

23 July 2025
14th IDPASC School, Orsay

Dark Matter

indirect detection

Marco Cirelli
(LPTHE Jussieu CNRS Paris)



Reviews/books on Dark Matter:

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

Bertone, Hooper, Silk, Phys.Rept. 405, 279-390, 2005

Peter, 1201.3942

Bertone, Hooper, *History of dark matter*, 1605.04909

S. Profumo, *An Introduction to Particle Dark Matter*, World Scientific (2017)

2021 Les Houches Summer School on Dark Matter: <https://indico.cern.ch/event/949654/>

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How do we search for
Dark Matter?

DM detection

direct detection

Xenon, LZ, Panda-X... (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic halo
and from secondary emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo

AMS, Dampe, Calet, Fermi...

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

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

GAPS

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

Icecube, Km³Net

DM detection

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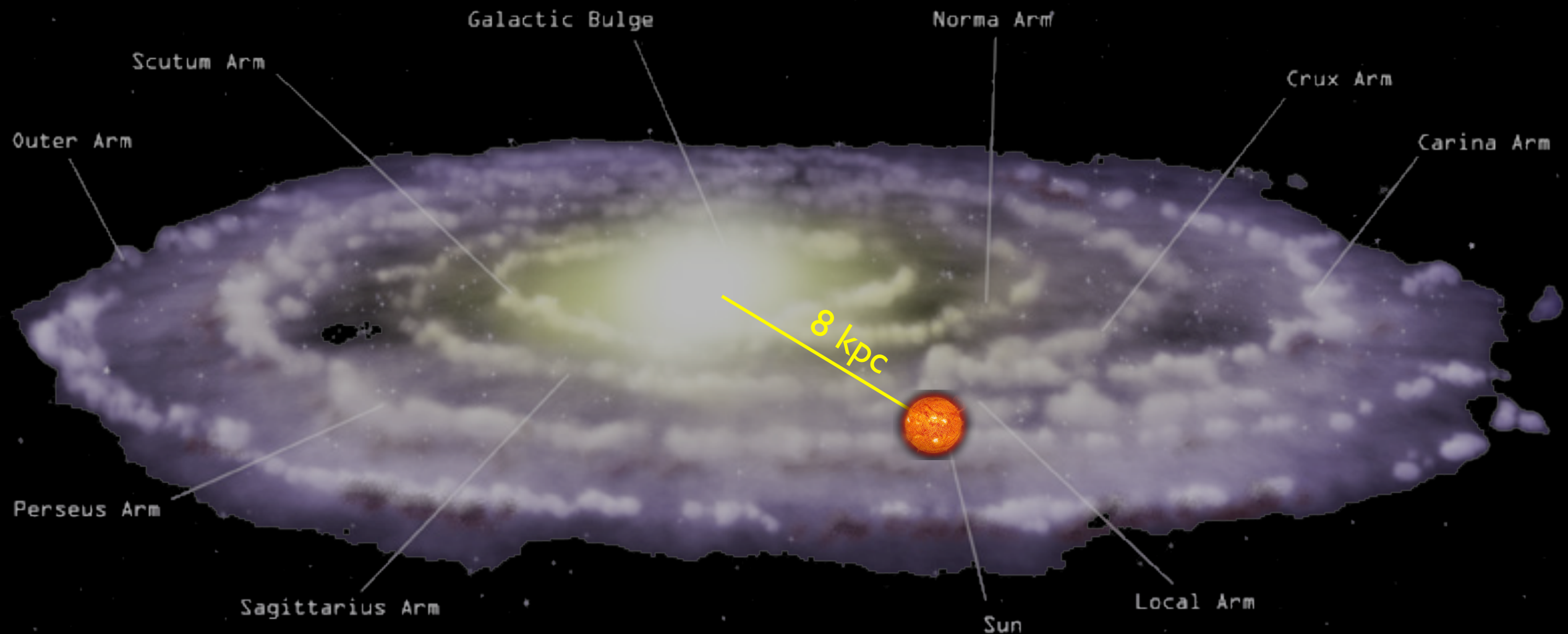
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Icecube, Km³Net

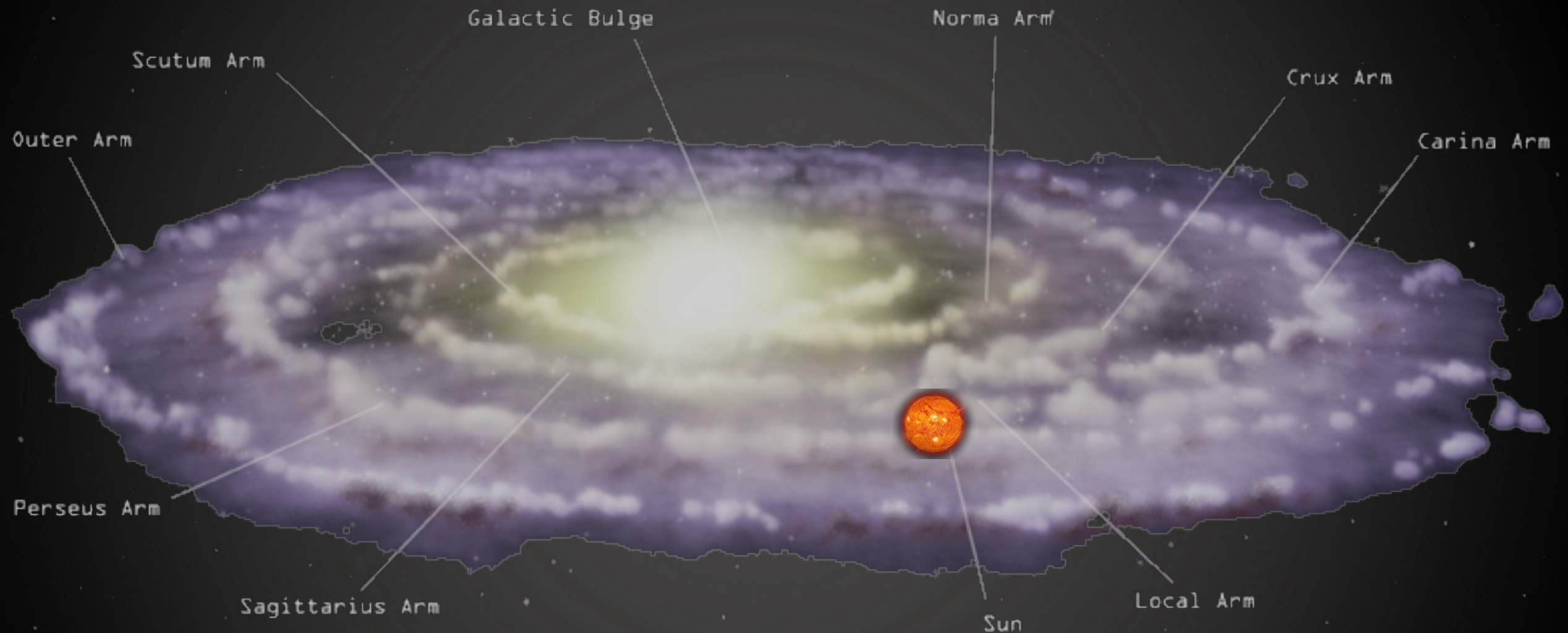
Indirect Detection: basics

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



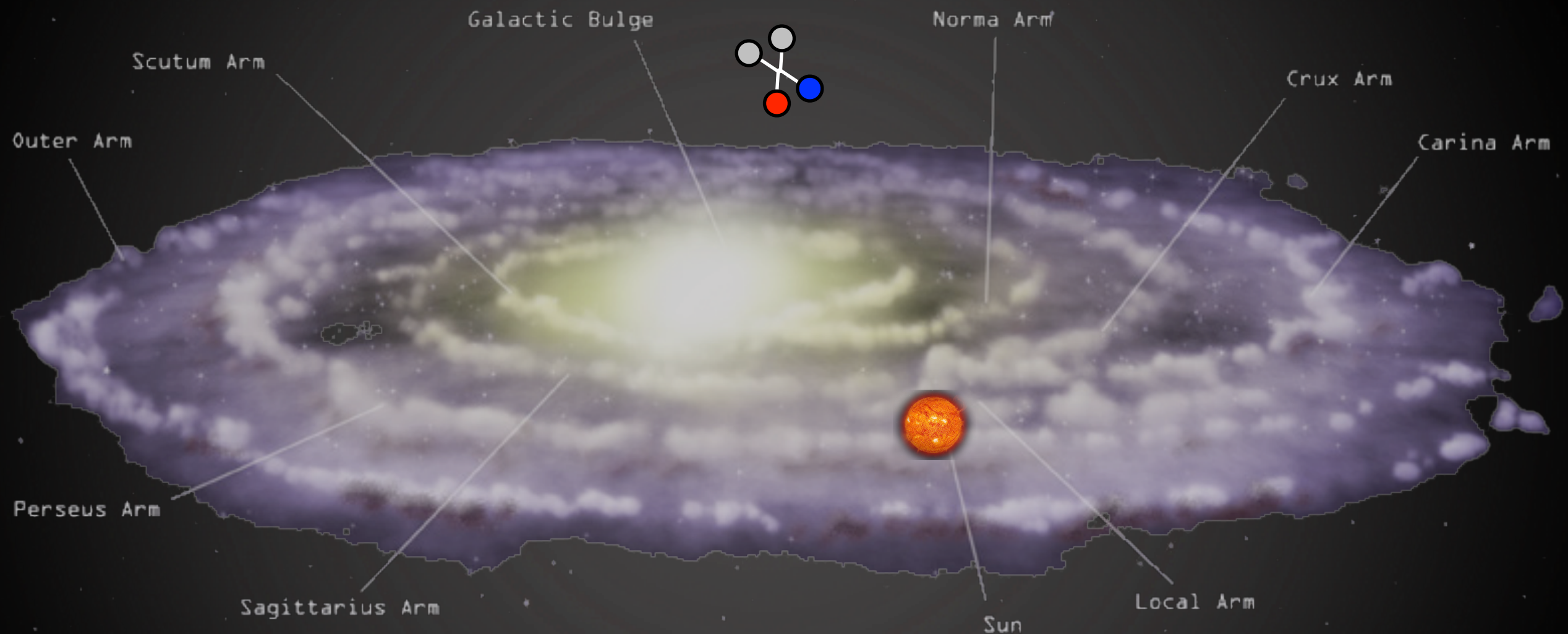
Indirect Detection: basics

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DM halo profiles

From N-body numerical simulations:

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

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

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

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

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

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

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

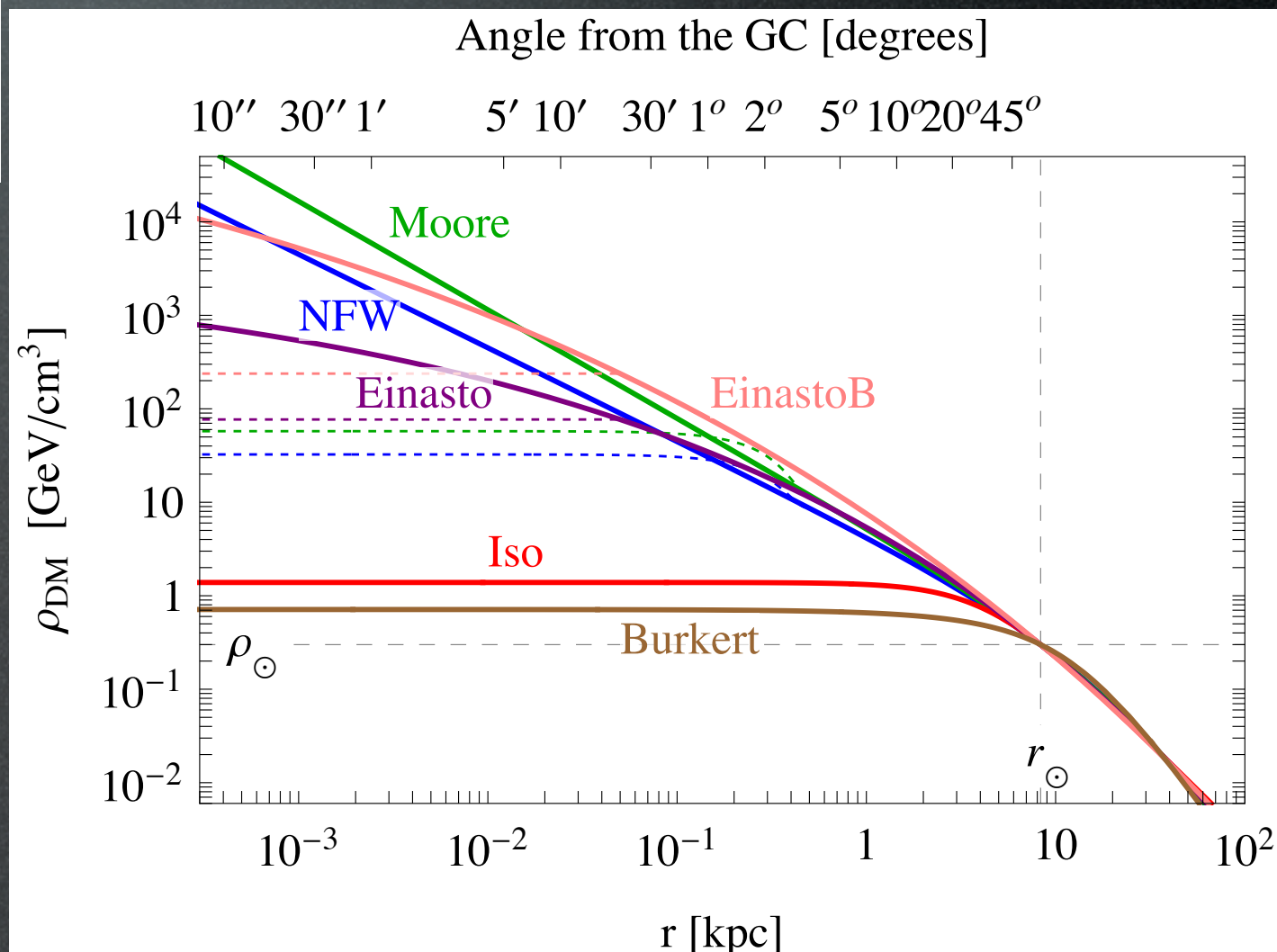
6 profiles:

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

mild: **Einasto**

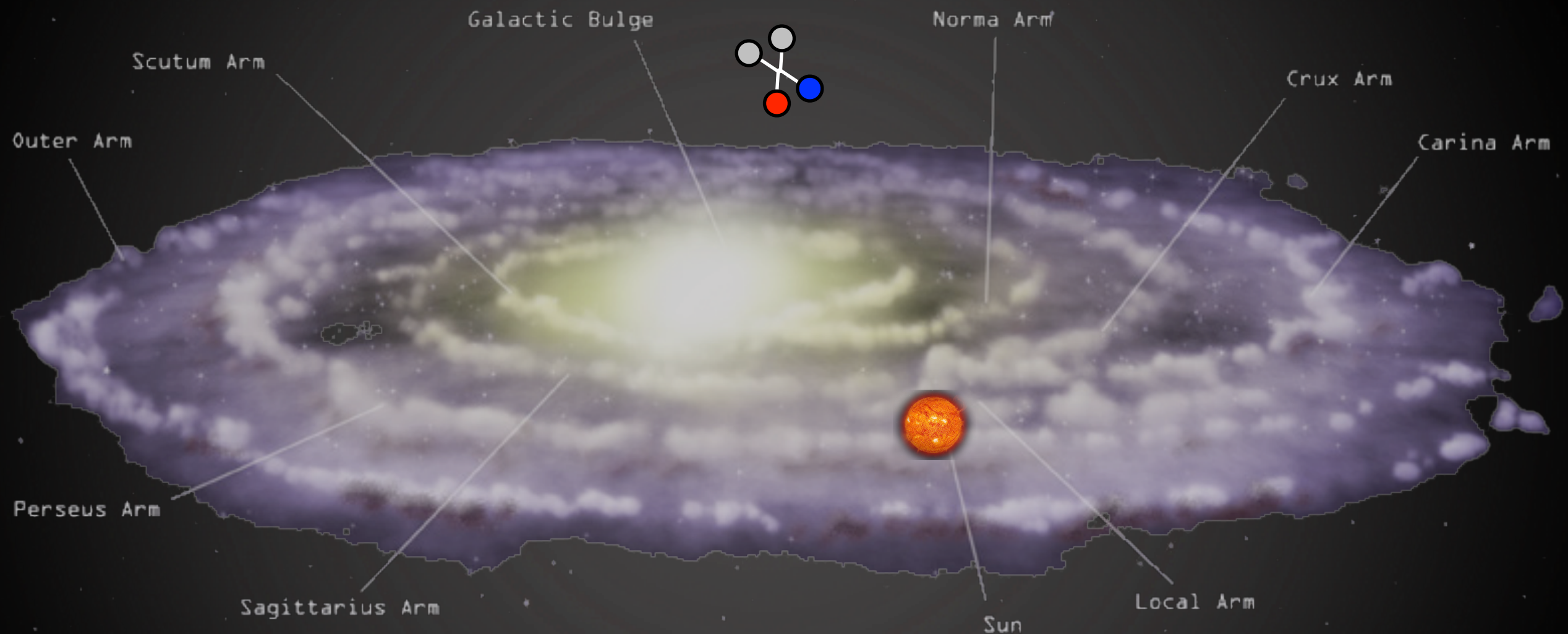
smooth: **isothermal**, **Burkert**

EinastoB = steepened Einasto
(effect of baryons?)

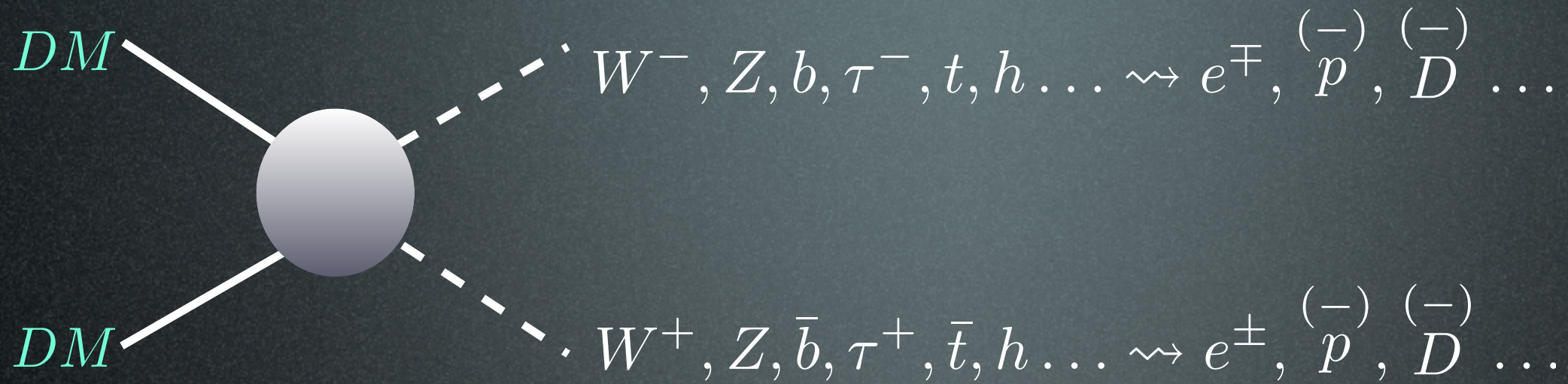


Indirect Detection: basics

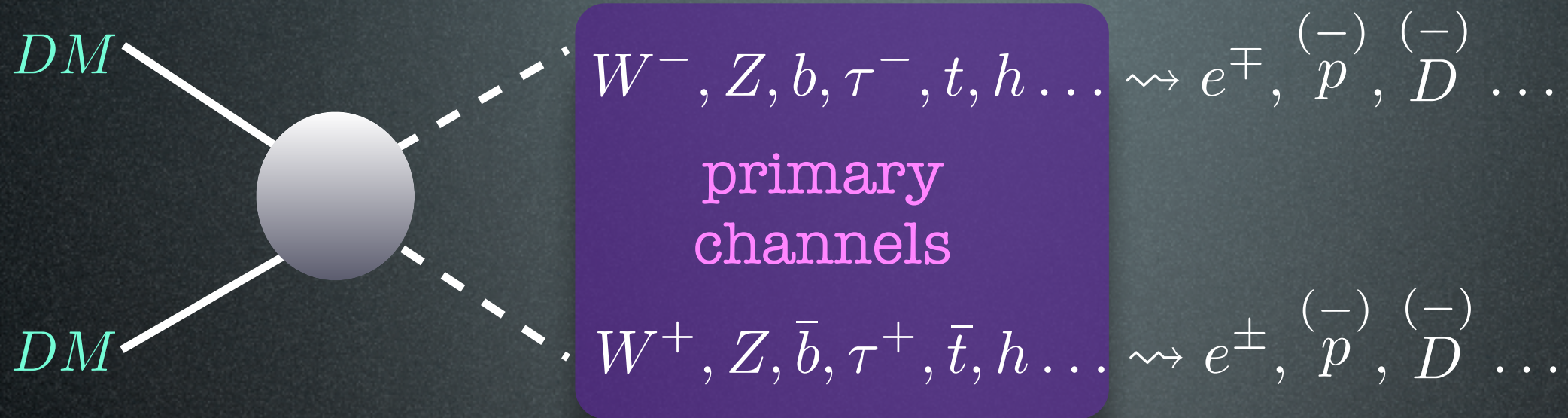
$\bar{p}$ and e^+ from DM annihilations in halo



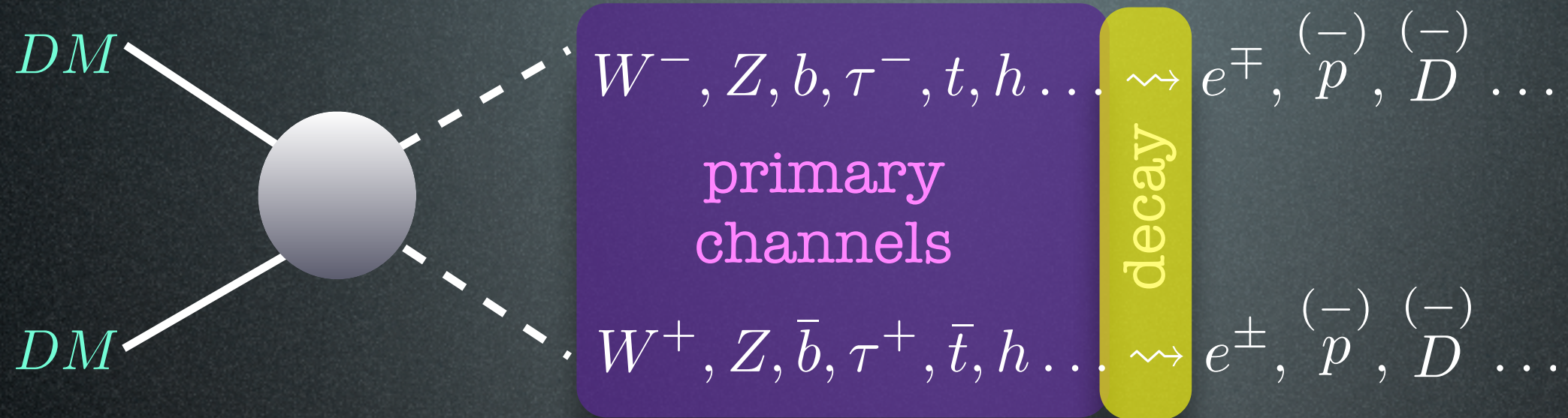
Indirect Detection: basics



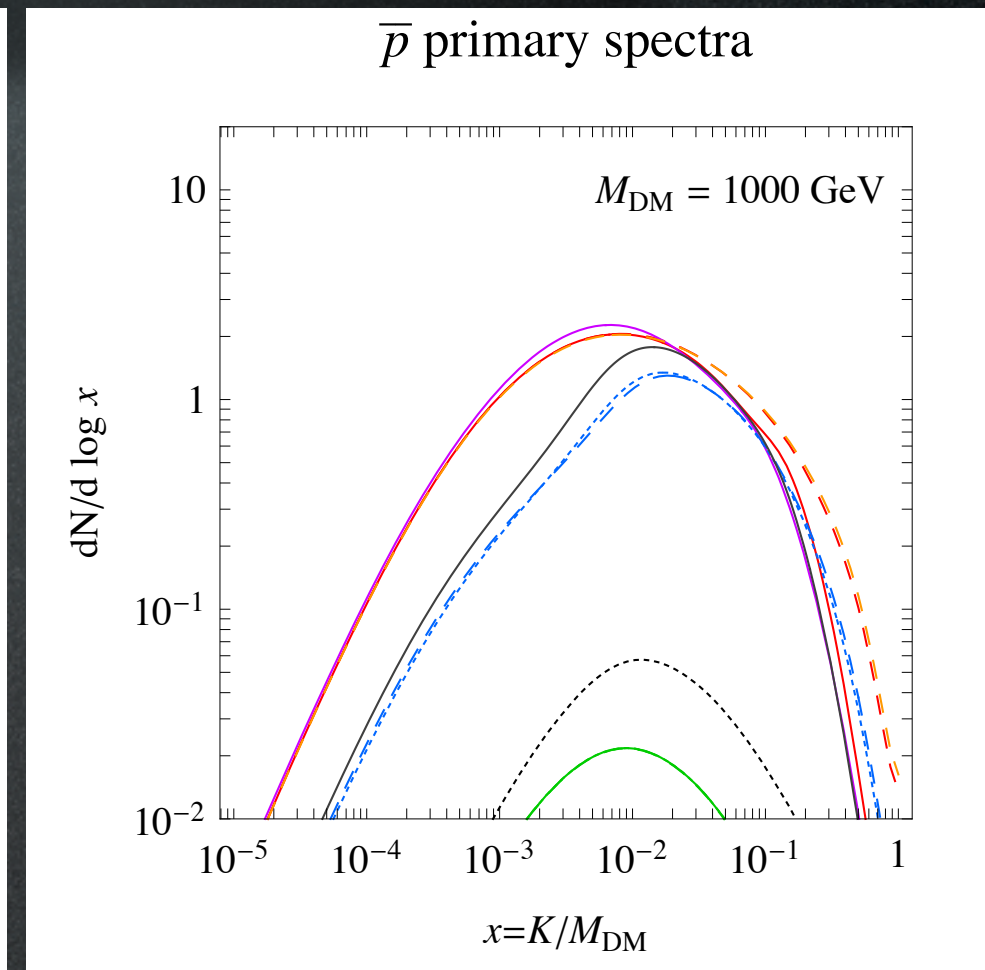
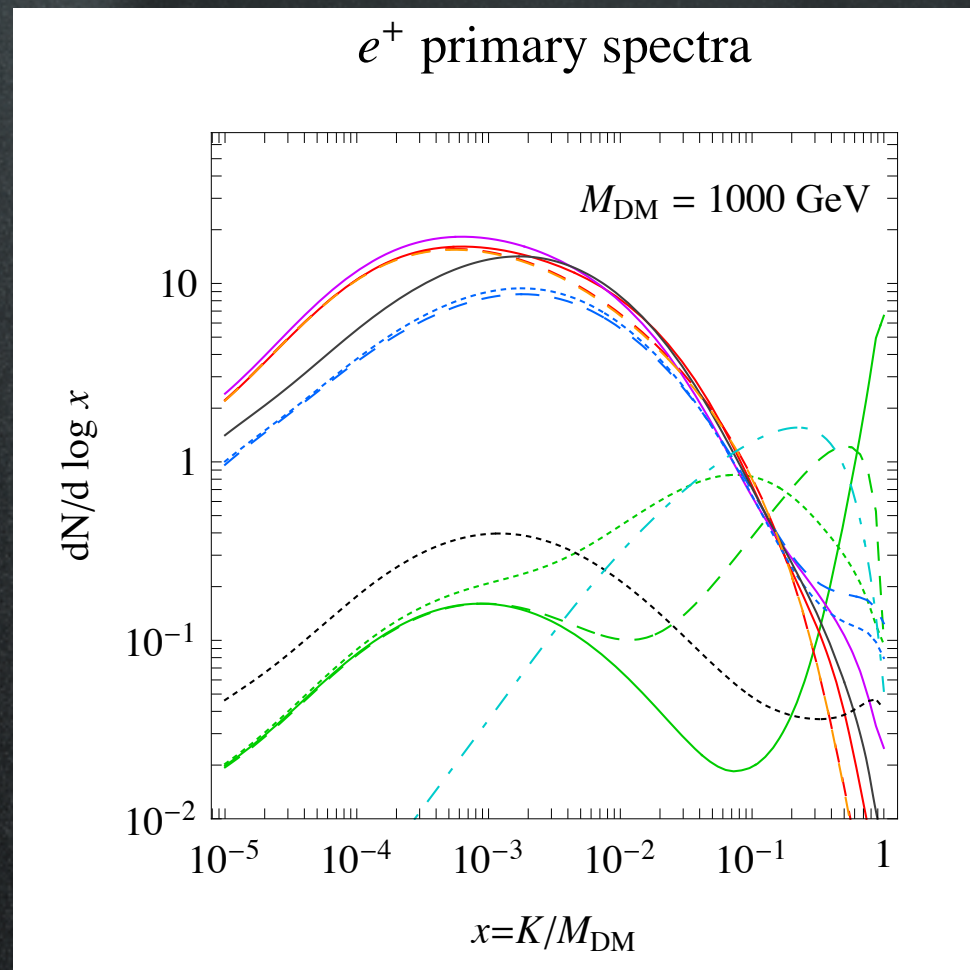
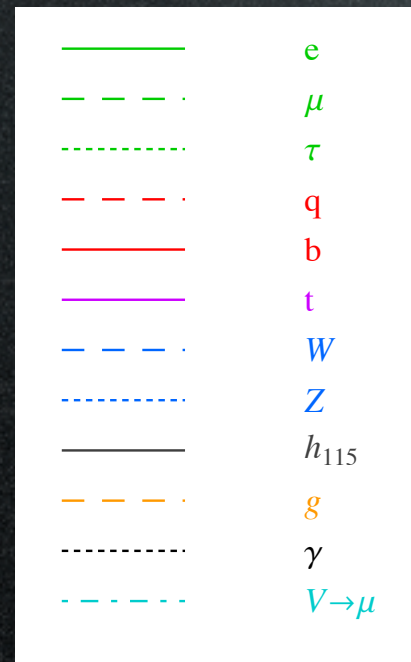
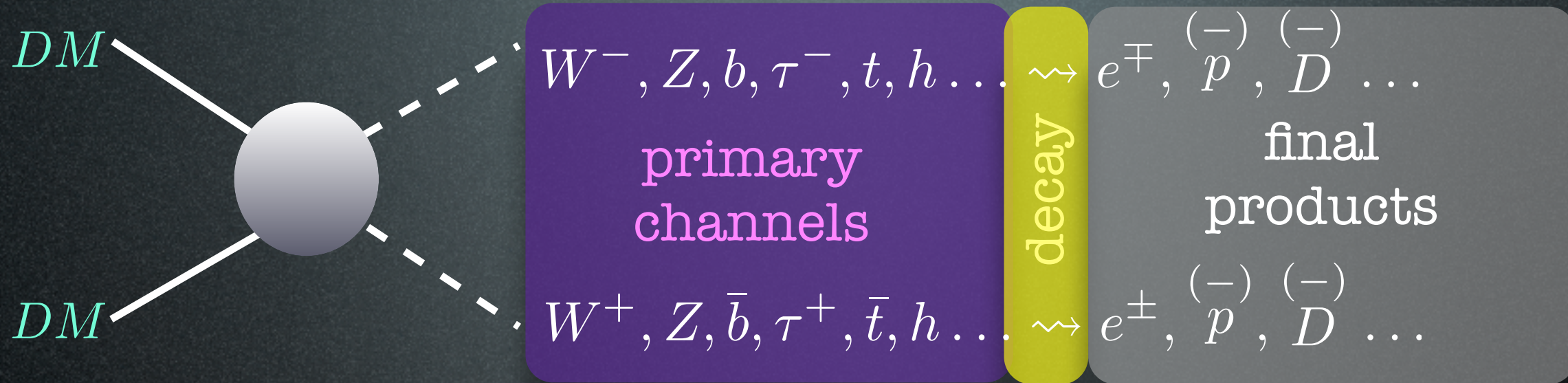
Indirect Detection: basics



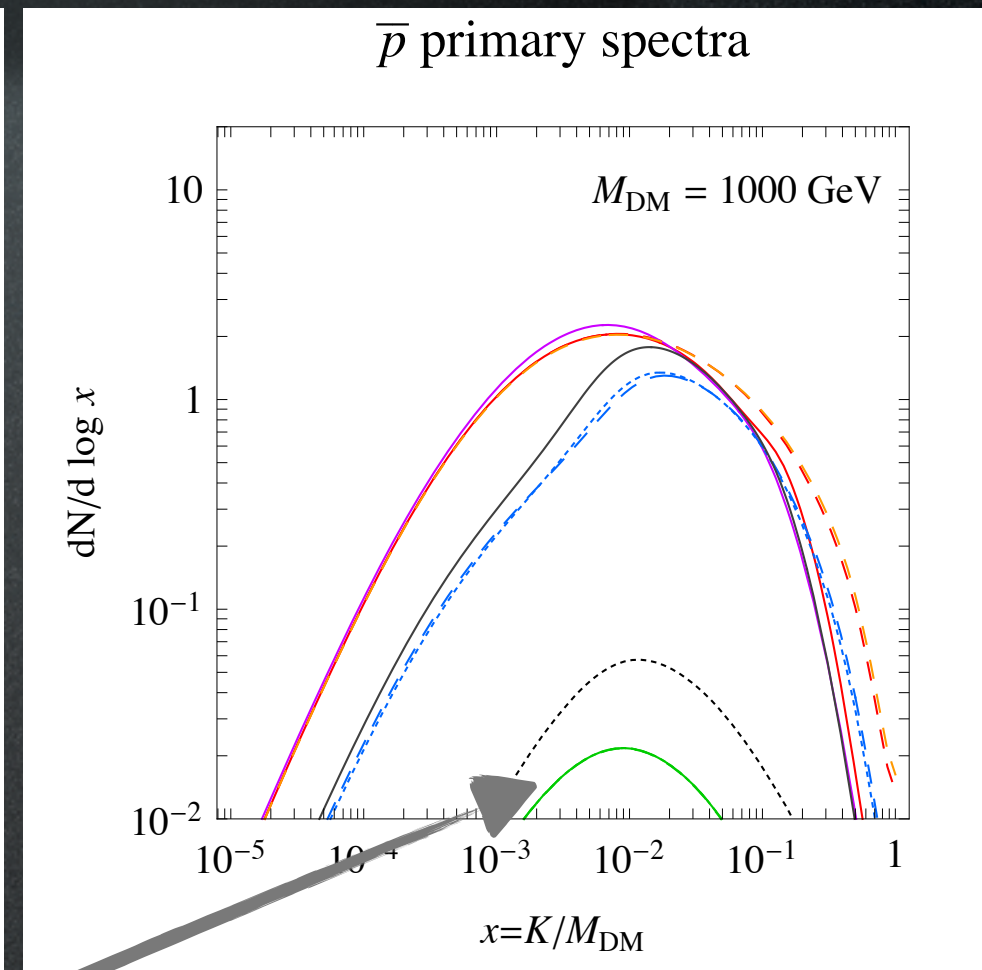
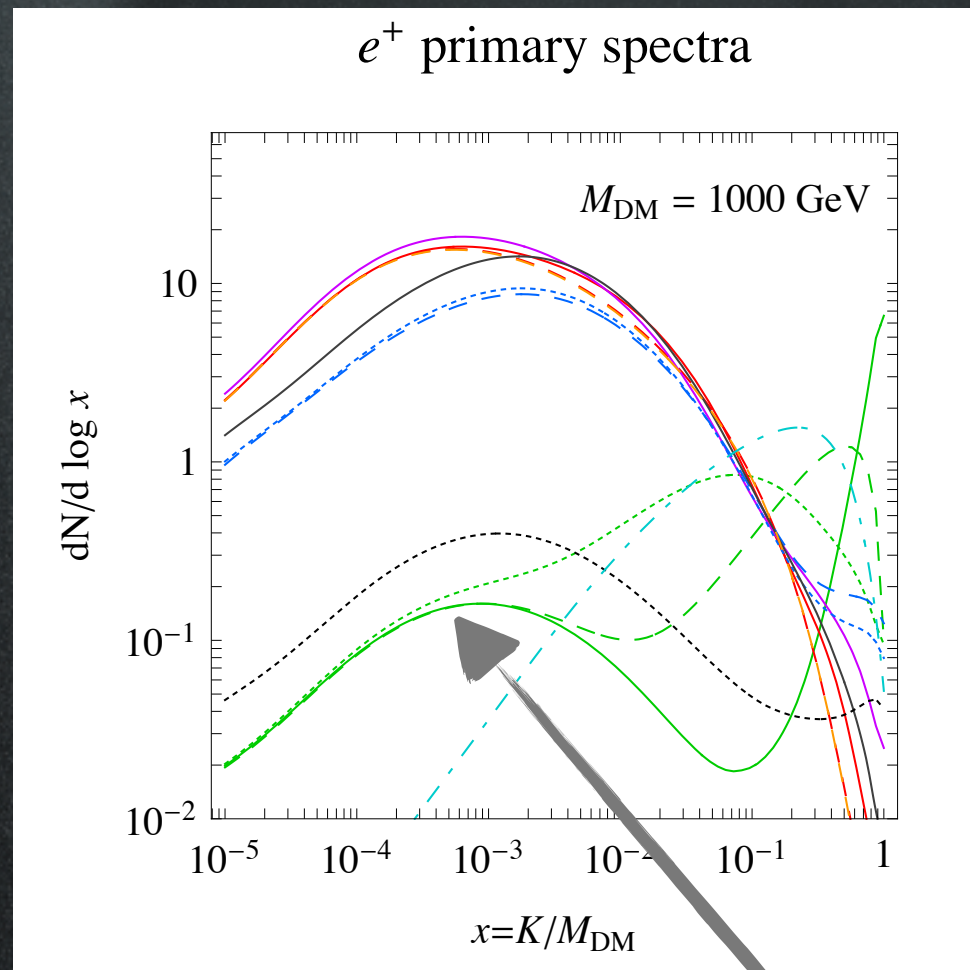
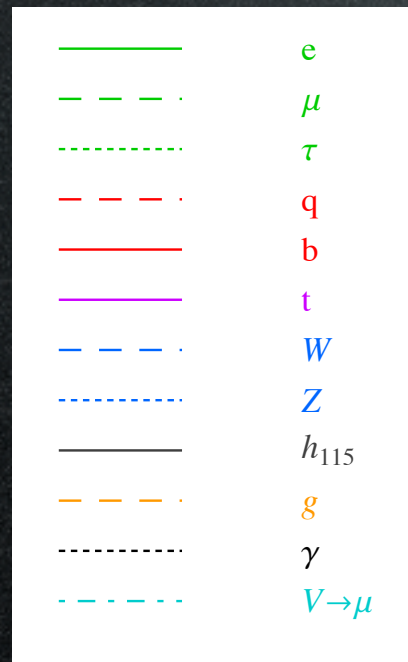
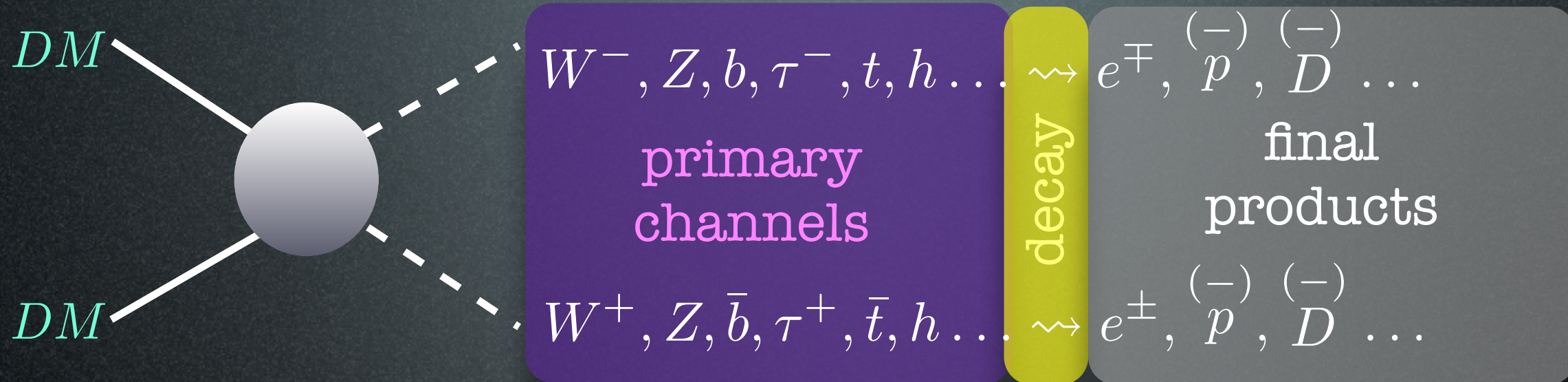
Indirect Detection: basics



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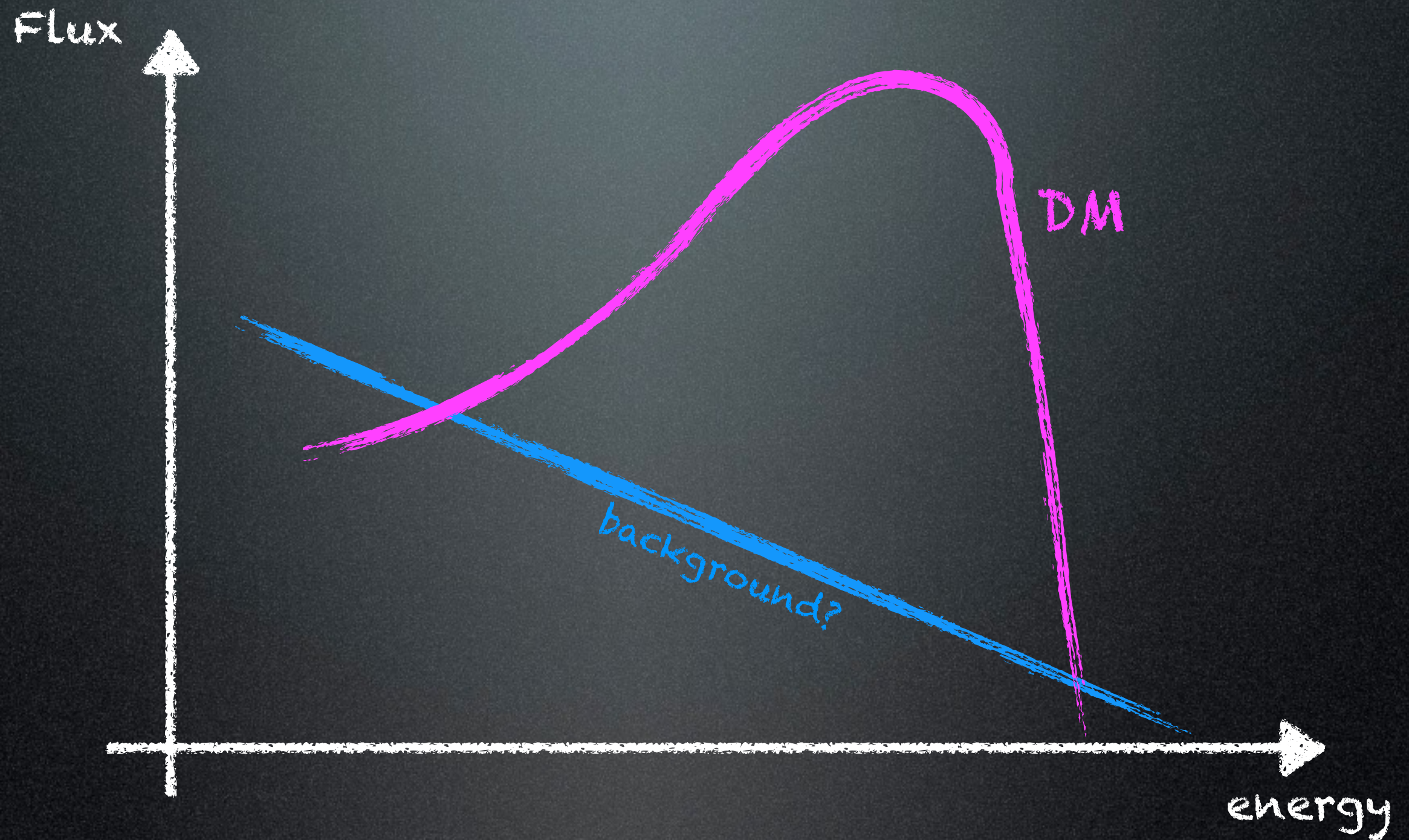


Indirect Detection: basics



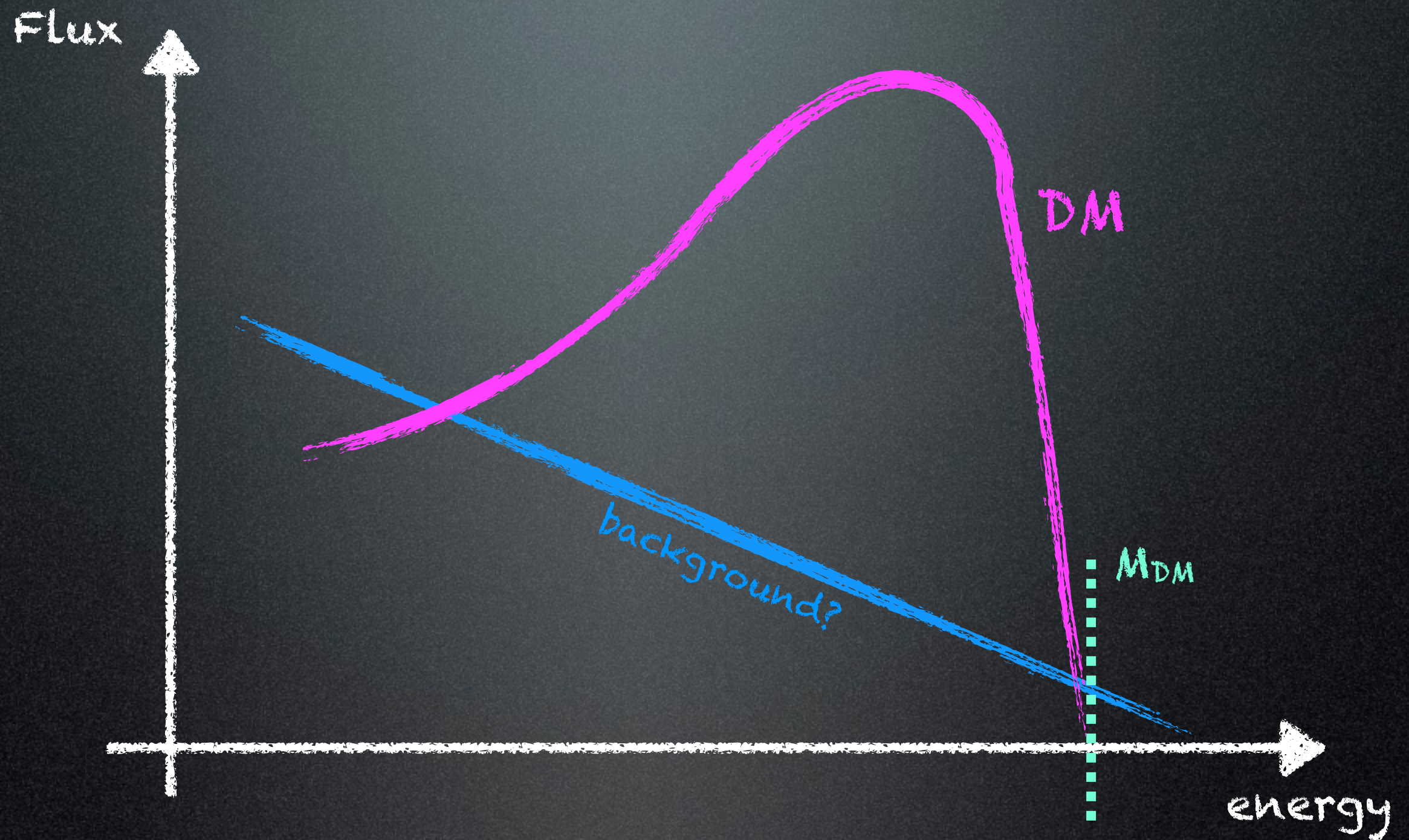
ElectroWeak corrections!

Fluxes at production



So what are the
particle physics
parameters?

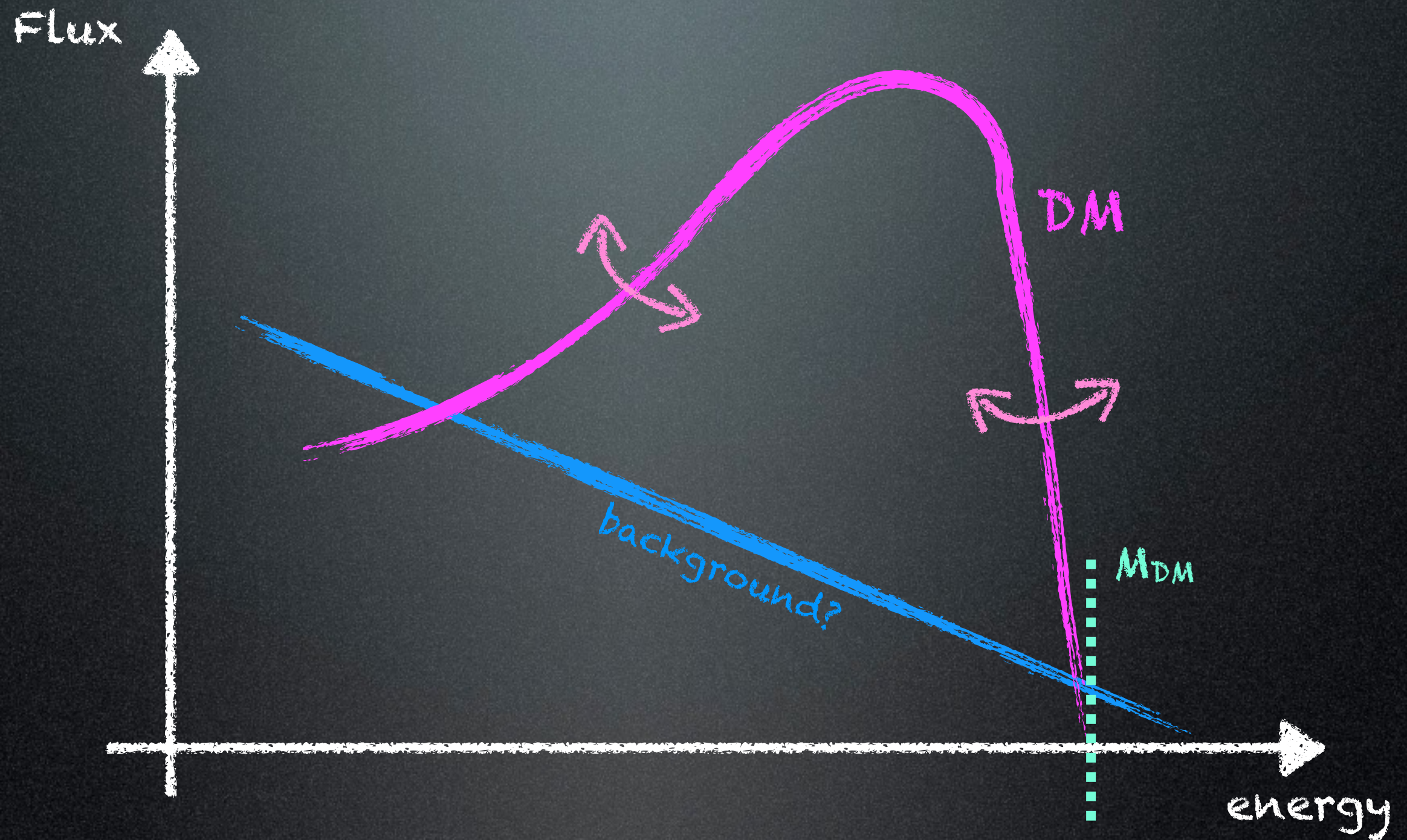
Fluxes at production



So what are the
particle physics
parameters?

