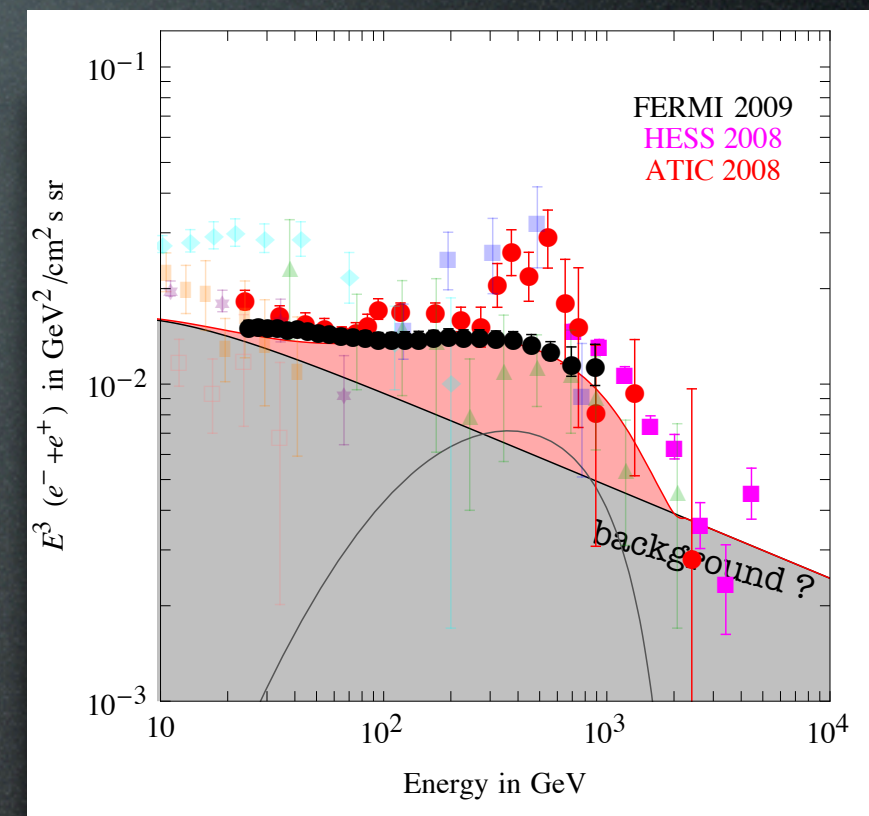
positron fraction



antiprotons



electrons + positrons

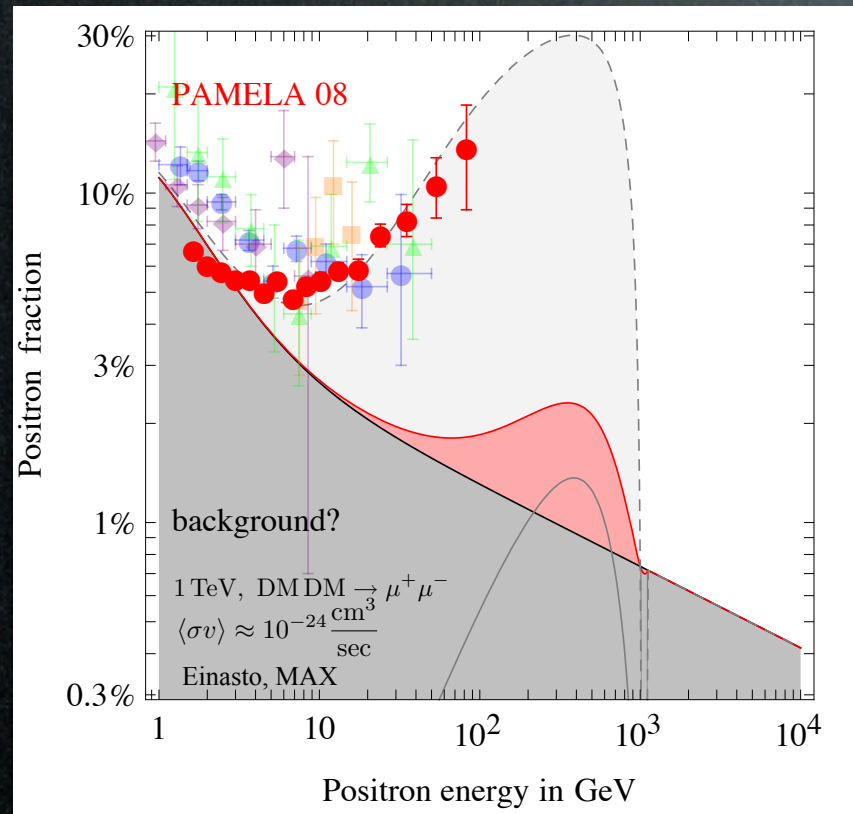


Are these signals of Dark Matter?

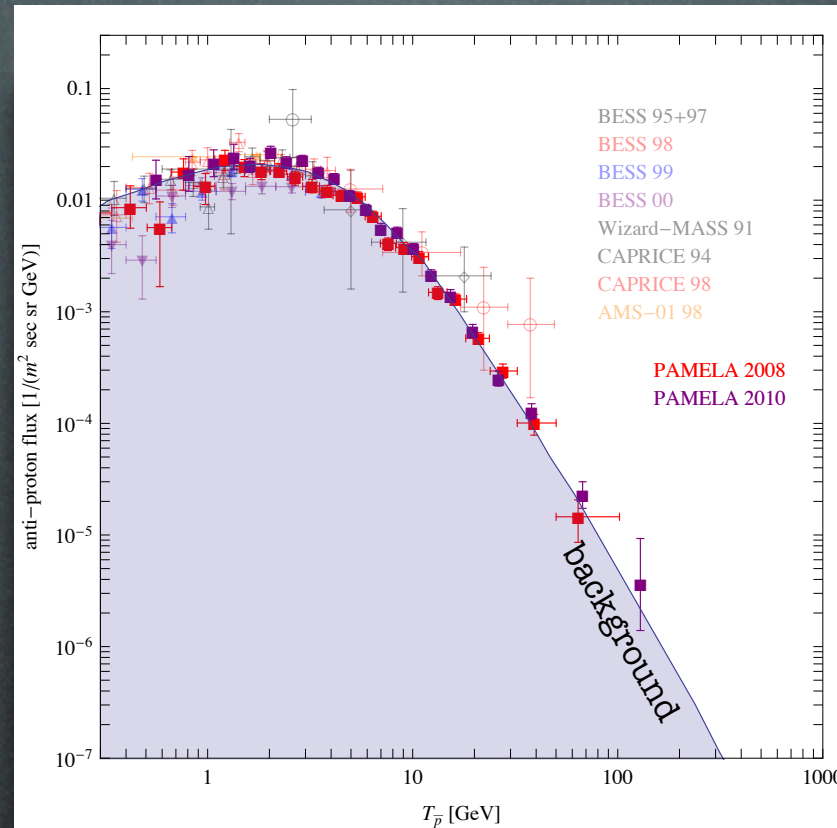
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23} \text{ cm}^3/\text{sec}$

Indirect Detection: hints

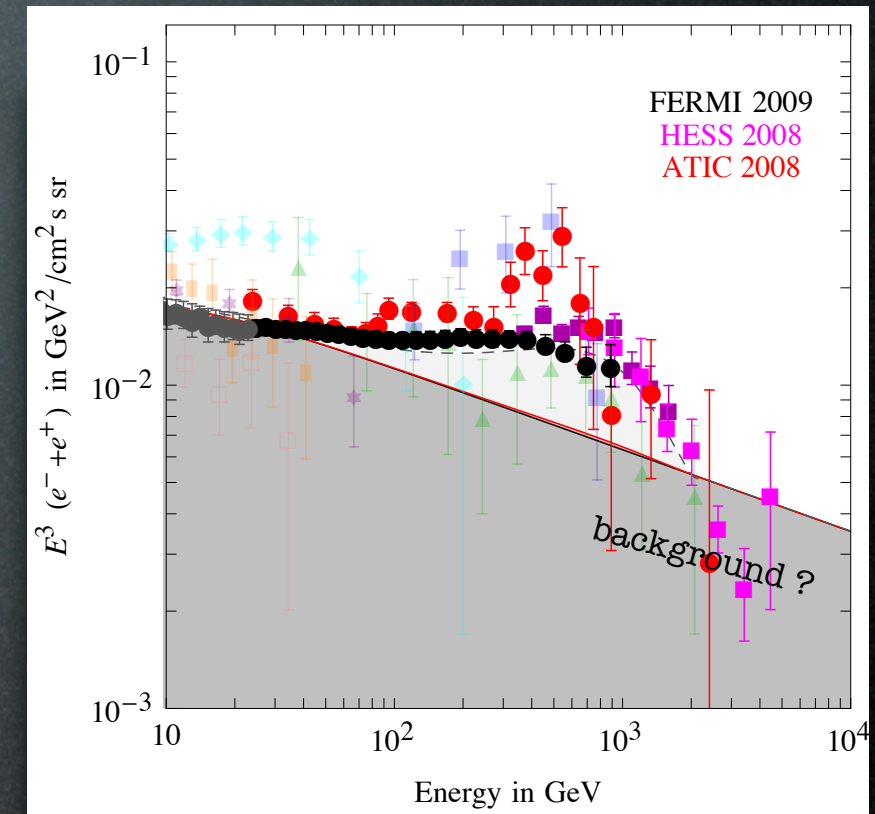
positron fraction



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, ICT, radio telescopes...

e^+ from annihil in galactic halo or center

PAMELA, Fermi, HESS, AMS, balloons...

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

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

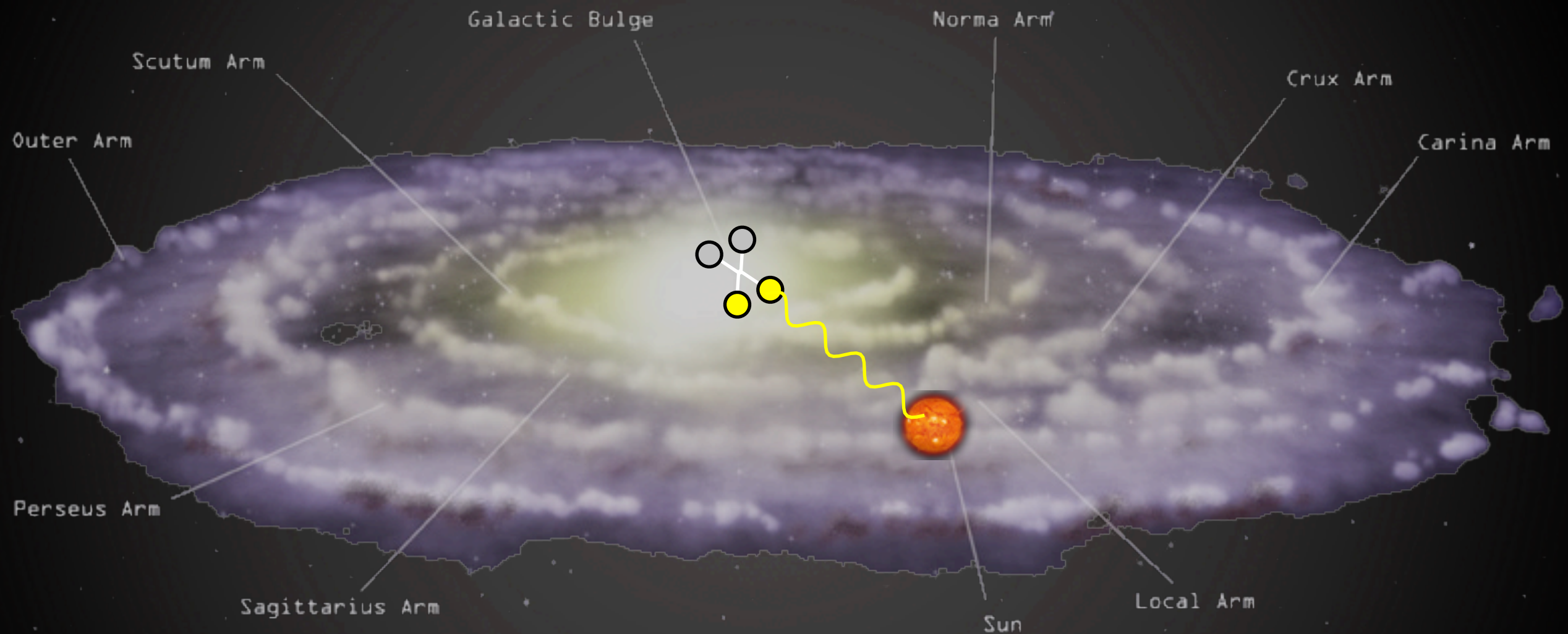
GAPS

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

SK, Icecube, Km3Net

Indirect Detection: constraints

γ from DM annihilations in galactic center



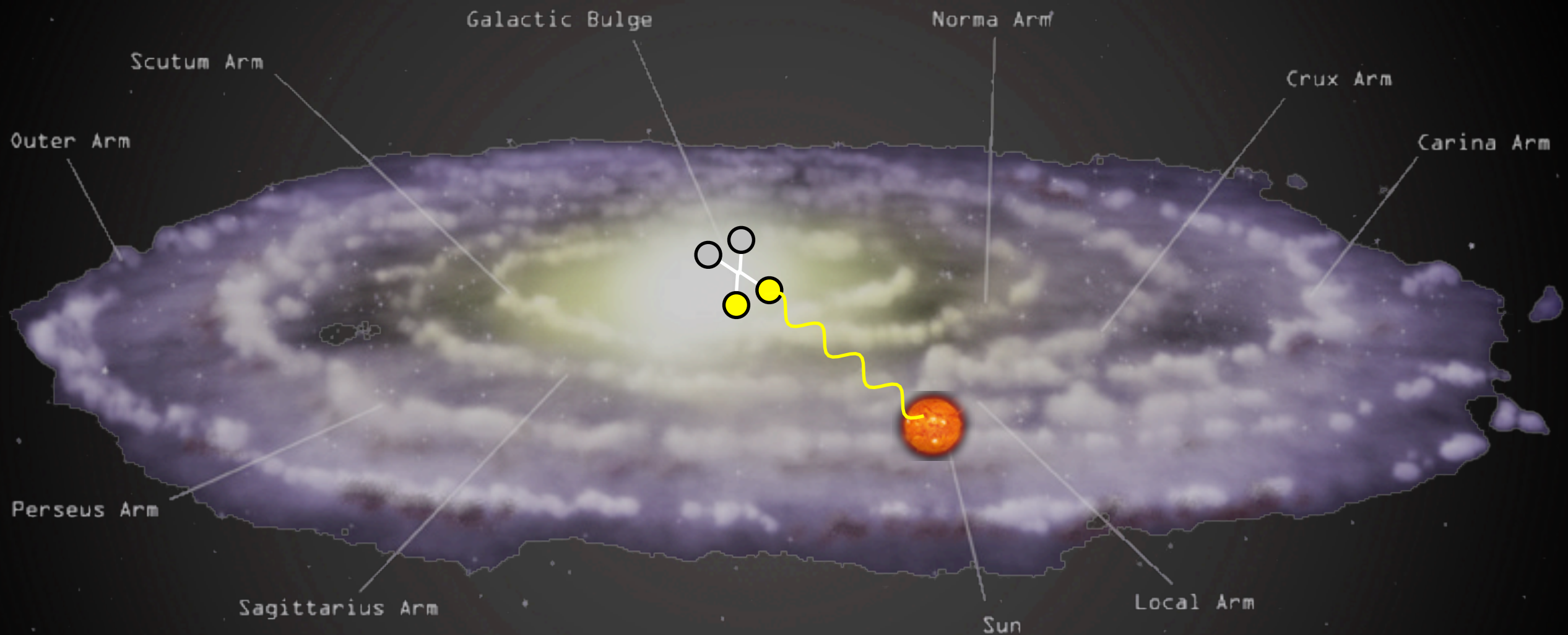
DM DM

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

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

Indirect Detection: constraints

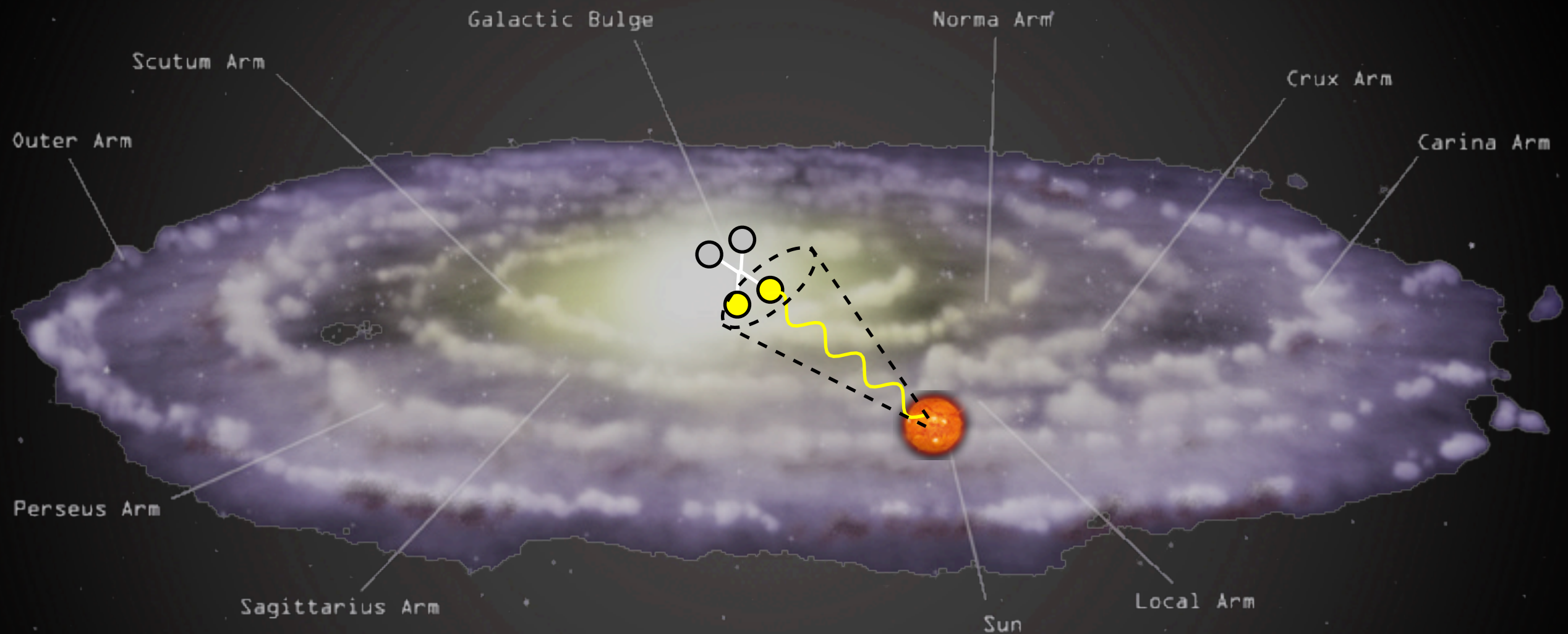
a. γ from DM annihilations in galactic center



$$\begin{aligned} DM & \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \\ DM & \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \end{aligned}$$

Indirect Detection: constraints

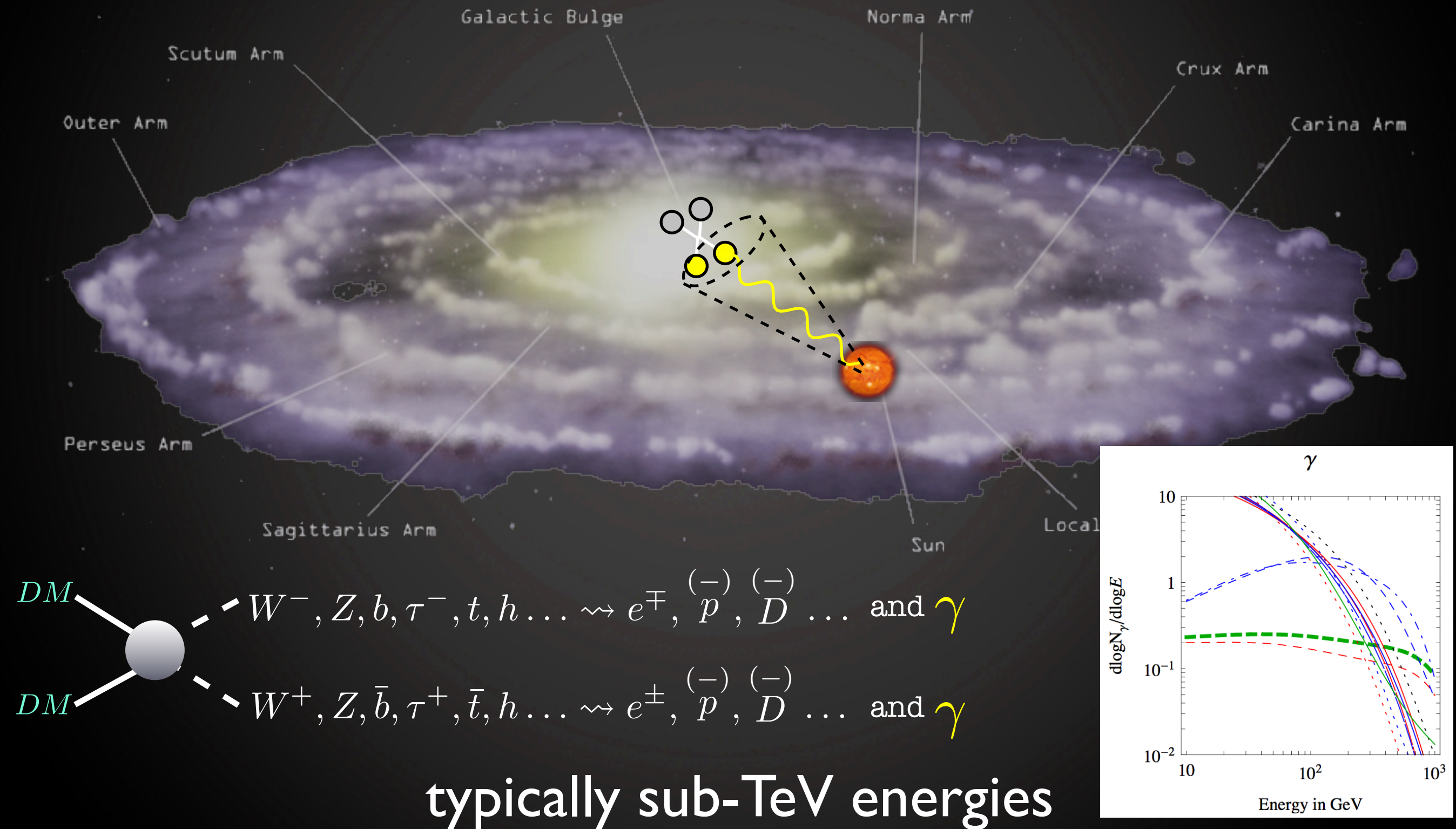
a. γ from DM annihilations in galactic center



$$\begin{aligned} DM & \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \\ DM & \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \end{aligned}$$

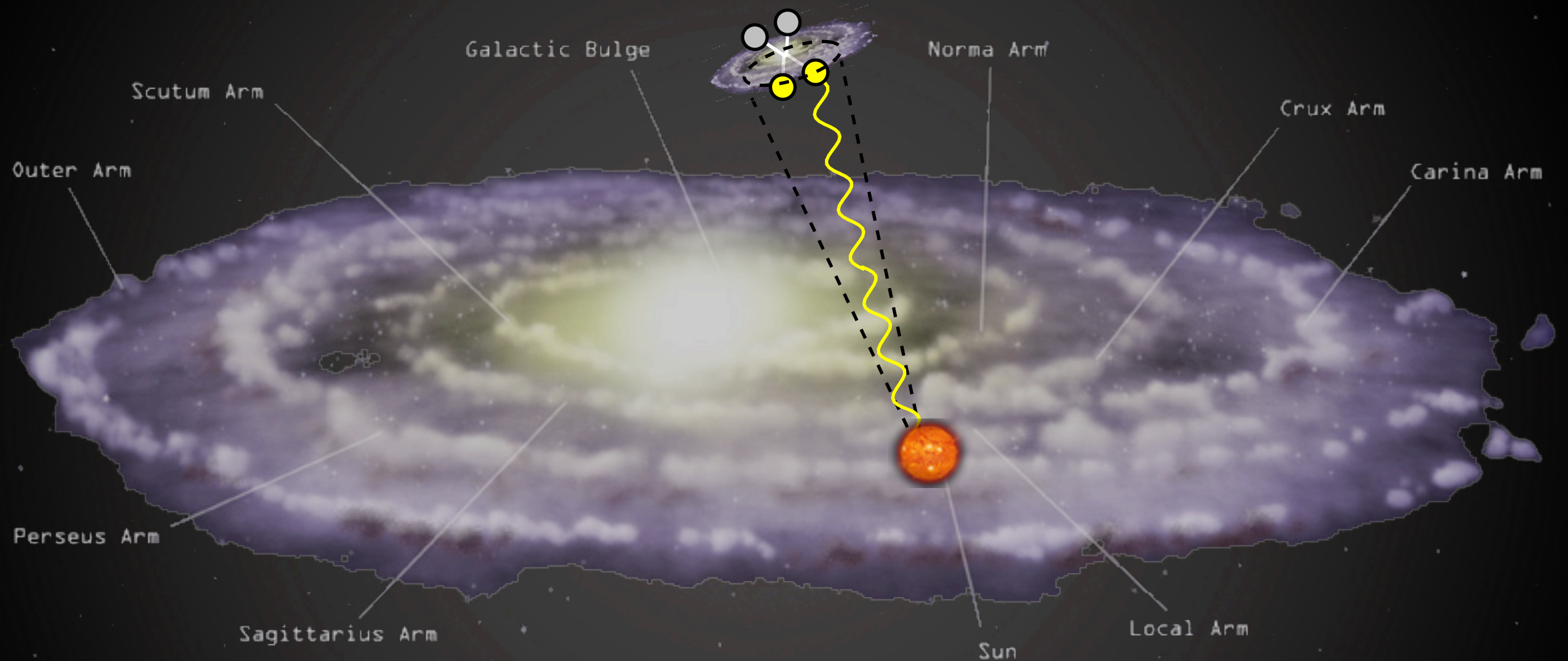
Indirect Detection: constraints

a. γ from DM annihilations in galactic center



Indirect Detection: constraints

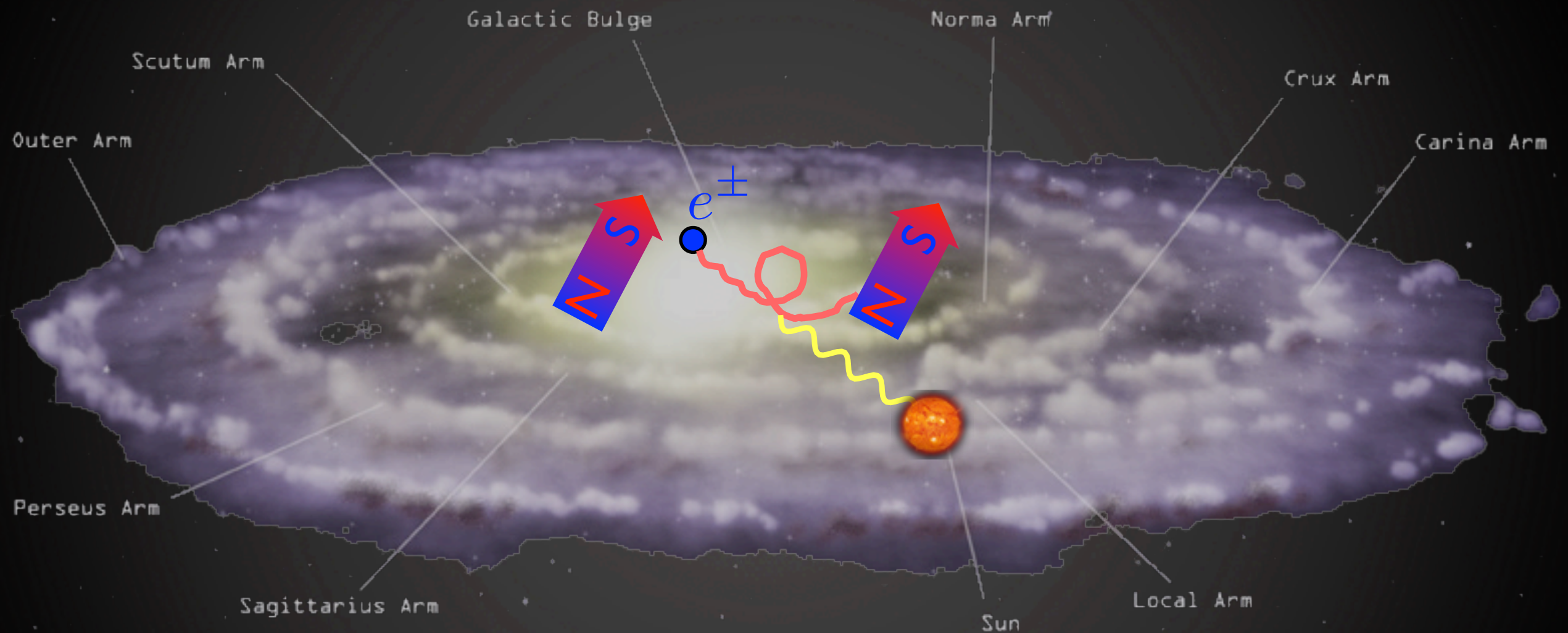
b. γ from DM annihilations in Satellite Galaxies



$$\begin{aligned} DM & \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \\ DM & \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \end{aligned}$$

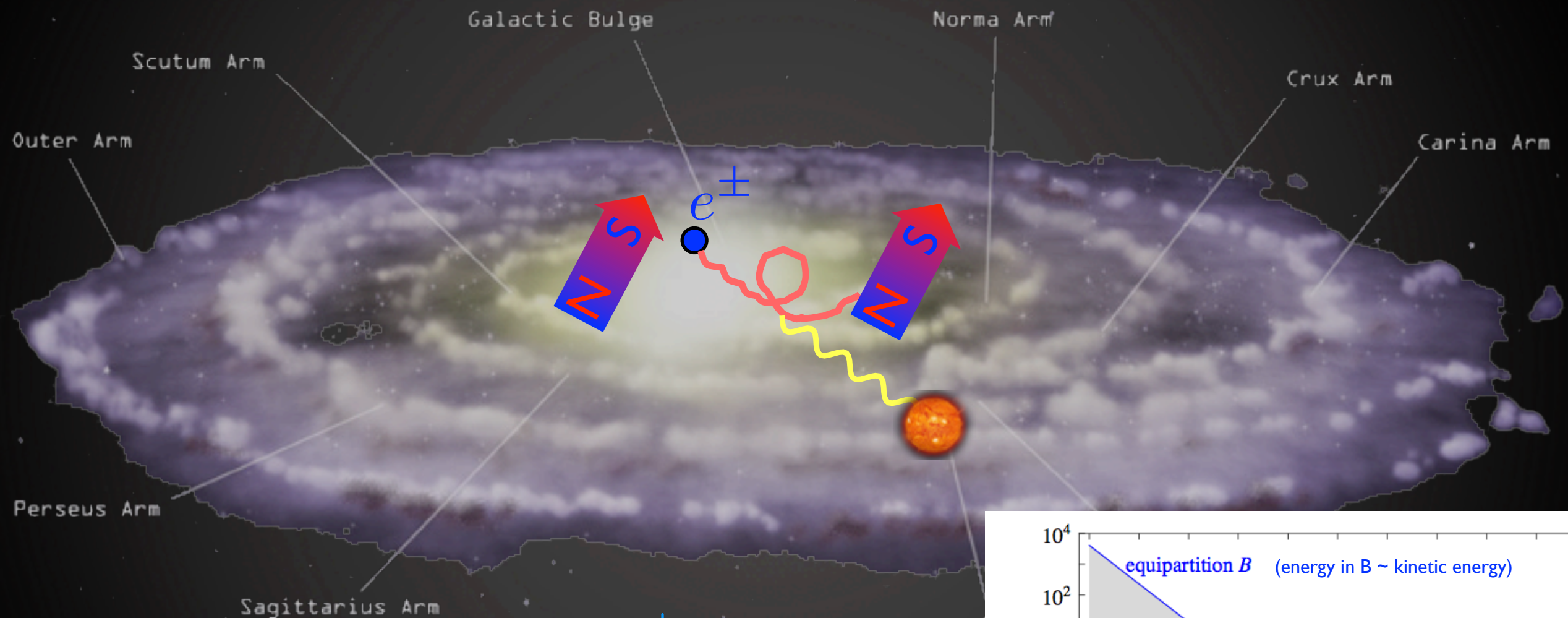
Indirect Detection: constraints

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

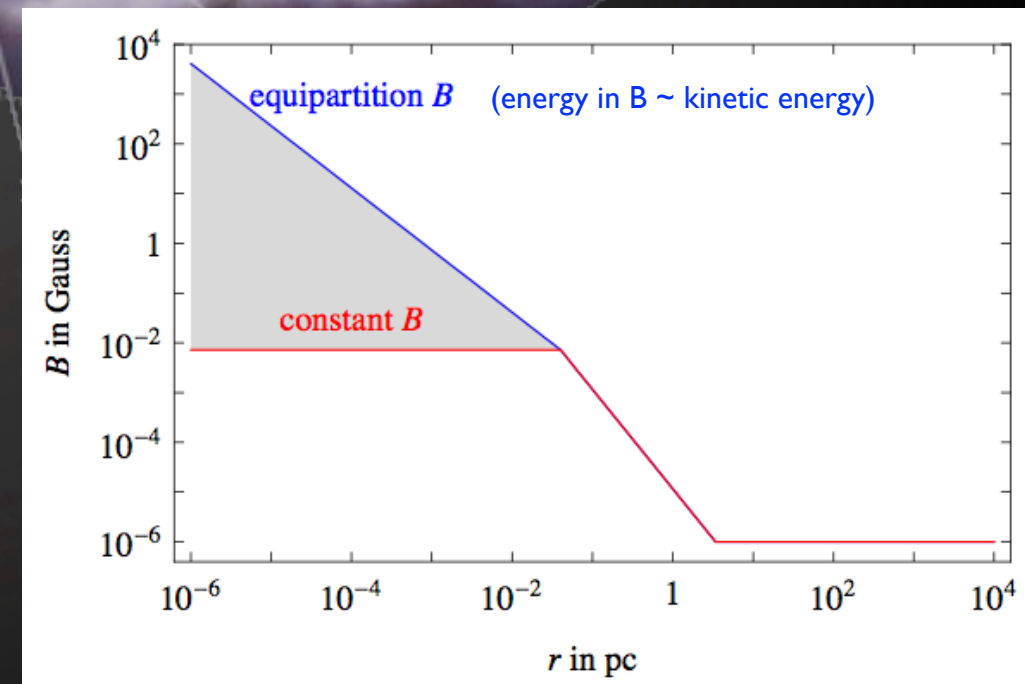


Indirect Detection: constraints

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

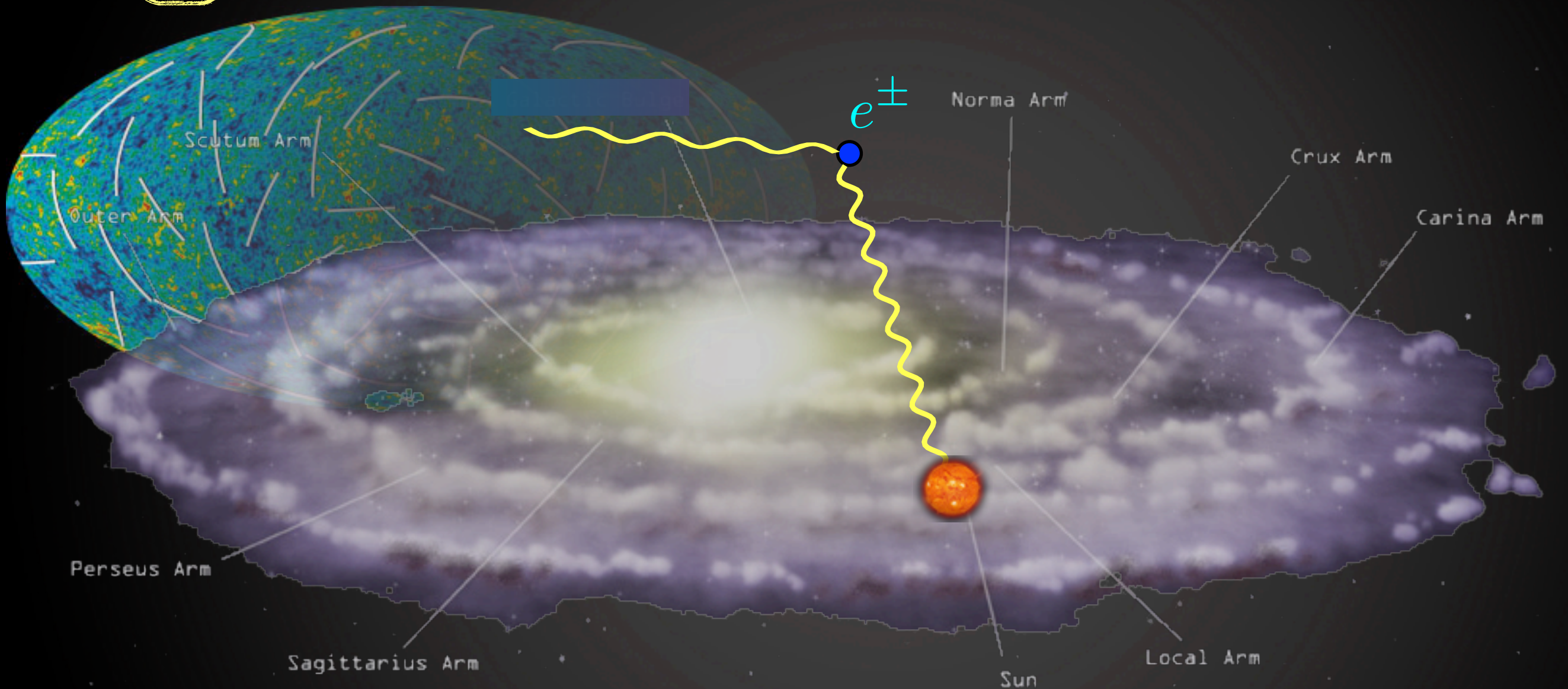


- compute the population of $e^\pm$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$
(assuming 'scrambled' B; in principle, directionality could focus emission, lift bounds by O(some))



Indirect Detection: constraints

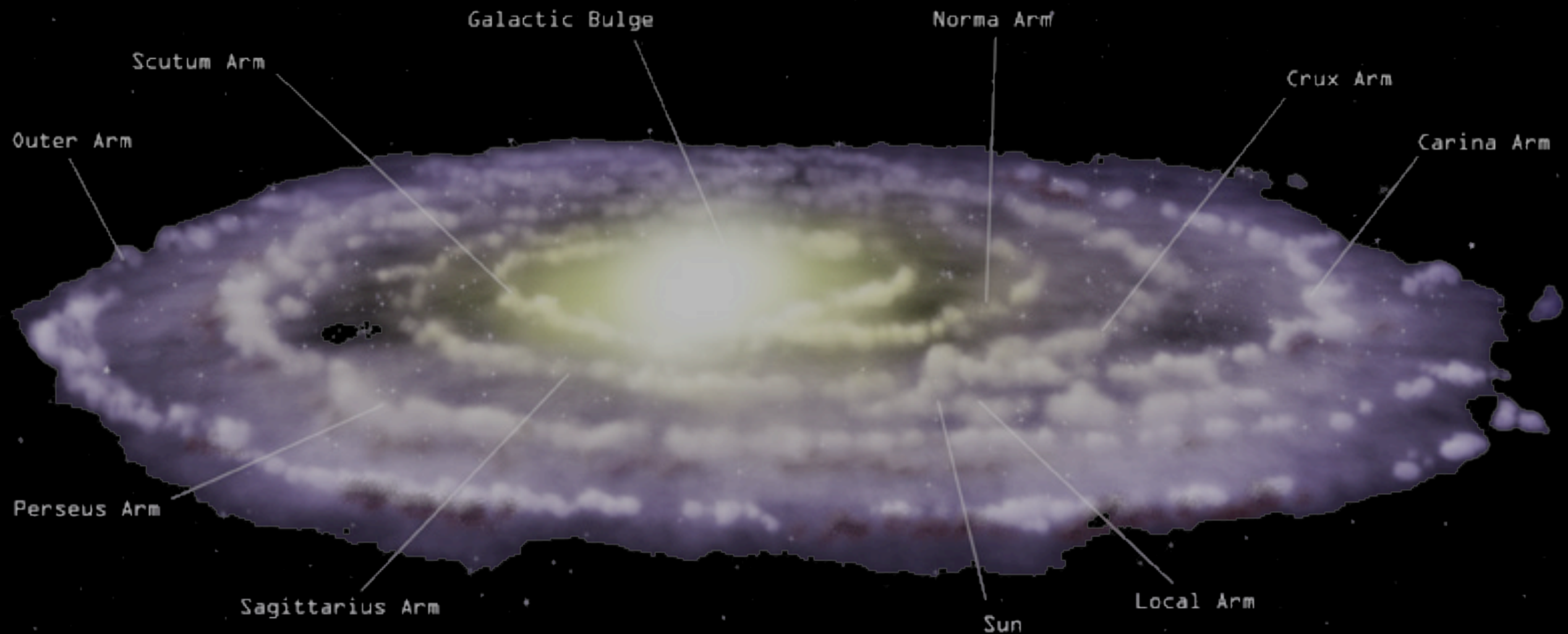
d. γ from Inverse Compton on $e^\pm$ in halo



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

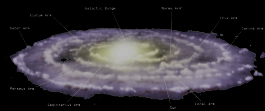
Indirect Detection: constraints

e. γ from outside the Galaxy



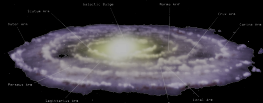
Indirect Detection: constraints

e. γ from outside the Galaxy



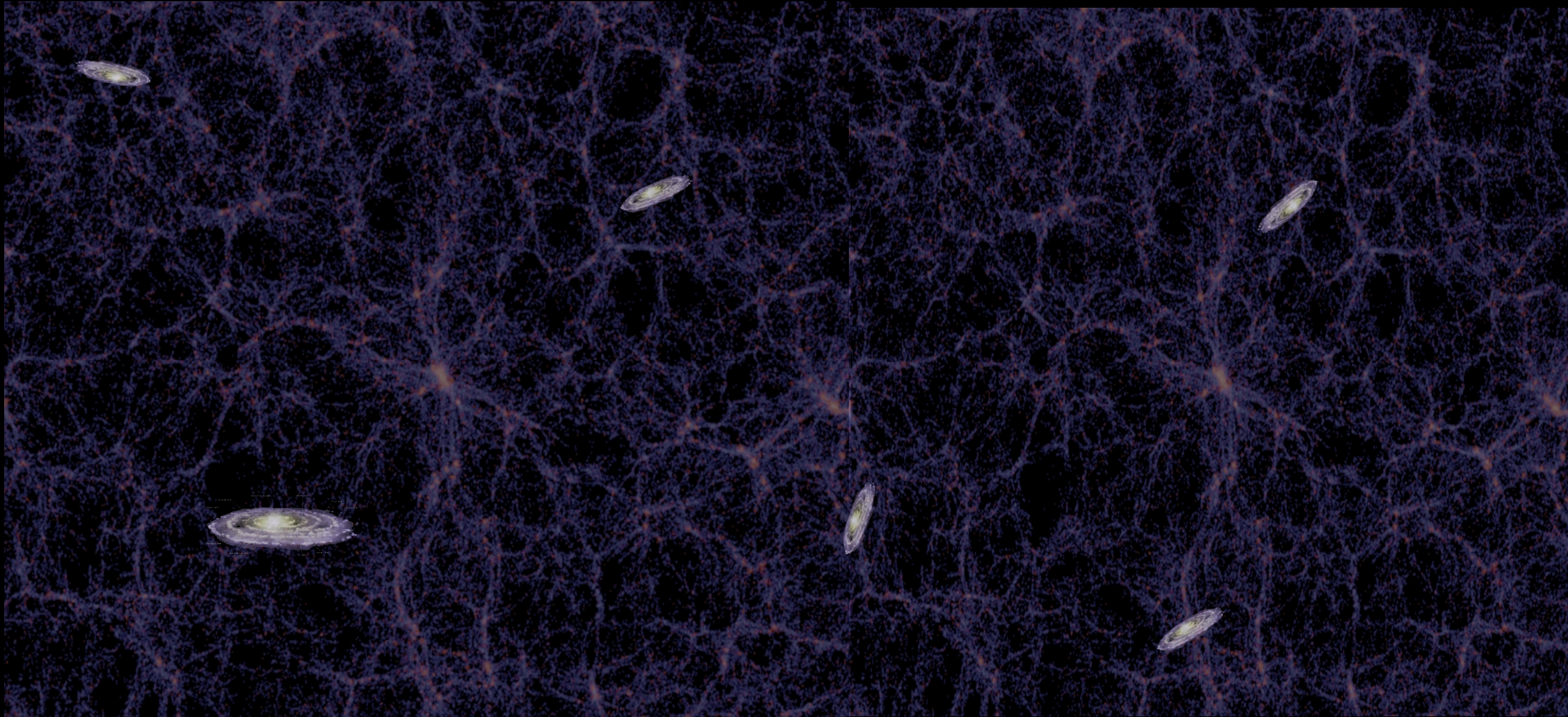
Indirect Detection: constraints

e. γ from outside the Galaxy



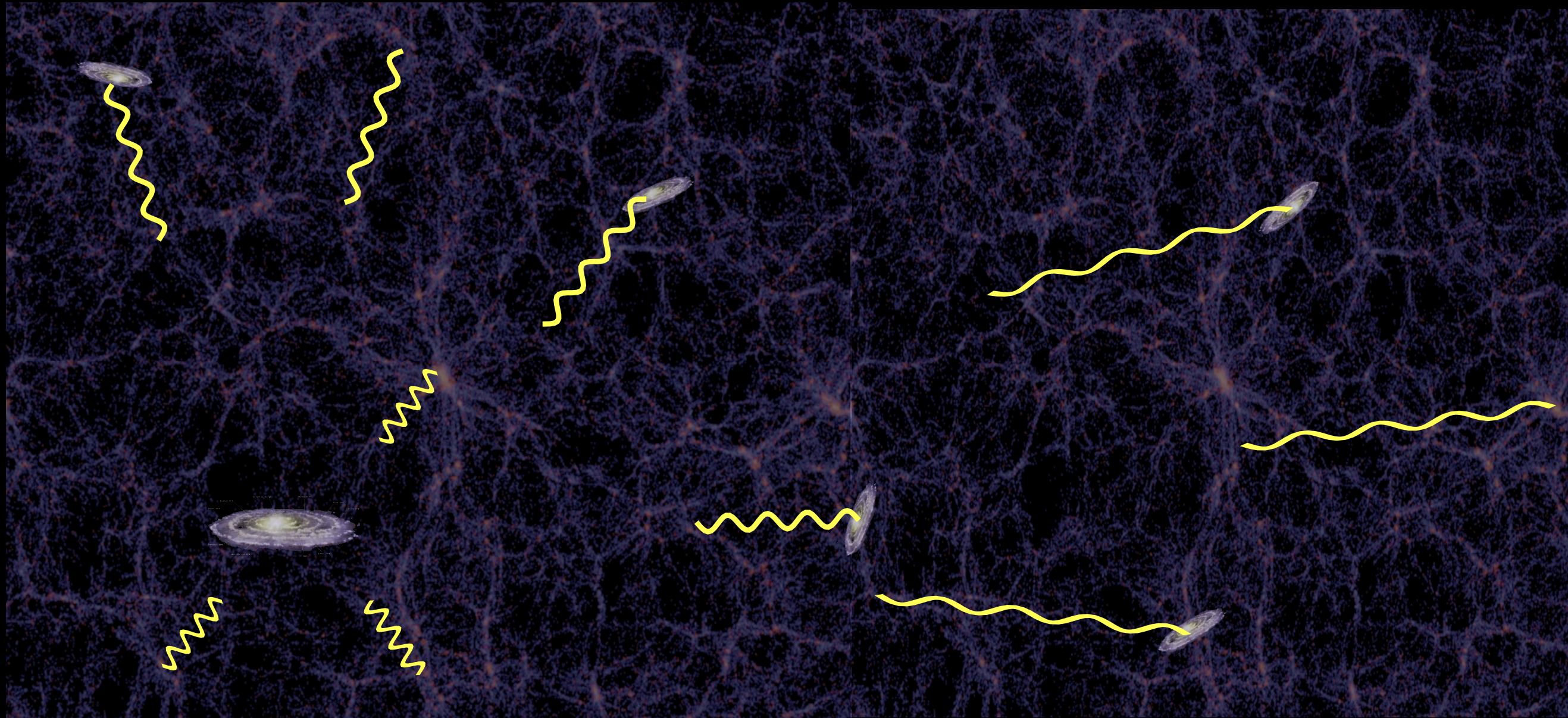
Indirect Detection: constraints

e. γ from outside the Galaxy



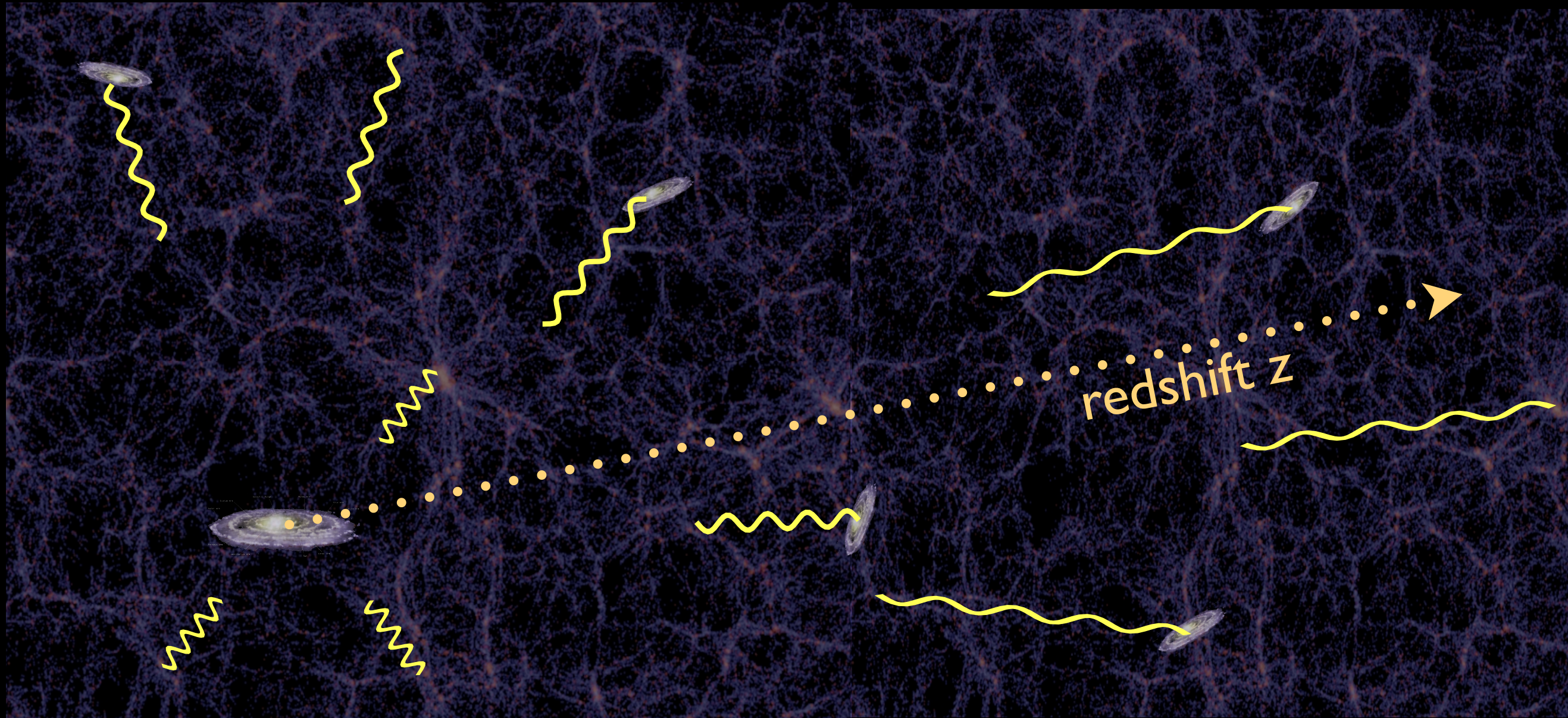
Indirect Detection: constraints

e. γ from outside the Galaxy



Indirect Detection: constraints

e. γ from outside the Galaxy

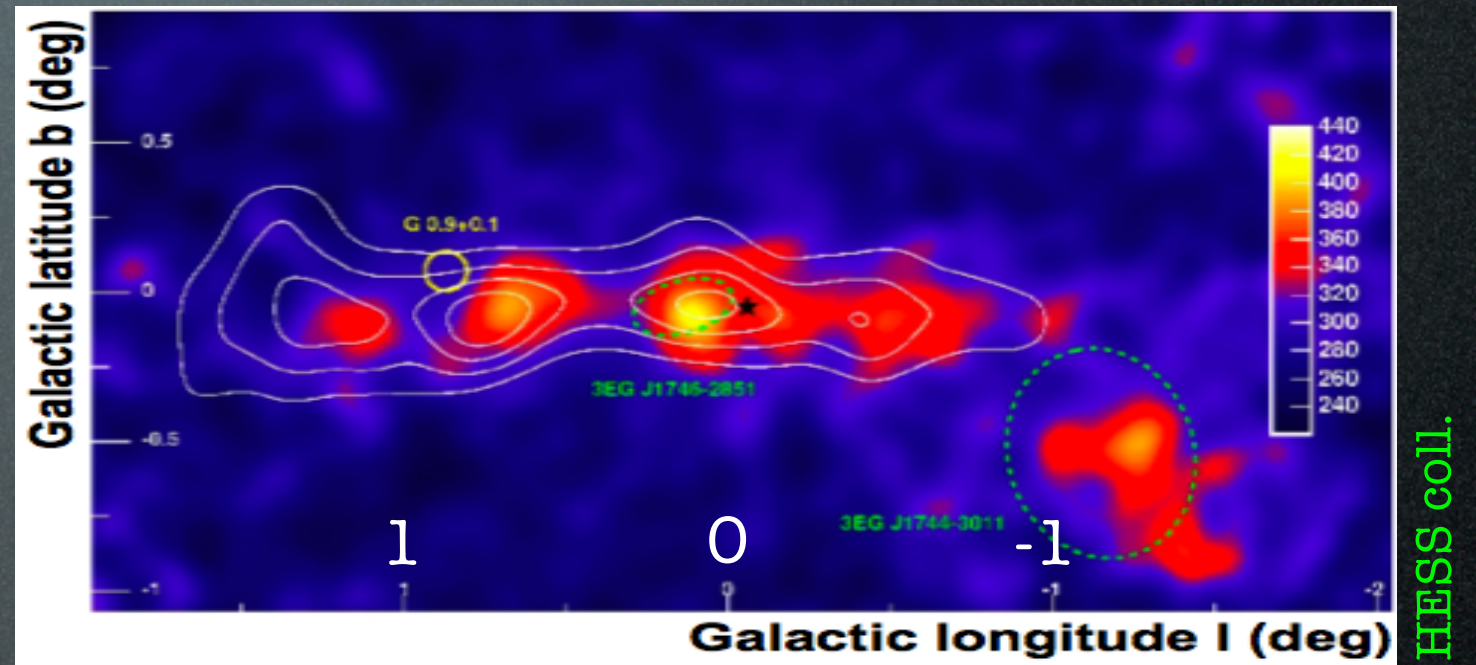


- **isotropic** flux of prompt and ICS gamma rays, integrated over **z** and **r**
- depends strongly on **halo formation details** and **history**

Gamma constraints

a. γ from DM annihilations in the Galactic Center

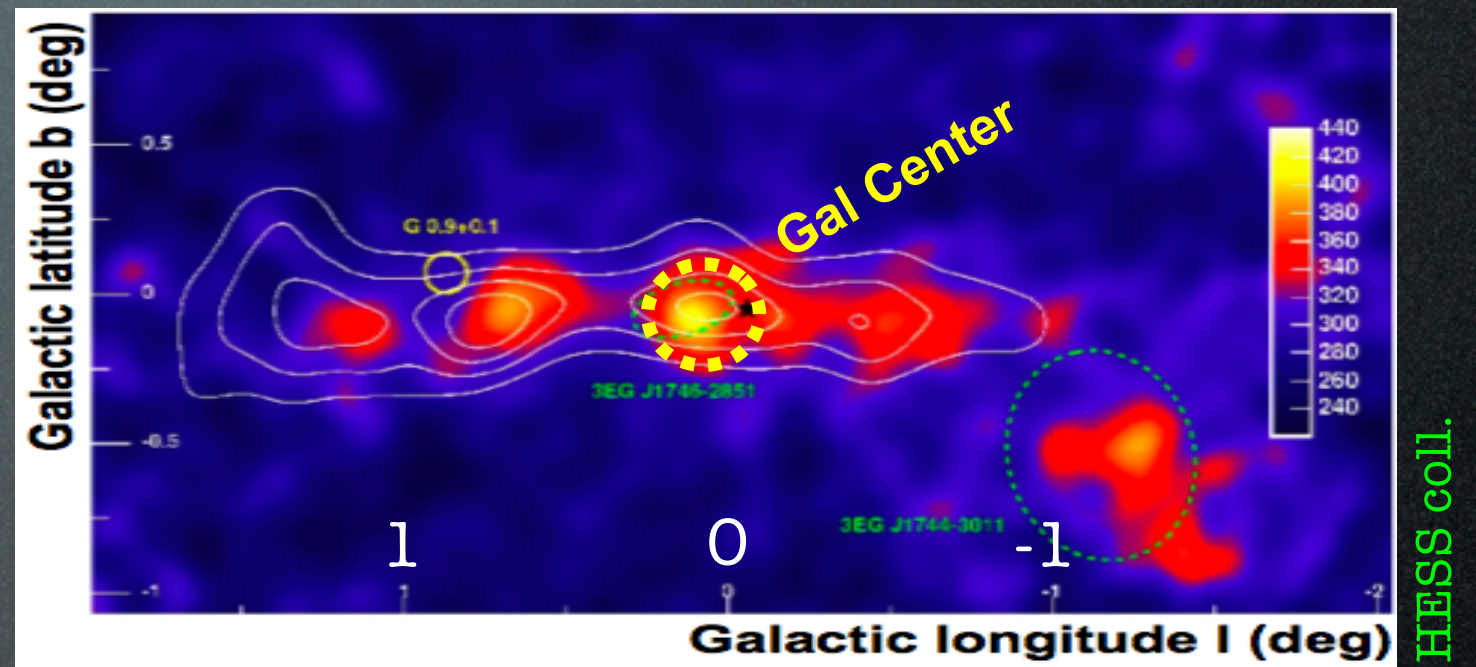
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



Gamma constraints

a. γ from DM annihilations in the Galactic Center

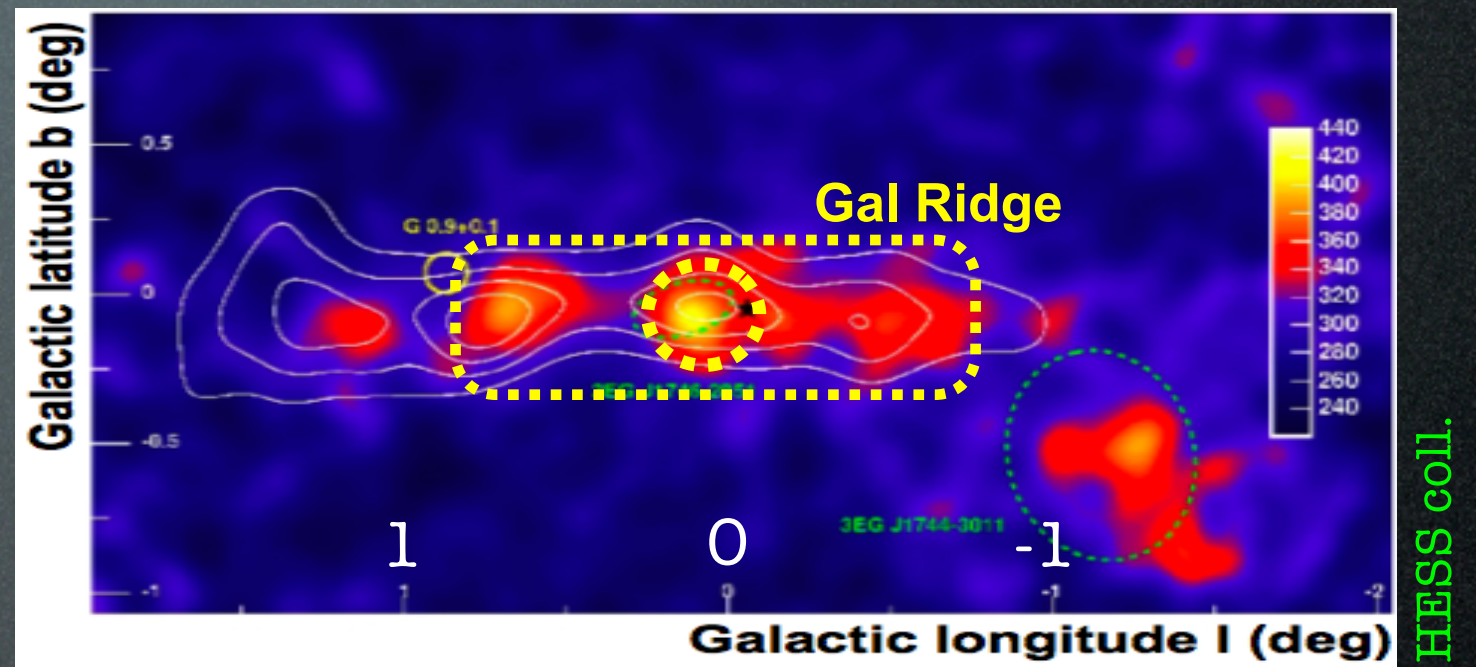
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



Gamma constraints

a. γ from DM annihilations in the Galactic Center

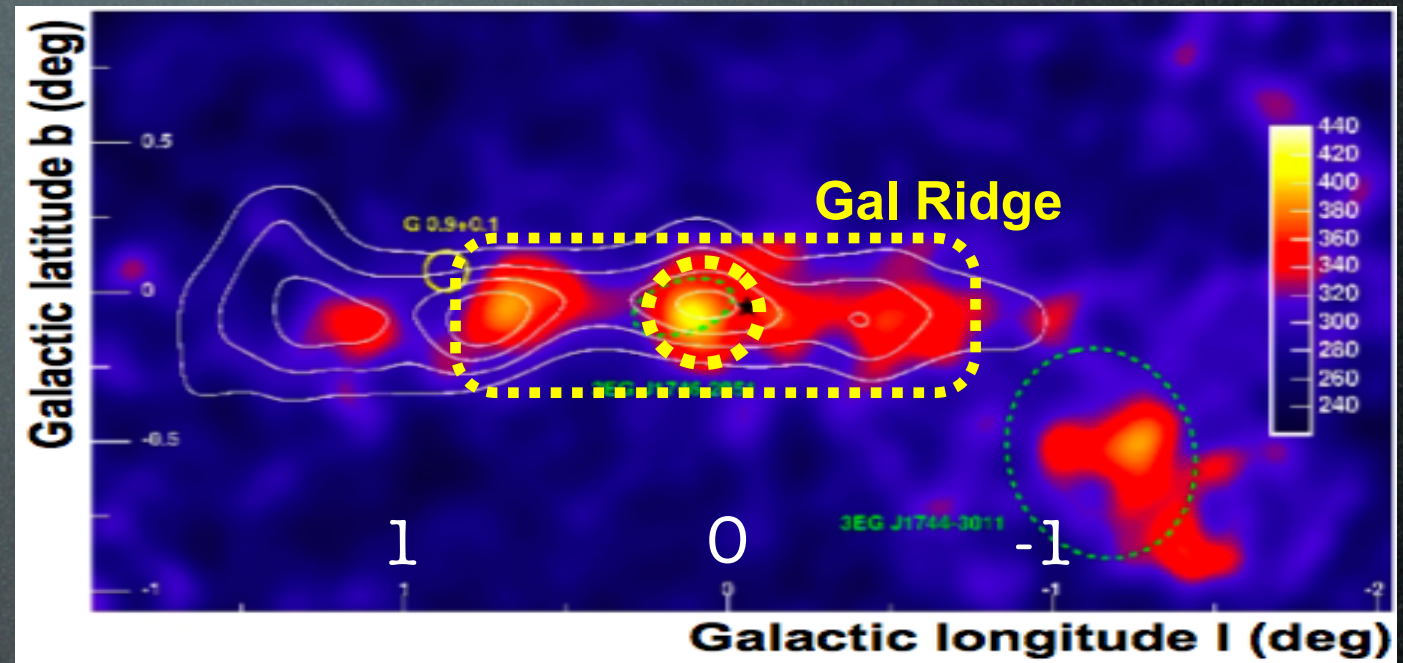
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



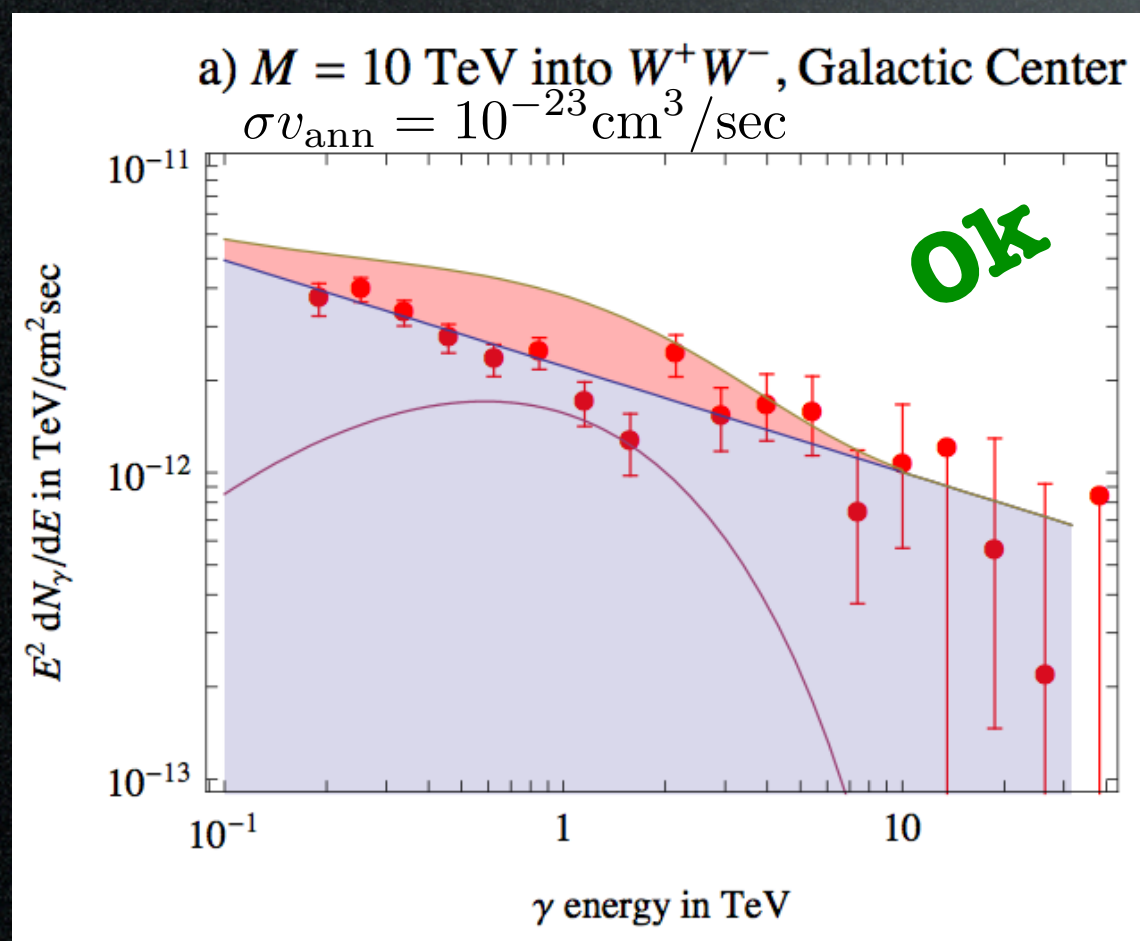
Gamma constraints

a. γ from DM annihilations in the Galactic Center

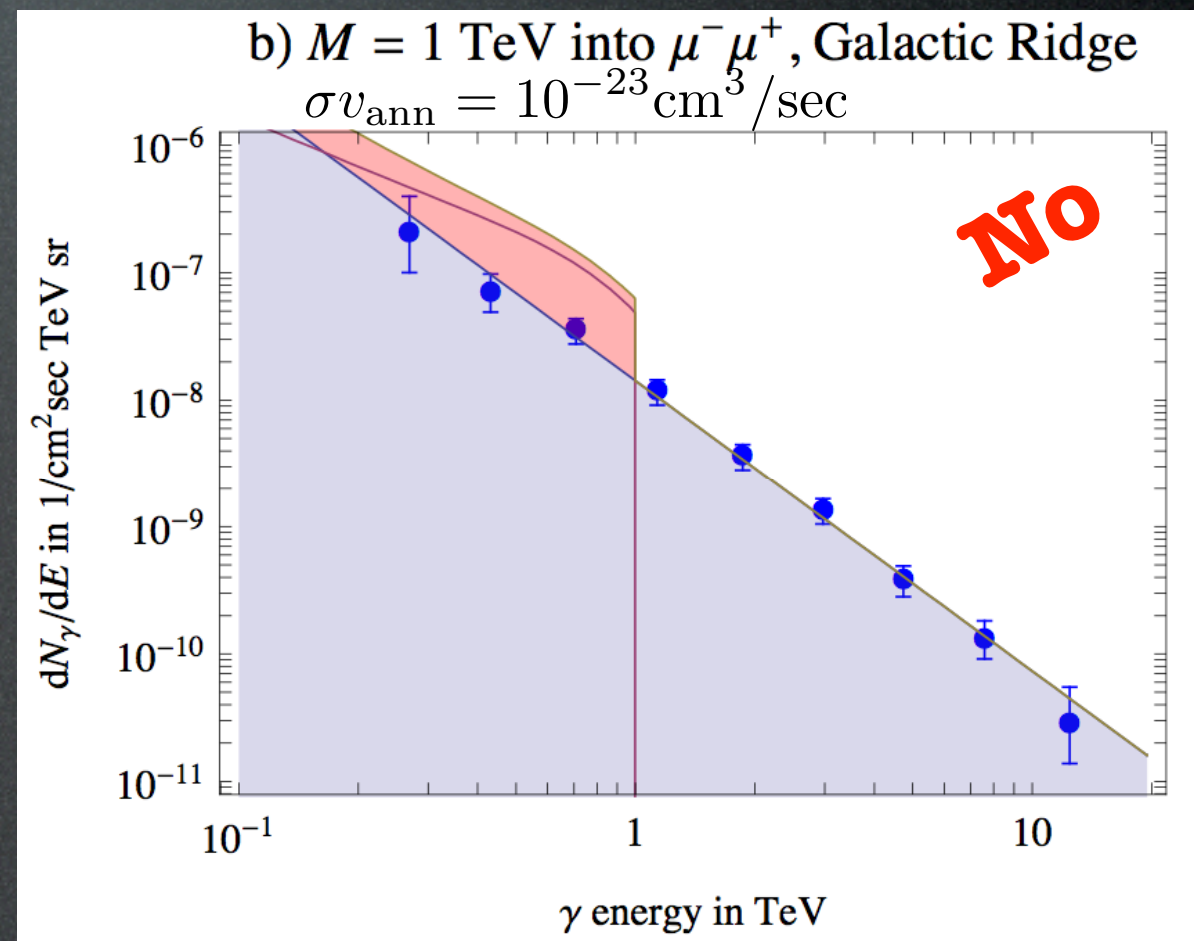
HESS has detected γ -ray emission from Gal Center and Gal Ridge. The DM signal must not exceed that.



