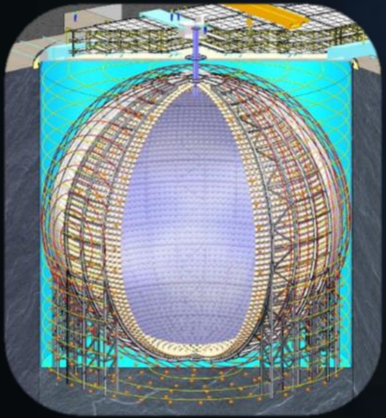
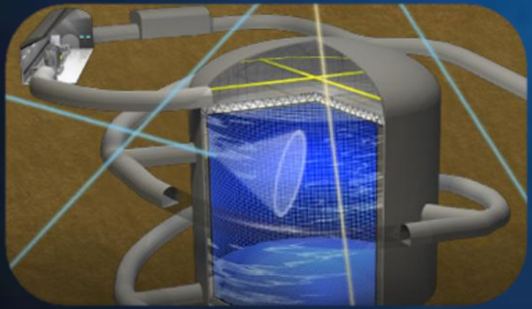
Exciting Prospects @ Neutrino Detectors

B. Dutta, W.C. Huang, D. Kim, J. Newstead, **JCP**, I. Shaukat Ali
[2401.09529]

Jong-Chul Park
CNU 충남대학교
CHUNGNAM NATIONAL UNIVERSITY





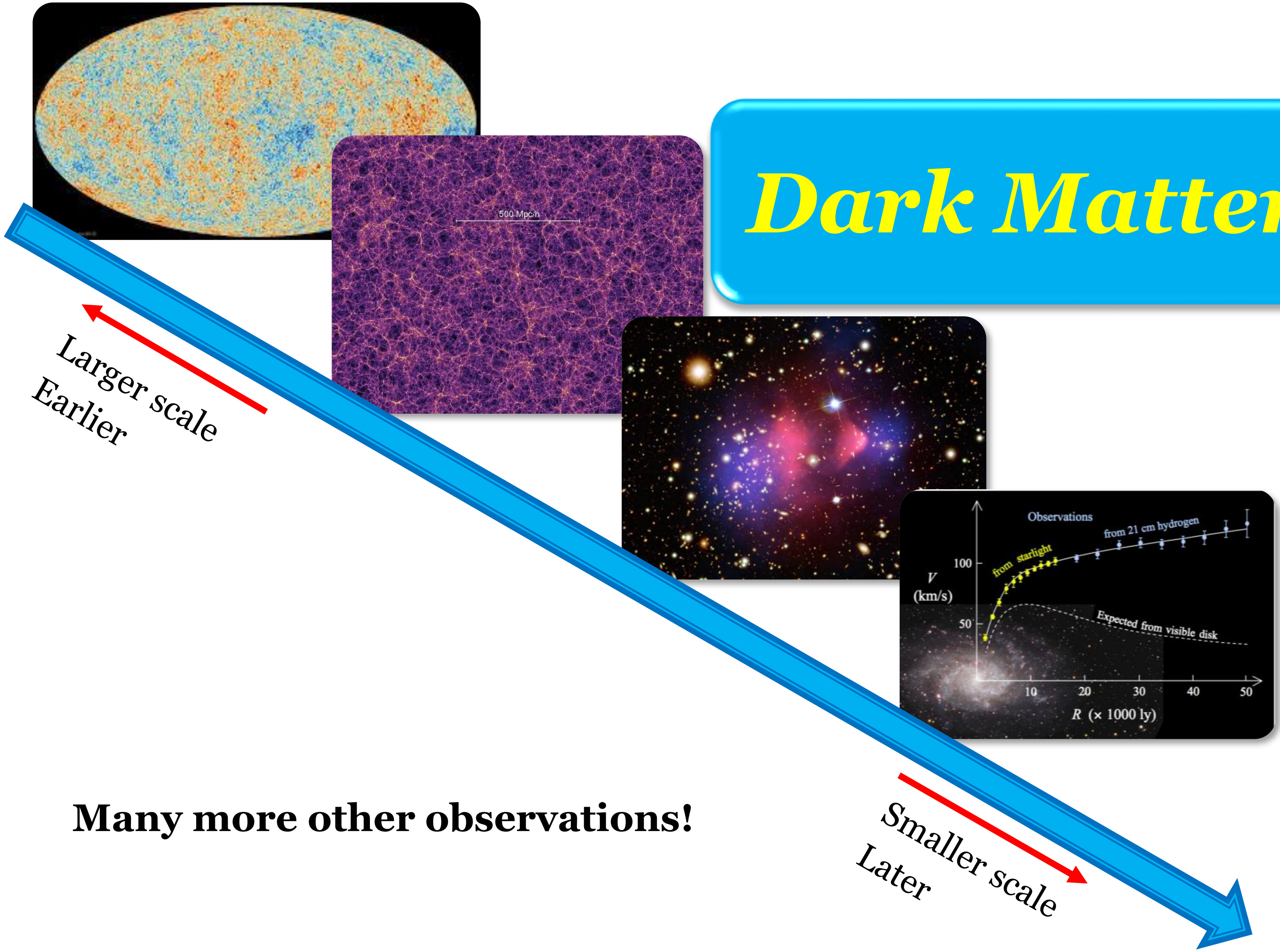
The XVIth Quark Confinement & Hadron Spectrum Conference
August 20 (2024)

