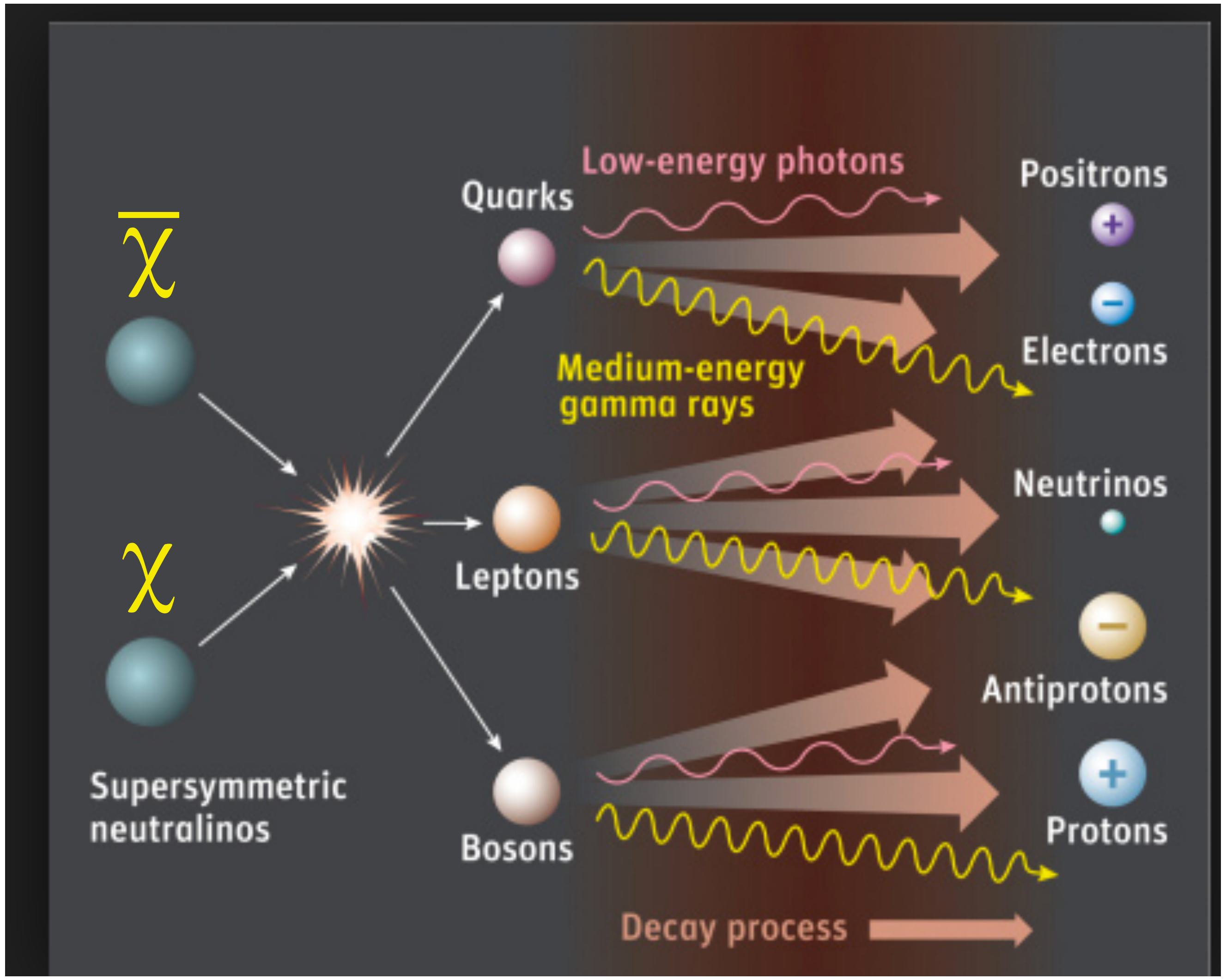
INDIRECT DARK MATTER DETECTION



http://www.mpi-hd.mpg.de/lin/research_DM.en.html

Ivone Freire Mota Albuquerque
IFUSP

Invisibles School - Durham - July 2013

Outline

Lecture 1

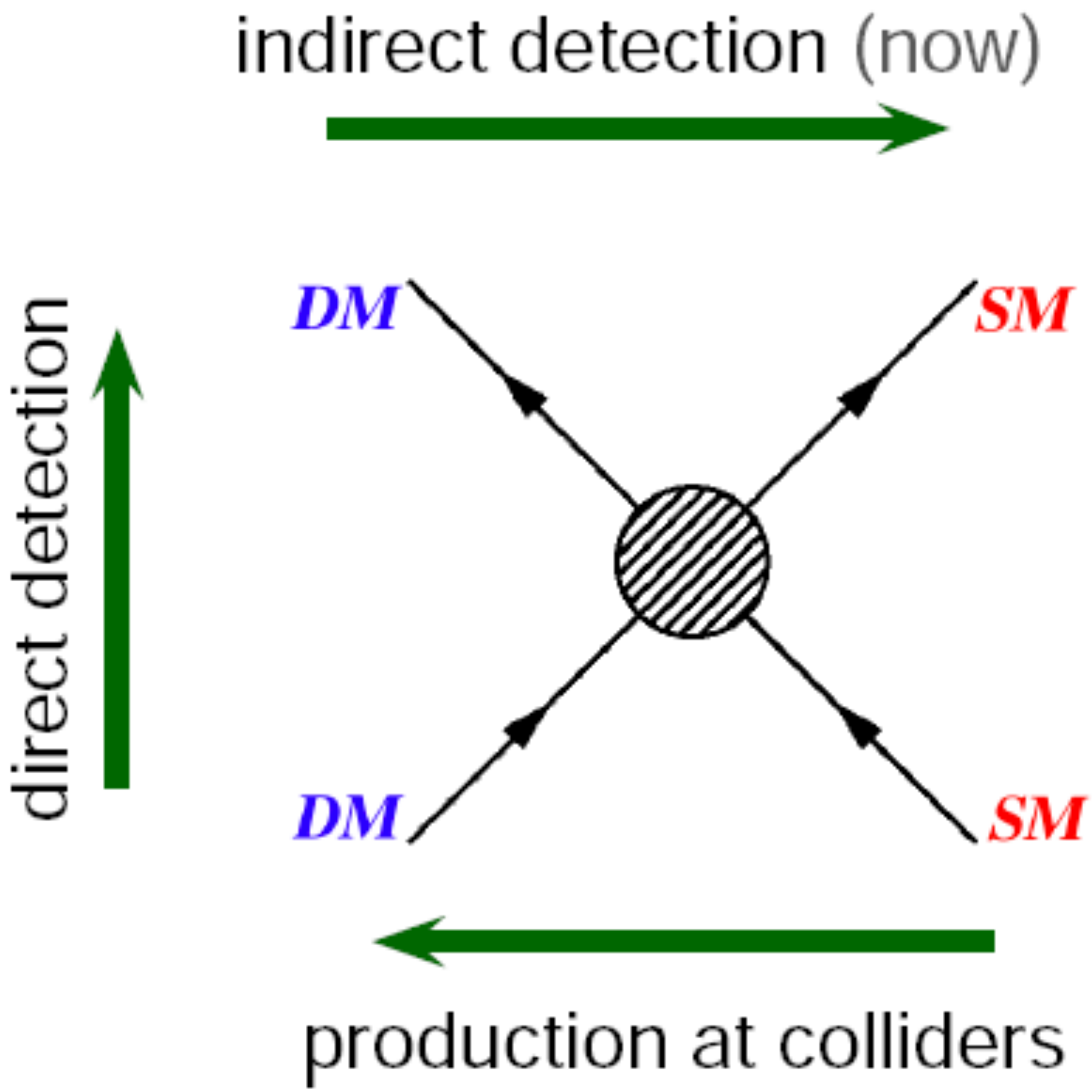
1. DM indirect searches
2. DM annihilation in the Early Universe
3. DM annihilation products
4. DM capture and annihilation rates
5. SIMPs exclusion as a study case

Neutrinos

Lecture 2

Neutrinos + Gammas

Indirect Detection



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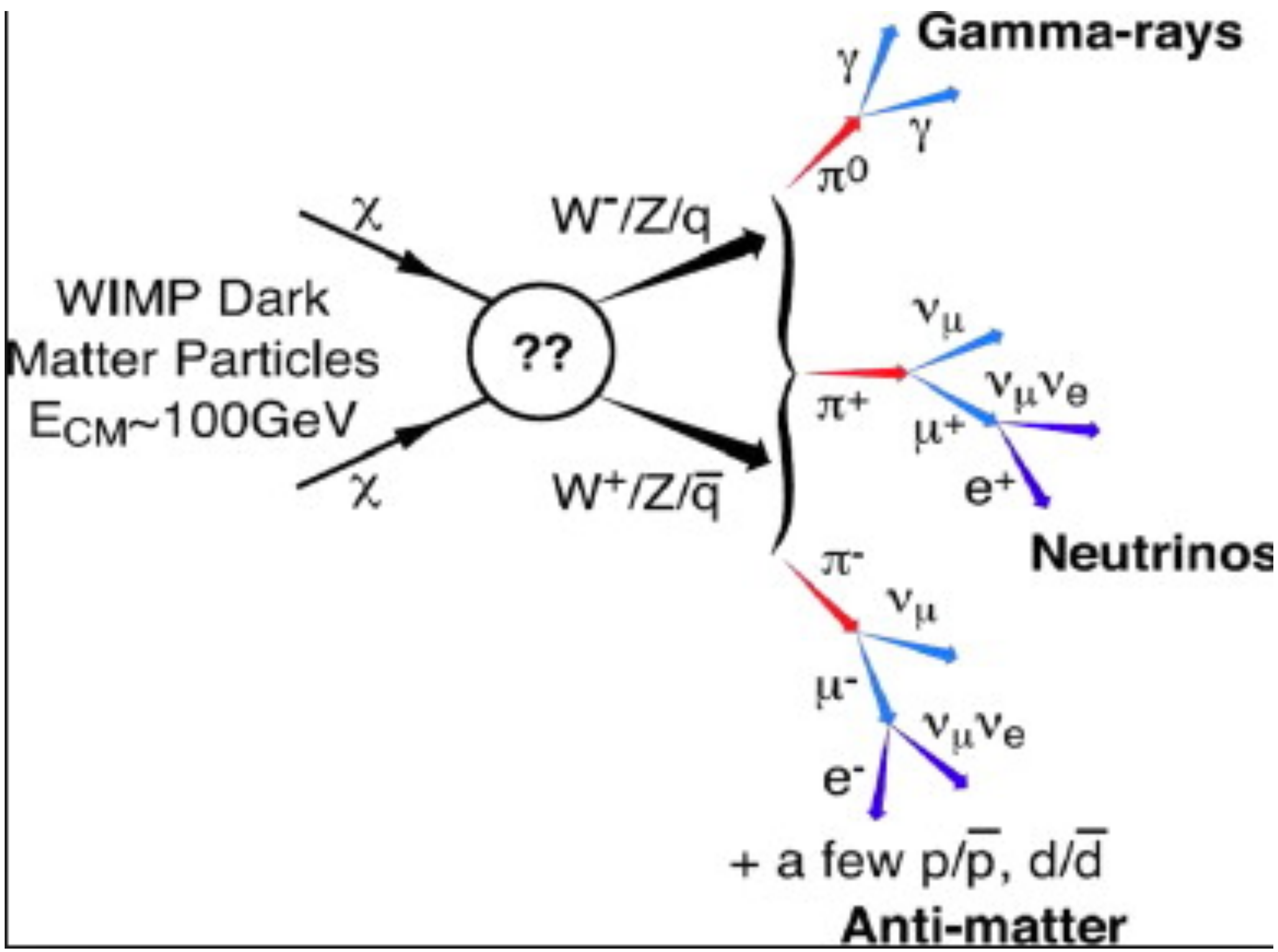
Possible Processes

DM Annihilation



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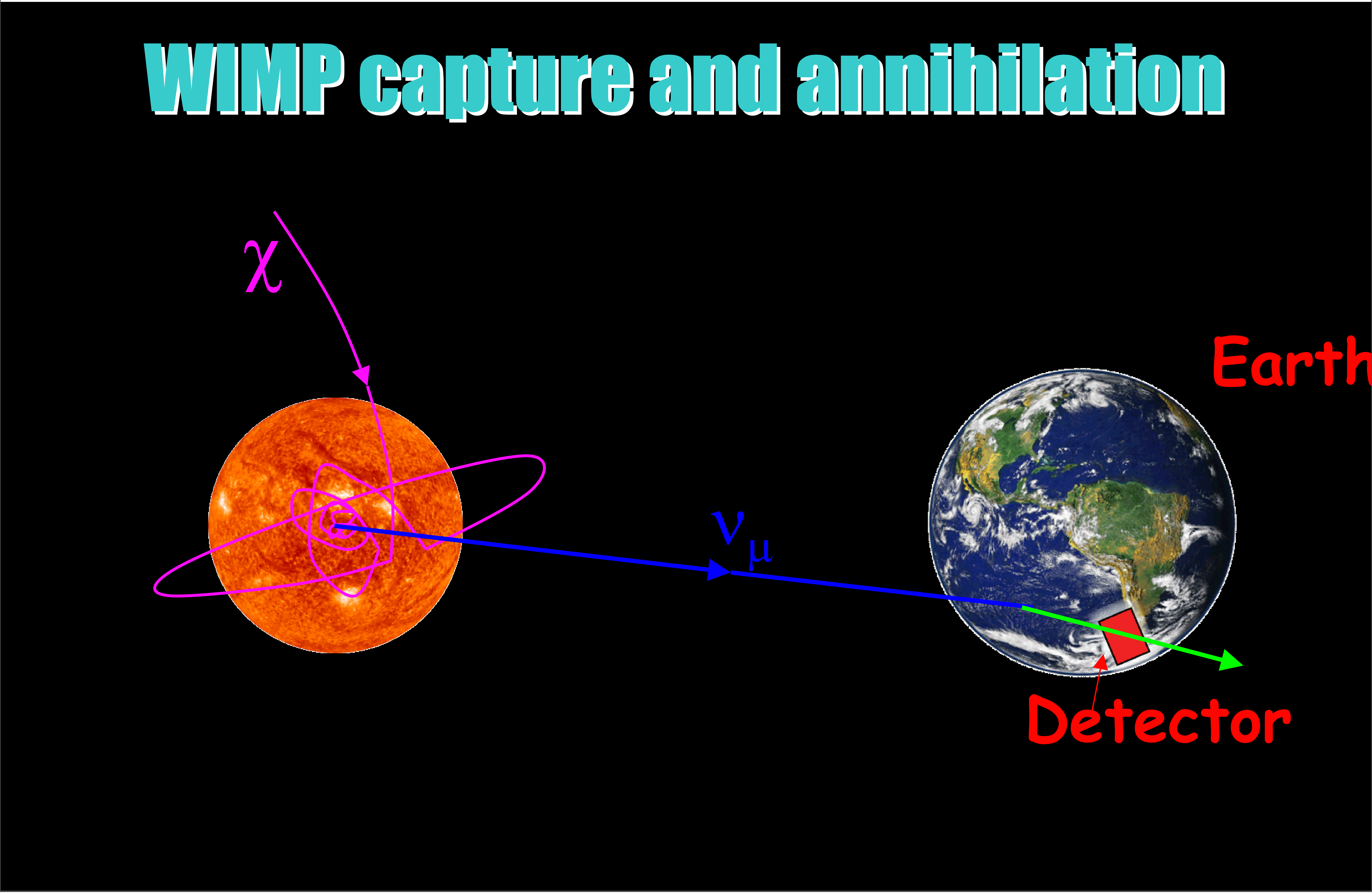
DM Decay