HESS coll.

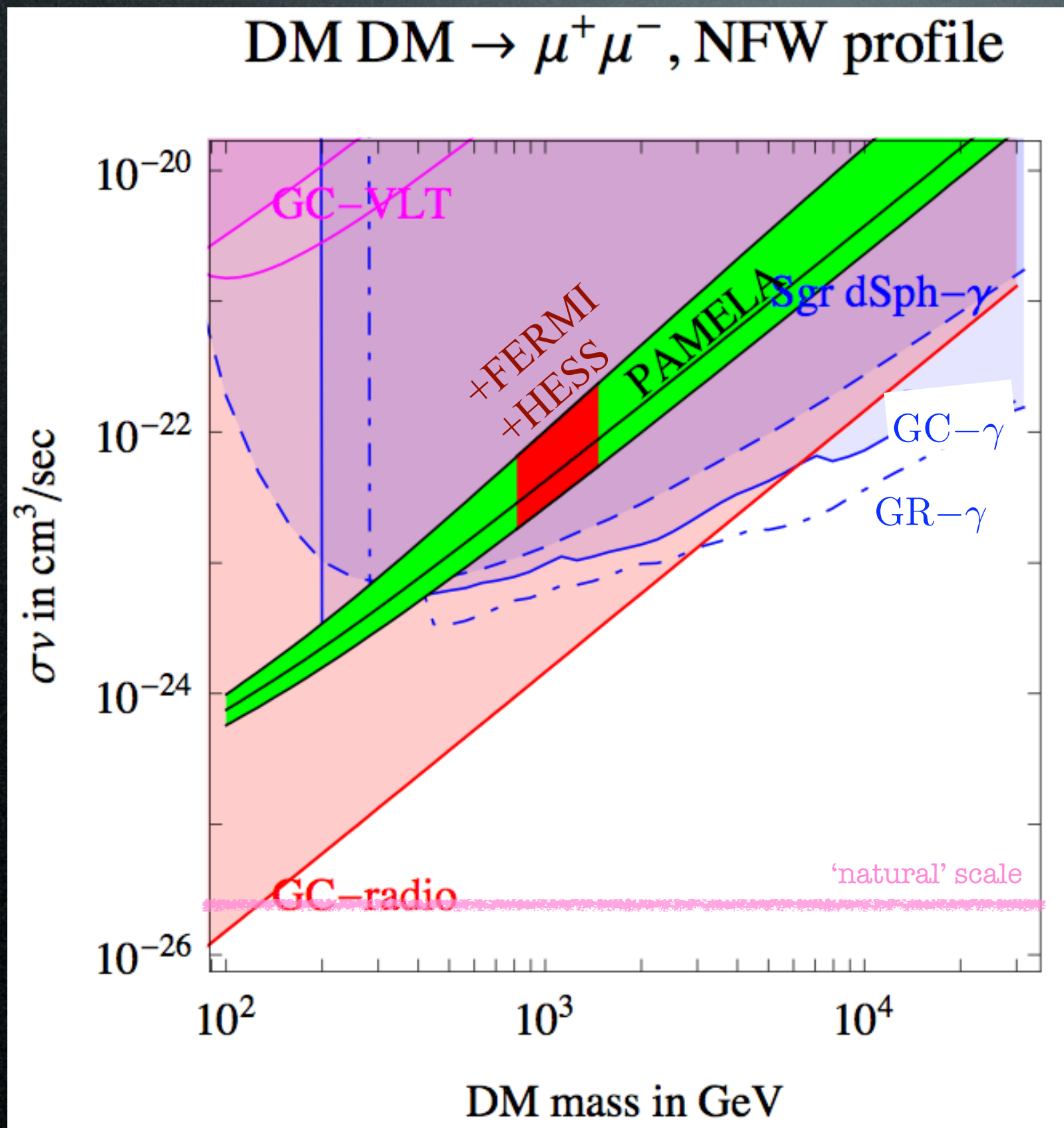


Data: HESS coll., astro-ph/0408145 and astro-ph/0610509



Data: HESS coll., astro-ph/0603021

Gamma constraints



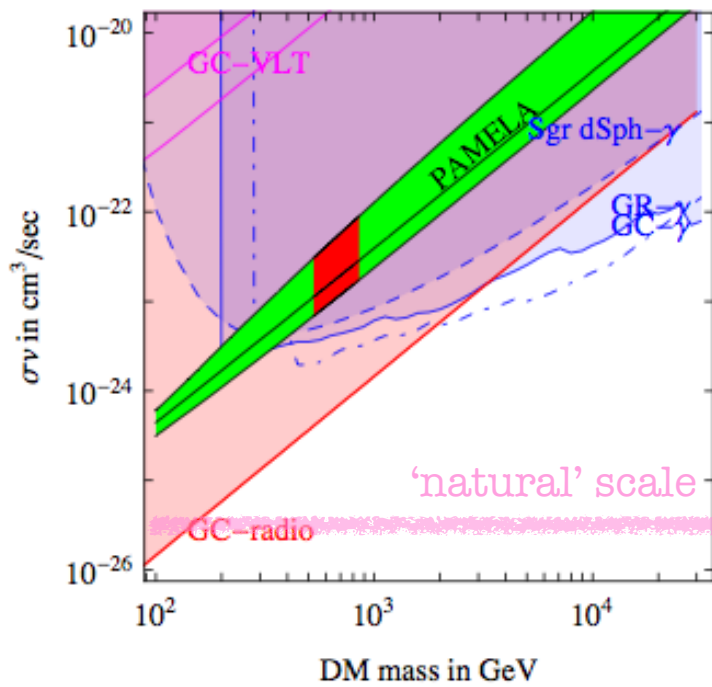
a+b+c.

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

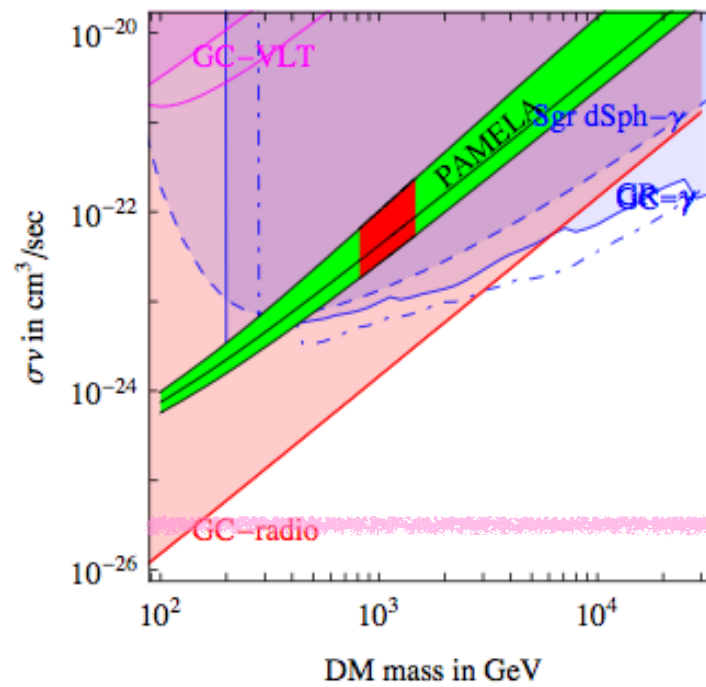
Gamma constraints

a+b+c.

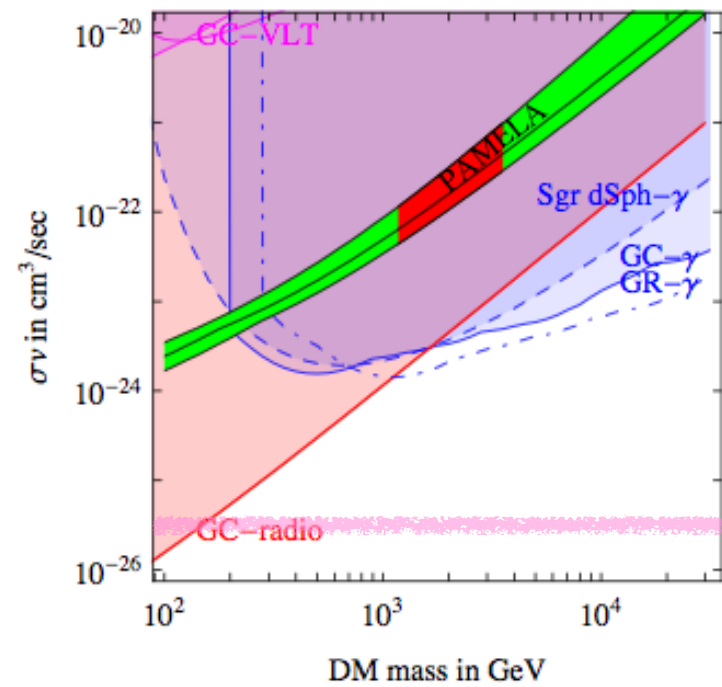
DM DM $\rightarrow e^+e^-$, NFW profile



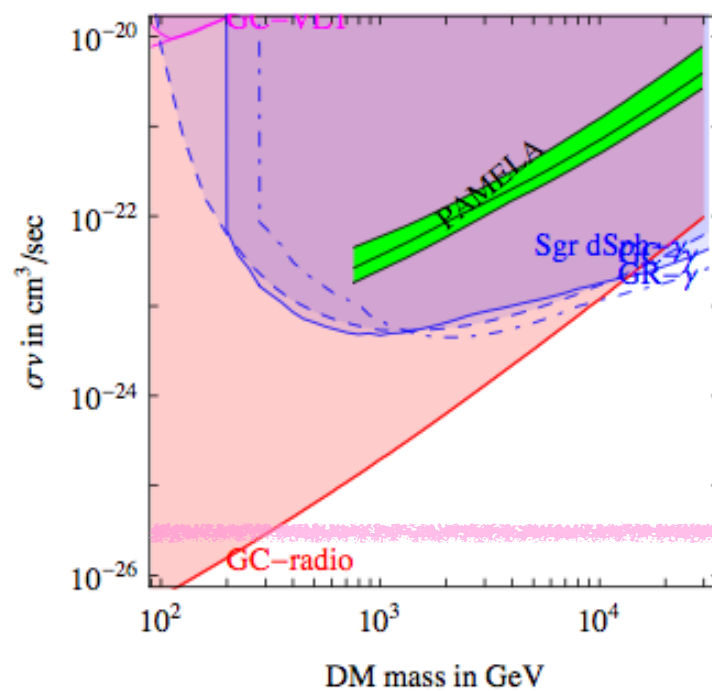
DM DM $\rightarrow \mu^+\mu^-$, NFW profile



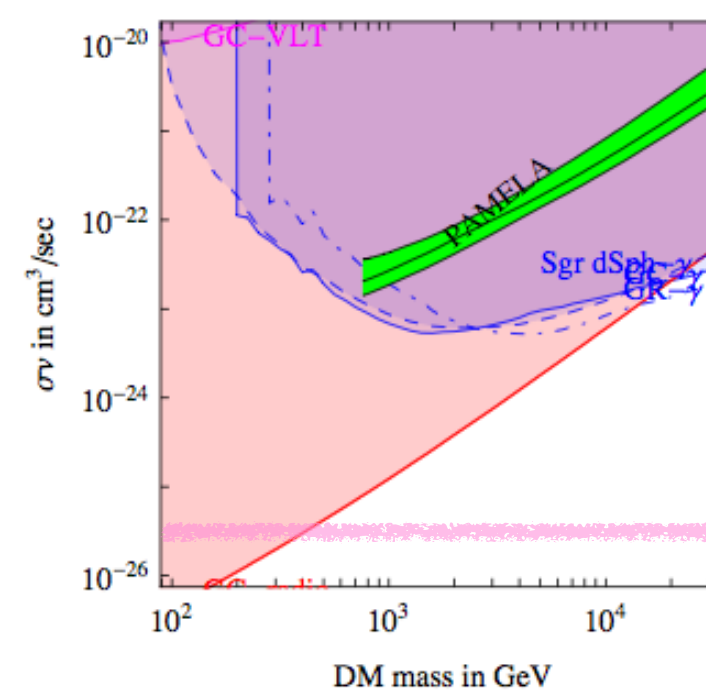
DM DM $\rightarrow \tau^+\tau^-$, NFW profile



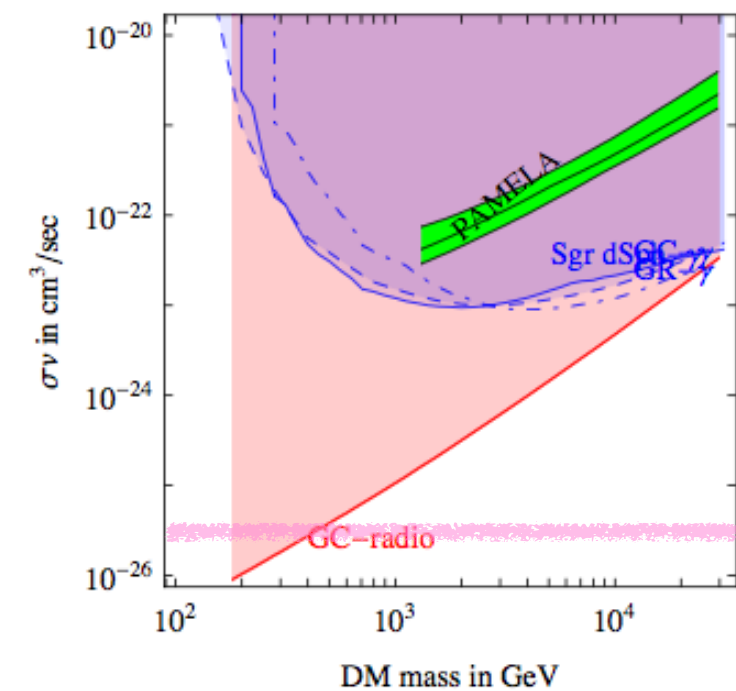
DM DM $\rightarrow W^+W^-$, NFW profile



DM DM $\rightarrow b\bar{b}$, NFW profile

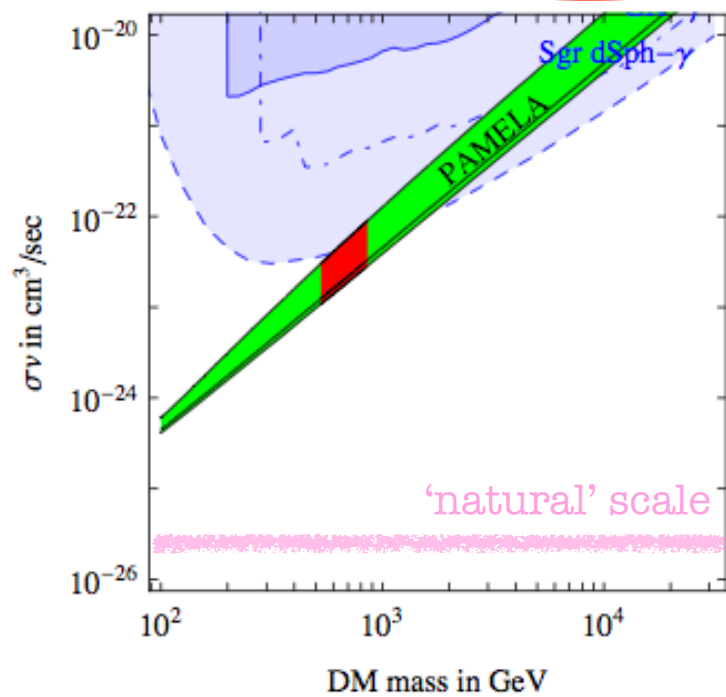


DM DM $\rightarrow t\bar{t}$, NFW profile

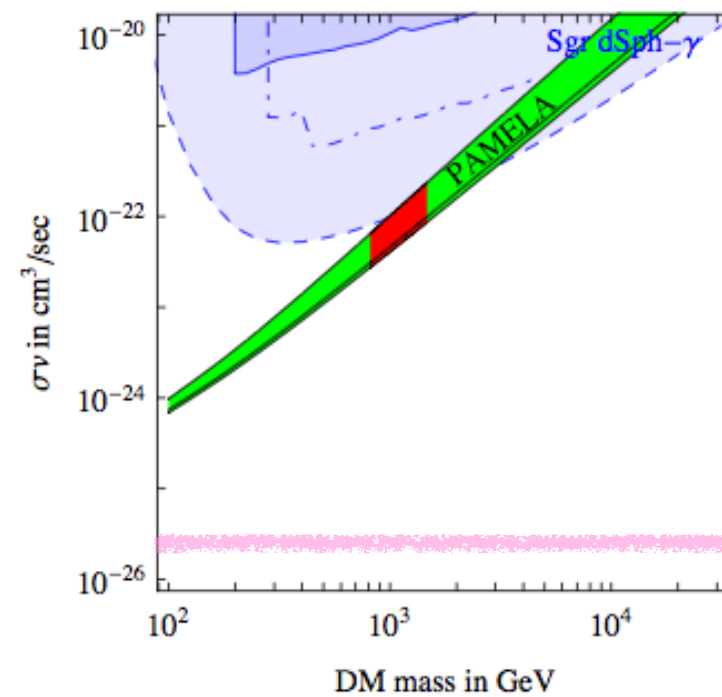


Gamma constraints

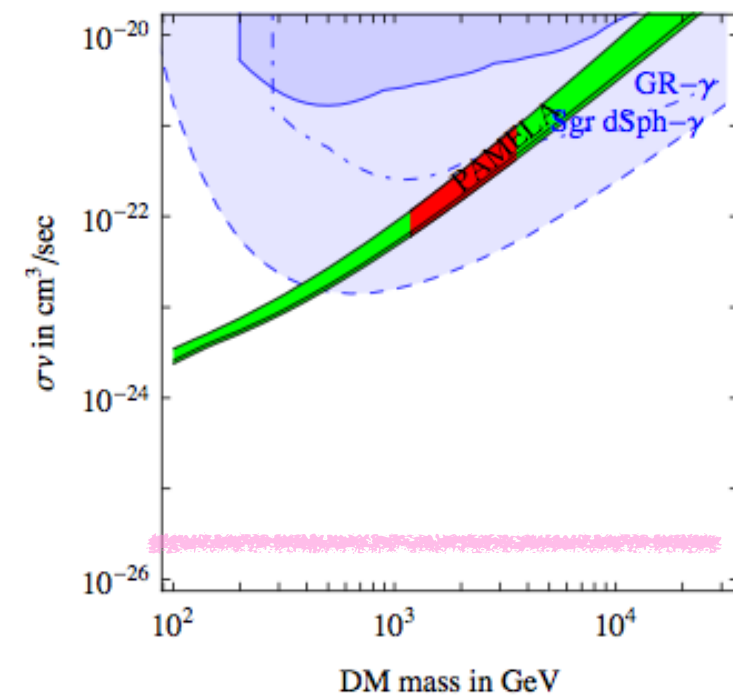
DM DM $\rightarrow e^+e^-$, isothermal profile



DM DM $\rightarrow \mu^+\mu^-$, isothermal profile

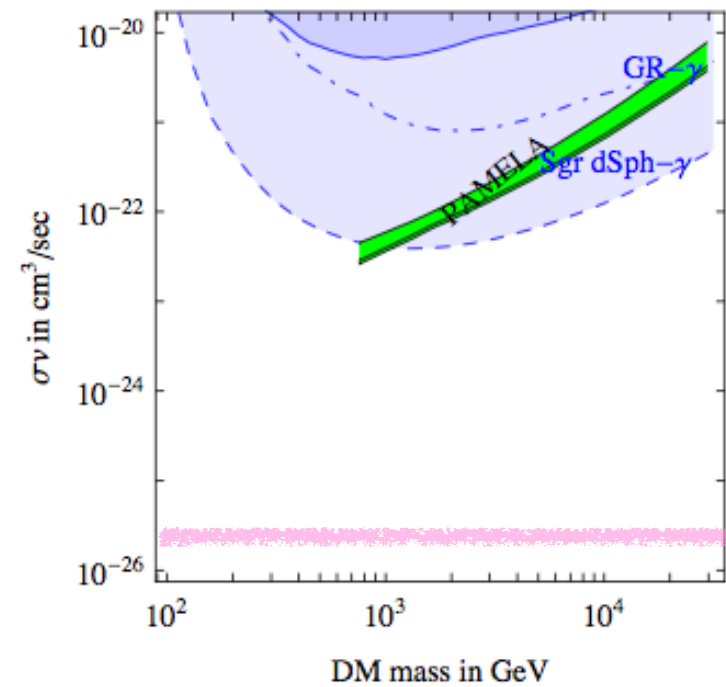


DM DM $\rightarrow \tau^+\tau^-$, isothermal profile

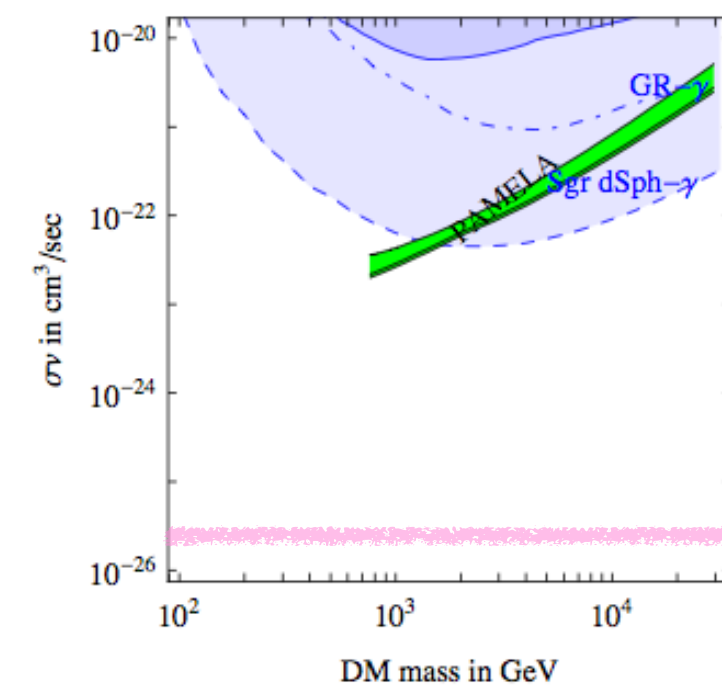


a+b+c.

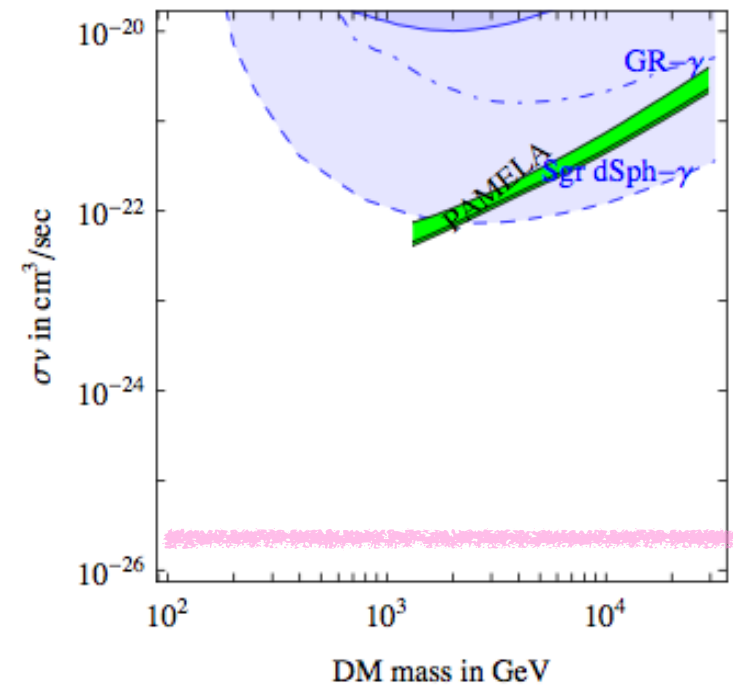
DM DM $\rightarrow W^+W^-$, isothermal profile



DM DM $\rightarrow b\bar{b}$, isothermal profile



DM DM $\rightarrow t\bar{t}$, isothermal profile



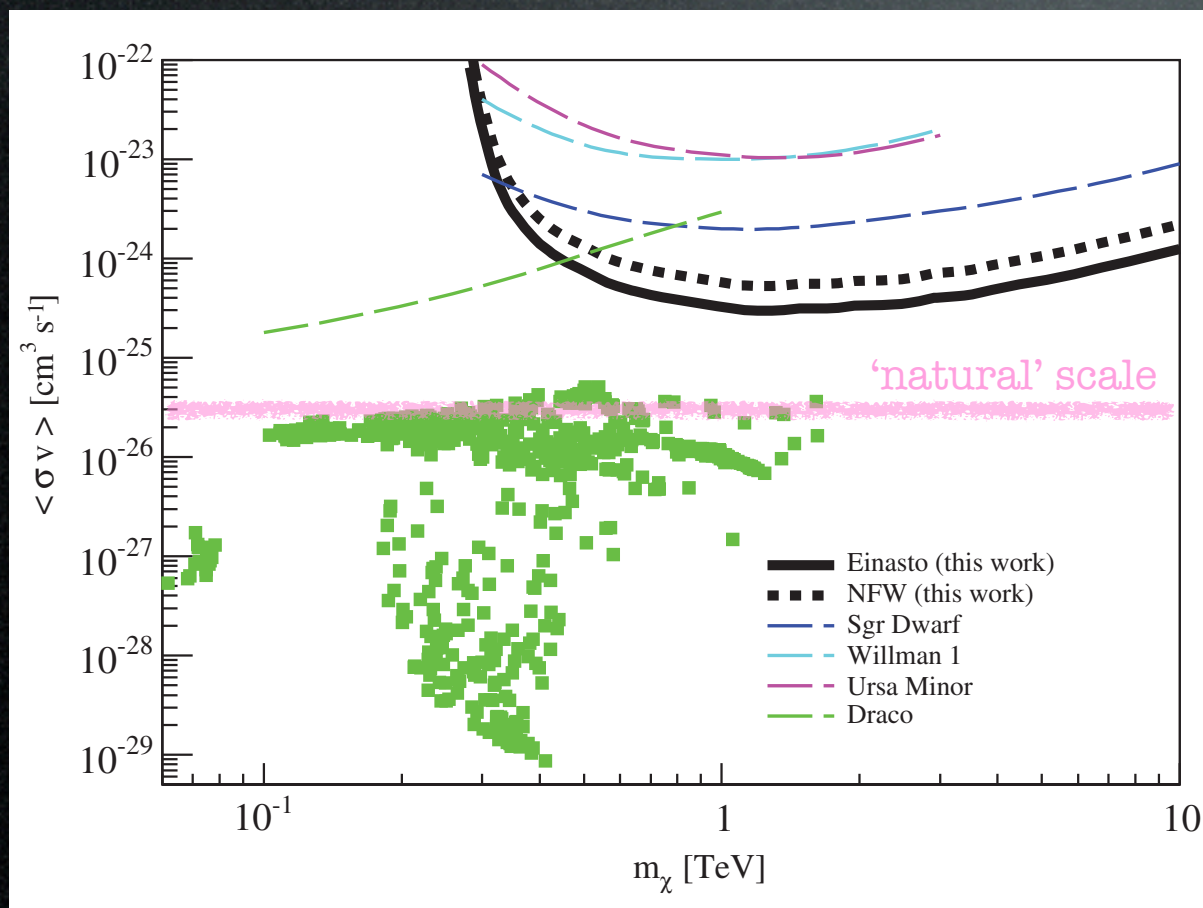
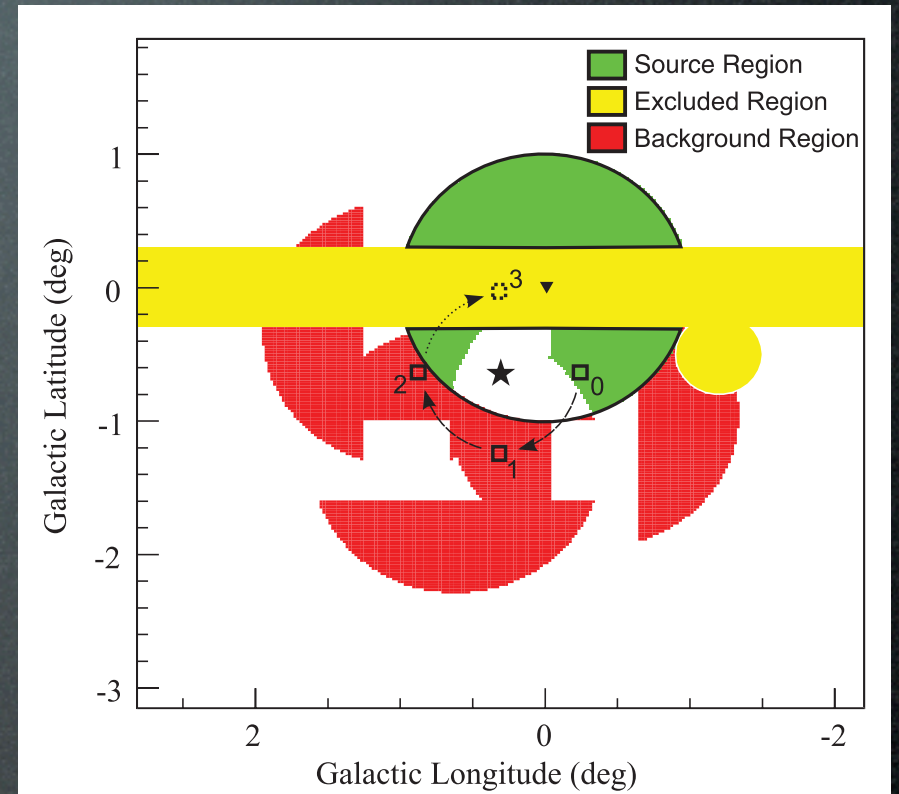
...not-too-steep profile needed.

Gamma constraints

a. γ from DM annihilations in the Galactic Center

HESS has detected γ -ray emission from **annulus** around GC.

Derive bounds from on/off comparison.



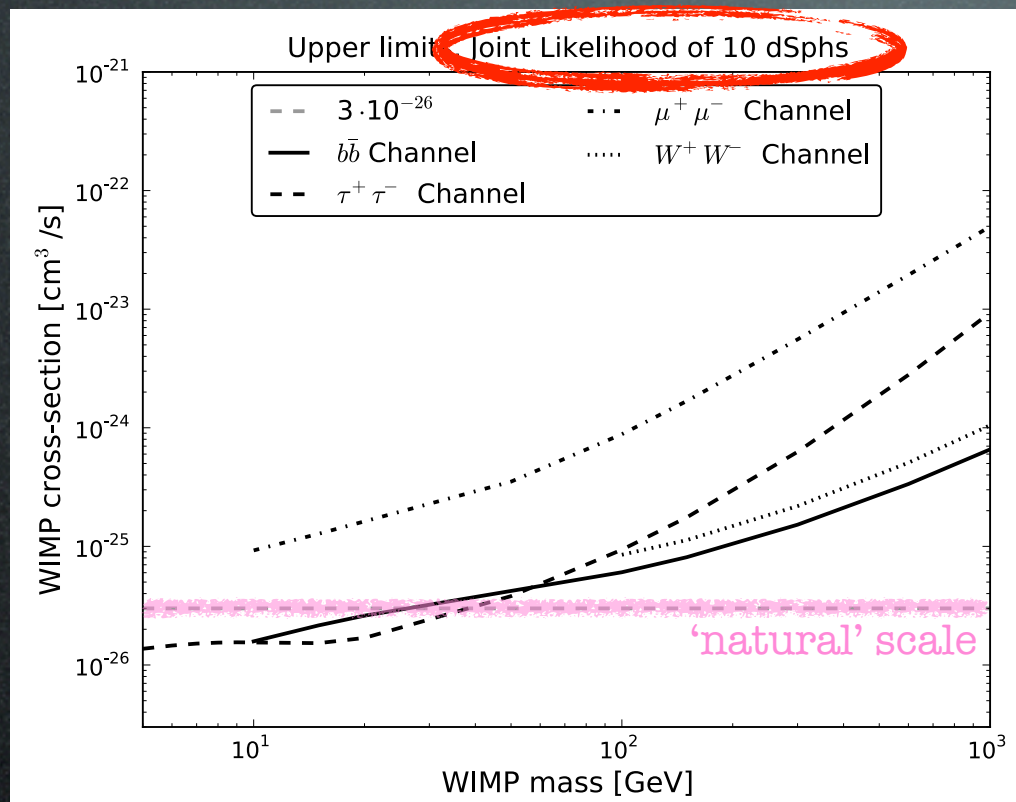
HESS coll., PRL 106, 2011

Gamma constraints

b. γ from DM annihilations in Satellite Galaxies

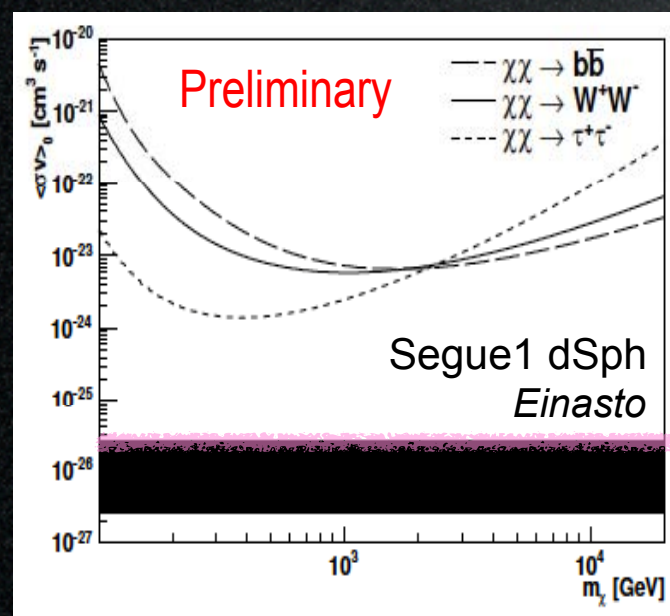
FERMI

FERMI coll.,
1108.3546



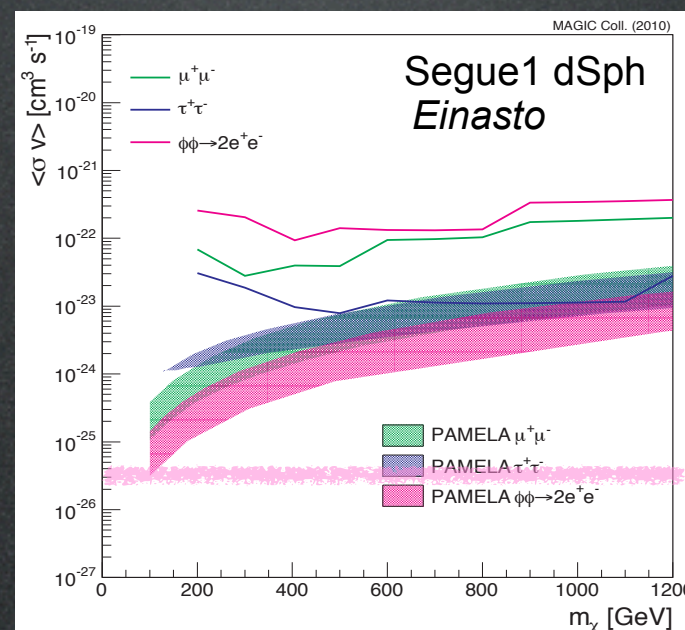
And the winner is...

VERITAS



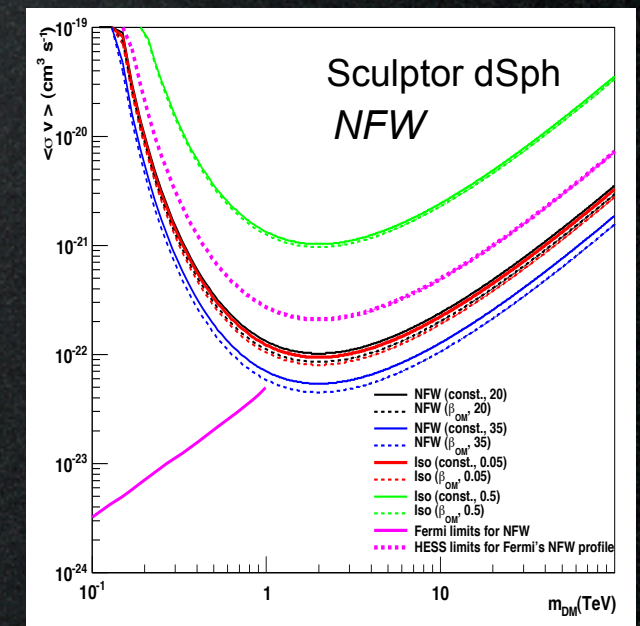
Veritas coll., courtesy of R.Ong

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

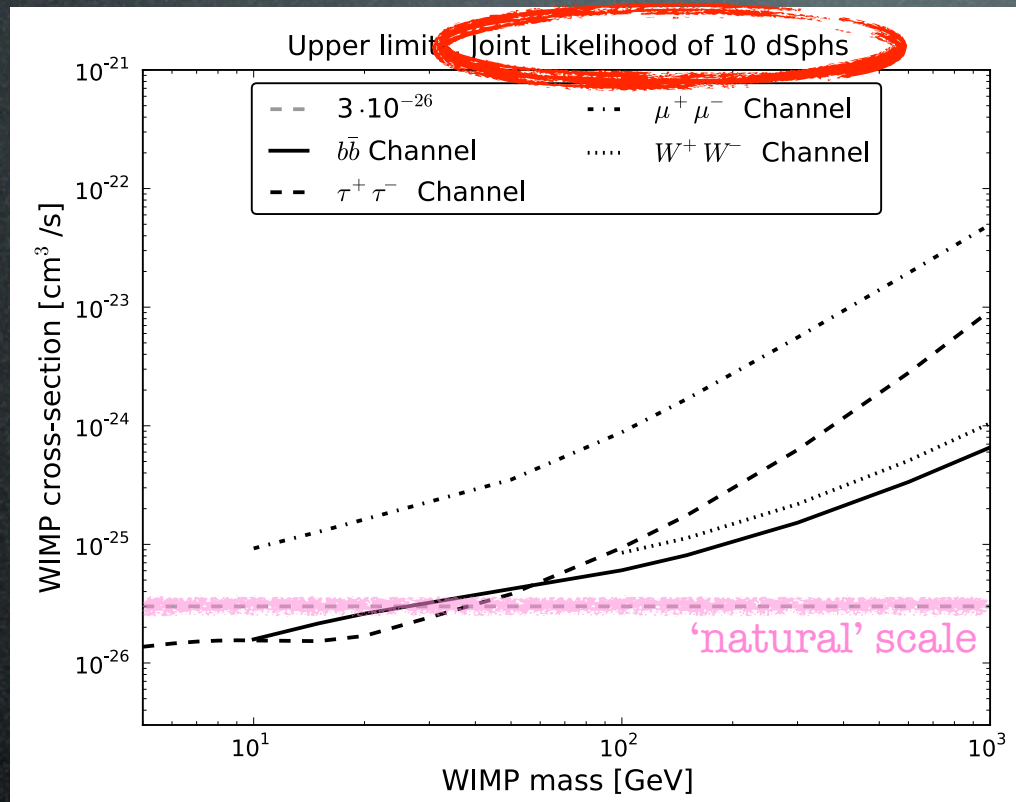
(HESS: Globular Clusters analysis too)

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...

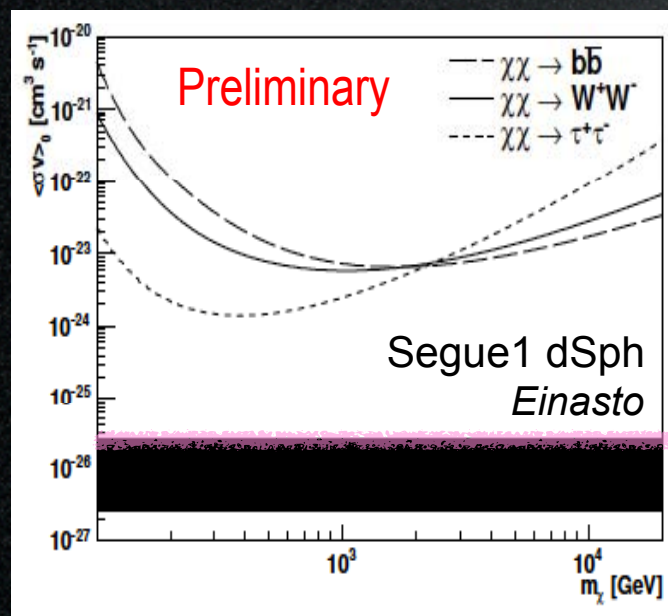
see also:

Geringer-Sameth, Koushiappas, 1108.2914

Strigari et al. (0902.4750, 1007.4199...)

Baxter, Dodelson et al.

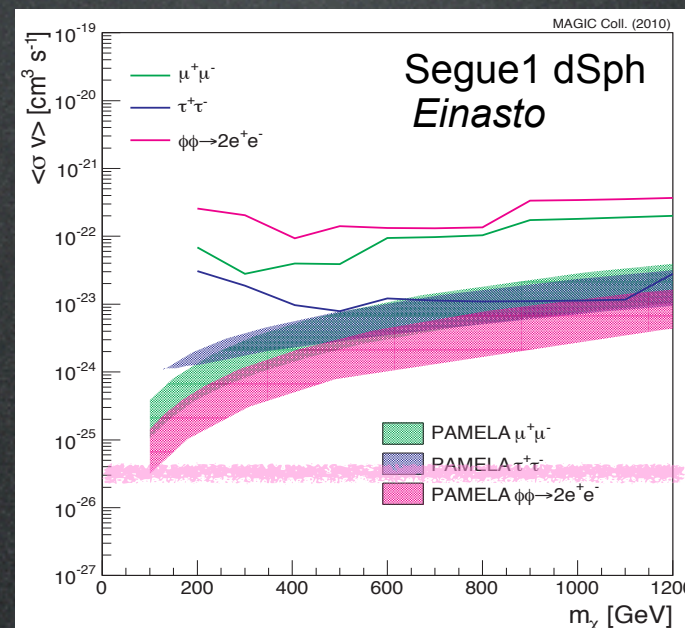
VERITAS



Veritas coll., courtesy of R. Ong

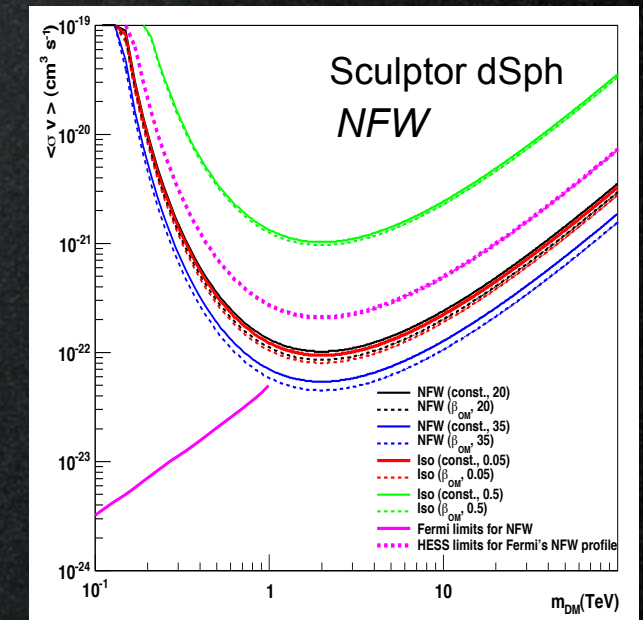
(currently the winner in the '1 dSph' category)

MAGIC



Magic coll., 1103.0477

HESS



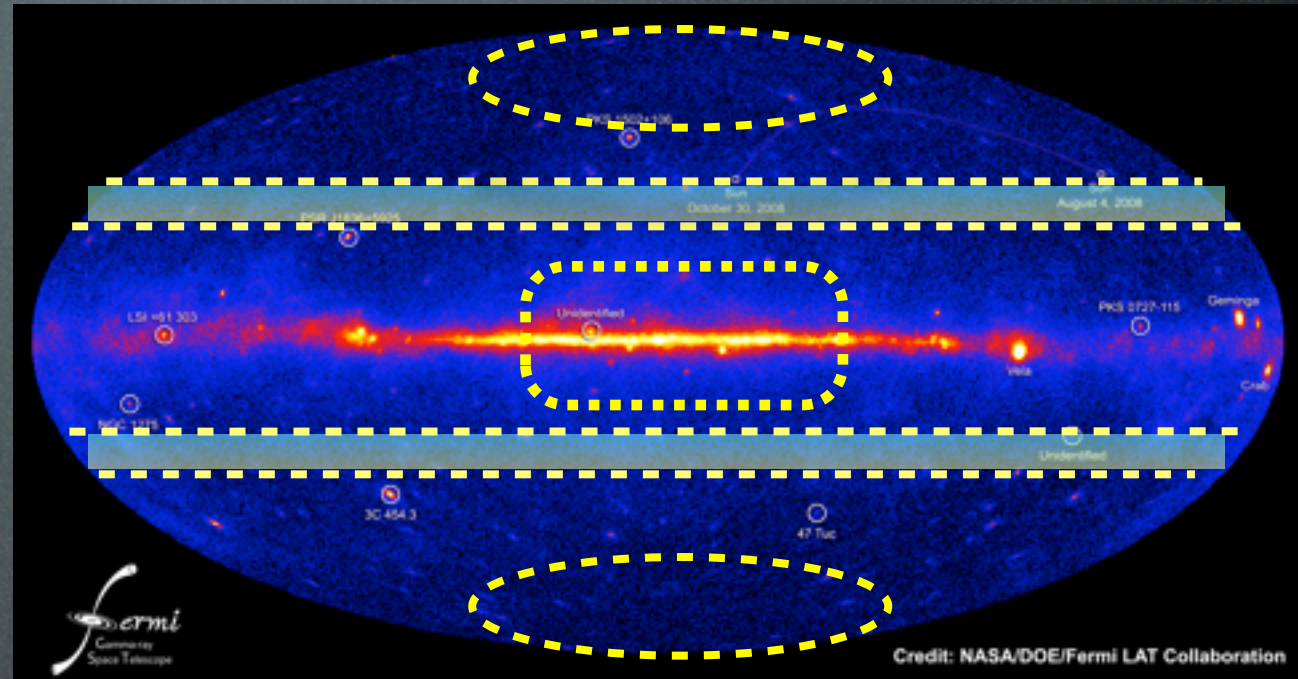
HESS coll., 1012.5602

(HESS: Globular Clusters analysis too)

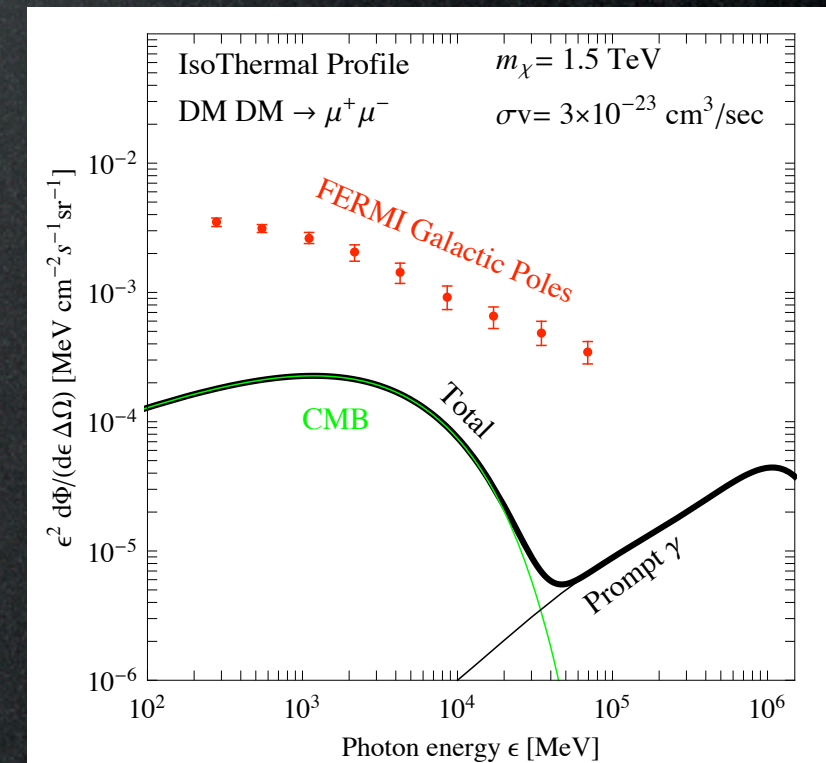
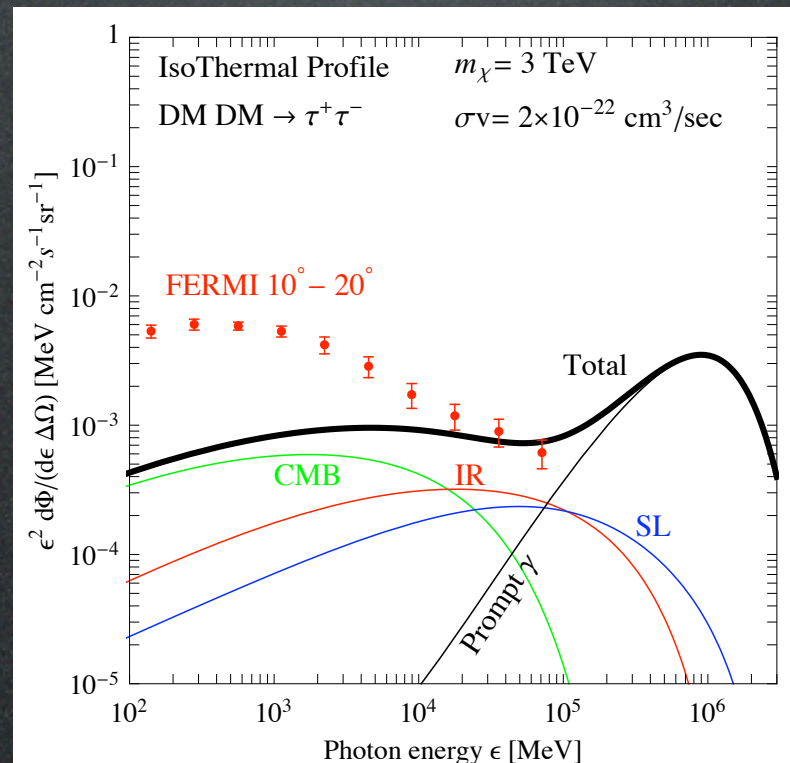
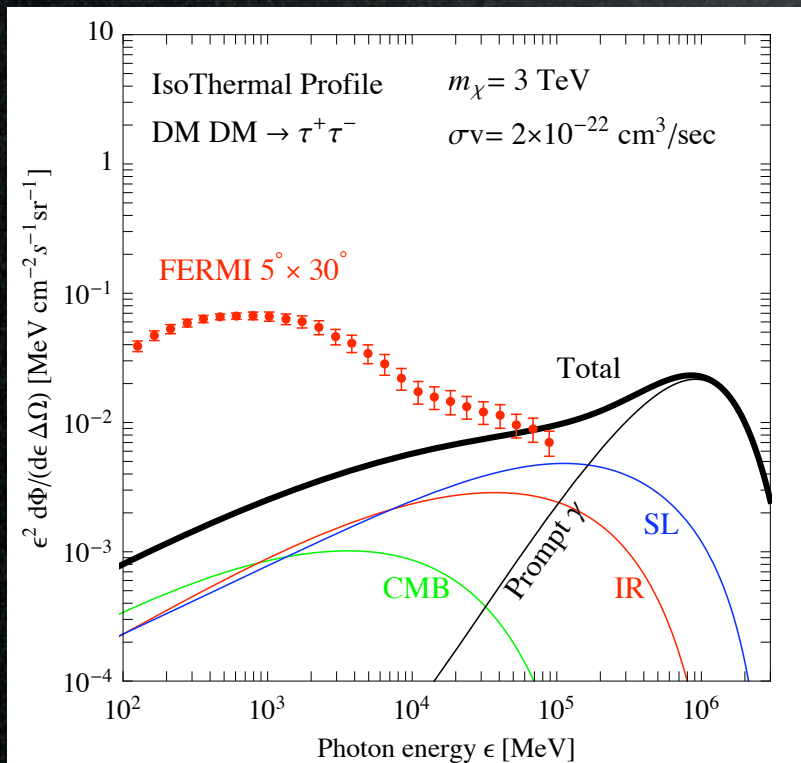
Gamma constraints

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

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

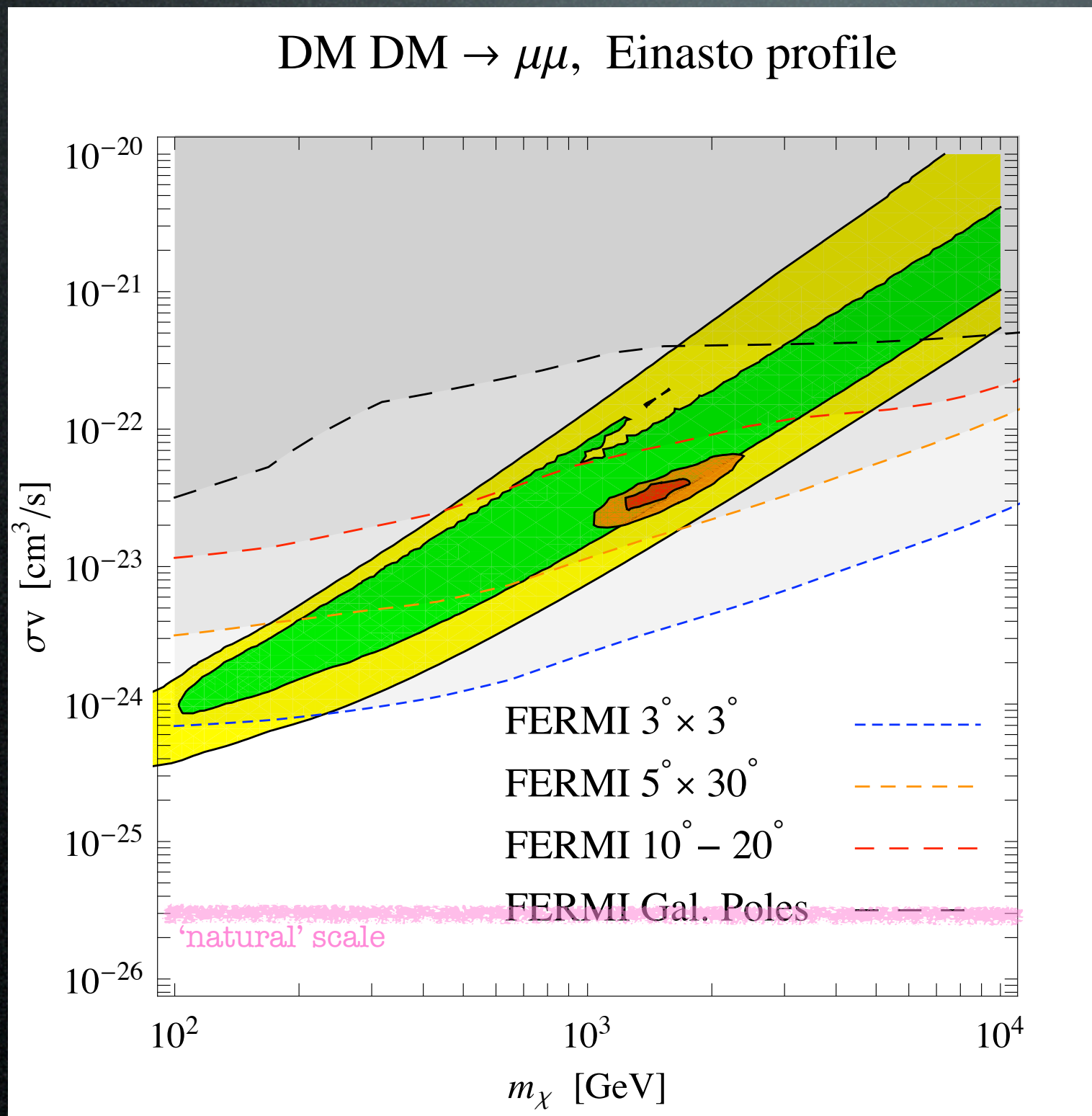


FERMI coll.



Gamma constraints

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

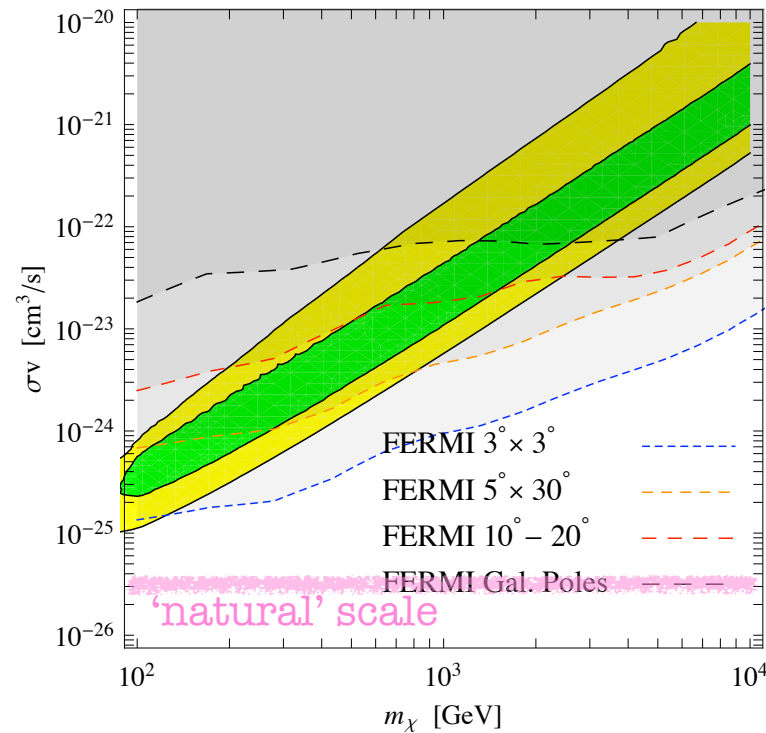


The PAMELA and ATIC regions are in **conflict** with these gamma constraints, and here...