1. Dark Matter mass

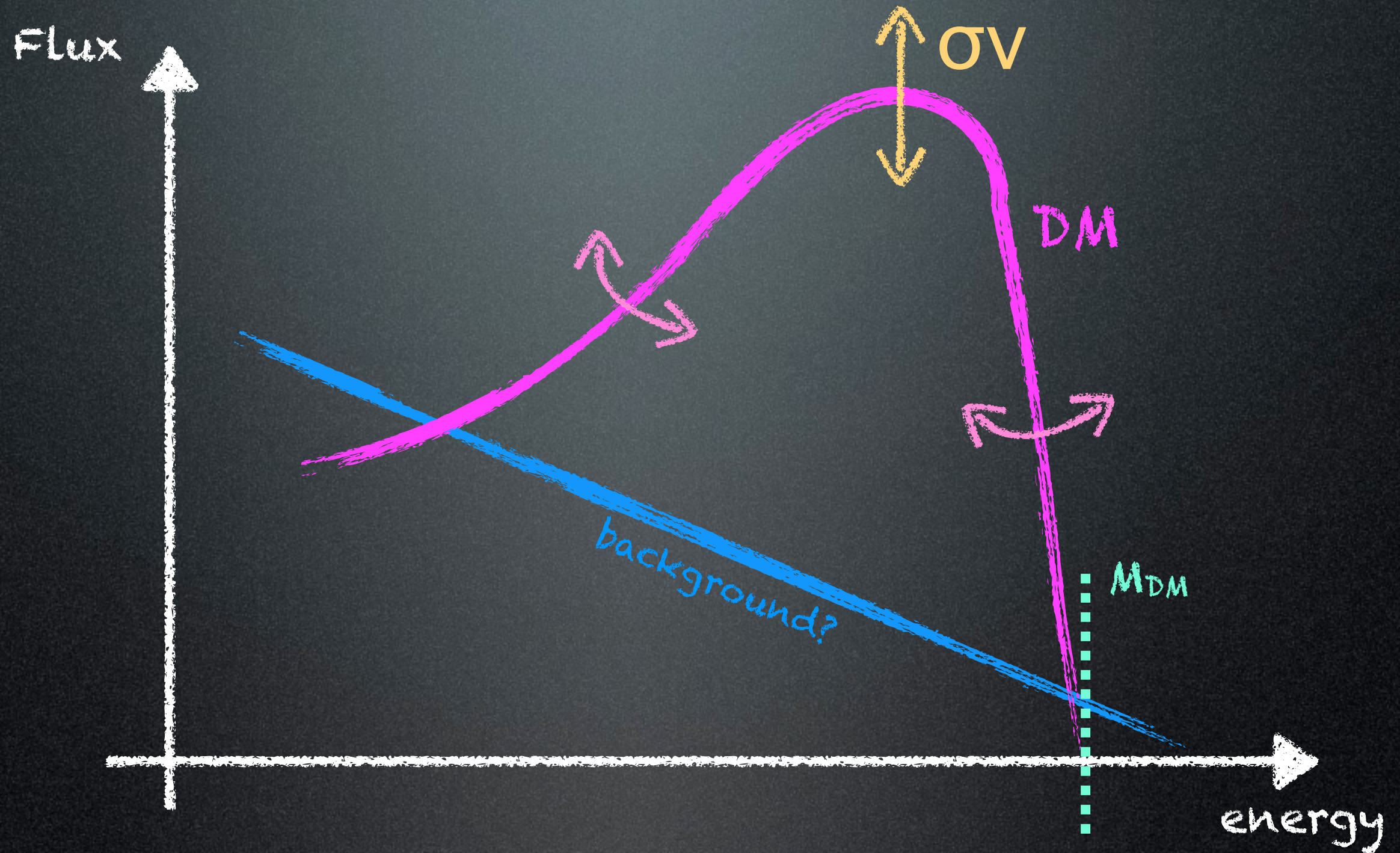
Fluxes at production



So what are the
particle physics
parameters?

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

Fluxes at production

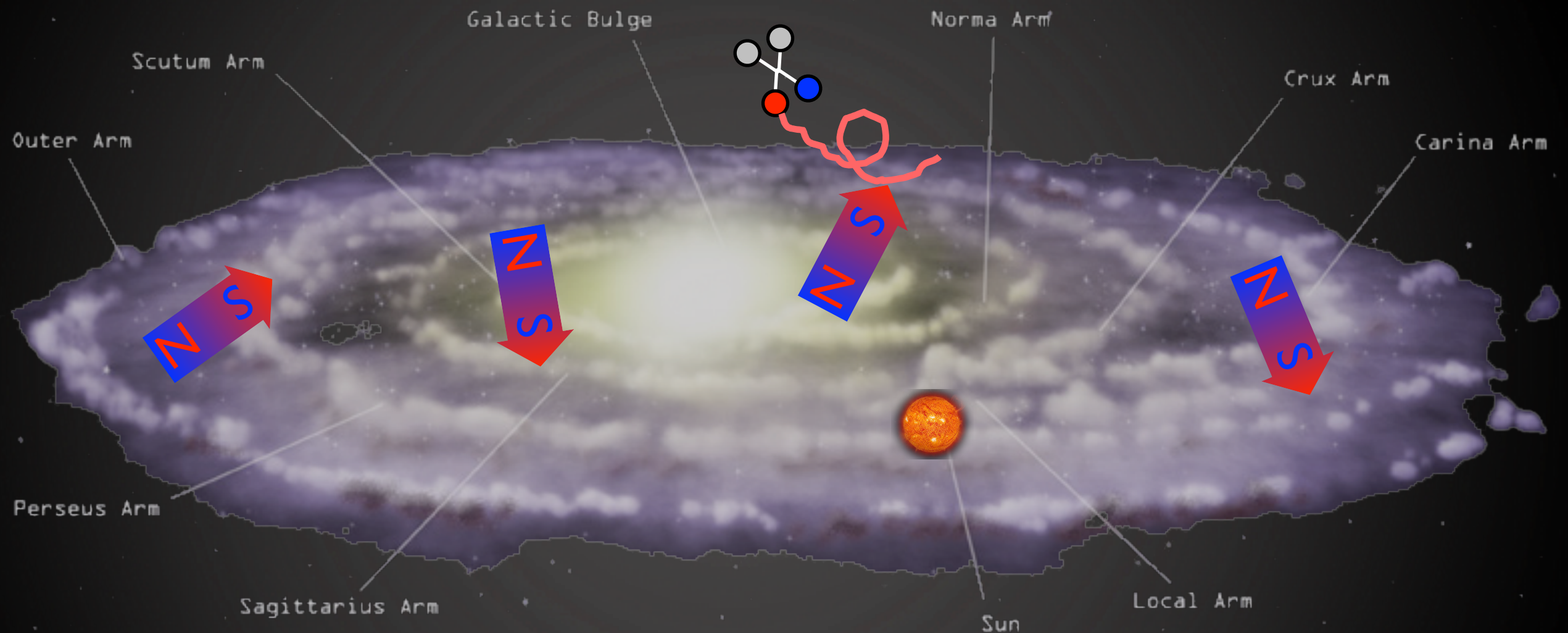


So what are the particle physics parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

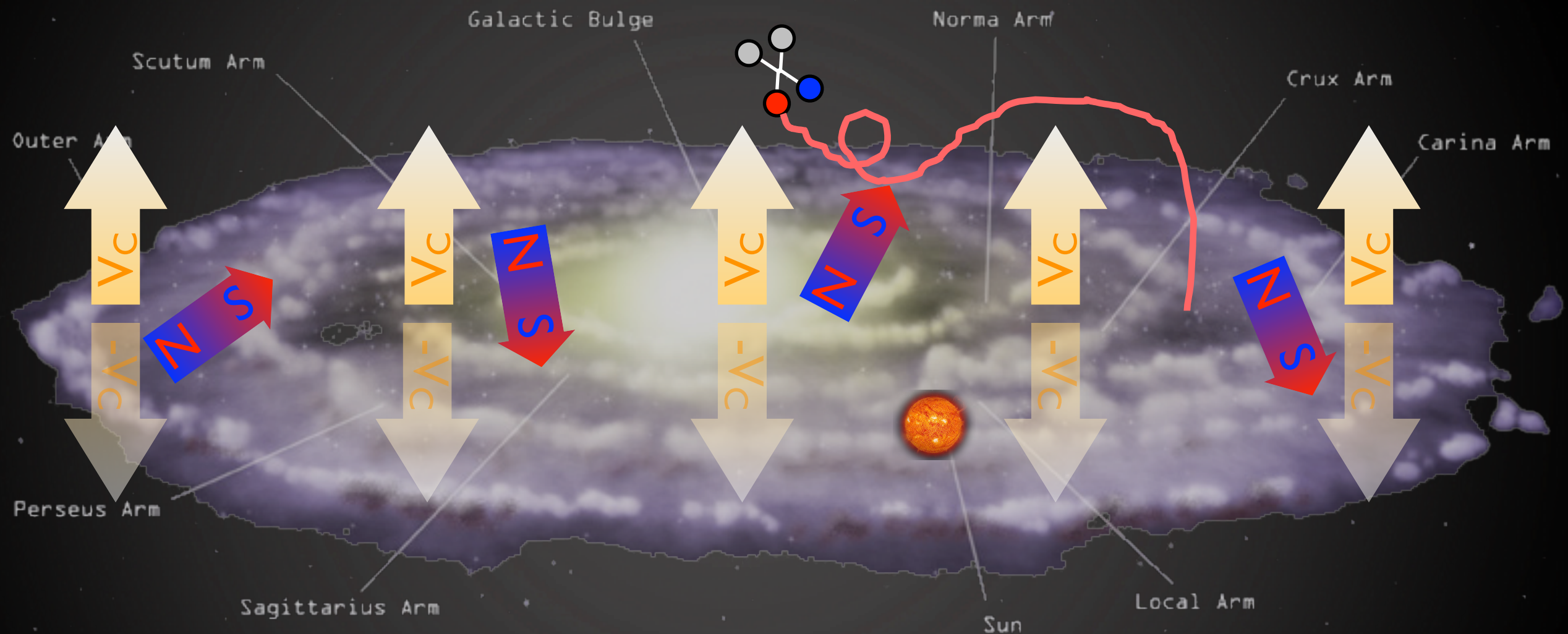
Indirect Detection: basics

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



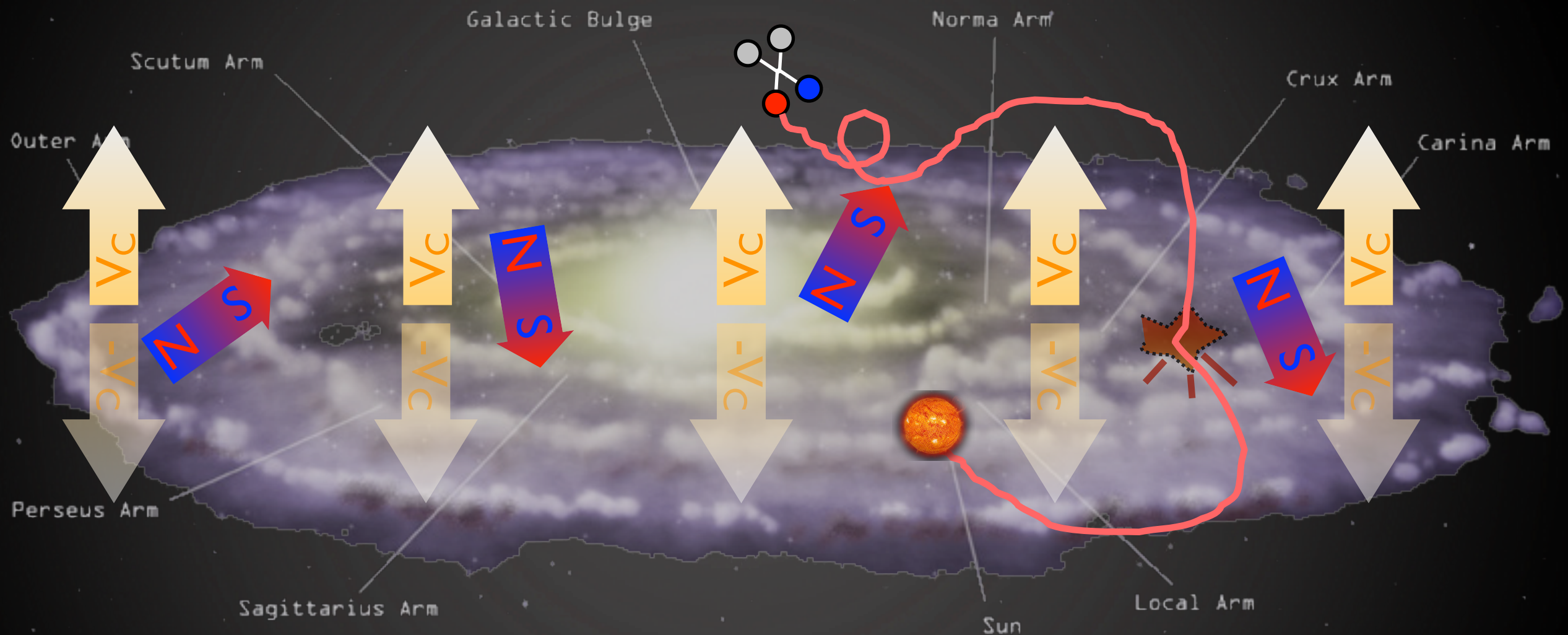
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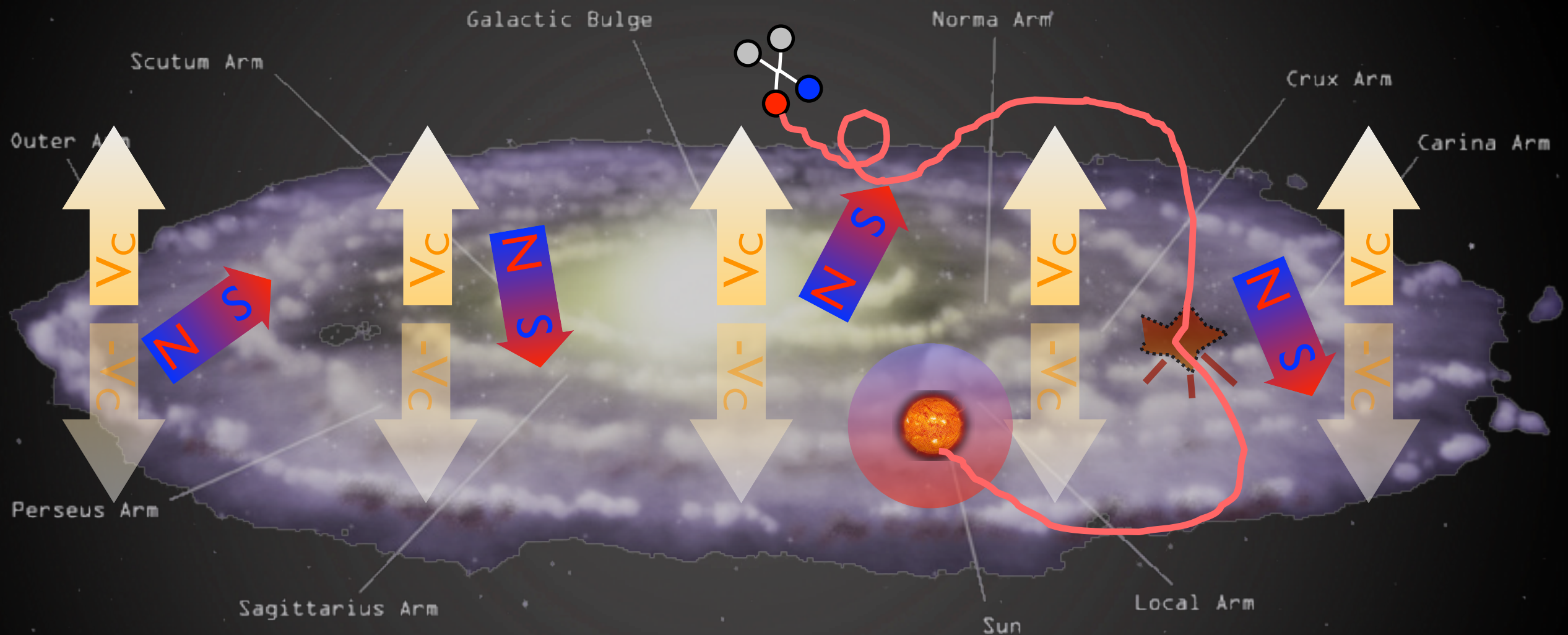
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$\bar{p}$ and e^+ from DM annihilations in halo



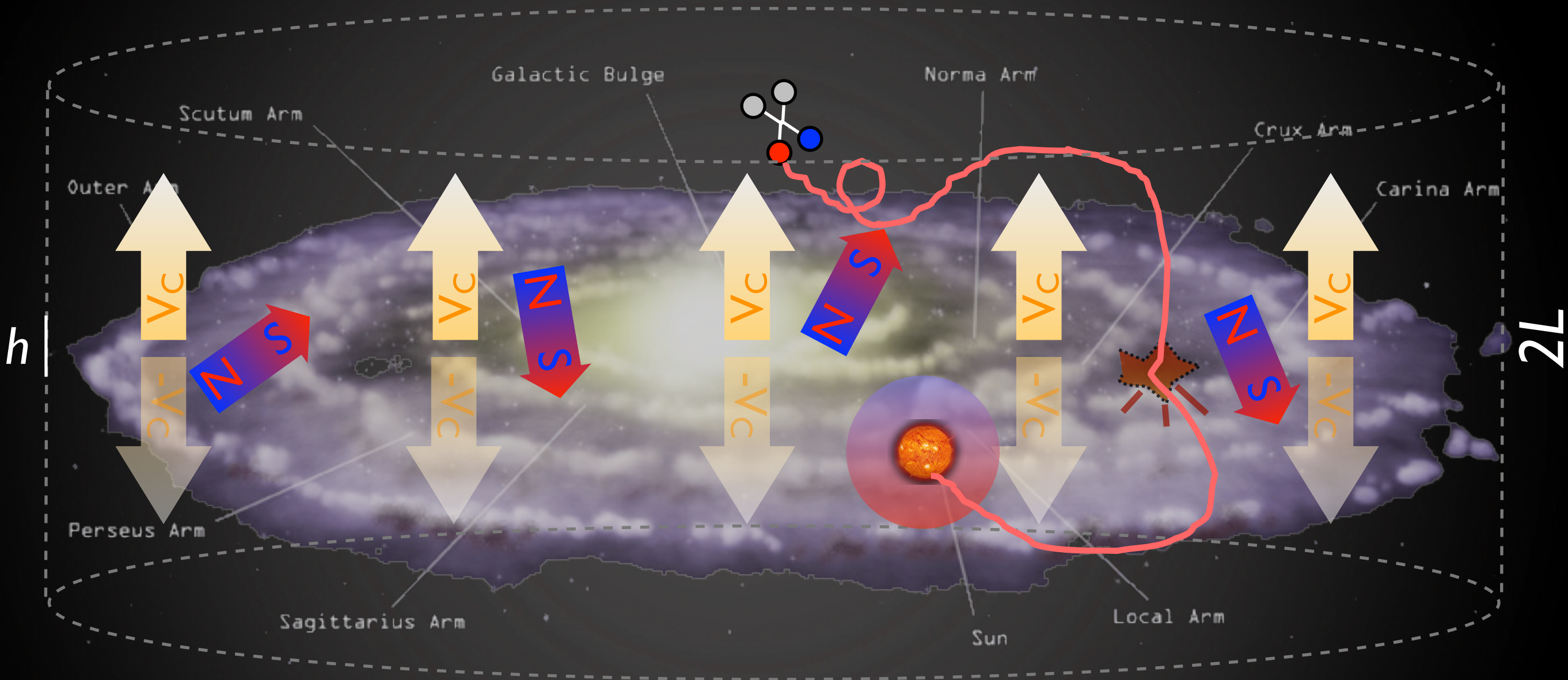
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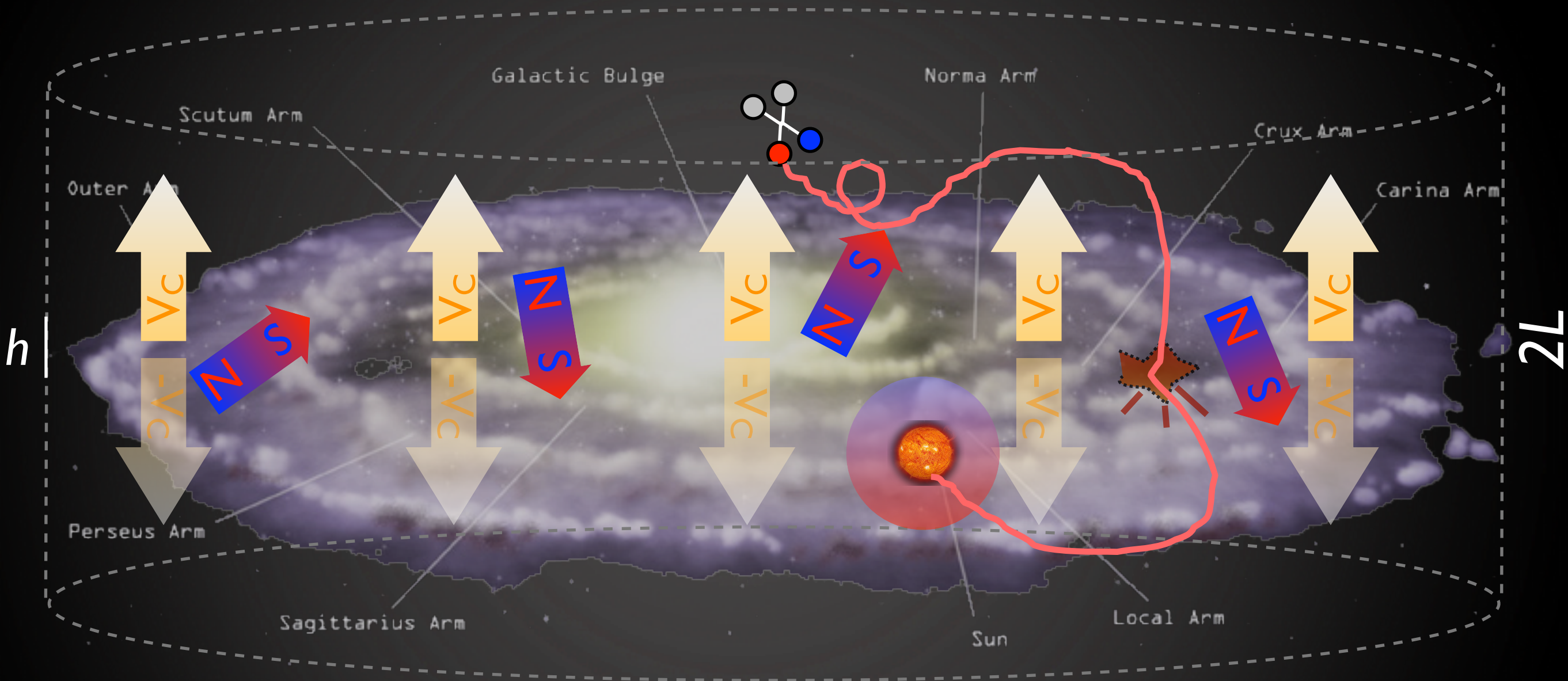
spectrum

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

diffusion energy loss convective wind source spallations

Indirect Detection: basics

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



spectrum

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

diffusion energy loss convective wind **source** spallations

Propagation

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T) \cdot \nabla^2 f + \frac{\partial}{\partial z} (\text{sign}(z) f V_{\text{conv}}) = Q - 2h \delta(z) \Gamma_{\text{ann}} f$$

diffusion

convective wind

spallations

$$K(T) = K_0 \beta (p/\text{GeV})^\delta$$

T kinetic energy

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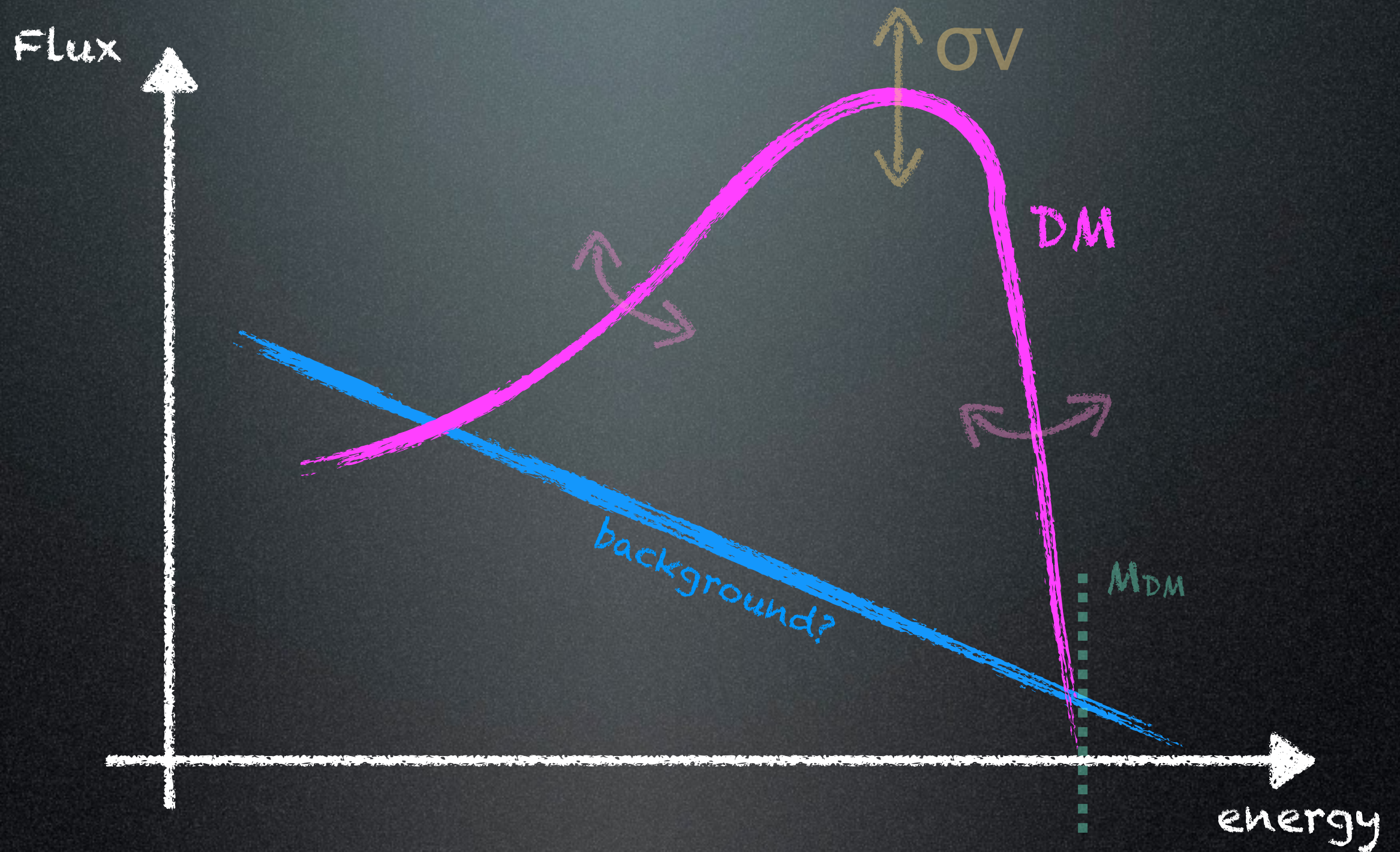
spallations

$$K(T) = K_0 \beta (p/\text{GeV})^\delta$$

T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

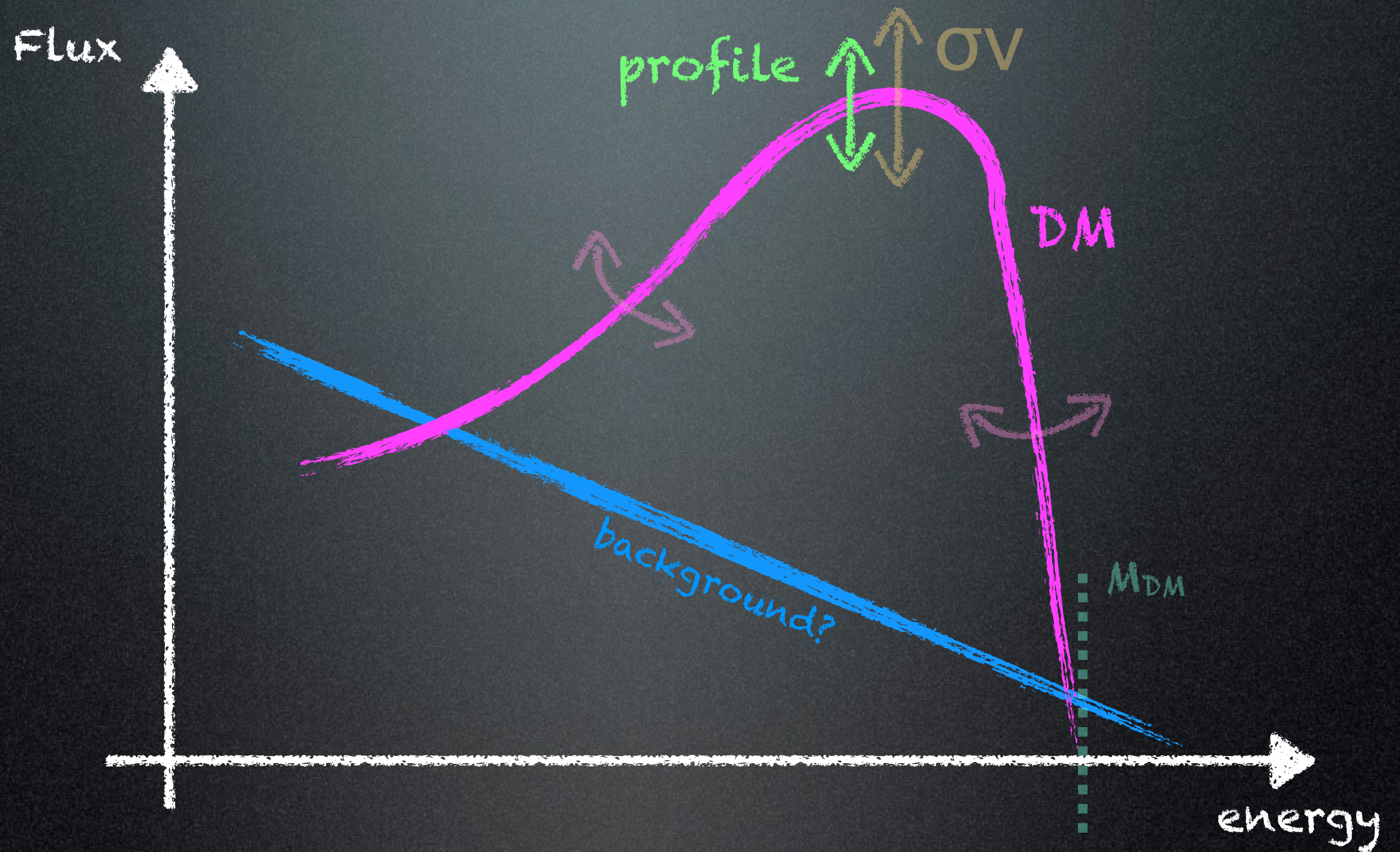
Fluxes at detection



So what are the
astrophysics
parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

Fluxes at detection

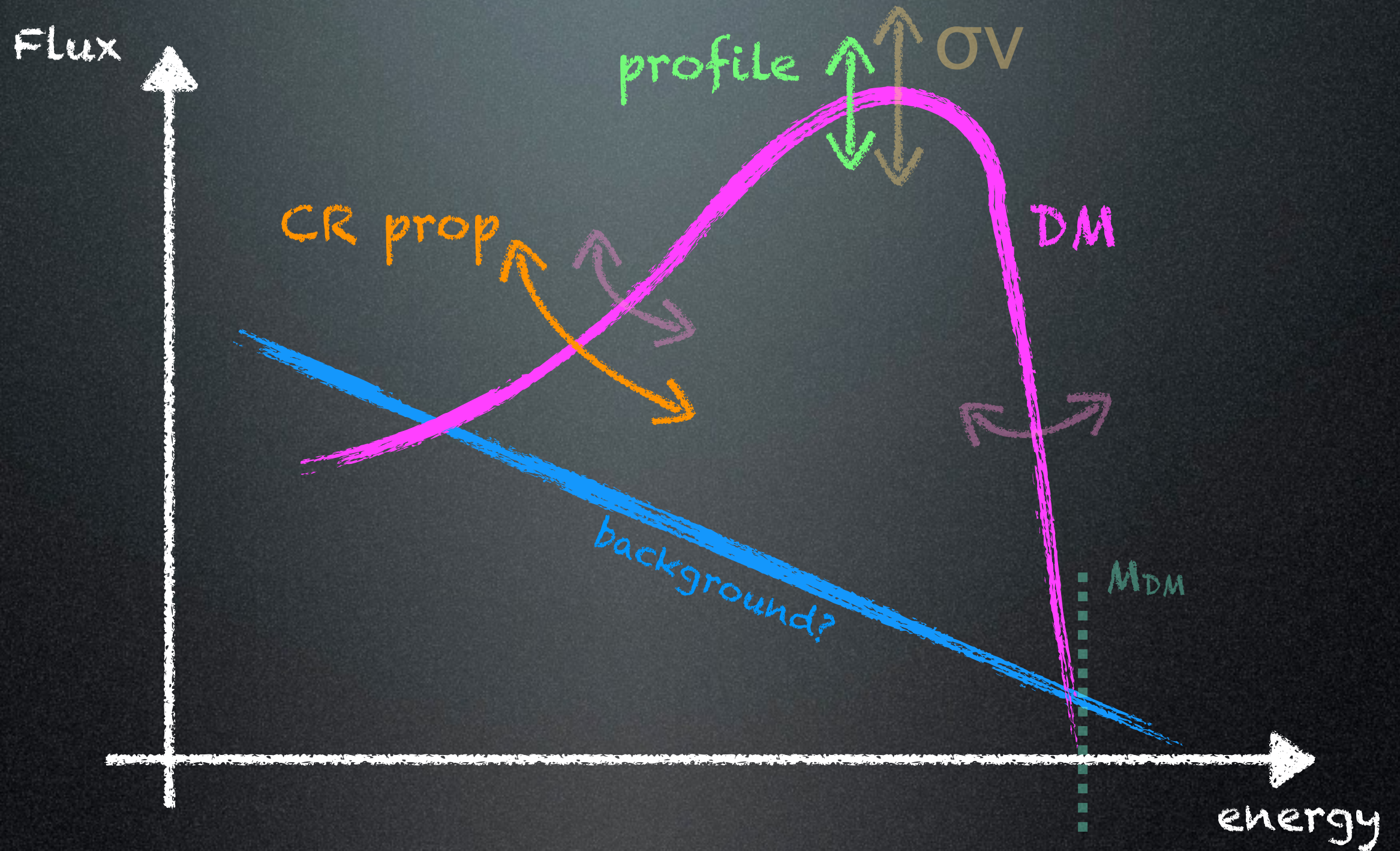


So what are the
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1. Dark Matter mass
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3. cross section

1. DM abundance/profile

Fluxes at detection

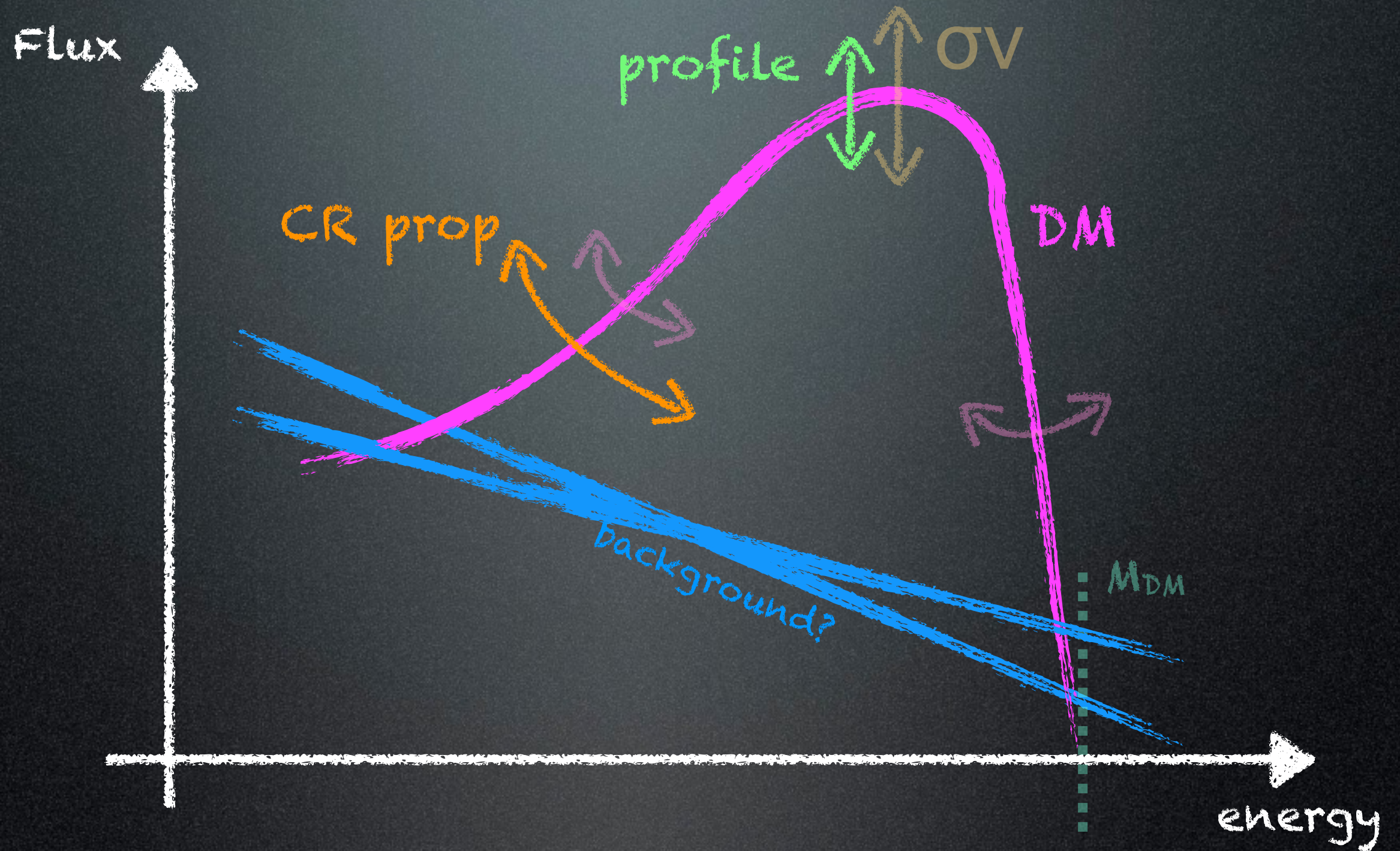


So what are the
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2. primary channel(s)
3. cross section

1. DM abundance/profile
2. propagation

Fluxes at detection

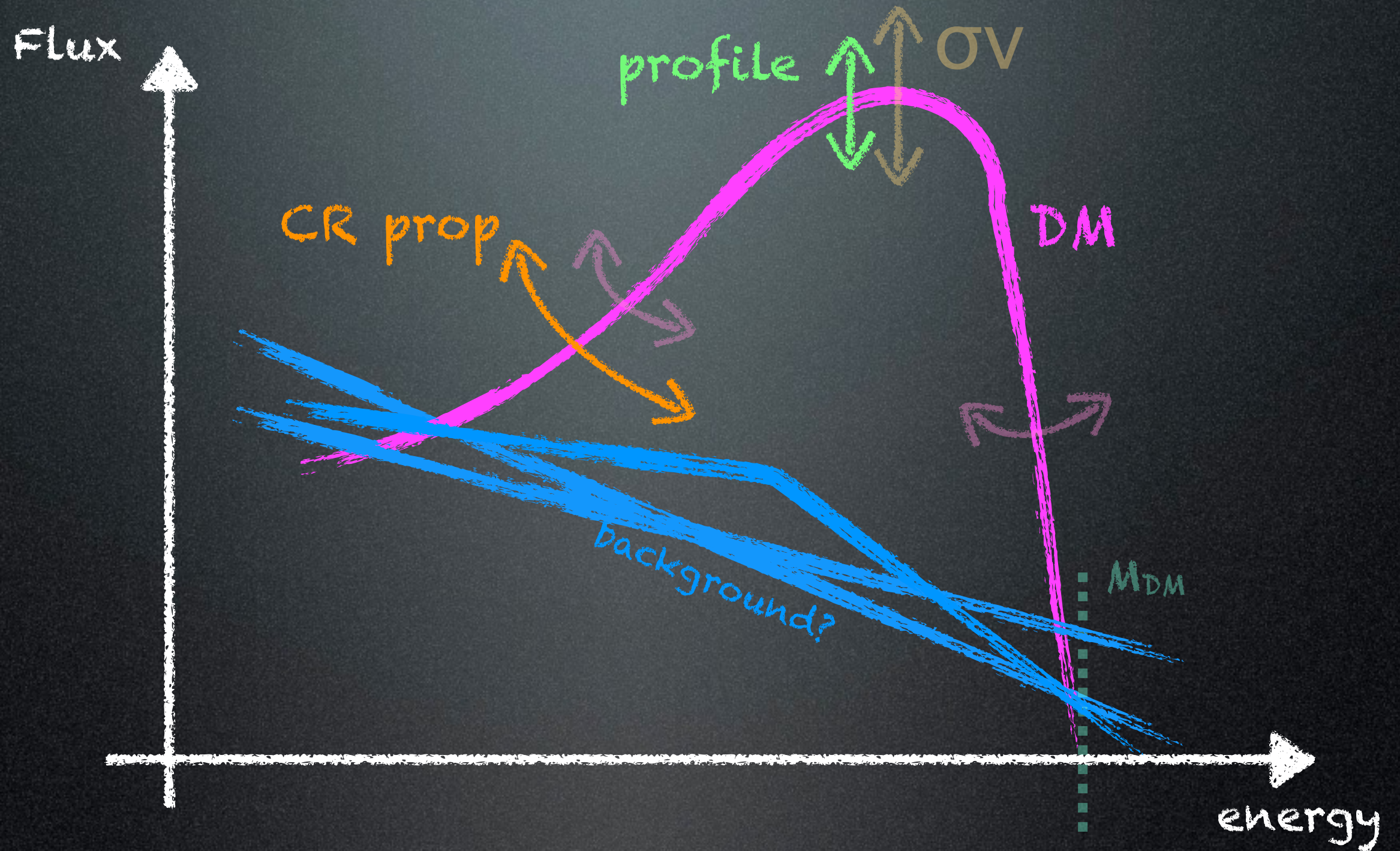


So what are the
astrophysics
parameters?

