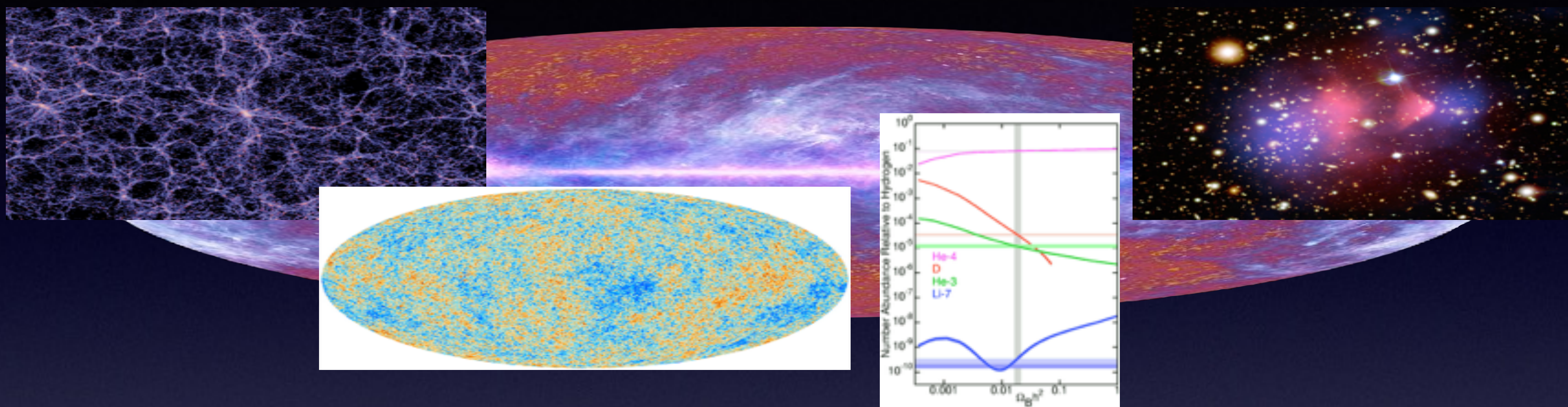
22 June 2016
MACROS 2016, Pennsylvania State University

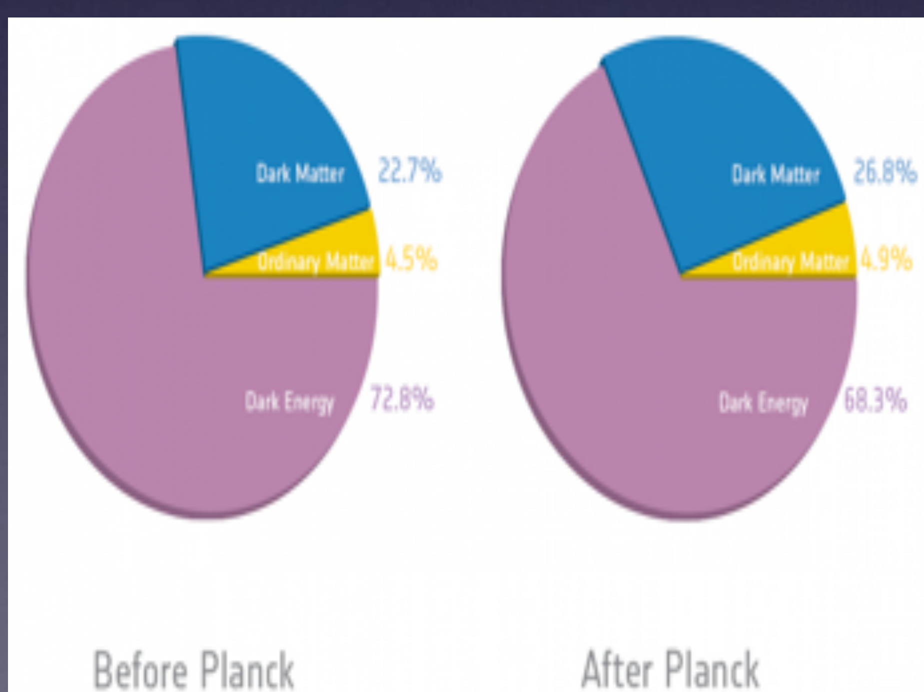
Indirect Dark Matter Detection: Brief review

Paolo Panci

Dark Side: Overview

Precise measurements on CMB, BBN, LSS, etc...





Planck reveals an almost perfect Universe

$$\Omega_{\rm tot} = \Omega_\Lambda + \Omega_{\rm M} + \Omega_{\rm Rad} \simeq 1 \qquad \Omega_{\rm M} = \Omega_{\rm b} + \Omega_{\rm DM}$$

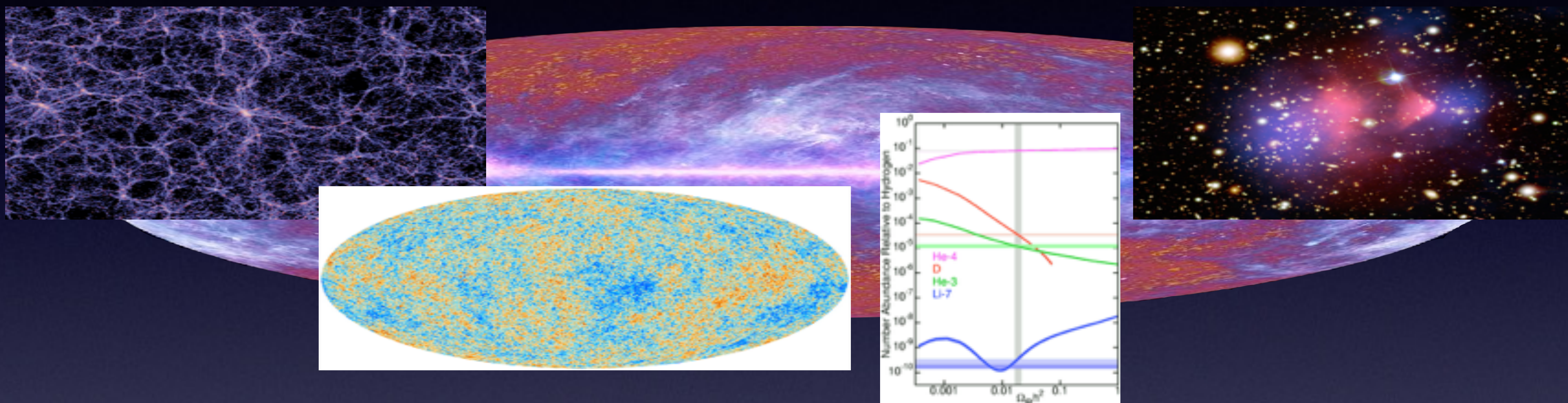
$\Omega_{\rm Rad} \sim 10^{-5}$ $\qquad$ $\Omega_\Lambda \simeq 0.68$

$\Omega_{\rm b} \simeq 0.05$ $\qquad$ $\Omega_{\rm DM} \simeq 0.27$

Dark Sector: $\Omega_{\rm DM} + \Omega_\Lambda = 0.95$

DM Open Questions

There are compelling and strong evidences of *non-baryonic matter* in the Universe; from galactic to cosmological scale



BUT !!

The microphysics of this new kind of matter is unknown yet

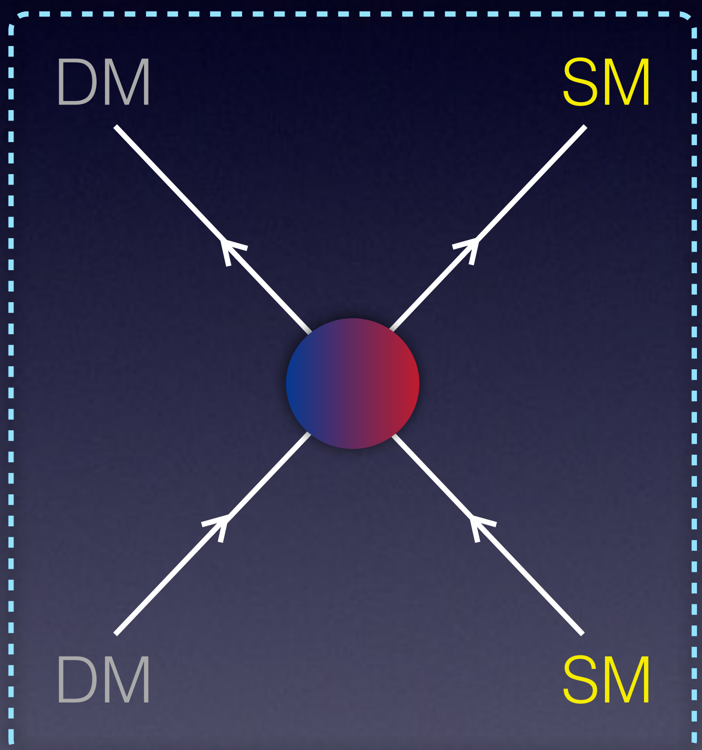
- ***DM candidate***: axions, wino, MDM, wimpzillas, primordial BH, etc…
- ***Underlying theory***: supersymmetry, technicolor, mirror models, etc...
- ***DM density profile***: cuspy profile (NFW, Einasto), cored profile (isothermal)

Dark Matter Detection

Common strategies to identify the microphysics nature of DM

production at collider

LHC



direct detection

DAMA/Libra, CoGeNT, CRESST.... (Edelweiss, LUX, XENON100, CDMS....)

indirect detection

γ from DM in the Galaxy

Fermi, radio telescopes....

e^+ from DM in the Galaxy

PAMELA, Fermi, HESS, AMS-02, balloons....

$\bar{p}$ from DM in the Galaxy

PAMELA, AMS-02

$\bar{d}$ from DM in the Galaxy

AMS-02, GAPS....

$\bar{\nu}, \nu$ from DM in the Galaxy

SuperK, Icecube....

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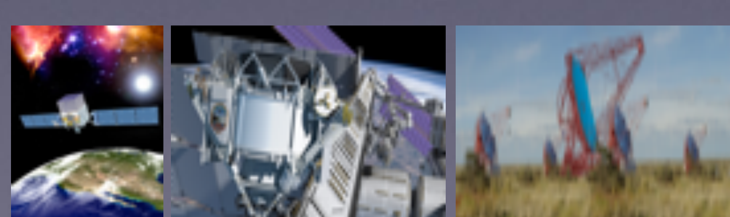

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Charged Particles

e^+ and $\bar{p}$ from annihilating/decaying DM in Milky Way

Indirect Detection: Overview

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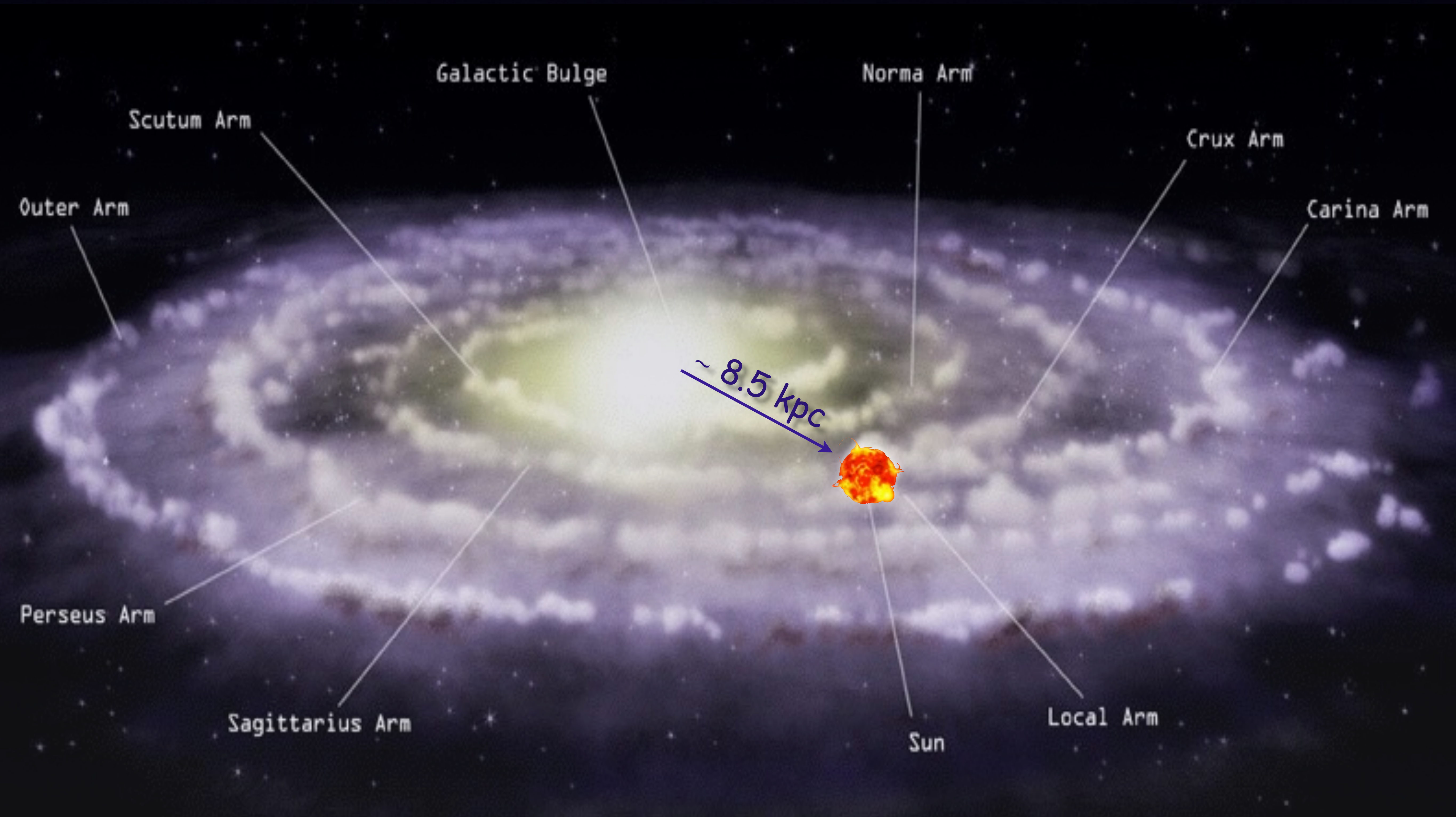

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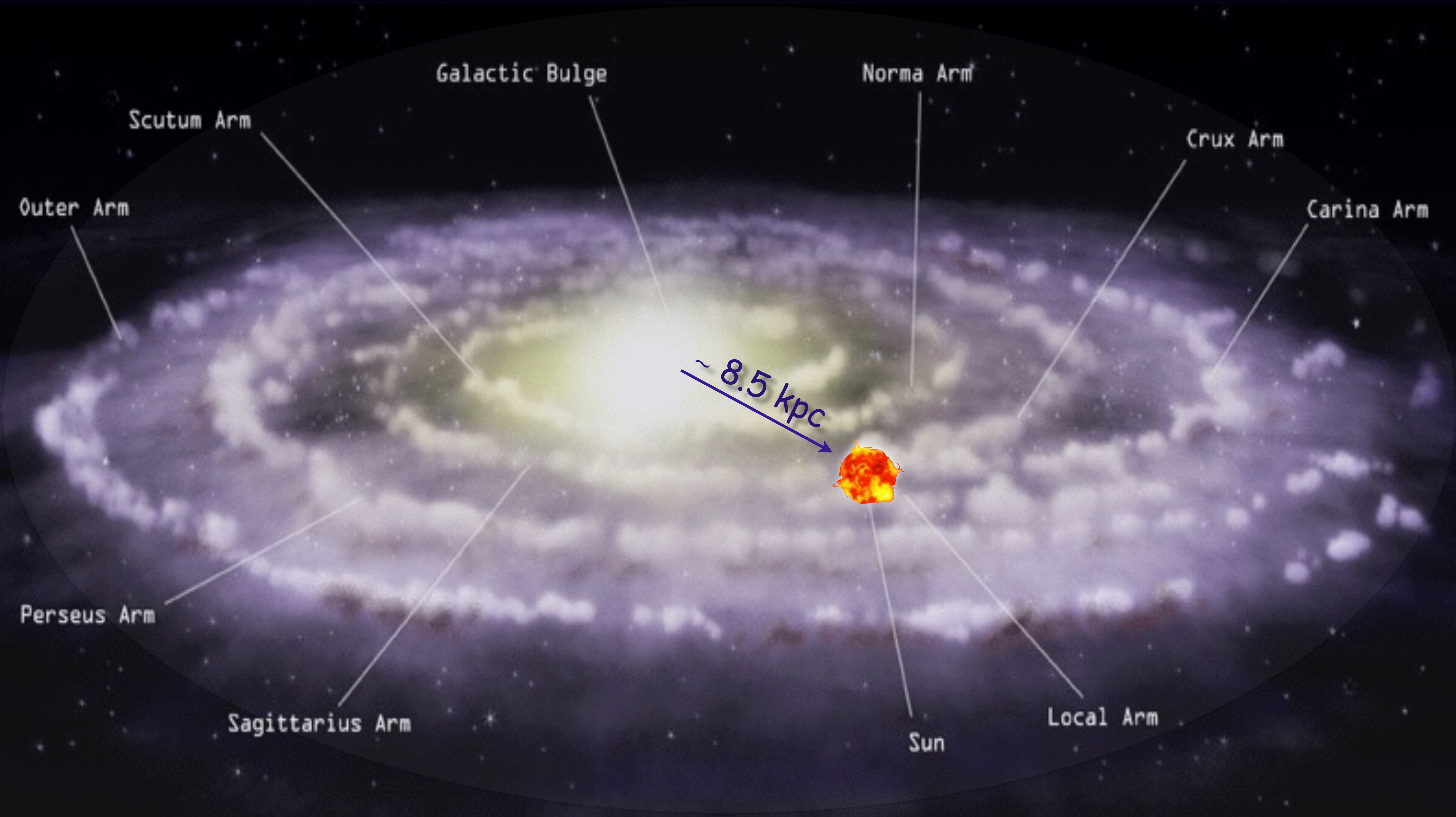

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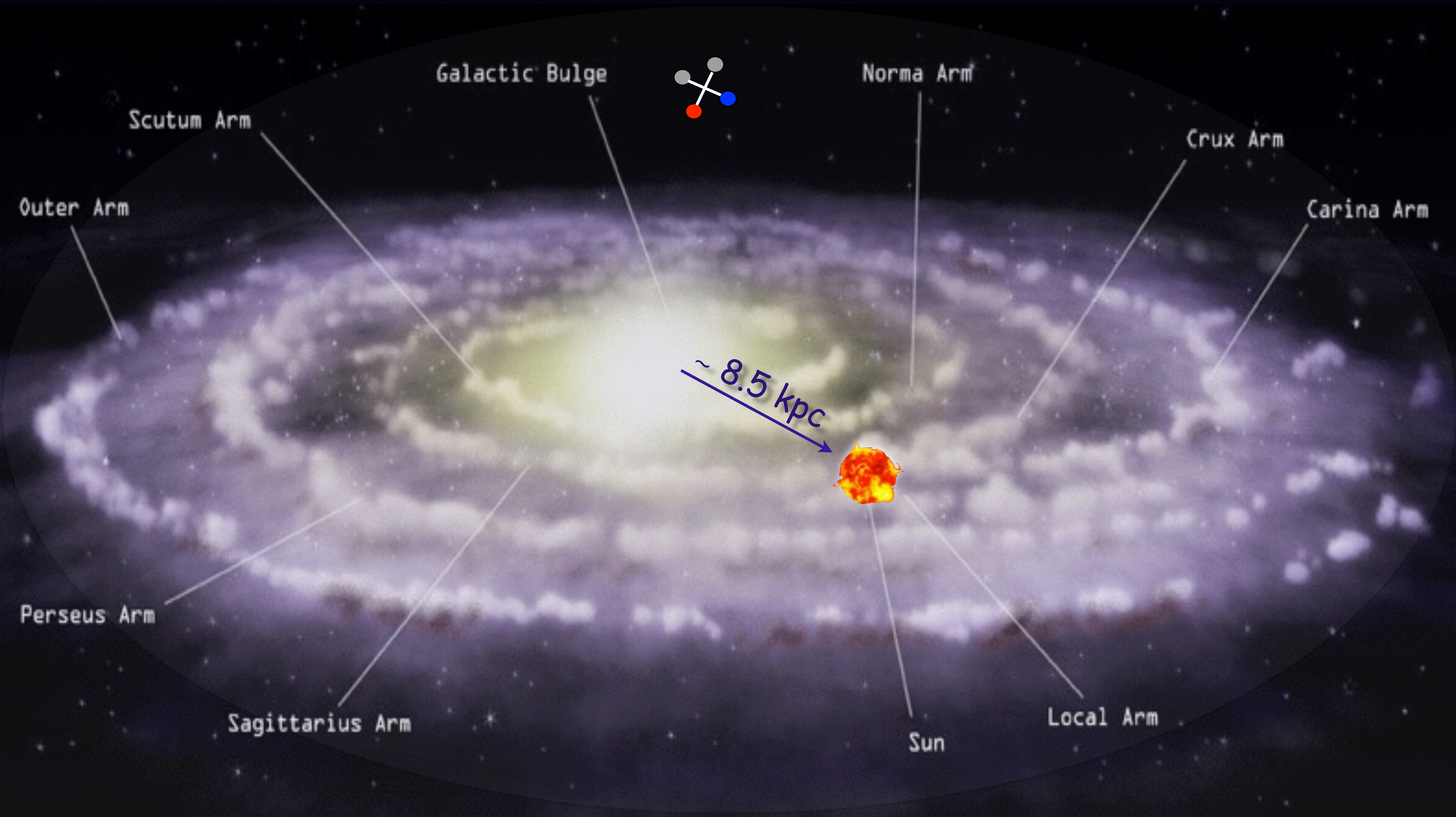
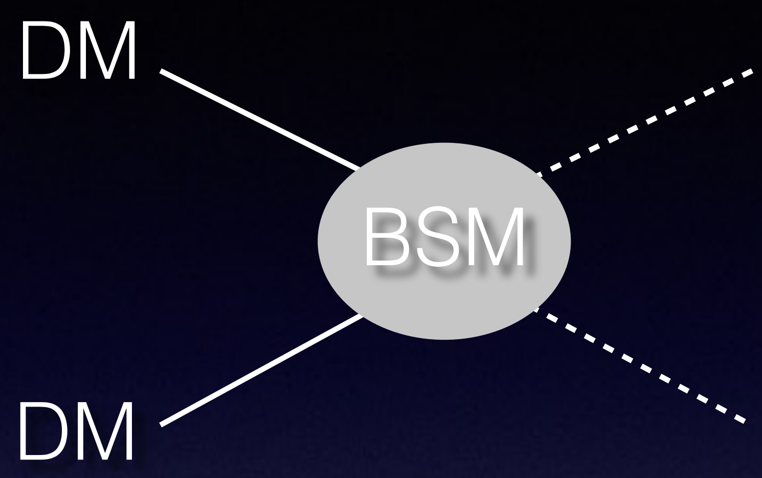


Fluxes at Production



$W^-, b, t, \mu^-, \tau^-, h...$ $\longrightarrow$ $e^\mp, \overset{(-)}{p}, \overset{(-)}{d}, \overset{(-)}{\nu}...$

primary modes — decay — stable SM products

$W^+, \bar{b}, \bar{t}, \mu^+, \tau^+, h...$ $\longrightarrow$ $e^\pm, \overset{(-)}{p}, \overset{(-)}{d}, \overset{(-)}{\nu}...$

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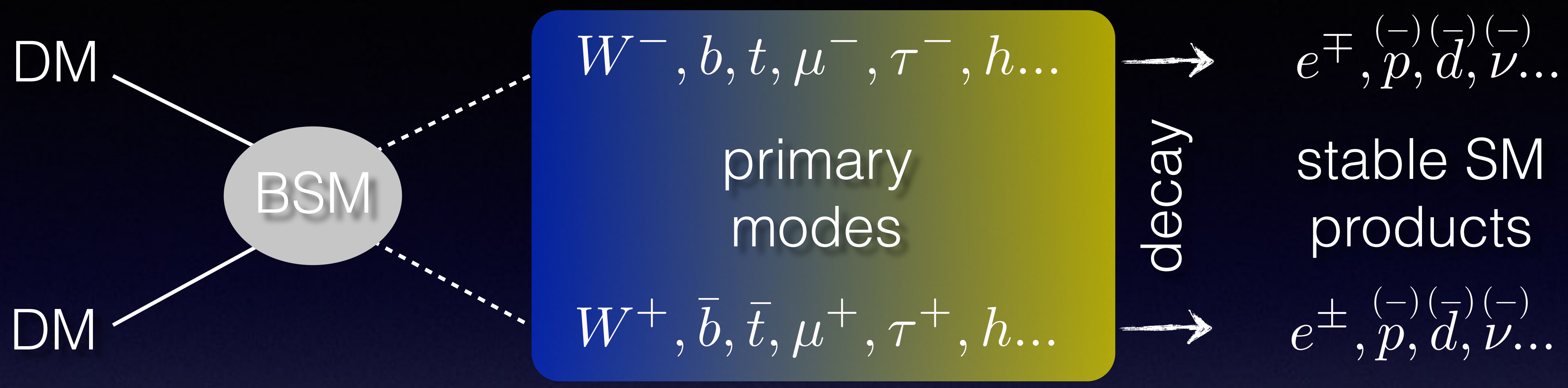

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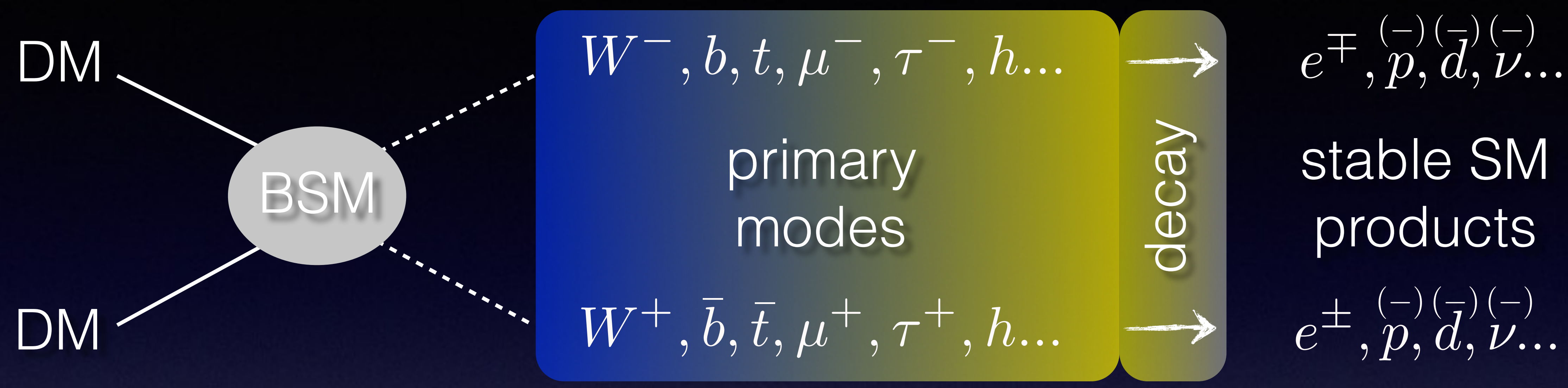

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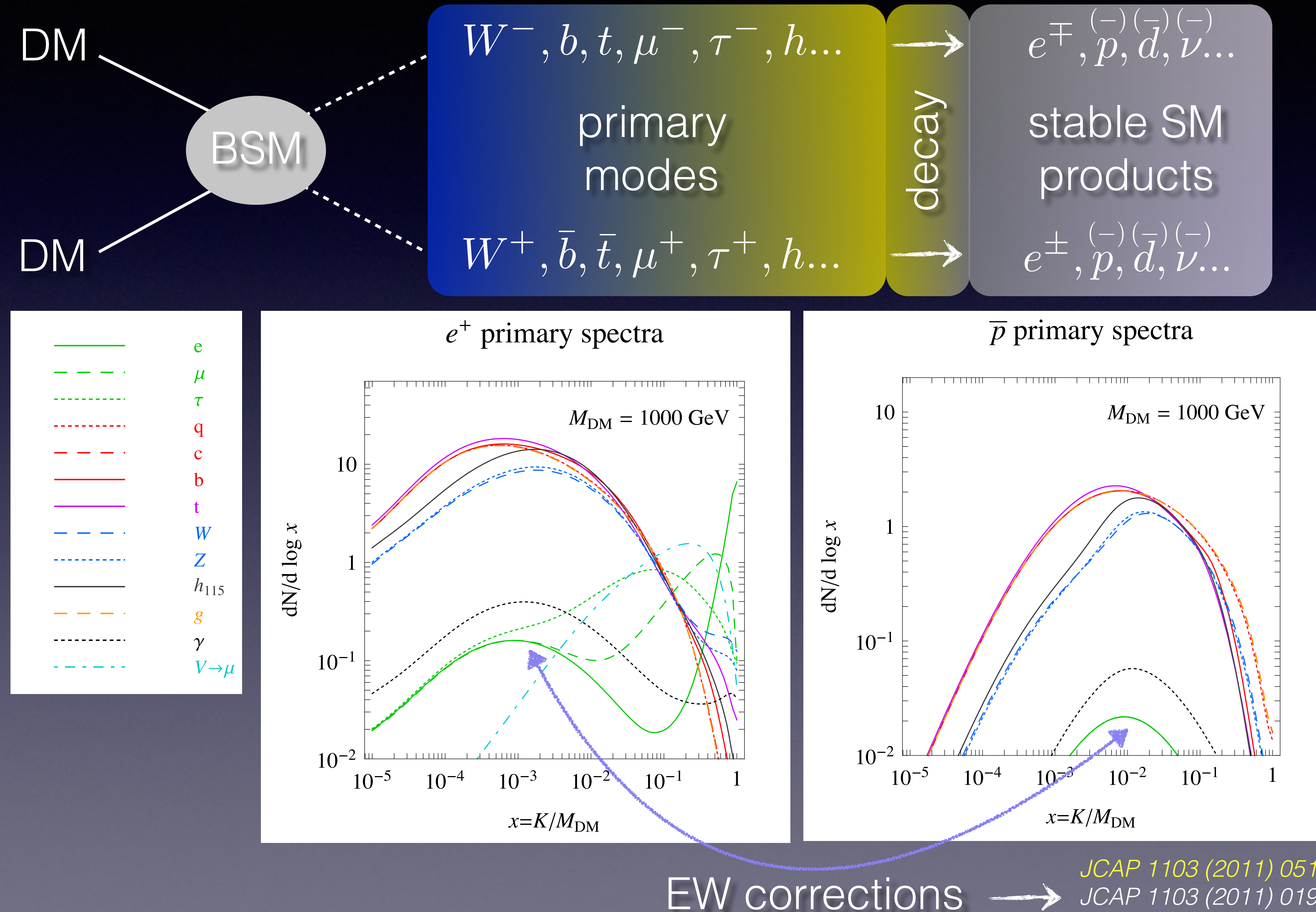

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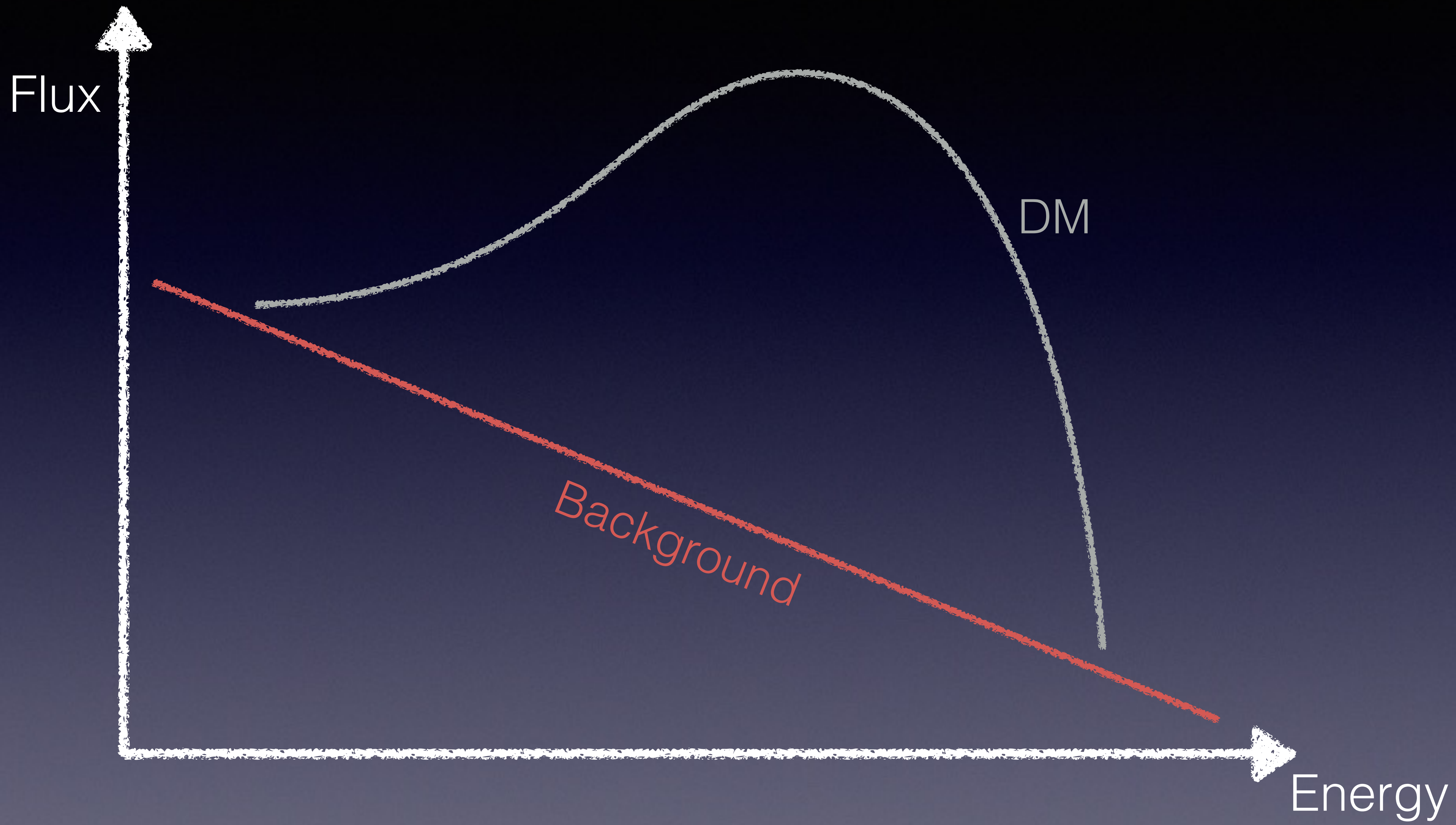
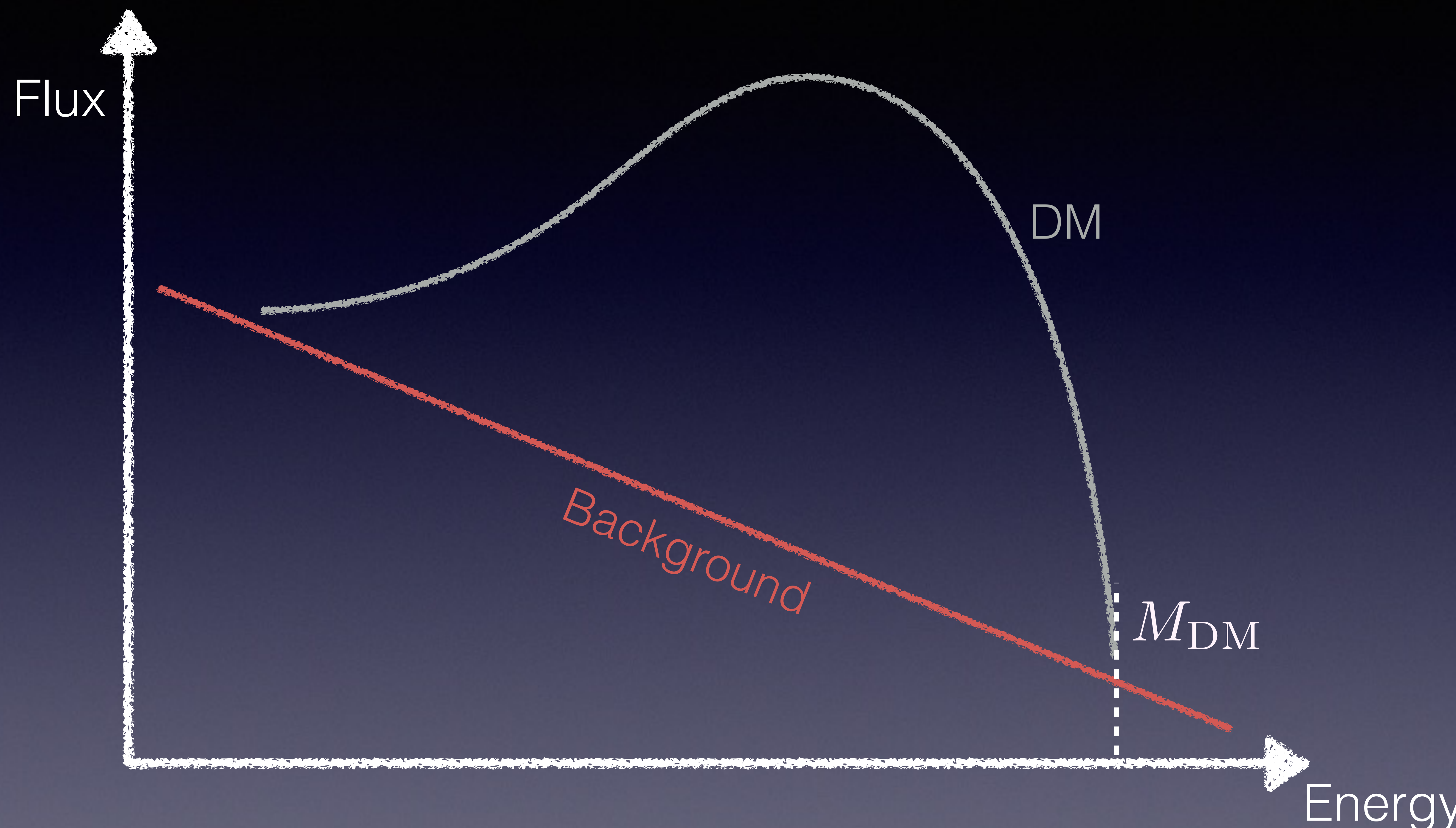


What are the particle physics parameters ?

