Theory

Sub-GeV DM?

- WIMPless Dark Matter
- 'SIMP miracle'
- Asymmetric DM
- 'MeV (scalar) DM' (Integral 511 KeV excess)
- 'simplified (light) DM models'
- ...

Asymmetric DM: a completely different relic

Consider a particle χ:

- subject to $\chi\bar{\chi} \rightarrow \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- Asymmetric abundance
- large annihilation cross sec

Like baryonic matter!

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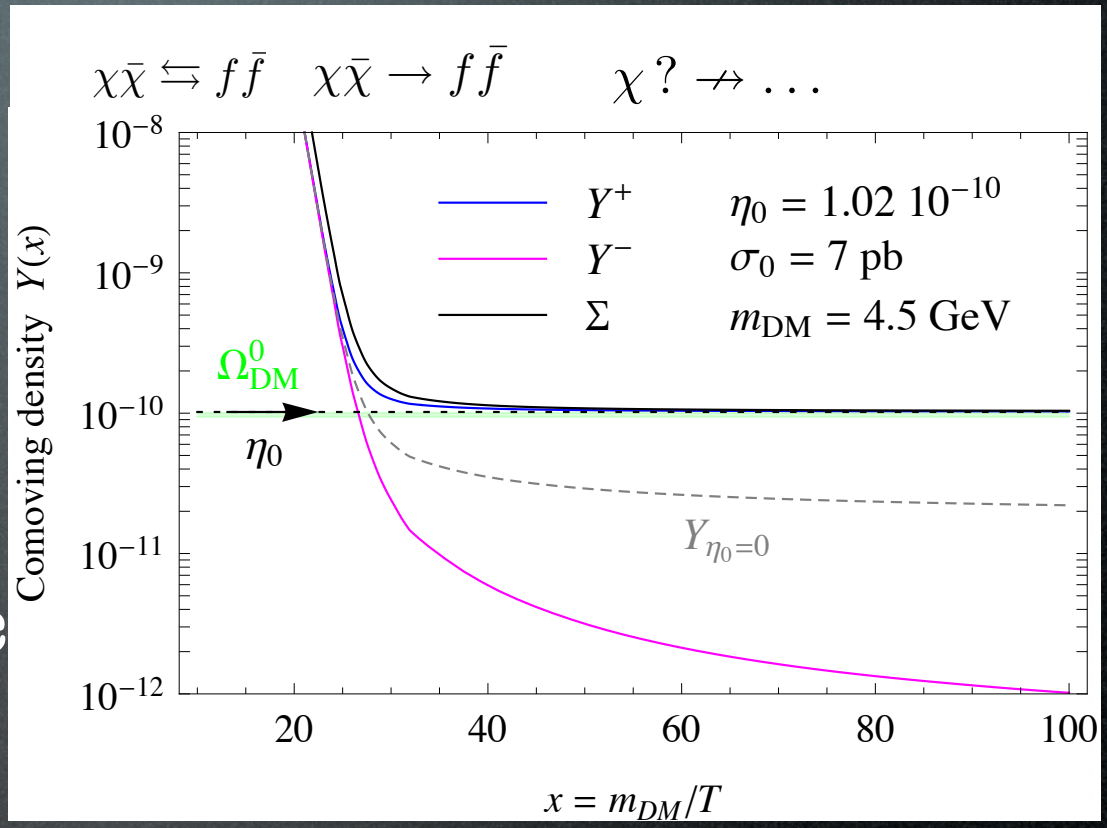

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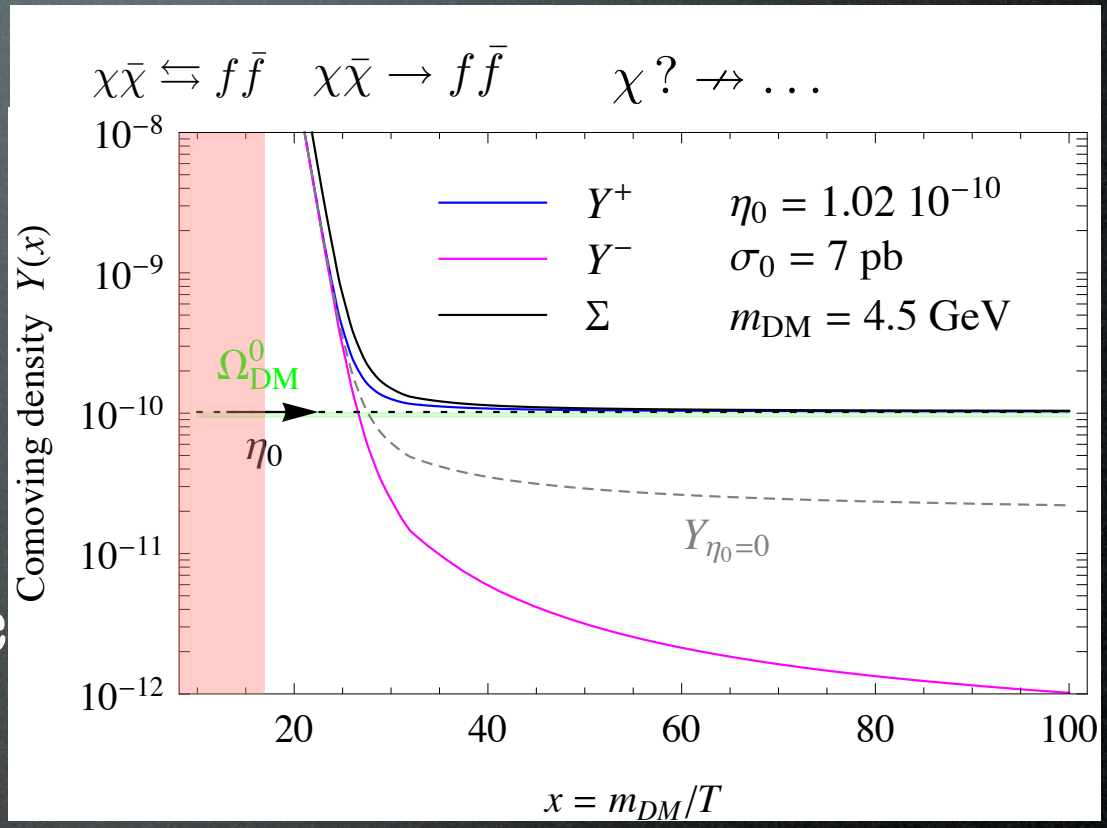

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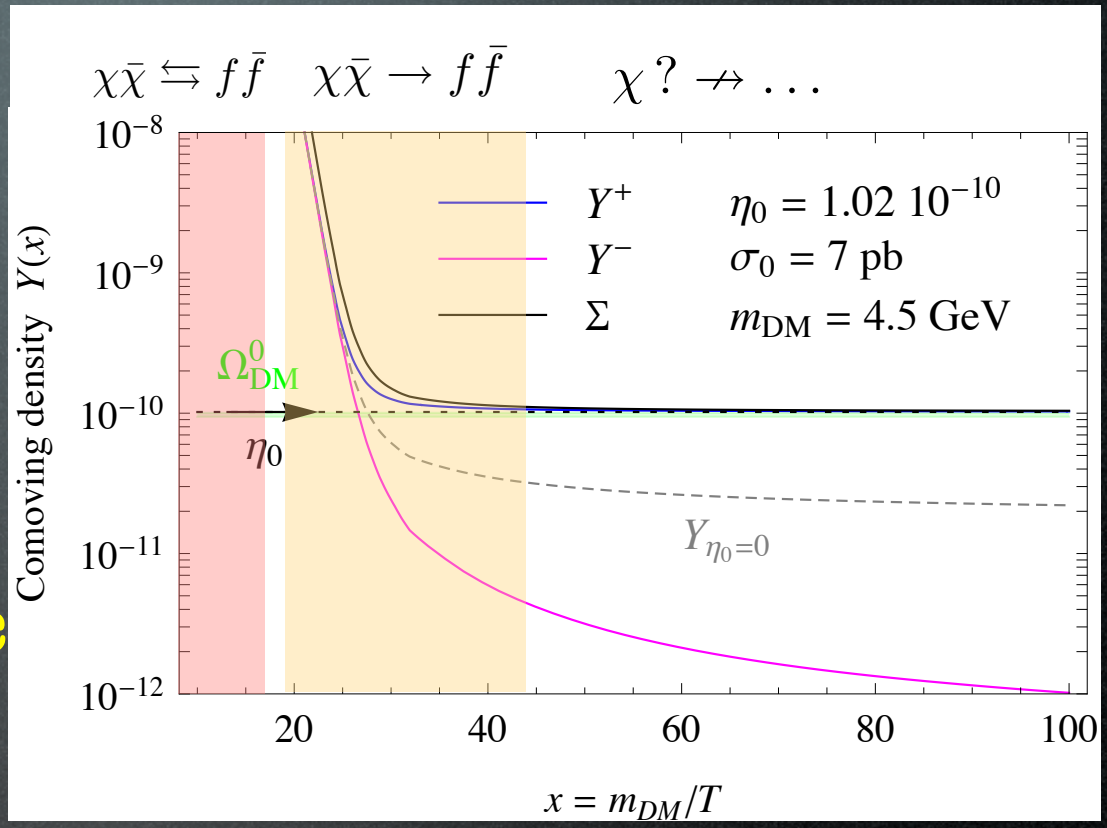

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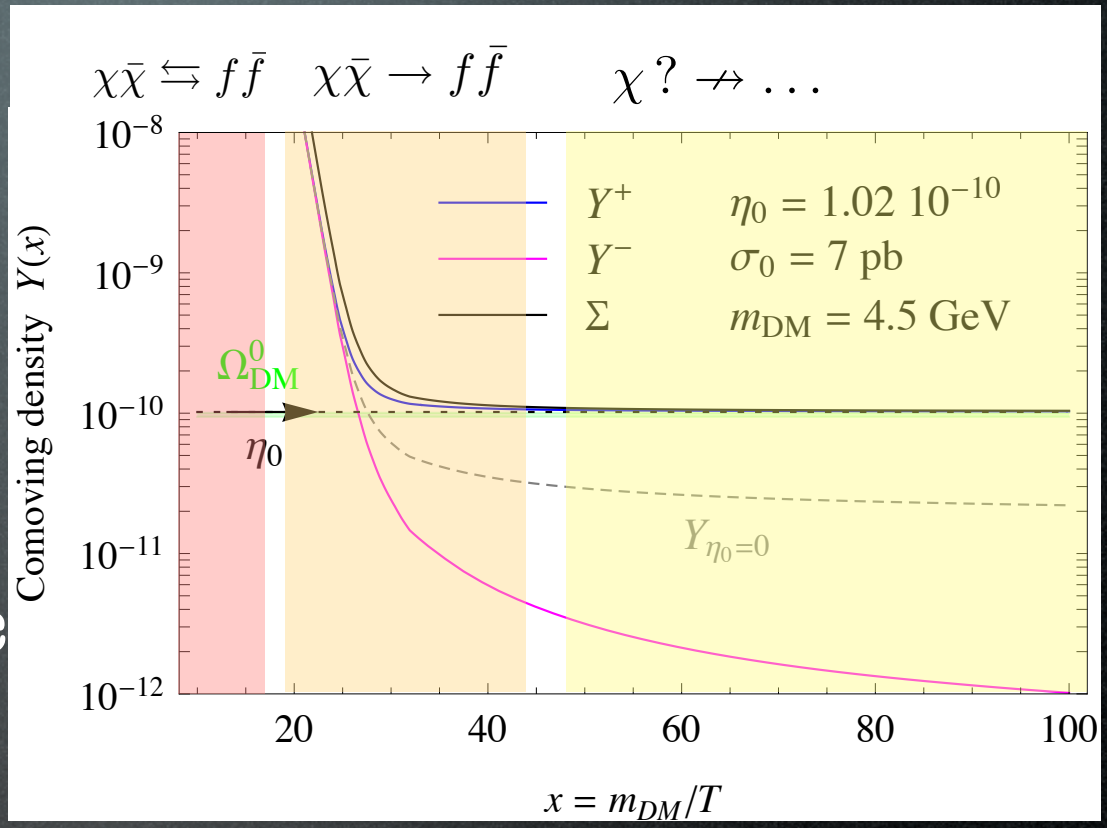

$$\Omega_{\rm X} \simeq \frac{m_{\rm X}\, s}{\rho_{\rm crit}}\eta_0$$

The relic abundance is determined by η_0 and $m_{\rm X}$.

NB: $s = \frac{2\pi^2}{45} g_{*s} T^3$ entropy density in the Universe at temperature T

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neutral ☑
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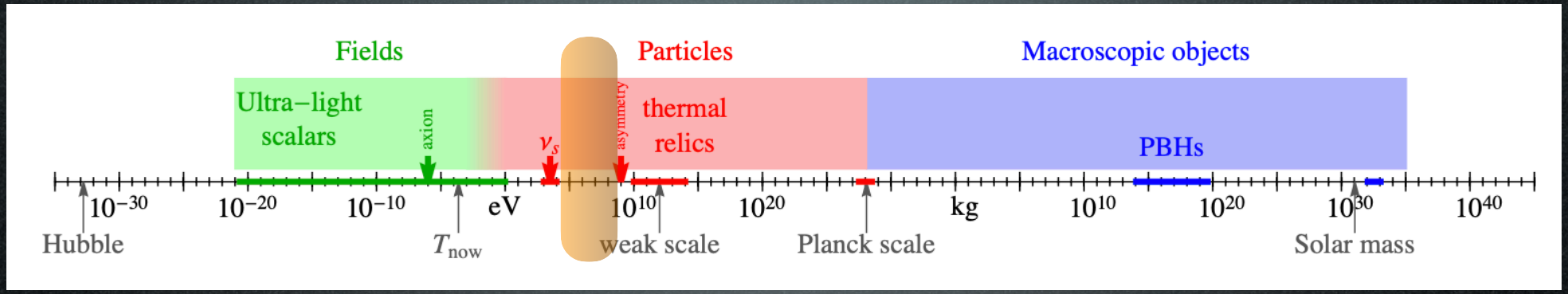
Candidates

A matter of perspective: plausible mass ranges



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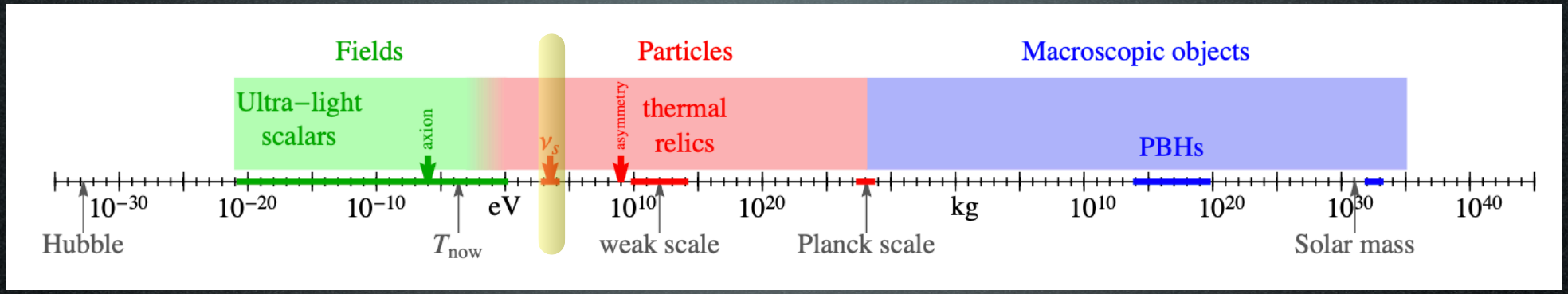


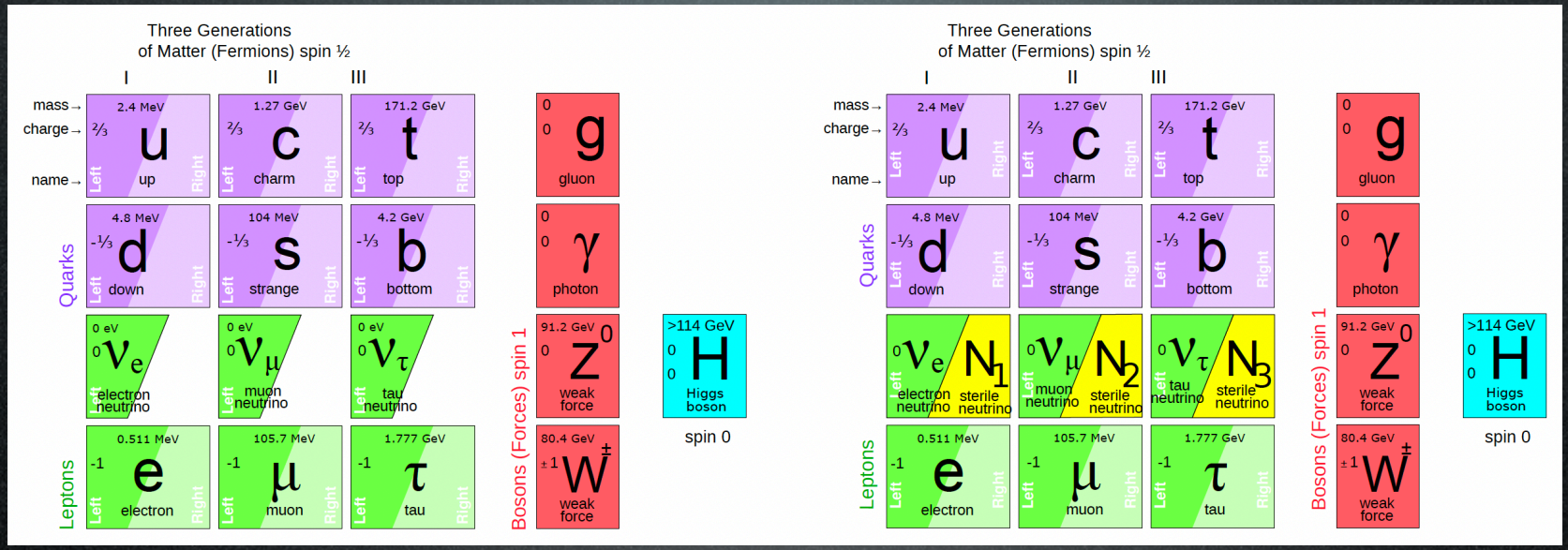
KeV DM

Sterile neutrinos

Sterile neutrinos

Theoretically ‘motivated’:

one can complete the SM lepton sector



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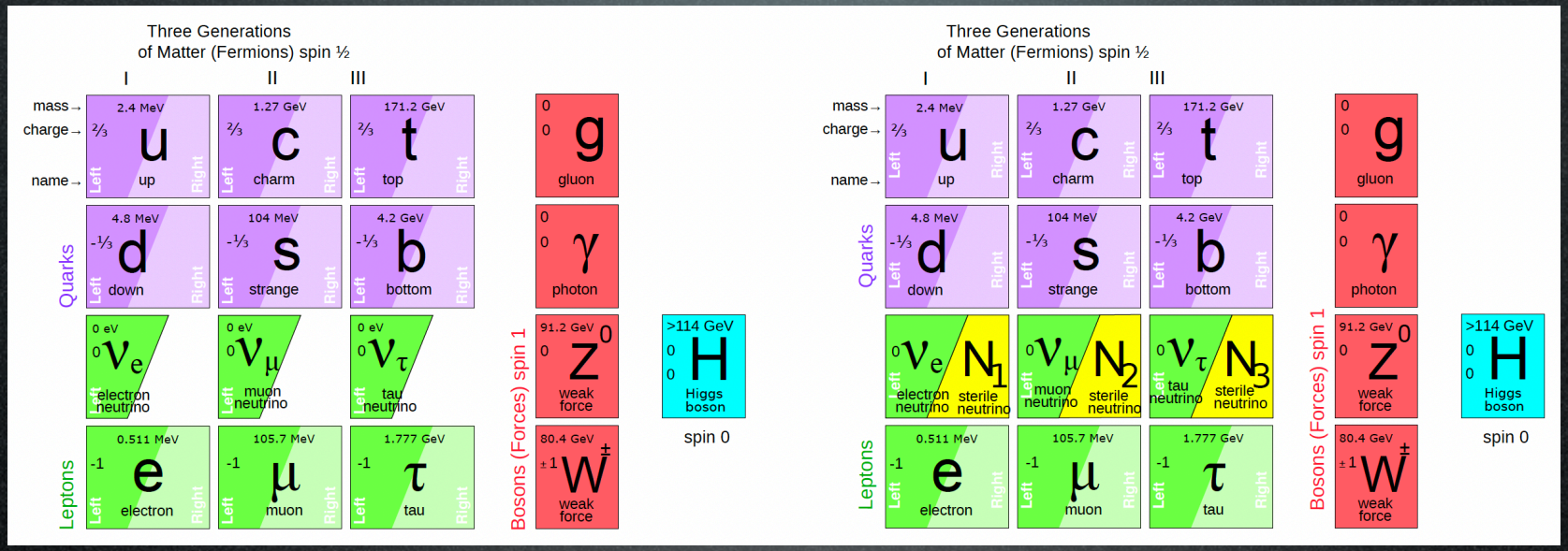

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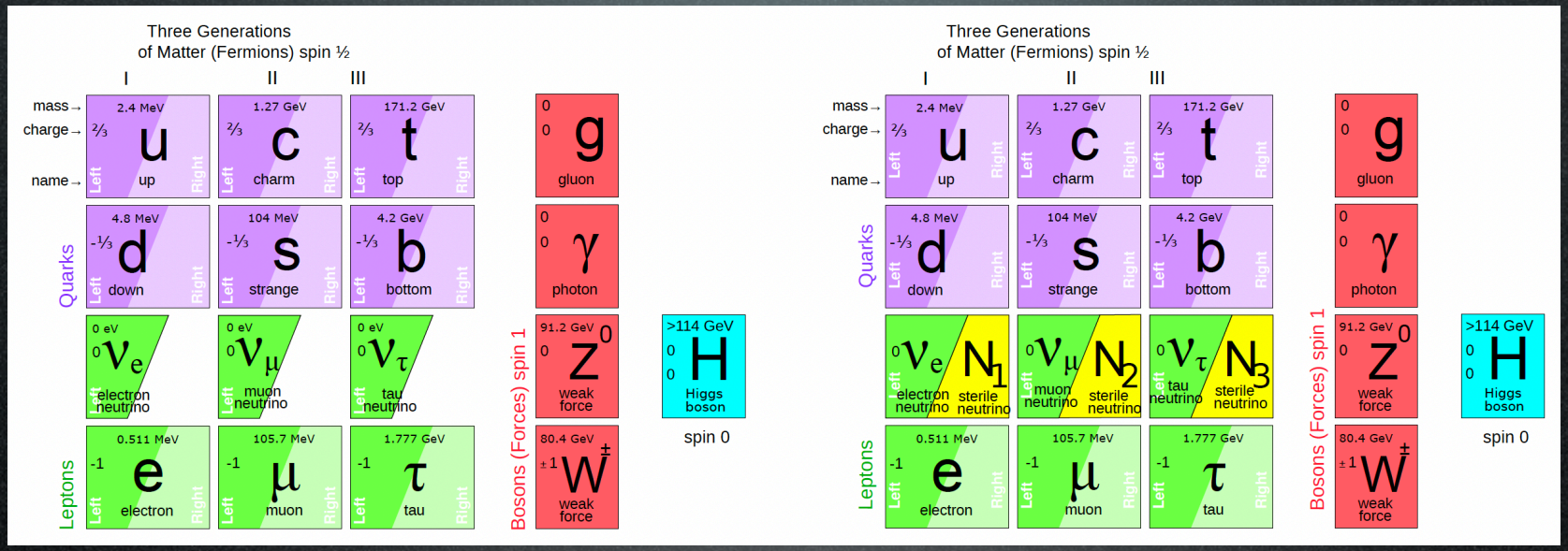

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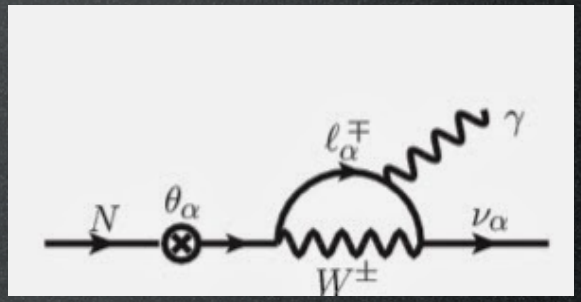
Sterile neutrino **decay**



X-ray line

Bulbul et al., 1402.2301

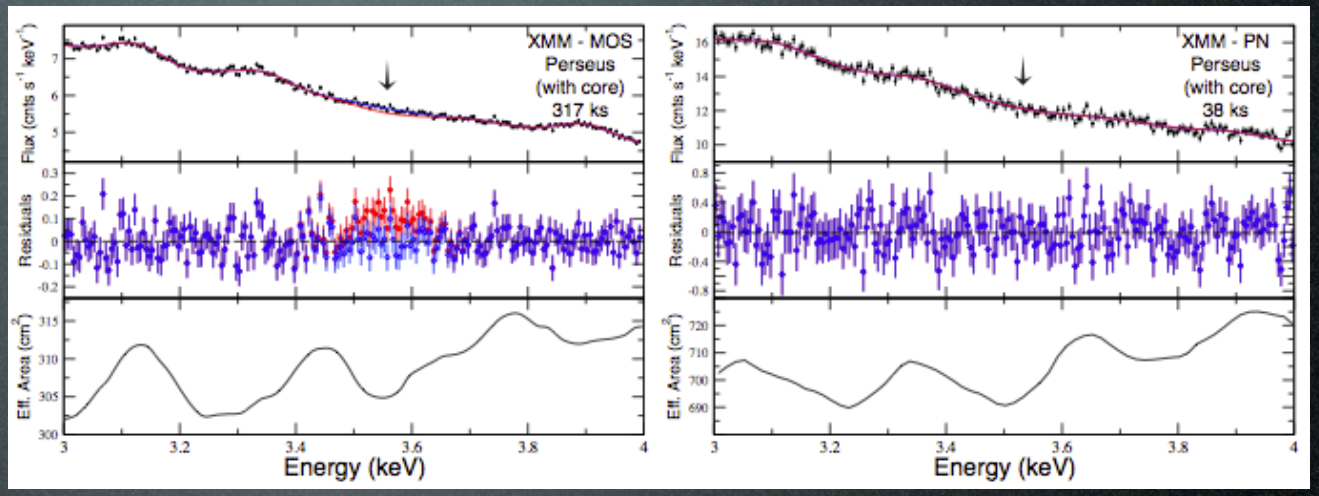
3.55 - 3.57 ± 0.03 KeV

73 clusters

(Chandra & XMM-Newton)

z = 0.01 - 0.35

$\gtrsim 4\sigma$



Boyarsky, Ruchayskiy, 1402.4119

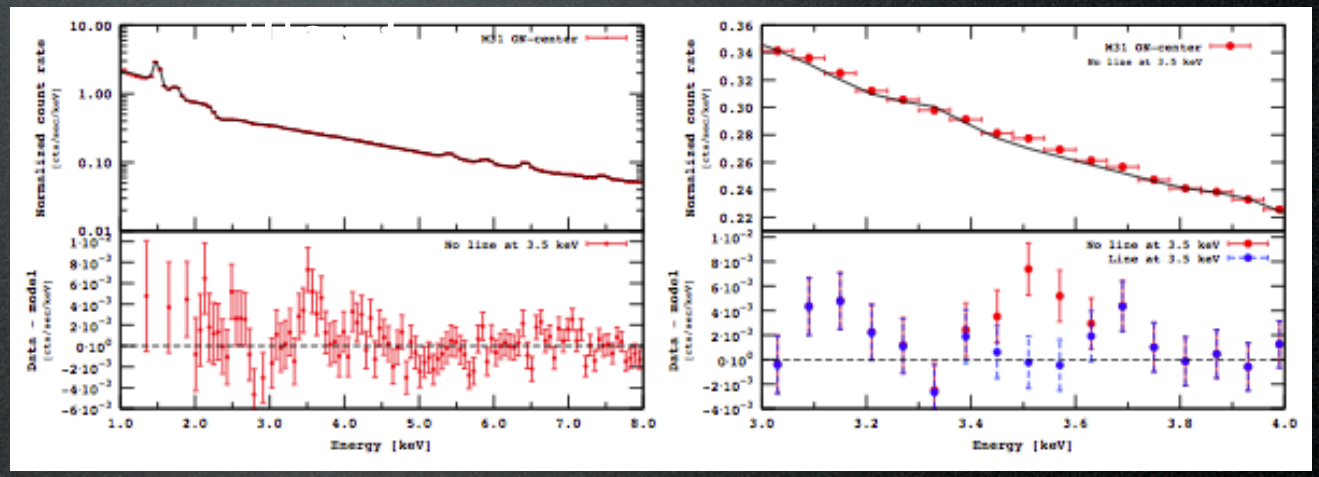
3.5 KeV

Andromeda galaxy
+ Perseus cluster

(XMM-Newton)

4.4σ

z = 0 and 0.0179



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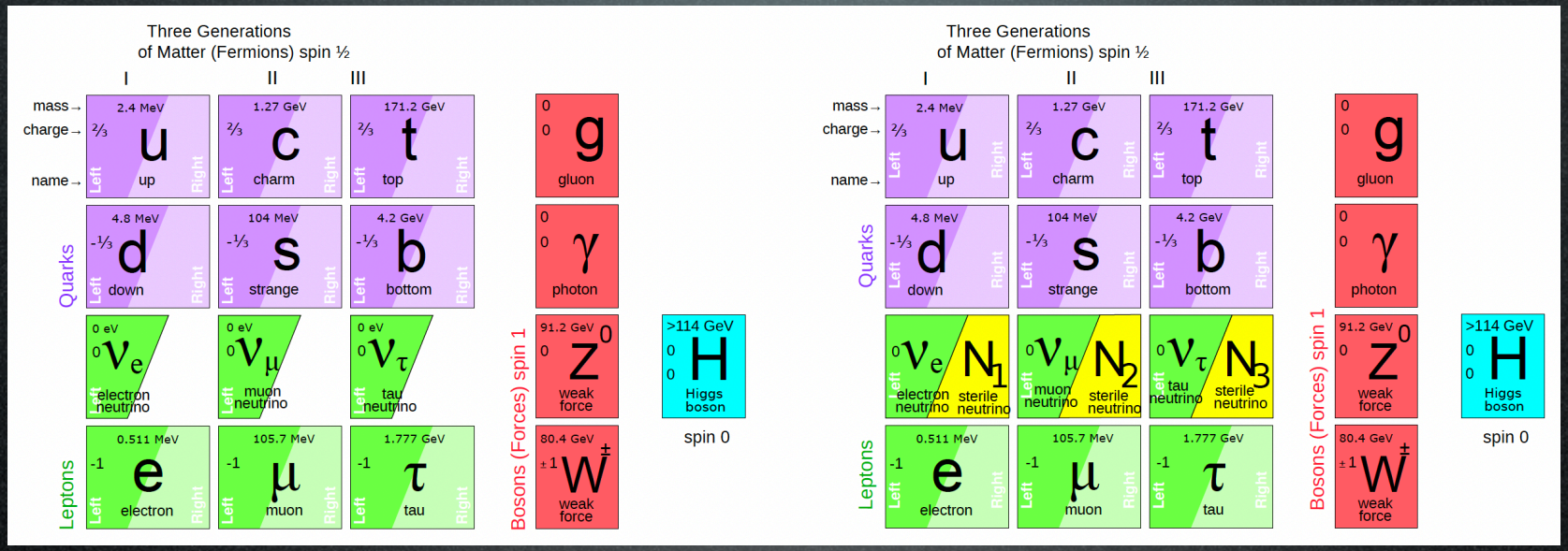

