11 September 2017
TOOLS workshop, Corfu

Tools for Dark Matter Indirect Detection

Marco Cirelli
(CNRS LPTHE Jussieu)

Based on:

Cirelli, Corcella, Hektor, Hutsi, Kadastik, Panci, Raidal, Sala, Strumia,
JCAP 1103 (2011) 051 [1012.4515]

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LPTHE
LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES

erc
NewDark

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Outline

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gory details of DM ID
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Outline

1. arouse your interest in DM ID

2. talk to you about the
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3. ...in order to convince you that
you can forget everything and
trust PPPC4DMID

www.marcocirelli.net/PPPC4DMID.html

DM detection

direct detection

production at colliders

indirect

- γ from annihil in galactic center or halo and from synchrotron 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
- $\bar{d}$ from annihil in galactic halo or center
  GAPS
- $\nu, \bar{\nu}$ from annihil in galaxy or massive bodies
  SK, Icecube, Km3Net

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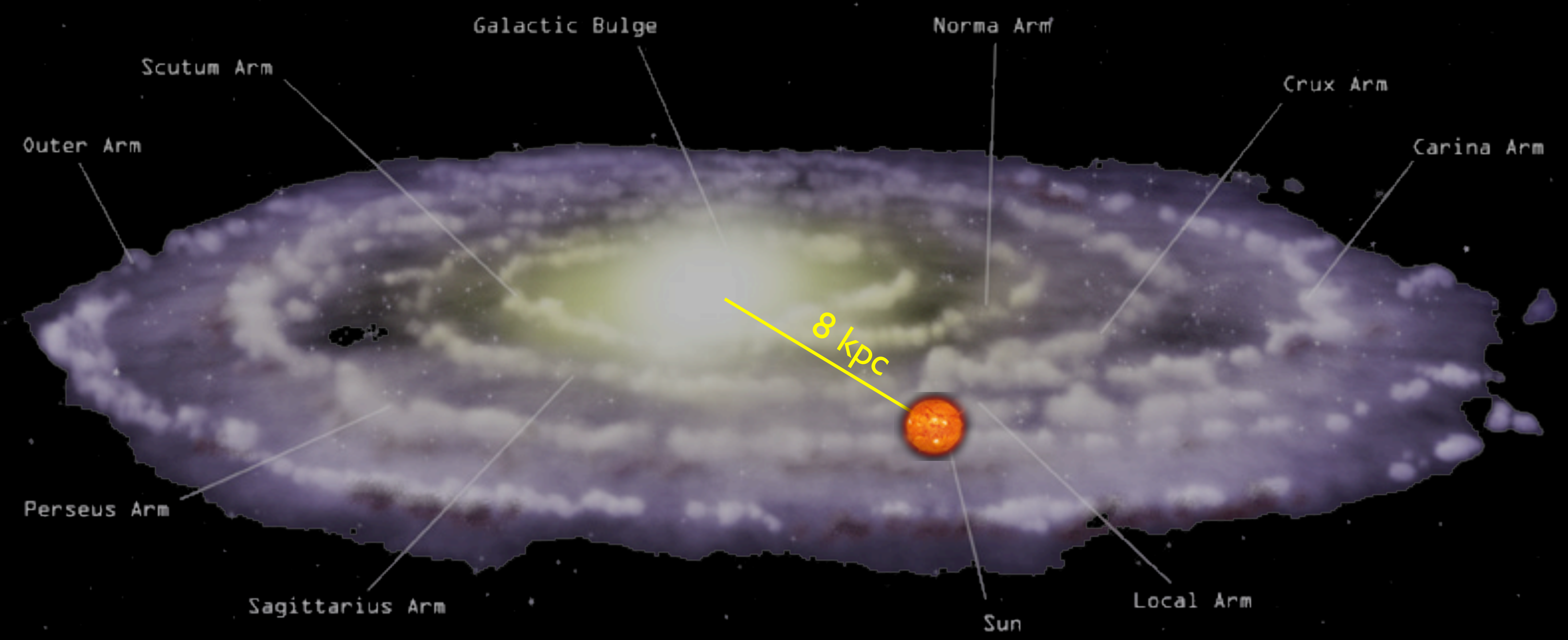
Indirect Detection: basics

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



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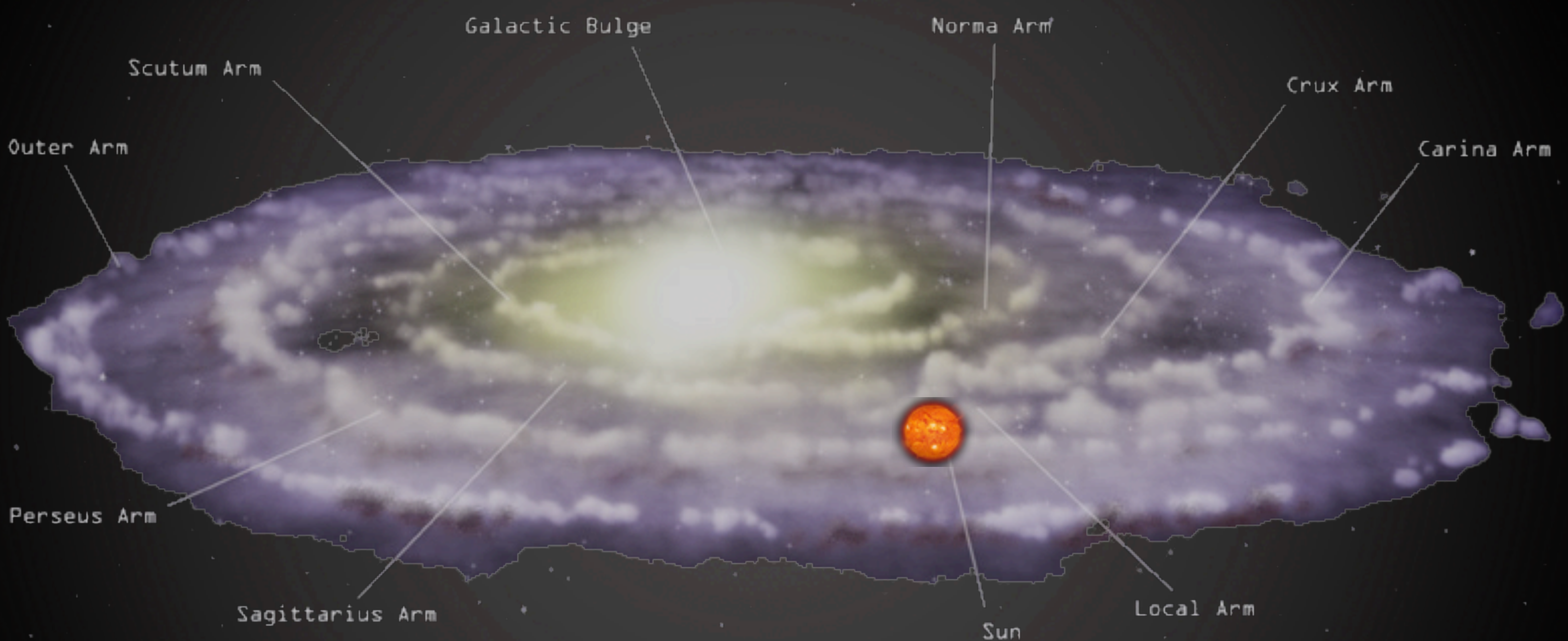

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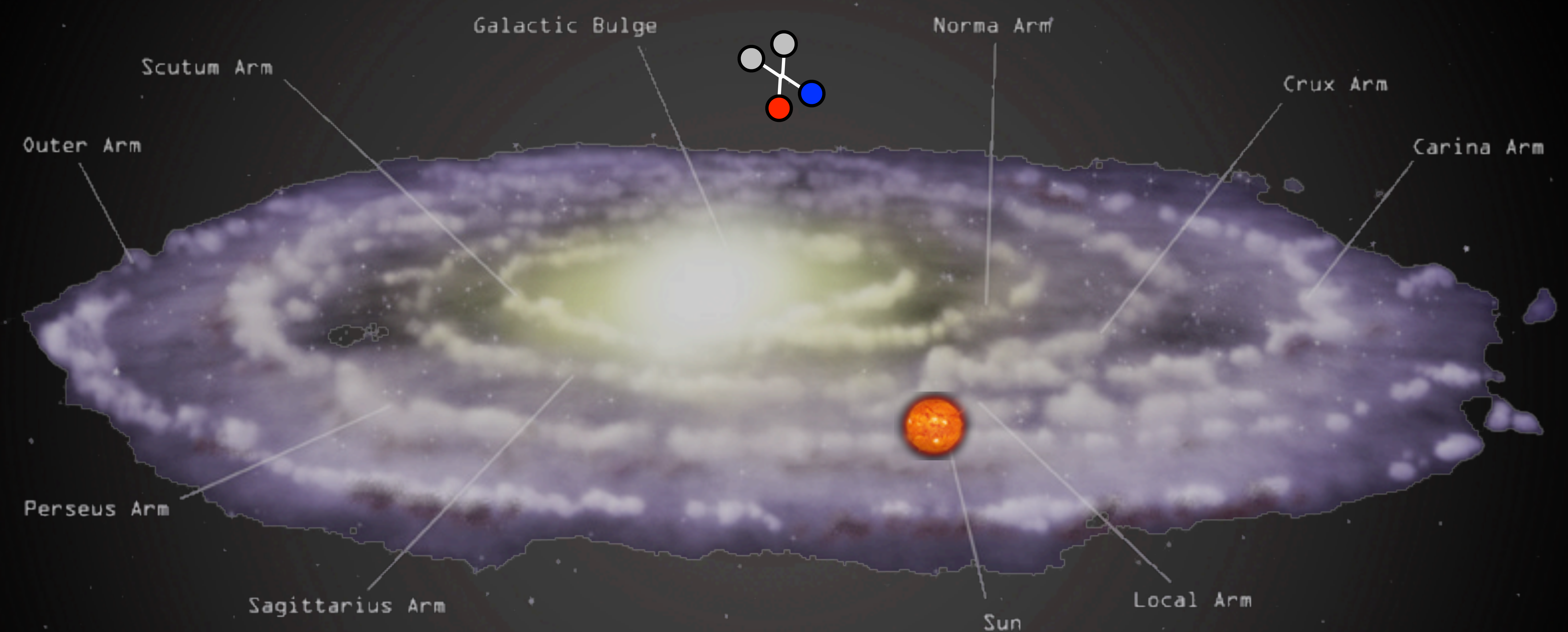
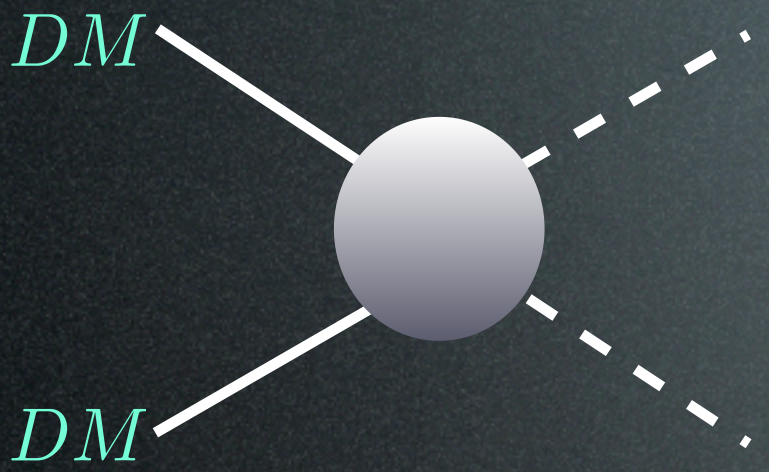


Fluxes at production



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

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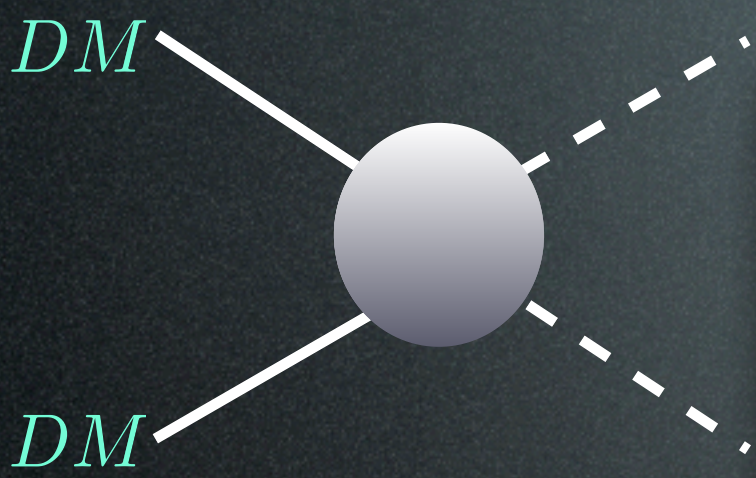

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primary
channels

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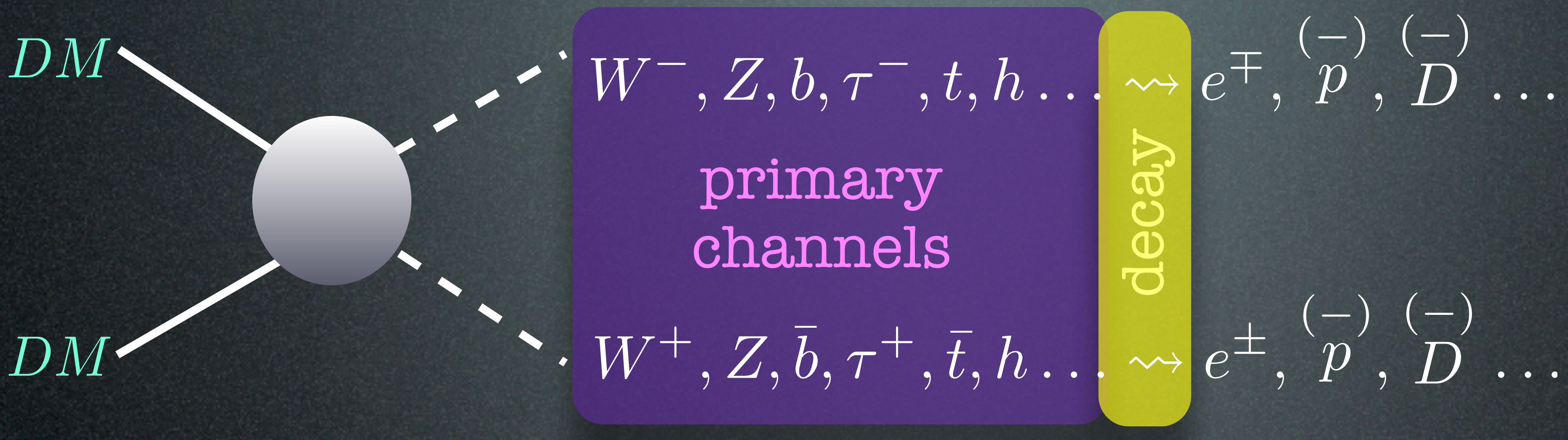

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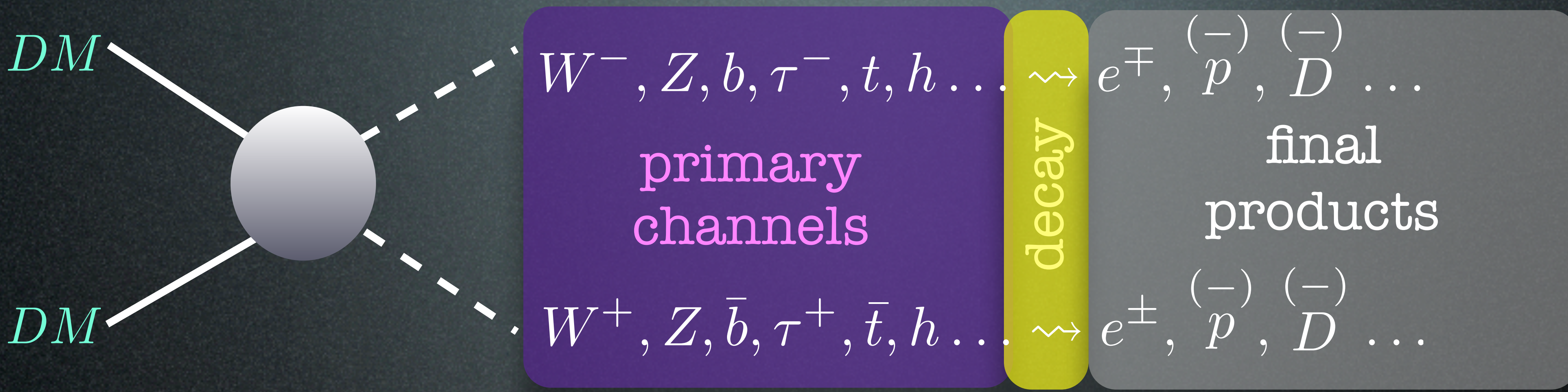

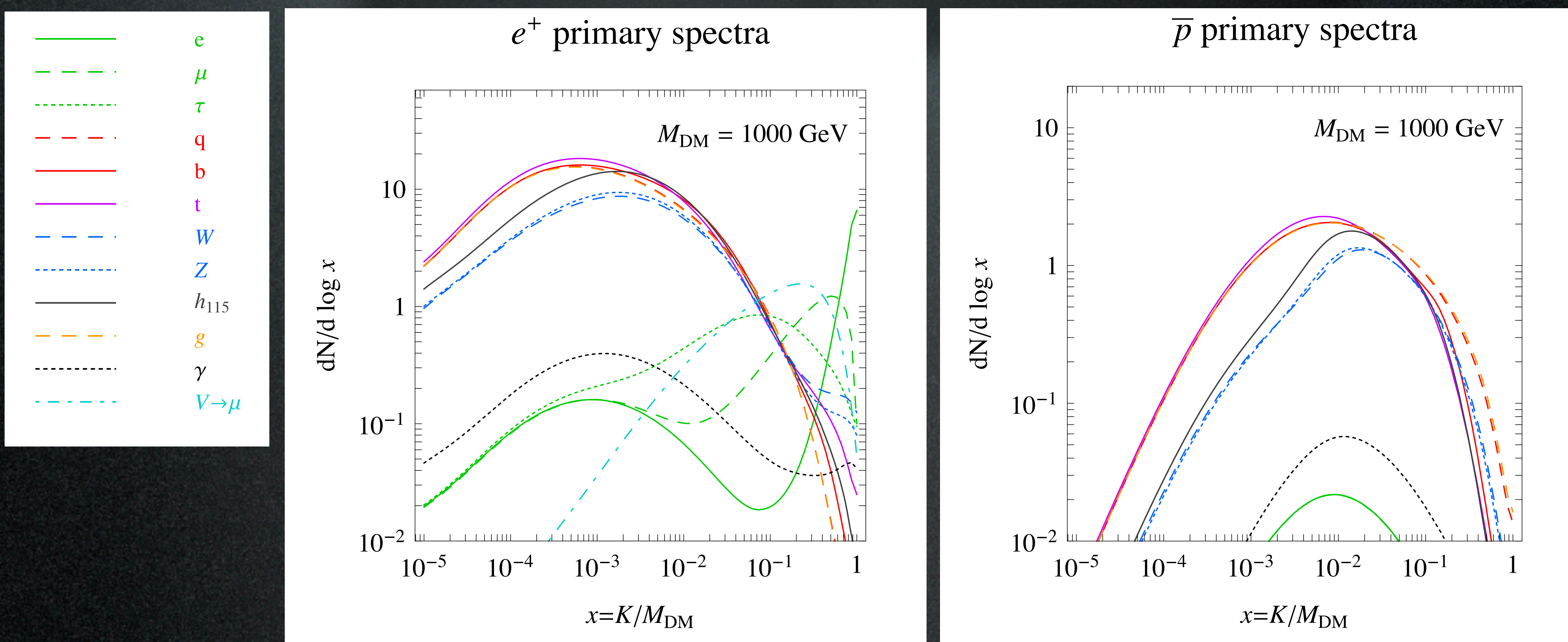

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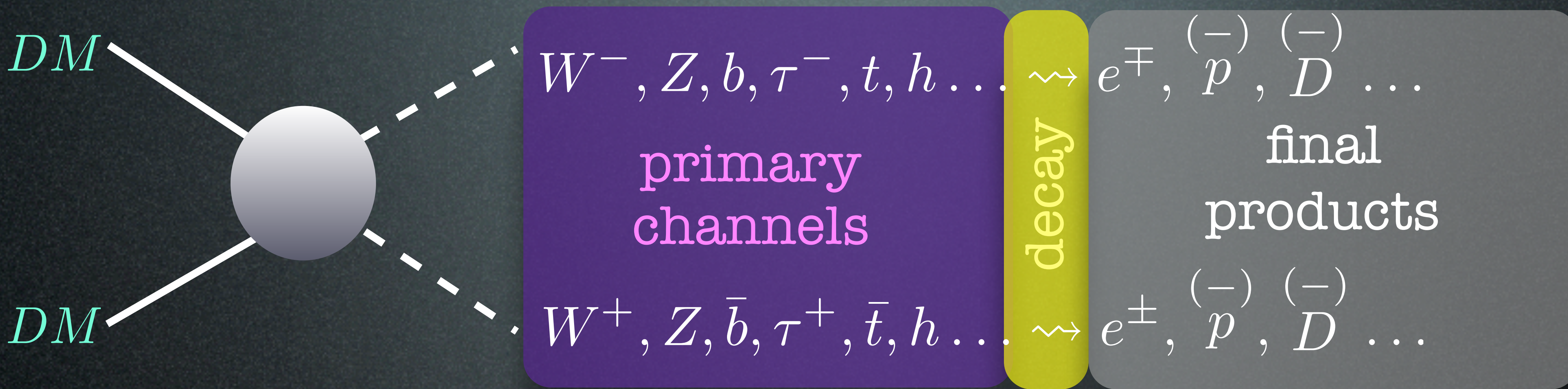
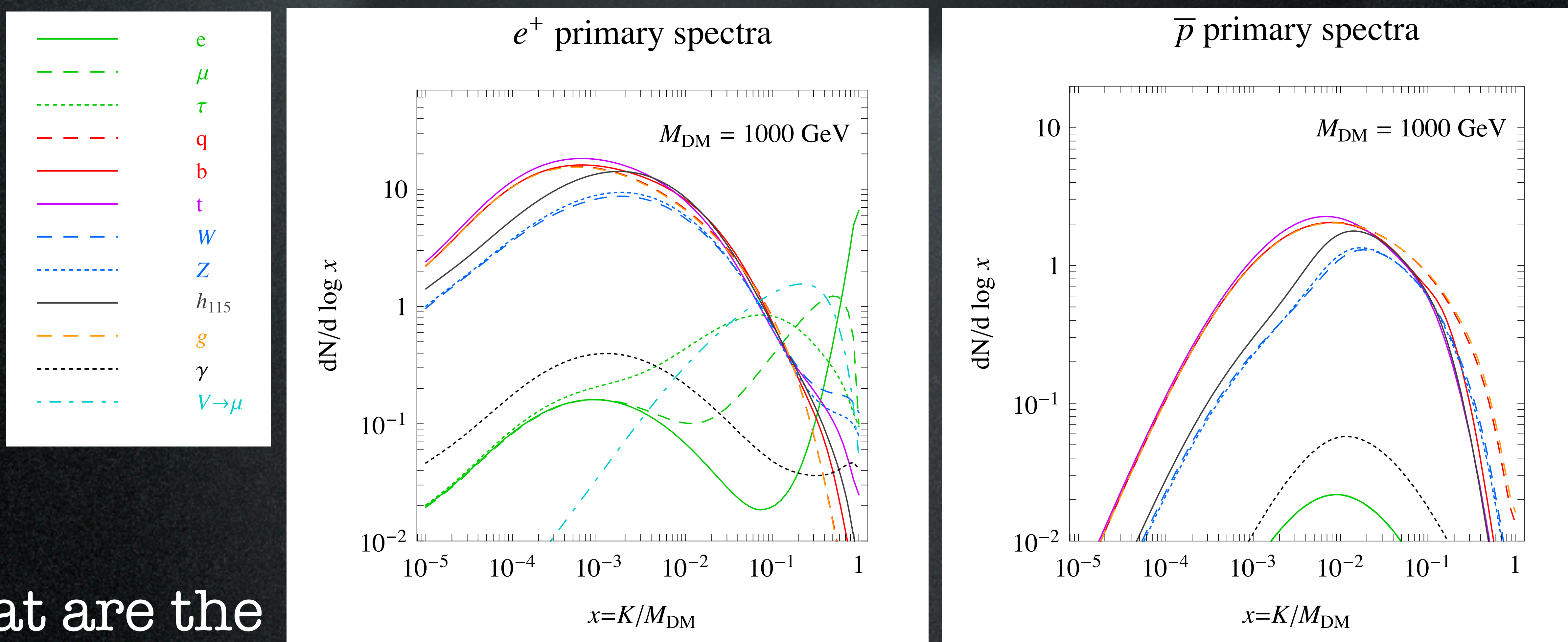
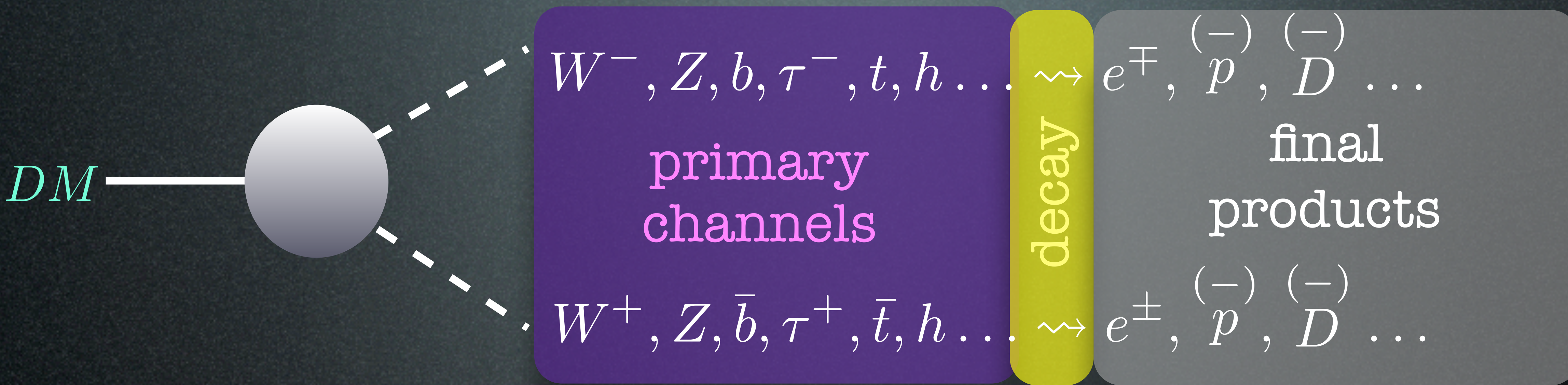


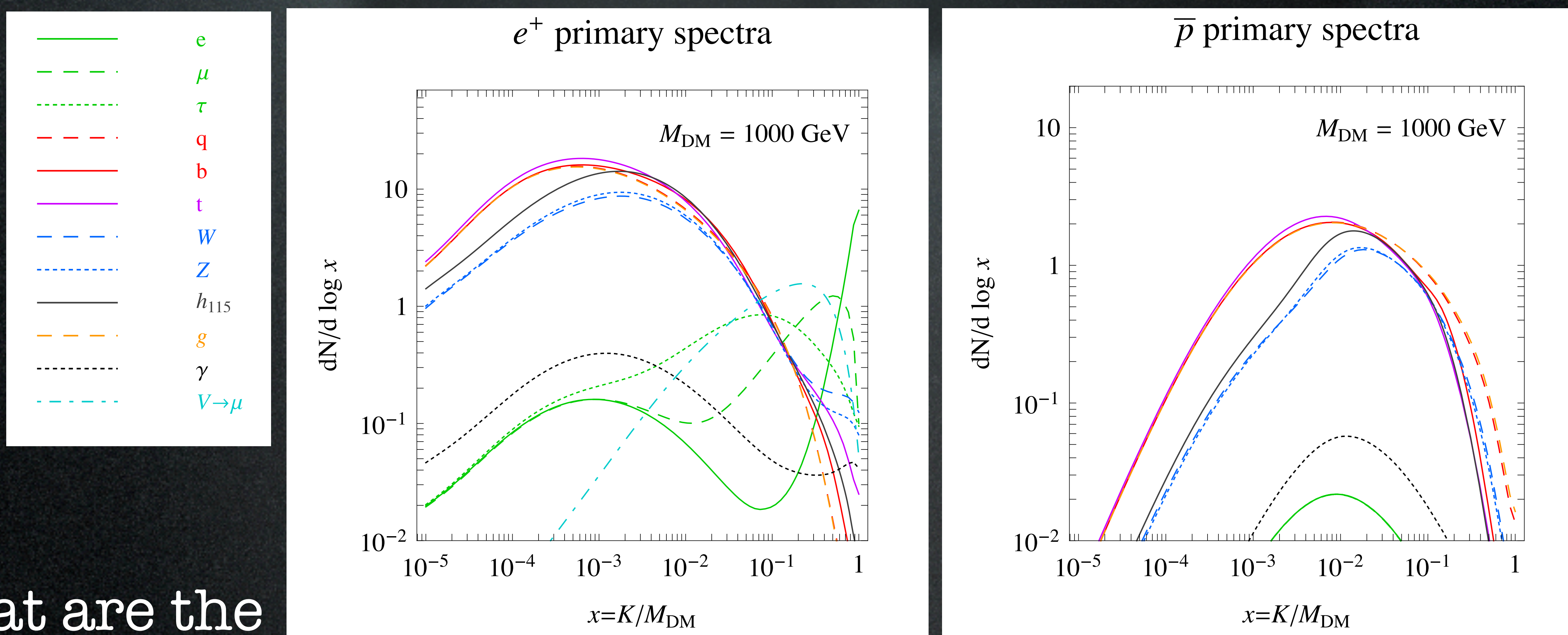


So what are the particle physics parameters?

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

Fluxes at production





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Fluxes at production

Different hadronic MonteCarlos could give different products

Or: what is the 'systematic' uncertainty?

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Pythia (8.135) vs **Herwig** (6.510)

e.g. lacks γ radiation from W^+W^- states (added)

e.g. lacks $\ell \to \ell\gamma$ and $\gamma \to f\bar{f}$ branchings

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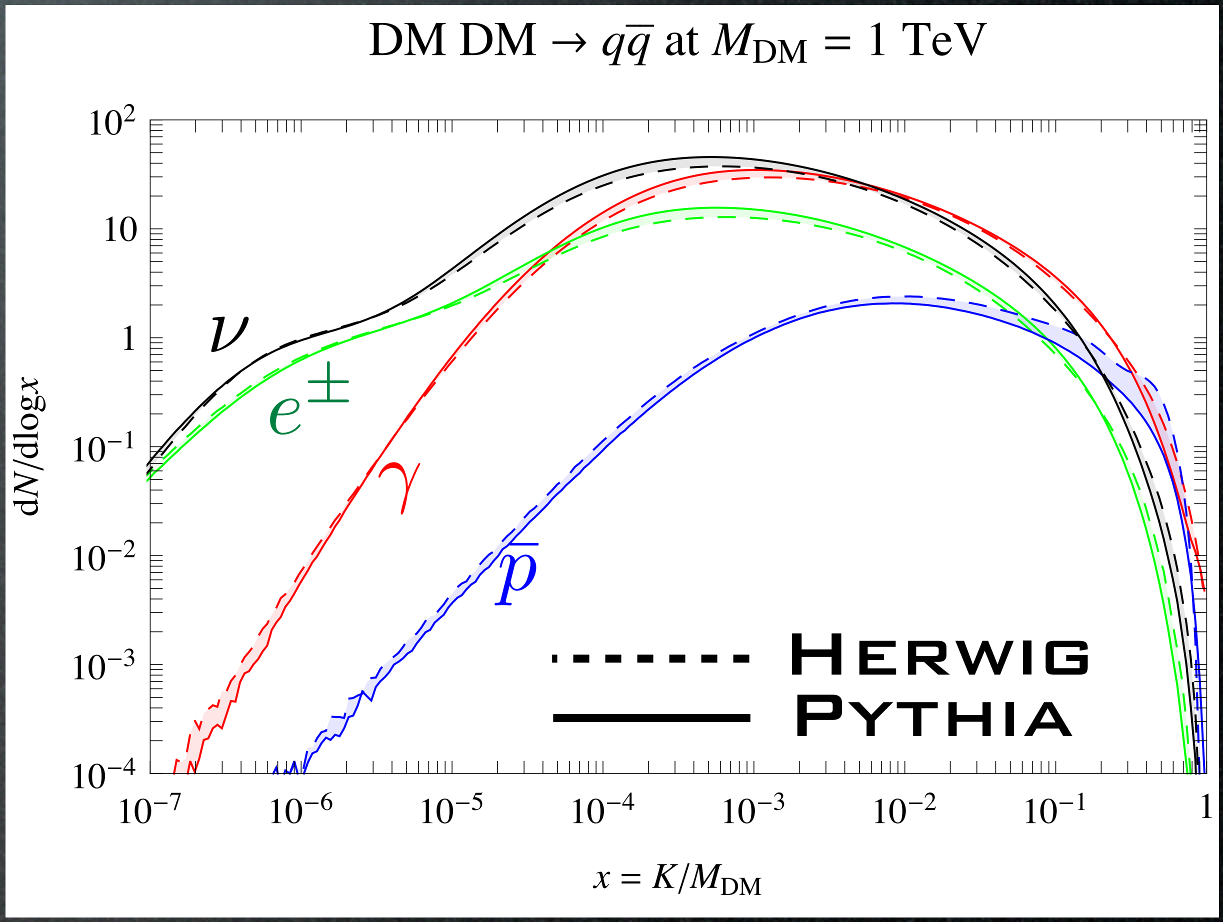

calibrated on LEP processes, good agreement, overall 20%

Fluxes at production

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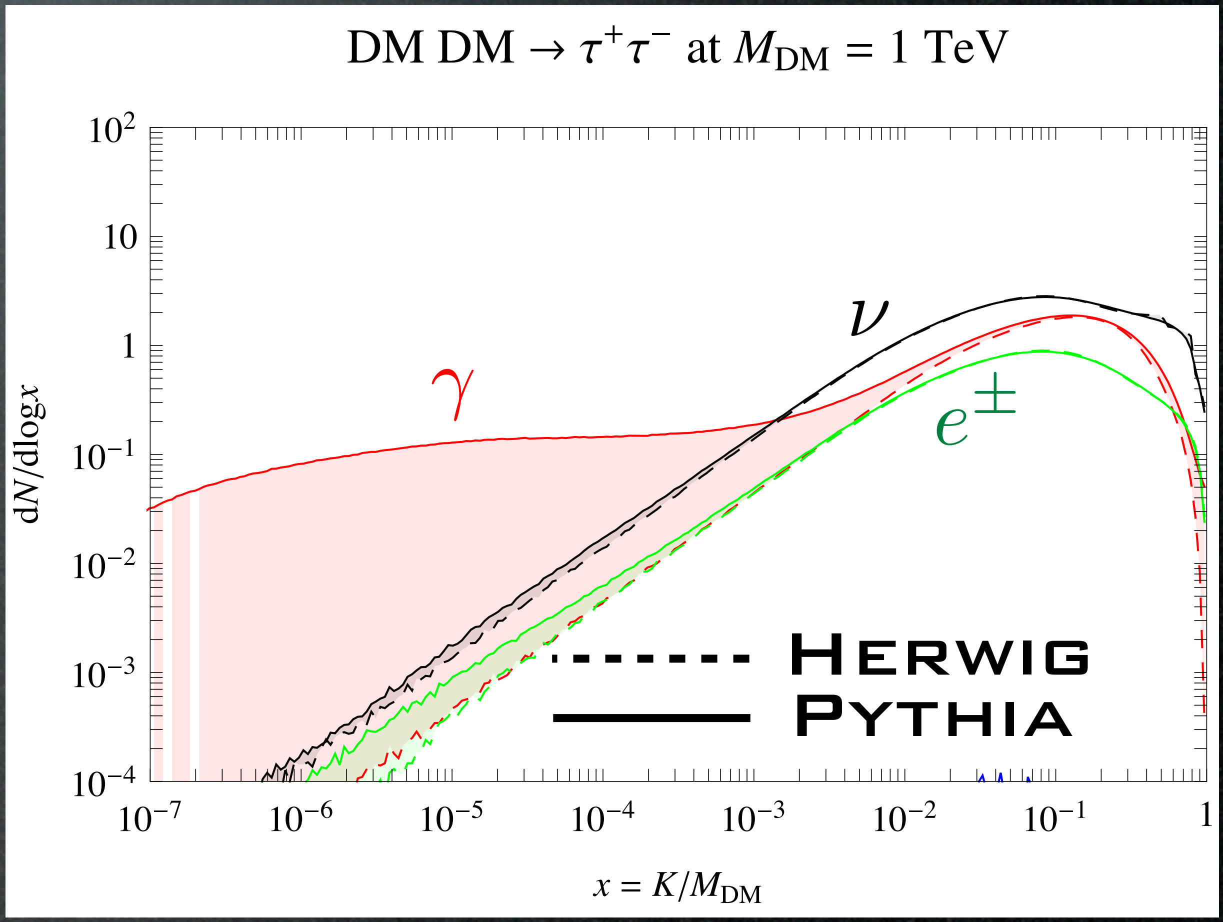

big discrepancy in γ ($e^{\pm}$) fluxes at low energy

Fluxes at production

Different hadronic MonteCarlos could give different products

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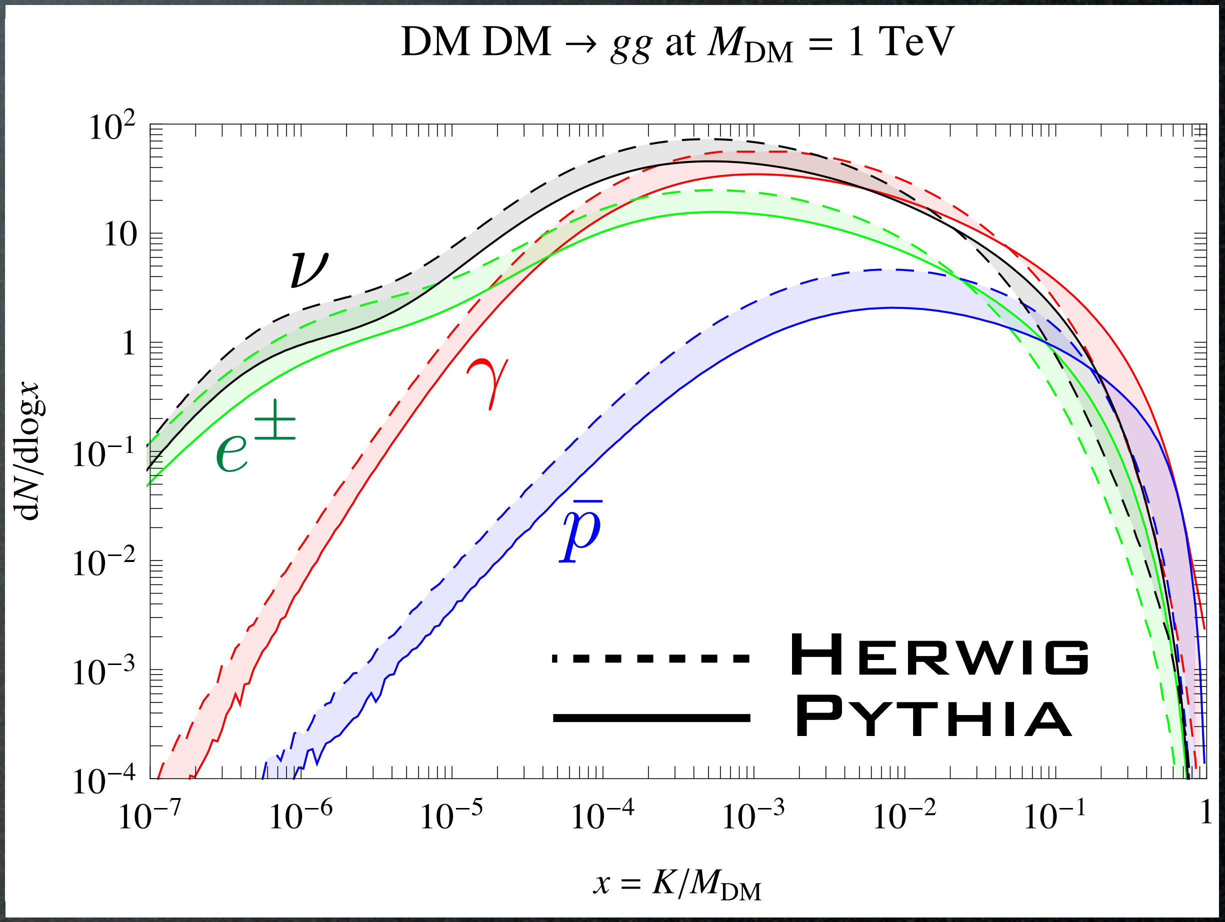

Factor 2: not calibrated on LEP?

Anyway not central for DM

Fluxes at production

Different hadronic MonteCarlos could give different products

Or: what is the 'systematic' uncertainty?

- overall around 20%
- with some surprises

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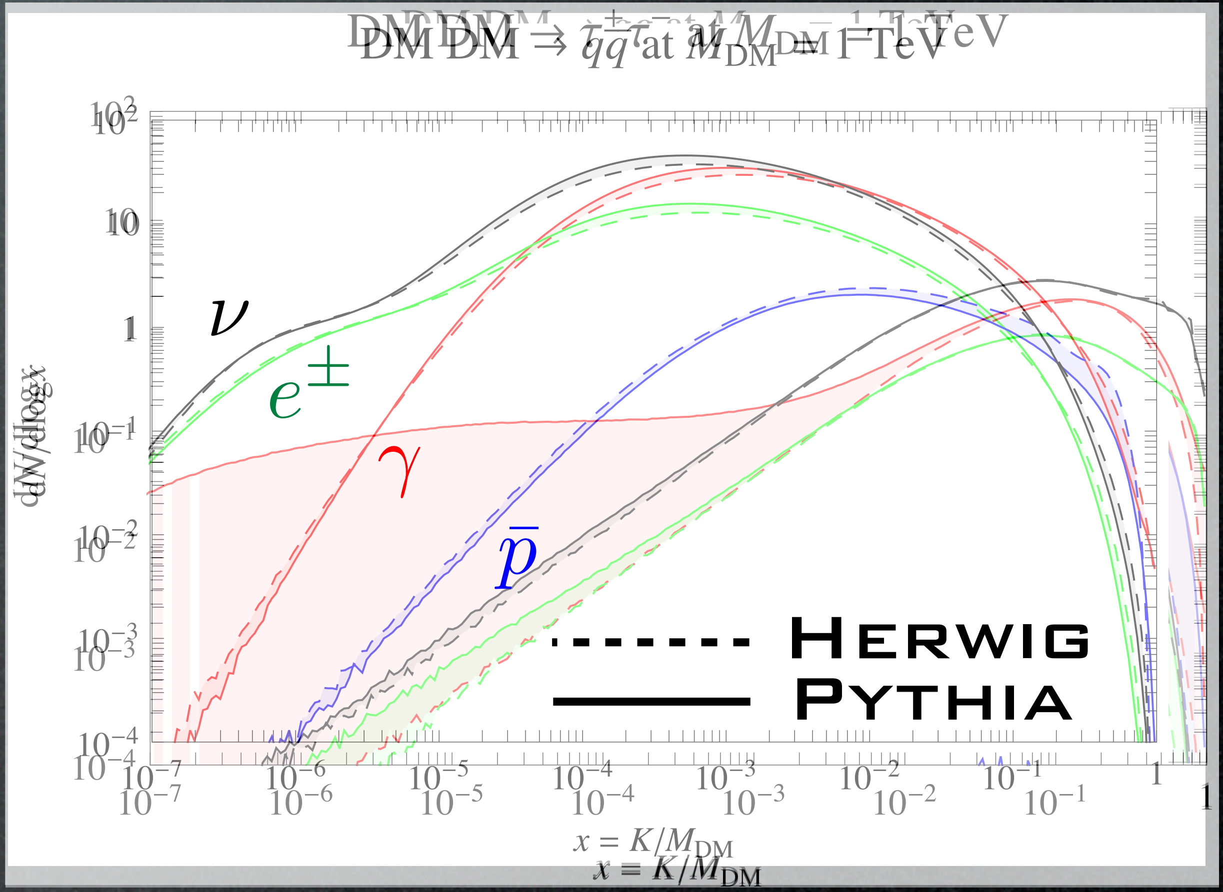

We use (modified) PYTHIA 8 for all computations.

Fluxes at production

ElectroWeak corrections are important!