1. Dark Matter mass
2. primary channel(s)
3. cross section

1. DM abundance/profile
2. propagation
3. background

Fluxes at detection



So what are the
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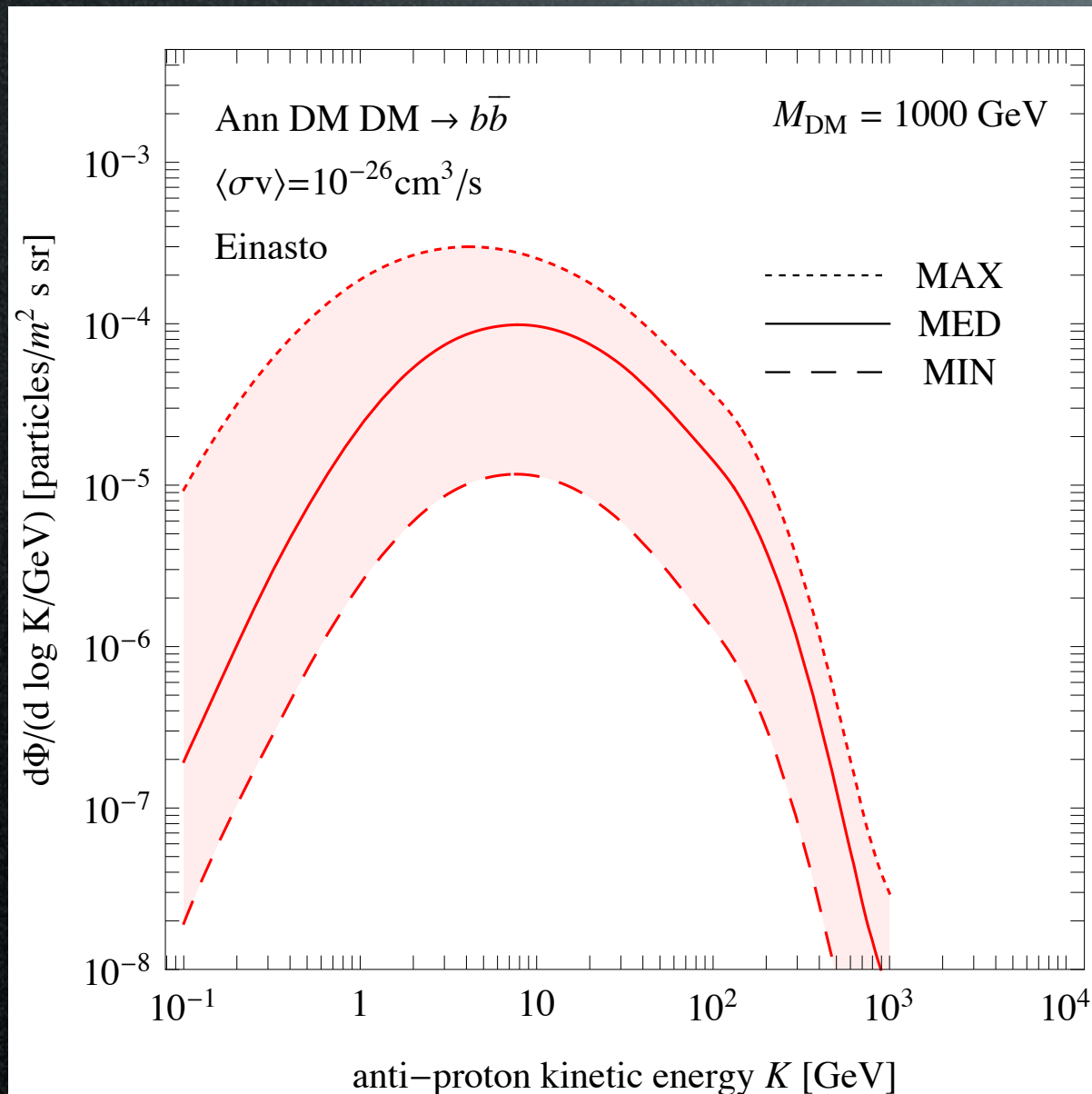
1. Dark Matter mass
2. primary channel(s)
3. cross section

1. DM abundance/profile
2. propagation
3. background

Propagated fluxes

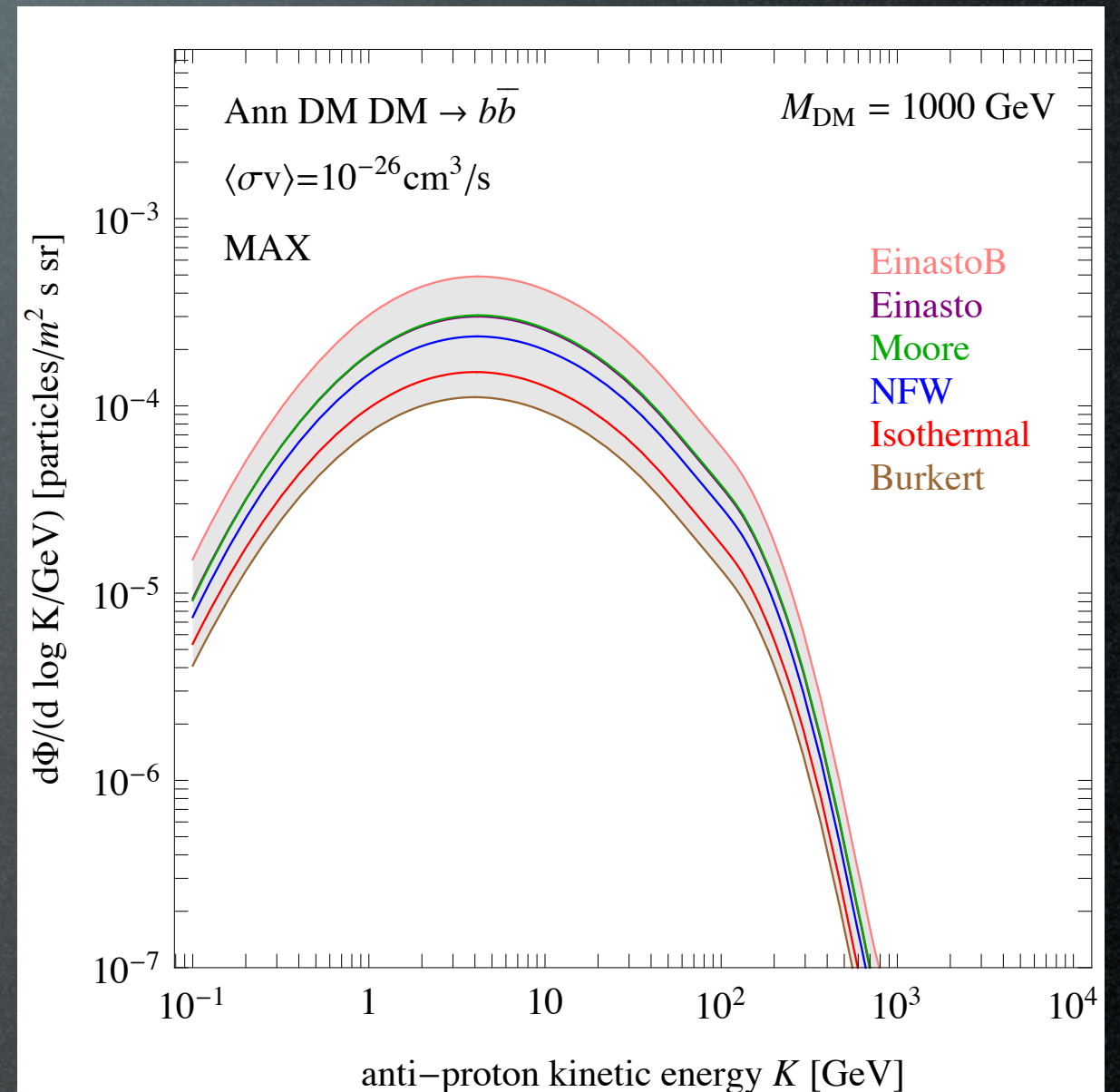
Antiprotons

Varying prop parameters



Almost 2 orders of magnitude

Varying halo profile



Almost 1 order of magnitude

Bottom line: Antiprotons are quite affected by propagation, but spectral shape somewhat preserved

Propagation

Propagation for **positrons**: conventional treatment

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E} (b(E)f) = Q$$

diffusion

(in turbulent $\bar{B} \approx \mu\text{G}$,
assumed space indep.)

$$K(E) = K_0 (E/\text{GeV})^\delta$$

energy loss (assumed space indep.)

$$b(E) = (E/\text{GeV})^2 / \tau_E$$

$$\tau_E = 10^{16} \text{ s}$$

$$Q = \frac{1}{2} \left(\frac{\rho}{M_{\text{DM}}} \right)^2 f_{\text{inj}}, \quad f_{\text{inj}} = \sum_k \langle \sigma v \rangle_k \frac{dN_{e^+}^k}{dE}$$

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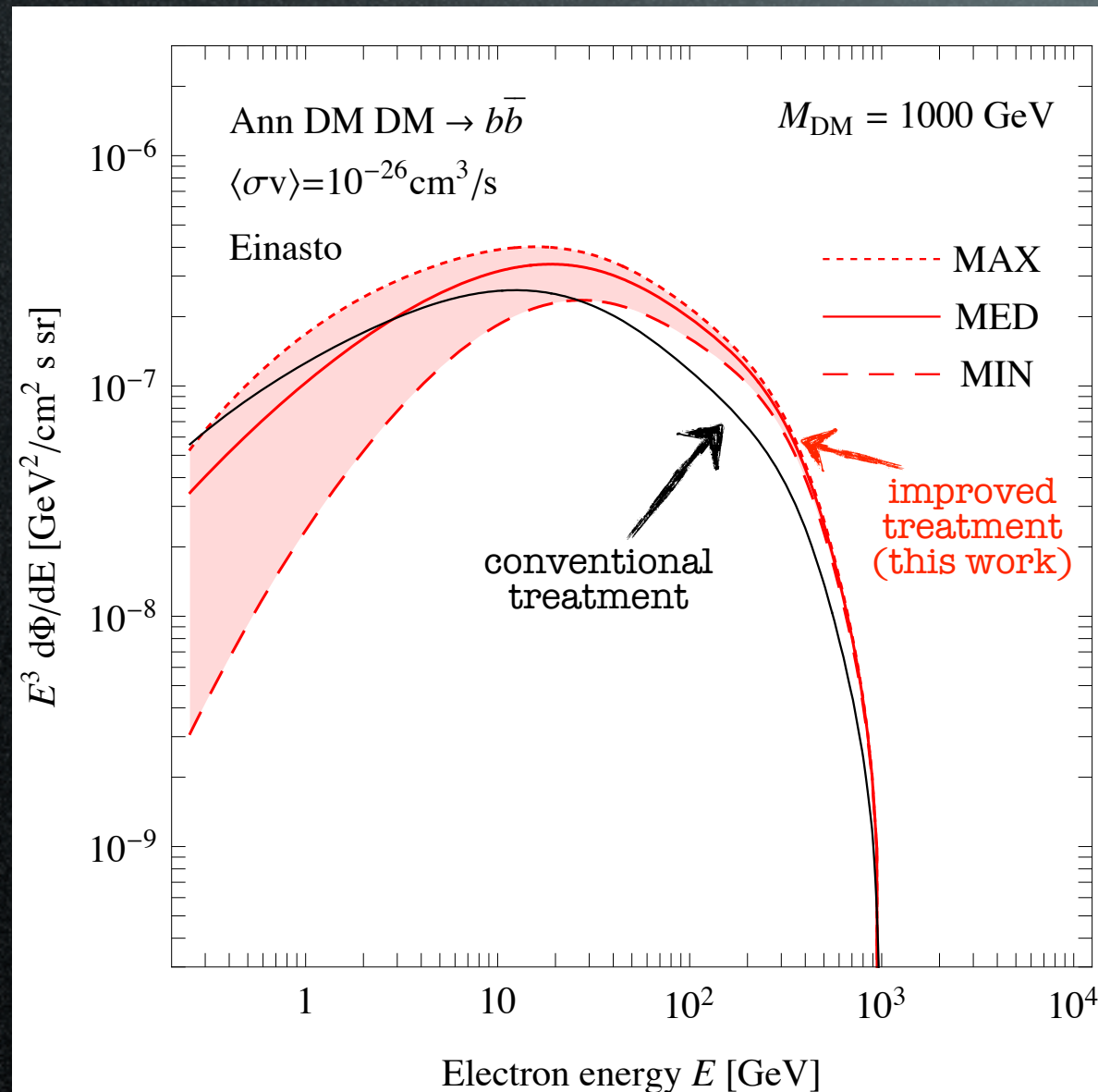
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min (M2)	0.55	0.00595	1
med	0.70	0.0112	4
max (M1)	0.46	0.0765	15

Propagated fluxes

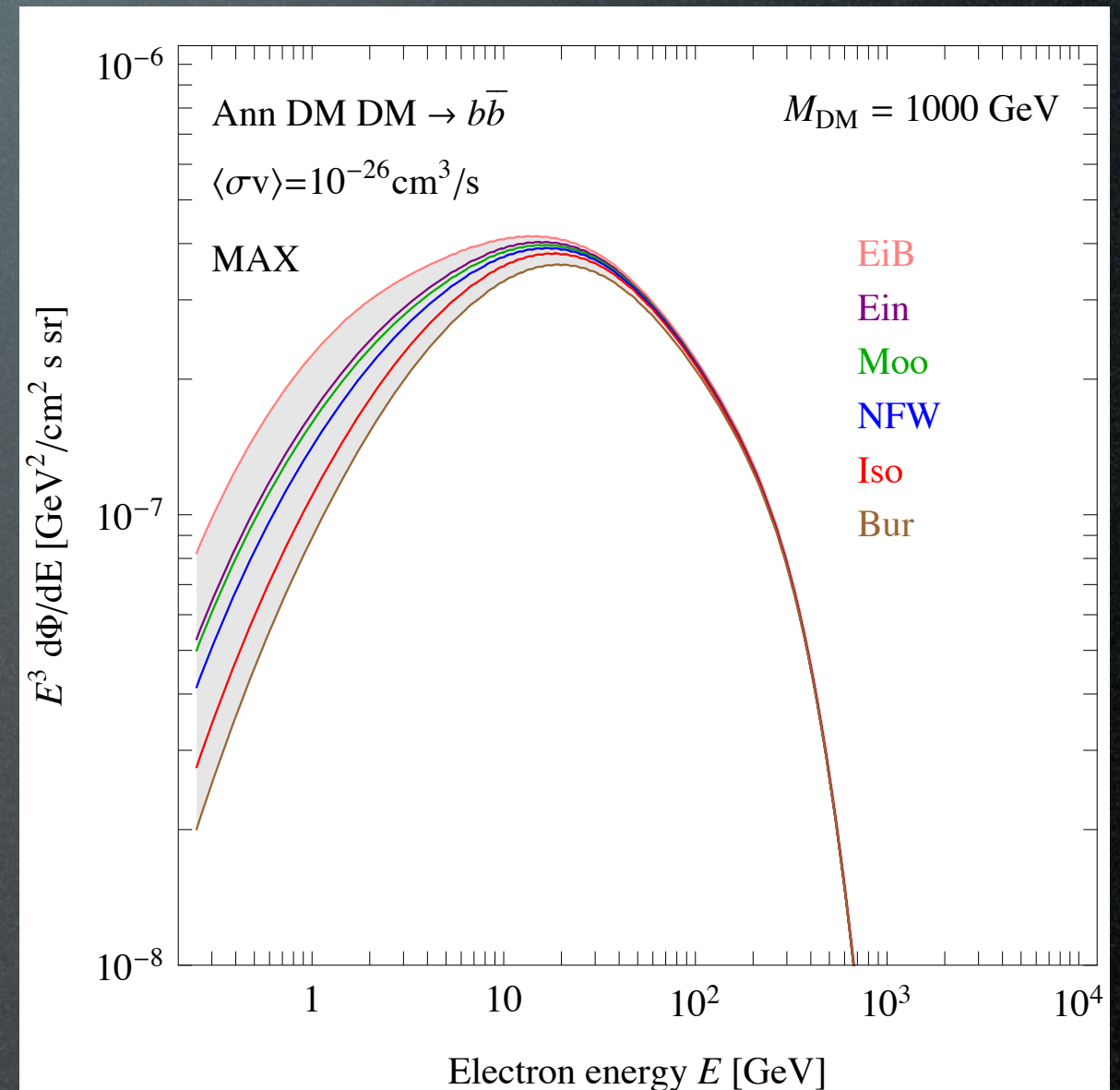
Positrons

Varying prop parameters



From factor 10 to no effect

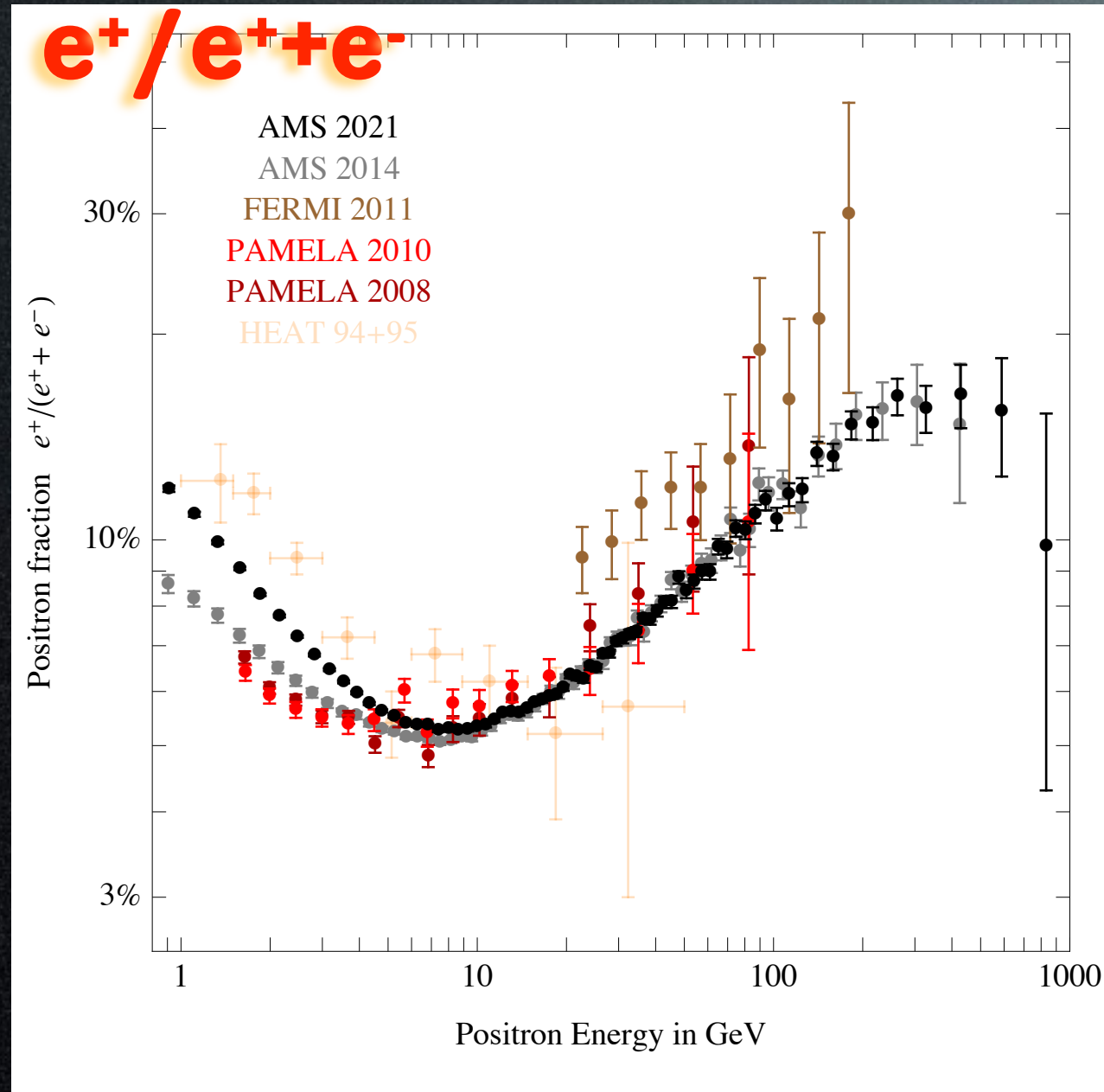
Varying halo profile



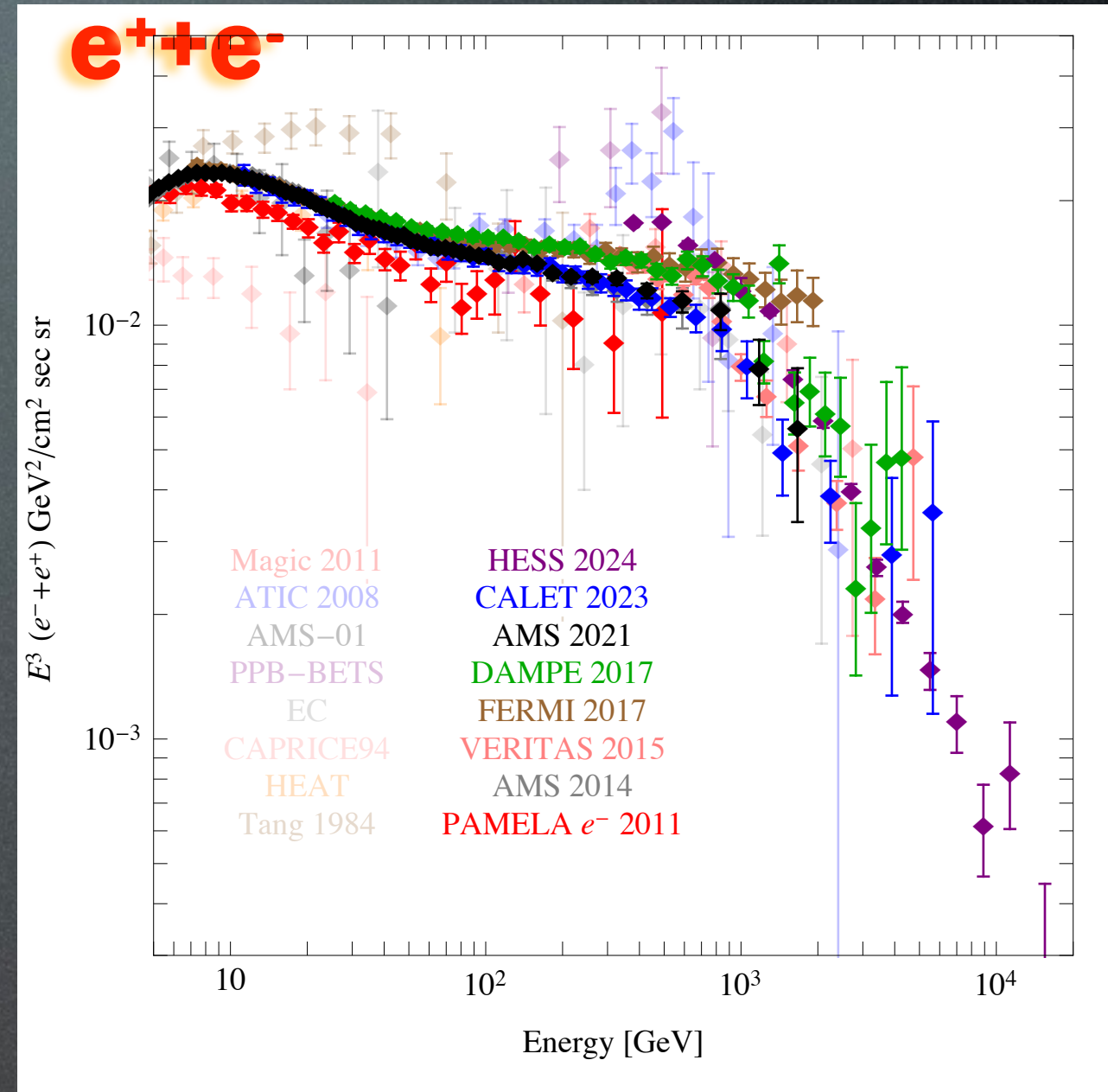
From factor 10 to no effect

Bottom line: Positrons are affected by propagation, mainly at low energy

Data: leptons

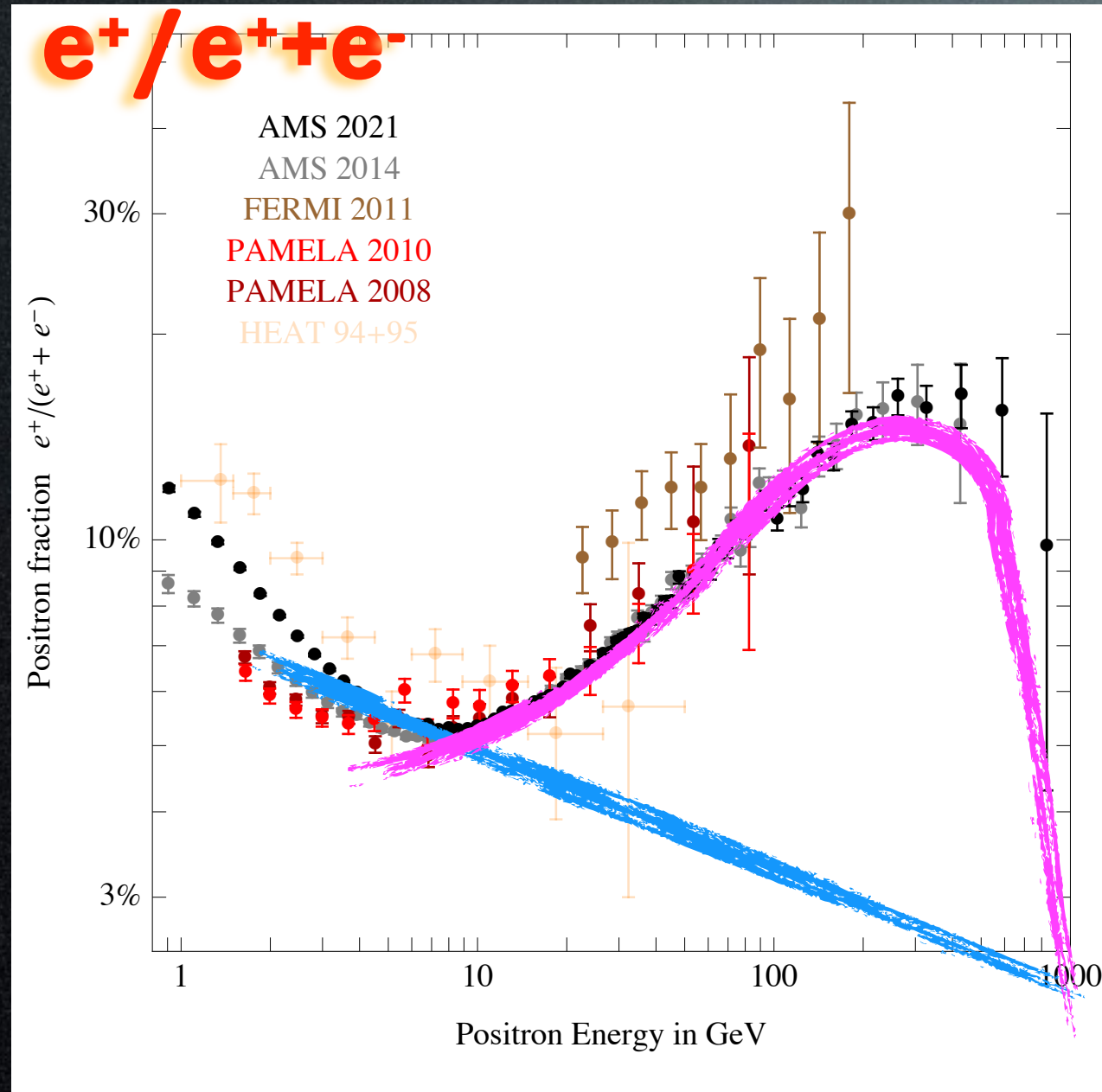


Cirelli, Strumia, Zupan 2406.01705

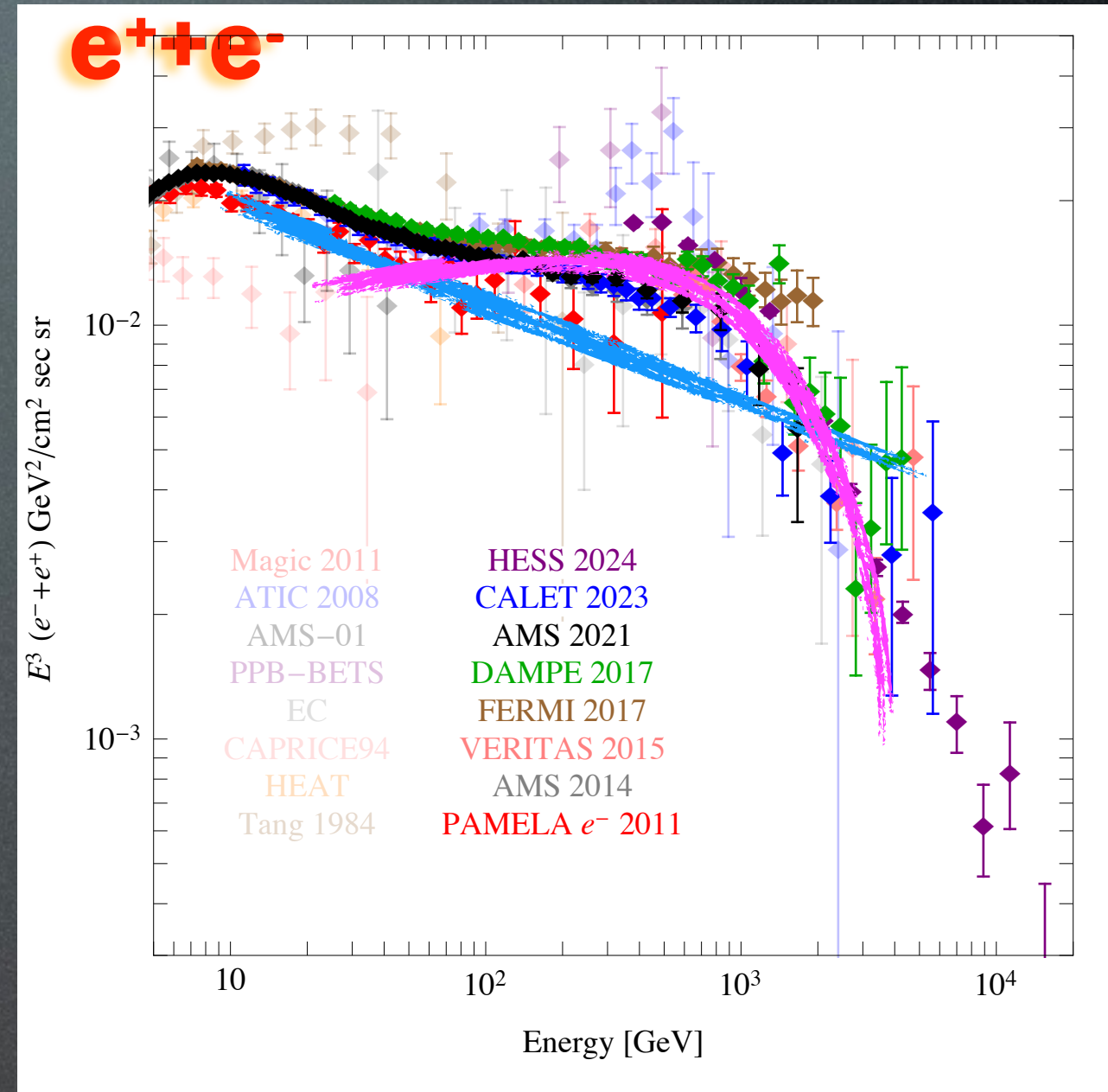


Cirelli, Strumia, Zupan 2406.01705

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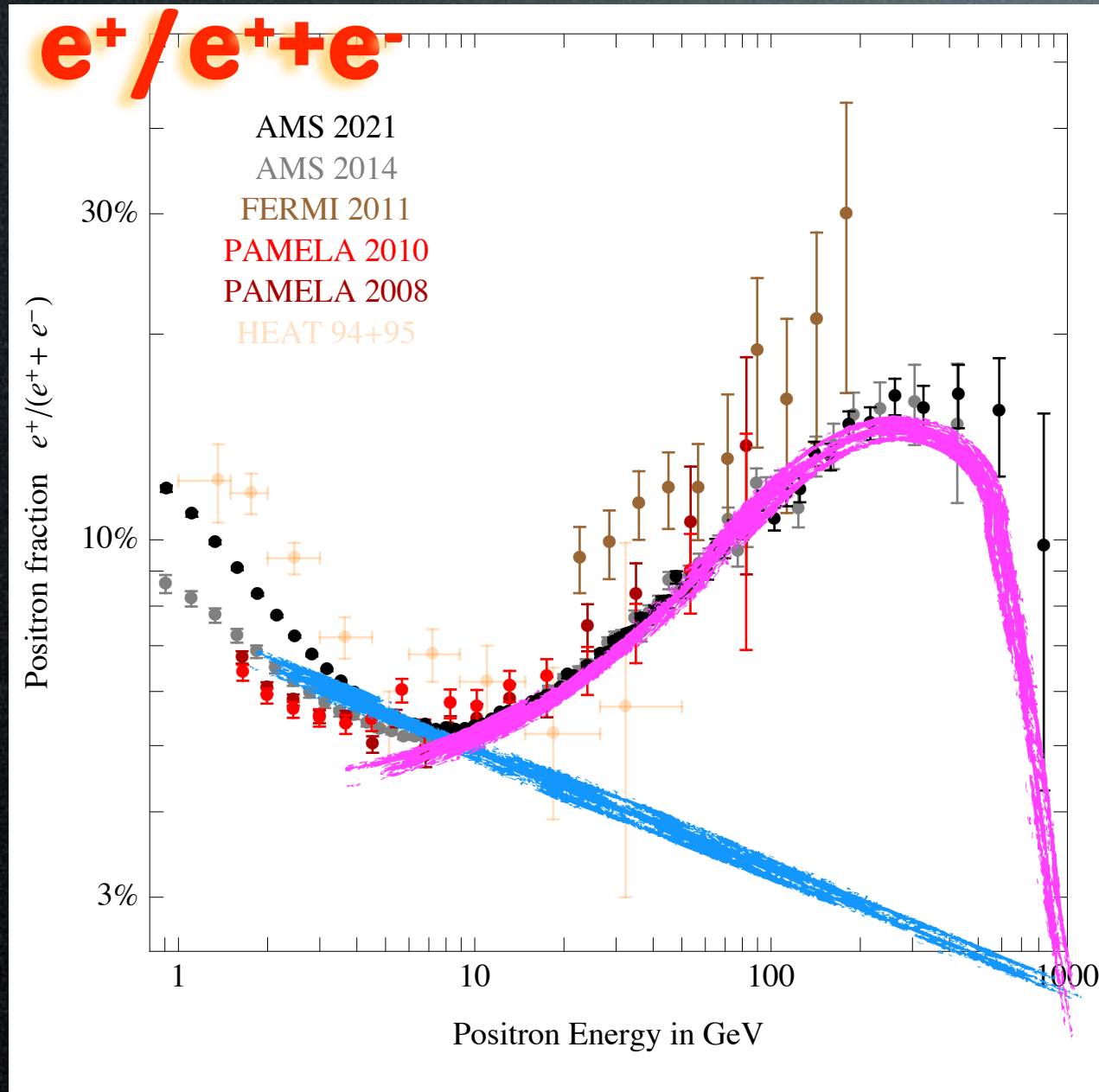


Cirelli, Strumia, Zupan 2406.01705

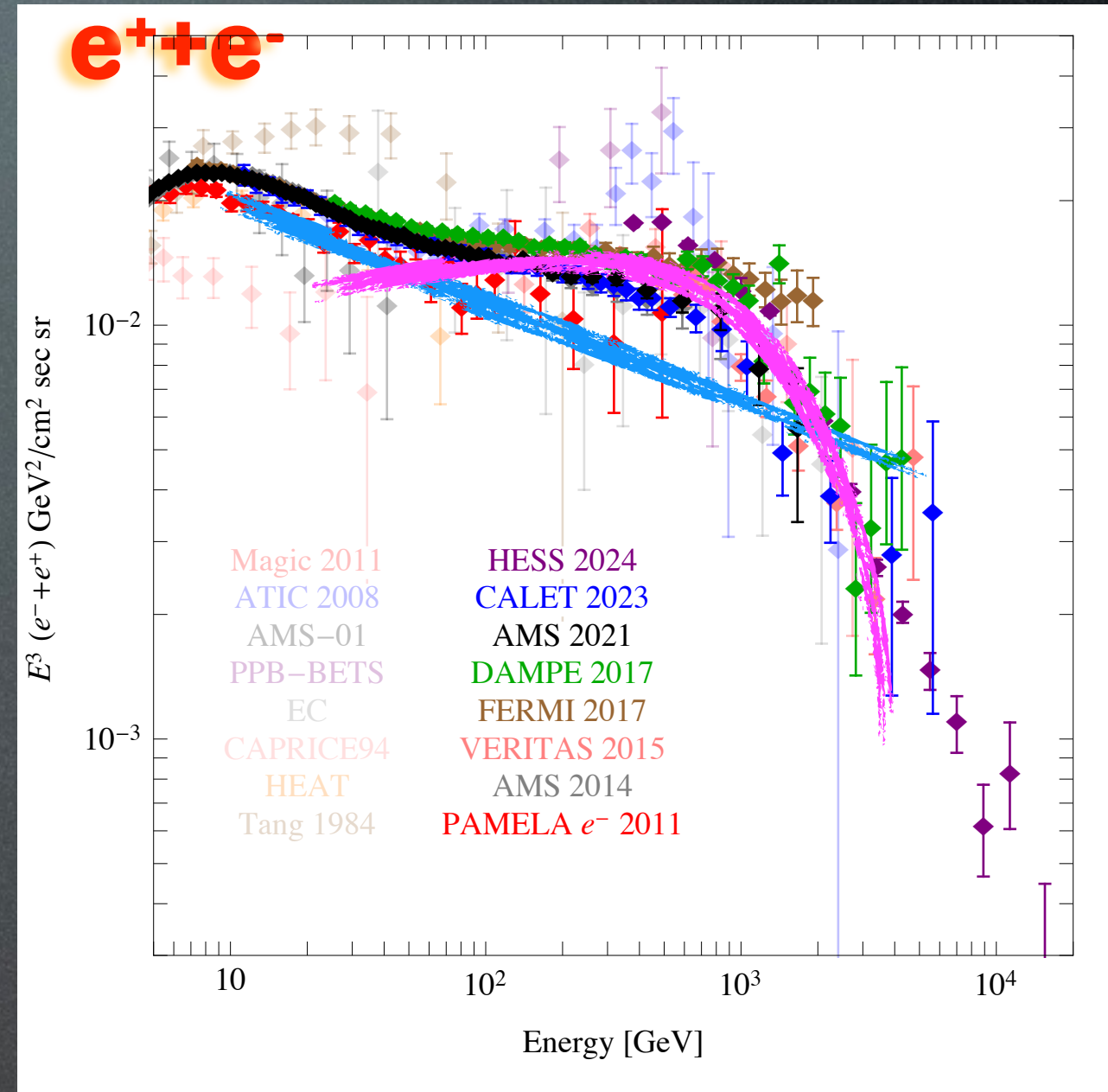


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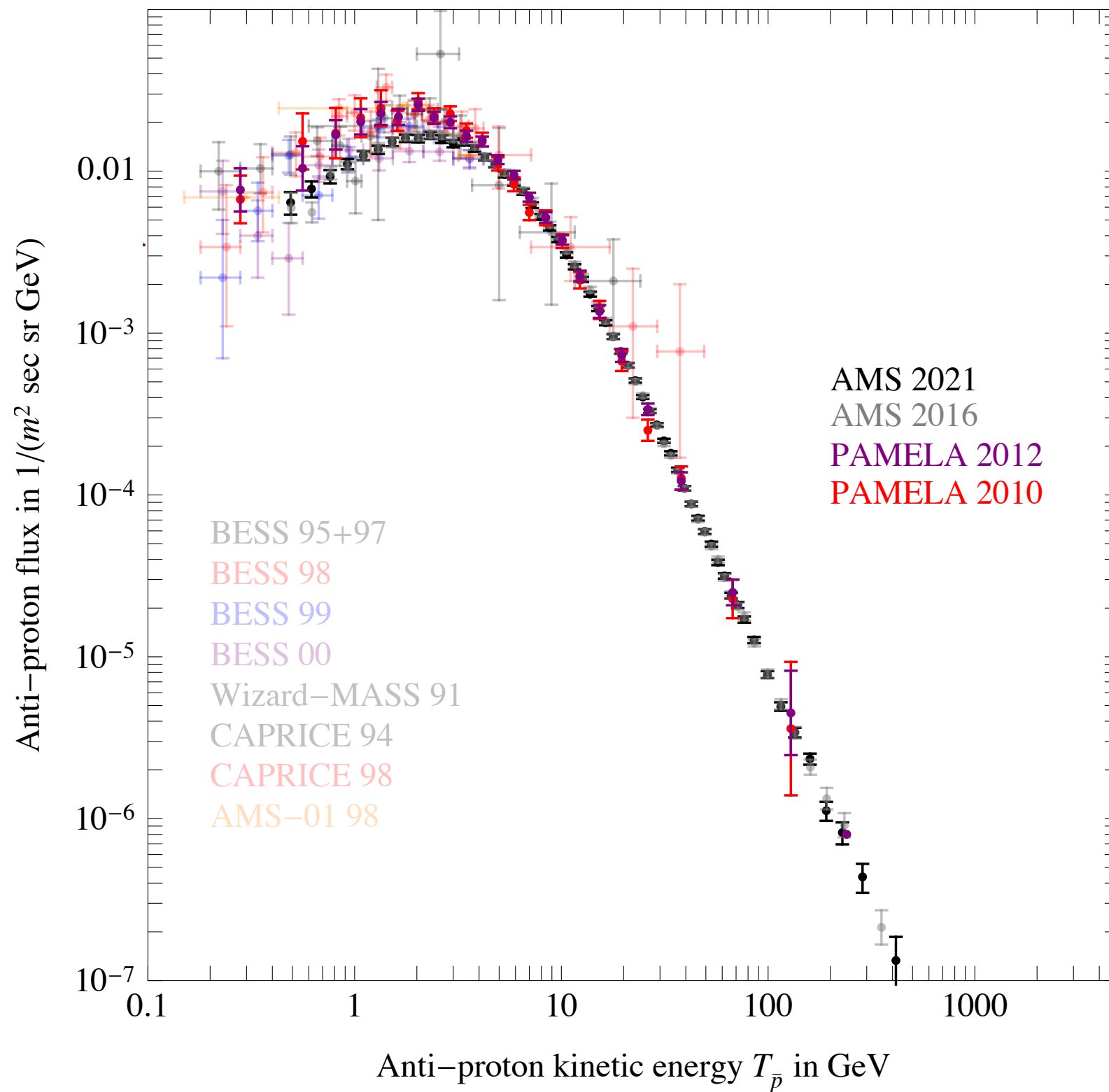
Cirelli, Strumia, Zupan 2406.01705



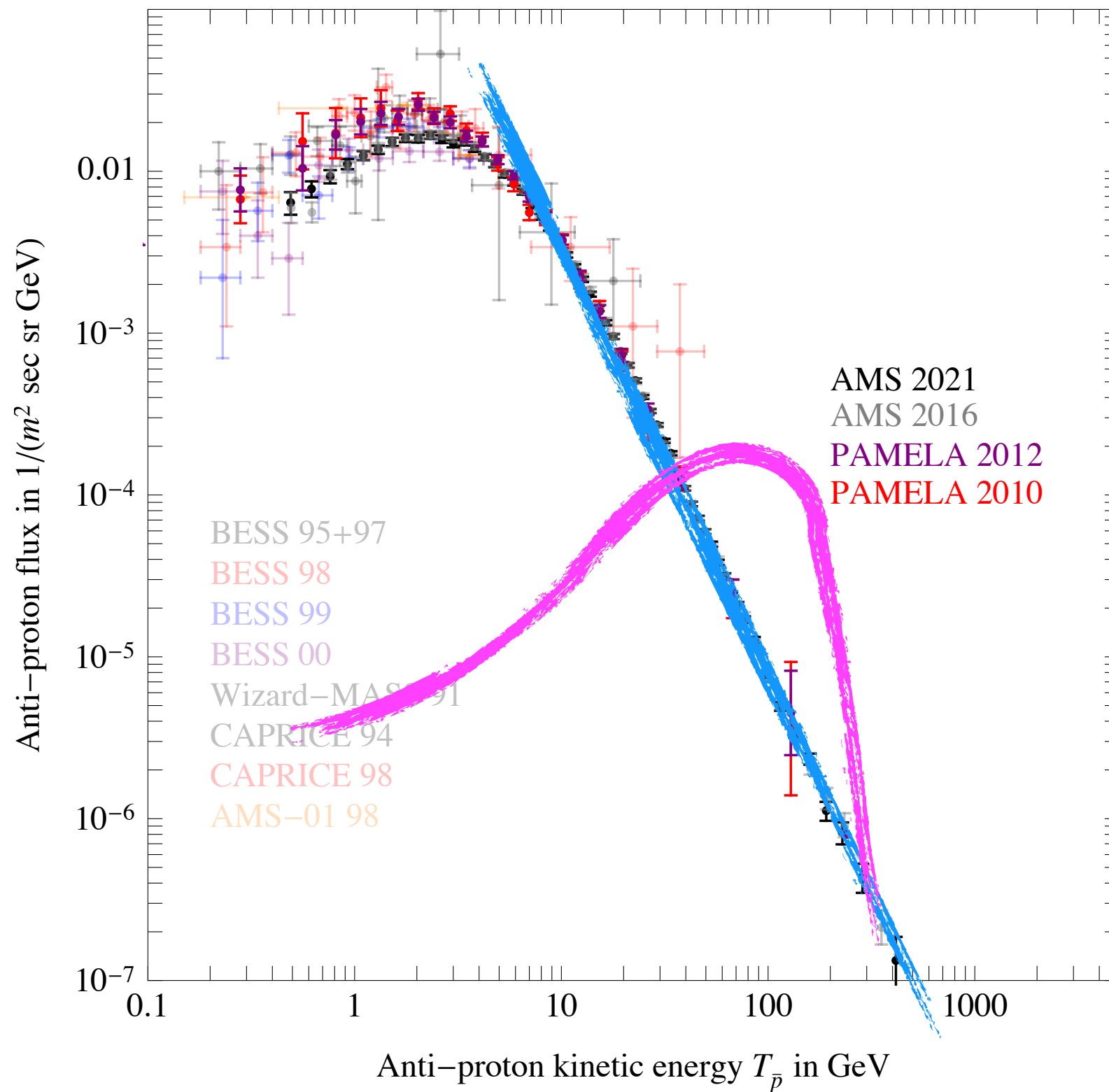
Cirelli, Strumia, Zupan 2406.01705

- leptophilic
- $m_{\text{DM}} \quad 1 \text{ TeV}$
- huge annihilation cross section

Data: antiprotons

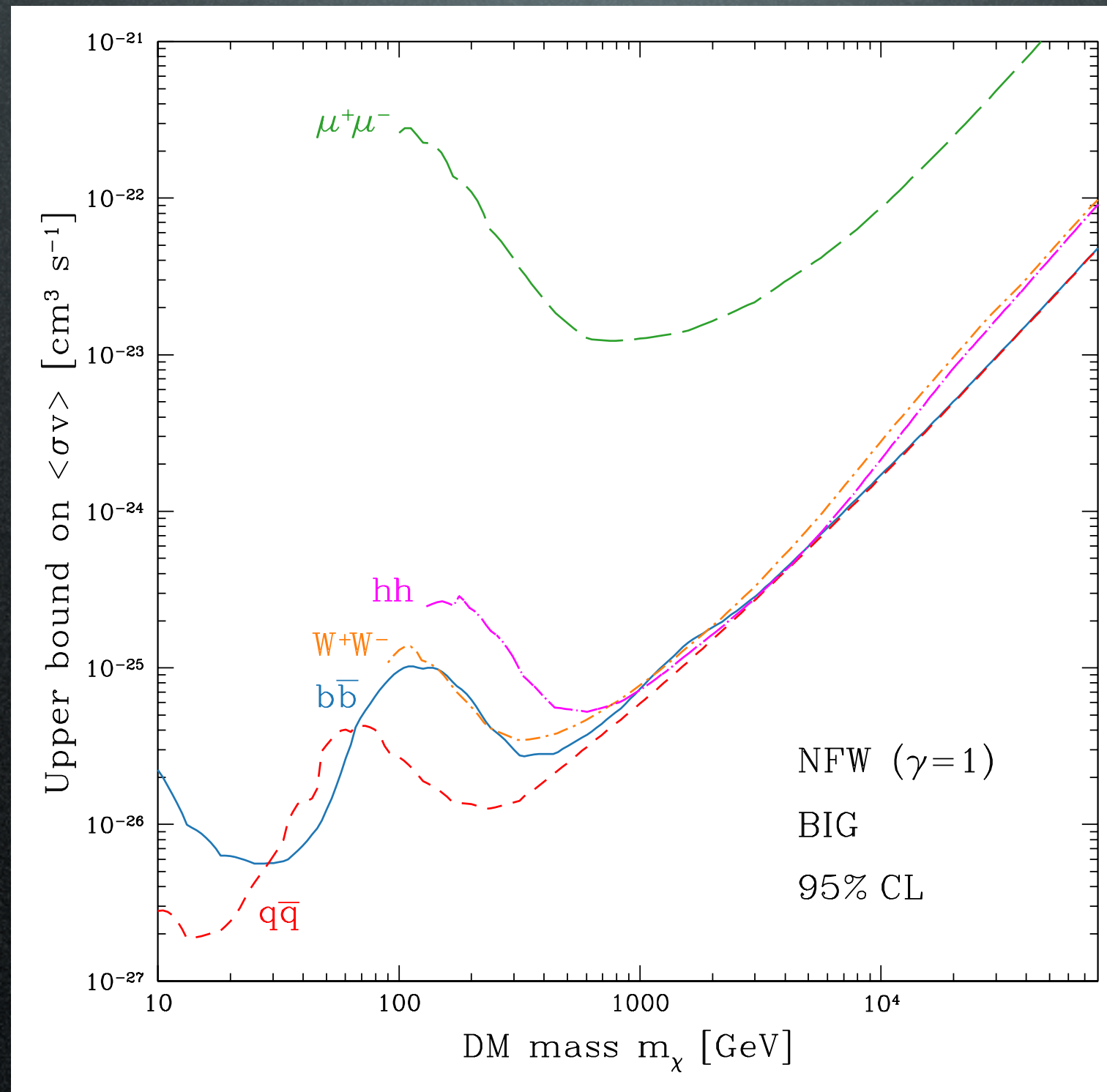


Data: antiprotons



Model independent bounds

Based on AMS-02 $\bar{p}$ data (2016)



Calore, Cirelli,
Derome, Génolini,
Maurin, Salati, Serpico
2202.03076

Giesen, Boudaud,
Génolini, Poulin,
Cirelli, Salati,
Serpico
1504.04276

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

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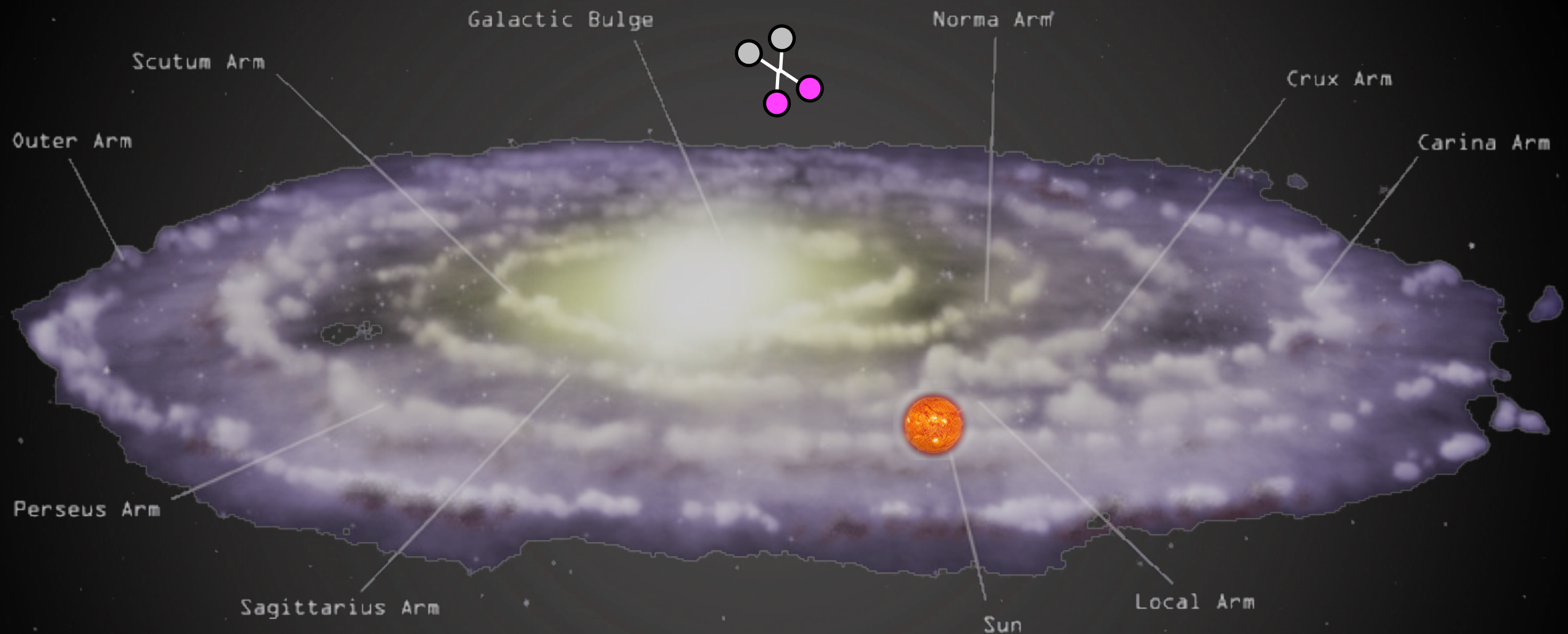
GAPS

