31 March 2021

3rd Dark Ghosts workshop, Granada

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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Cirelli, Koechler et al. - *Work in progress*

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Cirelli, Koechler et al. - *Work in progress*

Outline

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1. arouse your interest in DM ID

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1. arouse your interest in DM ID

2. talk to you about the
gory details of DM ID
for 2 hours...

Outline

1. arouse your interest in DM ID

2. talk to you about the
gory details of DM ID
for 20 minutes...

Outline

1. arouse your interest in DM ID

2. talk to you about the gory details of DM ID for 20 minutes...

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, ANTARES, Icecube, Km3Net

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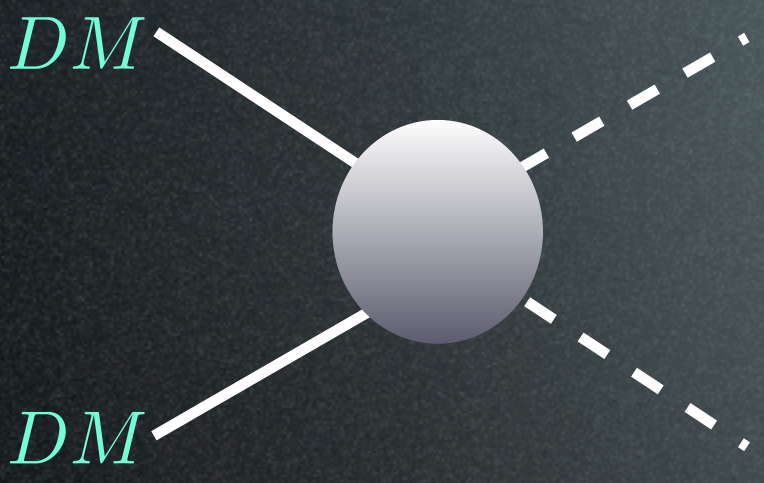
Annihilations in the Galaxy

Fluxes at production



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

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

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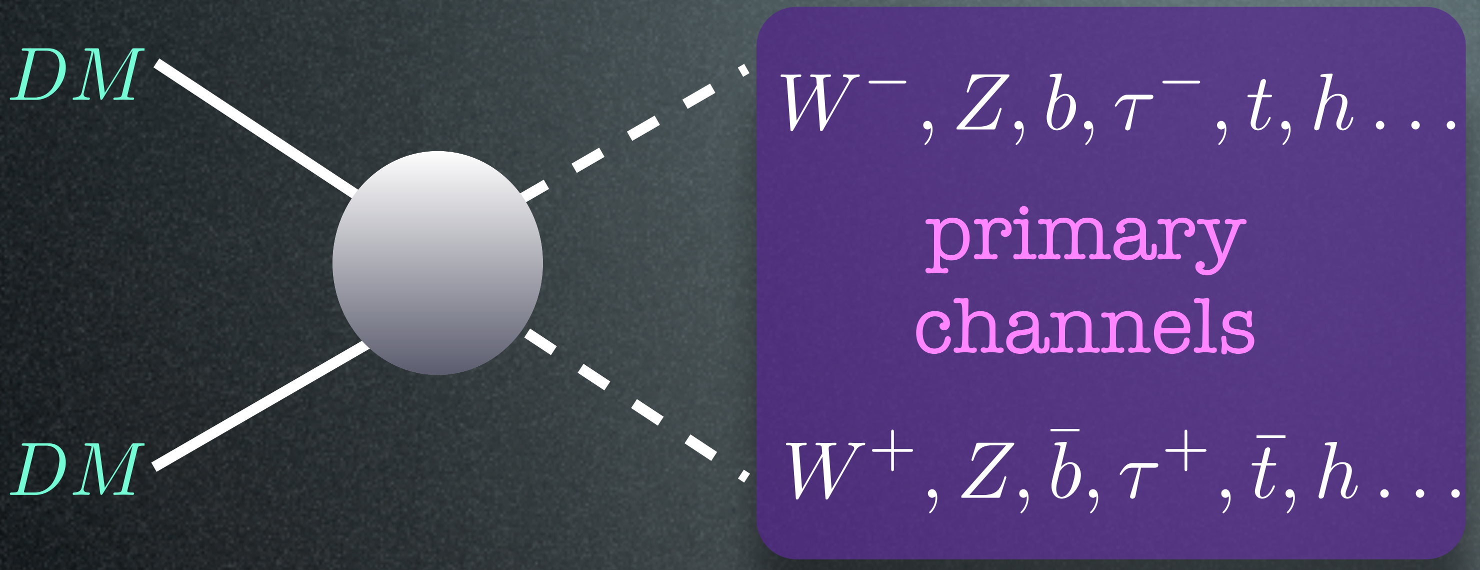

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primary channels

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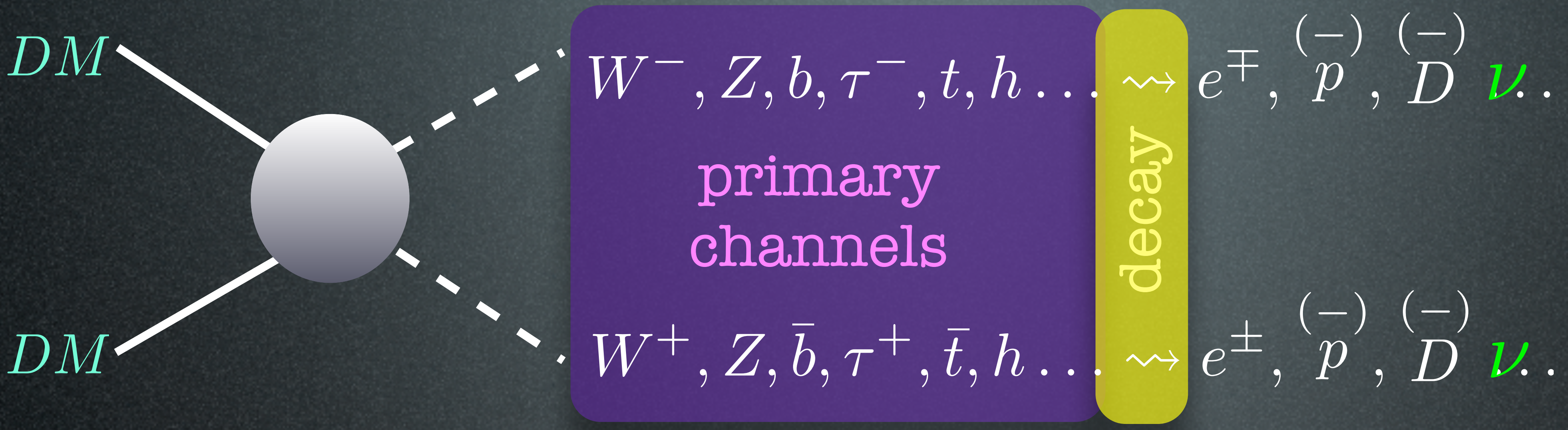


DM

DM

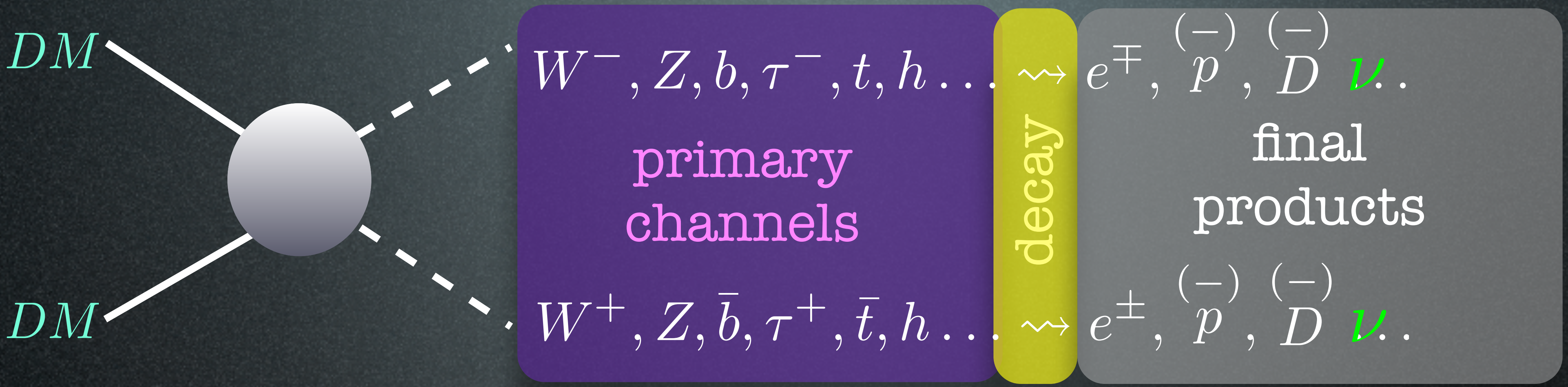
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D}\ \nu \ldots$

primary channels

decay

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

Fluxes at production



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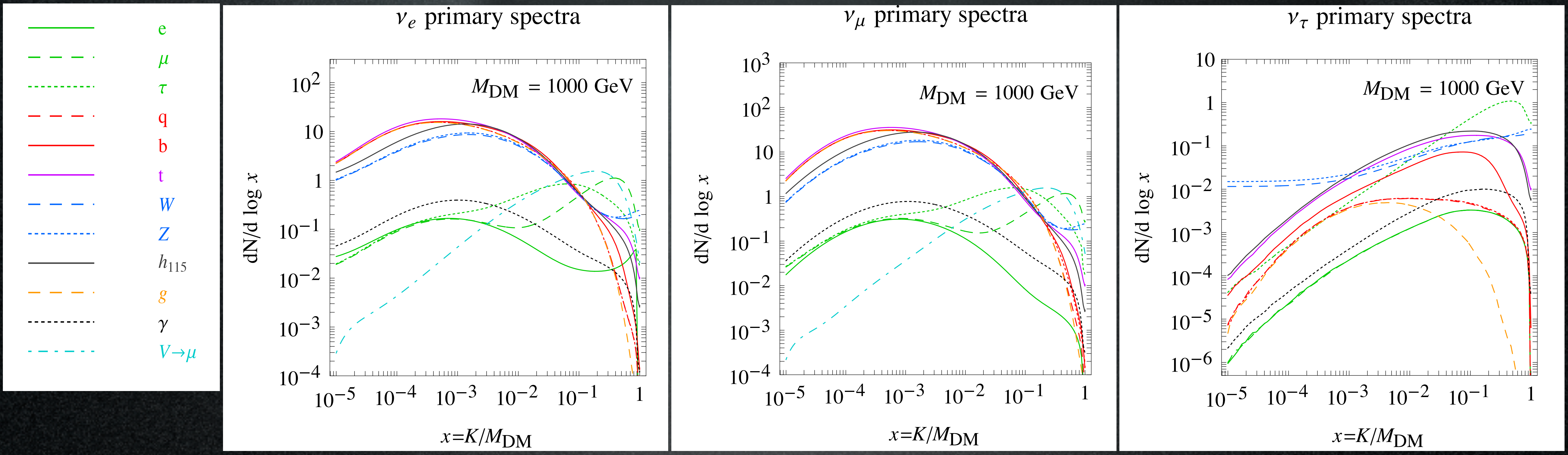
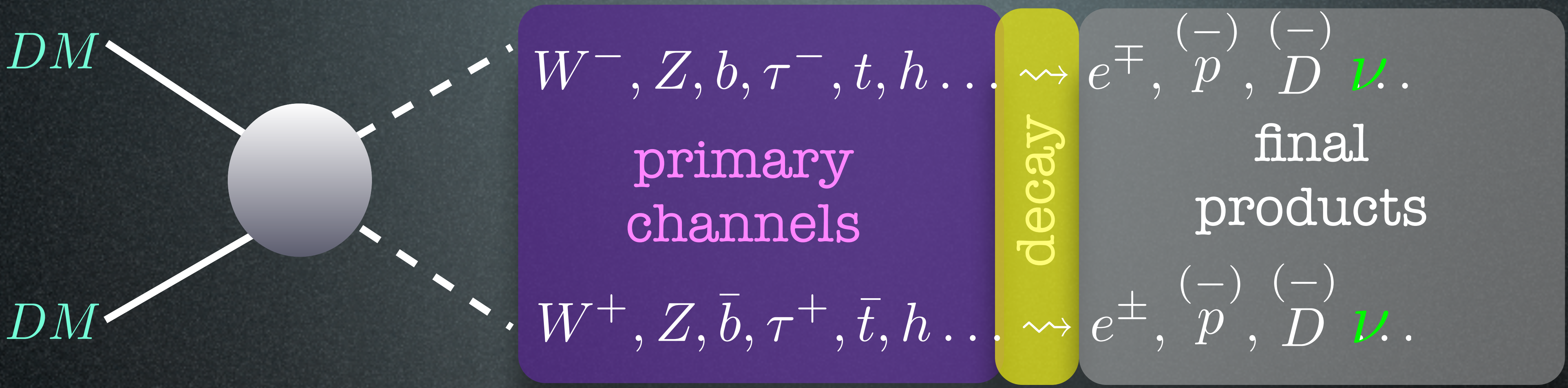


Fluxes at production



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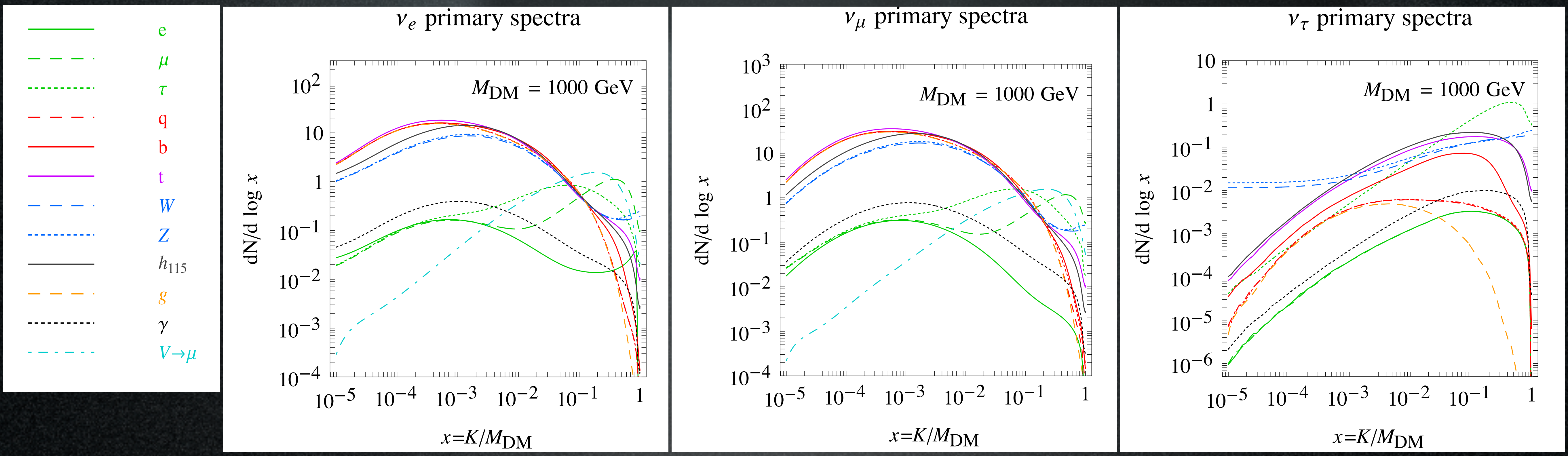


So what are the particle physics parameters?

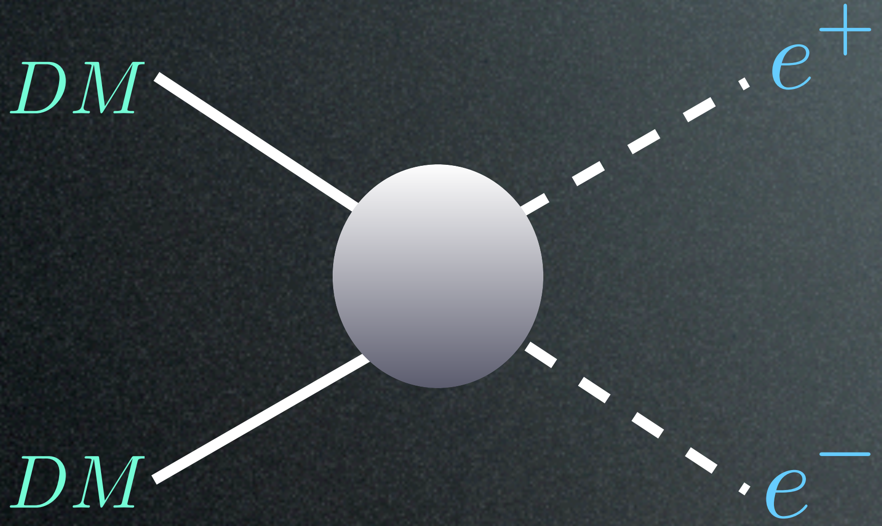
1. Dark Matter mass
2. primary channel(s)
3. annihilation cross section σ_{ann}

Fluxes at production

ElectroWeak corrections are important!

Fluxes at production

ElectroWeak corrections are important!



Fluxes at production

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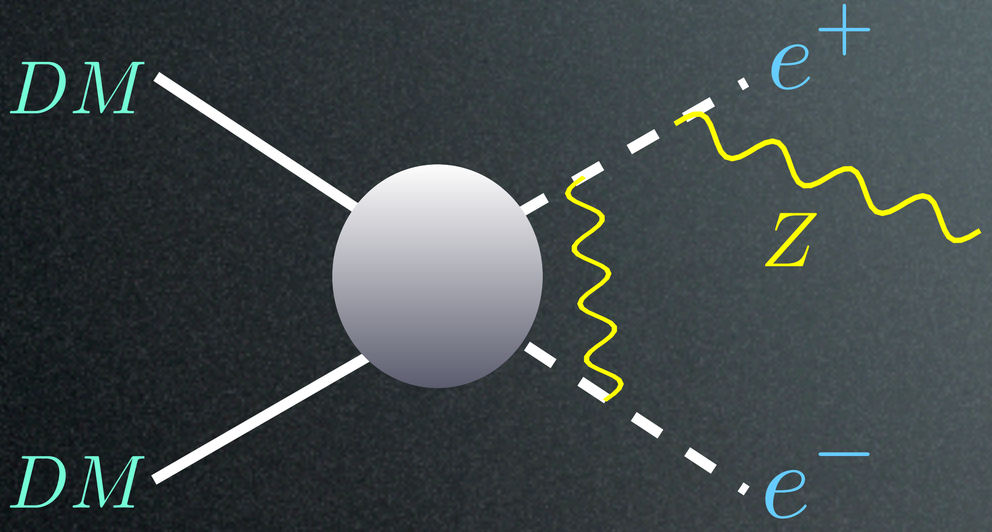

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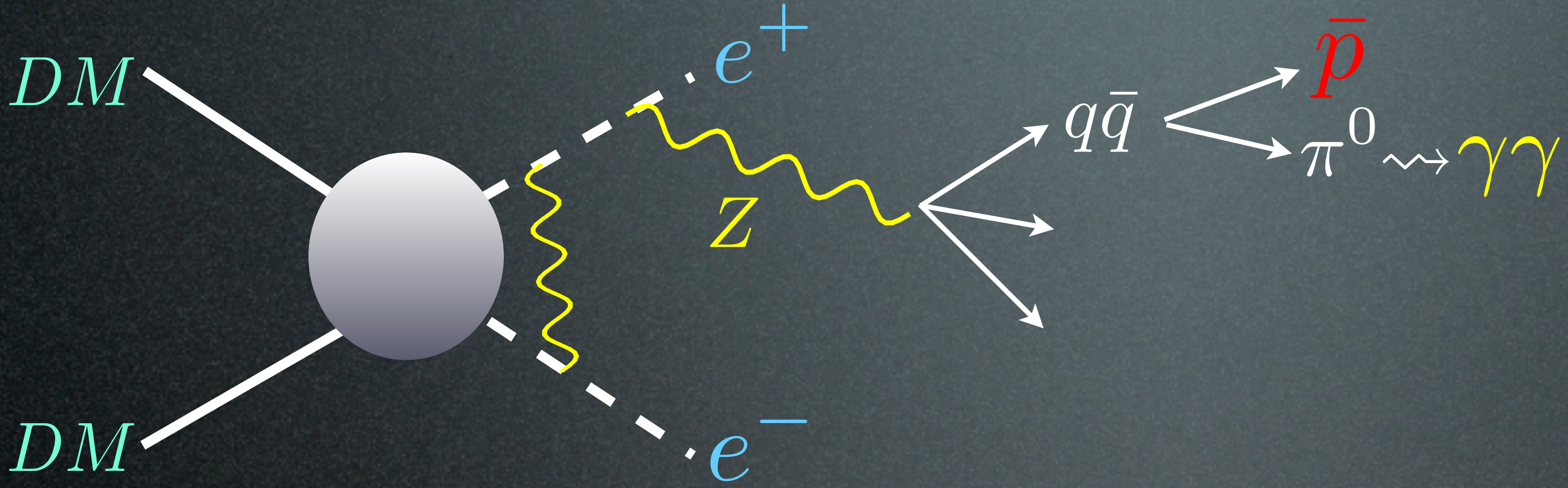

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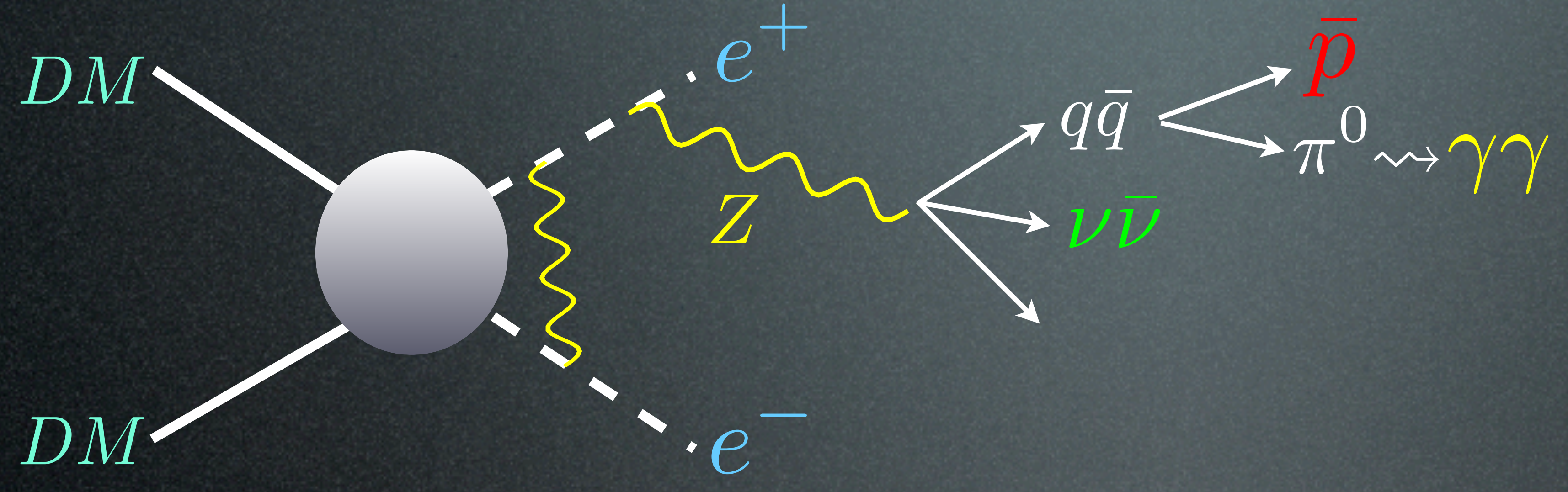

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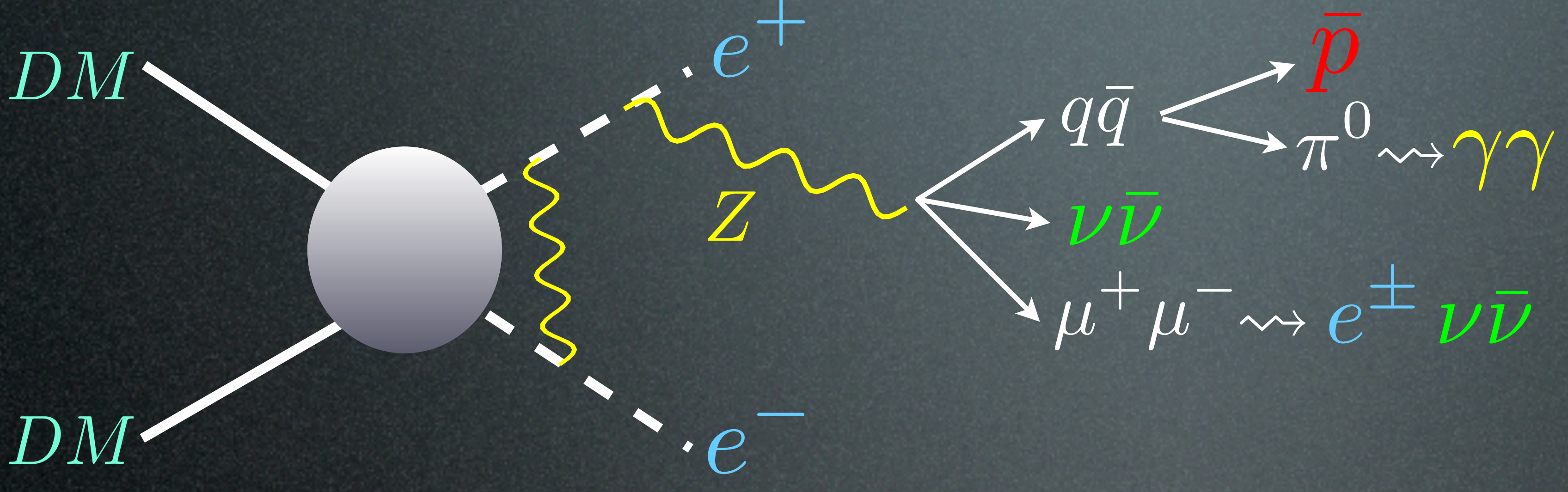

Ciafaloni et al., JCAP 1103 (2011)
See also: Serpico et al., Bell et al.

