23 October 2013
'New Perspectives in Dark Matter', Lyon

DM indirect detection with γ-rays:

status and some recent developments

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(CNRS IPhT Saclay)

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DM indirect detection with γ-rays:

status and some recent developments

(and maybe neutrinos)

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(CNRS IPhT Saclay)

OUTLINE

- How does DM produces γ-rays? An overview.

- Current status of searches: mainly constraints

- Some recent developments:
  - -- bremsstrahlung γ-rays from light DM
  - -- FERMI 130 GeV line
  - -- excesses near the Galactic Center

How does DM produce γ-rays?

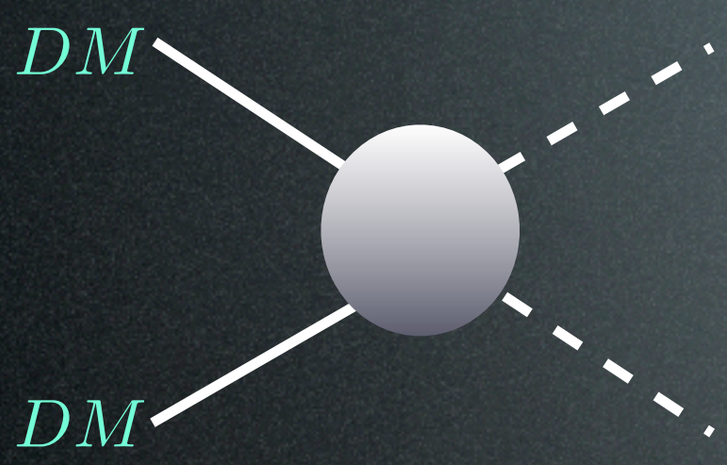
1. prompt emission

1a. continuum **1b.** line(s) **1c.** sharp features

2. secondary emission

2a. ICS **2b.** bremsstrahlung **2c.** synchrotron

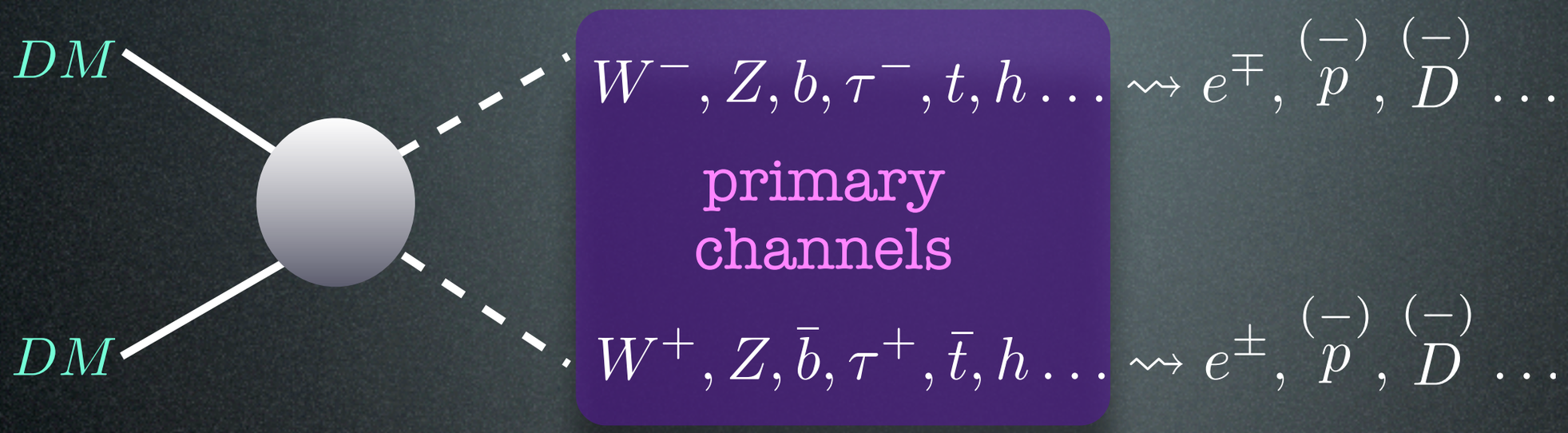
Prompt emission: continuum



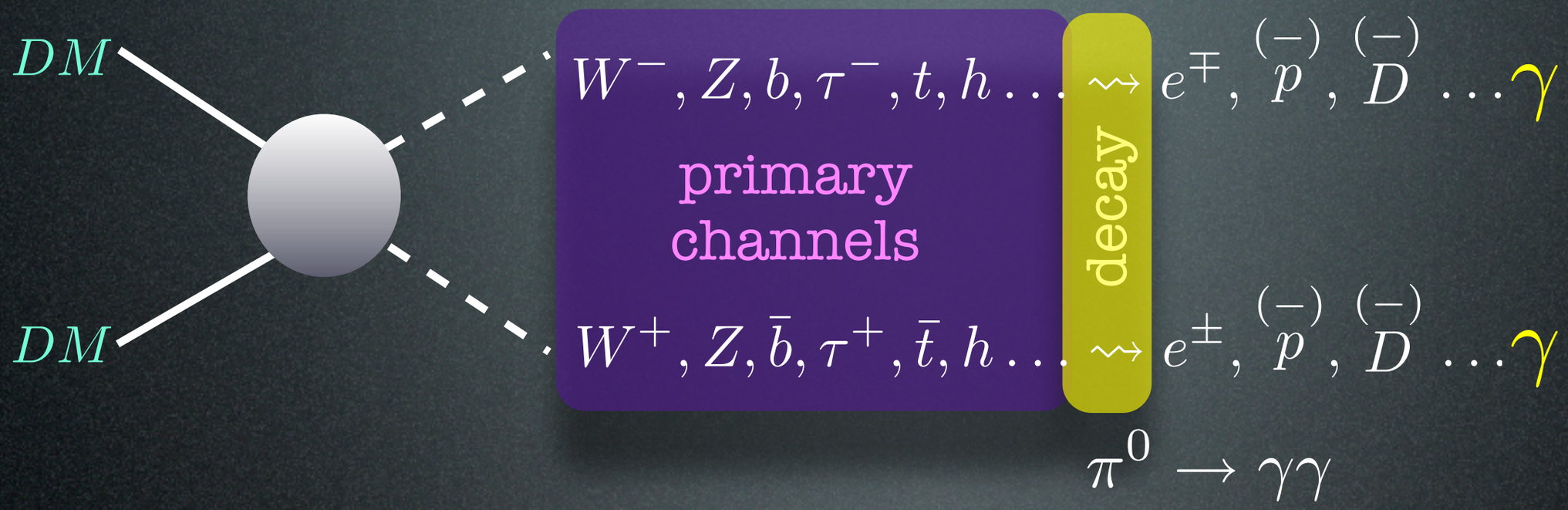
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

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

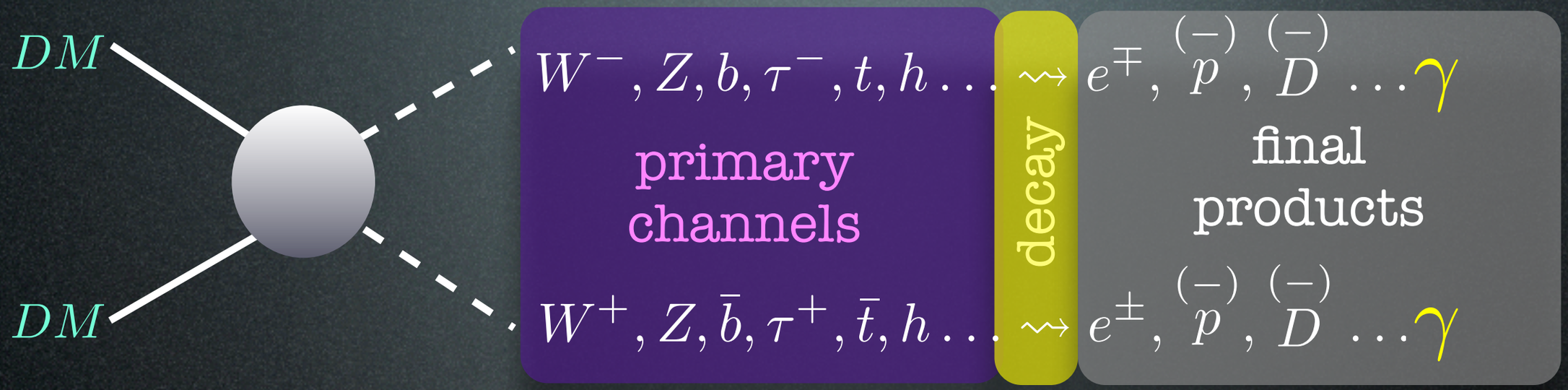
Prompt emission: continuum

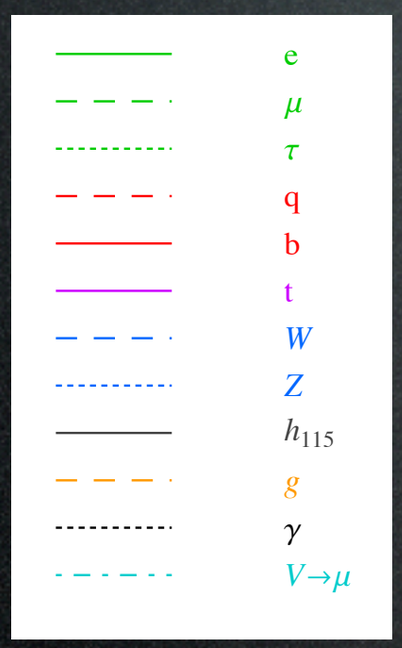


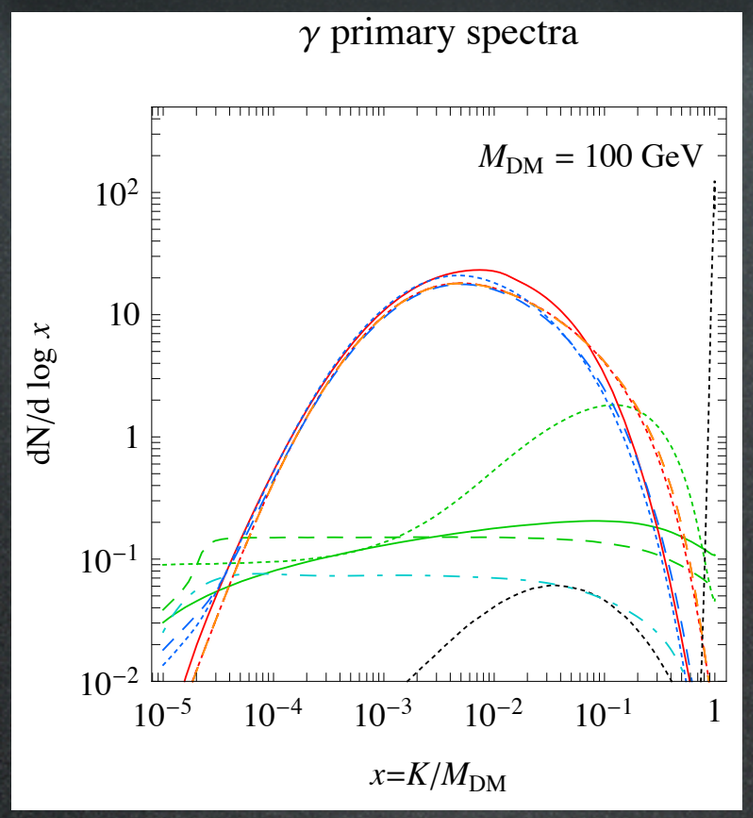
Prompt emission: continuum

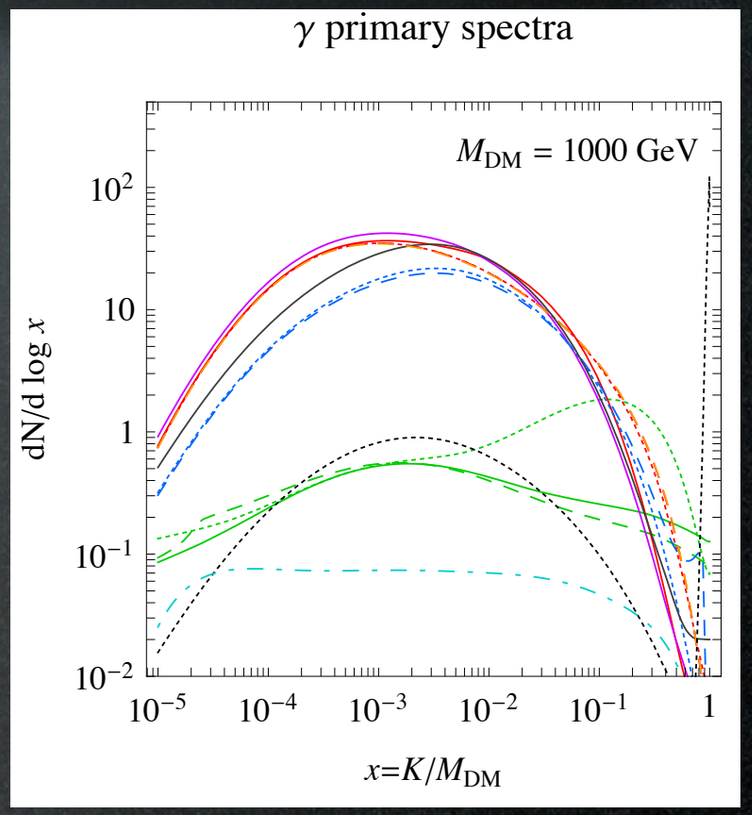


Prompt emission: continuum

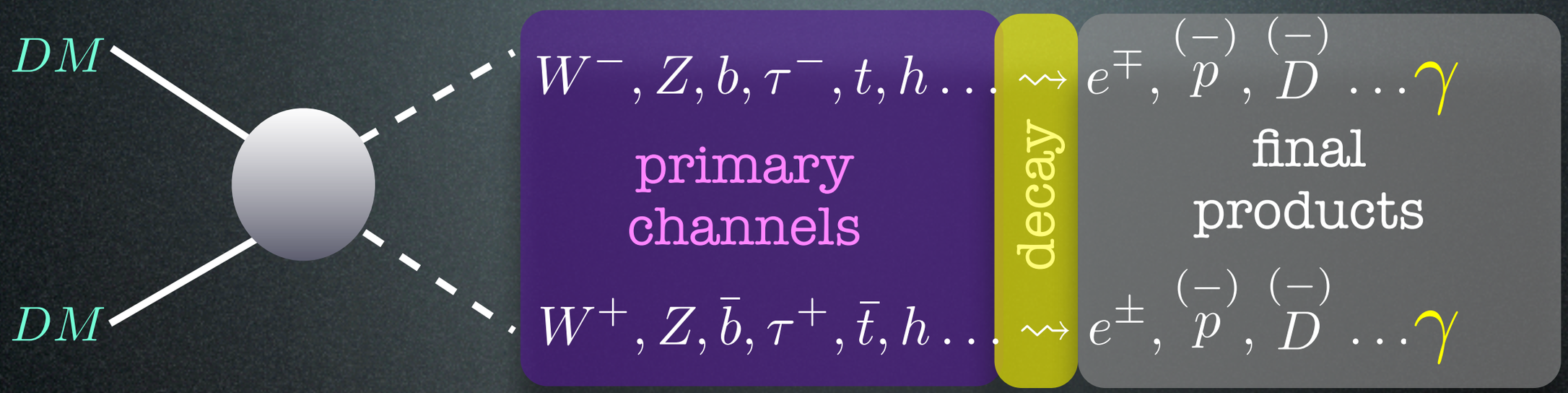


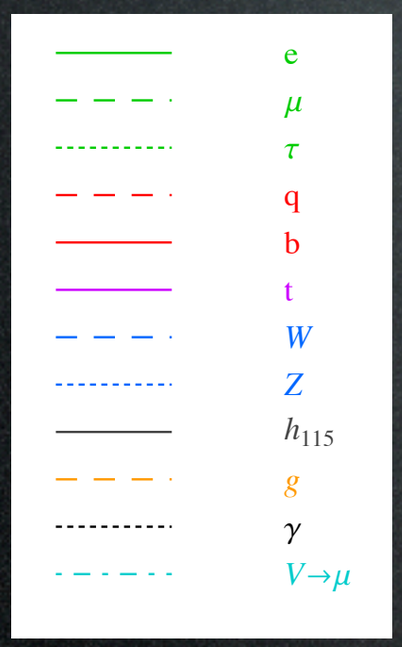


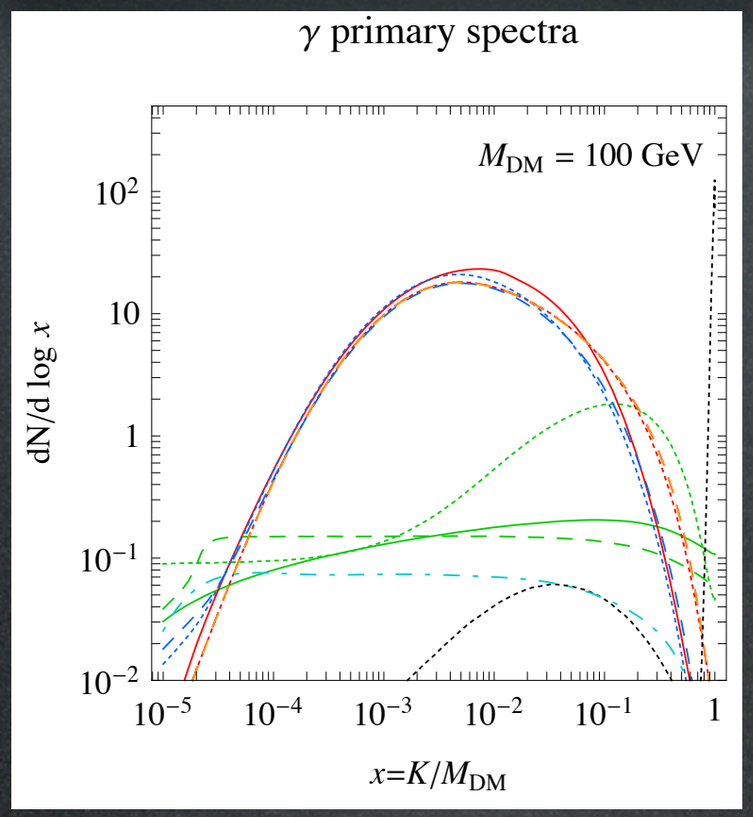


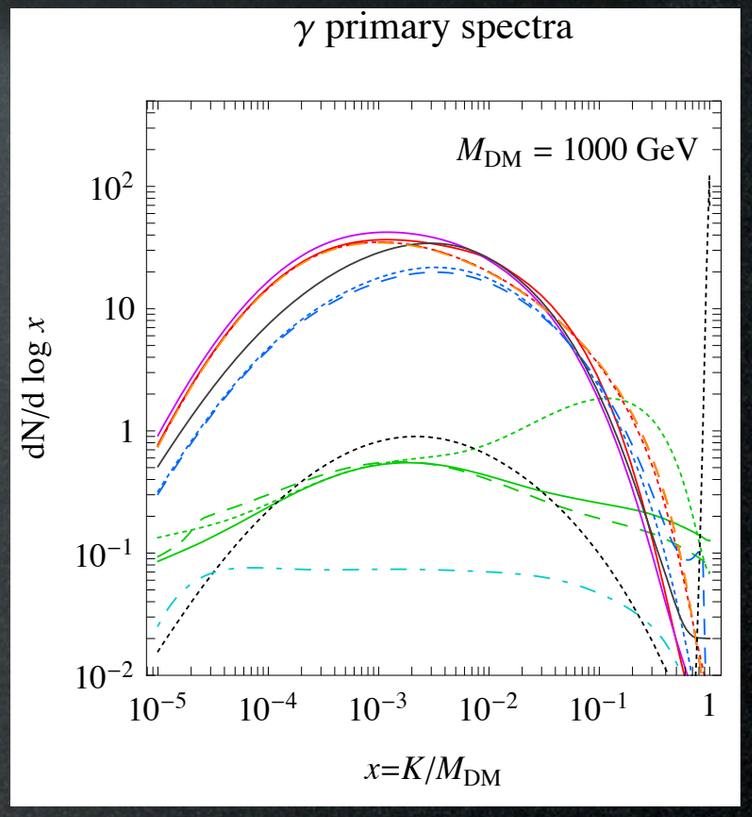


Prompt emission: continuum





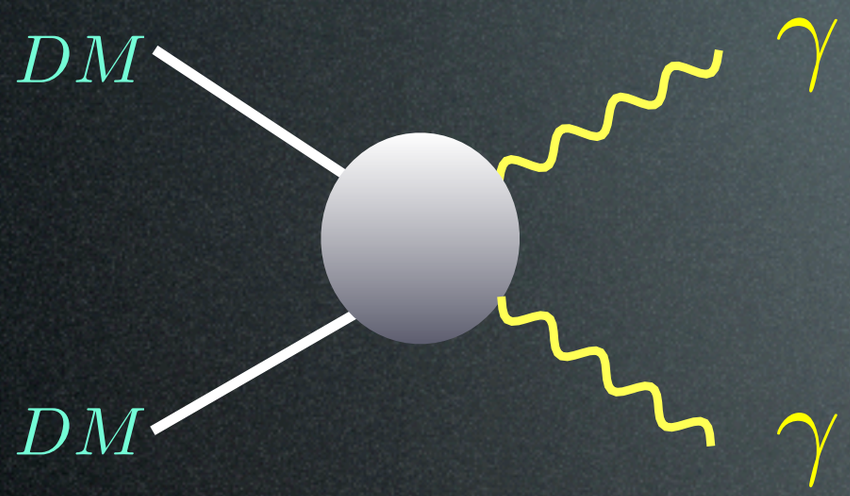




So what are the particle physics parameters?

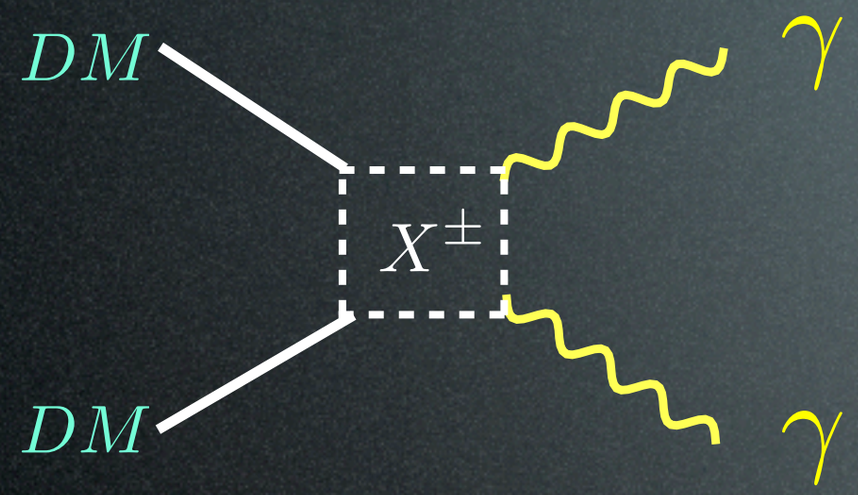
1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: line(s)



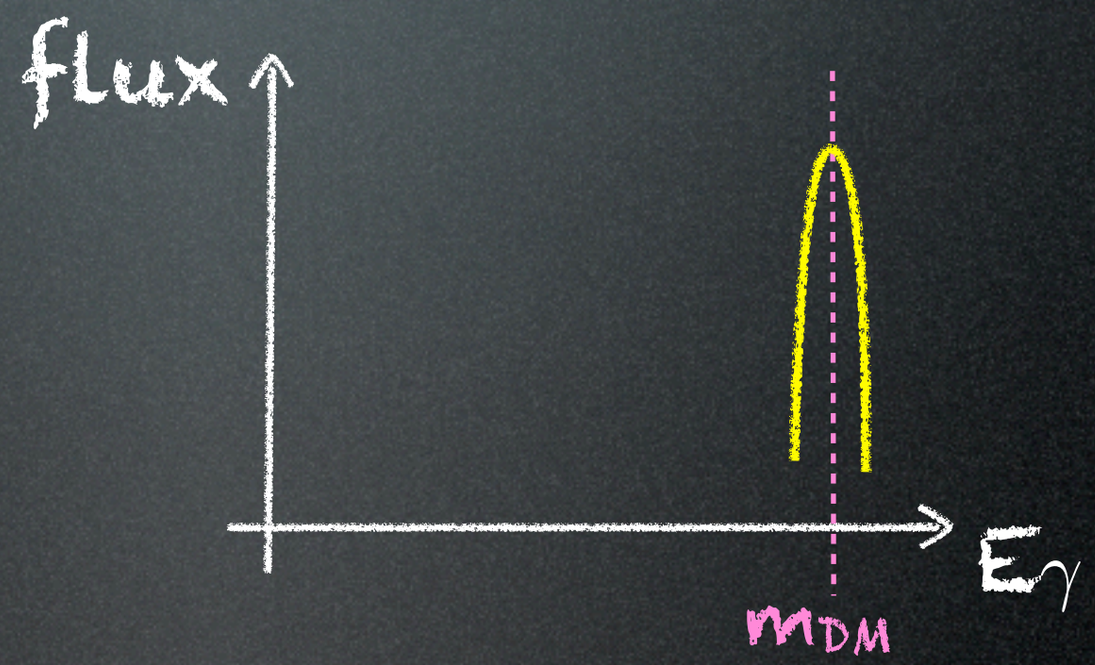
primary channels

Prompt emission: line(s)

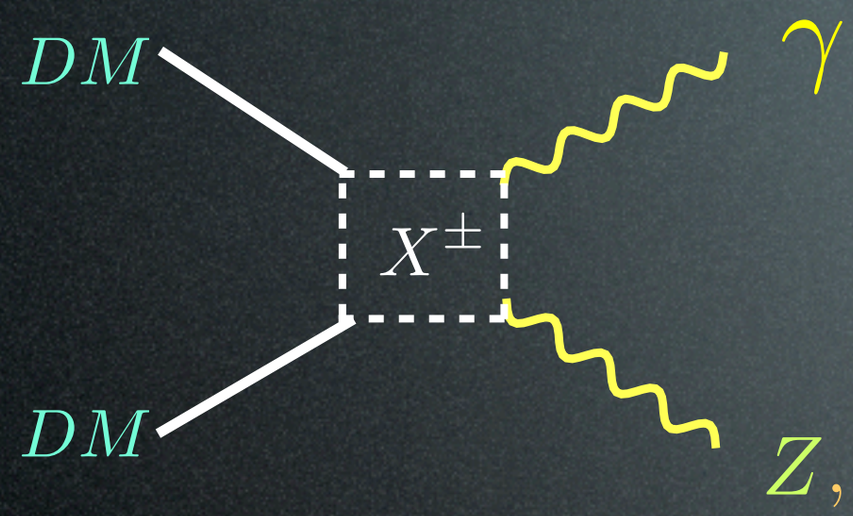


primary channels

$$E_\gamma = m_{\rm DM}$$



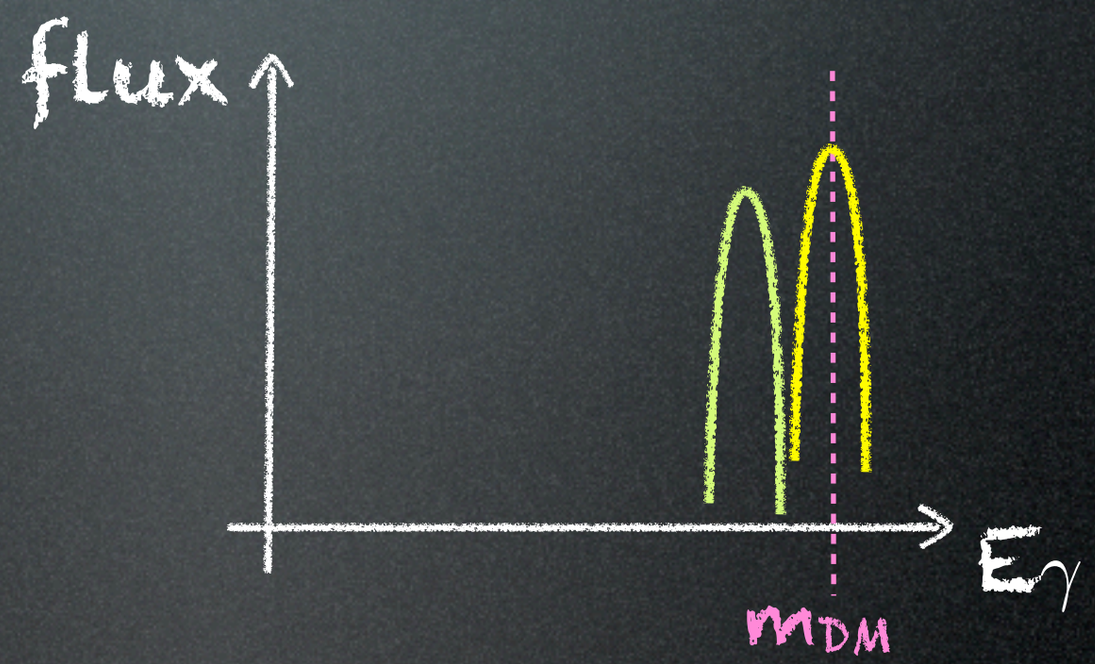
Prompt emission: line(s)



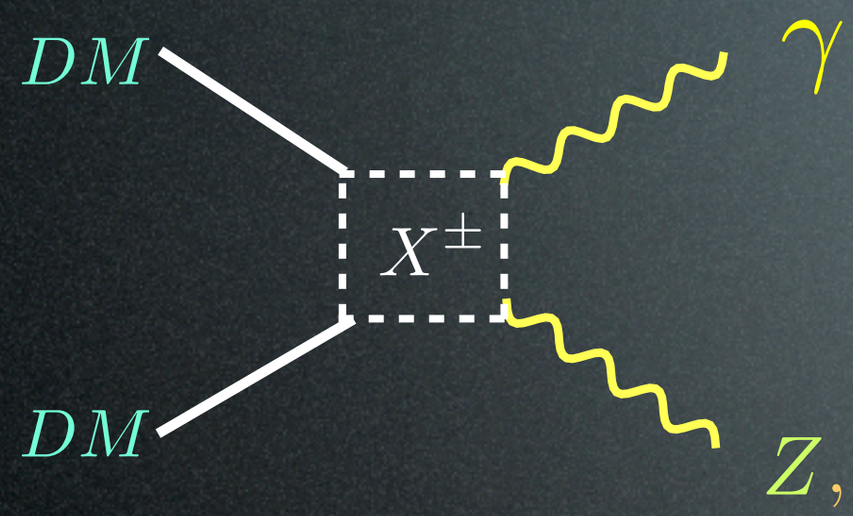
primary channels

$$E_\gamma = m_{\rm DM}$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_Z^2}{4\,m_{\rm DM}^2}\right)$$



Prompt emission: line(s)



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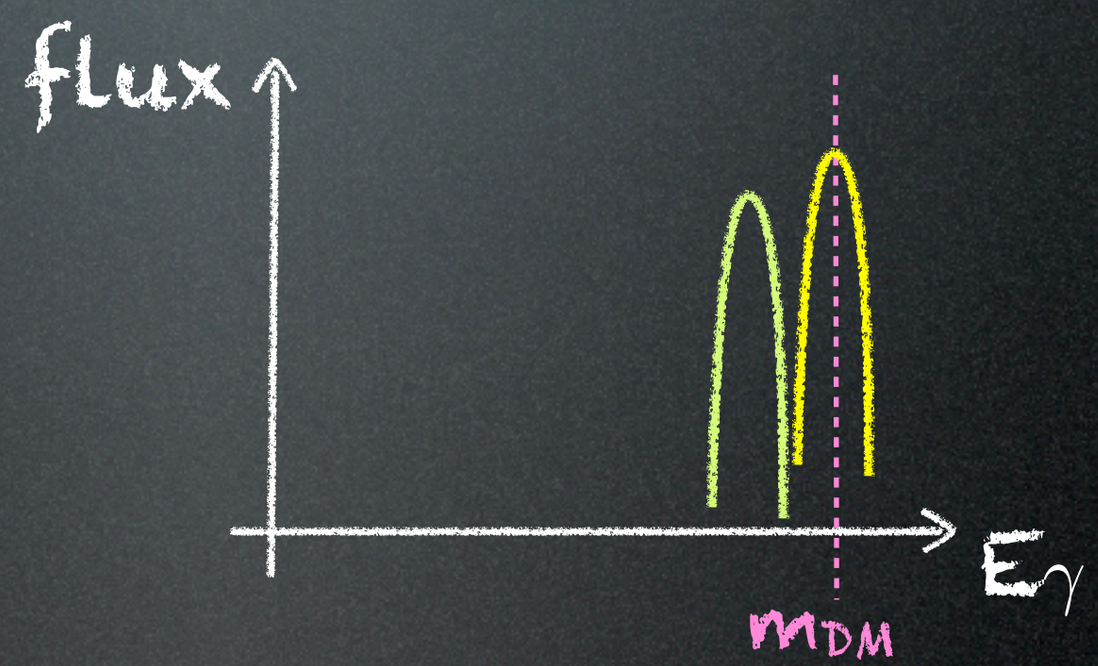
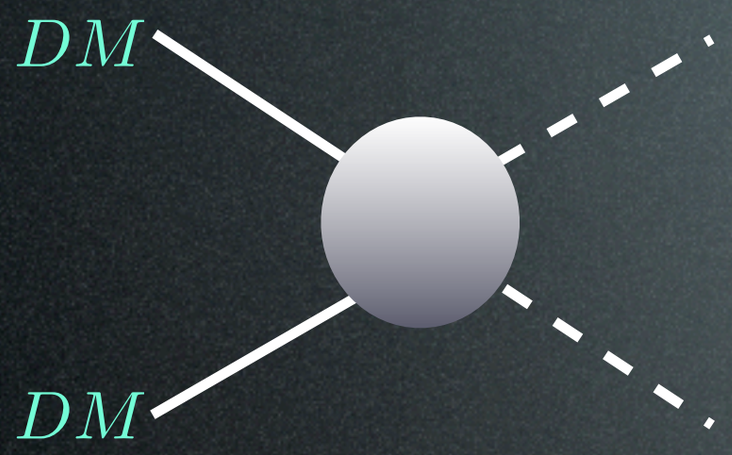


So what are the particle physics parameters?

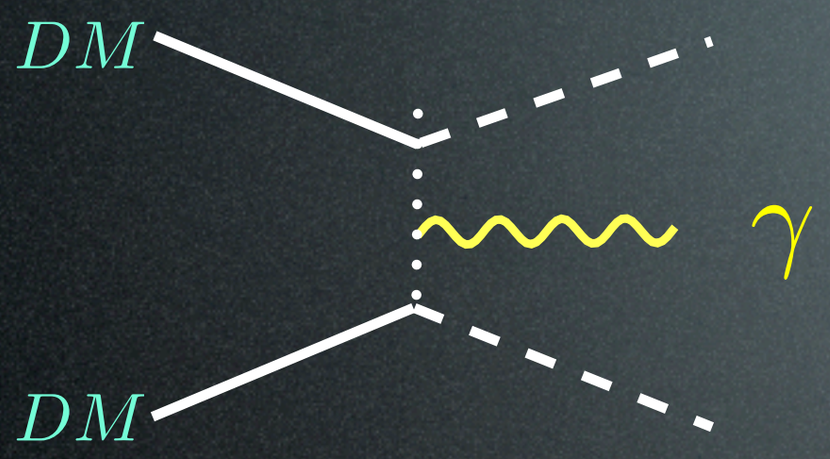
1. Dark Matter mass

2. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: sharp features



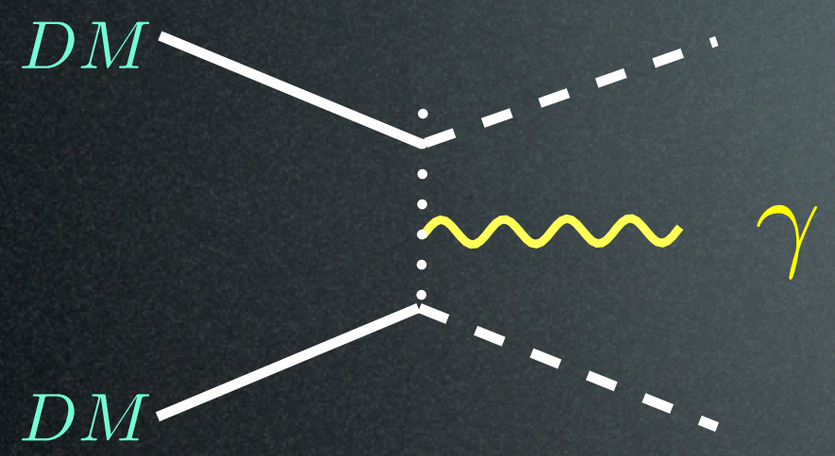
Prompt emission: sharp features



Internal Bremsstrahlung

Bergström 1989

Prompt emission: sharp features



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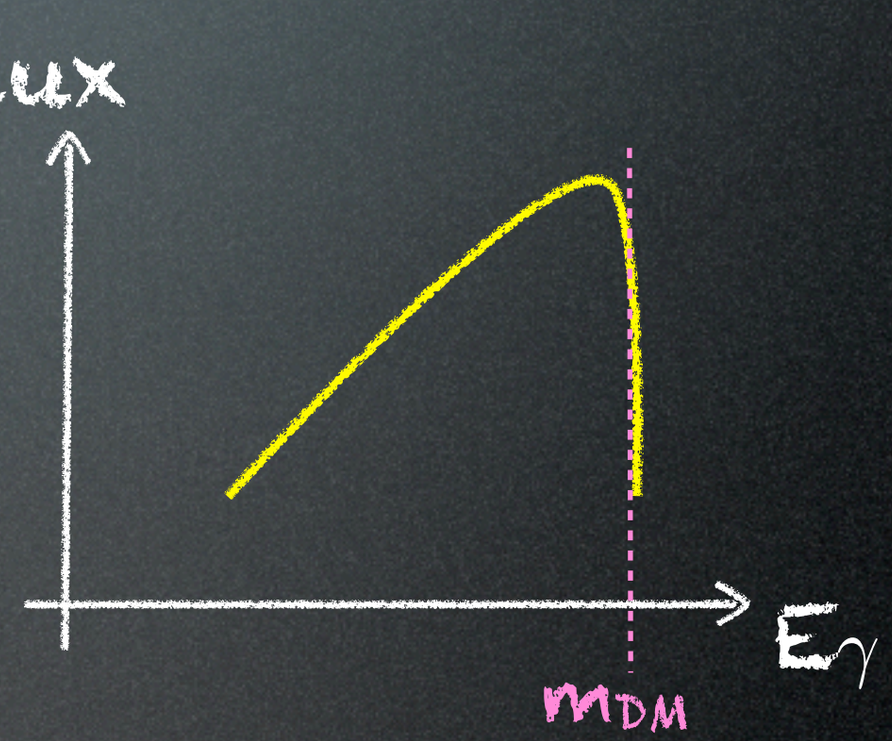
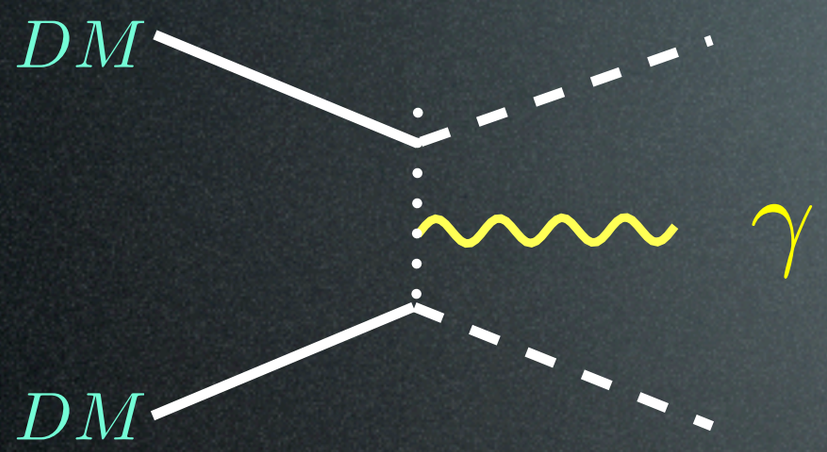
Bergström 1989



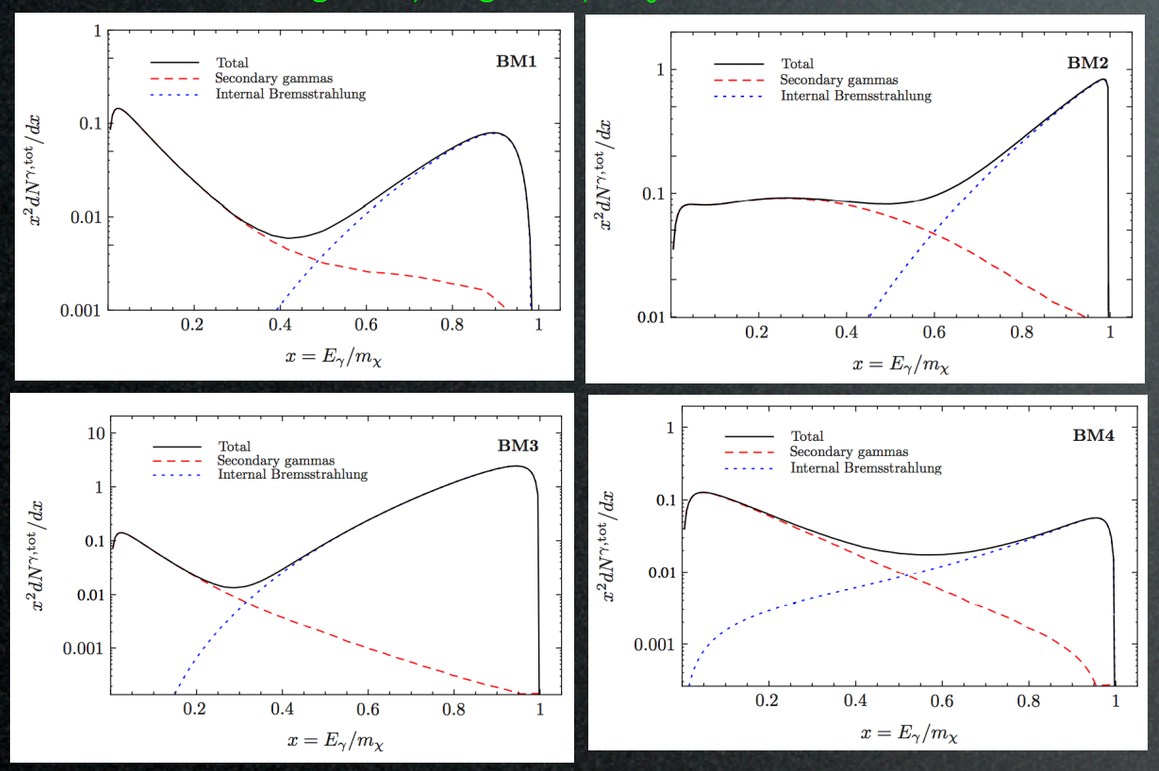
Prompt emission: sharp features

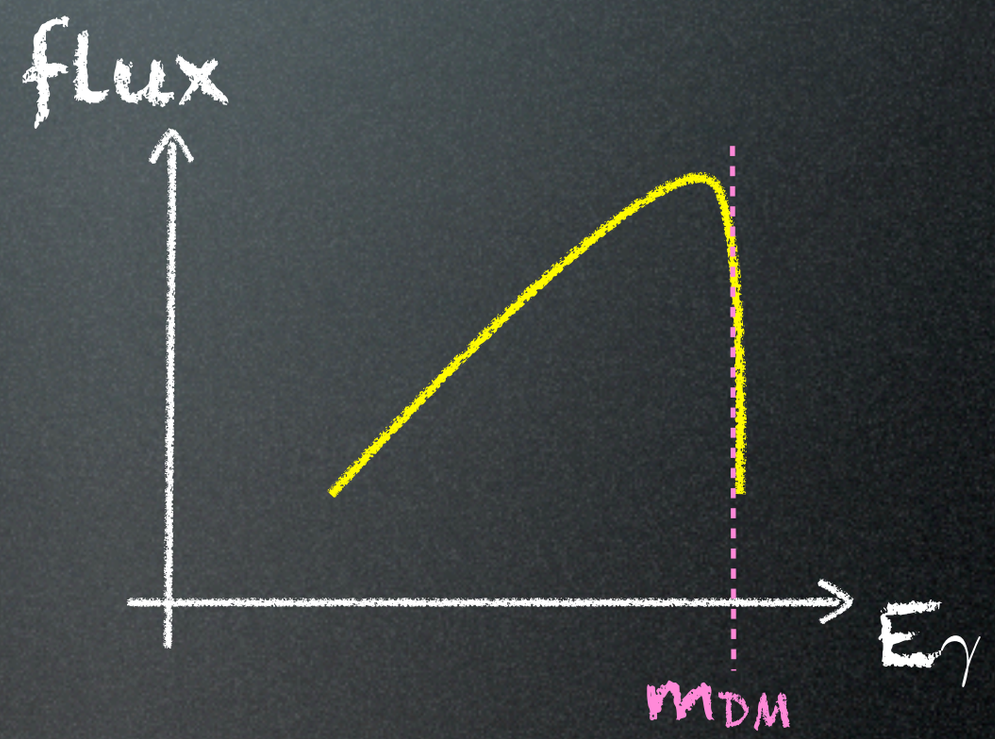


Internal Bremsstrahlung

Bergström 1989

Bringmann, Bergstrom, Edsjo 0710.3169



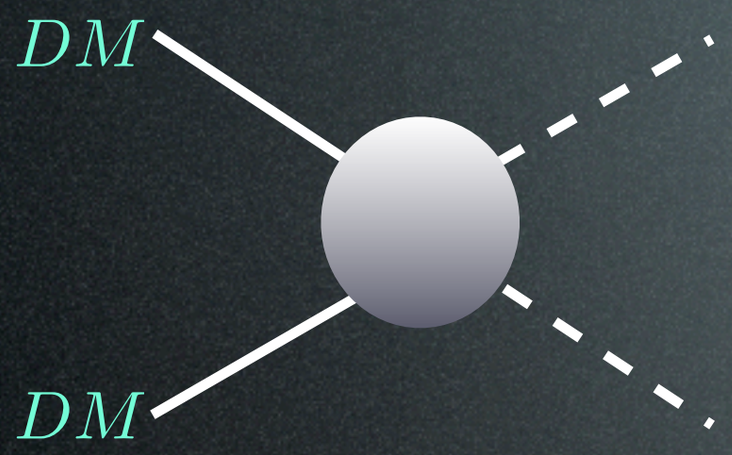


So what are the particle physics parameters?

