DARK MATTER PHENOMENOLOGY

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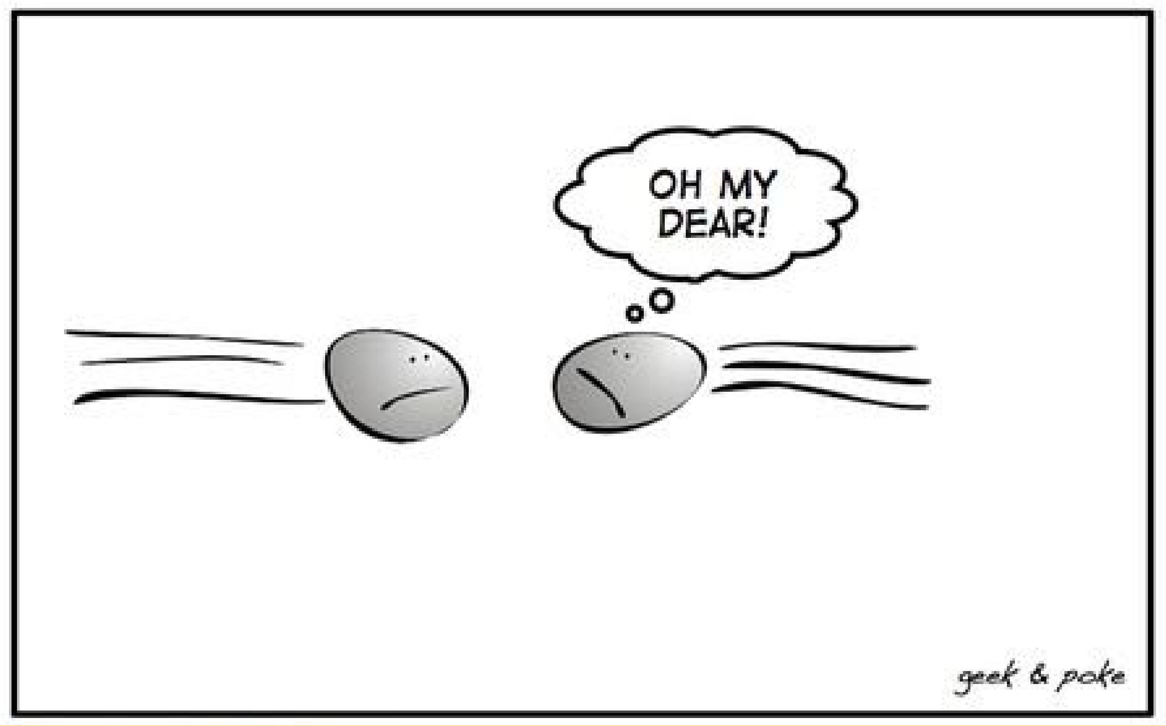
SOUP 20|21: INFN School on Underground Physics

Dark Matter

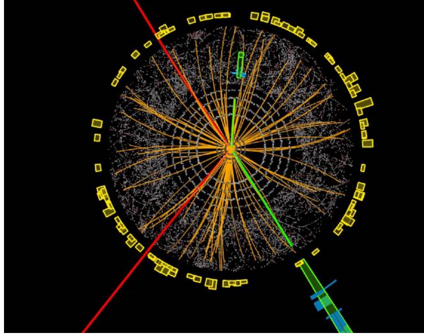
- DM evidence is purely gravitational
  - Galaxy clusters dynamics
  - Rotational curves of spiral galaxies
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Energy budget of the Universe
  - The same theory of structure formation

- This evidence can be ascribed either to:
  - Modification of the theory of Gravity (difficult to explain all observations)
  - Elementary particle, relic from the early Universe
    - No viable candidate in the SM: New Physics BSM
    - However, to demonstrate that DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is needed

NON – GRAVITATIONAL SIGNALS OF PARTICLE DM



A multiple approach

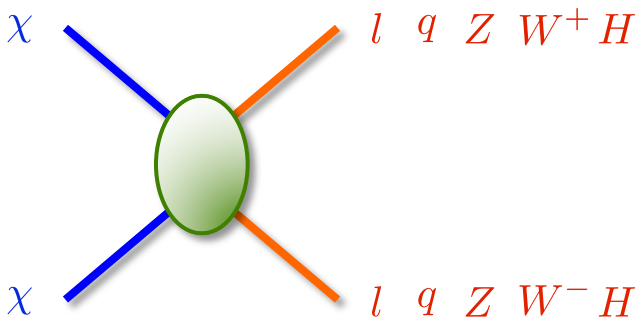


- Astrophysical signals
  - Tests DM as particle in its environment
  - Signals are not produced under our own direct control
  - Complex backgrounds
  - Multimessenger, multiwavelength, multitechnique strategy

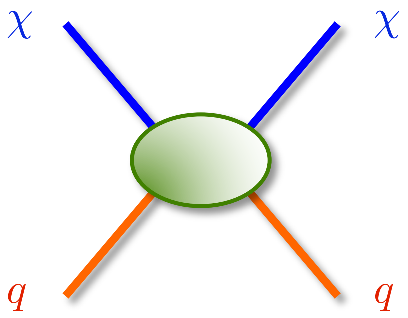
- Accelerator / Lab signals
  - Produce New Physics states and help in shaping the underlying model
  - Allows (hopefully) to identify the physical properties of the DM sector
  - Controlled environment

One does not fit all … profit of all opportunities

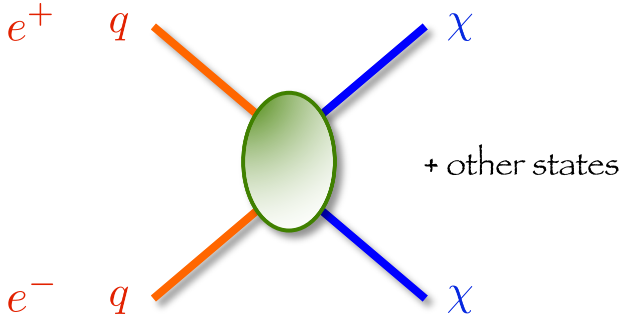
Mechanisms of DM signal production



Annihilation (or decay)

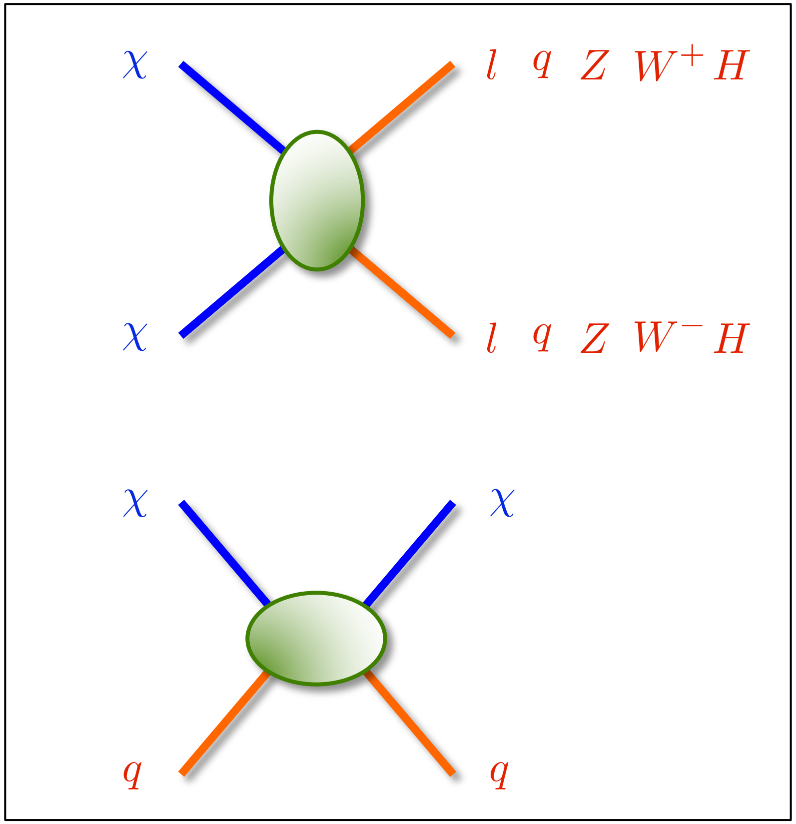


Scattering with ordinary matter



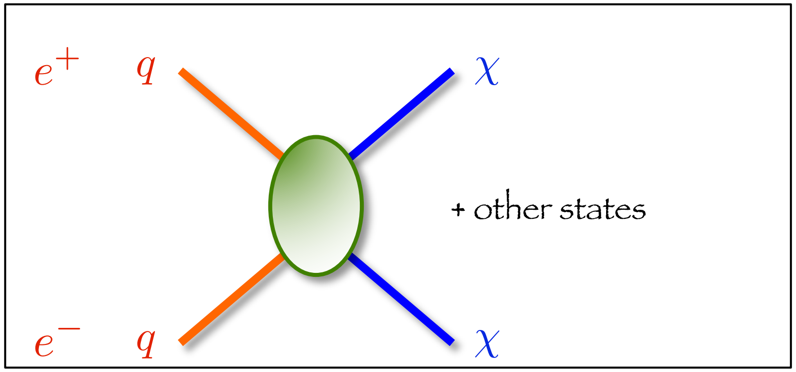
Production at accelerators

Mechanisms of DM signal production



Signals occur in astrophysical context

Directly test DM the particle-physics nature of DM



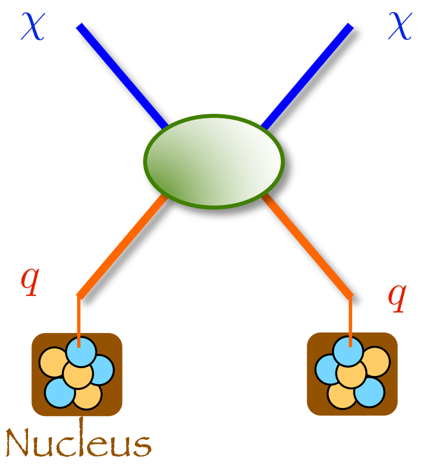
Signal produced in accelerators

Directly tests New Physics: compatibility with DM needs to be cross-checked with cosmology adn astrophysics

DM as a particle might ...

Interact with ordinary matter	Inside our detector Direct detection
	Produce effects in astrophysical environments, like in stars
Self annihilate or decay	Send us messengers Indirect detection
	Exotic injections that can alter properties of messengers (e.g. CMB: SZ, reionization; gamma-rays absorption)

Direct detection signal

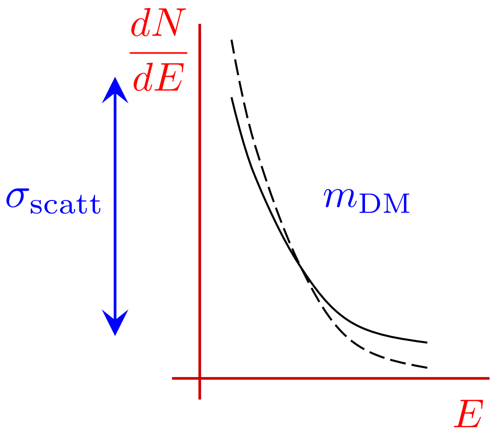


Scattering with ordinary matter

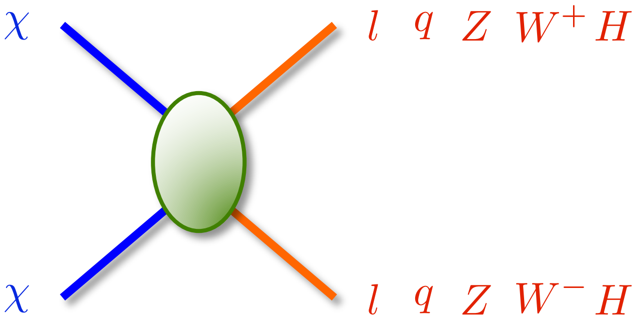
Relevant particle physics properties:

1. Scattering cross section
2. Mass of the DM particle

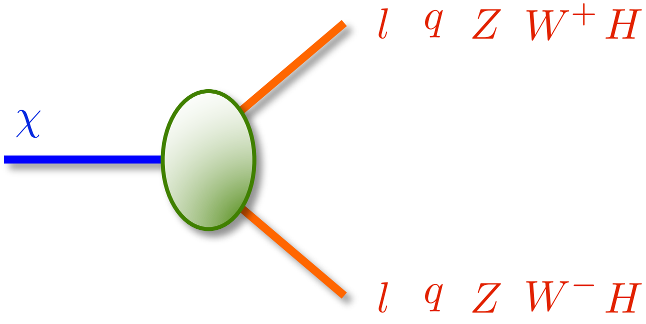
1 + 2 : Size of the signal
2 : Spectral features of nuclear recoil



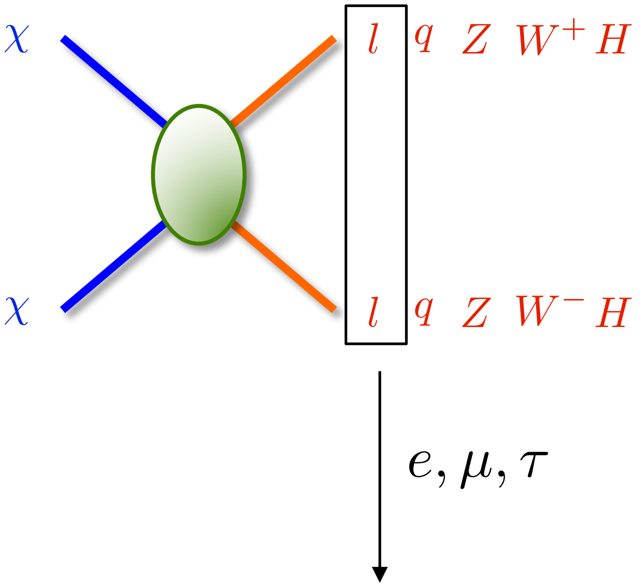
Indirect astrophysical signals



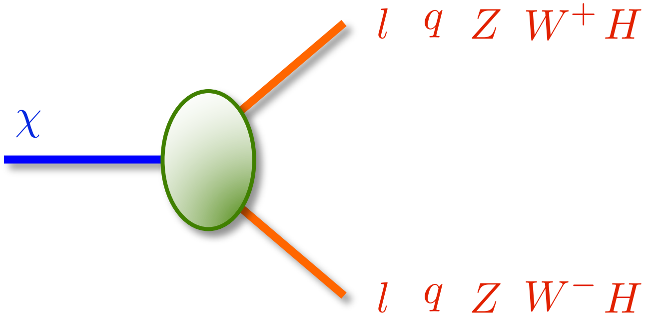
Annihilation
or decay



Indirect astrophysical signals



Annihilation
or decay



$e^{\pm}$

ν_e, ν_μ, ν_τ

γ_{FSR}

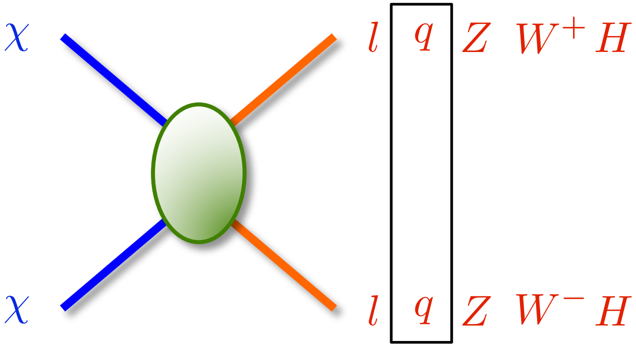
Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\mathrm{DM}}$	ann
$m_i < m_{\mathrm{DM}}/2$	decay

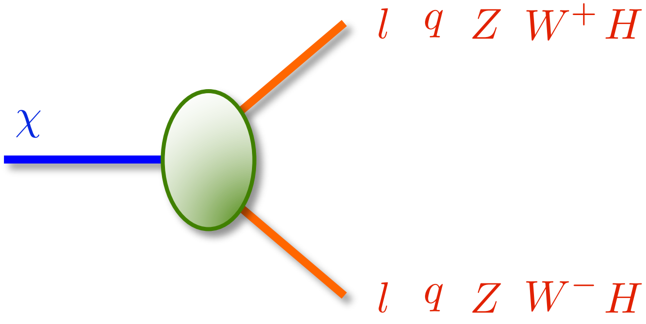
The maximal energy of the final product also depends on the mass of the DM particle

$E < m_{\mathrm{DM}}$	ann
$E < m_{\mathrm{DM}}/2$	decay

Indirect astrophysical signals



Annihilation
or decay



hadronizazion

$p, n,$ heavier Barions
$\pi^0, \pi^\pm,$ heavier Mesons

$\overline{p}, \overline{D}, \overline{He}$

γ

$e^\pm$

ν_e, ν_μ, ν_τ

$\gamma_{\rm FSR}$

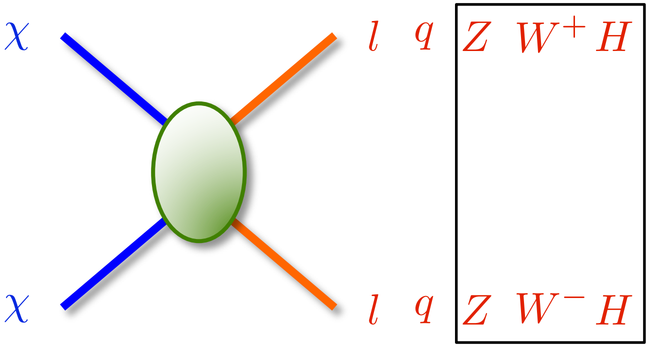
Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\rm DM}$	ann
$m_i < m_{\rm DM}/2$	decay

The maximal energy of the final product also depends on the mass of the DM particle

$E < m_{\rm DM}$	ann
$E < m_{\rm DM}/2$	decay

Indirect astrophysical signals



Annihilation
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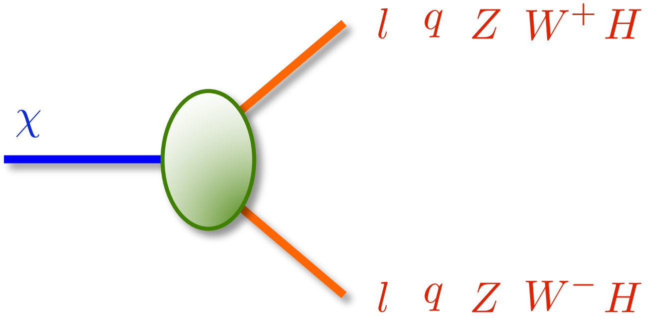


$$\overline{p}, \overline{D}, \overline{He}$$

$$\gamma$$

$$e^{\pm}$$

$$\nu_e, \nu_\mu, \nu_\tau$$

$$\gamma_{\mathrm{FSR}}$$

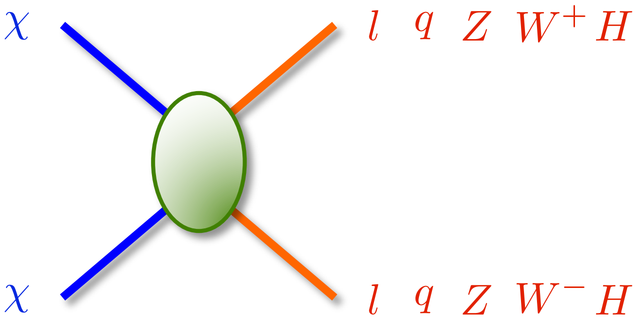
Which channel is open depends on the mass of the non-relativistic DM particle

$m_i < m_{\mathrm{DM}}$	ann
$m_i < m_{\mathrm{DM}}/2$	decay

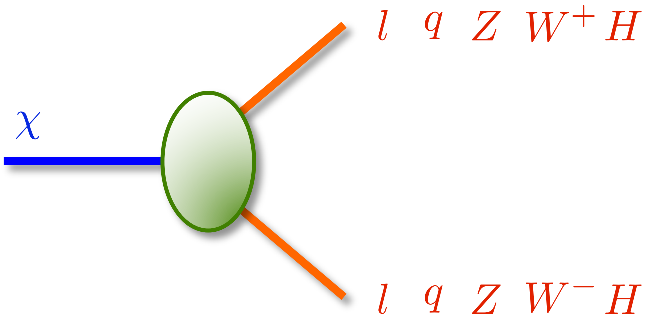
The maximal energy of the final product also depends on the mass of the DM particle

$E < m_{\mathrm{DM}}$	ann
$E < m_{\mathrm{DM}}/2$	decay

Indirect astrophysical signals

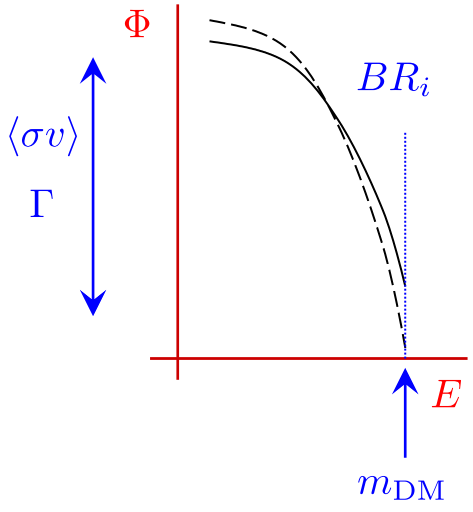


Annihilation
or decay



Relevant particle physics properties:

1. Annihilation cross section (*) (or decay rate)
2. Mass of the DM particle
3. BR in the different final states

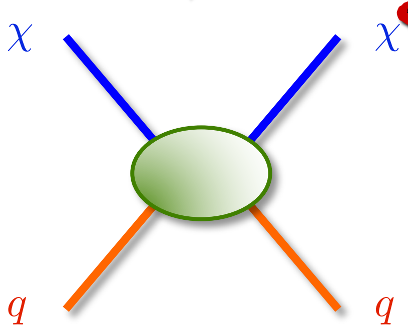


1 + 2 : Size of the signal
2 + 3 : Spectral features

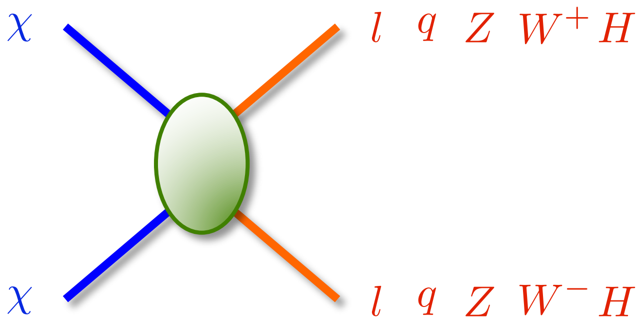
(*) Determines also the cosmological relic abundance (for a thermal DM)

$$\Omega h^2 = 0.11 \quad \longleftrightarrow \quad \langle \sigma_{\rm ann} v \rangle = 2.3 \times 10^{-26} \ {\rm cm}^3 \ {\rm s}^{-1}$$

Neutrino signals from Earth and Sun



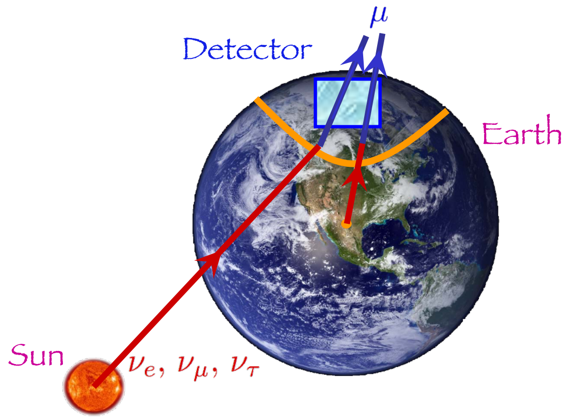
Scattering with ordinary matter
Capture



Annihilation (or decay)
Generation of the neutrino signal

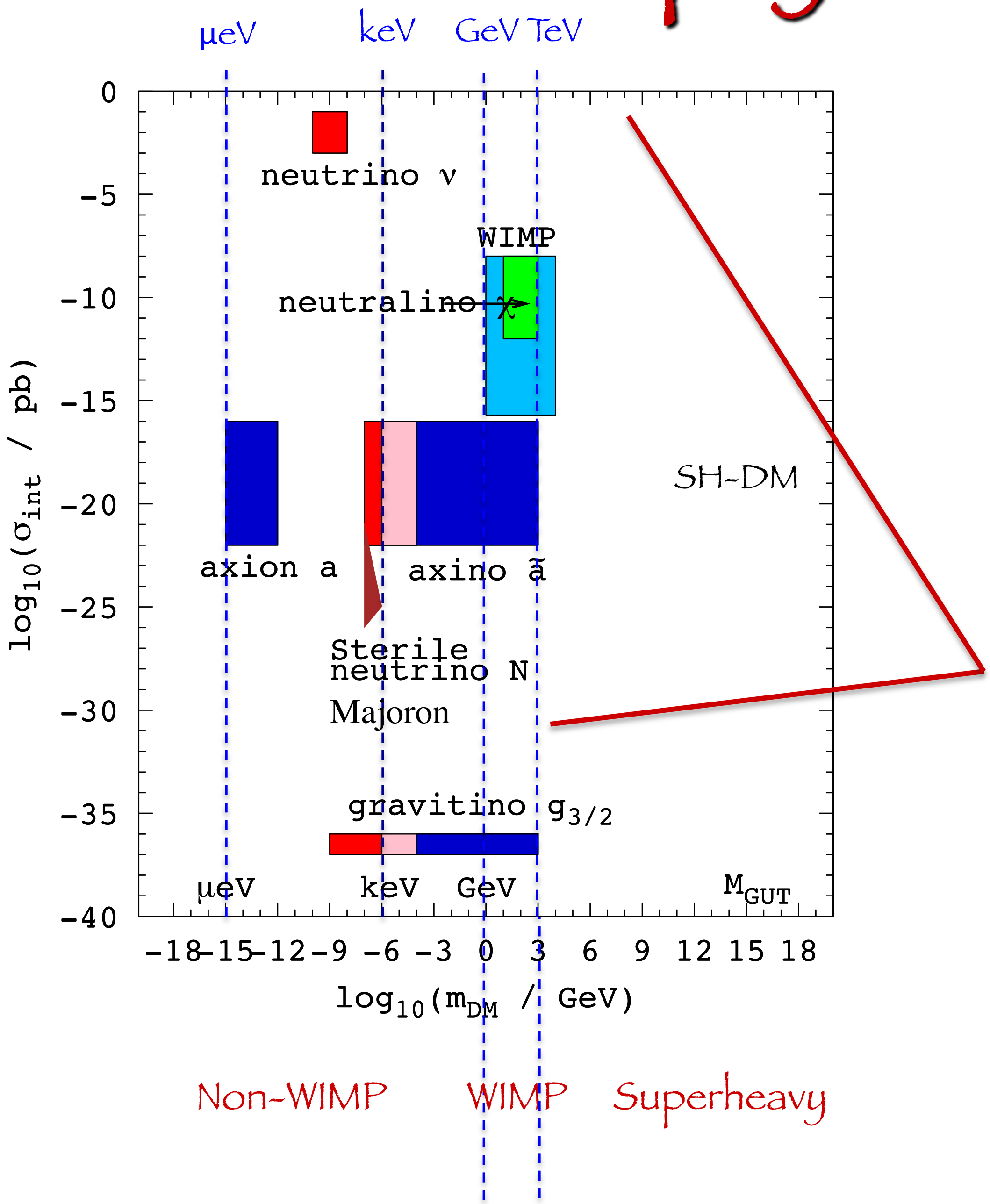
Relevant particle physics properties:

1. Scattering cross section
2. (Annihilation cross section)
3. Mass of the DM particle
4. BR in the different final states



1 + 2 : Size of the signal
3+4 : Spectral features

Particle physics scales



"Strong (-ish)"

Self-interacting
Technicolor DM
…

"EM (-ish)"

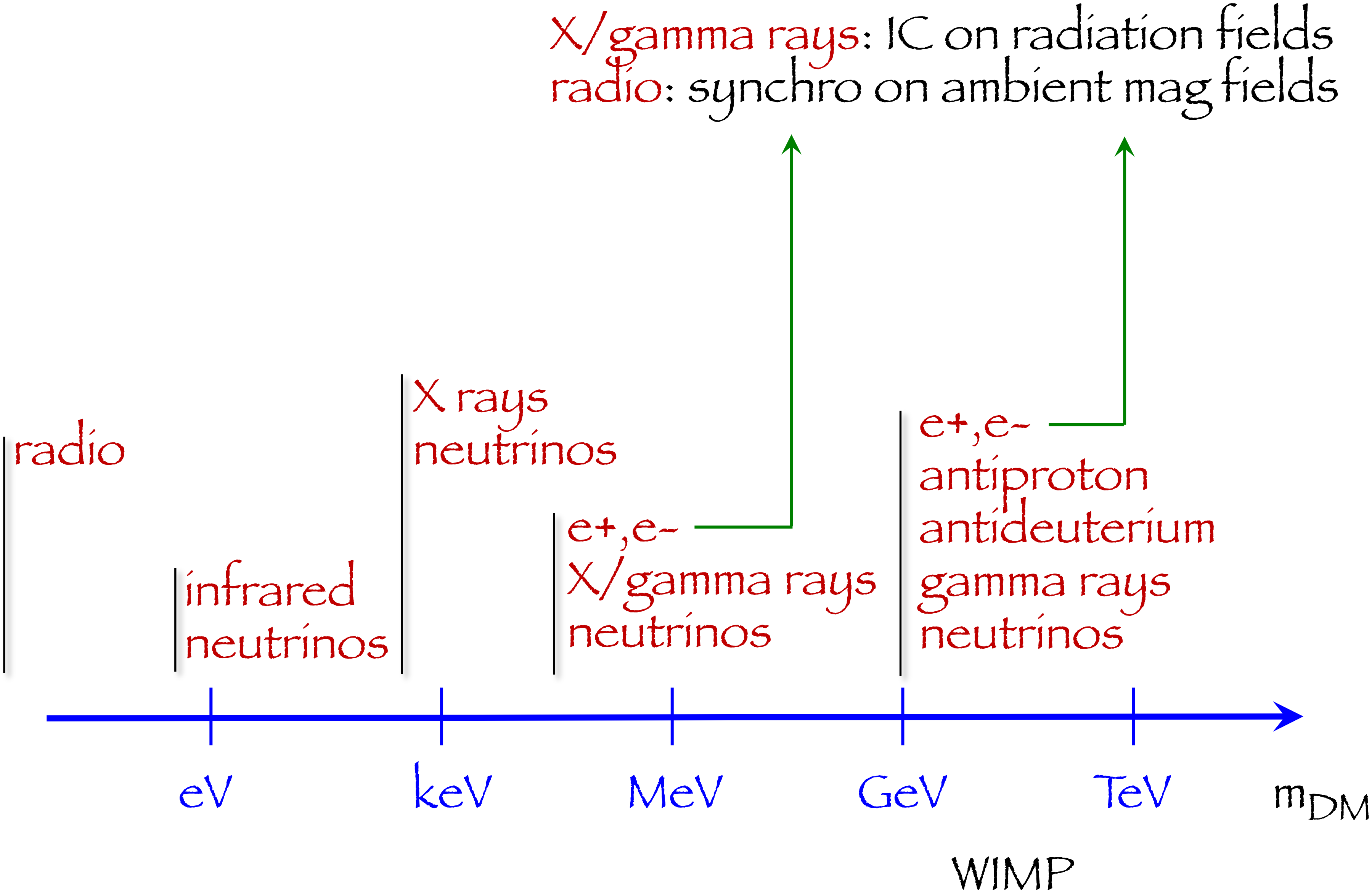
Millicharged DM
Electric/magnetic dipole
…

Weak

WIMP

Gravitational

The Multimessenger Landscape



X/gamma rays: IC on radiation fields
radio: synchro on ambient mag fields

radio

infrared
neutrinos

X rays
neutrinos

e+,e-
X/gamma rays
neutrinos

e+,e-
antiproton
antideuterium
gamma rays
neutrinos

eV keV MeV GeV TeV m_{DM}

WIMP

Multi: messenger/wavelength/technique

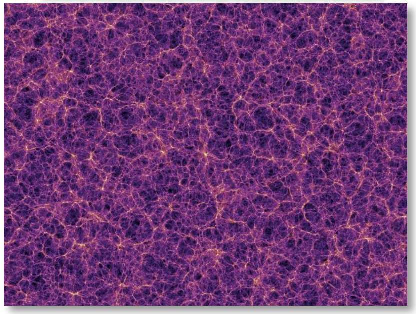
	radio	IR	X	gamma
	WIMP non WIMP		WIMP non WIMP	WIMP
Photons				

