13 April 2017
Ecole Polytechnique

Dark Matter

what can we learn with an MeV telescope?

Marco Cirelli

(CNRS LPTHE Jussieu Paris)

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

erc NewDark

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Executive summary

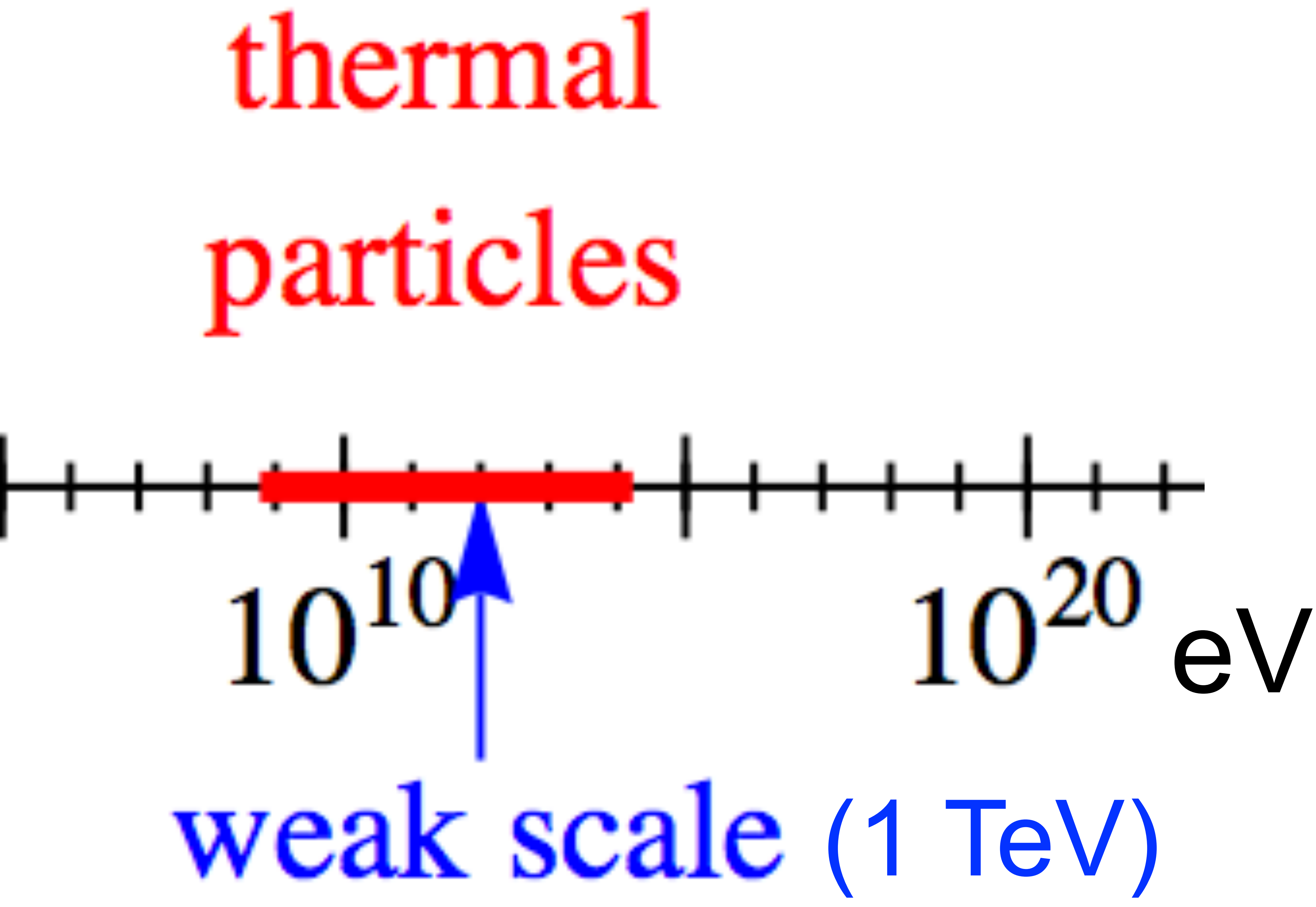
- DM exists
- it's a new, unknown particle — *no SM particle can fulfil* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle — *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself* *-with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17} {\rm sec}$
- possibly a relic from the EU

Mass??

Charge??
Interactions??

Candidates

A matter of perspective: plausible mass ranges



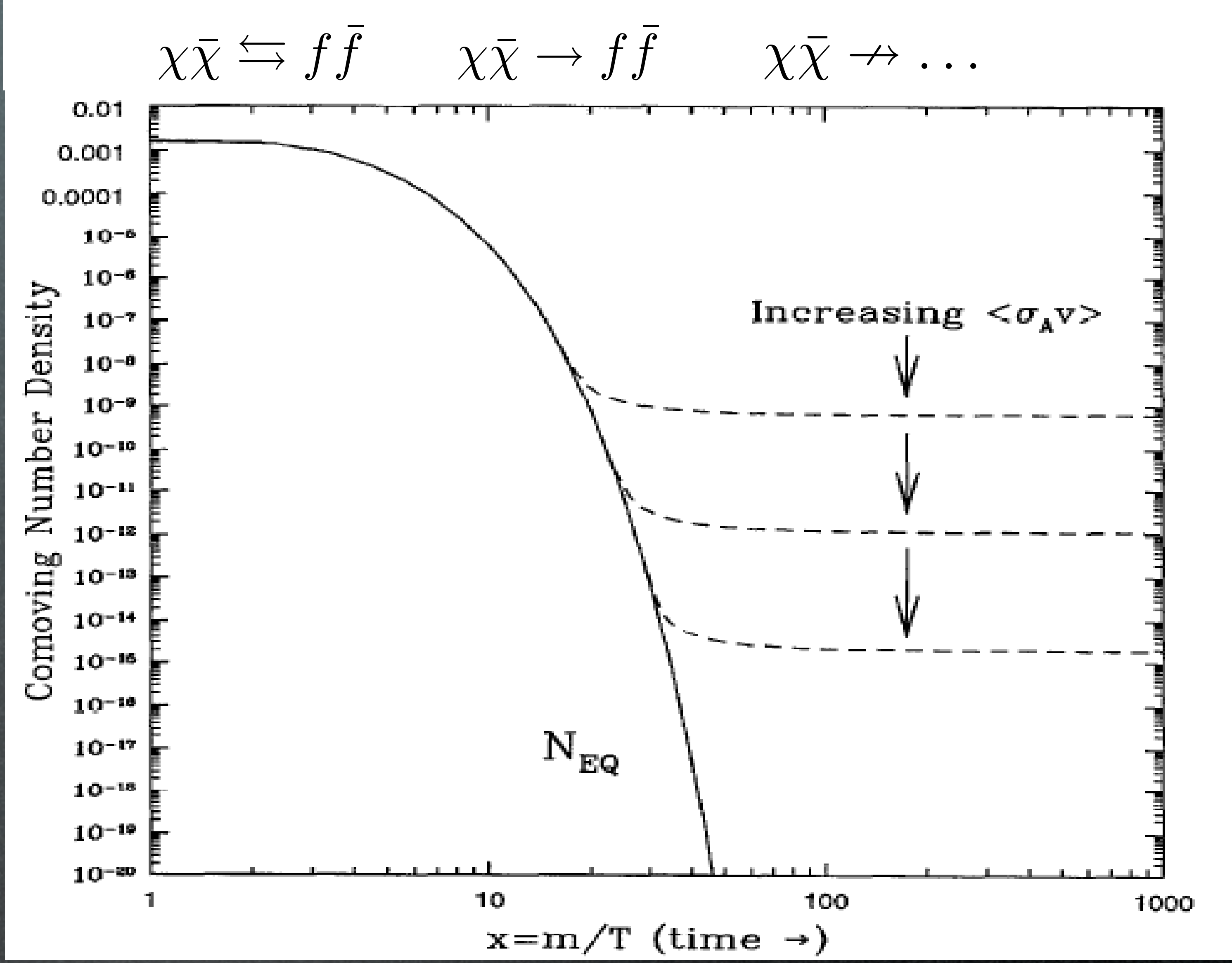
DM as a thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

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

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

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



Kolb,Turner, The Early Universe, 1995

Weak cross section:

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

(WIMP)

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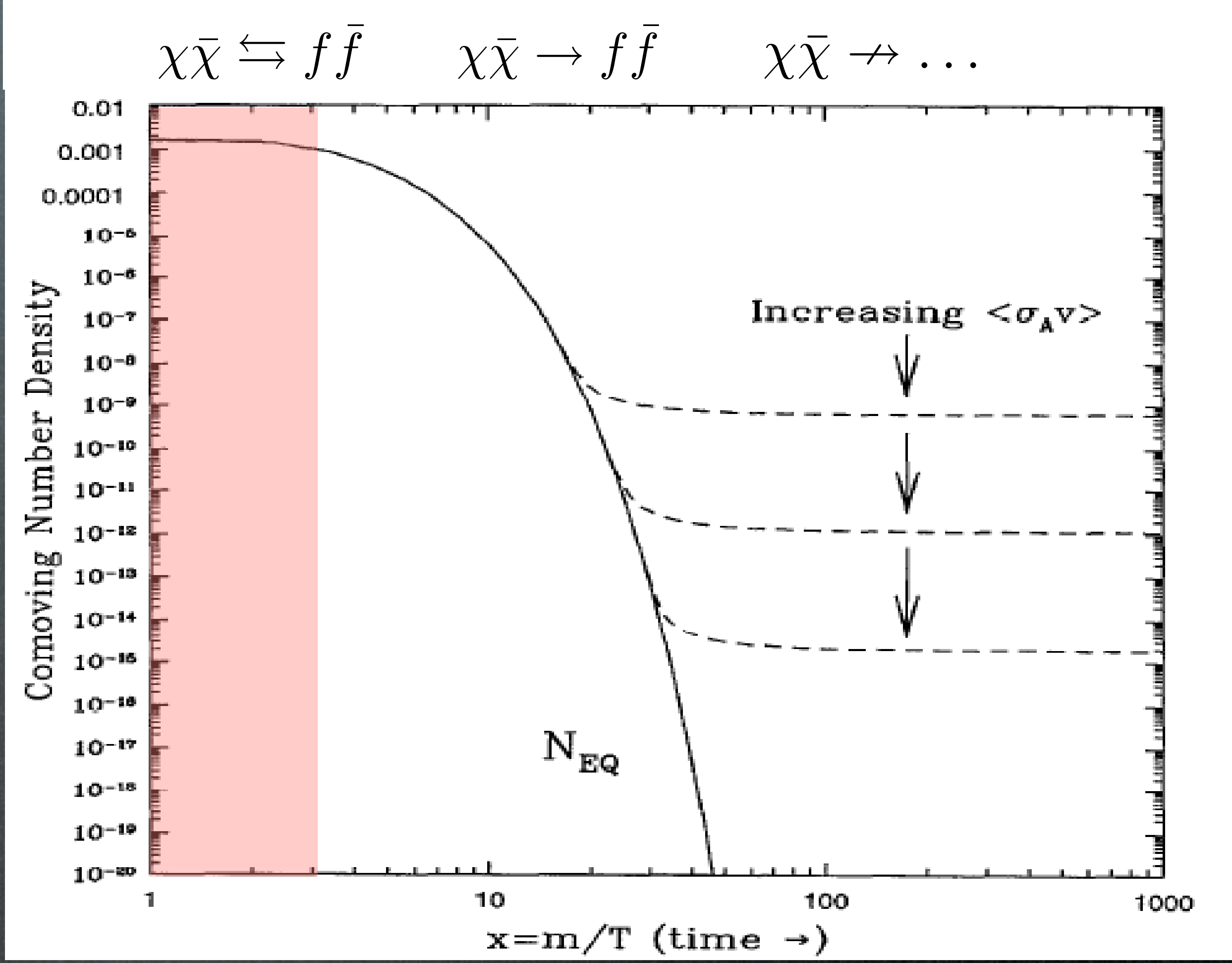

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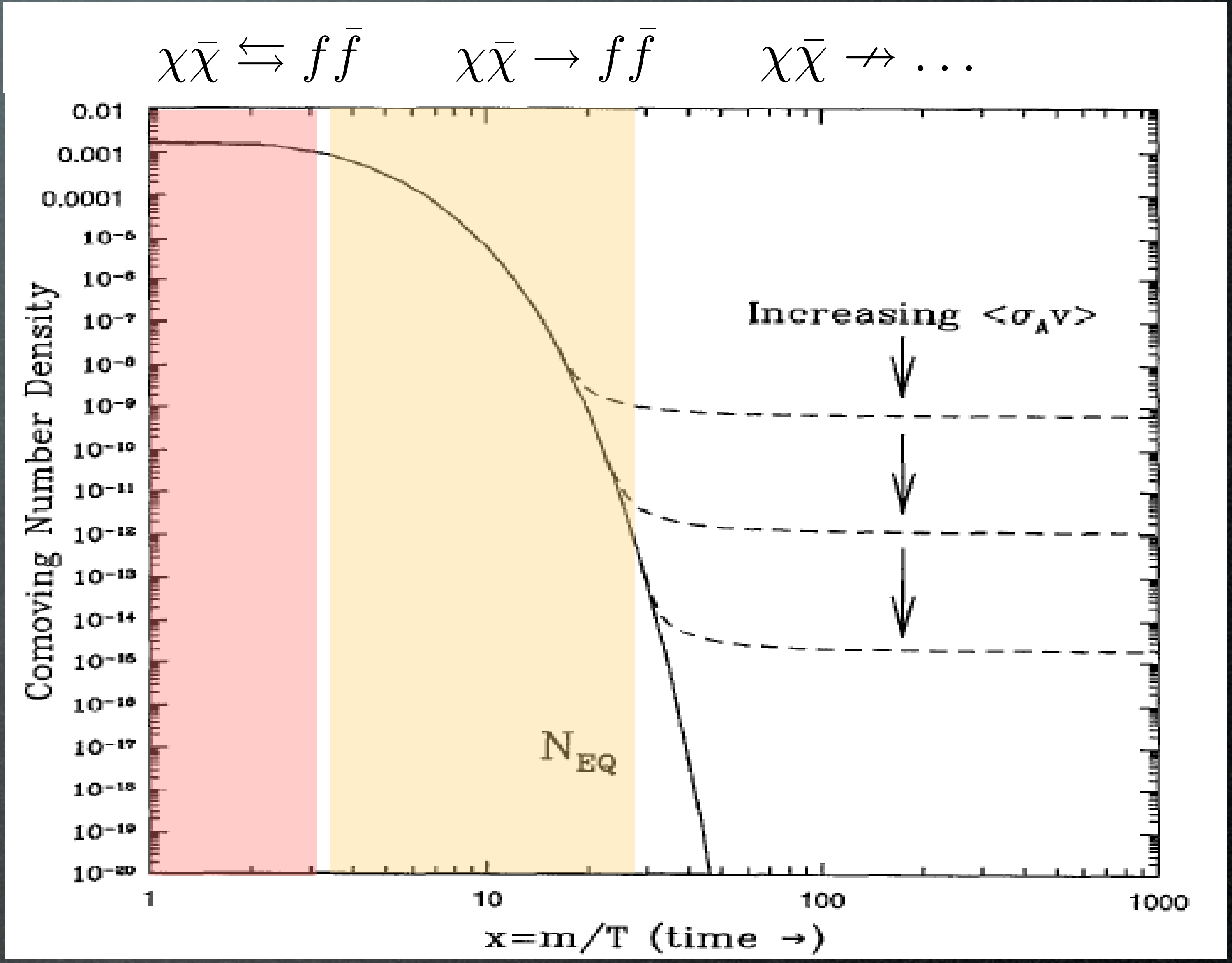

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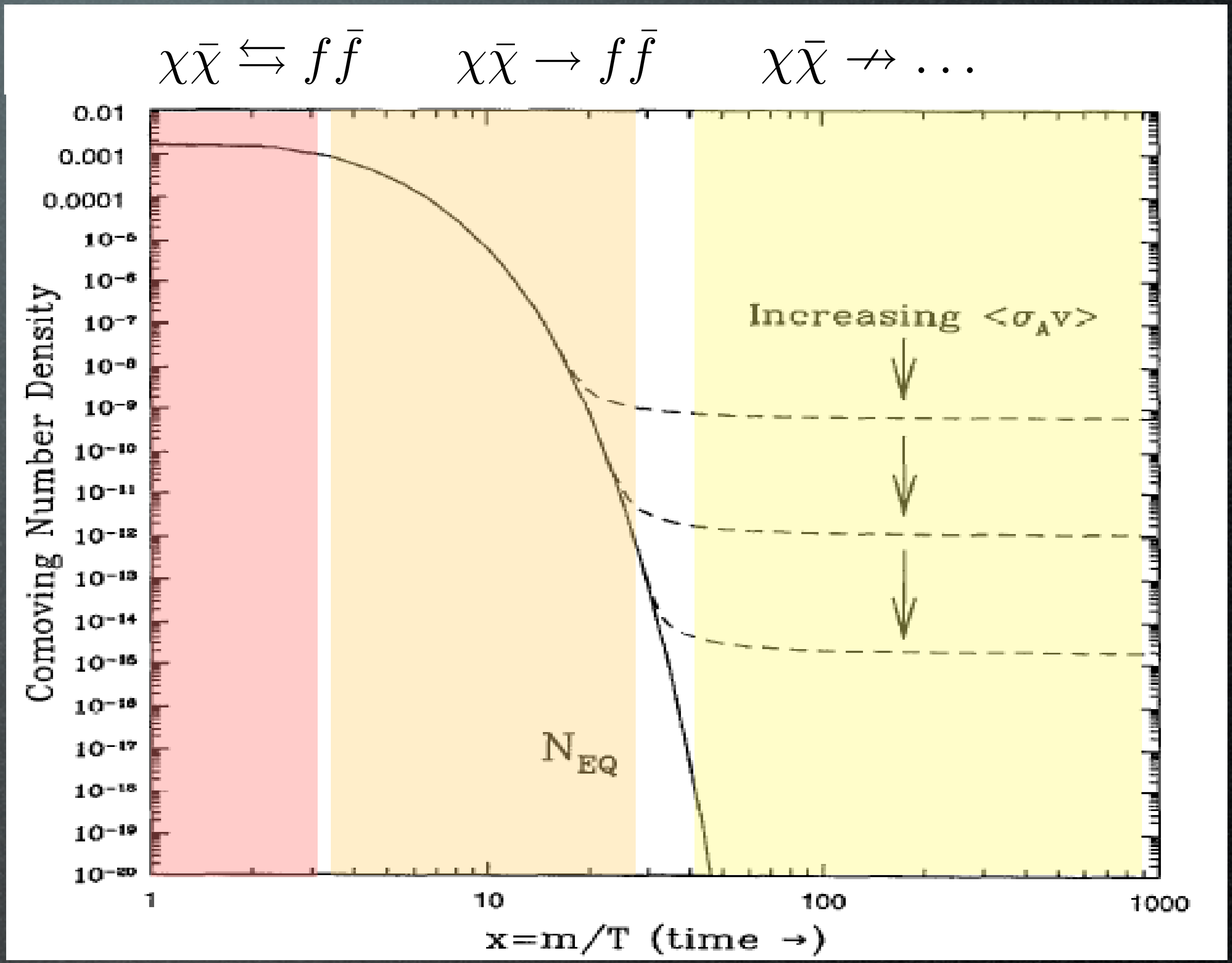

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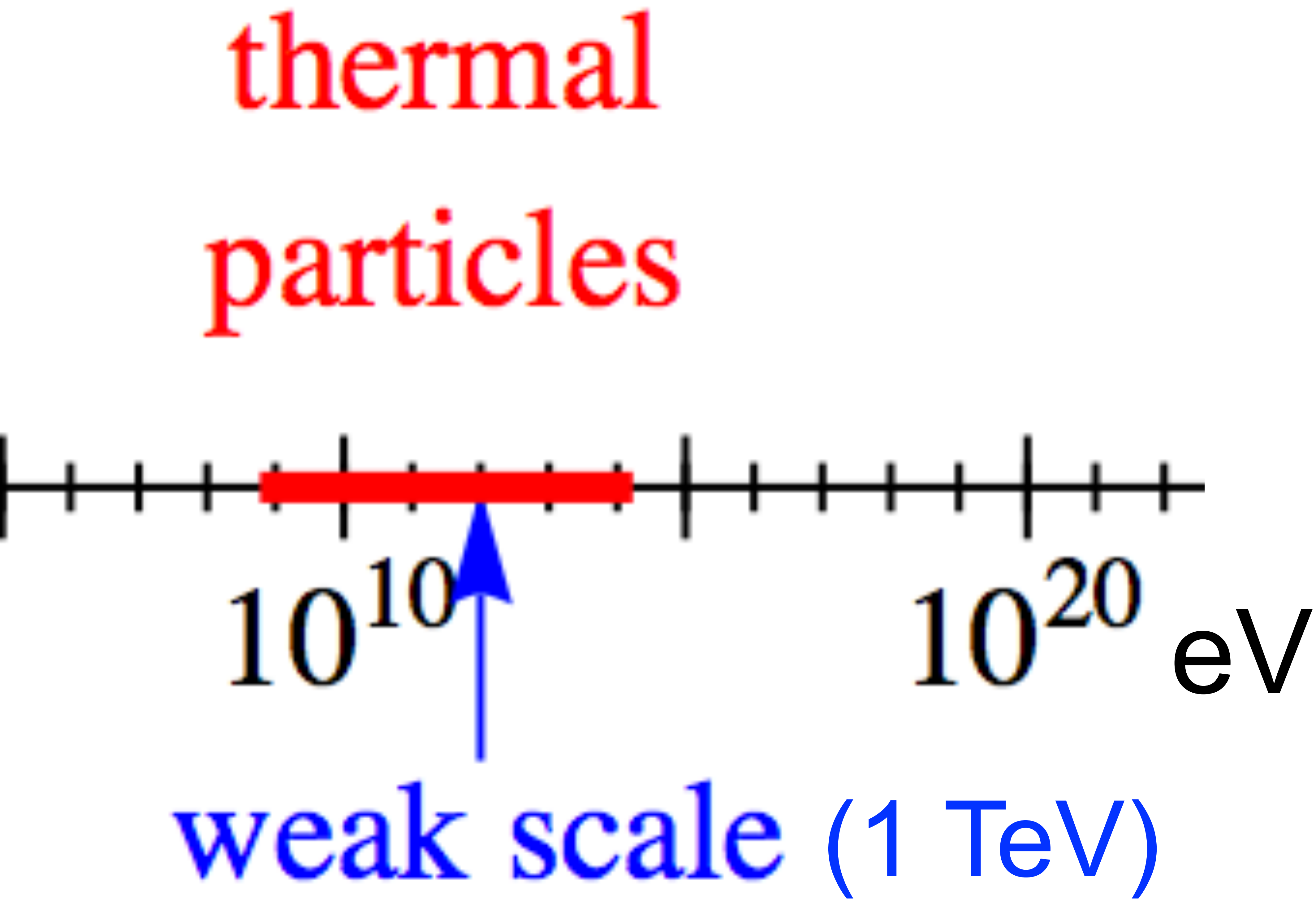
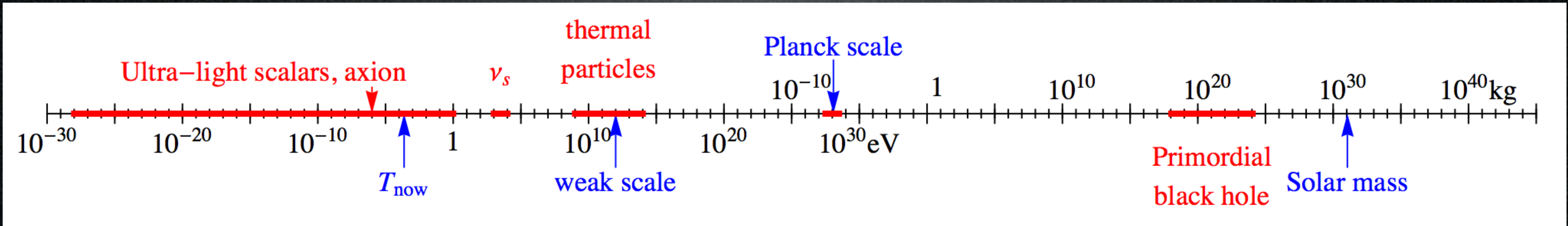
Candidates

A matter of perspective: plausible mass ranges



Candidates

A matter of perspective: plausible mass ranges

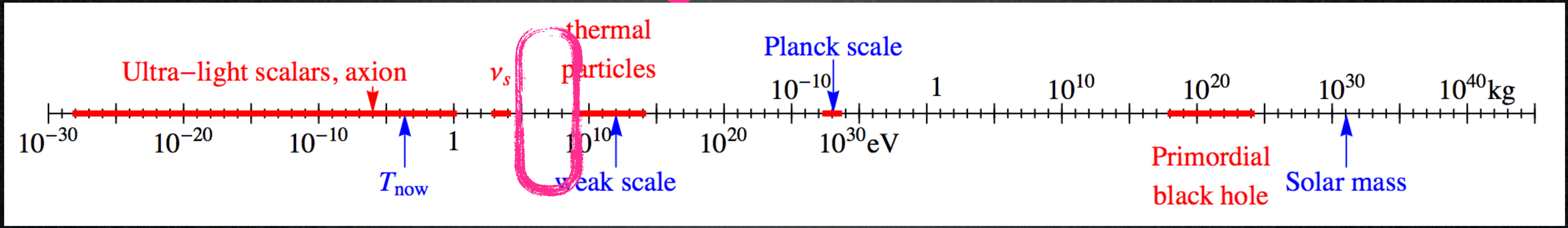


'only' 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

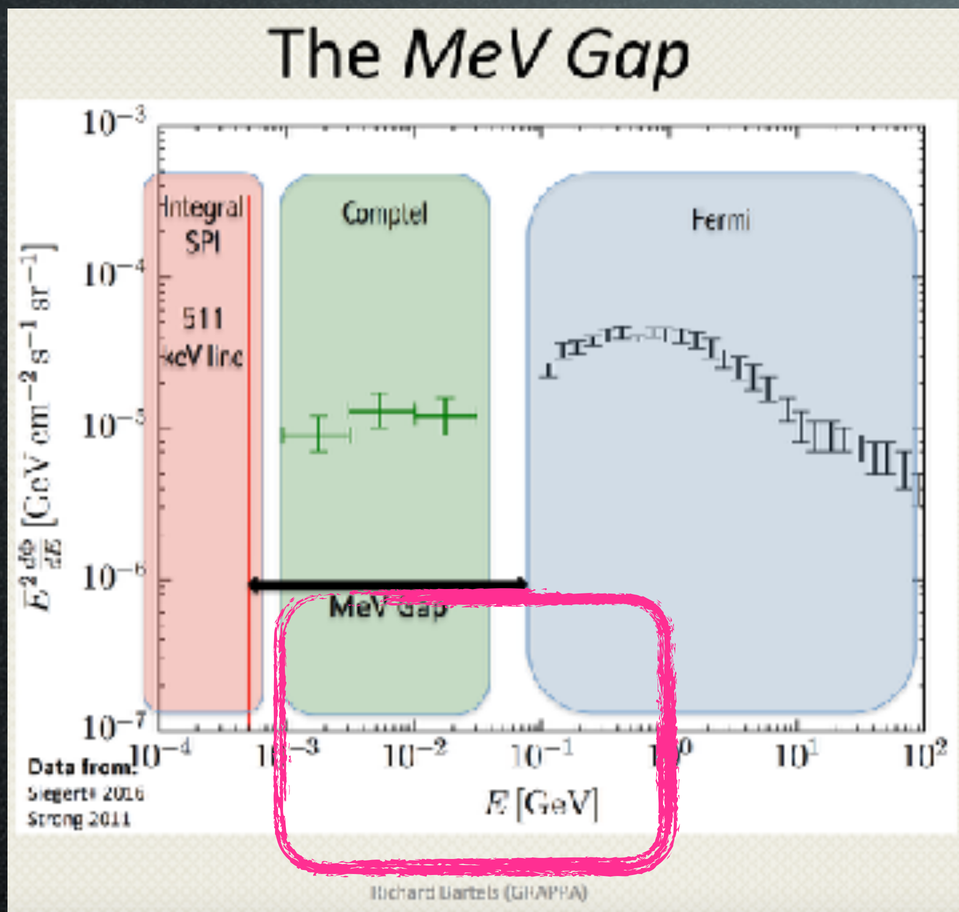
sub-GeV region

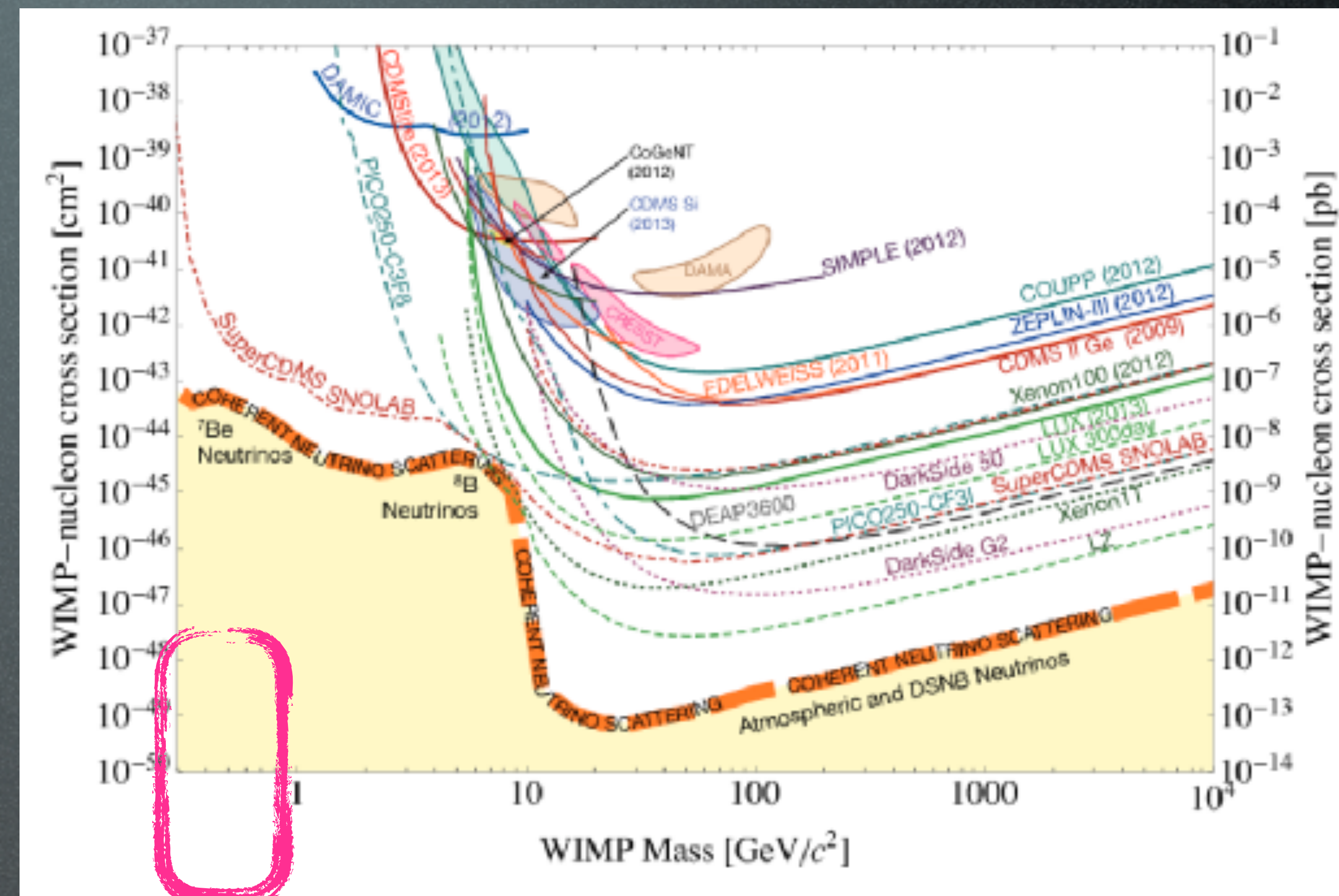


'only' 90 orders of magnitude!

Candidates

Motivation for DM in the sub-GeV region





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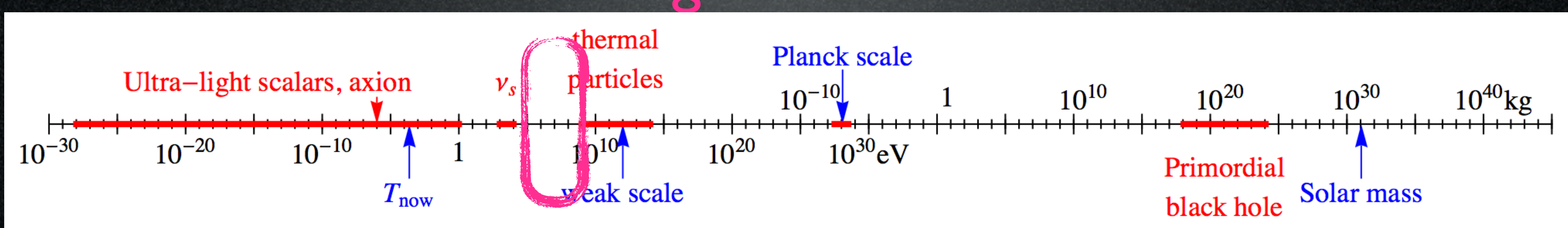
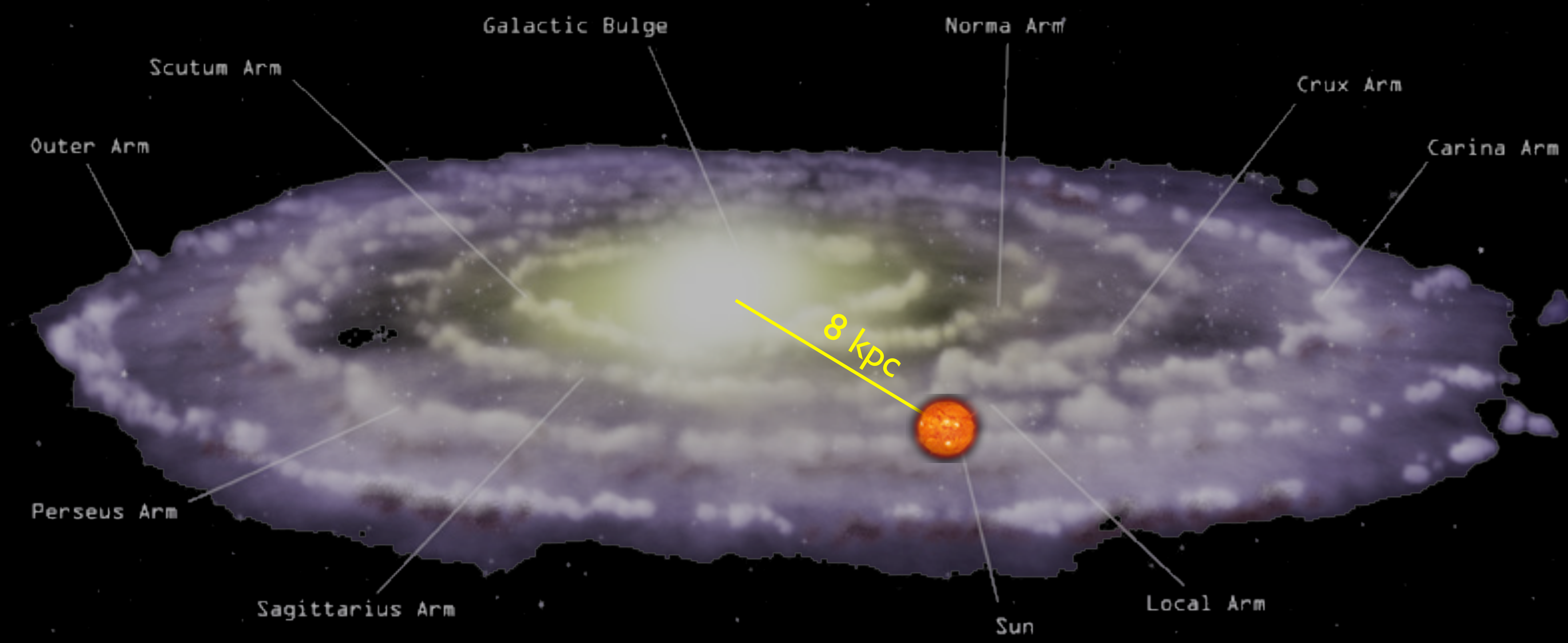


'only' 90 orders of magnitude!