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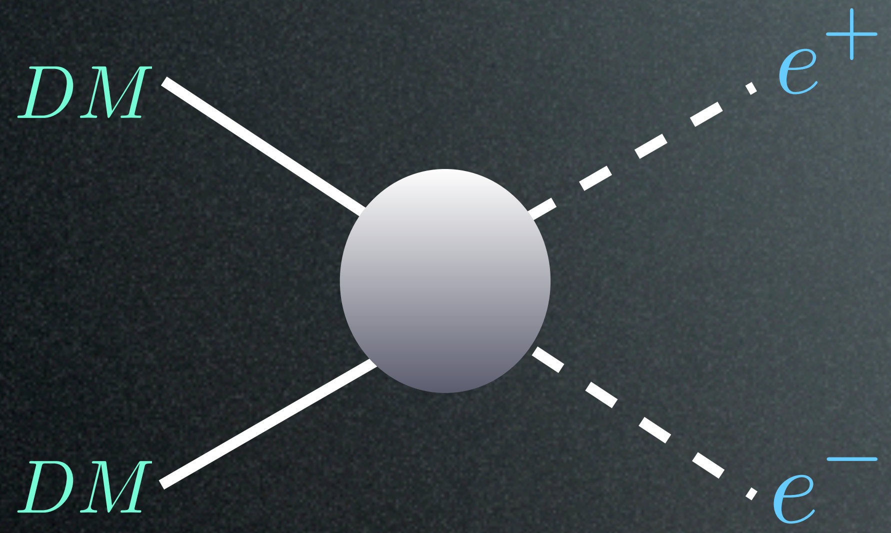

Fluxes at production

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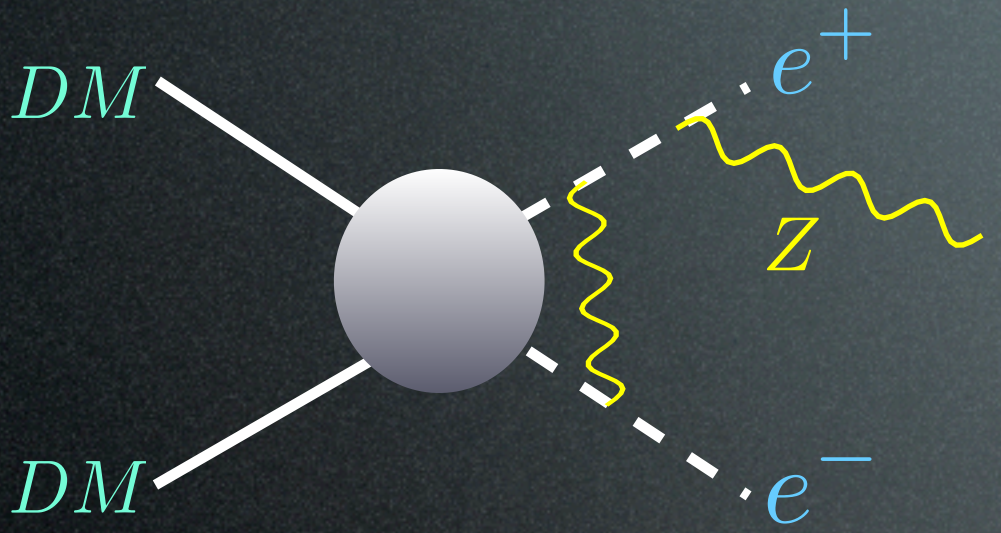

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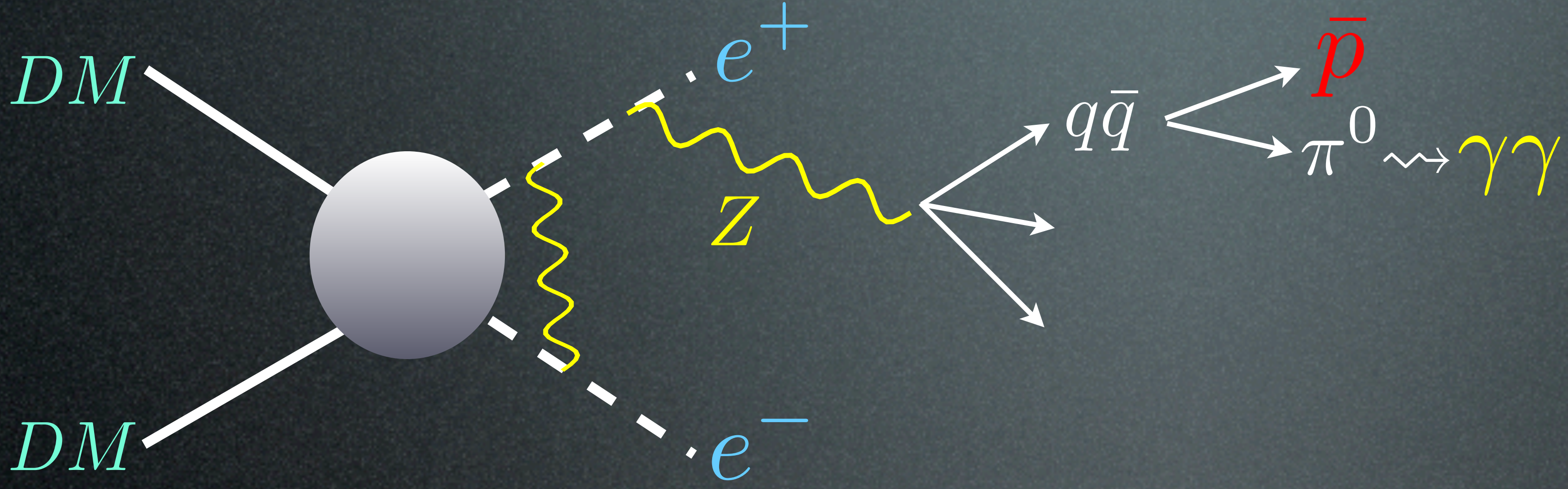

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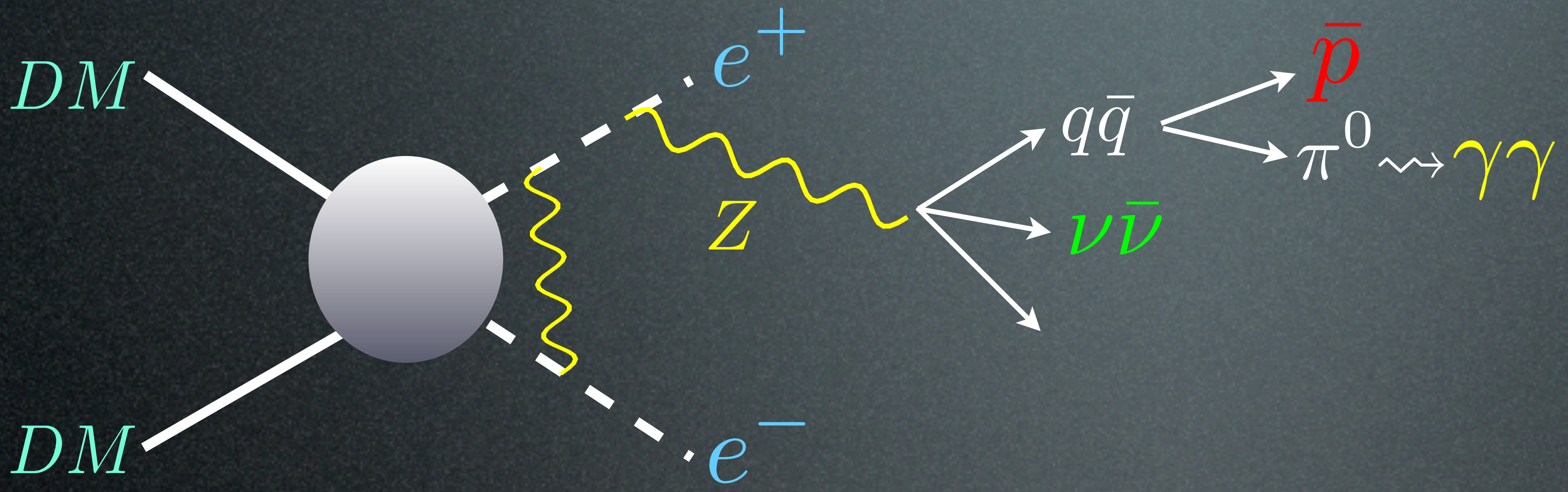

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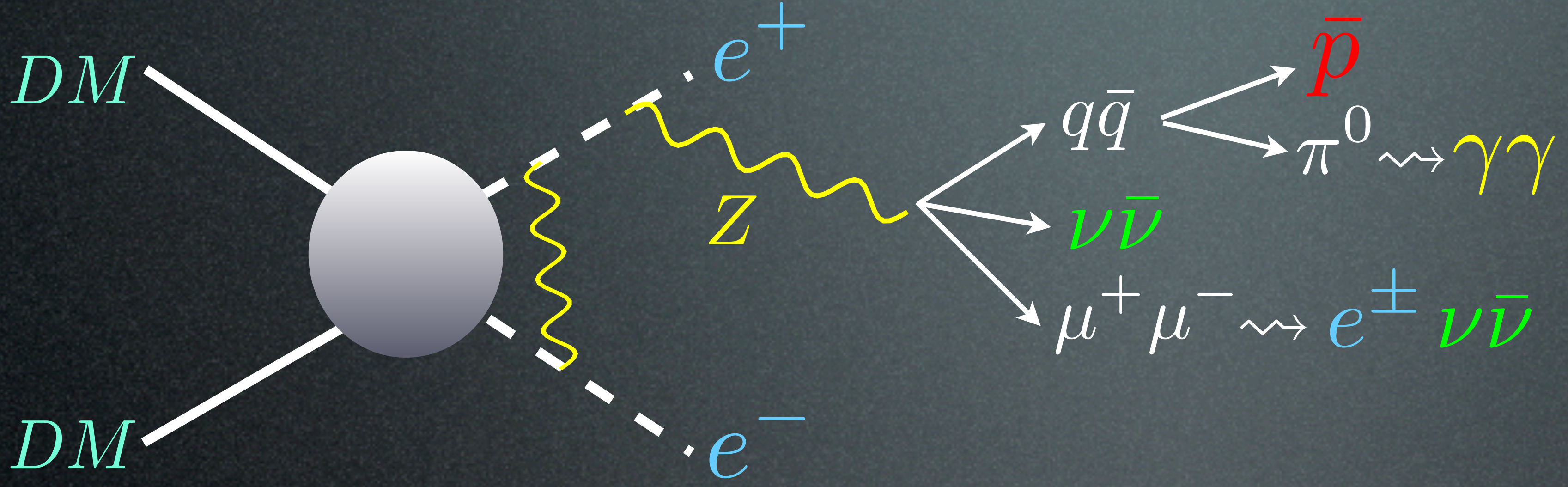

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

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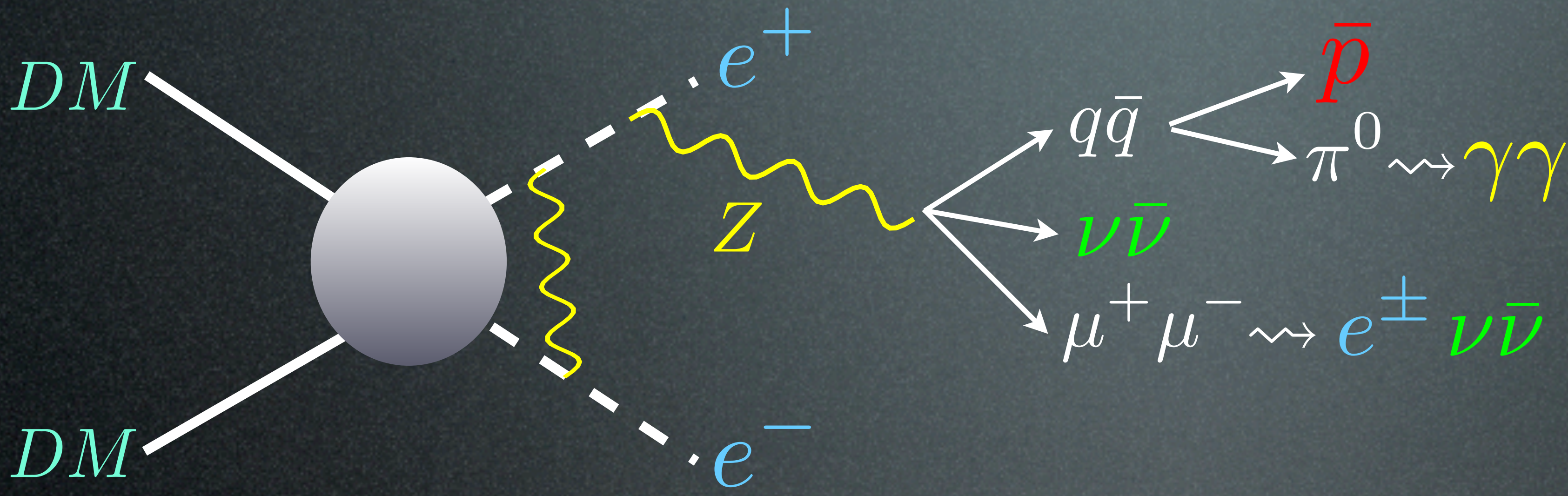

$$\frac{\Delta\sigma}{\sigma} \propto \alpha_{\rm weak} \ln^2\left(\frac{M_{\rm DM}^2}{M_{\rm Z}^2}\right)$$

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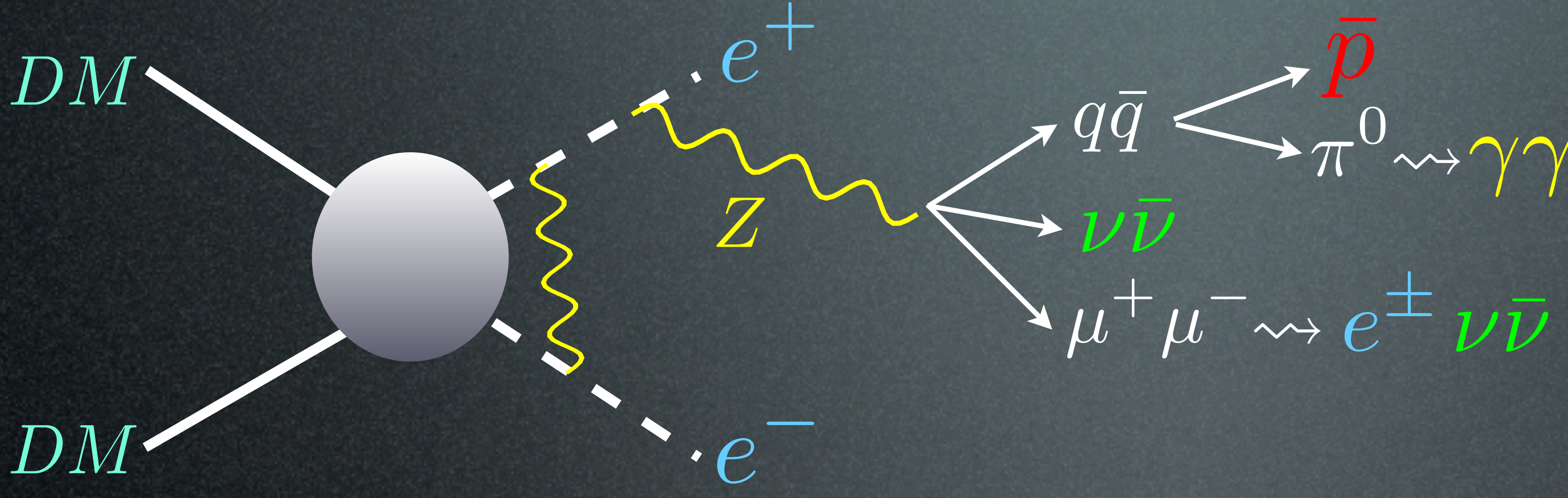

$$\frac{\Delta\sigma}{\sigma} \propto \underbrace{\alpha_{\rm weak}}_{\sim 0.03} \underbrace{\ln^2\left(\frac{M_{\rm DM}^2}{M_{\rm Z}^2}\right)}_{\sim 25}$$

$M_{\rm DM} \sim$ TeV

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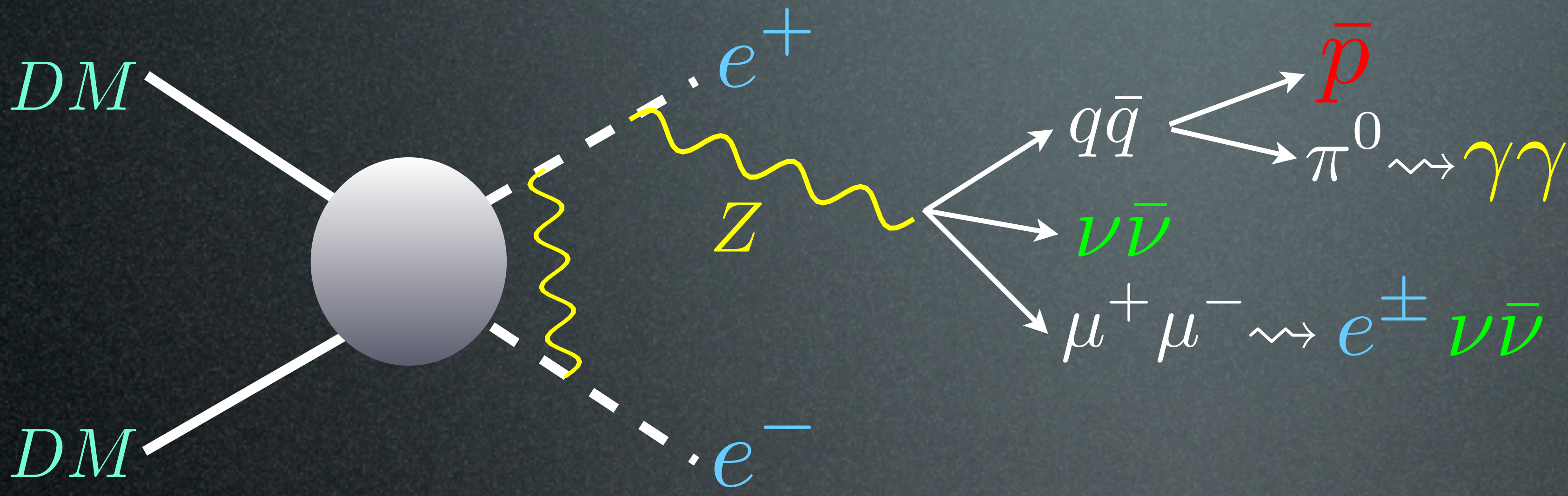

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~TeV ($M_{\rm DM}$); $\alpha_{\rm weak}$ ~ 0.03; $\ln^2$ term ~ 25; total ~ 75%

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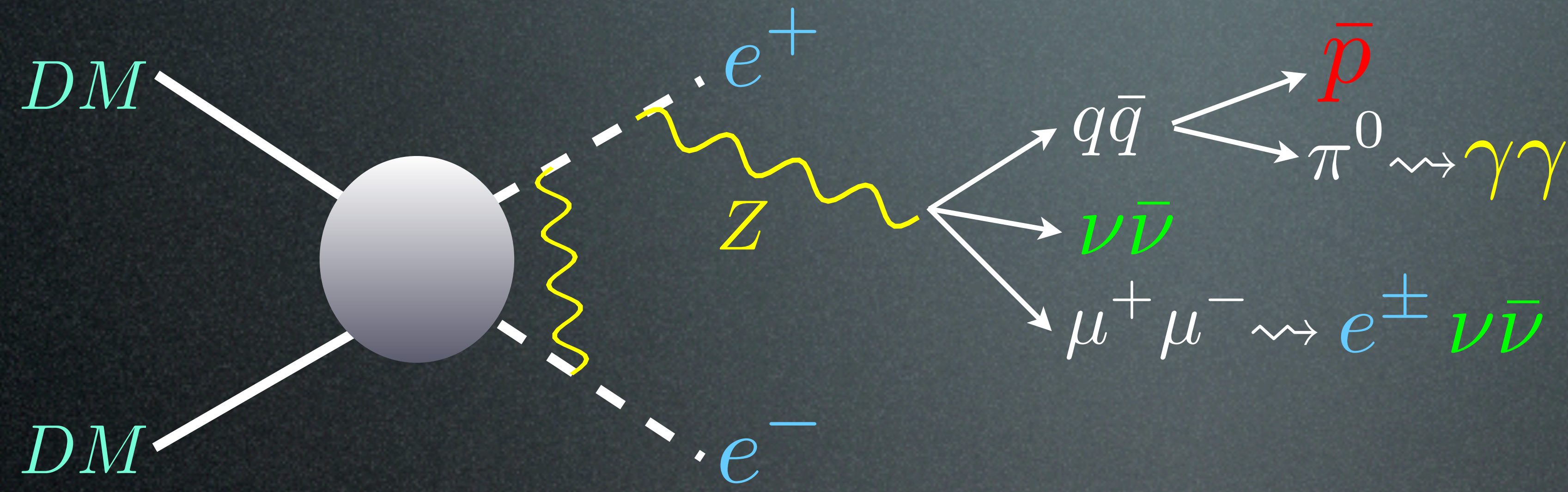

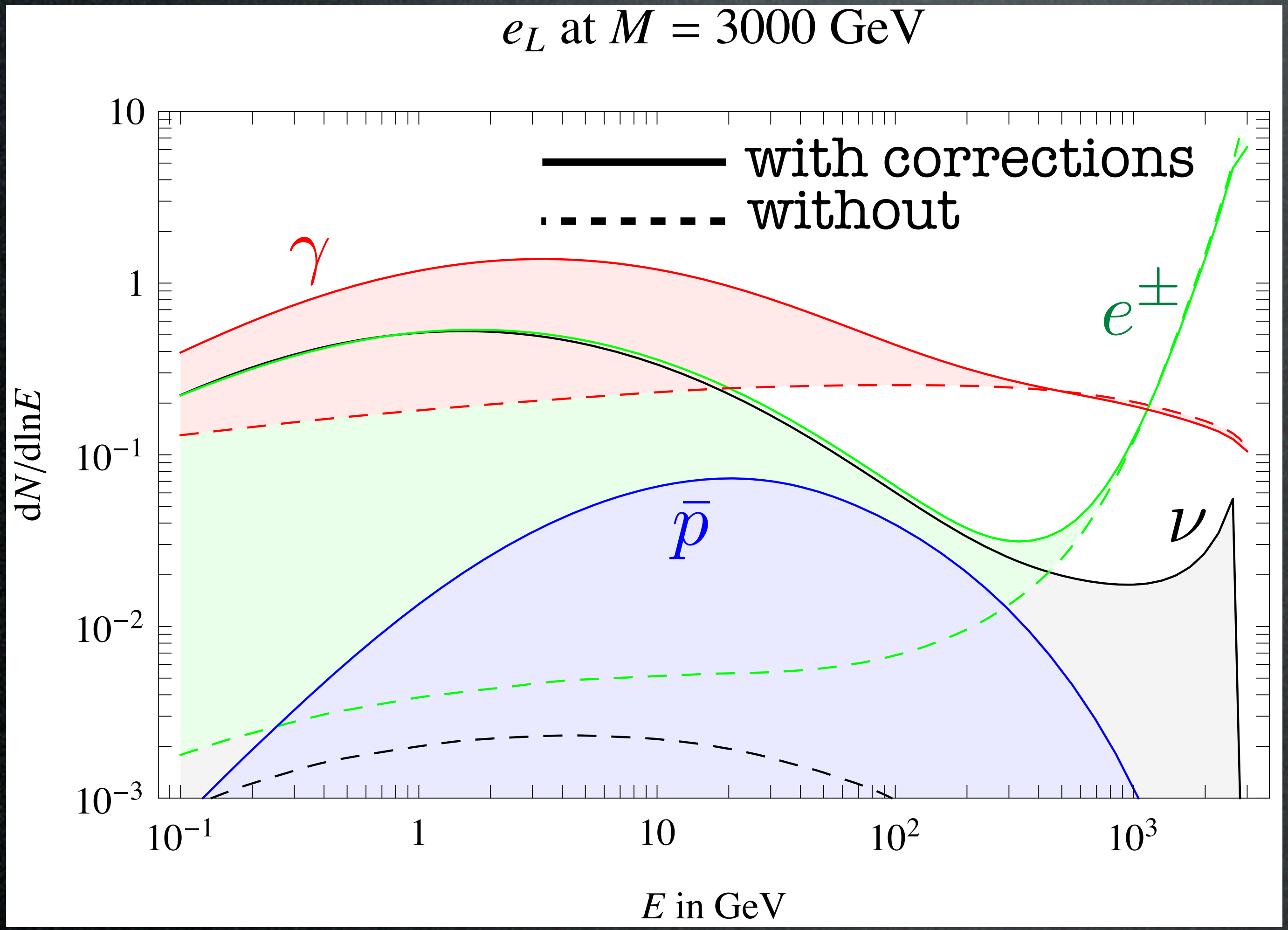

- unexpected species
- different spectra
  (especially at low energy, but not only)

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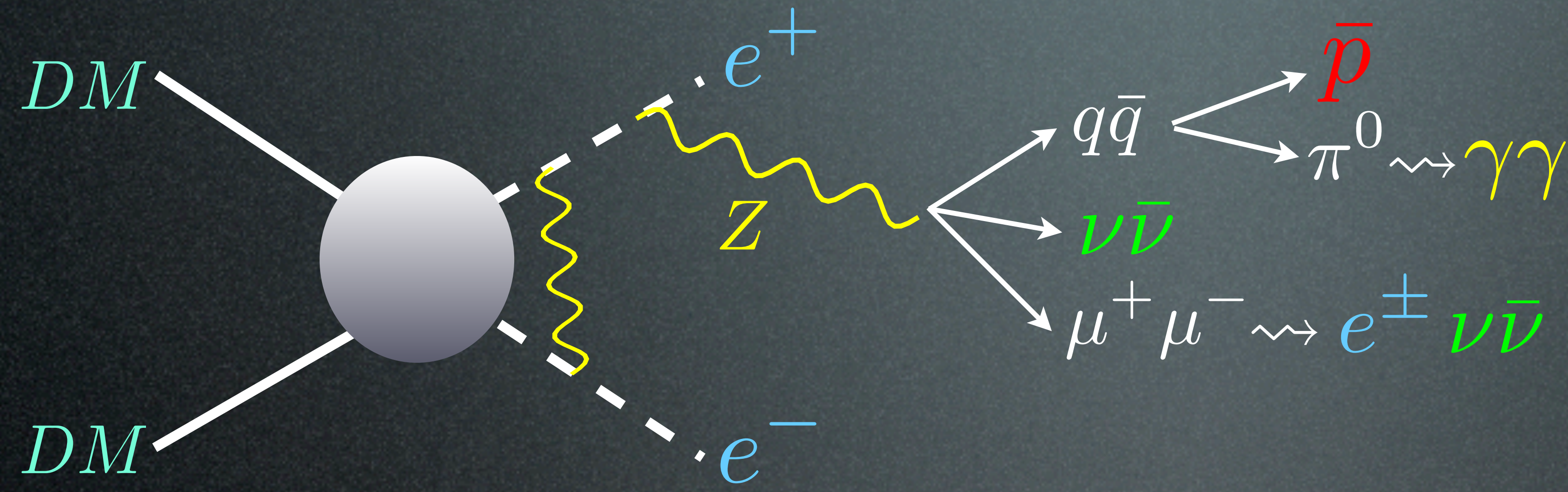

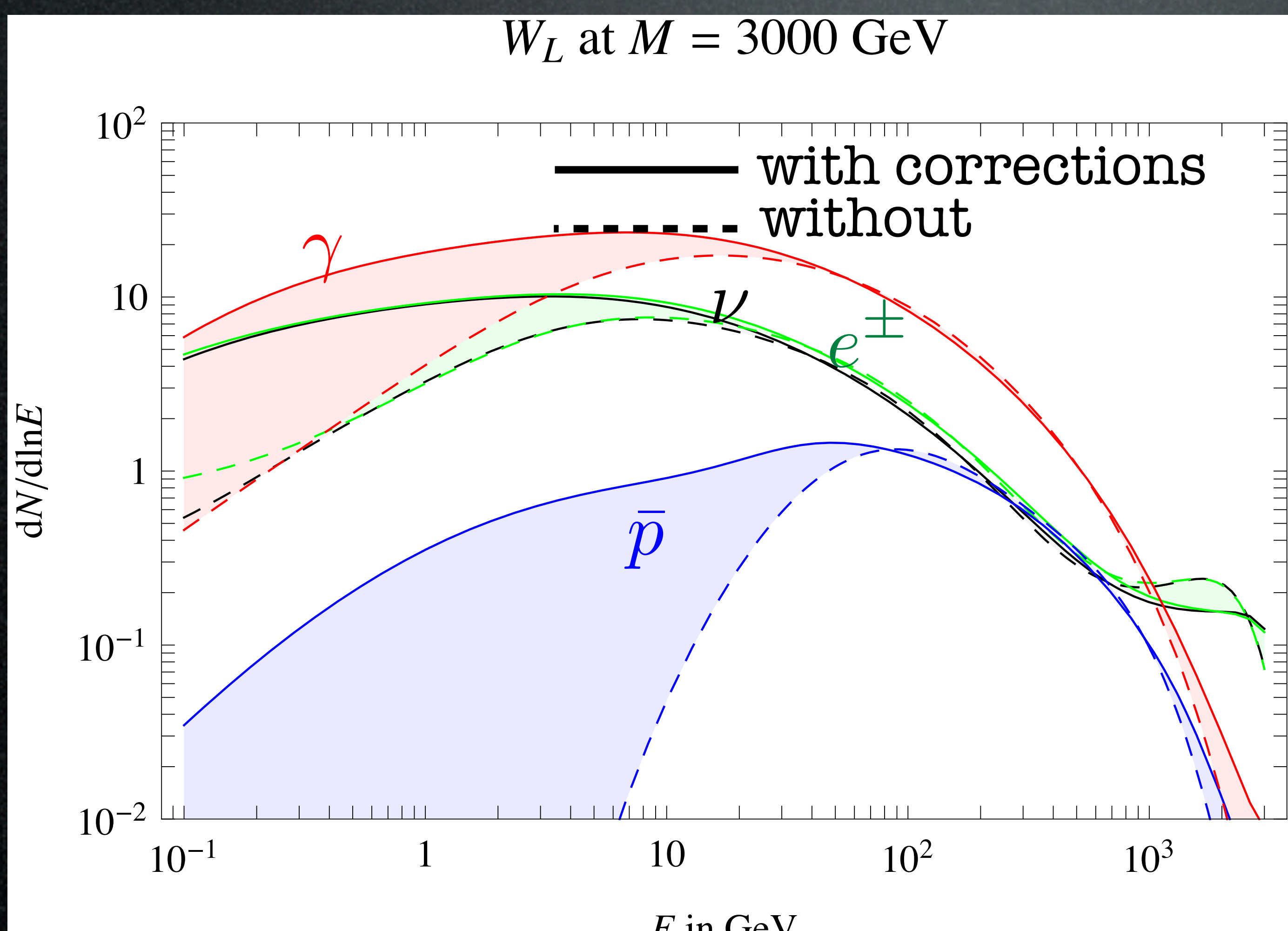

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Fluxes at production

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

Data and Results from 1012.4515 [hep-ph] (and 1009.0224 [hep-ph]), from 1312.6408 [hep-ph], 1412.5696 [astro-ph.HE], from 1505.01049 [hep-ph] and from 1511.08787 [hep-ph].

If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection",
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Erratum: JCAP 1210 (2012) E01.

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"PPPC 4 DM ID: A Poor Particle Physi
arXiv 1012.4515, JCAP 1103 (2011) 05
Erratum: JCAP 1210 (2012) E01.

Fluxes at production:

Complete fluxes at production, including EW corrections as computed in 1009.0224:

Mathematica functions:	The file dlNdlxEW.m provides the spectra Log_{10} [$d N/d\, Log_{10}\, x$]. The notebook Sample.nb shows how to load and use it.
Numerical tables:	Each table provides the spectra $dN/d\, Log_{10}x$ of stable SM particles (positrons, antiprotons...), normalized per one annihilation. The columns are: [m_{DM}, $Log_{10}x$, $dN/d\, Log_{10}x$ for 28 primary channels]. The primary channels are: $DM\, DM \to e_L^+e_L^-, e_R^+e_R^-, e^+e^-, \mu_L^+\mu_L^-, \mu_R^+\mu_R^-, \mu^+\mu^-, \tau_L^+\tau_L^-, \tau_R^+\tau_R^-, \tau^+\tau^-, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, W_L^+W_L^-, W_T^+W_T^-, W^+W^-, Z_L^+Z_L^-, Z_T^+Z_T^-, Z^+Z^-, gg, \gamma\gamma, hh, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$ $VV \to 4e, VV \to 4\mu, VV \to 4\tau$. The non-polarized fluxes are just obtained as the appropriate average of the *Left* and *Right* or *Longitudinal* and *Transverse* ones. The channel into Higgs bosons assumes a Higgs mass of *125 GeV*. Positrons Antiprotons Gamma rays Electron Neutrinos Muon Neutrinos Tau Neutrinos Antideuterons all of the above All the 7 tables, in a single zipped file.

Fluxes at production without EW corrections (for comparison with previous calculations):

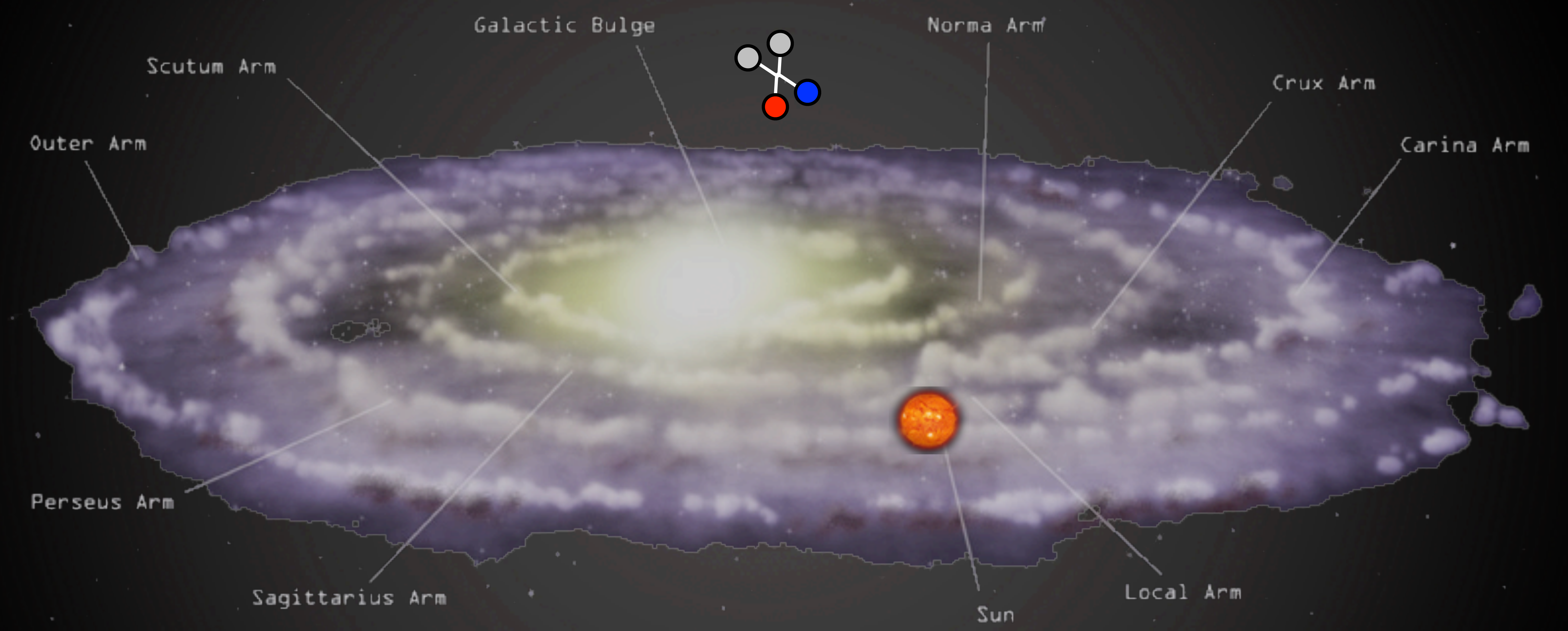
Mathematica functions:	The file dlNdlxPythia.m provides the spectra Log_{10} [$d N/d\, Log_{10}\, x$]. The notebook Sample.nb shows how to load and use it.
Numerical tables:	Same as above, but here the primary channels are the following 12: $DM\, DM \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, gg, \gamma\gamma, hh$. Positrons Antiprotons Gamma rays Electron Neutrinos Muon Neutrinos Tau Neutrinos Antideuterons all of the above All the 7 tables, in a single zipped file.

Fluxes at production in models with cascade decays in the hidden sector:

Numerical tables, *Mathematica* and *Python* functions:	Download here.

Indirect Detection: basics

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



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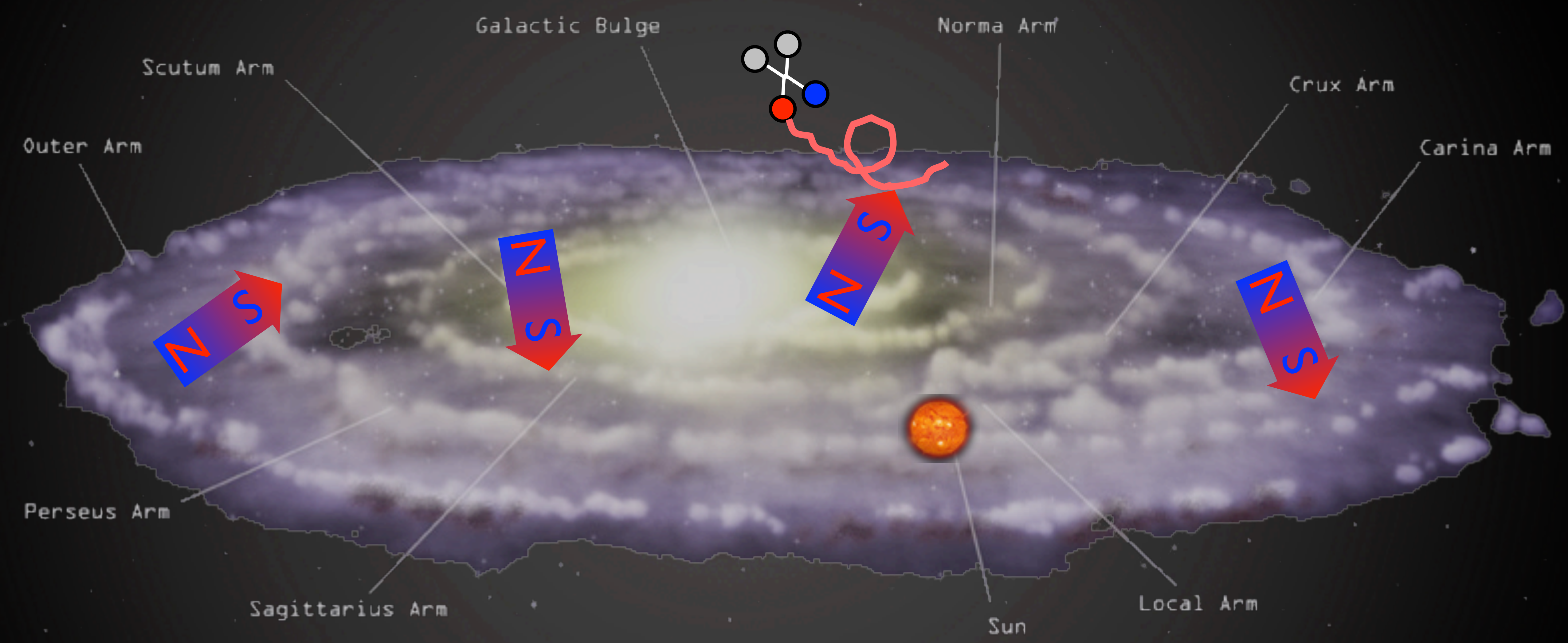

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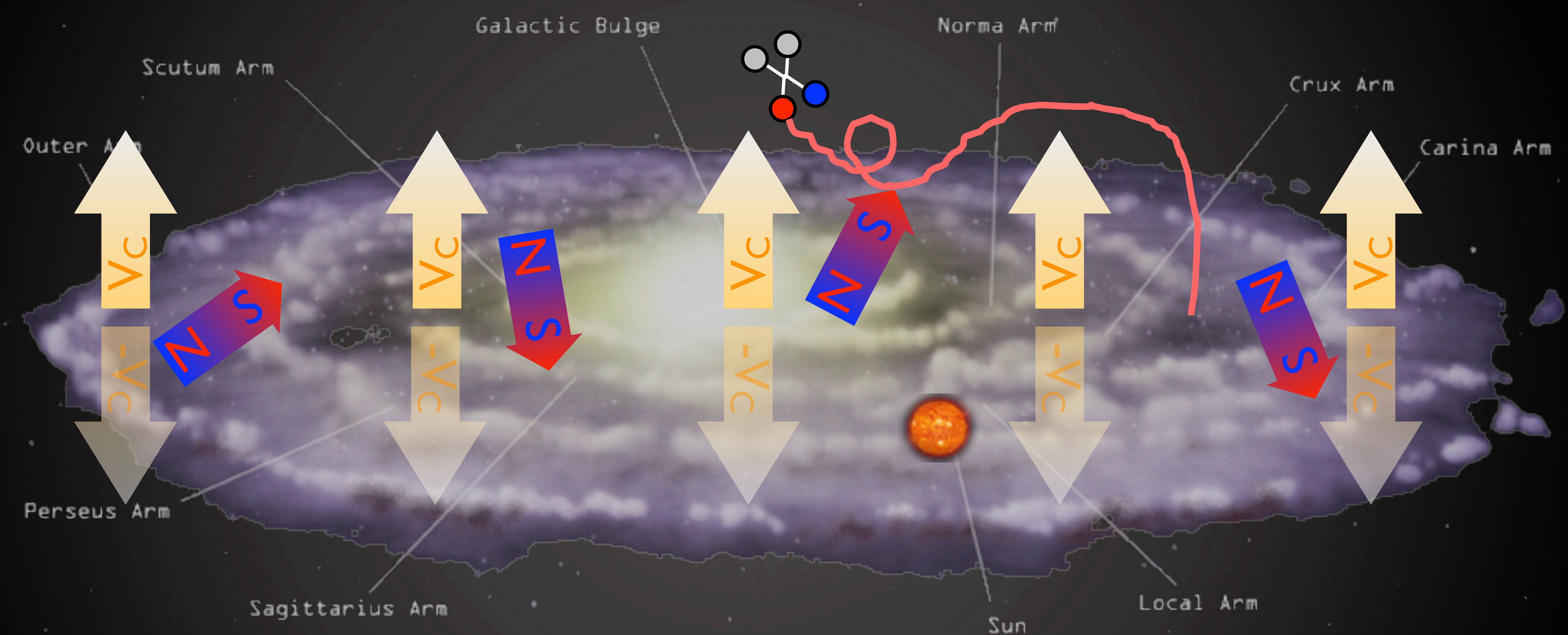

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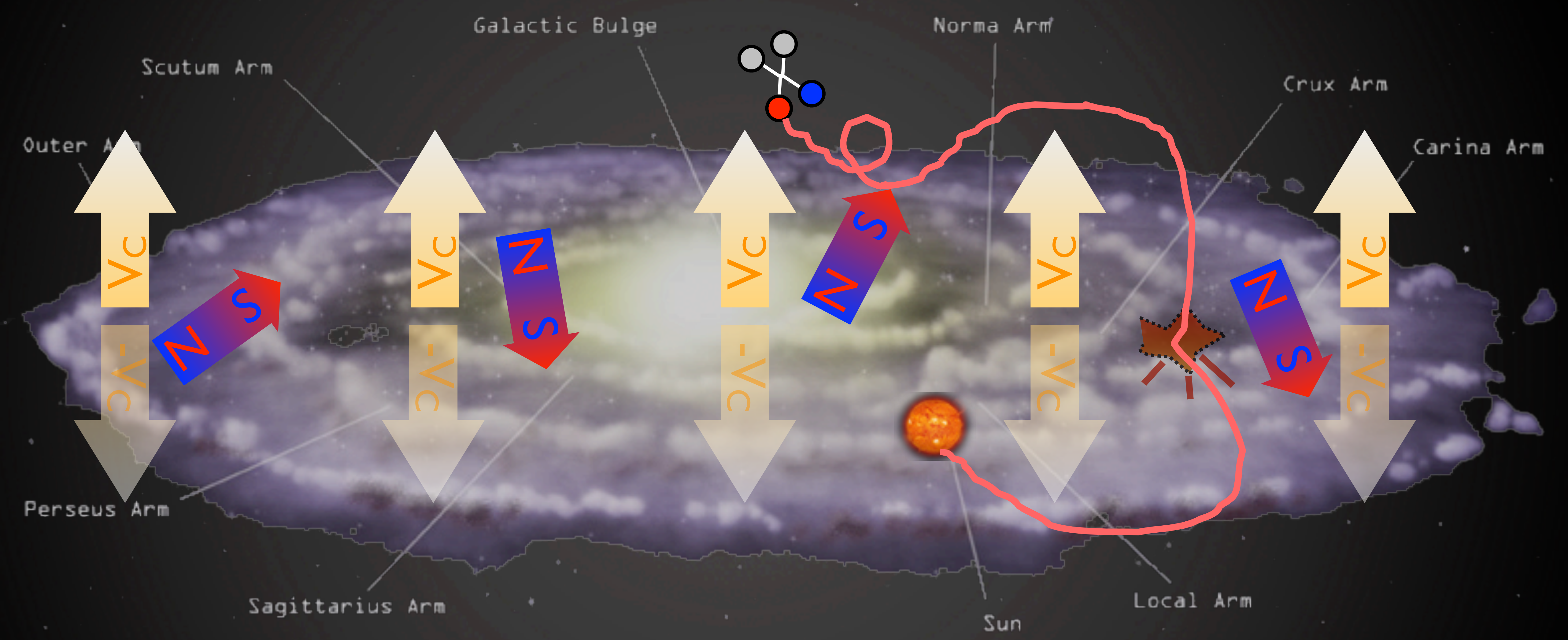

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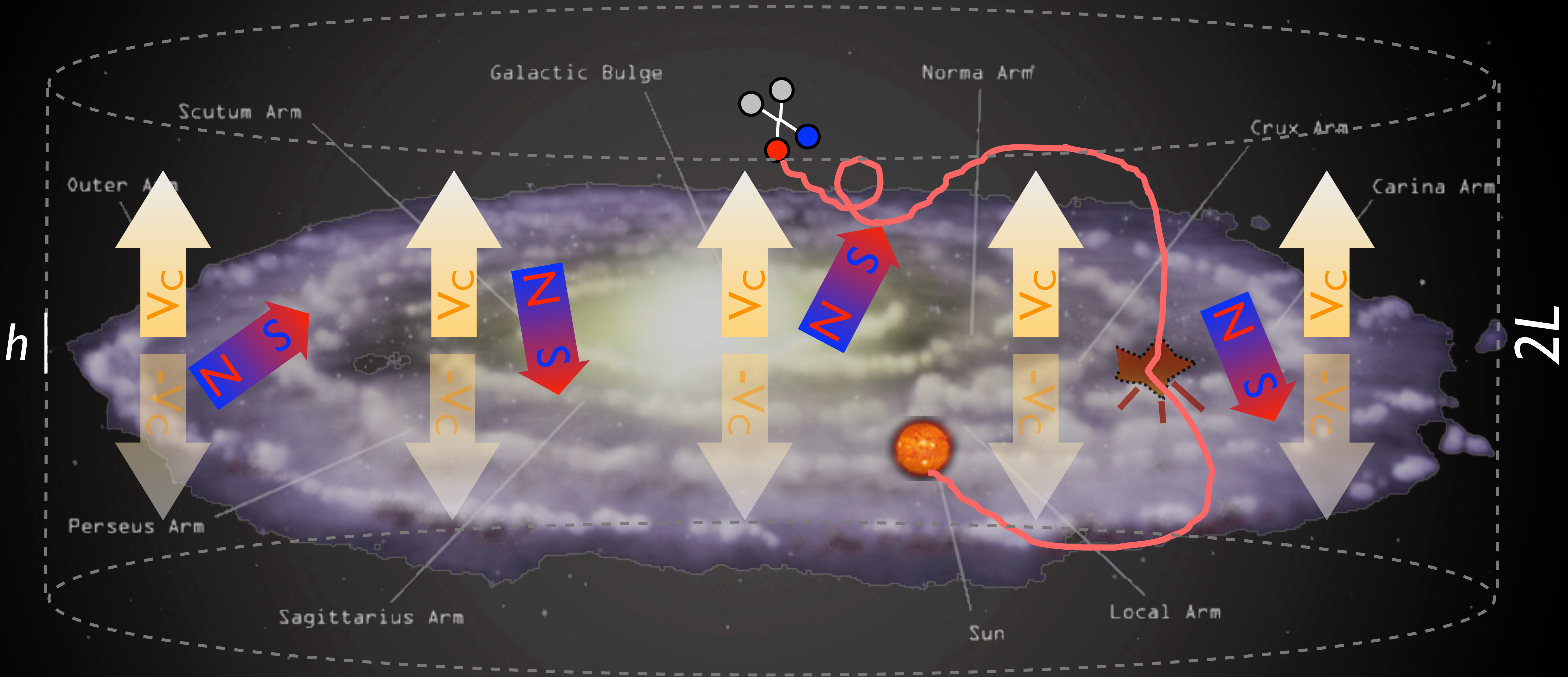


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

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

diffusion · energy loss · convective wind · source · spallations

DM halo profiles

From N-body numerical simulations:

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

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

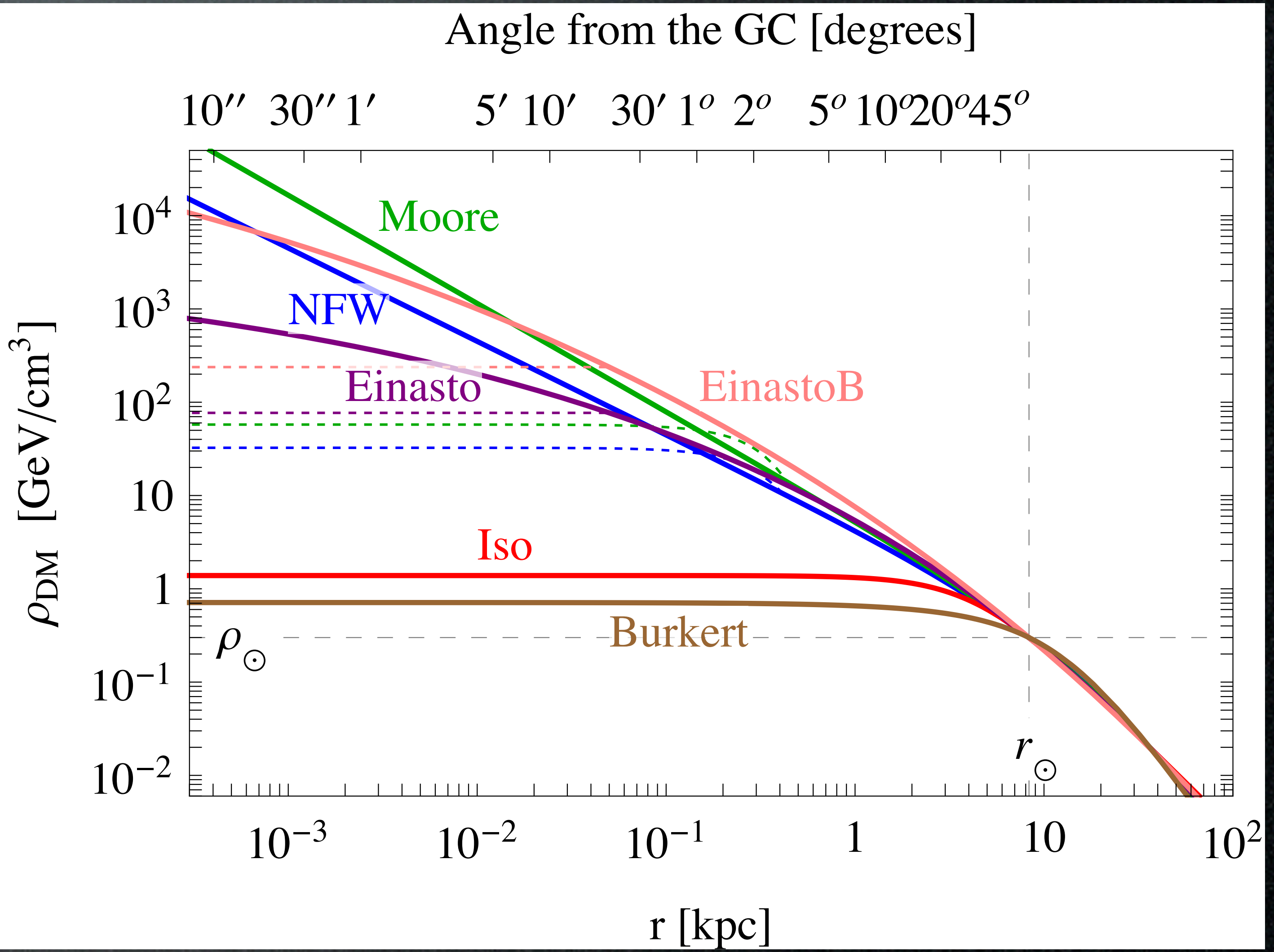
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