Cosmic rays	electrons/positrons	WIMP, non WIMP
	antiprotons, antideuterium, antinuclei	WIMP
Neutrinos		WIMP, non WIMP
Gravitational waves		non WIMP (DM = primordial BH)
Direct detection		WIMP, non WIMP
Accelerator searches for New Physics		WIMP, non WIMP

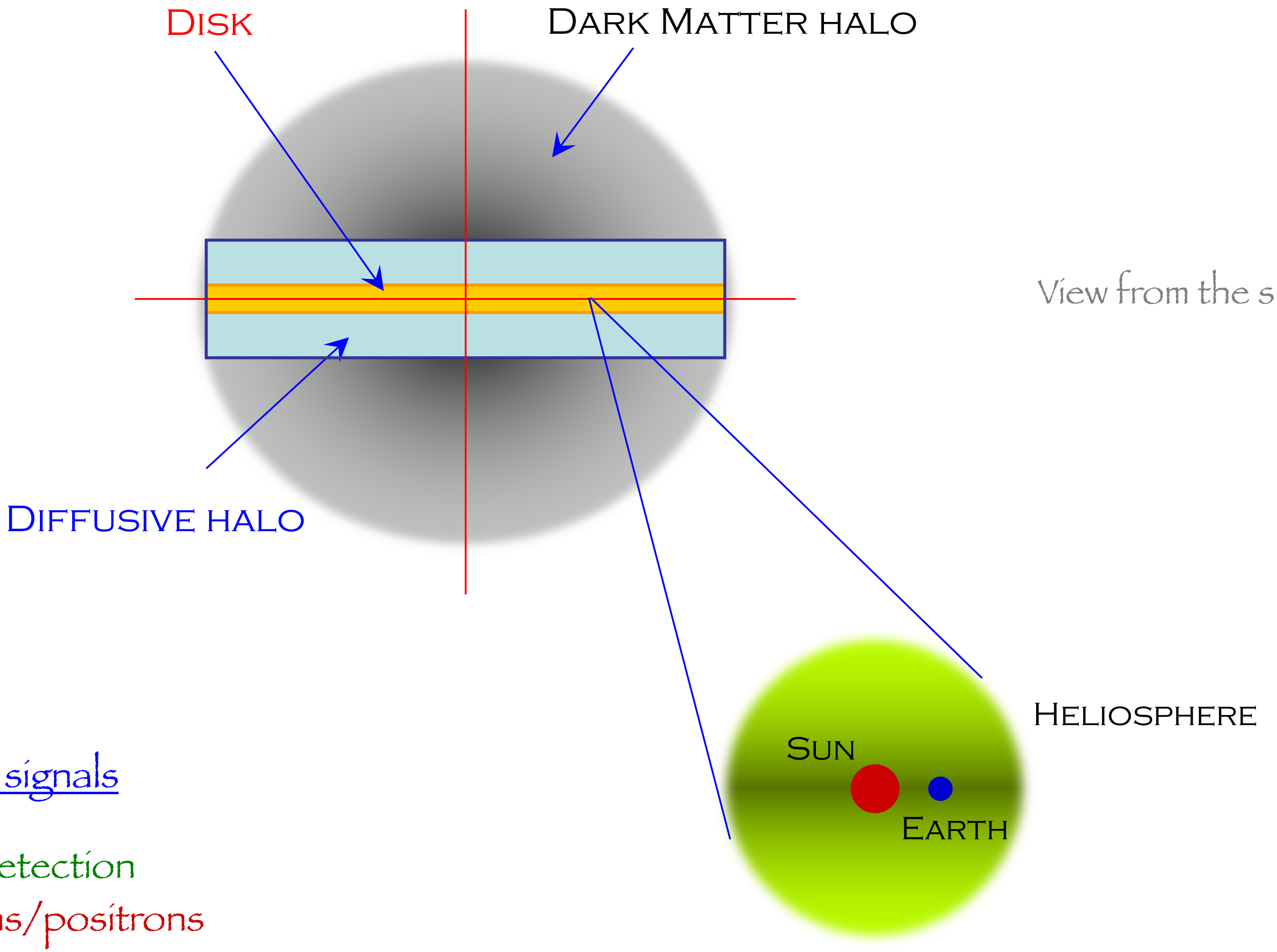
Where to search for a signal

DM is present in:

- Our Galaxy
  - smooth component
  - subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - smooth component
  - individual galaxies
  - galaxies subhalos
- "Cosmic web"



Galactic environment

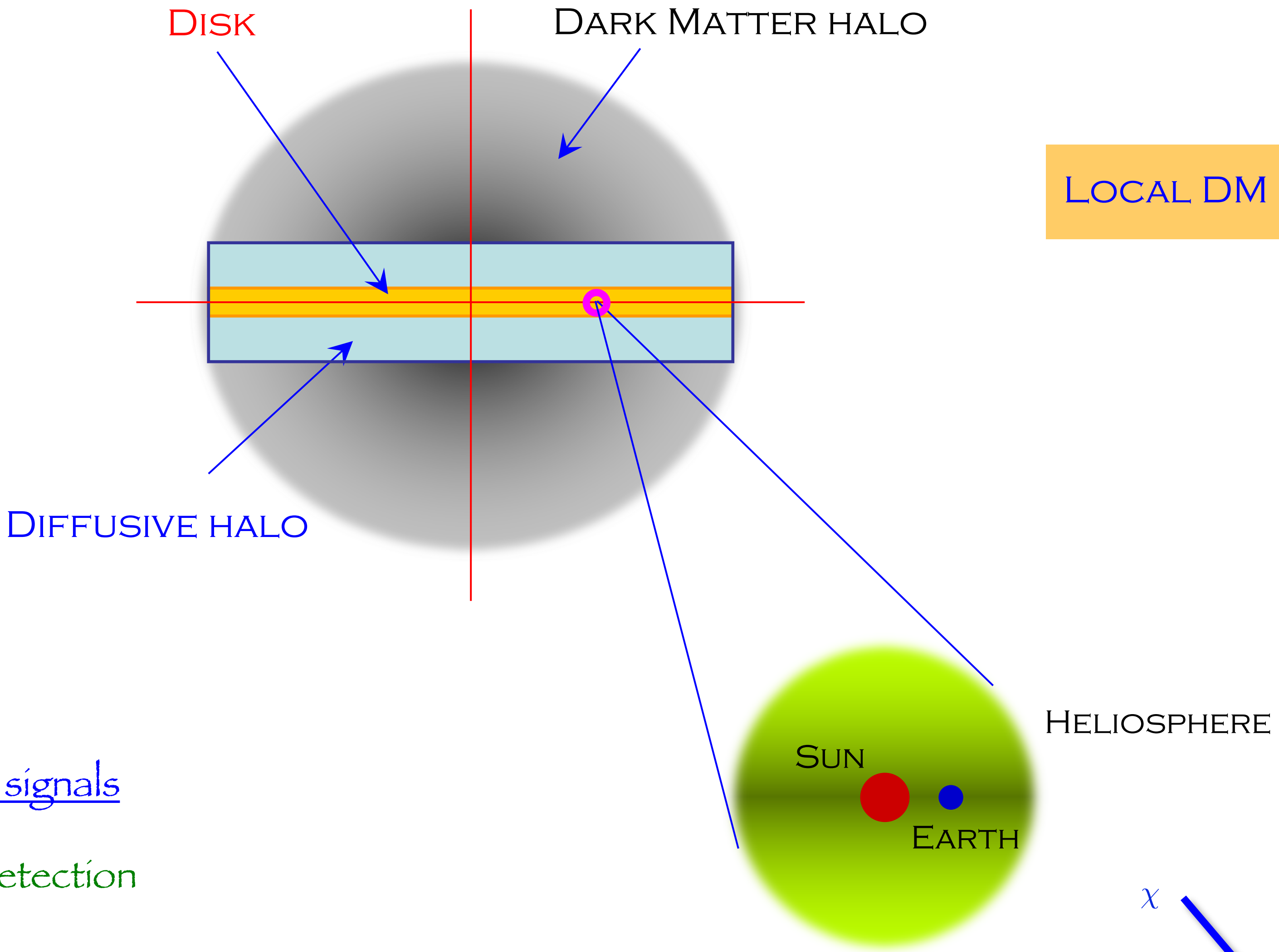


View from the side

Galactic signals

Direct detection
Electrons/positrons
Antiprotons
Antideuterons
Photons (from radio to gamma rays)
neutrinos

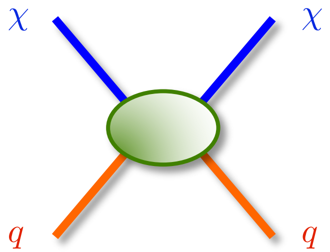
Local DM halo



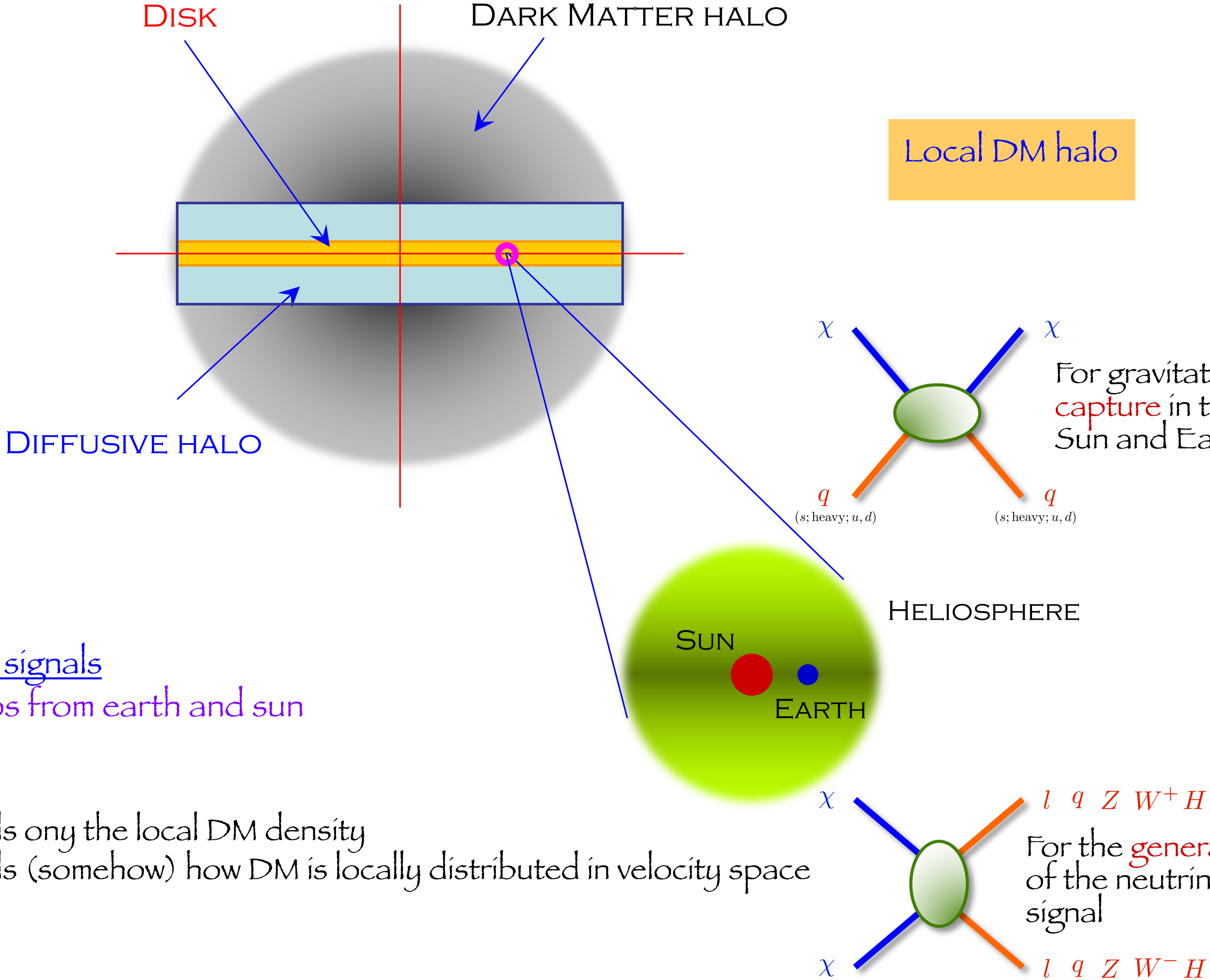
Galactic signals

Direct detection

Feels ony the local DM density
Feels how DM is locally distributed in velocity space



Local DM halo



For gravitational capture in the Sun and Earth

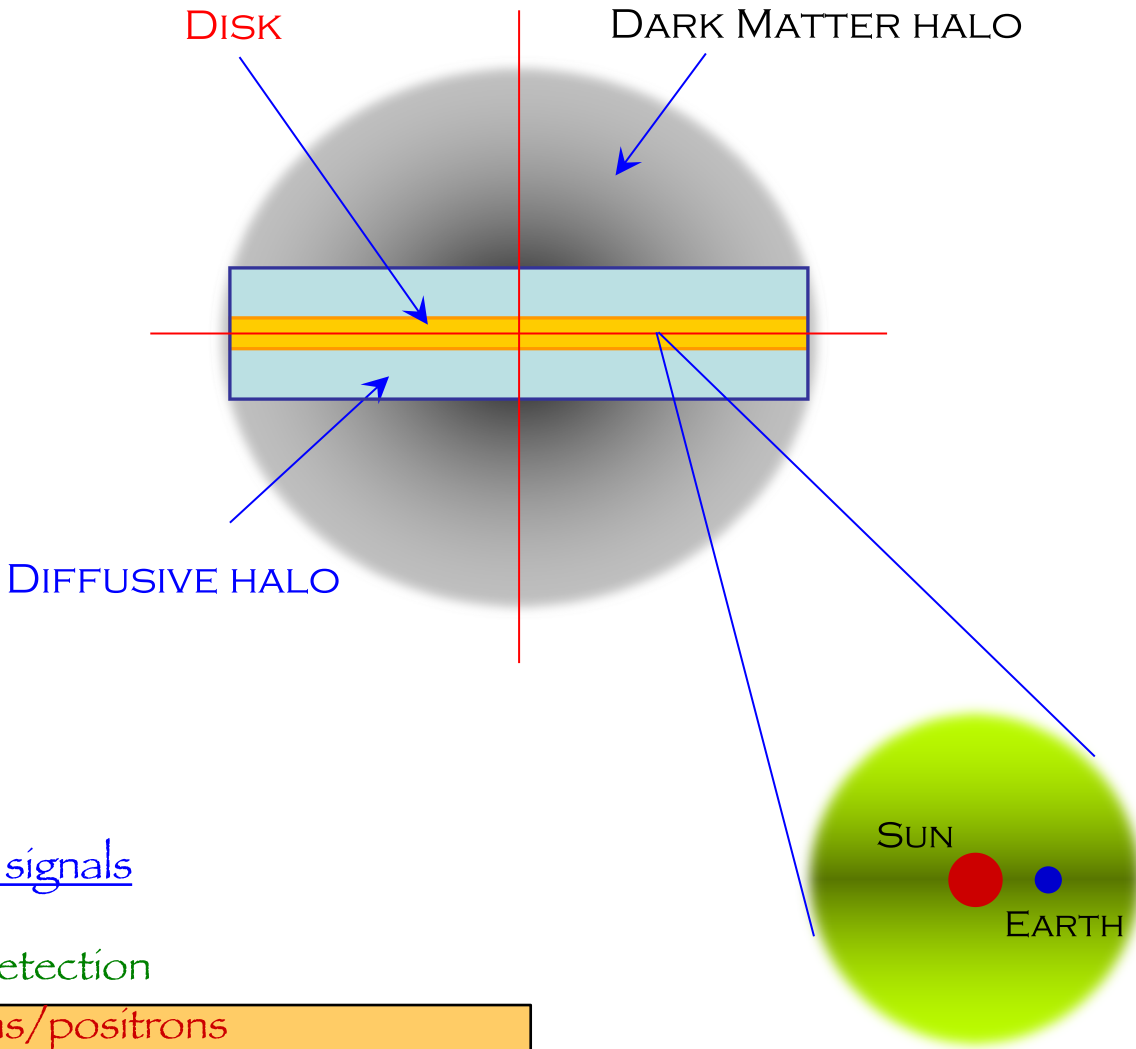
For the generation of the neutrino signal

Galactic signals

Neutrinos from earth and sun

Feels ony the local DM density

Feels (somehow) how DM is locally distributed in velocity space



DISK

DARK MATTER HALO

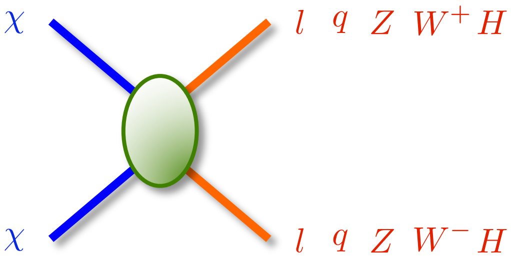
DIFFUSIVE HALO

SUN

EARTH

HELIOSPHERE

DM HALO PROFILE
SUBSTRUCTURES



χ

χ

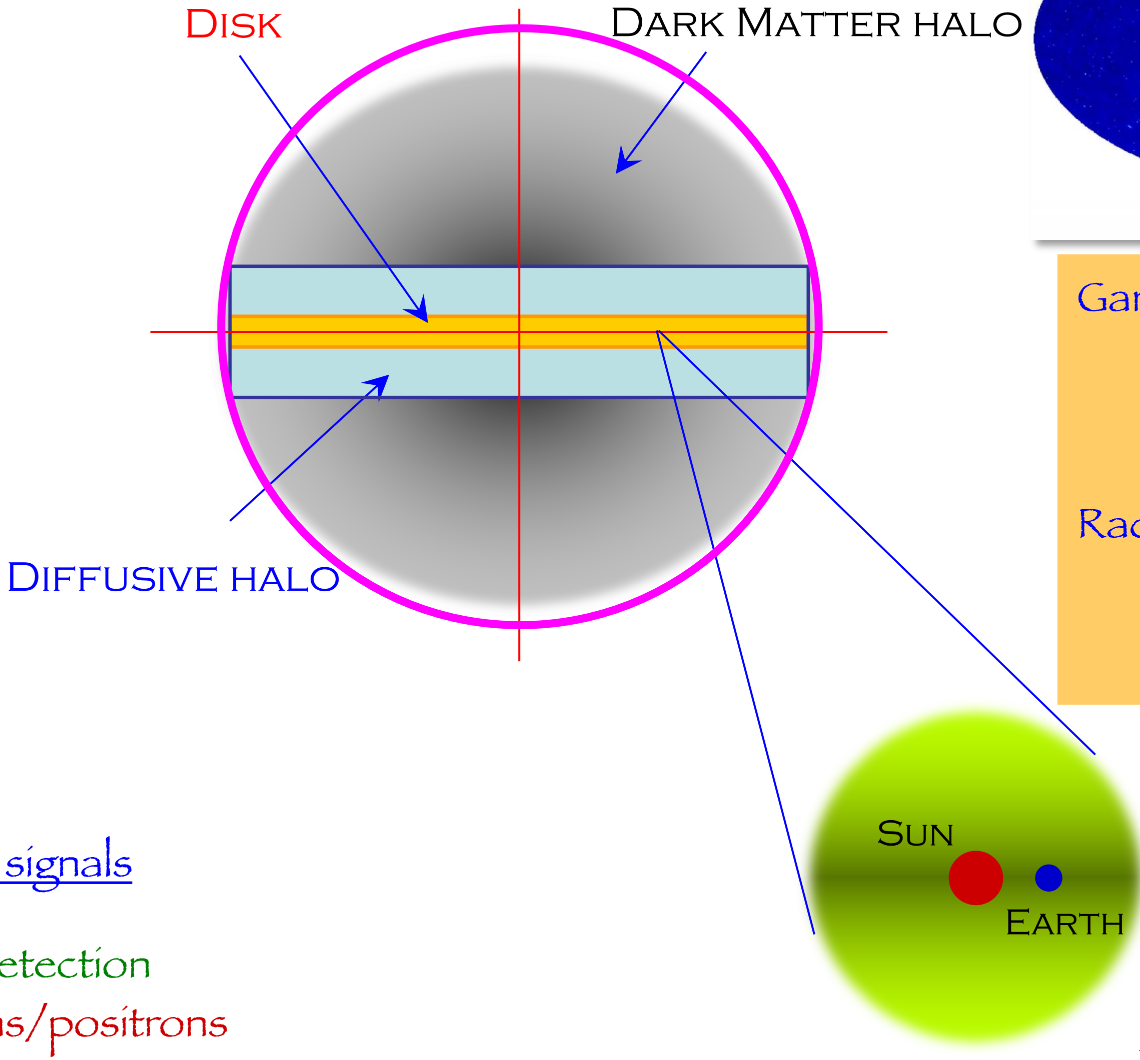
$l \quad q \quad Z \quad W^+ \; H$

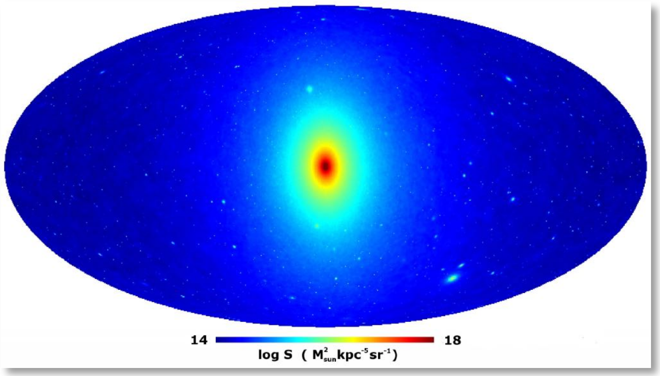
$l \quad q \quad Z \quad W^- \; H$

Galactic signals

Direct detection

Electrons/positrons
Antiprotons
Antideuterons
Photons (from radio to gamma rays)
Neutrinos from the Galaxy





Gamma rays
- prompt (π^0 decay)
- IC from e+/e- on ISRF

Radio
- synchrotron emission from e+/e- on galactic B

Galactic signals

Direct detection

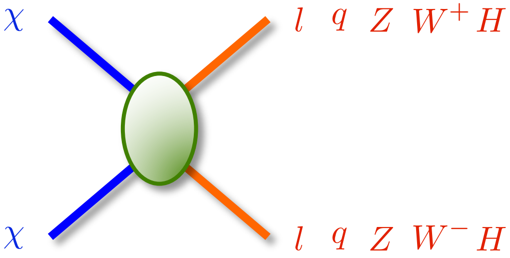
Electrons/positrons

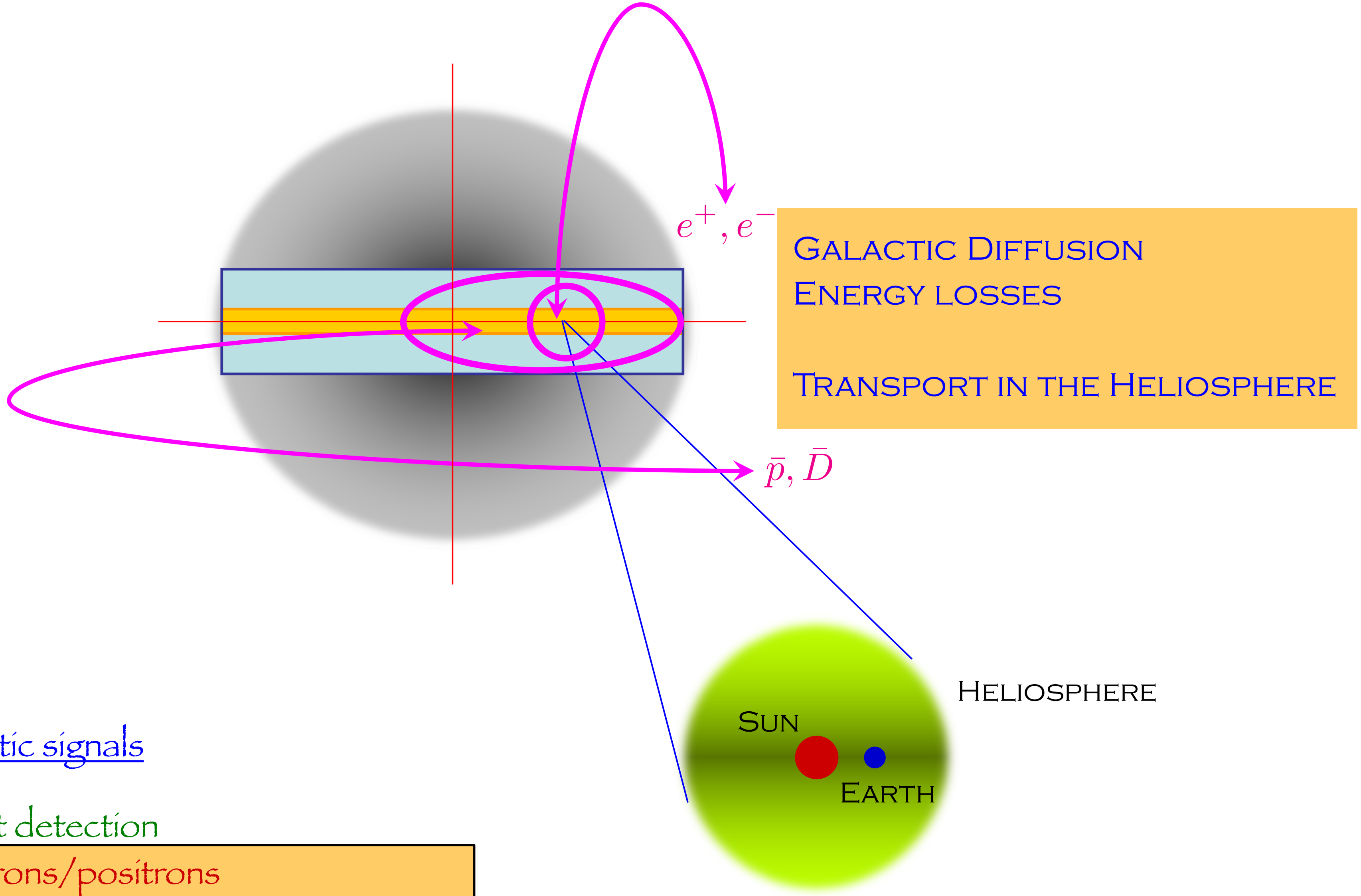
Antiprotons

Antideuterons

Photons (from radio to gamma rays)

Neutrinos from the Galaxy





Galactic Diffusion
Energy losses

Transport in the Heliosphere

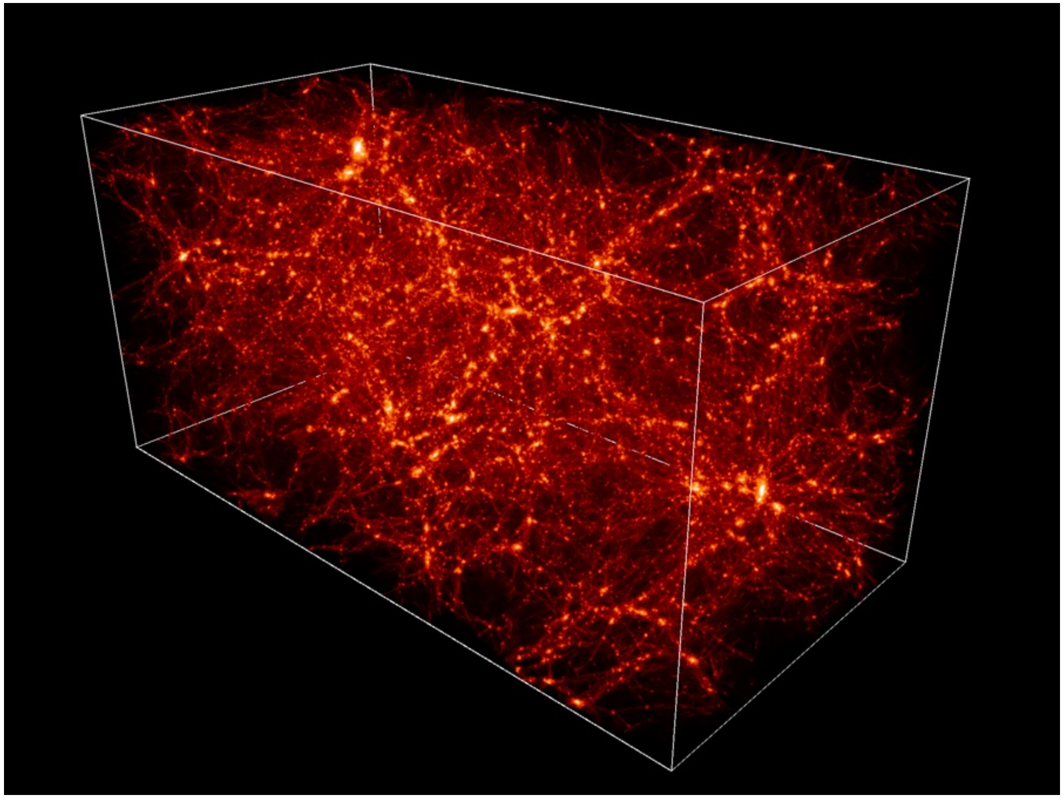
Galactic signals

Direct detection

- Electrons/positrons
- Antiprotons
- Antideuterons

Photons (from radio to gamma rays)
Neutrinos from the Galaxy

Extra-galactic environment



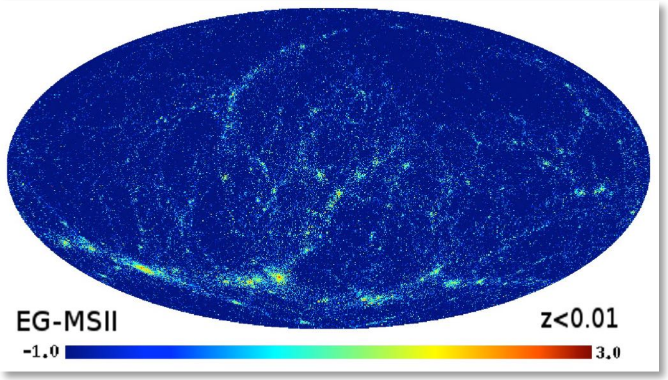
Extragalactic signals

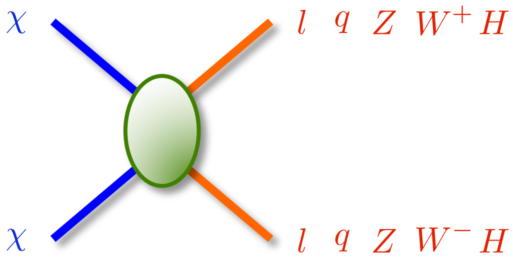
Photons: gamma, X, radio

Neutrinos

Sunyaev-Zeldovich effect on CMB

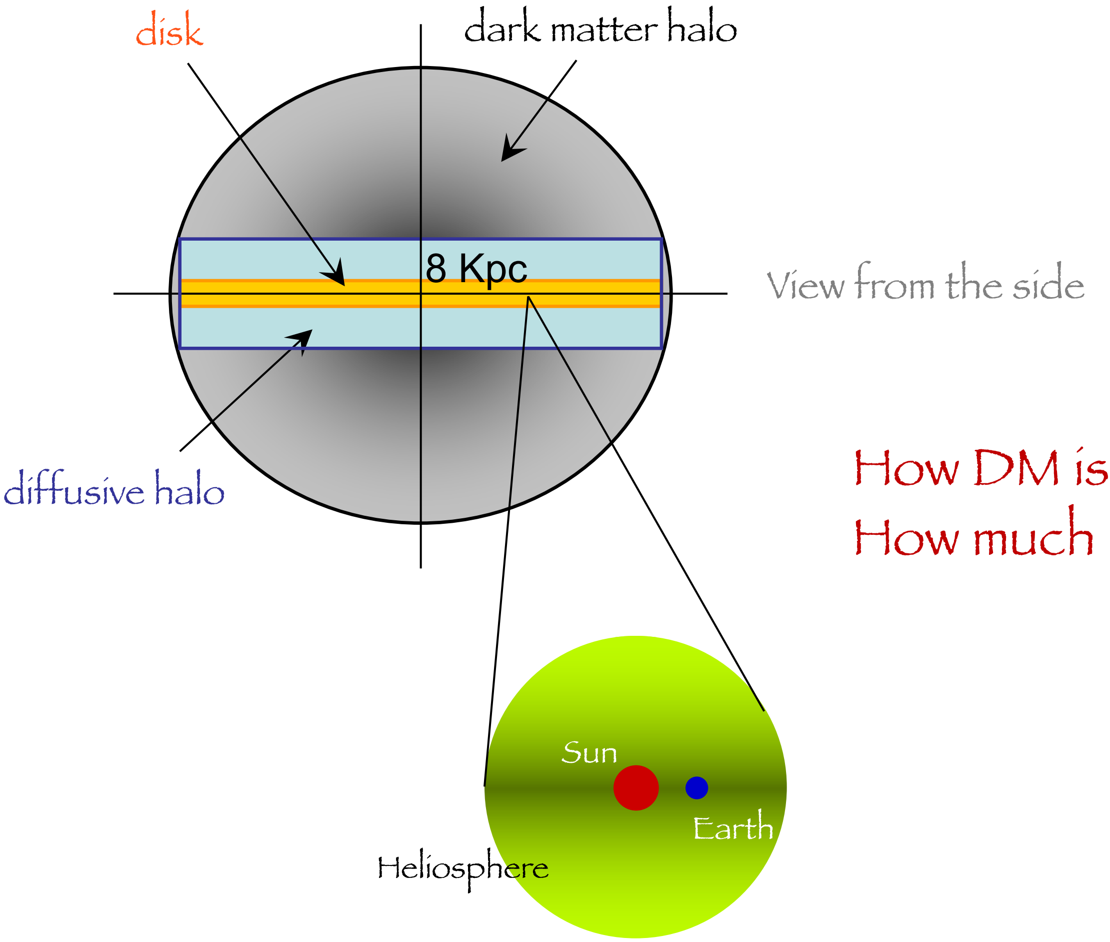
Optical depth of the Universe





DM distribution in Galaxies

Galactic environment



How DM is distributed in the Galaxy?