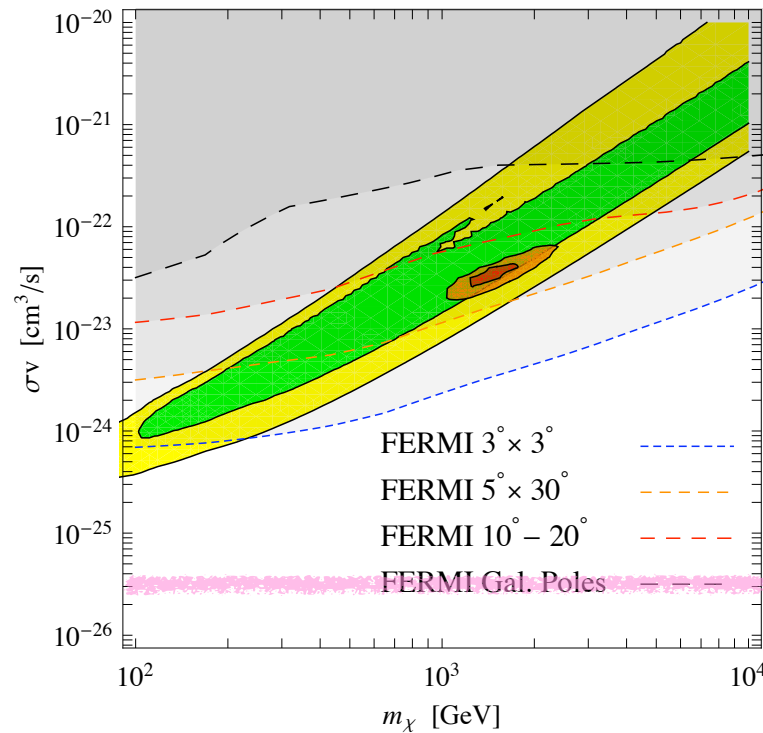
Gamma constraints

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

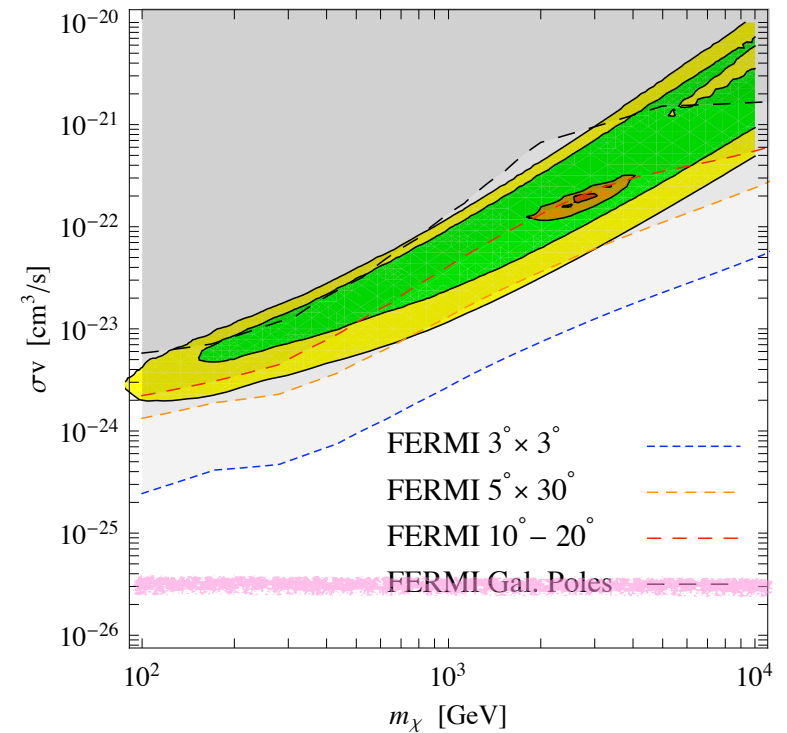
DM DM $\rightarrow ee$, Einasto profile



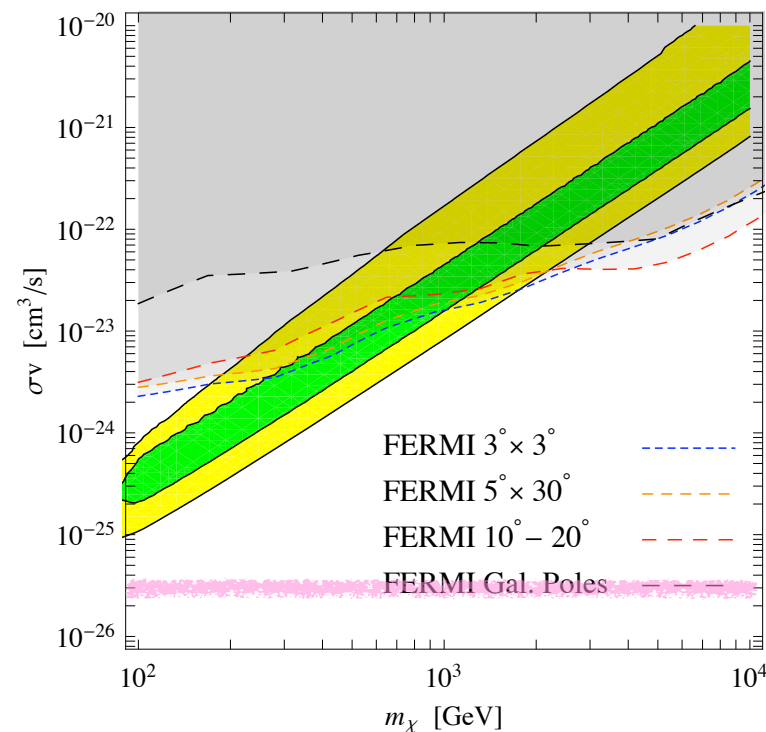
DM DM $\rightarrow \mu\mu$, Einasto profile



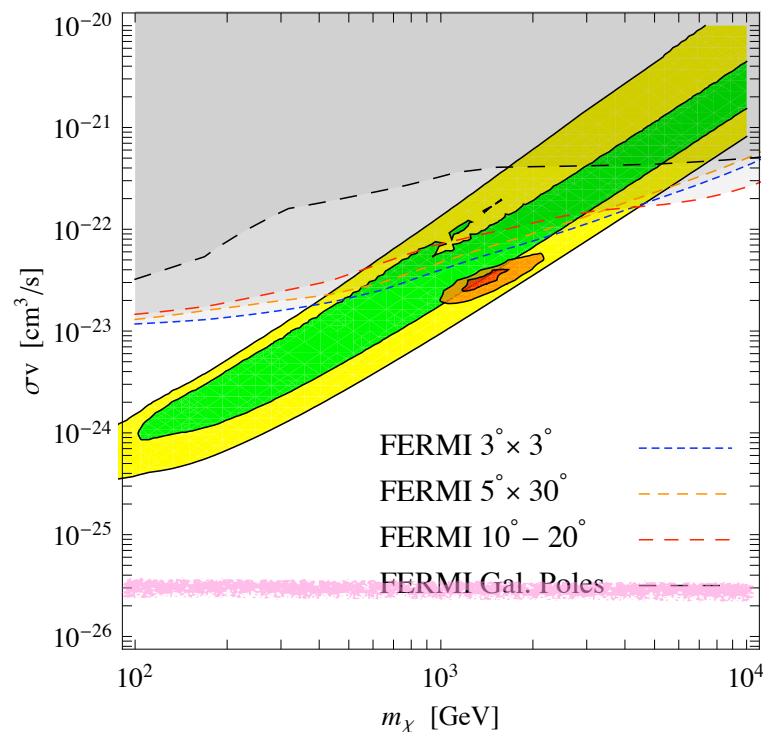
DM DM $\rightarrow \tau\tau$, Einasto profile



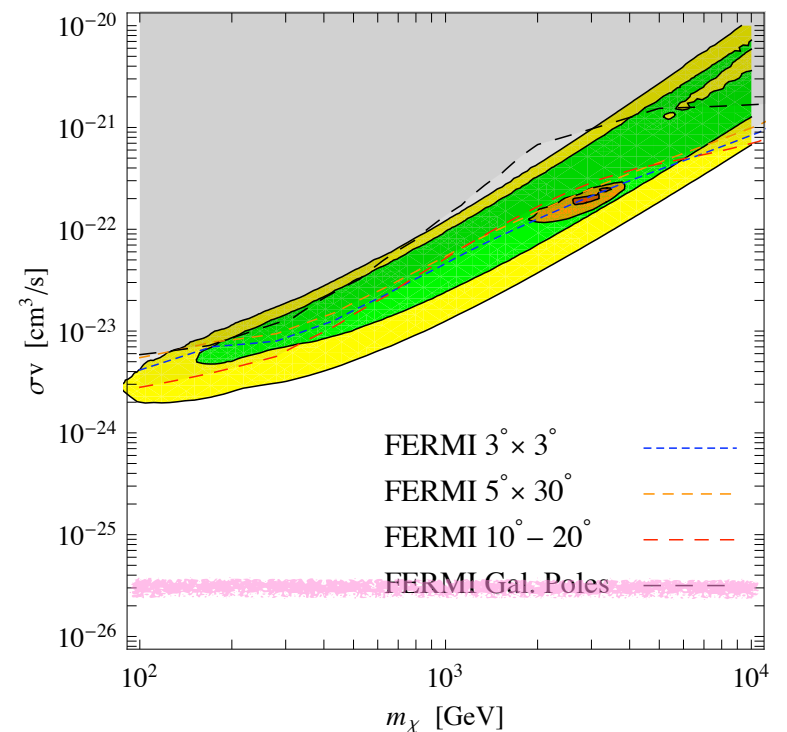
DM DM $\rightarrow ee$, Iso profile



DM DM $\rightarrow \mu\mu$, Iso profile



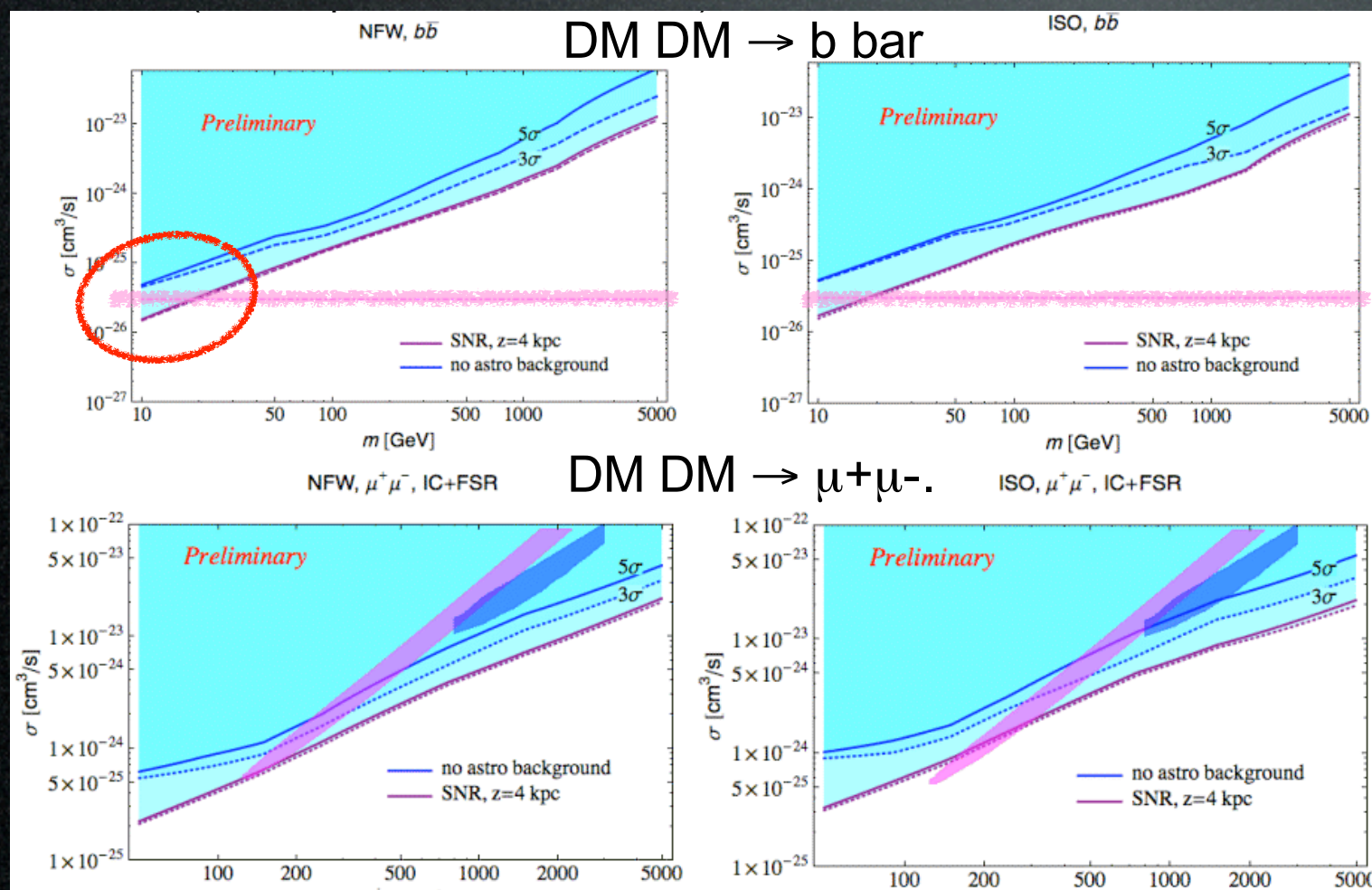
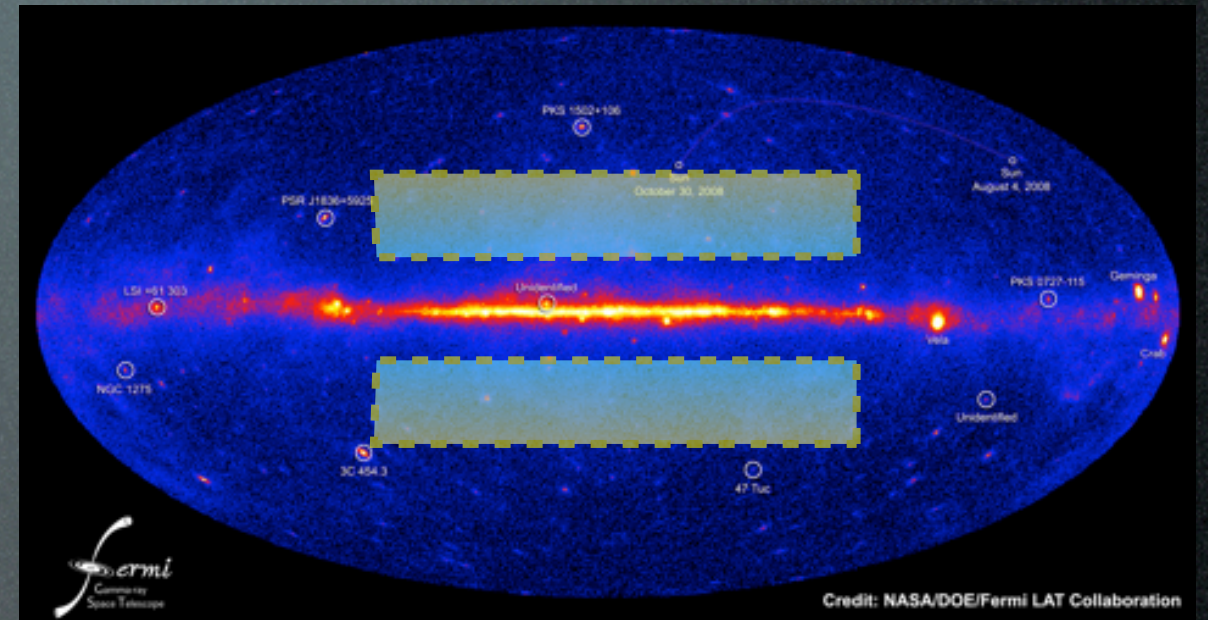
DM DM $\rightarrow \tau\tau$, Iso profile



Gamma constraints

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

Updated results from the **FERMI** coll. itself

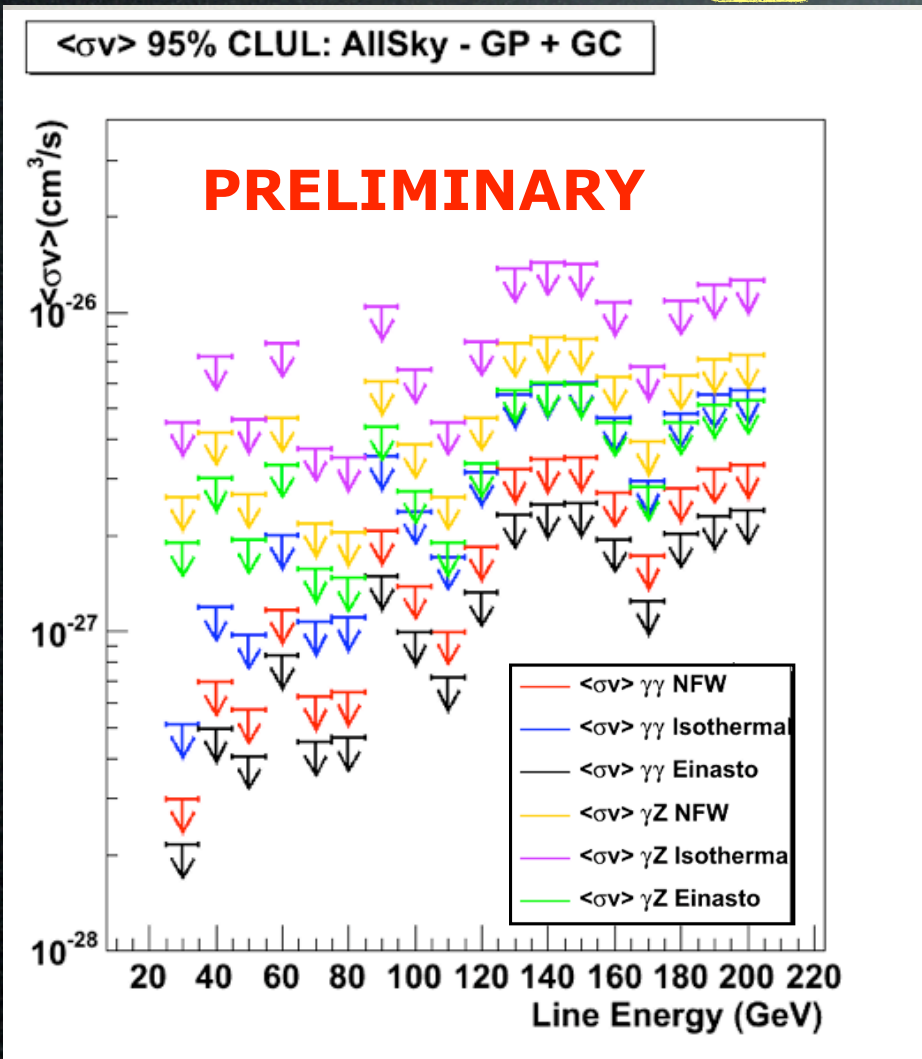


FERMI coll., Cuoco - Zaharijas, Fermi symposium 2011

See also:
Papucci, Strumia,
0912.0742

More FERMI γ constraints

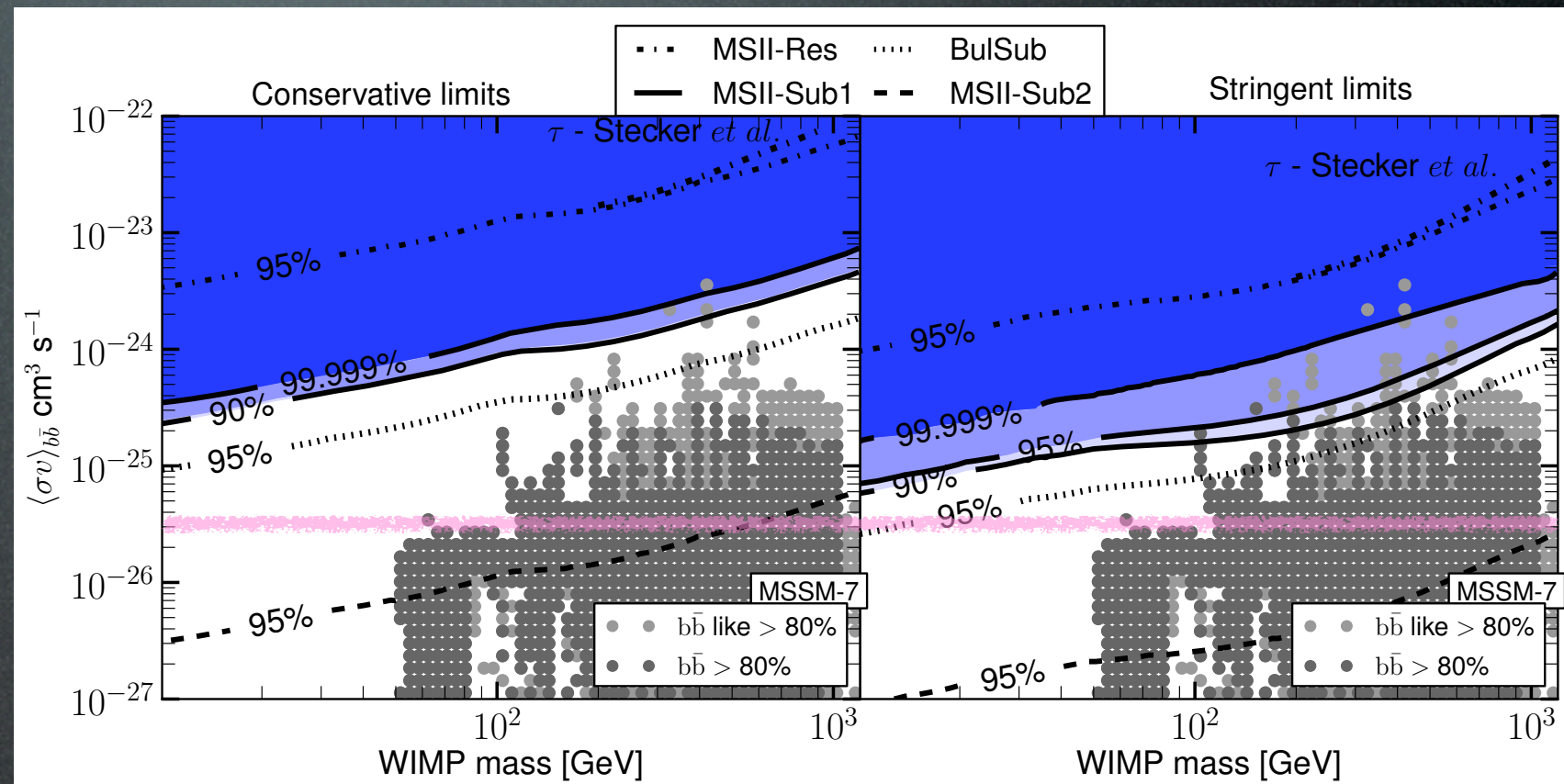
Gamma lines a.



FERMI Coll. 1001.4836

model dependent
constraints, can be
stringent

Isotropic gamma background e.



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

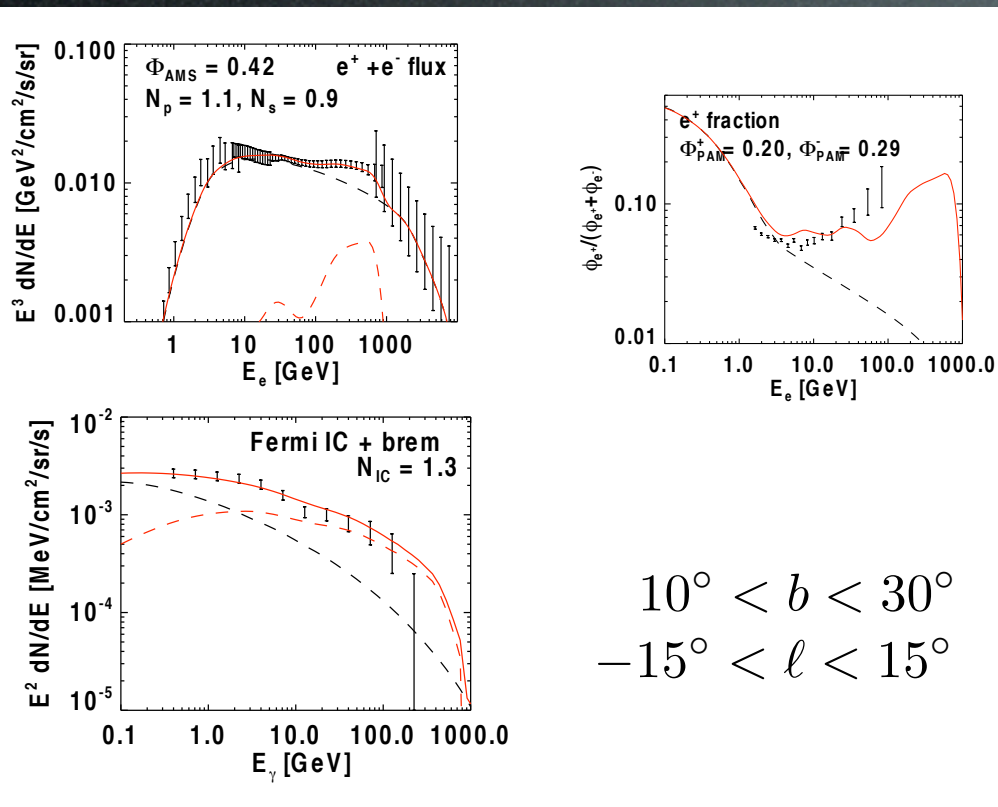
bounds are typically very sensitive to assumptions
on the cosmological evolution of DM halos

Gamma hints?

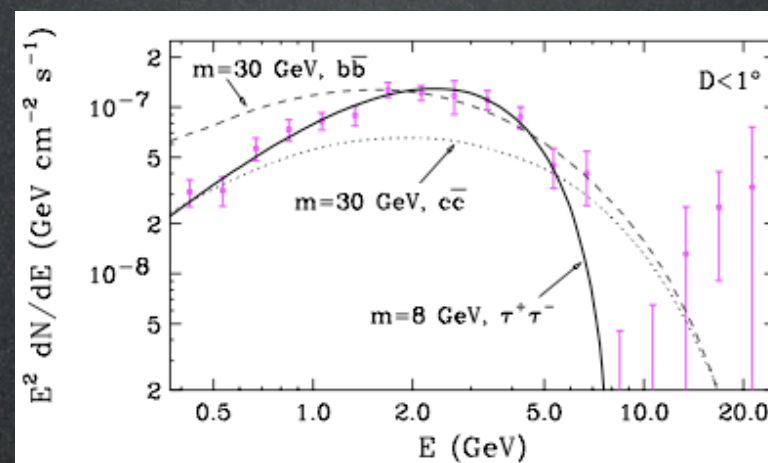
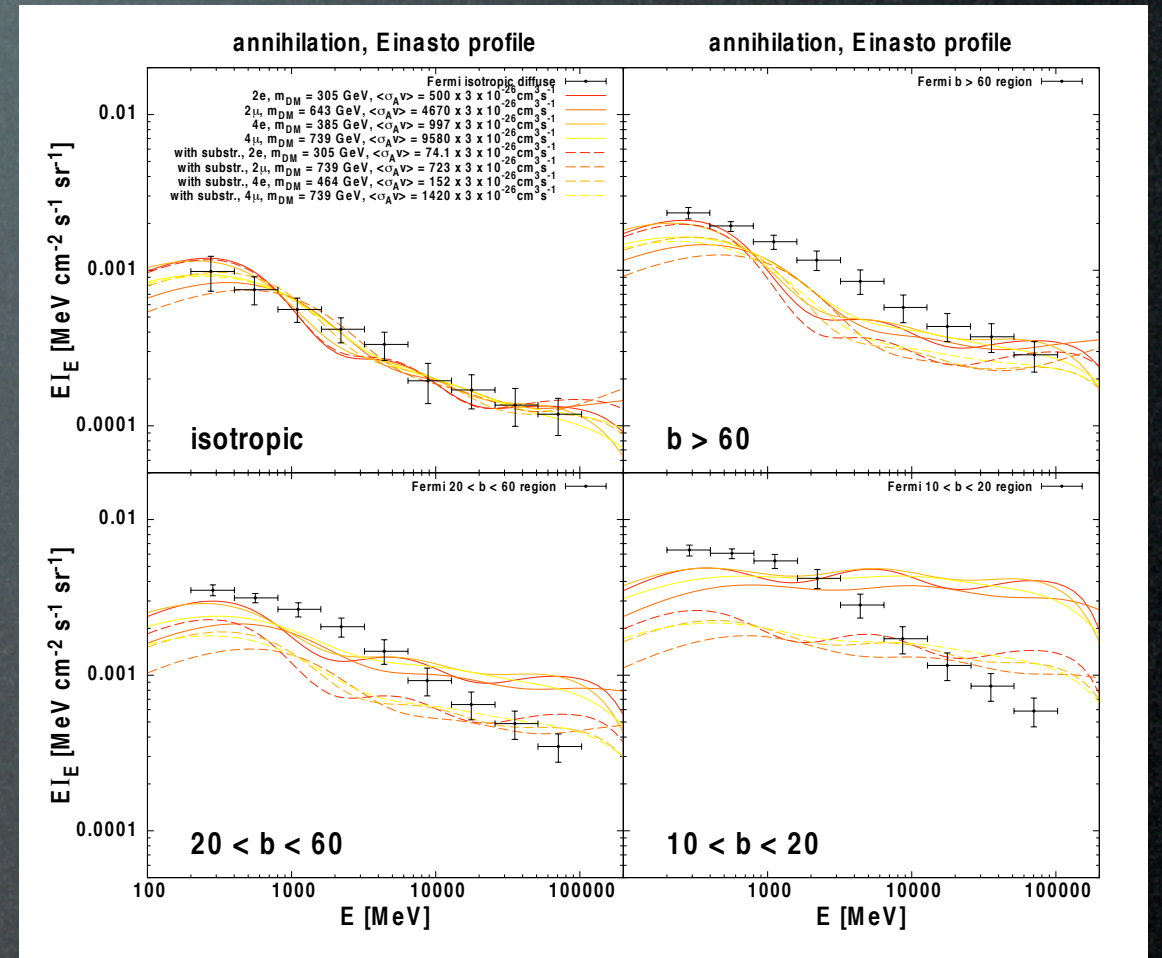
What if a signal of DM is *already* hidden
in Fermi diffuse γ data?

Gamma hints?

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



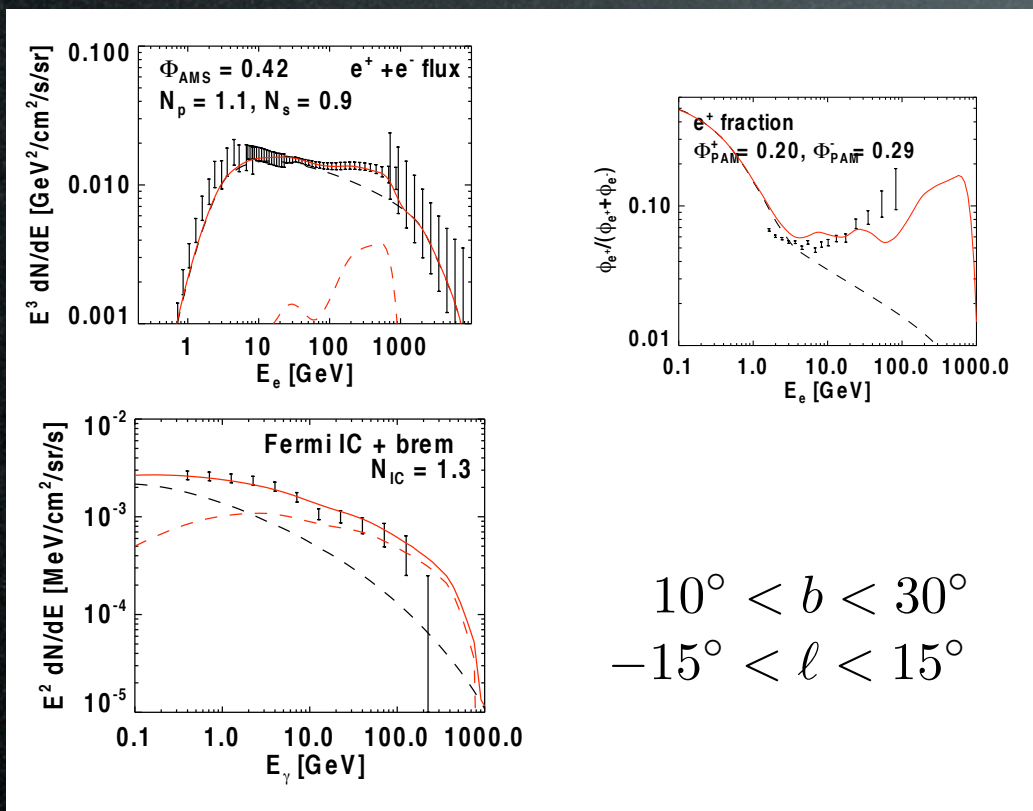
Lin, Finkbeiner, Dobler 1004.0989



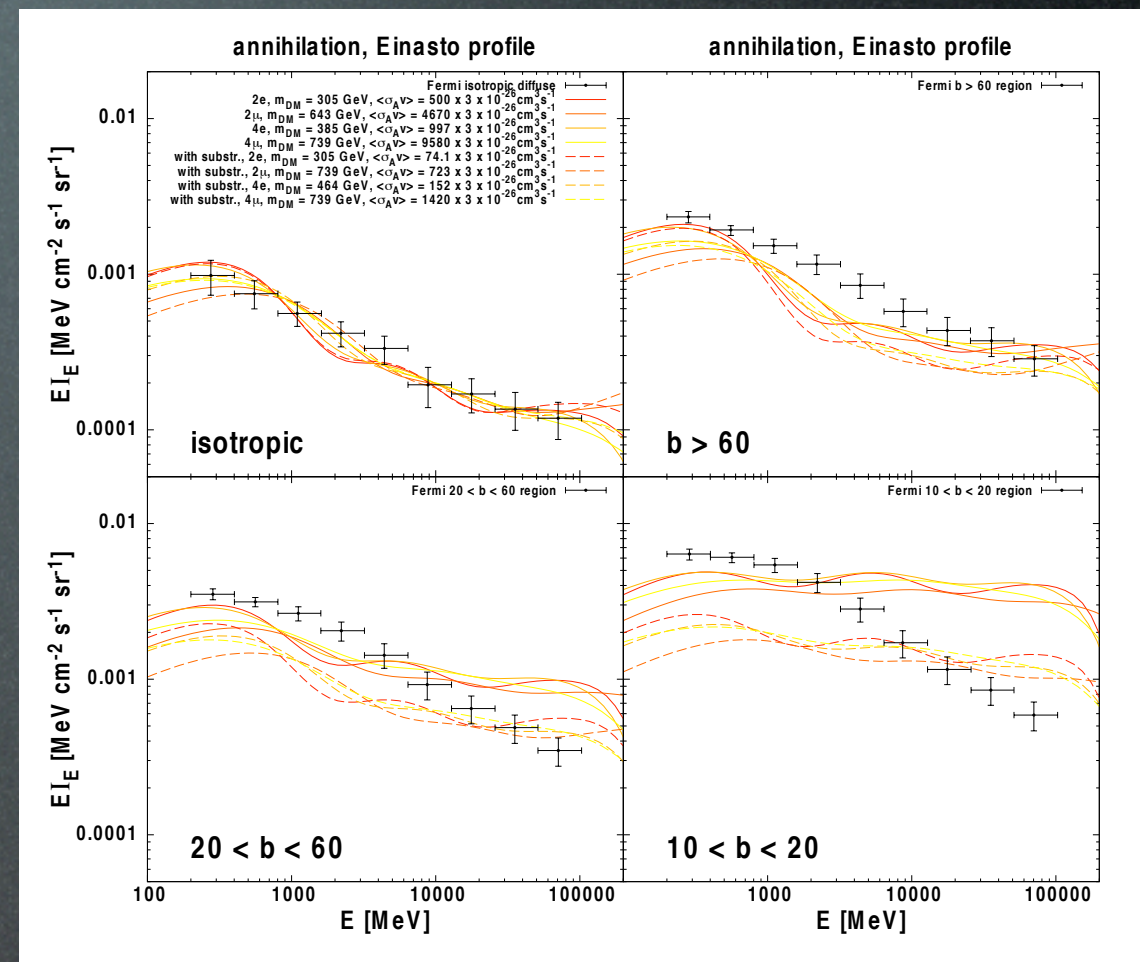
Hooper, Goodenough
1010.2752

Gamma hints?

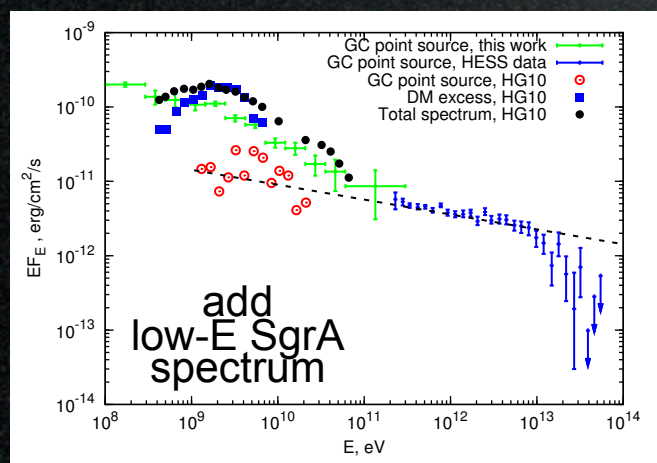
What if a signal of DM is *already* hidden in Fermi diffuse γ data?



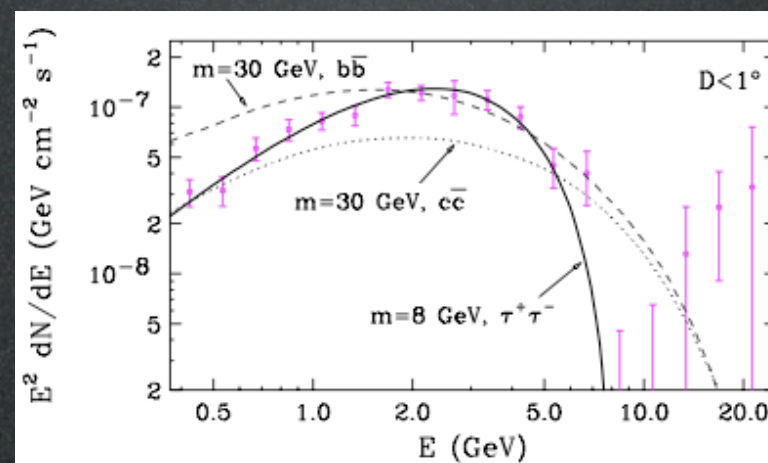
Lin, Finkbeiner, Dobler 1004.0989



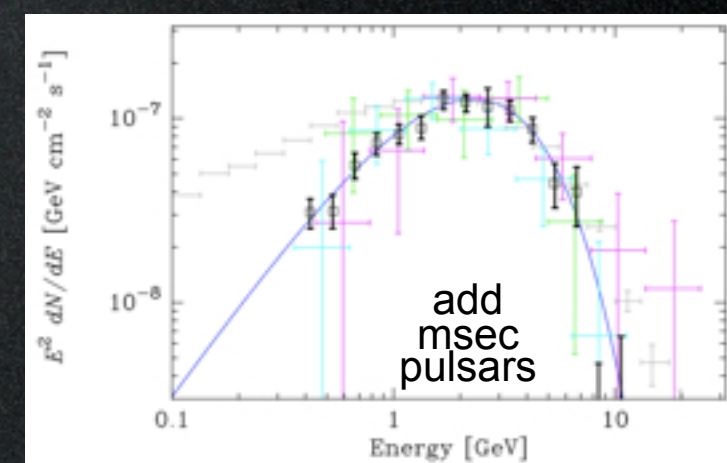
Hutsi, Hektor, Raidal 1004.2036



Boyarisky et al.,
1012.5839



Hooper, Goodenough
1010.2752

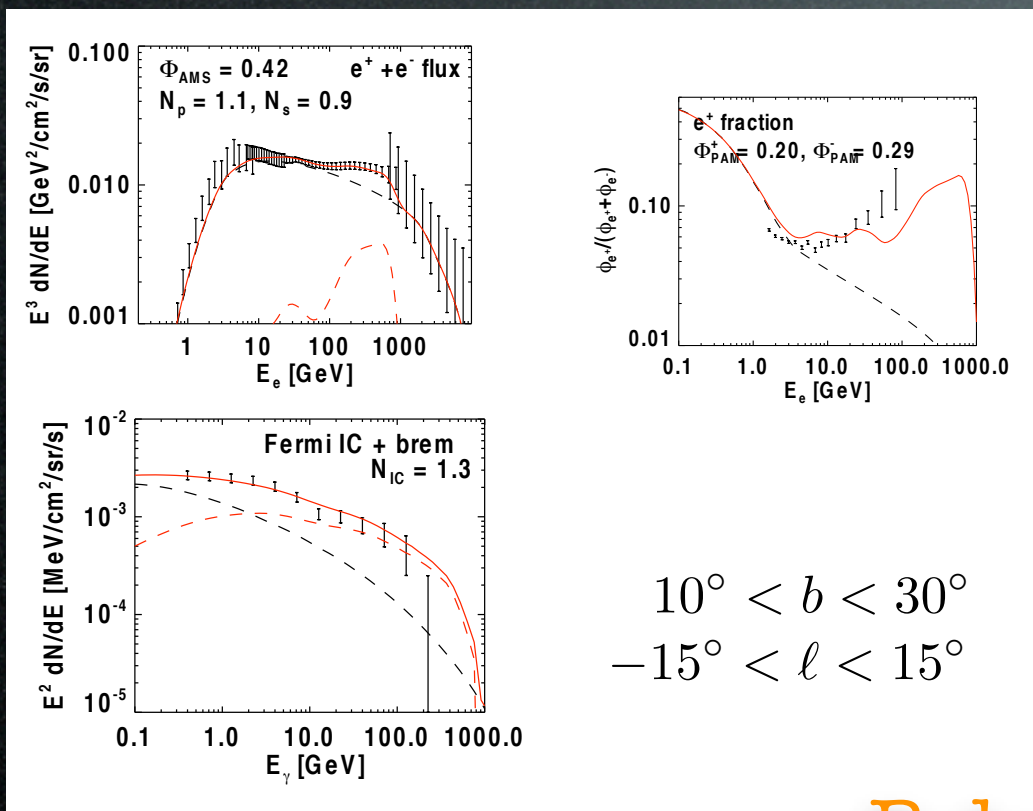


Abazajian 1011.4275

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

Gamma hints?

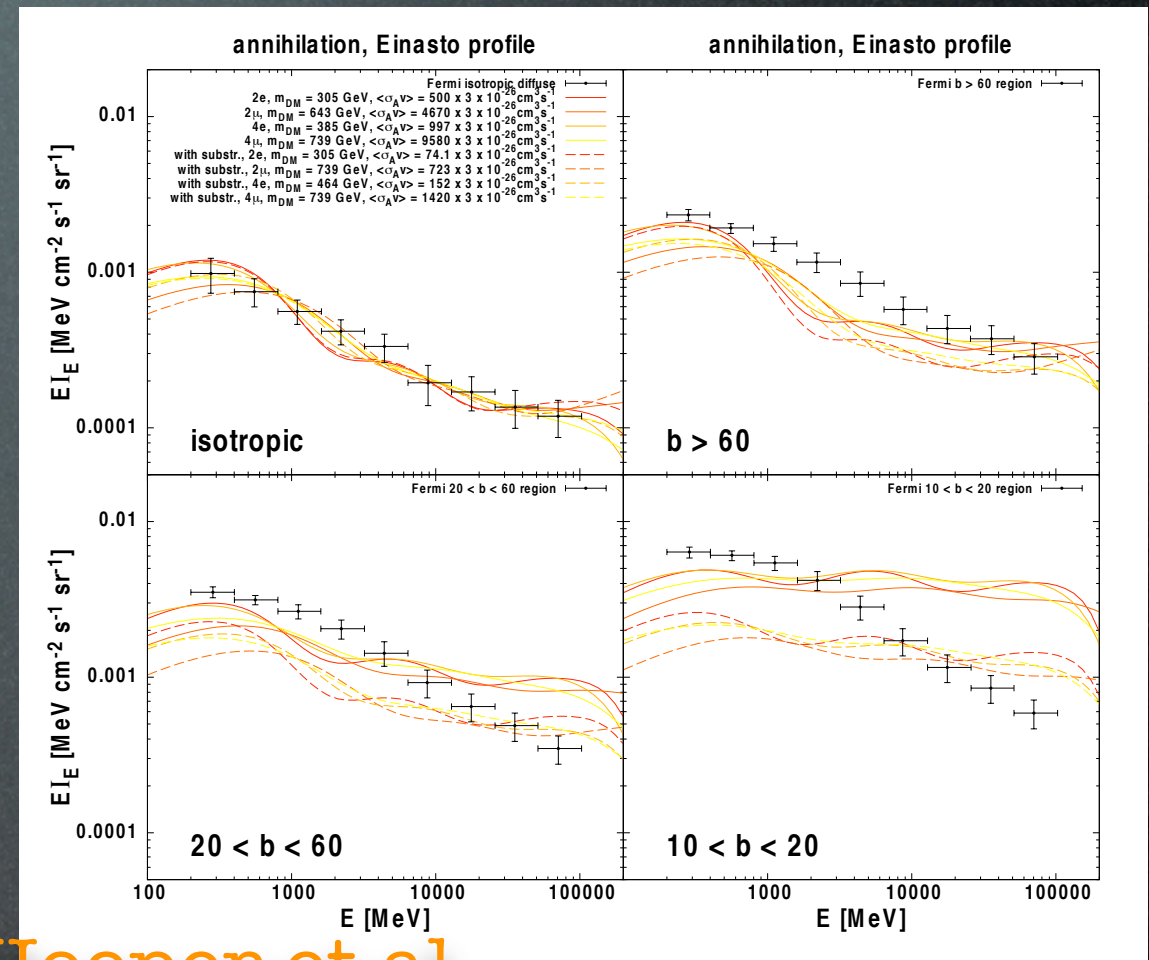
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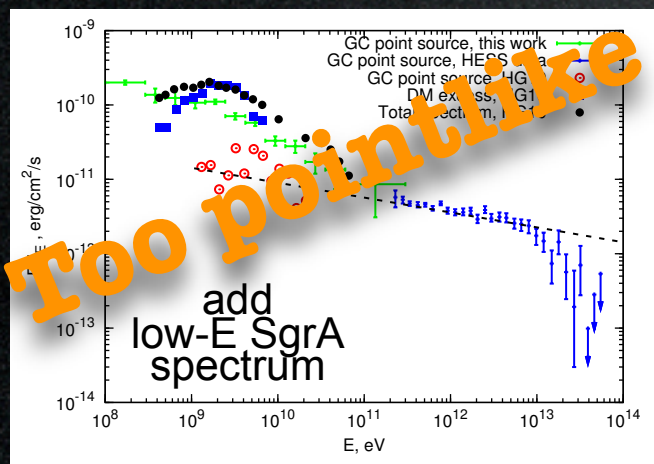
$$10^\circ < b < 30^\circ$$

$$-15^\circ < \ell < 15^\circ$$

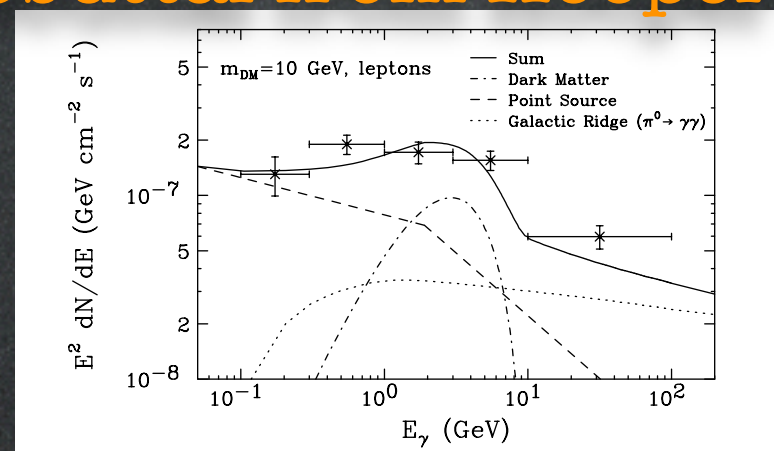
Lin, Finkbeiner, Dobler 1004.0989



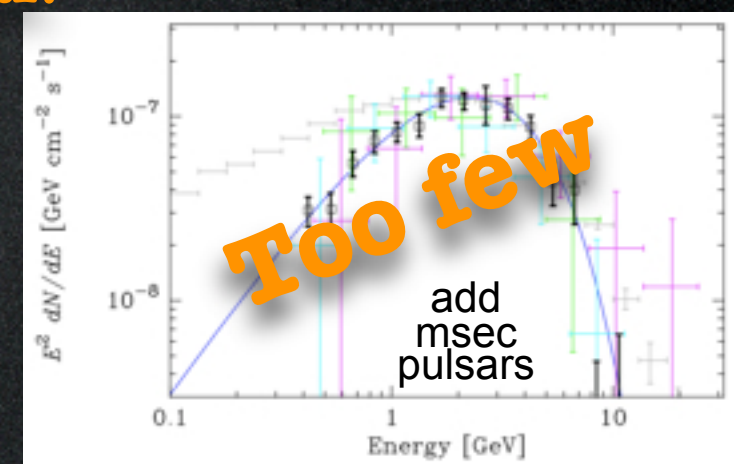
Rebuttal from Hooper et al.



Boyarsky et al.,
1012.5839



Hooper, Linden
1110.0006



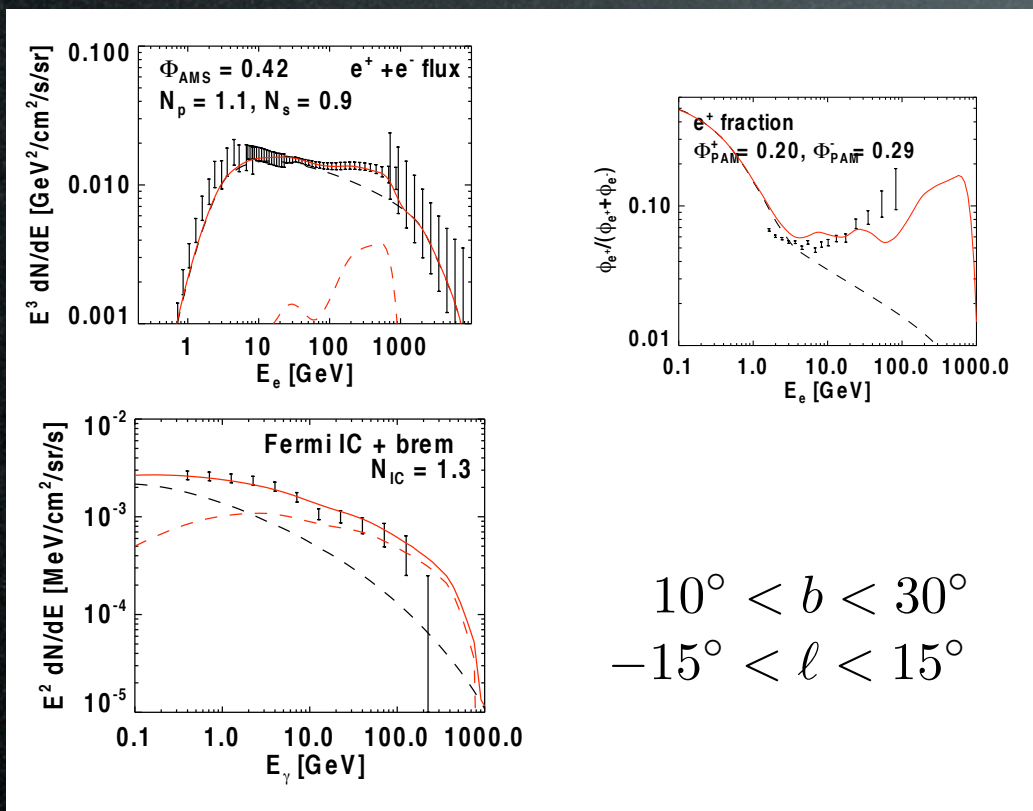
Hutsi, Hektor, Raidal 1004.2036

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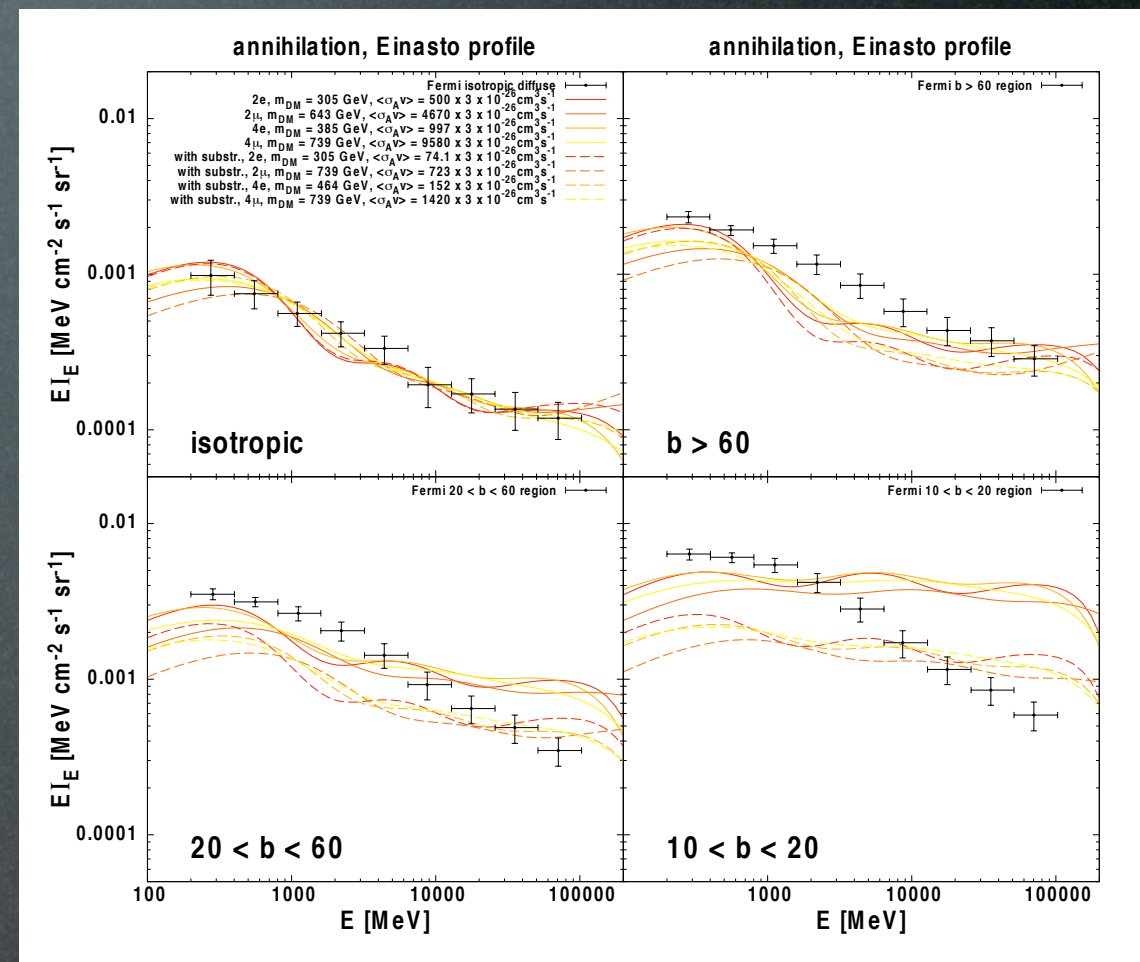
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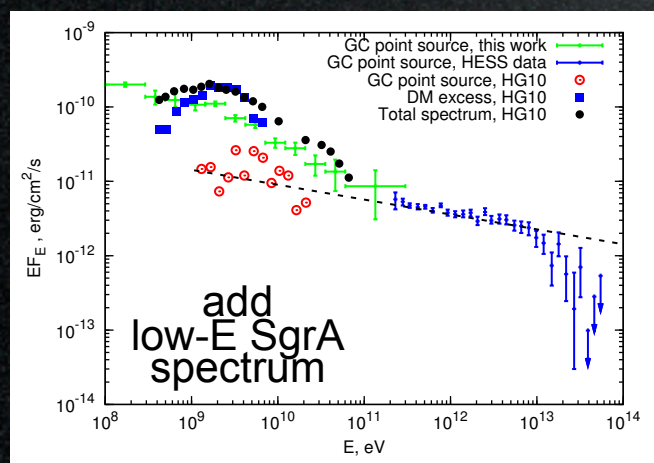
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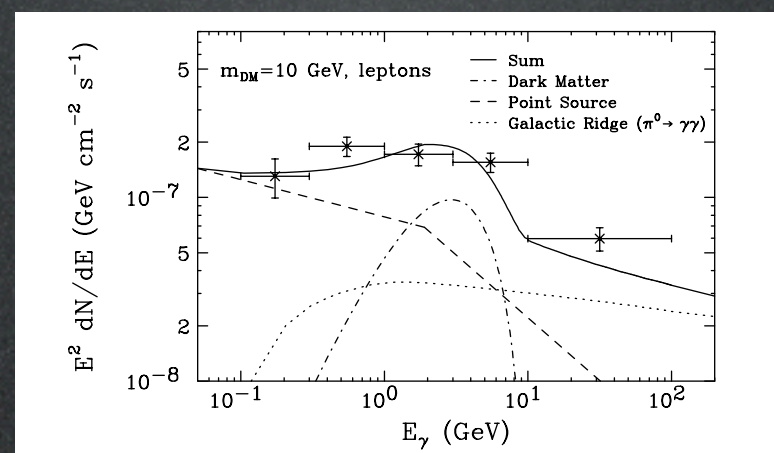
Lin, Finkbeiner, Dobler 1004.0989



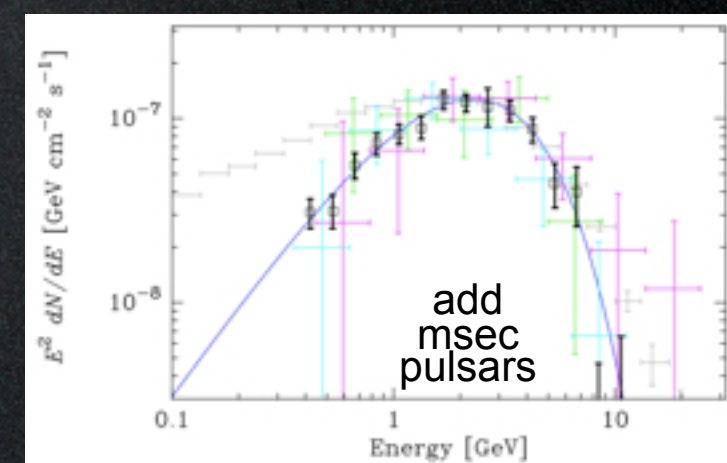
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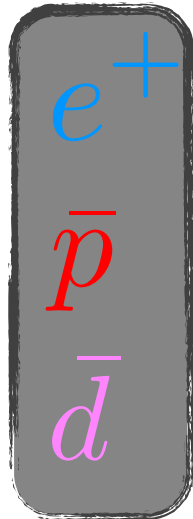
Abazajian 1011.4275

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Uncertainties, uncertainties...