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

Icecube, Km3Net

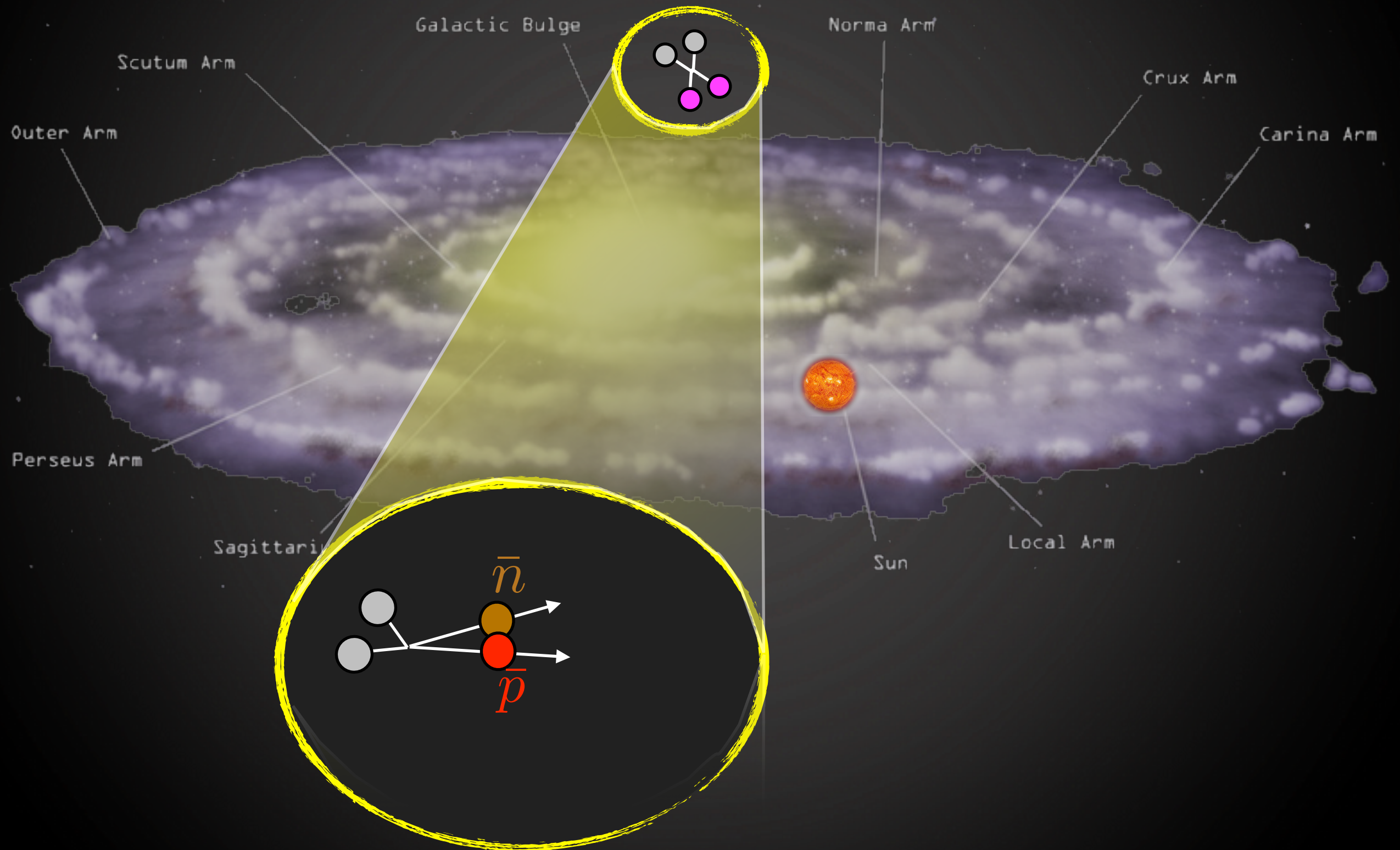
Indirect Detection

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



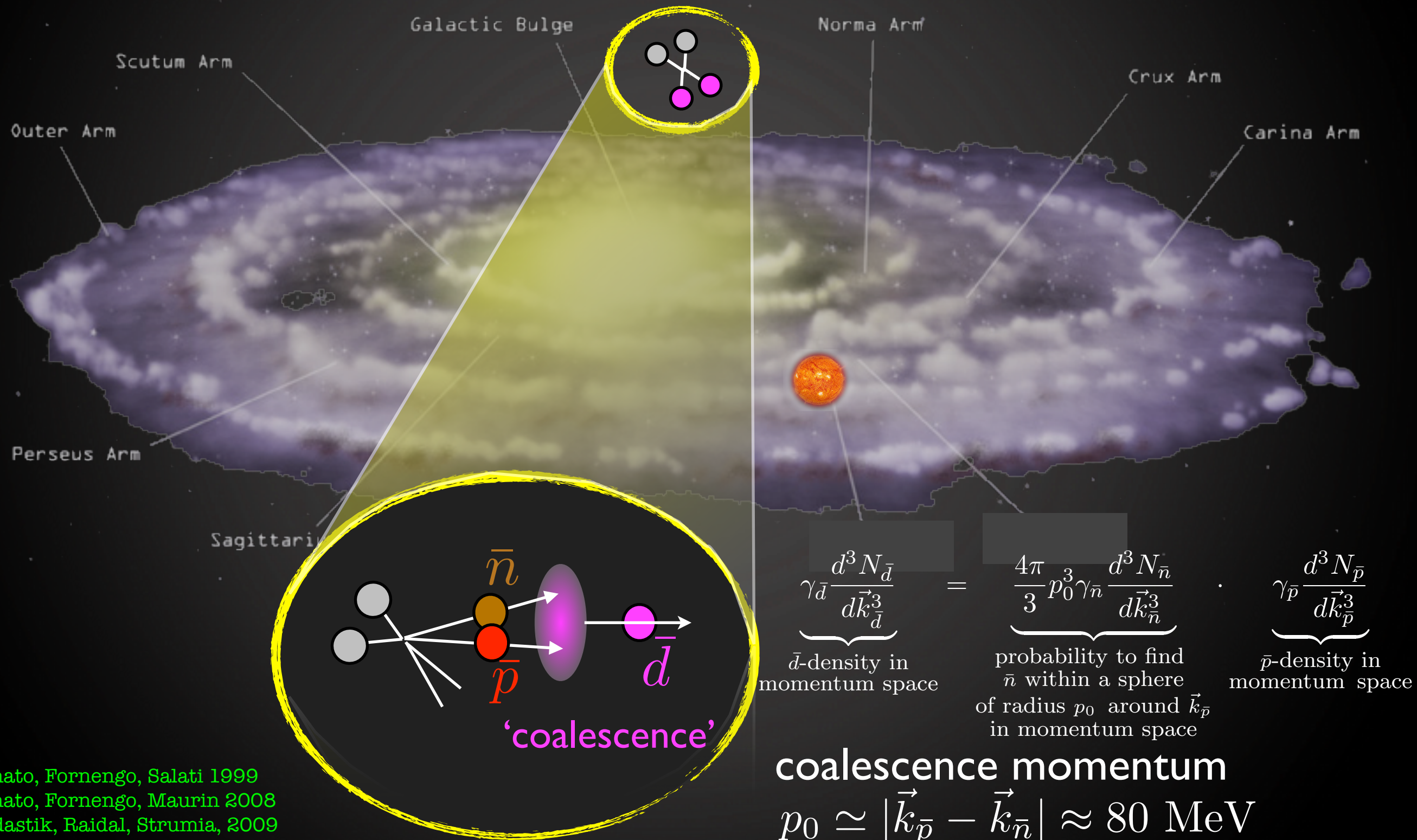
Indirect Detection

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



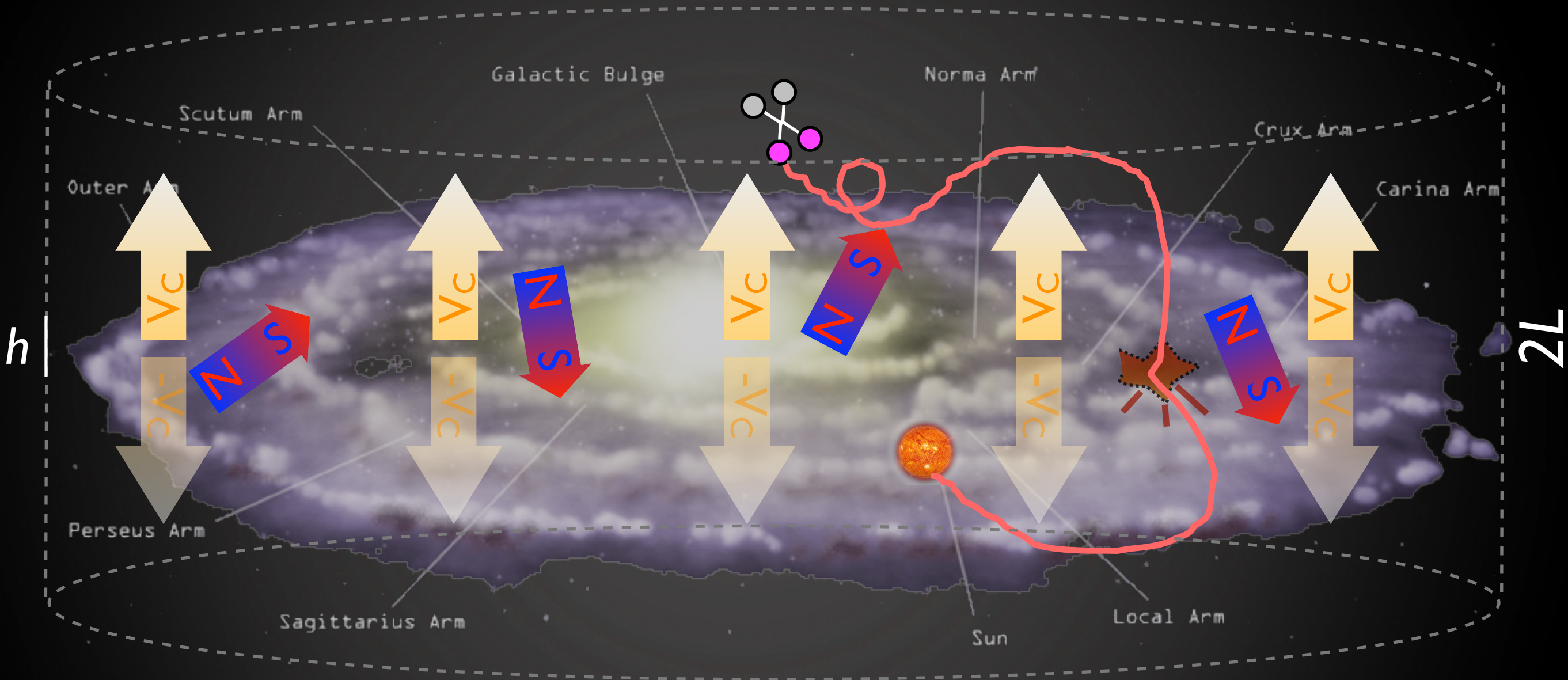
Indirect Detection

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



Indirect Detection

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



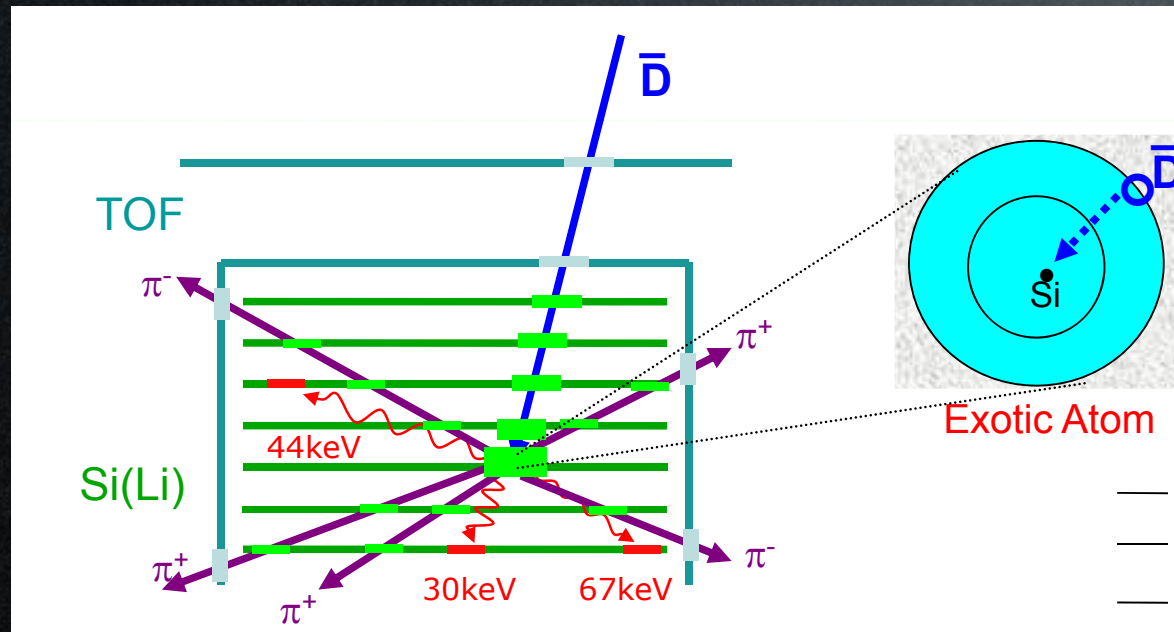
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diffusion
energy loss
convective wind
source
spallations

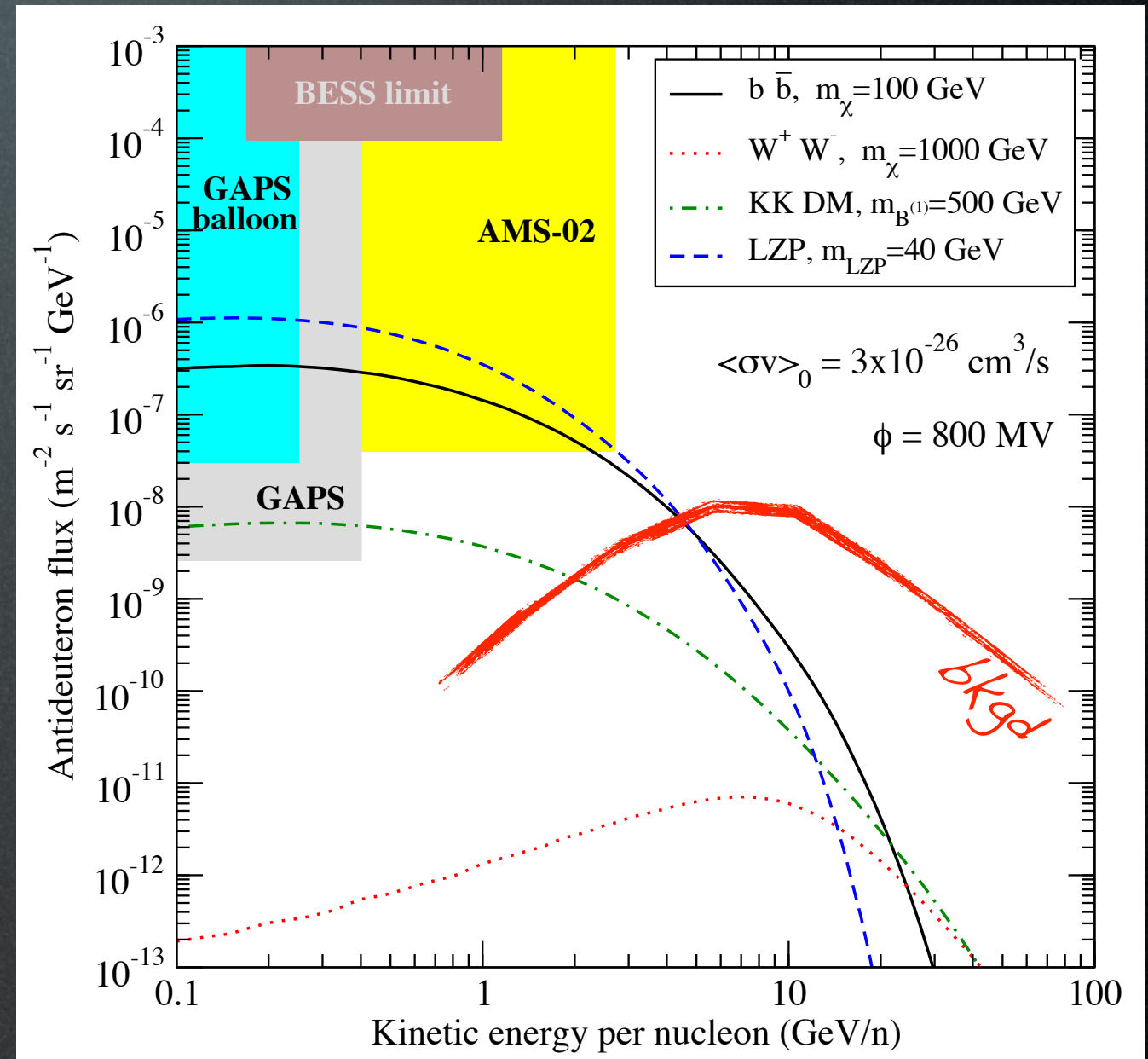
Indirect Detection

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

GAPS detection principle



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



DM signal in the reach
of GAPS and AMS-02

DM detection

direct detection

production at colliders

indirect

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

Fermi, ICT, radio telescopes...

e^+ from annihil in galactic halo or center

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

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

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GAPS, AMS

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

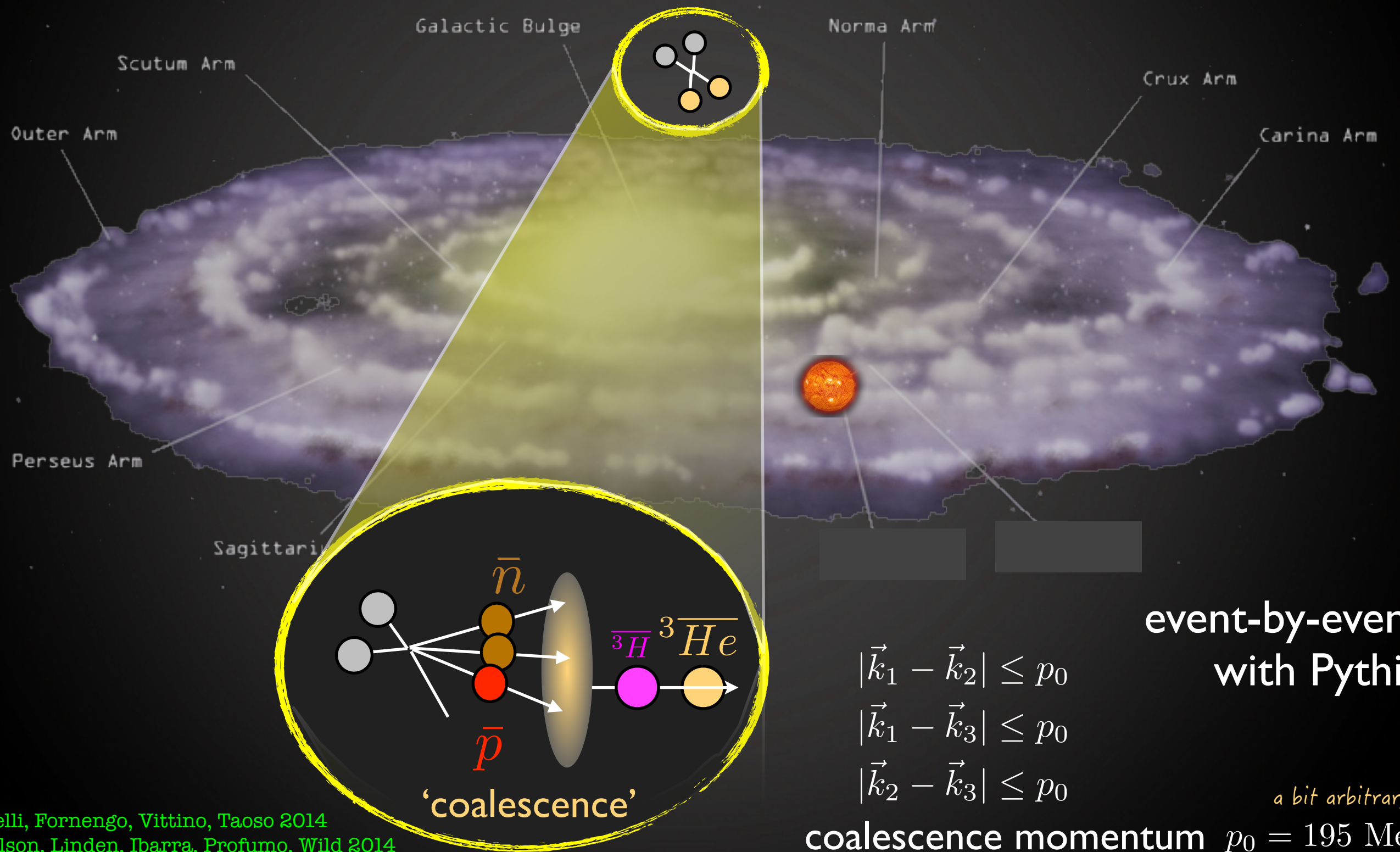
SK, Icecube, Km3Net

$\overline{He}$ from annihil in galactic halo or center

AMS?

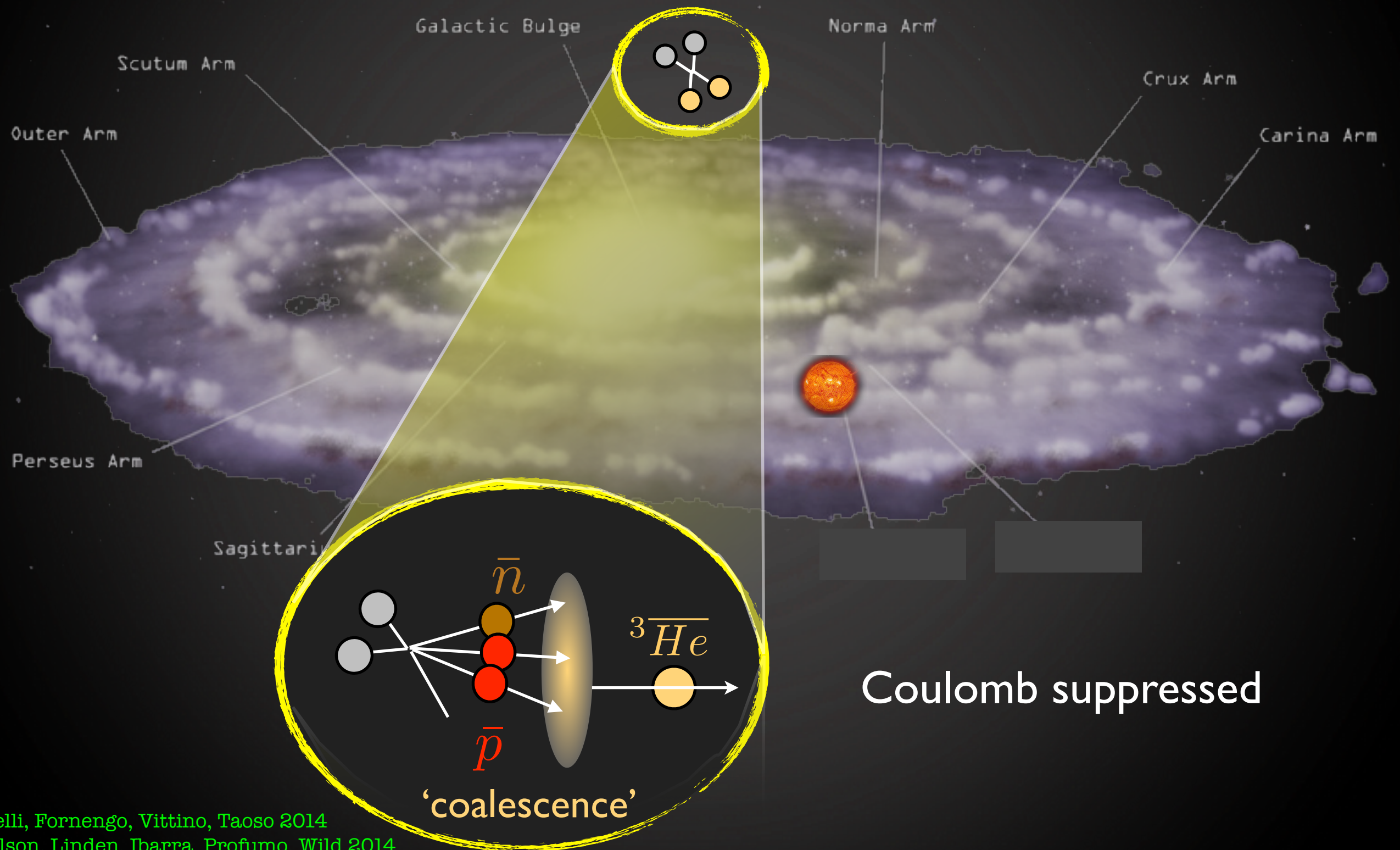
Indirect Detection

$\overline{He}$ from DM annihilations in halo



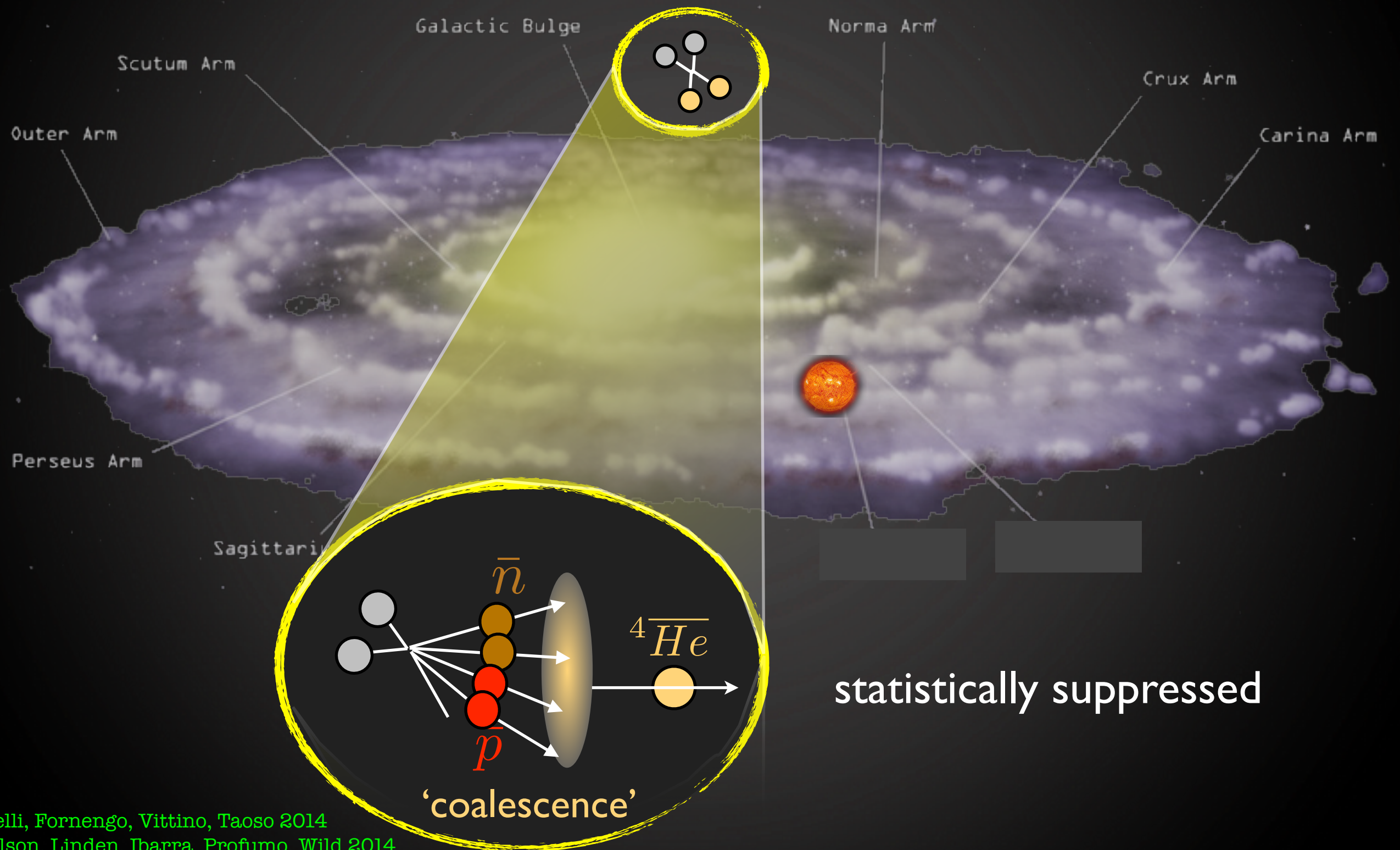
Indirect Detection

$\overline{He}$ from DM annihilations in halo



Indirect Detection

$\overline{He}$ from DM annihilations in halo



DM detection

direct detection

Xenon, LZ, Panda-X... (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic halo
and from secondary emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo

AMS, Dampe, Calet, Fermi...

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

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

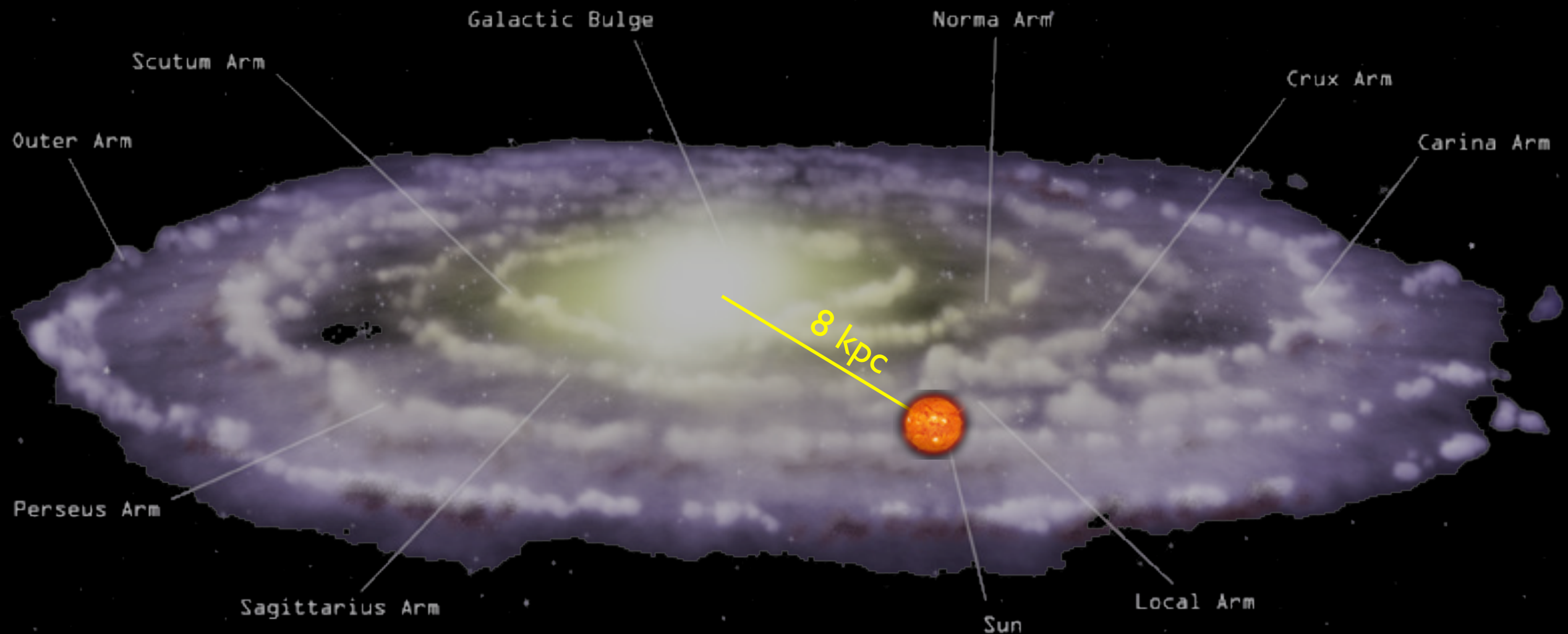
GAPS

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

Icecube, Km³Net

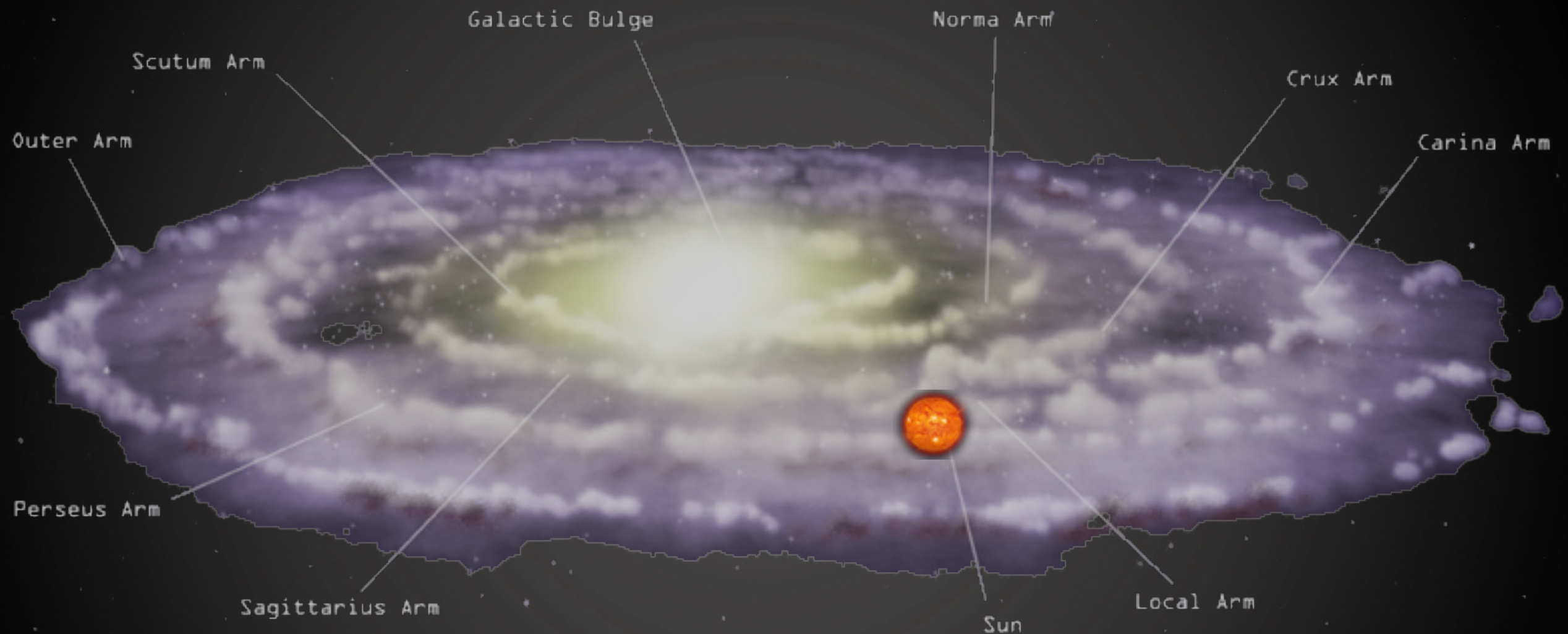
Basic picture

γ from DM annihilations in galactic center



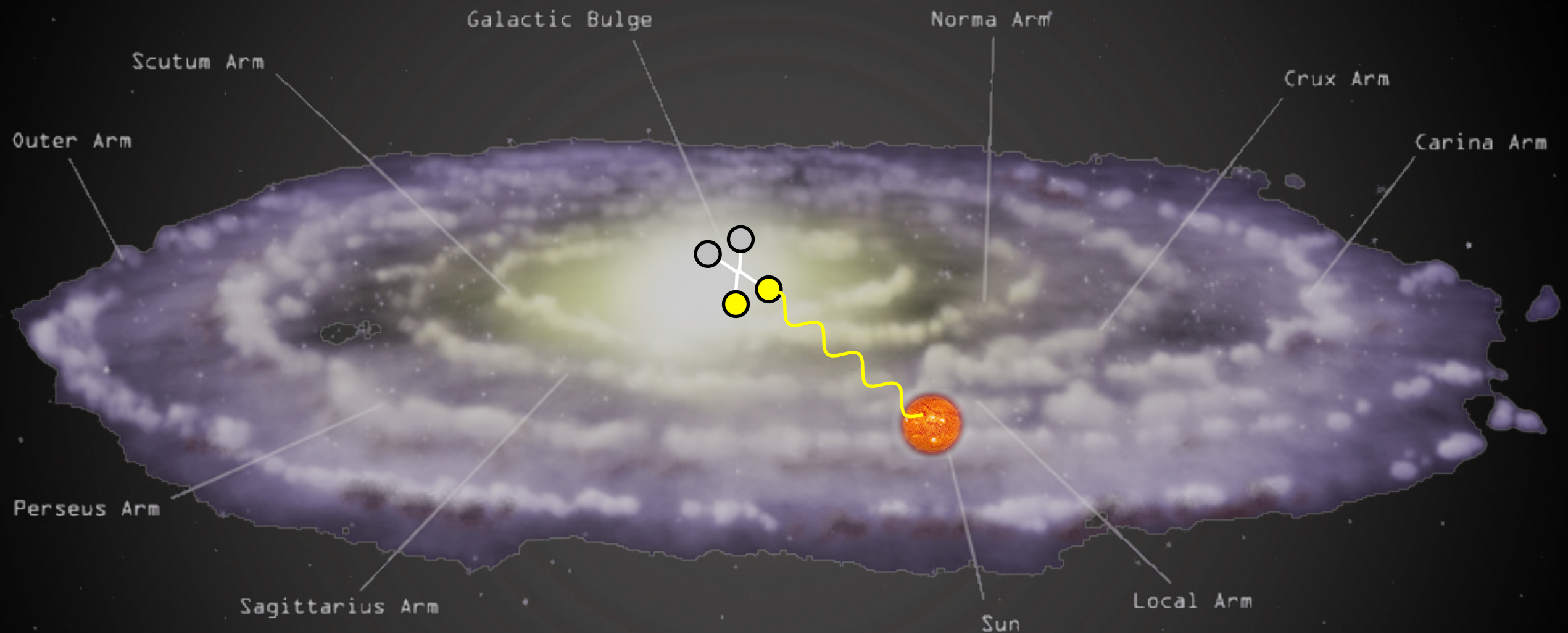
Basic picture

γ from DM annihilations in galactic center



Basic picture

γ from DM annihilations in galactic center



$$\begin{array}{l}
 \text{DM} \quad \swarrow \\
 \bullet \\
 \searrow \quad \text{DM}
 \end{array}
 \begin{array}{l}
 \text{--- } W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \\
 \text{--- } W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma
 \end{array}$$

How does DM produce γ -rays?

1. prompt emission

1a. continuum

1b. line(s)

1c. sharp features

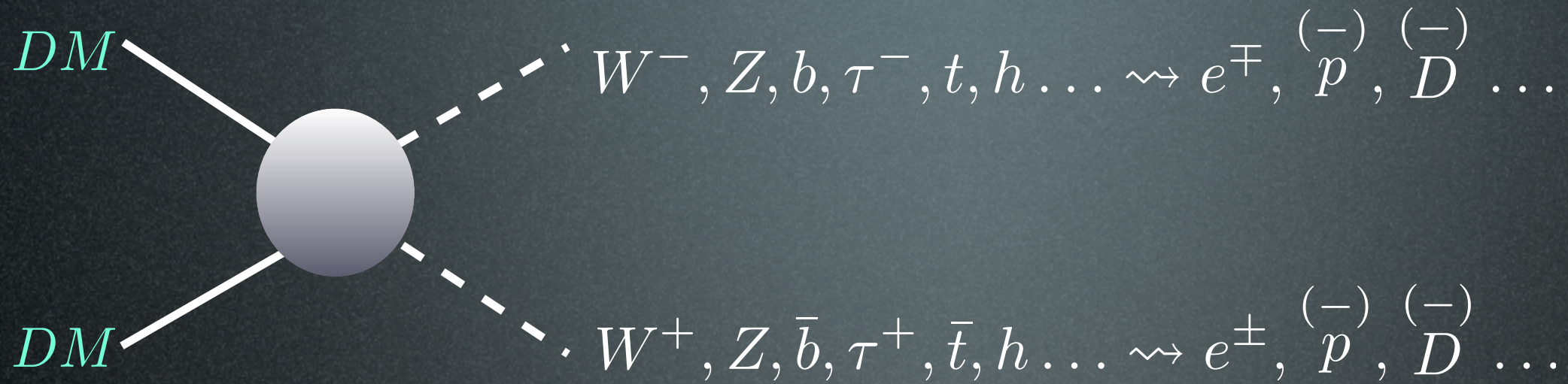
2. secondary emission

2a. ICS

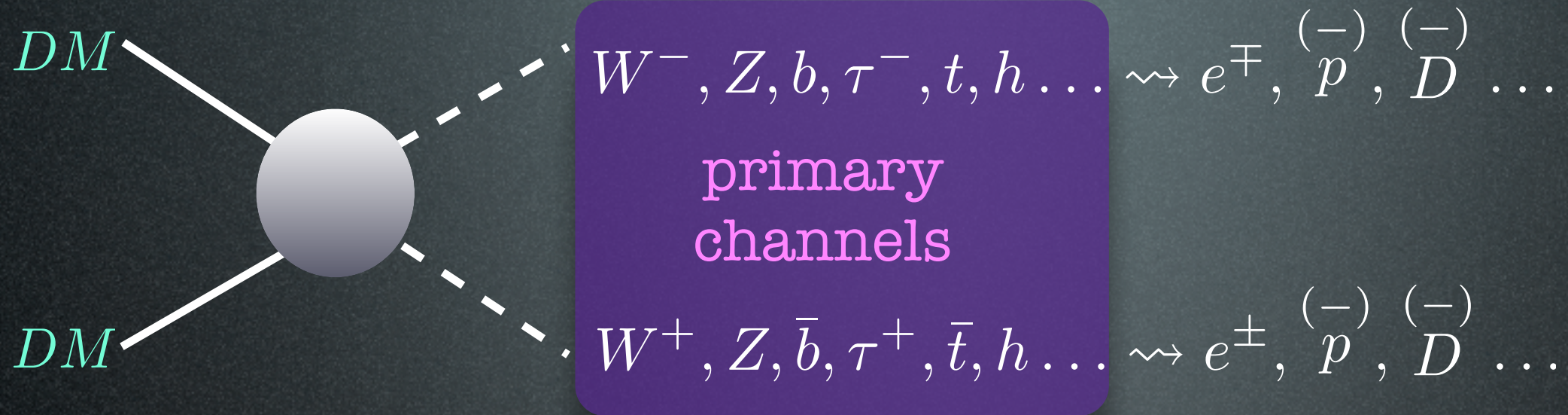
2b. bremsstrahlung

2c. synchrotron

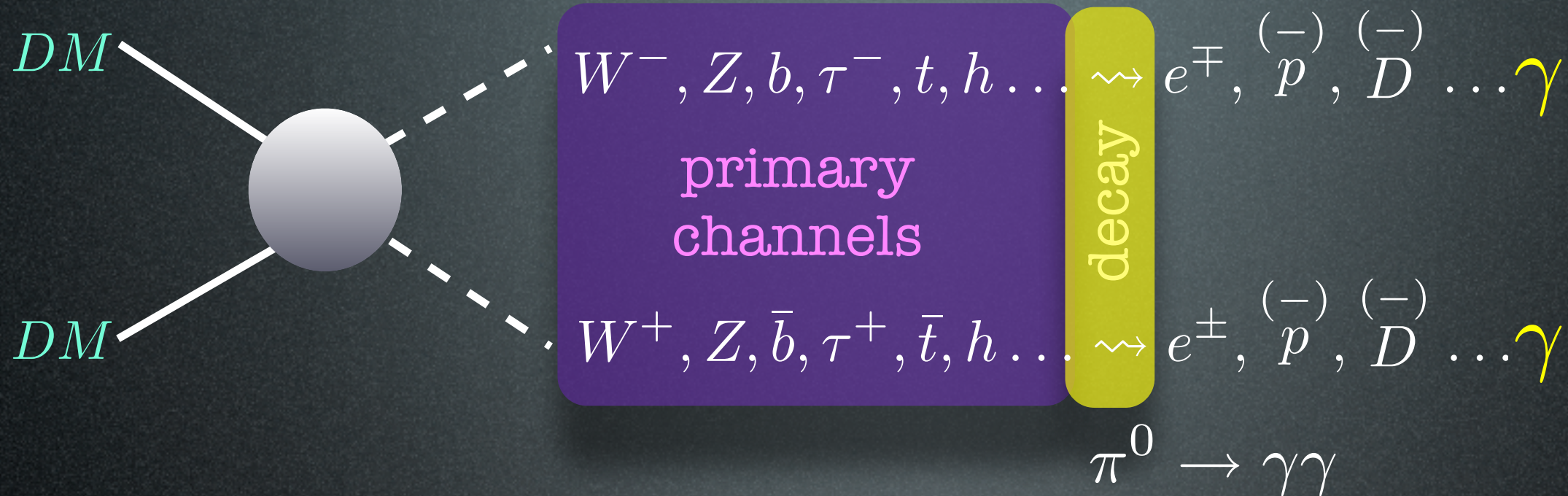
Prompt emission: continuum



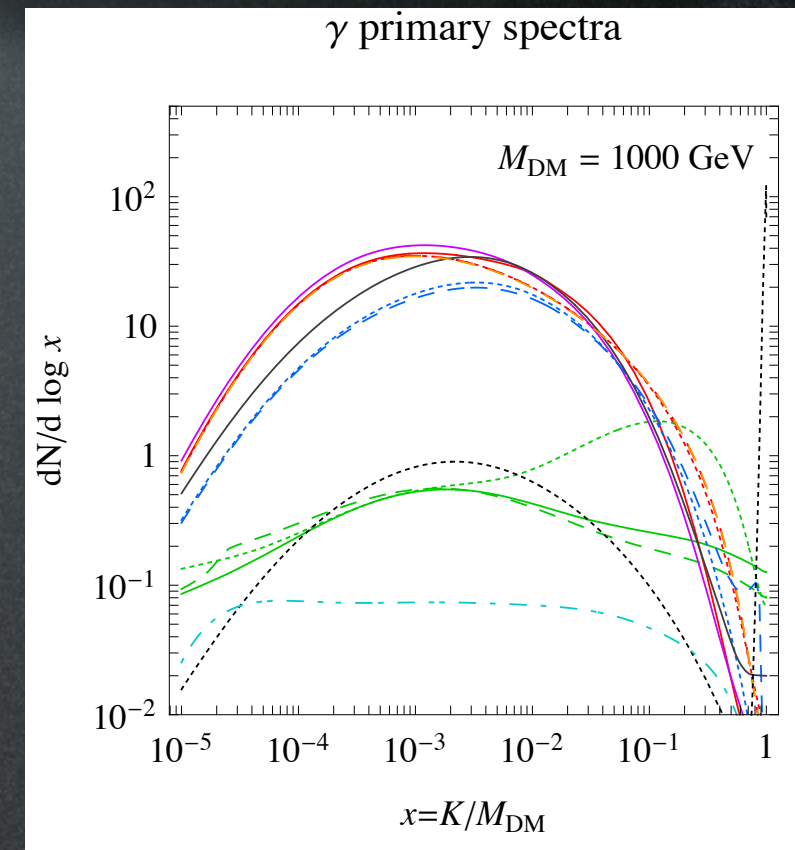
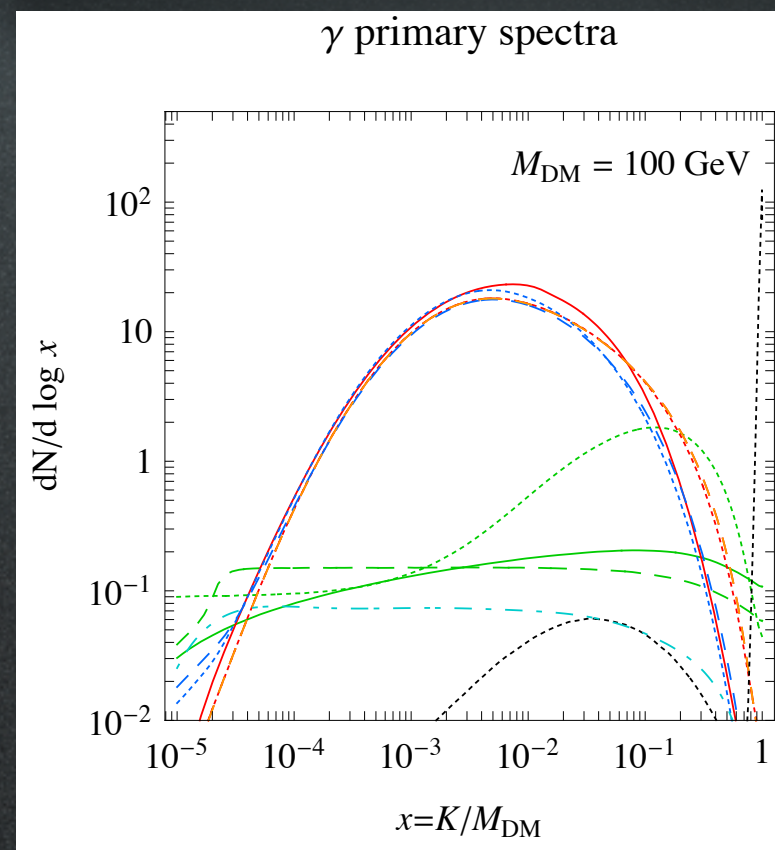
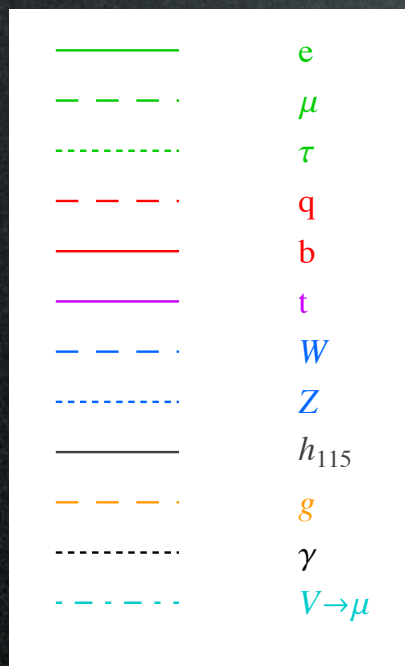
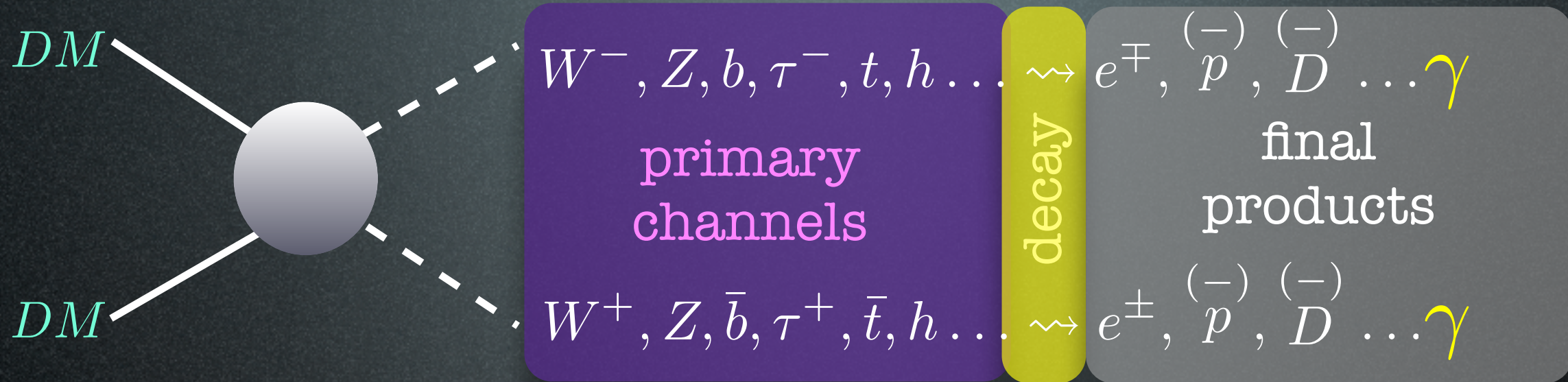
Prompt emission: continuum