How much DM is there?

1 pc = 3.26 ly

The vanilla model: isothermal sphere

$$v_0^2 \equiv v_{\rm rot}^2(R_\odot) \; = \; \frac{G}{R_\odot}\left[M_{\rm vis} + M_{\rm DM}\right]$$

- ❊ $$\rho_{\rm DM}(r) = \frac{v_0}{4\pi G}\,\frac{1}{r^2} \xrightarrow{\qquad\qquad} \frac{v_0}{4\pi G}\,\frac{r^2+3R_c^2}{(r^2+R_c^2)^2}$$

  unphysical at small r

- ❊ $$f(v) = N\exp\left(-v^2/v_0^2\right)$$

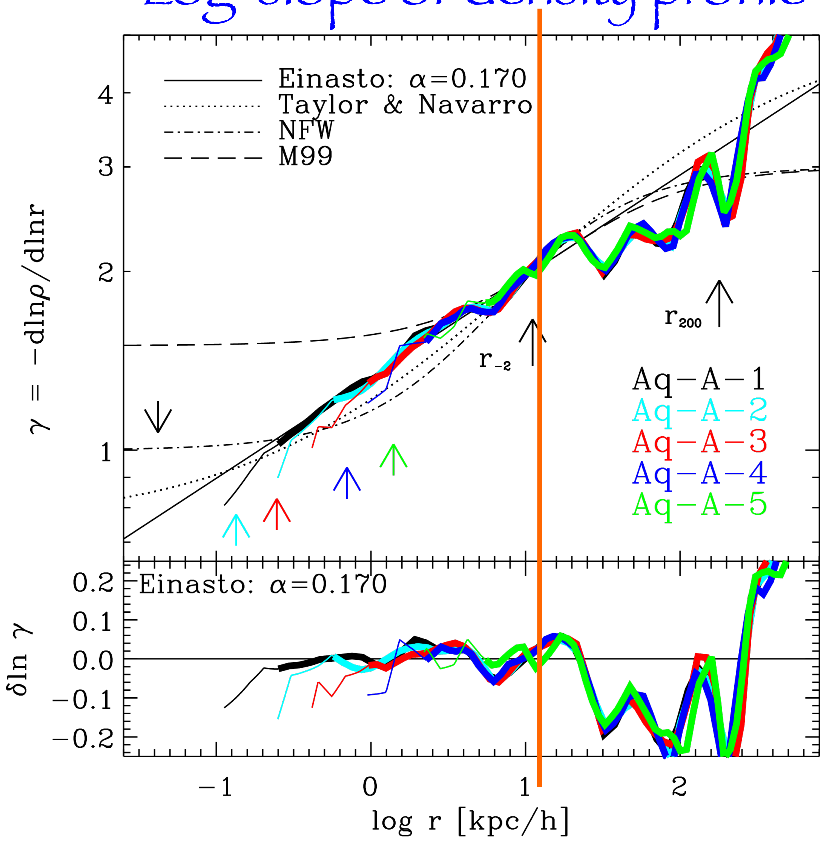
Numerical simulations

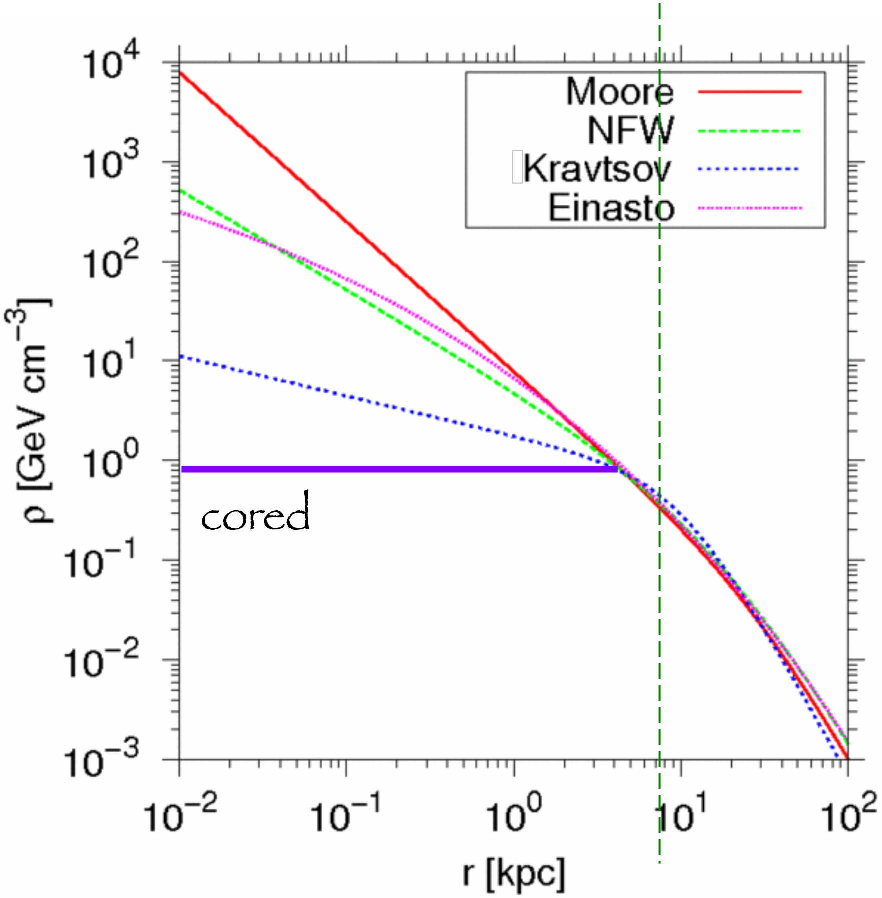
Cold Dark Matter	N-body
Gas coolings, photo-ionization Star formation, ISM model Stellar evolution Stellar feedback (winds) Black holes and SMBH feedback	Hydrodinamical

Volume: $(100\ \mathrm{Mpc})^3$
DM particles/cells: $10^9 - 10^{10}$

Density profile: smooth component

Log-slope of density profile

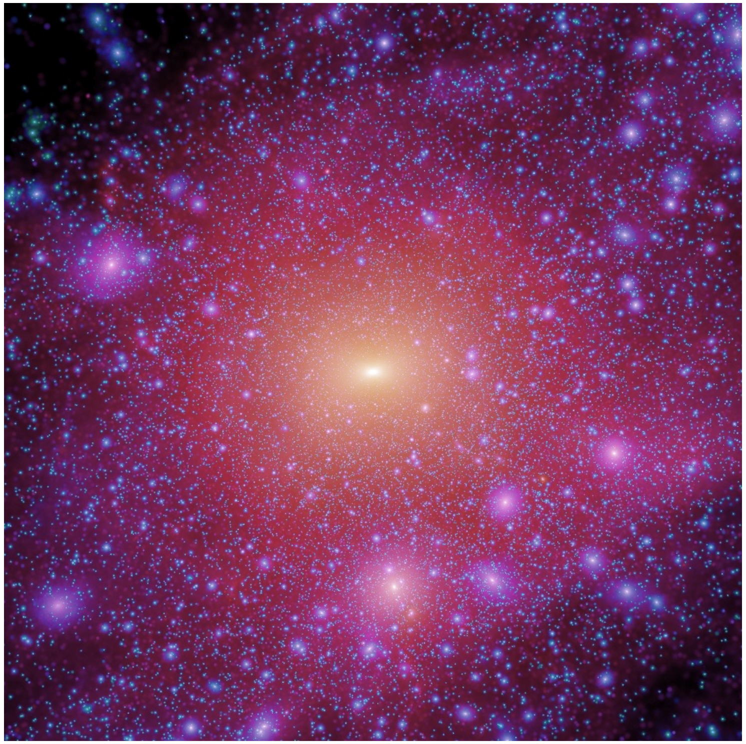




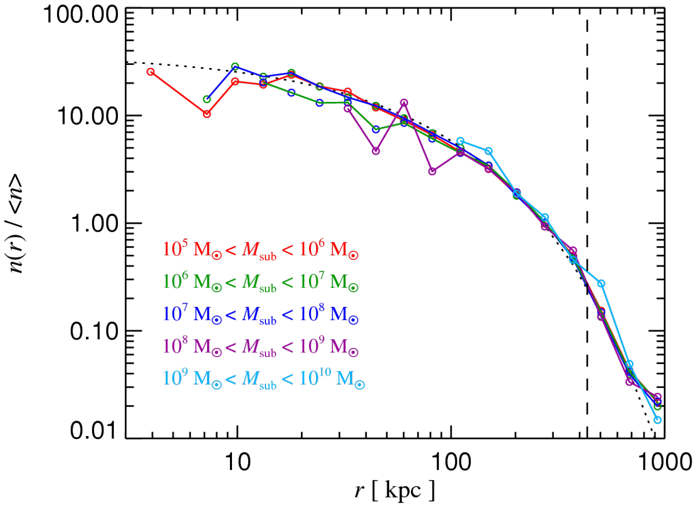
From numerical simulations

Navarro et al., arXiv:0810.1522

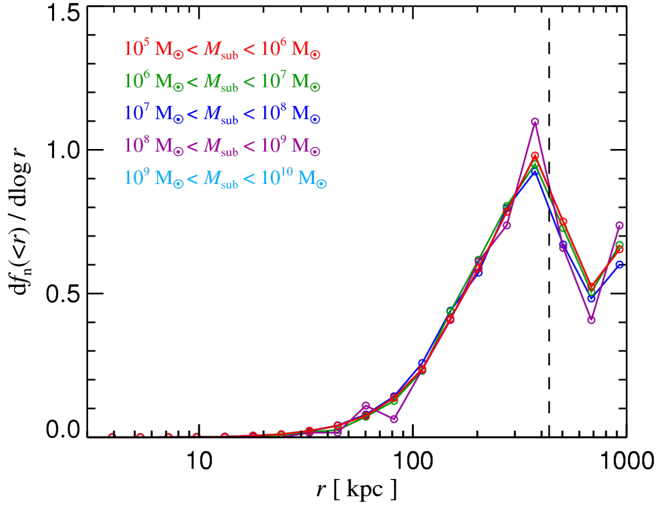
CDM: Subhalos



The Aquarius Project



Subhalo number density

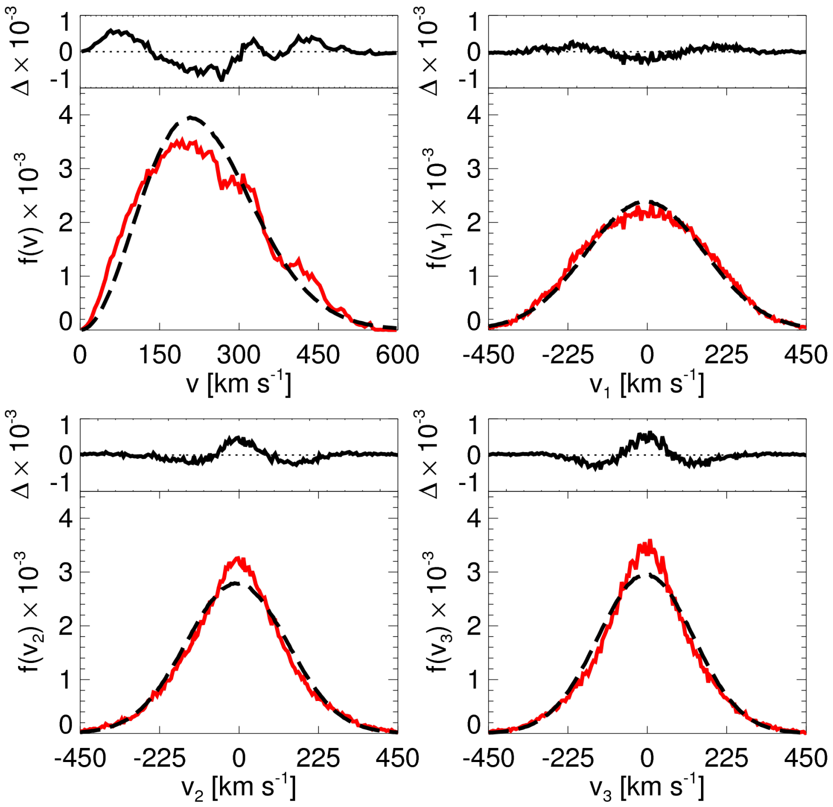


Subhalo fraction

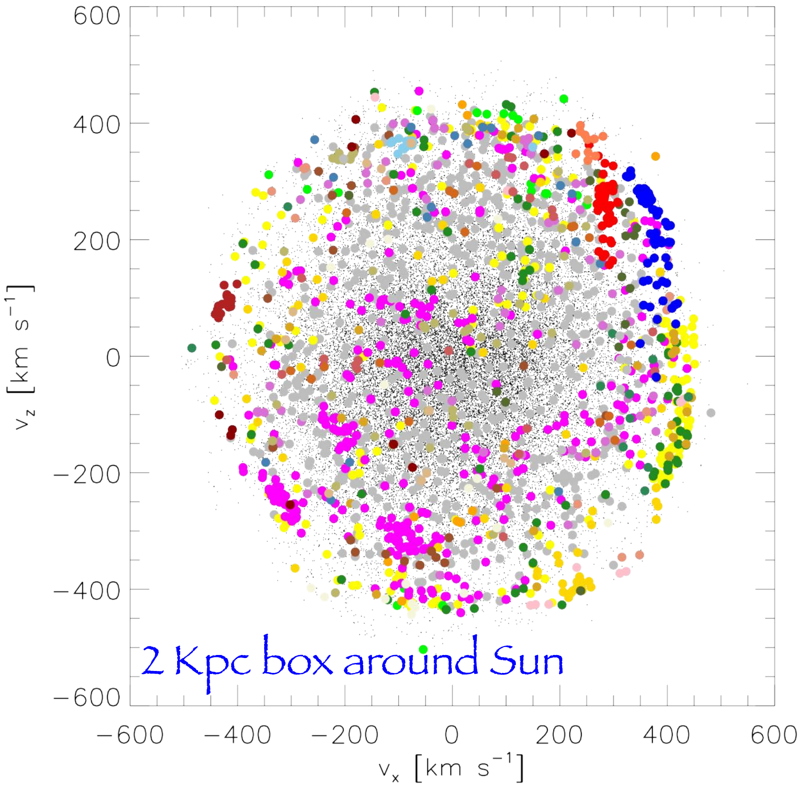
Most subhalos are in the outer halo

Springel et al., MNRAS 391 (2008) 1685

Velocity distribution (at Sun's position)



Velocity streams



2 Kpc box around Sun

From numerical simulations

Vogelsberger et al., arXiv:0812.0362

Vogelsberger et al., arXiv:0812.0362

“Canonical” halo

$$\rho(r) \longrightarrow \rho_0 = 0.3 \text{ GeV cm}^{-3}$$

$$\rho(r) \longrightarrow r^{-1} \quad [r \to 0]$$

Some determinations [1-3]

[1] $\rho_0 = 0.385 \pm 0.027 \text{ GeV cm}^{-3}$ (Einasto)
$\rho_0 = 0.389 \pm 0.025 \text{ GeV cm}^{-3}$ (NFW)

[2] $\rho_0 = 0.43(11)(10) \text{ GeV cm}^{-3}$

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm\ 50)\text{km s}^{-1}$$

$$v_{\rm esc} = (450 \div 650) \text{ km s}^{-1}$$

[1] Catena, Ullio, arXiv:0907.0018
[2] Salucci et al. arXiv:1003.3101
[3] Pato et al., arXiv:1006.1322

“Canonical” halo

$$\rho(r) \longrightarrow \rho_0 = 0.3 \text{ GeV cm}^{-3}$$

Debated whether cuspy or cored

Effect of baryons unclear

$$\rho(r) \longrightarrow r^{-1} \; [r \to 0]$$

Substructures likely are present (although sparsely distributed, mostly in the outer parts (anti-biased)

$$f(\vec{v}) = N \exp\left(-v^2/v_0^2\right)|_{v_{\rm esc}}$$

$$v_0 = (220 \pm \; 50)\text{km s}^{-1}$$

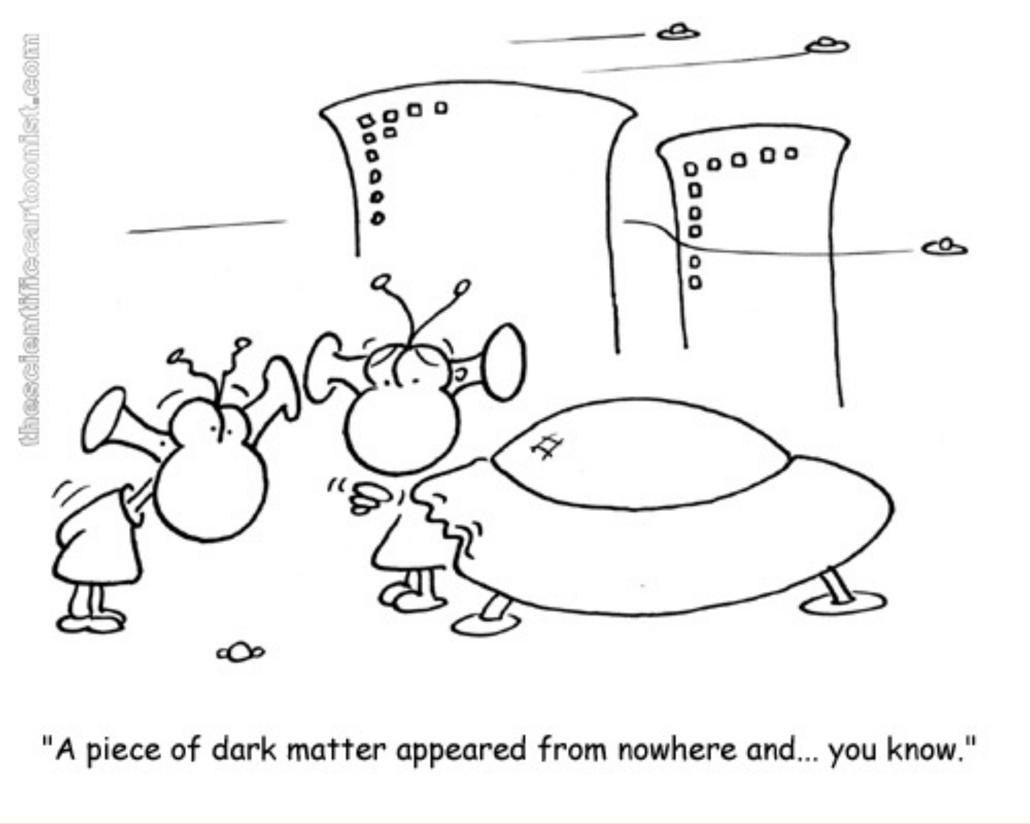
$$v_{\rm esc} = (450 \div 650) \text{ km s}^{-1}$$

Anisotropies may be present

The high-v tail may not be fully “thermal”

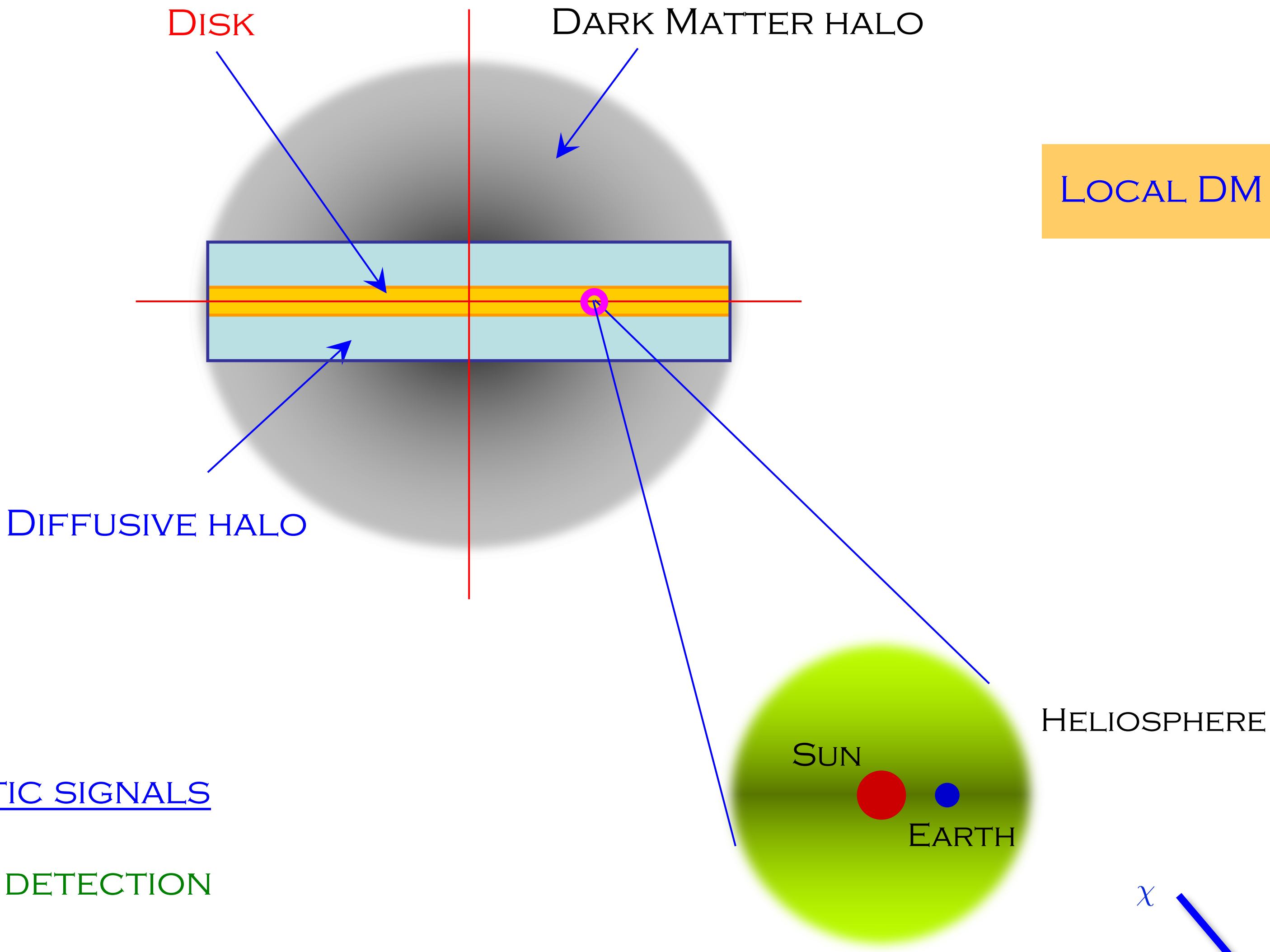
Streams may have impact

DIRECT DETECTION OF DM



"A piece of dark matter appeared from nowhere and... you know."

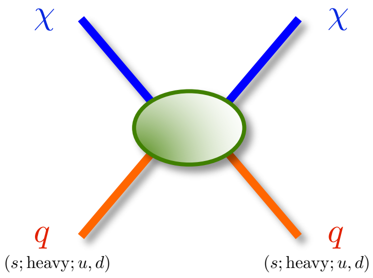
LOCAL DM HALO



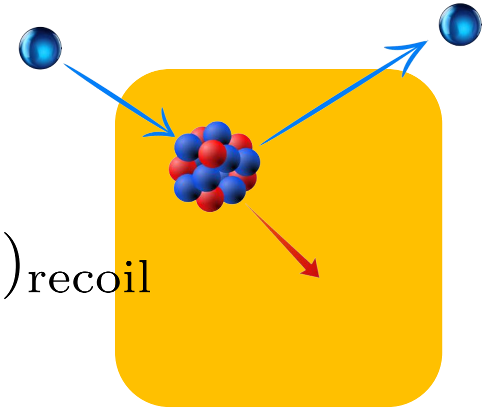
GALACTIC SIGNALS

DIRECT DETECTION

Feels ony the local DM density
Feels how DM is locally distributed in velocity space



Direct detection signal



Typical process for WIMP DM

$$\chi + \mathcal{N}(A_\mathcal{N}, Z_\mathcal{N})_{\text{at rest}} \to \chi + \mathcal{N}(A_\mathcal{N}, Z_\mathcal{N})_{\text{recoil}}$$

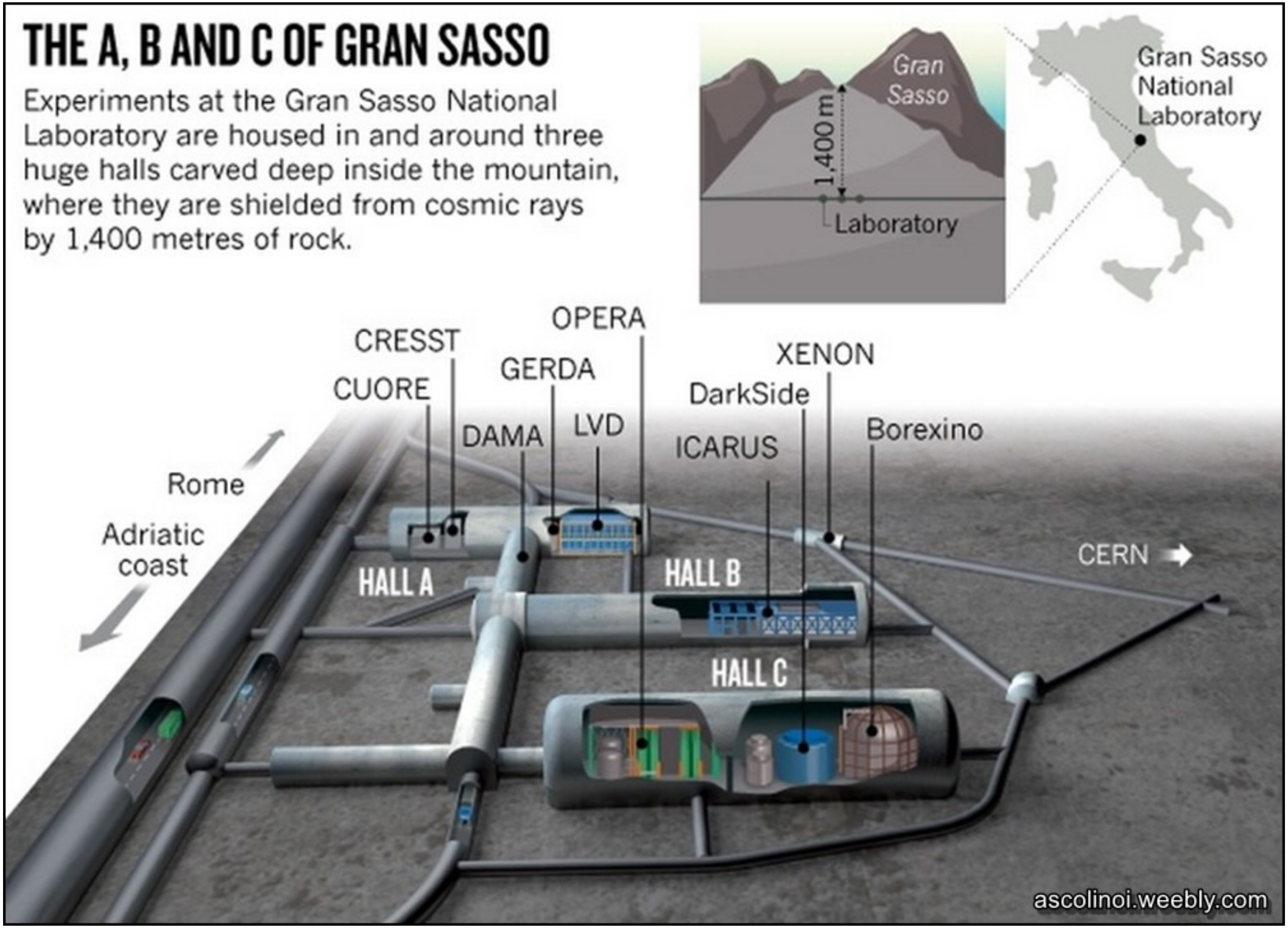
Recoil rate

$$\frac{dR}{dE_R} = \frac{\xi_\mathcal{N}}{m_\mathcal{N}} \frac{\rho_\odot}{m_\chi} \int_{v_{\min}(E_R)}^{v_{\text{esc}}} d^3v \, v \, f_E(\vec{v}) \frac{d\sigma_\mathcal{N}}{dE_R}(v, E_R)$$

For non-WIMP (kev, MeV) DM: interaction on electrons

Underground Labs

LNGS – Gran Sasso Lab (INFN)



THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

ascolinoi.weebly.com

Interaction mechanisms

- Elastic scattering with nuclei $\chi\,\mathcal{N} \longrightarrow \chi\,\mathcal{N}$
  - Coherent coupling to nucleons
  - Coupling the nucleus spin
  - Long-range mediators
  - Electric/magnetic dipole-moment interactions
  - ...
- Inelastic scattering with nuclei $\chi\,\mathcal{N} \longrightarrow \chi'\,\mathcal{N}$
  - Scatter requires a mass difference between X and X' of the order of 1-100 keV
- Scattering on electrons

Interaction mechanisms

- Elastic scattering with nuclei — WIMP DM (GeV-TeV$^+$)

$$E_R = \mu_{\mathcal{N}}^2 v^2 (1 - \cos\theta)/m_{\mathcal{N}}$$

$$\langle E_{\rm R} \rangle \sim {\rm KeV} \left(\frac{m_{\mathcal{N}}}{\rm GeV} \right) \left(\frac{m_\chi}{m_\chi + m_{\mathcal{N}}} \right)^2$$

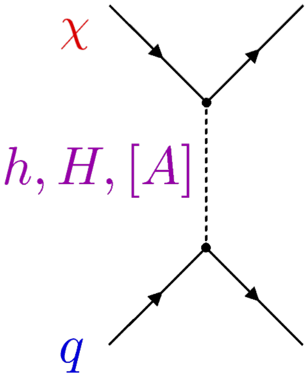
E_R > few KeV

- Inelastic scattering with nuclei — WIMP DM (GeV-TeV$^+$)

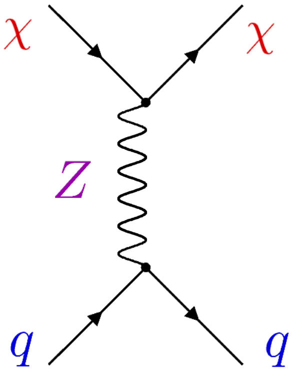
- Scattering on electrons — Light (keV) [pseudo]scalars

Example: Neutralino-quark scattering

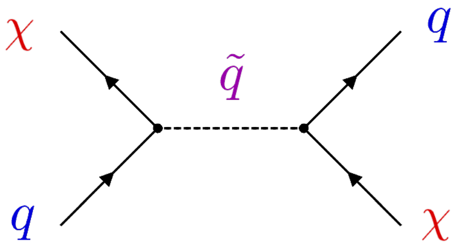
$\chi q \to \chi q$	$\tilde{q}_L, \tilde{q}_R$	s channel
	Z, h, H, A	t channel
	$\tilde{q}_L, \tilde{q}_L$	u channel



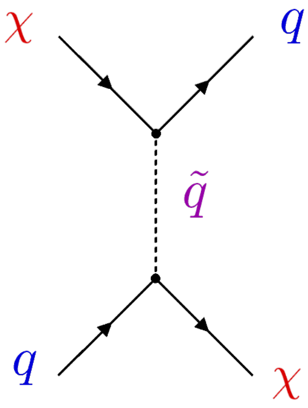
coherent



spin



coherent
spin



coherent
spin

Cross section

$$\mathcal{L}_{\text{eff}} = \sum_i \bar{\alpha}_i (\bar{q} O q)\, (\bar{\chi} O' \chi)_i$$

$$\mathcal{L}_{\text{eff}} \longrightarrow < N|\bar{q} O q|N > \propto \bar{\psi}_{\rm N} O \psi_{\rm N} \longrightarrow < \mathcal{N}\, \left|\bar{\psi}_{\rm N} O \psi_{\rm N}\right| \mathcal{N}\rangle$$

$$\begin{aligned}\mathcal{M} &= \langle \mathcal{N}, \chi\, |\mathcal{L}_{\text{eff}}\, |\, \mathcal{N}, \chi\rangle \\ &= \sum_i \langle \mathcal{N}\, \left|\bar{\psi}_{\rm N} O \psi_{\rm N}\right| \mathcal{N}\rangle \langle \chi\, |\bar{\chi} O' \chi|\, \chi\rangle_i\end{aligned}$$

Cross section

Scattering amplitude on nucleon n

$$\mathcal{M}_n = \sum_{i=1}^{16} c_i^n(\lambda, m_\chi)\, \mathcal{O}_i^{\mathrm{NR}}$$

Basis of 16 non–relativistic operators

λ: parameters of the underlying non-relativistic theory (mediator masses, couplings, ...)