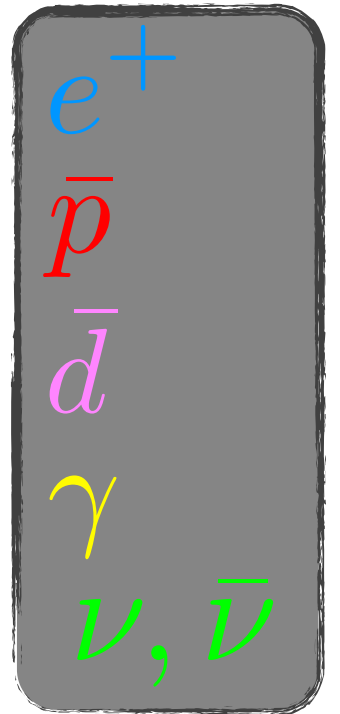
CR propagation

- diffusion
- energy losses
- solar modulation



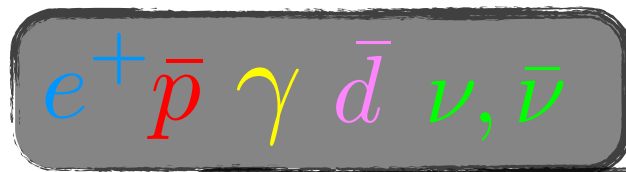
DM distribution in the Galaxy

- local DM density
- DM profile
- beware of extrapolations!
- effect of baryons in DM halos
- (velocity distribution)
- (escape velocity)

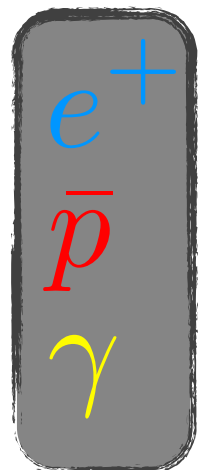


Particle Physics uncertainty

- Pythia at many TeV
- higher order corrections



The astrophysical background



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

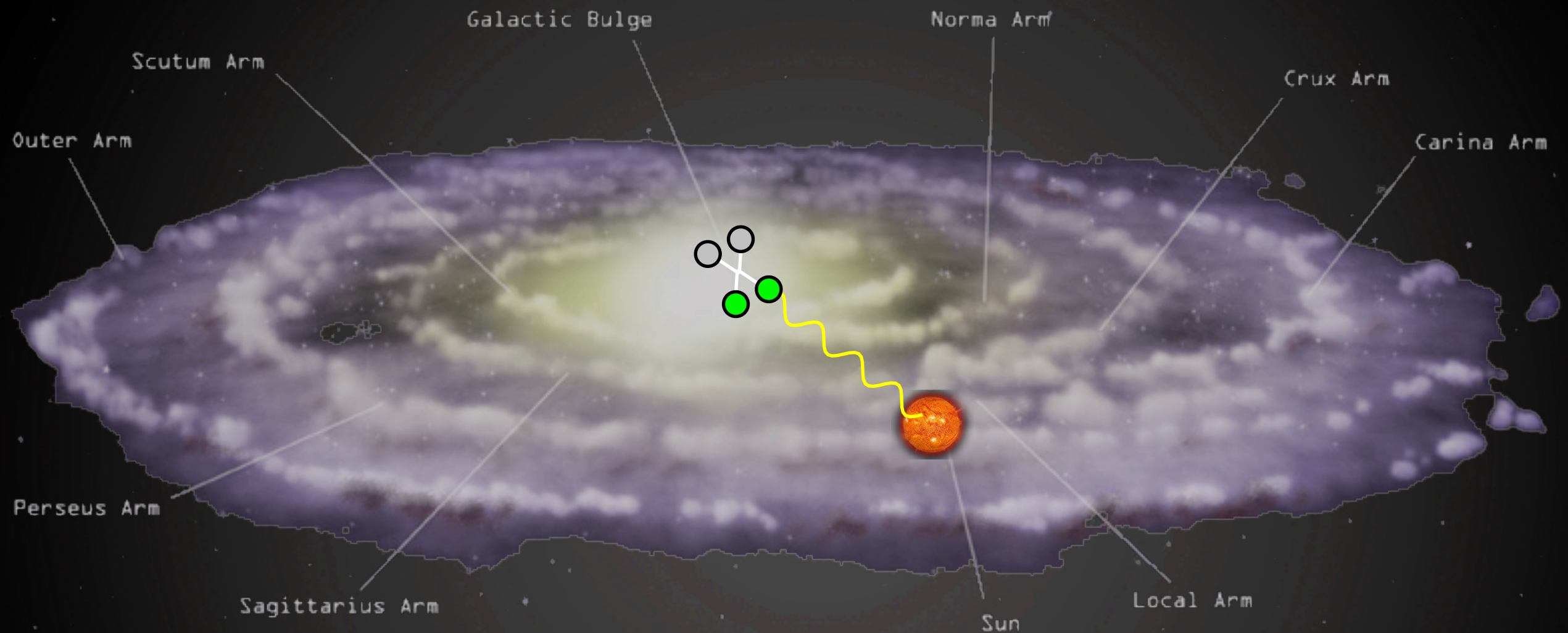
$\bar{p}$ from annihil in galactic halo or center

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

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

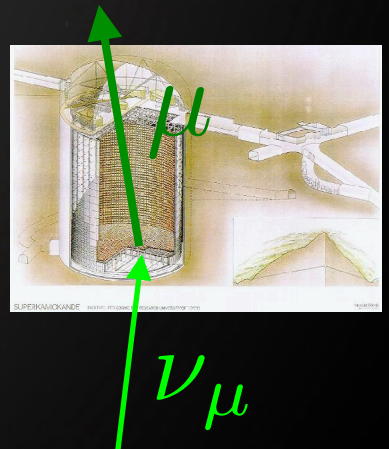
Indirect Detection

ν from DM annihilations in galactic center



$$\begin{aligned}
 &DM \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu \\
 &DM \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu
 \end{aligned}$$

up-going
muons:

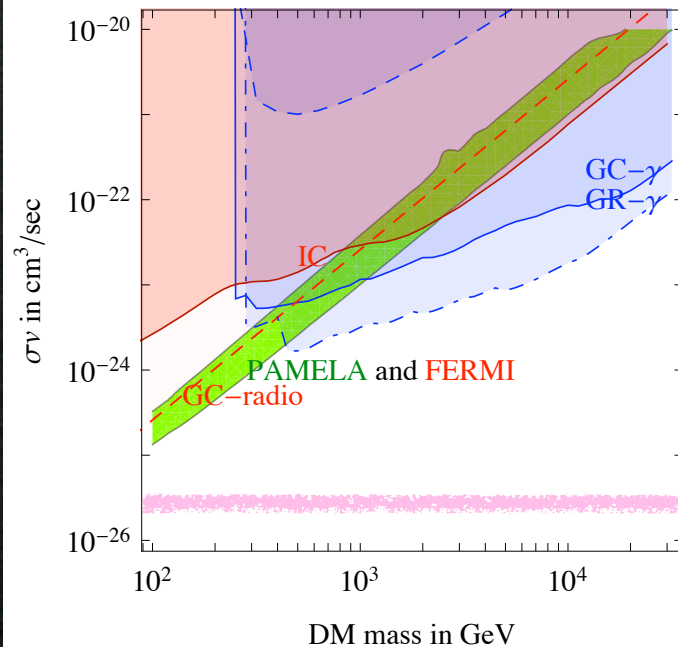


Neutrino constraints

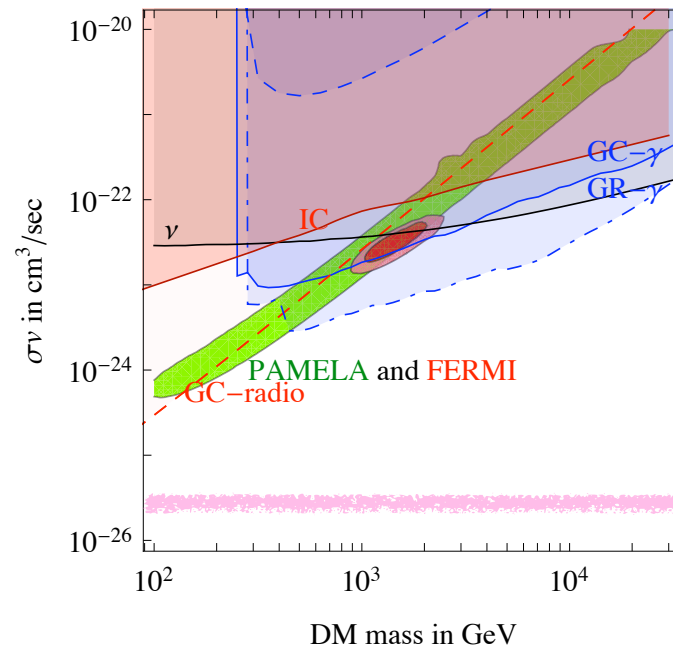
Comparing with SuperKamiokande data in 3° to 30°

- dependance on DM profile 'similar' to ICS gammas
- constraints large M_{DM} ($\sigma_{\nu N} \propto E_\nu$)

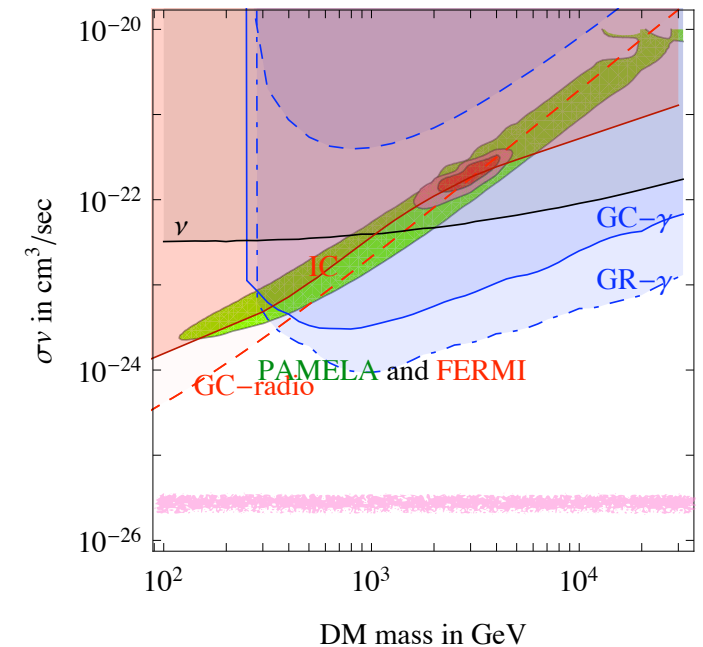
DM DM $\rightarrow e^+e^-$, Einasto profile



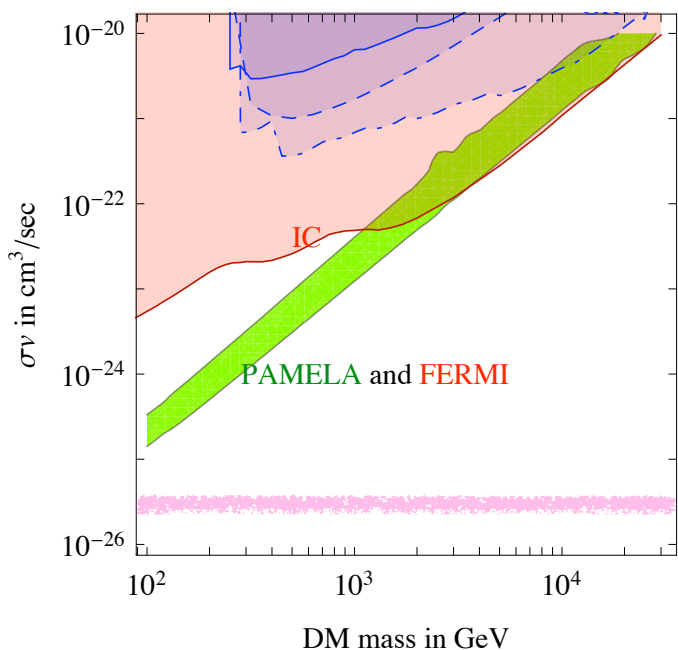
DM DM $\rightarrow \mu^+\mu^-$, Einasto profile



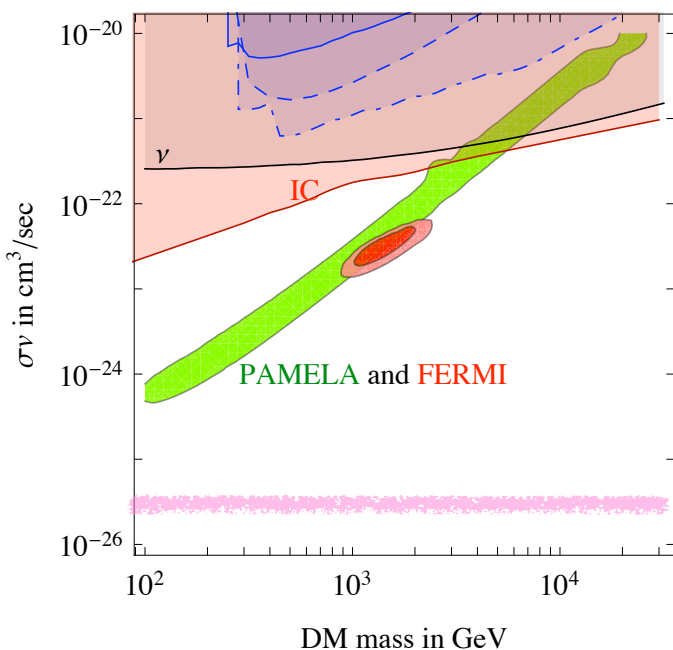
DM DM $\rightarrow \tau^+\tau^-$, Einasto profile



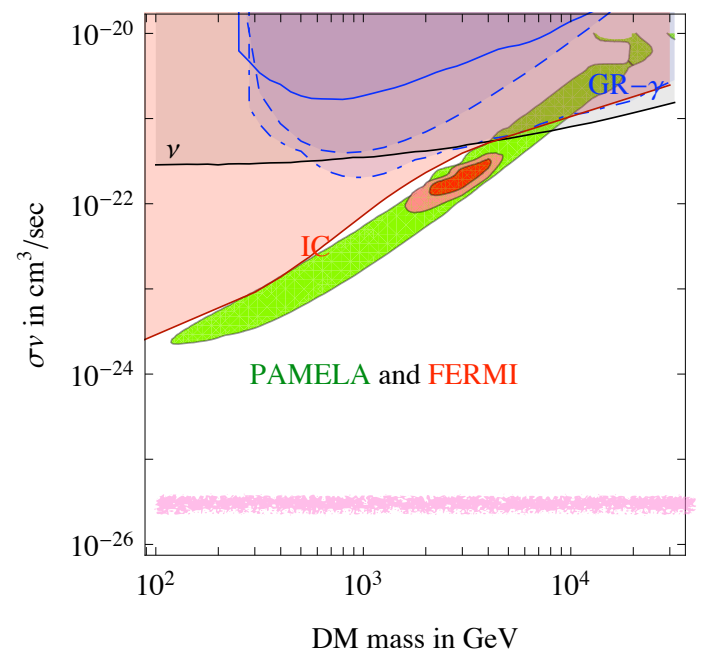
DM DM $\rightarrow e^+e^-$, isothermal profile



DM DM $\rightarrow \mu^+\mu^-$, isothermal profile



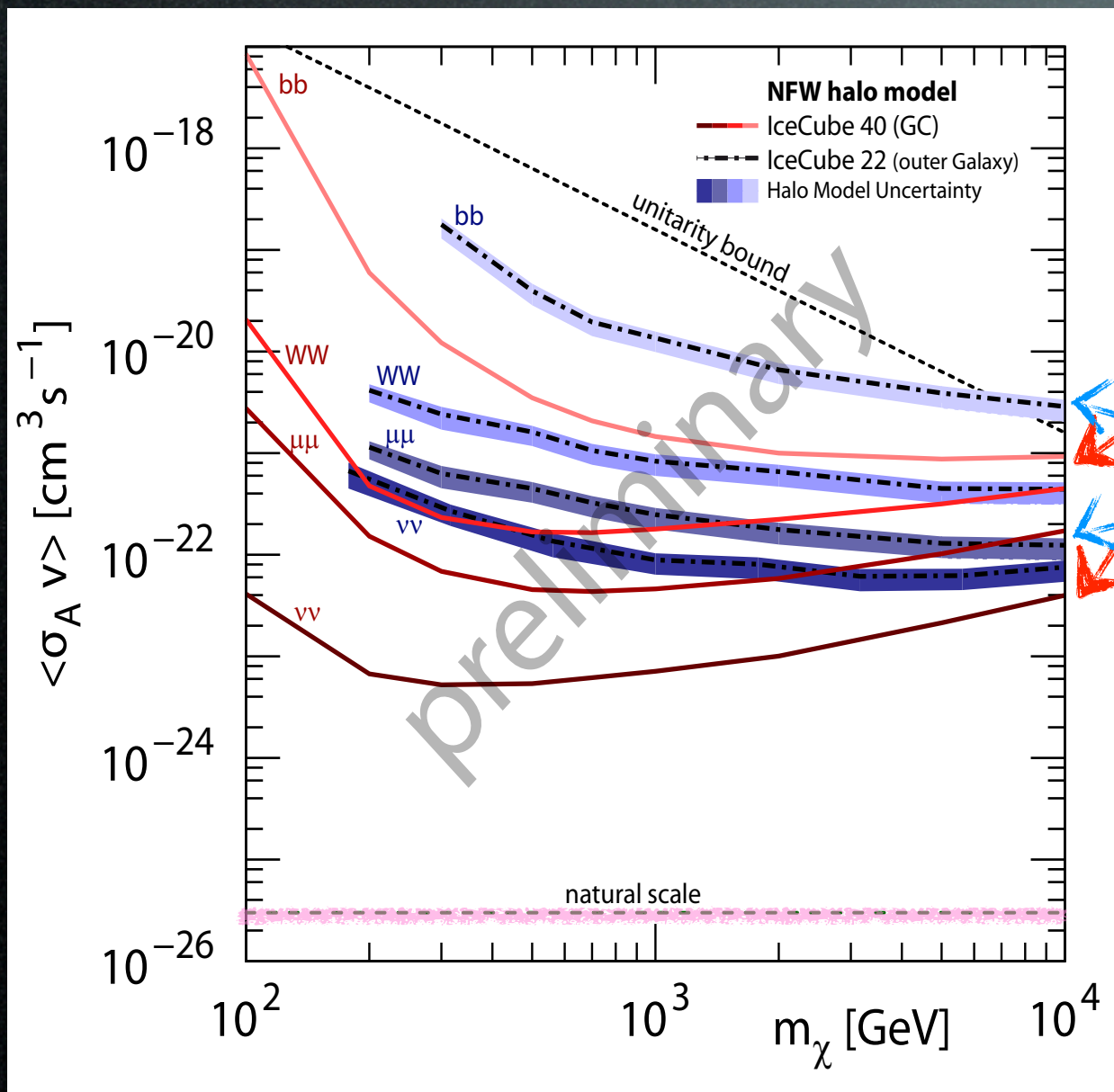
DM DM $\rightarrow \tau^+\tau^-$, isothermal profile



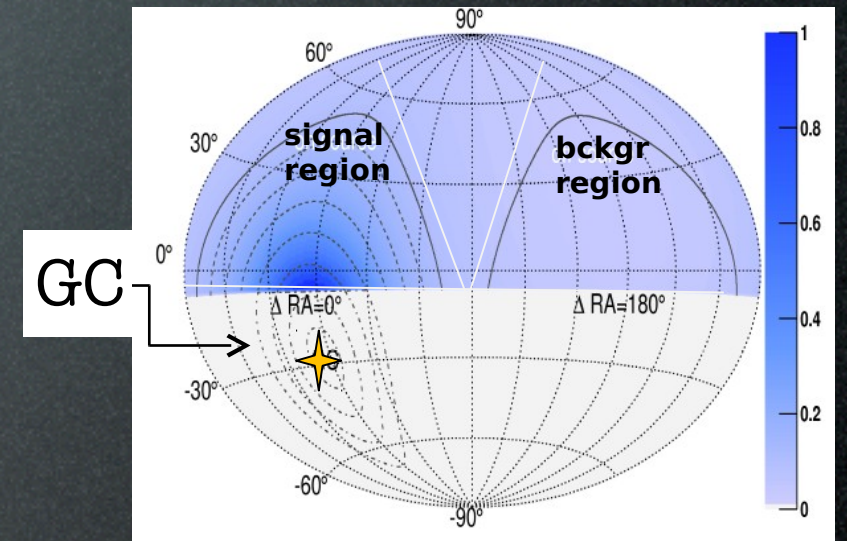
Neutrino constraints

✓ from DM annihilations in galactic center/halo

ICECUBE

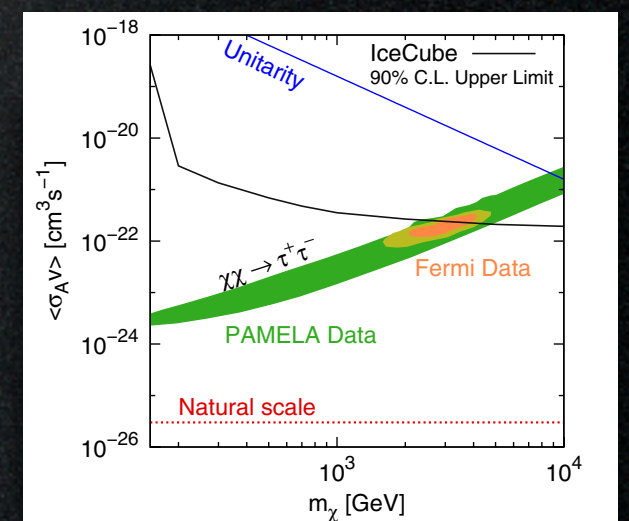


Gal halo: use on/off technique



Gal center: veto downgoing μ

Similarly competitive constraints



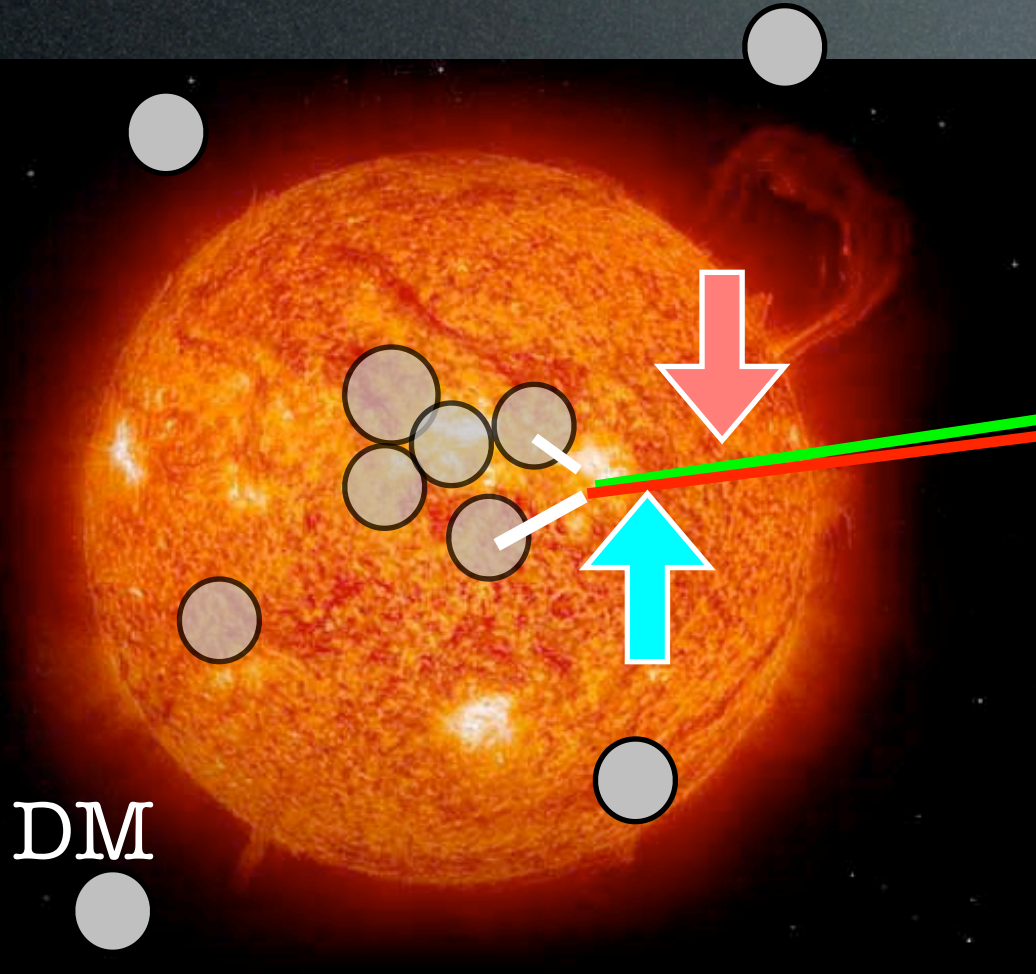
1101.3349 +

Carlos de los Heros, talk at TeVPA 2011, Stockholm

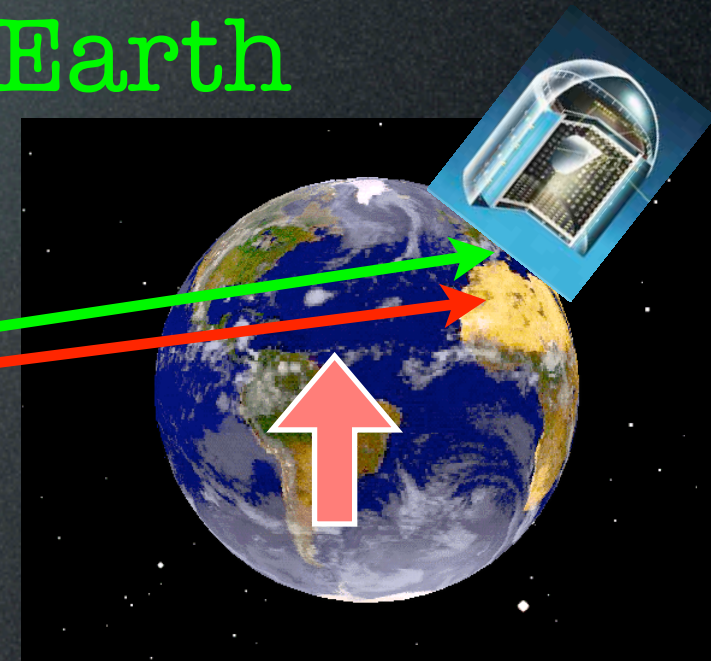
Indirect Detection

ν from DM annihilations in the Sun

Sun



Earth



Include oscillations + interactions:

- reshuffling of the 3 flavors
- distortions the spectra
- attenuations of the fluxes

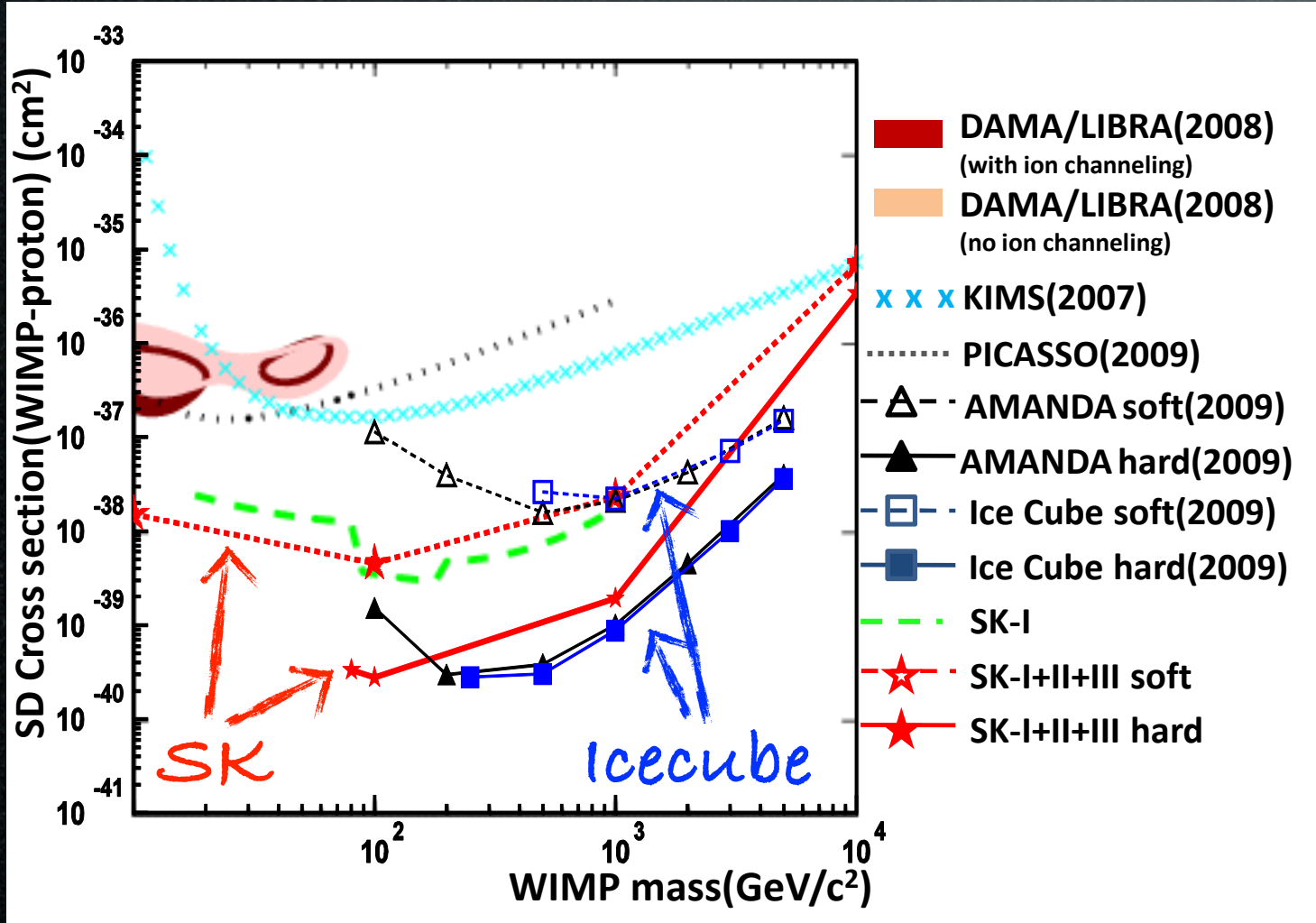
[more details]

Indirect Detection

ν from DM annihilations in the Sun

Probe the scattering cross section.

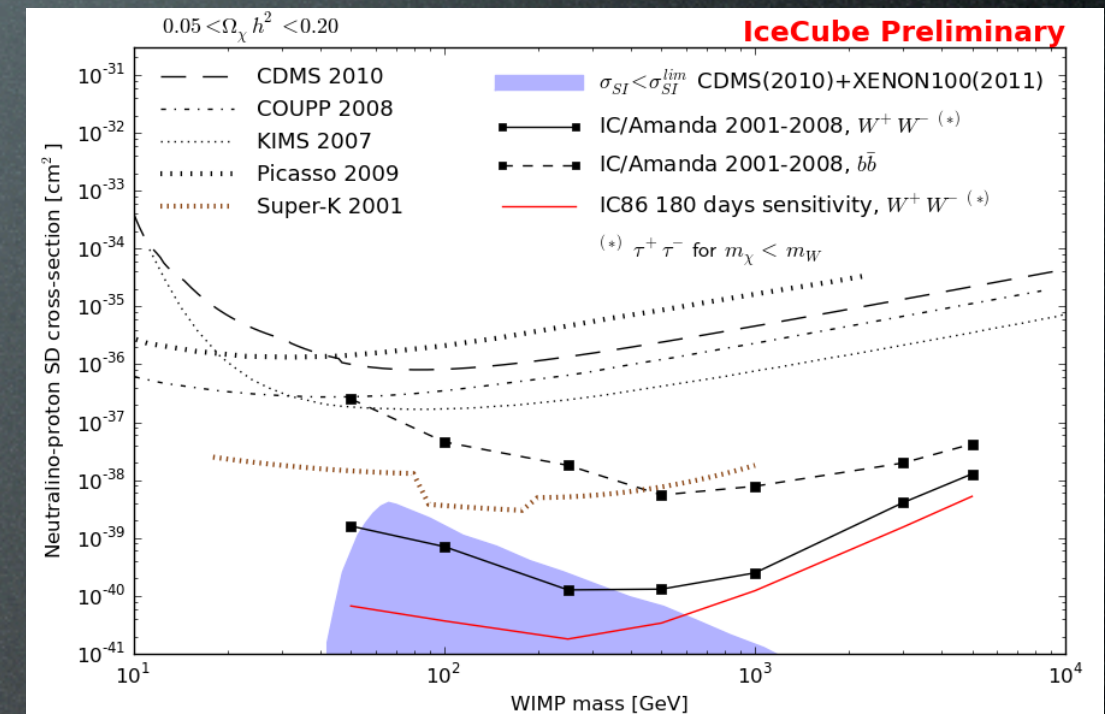
SuperKamiokande



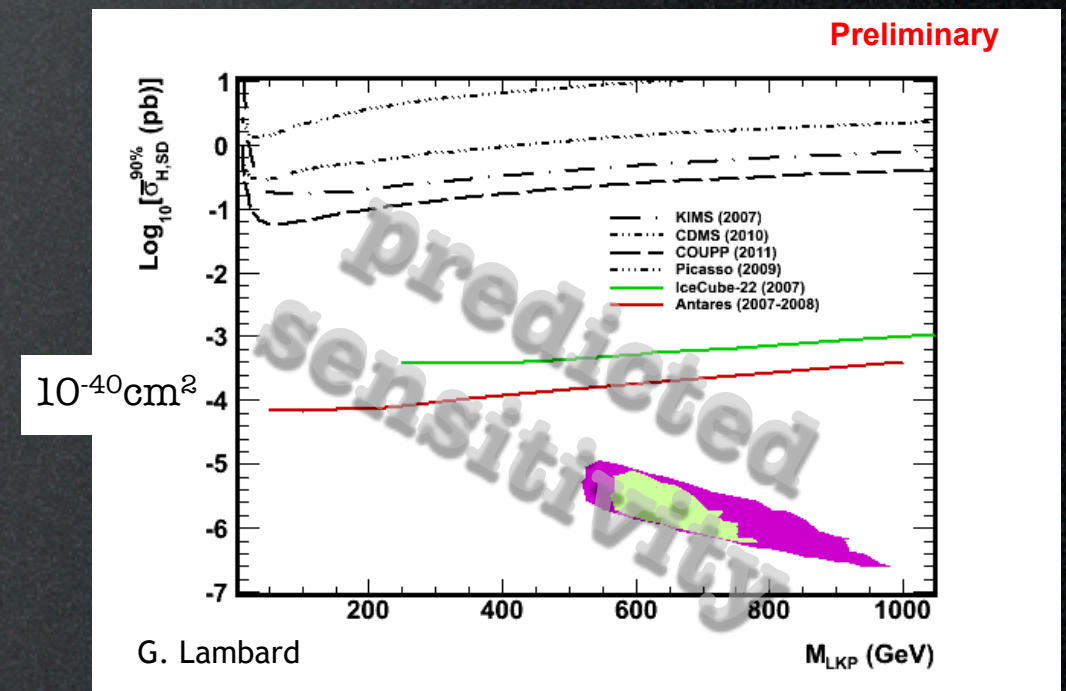
1108.3384

3109.6 days! (now beat that)

ICECUBE



Antares



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

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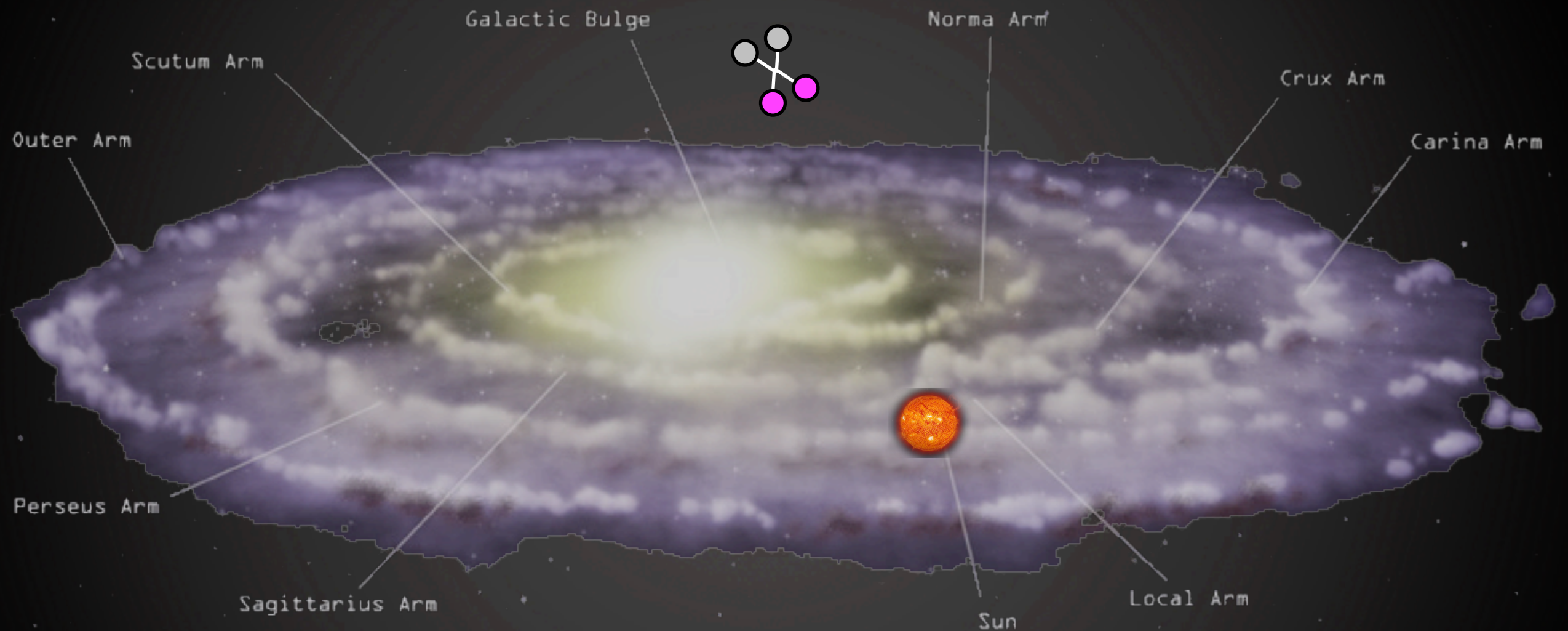
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$\bar{d}$ from annihil in galactic halo or center

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

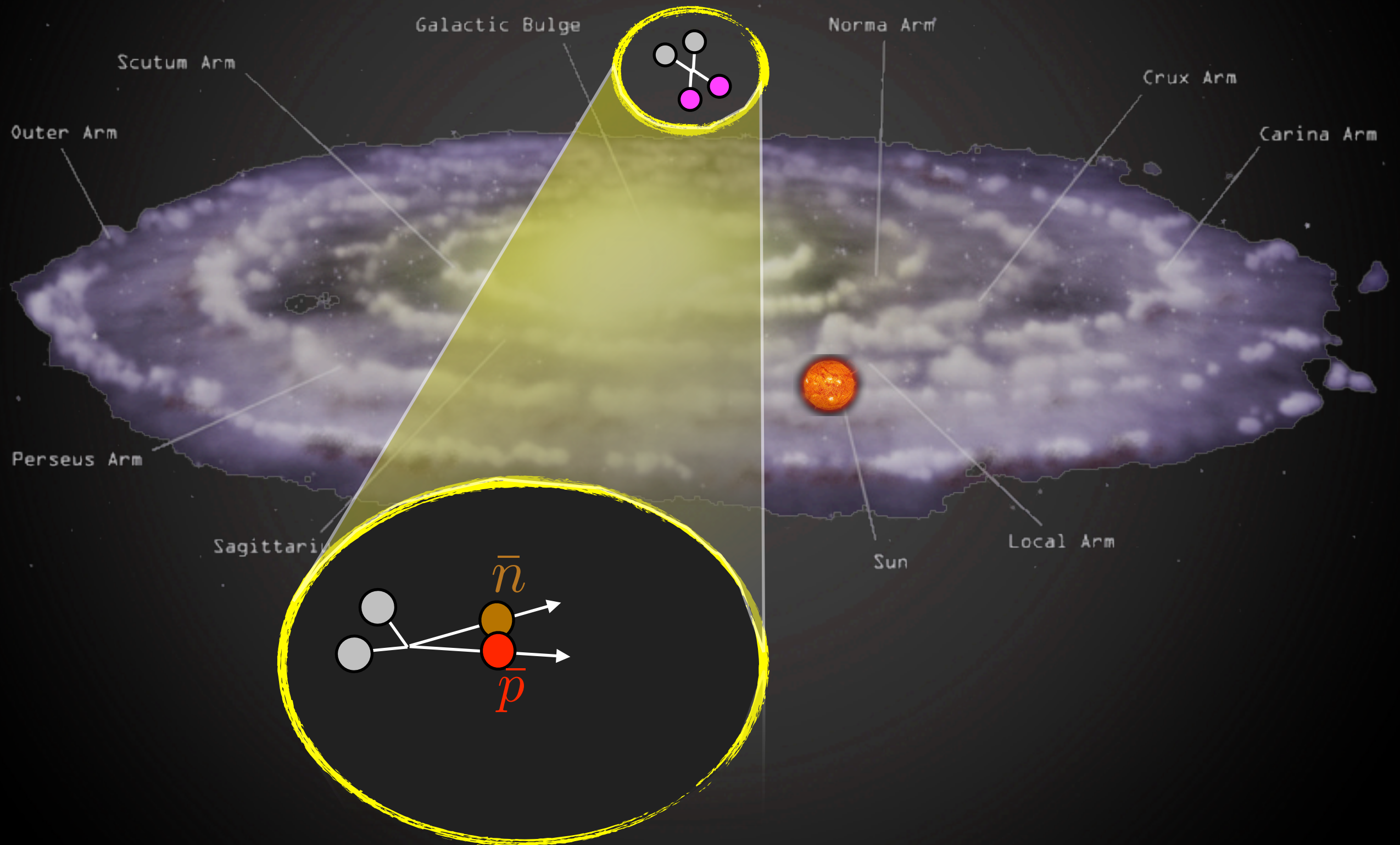
Indirect Detection

$\bar{d}$ from DM annihilations in halo



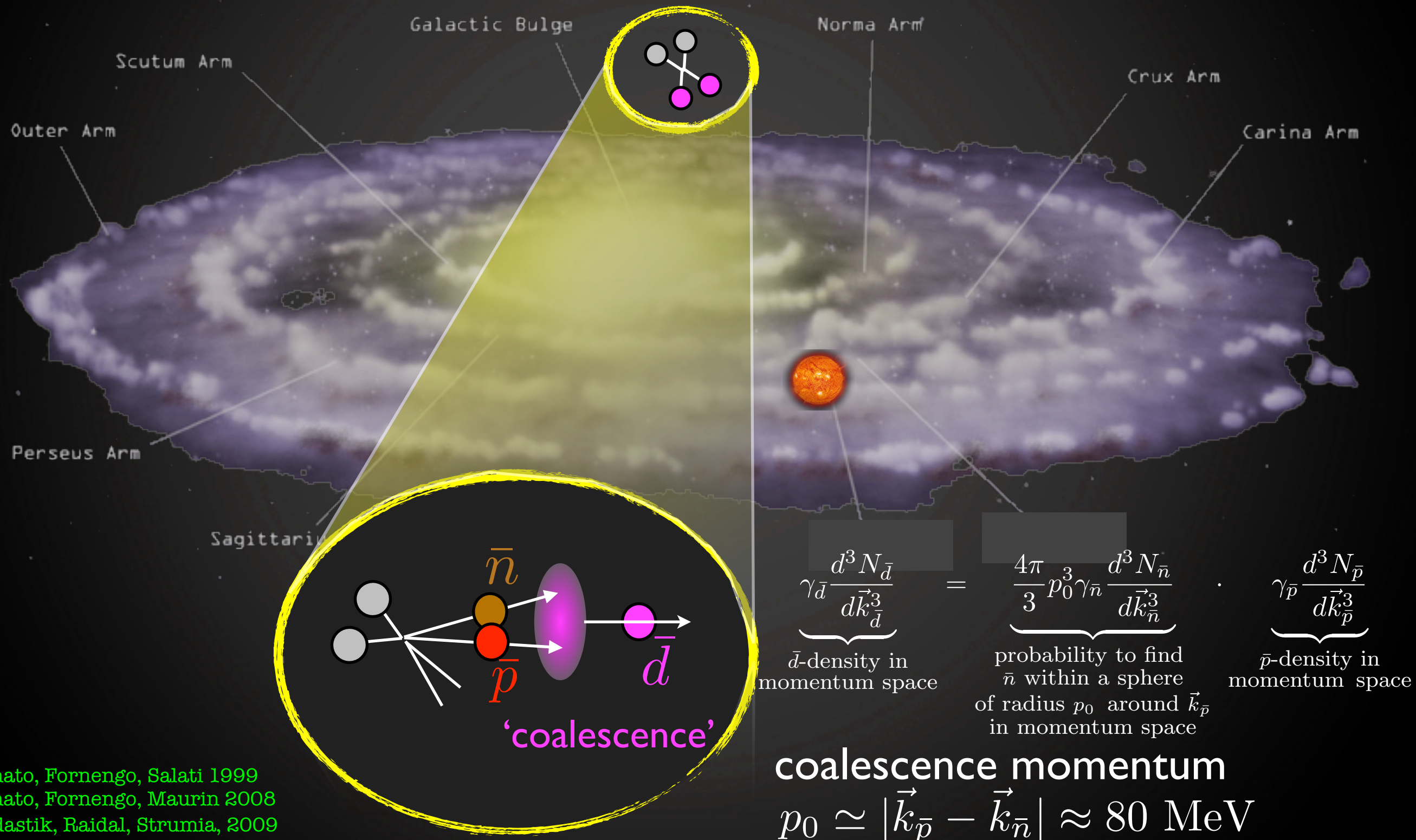
Indirect Detection

$\bar{d}$ from DM annihilations in halo



Indirect Detection

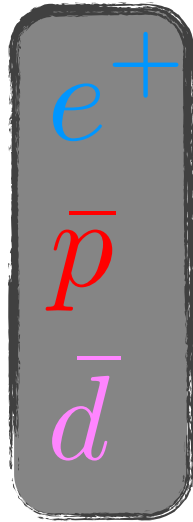
$\bar{d}$ from DM annihilations in halo



Uncertainties, uncertainties...

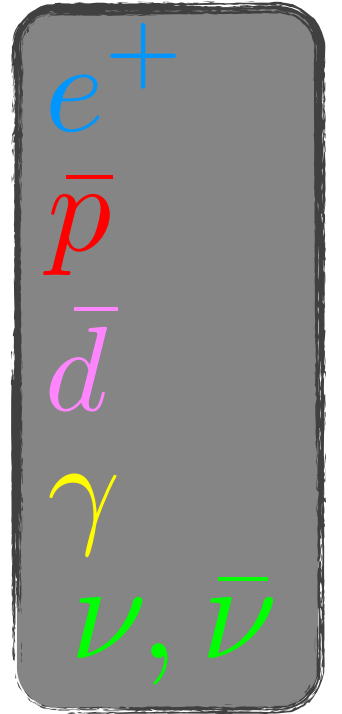
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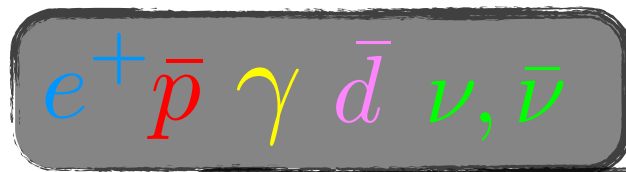
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- DM profile
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- (escape velocity)

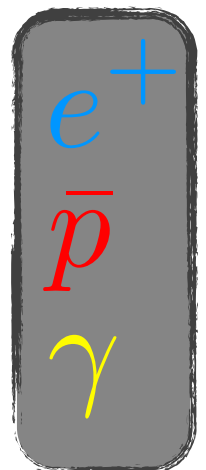


Particle Physics uncertainty

- Pythia at many TeV
- higher order corrections
- coalescence

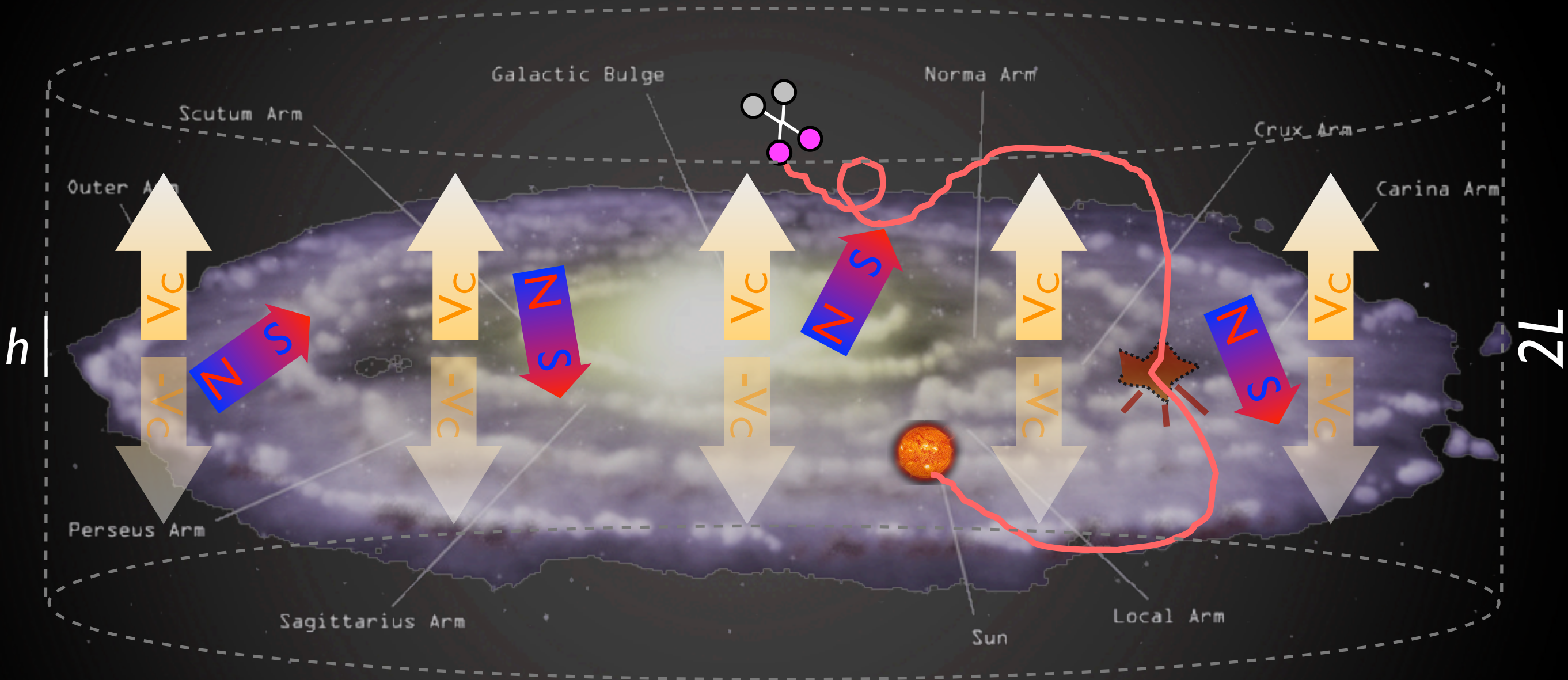


The astrophysical background



Indirect Detection

$\bar{d}$ from DM annihilations in halo



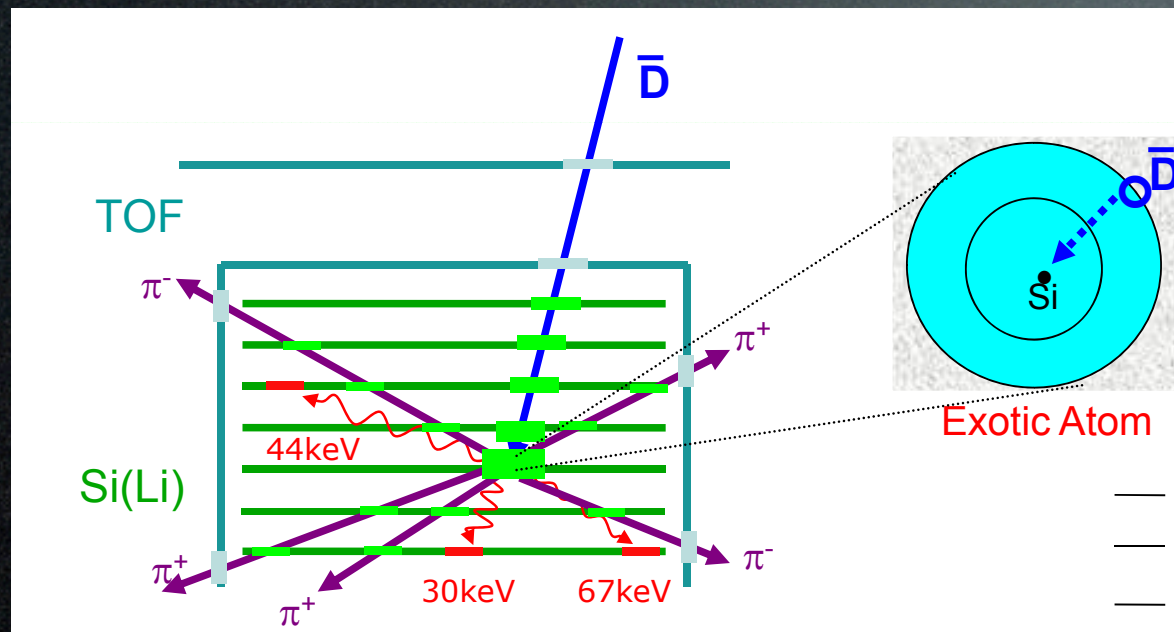
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E} (b(E)f) + \frac{\partial}{\partial z} (V_c f) = Q_{\text{inj}} - 2h\delta(z)\Gamma_{\text{spall}}f$$

diffusion energy loss convective wind source spallations

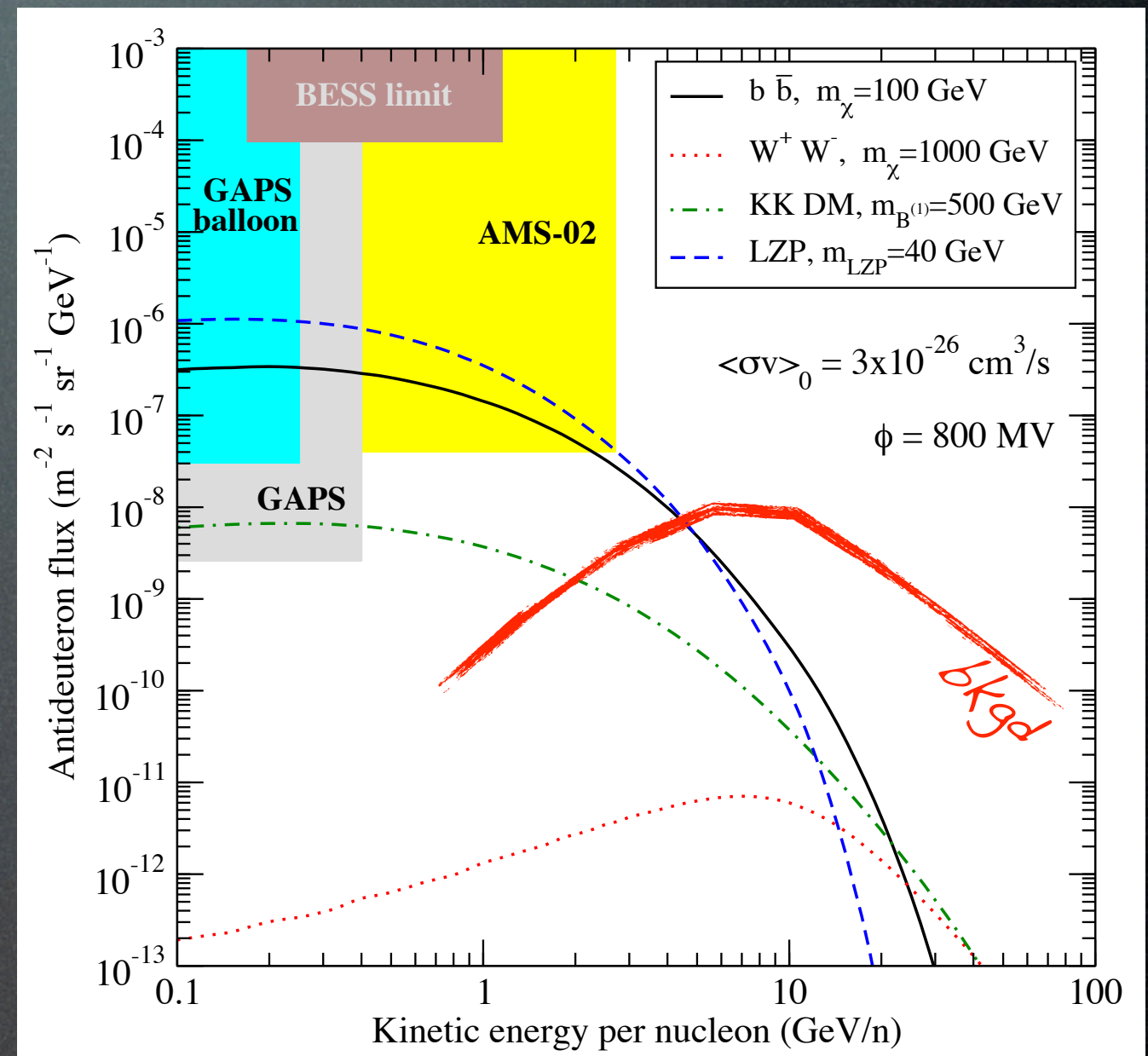
Indirect Detection

$\bar{d}$ from DM annihilations in halo

GAPS detection principle



$\bar{d}$ is slowed down,
captured (exotic atom),
annihilates w distinctive emissions



DM signal in the reach
of **GAPS** and **AMS-02**

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

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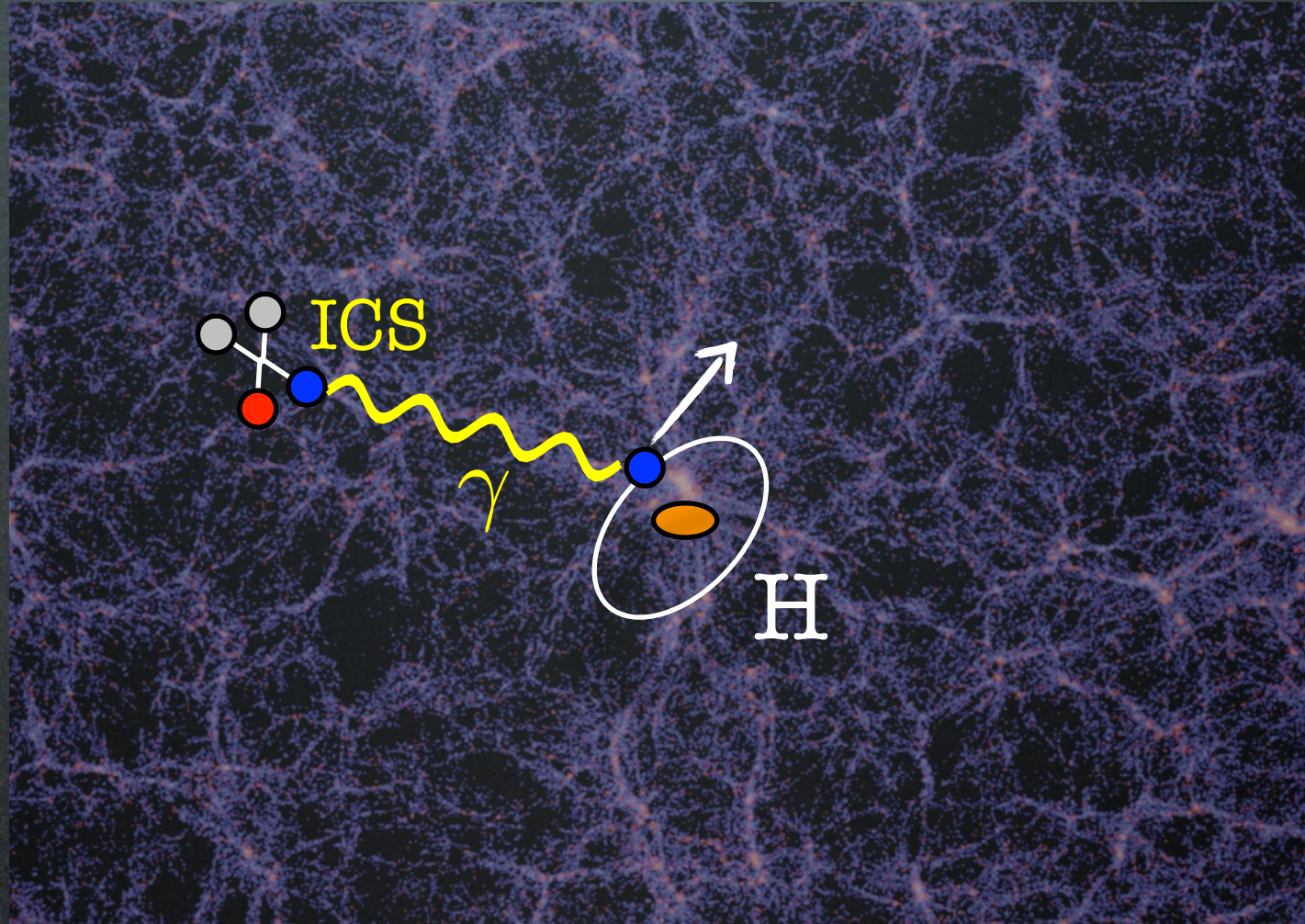
bonus track: cosmology

[jump to theory]

[jump to conclusions]

Cosmology: bounds from reionization

DM particle
annihilations
produce
free electrons



$$-n_A H_0 \sqrt{\Omega_M} (1+z)^{11/2} \frac{dx_{\text{ion}}(z)}{dz} = I(z) - R(z).$$

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

$$P(E_\gamma, z) = n_A (1+z)^3 [1 - x_{\text{ion}}(z)] \cdot \sigma_{\text{tot}}(E_\gamma),$$

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

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

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

$$\frac{dT_{\text{igm}}(z)}{dz} = \frac{2 T_{\text{igm}}(z)}{1+z}$$

$$- \frac{1}{H_0 \sqrt{\Omega_M} (1+z)^{5/2}} \left(\frac{x_{\text{ion}}(z)}{1+x_{\text{ion}}(z)+0.073} \frac{T_{\text{CMB}}(z) - T_{\text{igm}}(z)}{t_c(z)} + \frac{2 \eta_{\text{heat}}(x_{\text{ion}}(z)) \mathcal{E}(z)}{3 n_A (1+z)^3} \right).$$

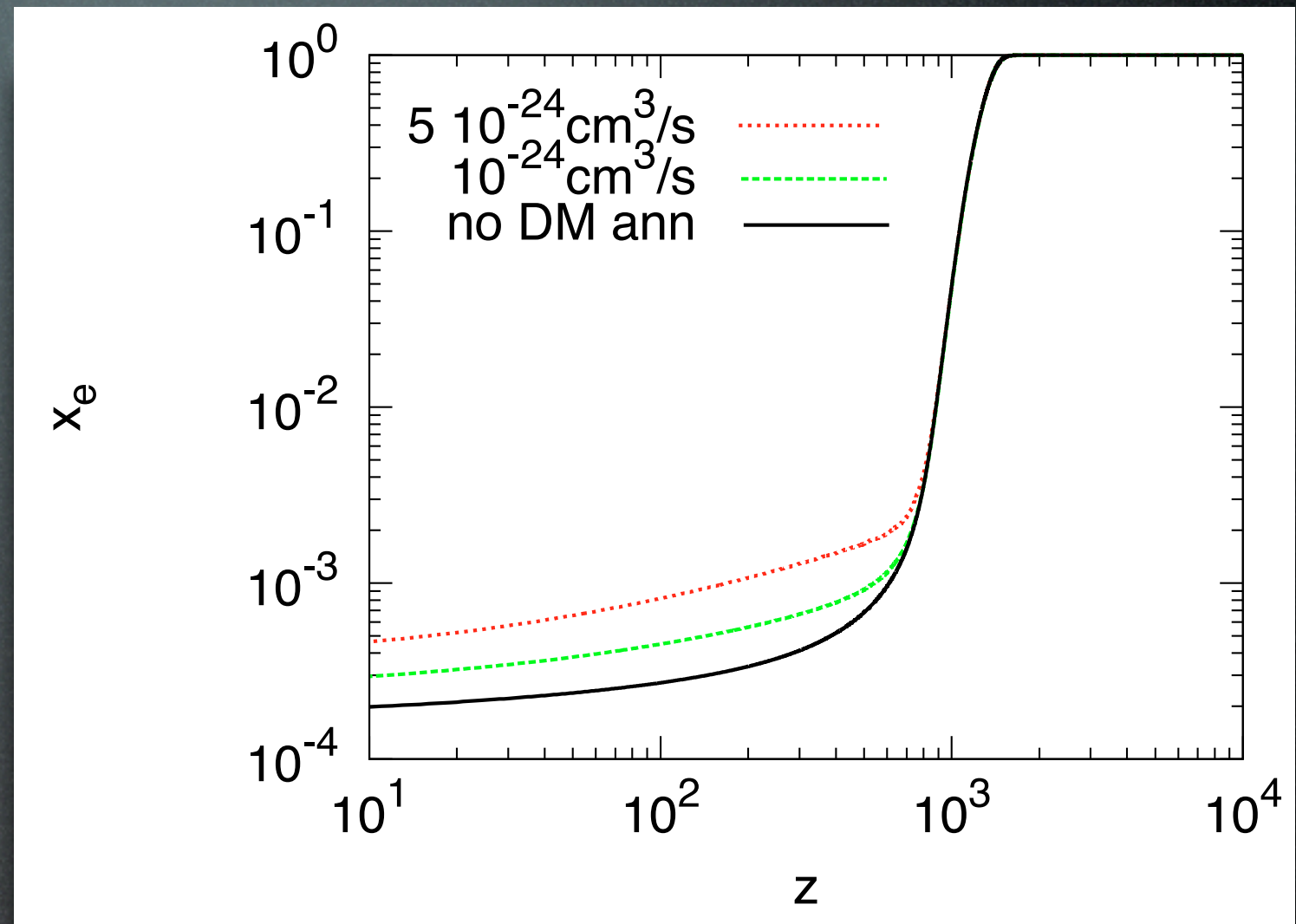
$$A(z) = \frac{\langle \sigma v \rangle}{2 m_\chi^2} \rho_{\text{DM},0}^2 (1+z)^6 (1 + \mathcal{B}_i(z)),$$

$$\mathcal{B}_i(z) = \frac{\Delta_{\text{vir}}(z)}{3 \rho_c \Omega_M} \int_{M_{\text{min}}}^{\infty} dM M \frac{dn}{dM}(z, M) F_i(M, z),$$

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

Cosmology: bounds from reionization

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



Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

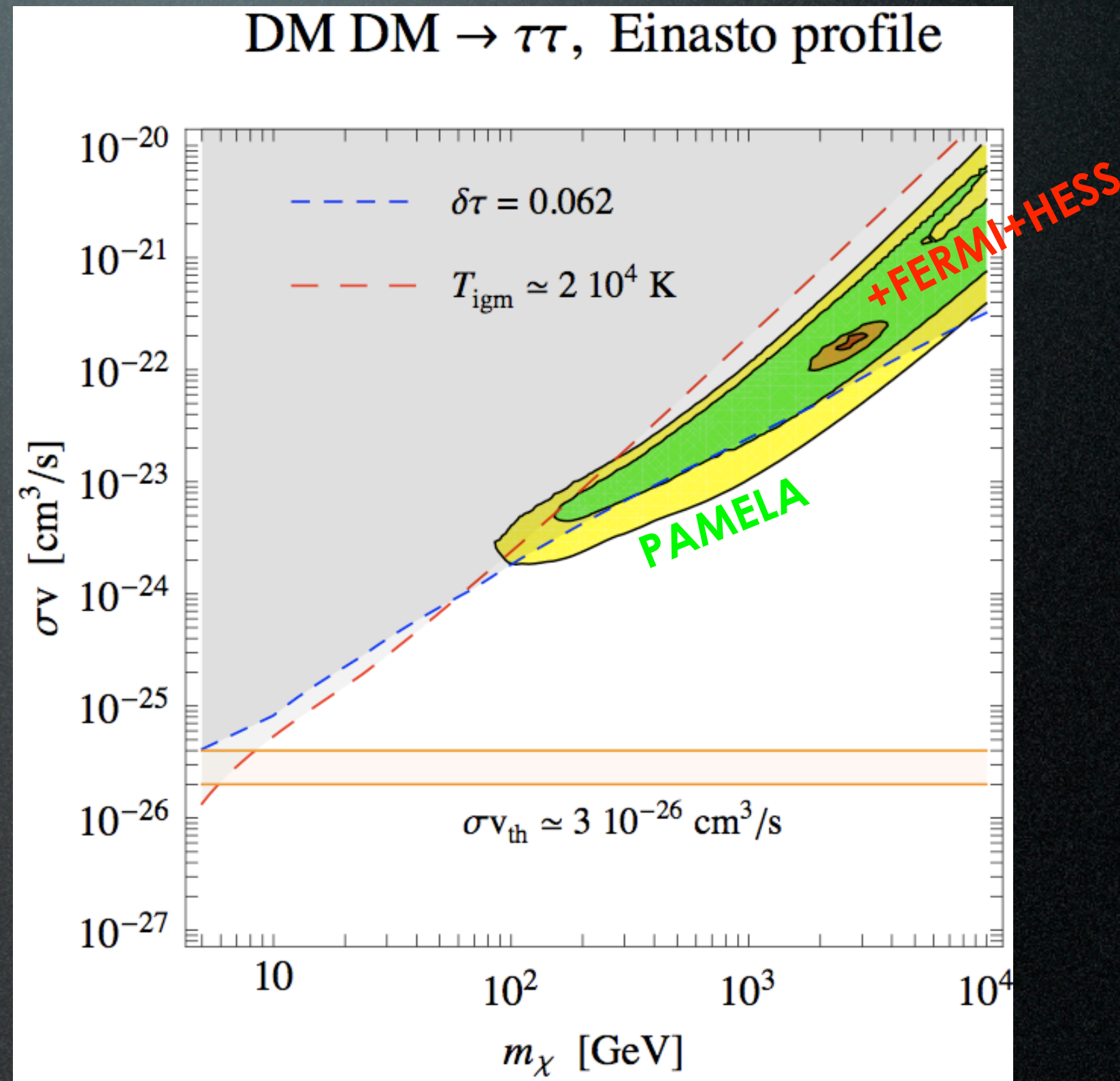
DM particles that fit
PAMELA+FERMI+HESS
produce **too many**
free electrons:
bounds on **optical depth**
of the Universe violated
 $\tau = 0.084 \pm 0.016$ (WMAP-5yr)

see also:

Huetsi, Hektor, Raidal 0906.4550

Kanzaki et al., 0907.3985

Huetsi et al., 1103.2766

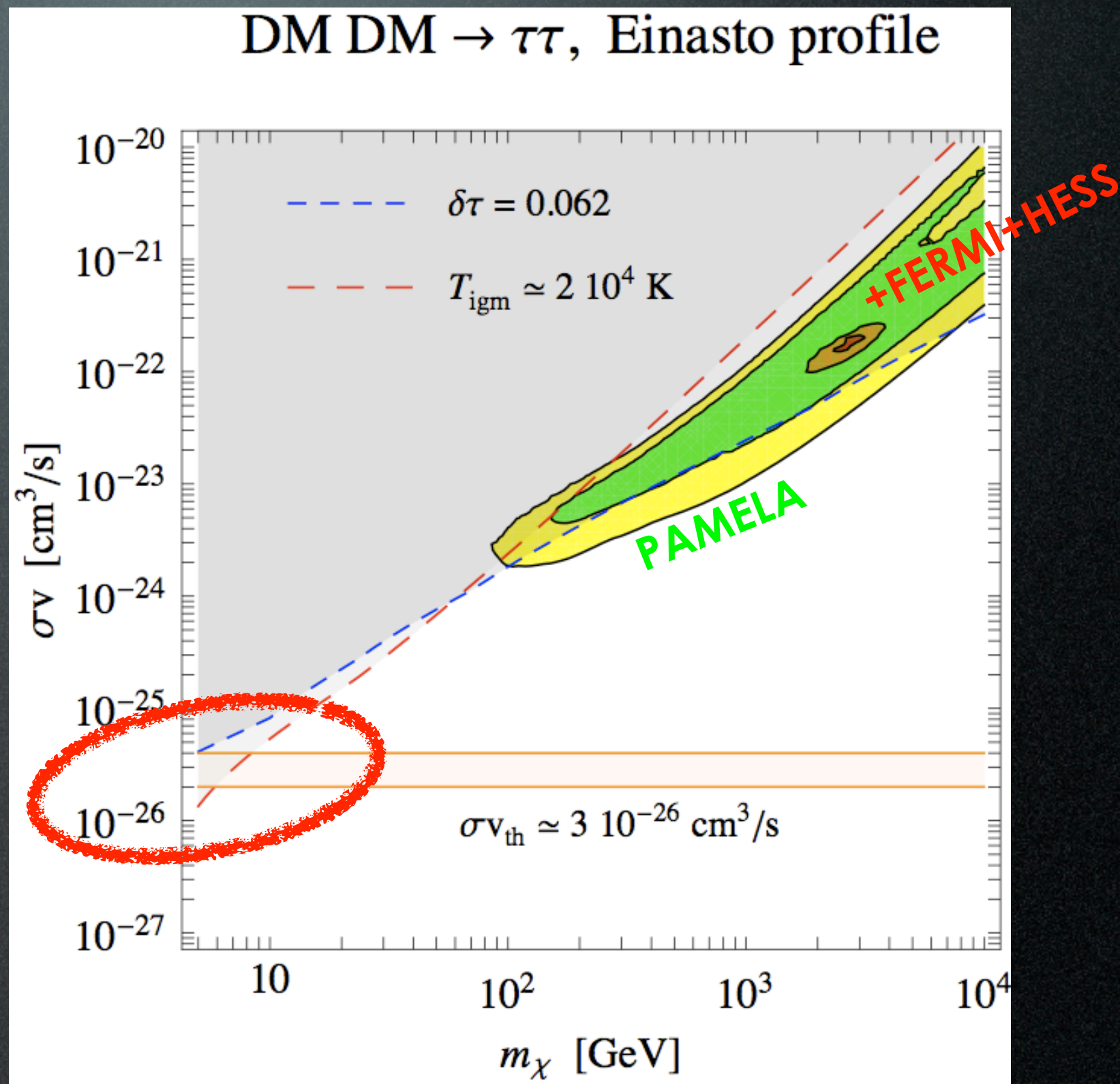


Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

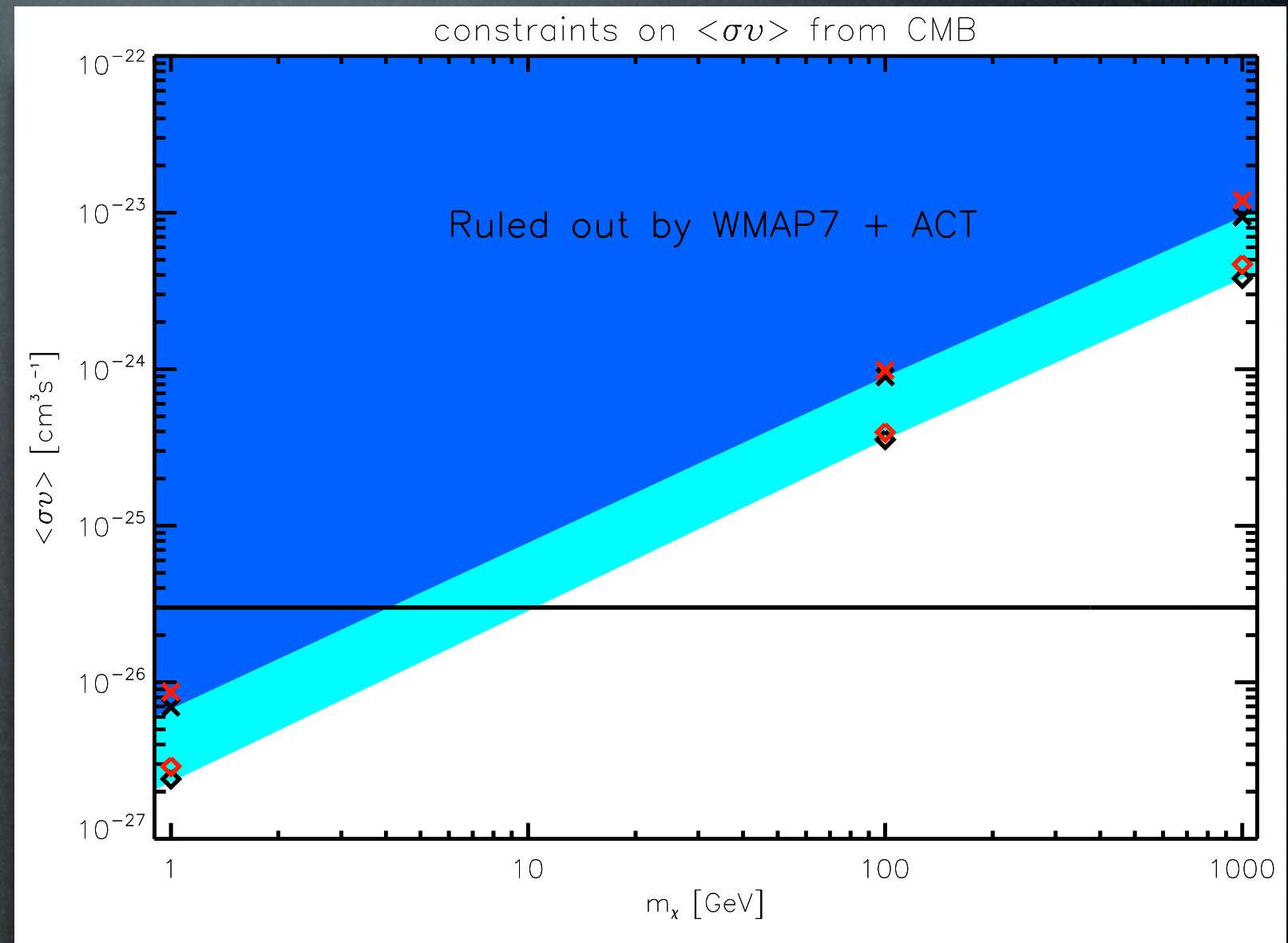
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PAMELA+FERMI+HESS
produce **too many**
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bounds on **optical depth**
of the Universe violated
 $\tau = 0.084 \pm 0.016$ (WMAP-5yr)

Starts constraining
even thermal DM!