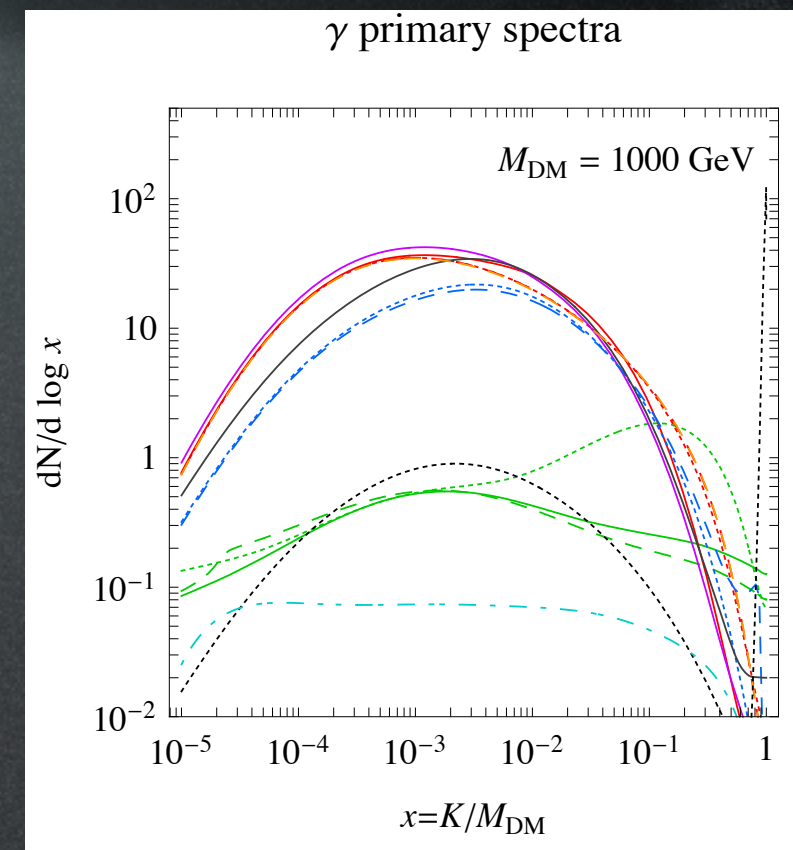
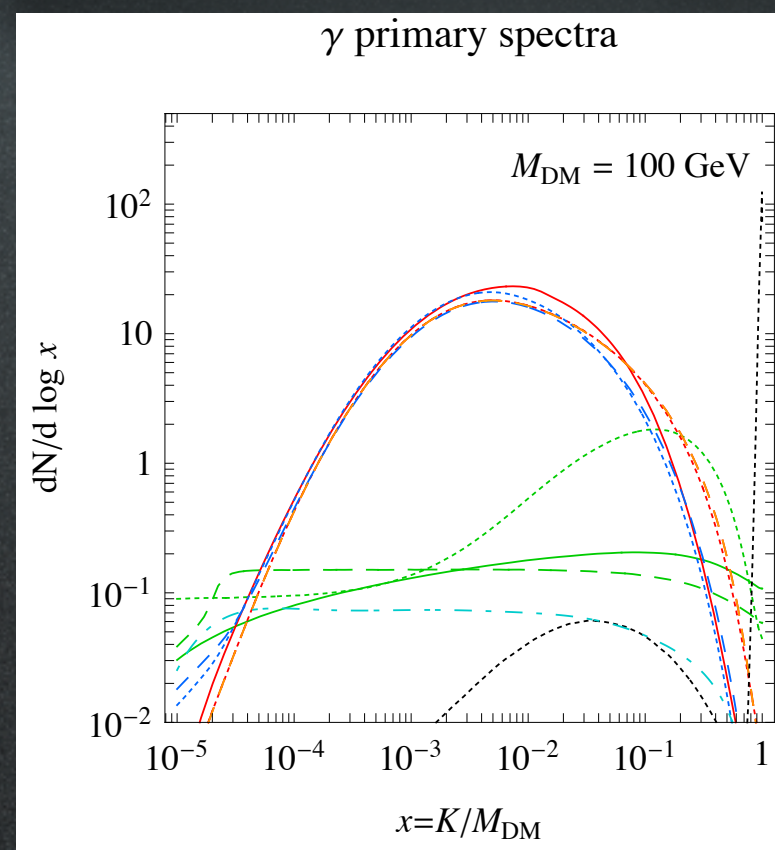
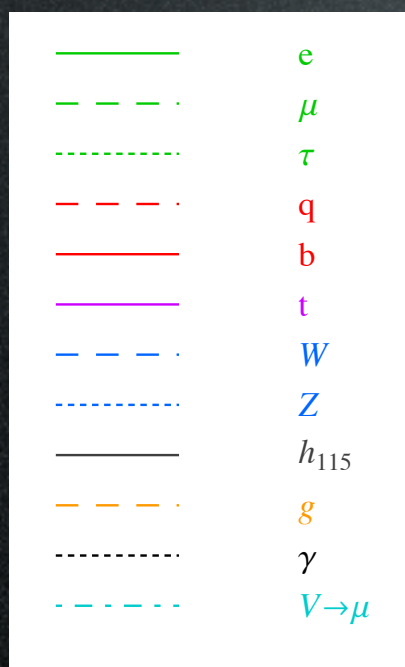
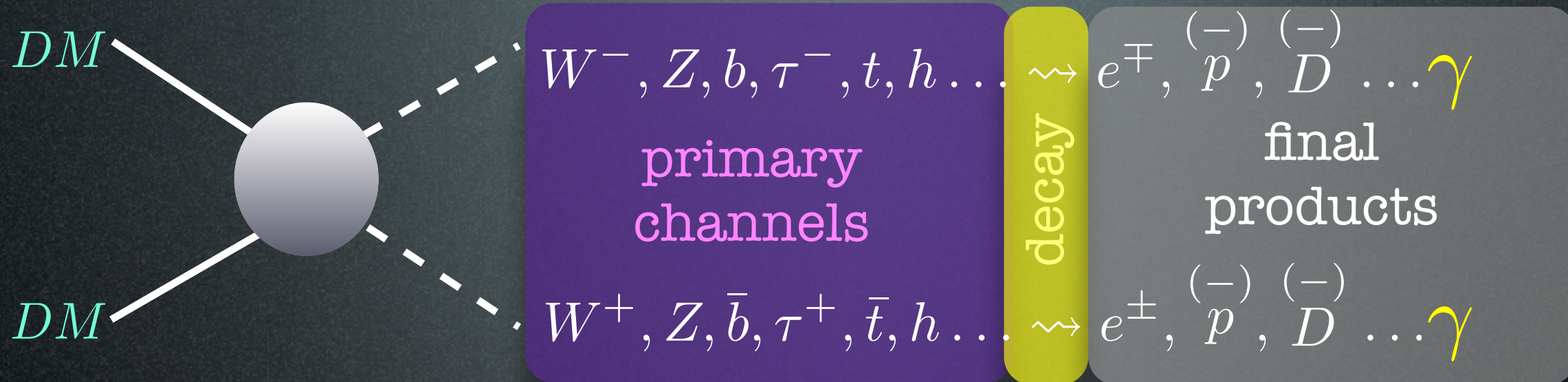
Prompt emission: continuum



Prompt emission: continuum



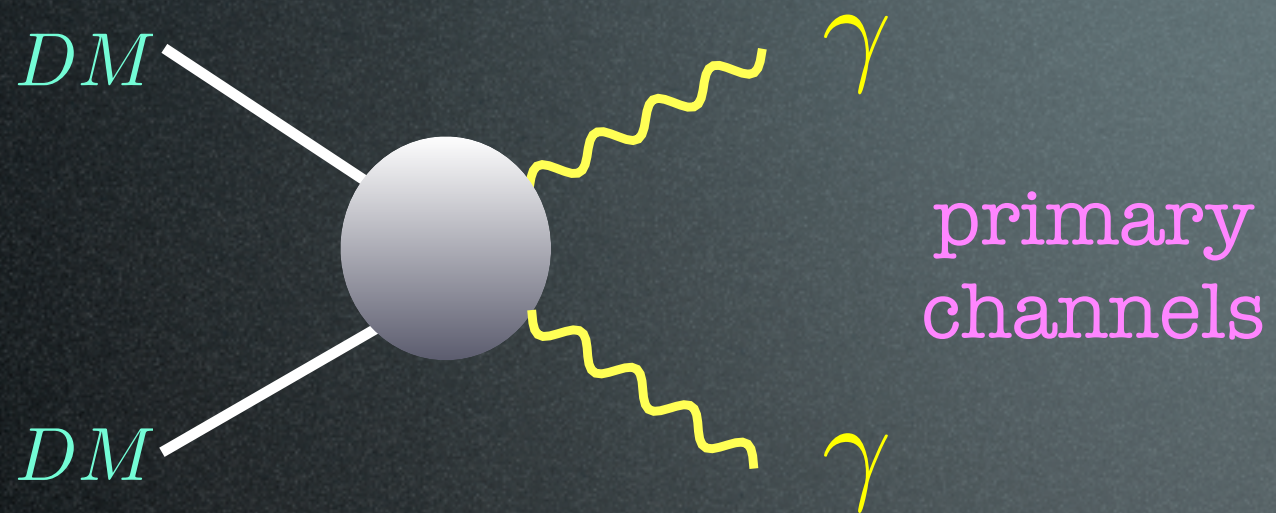
Prompt emission: continuum



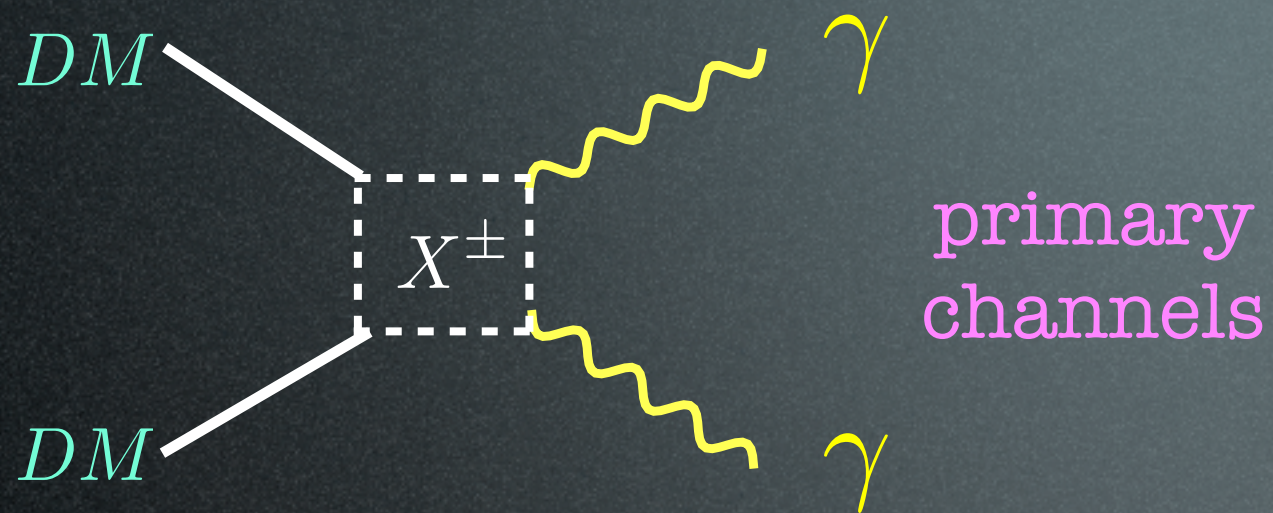
So what are the particle physics parameters?

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

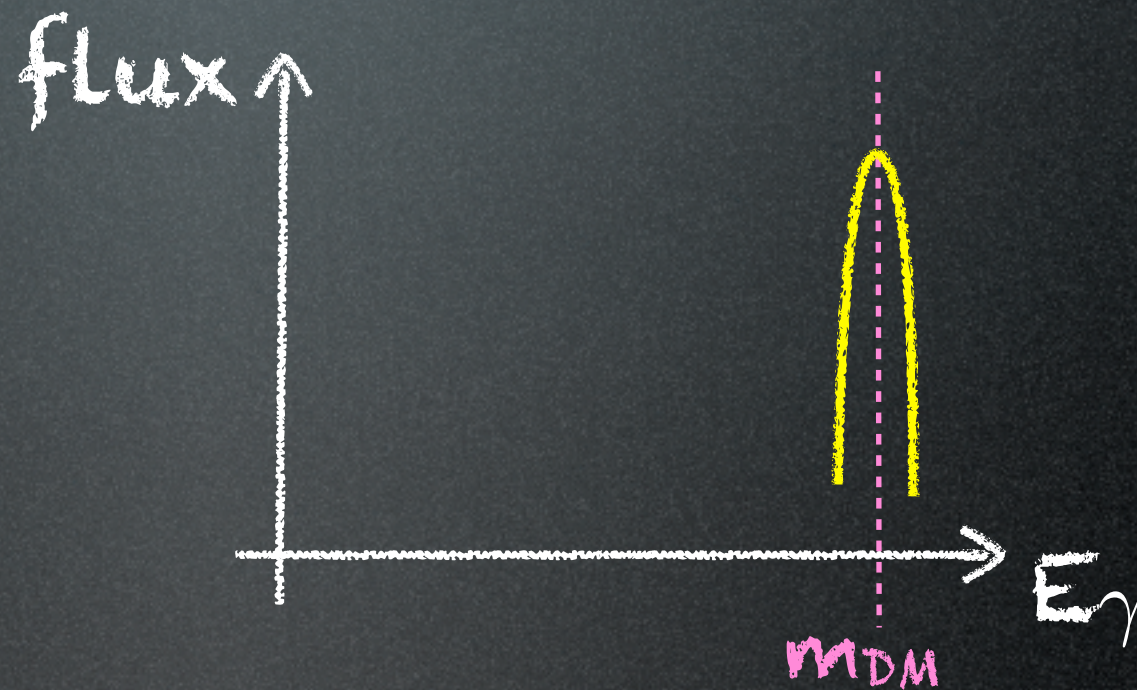
Prompt emission: line(s)



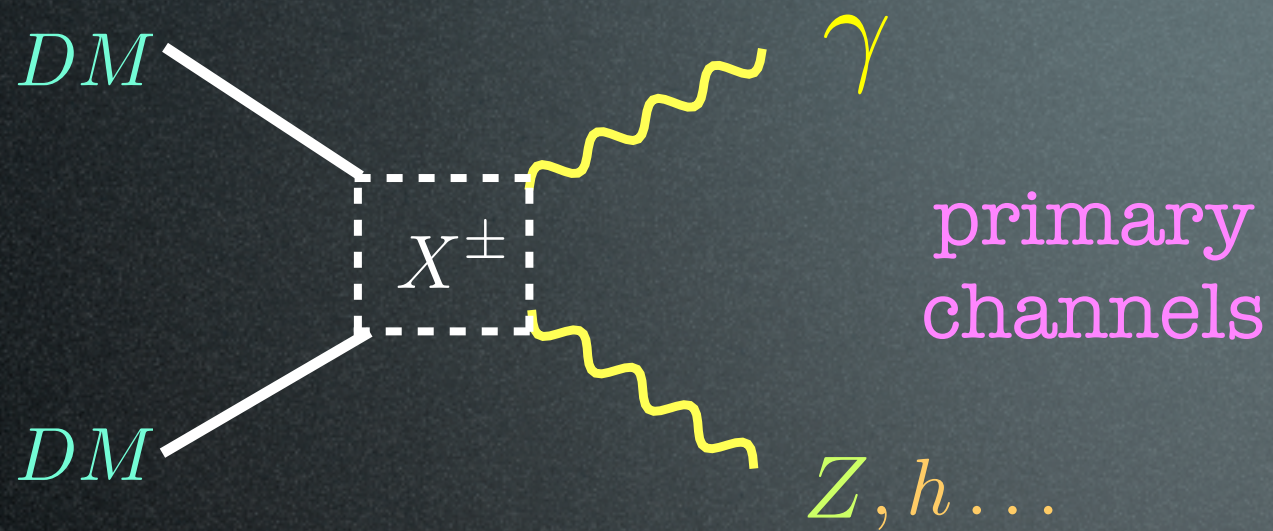
Prompt emission: line(s)



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

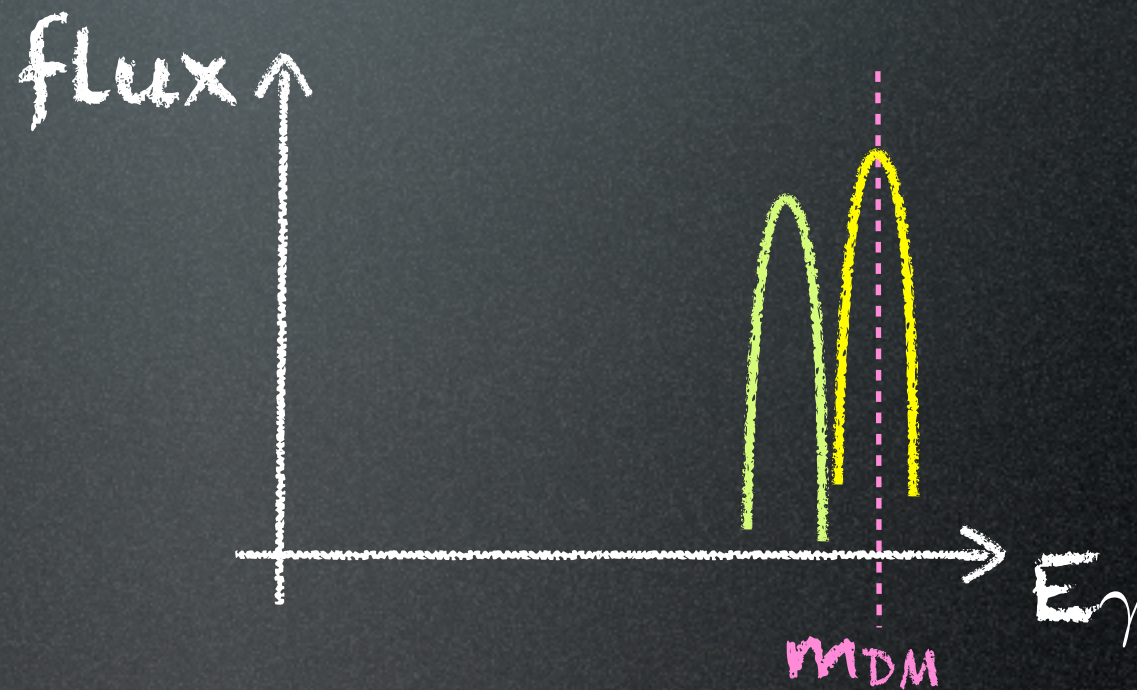


Prompt emission: line(s)

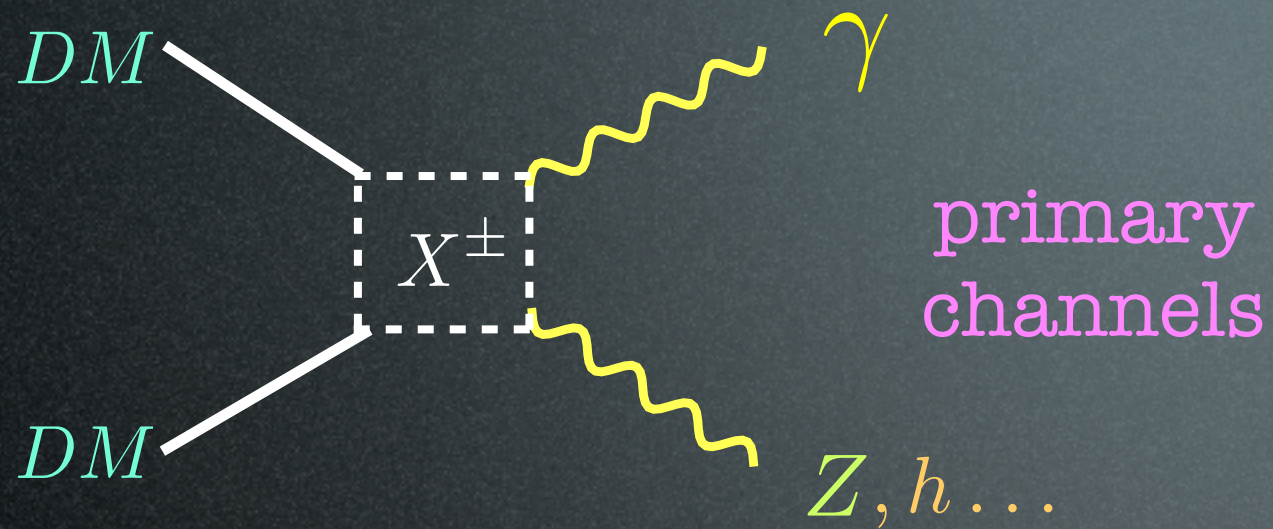


$$E_\gamma = m_{\text{DM}}$$

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

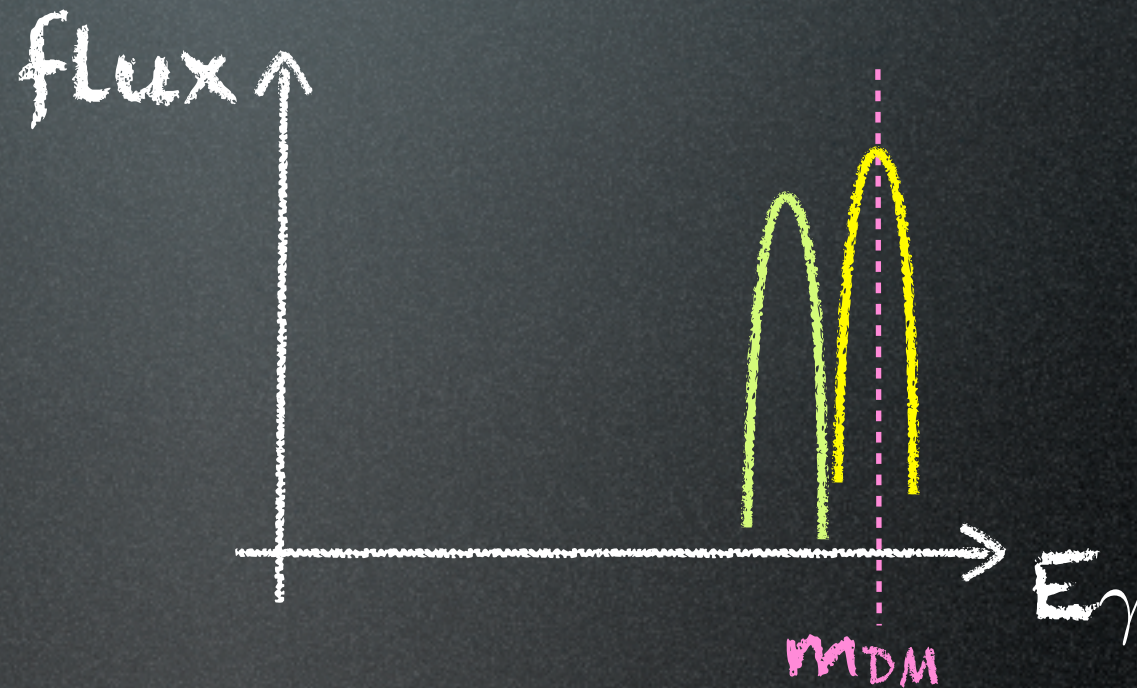


Prompt emission: line(s)



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

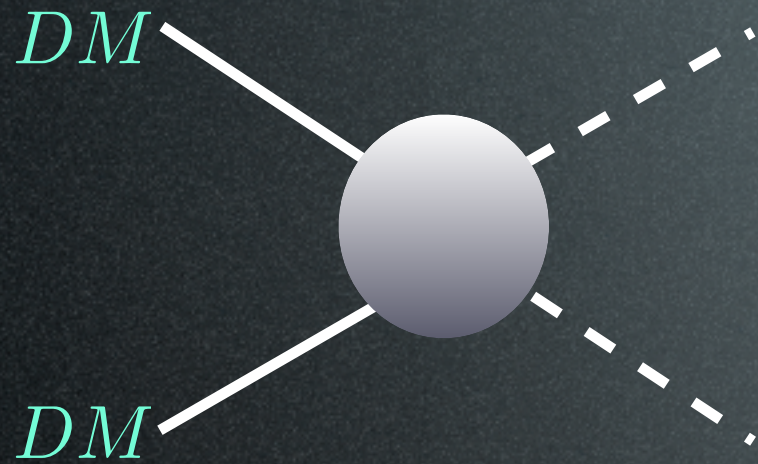
$$E_\gamma = m_{DM} \left(1 - \frac{m_Z^2}{4 m_{DM}^2} \right)$$



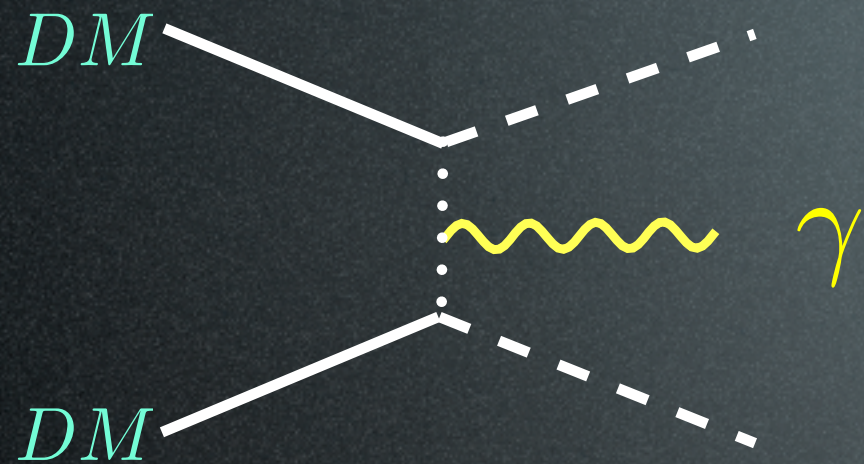
So what are the particle physics parameters?

1. Dark Matter mass
2. annihilation cross section σ_{ann}

Prompt emission: sharp features



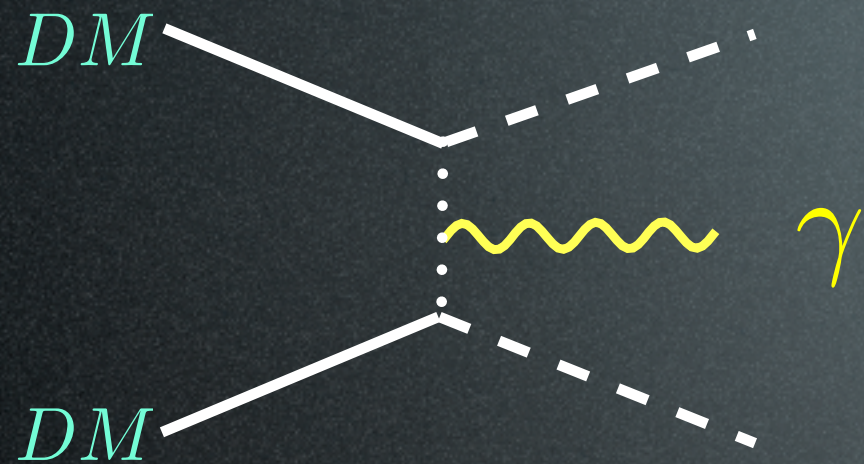
Prompt emission: sharp features



Internal Bremsstrahlung

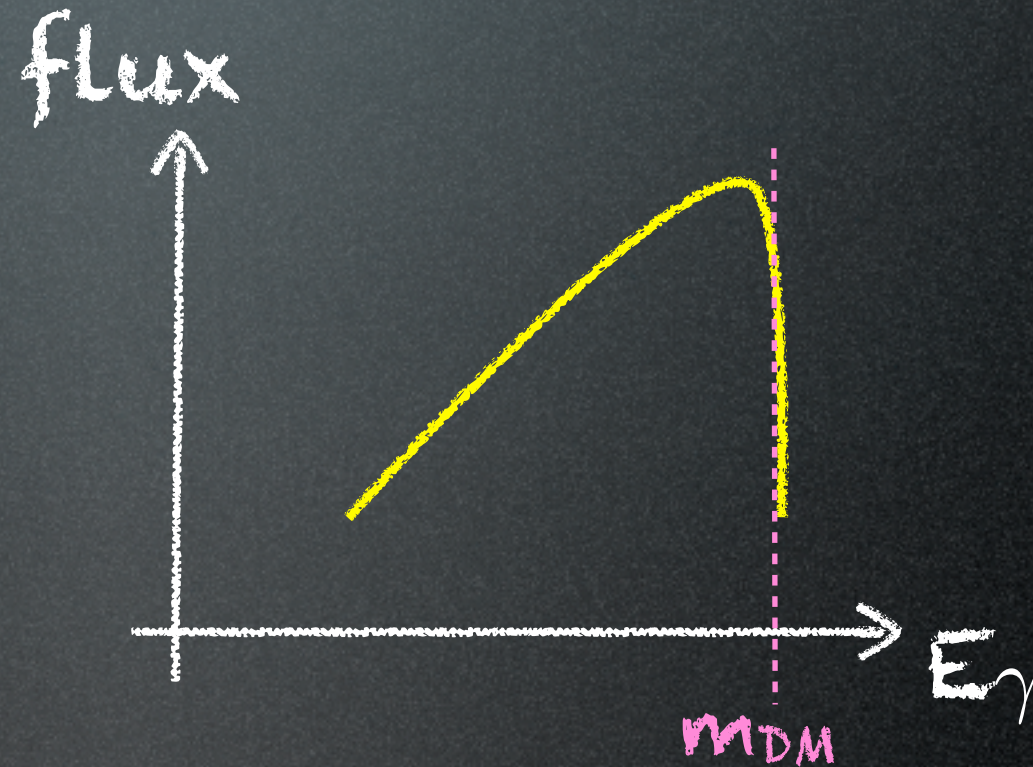
Bergström 1989

Prompt emission: sharp features

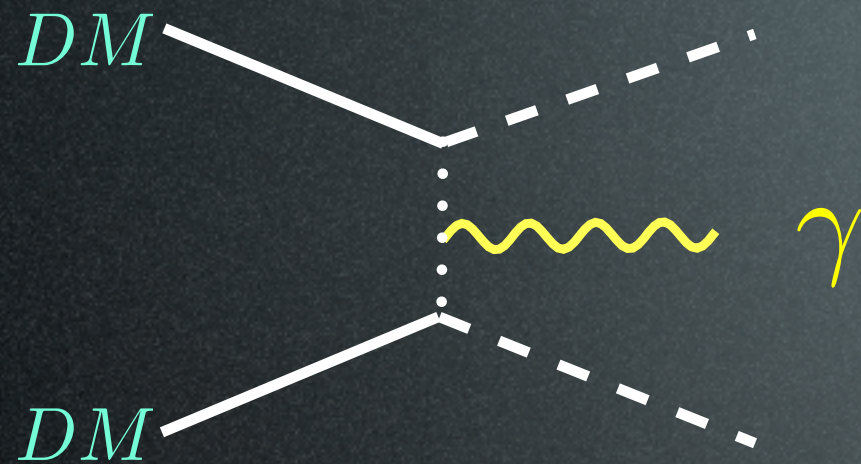


Internal Bremsstrahlung

Bergström 1989



Prompt emission: sharp features

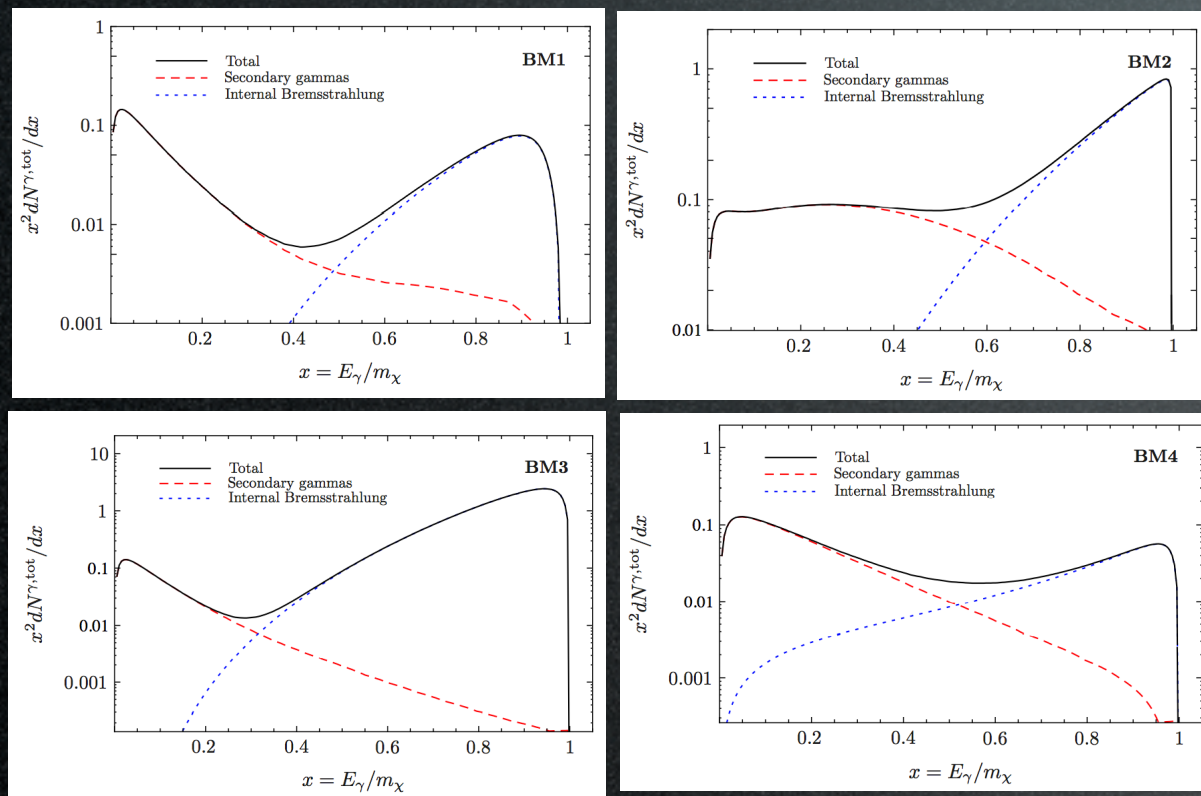
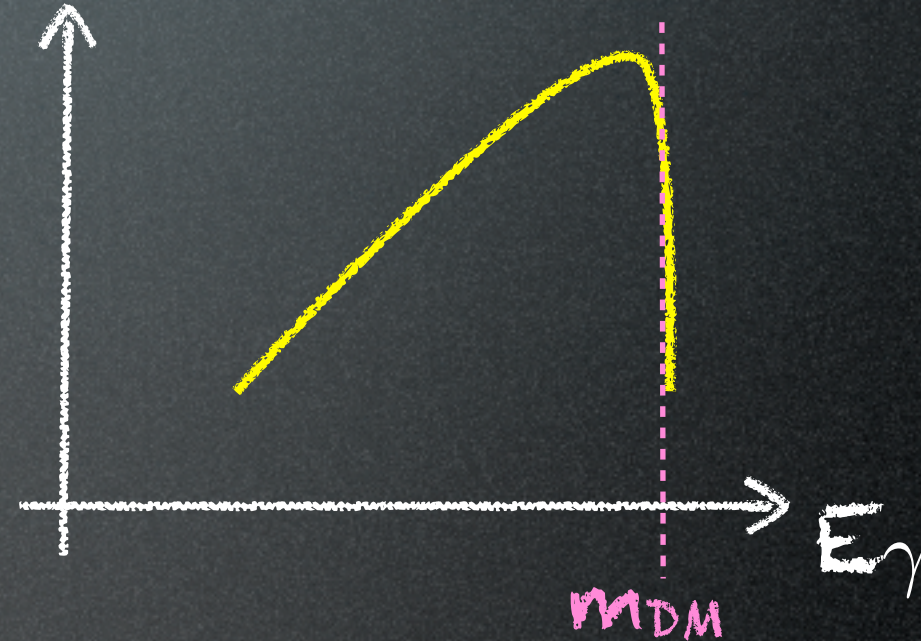


Internal Bremsstrahlung

Bergström 1989

Bringmann, Bergstrom, Edsjo 0710.3169

flux

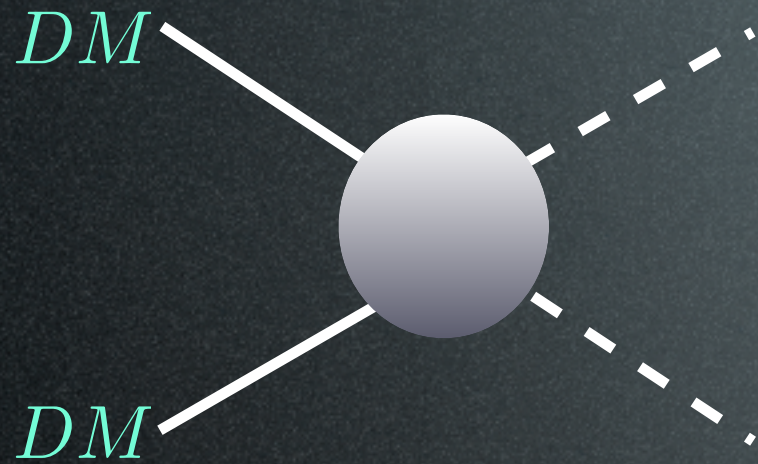


So what are the particle physics parameters?

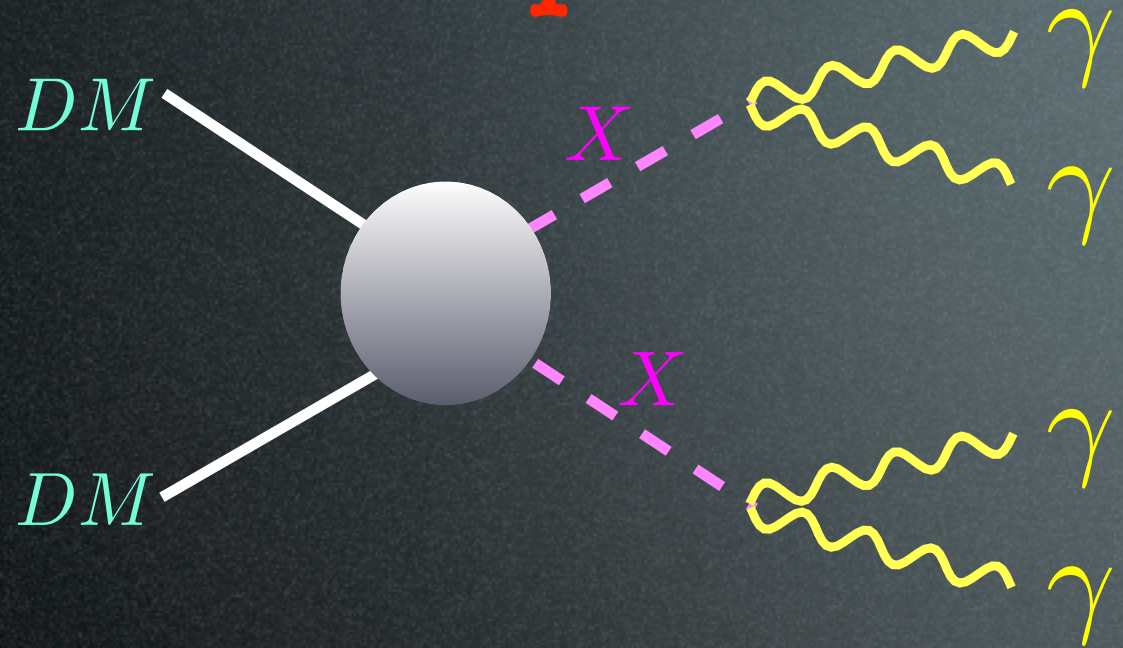
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



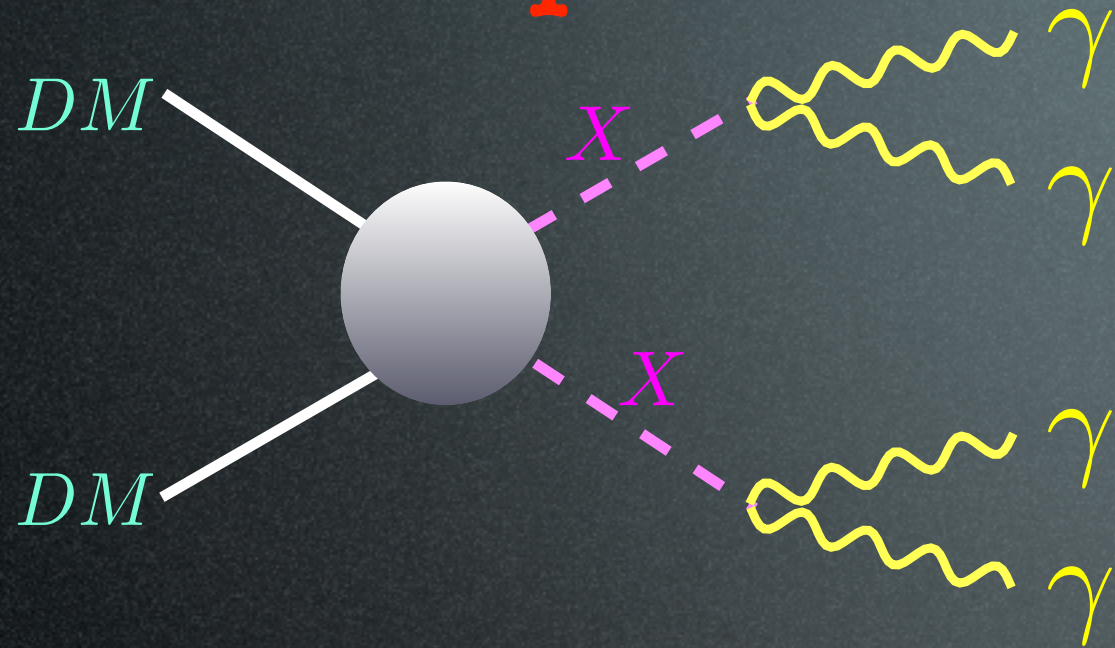
Prompt emission: sharp features



Metastable intermediate
states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

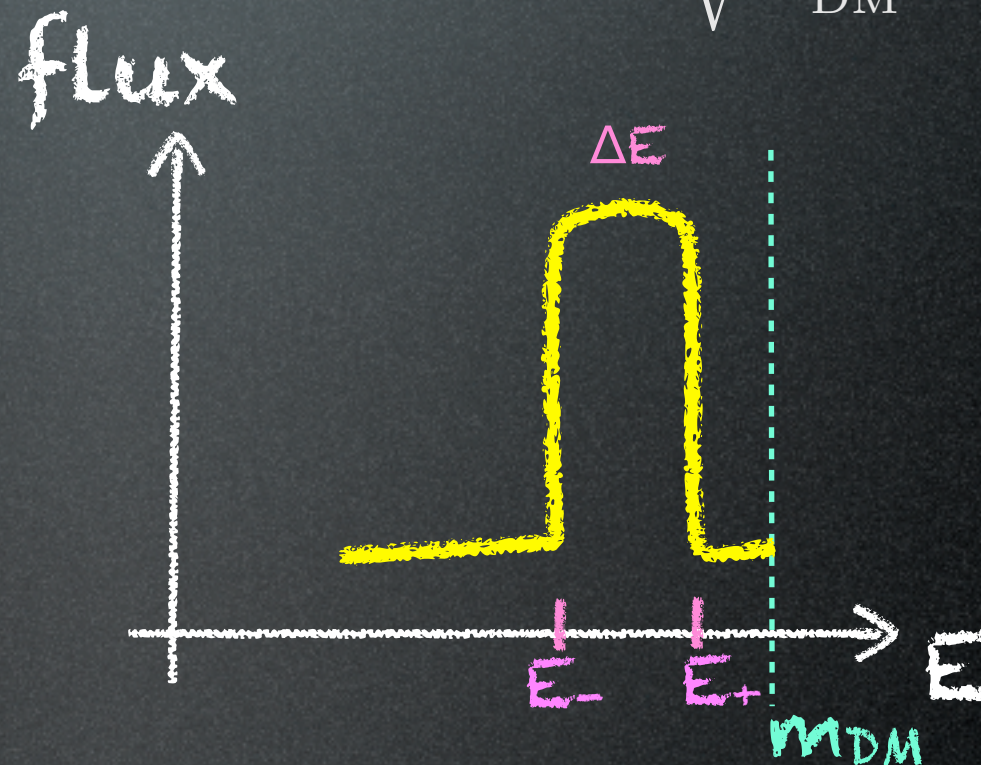


Metastable intermediate states

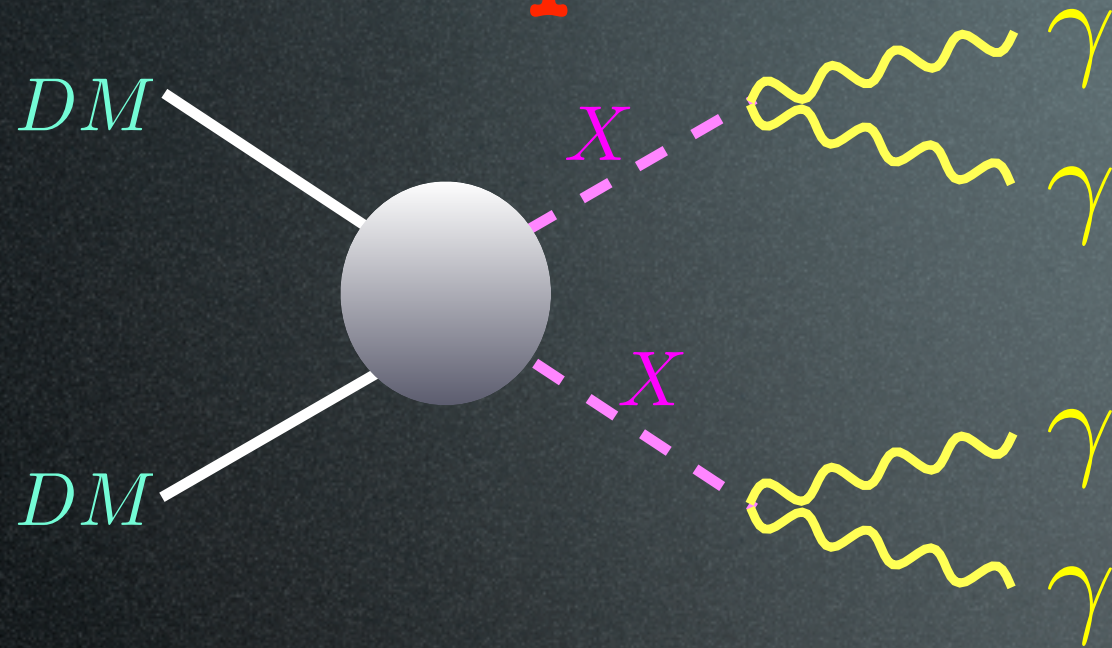
$$E_{\pm} = \frac{m_{\text{DM}}}{2} \left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\text{DM}}^2}} \right)$$

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

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097



Prompt emission: sharp features

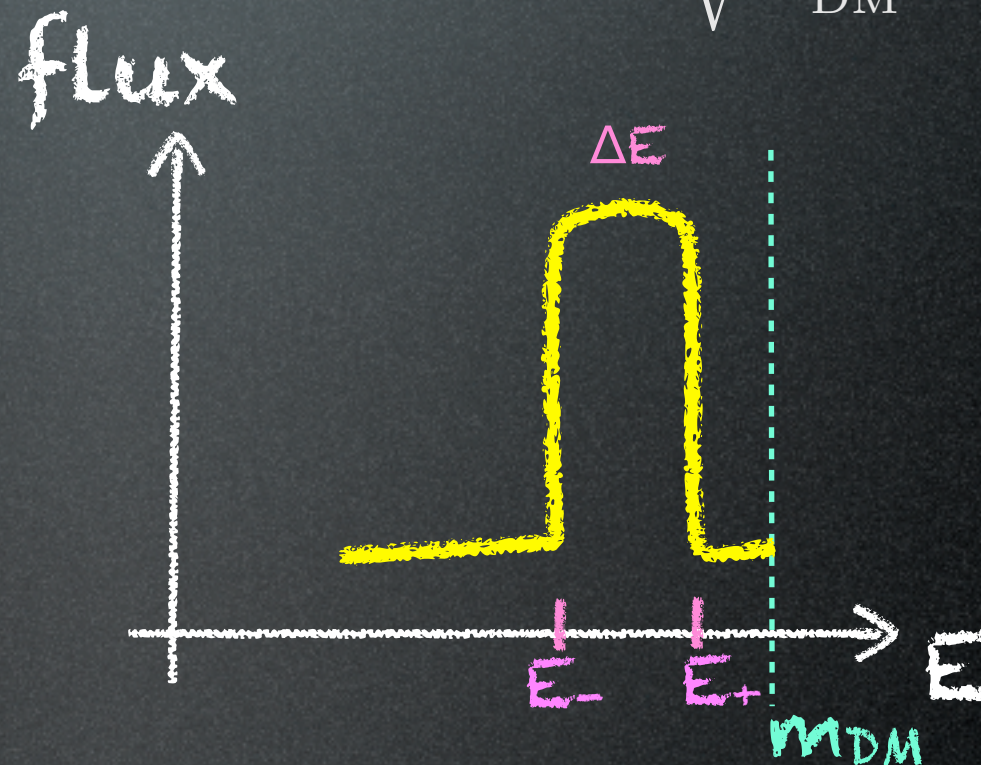


Metastable intermediate states

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

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

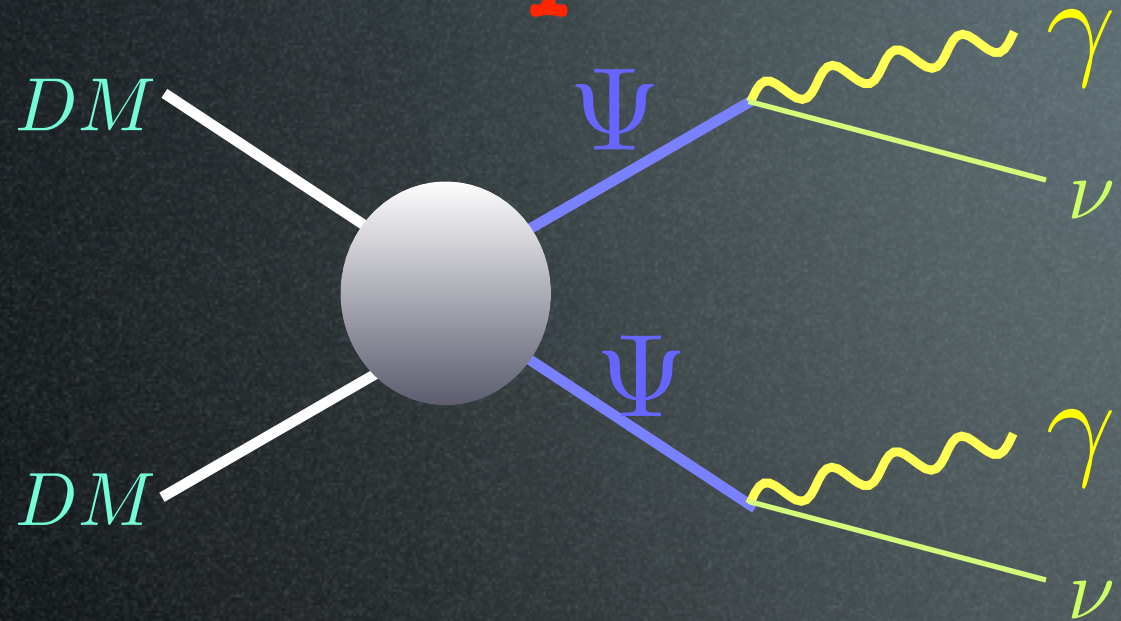
Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097



So what are the particle physics parameters?