Fitzpatrick et al, JCAP 1302 (2013) 004
Fitzpatrick et al, arXiv:1211.2818
Anand et al, PRC 89 (2014) 065501
Dent et al, PRD 92 (2015) 063515

Set of operators

$$\boxed{\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}}$$ scalar

$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\boxed{\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N}$$ spin

$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$

$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$

$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$

$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$

$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

$$\hat{\mathcal{O}}_{17} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp\right)$$

$$\hat{\mathcal{O}}_{18} = i\left(\frac{\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N\right)$$

Catena, JCAP 1407 (2014) 055
Arina, Del Nobile, Panci, PRL 114 (2015) 011301
Scopel, Yoon, JCAP 1507 (2015) 041
Catena, Gondolo, JCAP 08 (2015) 022
Gluscevic et al, JCAP 12 (2015) 057
Catena, Ibarra, Wild JCAP 05 (2016) 039
Kalhofer, Wild, arXiv:1607.04418
(...)

Fitzpatrick et al, JCAP 1302 (2013) 004
Fitzpatrick et al, arXiv:1211.2818
Anand et al, PRC 89 (2014) 065501
Dent et al, PRD 92 (2015) 063515

Cross section

Scattering amplitude on nucleon n

$$\mathcal{M}_n = \sum_{i=1}^{16} c_i^n(\lambda, m_\chi)\, \mathcal{O}_i^{\mathrm{NR}}$$

Basis of 16 non-relativistic operators

λ: parameters of the underlying non-relat. theory
(mediator masses, couplings, ...)

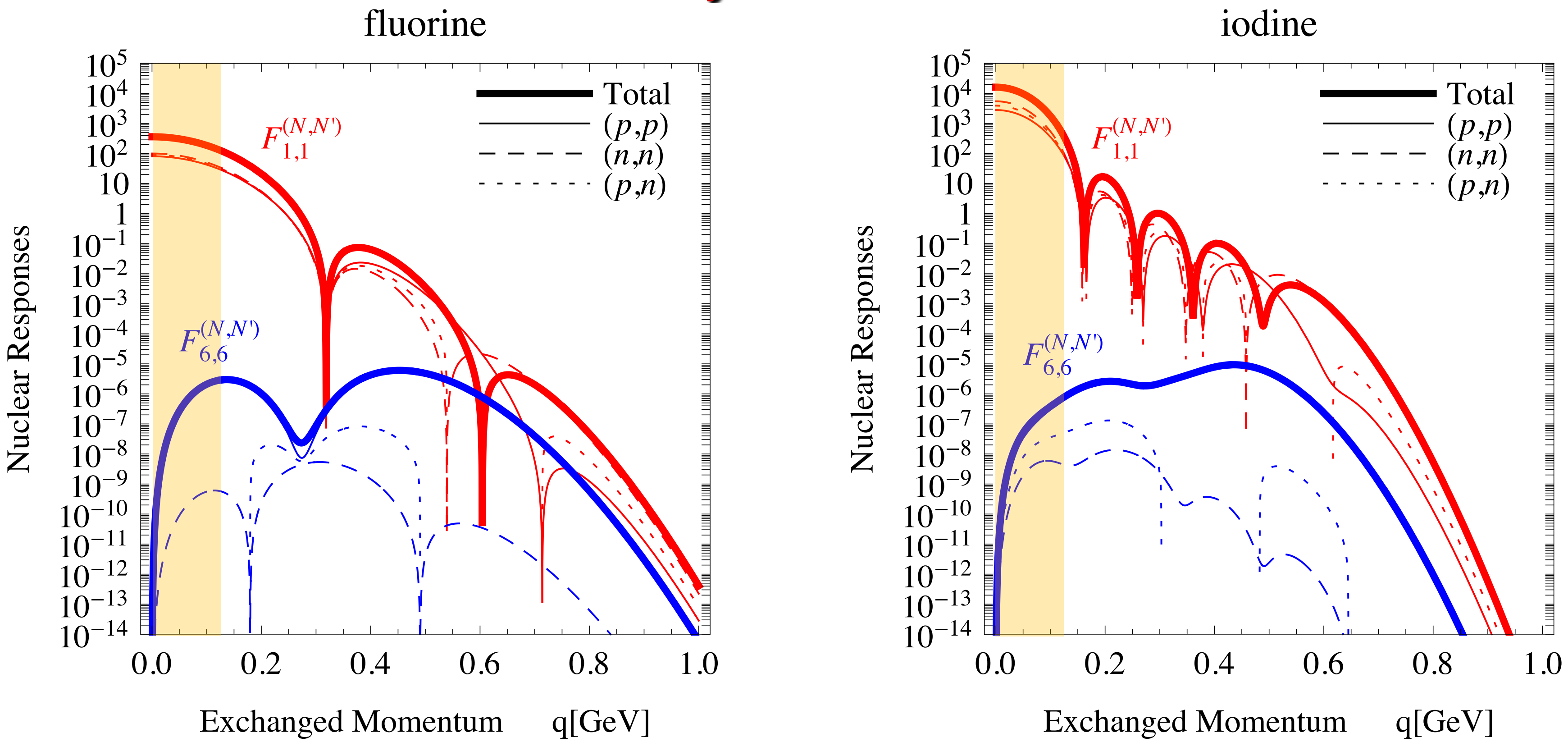
Transition probability on nucleus $\mathcal{N}$

$$\overline{|\mathcal{M}_\mathcal{N}|^2} = \frac{m_\mathcal{N}^2}{m_n^2} \sum_{i,j=1}^{16} \sum_{n,n'=p,n} c_i^n c_j^{n'} F_{i,j}^{(n,n')}(v, E_R|\mathcal{N})$$

nuclear response functions

Fitzpatrick et al, JCAP 1302 (2013) 004

Nuclear response functions



(1,1): $\mathcal{O}_1^{\rm NR} = \mathbb{1}$

"Vanilla" coherent scattering

A^2 enhanced

(6,6): $\mathcal{O}_6^{\rm NR} = (\vec{s}_\chi \cdot \vec{q})\,(\vec{s}_n \cdot \vec{q})$ e.g., pseudo-scalar mediator

scattering on p dominant (no unpaired n on F and I)

Cross section

Cross section on nucleus $\mathcal{N}$

$$\frac{d\sigma_{\mathcal{N}}}{dE_R}(v, E_R) = \frac{1}{32\pi} \frac{1}{m_\chi^2 m_{\mathcal{N}}} \frac{1}{v^2} \overline{|\mathcal{M}_{\mathcal{N}}|^2}$$

Non-relativistic scattering on nucleons -> nucleus

Relevant quantities:

$\vec{v}$	DM velocity	m_χ	DM mass
$\vec{q}$	Exchanged momentum	m_n	nucleon mass
$\vec{s}_n$	Nucleon spin	$m_{\mathcal{N}}$	nucleus mass
$\vec{s}_\chi$	DM spin		

Summarizing

$$\frac{dR_{\mathcal{N}}}{dE_R} = K \rho_{\odot} \, \xi_{\mathcal{N}} \sum_{i,j=1}^{16} \sum_{n,n'=p,n} c_i^n(\lambda, m_\chi) \, c_j^{n'}(\lambda, m_\chi) \, \mathcal{F}_{i,j}^{(n,n')}(E_R, \mathcal{N})$$

$$\mathcal{F}_{i,j}^{(n,n')}(E_R, \mathcal{N}) = \int_{v_{\min}(E_R)}^{v_{\rm esc}} d^3 v \, \frac{1}{v} \, f_{\rm G}(\vec{v} + \vec{v}_{\rm E}(t)) \, F_{i,j}^{(n,n')}(v, E_R, \mathcal{N})$$

Structure of the interaction

Nuclear response

Galactic modeling

Local motions

Sun/Earth revolution in the Galaxy	stationary boost
Earth revolution around the Sun	annual periodicity
Earth rotation around its axis	diurnal periodicity

Interaction rate (WIMP ; scalar interaction)

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\text{scalar}}^{(\text{nucleon }\,)}\right] F^2\left(E_R\right) \mathcal{I}\left(v_{\min}\right)$$

$$\mathcal{I}(v_{\min}) = \int_{w \geq v_{\min}} d^3w \; \frac{f_{\mathrm{ES}}(\vec{w})}{w}$$

$$f_{\mathrm{ES}}(\vec{w}) = f(\vec{w} + \vec{v}_{\oplus})\big|_{[v_{\text{rot}};v_{\text{esc}}]}$$

$$v_{\min} = \left[m_N E_R/(2\mu_A^2)\right]^{1/2}$$

Interaction rates

Spin-independent (scalar)

$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\text{scalar}}^{(\text{nucleon})}\right] F^2 \left(E_R\right) \mathcal{I}\left(v_{\min}\right)$$

Spin-dependent

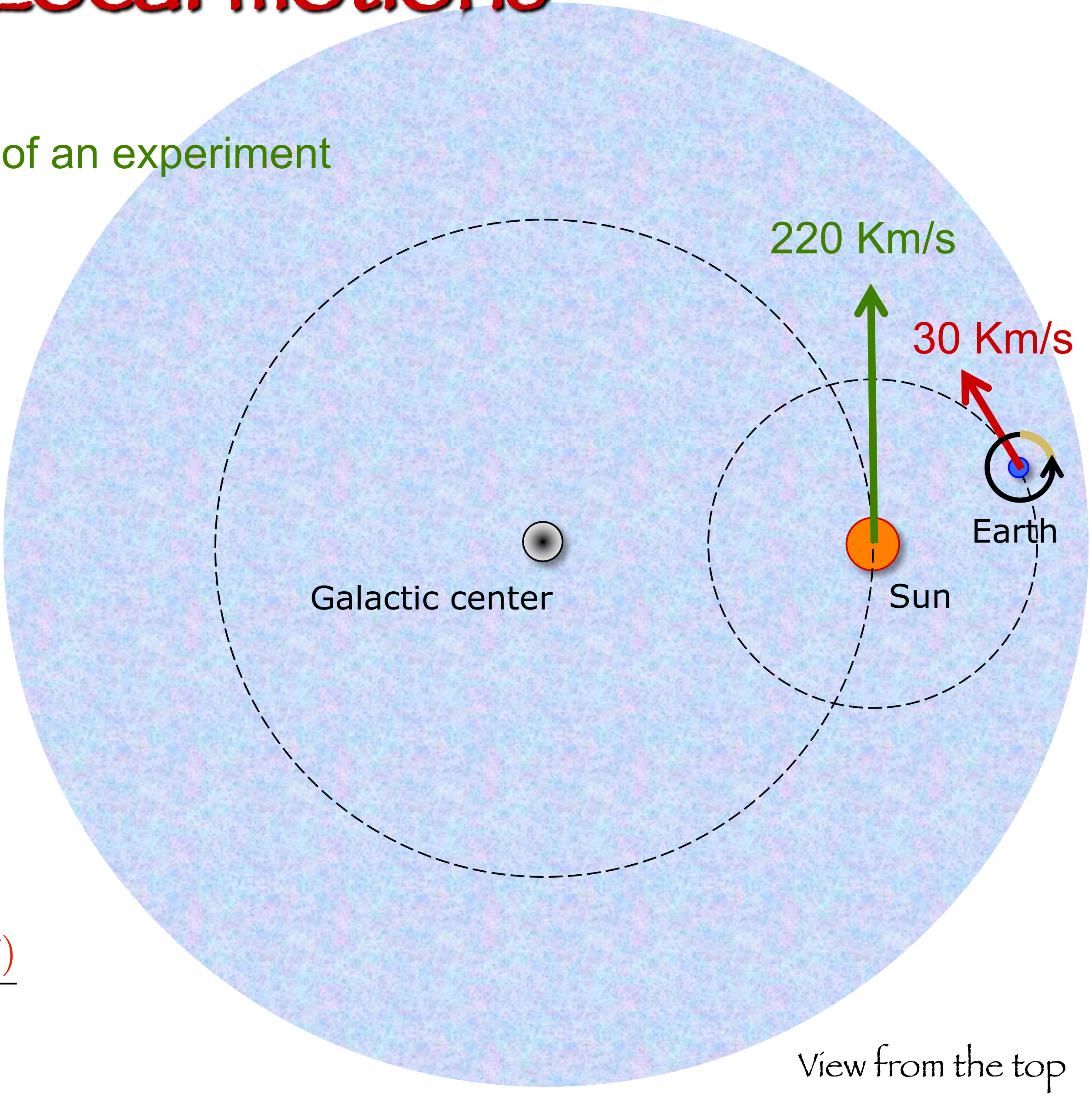
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{2m_N}{\mu_1^2} \lambda J(J+1) \left[\sigma_{\text{spin}}^{(\text{nucleon})}\right] F^2 \left(E_R\right) \mathcal{I}\left(v_{\min}\right)$$

Local motions

Stationary over the lifetime of an experiment

Directional boost

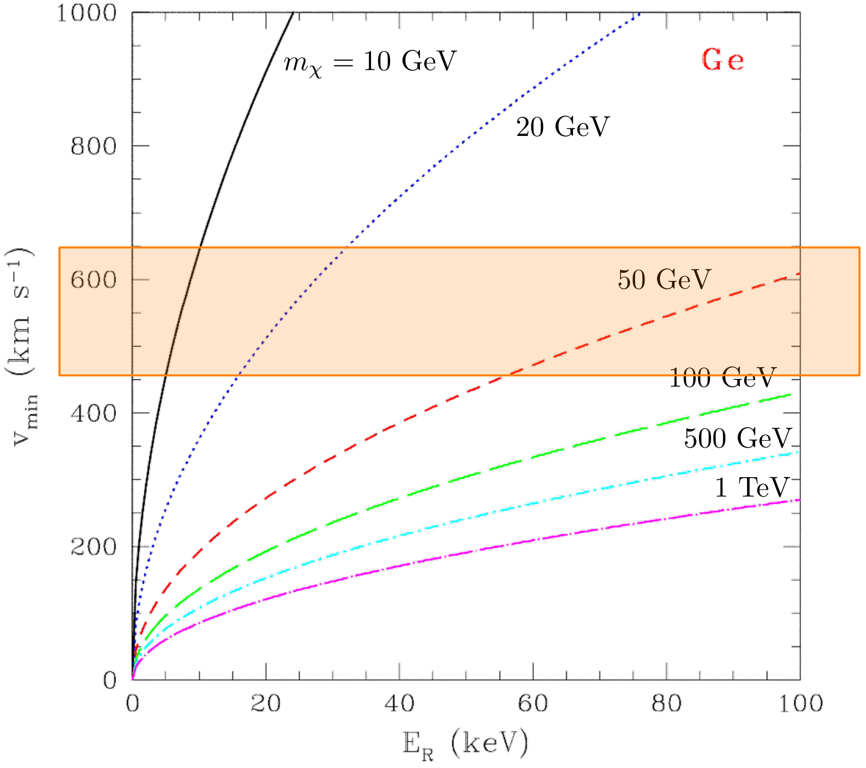


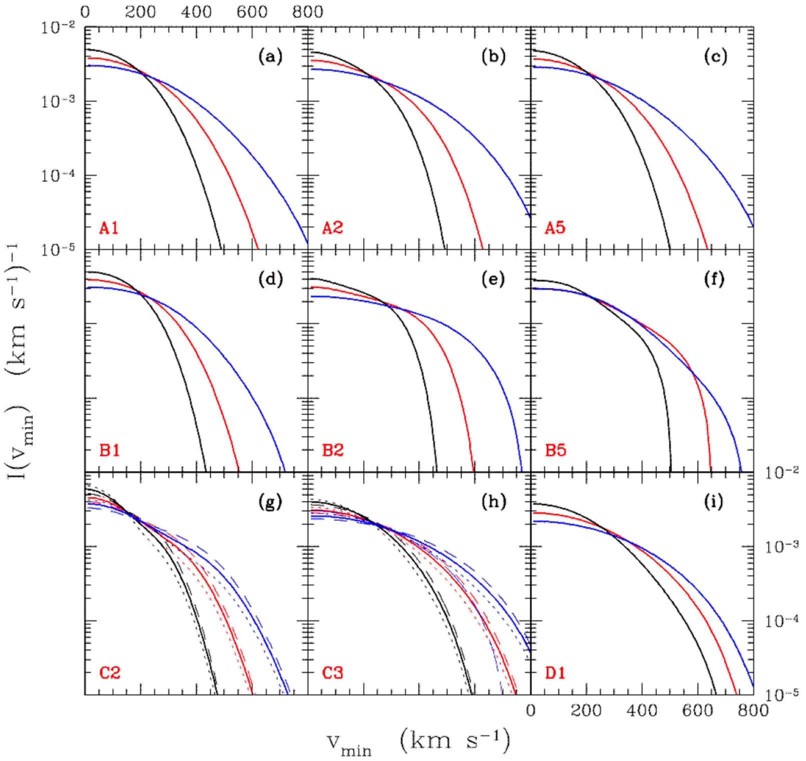
$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_{\oplus})|_{[v_{\rm rot}; v_{\rm esc}]}$$

View from the top

Response function

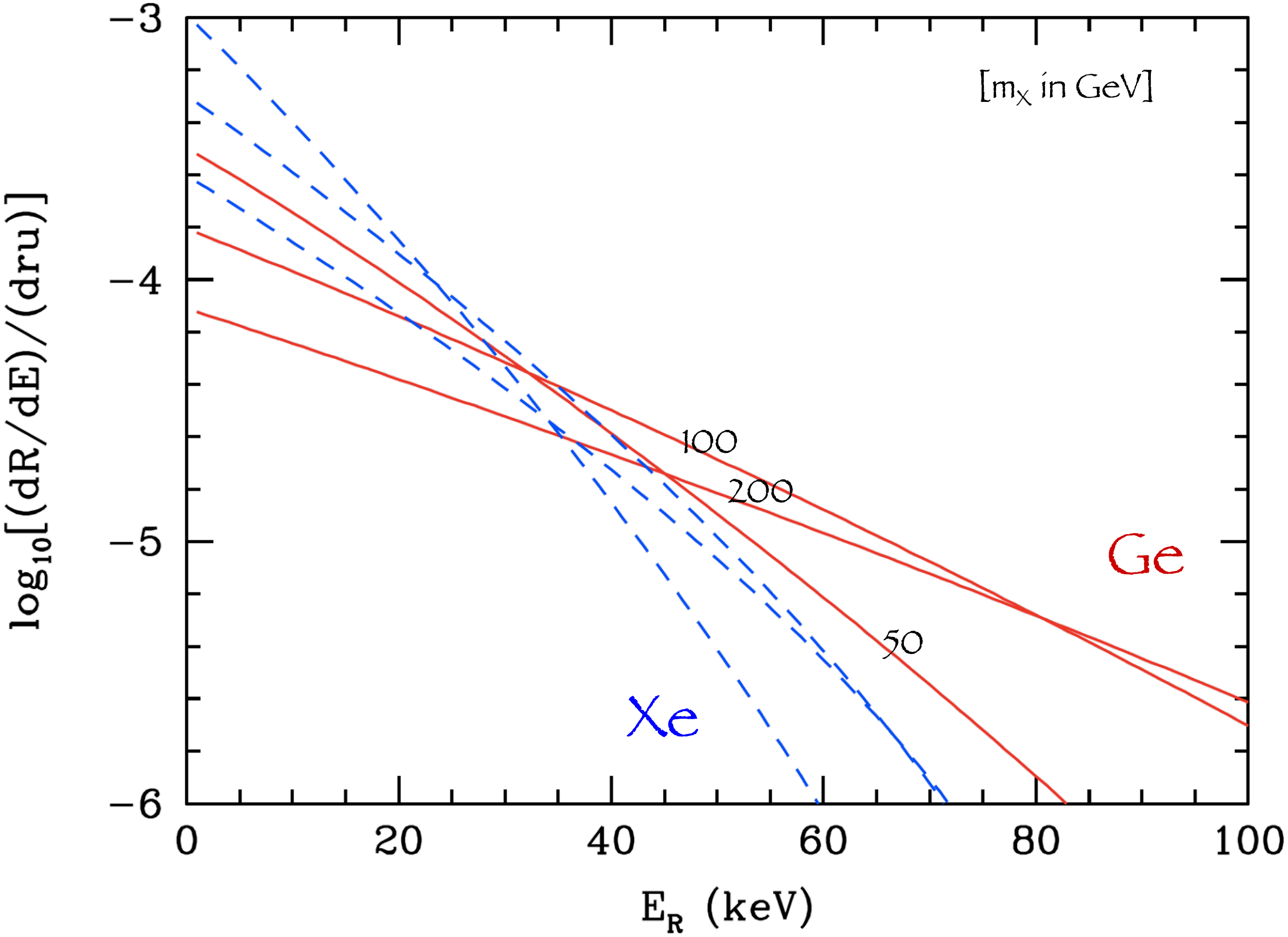




$$v_{\rm min} = [m_N E_R/(2\mu_A^2)]^{1/2}$$

$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

Differential Rate – Energy Dependence



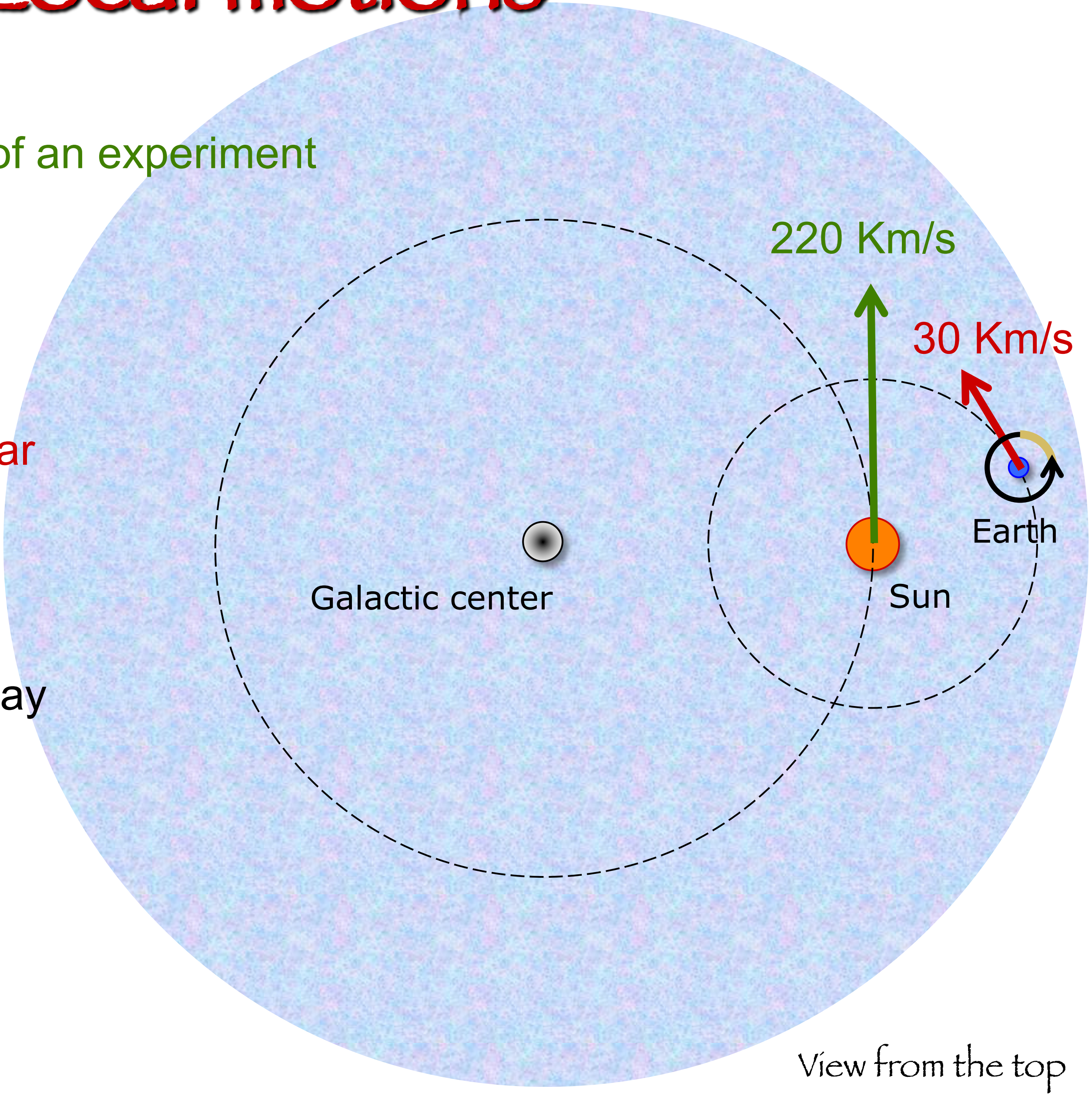
Local motions

Stationary over the lifetime of an experiment

Directional boost

Orbital motion - Period: 1 year

Diurnal rotation - Period: 1 day



$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3w \;\; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot}; v_{\rm esc}]}$$

View from the top

Typical signatures of direct detection

Stationary over the lifetime of an experiment

Directional boost

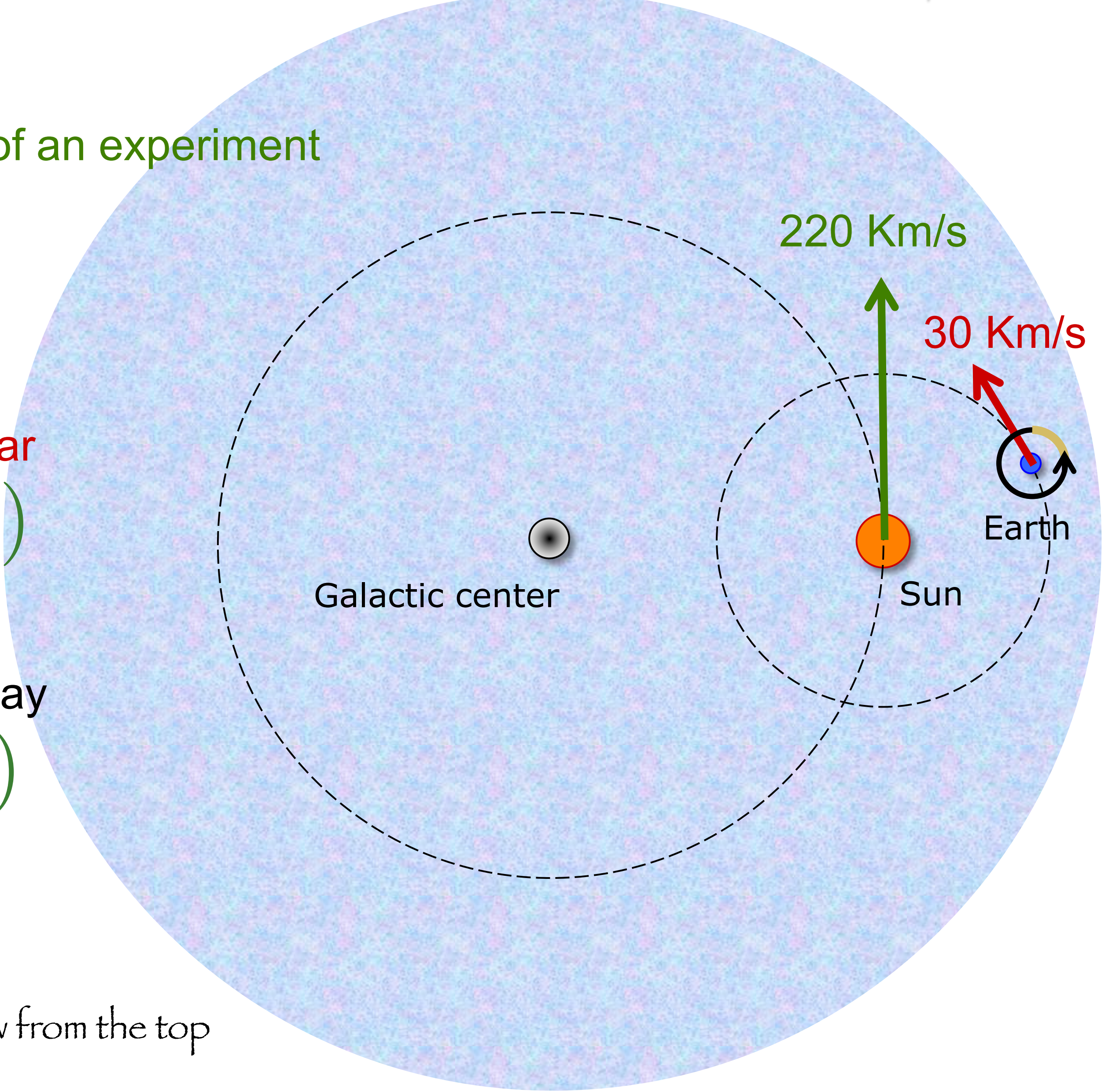
Directionality $\vec{v}$

Orbital motion - Period: 1 year

Annual modulation $\vec{v}(t)$

Diurnal rotation - Period: 1 day

Diurnal modulation $\vec{v}(t)$



View from the top

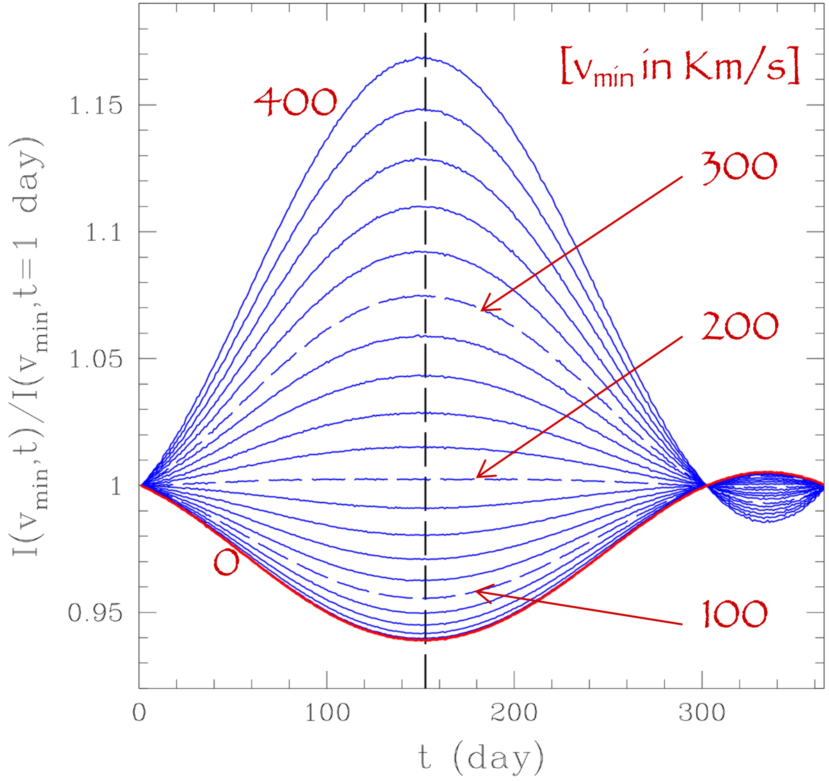
Annual Modulation of the rate

$$\frac{dR}{dE_R}[\eta(t)] = \frac{dR}{dE_R}[\eta_0] + \frac{\partial}{\partial\eta}\left(\frac{dR}{dE_R}\right)_{\eta=\eta_0} \Delta\eta \; \cos[\omega(t-t_0)]$$