Fluxes at production

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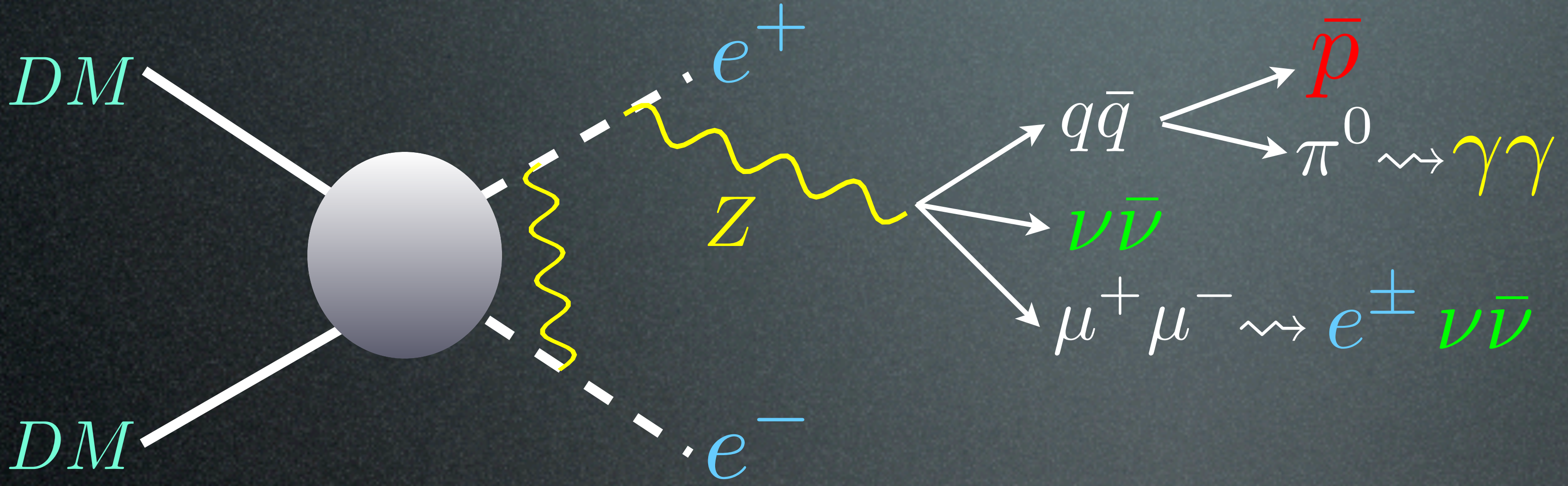

$$\frac{\Delta\sigma}{\sigma} \propto \alpha_{\rm weak} \ln^2\left(\frac{M_{\rm DM}^2}{M_{\rm Z}^2}\right)$$

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

Fluxes at production

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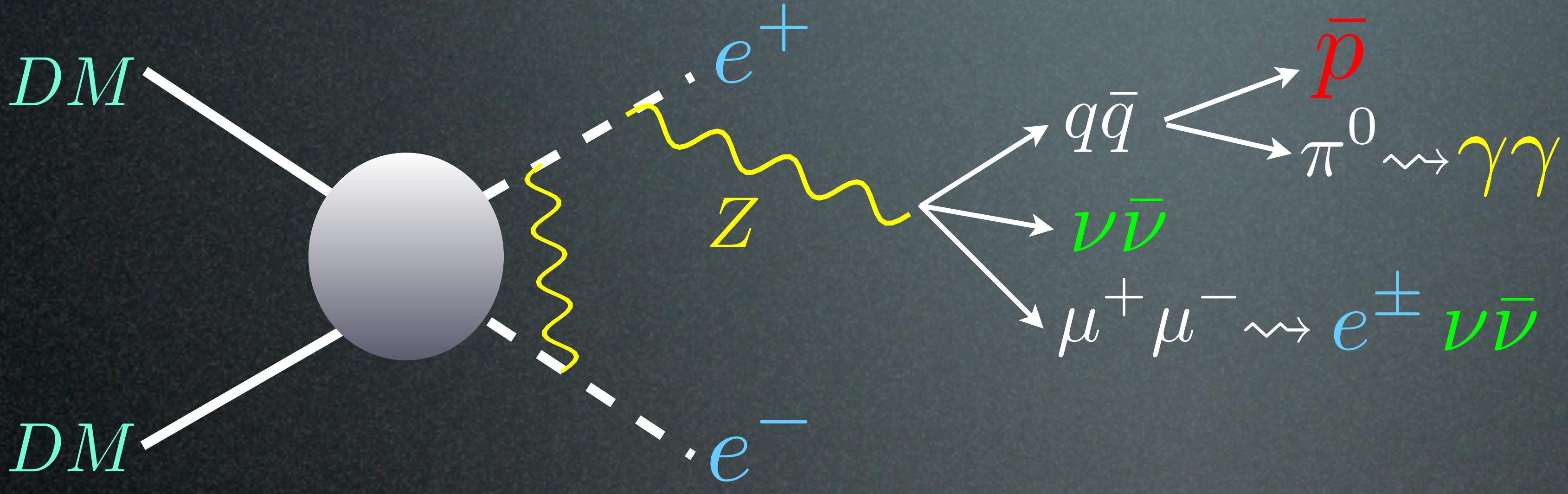

$$Z \to q\bar{q} \to \bar{p},\ \pi^0 \rightsquigarrow \gamma\gamma$$

$$Z \to \nu\bar{\nu}$$

$$Z \to \mu^+\mu^- \rightsquigarrow e^\pm\, \nu\bar{\nu}$$

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

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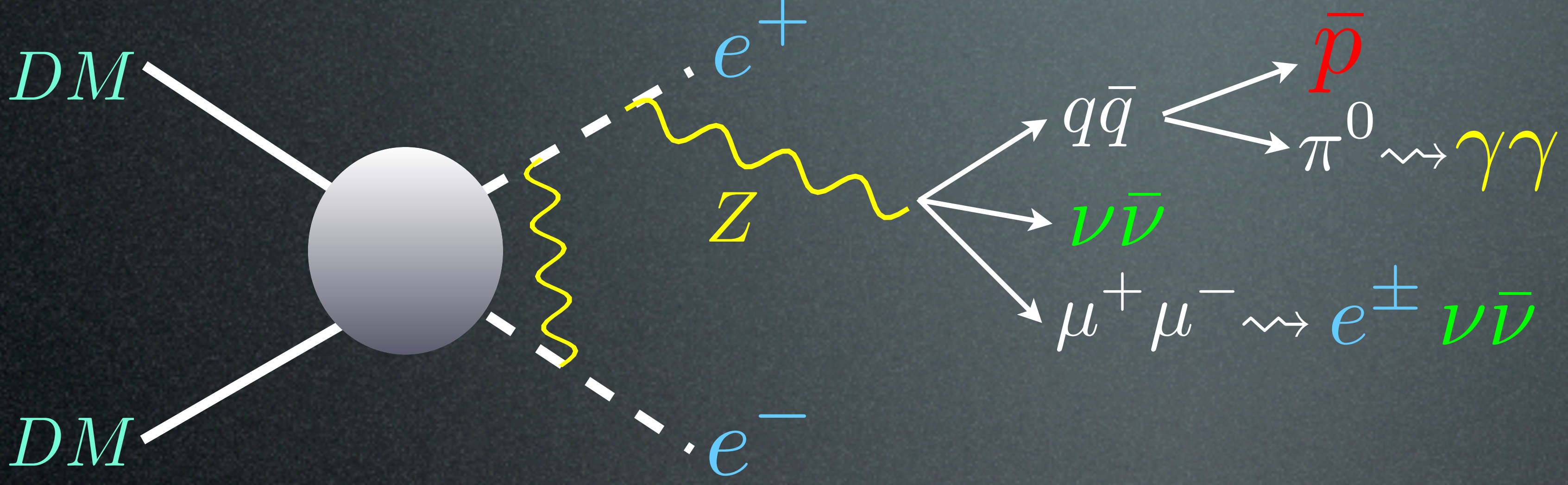

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Ciafaloni et al., JCAP 1103 (2011)
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Fluxes at production

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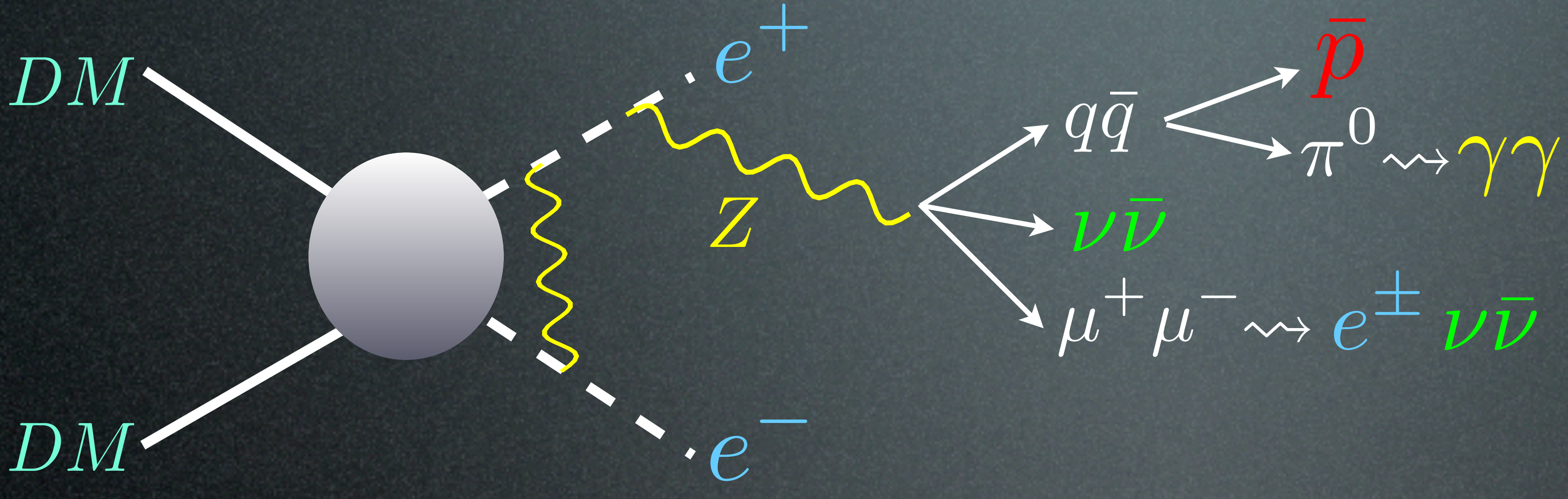

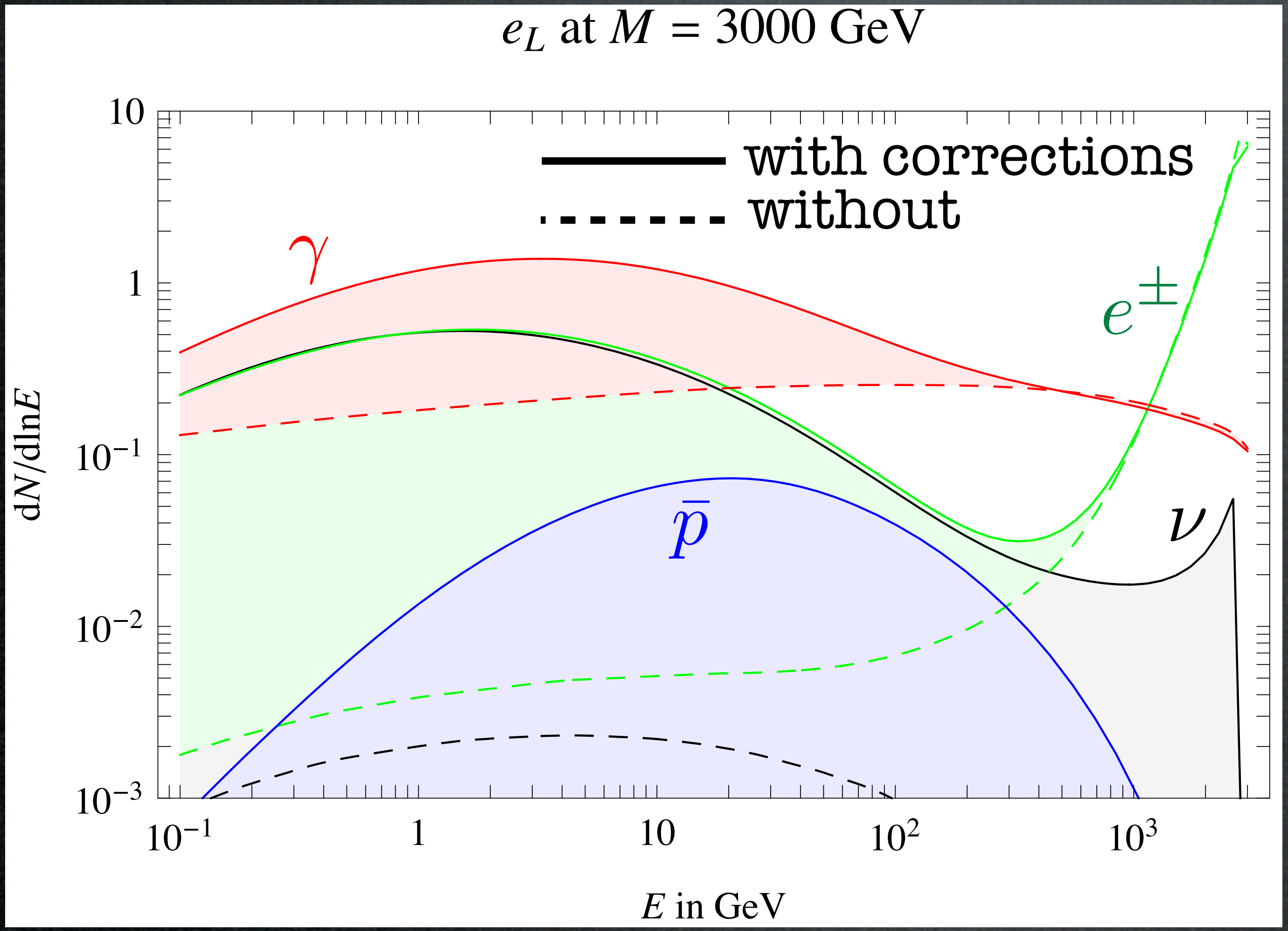

- unexpected species
- different spectra

  (especially at low energy, but not only)

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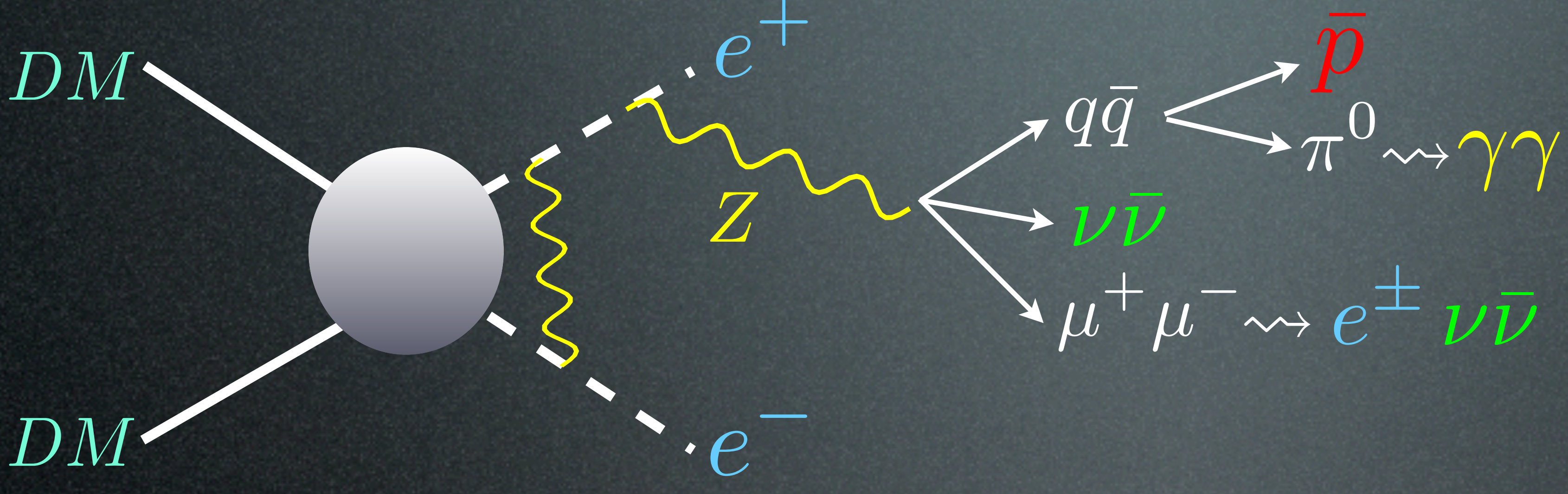
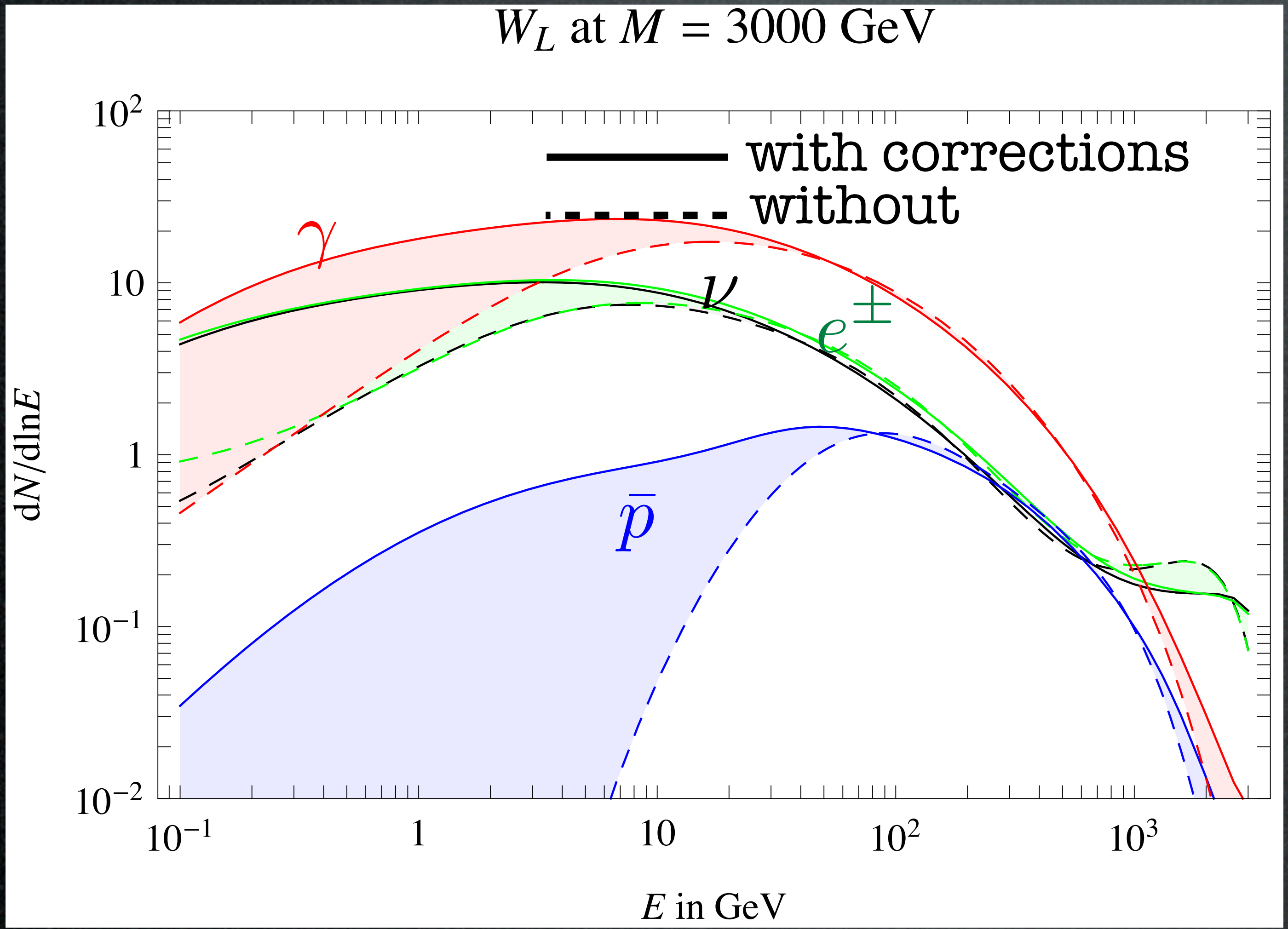




- unexpected species
- different spectra

(especially at low energy, but not only)

Extension at large DM mass:
Bauer, Rodd, Webber 2007.15001

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

Propagation

Flavor oscillations in vacuum
over astrophysical distances

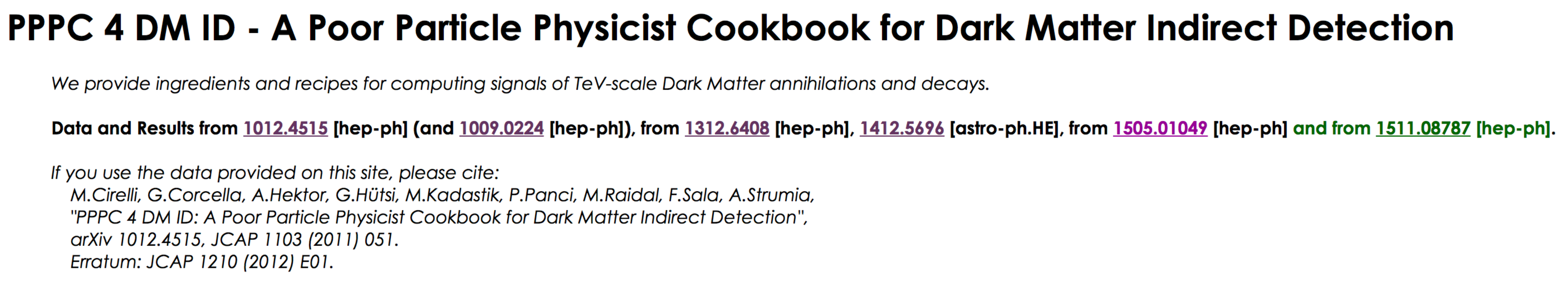
Averaged (under $\Delta m^2 E/L \gg 1$) with

$$P_{\ell\ell'} = \sum_{i=1}^{3} |V_{\ell i} V_{\ell' i}|^2 \approx \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

Pure $\nu_e \rightarrow (0.6\nu_e : 0.2\nu_\mu : 0.2\nu_\tau)$
Pure $\nu_\mu \rightarrow (0.2\nu_e : 0.4\nu_\mu : 0.4\nu_\tau)$
Pure $\nu_\tau \rightarrow (0.2\nu_e : 0.4\nu_\mu : 0.4\nu_\tau)$
Democratic $(1\nu_e : 1\nu_\mu : 1\nu_\tau)$
$\pi^{\pm}$ decay $\rightarrow \sim (1\nu_e : 1\nu_\mu : 1\nu_\tau)$

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",
arXiv 1012.4515, JCAP 1103 (2011) 051.
Erratum: JCAP 1210 (2012) E01.