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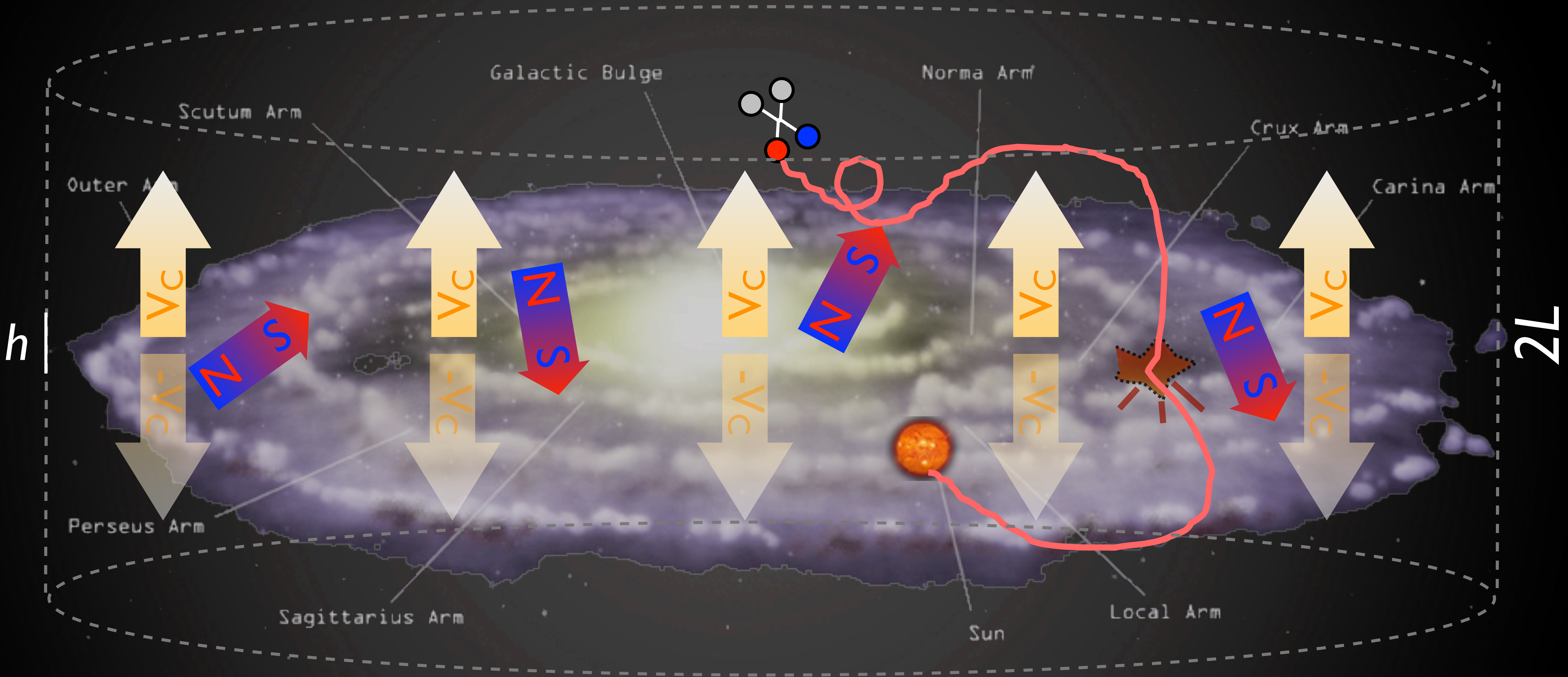

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Brun... '90s, '00s

spectrum

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

diffusion · energy loss · convective wind · source · spallations

Propagation

Propagation for antiprotons:

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

diffusion

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

T kinetic energy

convective wind

spallations

Propagation

Propagation for antiprotons:

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diffusion — convective wind — spallations

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

T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	$V_{\rm conv}$ 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

Propagation

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min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

Solution:

$$\Phi_{\bar p}(T,\vec r_\odot) = B\,\frac{v_{\bar p}}{4\pi}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 R(T)\sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar p}}{dT}$$

Propagation

Propagation for antiprotons:

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

diffusion — convective wind — spallations

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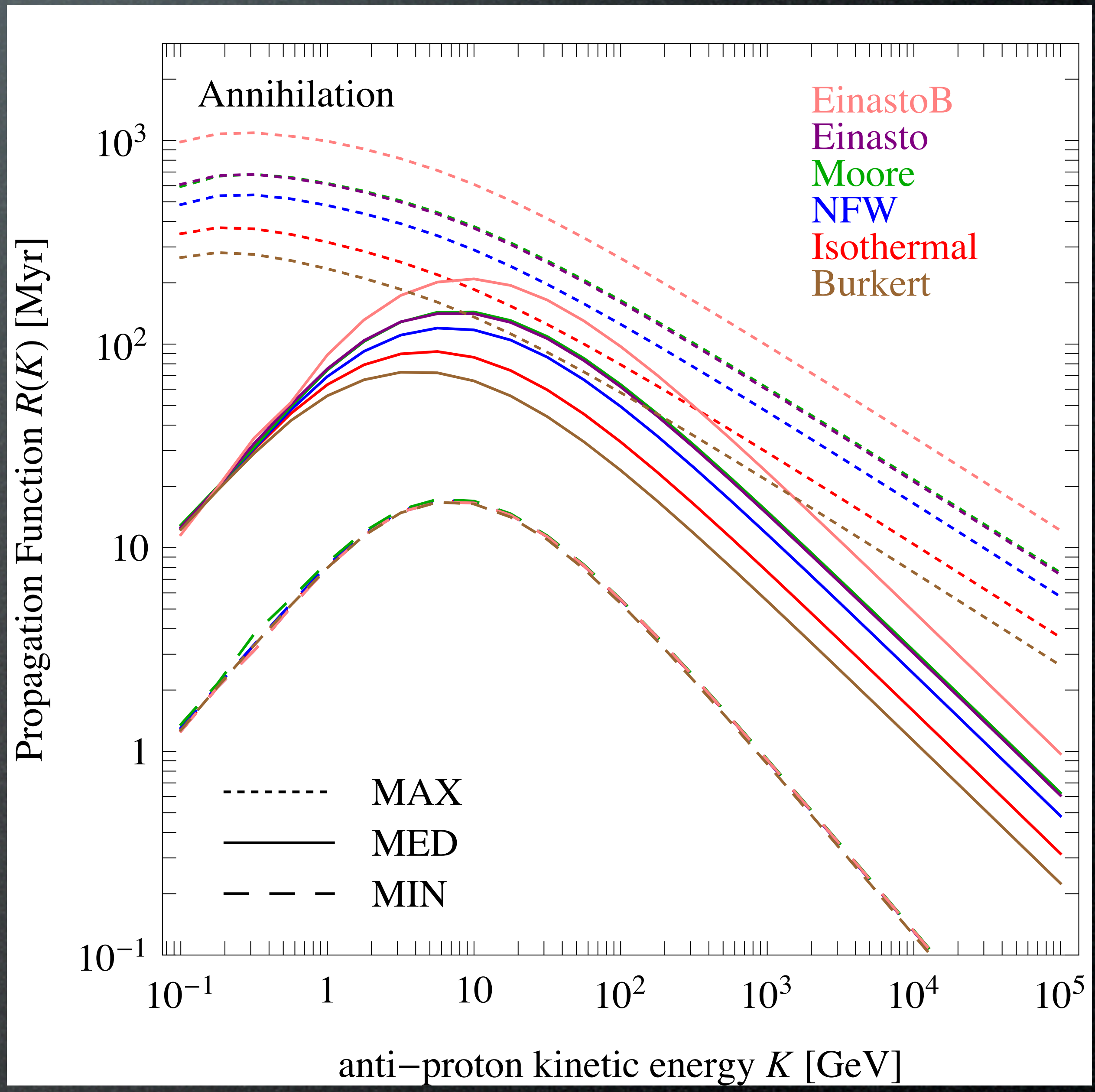

Propagation

Propagation for antiprotons:

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diffusion — convective wind — spallations

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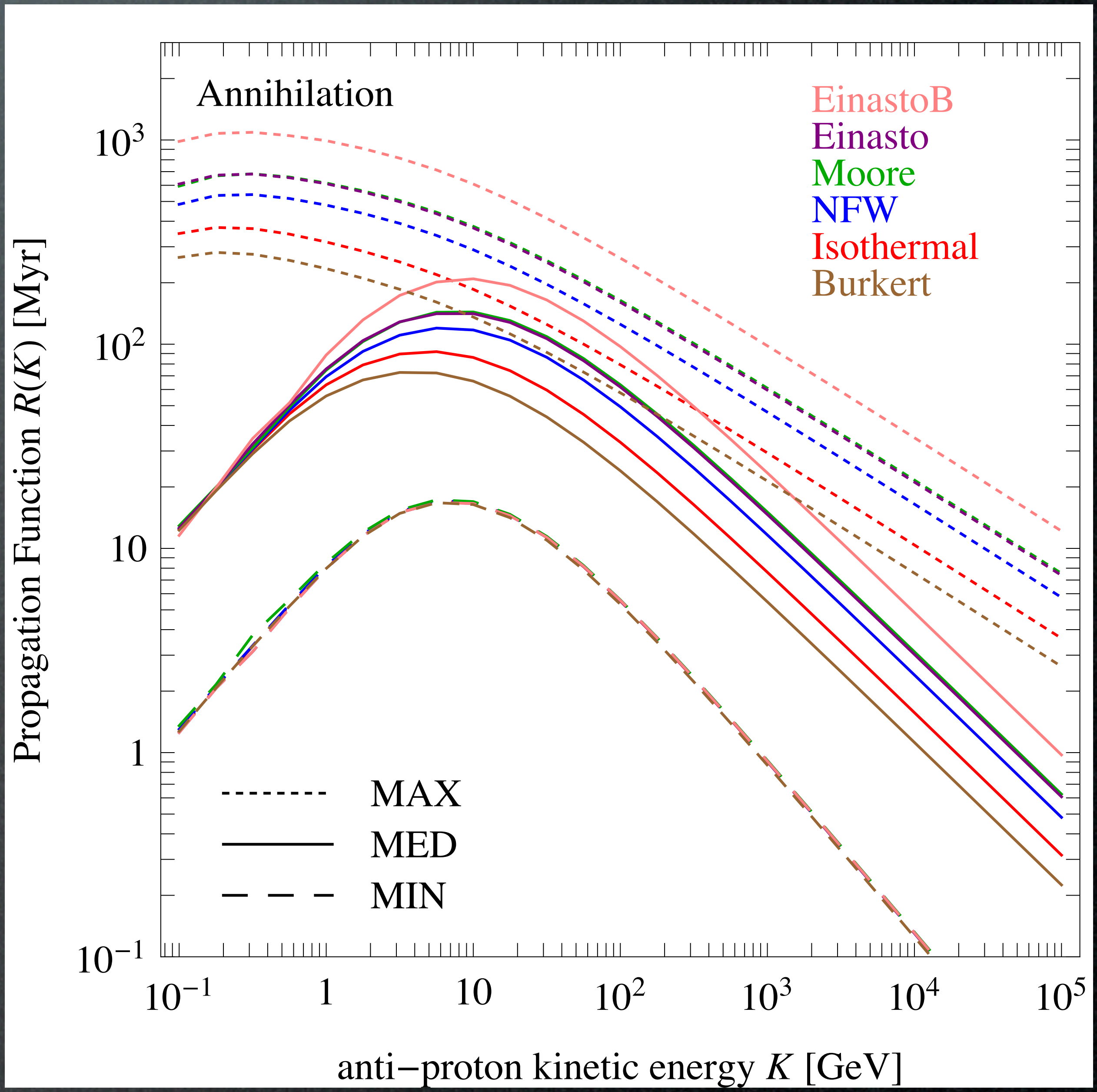


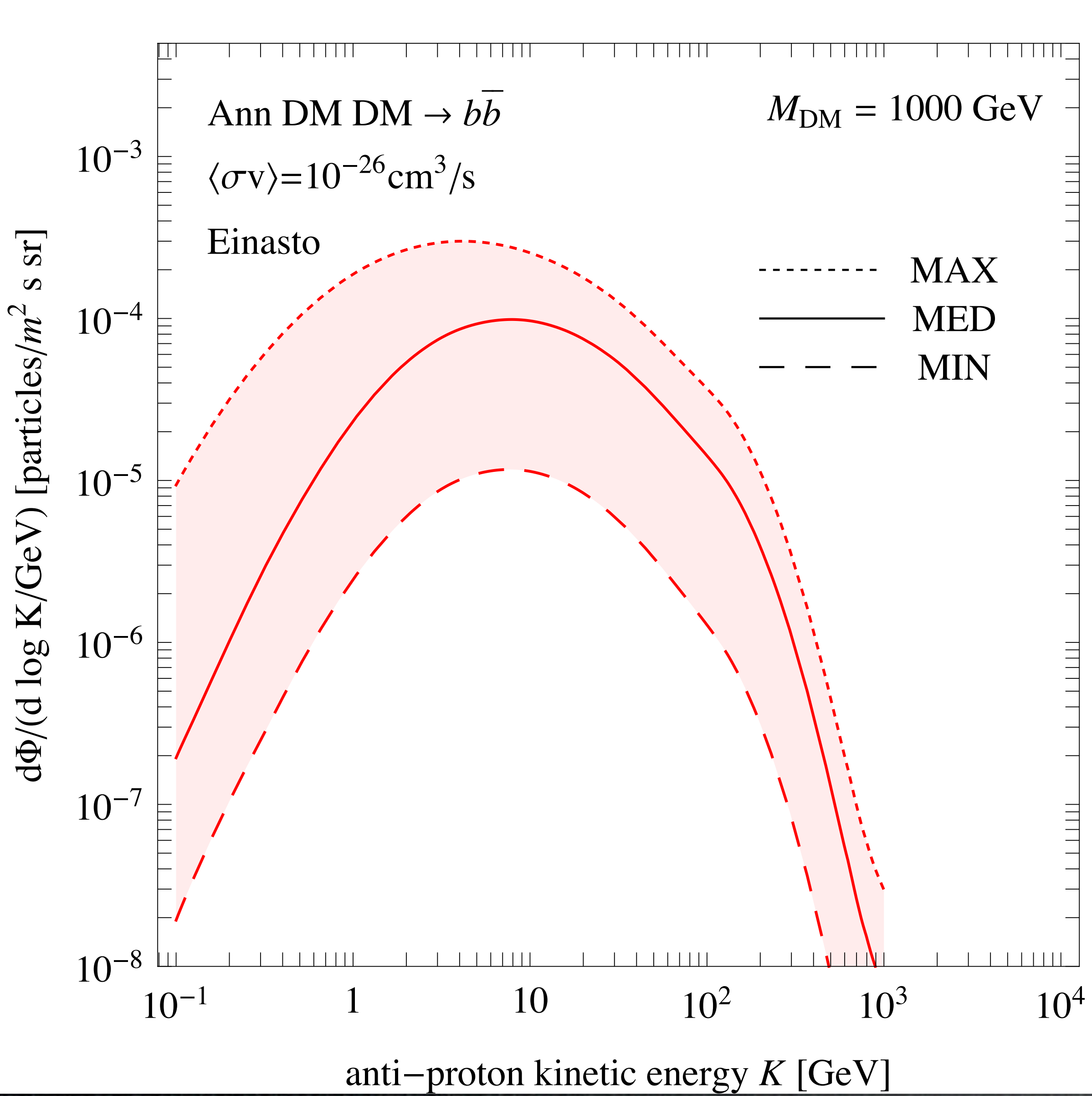
Improvement: added Energy Losses & Diffusive Reacceleration

Boudaud, Cirelli, Giesen, Salati 1412.5695

Propagated fluxes

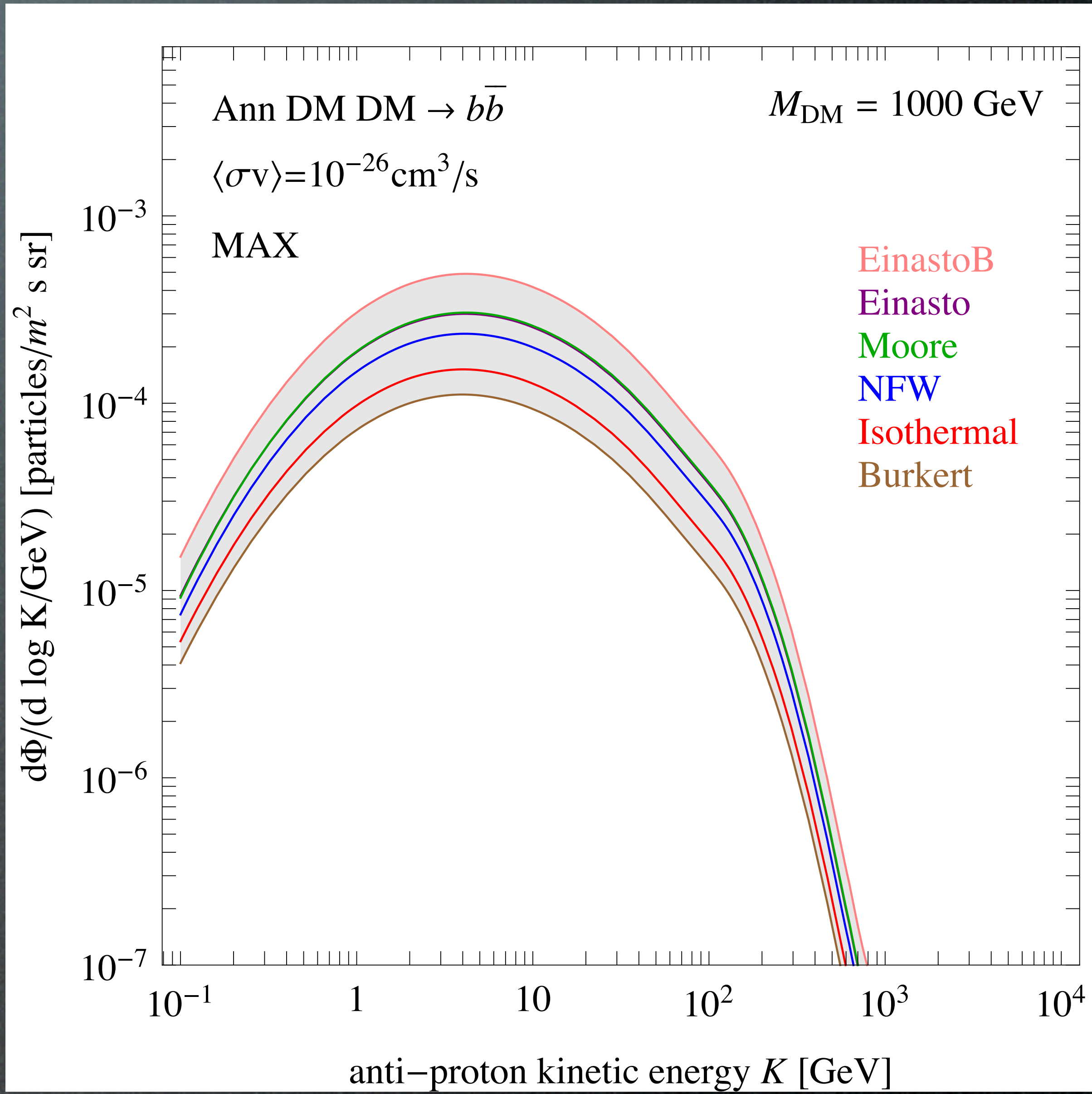
Antiprotons

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

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

Data and Results from 1012.4515 [hep-ph] (and 1009.0224 [hep-ph]), from 1312.6408 [hep-ph], 1412.5696 [astro-ph.HE], from 1505.01049 [hep-ph] and from 1511.08787 [hep-ph].

If you use the data provided on this site, please cite:
M.Cirelli,
"PPPC 4
arXiv 10
Erratum:

Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation

Positrons: The file ElectronHaloFunctEarthAnn.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth.
The notebook Sample.nb shows how to load and use it.

Table of fit coefficients for the reduced halo function $I(\lambda)$
[in the approximated formalism - see paper].

Antiprotons: Table of fit coefficients for the propagation function R[T].

Antideuterons: Table of fit coefficients for the propagation function R[T].

Decay

Positrons: The file ElectronHaloFunctEarthDec.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth.
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[in the approximated formalism - see paper].

Antiprotons: Table of fit coefficients for the propagation function R[T].

Antideuterons: Table of fit coefficients for the propagation function R[T].

Fluxes of charged cosmic rays at the Earth, after propagation:

Annihilation

Antiprotons: *Mathematica function:* the file ProtonFluxELDRAnn.m provides the spectra Log_{10} [$d\Phi/d\, Log_{10} K$].
Refer to the notebook Sample.nb for usage.

Numerical table: provides the spectra $d\Phi/d\, Log_{10}K$.
The columns are: [m_{DM}, halo, propagation, $Log_{10}K$, $d\Phi/d\, Log_{10}K$ for 28 primary channels].
The spectra are computed at a benchmark annihilation cross of $\langle\sigma v\rangle = 10^{-26}$ cm³/s and renormalized multiplying by $(m_{DM}/\text{GeV})^2$.
Units are particles/(m² s sr).

The file ProtonFluxAnn.m provides the spectra without ELDR (*Energy Losses including tertiaries and Diffusive Reacceleration*, see 1412.5696 for details): this is now superseded and provided here only for the purpose of comparison with previous calculations.

Decay

Antiprotons: *Mathematica function:* the file ProtonFluxELDRDec.m provides the spectra Log_{10} [$d\Phi/d\, Log_{10}$ K].
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The file ProtonFluxDec.m provides the spectra without ELDR (*Energy Losses including tertiaries and Diffusive Reacceleration*, see 1412.5696 for details): this is now superseded and provided here only for the purpose of comparison with previous calculations.

Propagation

Propagation for positrons: conventional treatment

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

diffusion
(in turbulent $\bar{B} \approx \mu\mathrm{G}$, assumed space indep.)
$K(E) = K_0 (E/\mathrm{GeV})^\delta$

energy loss (assumed space indep.)
$b(E) = (E/\mathrm{GeV})^2/\tau_E$
$\tau_E = 10^{16}\,\mathrm{s}$

$$Q = \frac{1}{2}\left(\frac{\rho}{M_{\rm DM}}\right)^2 f_{\rm inj}, \qquad f_{\rm inj} = \sum_k \langle\sigma v\rangle_k \frac{dN^k_{e^+}}{dE}$$

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Model	δ	K_0 in kpc^2/Myr	L in kpc
min (M2)	0.55	0.00595	1
med	0.70	0.0112	4
max (M1)	0.46	0.0765	15

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max (M1)	0.46	0.0765	15

Solution:

$$\Phi_{e^+}(E,\vec{r}_\odot) = B\frac{v_{e^+}}{4\pi}\frac{\tau_E}{E^2}\int_E^{M_{\rm DM}} dE'\; Q(E')\cdot I\left(\lambda_D(E,E')\right)$$

$$\lambda_D^2 = 4K_0\tau_E\left[\frac{(E/\mathrm{GeV})^{\delta-1} - (E'/\mathrm{GeV})^{\delta-1}}{\delta - 1}\right]$$

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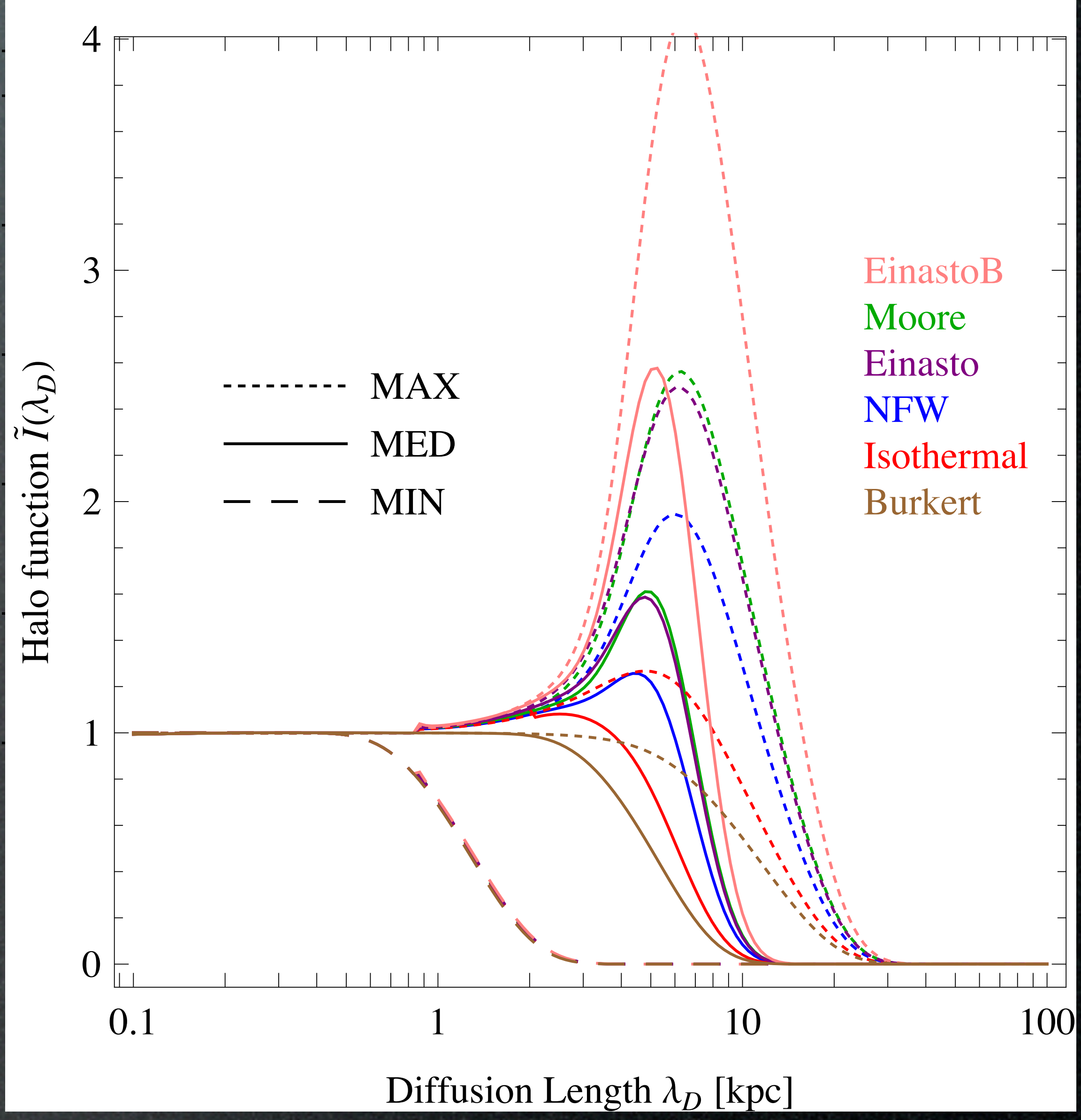

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!

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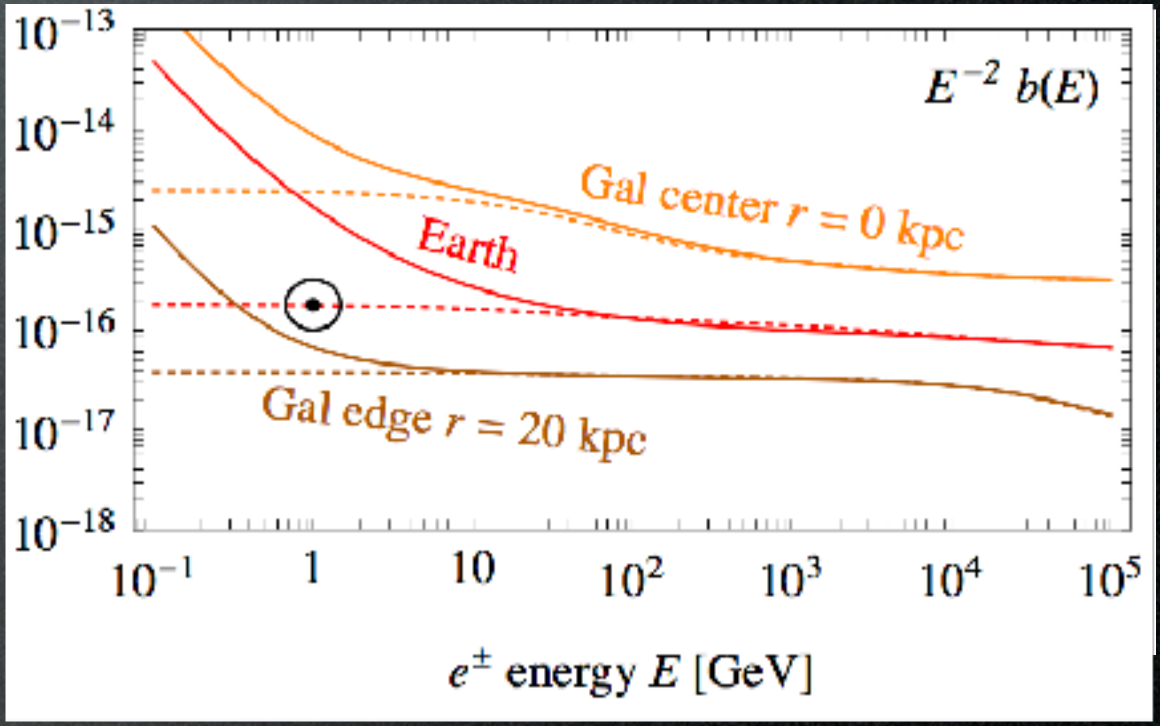
!

- it is not space independent
- it is not simple E^2



Buch, Cirelli, Giesen, Taoso 1505.01049

Propagation

Propagation for positrons: improved treatment

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

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

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

energy loss function extracted using GalProp simulations

Model	δ	K_0 in kpc^2/Myr	L in kpc
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max (M1)	0.46	0.0765	15

Solution:

$$\Phi_{e^\pm}(E,\vec{r}_\odot) = \frac{v_{e^\pm}}{4\pi\, b(E,\vec{x})} \frac{1}{2} \left(\frac{\rho(\vec{x})}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \int_E^{M_{\rm DM}} dE_s \frac{dN^f_{e^\pm}}{dE}(E_s)\, I(E,E_s,\vec{x})$$

Propagation

Propagation for positrons: improved treatment

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

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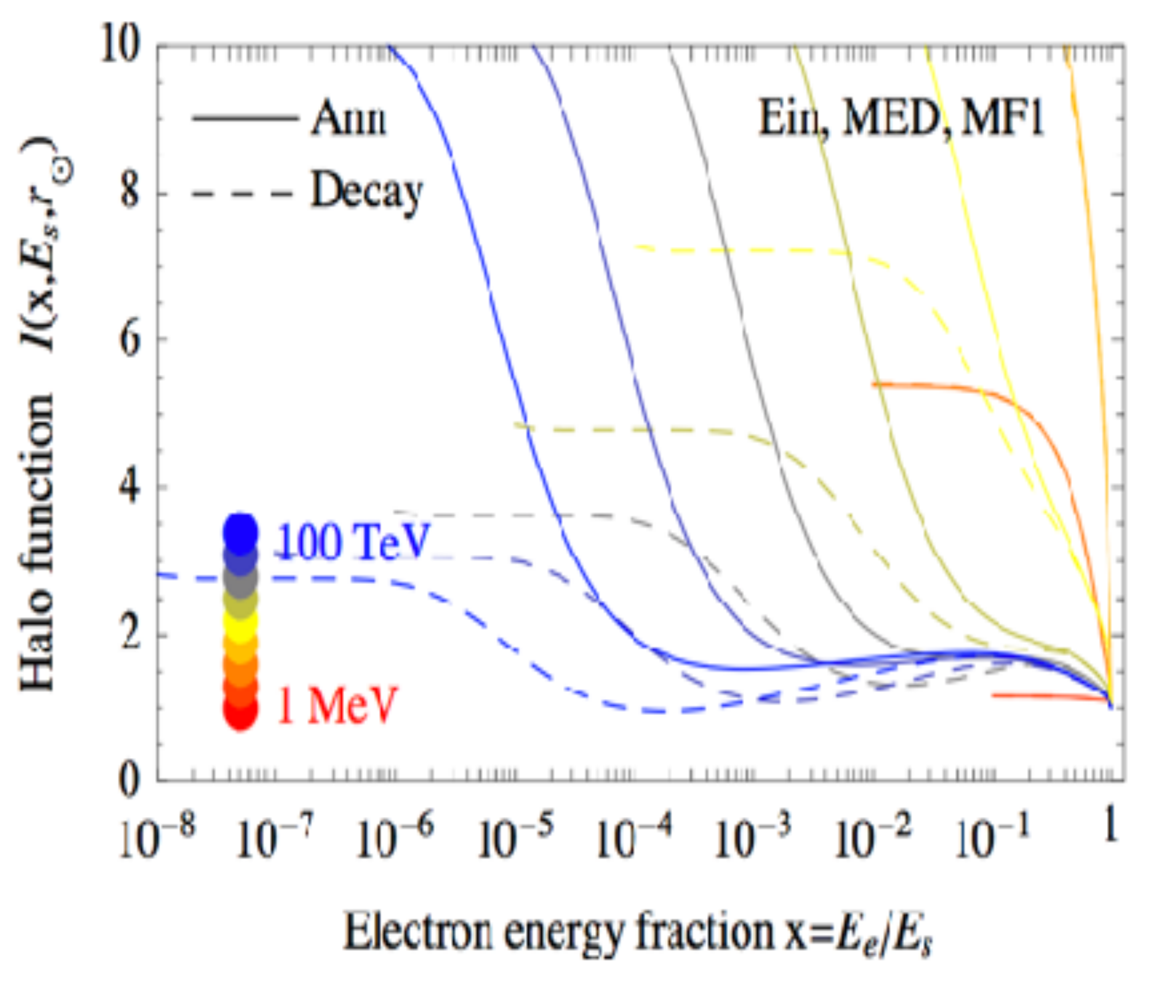
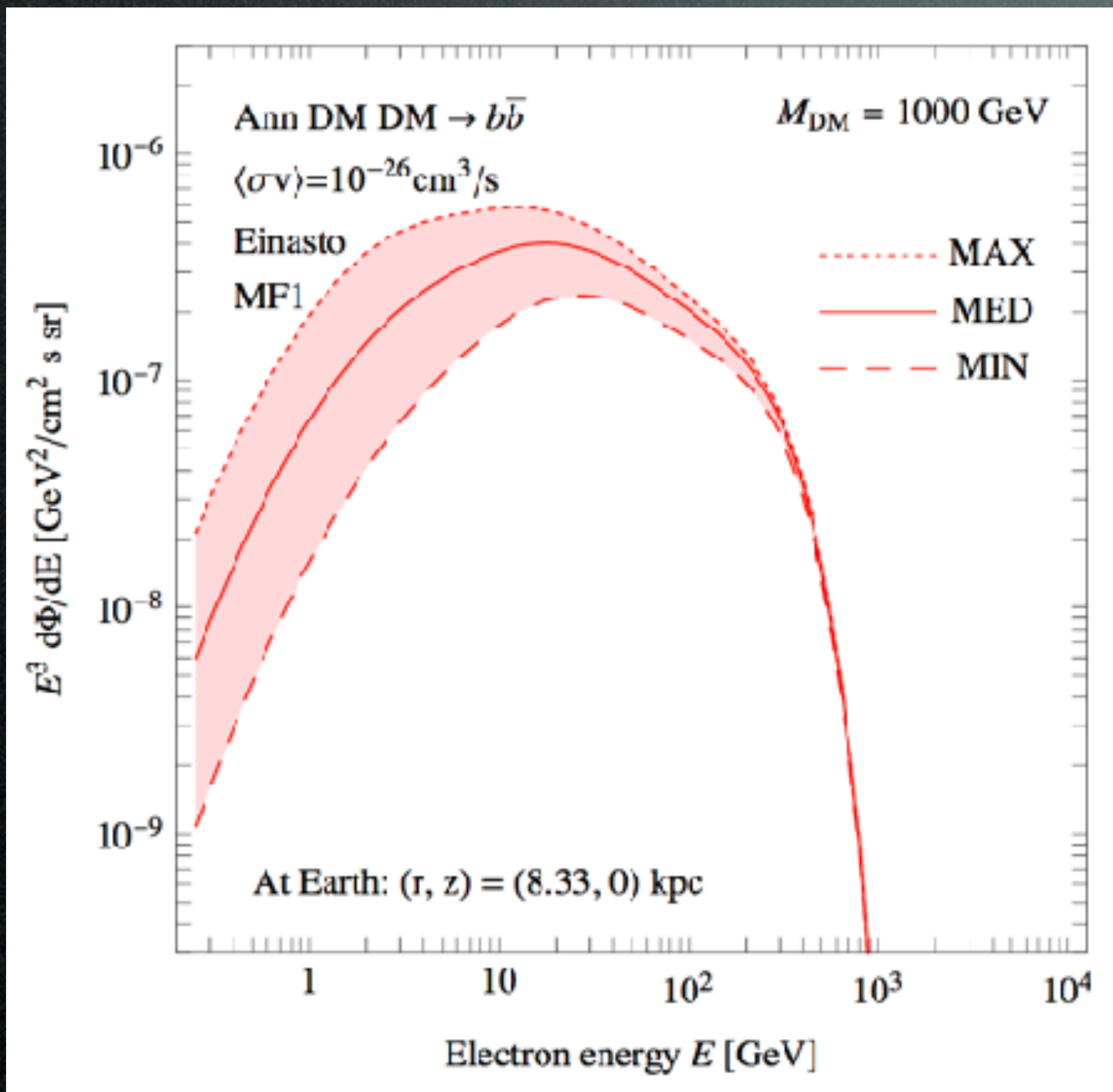


There is now a ‘halo function’ per each positron injection energy

Propagated fluxes

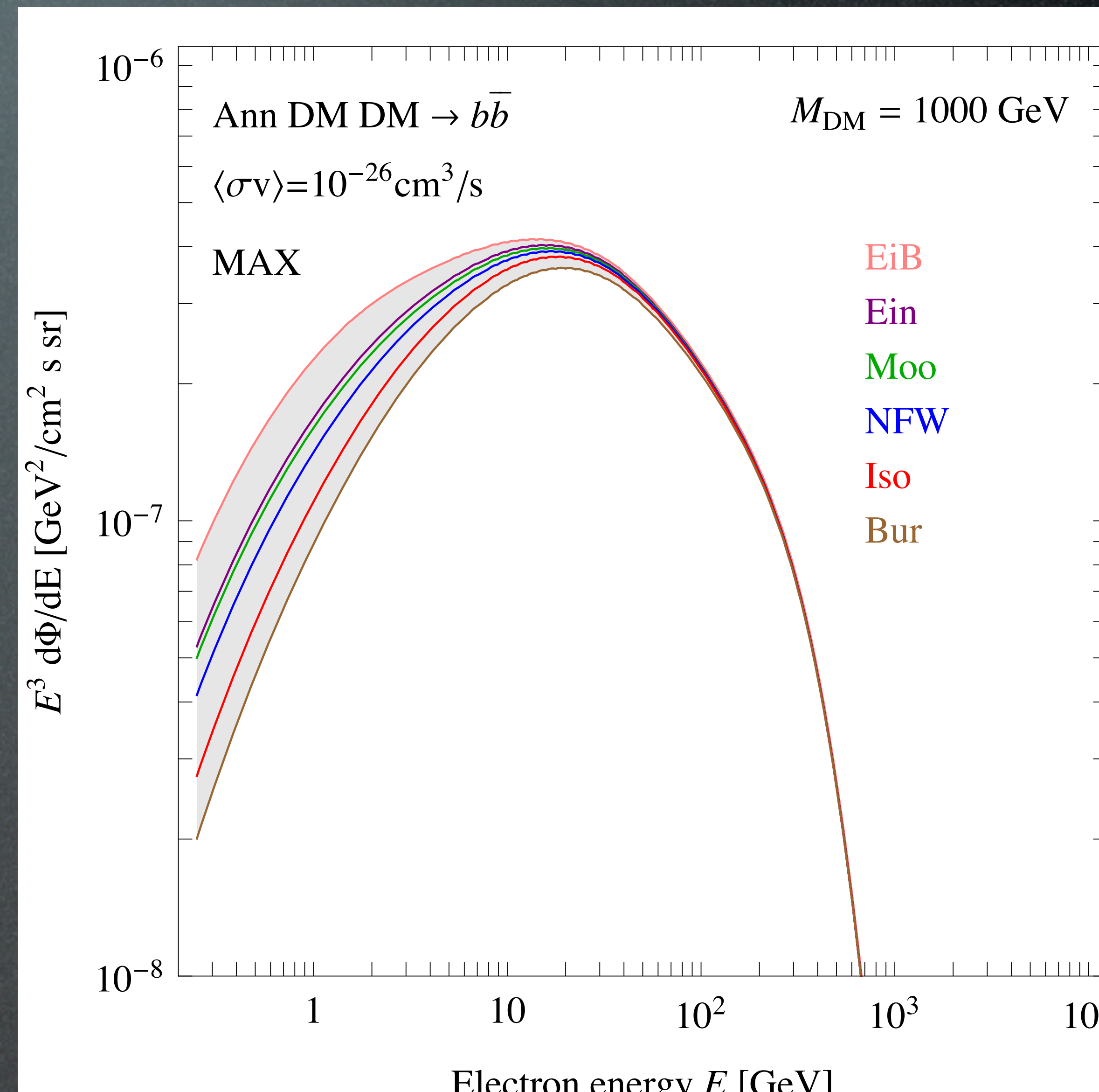
Positrons

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

Propagated fluxes

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

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If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4
arXiv 10
Erratum:

Propagation functions for electrons and positrons everywhere in the Galaxy:

Energy loss coefficient function b[E, r, z] for electrons and positrons in the Galaxy: *Mathematica* function btot.m, refer to the notebook Sample.nb for usage.

Annihilation	Decay
Positrons: The file ElectronHaloFunctGalaxyAnn.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy. [Note: very large file, almost 4GB.] The notebook Sample.nb shows how to load and use it.	Positrons: The file ElectronHaloFunctGalaxyDec.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy. [Note: very large file, almost 4GB.] The notebook Sample.nb shows how to load and use it.

Propagation functions for charged cosmic rays at the location of the Earth:

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DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo and from synchrotron 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

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

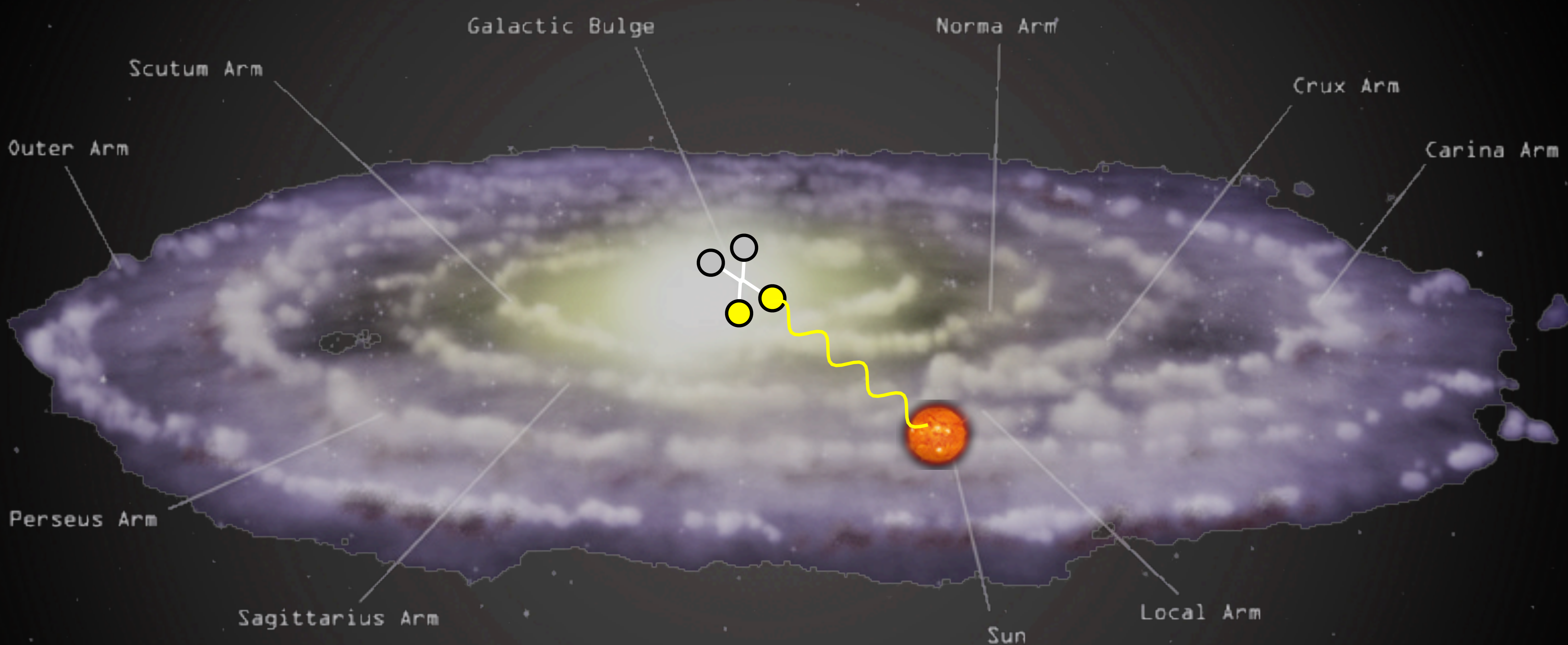
GAPS

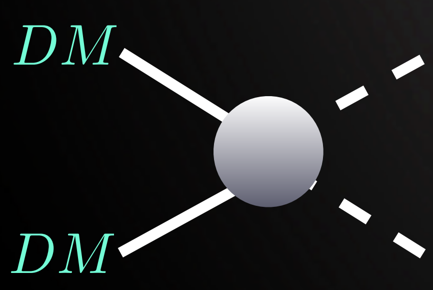
$\nu, \bar{\nu}$ from annihil in massive bodies

SK, Icecube, Km3Net

Indirect Detection: basics

γ from DM annihilations in galactic center



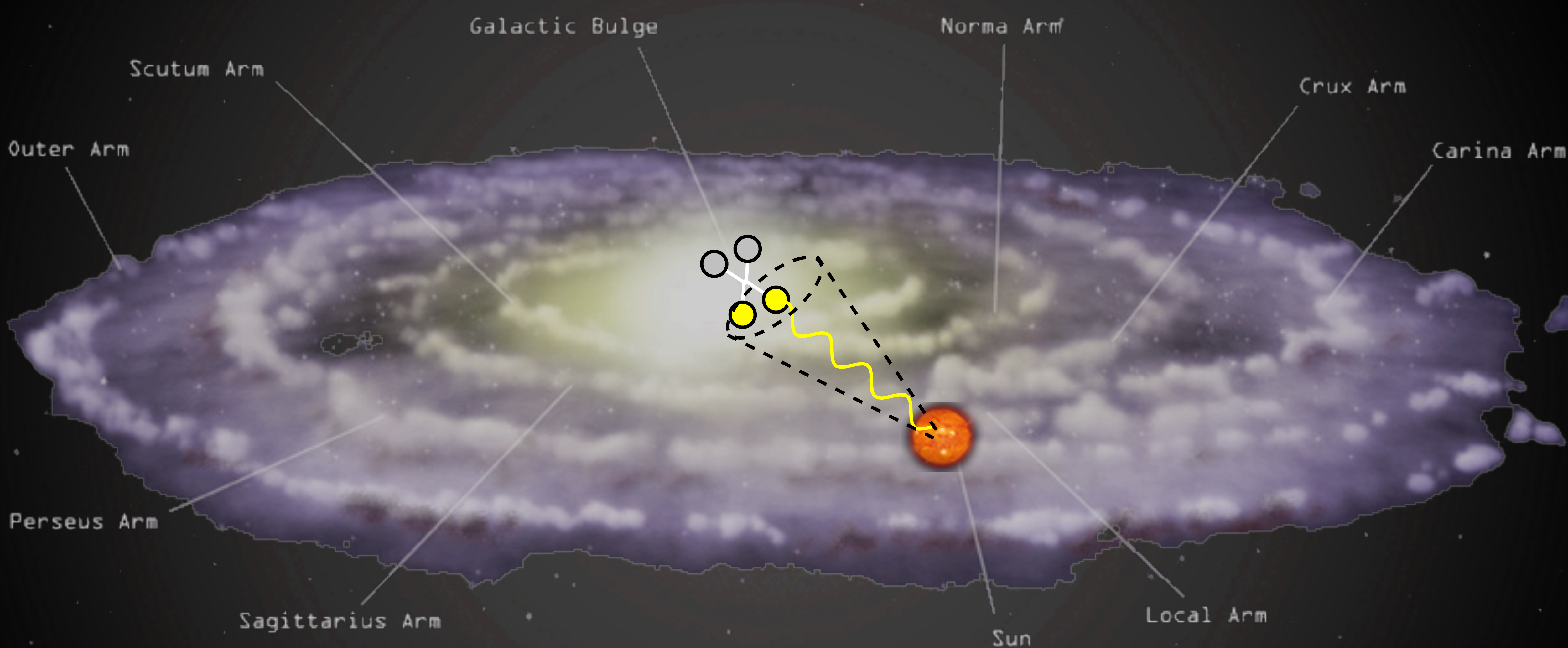


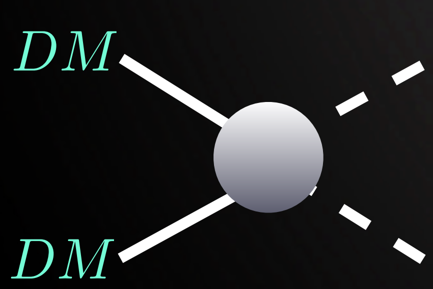
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

