NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

2212.02286
2111.04000
2012.09751
2006.11837
1912.09904

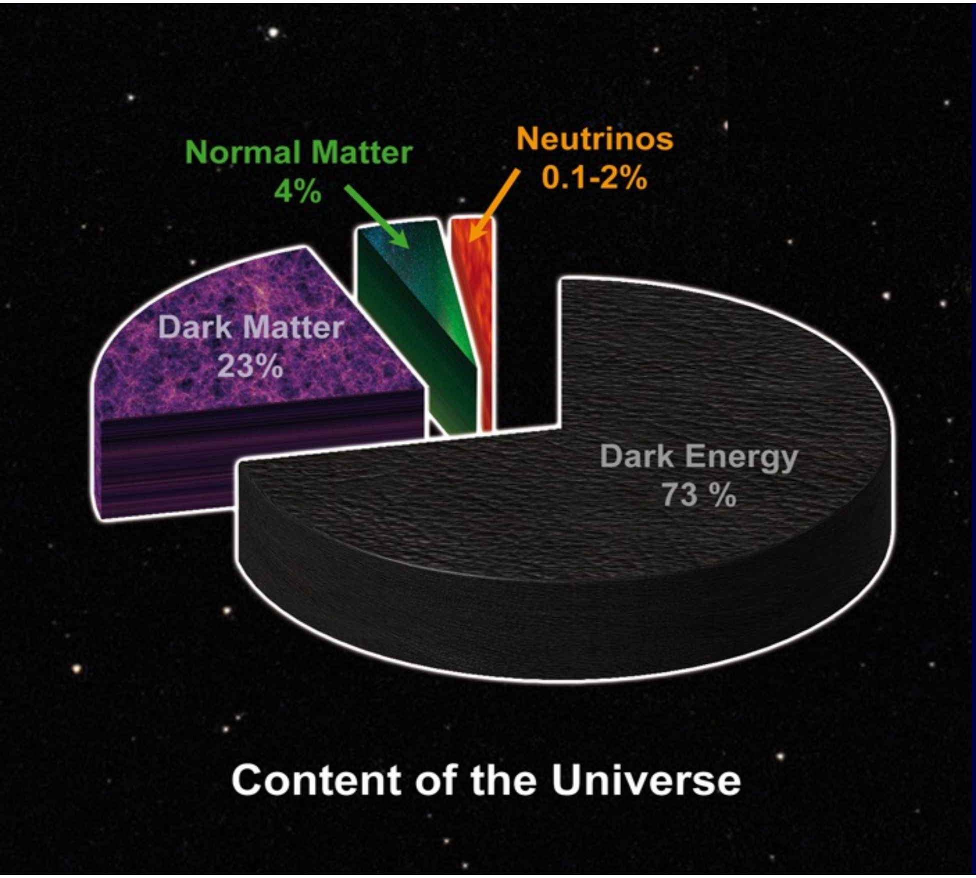
Probing Boosted Dark Matter in Direct Detections

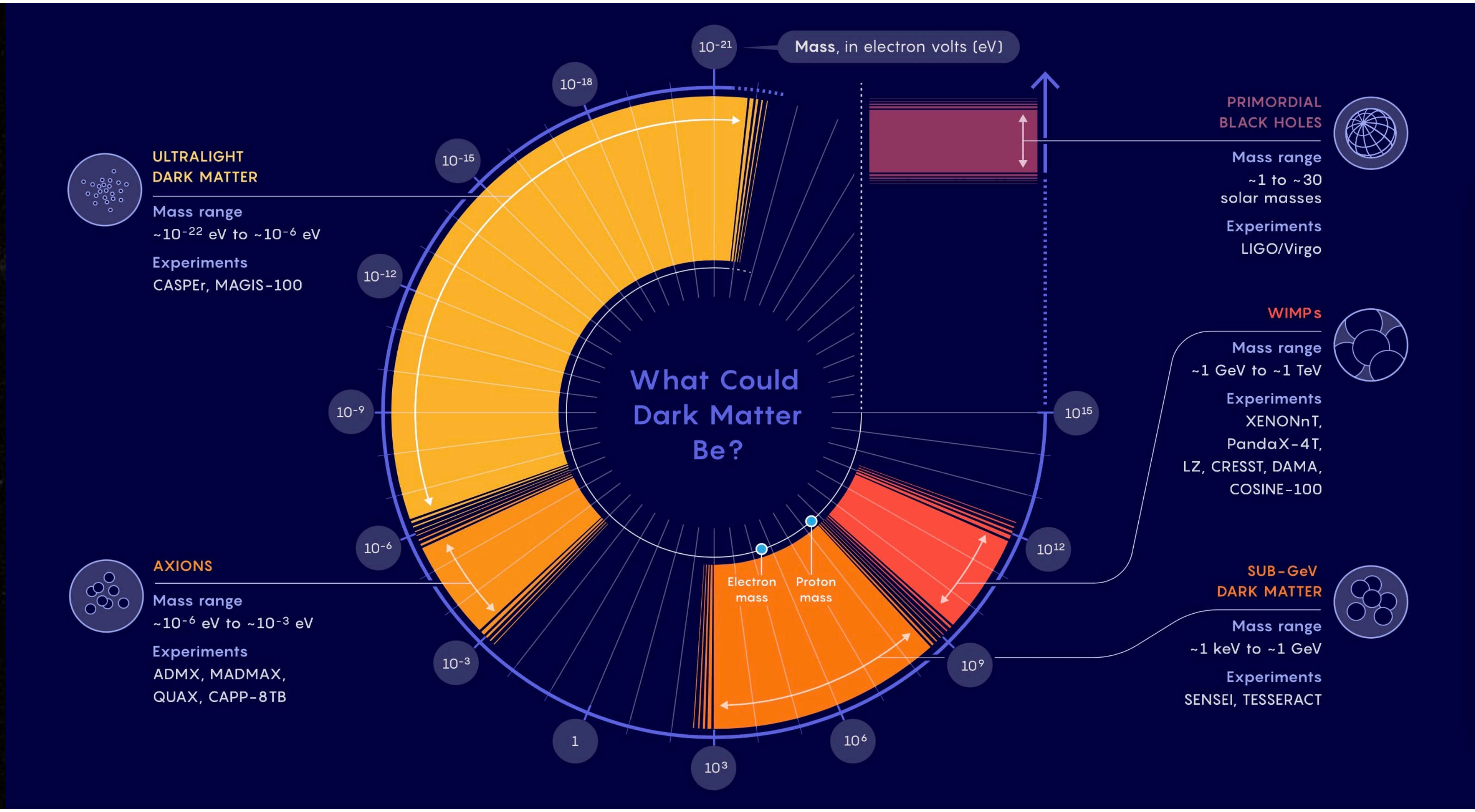
武 雷

Outline

- Detections of DM
- Cosmic Ray Boosted Dark Matter
- Inelastic Effects in Earth Stopping
- Conclusions

1. Detections of DM





Mass range: ~ 10^{-22} eV to ~ 10 solar Mass

1. Detections of DM

Particle-like DM

Accelerator

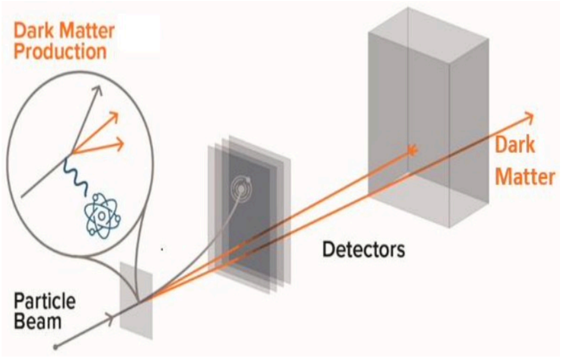
- **Can only produce DM**
- **Model dependent**
- **LHC, Belle-II, Faser…**

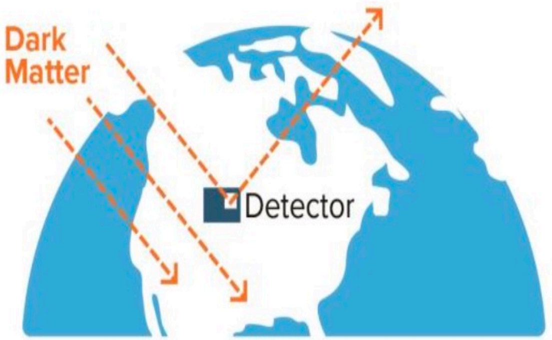
Direct Detection

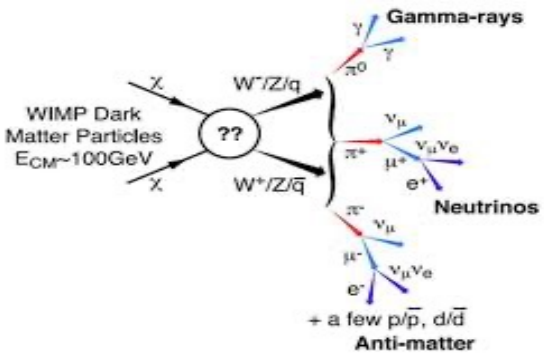
- **Local DM Distribution**
- **Background**
- **CDEX, PandaX, Xenon, DAMIC…**

Indirect Detection

- **DM distribution in halos**
- **Product propagation**
- **DAMPE, FermiLAT, AMS-02…**





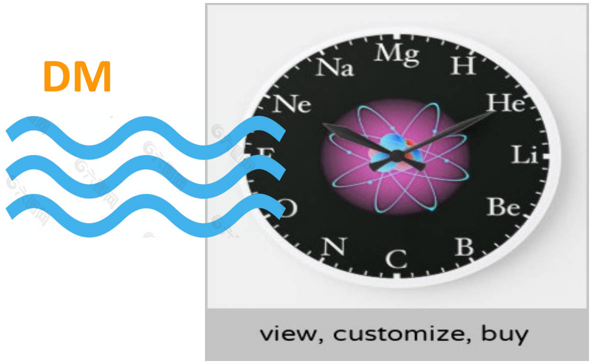


1. Detections of DM

Wave-like DM

Quan. Tech. / Astronomy

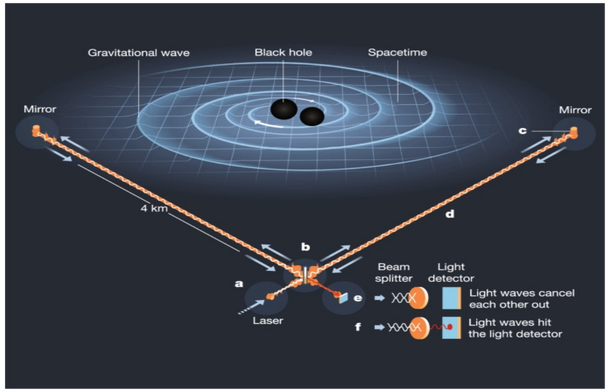
- **Ultralight bosonic DM**
- **Cavity, Atomic Clock…**



Compact Object DM

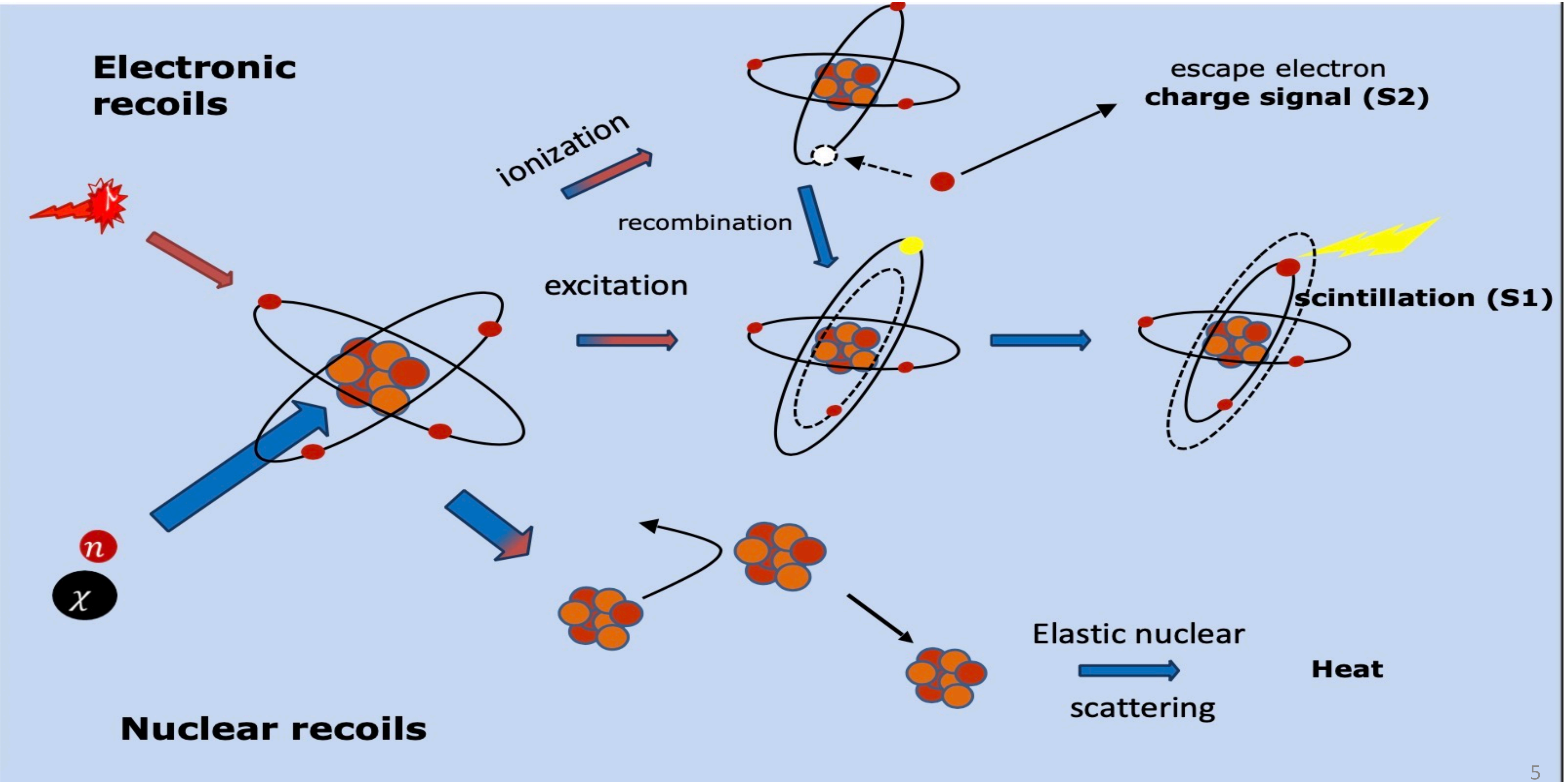
Gravitational Wave/Pulsar Timing

- **Primordial Black Hole**
- **LISA, TianQin, Taiji…**



The Search for Dark Matter Is Dramatically Expanding !