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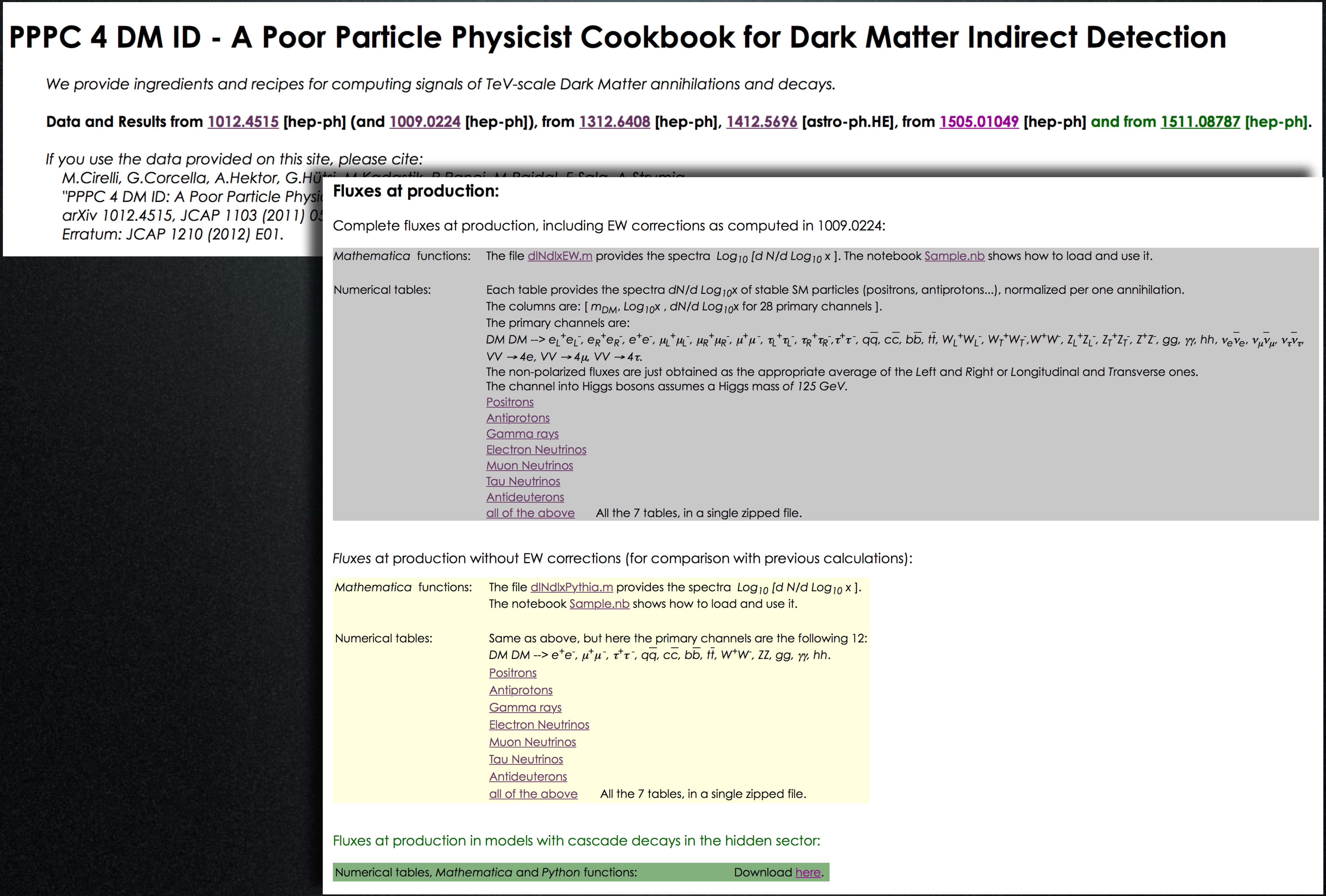

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"PPPC 4 DM ID: A Poor Particle Physi
arXiv 1012.4515, JCAP 1103 (2011) 0
Erratum: JCAP 1210 (2012) E01.

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 --> $e_L^+e_L^-$, $e_R^+e_R^-$, 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, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, $VV \rightarrow 4e$, $VV \rightarrow 4\mu$, $VV \rightarrow 4\tau$. The non-polarized fluxes are just obtained as the appropriate average of the *L*eft and *R*ight or *L*ongitudinal and *T*ransverse 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.

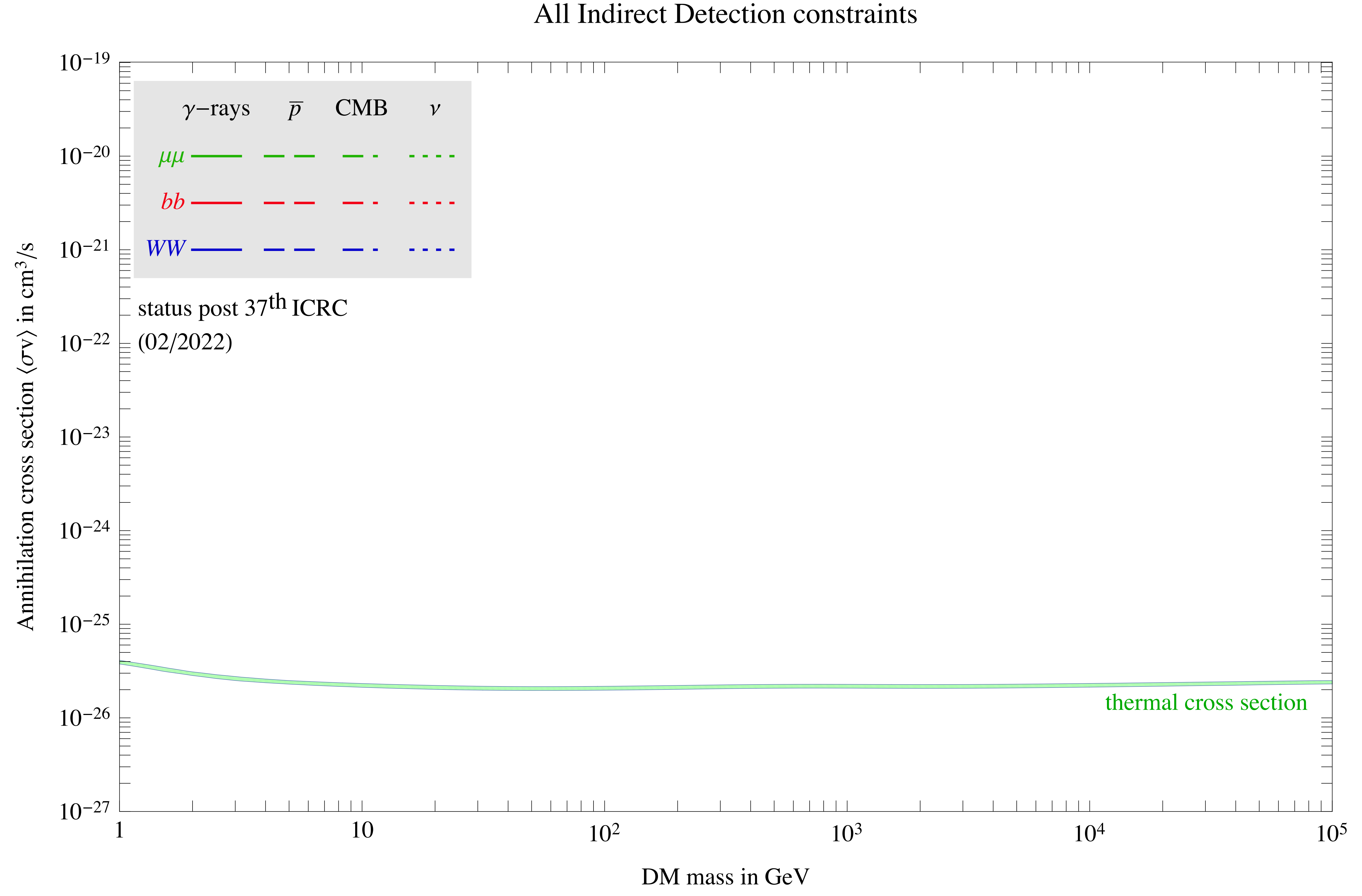
Fluxes at production without EW corrections (for comparison with previous calculations):

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 --> 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.

Bounds on DM annihilations



updated from M. Cirelli 1511.02031; M. Cirelli, A. Strumia, J. Zupan to appear

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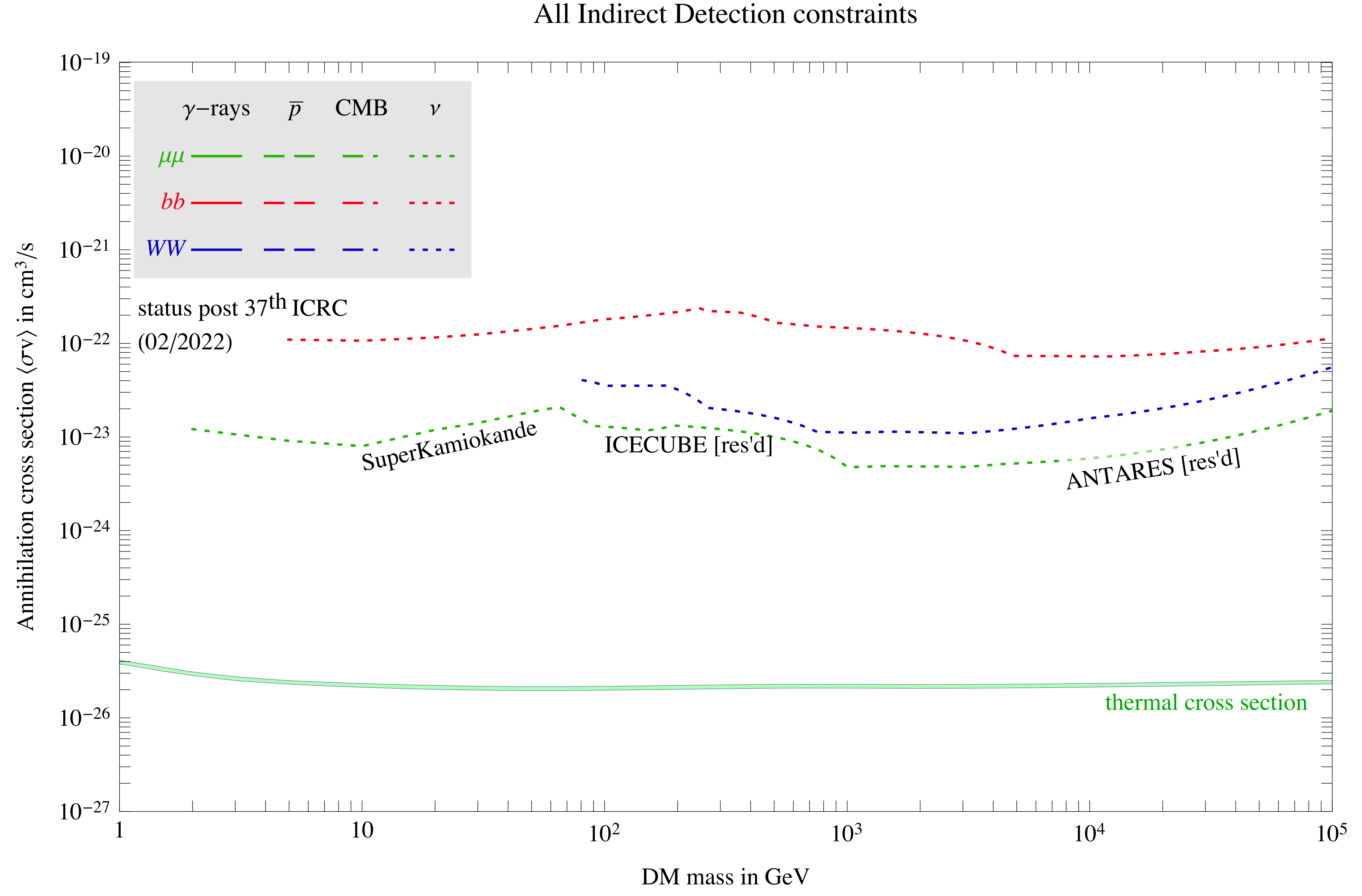

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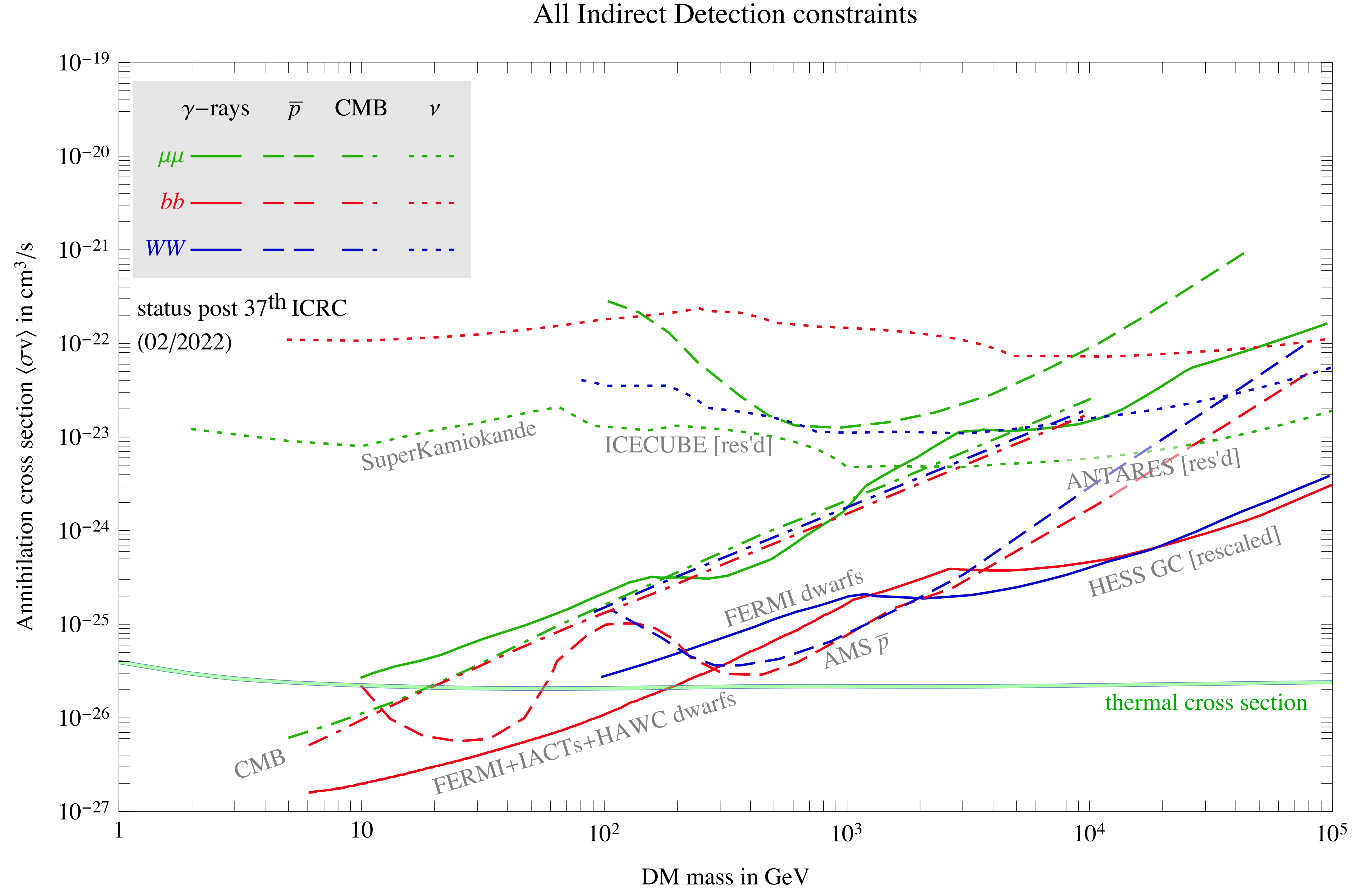
Comparing all bounds



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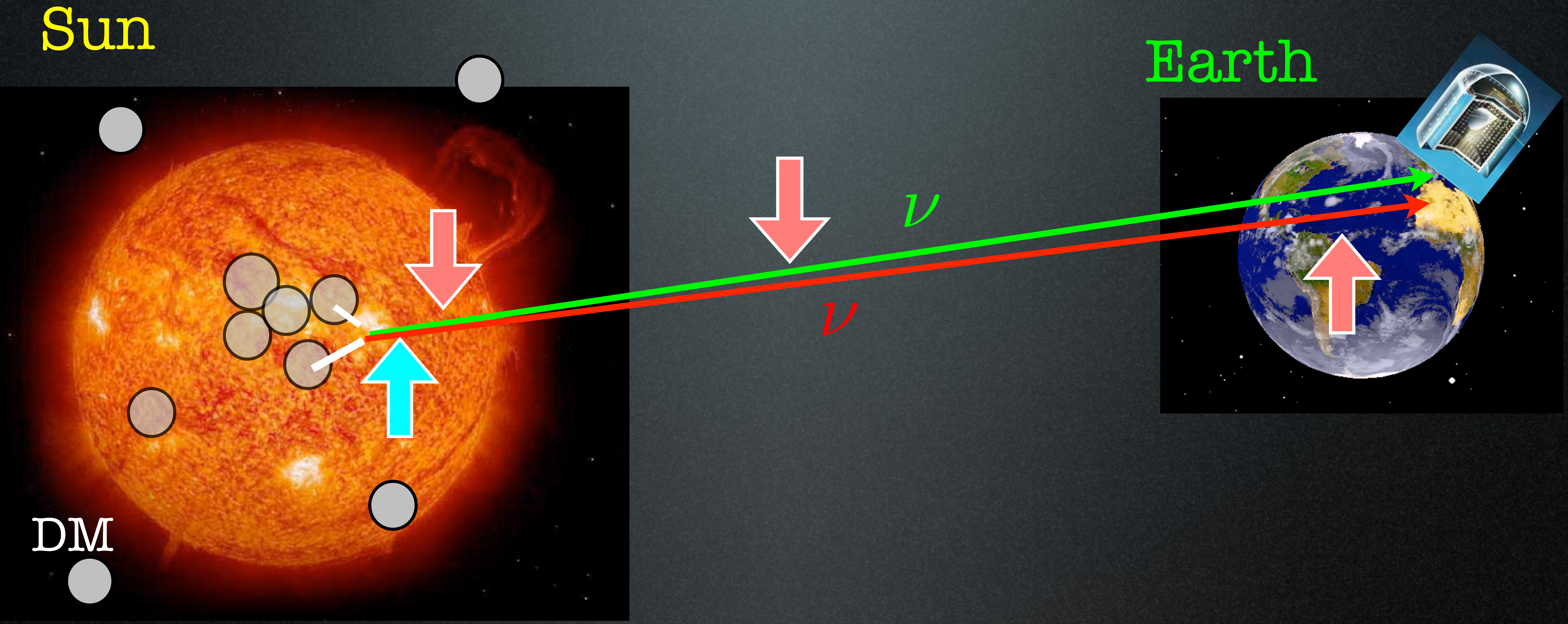
Annihilations in the Sun

ID with neutrinos

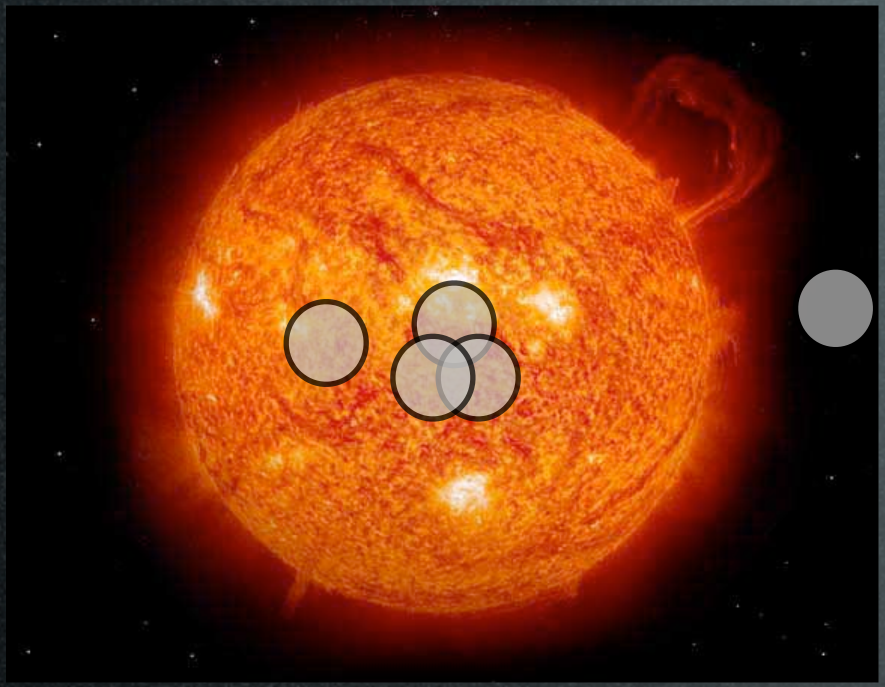
ν from DM annihilations in the Sun



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

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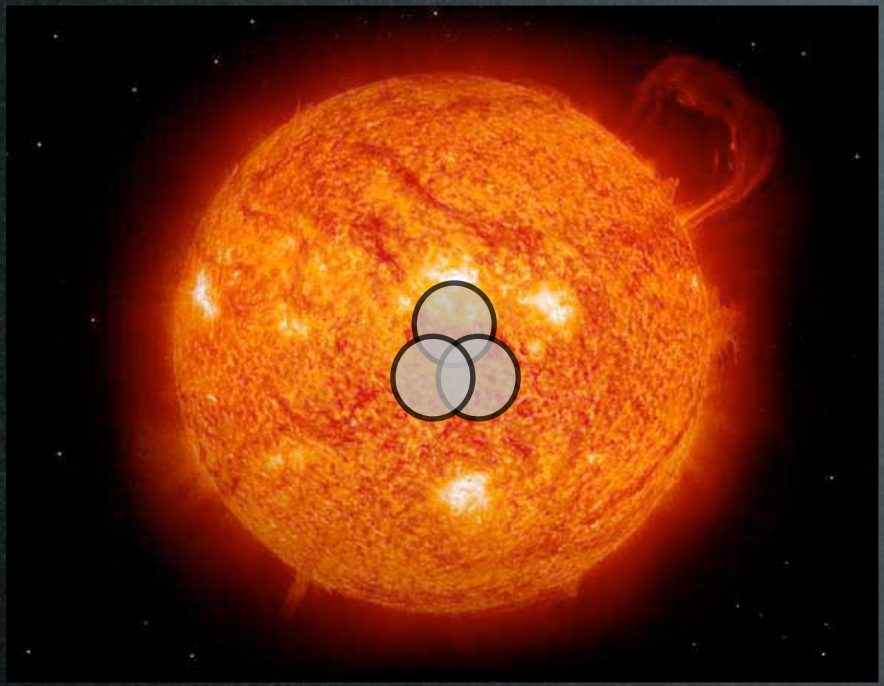

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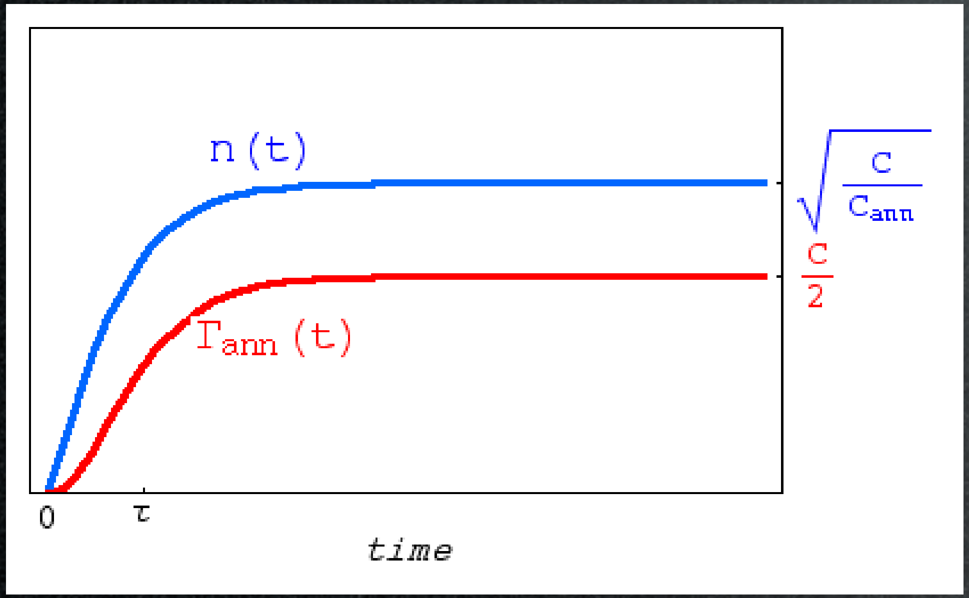
equilibrium attained:



$$\dot{n} = \overset{\sigma_N}{\Gamma_{\rm capt}} - \overset{\langle \sigma_{\rm ann} v \rangle}{C_{\rm ann}}\, n^2$$