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

Indirect Detection: basics

γ from DM annihilations in galactic center



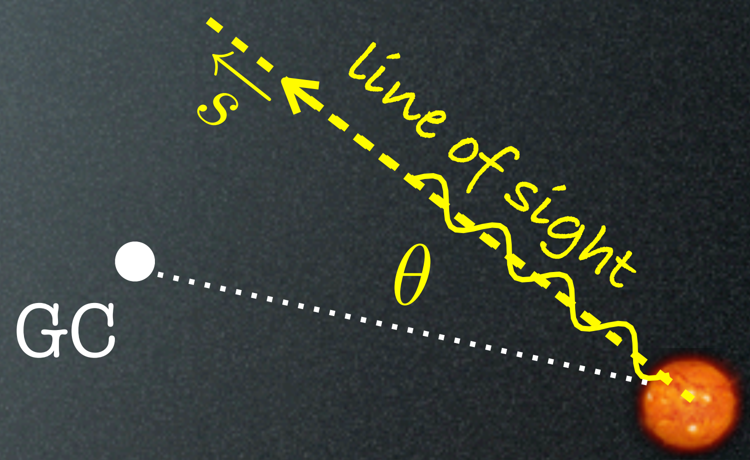


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

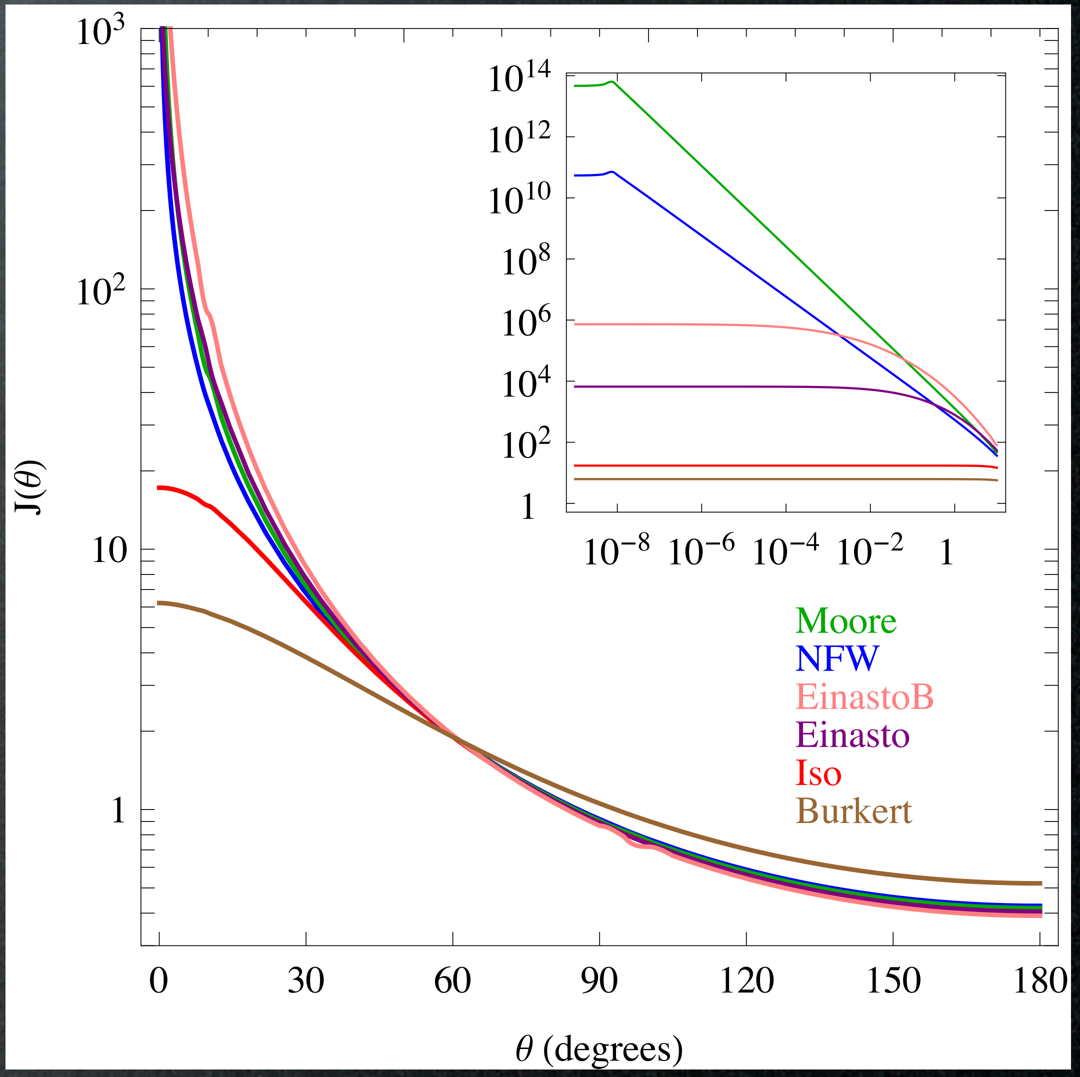
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ and γ

'Prompt' gamma rays

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

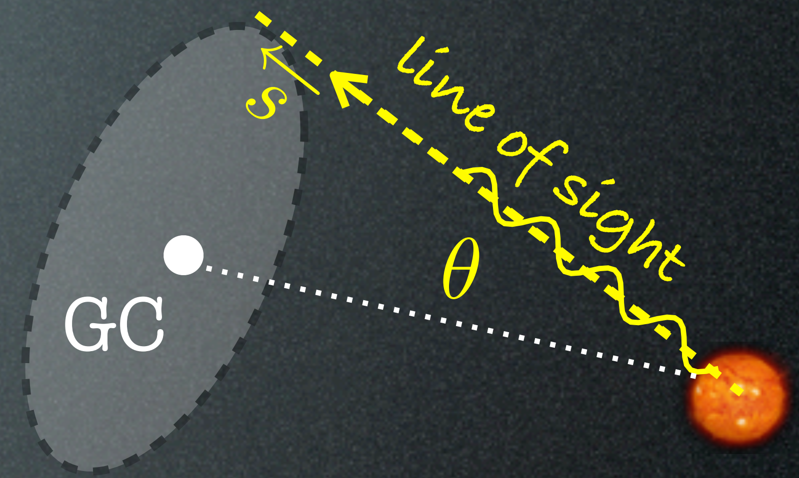


$$J = \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\theta))}{\rho_\odot}\right)^2$$



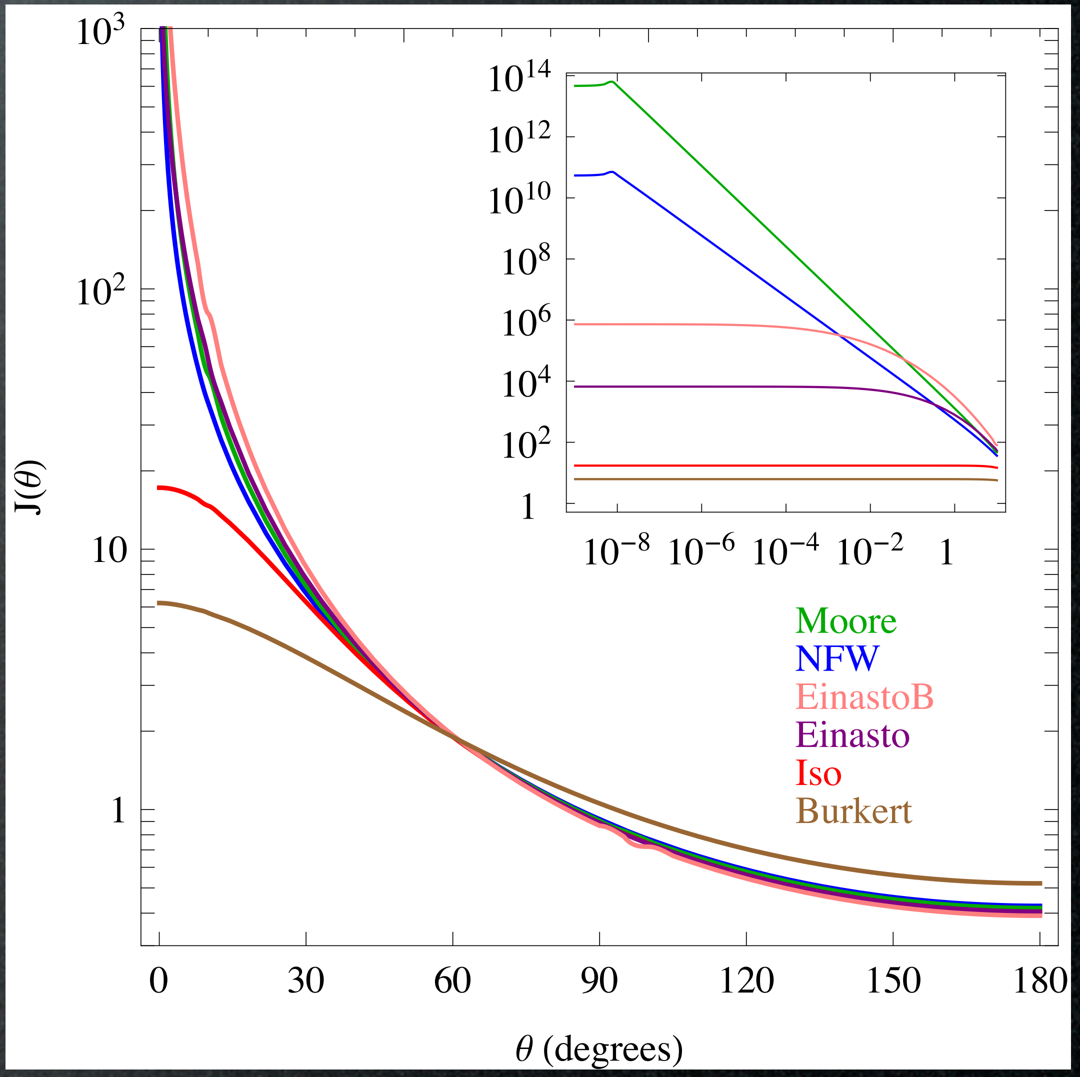
‘Prompt’ gamma rays

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



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

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

‘Prompt’ gamma rays

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

Data and Results from 1012.4515 [hep-ph] (and 1009.0224 [hep-ph]), from 1312.6408 [hep-ph], 1412.5696 [astro-ph.HE], from 1505.01049 [hep-ph] and from 1511.08787 [hep-ph].

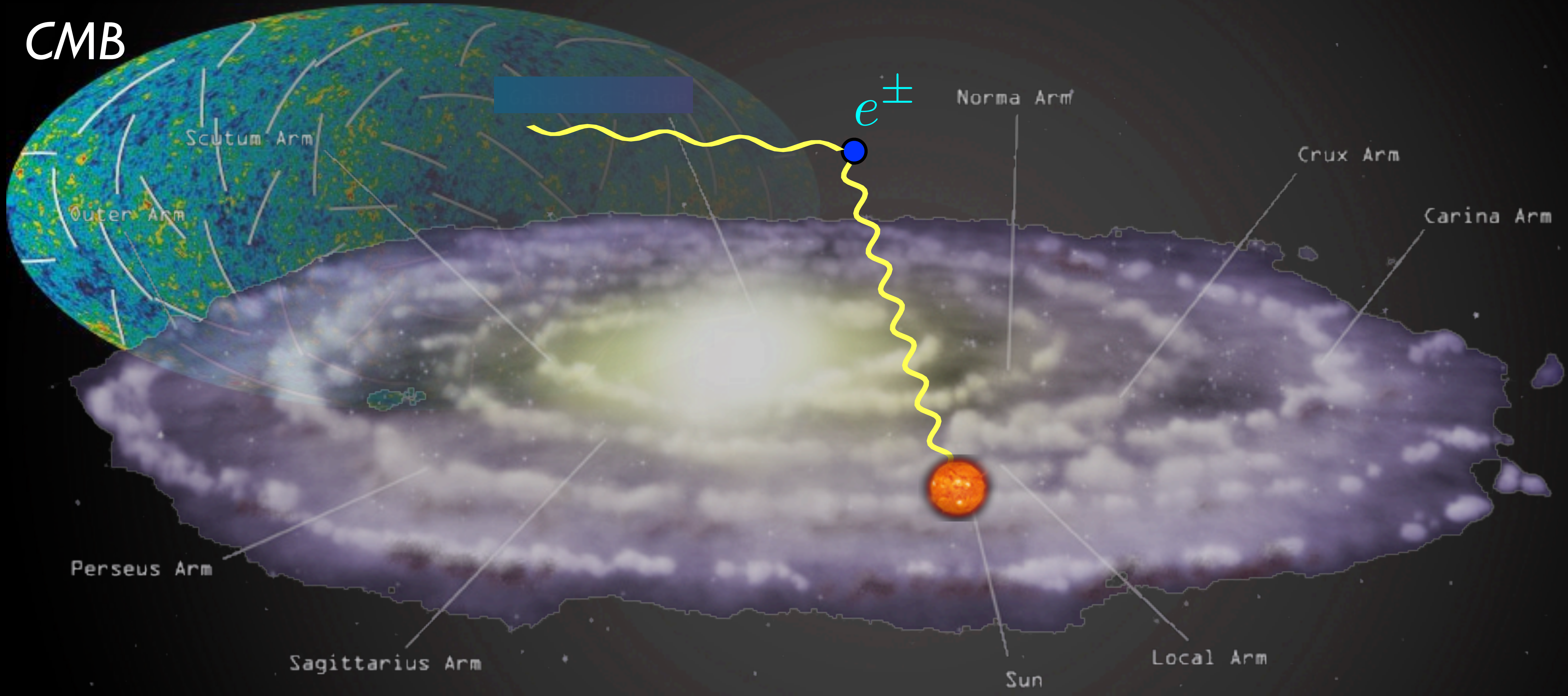
If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection",
arXiv 1012.4515, JCAP 1103 (2011) 051.
Erratum: JCAP 1210 (2012) E01.

J factors for prompt gamma rays:

Annihilation	Decay
Mathematica function: the file JAnn.m provides $\mathrm{Log}_{10}[J(\theta)]$. Refer to the notebook Sample.nb for usage.	*Mathematica* function: the file JDec.m provides $\mathrm{Log}_{10}[J(\theta)]$. Refer to the notebook Sample.nb for usage.

Indirect Detection: basics

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

Indirect Detection: basics

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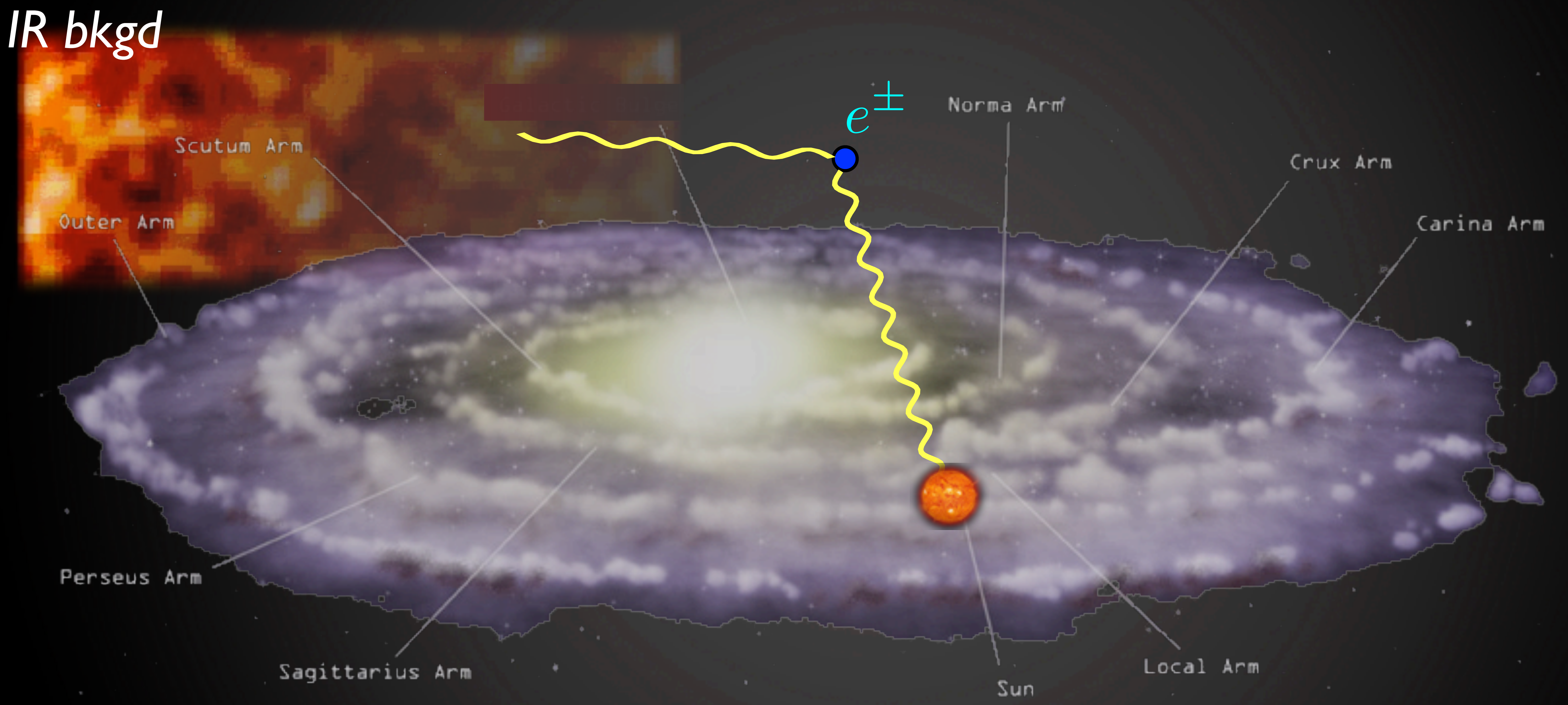

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Indirect Detection: basics

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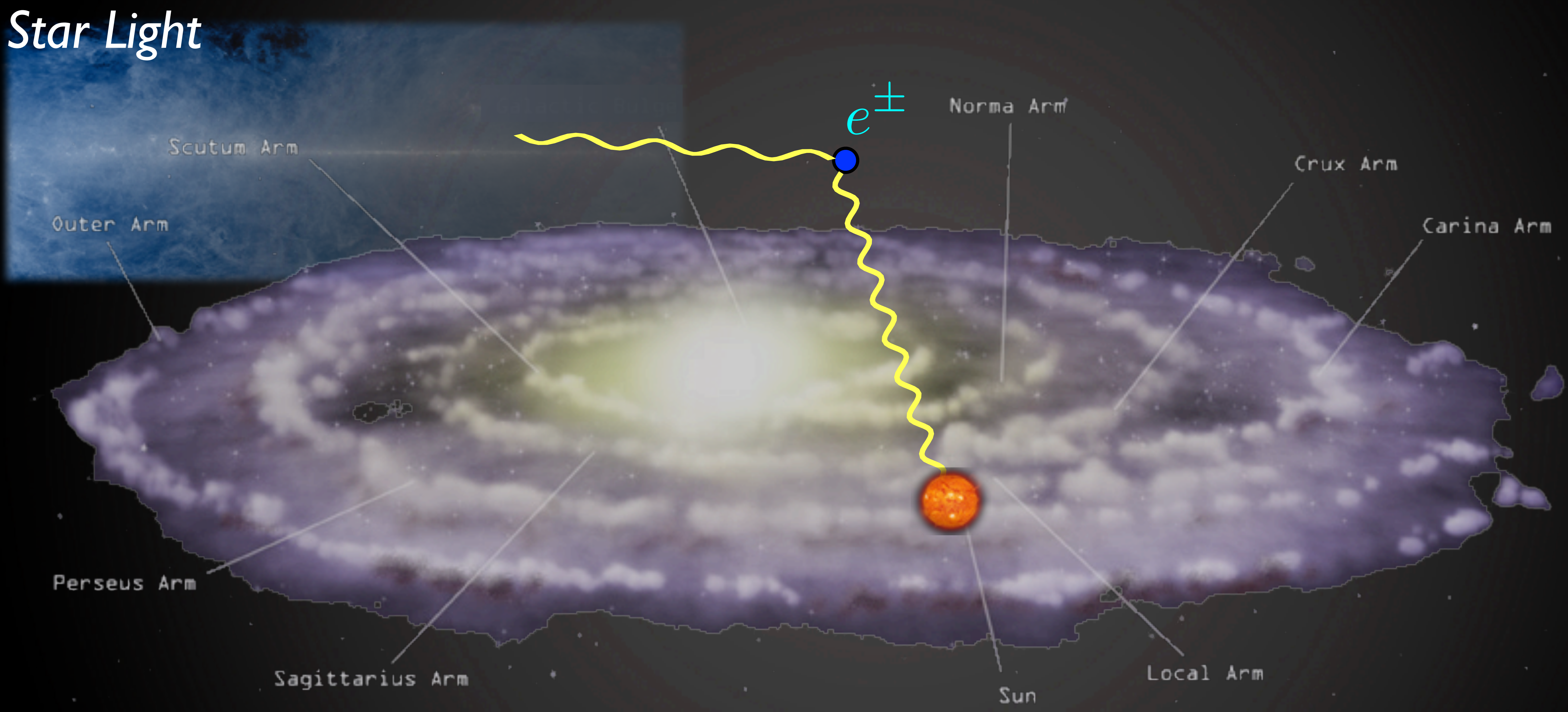

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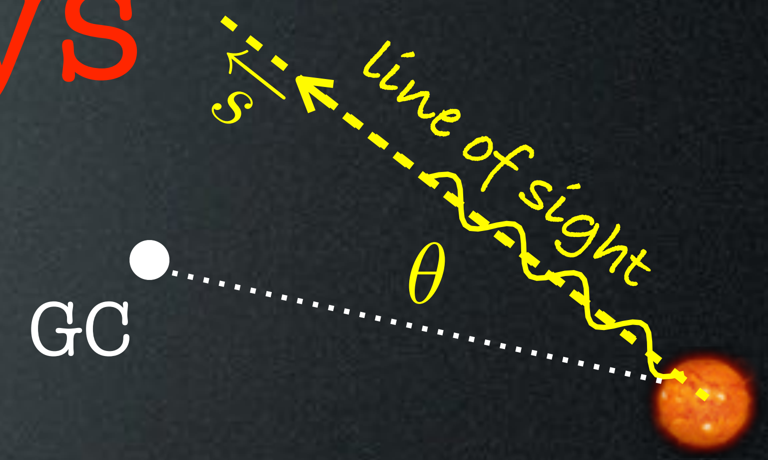
ICS gamma rays



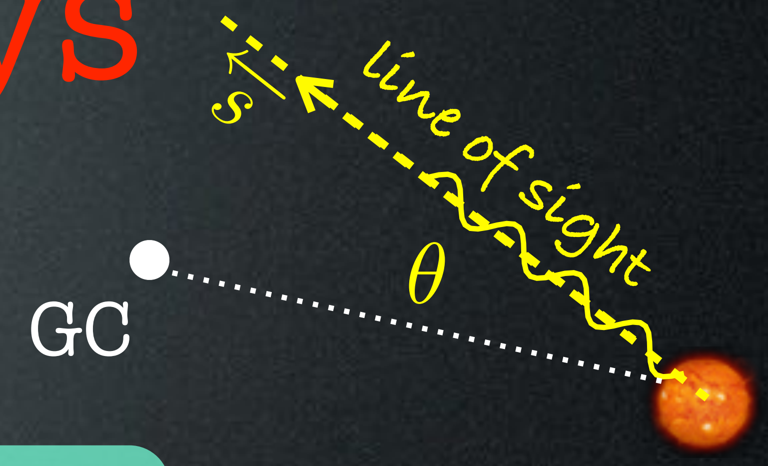
Flux of ICS γ
from direction θ:

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

integral over s

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

ICS gamma rays



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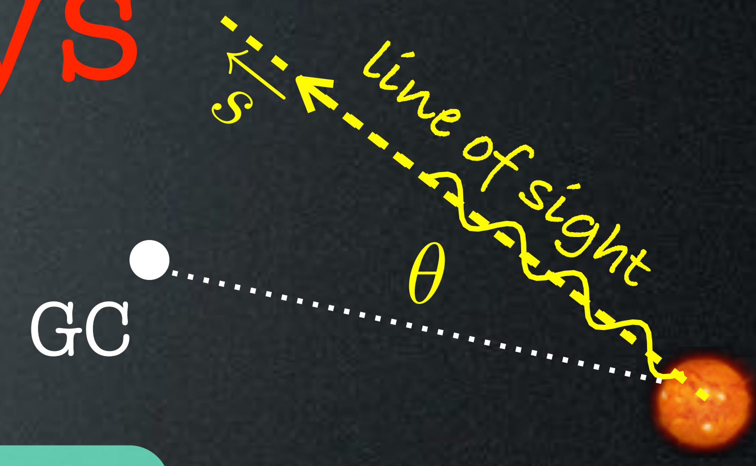
spectral densities of emitting $e^\pm$

ICS gamma rays



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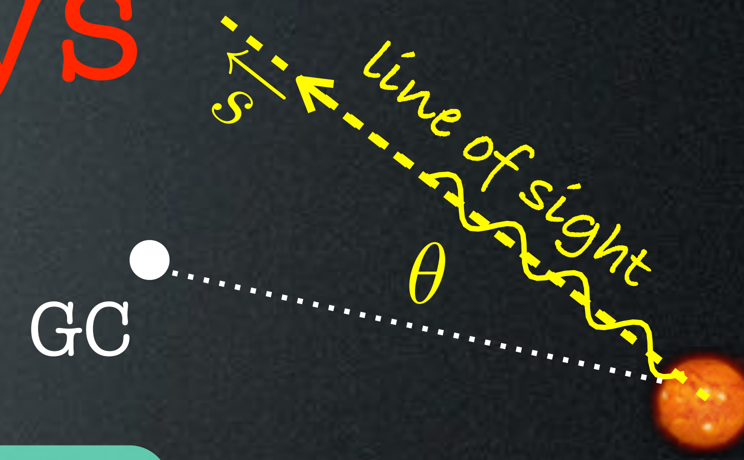
spectral densities of emitting $e^\pm$

power emitted by individual 'cell':

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

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

ICS gamma rays



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spectral densities of emitting $e^\pm$

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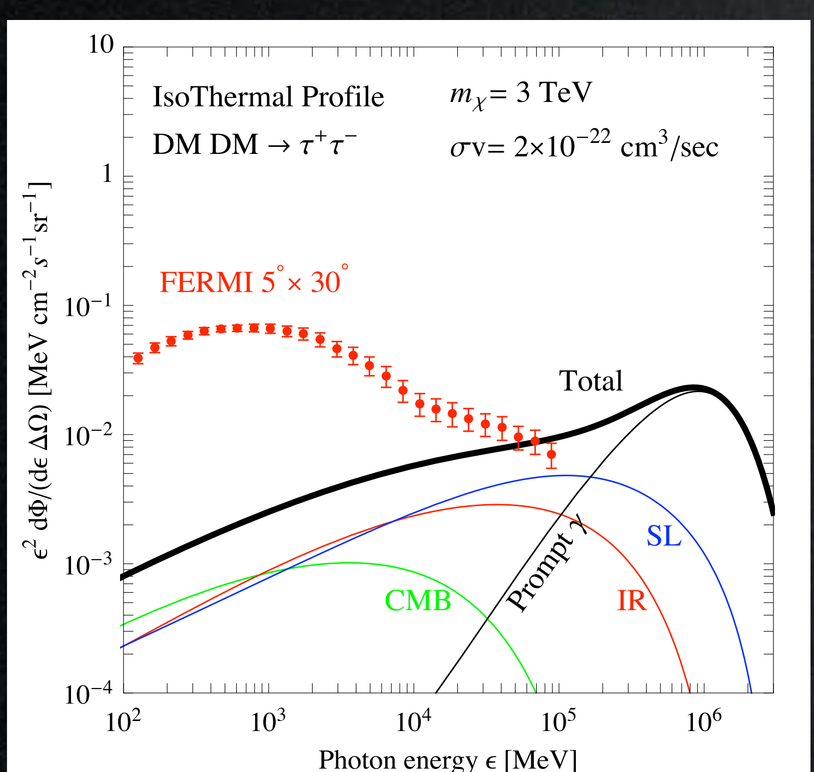
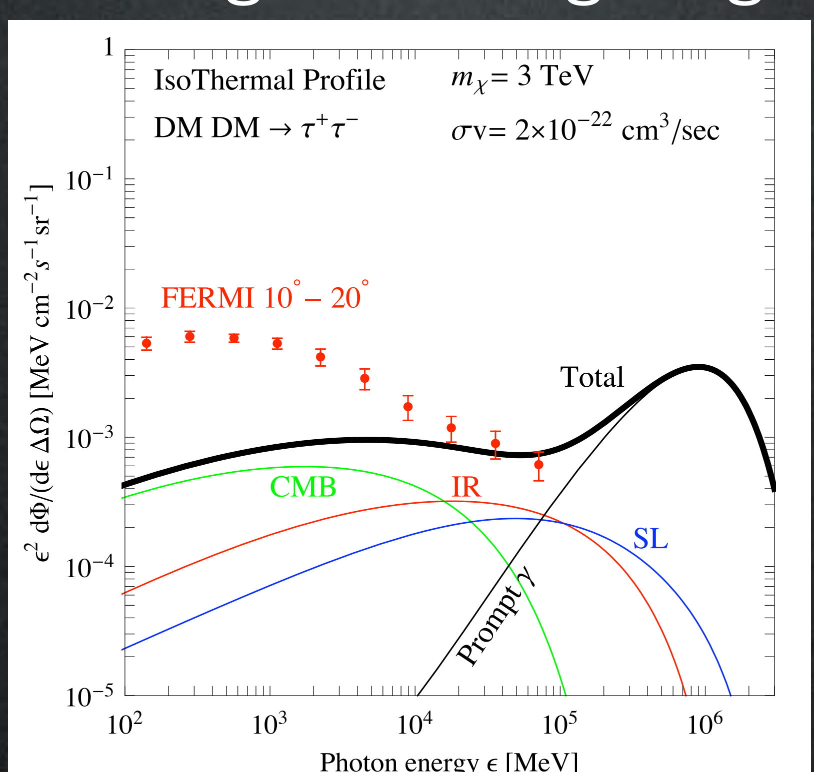
spectral densities of target lights

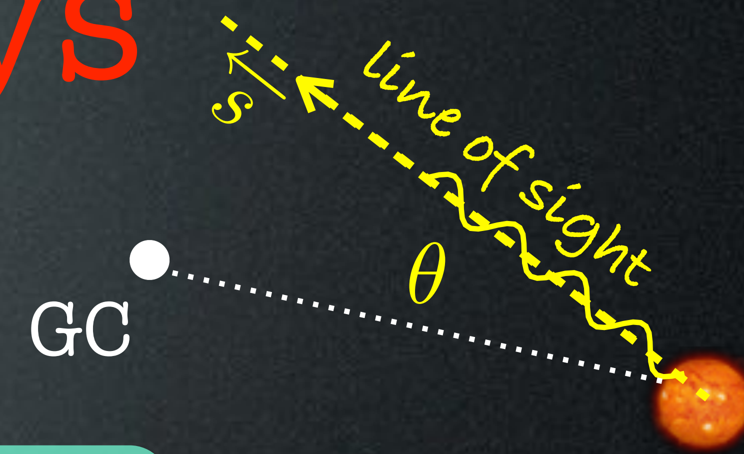
Different windows = different weights of target lights:





Cirelli, Panci, Serpico 0912.0663

ICS gamma rays



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spectral densities of emitting $e^\pm$

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

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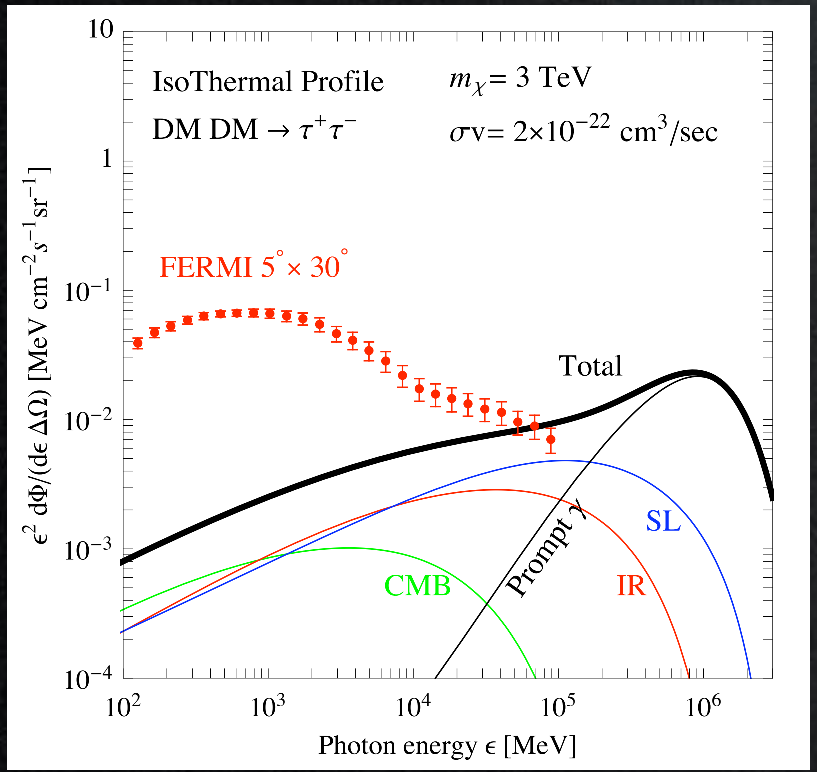
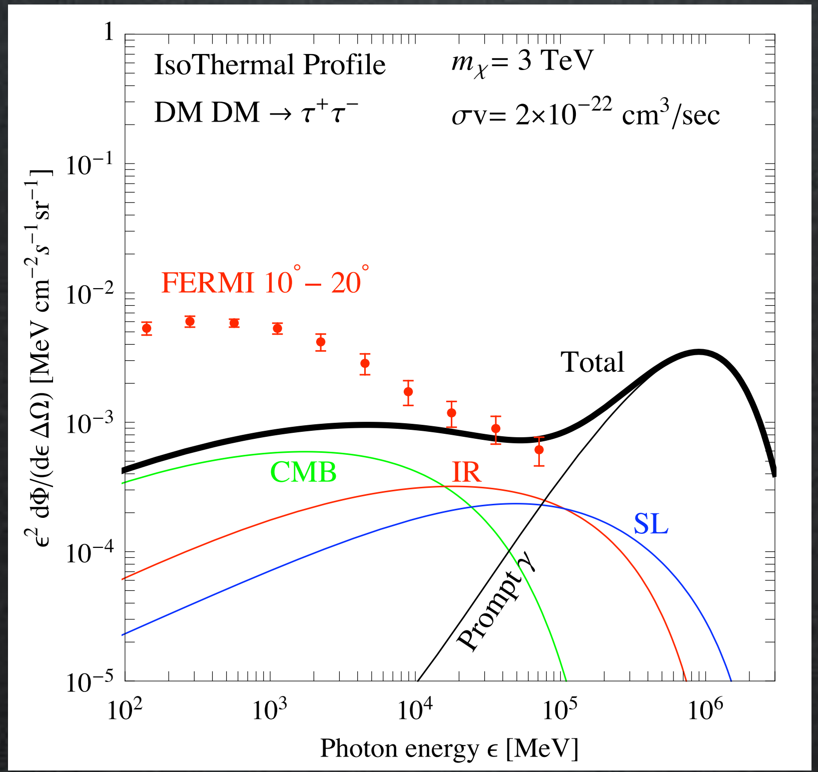




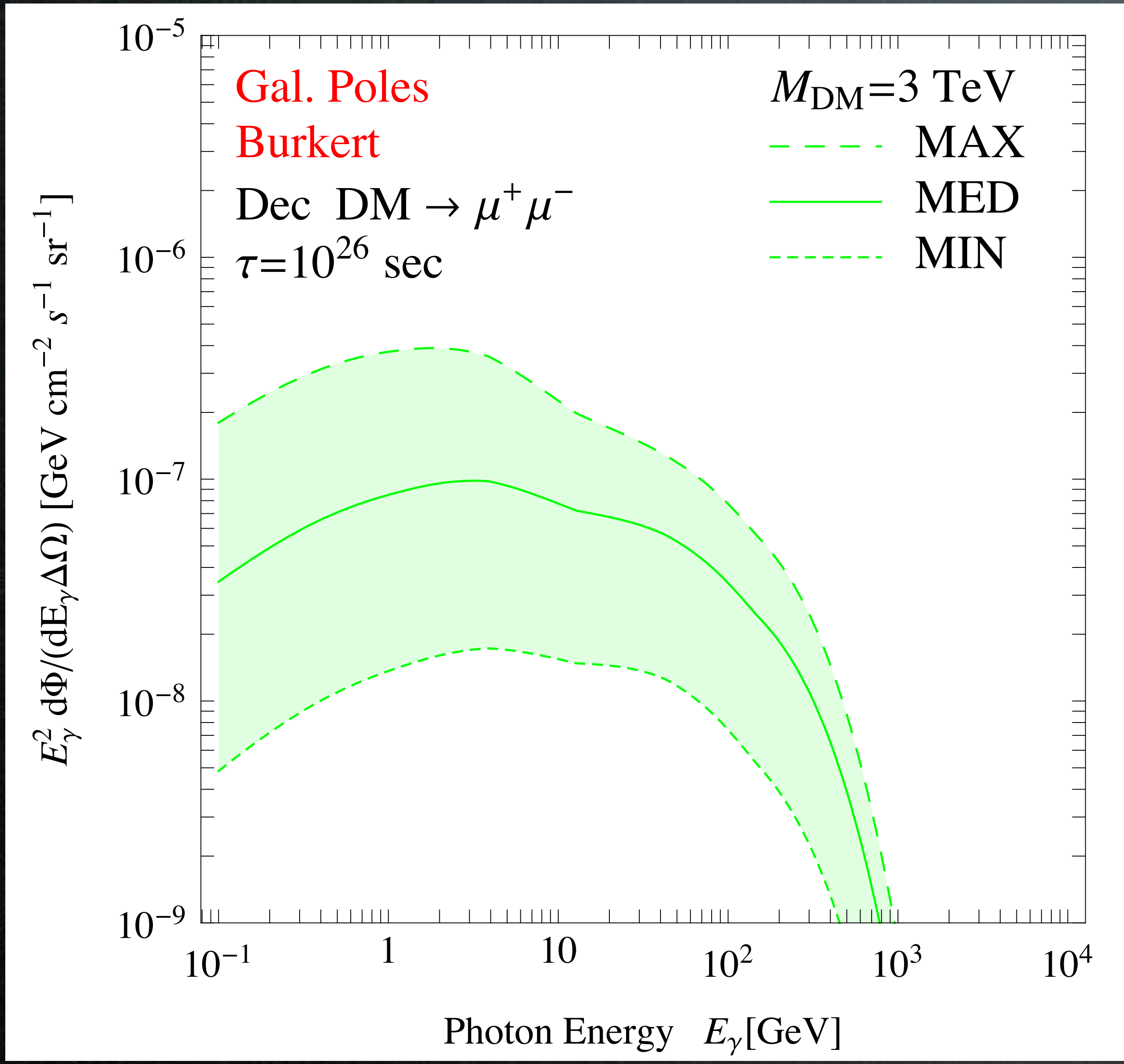
Cirelli, Panci, Serpico 0912.0663

Everything can be rearranged in terms of ICS halo functions

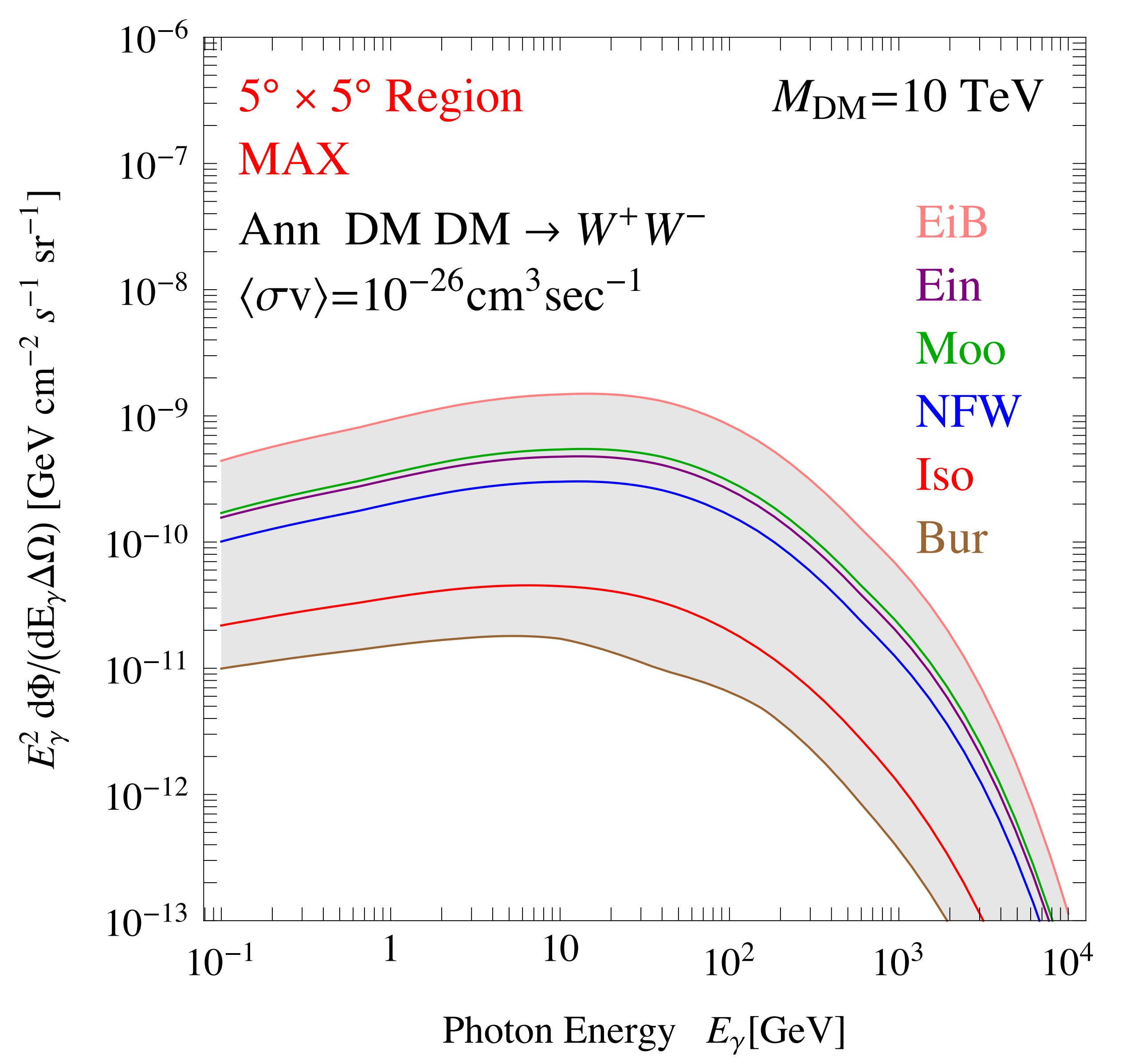
(see 1012.4515 for details)

ICS gamma rays

Varying prop parameters

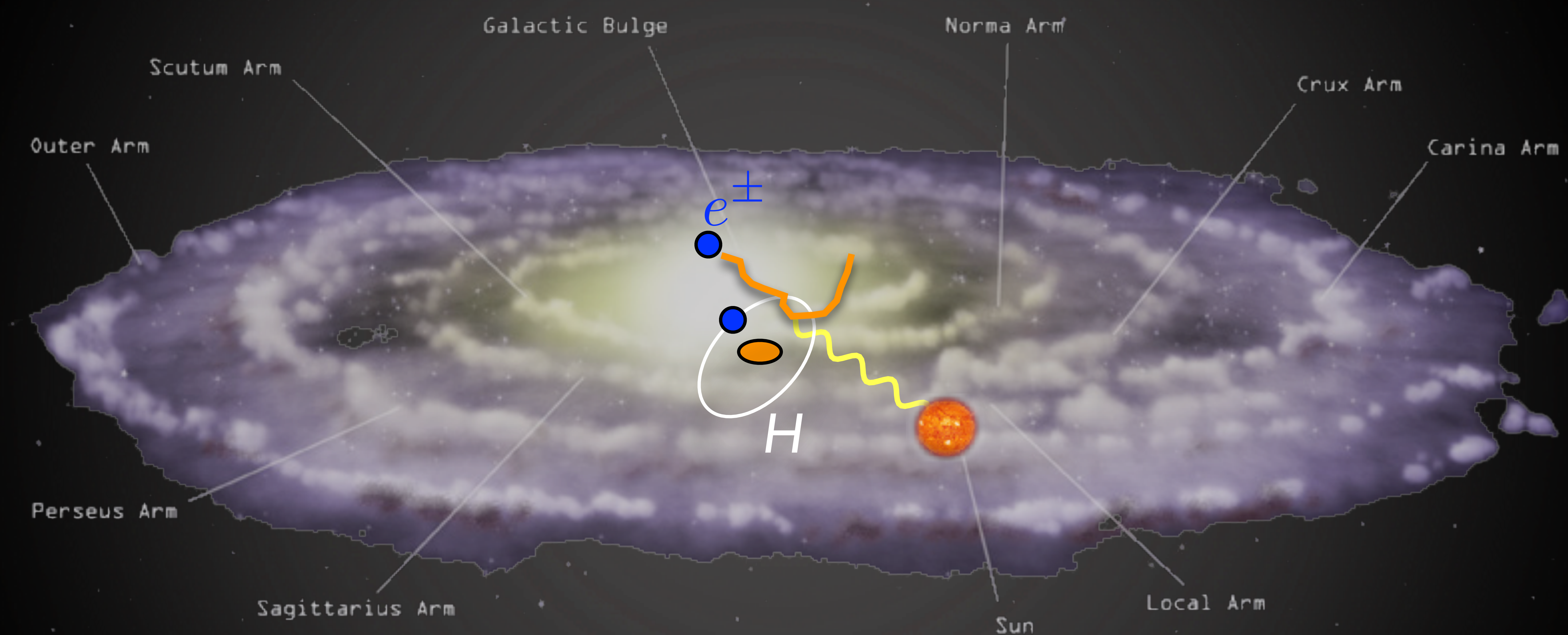


Varying halo profile



Secondary emission

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

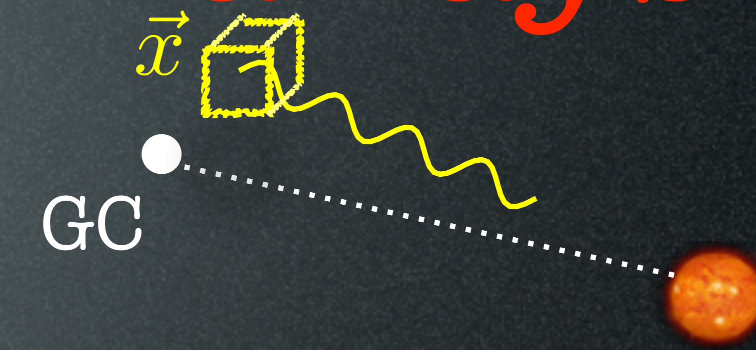


Bremsstrahlung gamma rays

Emission of bremsstrahlung γ from a cell located in $\vec{x}$:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \sum_i n_i(\vec{x}) \int_{E_L} \mathrm{d}E_{e^\pm}\; 2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

Bremsstrahlung gamma rays



Emission of bremsstrahlung γ from a cell located in $\vec{x}$:

$$\frac{\mathrm{d}\mathcal{E}_{\gamma,\mathrm{brem}}(\vec{x})}{\mathrm{d}E_\gamma} = \underbrace{\sum_i n_i(\vec{x})}_{\text{gas densities}} \int_{E_L} \mathrm{d}E_{e^\pm}\ \underbrace{2\frac{\mathrm{d}\Phi_{e^\pm}(\vec{x})}{\mathrm{d}E_{e^\pm}}}_{e^\pm \text{ input spectrum (after propagation!)}} \cdot \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_\gamma}$$

gas densities

$e^\pm$ input spectrum
(after propagation!)