Outline

- ❖ Dark Matter: WIMP?
- ❖ Nuclear Scattering
- ❖ Boosted Dark Matter (BDM)
- ❖ Exciting Prospects for Dark Matter
- ❖ Summary

Dark Matter: WIMP?

Message from Cosmology: Dark Matter (DM)



Larger scale
Earlier

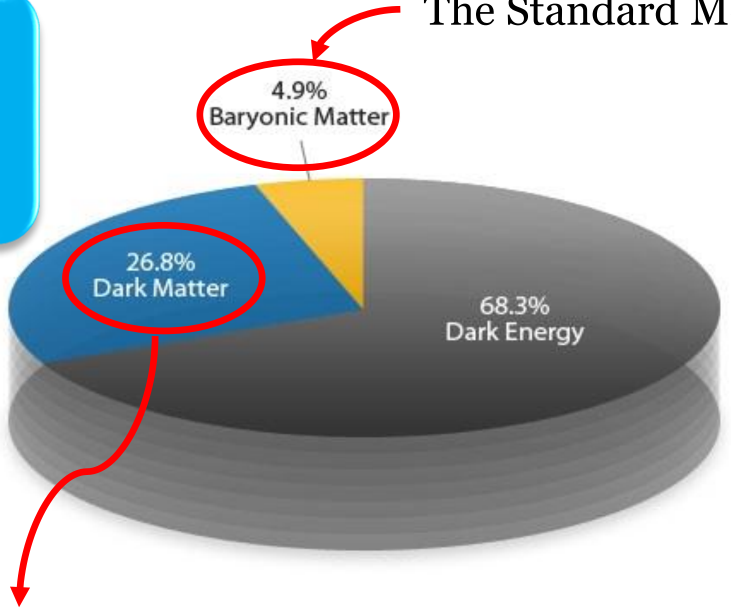
Smaller scale
Later

Many more other observations!

Dark Matter?

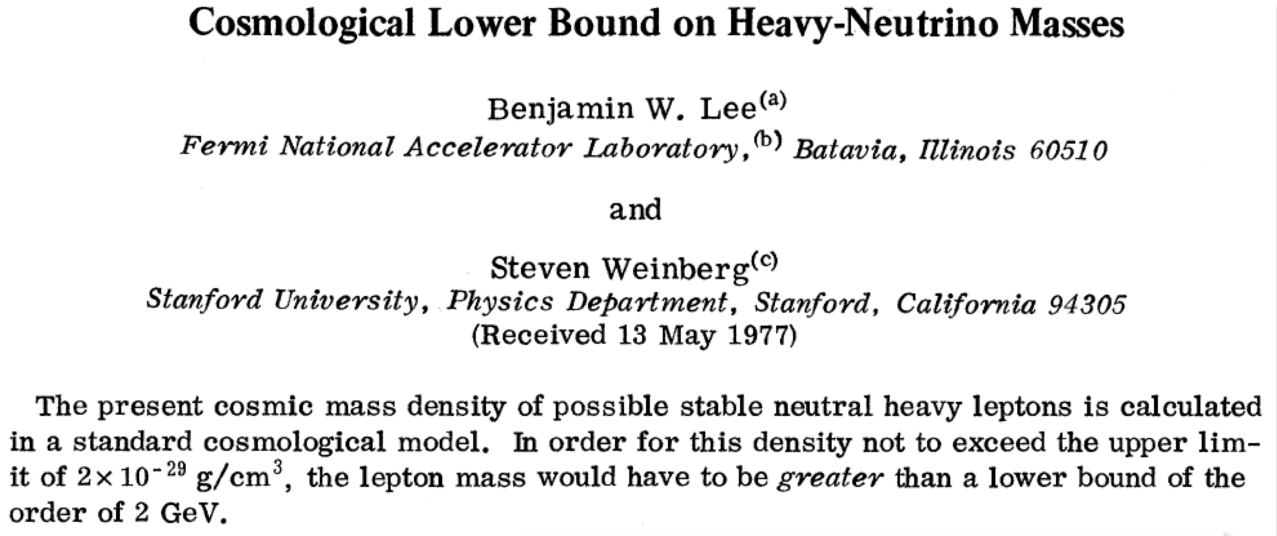
- **Modern cosmology**:

The Standard Model



- **Compelling paradigm**:
  - ✓ Massive,
  - ✓ Non-relativistic ($v \ll c$),
  - ✓ Non-luminous (no/tiny EM interaction),
  - ✓ Stable particles