Indirect Searches



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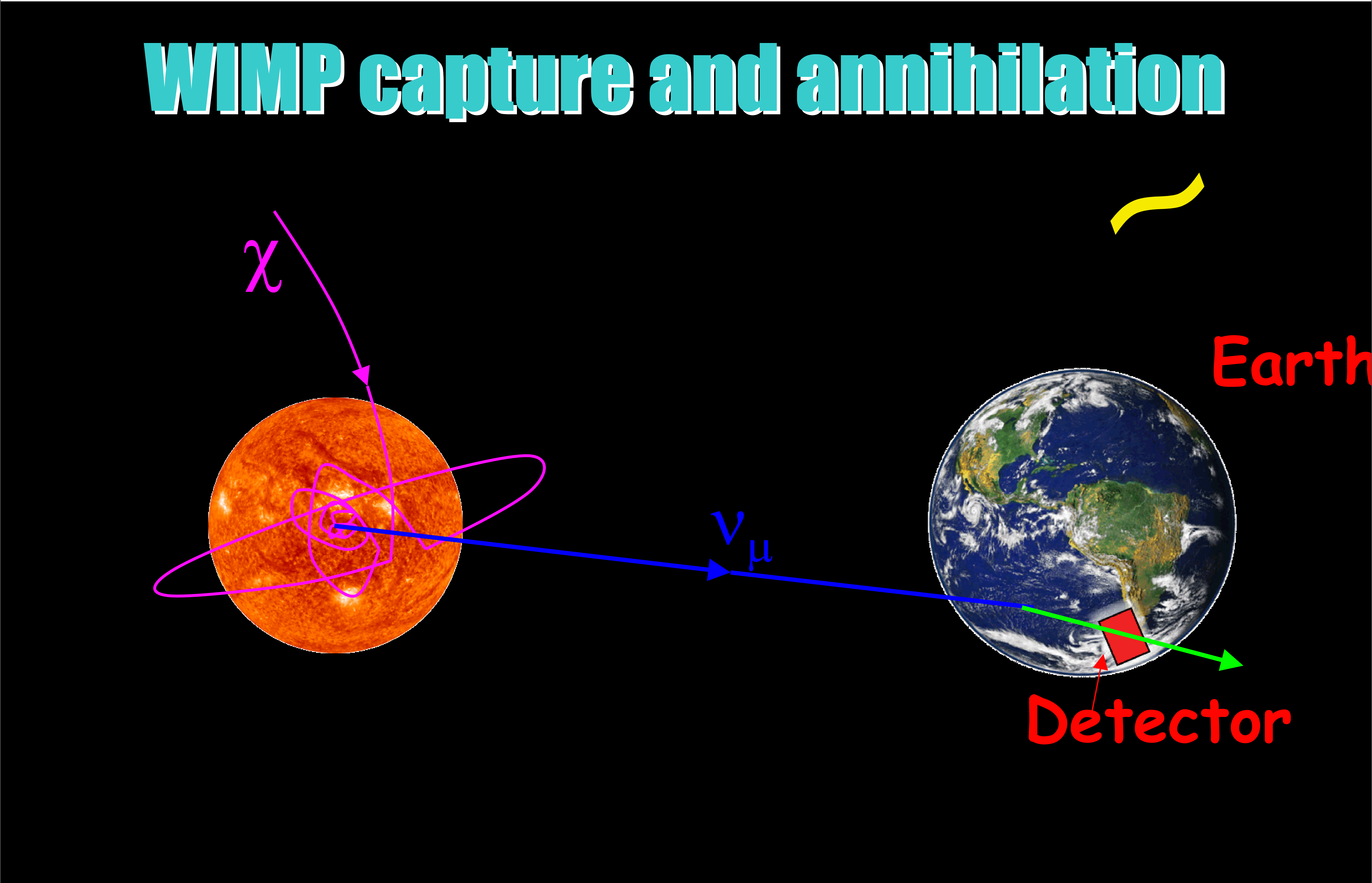
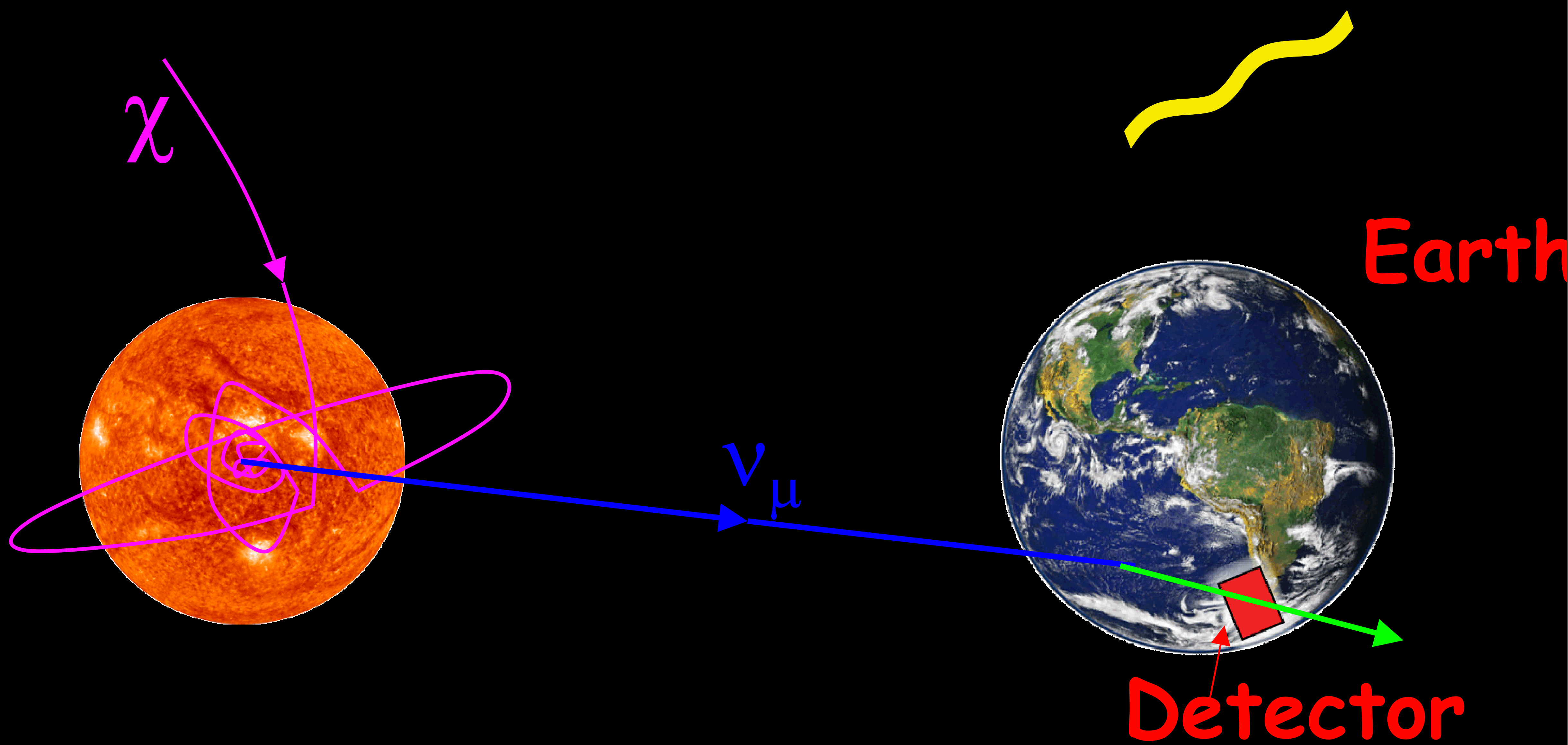


Indirect Searches

WIMP capture and annihilation



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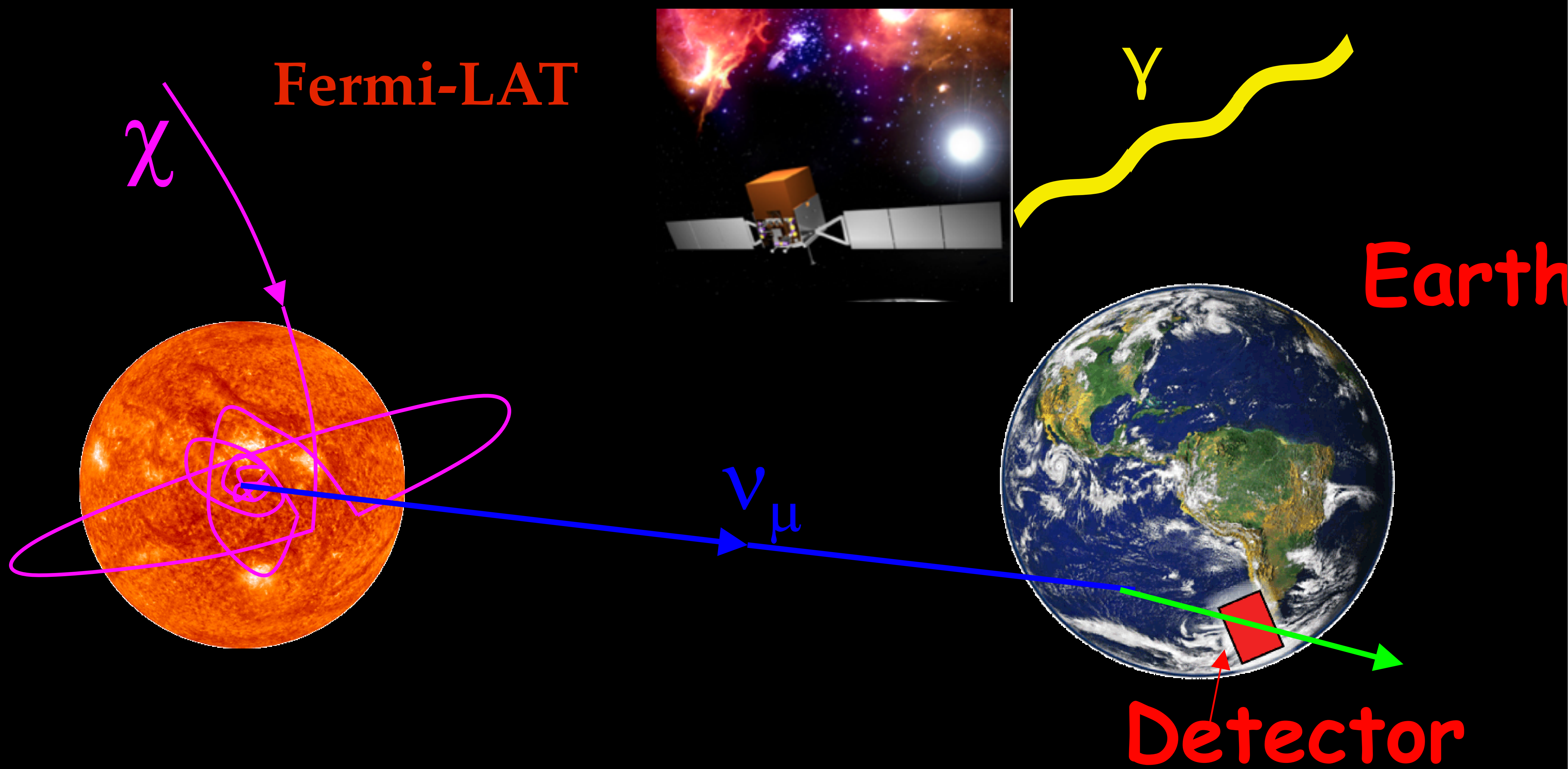

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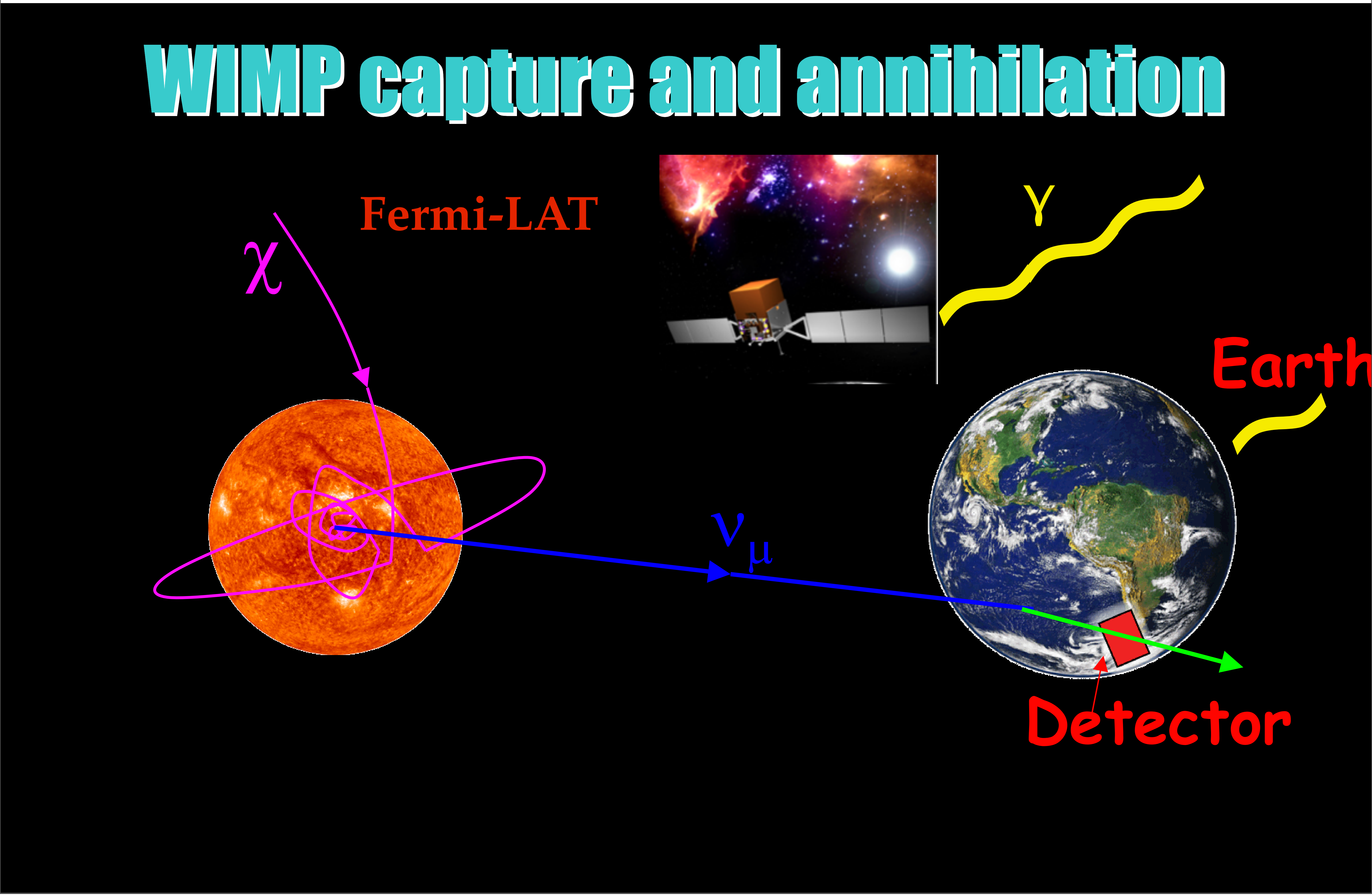

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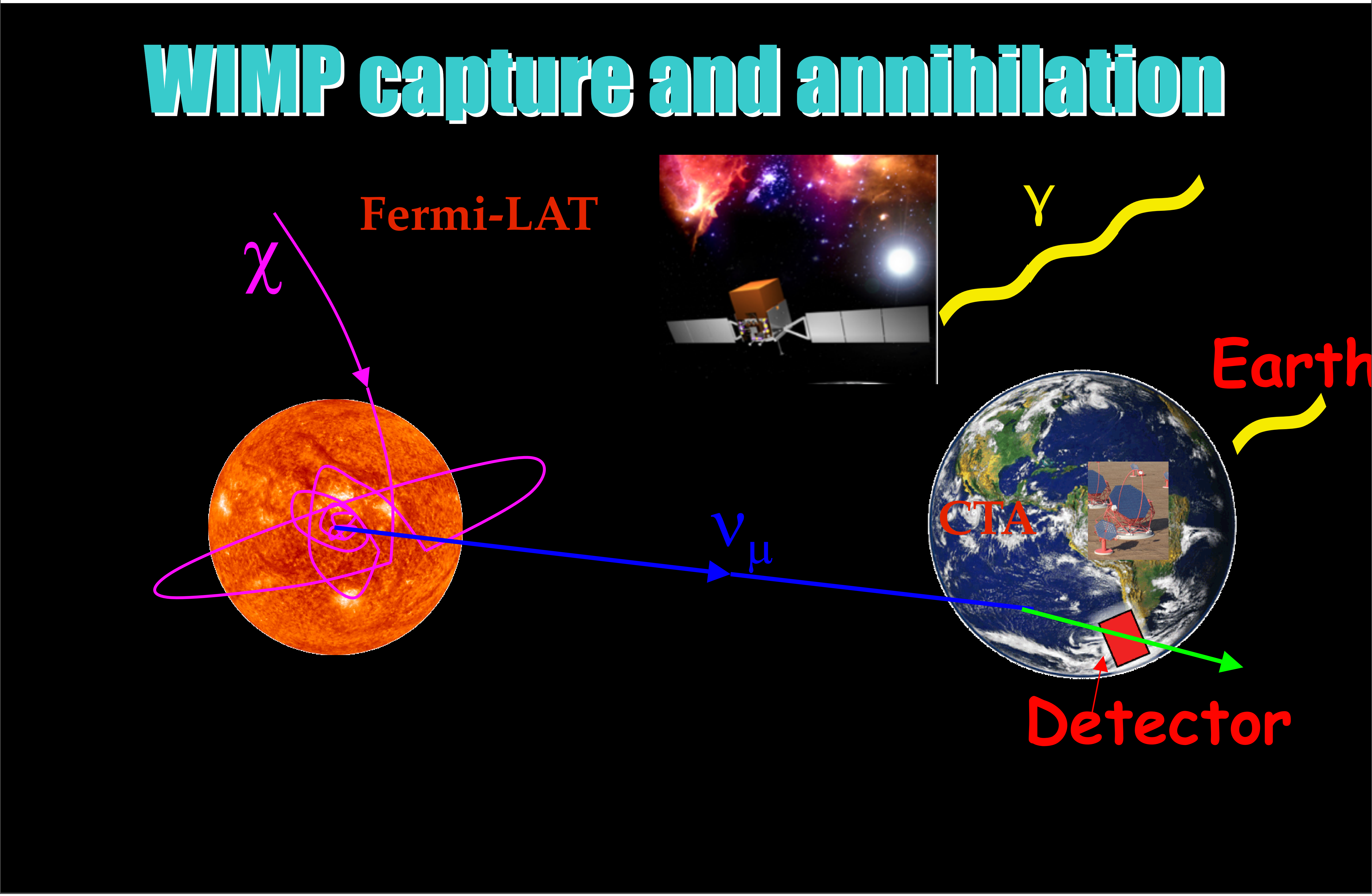

DM Capture and Annihilation

- DM Capture

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  $\rightarrow \rho_\chi$; m_χ ; $\sigma_{\chi N}$ (sd or si) ; v_χ

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Production at Early Universe

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- Annihilation products (SM particles)

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ν: point to their sources; easily reach us;

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backgrounds

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backgrounds

- Detection rate

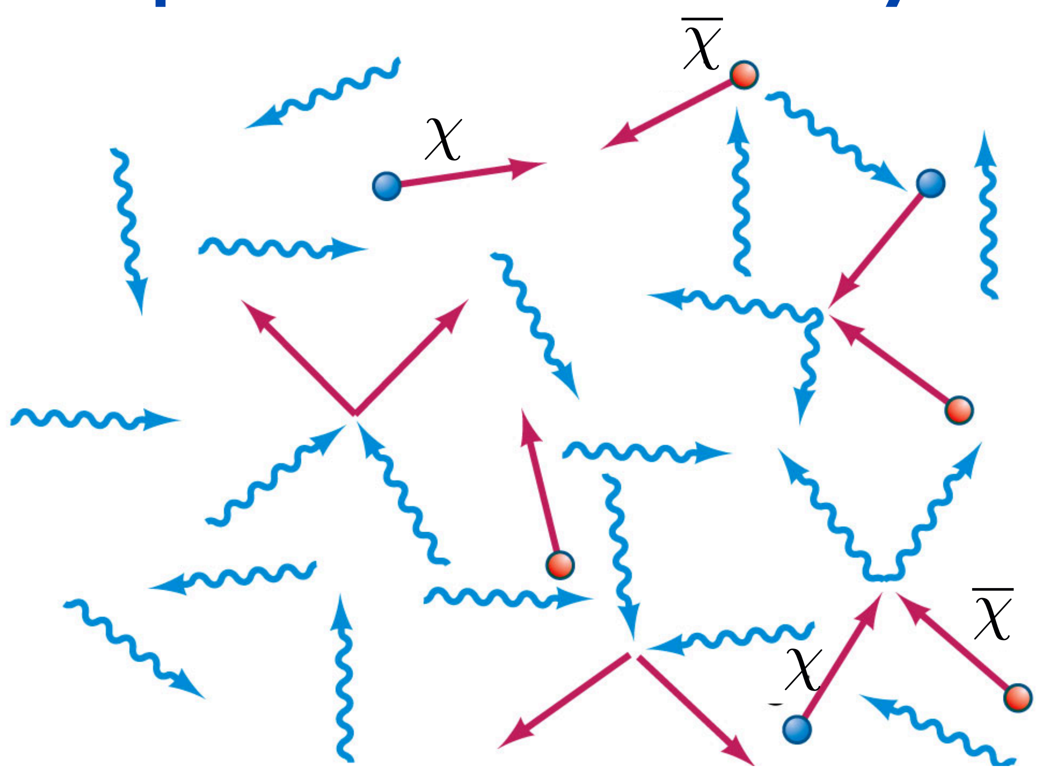
  → propagation / energy losses

DM Production

- Annihilation XS

→ production mechanism (Early Universe)