Basic picture

γ from DM annihilations in galactic center



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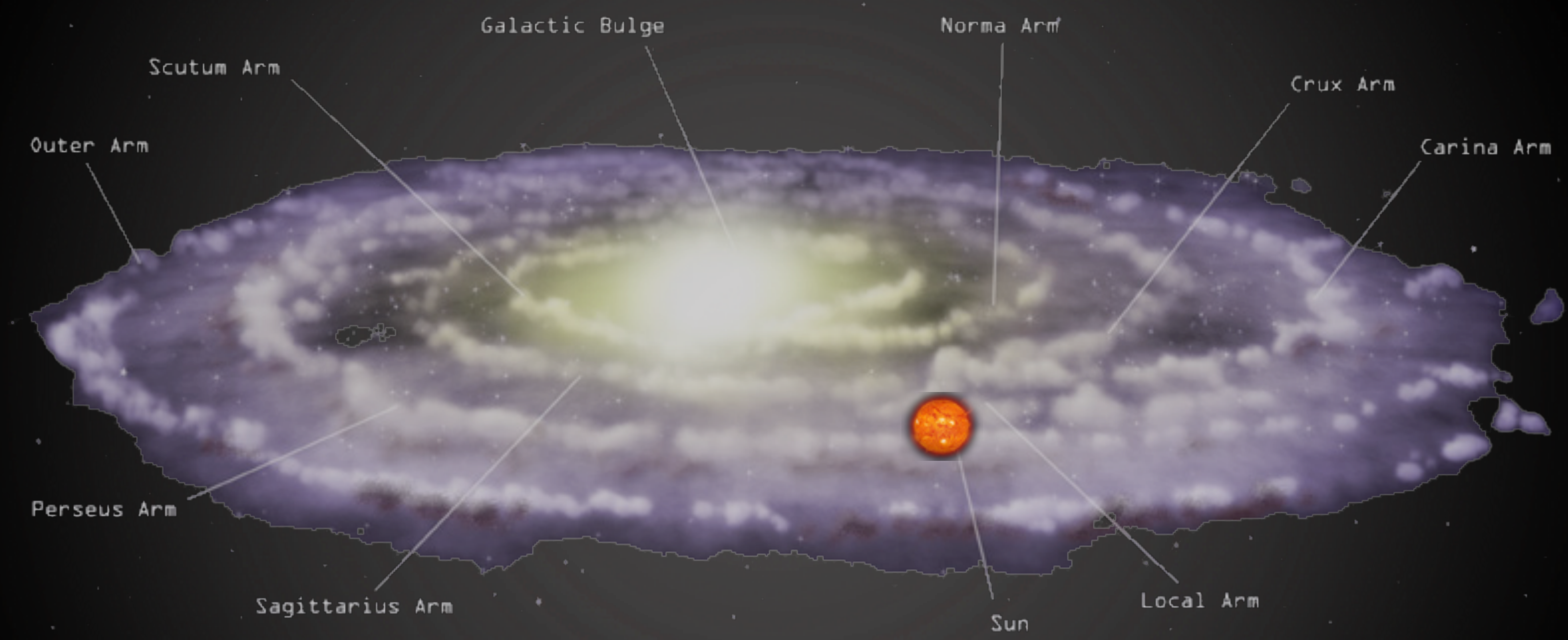


DM halo profiles

From N-body numerical simulations:

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

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

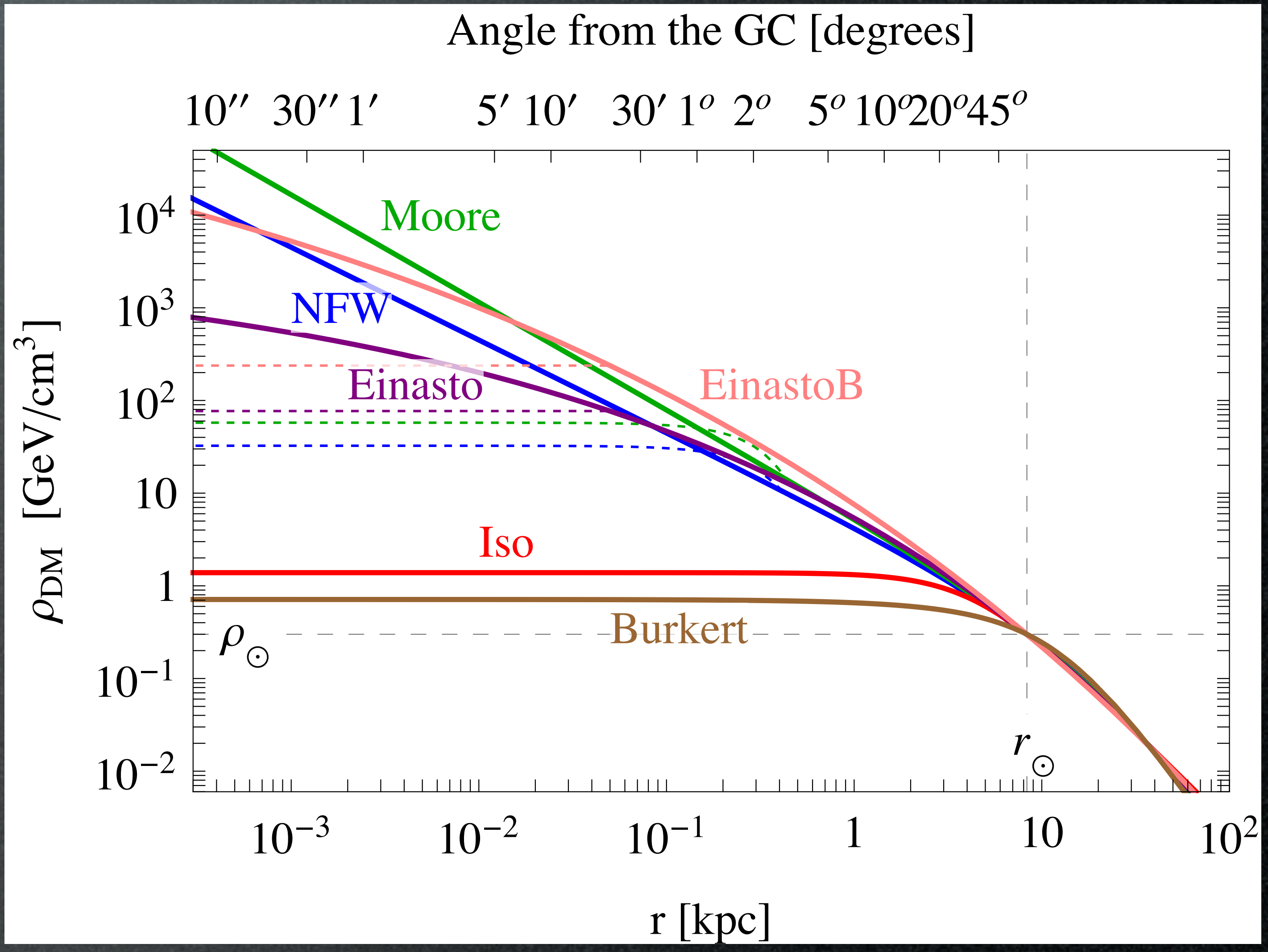
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

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



6 profiles:

- cuspy: NFW, Moore
- mild: Einasto
- smooth: isothermal, Burkert

EinastoB = steepened Einasto (effect of baryons?)

Basic picture

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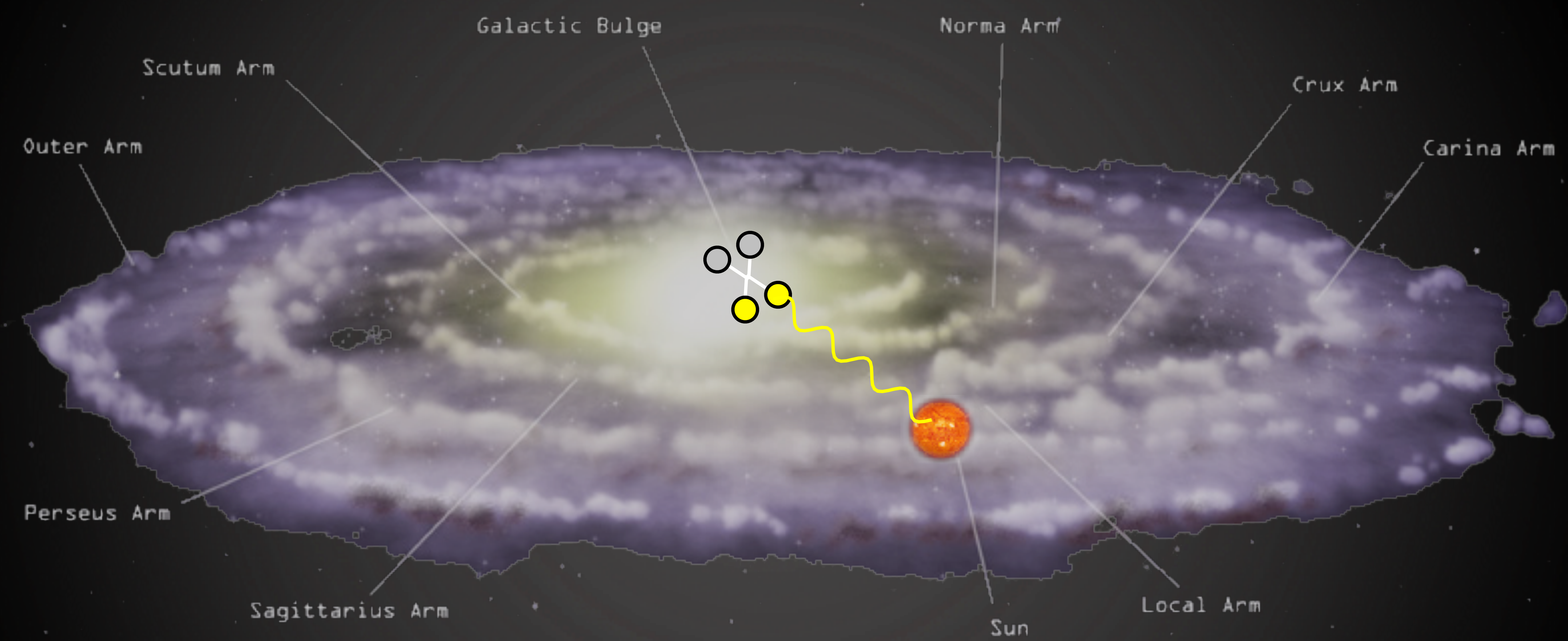
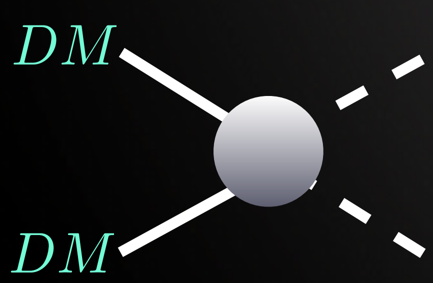




$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

How does DM produce γ-rays?

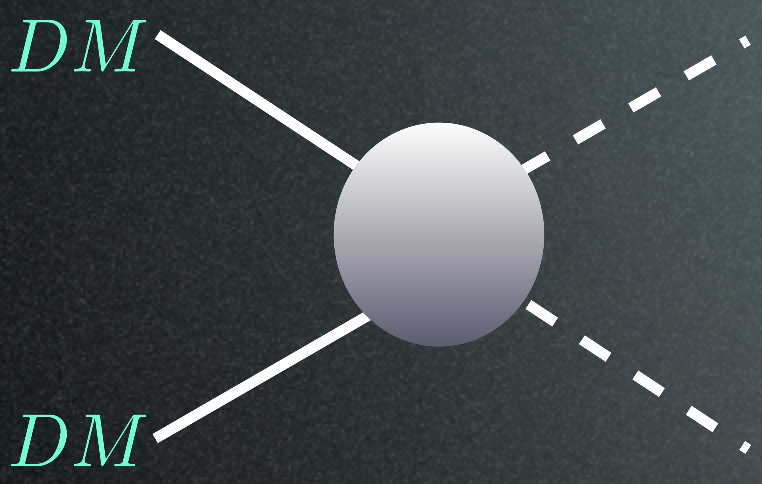
1. prompt emission

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

2. secondary emission

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

Prompt emission: continuum



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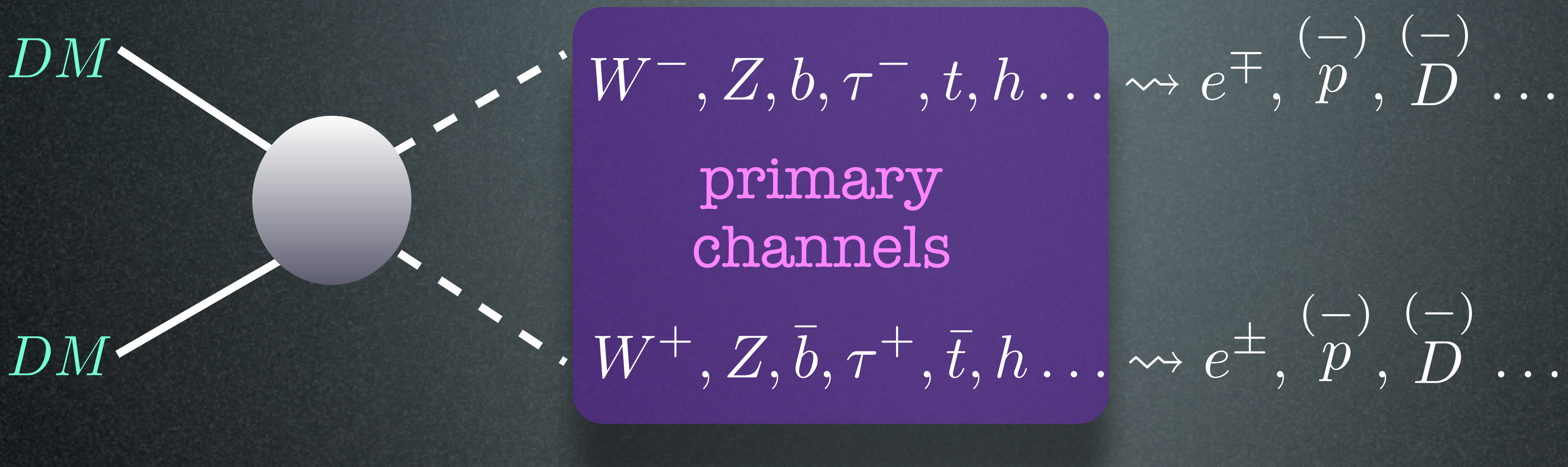
Prompt emission: continuum



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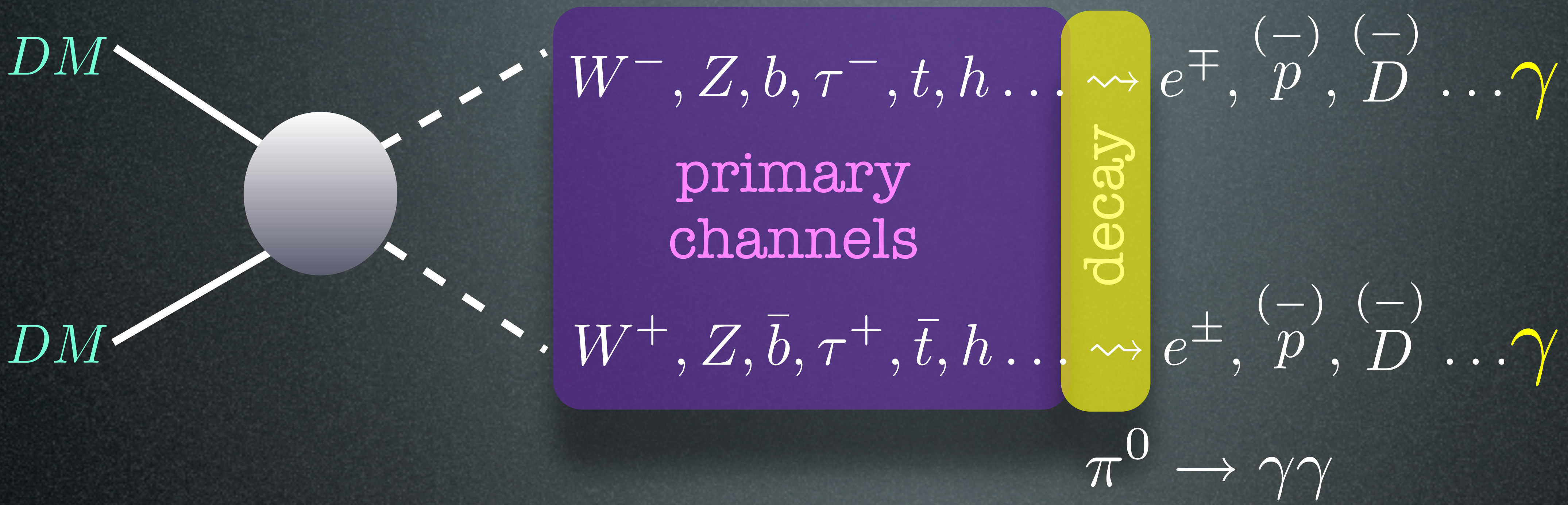

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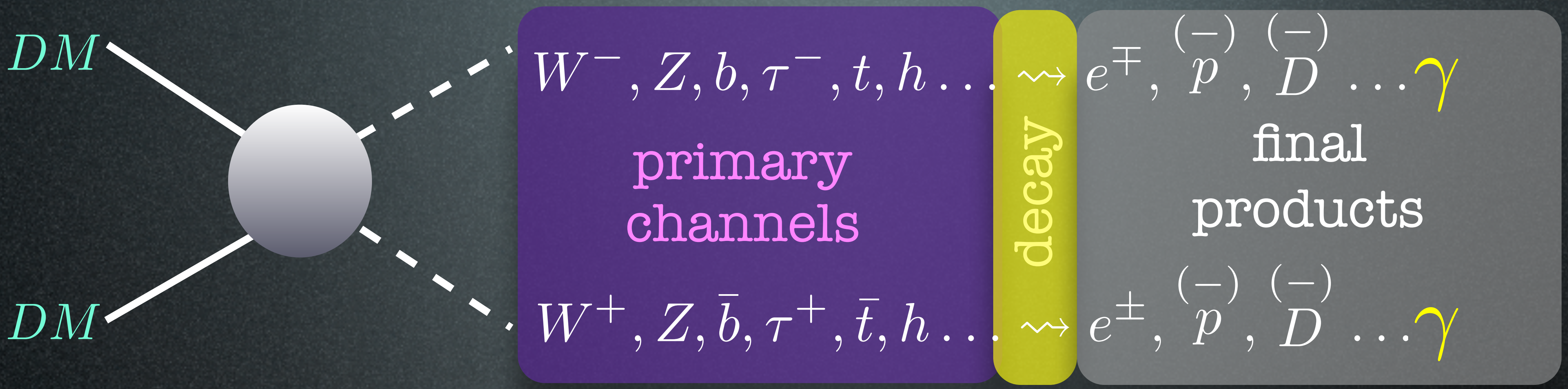

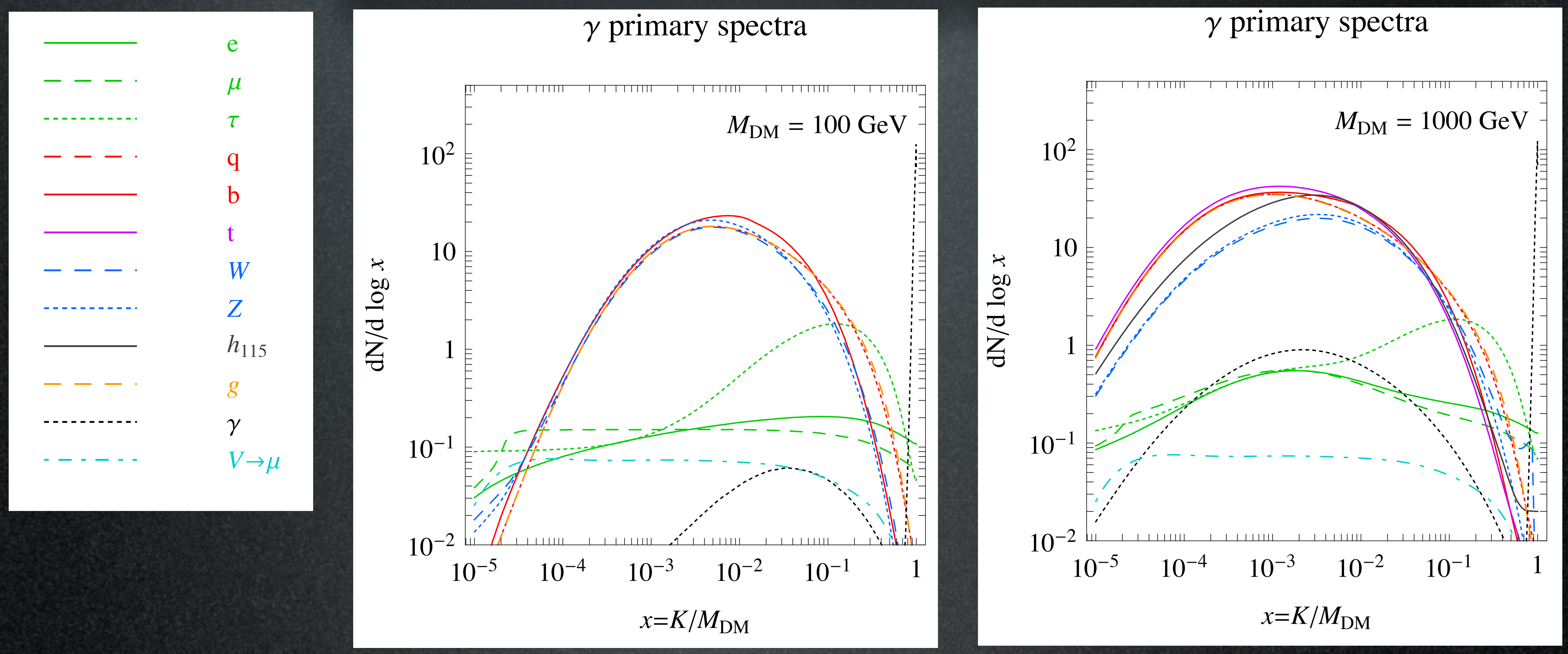

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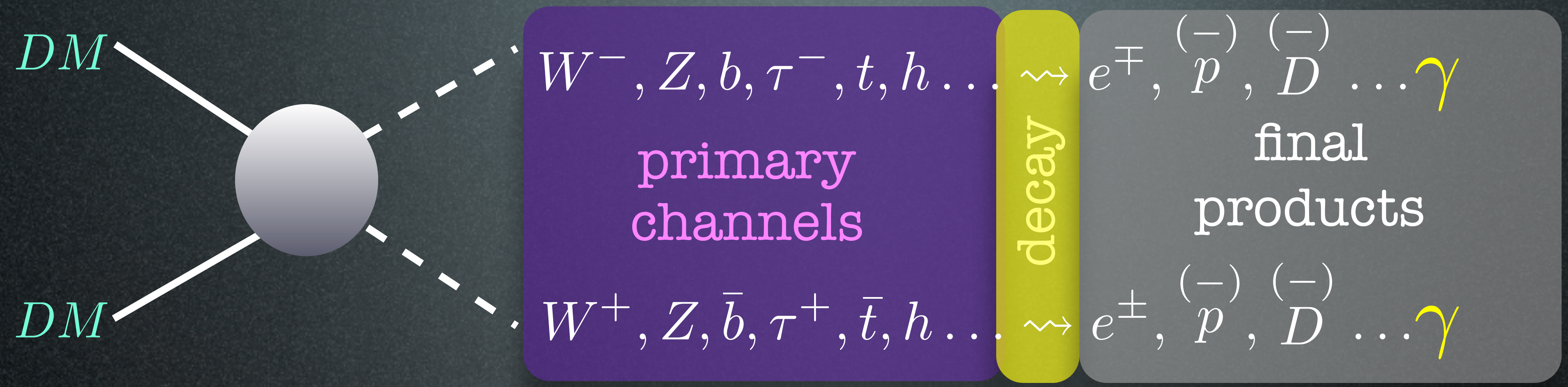
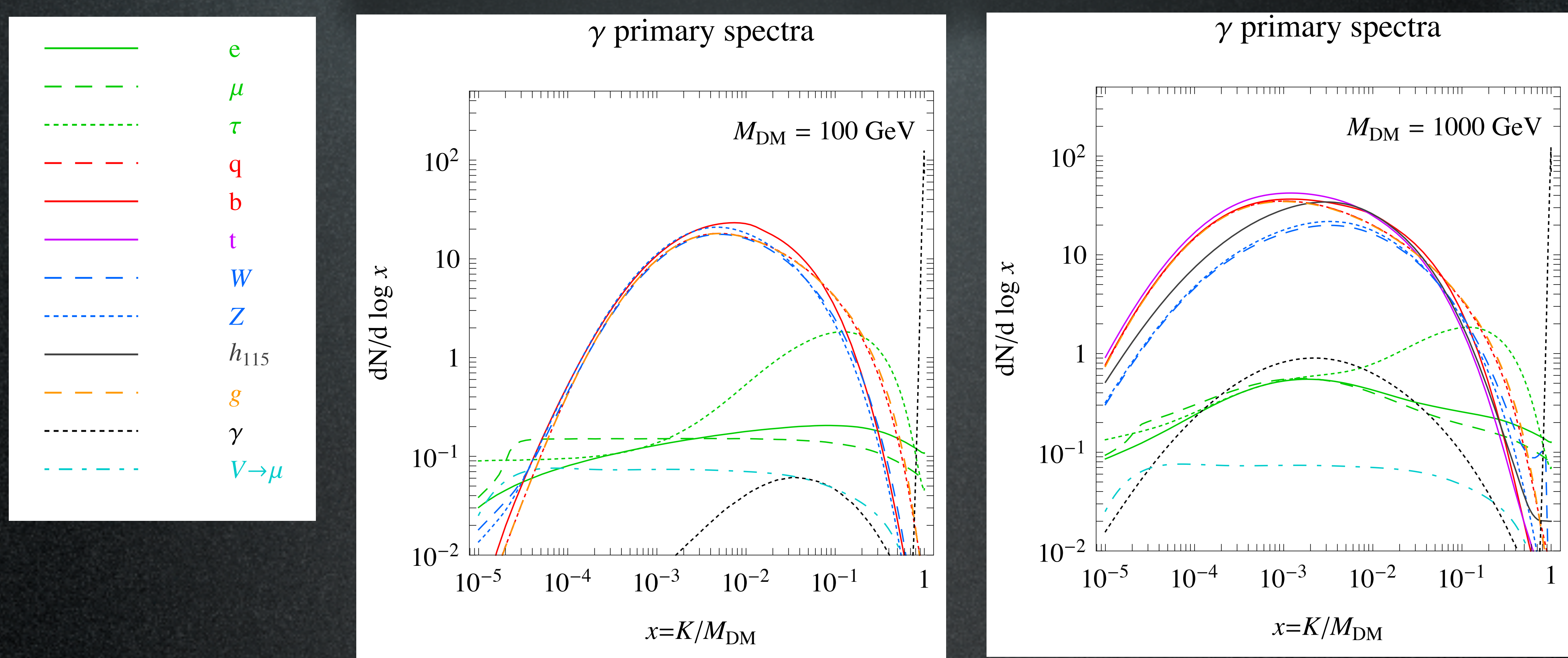
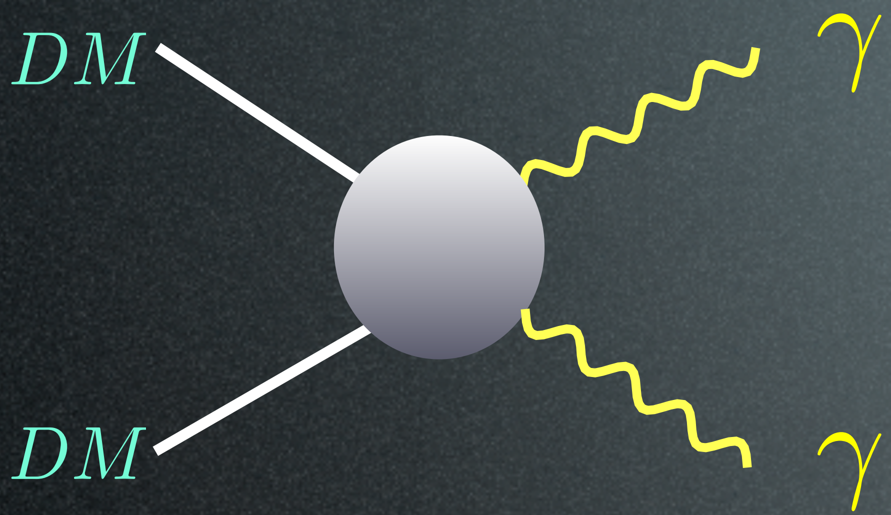




So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section σ_{ann}

Prompt emission: line(s)



primary
channels

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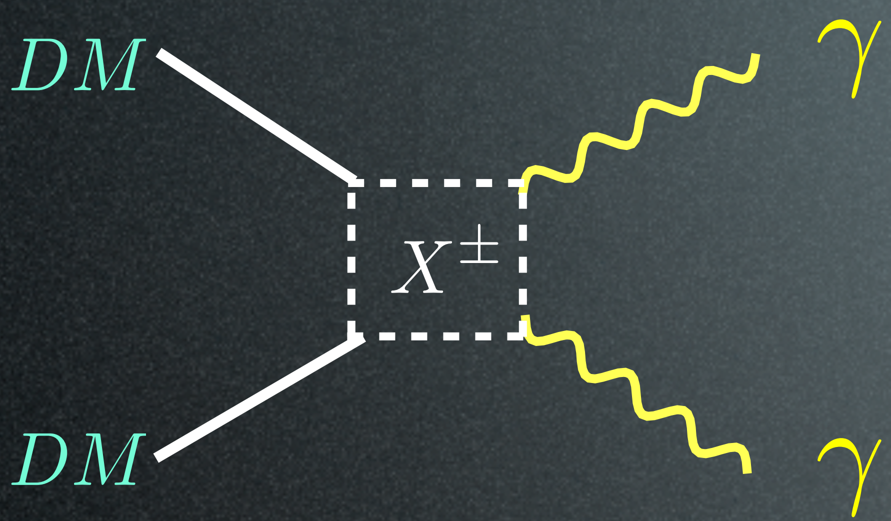
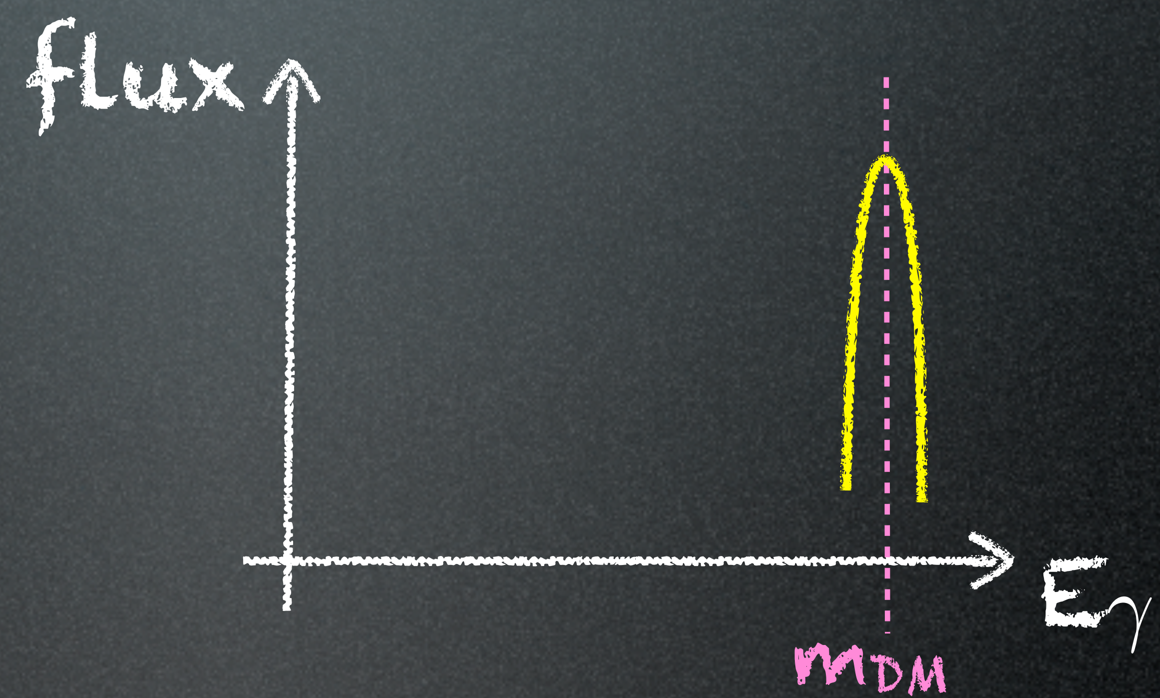


primary channels

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



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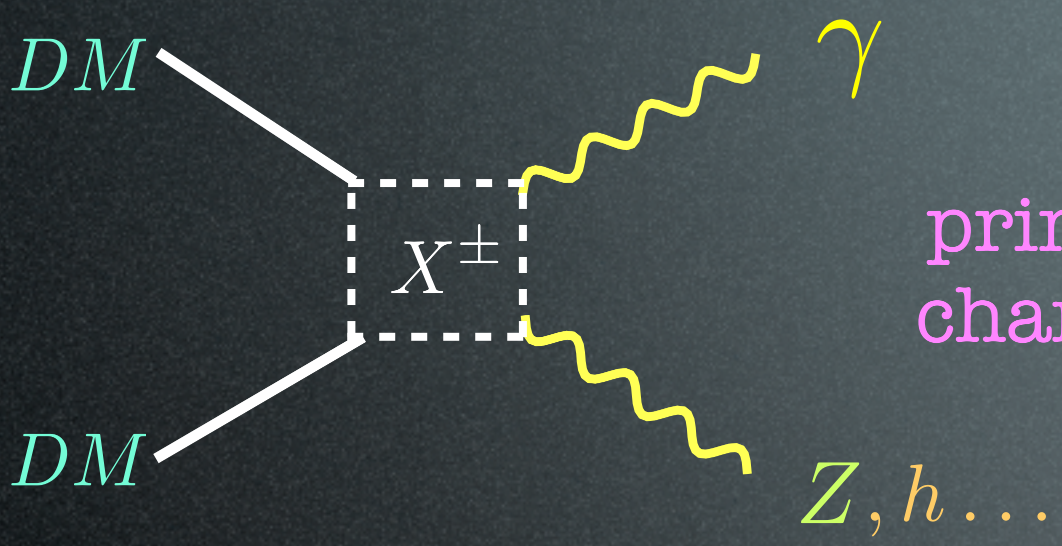

primary channels

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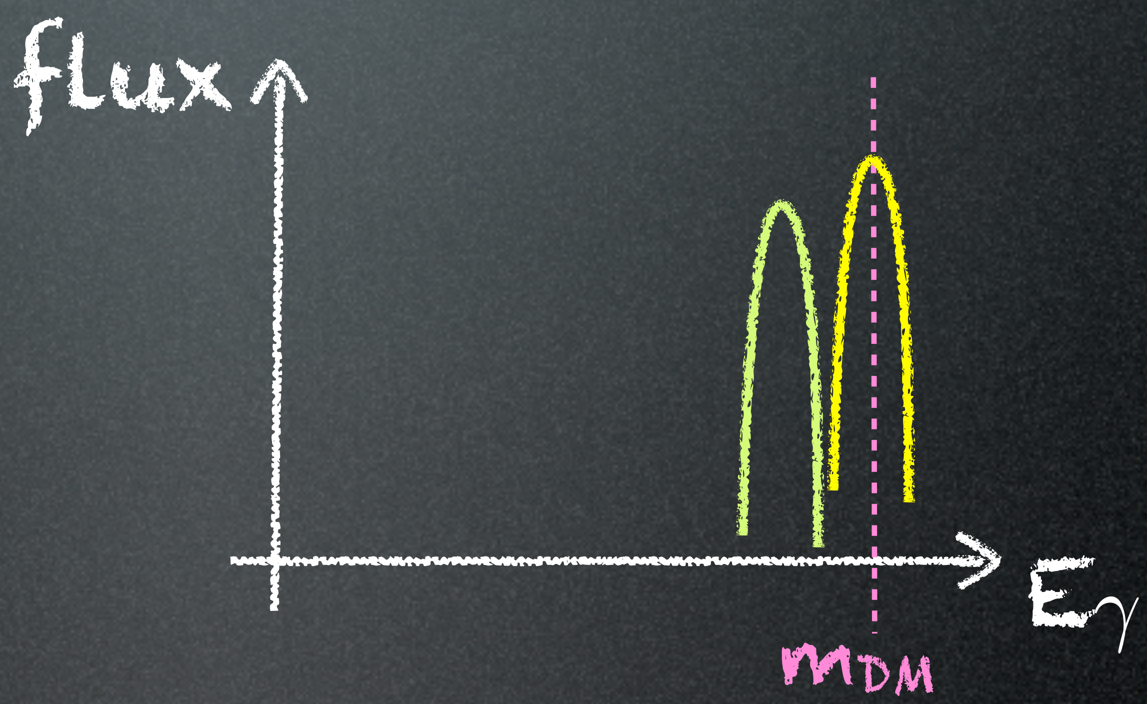