Classic Solution*: WIMP



Cosmological Lower Bound on Heavy-Neutrino Masses

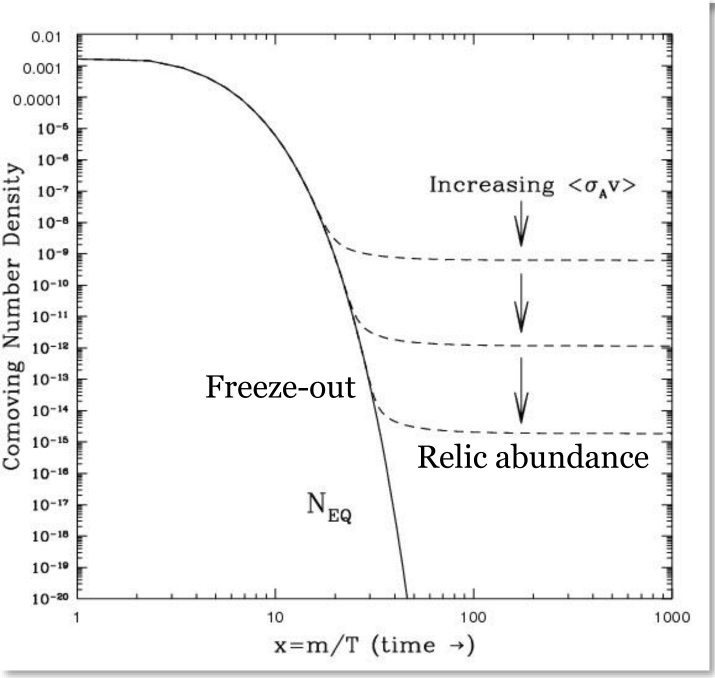
Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

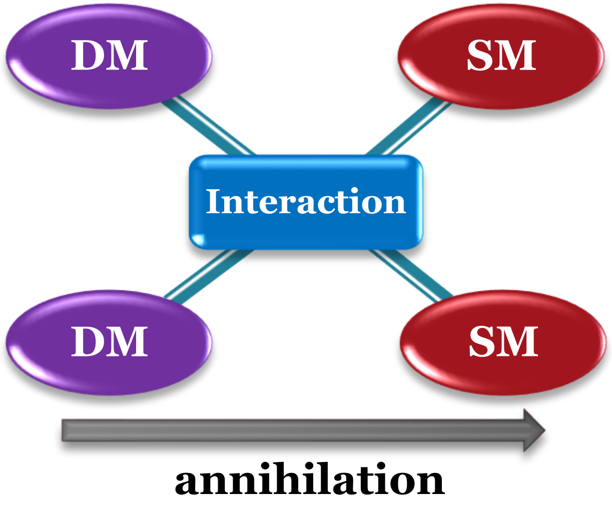
and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

PRL (1977)





- Correct thermal relic abundance:

$$\Omega h^2 \sim \frac{0.1\,pb}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\alpha_\chi^2 m_\chi^2}{M^4} \ (M\text{: dark scale/mediator})$$

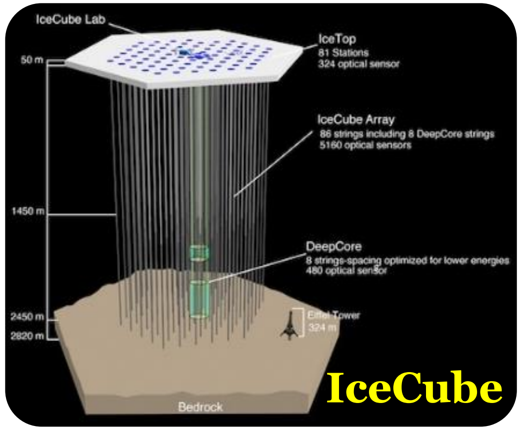
- Weak coupling ➔ naturally weak scale mass:

~ 1 GeV – 100 TeV mass range favored

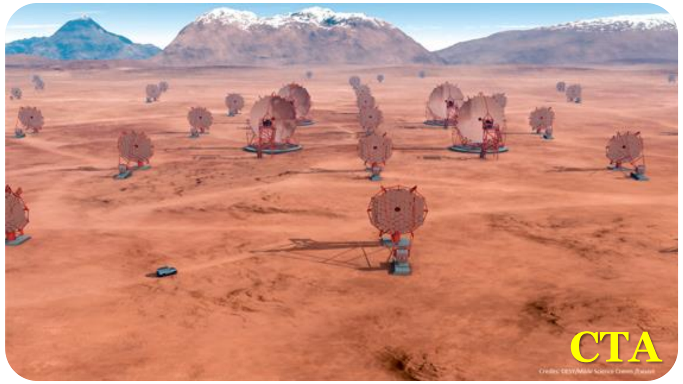
➔ weak scale (new) physics

* Of course also **axion**

Diverging Efforts for WIMP Searches



IceCube

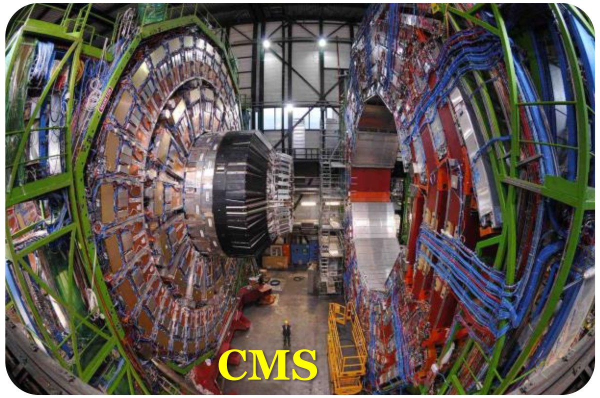


CTA

SNO

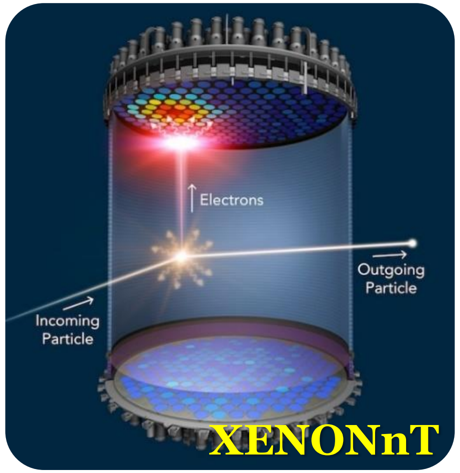