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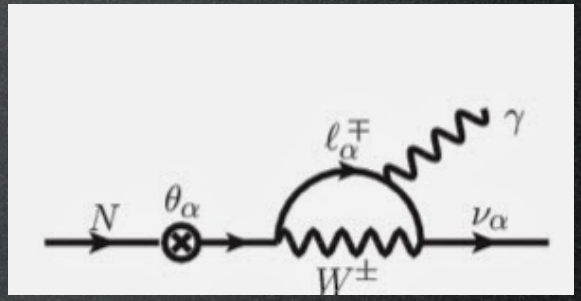

Freeze-in:
like rodents in the paleocene

Hall, Jedamzik, March-Russell, West 2009

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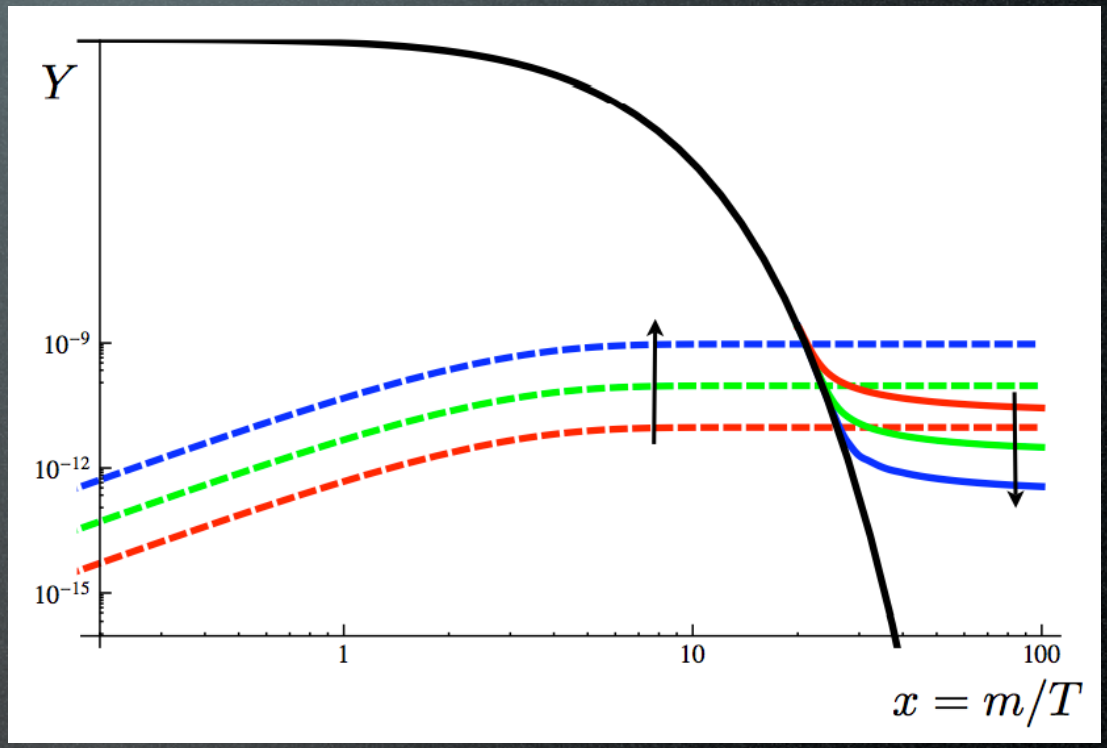

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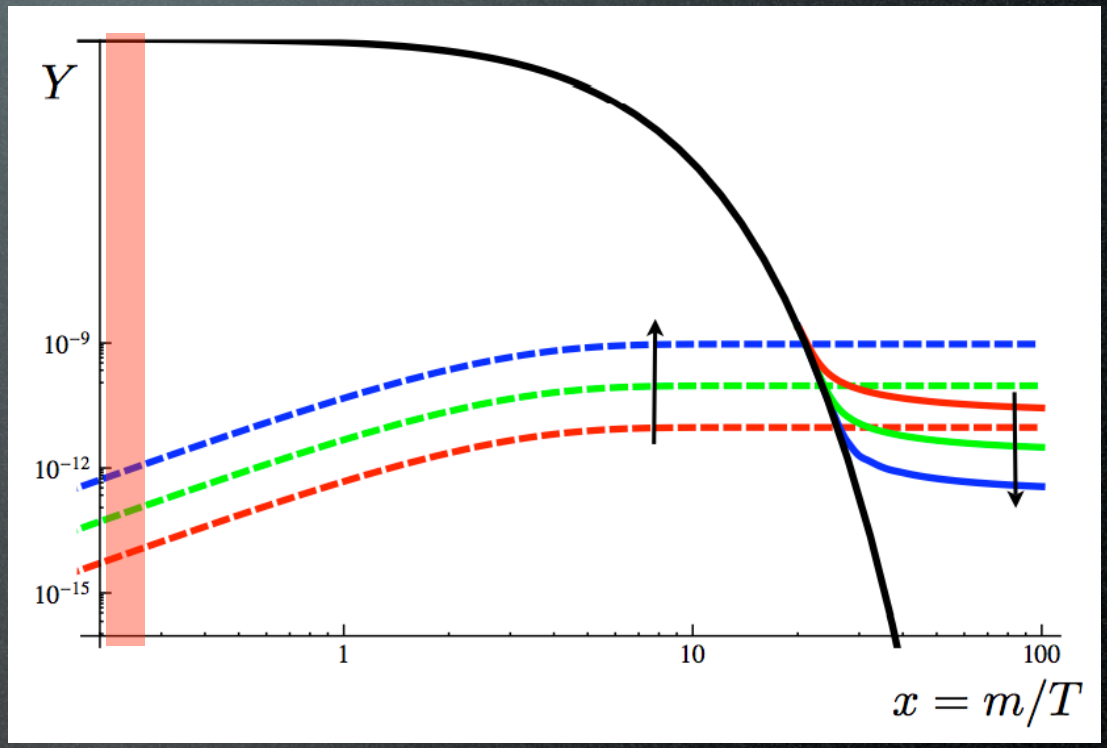
e.g. because it does not couple to the inflaton, hence not produced in the initial thermal bath, or washed away by inflation



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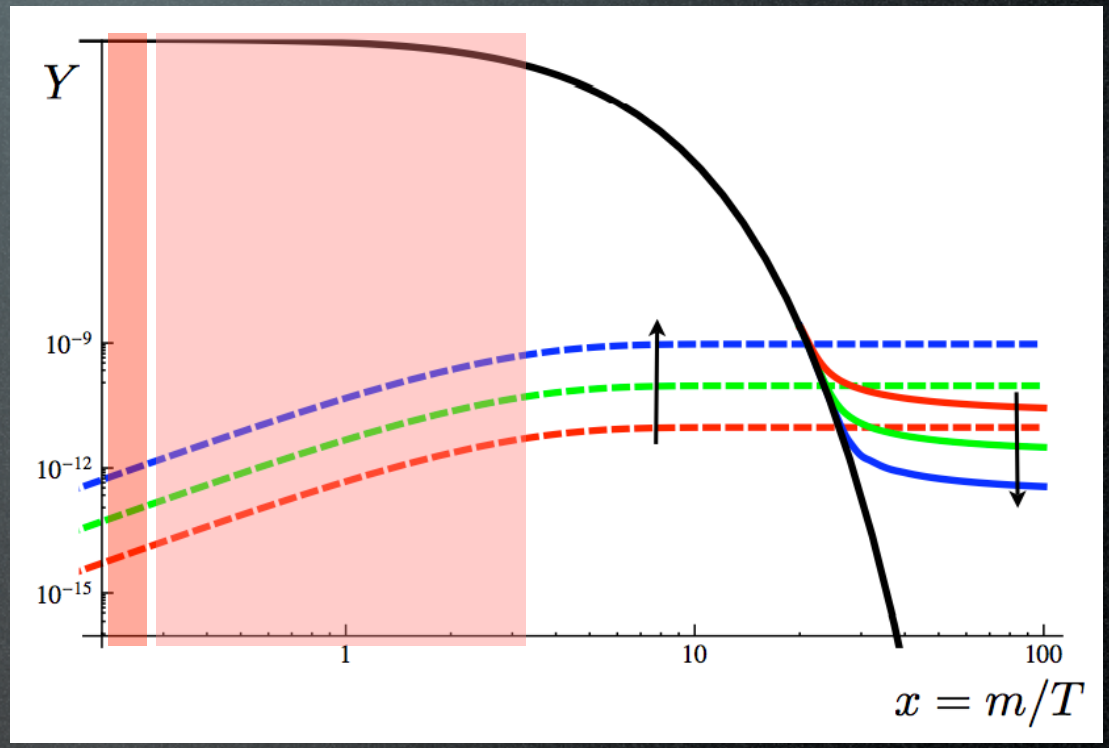

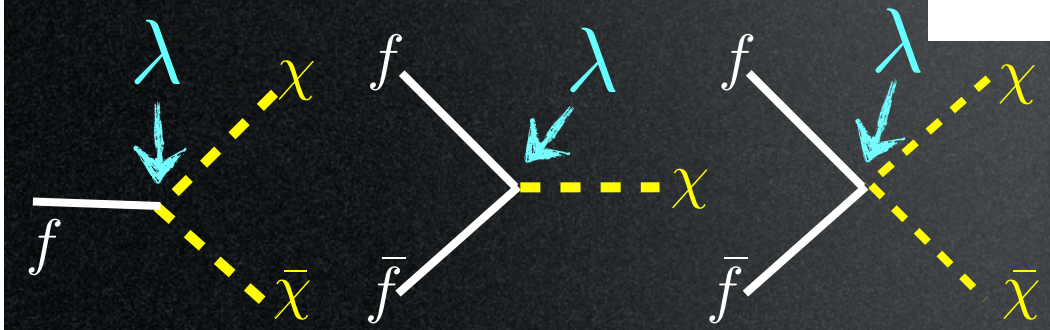

actually this dominates, for phase space reasons

$\lambda \sim 10^{-12}$

very slowly but steadily produced

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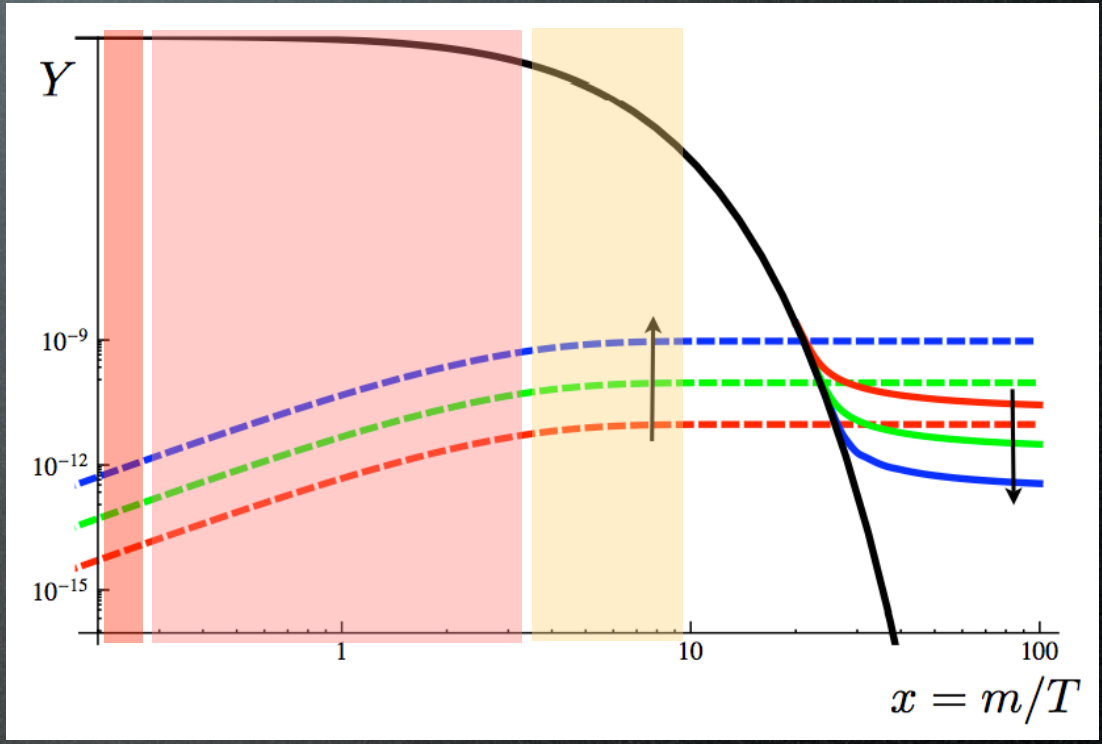

(*) Alternatively: f is 'heavy', χ production stops as abundance of f is Boltzmann suppressed

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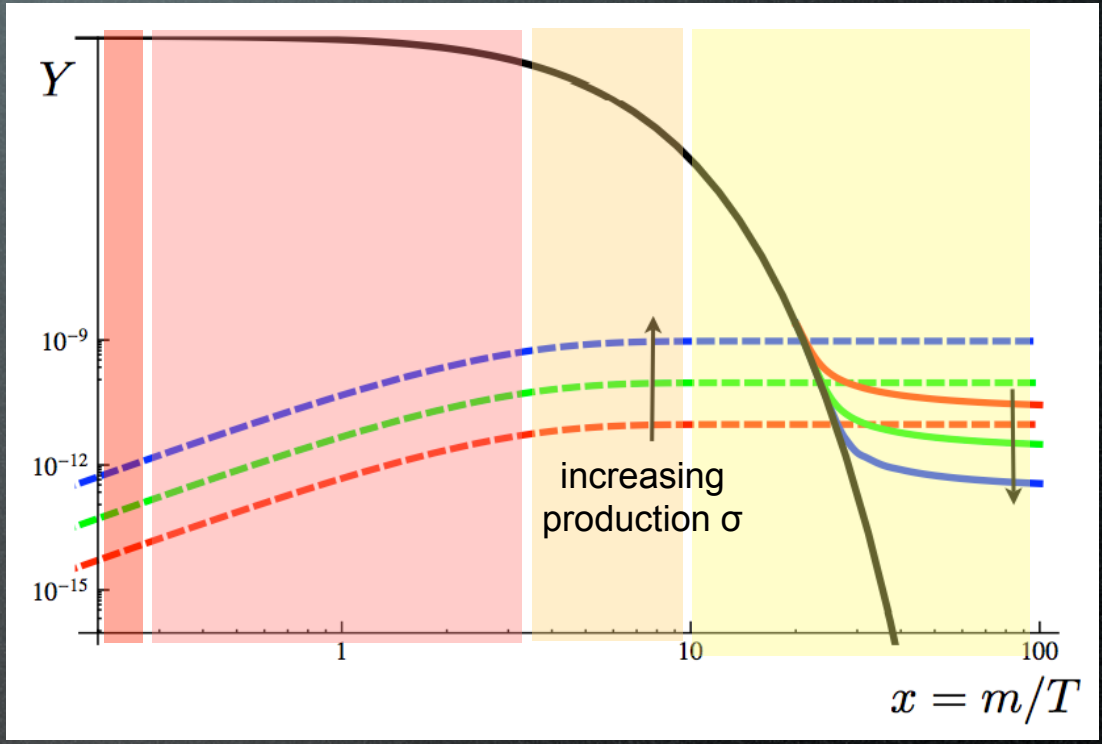

The final abundance is determined by σ (or rather λ).

Sterile neutrinos

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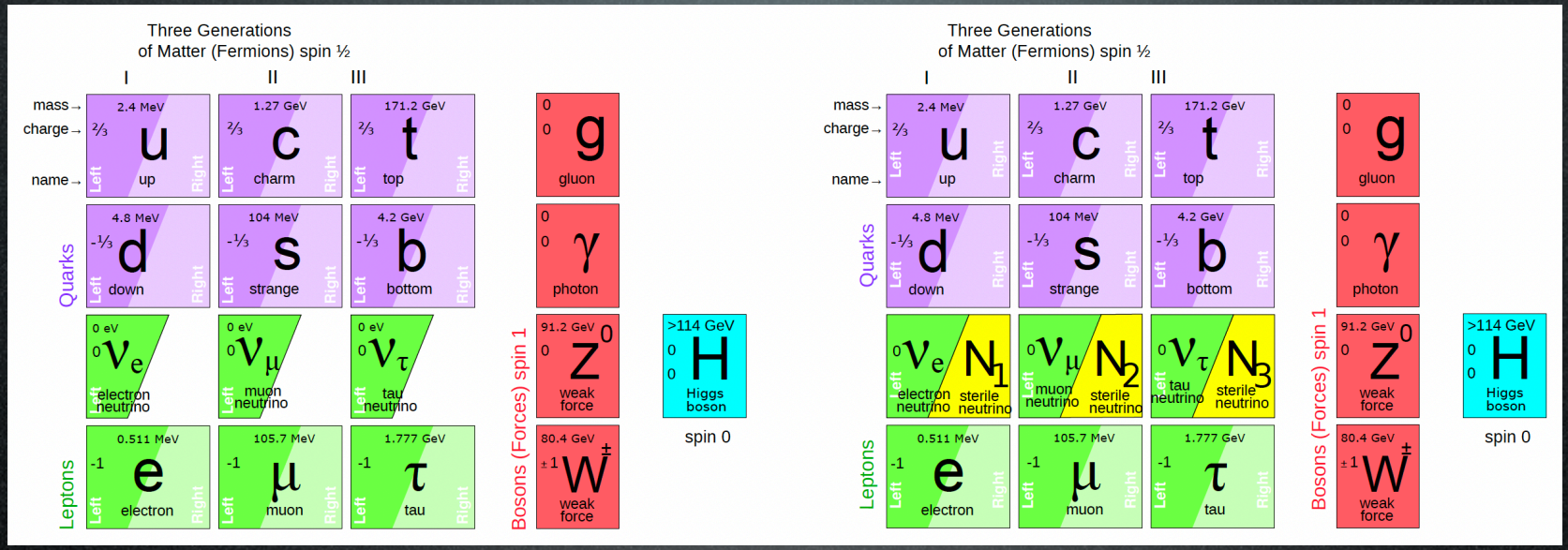

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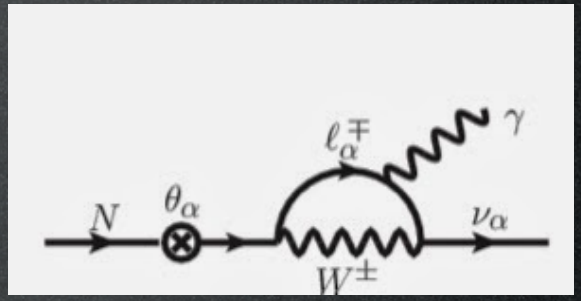

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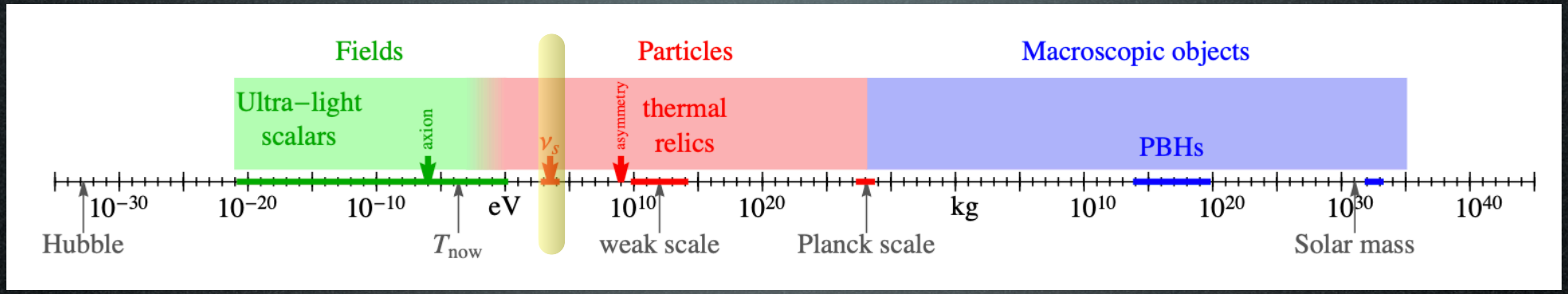

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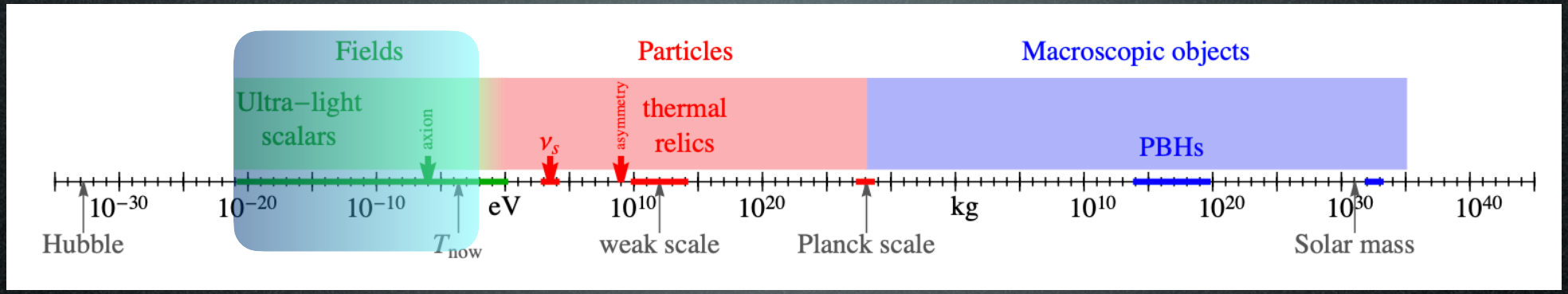

Ultralight DM

Axions

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Theoretically motivated:

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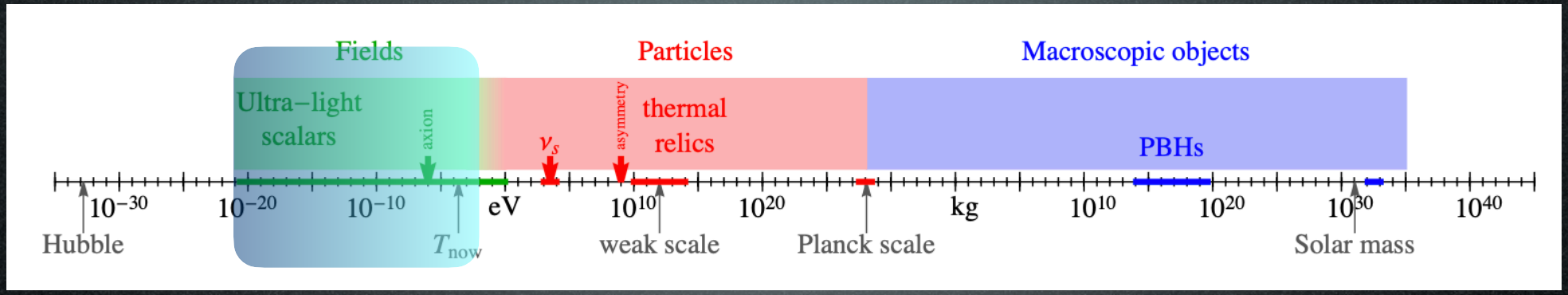

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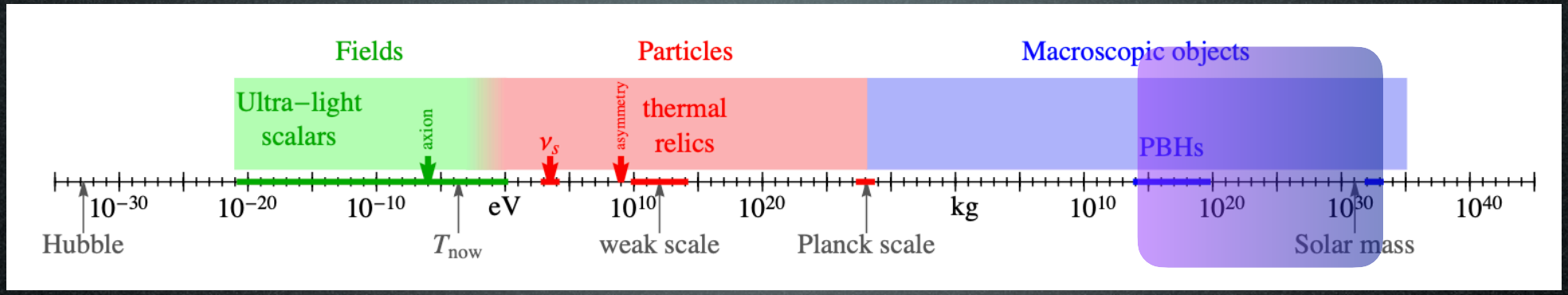

PBH DM

Primordial Black Holes

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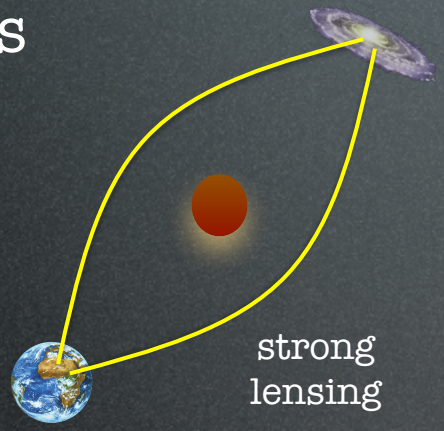
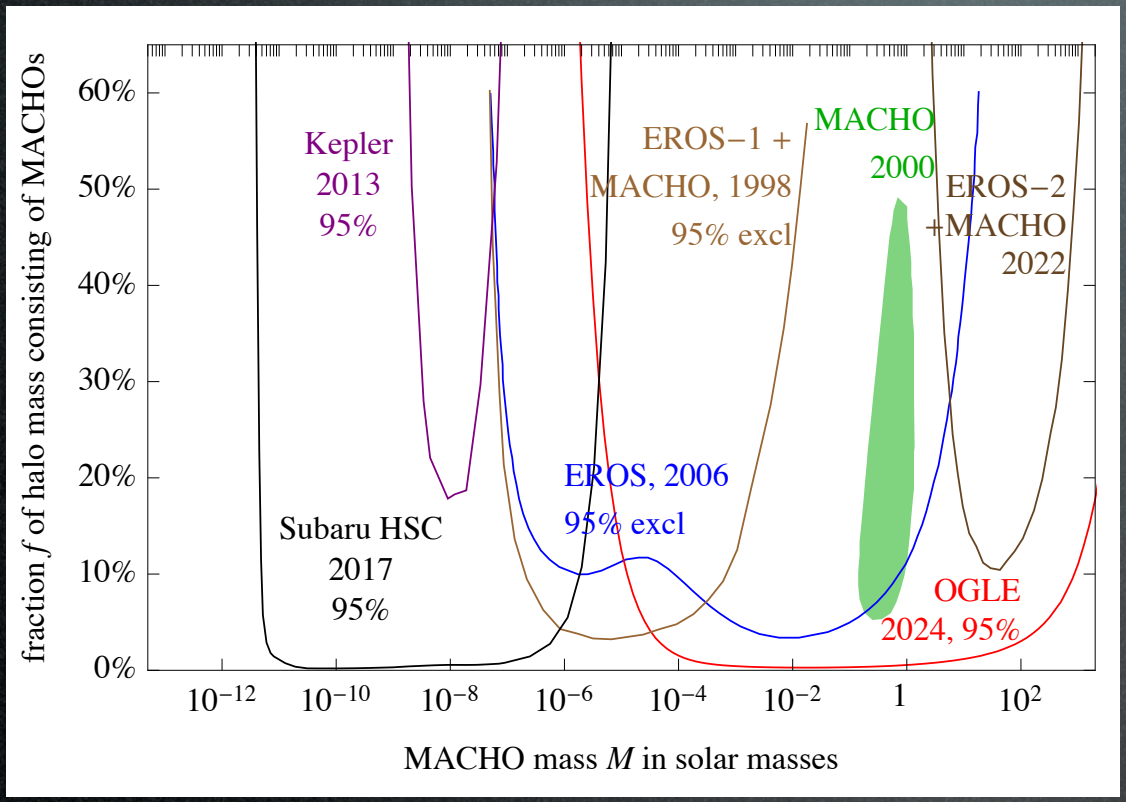


MACHOs or PBHs as DM



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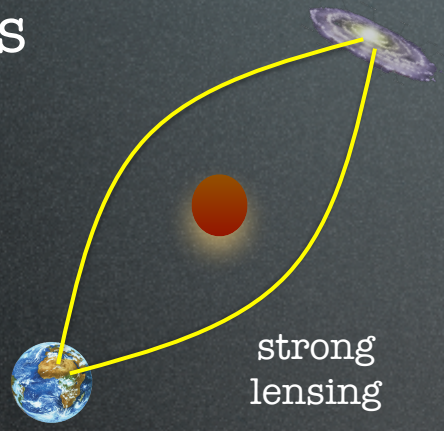

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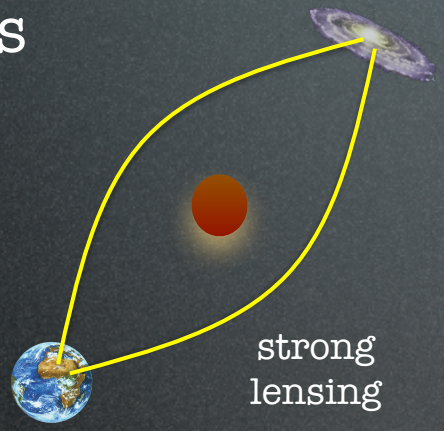

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- BBN computes the abundance of He in terms of primordial baryons:
  too much baryons => Universe full of Helium
- CMB says baryons are 4% max

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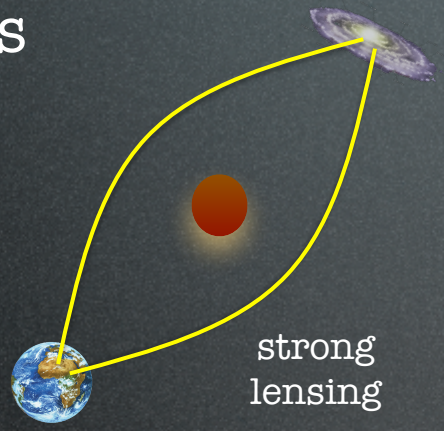

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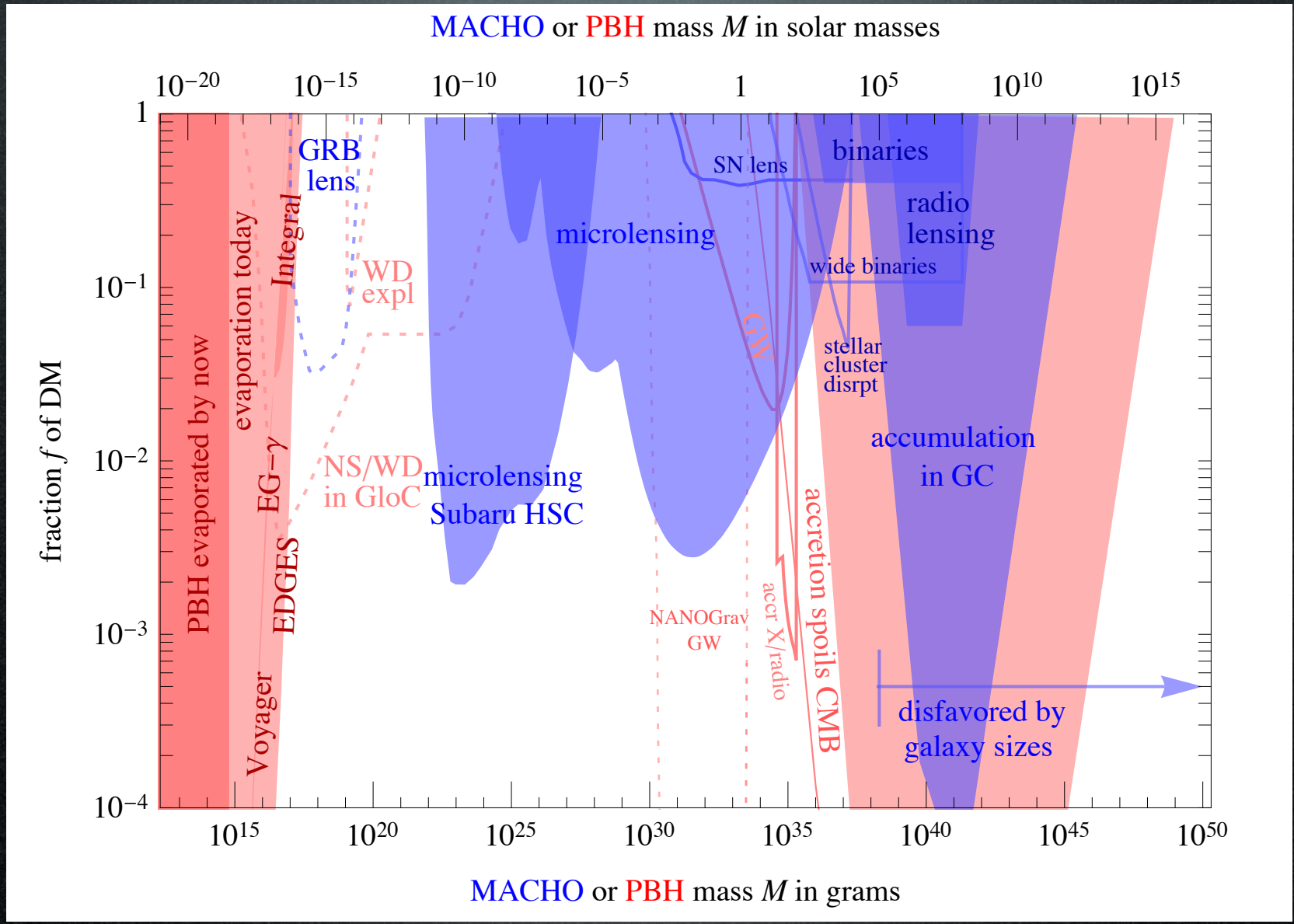
A loophole: Primordial Black Holes!