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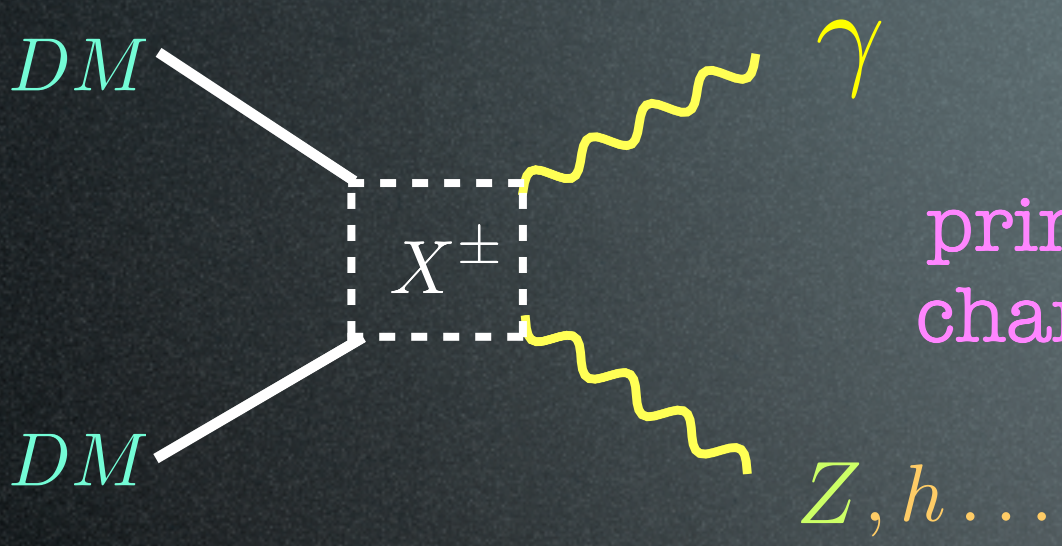

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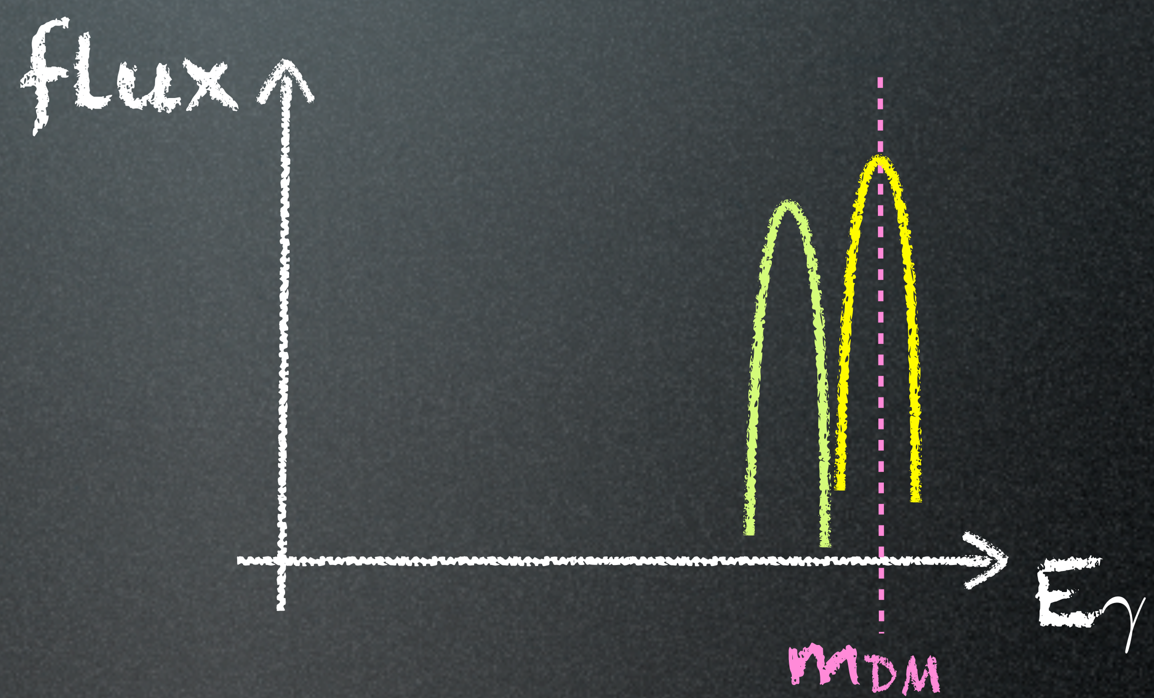

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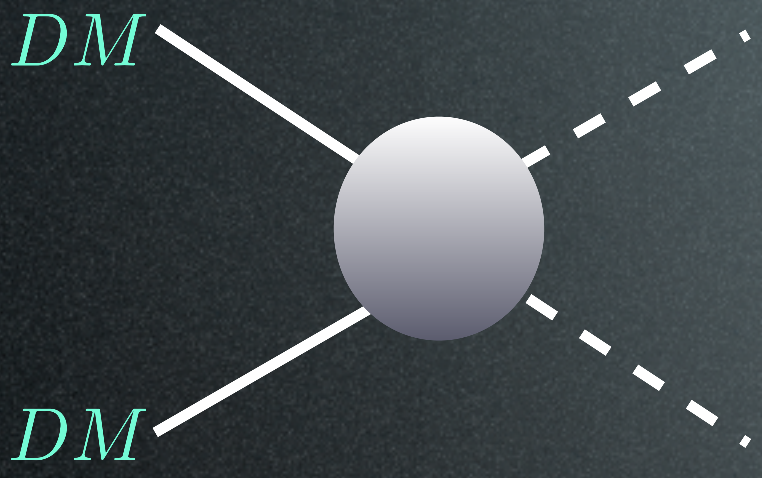
1. Dark Matter mass

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

Prompt emission: sharp features



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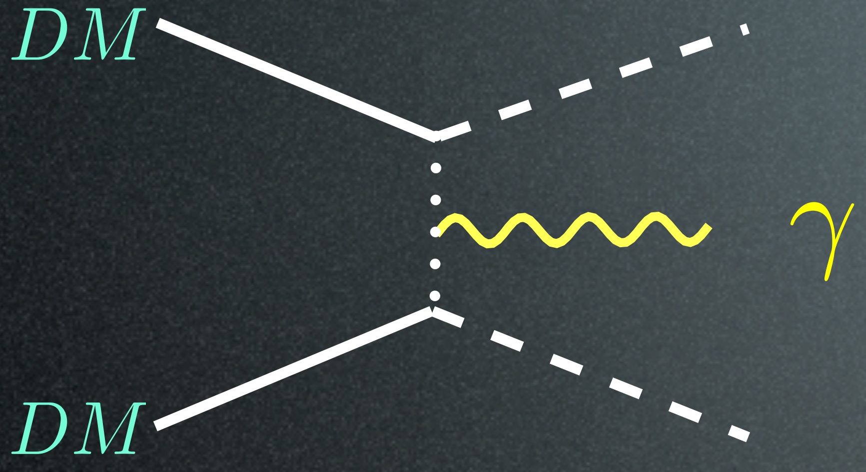
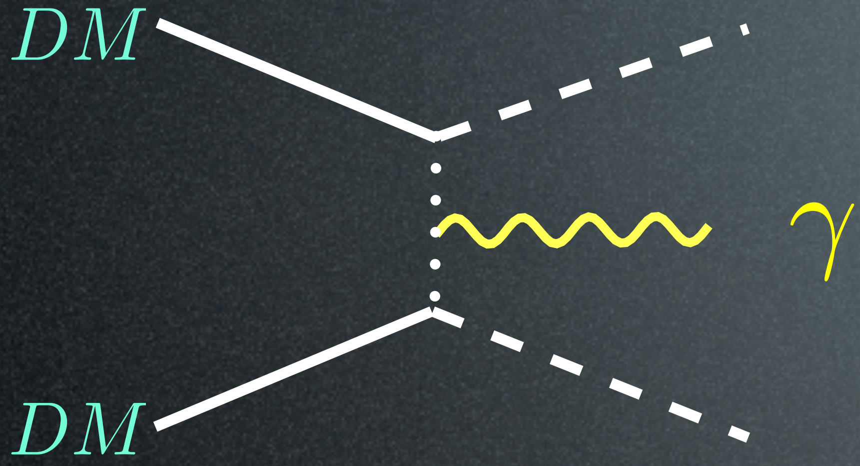


Internal Bremsstrahlung

Bergström 1989

Prompt emission: sharp features



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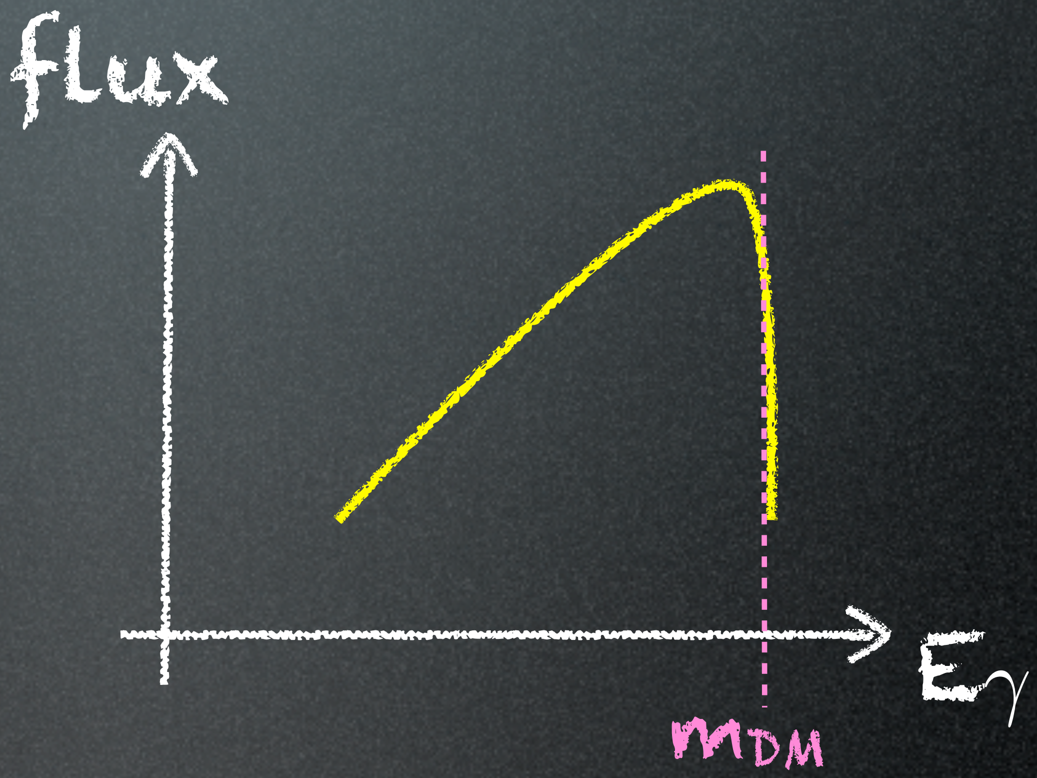

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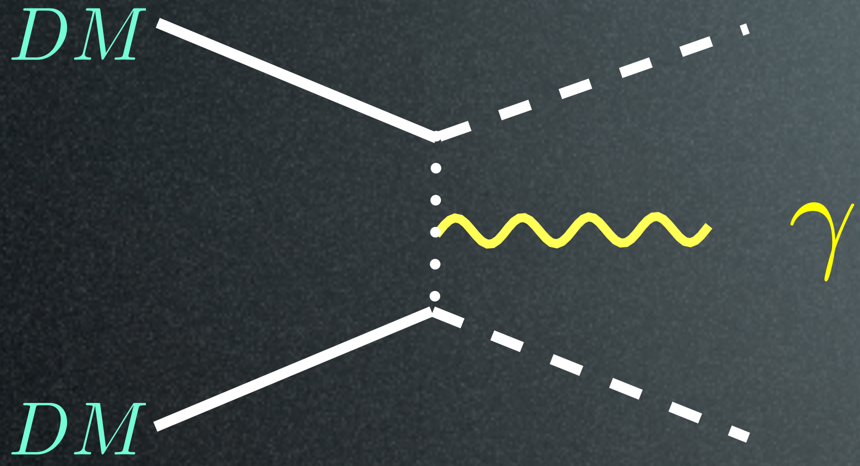

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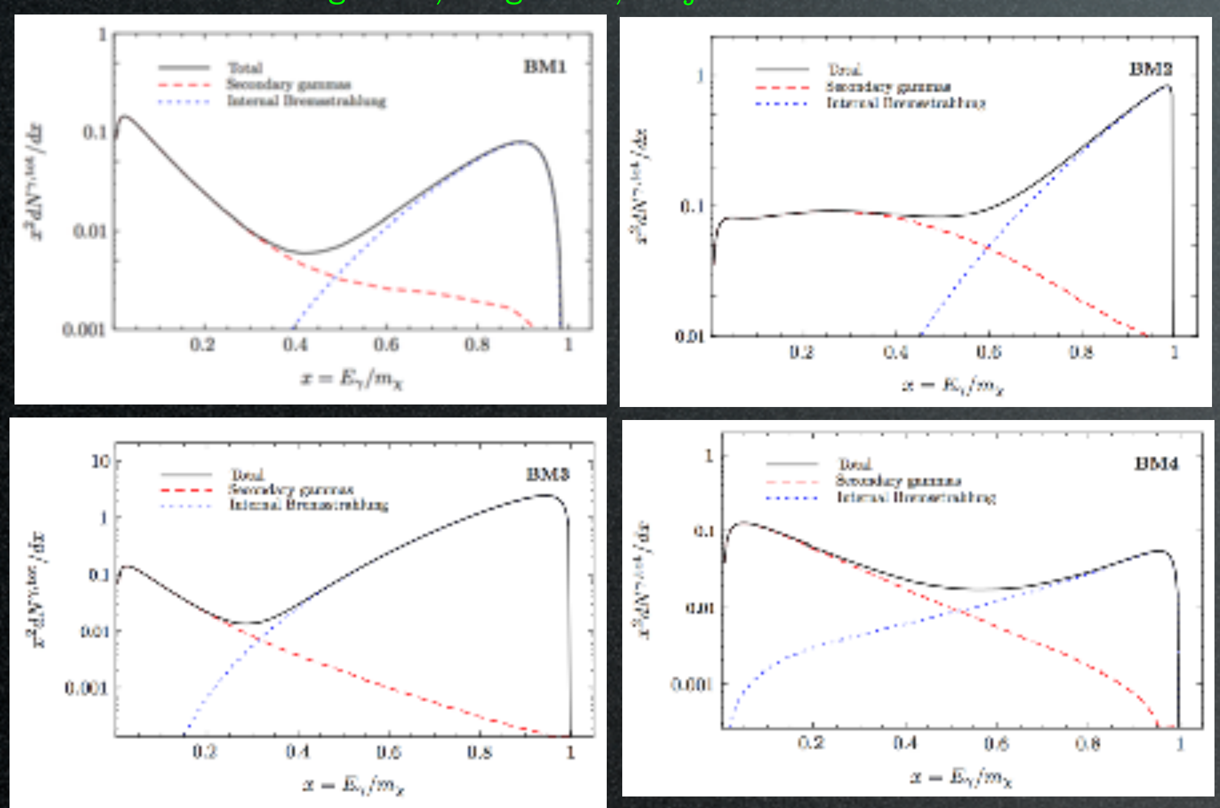
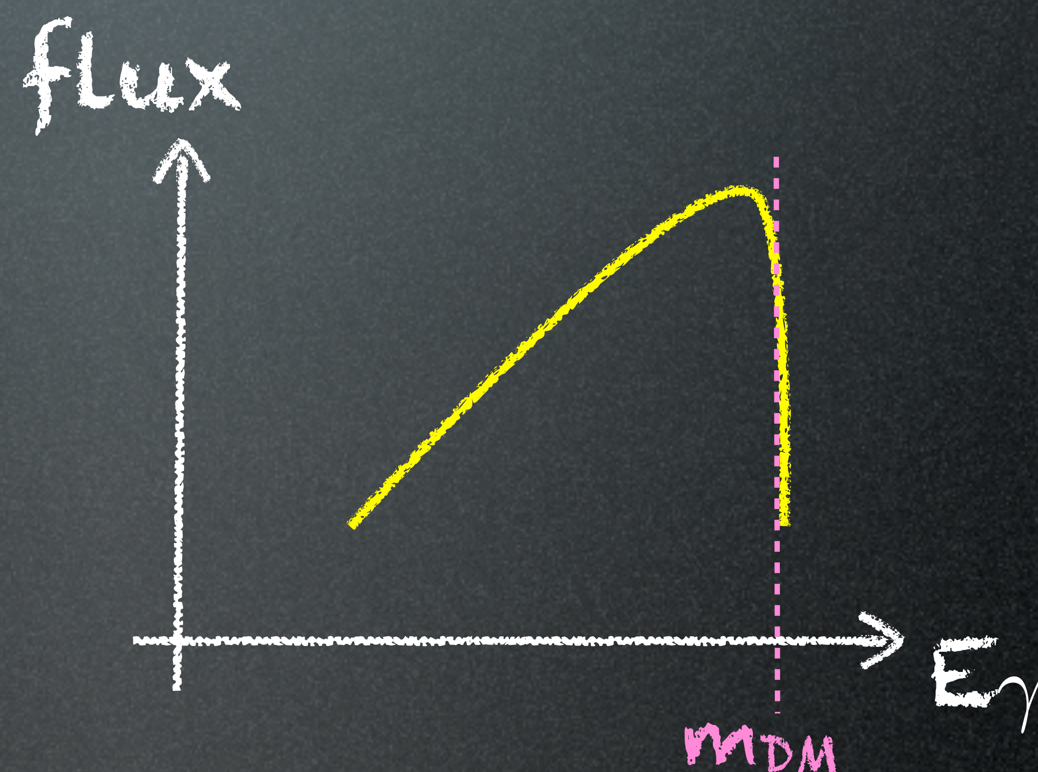
Bringmann, Bergstrom, Edsjo 0710.3169



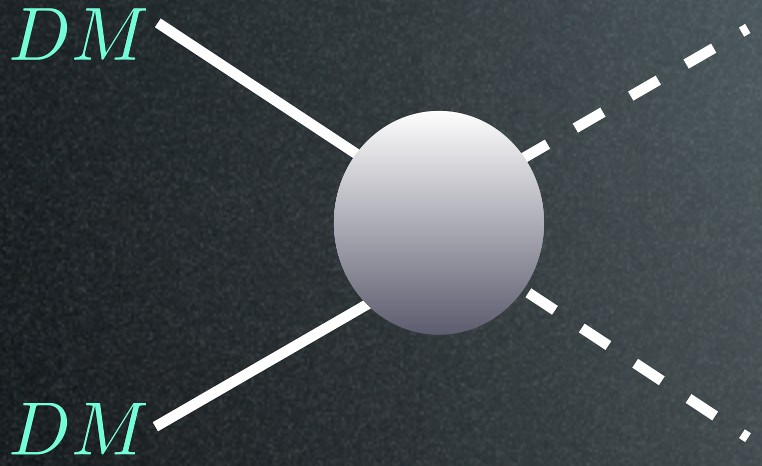


So what are the particle physics parameters?

1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



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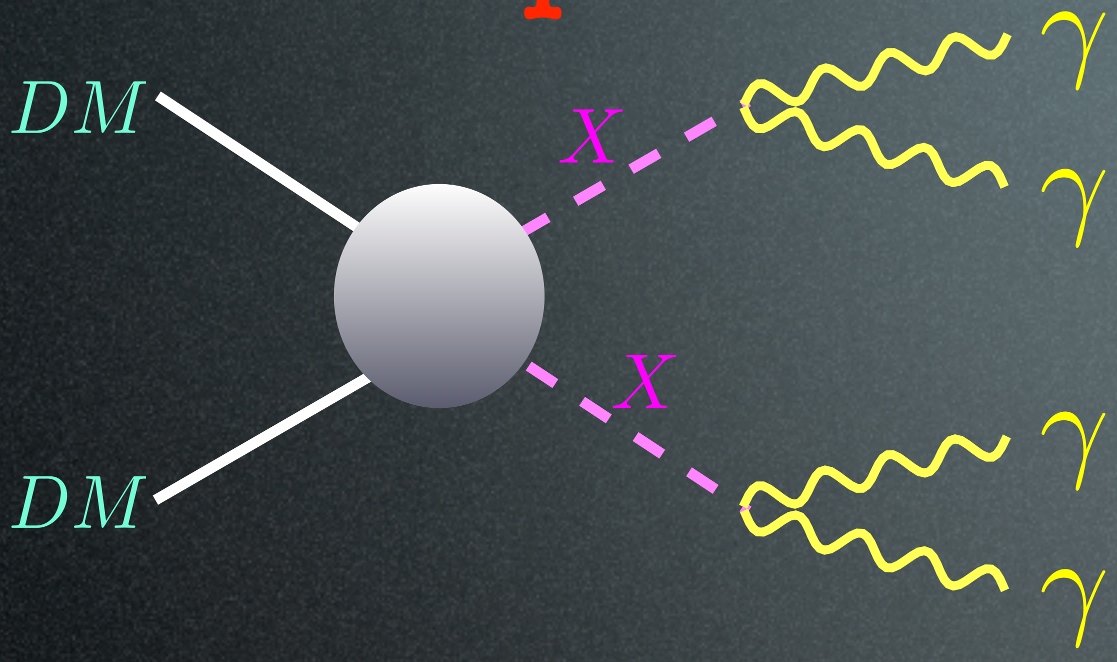
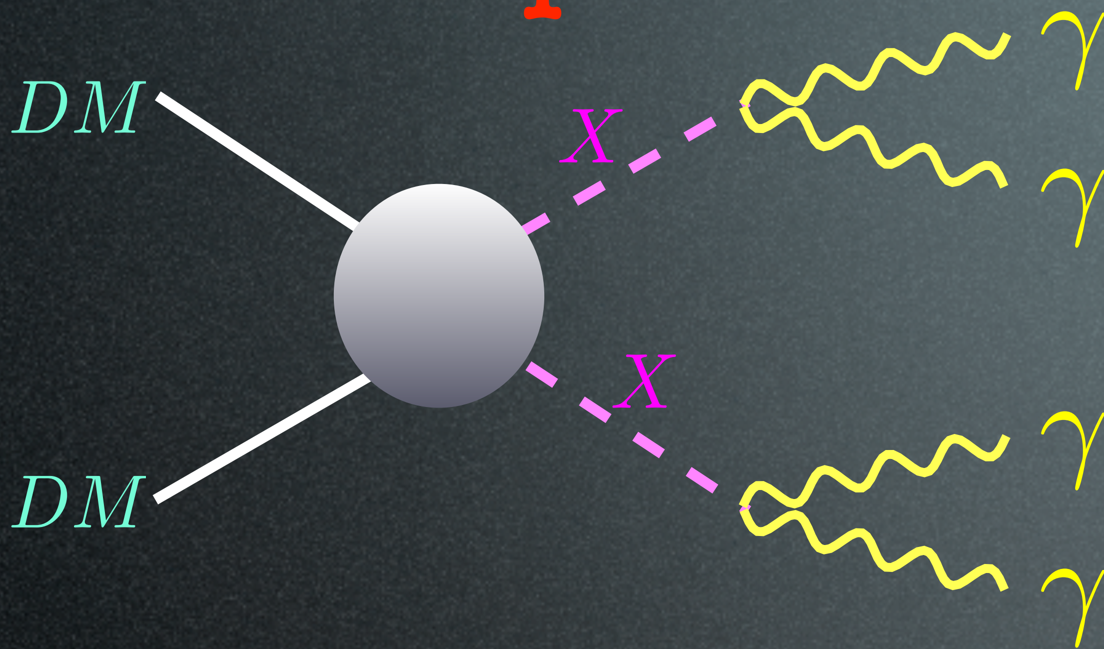


Metastable intermediate states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

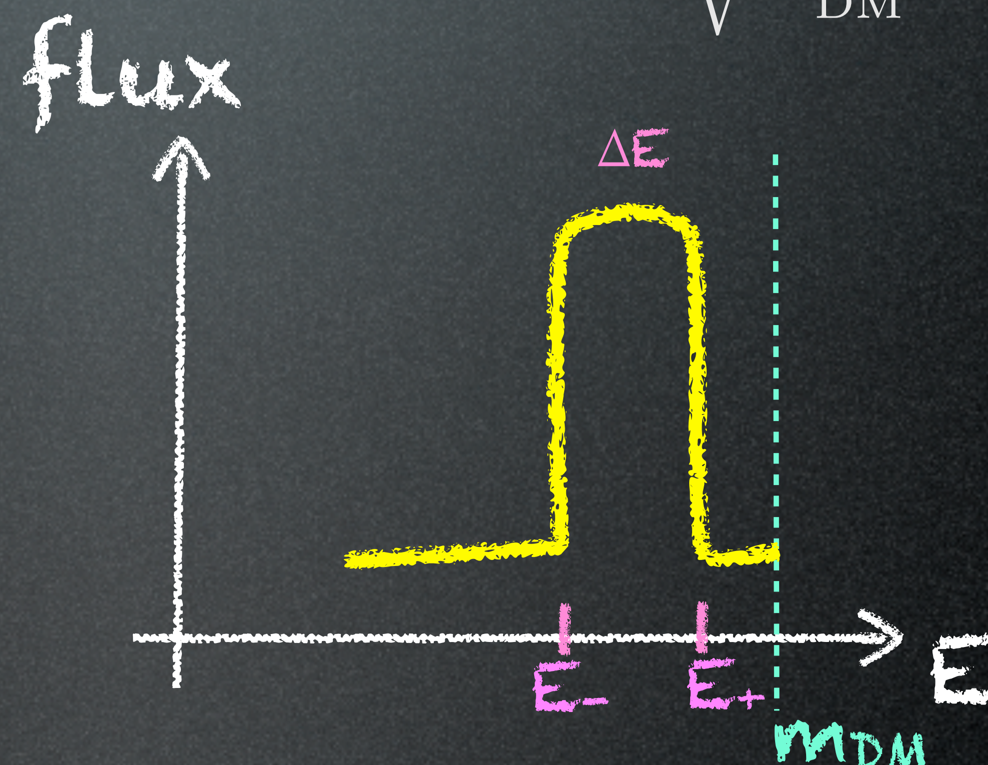


Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Metastable intermediate states

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

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



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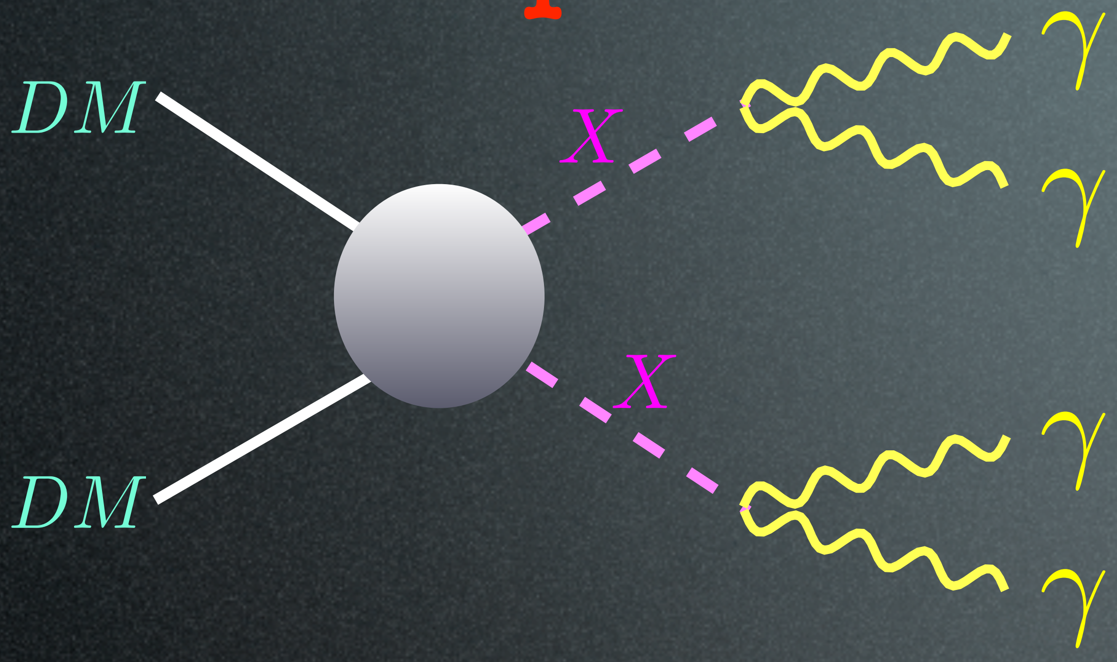

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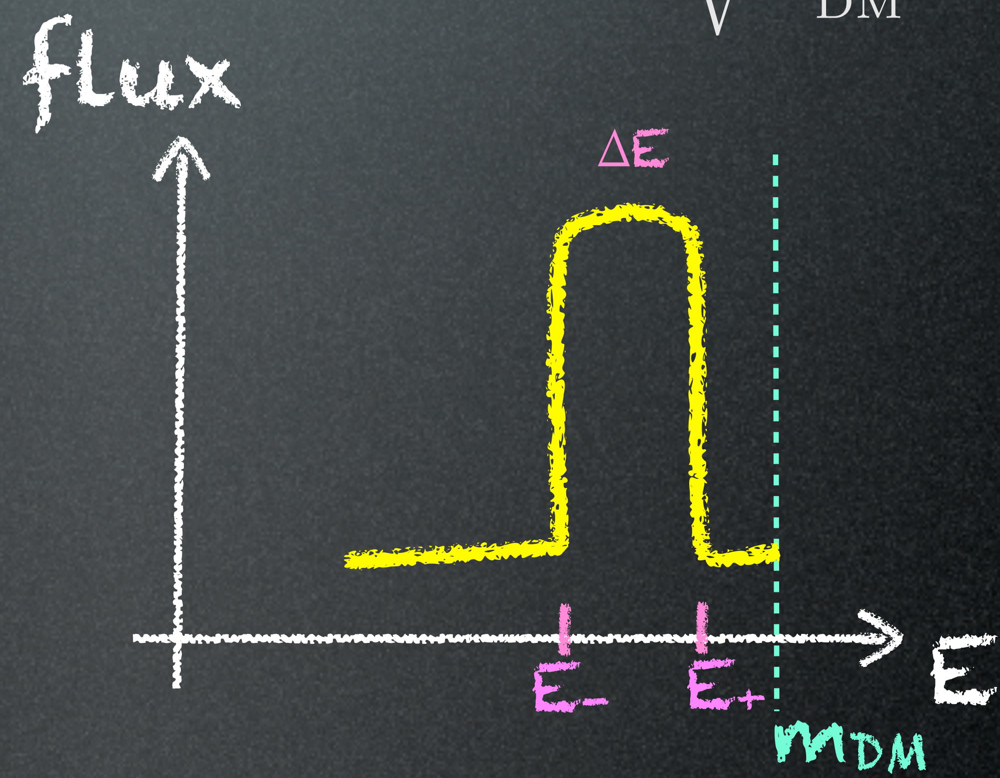
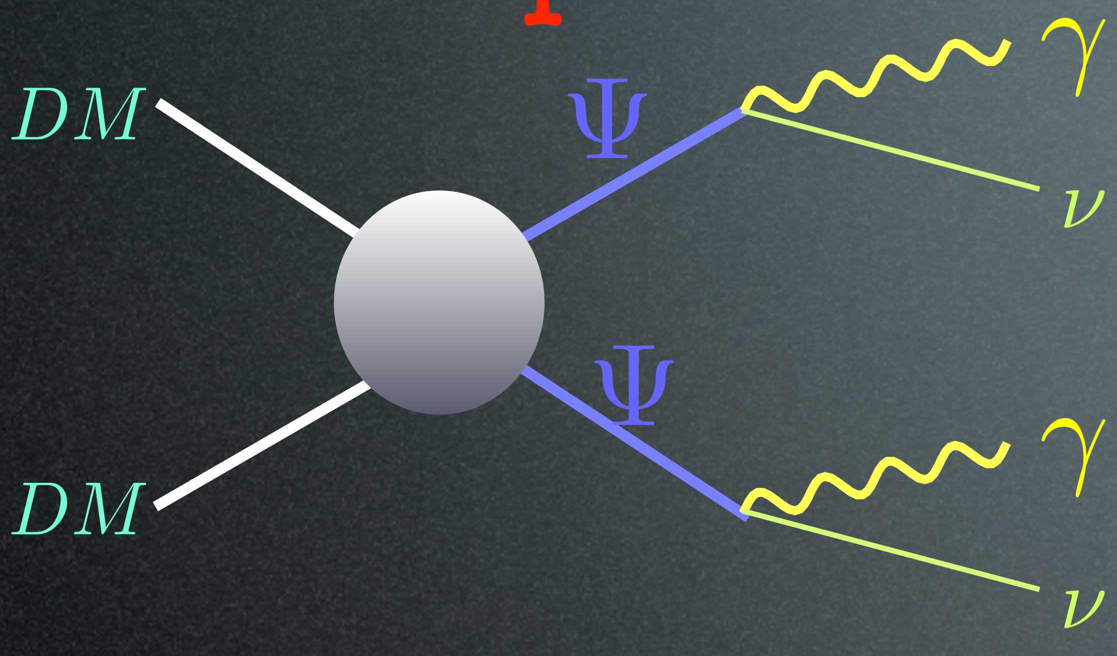


So what are the particle physics parameters?