Cosmology: bounds from CMB

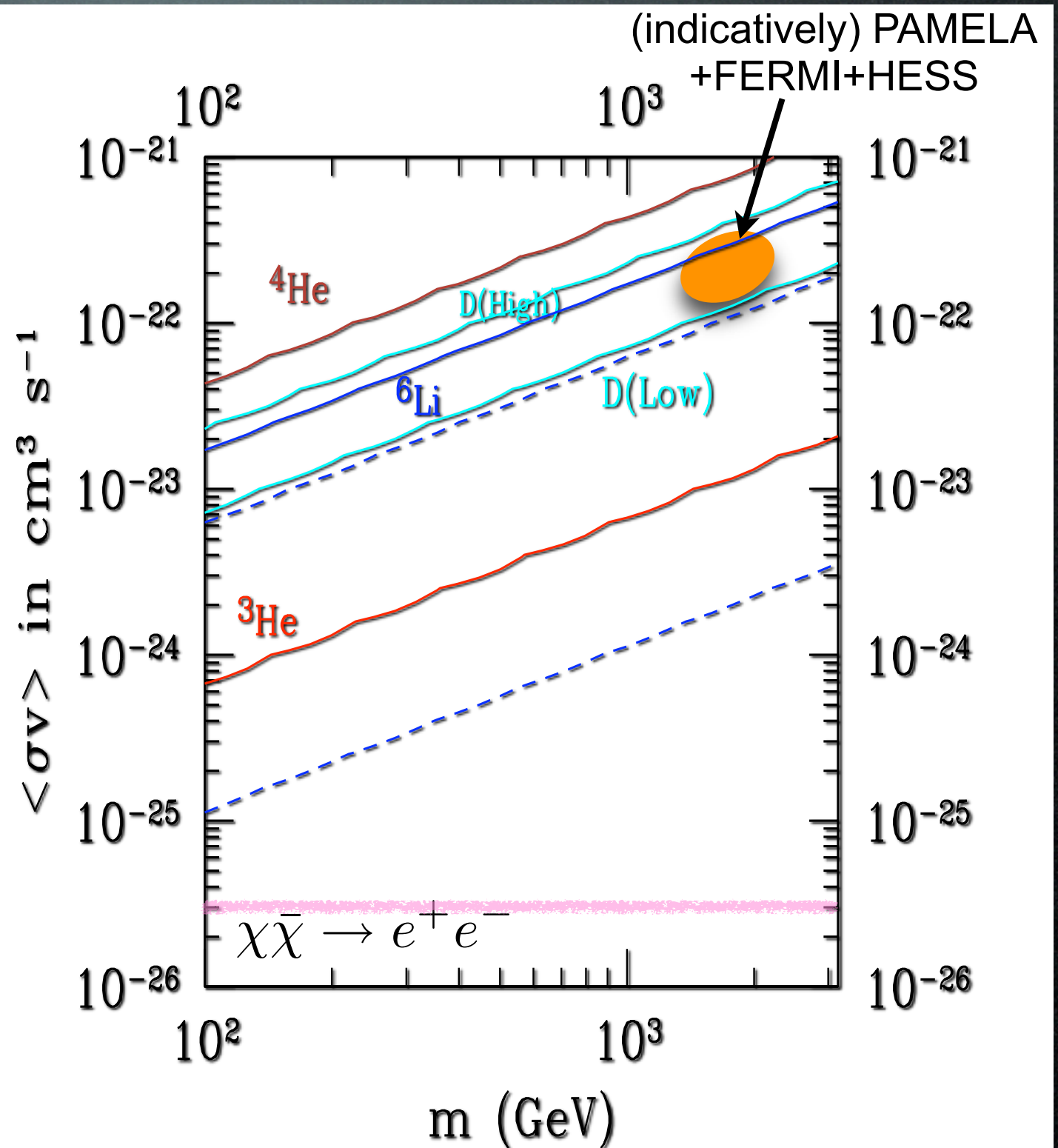
Similar conclusion
from global CMB fits



Galli, Iocco, Bertone, Melchiorri, PRD 80 (2009)
Slatyer, Padmanabahn, Finkbeiner, PRD 80 (2009)
Galli, Iocco, Bertone, Melchiorri, 1106.1528 (2011)

Cosmology: bounds from BBN

DM particles that fit
PAMELA+FERMI+HESS
inject **too much energy**
that destroys forming
nuclei: stringent bounds!



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

$$\sigma_{\text{ann}}(\text{DM } \bar{\text{DM}} \rightarrow f \bar{f}) \propto \left(\frac{m_f}{M_{\text{DM}}} \right)^2$$

Enhancement

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

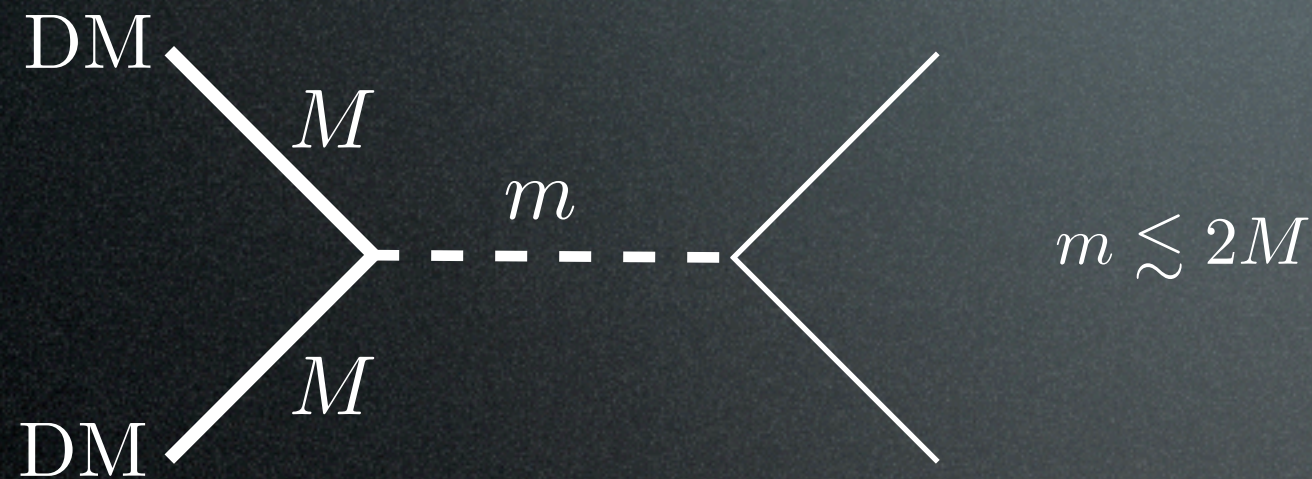
- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

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

Resonance Enhancement

Cirelli, Kadastik, Raidal, Strumia, 2008, Sec.2
Ibe, Murayama, Yanagida 0812.0072
P.Nath et al. 0810.5762

DM annihilation via a narrow **resonance** just below the threshold:

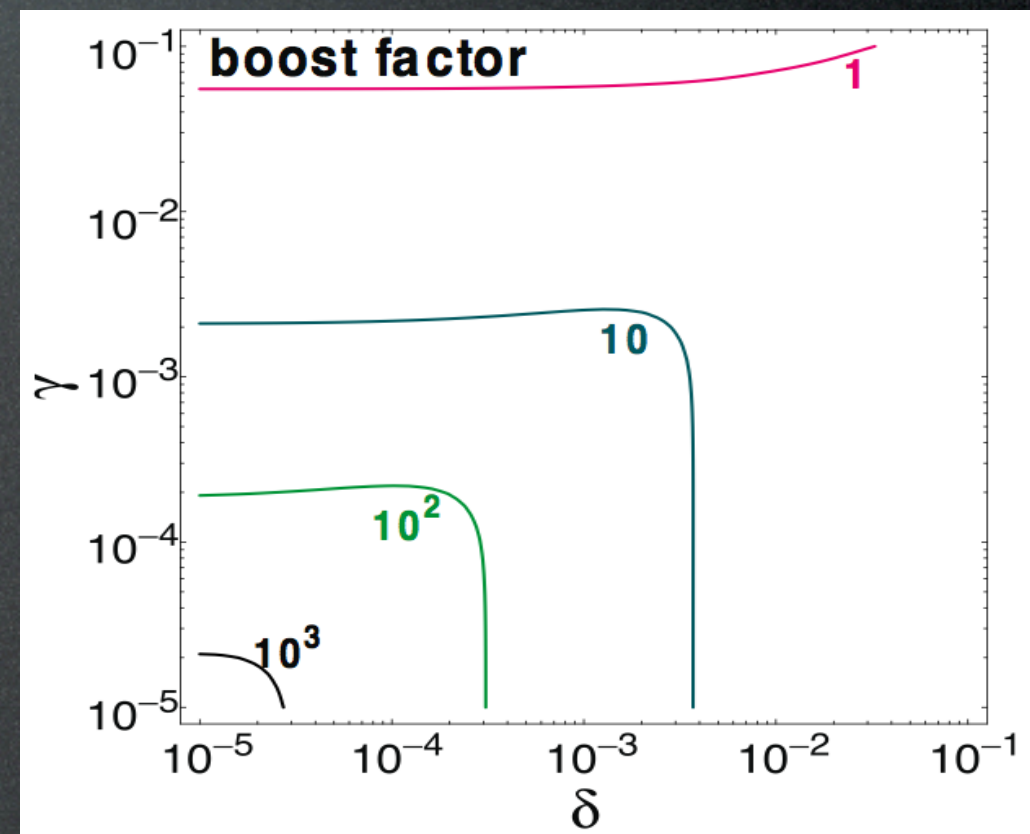
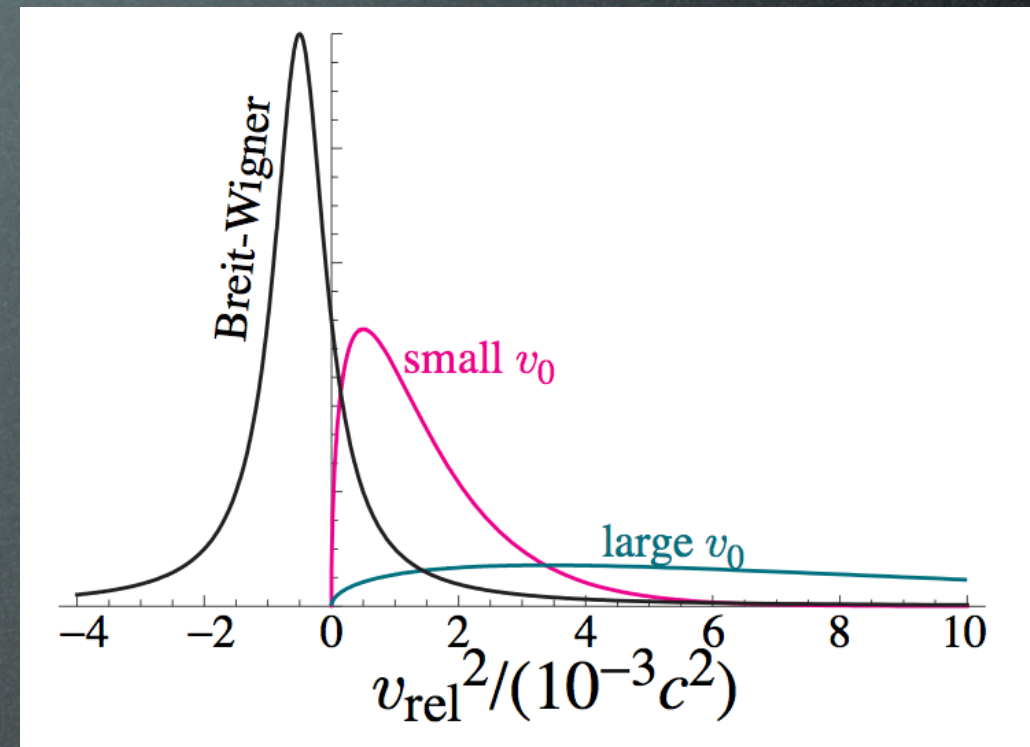


$$\sigma = \frac{16\pi}{E^2 \bar{\beta}_i \beta_i} \frac{m^2 \Gamma^2}{(E_{\text{cm}}^2 - m^2)^2 + m^2 \Gamma^2} B_i B_f$$

$$\langle \sigma v_{\text{rel}} \rangle \simeq \frac{32\pi}{m^2 \bar{\beta}_i} \frac{\gamma^2}{(\delta + \xi v_0^2)^2 + \gamma^2} B_i B_f$$

$$m^2 = 4M^2(1 - \delta) \quad \gamma = \Gamma/m$$

Enhancement can reach 10^3 with very **fine tuned** models.



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, Ann.Phys. 403, 257 (1931)

Hisano et al., 2003-2006:
in part. hep-ph/0307216, 0412403, 0610249

Cirelli, Tamburini, Strumia 0706.4071

Arkani-Hamed et al., 0810.0713

Sommerfeld Enhancement

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A classical analogy:

Arkani-Hamed et al. 0810.0713



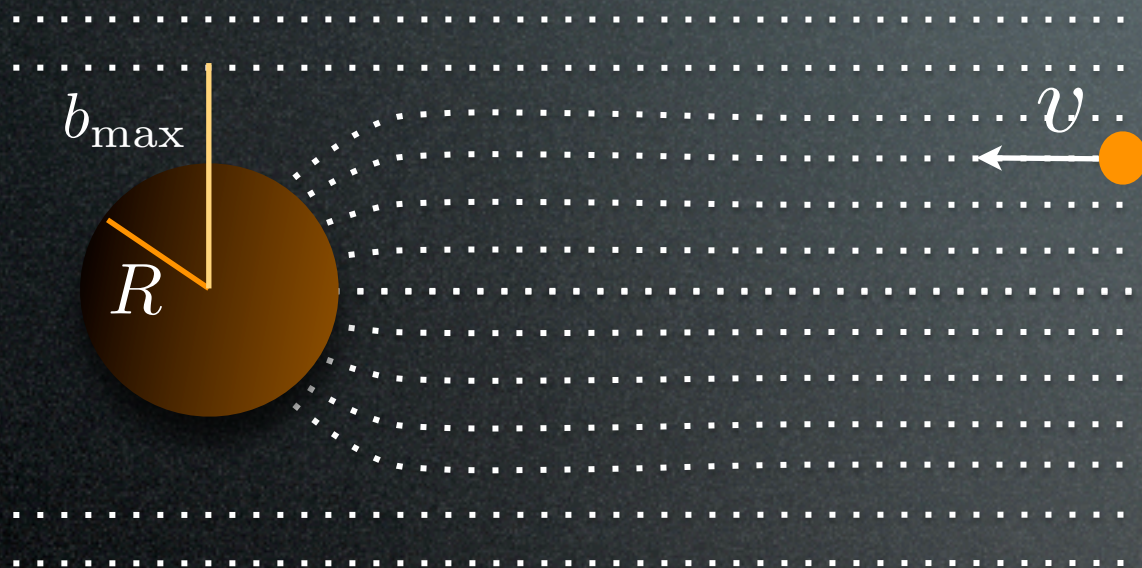
$$\sigma_0 = \pi R^2$$

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.

A classical analogy:

Arkani-Hamed et al. 0810.0713



$$\sigma_0 = \pi R^2$$

$$\sigma = \pi R^2 \left(1 + \frac{2G_N M/R}{v^2} \right)$$

$$\text{with } v_{\text{esc}}^2 = 2G_N M/R$$

For $v \gg v_{\text{esc}}$ then $\sigma \rightarrow \sigma_0$

For $v \ll v_{\text{esc}}$ then $\sigma \gg \sigma_0$

i.e. $E_{\text{kin}} < U_{\text{pot}}$ (i.e. the deforming potential is not negligible)

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Cirelli, Strumia, Tamburini 0706.4071

$\psi(\vec{r})$ wave function of two DM particles ($\vec{r} = \vec{r}_1 - \vec{r}_2$) obeys (reduced) Schrödinger equation:

$$-\frac{1}{M} \frac{d^2 \psi}{dr^2} + V \cdot \psi = M v^2 \psi$$

(V does not depend on time)

velocity

potential due to exchange of force carriers

At $r = 0$: annihilation

$$\sigma_{\text{ann}} \propto \psi \Gamma \psi \quad \text{with } \Gamma \text{ such that } \langle \text{DM DM} | \Gamma | \text{final} \rangle$$

Sommerfeld enhancement:

$$R = \frac{\sigma_{\text{ann}}}{\sigma_{\text{ann}}^0} = \left| \frac{\psi(\infty)}{\psi(0)} \right|^2$$

unperturbed cross section

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Yukawa potential:

Cirelli, Strumia, Tamburini 0706.4071

$$-\frac{1}{M} \frac{d^2 \psi}{dr^2} + V \cdot \psi = M \nu^2 \psi$$

$$\text{with } V = -\frac{\alpha}{r} e^{-m_V r}$$

$$\text{parameters are: } \alpha, \nu, m_V, M \quad \left(\alpha = \frac{g^2}{4\pi} \approx \frac{1}{137} \right)$$

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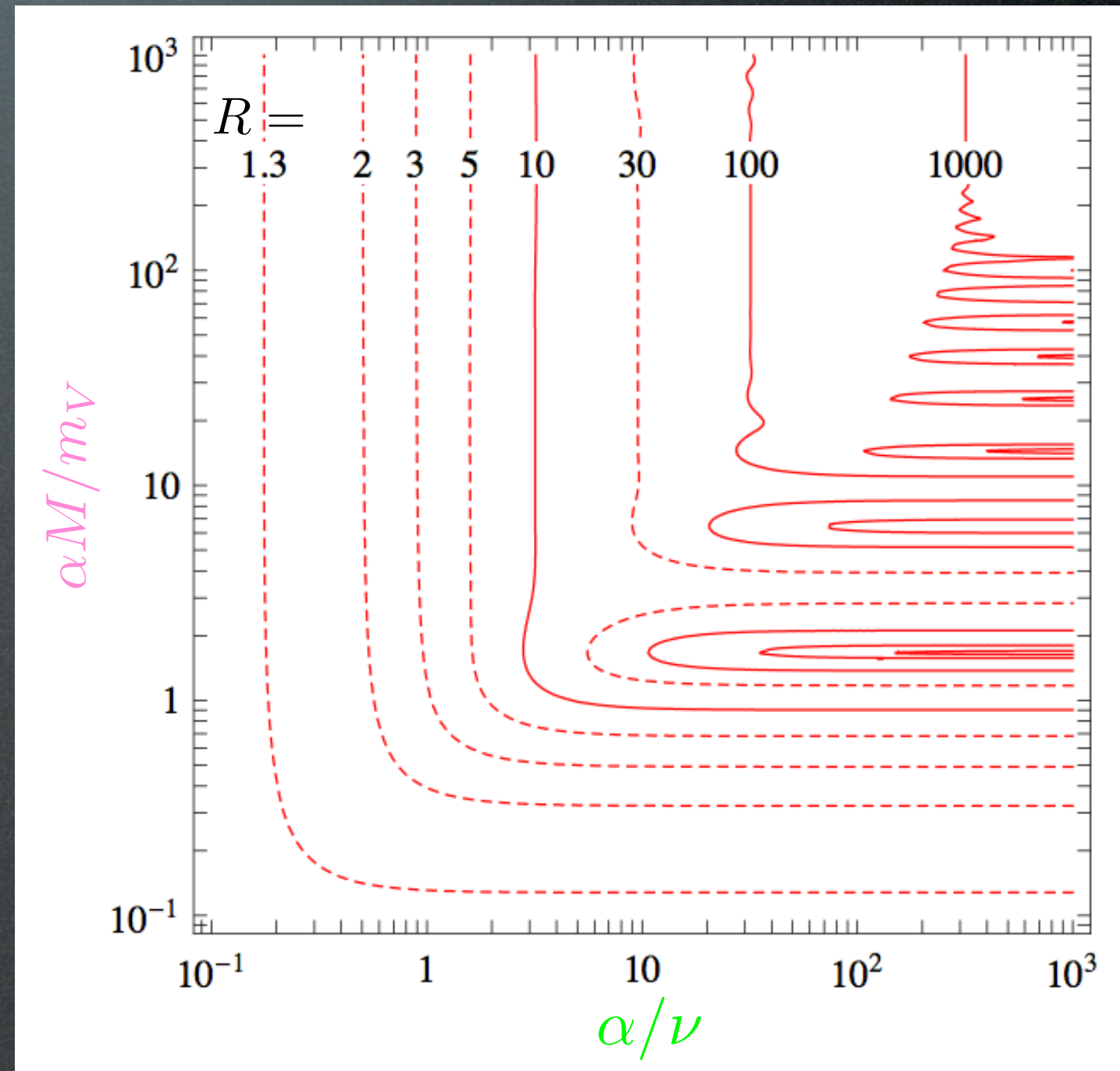
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Cirelli, Strumia, Tamburini 0706.4071



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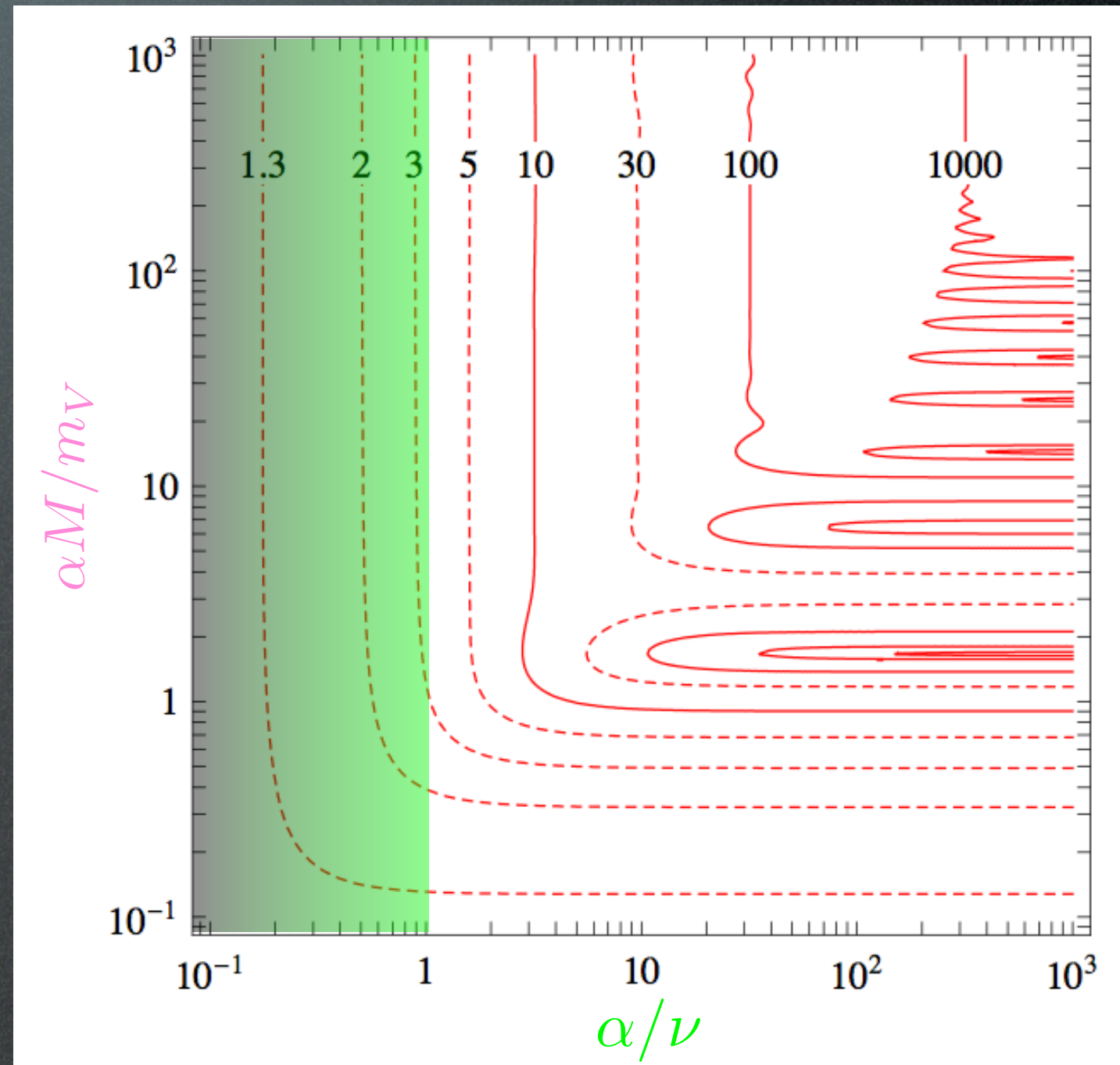
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The effect is relevant for:

$\alpha/\nu \gtrsim 1$ i.e. **small velocities**
i.e **today** but not at f.o.

Cirelli, Strumia, Tamburini 0706.4071



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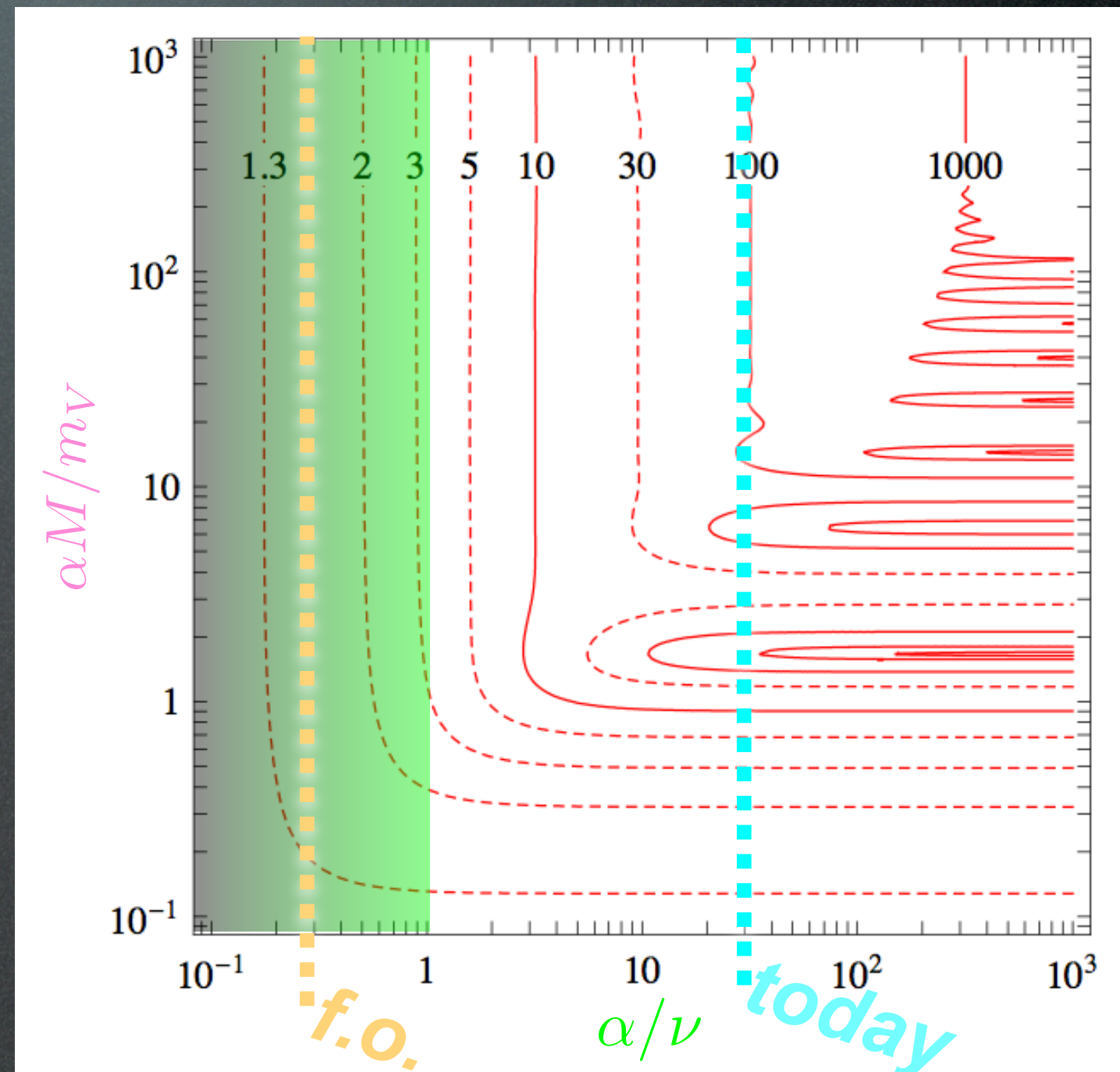
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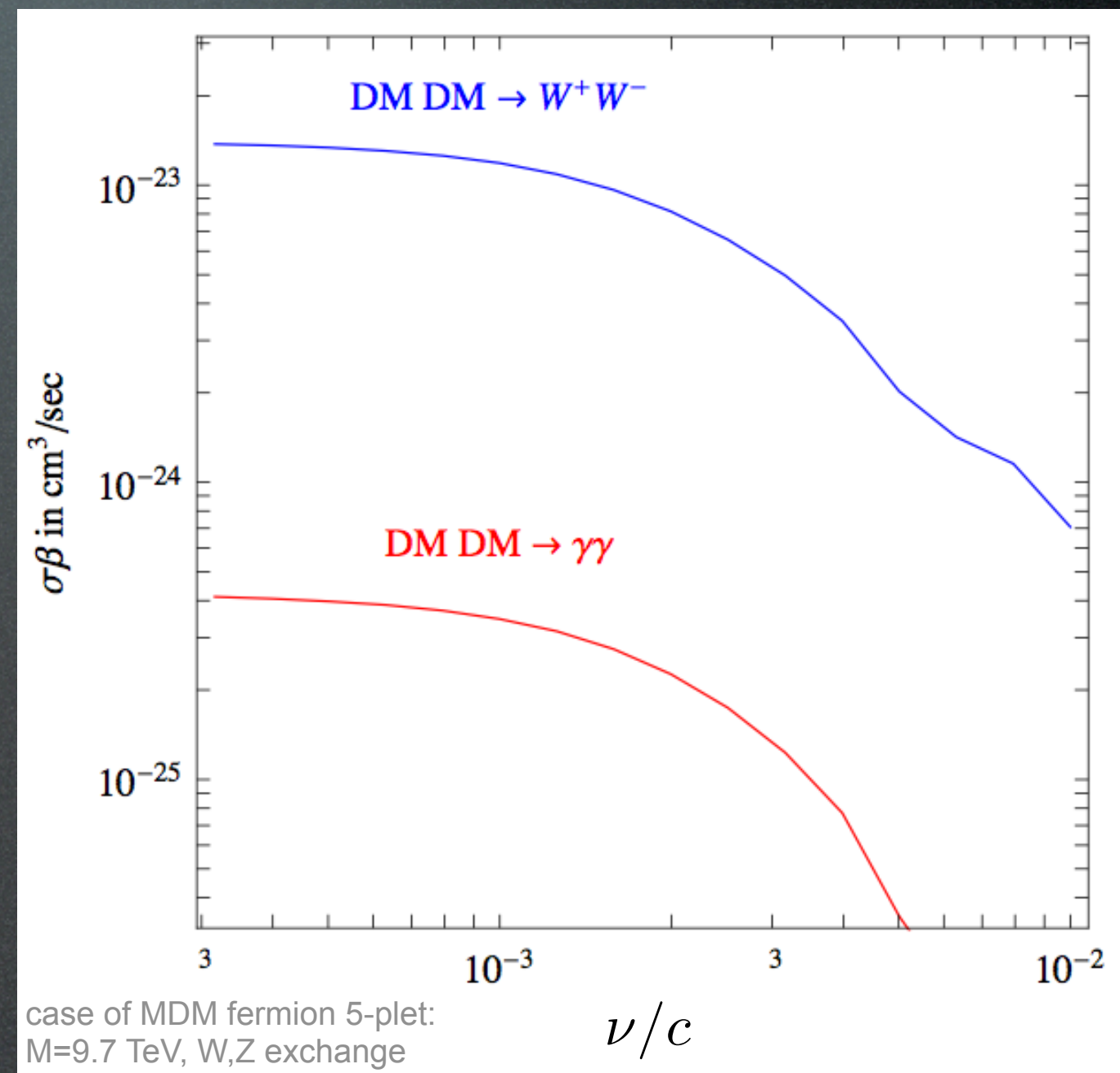
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Cirelli, Franceschini, Strumia 0802.3378



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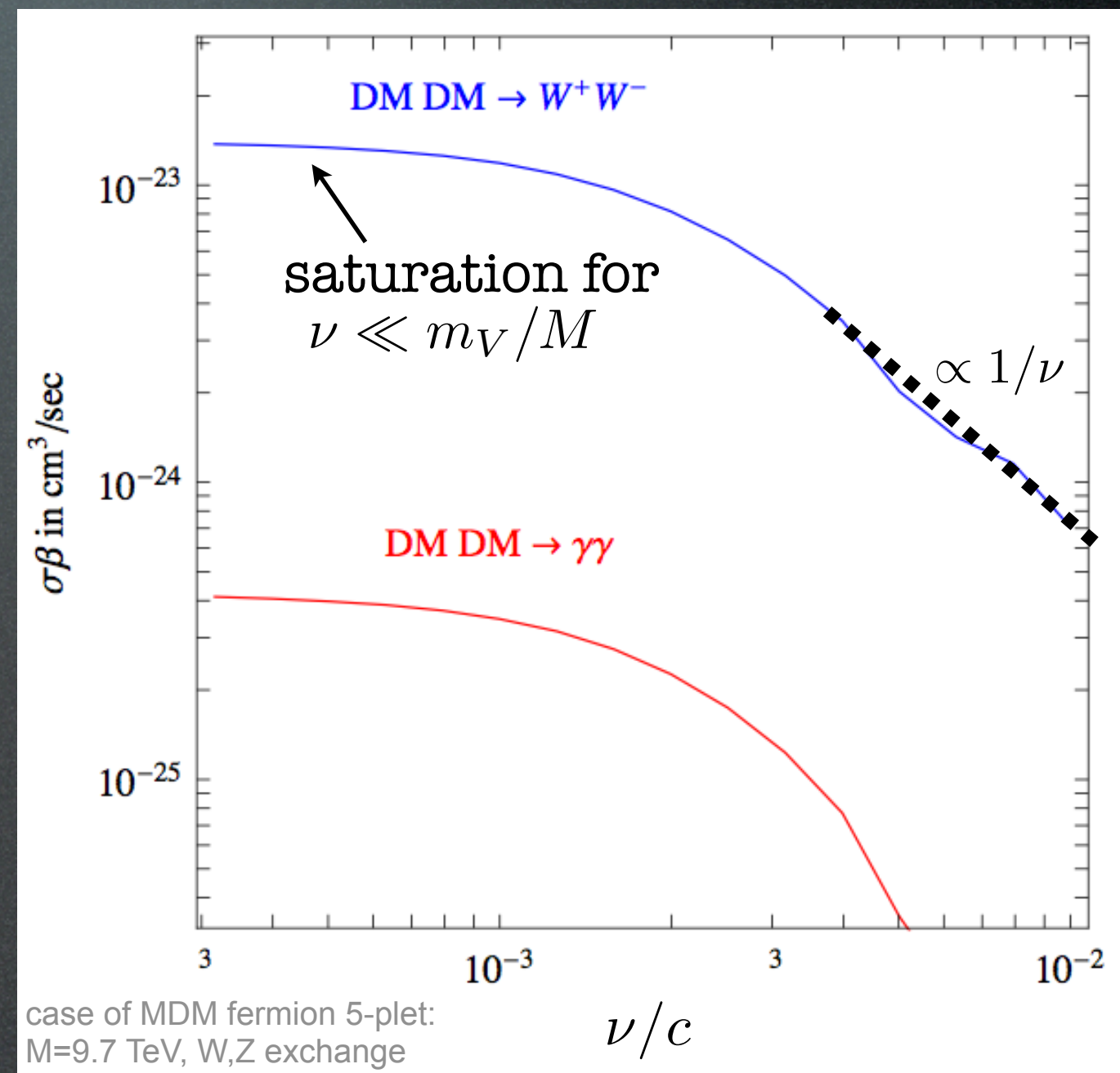
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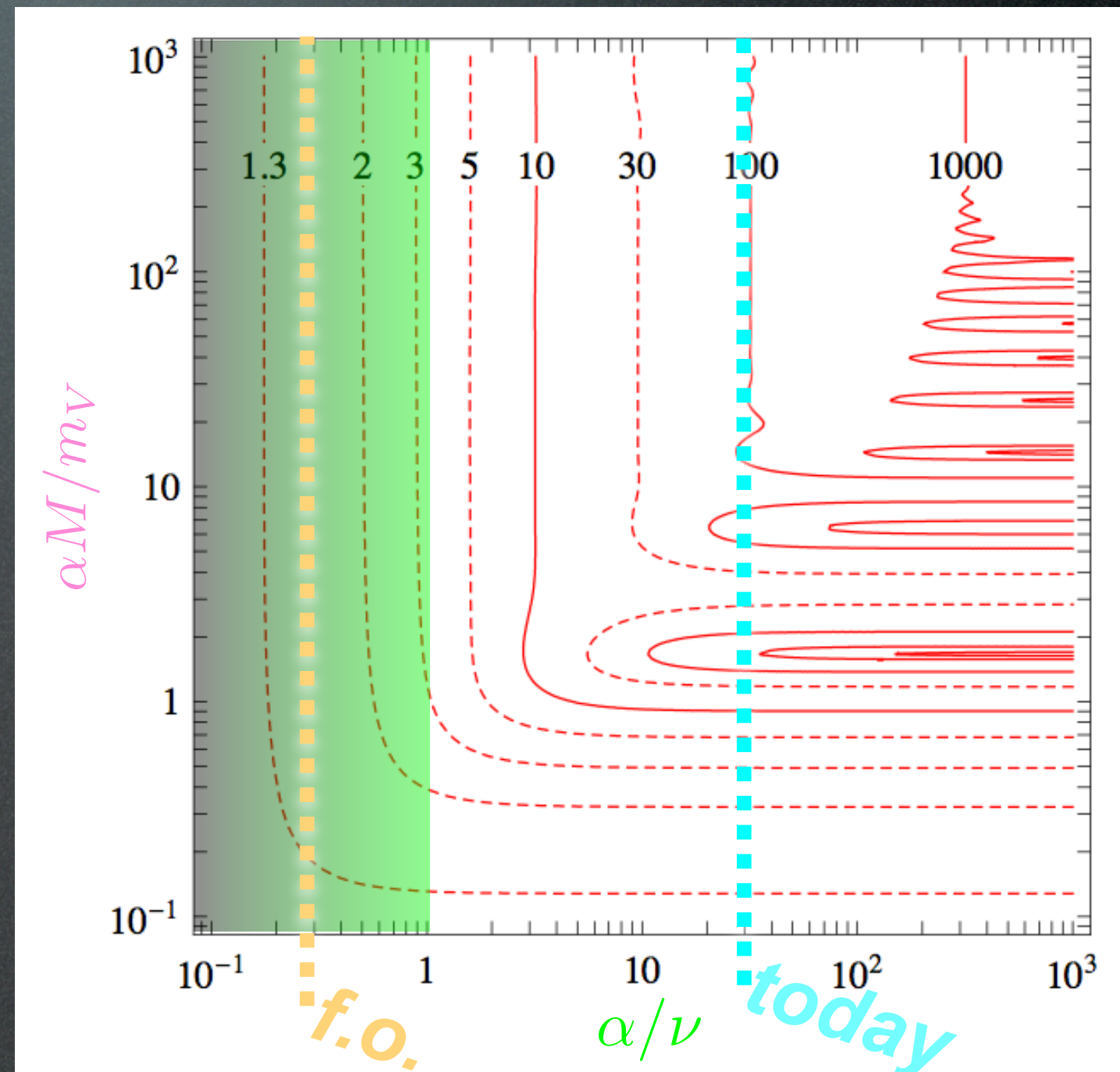
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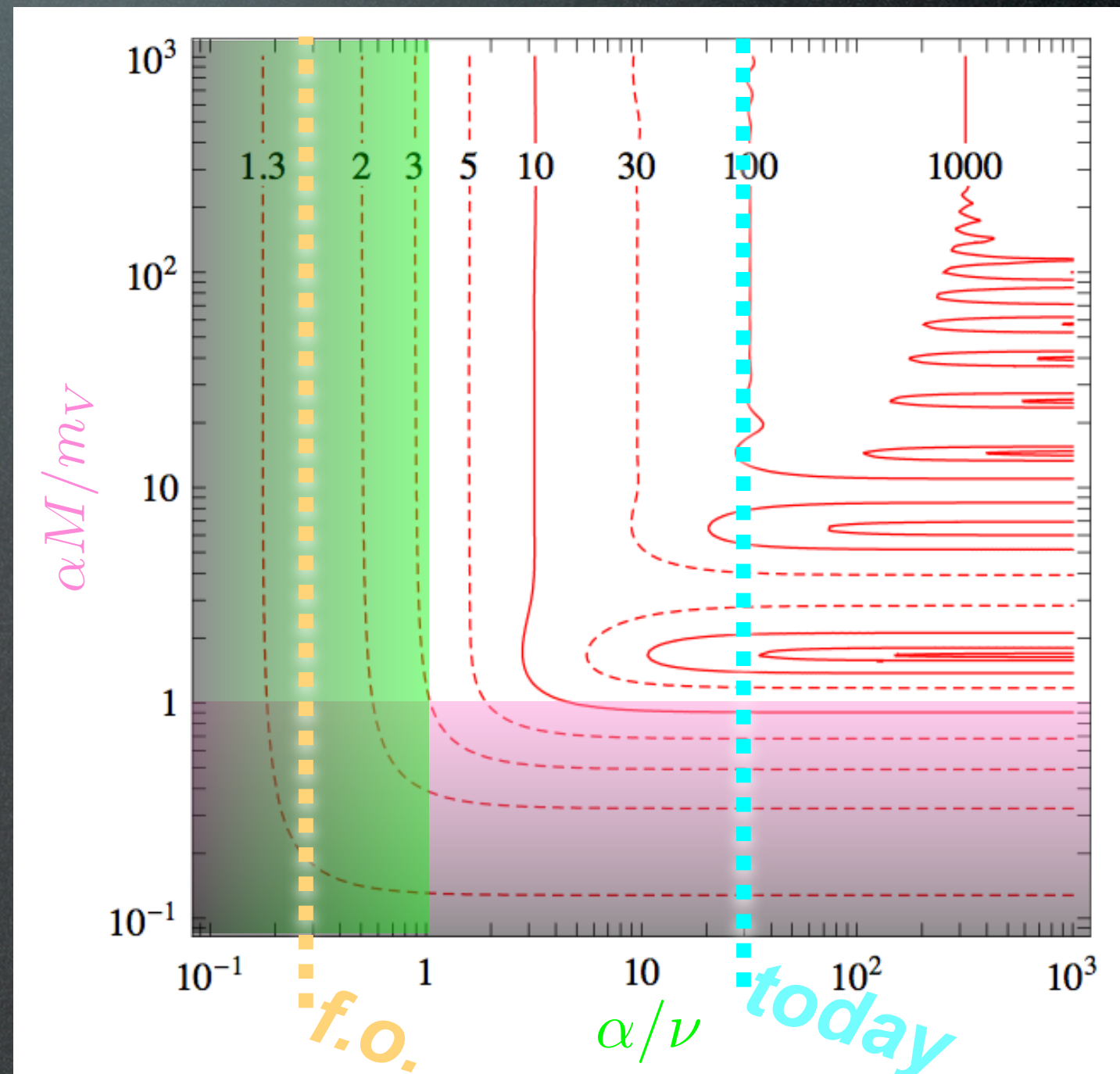
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$\alpha M/m_V \gtrsim 1$ i.e. **long range** forces

for SM weak: $m_V \rightarrow M_{W,Z}$
 $M \rightarrow \text{multi-TeV}$

for 1 TeV DM: need $m_V \rightarrow \text{GeV}$

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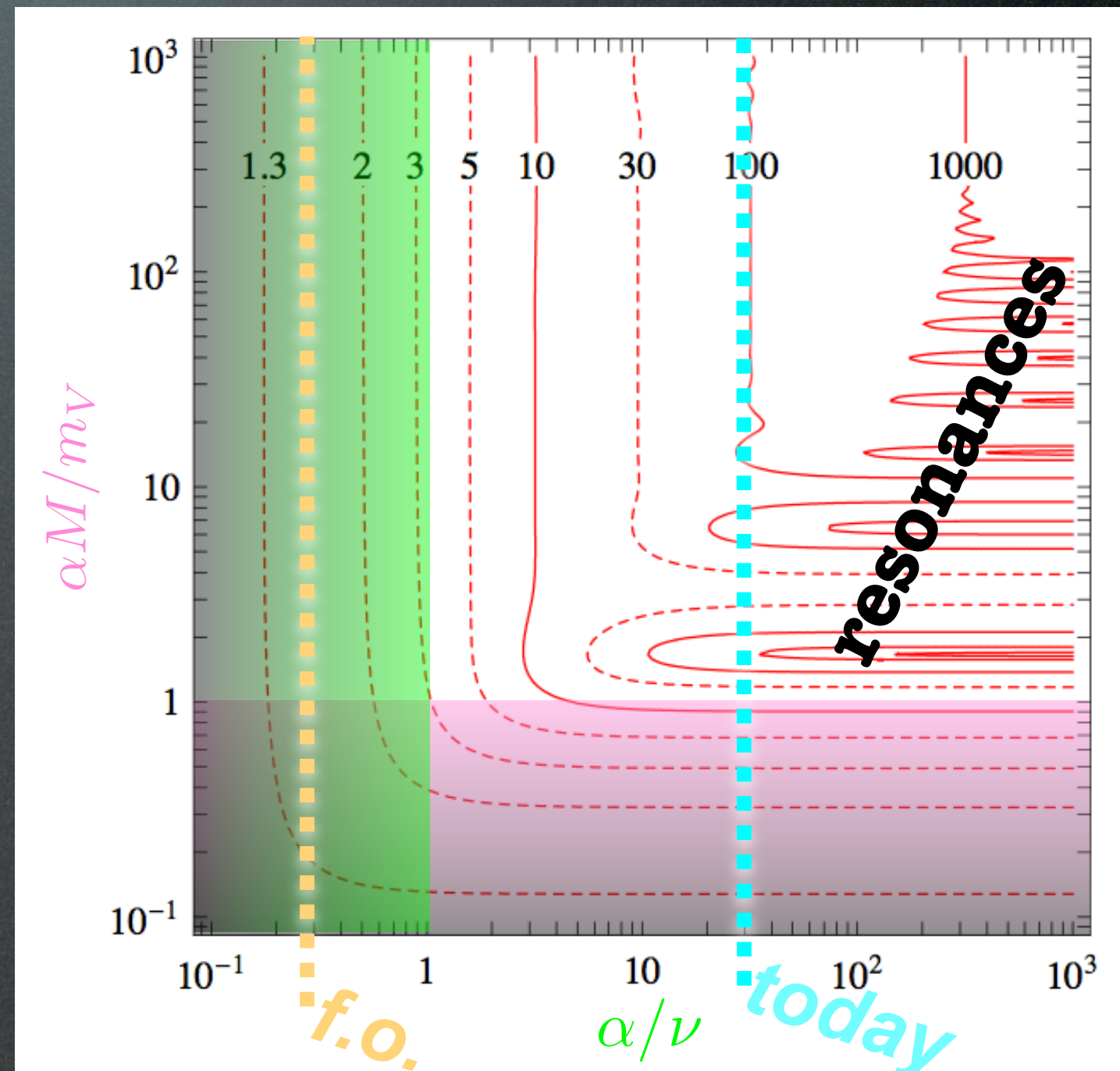
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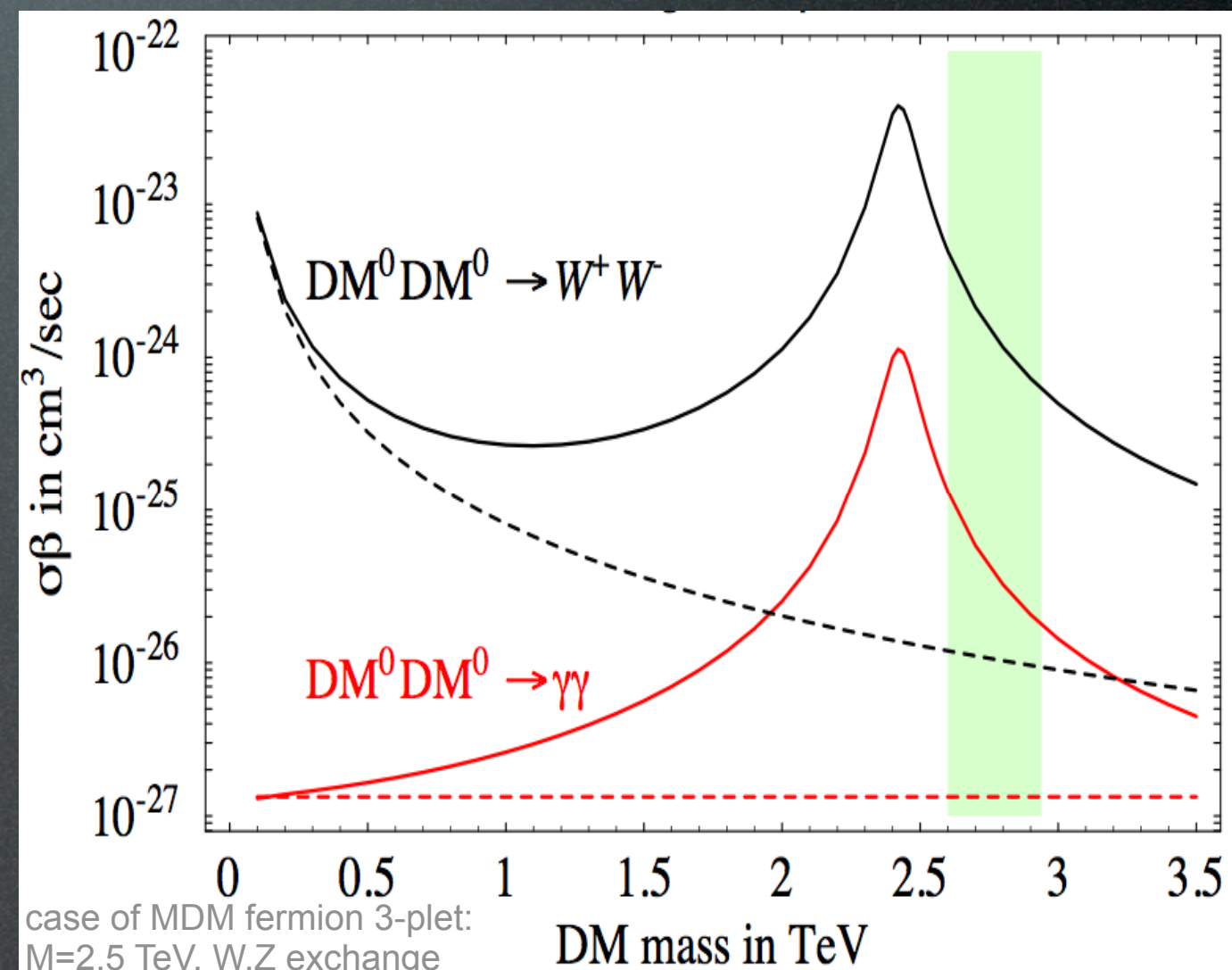
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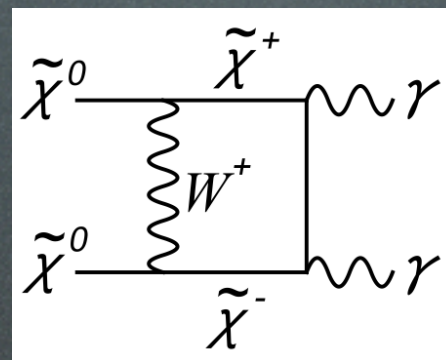
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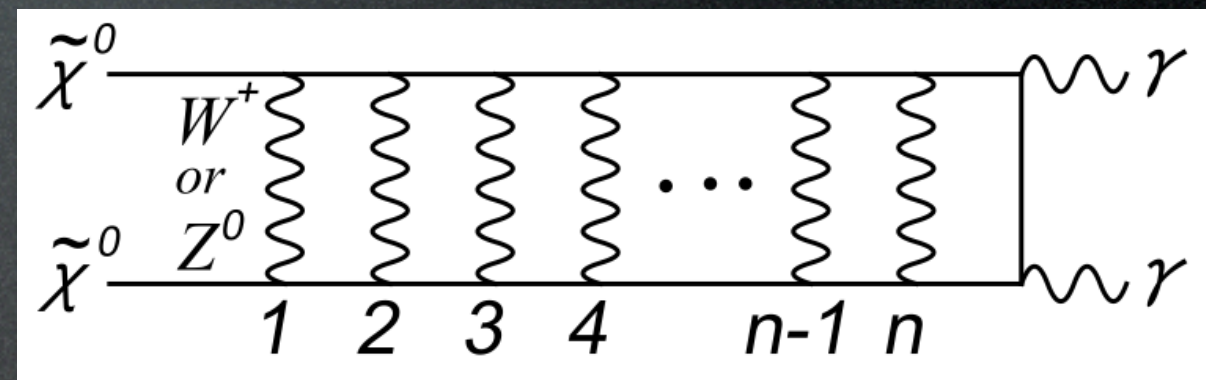
In terms of Feynman diagrams:

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.

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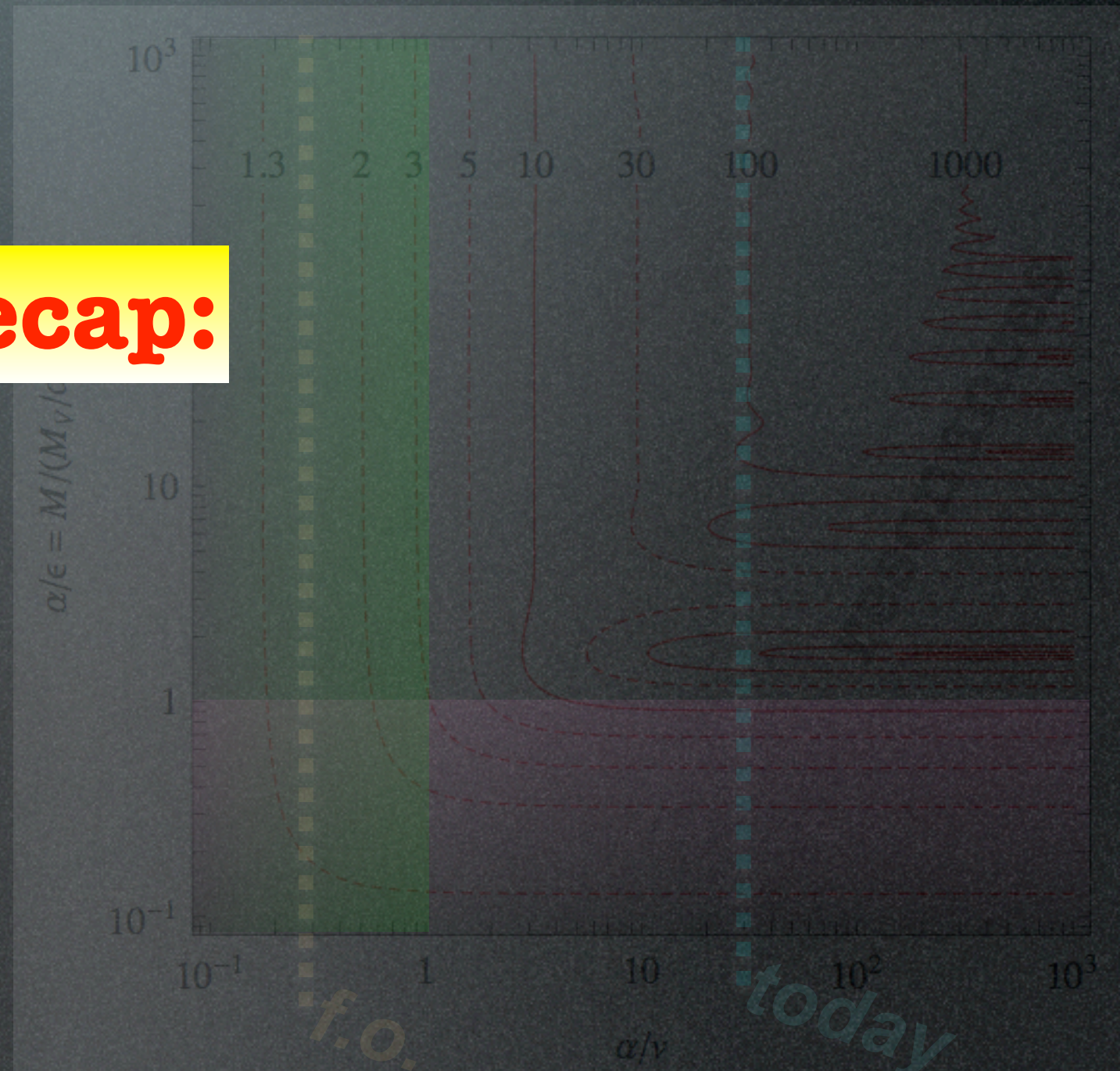
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Cirelli, Strumia, Tamburini 0706.4071

Recap:



Model building

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

Cirelli, Strumia et al. 2006-2009

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 $\tau_{\text{DM}} \gtrsim \tau_{\text{universe}} \simeq 4.3 \cdot 10^{17} \text{sec}$.

The current CR anomalies can be due to decay with:

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

Motivations from theory?

- dim 6 suppressed operator in GUT

Arvanitaki, Dimopoulos et al., 2008+09

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

- or in TechniColor

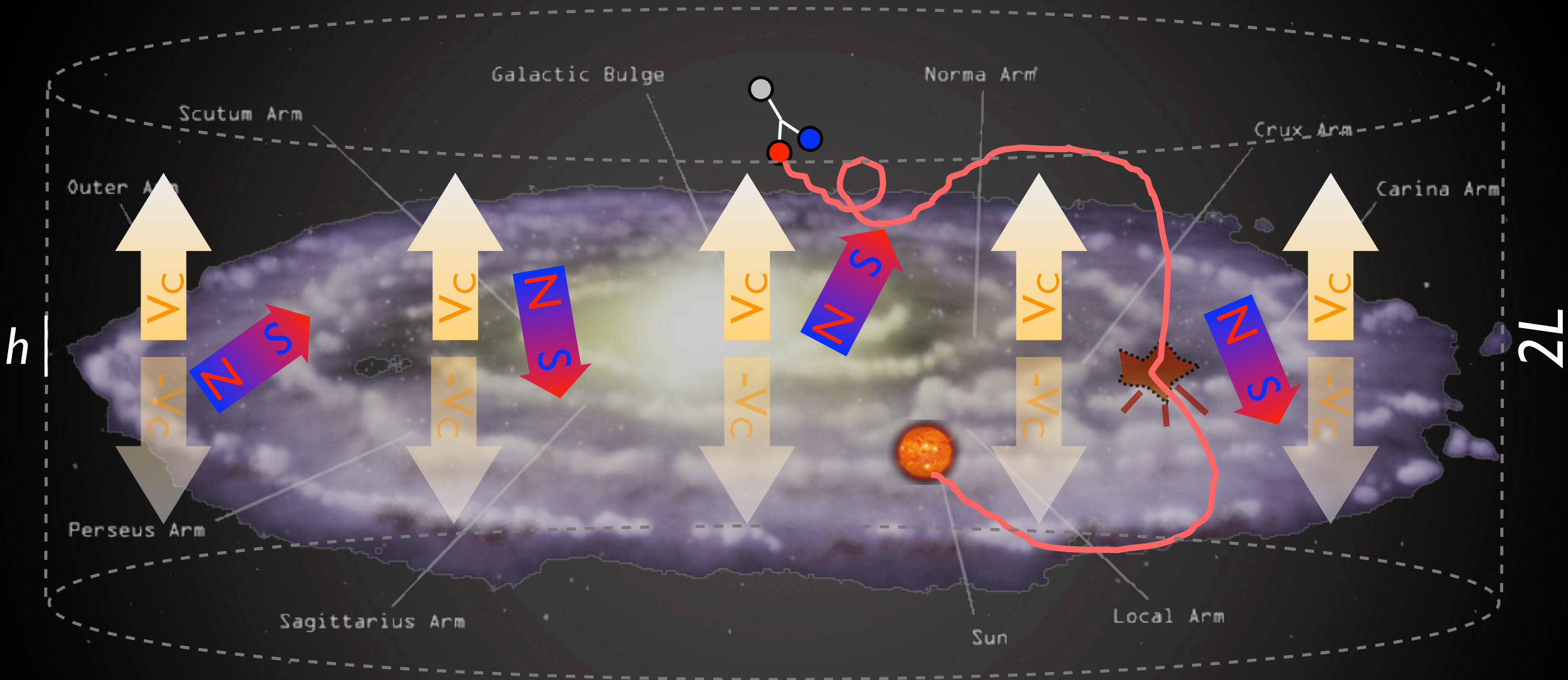
Nardi, Sannino, Strumia 2008

- gravitino in SuSy with broken R-parity...

e.g. Covi, Buchmüller, Ibarra etc etc

Indirect Detection

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



What sets the overall expected flux?