1. Dark Matter **mass**
2. The mediator **mass**

Prompt emission: sharp features

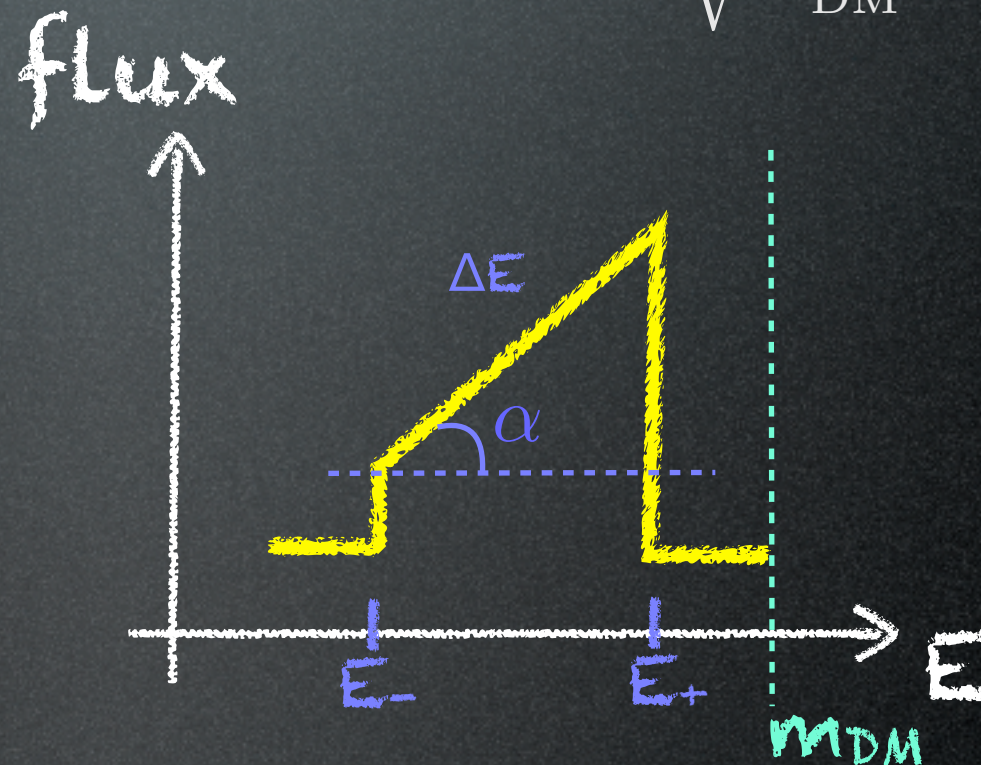


Ibarra, Lopez Gehler, Molinaro, Pato
1604.01899

Metastable intermediate fermions

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

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



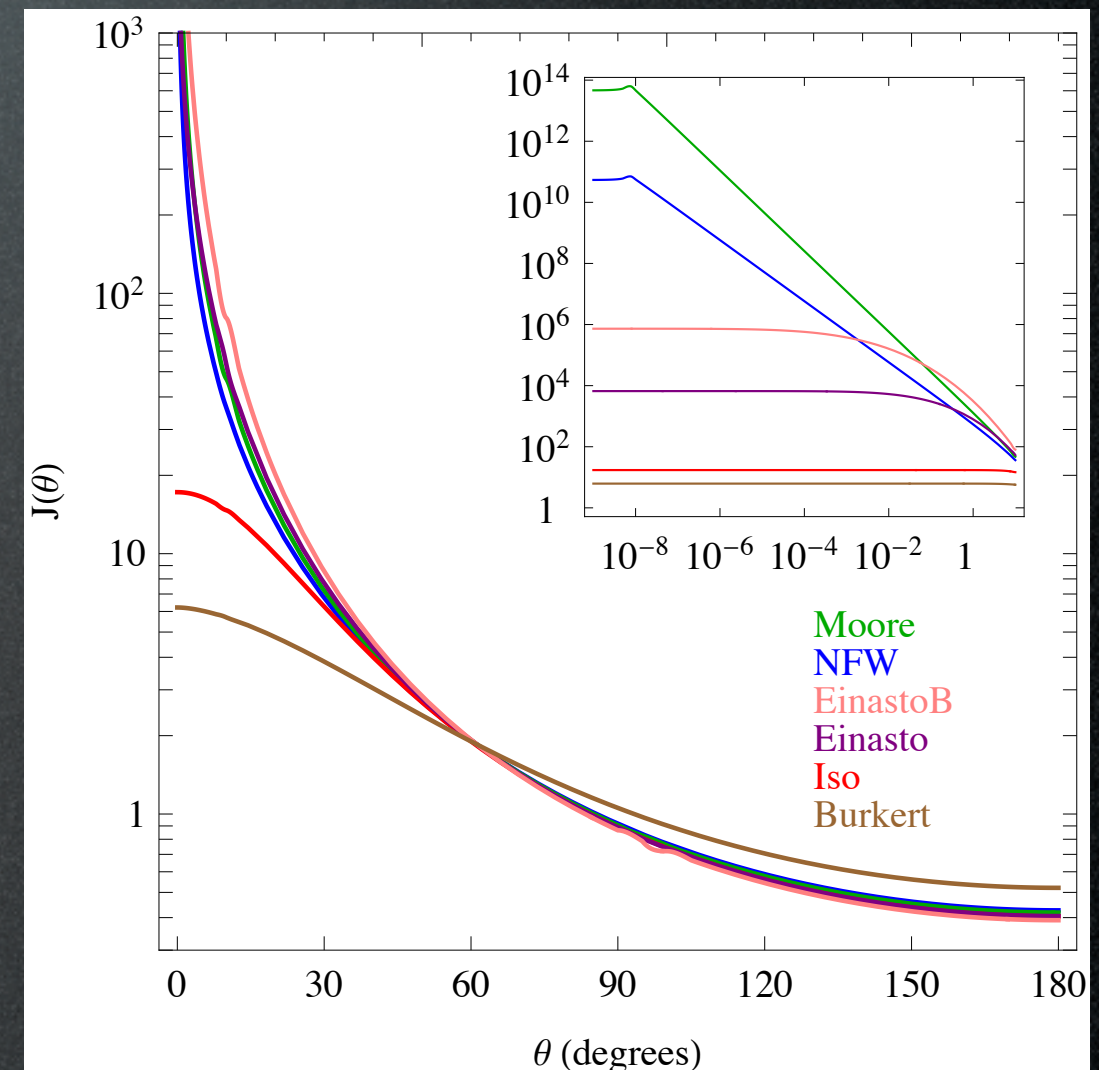
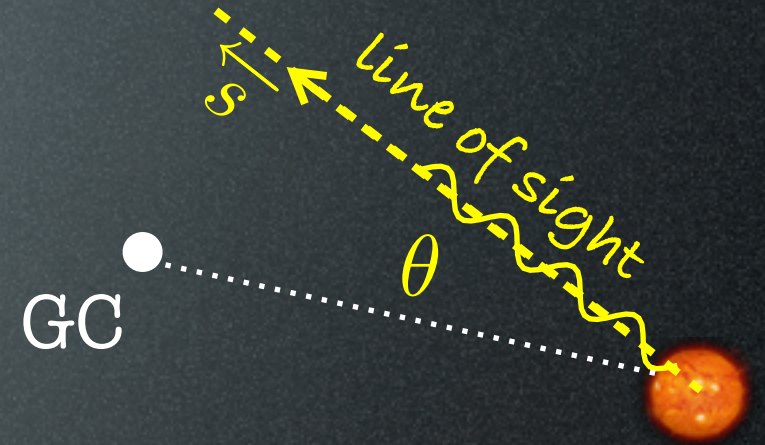
So what are the particle physics parameters?

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

'Prompt' gamma rays

$$\frac{d\Phi_\gamma}{d\Omega dE} = \frac{1}{2} \frac{r_\odot}{4\pi} \left(\frac{\rho_\odot}{M_{\text{DM}}} \right)^2 \boxed{J} \sum_f \langle \sigma v \rangle_f \boxed{\frac{dN_\gamma^f}{dE}}$$

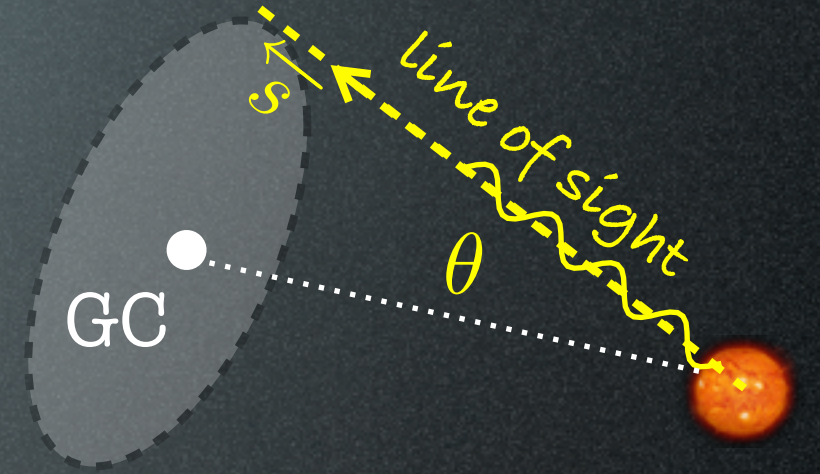
$$\boxed{J} = \int_{\text{l.o.s.}} \frac{ds}{r_\odot} \left(\frac{\rho(r(s, \theta))}{\rho_\odot} \right)^2$$



'Prompt' gamma rays

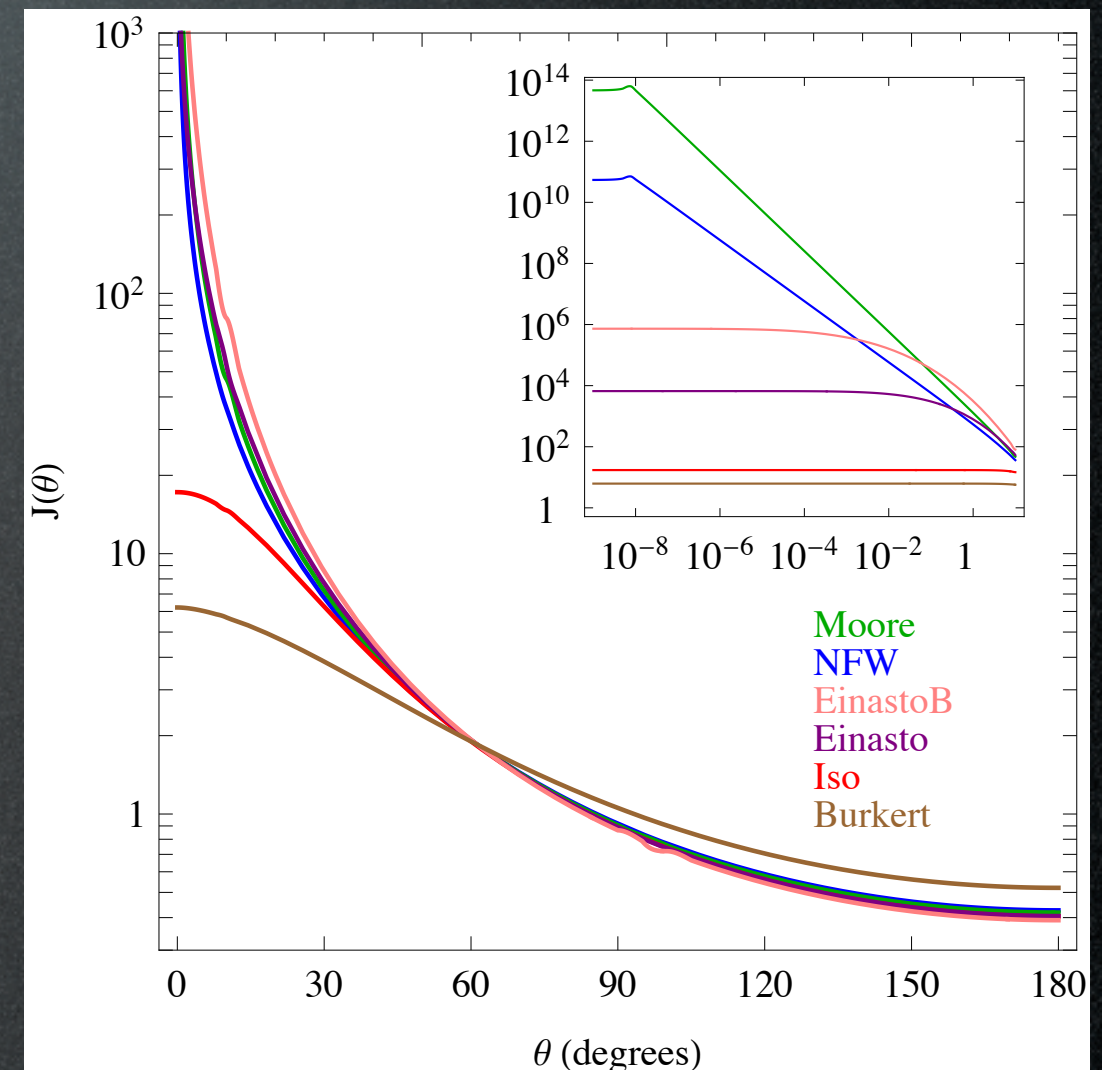
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{2} \frac{r_\odot}{4\pi} \left(\frac{\rho_\odot}{M_{\text{DM}}} \right)^2 \bar{J} \Delta\Omega \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE_\gamma}$$

$$\bar{J} = \frac{1}{\Delta\Omega} \int_{\text{l.o.s.}} \frac{ds}{r_\odot} \left(\frac{\rho(r(s, \theta))}{\rho_\odot} \right)^2$$



Region	$\Delta\Omega$ [steradians]	$\bar{J}_{\text{ann}}$					
		NFW	Ein	EinB	Iso	Bur	Moore
'GC 0.1°'	$0.96 \cdot 10^{-5}$	11579	3579	55665	17.2	6.21	81751
'GC 0.14°'	$0.19 \cdot 10^{-4}$	8255	3206	43306	17.2	6.21	52395
'GC 1°'	$0.96 \cdot 10^{-3}$	1118	1196	6945	17.2	6.21	3855
'GC 2°'	0.004	542	711	3103	17.2	6.19	1521
'Gal Ridge'	$0.29 \cdot 10^{-3}$	1904	1605	11828	17.2	6.21	7927
'3 × 3'	0.011	306	443	1577	17.1	6.16	741
'5 × 5'	0.030	174	264	783	16.8	6.10	367
'5 × 30'	0.183	47.7	70.5	170	12.1	5.16	84.8
'10 × 10'	0.121	77.7	118	280	15.5	5.85	138
'10 × 30'	0.364	35.5	51.8	109	11.7	5.09	57.2

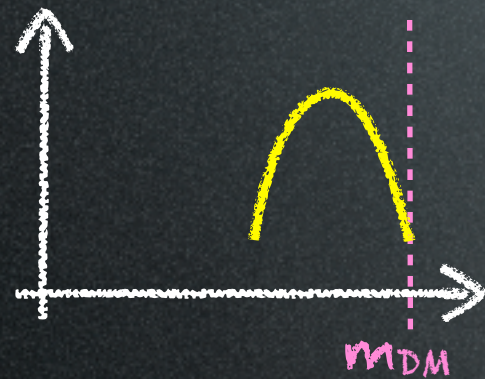
Spread is very large
for small regions close to GC



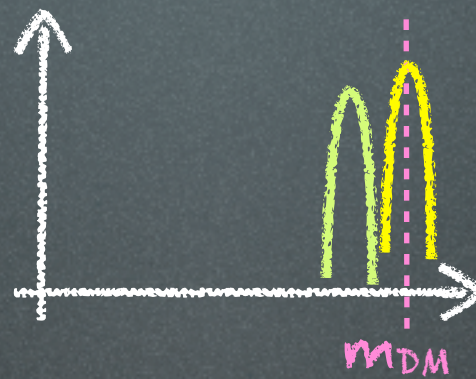
How does DM produce γ -rays?

1. prompt emission

1a. continuum



1b. line(s)



1c. sharp features



2. secondary emission

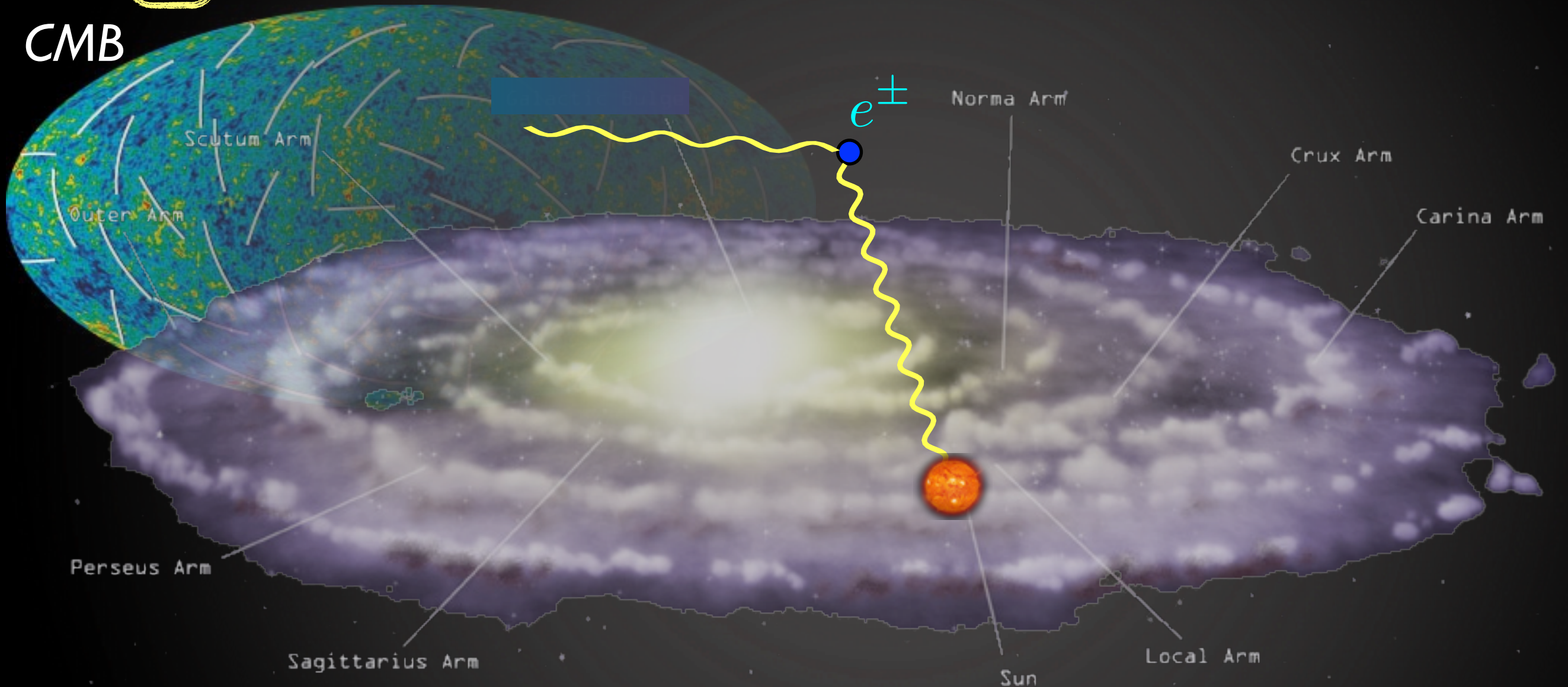
2a. ICS

2b. bremsstrahlung

2c. synchrotron

Secondary emission

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

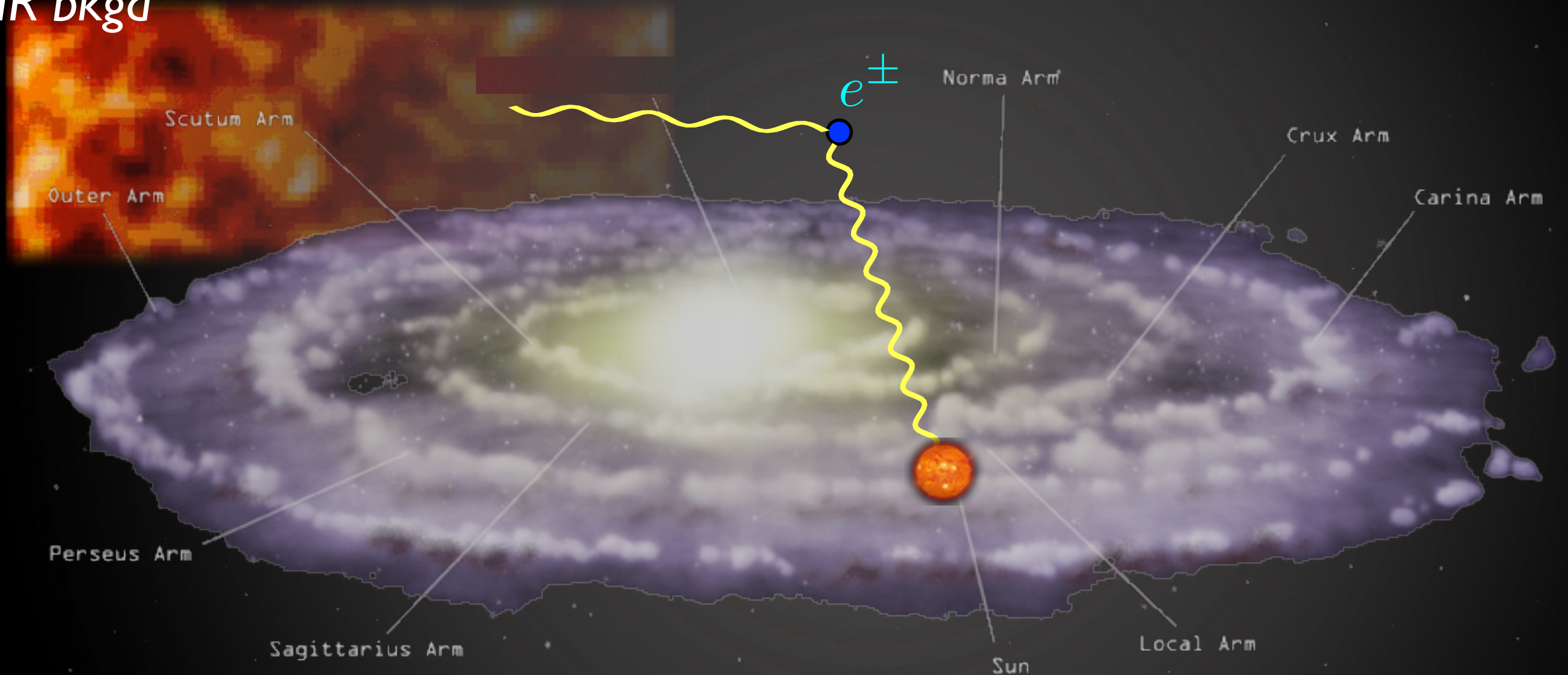


- upscatter of CMB, infrared and starlight photons on energetic $e^\pm$
- probes regions outside of Galactic Center

Secondary emission

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

IR bkgd

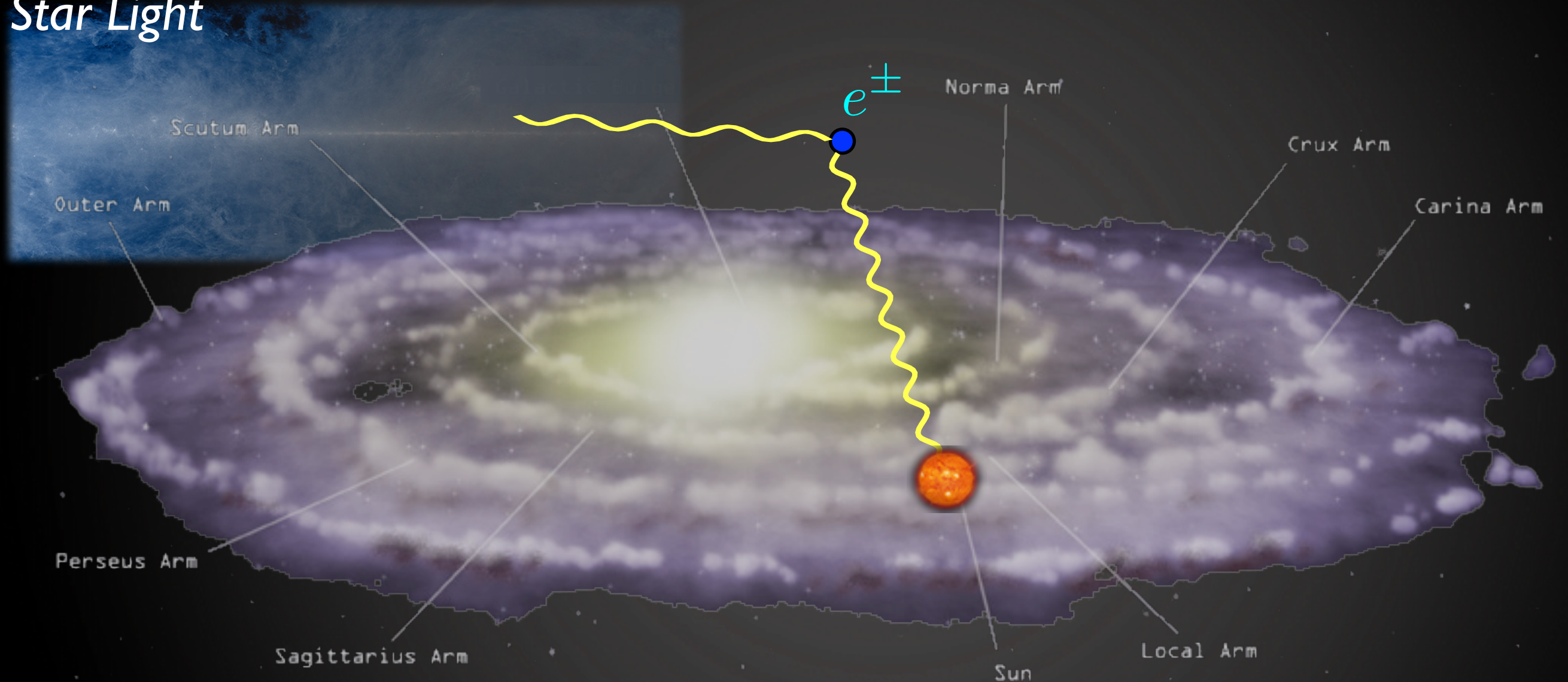


- upscatter of CMB, infrared and starlight photons on energetic $e^\pm$
- probes regions outside of Galactic Center

Secondary emission

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

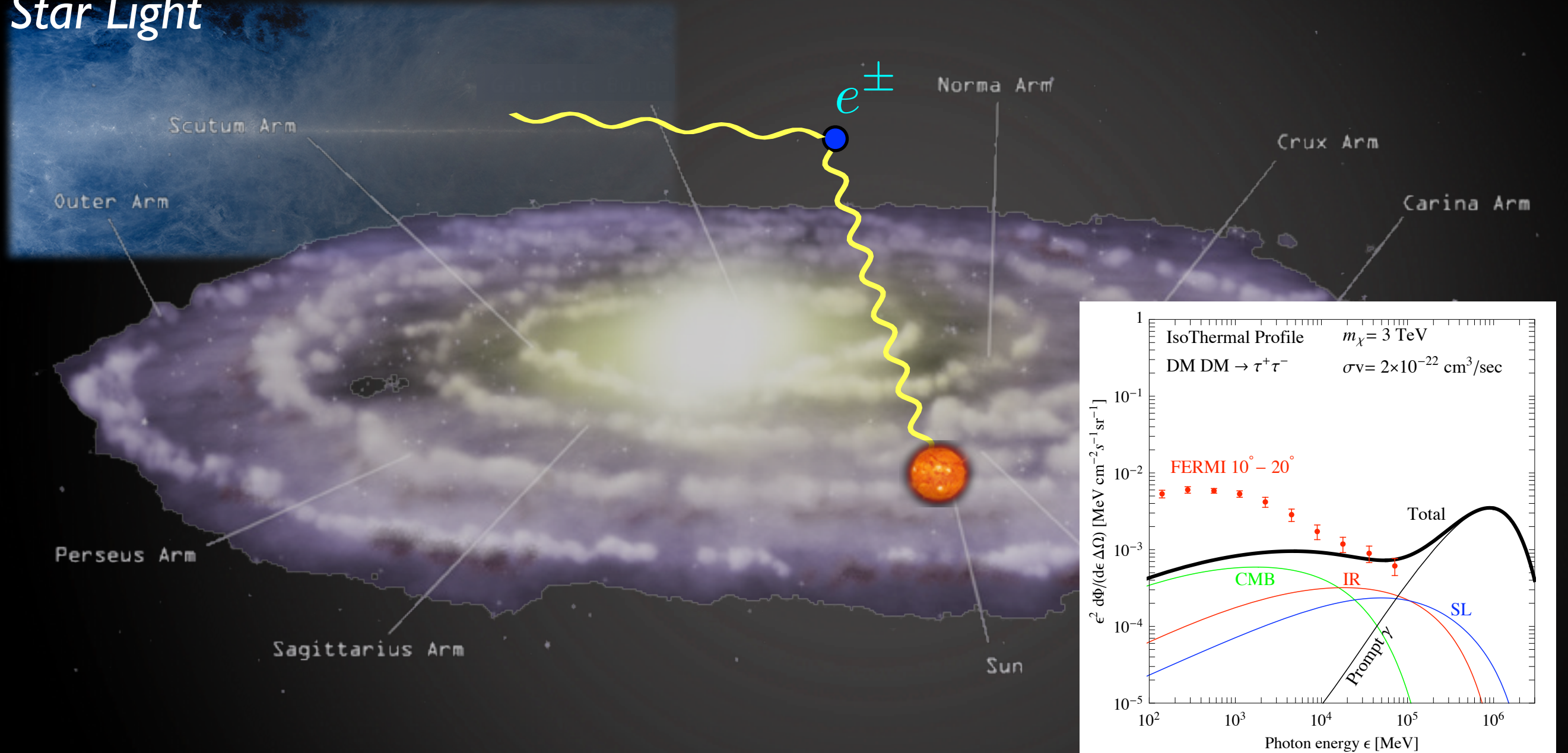
Star Light



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

Secondary emission

a. γ from Inverse Compton on $e^\pm$ in halo
 Star Light



Cirelli, Panci, Serpico 0912.0663

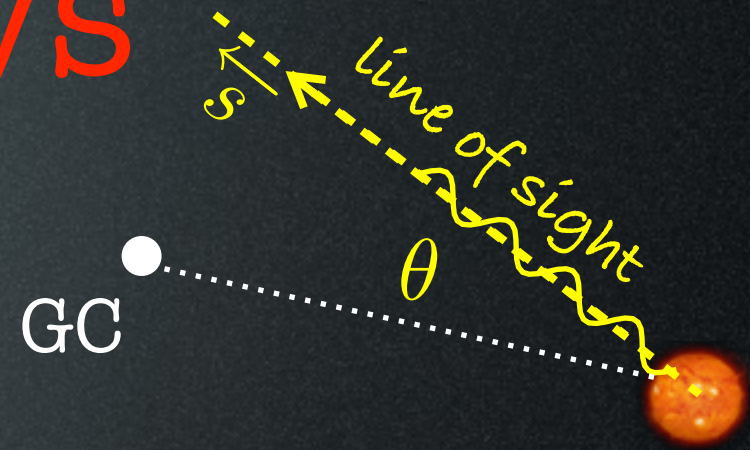
- upscatter of CMB, infrared and starlight photons on energetic $e^\pm$
- probes regions outside of Galactic Center

ICS gamma rays

Flux of ICS γ
from direction θ :

$$\frac{d\Phi_{\text{IC}\gamma}}{dE_\gamma d\theta} = \frac{1}{E_\gamma} \int_{\text{l.o.s.}} \frac{ds}{4\pi} \underbrace{2 \int_{m_e}^{M_{\text{DM}}} dE_e \sum_i \mathcal{P}_{\text{IC}}^i \frac{dn_{e^\pm}}{dE_e}}_{\text{emission from a 'cell' in } \vec{s}}$$

integral over s
emission from a 'cell' in $\vec{s}$

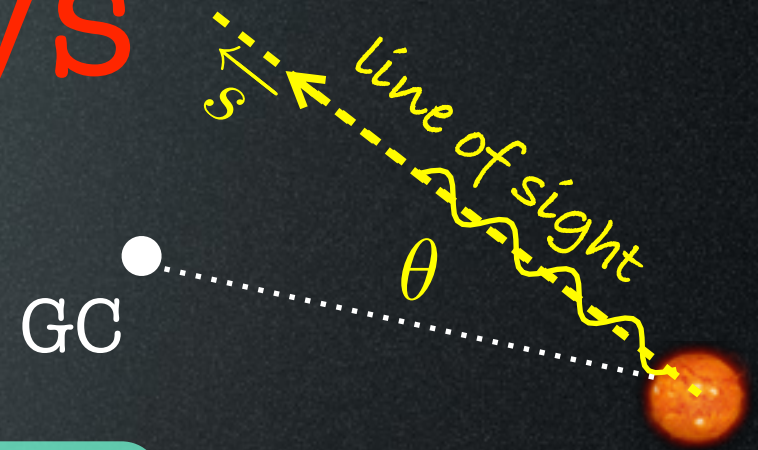


ICS gamma rays

Flux of ICS γ
from direction θ :

$$\frac{d\Phi_{\text{IC}\gamma}}{dE_\gamma d\theta} = \frac{1}{E_\gamma} \int_{\text{l.o.s.}} \frac{ds}{4\pi} 2 \int_{m_e}^{M_{\text{DM}}} dE_e \sum_i \mathcal{P}_{\text{IC}}^i \boxed{\frac{dn_{e^\pm}}{dE_e}}$$

spectral densities
of emitting $e^\pm$



ICS gamma rays

Flux of ICS γ
from direction θ :

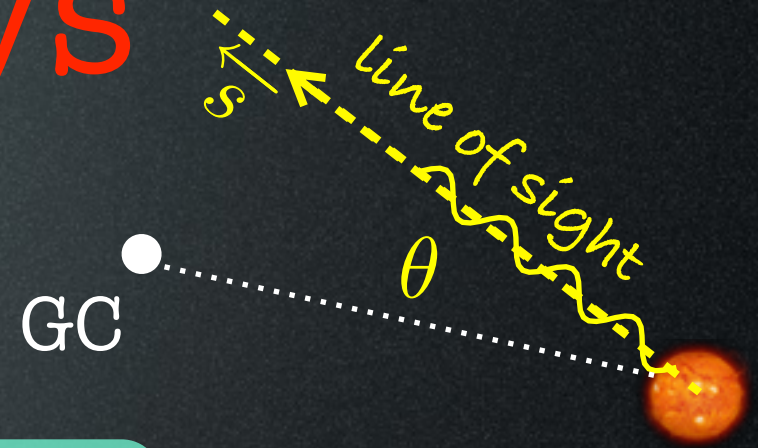
$$\frac{d\Phi_{\text{IC}\gamma}}{dE_\gamma d\theta} = \frac{1}{E_\gamma} \int_{\text{l.o.s.}} \frac{ds}{4\pi} 2 \int_{m_e}^{M_{\text{DM}}} dE_e \sum_i \mathcal{P}_{\text{IC}}^i \left[\frac{dn_{e^\pm}}{dE_e} \right]$$

spectral densities
of emitting $e^\pm$

power emitted by individual 'cell':

$$\mathcal{P}_{\text{IC}}^i(E_\gamma, E_e, \vec{x}) = \frac{3\sigma_{\text{T}}}{4\gamma^2} \int_{1/4\gamma^2}^1 dq \left(E_\gamma - \frac{E_\gamma}{4q\gamma^2(1-\epsilon)} \right) \frac{n_i(E_\gamma^0(q), \vec{x})}{q} \left[2q \ln q + q + 1 - 2q^2 + \frac{1}{2} \frac{\epsilon^2}{1-\epsilon} (1-q) \right]$$

$$q = \frac{\epsilon}{\Gamma_E(1-\epsilon)}, \quad \Gamma_E = \frac{4E_\gamma^0 E_e}{m_e^2}, \quad \epsilon = \frac{E_\gamma}{E_e}$$



ICS gamma rays

Flux of ICS γ
from direction θ :

$$\frac{d\Phi_{\text{IC}\gamma}}{dE_\gamma d\theta} = \frac{1}{E_\gamma} \int_{\text{l.o.s.}} \frac{ds}{4\pi} 2 \int_{m_e}^{M_{\text{DM}}} dE_e \sum_i \mathcal{P}_{\text{IC}}^i \left[\frac{dn_{e^\pm}}{dE_e} \right]$$

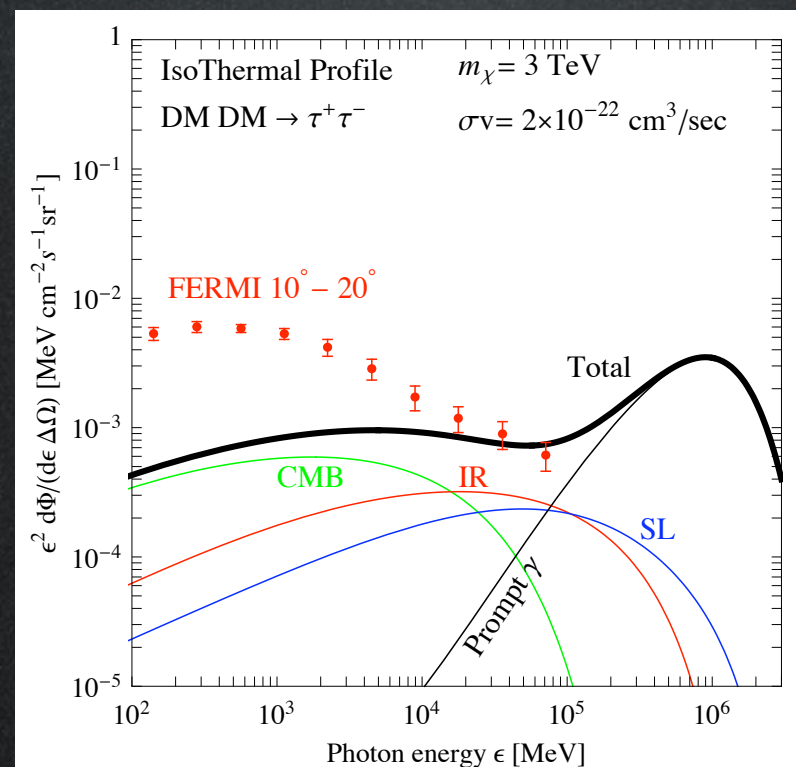
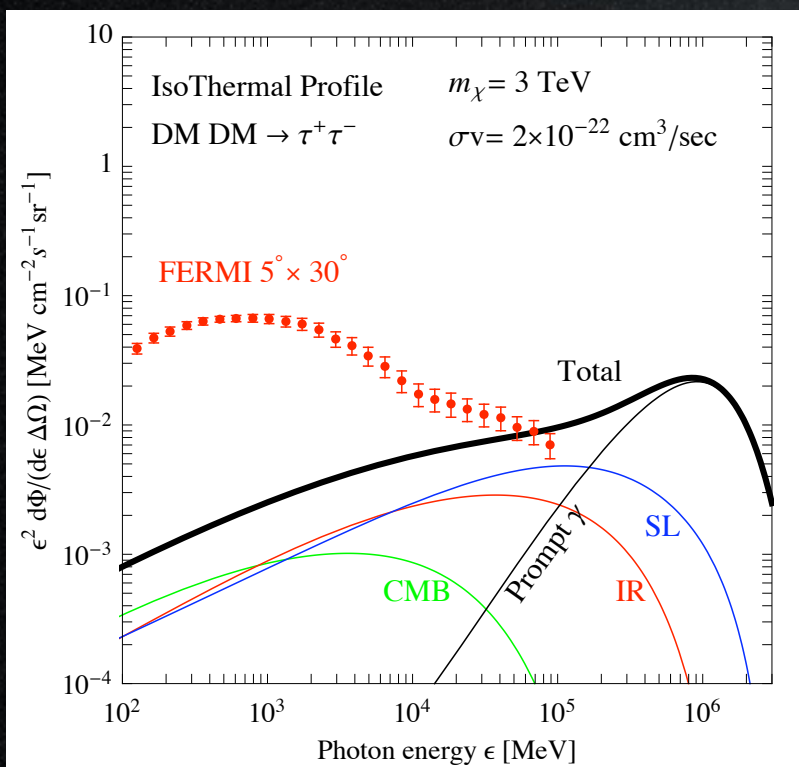
spectral densities of emitting $e^\pm$

power emitted by individual 'cell':

$$\mathcal{P}_{\text{IC}}^i(E_\gamma, E_e, \vec{x}) = \frac{3\sigma_T}{4\gamma^2} \int_{1/4\gamma^2}^1 dq \left(E_\gamma - \frac{E_\gamma}{4q\gamma^2(1-\epsilon)} \right) \frac{n_i(E_\gamma^0(q), \vec{x})}{q} \left[2q \ln q + q + 1 - 2q^2 + \frac{1}{2} \frac{\epsilon^2}{1-\epsilon} (1-q) \right]$$

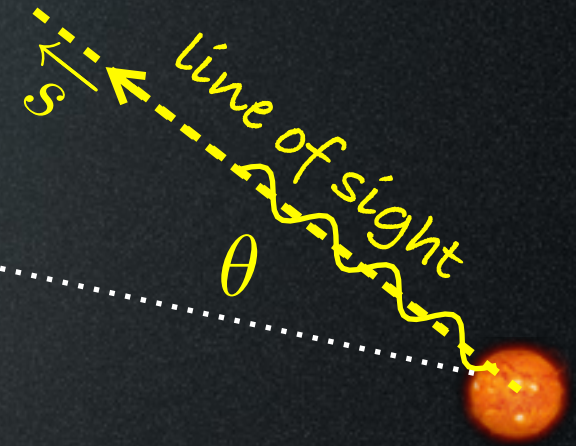
$$q = \frac{\epsilon}{\Gamma_E(1-\epsilon)}, \quad \Gamma_E = \frac{4E_\gamma^0 E_e}{m_e^2}, \quad \epsilon = \frac{E_\gamma}{E_e}$$

Different windows = different weights of target lights:



Cirelli, Panci, Serpico 0912.0663

spectral densities
of target lights



ICS gamma rays

Flux of ICS γ
from direction θ :

$$\frac{d\Phi_{\text{IC}\gamma}}{dE_\gamma d\theta} = \frac{1}{E_\gamma} \int_{\text{l.o.s.}} \frac{ds}{4\pi} 2 \int_{m_e}^{M_{\text{DM}}} dE_e \sum_i \mathcal{P}_{\text{IC}}^i \left[\frac{dn_{e^\pm}}{dE_e} \right]$$

spectral densities of emitting $e^\pm$

power emitted by individual 'cell':

$$\mathcal{P}_{\text{IC}}^i(E_\gamma, E_e, \vec{x}) = \frac{3\sigma_T}{4\gamma^2} \int_{1/4\gamma^2}^1 dq \left(E_\gamma - \frac{E_\gamma}{4q\gamma^2(1-\epsilon)} \right) \frac{n_i(E_\gamma^0(q), \vec{x})}{q} \left[2q \ln q + q + 1 - 2q^2 + \frac{1}{2} \frac{\epsilon^2}{1-\epsilon} (1-q) \right]$$

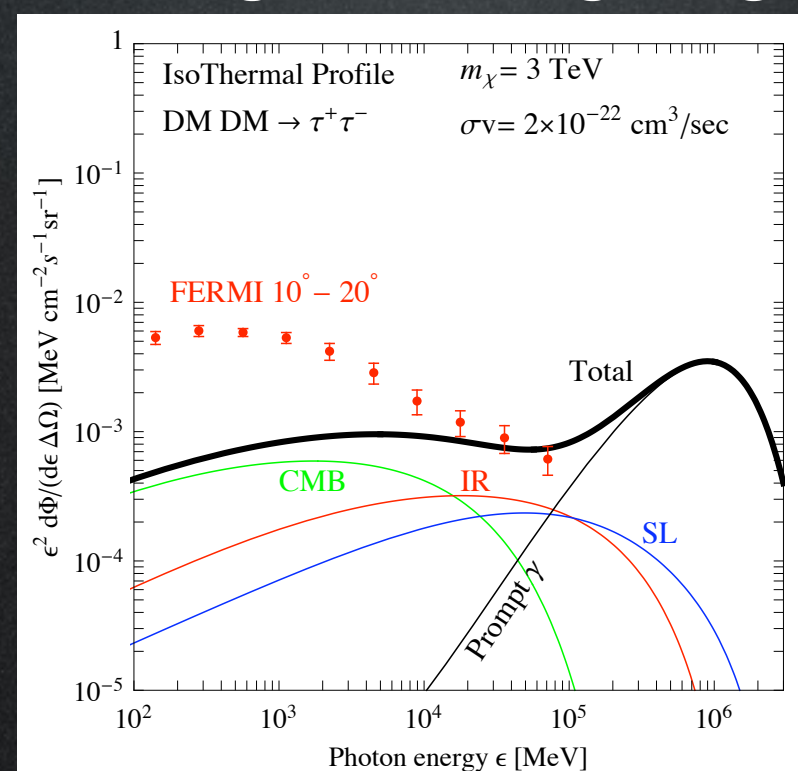
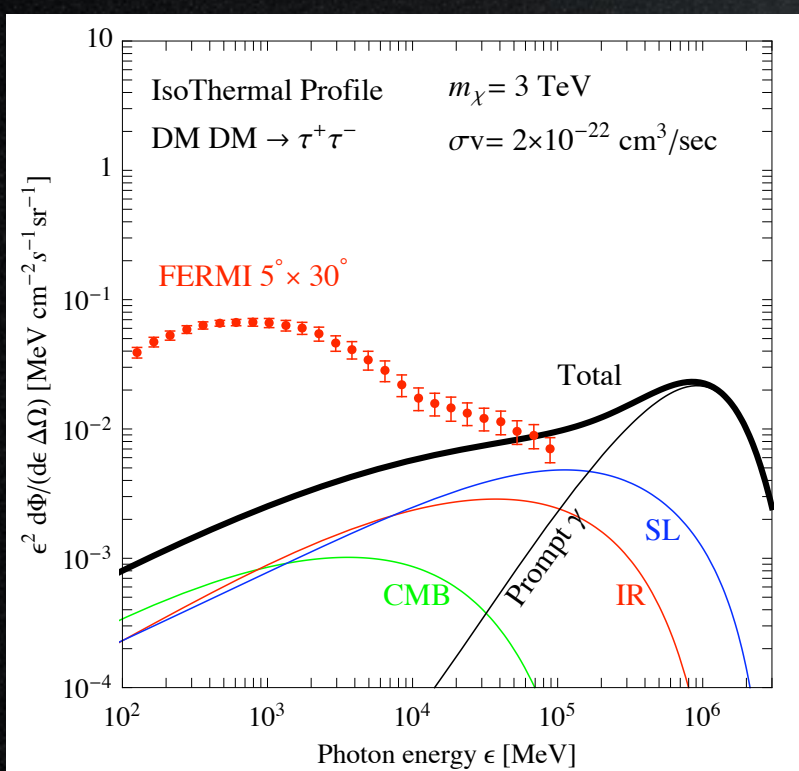
$$q = \frac{\epsilon}{\Gamma_E(1-\epsilon)}, \quad \Gamma_E = \frac{4E_\gamma^0 E_e}{m_e^2}, \quad \epsilon = \frac{E_\gamma}{E_e}$$

spectral densities of target lights

Rule of thumb:

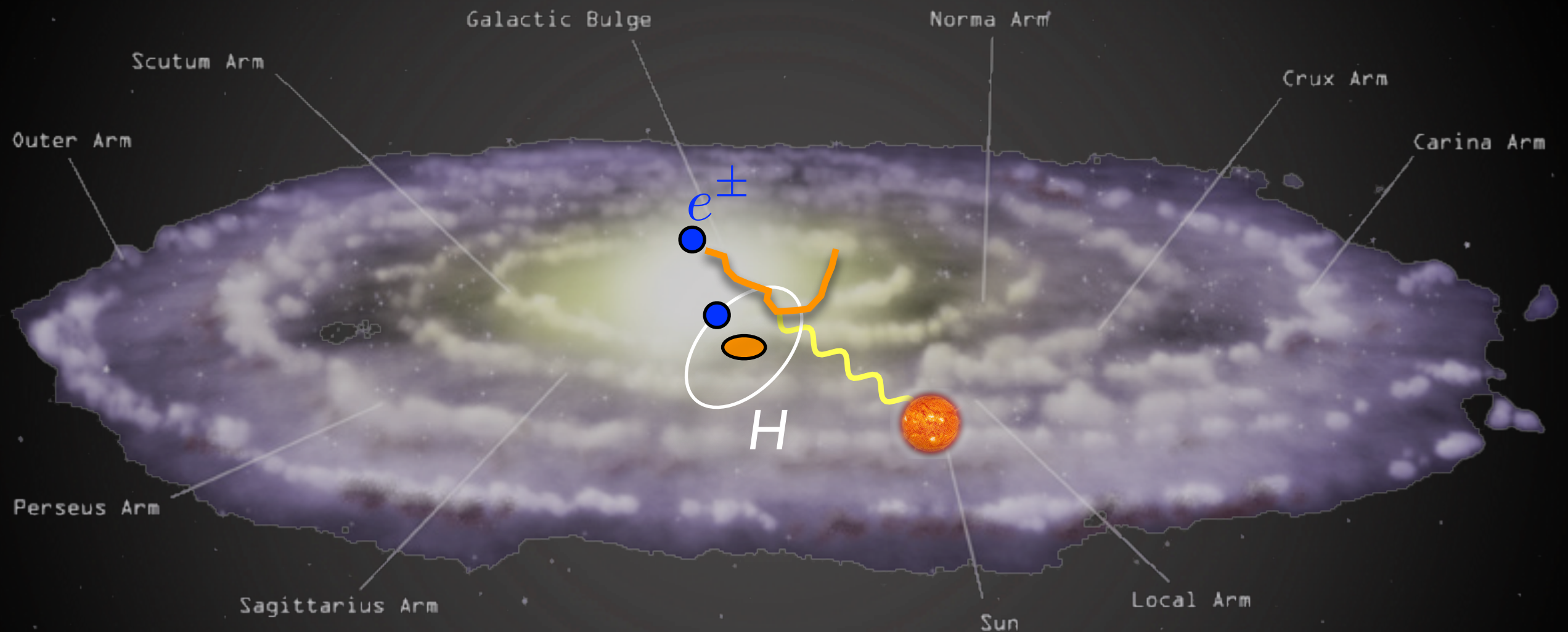
$$E_\gamma \leq 4\gamma^2 E_\gamma^0$$

Cirelli, Panci, Serpico 0912.0663



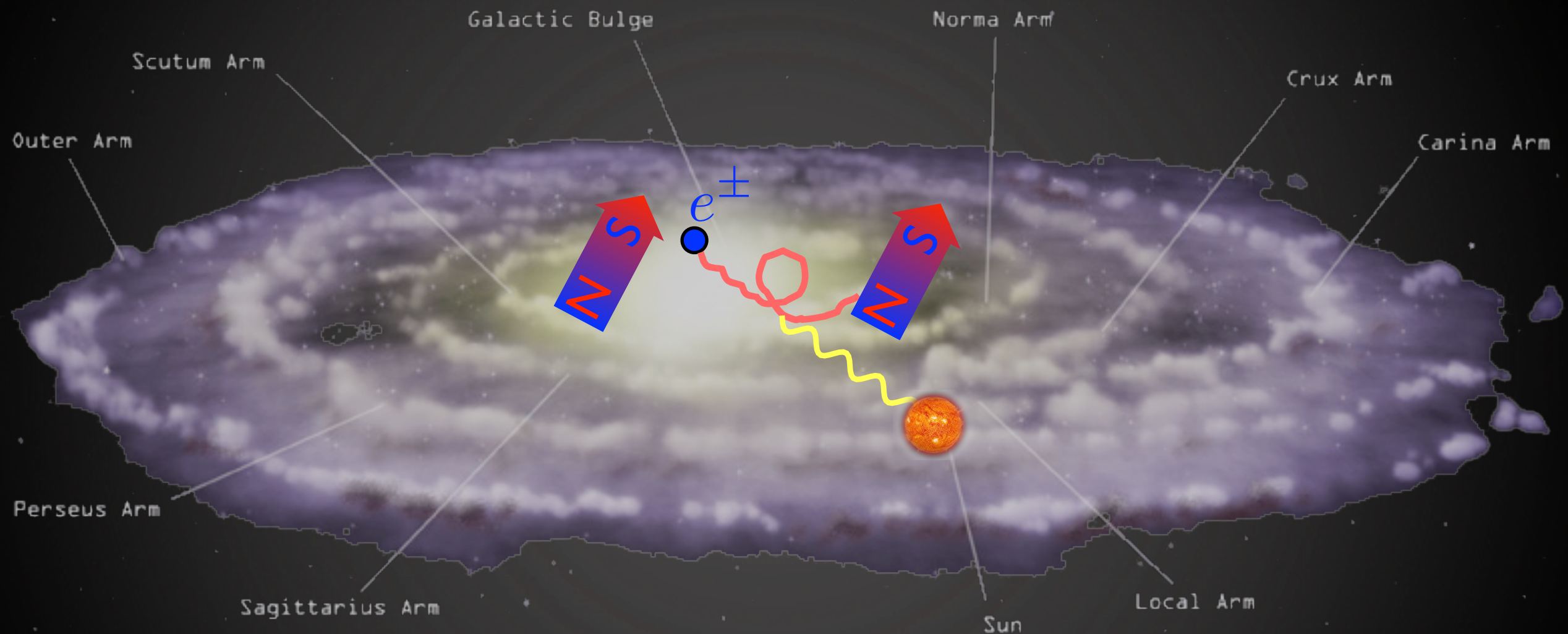
Secondary emission

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



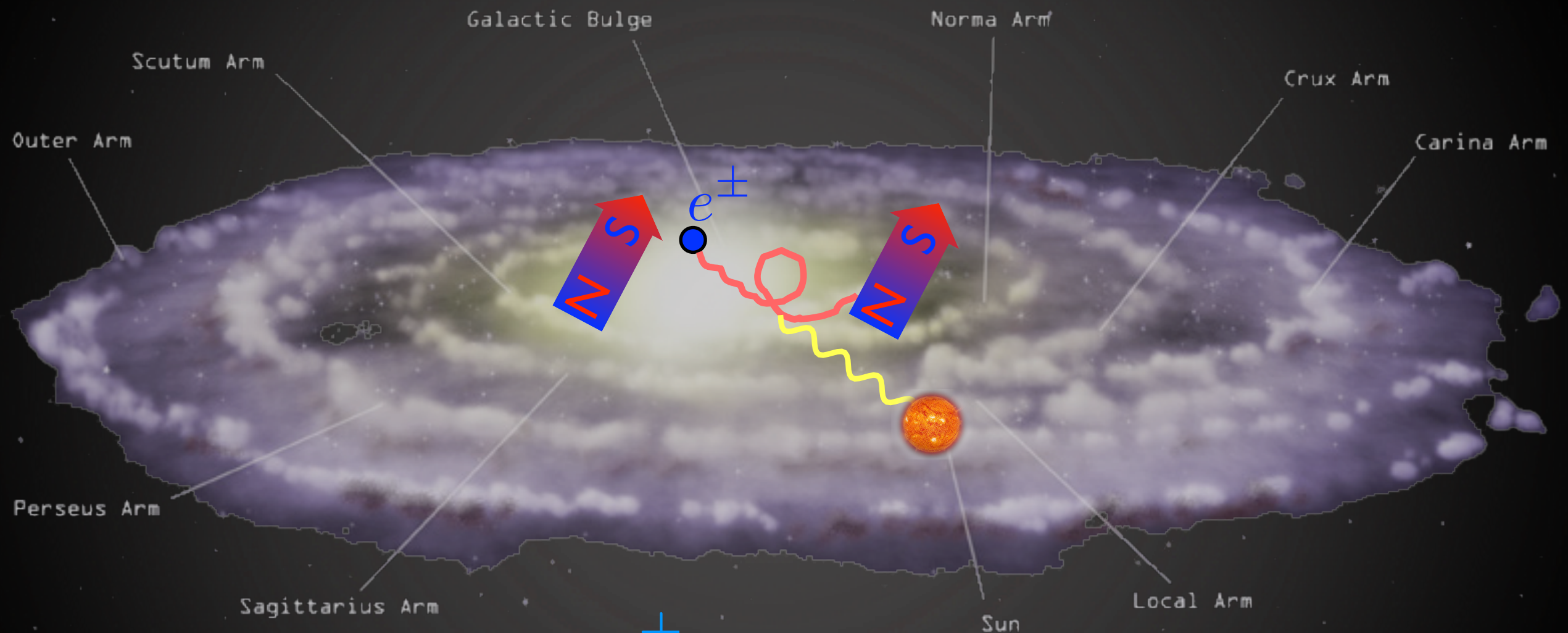
Secondary emission

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



Secondary emission

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

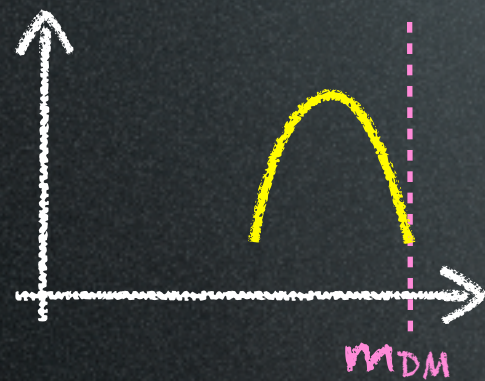


- compute the population of $e^\pm$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$
(assuming 'scrambled' B ; in principle, directionality could focus emission, lift bounds by $O(\text{some})$)

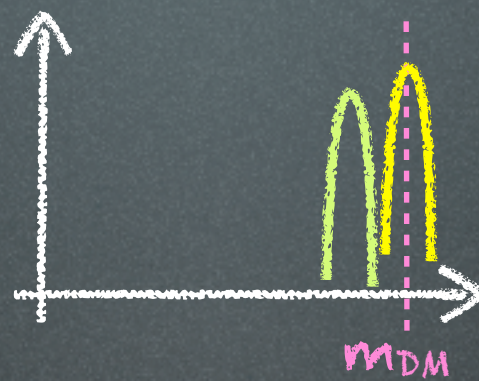
How does DM produce γ -rays?