1. Dark Matter mass
2. The mediator mass

Prompt emission: sharp features



Ibarra, Lopez Gehler, Molinaro, Pato
1604.01899

Metastable intermediate fermions

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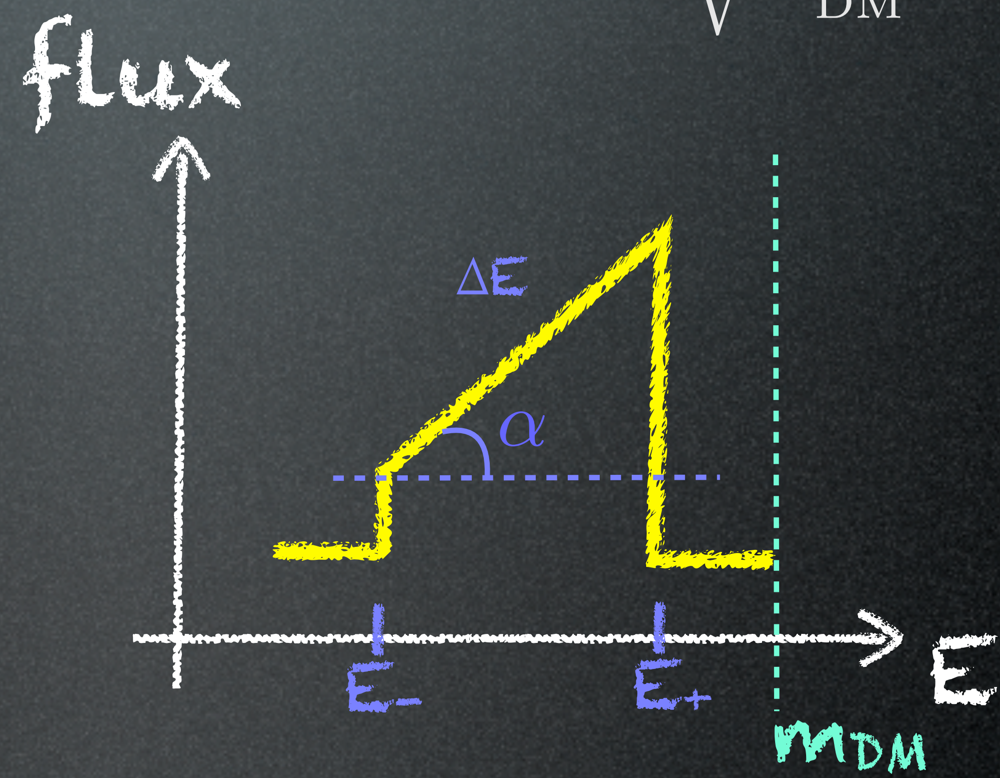
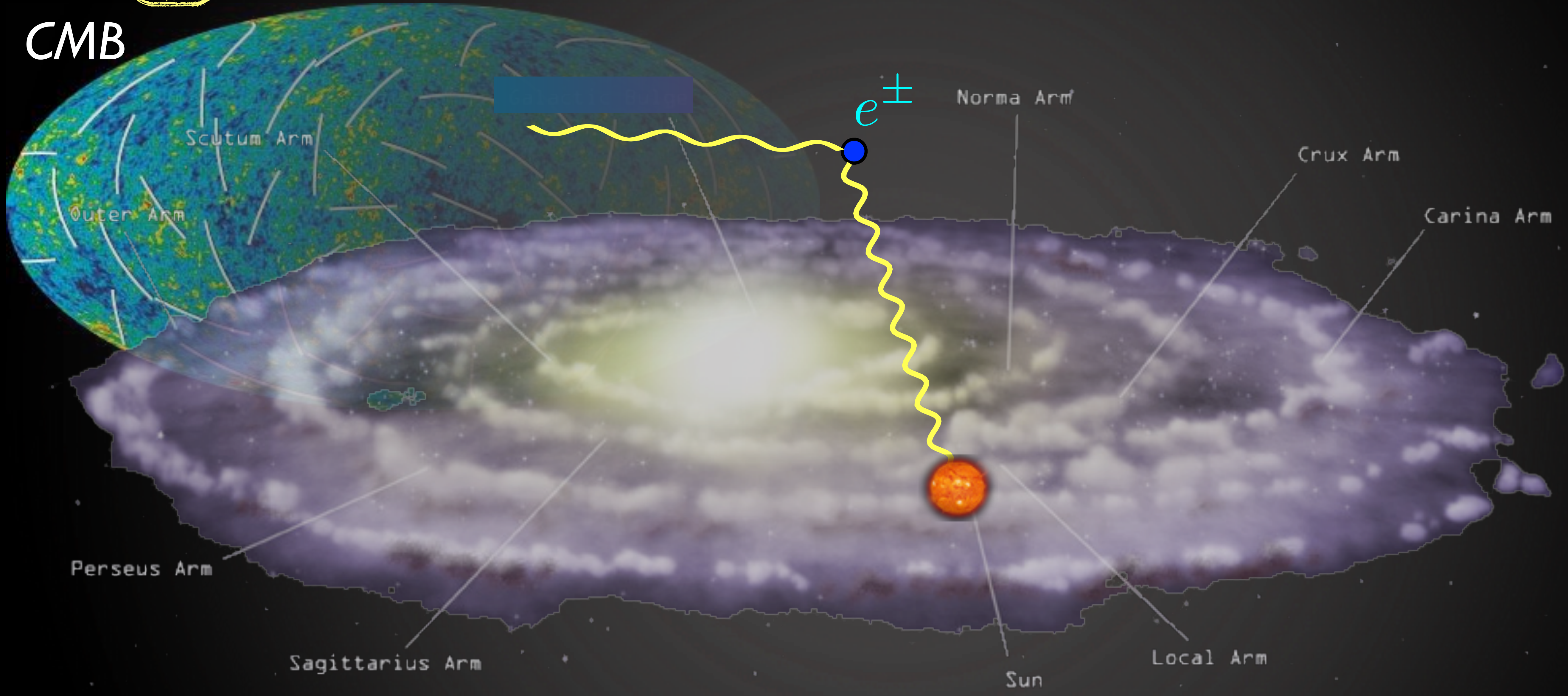


So what are the particle physics parameters?

1. Dark Matter mass
2. The fermionic mediator mass
3. The polarization α of the mediator

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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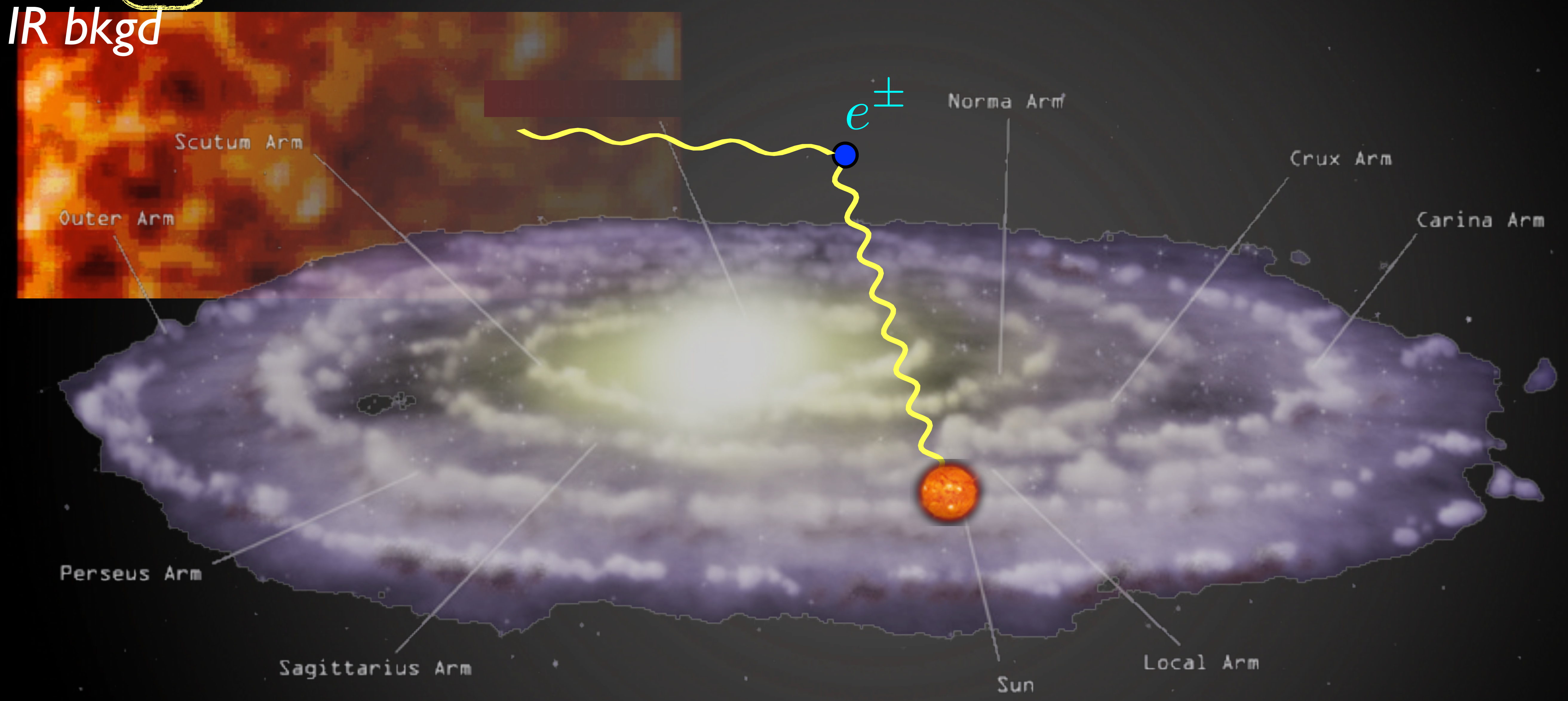

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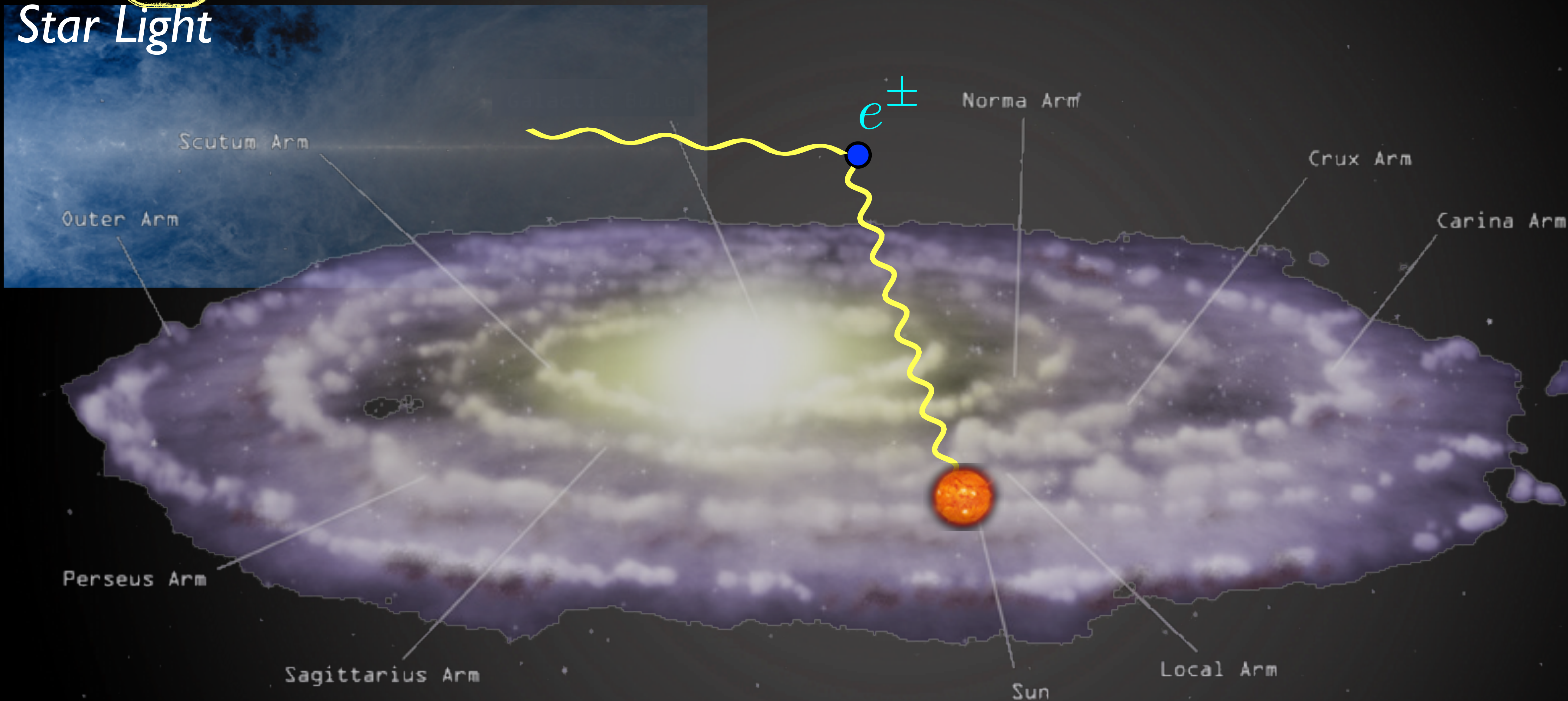

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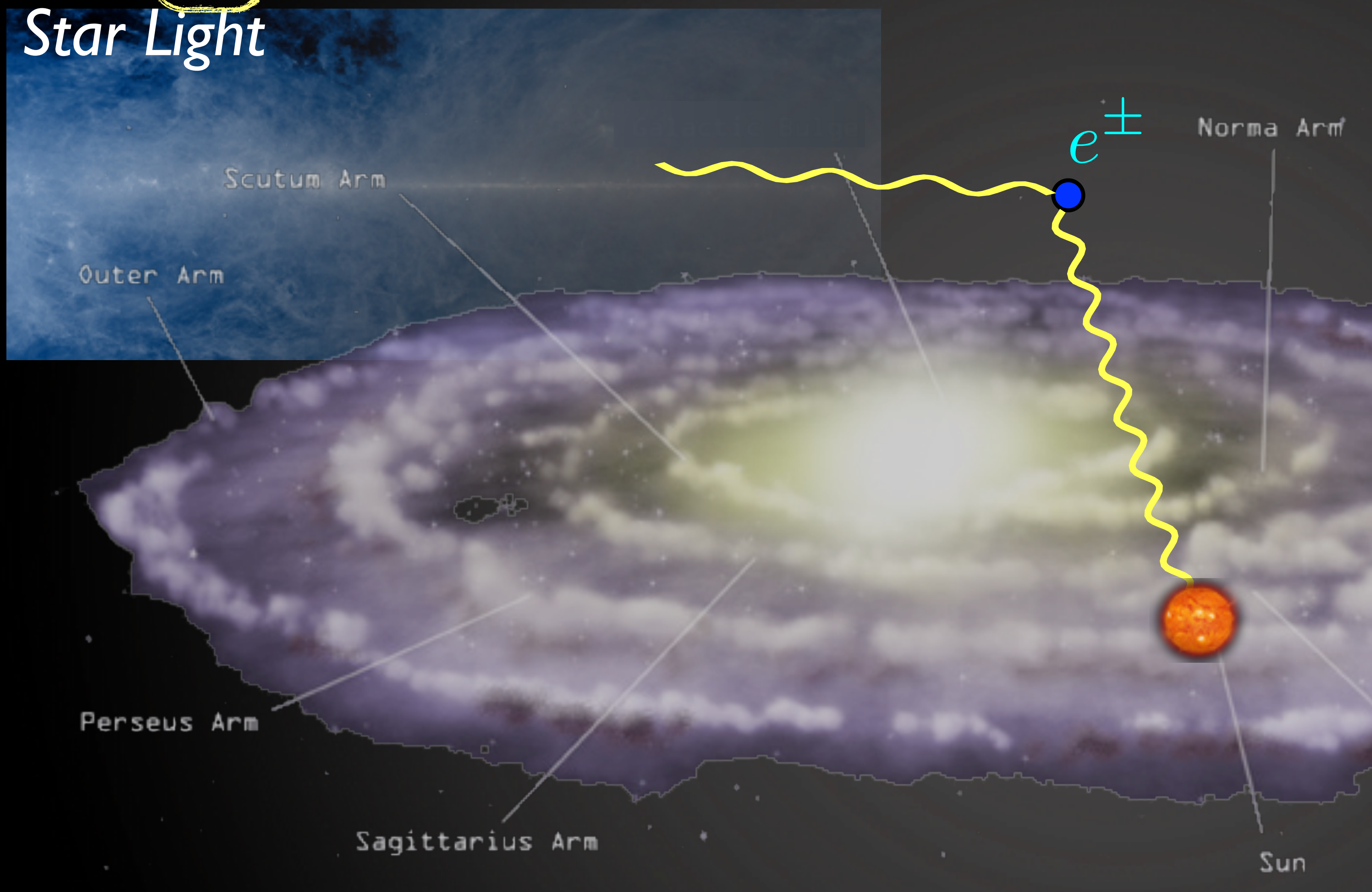
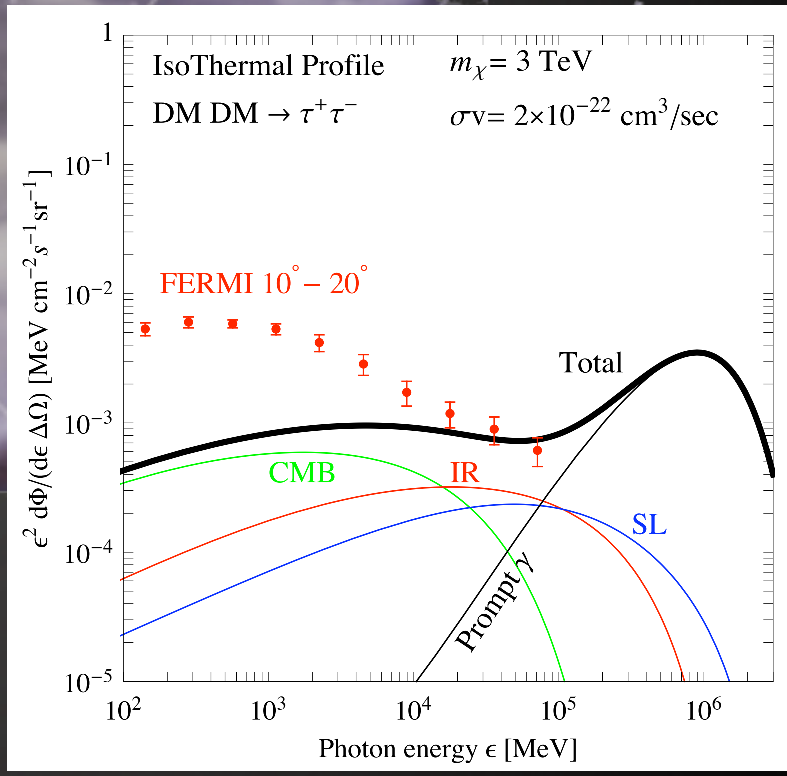
a. γ from Inverse Compton on $e^{\pm}$ in halo



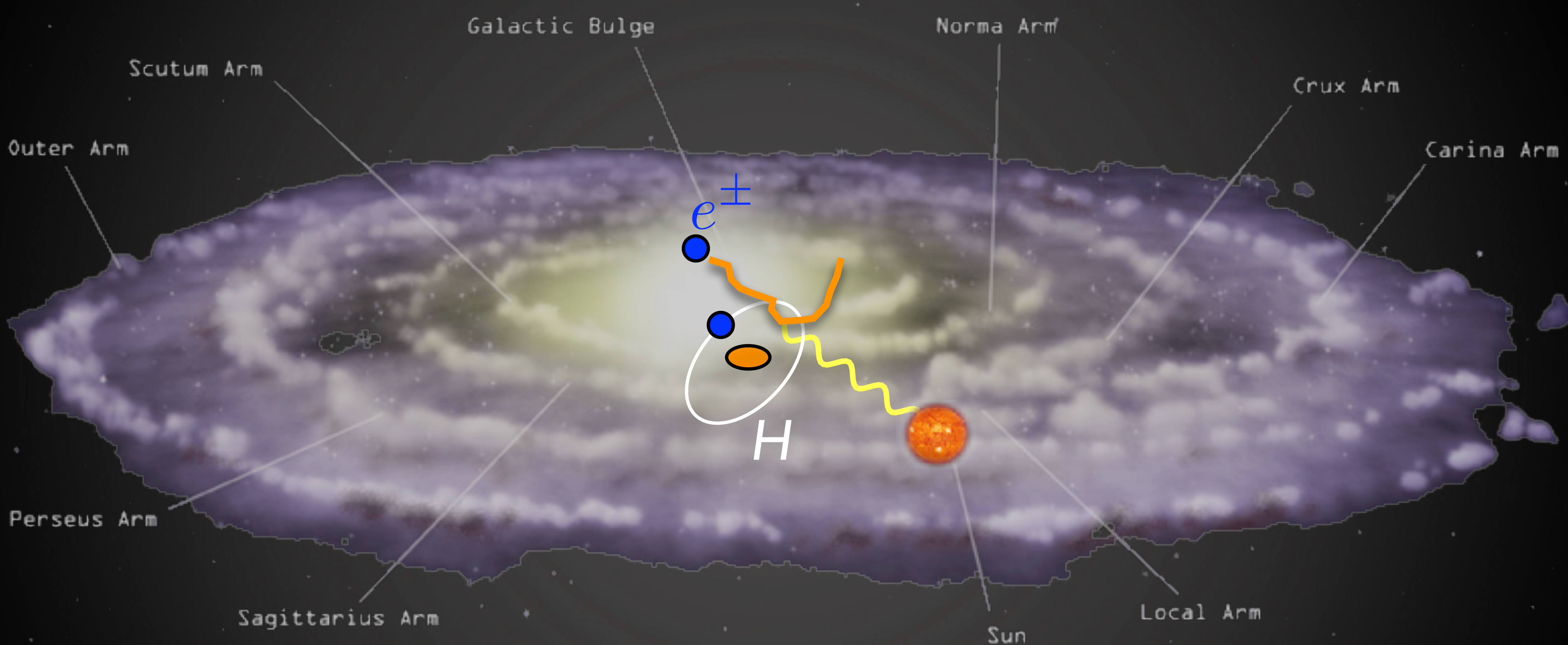


Cirelli, Panci, Serpico 0912.0663

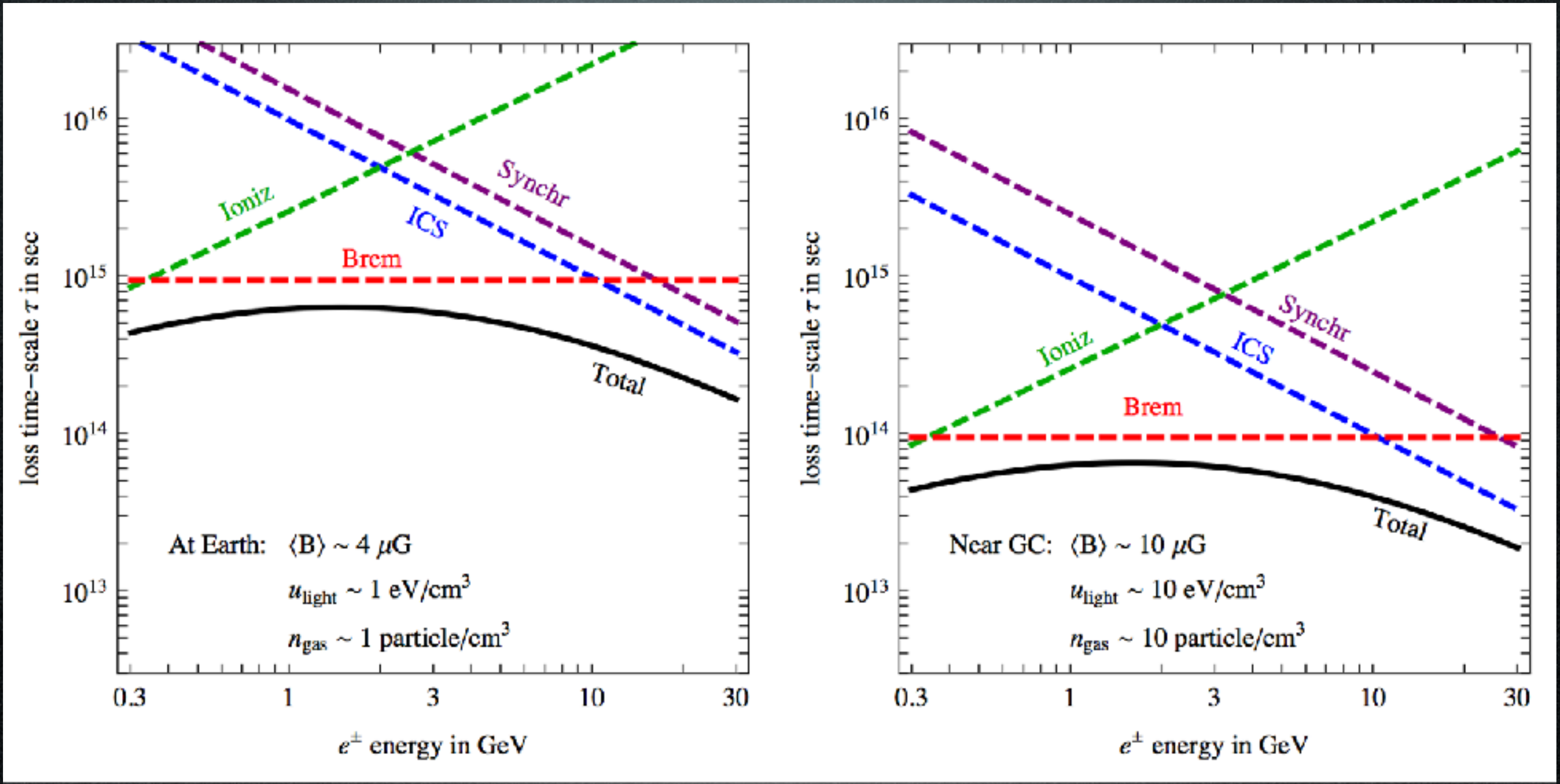
- upscatter of CMB, infrared and starlight photons on energetic $e^{\pm}$
- probes regions outside of Galactic Center

Secondary emission

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

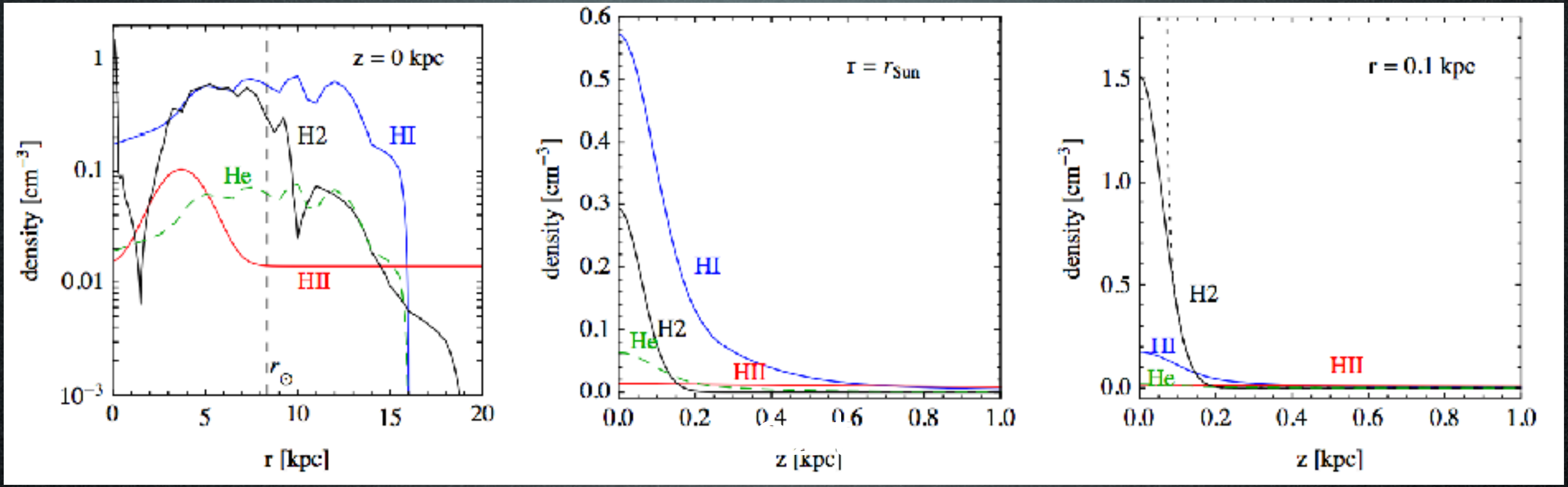


Relative importance of secondary emissions



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

Gas maps



Gas-tronomy 101:

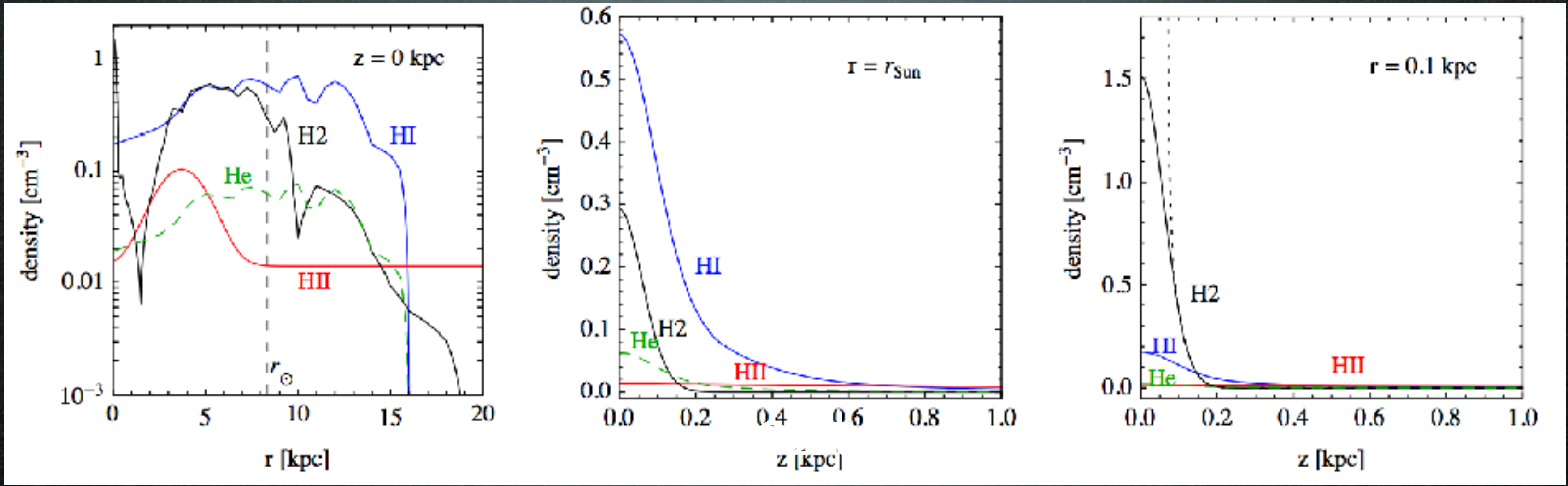
HI = neutral atomic hydrogen

HII = ionized hydrogen

H2 = neutral molecular hydrogen

(He = Helium)

Gas maps

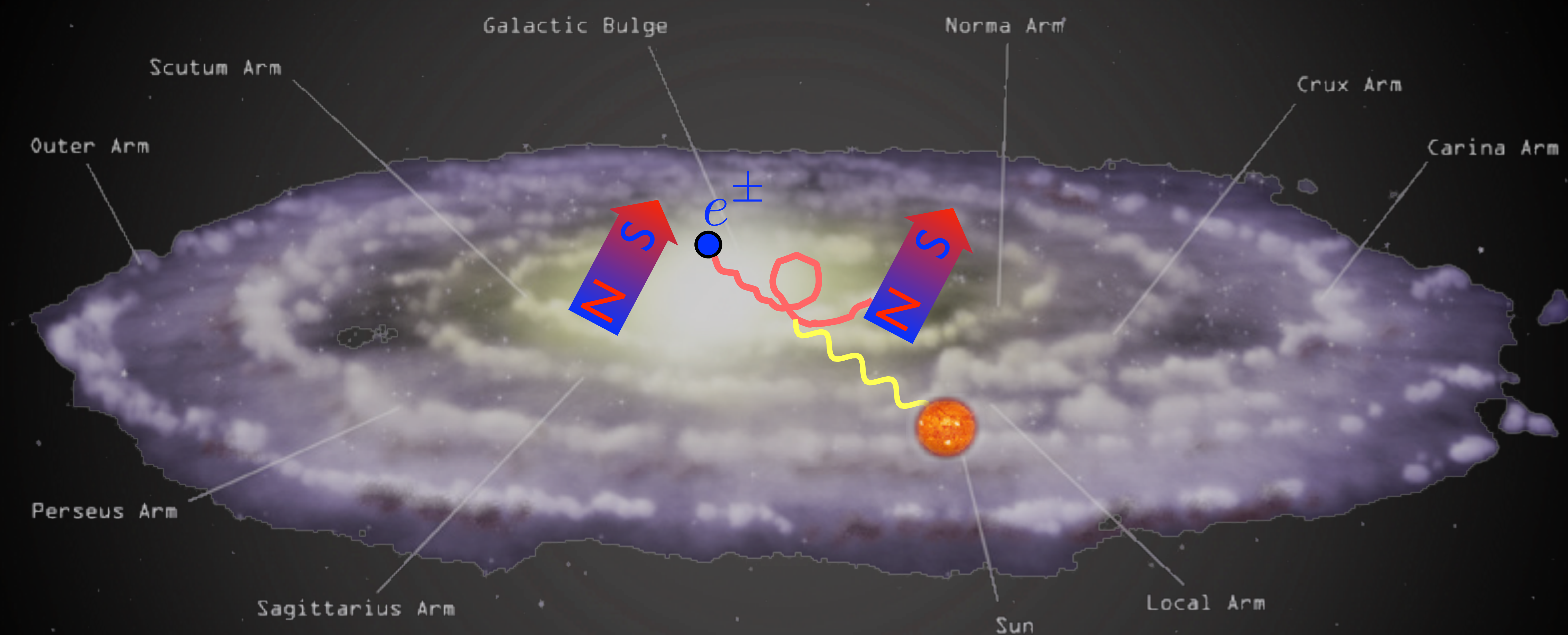


But: inner kpc of the Galaxy is denser (and more uncertain)

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

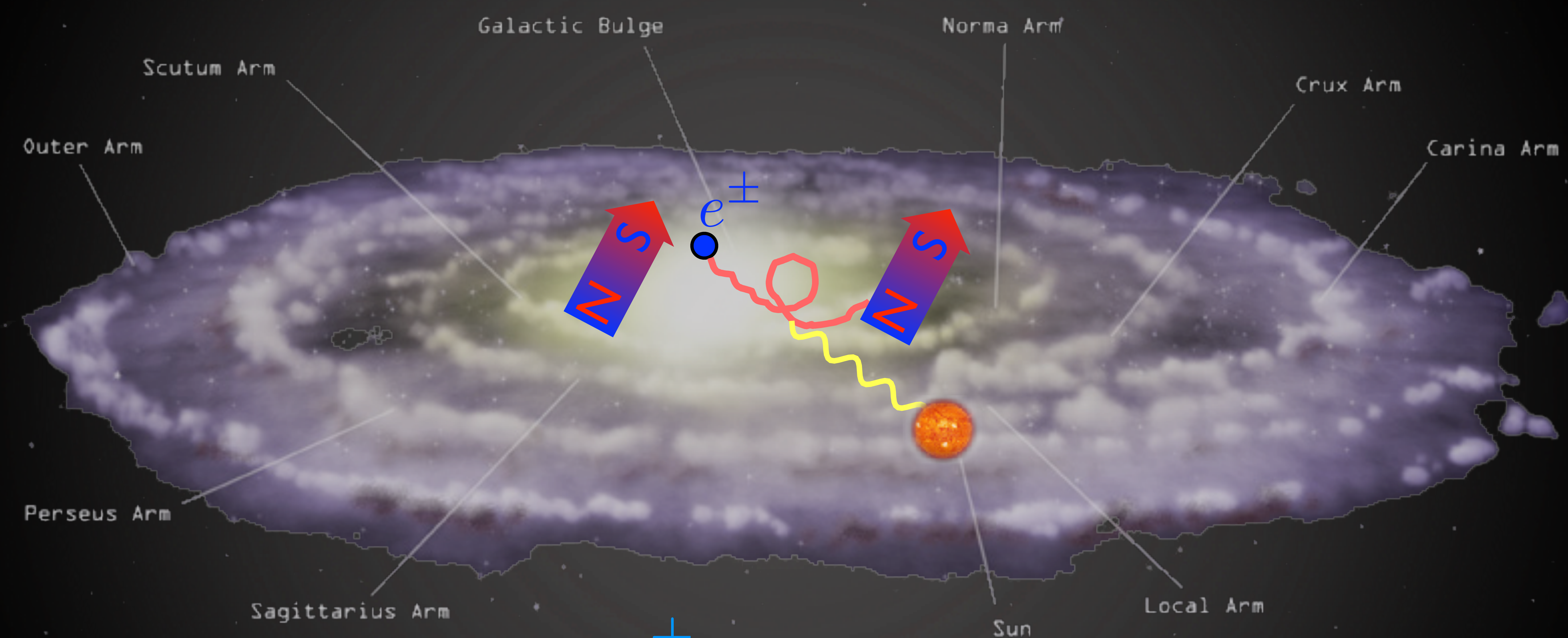
Secondary emission

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



Secondary emission

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



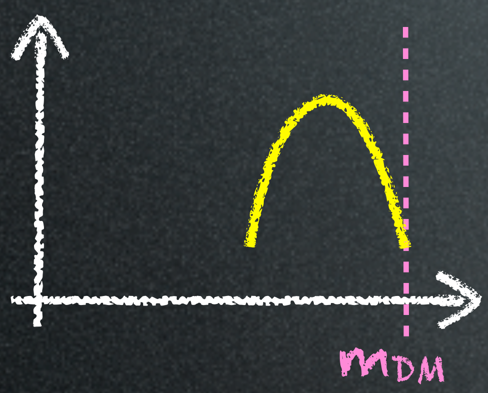
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

How does DM produce γ-rays?