- produced before BBN
- with masses too small/large to lens
- perhaps GW observatories are seeing them?

PBHs as DM

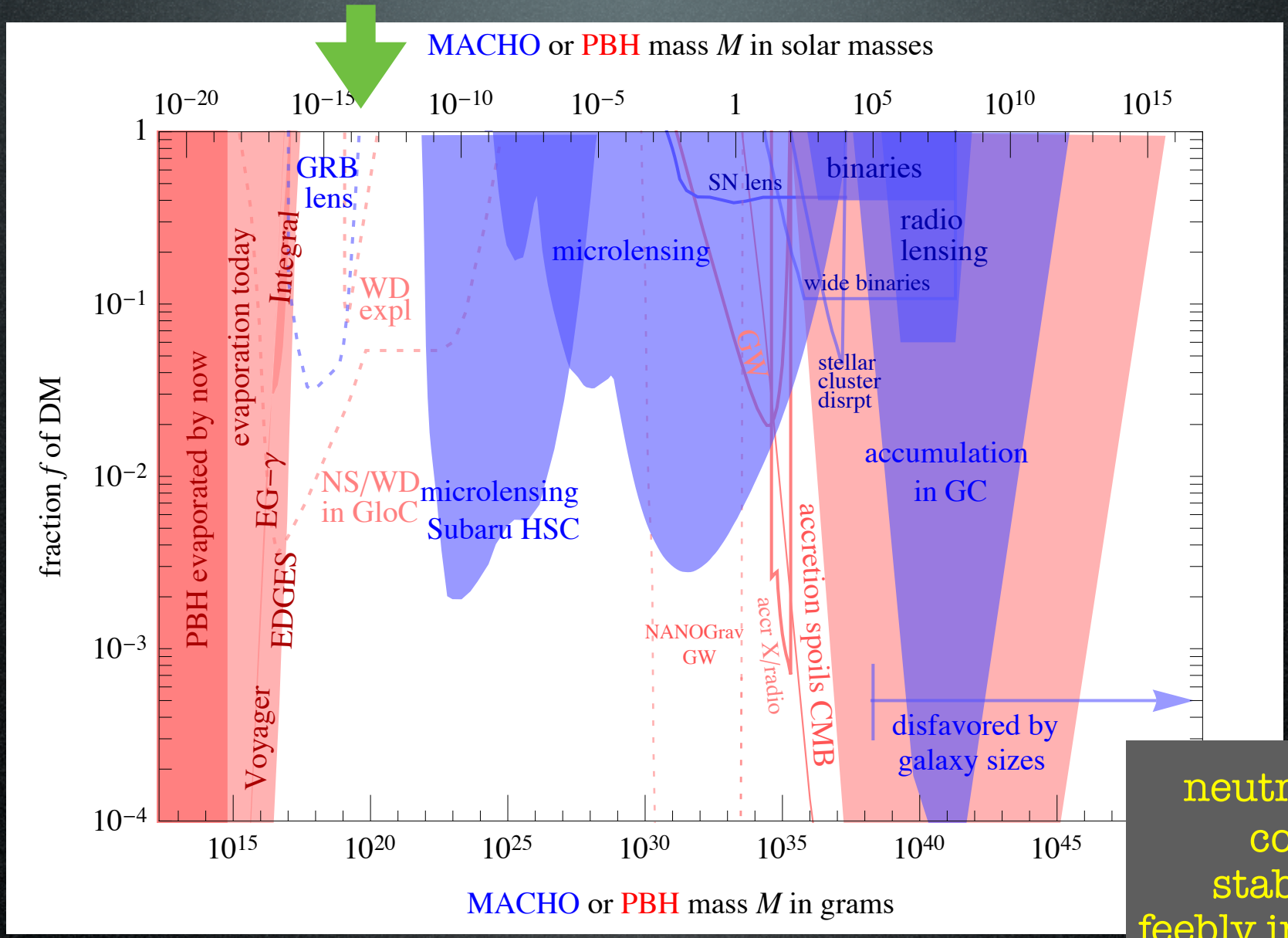
huge range of sizes: $M \simeq 10^{15}(t/10^{-23}\ \text{sec})\ \text{g}$ (with many constraints)



M. Cirelli, A. Strumia, J. Zupan 2406.01705

PBHs as DM

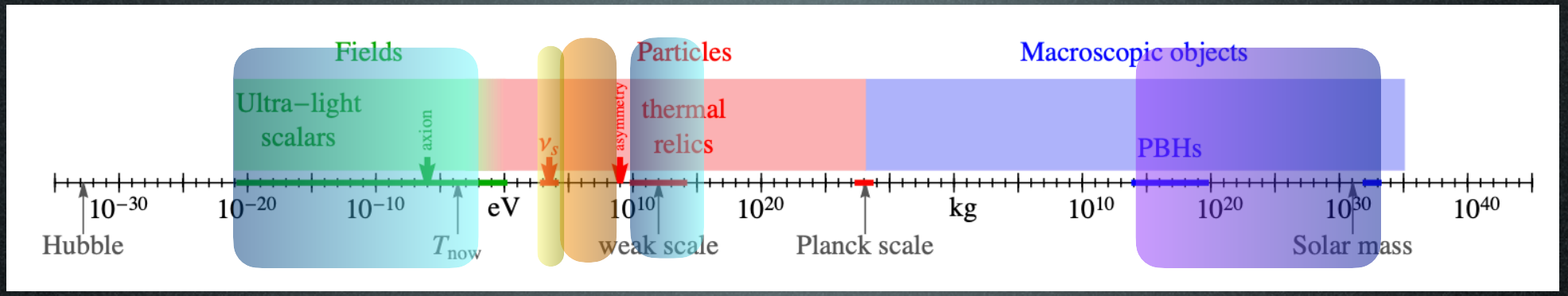
window still open?



neutral ☑
cold ☑
stable ☑
feebly int. ☑

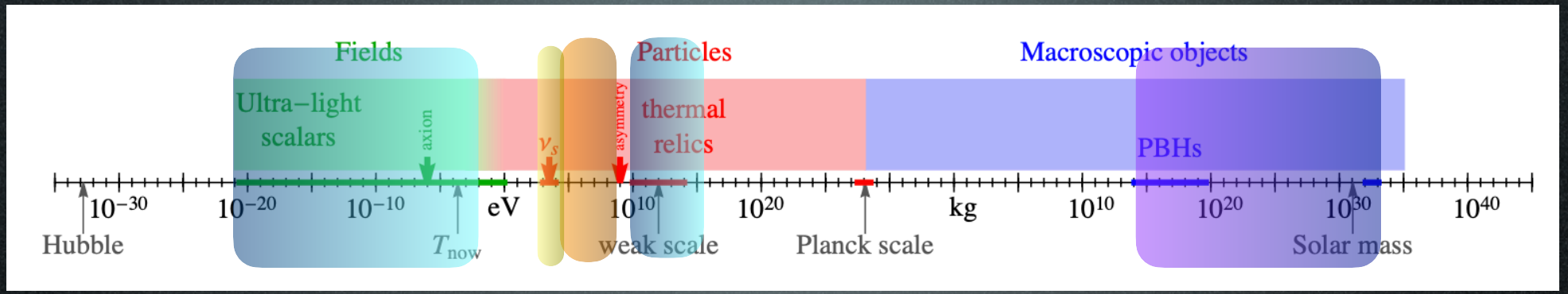
M. Cirelli, A. Strumia, J. Zupa

Candidates recap



90 orders of magnitude!

Candidates recap

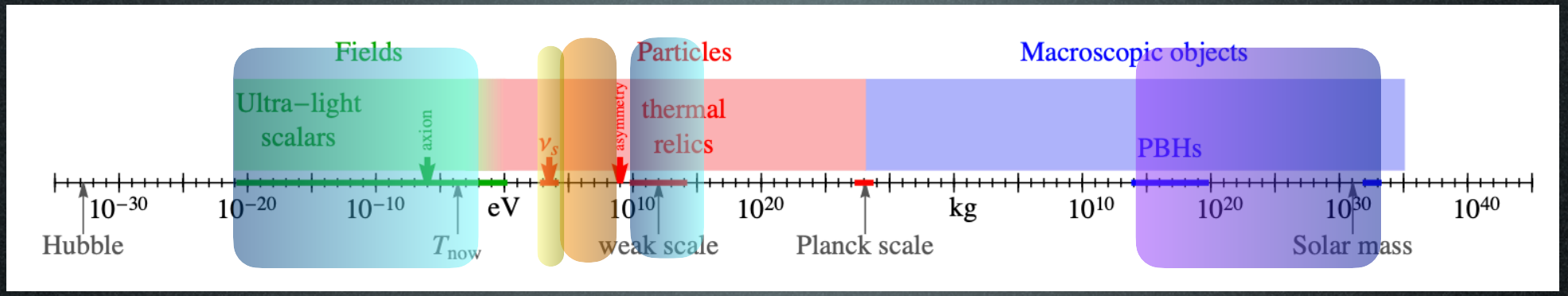


90 orders of magnitude!

neutral ☐
cold ☐
stable ☐
feebly int. ☐

Basic concept: add **something** to the SM

Candidates recap



90 orders of magnitude!

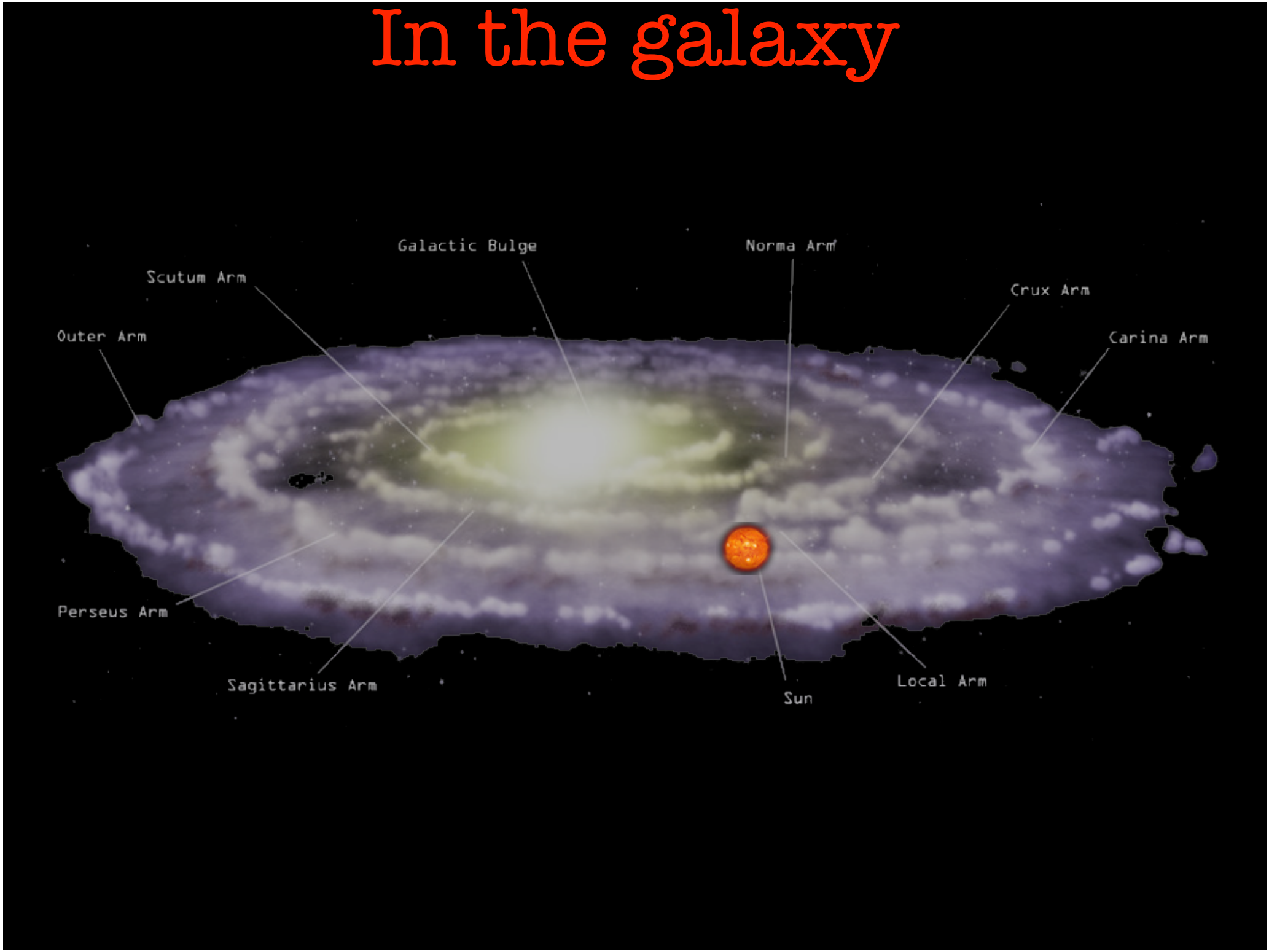
neutral ☐
cold ☐
stable ☐
feebly int. ☐

Basic concept: add **something** to the SM

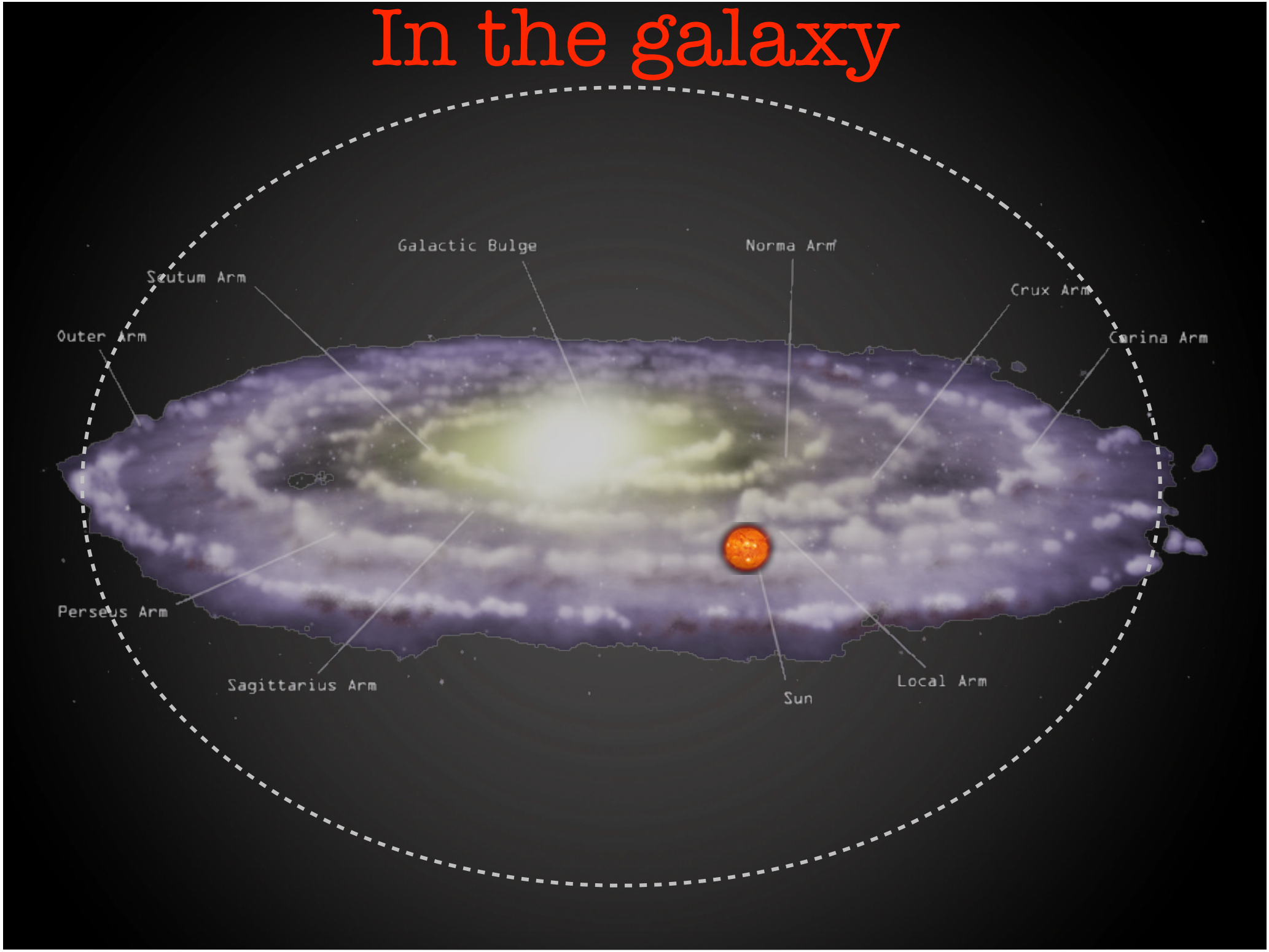
- SuSy DM — byproduct of wider theories
- Scalar singlet DM — 'ad hoc' theories
- Sub-GeV DM — byproduct or pheno motivated
- Sterile neutrinos — theory/pheno motivated
- Axions — byproduct of wider theory
- PBHs — non-particle DM
- ..... — .....

Where is Dark Matter?

In the galaxy



In the galaxy



In the galaxy

In the galaxy

DM halo profiles

From N-body numerical simulations:

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

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

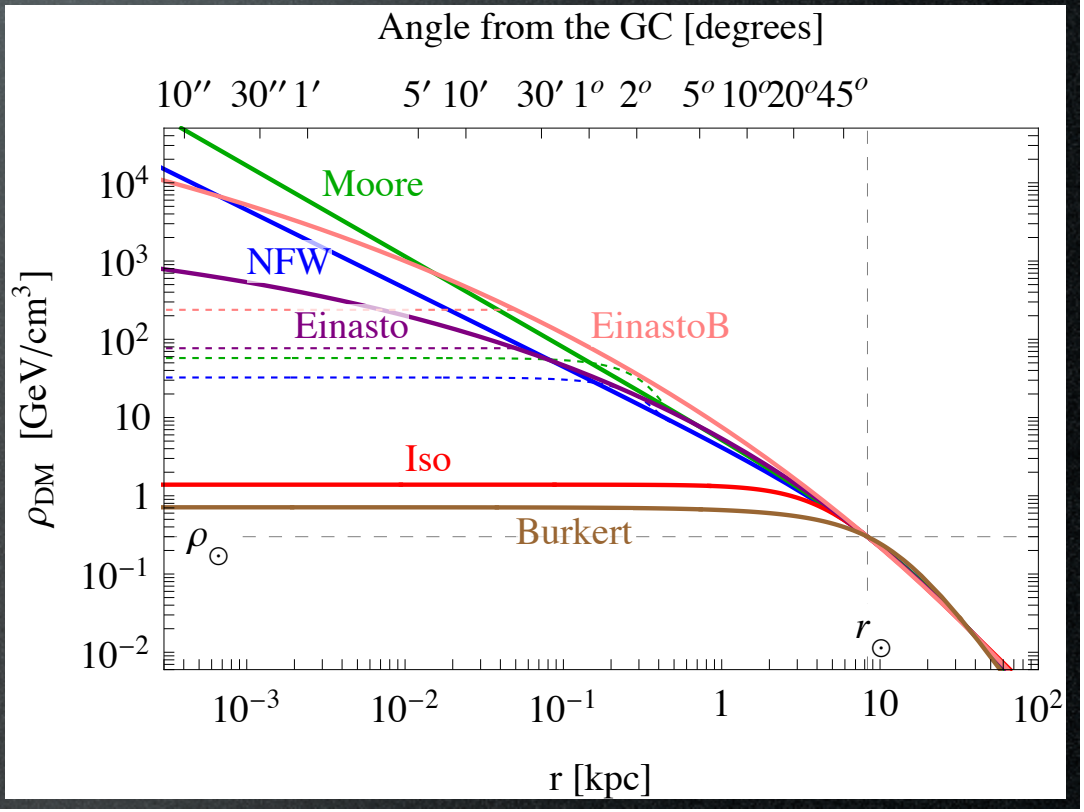
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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?)

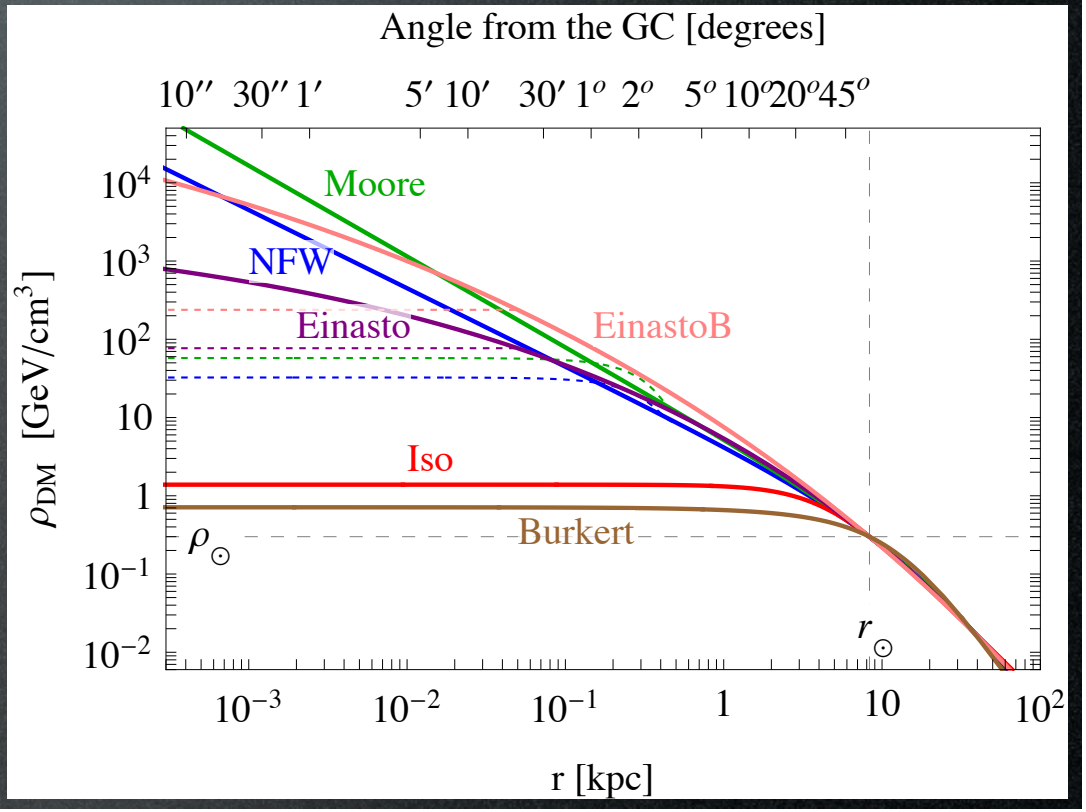
DM halo profiles

From N-body numerical simulations:

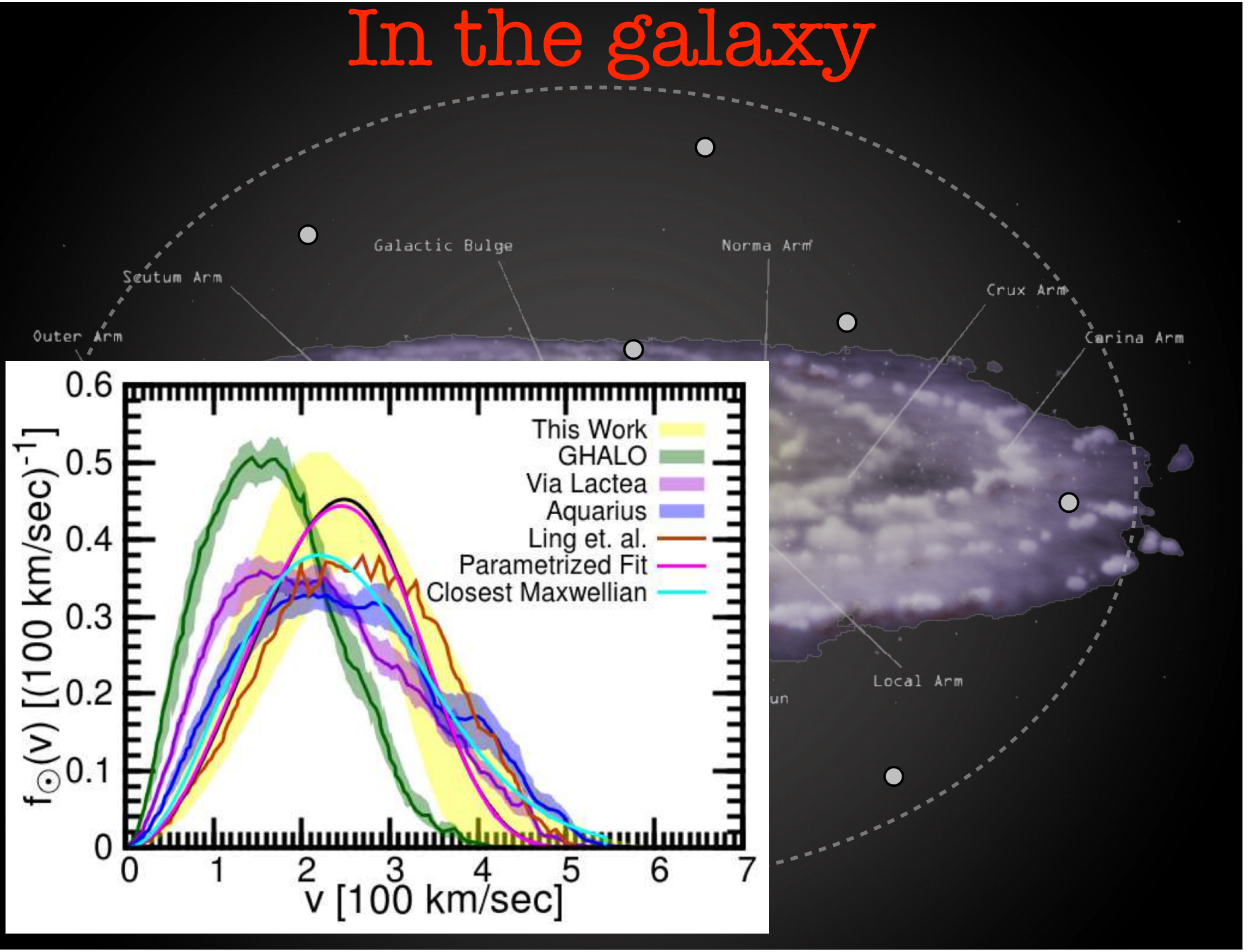
Common features:

$\rho_\odot \simeq 0.4$ GeV/cm^3

Total mass of the MW: $\simeq 10^{12}\ M_\odot$



In the galaxy



How do we search for Dark Matter?