$$= S_0(E_R) + S_m(E_R) \; \cos[\omega(t-t_0)]$$

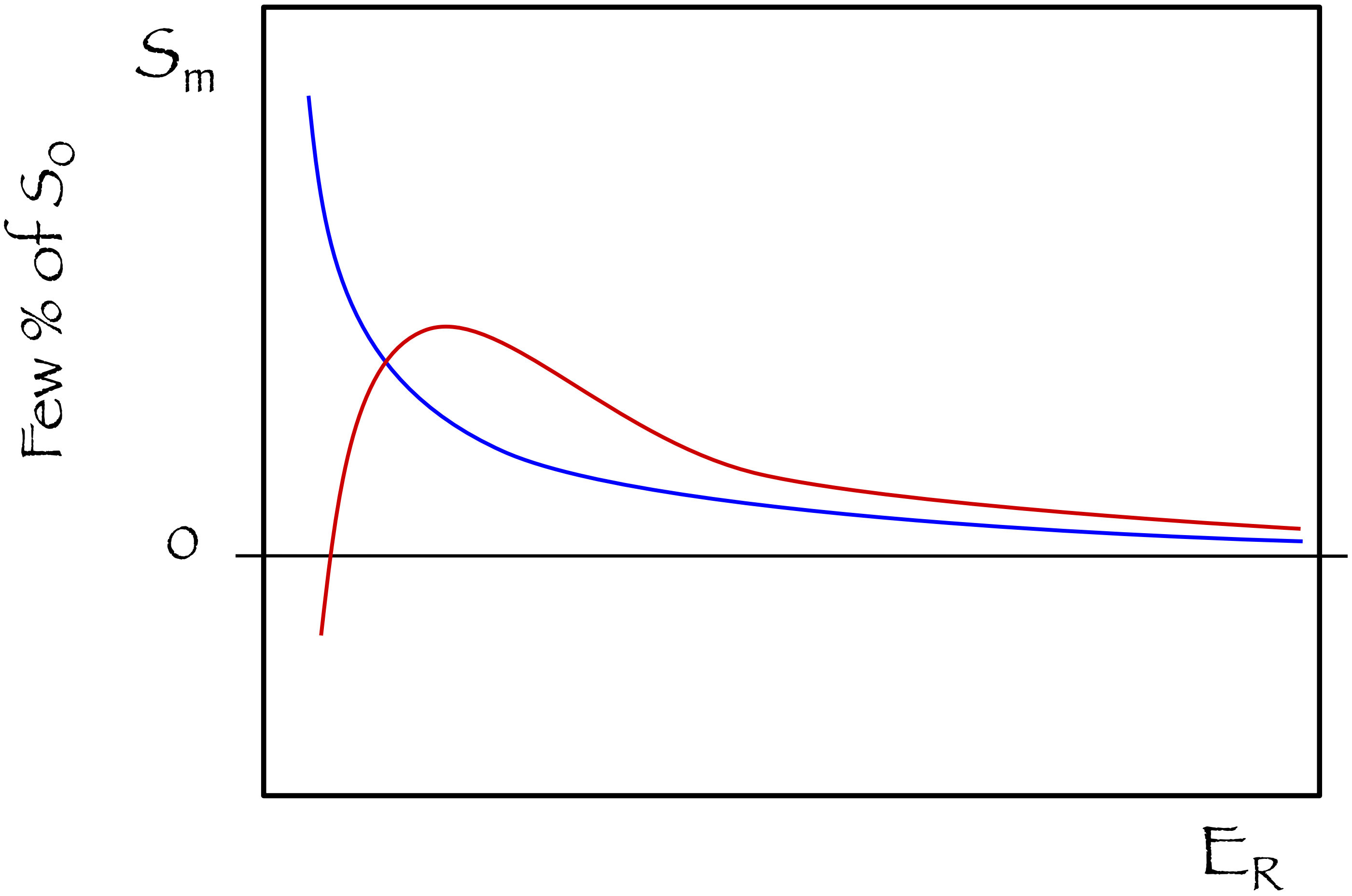
$\eta(t) = v(t)/v_0$

Annual modulation



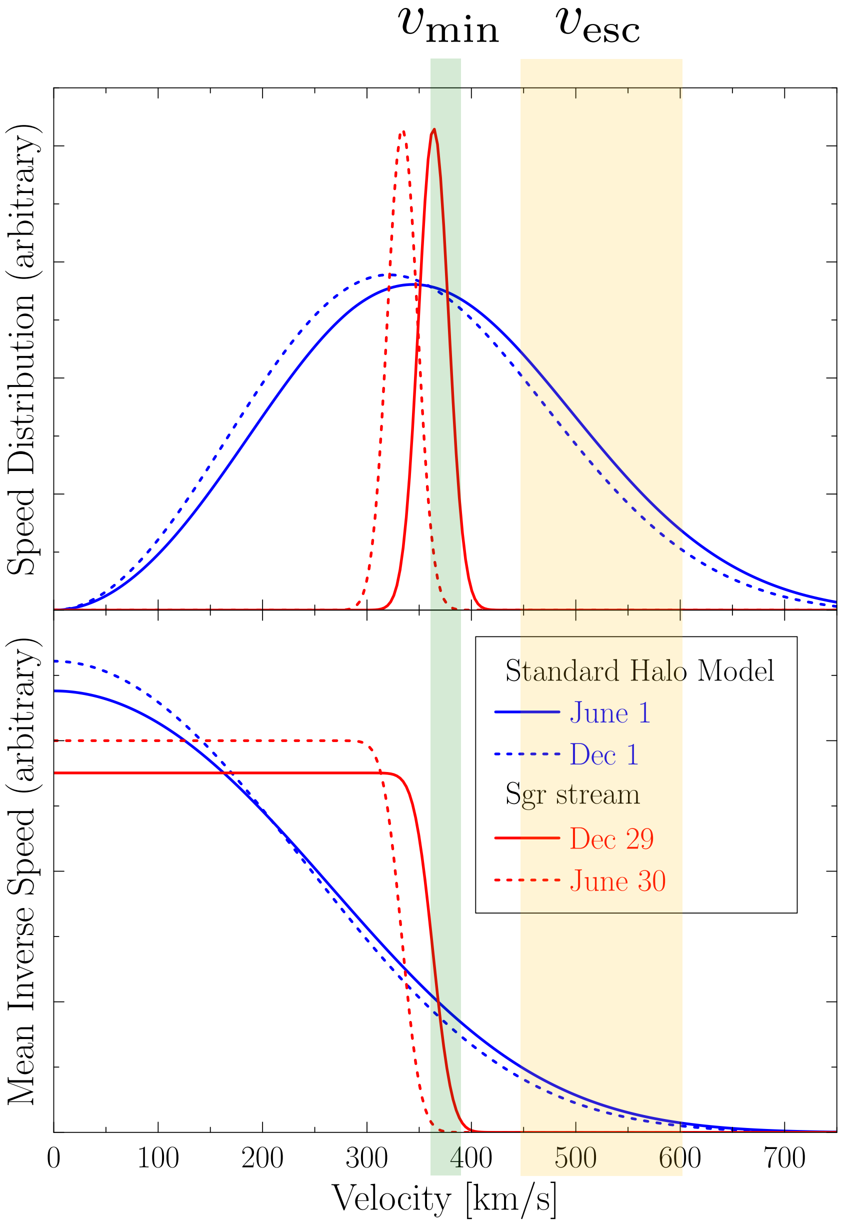
f(v): isotropic maxwellian

Modulation amplitude – energy dependence

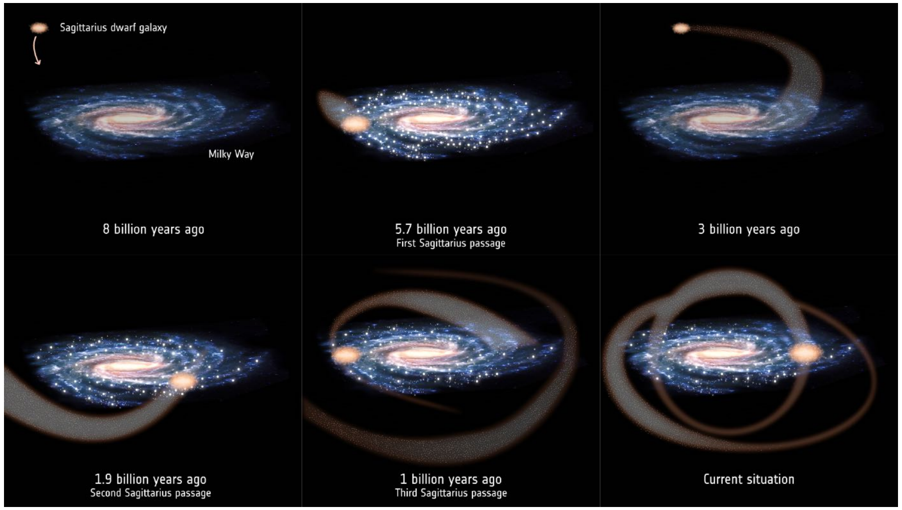


DM velocity distribution: streams?

Freese, Lisanti, Savage, 1209.3339

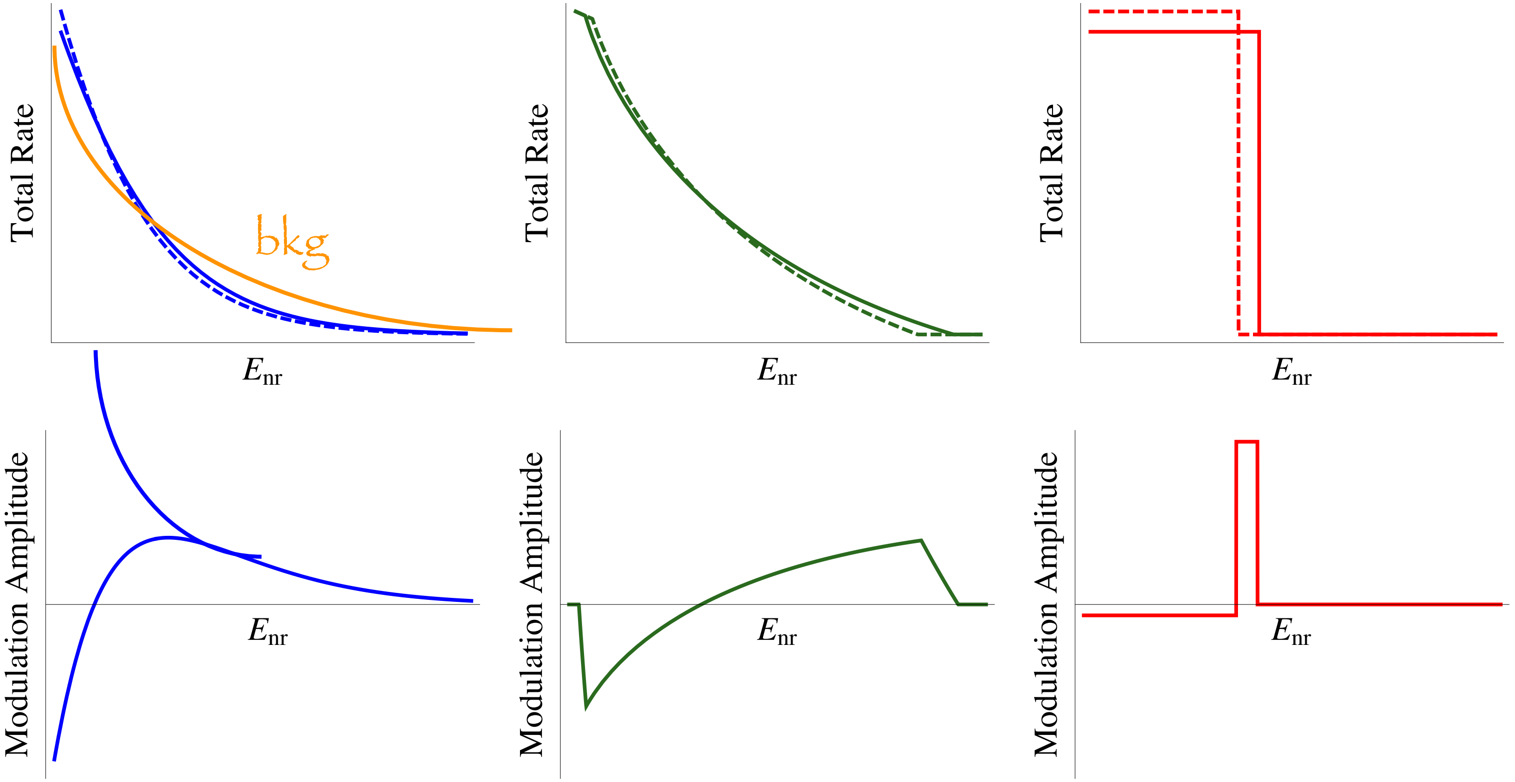


Sagittarius stream



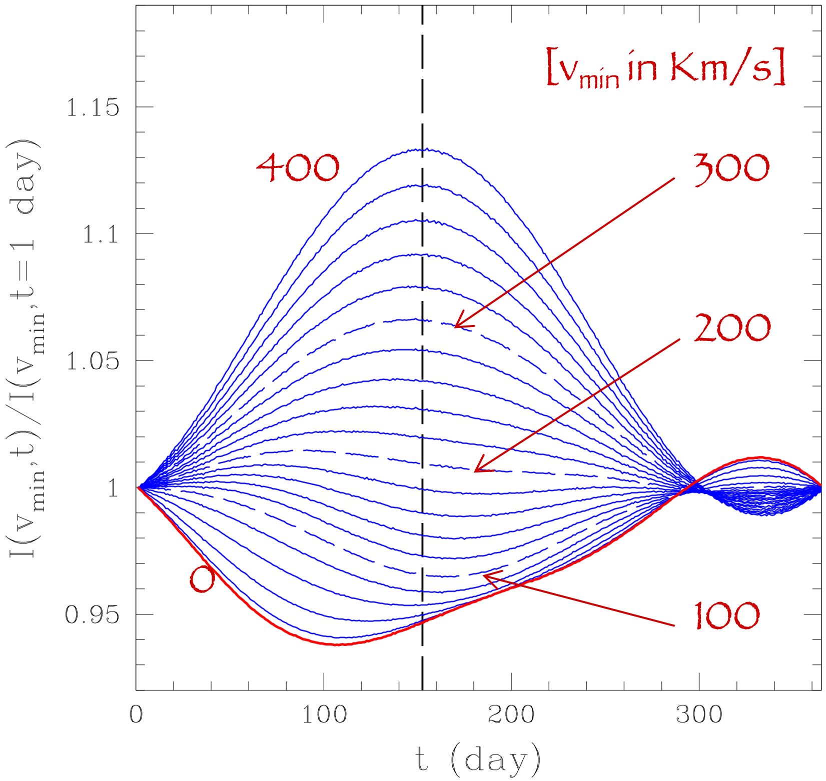
DM velocity distribution

SHM Debris Flow Stream



Freese, Lisanti, Savage, 1209.3339

Annual modulation: effect of anisotropies



f(v): anisotropic maxwellian

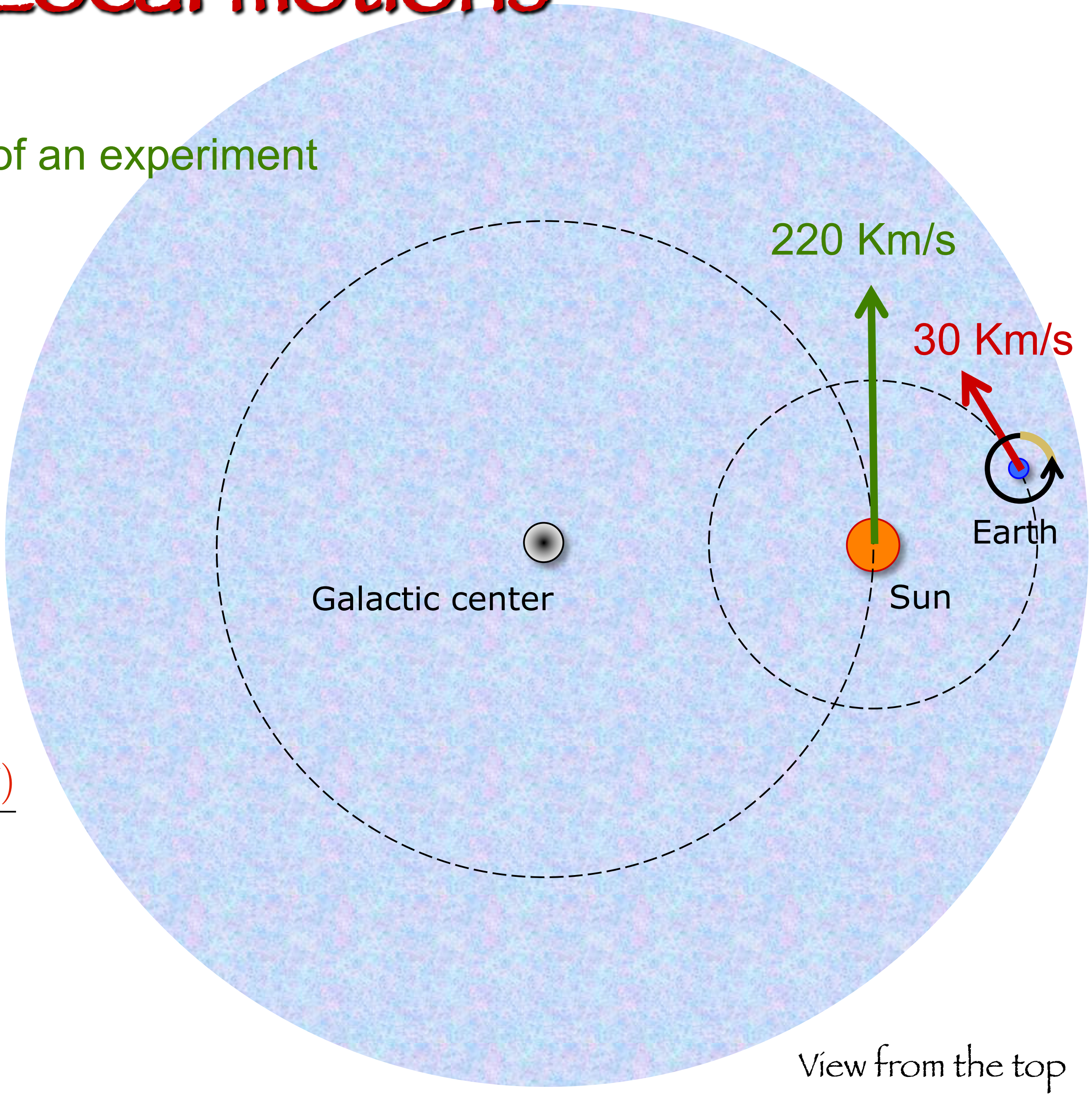
Local motions

Stationary over the lifetime of an experiment

Directional boost

Directionality

$\vec{v}$



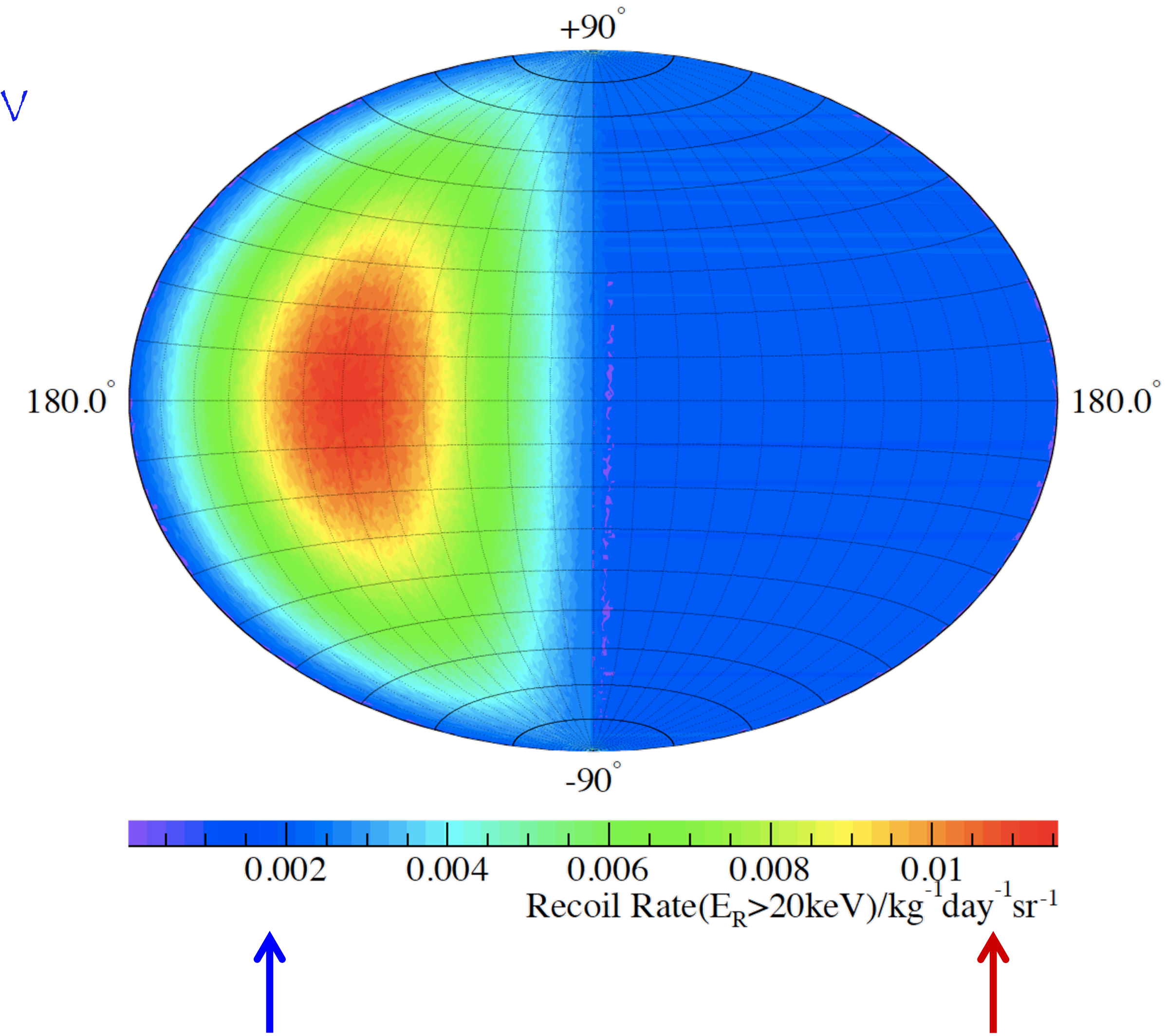
View from the top

$$\mathcal{I}(v_{\min}) = \int_{w\geq v_{\min}} d^3w \; \frac{f_{\mathrm{ES}}(\vec{w})}{w}$$

$$f_{\mathrm{ES}}(\vec{w}) = f(\vec{w}+\vec{v}_{\oplus})\big|_{[v_{\mathrm{rot}};v_{\mathrm{esc}}]}$$

Directionality of the recoil

$m_\chi = 100$ GeV



DM particle features extraction

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \frac{m_N}{2\mu_1^2} A^2 \left[\sigma_{\text{scalar}}^{(\text{nucleon }\,)}\right] F^2\left(E_R\right) \mathcal{I}\left(v_{\text{min}}\right)$$

$$\mathcal{I}(v_{\text{min}}) = \int_{w \geq v_{\text{min}}} d^3w \; \frac{f_{\text{ES}}(\vec{w})}{w}$$

$$f_{\text{ES}}(\vec{w}) = f(\vec{w} + \vec{v}_{\oplus})\big|_{[v_{\text{rot}};v_{\text{esc}}]}$$

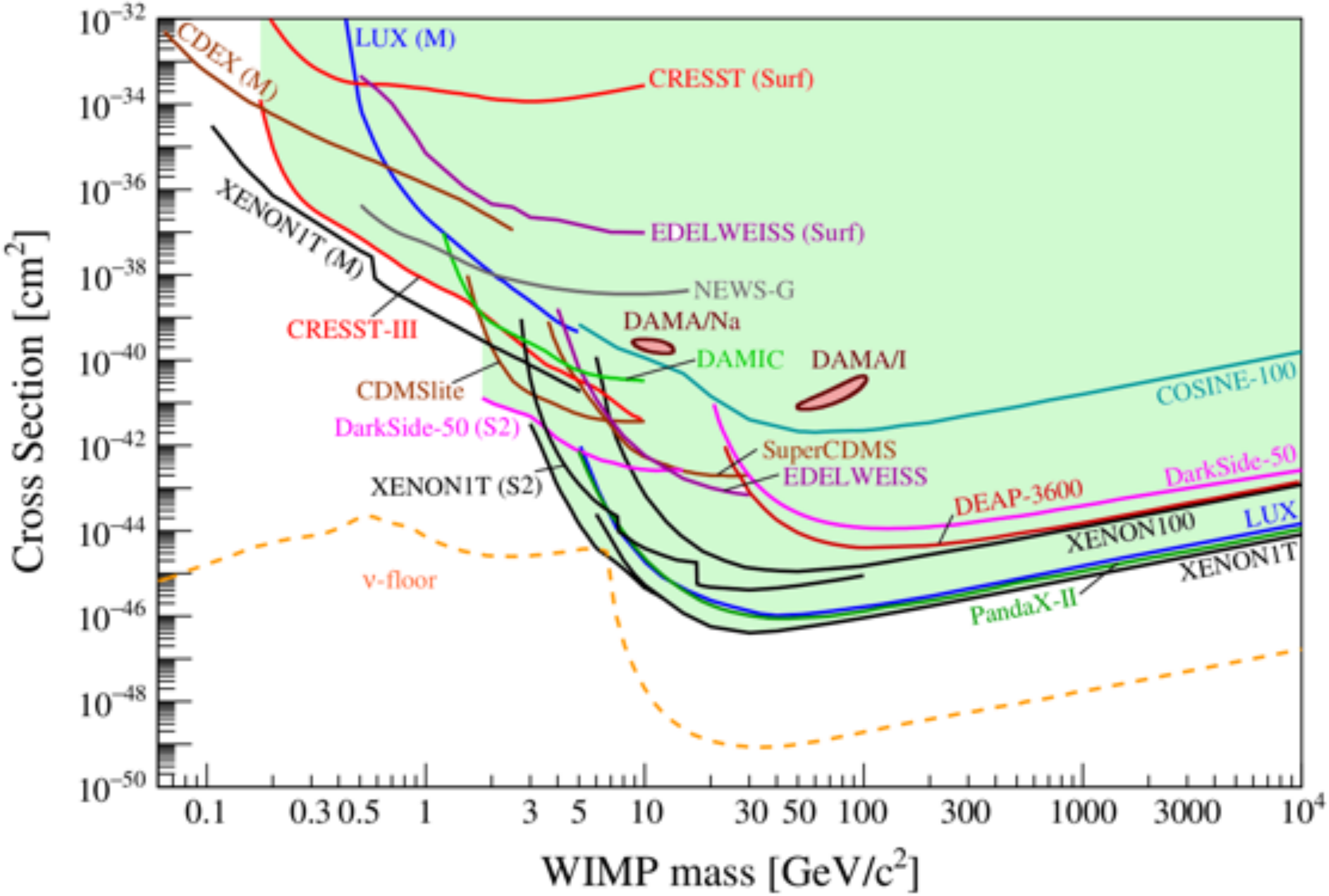
$$v_{\text{min}} = \left[m_N E_R/(2\mu_A^2)\right]^{1/2}$$

$$\downarrow$$

$$E_R \to E_{\text{det}}$$

$$E_{\text{ee}} = q(E)\, E_R$$

Current status (Spin-independent = O_1 operator)

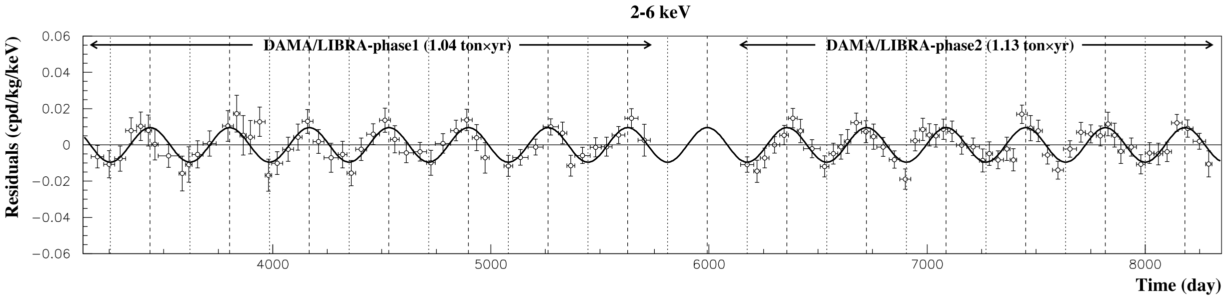


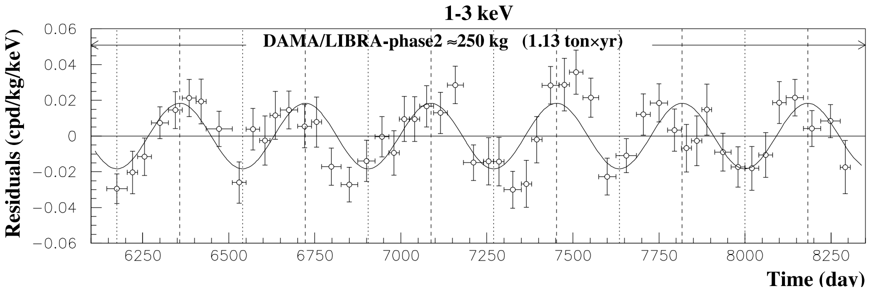
APPEC Committee Report, arXiv:2104.07634

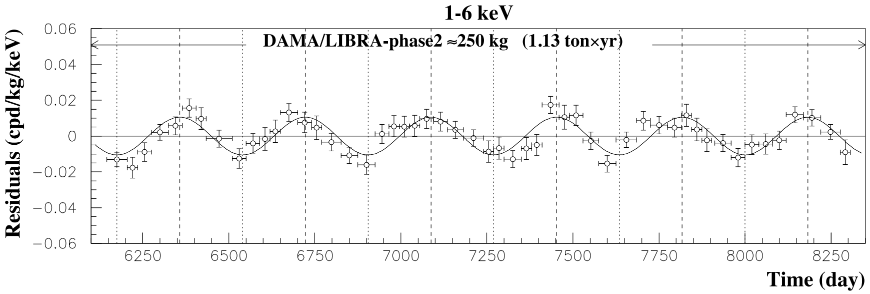
DAMA/Libra

The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at 12.9s CL (2.46 ton × yr)

Sm ≈(0.0103±0.0008) cpd/kg/keV

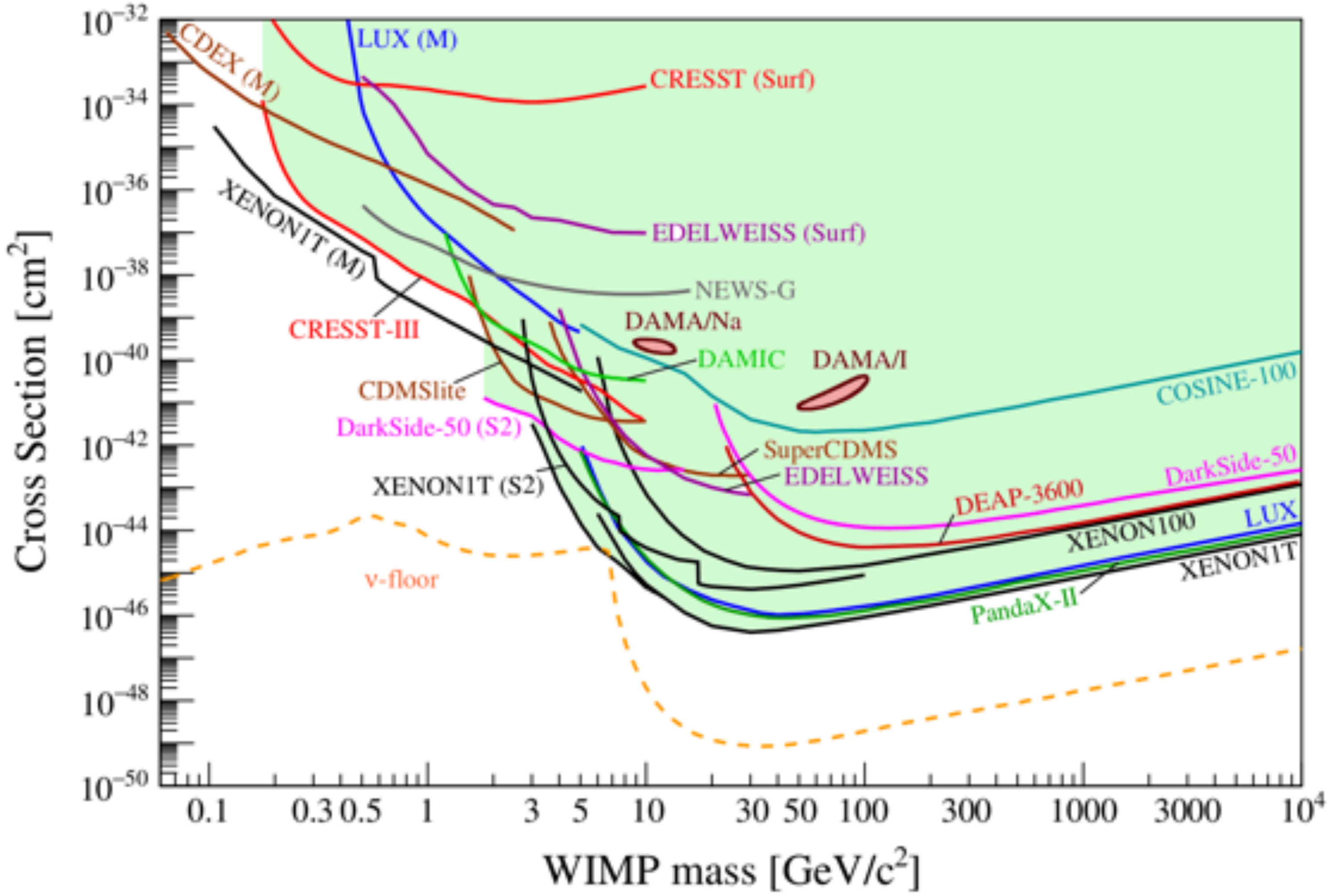






Current status (Spin-independent = O_1 operator)