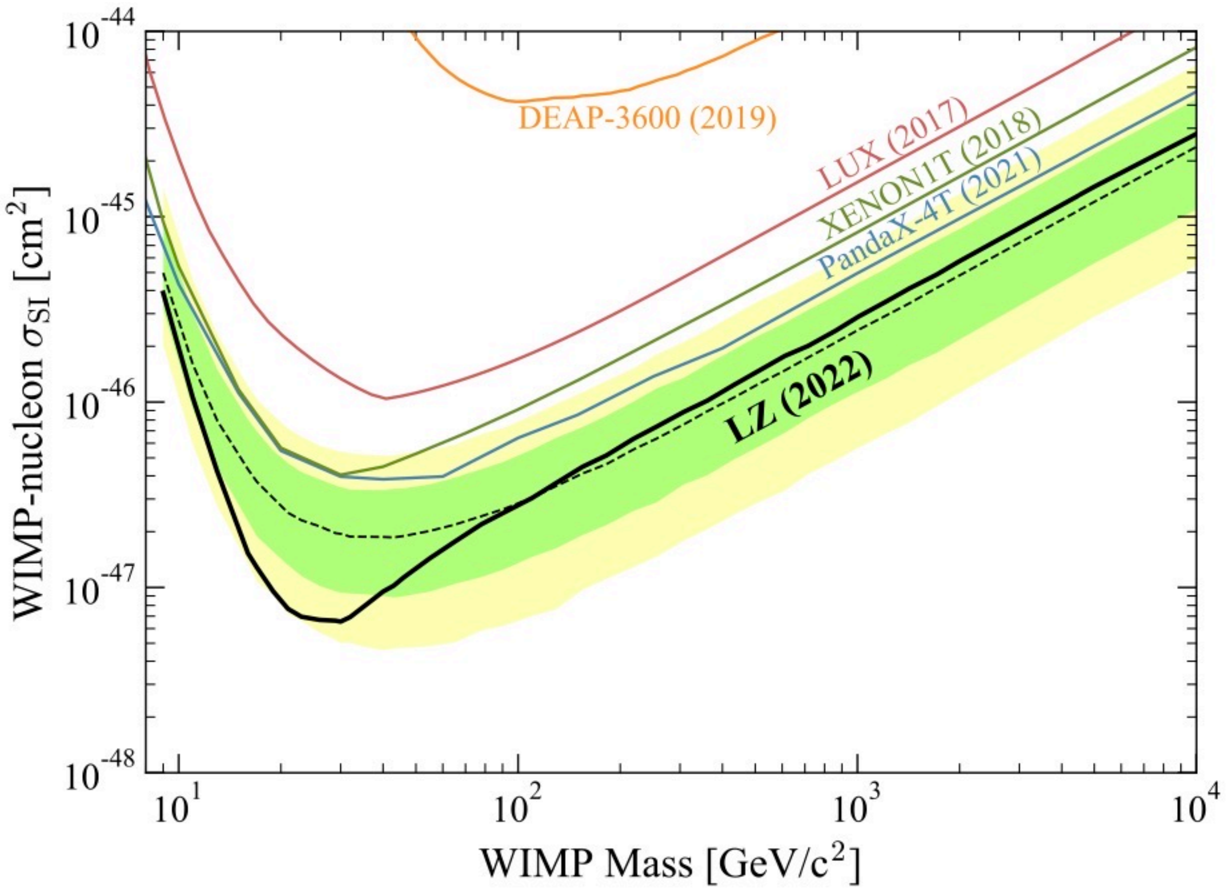
1. Detections of DM



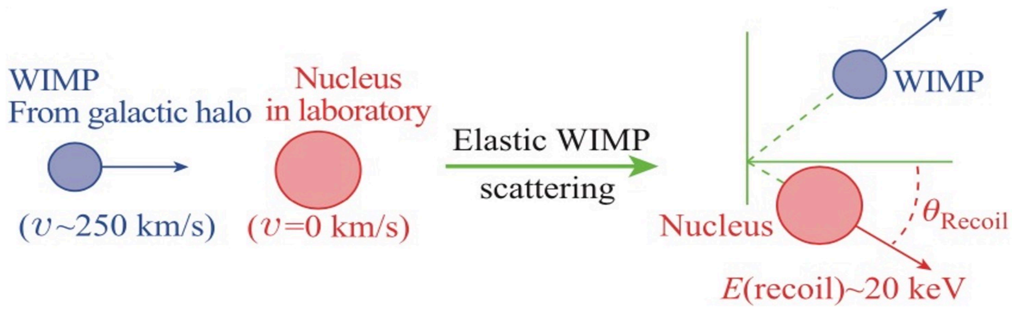
1. Detections of DM

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioke
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	40,000 kg	200 t yr	Planning	2028	2033	LNGS / SURI
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Construction	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	NaI	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	NaI	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	NaI	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	NaI	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	NaI	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	NaI	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg		Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	SNOLAB
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Construction	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g		Running	2019		LSM
CRESST-II	Bolometer Scintillation	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillation	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Construction	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction	2021	2023	SNOLAB

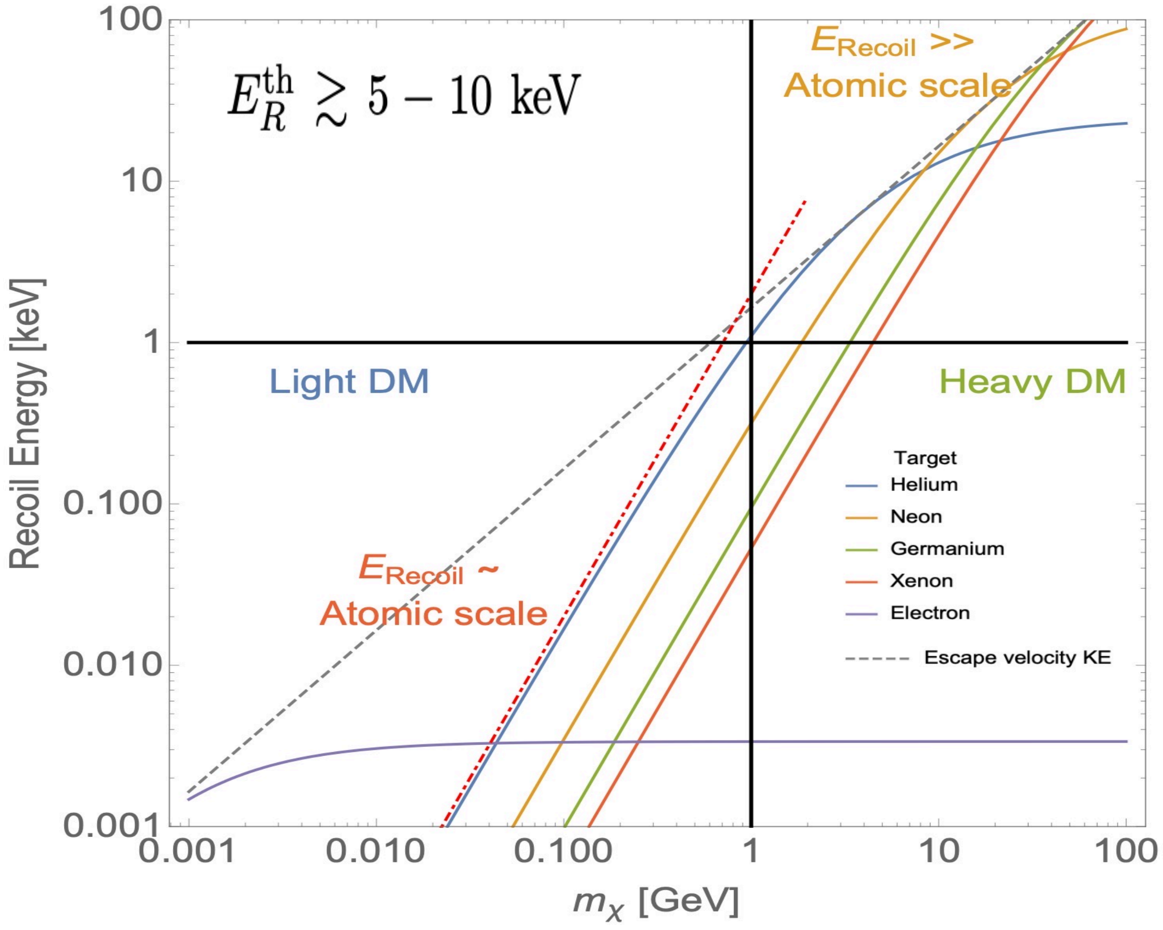
about 20



1. Detections of DM

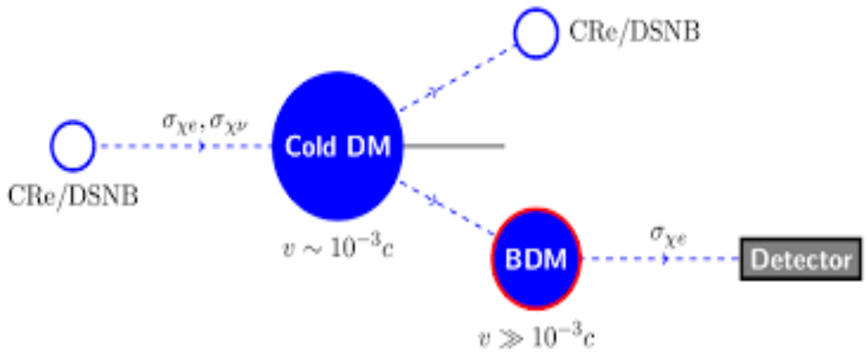


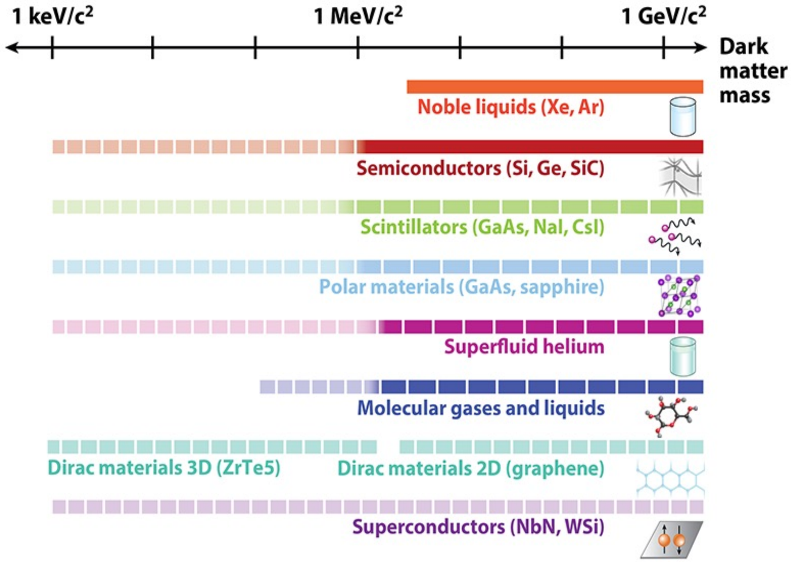
$$E_R = \frac{q}{2m_A} = \frac{1}{2} m_\chi v^2 \left(\frac{4 m_\chi m_A}{(m_A^2 + m_\chi^2)} \right) \cos^2 \theta_R$$

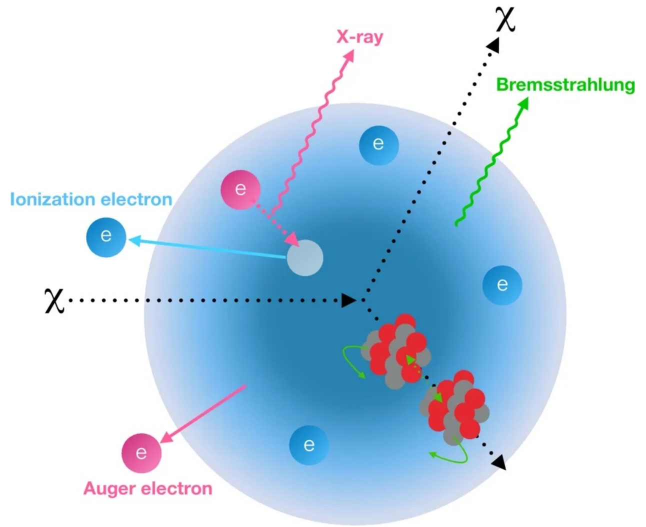


1. Detections of DM

1. Boosted Dark Matter: astrophysical sources…
2. Low Threshold Detectors: electron/ semiconductors/superconductor…
3. New effects: bremsstrahlung/Migdal/phonon…