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

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

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

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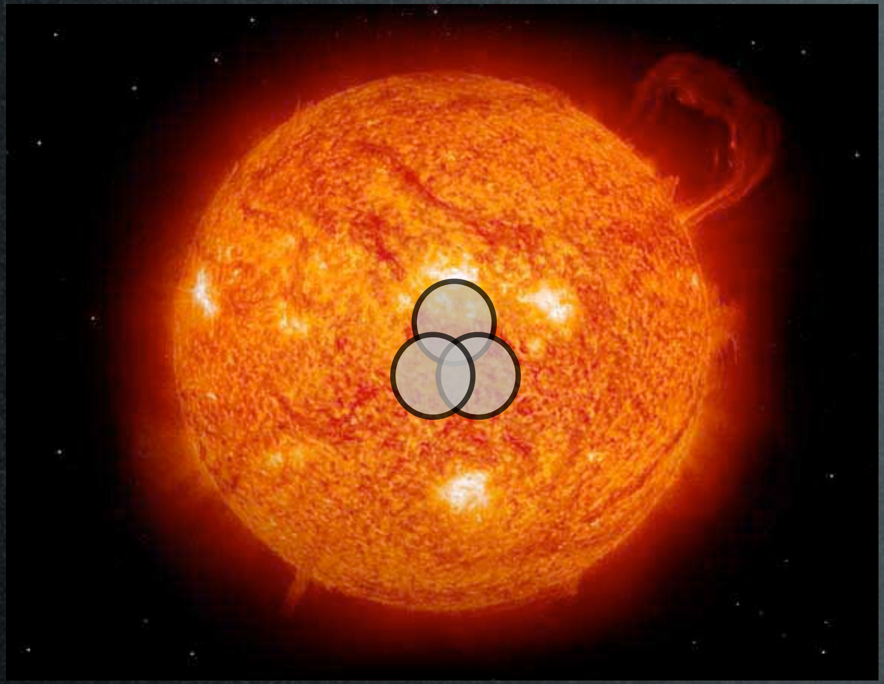

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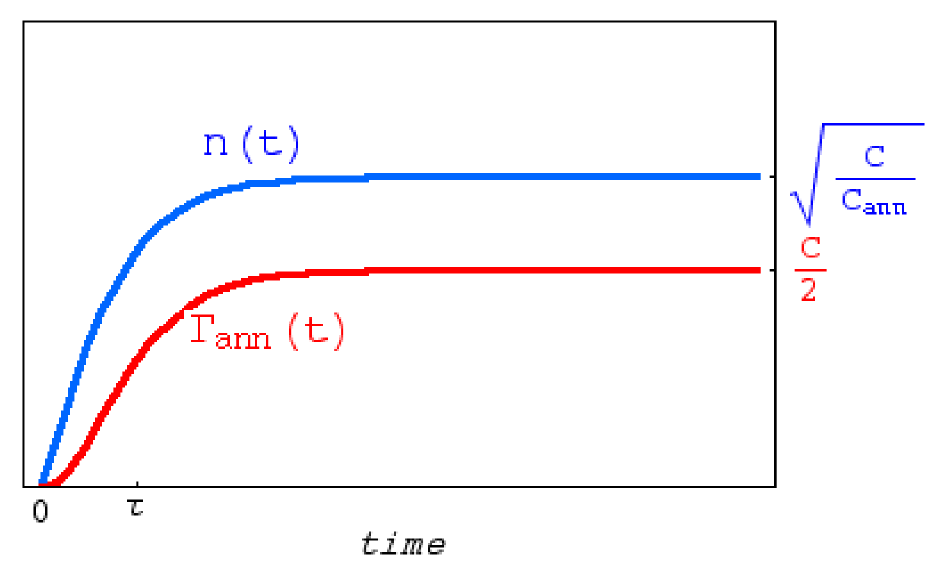

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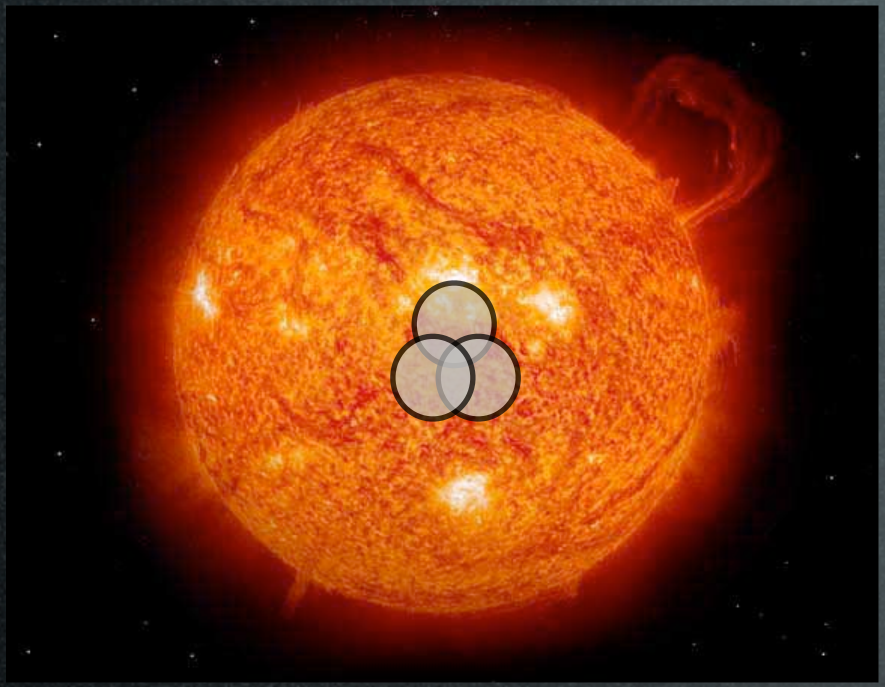
The main physical parameter is: σ_N (DM-nucleon scattering cross section)

1. Capture & annihilation



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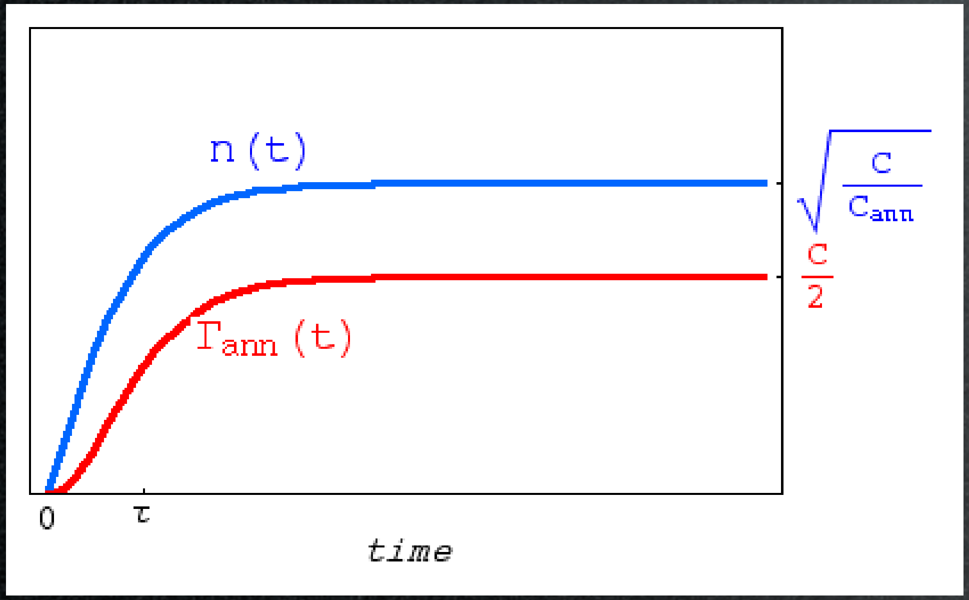
$$v_{{\rm esc},\oplus} \simeq 12\ {\rm km/s}$$

equilibrium attained:



$$\dot{n} = \overset{\sigma_N}{\Gamma_{\rm capt}} - \overset{\langle \sigma_{\rm ann} v\rangle}{C_{\rm ann}}\, n^2$$

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

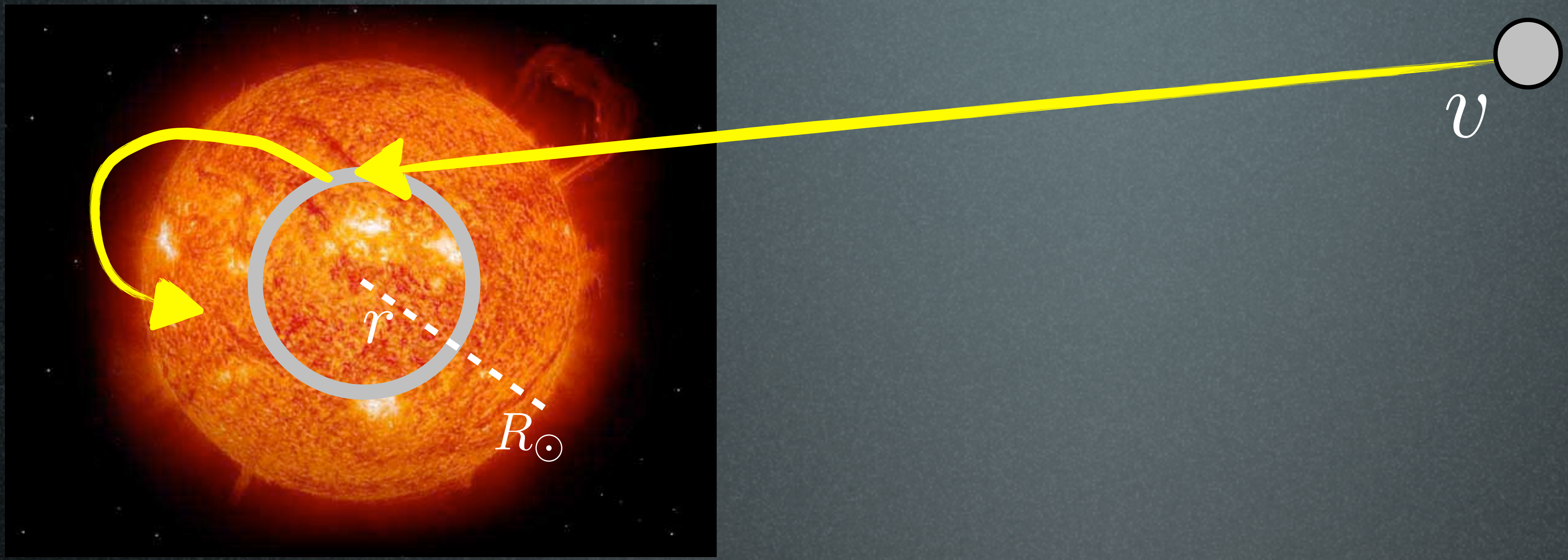
$$n(t) = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}}\, \tanh\left(\frac{t}{\tau}\right)$$

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

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

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

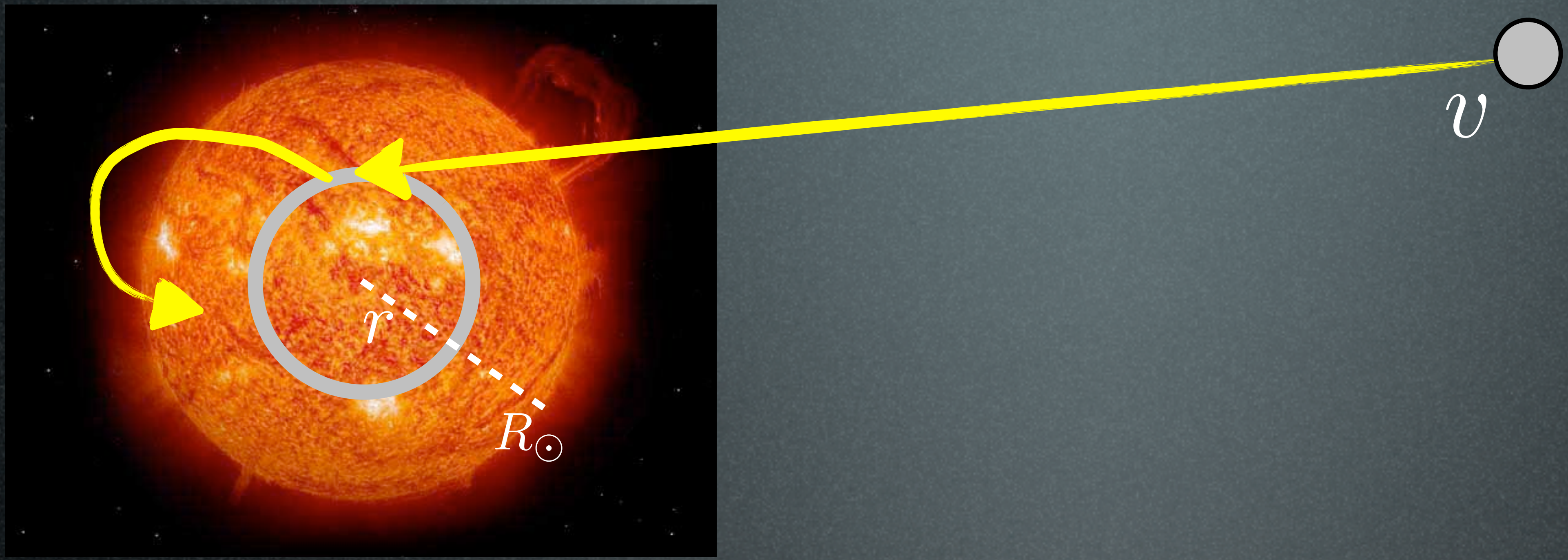
1. Capture & annihilation



A.Gould 1987, 1988, 1990

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

1. Capture & annihilation



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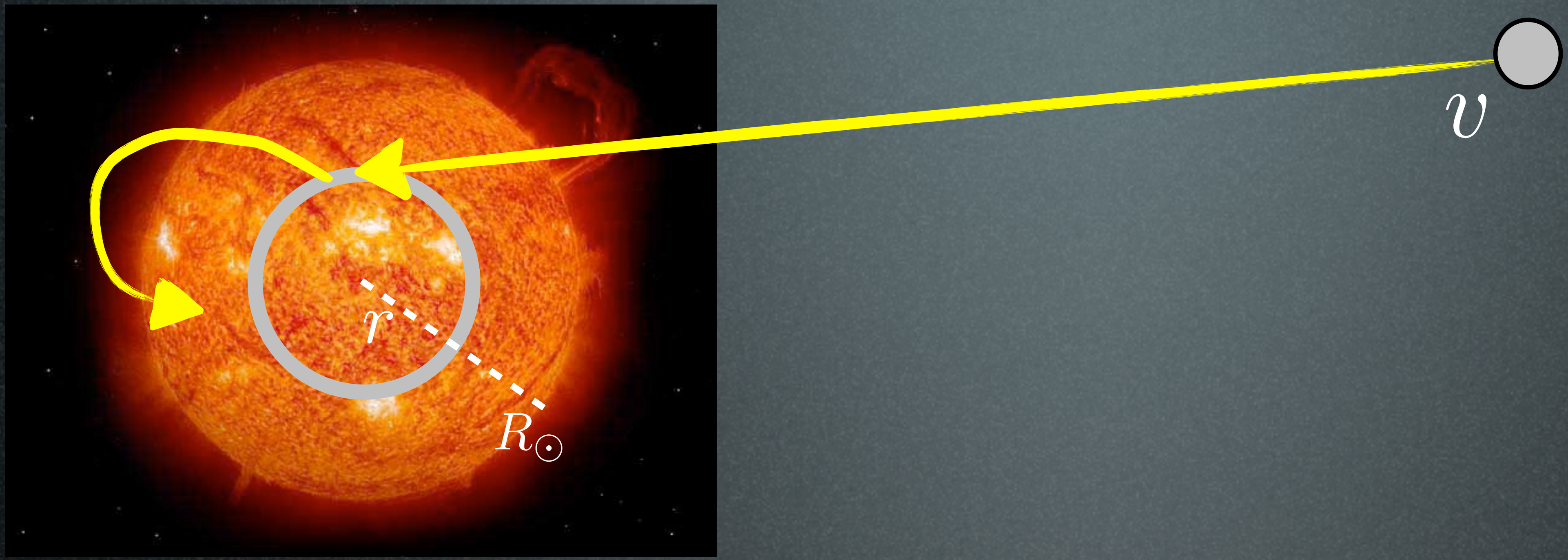
DM
number
density

1. Capture & annihilation



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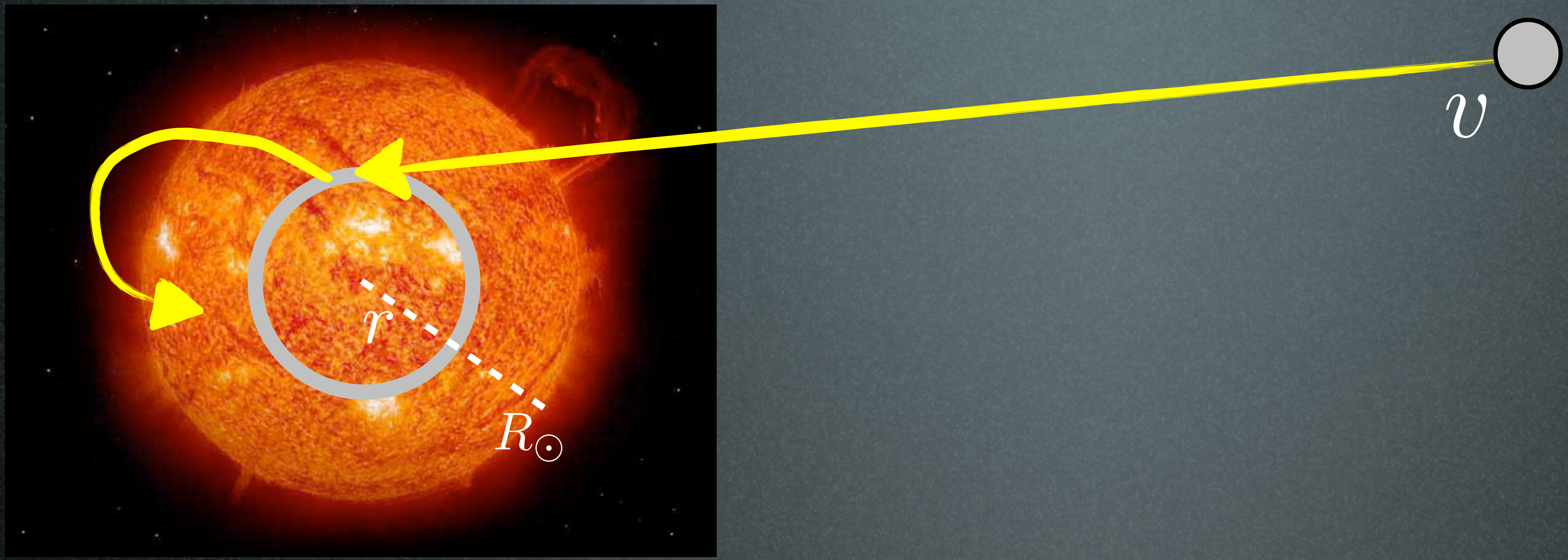
DM number density

scattering cross section on element **i**

1. Capture & annihilation



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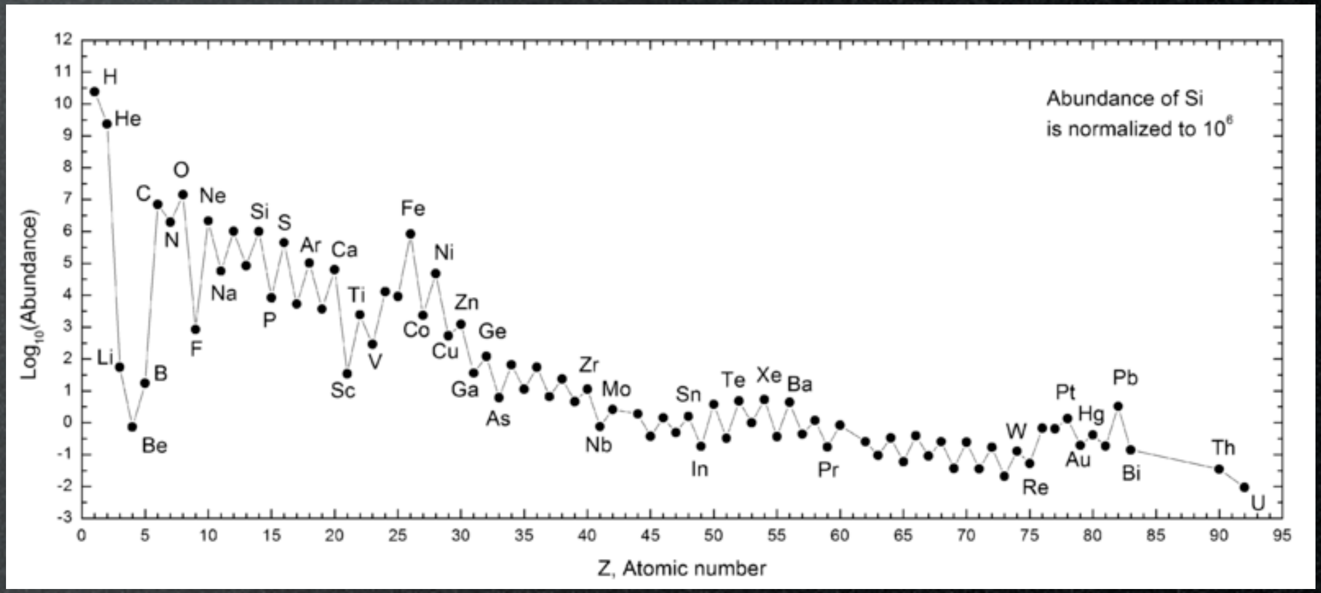
DM number density

scattering cross section on element **i**

number density of element **i**



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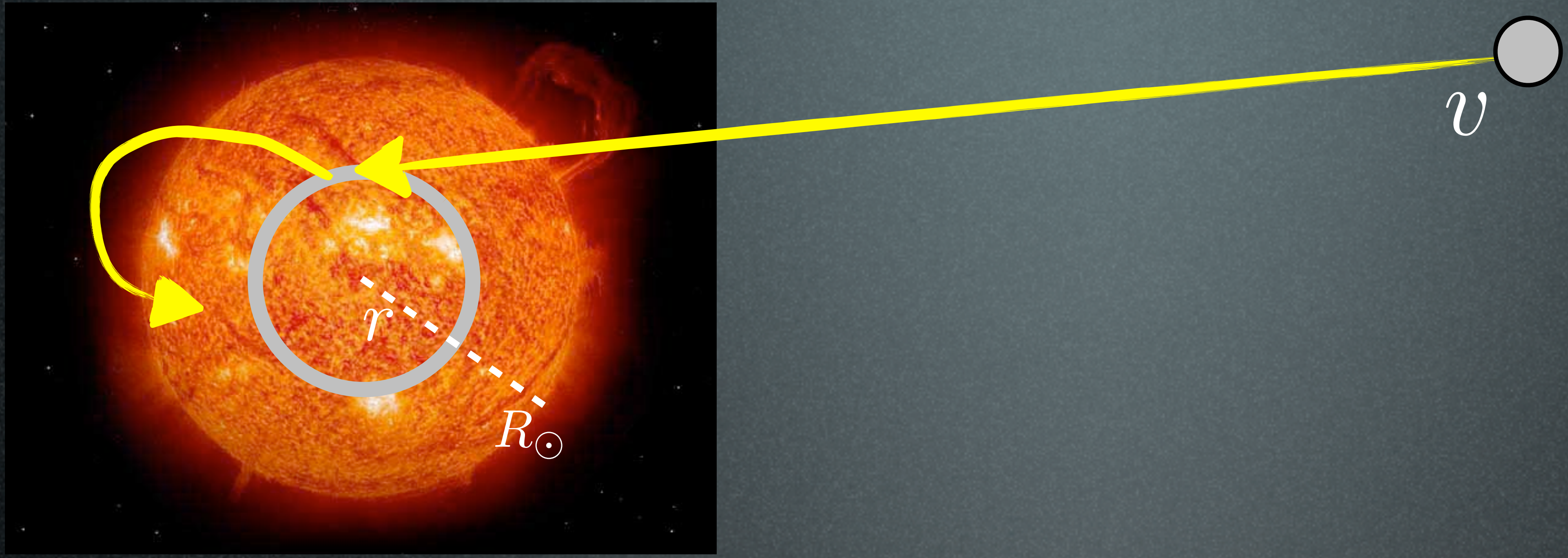

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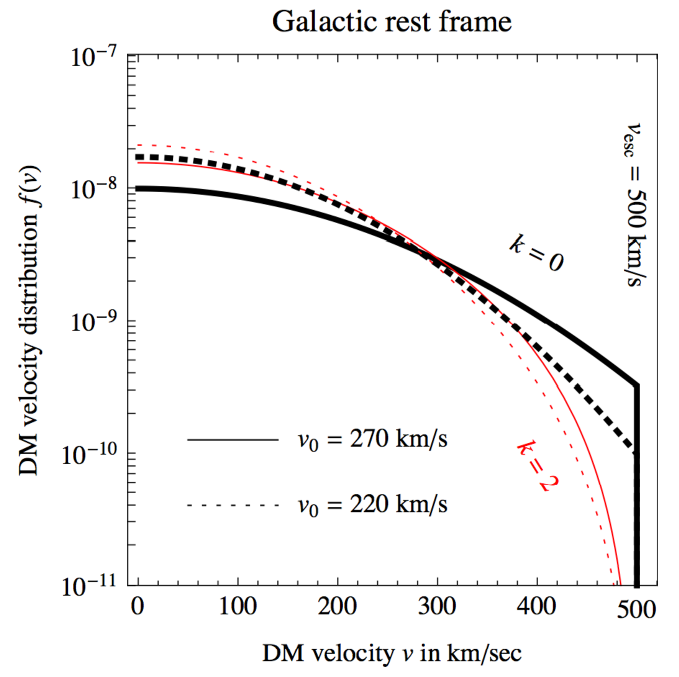
DM number density