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi}\frac{m_N}{2\mu_1^2} A^2 \left[\sigma^{(\text{nucleon})}_{\text{scalar}}\right] F^2\left(E_R\right) \mathcal{I}\left(v_{\min}\right)$$

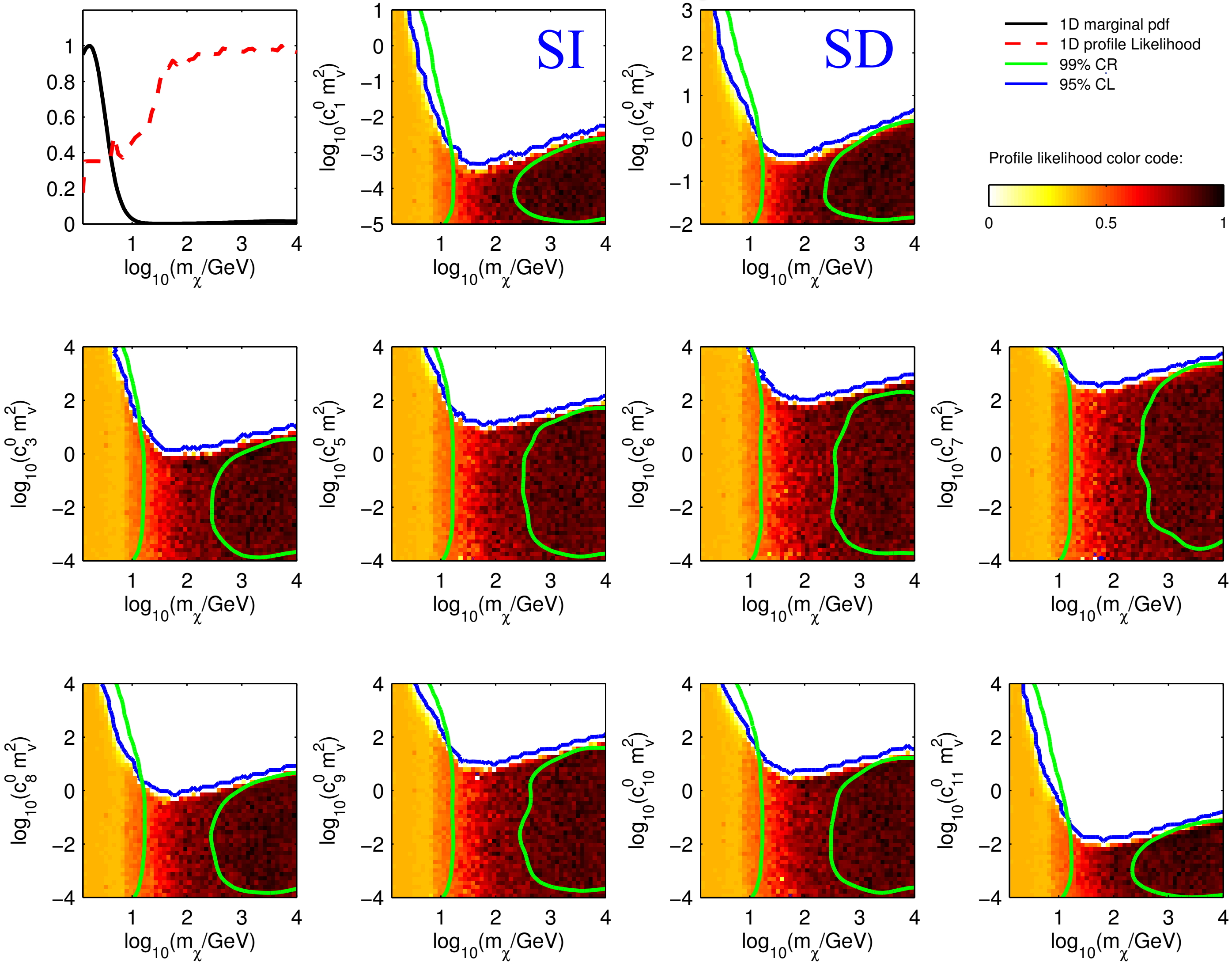


APPEC Committee Report, arXiv:2104.07634

Full set of operators

Catena, Gondolo, JCAP 09 (2014) 045

See also: Scheck et al (SuperCDMS), PRD 91 (2015) 092004



Combined analysis of

CDMS, XENON, LUX, COUPP, PICASSO, SIMPLE

Light WIMPs - Migdal effect

When the nucleus recoils, electrons do not 'rigidly' follow, but can have transition to a different energy level or to the continuum, resulting in:

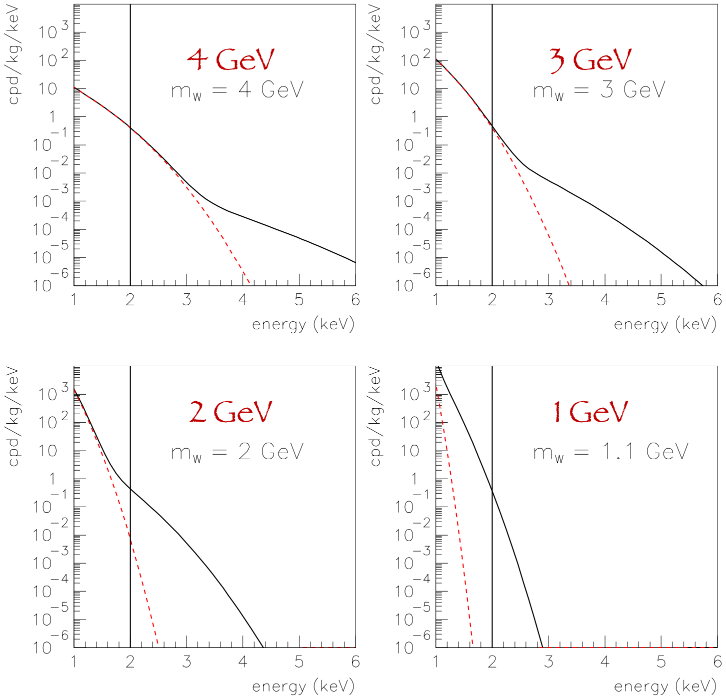
excitation
ionization

with e.m. released in addition to the recoil signal

Transition to the continuum: emission of radiation

Rearrangement of atomic shells
Emission of radiation
Meitner-Auger electrons(*)

Relevant especially for light WIMPs



(*) Filling the inner shell vacancy, energy is transfered to another electron which is then emitted

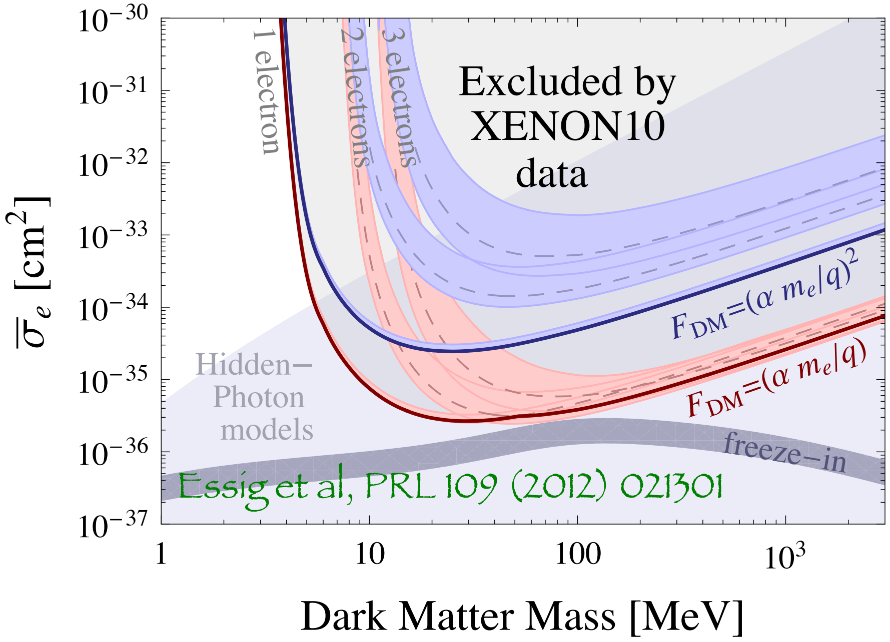
Very light DM

- Very light DM (down to the warm regime):
  - Available kinetic energy can be as low as meV (for KeV DM)
  - Too low deposited energy on nuclear target

- Possibilites:
  - Nuclear interactions on light targets, e.g. liquid He
  - Electron recoils

Guo, McKinsey, PRD 87 (2013) 115001

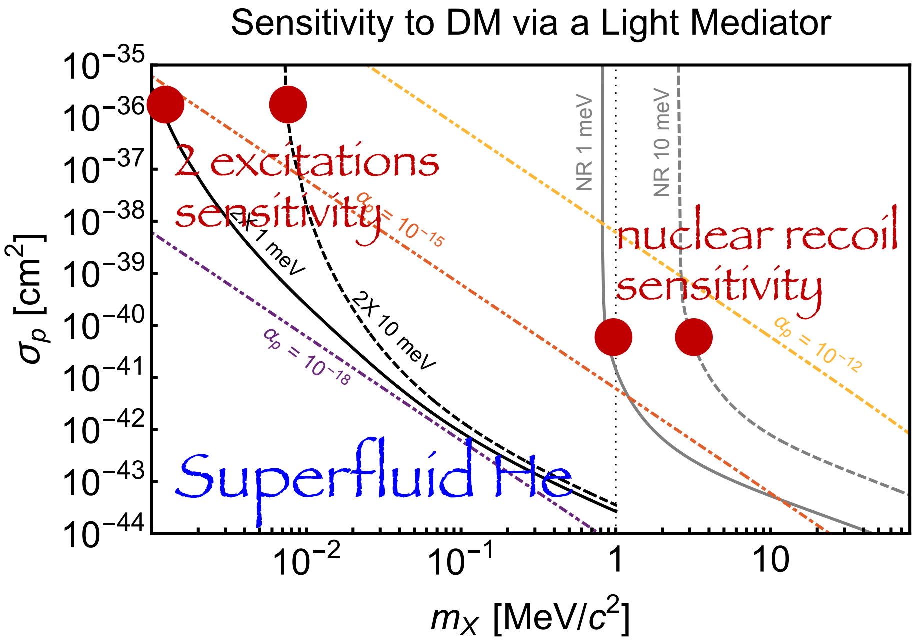
Essig et al, PRD 85 (2012) 076007
Essig et al, 1509.01598
Agnese et al (SuperCDMS) PRL 112 (2014) 041302
Essig et al, PRL 109 (2012) 021301



Essig et al, PRL 109 (2012) 021301

Super light DM

Sensitivity to DM via a Light Mediator

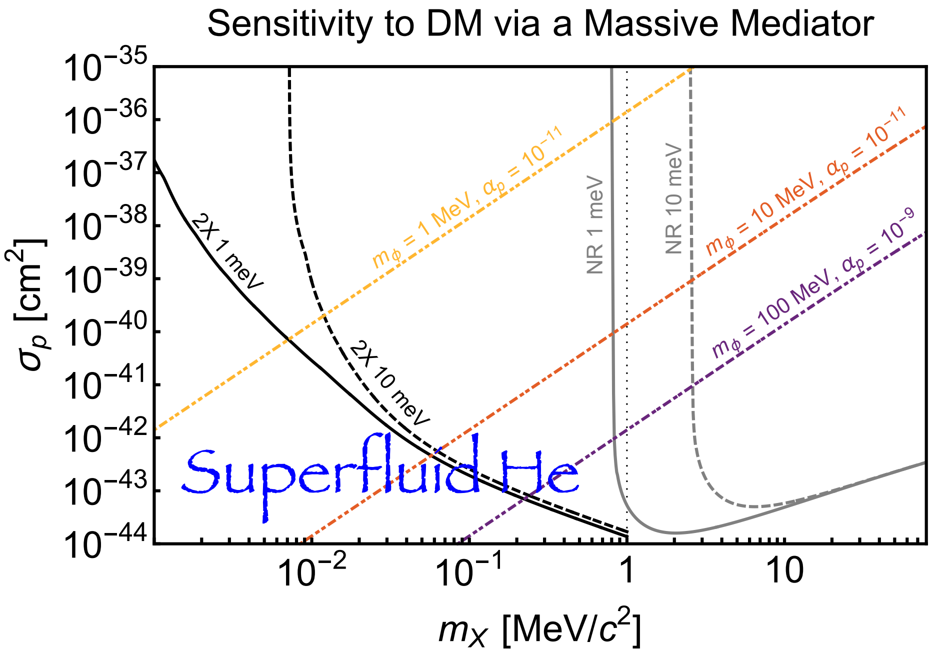


2 excitations sensitivity

nuclear recoil sensitivity

Superfluid He

Sensitivity to DM via a Massive Mediator



Superfluid He

To go below 10 MeV DM: conversion of the full tiny energy needed

» Superconductors — electron interactions

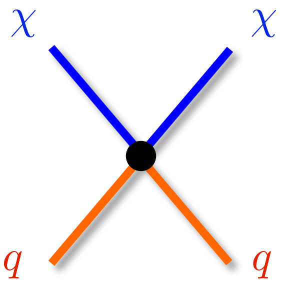
Hochberg et al, 1512.04533

Hochberg et al, PRL 116 (2016) 011301

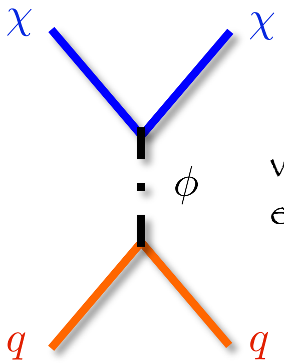
» Superfluid He — nuclear interactions

Schutz, Zurek, 1604.08206

Other type of interactions: e.g. long range



contact



long-range

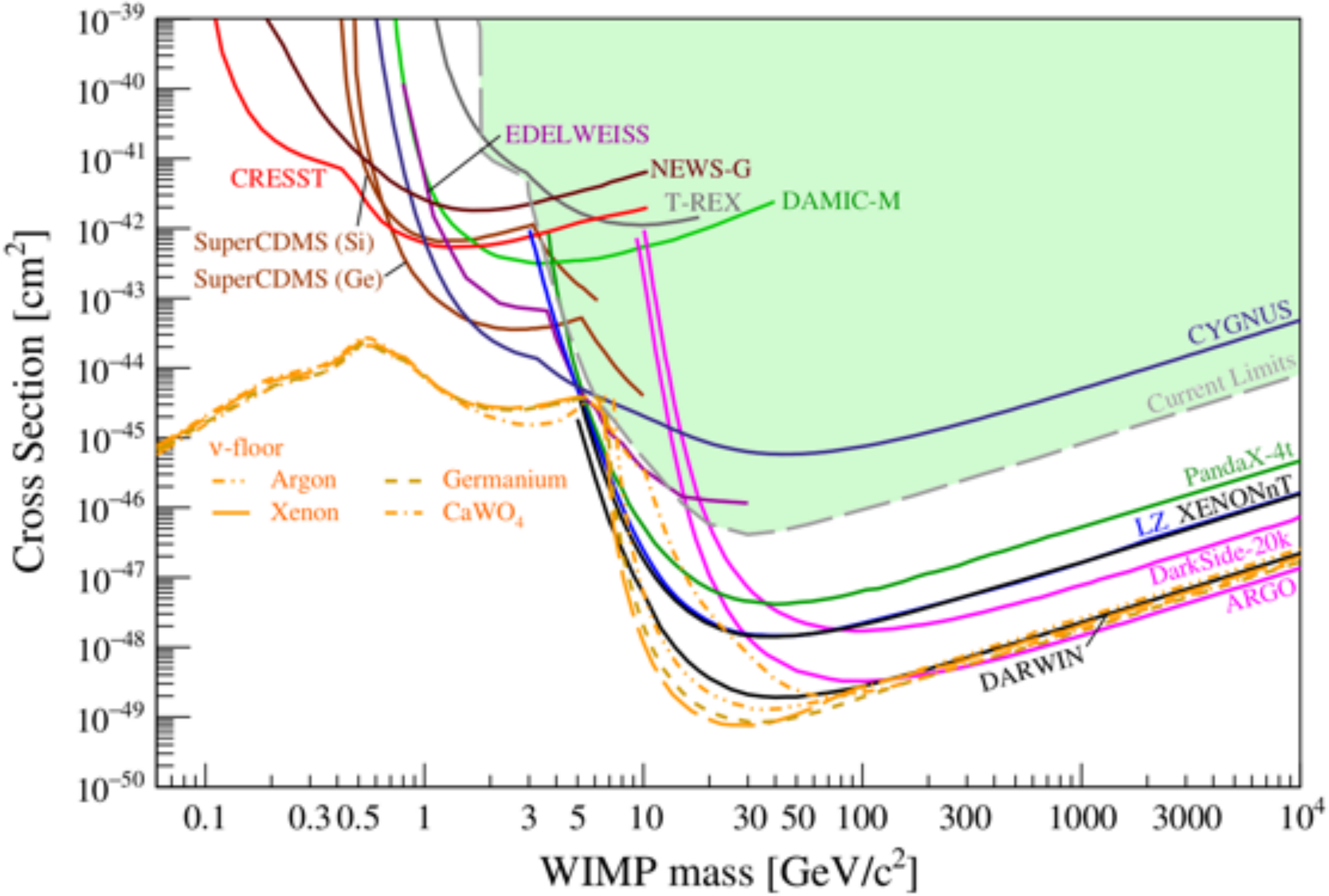
very light mediator
e.g. dark photon or mirror photon

$$\frac{d\sigma\left(v,E_R\right)}{dq^2} = \frac{2m_N\lambda}{\underline{\left(q^2+m_\phi^2\right)^2}}\frac{1}{v^2}F^2\left(E_R\right)$$

$q^2 = 2m_N E_R$ momentum transfer
m_ϕ mass of the mediator

$$\left\{\begin{array}{lr} \dfrac{d\sigma\left(v,E_R\right)}{dE_R} = \dfrac{m_N}{2\mu_{\chi p}^2}\dfrac{1}{v^2}Z^2\sigma_{\phi\gamma}F^2\left(E_R\right) & m_\phi^2 \gg q^2 \\[2em] \dfrac{d\sigma\left(v,E_R\right)}{dE_R} = \dfrac{\lambda}{E_R^2}\dfrac{1}{v^2}F^2\left(E_R\right) \propto E_R^{-2} & m_\phi^2 \ll q^2 \end{array}\right.$$

Prospects: Projected Sensitivities



APPEC Committee Report, arXiv:2104.07634

Prospects

- Annual modulation: ANAIS
  KIMS + DM Ice = COSINE 100
  SABRE

- Diurnal modulation: DAMA with larger mass might access it

- Directionality:
  - Nuclear emulsion (NEWS)
  - Gas TPC (CYGNO)
  - Negative Ion Time Expansion Chamber
  - Carbon nanotubes, grafene
  - Anysotropic crystals (ADAMO)
  - DRIFT
  - MIMAC, DMTPC, NEWAGE, D3, …

Neutrino signal

Neutrino signals from DM

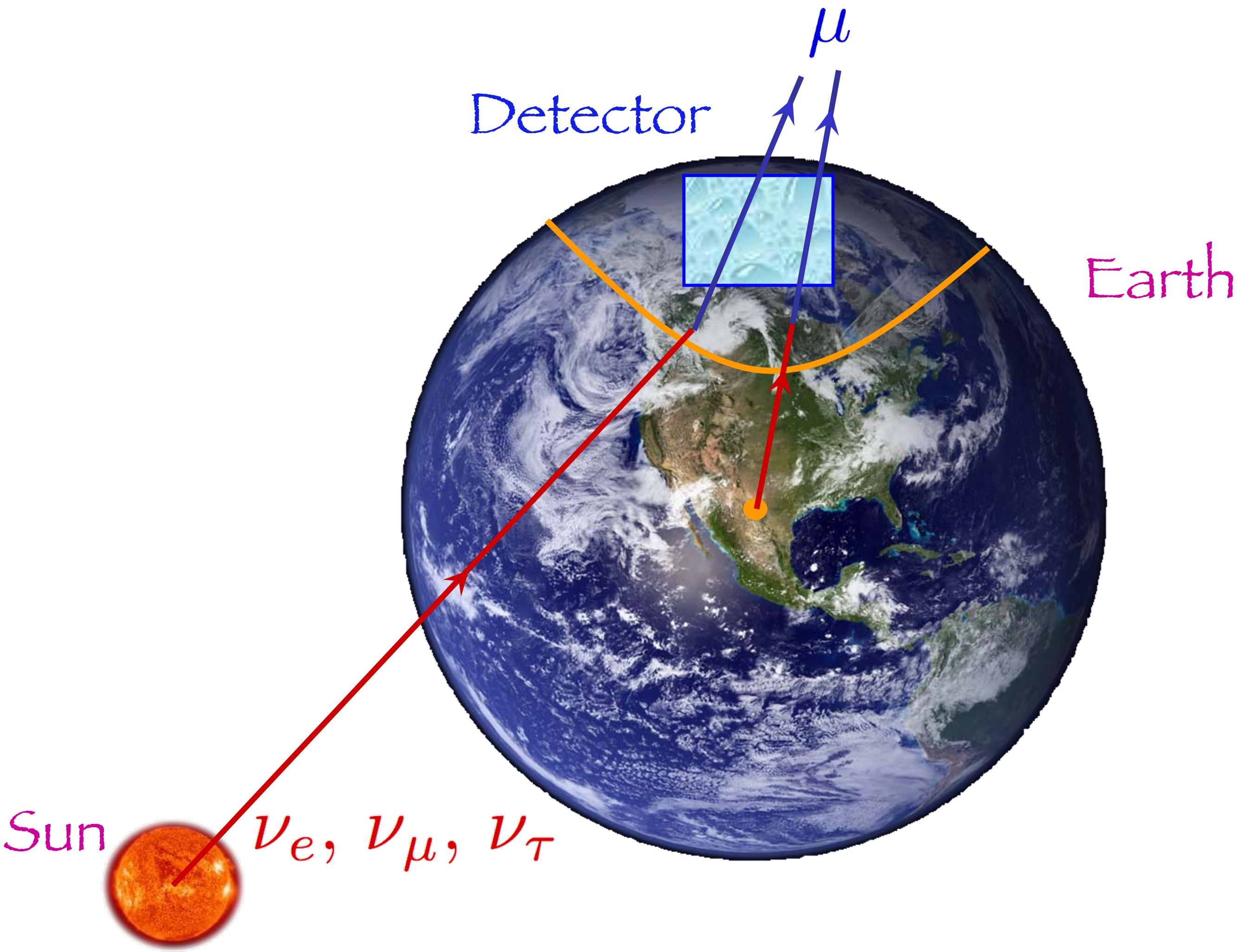
- Neutrino flux produced by DM annihilation (or decay) inside the Sun/Earth, where DM may be gravitationally captured
  - Because of capture, the flux may have a detectable size
  - Directionality (point source)

- Diffuse emission from DM annihilation (or decay) in the galactic halo
  - Size of signal is low (target for next-generation nu-telescopes)
  - Possible correlation with diffuse galactic gamma rays

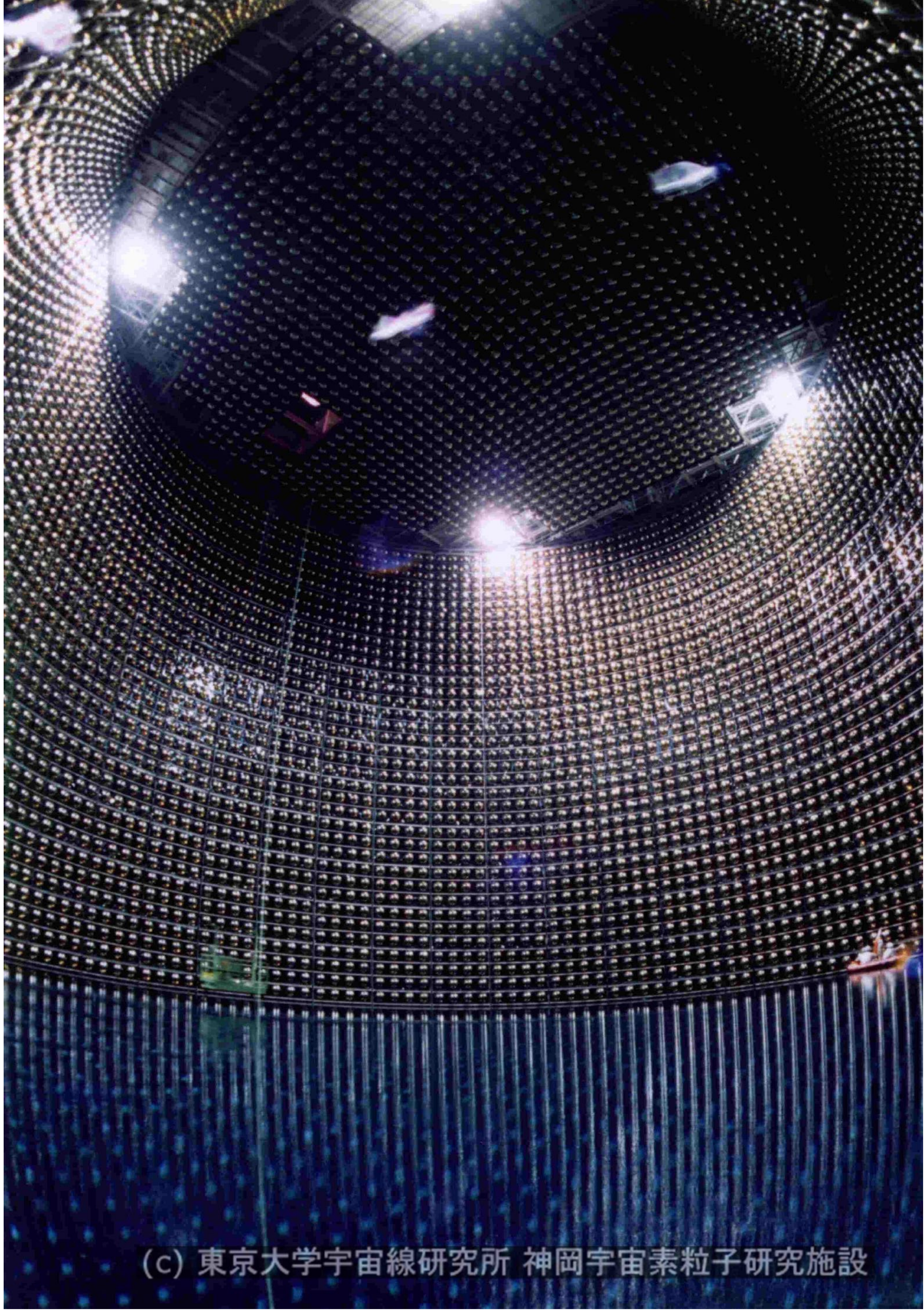
Neutrinos from Earth and Sun

- Capture:
  - Galactic DM particles that cross the Earth and the Sun, can interact with the nuclei in these bodies and loose enough energy to remain gravitationally captured
- Accumulation:
  - After subsequent interactions they tend to drop into the innermost parts of the Earth and the Sun, where they accumulate
- Annihilation:
  - When the energy density in the inner parts of the Earth and the Sun increases enough, they may start to annihilate

neutrino flux


μ
Detector
Earth
Sun
ν_e, ν_μ, ν_τ

Super Kamiokande



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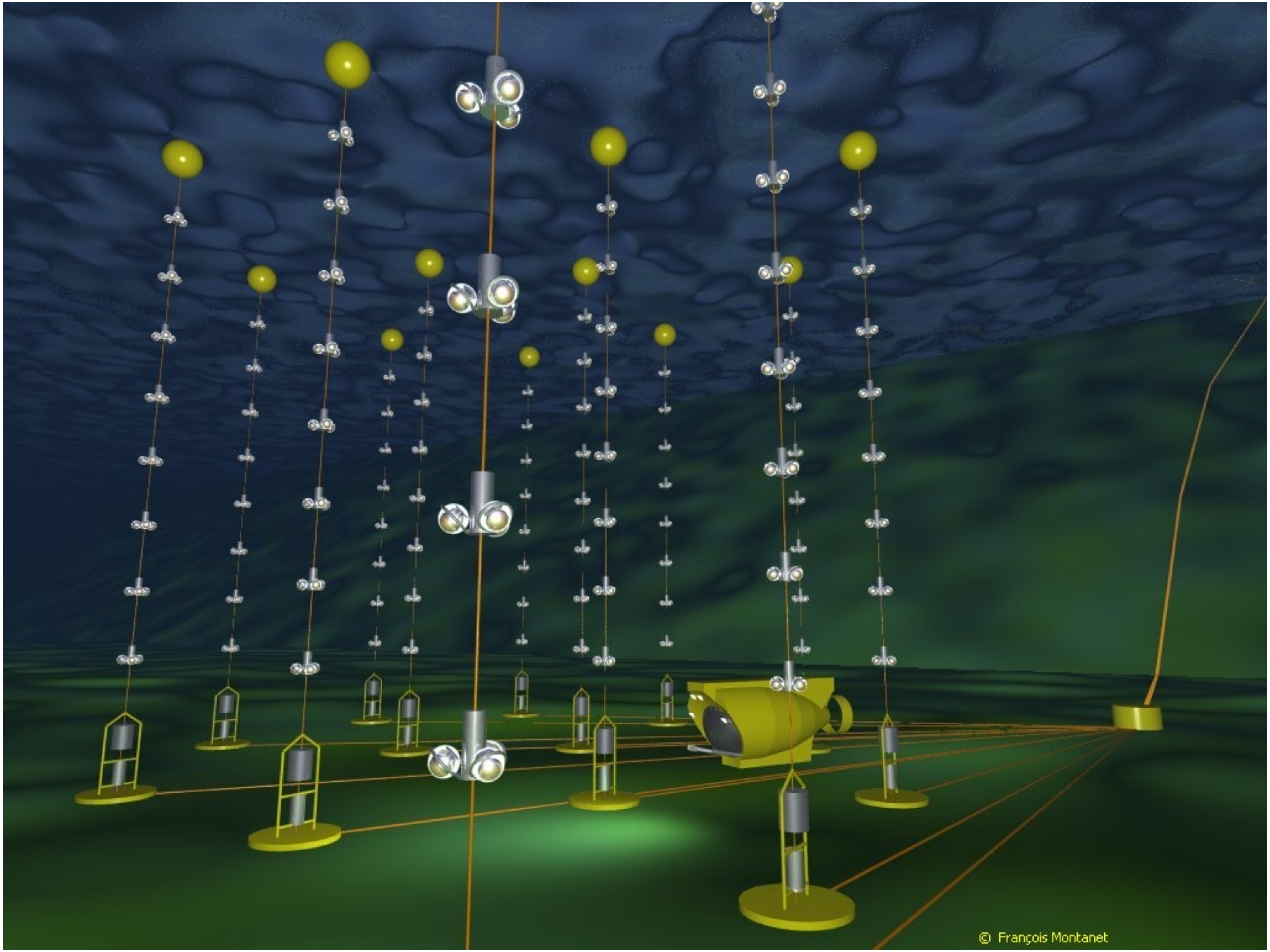
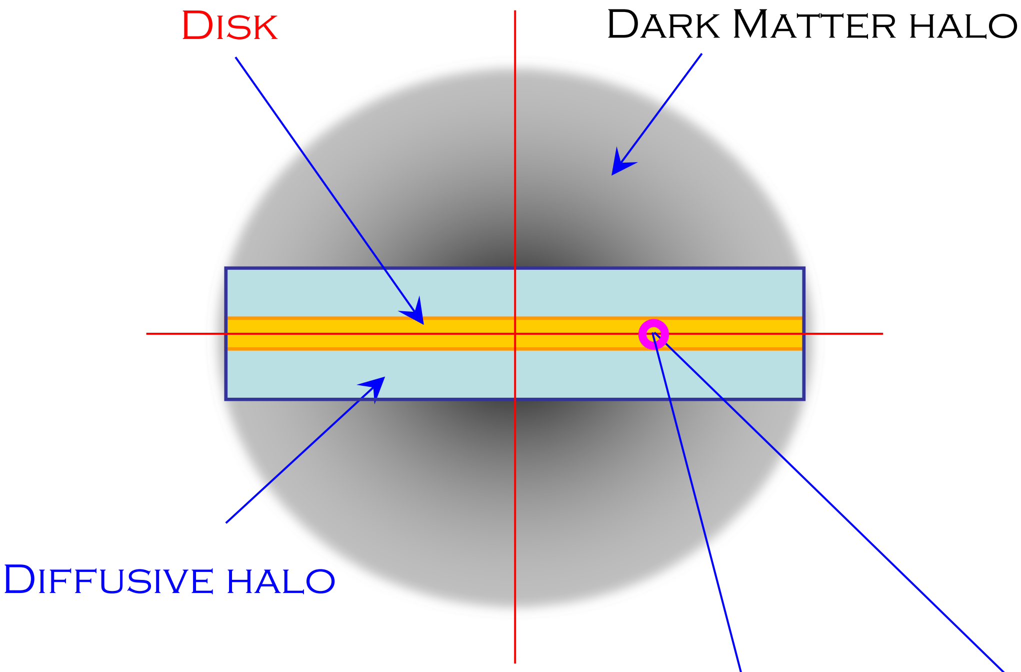
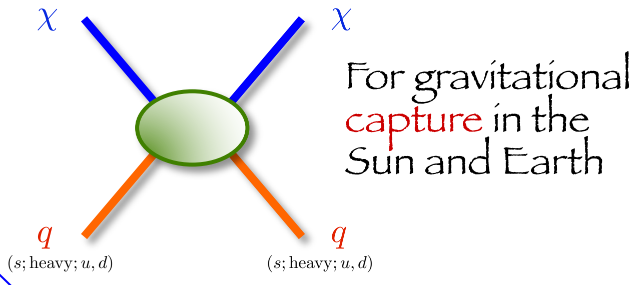