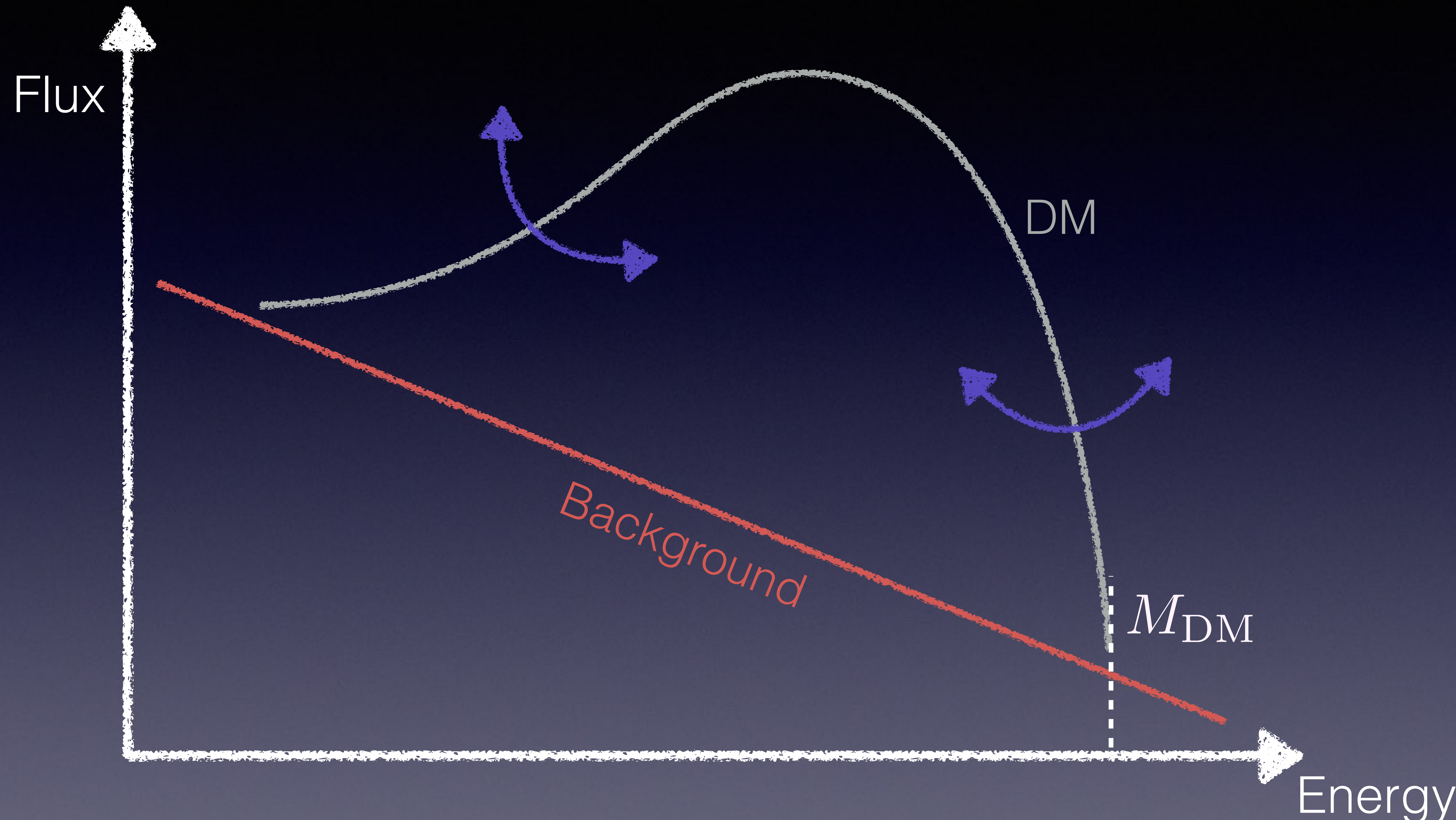
Fluxes at Production



What are the particle physics parameters ?

- DM Mass

Fluxes at Production



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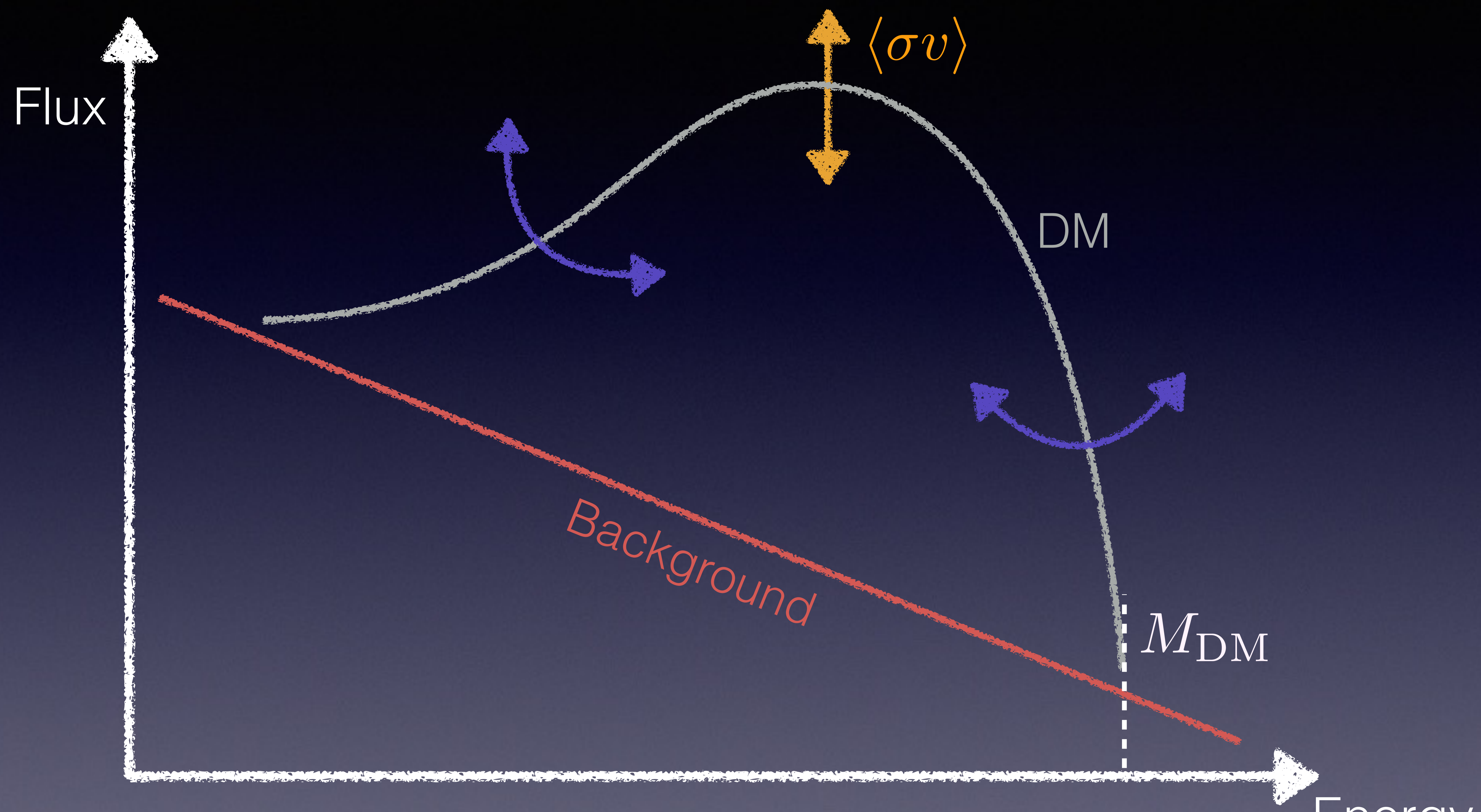
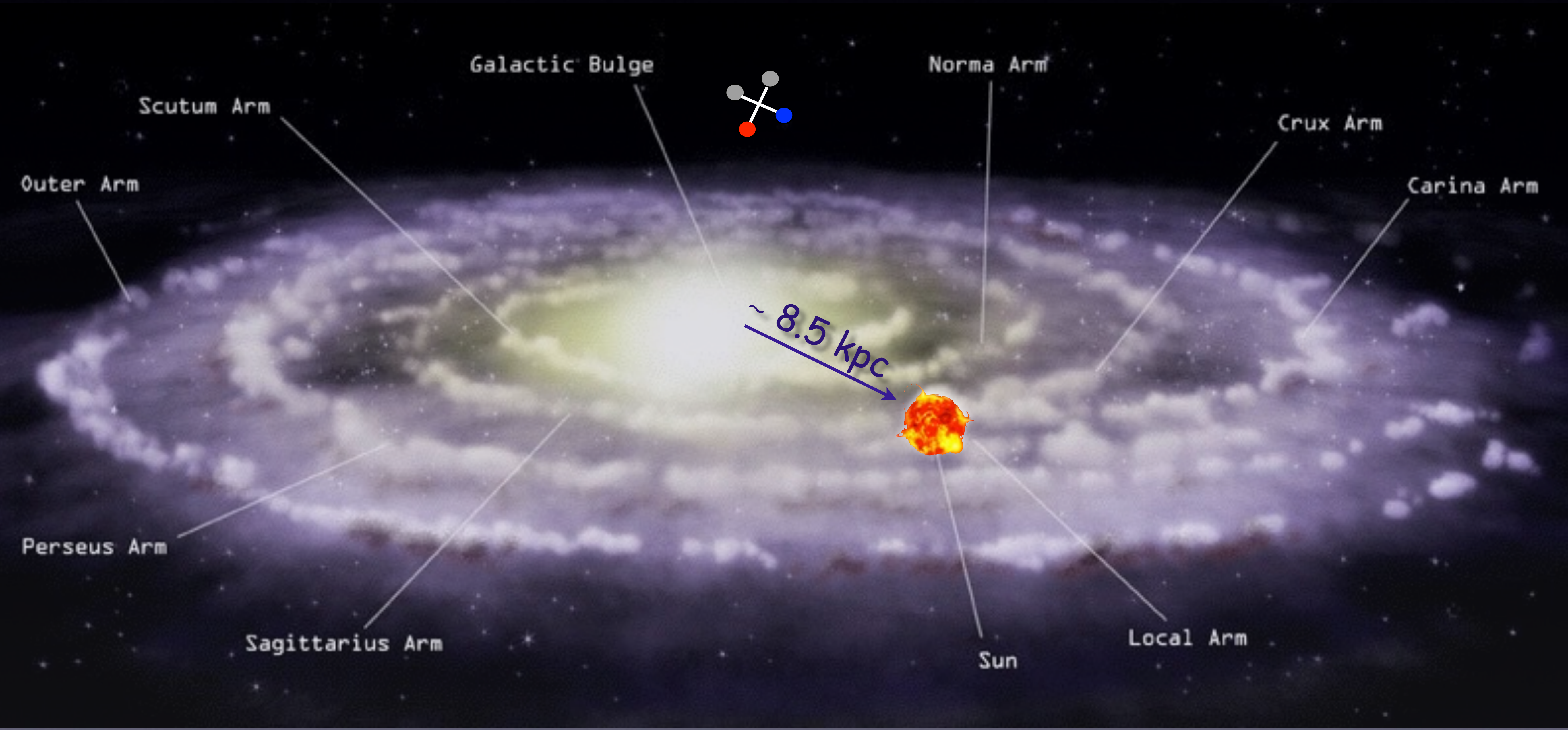


What are the particle physics parameters ?

- DM Mass
- Primary Channel
- Annihilation XS

Indirect Detection: Overview

e^+ and $\bar{p}$ from annihilating/decaying DM in Milky Way



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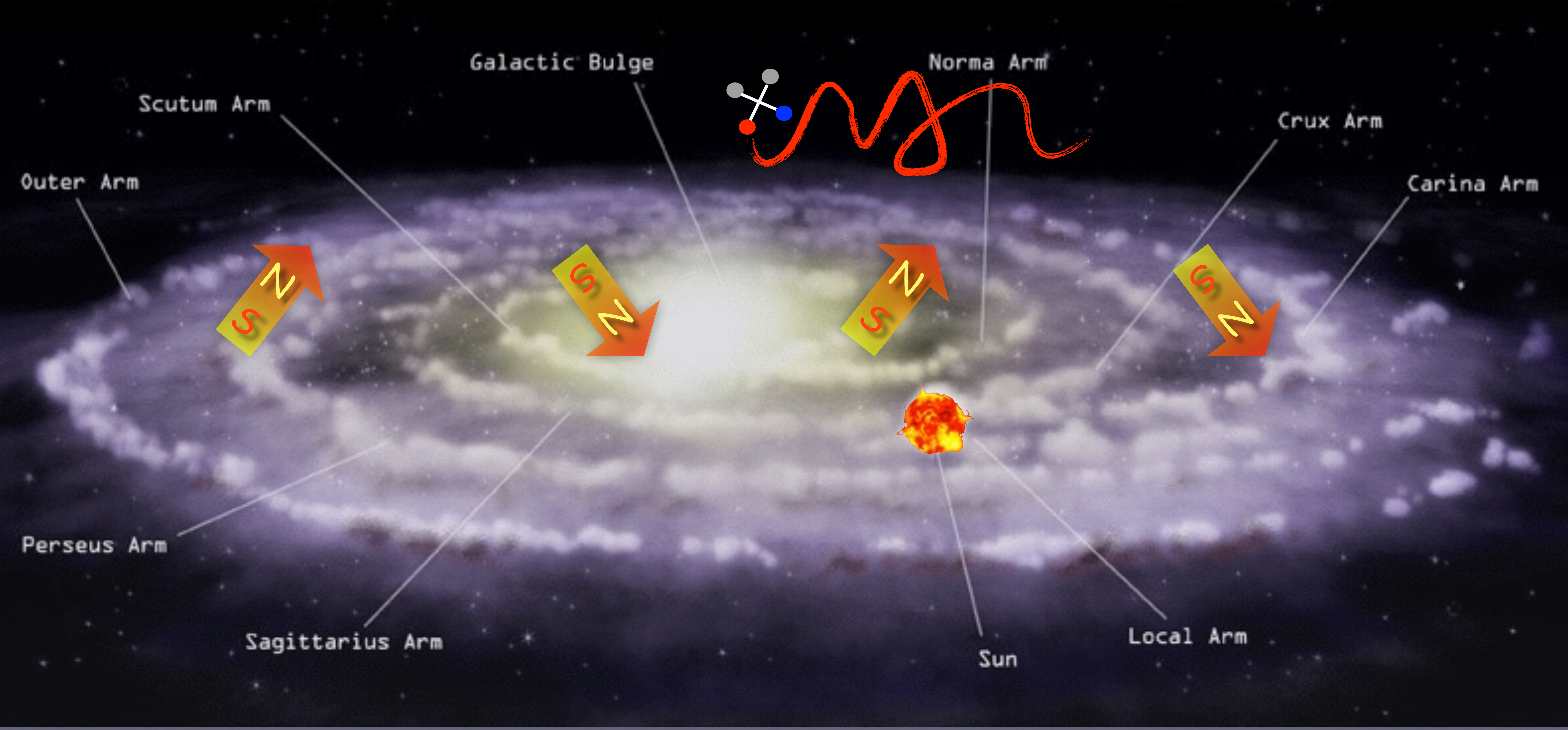

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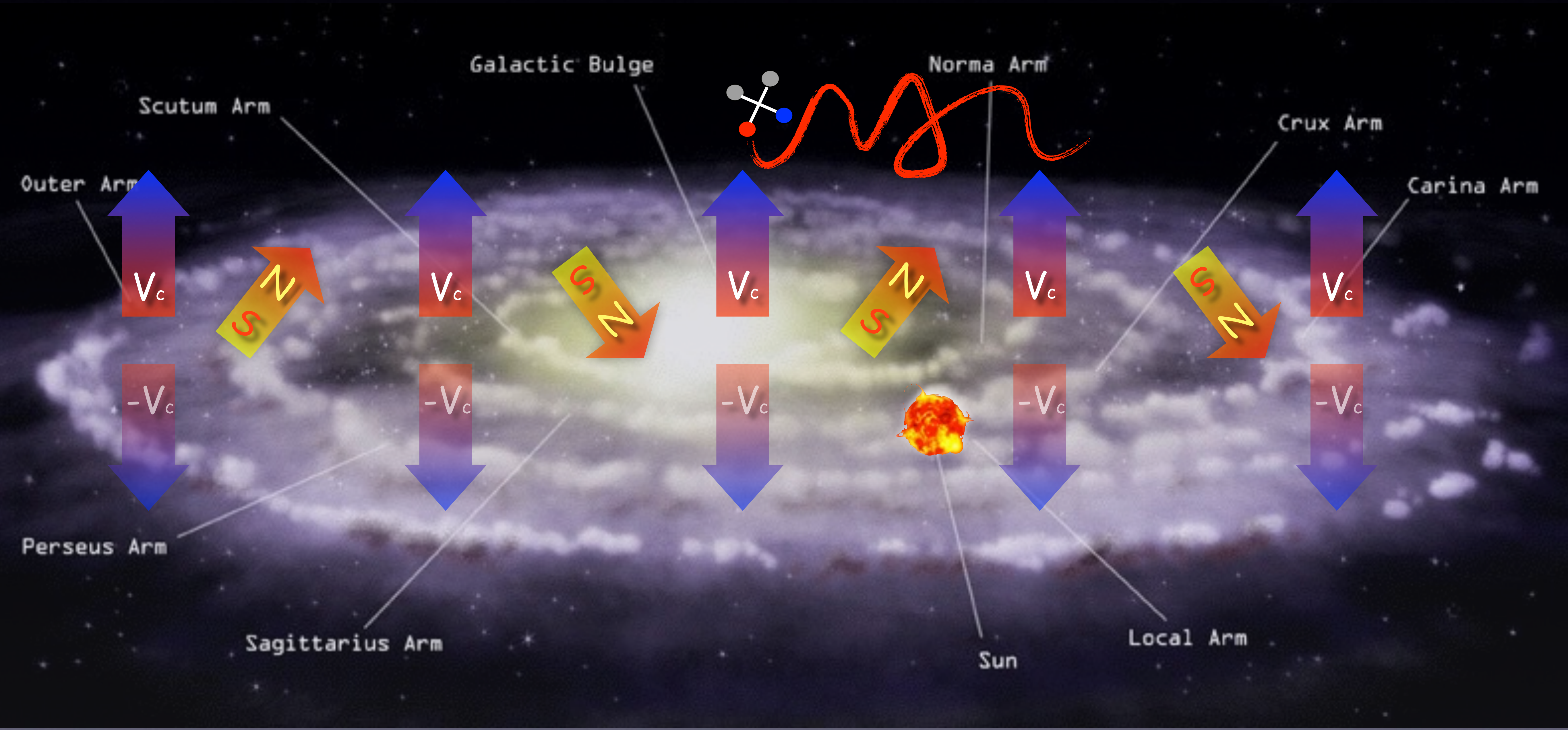

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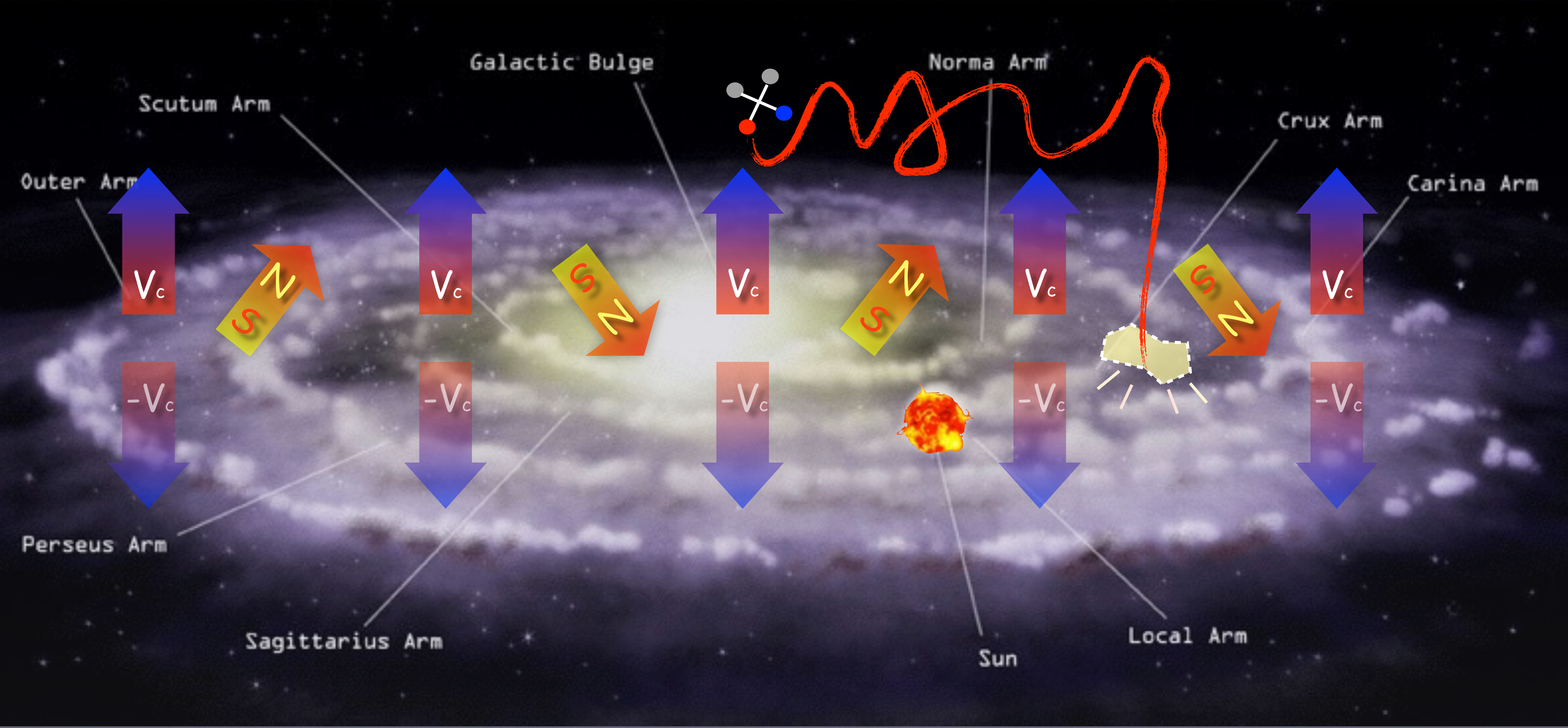

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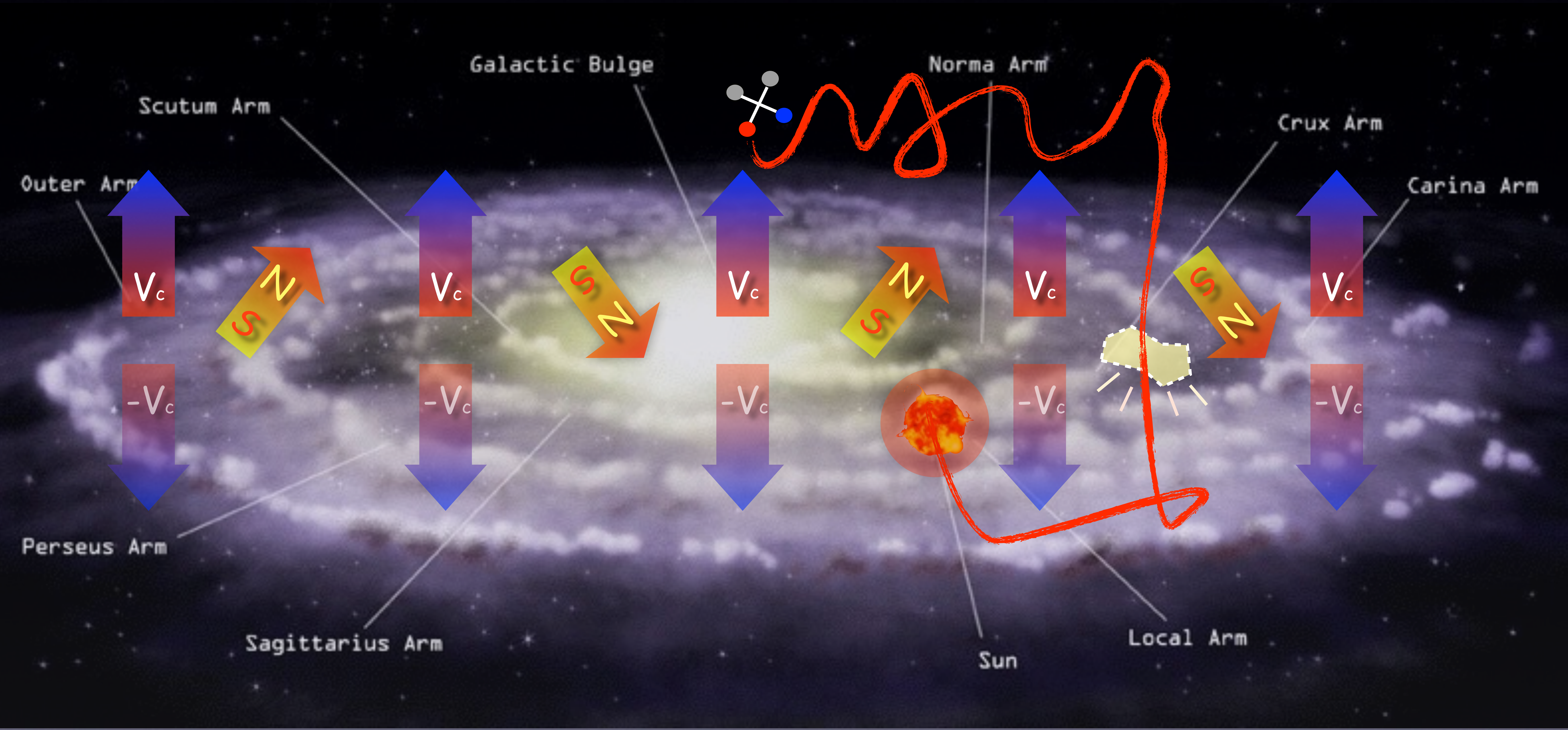

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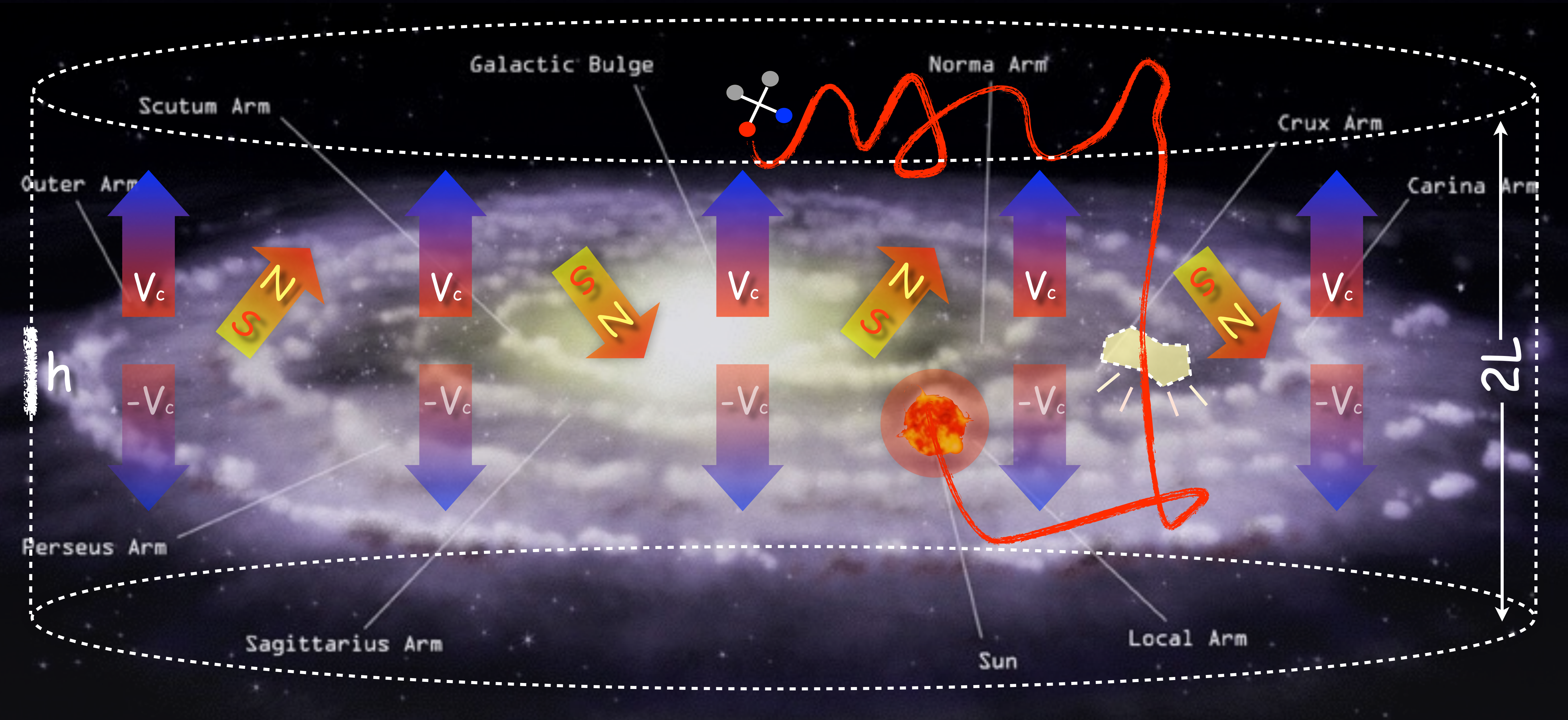

$$\frac{\partial f}{\partial t} - \nabla(\mathcal{K}(E,\vec{x})\nabla f) - \frac{\partial}{\partial E}(b(E,\vec{x})f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

spectrum — diffusion — energy losses — convective wind — source — spallation

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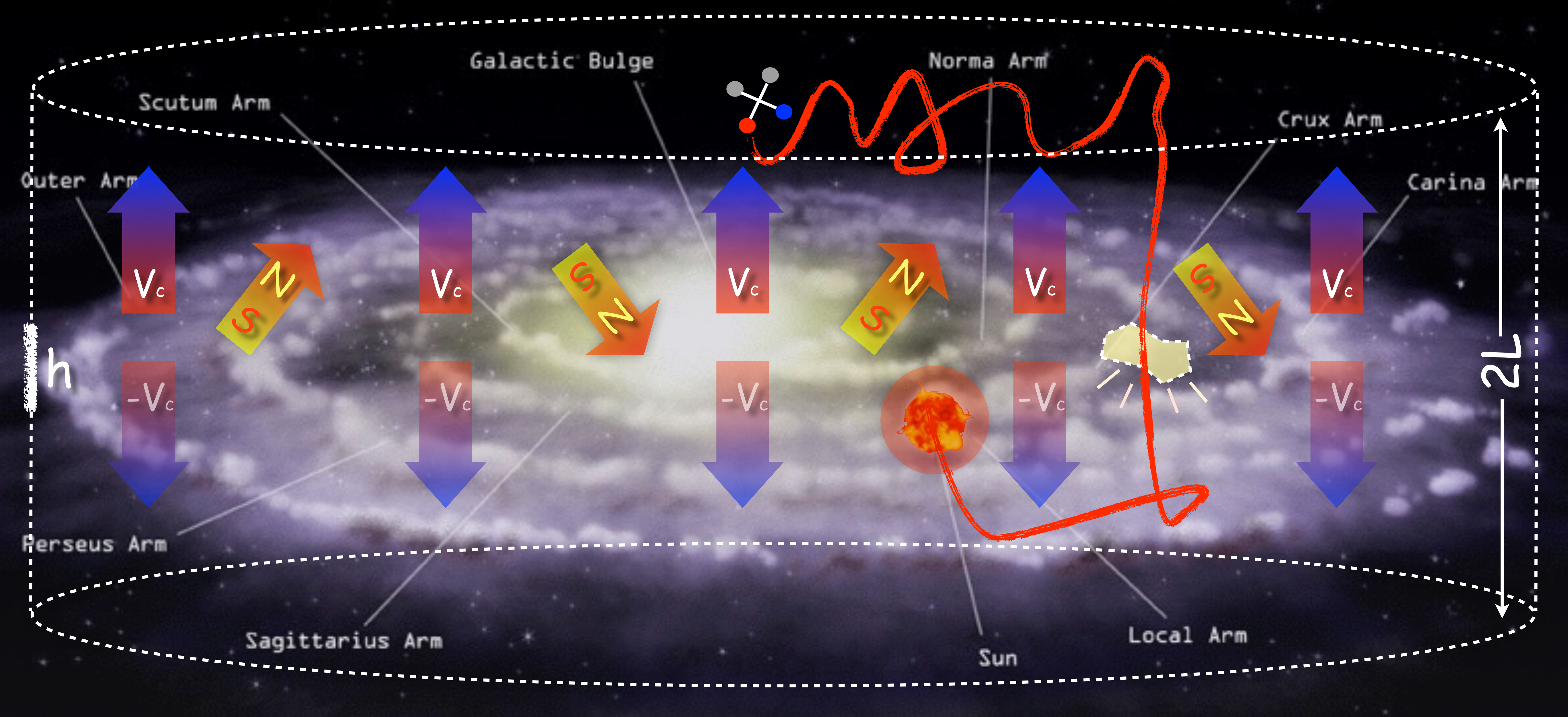