1. prompt emission

1a. continuum



1b. line(s)

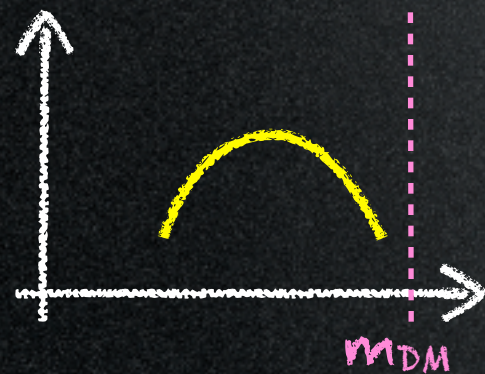


1c. sharp features

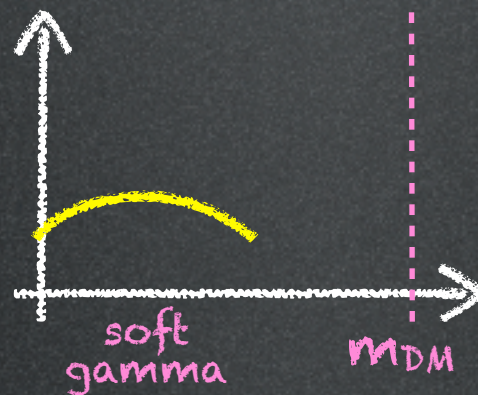


2. secondary emission

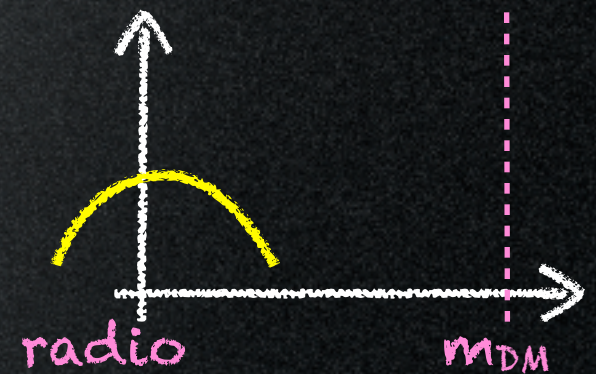
2a. ICS



2b. bremsstrahlung



2c. synchrotron

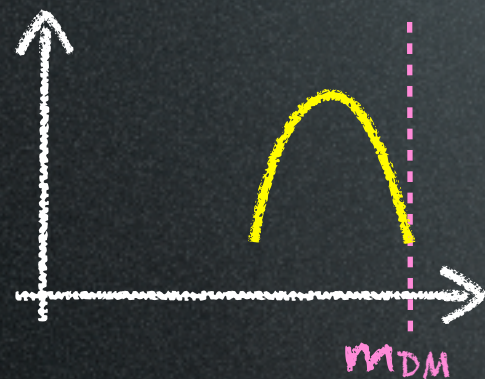


How does DM produce γ -rays?

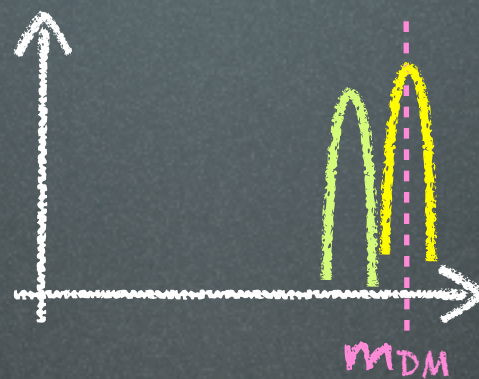
1. prompt emission

environment-independent

1a. continuum



1b. line(s)



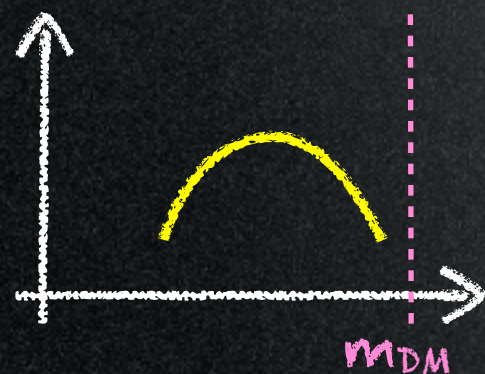
1c. sharp features



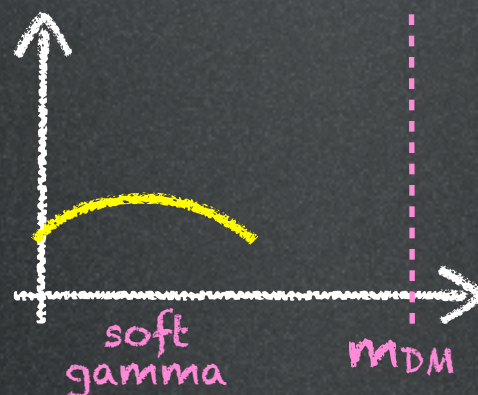
2. secondary emission

environment-dependent

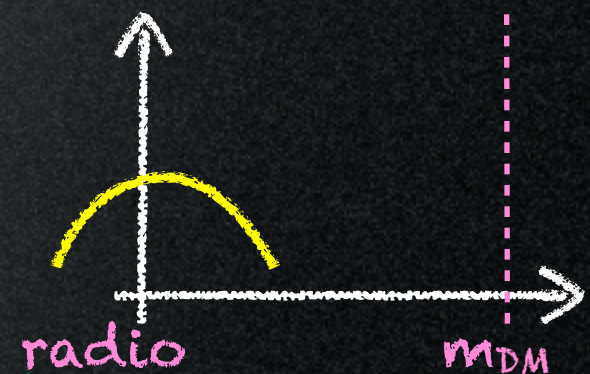
2a. ICS



2b. bremsstrahlung

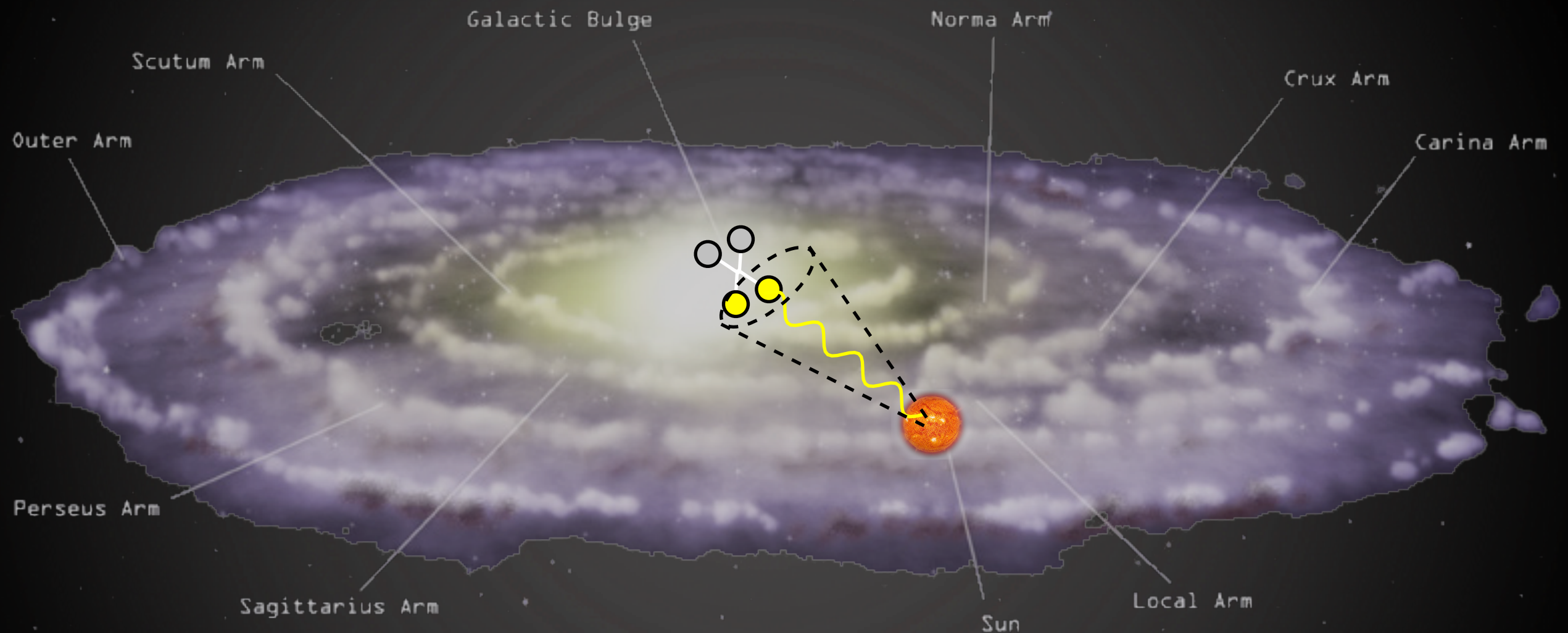


2c. synchrotron



Basic picture: targets

γ from DM annihilations in galactic center

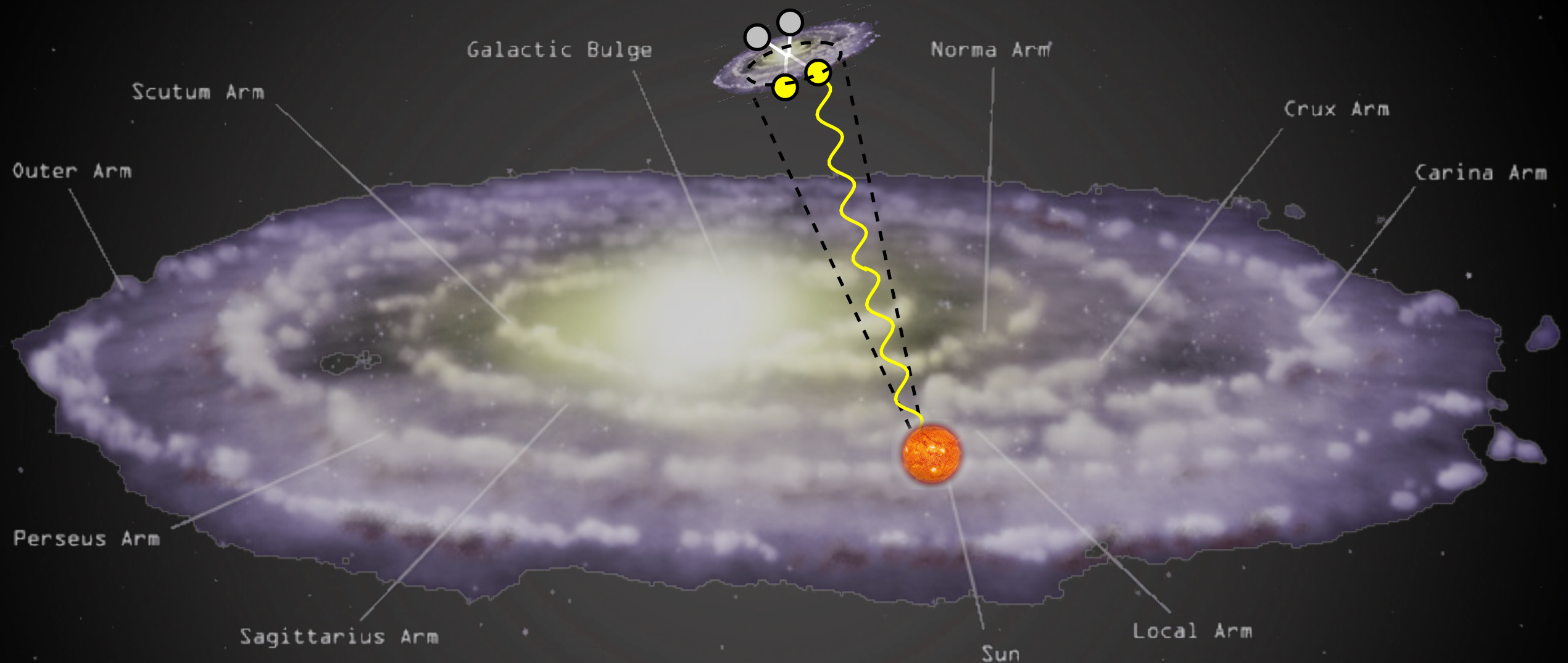


DM DM $\rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots$ and γ

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

Basic picture: targets

γ from DM annihilations in dwarf galaxies

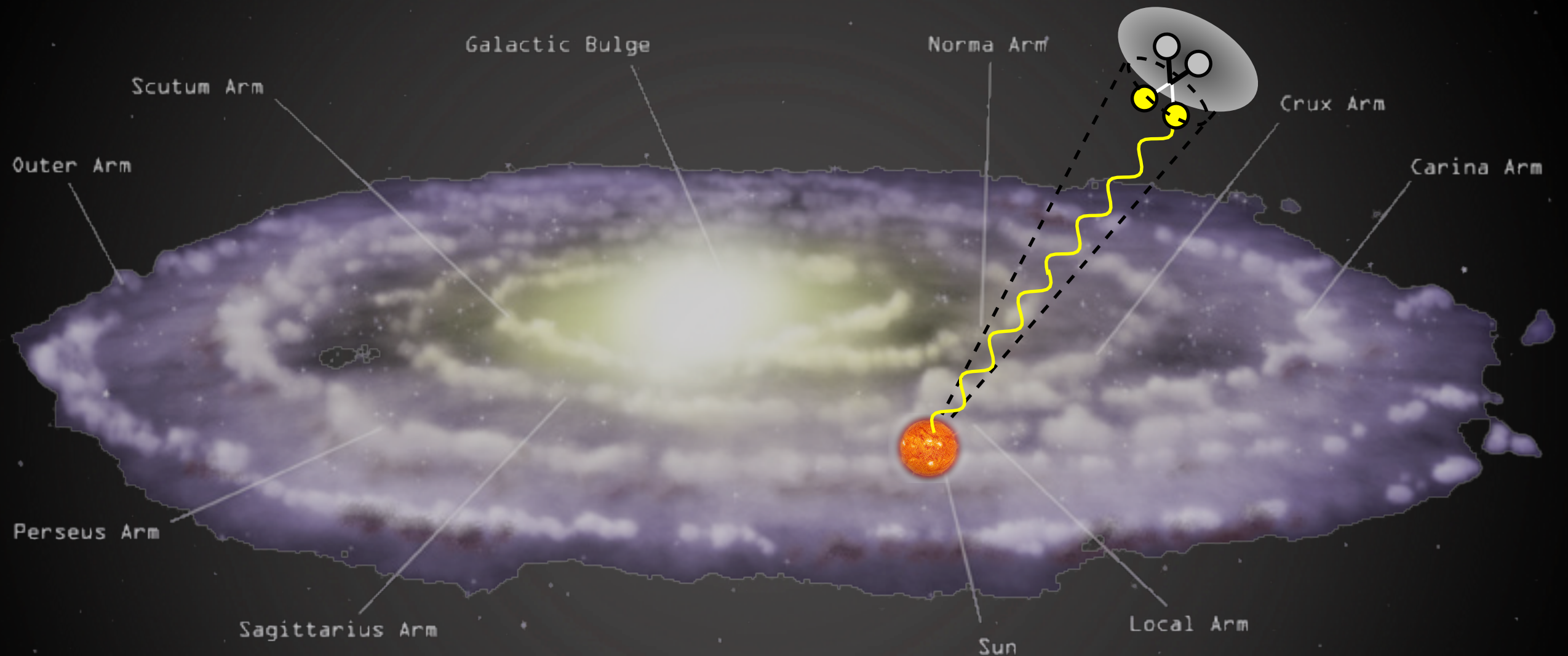


DM DM $\rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots$ and γ

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

Basic picture: targets

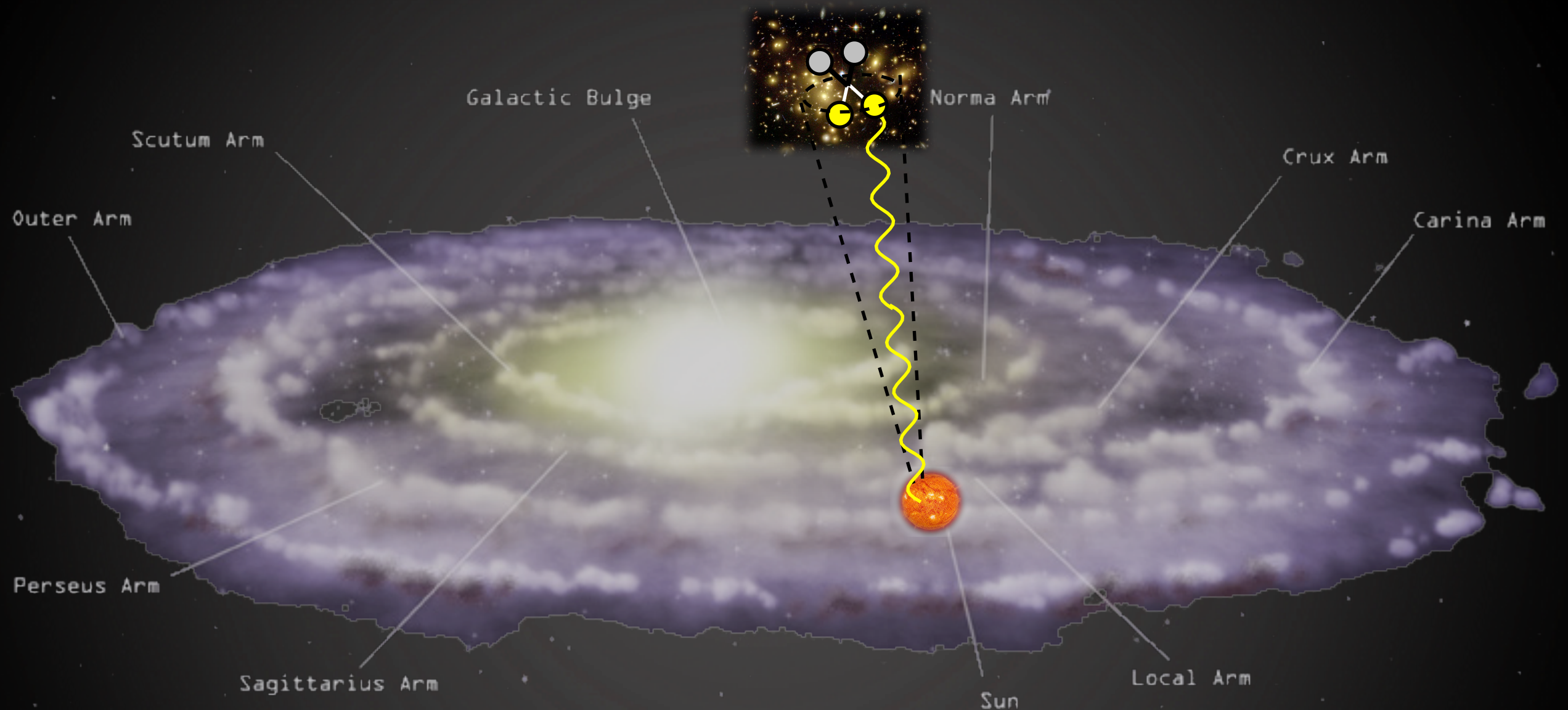
γ from DM annihilations in subhaloes



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

Basic picture: targets

γ from DM annihilations in galaxy clusters



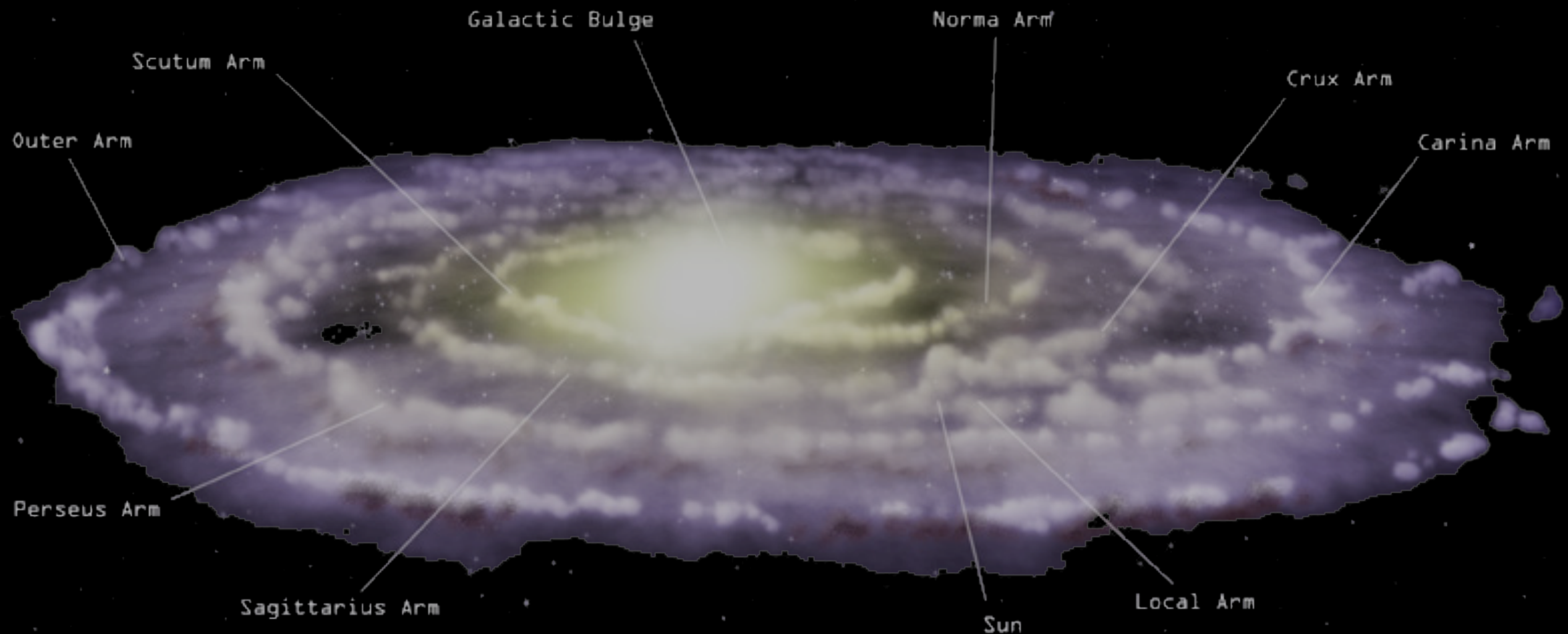
DM DM

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

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

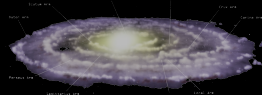
Basic picture: targets

γ from outside the Galaxy



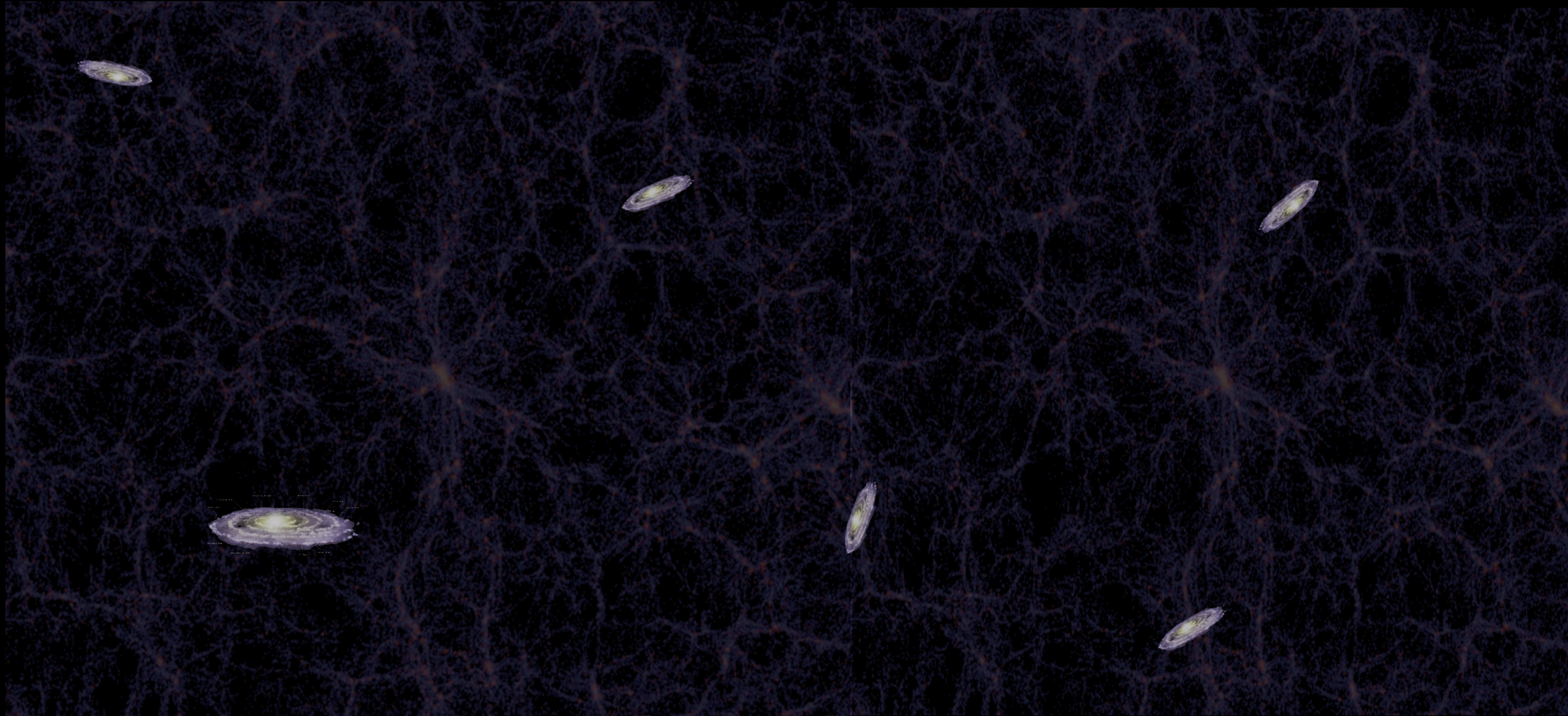
Basic picture: targets

γ from outside the Galaxy



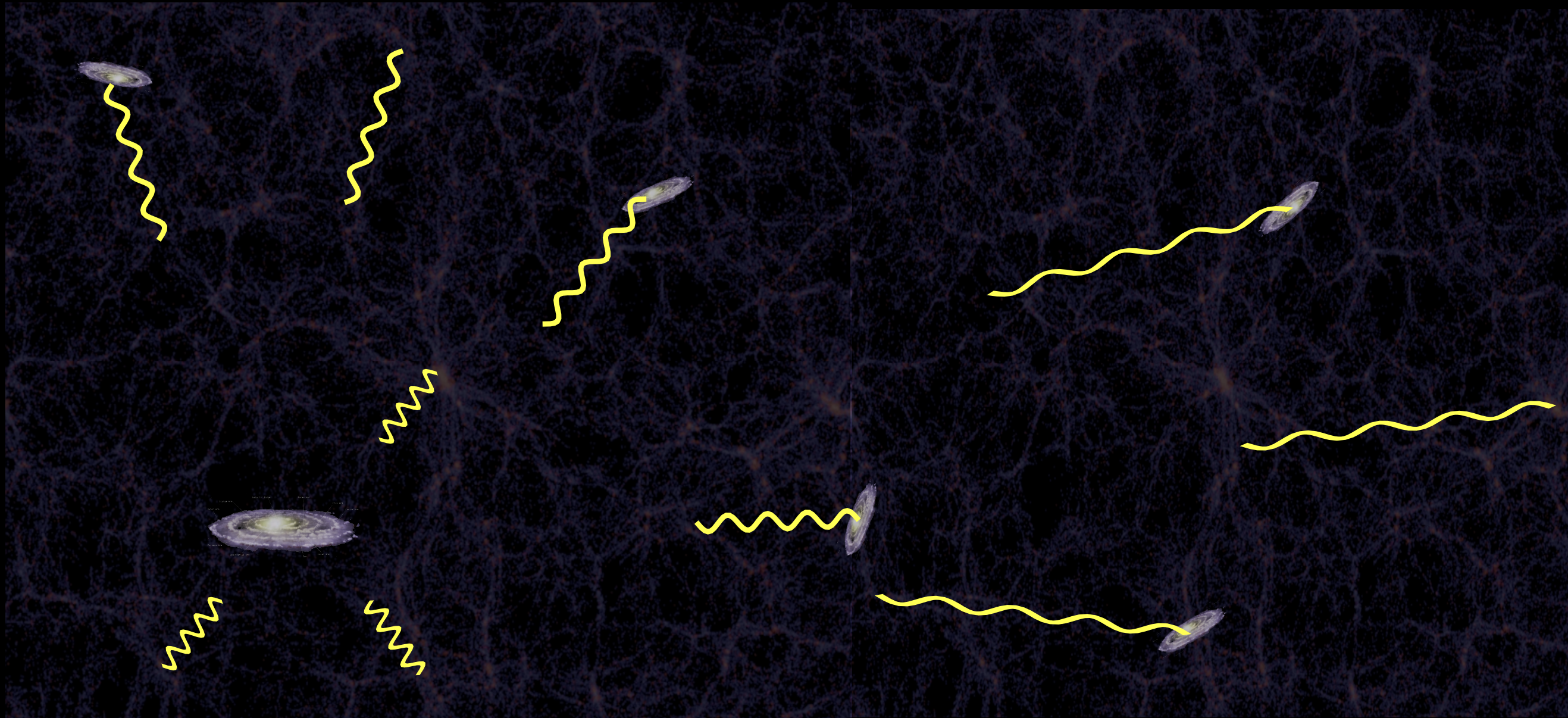
Basic picture: targets

γ from outside the Galaxy



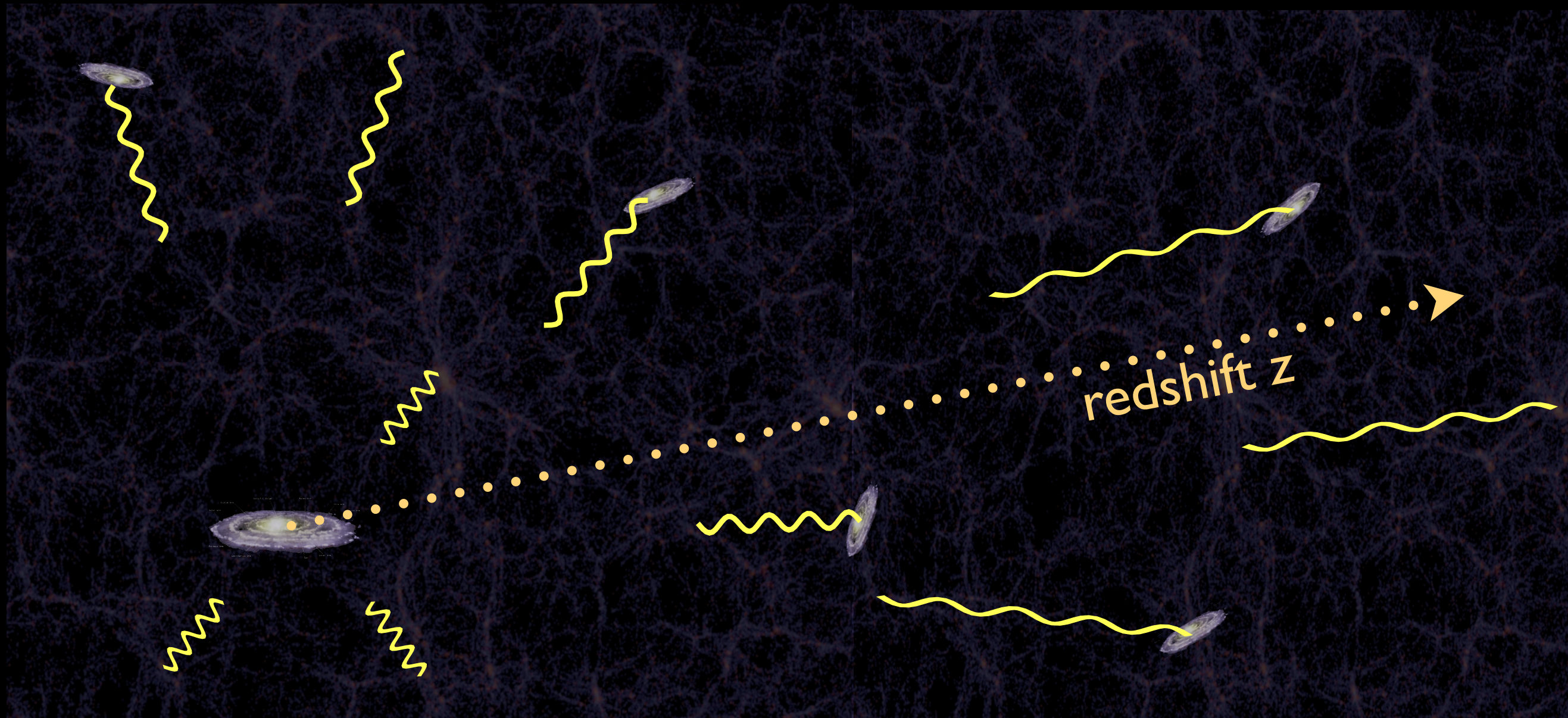
Basic picture: targets

γ from outside the Galaxy



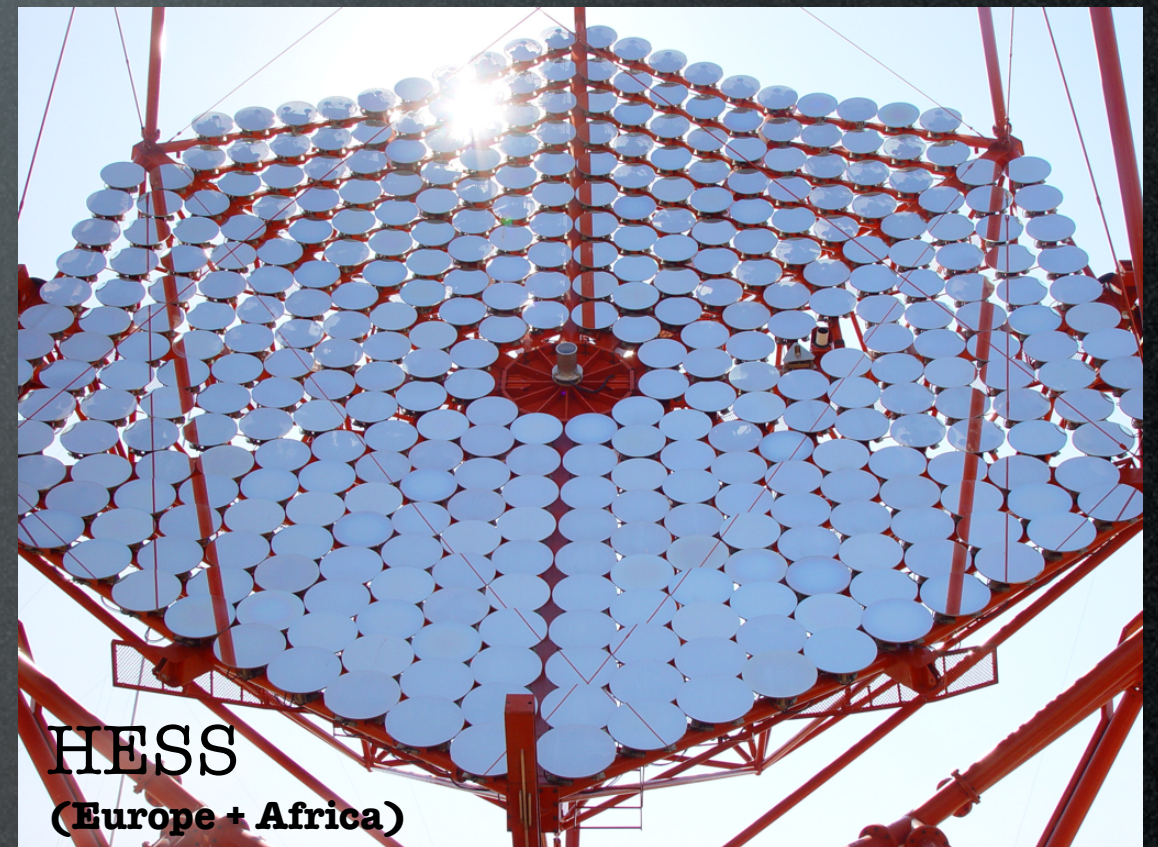
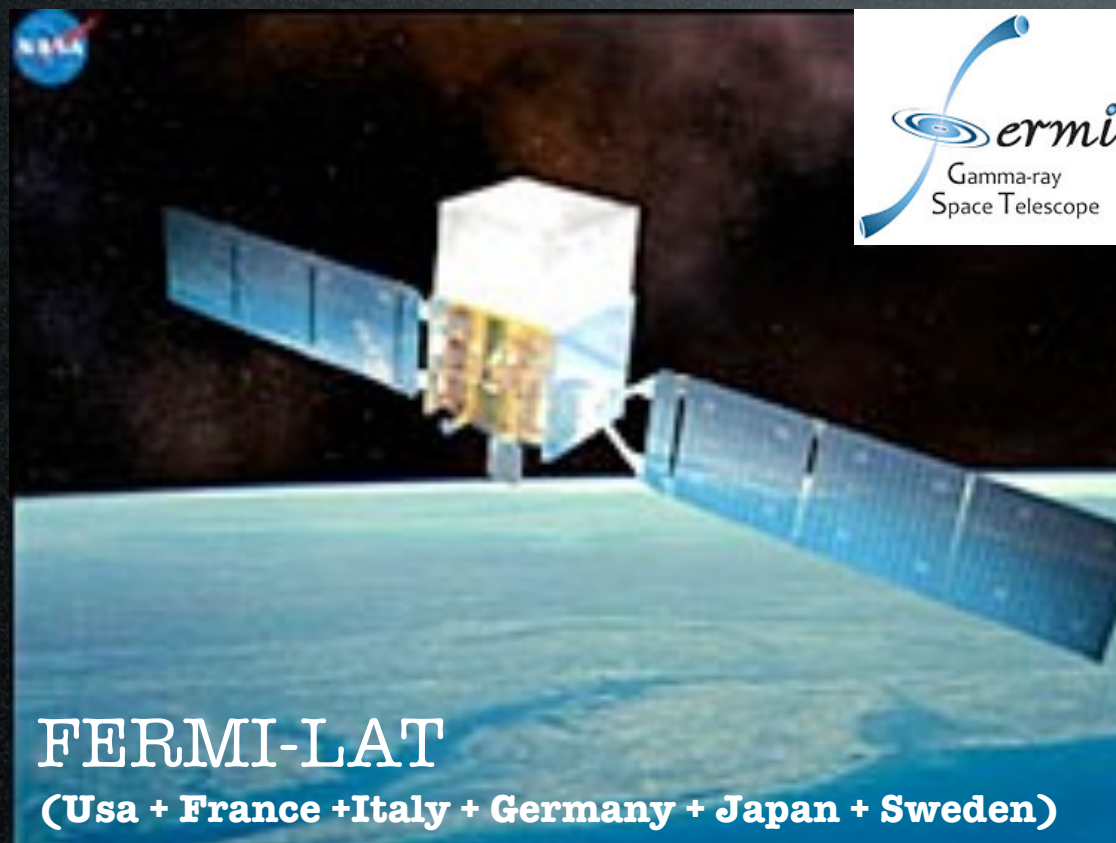
Basic picture: targets

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**

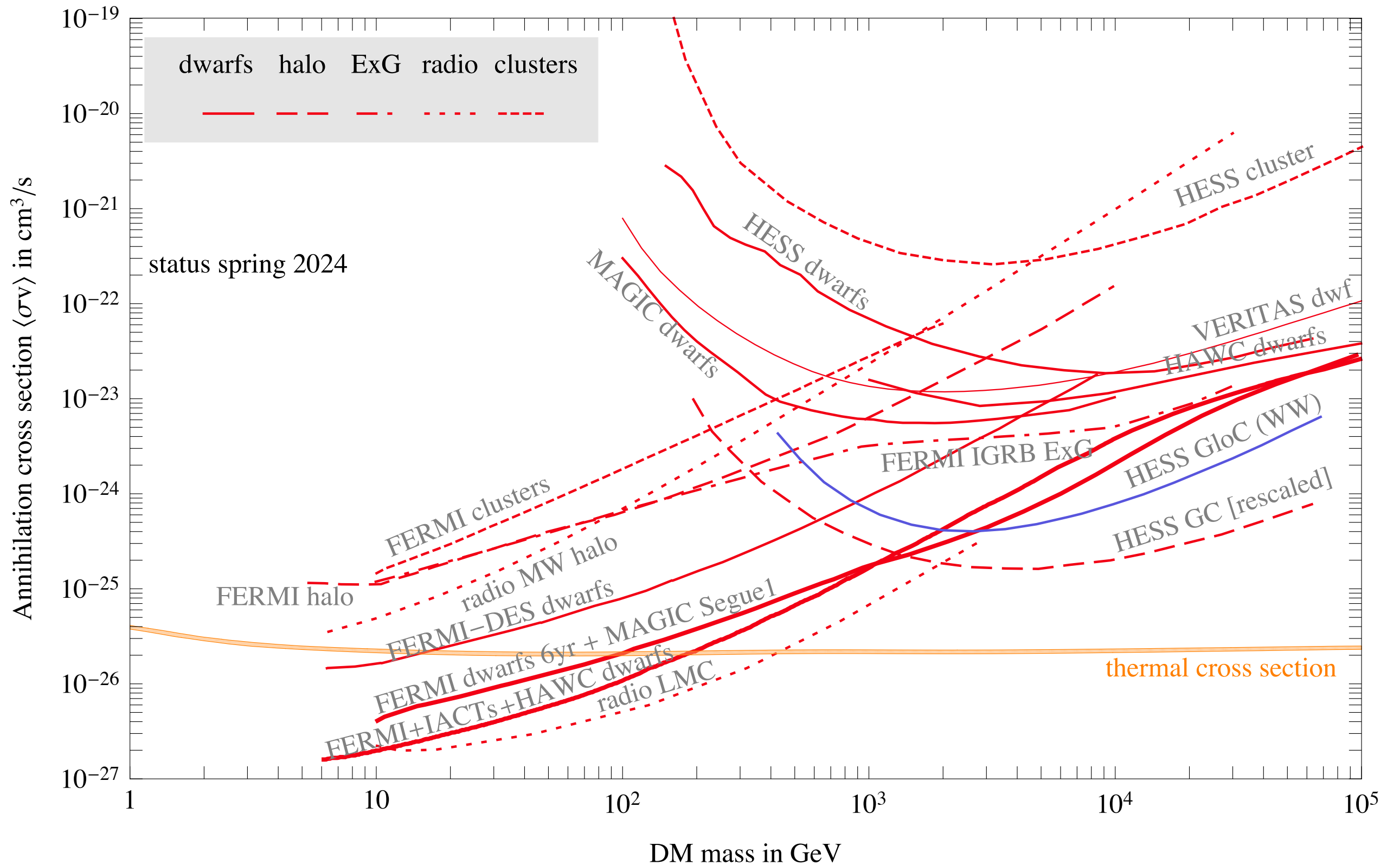
Gamma rays



many constraints and a few hints

Constraints

Gamma-ray constraints, $\text{DM DM} \rightarrow b\bar{b}$



GC GeV excess

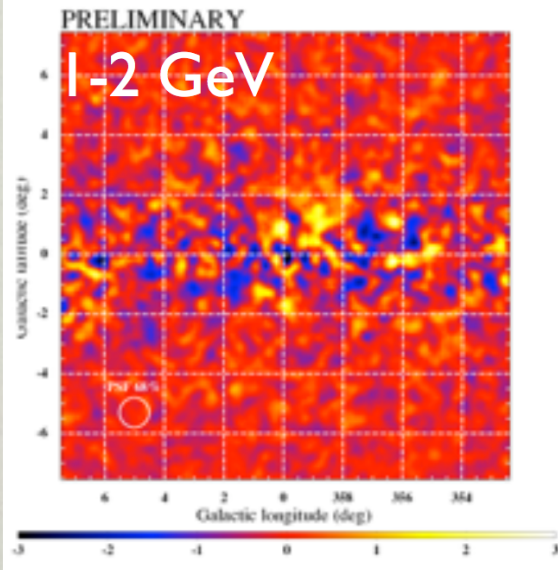
Dark Matter interpretation:

ADDITIONAL TEMPLATES

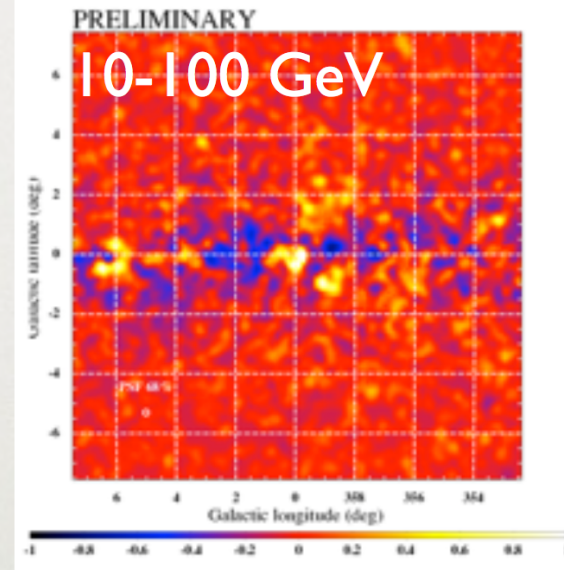
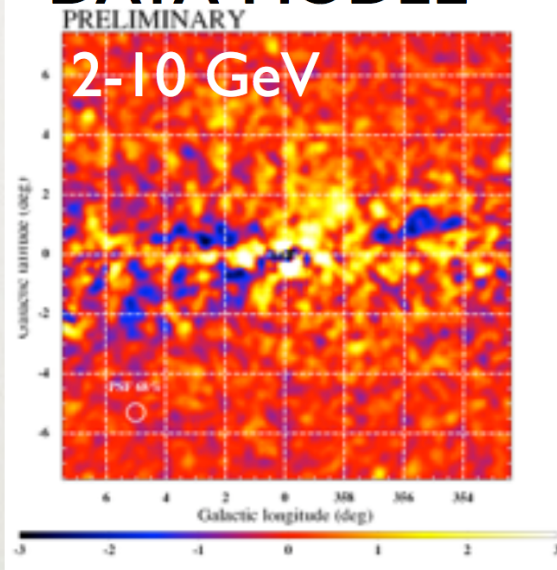
Counts in $0.1^\circ \times 0.1^\circ$ pixels
 0.3° radius gaussian smoothing

Pulsars, tuned-index

Without NFW:

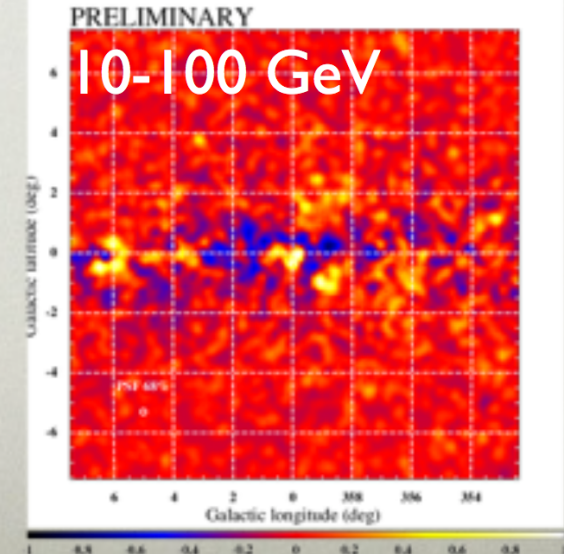
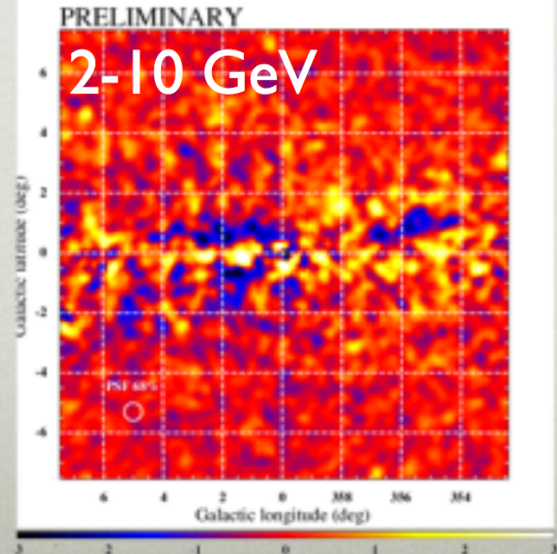
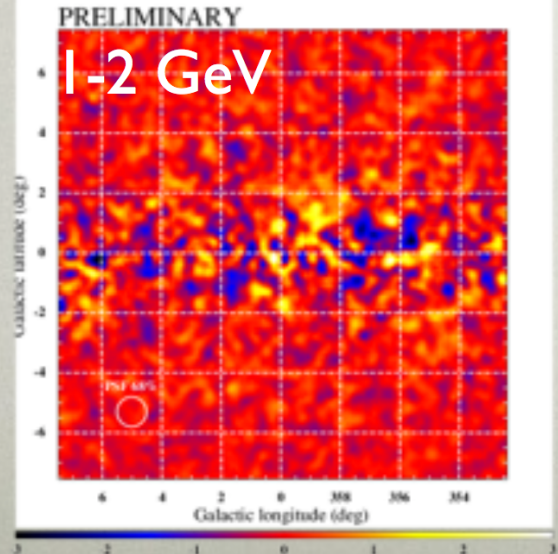


DATA-MODEL



Pulsars, tuned-index

With NFW:



S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815

GC GeV excess

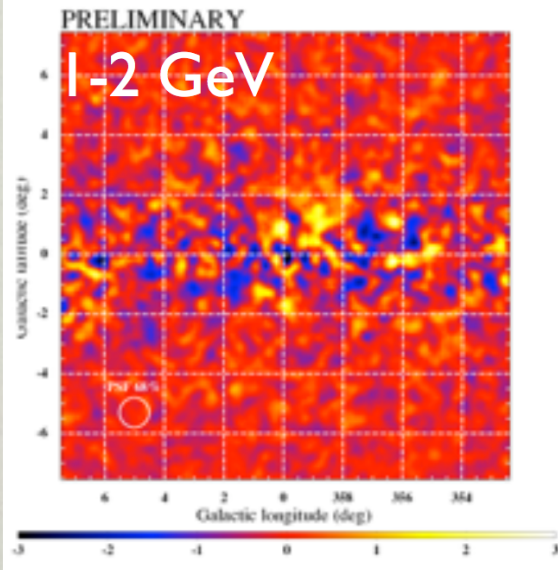
Dark Matter interpretation:

ADDITIONAL TEMPLATES

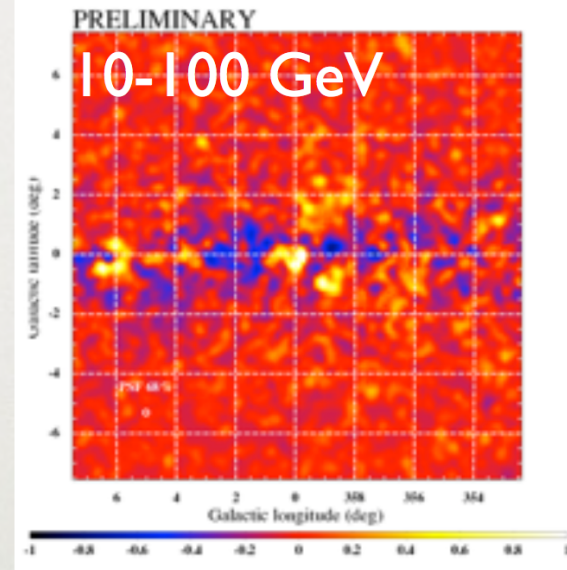
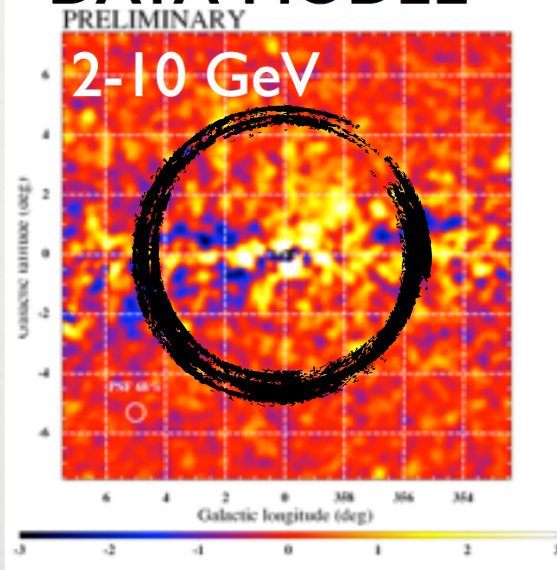
Counts in $0.1^\circ \times 0.1^\circ$ pixels
 0.3° radius gaussian smoothing

Pulsars, tuned-index

Without NFW:

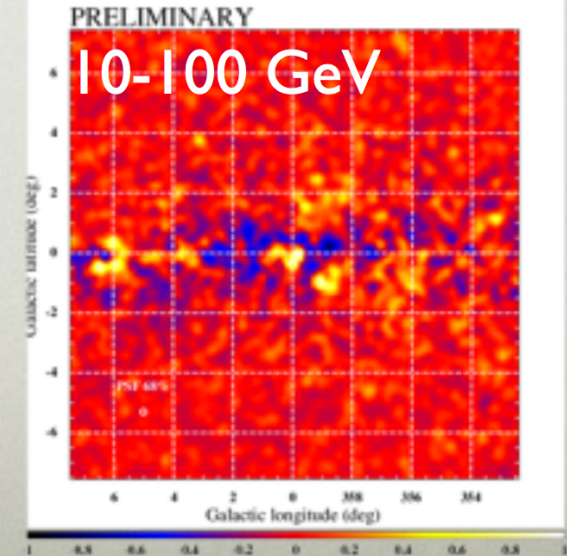
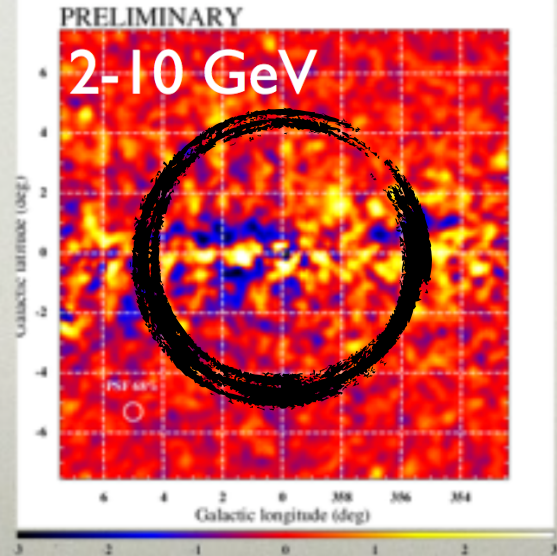
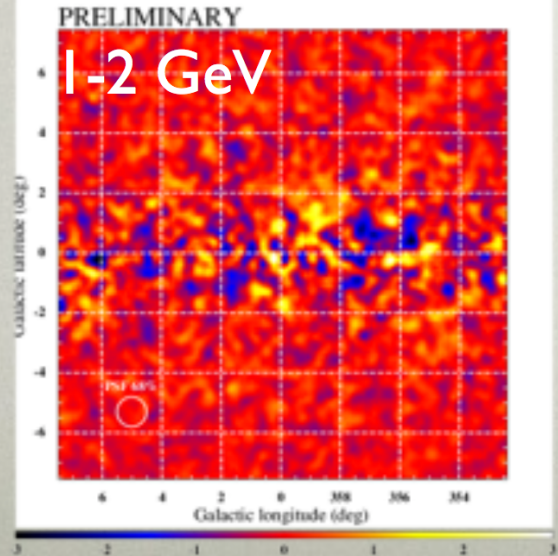


DATA-MODEL



Pulsars, tuned-index

With NFW:



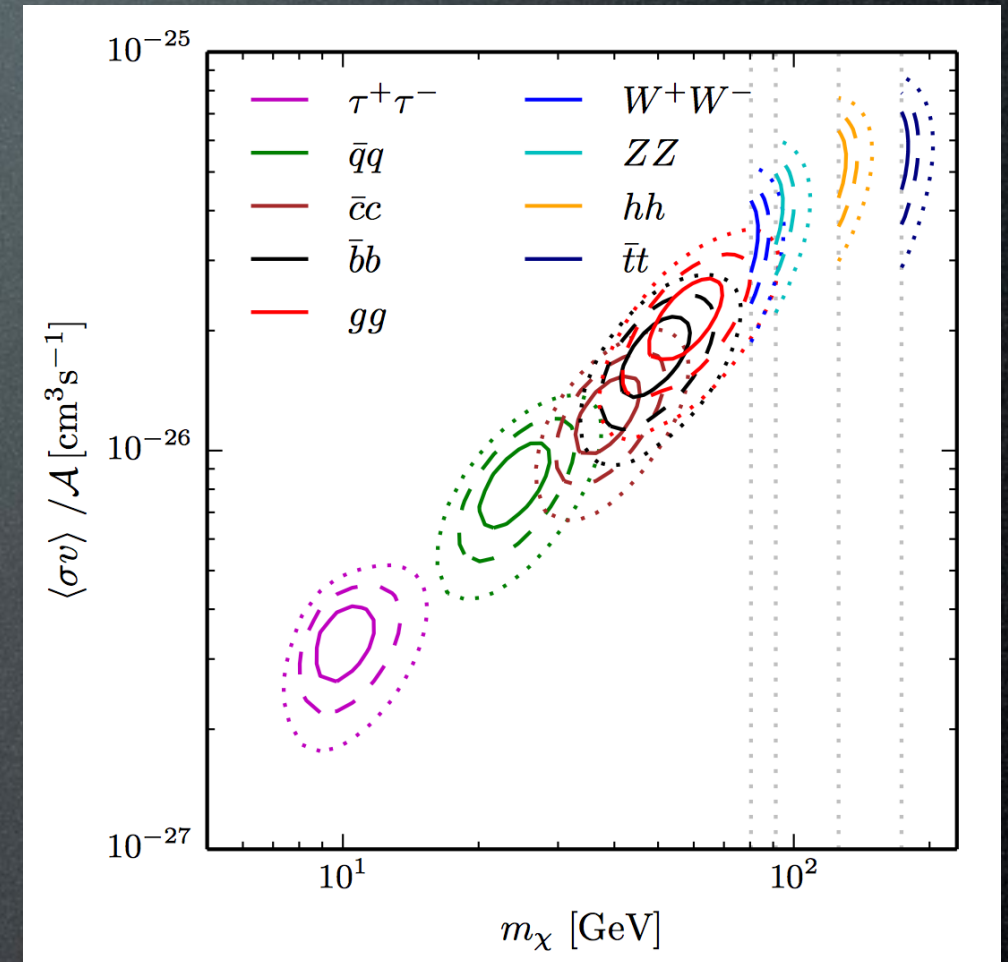
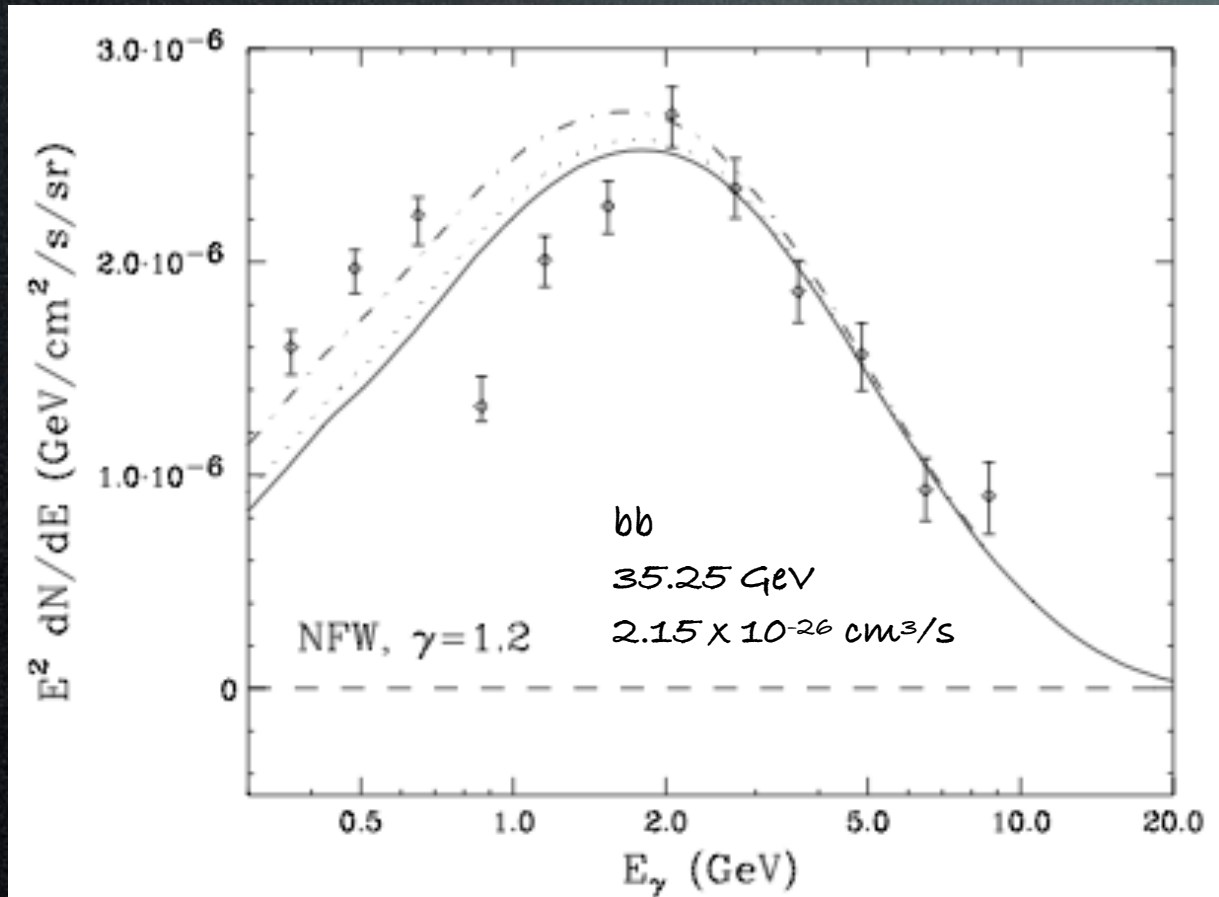
S. Murgia for FERMI-LAT - ICRC 2015
T. Porter for FERMI-LAT - ICRC 2015 #815

GC GeV excess

Dark Matter interpretation:

Best fit:

~35 GeV, quarks, ~thermal σv



F. Calore et al. 1411.4647
ICRC2015 #915

A compelling case
for annihilating DM

Daylan, Finkbeiner, Hooper, Linden,
Portillo, Rodd, Slatyer 1402.6703

...as good as it can get.

DM detection

direct detection

Xenon, LZ, Panda-X... (Dama/Libra?)

production at colliders

LHC

indirect

γ from annihil in galactic halo
and from secondary emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo

AMS, Dampe, Calet, Fermi...

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

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

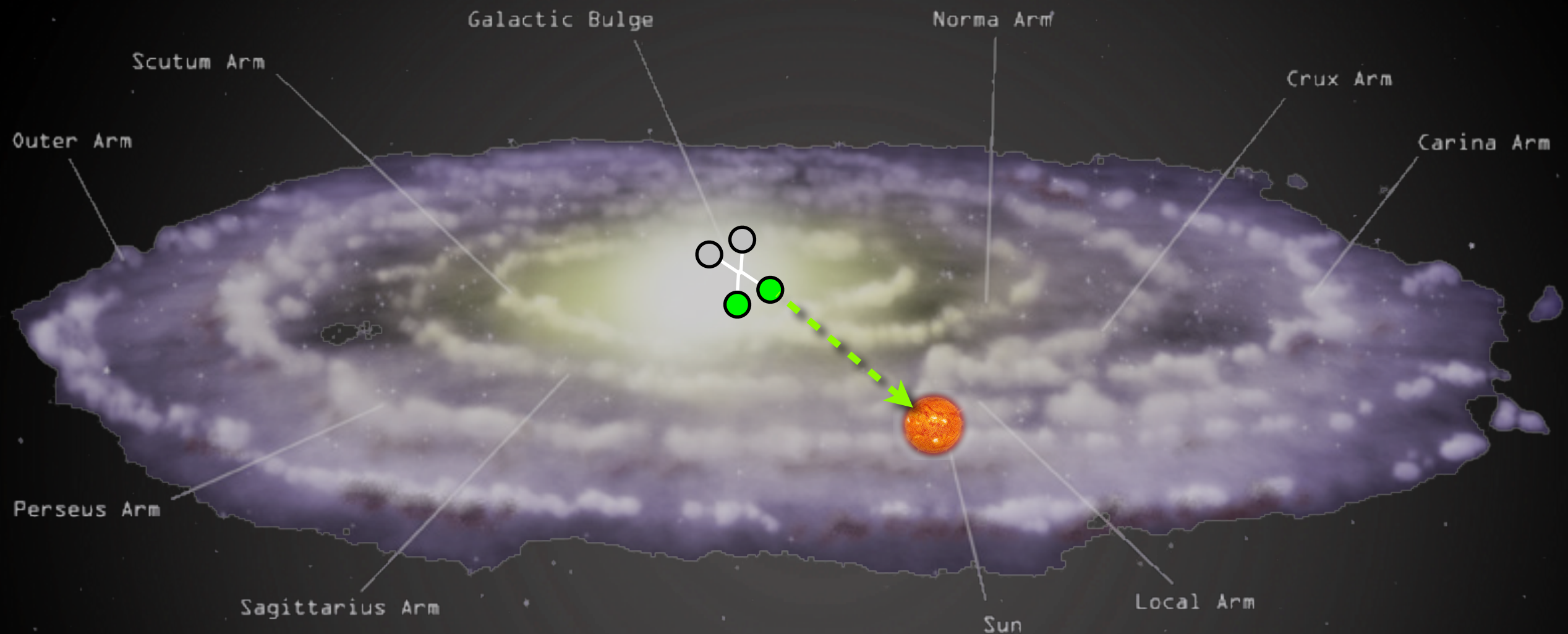
GAPS

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

Icecube, Km³Net

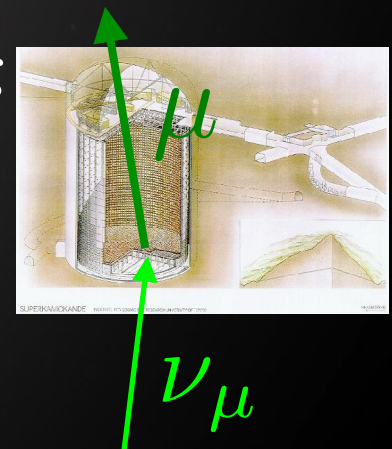
ID with neutrinos

ν from DM annihilations in galactic center



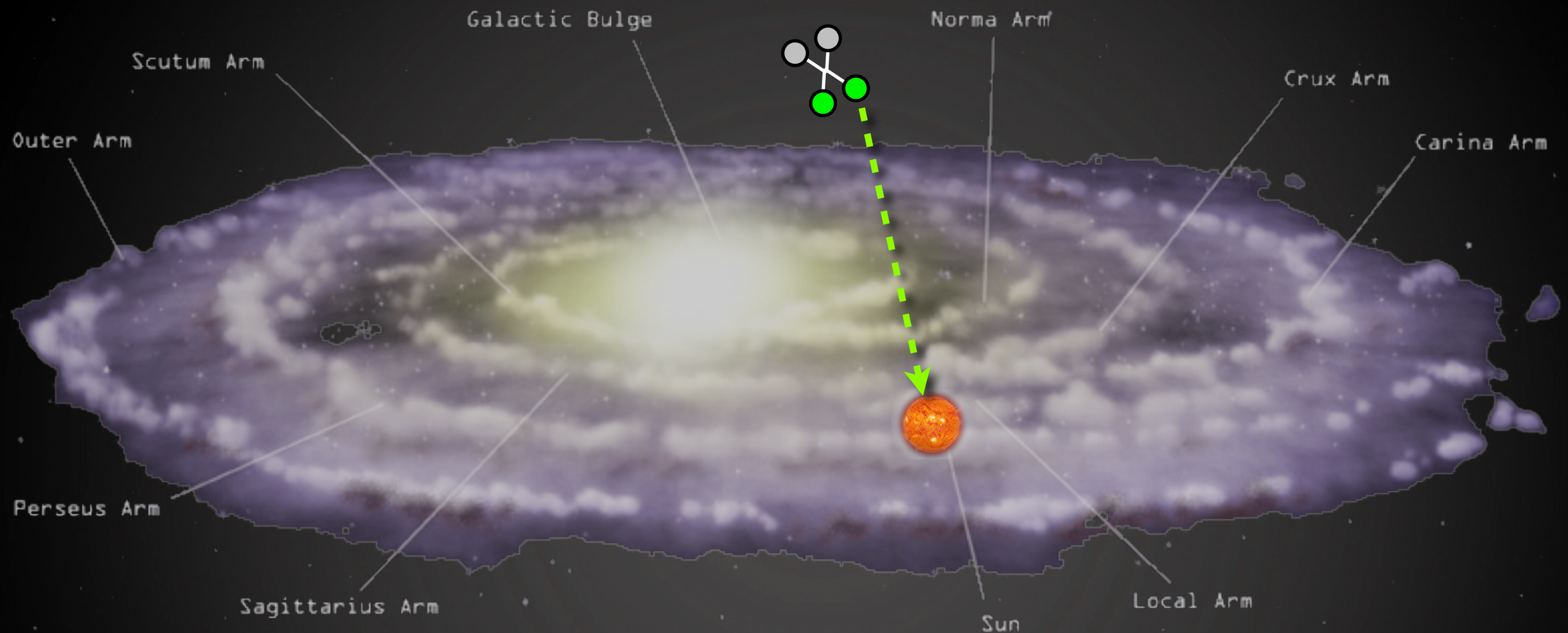
$$\begin{aligned}
 &DM \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu \\
 &DM \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu
 \end{aligned}$$

up-going
muons:



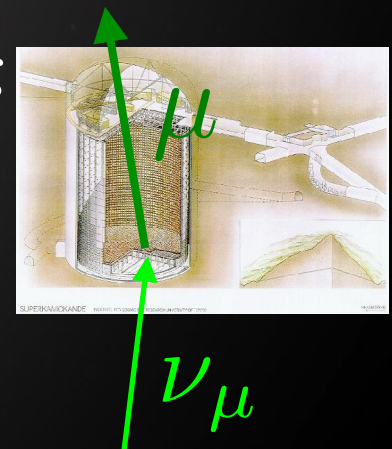
ID with neutrinos

ν from DM annihilations in galactic halo

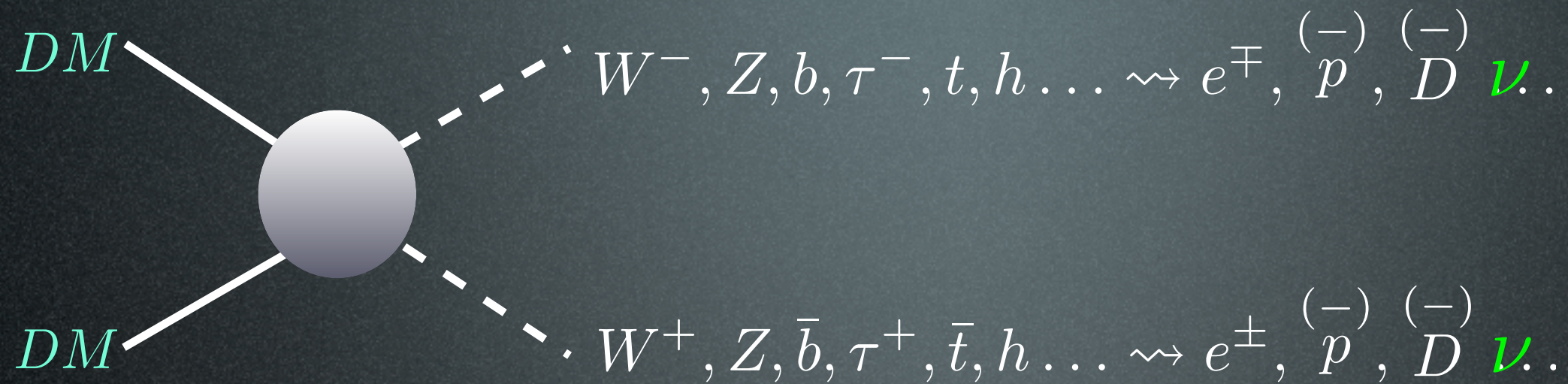


$$\begin{aligned}
 &DM \rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu \\
 &DM \rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \nu
 \end{aligned}$$

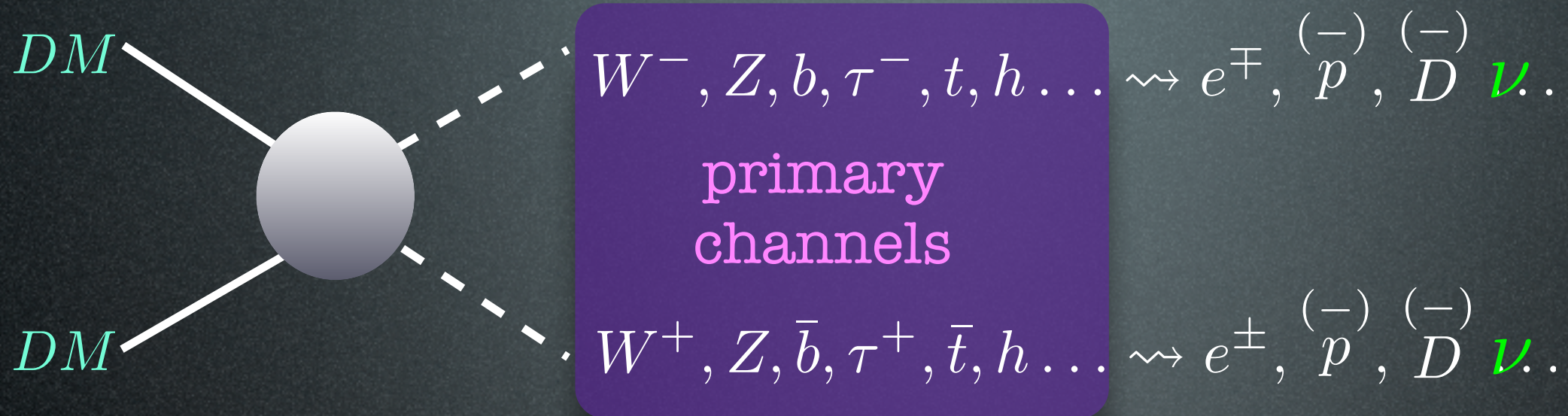
up-going
muons:



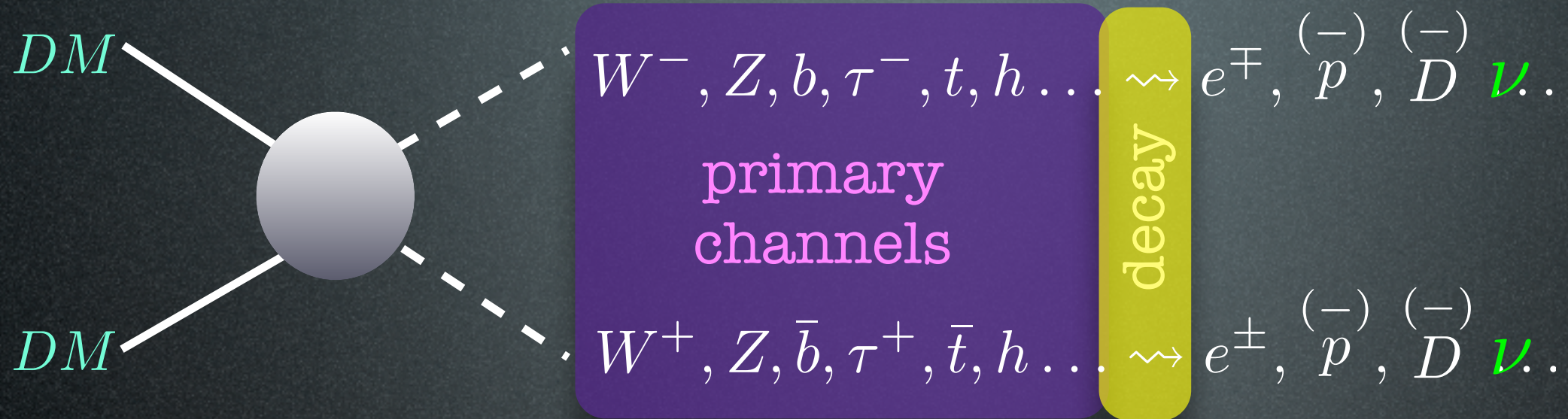
ID with neutrinos



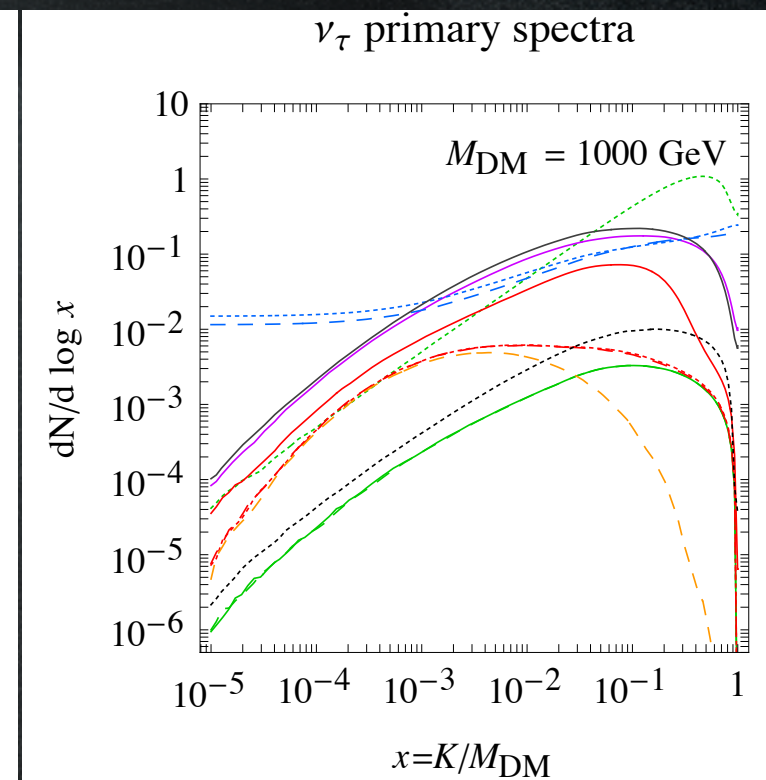
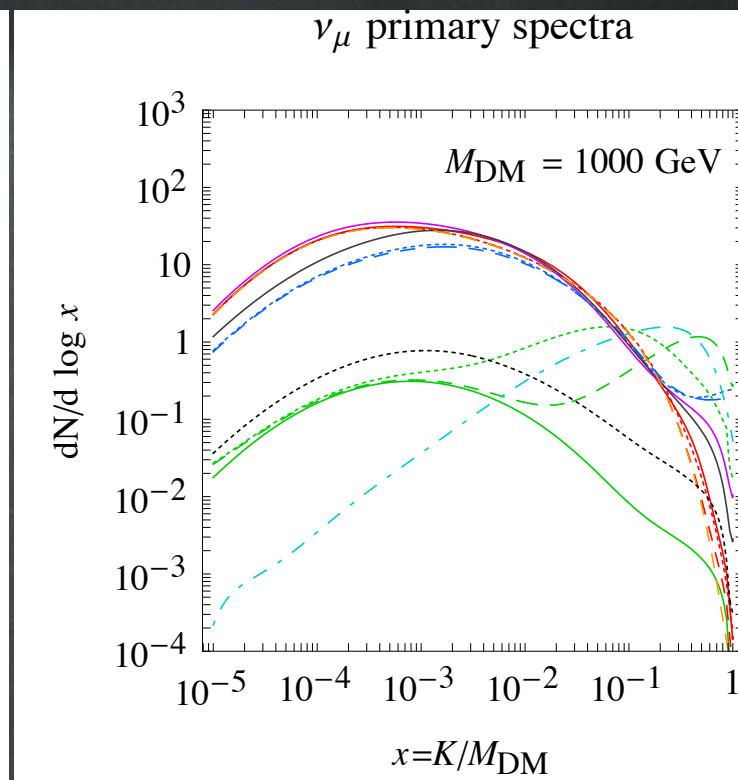
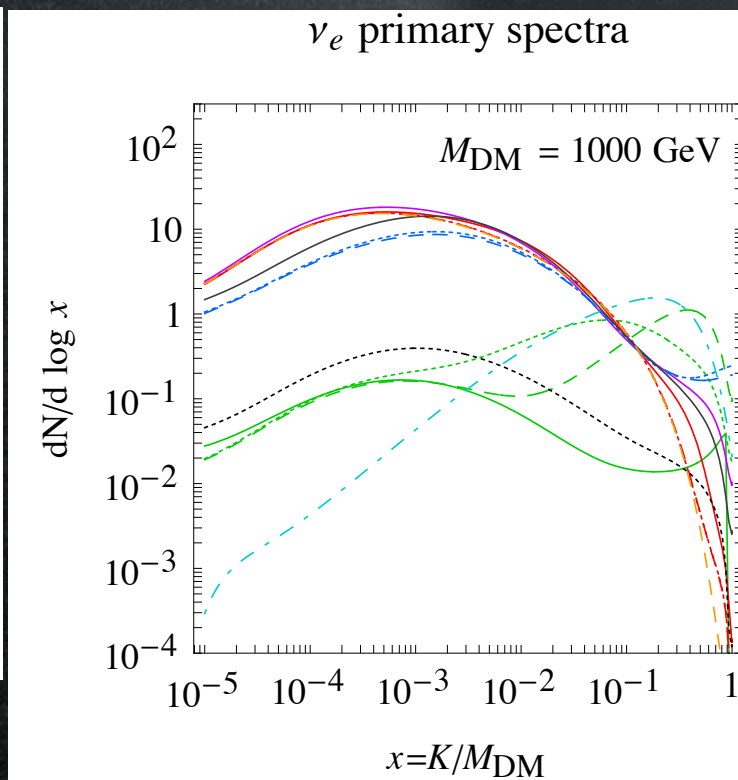
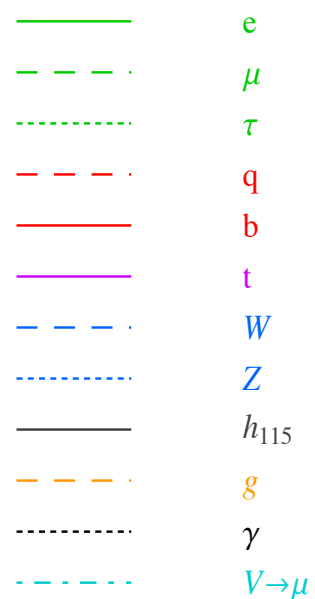
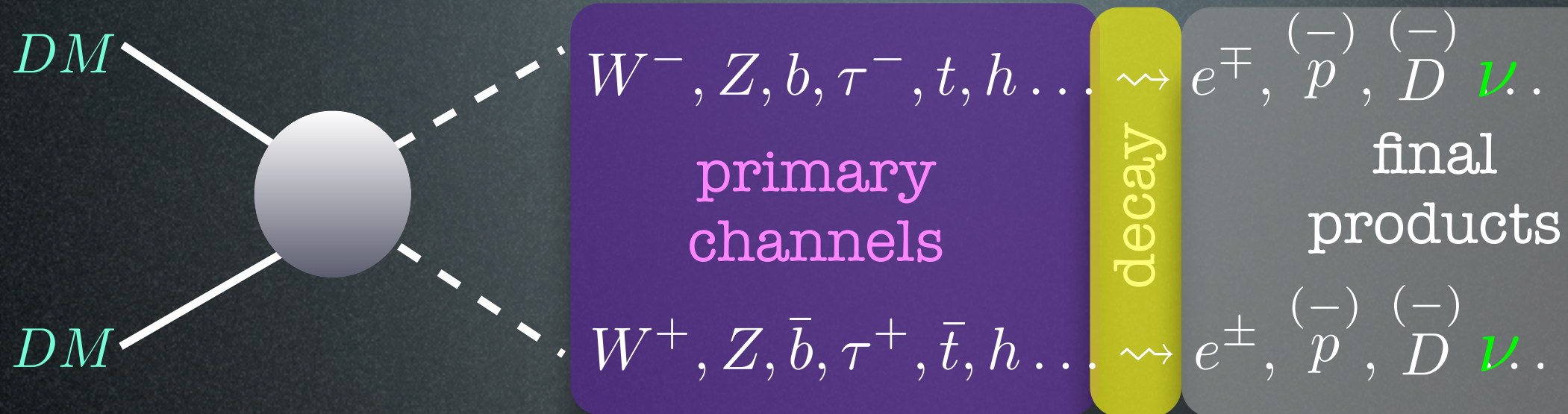
ID with neutrinos



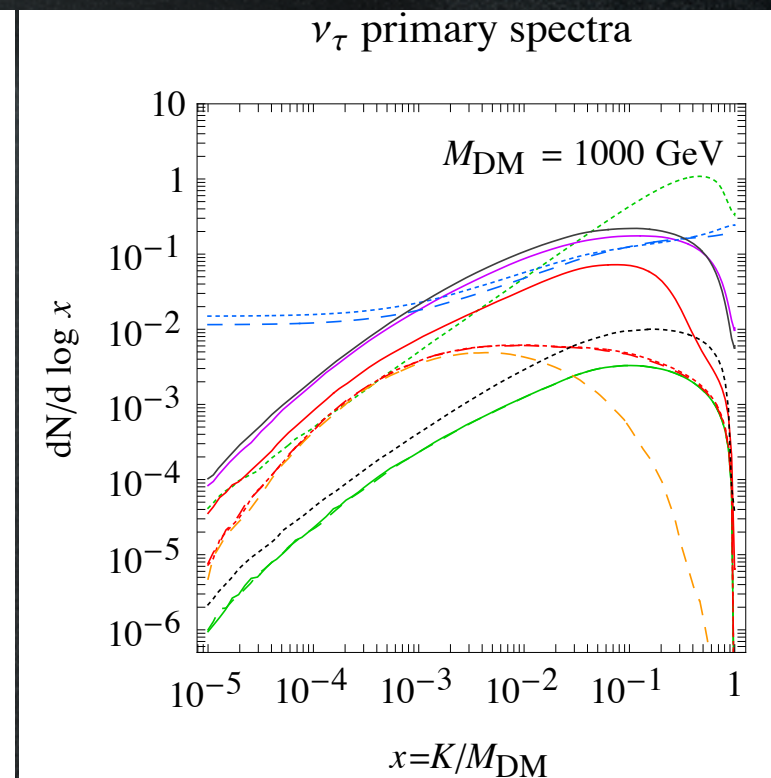
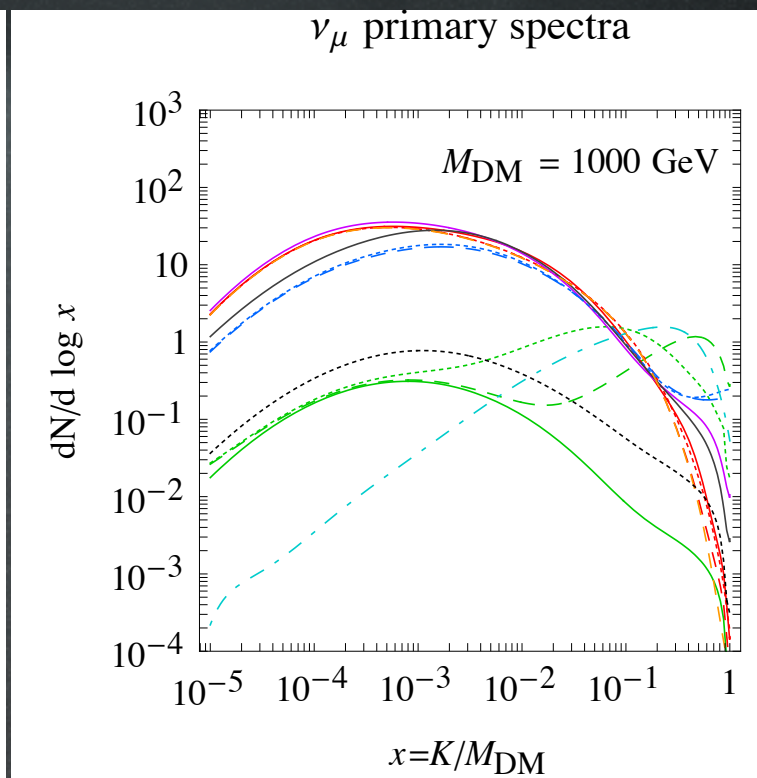
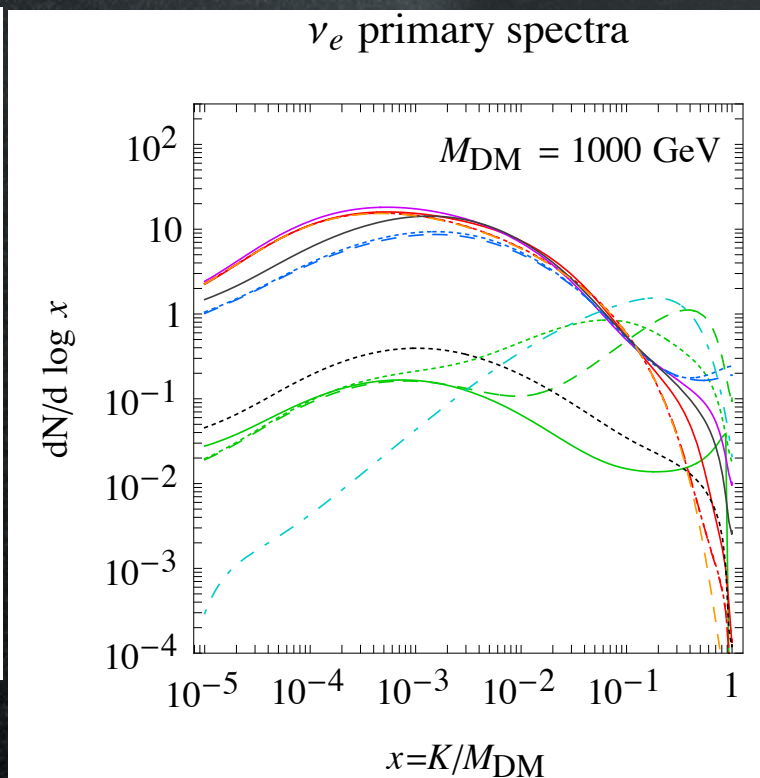
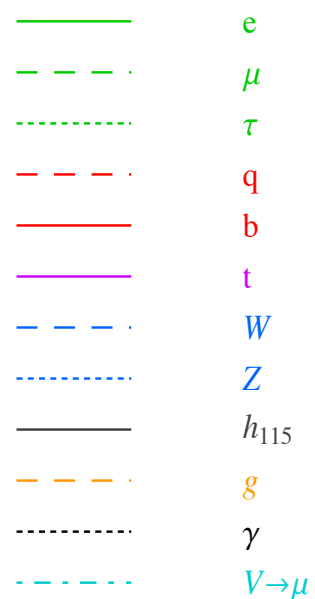
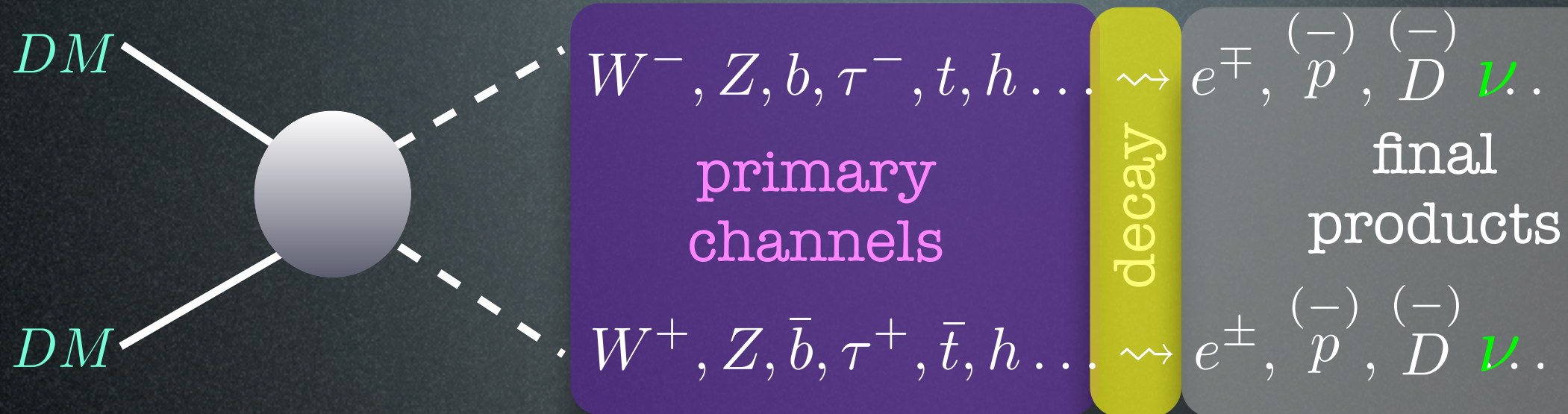
ID with neutrinos



ID with neutrinos



ID with neutrinos

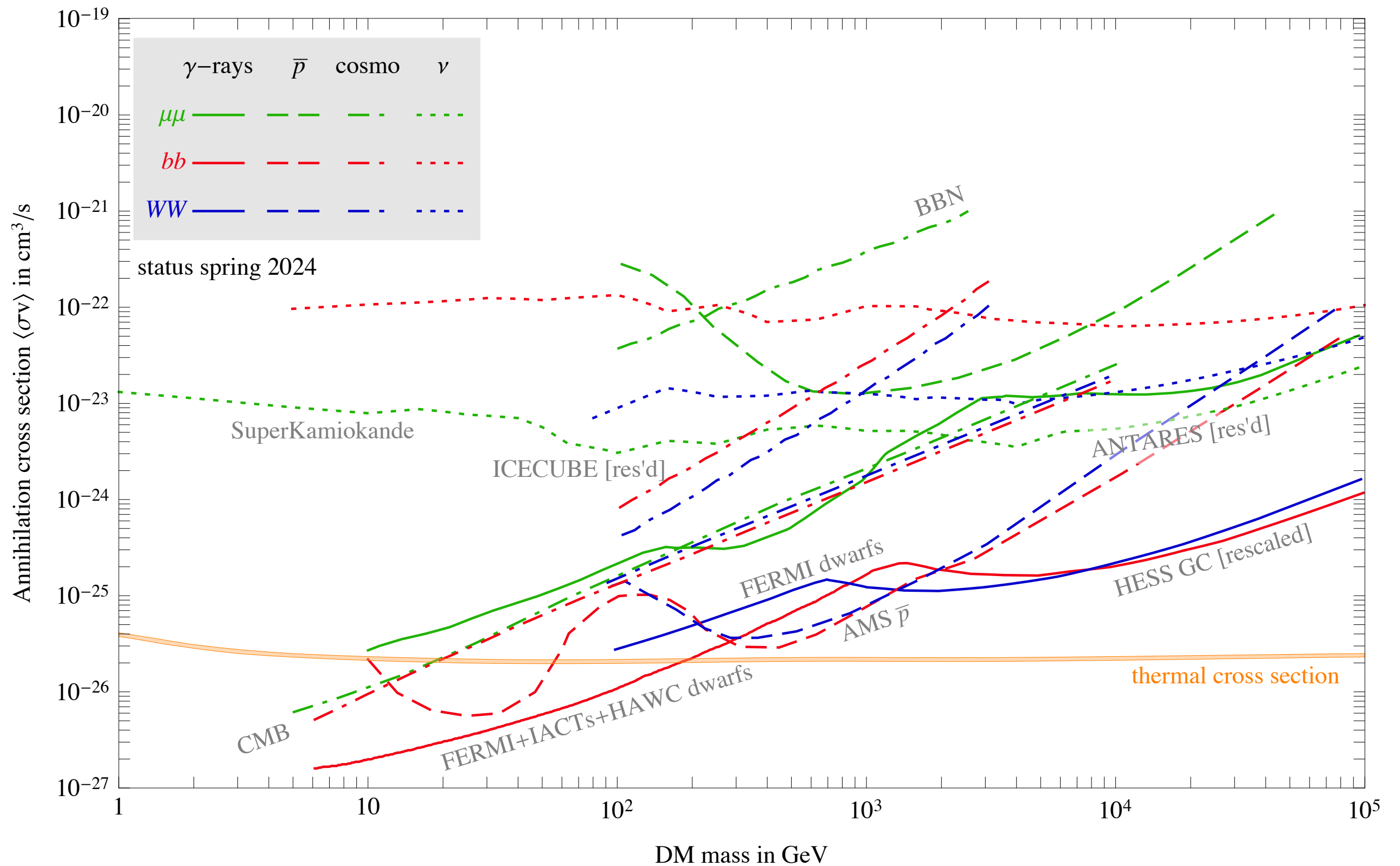


So what are the particle physics parameters?

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

Constraints

All Indirect Detection constraints



Conclusions

DM not seen yet (Damn!...)

Conclusions

DM not seen yet (Damn!...)

ID with cosmic rays is in principle
a very powerful tool, but:

Conclusions

DM not seen yet (Damn!...)

ID with cosmic rays is in principle a very powerful tool, but:

in $e^\pm$: long standing HE 'excesses', new LE chances

in $\bar{p}$: still large uncertainties, but improving

in $\bar{d}$: challenging flux

in $\overline{He}$: hopeless? who knows!...

in ν : challenging detection

in γ : astrophysical background

Solution:

Conclusions

DM not seen yet (Damn!...)

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Solution:

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Conclusions

DM not seen yet (Damn!...)

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Solution:

- multimessenger
- switch-off astrophysics