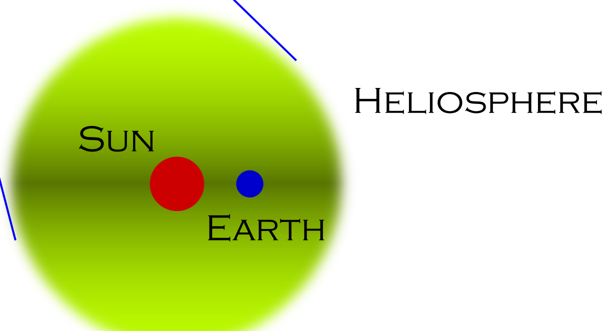
© François Montanet

Local DM halo





For gravitational capture in the Sun and Earth



Galactic signals

Neutrinos from earth and sun

Feels ony the local DM density

Feels (somehow) how DM is locally distributed in velocity space

For the generation of the neutrino signal

Capture Rate

- Elastic scattering of the DM particle with a nucleus *i* in a spherical shell at a distance *r* from the center of the Earth (or Sun)

- In order to be captured, the velocity of the DM particle after the interaction must be smaller than the escape velocity at the shell

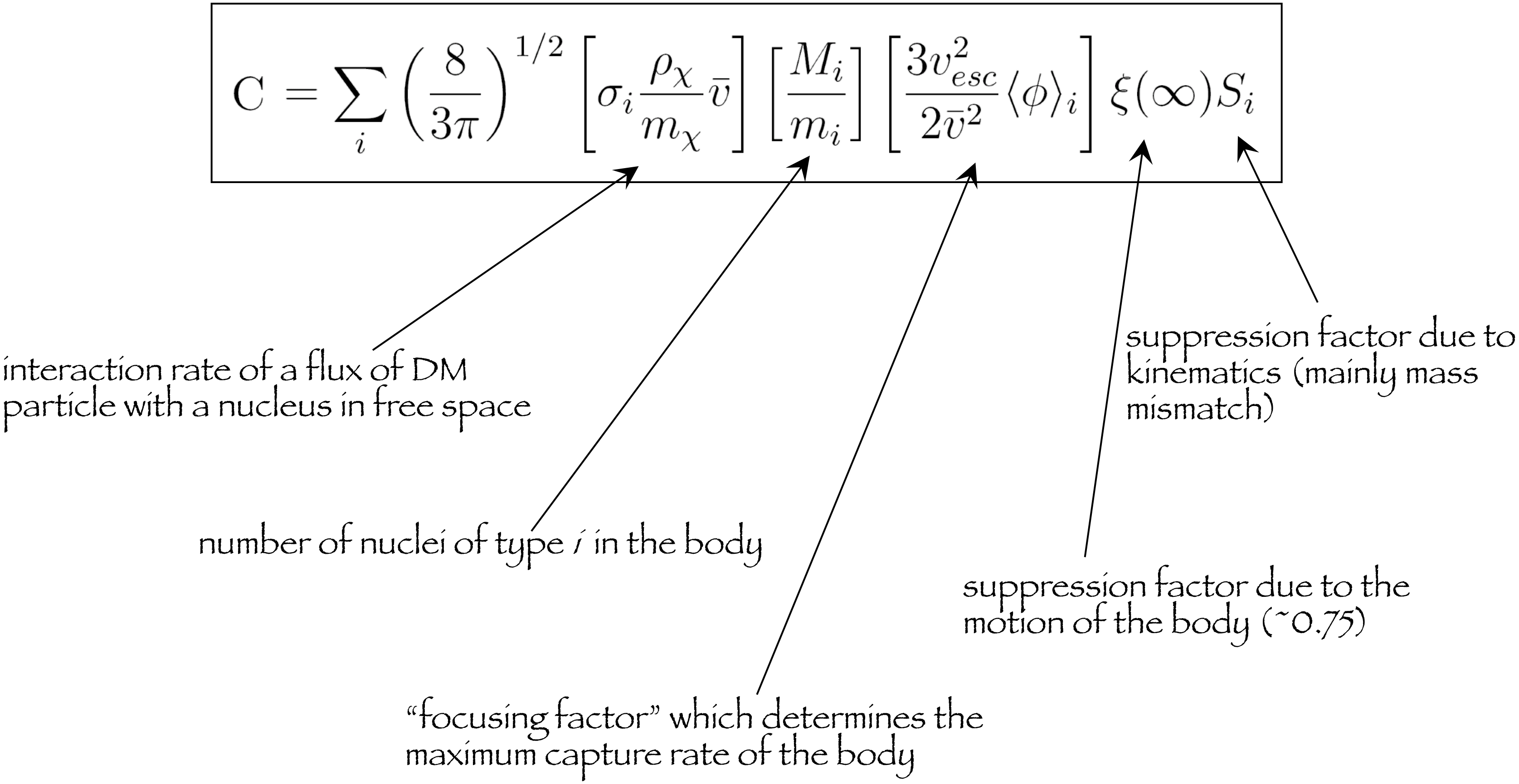
$$v_{\rm esc}^{\rm Sun} = 618 \text{ Km s}^{-1}$$
$$v_{\rm esc}^{\rm Earth} = 11.2 \text{ Km s}^{-1}$$

at the surface

$$\langle v \rangle \sim 300 \text{ Km s}^{-1}$$

mean DM particle velocity

Capture Rate



$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\sigma_i \frac{\rho_\chi}{m_\chi}\bar{v}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2}\langle\phi\rangle_i\right] \xi(\infty) S_i$$

interaction rate of a flux of DM particle with a nucleus in free space

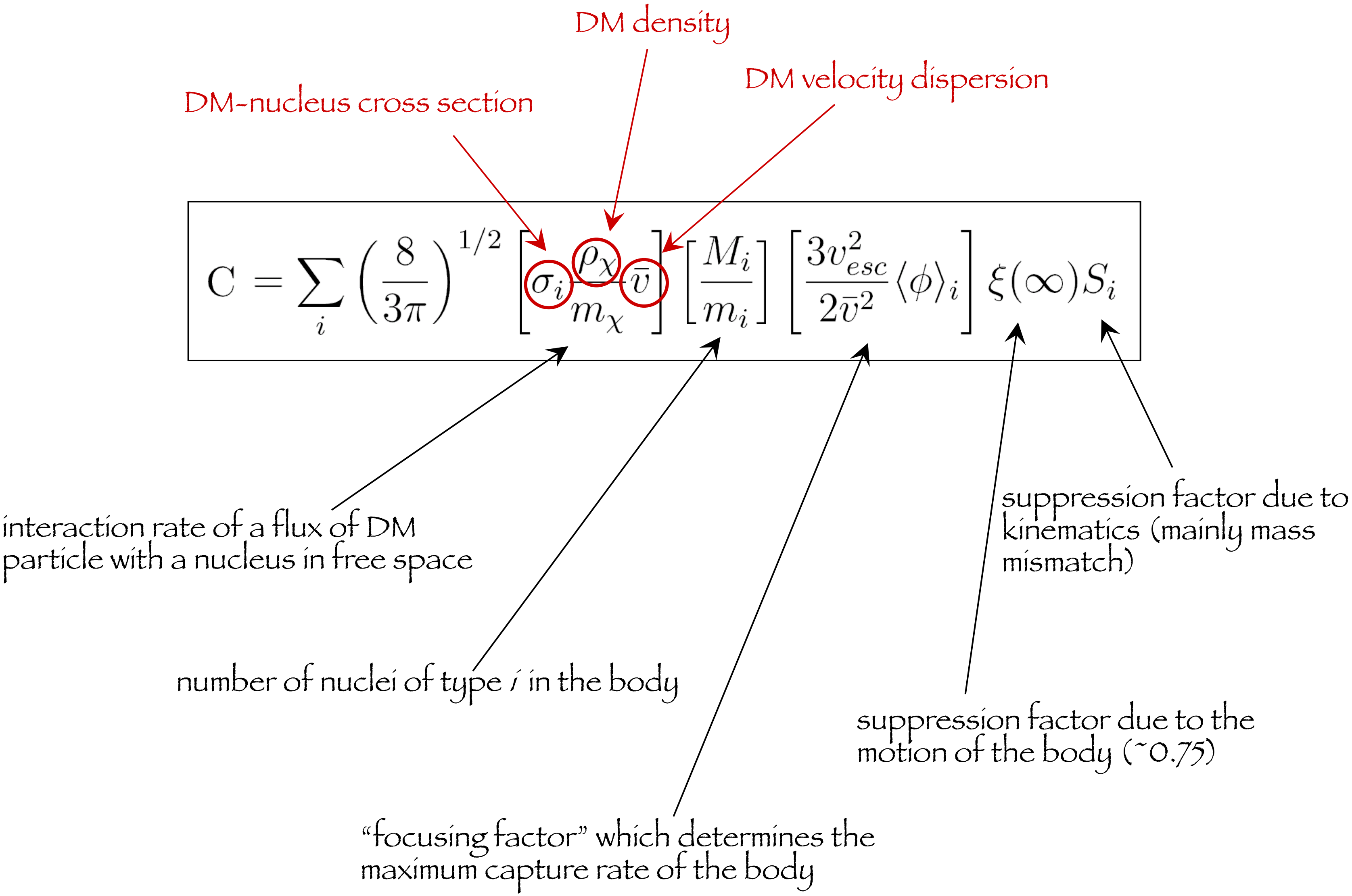
number of nuclei of type *i* in the body

“focusing factor” which determines the maximum capture rate of the body

suppression factor due to the motion of the body (~0.75)

suppression factor due to kinematics (mainly mass mismatch)

M_i	Total mass in terms of element *i*
$\langle\phi\rangle_i$	Gravitational potential averaged over the mass distribution of element *i*



DM density

DM-nucleus cross section

DM velocity dispersion

$$C = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \left[\frac{\sigma_i \rho_\chi \bar{v}}{m_\chi}\right] \left[\frac{M_i}{m_i}\right] \left[\frac{3v_{esc}^2}{2\bar{v}^2}\langle\phi\rangle_i\right] \xi(\infty) S_i$$

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Sun

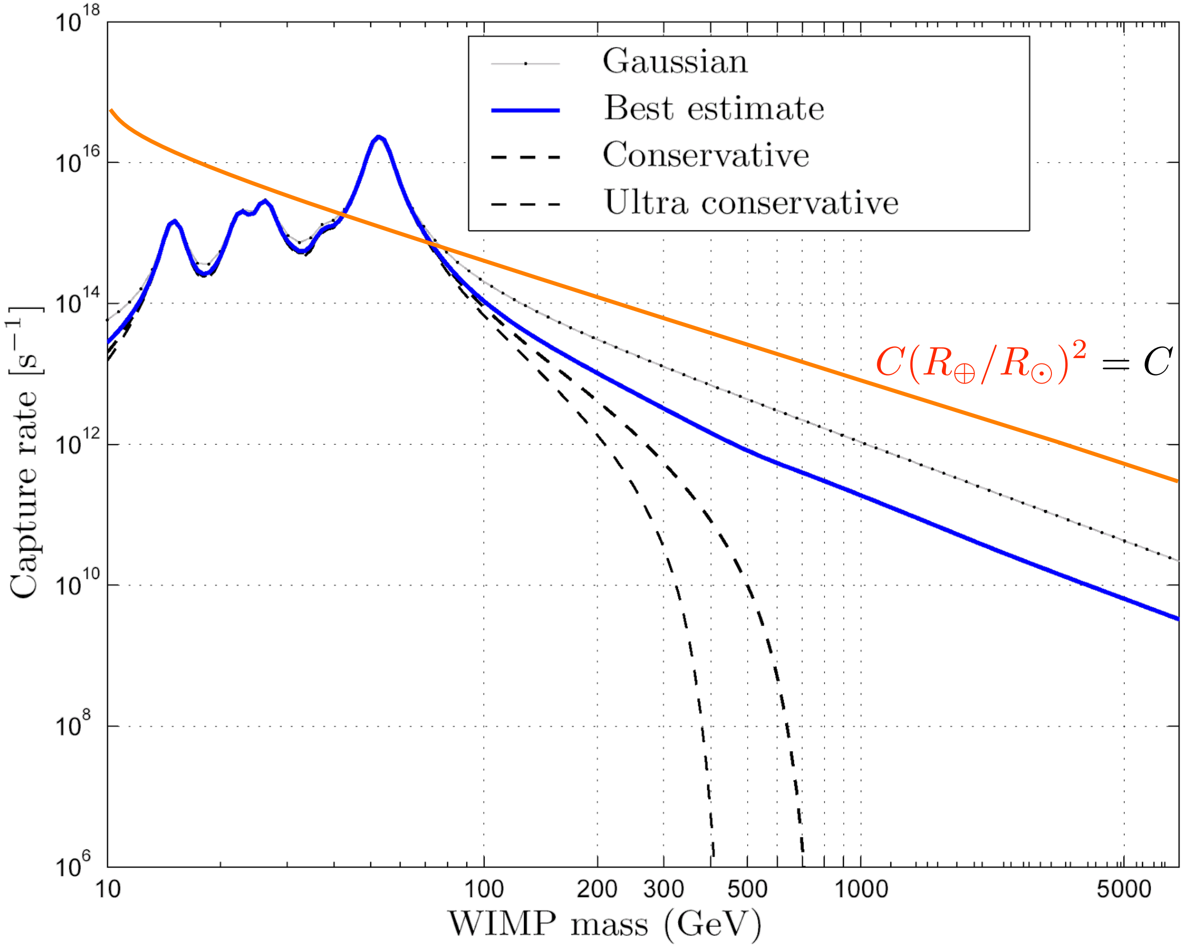
Nuc	H	He	O	C	Ne	Fe	N	Si	Mg
f	0.77	0.21	8.10^{-3}	4.10^{-3}	1.10^{-3}	1.10^{-3}	9.10^{-4}	8.10^{-4}	7.10^{-4}
A	1	4	16	12	20	56	14	28	24

nuclei of type *i* in the body

Earth

	core			mantle					
Nuc	Fe	Si	Ni	O	Si	Mg	Fe	Ca	Al
f	0.24	0.05	0.03	0.30	0.15	0.14	0.06	0.02	0.01
A	56	32	59	16	28	24	56	40	27

Capture rate on the Earth



$C(R_\oplus/R_\odot)^2 = C \times 1.8 \cdot 10^{-9}\ [s^{-1}]$

Lundberg, Edsjo, PRD 69 (2004) 123505

Solar bound orbits

- Numerical simulation of Near Earth Asteroids show that many of these have life times in the solar system less than 2 Myr

- After that, they are either:
  - Driven into the Sun
  - Escape the solar system

- If this would occur also to the DM particles, this would significantly reduce the number of these particles bound to the solar system, and therefore reduce the capture rate on Earth

and consequently the neutrino signal

Accumulation and concentration

- DM particles which have been captured inside Earth or Sun can suffer subsequent scatterings
- This may lead to:
  - Concentration in the innermost parts of the Earth or Sun
  - Development of an equilibrium distribution of these particles

distribution $n(r) = n_0 \mathrm{e}^{-\alpha_B m_\chi r^2}$

n_0 central density

$\alpha_B = 2\pi G \rho_0 / (3T_0)$

Earth $R_{\text{prod}} \sim 500 \text{ km} \sqrt{100 \text{ GeV}/m_{\text{DM}}}$

Sun $R_{\text{prod}} \sim 0.01 R_\odot \sqrt{100 \text{ GeV}/m_{\text{DM}}}$

Annihilation rate

Evolution equation $$\frac{dN}{dt} = C - 2\Gamma_A$$

Total number of captures DM particles $$N = C\,\tau_A\ \tanh(t_0/\tau_A)$$

Annihilation rate $$\Gamma_A = \frac{1}{2}\langle\sigma_{\rm annv}\rangle \int d^3r\ n^2(r)$$

$$\boxed{\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t_0}{\tau_A}\right)}$$

Capture rate C

Age of the body $t_0 = 4.6\ \mathrm{Gyr}$

Relaxation time $\tau_A = [CC_A]^{-1/2}$

$$C_A = \langle\sigma_{\rm ann} v\rangle_0 V_2/V_1^2$$

$$V_j = c_B(jm_\chi/10\ \mathrm{GeV})^{-3/2}\ \mathrm{cm}^3$$

$$c_B = \underset{\text{Earth}}{1.8\cdot 10^{25}}\ /\ \underset{\text{Sun}}{6.6\cdot 10^{28}}$$

Effective volumes of DM concentrations
More concentrated for larger masses

Neutrino flux

$$\frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_{\mathcal{F}} \mathrm{BR}(\chi\chi \to \mathcal{F}) \frac{dN_\nu^{\mathcal{F}}}{dE_\nu}$$

Neutrino Production

- Neutrinos are produced by DM annihilation
  - Available channels depend on mass threshold

$$\chi\chi \to \nu\nu,\ l\bar{l},\ q\bar{q},\ W^+W^-,\ ZZ,\ \text{Higgses},\ \text{Higgs} + \text{gauge}$$

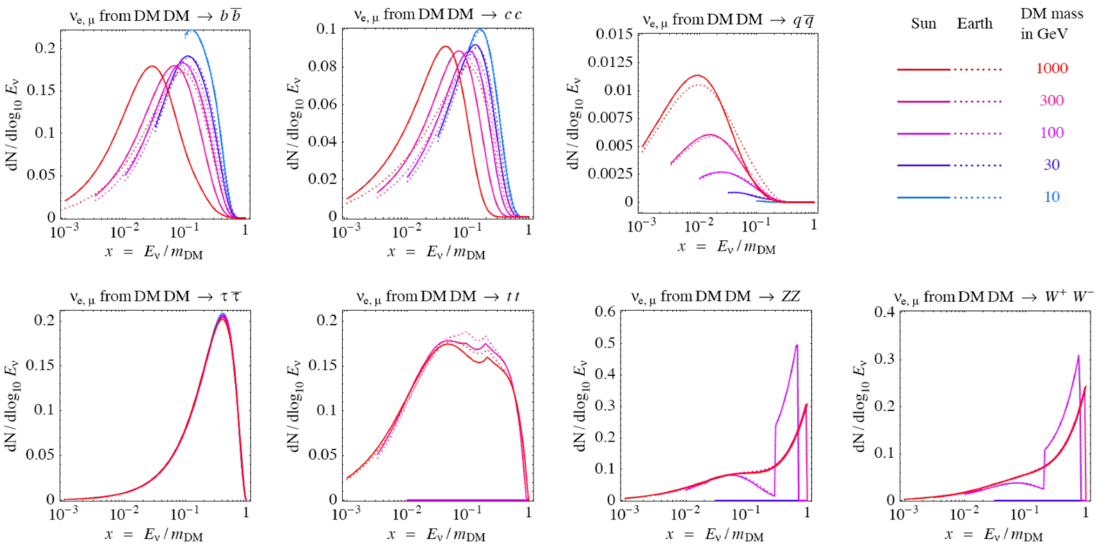
  - Quark hadronize → neutrinos from hadron decay

- Productions in Earth
  - Muons: stopped before decay → neutrinos below typical thresholds
  - Taus: decay almost as in vacuum
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: typically decay before loosing significant energy

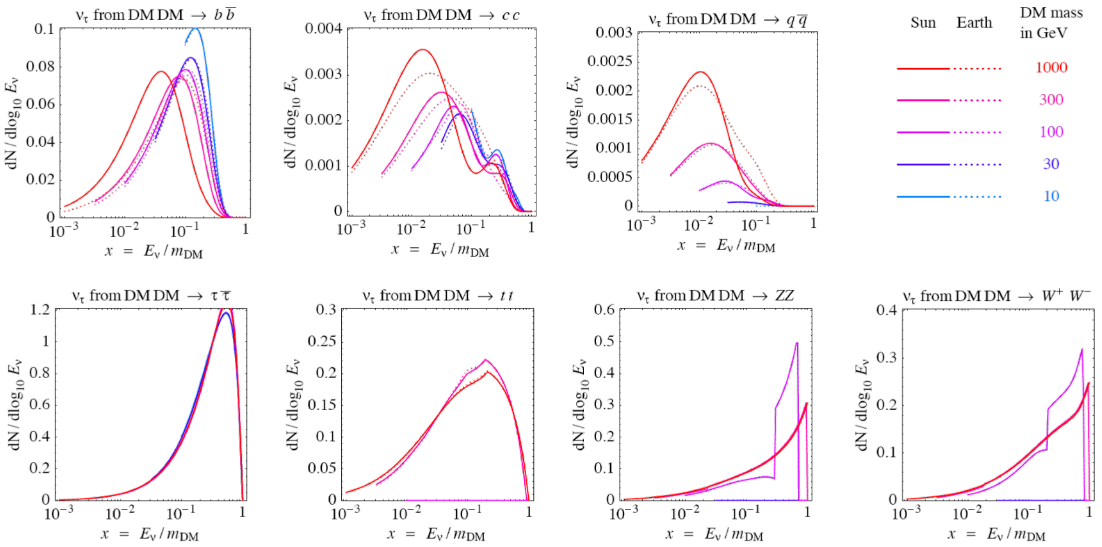
- Production in Sun
  - Leptons: stopping power of medium is stronger → softer neutrino spectra
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: energy losses important, need modeling

Spectra at production

ν_e, ν_μ



ν_τ



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Neutrino Propagation

Density matrix evolution

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

$$\rho = \sum_j p_j |\psi_i\rangle\langle\psi_j| \qquad i = e\,,\ \mu\,,\ \tau$$

diag(ρ):	population of flavour i
non-diag(ρ):	superposition of flavour i and j

mixing, oscillations, decoherence

Neutrino Propagation

Density matrix evolution

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

Vacuum oscillation
MSW matter effect

source

CC interactions
(absorption and ν_τ regeneration)

NC scatterings
(absorption and re-injection)

Neutrino Propagation

Density matrix evolution

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

source

Vacuum oscillations and MSW matter effect

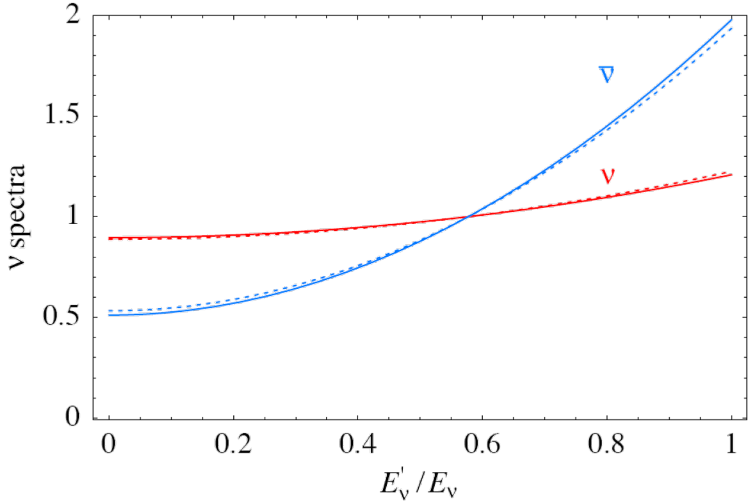
$$\boldsymbol{H} = \frac{\boldsymbol{m}^{\dagger}\boldsymbol{m}}{2E_{\nu}} + \sqrt{2}G_{\mathrm{F}}\left[N_e\ \mathrm{diag}\,(1,0,0) - \frac{N_n}{2}\ \mathrm{diag}\,(1,1,1)\right]$$

NC scatterings

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

absorption re-injection

$$\Gamma_{\rm NC}(E_\nu, E'_\nu) = N_p(r)\ \mathrm{diag}\,\sigma(\nu_\ell p \to \nu'_\ell X) + N_n(r)\ \mathrm{diag}\,\sigma(\nu_\ell n \to \nu'_\ell X)$$



$$E_\nu \longrightarrow E_{\nu'}$$

CC absorptions and ν_τ regeneration

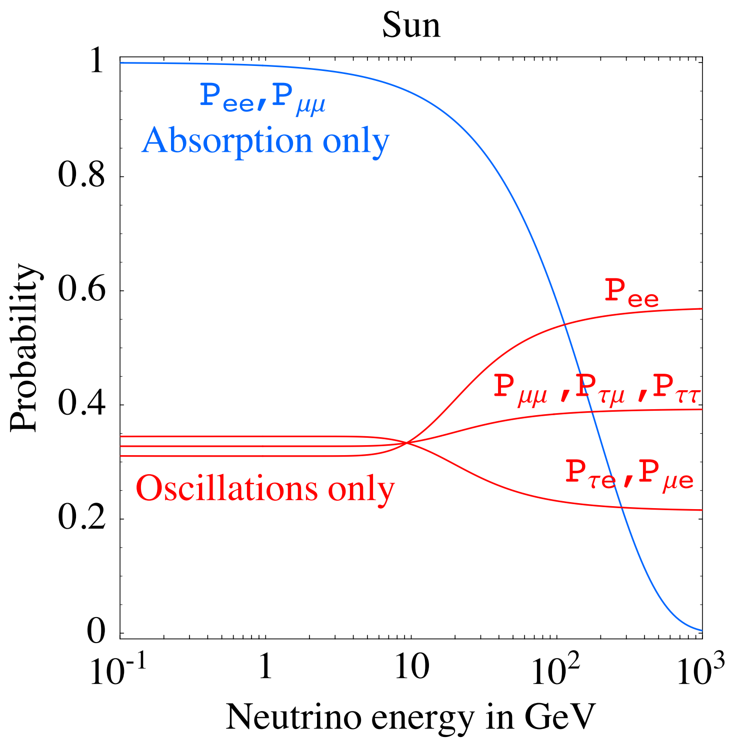
$$\boxed{\begin{array}{lllllll}
\nu_\tau & \rightarrow & \tau^- & \rightarrow X\,\nu_\tau & \qquad \bar\nu_\tau & \rightarrow & \tau^+ \quad \rightarrow X\,\bar\nu_\tau \\
 & & & \rightarrow e^-\,\bar\nu_e\,\nu_\tau & & & \qquad\;\; \rightarrow e^+\,\nu_e\,\bar\nu_\tau \\
 & & & \rightarrow \mu^-\,\bar\nu_\mu\,\nu_\tau & & & \qquad\;\; \rightarrow \mu^+\,\nu_\mu\,\bar\nu_\tau
\end{array}}$$

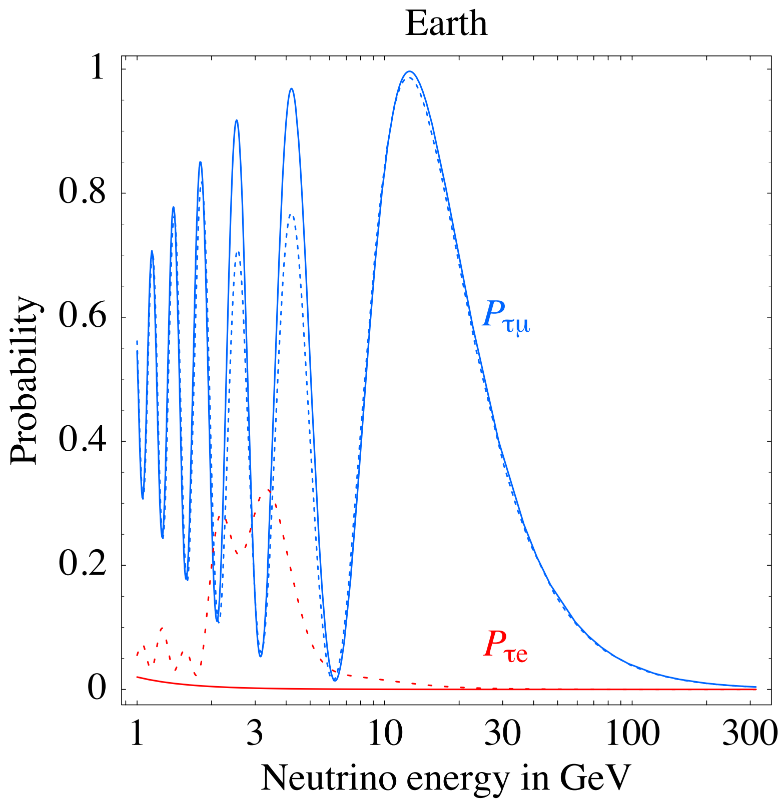
$$\begin{aligned}
\left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} &= -\frac{\{\boldsymbol{\Gamma}_{\rm CC},\boldsymbol{\rho}\}}{2} + \int \frac{dE_\nu^{\rm in}}{E_\nu^{\rm in}}\Big[\boldsymbol{\Pi}_\tau \rho_{\tau\tau}(E_\nu^{\rm in})\Gamma^\tau_{\rm CC}(E_\nu^{\rm in}) f_{\tau\rightarrow\tau}(E_\nu^{\rm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

$$\boldsymbol{\Gamma}_{\rm CC}(E_\nu) = {\rm diag}\,(\Gamma^e_{\rm CC},\Gamma^\mu_{\rm CC},\Gamma^\tau_{\rm CC}), \quad \Gamma^\ell_{\rm CC} = N_p(r)\,\sigma(\nu_\ell p\rightarrow \ell X) + N_n(r)\,\sigma(\nu_\ell n\rightarrow \ell X)$$