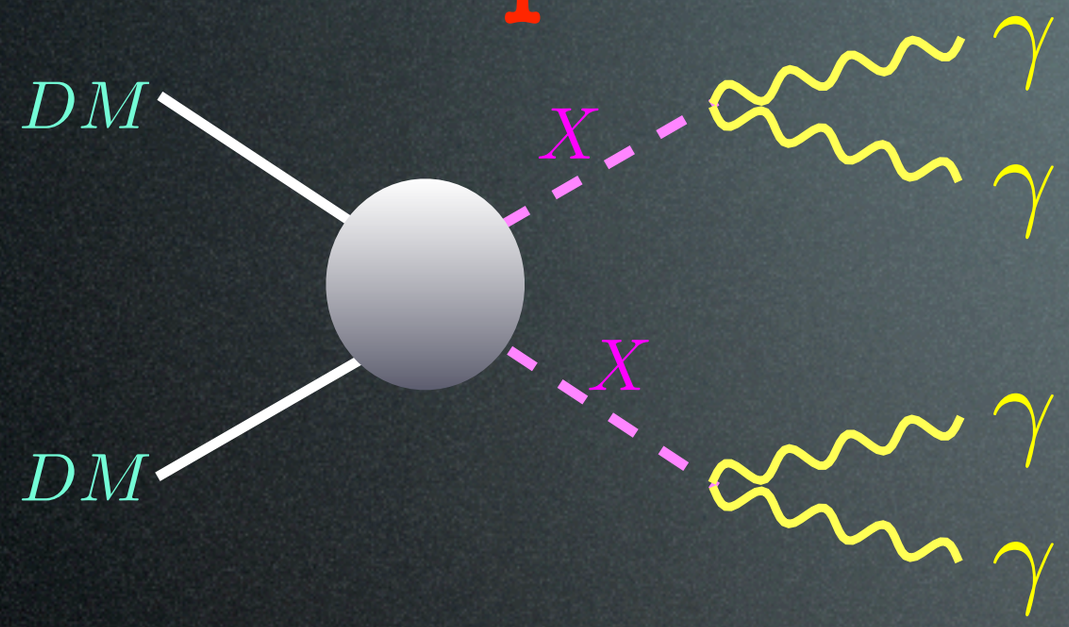
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



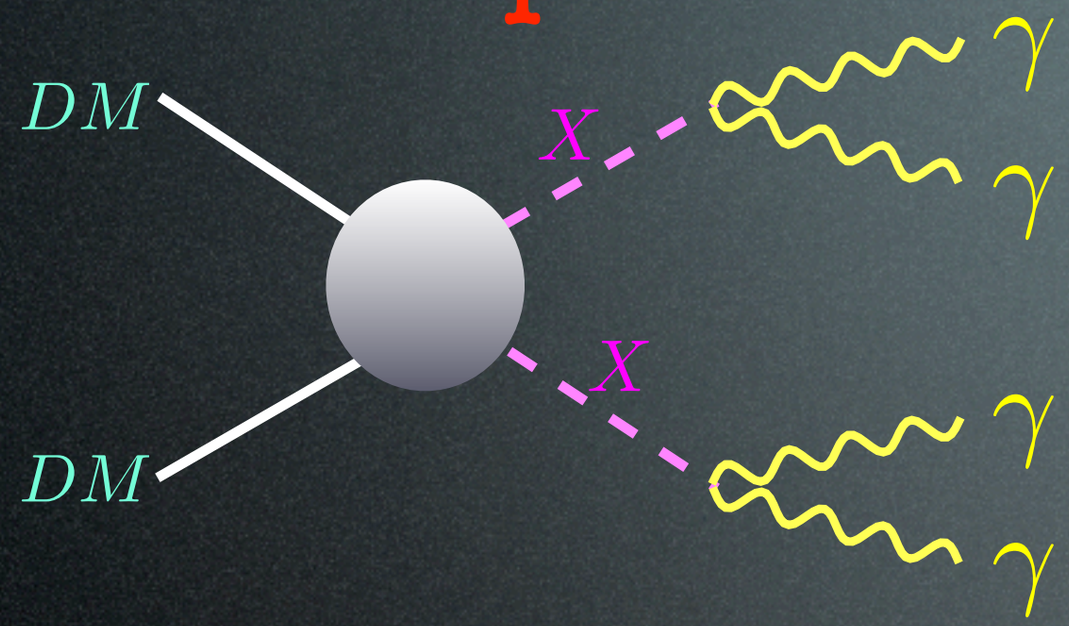
Prompt emission: sharp features



Metastable intermediate states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

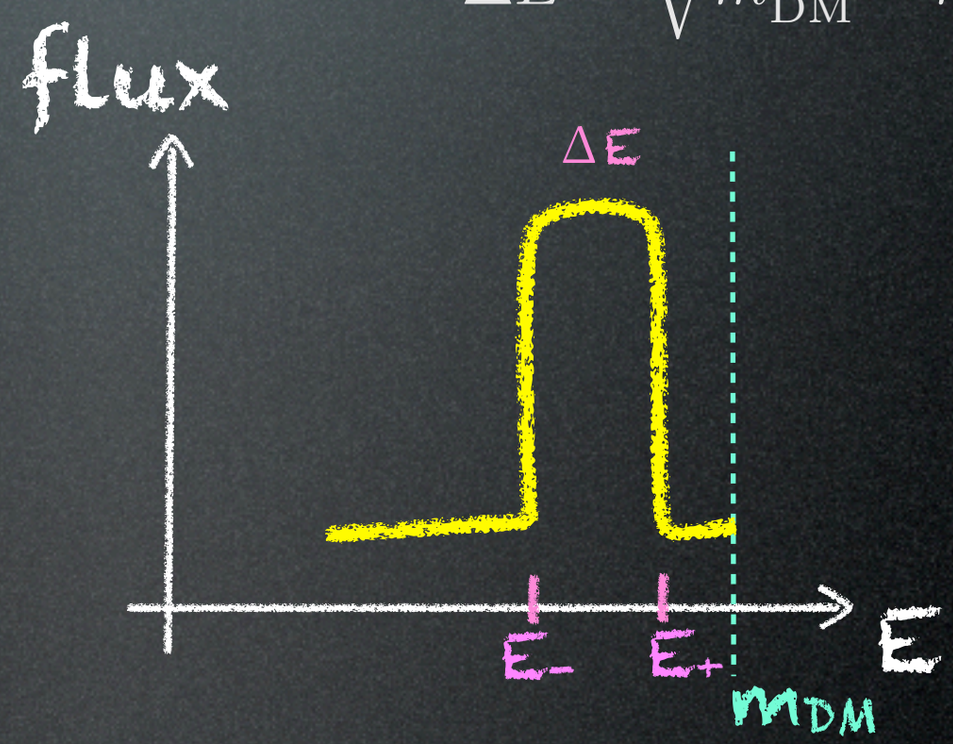


Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

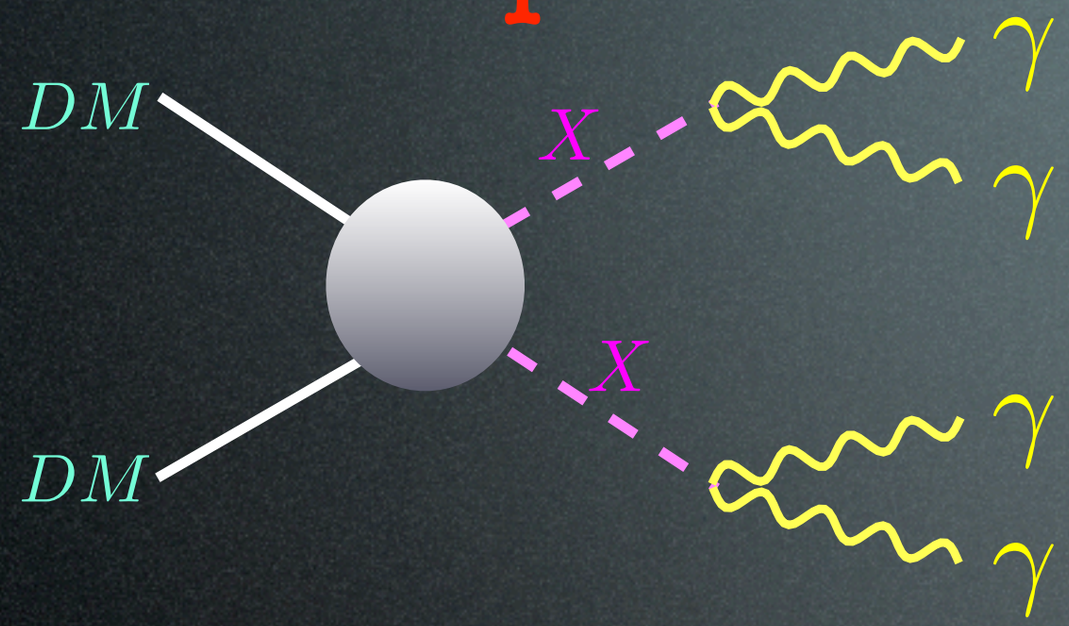
Metastable intermediate states

$$E_\pm = \frac{m_{\rm DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_{\rm X}^2}{m_{\rm DM}^2}}\right)$$

$$\Delta E = \sqrt{m_{\rm DM}^2 - m_{\rm X}^2}$$



Prompt emission: sharp features



Ibarra, Lopez Gehler, Pato 1205.0007
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Metastable intermediate states

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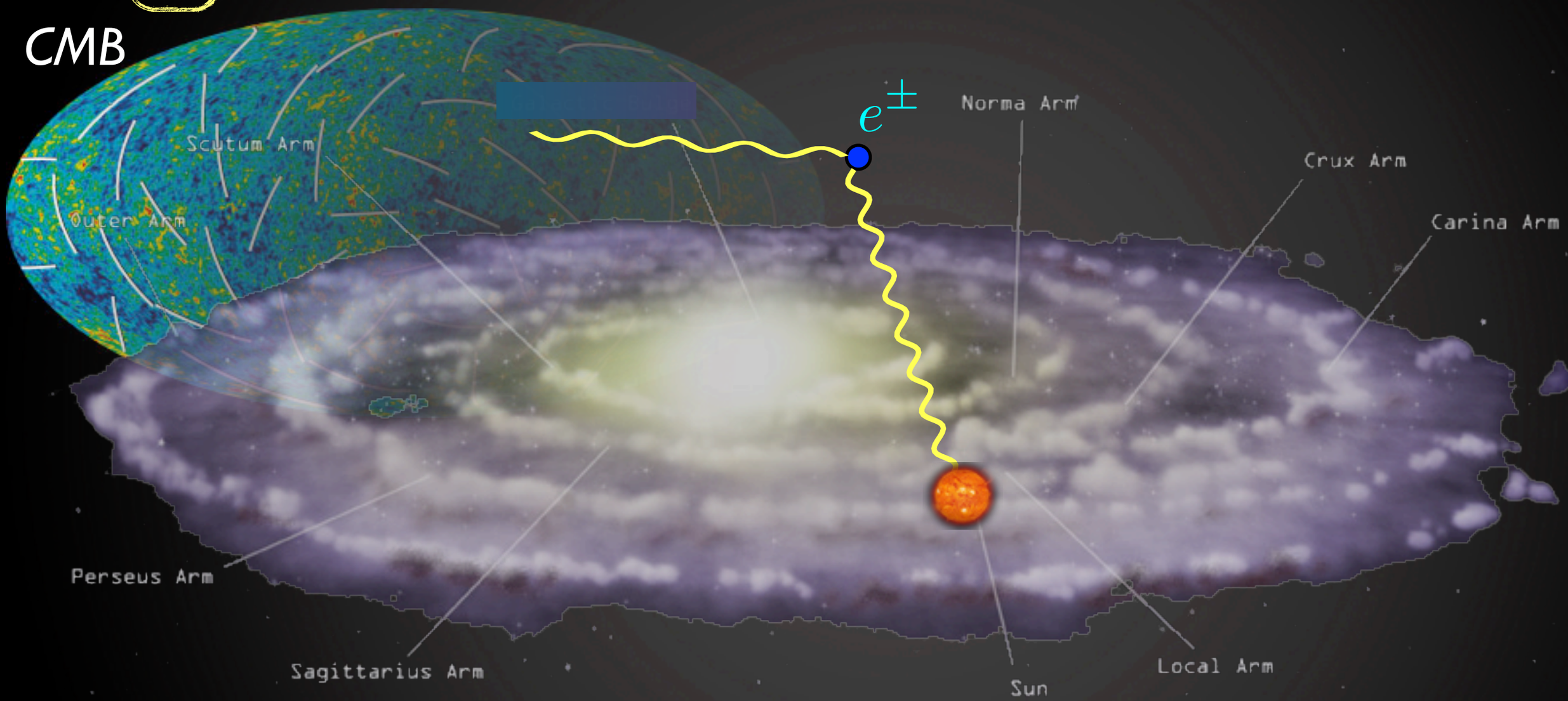
$$\Delta E = \sqrt{m_{\rm DM}^2 - m_{\rm X}^2}$$

So what are the particle physics parameters?

1. Dark Matter mass
2. The mediator mass

Secondary emission

a. 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

Secondary emission

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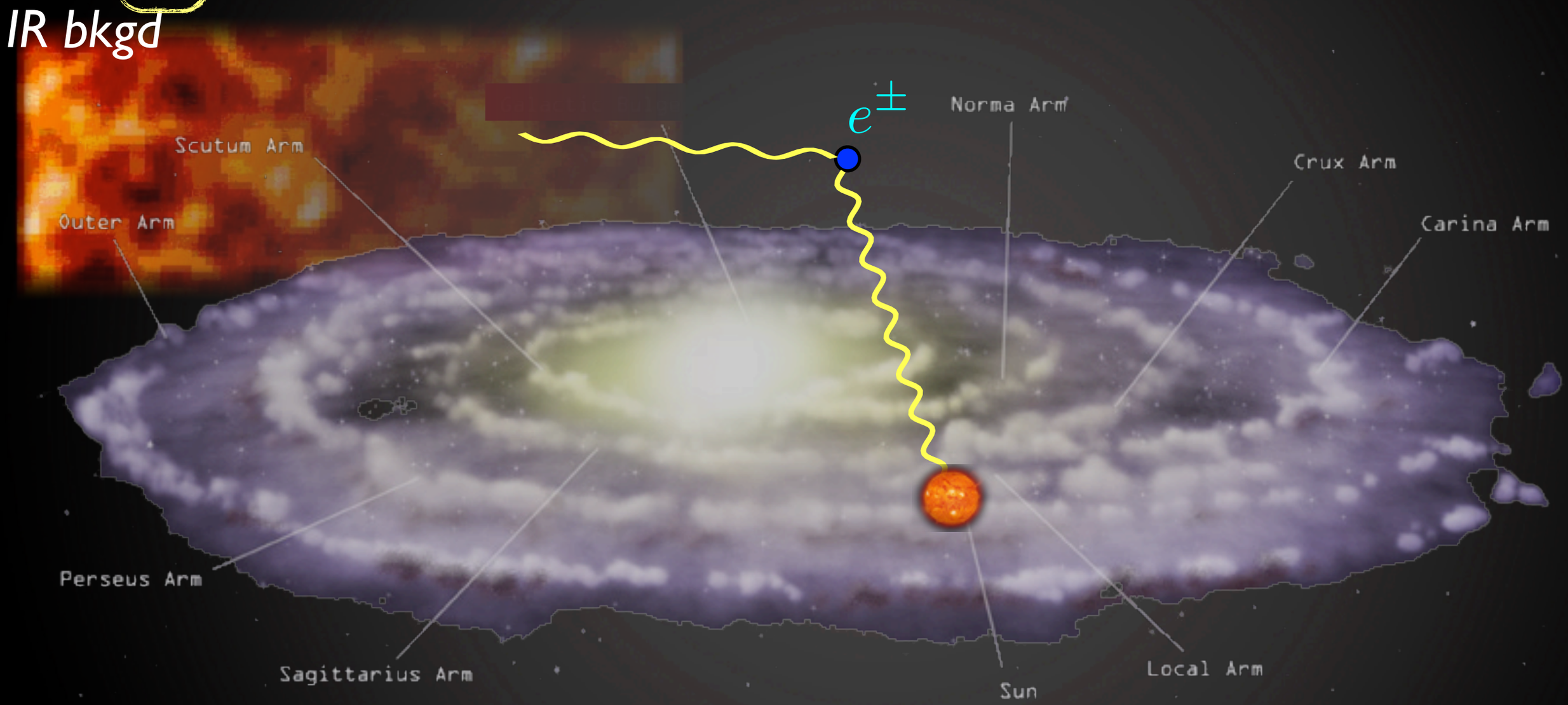

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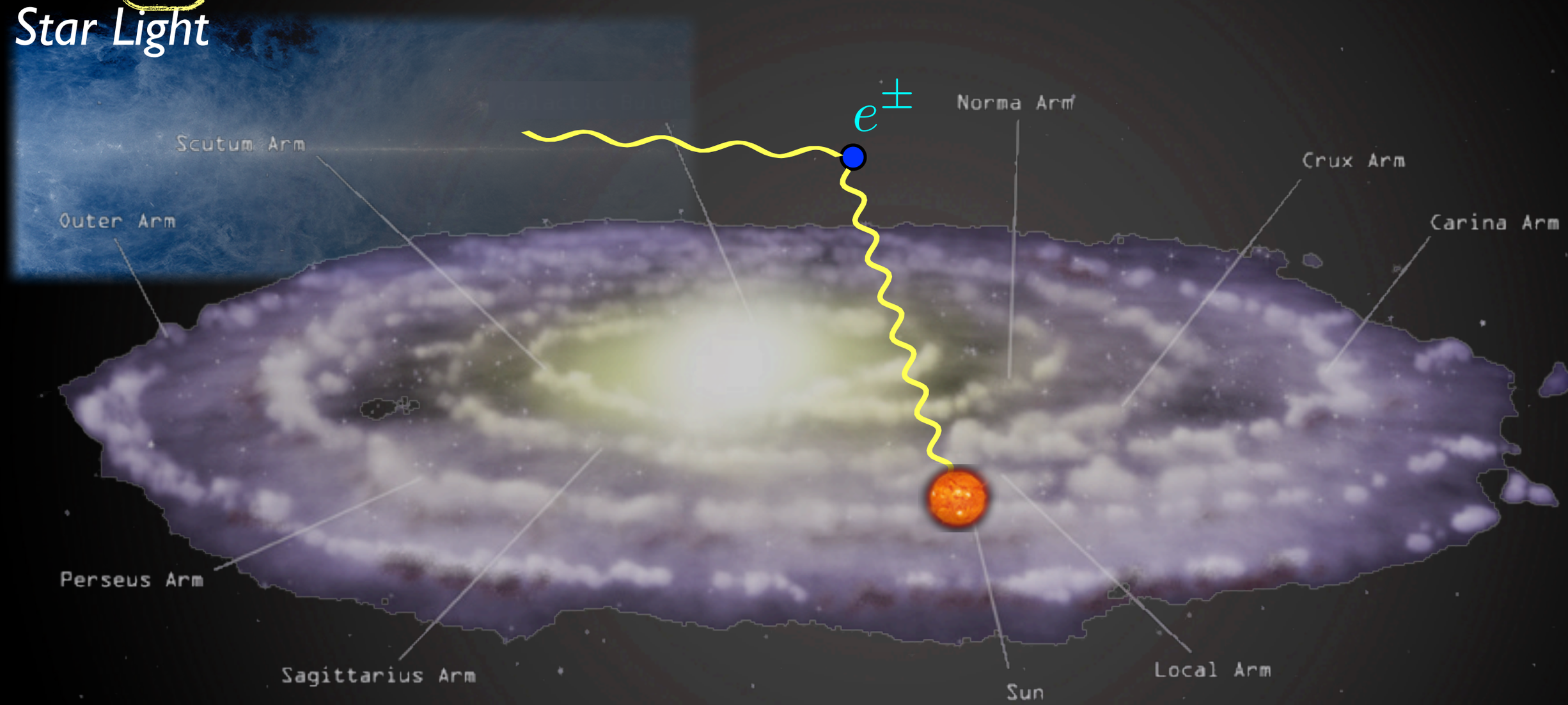
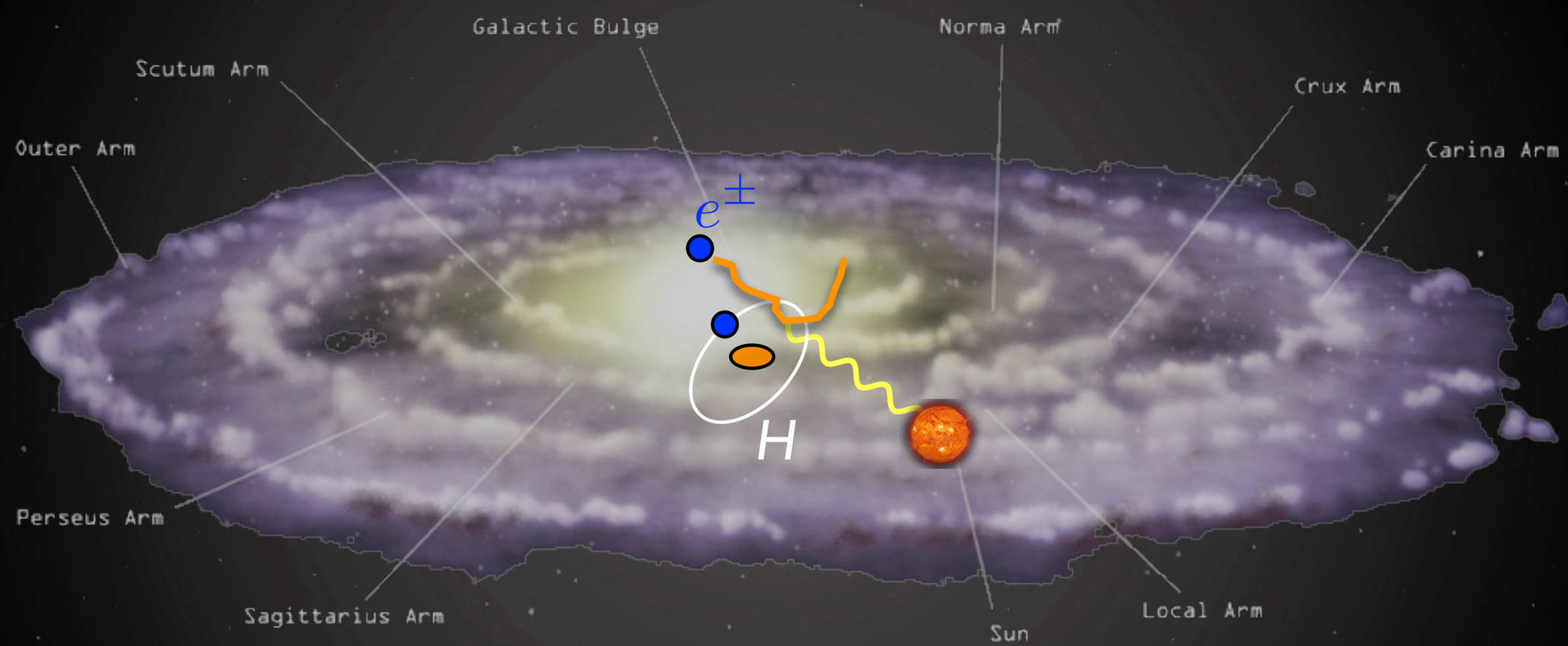


- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Secondary emission

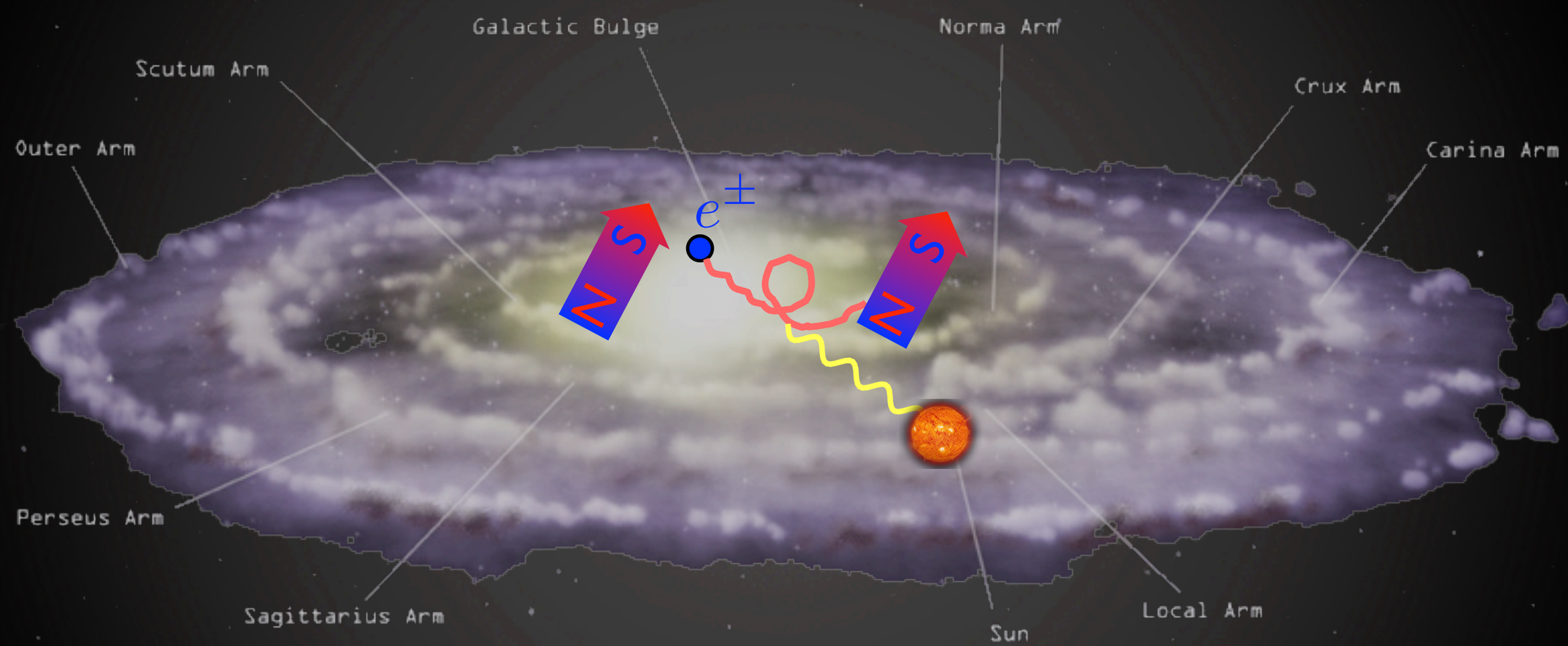
b. soft gammas from bremsstrahlung of $e^{\pm}$ on ISM



- (very) relevant at low energy, in the disk and at the GC

Secondary emission

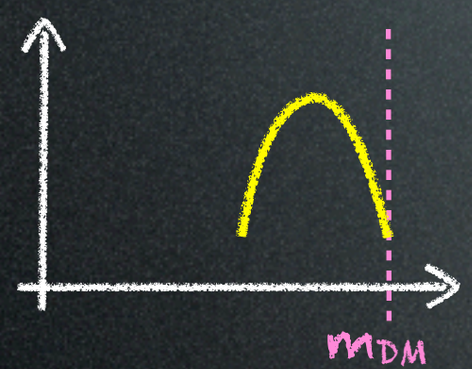
c. radio-waves from synchro radiation of $e^{\pm}$ in GC



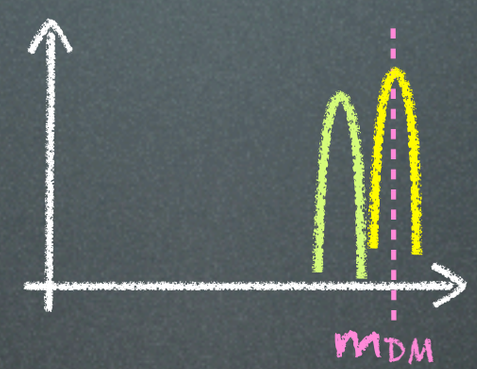
How does DM produce γ-rays?

1. prompt emission

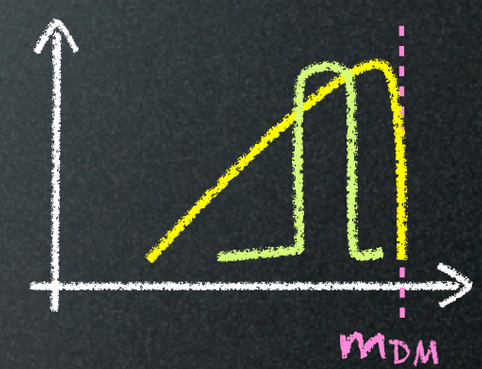
1a. continuum



1b. line(s)

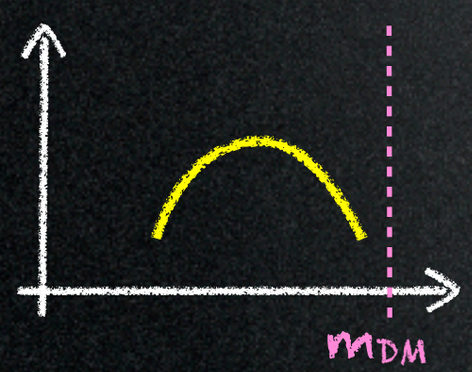


1c. sharp features

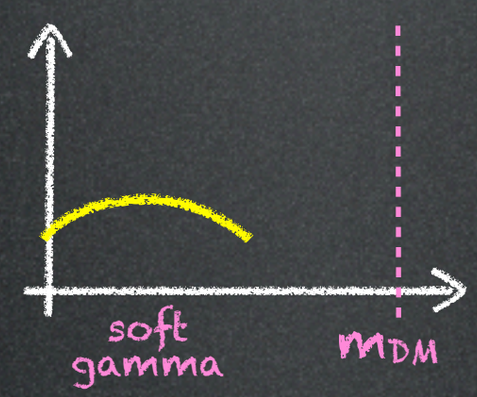


2. secondary emission

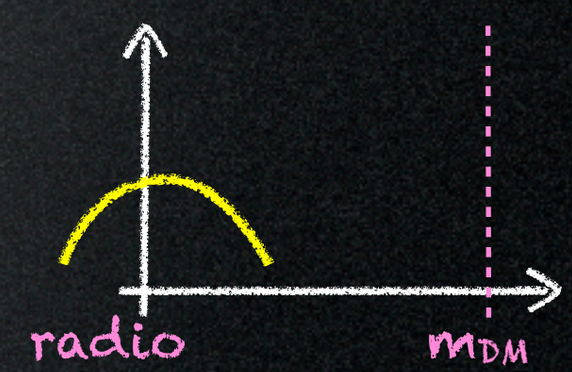
2a. ICS



2b. bremsstrahlung



2c. synchrotron

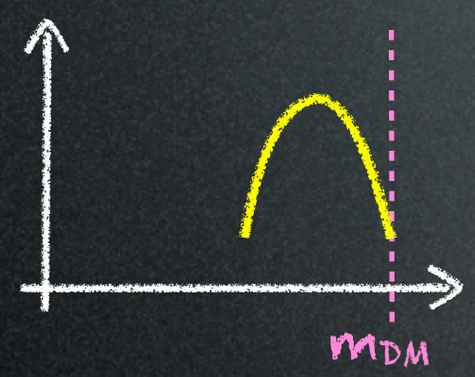


How does DM produce γ-rays?

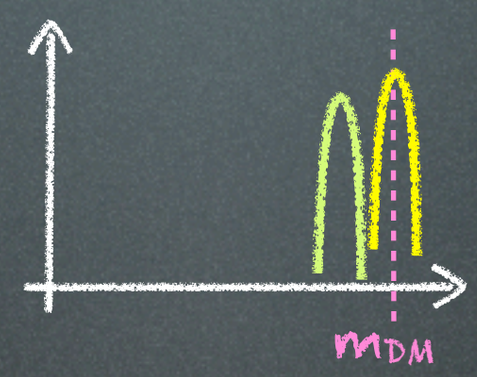
environment-independent

1. prompt emission

1a. continuum



1b. line(s)

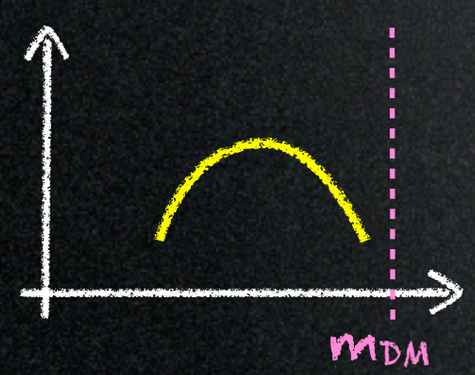


1c. sharp features

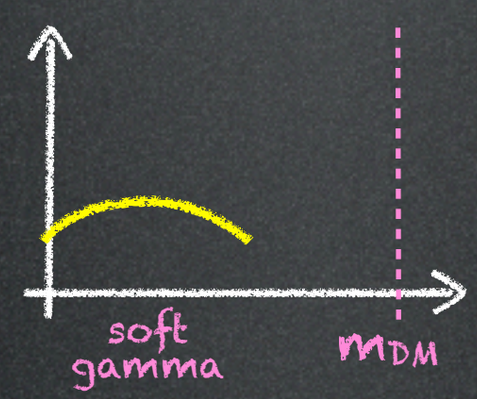
environment-dependent

2. secondary emission

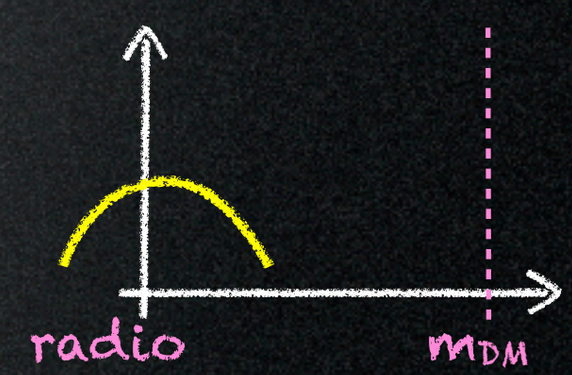
2a. ICS



2b. bremsstrahlung

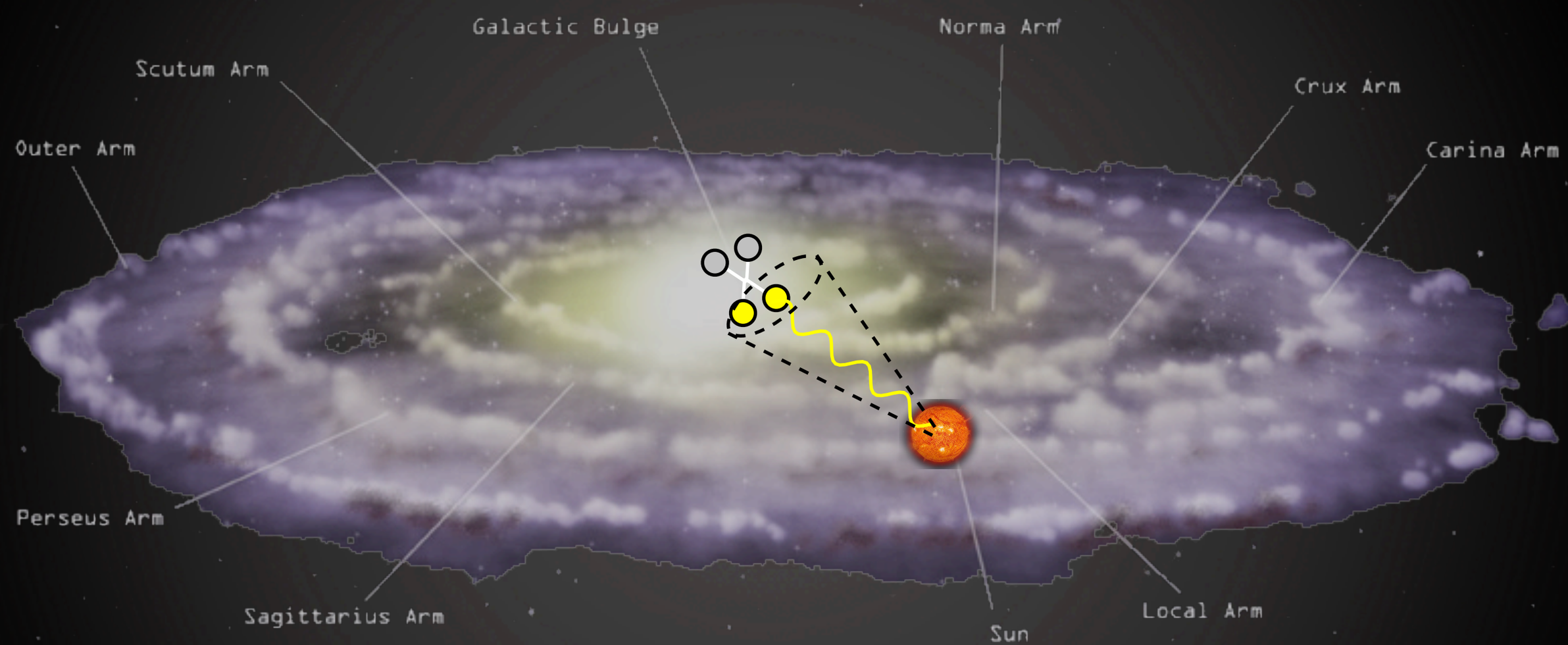


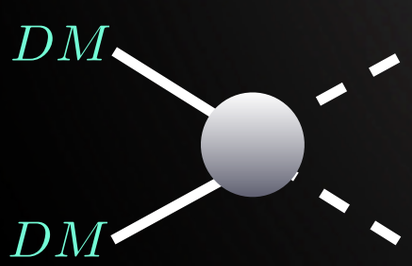
2c. synchrotron



Basic picture: targets

γ from DM annihilations in galactic center



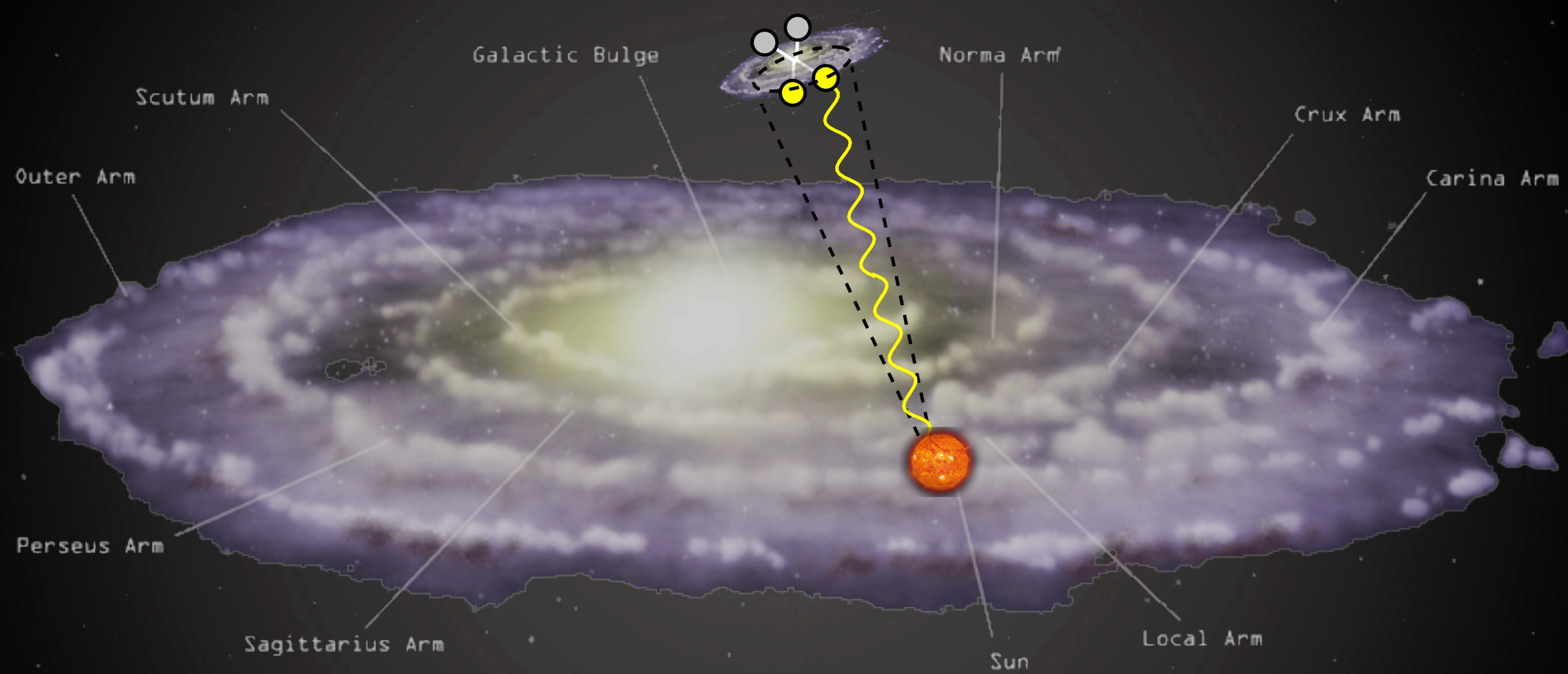


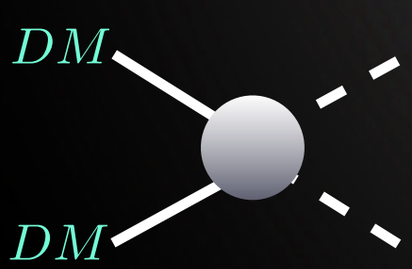
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Basic picture: targets