Bremsstrahlung gamma rays

Emission of bremsstrahlung γ
from a cell located in $\vec{x}$:

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bremsstrahlung
differential cross section:

$$\frac{\mathrm{d}\sigma_i(E_{e^\pm}, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{3\,\alpha_{\mathrm{em}}\sigma_T}{8\pi\,E_\gamma}\left\{\left[1+\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)^2\right]\phi_1^i - \frac{2}{3}\left(1-\frac{E_\gamma}{E_{e^\pm}}\right)\phi_2^i\right\}$$

Bremsstrahlung gamma rays

Emission of bremsstrahlung γ
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on ionized gas: $\phi_1^{\mathrm{ion}}(E_{e^\pm},E_\gamma) = \phi_2^{\mathrm{ion}}(E_{e^\pm},E_\gamma) = 4(Z^2+Z)\left\{\log\left[\frac{2E_{e^\pm}}{m\,c^2}\left(\frac{E_{e^\pm}-E_\gamma}{E_\gamma}\right)\right] - \frac{1}{2}\right.$

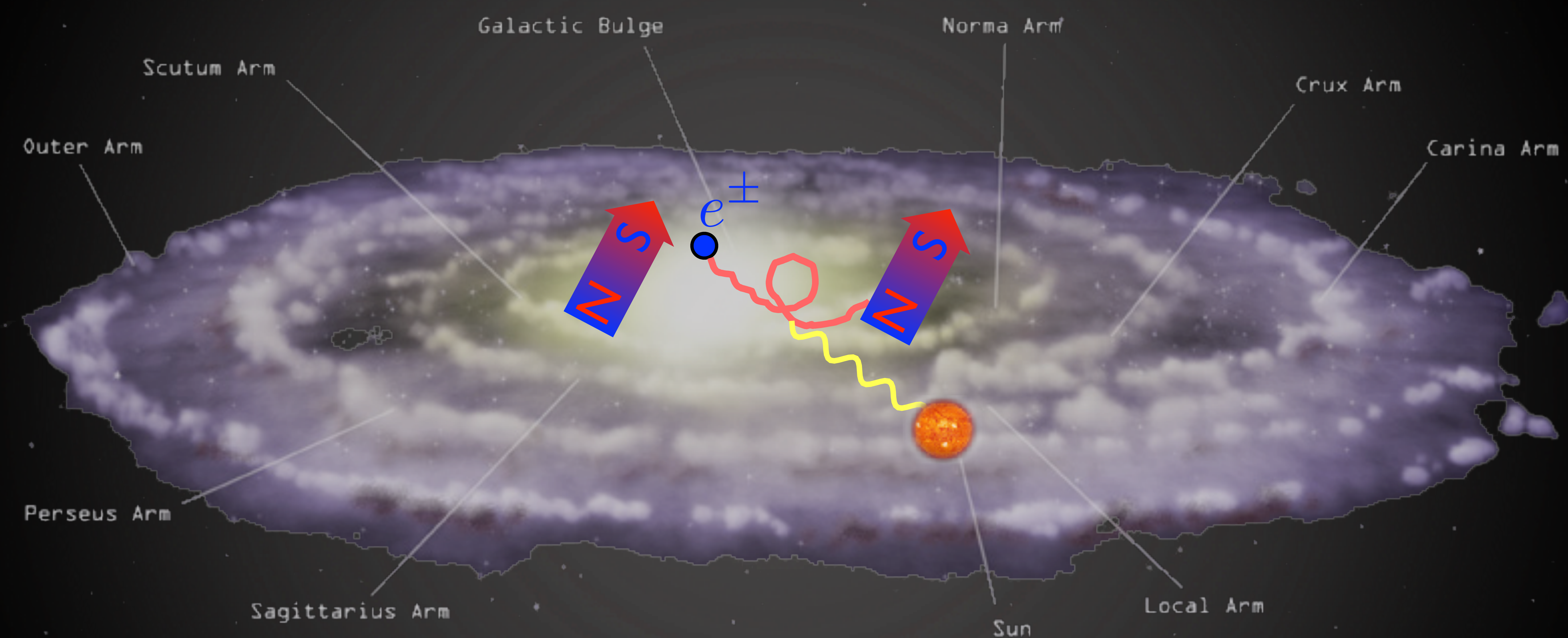
on neutral gas: $\phi_1^{\mathrm{H}}(\Delta=0) \equiv \phi_{1,\mathrm{ss}}^{\mathrm{H}} = 45.79, \phi_2^{\mathrm{H}}(\Delta=0) \equiv \phi_{2,\mathrm{ss}}^{\mathrm{H}} = 44.46, \phi_1^{\mathrm{He}}(\Delta=0) \equiv \phi_{1,\mathrm{ss}}^{\mathrm{He}} = 134.60,$

$\phi_2^{\mathrm{He}}(\Delta=0) \equiv \phi_{2,\mathrm{ss}}^{\mathrm{He}} = 131.40, \phi_{(1,2)}^{\mathrm{H}_2}(\Delta=0) \simeq 2\,\phi_{(1,2),\mathrm{ss}}^{\mathrm{H}}$

$$\left(\Delta = \frac{E_\gamma m_e}{4\alpha_{\mathrm{em}}E_{e^\pm}(E_{e^\pm}-E_\gamma)}\right)$$

Secondary emission

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



Secondary emission

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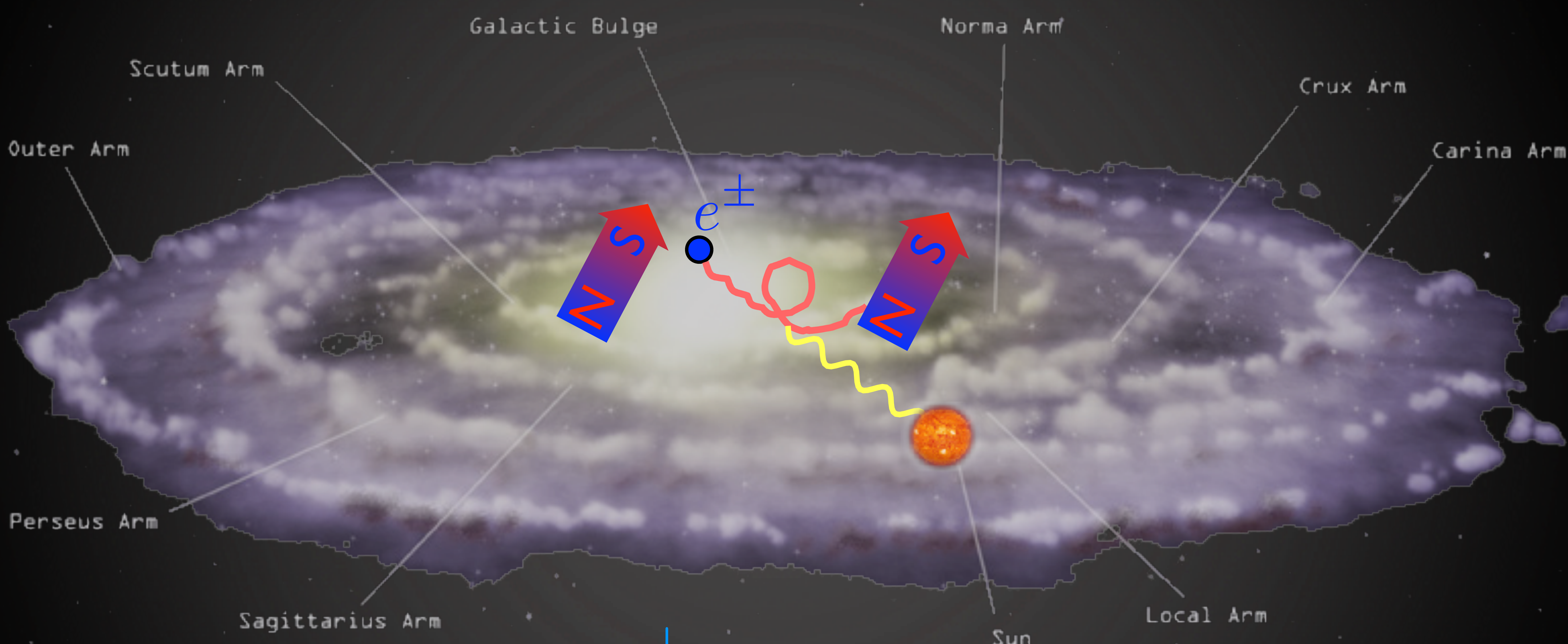

- compute the population of $e^\pm$ from DM annihilations in the GC
- compute the synchrotron emitted power for different configurations of galactic $\vec{B}$

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

Synchrotron radiation

Spectrum of synchrotron emission
from region $\Delta\Omega$:

$$\frac{dW_{\rm syn}}{d\nu\, d\Omega} = \frac{2}{4\pi}\int_{\rm l.o.s.} ds \int dE_e \frac{dn_{e^\pm}}{dE_e}\frac{dW_{\rm syn}}{d\nu}$$

Synchrotron radiation

Spectrum of synchrotron emission
from region $\Delta\Omega$:

spectral densities
of emitting $e^\pm$

$$\frac{dW_{\rm syn}}{d\nu\, d\Omega} = \frac{2}{4\pi} \int_{\rm l.o.s.} ds \int dE_e \frac{dn_{e^\pm}}{dE_e} \frac{dW_{\rm syn}}{d\nu}$$

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synchr power emitted by individual electron:

$$\frac{dW_{\rm syn}}{d\nu} = \frac{\sqrt{3}}{6\pi}\frac{e^3 B}{m_e} F\left(\frac{\nu}{\nu_{\rm syn}}\right)$$

$$F(x) = x\int_x^\infty K_{5/3}(\xi)d\xi \approx \frac{8\pi}{9\sqrt{3}}\delta(x-1/3)$$

$$\nu_{\rm syn} = \frac{3eBp^2}{4\pi m_e^3}$$

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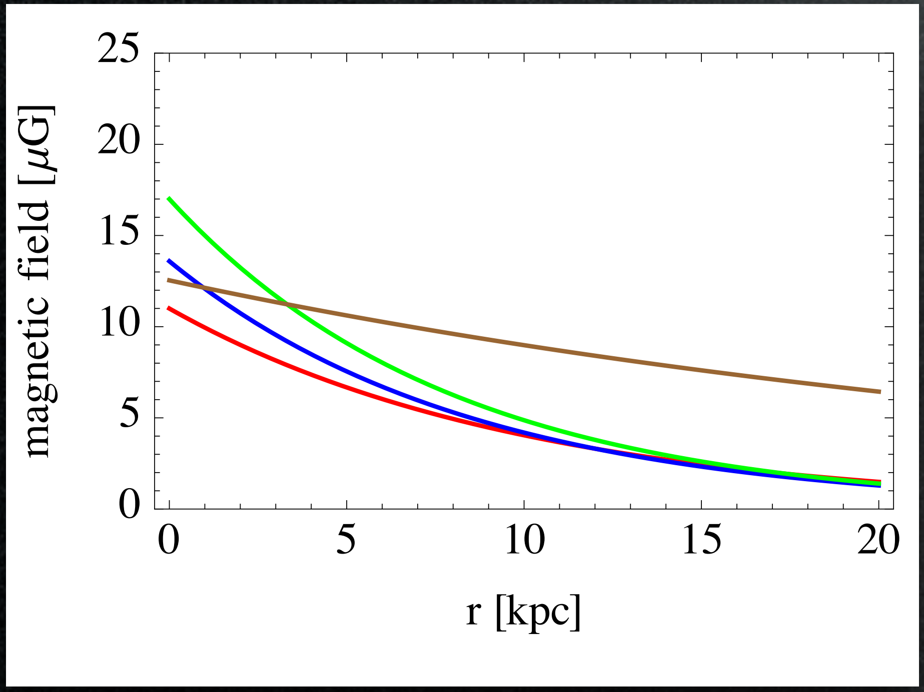

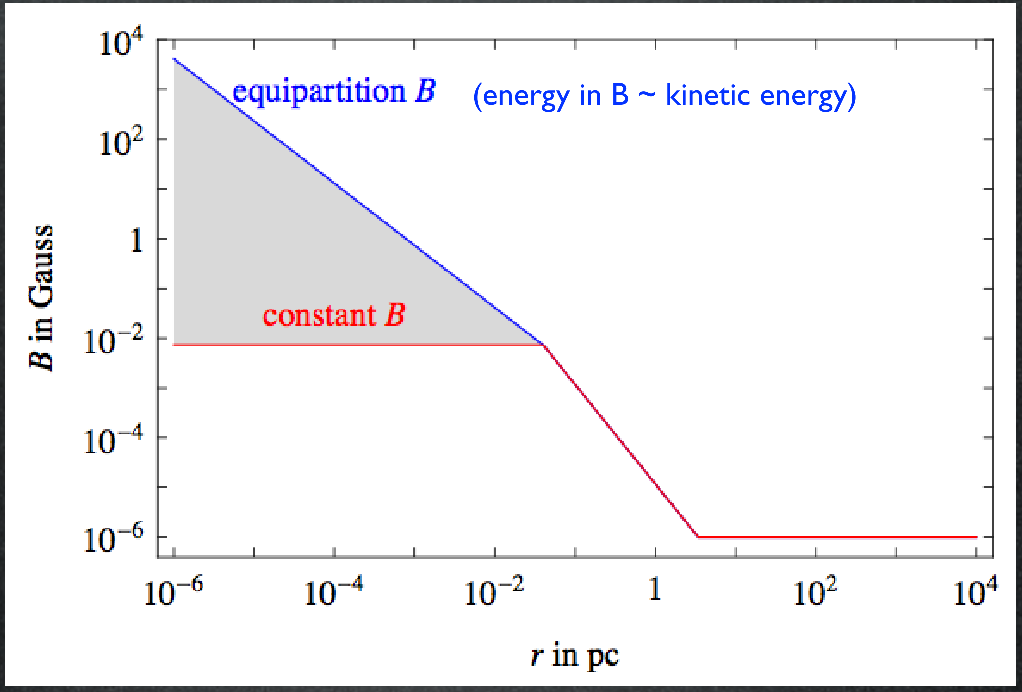

Synchrotron radiation

Spectrum of synchrotron emission from region $\Delta\Omega$:

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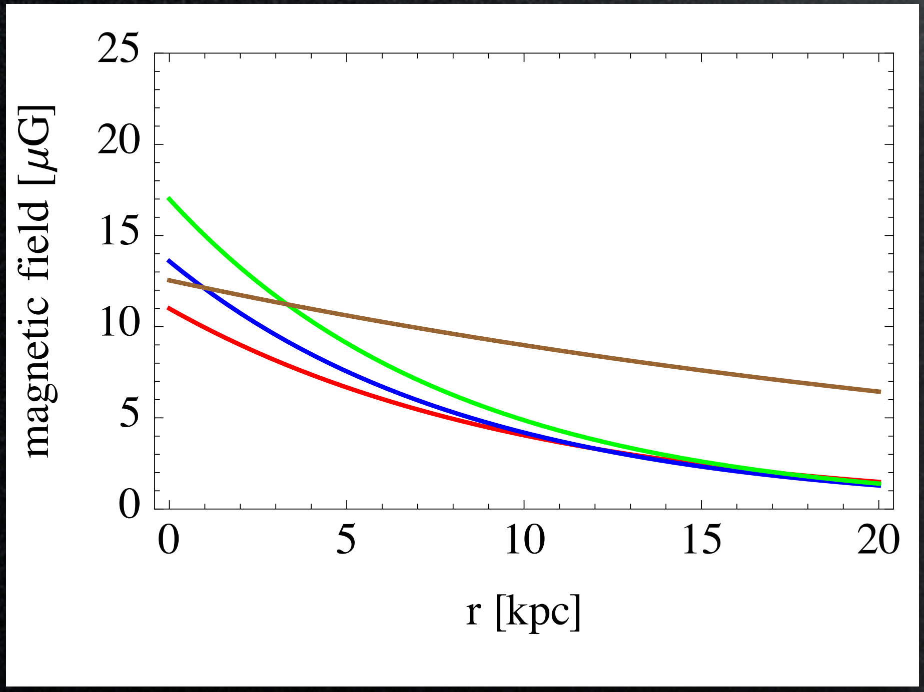

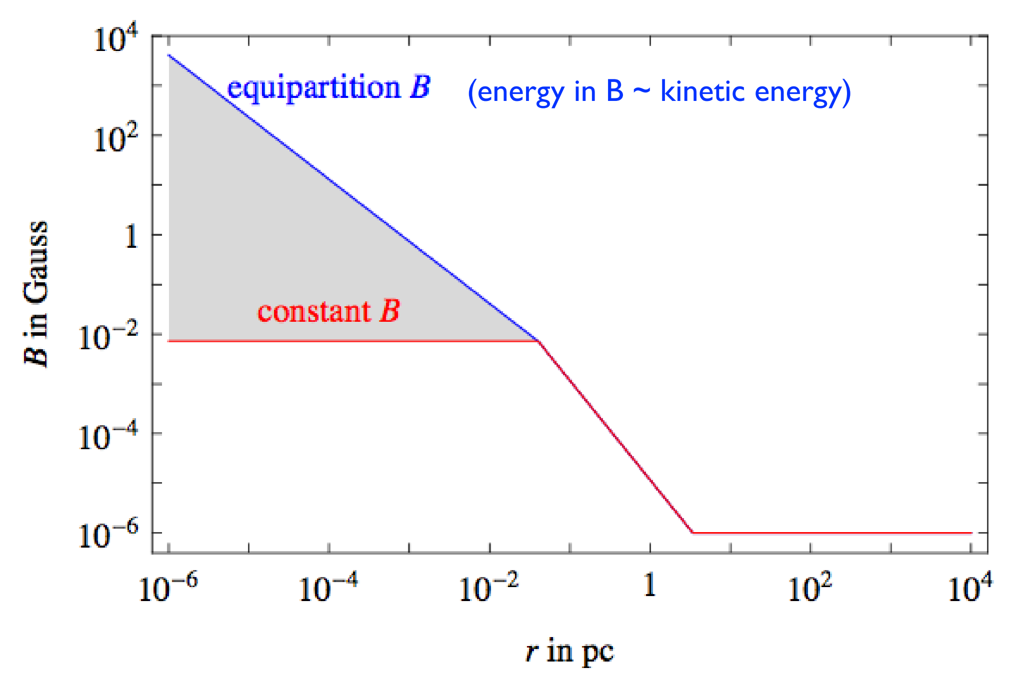

Rule of thumb:

$$p_{e^\pm} \longrightarrow \nu_{\rm syn}/3$$

$$\nu_{\rm syn} = 4.2\,{\rm MHz}\frac{B}{\rm G}\left(\frac{p}{m_e}\right)^2$$

Synchrotron radiation

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spectral densities of emitting $e^{\pm}$

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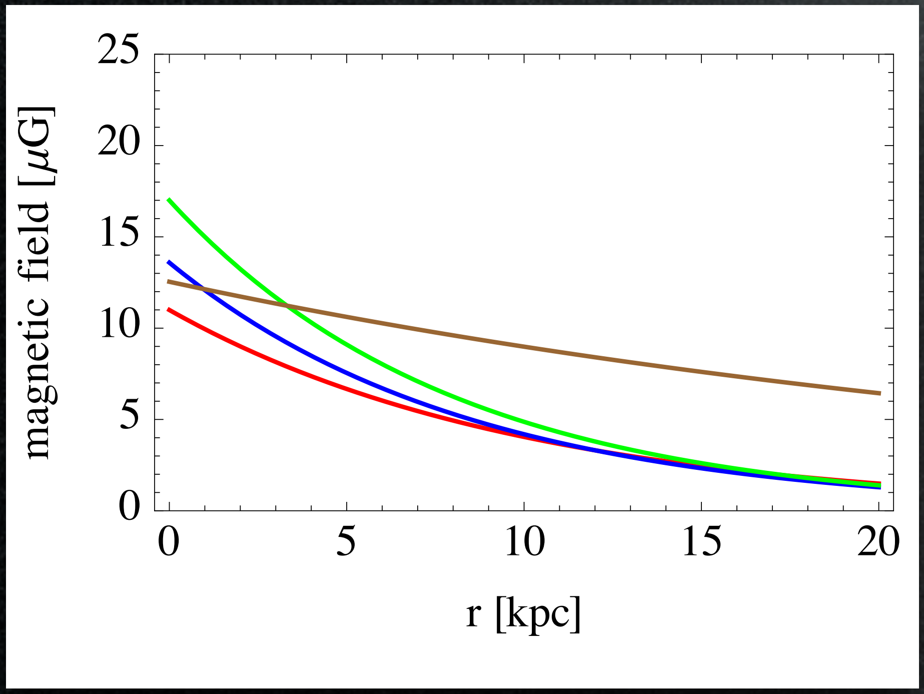

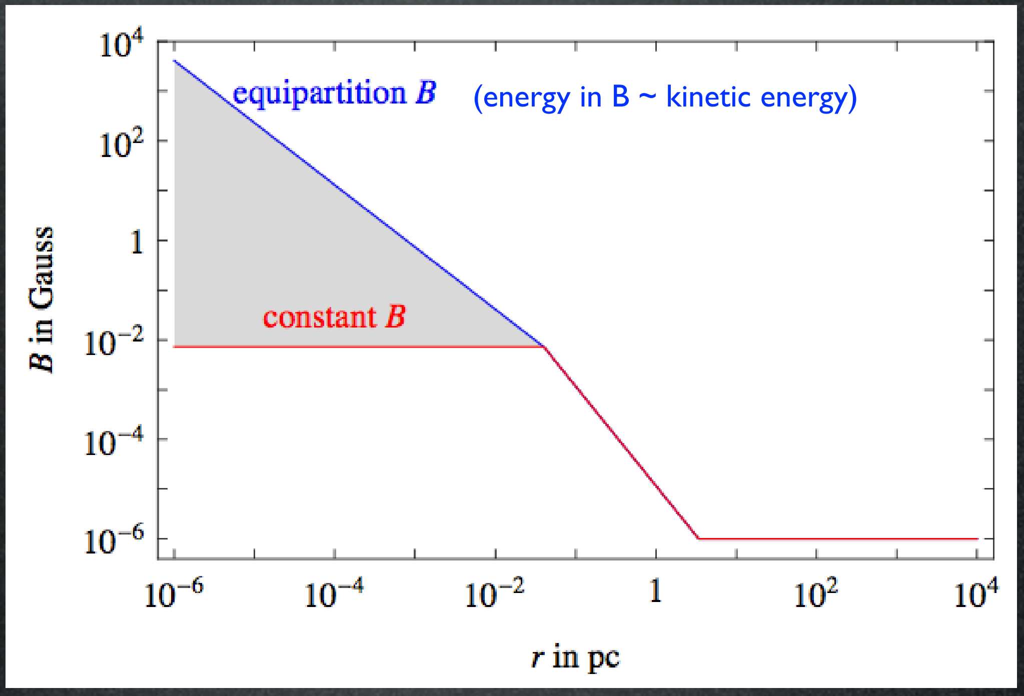

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If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection",
arXiv 10
Erratum

Fluxes of Inverse Compton gamma rays:

Annihilation	Decay
Mathematica function: the file IICAnn.m provides the Inverse Compton halo functions $I_{IC}(E_s, E_\gamma, l, b)$. Refer to the notebook Sample.nb for usage. Such notebook contains also a Mathematica code bite to compute the resulting IC flux.	*Mathematica function:* the file IICDec.m provides the Inverse Compton halo functions $I_{IC}(E_s, E_\gamma, l, b)$. Refer to the notebook Sample.nb for usage. Such notebook contains also a Mathematica code bite to compute the resulting IC flux.

Fluxes of bremsstrahlung gamma rays:

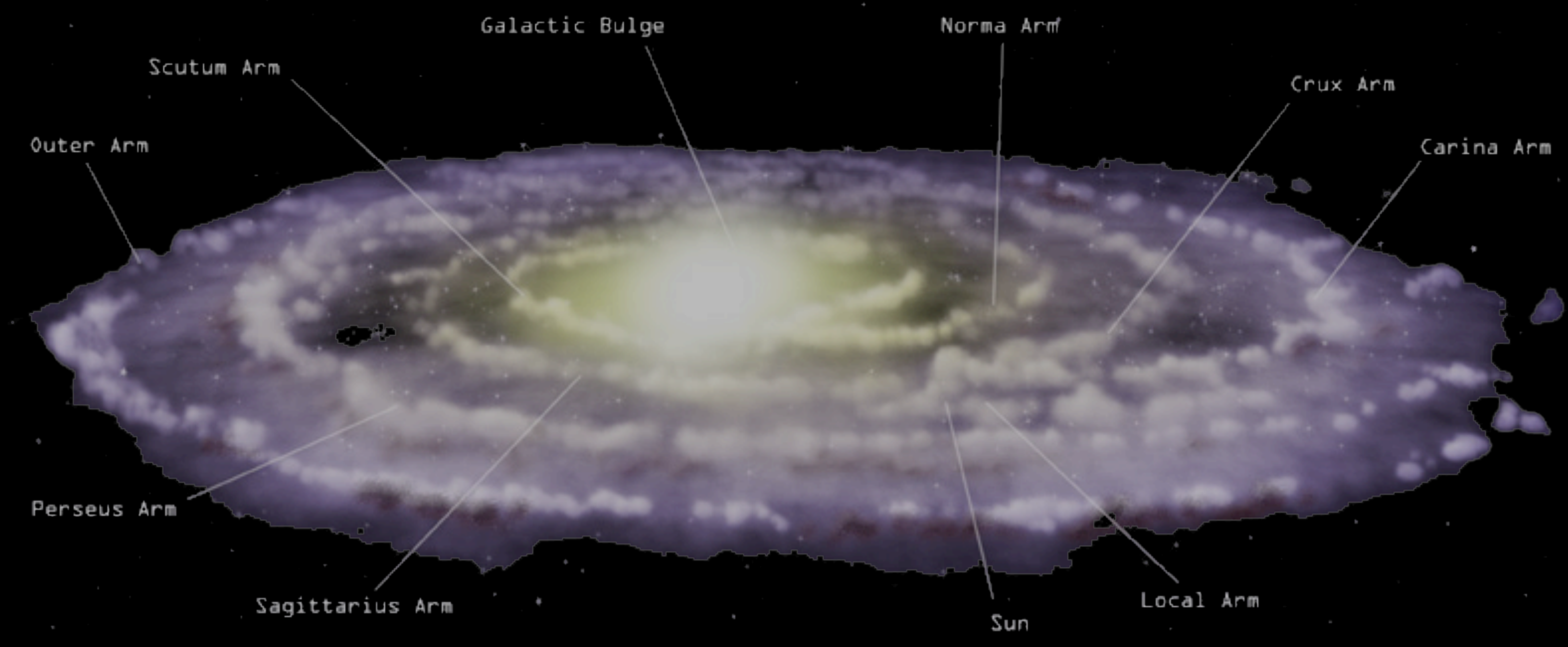
Annihilation	Decay
Mathematica function: the file IBremAnn.m provides the bremsstrahlung halo functions $I_{brem}(E_s, E_\gamma, l, b)$. Refer to the notebook Sample.nb for usage.	*Mathematica function:* the file IBremDec.m provides the bremsstrahlung halo functions $I_{brem}(E_s, E_\gamma, l, b)$. Refer to the notebook Sample.nb for usage.

Fluxes of synchrotron radiation:

Annihilation	Decay
Mathematica function: the file ISynAnn.m provides the synchrotron halo functions $I_{syn}(E_s, \nu, l, b)$. Refer to the notebook Sample.nb for usage.	*Mathematica function:* the file ISynDec.m provides the synchrotron halo functions $I_{brem}(E_s, \nu, l, b)$. Refer to the notebook Sample.nb for usage.

Indirect Detection: basics

γ from outside the Galaxy

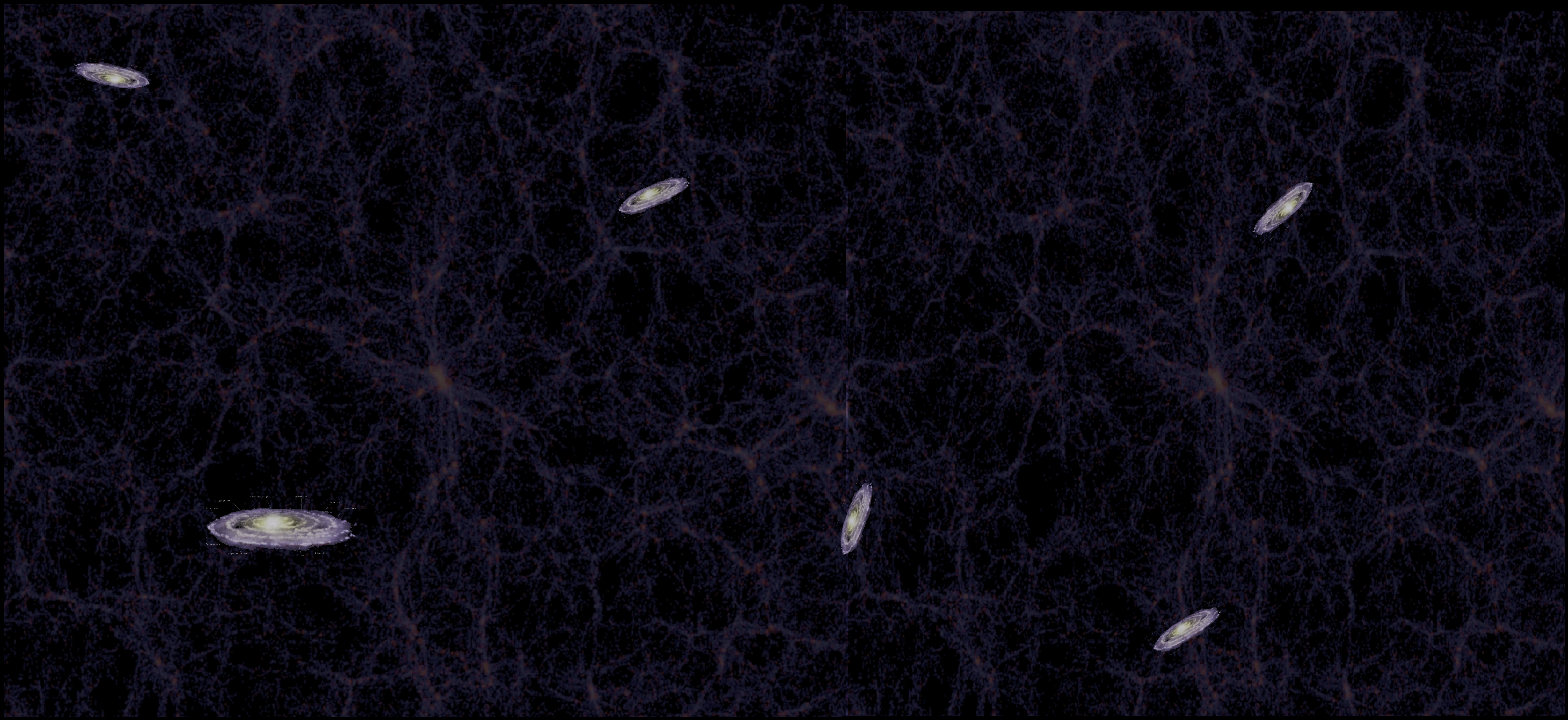


Indirect Detection: basics

γ from outside the Galaxy

Indirect Detection: basics

γ from outside the Galaxy



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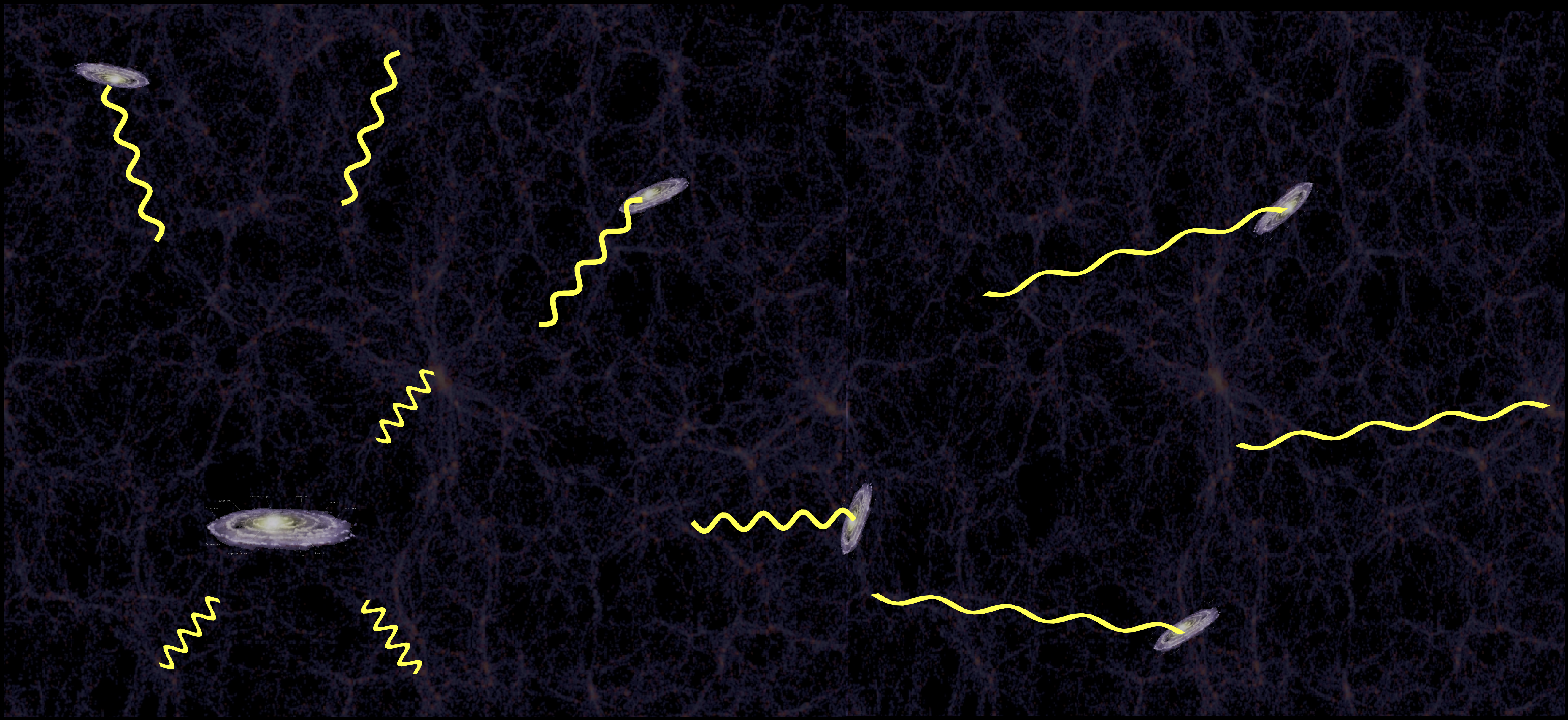

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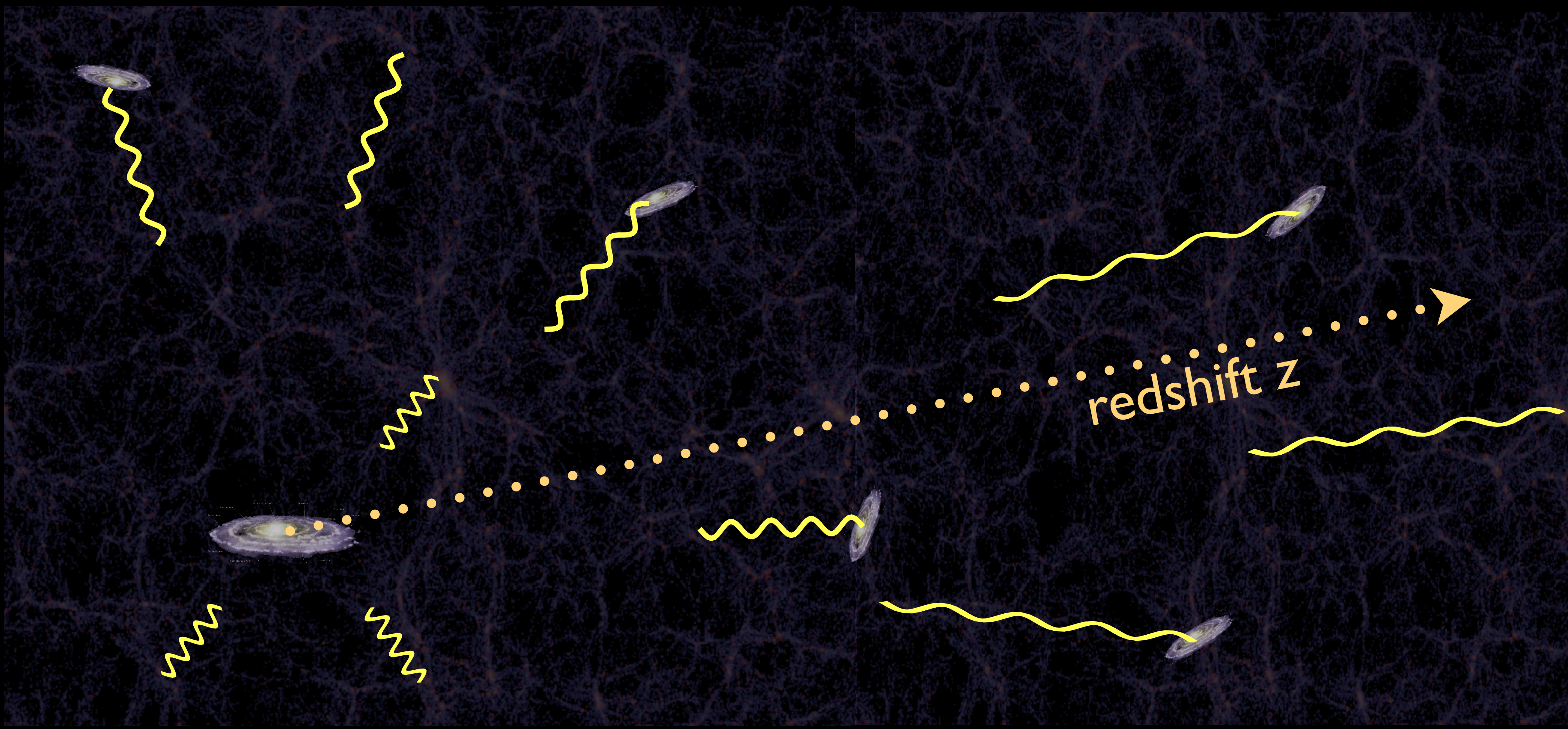

- isotropic flux of prompt and ICS gamma rays, integrated over z and r
- depends strongly on halo formation details and history

Extragalactic gamma rays

Flux of ExGal γ:

$$\frac{d\Phi_{\mathrm{EG}\gamma}}{dE_\gamma} = \frac{c}{E_\gamma} \int_0^\infty dz' \, \frac{1}{H(z')(1+z')^4} \, \frac{j_{\mathrm{EG}\gamma}(E'_\gamma, z')}{4\pi} \, e^{-\tau(E'_\gamma, z')}$$

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emissivities:

$$j^{\rm prompt}_{\rm EG\gamma}(E', z') = \frac{1}{2}B(z')\left(\frac{\bar\rho(z')}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_\gamma}{dE'_\gamma}$$

$$j^{\rm IC}_{\rm EG\gamma}(E', z') = 2\int_{m_e}^{M_{\rm DM}} {\rm d}E_e \frac{\mathcal{P}^{\rm CMB}_{\rm IC}(E'_\gamma, E_e, z')}{b^{\rm CMB}_{\rm IC}(E_e, z')} \int_{E_e}^{M_{\rm DM}} {\rm d}\widetilde{E}_e \frac{{\rm d}N_e}{{\rm d}\widetilde{E}_e} \frac{1}{2}B(z')\left(\frac{\bar\rho(z')}{M_{\rm DM}}\right)^2 \sum_f \langle\sigma v\rangle_f$$

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cluster boost

$$B(z, M_{\mathrm{min}}) = 1 + \frac{\Delta_c}{3\bar\rho_{m,0}} \int_{M_{\mathrm{min}}}^\infty dM\, M \frac{dn}{dM}(M, z)\, f\,[c(M, z)]$$

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minimal
halo
mass

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minimal halo mass

halo mass fct
(number of halos with mass M at redshift z)

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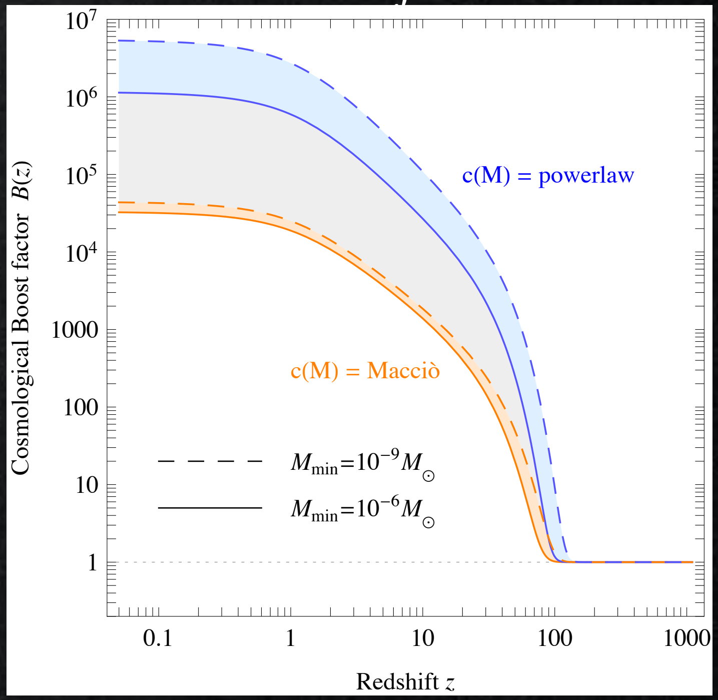
concen-tration function



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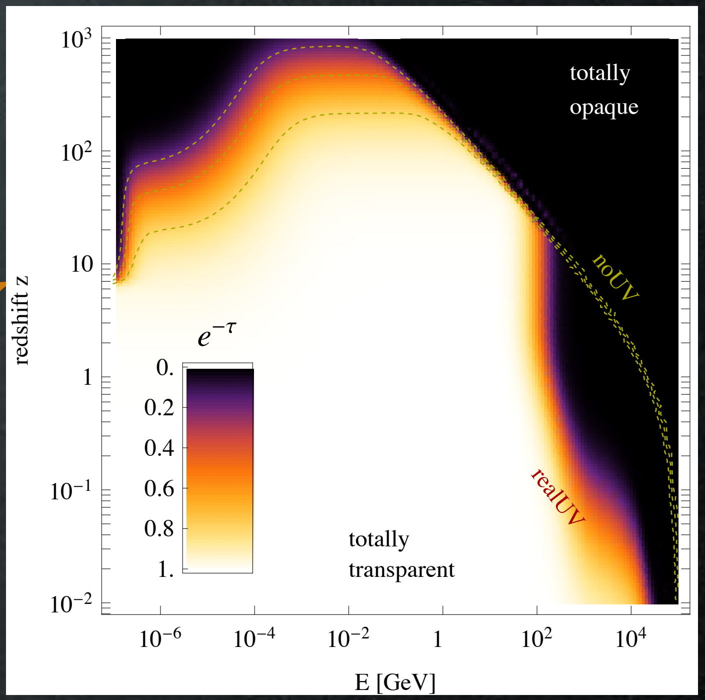
absorption



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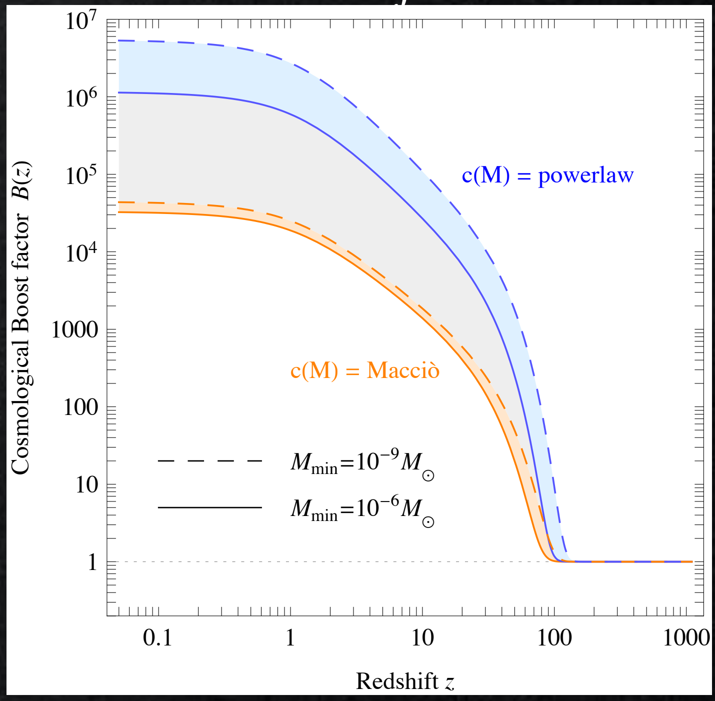
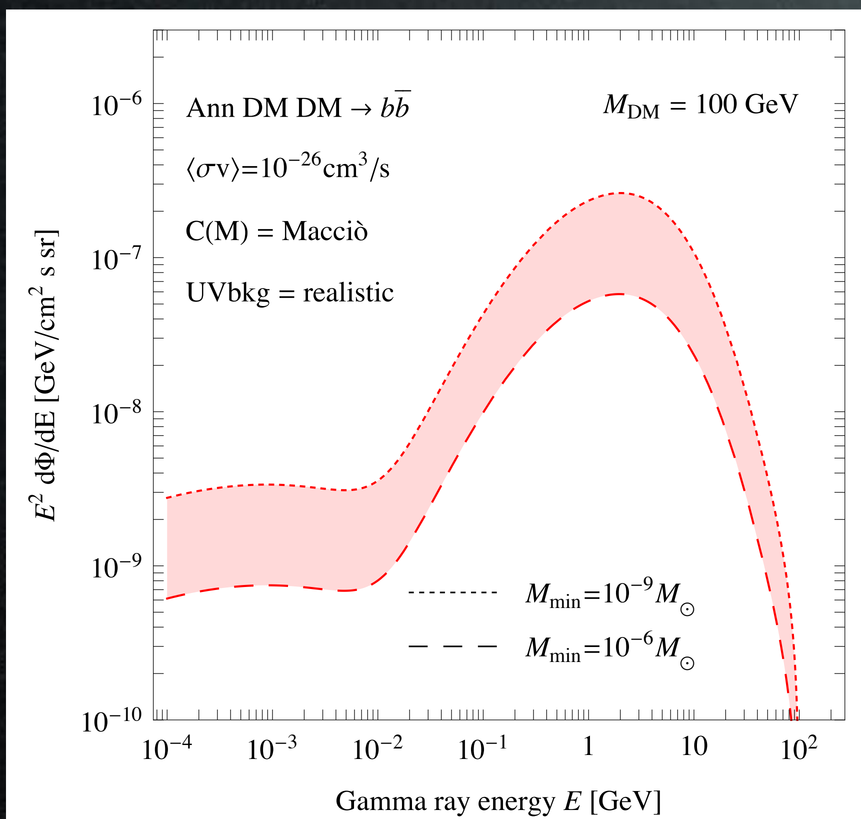


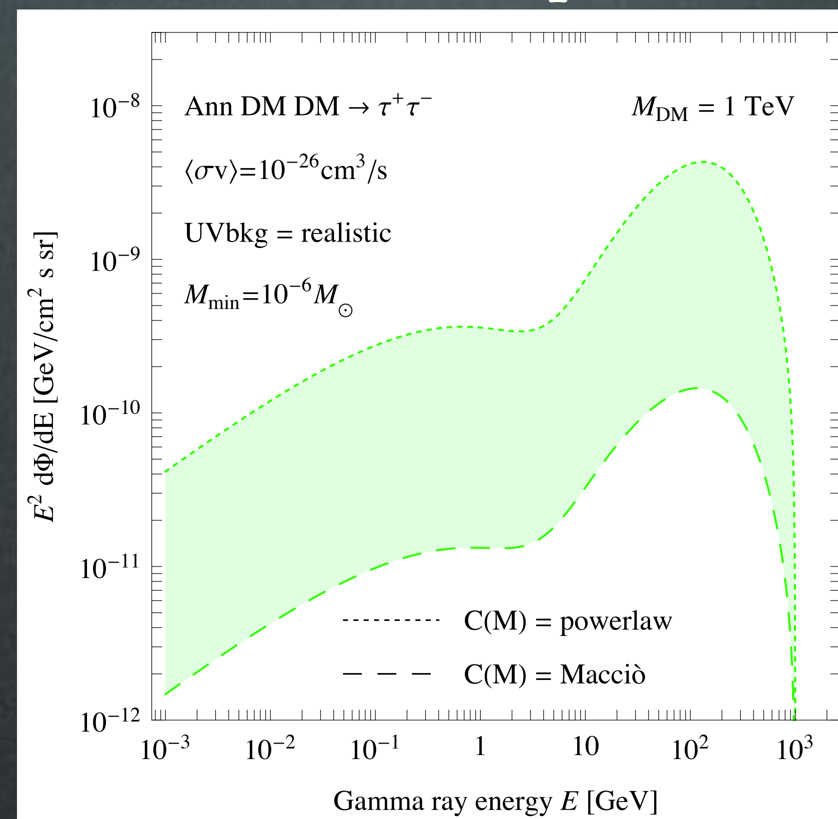
Extragalactic gamma rays

Varying:

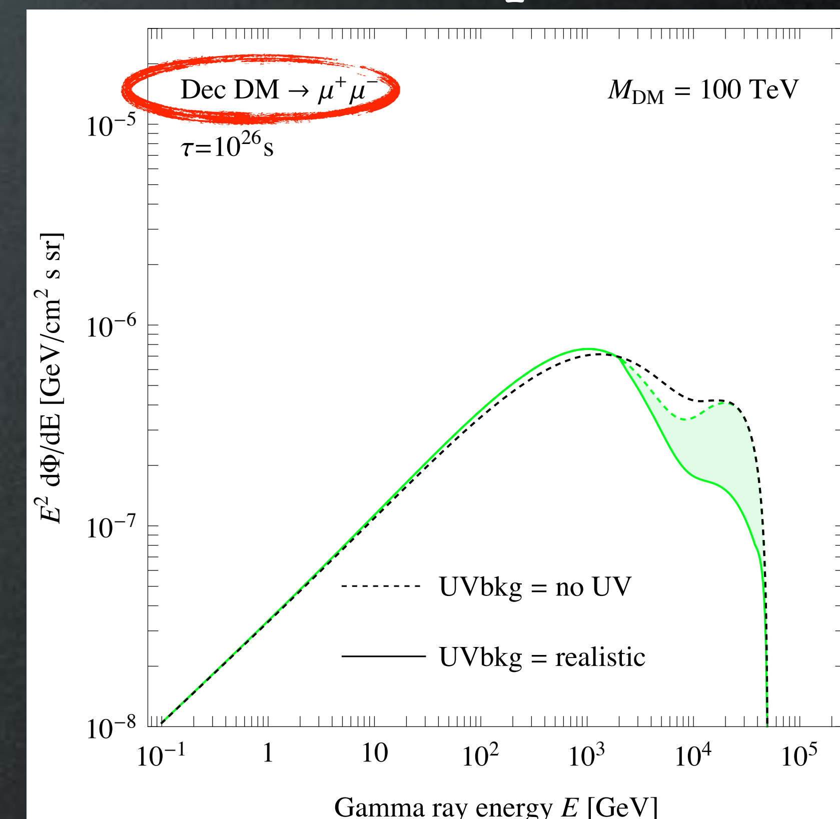
minimal halo mass



concentration param



UV absorption



Bottom line: ExGal gamma rays are affected by uncertainties of a few order orders of magnitude due to cosmic history, for annihilations.
Much less for decay.