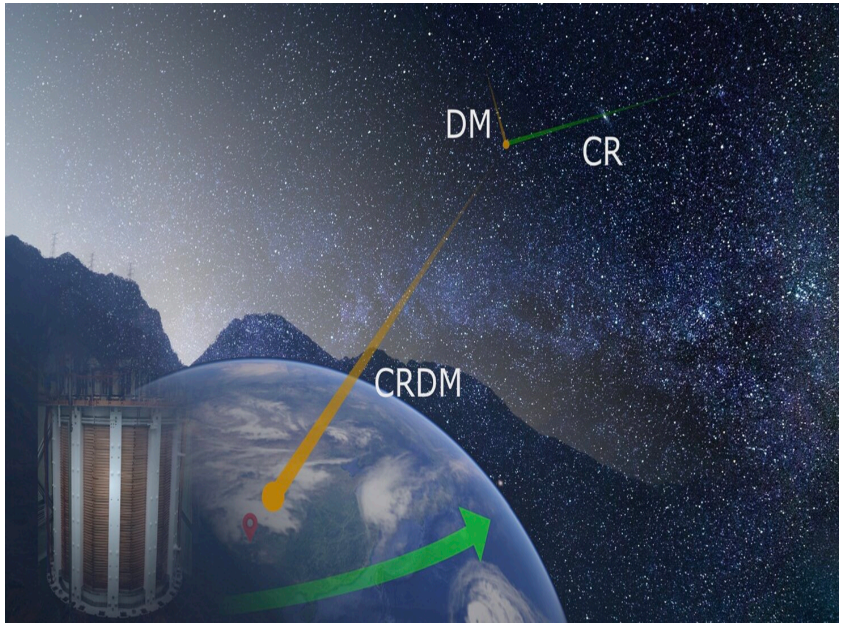






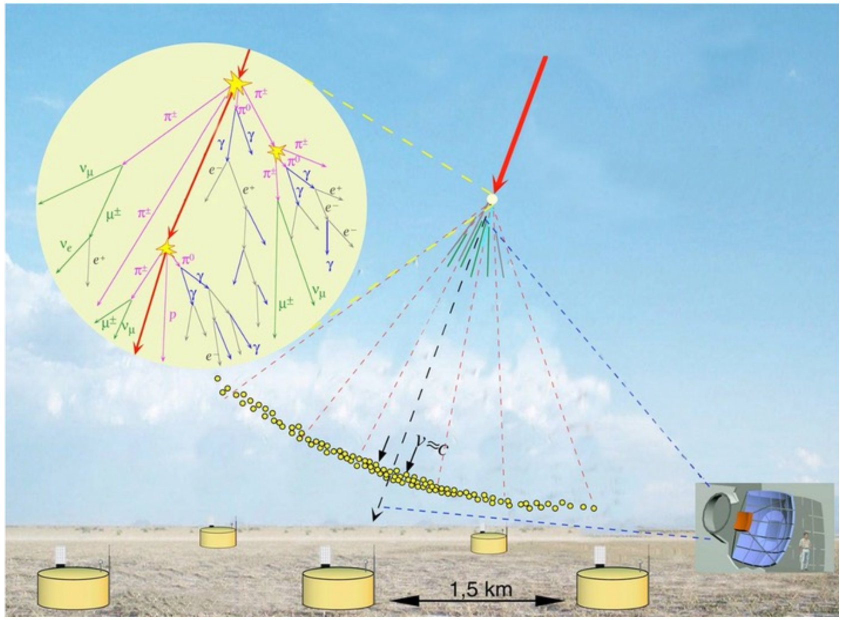
2. Cosmic Ray Boosted Dark Matter

Cosmic ray upper-scattering DM



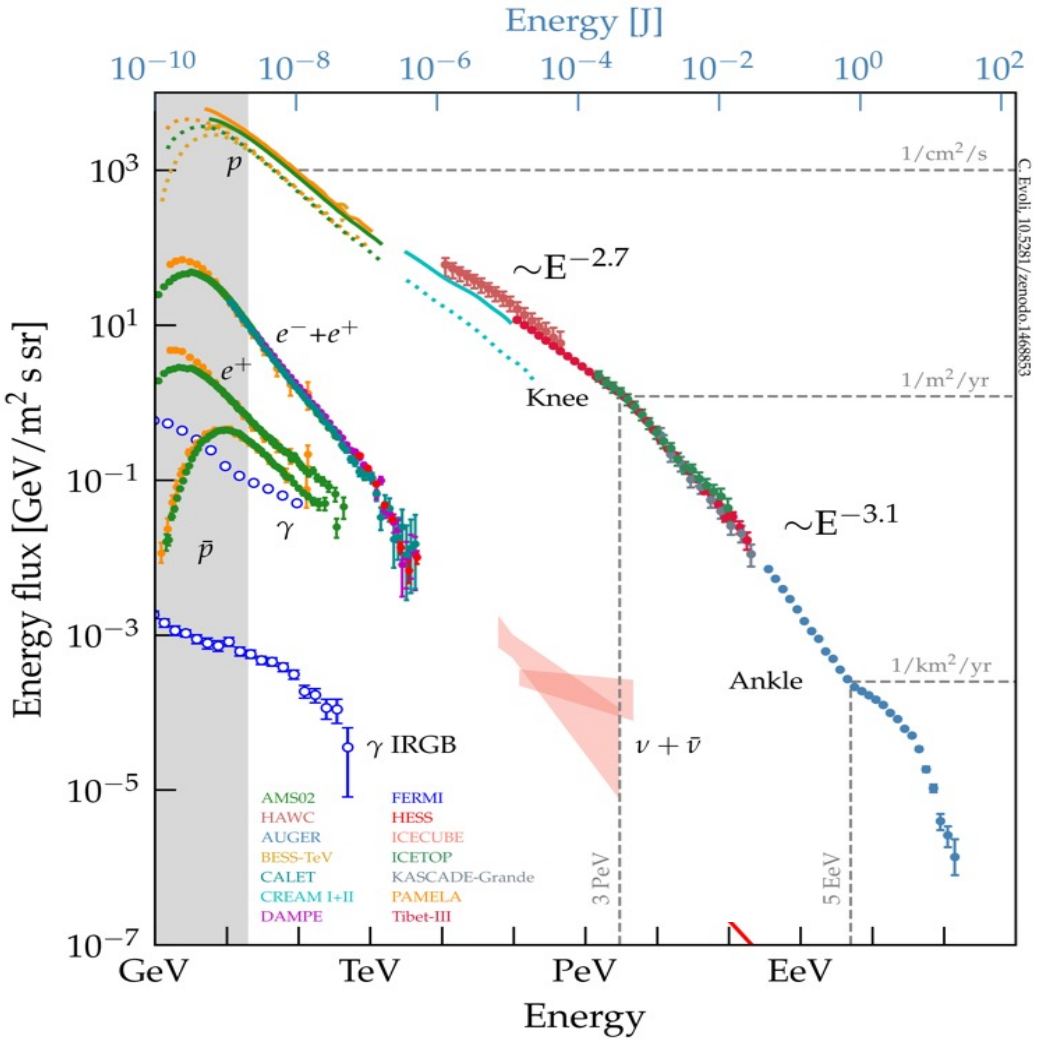
1810.07705, 1810.10543,
1912.09904, 2005.09480,
2006.12767, 2009.00353,
…

Cosmic beam-dump DM



1905.05776, 2006.11837,
2012.09751, 2211.11469,
2212.02286, 2301.03010
…

2. Cosmic Ray Boosted Dark Matter



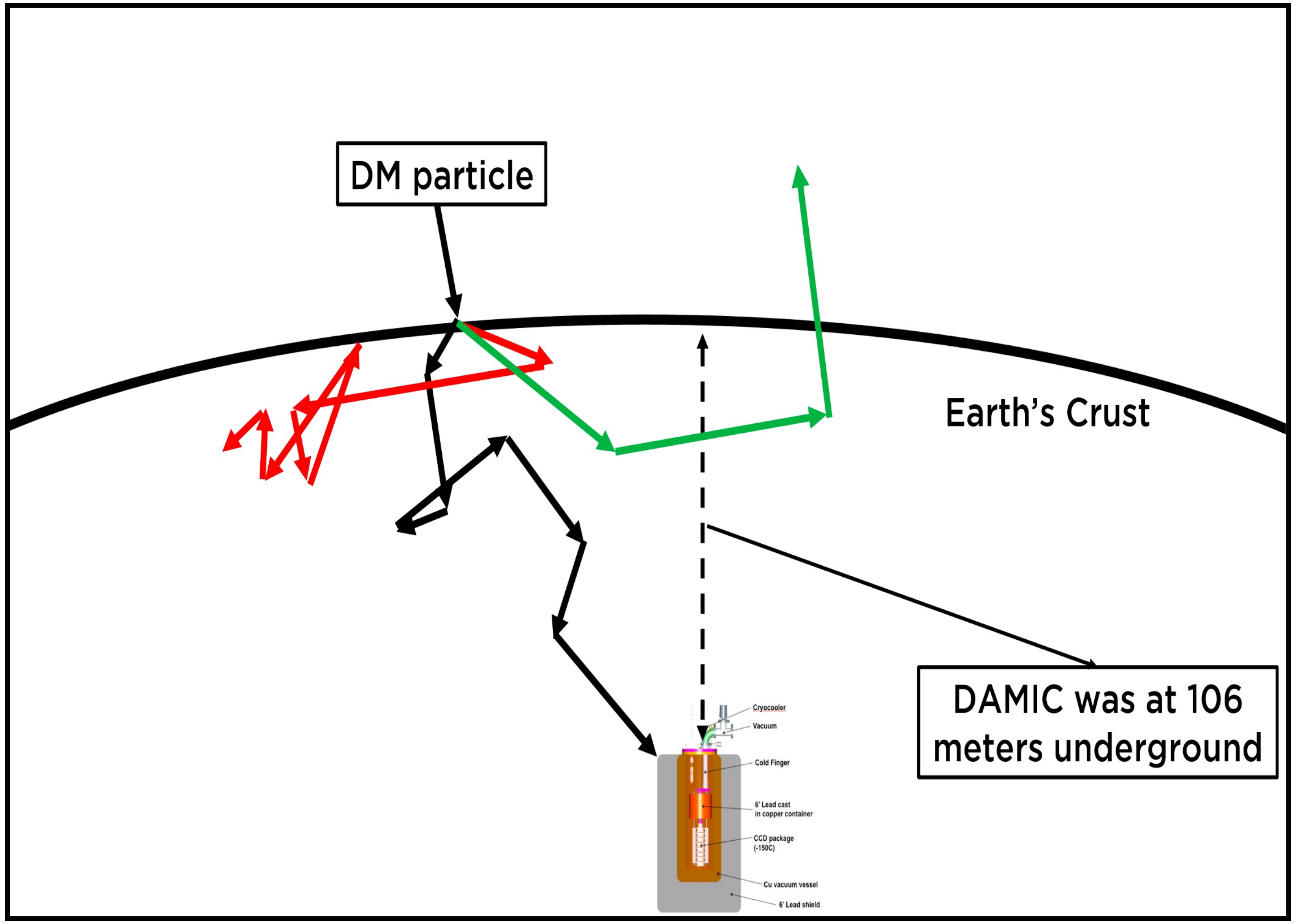
Power law:

$$\frac{d^4N}{dt\,dA\,d\Omega\,dE} \approx \frac{1.8 \text{ nucleons}}{\text{sec cm}^2 \text{ sr GeV}} \left(\frac{1 \text{ GeV}}{E}\right)^{\alpha}$$

Components:

90% proton
9% α

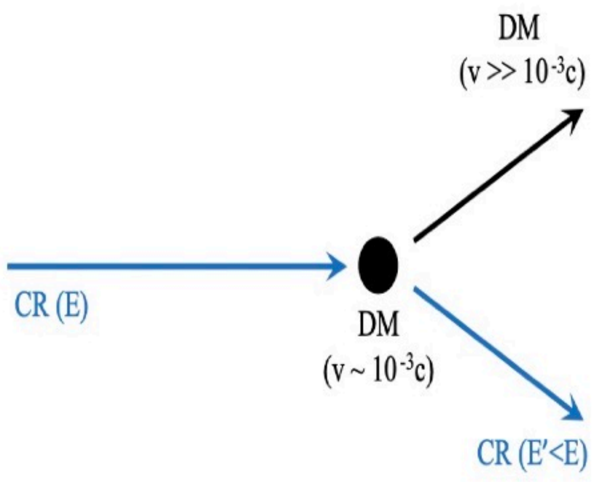
2. Cosmic Ray Boosted Dark Matter



$$\frac{d\Phi_\chi}{dT_\chi^z} = \boxed{\left(\frac{dT_\chi}{dT_\chi^z}\right)} \frac{d\Phi_\chi}{dT_\chi}$$

2. Cosmic Ray Boosted Dark Matter

Cosmic ray upper-scattering DM



$$\frac{d\Phi_\chi}{dT_\chi} = \boxed{D_{\rm eff}} \frac{\rho_\chi^{\rm local}}{m_\chi} \int_{T_{CR}^{\rm min}}^{\infty} dT_{CR} \boxed{\frac{d\sigma_{\chi N}}{dT_\chi}} \boxed{\frac{d\Phi_{CR}^{\rm LIS}}{dT_{CR}}}$$

Nucleus form factor:
dipole for CR, Helm for Xe
DM form factor

$$D_{\rm eff} = \int_{l.o.s} d\ell \left(\frac{\rho_\chi}{\rho_\chi^{\rm loc}} \right)$$

$$\frac{d\Phi_{\rm CR}}{dT_{\rm CR}} \simeq \frac{d\Phi_{\rm CR}^{\rm LIS}}{dT_{\rm CR}}$$

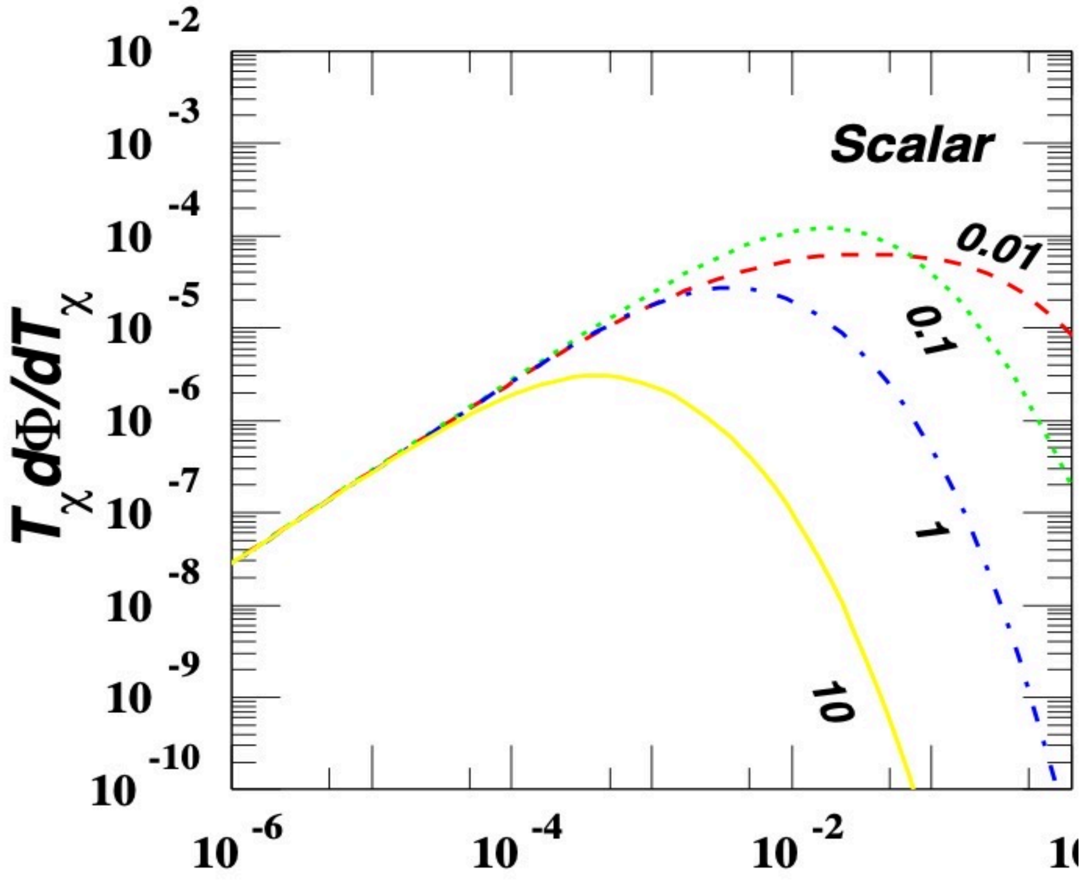
Assumptions:

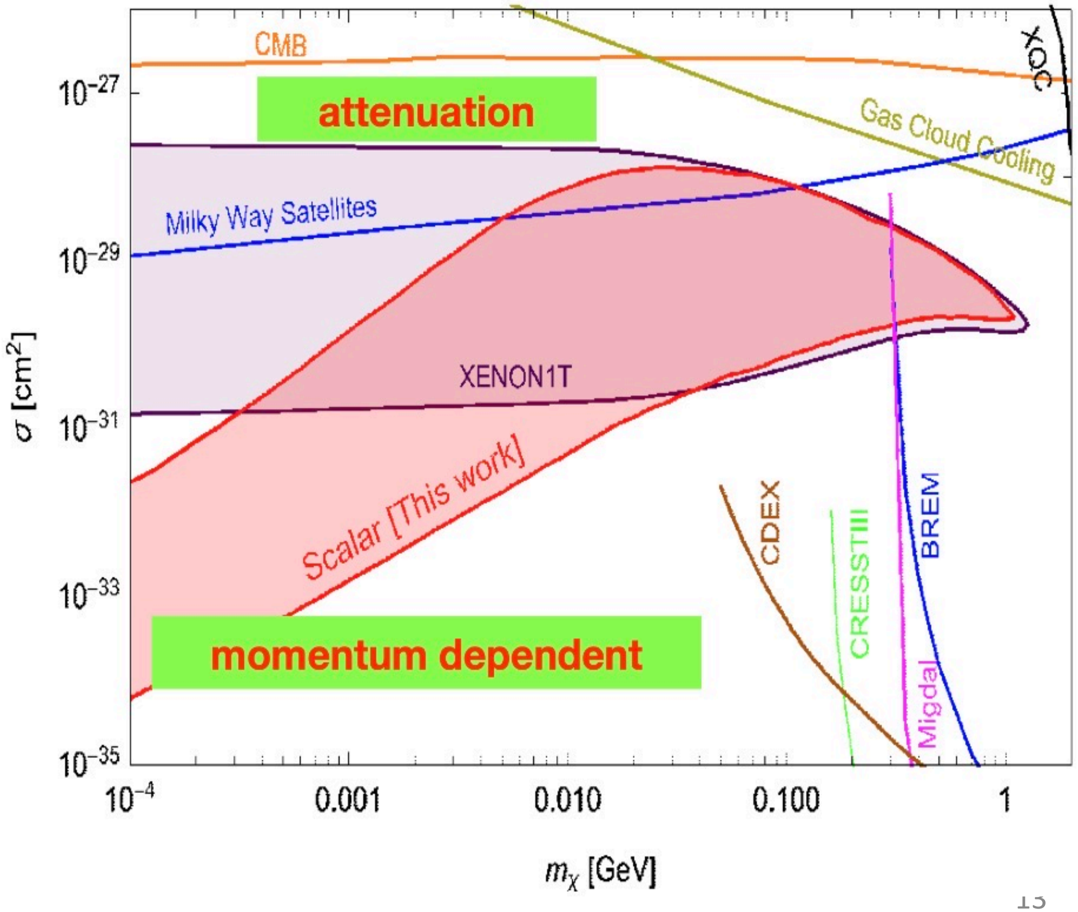
1. Homogeneous CR distribution

2. Isotropic CR-DM scattering

2. Cosmic Ray Boosted Dark Matter

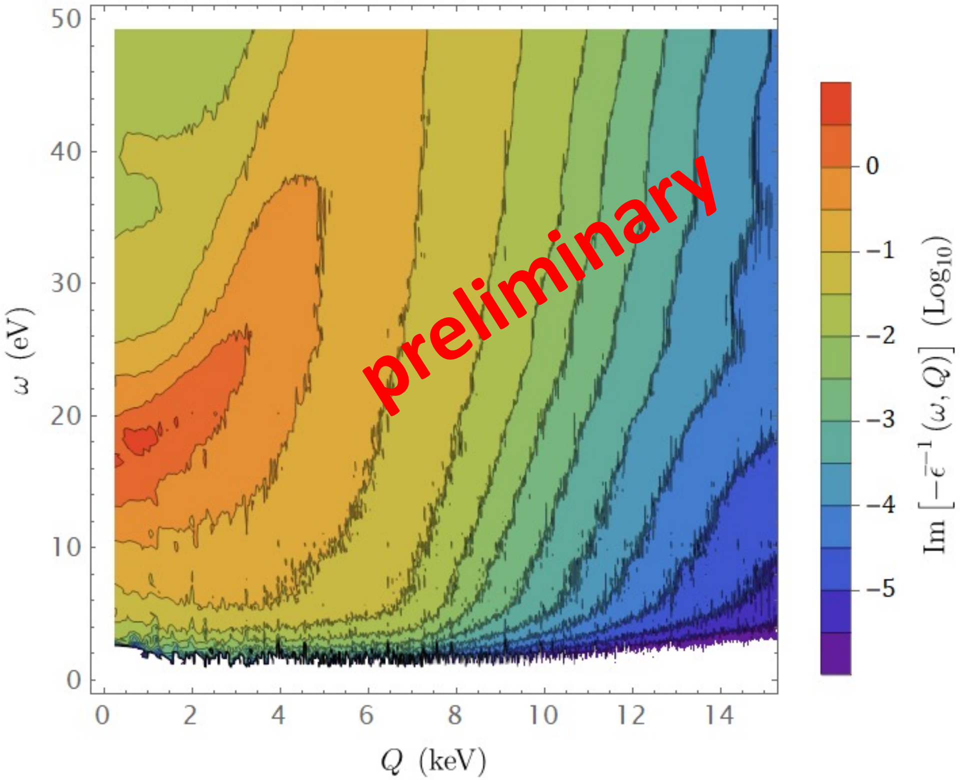
Wang, Wu, Yang, Zhou, Zhu, 1912.09904

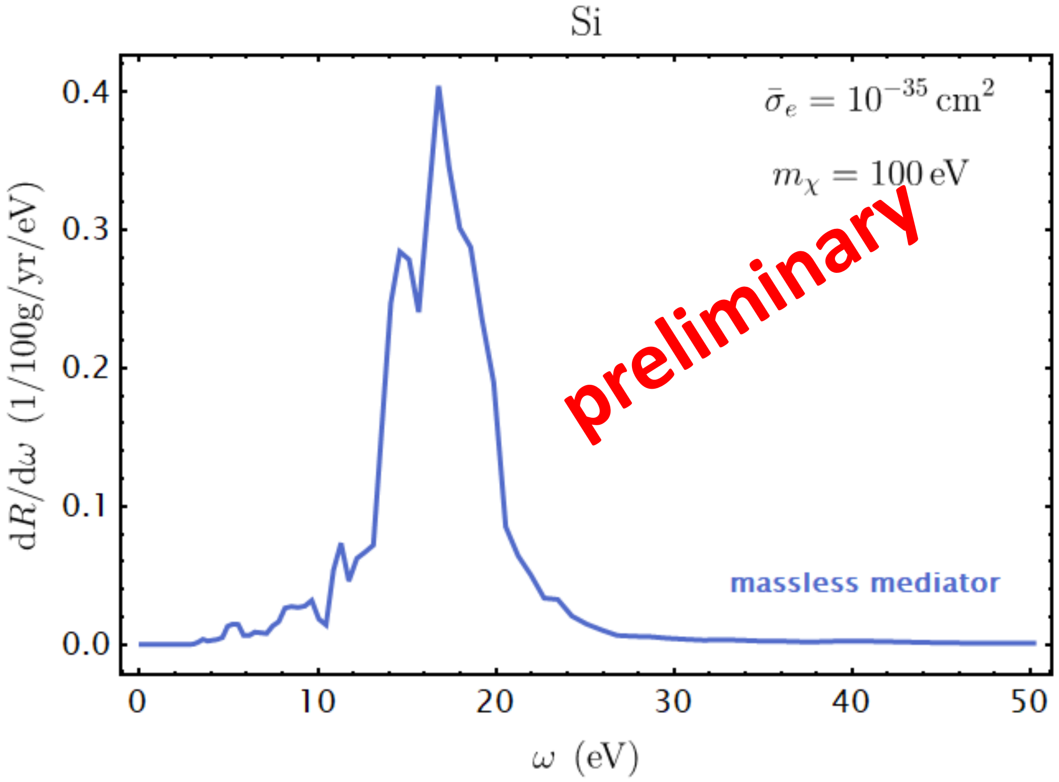




2. Cosmic Ray Boosted Dark Matter

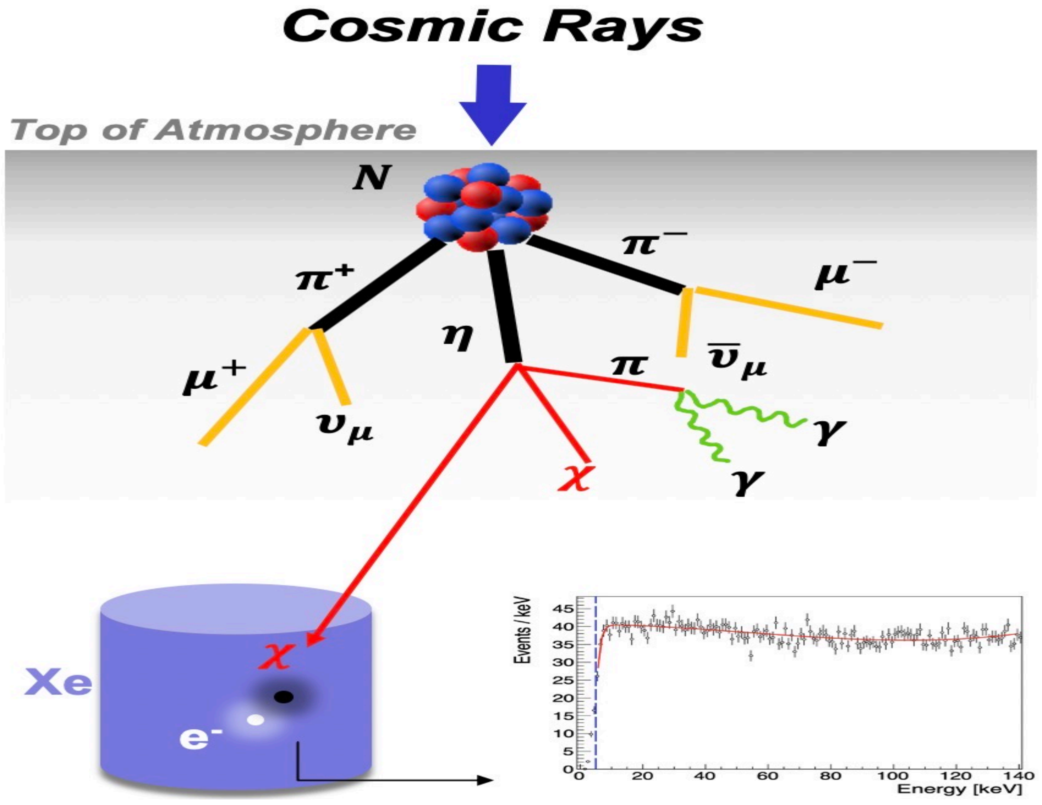
Liang, Su, Wu, Zhu, 2306.xxxx





2. Cosmic Ray Boosted Dark Matter

Cosmic beam-dump DM



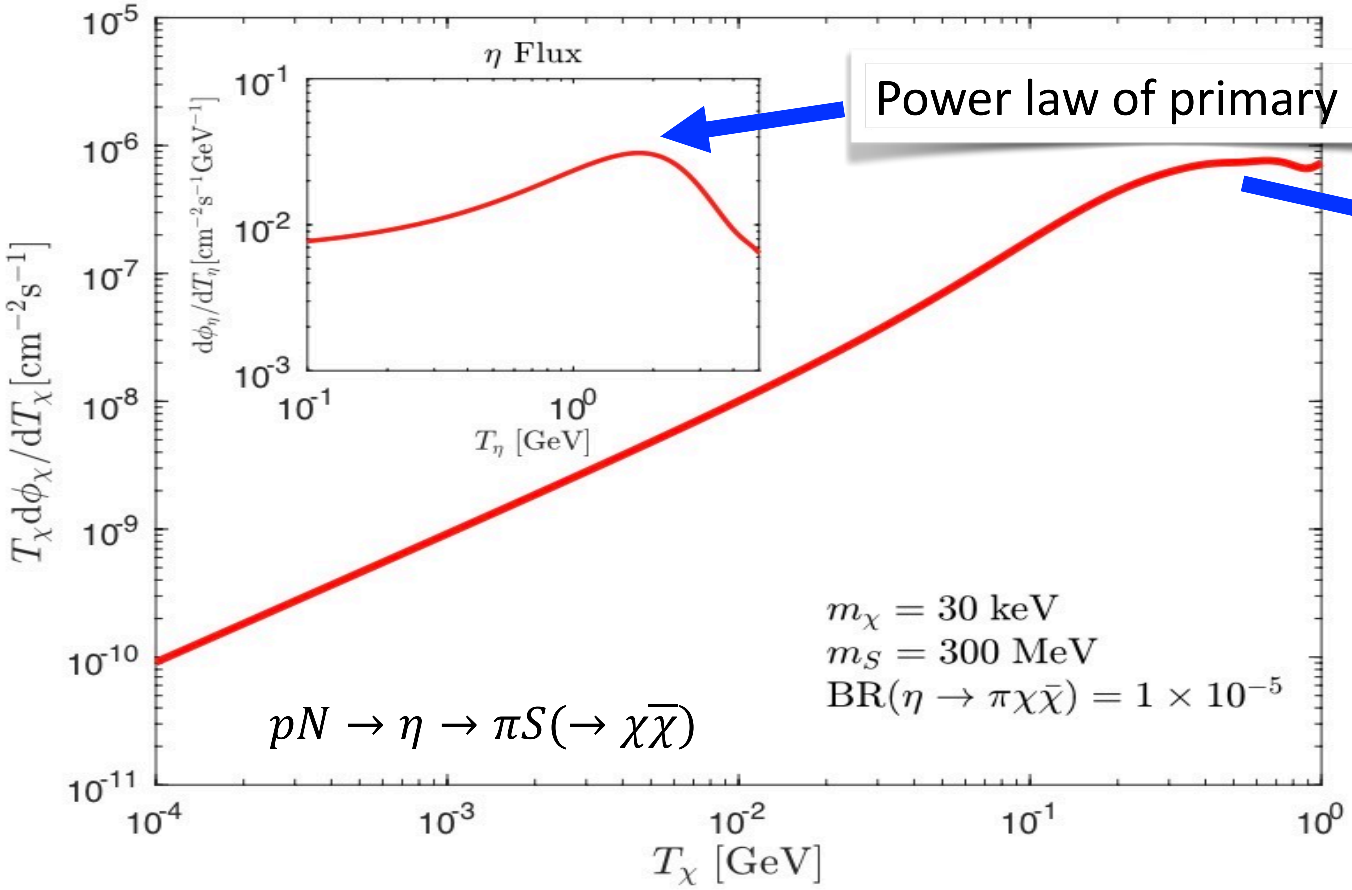
Wang, Su, Wu, Yang, Zhu, 2006.11837

$$\boxed{p+N \to \text{Mesons} \to \text{DM}}$$

$$p+N \to P+N+\text{DM}$$