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DM Density Profiles

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

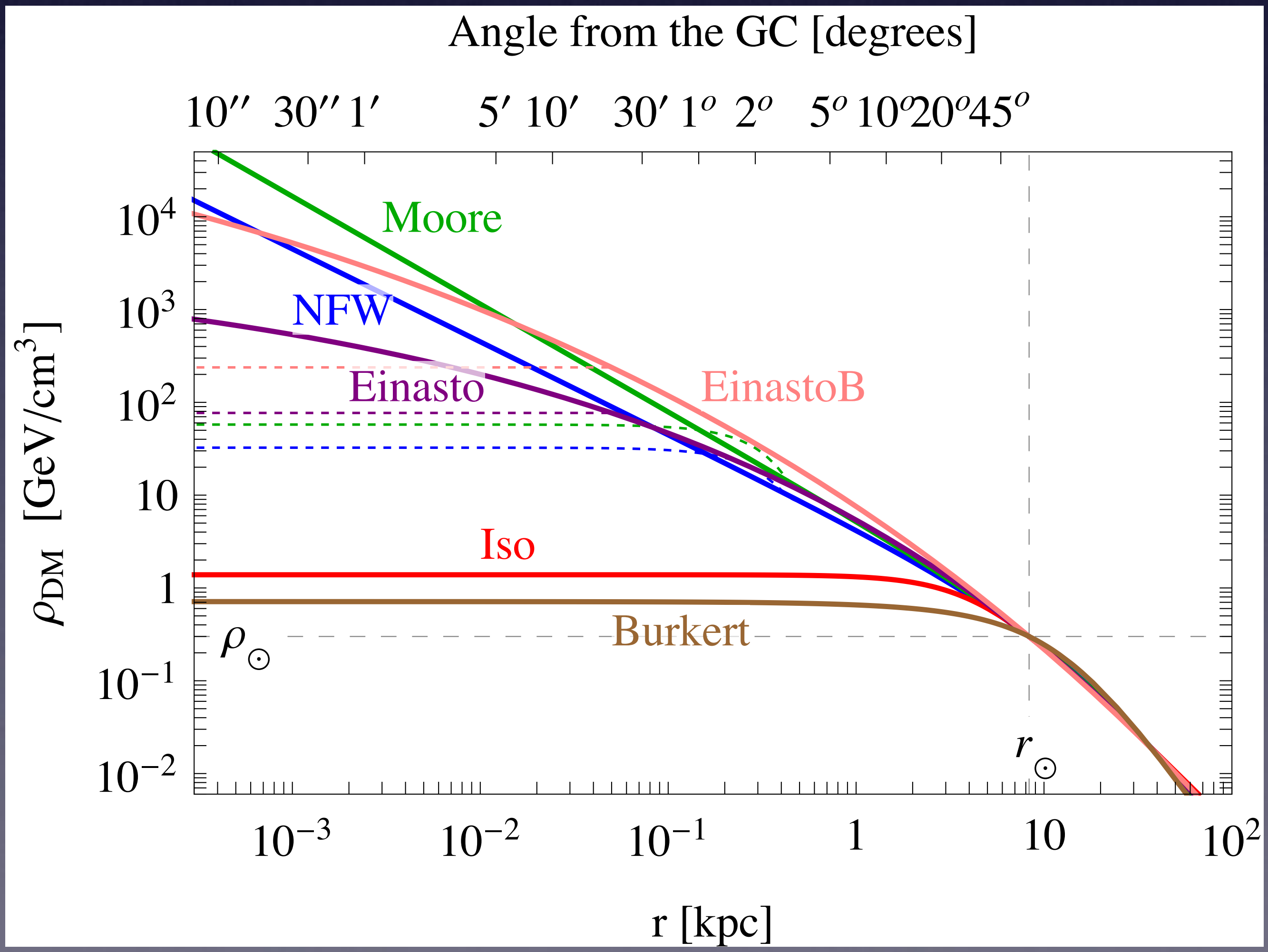
$$\text{Einasto}: \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

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

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

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

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

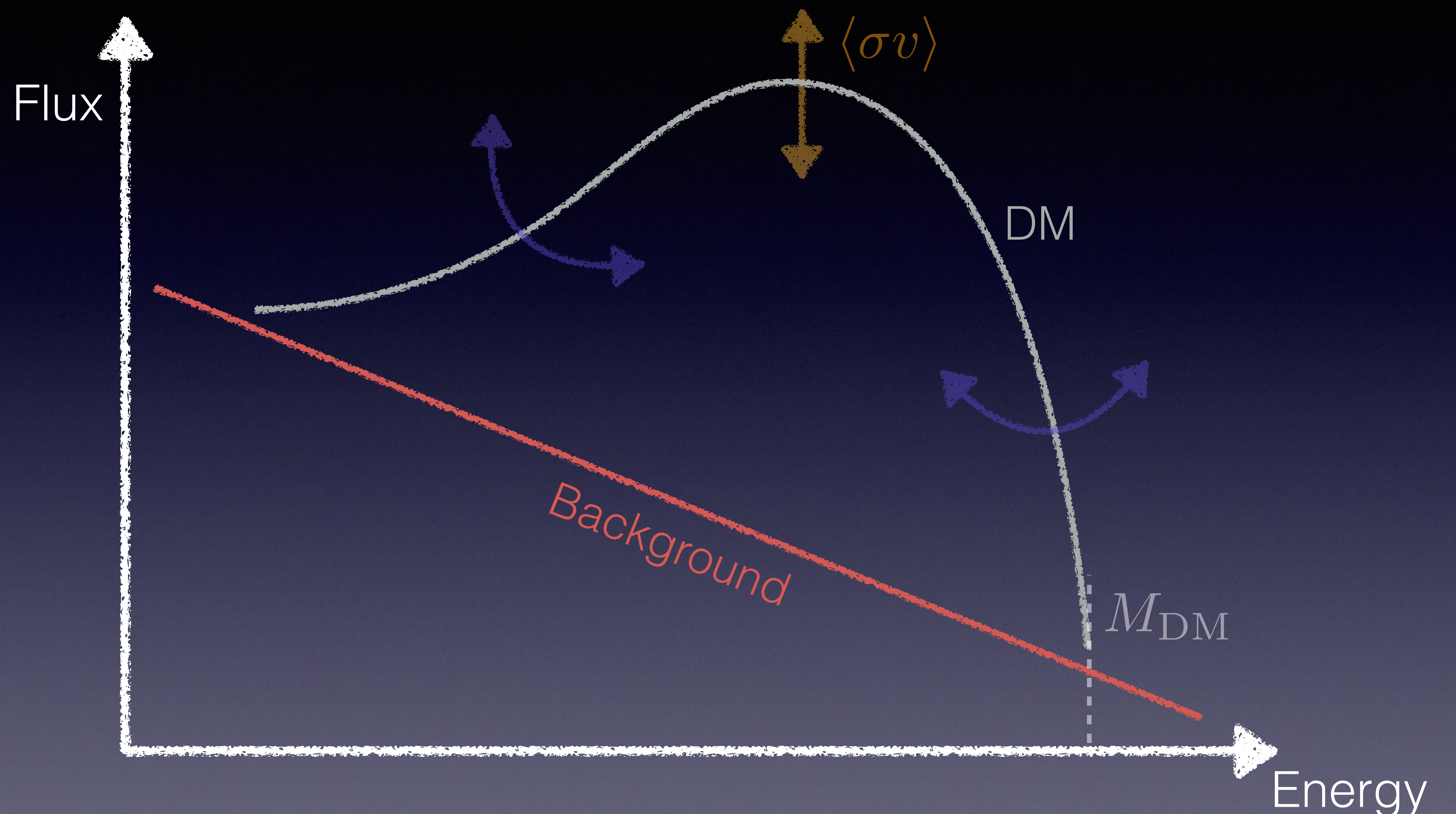


Normalized to: $\rho_i(r_\odot) = 0.3\ \text{GeV/cm}^3$

at least 6 DM density profiles:

cuspy: Moore, NFW
mild: Einasto
smooth: Isothermal, Burkert
EinastoB = Steepened Einasto
(effect of baryons ??)

Fluxes at Earth



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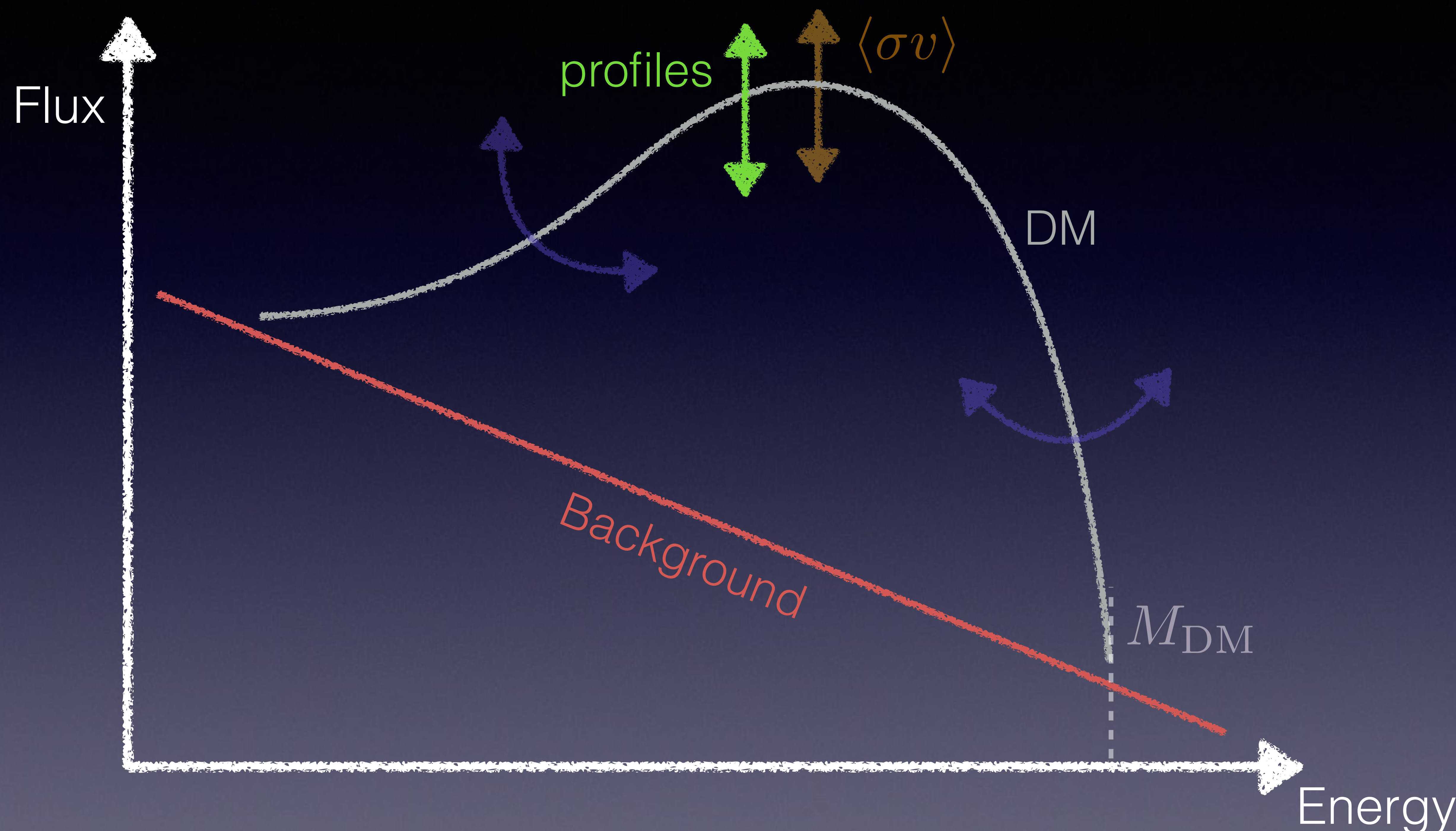

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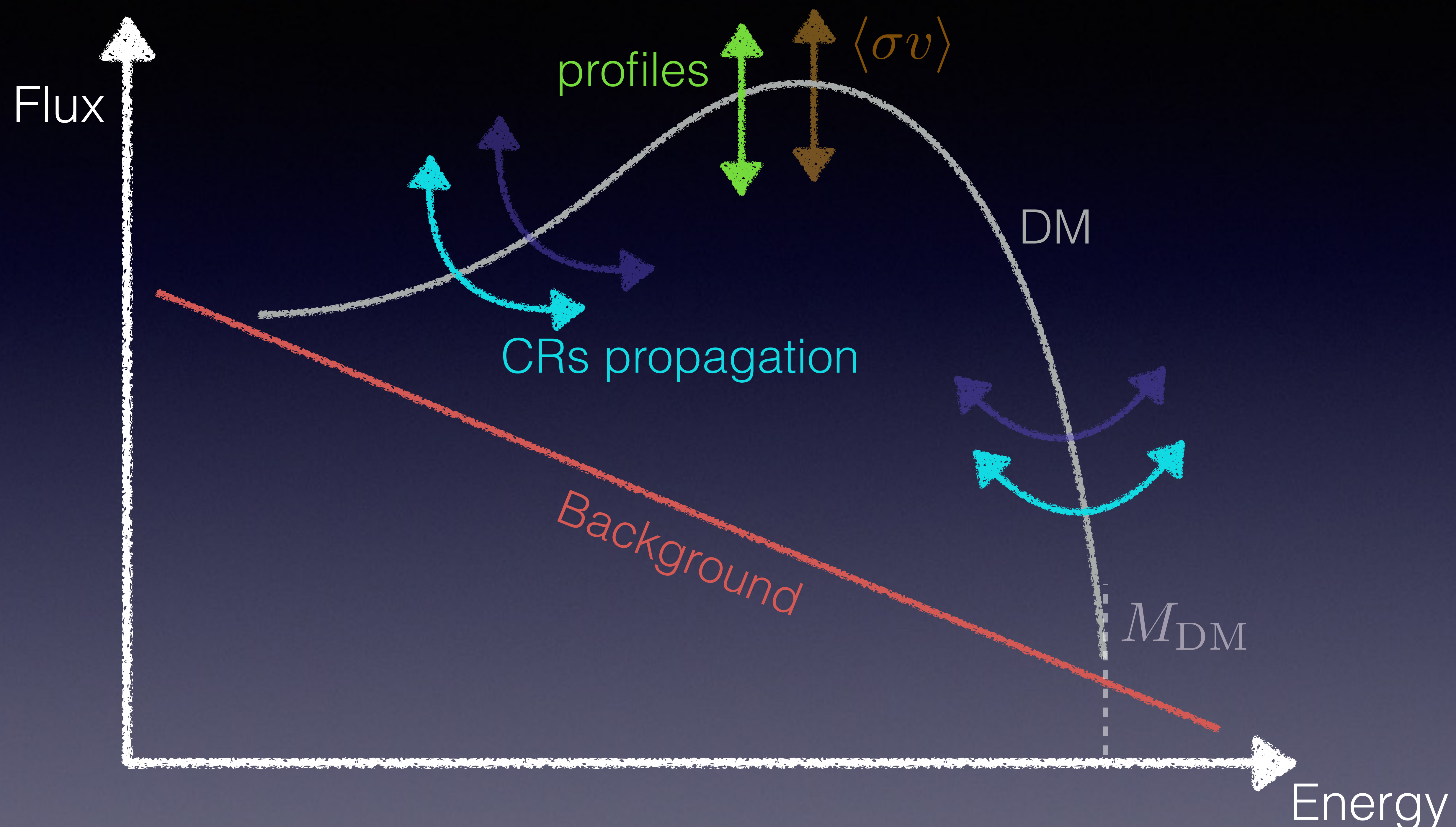

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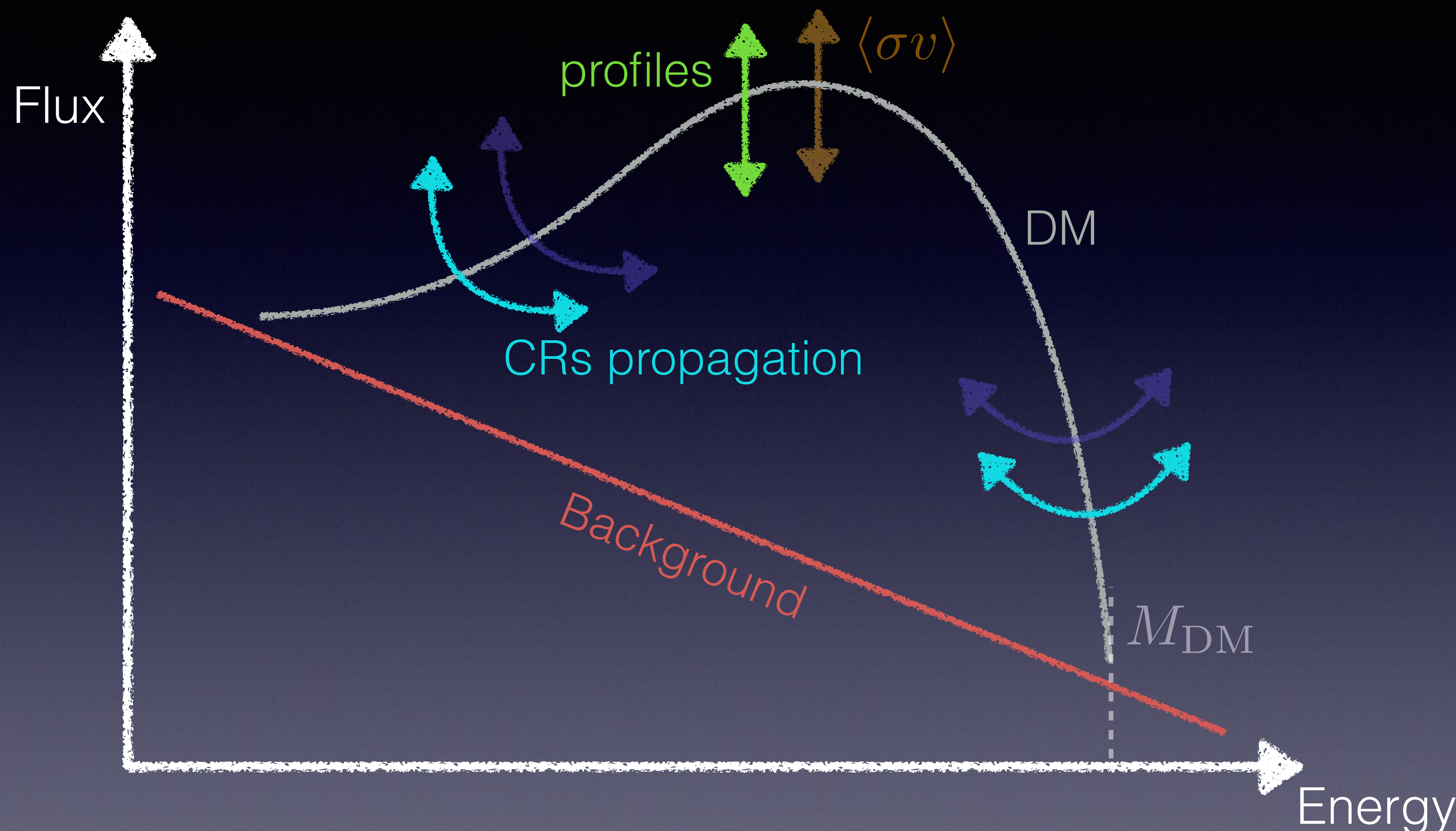

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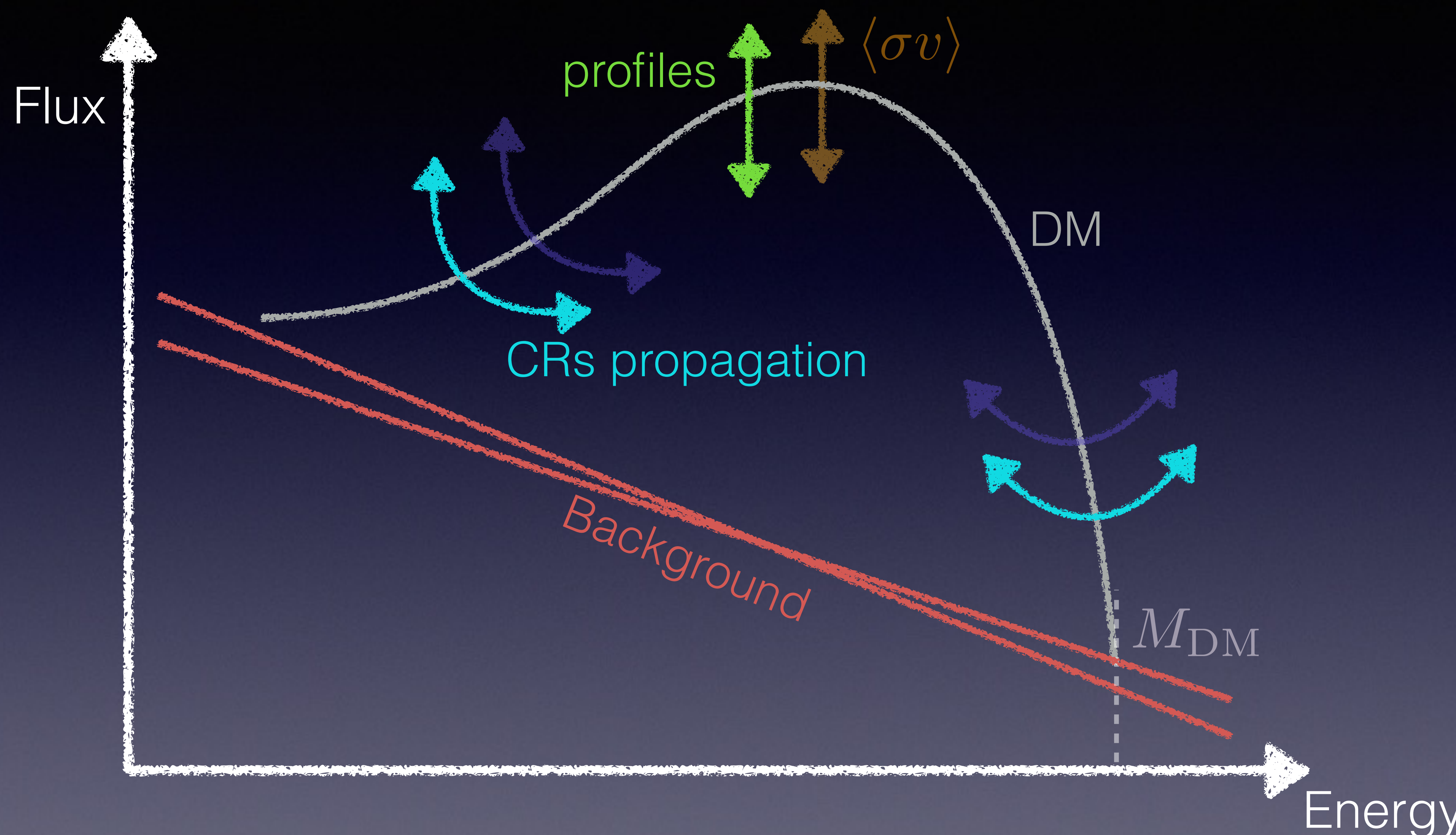

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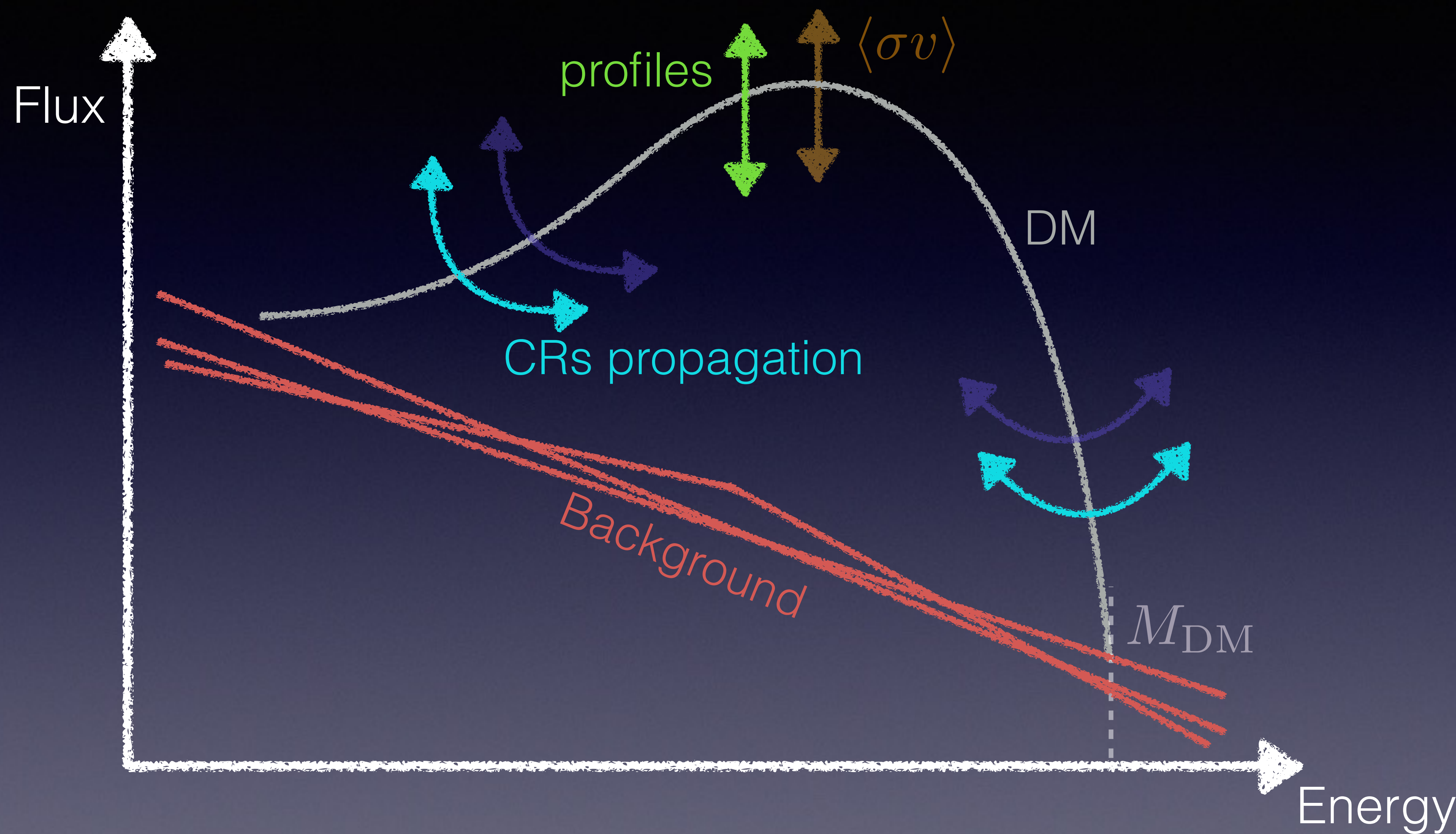

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Data: positrons

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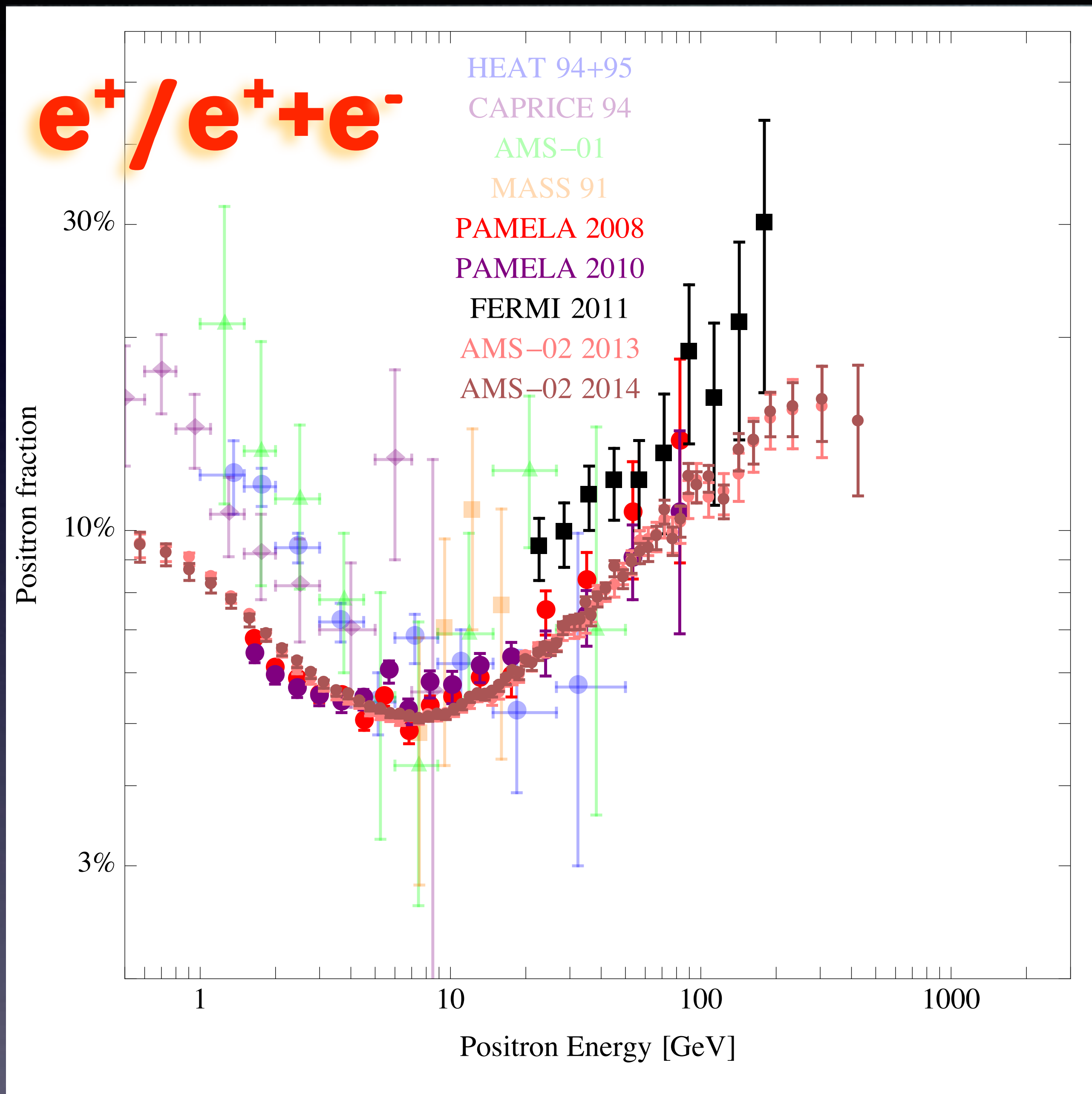