Fermi-LAT

HESS



CMS

COSINE-100



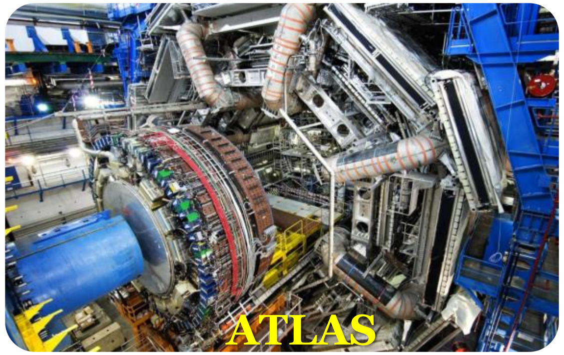
XENONnT

AMS-02

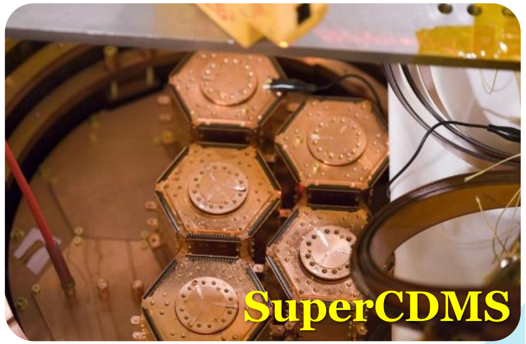
AMS-02 on the ISS

Planck

DEAP-3600

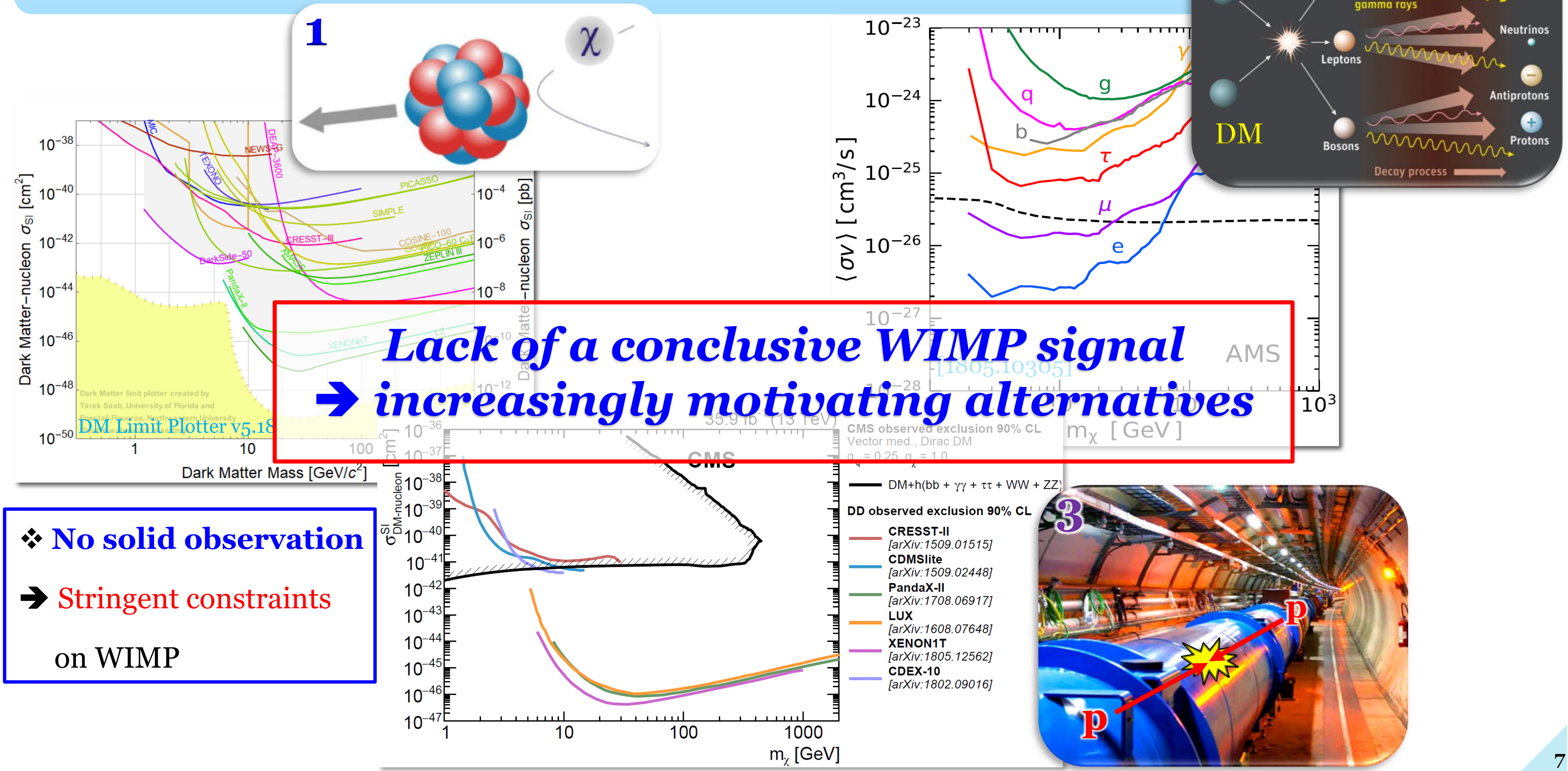


ATLAS



SuperCDMS

Current Search Status of DM (WIMP)