$$p+N \to \text{DM}$$

2. Cosmic Ray Boosted Dark Matter

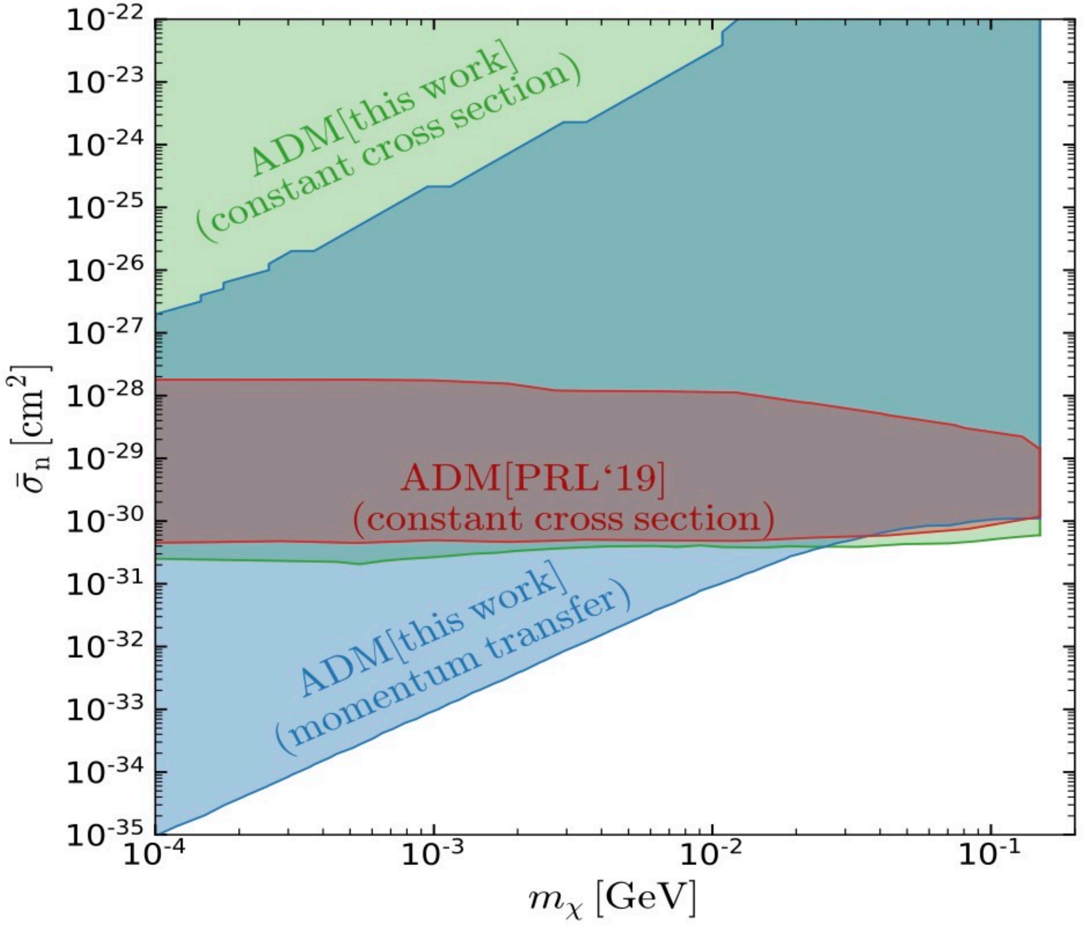


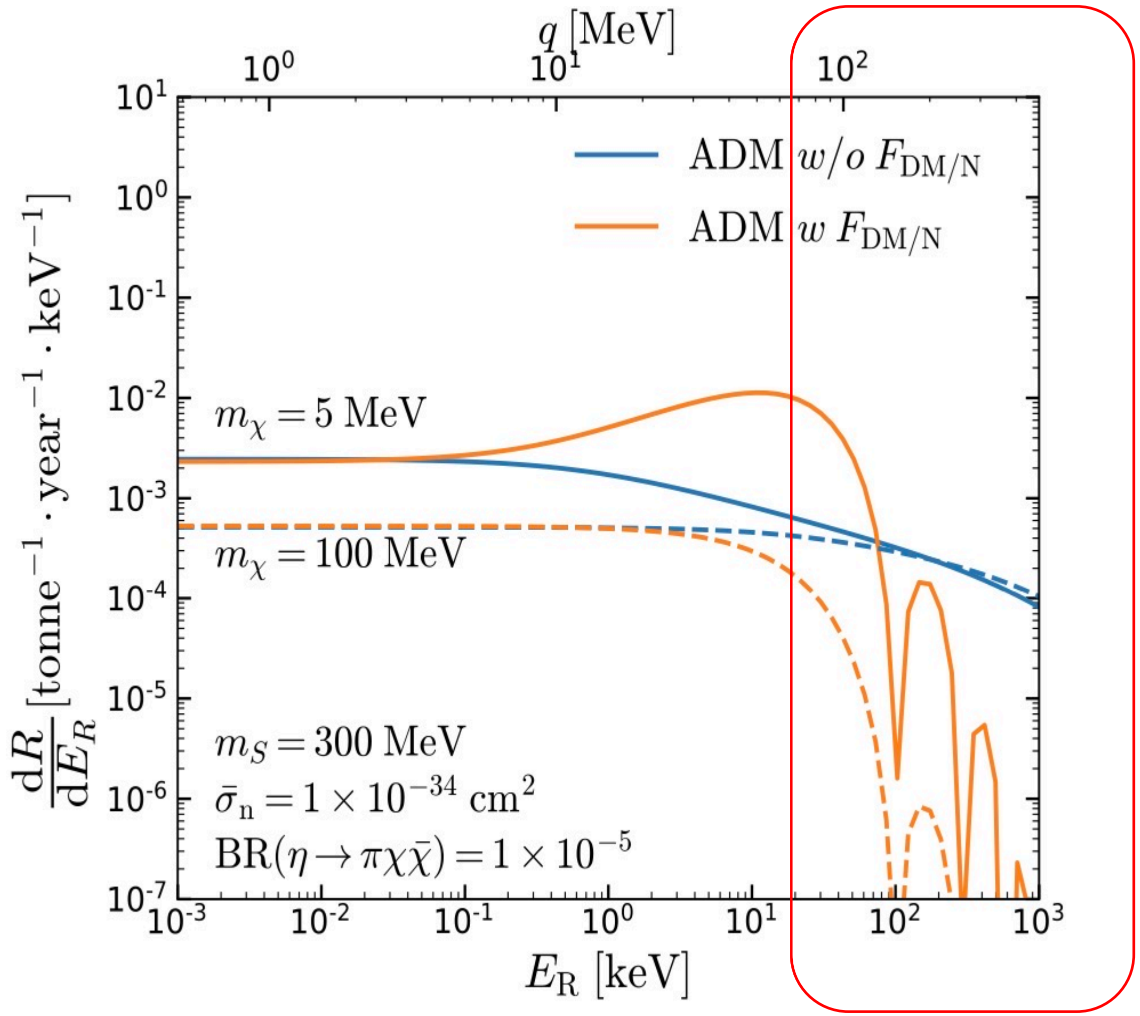
Power law of primary CRs

$$T_\chi = T_\eta \cdot \frac{m_\eta^2 + m_S^2 - m_\pi^2}{4m_\eta^2} \simeq \frac{T_\eta}{4}$$

$$\frac{d\Phi_\chi}{dT_\chi} = \int_{R_E}^{R_E+h} R^2 dR \int_0^{2\pi} d\phi \int_{\cos\theta_{\max}(T_\chi)}^{1} \frac{d(\cos\theta)}{2\pi l(R,\theta,z_d)^2} \times y(R') \int_{T_p^{\min}}^{T_p^{\max}} dT_p \frac{d\Phi_p}{dT_p} n_{\mathrm{air}}(R') \frac{\sigma_{pN}}{\Gamma_{pN}} \frac{d\Gamma_{pN\to M\to\chi\chi}}{dT_p},$$