γ from DM annihilations in dwarf galaxies



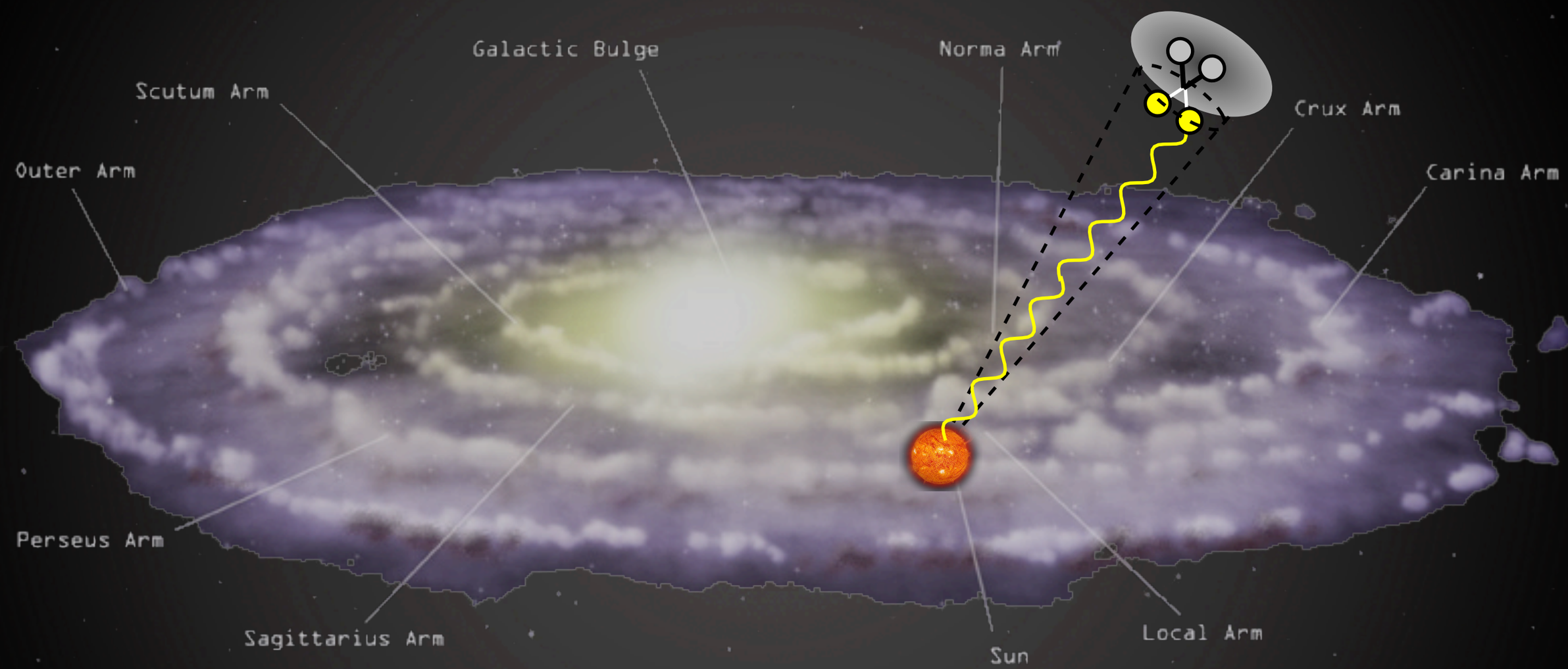


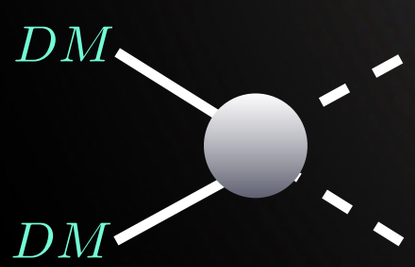
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Basic picture: targets

γ from DM annihilations in subhaloes



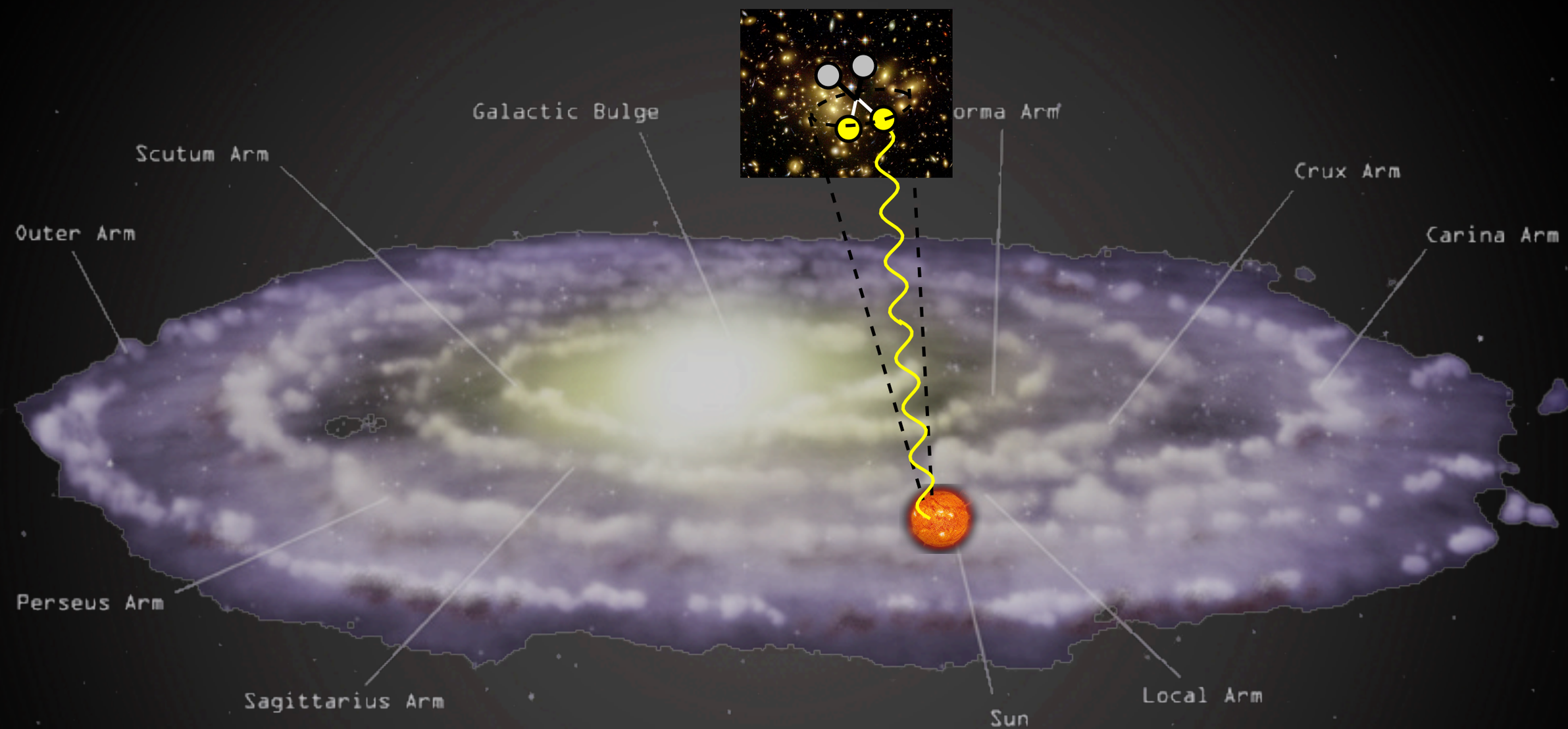


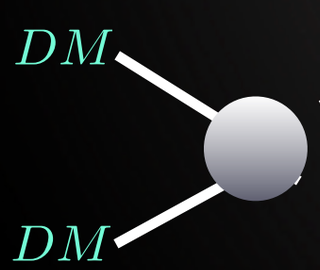
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Basic picture: targets

γ from DM annihilations in galaxy clusters



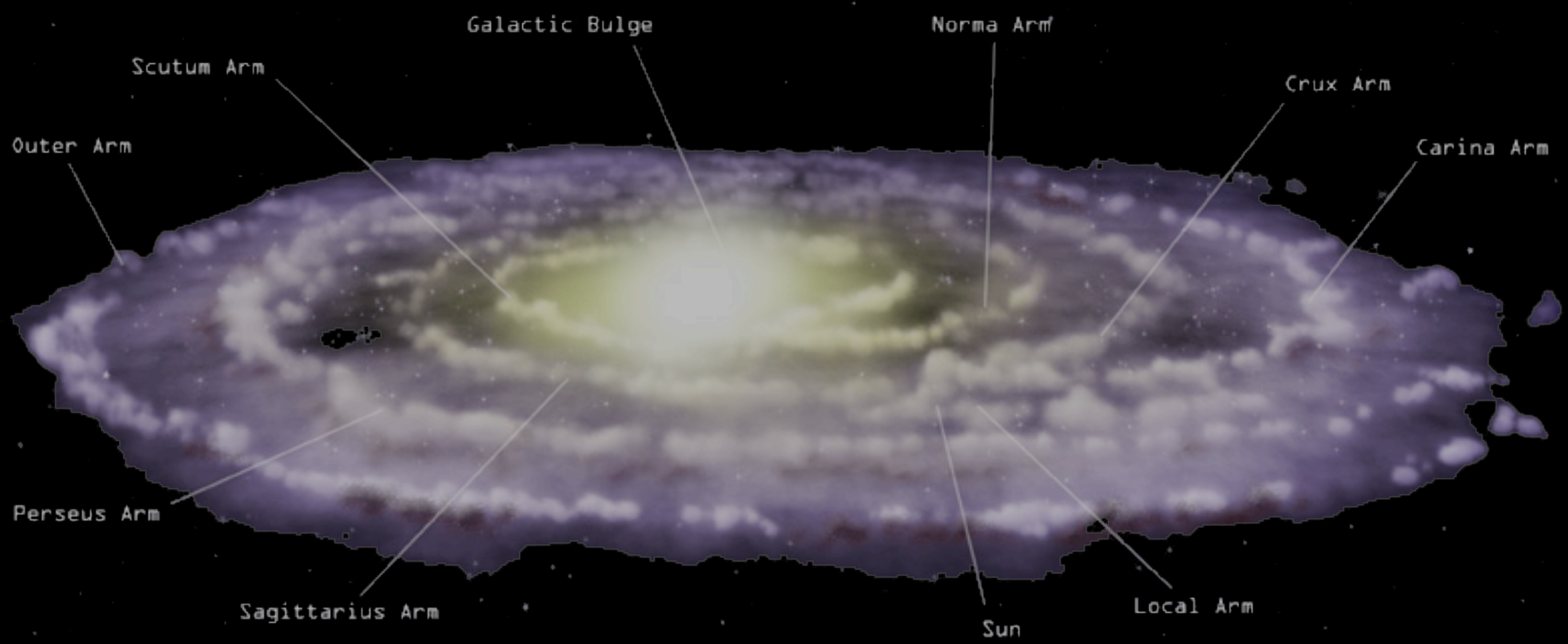


$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

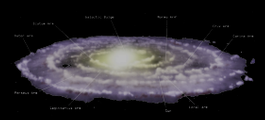
Basic picture: targets

γ from outside the Galaxy



Basic picture: targets

γ from outside the Galaxy

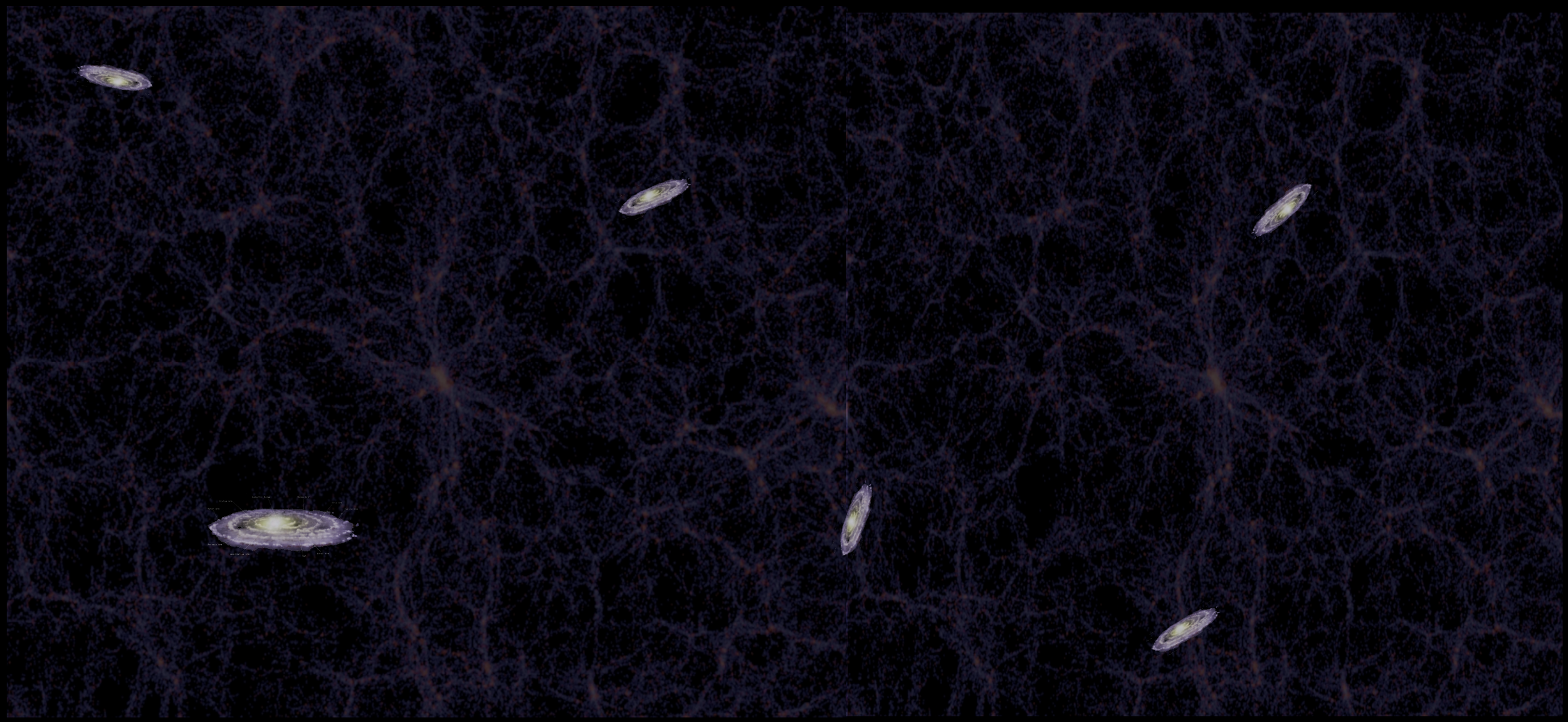


Basic picture: targets

γ from outside the Galaxy

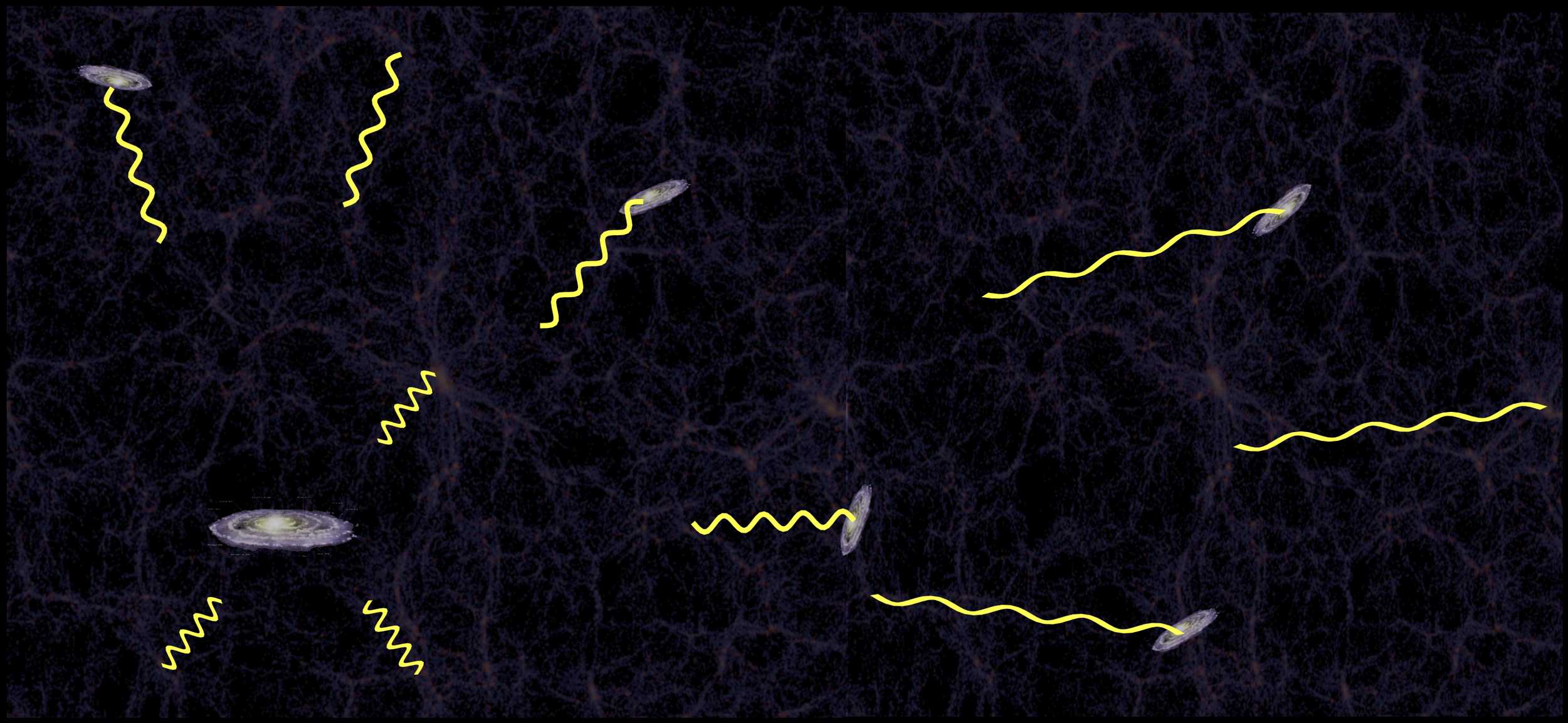
Basic picture: targets

γ from outside the Galaxy



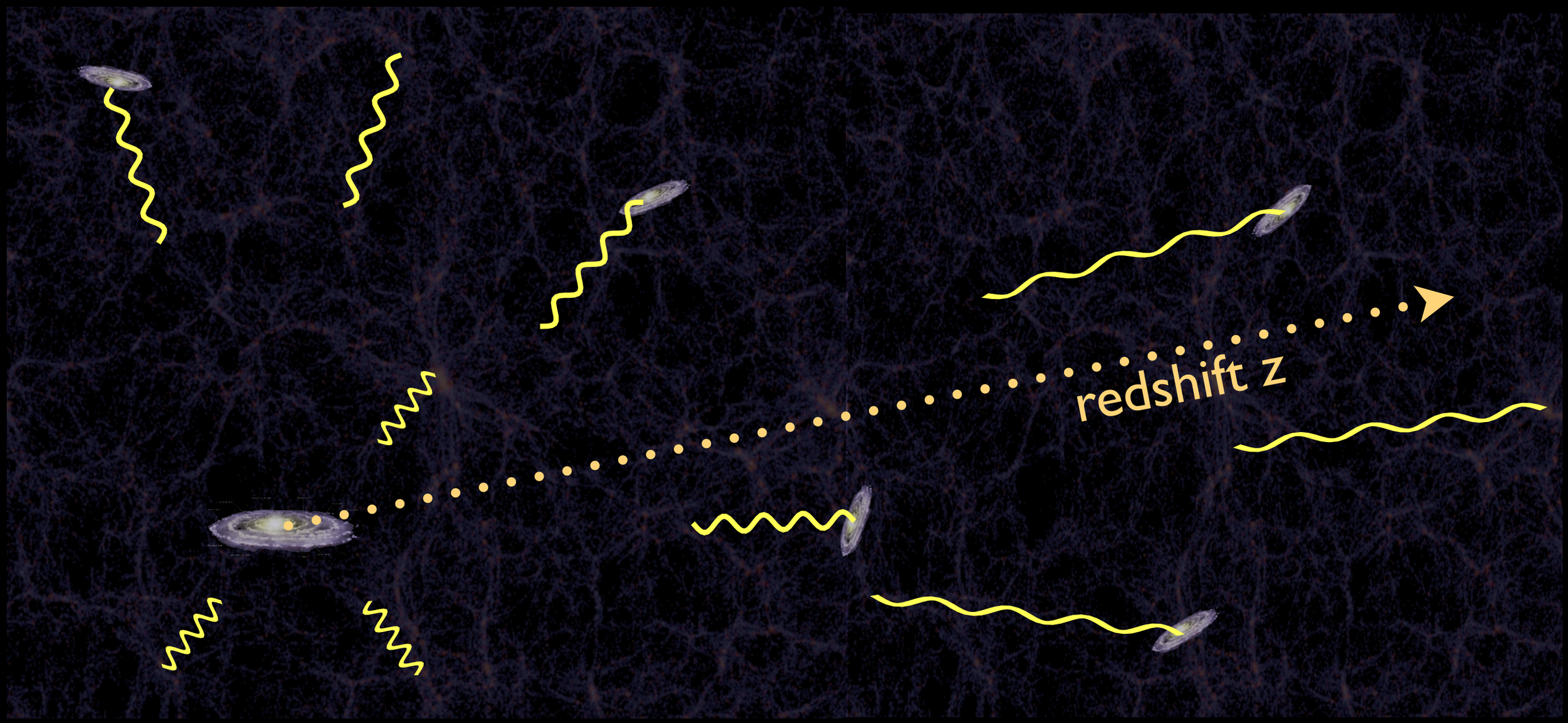
Basic picture: targets

γ from outside the Galaxy



Basic picture: targets

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

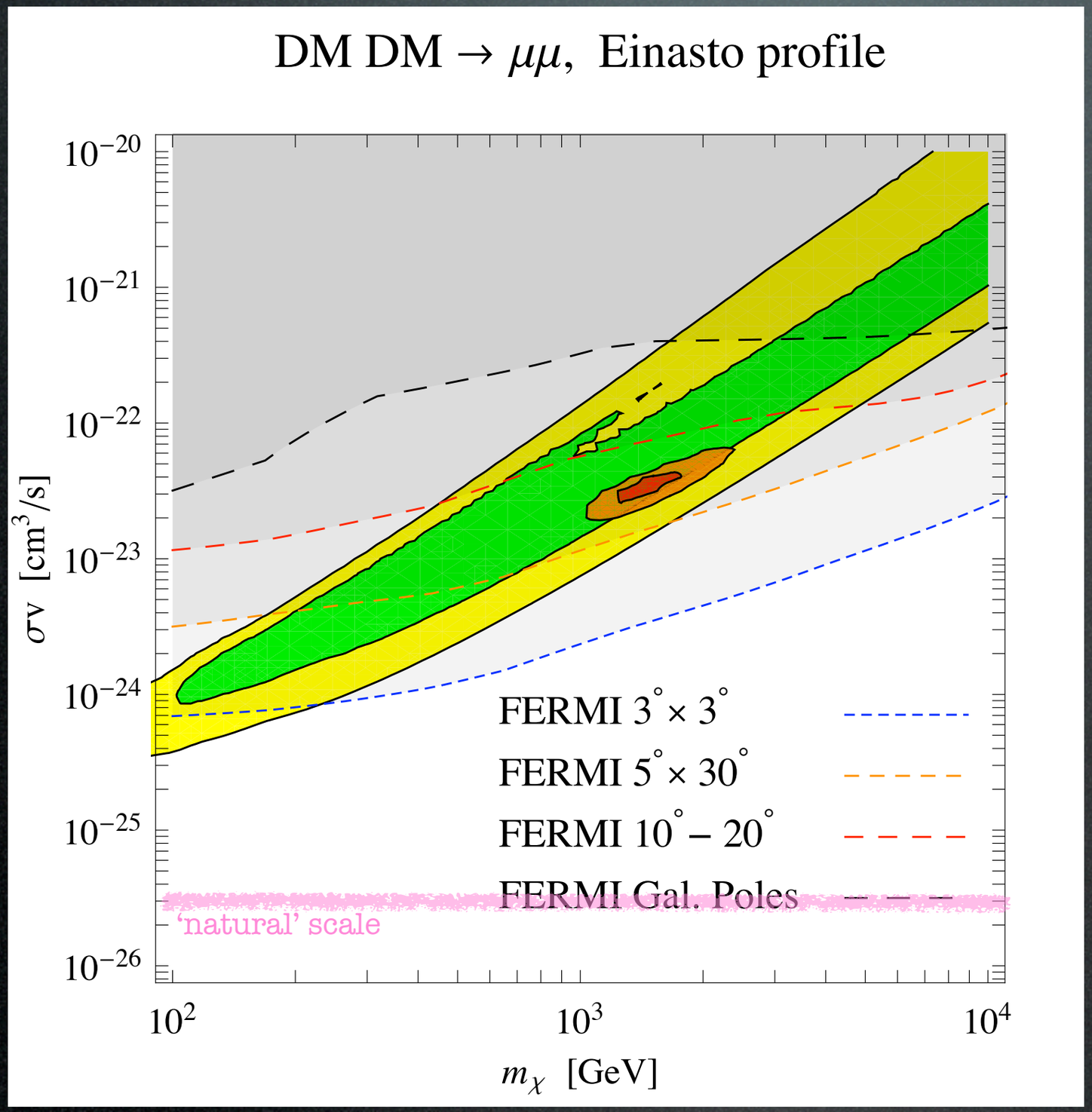
Status of the constraints

Status of the constraints

(a selection)

Gamma constraints

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

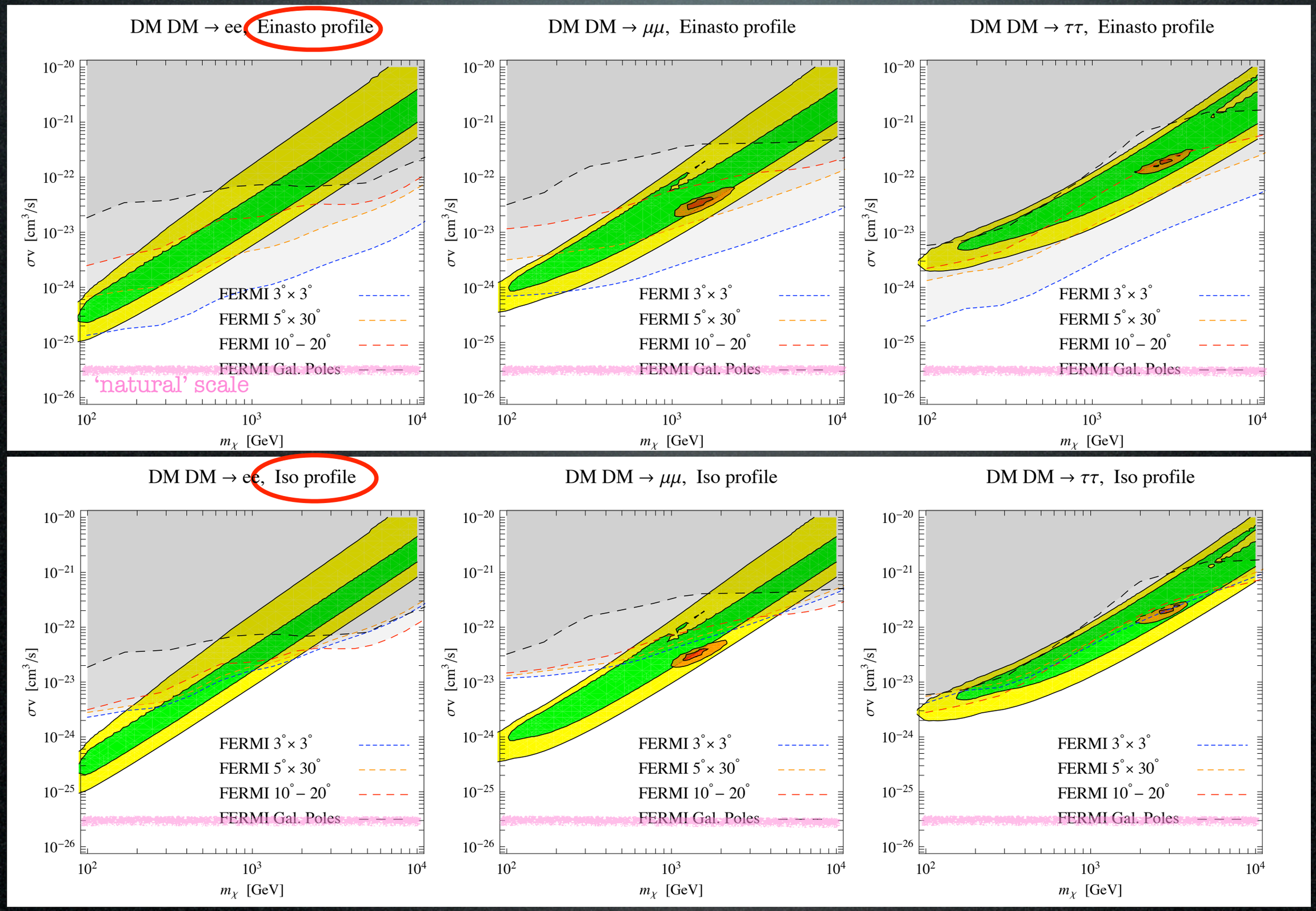


Gamma ray constraints on the charged CR excesses

Cirelli, Panci, Serpico 0912.0663

Gamma constraints

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



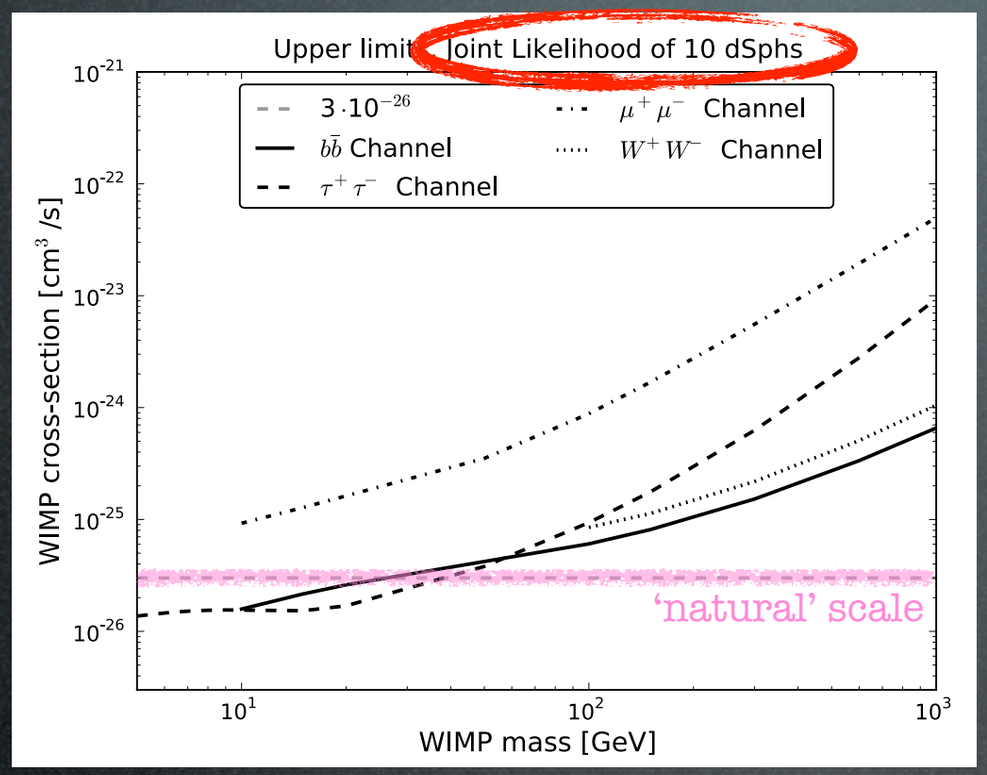
Cirelli, Panci, Serpico 0912.0663

Gamma constraints

γ from DM annihilations in Satellite Galaxies

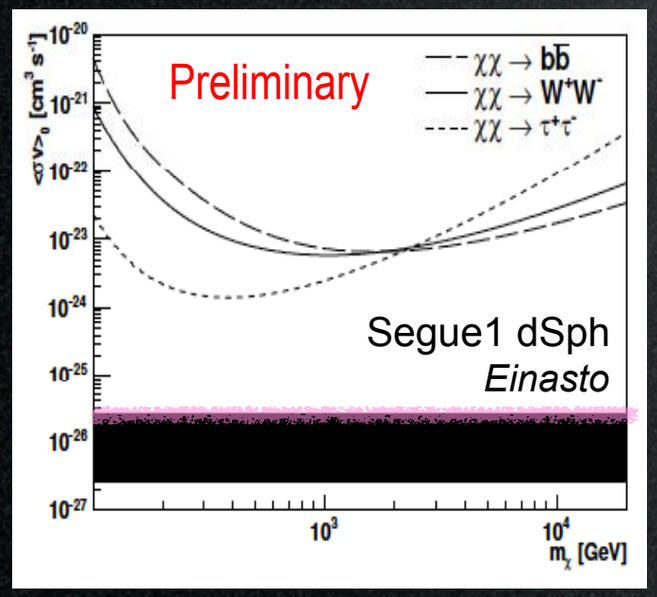
FERMI

FERMI coll., 1108.3546



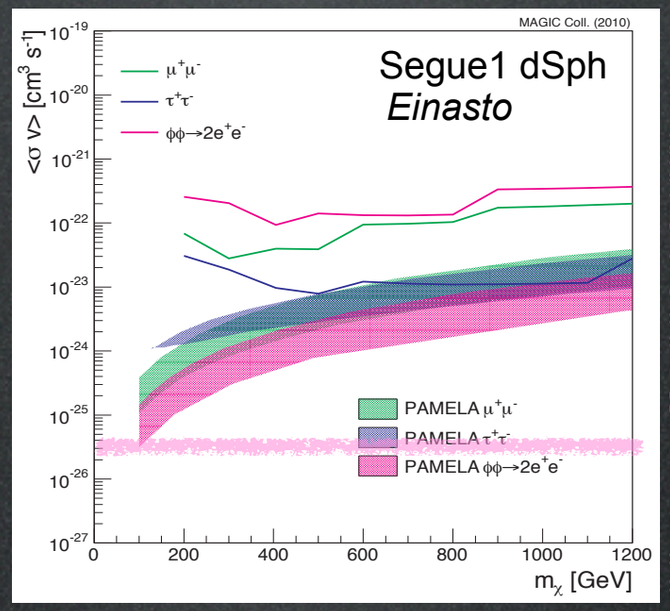
And the winner is...

VERITAS



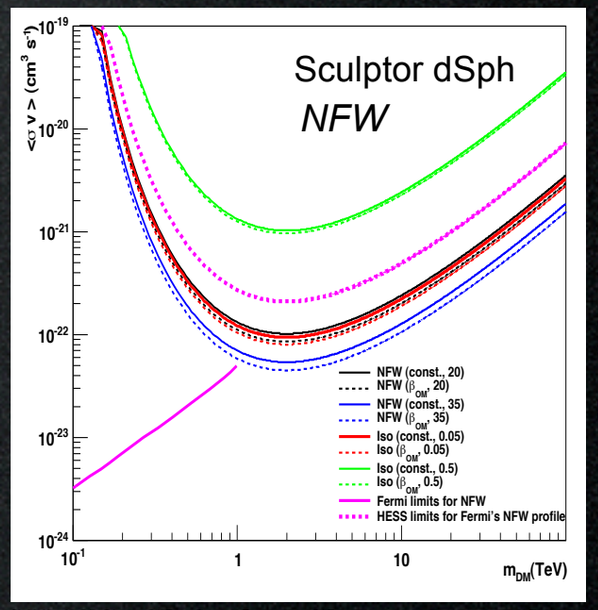
Veritas coll., courtesy of R.Ong

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

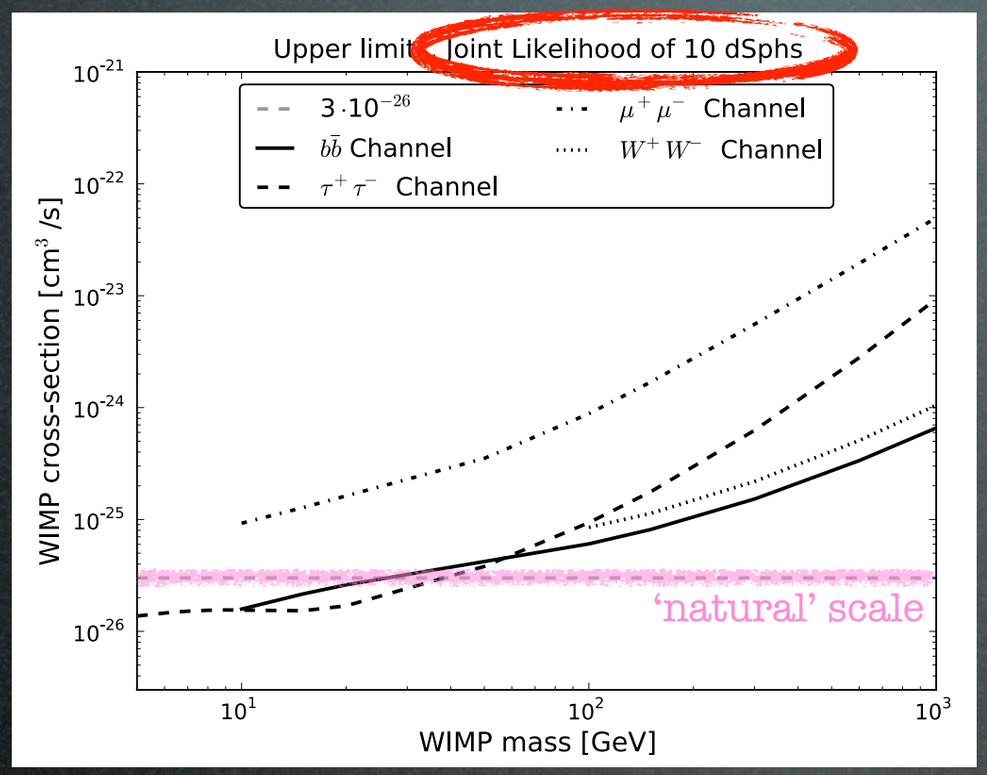
(HESS: Globular Clusters analysis too)

Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

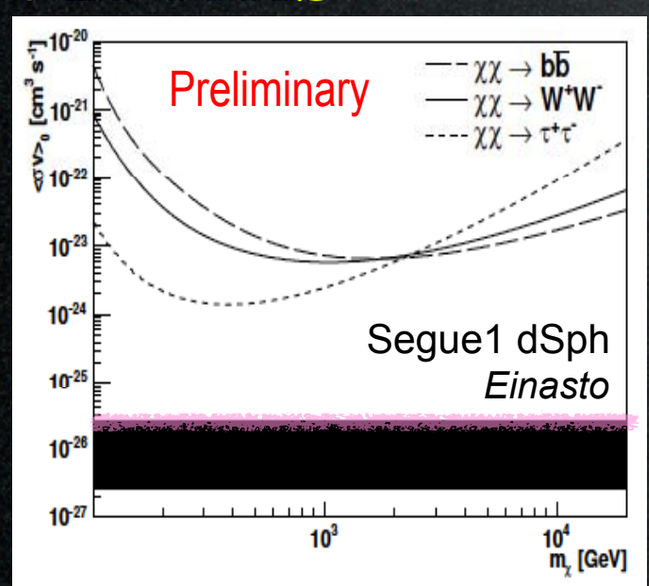
FERMI coll., 1108.3546



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.