(WIMP) DM detection

direct detection

Xenon, LZ, DarkSide, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

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

  Fermi, HESS, X-ray satellites, radio telescopes
- e^+ from annihil in galactic halo or center

  AMS, Fermi
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center

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

  Icecube, Km3Net

Indirect Detection

DM detection

direct detection

Xenon, LZ, DarkSide, CDMS (Dama/Libra?)

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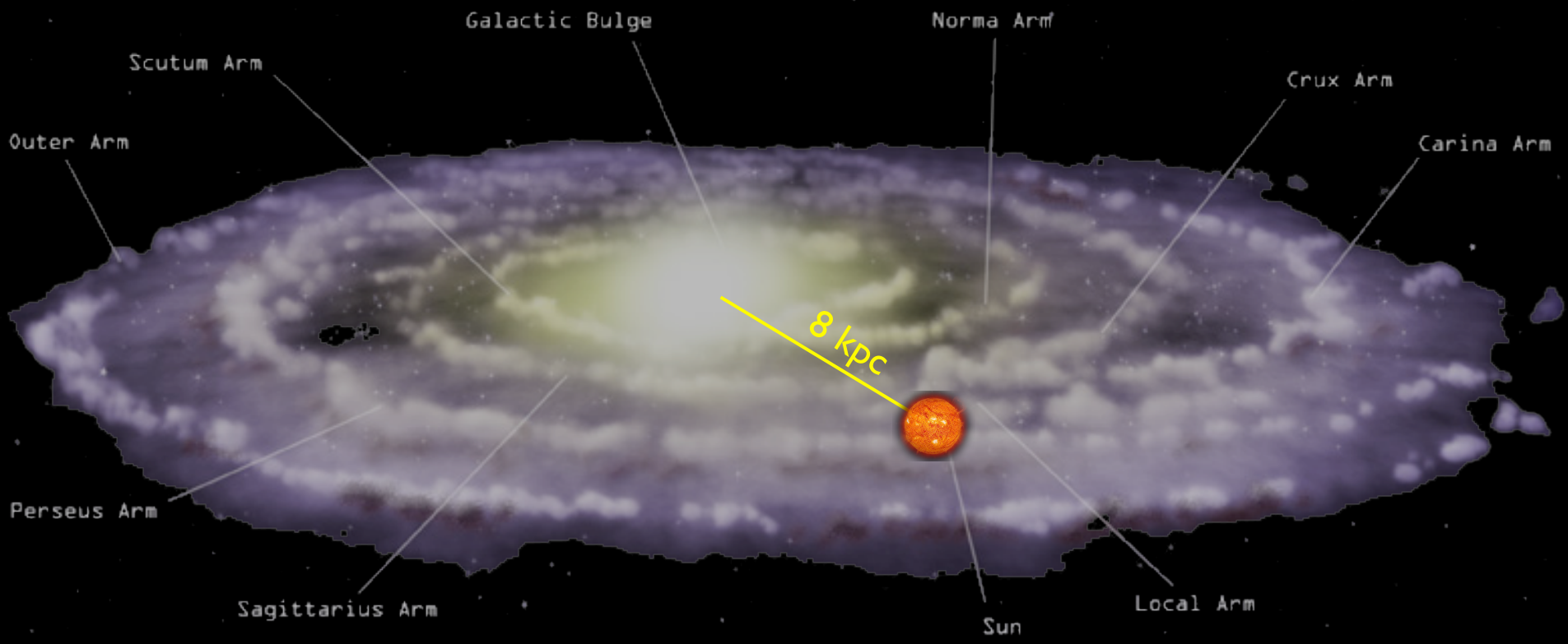
  Icecube, Km3Net

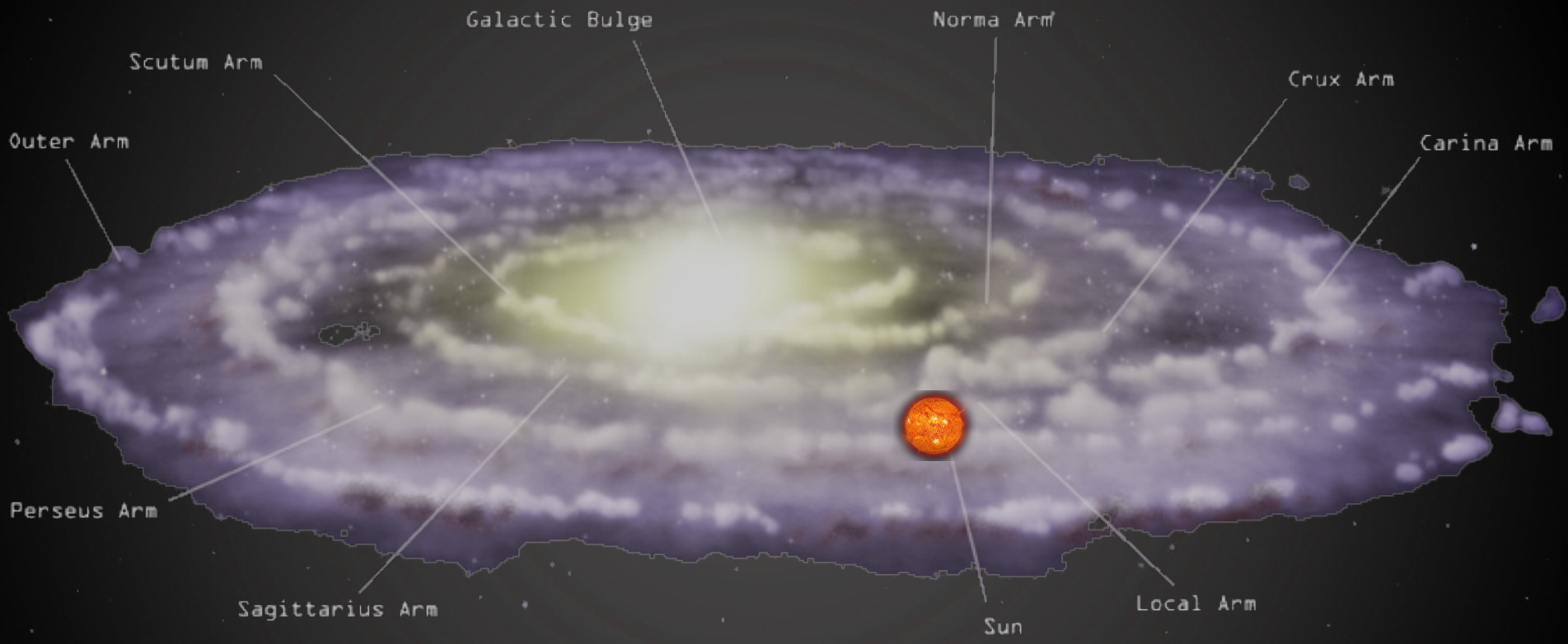
Indirect Detection: basics

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



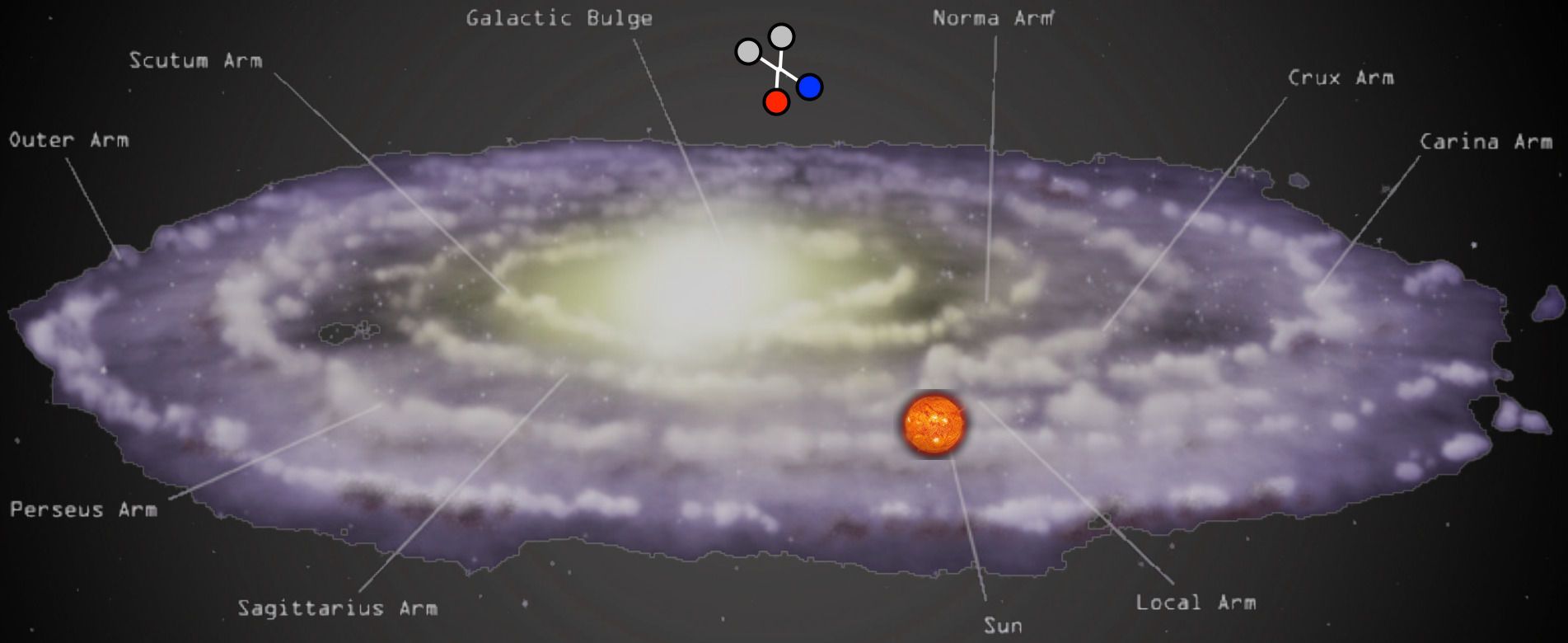
Indirect Detection: basics

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



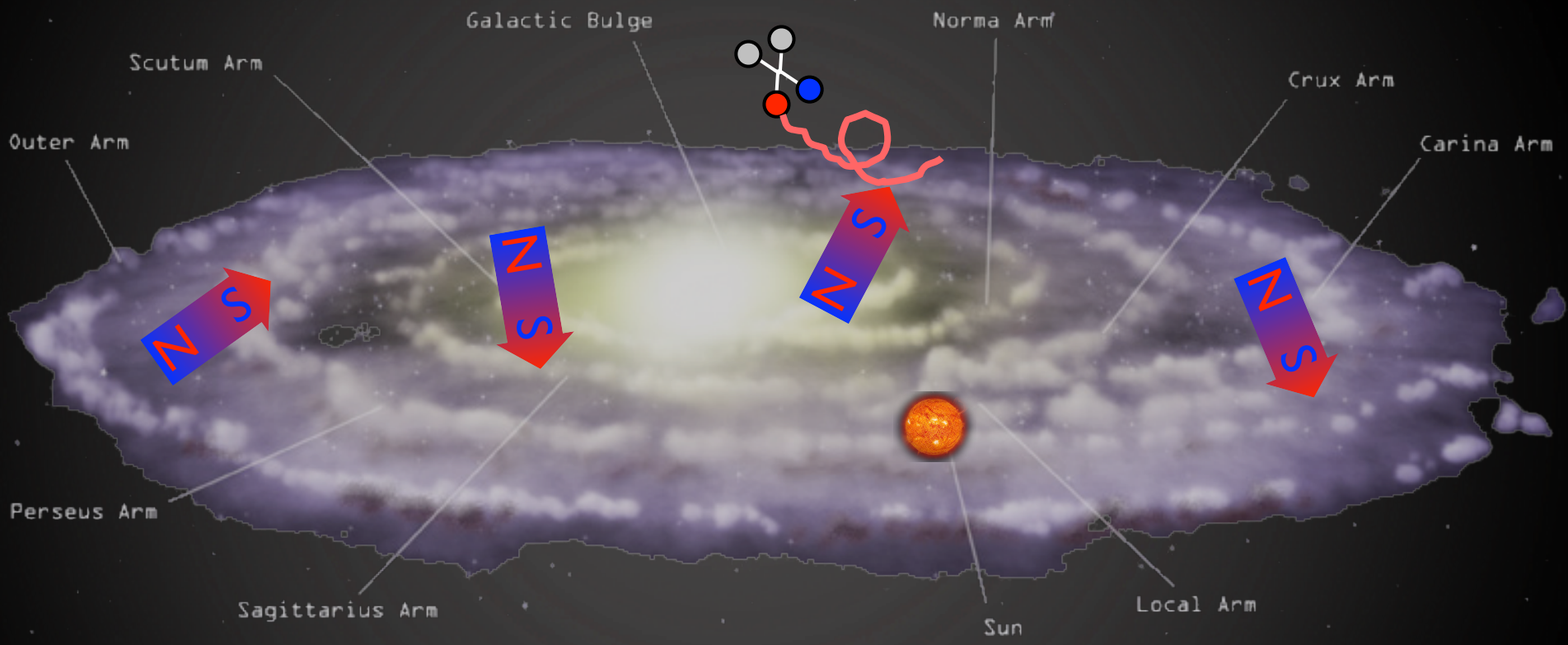
Indirect Detection: basics

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



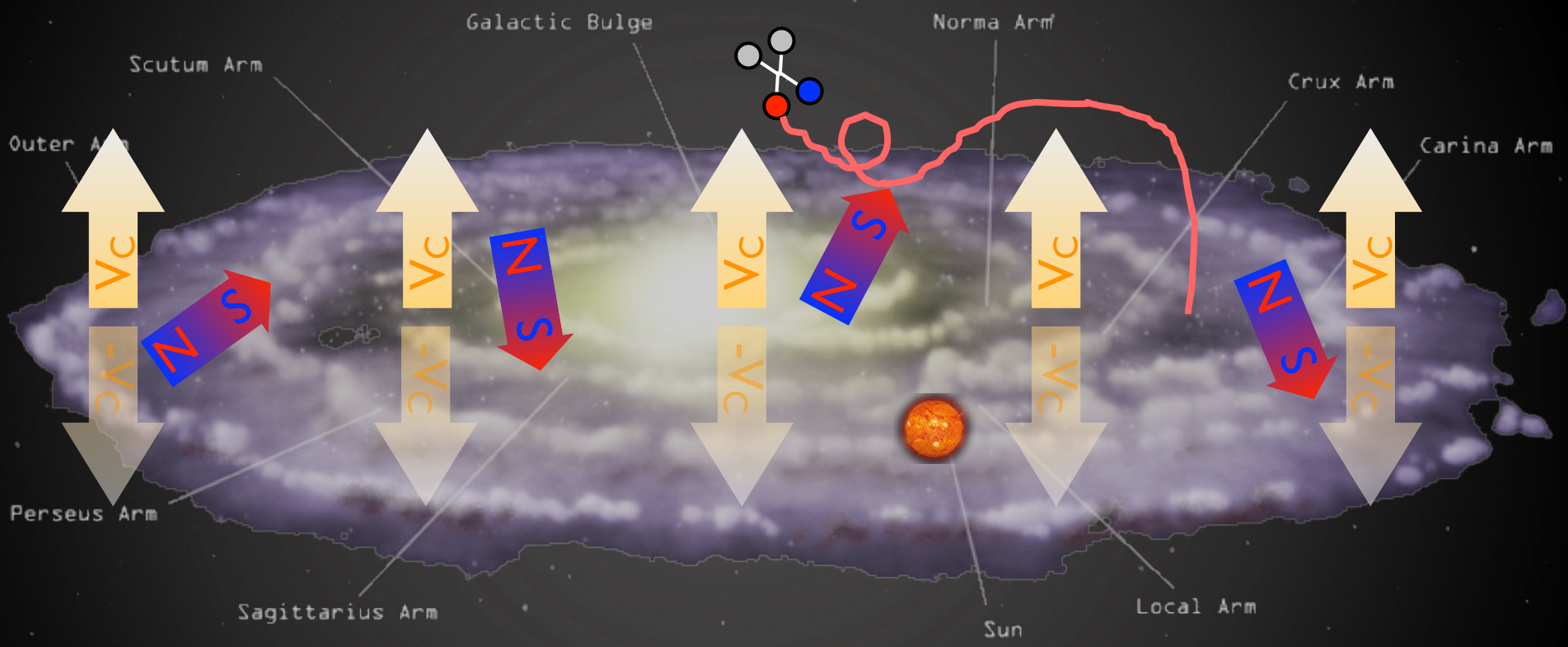
Indirect Detection: basics

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



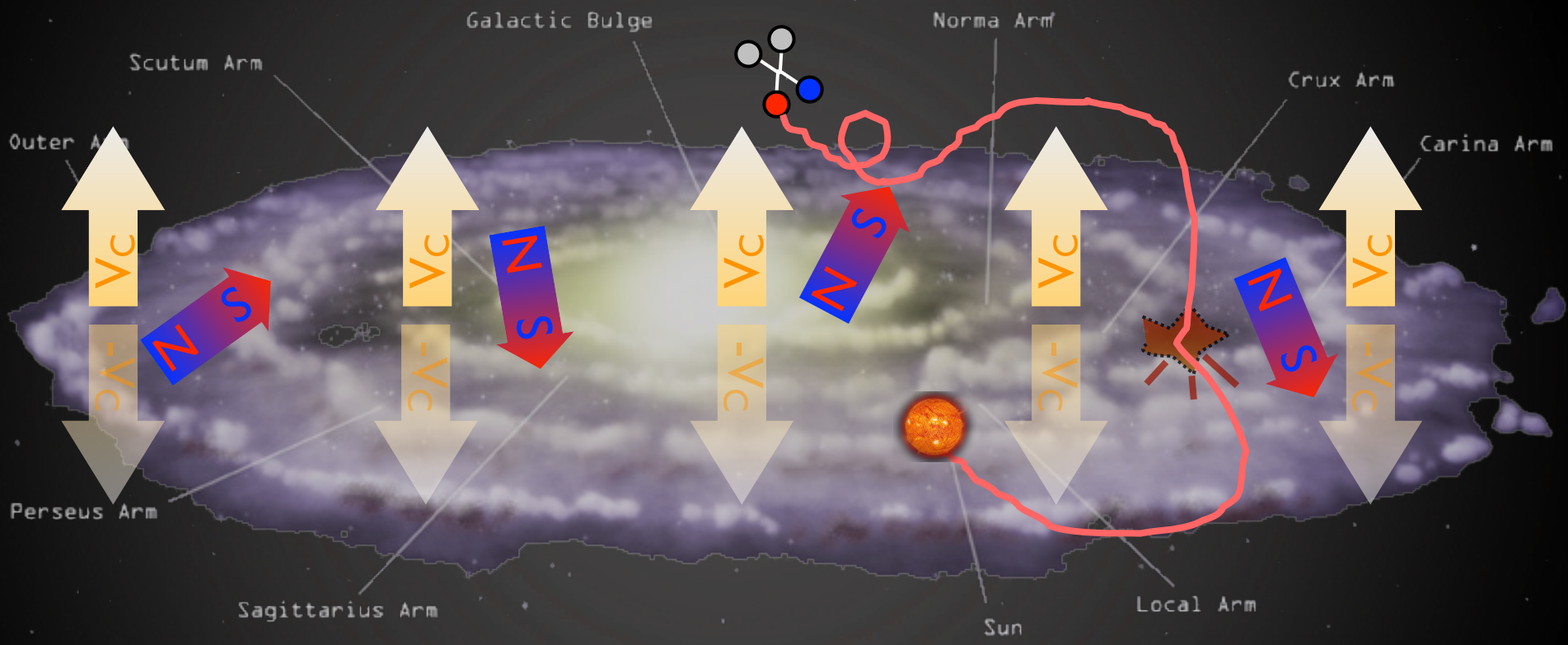
Indirect Detection: basics

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



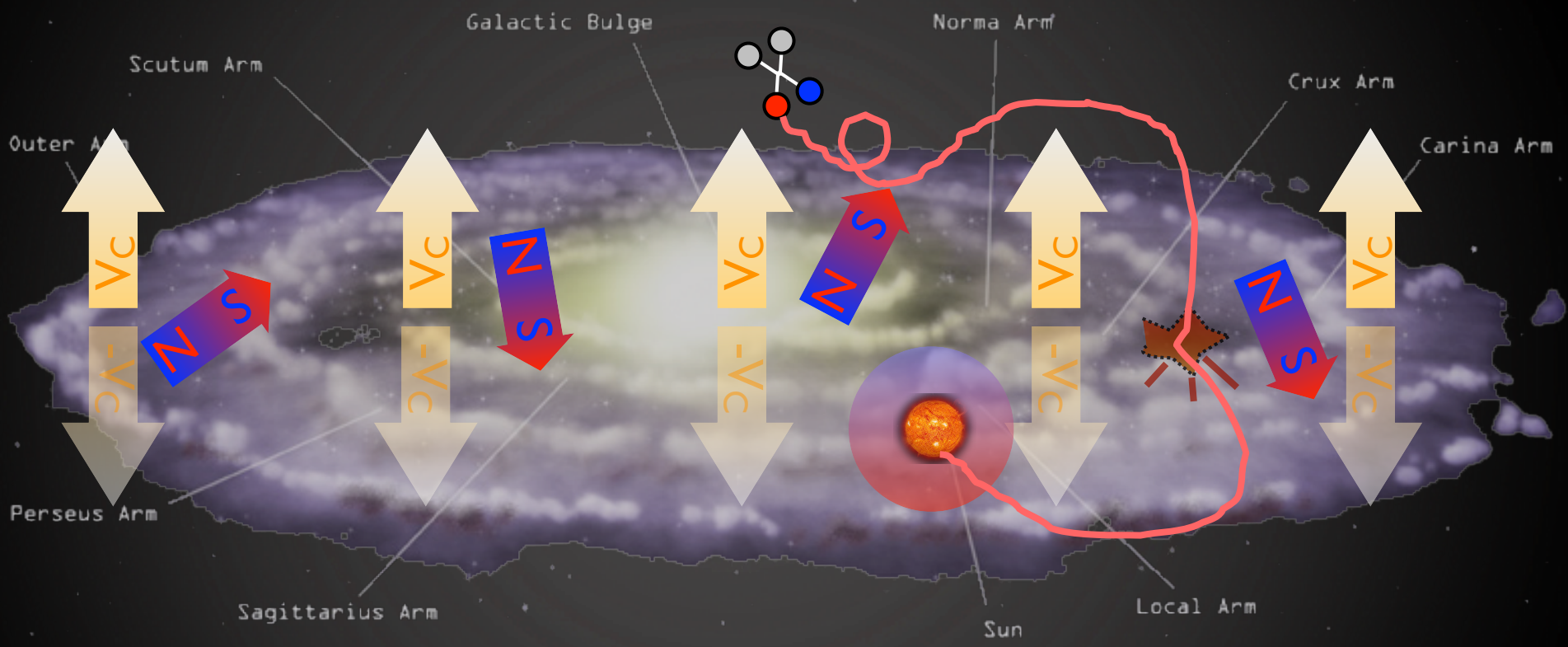
Indirect Detection: basics

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

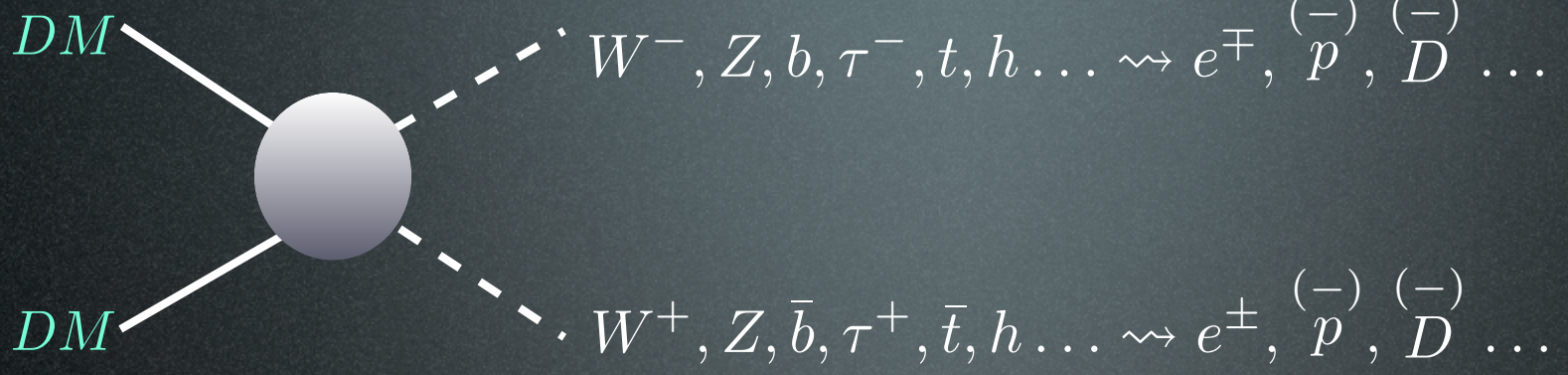


Indirect Detection: basics

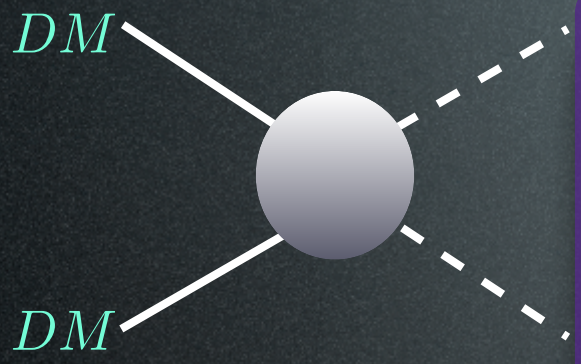
$\bar{p}$ and e^+ from DM annihilations in halo



Indirect Detection: basics



Indirect Detection: basics

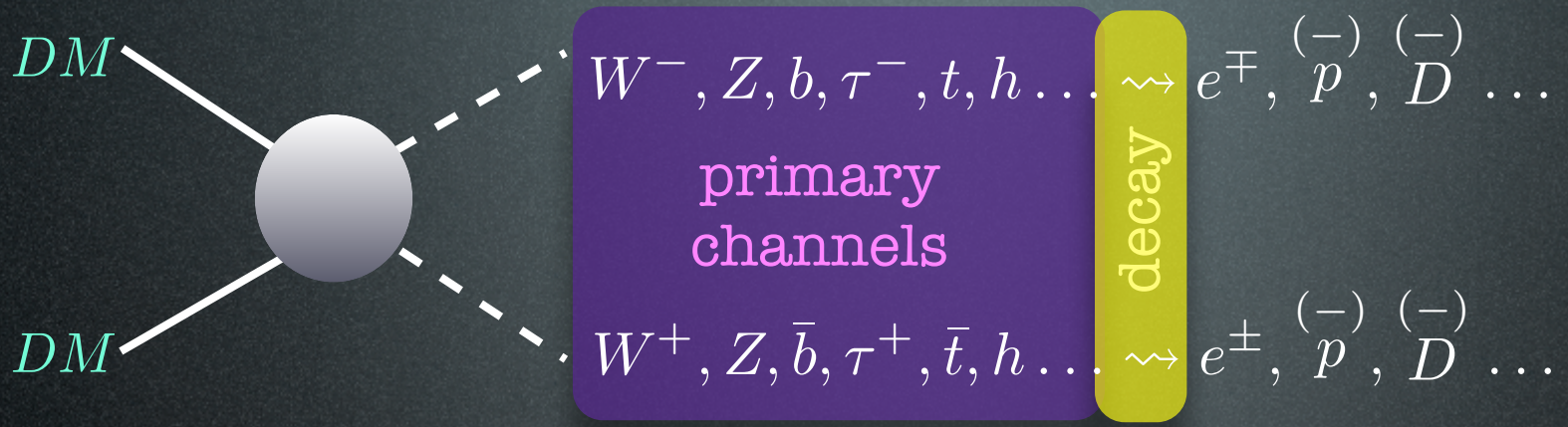


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

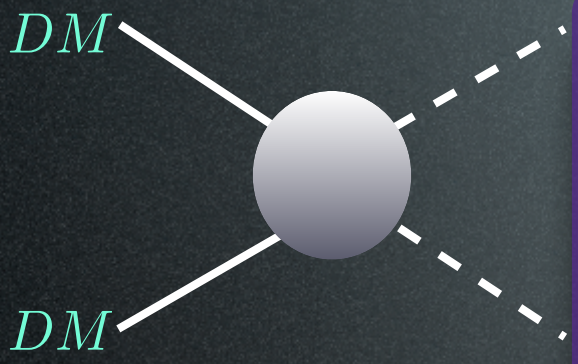
primary channels

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

Indirect Detection: basics



Indirect Detection: basics



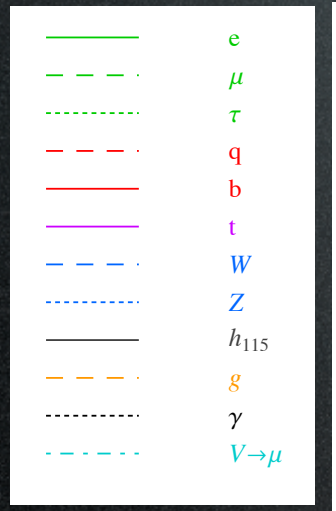
$W^-, Z, b, \tau^-, t, h \ldots$ ⇝ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