1. prompt emission

1a. continuum

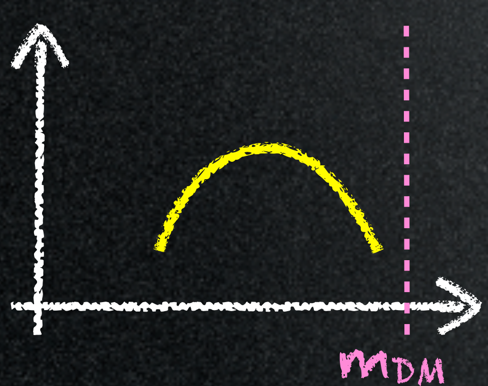


1b. line(s)

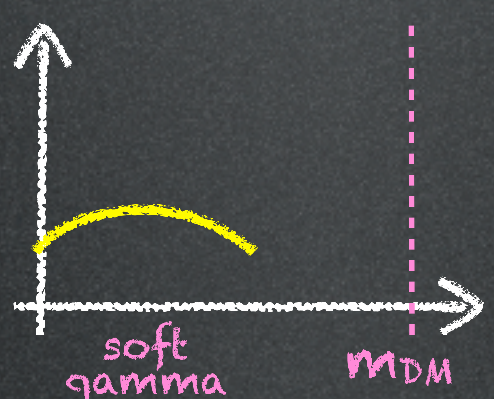
1c. sharp features

2. secondary emission

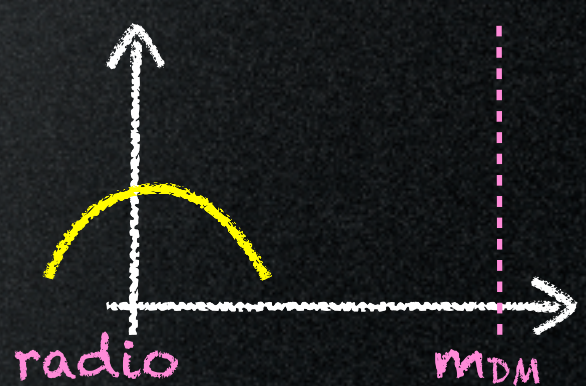
2a. ICS



2b. bremsstrahlung



2c. synchrotron

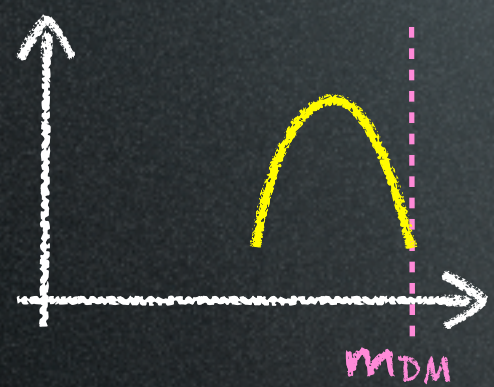


How does DM produce γ-rays?

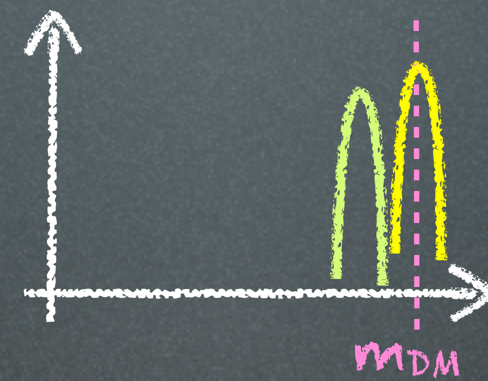
environment-independent

1. prompt emission

1a. continuum



1b. line(s)

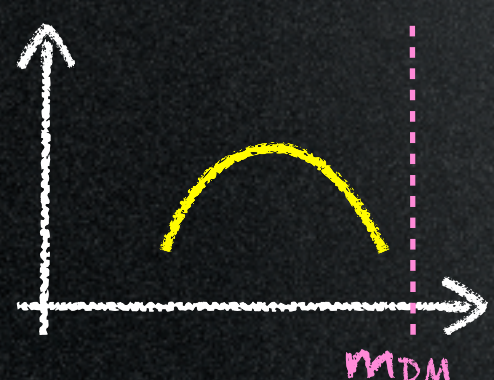


1c. sharp features

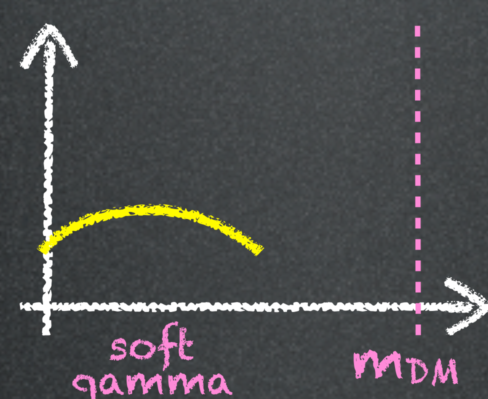
environment-dependent

2. secondary emission

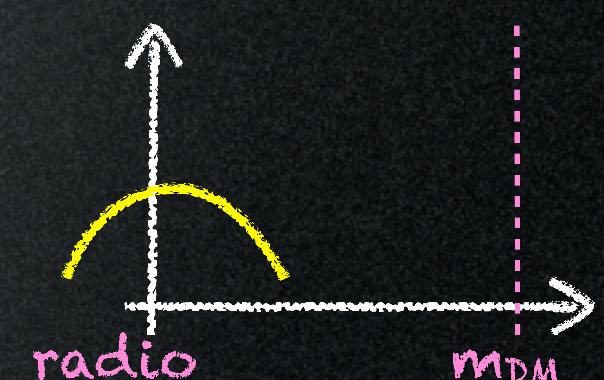
2a. ICS



2b. bremsstrahlung



2c. synchrotron

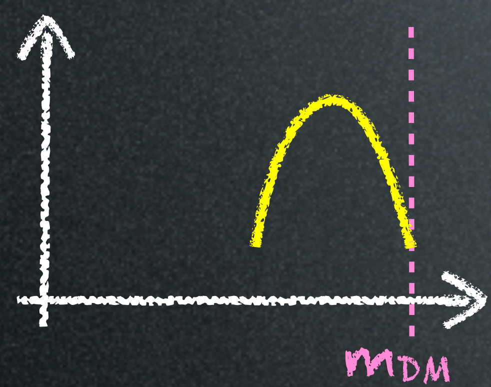


How does DM produce γ-rays?

environment-independent

1. prompt emission

1a. continuum



1b. line(s)

1c. sharp features

1.5. semi-prompt emission from de-excitations

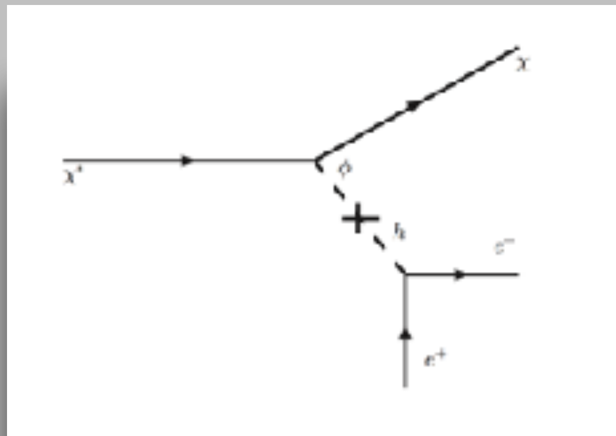
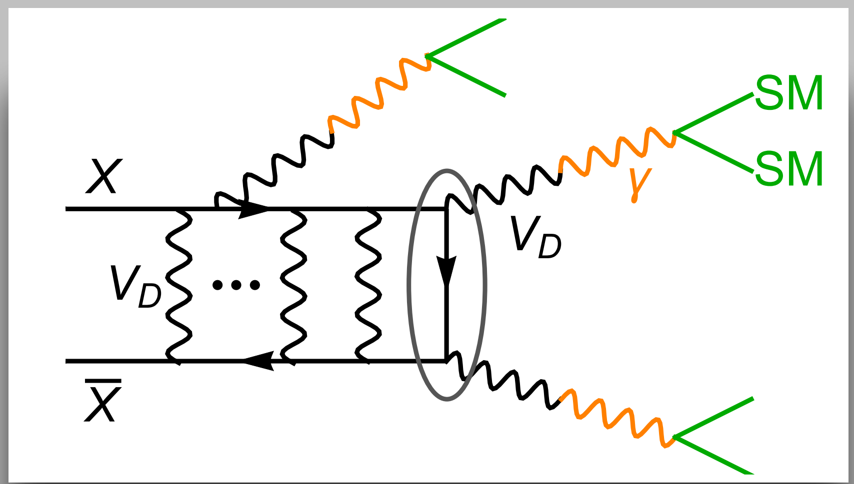


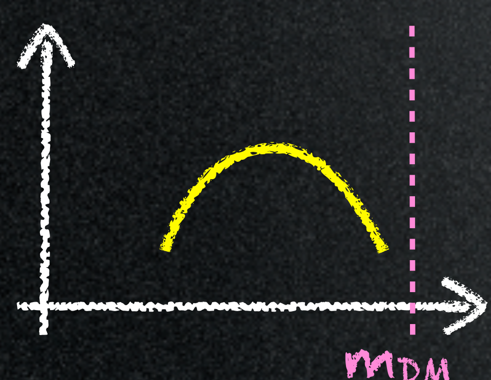
FIG. 5: Decay of the excited state into the ground state.

excited DM (astro-ph/0702587)

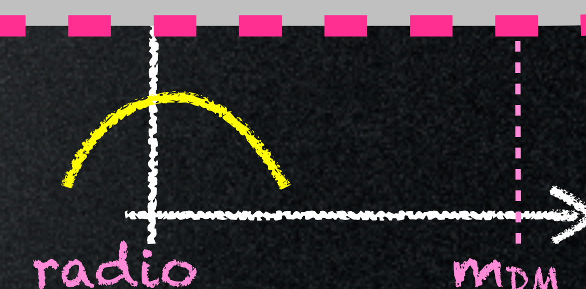


2. secondary em...

2a. ICS



2b.



Dark U(1) DM

inspired by:
Boehm, **Fayet** 2003+

Dark U(1) DM

inspired by:
Boehm, **Fayet** 2003+

$$\mathcal{L} = \bar{X}(i\not{D} - M_{\rm DM})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

parameters are: $\alpha, \epsilon, m_{V_D}, M_{\rm DM}$

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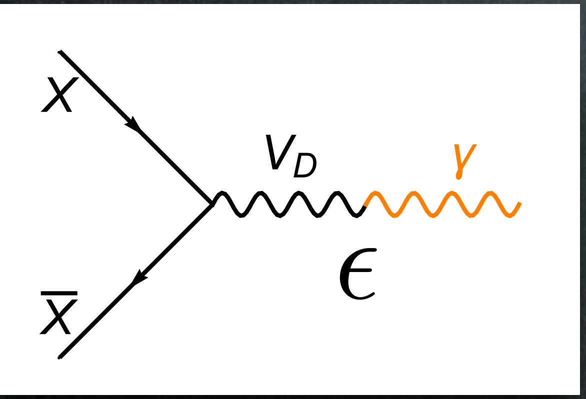

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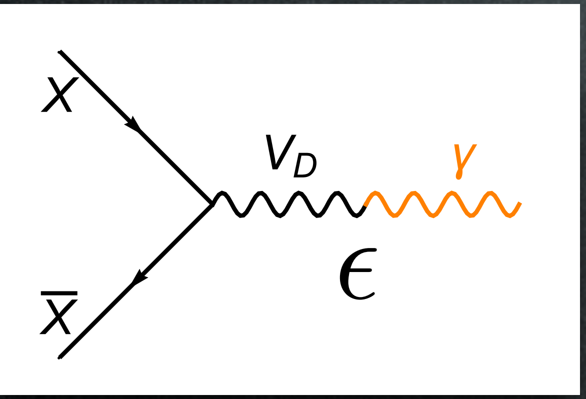

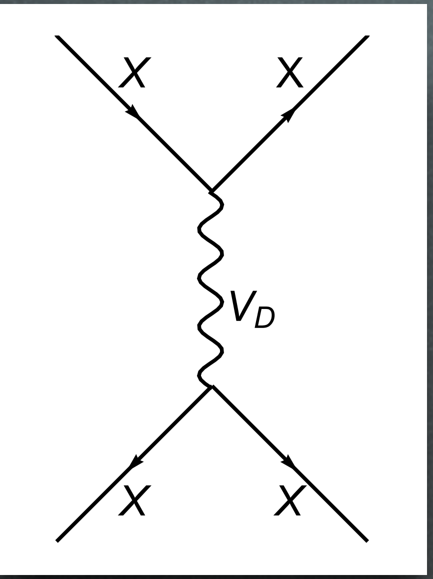

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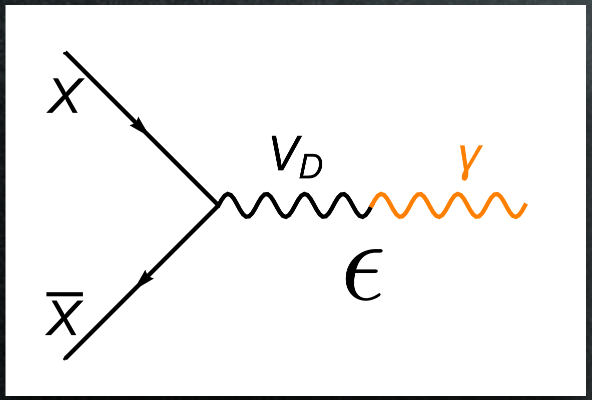

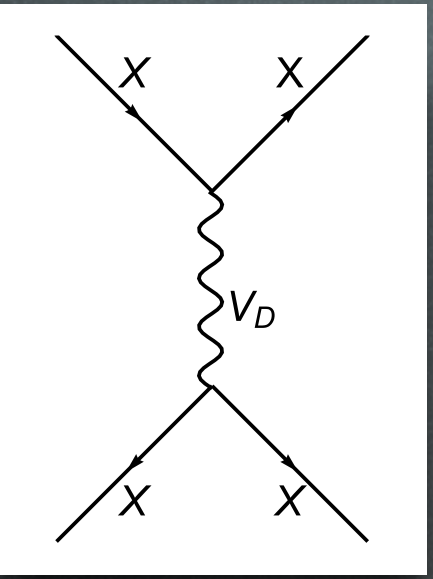

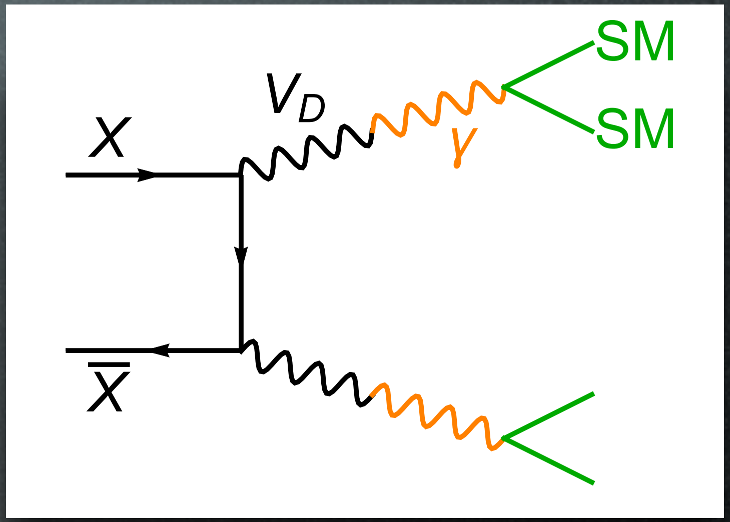

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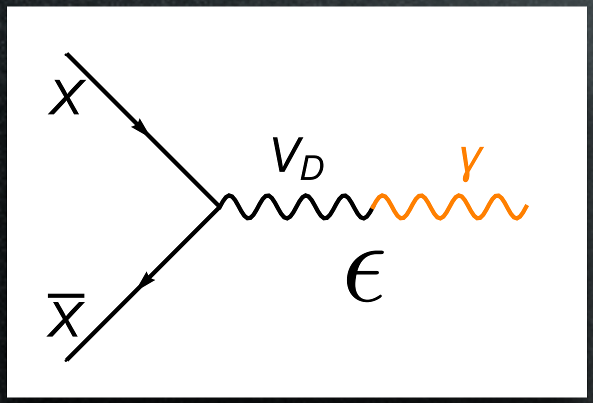

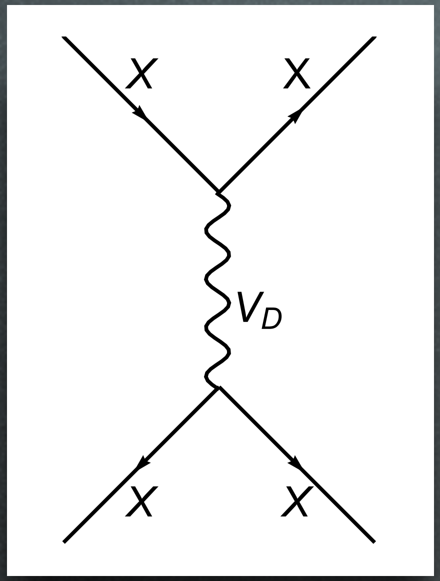

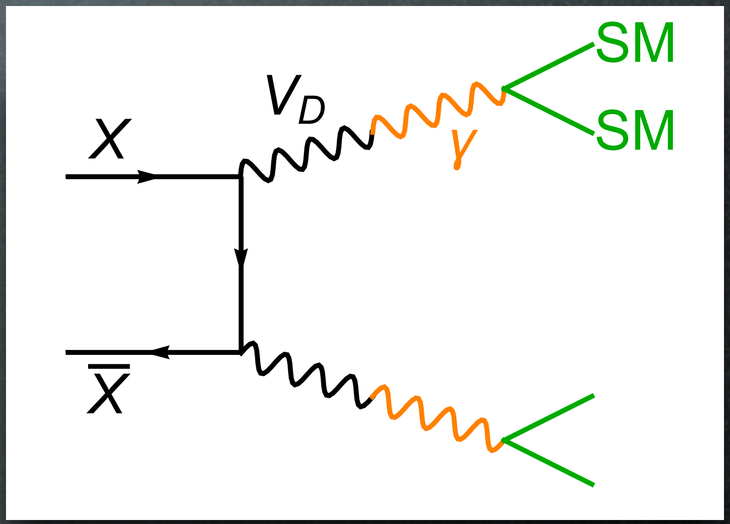

size of the XX system

If $\alpha M/m_V \gtrsim 1$, the force is long range:

range

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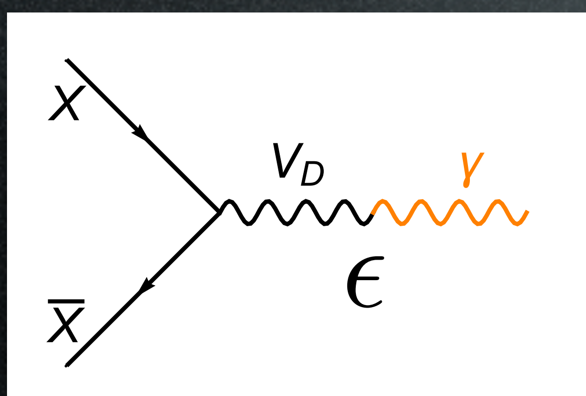

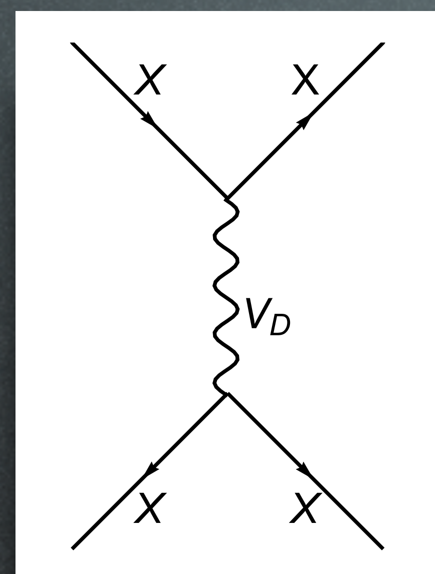

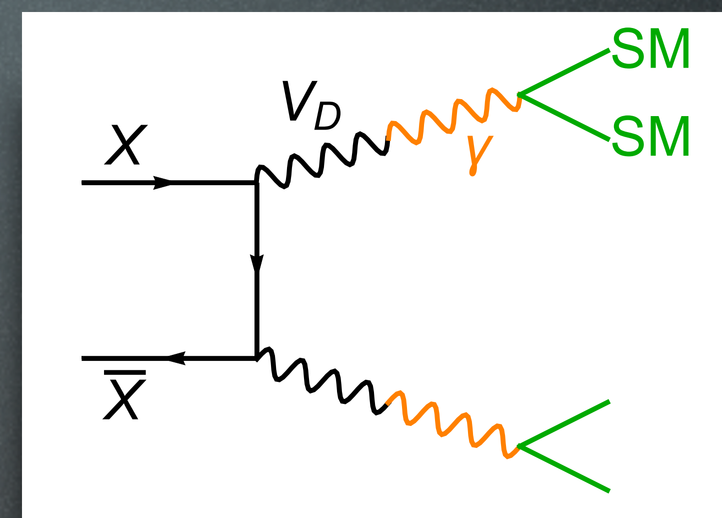

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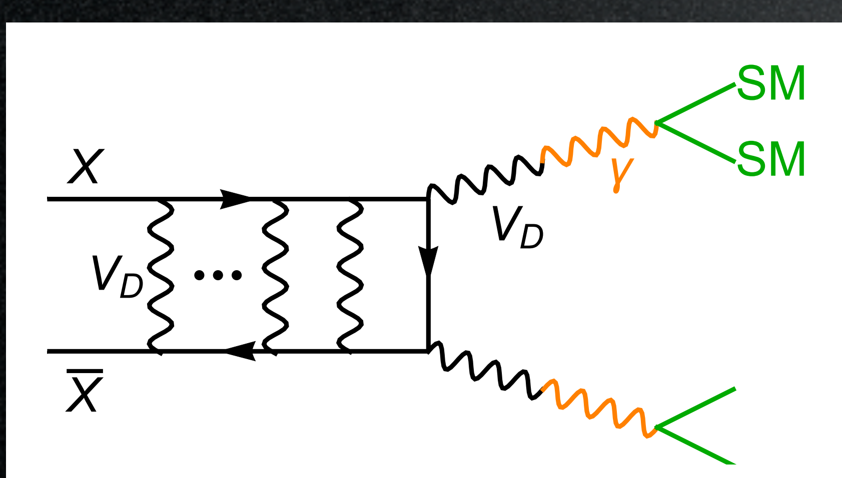
Sommerfeld enhanced



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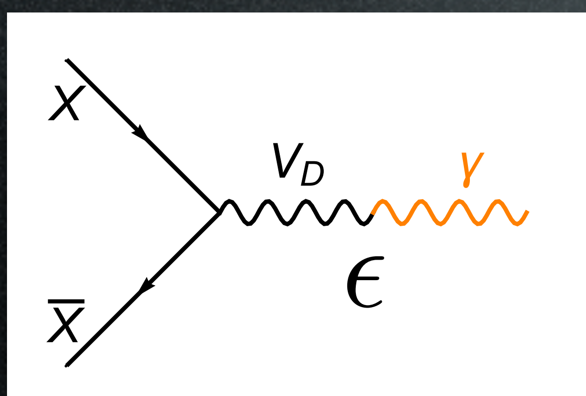

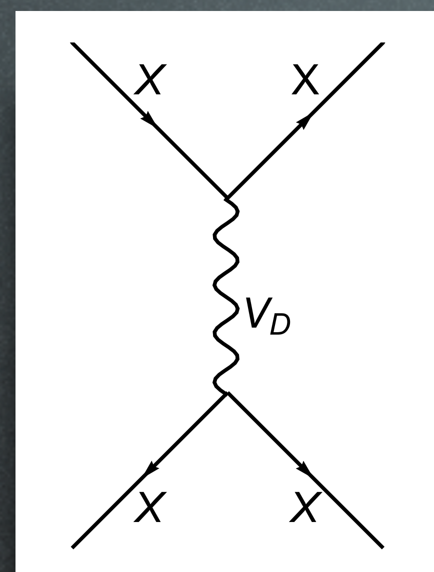

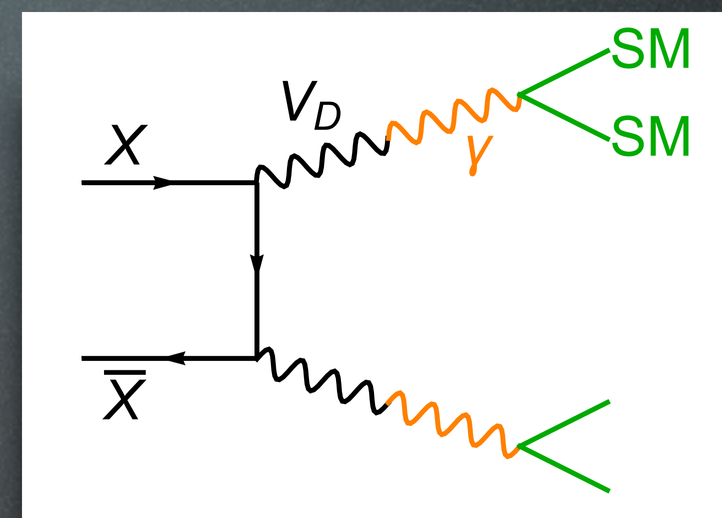

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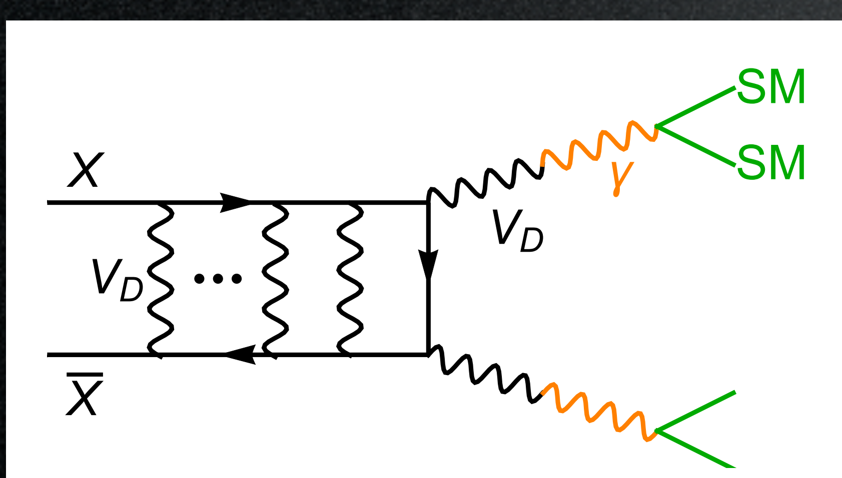
Sommerfeld enhanced

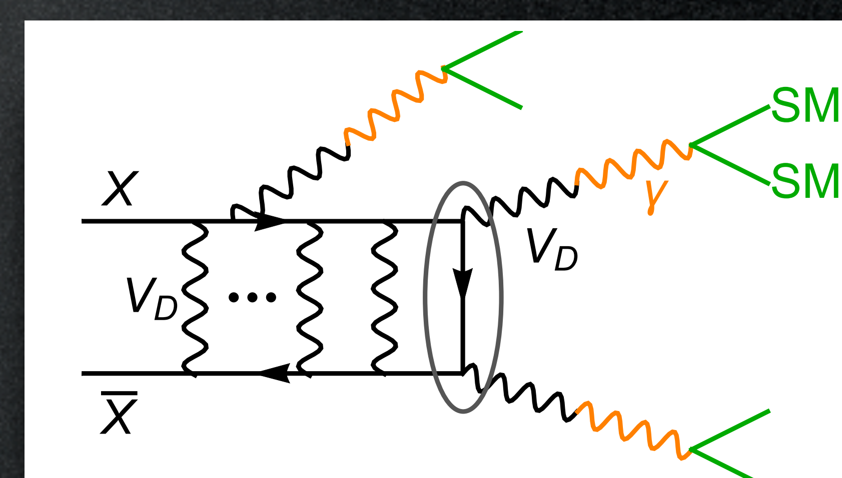
binding energy of the XX system

If $\alpha^2 M/2m_V \gtrsim 1$, bound states form

emitted dark photon



Petraki+ 2015+,



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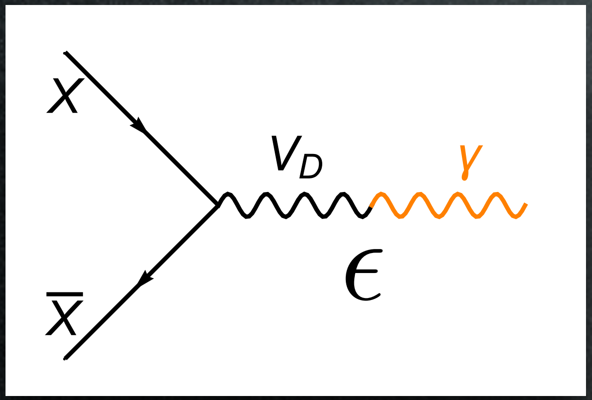

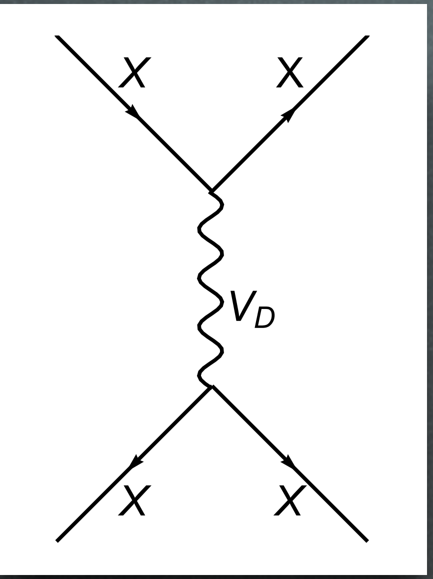

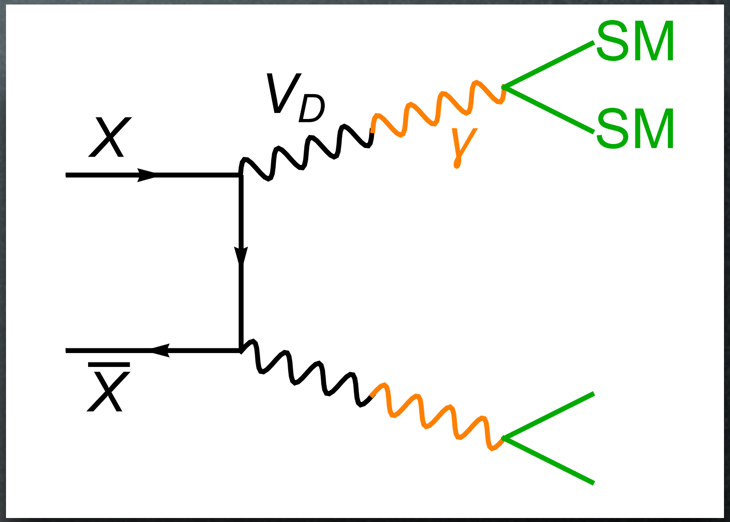

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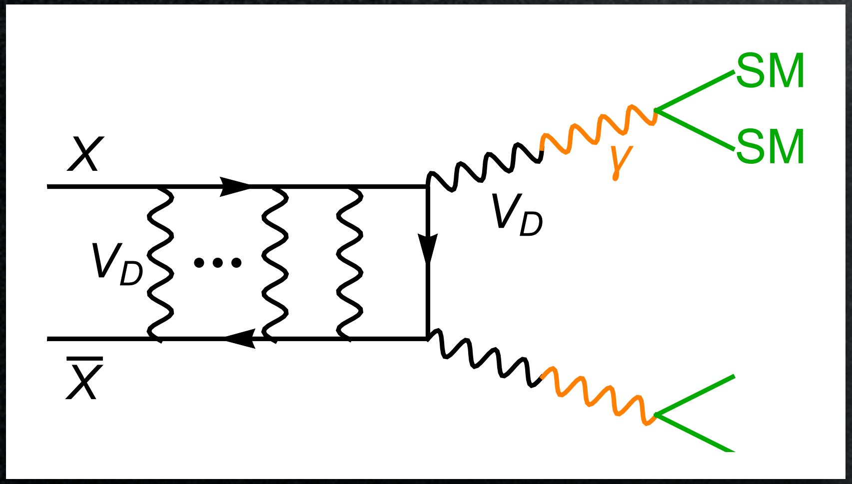

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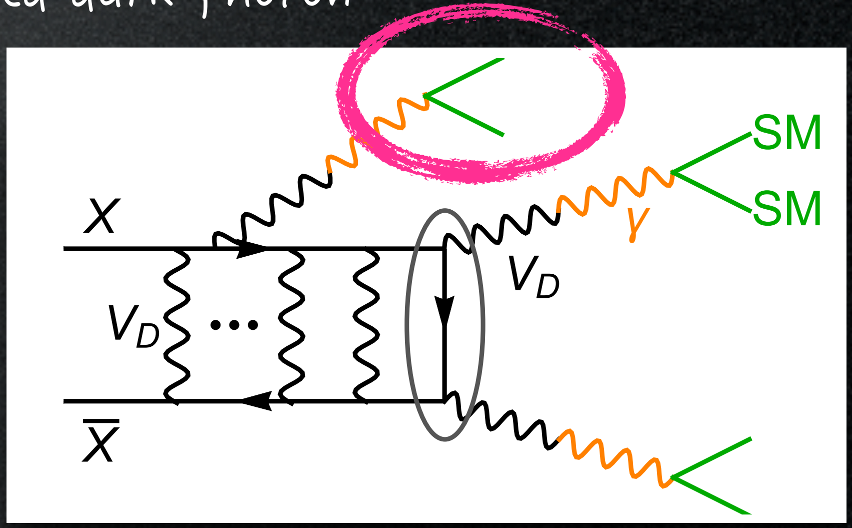


Wrapping up

How do we see DM with an MeV telescope?