★ thermal equilibrium in Early Universe



$$\mathbf{\Gamma = n < \sigma_A v >}$$

$$\mathbf{\Gamma > H(t)}$$

★ connection to key parameters (ρ_χ ; m_χ ; σ_A ; v_χ)

★ non thermal production (axions, super massive DM)

Early Universe

Thermodynamics & Statistical Mechanics

-N DM particles => Boltzmann equation:

Expansion of the Universe

Annihilation Rate

$$\frac{dn_i}{dt} = -3\,H\,n_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i\, n_j - n_i^{eq}\, n_j^{eq} \right)$$

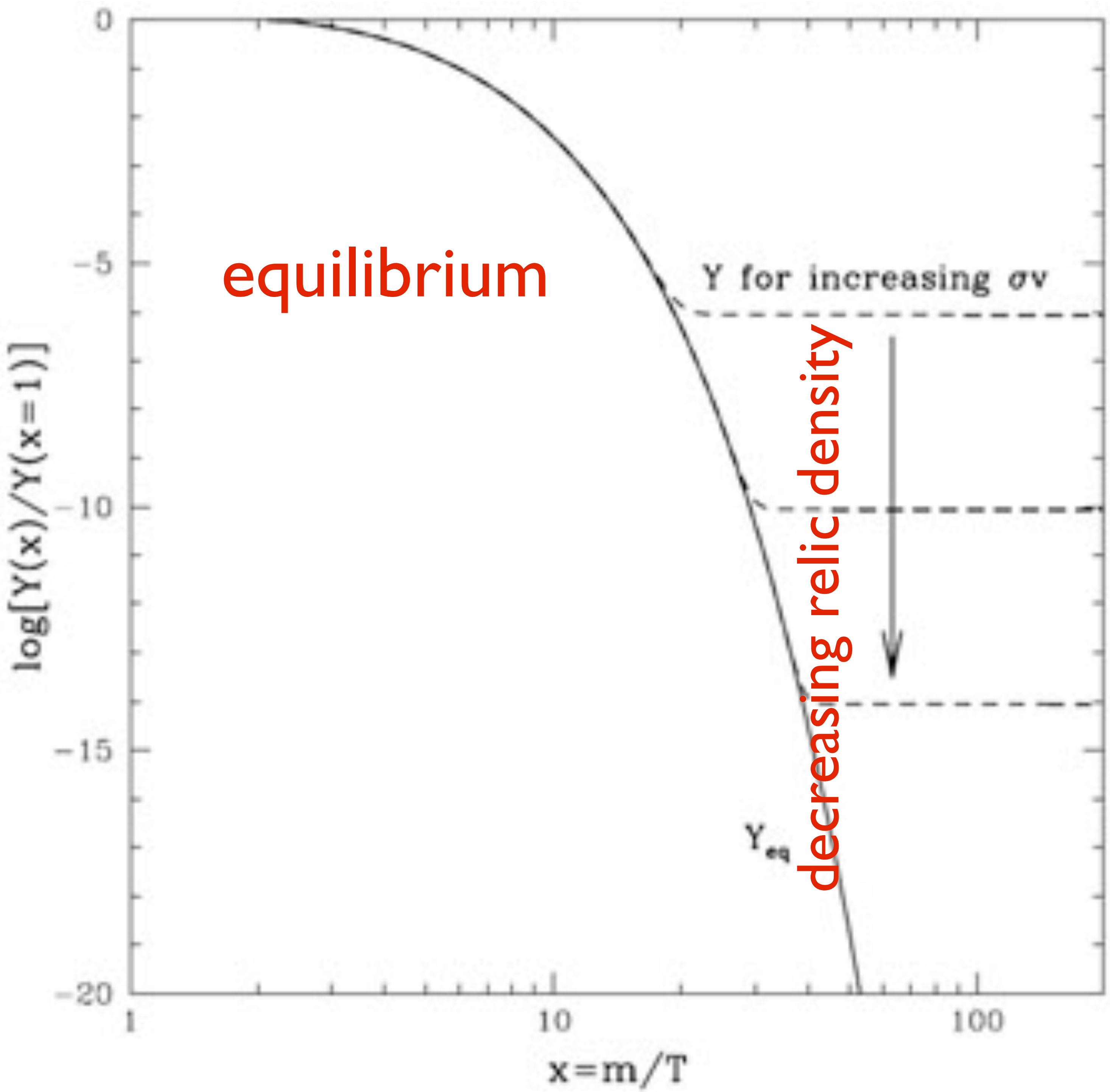
$\chi\bar{\chi} \to f\bar{f}$

$f\bar{f} \to \chi\bar{\chi}$

Katherine Garrett and Gintaras Dūda, "Dark Matter: A Primer," Advances in Astronomy, (2011)

DM Freezes Out

comoving relic density



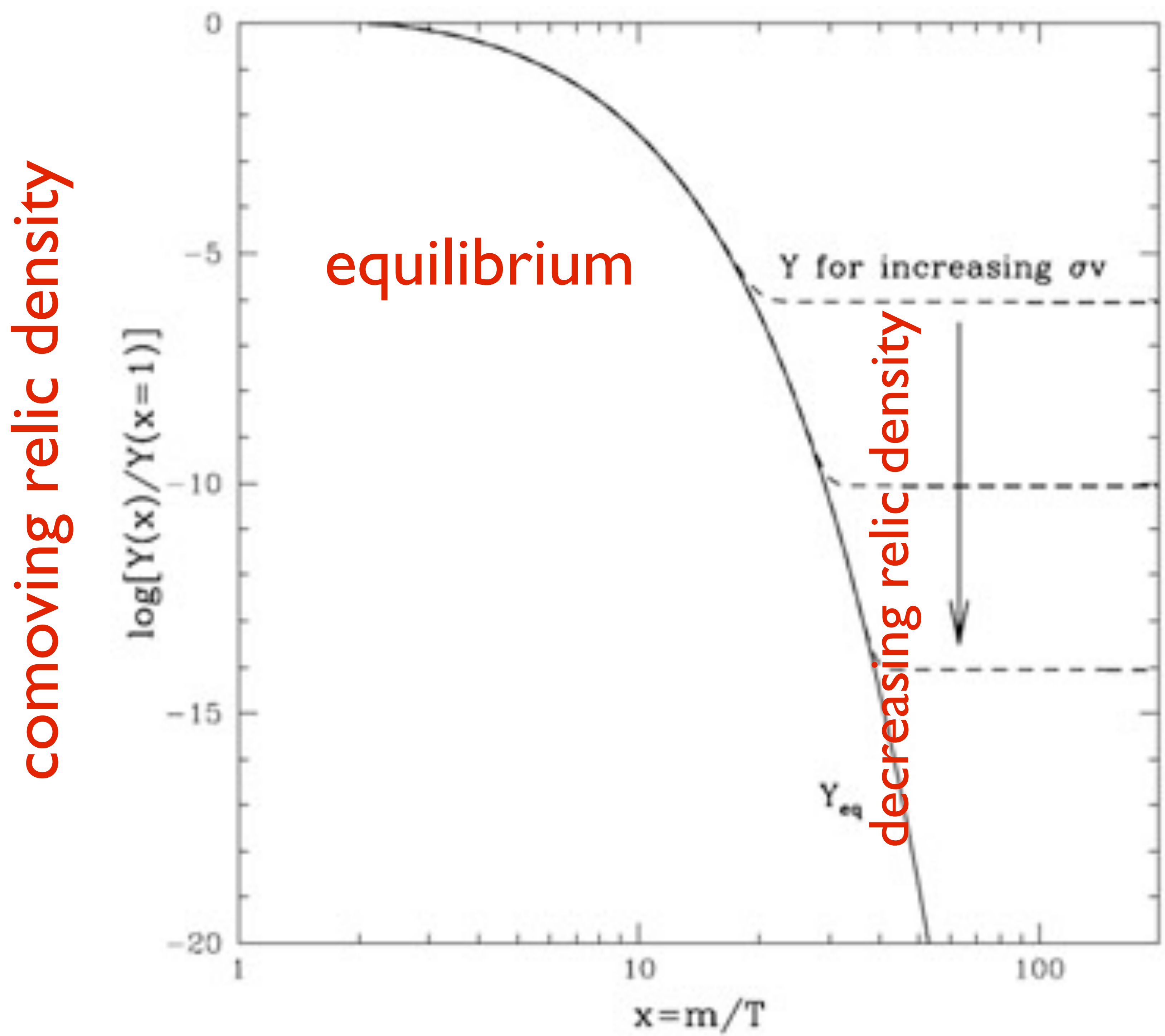
$Y = n / s$

--- freeze out
(current abundance)

analytical approximation
to Boltzmann eq.

Plot: Rocky Kolb and M. Turner: The Early Universe
Frontiers in Physics

DM Freezes Out



$Y = n / s$

--- freeze out
(current abundance)

weakest
larger abundance

analytical approximation
to Boltzmann eq.

Plot: Rocky Kolb and M. Turner: The Early Universe
Frontiers in Physics

WIMP Abundance

If DM is a thermal relic, massive and weakly interacting

Freeze out condition: $\mathbf{\Gamma_A = n_\chi < \sigma_A v > = H(t)}$

Freeze out temperature can be determined: $T_{fo} \sim m_\chi/\mathbf{20}$

Early Universe (radiation dominated):

$$\mathbf{H = \frac{1.66 g_*^{0.5} T^2}{m_{pl}}} \qquad \mathbf{s \simeq 0.4 g_* T^3}$$

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$$Y_{fo} = \left(\frac{n_\chi}{s}\right)_{fo} = \left(\frac{n_\chi}{s}\right)_o \simeq \frac{100}{m_\chi \, m_{pl} \, g_*^{0.5} \, \sigma_A < v >}$$

$$\left(\frac{n_\chi}{s}\right)_o \simeq \frac{10^{-8}}{(m_\chi/\mathrm{GeV})(\sigma_A < v > /10^{-27} \mathrm{cm}^3 \, \mathrm{s}^{-1})}$$

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$$\Omega_\chi h^2 = \frac{h^2 \rho_\chi}{\rho_c} = \frac{h^2 \, m_\chi \, n_\chi}{\rho_c} \qquad \rho_c \simeq 10^{-5} \, h^2 \, \mathrm{GeV \, cm}^{-3}$$

WIMP ``Miracle''

$$\Omega_\chi h^2 \simeq \left(\frac{3 \times 10^{-27} \mathrm{cm}^3\, \mathrm{s}^{-1}}{< \sigma_A v >}\right)$$

$$\sigma(\mathrm{weakscale}) \sim \frac{G_F^2}{m_W^2} \qquad m_W \sim 100\, \mathrm{GeV} \qquad v = c/3$$

$$\Rightarrow \sigma_A v \sim \vartheta(10^{-26})\, \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\Omega_\chi = 0.1\, h^{-2}$$

DM abundance!

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DM abundance!

Exercise 1: Redo this calculation.

Non Thermal Production

$$\underline{\mathbf{m}_\chi \ \ \mathbf{upper\ \ limit:}} \quad \sigma_{\mathbf{A}} \downarrow \quad \mathbf{m}_\chi \uparrow$$

$$\Rightarrow \ \Omega_\chi \mathbf{h}^2 \leq \mathbf{1} \ + \ \mathbf{Unitarity} \ \Rightarrow \ \mathbf{m}_\chi \leq \vartheta(\mathbf{100TeV})$$

(thermally produced)

- super massive DM (wimpzillas, simpzillas):

→ non-thermally produced at much later times

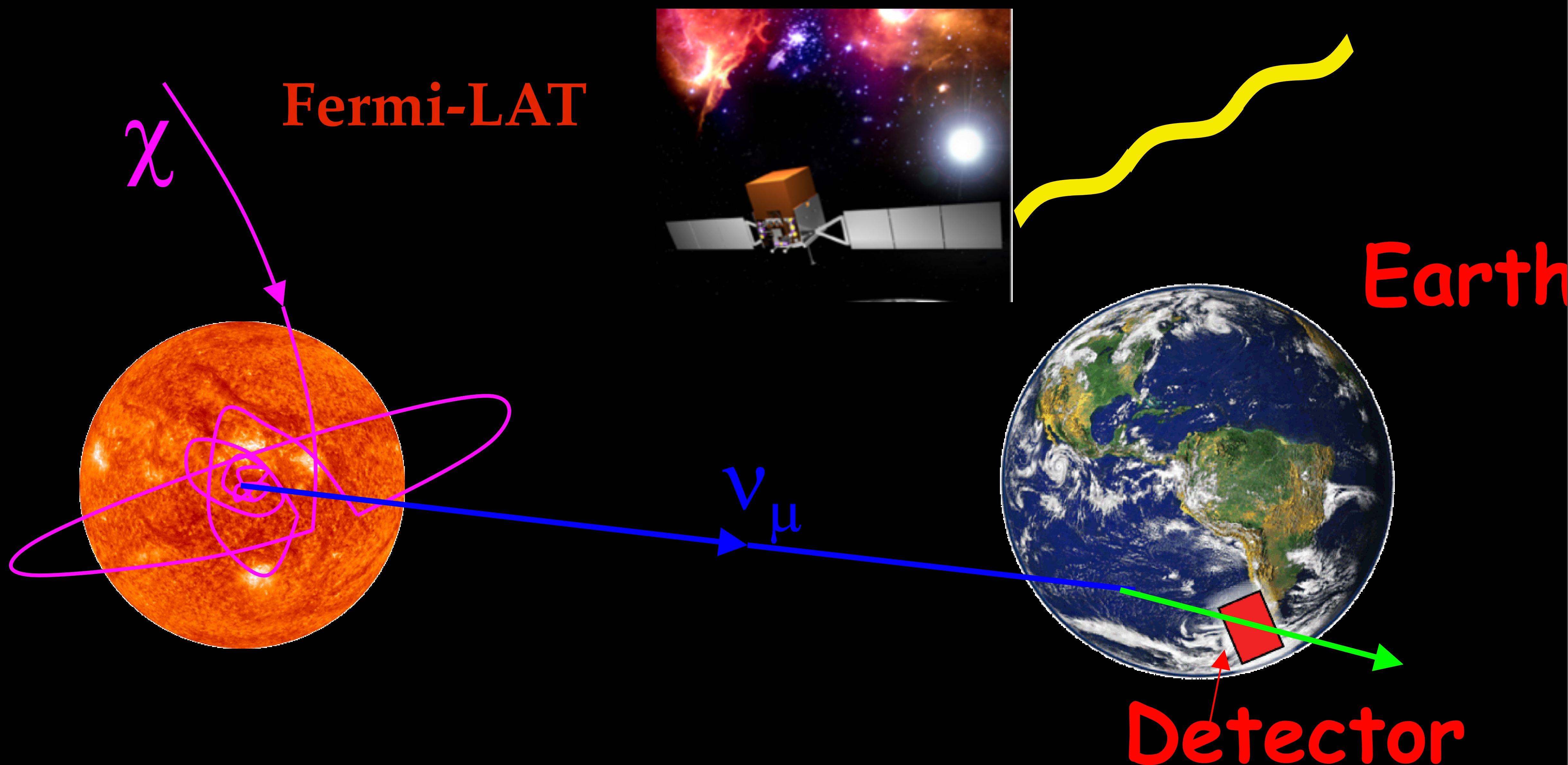
→ low interaction rate such that thermal equilibrium never happened