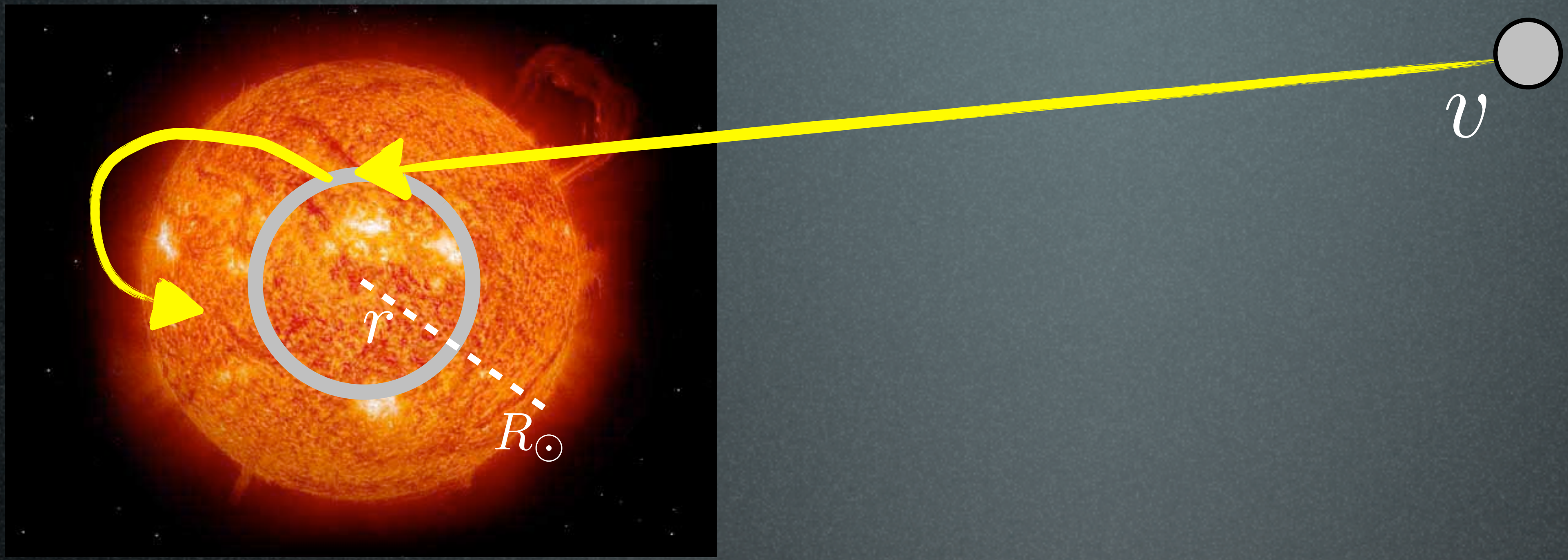
scattering cross section on element **i**

number density of element **i**

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



1. Capture & annihilation



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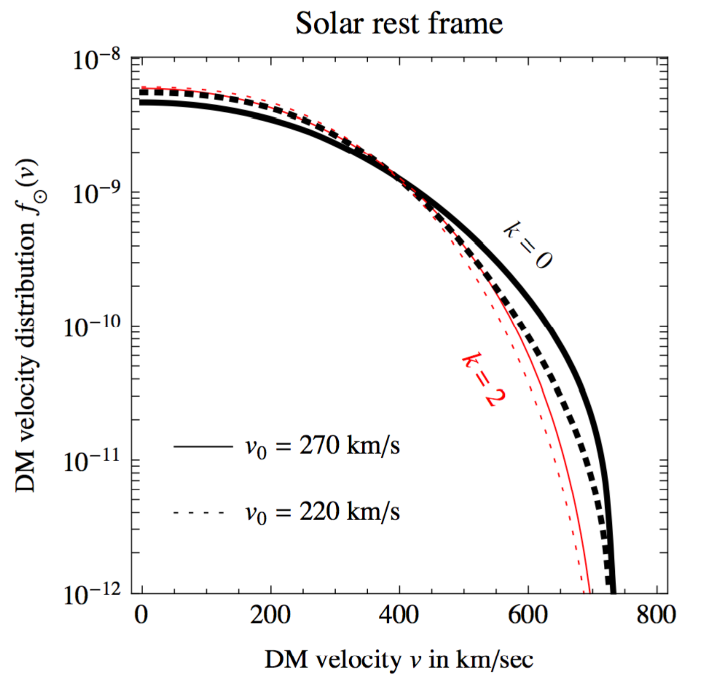
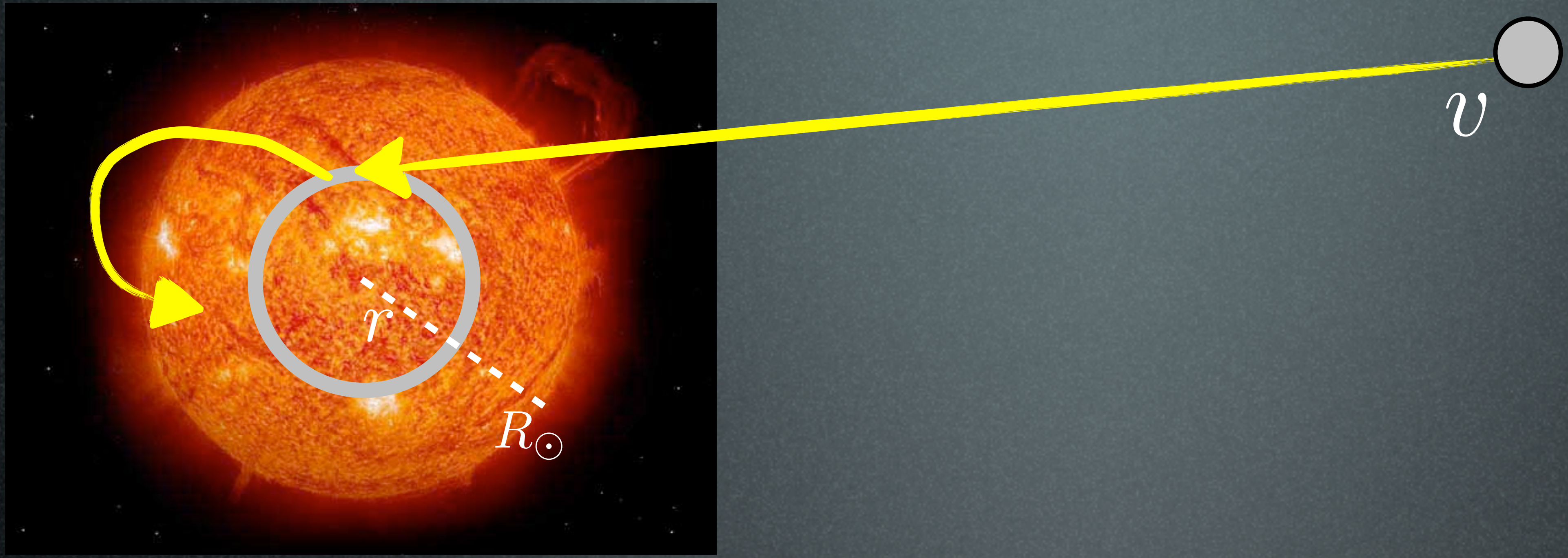


1. Capture & annihilation



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DM number density

scattering cross section on element **i**

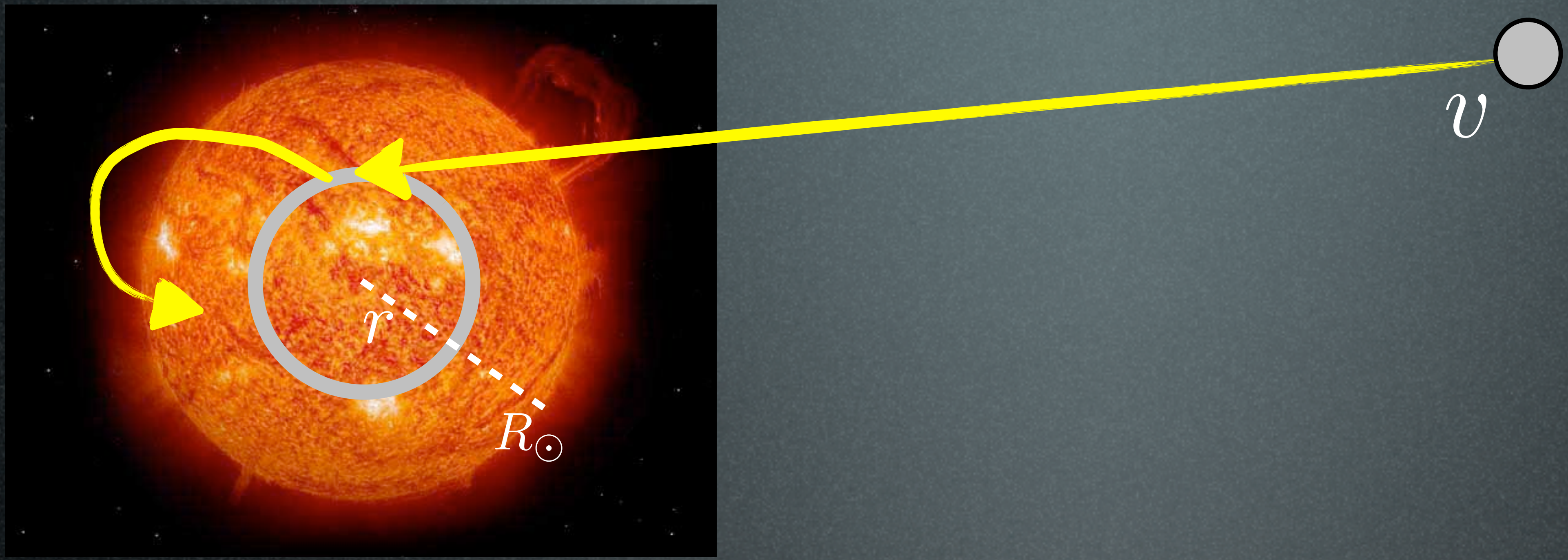
number density of element **i**

velocity distribution

(in solar frame, without Sun’s gravity)

effect of solar gravity

1. Capture & annihilation



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DM number density

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number density of element **i**

velocity distribution

(in solar frame, without Sun's gravity)

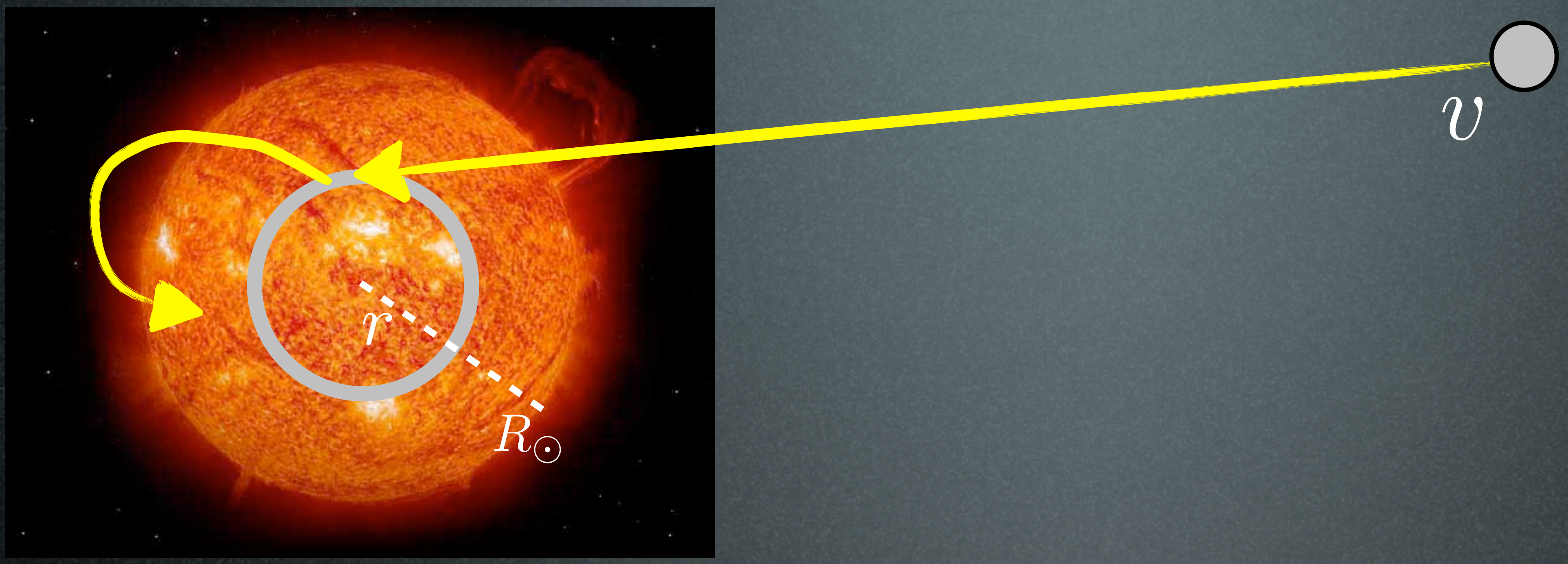
effect of solar gravity

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



A.Gould 1987, 1988, 1990

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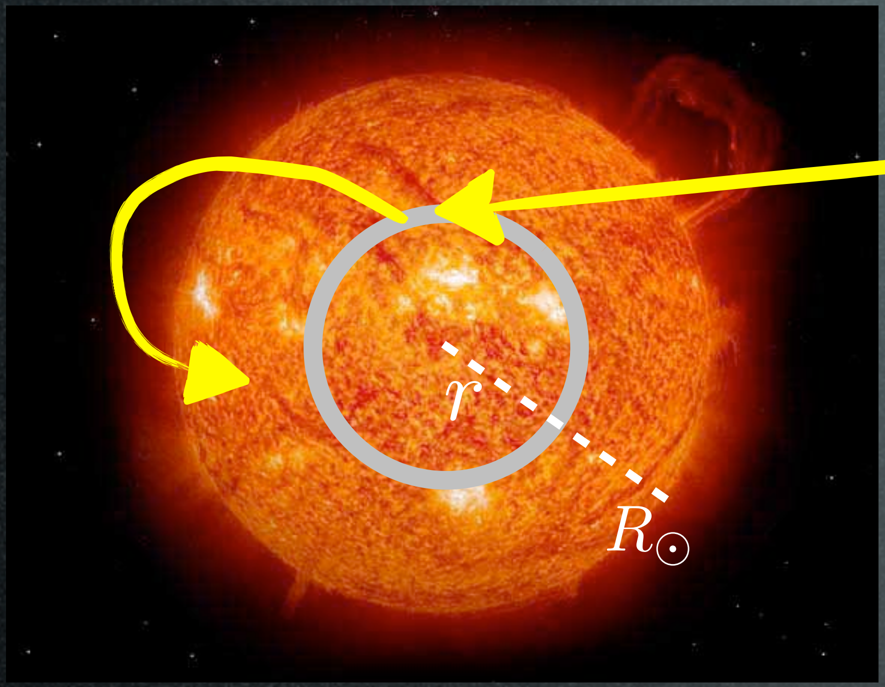
$$\wp_i(v, v_{\odot\rm esc}) = \frac{1}{E\,\Delta_{\rm max}} \int_{E\,\Delta_{\rm min}}^{E\,\Delta_{\rm max}} {\rm d}(\Delta E)\, |F_i(\Delta E)|^2$$

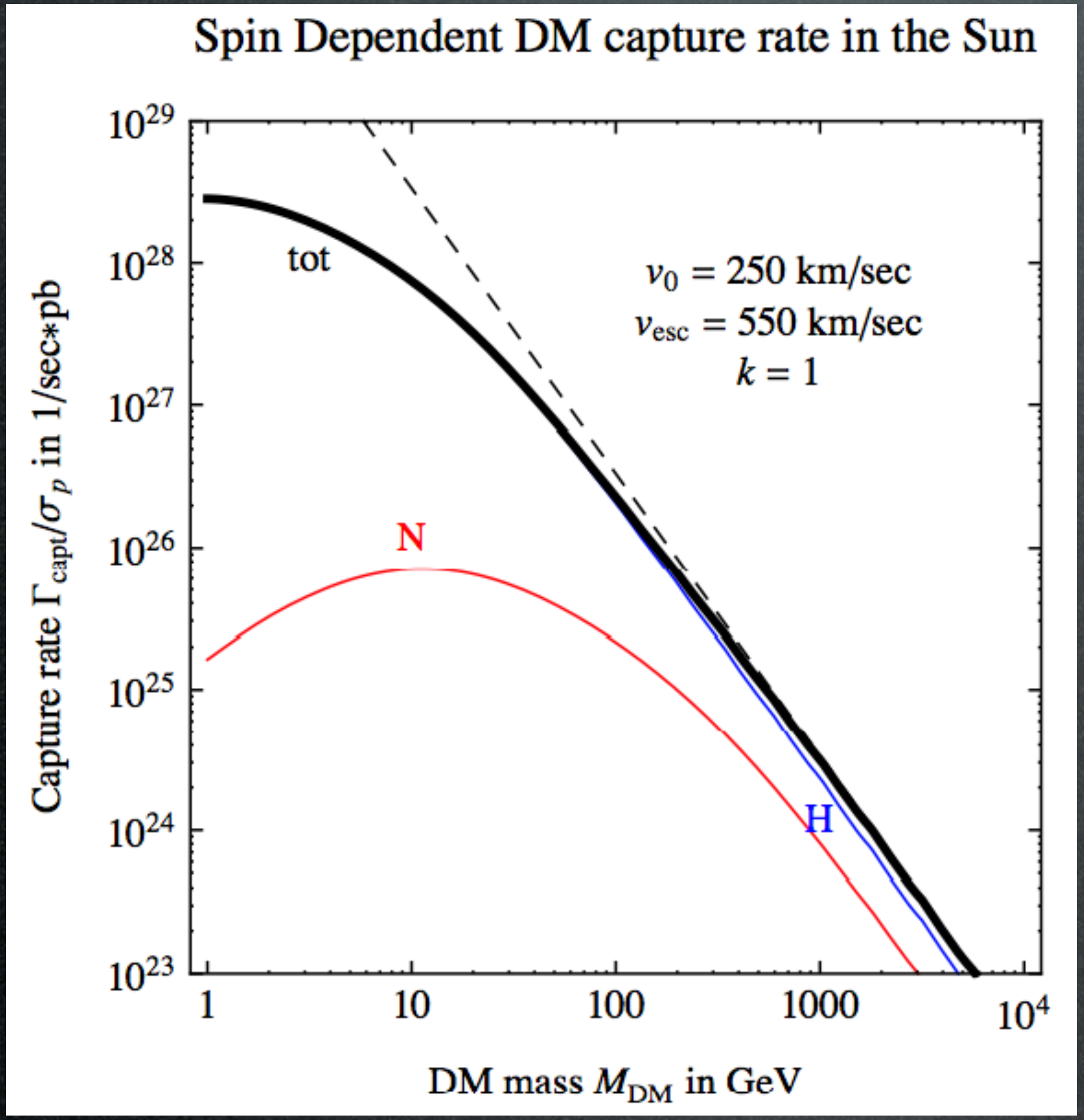
$$|F_i(\Delta E)|^2 = e^{-\Delta E/E_0} \qquad E_0^{\rm SI} = 5/2 m_i r_i^2$$