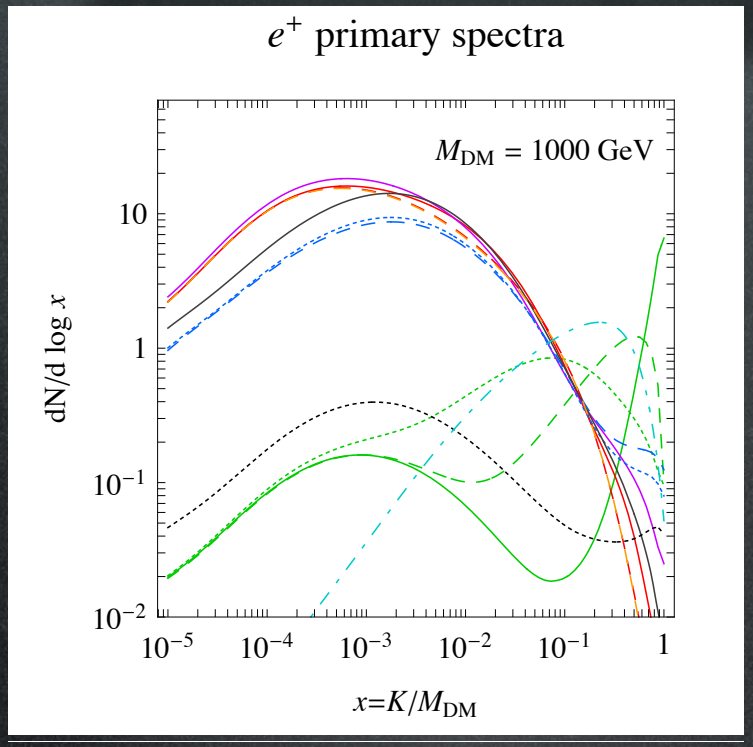
primary channels

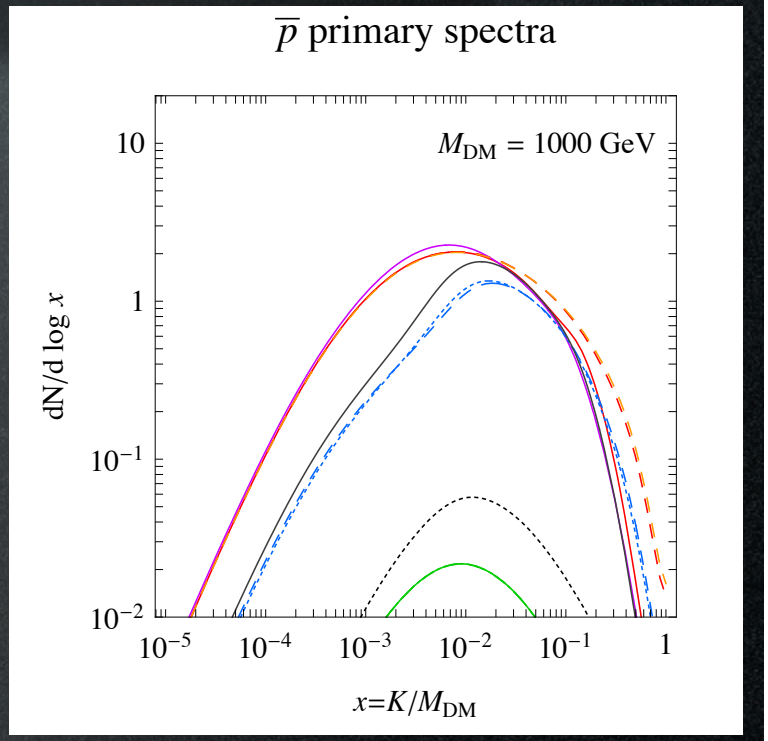
decay

final products

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



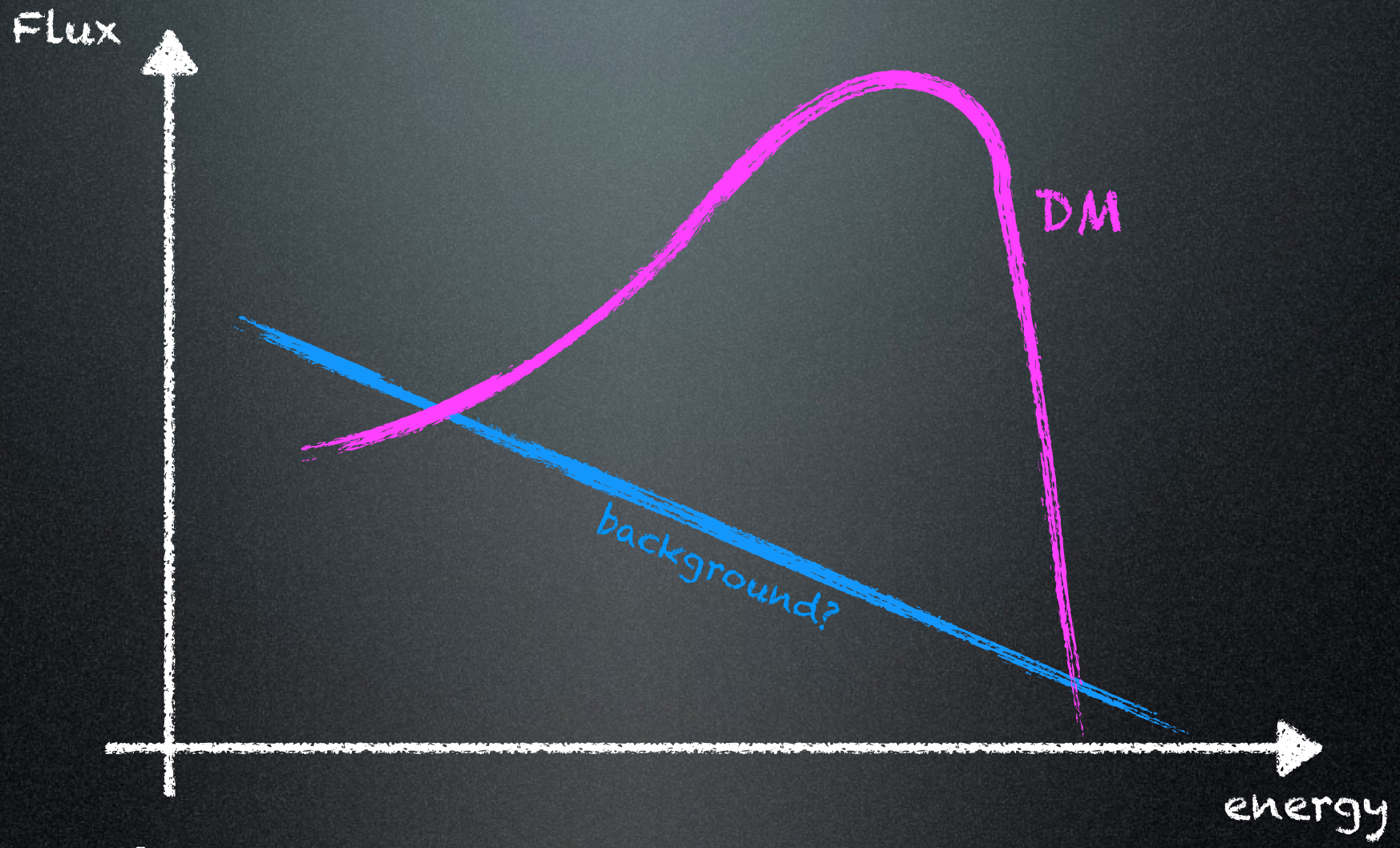




$$\frac{dN_{e^\pm}}{dE}$$

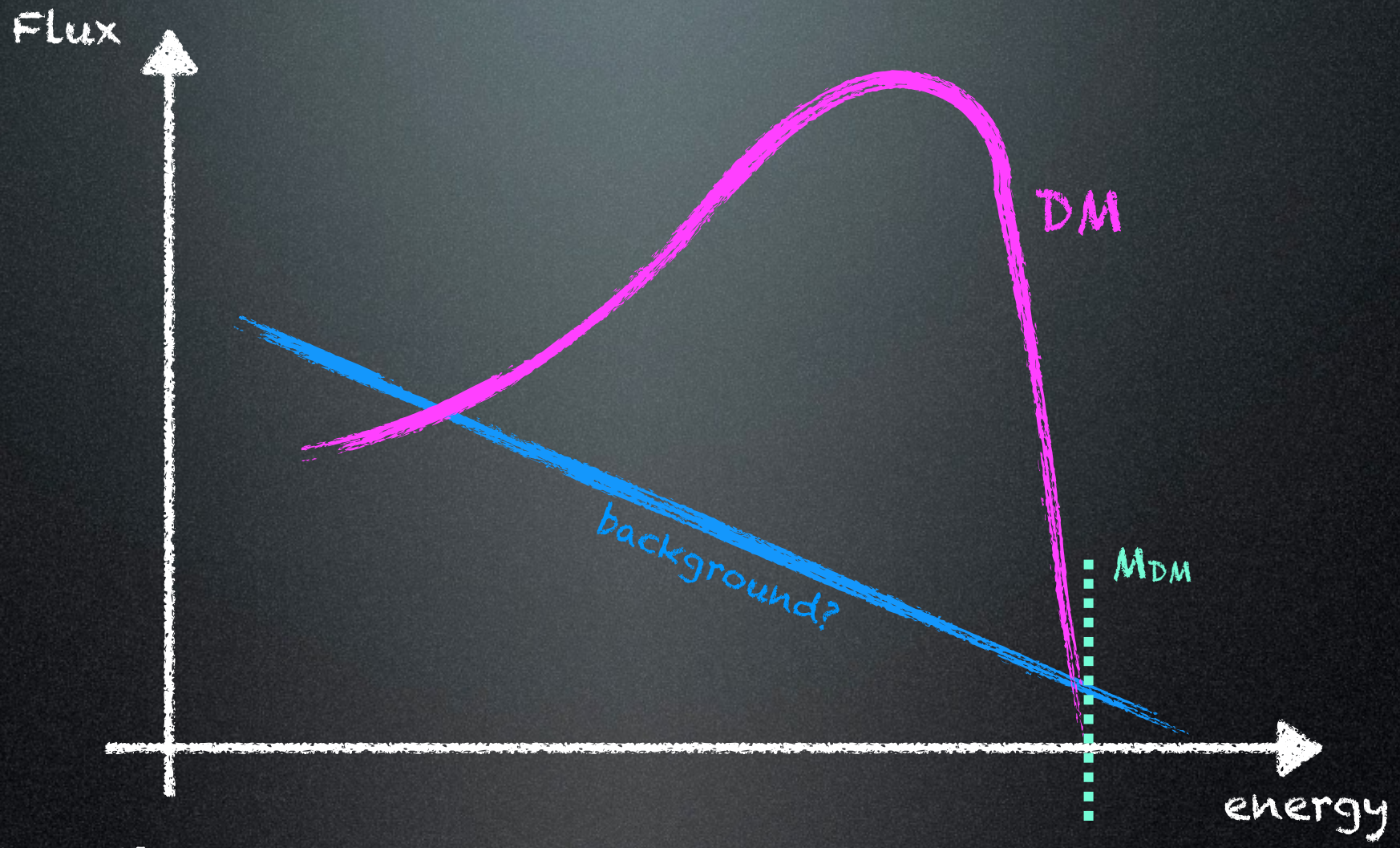
$$\frac{dN_{\bar{p}}}{dE}$$

Fluxes at production



So what are the particle physics parameters?

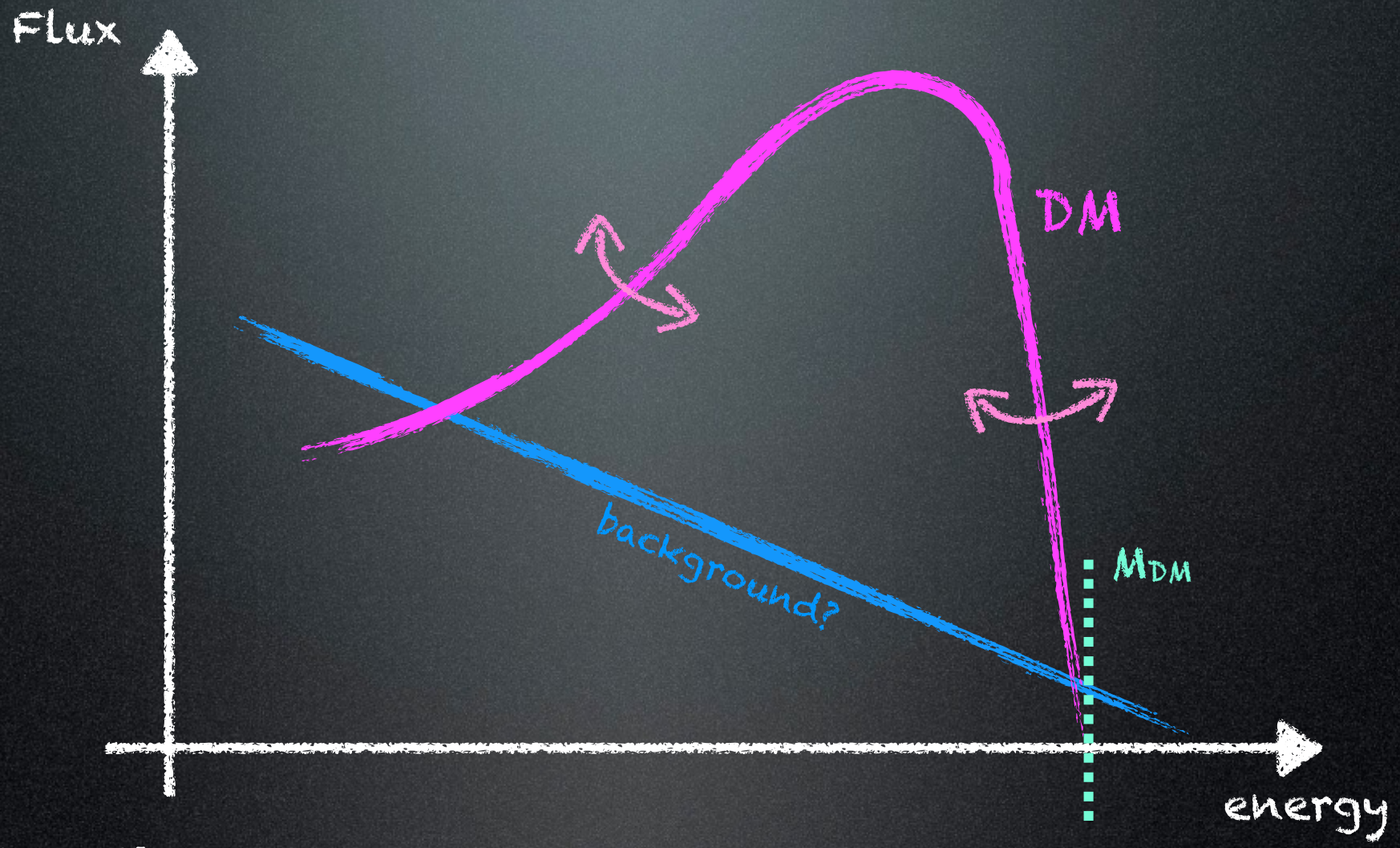
Fluxes at production



So what are the particle physics parameters?

1. Dark Matter mass

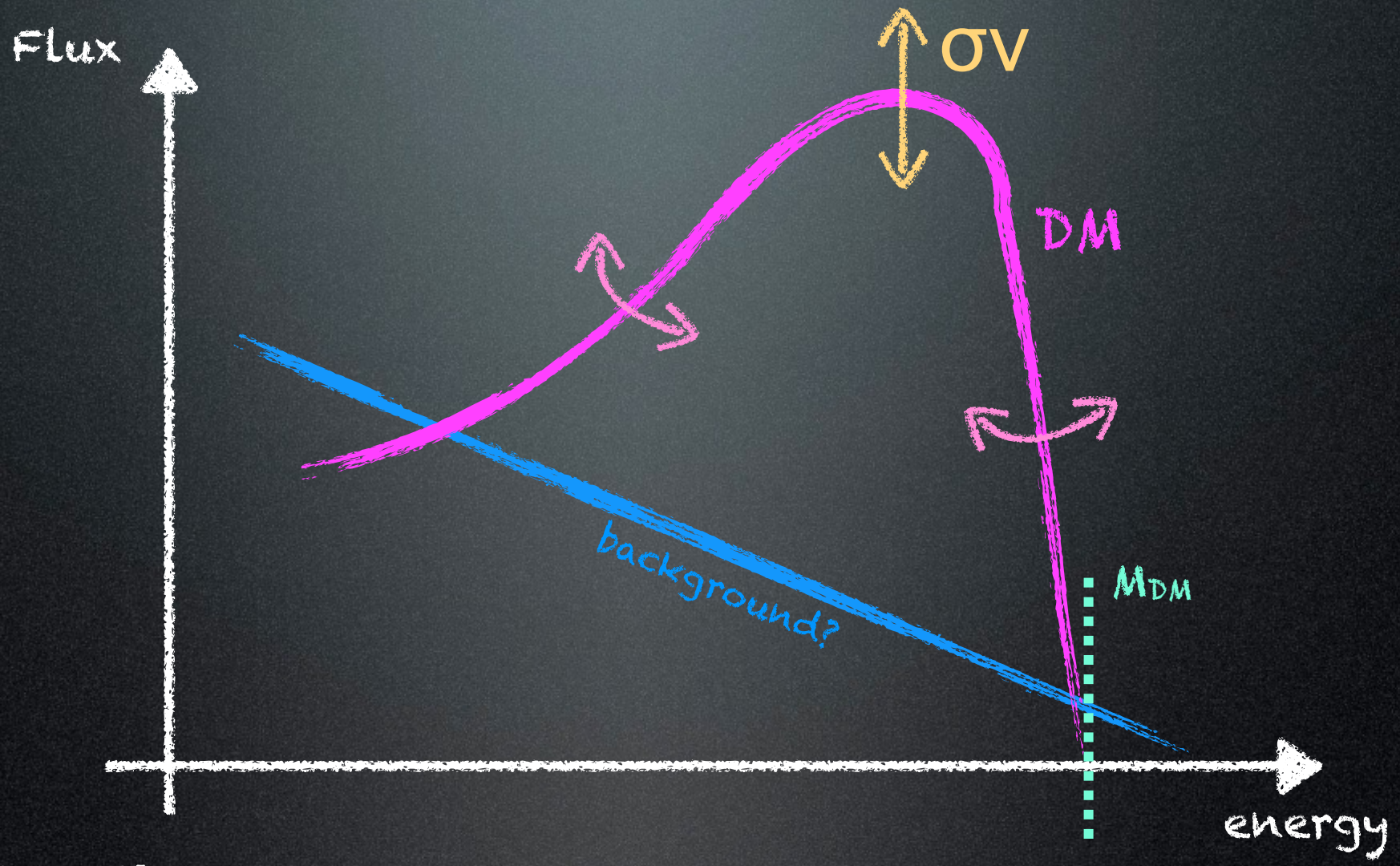
Fluxes at production



So what are the particle physics parameters?

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

Fluxes at production

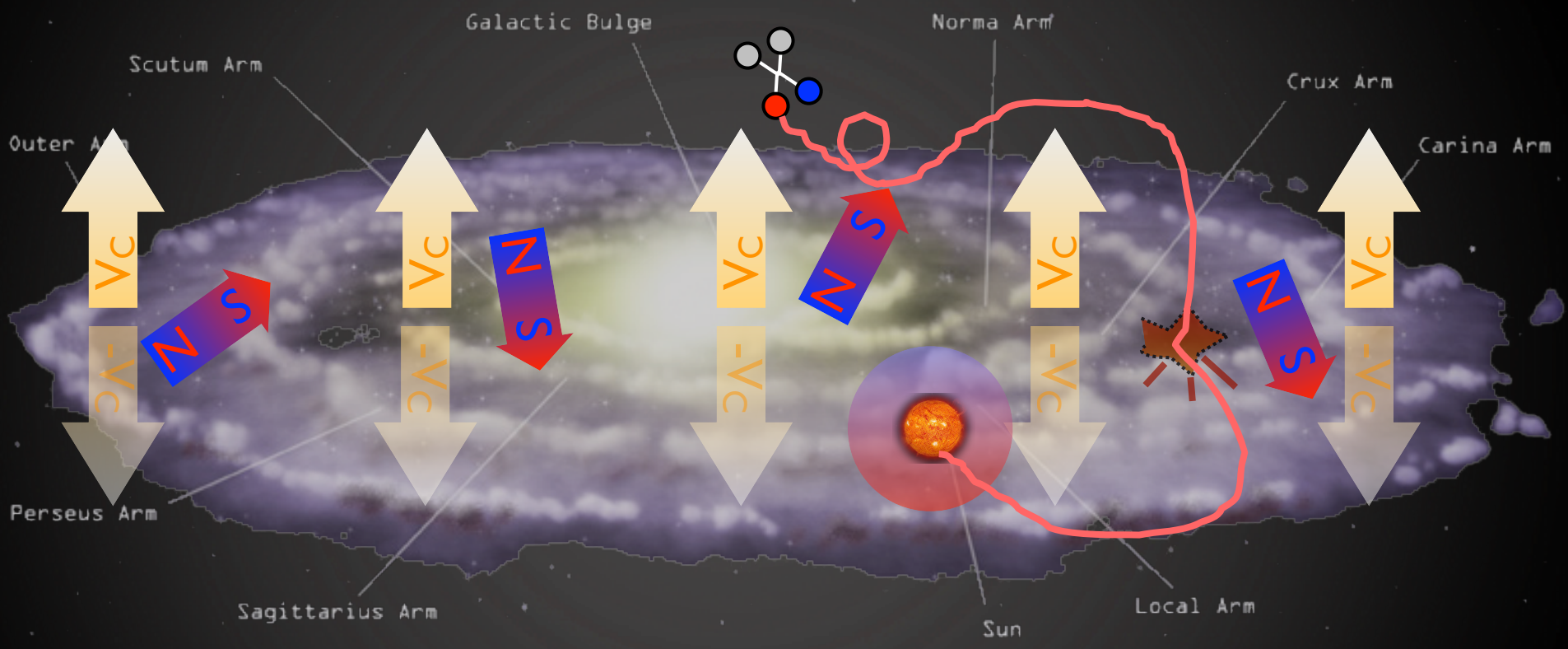


So what are the particle physics parameters?

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

Indirect Detection: basics

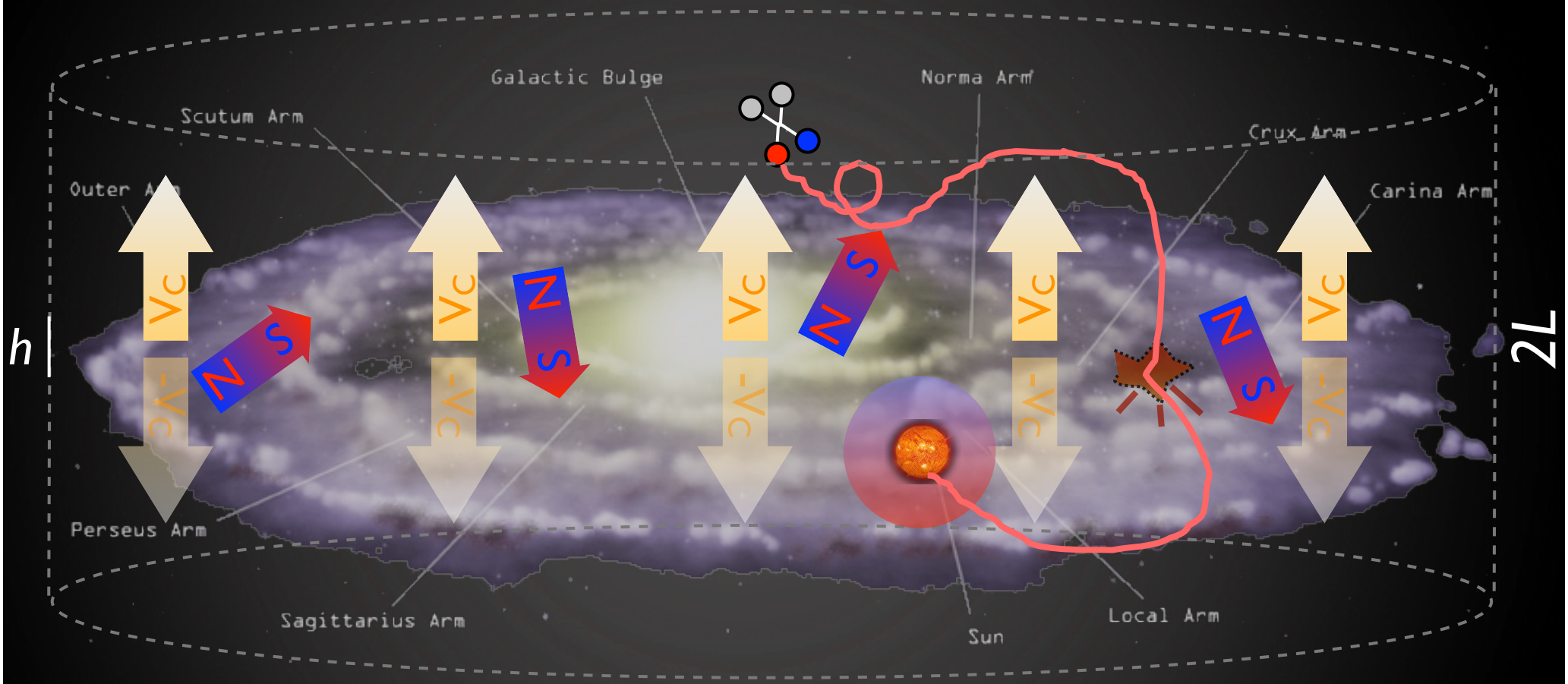
$\bar{p}$ and e^+ from DM annihilations in halo



1.diffusion (on magnetic field granularities)
2.energy losses (ICS, bremsstrahlung, synchrotron)
3.convection
4.spallations
5.solar influence

Indirect Detection: basics

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



spectrum

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

$K(E) = K_0 E^\delta$

diffusion | energy loss | convective wind | source | spallations

Indirect Detection: basics

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

Model	Electrons or positrons δ	$\mathcal{K}_0$ [kpc^2/Myr]	Antiprotons (and antideuterons) δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.55	0.00595	0.85	0.0016	13.5	1
MED	0.70	0.0112	0.70	0.0112	12	4
MAX	0.46	0.0765	0.46	0.0765	5	15

Donato et al., 2003+

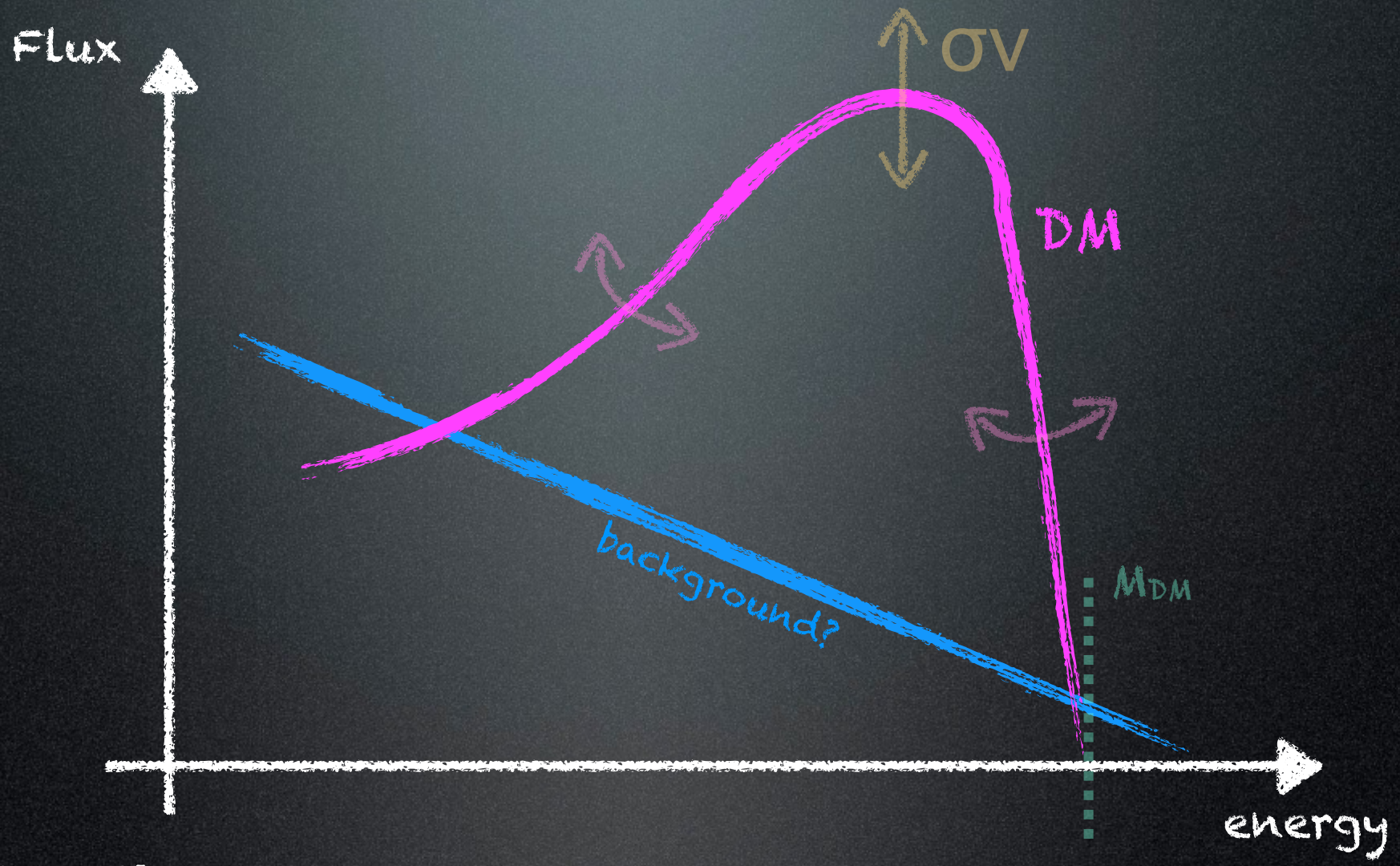
TABLE I: Propagation parameters for the MIN, MED, and MAX benchmarks for SLIM.