- axions

- asymmetric DM: dark baryon with m ~ 5 GeV

Indirect Searches

WIMP capture and annihilation



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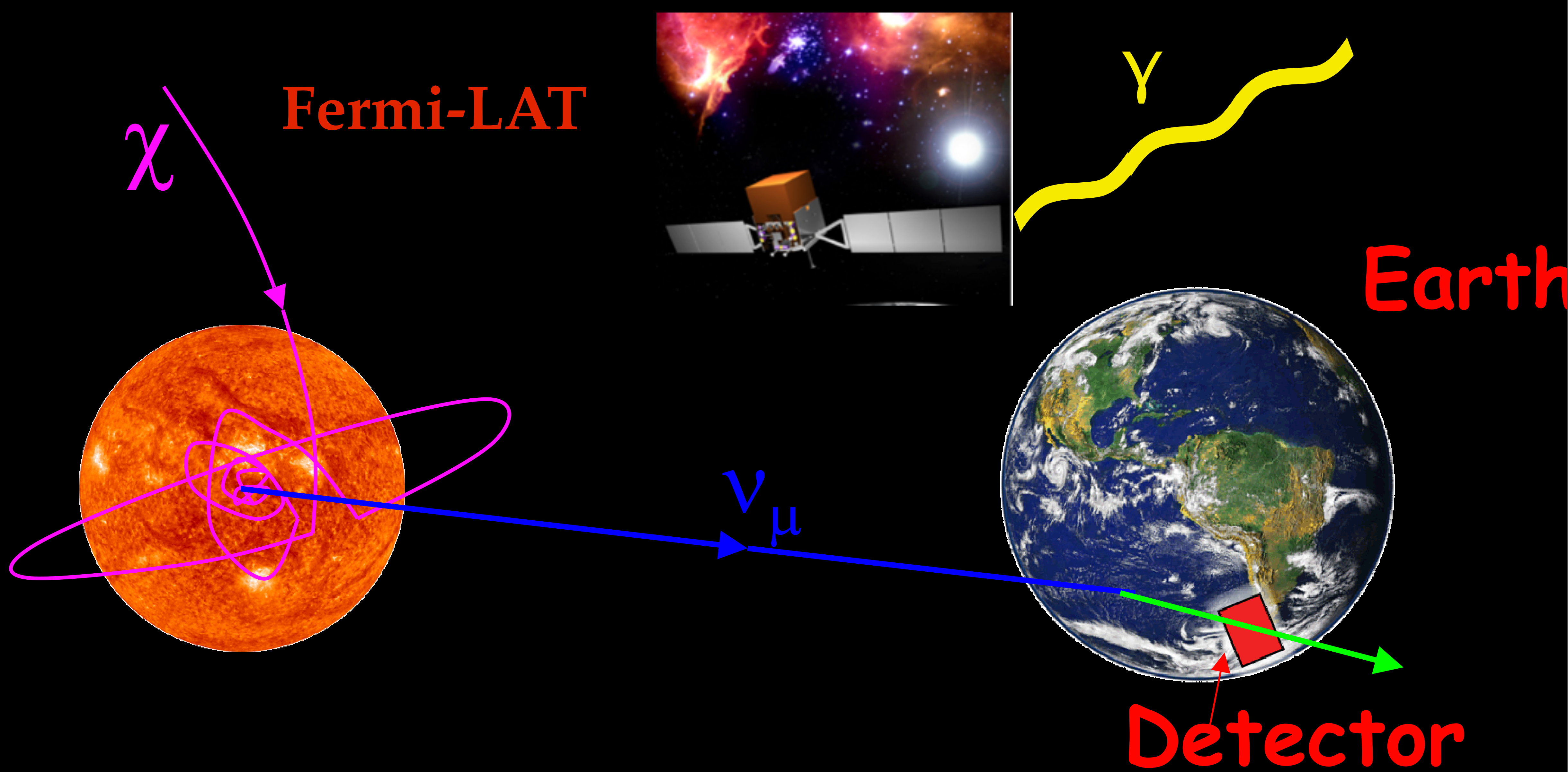
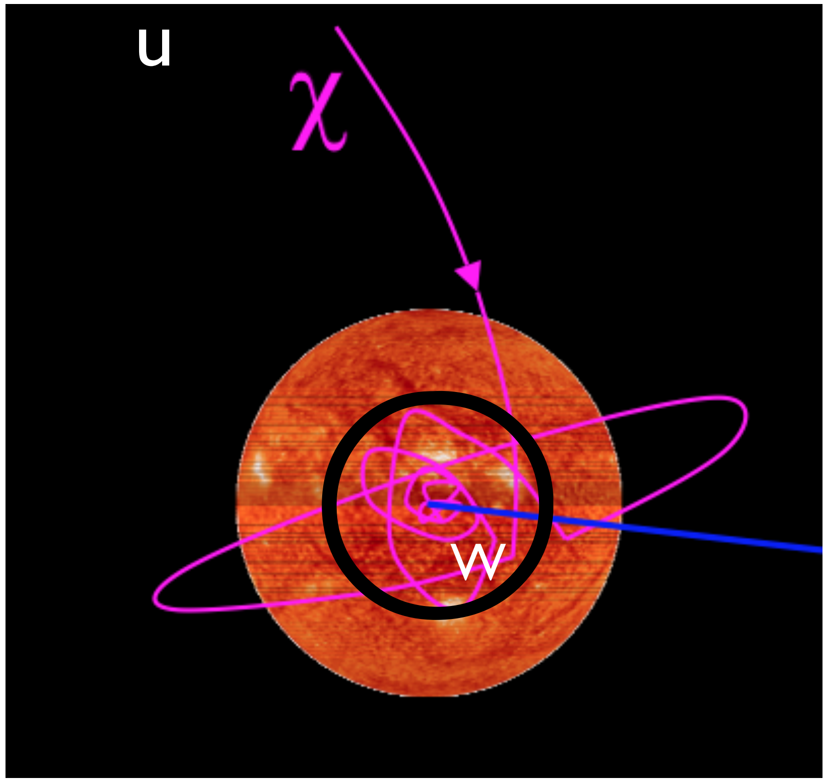


DM Capture

- take Sun and/or Earth as examples



- capture probability:

$$\mathbf{M}_\chi\ ;\ \ \sigma_{\chi\mathbf{N}}\ ;\ \ \mathbf{v}_\chi\ ;\ \ \mathbf{n_t}\ ;\ \ \rho_\chi$$

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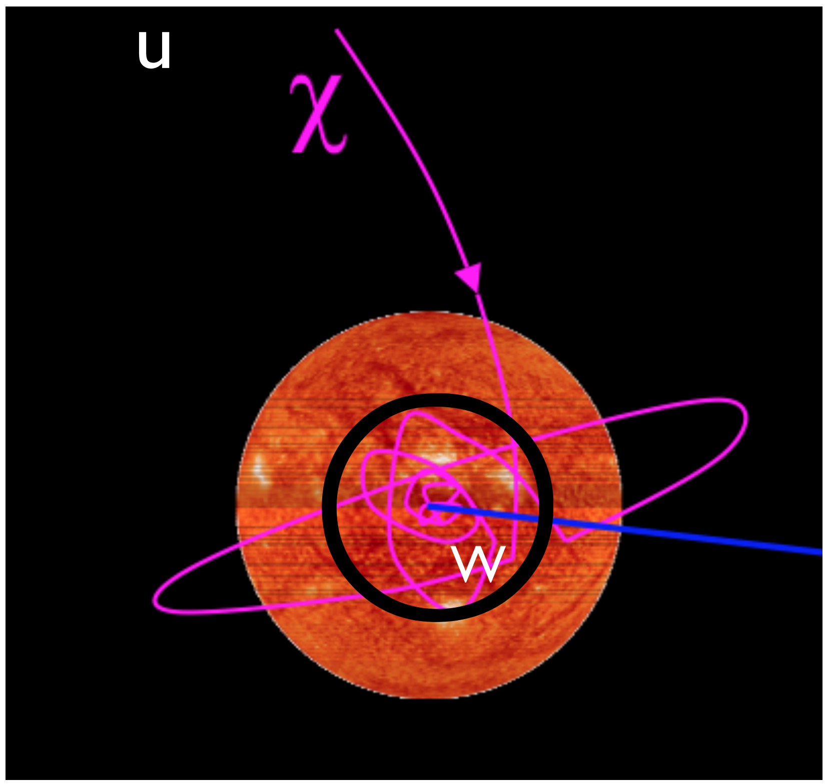

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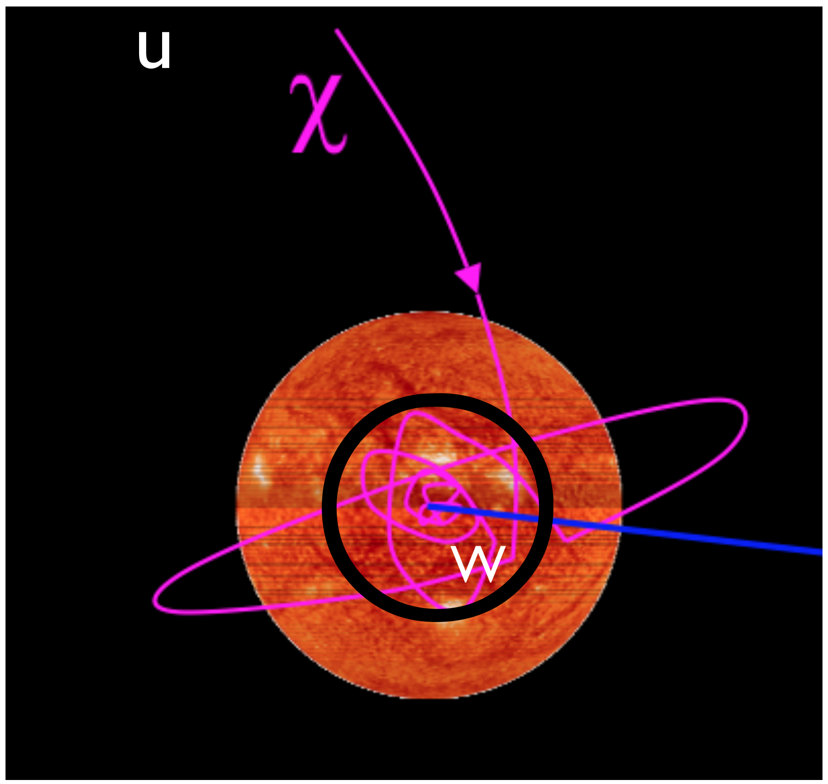

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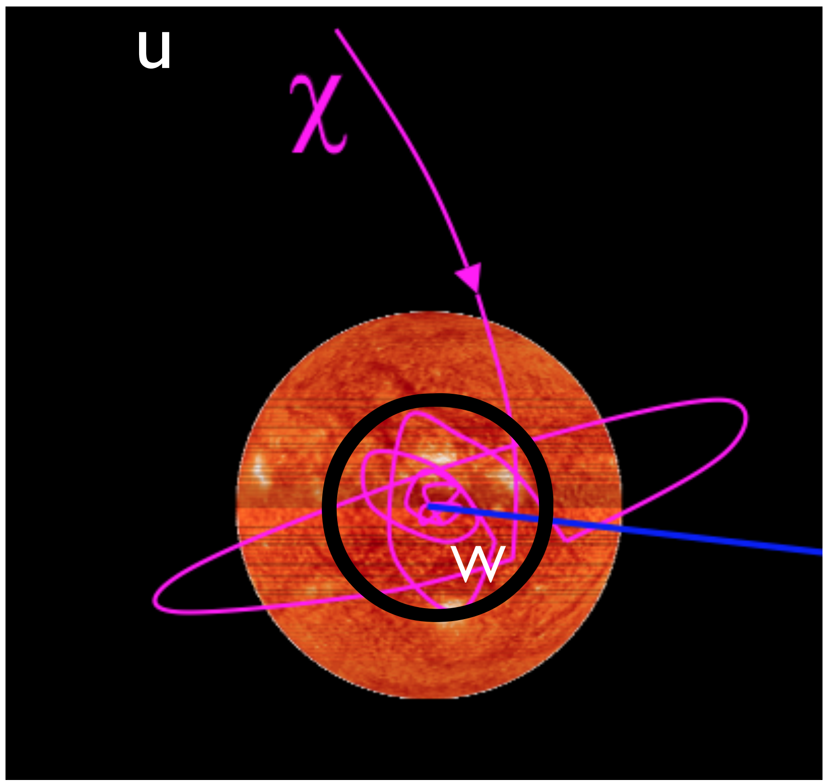

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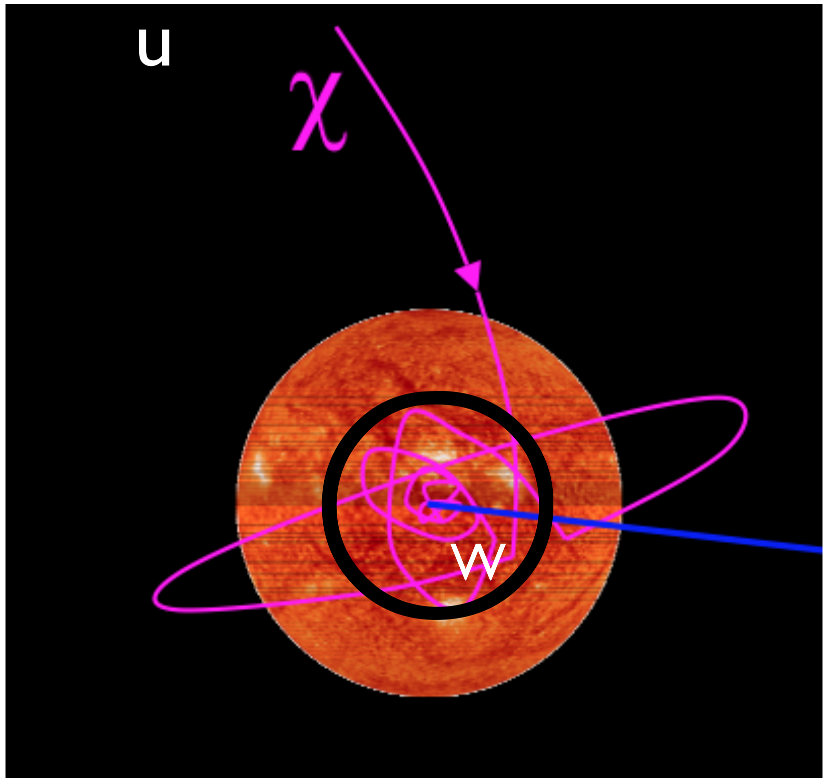

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- χ speed distribution f(u): $\mathbf{f(\vec{u})d^3u}$

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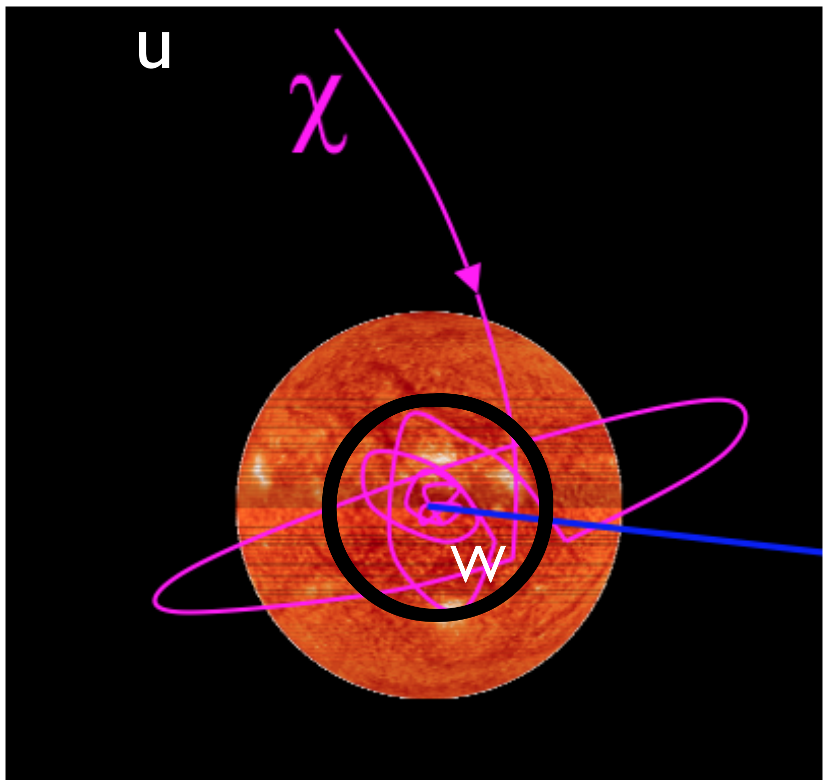

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$$\mathbf{F}_{\mathbf{in}} = \frac{\mathbf{1}}{\mathbf{2}} \int\int \mathbf{f}(\mathbf{u})\mathbf{du}\,\vec{\mathbf{u}} \cdot \hat{\mathbf{n}}\mathbf{dS}$$

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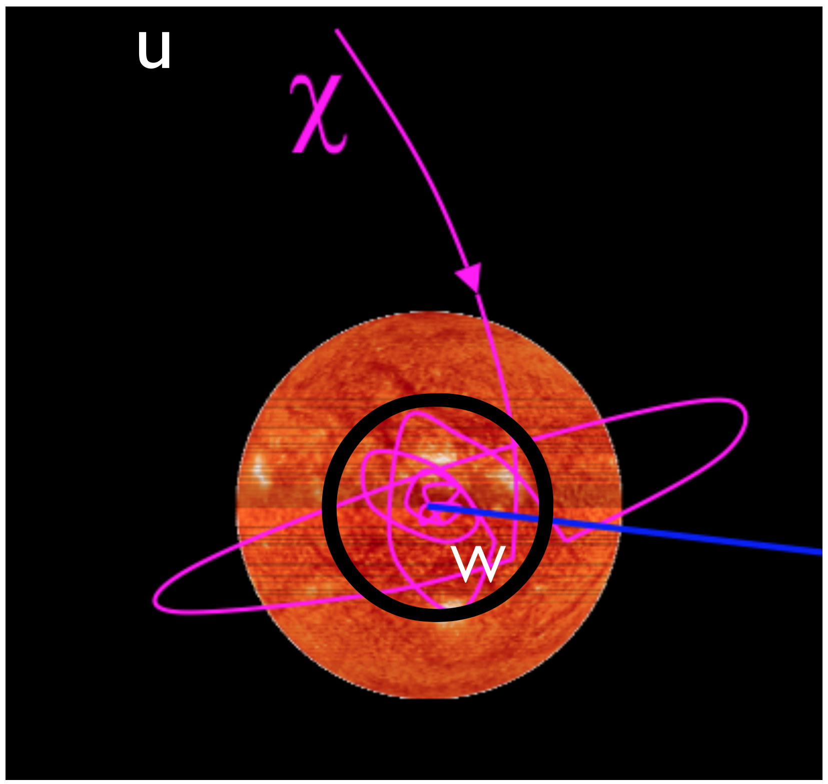

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$$\mathbf{J} = \mathbf{R\,u}\sin\theta$$