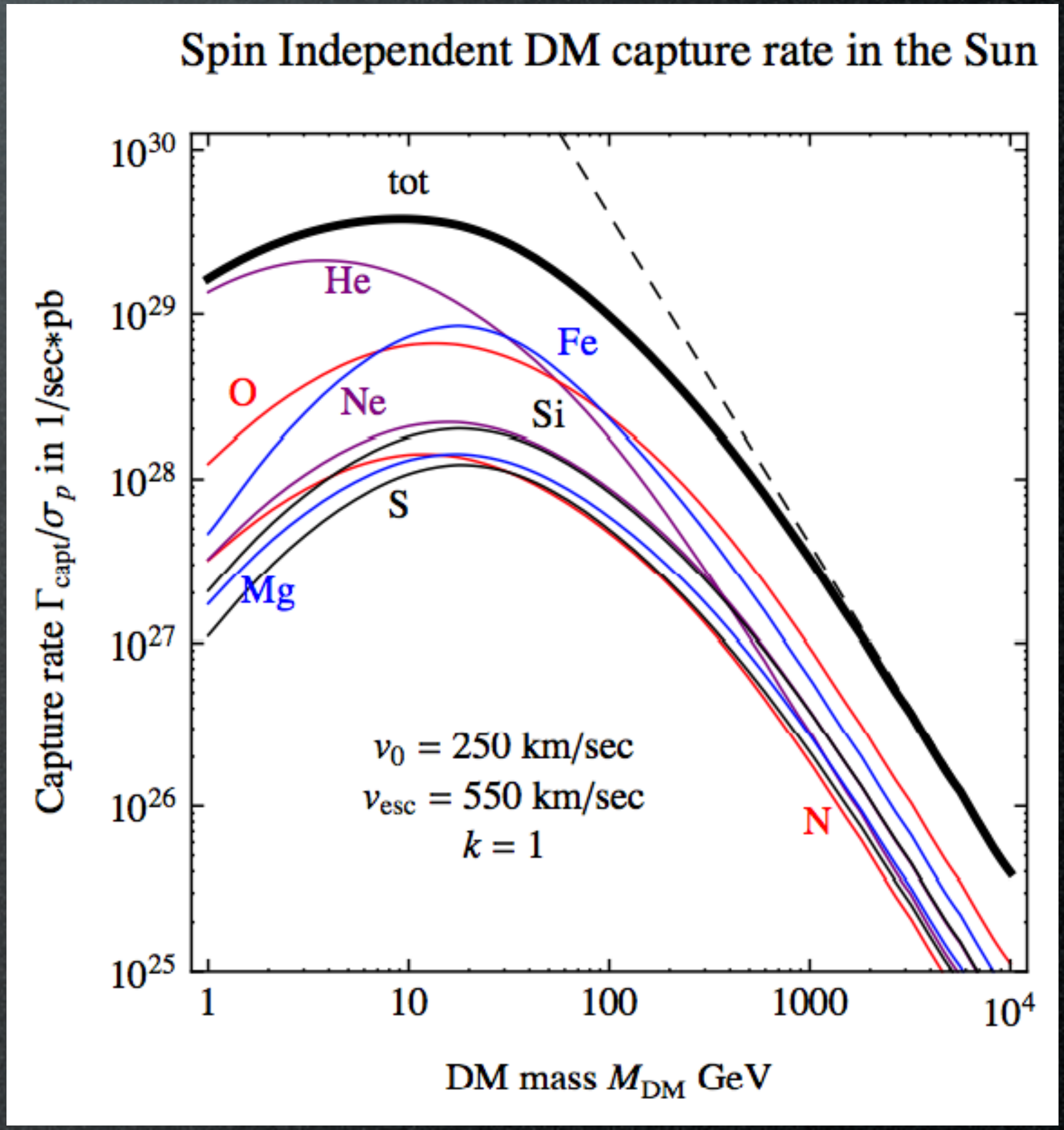
$$E_0^{\rm SD} = 3/2 m_i r_i^2$$

1. Capture & annihilation

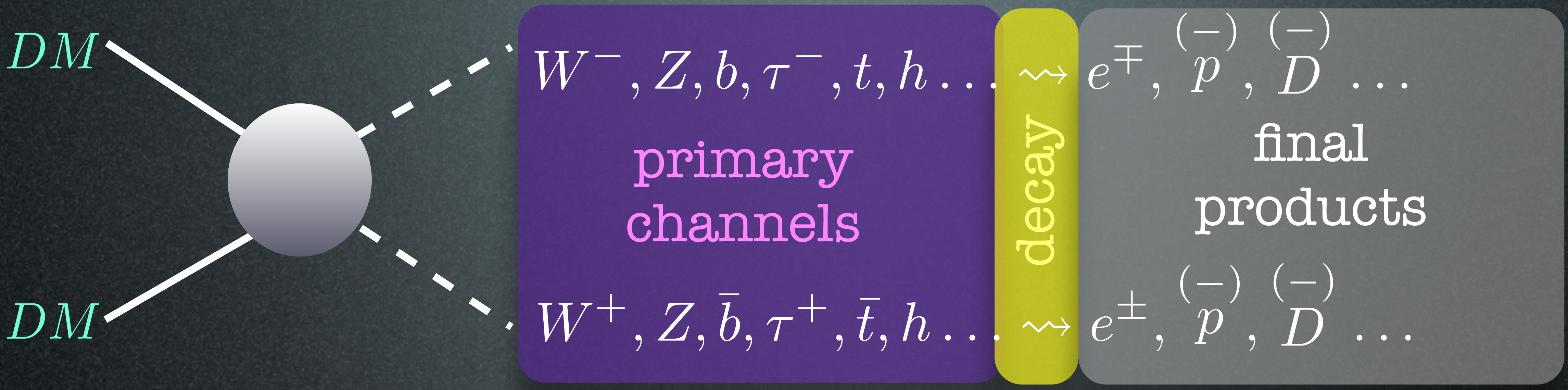


A.Gould 1987, 1988, 1990





1b. Spectra at production



DM

DM

$W^-, Z, b, \tau^-, t, h \ldots$

primary channels

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

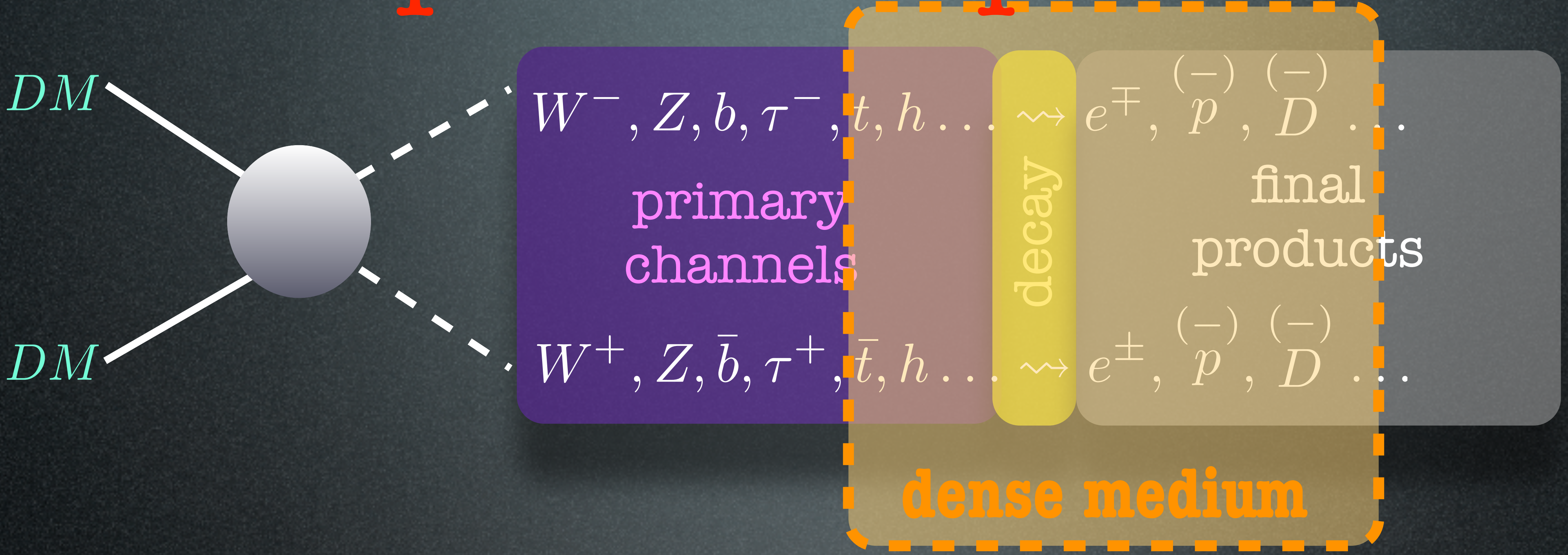
decay

$\rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

final products

$\rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$

1b. Spectra at production



DM

DM

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

primary channels

decay

final products

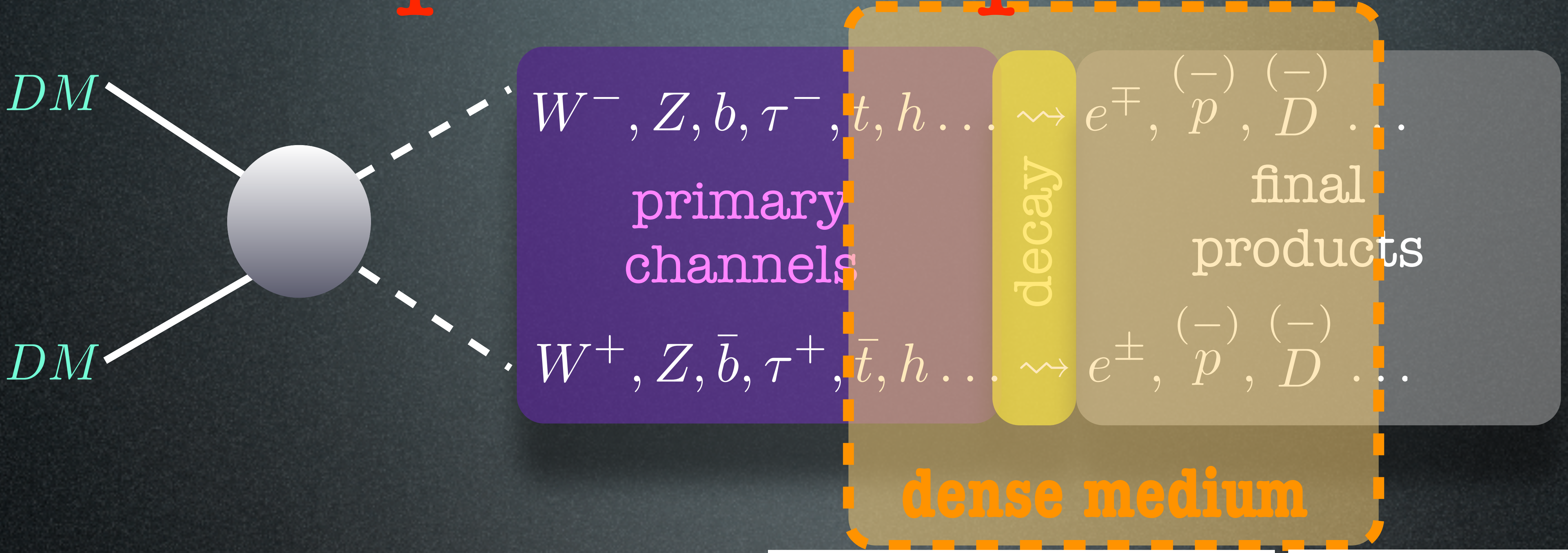
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

dense medium

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

1b. Spectra at production



DM

DM

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

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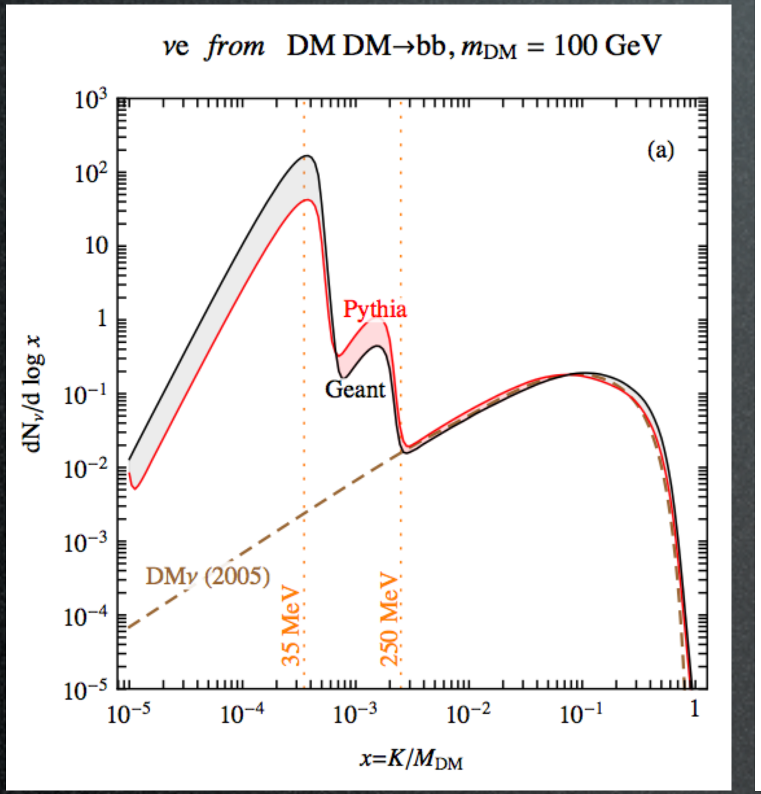
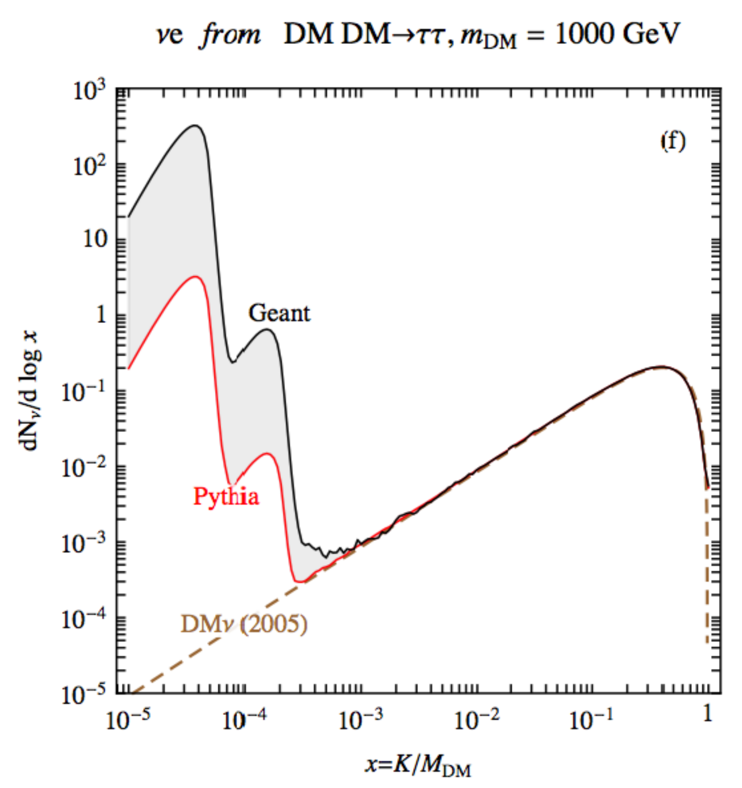
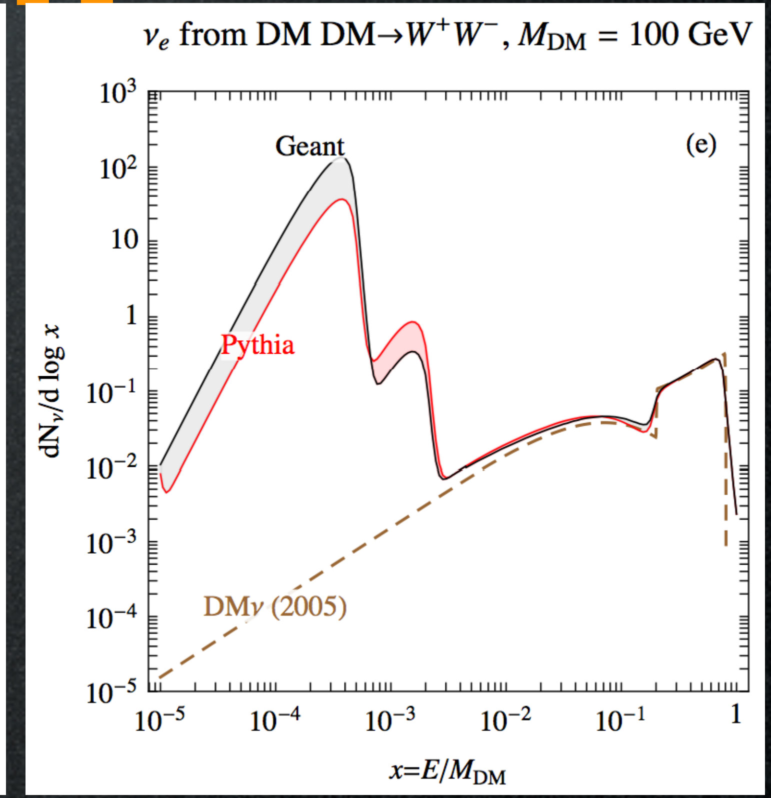
dense medium



νe *from* DM DM→bb, $m_{\rm DM}$ = 100 GeV



νe *from* DM DM→ττ, $m_{\rm DM}$ = 1000 GeV



ν_e from DM DM→W^+W^-, $M_{\rm DM}$ = 100 GeV

Effects of the medium:

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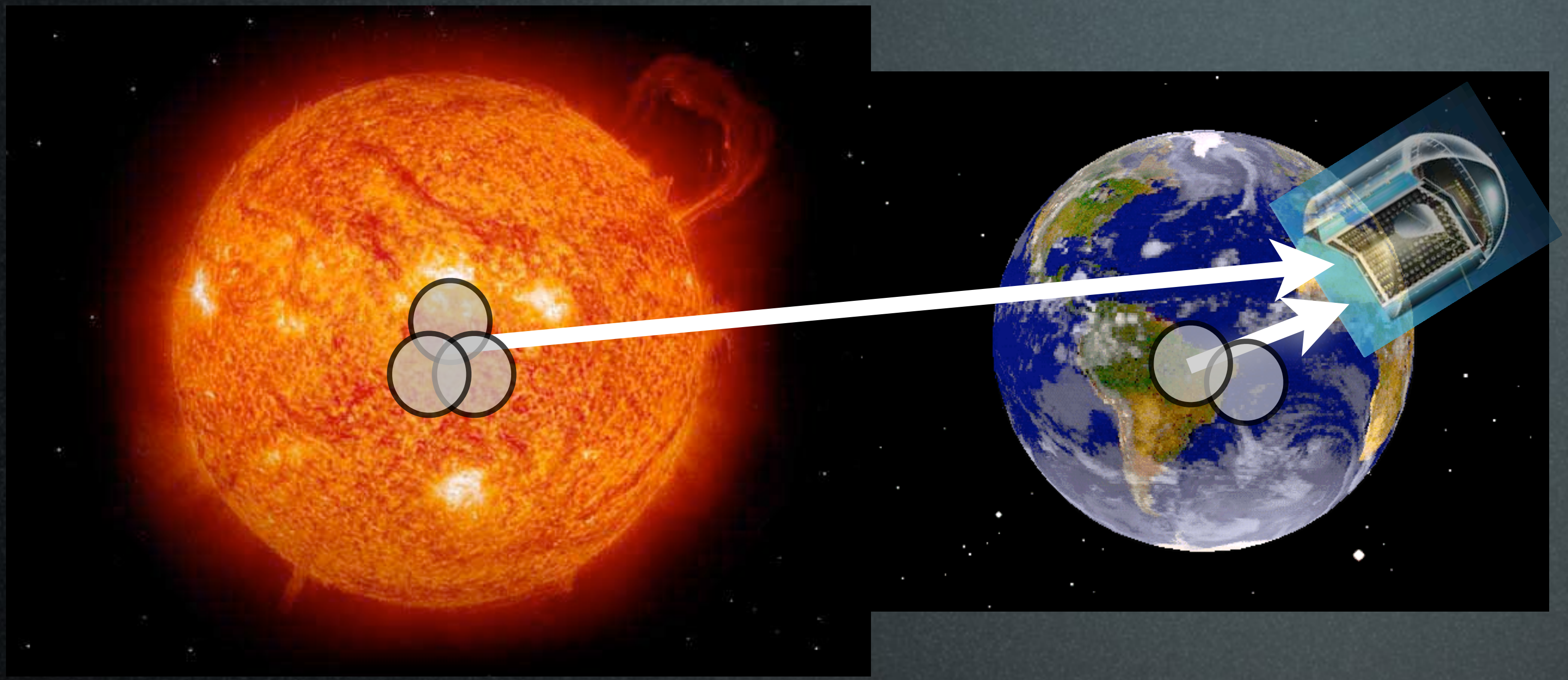
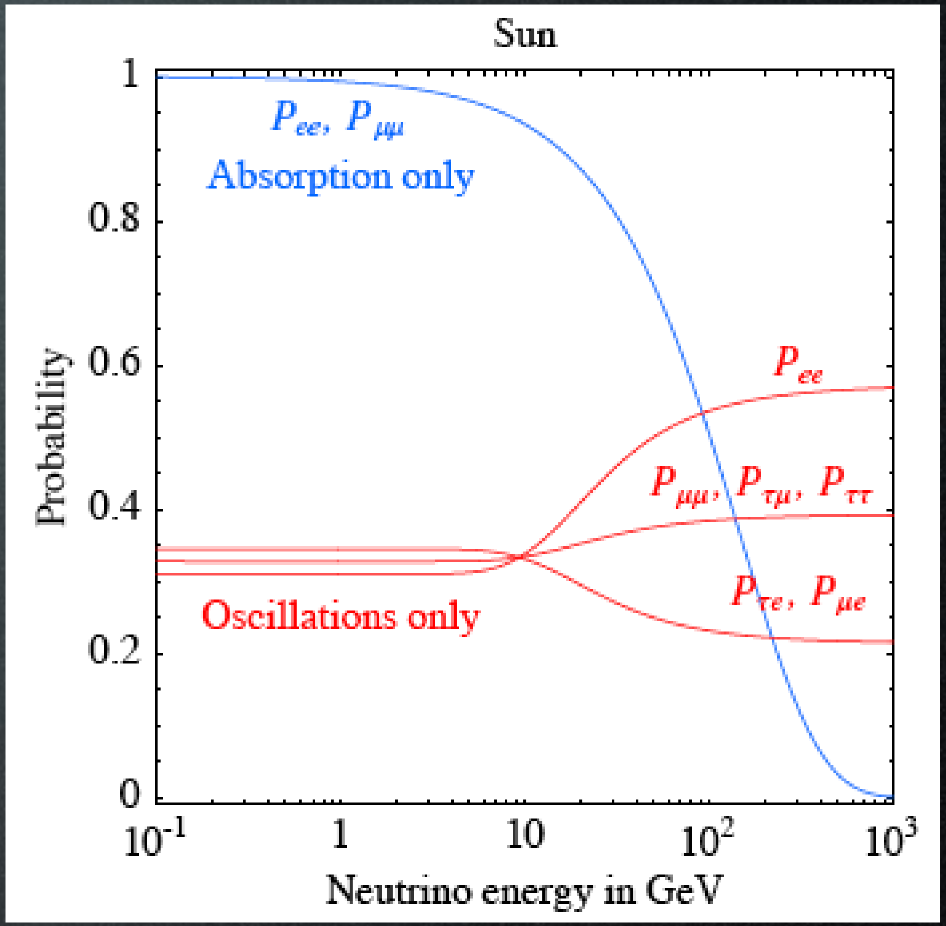
2. Propagation



oscillations + interactions



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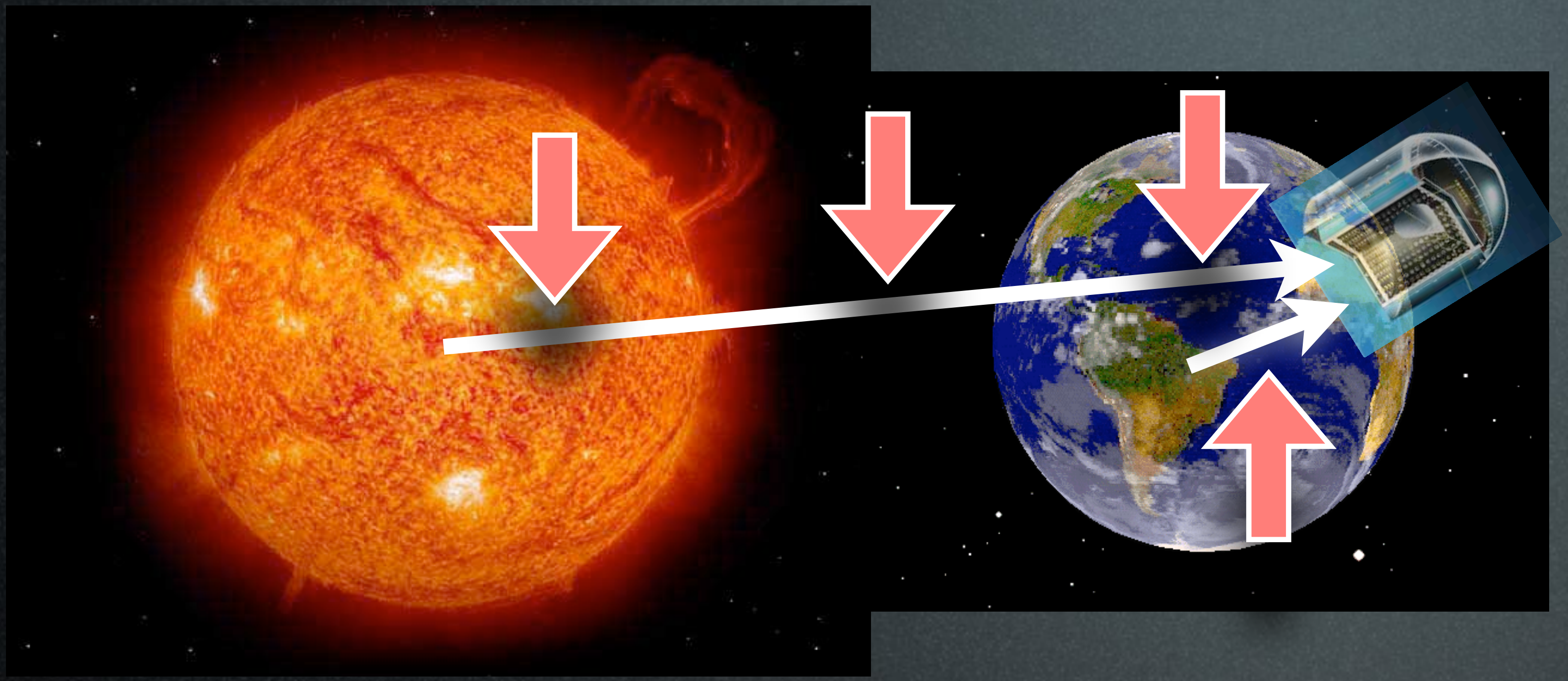

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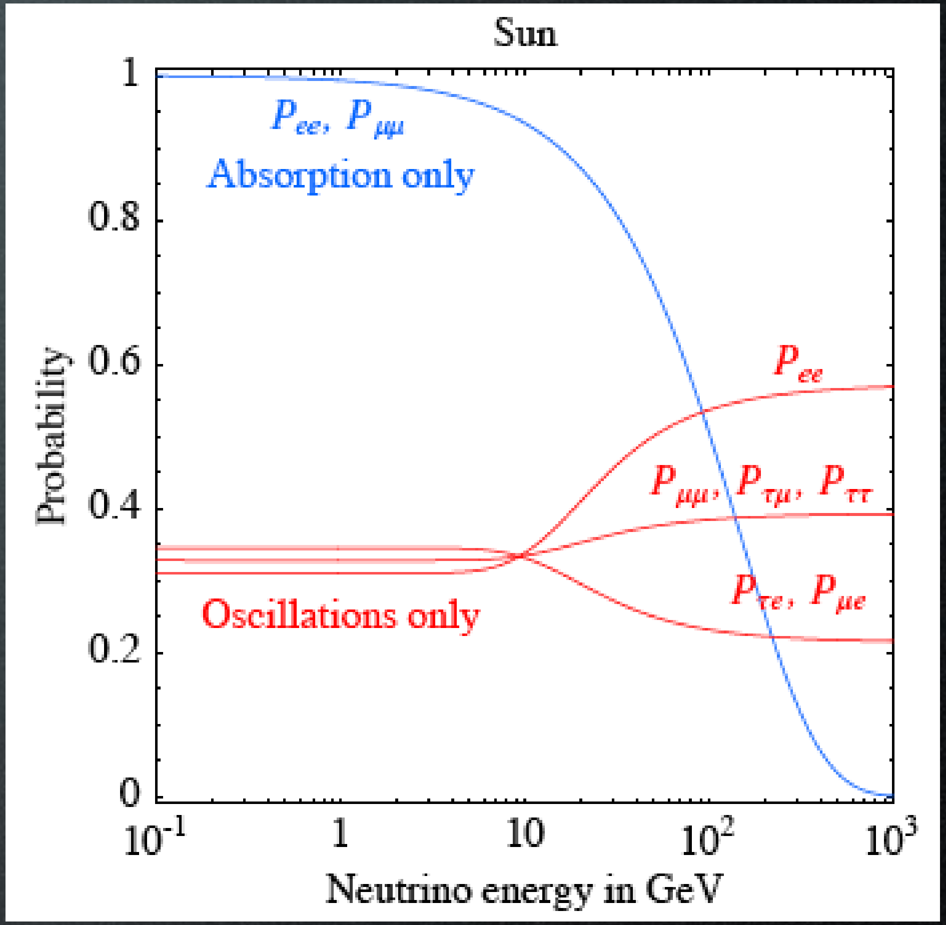