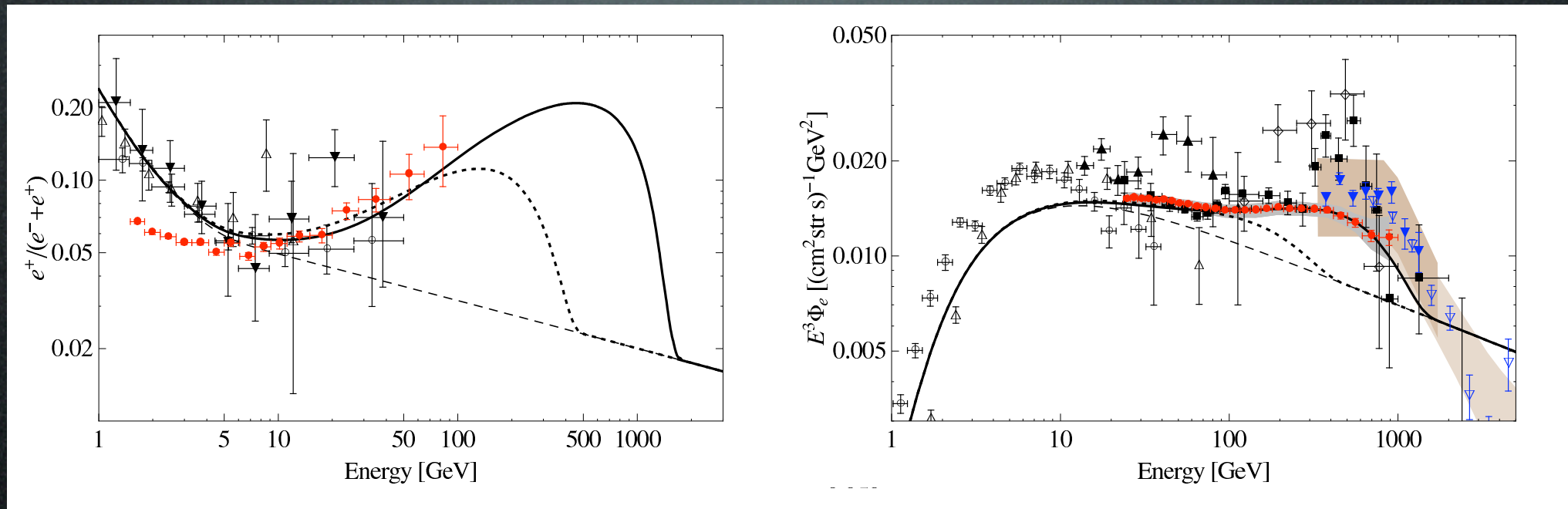
$$\text{flux} \propto n \Gamma_{\text{decay}}$$

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

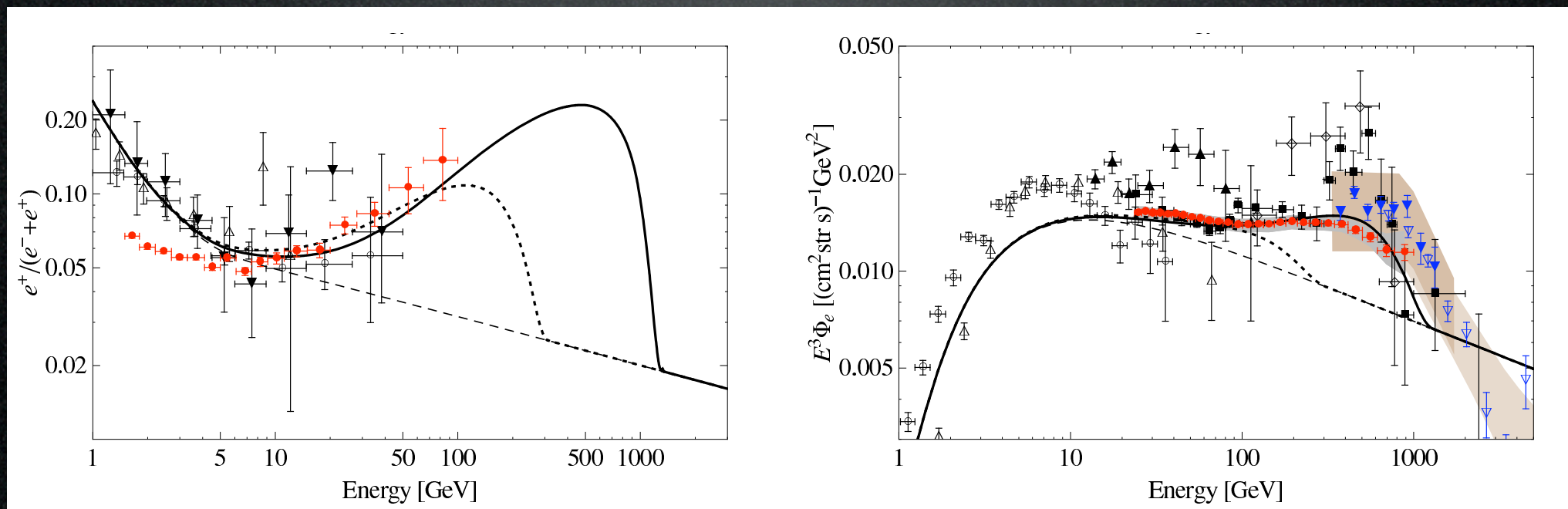
Decaying DM

Which DM spectra can fit the data?

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



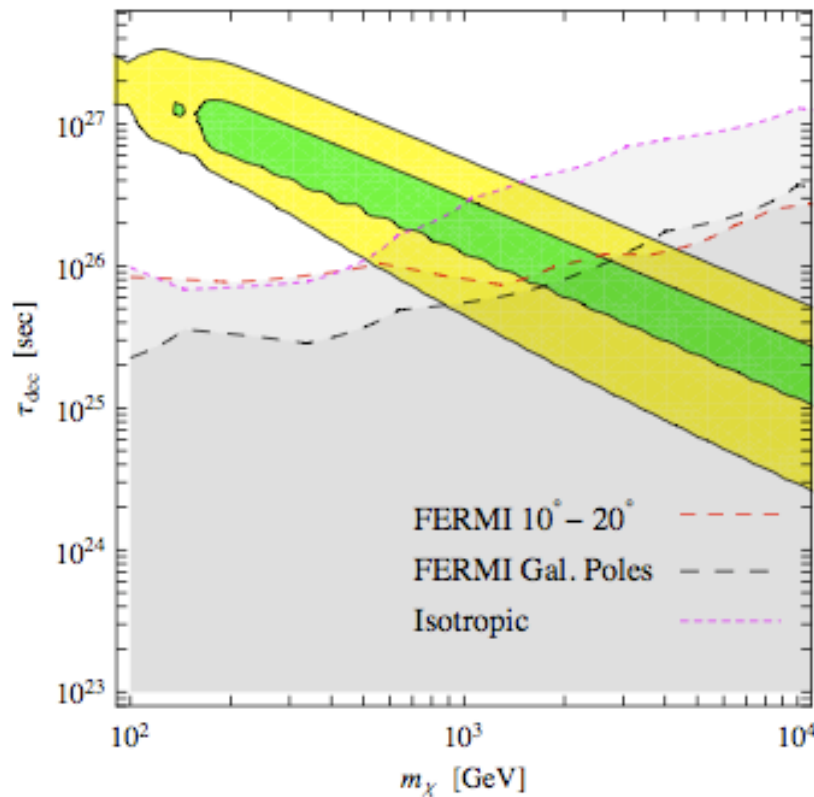
E.g. a scalar $\text{DM} \rightarrow \mu^+ \mu^-$ with $M_{\text{DM}} = 2.5 \text{ TeV}$:



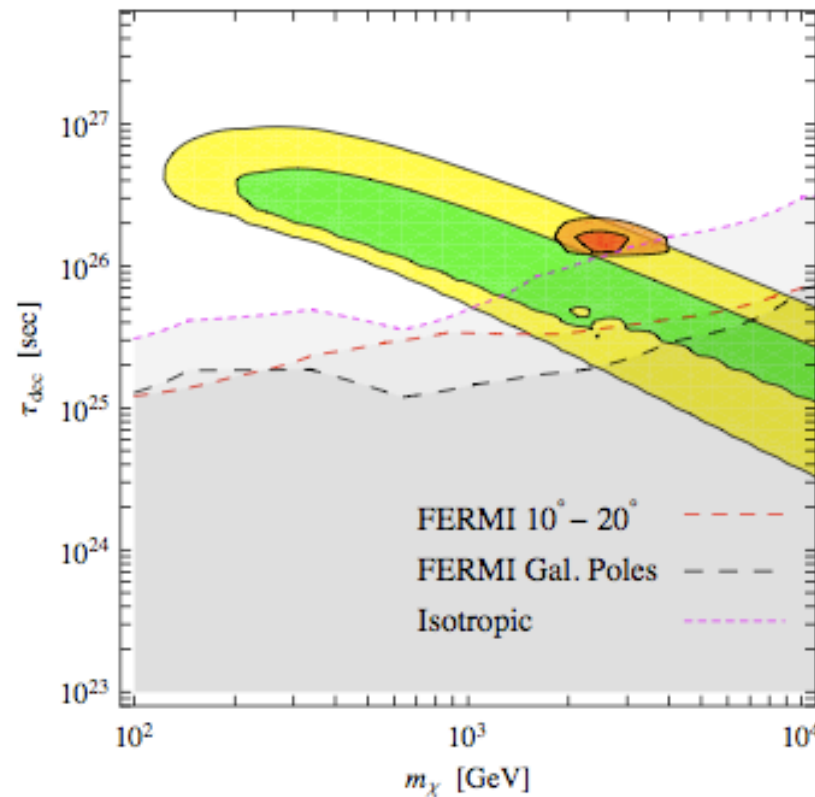
Decaying DM

Beware of gamma ray constraints
(but no radio, neutrino constraints)

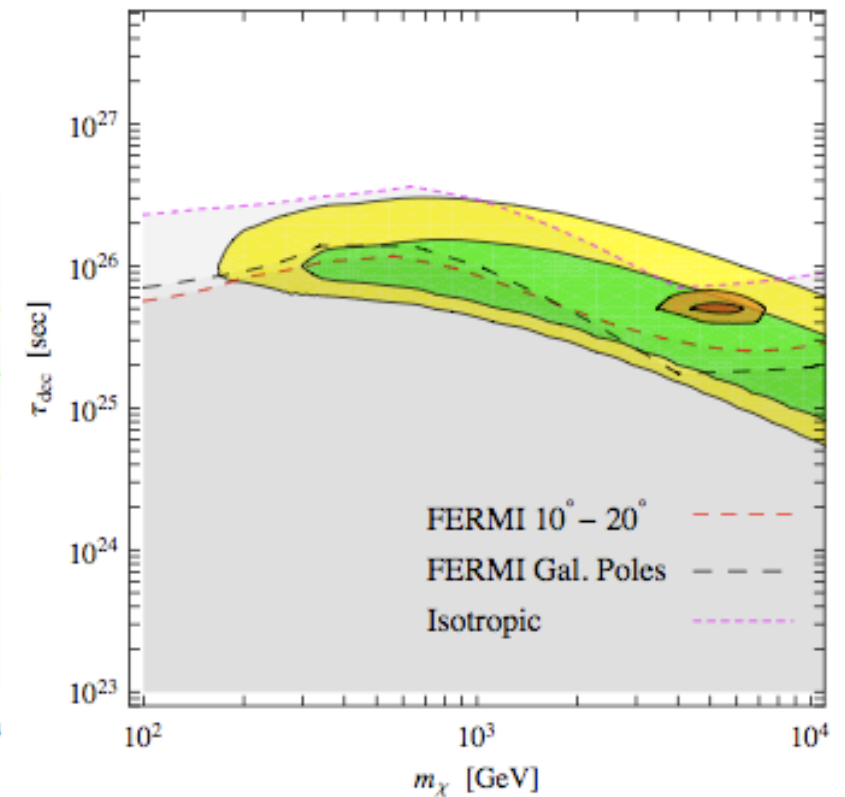
DM $\rightarrow ee$, Einasto profile



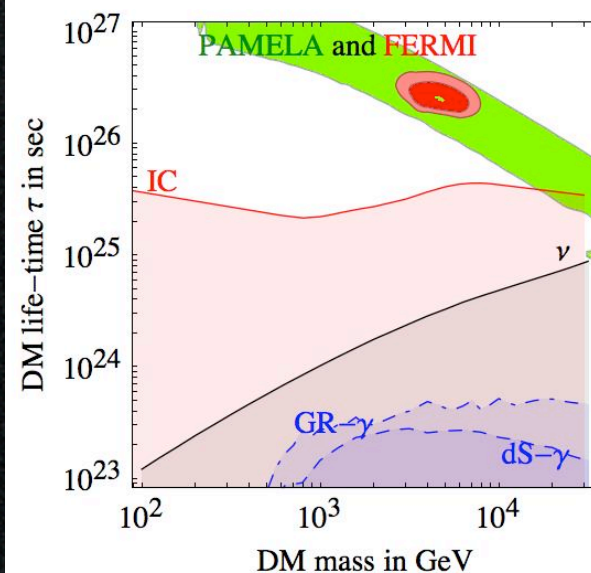
DM $\rightarrow \mu\mu$, Einasto profile



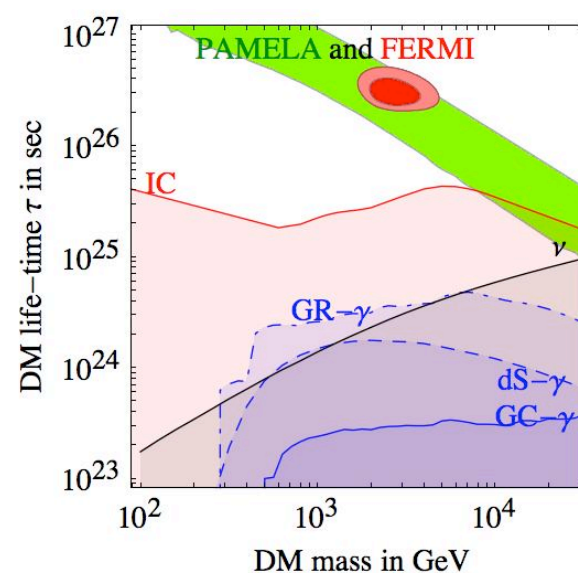
DM $\rightarrow \tau\tau$, Einasto profile



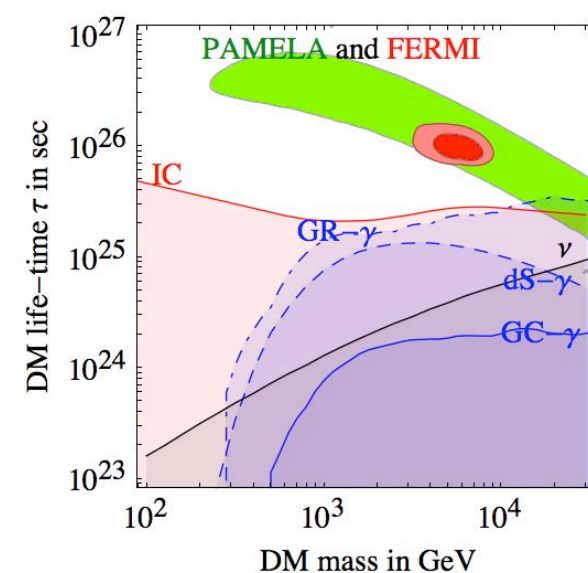
DM $\rightarrow 4\mu$, isothermal profile



DM $\rightarrow \mu^+\mu^-$, isothermal profile



DM $\rightarrow \tau^+\tau^-$, isothermal profile



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Cirelli, Strumia et al. 2005-2009

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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”

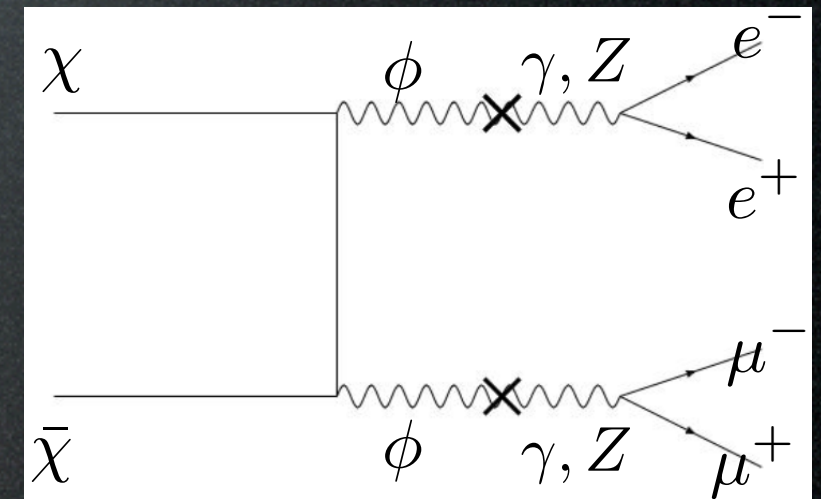
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

- χ Dark Matter particle, decoupled from SM, mass $M \sim 700+ \text{ GeV}$
- ϕ new gauge boson (“Dark photon”),
couples only to DM, with typical gauge strength, $m_\phi \sim \text{few GeV}$
 - mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:

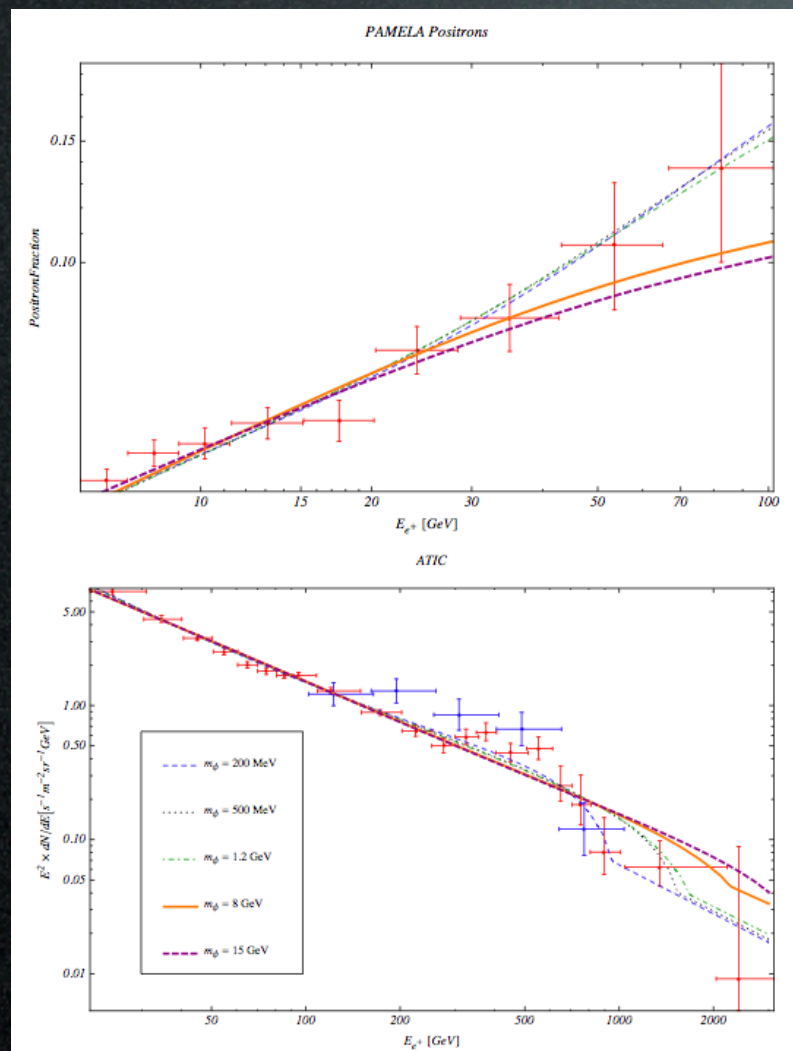
$$\alpha M/m_V \gtrsim 1 \quad \text{fulfilled}$$

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

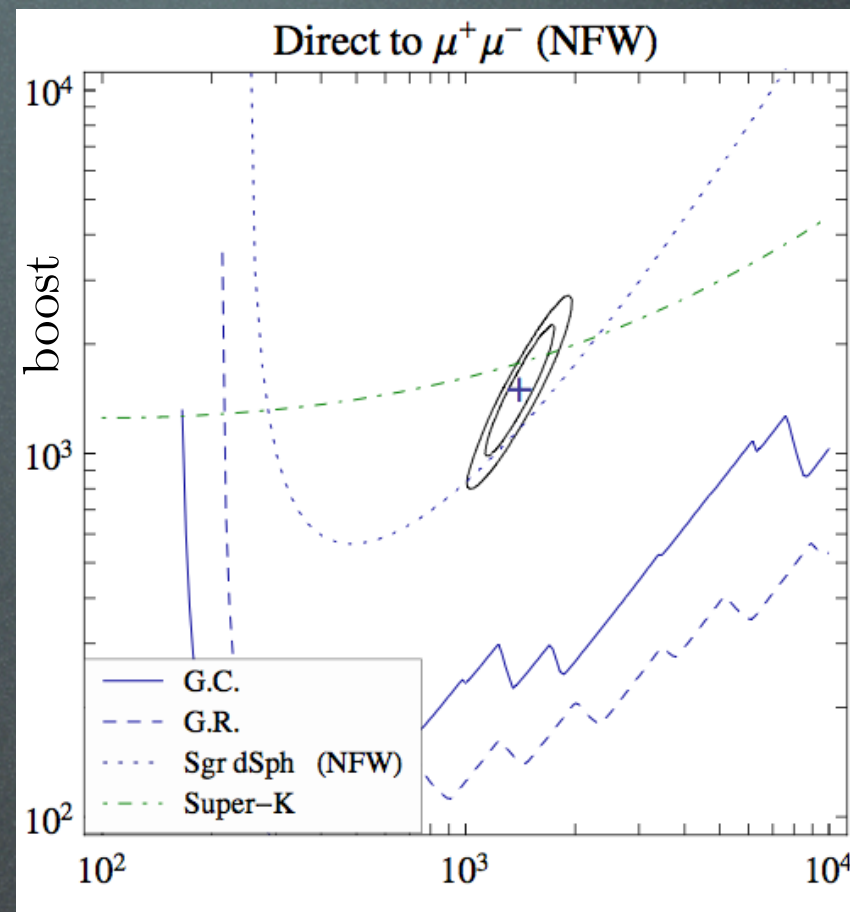


The “Theory of DM”

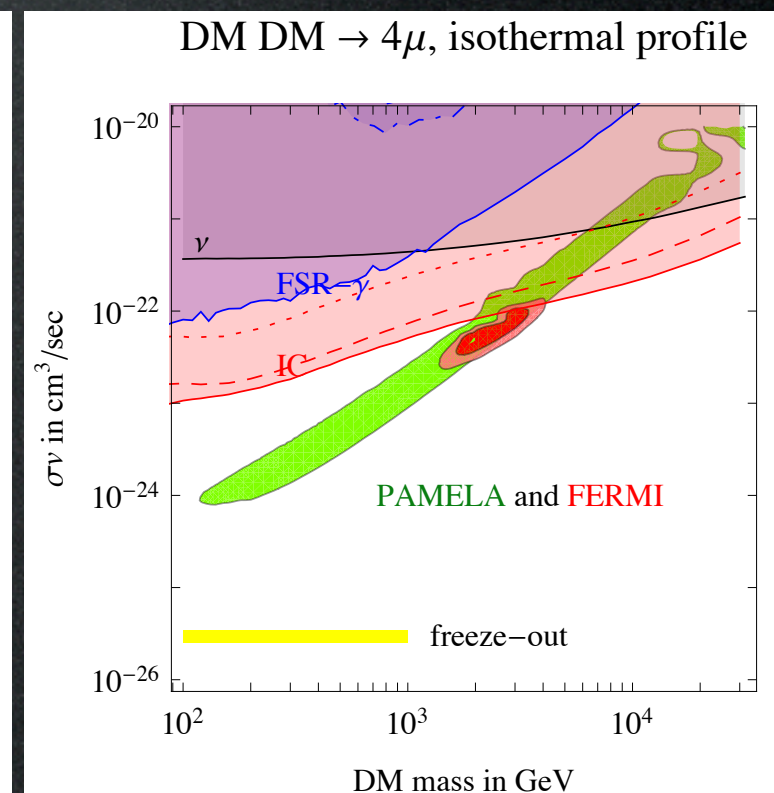
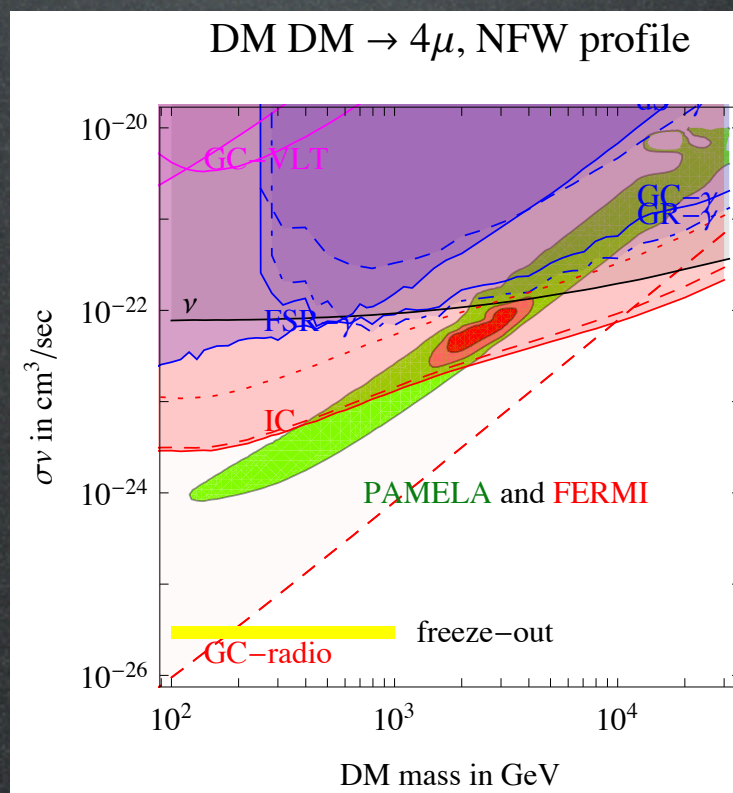
Phenomenology:



Meade, Papucci, Volanski 0901.2925



Mardon, Nomura, Stolarski, Thaler 0901.2926



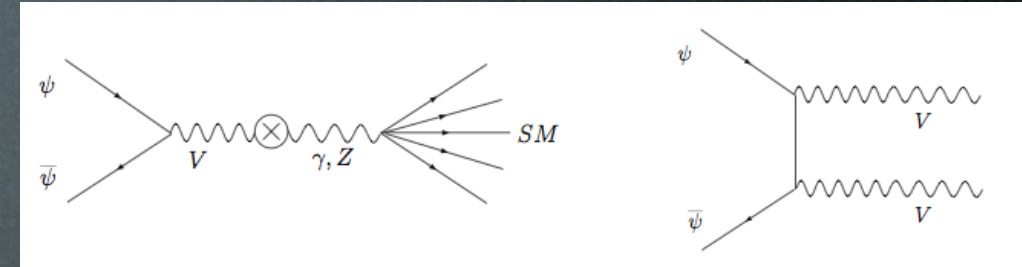
Strumia, Papucci 0912.0742

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

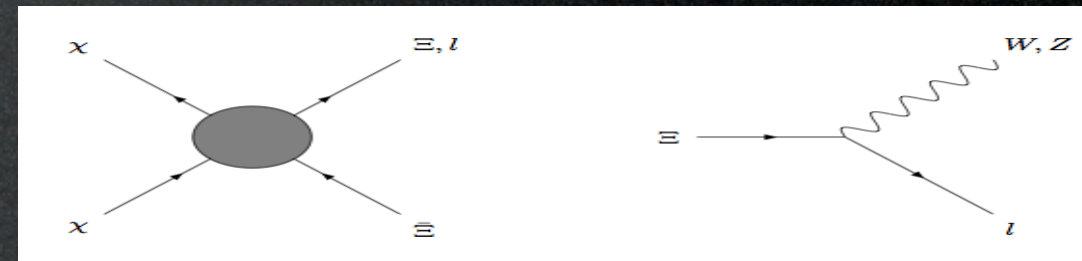
- ★ DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson ($m_\phi \sim$ tens GeV)

Cirelli, Kadastik, Raidal, Strumia 0809.2409

Fox, Poppitz 0811.0399

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

Phalen, Pierce, Weiner 0901.3165



- ★

[jump to conclusions]

Advertisement

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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but you don't want to mess around with astrophysics?

‘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.
The notebook [Sample.nb](#) shows how to load and use it.

Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation

Positrons: The file [ElectronHaloFunctEarthAnn.m](#) provides the halo functions $I(x, E_s, r_{\text{Earth}})$ 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 $R(T)$.

Antideuteron: [Table](#) of fit coefficients for the propagation function $R(T)$.

Decay

Positrons: The file [ElectronHaloFunctEarthDec.m](#) provides the halo functions $I(x, E_s, r_{\text{Earth}})$ at the location of the Earth.
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Antideuteron: [Table](#) of fit coefficients for the propagation function $R(T)$.

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

Annihilation

Positrons: Mathematica function: the file [ElectronFluxAnn.m](#) provides the

Decay

Positrons: Mathematica function: the file [ElectronFluxDec.m](#) provides the

Advertisement

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?

Main added value features:



compare different MCs



include EW corrections

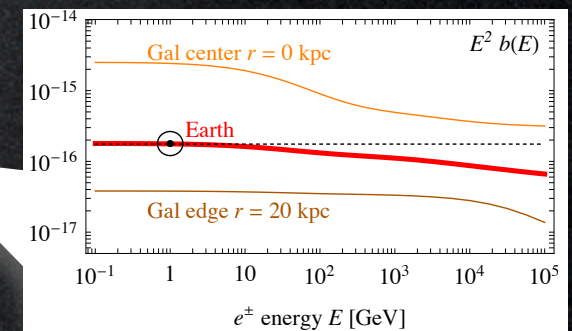
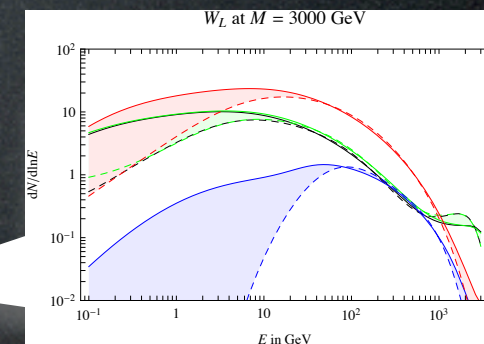
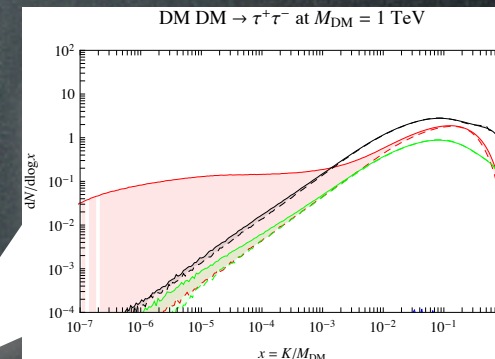
Ciafaloni, Riotto et al., 1009.0224



improved $e^\pm$ propagation



improved ICS γ -ray computation



Conclusions & Outlook

Hints

Constraints

Hopes

Conclusions & Outlook

Hints

$e^{\pm}$

PAMELA

FERMI

HESS

Constraints

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Conclusions & Outlook

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$e^{\pm}$

PAMELA
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Constraints

γ

FERMI, HESS,
VERITAS etc

$\nu, \bar{\nu}$

SK,
ICECUBE

Cosmology

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Hopes

$\bar{d}$ GAPS, AMS-02

γ $\nu, \bar{\nu}$

$\bar{p}$

AMS-02

- ‘enhancements’

- new theory
directions

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Old wise remarks:

Conclusions & Outlook

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Old wise remarks:

- any convincing result must be **multimessenger**

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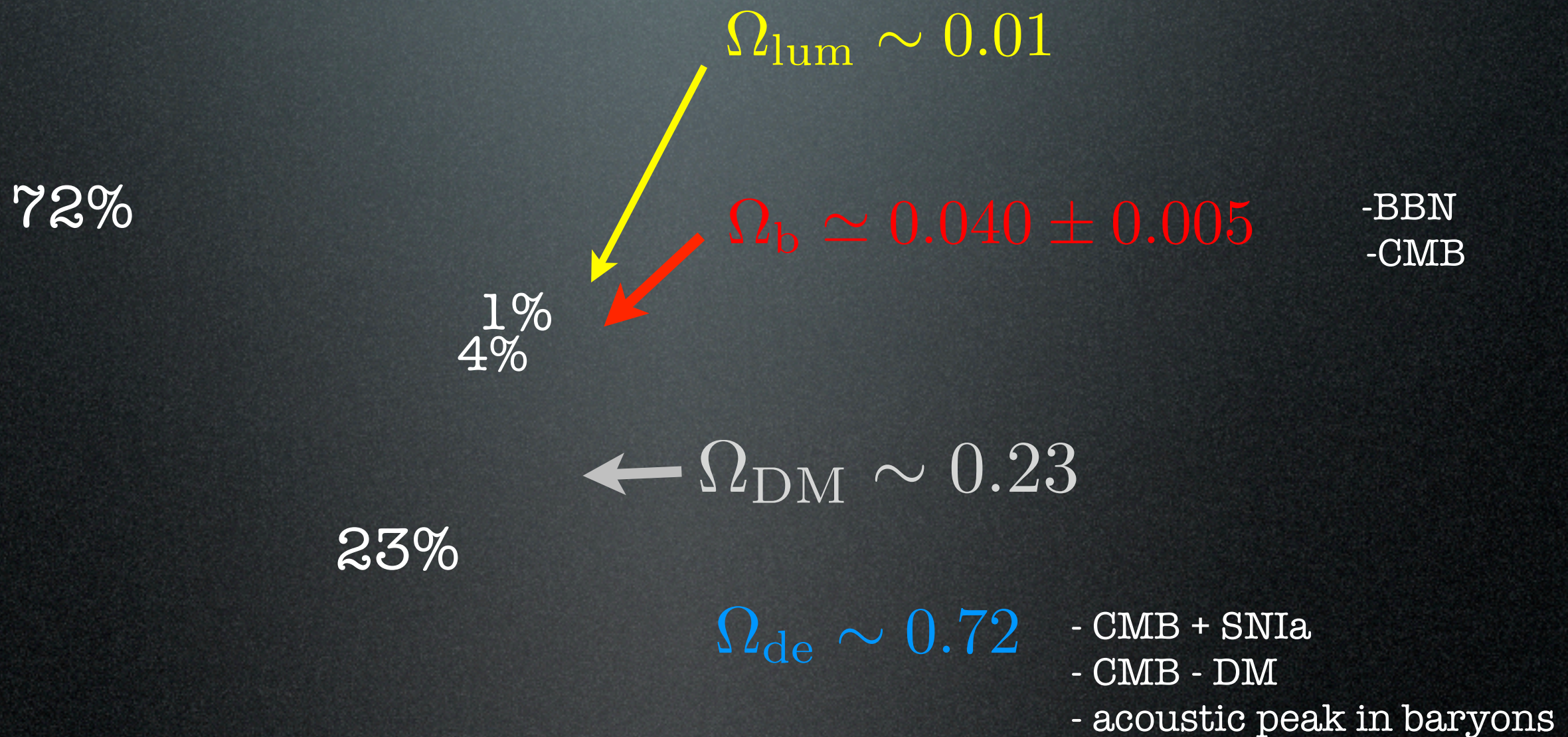
Old wise remarks:

- any convincing result must be **multimessenger**
- beware of **uncertainties**, beware of **astrophysics**

Back up slides

The cosmic inventory

Most of the Universe is Dark



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

what's the difference
between DM and DE?

The Evidence for DM

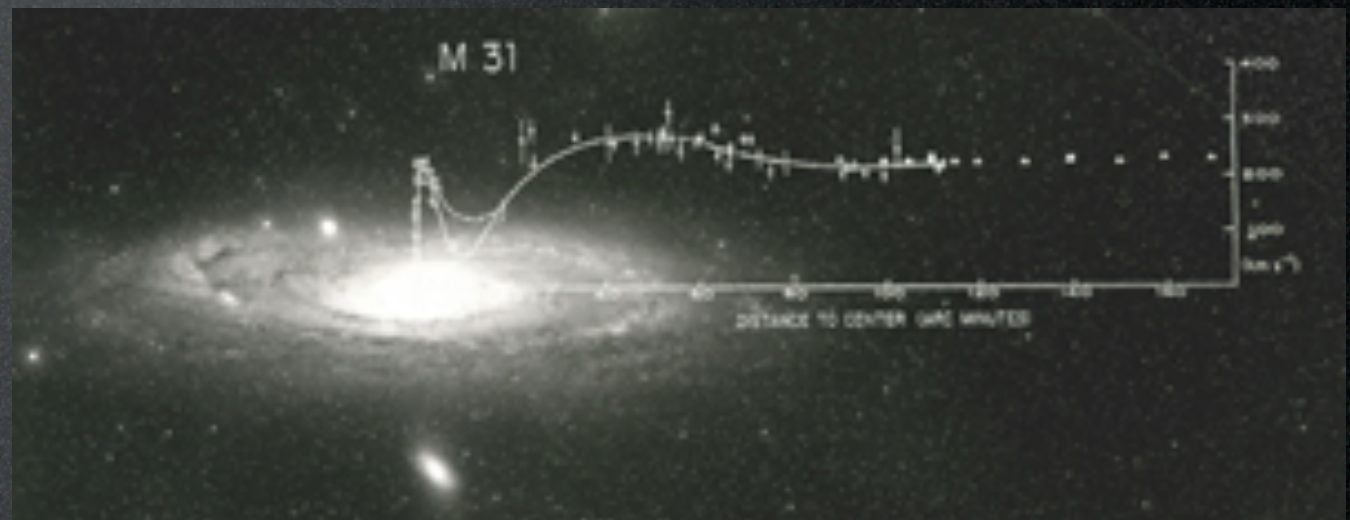
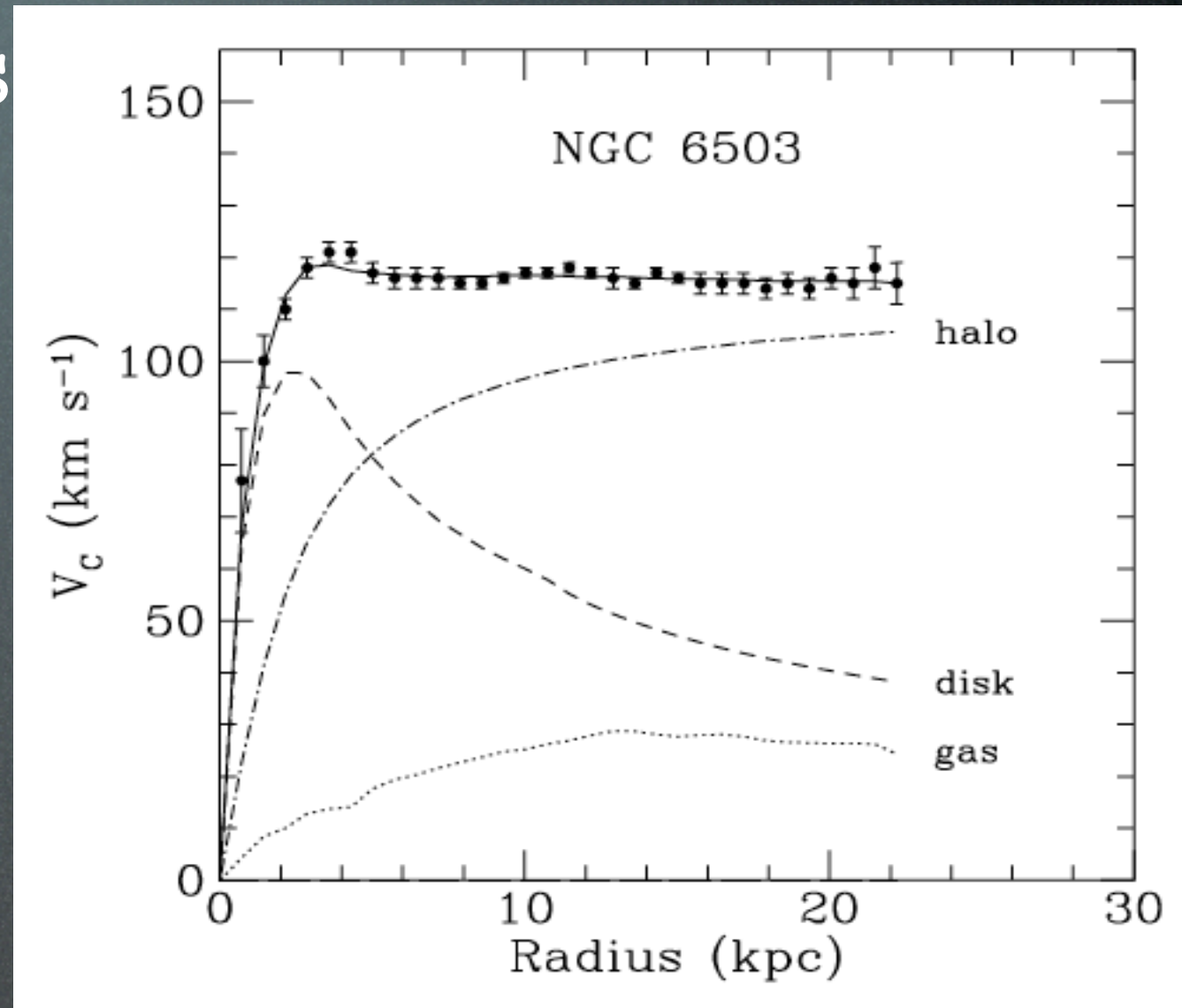
1) galaxy rotation curves

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

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



$$\Omega_M \gtrsim 0.1$$



The Evidence for DM

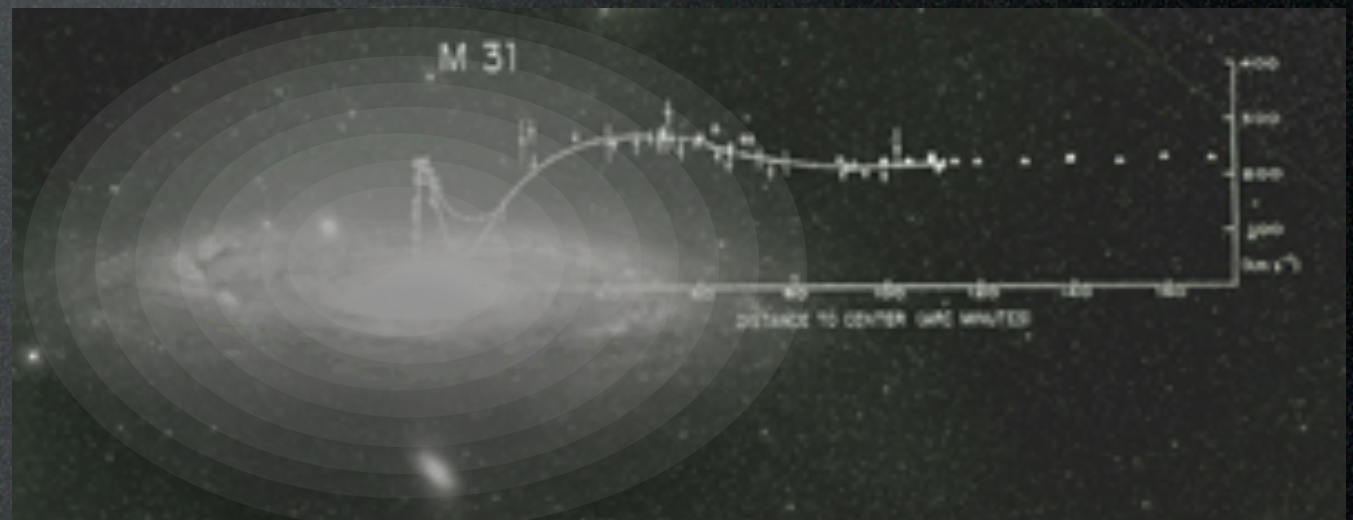
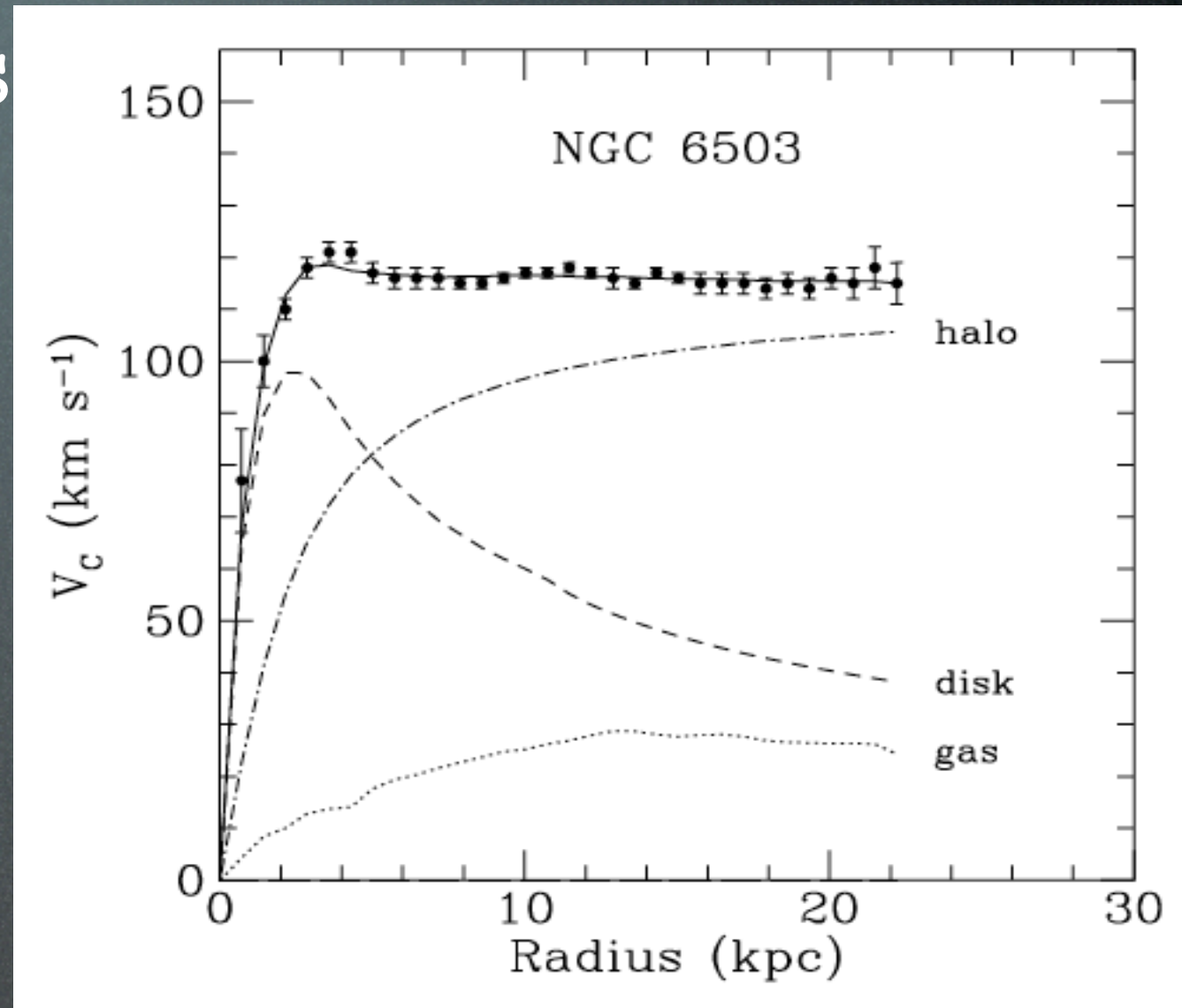
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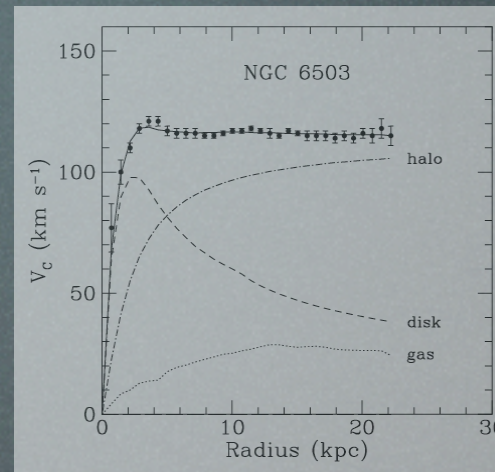


$$\Omega_M \gtrsim 0.1$$



The Evidence for DM

1) galaxy rotation curves



$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

- “rotation curves”
- gravitation lensing



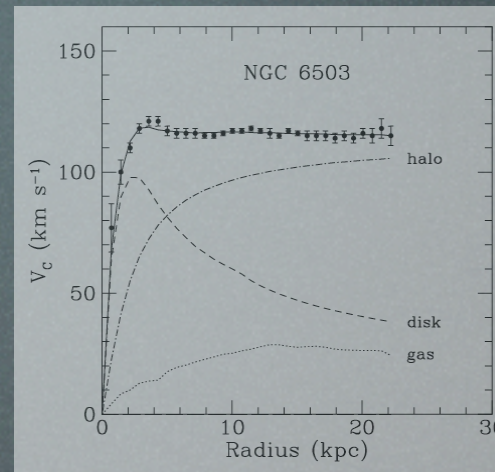
$$\Omega_M \sim 0.2 \div 0.4$$



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

The Evidence for DM

1) galaxy rotation curves



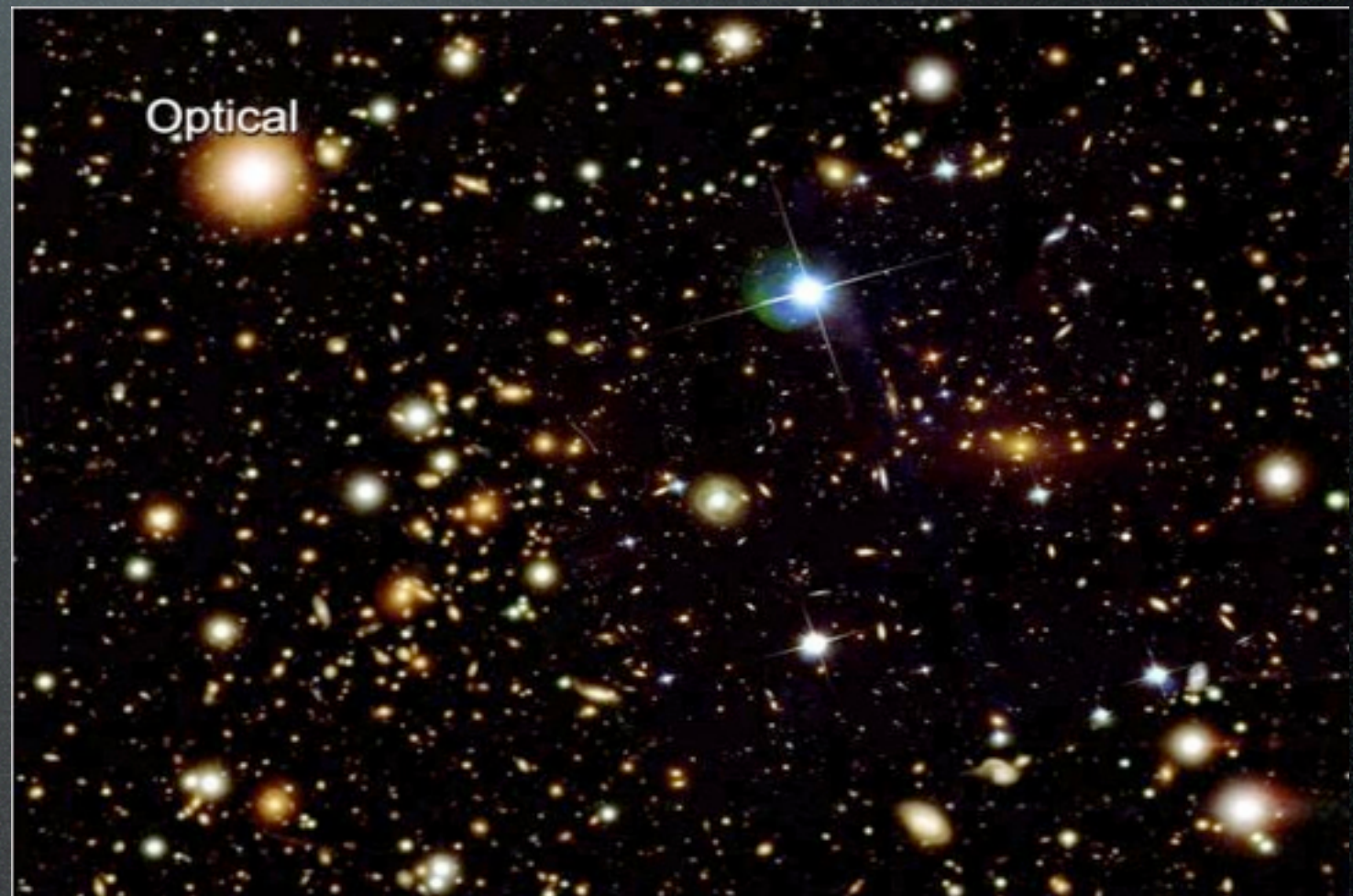
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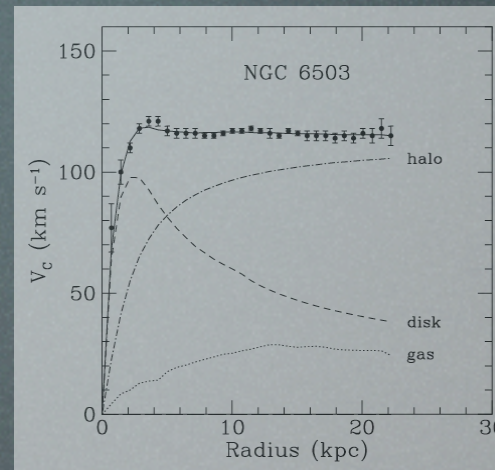
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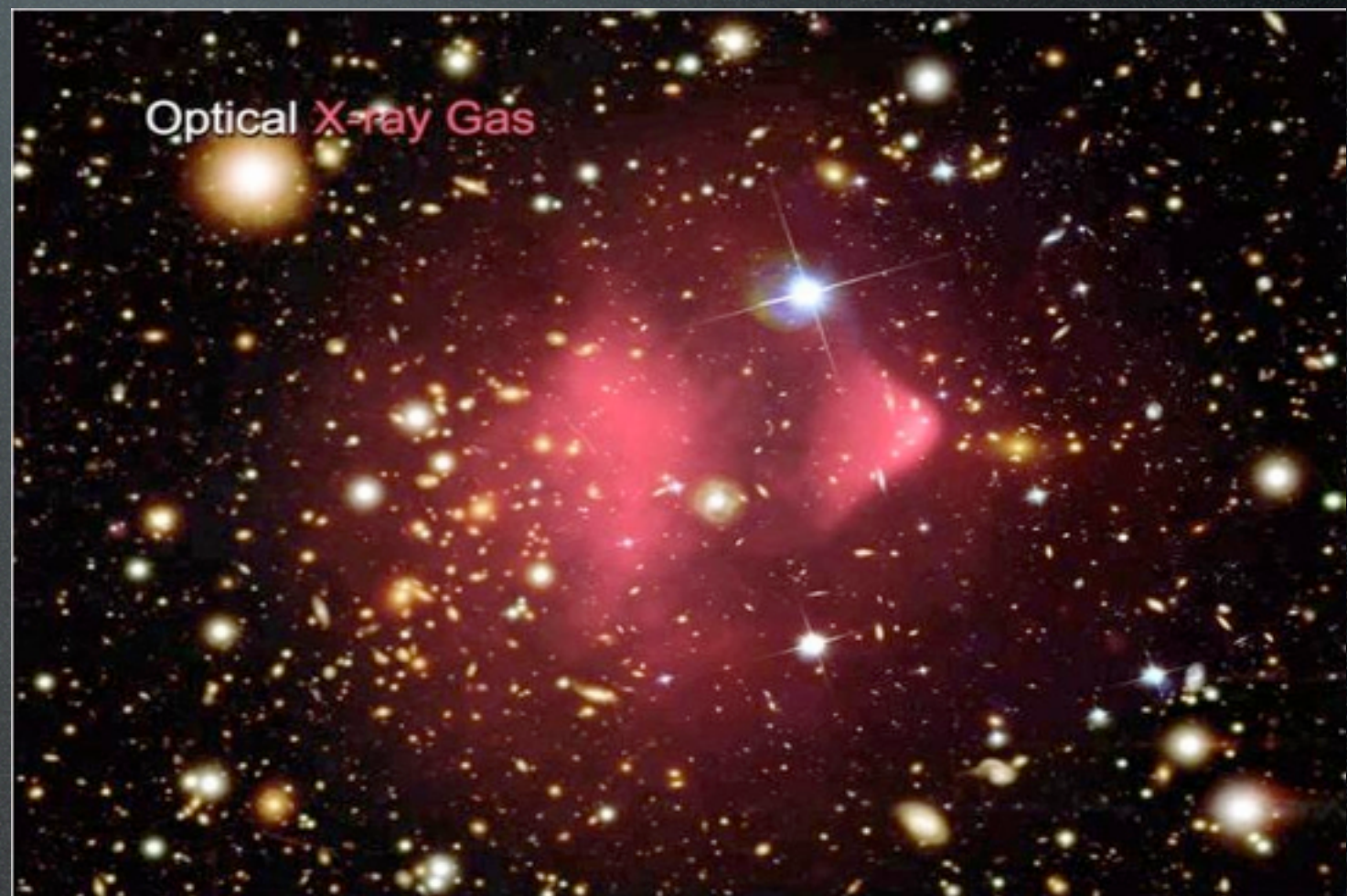
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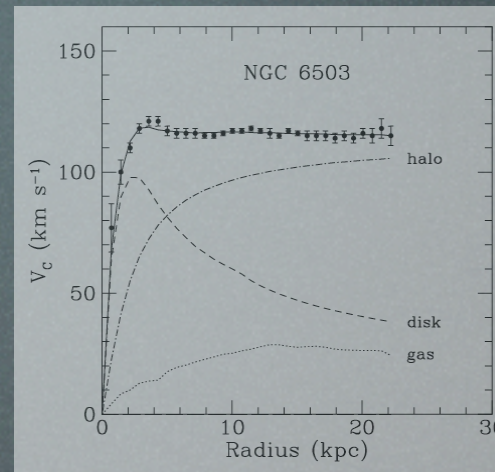
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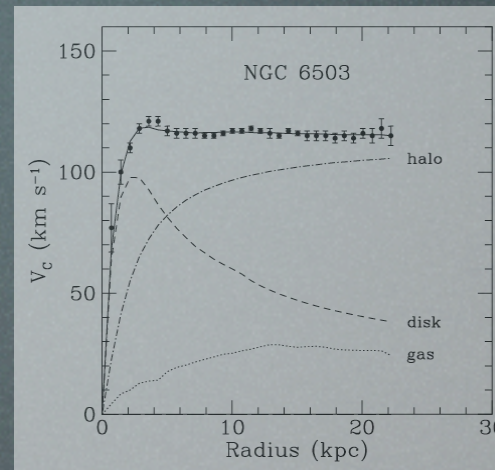
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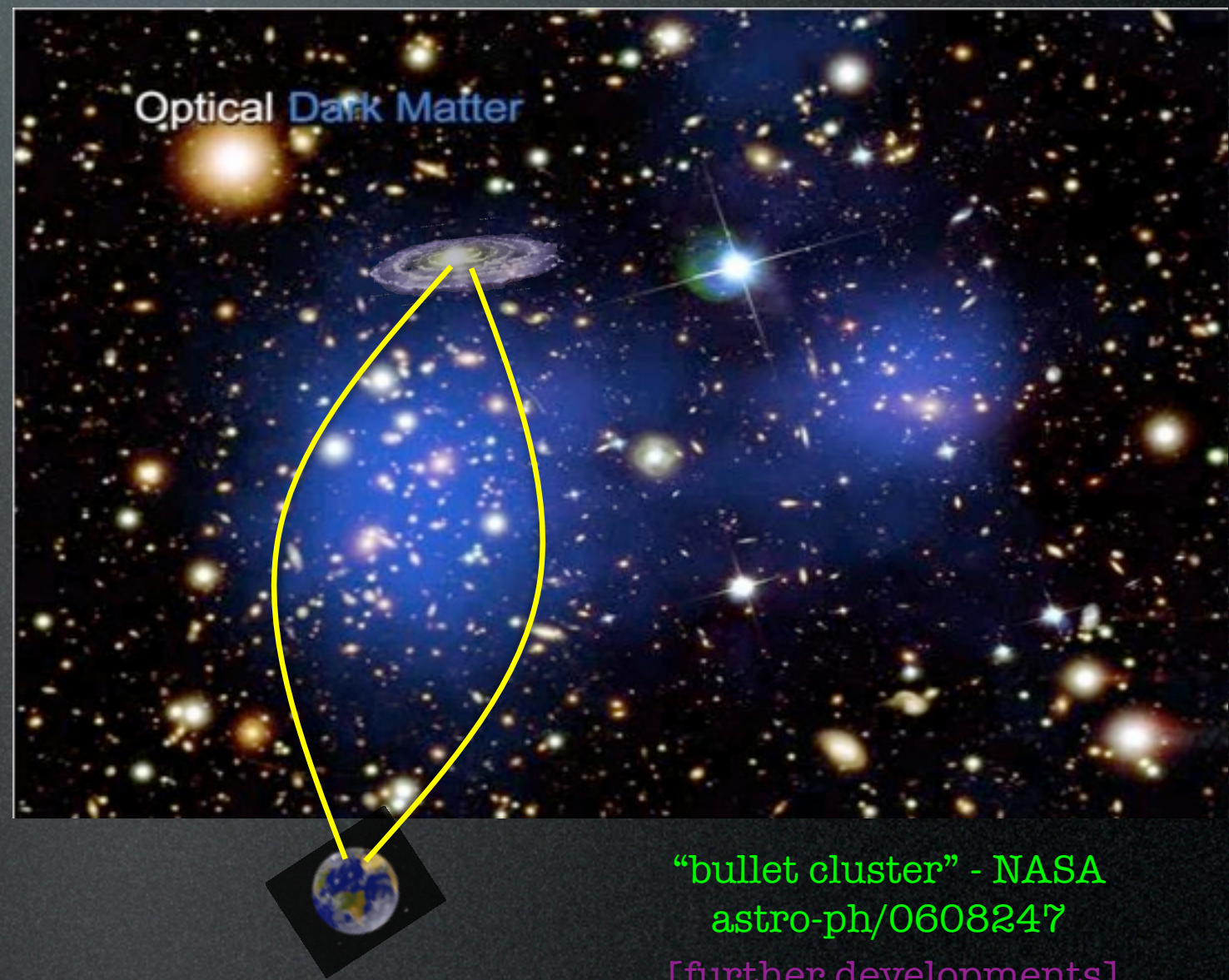
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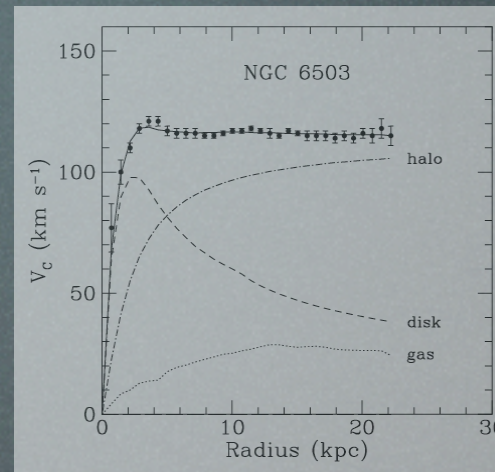
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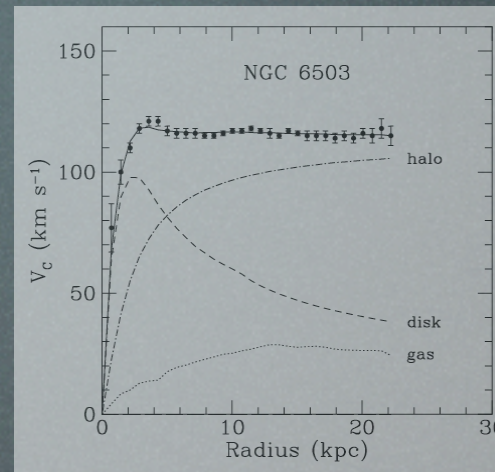
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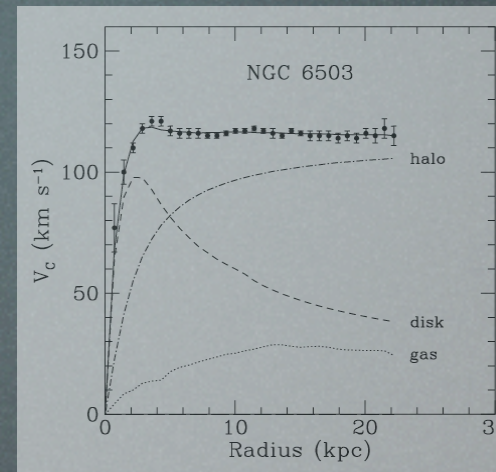
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[further developments]