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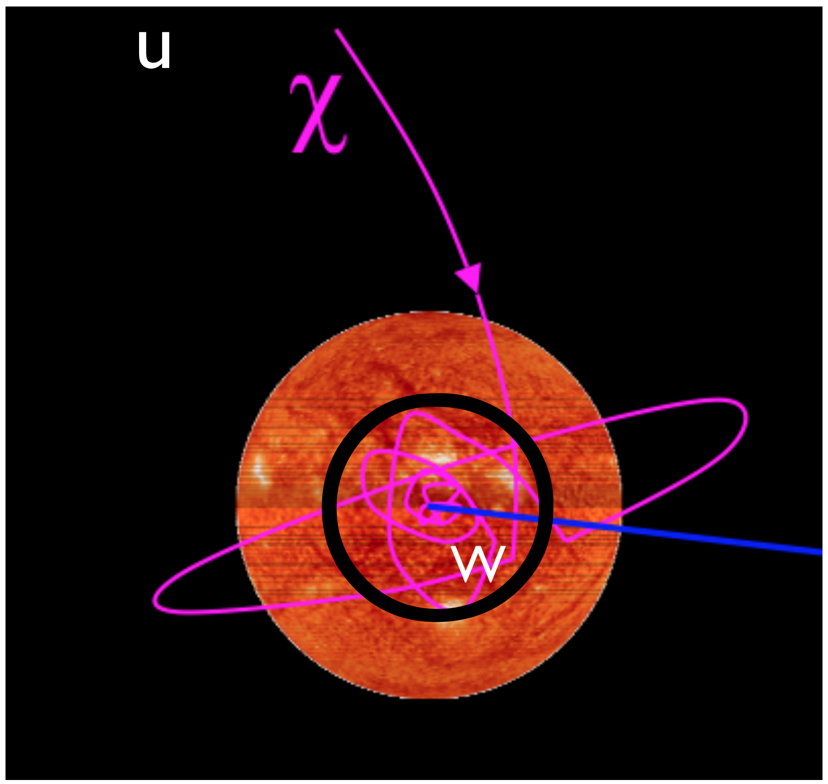

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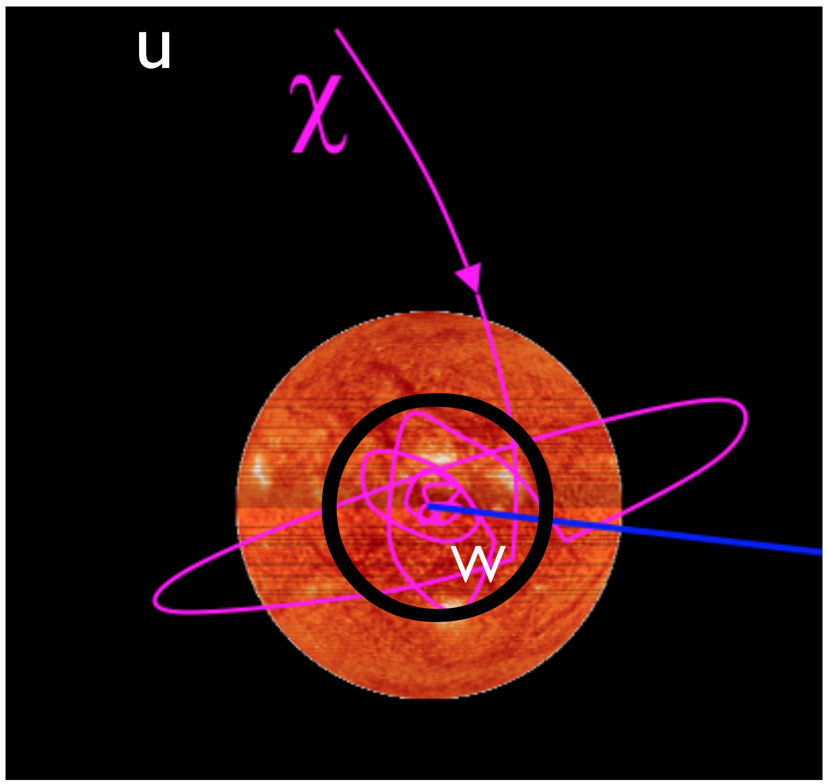

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Press & Spergel - Astrophys.J. 296 (1985)
A. Gould - Astrophys.J. 388 (1991)
Jungman,Kamionkowski, Griest - Phys. Rep. 267 (1995)

DM Capture

- scattering rate: $\mathbf{\Omega(w) = n_t \, \sigma_{\chi N} \, w}$

DM Capture

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- fractional energy loss:

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DM Capture

- scattering is isotropic: $$\mathbf{P_{cap}} = \frac{\frac{4M_\chi m_N}{(M_\chi + m_N)^2} - \left(\frac{u}{w}\right)^2}{\frac{4M_\chi m_N}{(M_\chi + m_N)^2}}$$

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$$\frac{d\Gamma_c}{dV} = \int \frac{f(u)}{u}\, w\, n_t\, \sigma_{\chi N}\, P_{cap}\, du$$

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capture is more efficient for $M_\chi \sim m_N$

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capture is more efficient for $M_\chi \sim m_N$

otherwise kinematically suppressed

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otherwise kinematically suppressed

- capture rate per shell volume: $$\frac{d\Gamma_C}{dV} = \int \frac{f(u)}{u}\, w\, \Omega(w)\, P_{cap}\, du$$

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- XS form factor suppression => if momentum transfer is not small compared to nucleus radius

Capture in the Sun and Earth

$$\mathbf{\Gamma_{C^{SI}} = K \frac{\rho_\chi}{0.3\,GeV/cm^3} \frac{270\,km/s}{v_\chi} \frac{100\,GeV}{M_\chi} \sum_{i_{nuc}} F_i(M_\chi) \frac{\sigma_{\chi N_i}}{10^{-42}\,cm^2} f_i \phi_i\, S(M_\chi/m_{N_i})\, s^{-1}}$$

form factor

kin suppression

$K_{\odot} \sim 10^{21}$ $K_{\oplus} \sim 10^{12}$

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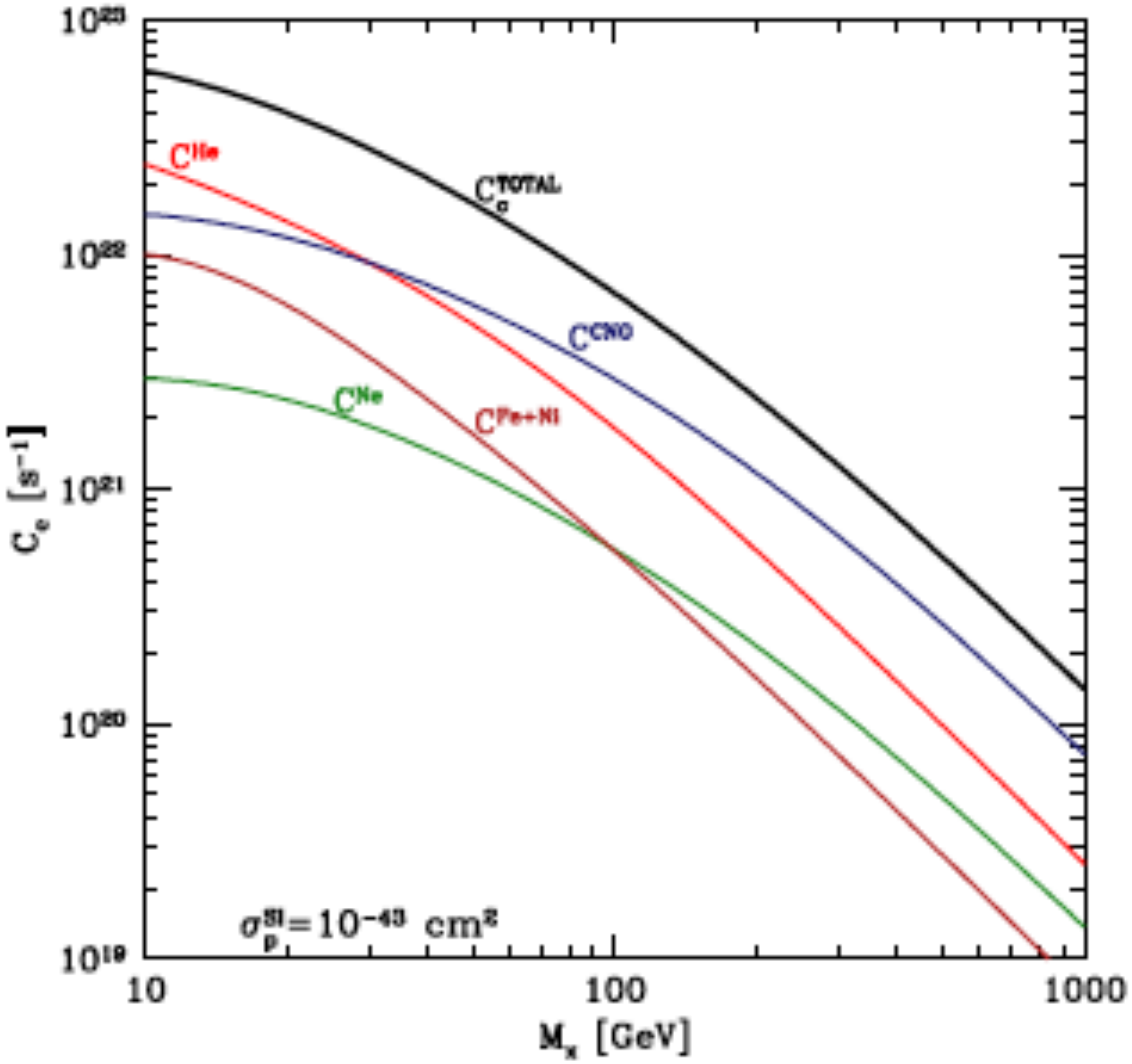
EARTH: XS is spin independent
SUN: SD (H) + SI

Capture in the Sun



Zentner, PRD 80 (2009)

XS: spin independent

Annihilation Rate

- DM time evolution: $\dot{\mathbf{N}} = \mathbf{\Gamma_C} - \mathbf{2\Gamma_A}$

$$\mathbf{\Gamma_A} = \frac{\mathbf{N}}{\mathbf{2}}\mathbf{\Gamma_I}$$

$$\mathbf{\Gamma_I} = \mathbf{n} < \sigma_{\mathbf{A}}\mathbf{v} > \quad \textbf{where } \mathbf{n} \equiv \chi \textbf{ density in the Sun}$$

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Annihilation rate is maximum at equilibrium

Annihilation in the Sun and Earth

1 TeV DM ; $\sigma_{\chi N} = 10^{-42}\mathrm{cm}^2$

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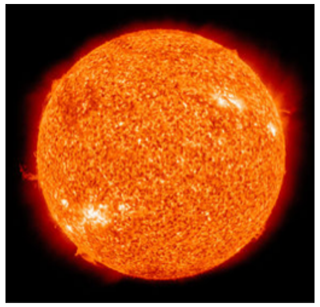

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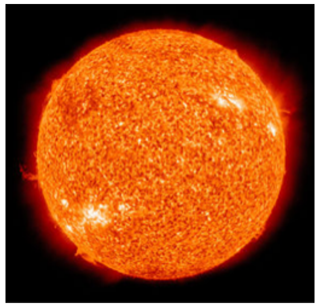

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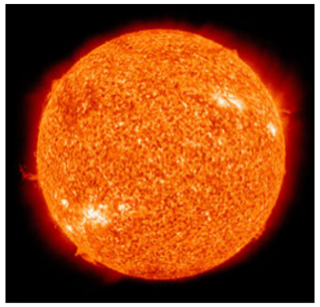

$$\tau_\odot \sim 5 \times 10^7\, y$$

In equilibrium for a long time

Beyond the SM

Cosmology and particle physics complement each other

While cosmology requires DM, particle physics (extensions of the SM) independently offers many candidates (LSP, LKKP, ...)

→ stable particles which annihilate into SM particles

Annihilation Products

$$\chi + \overline{\chi} \to \textbf{SM} \quad \textbf{particles}$$

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Entirely model dependent!

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Look for channels which produce these particles

Possible SM Products

$$\chi + \overline{\chi} \rightarrow \mathbf{SM \quad particles}$$

- primary products: $\mathbf{t\bar{t}}\,,\ \mathbf{b\overline{b}}\,,\ \mathbf{W^+W^-}\,,\ \mathbf{Z^0Z^0}\,,\ \mathbf{l\bar{l}}\,,\ \ldots$

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- LSP: neutralino (depending on its mass) produces all these states

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Choose your favorite model!

ν as Annihilation Product

$$\chi\overline{\chi} \;\rightarrow\; \mathbf{q}\overline{\mathbf{q}}$$

$$\rightarrow\; \nu\overline{\nu} \qquad (\mathbf{E}_\nu \;=\; \mathbf{M}_\chi)$$

$$\chi\overline{\chi} \;\rightarrow\; \mathbf{t}\overline{\mathbf{t}} \;\rightarrow\; \mathbf{W}^+\mathbf{W}^- \;\rightarrow\; l\nu$$

$$\chi\overline{\chi} \;\rightarrow\; \mathbf{b}\overline{\mathbf{b}} \;\rightarrow\; l\,\nu\,\mathbf{X}$$

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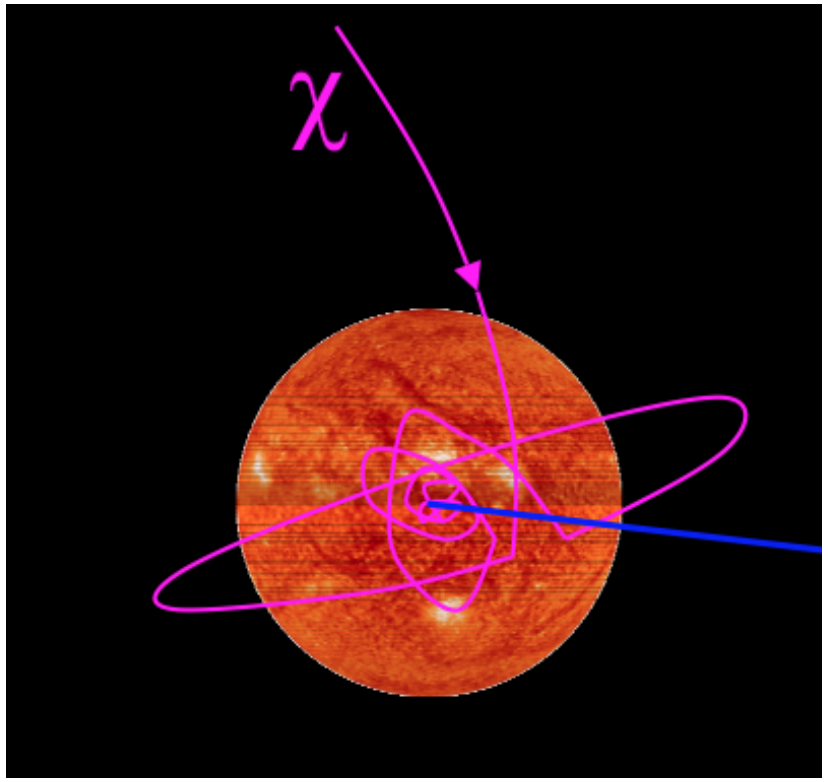
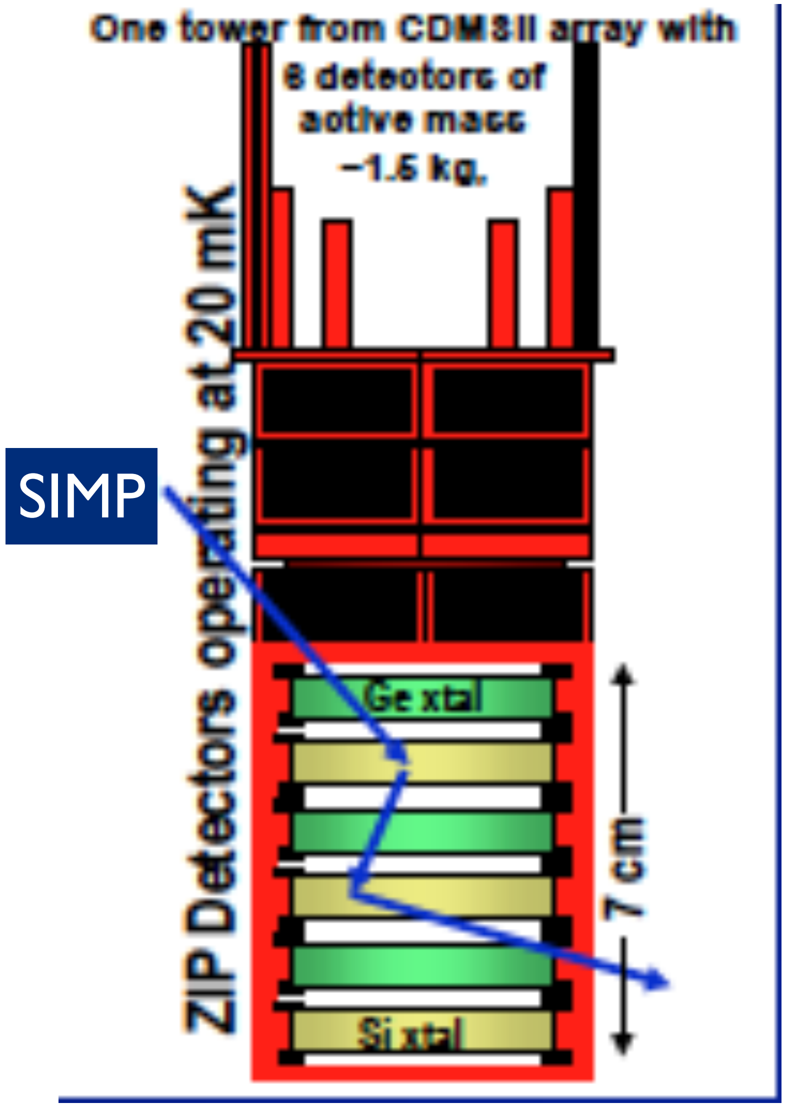
SM
physics

SIMPS as a Case Scenario

Strongly Interacting Massive Particles





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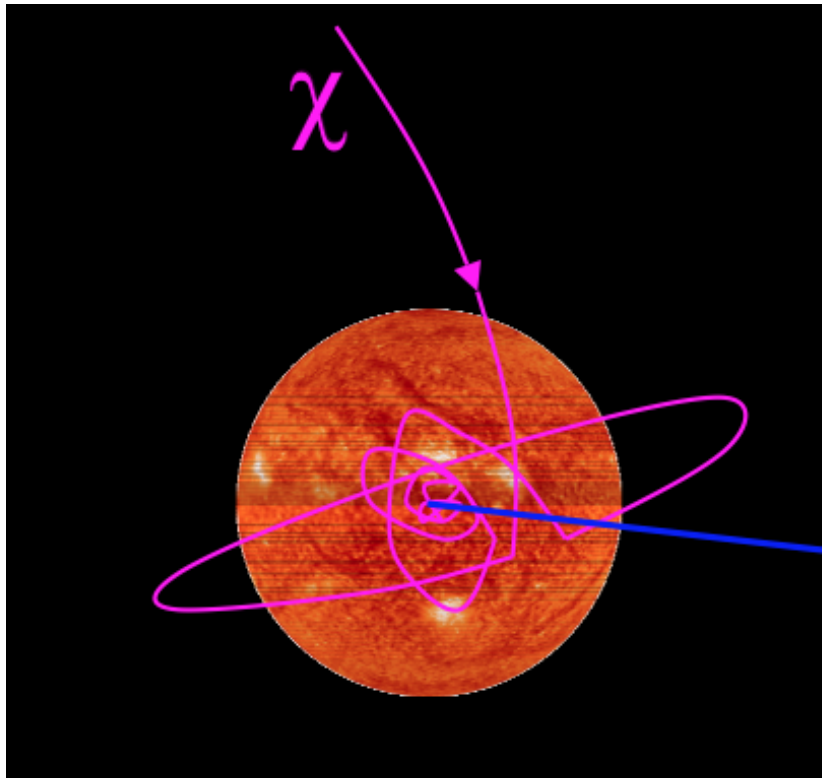