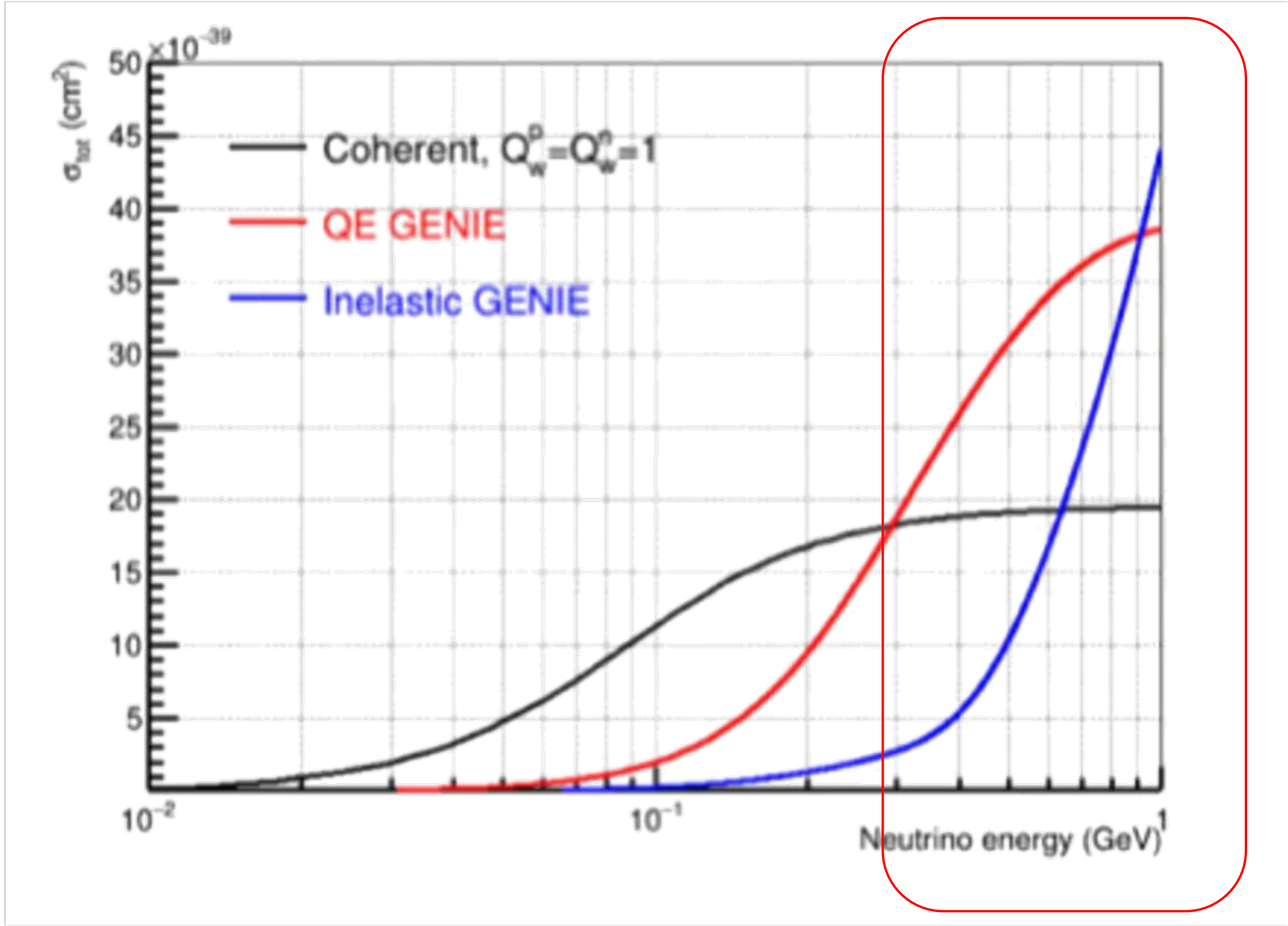
2. Cosmic Ray Boosted Dark Matter





Flambaum, Su, Wu, Zhu, 2012.09751

3. Inelastic Effect in Earth Stopping

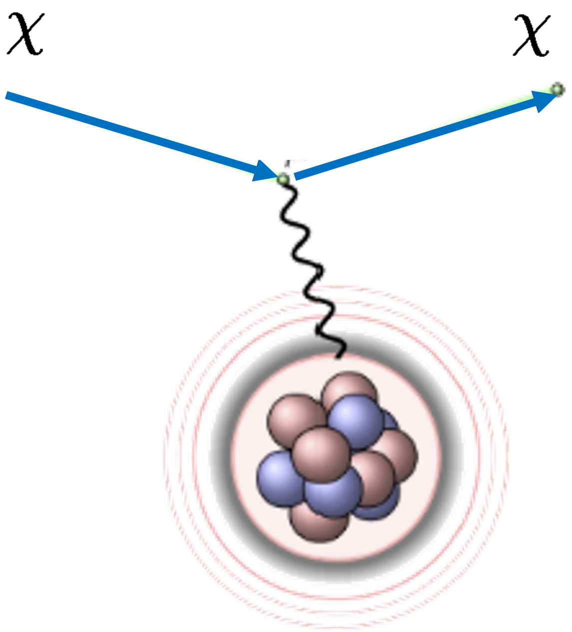


Quasi-elastic scattering

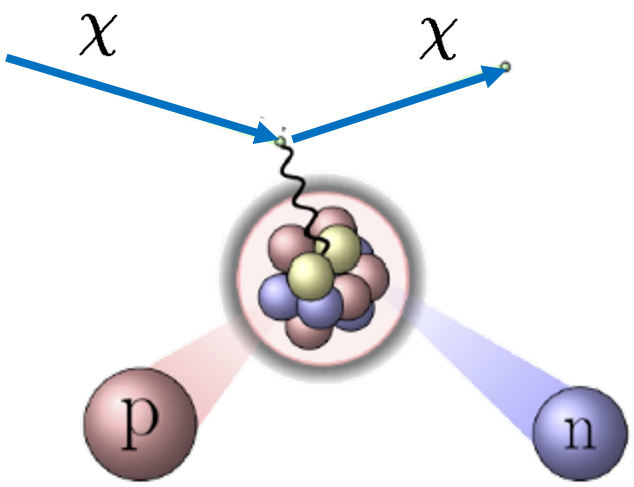
Deep-inelastic scattering

3. Inelastic Effect in Earth Stopping

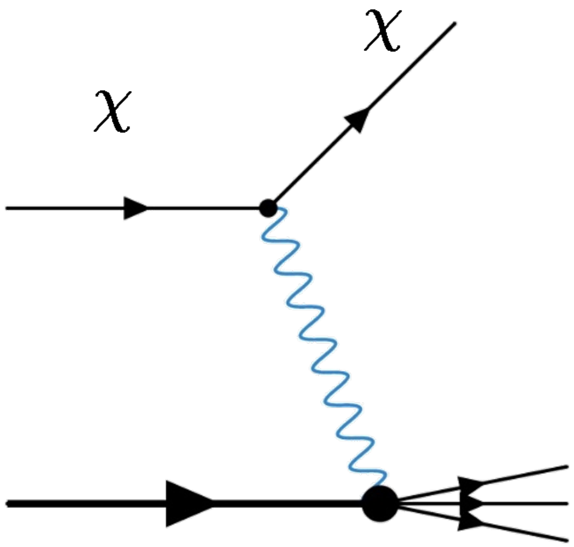
Su, Wu, Zhou, Zhu, 2212.02286



- DM-nucleus ES



- DM-nucleus QES



- DM-nucleus DIS

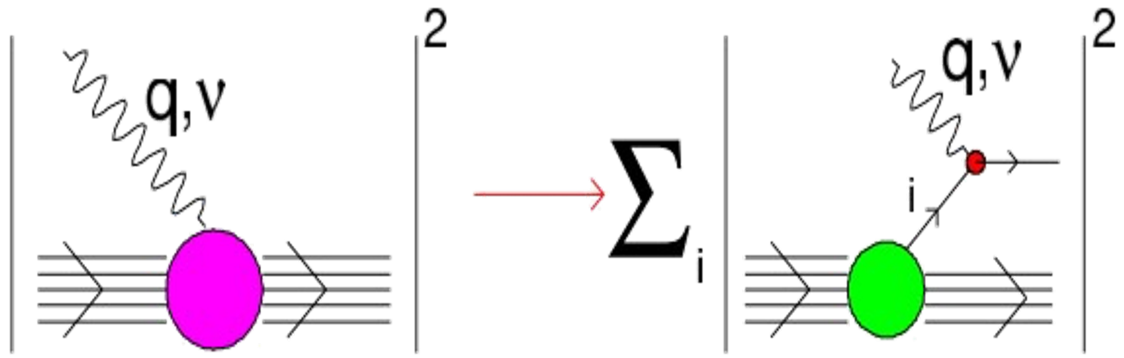
3. Inelastic Effect in Earth Stopping

QE Scattering

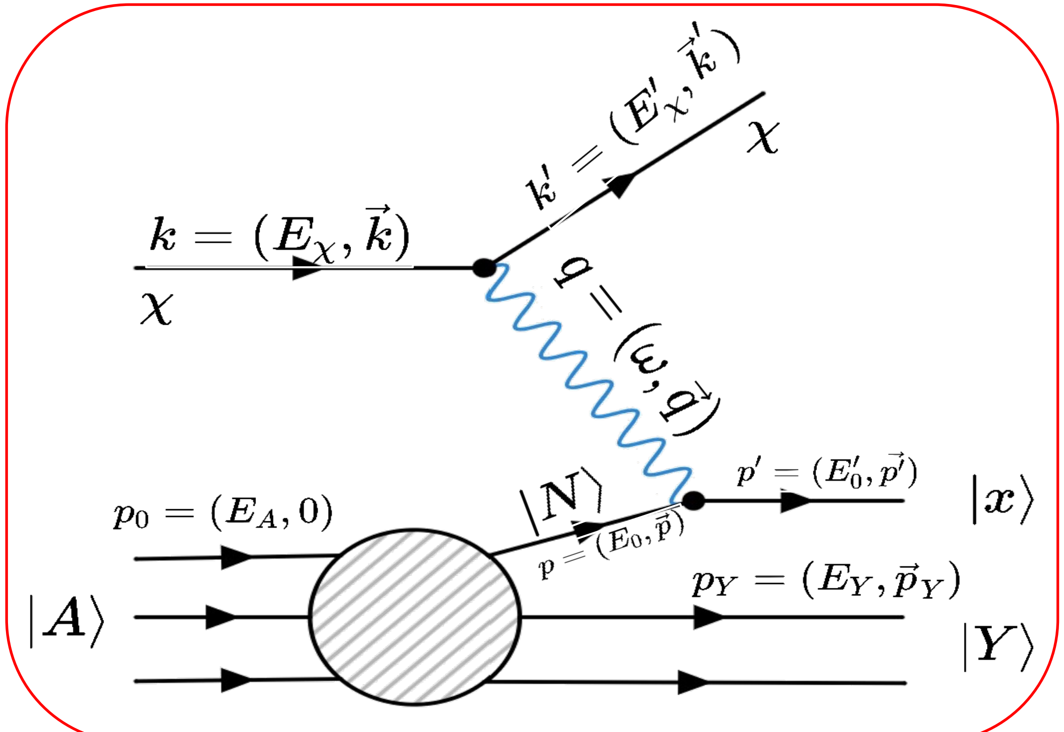
$$\chi(k) + A(p_0) \to \chi(k') + X(\to \boxed{(A-1)} + n/p)$$

residual nucleus

Impulse Approximation



Omar Benhar, et al



The final state can be written as :

$$|X\rangle \to |x, \vec{p'}\rangle \otimes |Y, \vec{p}_Y\rangle.$$

3. Inelastic Effect in Earth Stopping

$$\frac{d\sigma_{\chi A}}{dE'_\chi d\Omega} = \frac{1}{4(2\pi)^2}\frac{\left|\vec{k}'\right|}{|\vec{k}|}\lambda_1^2\lambda_2^2 D_{\mu\nu}(D_{\alpha\beta})^\dagger \mathcal{X}^{\mu\alpha}W^{\nu\beta}$$

Coupling constants   Propagator   DM(hadron) tensor

$$\mathcal{X}^{\mu\nu} = \overline{\sum}\langle\chi|\mathcal{J}_\chi^\mu|\chi'\rangle\langle\chi'|\mathcal{J}_\chi^\nu|\chi\rangle;$$

$$W^{\mu\nu} = \overline{\sum}\langle A|\mathcal{J}_A^\mu|X\rangle\langle X|\mathcal{J}_A^\nu|A\rangle\delta^{(4)}(p_X + k' - p_0 - k)$$

$\mathcal{J}_\chi^\mu(\mathcal{J}_A^\nu)$ is DM (hadron) current operator: Scalar, Vector or etc.

3. Inelastic Effect in Earth Stopping

The tensor describes the interactions of *i*-th nucleon in free space.

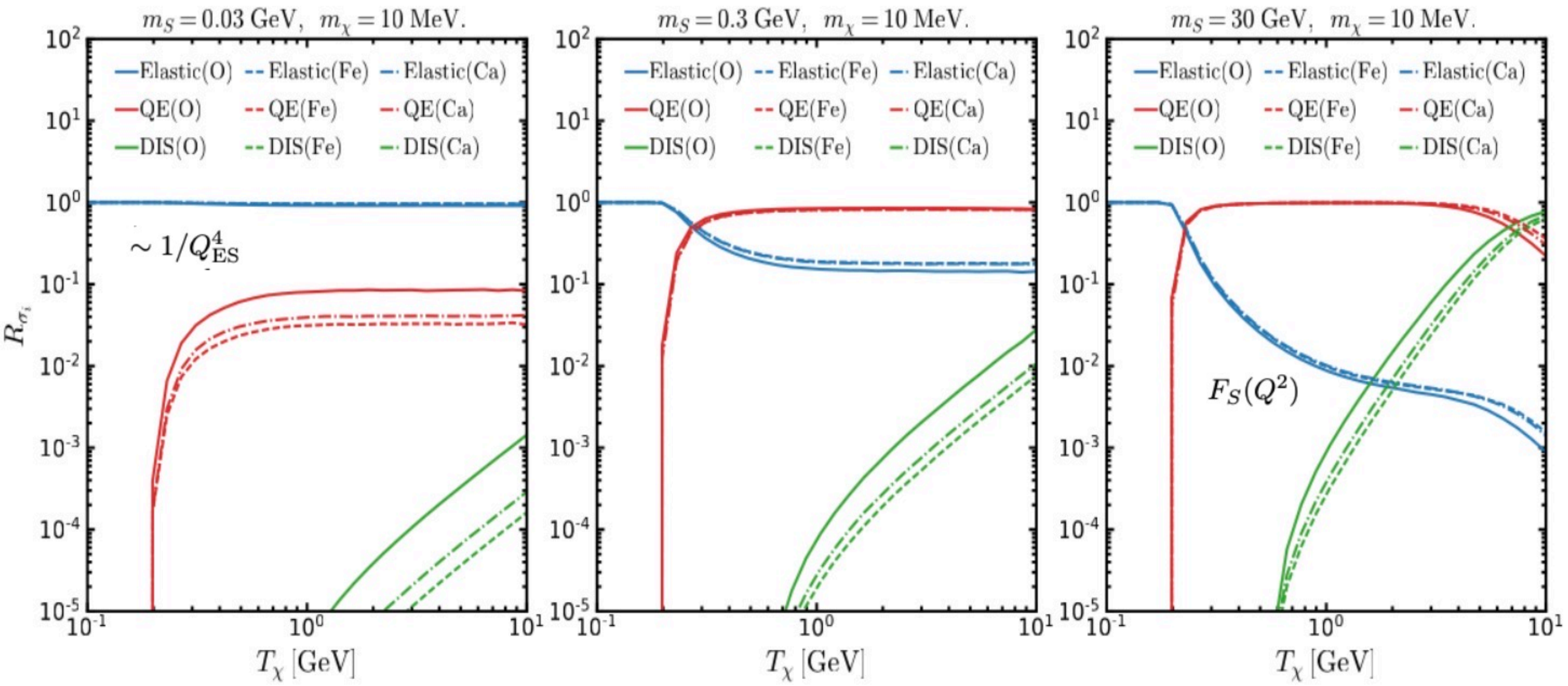
$$W^{\mu\nu} = \sum_i \int \mathrm{d}^3\vec{p}\ \mathrm{d}E \boxed{\tilde{W}_i^{\mu\nu}} \frac{1}{E_{\vec{p}} E_{\vec{p}'}} P(\vec{p}, E) \delta(\omega - E + m_N - E_0'),$$

Spectral Function (probability)

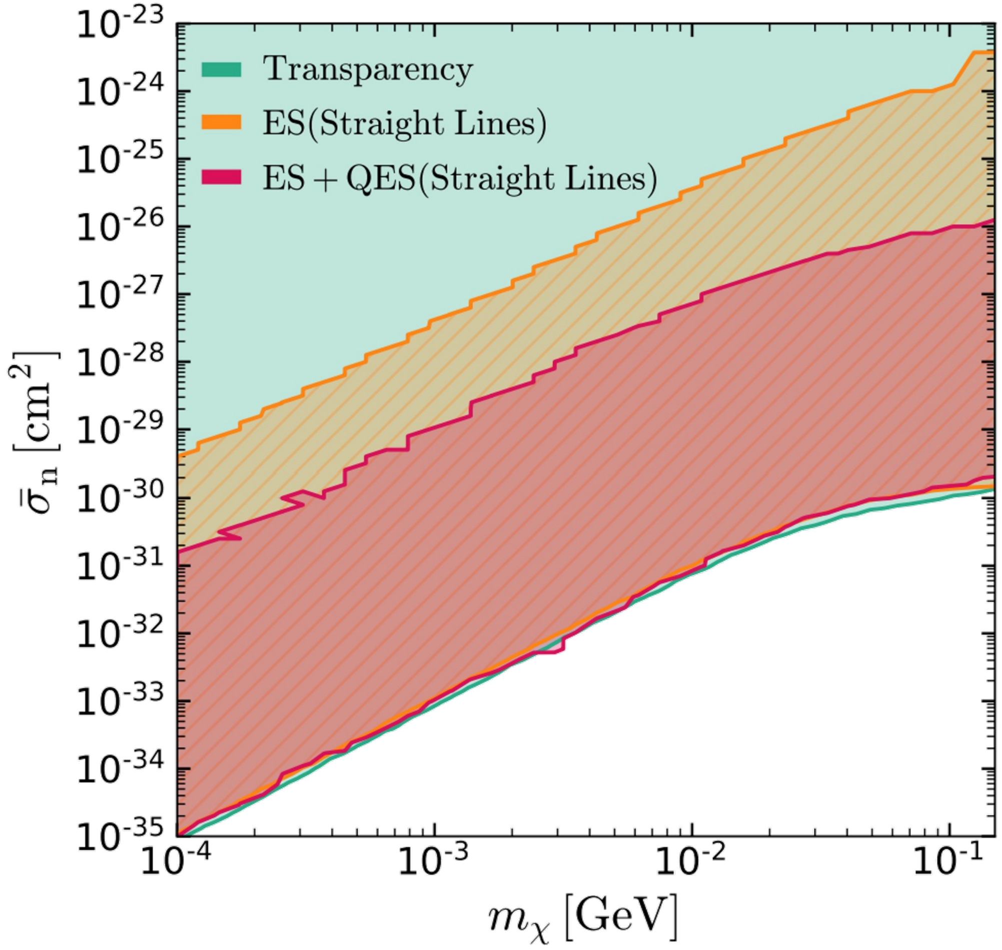
$$P(\vec{p}, E) = \sum_Y |\langle A \mid Y, -\vec{p}\rangle |N, \vec{p}\rangle|^2 \delta(E - m_N + E_0 - E_Y).$$