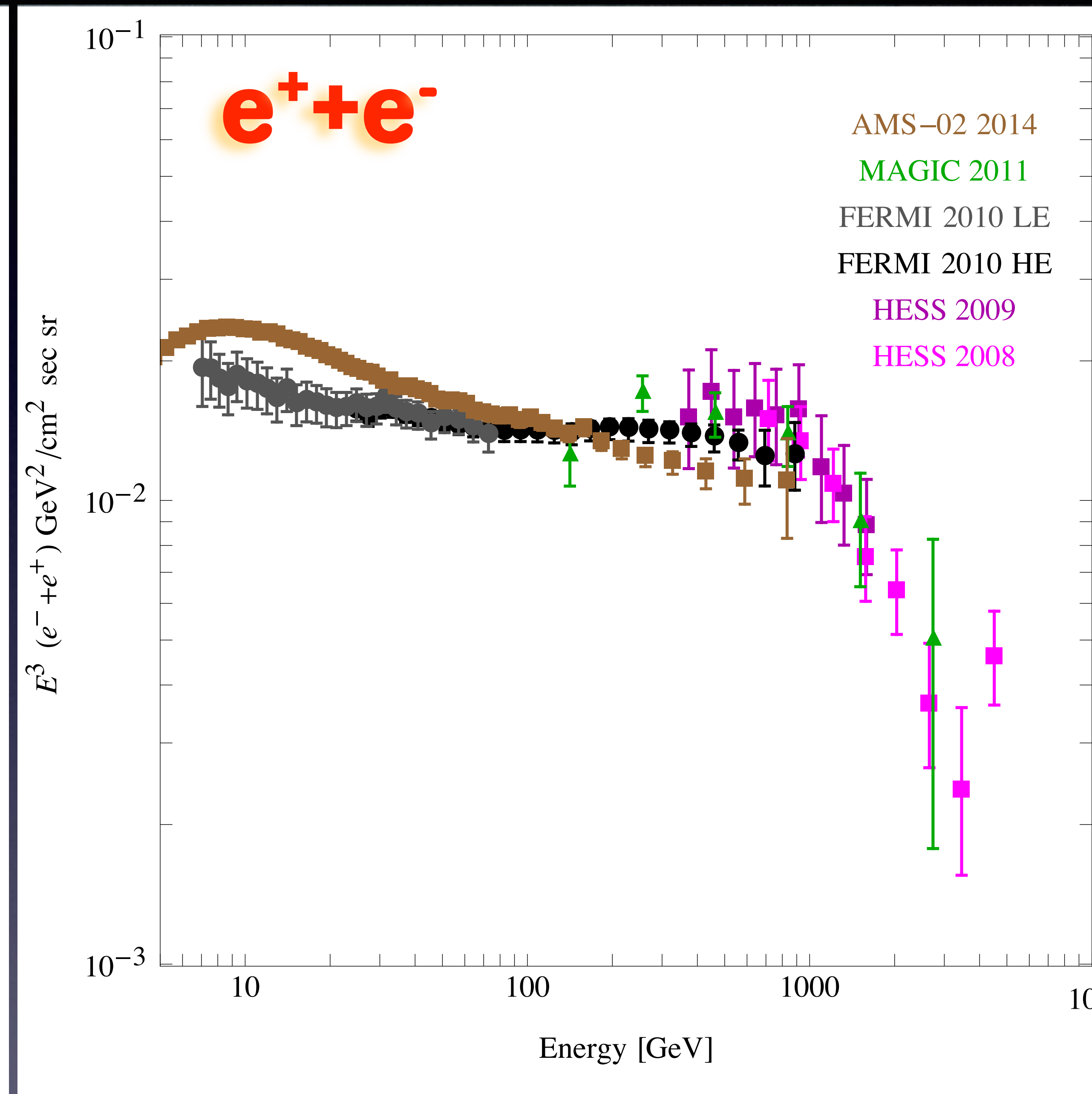

Courtesy of Marco Cirelli

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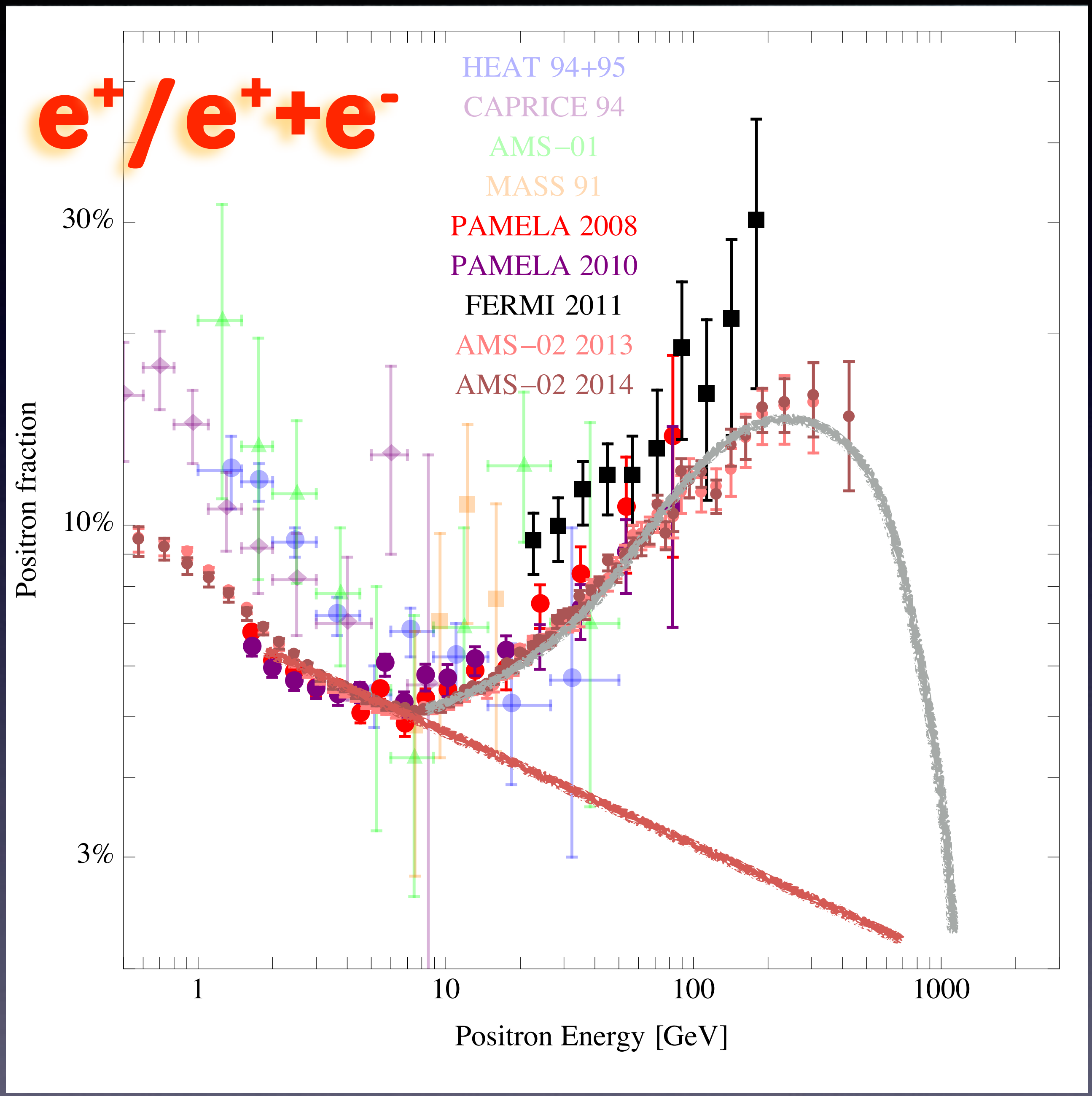
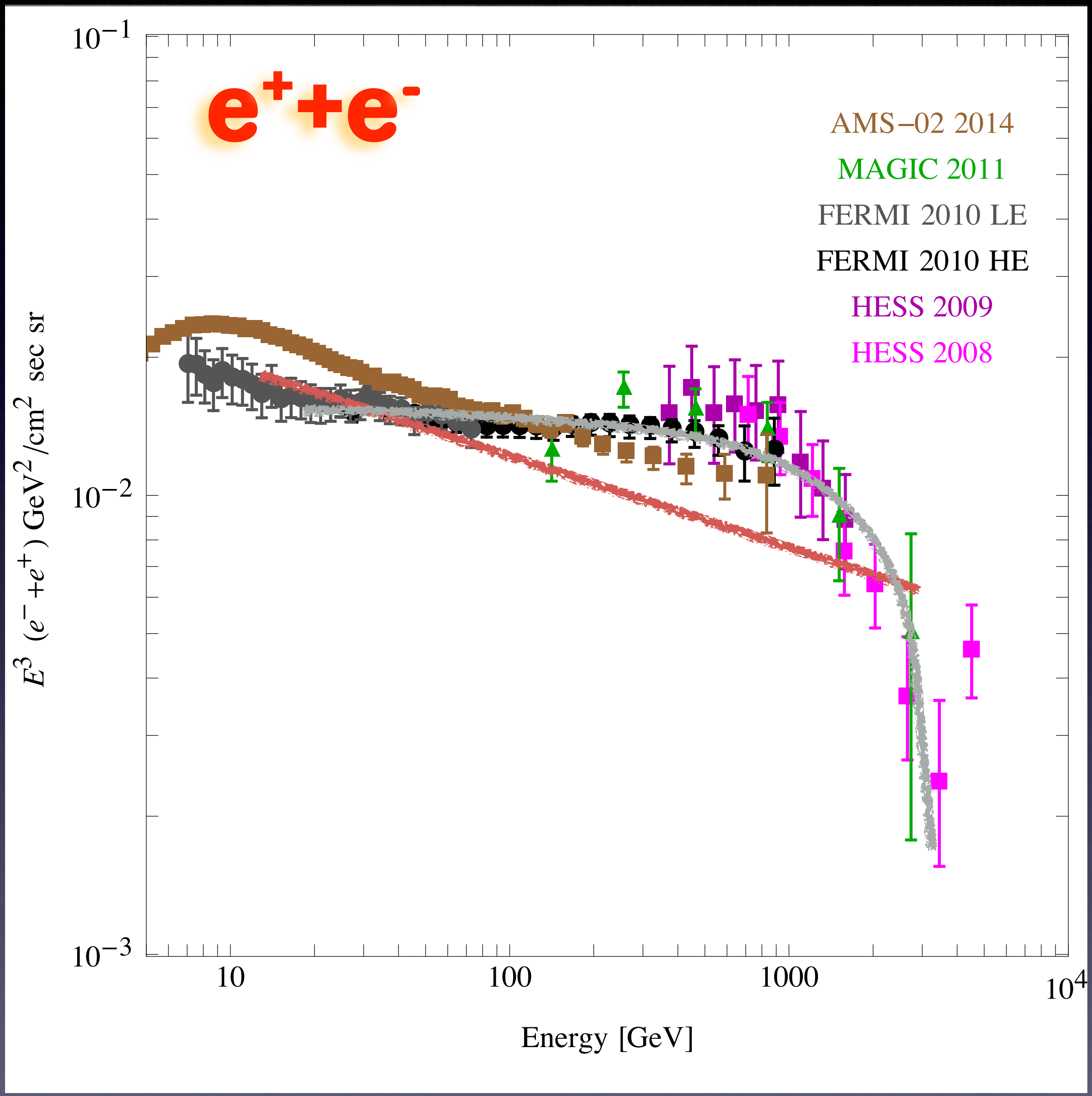




Courtesy of Marco Cirelli

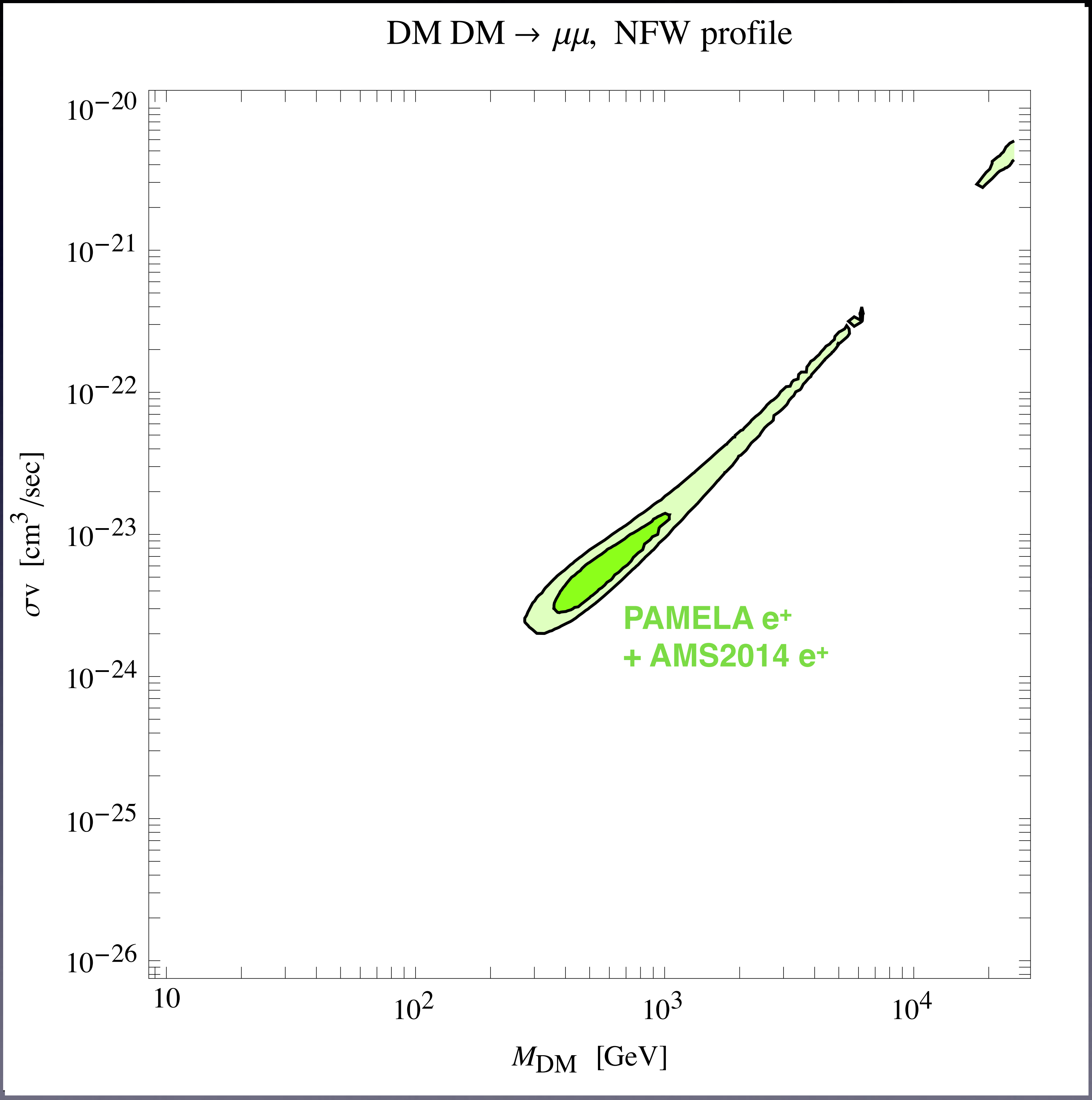
- Steep rise of $e^+/(e^+ + e^-)$ above roughly 10 GeV
- The $e^+ + e^-$ shows a plateau and it drops at $E_e \simeq 2$ TeV

New Source of positrons is needed

DM Interpretation

BEST FIT PARAMETERS

- Leptophilic
- Mass of $\simeq 1\ \mathrm{TeV}$
- Huge Ann. Xs order of $10^{-23}\ \mathrm{cm}^3/\mathrm{s}$



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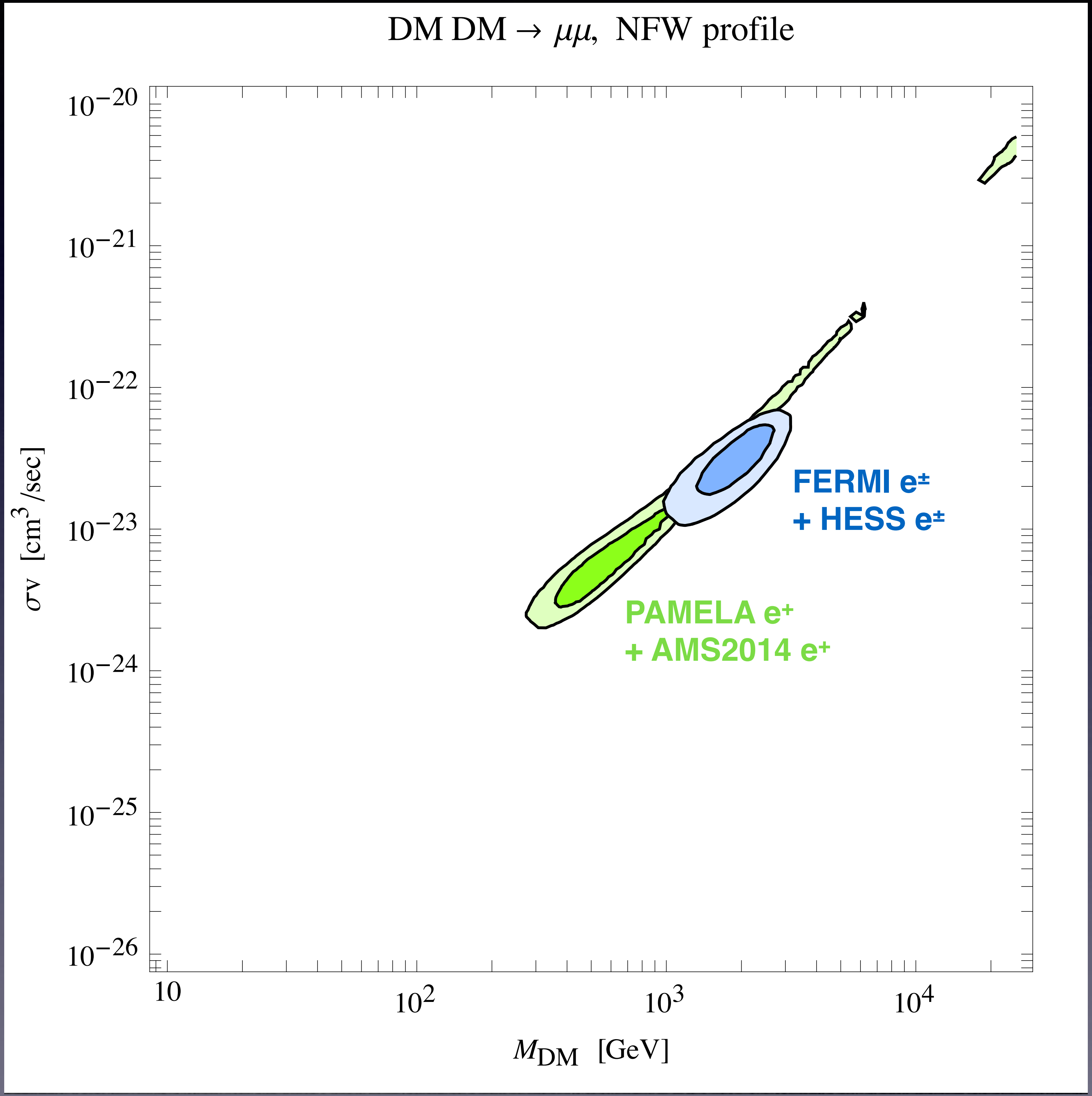

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Leptophilic DM models provide good fit of the e^+ anomaly

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- ☑ Combination of primary channels may spoil the fit
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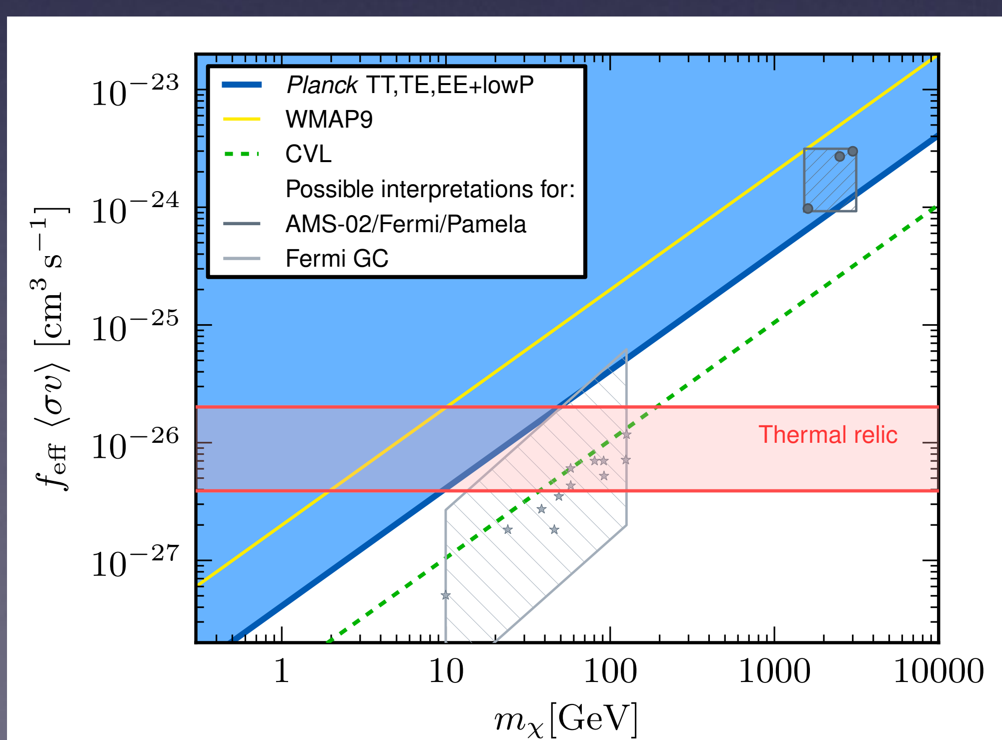
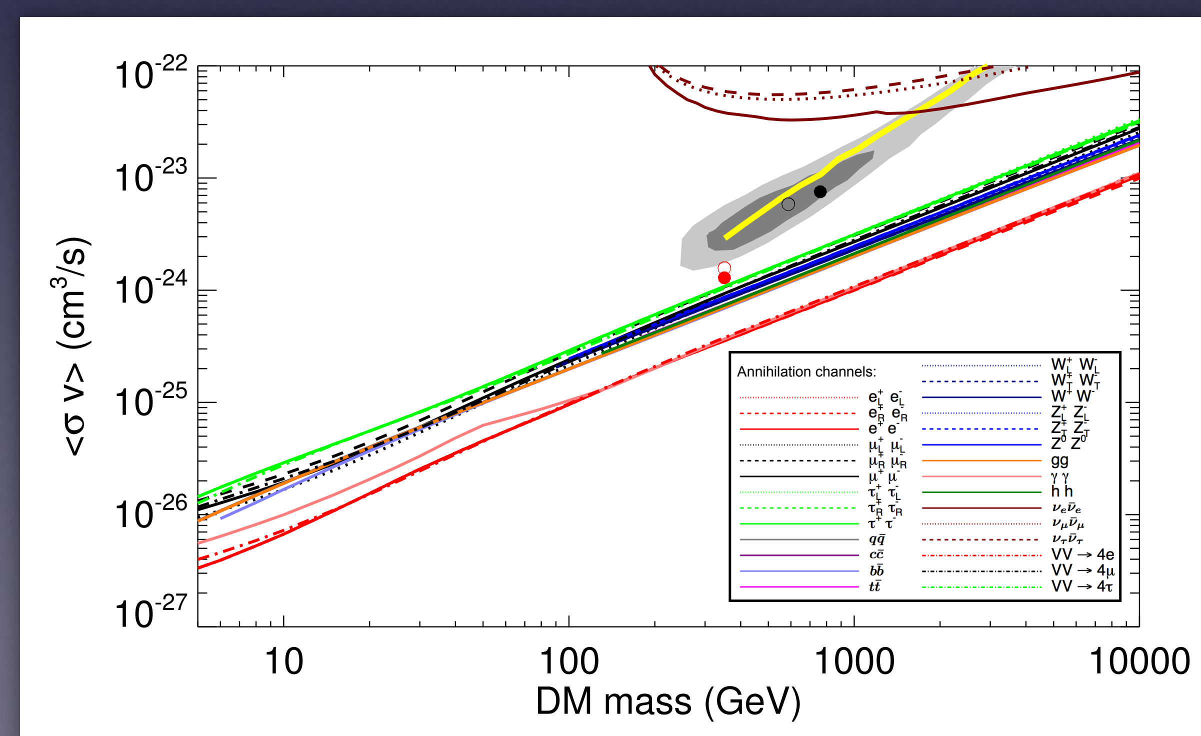
  - In general, particle physics models predict branching ratio in several channels
- ☑ Complementary Bounds: CMB, neutrinos, gamma-rays,….

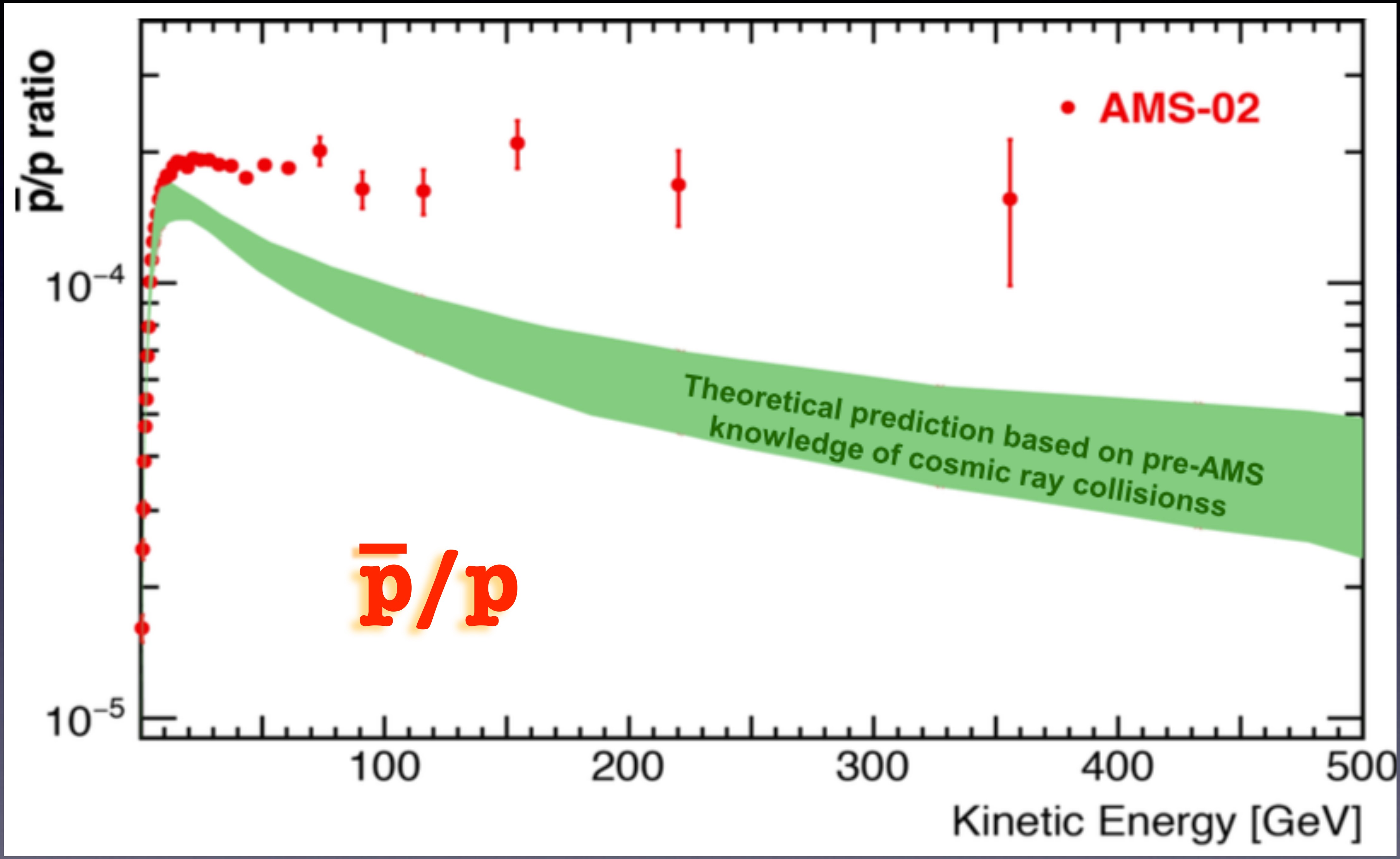


Planck Collaboration; arXiv:1502.01589



T.Slatyer; arXiv:1506.03811

Data: anti-protons

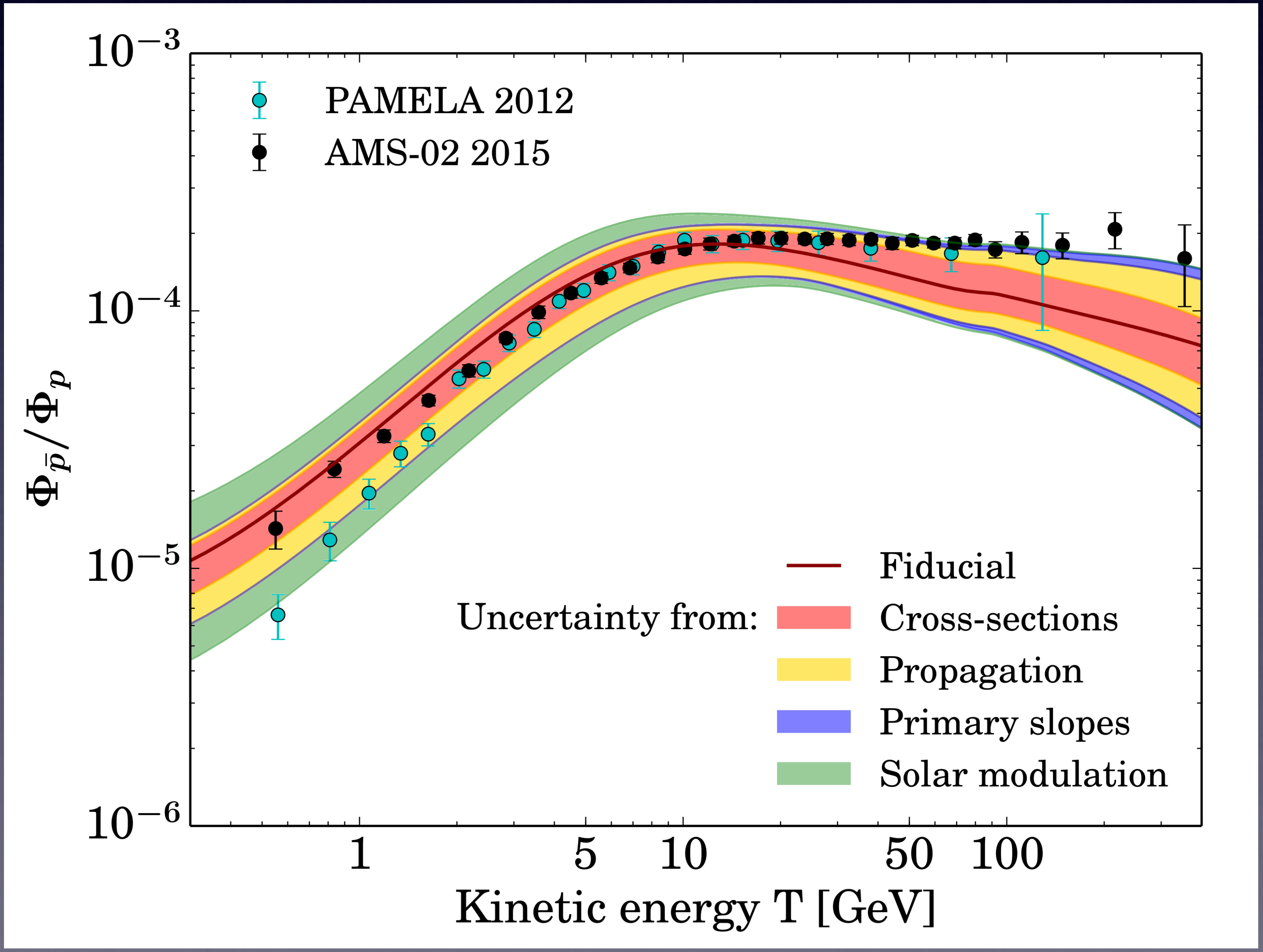


A. Kounine - AMS Days@CERN 2015
S. Ting - AMS Days@CERN 2015

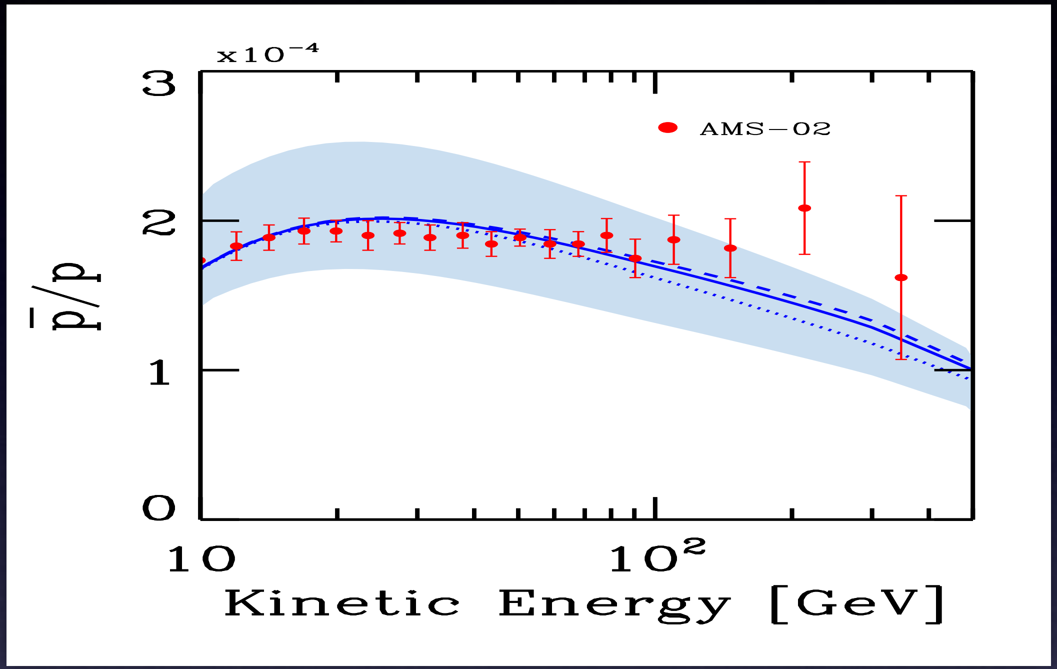
Data: anti-protons vs bkg.