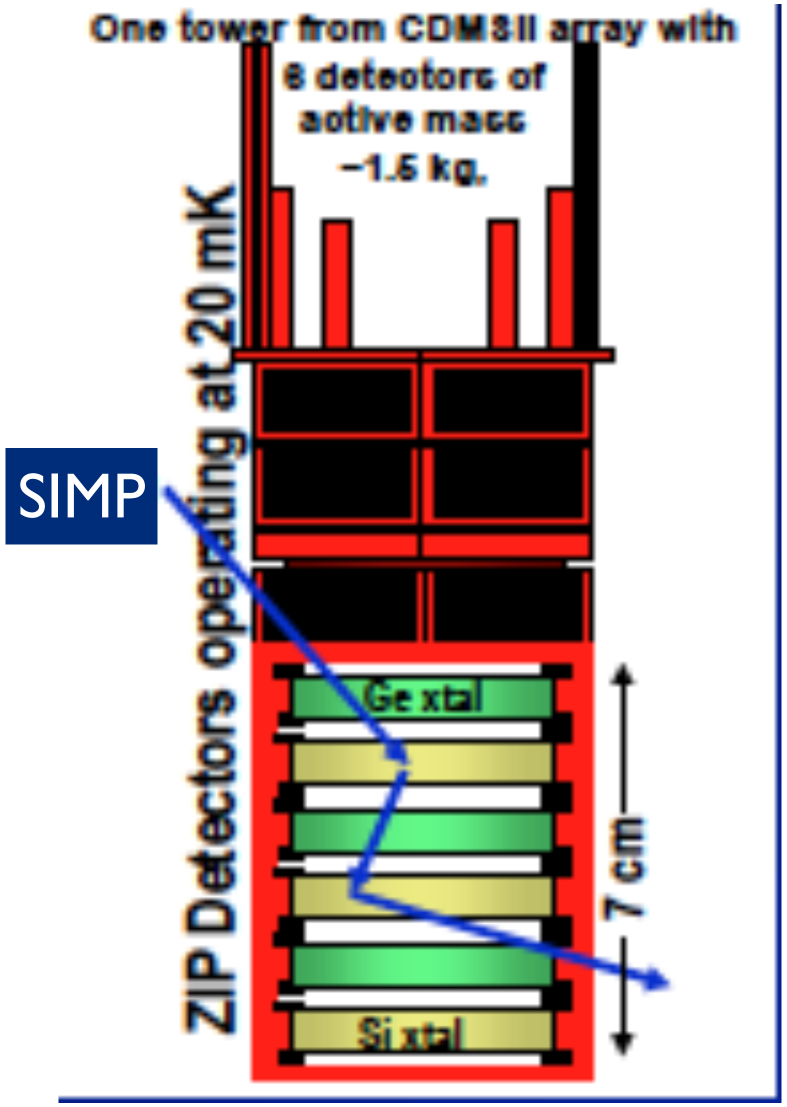

WIMPs: interact at most once in a target (Sun, Earth or a detector)

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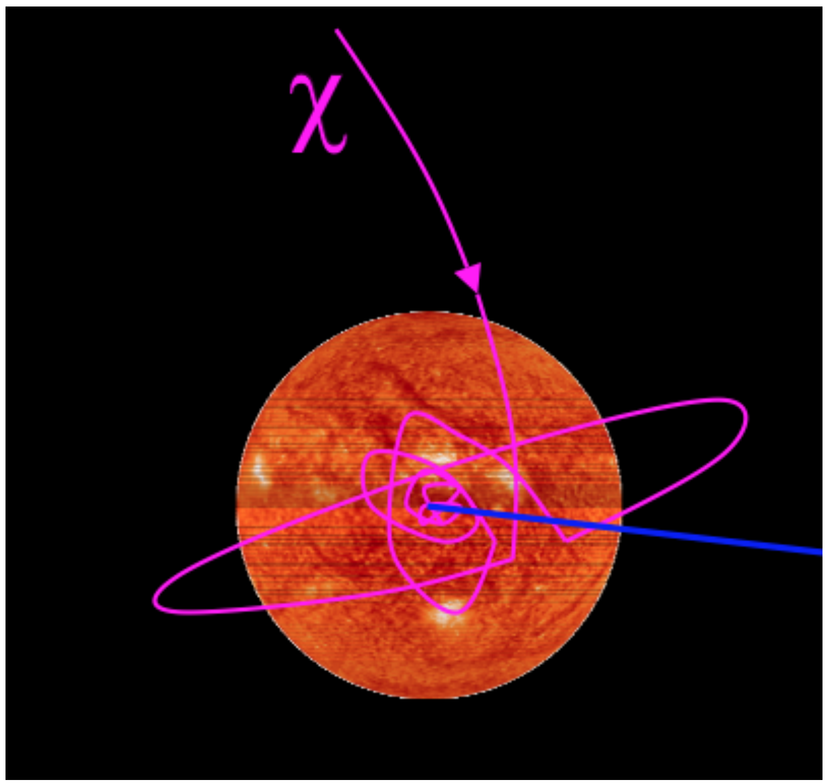

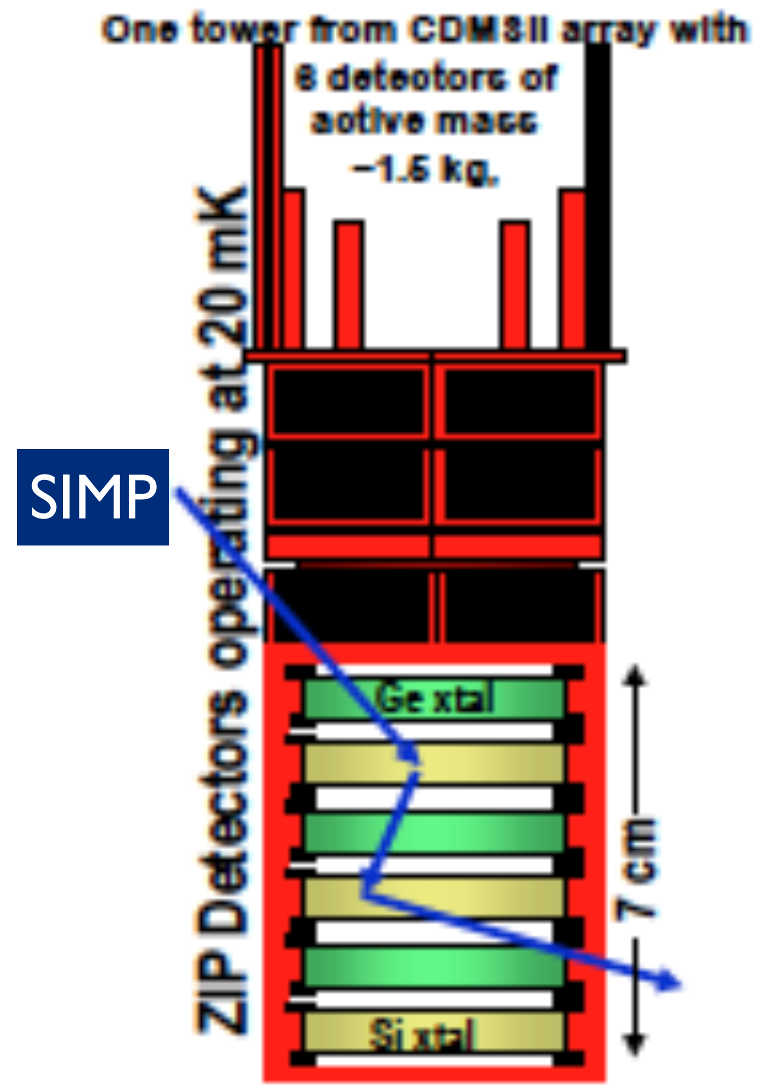

WIMPs: interact at most once in a target (Sun, Earth or a detector)

SIMPs: interact many times => much easier to capture or detect

SIMP Production

- Thermal: mass limit of $\mathbf{m_\chi} \leq \vartheta(\mathbf{100TeV})$

- Non-thermal and extremely massive: Simpzillas (wimpzillas)

D. Chung; A. Riotto; R. Kolb

→ expanding production beyond thermal

* low interaction rate in order to avoid thermal equilibrium

$$\mathbf{\Gamma_A} < \mathbf{H(t)}$$

* extremely massive: close to the inflaton mass (10^{12} GeV) large mass prevents from thermalizing

* production mechanism: decay of inflaton; gravitational at end of inflation, ...

Why (w) simpzillas?

"In lustra past, theorists explained particles that were known to exist (...) and predicted others that had to exist (...). Overwhelmed by the sucesses of the standard model, they now find themselves all too often enumerating the properties of particles that have no reason not to exist."

CHAMPS, A.de Rujula, S.L.Glashow, U.Sarid - Nuc. Phys. B **333** (1990)

Simpzilla capture and annihilation in the Sun

ESTIMATED RATES

- Number of Simpzillas that hit the Sun:

→ local DM density: 0.3 GeV/cm^3

$$\mathbf{n_\chi = \frac{0.3}{M_\chi}\,cm^{-3} = 3 \times 10^{-13}\left(\frac{10^{12}\,GeV}{M_\chi}\right)cm^{-3}}$$

→ flux in the solar neighborhood: $\mathbf{F = \frac{n < v >}{4\pi}}$

→ Sun's area ~ 6 x 10^{22} cm^2

$\mathbf{\sim 4 \times 10^{16}\left(\frac{10^{12}\,GeV}{M_\chi}\right)s^{-1}}$ Simpzillas hitting the Sun:

Simpzilla's trapped in the Sun

- number of interactions in the Sun:

$$\mathbf{N_{int}} \;=\; \mathbf{n_\odot}\,\sigma_{\chi\mathbf{n}}\,\mathbf{R_\odot} \;\sim\; \mathbf{10^{12}}\left(\frac{\sigma_{\chi\mathbf{n}}}{\mathbf{10^{-24}\,cm^2}}\right)$$

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- assume DM impacts the Sun with $v_{esc} = 600$ Km/s $= 2 \times 10^{-3}$ c

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- energy loss per collision:

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- energy loss per collision: $\mathbf{M_\chi \; >> \; m_n \; \Rightarrow \; \Delta E \; = \; \frac{m_p v^2}{2}}$

$$\mathbf{\Delta E_{tot} \; = \; N_{int}\,\Delta E = 2 \times 10^{6} \left(\frac{\sigma \;\; \chi n}{10^{-24}\,cm^2}\right) \; GeV}$$

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- simpzilla initial energy: $\mathbf{E}_{\chi} \;\sim\; \mathbf{2}\times\mathbf{10^6}\left(\frac{\mathbf{M}_{\chi}}{\mathbf{10^{12}\,GeV}}\right)\;\mathbf{GeV}$

Simpzilla's trapped in the Sun

- number of interactions in the Sun:

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- simpzilla initial energy: $\mathbf{E_\chi \sim 2\times 10^6\left(\frac{M_\chi}{10^{12}\,GeV}\right)\ GeV}$

Most simpzillas are captured!
$\Gamma_C \sim 4 \times 10^{16}\ s^{-1}$

Simpzilla's capture rate

- depends on efficiency of losing energy in the Sun: $\mathbf{q}(\mathbf{M}_\chi,\ \sigma_{\chi\mathbf{n}},\ \mathbf{R}_\odot,\ \mathbf{M}_\odot)$

→ q ≤ 1: efficient in losing energy => most will be captured

$$\mathbf{\Gamma_C \ = \ 10^{17}\,(1\ +\ y^2)\left(\frac{10^{12}}{m_\chi}\right)\left(\frac{v_\chi}{240\,km/s}\right)\left(\frac{R_\odot}{7\times 10^{10}cm}\right)\left(\frac{2\times 10^{33}\,g}{M_\odot}\right)\ s^{-1}}$$

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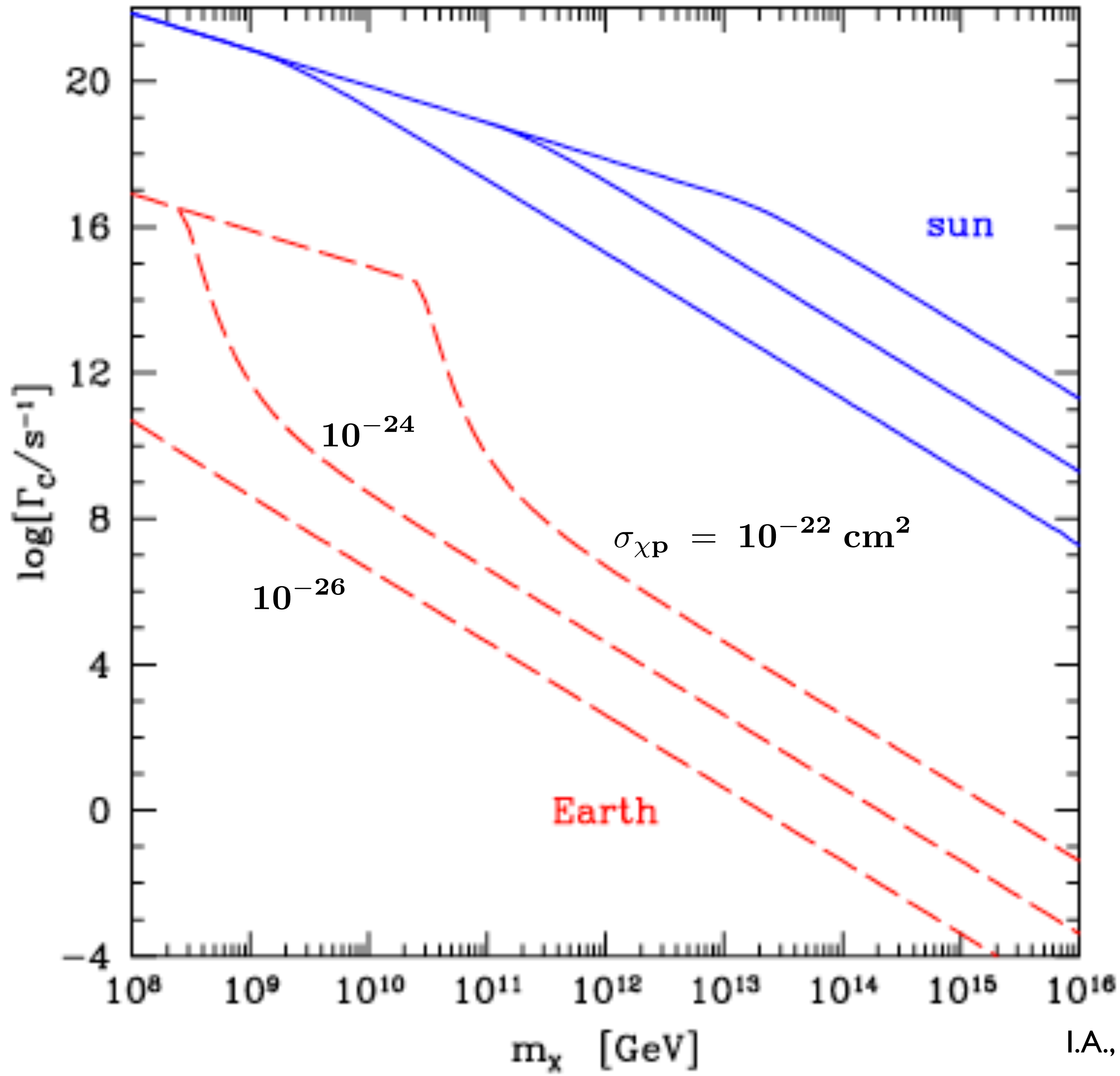
→ q ≤ 1: not efficient => only low velocity ones will be captured

$$\Gamma_C = 10^{17}\left[1 + y^2 - e^{-x^2}(1 + y^2 + x^2)\right]\left(\frac{10^{12}}{m_\chi}\right)\left(\frac{v_\chi}{240\,\mathrm{km/s}}\right)\left(\frac{R_\odot}{7\times10^{10}\mathrm{cm}}\right)\left(\frac{2\times10^{33}\,\mathrm{g}}{M_\odot}\right)\,s^{-1}$$

$$y \equiv 2.5\left(\frac{v_{esc}}{600\,\mathrm{km/s}}\right)\left(\frac{v_\chi}{240\,\mathrm{km/s}}\right)^{-1}\,s^{-1}$$

$$x \equiv \frac{y}{\sqrt{q - 1}}$$

Simpzilla's capture rate



I.A., Lam Hui, Rocky Kolb, PRD **64**, 2001

Simpzilla's annihilation

$$\chi\bar{\chi}$$

$$\swarrow \qquad\qquad \searrow$$

$$q\bar{q} \qquad\qquad\qquad gg$$

$$\downarrow \qquad\qquad\qquad \downarrow$$

$$\text{hadronic jets}$$

$$\mathbf{\Gamma_A = \frac{\Gamma_C}{2}}$$

$$\mathbf{N_H = 6 \times 10^6 \left(\frac{10^{12}}{m_\chi}\right)}$$

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$$\mathbf{\frac{dN_H}{dx} = \frac{15}{16}\,x^{-3/2}\,(1 - x)^2} \qquad \mathbf{x \equiv \frac{E}{E_{jet}} = \frac{E}{m_\chi}}$$

(fragmentation function: C. Hill, Nuc. Phys. B **224** (1983))