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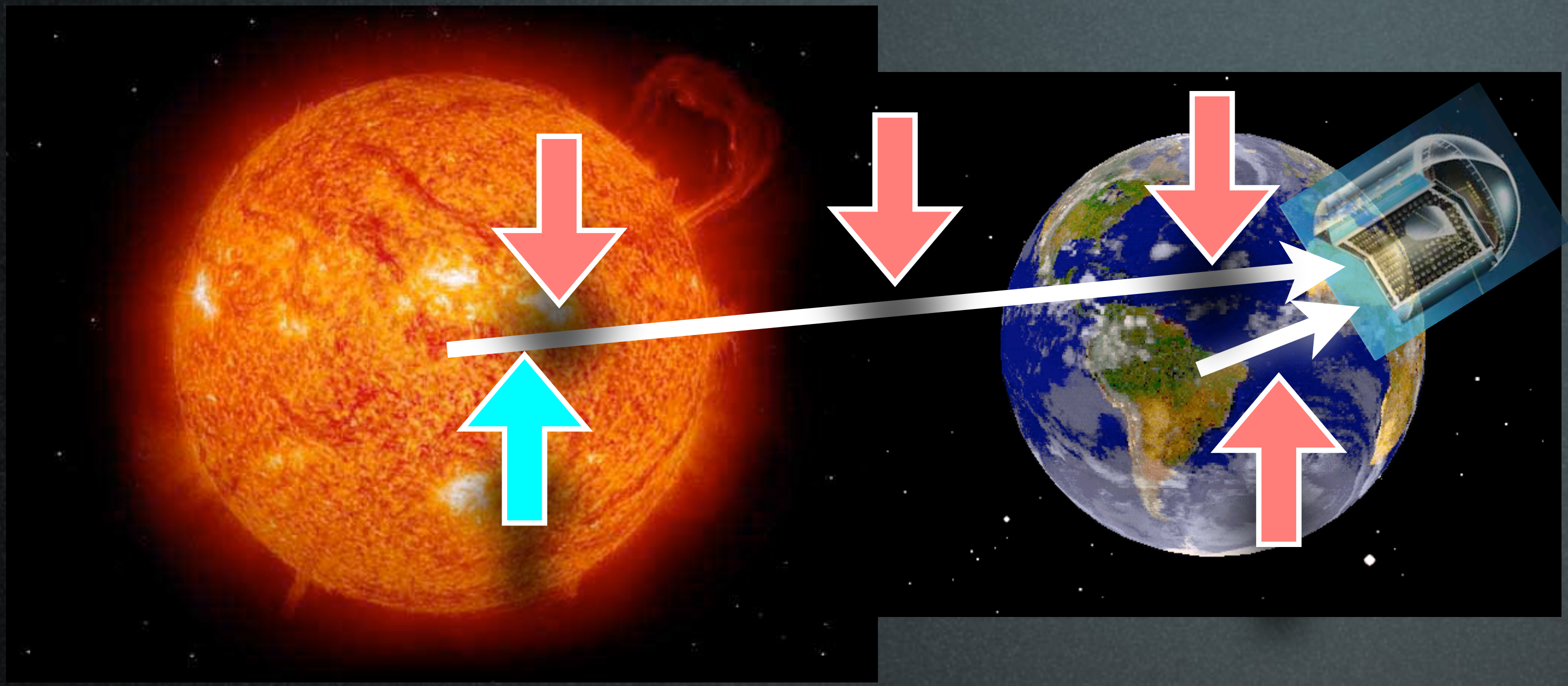

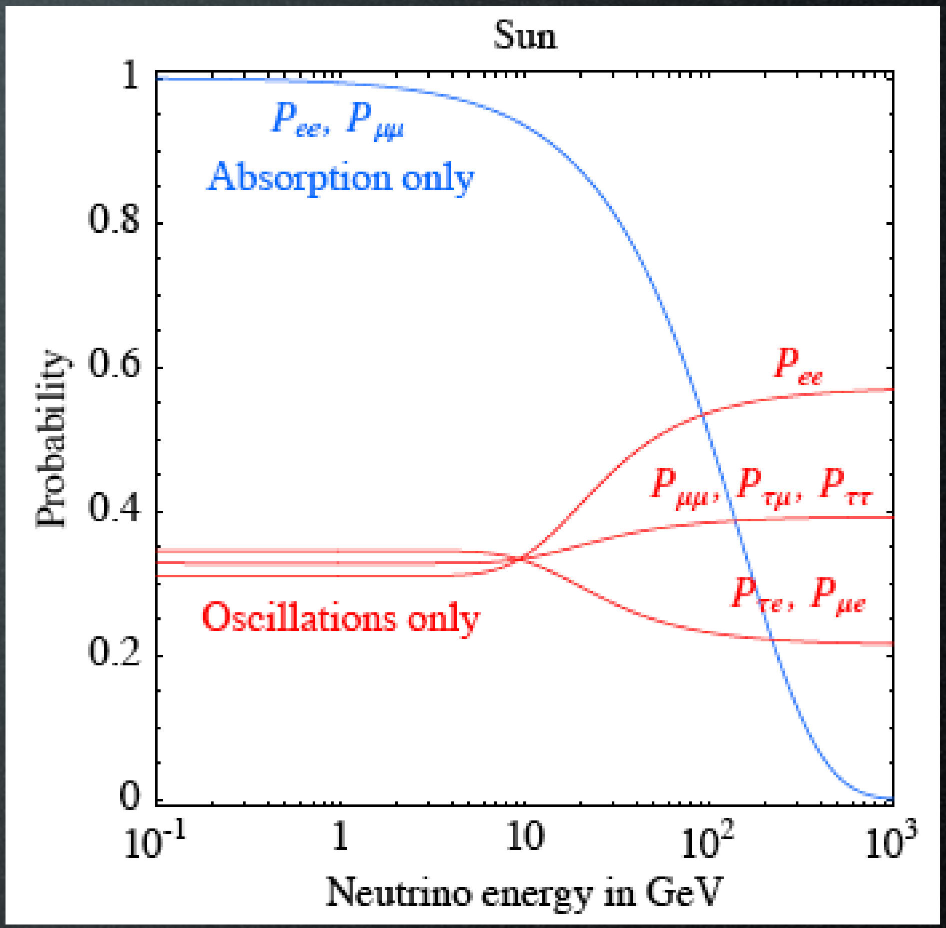

oscillations + interactions

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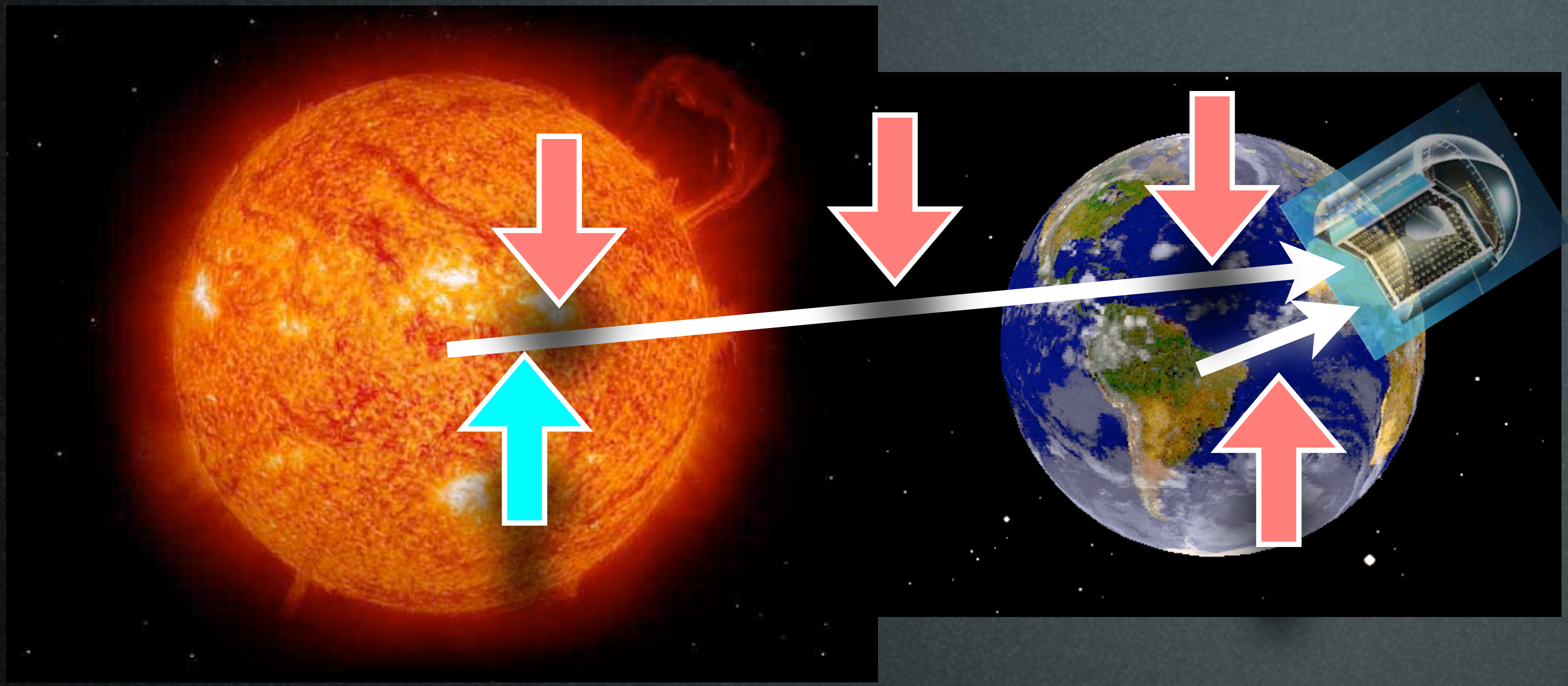
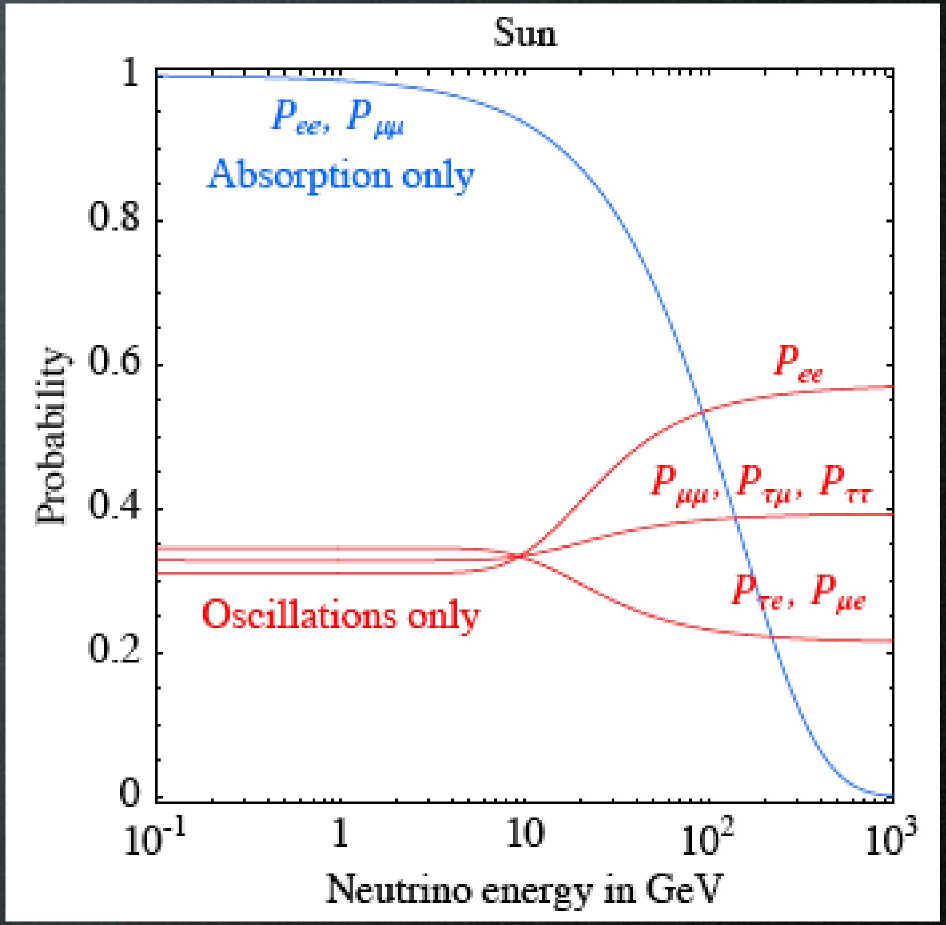
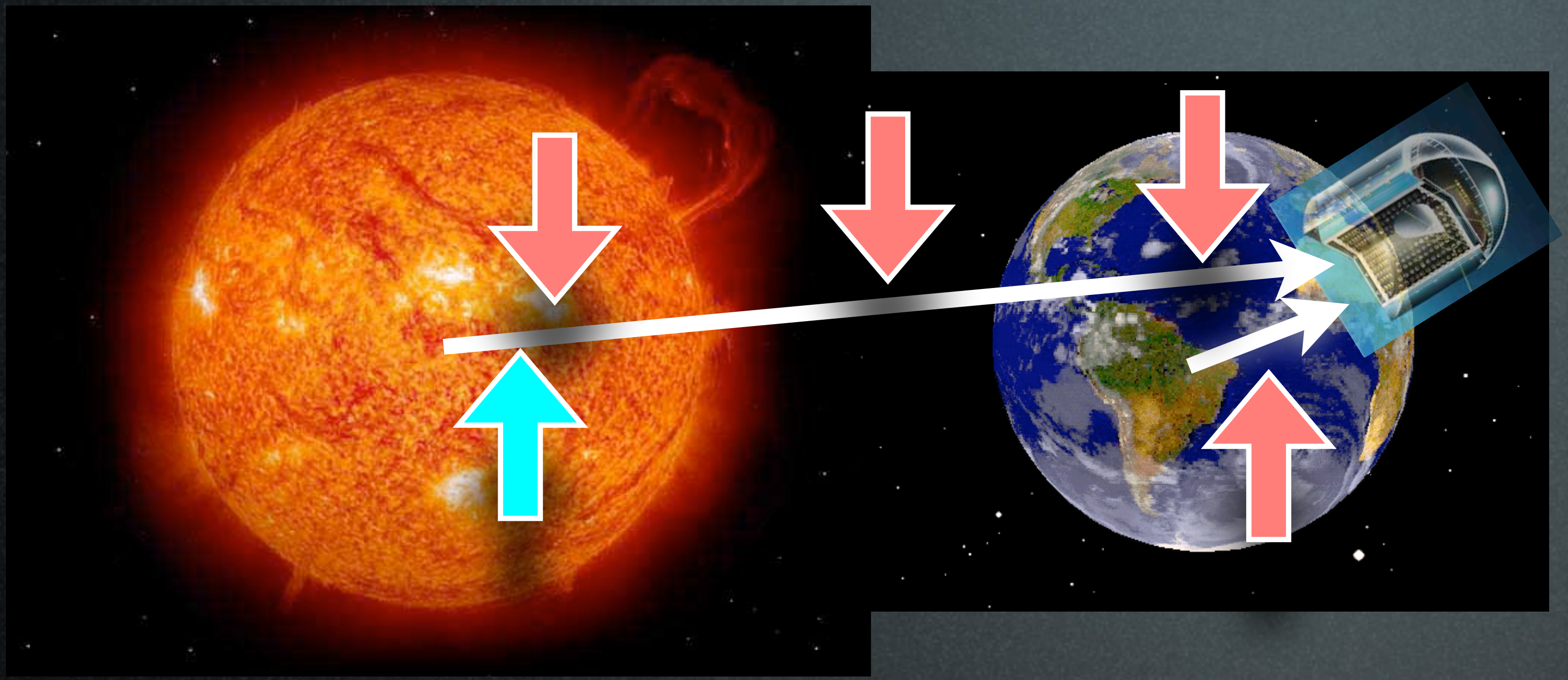


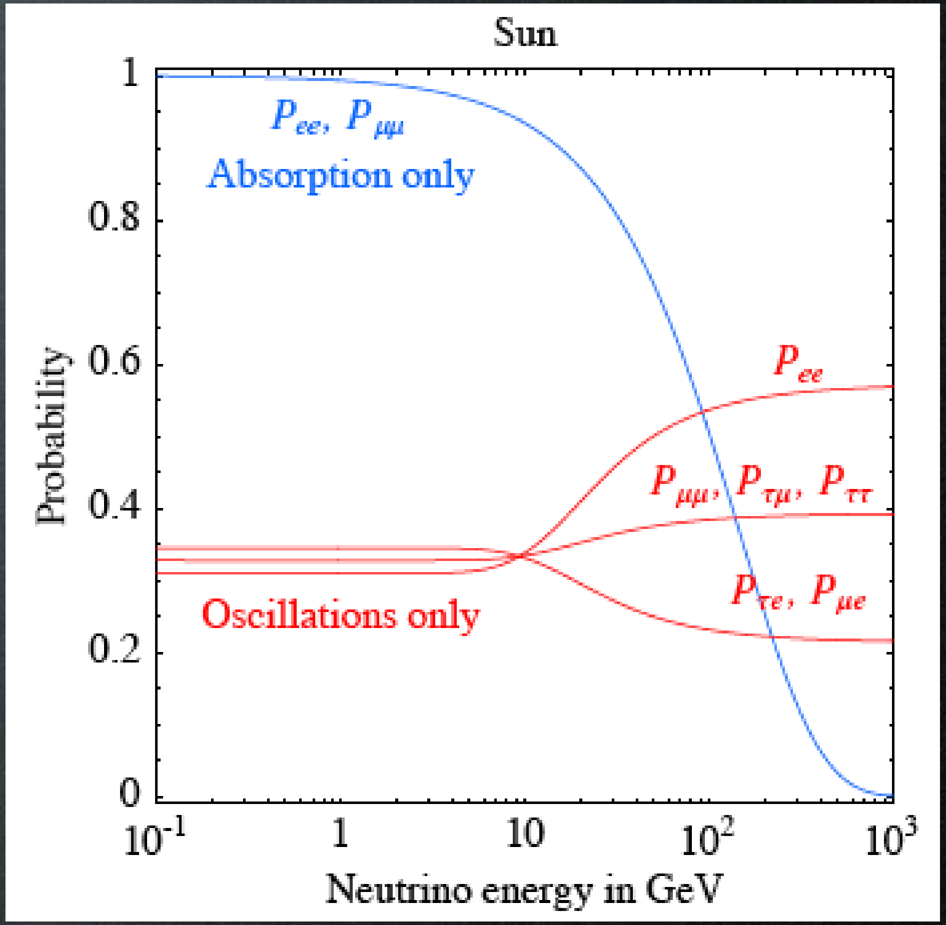


oscillations + interactions

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

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:

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

2. Propagation: oscillations

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

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

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✓

vacuum mixing:

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

$\theta_{\rm sun} = 32°$

$\theta_{\rm atm} = 45°$

$\theta_{13} = 8.8°$

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

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

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$\Delta m^2_{\mathrm{sun}} = 8.0\ 10^{-5}\mathrm{eV}^2$
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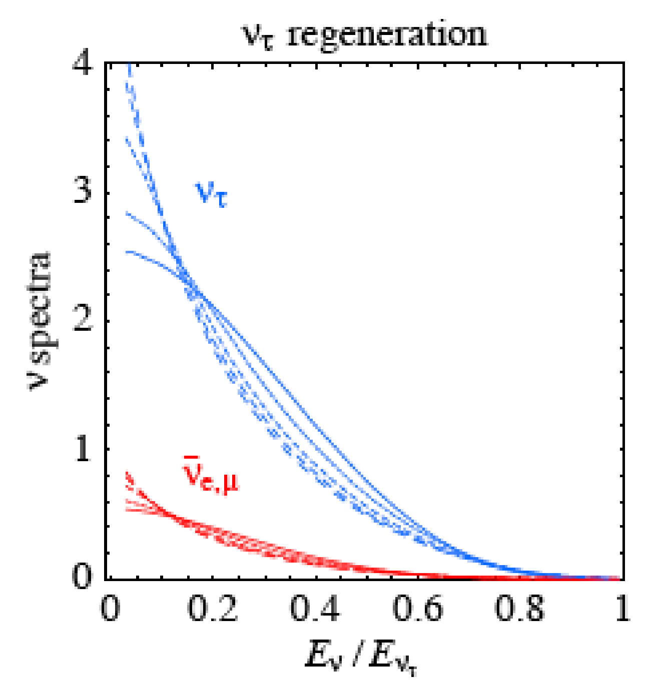
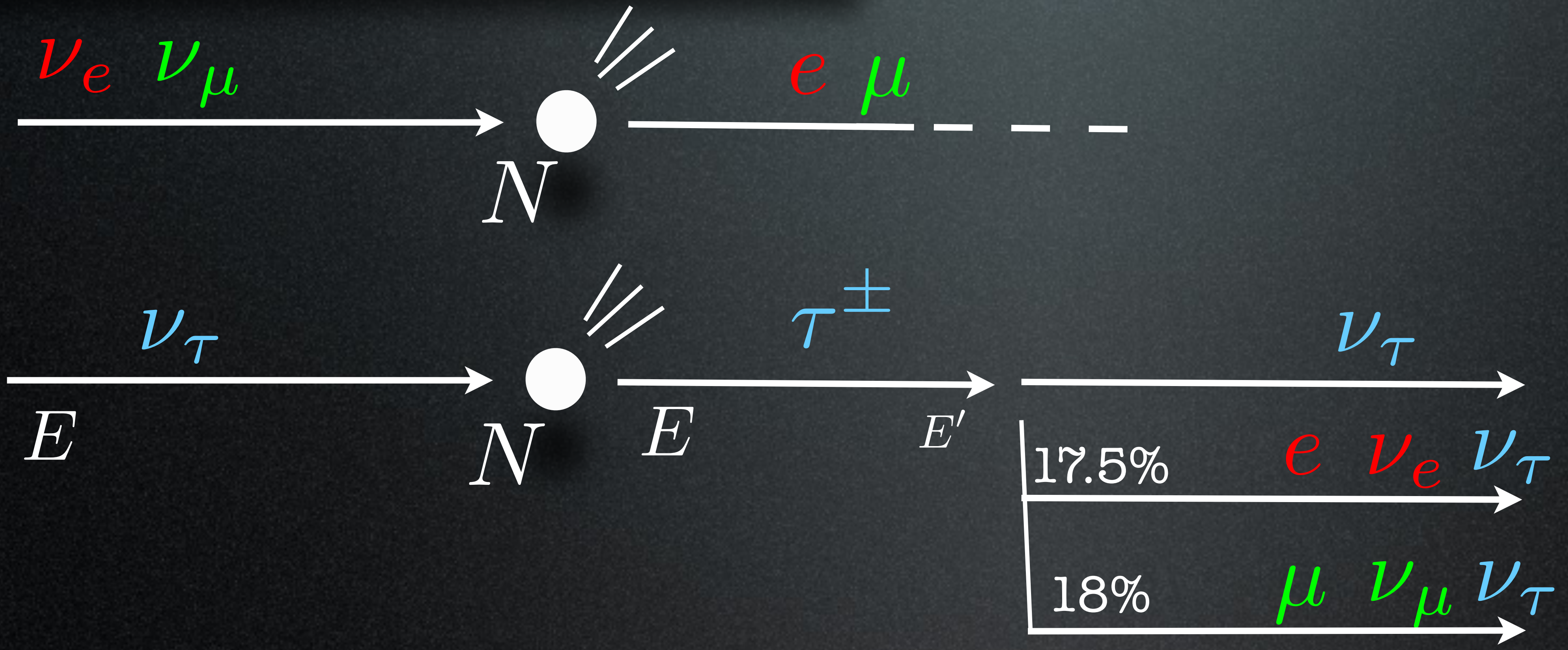
matter effect (MSW):

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

2. Propagation: CC absorption & tau regeneration

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



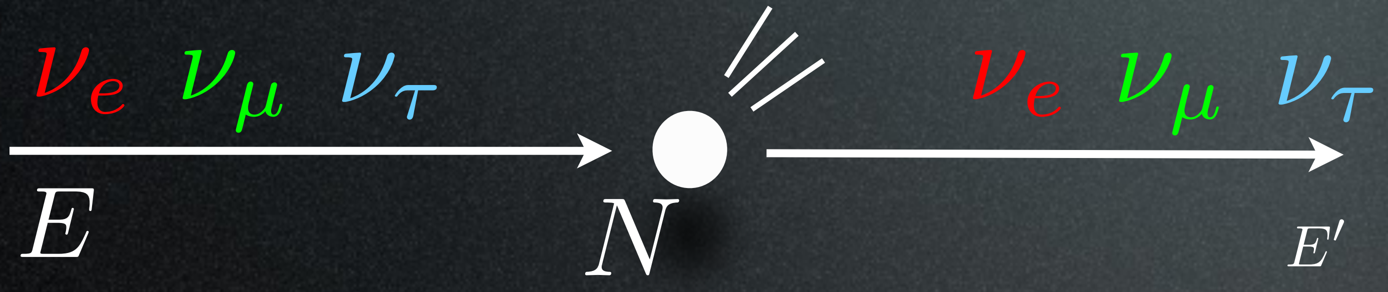


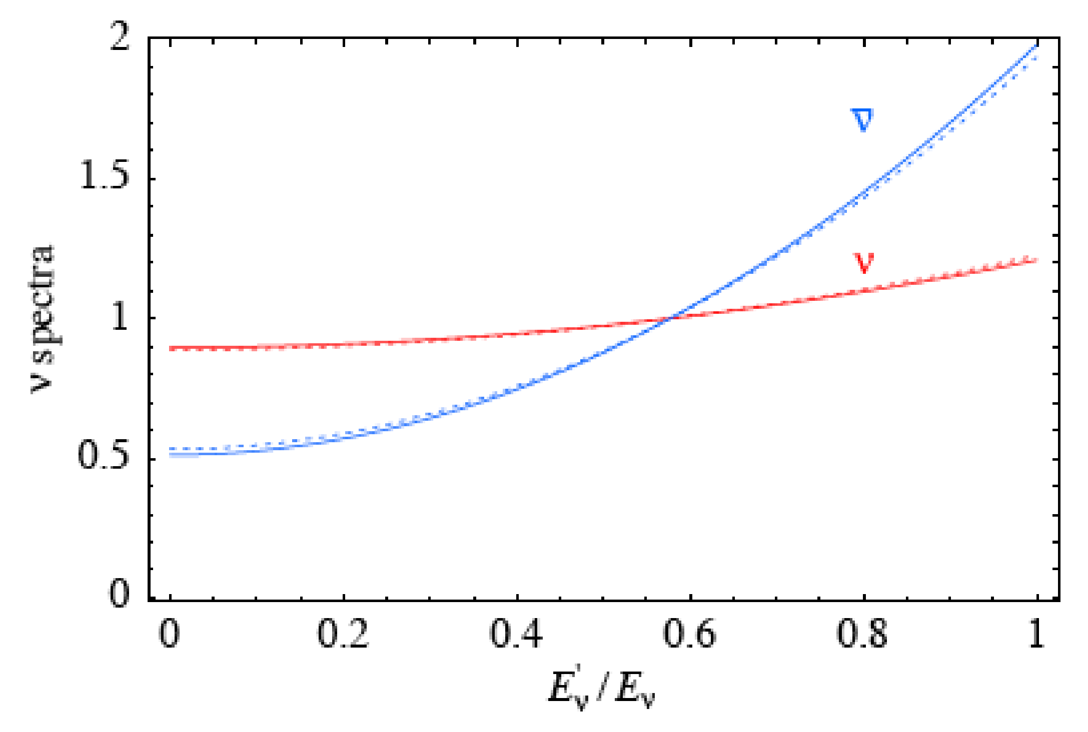
(re)generation

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

2. Propagation: NC scatterings

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

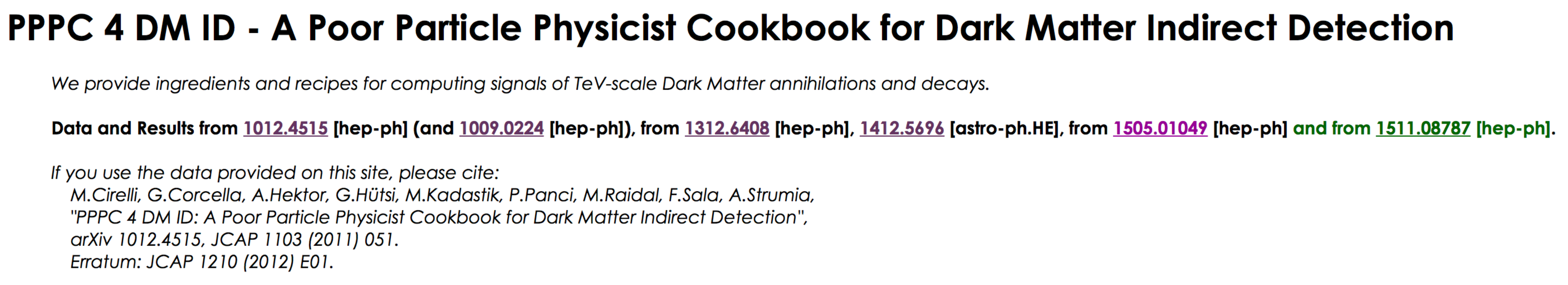




$$\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\mathrm{NC}} = -\int_0^{E_\nu} dE'_\nu \frac{d\Gamma_{\mathrm{NC}}}{dE'_\nu}(E_\nu, E'_\nu)\boldsymbol{\rho}(E_\nu) + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\Gamma_{\mathrm{NC}}}{dE_\nu}(E'_\nu, E_\nu)\boldsymbol{\rho}(E'_\nu)$$

Neutrinos from the Sun

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].