Uncertainties on production and propagation are crucial

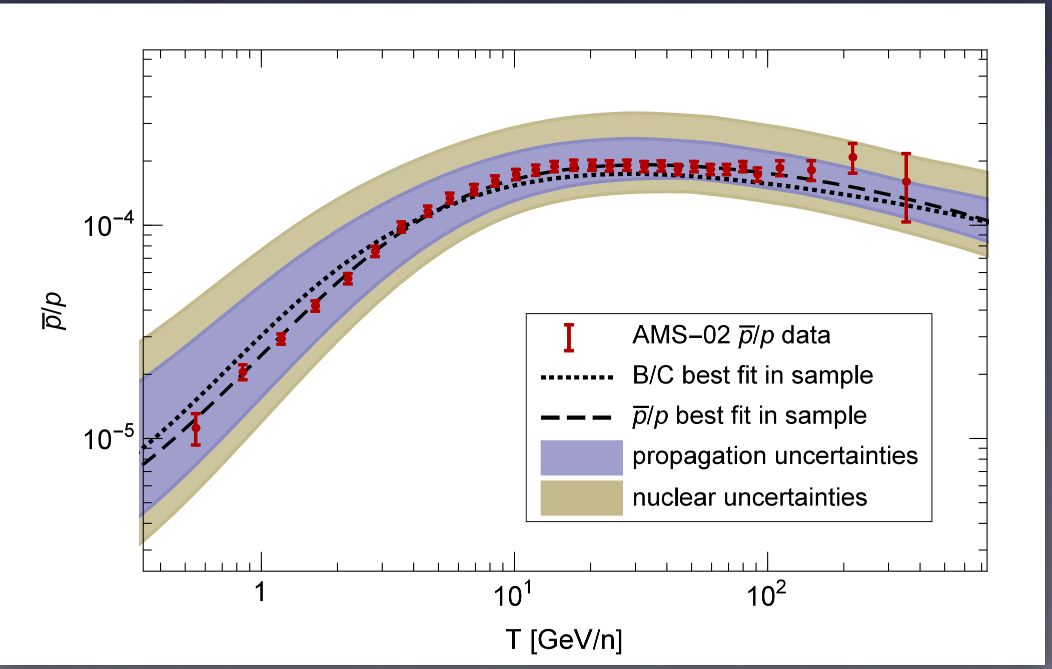
- ✓ **NO** Evident **Excess**
- ✓ Small preference for flatness



M. Boudaud et al. - arXiv:1504.04276



C. Evoli et al.- arXiv:1504.05175

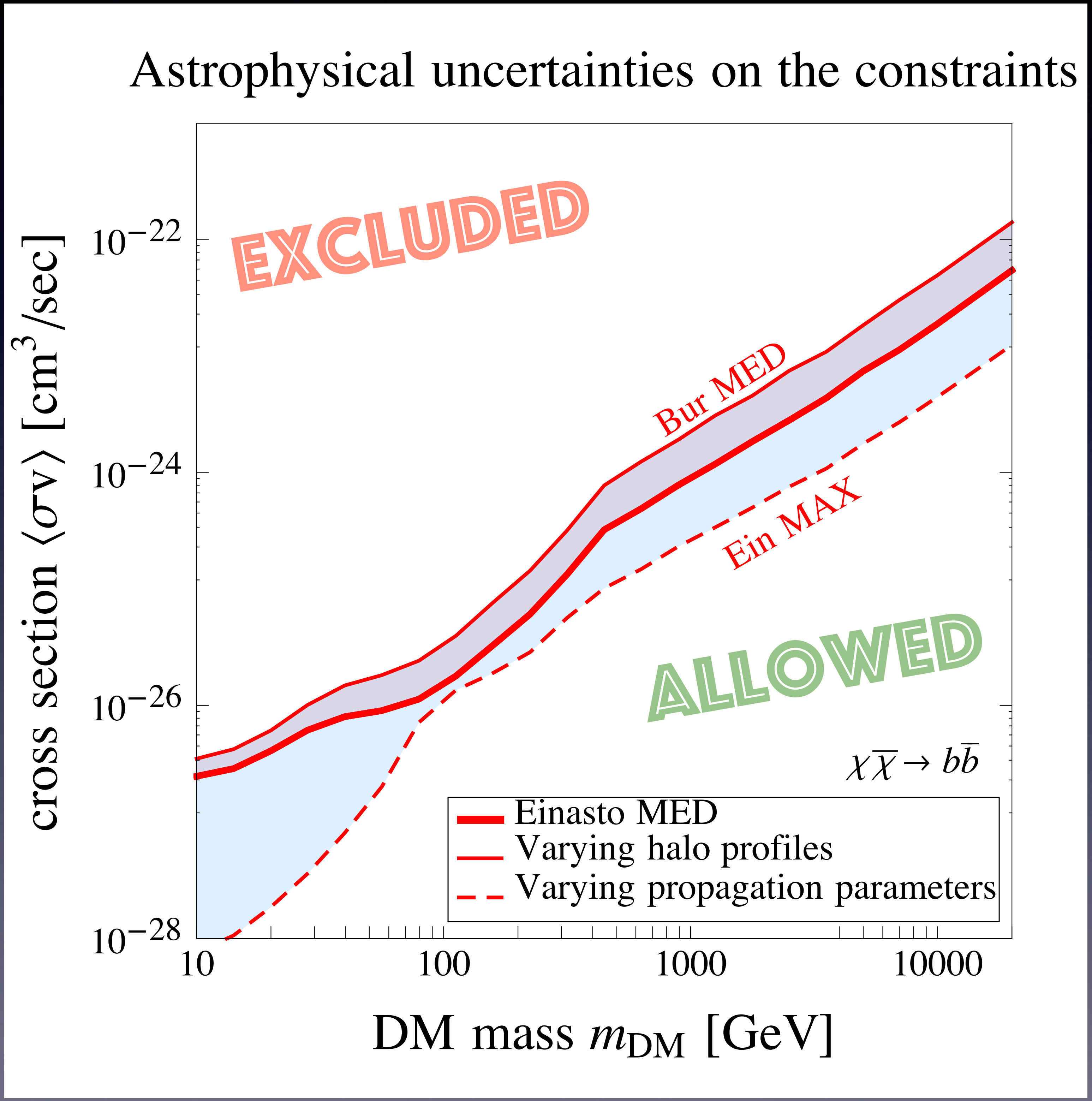


R. Kappl at al. - arXiv:1506.04145

DM Interpretation

Constraint based on the AMS-02 $\bar{p}/p$ data

- Anti-protons bound depend on the propagation parameters
- Hadronic primary modes are of course more constrained



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Photons from DM

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Prompt emission

Secondary emission

Photons from DM

Prompt emission

- ☑ Continuum
- ☑ Gamma Lines
- ☑ Sharp features

Secondary emission

- ☑ ICS
- ☑ Breamstrahlung
- ☑ Synchrotron

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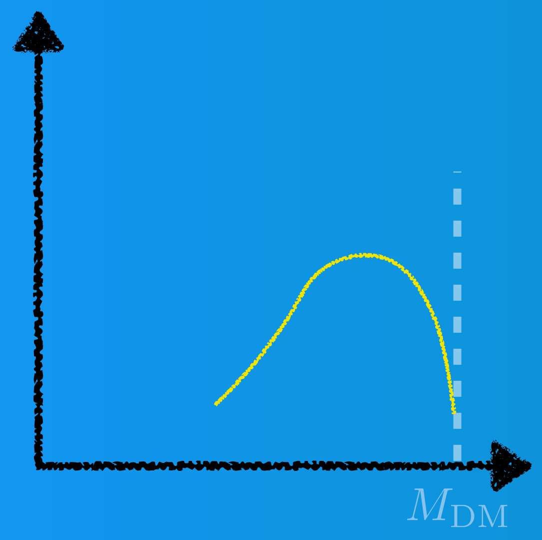

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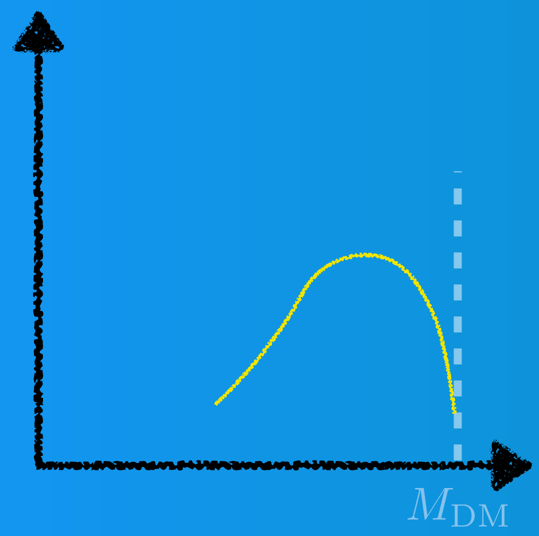

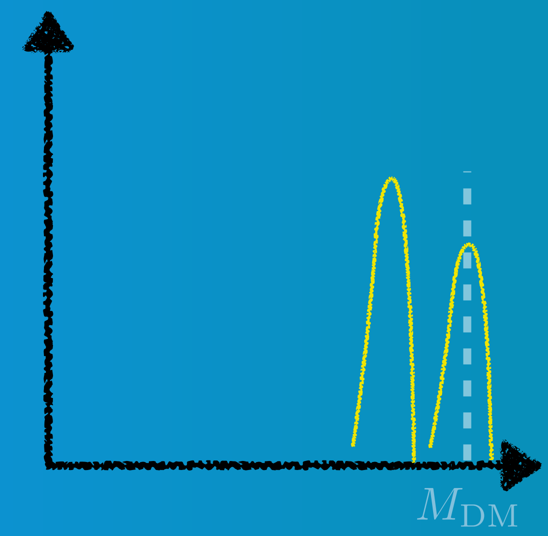

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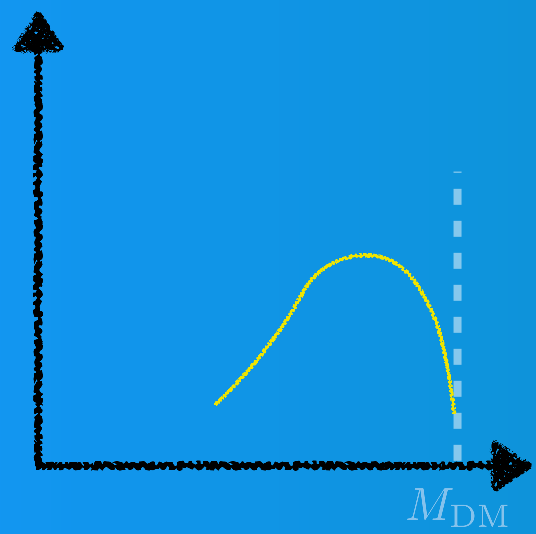
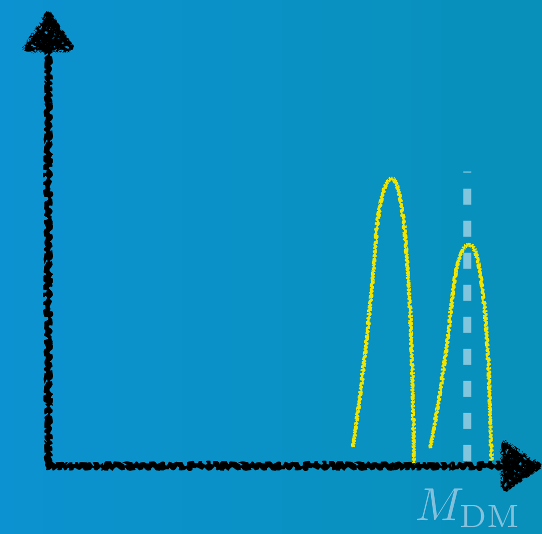
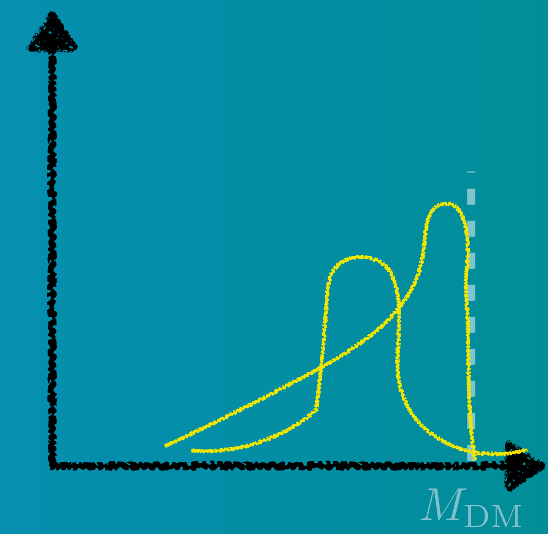


- ☑ Gamma Lines



- ☑ Sharp features



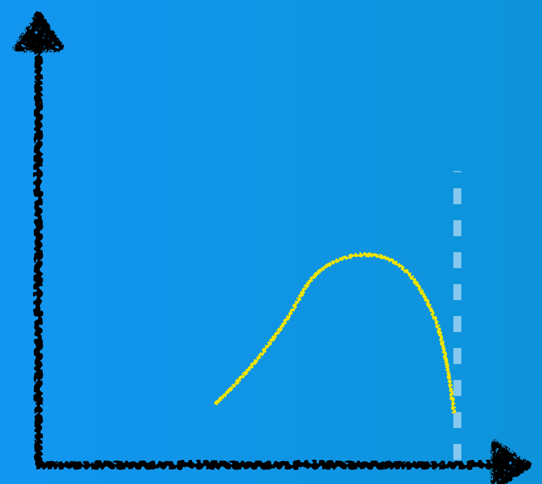
Secondary emission

- ☑ ICS
- ☑ Breamstrahlung
- ☑ Synchrotron

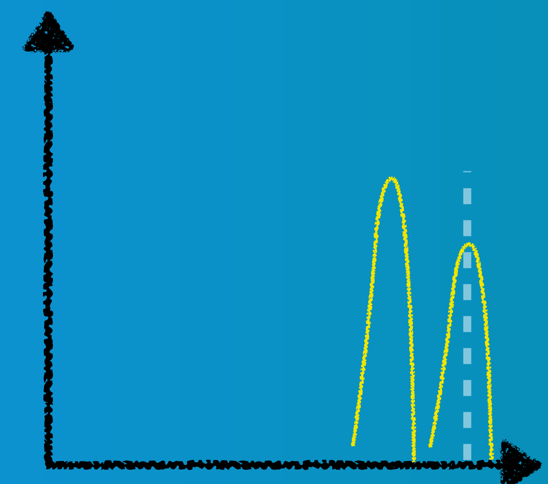
Photons from DM

Prompt emission

- ☑ Continuum



- ☑ Gamma Lines



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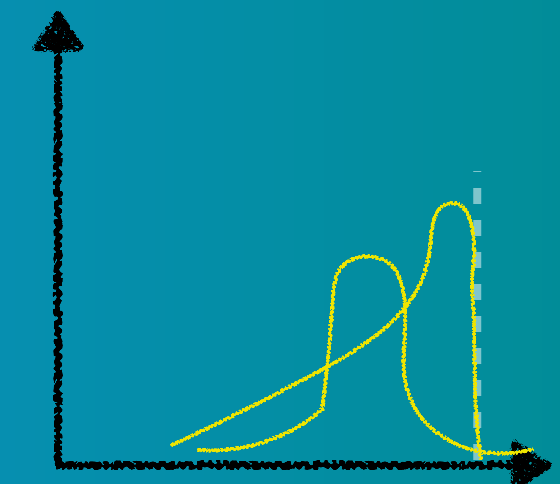

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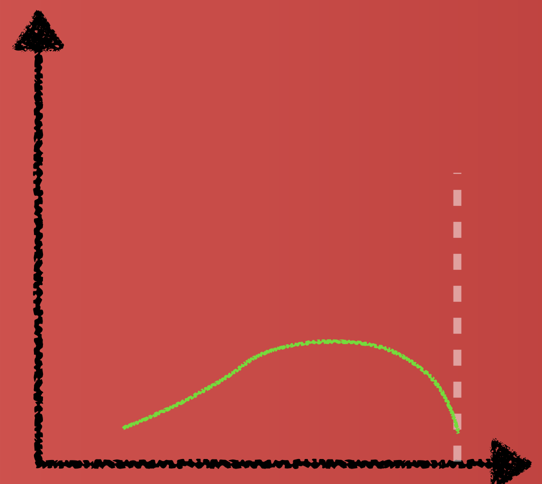

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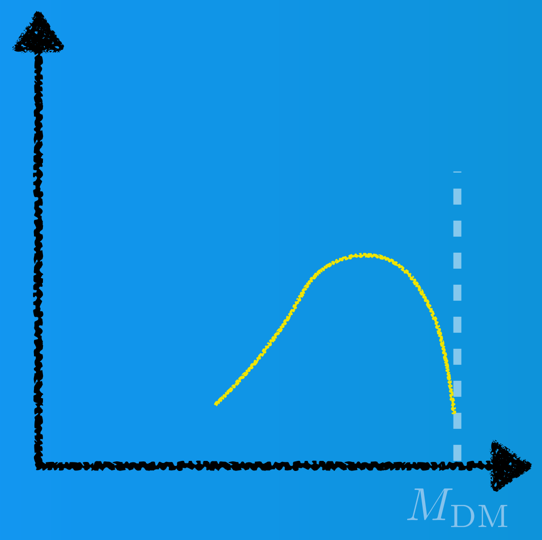

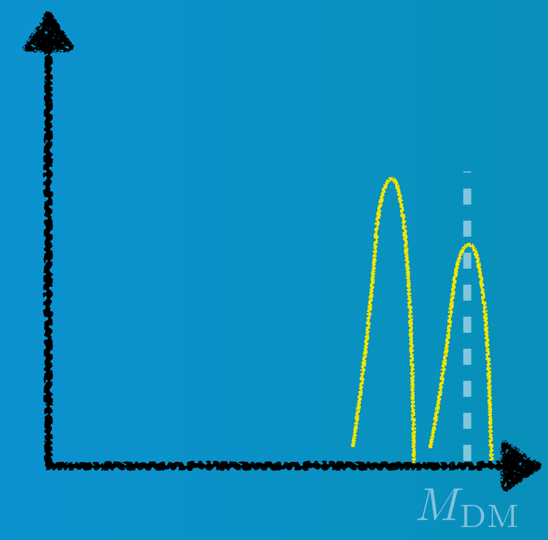

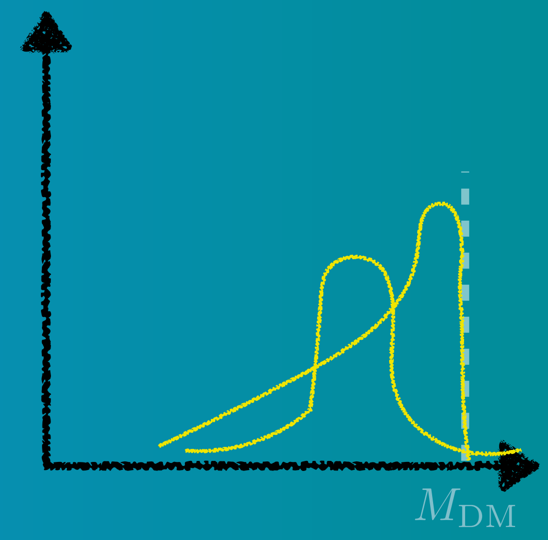

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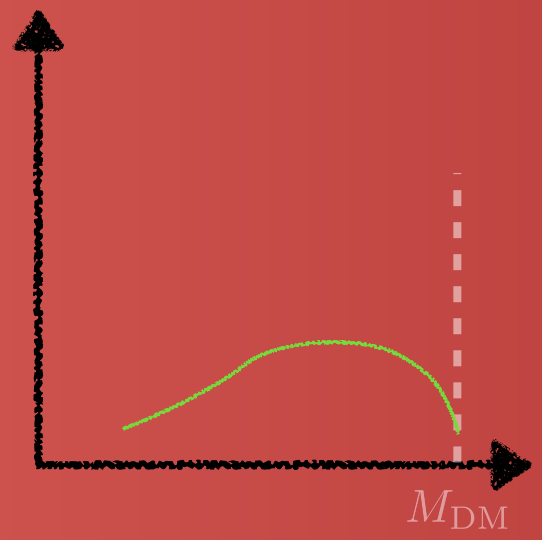
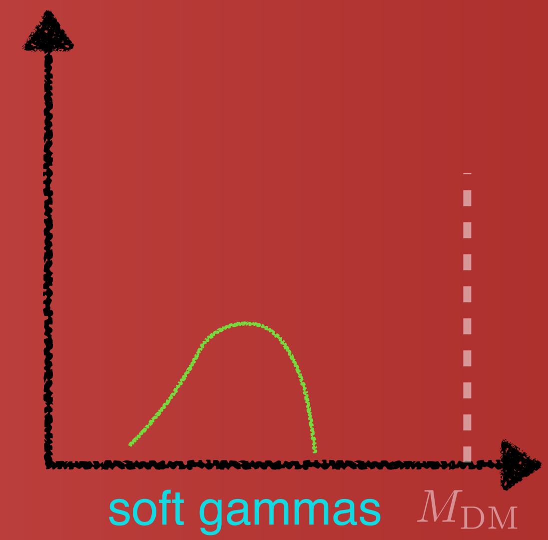
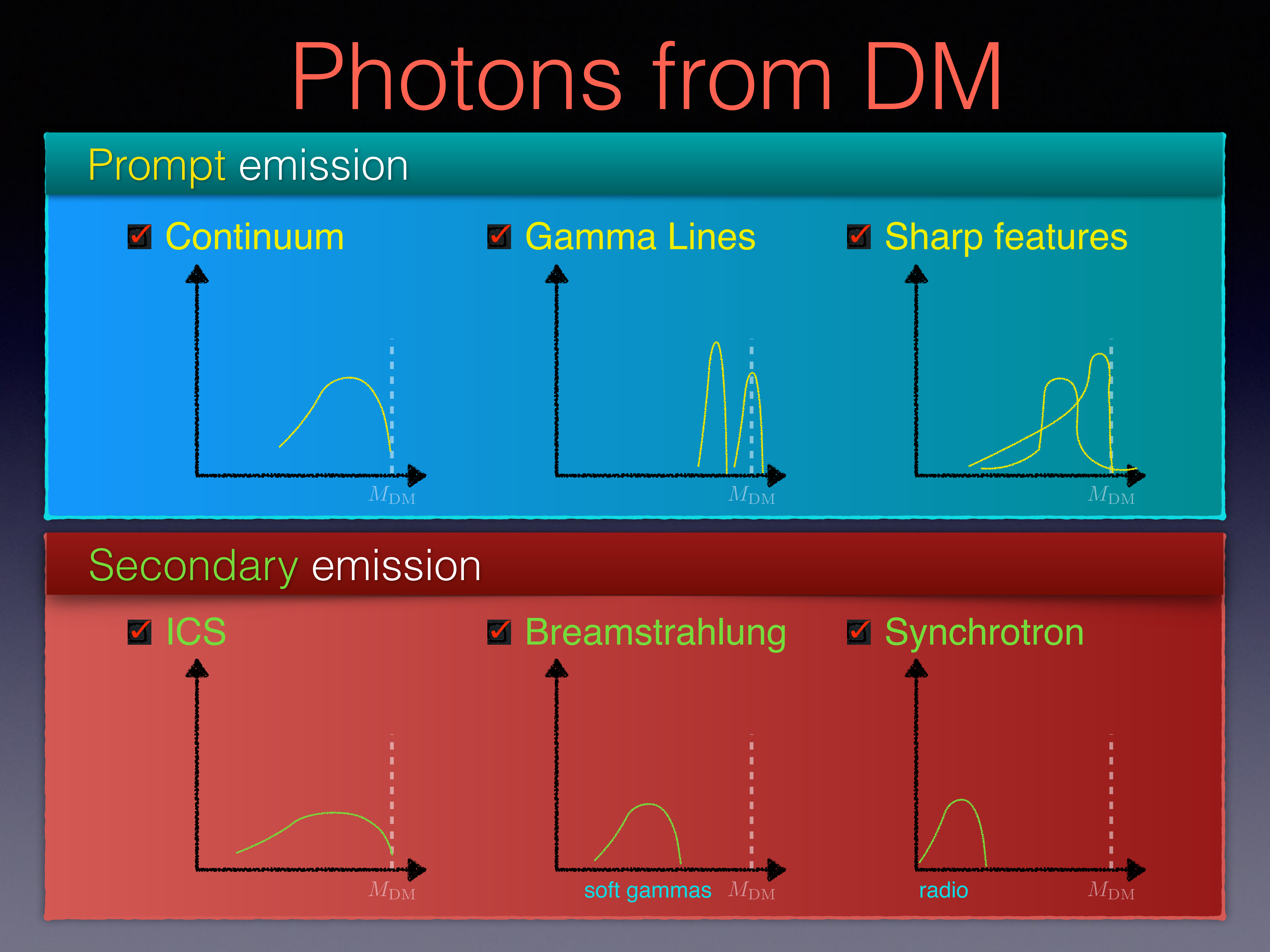




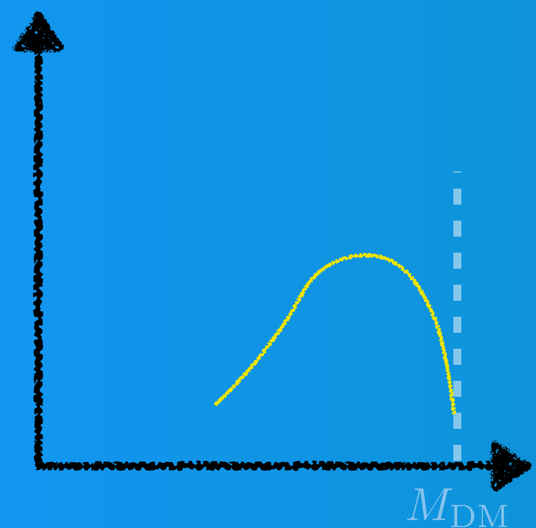

Photons from DM
Prompt emission
Continuum
Gamma Lines
Sharp features
$M_{\rm DM}$
$M_{\rm DM}$
$M_{\rm DM}$
Secondary emission
ICS
Breamstrahlung
Synchrotron
soft gammas
radio
$M_{\rm DM}$
$M_{\rm DM}$
$M_{\rm DM}$

Photons from DM

Prompt emission

environment independent

☑ Continuum



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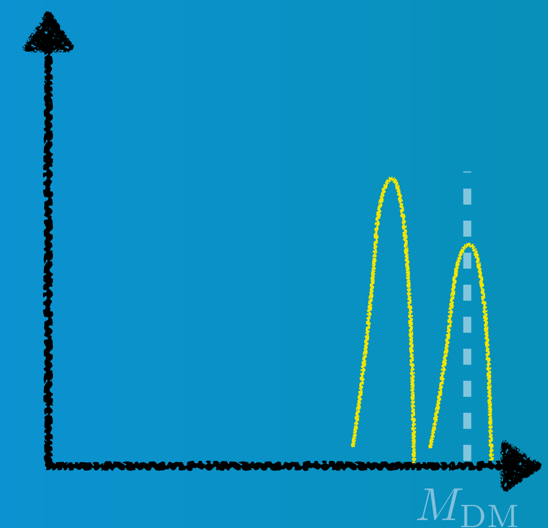
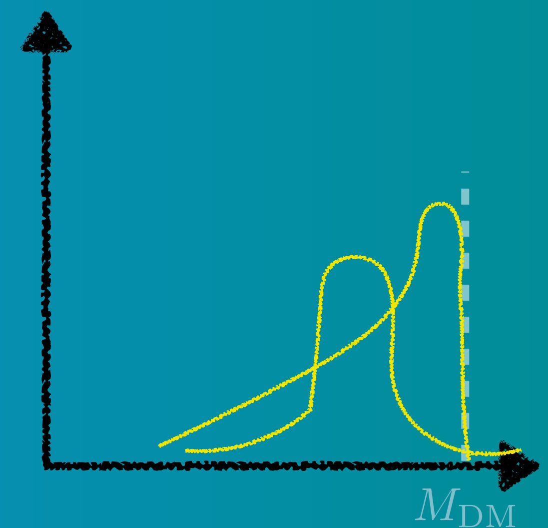


☑ Sharp features



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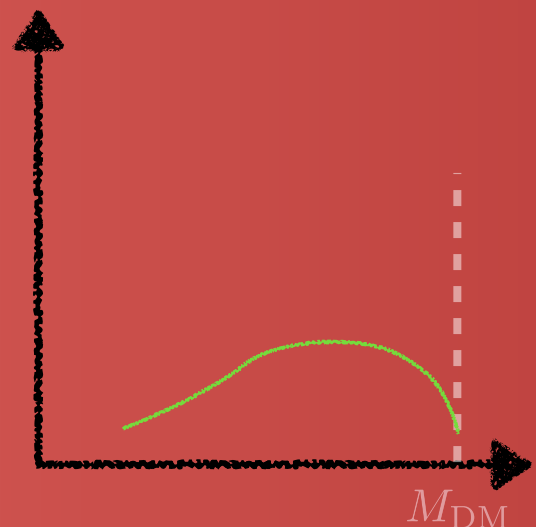

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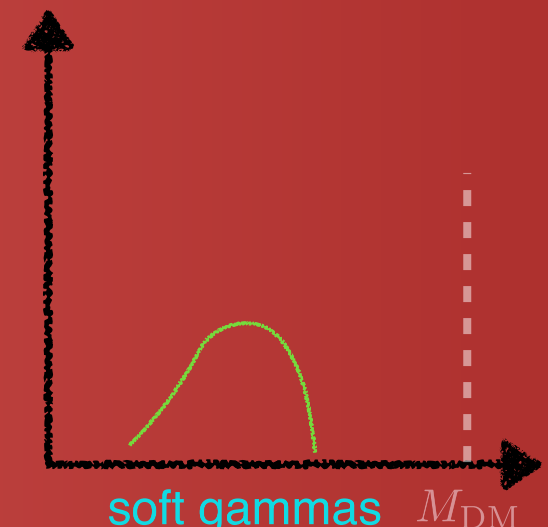
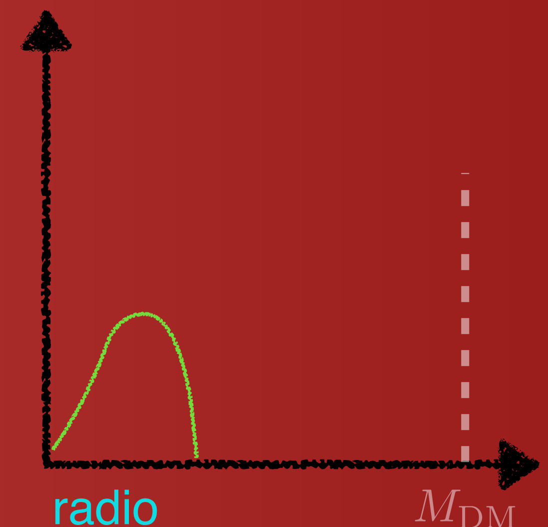
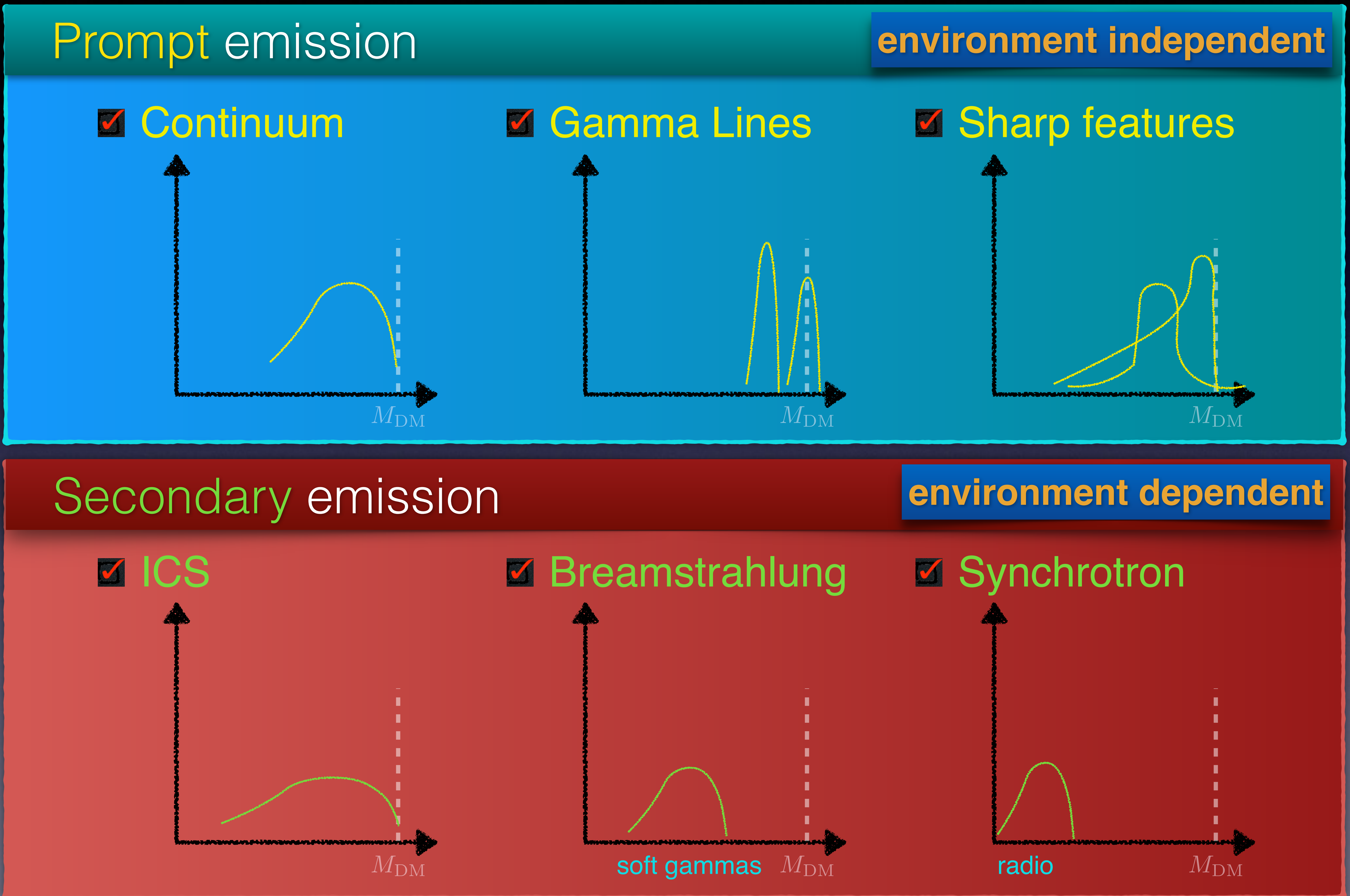