Nuclear Physics

3. Inelastic Effect in Earth Stopping



3. Inelastic Effect in Earth Stopping



Over-estimated by about 1 order

4. Conclusions

- Light DM physics is rich
- Precision Calculations of DD is essential

Thanks

Backup-1

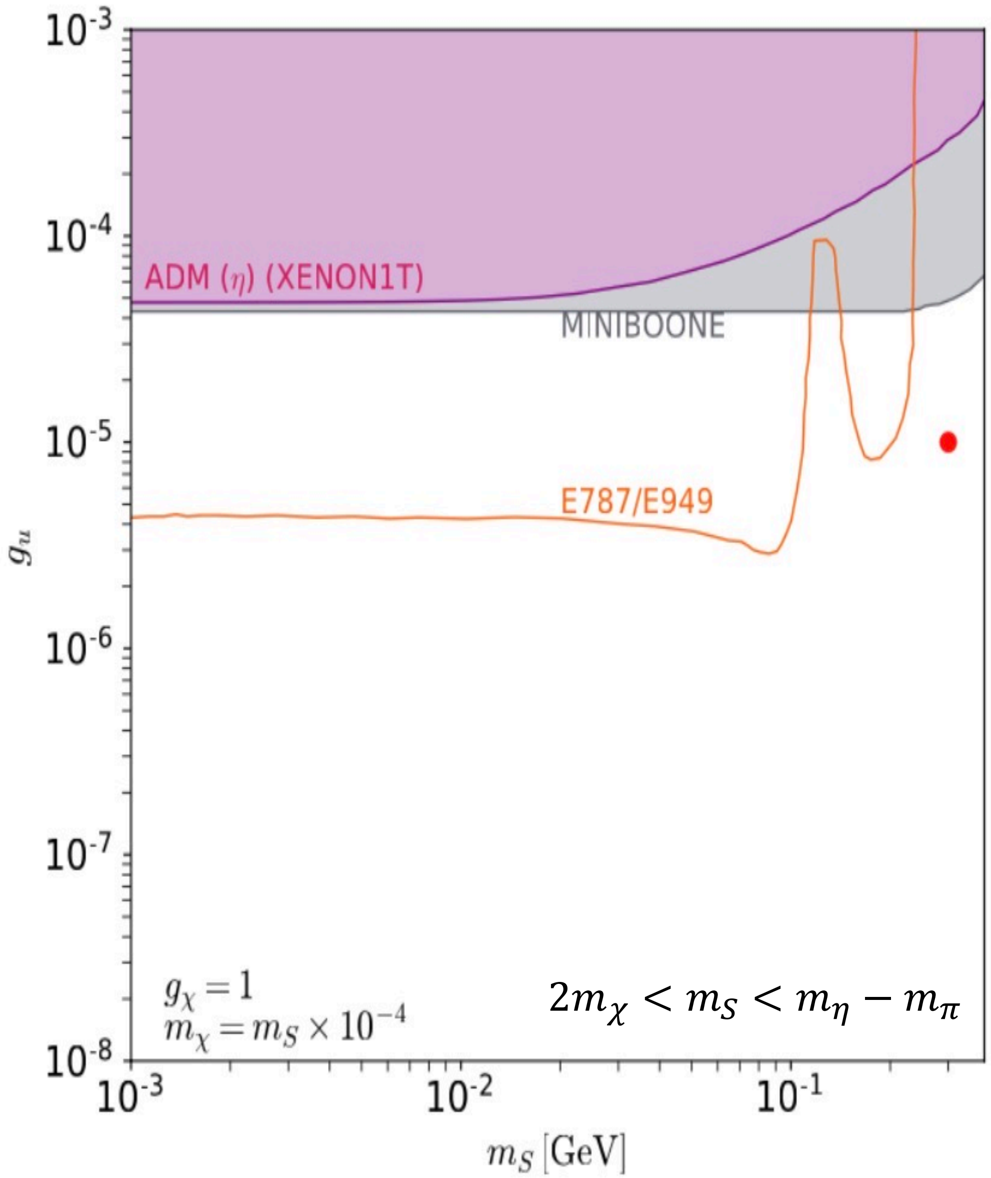
Model, Boosted and Attenuation Effects

Simplified Hadrophilic DM model

$$\mathcal{L} = i\bar{\chi}\left(\not{D} - m_\chi\right)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_s^2 S^2 - \left(g_\chi S \bar{\chi}_L \chi_R + g_q S \bar{q}_L q_R + \text{h.c.}\right)$$

couple to quark

UV model, see e.g. 1507.00009, 1712.01847



Constraints:

Pion decay: $Br(\pi \to \gamma\chi\chi) \lesssim 10^{-7}$

Kaon invisible decay @ E787/E949: $K \to \pi\nu\bar{\nu}$

MiniBooNE (downstream): $pN \to \eta \to \pi^0 S(\to \chi\bar{\chi})$

BBN: $g_u > (2{\times}10^{-8})(\frac{m_S}{\mathrm{GeV}})^{-3/2}$

Xenon1T DM-nucleus scattering

$$\mathrm{Br}\left(\eta \to \pi^0 S\right) = \frac{c_{S\pi^0\eta}^2 g_u^2 B^2}{16\pi m_\eta \Gamma_\eta} \lambda^{1/2}\left(1, \frac{m_S^2}{m_\eta^2}, \frac{m_{\pi^0}^2}{m_\eta^2}\right)$$

$$\sim 10^{-5}$$

With the data from PAMELA, the fitting formula of the Local Interstellar Spectra (LIS) of CRs are parameterized

- Local Interstellar Spectra (LIS) of CRs are parameterized

$$\frac{d\Phi_i}{dR} \times R^{2.7} = \begin{cases} \sum_{j=0}^{5} a_j R^j & R \le 1 \text{ GV}, \\ b + \frac{c}{R} + \frac{d_1}{d_2 + R} + \frac{e_1}{e_2 + R} + \frac{f_1}{f_2 + R} + gR & R > 1 \text{ GV}, \end{cases}$$

- $\frac{T_i}{R} = Ze$
- $\frac{d\Phi_i}{dT_i} = 4\pi \frac{d\Phi_i}{dR} \frac{dR}{dT_i}$

	a_0	a_1	a_2	a_3	a_4	a_5	b	c
p	94.1	-831	0	16700	-10200	0	10800	8500
He	1.14	0	-118	578	0	-87	3120	-5530
	d_1	d_2	e_1	e_2	f_1	f_2	g	
p	-4230000	3190	274000	17.4	-39400	0.464	0	
He	3370	1.29	134000	88.5	-1170000	861	0.03	

$$d\Gamma_{CR\to\chi} = \sum_i \frac{\rho_\chi}{m_\chi} \times \frac{d\sigma^0_{\chi i}}{dT_\chi} G_i^2(2m_\chi T_\chi) \times \frac{d\Phi_i}{dT_i} dT_i dT_\chi dV$$

$$\frac{d\Phi_\chi}{dT_\chi} = \sum_i \int \frac{d\Omega}{4\pi} \int dl \int_{T_i^{min}}^{\infty} \frac{\rho_\chi}{m_\chi} \frac{d\sigma^0_{\chi i}}{dT_\chi} G_i^2(2m_\chi T_\chi) \frac{d\Phi_i}{dT_i} dT_i = D_{\mathrm{eff}} \frac{\rho_{\chi 0}}{m_\chi} \sum_i \sigma_{\chi i} \int_{T_i^{\mathrm{min}}}^{\infty} \frac{1}{T_\chi^{\mathrm{max}}(T_i)} \frac{d\Phi_i}{dT_i} dT_i$$

Boosted effect: elastic case

Kinetic energy of CRDM

$$\frac{dT_\chi}{dz} = -\sum_N n_N \int_0^{T_N^{\max}} \boxed{\frac{d\sigma_{\chi N}}{dT_N}} T_N \, dT_N .$$

$\boxed{\sigma_N / T^{\max}_{\mathrm{N}}}$

Average density of Earth's elements

Nucleus recoil

$$\frac{d\Phi_\chi}{dT_\chi^z} = \boxed{\left(\frac{dT_\chi}{dT_\chi^z}\right)} \frac{d\Phi_\chi}{dT_\chi}$$

$$\boxed{R = \int_{T_1}^{T_2} dE_T \frac{1}{m_{\mathrm{T}}} \int_{T_\chi^{z,\min}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T} .}$$

Compare with data

Boosted effect: inelastic case

Step-1. Differential Cosmic Ray Flux

$$\frac{\mathrm{d}\phi_p\left(T_p, h\right)}{\mathrm{d}T_p} = y_p(h)\frac{\mathrm{d}\phi_p\left(T_p, h_{\max}\right)}{\mathrm{d}T_p}$$

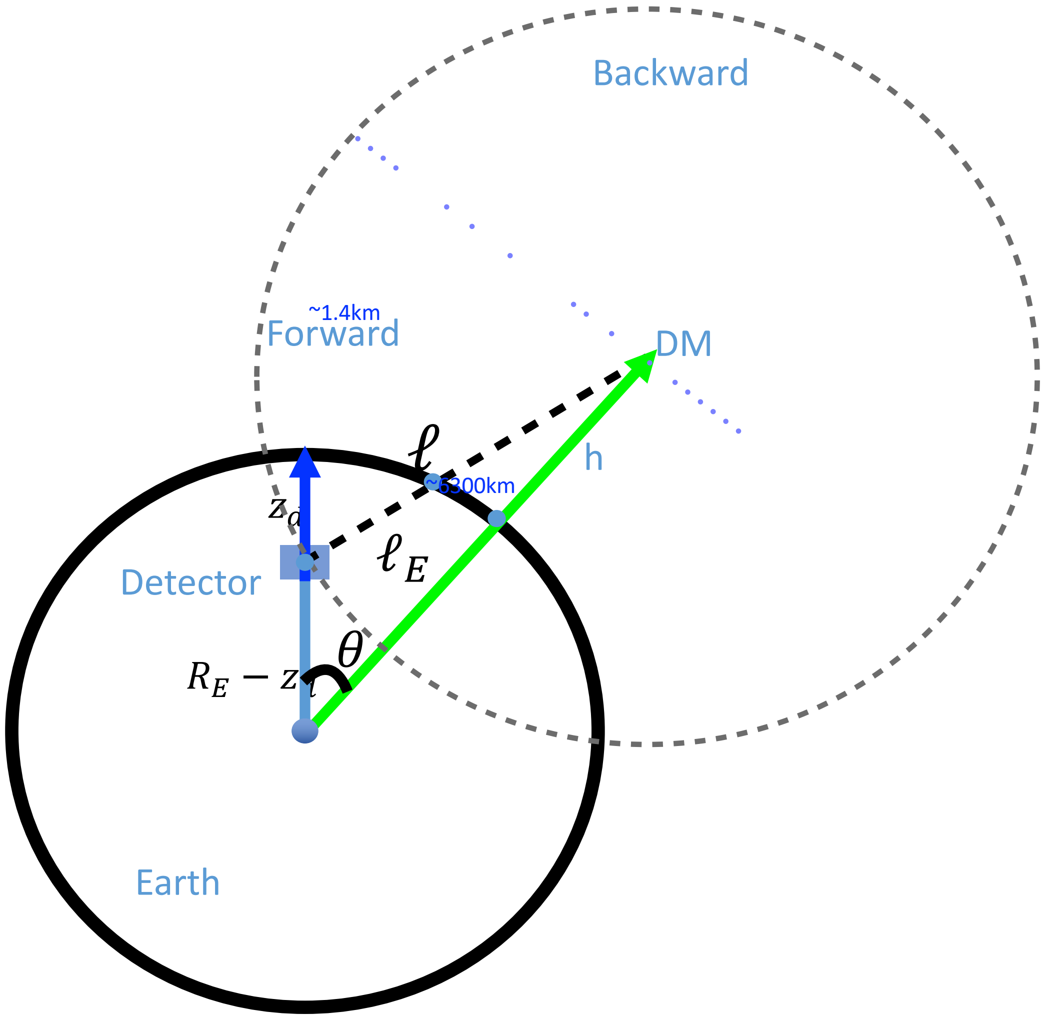
Dilution factor: $$y_p(h) = \exp\left(-\sigma_{pN}\int_h^{h\,\max} \mathrm{d}\tilde{h} n_N(\tilde{h})\right)$$

$h_{max} = 180\mathrm{km}$

$\sigma_{pN} \simeq 255$ mb

CRMC: simulate the collision of incoming CRs with the nitrogen

Boosted effect: inelastic case



Step-2. attenuation of ADM flux

$$\frac{d\Phi_\chi}{dT_\chi} = \int_{R_E}^{R_E+h} R^2 dR \int_0^{2\pi} d\phi \int_{\cos\theta_{\max}(T_\chi)}^{1} \frac{d(cos\theta)}{2\pi l(R,\theta,z_d)^2} \times y_p(R') \int_{T_p^{\min}}^{T_p^{\max}} dT_p \frac{d\Phi_p}{dT_p} n_{\rm air}(R') \frac{\sigma_{pN}}{\Gamma_{pN}} \frac{d\Gamma_{pN\to M\to\chi\chi}}{dT_p} ,$$

Backup-2

Quasi-elastic and Deep inelastic Scattering

DM-nucleus Quasi-elastic (QE) Scattering

- The calculation of hadron tensor
  - At moderate momentum transfers: $|\mathbf{q}| \lesssim 0.5\ \mathrm{GeV}$

    Nuclear Many-Body Theory (NMBT): using nonrelativistic wave function to describe the initial and final states and expanding in the current operator in powers of $|\mathbf{q}|/m_N$, m_N is the nucleon mass.

  - At higher momentum transfers

    The description of the final states $|X\rangle$ in the terms of nonrelativistic nucleons is no longer possible. In this regime, the calculation require a set of simplifying assumptions, allowing one to take into account the relativistic motion of final state particles , and inelastic processes leading to the appearance of hadrons other than protons and neutrons. An effective calculation way is the impulse approximation.