'Prompt' gamma rays

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

Data and Results from 1012.4515 [hep-ph] (and 1009.0224 [hep-ph]), from 1312.6408 [hep-ph], 1412.5696 [astro-ph.HE], from 1505.01049 [hep-ph] and from 1511.08787 [hep-ph].

If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia, "PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection", arXiv 1012.4515, JCAP 1103 (2011) 051. Erratum: JCAP 1210 (2012) E01.

Fluxes of extragalactic gamma rays:

Cosmological Boost factor B: *Mathematica* function BoostF.m, refer to the notebook Sample.nb for usage.

Optical Depth of the Universe: transparency factor *Exp[-τ]* for gamma rays: *Mathematica* function OpticalDepth.m, refer to the notebook Sample.nb for usage.

Annihilation	Decay
Mathematica function: the file EGgammaFluxAnn.m provides the spectra Log_{10} [d Φ/d Log_{10} E]. Refer to the notebook Sample.nb for usage.	*Mathematica* function: the file EGgammaFluxDec.m provides the spectra Log_{10} [d Φ/d Log_{10} E]. Refer to the notebook Sample.nb for usage.

DM detection

direct detection

production at colliders

indirect

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

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

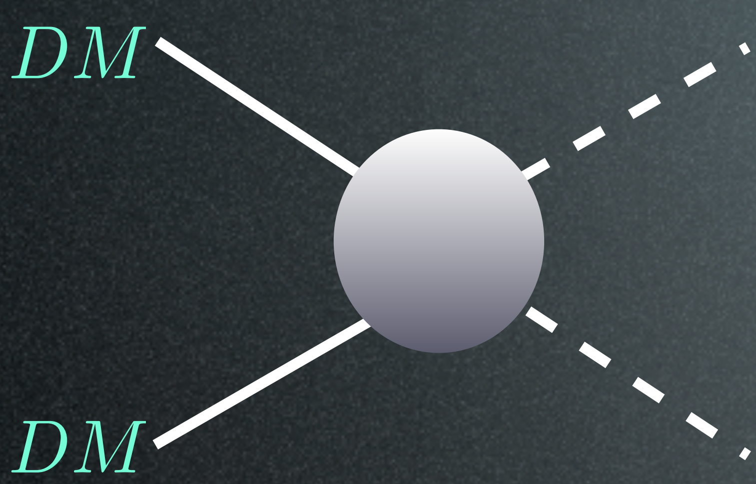
PAMELA, ATIC, Fermi

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

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

$\nu, \bar{\nu}$ from annihil in galactic center/halo/Sun

ID with neutrinos



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

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

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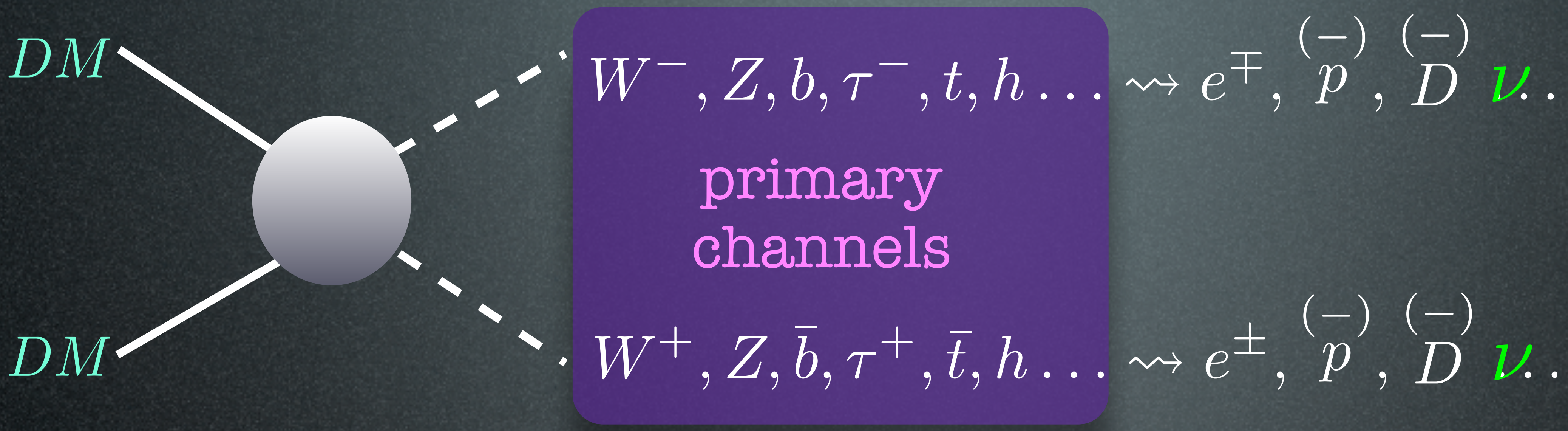

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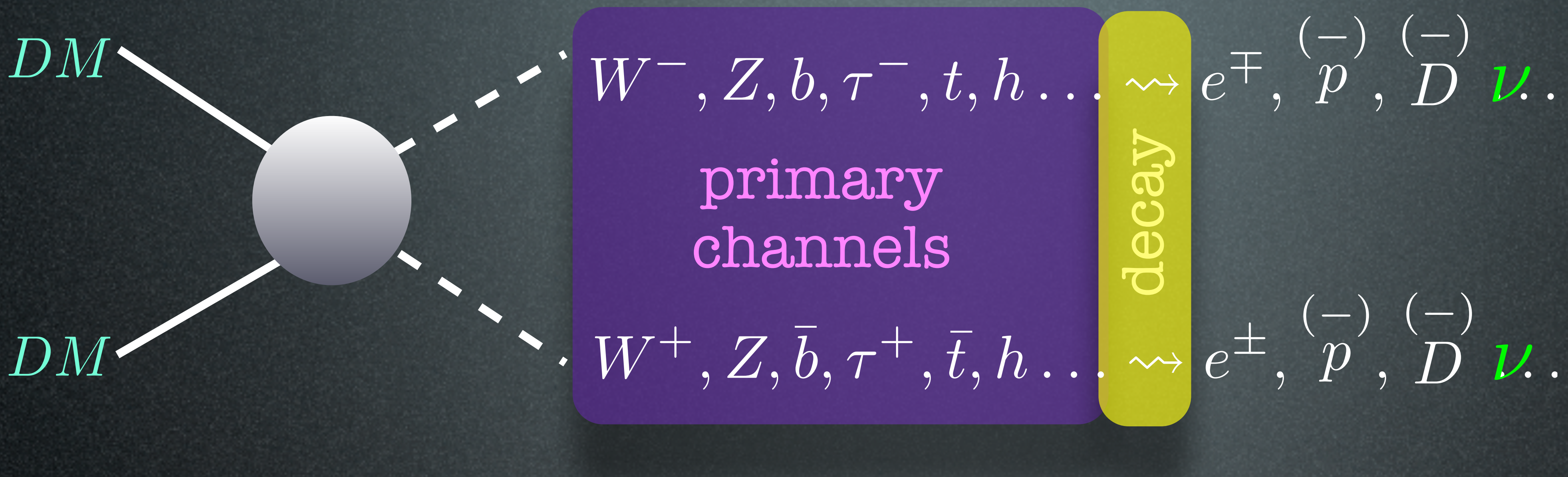

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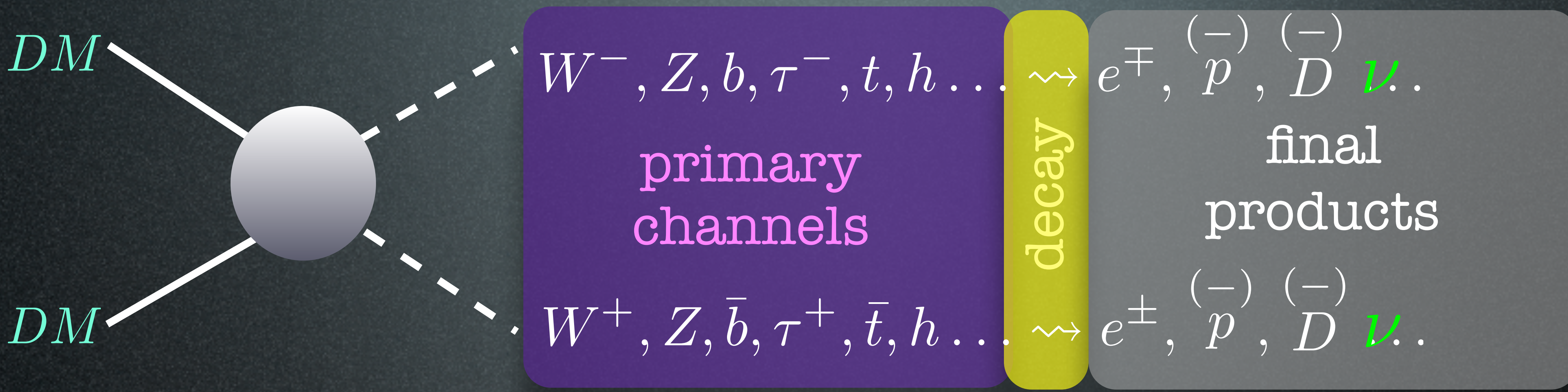

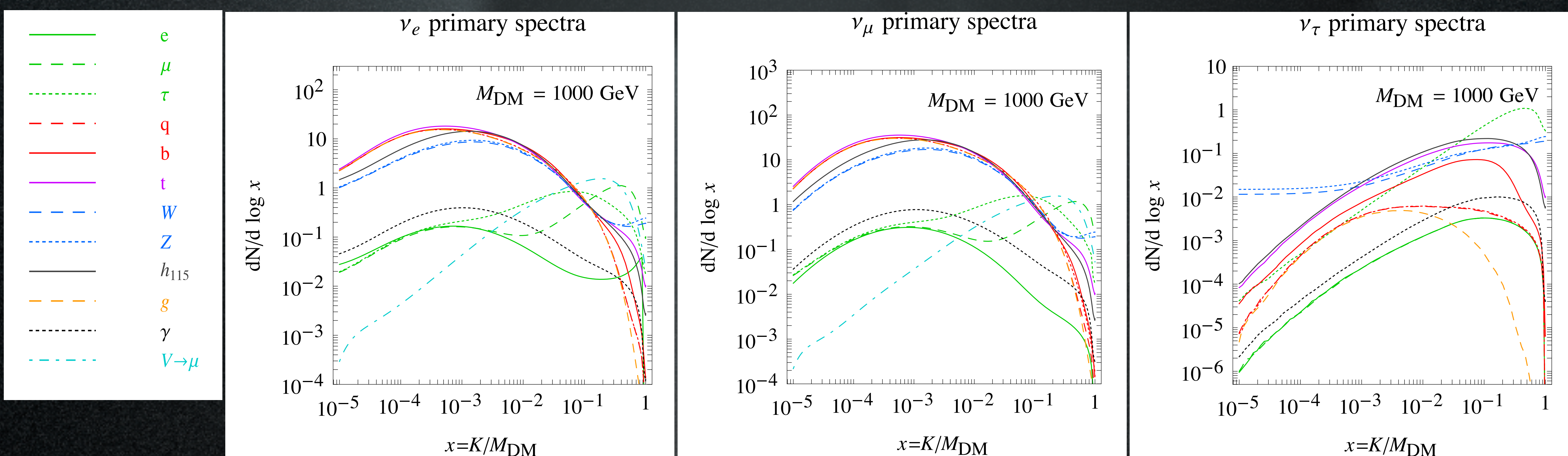

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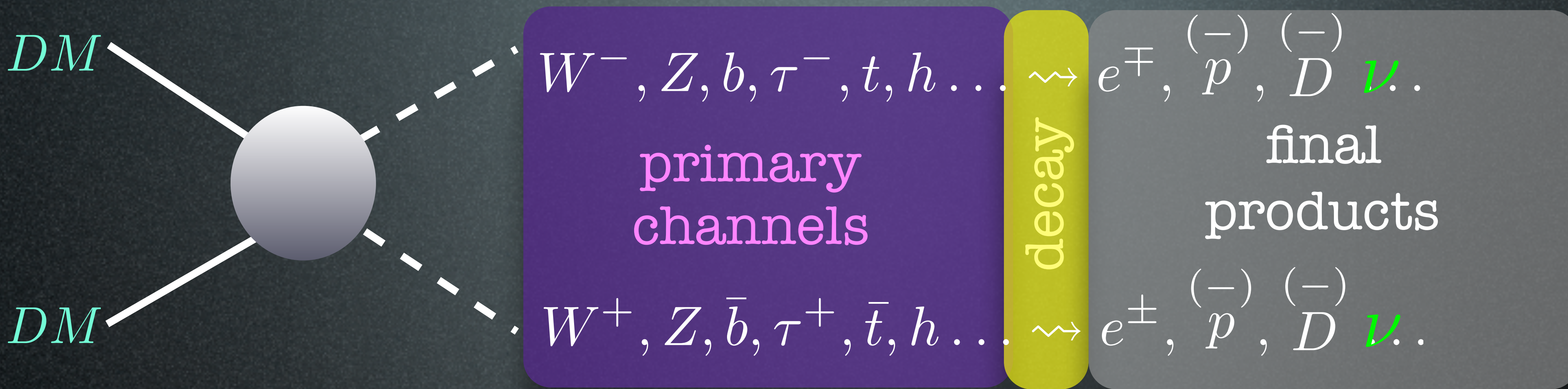
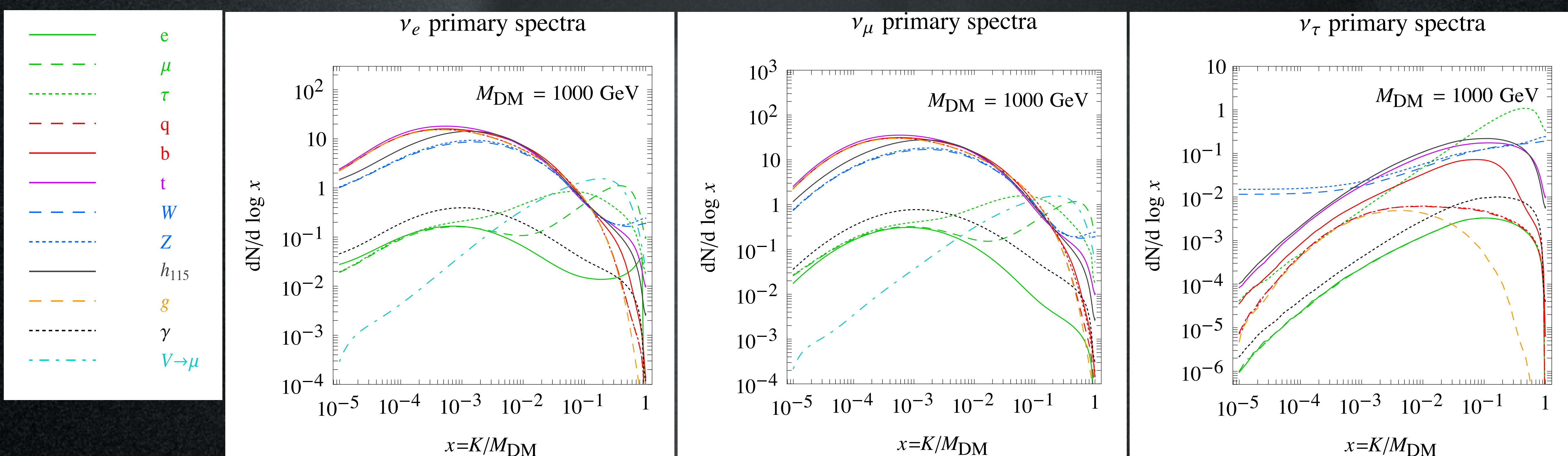


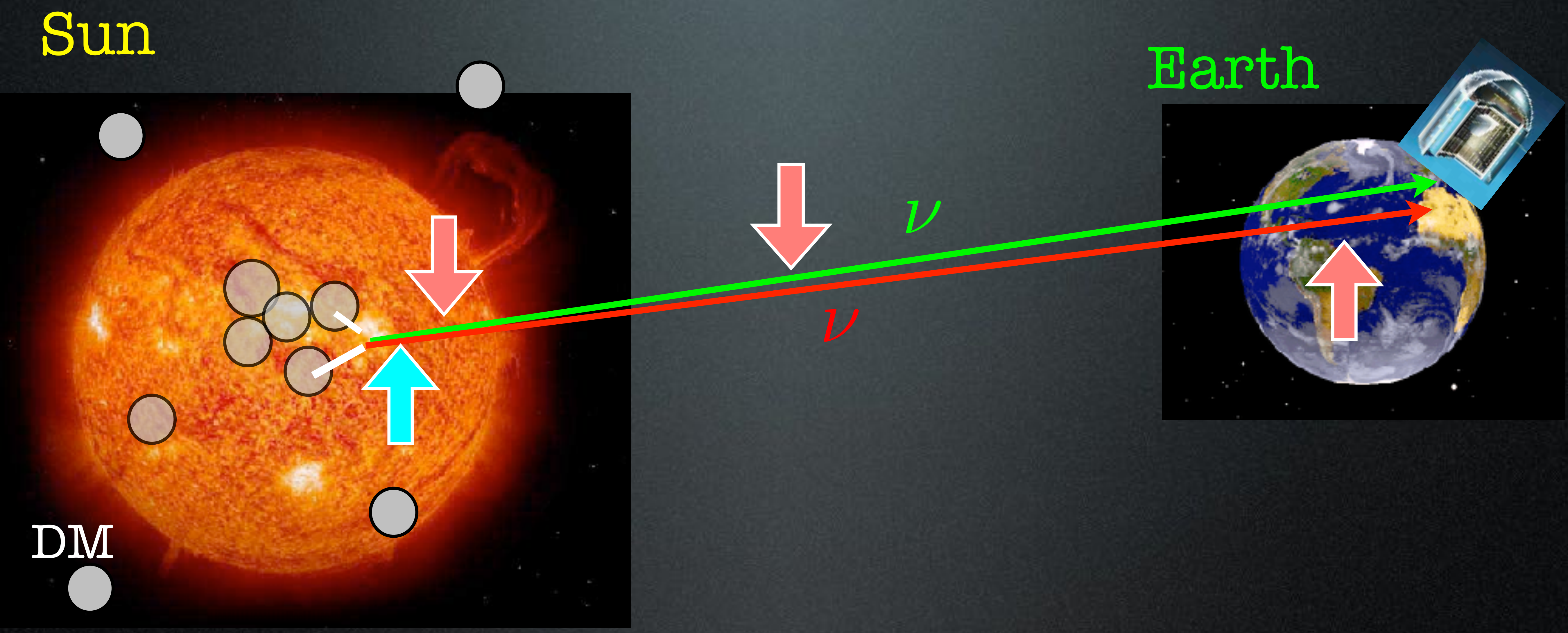


So what are the particle physics parameters?

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

ID with neutrinos

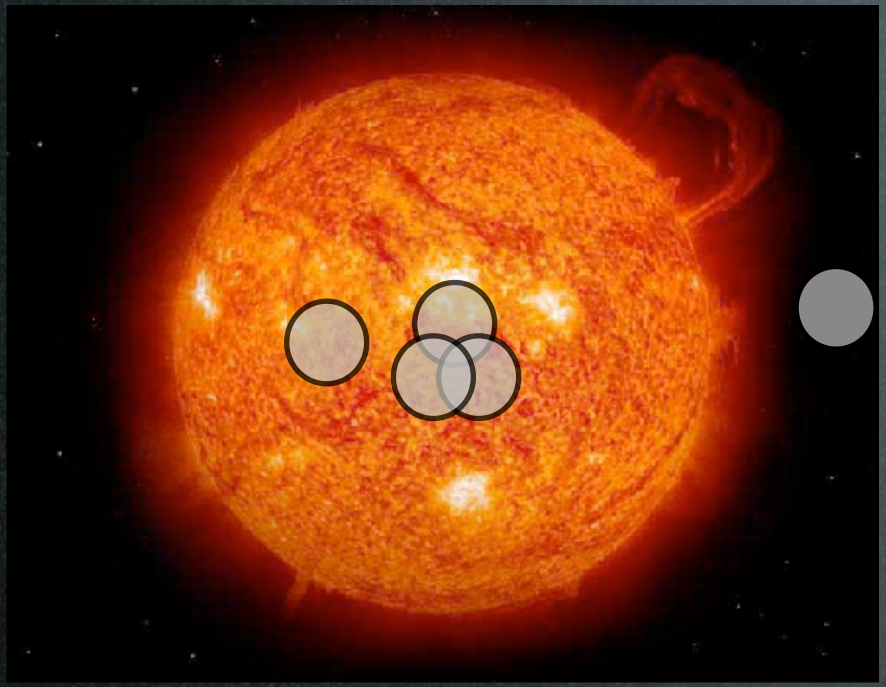
ν from DM annihilations in the Sun



Include oscillations + interactions:

- reshuffling of the 3 flavors
- distortions the spectra
- attenuations of the fluxes

1. Capture & annihilation



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

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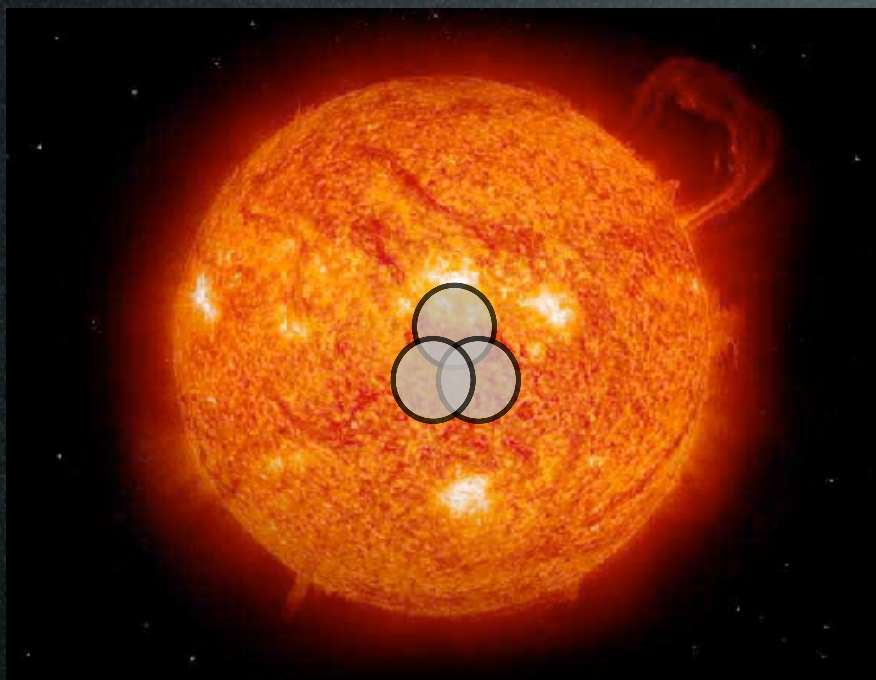

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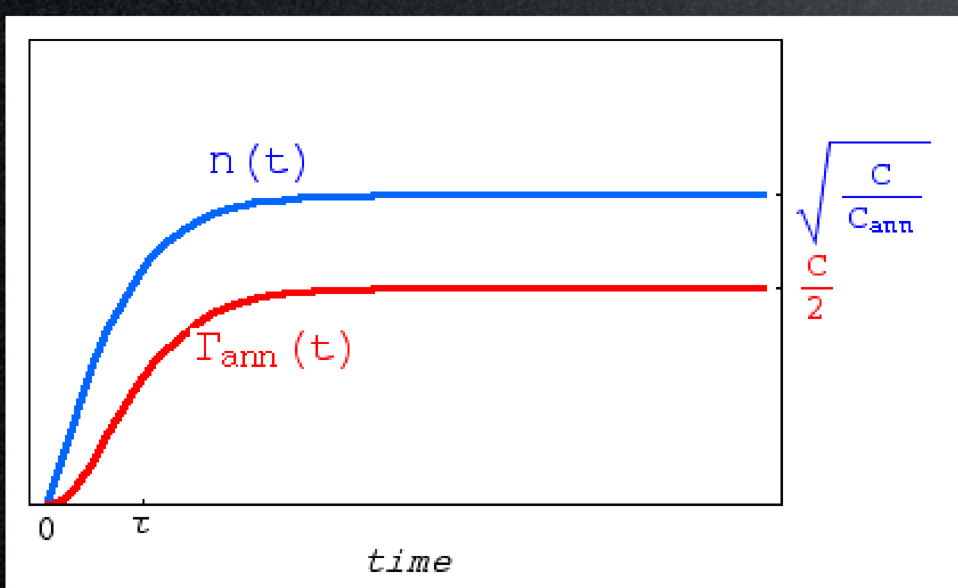
equilibrium attained:



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

$$\dot{n} = \Gamma_{\rm capt} - C_{\rm ann}\, n^2$$

$$C_{\rm ann} = \langle \sigma v \rangle \left(\frac{G_N M_{\rm DM} \rho_\odot}{3 T_\odot} \right)^{3/2}$$

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

$$\tau = \frac{1}{\sqrt{\Gamma_{\rm capt} C_{\rm ann}}}$$

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

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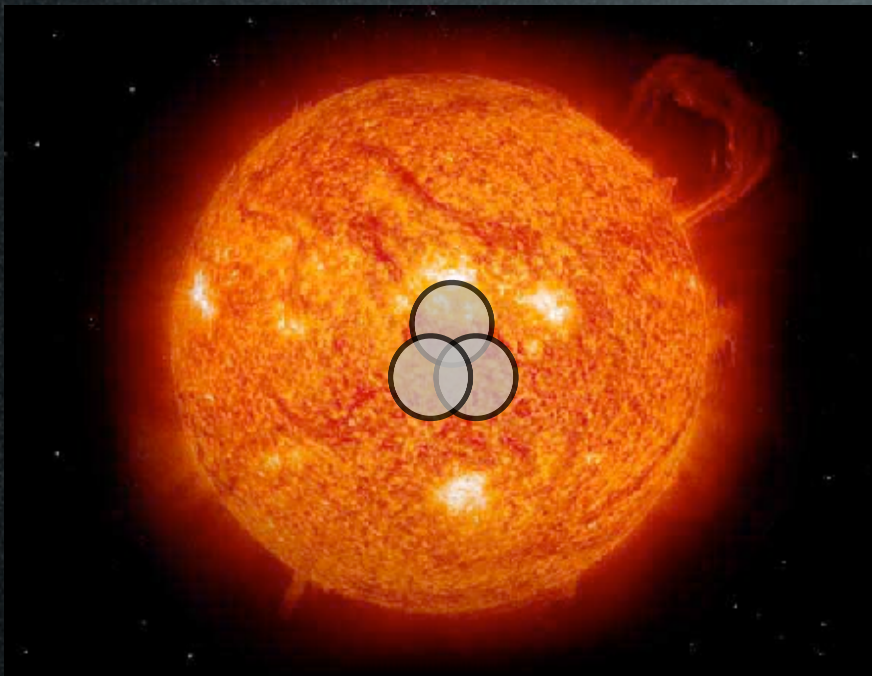

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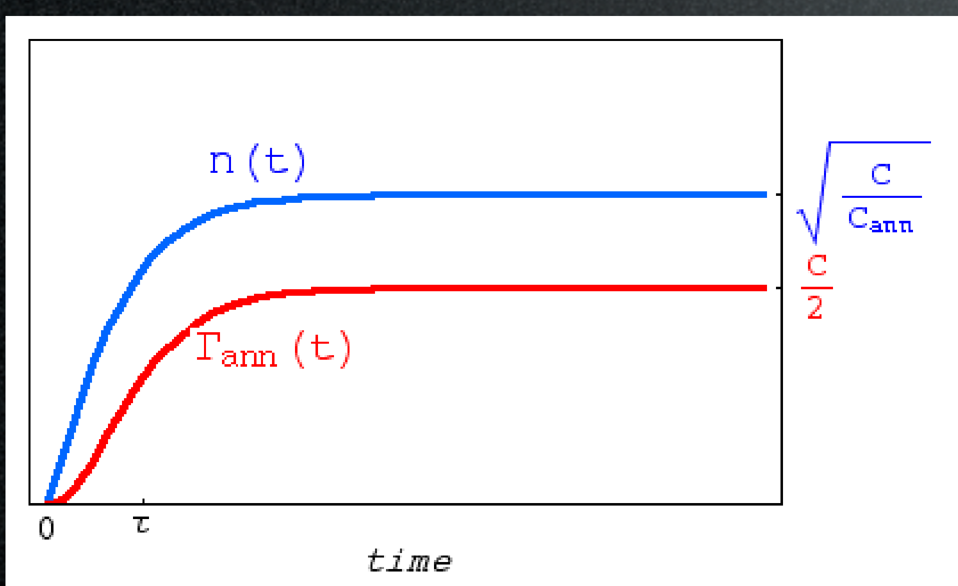

σ_N → $\Gamma_{\rm capt}$; $\langle \sigma_{\rm ann} v \rangle$ → $C_{\rm ann}$

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

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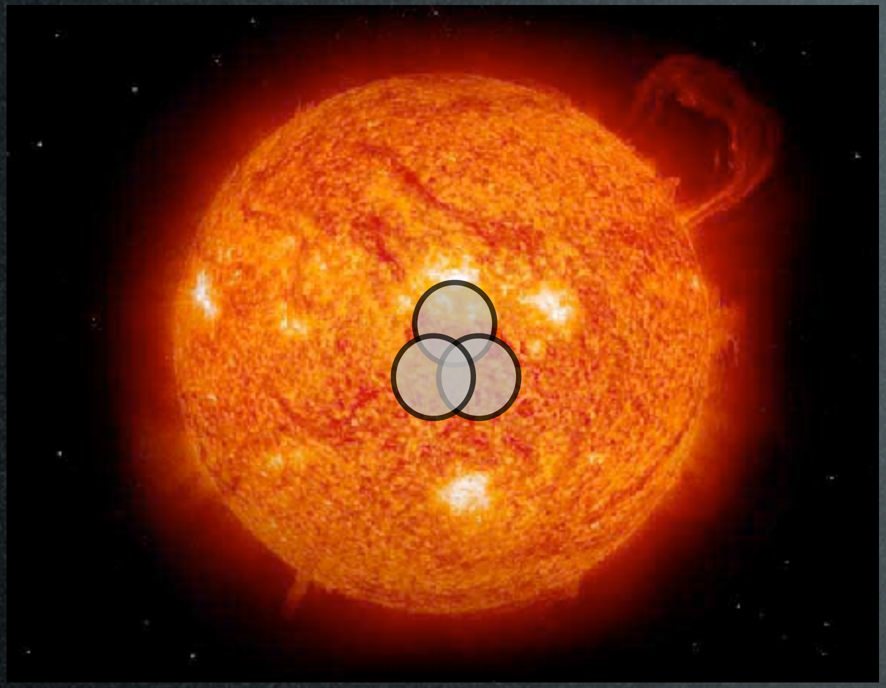

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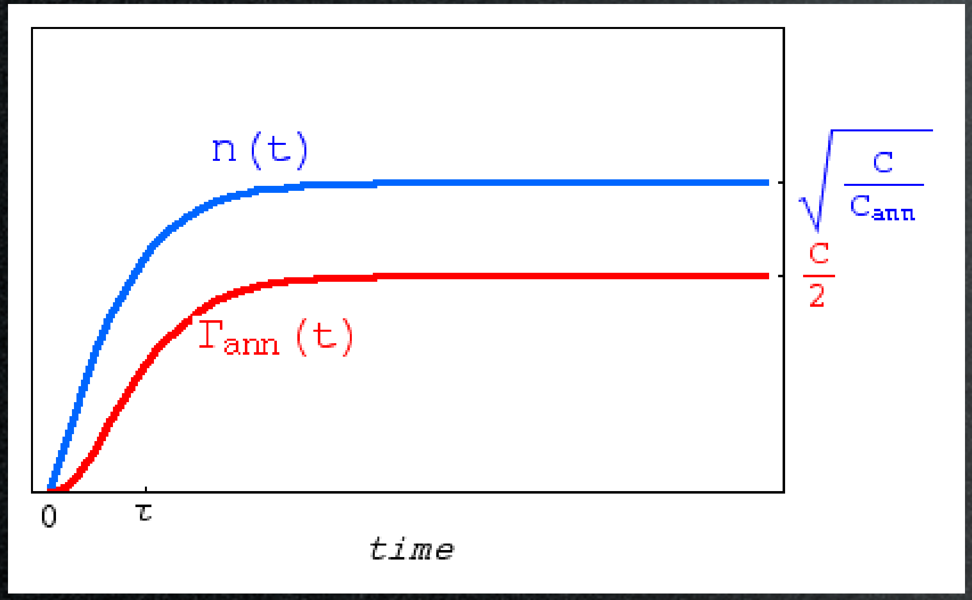

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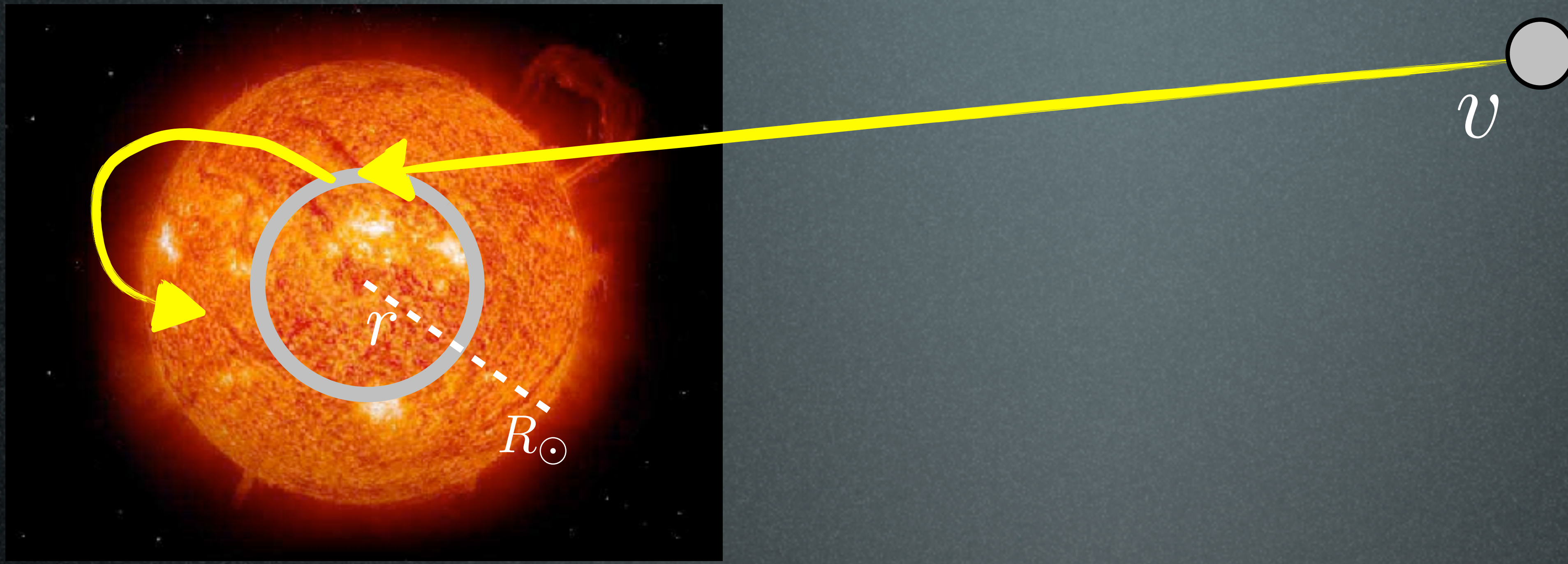

A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot{\rm esc}}^2}{v} \wp_i(v, v_{\odot{\rm esc}})$$

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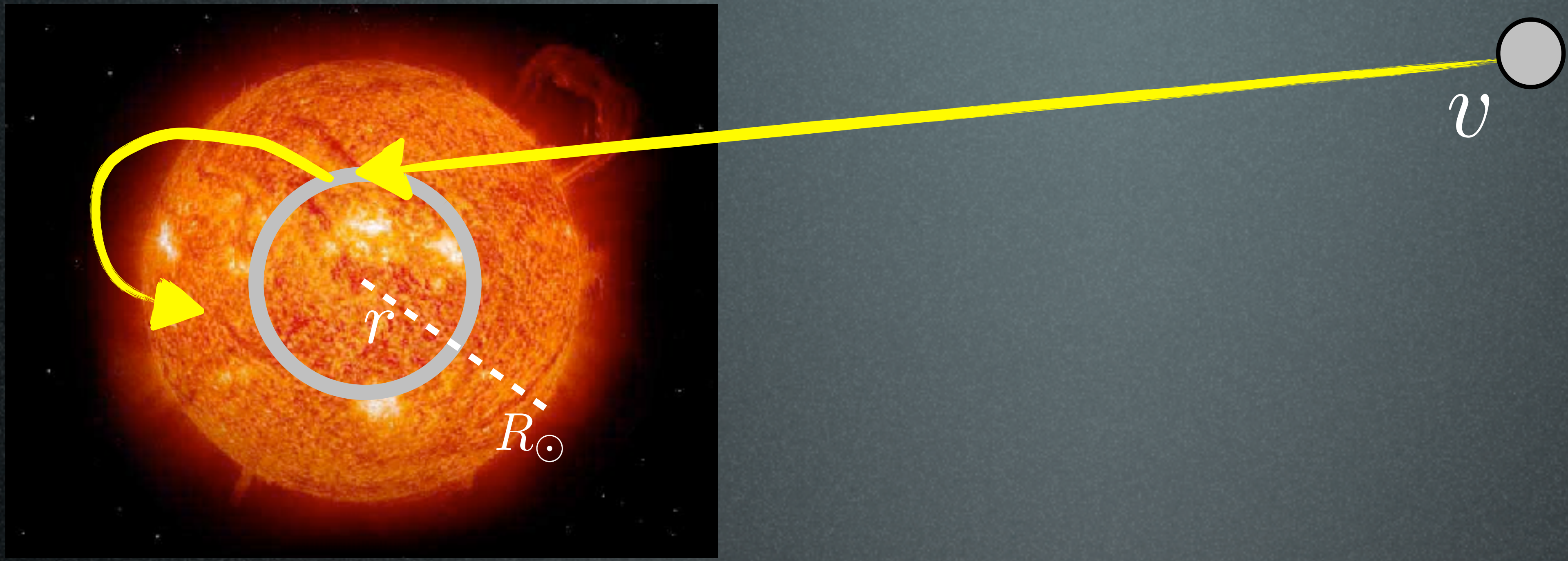

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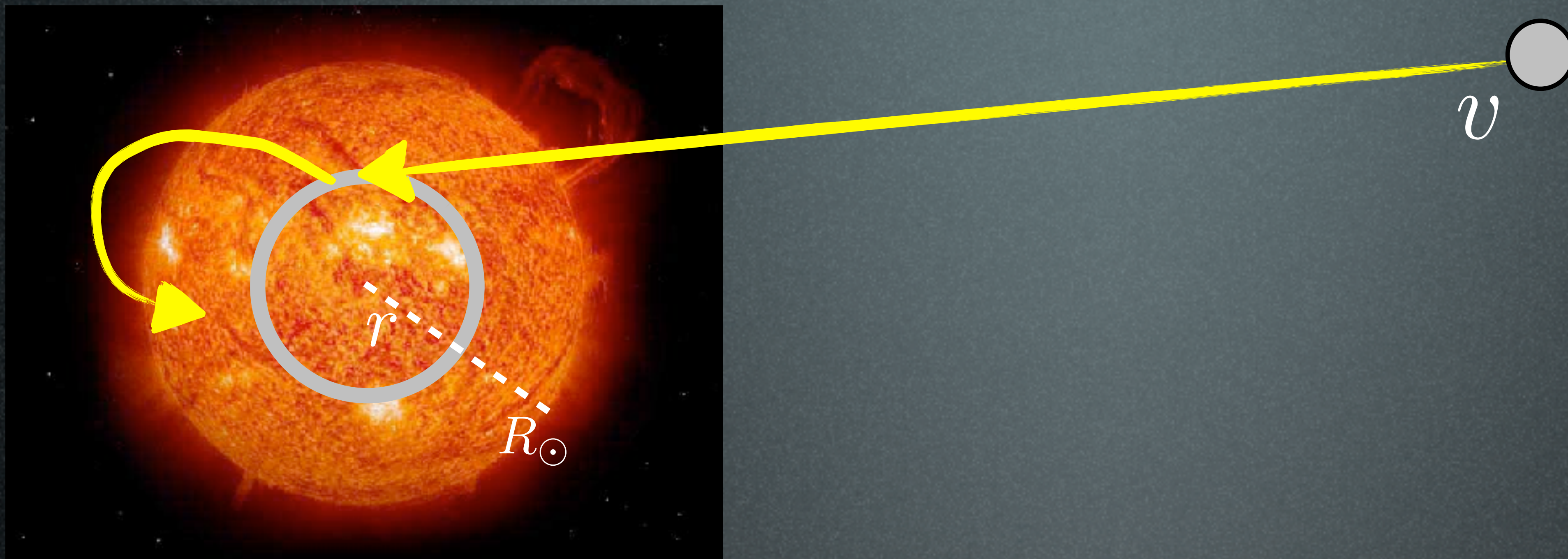
DM number density

1. Capture & annihilation



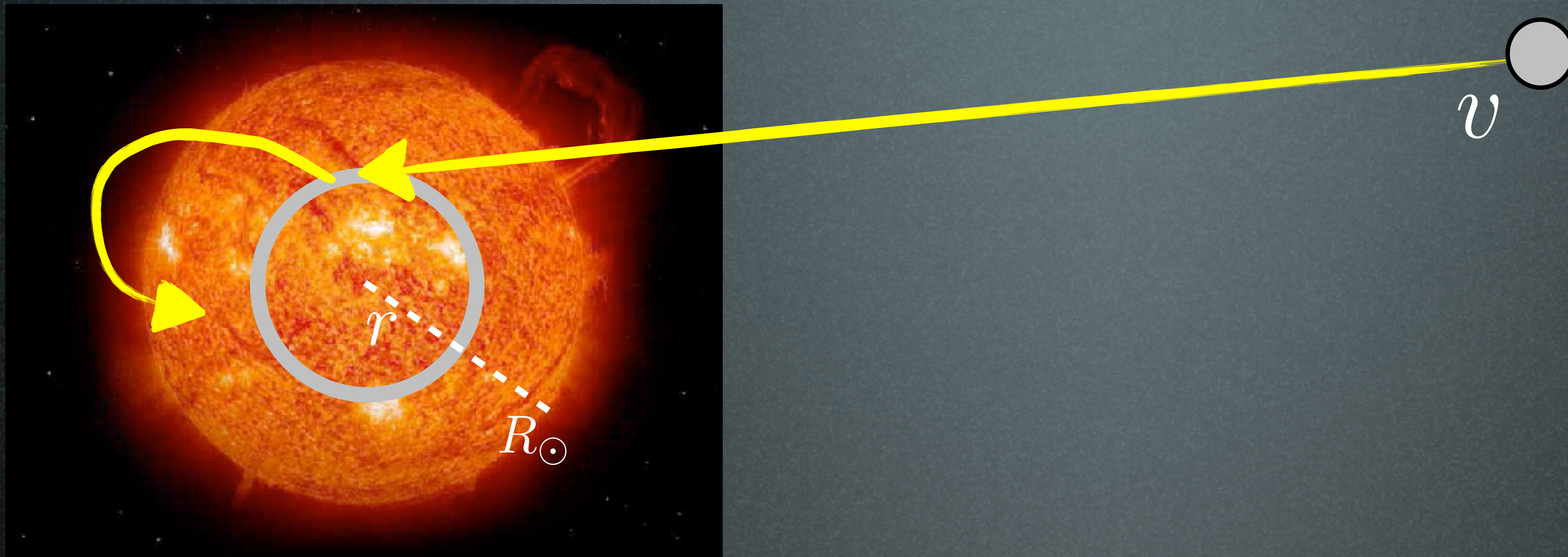
A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

DM number density

scattering cross section on element **i**

1. Capture & annihilation



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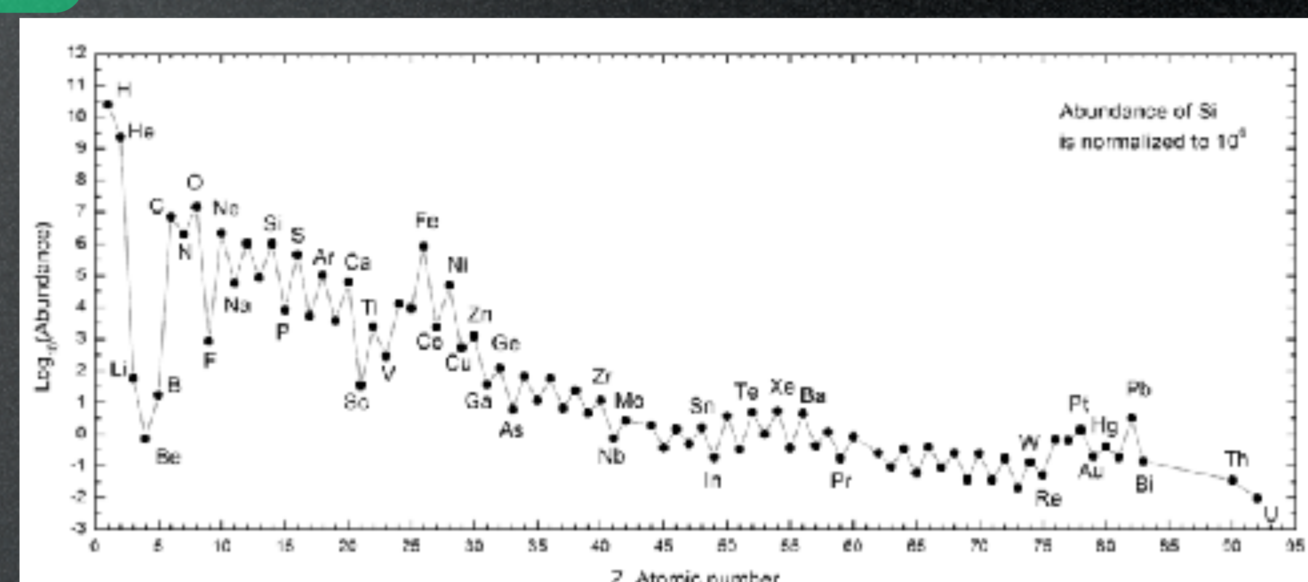
$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\; 4\pi r^2\, n_i(r) \int_0^\infty dv\; 4\pi v^2 f_\odot(v)\, \frac{v^2 + v_{\odot \rm esc}^2}{v}\, \wp_i(v, v_{\odot \rm esc})$$

DM number density

scattering cross section on element **i**

number density of element **i**



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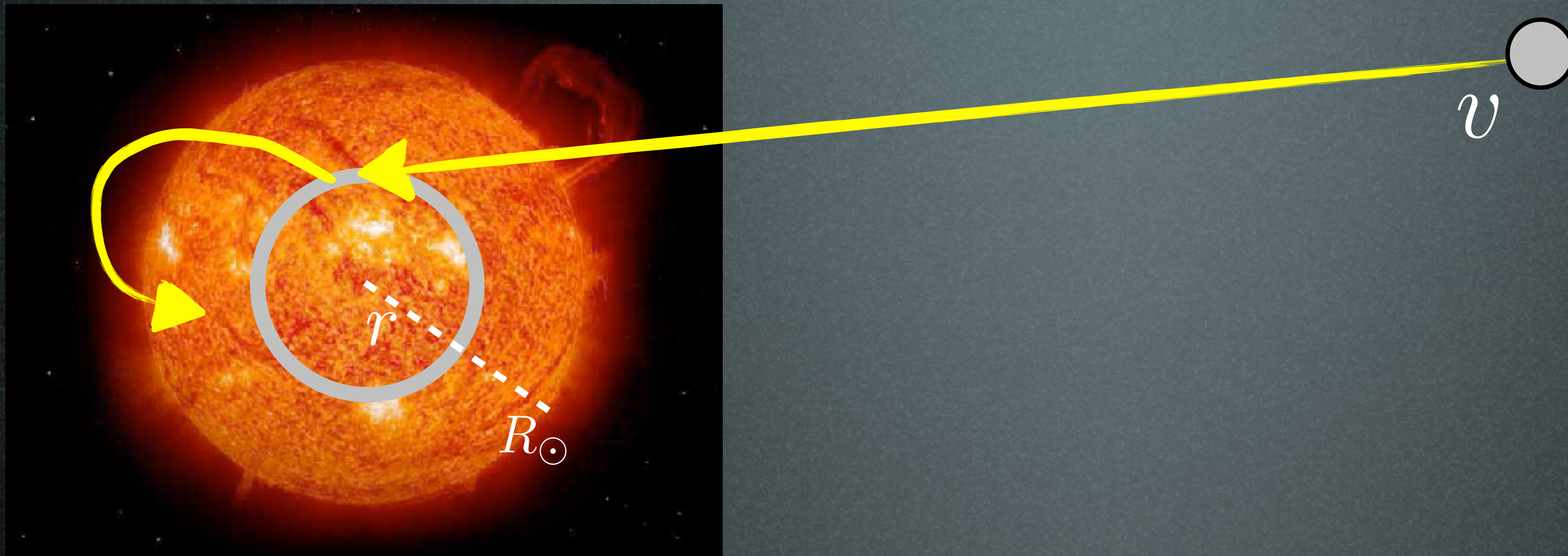