1. Prompt gamma-ray emission of MeV DM
   - + traces DM distribution
   - + spectral features

2. Secondary gamma-ray emission of light 'WIMP' DM
   - \- does not trace DM distribution
   - \- smooth spectra

3. De-excitation gamma-ray emissions
   - + traces DM distribution
   - + spectral features

Some recent studies

Bartels, Gaggero, Weniger 1703.02546

- $\chi\chi \to \gamma\gamma$: A photon pair
- $\chi\chi \to \gamma\pi^0$: A neutral pion and a photon
- $\chi\chi \to \pi^0\pi^0$: Neutral pions
- $\chi\chi \to \bar{\ell}\ell$: Light leptons (with $\ell = e, \mu$)
- $\chi\chi \to \phi\phi$ and $\phi \to e^+e^-$: Cascade annihilation

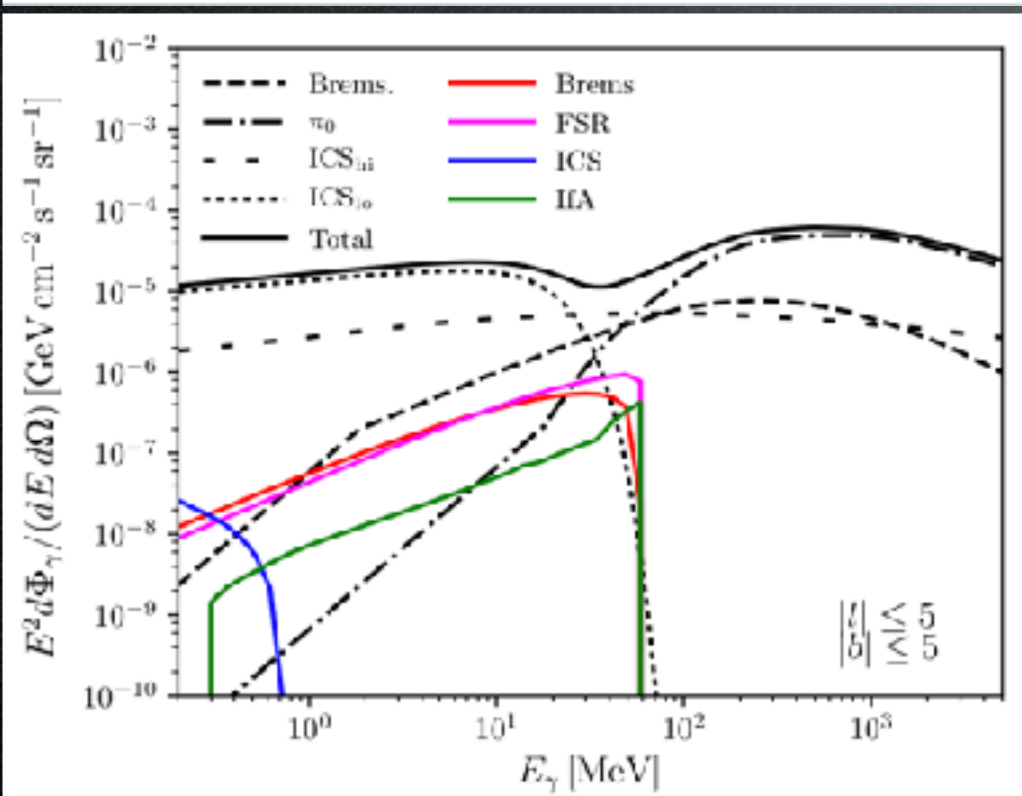
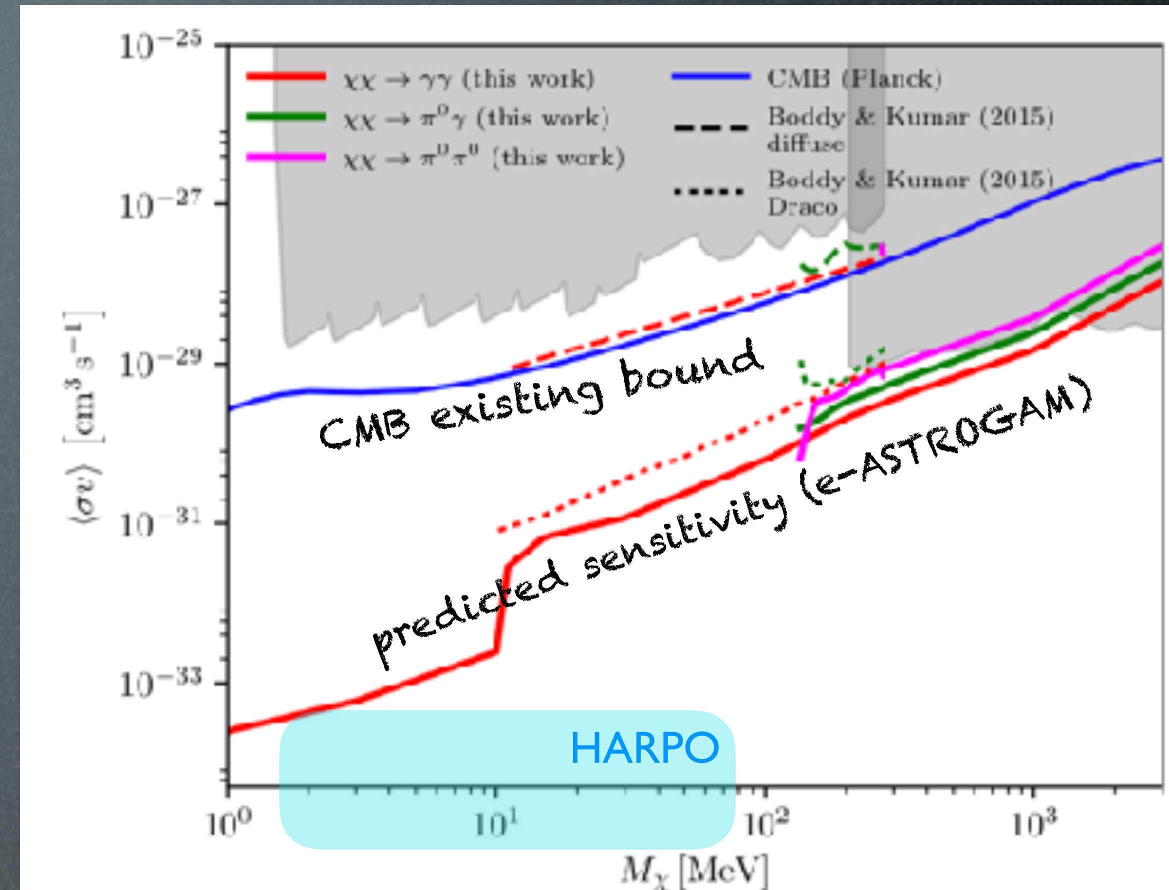
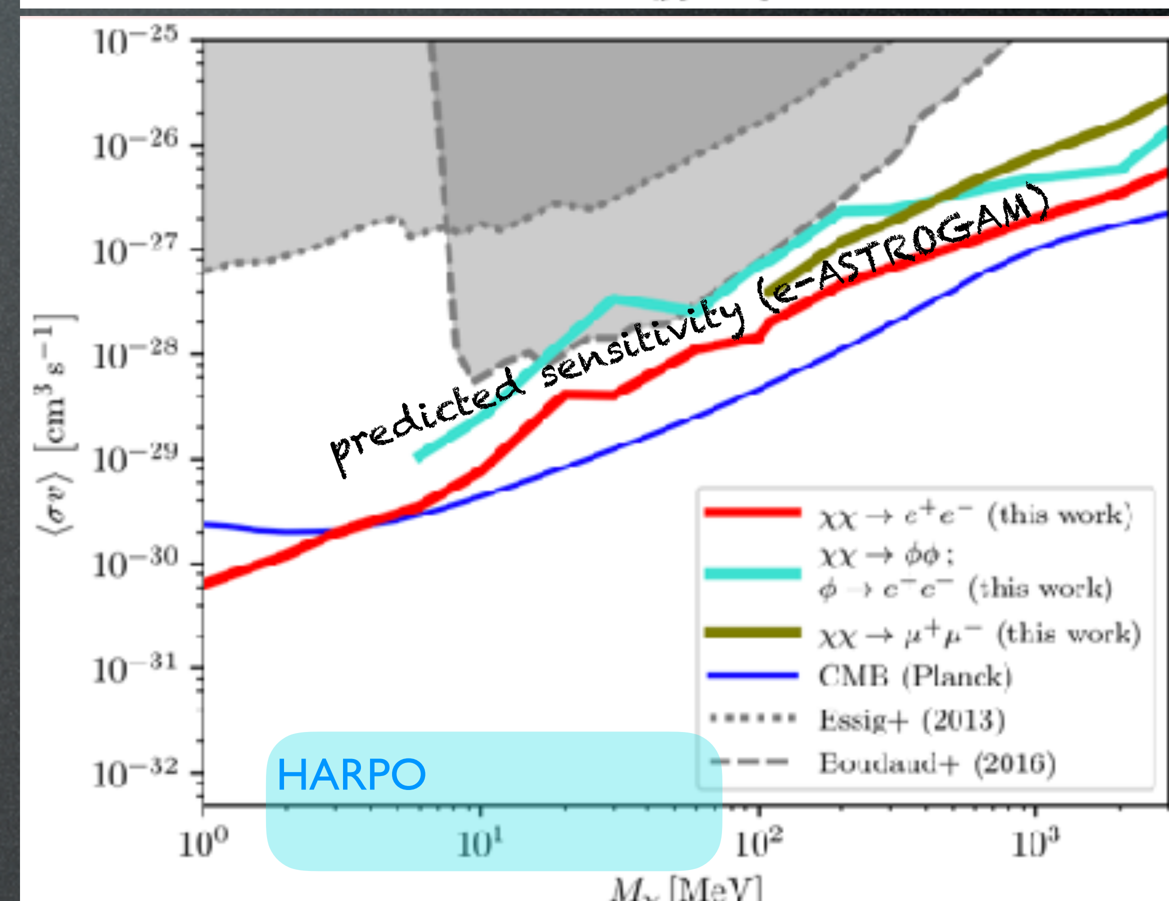


FIG. 2: γ-ray spectrum resulting from $\chi\chi \to e^+e^-$ with $\langle\sigma v\rangle = 10^{-28}\,\mathrm{cm^3\,s^{-1}}$ in the inner $10° \times 10°$ of the

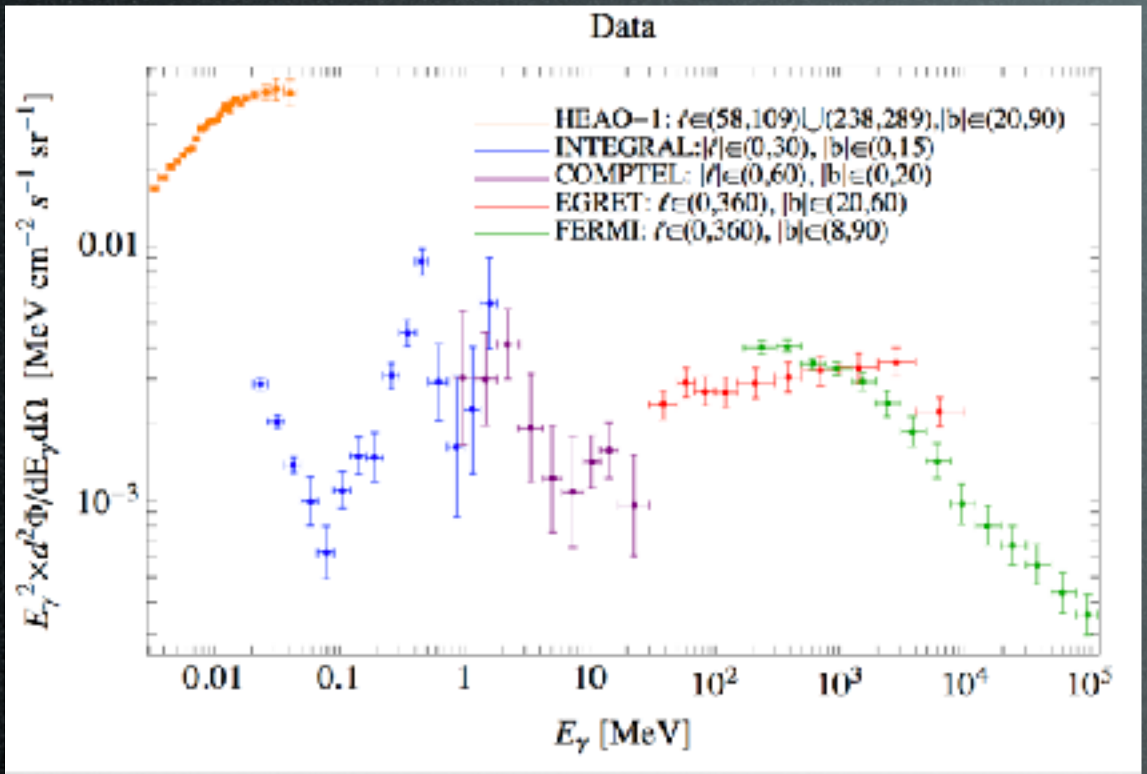
	e-ASTROGAM	COMPAIR	ADEPT
Compton domain			
Energy range [MeV]	0.3–10	0.2–10	
$\Delta E/E$	1.3%	2%–6%	–
A_{eff} [cm^2]	50–560	50 – 250	–
FoV [sr]	2.9	3	–
Pair-conversion domain			
Energy range [MeV]	10–3000	10–500	5–200
$\Delta E/E$	20–30%	12%	30%
A_{eff} [cm^2]	215–1810	20–1200	50–730
FoV [sr]	2.5	3	3





Some recent studies

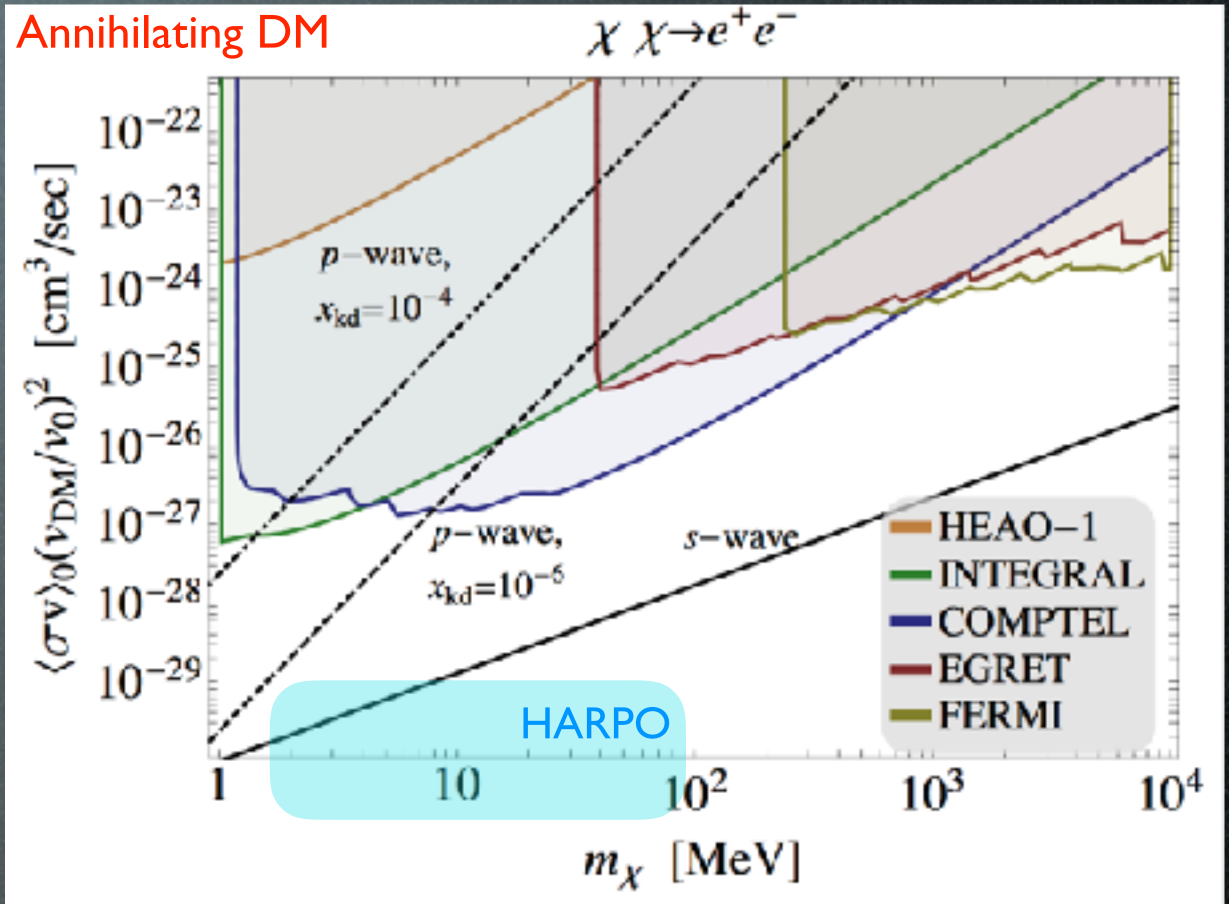
Essig, Kuflik, McDermott, Volansky et al., 1309.4091

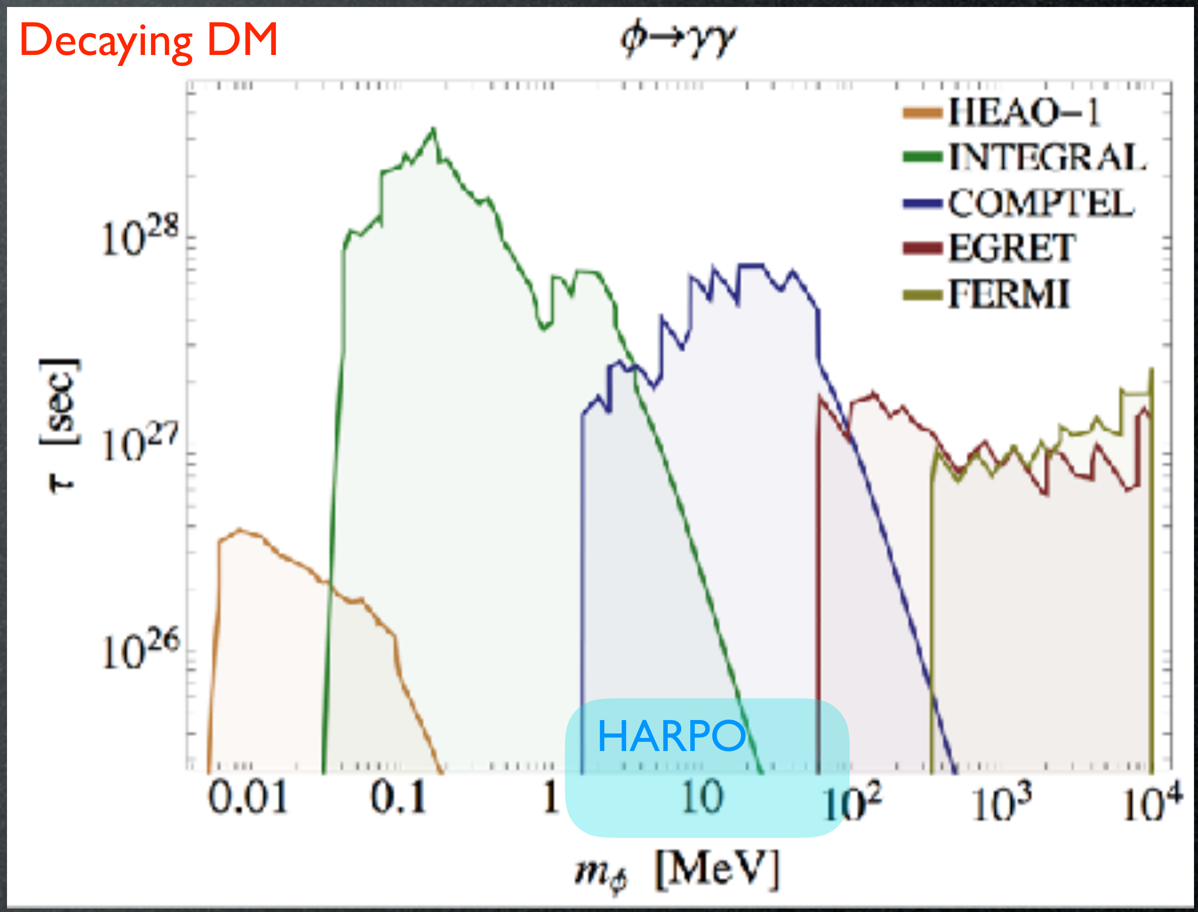


Experiment	E_{min}	E_{max}	Ω	$J_{D(A)}^{NFW}$	$J_{D(A)}^{Moore}$	$J_{D(A)}^{isoT}$	$J_{D(A)}^{Ein,0.17}$	$J_{D(A)}^{Ein,0.12}$	$J_{D(A)}^{Ein,0.20}$
HEAO-1 [63]	4 keV	30 keV	$58 \le \ell \le 109^\circ \cup$ $238 \le \ell \le 289^\circ$, $20^\circ \le \lvert b\rvert \le 90^\circ$	3.88 (2.16)	4.06 (2.22)	4.33 (2.24)	3.79 (2.09)	3.76 (2.05)	3.80 (2.11)
INTEGRAL [64]	20 keV	1 MeV	$\lvert\ell\rvert \le 30^\circ$, $\lvert b\rvert \le 15^\circ$	3.65 (18.4)	3.80 (24.4)	2.77 (5.08)	4.20 (30.9)	4.73 (59.9)	3.95 (23.2)
COMPTEL [65]	1 MeV	15 MeV	$\lvert\ell\rvert \le 60^\circ$, $\lvert b\rvert \le 20^\circ$	6.82 (23.1)	7.03 (29.1)	5.91 (8.69)	7.48 (36.4)	8.10 (66.0)	7.19 (28.3)
EGRET [66]	20 MeV	6 GeV	$0 \le \ell \le 360^\circ$, $20^\circ \le \lvert b\rvert \le 60^\circ$	13.0 (10.9)	13.5 (11.0)	14.0 (10.1)	12.9 (11.5)	13.0 (12.0)	12.9 (11.3)
Fermi [67]	200 MeV	10 GeV	$0 \le \ell \le 360^\circ$, $8^\circ \le \lvert b\rvert \le 90^\circ$	21.9 (22.0)	22.8 (22.5)	23.3 (17.9)	22.0 (25.4)	22.3 (28.5)	21.9 (24.0)

‘Obtain conservative bounds by requiring that the predicted count from the DM signal in each bin does not exceed the observed central value plus twice the error bar’

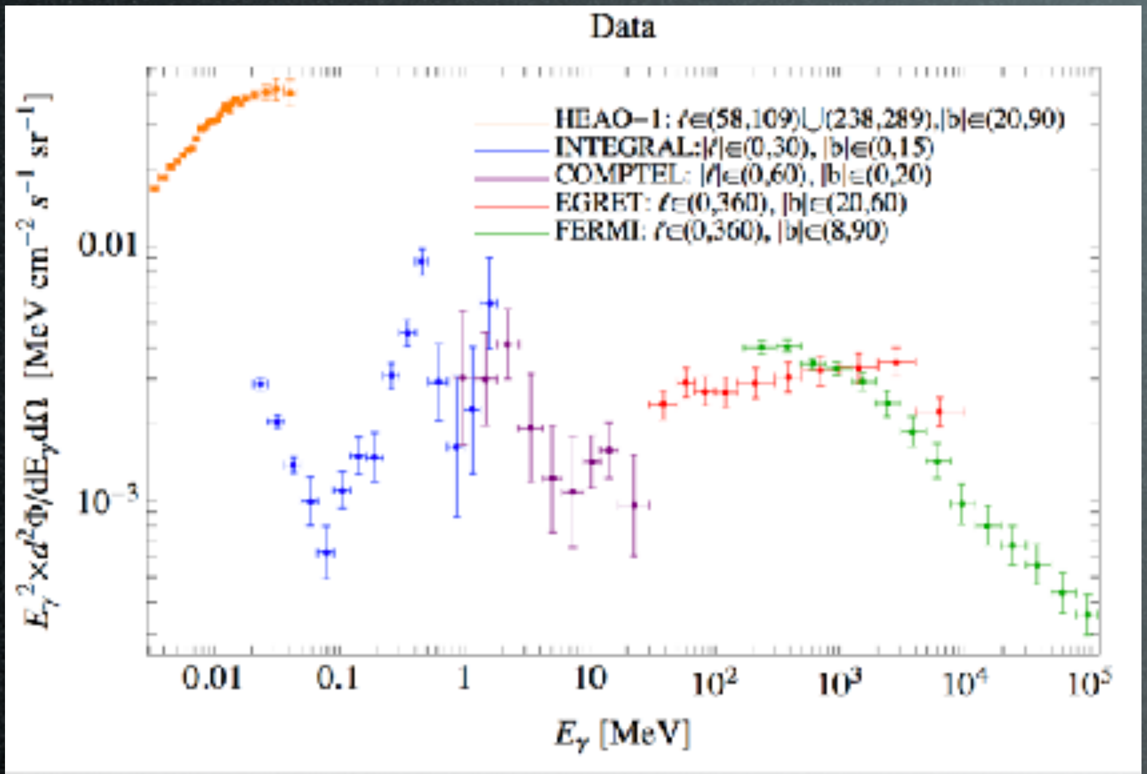
NB: prompt emission only





Some recent studies

Essig, Kuflik, McDermott, Volansky et al., 1309.4091



Experiment	E_{min}	E_{max}	Ω	$J^{NFW}_{D(A)}$	$J^{Moore}_{D(A)}$	$J^{IsoT}_{D(A)}$	$J^{Ein,0.17}_{D(A)}$	$J^{Ein,0.12}_{D(A)}$	$J^{Ein,0.20}_{D(A)}$
HEAO-1 [63]	4 keV	30 keV	$58 \le \ell \le 109° \cup 238 \le \ell \le 289°$, $20° \le \lvert b\rvert \le 90°$	3.88 (2.16)	4.06 (2.22)	4.33 (2.24)	3.79 (2.09)	3.76 (2.05)	3.80 (2.11)
INTEGRAL [64]	20 keV	1 MeV	$\lvert\ell\rvert \le 30°$, $\lvert b\rvert \le 15°$	3.65 (18.4)	3.80 (24.4)	2.77 (5.08)	4.20 (30.9)	4.73 (59.9)	3.95 (23.2)
COMPTEL [65]	1 MeV	15 MeV	$\lvert\ell\rvert \le 60°$, $\lvert b\rvert \le 20°$	6.82 (23.1)	7.03 (29.1)	5.91 (8.69)	7.48 (36.4)	8.10 (66.0)	7.19 (28.3)
EGRET [66]	20 MeV	6 GeV	$0 \le \ell \le 360°$, $20° \le \lvert b\rvert \le 60°$	13.0 (10.9)	13.5 (11.0)	14.0 (10.1)	12.9 (11.5)	13.0 (12.0)	12.9 (11.3)
Fermi [67]	200 MeV	10 GeV	$0 \le \ell \le 360°$, $8° \le \lvert b\rvert \le 90°$	21.9 (22.0)	22.8 (22.5)	23.3 (17.9)	22.0 (25.4)	22.3 (28.5)	21.9 (24.0)

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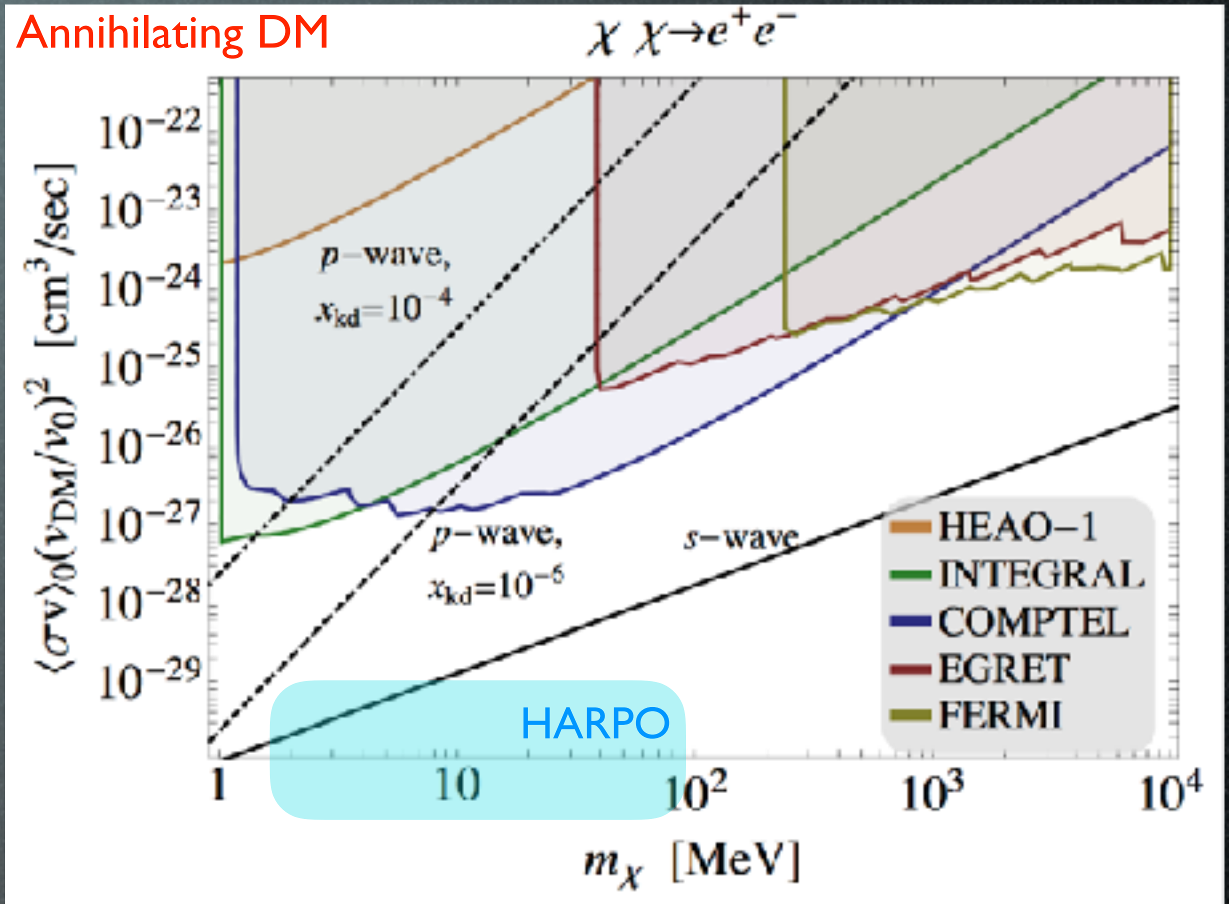
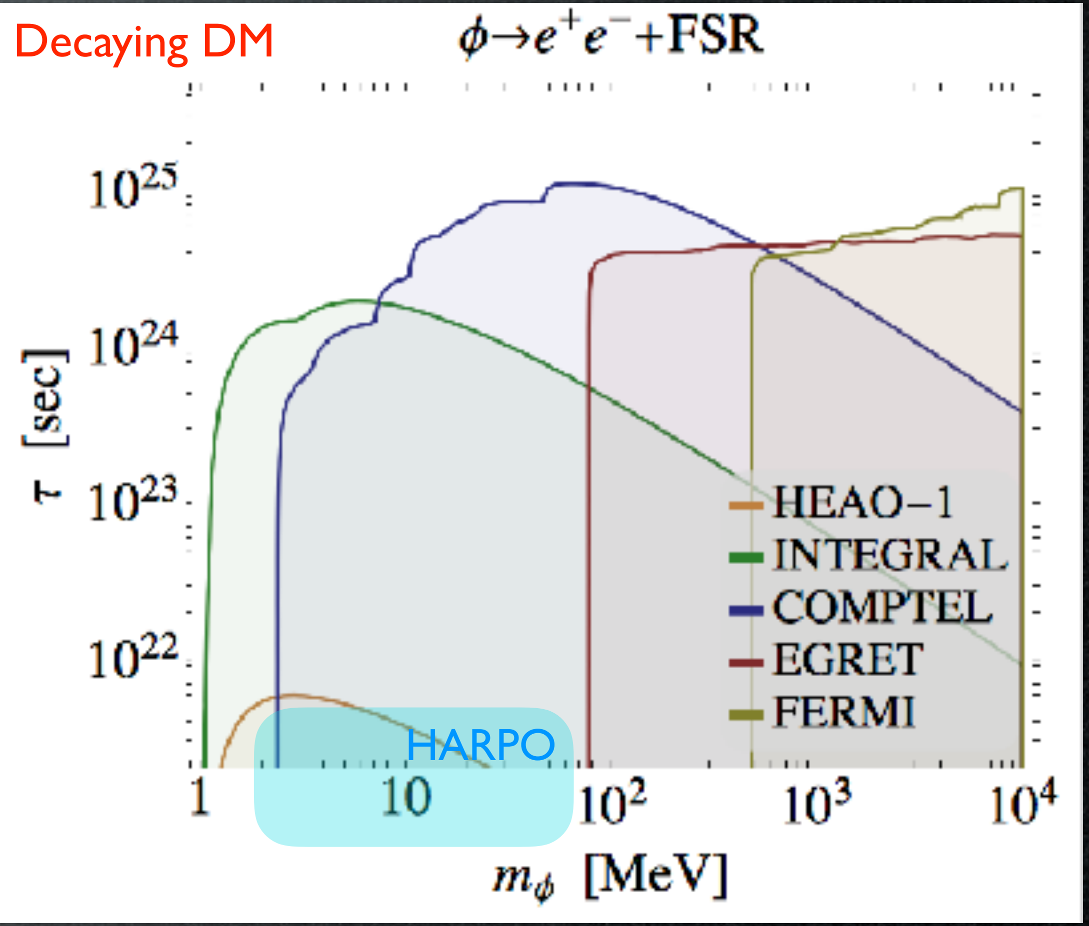
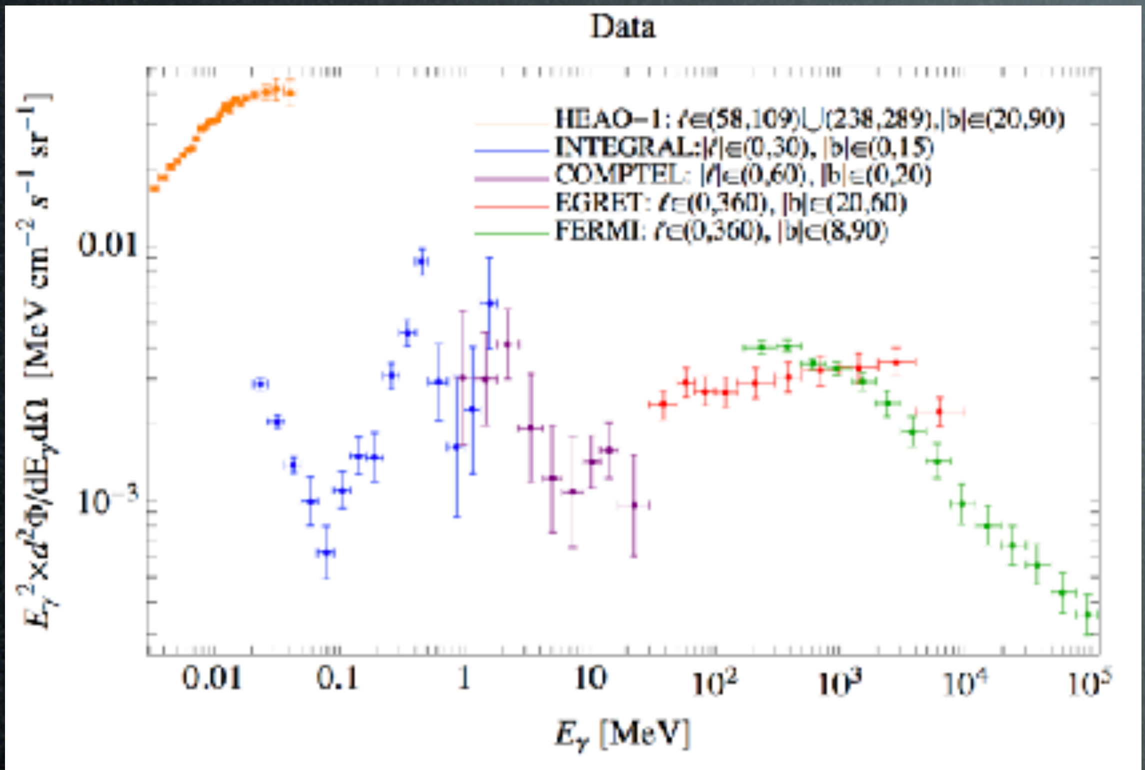