☑ Synchrotron



Photons from DM



Bounds from continuum

Constraints from the measurement of the Gal. diffuse emission

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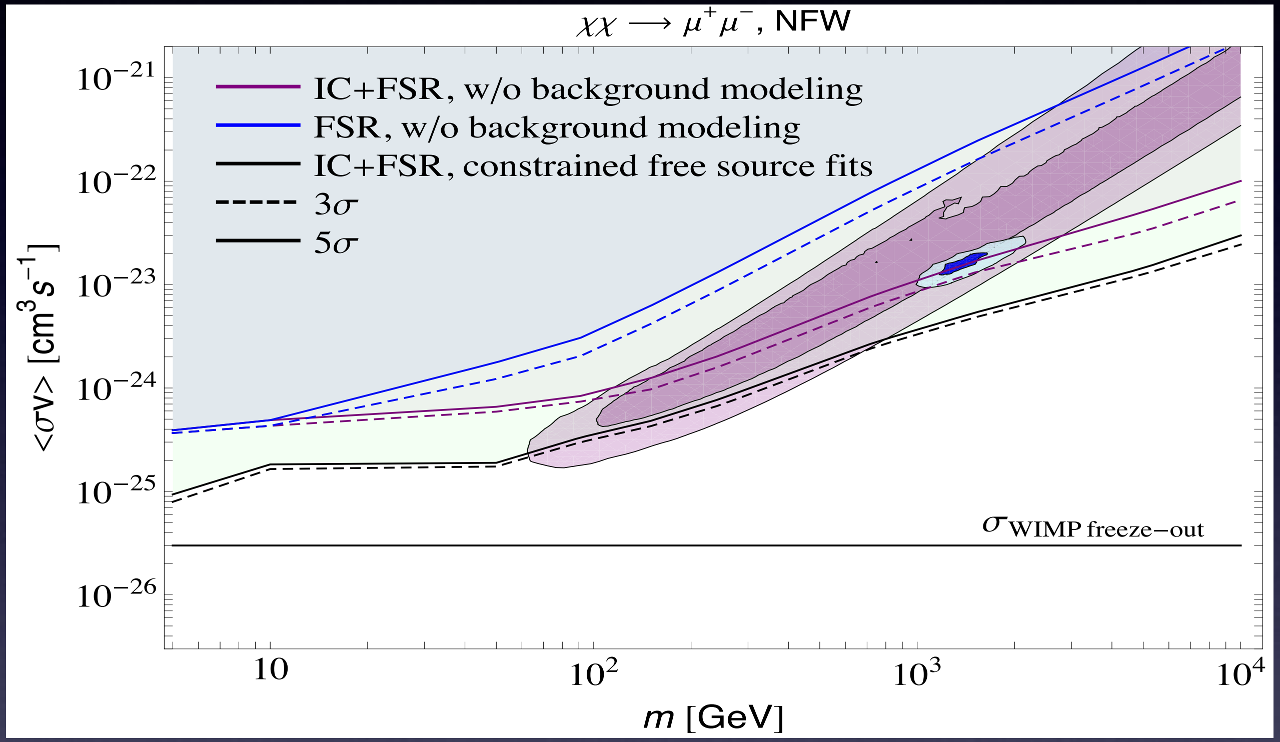
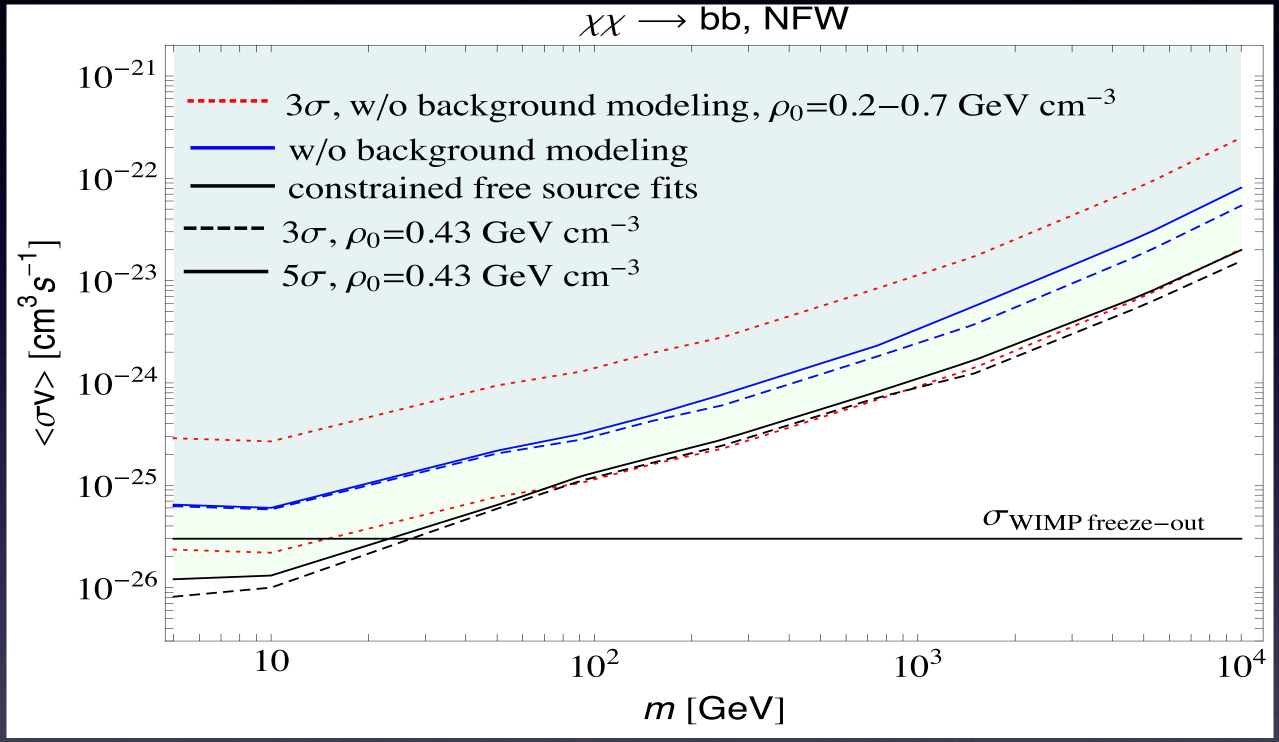
FERMI: *(M. Ackermann et al. - arXiv:1205.6474)*





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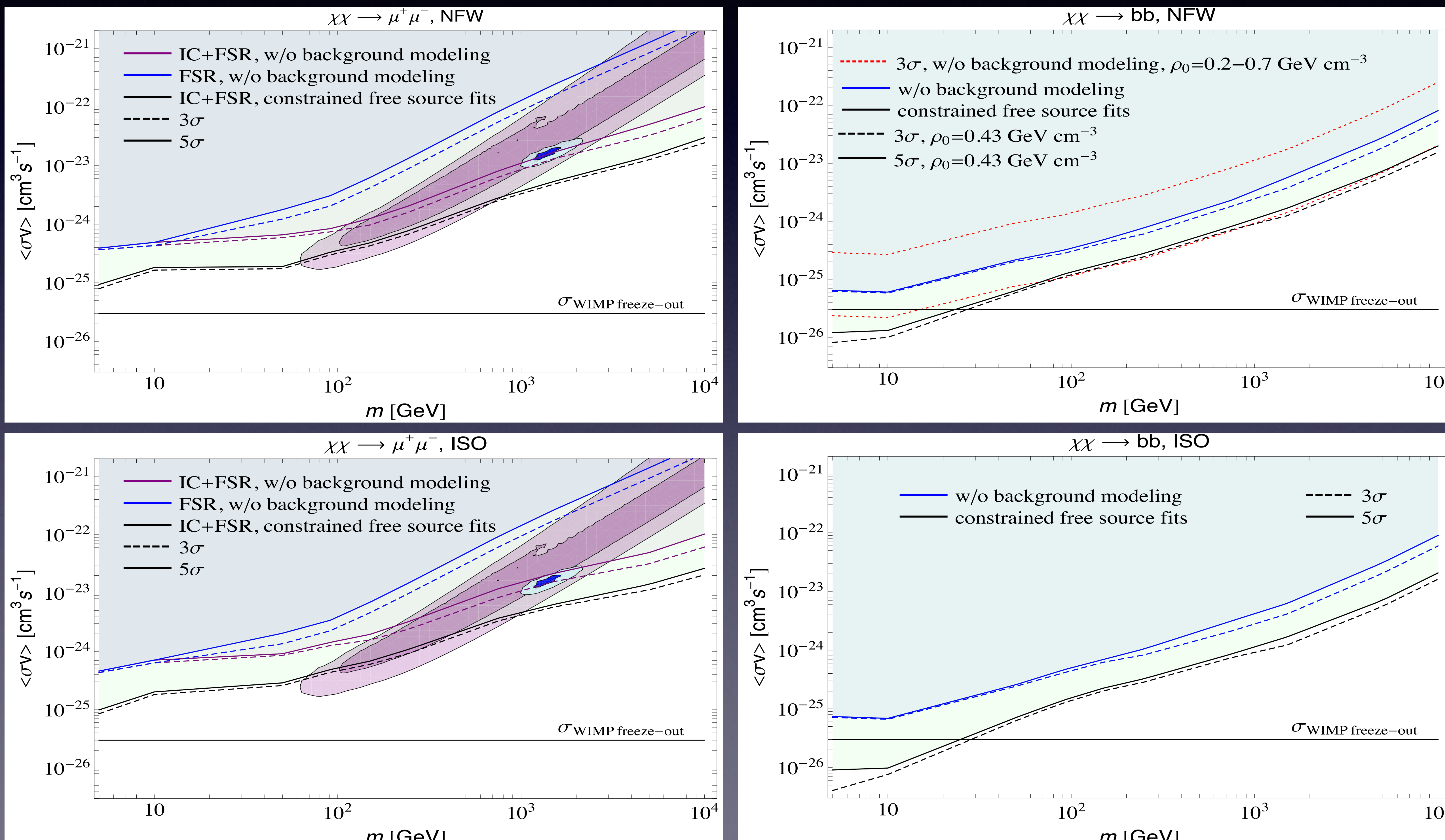

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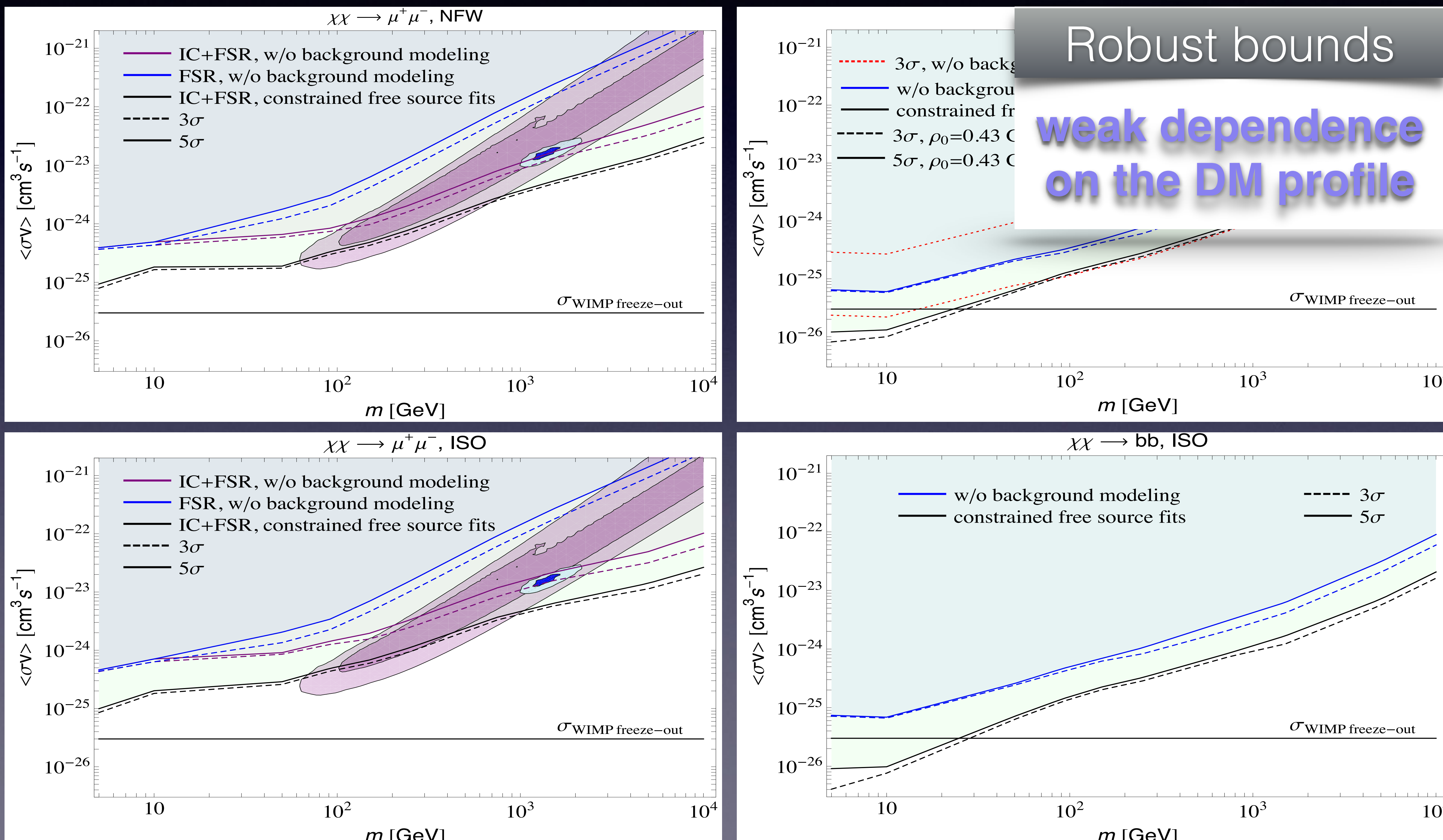


Robust bounds

weak dependence on the DM profile

Bounds from continuum

dSph galaxies are probably the cleanest laboratory for looking at DM signals

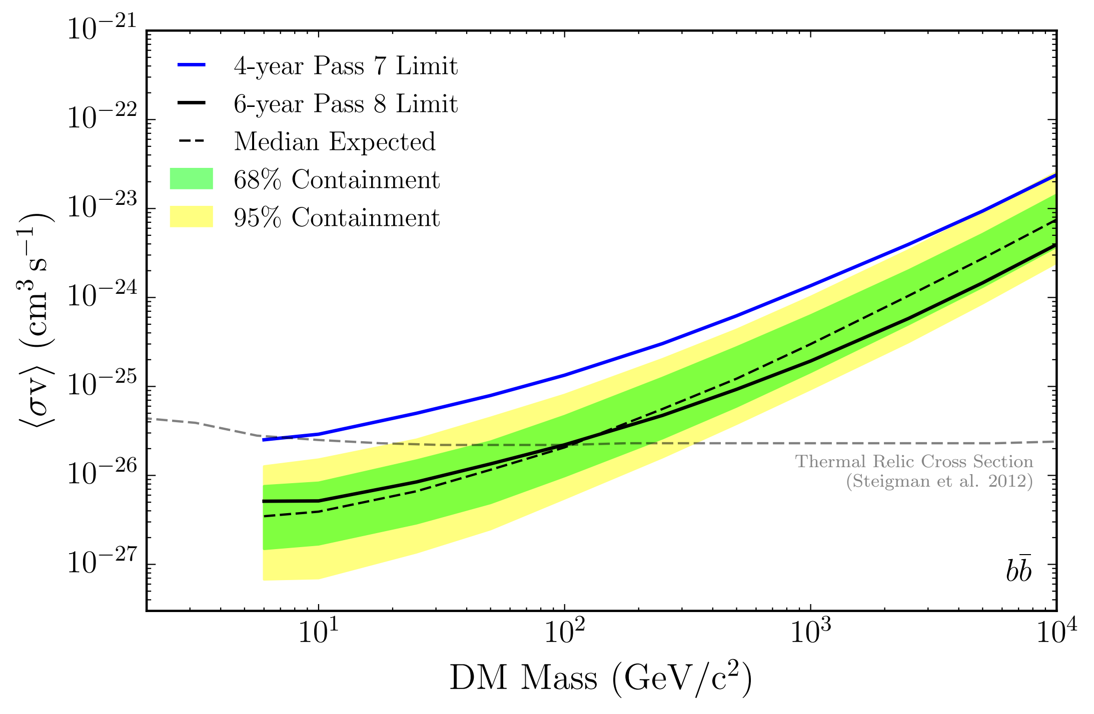
- high Dark Matter content
- low stellar foreground emission

→ this is why they are good target !!

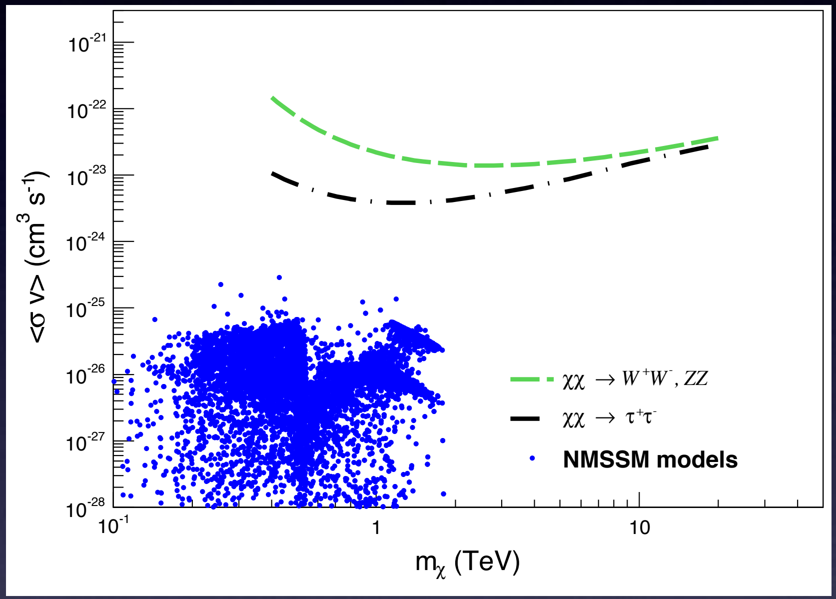
Bounds from continuum

dSph galaxies are probably the cleanest laboratory for looking at DM signals

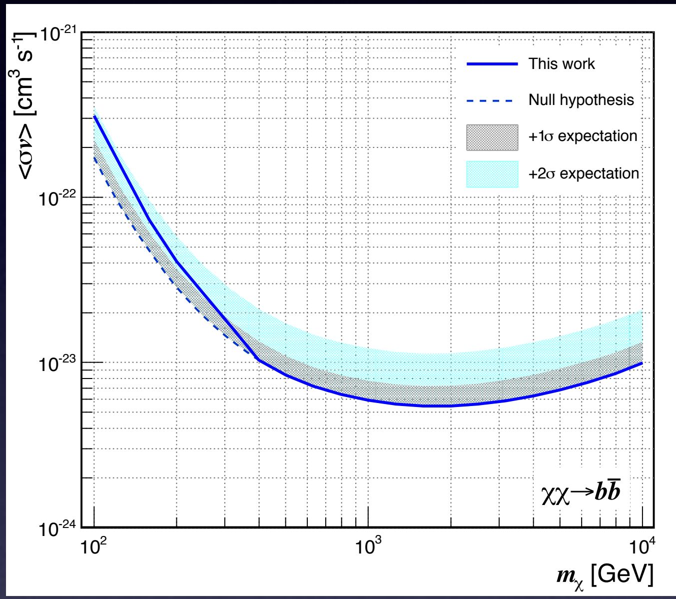
FERMI:
staking analysis of 15 dSphs
(Ackermann et al. arXiv:1503.02641



HESS:
4 dSphs + Sagittarius
(Abramowski et al. arXiv:1410.2589)



MAGIC:
only Segue 1
(Aleksic et al. arXiv:1312.1535)



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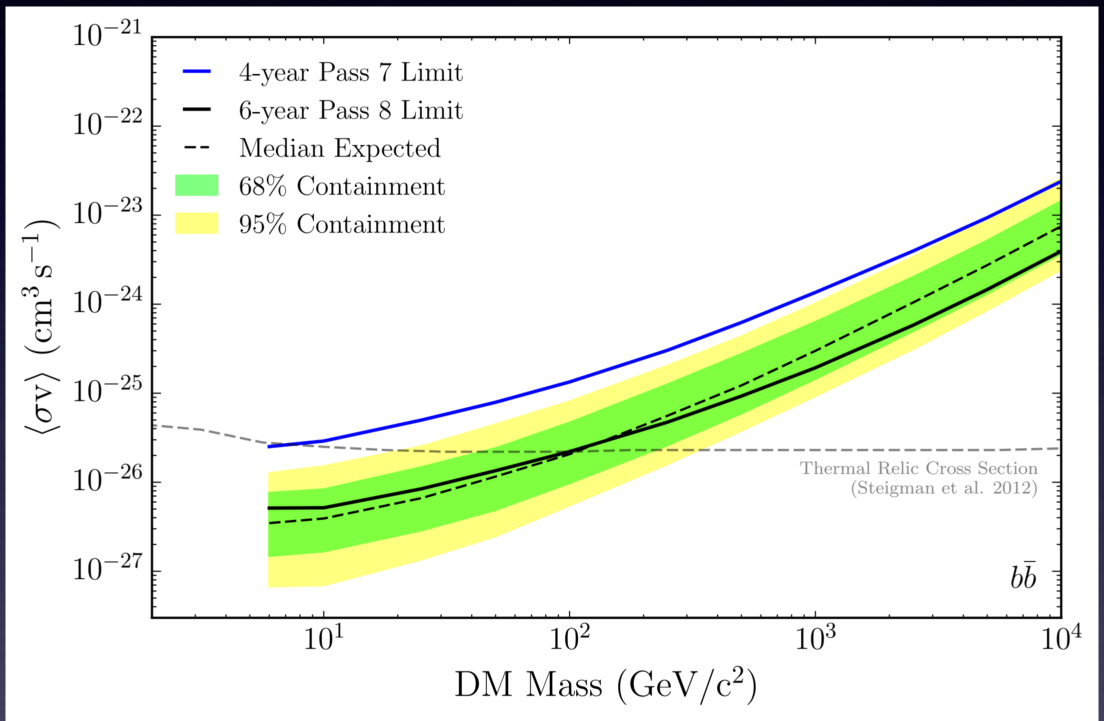

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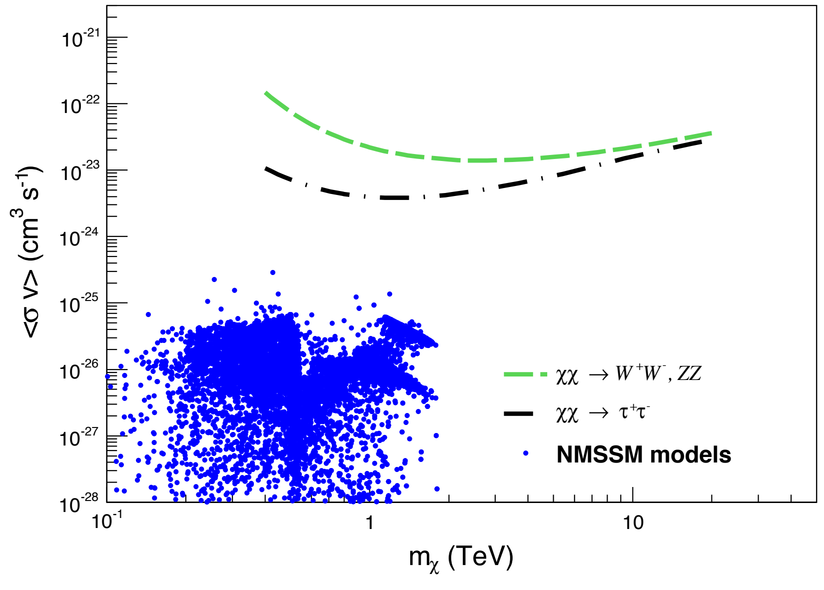

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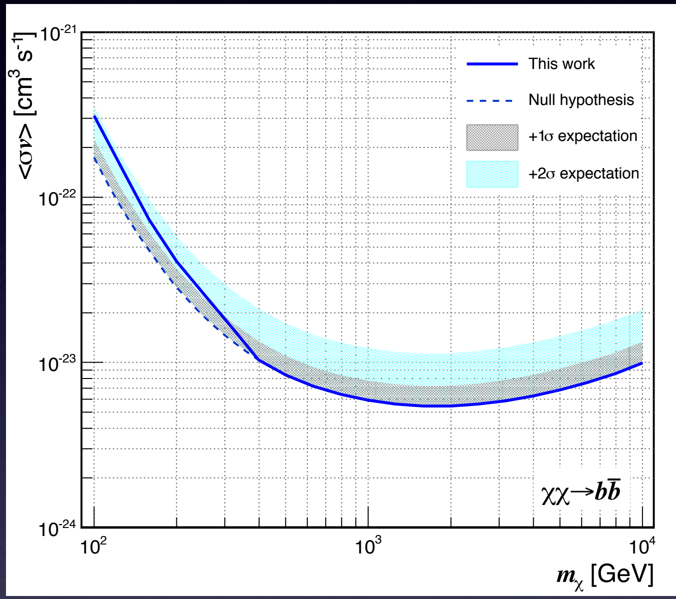
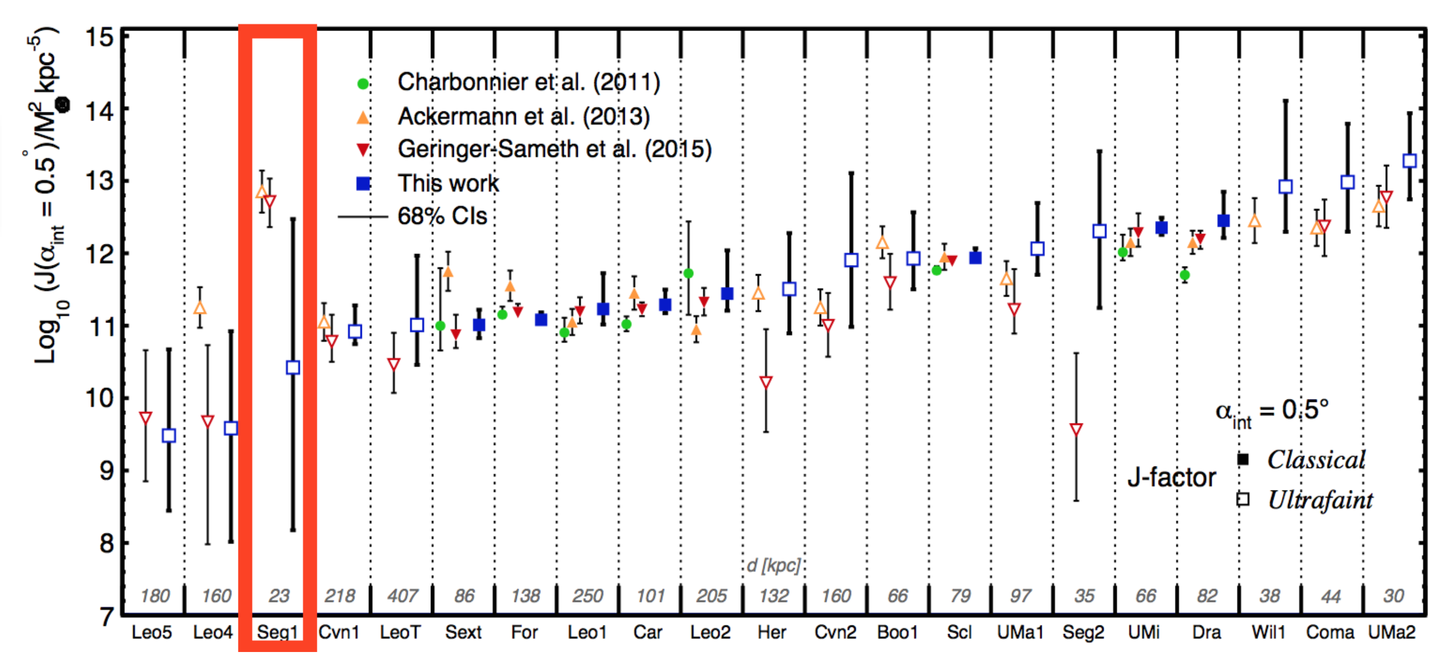


Beware of Uncertainties !!

K. Hayashi et al. - arXiv:1603.08046
P. Ullio & M. Valli - arXiv:1603.07721
N.W. Evans et al. - arXiv:1604.05599
A. Genina & M. Fairbairn - arXiv:1604.00838

dSphs are powerful

BUT !! we need more stellar tracers to control the uncertainties



Bonnivard et al 1504.02048

Bounds from continuum

Constraints from the GC by Cherenkov telescopes

Bounds from continuum

Constraints from the GC by Cherenkov telescopes

The DM profile must exhibit a spatial gradient between the ON & OFF regions

→ - we have to discriminate the DM continuum from the astro bkg.
- Cherenkov arrays are performant only if the DM profile is peaked

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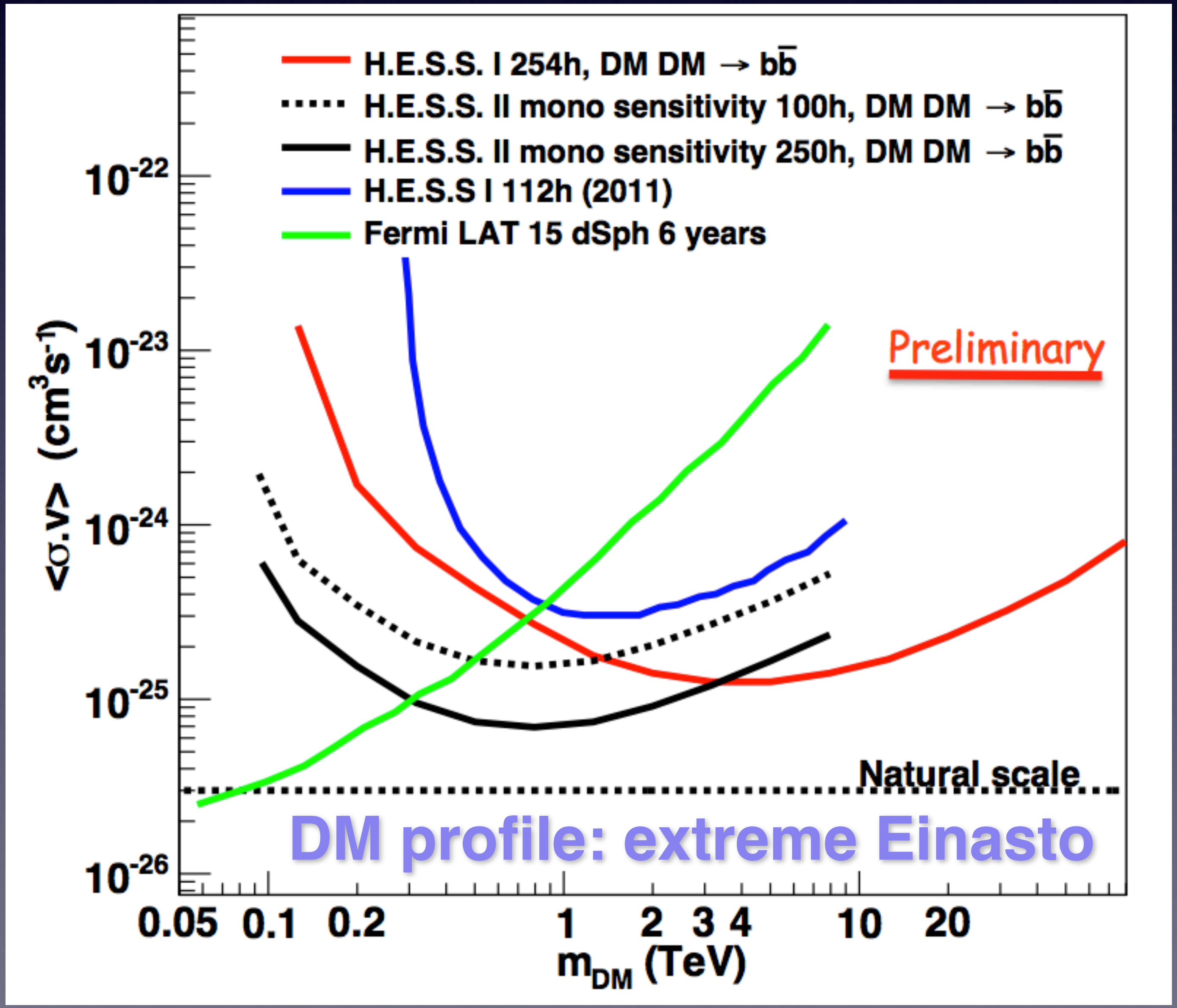
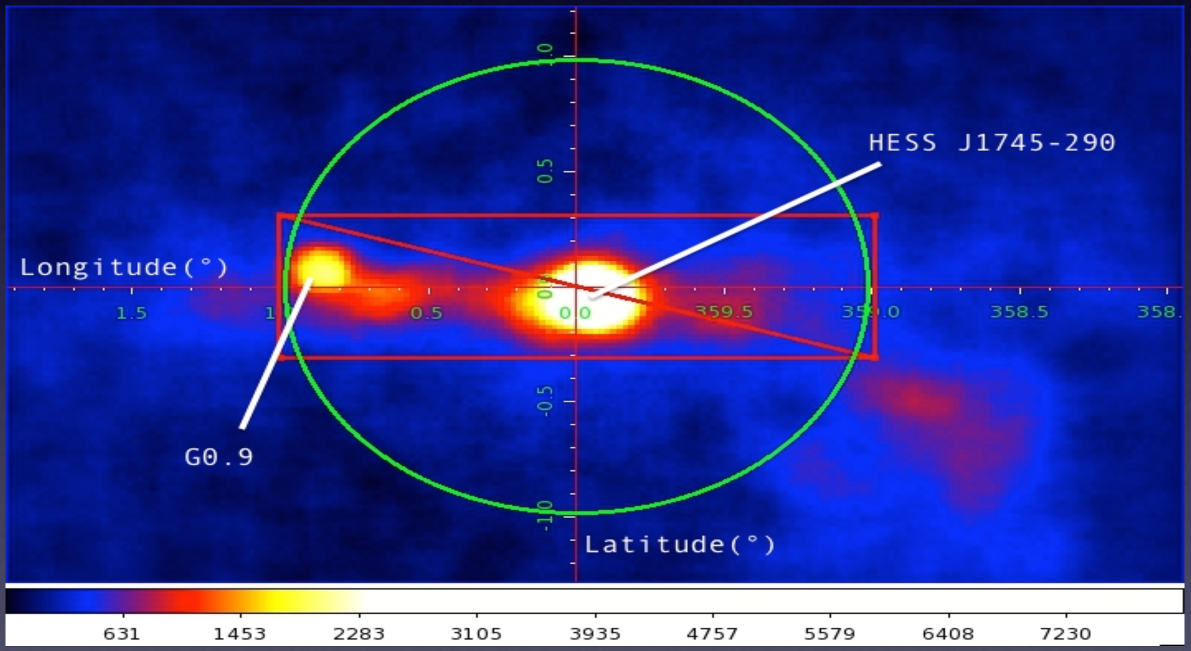