SLIM	L [kpc]	δ	$\log_{10} K_0$ [kpc^2 Myr^{-1}]	$R_{\rm l}$ [GV]	$\delta_{\rm l}$
MAX	8.40	0.490	-1.18	4.74	-0.776
MED	4.67	0.499	-1.44	4.48	-1.11
MIN	2.56	0.509	-1.71	4.21	-1.45

Génolini, Cirelli et al. 2103.04108

Previous historical determinations:
Delahaye et al. 0712.2312
Cirelli et al. 1012.4515
Evoli et al. 1108.0664
…
See also:
Génolini et al. 1904.08917

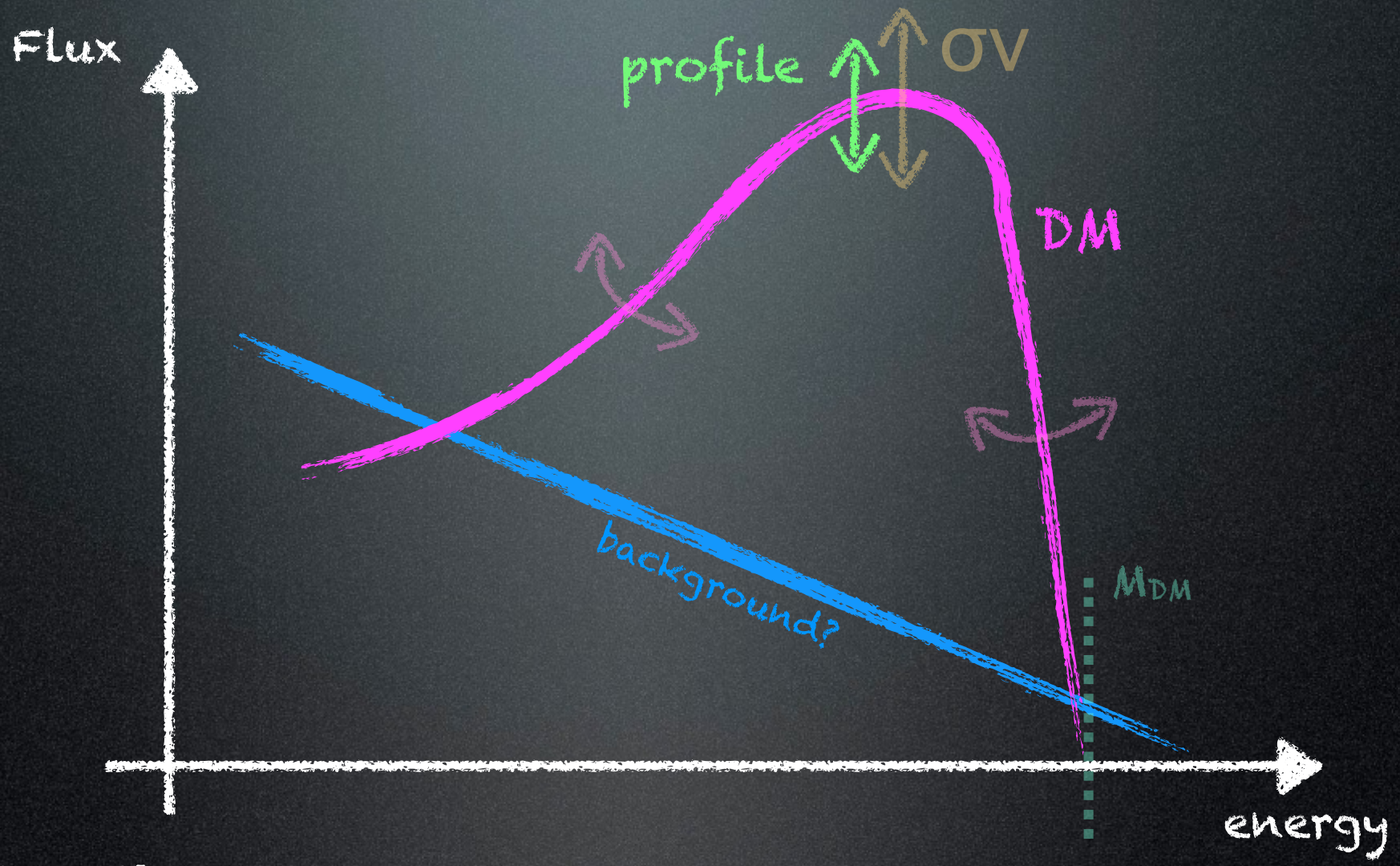
Fluxes at detection



So what are the astrophysics parameters?

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

Fluxes at detection

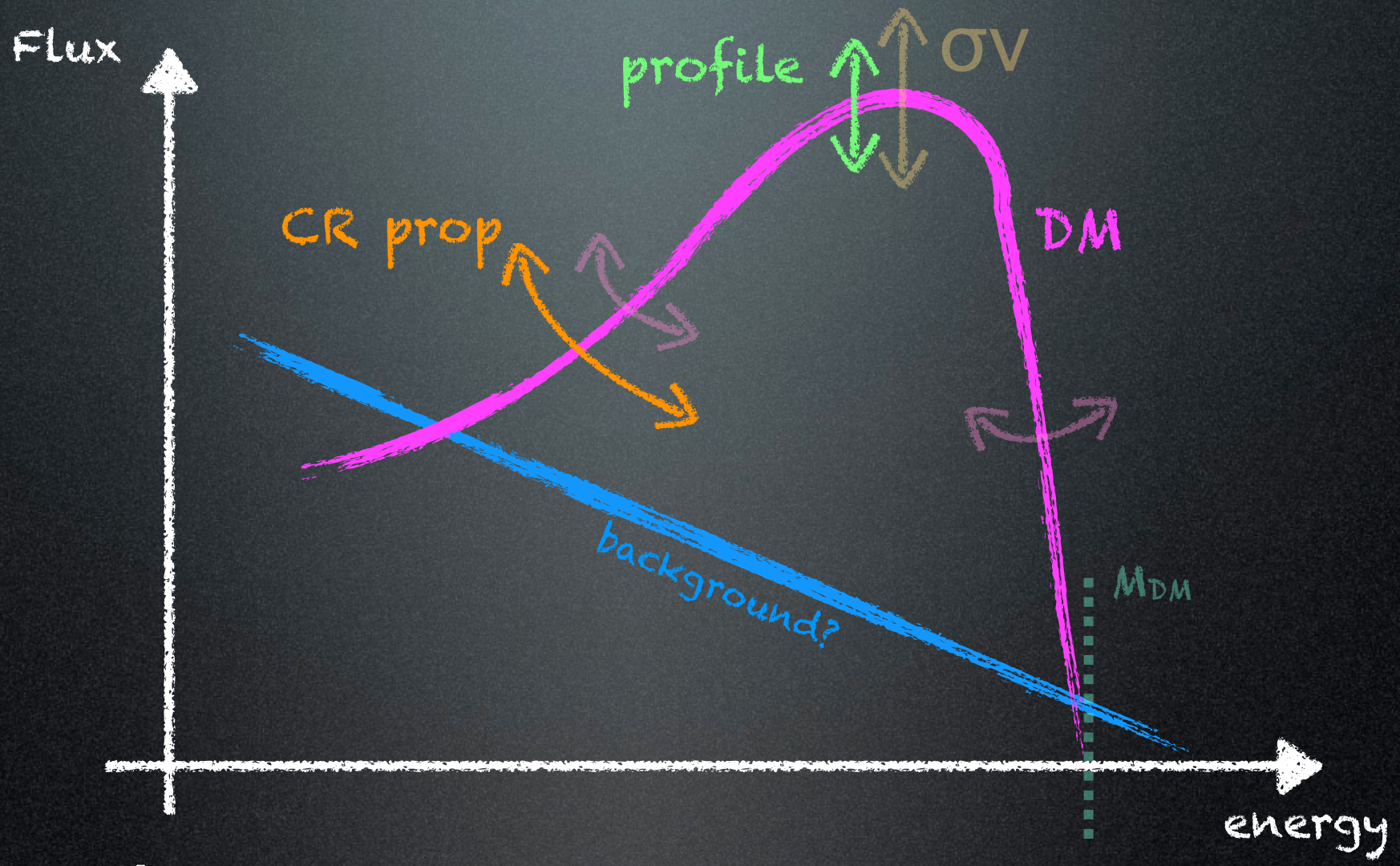


So what are the astrophysics parameters?

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

1. DM abundance/profile

Fluxes at detection

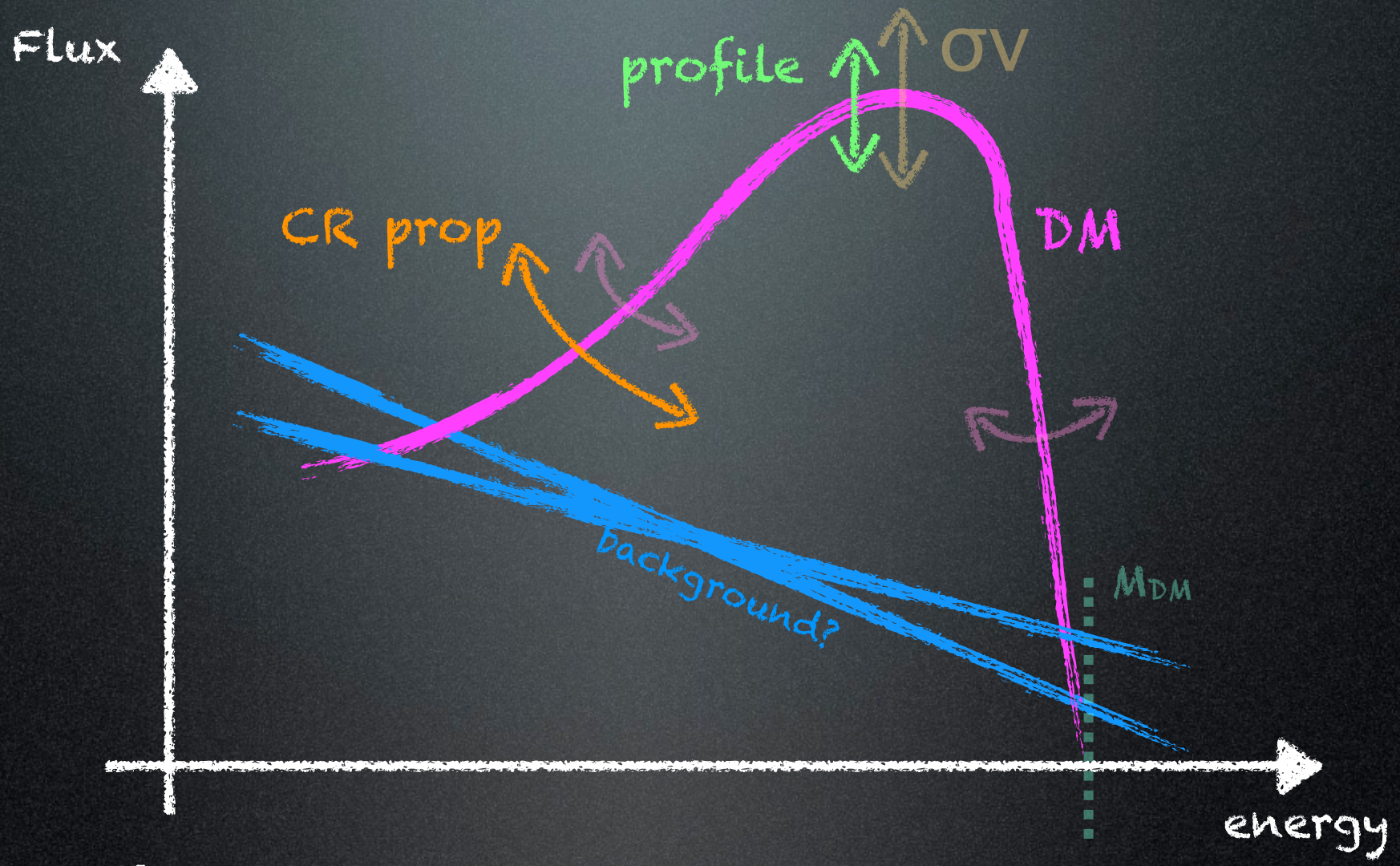


So what are the astrophysics parameters?

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

1. DM abundance/profile
2. propagation

Fluxes at detection

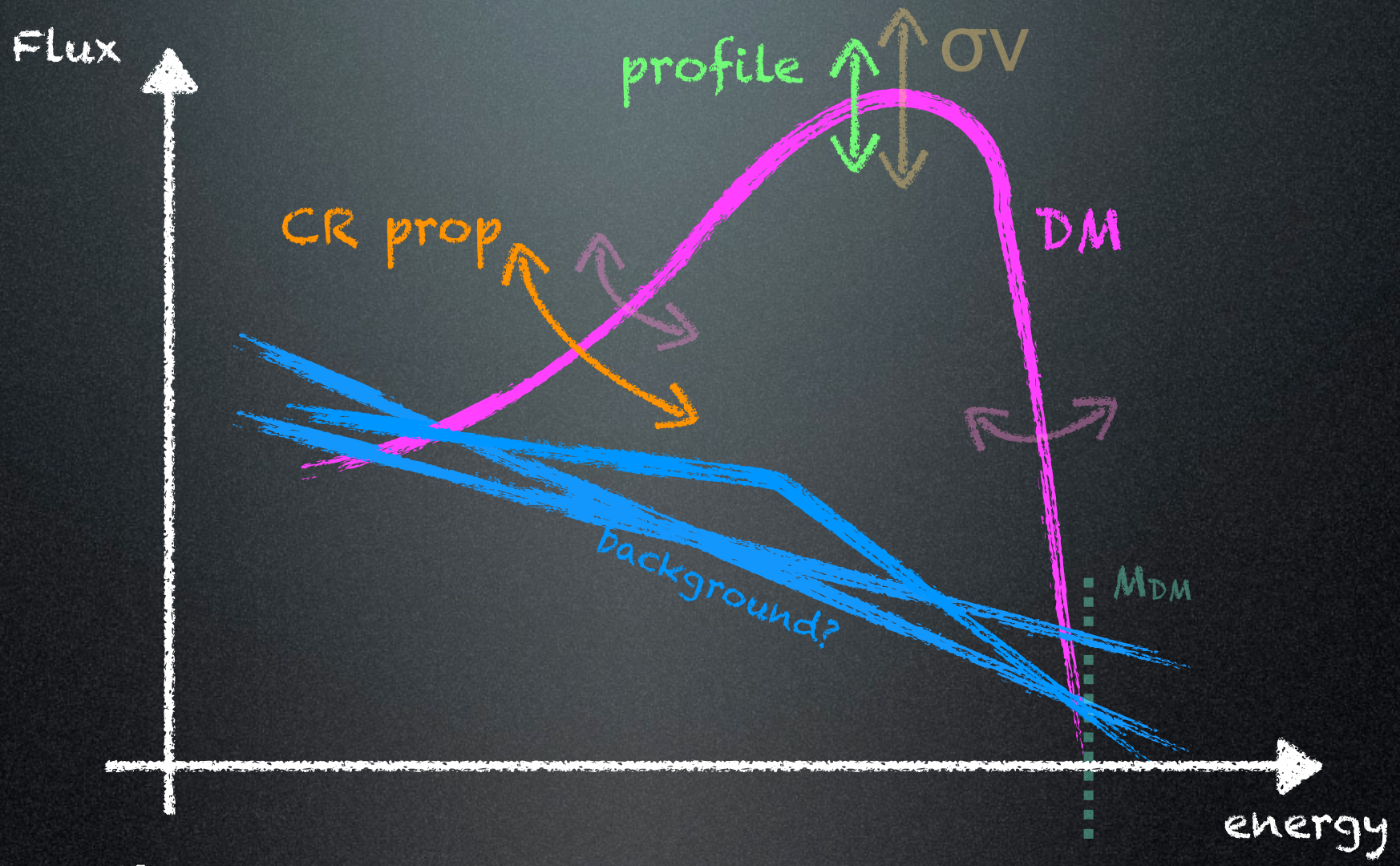


So what are the astrophysics parameters?

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 astrophysics parameters?

1. Dark Matter mass
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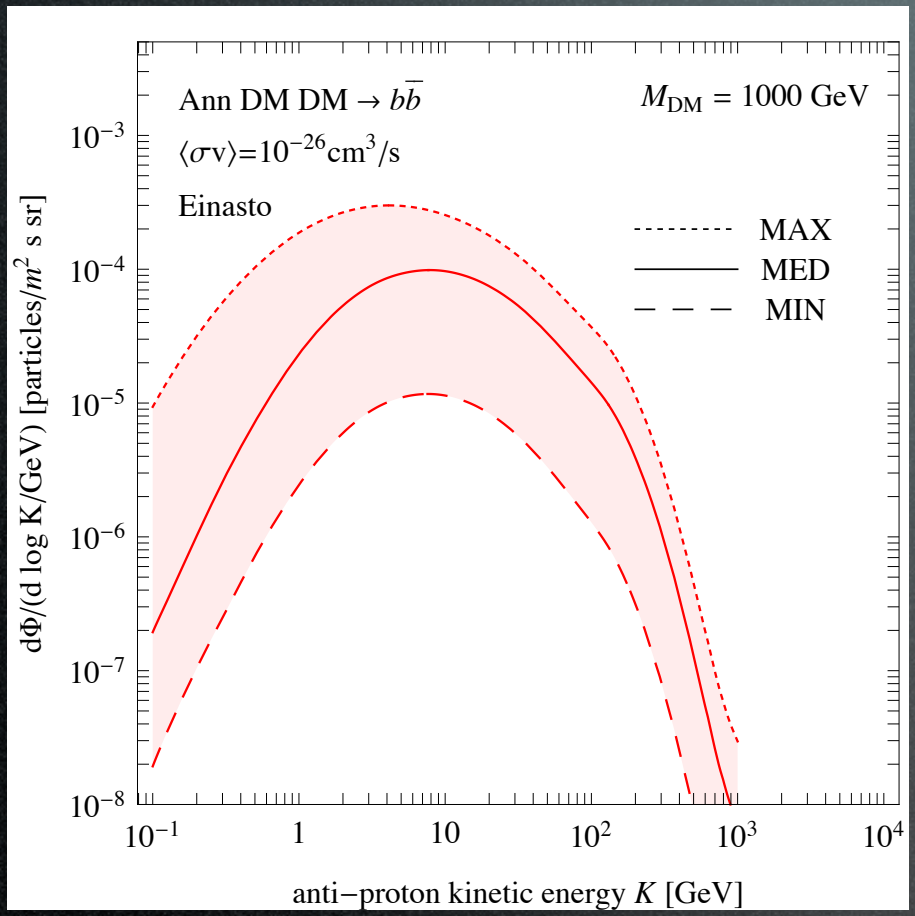
1. DM abundance/profile
2. propagation
3. background

Propagated fluxes

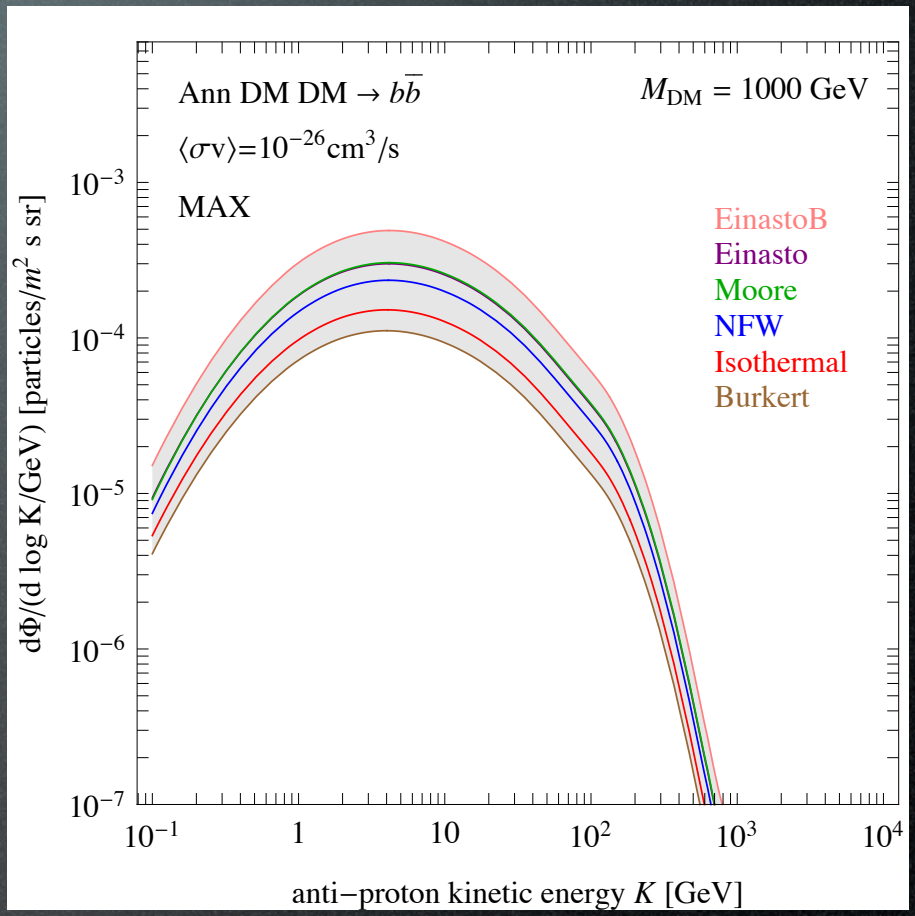
Antiprotons

Varying prop parameters



Almost 2 orders of magnitude

Varying halo profile



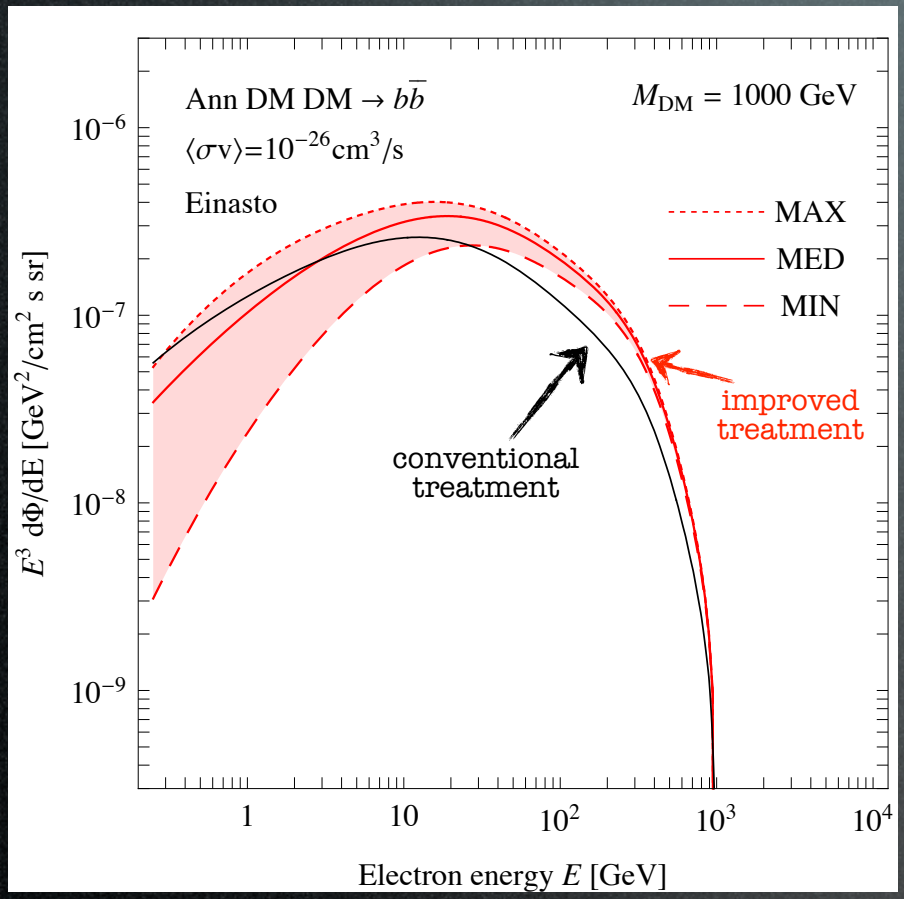
Almost 1 order of magnitude

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

Propagated fluxes

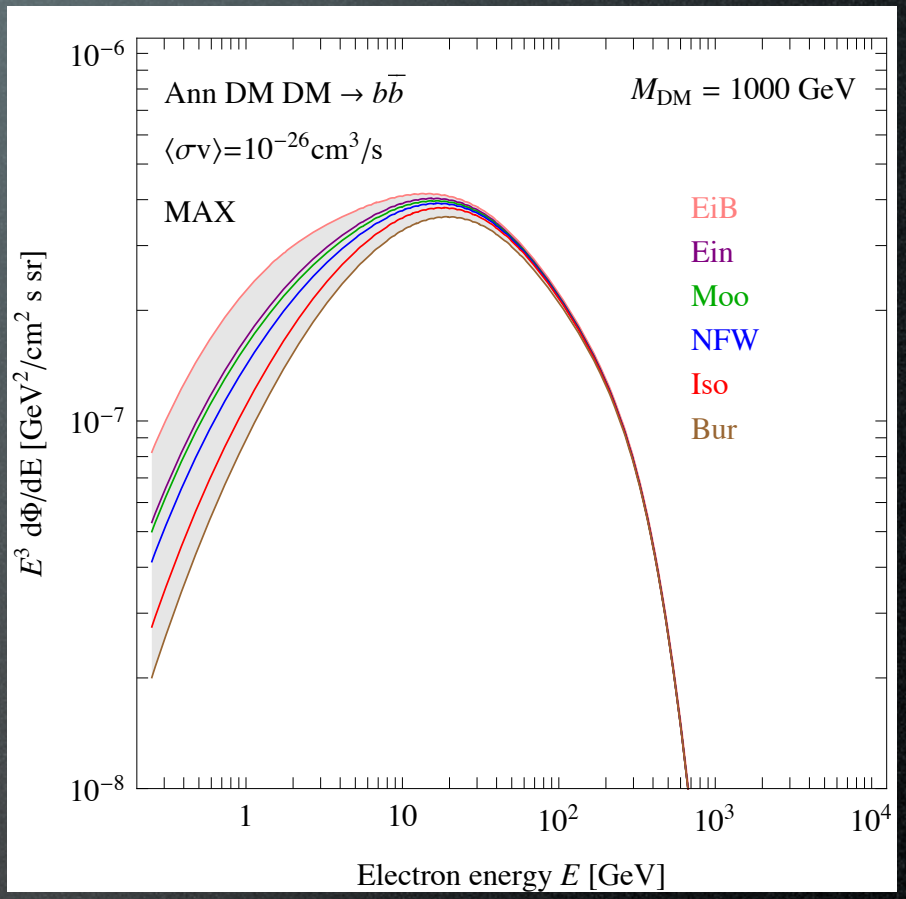
Positrons

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

DM detection

direct detection

Xenon, LZ, DarkSide, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

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

  Fermi, HESS, X-ray satellites, radio telescopes
- e^+ from annihil in galactic halo or center

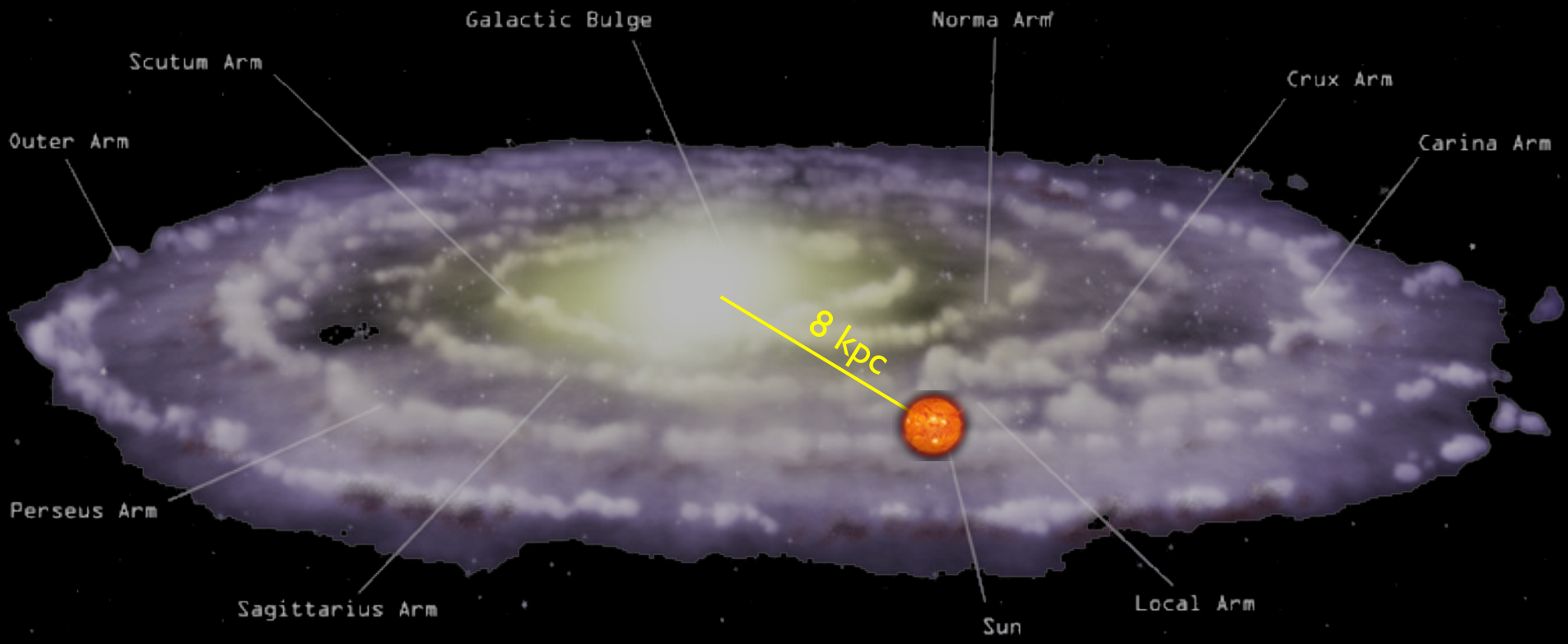
  AMS, Fermi
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center

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

  Icecube, Km3Net

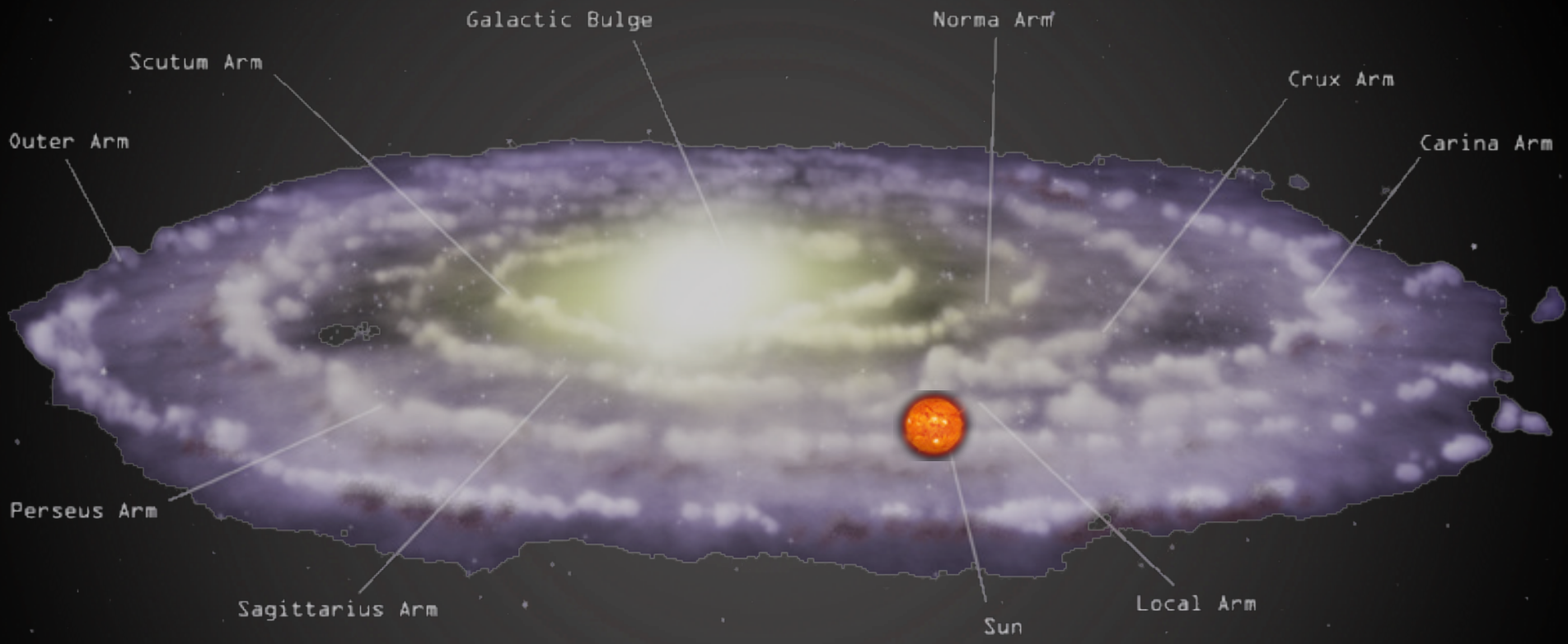
Basic picture

γ from DM annihilations in galactic center



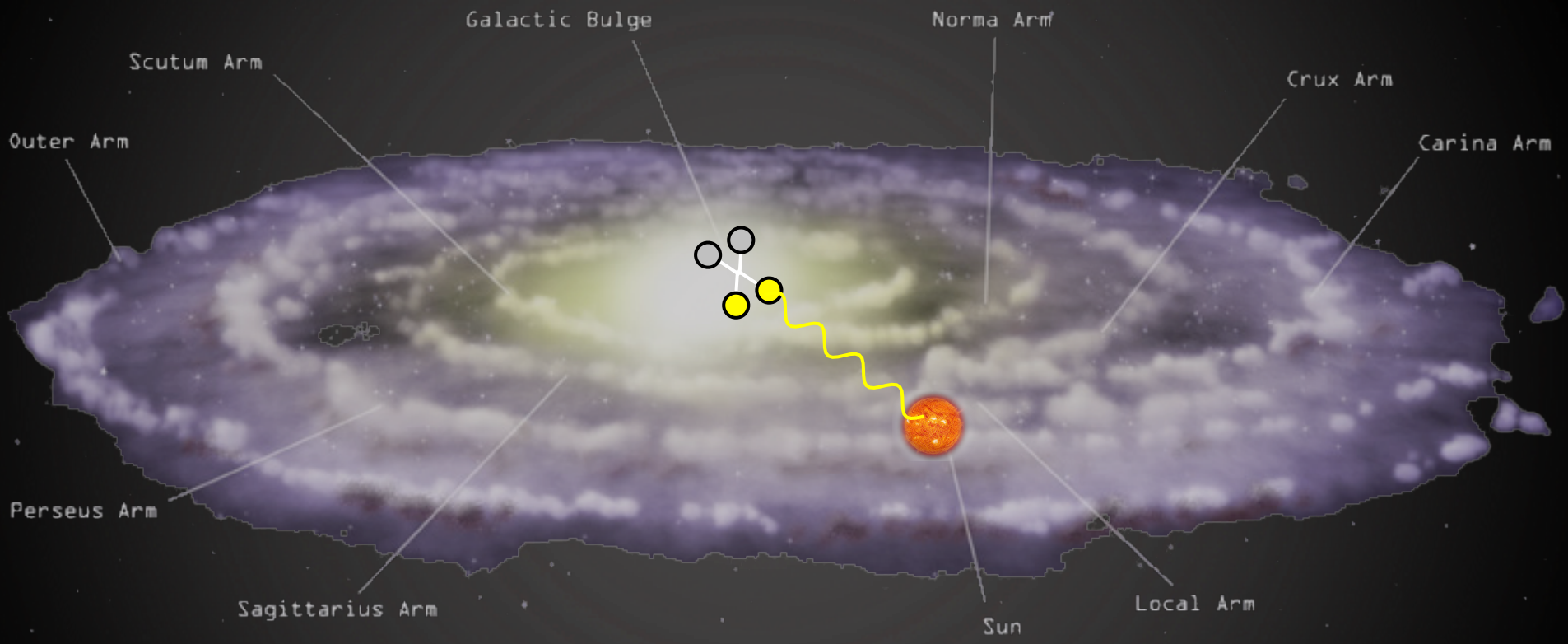
Basic picture

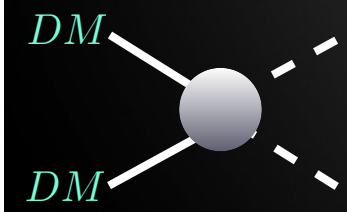
γ from DM annihilations in galactic center



Basic picture

γ from DM annihilations in galactic center





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

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

How does DM produce γ-rays?