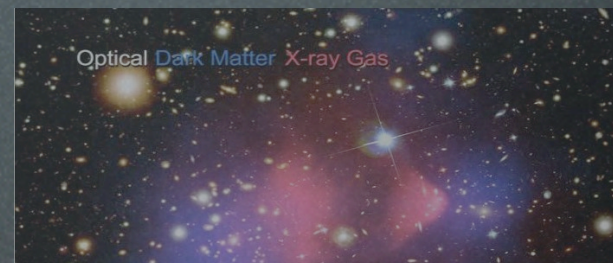
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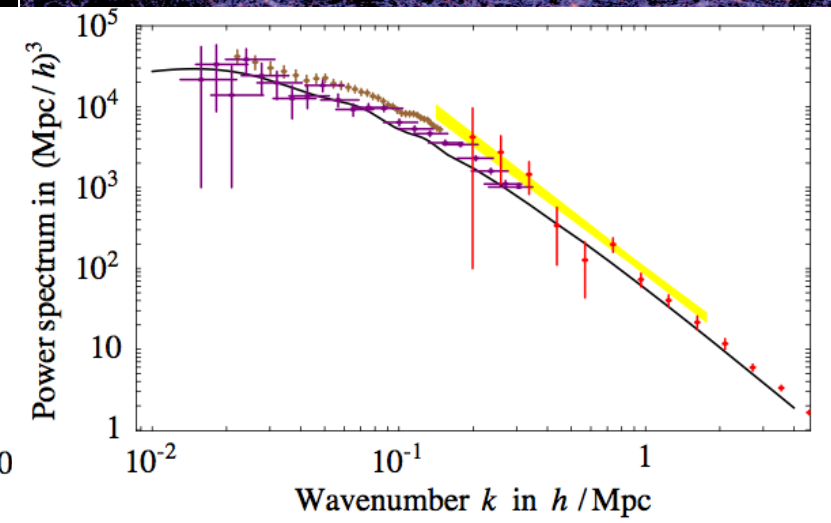
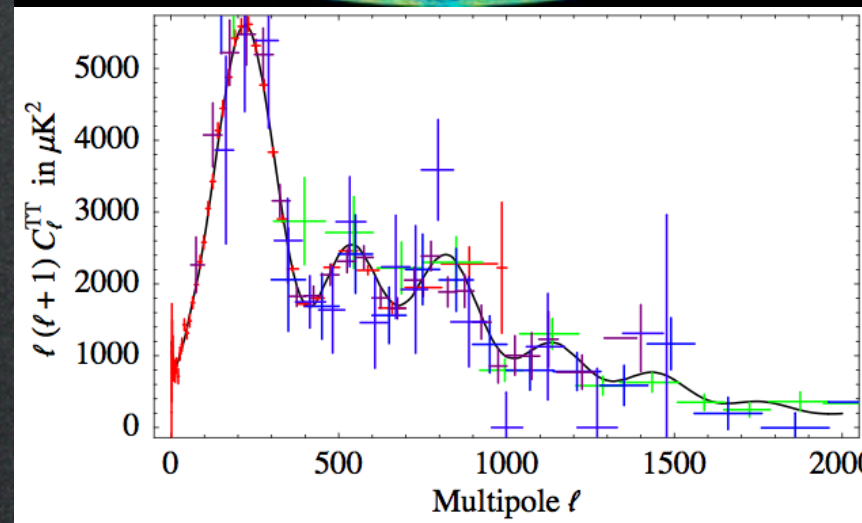
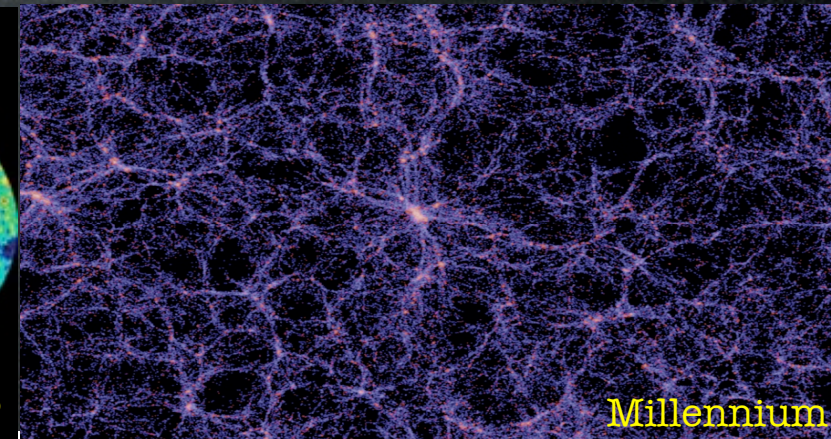
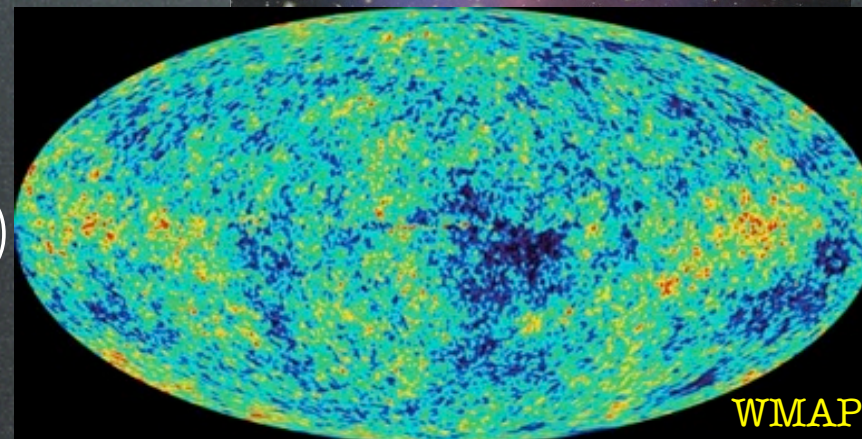
$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies



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

3) CMB+LSS(+SNIa:)

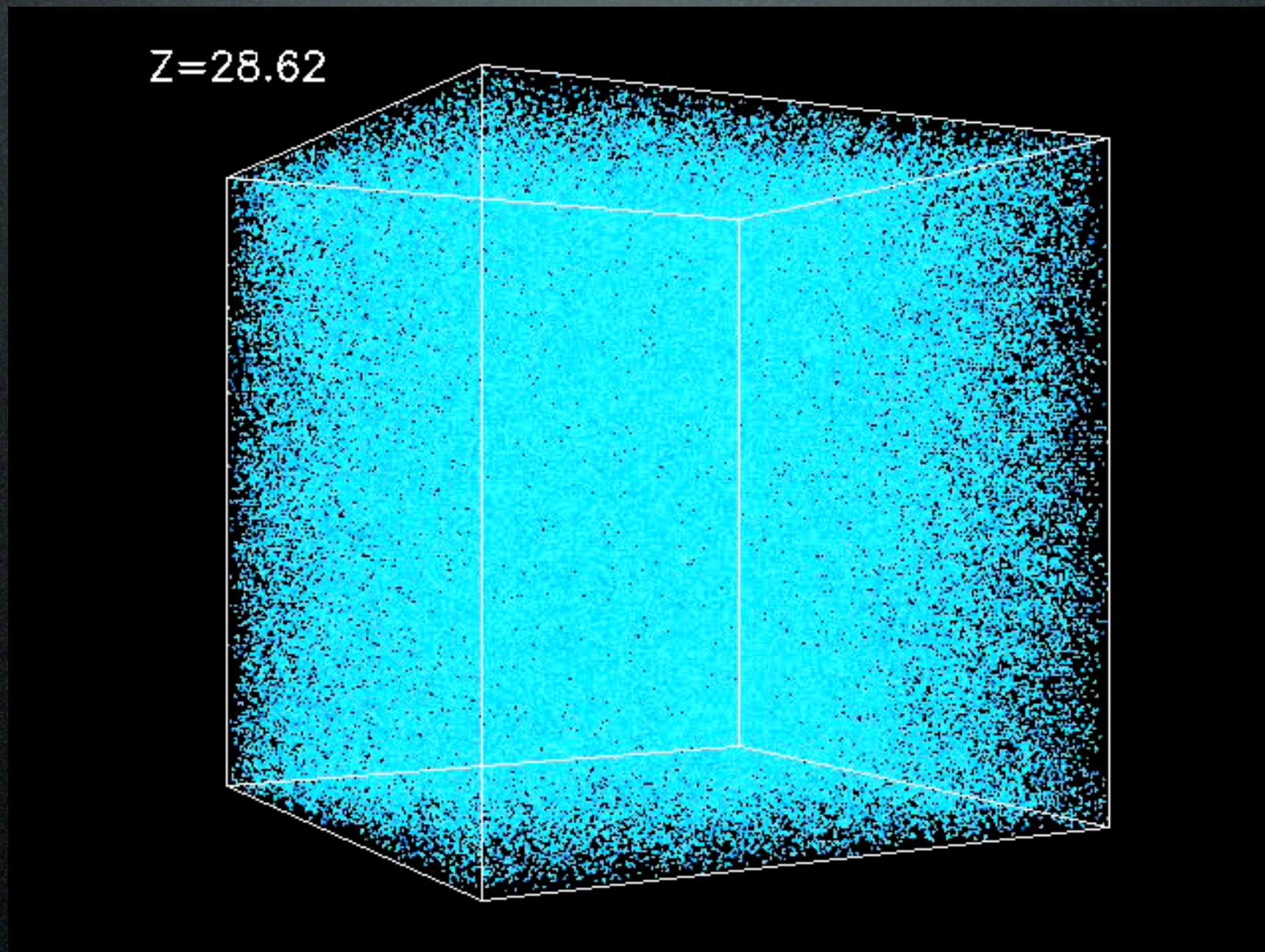


DM N-body simulations

2×10^6 CDM particles, 43 Mpc cubic box

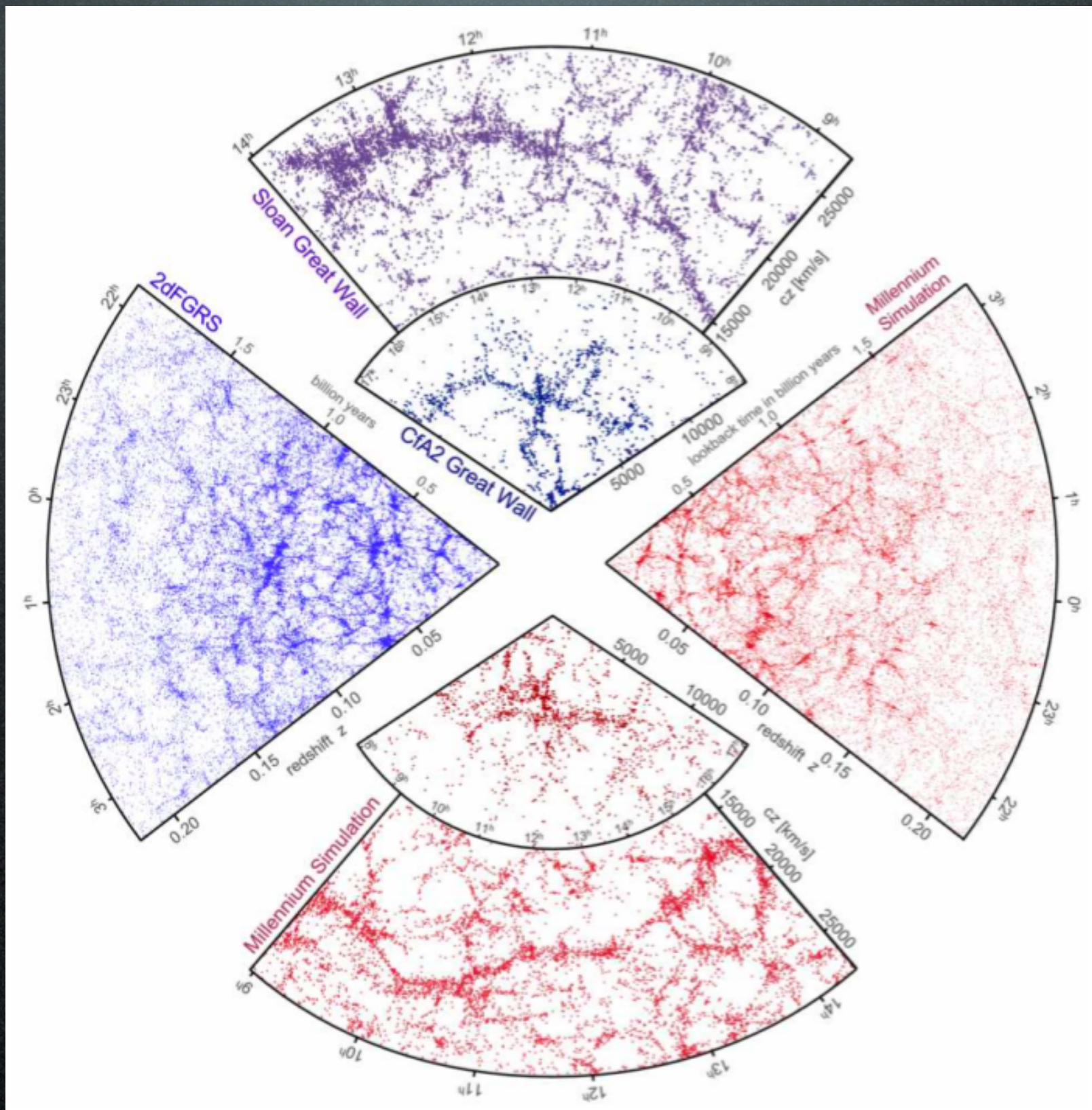
DM N-body simulations

2×10^6 CDM particles, 43 Mpc cubic box



DM N-body simulations

2dF: 2.2×10^5 galaxies
SDSS: 10^6 galaxies,
2 billion yr



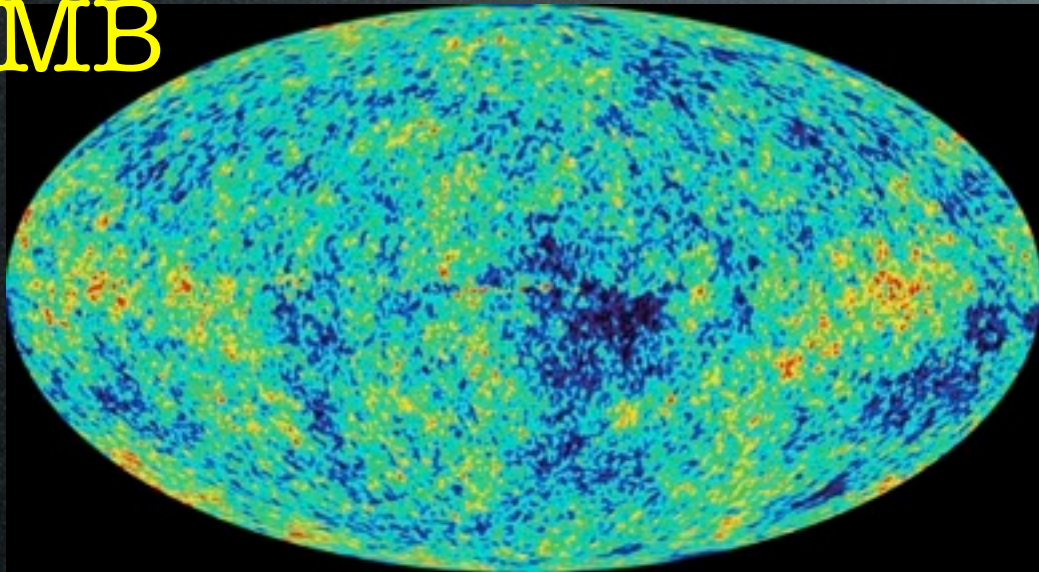
Millennium:
 10^{10} particles,
 $500 h^{-1} \text{ Mpc}$

Springel, Frenk, White, Nature 440 (2006)

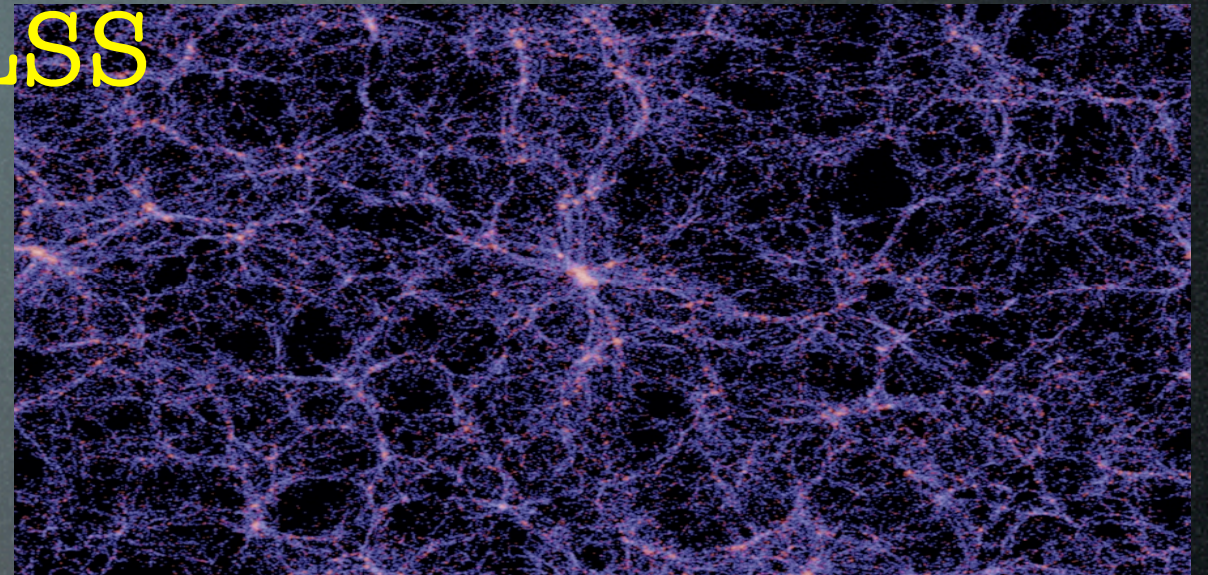
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The Evidence for DM

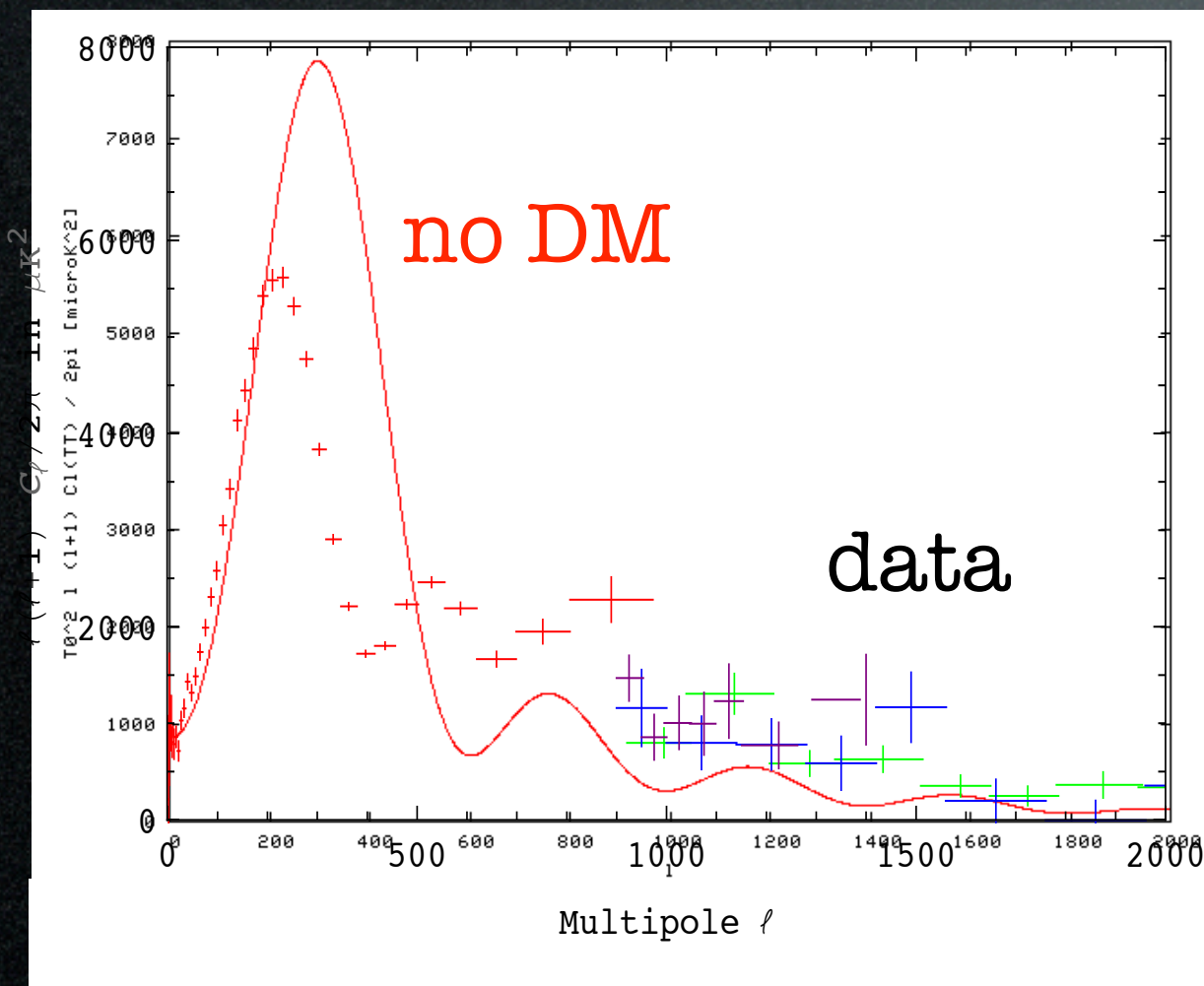
CMB



LSS

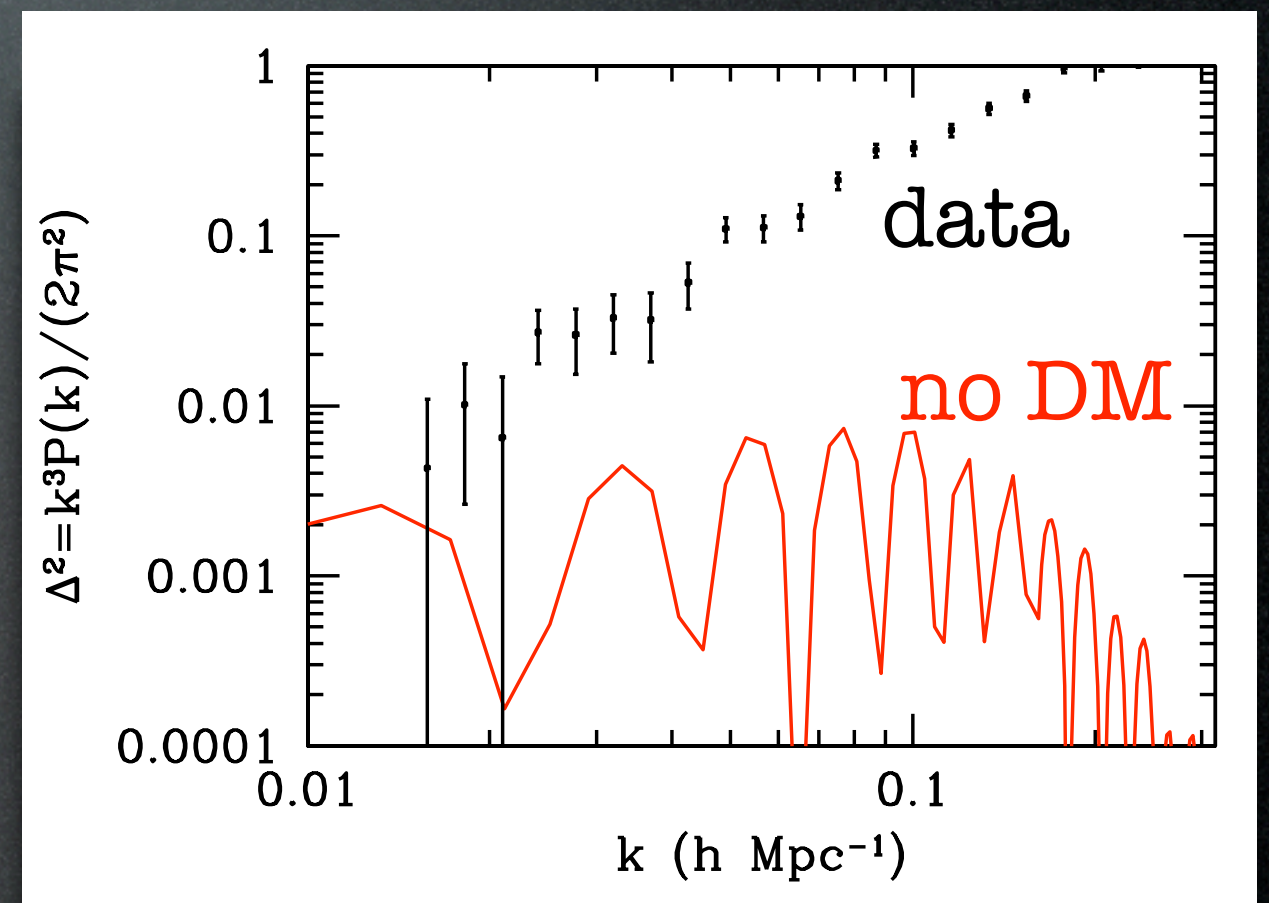


How would the power spectra be **without DM**? (and no other extra ingredient)



CAMB online

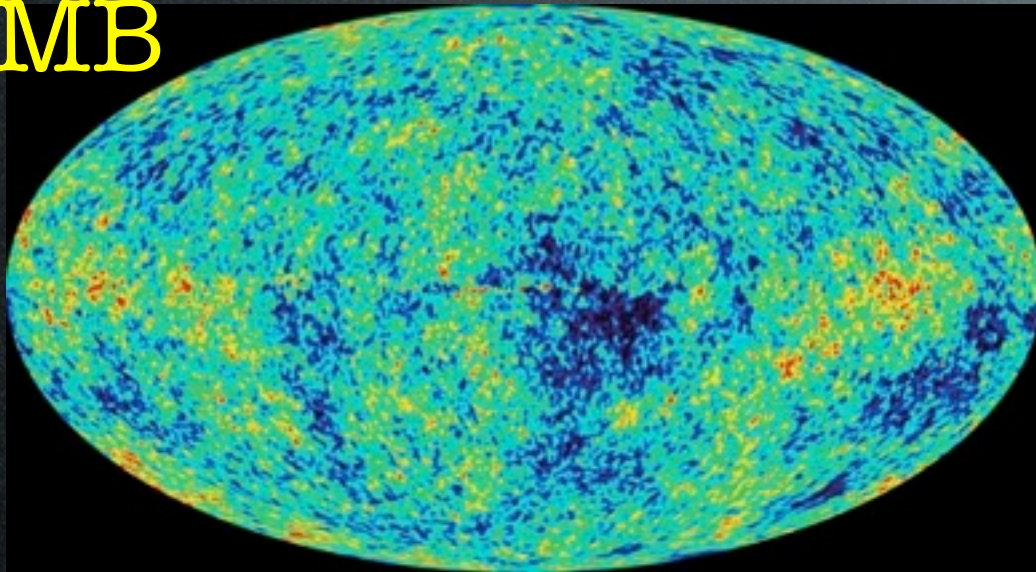
(in particular: no DM => no 3rd peak!)



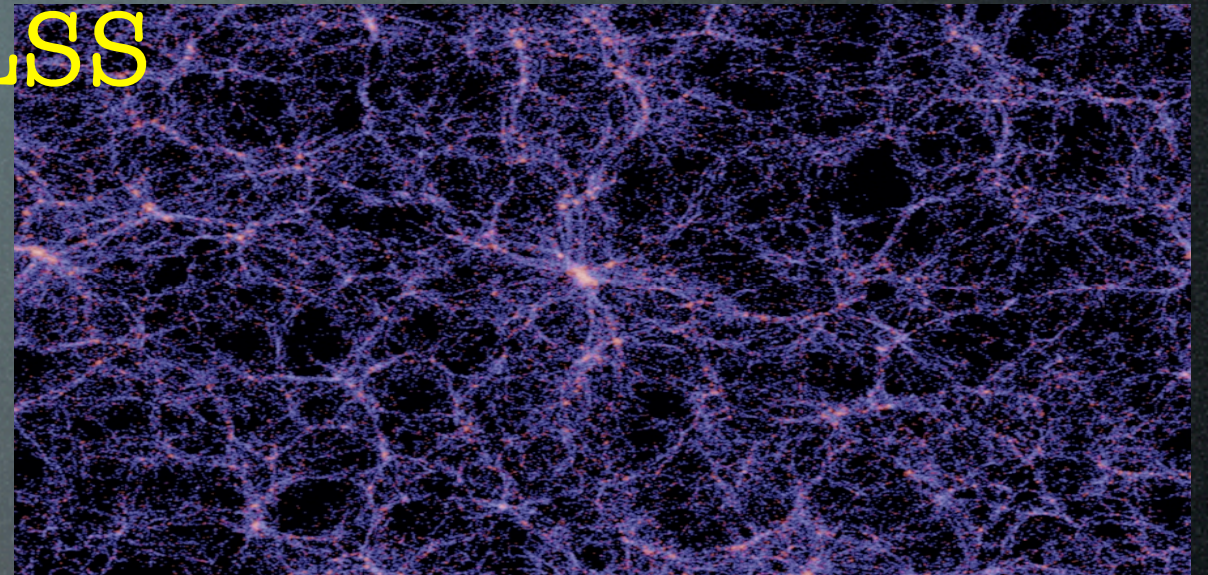
(you need DM to gravitationally
“catalyse” structure formation)

The Evidence for DM

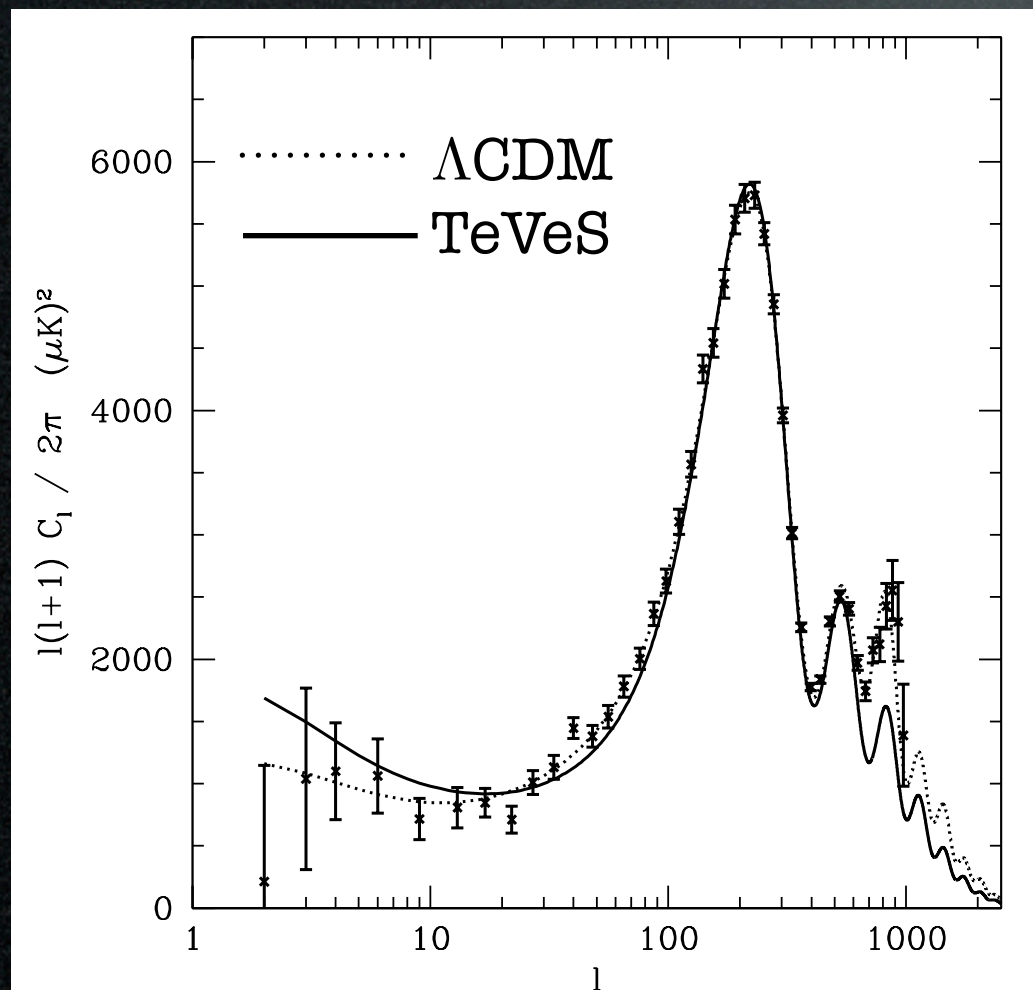
CMB



LSS

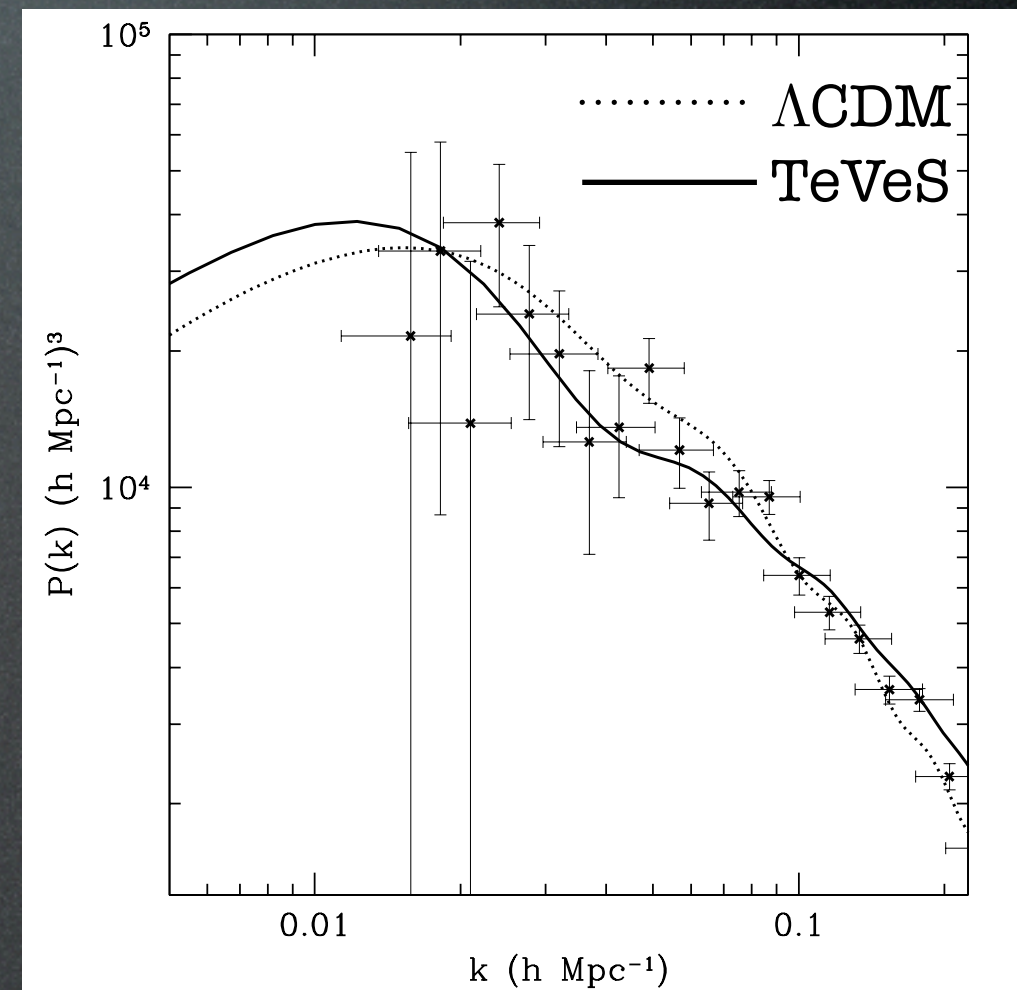


How would the power spectra be in MOND/TeVSe, without DM ?



C.Skordis, Review, 0903.3602

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

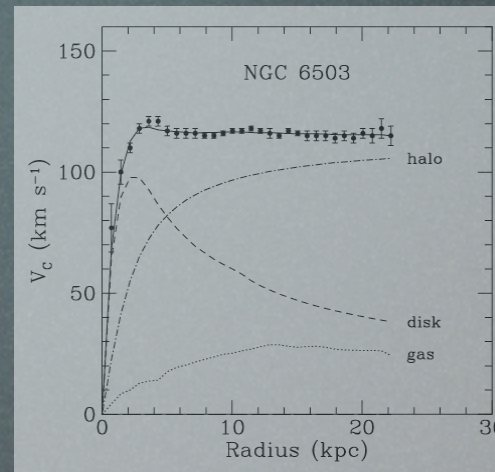


C.Skordis, Review, 0903.3602

(here you can make it)

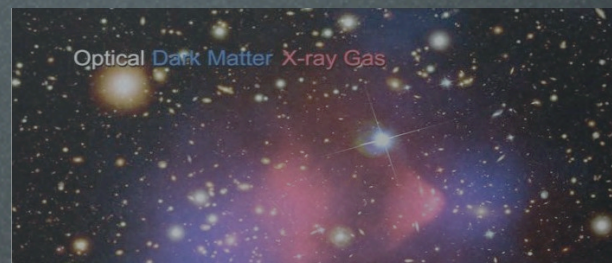
The Evidence for DM

1) galaxy rotation curves



$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

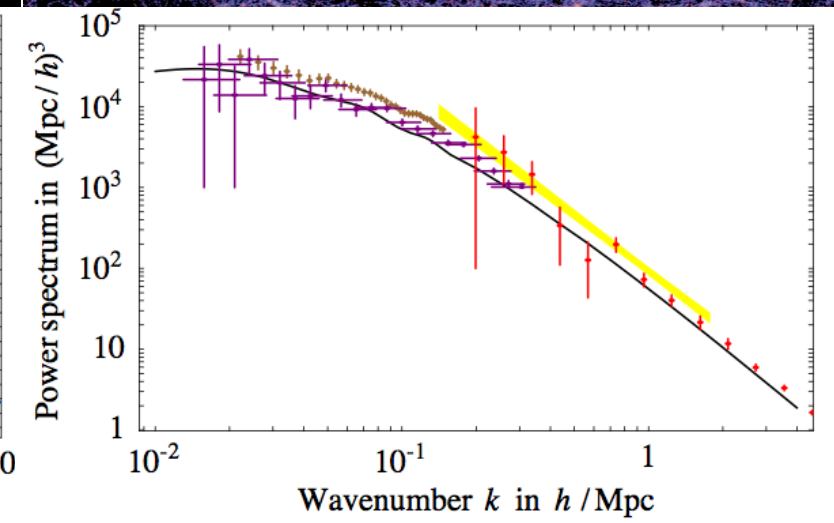
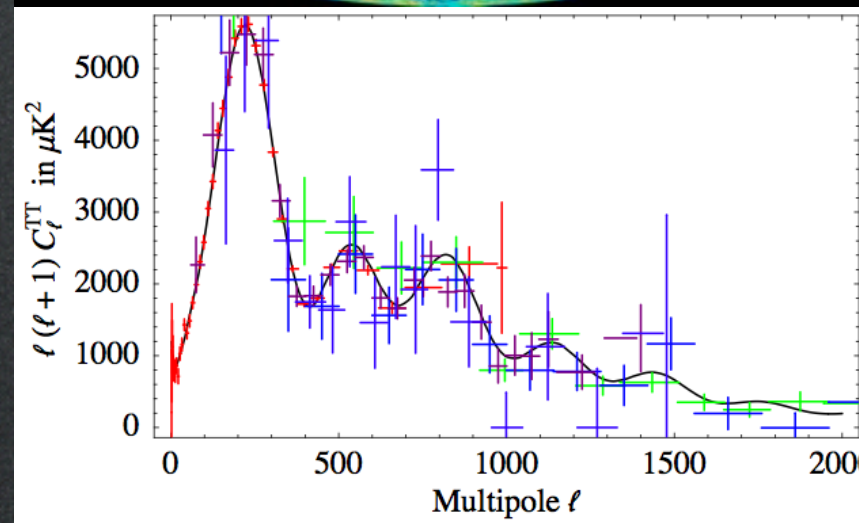
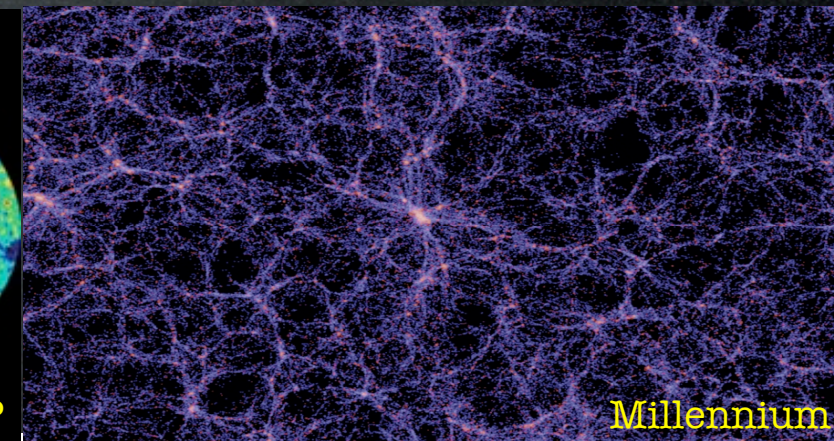
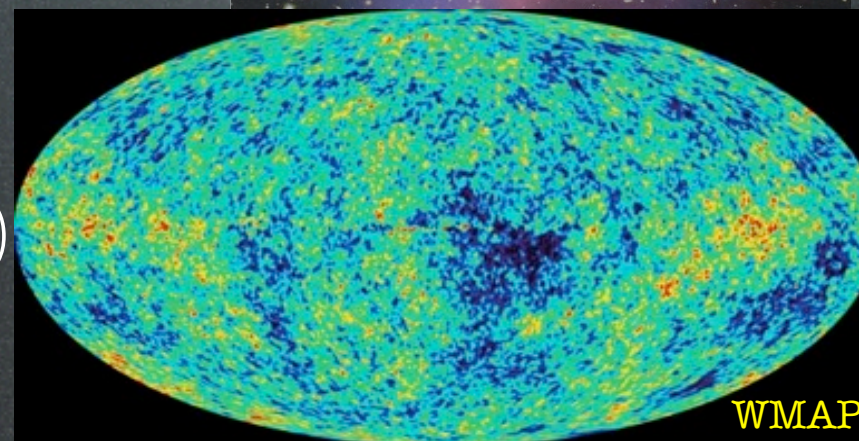


$$\Omega_M \sim 0.2 \div 0.4$$

3) CMB+LSS(+SNIa:)

WMAP-3yr Boomerang
ACbar DASI
CBI VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS



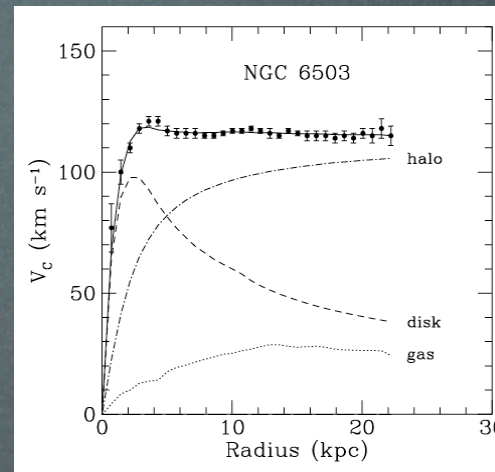
$$\Omega_M \approx 0.26 \pm 0.05$$

(spectra w/o DM)

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

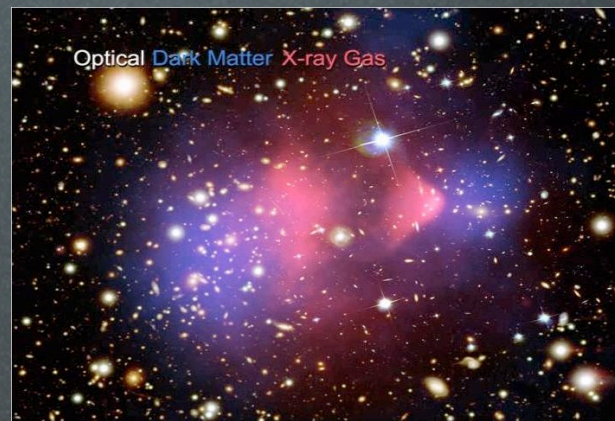
The Evidence for DM

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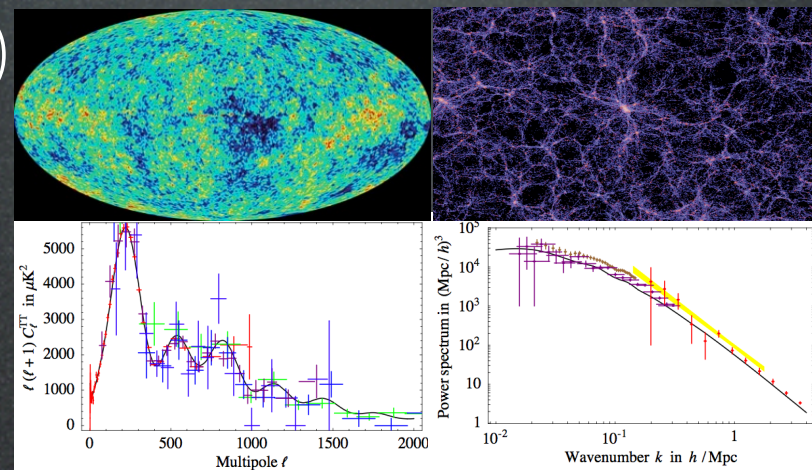
$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies



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

3) CMB+LSS(+SNIa:)



$$\Omega_M \approx 0.26 \pm 0.05$$

[back]

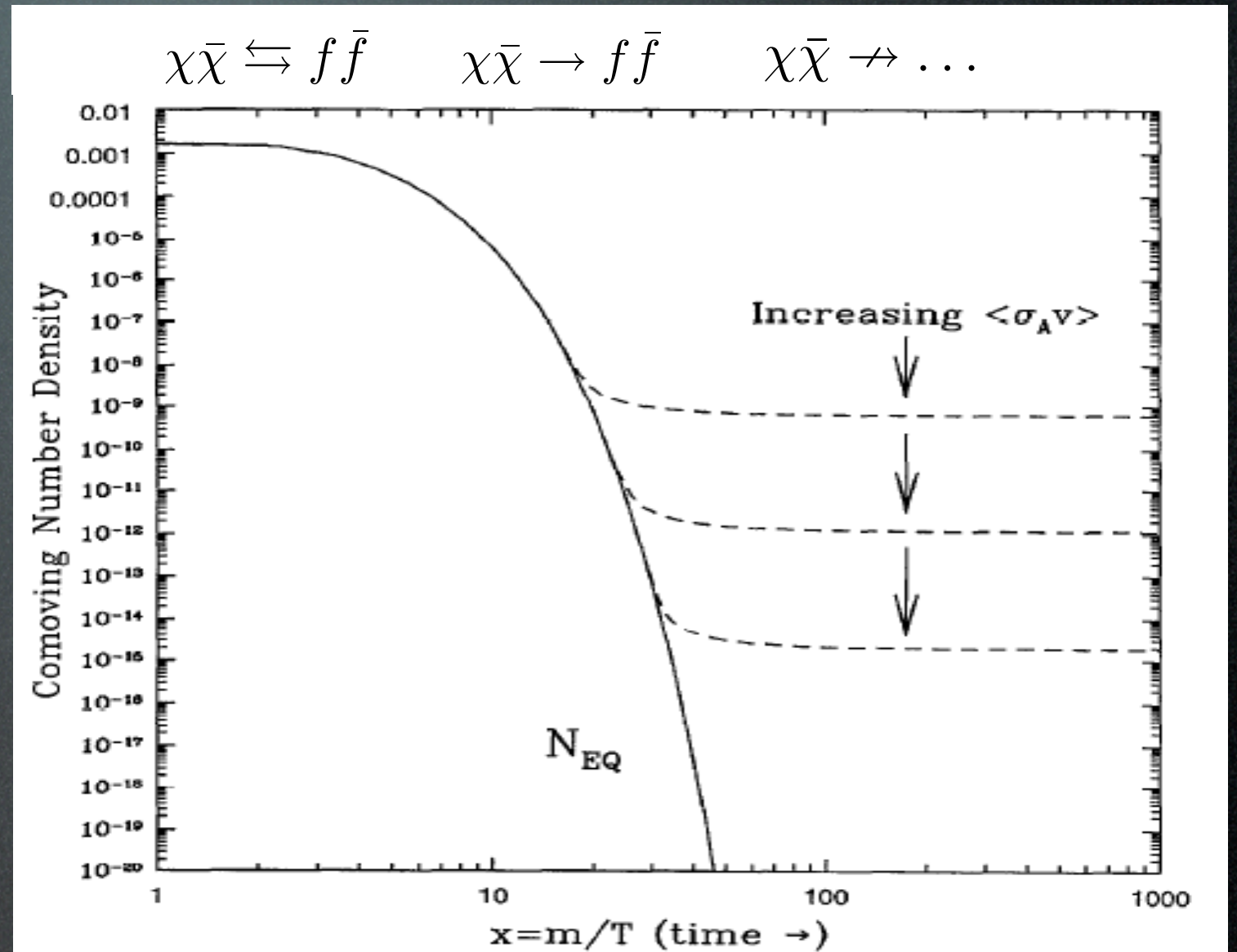
A thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

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

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

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



Weak cross section:

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

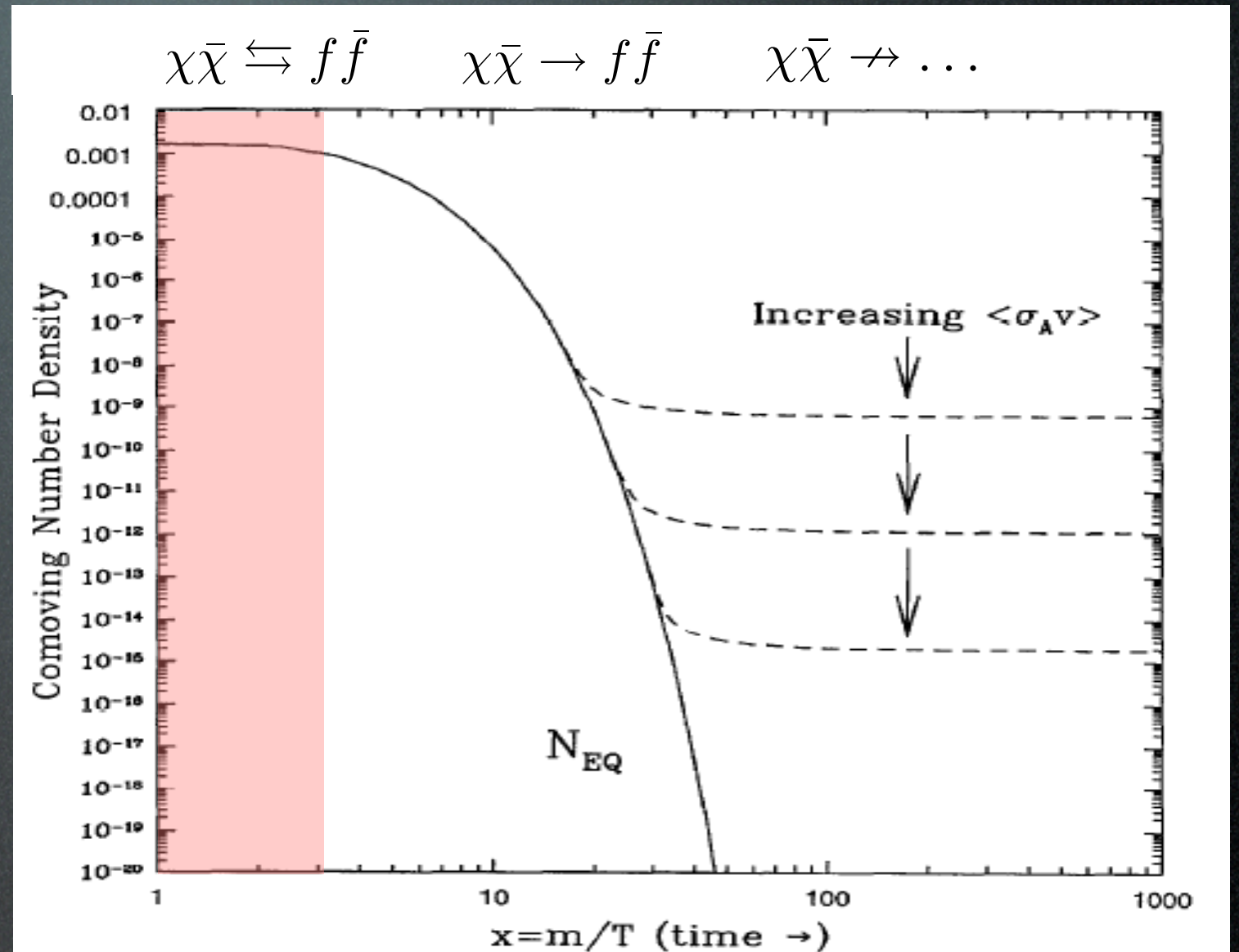
A thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

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

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

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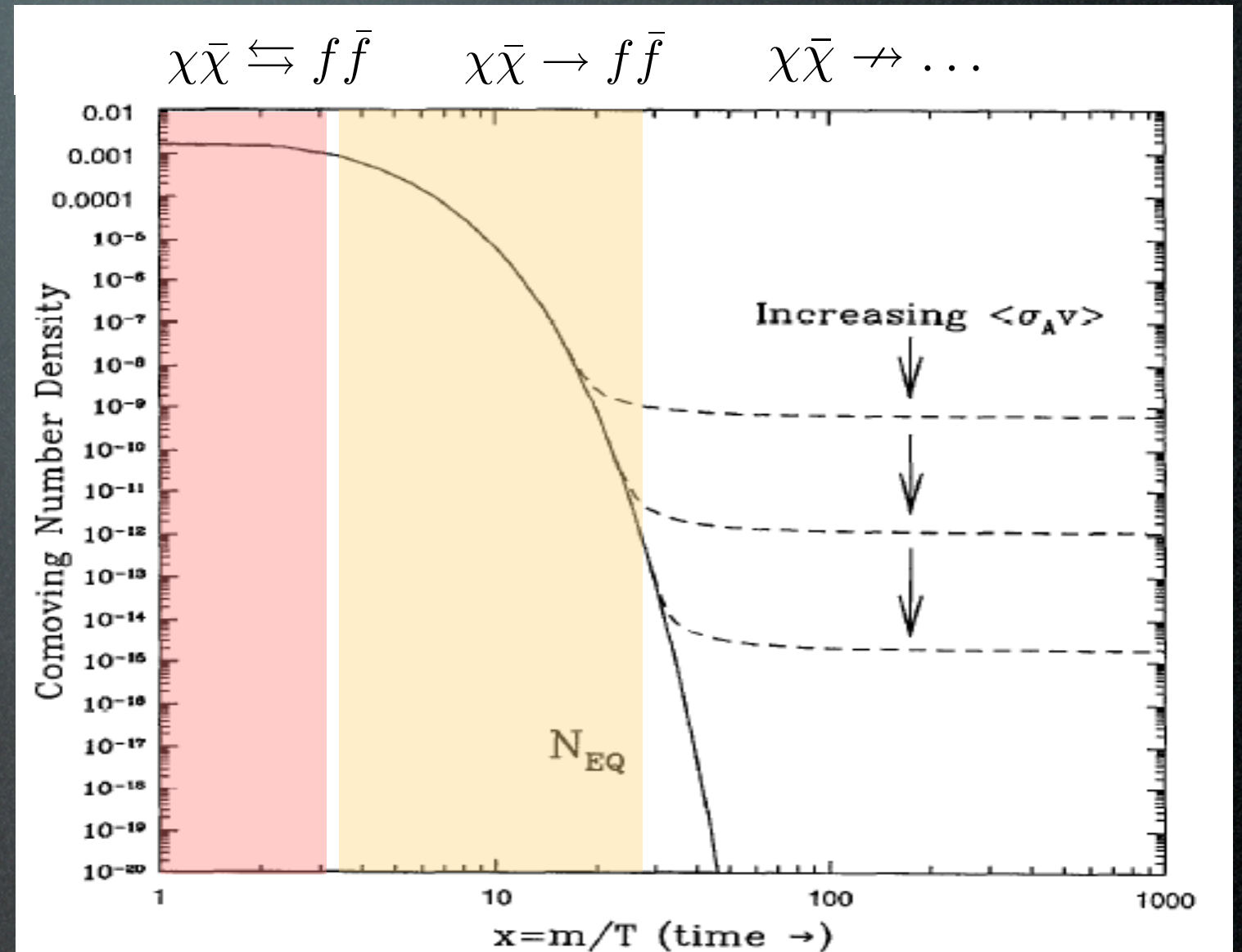
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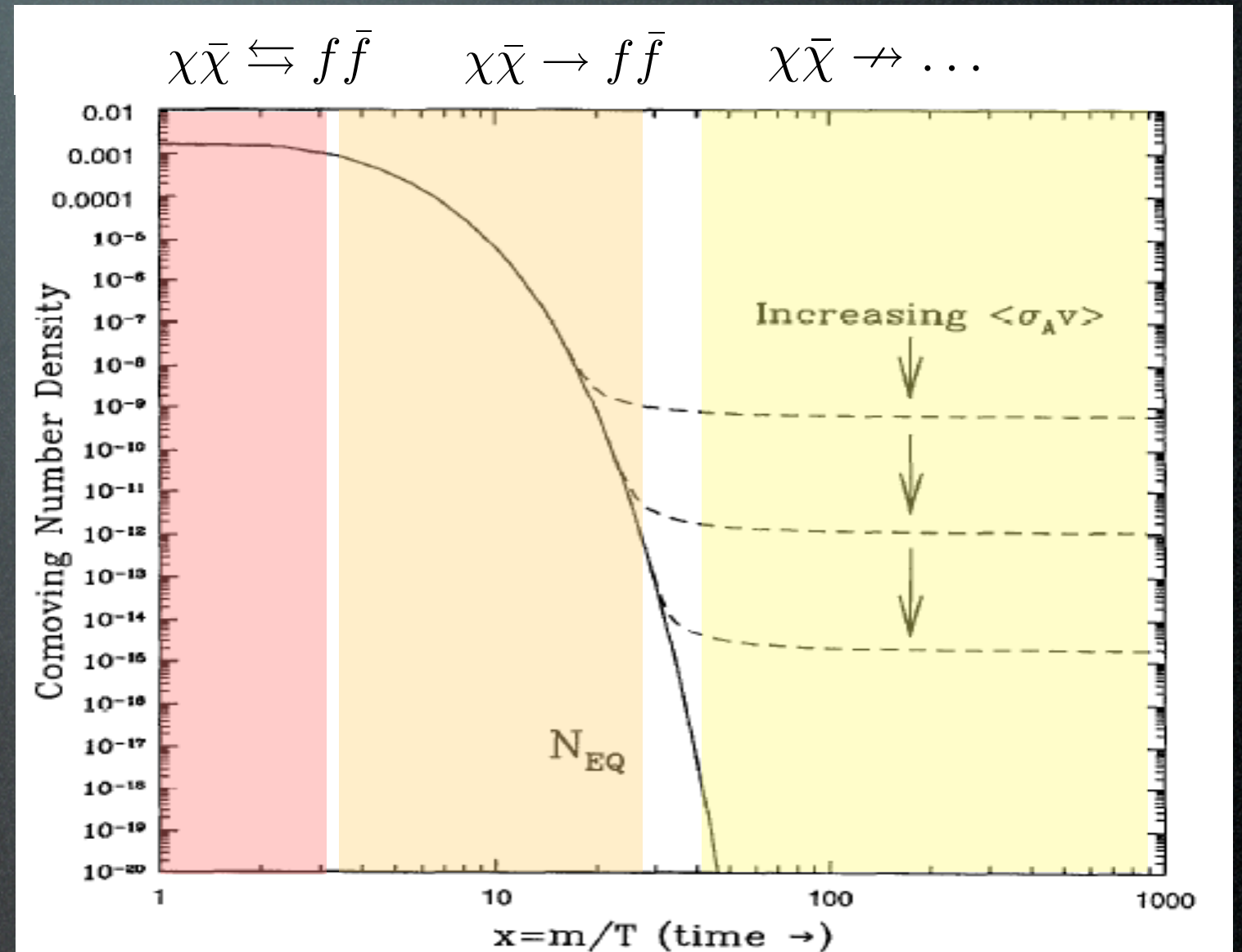
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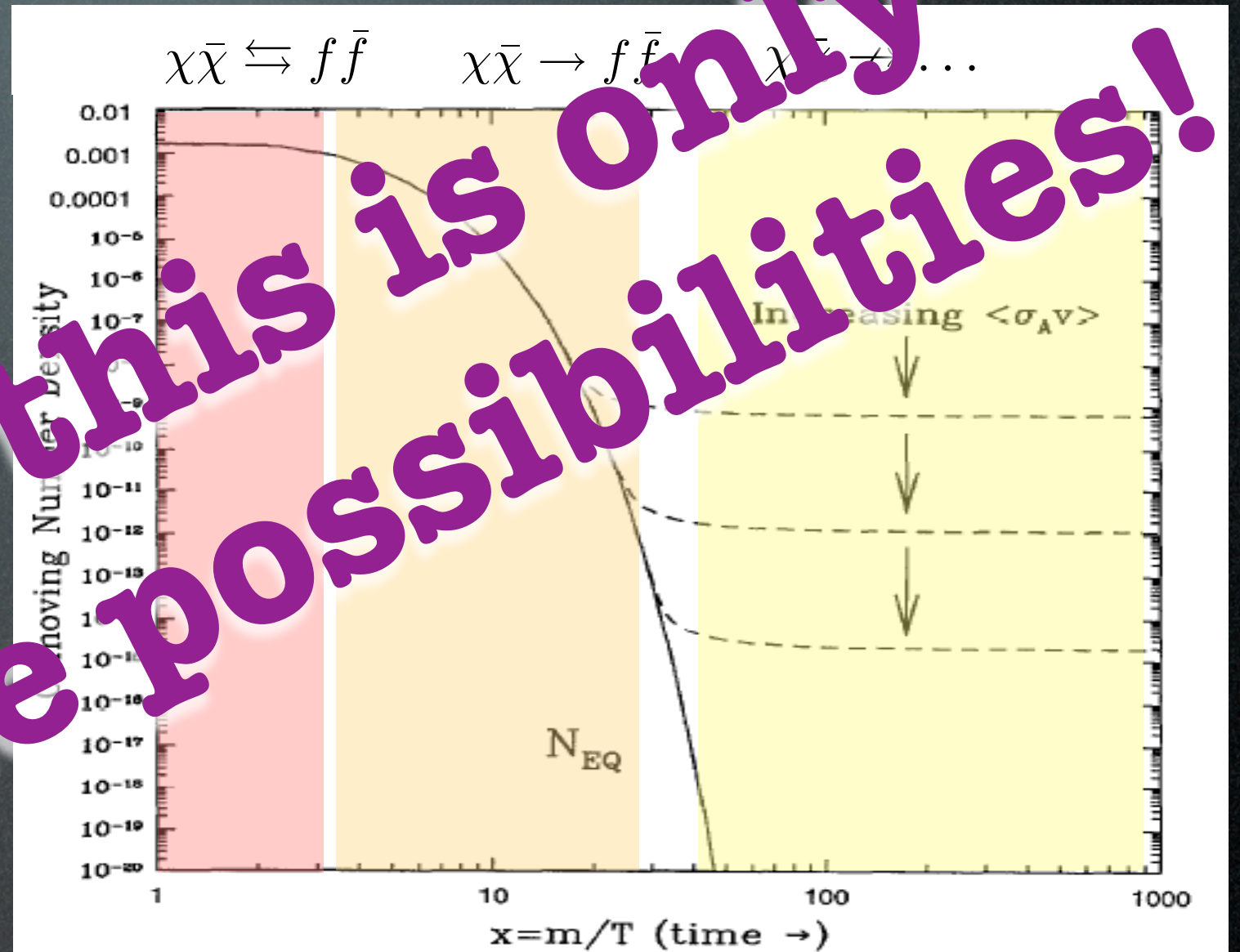
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(WIMP)



Kolb, Turner, The Early Universe, 1995

[back]

Indirect Detection

Solar wind Modulation of cosmic rays:

$$\frac{d\Phi_{\bar{p}\oplus}}{dT_{\oplus}} = \frac{p_{\oplus}^2}{p^2} \frac{d\Phi_{\bar{p}}}{dT},$$