ROI: *annulus of 1 degree -> HUGE J-factor*



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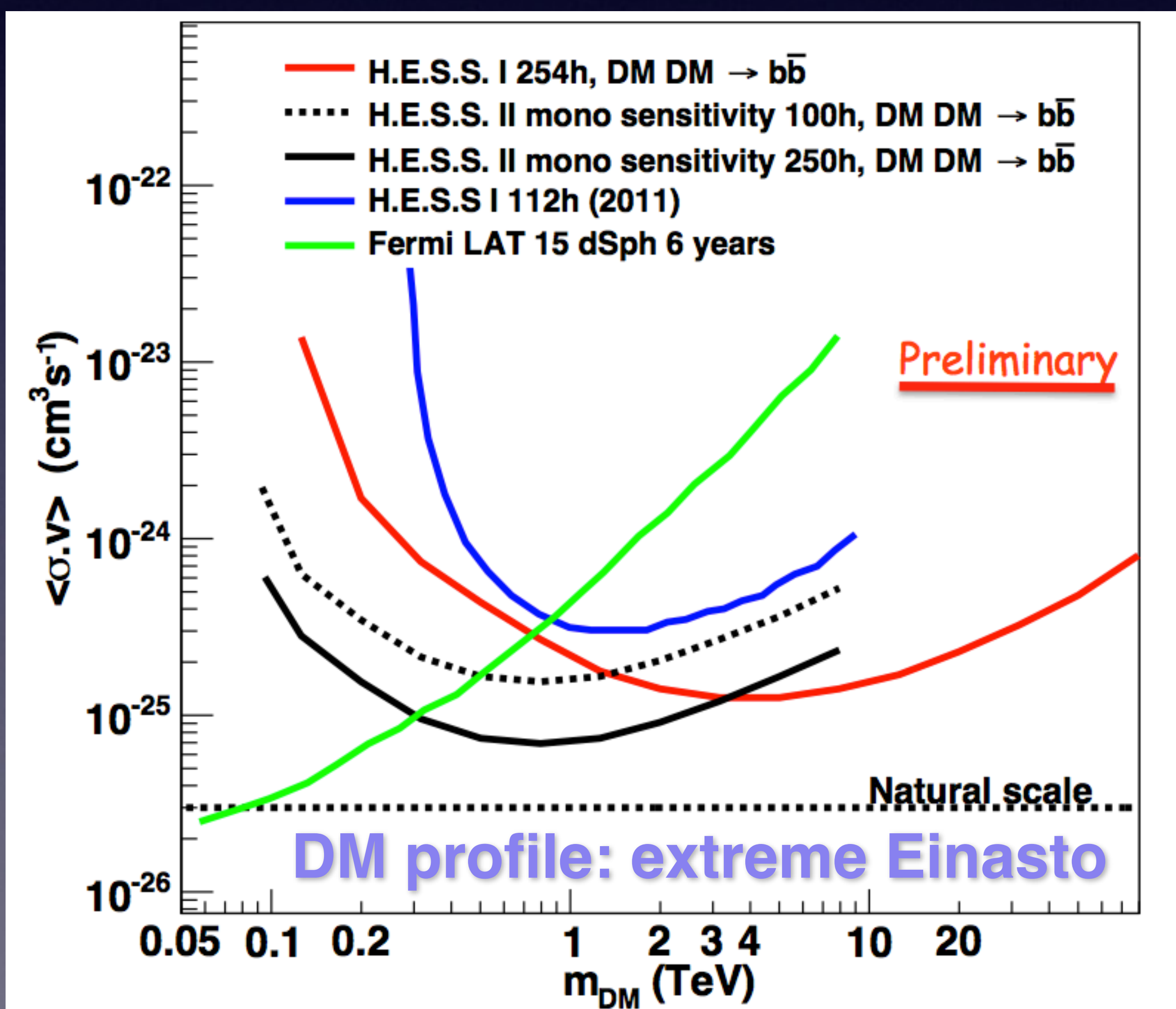

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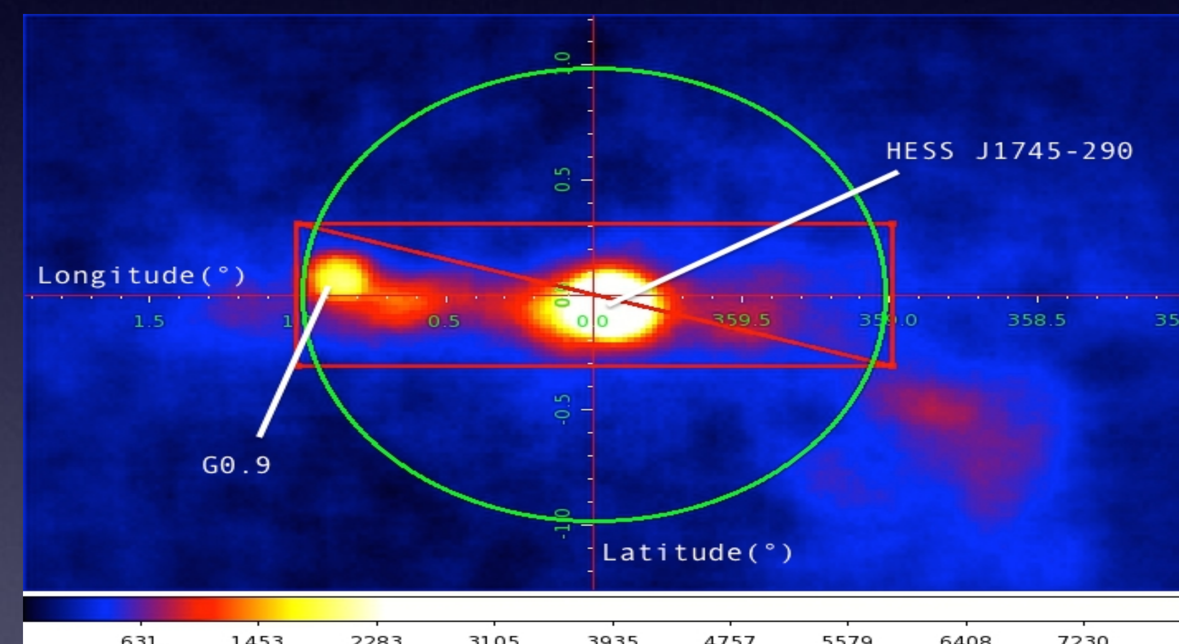

Use the GC with caution !!

The GC bounds:

- critically depend on the DM profile
- for cored profile (>1kpc) **NO** bound

Bounds from gamma lines

gamma ray lines are often considered as a smoking gun for DM

experiments looking for gamma ray lines need →

- good energy resolution
- high energy thresholds

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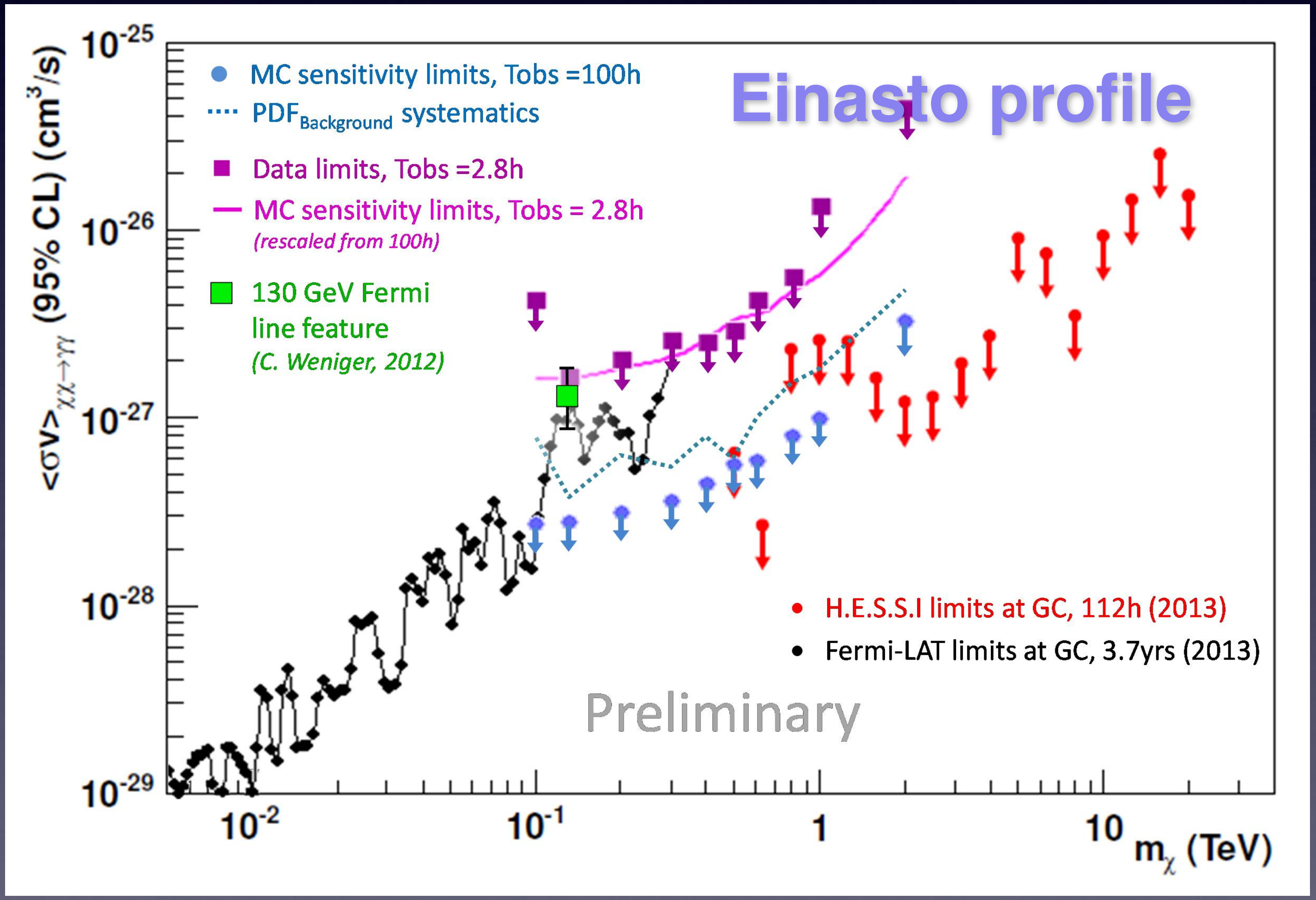
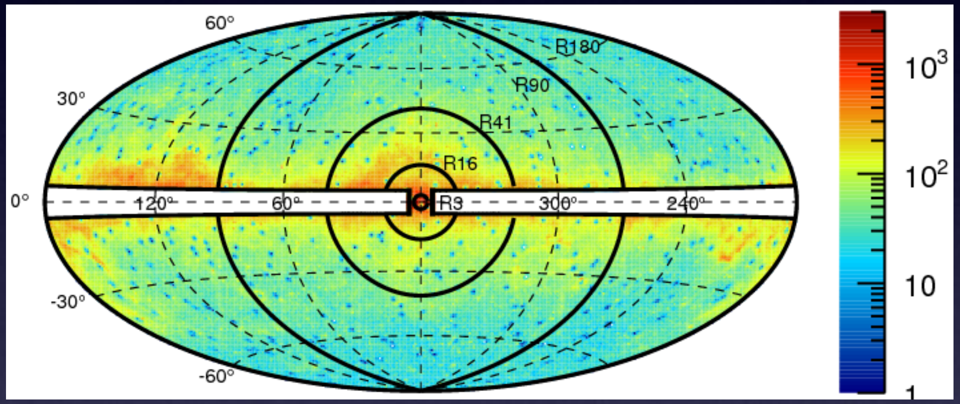


FERMI RoI: *depends on the DM profile*



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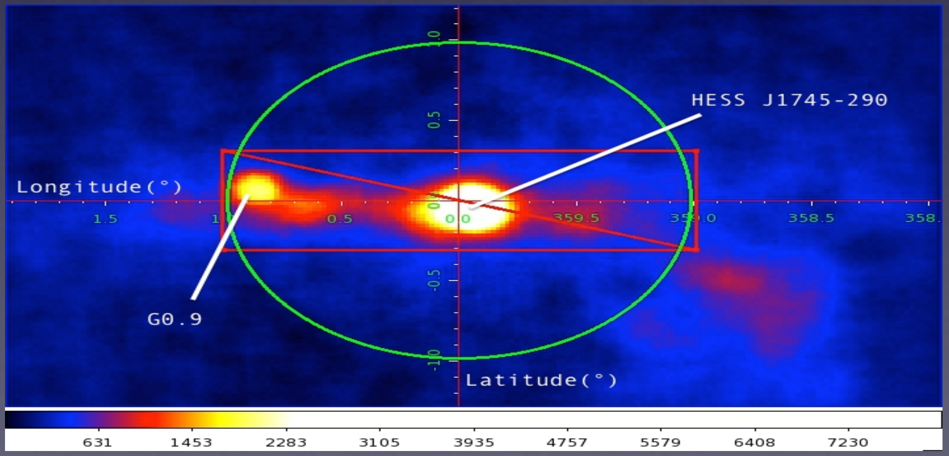

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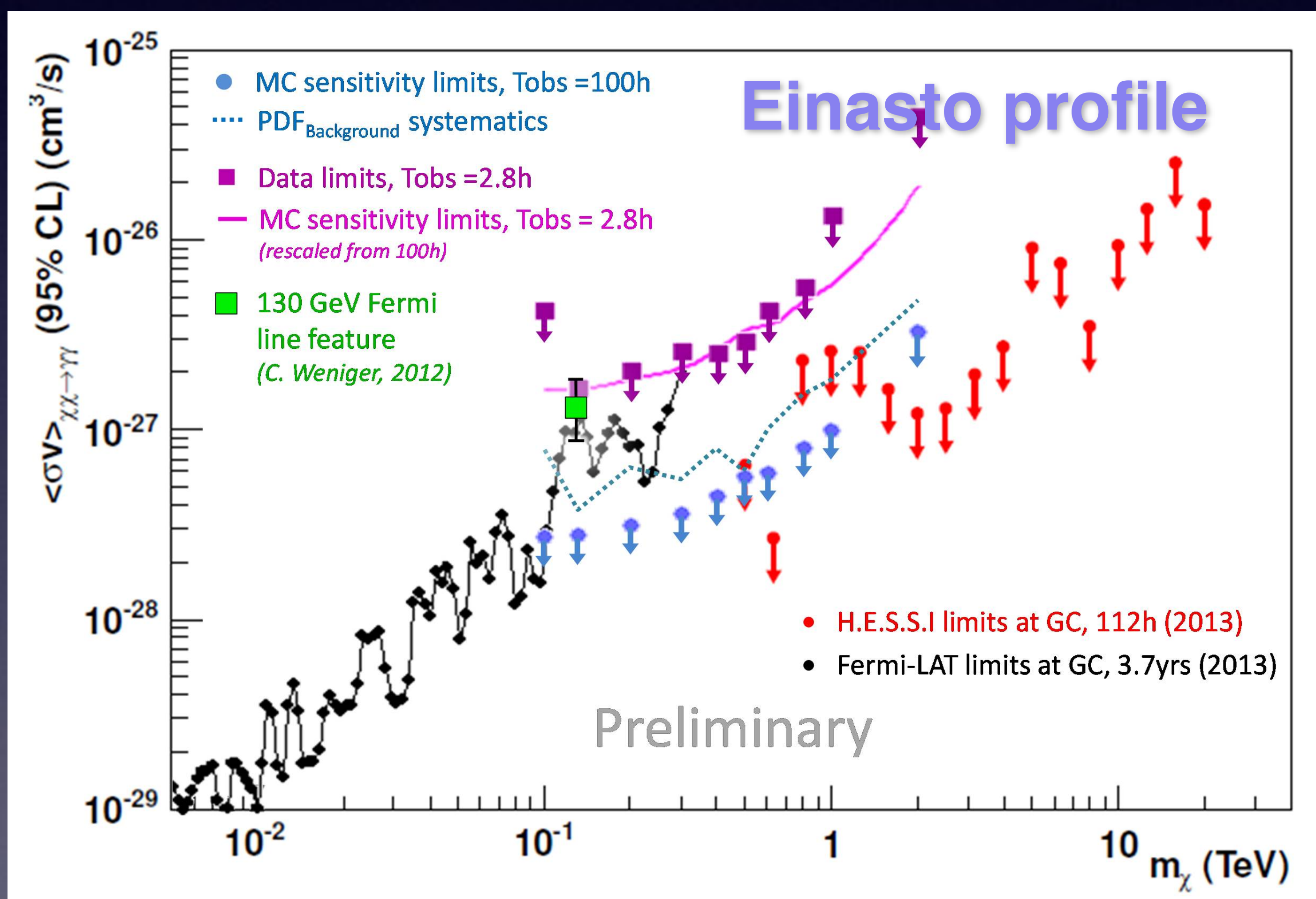
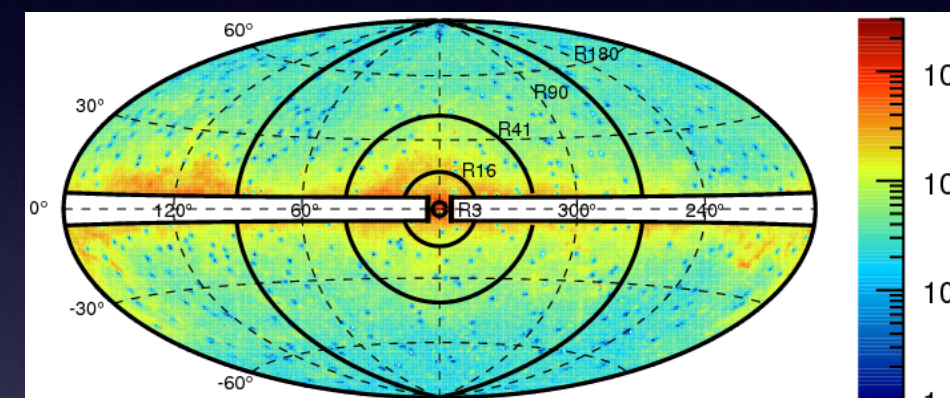


FERMI RoI: *depends on the DM profile*



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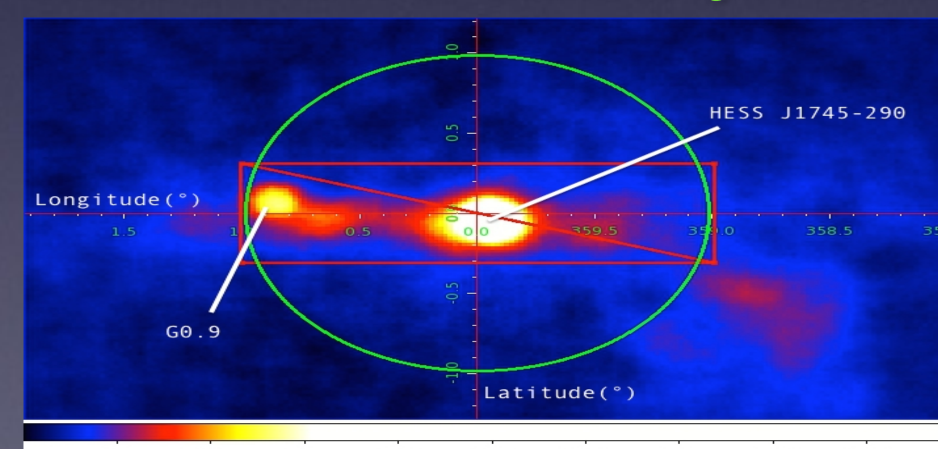

The bounds from the GC depend on the DM profile !!

FERMI: full sky detector -> we can optimise the RoI for different DM profile

HESS: limited foV -> the bounds from the GC critically depend on the profile

CTA Sensitivity for lines

Gamma-ray lines searches towards dSphs by Cherenkov array is important

- the uncertainties on the *J*-factors towards dSphs are smaller than in the GC
- well motivated models with EW interactions predict large XS in lines due to NP Sommerfeld corrections

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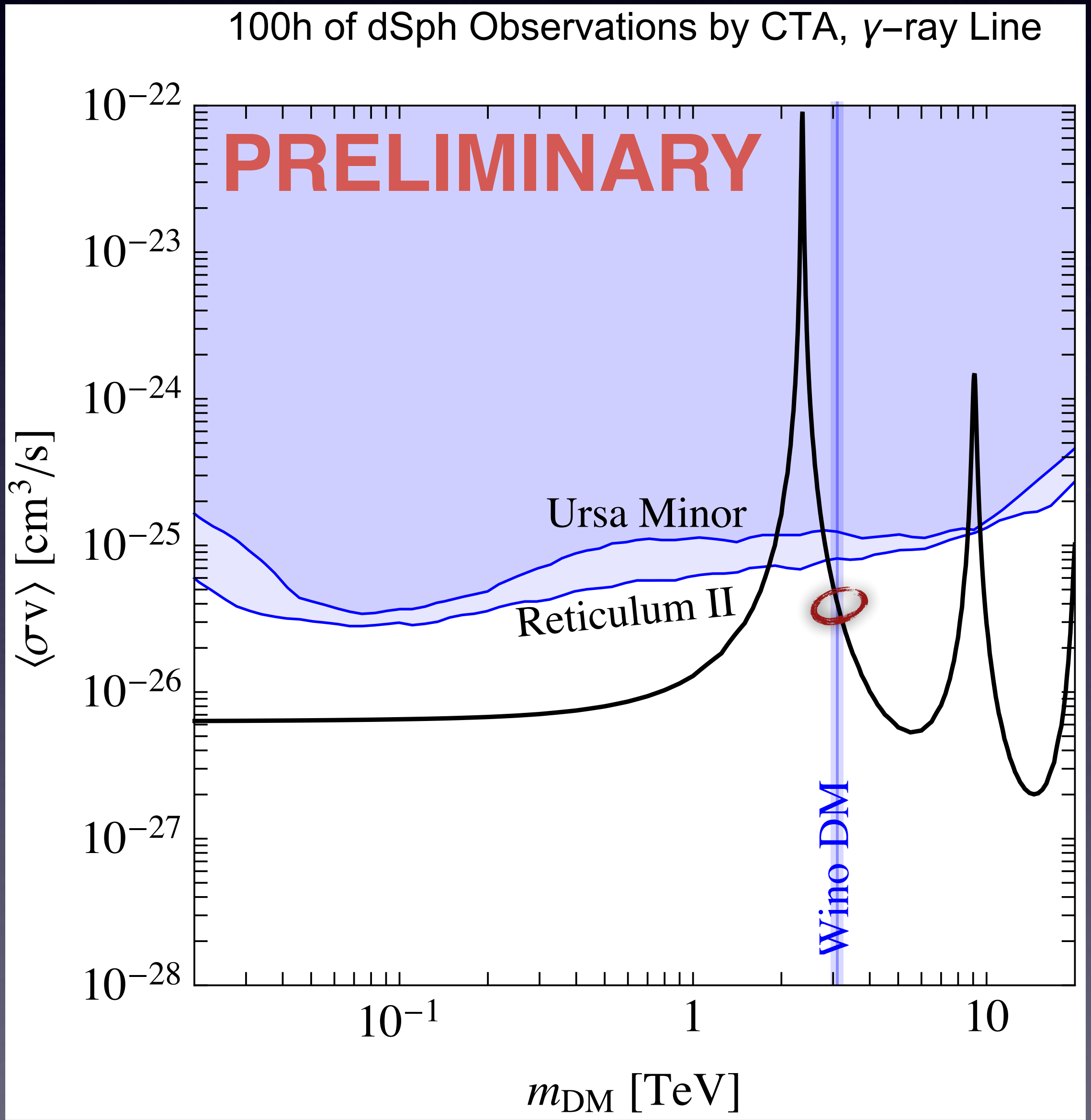

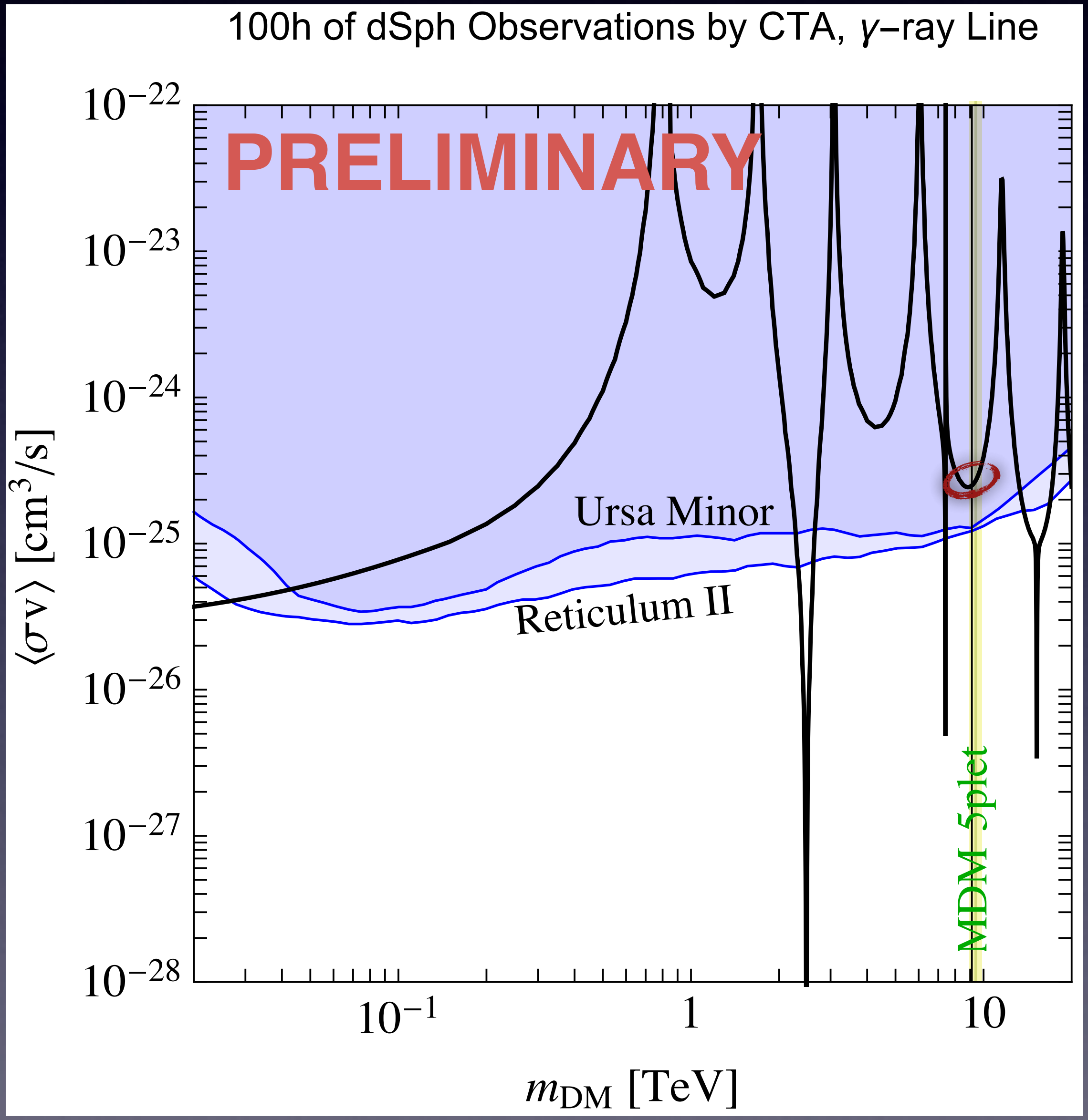

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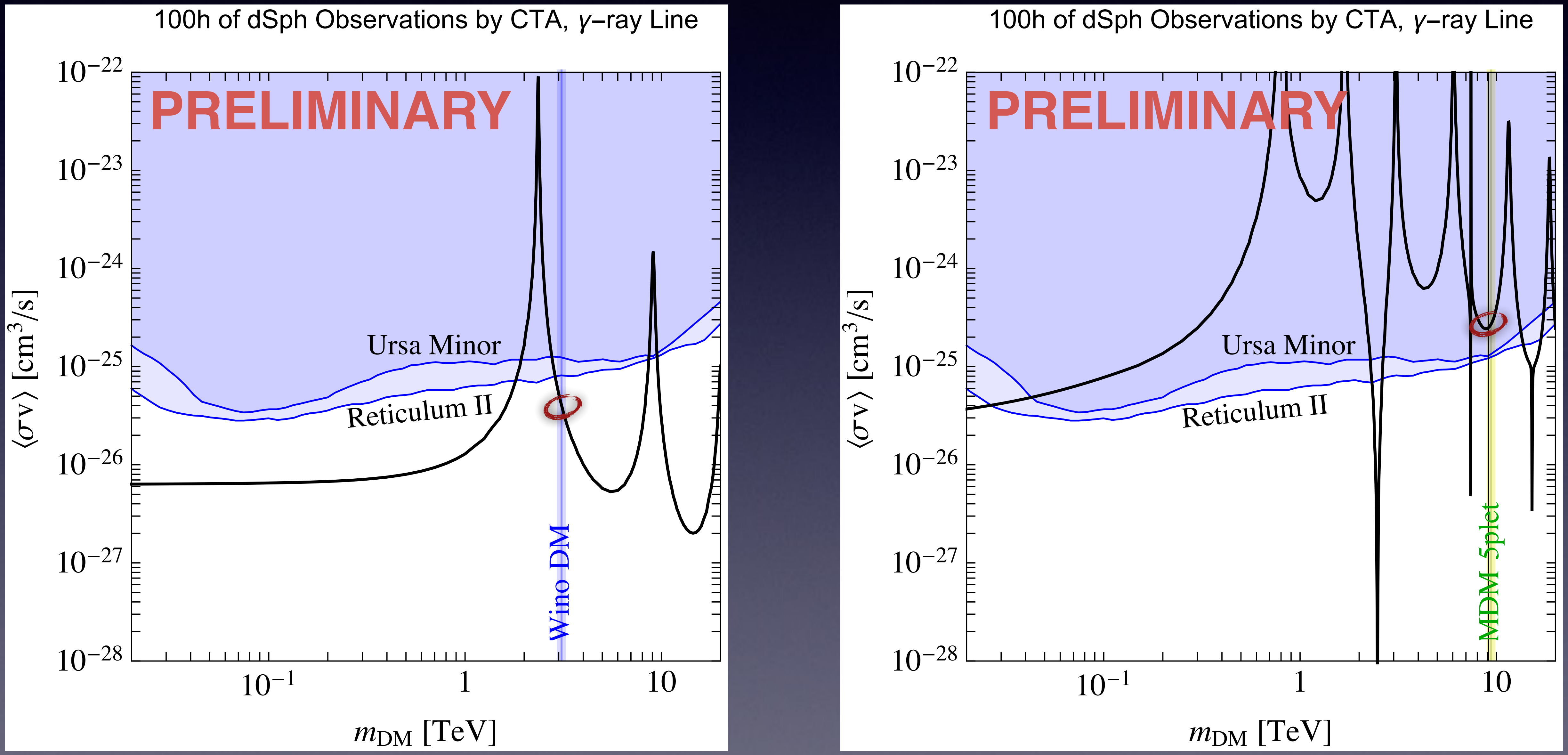


Bottom Line: with 100h of observations towards Reticulum II by CTA the parameter space of well motivated EW multiplets can be probed

Summary

Constraints	Channel	DM mass	Robustness
AMS-02 anti-proton	mostly hadronic	light (tens of GeV)	weak (dependence on the prop. parameters)
γ-ray continuum			
diffuse emission by FERMI	hadronic & leptonic	light (tens of GeV)	solid (light dependence on DM profiles)
dSph galaxies by FERMI & Cherenkov tel.	hadronic & leptonic	light (tens of GeV)	mild (uncertainties on the *J*-factors from dSphs)
GC observation by Cherenkov tel.	hadronic & leptonic	heavy (few TeV)	very weak (critically dependence on profiles)
γ-ray lines			
Galactic halo by FERMI	hadronic & leptonic	< 500 GeV	mild (dependence on the DM profiles)
GC observation by Cherenkov tel.	hadronic & leptonic	> 500 GeV	very weak (critically dependence on profiles)
dSph galaxies by Cherenkov tel.	hadronic & leptonic	> 500 GeV	mild (uncertainties on the *J*-factors from dSphs)

Back up slides

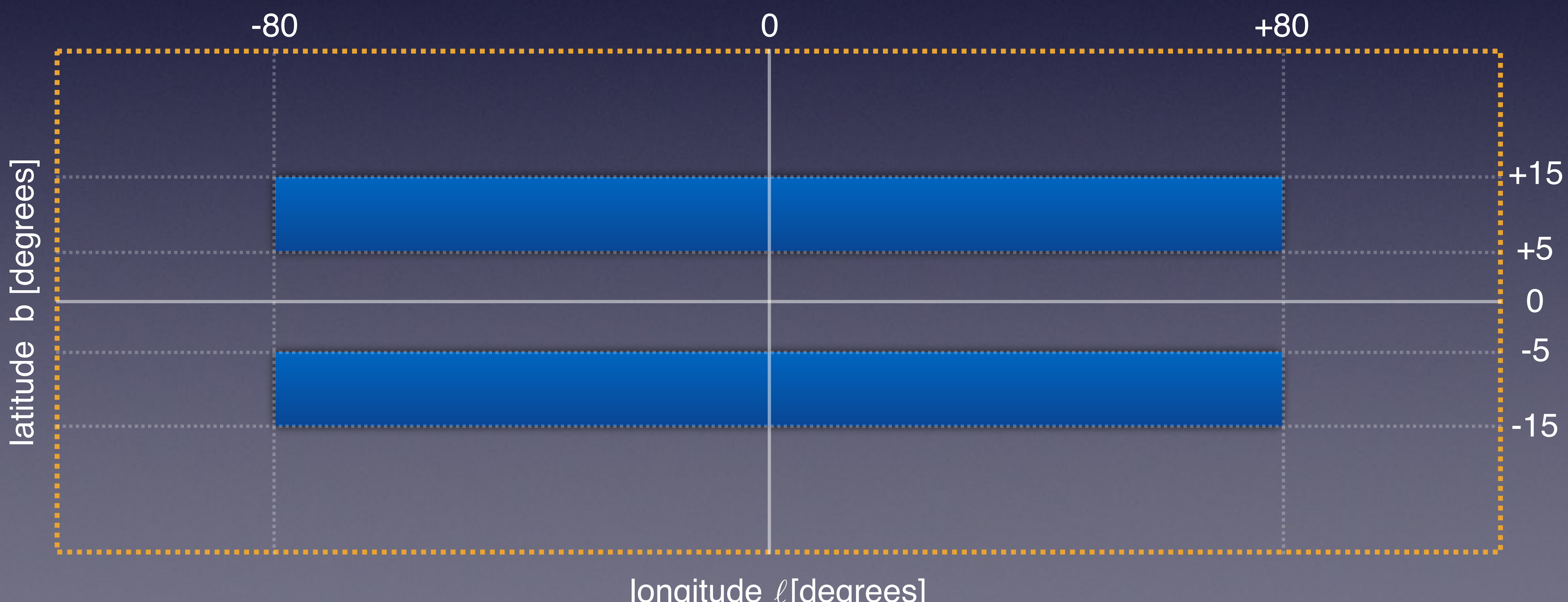
Bounds from continuum

Constraints from the measurement of the Gal. diffuse emission

- ✓ divide the gamma sky in non-overlapping regions
- ✓ in each region, model the diffuse bkg. considering several components:

  i) a template for the Gal. diffuse emission produced by charged CR
  ii) a template for point-like sources
  iii) a template for the so-called “Fermi bubbles”
  iv) the isotropic γ-ray bkg.