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$$\mathbf{N_H = \int_\varepsilon^1 \frac{dN_H}{dx}\, dx} \qquad \varepsilon \equiv \mathbf{\frac{\Lambda_{QCD}}{m_\chi}}$$

$$\mathbf{N_H = 6 \times 10^6 \left(\frac{10^{12}}{m_\chi}\right)}$$

Simpzilla's annihilation

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$$\boxed{N_H = 6 \times 10^6 \left(\frac{10^{12}}{m_\chi}\right) \text{ per jet}}$$

Hadron Spectrum at Sun's Core

Annihilation products: $$\mathbf{N_{t+\bar{t}} = 2.8 \times 10^5 \left(\frac{10^{12}}{m_\chi}\right)}$$

$$\mathbf{N_H} \Rightarrow \varepsilon \equiv \frac{\mathbf{m_Q}}{\mathbf{m}_\chi}$$

Bs = 1.6 x 10^6

Cs = 2.8 x 10^6

light qs = 7.4 x 10^6

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Bs = 1.6 x 10^6

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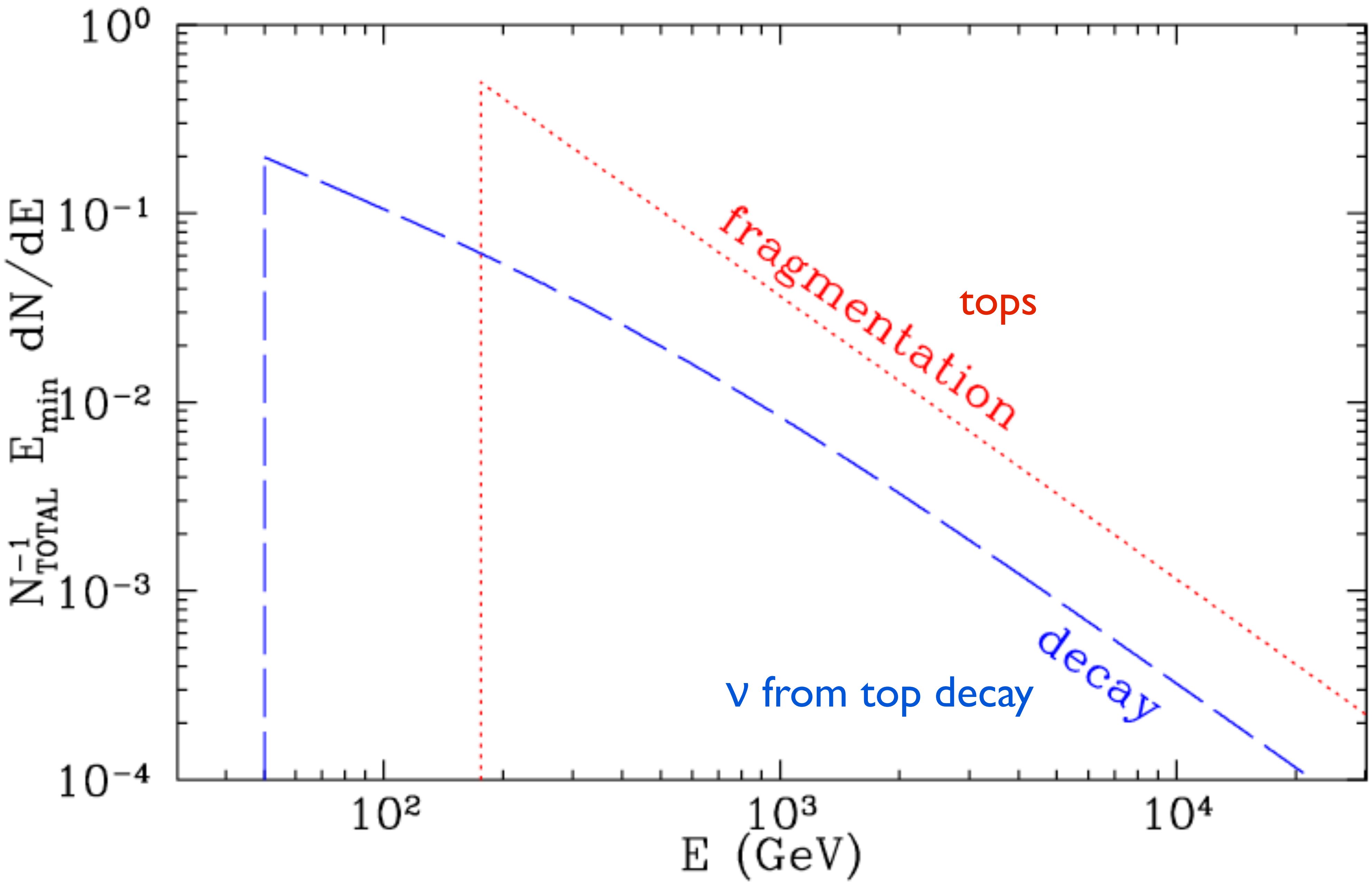
light qs = 7.4 x 10^6

H spectrum at Sun's core:

$$\mathbf{x} = \frac{\mathbf{E}}{\mathbf{m}_\chi} \Rightarrow \frac{\mathbf{m_Q}}{\mathbf{N_{tot}}}\frac{\mathbf{dN}}{\mathbf{dE}} \sim \frac{\mathbf{1}}{\mathbf{2}}\left(\frac{\mathbf{E}}{\mathbf{m_q}}\right)^{\mathbf{-3/2}} \qquad \mathbf{E > m_Q}$$

Top Spectrum at Sun's Core



I.A., Lam Hui, Rocky Kolb, PRD **64**, 2001

Secondary ν from Simpzilla Annihilation

$$\begin{aligned}\mathbf{t} \;\rightarrow\; \mathbf{W} + \mathbf{b} \quad &(\sim \mathbf{100\%}) \\ \hookrightarrow\; \mathbf{e}\,\nu_{\mathbf{e}} \quad &(\mathbf{10\%}) \\ \hookrightarrow\; \mu\,\nu_{\mu} \quad &(\mathbf{10\%}) \\ \hookrightarrow\; \tau\,\nu_{\tau} \quad &(\mathbf{10\%})\end{aligned}$$

$$\begin{aligned}\tau \;\rightarrow\; &\mu\,\nu_{\mu}\,\nu_{\tau} \quad (\mathbf{18\%}) \\ &\mathbf{e}\,\nu_{\mathbf{e}}\,\nu_{\tau} \quad (\mathbf{18\%})\end{aligned}$$

$$\nu_{\tau} \xrightarrow{\mathbf{CC}} \tau$$

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$$\hookrightarrow \; \mathbf{e}\,\nu_{\mathbf{e}} \quad (\mathbf{10\%})$$
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$$\tau \;\rightarrow\; \mu\,\nu_{\mu}\,\nu_{\tau} \quad (\mathbf{18\%})$$
$$\mathbf{e}\,\nu_{\mathbf{e}}\,\nu_{\tau} \quad (\mathbf{18\%})$$

$$\nu_{\tau} \xrightarrow{\mathbf{CC}} \tau$$

ν spectrum at Sun's core:

$$\frac{\mathbf{dN}}{\mathbf{dE}} = \mathbf{N}\frac{\mathbf{E} + \mathbf{m_W}}{\sqrt{(\mathbf{E} + \mathbf{m_t})[(\mathbf{E} + \mathbf{m_t})^{\mathbf{2}} - \mathbf{m_t^2}][(\mathbf{E} + \mathbf{m_W})^{\mathbf{2}} - \mathbf{m_W^2}]}}$$

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ν spectrum at Sun's core:

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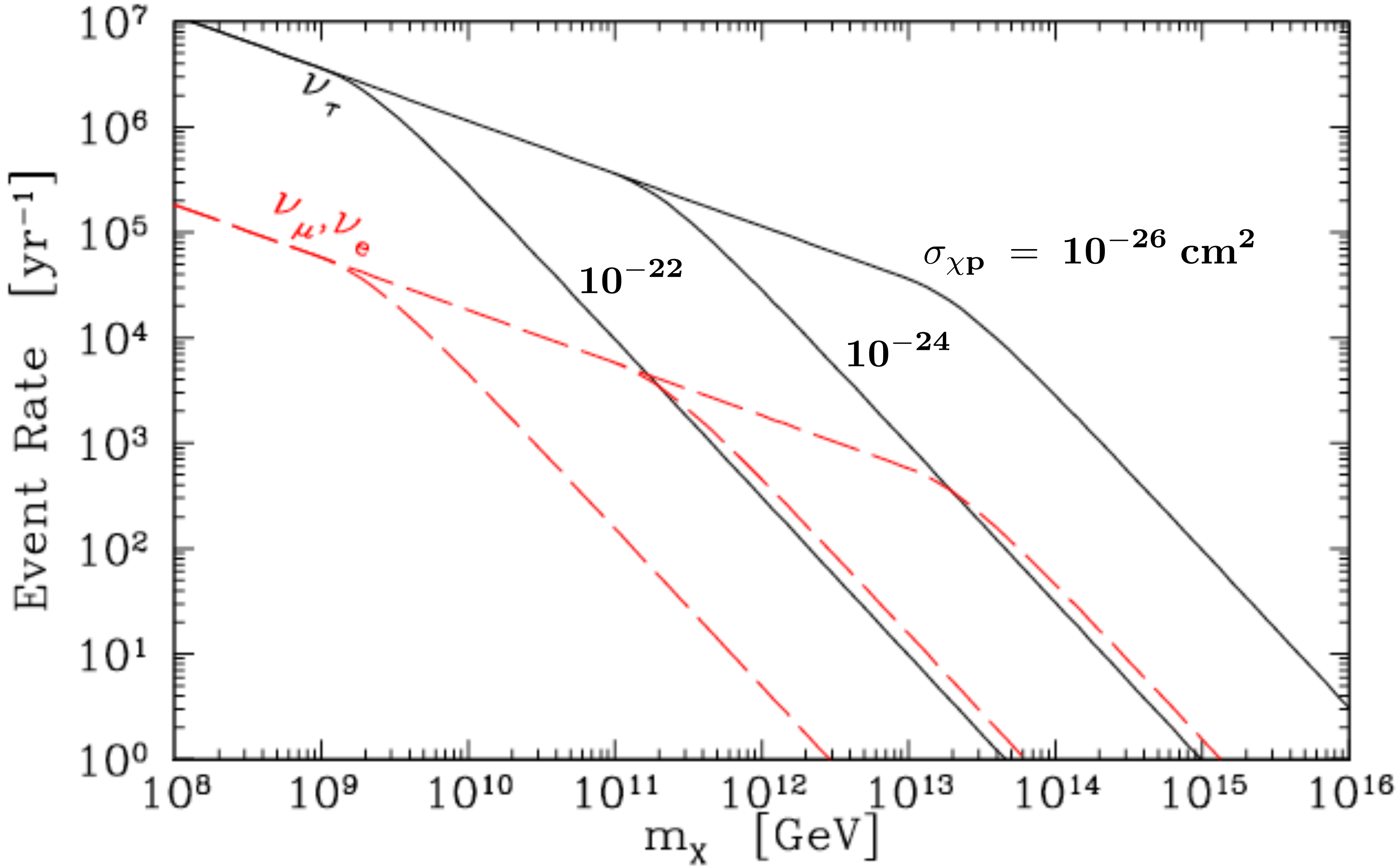
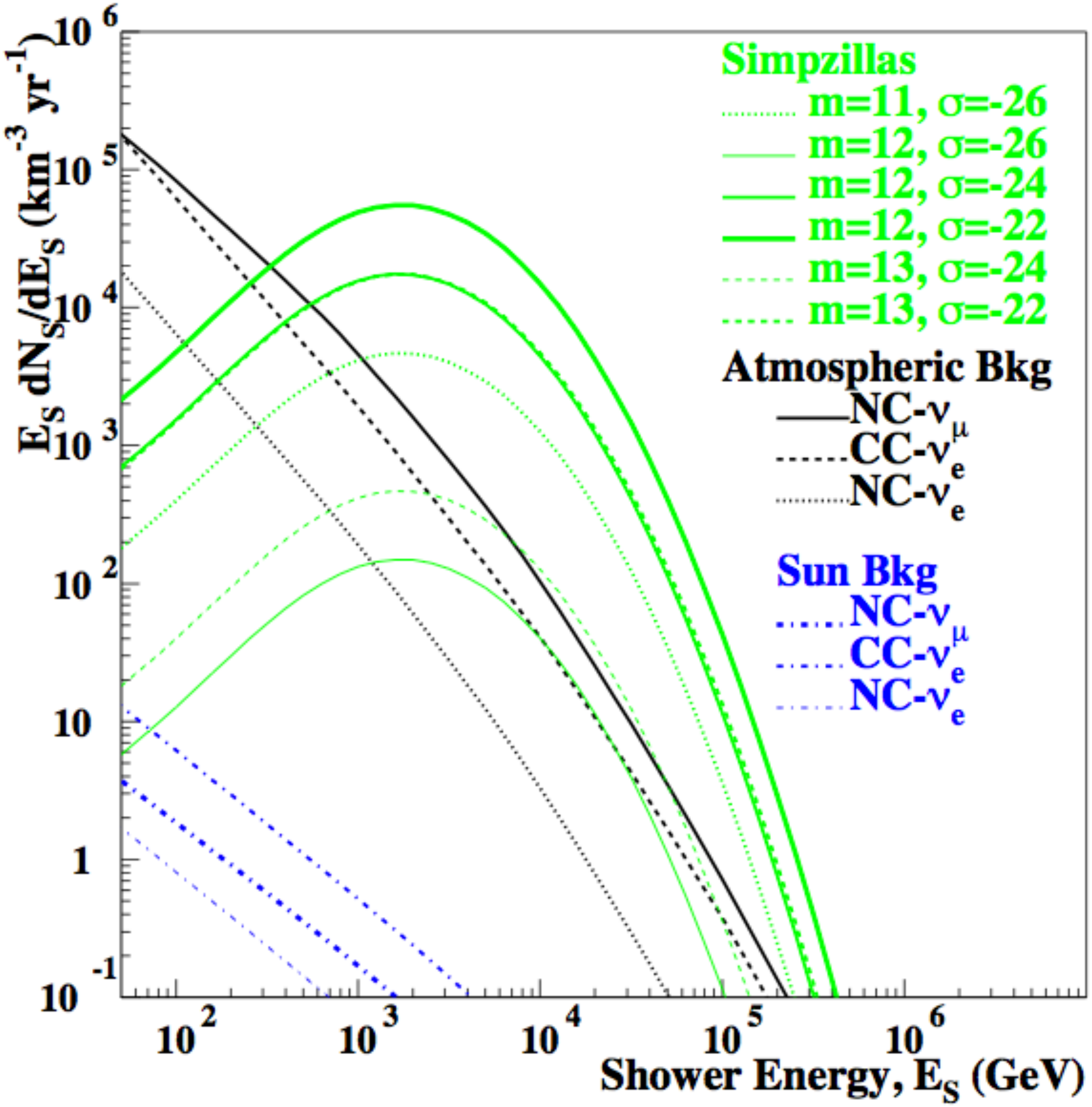
ν emission rate (above 50 GeV): $\mathbf{N}_{\nu_\tau} \sim \mathbf{10^4}\left(\frac{\mathbf{10^{12}}}{\mathbf{m}_\chi}\right)$
at the Sun's core

Estimated Event Rate in IceCube



I.A., Lam Hui, Rocky Kolb, PRD **64**, 2001

Signal vs Background



I.A., Jodi Lamoureux, George Smoot,
PRD **66**, 2002

Simpzilla Indirect Detection

ν_μ propagation from Sun's core to Earth

Monte Carlo Simulation: WIMPSIM code

(M. Blennow, J. Edsjo, T. Ohlsson - JCAP **01** 2008)

=> CC and NC interactions

=> ν oscillations

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→ Input: ν_μ spectrum at Sun's core

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=> CC and NC interactions

=> ν oscillations

→ Input: ν_μ spectrum at Sun's core

→ Output: ν_μ flux $\left(\frac{d\phi_\nu}{dE_\nu}\right)_d$ at the detector

ν_μ Rate at IceCube

Number of μ at given angular region Ω at IceCube:

$$\int \left(\frac{d\phi_\nu}{dE_\nu\, dA\, dt\, d\Omega} \right)_d dE_\nu\, t_{\mathrm{exp}}\, A_{\mathrm{eff}}\, \Omega$$

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Effective area: efficiency of detector (energy dependent)

$\nu_\mu \xrightarrow{\text{CC}} \mu$ probability

μ energy loss

detector and analysis efficiency

ν_μ Rate at IceCube

Number of μ at given angular region Ω at IceCube:

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Effective area: efficiency of detector (energy dependent)