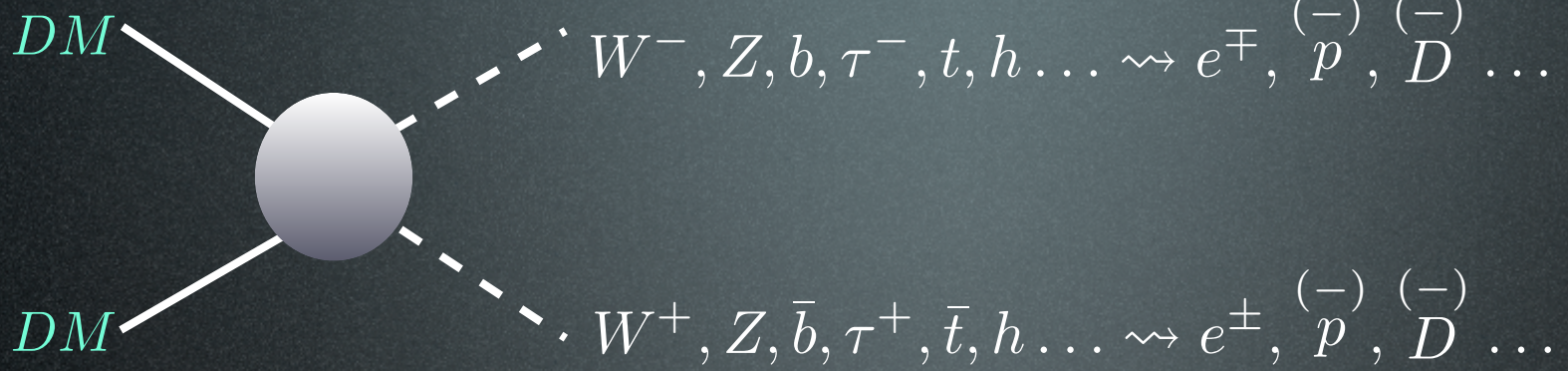
1. prompt emission

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

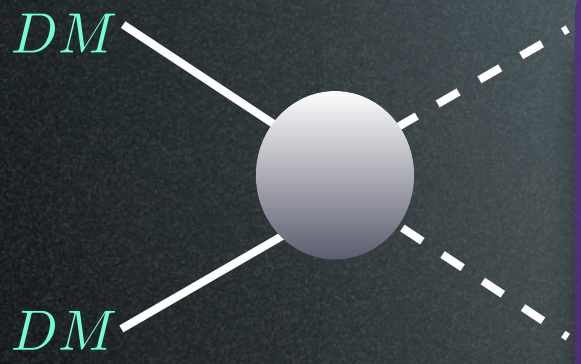
2. secondary emission

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

Prompt emission: continuum



Prompt emission: continuum

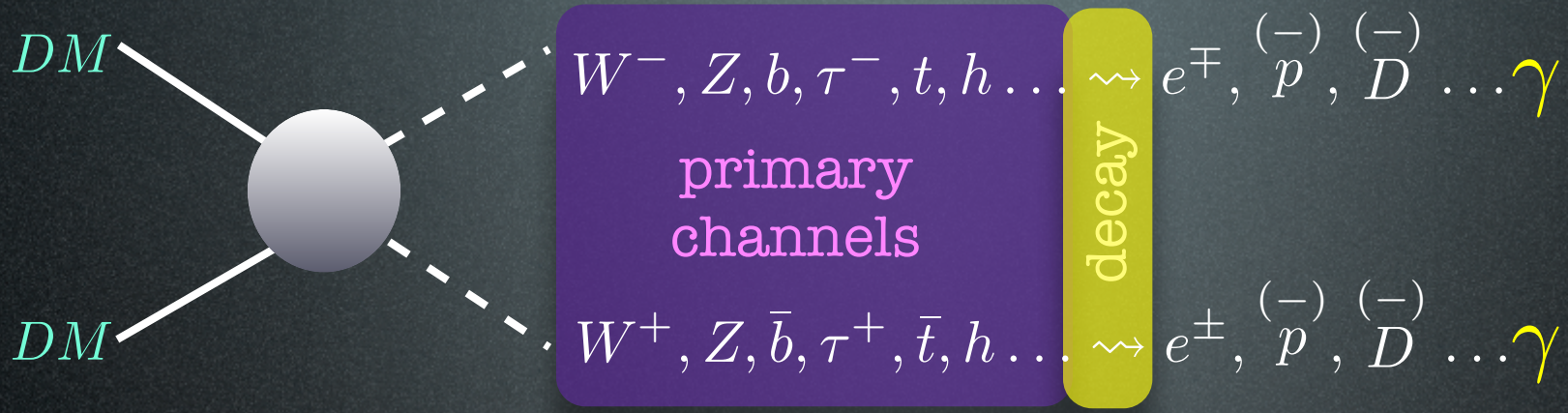


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

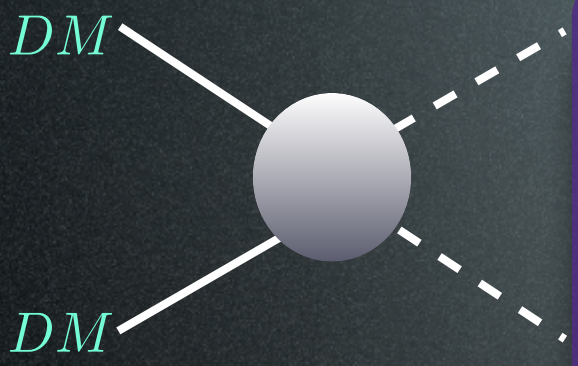
primary channels

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

Prompt emission: continuum



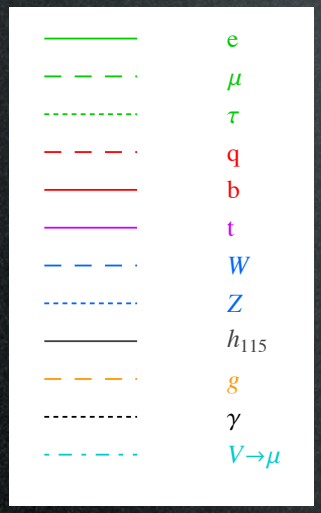
Prompt emission: continuum

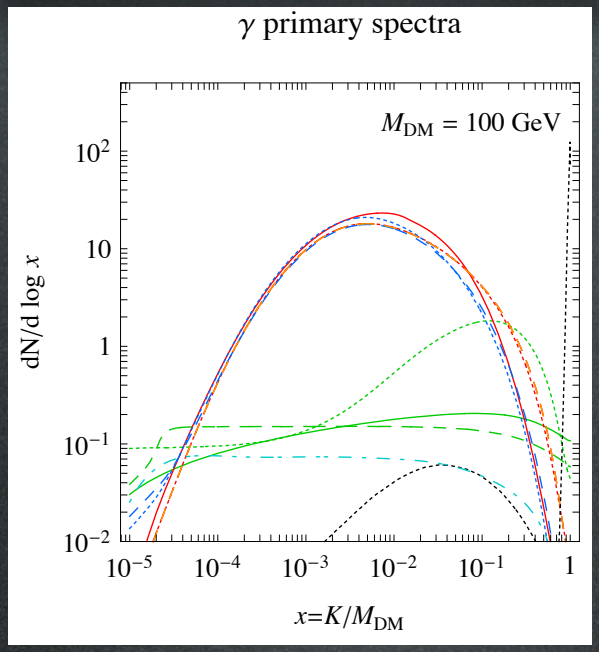


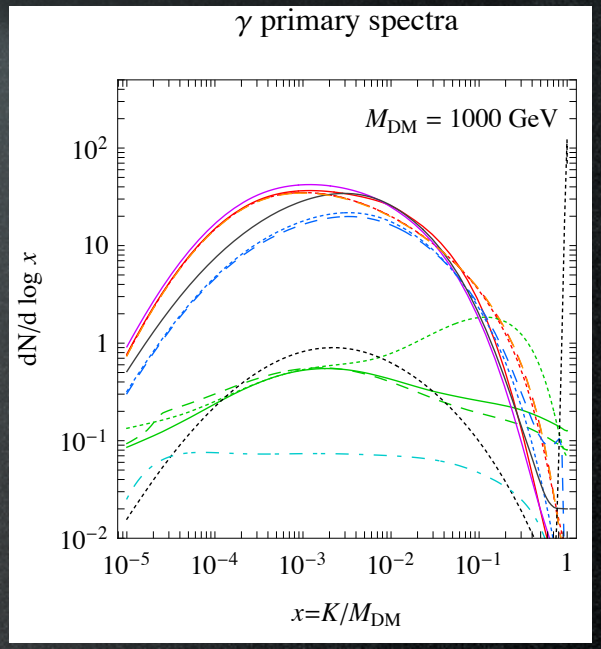
$W^-, Z, b, \tau^-, t, h \ldots$ primary channels $W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

decay $\rightsquigarrow$

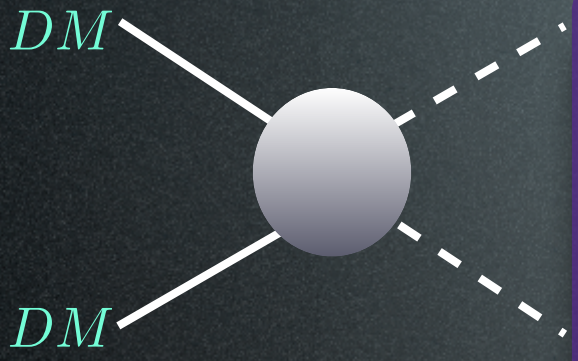
$e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$ final products $e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$





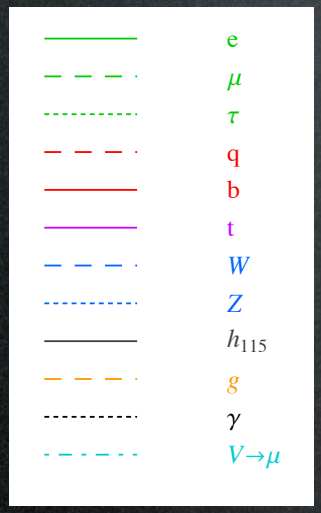


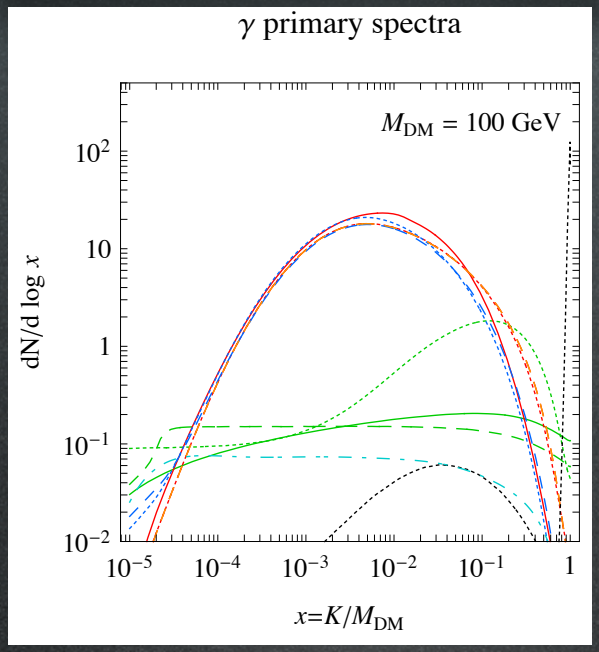
Prompt emission: continuum

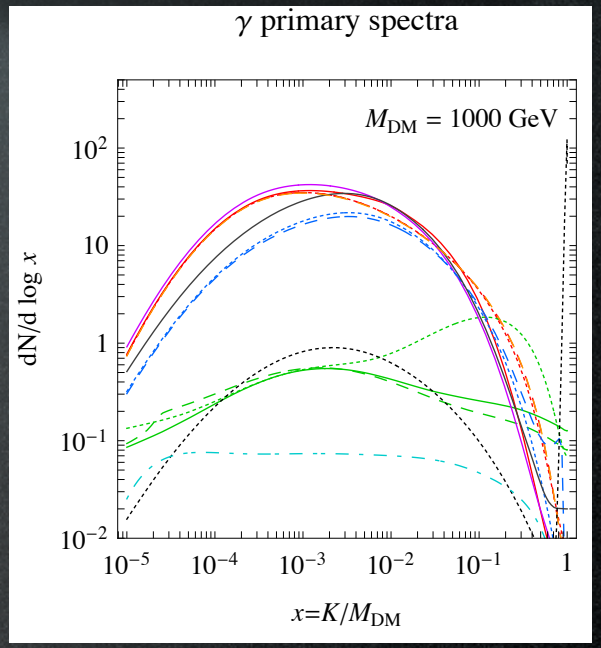


$W^-, Z, b, \tau^-, t, h \ldots$ primary channels $\rightsquigarrow$ (decay) $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma$ final products

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



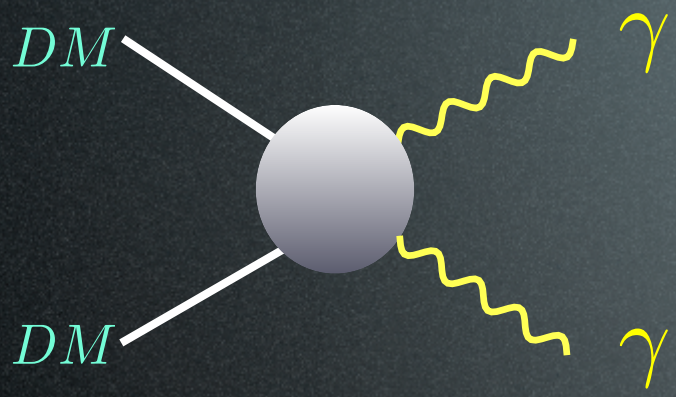




So what are the particle physics parameters?

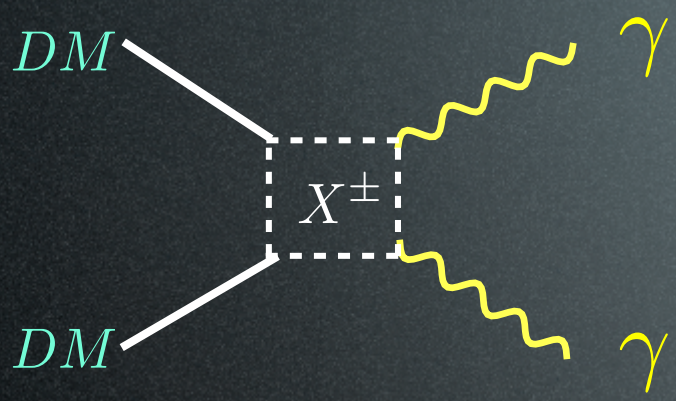
1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: line(s)



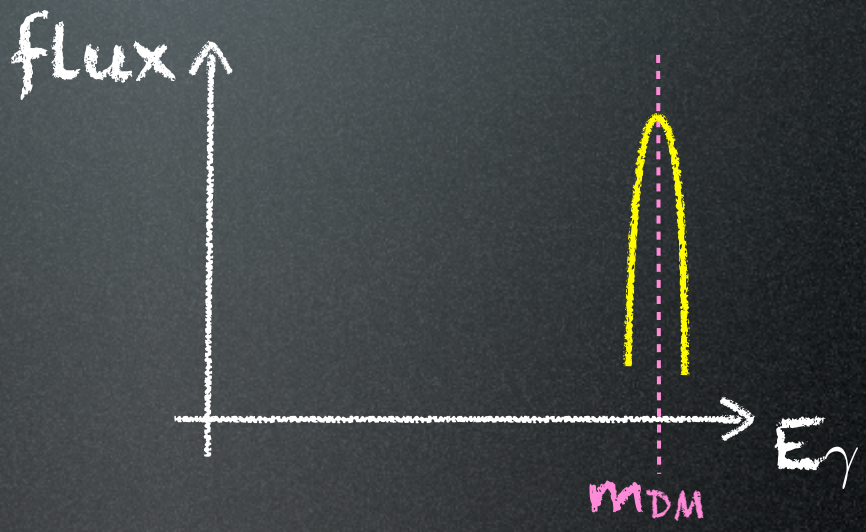
primary
channels

Prompt emission: line(s)

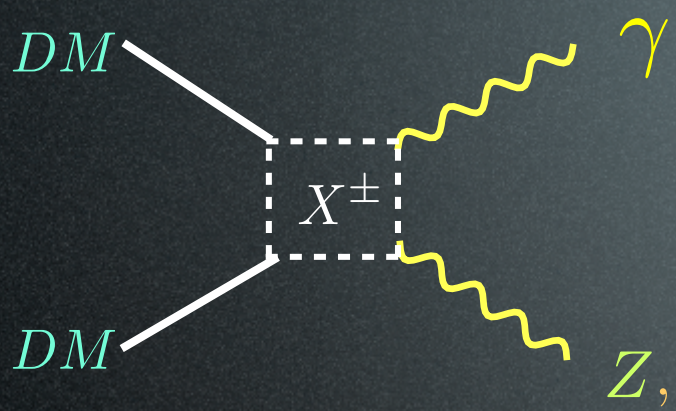


primary channels

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



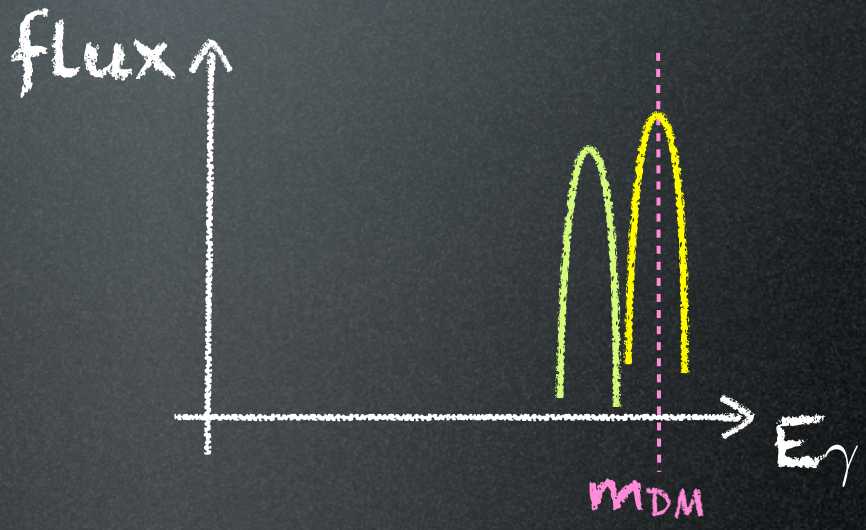
Prompt emission: line(s)



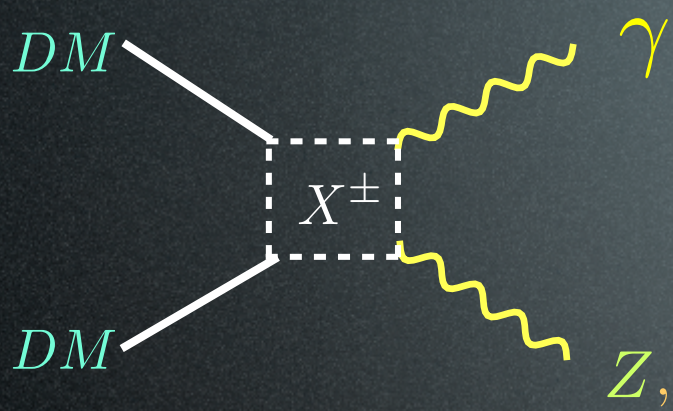
primary channels

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

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



Prompt emission: line(s)



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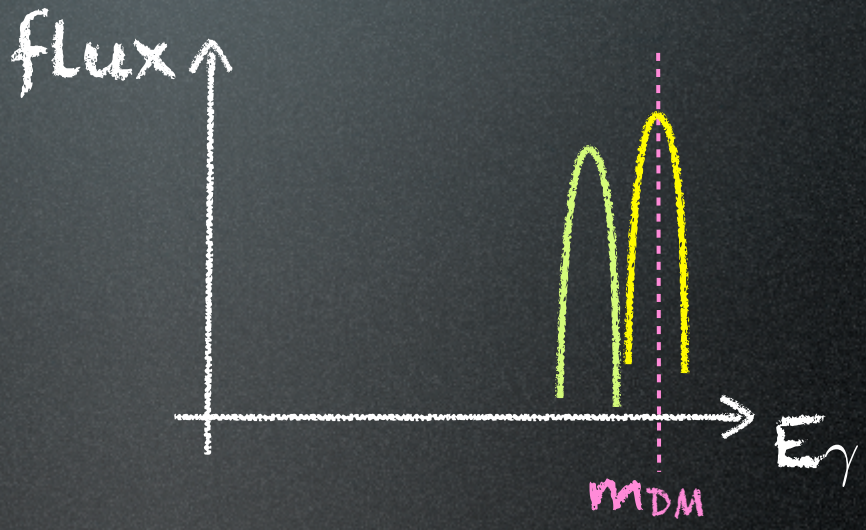


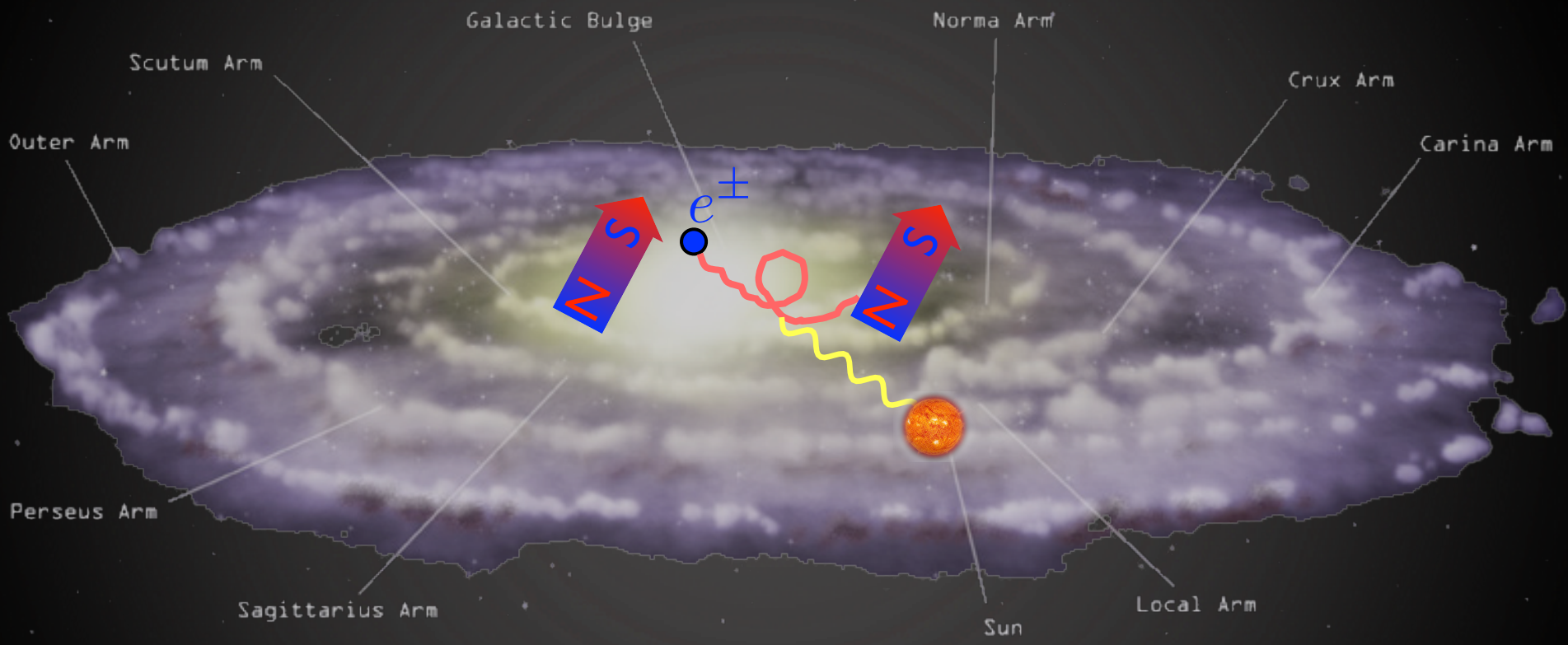
So what are the particle physics parameters?