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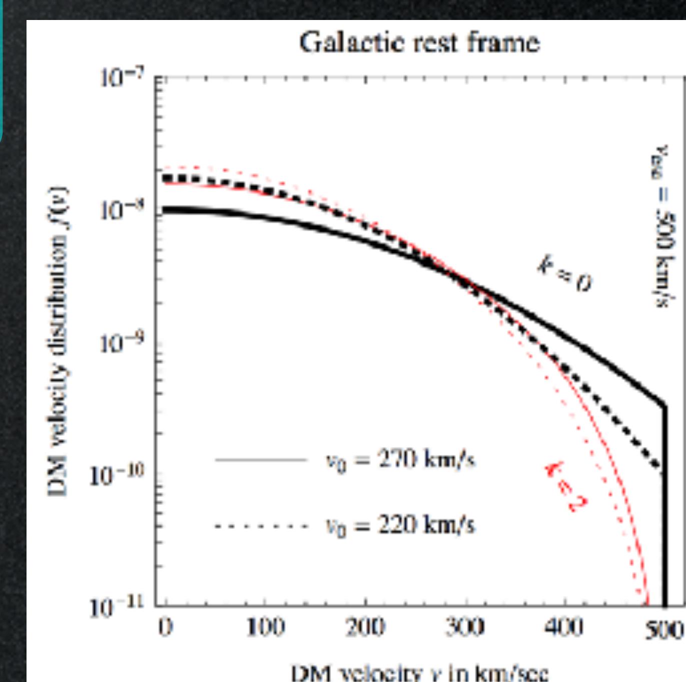
DM number density

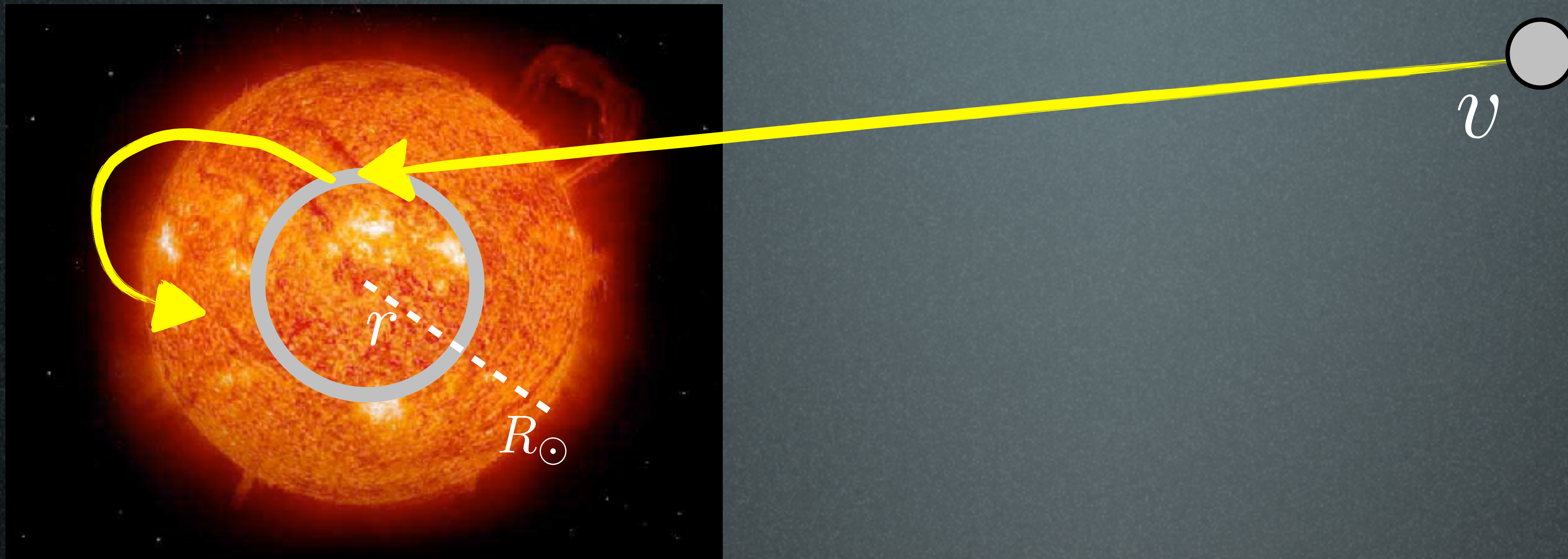
scattering cross section on element **i**

number density of element **i**

velocity distribution
(in solar frame, without Sun's gravity)



1. Capture & annihilation



A.Gould 1987, 1988, 1990

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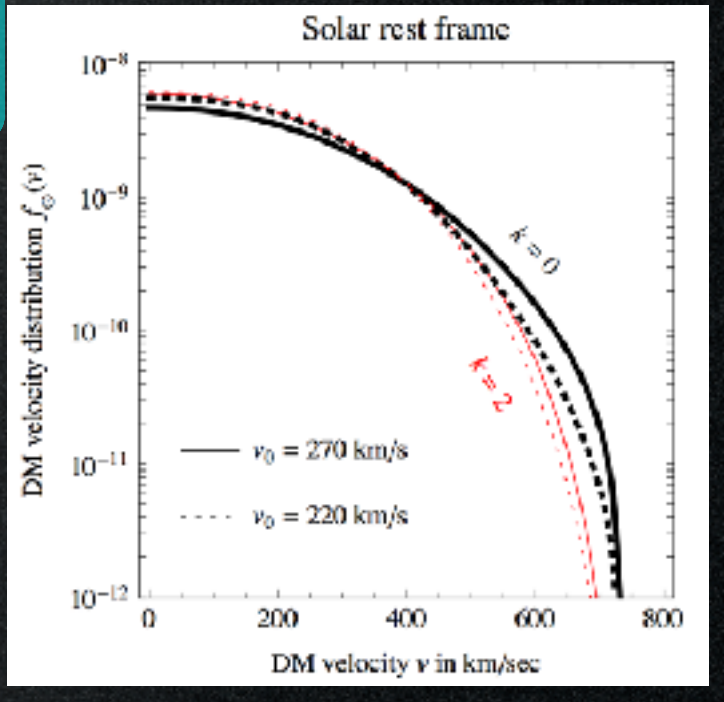

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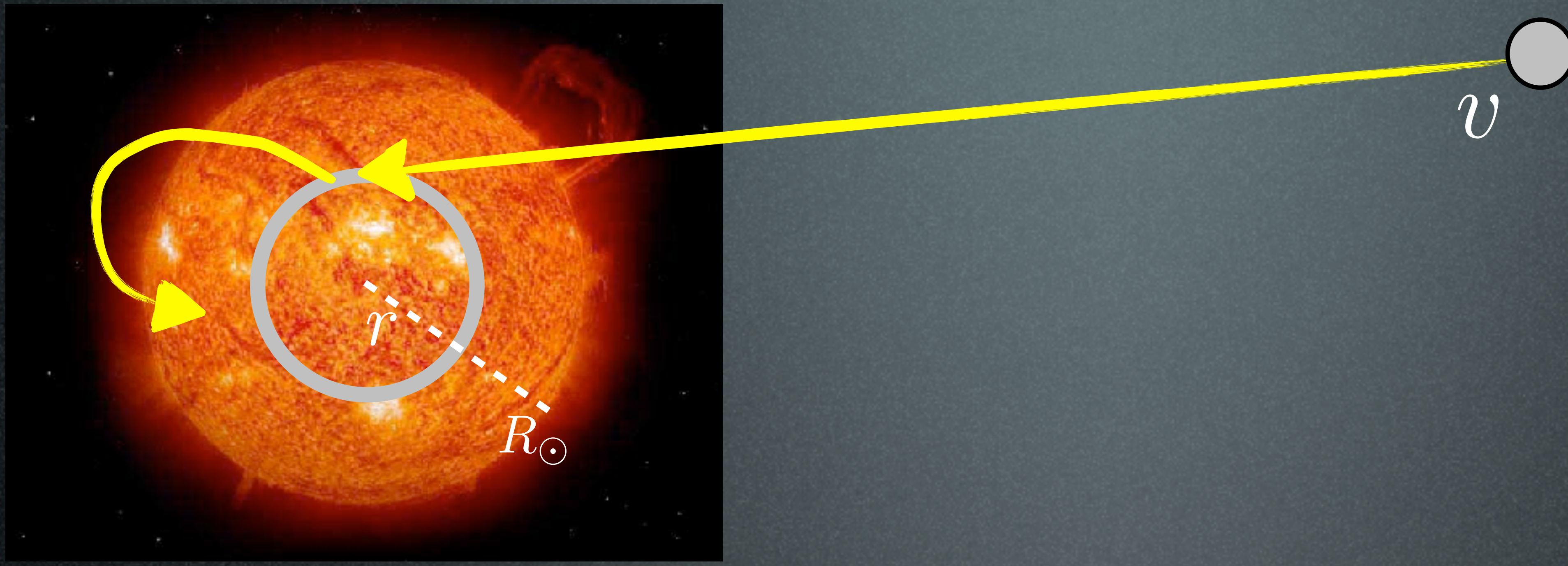

A.Gould 1987, 1988, 1990

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DM number density

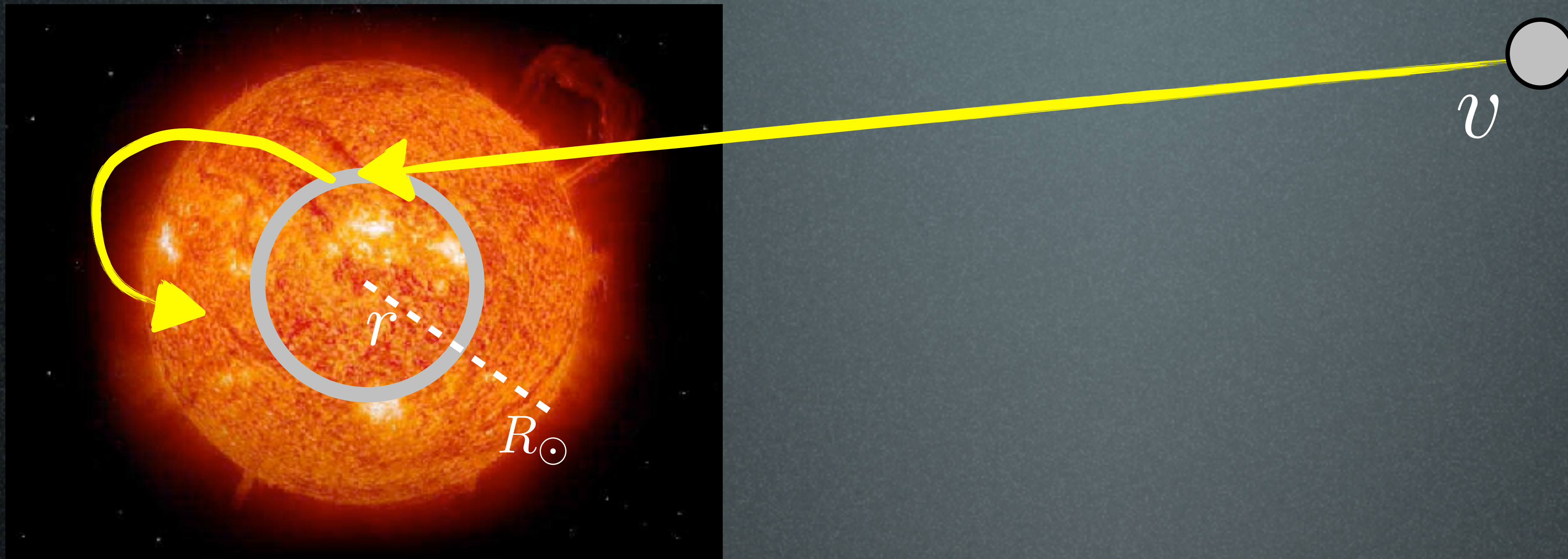
scattering cross section on element **i**

number density of element **i**

velocity distribution (in solar frame, without Sun's gravity)

effect of solar gravity

1. Capture & annihilation



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DM number density

scattering cross section on element **i**

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velocity distribution (in solar frame, without Sun's gravity)

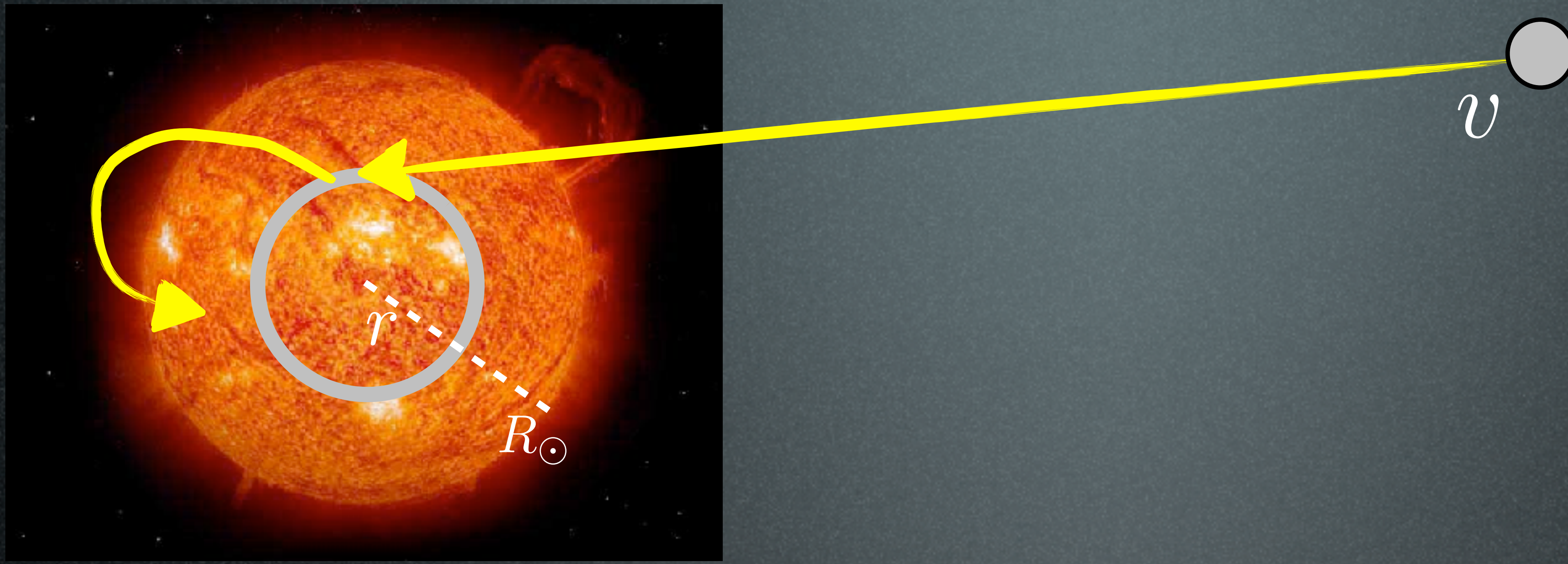
effect of solar gravity

scattering probability:

$$\wp_i(v, v_{\odot\rm esc}) = \max\left(0, 1 - \frac{\Delta_{\rm min}}{\Delta_{\rm max}}\right)$$

$$\Delta_{\rm max} = \frac{4\, m_i\, M_{\rm DM}}{(M_{\rm DM} + m_i)^2} \qquad \Delta_{\rm min} = \frac{v^2}{v^2 + v_{\odot\rm esc}^2}$$

1. Capture & annihilation



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- $\frac{\rho_{\rm DM}}{M_{\rm DM}}$: DM number density
- σ_i: scattering cross section on element **i**
- $n_i(r)$: number density of element **i**
- $f_\odot(v)$: velocity distribution (in solar frame, without Sun's gravity)
- $\frac{v^2 + v^2_{\odot\rm esc}}{v}$: effect of solar gravity

scattering probability:

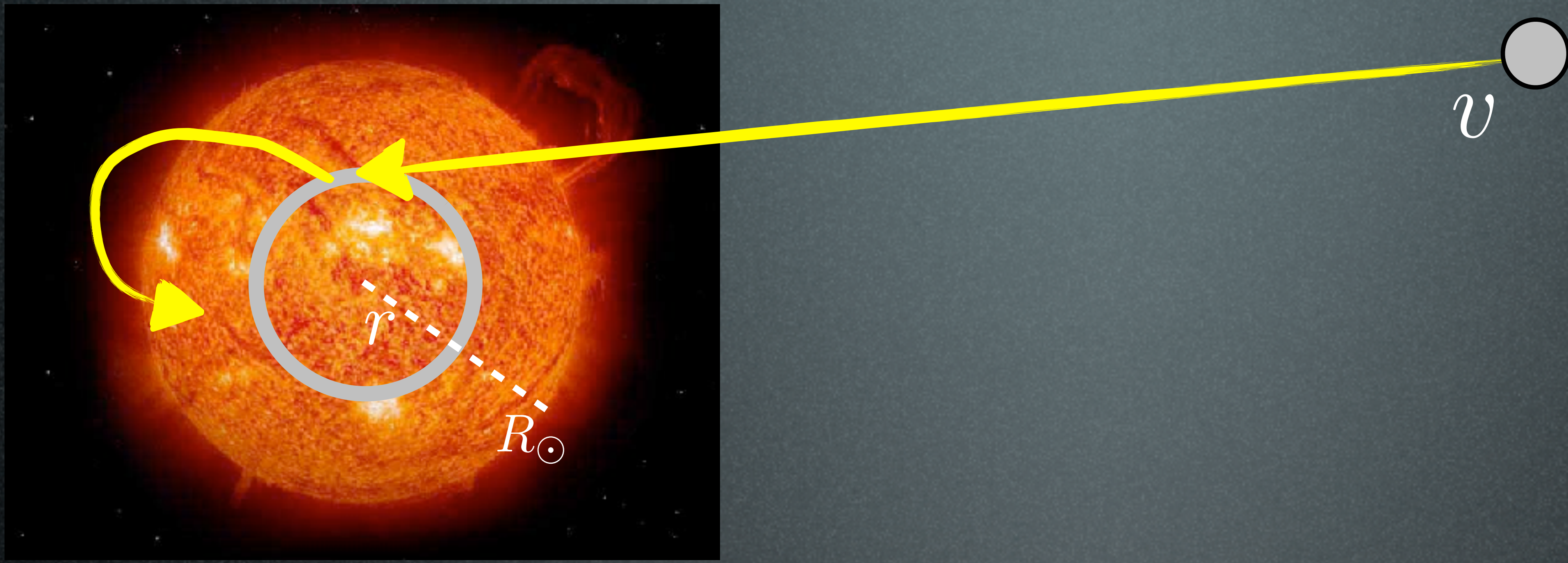
$$\wp_i(v, v_{\odot\rm esc}) = \max\left(0, 1 - \frac{\Delta_{\rm min}}{\Delta_{\rm max}}\right) \qquad \Delta_{\rm max} = \frac{4\, m_i\, M_{\rm DM}}{(M_{\rm DM} + m_i)^2} \qquad \Delta_{\rm min} = \frac{v^2}{v^2 + v^2_{\odot\rm esc}}$$

$$\wp_i(v, v_{\odot\rm esc}) = \frac{1}{E\,\Delta_{\rm max}} \int_{E\,\Delta_{\rm min}}^{E\,\Delta_{\rm max}} {\rm d}(\Delta E)\, |F_i(\Delta E)|^2 \qquad |F_i(\Delta E)|^2 = e^{-\Delta E/E_0}$$

$$E_0^{\rm SI} = 5/2 m_i r_i^2$$

$$E_0^{\rm SD} = 3/2 m_i r_i^2$$

1. Capture & annihilation



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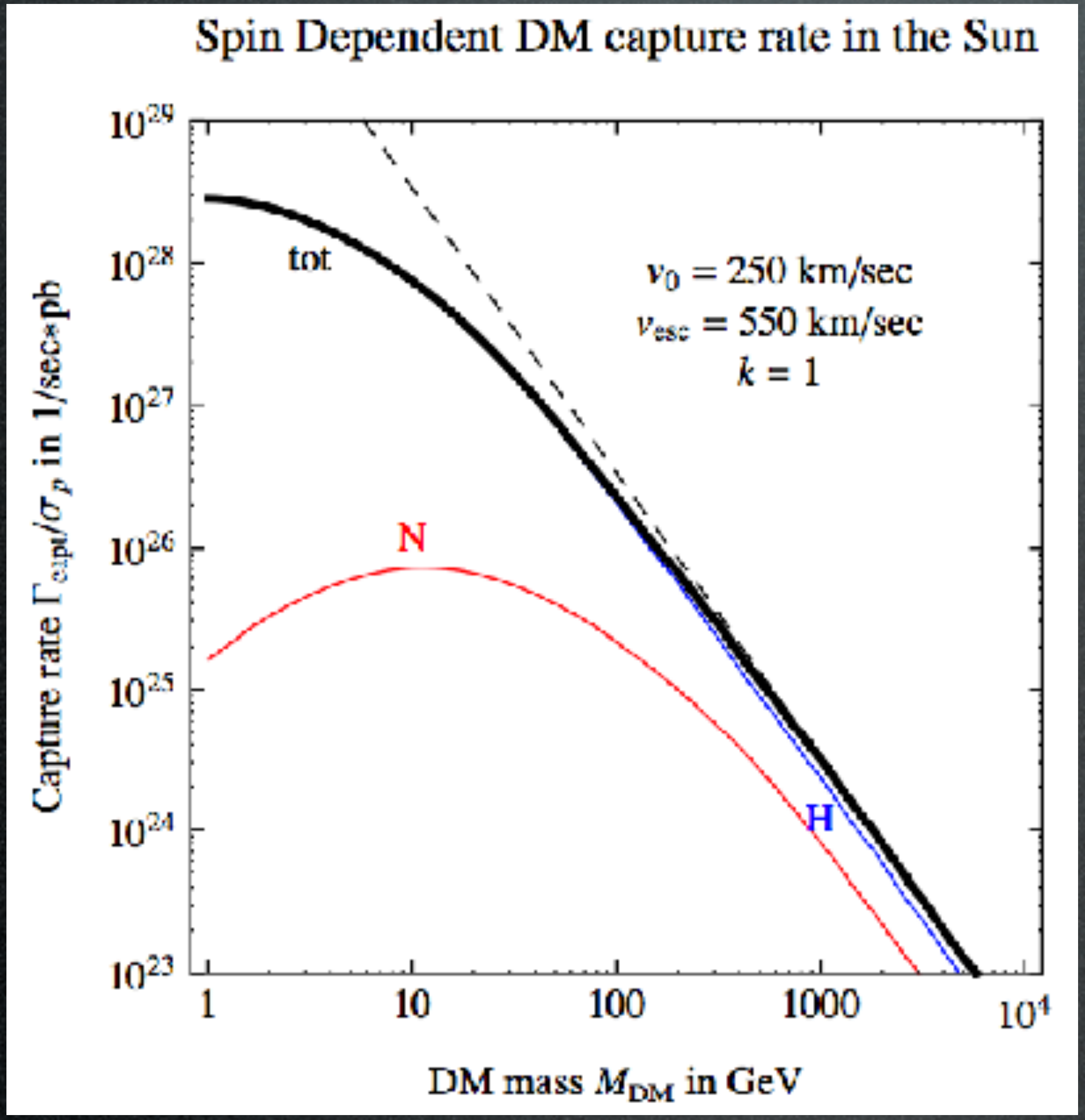

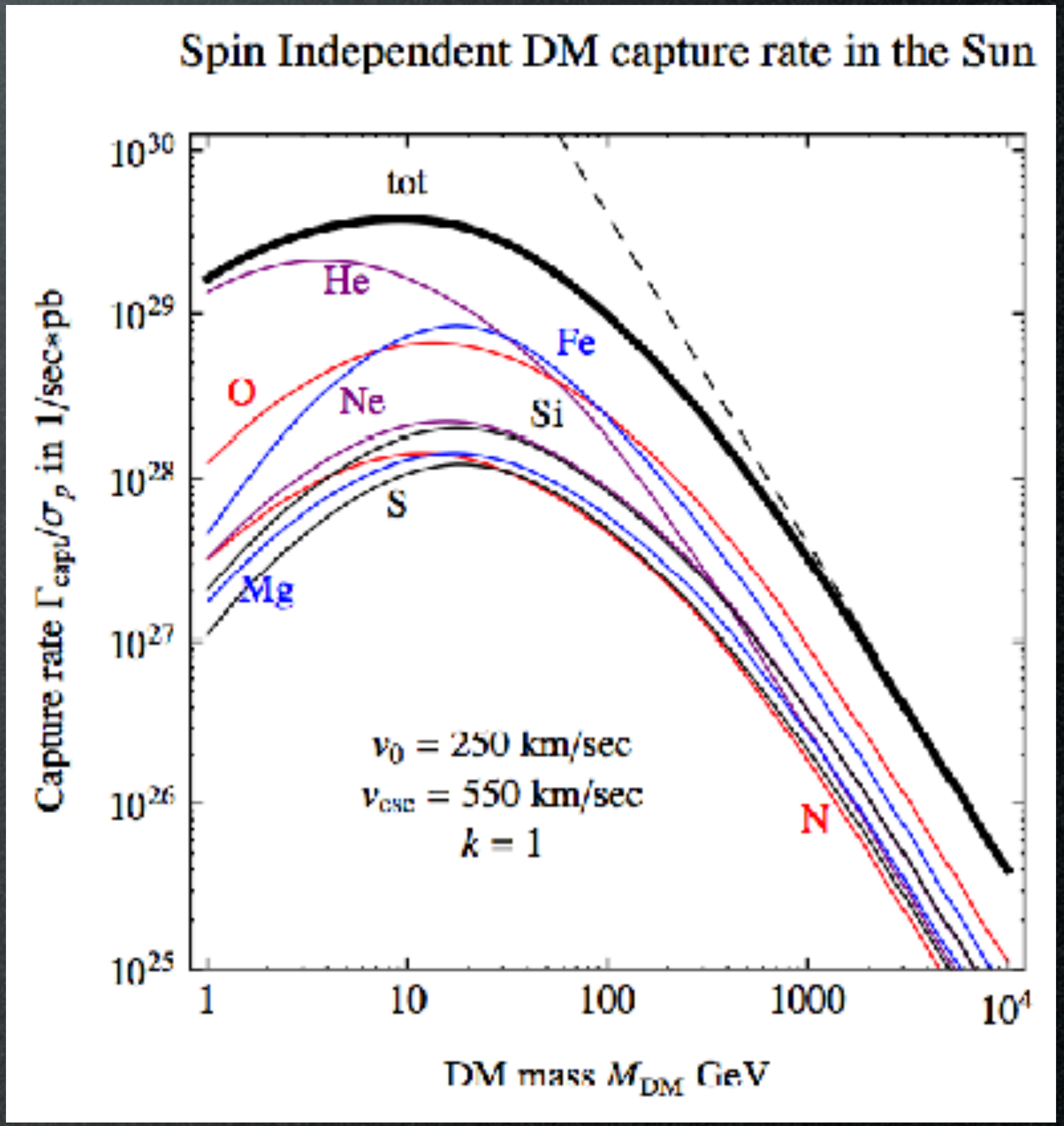

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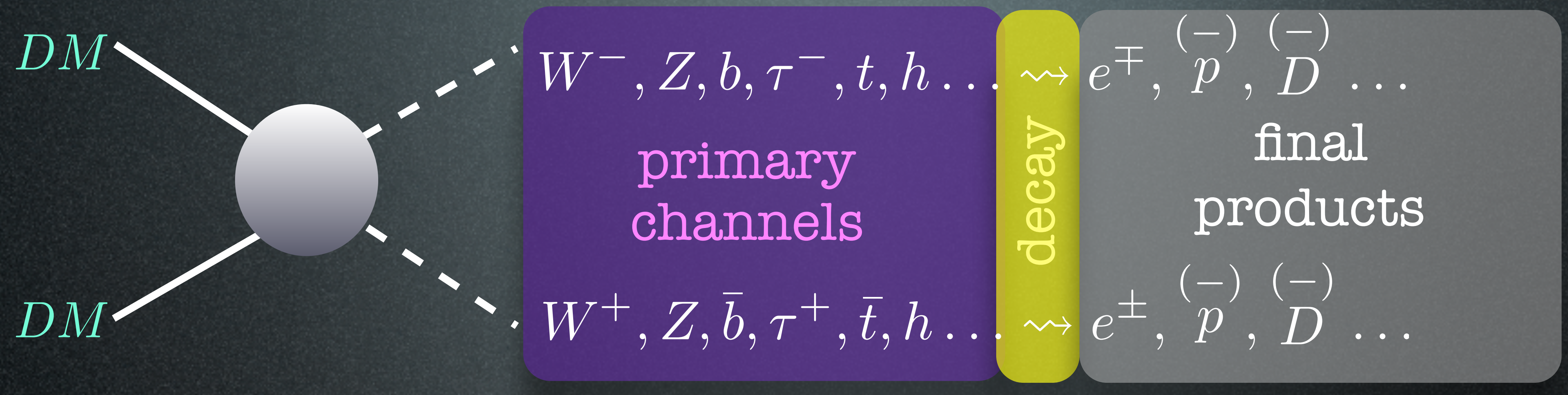
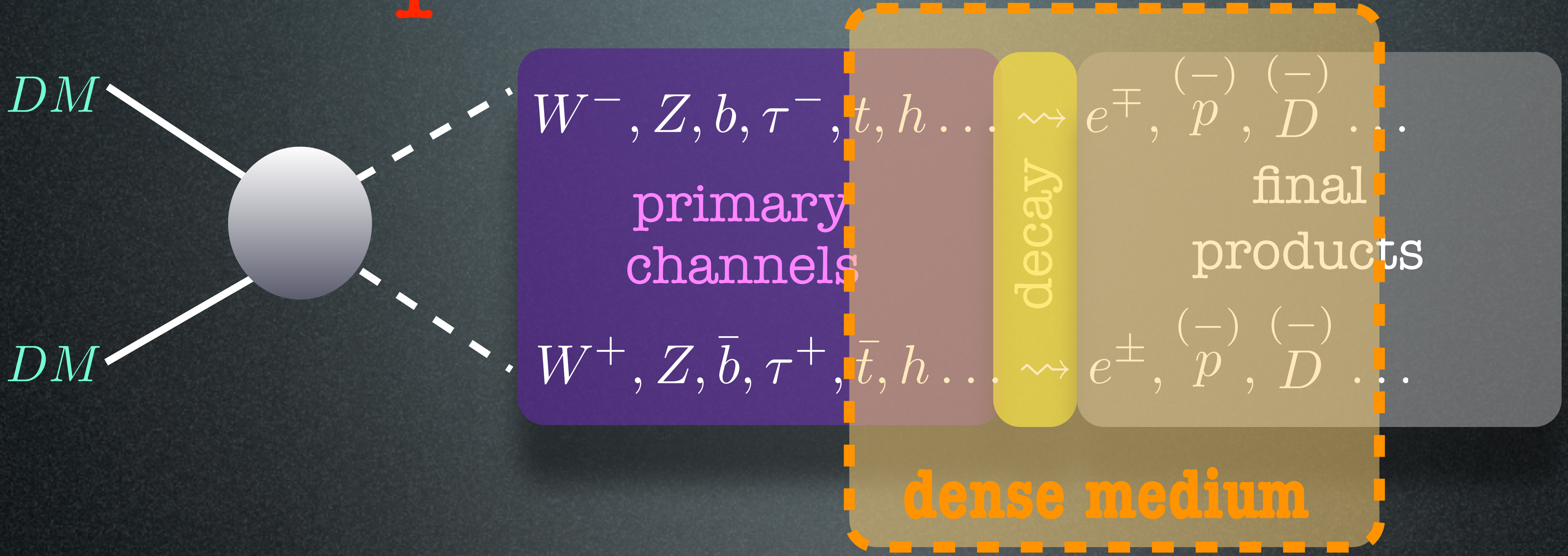


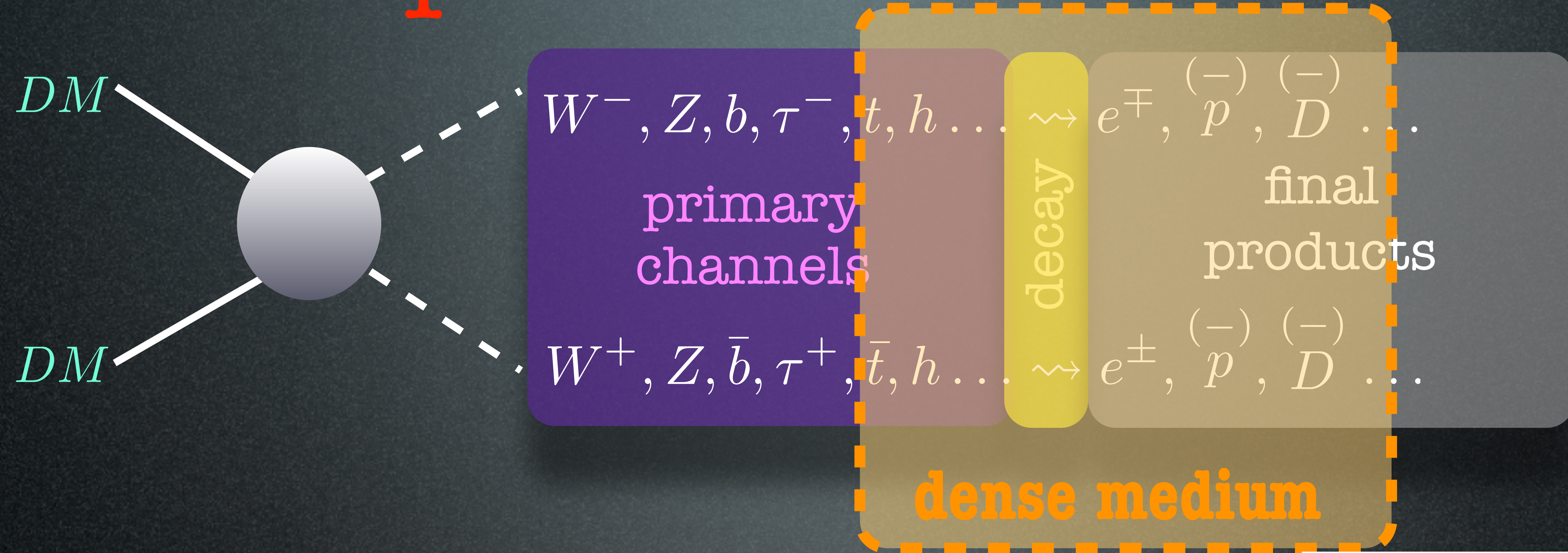
1. Capture & annihilation

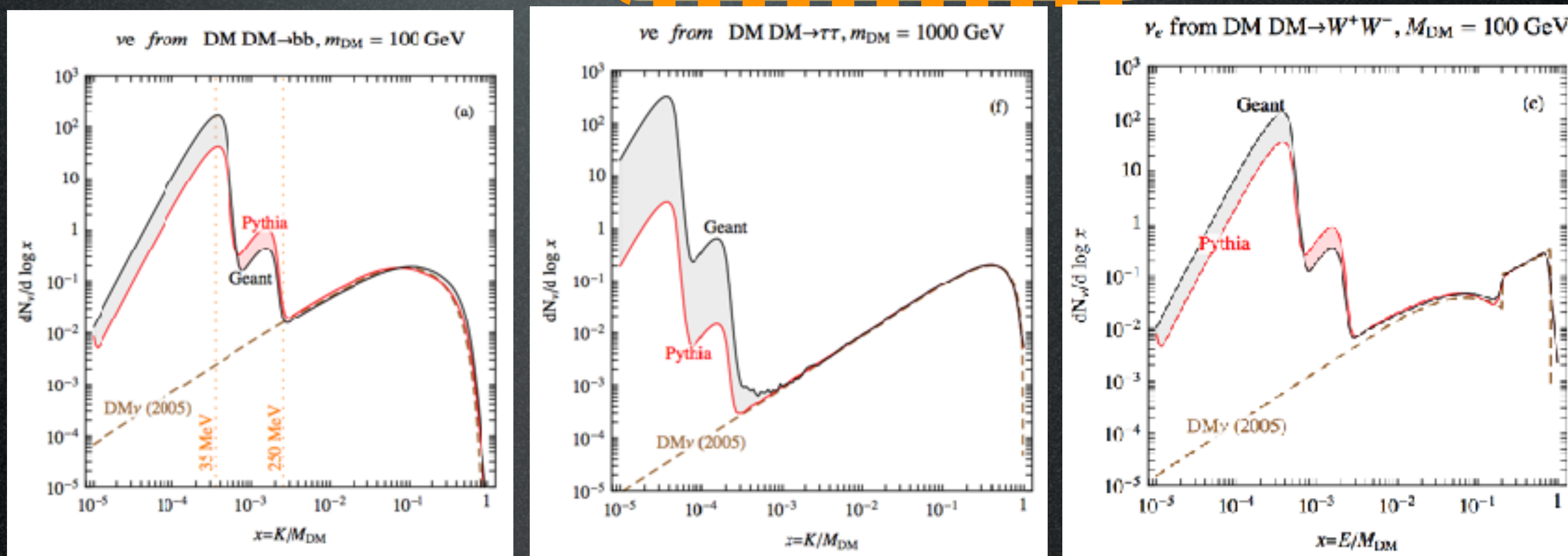


Effects of the medium:

1) light hadrons (π, K...) and leptons (μ) are stopped and decay at rest
2) heavy hadrons/leptons lose some energy before decaying

1. Capture & annihilation





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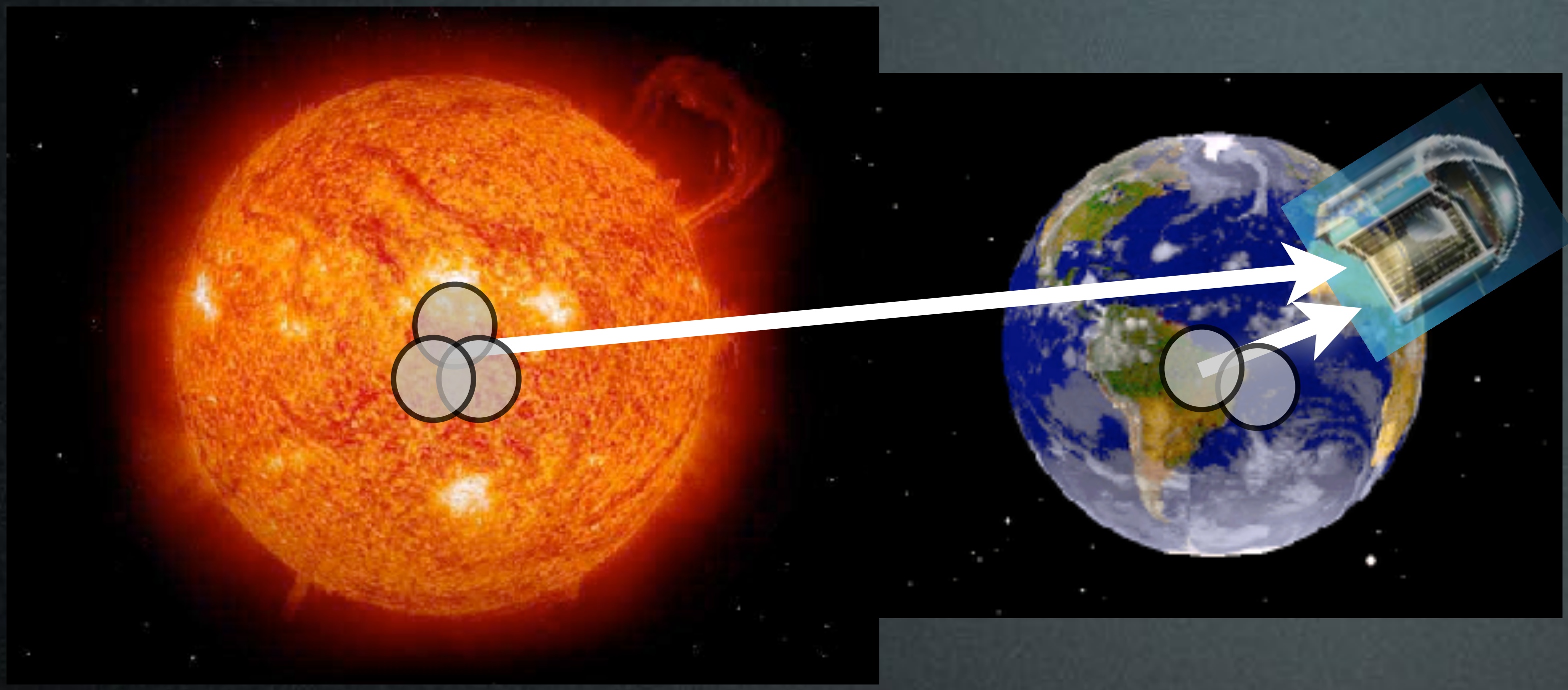
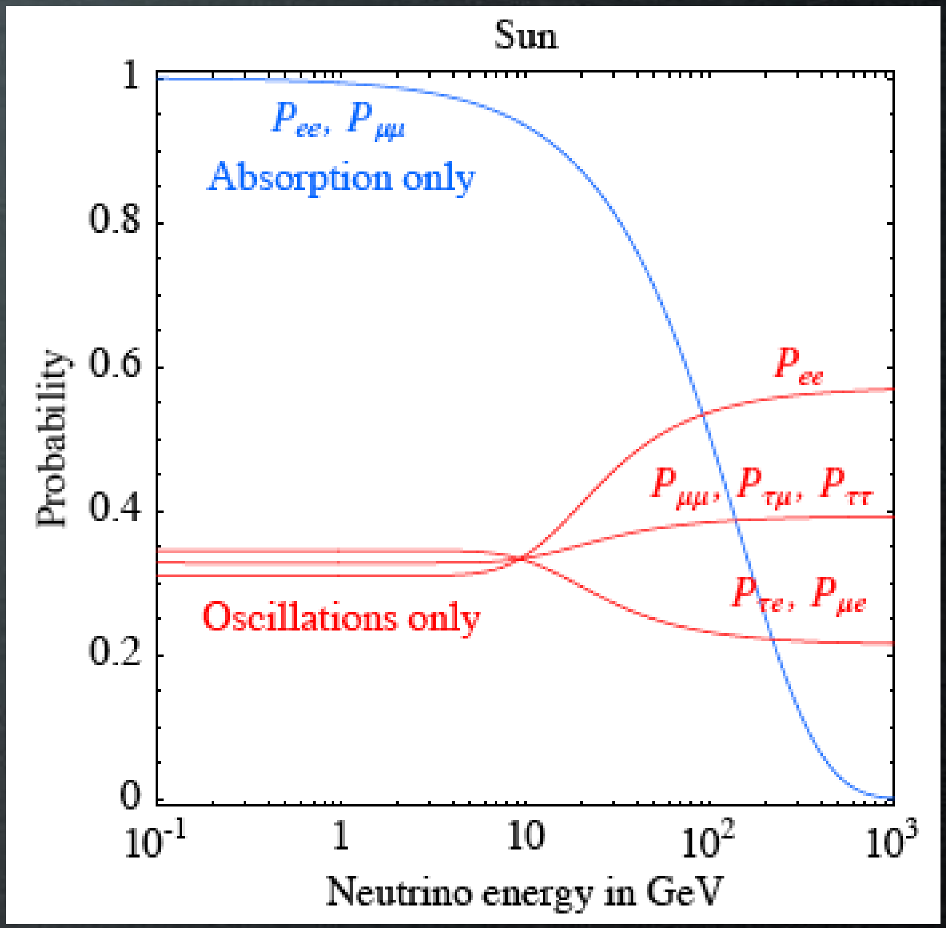
2. Propagation



oscillations + interactions



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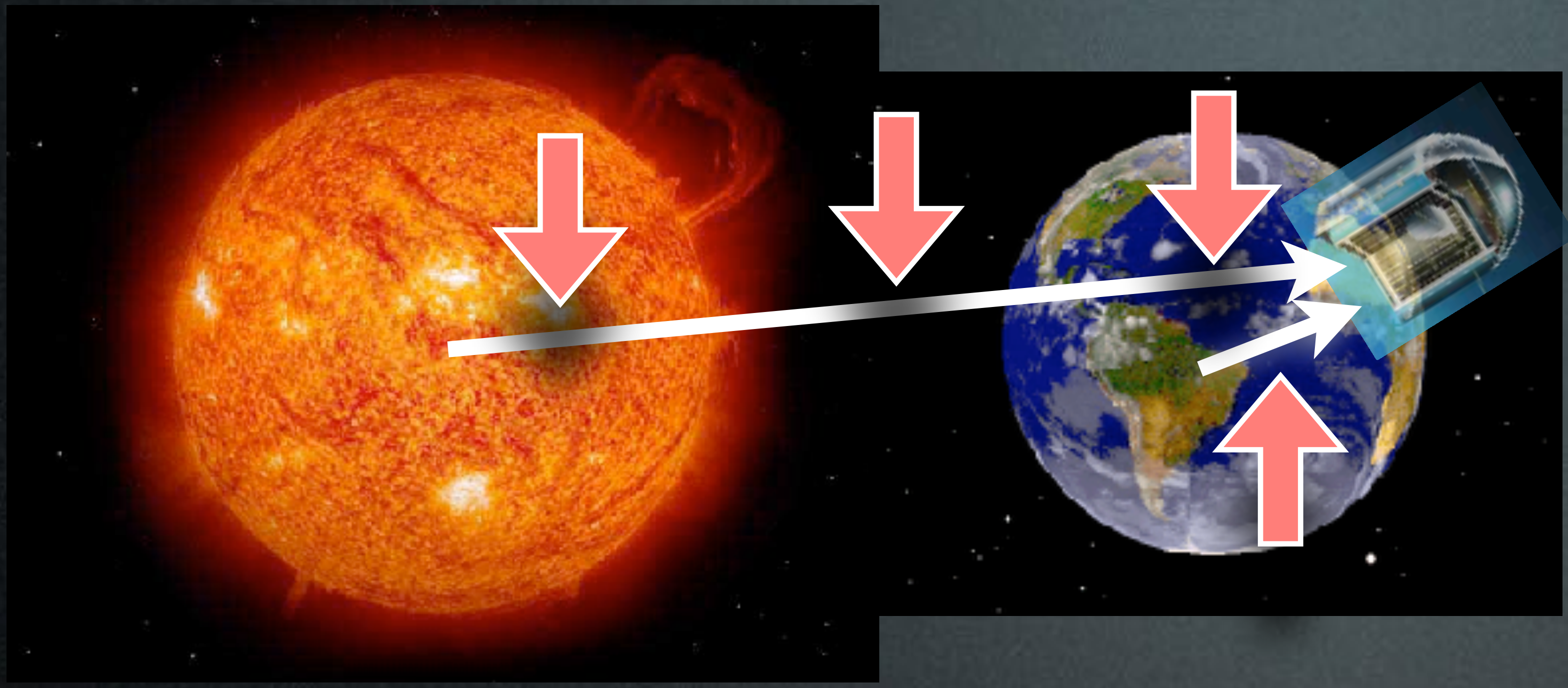

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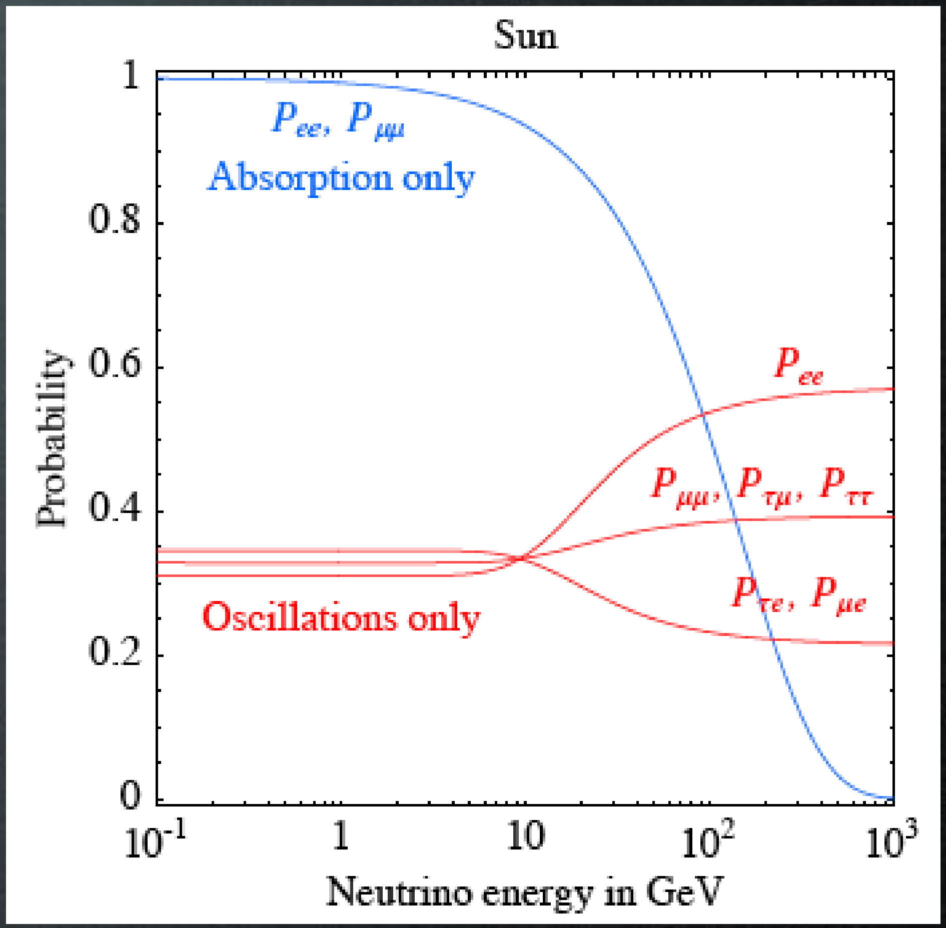