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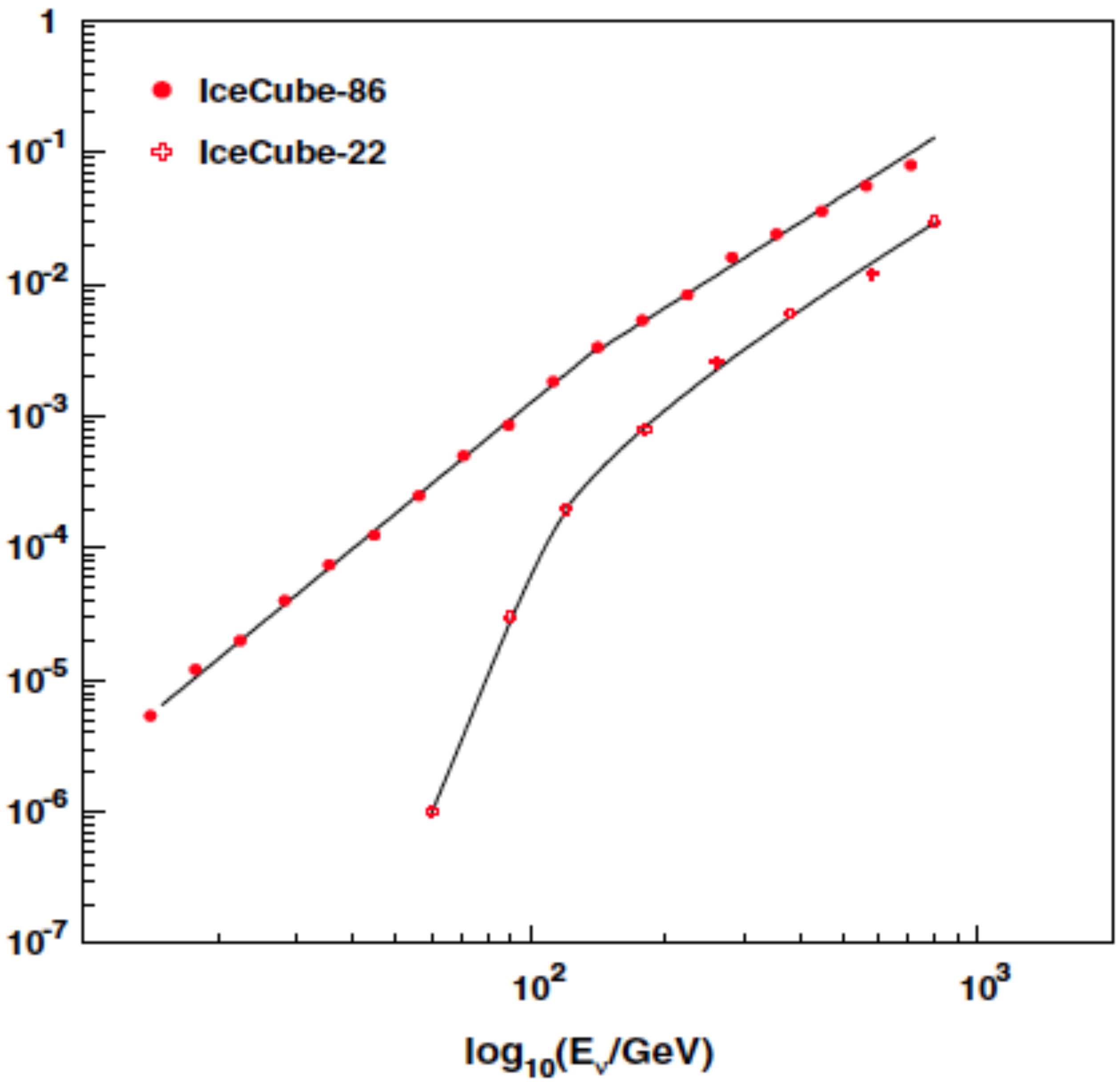
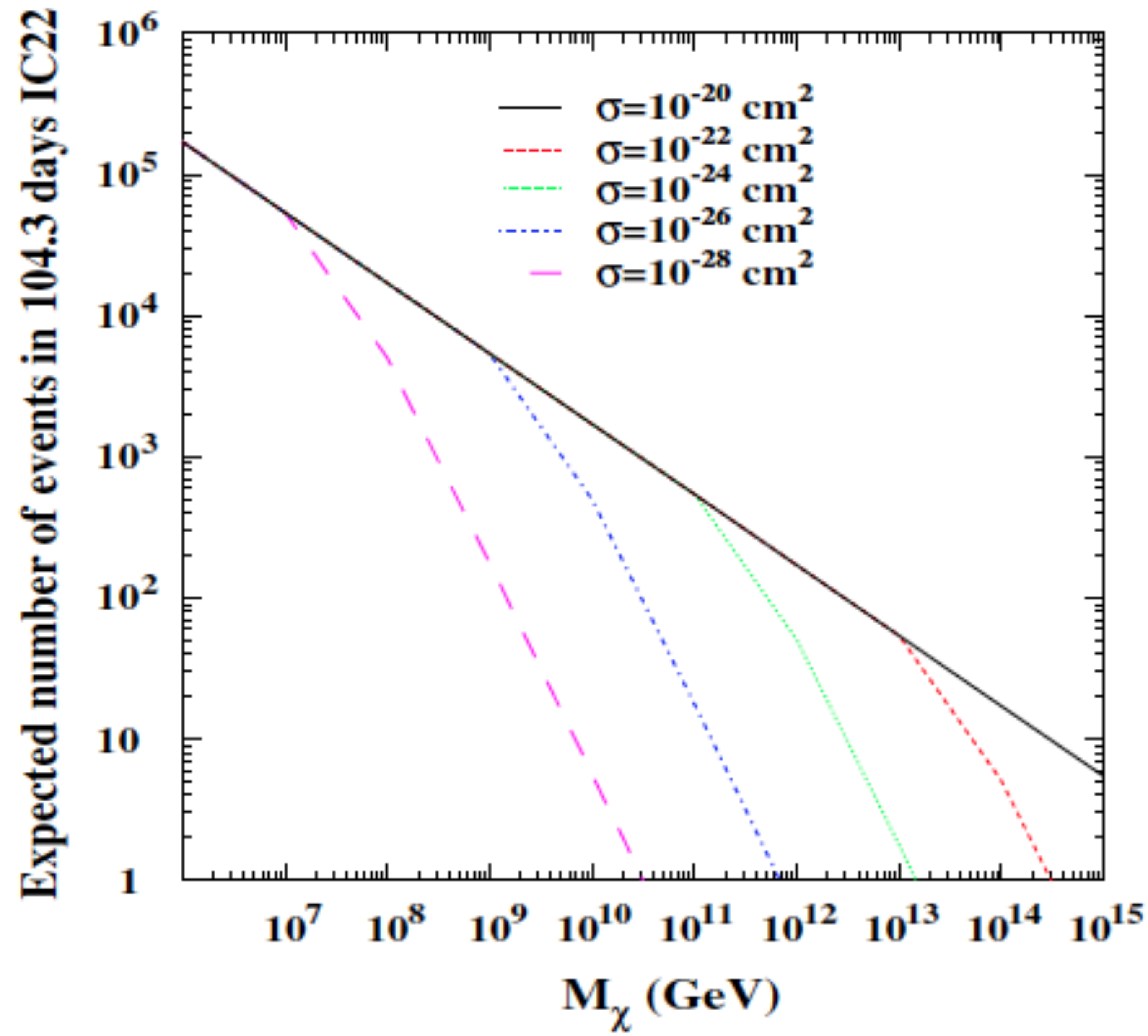
μ energy loss

detector and analysis efficiency

Comparison of detected events with predicted rate

Expected Rate in IceCube

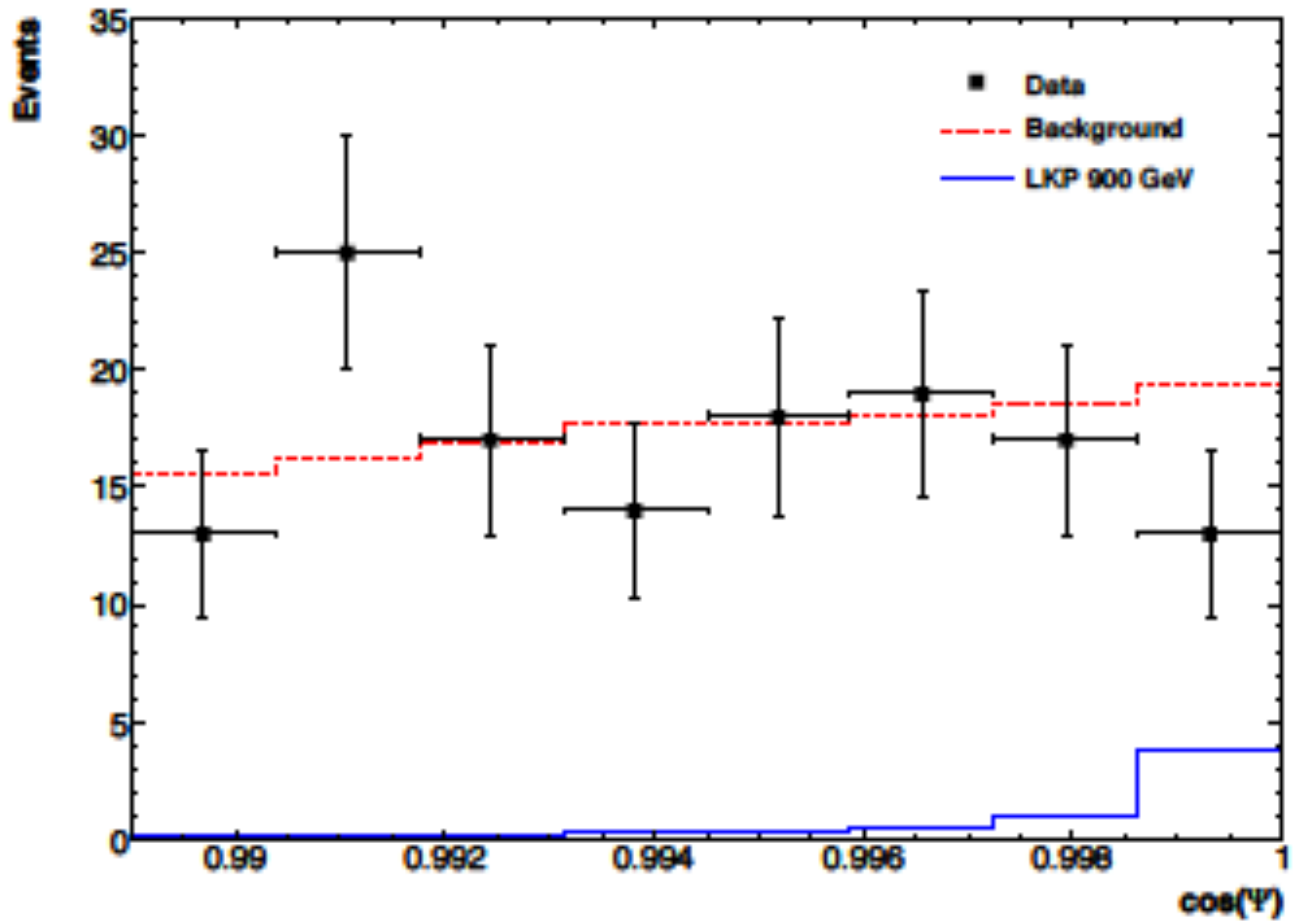




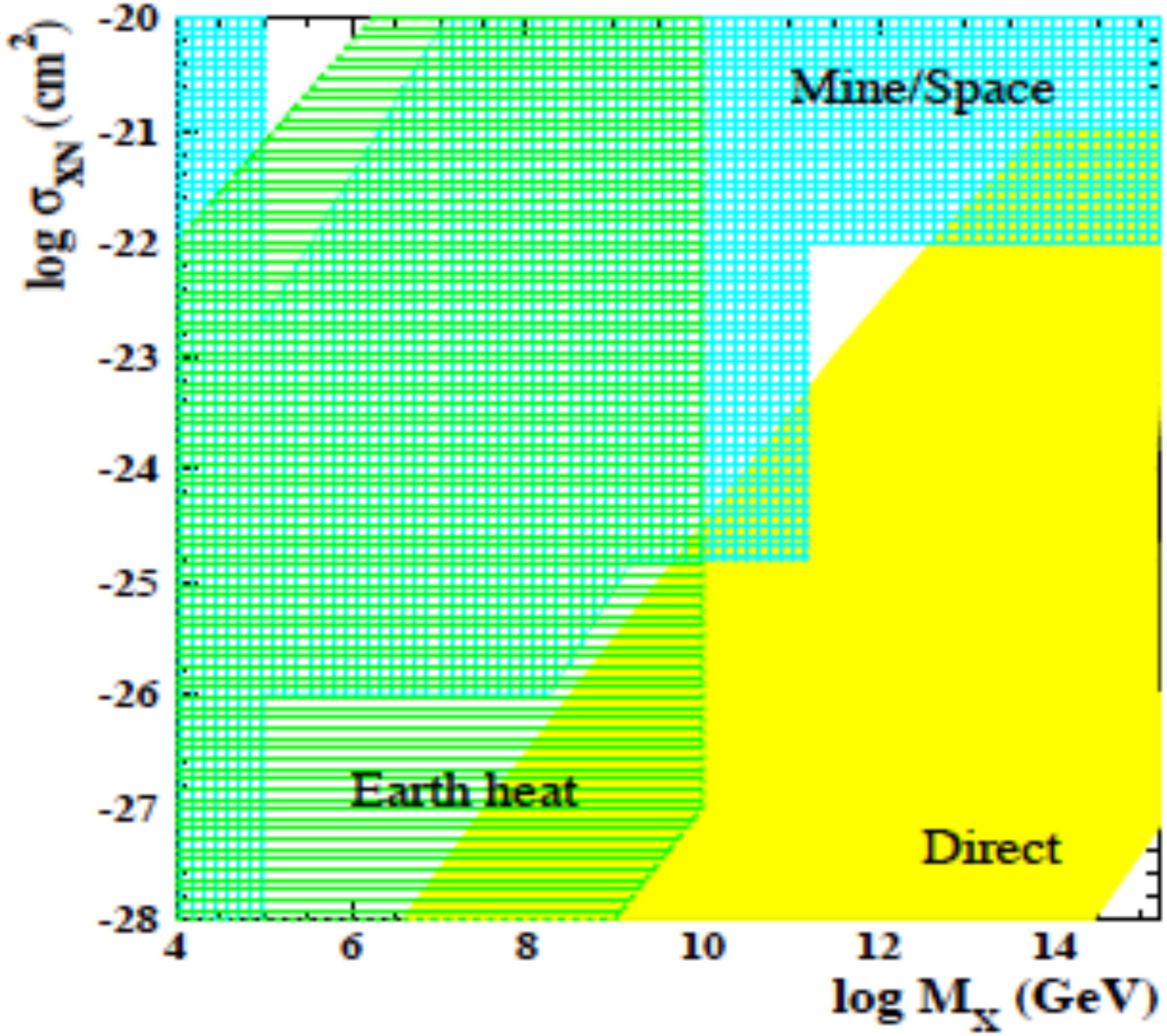
I.A., Carlos de Los Heros, PRD **81**, 2010

IceCube-22 Results

IceCube-22 published results: Phys. Rev. D **81** (2010)



Closing the SIMP window



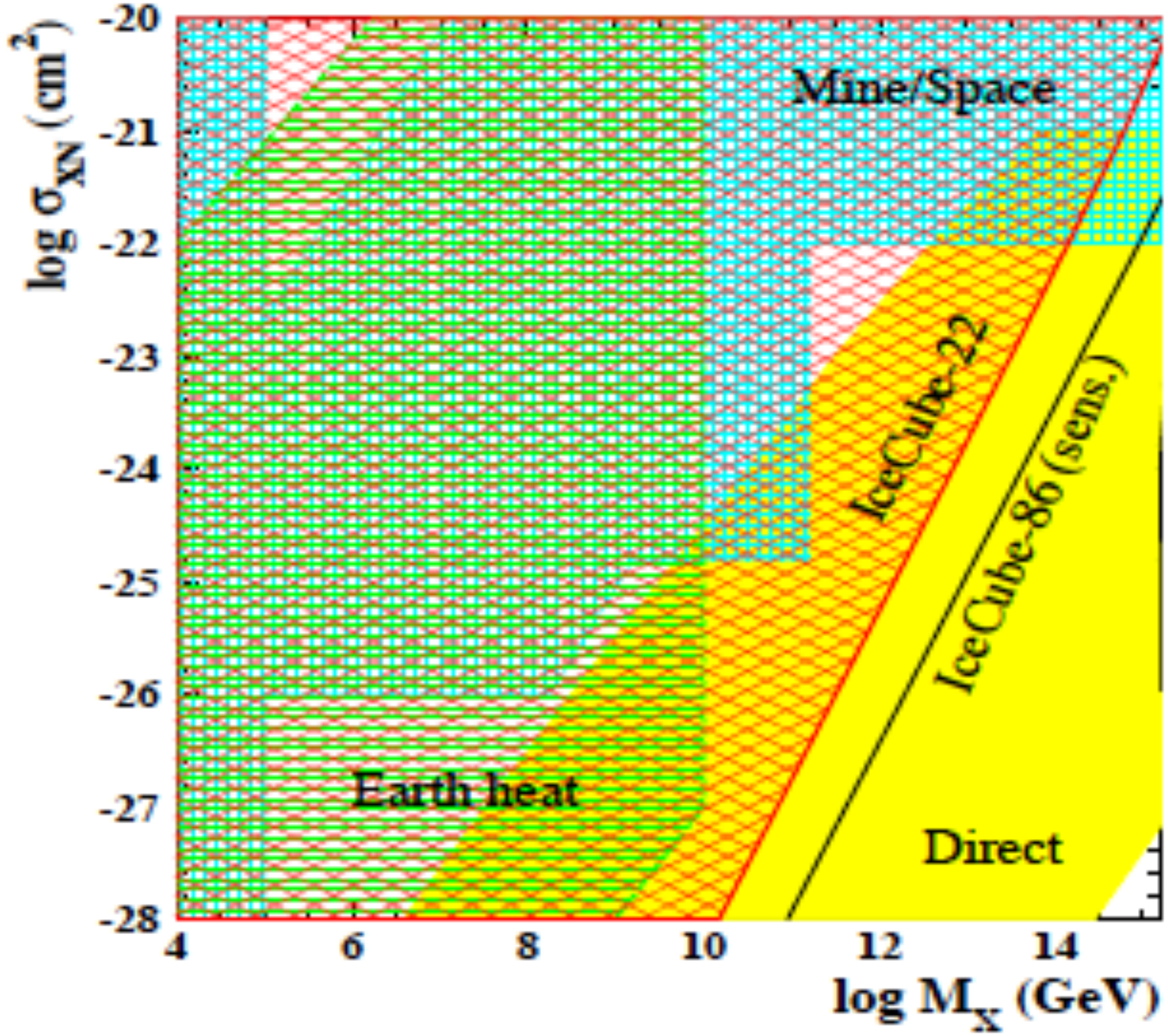
IA, Laura Baudis, PRL **90**, 2003

Mack et al, PRD **76**, 2007

Starkman et al, PRD **41**, 1990

I.A., Carlos de Los Heros, PRD **81**, 2010

Closing the SIMP window



IA, Laura Baudis, PRL **90**, 2003

Mack et al, PRD **76**, 2007

Starkman et al, PRD **41**, 1990

I.A., Carlos de Los Heros, PRD **81**, 2010

Exercise 2: Do a rough estimate on the number of WIMPs captured by the Sun, following the steps done for Simps. Find out the ratio between the capture rate of Simps over the one for wimps, for a mass and cross section value of your choice.

Exercise 3: Suppose you have a beyond the SM favorite DM candidate. List the necessary steps to estimate if it is possible to indirectly detect it.