Lack of a conclusive WIMP signal
➔ increasingly motivating alternatives

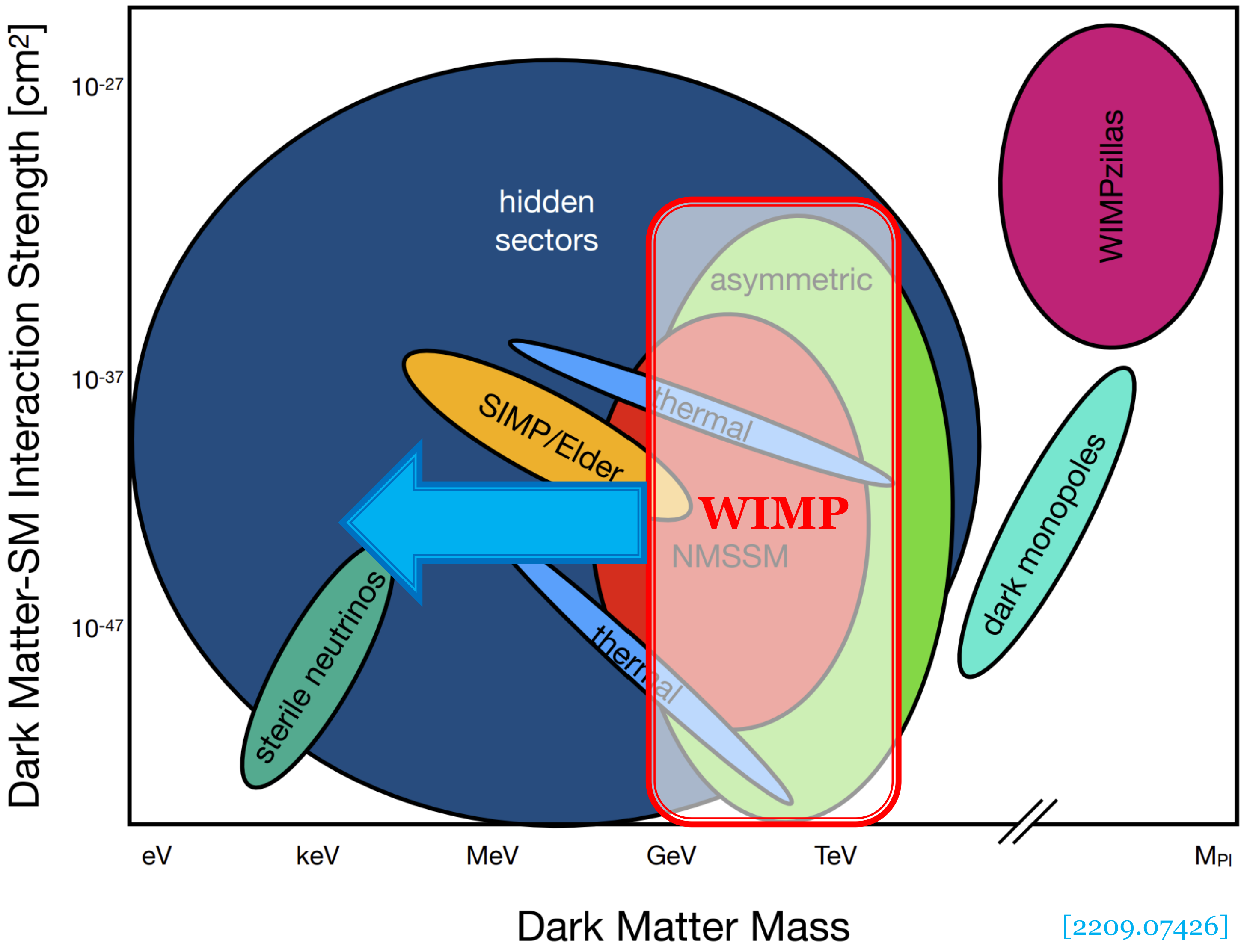
- ❖ **No solid observation**

➔ Stringent constraints

on WIMP

Particle DM: Larger Space beyond WIMP

Report of the Topical Group on Particle Dark Matter for Snowmass 2021



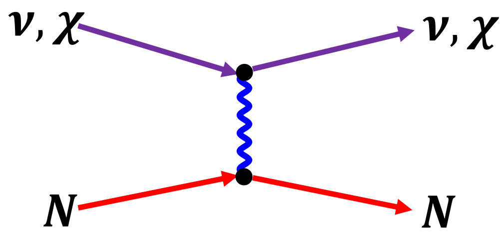
[2209.07426]

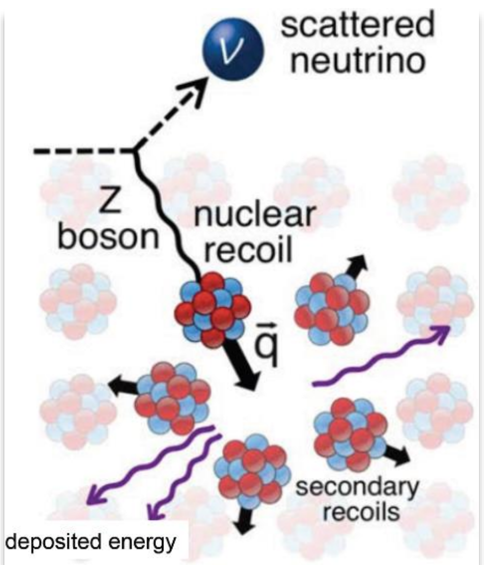
- ❖ Light DM models involving new light mediators: growing attention.
- ❖ The experimental detection of such light DM candidates: challenging as the conventional search efforts are designed and optimized for WIMP.