Some recent studies

Essig, Kuflik, McDermott, Volansky et al., 1309.4091



Experiment	E_{min}	E_{max}	Ω	$J_{D(A)}^{NFW}$	$J_{D(A)}^{Moore}$	$J_{D(A)}^{IsoT}$	$J_{D(A)}^{Ein,0.17}$	$J_{D(A)}^{Ein,0.12}$	$J_{D(A)}^{Ein,0.20}$
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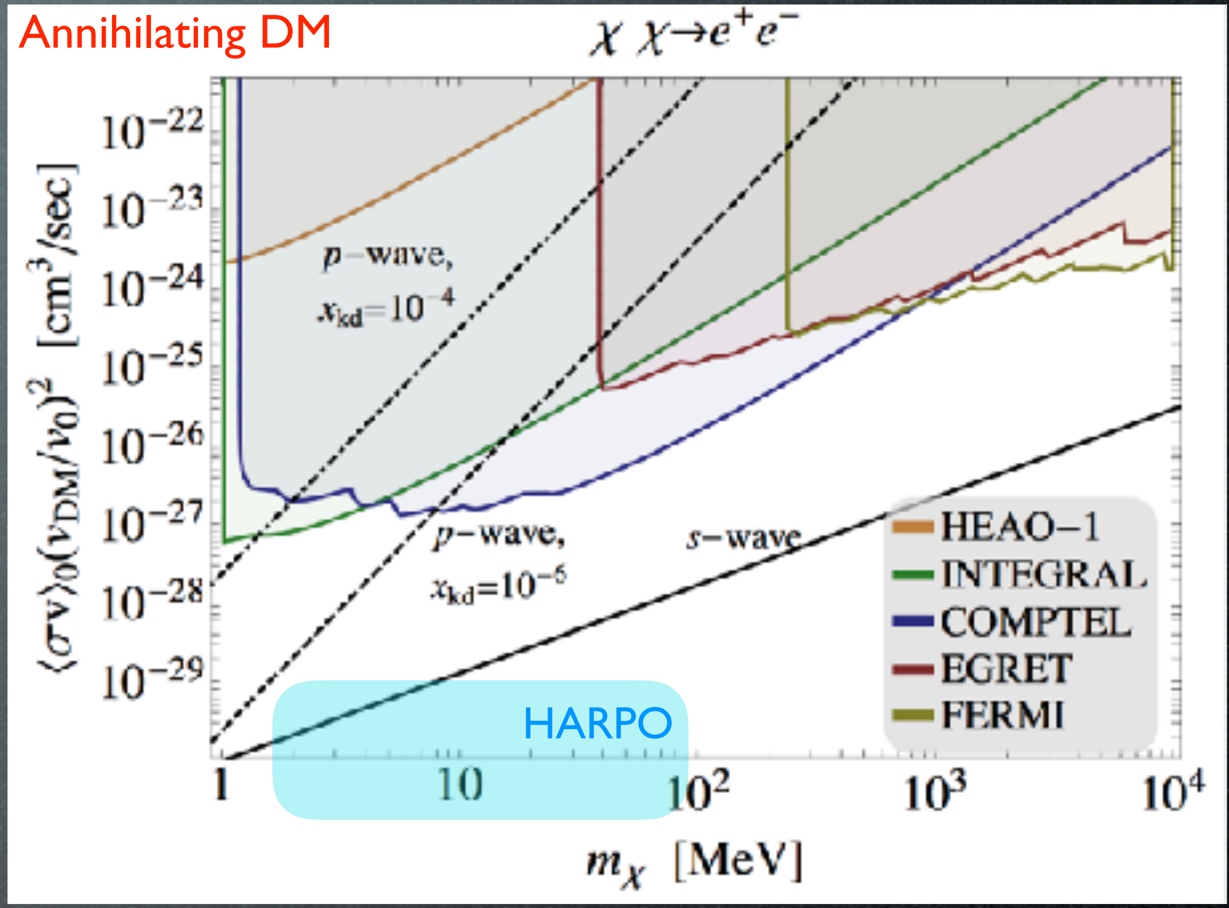
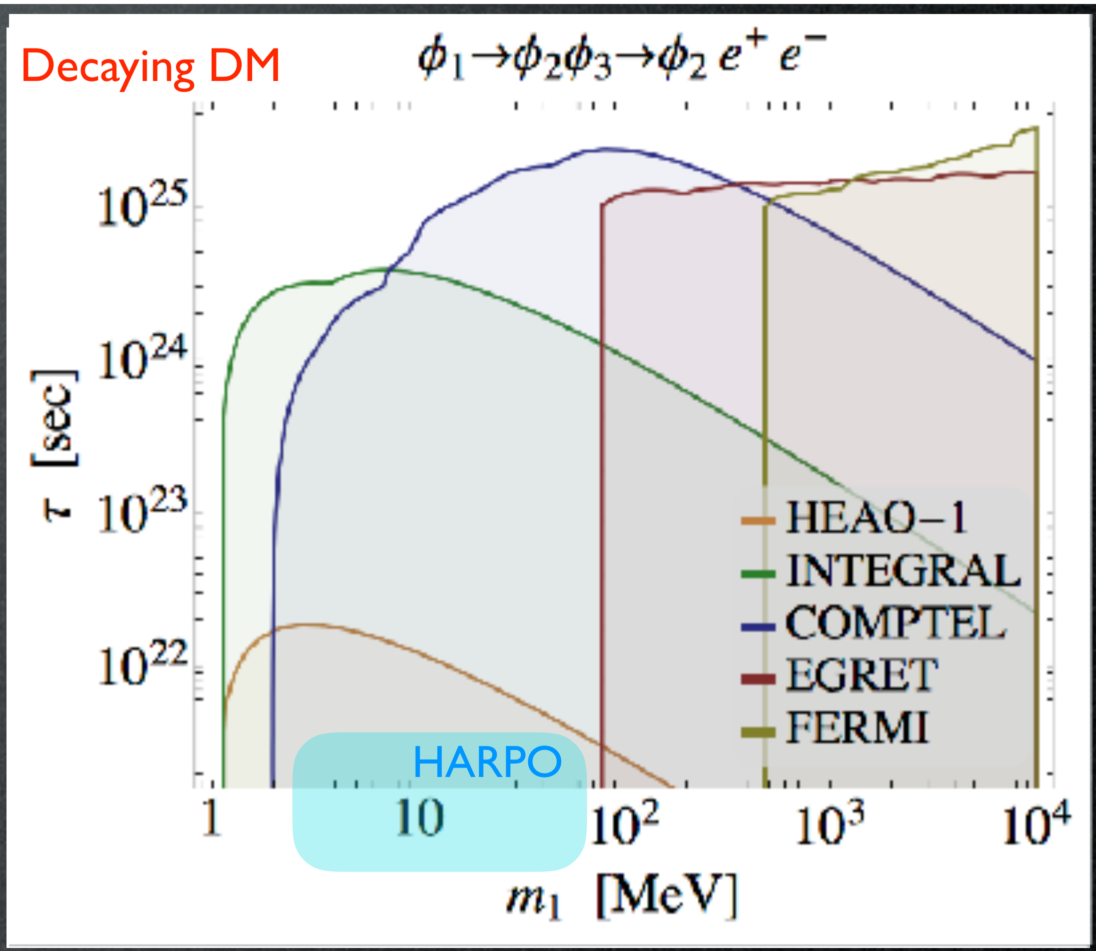
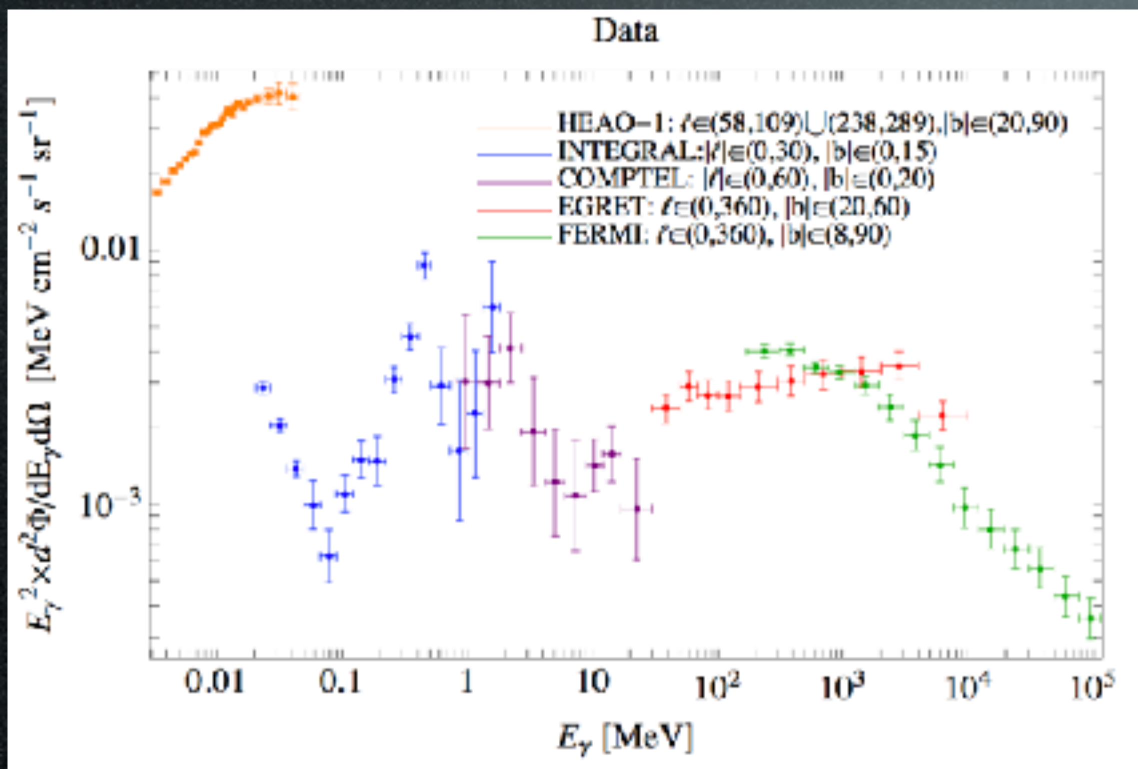




Some recent studies

Essig, Kuflik, McDermott, Volansky et al.,
1309.4091



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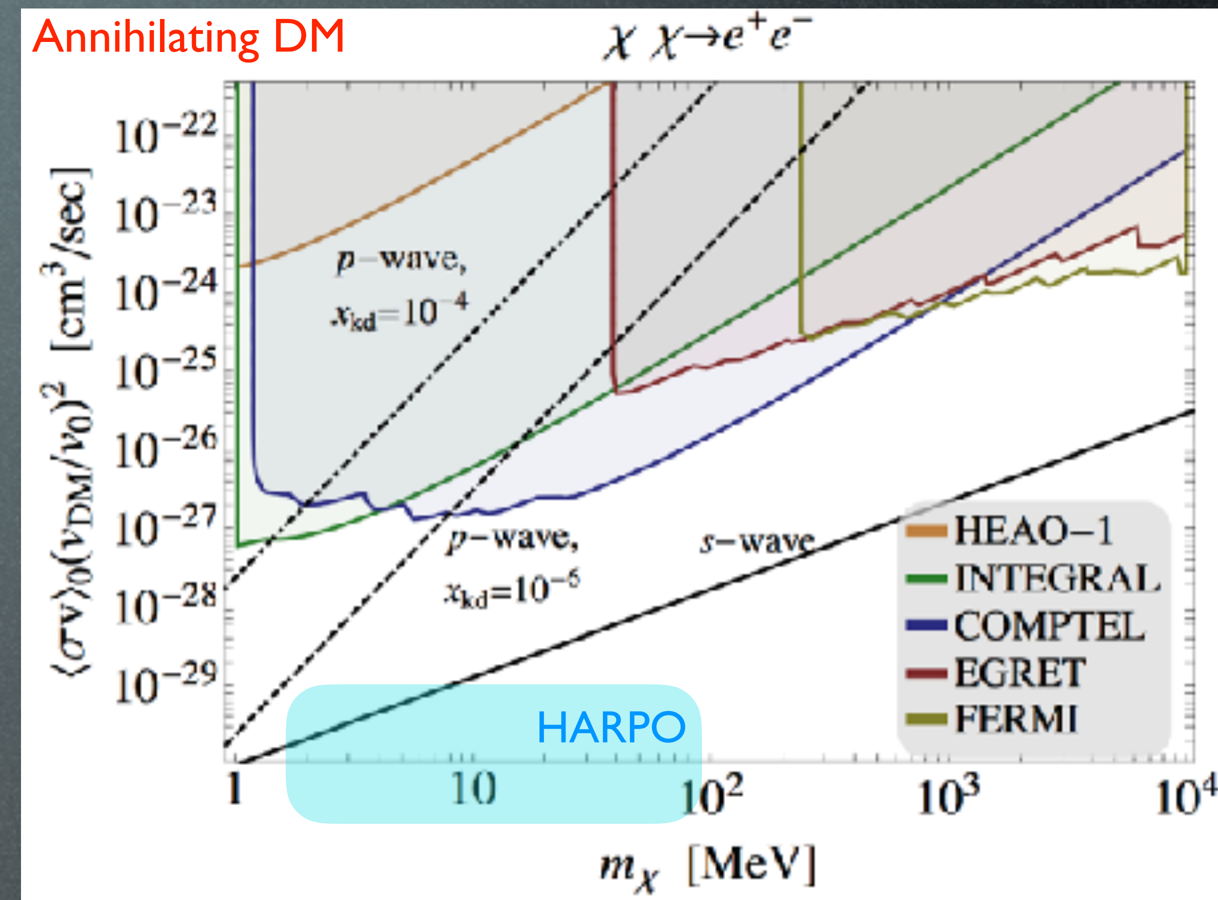

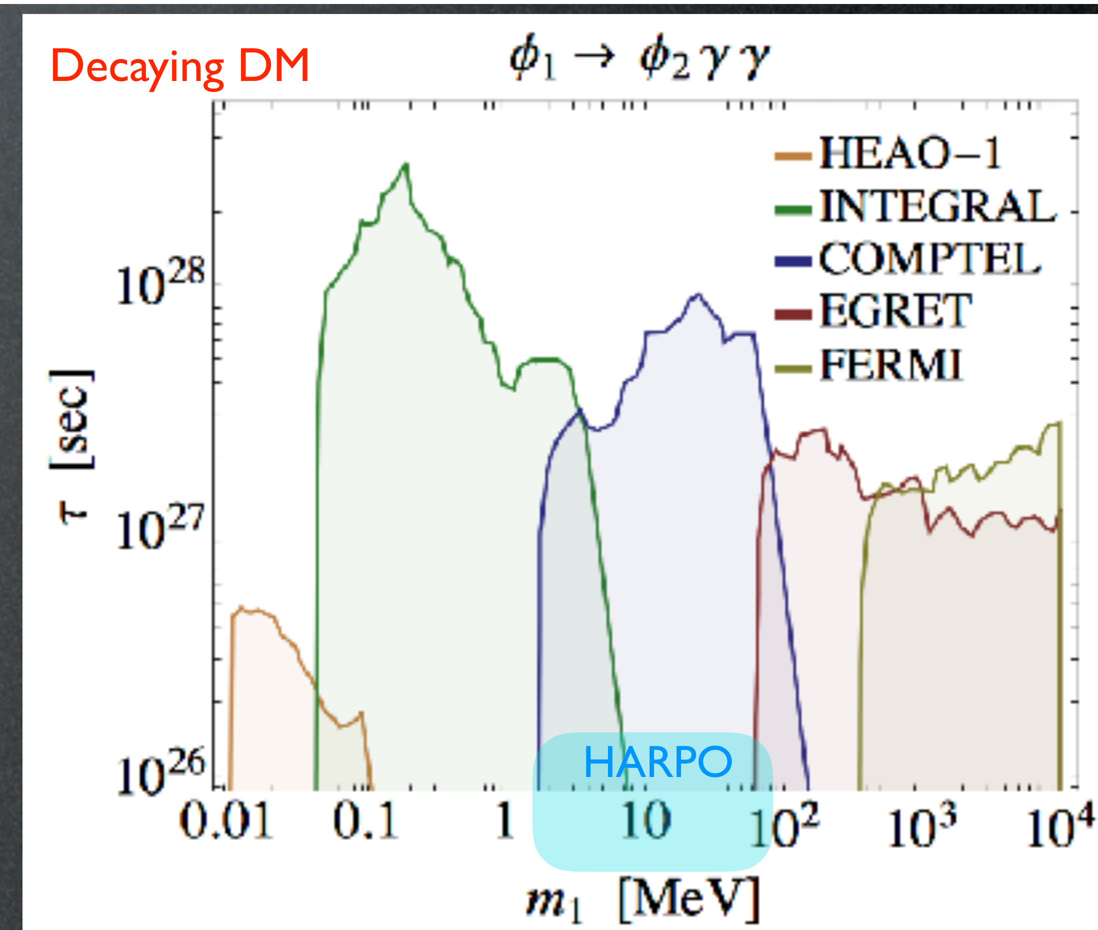

Some recent studies

Boddy, Kumar 1504.04024

(i) $\gamma\gamma$: Accessible at all energies.

(ii) $\gamma\pi^0$: Accessible for $\sqrt{s} > m_{\pi^0}$.

(iii) $\pi^0\pi^0$: Accessible for $\sqrt{s} \geq 2m_{\pi^0}$.

(iv) $\pi^+\pi^-$: Accessible for $\sqrt{s} \geq 2m_{\pi^\pm}$.

(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$.

Detector	Source	Energy Range [MeV]	ϵ	PSF	$A_{\rm eff}$ [cm^2]
ACT *	[8]	0.2–10	1%	1°	1000
GRIPS *	[7]	0.2–80	3%	1.5°	200
AdEPT *	[10]	5–200	15%	0.5°	600
COMPTEL	[59, 60]	0.8–30	2%	2°	50
EGRET	[61]	30 MeV–10 GeV	12.5%	2.8°	1000
Fermi-LAT	[62]	20 MeV–300 GeV	7.5%	2°	4000
GAMMA-400	[6]	100 MeV–3 TeV	12%	2°	3000

* aborted?

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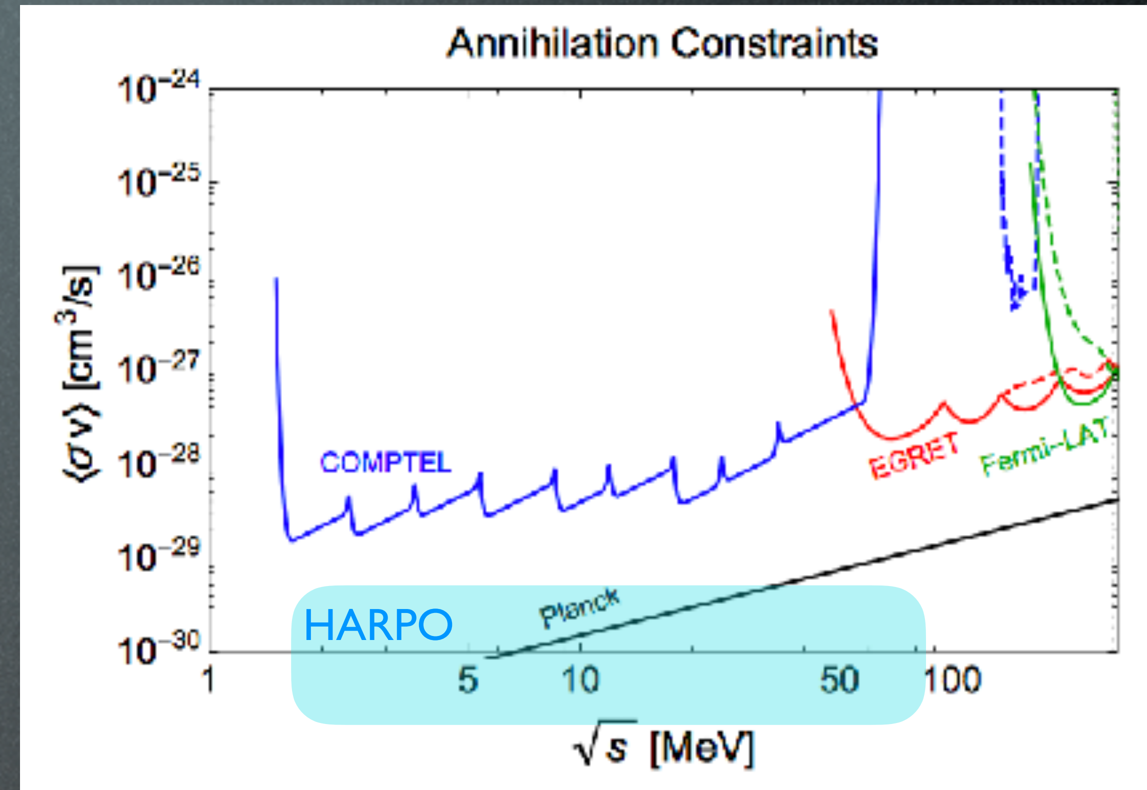
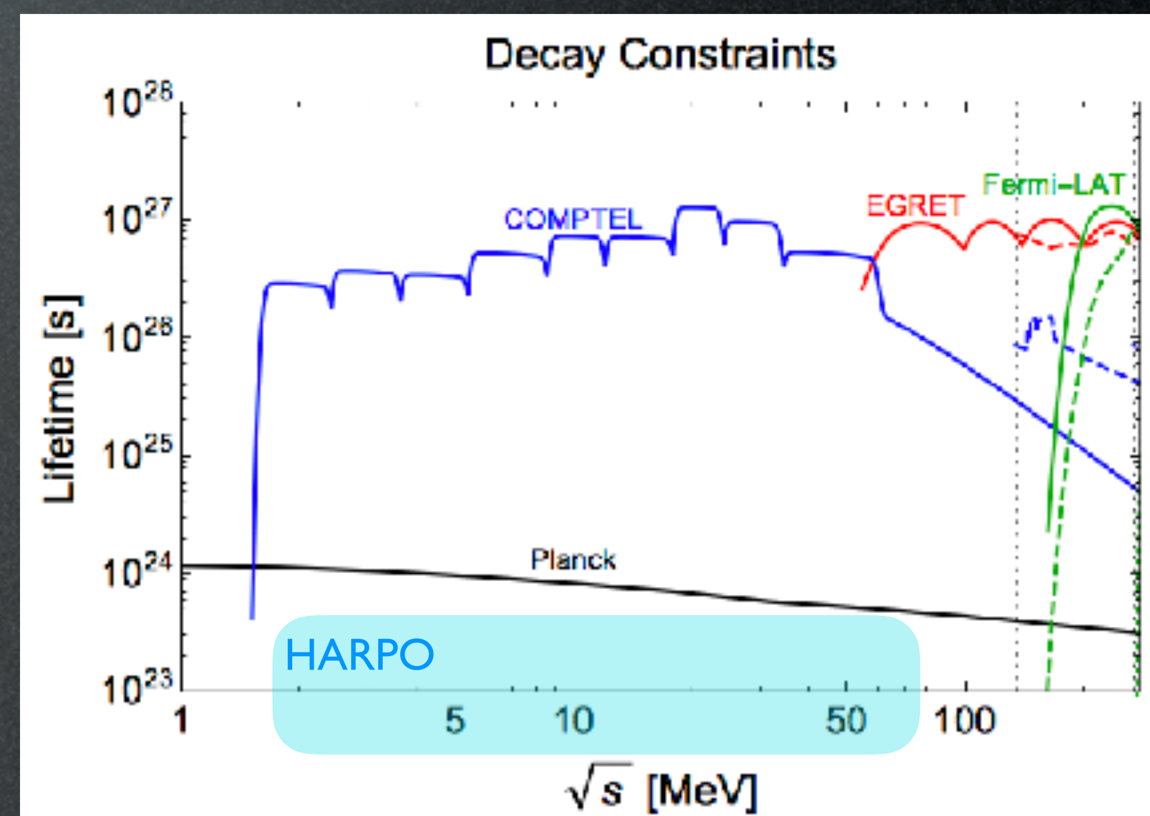
Galactic halo diffuse:





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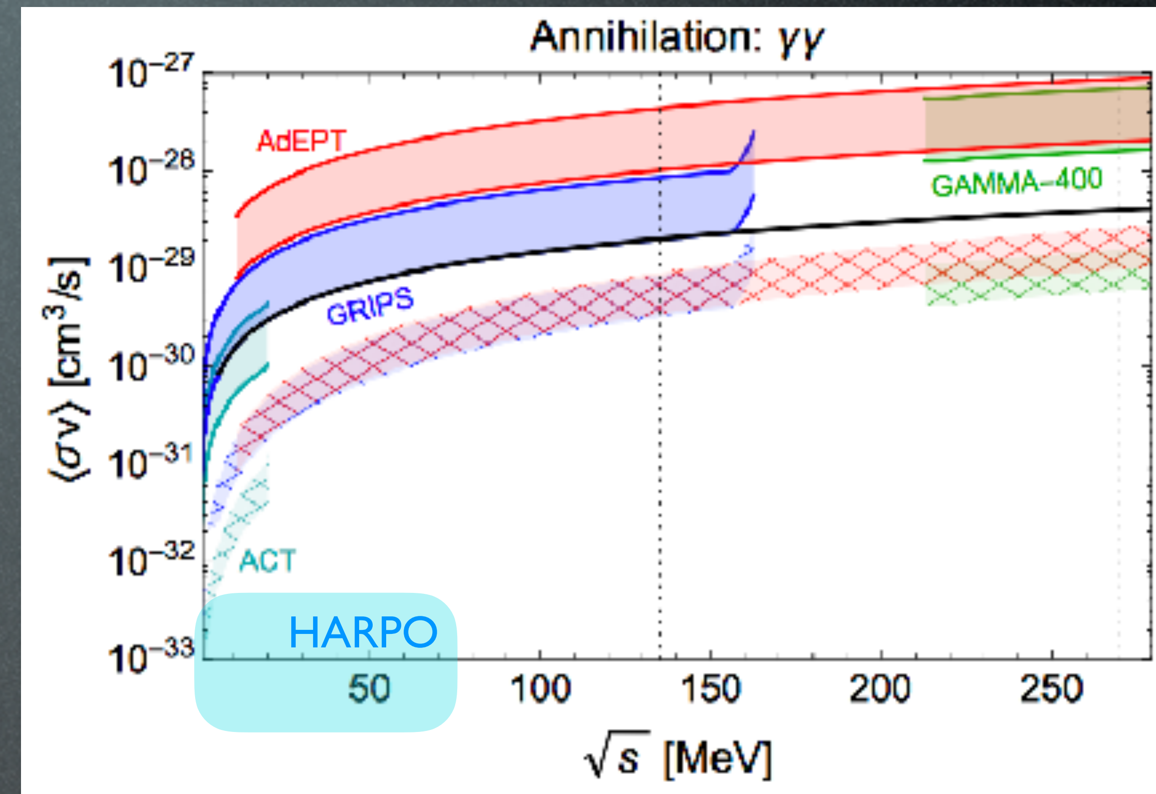
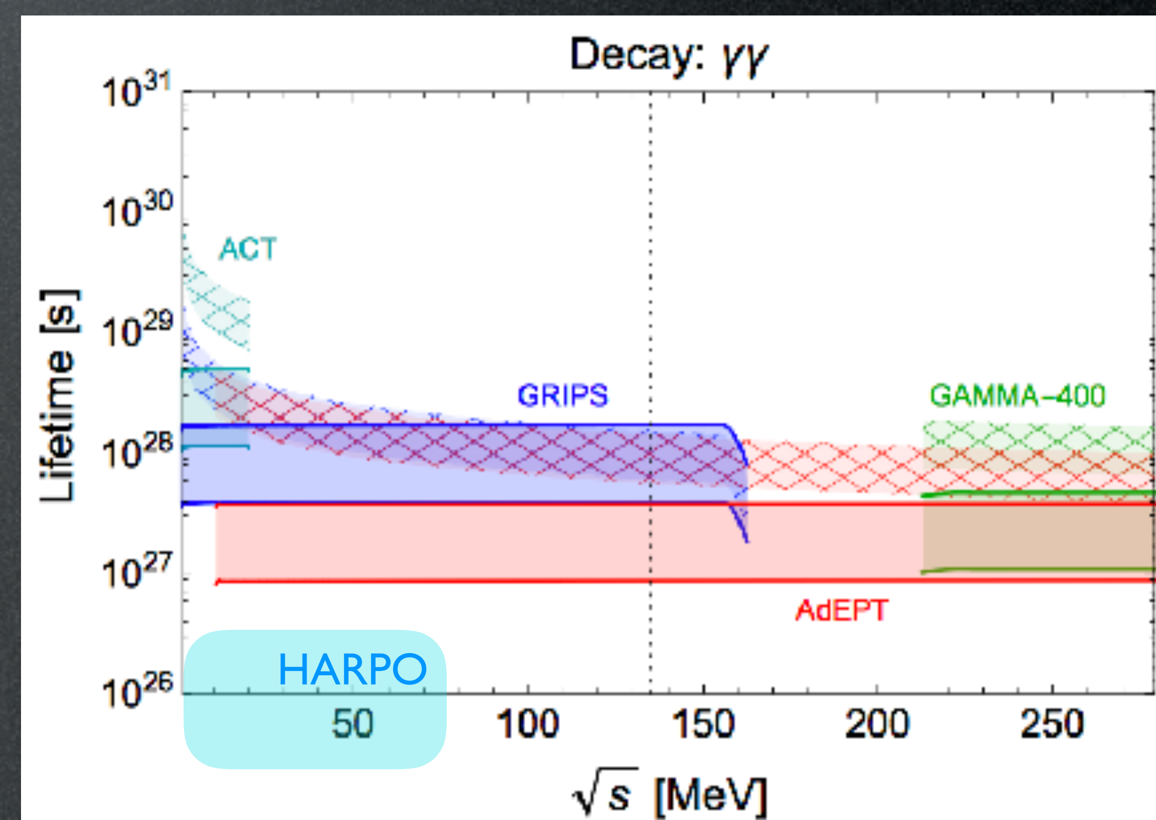
Dwarf galaxies (future sensitivities):