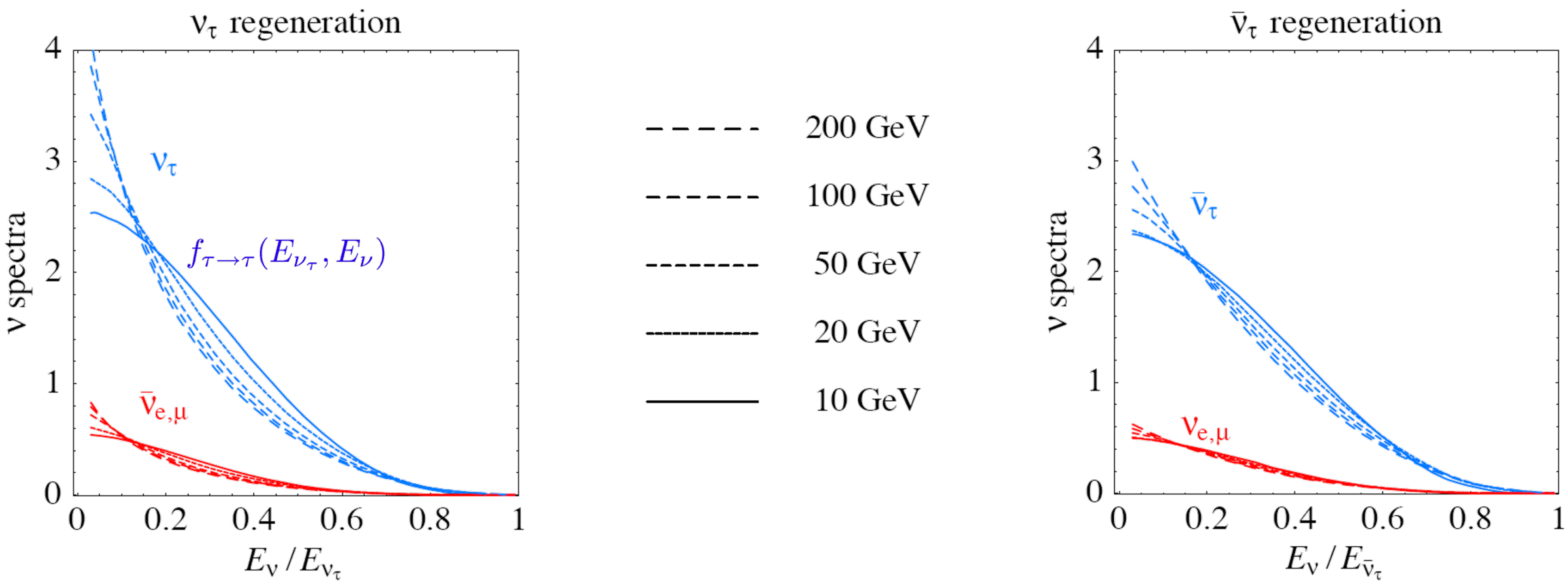
$$\bar{\boldsymbol{\Gamma}}_{\rm CC}(E_\nu) = {\rm diag}\,(\bar\Gamma^e_{\rm CC},\bar\Gamma^\mu_{\rm CC},\bar\Gamma^\tau_{\rm CC}), \quad \bar\Gamma^\ell_{\rm CC} = N_p(r)\,\sigma(\bar\nu_\ell p\rightarrow \bar\ell X) + N_n(r)\,\sigma(\bar\nu_\ell n\rightarrow \bar\ell X)$$

Oscillations probabilities and absorption



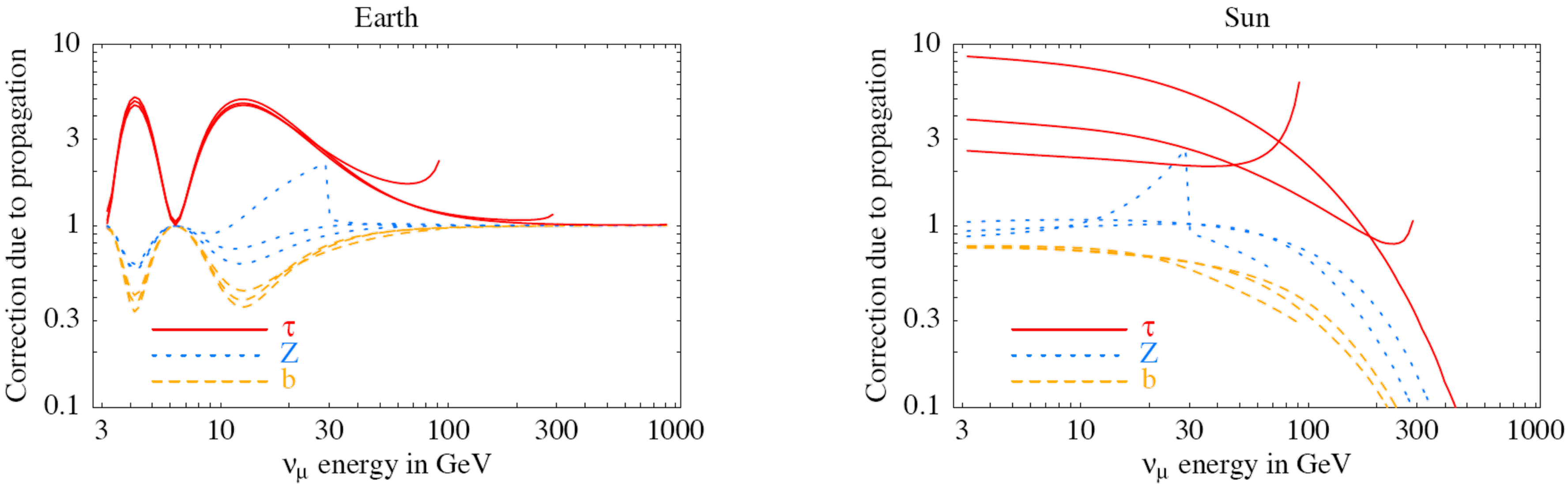


Tau-neutrino regeneration



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Effect of propagation



Earth:

- Affected only by "atmospheric" oscillation $\nu_\mu \leftrightarrow \nu_\tau$ at $E < 100$ GeV

Sun:

- Affected by average "solar" and "atmospheric" oscillations
- Absorption suppresses neutrinos for $E > 100$ GeV (partially converted to lower energy neutrinos (by NC and regeneration)

M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99
See also: M. Blennow, J. Edsjo, T. Ohlsson, JCAP 0801 (2008) 021 for an event-based MC approach

Signal at Neutrino Telescopes: upgoing muons

$$\frac{\mathrm{d}^2 N_\mu^{(\nu)}}{\mathrm{d}E_\mu \mathrm{d}E_\nu} = N_A \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^X dX \int_{E_\mu}^{E_\nu} \mathrm{d}E'_\mu \frac{\mathrm{d}\sigma_\nu(E_\nu, E'_\mu)}{\mathrm{d}E'_\mu} \cdot g(E_\mu, E'_\mu; X)$$

Probability that a muon with energy E'_μ emerges with energy E_μ after traveling a path X in rock

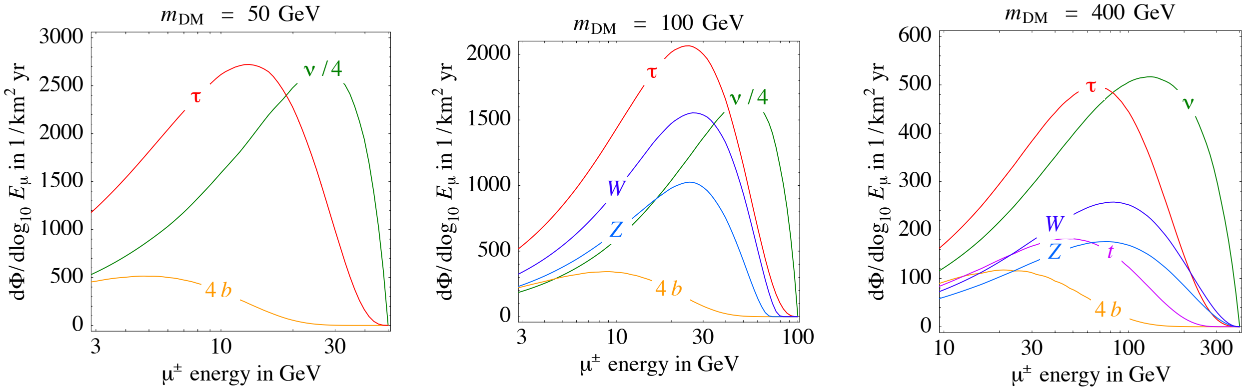
neutrino flux

muon pathlenght in rock

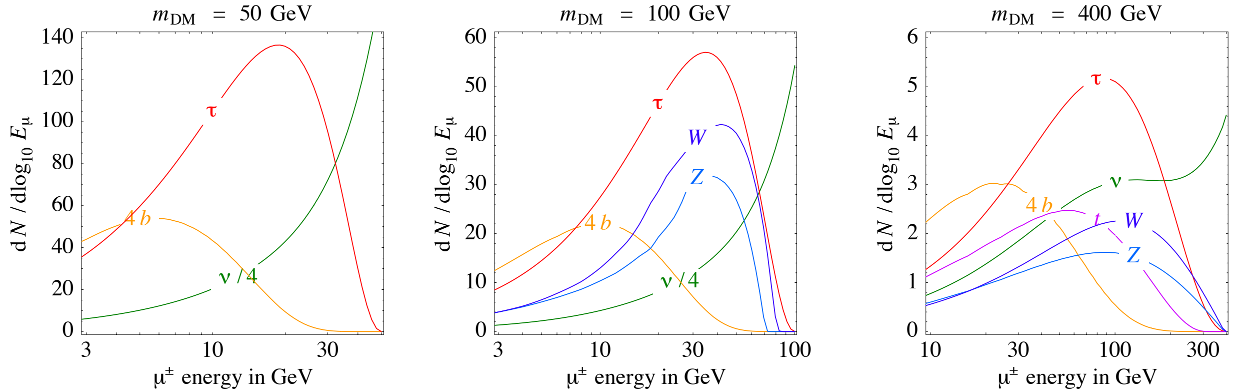
CC cross section neutrino-nucleus

Neutrino telescope signal from the Sun

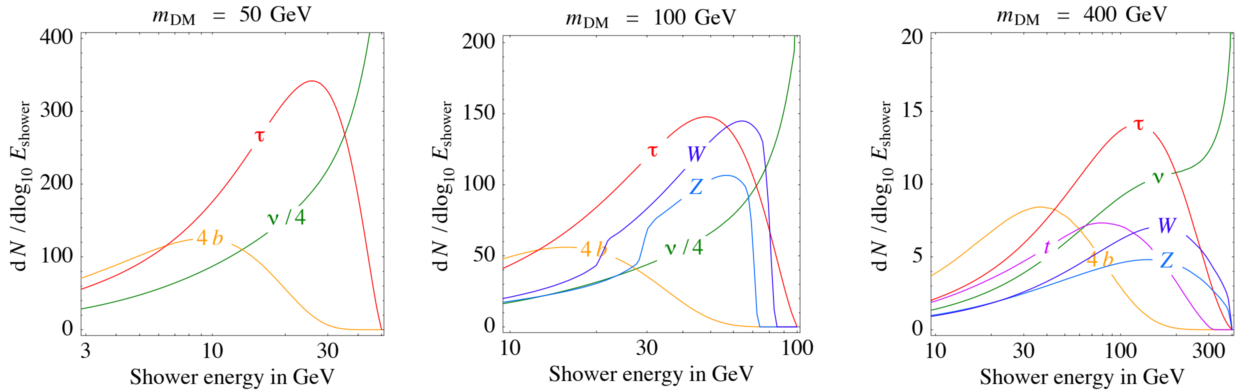
Thru-going muons



Fully-contained muons



"Showers"

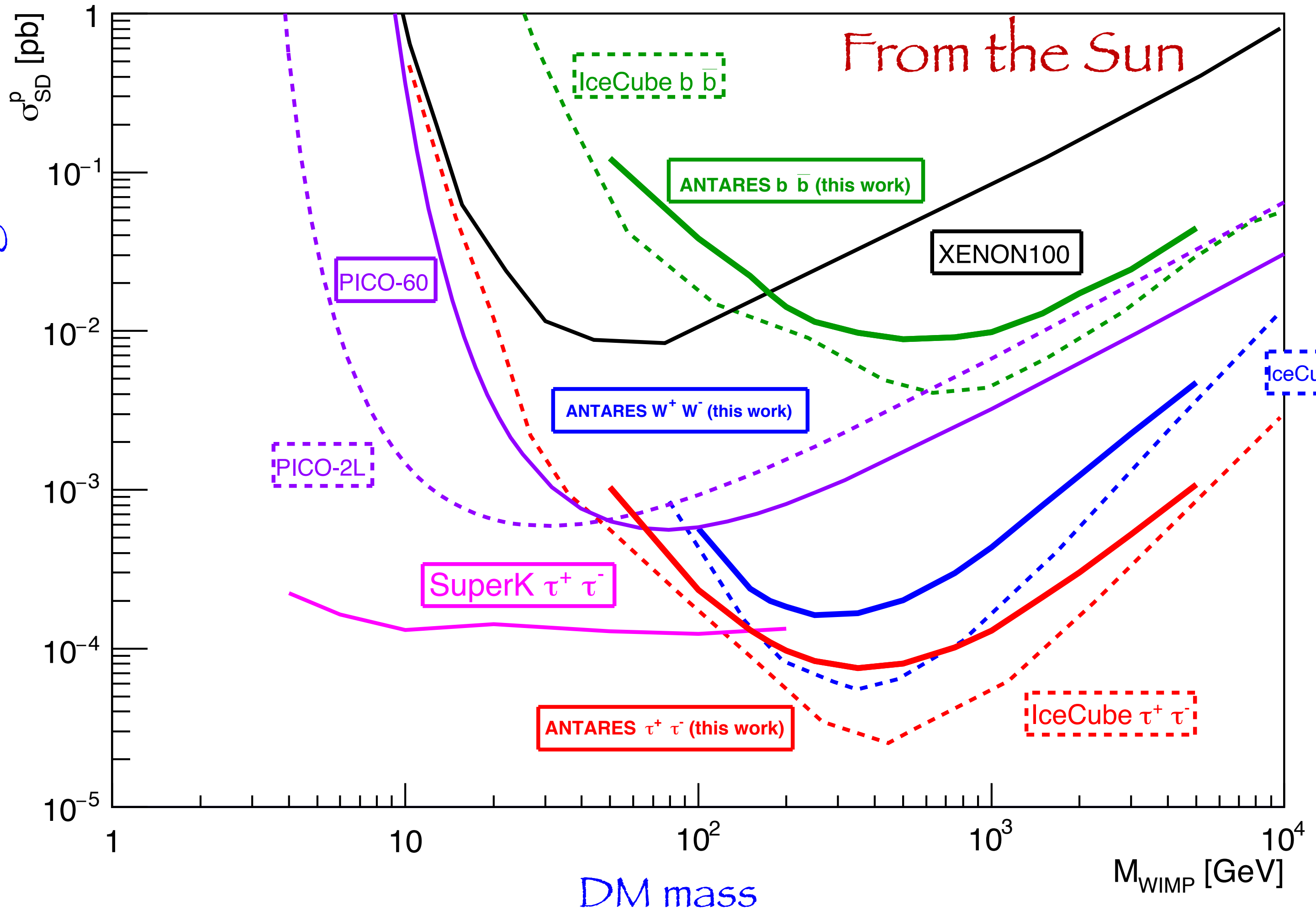


M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Bounds on capture cross section

Spin dependent interaction

Nucleon scattering

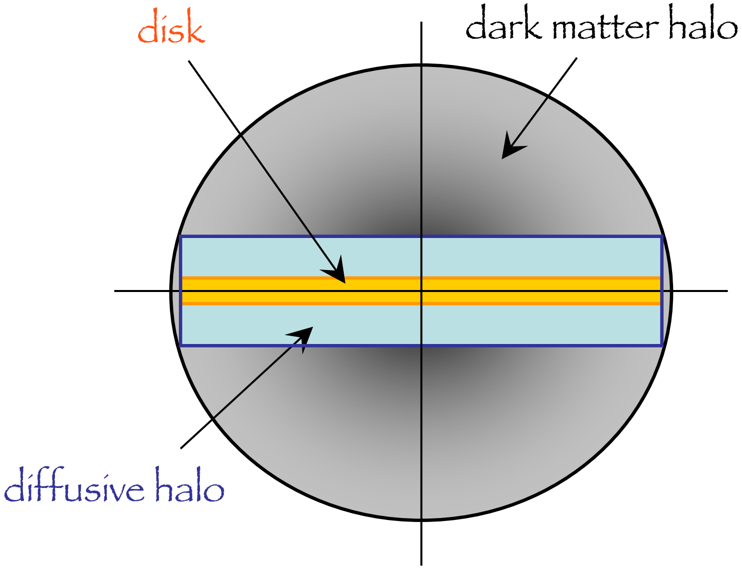


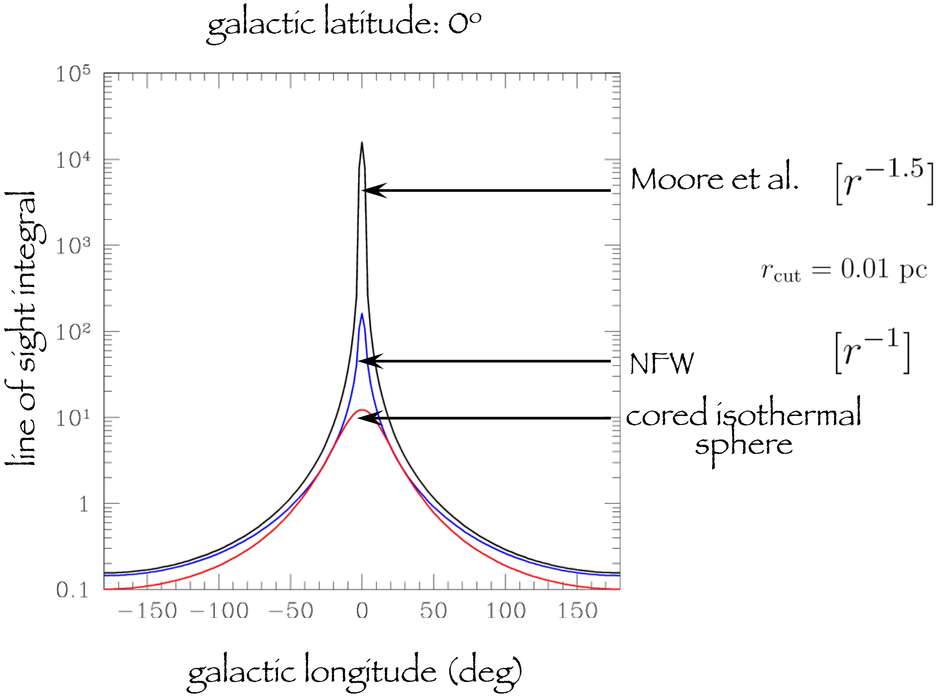
DM mass

ANTARES Collab, PLB 759 (2016) 69

Warning: bounds are typically derived under the assumption of perfect equilibration between capture and annihilation (and contact interactions)

Annihilation in the galactic halo





DM signal

$$\boxed{\chi\chi \longrightarrow (.....) \longrightarrow \nu\bar{\nu}}$$

The flux is sensitive to the DM density profile

Flux from galactic DM

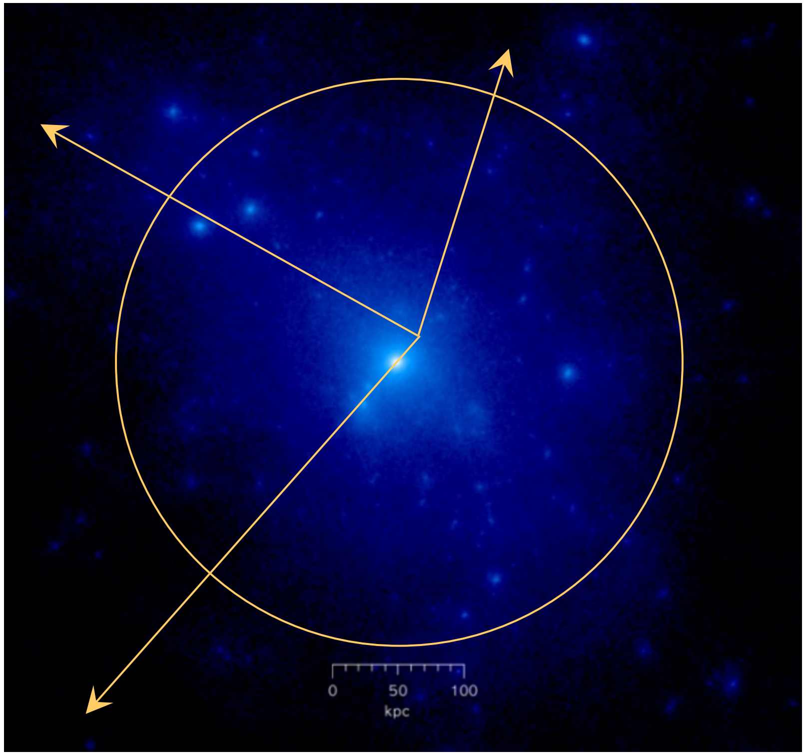
Flux:

$$\boxed{\Phi_\gamma^{\rm DM}(E_\gamma,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle_0}{2m_\chi^2}\, g_\gamma(E_\gamma)\; I(\psi)}$$

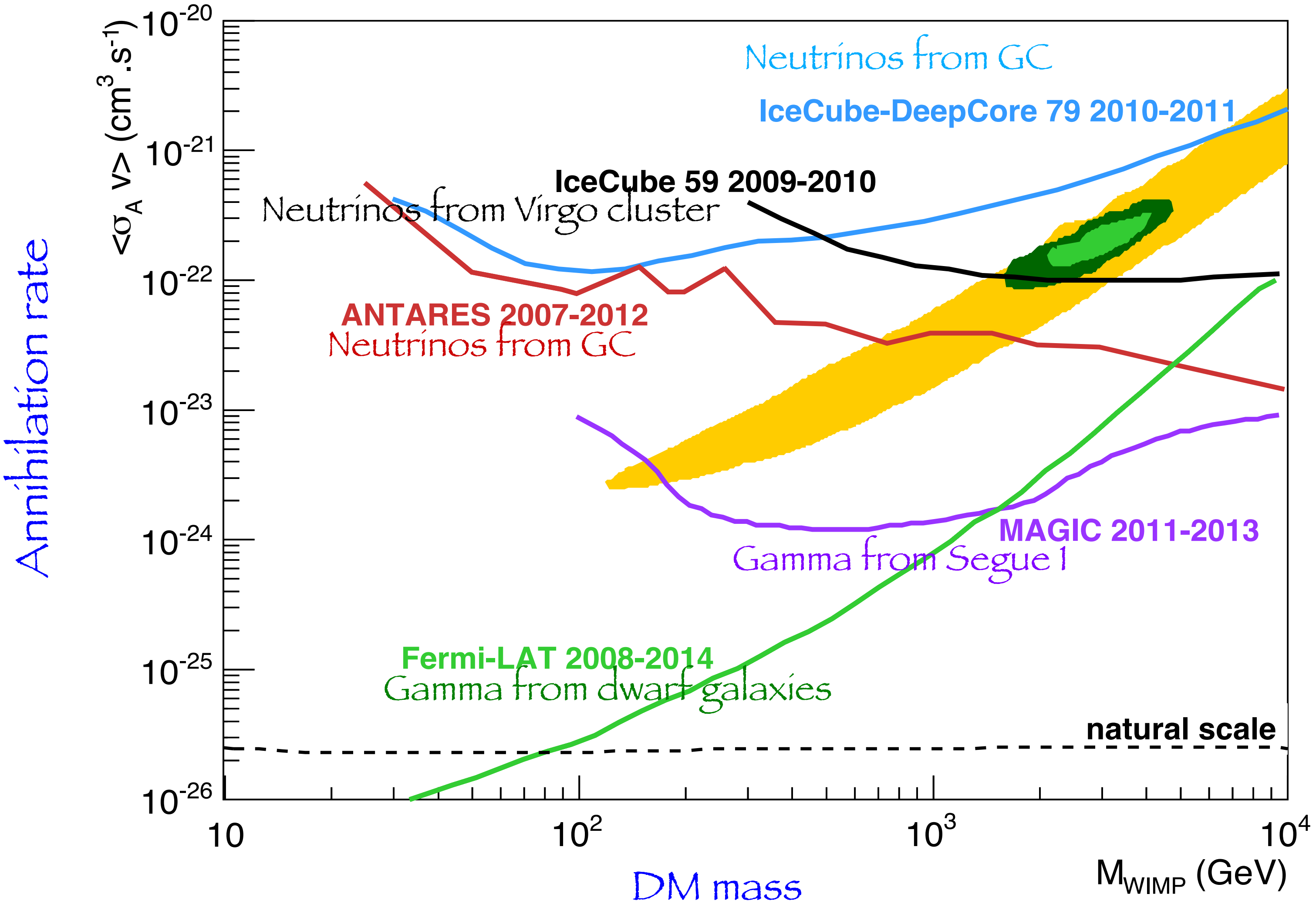
$$I(\psi) = \int_{\rm l.o.s.} \rho^2(r(\lambda,\psi))d\lambda$$

$$\rho(\vec{r}) = \rho_{\rm halo}(\vec{r}) + \sum_i \rho_{\rm sub}(\vec{r}_s)_{\vec{r}}$$

$$g(E) = \sum_{\mathcal{F}} {\rm BR}(\chi\chi\to\mathcal{F})\left(\frac{dN}{dE}\right)_{\mathcal{F}}$$



Bounds on annihilation cross section



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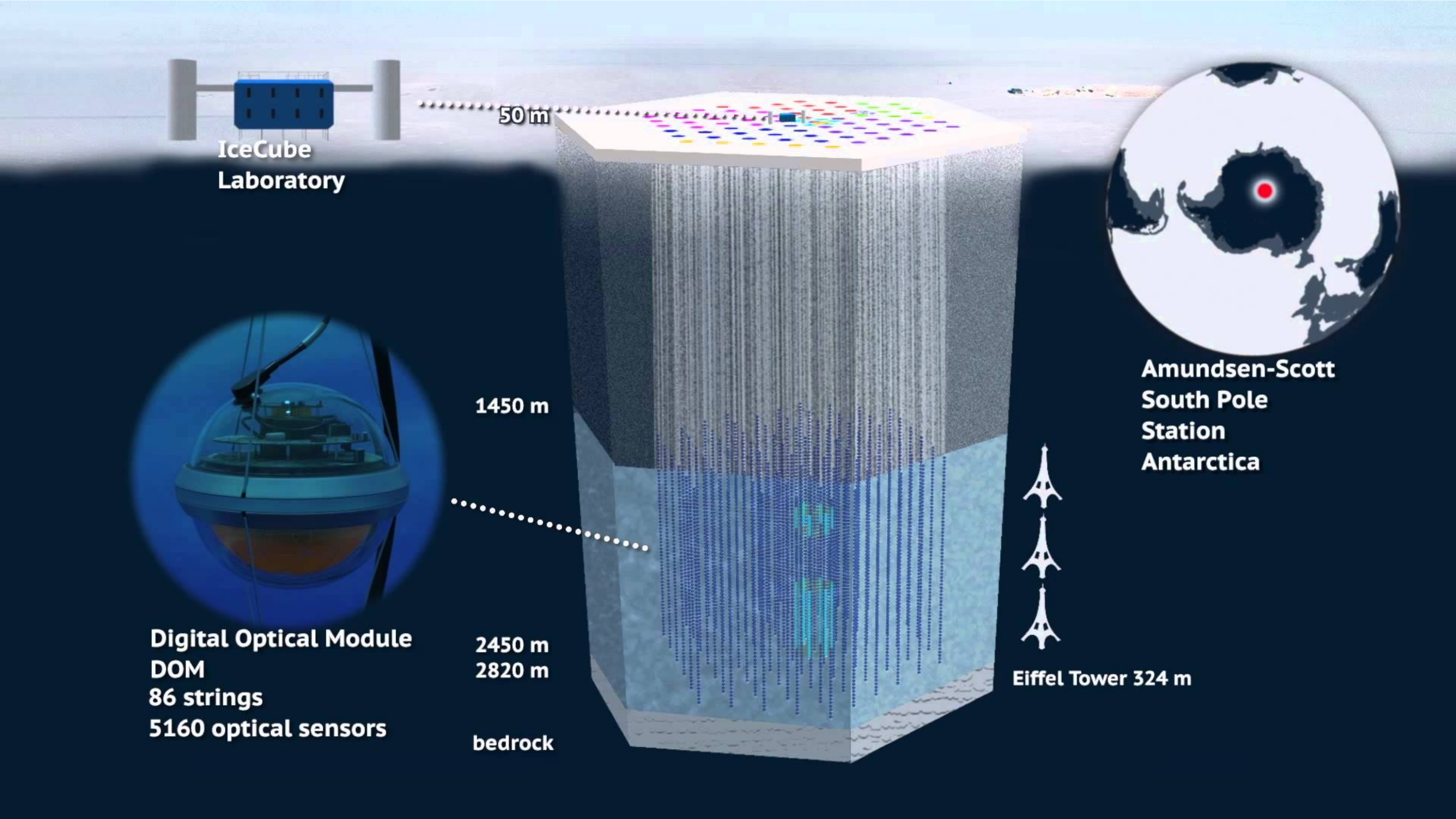
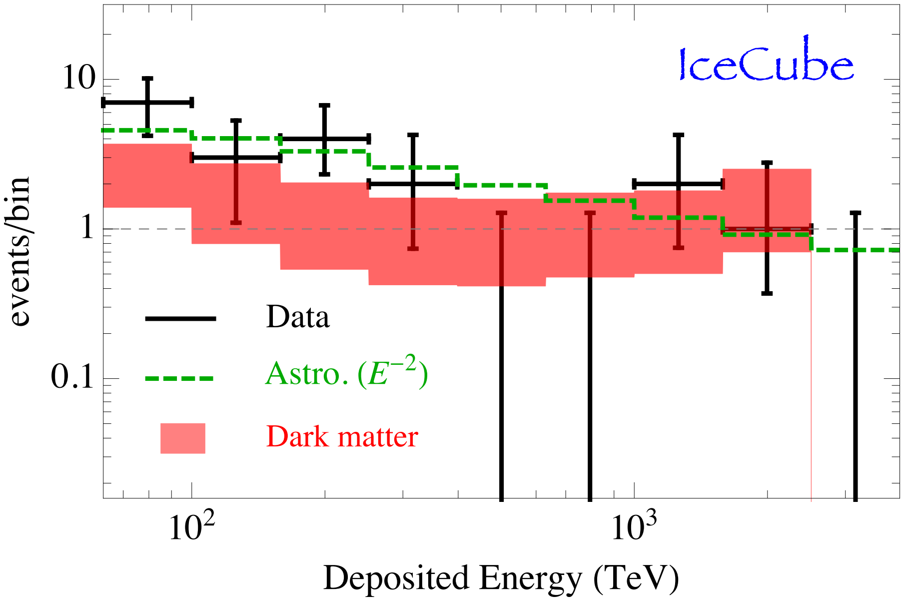
IceCube

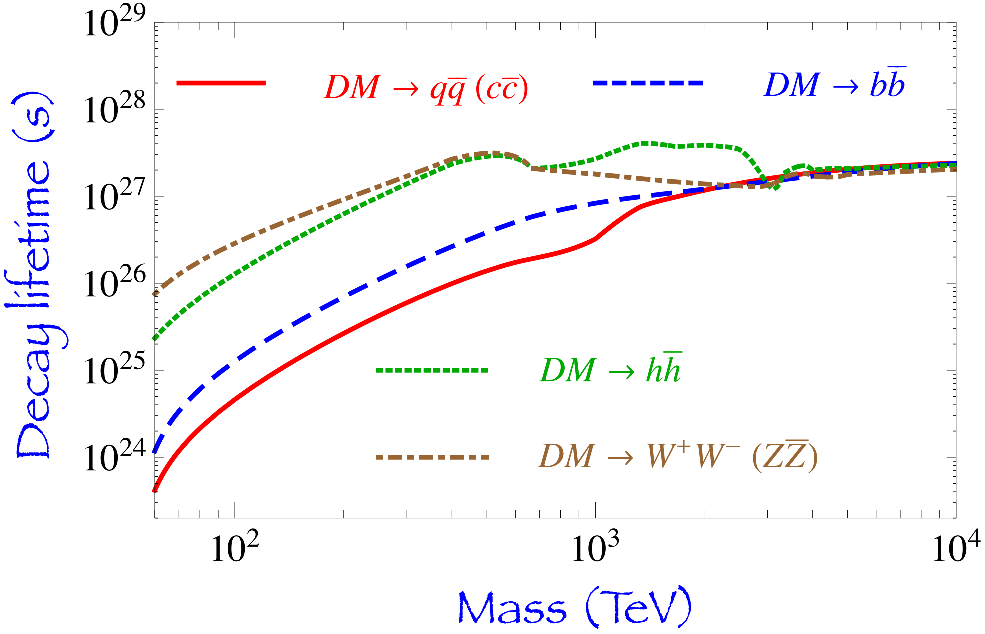

IceCube
Laboratory
50 m
Amundsen-Scott
South Pole
Station
Antarctica
1450 m
Digital Optical Module
DOM
86 strings
5160 optical sensors
2450 m
2820 m
bedrock
Eiffel Tower 324 m

IceCube PeV neutrinos

The spectral feature of the IceCube PeV events could refer to decaying very heavy DM: PeV scale

e.g. $m_{DM} \simeq 4$ PeV lifetime $\simeq 10^{28}$ s





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