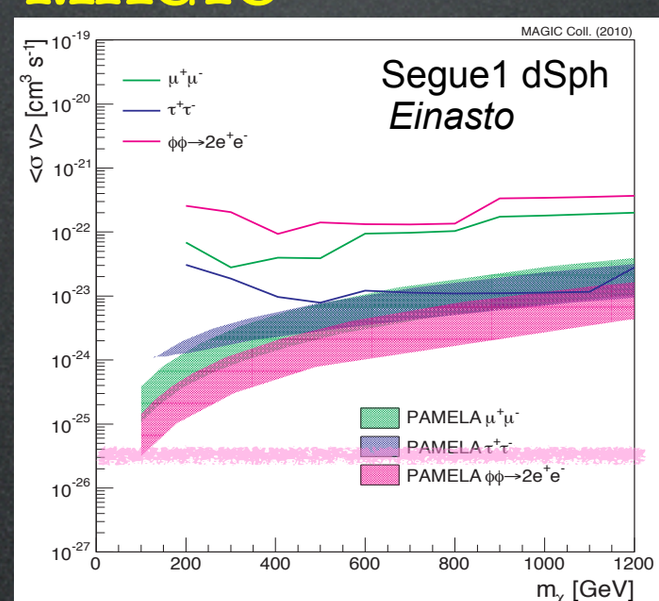
VERITAS



Veritas coll., courtesy of R.Ong

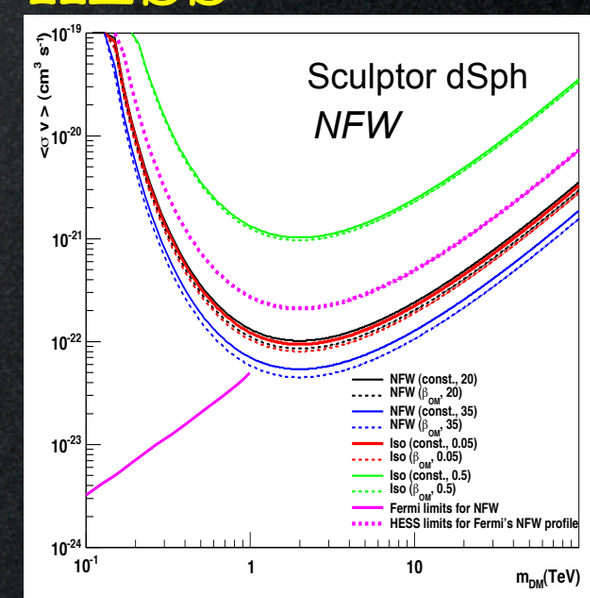
(currently the winner in the '1 dSph' category)

MAGIC



Magic coll., 1103.0477

HESS



HESS coll., 1012.5602

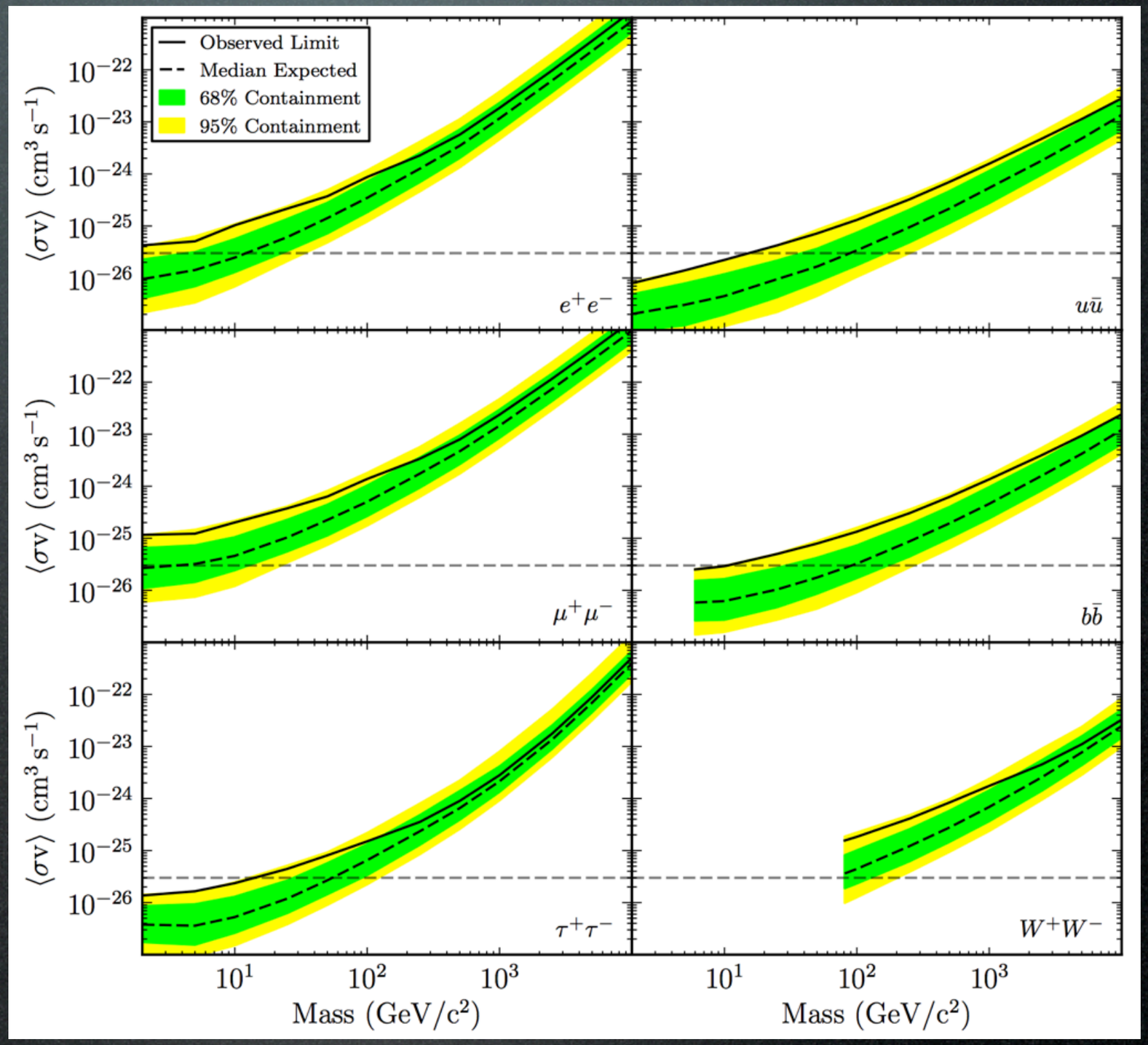
(HESS: Globular Clusters analysis too)

Gamma constraints

γ from DM annihilations in Satellite Galaxies

FERMI

1310.0828 Fermi coll.,
Alex Drlica-Wagner



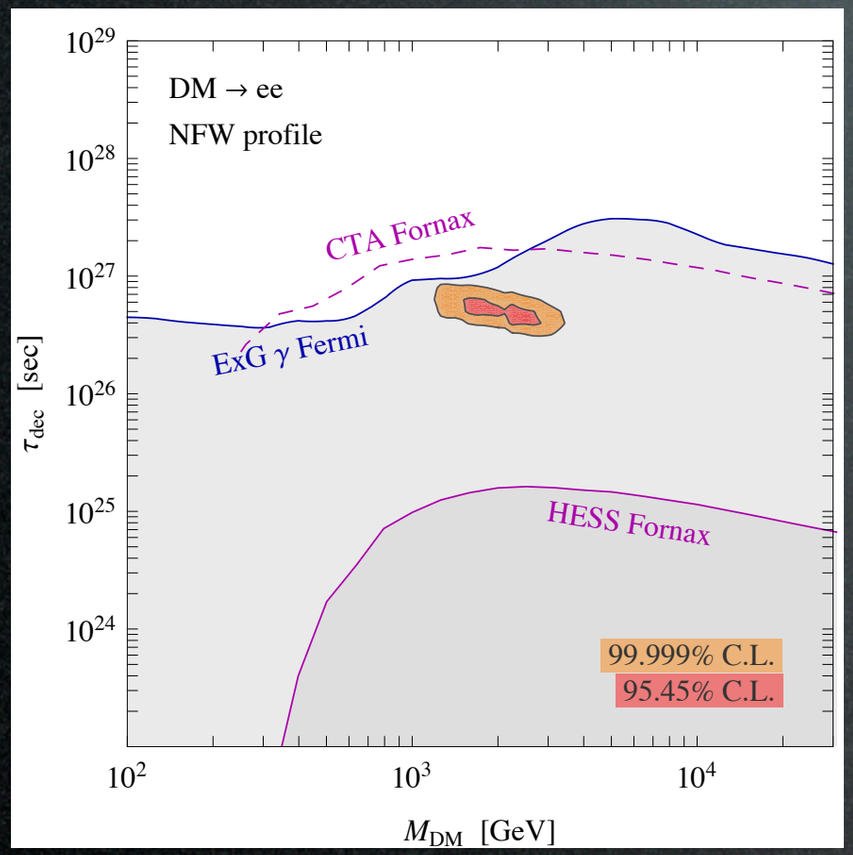
4 years data:
weaker bound

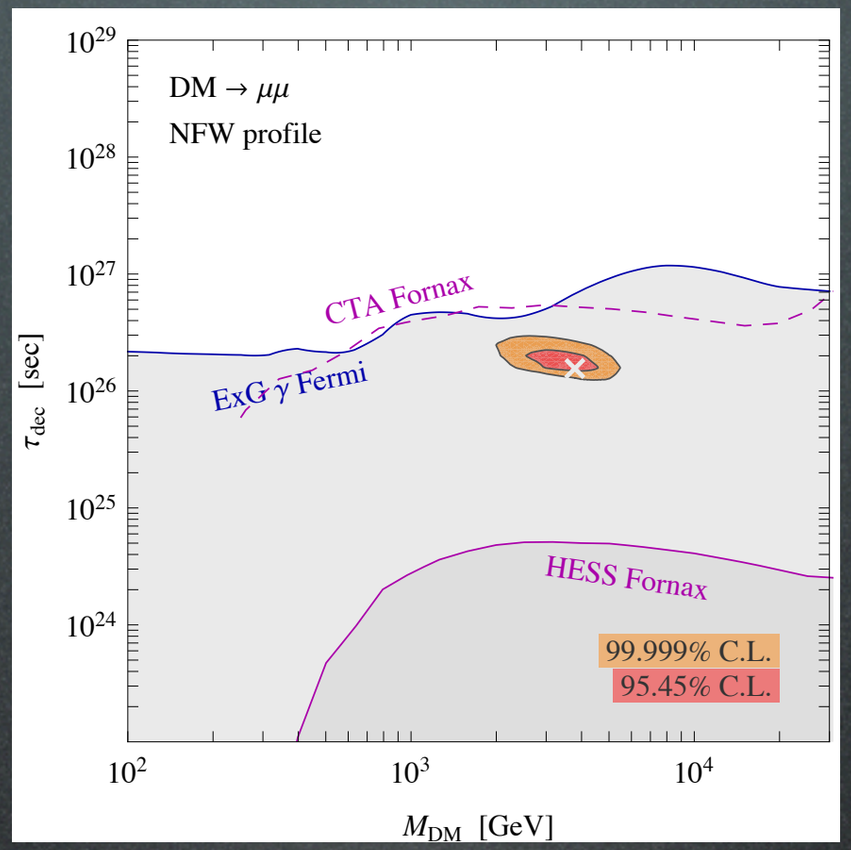
(or 10 GeV DM
peeping out?)

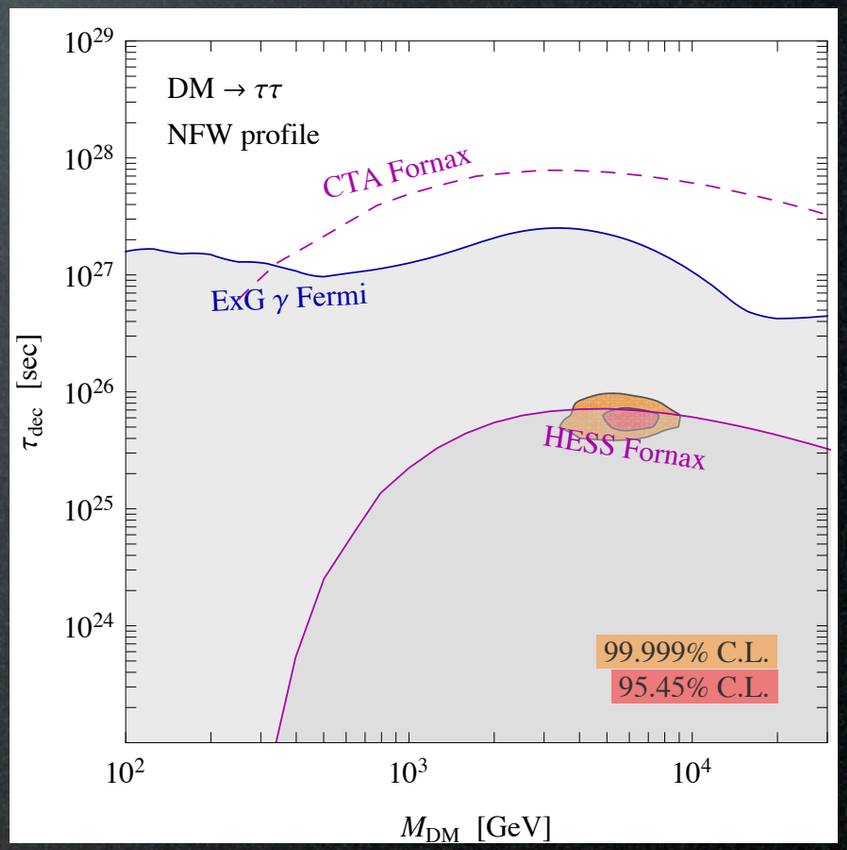
Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)







Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

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

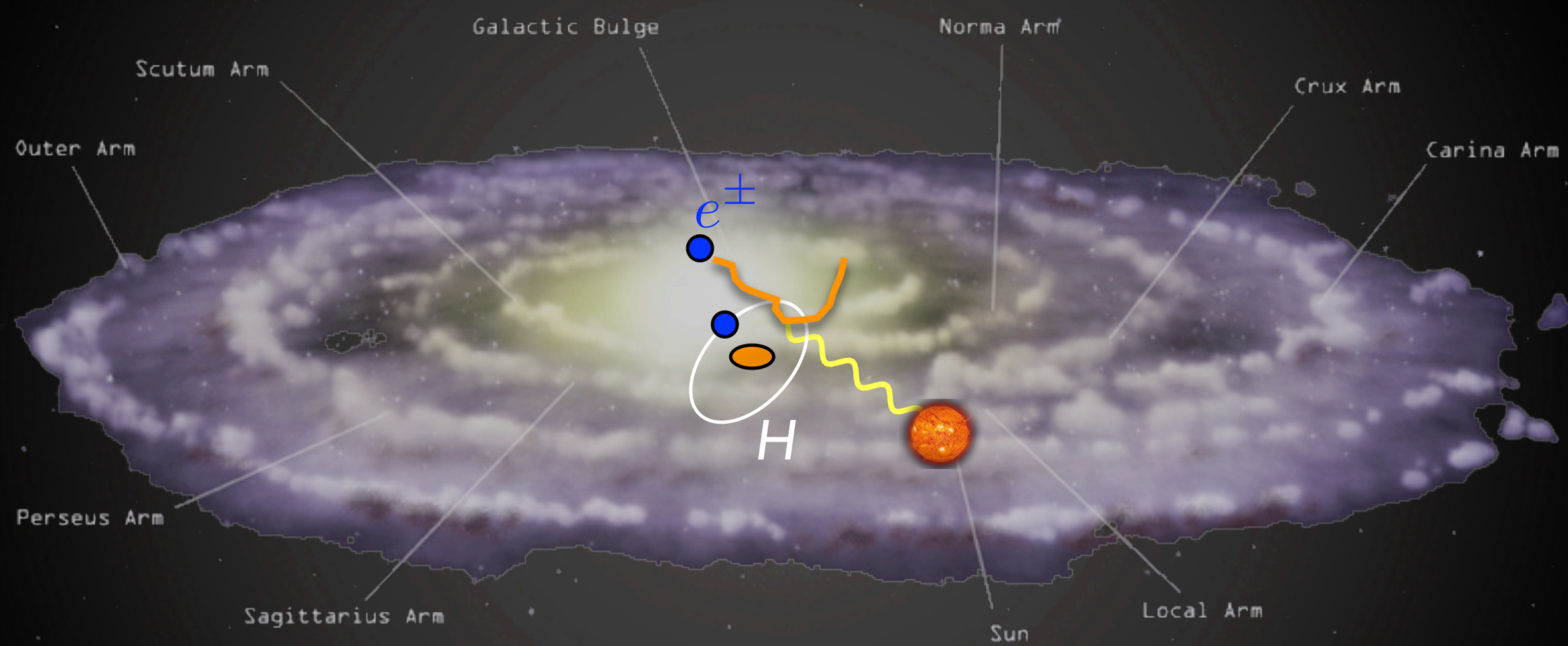
Some recent developments

Some recent developments:

- bremsstrahlung γ-rays from light DM
- FERMI 130 GeV line
- excesses near the Galactic Center

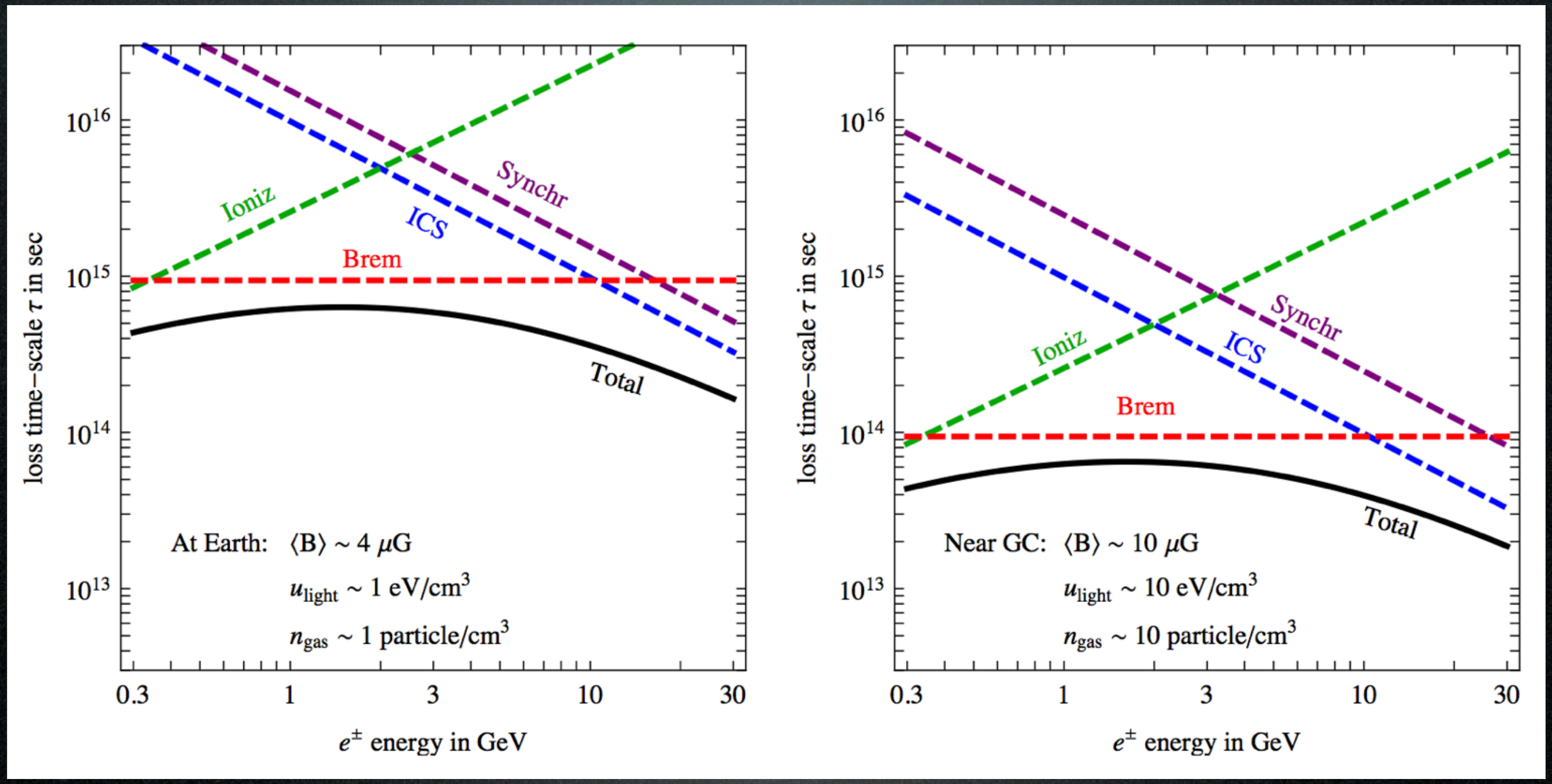
Secondary emission

b. soft gammas from bremsstrahlung of $e^{\pm}$ on ISM



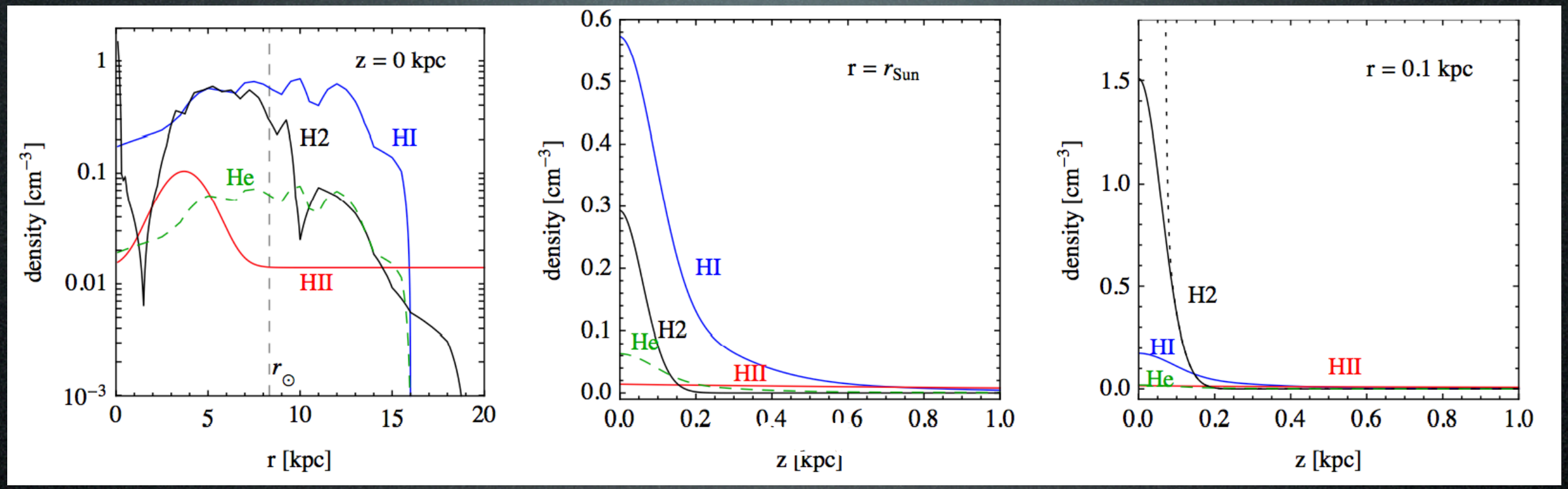
- (very) relevant at low energy, in the disk and at the GC

Relative importance of secondary emissions



=> brem is the dominant energy loss for low energy $e^{\pm}$!

Gas maps

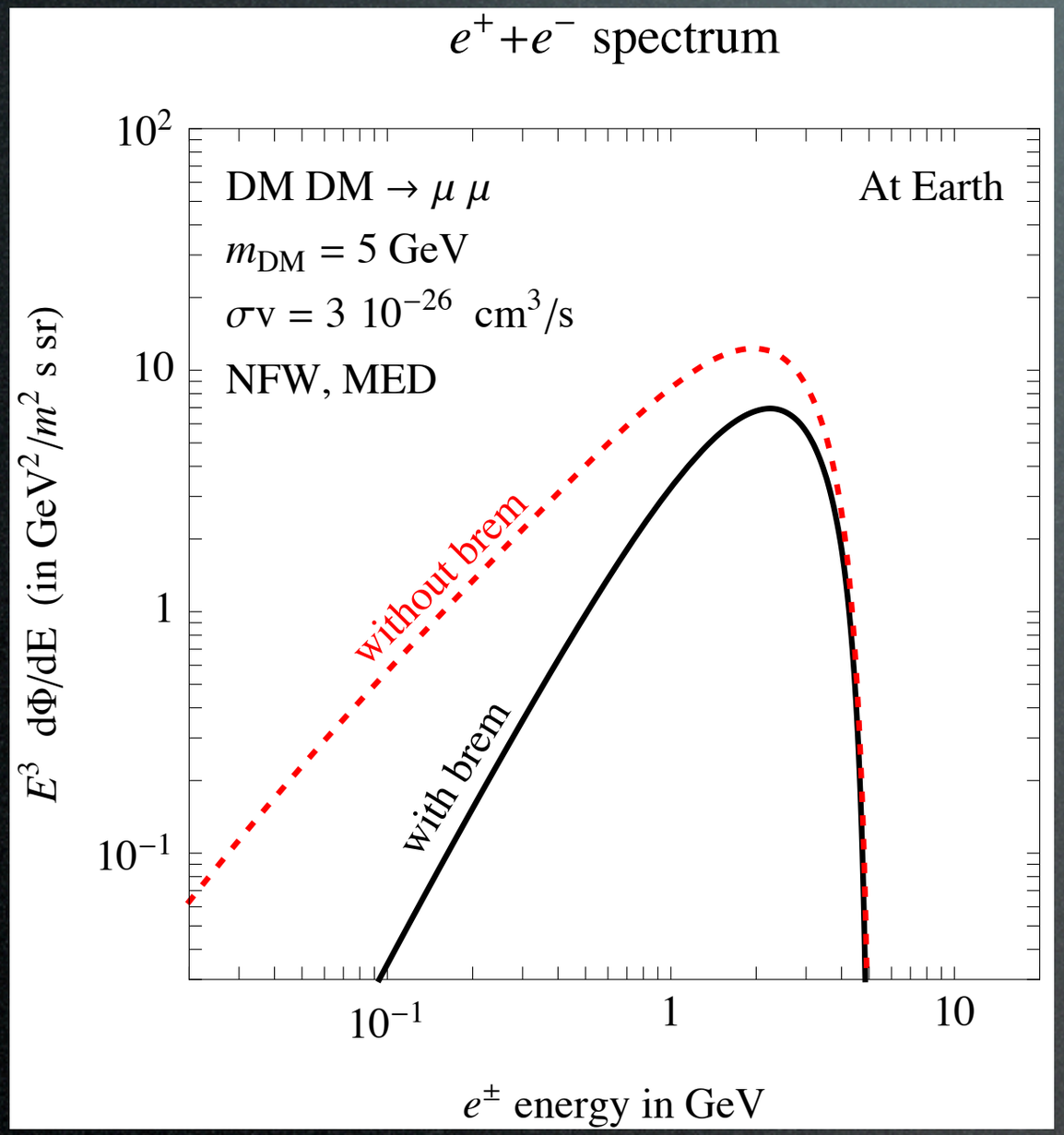


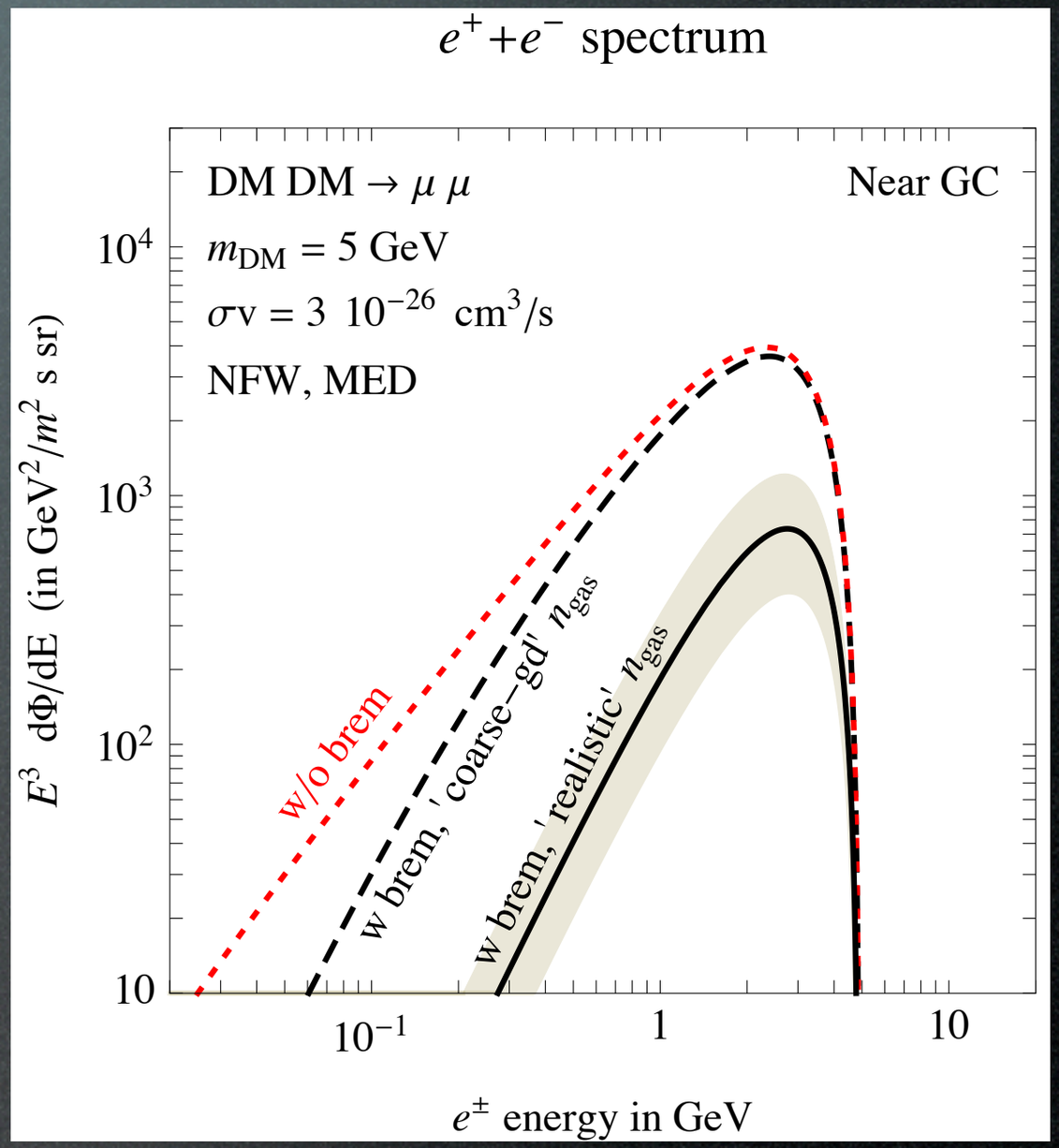
But: inner kpc of the Galaxy is denser
(and more uncertain)

SNB	CMZ	CNR
Stellar Nuclear Bulge	Central Molecular Zone	Circum-Nuclear Ring
< 1 kpc	< 200 pc	< 3 pc
?	10^2-10^3 /cm^3	10^5/cm^3

Results

The $e^{\pm}$ population is affected by bremsstrahlung

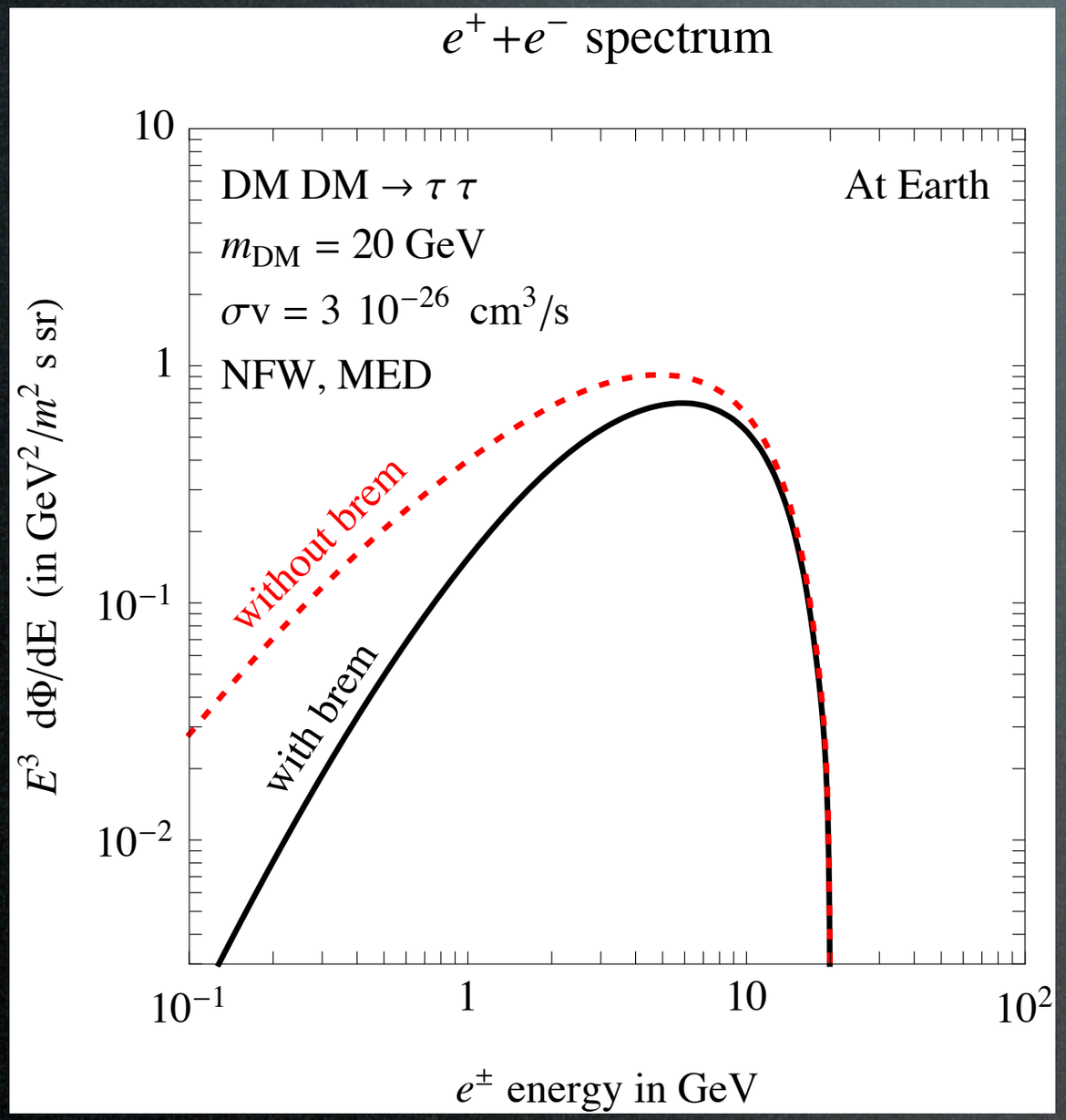


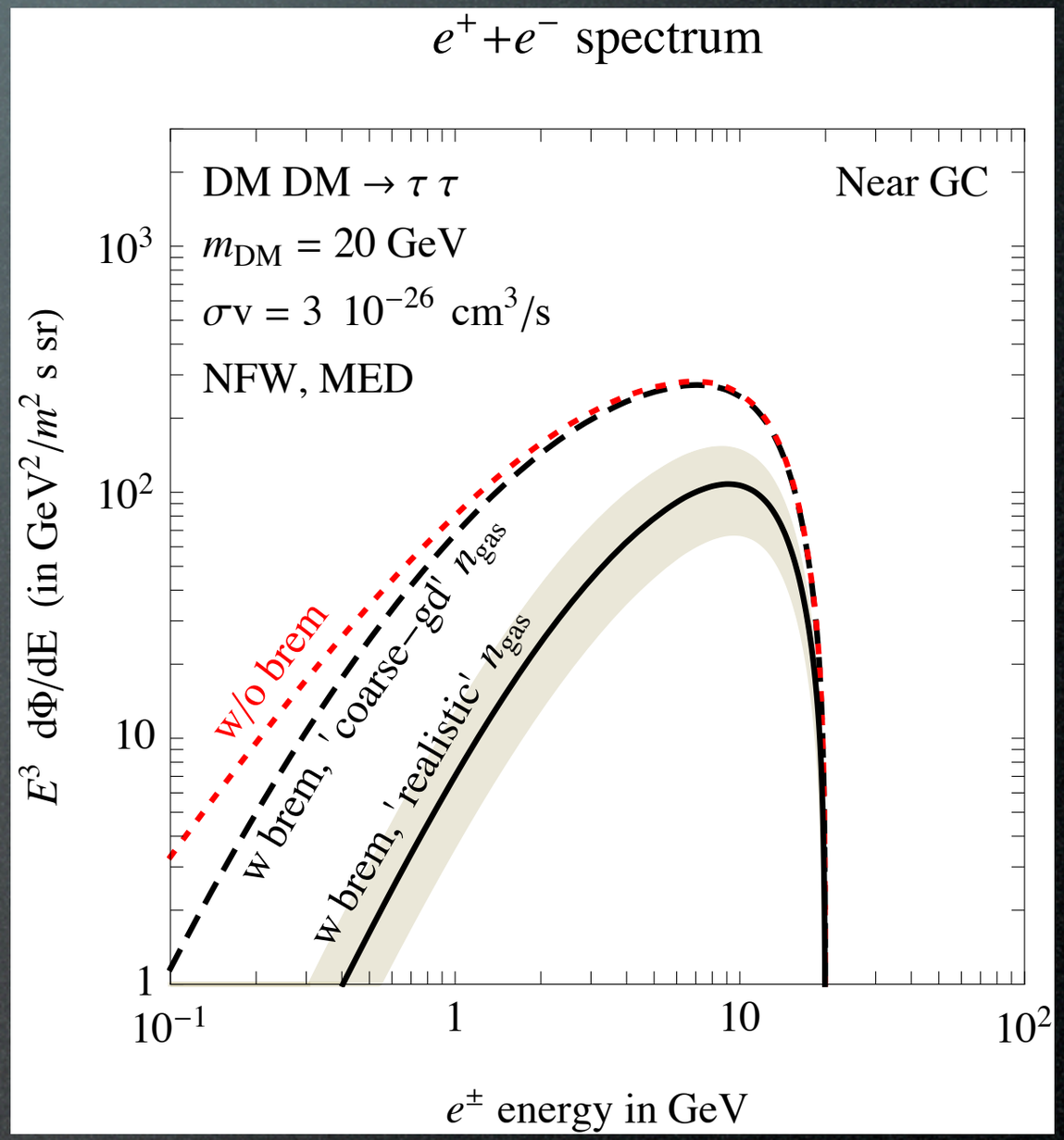


= factor 2 uncertainty in n_{gas}

Results

The $e^{\pm}$ population is affected by bremsstrahlung





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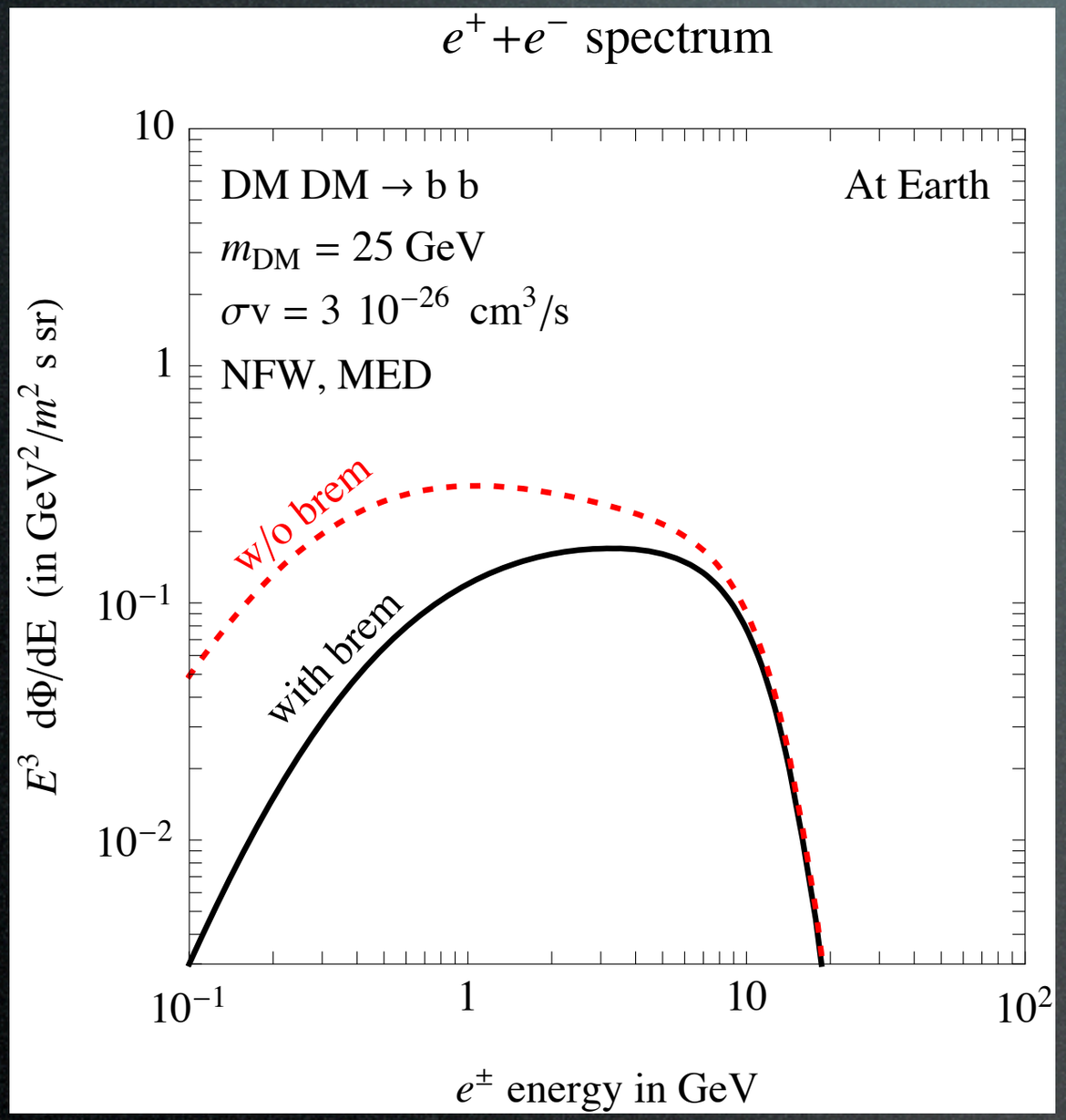

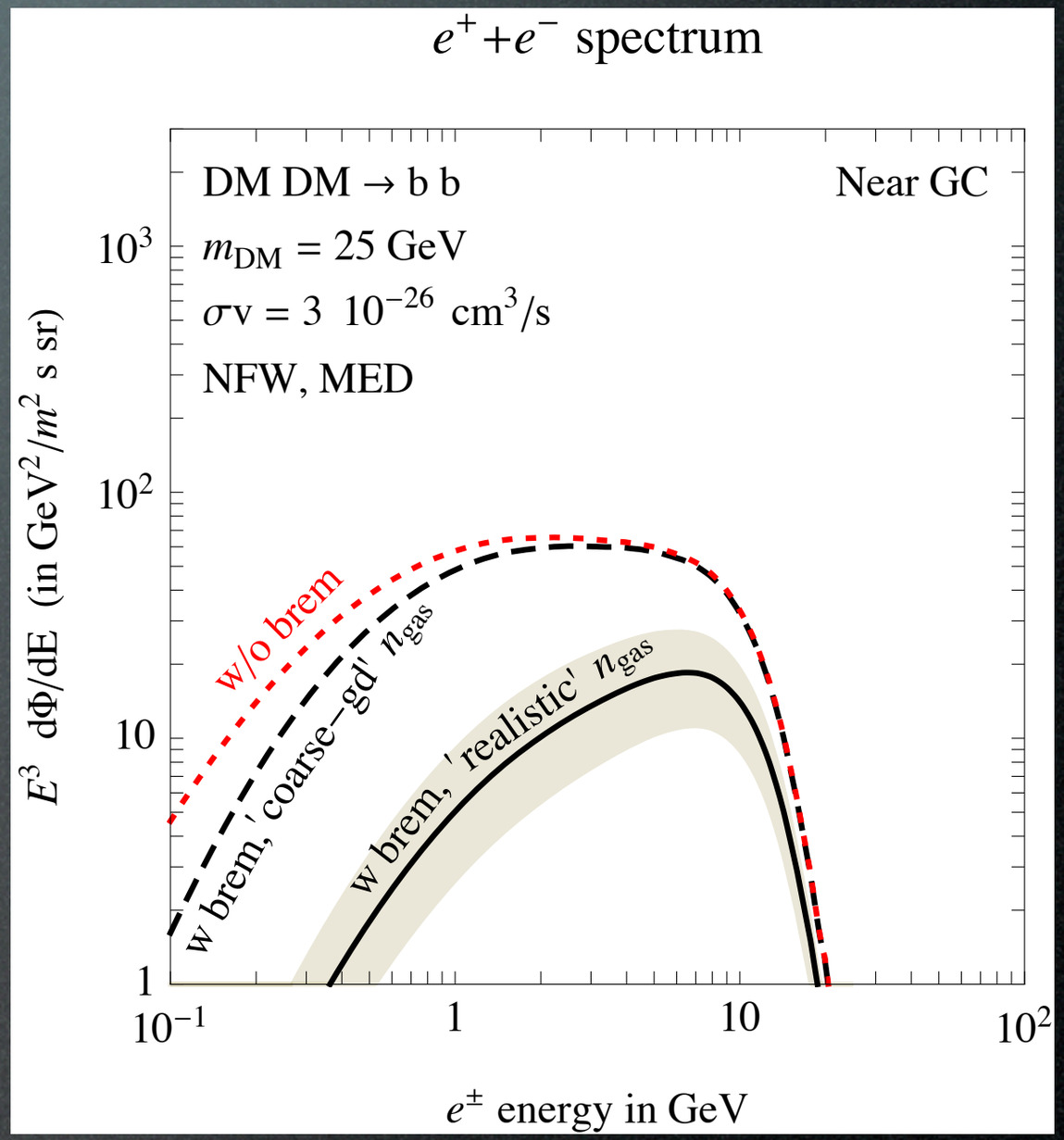

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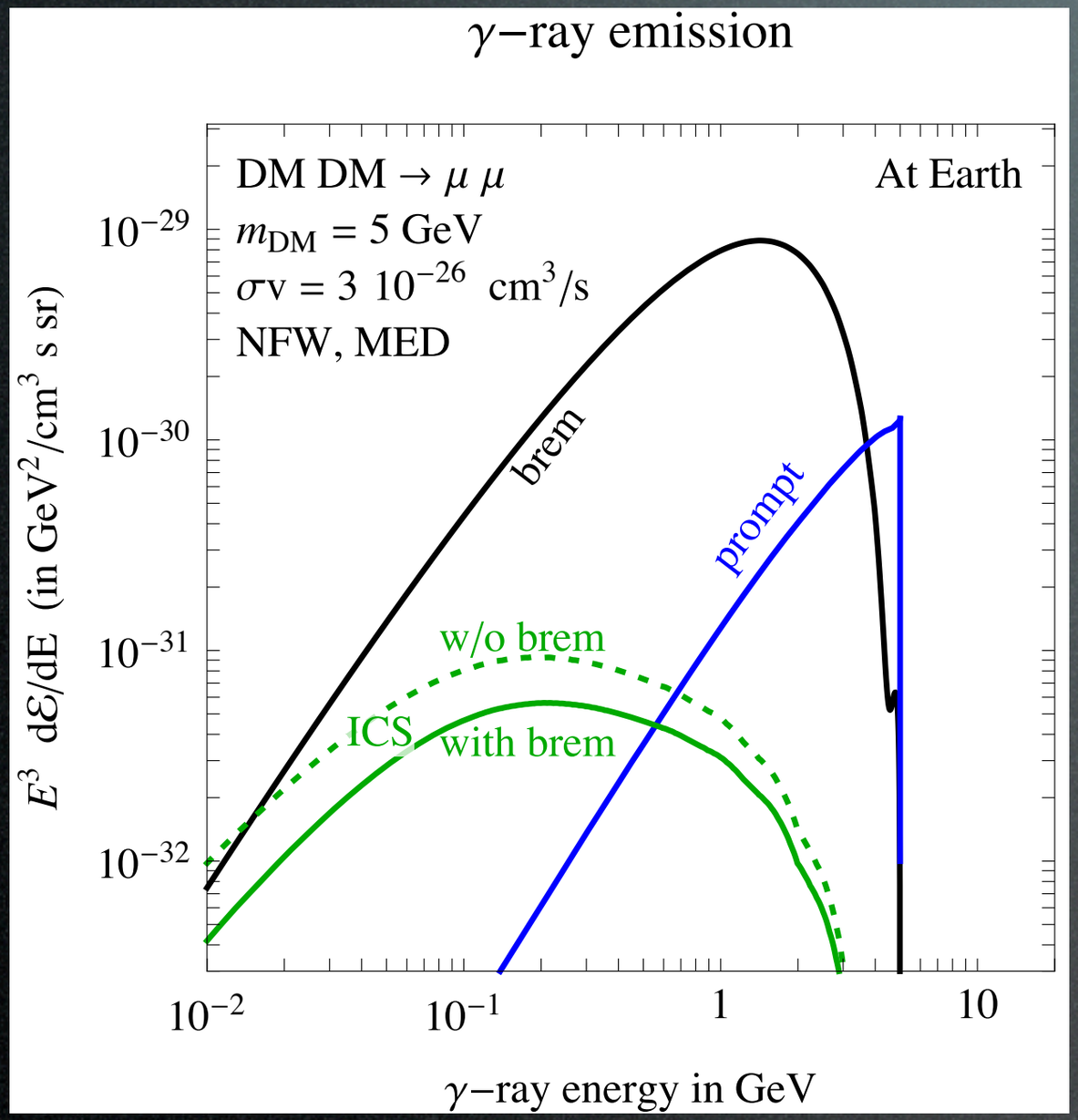
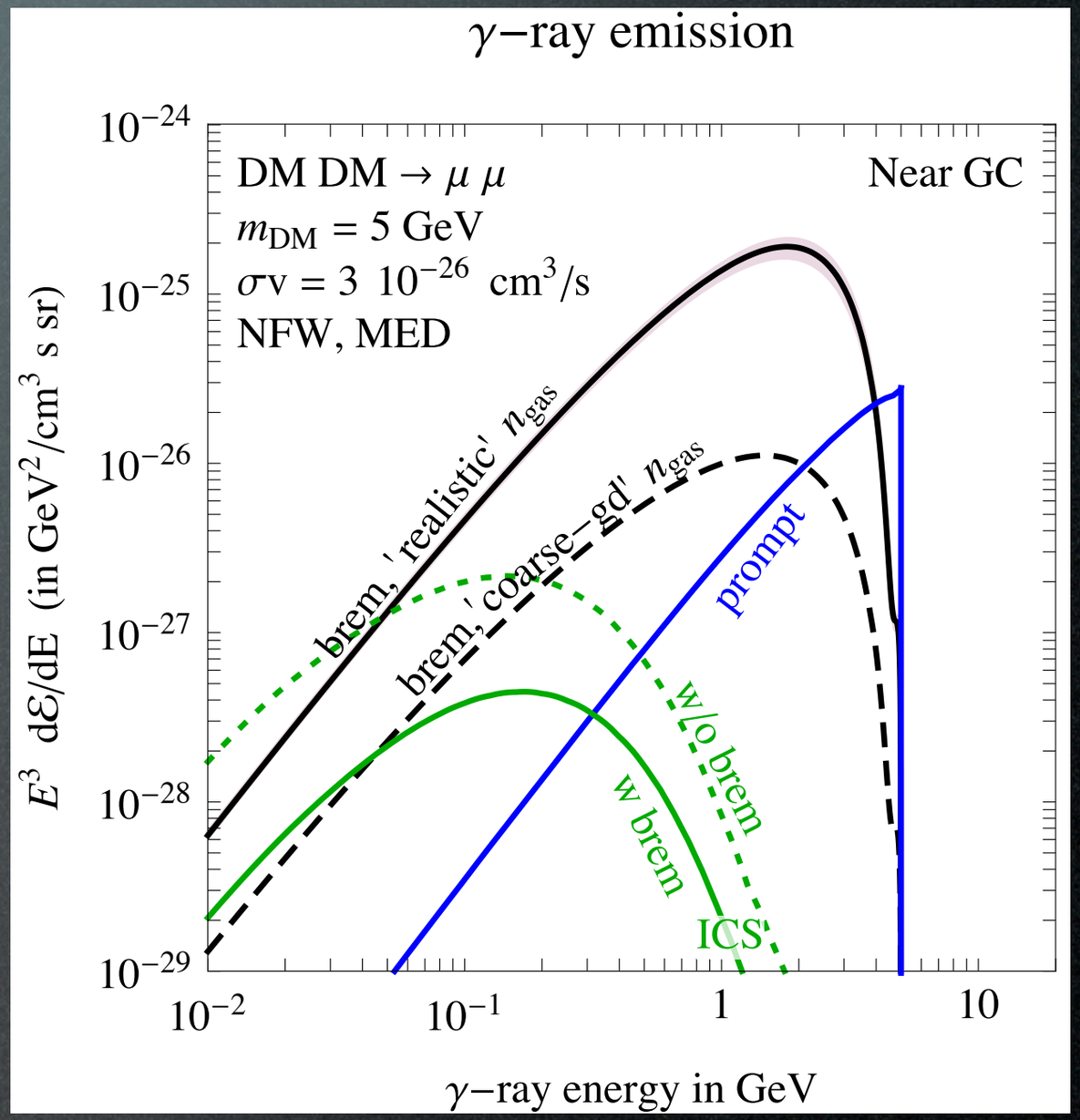
Results