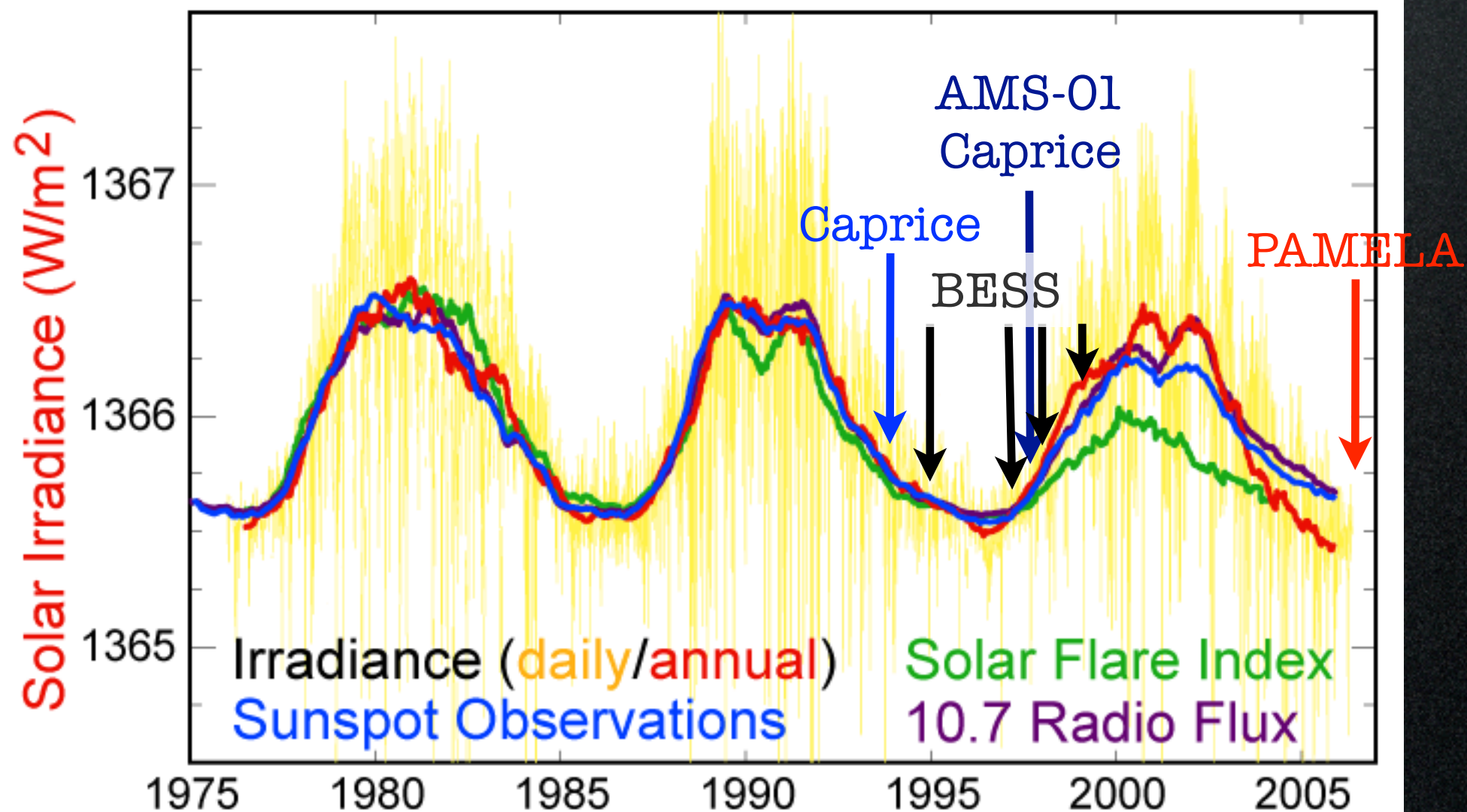
spectrum
at Earth

spectrum
far from Earth

$$T = T_{\oplus} + |Ze|\phi_F$$

Fisk
potential $\phi_F \simeq 500$ MV

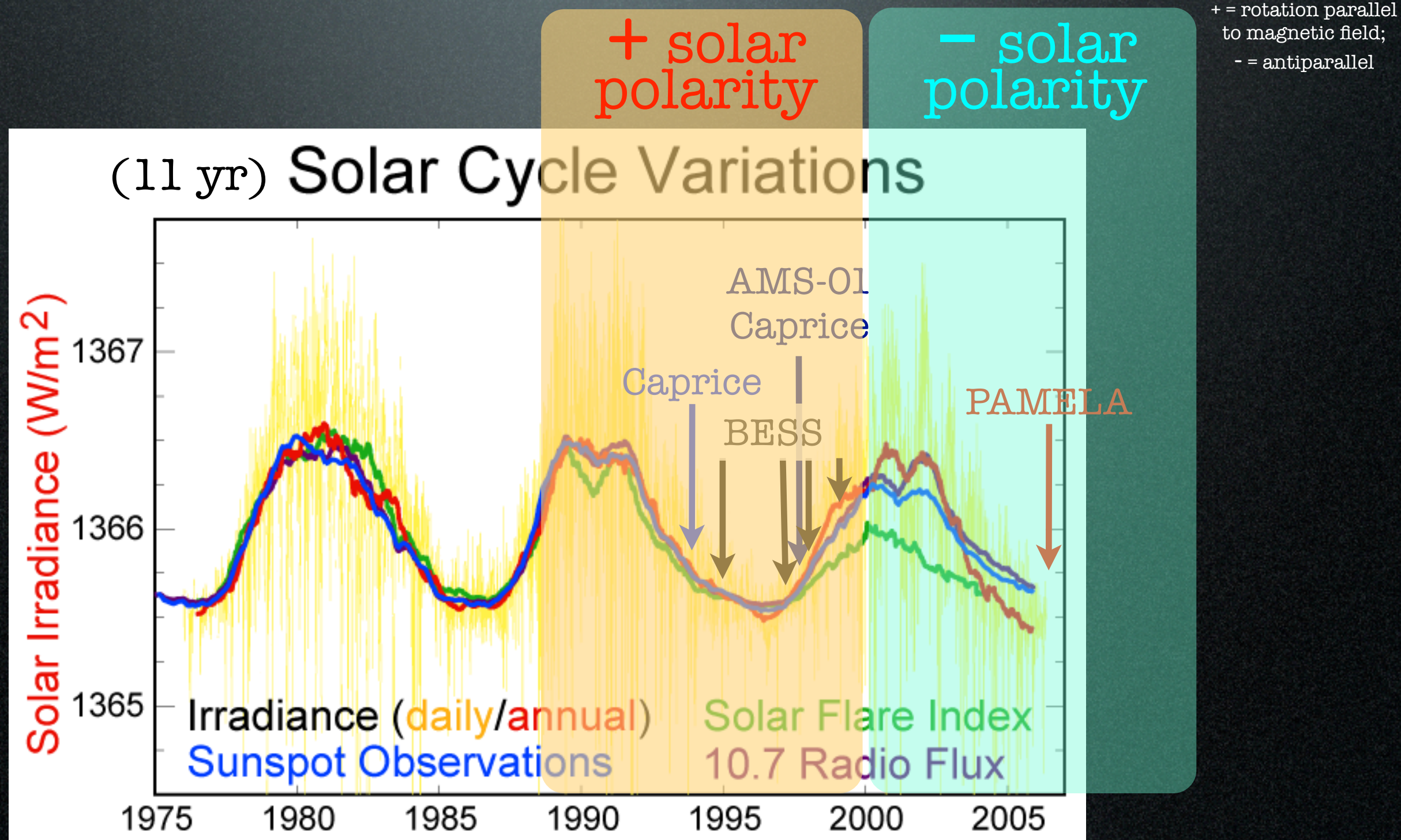
(11 yr) Solar Cycle Variations



Indirect Detection

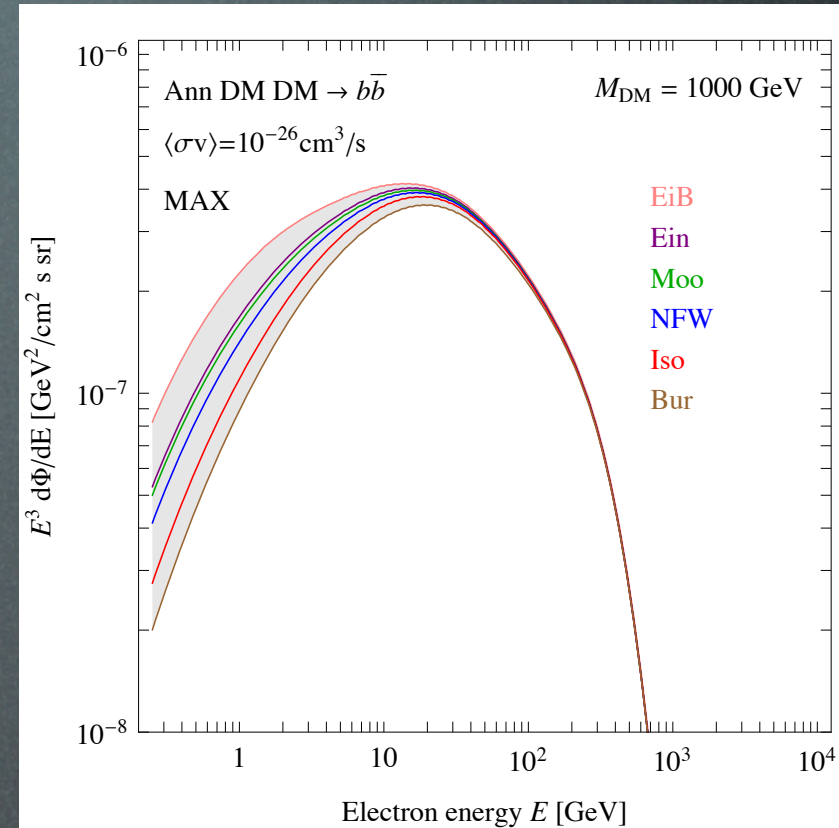
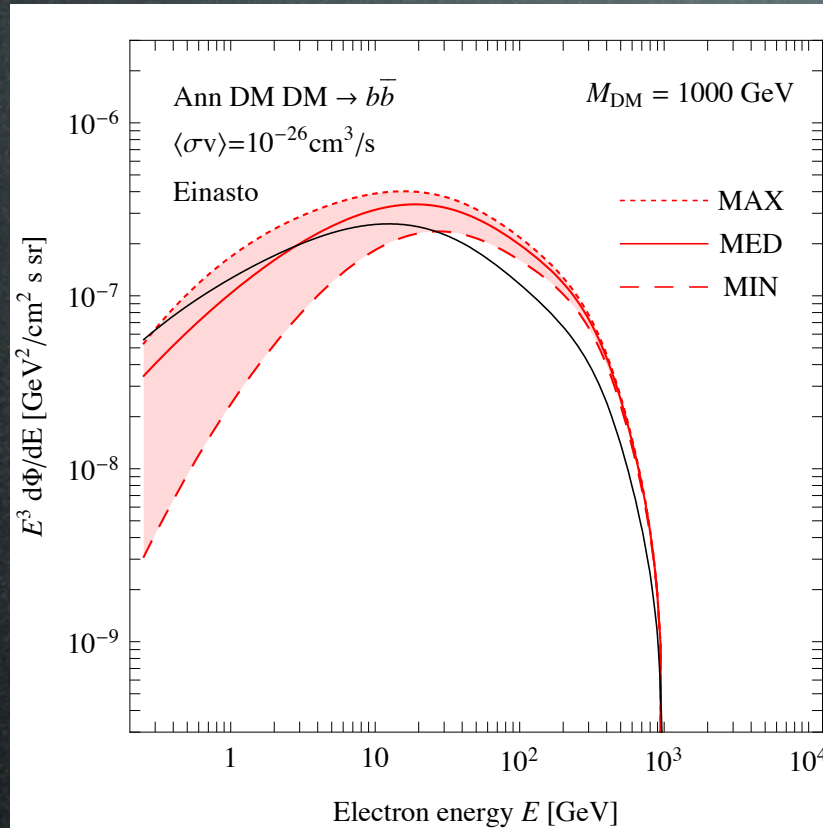
Solar polarity Modulation of cosmic rays:

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

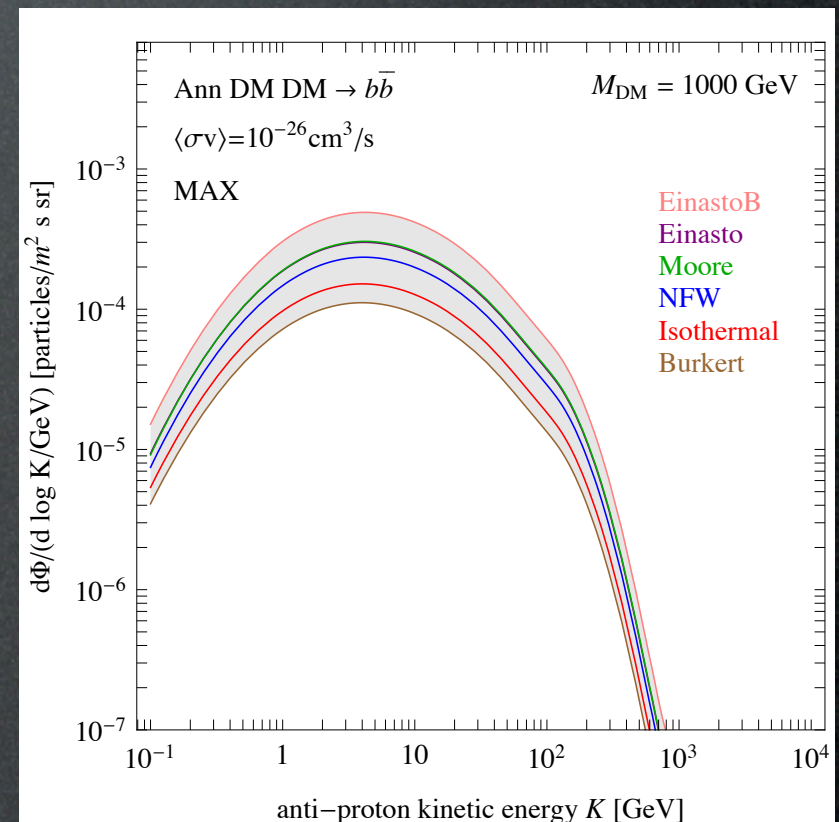
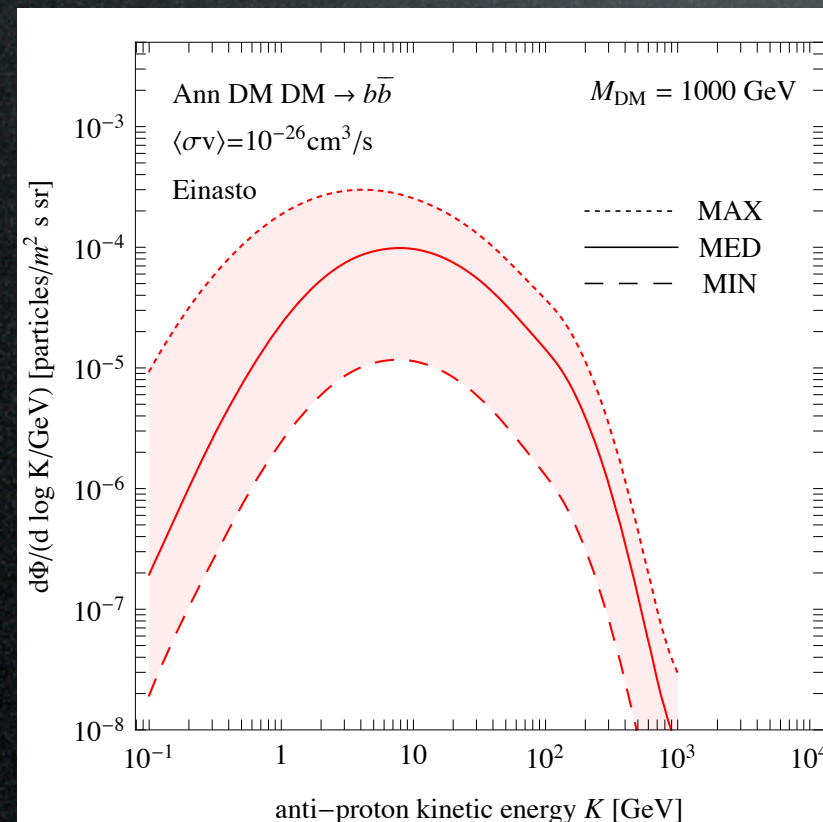


'Astro' uncertainties

$e^\pm$



$\bar{p}$

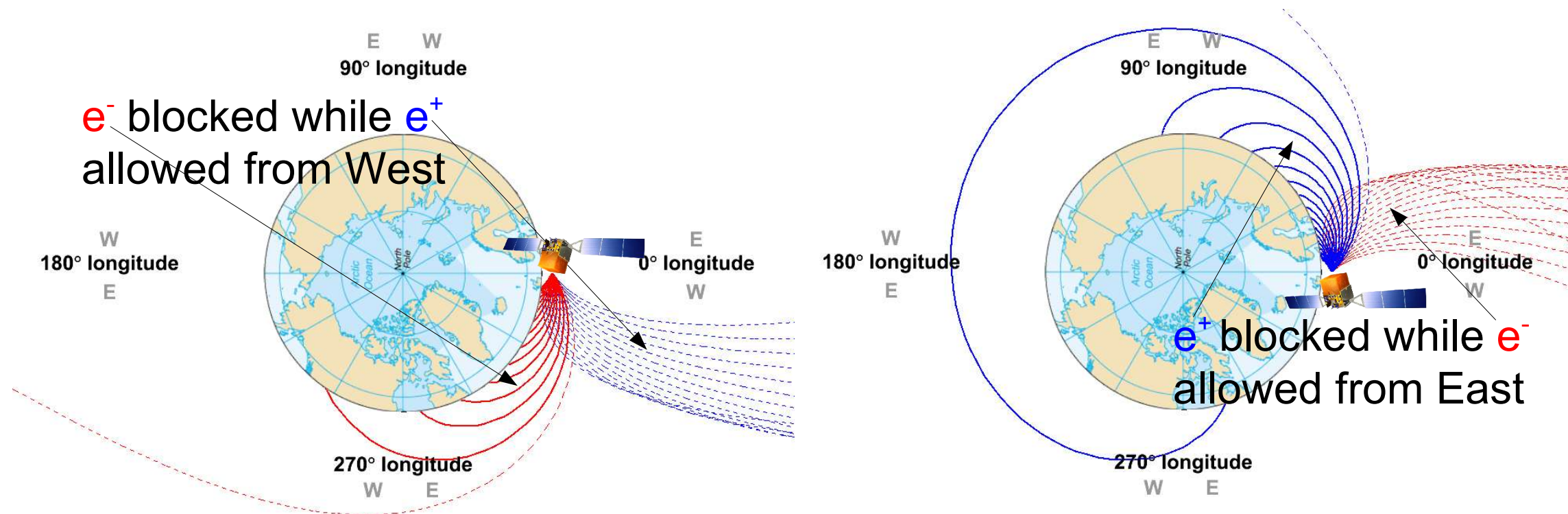


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FERMI positrons



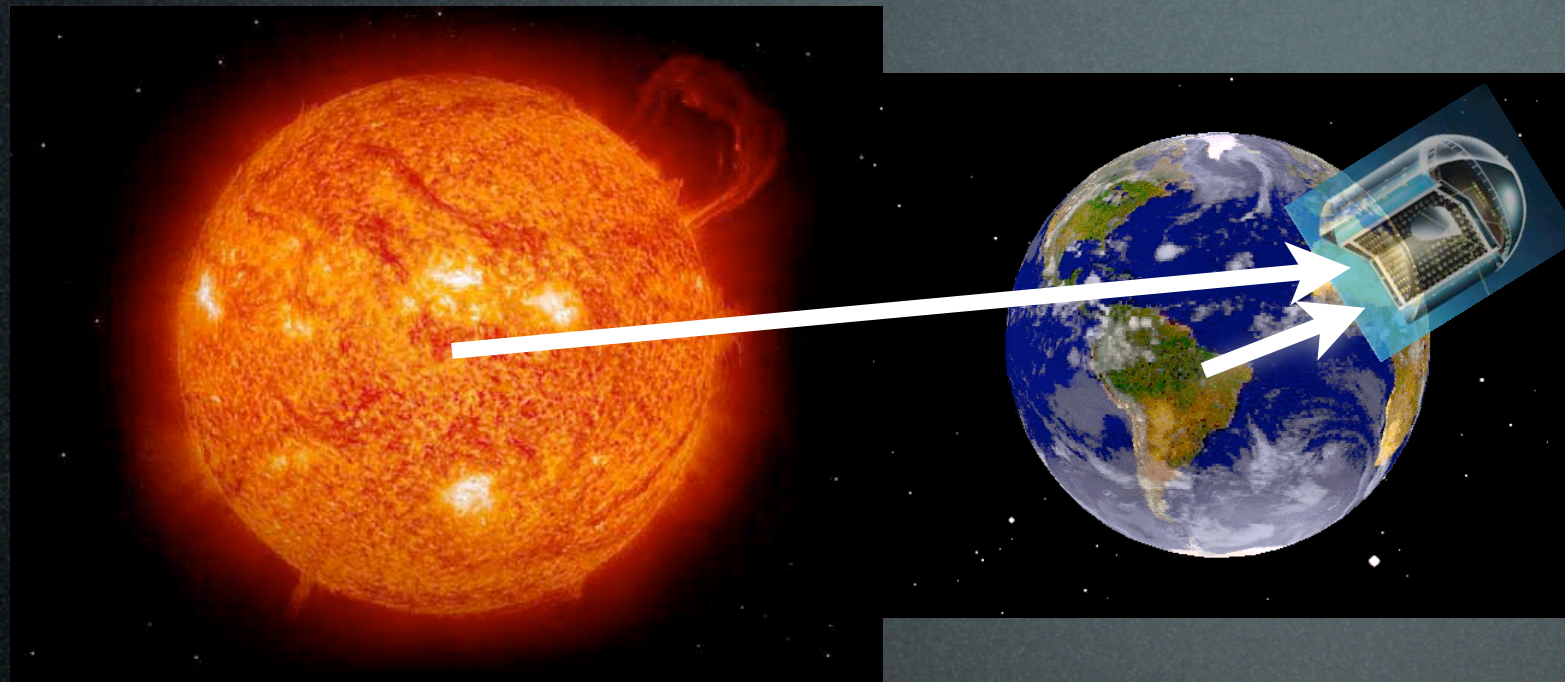
Principle: Use the Earth's Magnetic Field to Distinguish e^+ and e^-



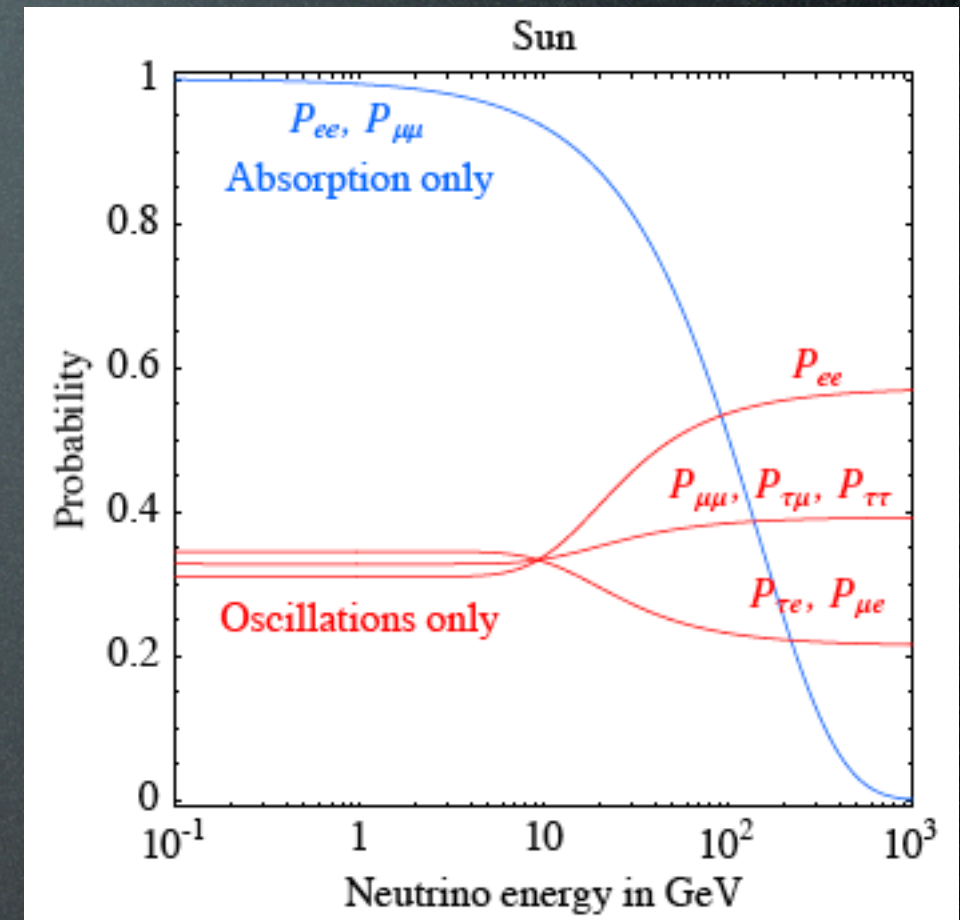
- Pure e^+ region is in the west and same for e^- in the east
- The regions vary with particle energy and the LAT position
- To locate these regions, we use a code written by Smart, D. F. and Shea, M. A.* which numerically calculates a particle's trajectory in the geomagnetic field

**Center for Space Plasmas and Aeronomic Research, The University of Alabama in Huntsville*

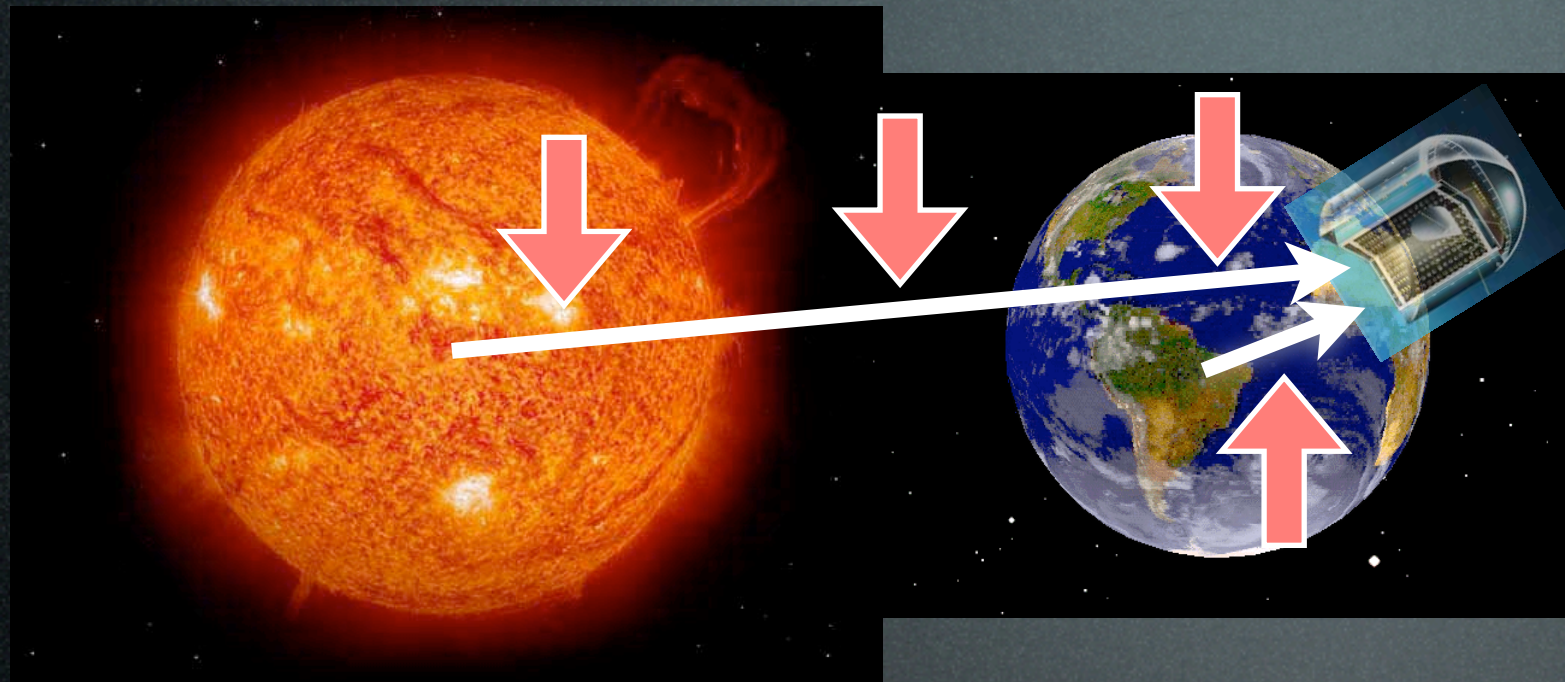
Propagation



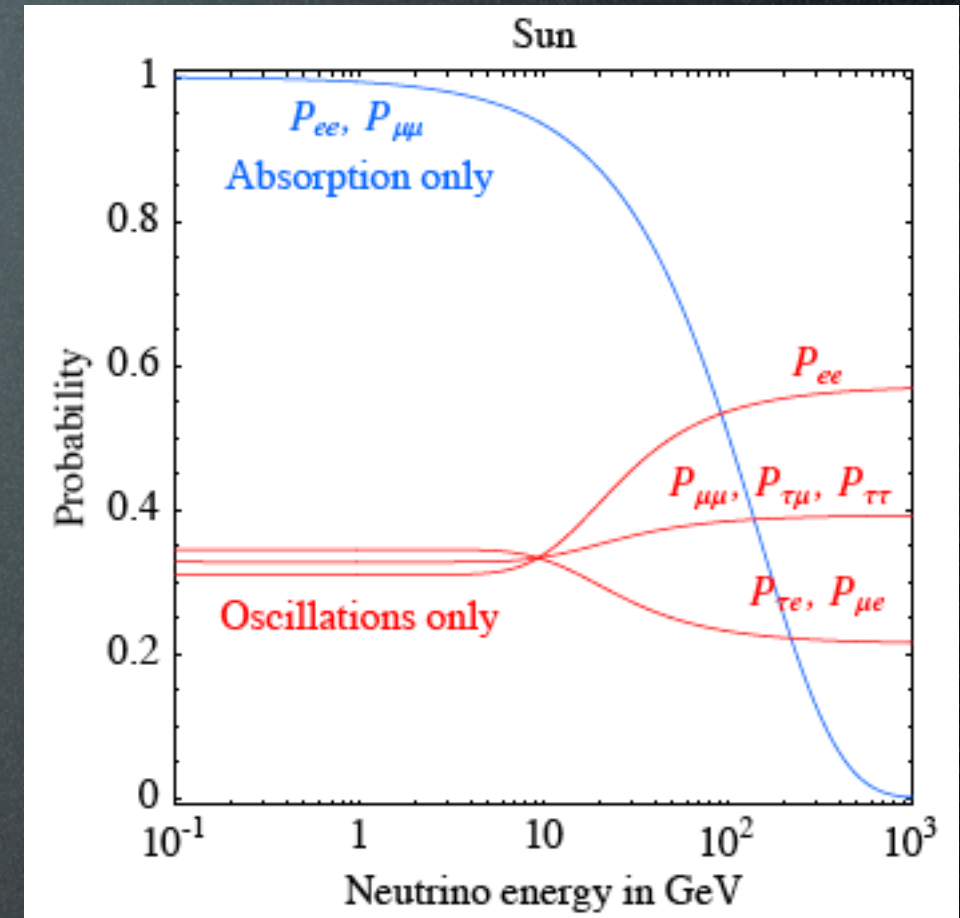
oscillations + interactions



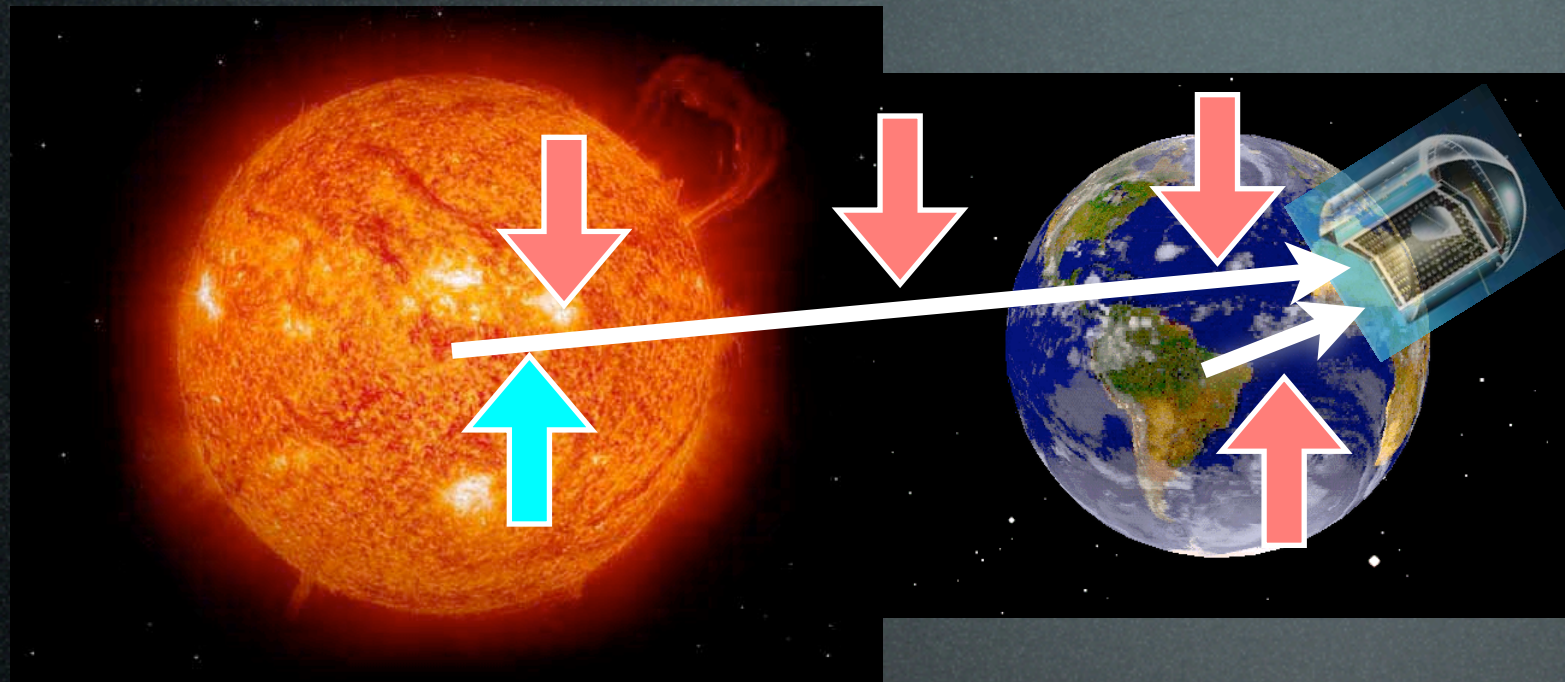
Propagation



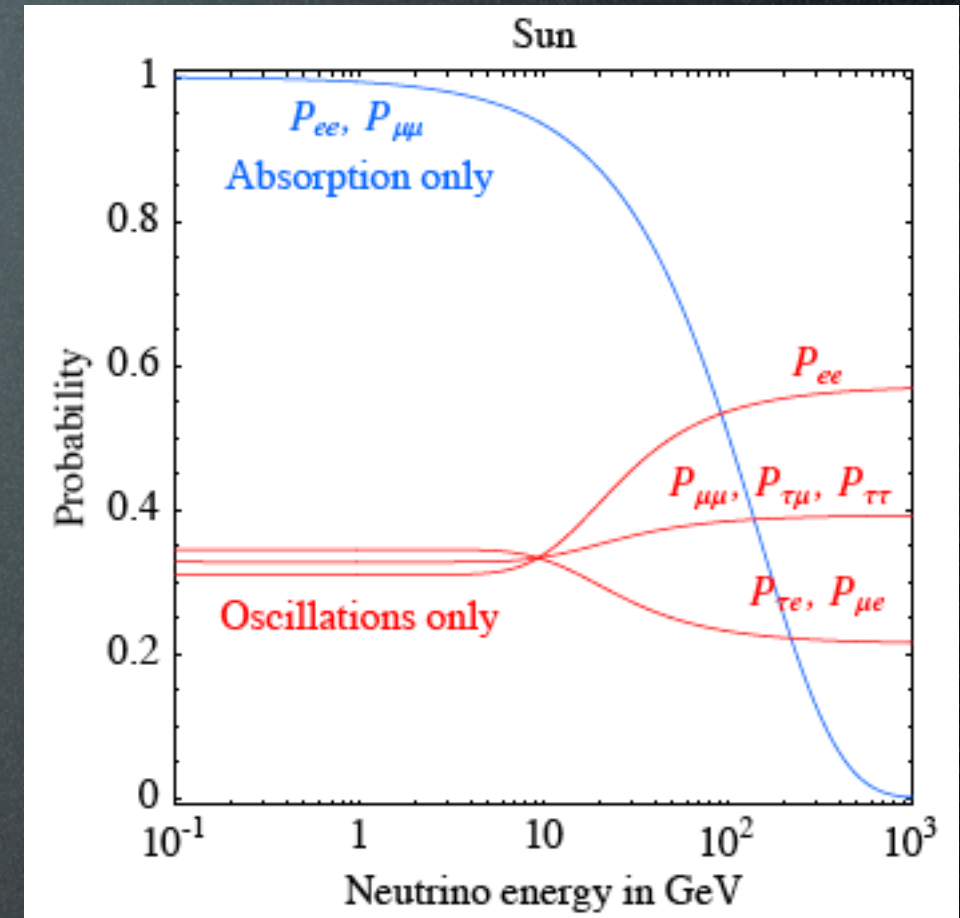
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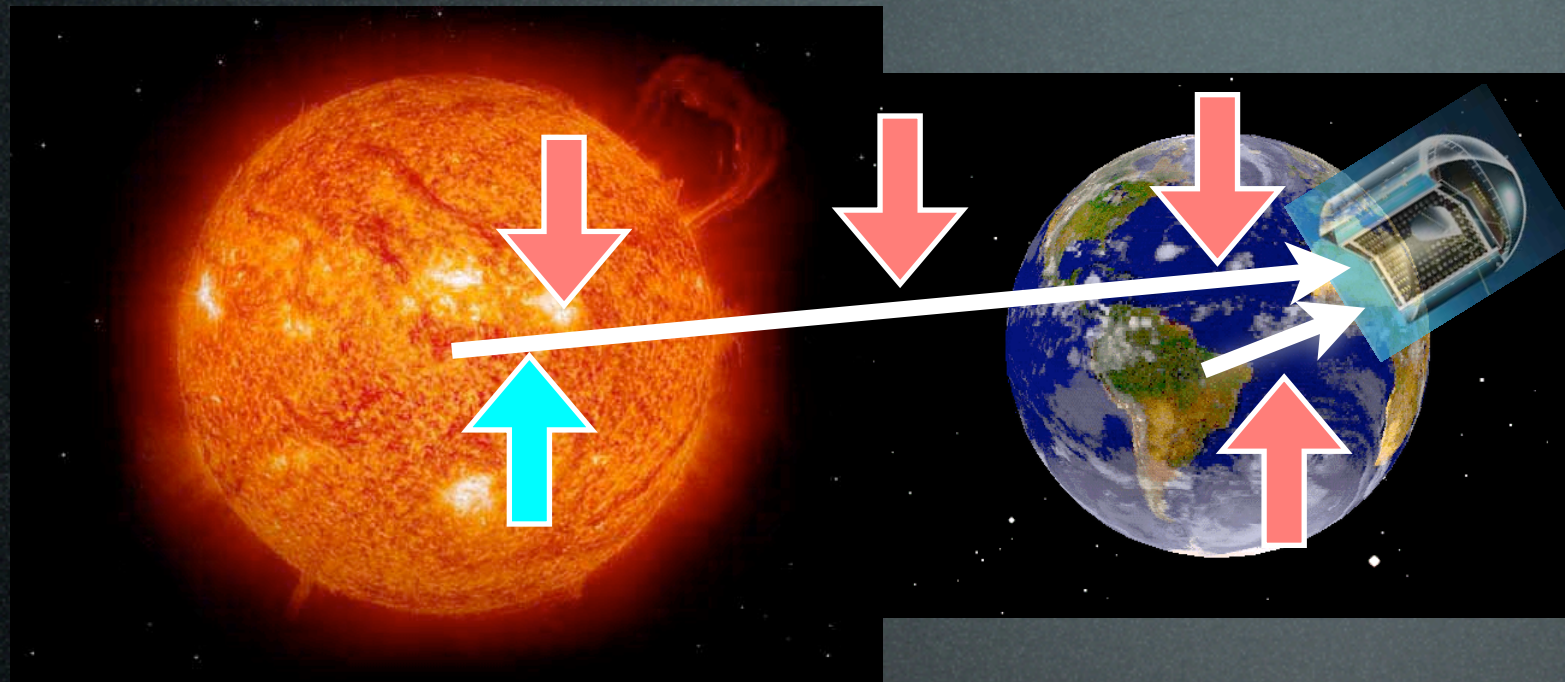
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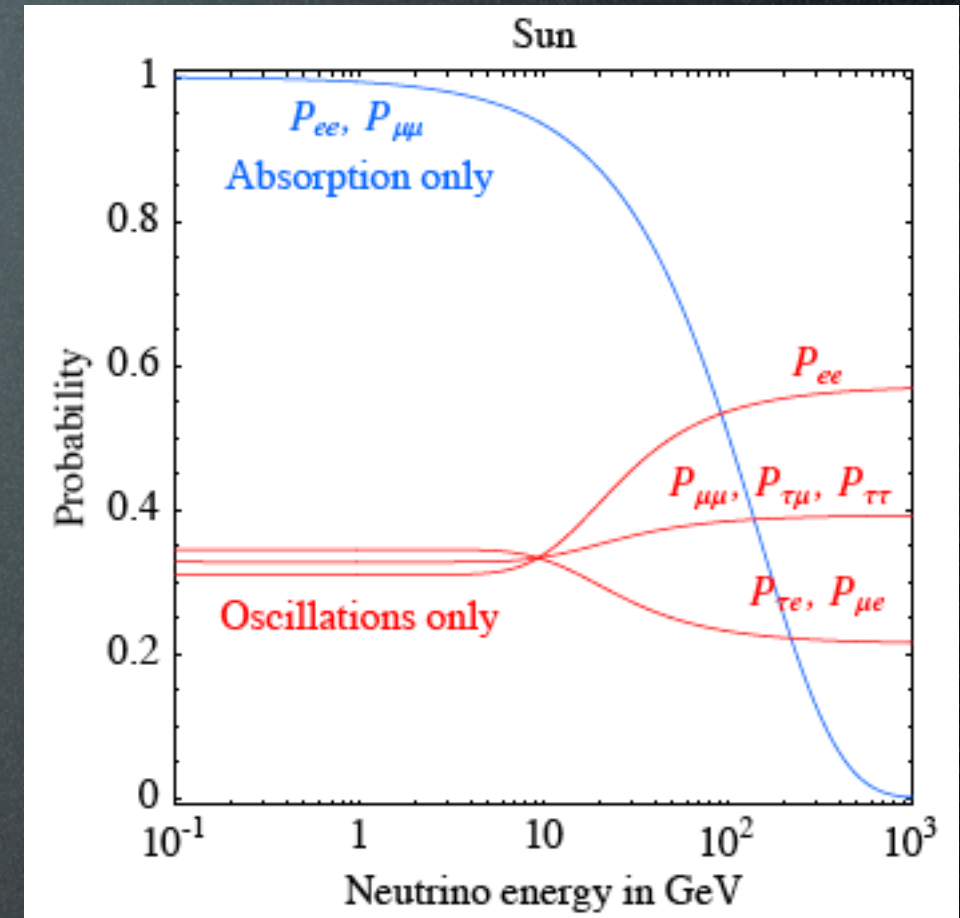
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Propagation

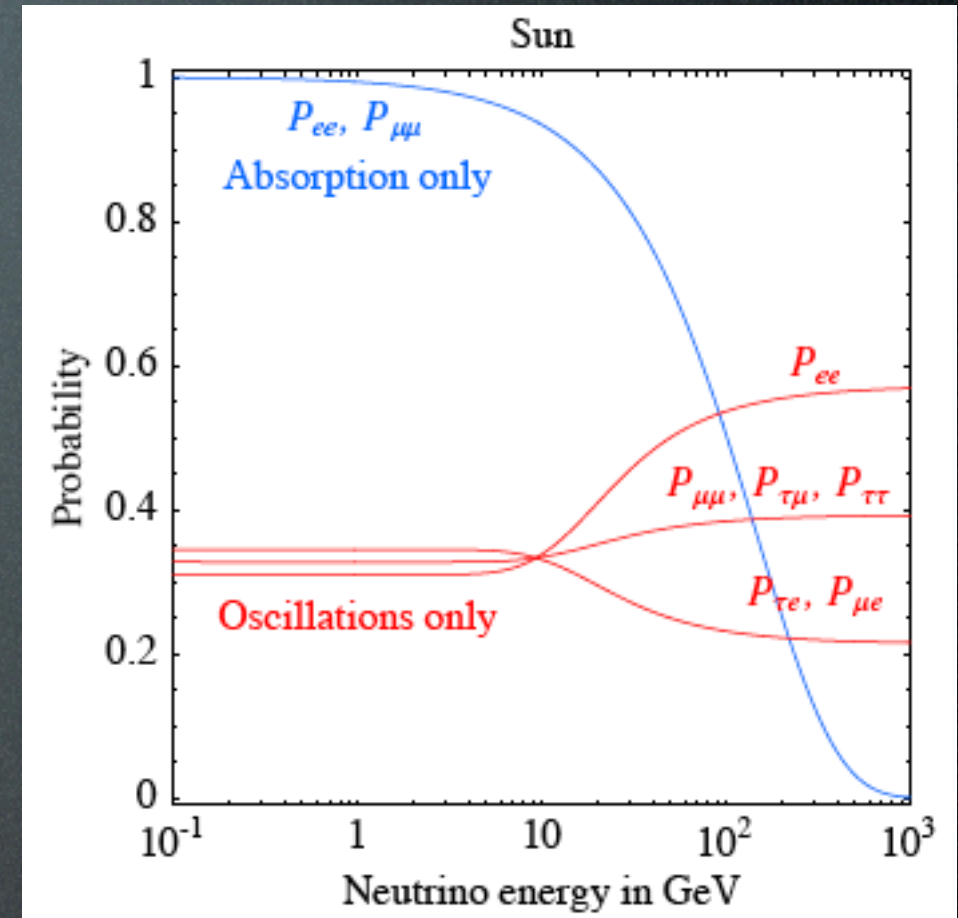
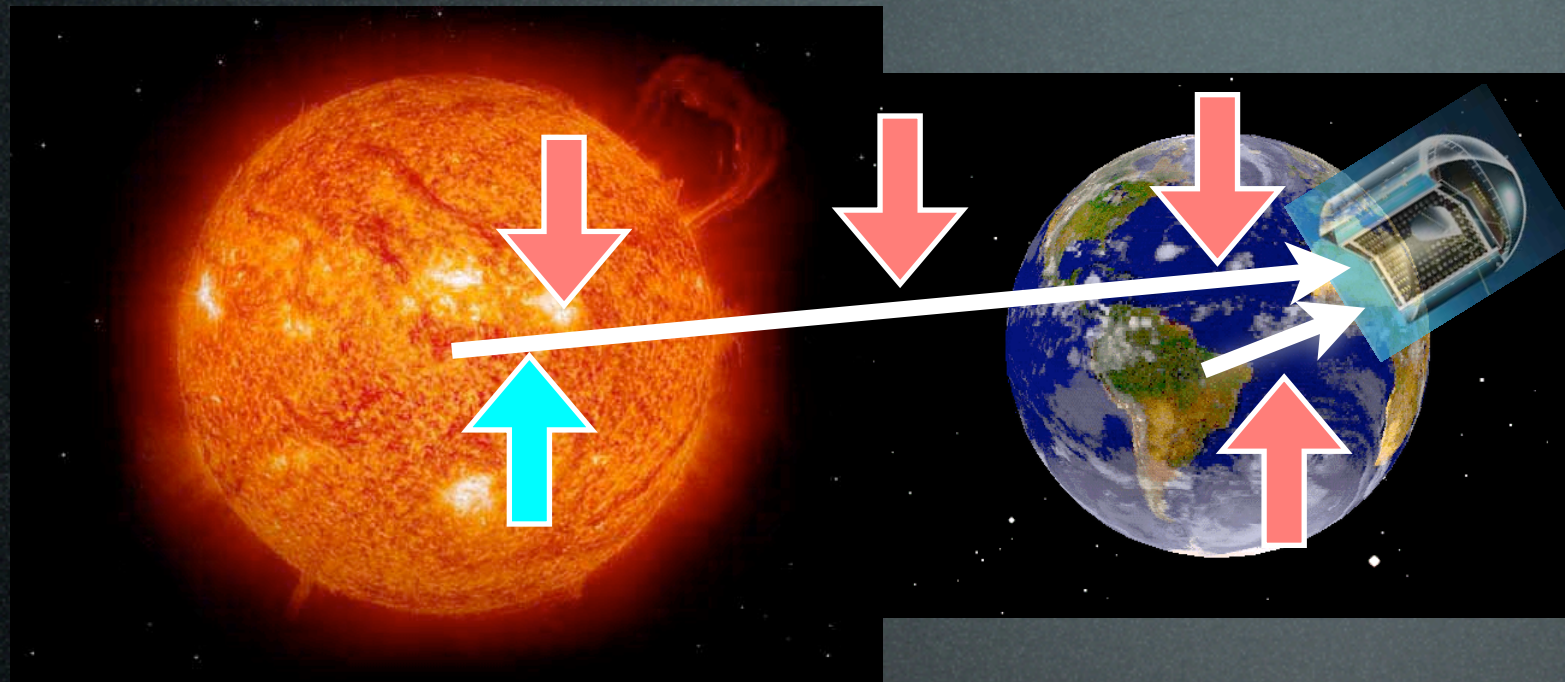


oscillations + interactions



production $\longrightarrow \begin{pmatrix} \Phi_{\nu_e} \\ \Phi_{\nu_\mu} \\ \Phi_{\nu_\tau} \end{pmatrix} \longrightarrow \text{detection}$

Propagation



oscillations + interactions

density matrix

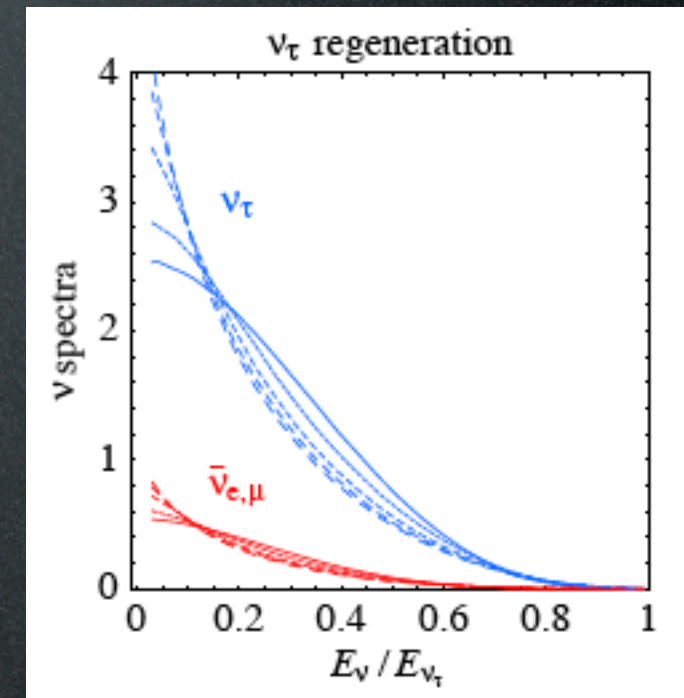
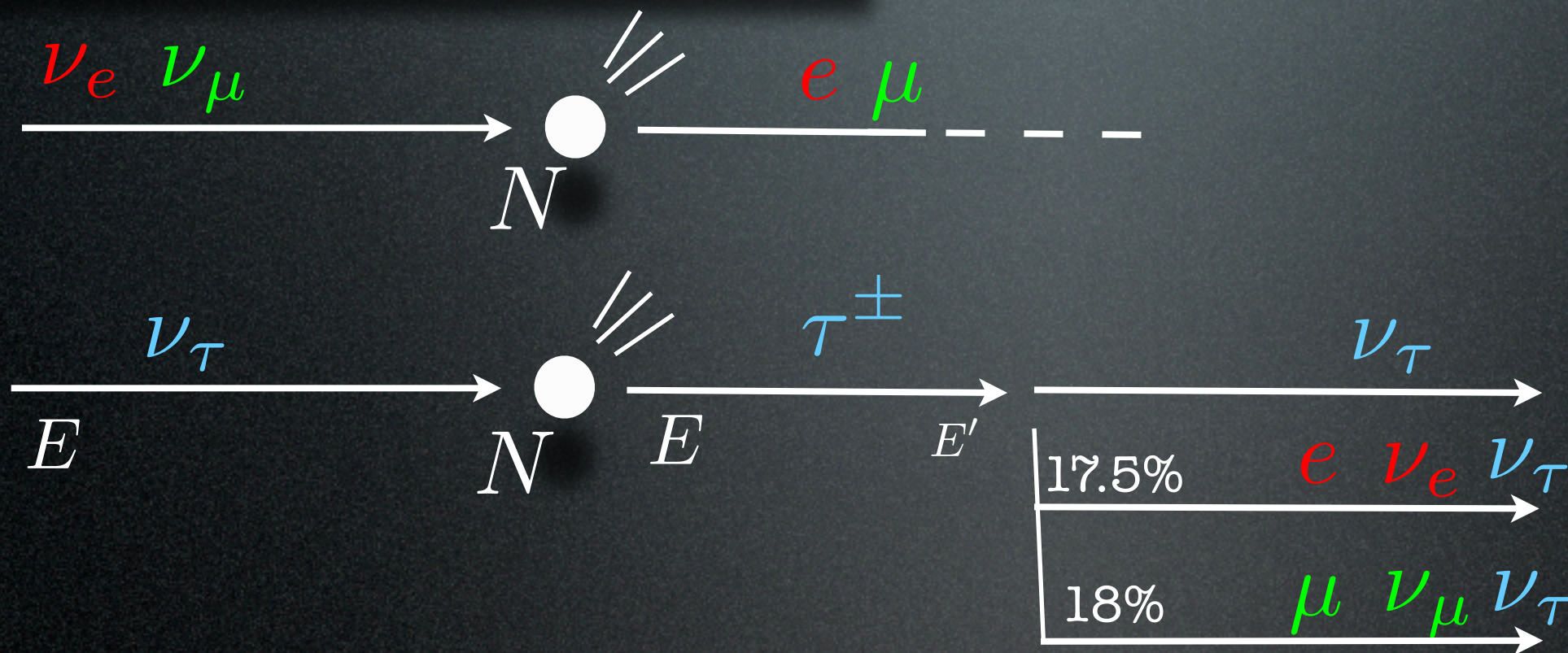
$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

full evolution equation:

$$\frac{d\rho}{dr} = -i[\mathbf{H}, \rho] + \left. \frac{d\rho}{dr} \right|_{\text{CC}} + \left. \frac{d\rho}{dr} \right|_{\text{NC}} + \left. \frac{d\rho}{dr} \right|_{\text{in}}$$

Propagation: CC absorption and tau regeneration

$$\frac{d\rho}{dr} = -i[\mathbf{H}, \rho] + \left. \frac{d\rho}{dr} \right|_{\text{CC}}$$



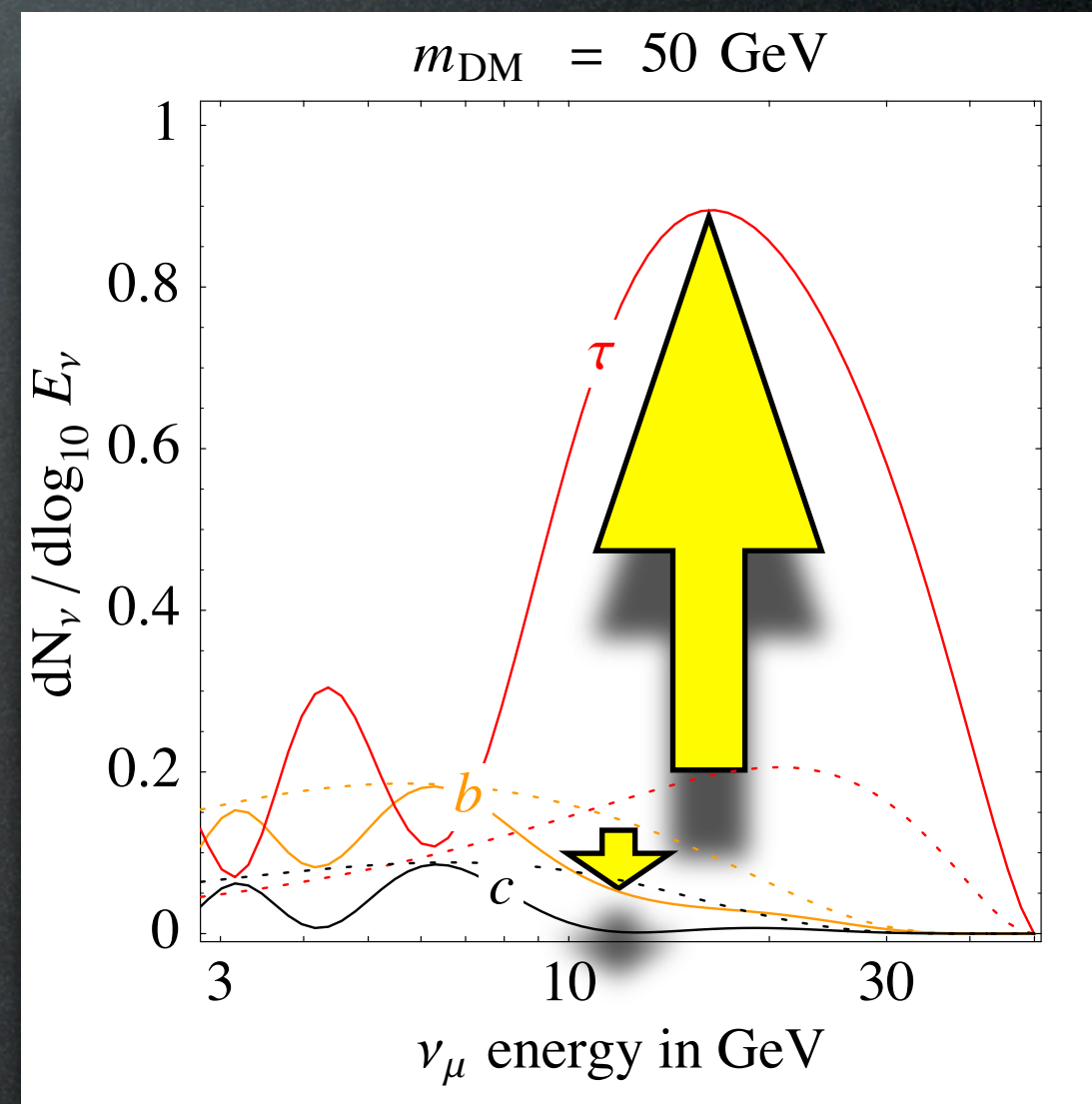
(re)generation

$$\left. \frac{d\rho}{dr} \right|_{\text{CC}} = -\frac{\{\Gamma_{\text{CC}}, \rho\}}{2} + \int \frac{dE_\nu^{\text{in}}}{E_\nu^{\text{in}}} \left[\mathbf{\Pi}_\tau \rho_{\tau\tau}(E_\nu^{\text{in}}) \Gamma_{\text{CC}}^\tau(E_\nu^{\text{in}}) f_{\tau \rightarrow \tau}(E_\nu^{\text{in}}, E_\nu) \right. \\ \left. + \mathbf{\Pi}_{e,\mu} \bar{\rho}_{\tau\tau}(E_\nu^{\text{in}}) \bar{\Gamma}_{\text{CC}}^\tau(E_\nu^{\text{in}}) f_{\bar{\tau} \rightarrow e,\mu}(E_\nu^{\text{in}}, E_\nu) \right]$$

Propagation: summary

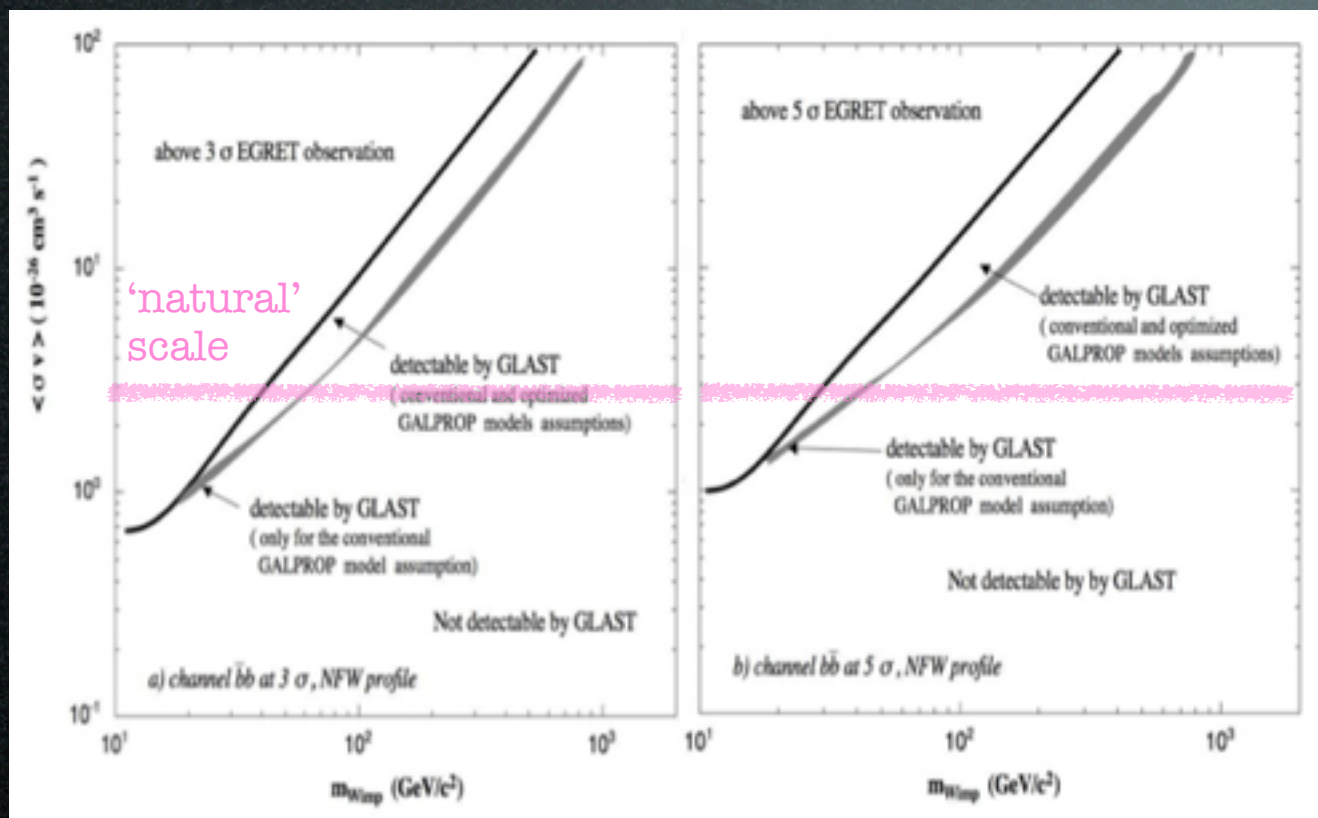
Effects of oscillations and interactions:

- reshuffle of the 3 flavors
(oscillations and regeneration)
- attenuation of the fluxes
- degradation of energy
(distortion of spectra)

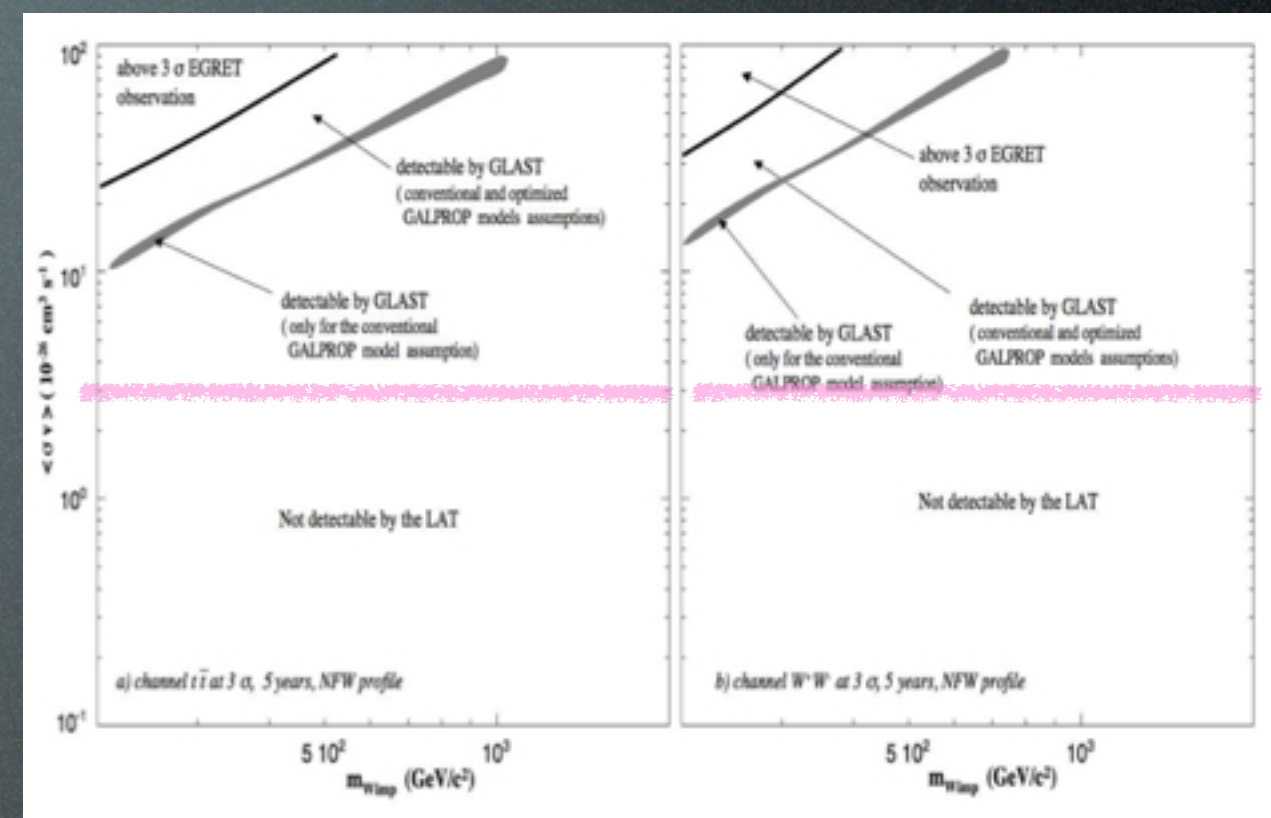


Gamma reach

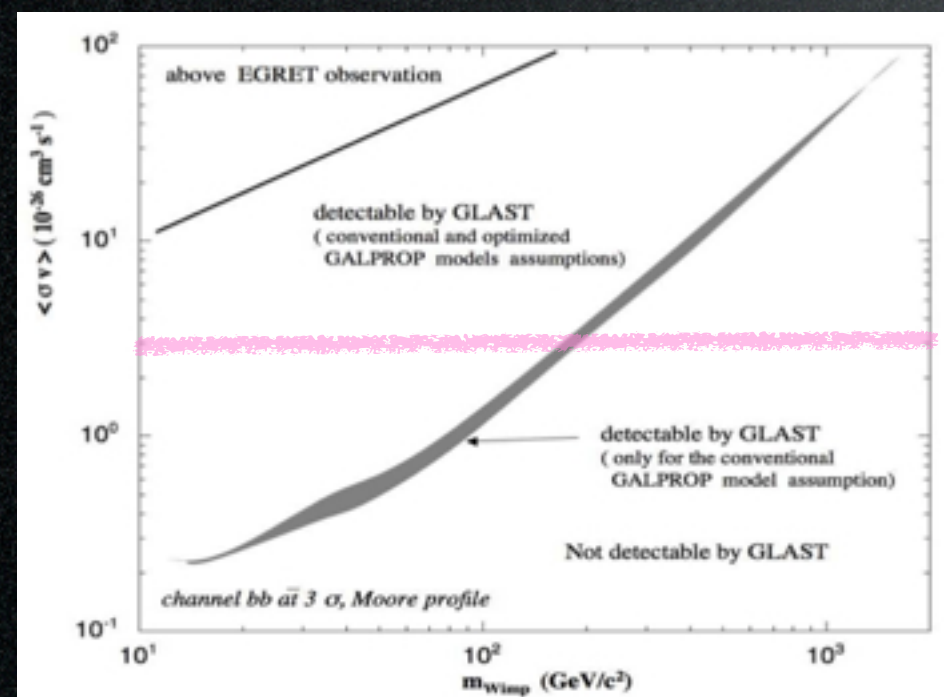
'Fermi pre-launch estimates', Baltz et al., 0806.2911



Diffuse galactic gamma ($b\bar{b}$ channel)



($t\bar{t}$, W^+W^- channel)



With a bit of luck,
Fermi will see signals.

Dwarf Satellites