1. Dark Matter mass

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

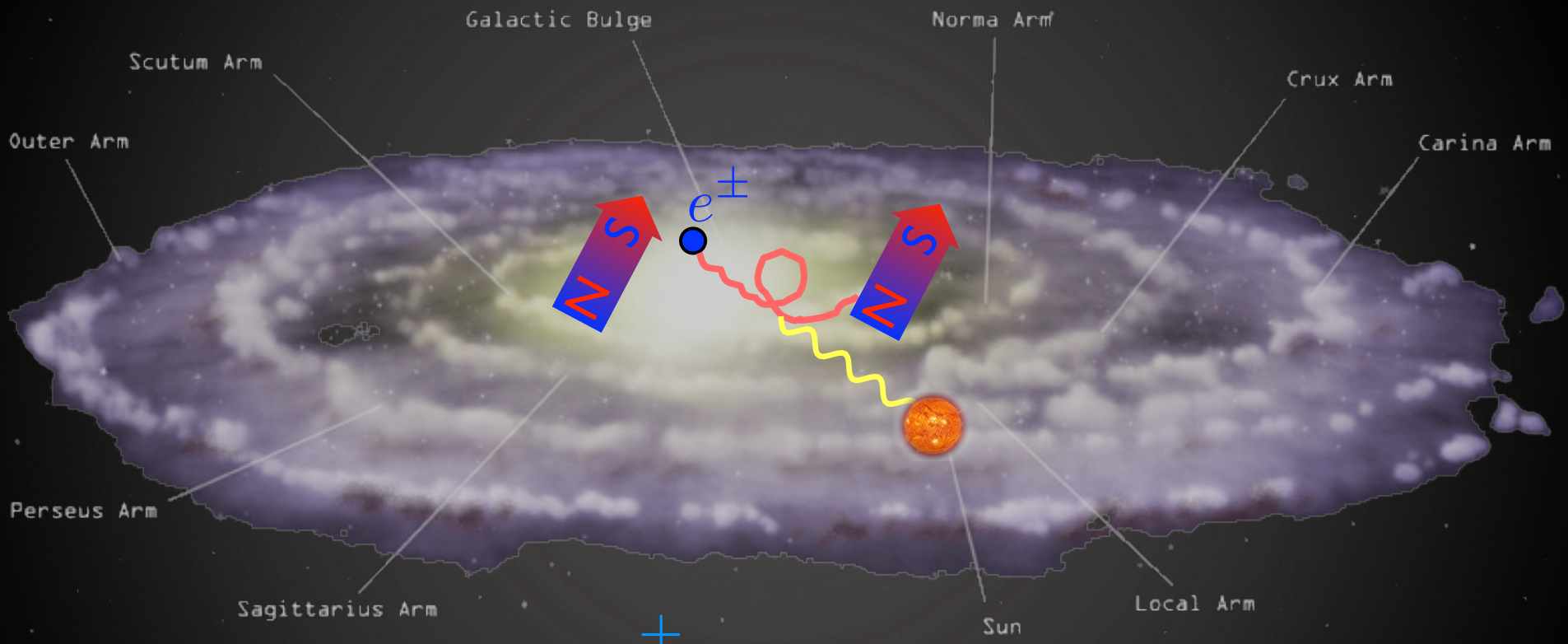
Secondary emission

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



Secondary emission

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

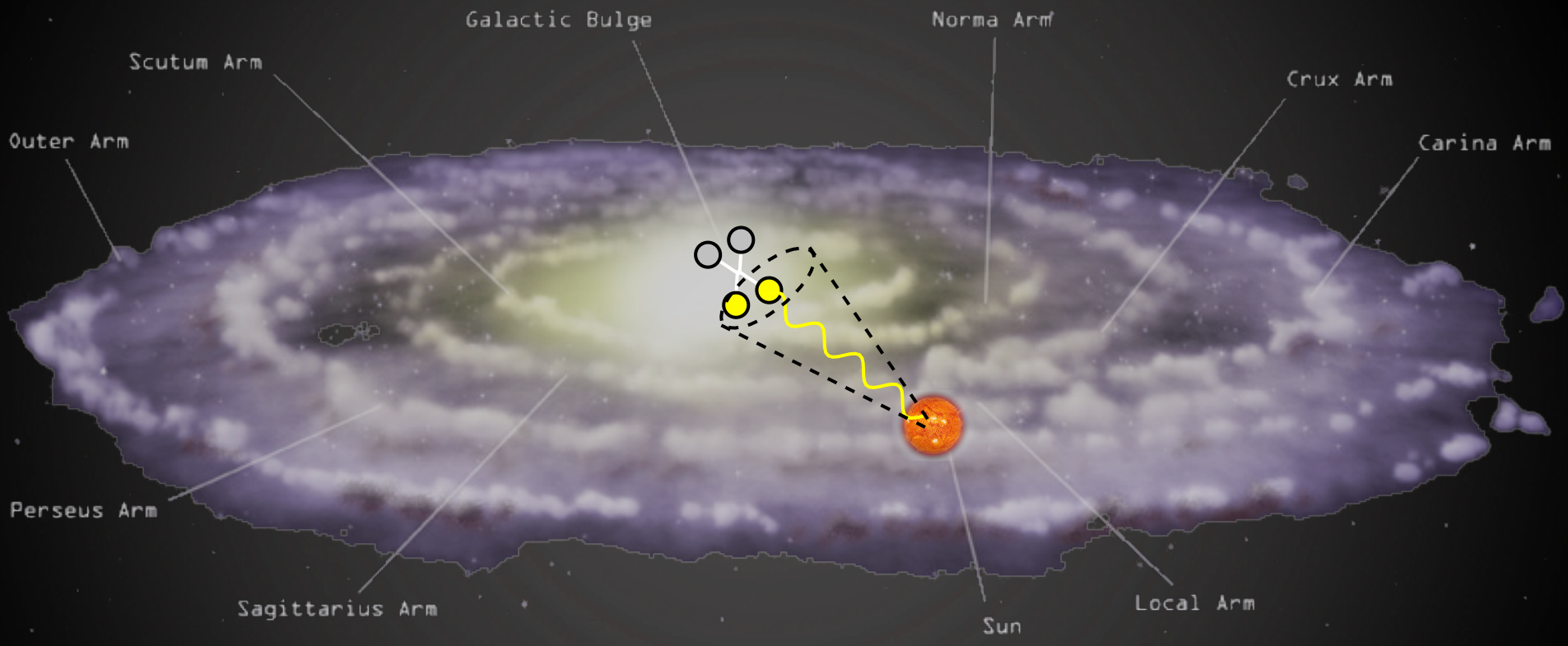


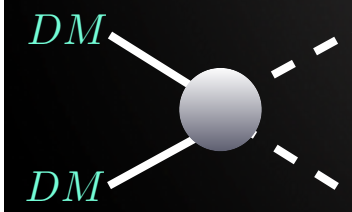
- compute the population of $e^{\pm}$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Basic picture: targets

γ from DM annihilations in galactic center



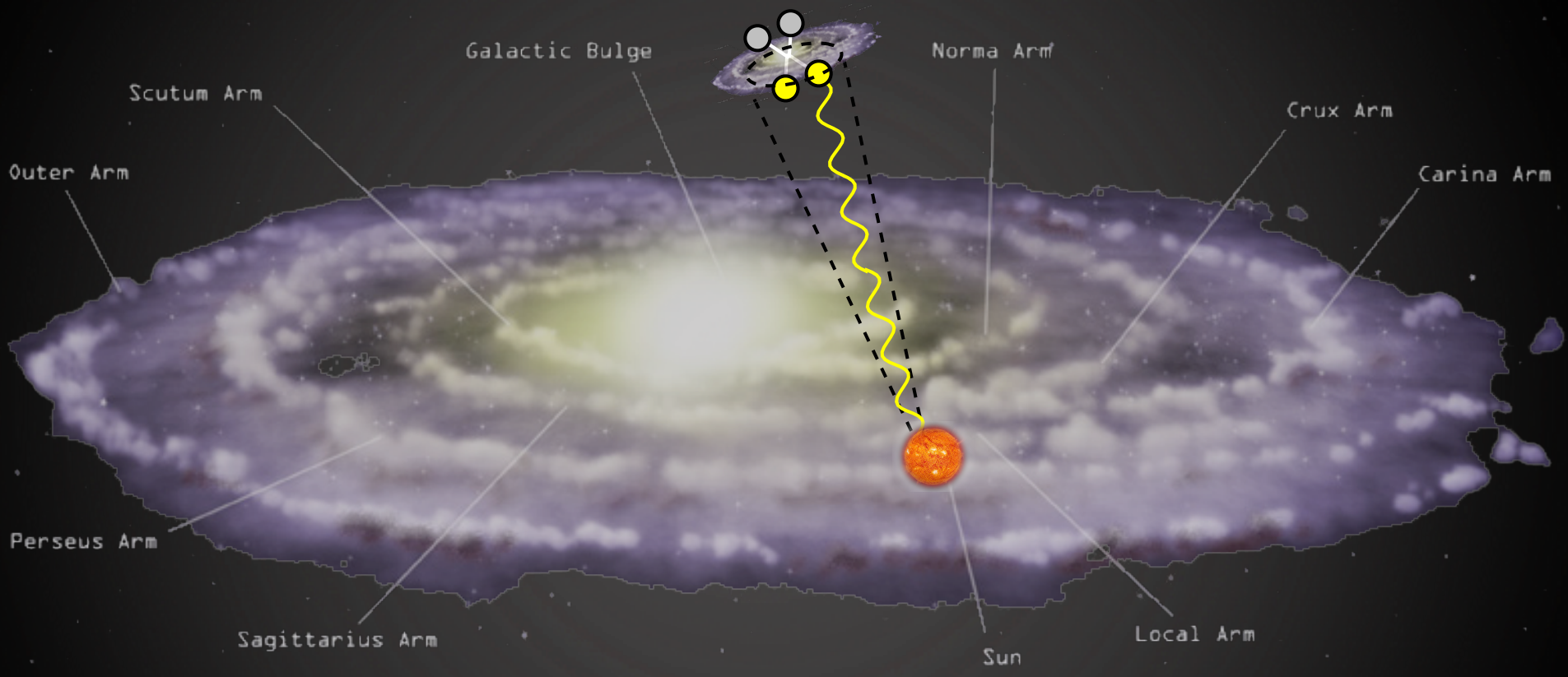


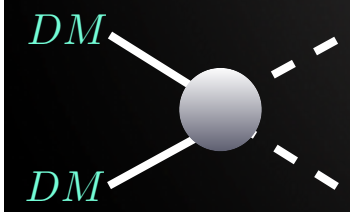
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Basic picture: targets

γ from DM annihilations in dwarf galaxies



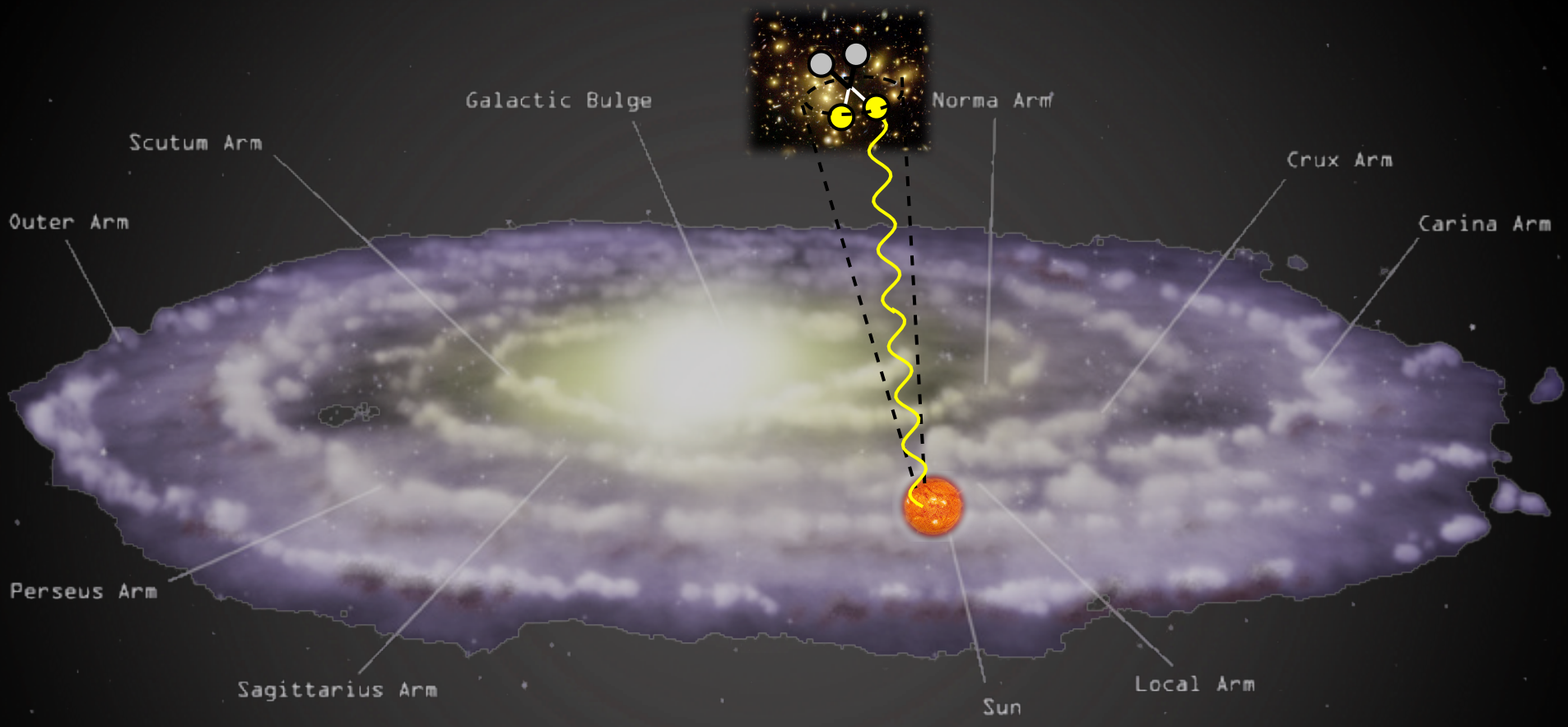


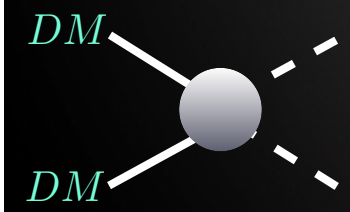
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

Basic picture: targets

γ from DM annihilations in galaxy clusters





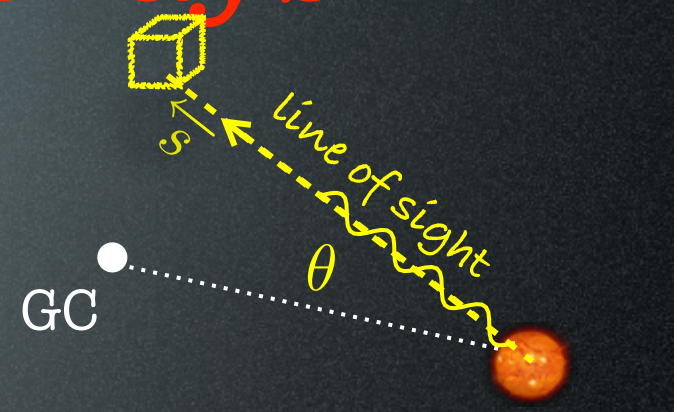
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

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

‘Prompt’ gamma rays

Expected flux:

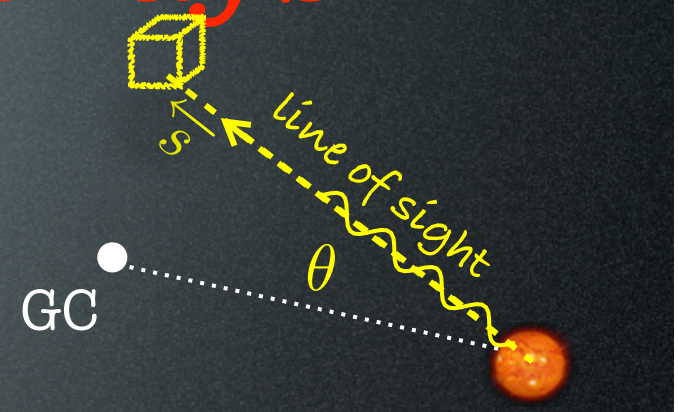
$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{n^2}{4\pi}\sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}$$



‘Prompt’ gamma rays

Expected flux:

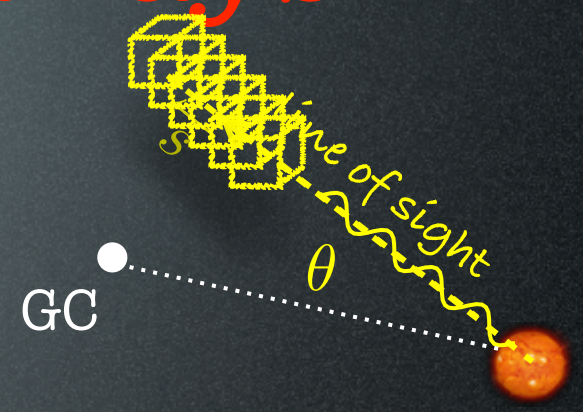
$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{1}{4\pi}\left(\frac{\rho}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}$$



‘Prompt’ gamma rays

Expected flux:

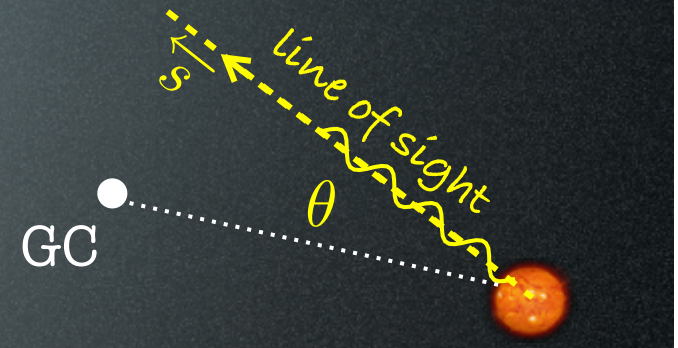
$$\frac{d\Phi_\gamma}{d\Omega\, dE} = \frac{1}{2}\frac{1}{4\pi}\int_{l.o.s.}\left(\frac{\rho(x)}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}$$



‘Prompt’ gamma rays

Expected flux:

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



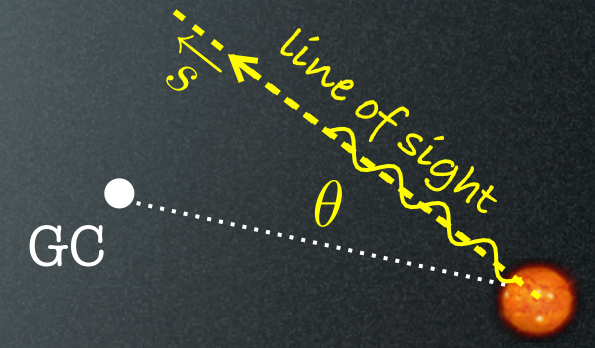
$$J = \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2$$

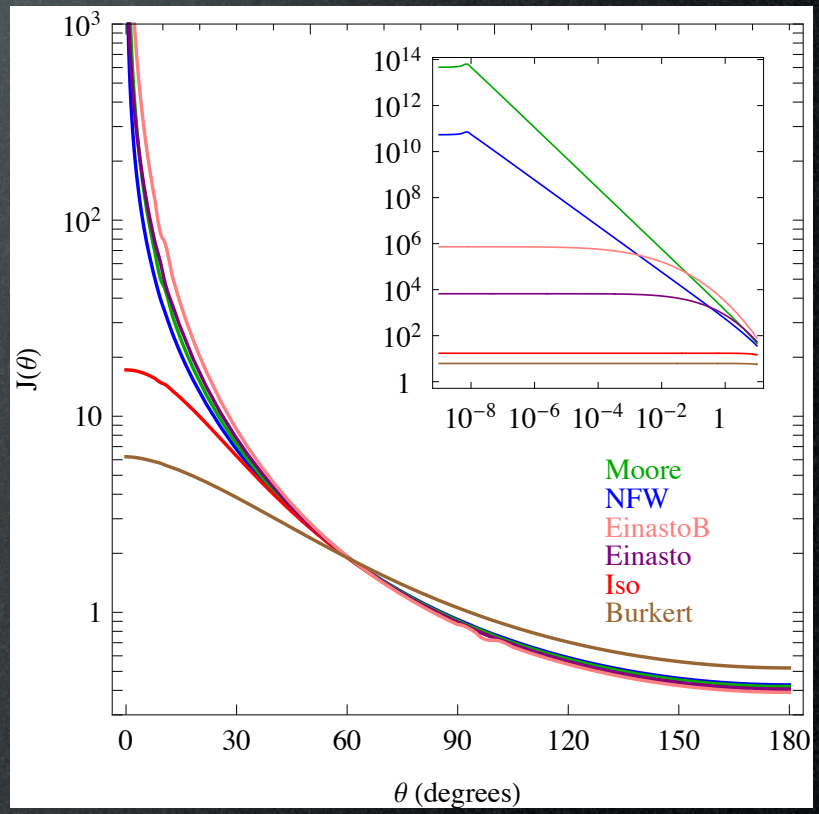
‘Prompt’ gamma rays

Expected flux:

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

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



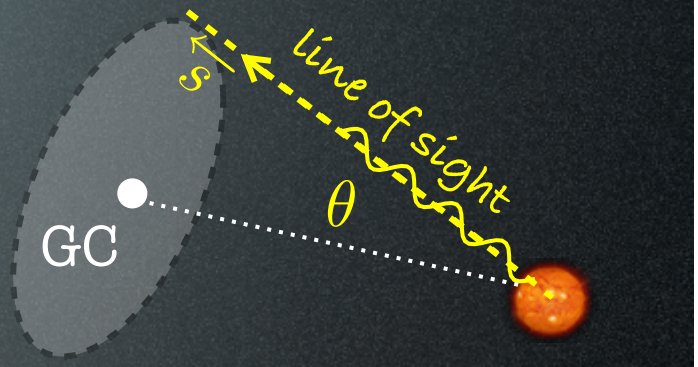


‘Prompt’ gamma rays

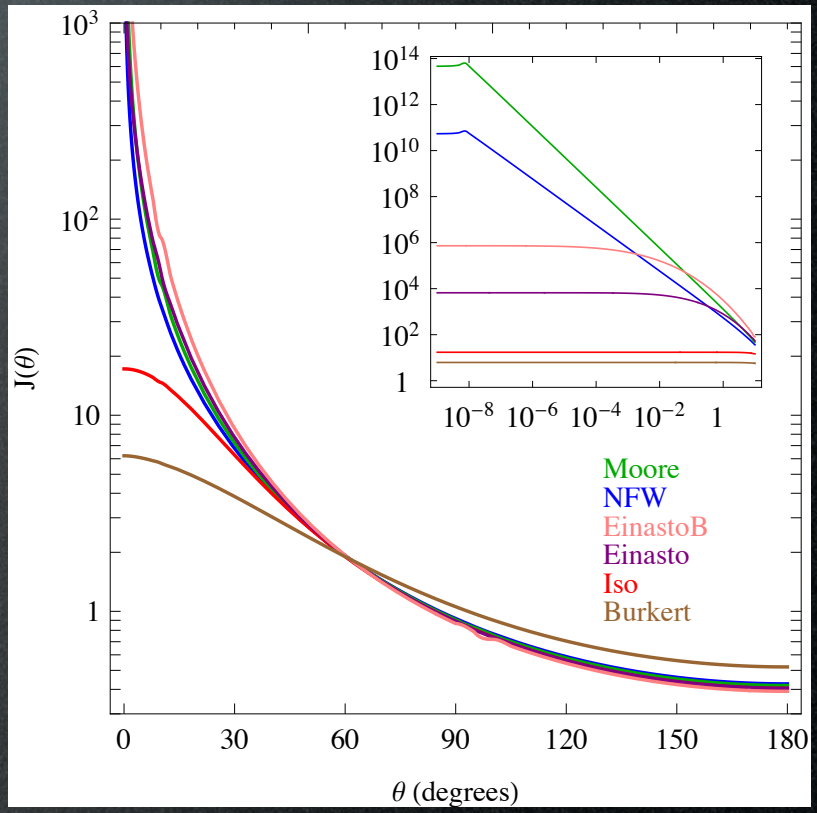
Expected flux:

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

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

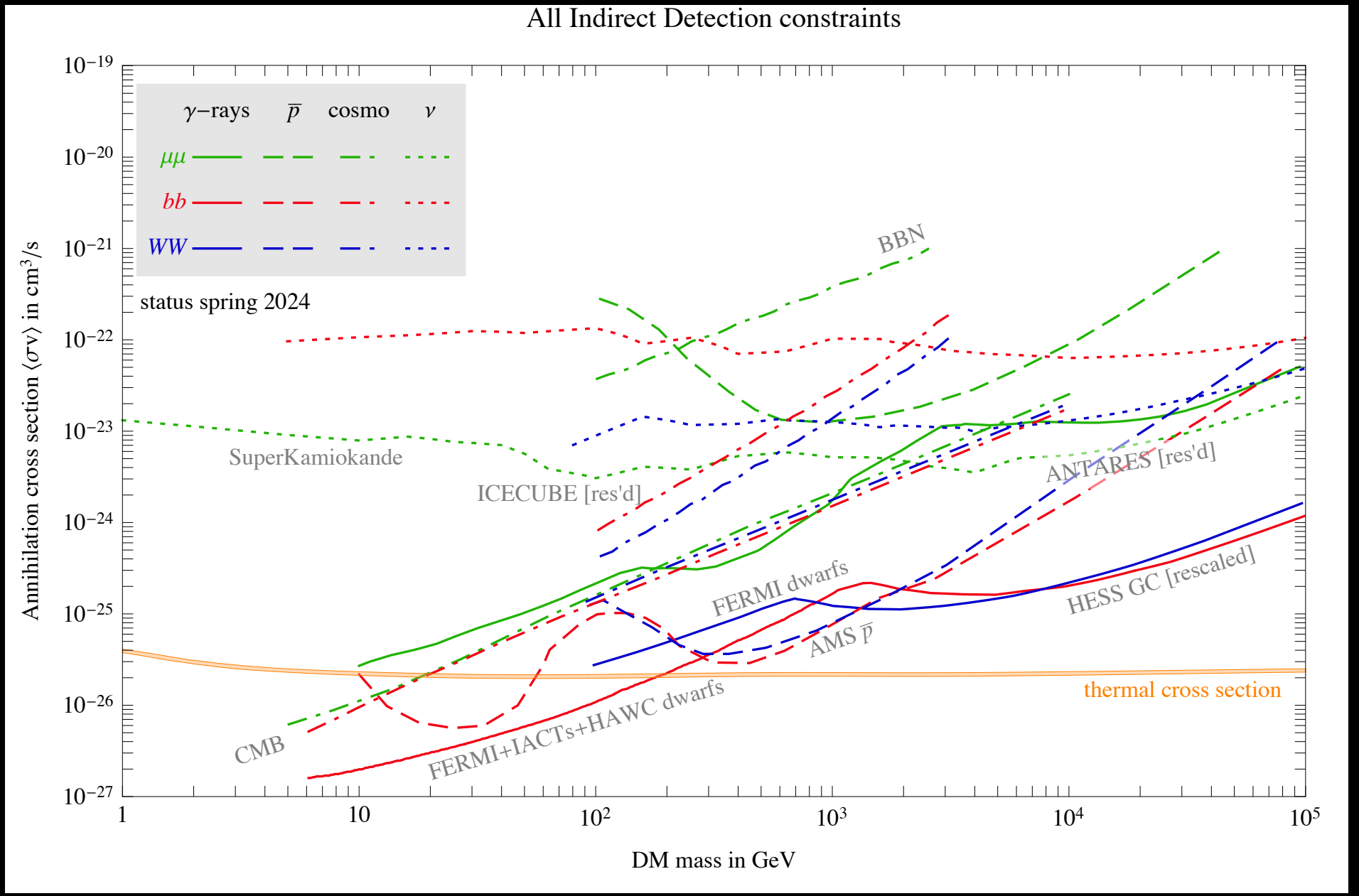


Region	$\Delta\Omega$ [steradians]	$\bar{J}_{\rm ann}$ NFW	Ein	EinB	Iso	Bur	Moore
‘GC 0.1°’	$0.96\ 10^{-5}$	11579	3579	55665	17.2	6.21	81751
‘GC 0.14°’	$0.19\ 10^{-4}$	8255	3206	43306	17.2	6.21	52395
‘GC 1°’	$0.96\ 10^{-3}$	1118	1196	6945	17.2	6.21	3855
‘GC 2°’	0.004	542	711	3103	17.2	6.19	1521
‘Gal Ridge’	$0.29\ 10^{-3}$	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

WIMP Indirect Detection



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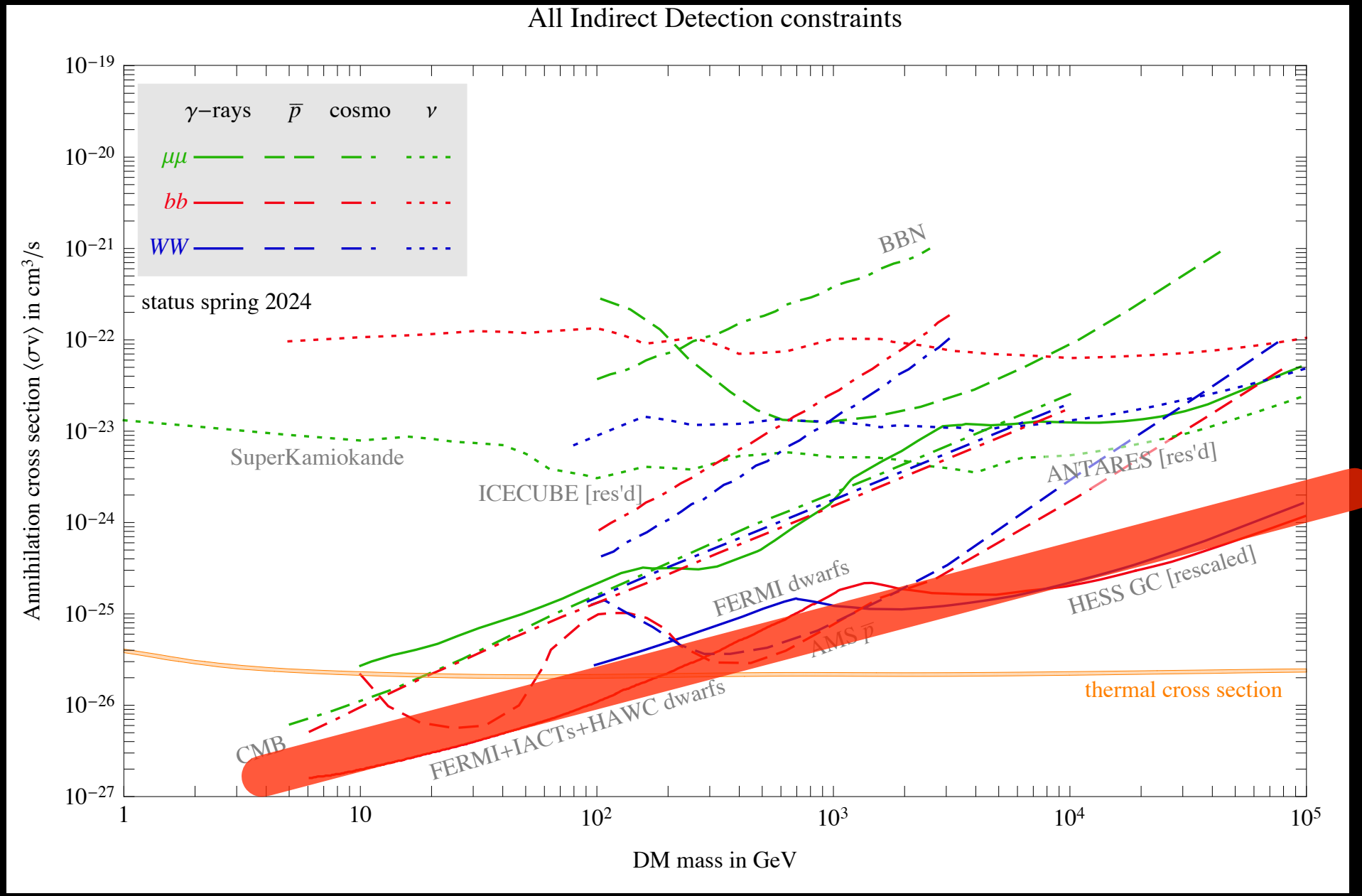
WIMP Indirect Detection



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