The total γ ray spectrum





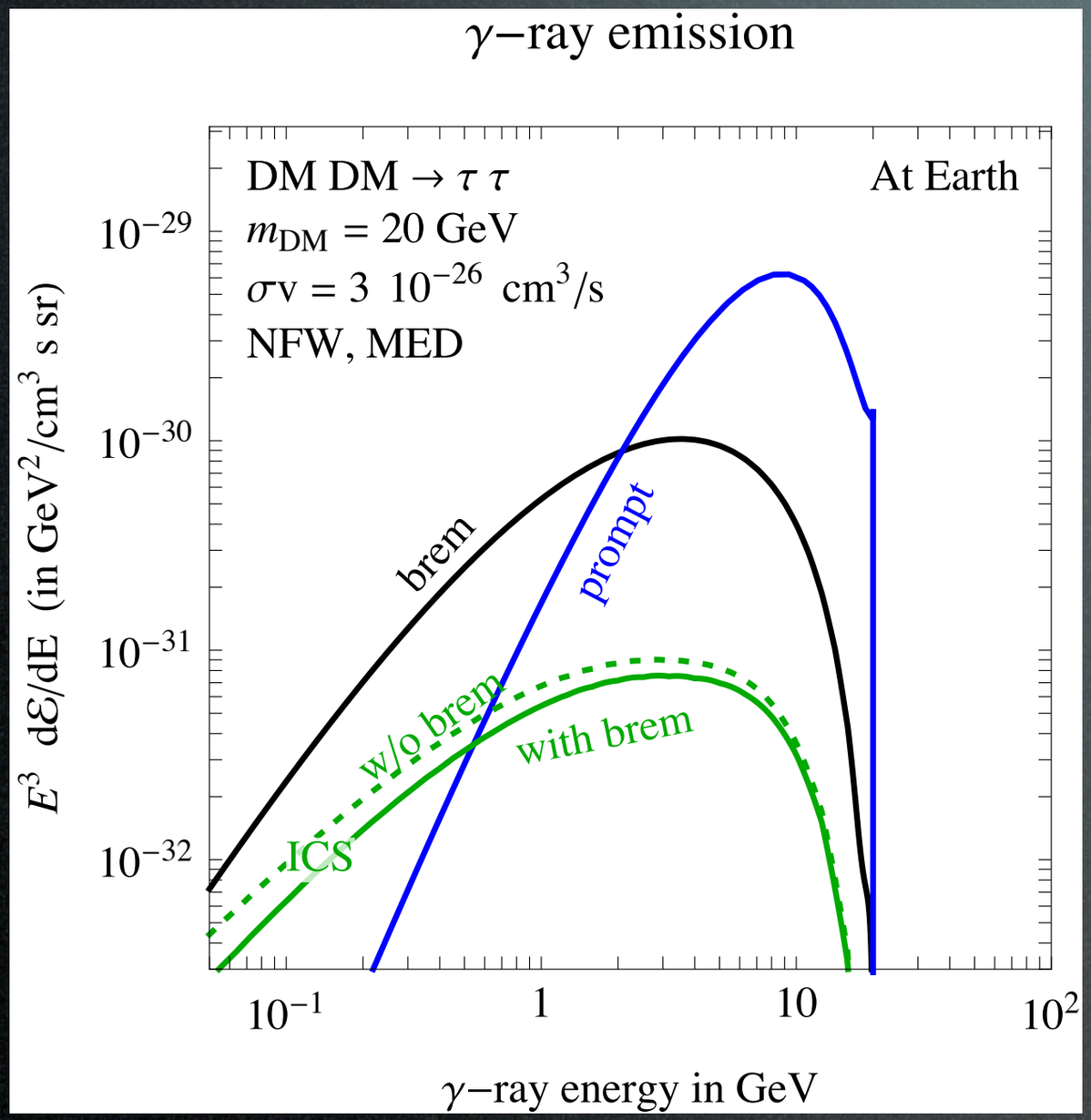
- brem is dominant
- ICS is affected

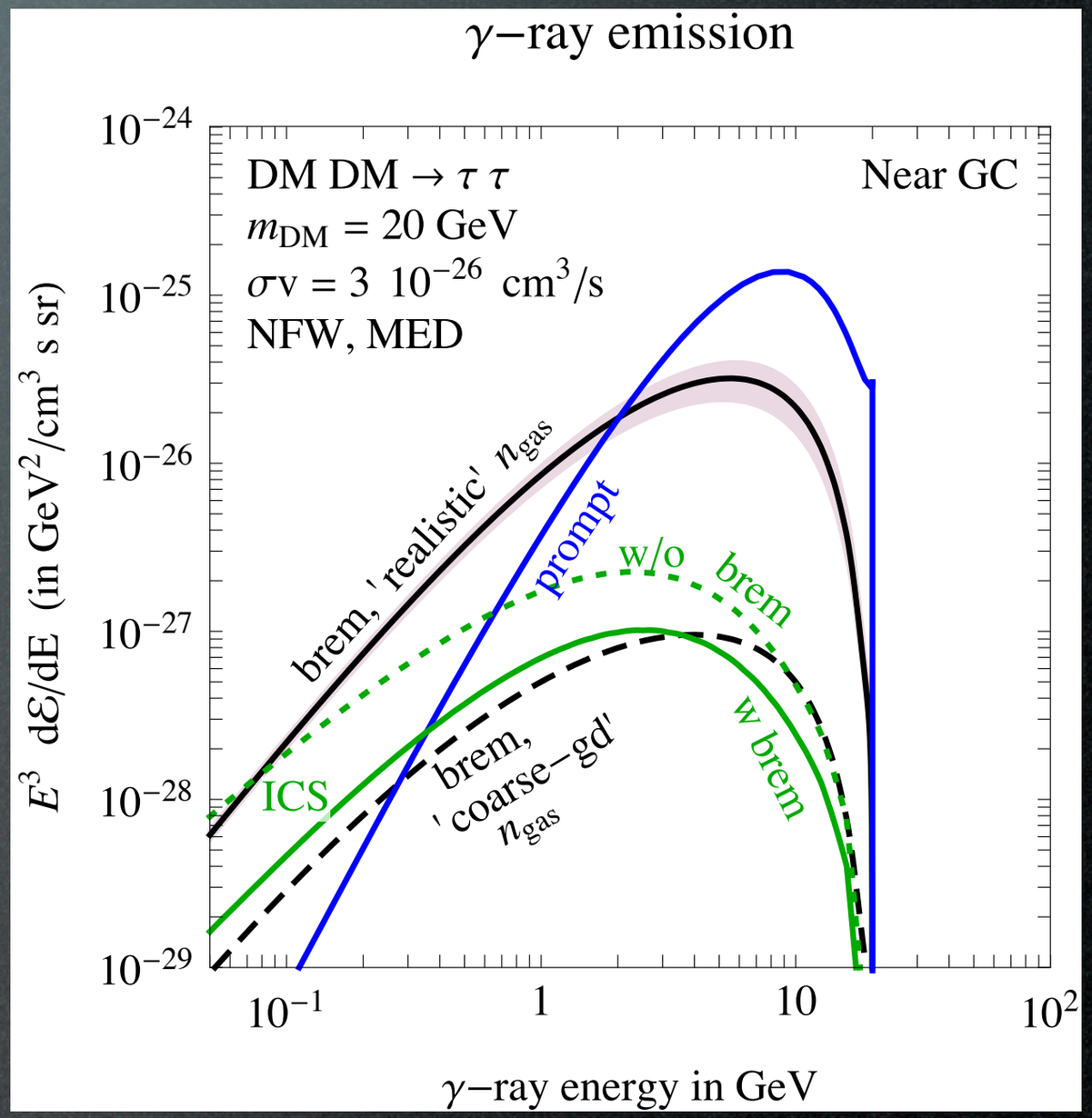
- uncertainty is somewhat reabsorbed:

large n_{gas} ⇨ more loss **and** more emission

Results

The total γ ray spectrum





- brem is important
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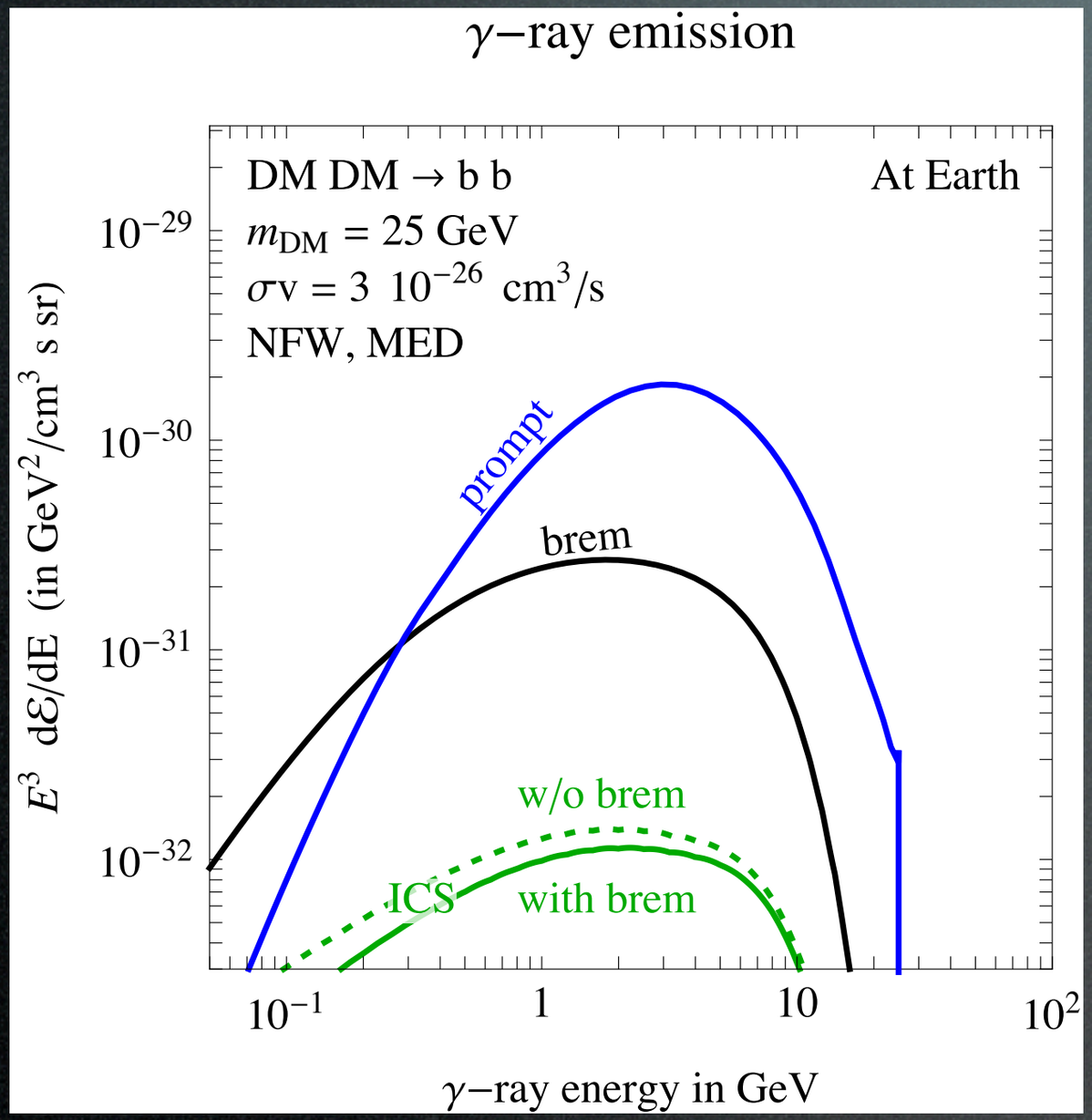
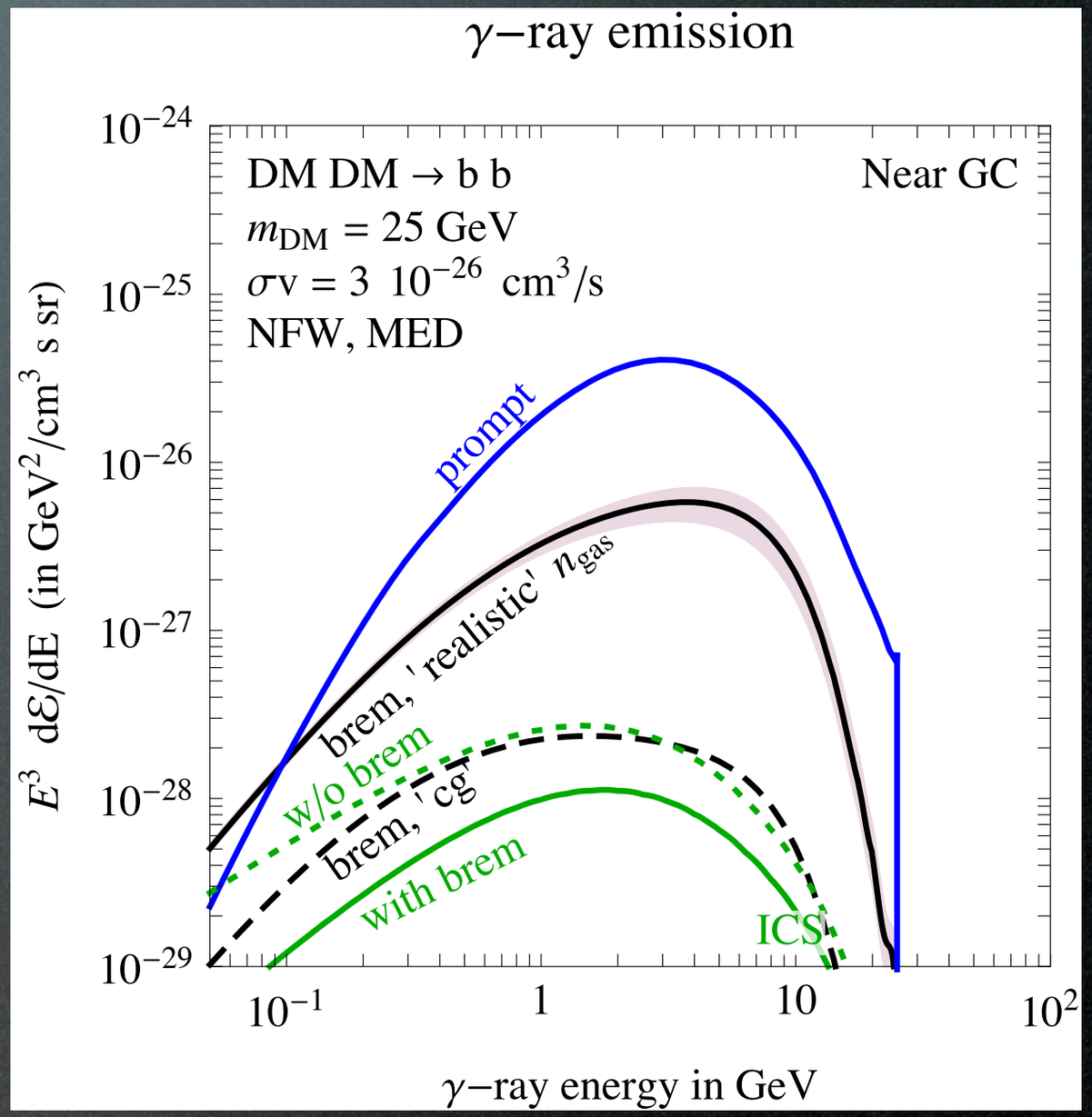
large n_{gas} ⇨ more loss **and** more emission

Results

The total γ ray spectrum





- brem is important
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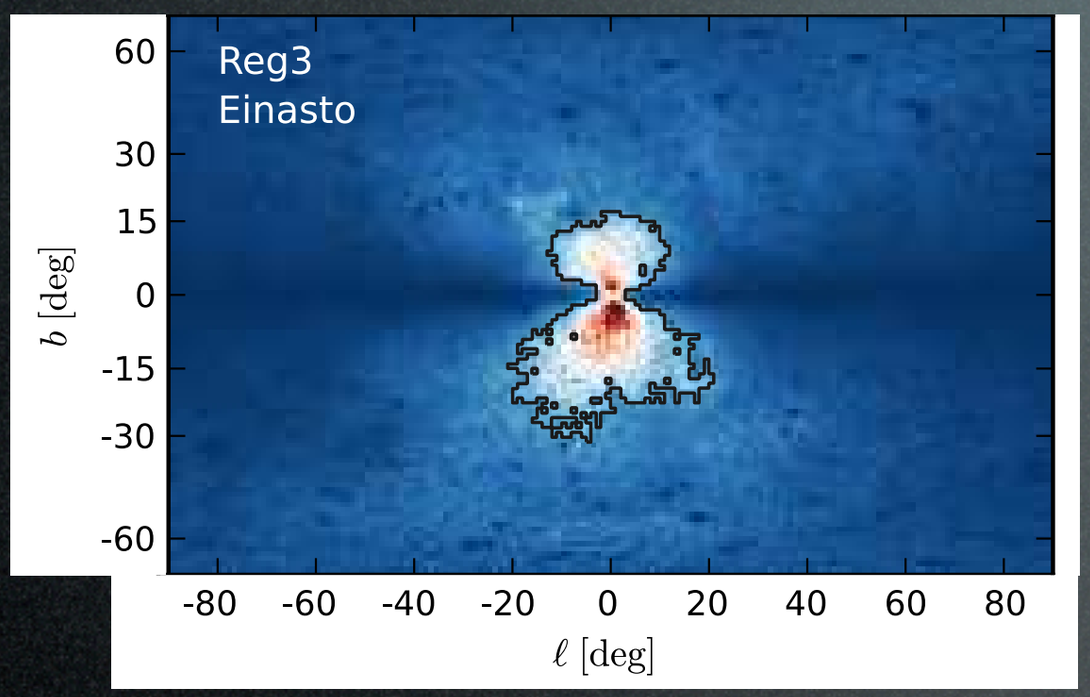
large n_{gas} ⇨ more loss **and** more emission

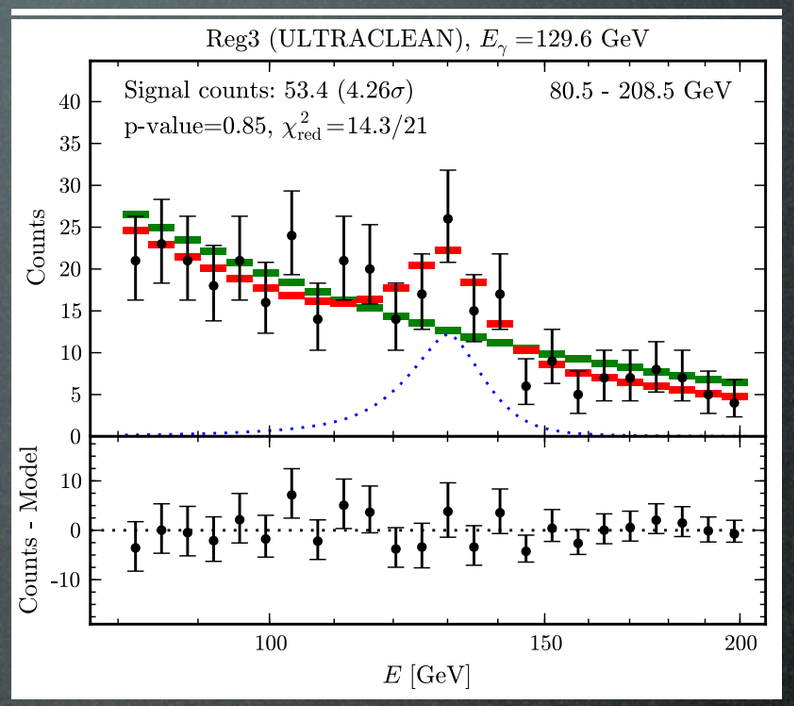
Some recent developments:

- bremsstrahlung γ-rays from light DM
- FERMI 130 GeV line
- excesses near the Galactic Center

Fermi 130 GeV line

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





Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

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

Fermi 130 GeV line

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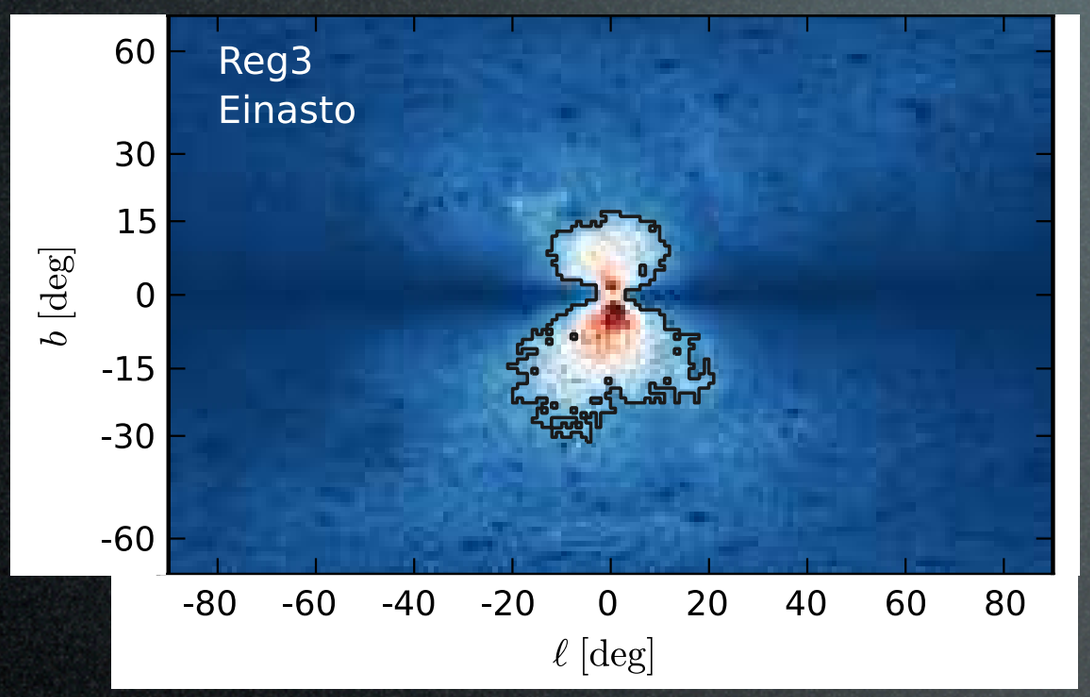

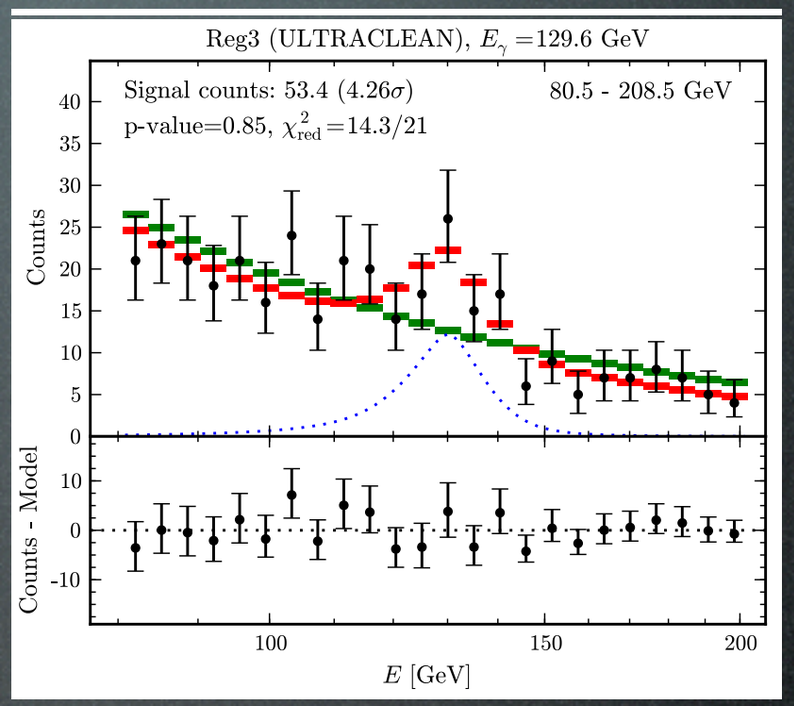

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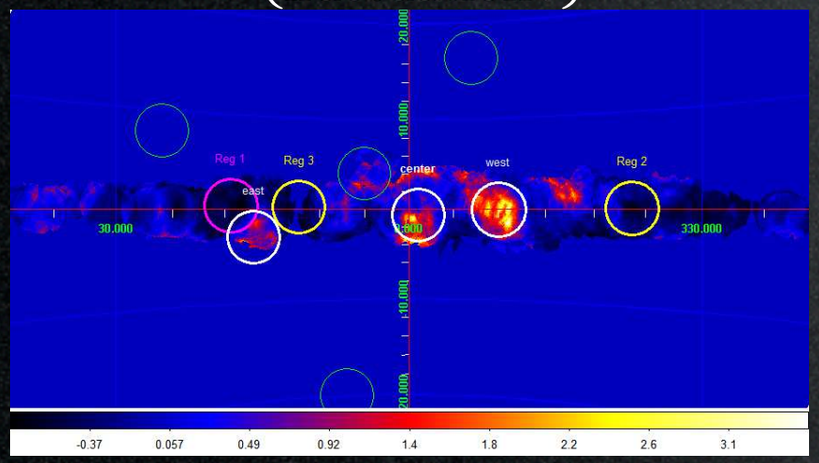
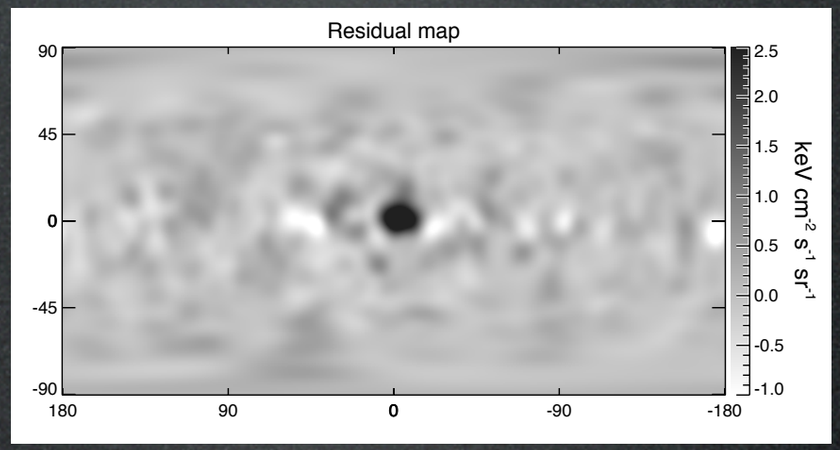
Similar excesses found elsewhere (fluctuation?)



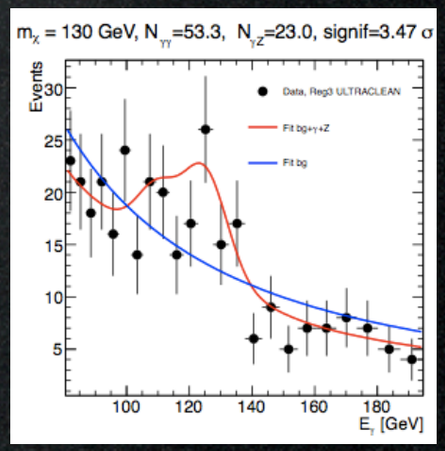
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is only in the GC (actually, a bit off-set)



Su, Finkbeiner, 1206.1616

And there might be 2 lines: 111 GeV, 129 GeV



Rajaraman, Tait, Whiteson 1205.4723
Su, Finkbeiner 1206.1616
Su Finkbeiner 1207.7060

Fermi 130 GeV line

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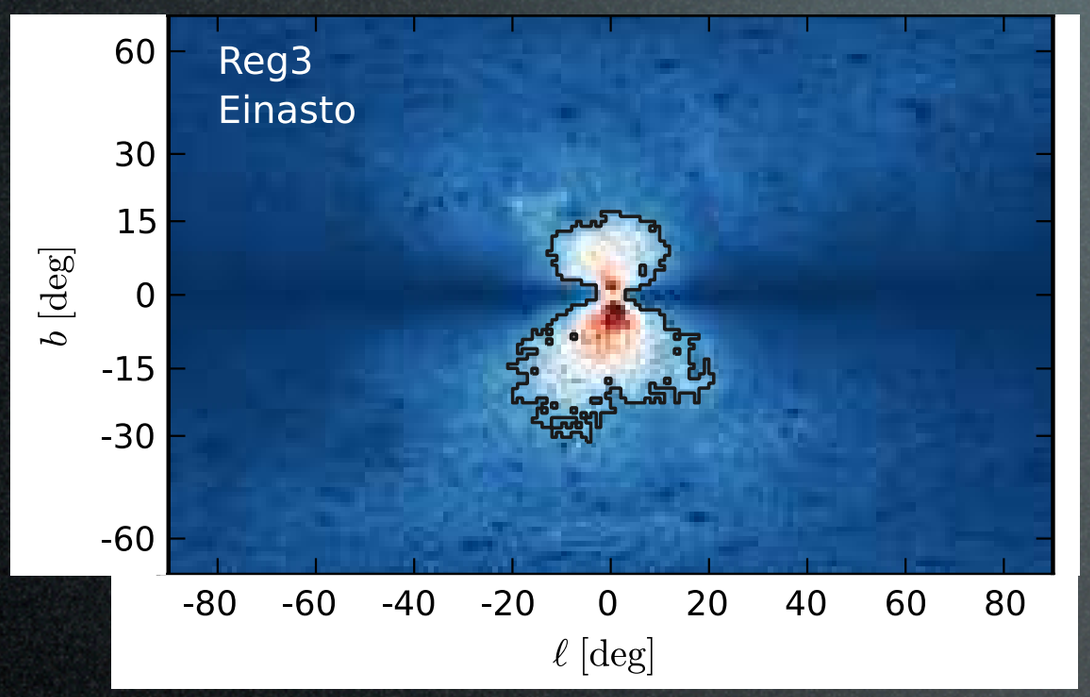

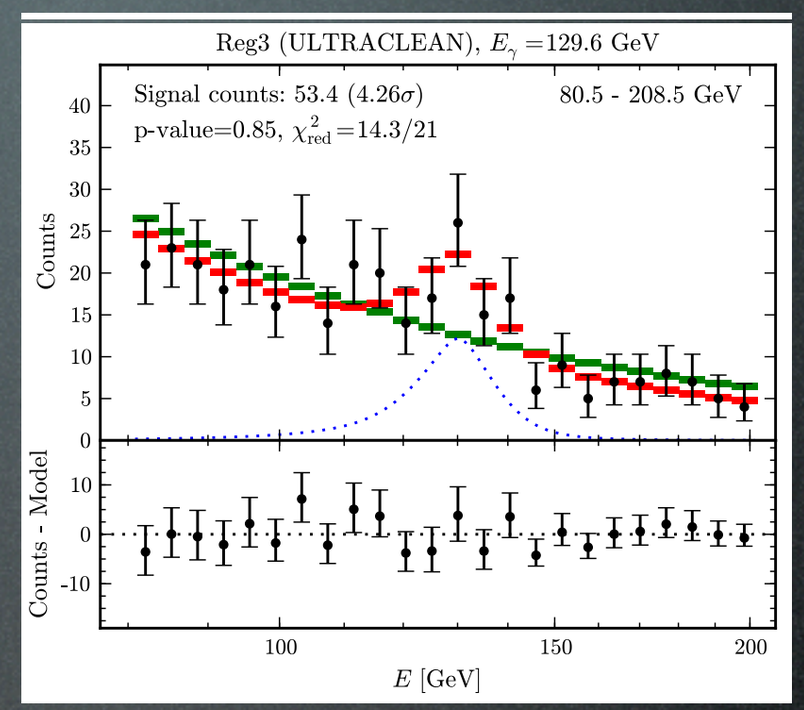

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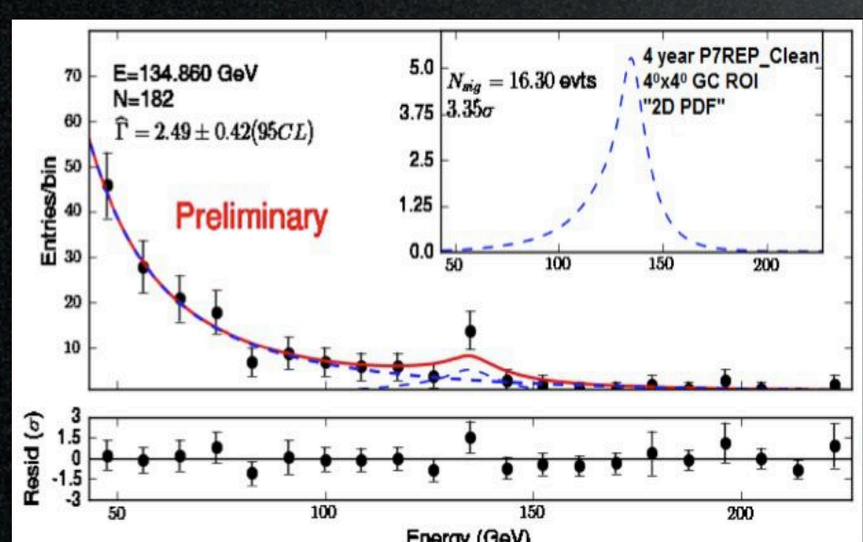
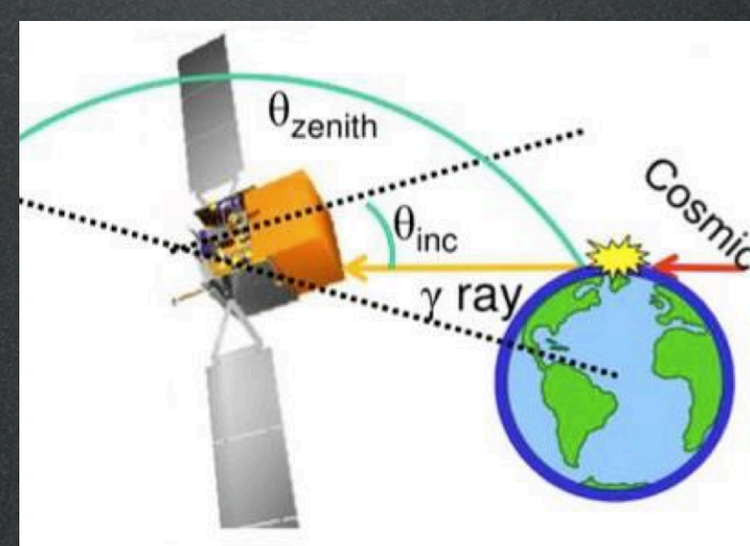
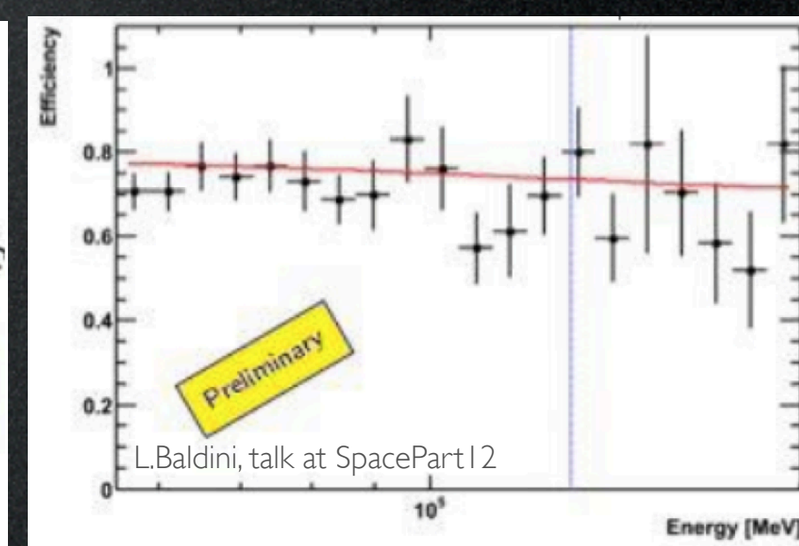
$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{s}$ (large!)

The Fermi coll's cold shower. An instrumental effect?







L.Baldini, talk at SpacePart12

Some recent developments:

- bremsstrahlung γ-rays from light DM
- FERMI 130 GeV line
- excesses near the Galactic Center

Gamma hints?