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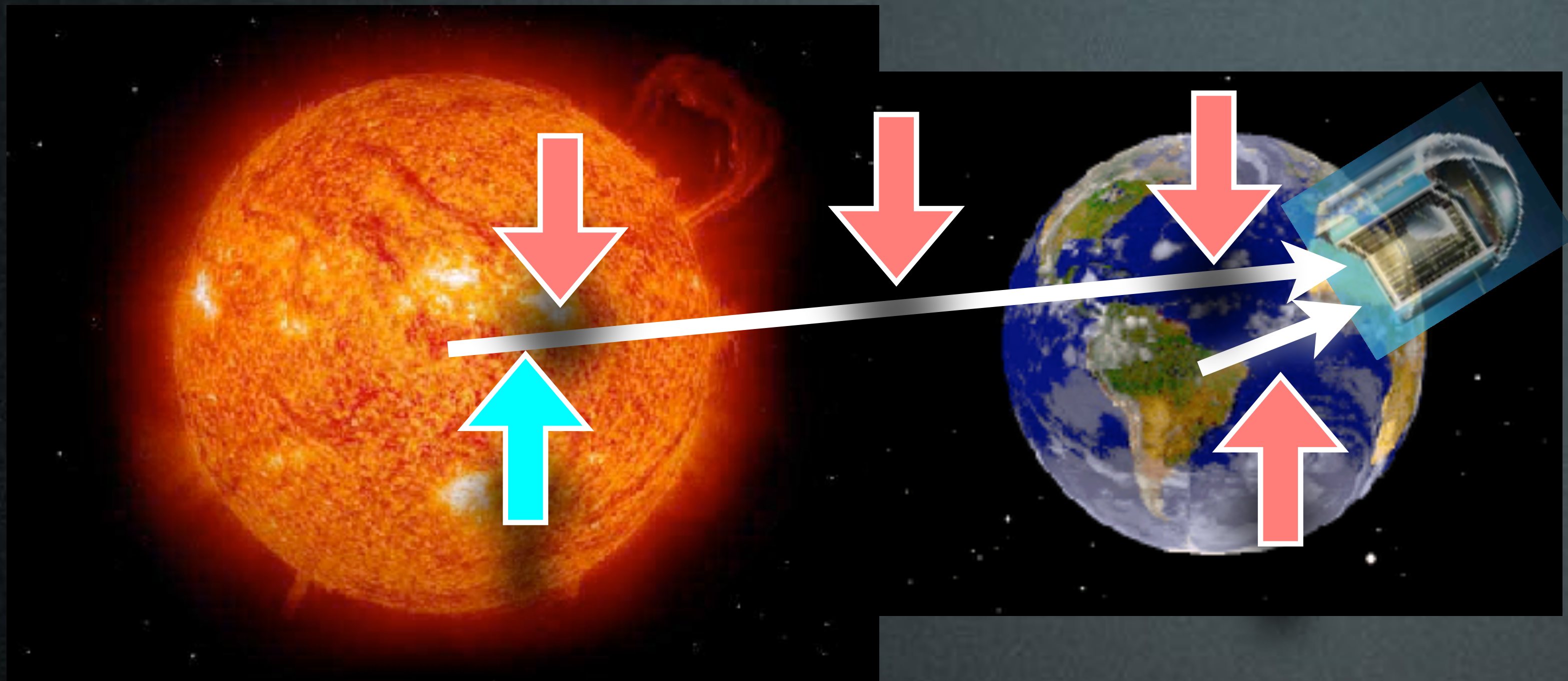
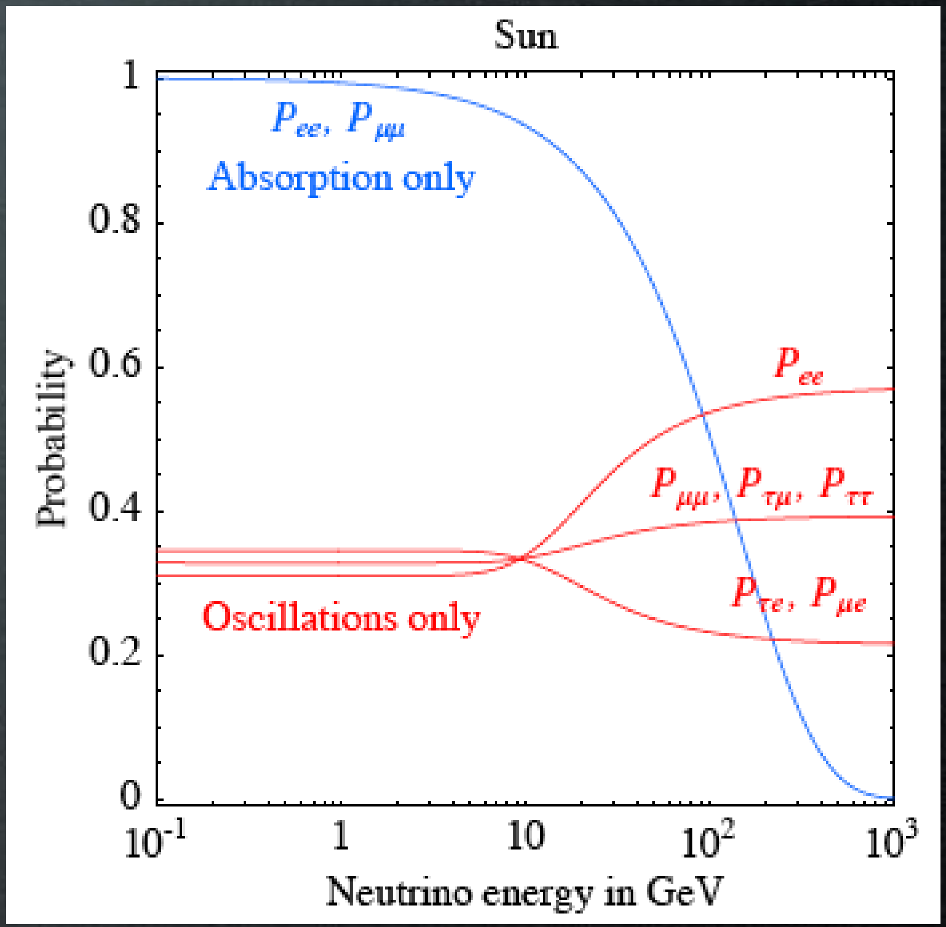
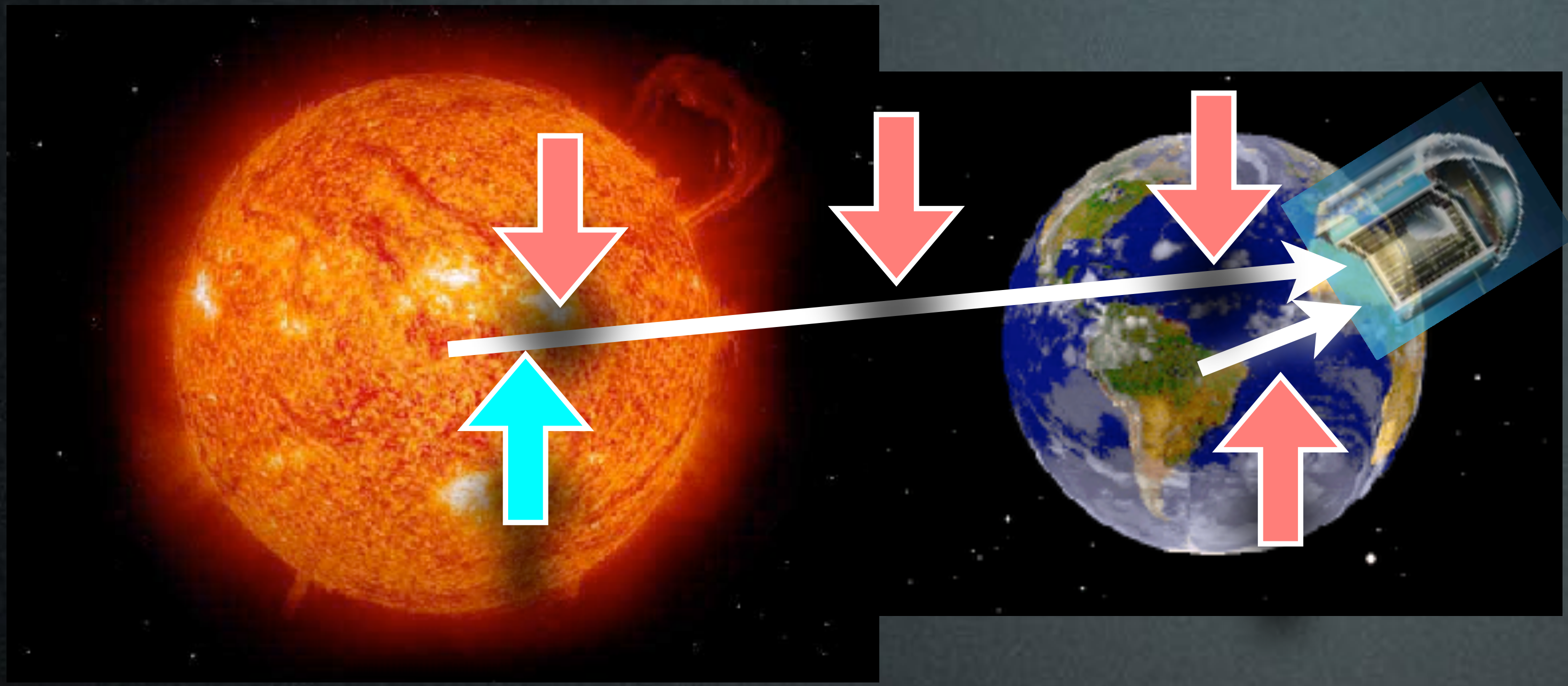
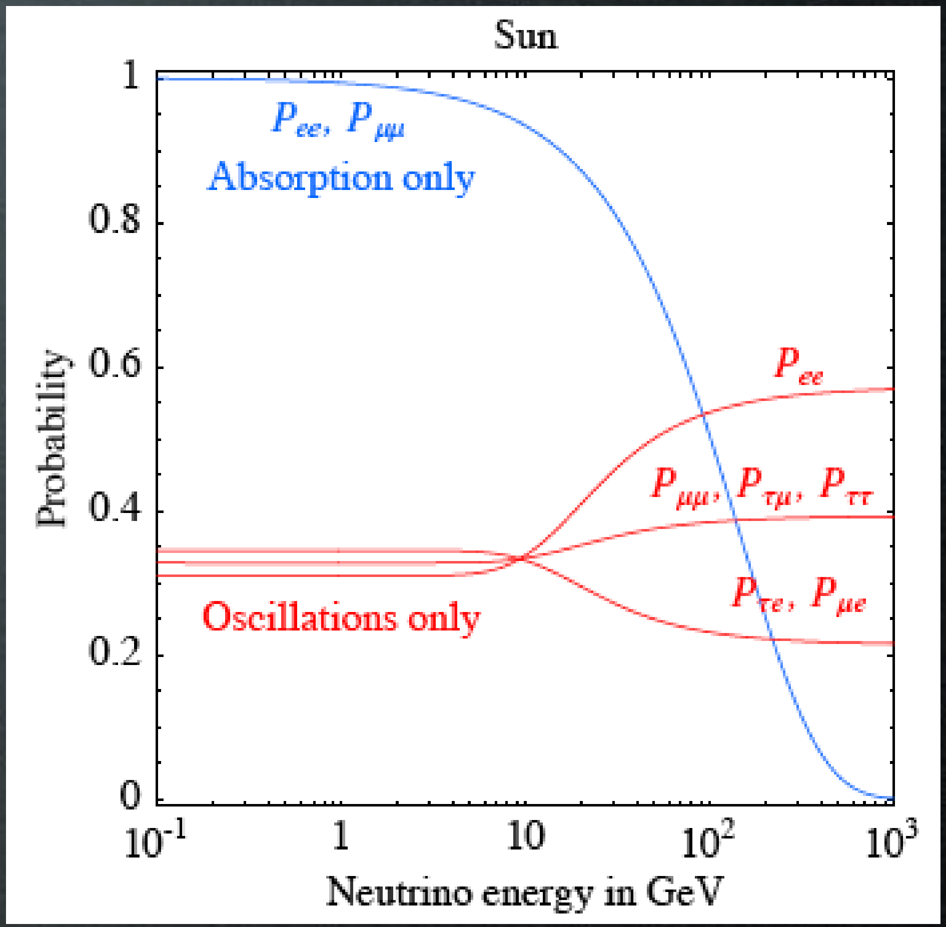




oscillations + interactions

2. Propagation

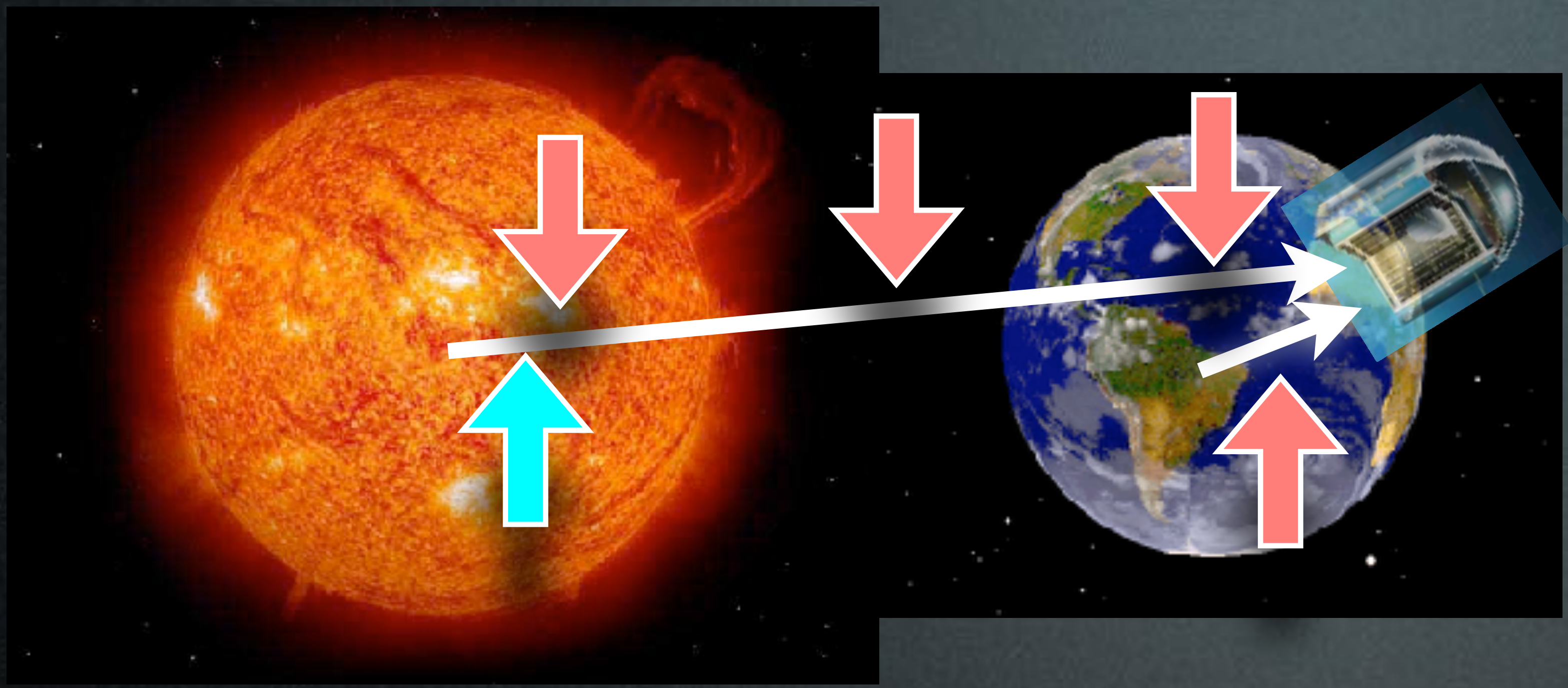


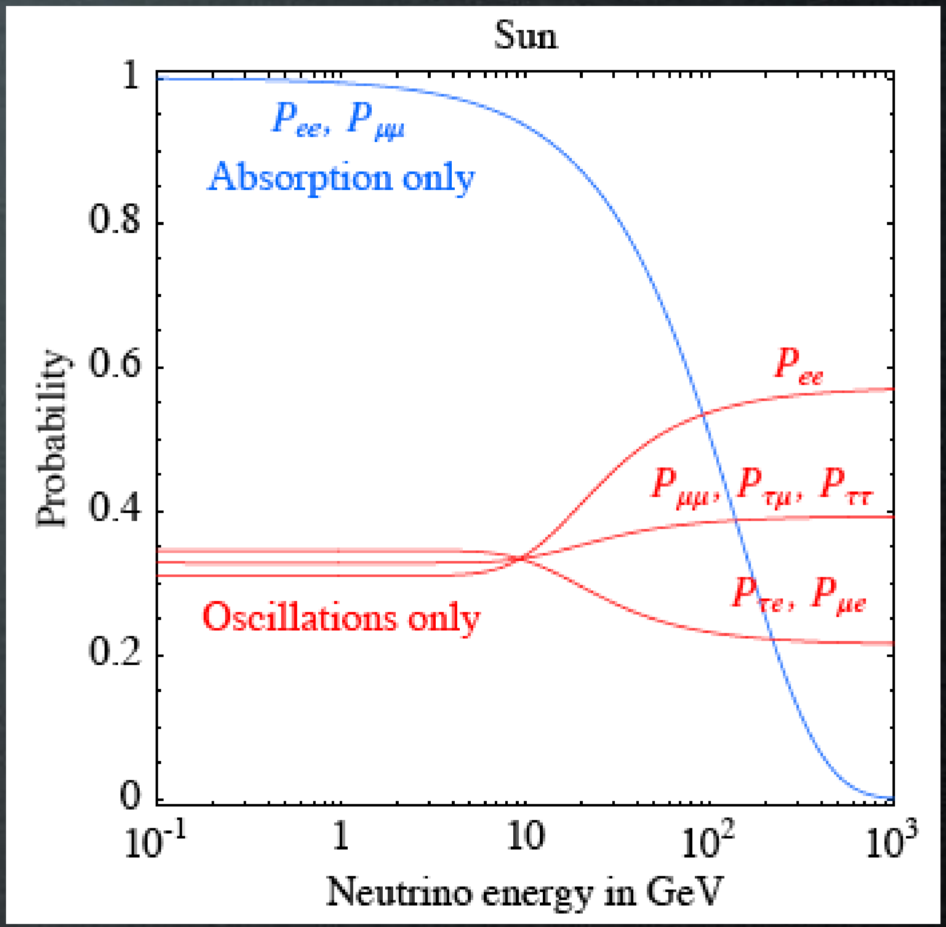


oscillations + interactions

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

2. Propagation





oscillations + interactions

density matrix

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

full evolution equation:

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

2. Propagation: oscillations

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

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

2. Propagation: oscillations

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

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

vacuum mixing:

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

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

2. Propagation: oscillations

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$\Delta m^2_{\rm sun} = 8.0\ 10^{-5} {\rm eV}^2$

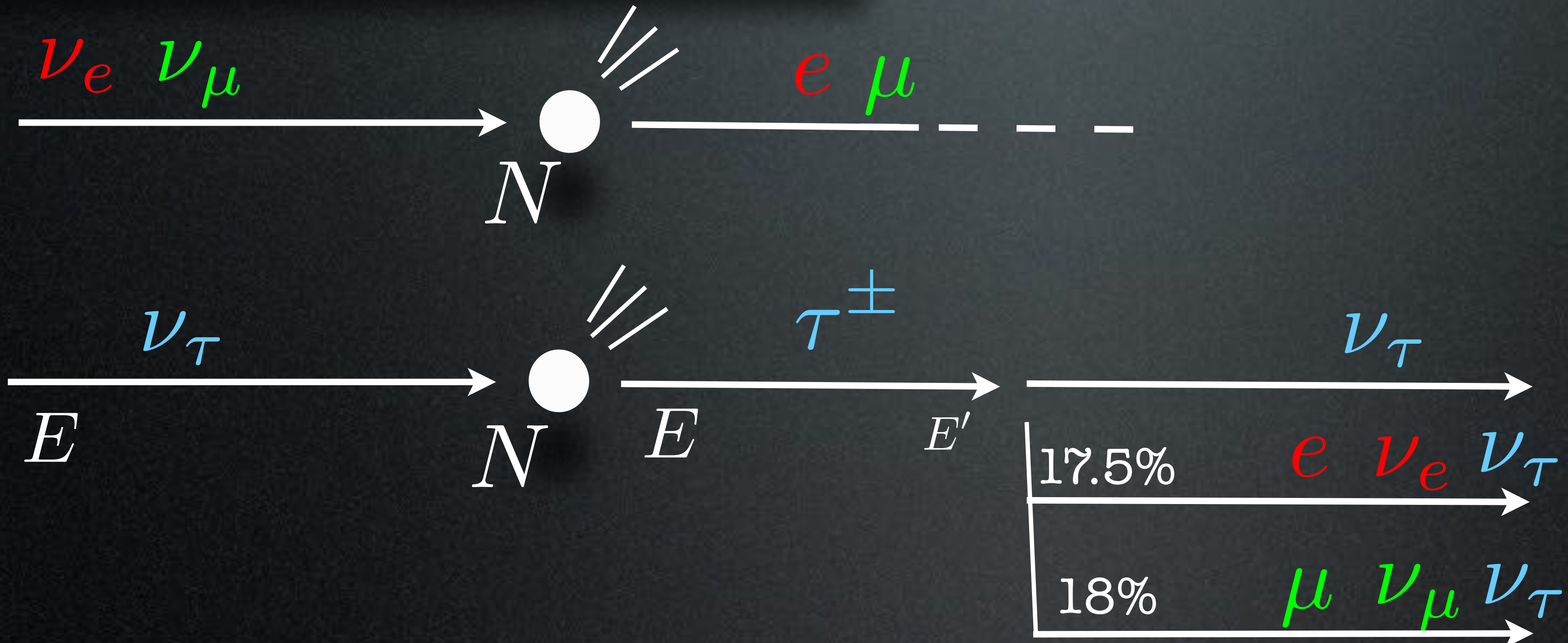
$|\Delta m^2_{\rm atm}| = 2.5\ 10^{-3} {\rm eV}^2$

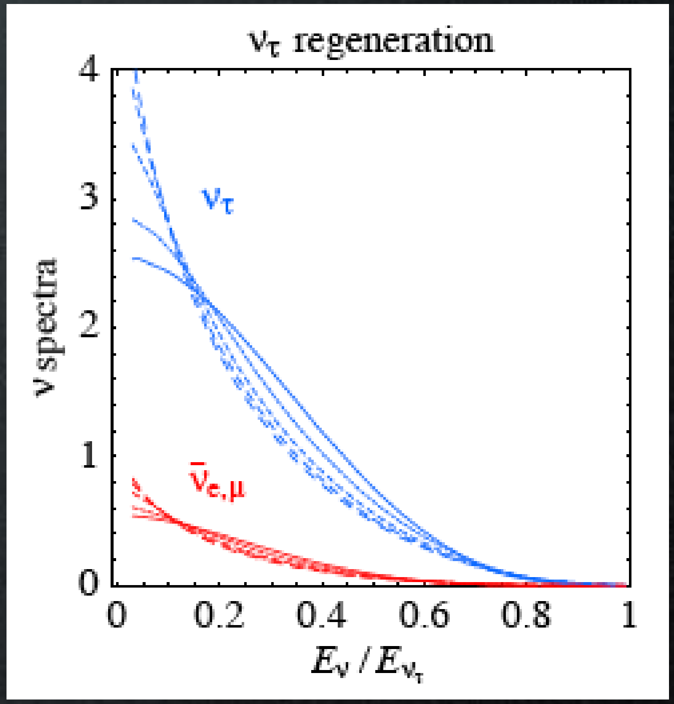
matter effect (MSW):

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

2. Propagation: CC absorption & tau

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



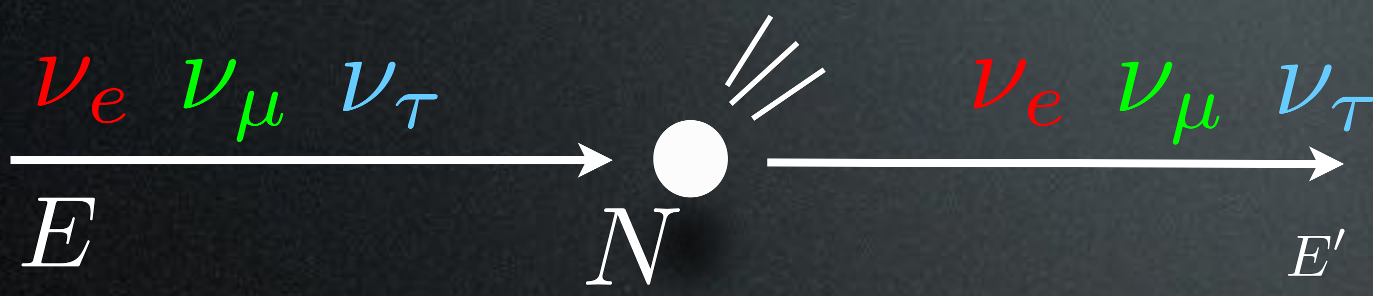


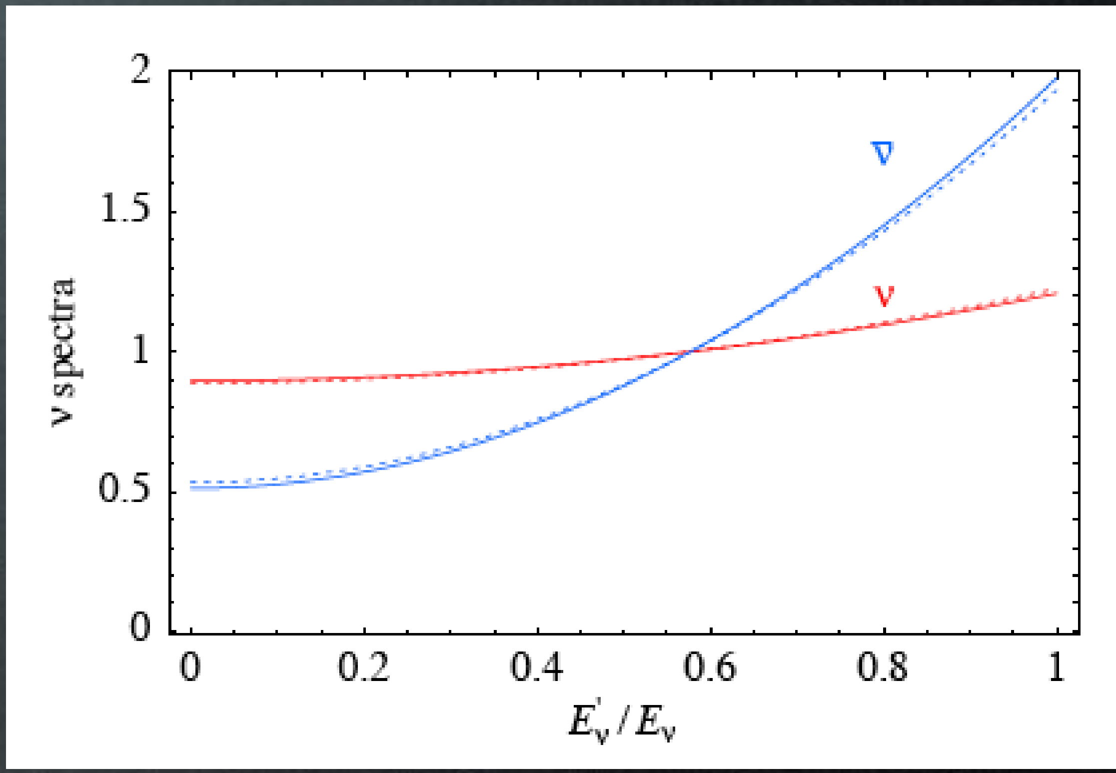
(re)generation

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

2. Propagation: NC scatterings

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





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

'Prompt' gamma rays

www.marcocirelli.net/PPPC4DMID.html

PPPC 4 DM ID - A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

We provide ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays.

Data and Results from 1012.4515 [hep-ph] (and 1009.0224 [hep-ph]), from 1312.6408 [hep-ph], 1412.5696 [astro-ph.HE], from 1505.01049 [hep-ph] and from 1511.08787 [hep-ph].

If you use the data provided on this site, please cite:
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection",
arXiv 1012.4515, JCAP 1103 (2011) 051.
Erratum: JCAP 1210 (2012) E01.

DMν : Neutrinos from the Sun:

DM annihilation rate in the Sun: *Mathematica* function GammaAnn.m, refer to the notebook Sample.nb for usage.

Neutrino energy spectra at production: *Mathematica* function dlNnudlxEW.m, refer to the notebook Sample.nb for usage.
[03 jun 2015] Warning: some bugs in these files have been brought to our attention, we are working to fix them. Sorry for the inconvenience.

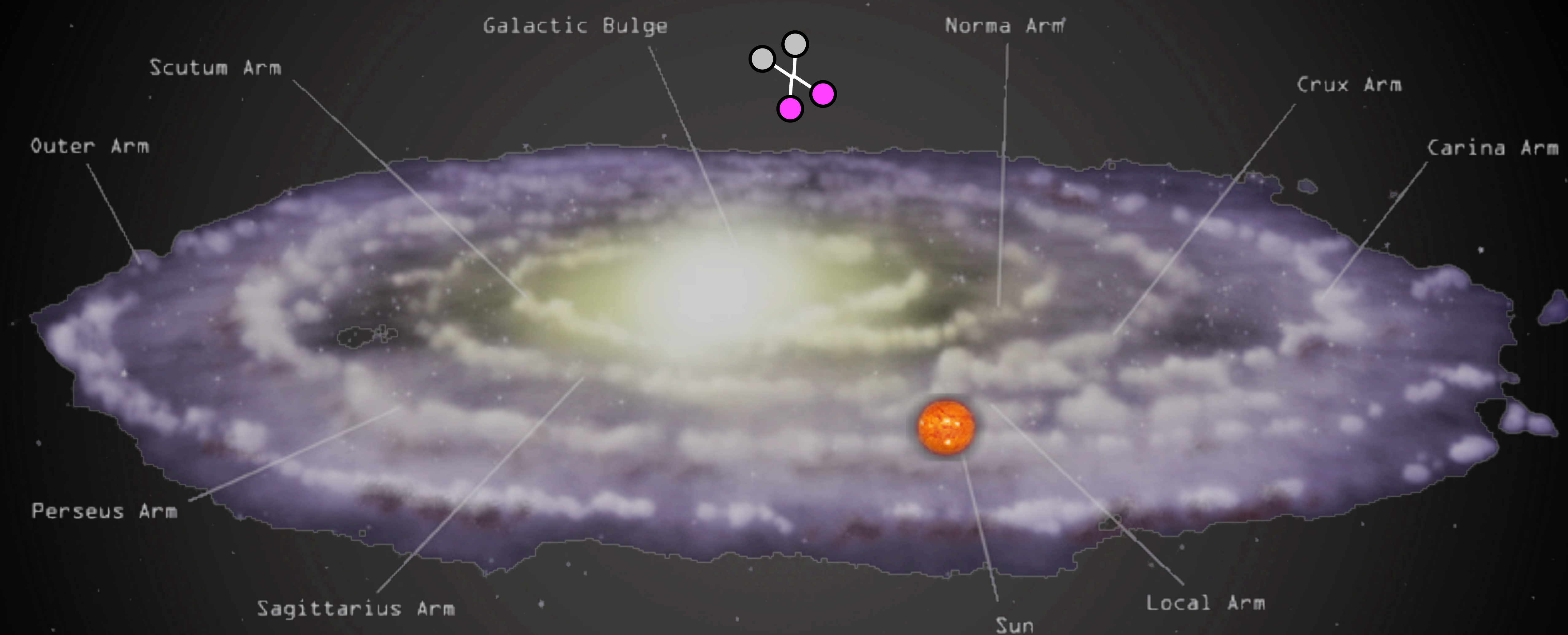
Neutrino energy spectra at detection: *Mathematica* function dlNnudlxEarth.m, refer to the notebook Sample.nb for usage.
[03 jun 2015] Warning: some bugs in these files have been brought to our attention, we are working to fix them. Sorry for the inconvenience.

DM detection

- direct detection
- production at colliders
- indirect
  - γ from annihil in galactic center or halo and from synchrotron emission
    Fermi, HESS, radio telescopes
  - e^+ from annihil in galactic halo or center
    PAMELA, ATIC, Fermi
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{d}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in galactic center

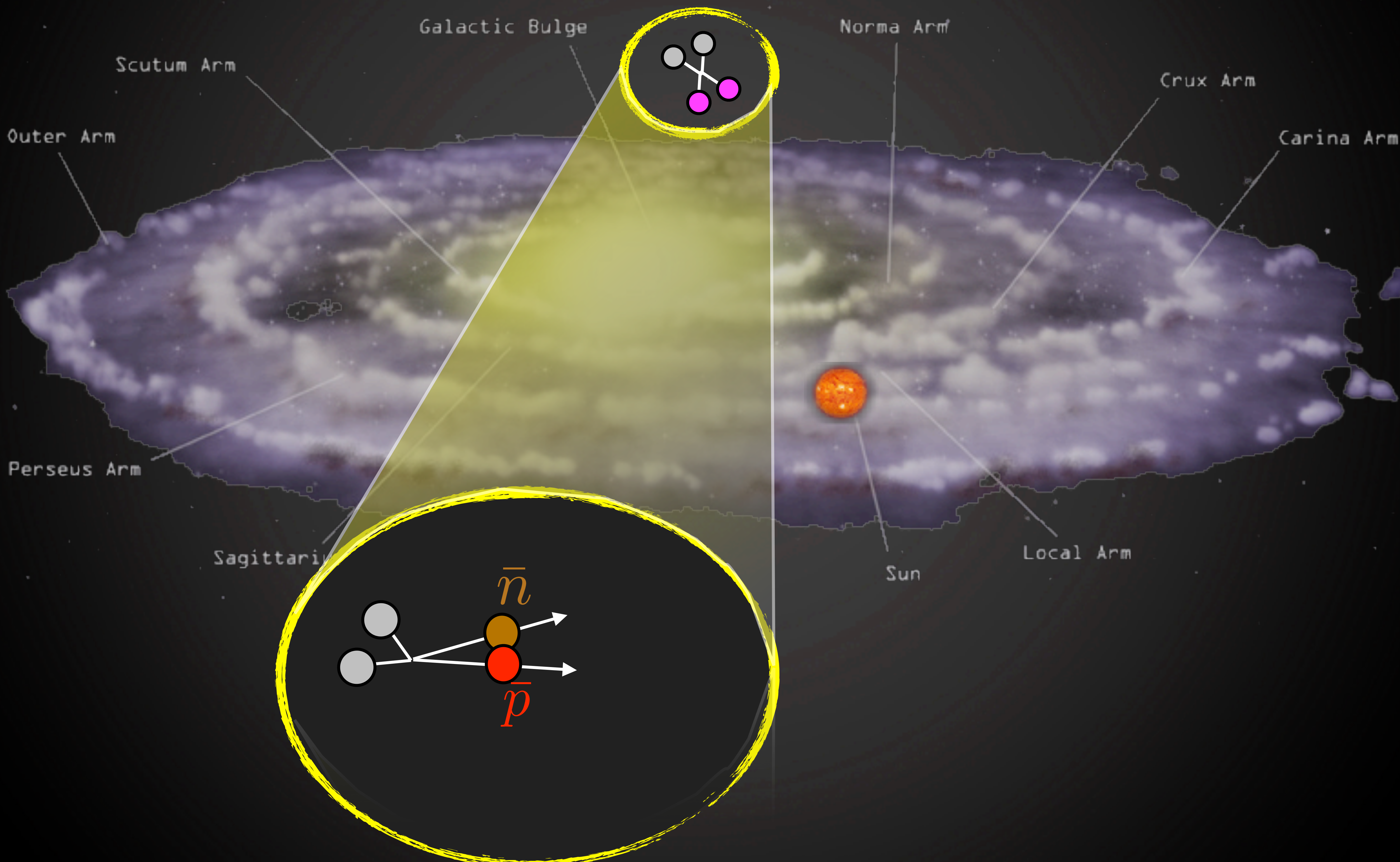
Indirect Detection: basics

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



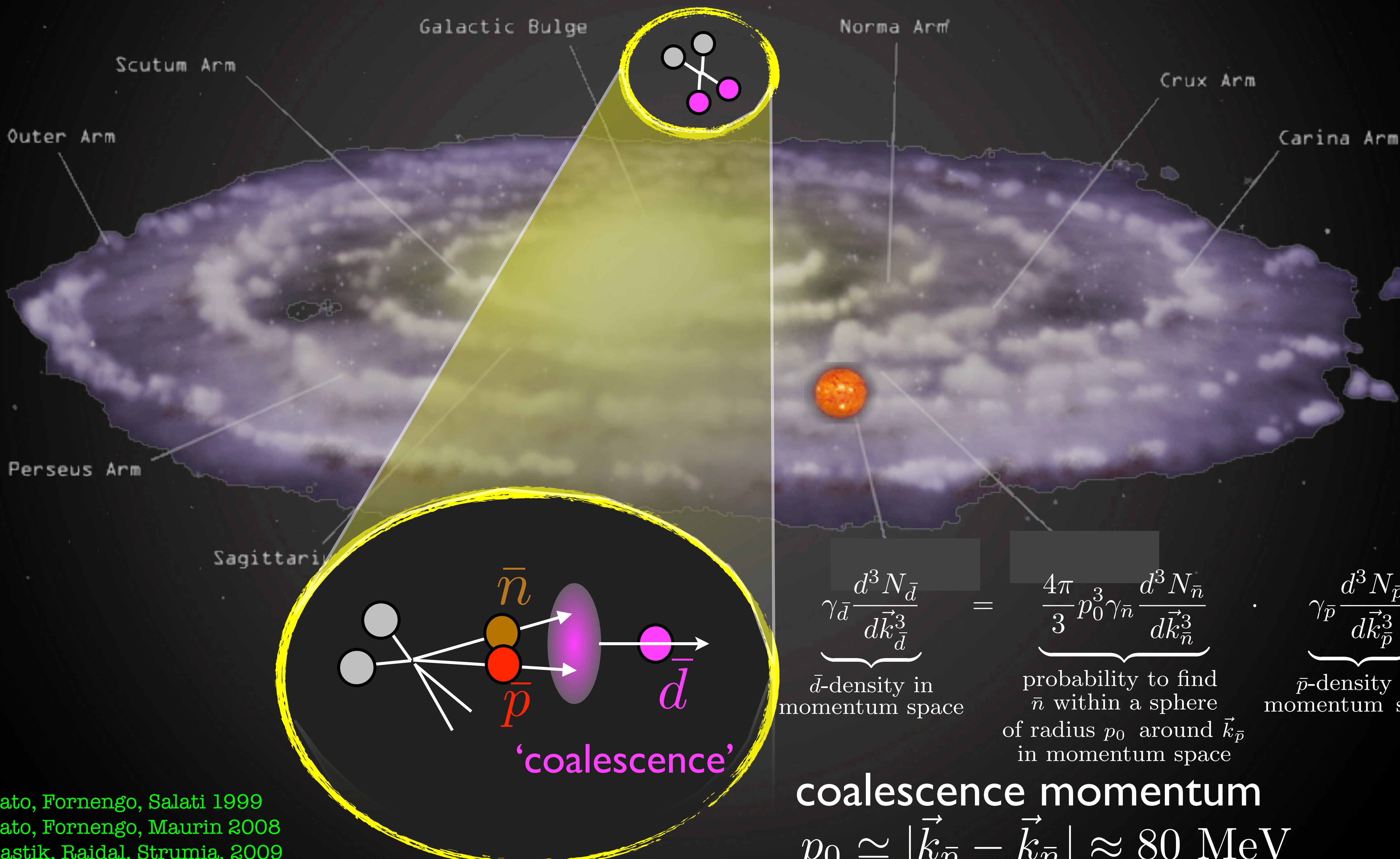
Indirect Detection: basics

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



Indirect Detection: basics

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



$$\gamma_{\bar{d}} \frac{d^3 N_{\bar{d}}}{d\vec{k}^3_{\bar{d}}} = \frac{4\pi}{3} p_0^3 \gamma_{\bar{n}} \frac{d^3 N_{\bar{n}}}{d\vec{k}^3_{\bar{n}}} \cdot \gamma_{\bar{p}} \frac{d^3 N_{\bar{p}}}{d\vec{k}^3_{\bar{p}}}$$

$\bar{d}$-density in momentum space

probability to find $\bar{n}$ within a sphere of radius p_0 around $\vec{k}_{\bar{p}}$ in momentum space

$\bar{p}$-density in momentum space

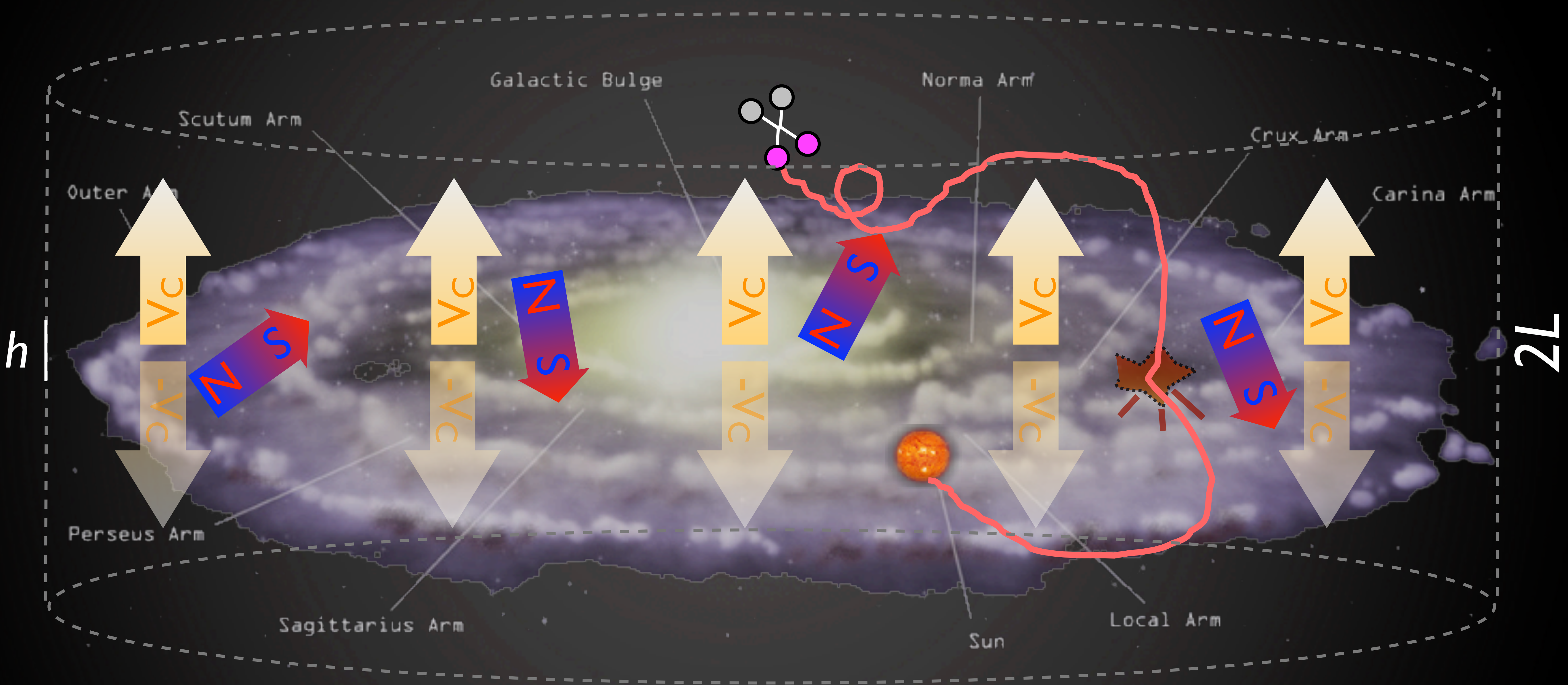
coalescence momentum

$$p_0 \simeq |\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}| \approx 80 \text{ MeV}$$

Donato, Fornengo, Salati 1999
Donato, Fornengo, Maurin 2008
Kadastik, Raidal, Strumia, 2009

Indirect Detection: basics

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



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

diffusion energy loss convective wind source spallations

Advertisement

You need a quick **reference** for formulæ and methods to compute indirect detection signals?

You want to compute all **signatures** of your DM model in positrons, electrons, neutrinos, gamma rays...
but you don't want to mess around with astrophysics?

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1012.4515 [hep-ph]

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Propagation functions for electrons and positrons everywhere in the Galaxy:

Energy loss coefficient function ***b[E, r, z]*** for electrons and positrons in the Galaxy: *Mathematica* function b.m, refer to the notebook Sample.nb for usage.

Annihilation	Decay
Positrons: The file ElectronHaloFunctGalaxyAnn.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy. The notebook Sample.nb shows how to load and use it.	Positrons: The file ElectronHaloFunctGalaxyDec.m provides the halo functions $I(x,E_s,r,z)$ at a point (r,z) in the Galaxy The notebook Sample.nb shows how to load and use it.

Propagation functions for charged cosmic rays at the location of the Earth:

Annihilation	Decay
Positrons: The file ElectronHaloFunctEarthAnn.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth. The notebook Sample.nb shows how to load and use it. Table of fit coefficients for the reduced halo function $I(\lambda)$ (in the approximated formalism - see paper).	Positrons: The file ElectronHaloFunctEarthDec.m provides the halo functions $I(x,E_s,r_{Earth})$ at the location of the Earth. The notebook Sample.nb shows how to load and use it. Table of fit coefficients for the reduced halo function $I(\lambda)$ (in the approximated formalism - see paper).
Antiprotons: Table of fit coefficients for the propagation function R(T).	Antiprotons: Table of fit coefficients for the propagation function R(T).
Antideuterons: Table of fit coefficients for the propagation function R(T).	Antideuterons: Table of fit coefficients for the propagation function R(T).

Fluxes of charged cosmic rays at the Earth, after propagation:

Annihilation	Decay
Positrons: *Mathematica* function: the file ElectronFluxAnn.m provides the	Positrons: *Mathematica* function: the file ElectronFluxDec.m provides the

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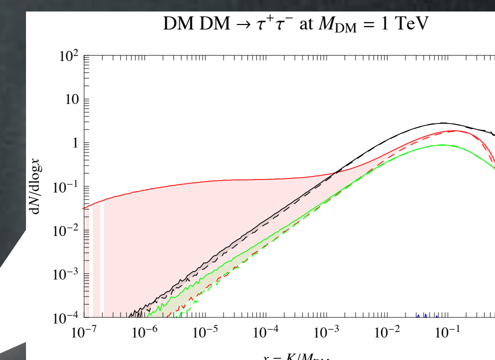
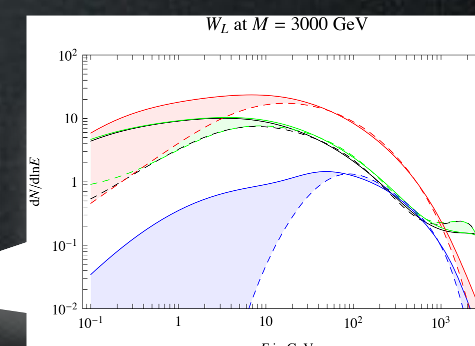
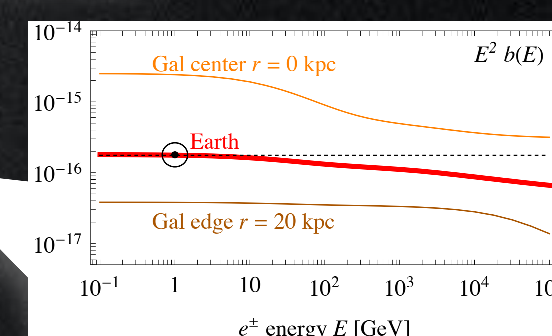


- ✓ compare different MCs



- ✓ include EW corrections

Ciafaloni, Riotto et al., 1009.0224



- ✓ improved $e^{\pm}$ propagation
- ✓ improved ICS γ-ray computation

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