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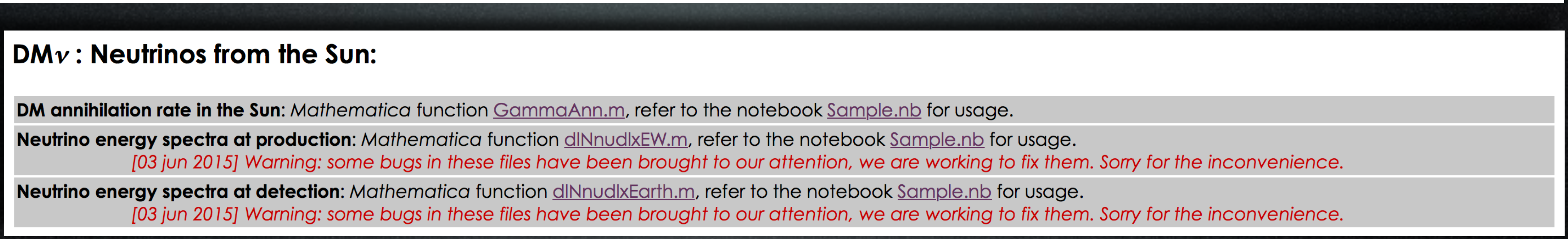
M.Cirelli, G.Corcella, A.Hektor, G.Hütsi, M.Kadastik, P.Panci, M.Raidal, F.Sala, A.Strumia,
"PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection",
arXiv 1012.4515, JCAP 1103 (2011) 051.
Erratum: JCAP 1210 (2012) E01.



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.

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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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but you don't want to mess around with astrophysics?

'The Poor Particle Physicist Cookbook for Dark Matter Indirect Direction'

PPPC 4 DM ID

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

Cirelli, Corcella, Hektor,
Hütsi, Kadastik, Panci,
Raidal, Sala, Strumia

1012.4515 [hep-ph]

www.marcocirelli.net/PPPC4DMID.html

Back up slides

Fluxes at production

Different hadronic MonteCarlos could give different products

Or: what is the ‘systematic’ uncertainty?

Fluxes at production

Different hadronic MonteCarlos could give different products

Or: what is the 'systematic' uncertainty?

PYTHIA (8.135) vs **HERWIG** (6.510)

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

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

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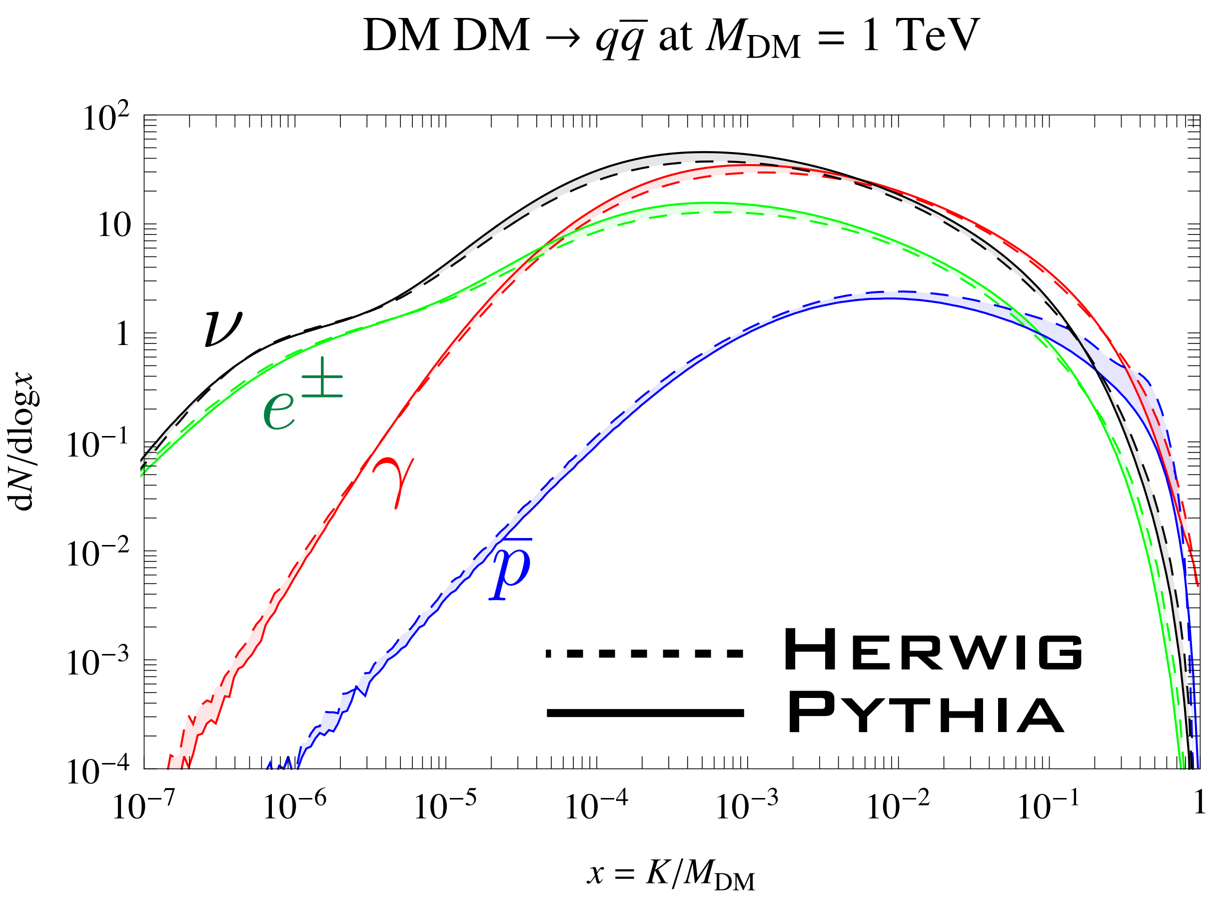
DM DM → $q\bar{q}$ at $M_{\rm DM}$ = 1 TeV

calibrated on LEP processes, good agreement, overall 20%

Fluxes at production

Different hadronic MonteCarlos could give different products

Or: what is the ‘systematic’ uncertainty?

PYTHIA (8.135) vs **HERWIG** (6.510)

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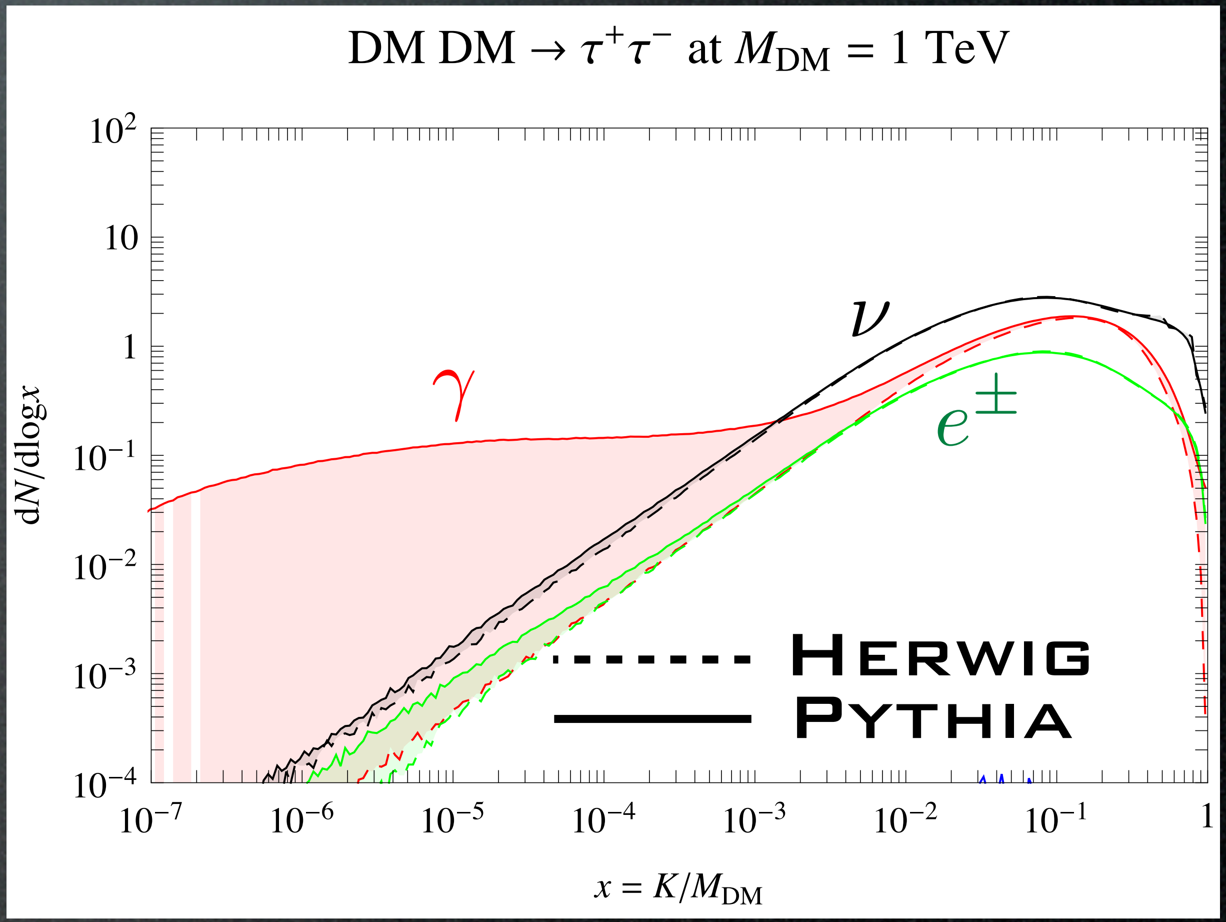


big discrepancy in γ $(e^{\pm})$ fluxes at low energy

Fluxes at production

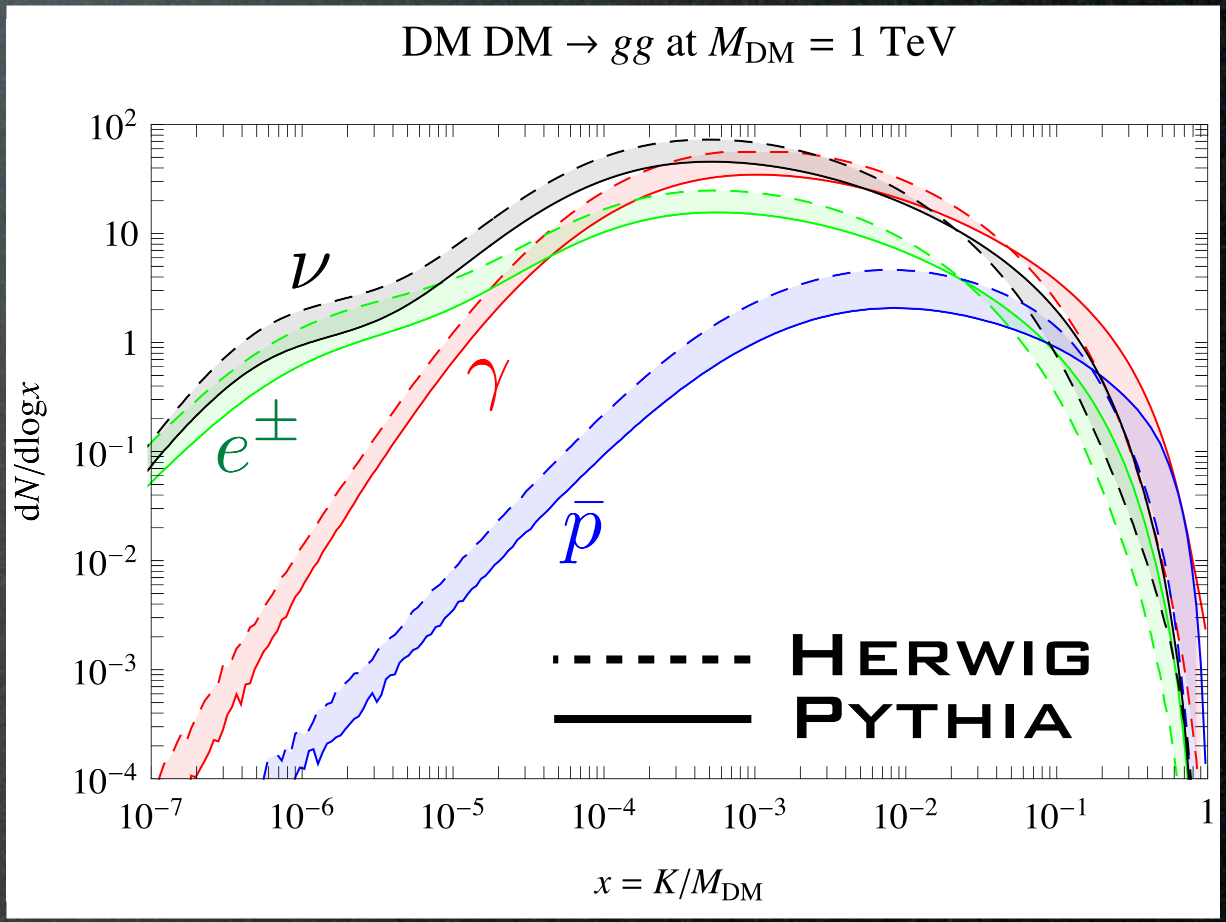
Different hadronic MonteCarlos could give different products

Or: what is the 'systematic' uncertainty?

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



Factor 2: not calibrated on LEP?
Anyway not central for DM

Fluxes at production

Different hadronic MonteCarlos could give different products

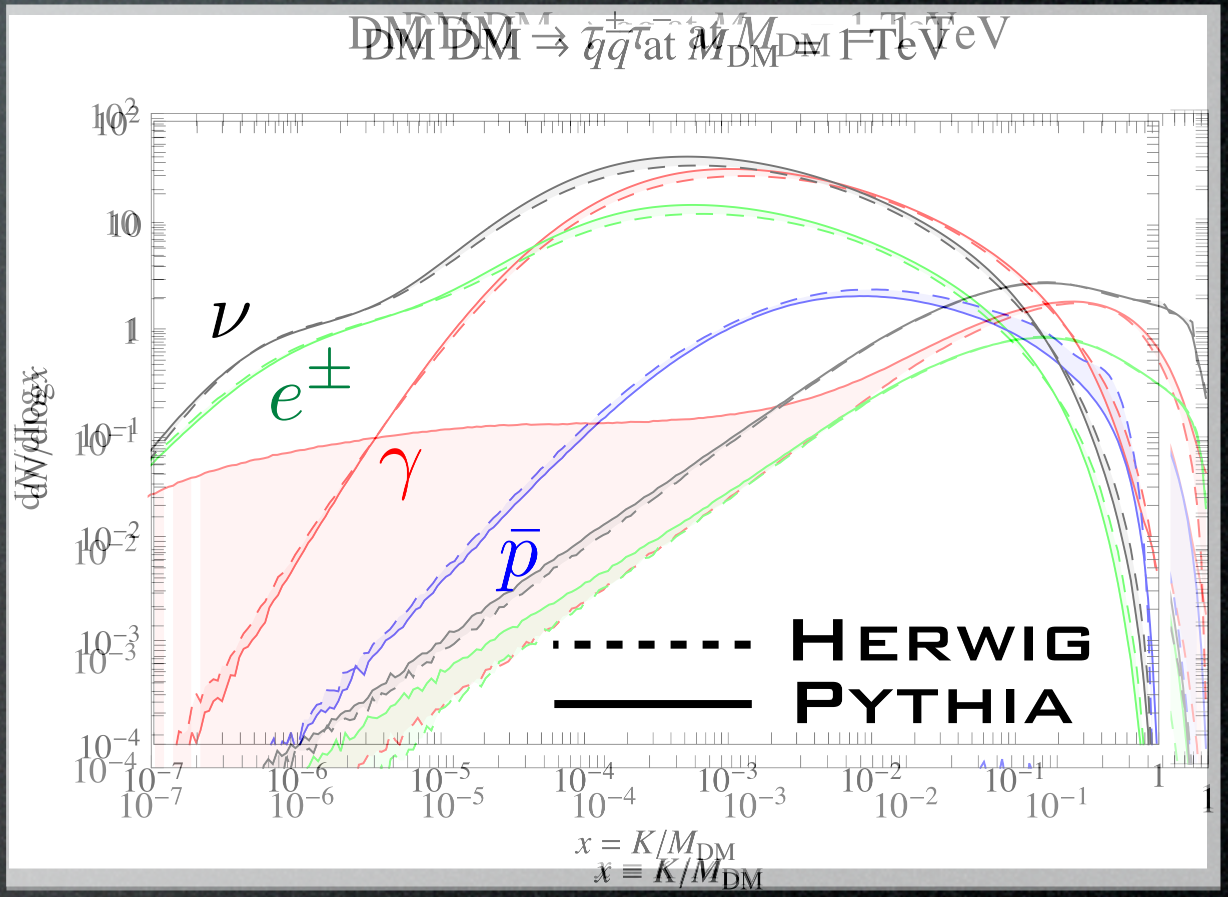
Or: what is the ‘systematic’ uncertainty?

- overall around 20%
- with some surprises

PYTHIA (8.135) vs **HERWIG** (6.510)

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

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



We use (modified) **PYTHIA 8** for all computations.

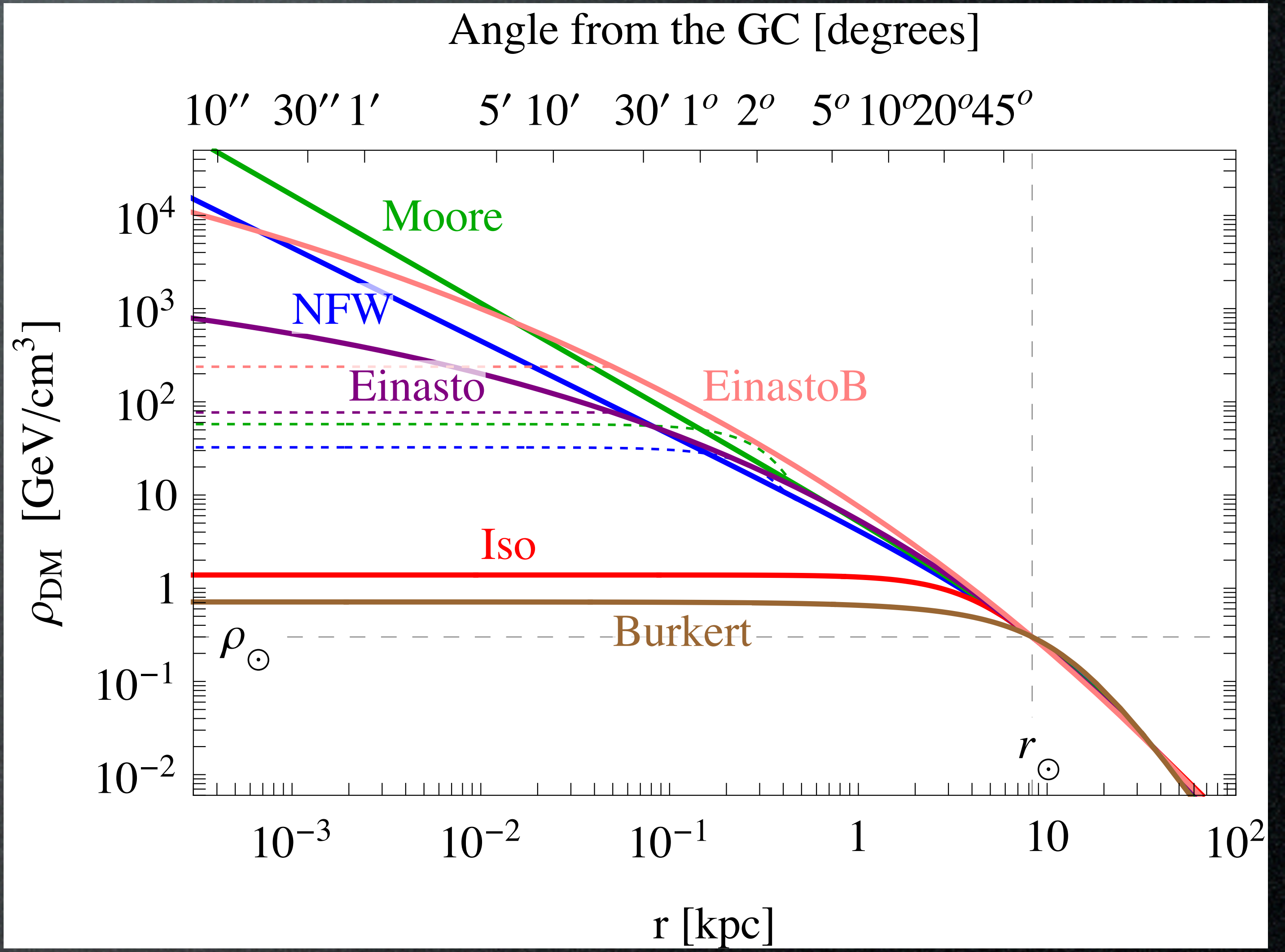
DM halo profiles

From N-body numerical simulations:

$$\begin{aligned}
\text{NFW}: \quad \rho_{\rm NFW}(r) &= \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \\
\text{Einasto}: \quad \rho_{\rm Ein}(r) &= \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\} \\
\text{Isothermal}: \quad \rho_{\rm Iso}(r) &= \frac{\rho_s}{1+(r/r_s)^2} \\
\text{Burkert}: \quad \rho_{\rm Bur}(r) &= \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)} \\
\text{Moore}: \quad \rho_{\rm Moo}(r) &= \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}
\end{aligned}$$

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?)