Nuclear Scattering

Nuclear Scattering: Elastic

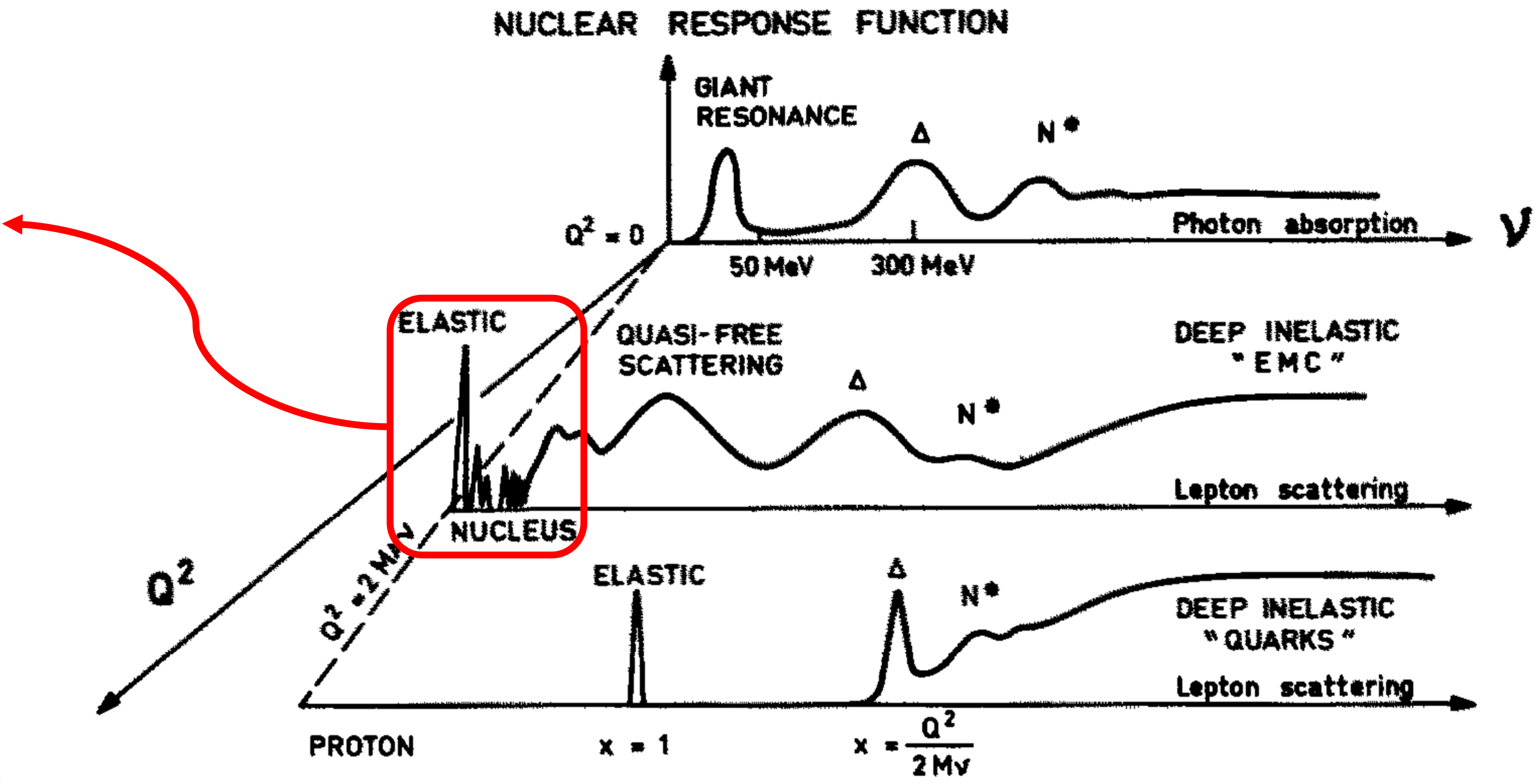
- Coherent elastic nuclear scattering





$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

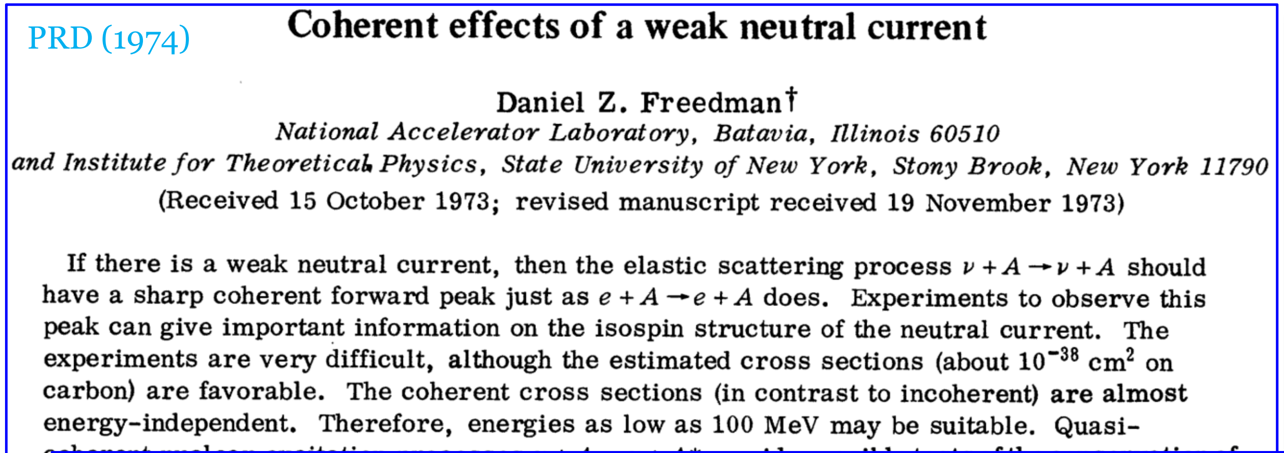


B. Frois, Nuclear Structure (1985)

Nuclear Scattering: Elastic Neutrino

❖ Coherent Elastic ν Nucleus Scattering (CEνNS)

PRD (1974)