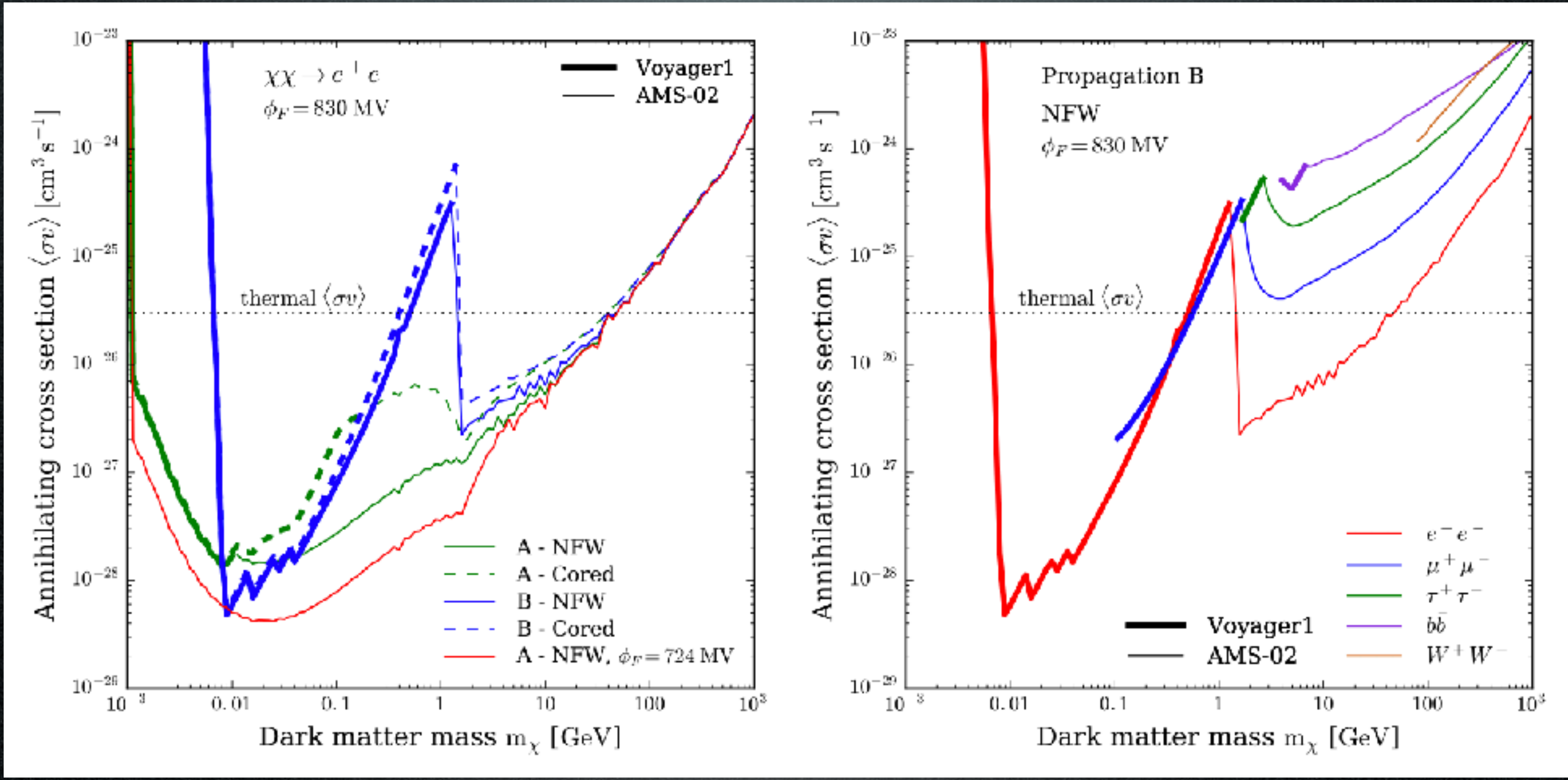




Some recent studies

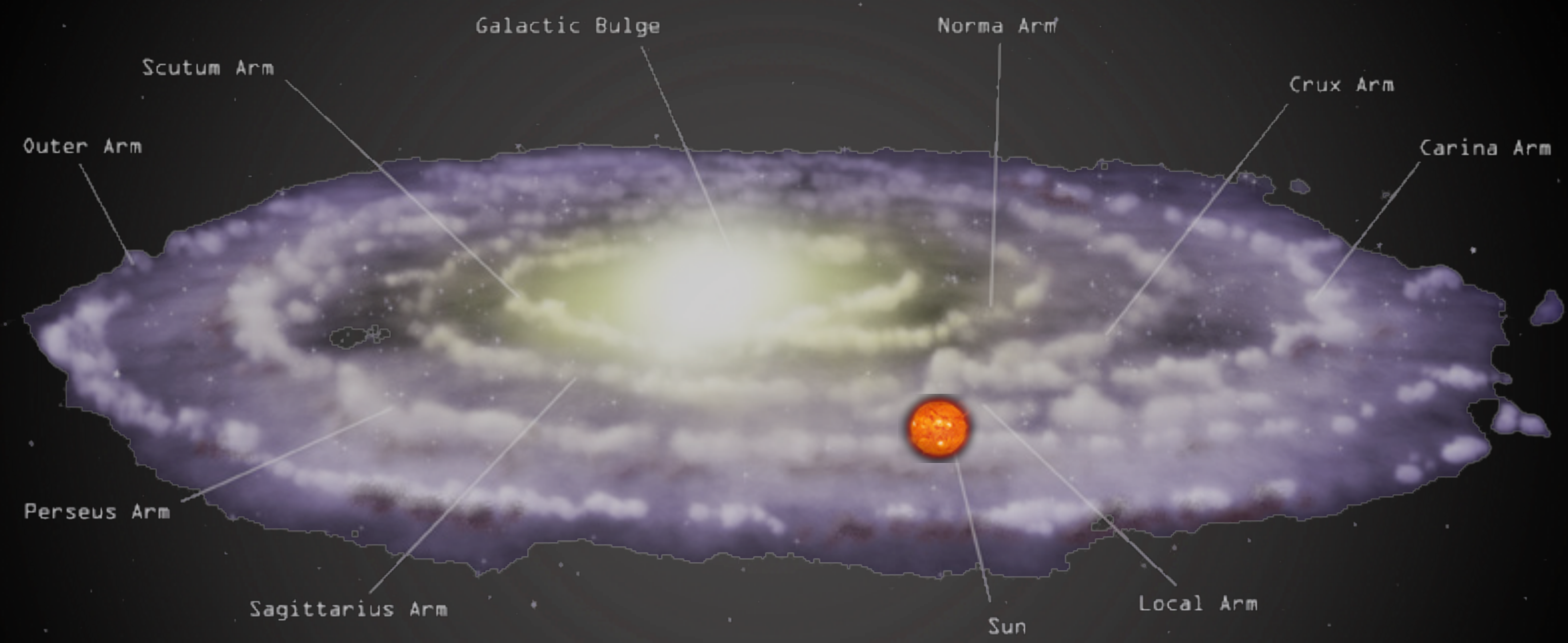
Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I



Indirect Detection: charged CRs

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



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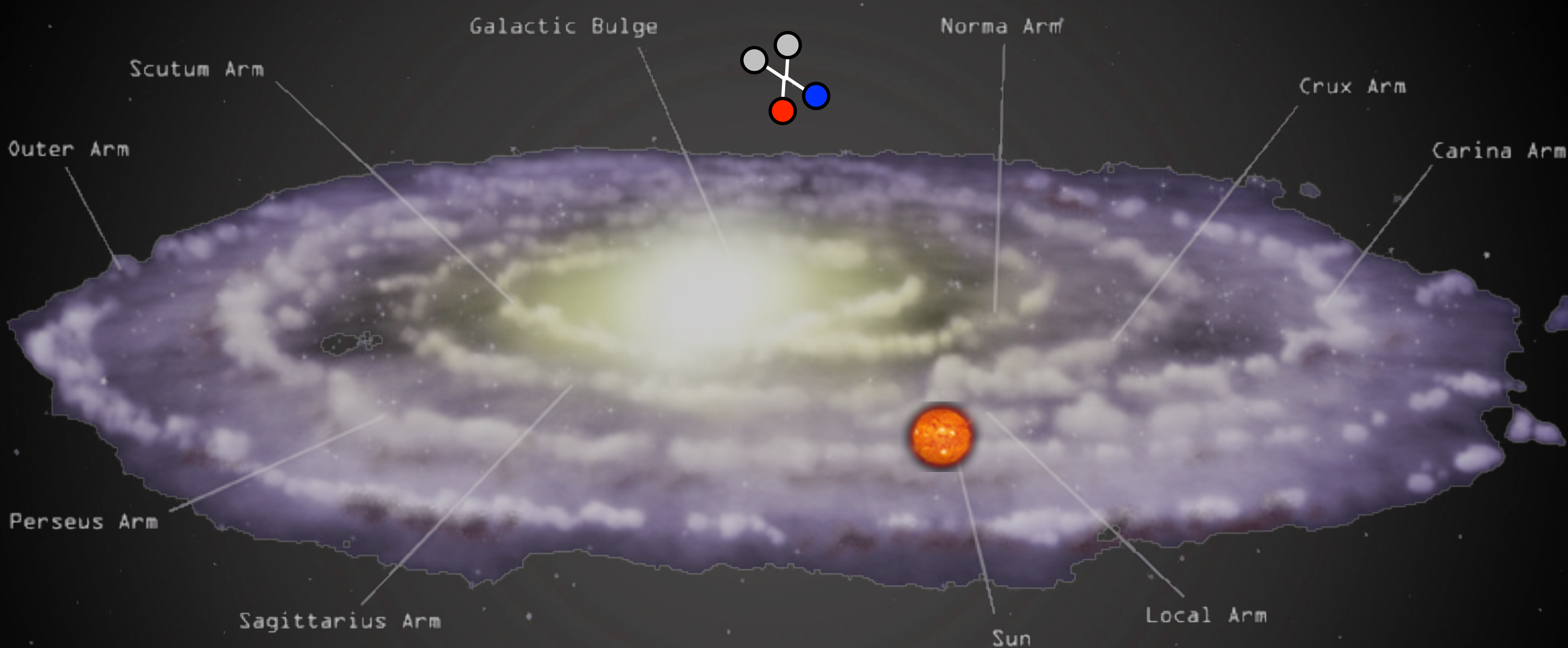

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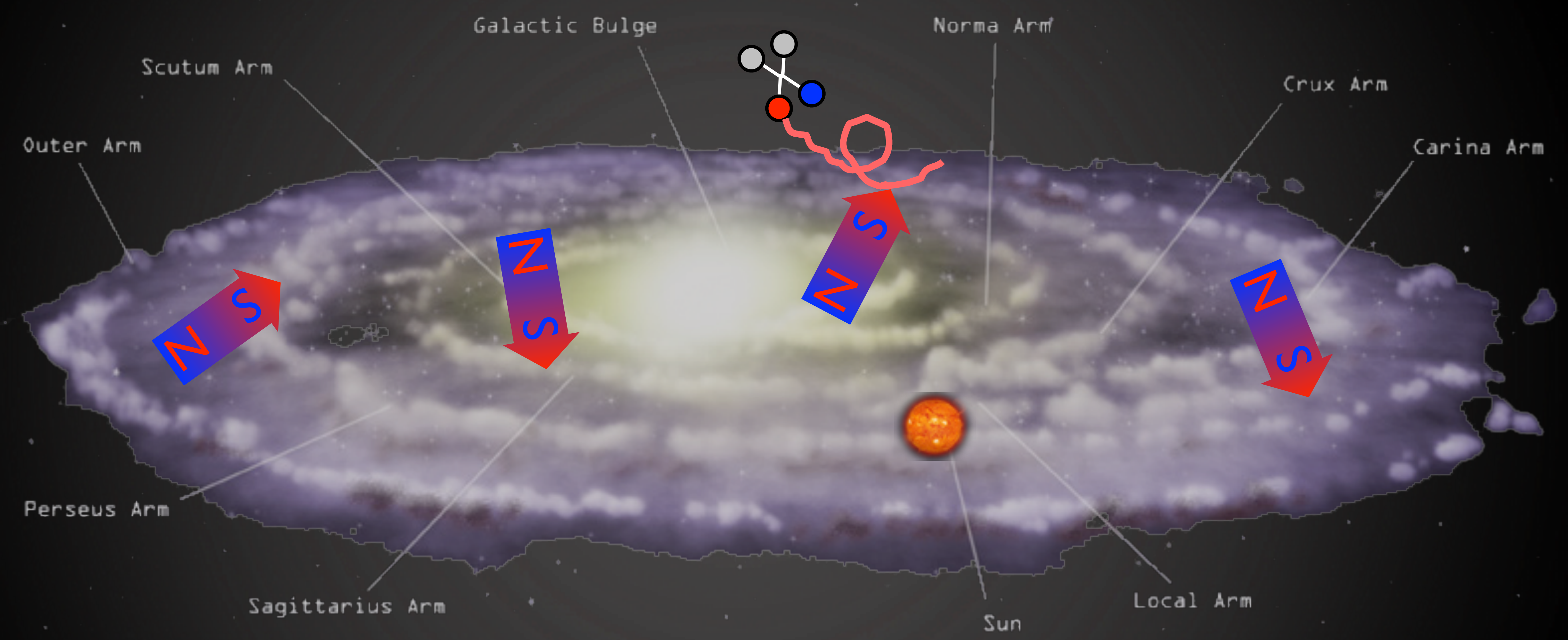

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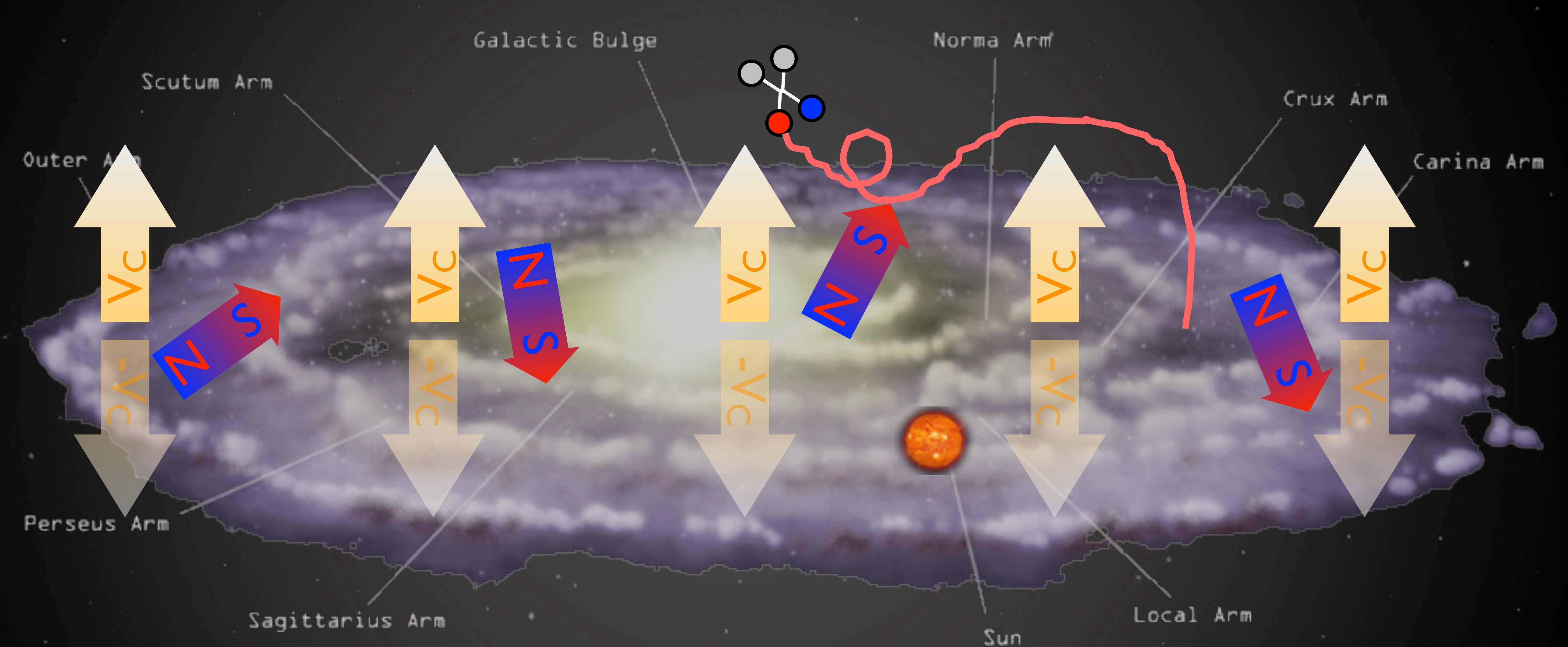

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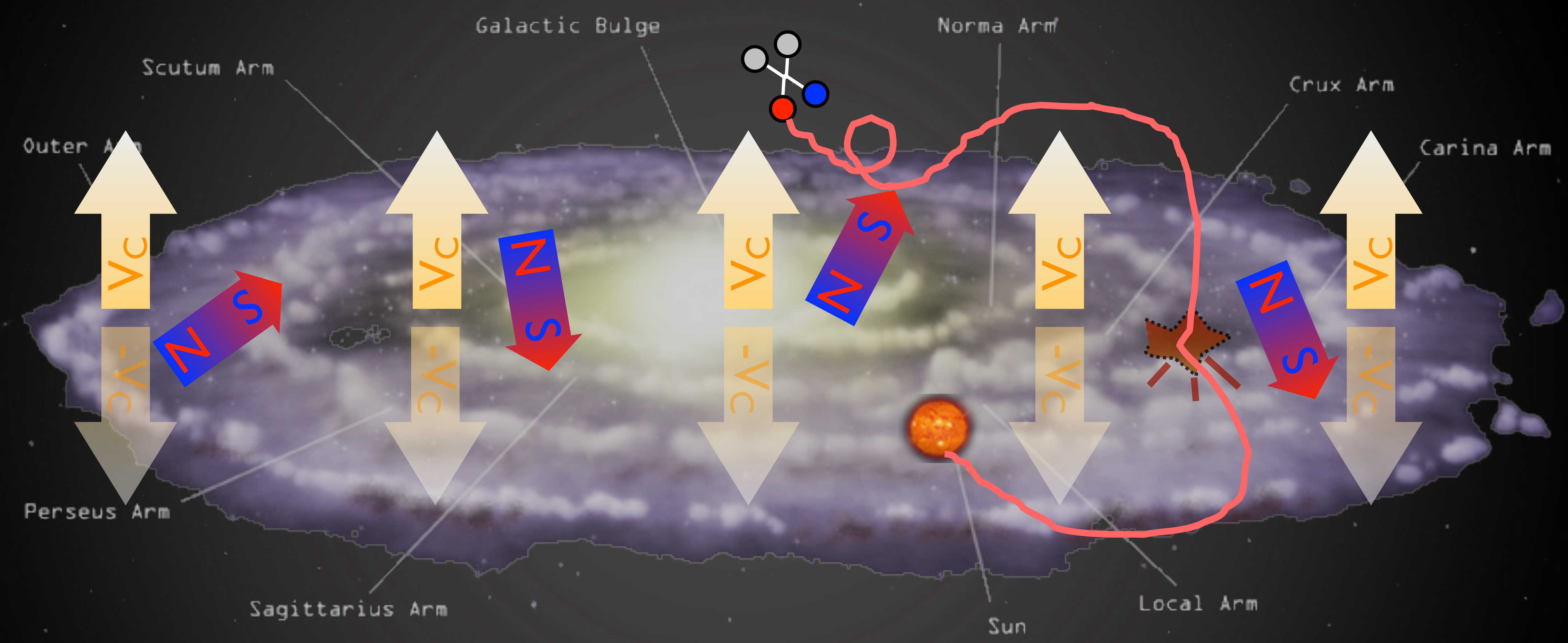

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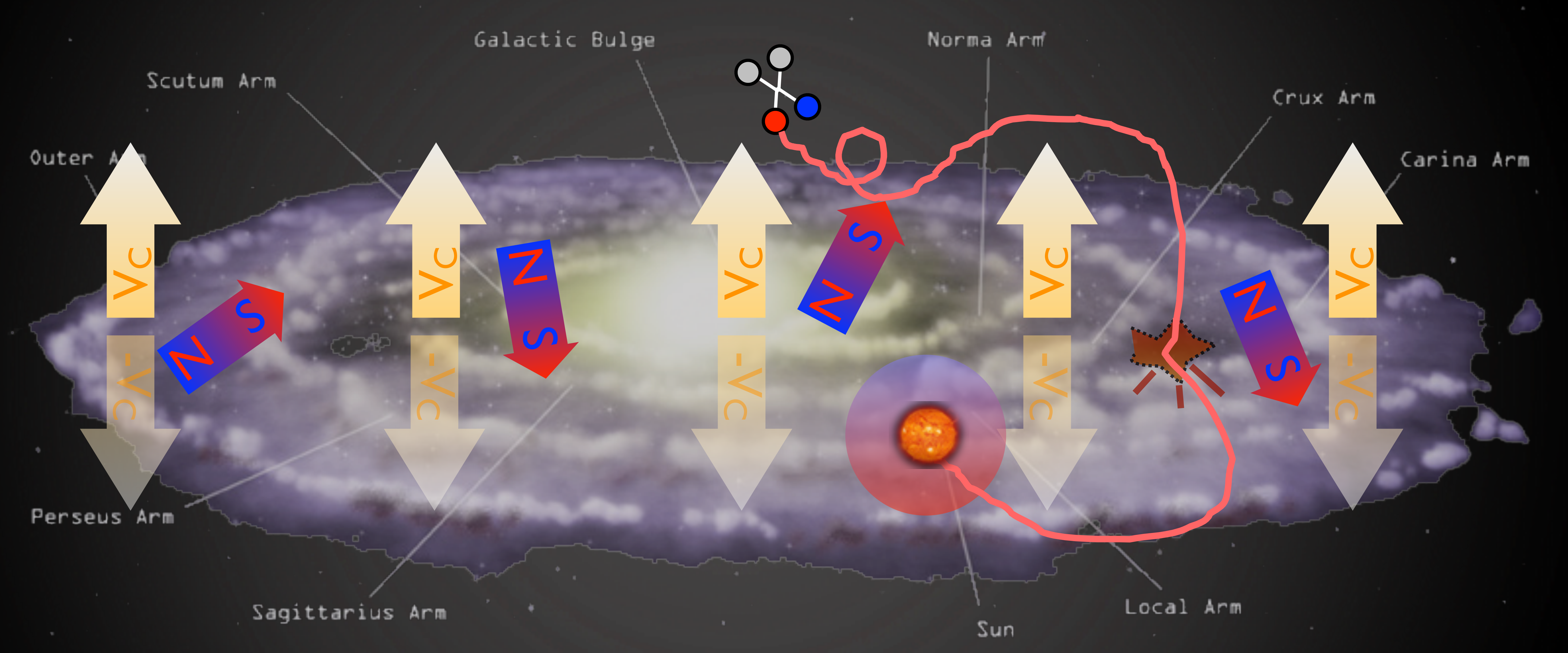

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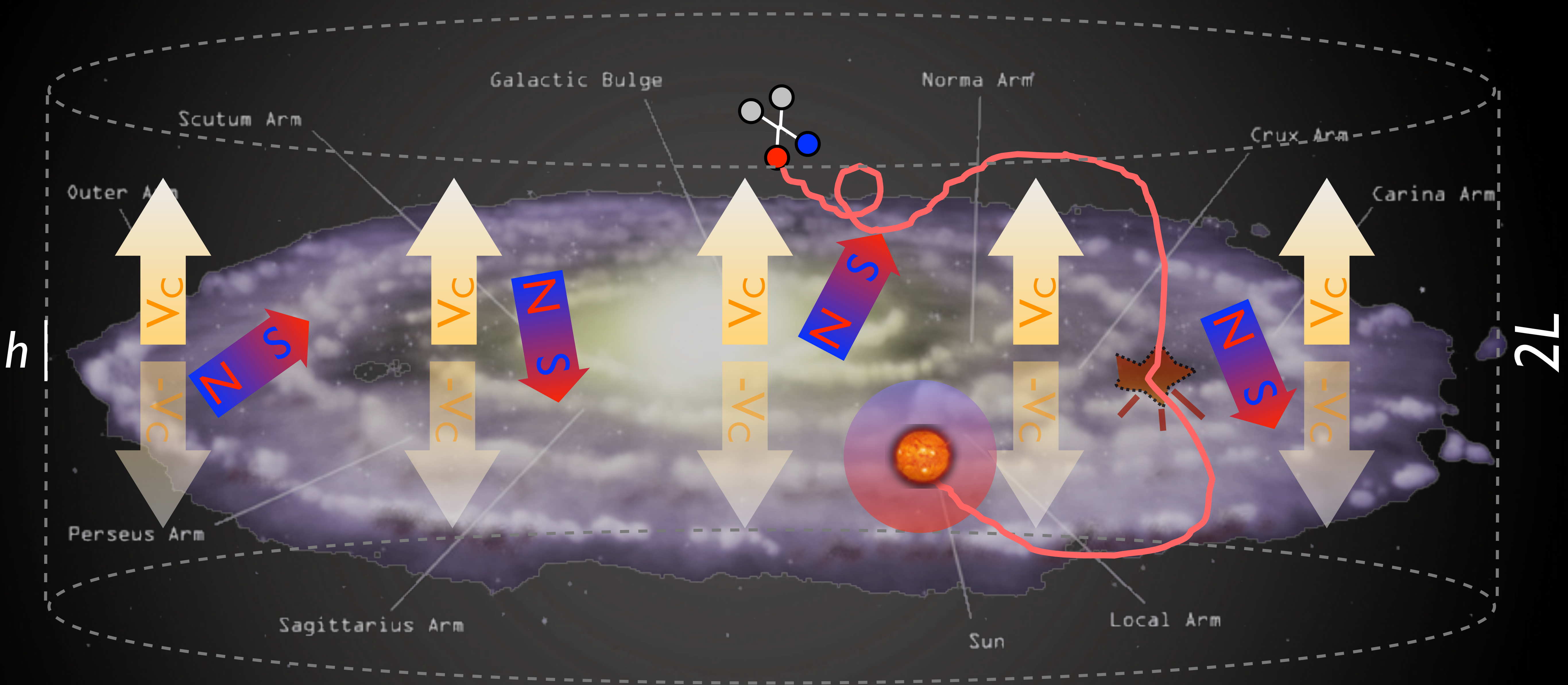


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur Brun... '90s, '00s

spectrum

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

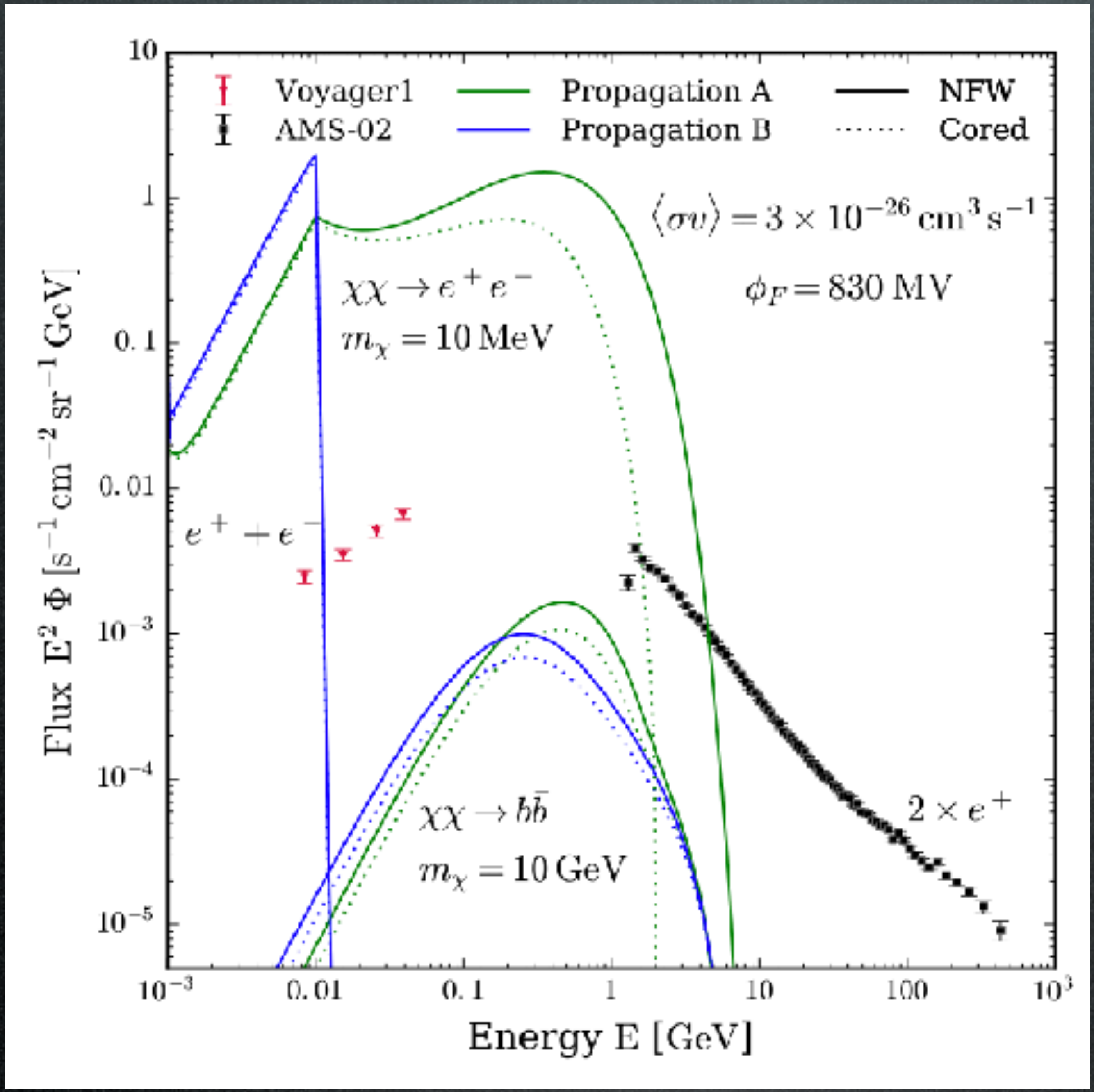
diffusion — energy loss — convective wind — source — spallations

[uncert]

Some recent studies

Boudaud, Lavalle, Salati 1612.07698

Electron+positron measurements by Voyager I



Propagation A = strong reacceleration
Propagation B = weak/no reacceleration

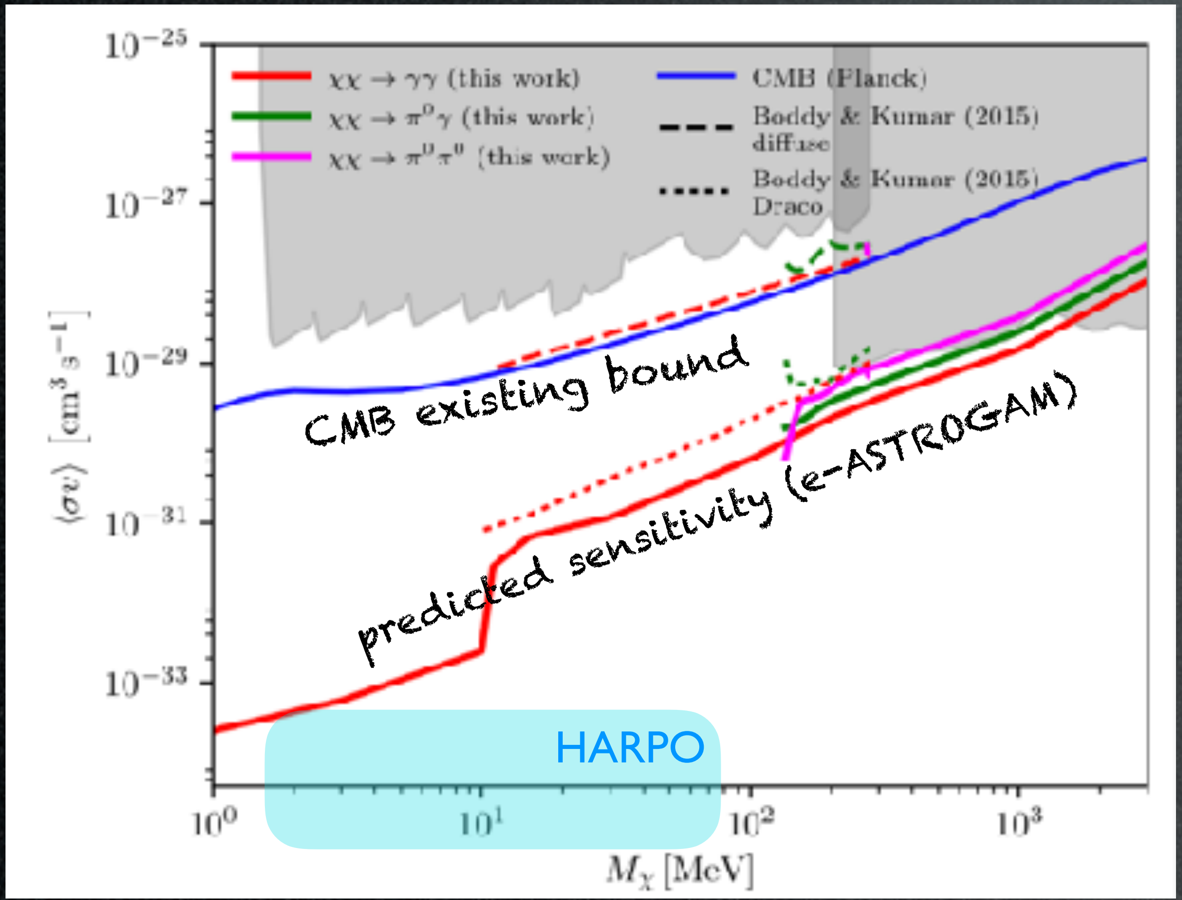
Conclusions

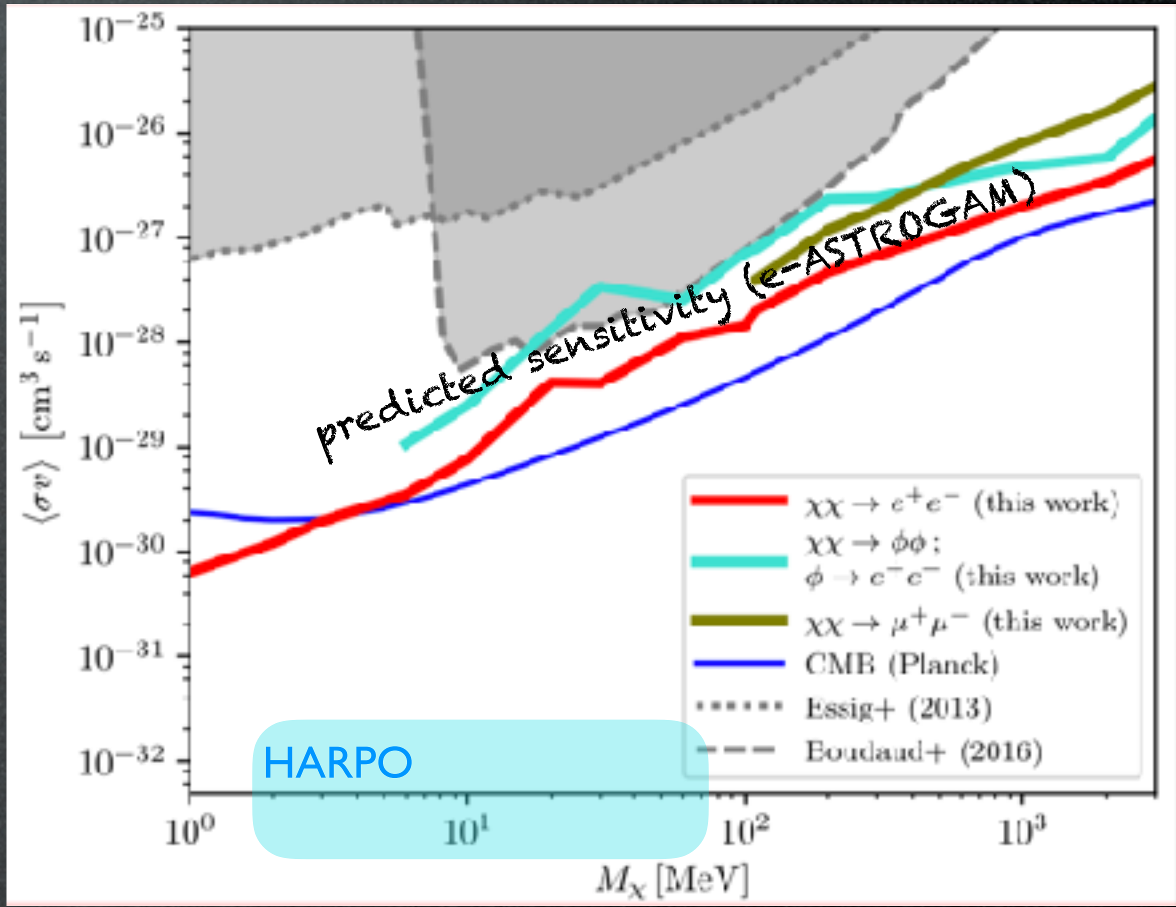
How do we see DM with an MeV telescope?

1. **Prompt** gamma-ray emission of **MeV DM**
   - + traces DM distribution
   - + spectral features

2. **Secondary** gamma-ray emission of **light 'WIMP' DM**
   - \- does not trace DM distribution
   - \- smooth spectra

3. **De-excitation** gamma-ray emissions





Back-up slides