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

A diffuse GeV excess from around the GC

Dan Hooper

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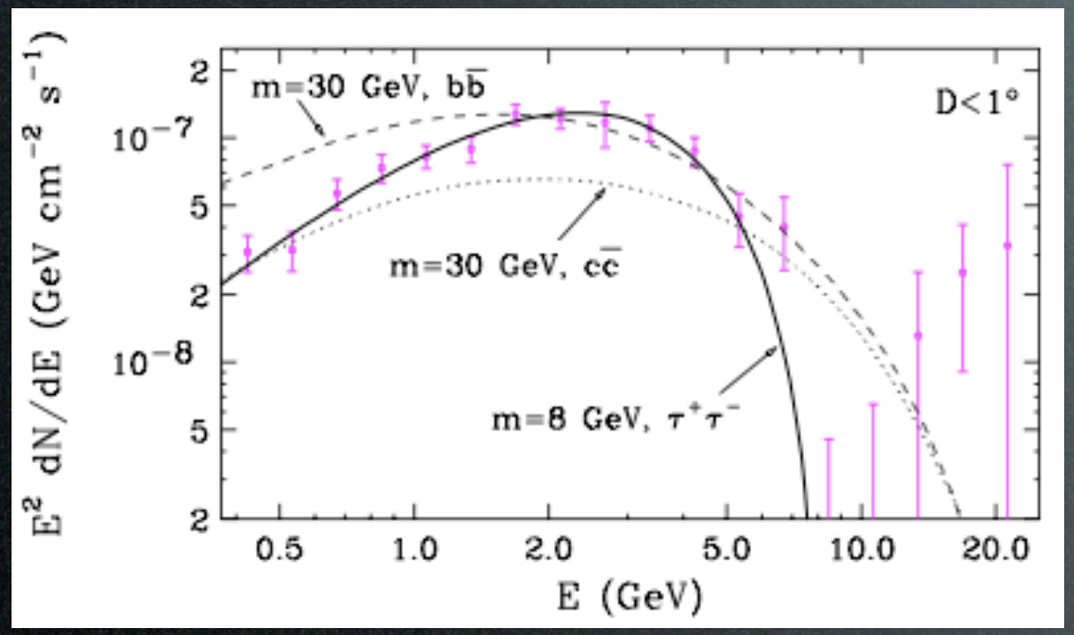

Hooper, Goodenough 1010.2752

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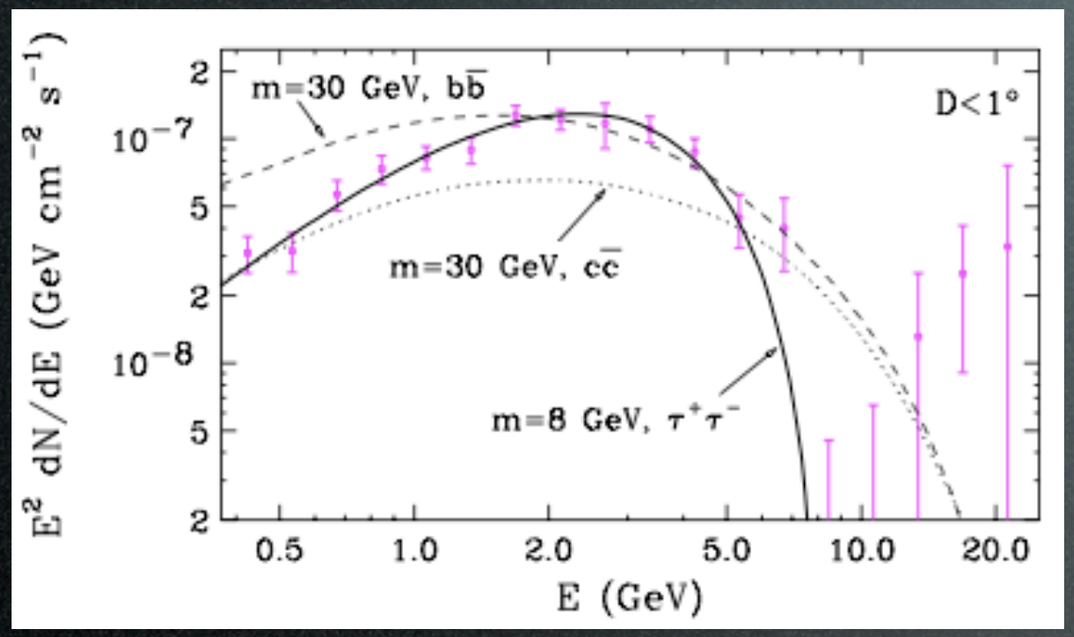
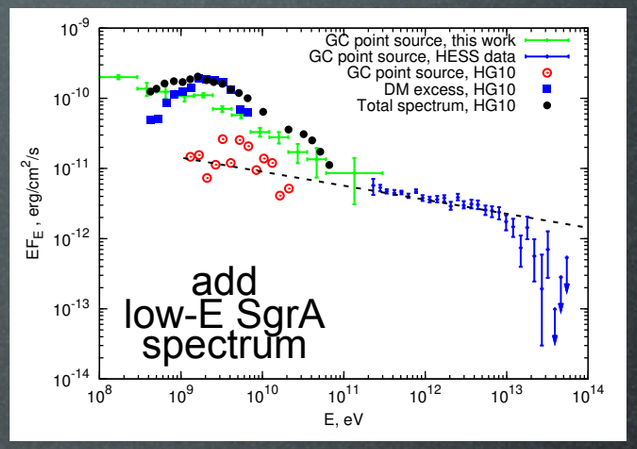
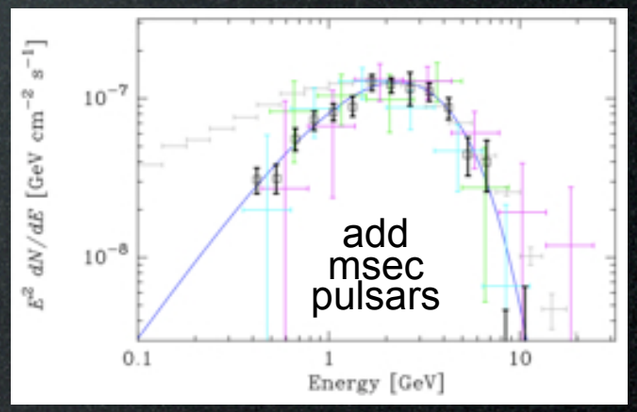


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

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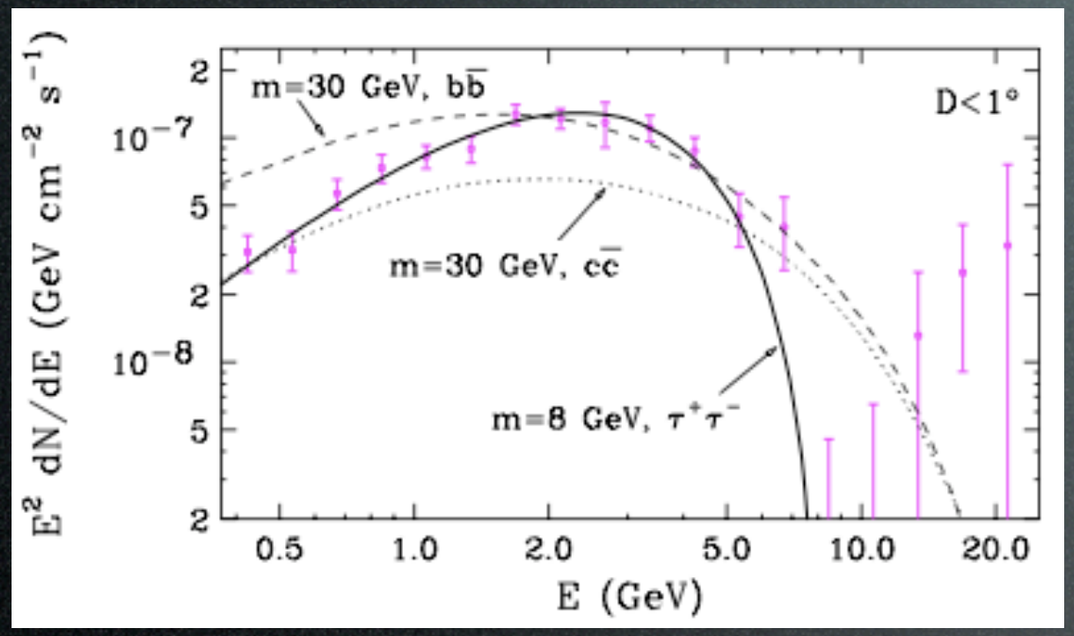

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Best fit: 8 GeV, $\tau^+ \tau^-$, ~thermal σv

A diffuse GeV excess from around the GC

Dan Hooper

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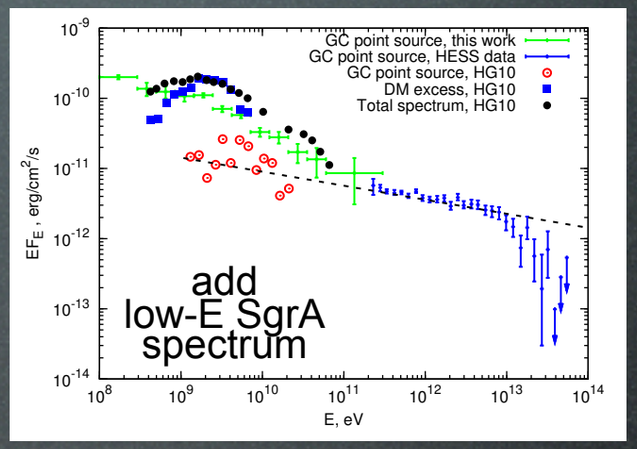

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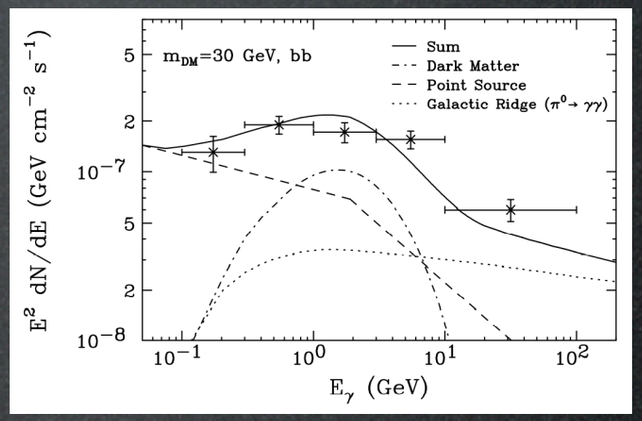
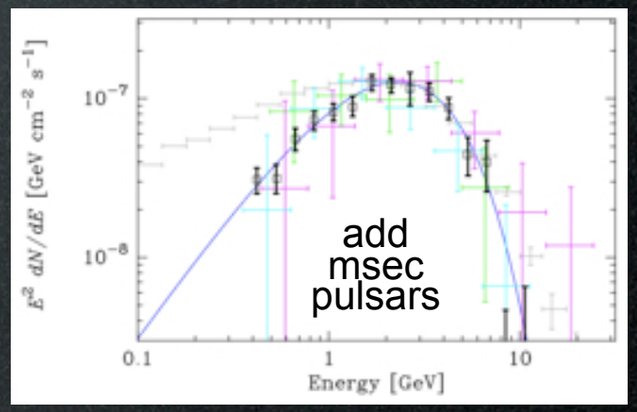
Still works...



Hooper, Linden 1110.0006



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No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

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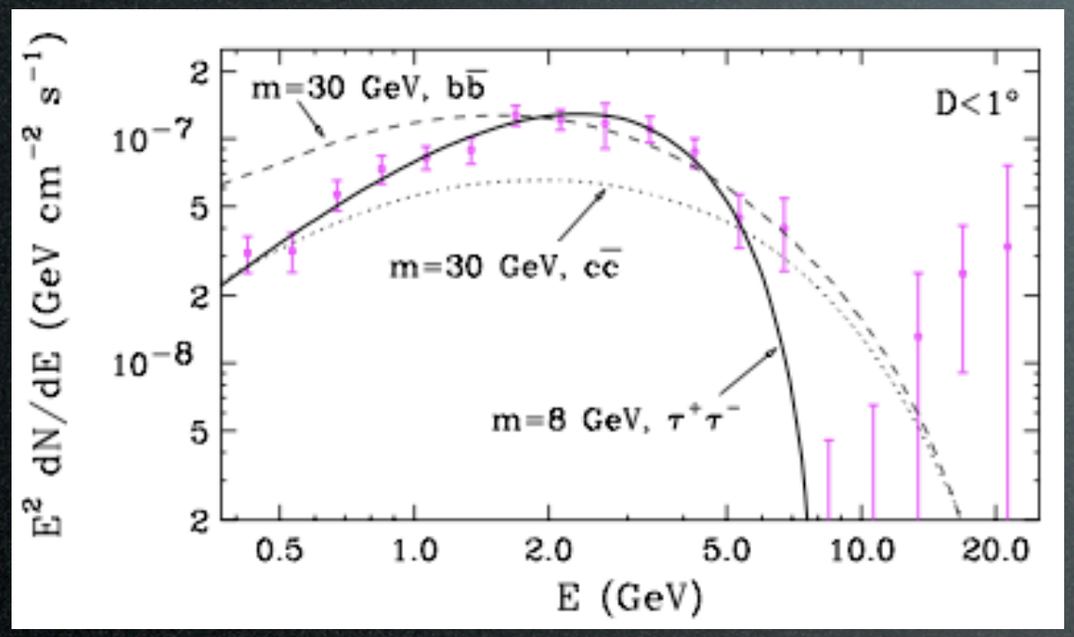

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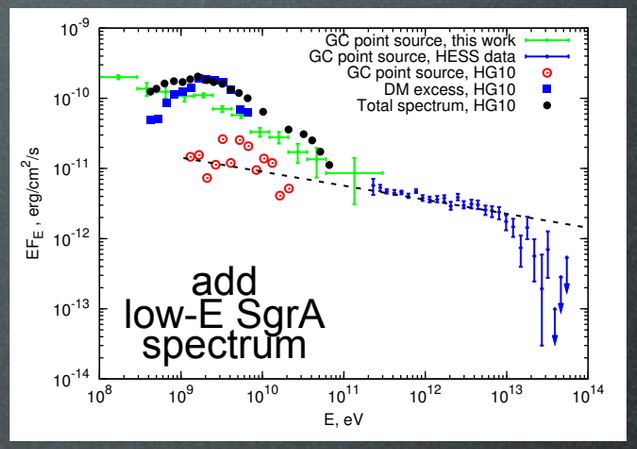
A diffuse GeV excess from around the GC

Dan Hooper

+ synchr from radio filaments
+ WMAP/Planck haze
+ Direct Detection... Hooper, 1201.1303

Objection: know your backgrounds!



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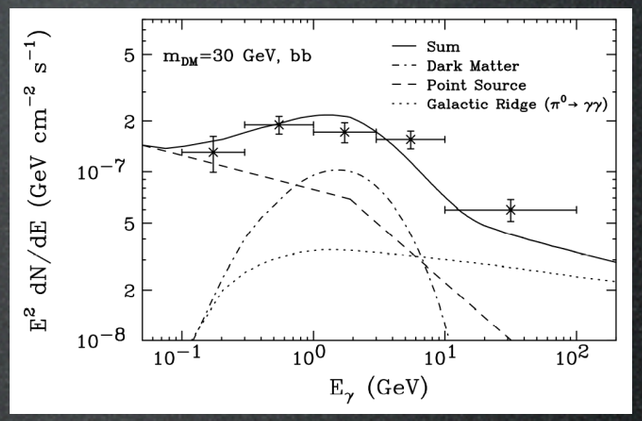

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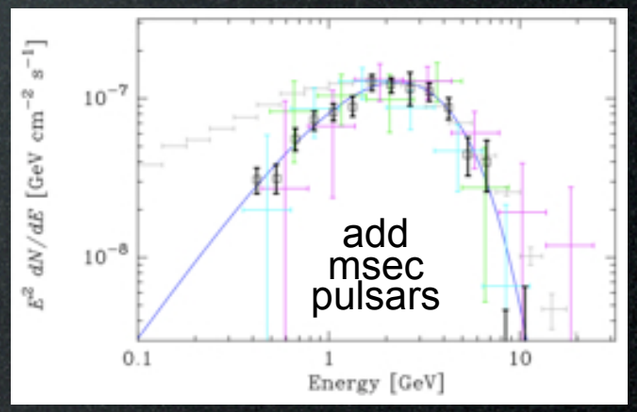

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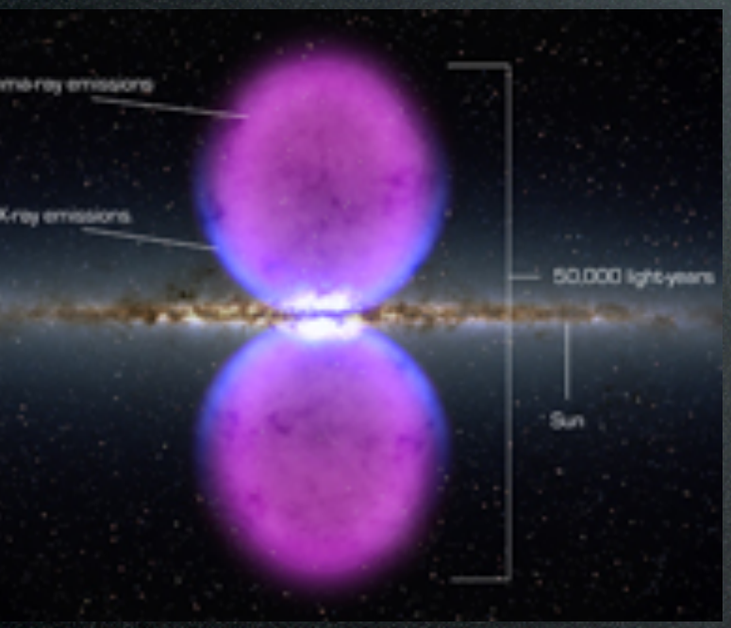

Fermi bubbles

Dan Hooper

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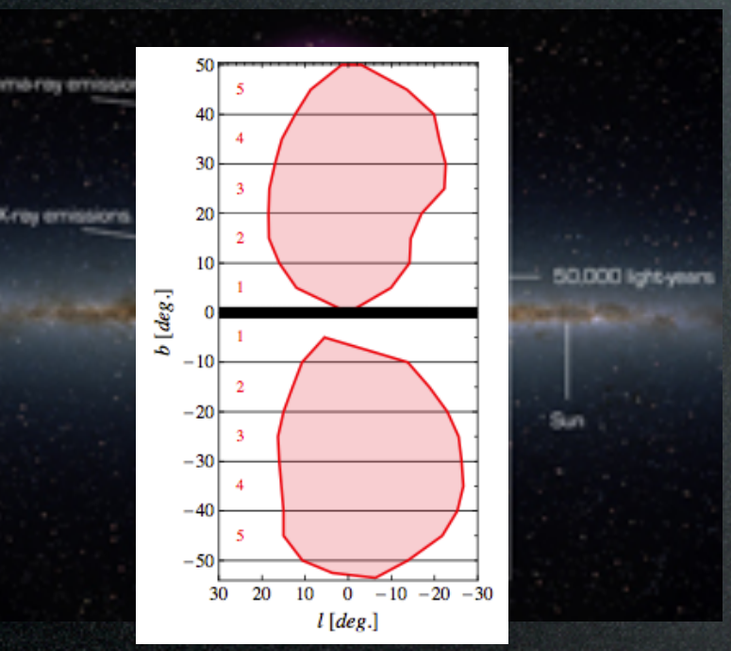

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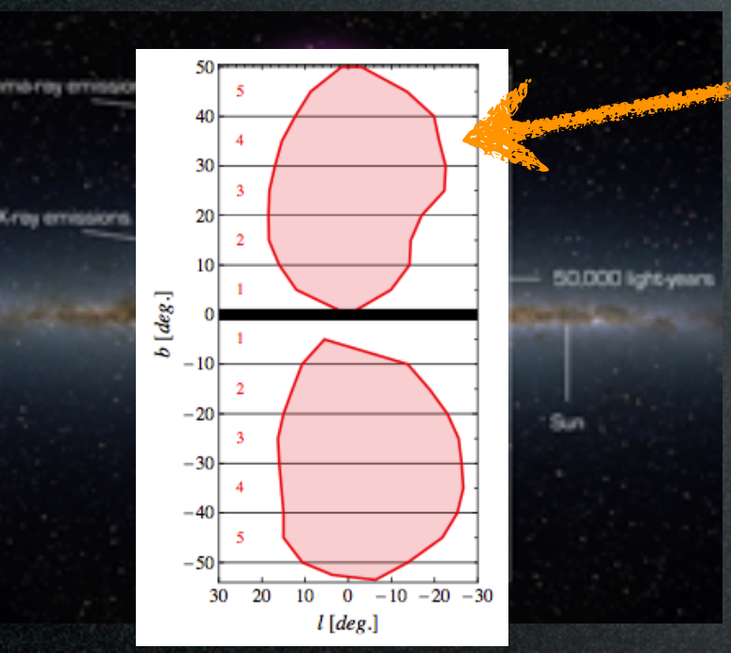

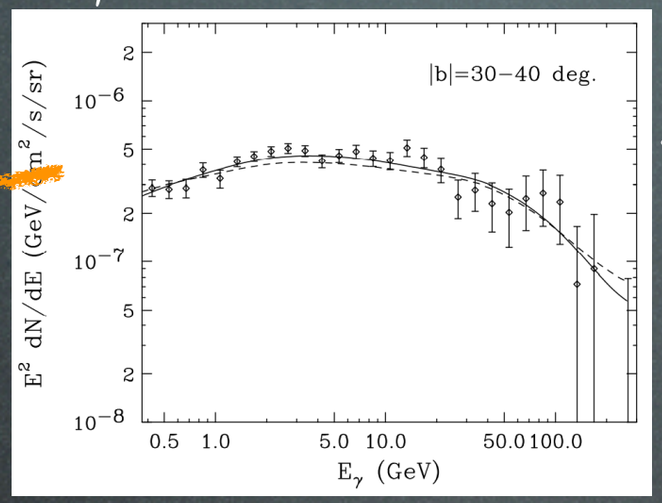

Here there's no excess which cannot be explained in terms of ordinary ICS.

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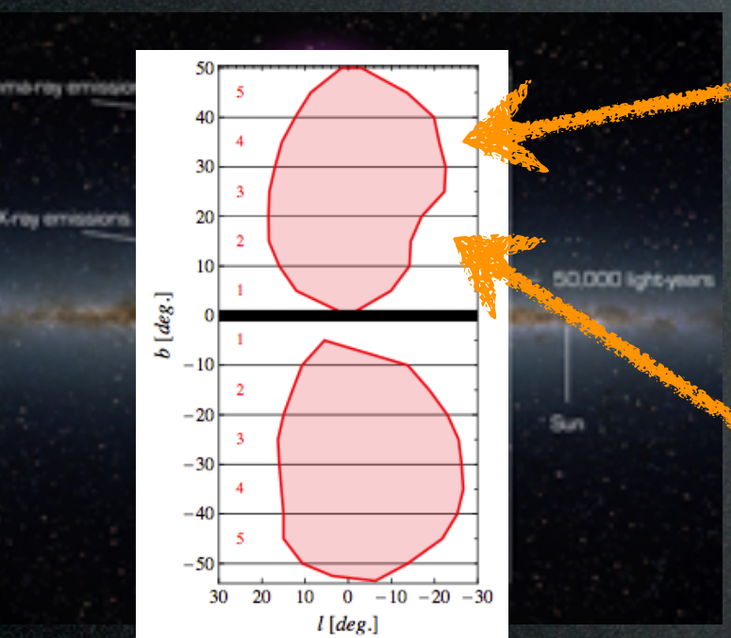

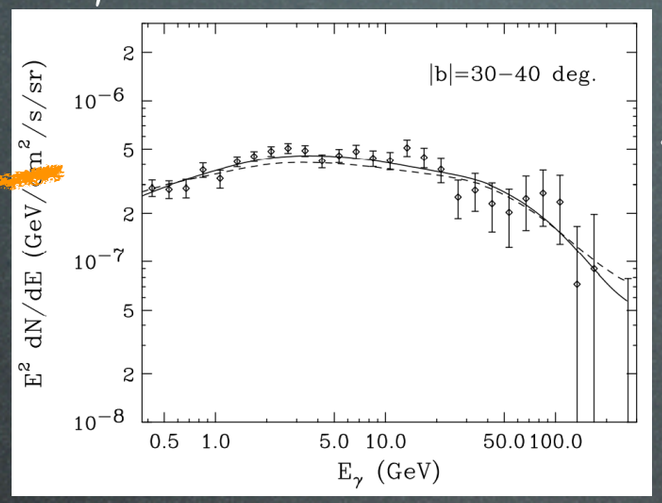

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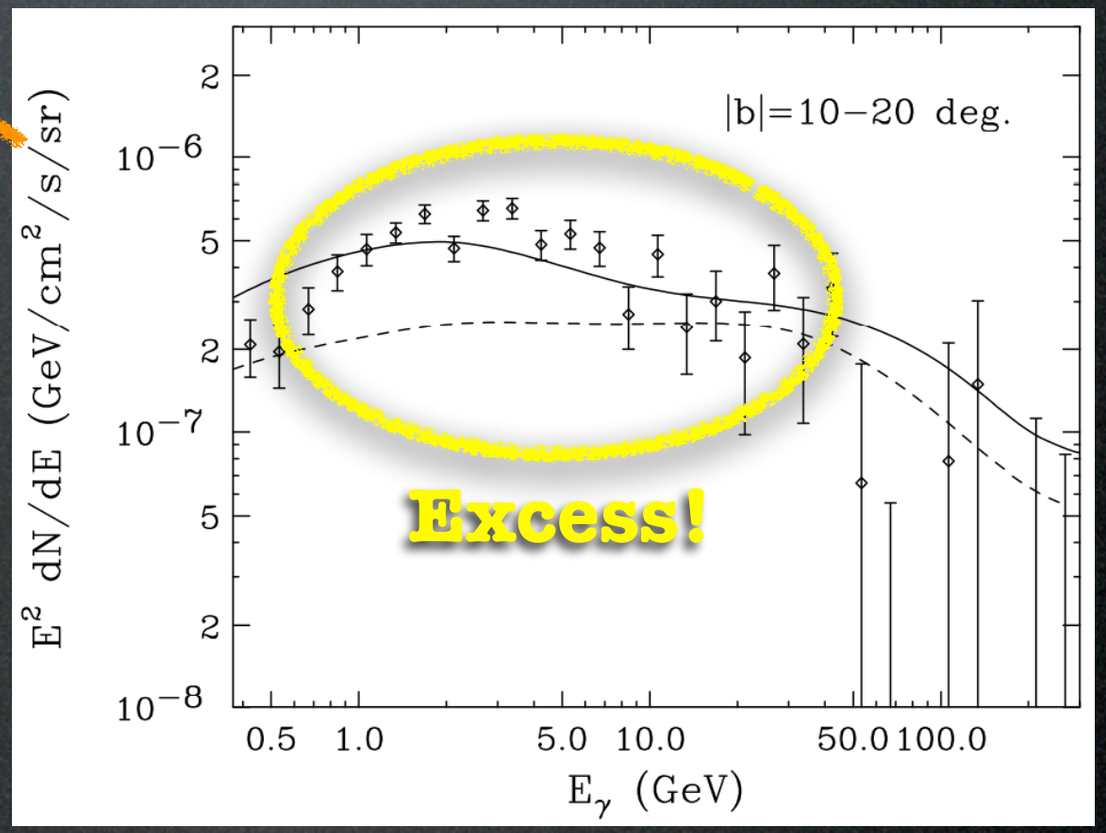

Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles

Dan Hooper

Hooper, Slatyer 1302.6589

Essentially confirmed by: Huang, Urbano, Xue 1307.6862

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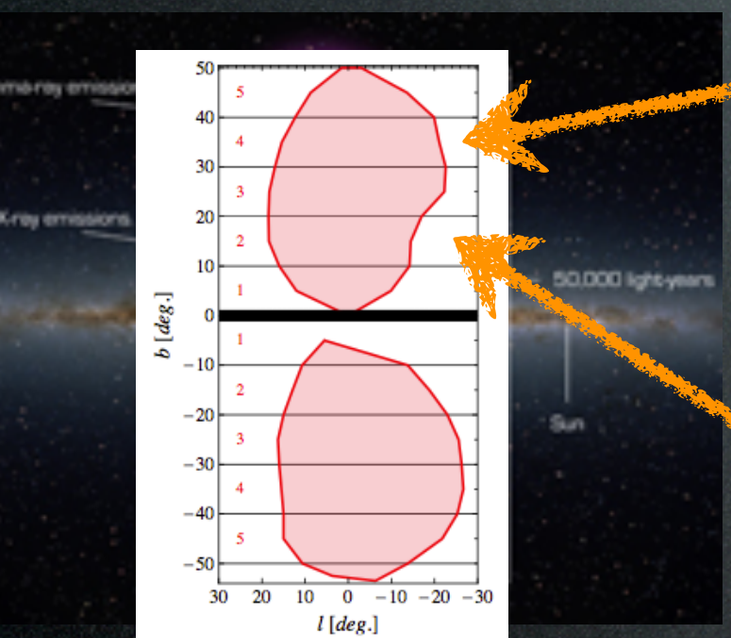

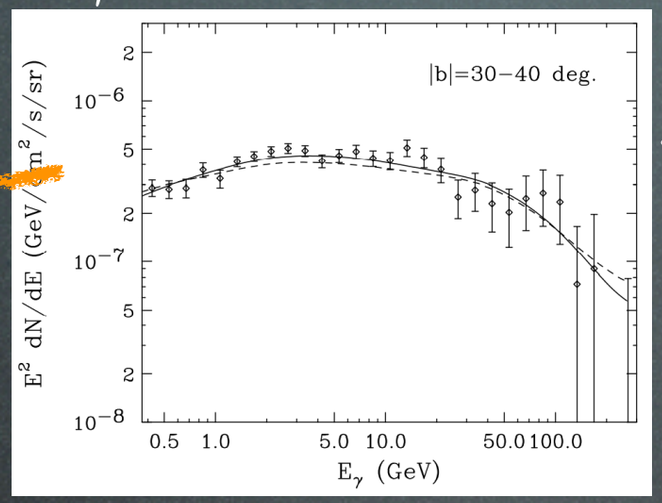

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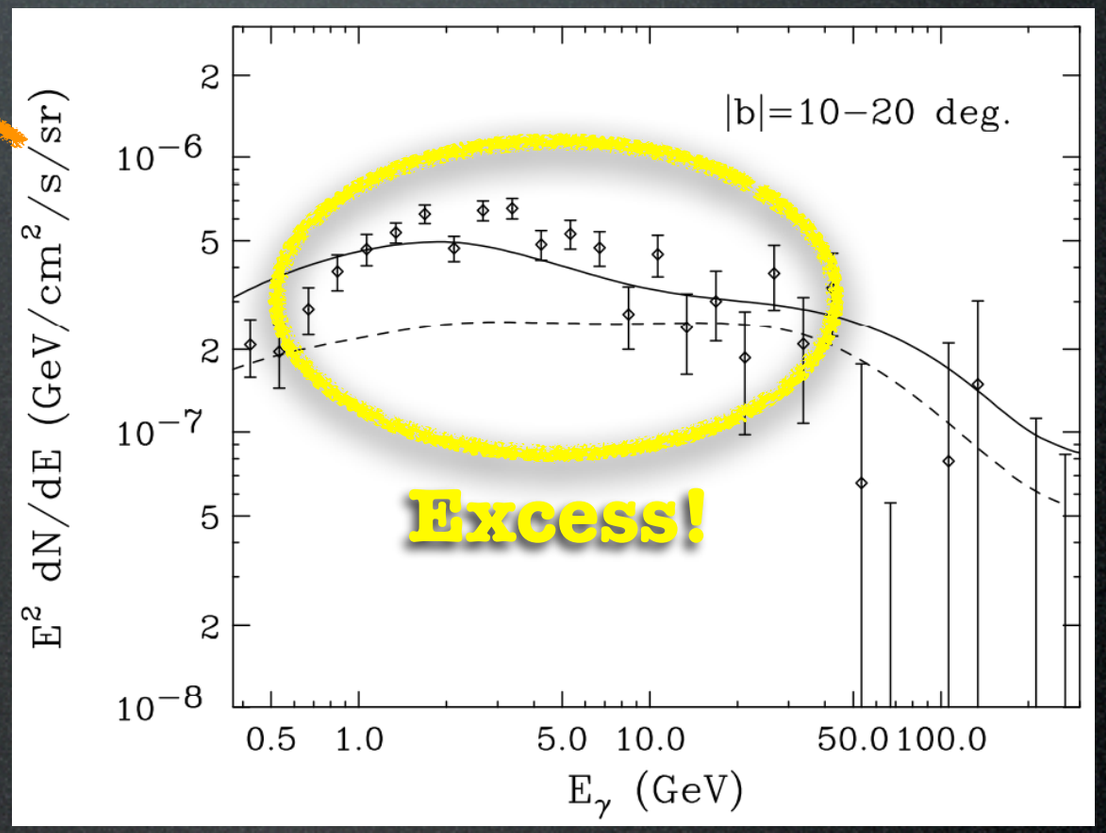

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Fermi bubbles

Dan Hooper

Objection:
nothing tells you that the input $e^{\pm}$ spectrum stays the same at high and low latitudes
(the ISRF too, but one can better model that)

Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

Conclusions

Conclusions

Huang, Urbano, Xue 1307.6862

Since the dawn of civilization, the desire to gaze, study and understand the mysteries hedged in the astonishing beauty of the sky has been an unavoidable and innate prerogative of human nature. In March 1610 Galileo Galilei published the *Sidereus Nuncius*, the first scientific work based on telescope observations. Through the eye of this revolutionary instrument Galileo was able to take the first steps in the exploration of a completely unknown world, describing the results of his studies about the mountainous surface of the Moon, a myriad of stars never seen before with the naked eye, and the discovery of four Erratic Stars that appeared to be orbiting around the planet Jupiter.

After more than four hundred years, telescopes are becoming the most important scientific instrument in astronomy and astrophysics, reaching a degree of technical perfection that enables us to study in great detail the Universe. Among them, the Fermi Large Area Telescope (LAT) [1] is devoted to the study of photons in the high energy region of gamma-rays, and one of the most challenging goals of the mission is to shed light on the elusive nature of Dark Matter (DM).

Many efforts have been made, for instance, to study and understand the nature of a spatially extended excess, peaked at few GeV, found in the gamma-ray emission from the Galactic center [2, 3, 4, 5, 6]. The signal can be explained by $\mathcal{O}(10)$ GeV DM annihilating into $\tau^+\tau^-$, $b\bar{b}$, or by model with dark forces [7].

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Gamma rays are promising for DM searches, but they are difficult.

environmental dependence, backgrounds...

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Huang, Urbano, Xue 1307.6862

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environmental dependence, backgrounds...

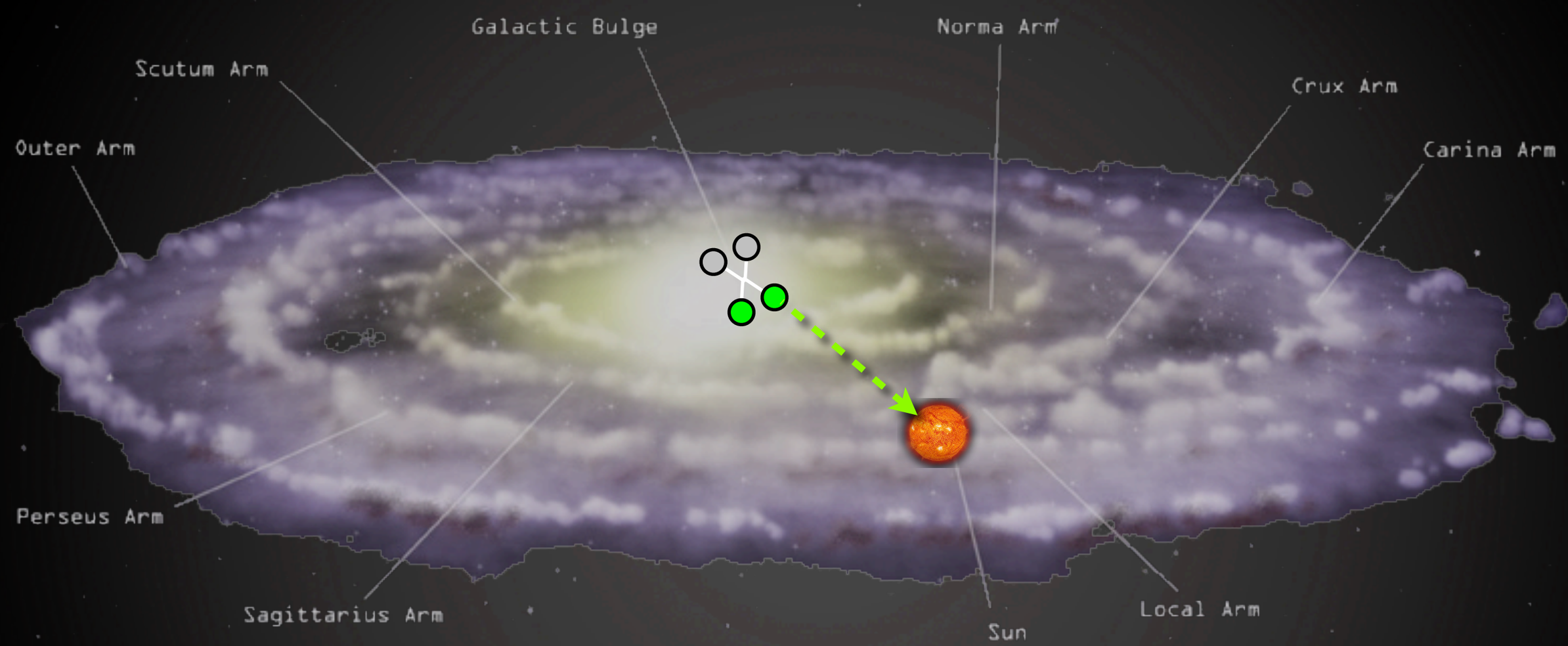
So far only solid constraints and maybe some hint.

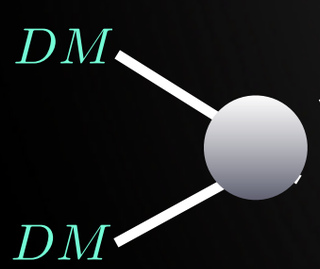
(Even the best smoking guns have proven to be a bit wet...)

Bonus track: neutrinos

Bonus track: neutrinos

ν from DM annihilations in galactic center

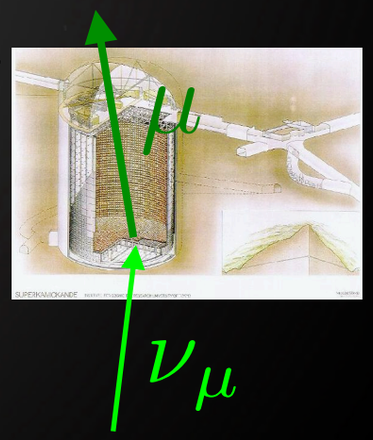




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \nu$$

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

up-going muons:



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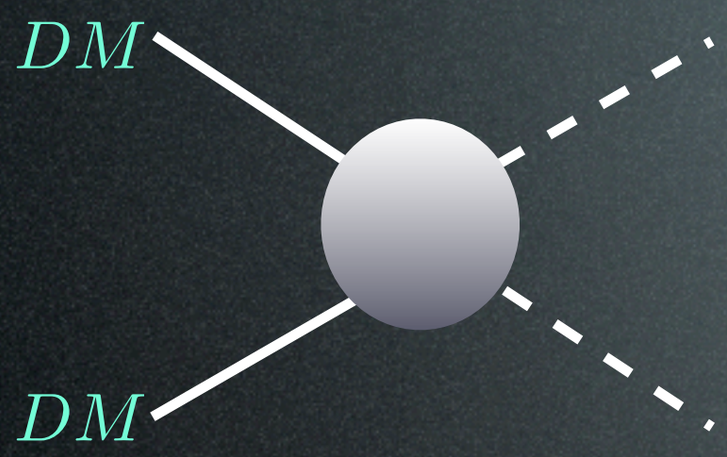

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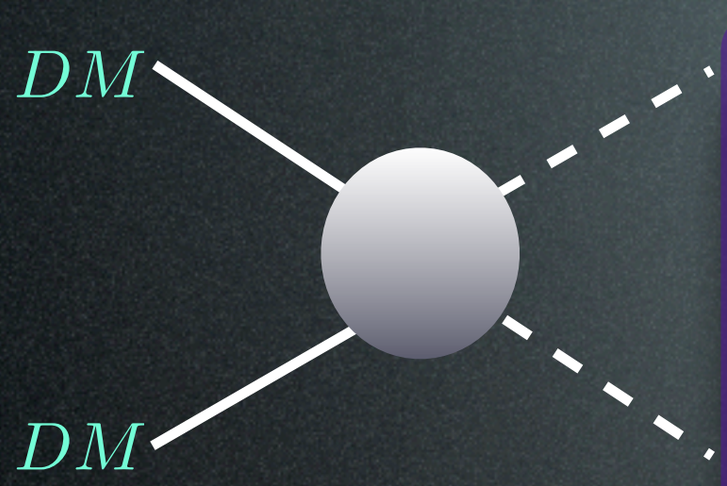

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

primary channels

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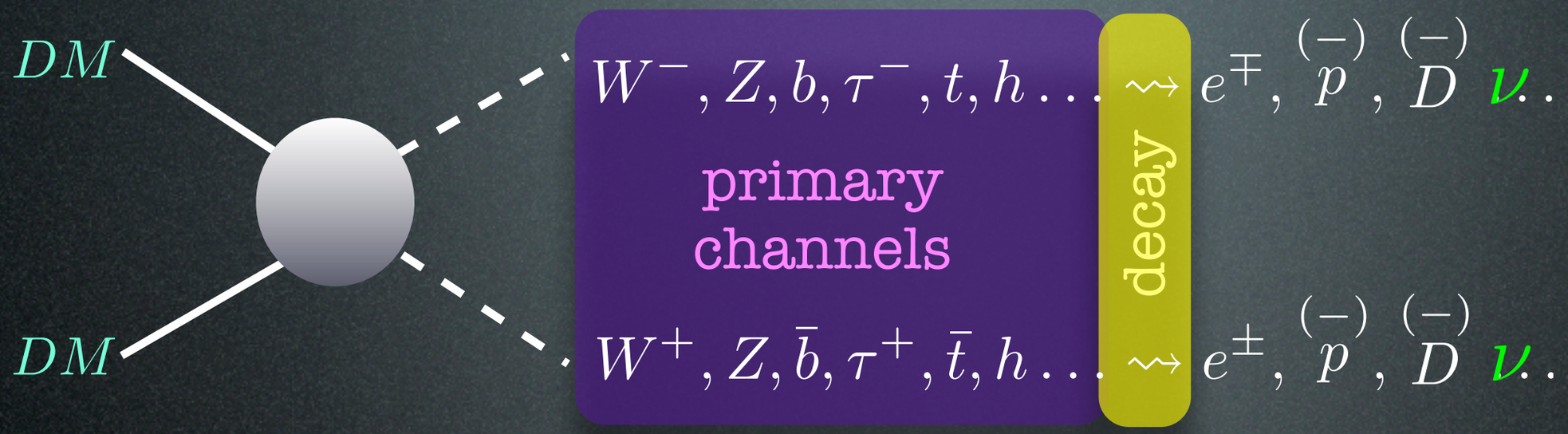

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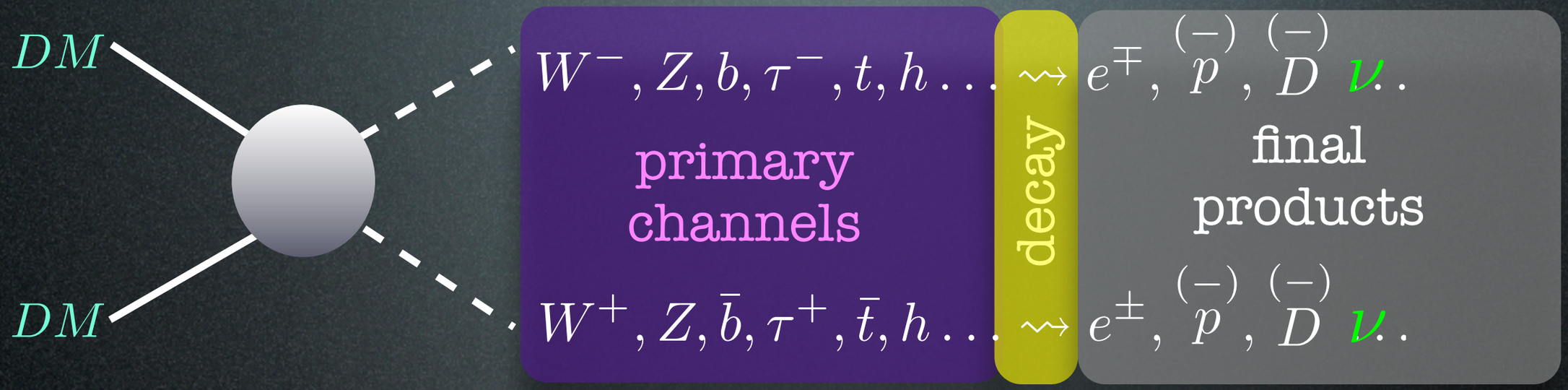