- ✓ For DM ann. the best sensitivity is obtained in this ROI:



Bounds from continuum

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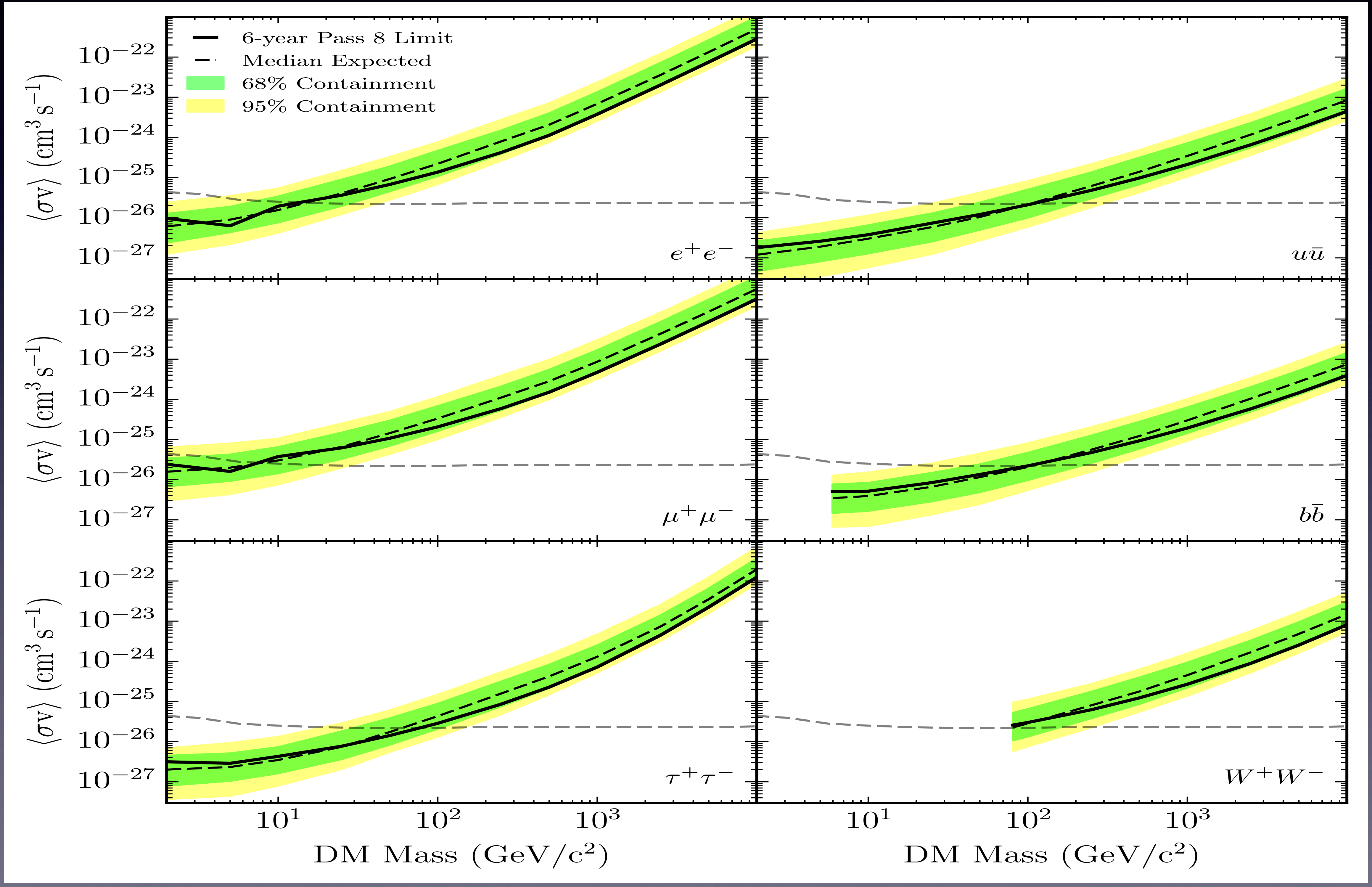
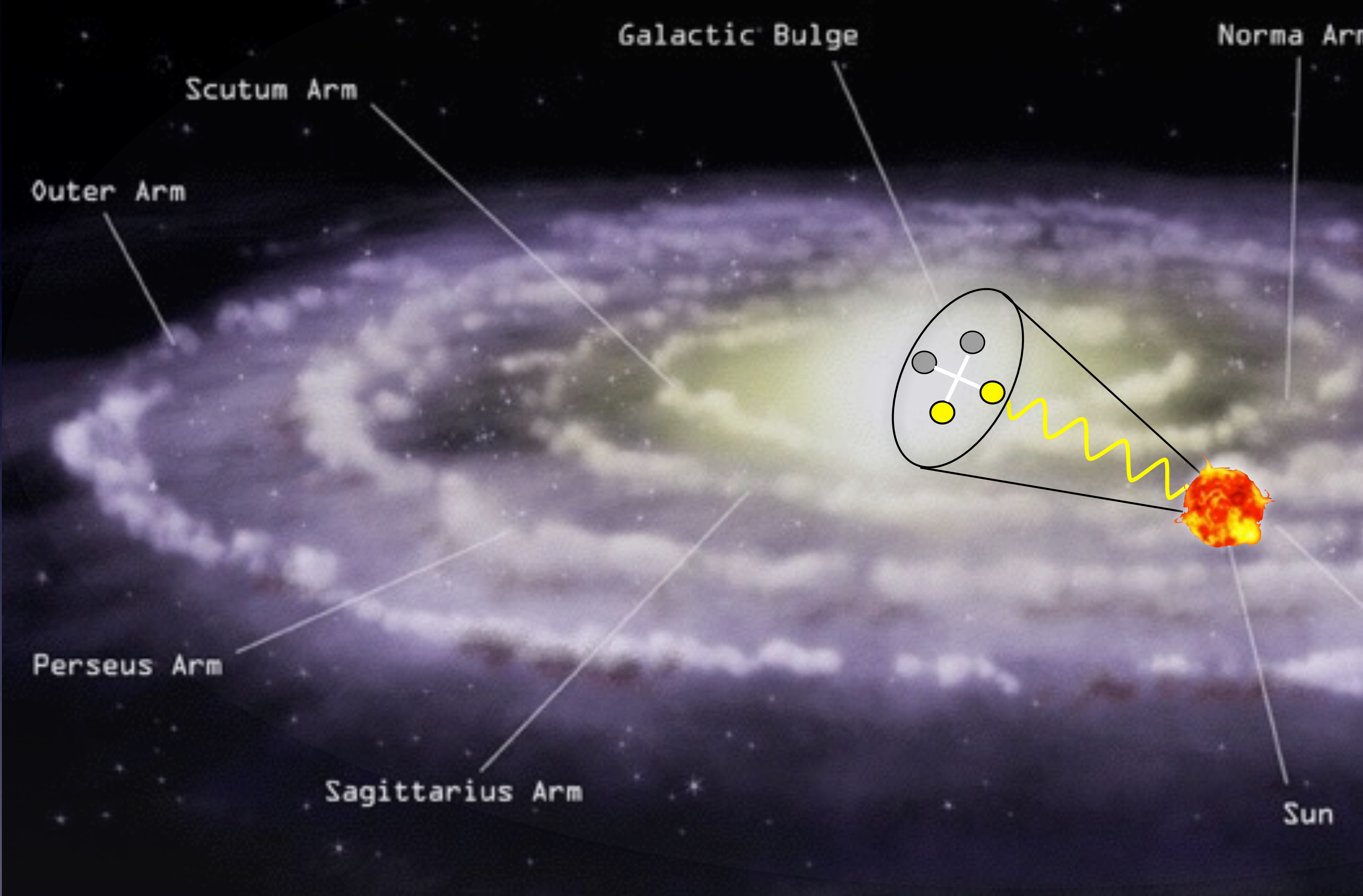


Indirect Detection: Overview

γ from annihilating/decaying DM in dense regions

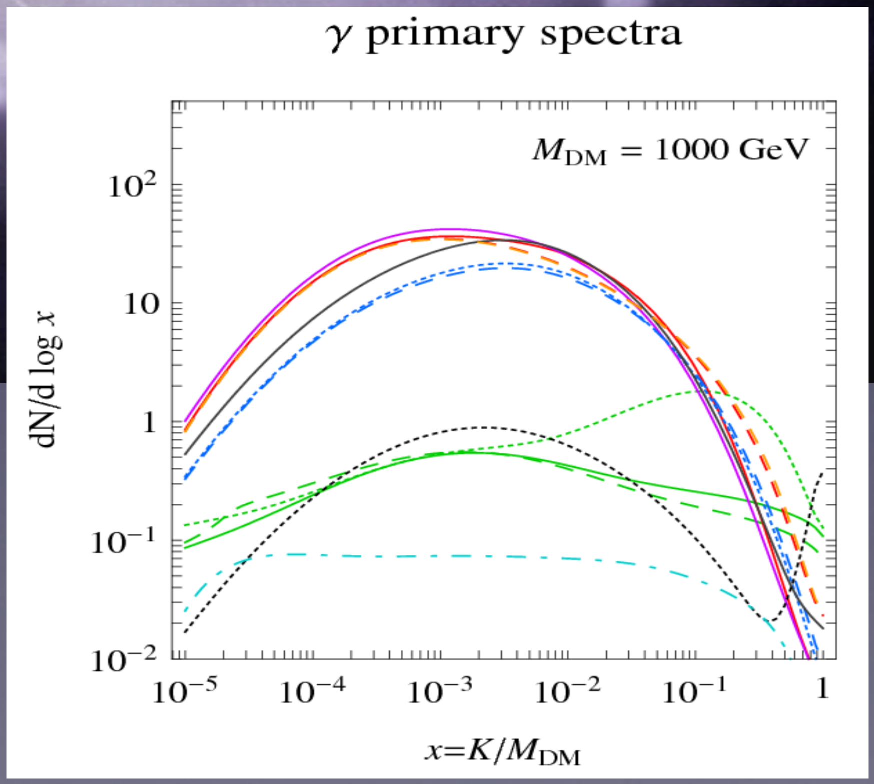


DM, DM → BSM

$W^-, b, t, \mu^-, \tau^-, h... \longrightarrow e^\mp, p, d, \nu...$ and γ

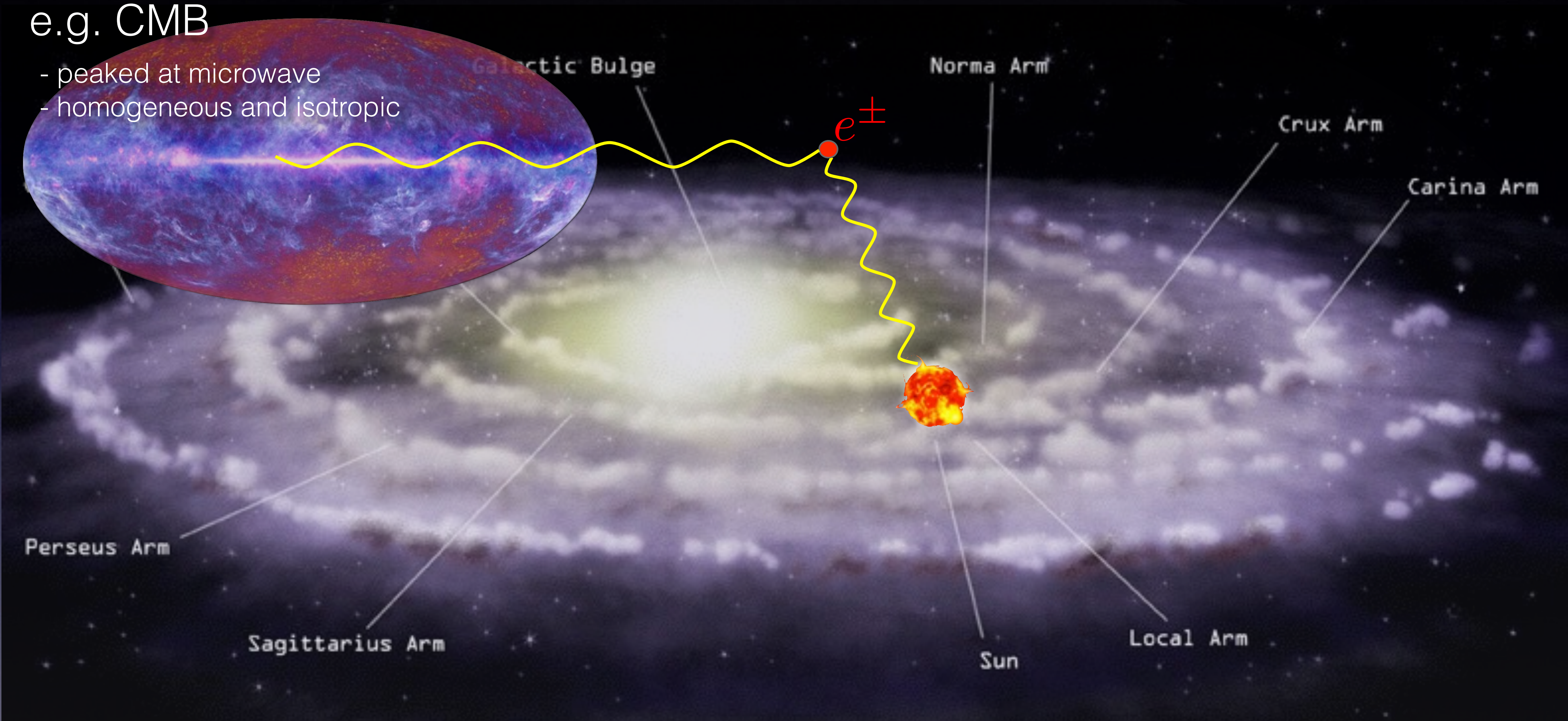
$W^+, \bar{b}, \bar{t}, \mu^+, \tau^+, h... \longrightarrow e^\pm, p, d, \nu...$ and γ

typically sub-TeV energies



Indirect Detection: Overview

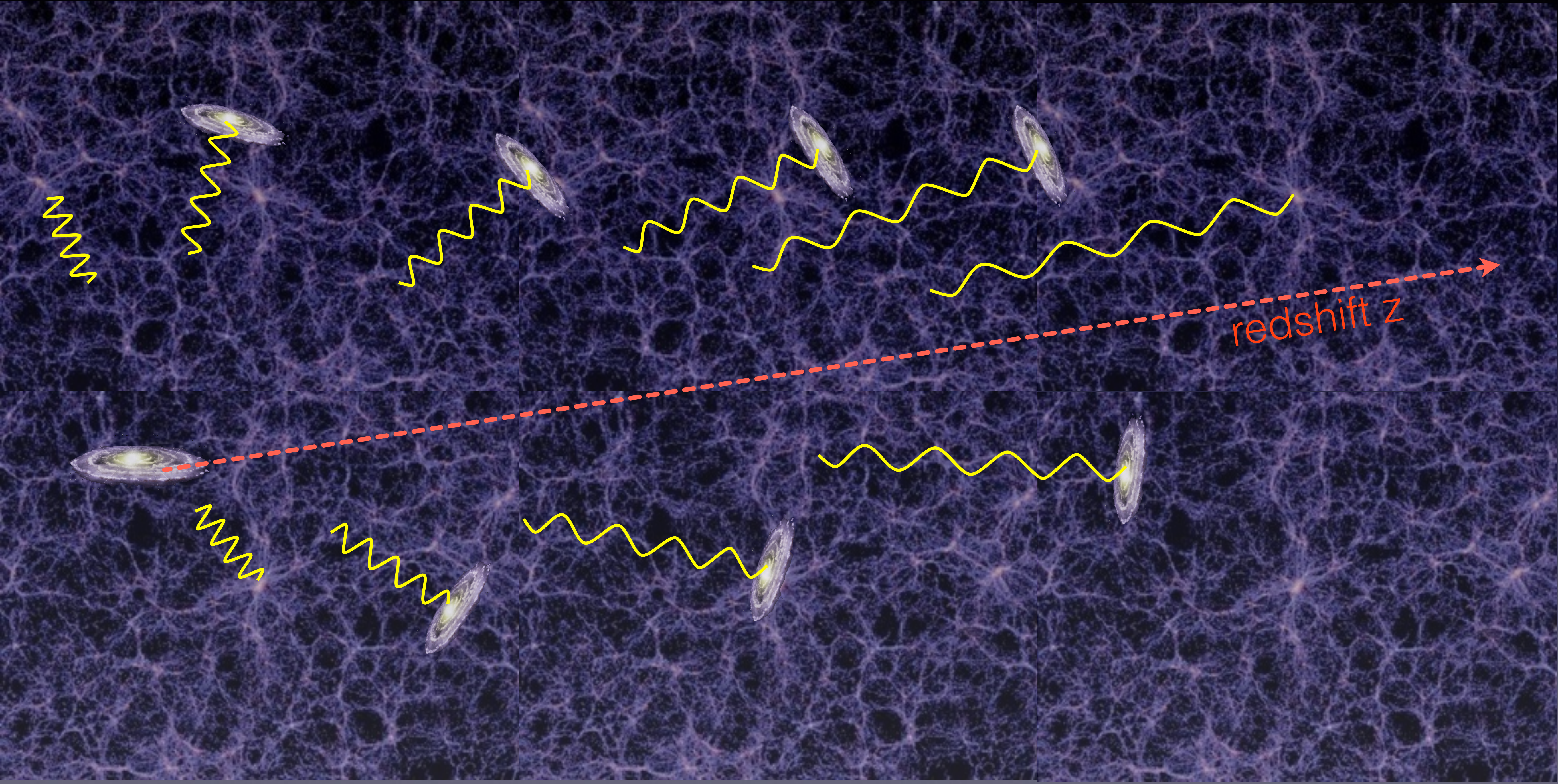
γ from Inverse Compton on $e^{\pm}$ in halo



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

Indirect Detection: Overview

γ from outside the Milky Way



- isotropic flux of 'prompt' and IC gamma-rays, integrated over z and r
- for ann. DM, depends strongly on halo formation details and history

PPPC 4DM ID: Tools

Indirect detection of DM particles:

Tools for computing the main signatures of TeV-scale DM annihilations or decays in our Galaxy and beyond

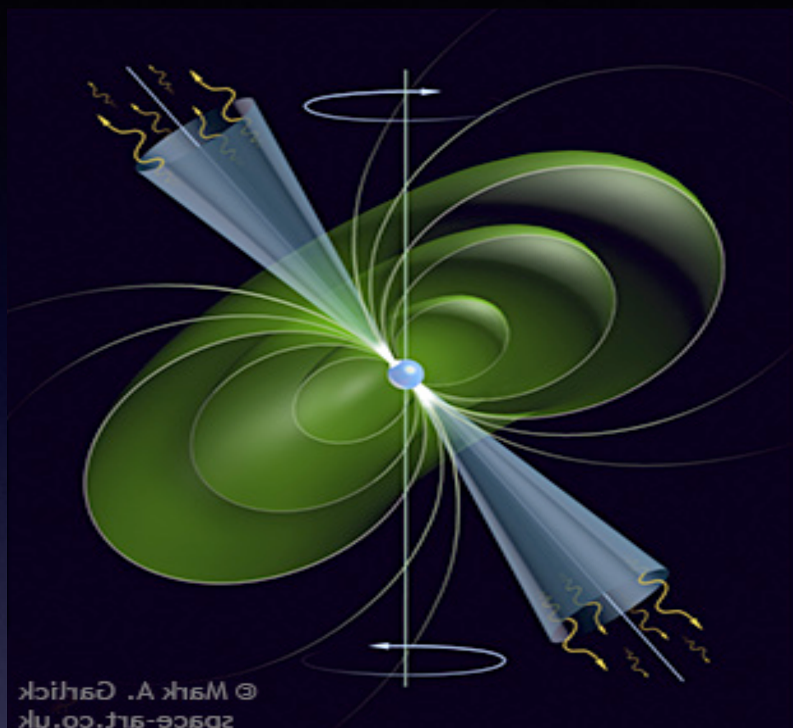
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for DM Indirect Detection", JCAP 1103 (2011) **051**

The tools & Receipts that we provided in numerical form are:

- ✔ The primary fluxes of stable SM products in a large range of DM masses considering a DM ann./dec. into the main SM primary channels
- ✔ The energy losses coefficient of $e^{\pm}$ due to Inverse Compton scattering and Synchroton emission everywhere in the Galaxy
- ✔ The propagation functions for $e^{\pm}$ in a large range of $e^{\pm}$ injection energy for different choices of DM distribution and propagation parameters
- ✔ The propagation functions for antiproton at Earth considering as above several choices of DM parameters
- ✔ The fluxes of $e^{\pm}$ and $\bar{p}$ at Earth after propagation by using the propagation functions for charged particles above
- ✔ The gamma rays fluxes, both from prompt and Inverse Compton scattering emissions in the galactic halo and beyond

Astrophysical Explanation?

The raise of the positrons fraction is produced by a young, nearby pulsar…



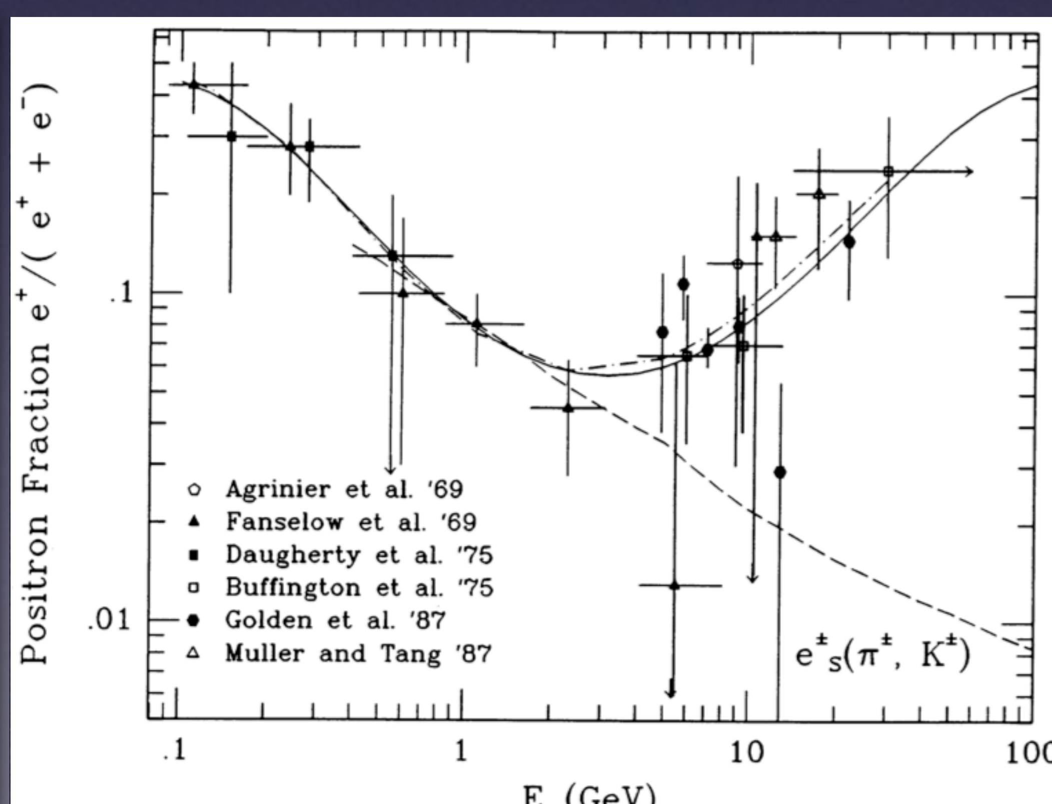
Mechanism: the spinning $\vec{B}$ of the pulsar strips e^- that emit γ
the γ make production of $e^\pm$ that are trapped in the cloud
further acceleration and later released at $\tau_{\rm rel} \sim 0 \to 10^5$ yrs

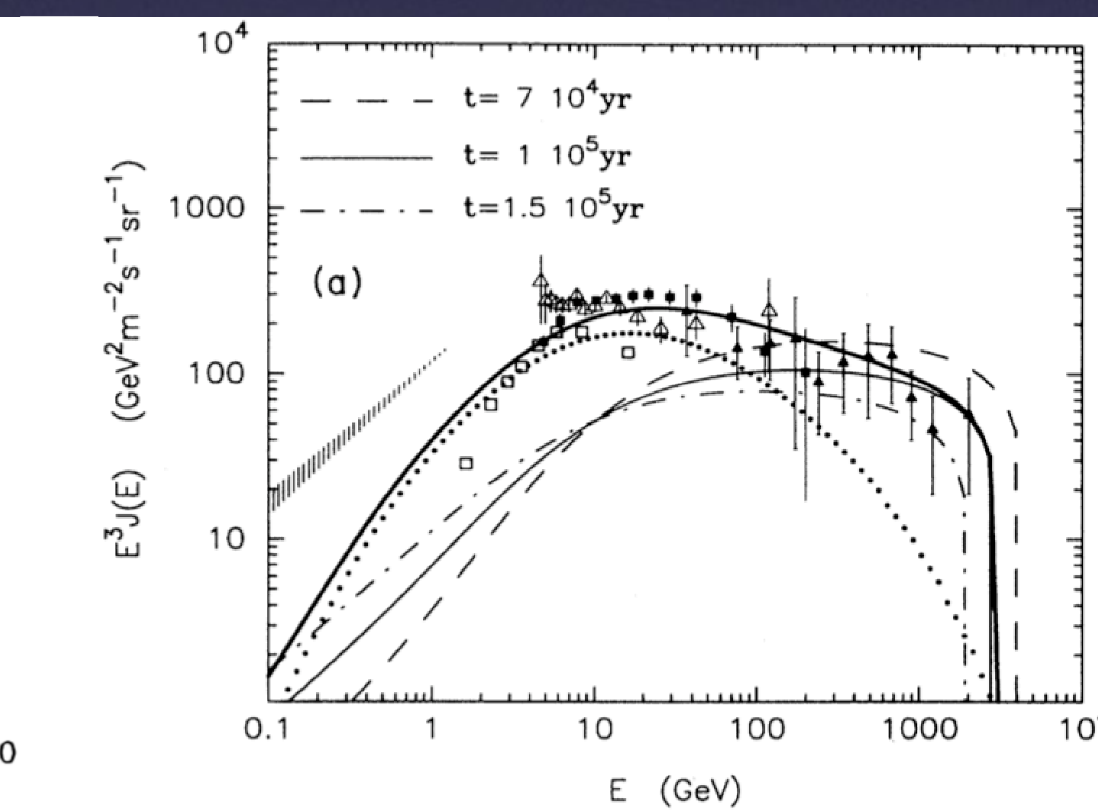
The pulsar must be young ($< 10^5$ yrs) and nearby ($<$ 1 kpc)
If not: too much diffusion, too low flux, low energy

Predicted flux: $\Phi_{e_\pm} \propto E_{e^\pm}^{-p} \exp\left(E_{e^\pm}/E_c\right)$ with $p = 2$
and $E_c \sim {\rm TeV}$

Old idea:

see e.g.: A. Boulares, ",Astrophys.J 342 (1989)

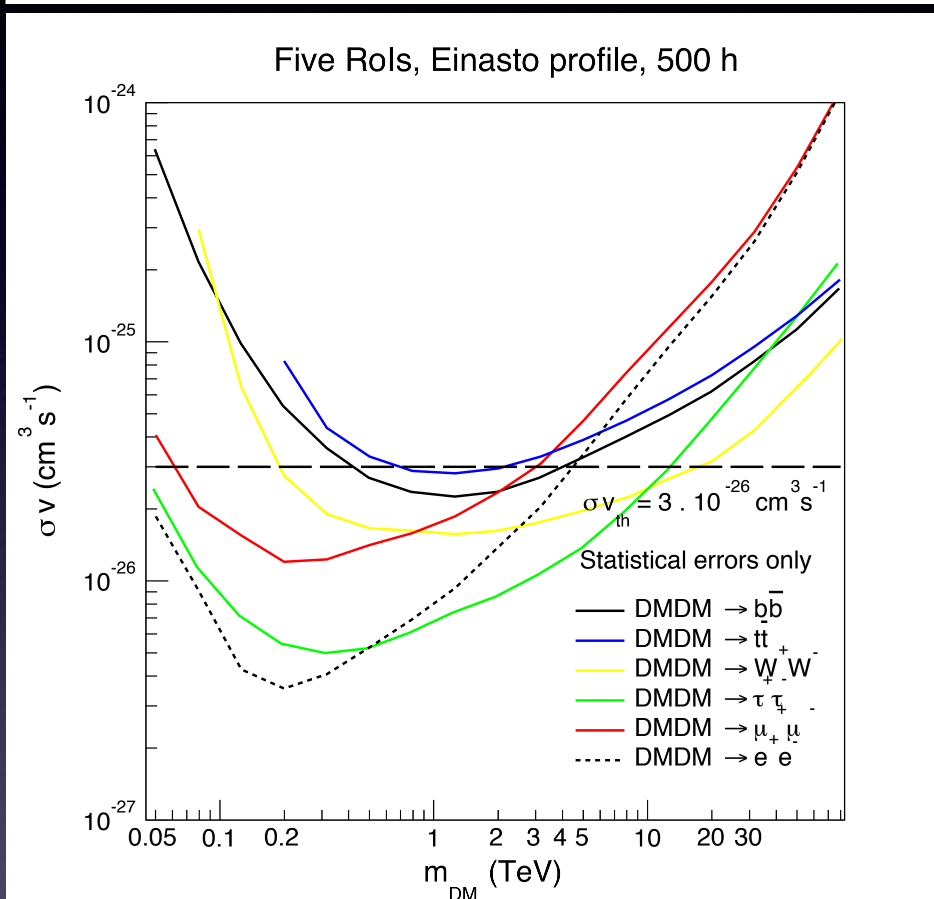


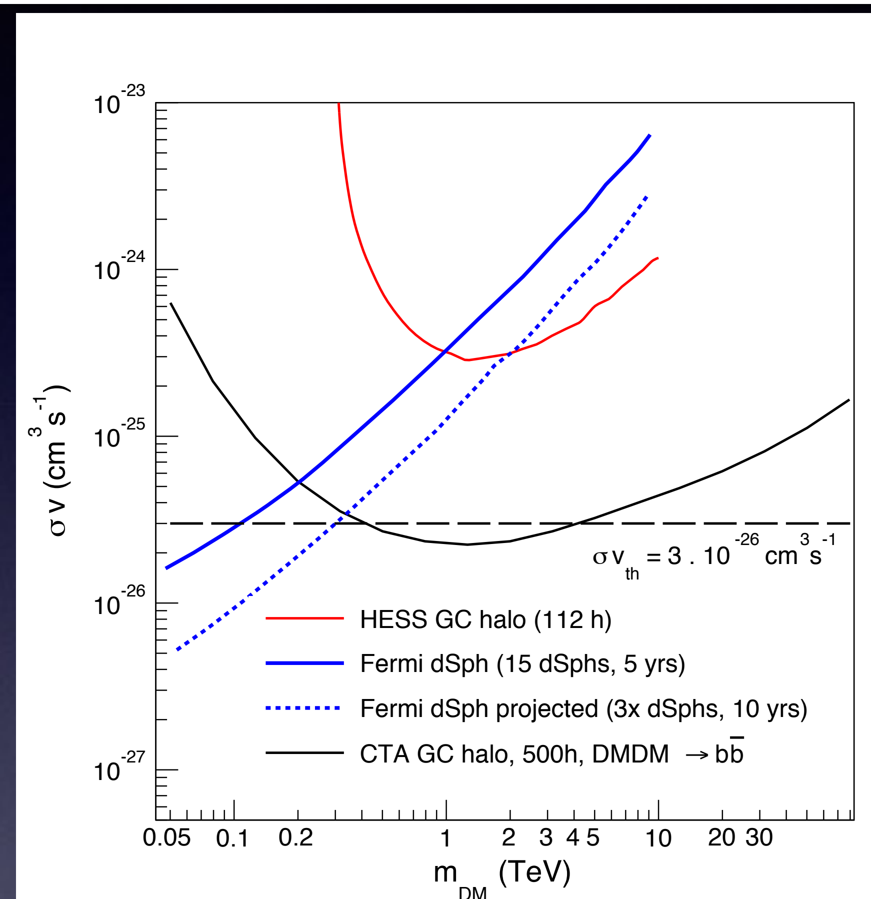


Prospects for CTA

Assessment of the CTA sensitivity for annihilating DM in the Galactic Center

"Prospects for annihilating DM in the inner Galactic halo by the Cherenkov Telescope Array", arXiv:1502.05064





The CTA constraints in the Galactic center apply only for cuspy DM profiles

Fermi & CTA will be able to survey thermal DM in a broad range of masses

Assessment of the CTA sensitivity for annihilating DM in dwarf galaxies

"Prospects for annihilating DM in dwarf Galaxy by the Cherenkov Telescope Array", In preparation

sensitive for cored profiles as well

Assessment of the CTA sensitivity for decaying DM in galaxy-clusters

"Prospects for decaying DM in galaxy-clusters by the Cherenkov Telescope Array", In preparation

sensitive for decaying DM as well

End