DM-nucleus Quasi-elastic Scattering

- Spectral function:

$$P(\vec{p},E)=\sum_{Y}\left|\langle A\mid Y,-\vec{p}\rangle|N,\vec{p}\rangle\right|^{2}\delta(E-m_N+E_0-E_Y).$$

The probability of removing a nucleon of momentum (p) from ground state of the nucleus (A) leaving the residual nucleus (X) with excitation energy (E), can be obtain from *ab initio* many-body calculations. For example,

$$P(p,E)_{^{16}O\to n+^{15}O^{\star}}\ \text{or}\ P(p,E)_{^{16}O\to p+^{15}N^{\star}}$$

DM-nucleus Quasi-elastic Scattering

Therefore, the differential cross section is given by

$$\frac{\mathrm{d}\sigma_A}{\mathrm{d}E'_\chi \mathrm{d}\Omega} = Z\frac{\mathrm{d}\sigma_p}{\mathrm{d}E'_\chi \mathrm{d}\Omega} + (A-Z)\frac{\mathrm{d}\sigma_n}{\mathrm{d}E'_\chi \mathrm{d}\Omega}$$

- Vector:

$$\frac{\mathrm{d}\sigma_N}{\mathrm{d}E'_\chi \mathrm{d}\Omega} = \frac{g_N^2 g_\chi^2}{16\pi^2 (q^2 - m_V^2)^2} \frac{\left|\vec{k}'\right|}{|\vec{k}||\vec{q}|} \int \mathrm{d}|\vec{p}|\mathrm{d}\phi_p\, \mathrm{d}E \frac{|\vec{p}|}{E_{\vec{p}}} P(\vec{p},E)\theta(|\vec{p}+\vec{q}|-p_F)\boxed{L_{\mu\nu}\tilde{W}_N^{\mu\nu}}.$$

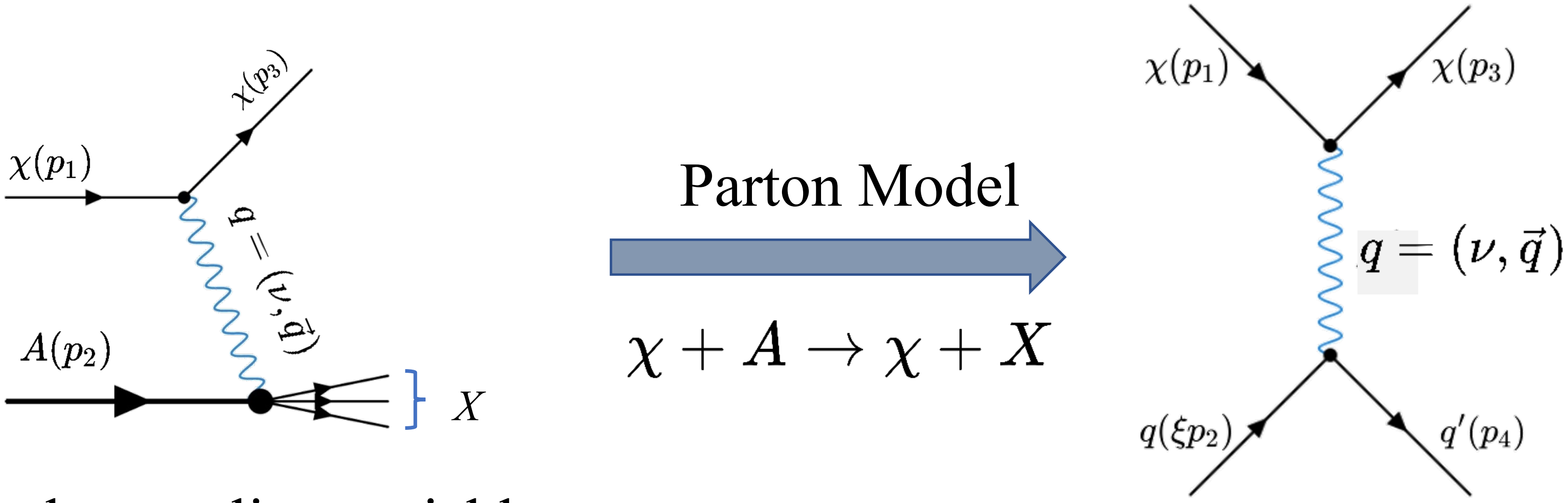
Pauli blocking

Model depended

- Scalar:

$$\frac{\mathrm{d}\sigma_N}{\mathrm{d}E'_\chi \mathrm{d}\Omega} = \frac{g_\chi^2 g_N^2}{16\pi^2 (q^2 - m_S^2)^2} \frac{\left|\vec{k}'\right|}{|\vec{k}||\vec{q}|} \int \mathrm{d}|\vec{p}|\mathrm{d}\phi_p\, \mathrm{d}E \frac{|\vec{p}|}{E_{\vec{p}}} P(\vec{p},E)\theta(|\vec{p}+\vec{q}|-p_F)\boxed{L_S\tilde{W}_N^S}$$

DM-nucleus Deep Inelastic Scattering(DIS)



- Bjorken scaling variable

$$x = \frac{Q^2}{2m_A \nu}$$

$$Q^2 = -q^2 = -2m_l^2 + 2p_1 \cdot p_3 = 2E(E-\nu) - 2kk' \cos\theta - 2m_\chi^2;$$

DM-nucleus Deep Inelastic Scattering

- Differential Cross Section

$$\mathrm{d}\sigma = \int_0^1 f(\xi)\mathrm{d}\xi \frac{|\mathcal{M}|^2 (2\pi)^4 \delta^4(\xi p_2 + q - p_4)}{4\sqrt{(p_1 \cdot \xi p_2)^2 - (\xi m_A m_\chi)^2}} \frac{\mathrm{d}^3 \vec{k}'}{(2\pi)^3 2E'} \frac{\mathrm{d}^3 \vec{p}_4}{(2\pi)^3 2E_4}$$

$$= \frac{\mathrm{d}\nu \mathrm{d}Q^2}{64\pi m_A^2 \nu (E^2 - m_\chi^2)} \int_0^1 \frac{\boxed{f(\xi)}}{\xi} \mathrm{d}\xi \boxed{\overline{|\mathcal{M}(\xi)|^2}} \delta(\xi - x)$$

Parton Distribution Function (PDF)

Spin-average Amplitude

Results

- A typical Accelerating DM: ADM with scalar mediator $T_\chi \gtrsim 0.25$ GeV
- A simple attenuation model: the DM scatters at most once.

The survival probability :

$$p_{\rm surv}(T_\chi) = \exp\left(-\sum_i^{\rm species} \frac{d_{{\rm eff},i}(\cos\theta)}{\bar{\lambda}_i(T_\chi)}\right)$$

Average mean free path : $\bar{\lambda}_i(T_\chi) = [\sigma_i(T_\chi)\bar{n}_i]^{-1}$

Element	A	m_A [GeV]	$\bar{n}$ [cm^{-3}]	Core	Mantle
Oxygen	16	14.9	3.45×10^{22}	0.0	0.440
Silicon	28	26.1	1.77×10^{22}	0.06	0.210
Magnesium	24	22.3	1.17×10^{22}	0.0	0.228
Iron	56	52.1	6.11×10^{22}	0.855	0.0626
Calcium	40	37.2	7.94×10^{20}	0.0	0.0253
Sodium	23	21.4	1.47×10^{20}	0.0	0.0027
Sulphur	32	29.8	2.33×10^{21}	0.019	0.00025
Aluminium	27	25.1	1.09×10^{21}	0.0	0.0235

ArXiv: 1611.05453

Effective distance : $$d_{{\rm eff},i}(\cos\theta) \approx \begin{cases} 2\int_{R_E\sin\theta}^{R_E} \frac{n_i(r)}{\bar{n}_i} \frac{r{\rm d}r}{\sqrt{r^2 - R_E^2\sin^2\theta}} & \theta\in[0,\pi/2] \\ \int_{R_E-l_D}^{R_E} \frac{n_i(r)}{\bar{n}_i}{\rm d}r & \theta\in[\pi/2,\pi] \end{cases}$$

Earth-stopping model

M1: “Signal Scatter”

$$\frac{\mathrm{d}\Phi_\chi^z}{\mathrm{d}T_\chi^z} = \int \boxed{\mathcal{P}_{\rm surv}(T_\chi, \cos\theta)} \frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi \mathrm{d}\Omega} \mathrm{d}\Omega$$

The survival probability :

$$\mathcal{P}_{\rm surv} = \exp\left(-\sum_i^{\rm species} \frac{d_{\mathrm{eff},i}(\cos\theta)}{\boxed{\bar{\lambda}_i(T_\chi)}}\right)$$

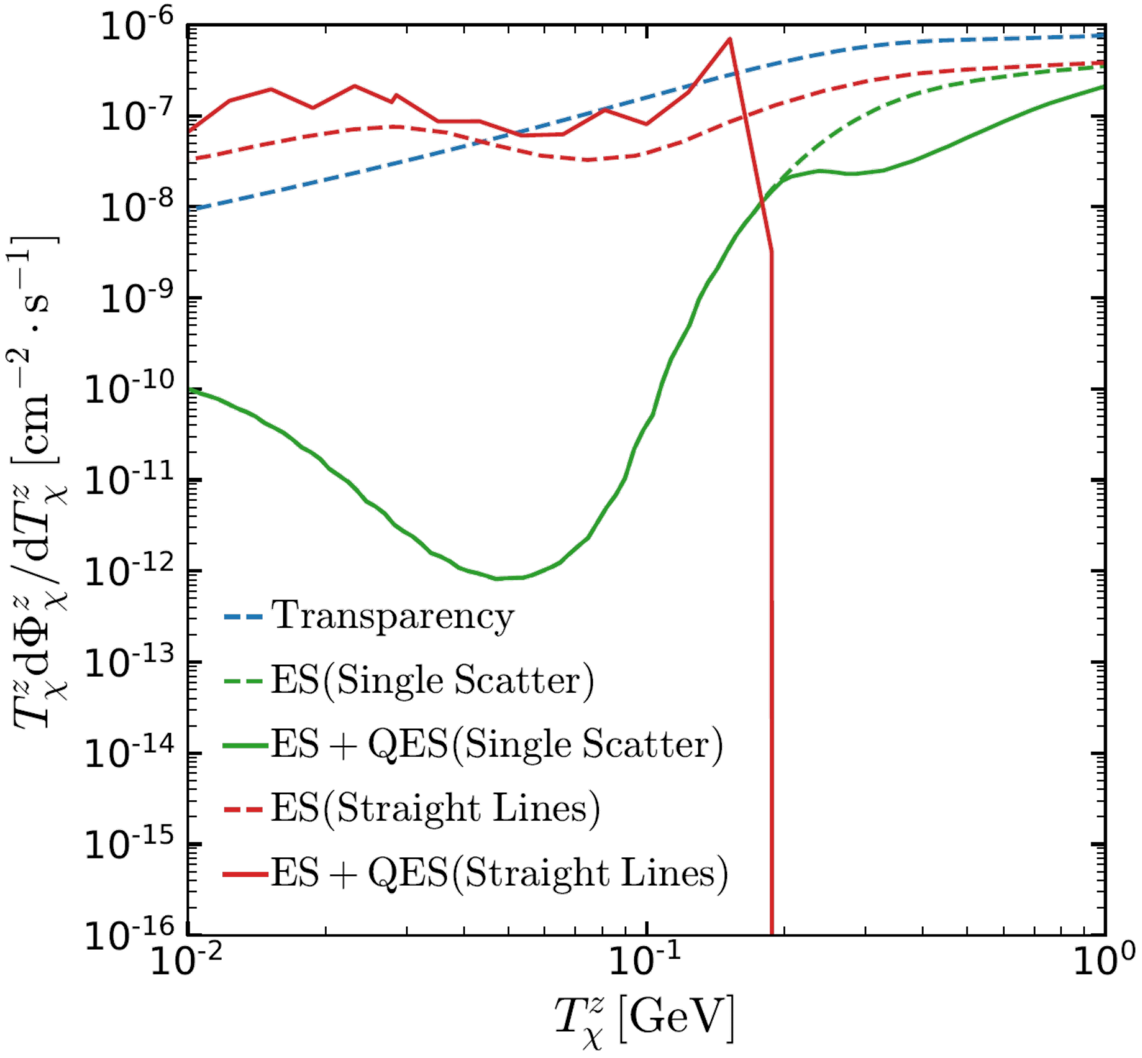
Average mean free path : $\bar{\lambda}_i(T_\chi) = [\sigma_i(T_\chi)\bar{n}_i]^{-1}$

M2: “Straight Lines”

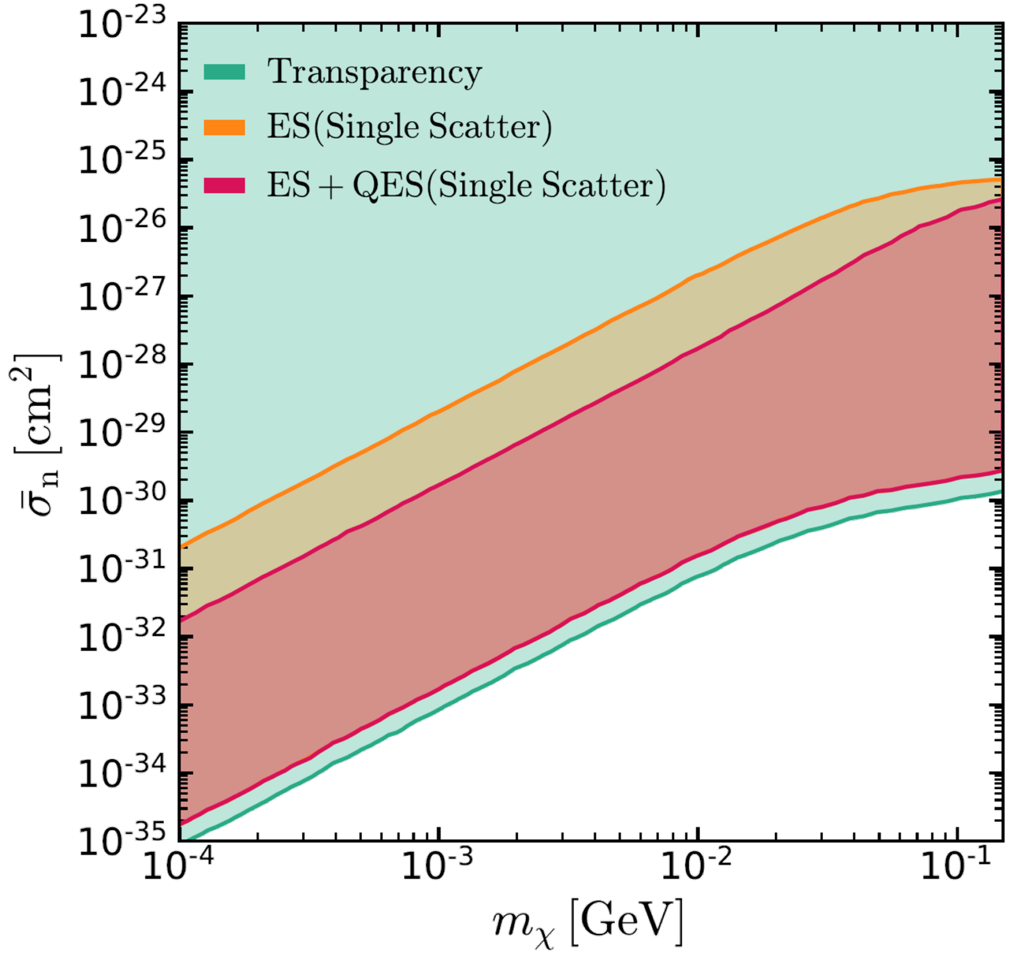
$$\frac{\mathrm{d}\Phi_\chi^z}{\mathrm{d}T_\chi^z} = \int \boxed{\frac{\mathrm{d}T_\chi}{\mathrm{d}T_\chi^z}} \frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi \mathrm{d}\Omega} \mathrm{d}\Omega$$

By solving the energy loss function:

$$\frac{\mathrm{d}T_\chi^z}{\mathrm{d}z} = -\sum_i n_i(r) \int_0^{\omega_\chi^{\max}} \mathrm{d}\omega_\chi \frac{\mathrm{d}\sigma_{i\chi}}{\mathrm{d}\omega_\chi}\omega_\chi .$$



$T_\chi^z \mathrm{d}\Phi_\chi^z/\mathrm{d}T_\chi^z\ [\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}]$
T_χ^z [GeV]
Transparency
ES(Single Scatter)
ES + QES(Single Scatter)
ES(Straight Lines)
ES + QES(Straight Lines)



$\bar{\sigma}_\mathrm{n}\ [\mathrm{cm}^2]$
m_χ [GeV]
Transparency
ES(Single Scatter)
ES + QES(Single Scatter)