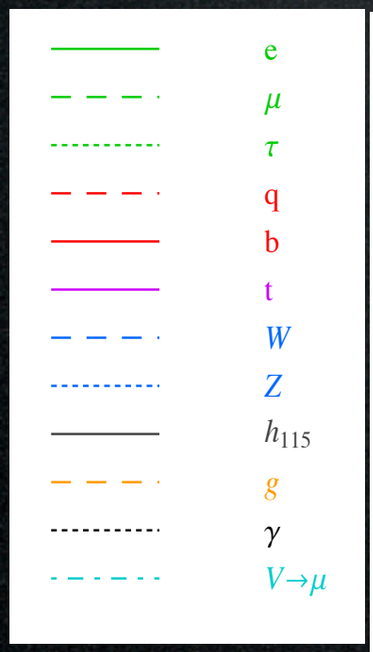

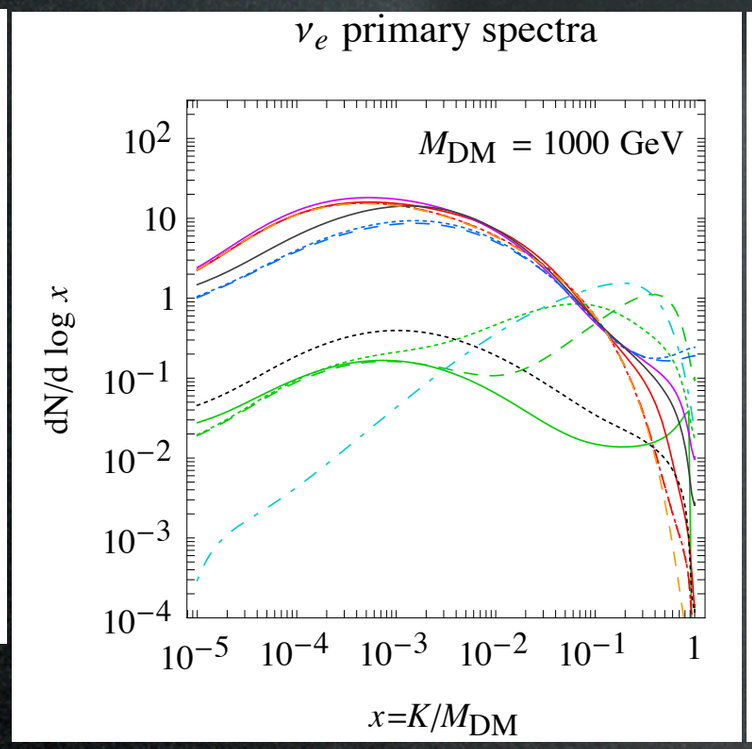

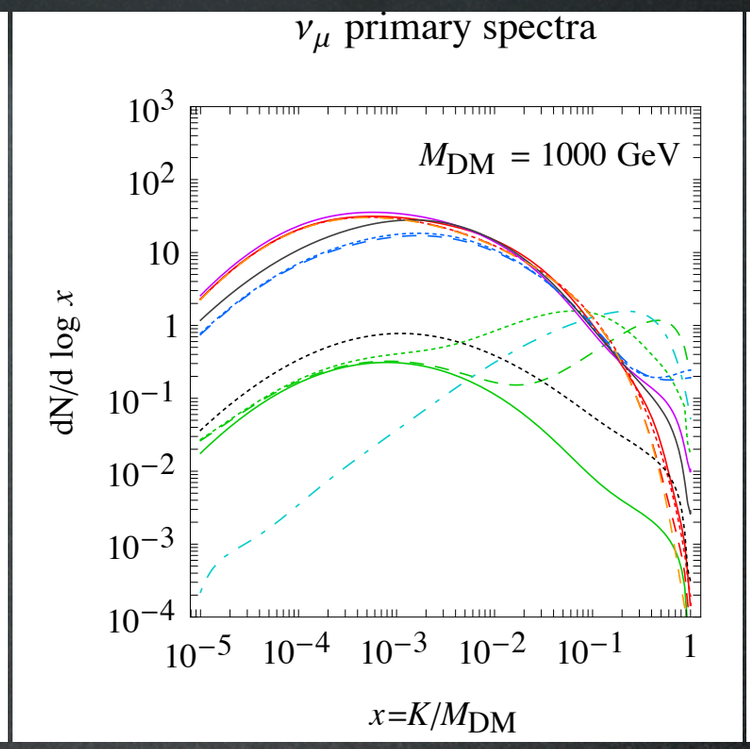

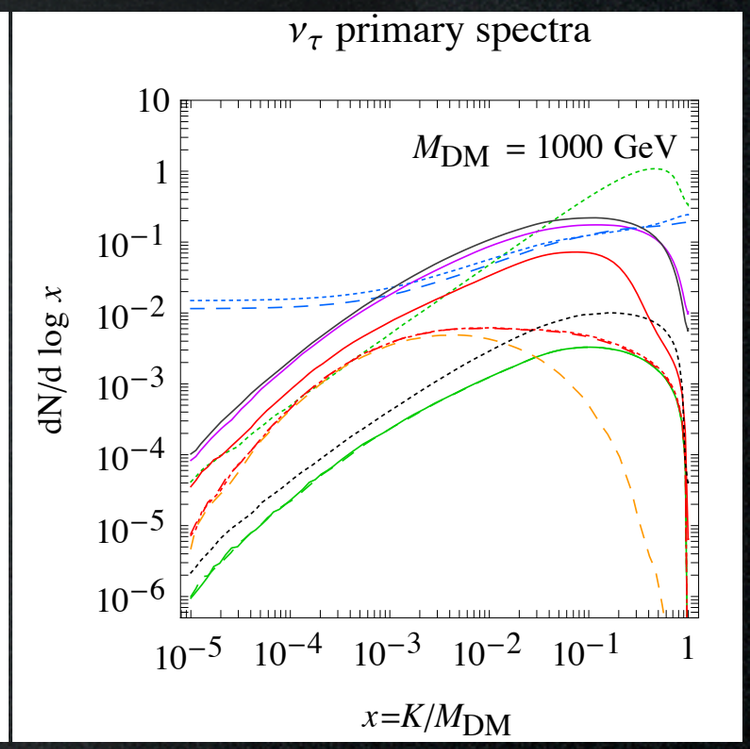

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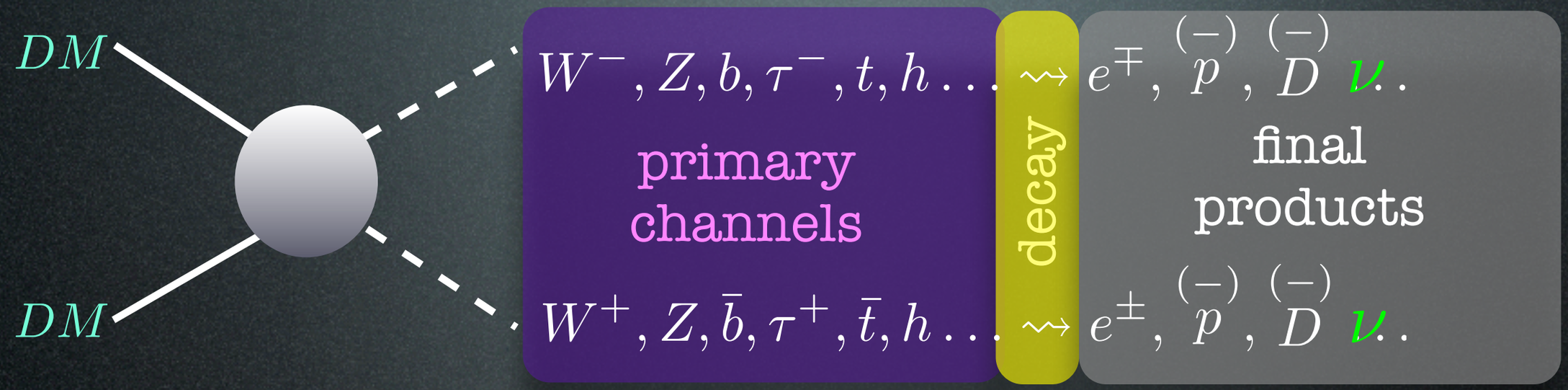
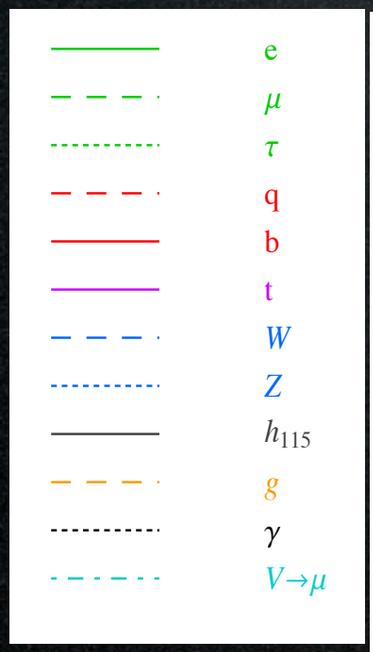
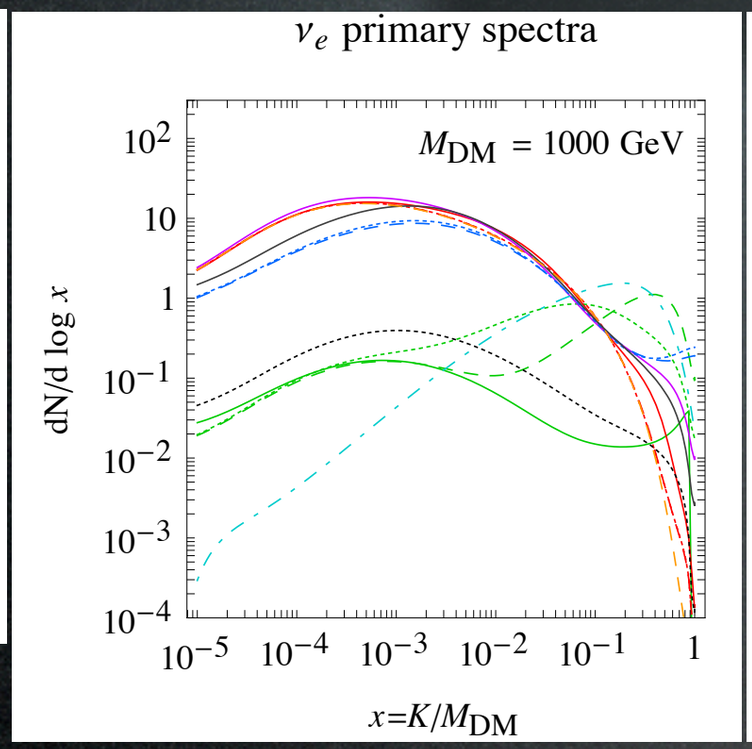
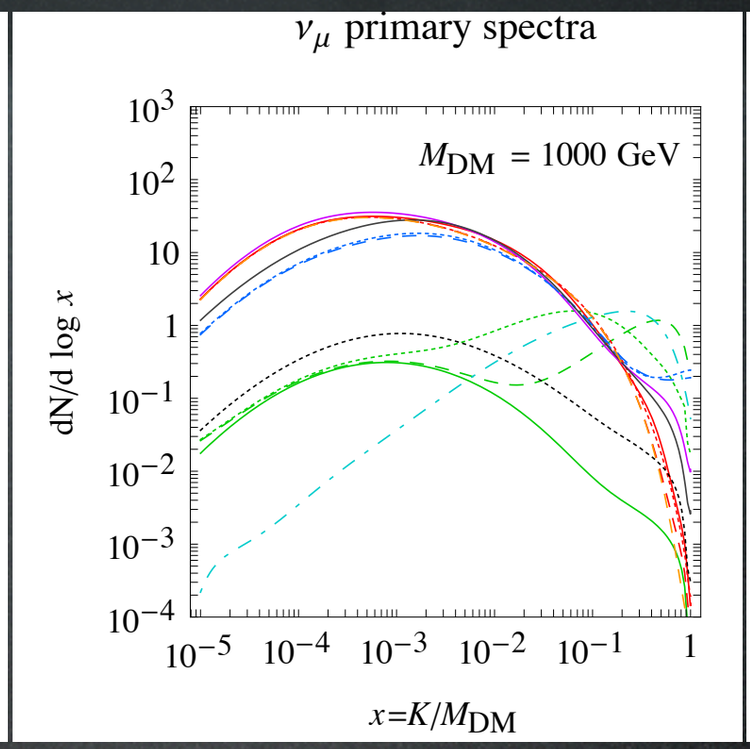
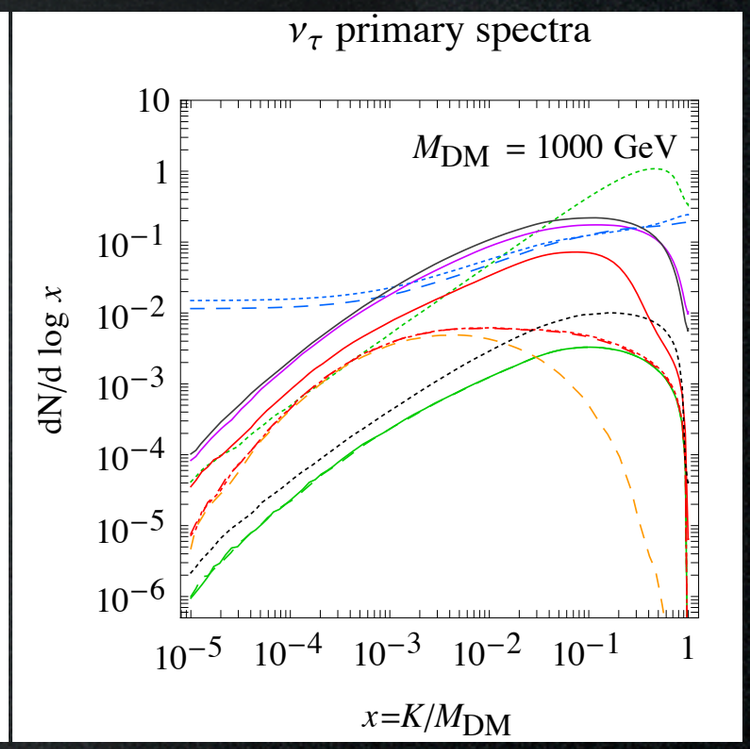










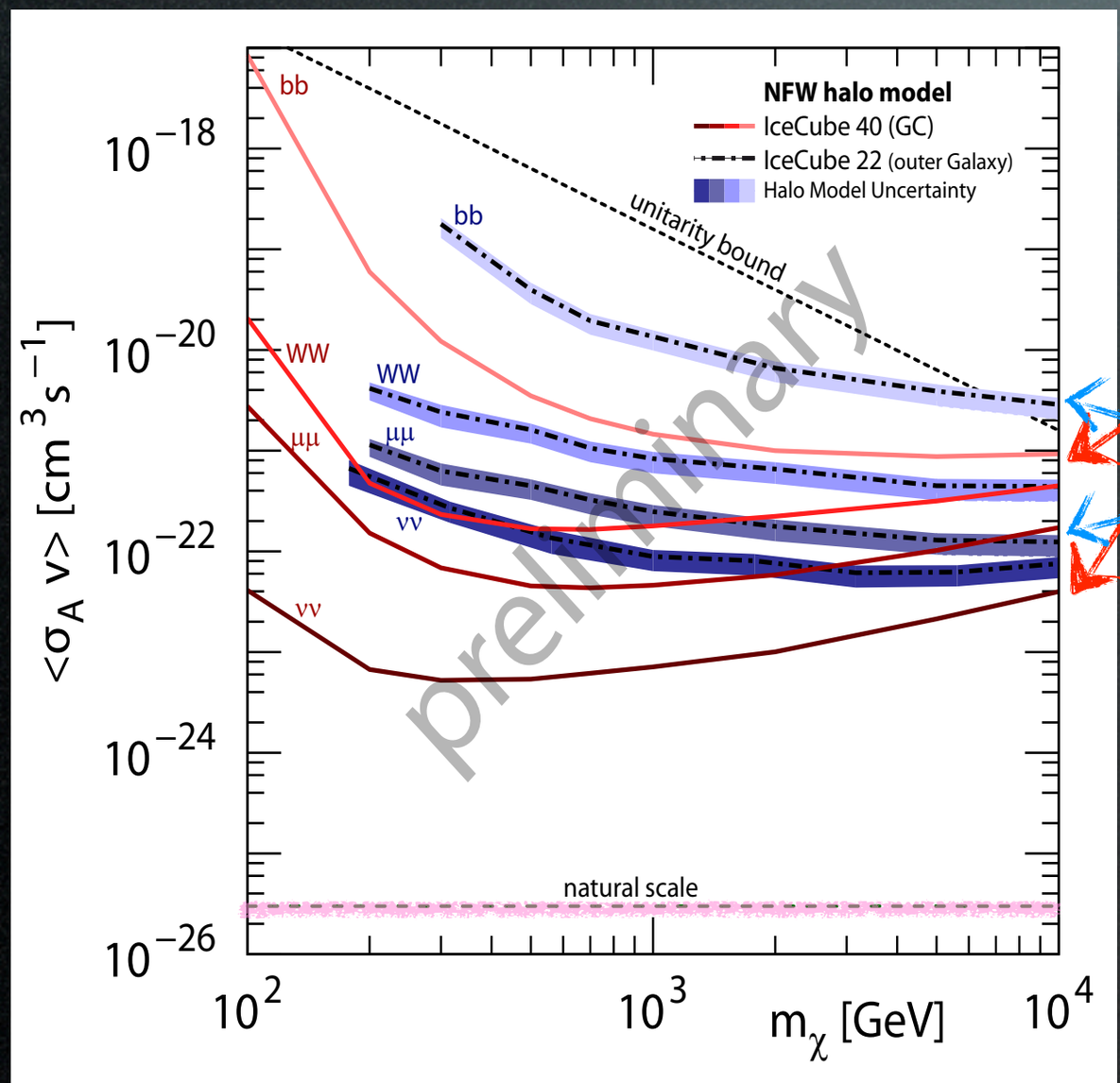
So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section $\sigma_{\rm ann}$

Neutrino constraints

ν from DM annihilations in galactic center/halo

ICECUBE

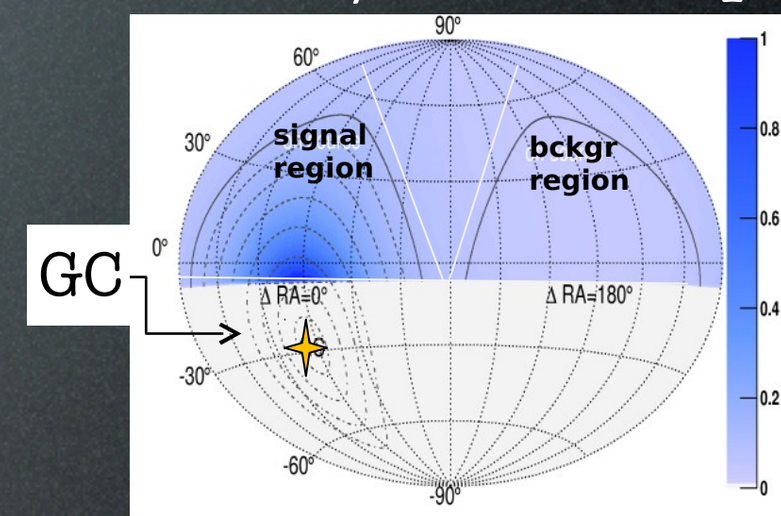


GC

GH

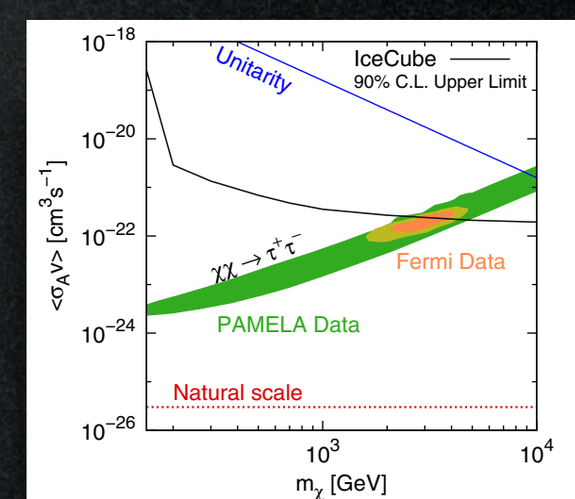
Icecube Coll., 1101.3349 +
Carlos de los Heros, talk at TeVPA 2011, Stockholm +
Icecube Coll., 1111.2738

Gal halo: use on/off technique

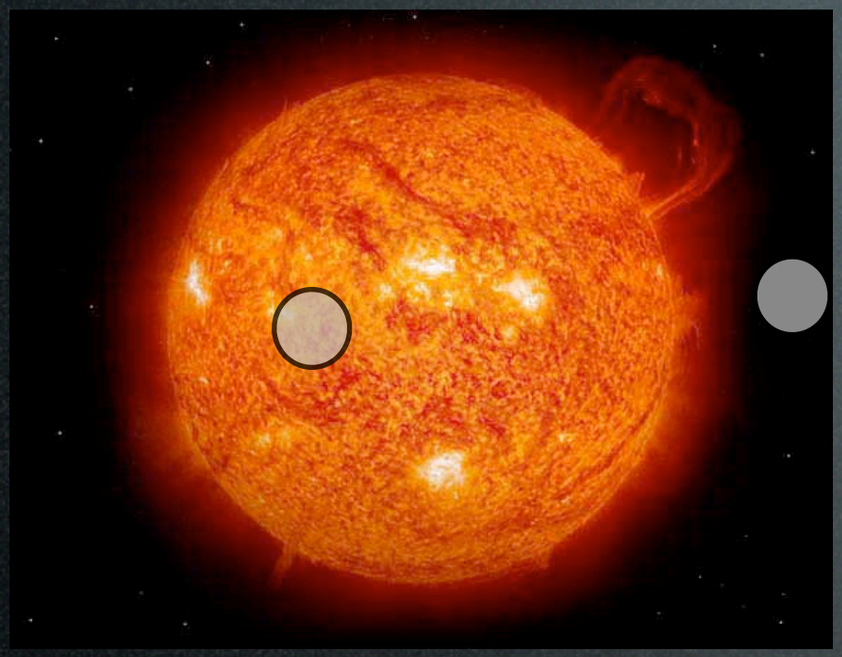


Gal center: veto downgoing μ

Competitive constraints



1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy
if $v_f < v_{\rm esc}$ particle is gravitationally trapped
it spirals to center of body and accumulates
annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
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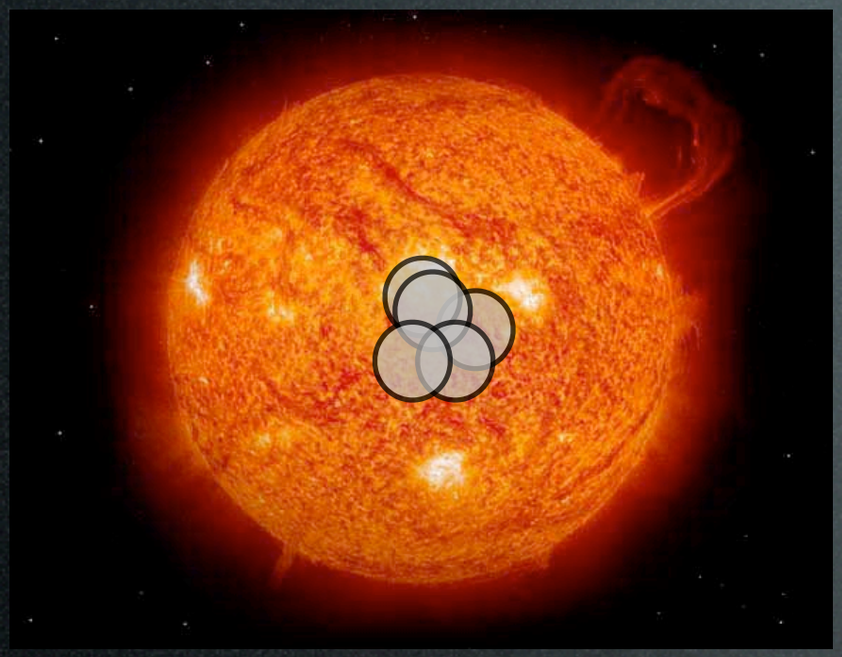

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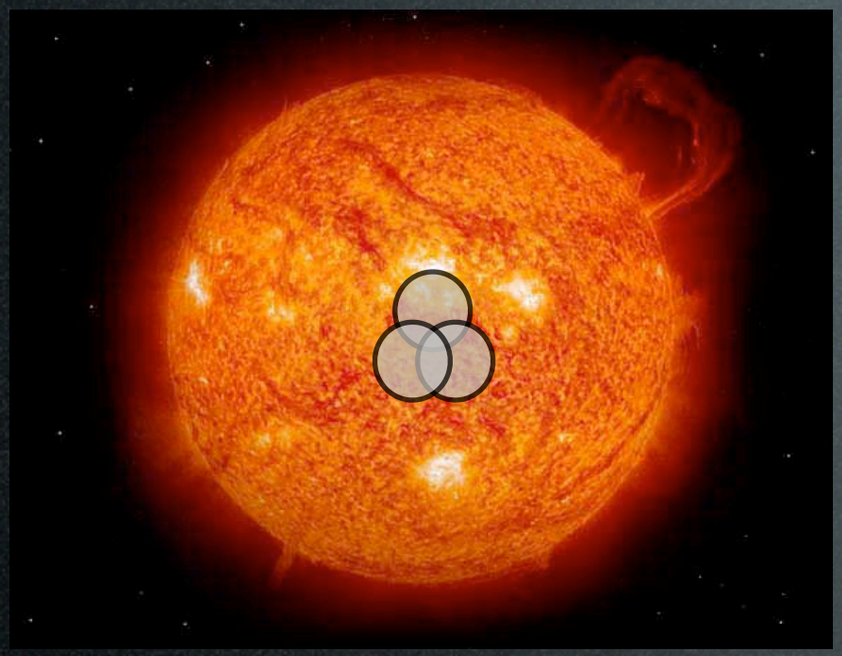

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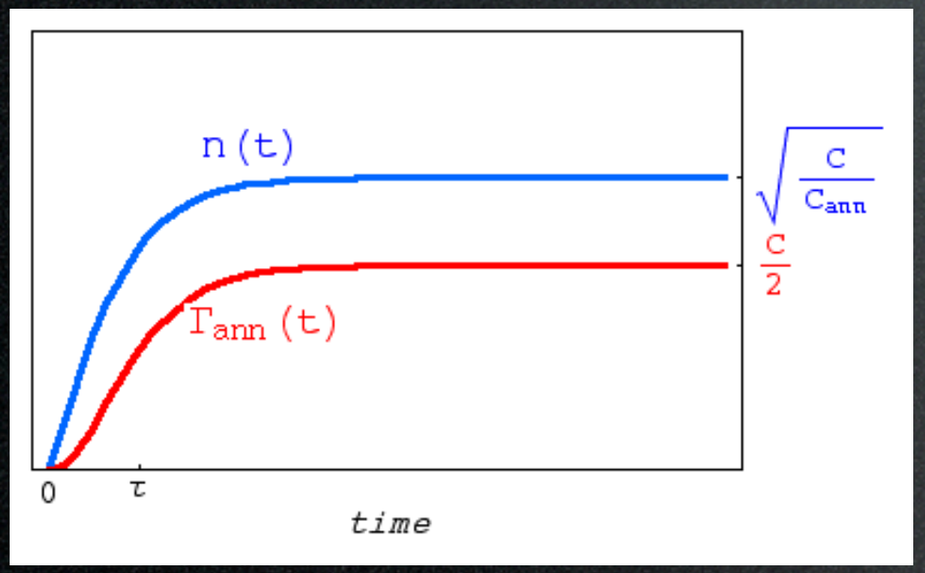

$$\dot{n} = \overset{\sigma_N}{C_{\rm capt}} - \overset{\langle\sigma_{\rm ann} v\rangle}{C_{\rm ann}}\, n^2$$

$$n(t) = \sqrt{\frac{C_{\rm capt}}{C_{\rm ann}}}\tanh\left(\frac{t}{\tau}\right) \qquad \left(\tau = \frac{1}{\sqrt{C_{\rm capt} C_{\rm ann}}}\right)$$

$$\Gamma_{\rm ann}(t) = \frac{C_{\rm capt}}{2}\tanh^2\left(\frac{t}{\tau}\right)$$

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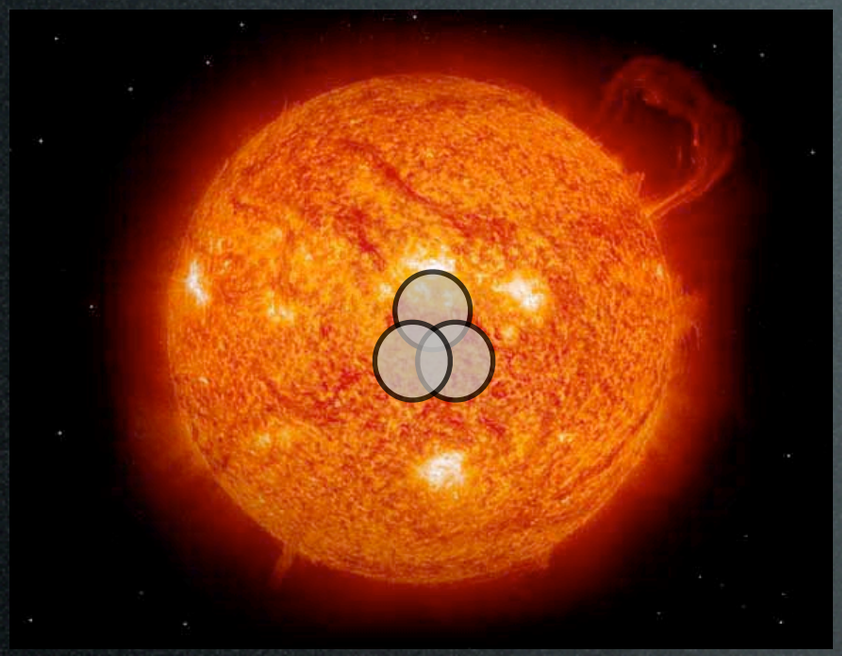

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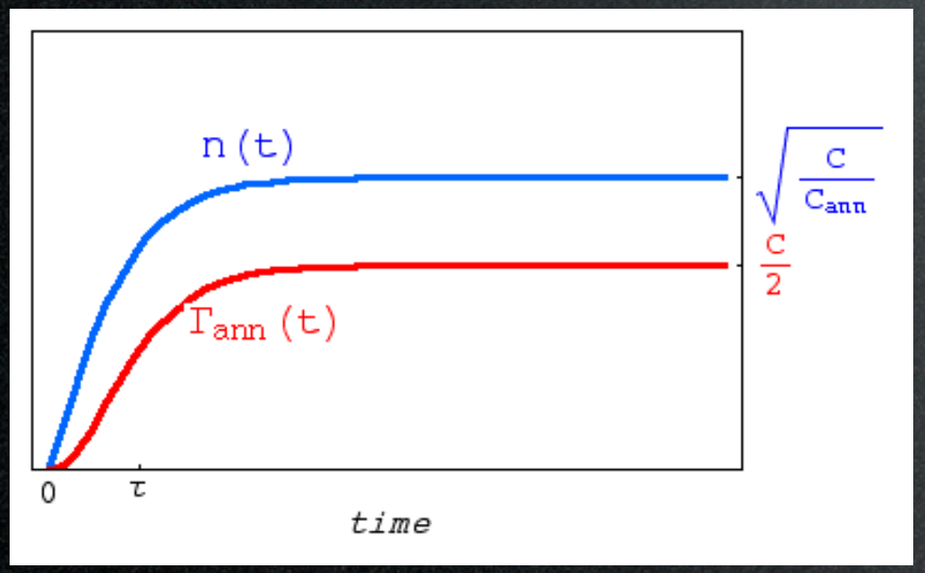

σ_N $\langle \sigma_{\rm ann} v \rangle$

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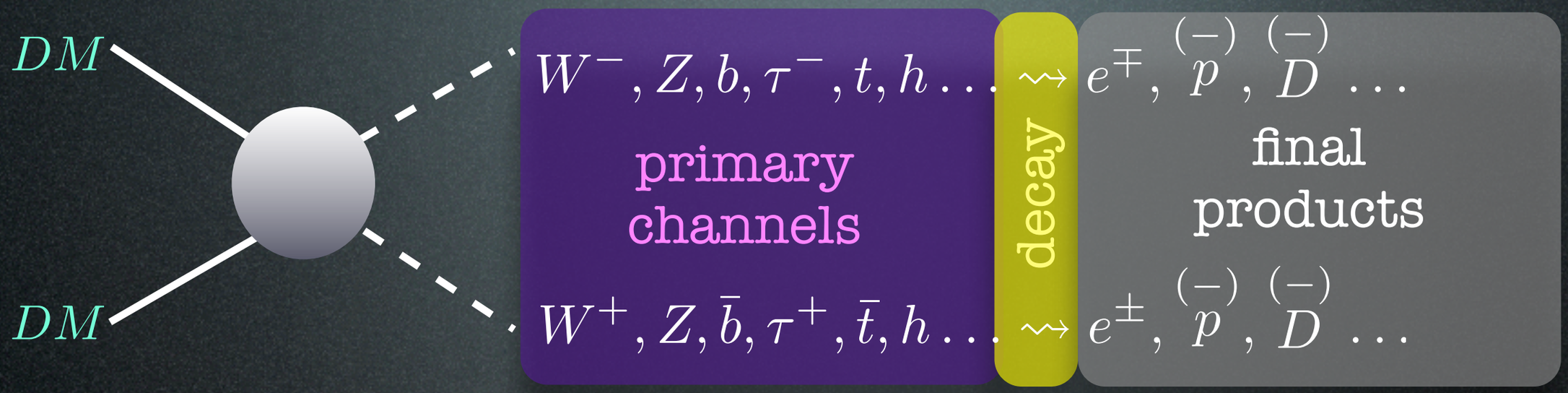
The main physical parameter is: σ_N (DM-nucleon scattering cross section)

1. Capture & annihilation



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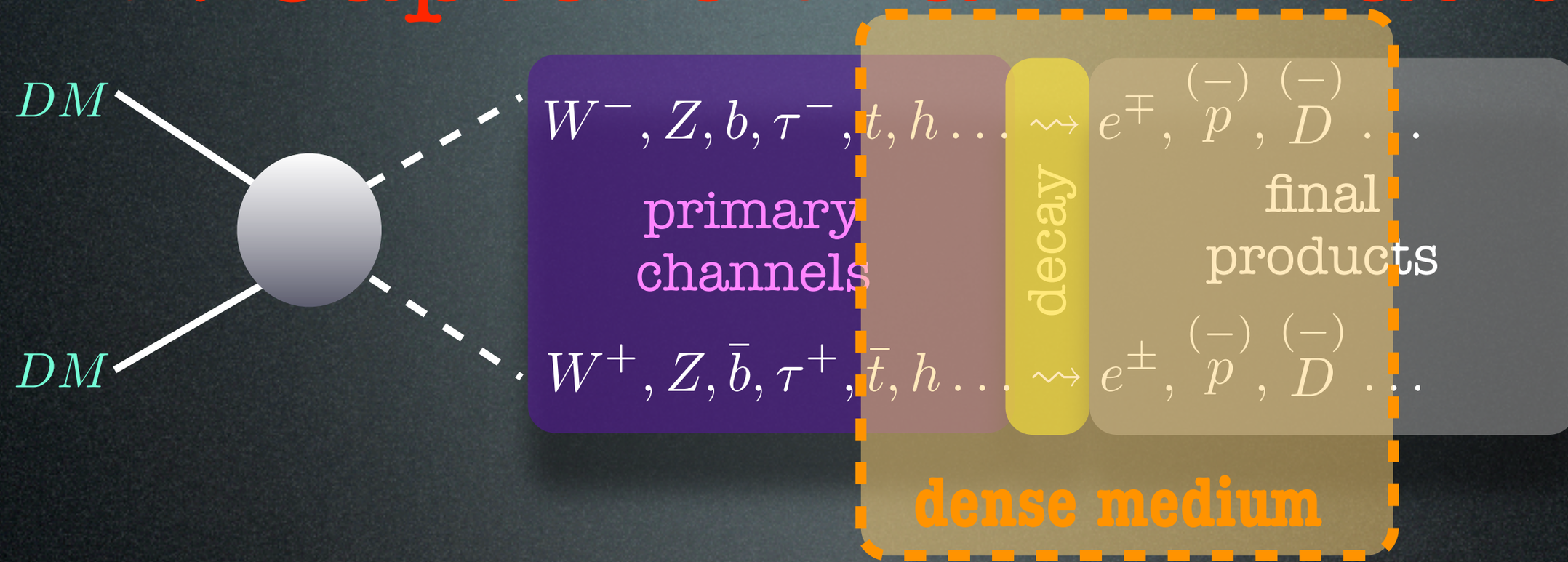

Effects of the medium:

1) light hadrons (π, K...) and leptons (μ) are stopped and absorbed (unless energetic)
2) heavy hadrons/leptons lose some energy before decaying

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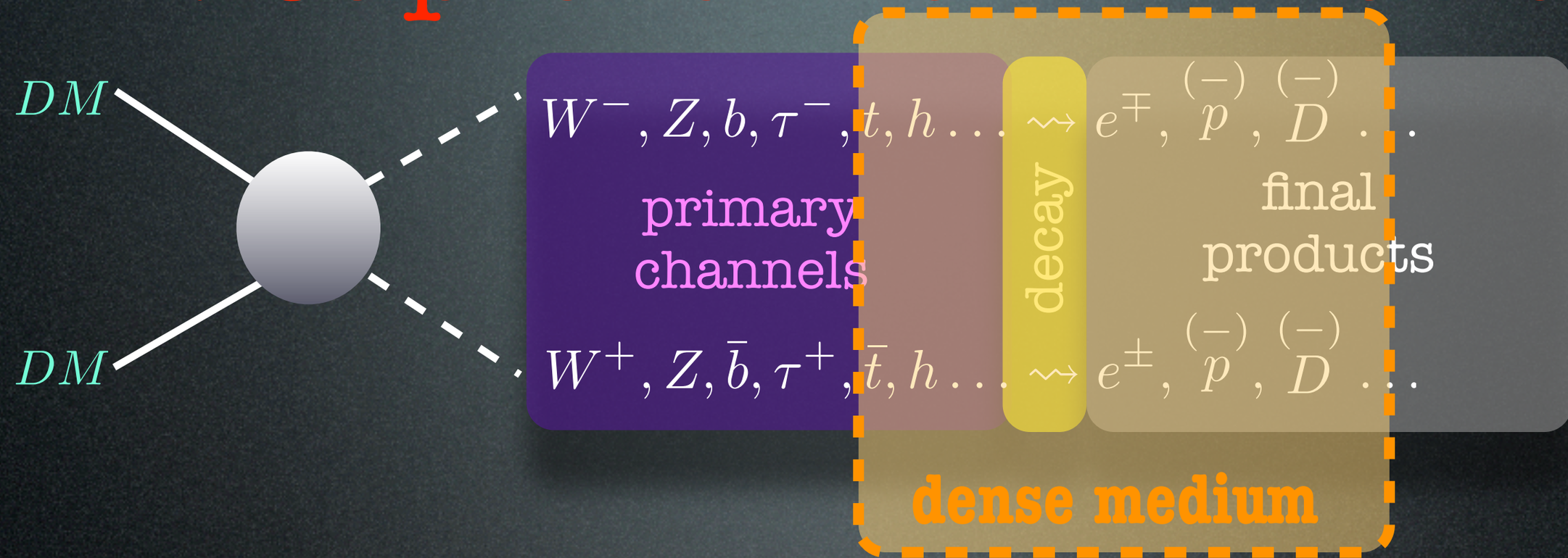
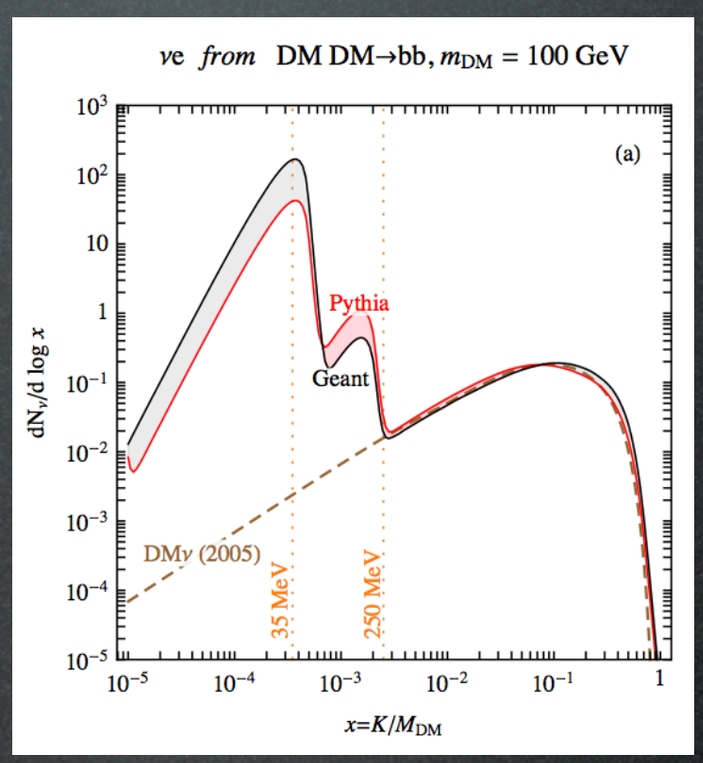
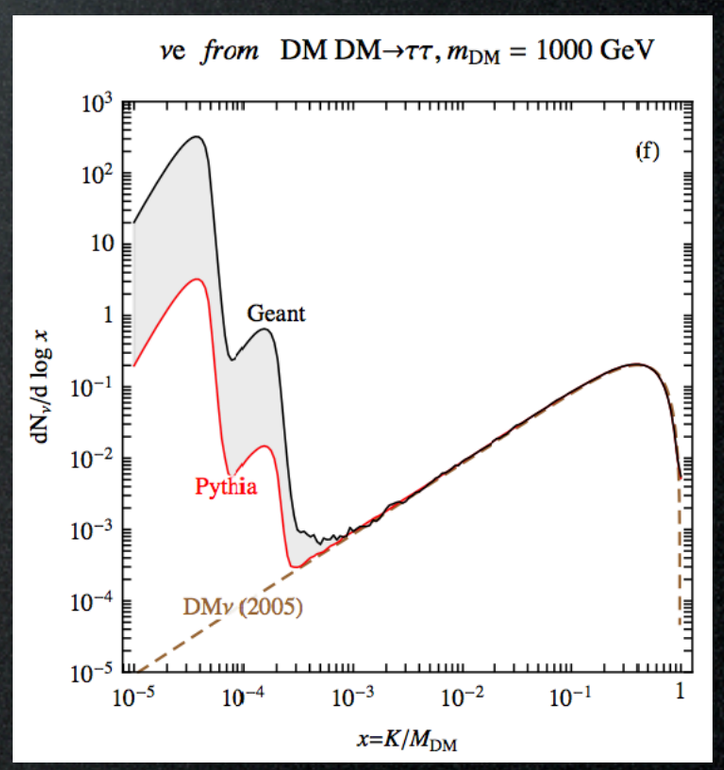




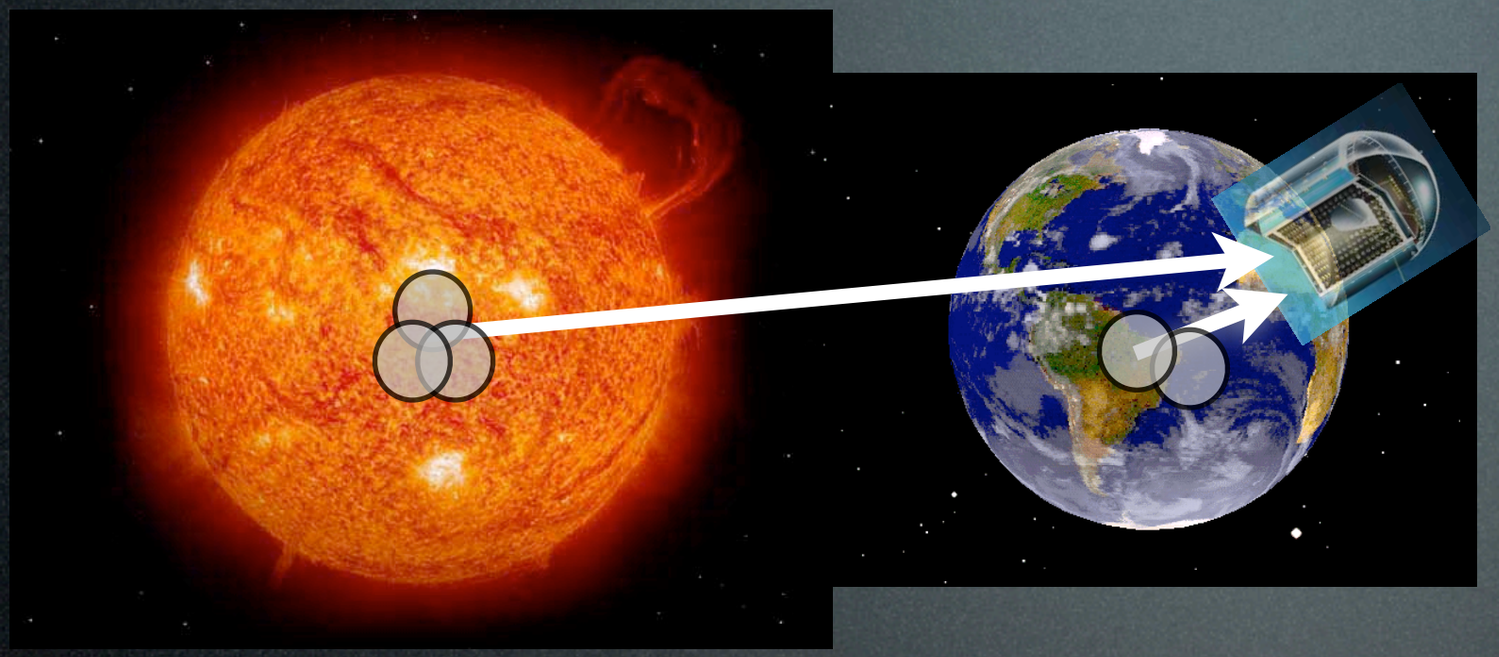


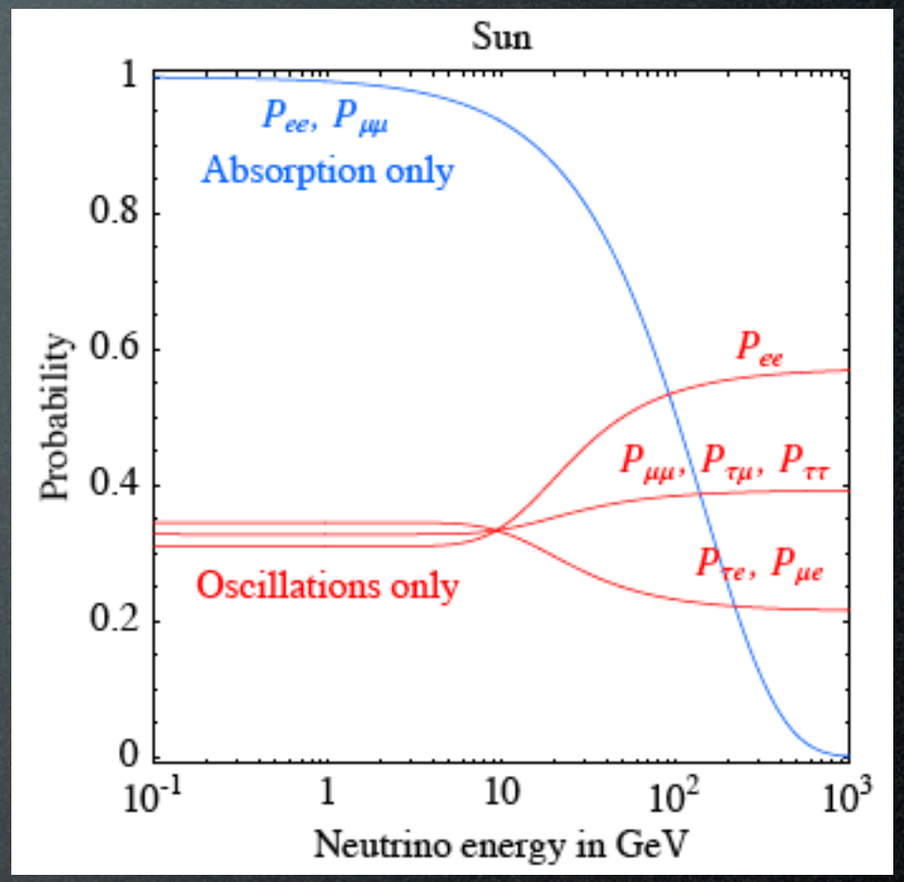
Effects of the medium:

1) light hadrons (π, K...) and leptons (μ) are stopped and decay at rest

2) heavy hadrons/leptons lose some energy before decaying

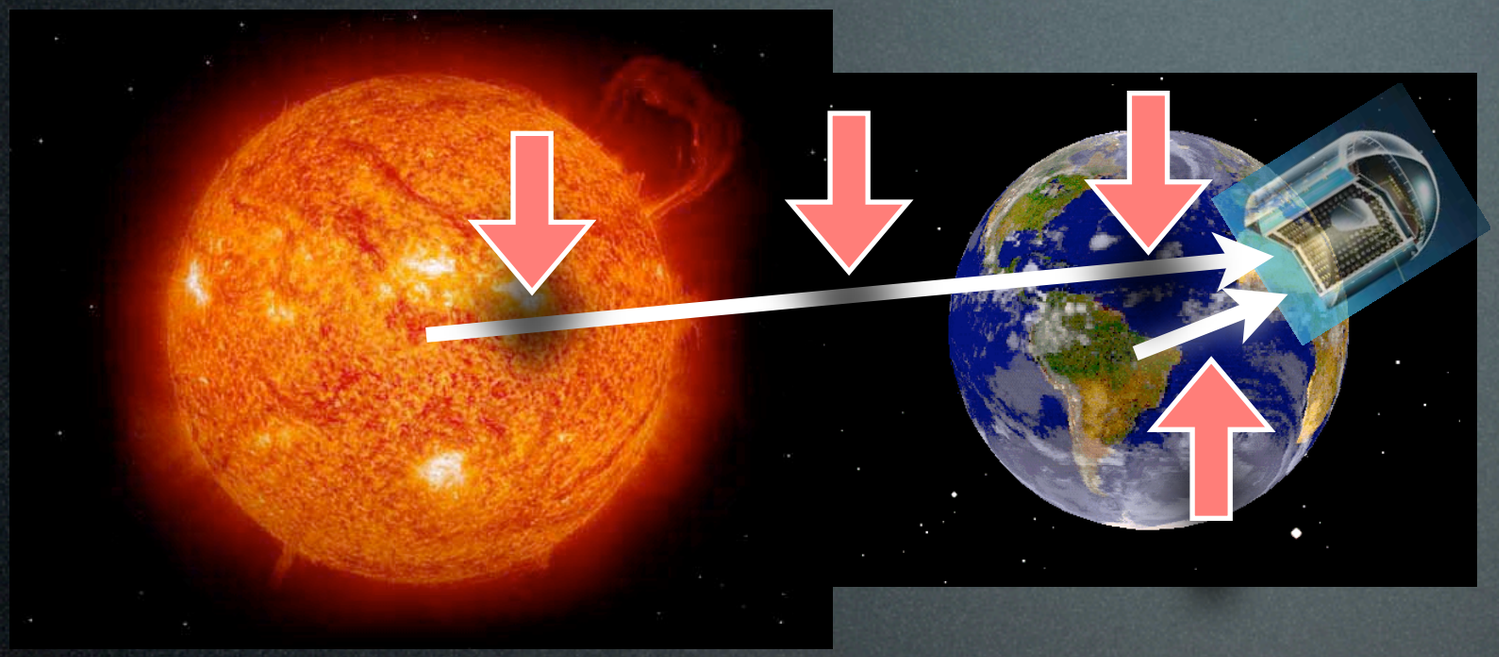
2. Propagation

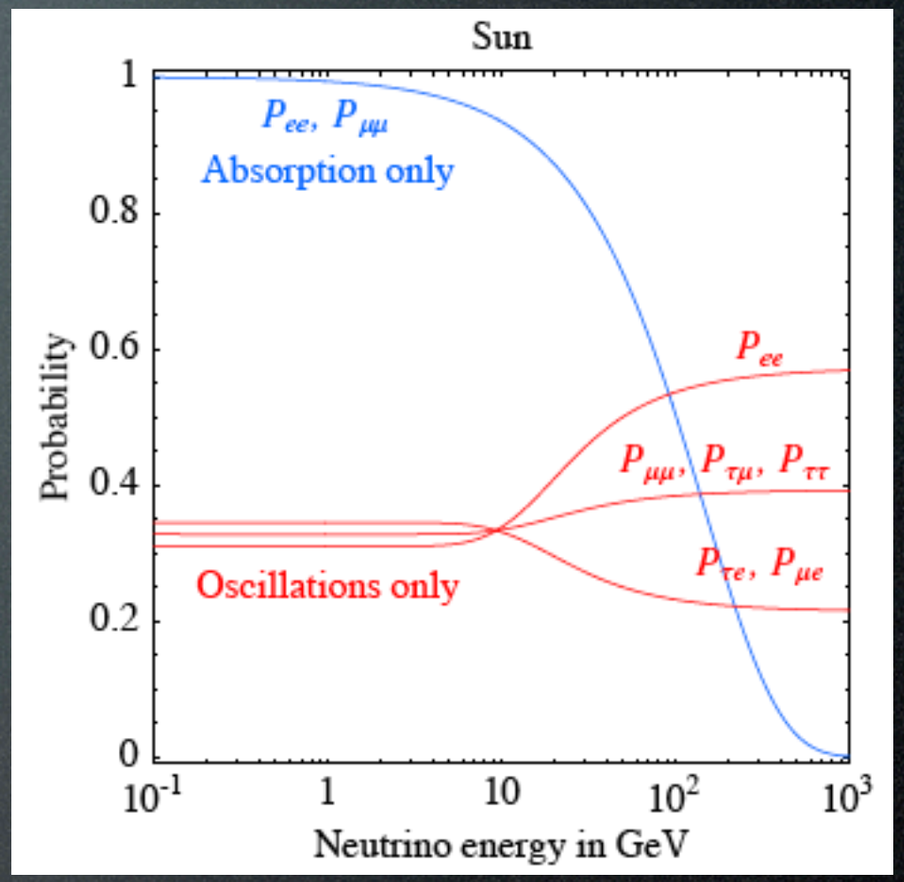




oscillations + interactions

2. Propagation





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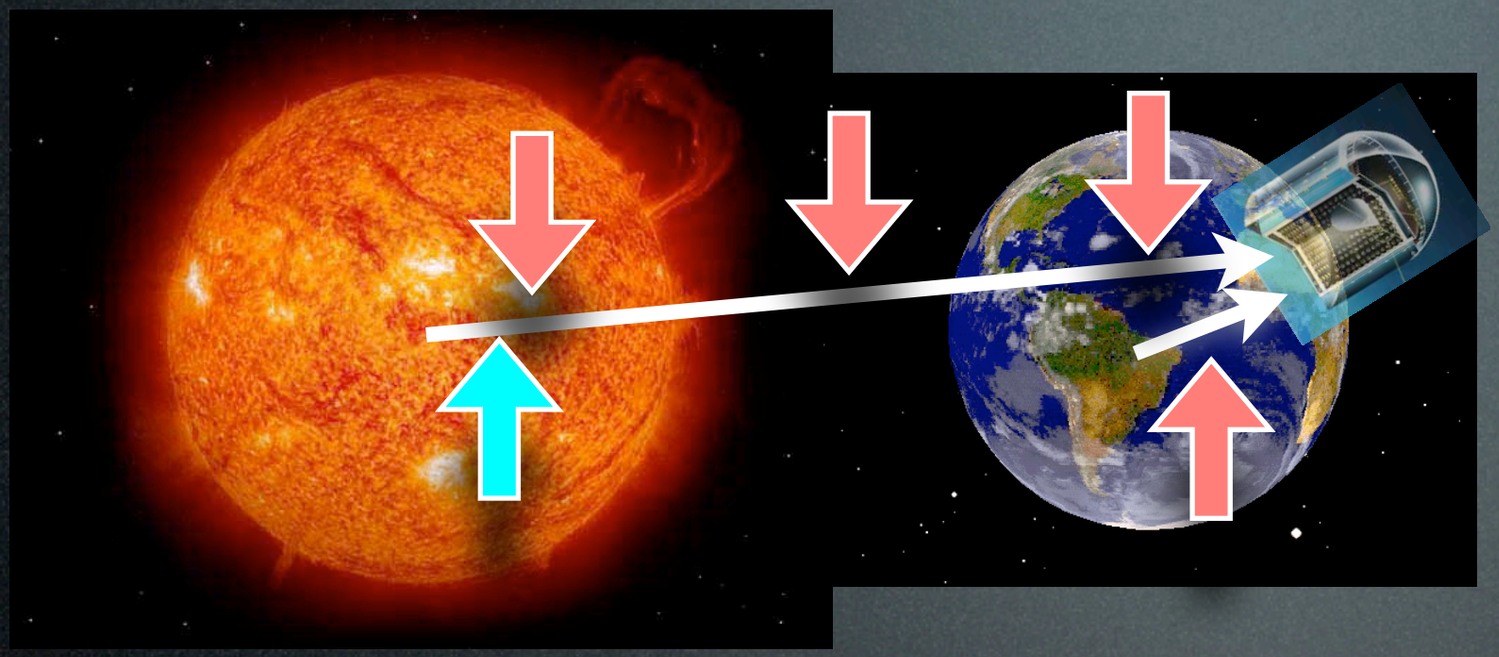

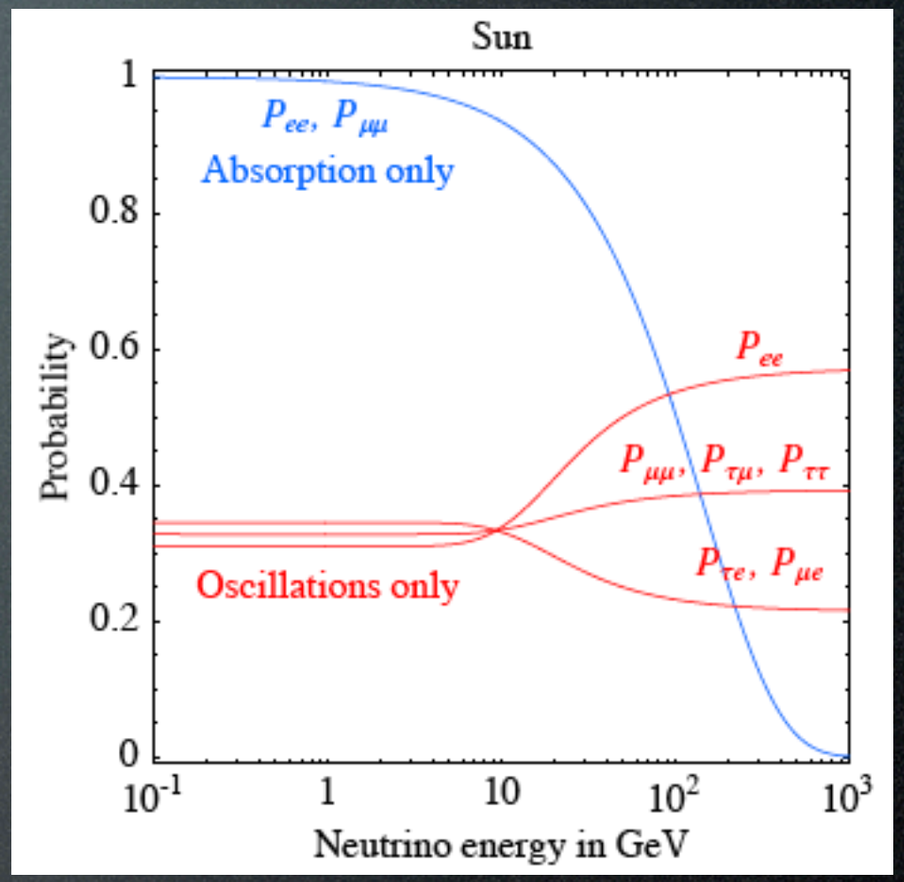

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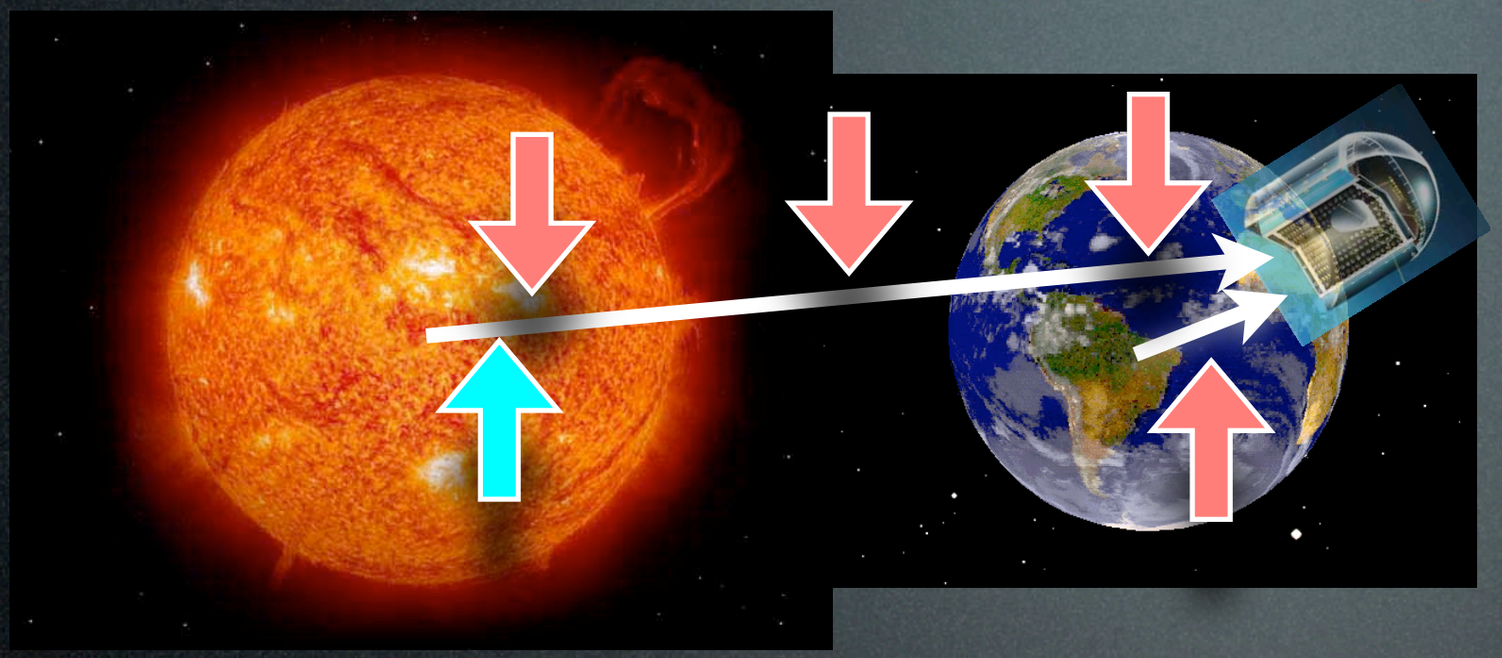
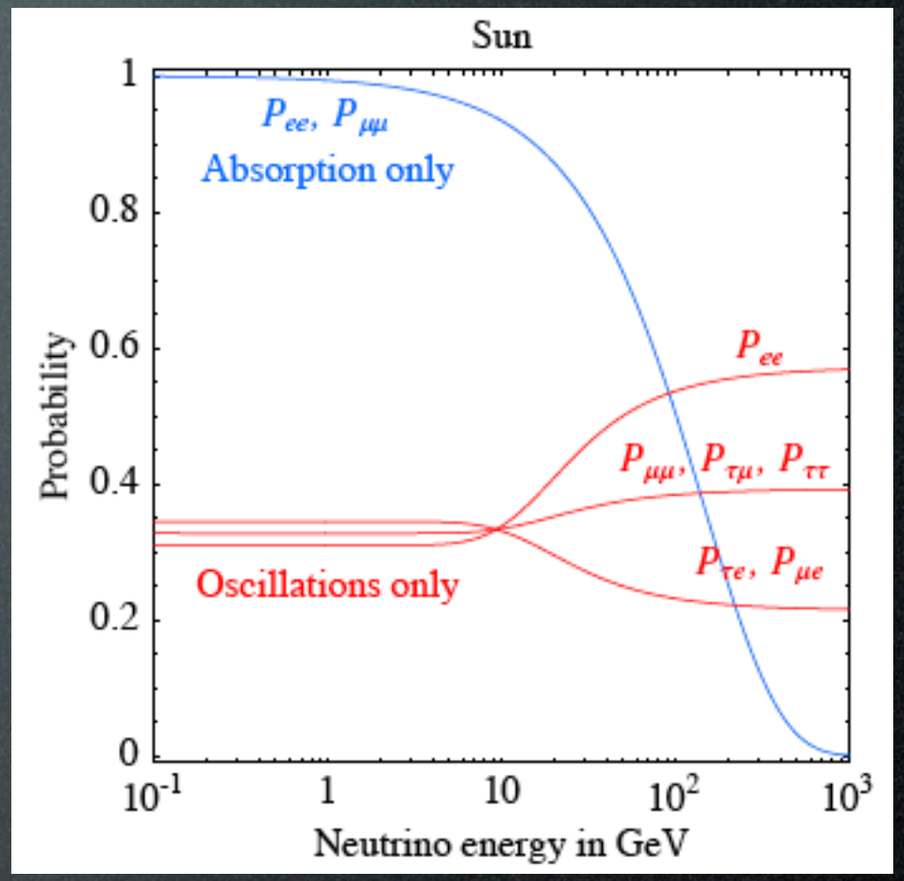
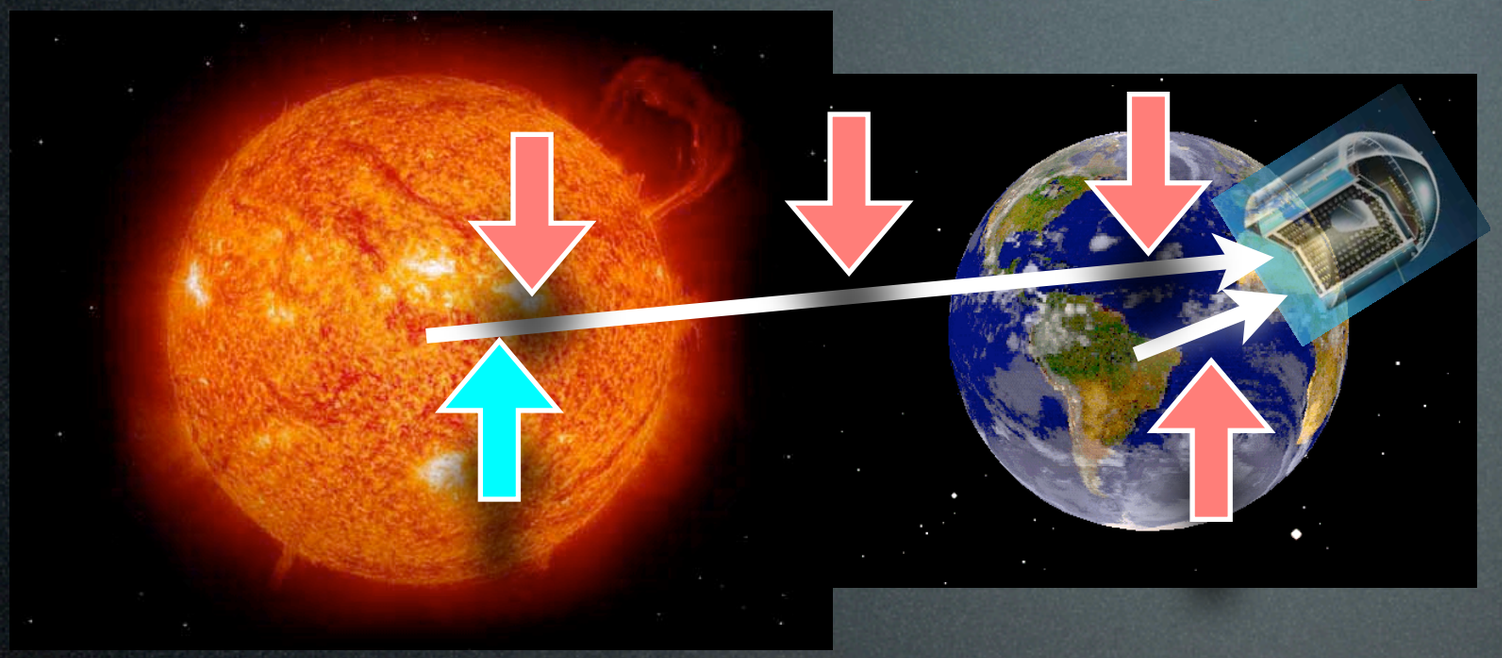


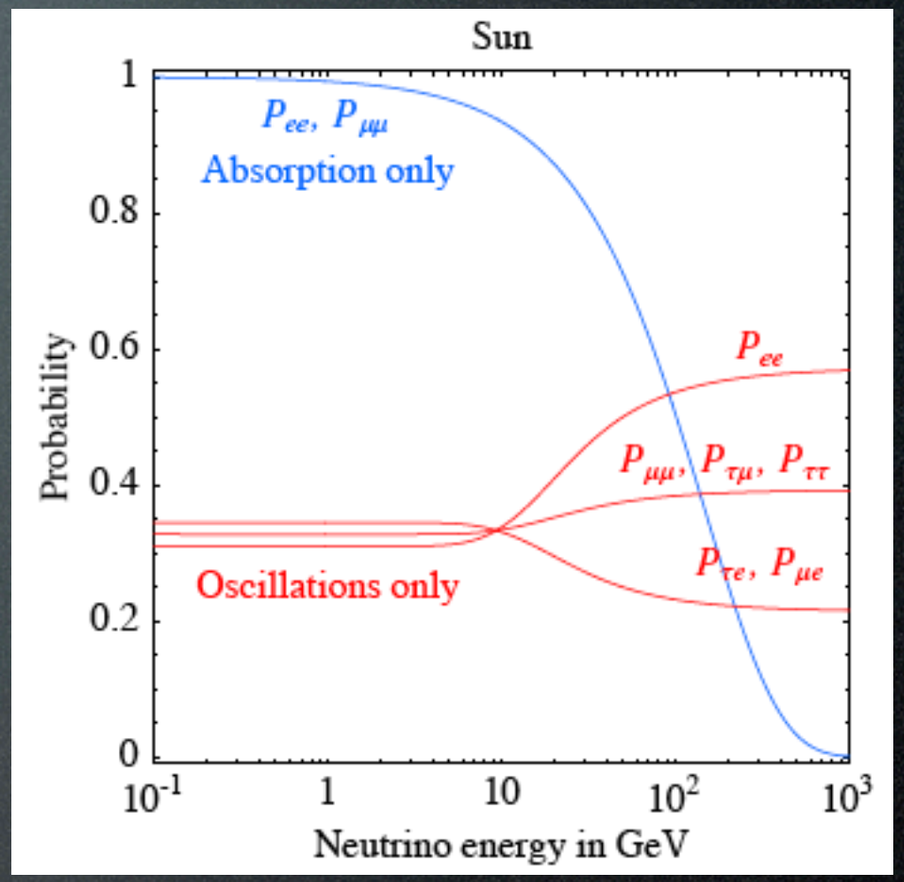


oscillations + interactions

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

2. Propagation





oscillations + interactions

density matrix

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

full evolution equation:

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

2. Propagation: oscillations

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}]$$

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2}G_{\mathrm{F}}\left[N_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} - \frac{N_n}{2}\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}\right]$$

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vacuum mixing:

$$\boldsymbol{m}^\dagger \boldsymbol{m} = \boldsymbol{V} \cdot \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} \cdot \boldsymbol{V}^\dagger$$

$\theta_{\mathrm{sun}} = 32^\circ$
$\theta_{\mathrm{atm}} = 45^\circ$
$\theta_{13} = 8.8^\circ$
$\Delta m^2_{\mathrm{sun}} = 8.0\ 10^{-5}\mathrm{eV}^2$
$|\Delta m^2_{\mathrm{atm}}| = 2.5\ 10^{-3}\mathrm{eV}^2$

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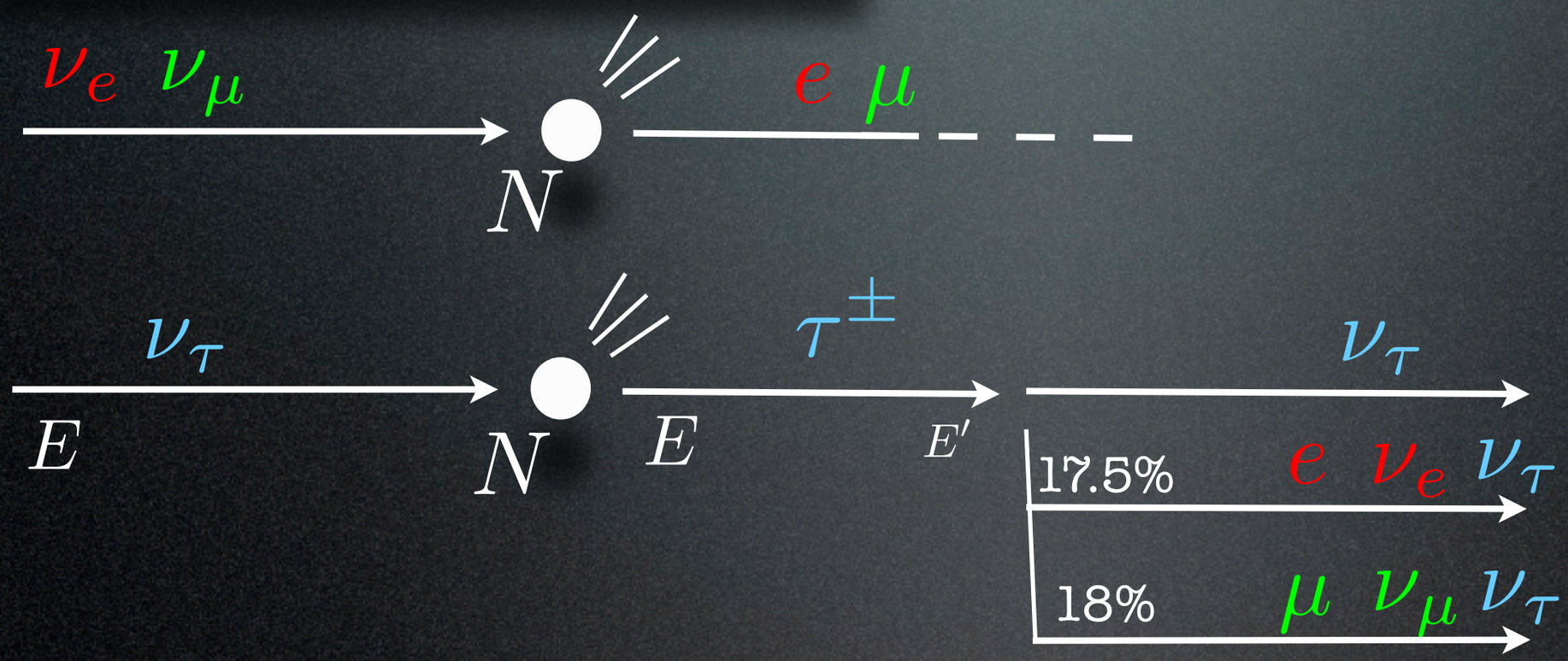
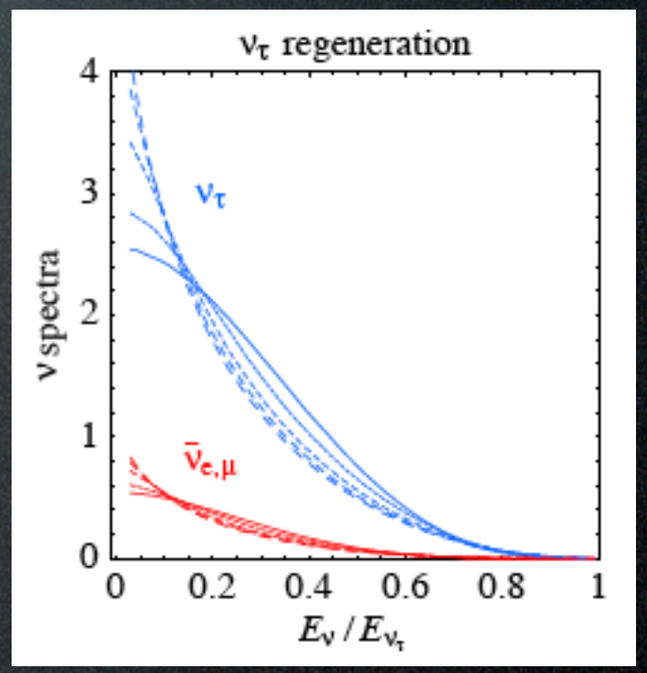
matter effect (MSW):

$N_e(r), N_n(r)$ from solar/ Earth models

2. Propagation: CC absorption & tau regeneration

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



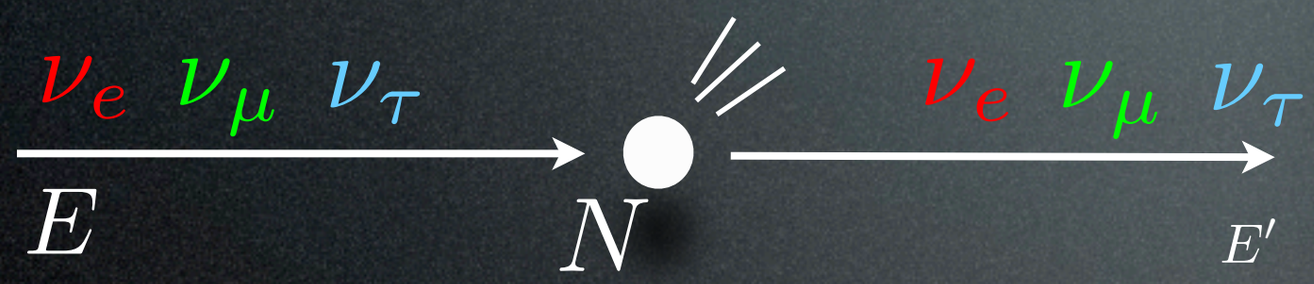


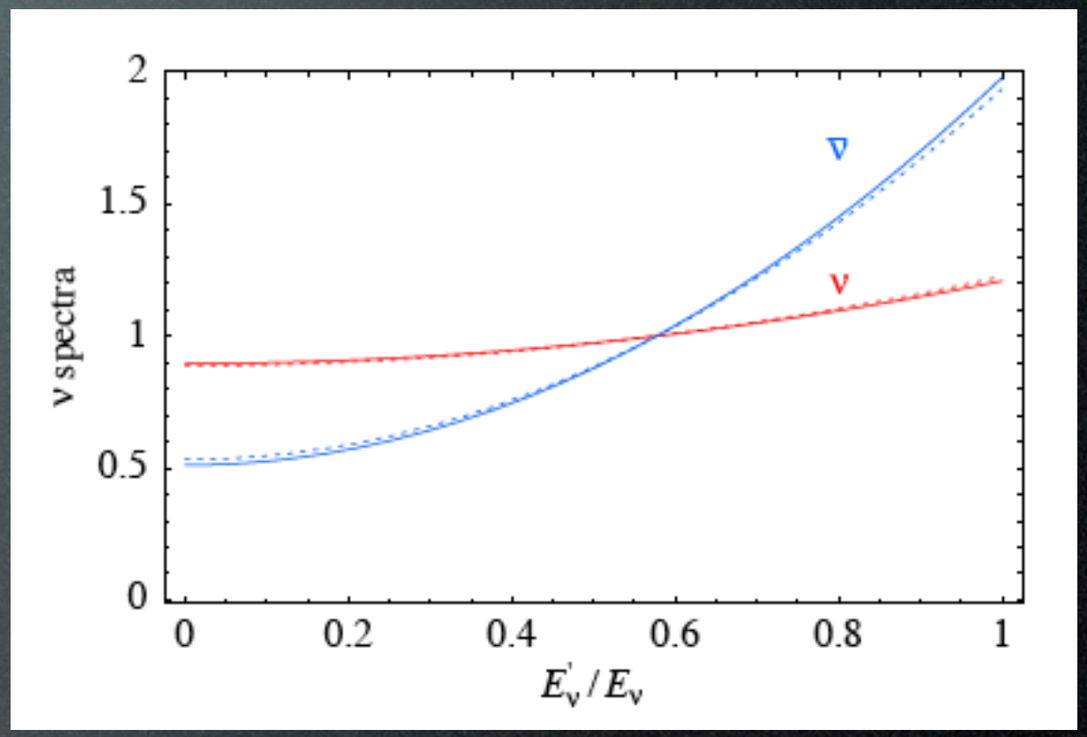
(re)generation

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

2. Propagation: NC scatterings

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





$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{NC}} = -\int_0^{E_\nu} dE'_\nu \frac{d\Gamma_{\mathrm{NC}}}{dE'_\nu}(E_\nu, E'_\nu)\boldsymbol{\rho}(E_\nu) + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\Gamma_{\mathrm{NC}}}{dE_\nu}(E'_\nu, E_\nu)\boldsymbol{\rho}(E'_\nu)$$

2. Propagation: summary

Effects of oscillations and interactions:

- reshuffle of the 3 flavors
  (oscillations and regeneration)

- attenuation of the fluxes

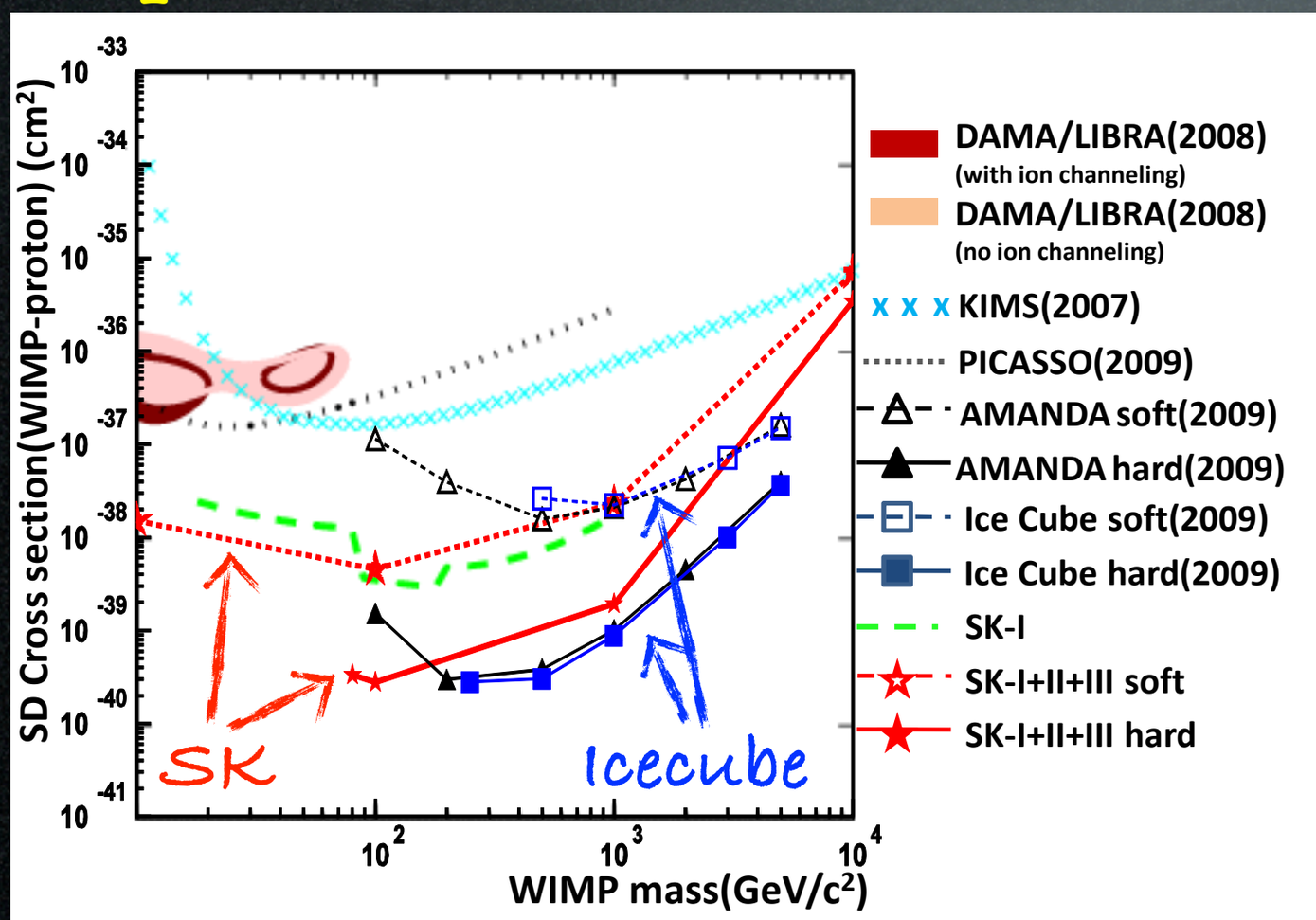
- degradation of energy
  (distortion of spectra)

Bonus track: neutrinos

ν from DM annihilations in the Sun

Probe the <u>scattering</u> cross section.

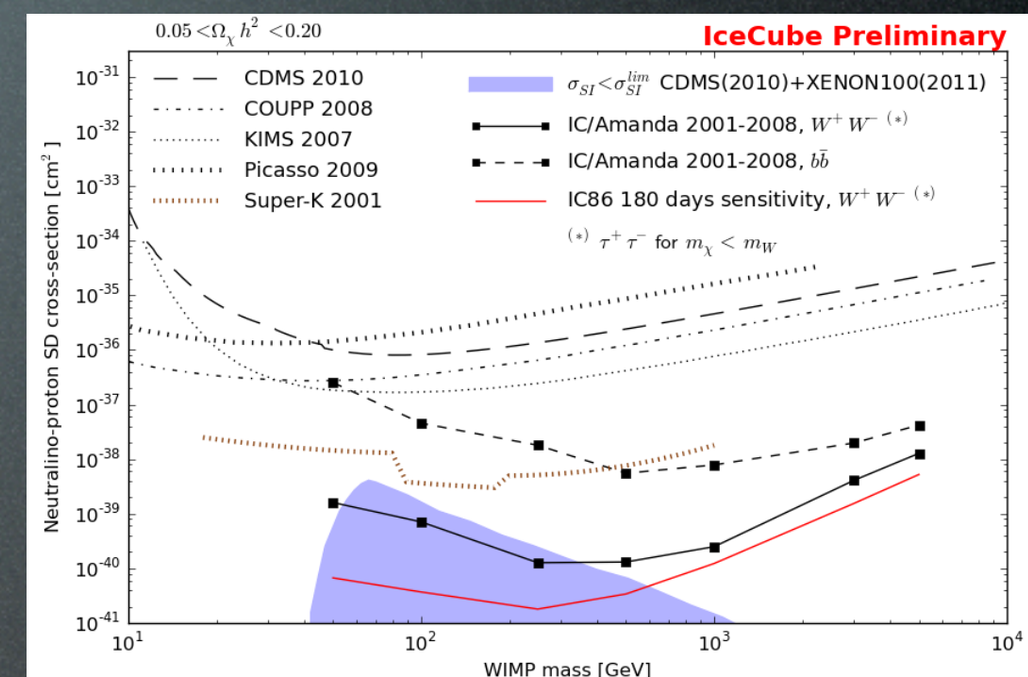
SuperKamiokande



1108.3384

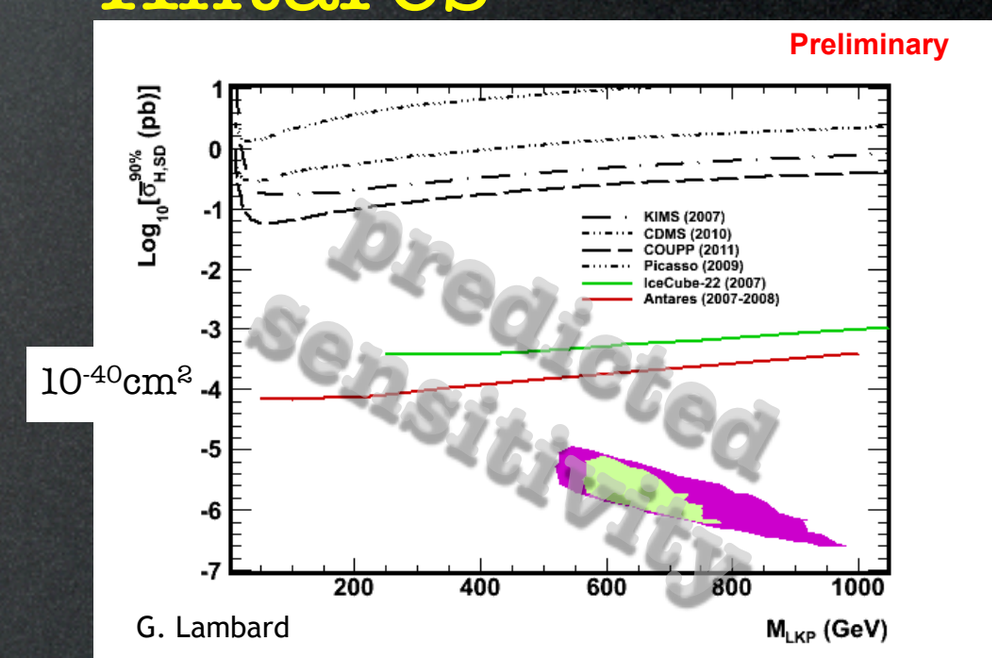
3109.6 days! (now beat that)

ICECUBE



Icecube Coll., 1111.2738

Antares



Juande Zornoza, talk at TeVPA 2011, Stockholm

Conclusions

(this time for real)

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complementary to other messengers

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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?

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PPPC 4 DM ID

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

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

1012.4515

www.marcocirelli.net/PPPC4DMID.html

DMnu

'Spectra of neutrinos from Dark Matter anihilations'

hep-ph/0506298

Cirelli, Fornengo, Montaruli, Sokalski, Strumia, Vissani

www.marcocirelli.net/DMnu.html