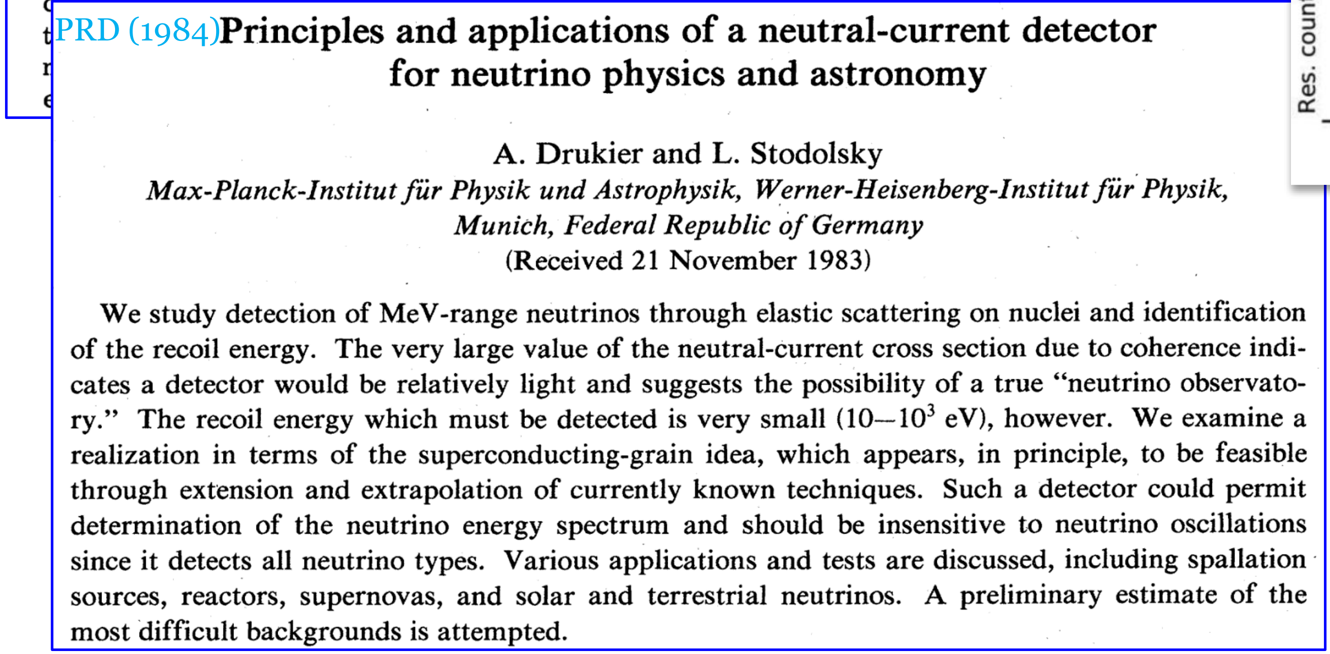


Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-

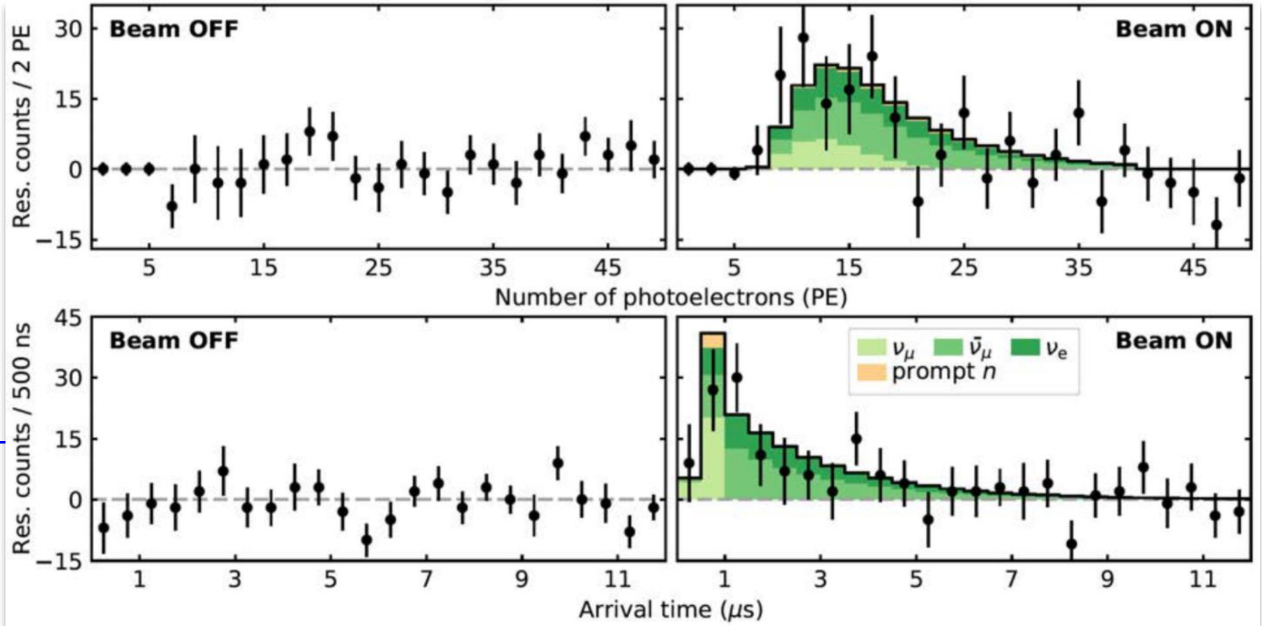
PRD (1984)



Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10—10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

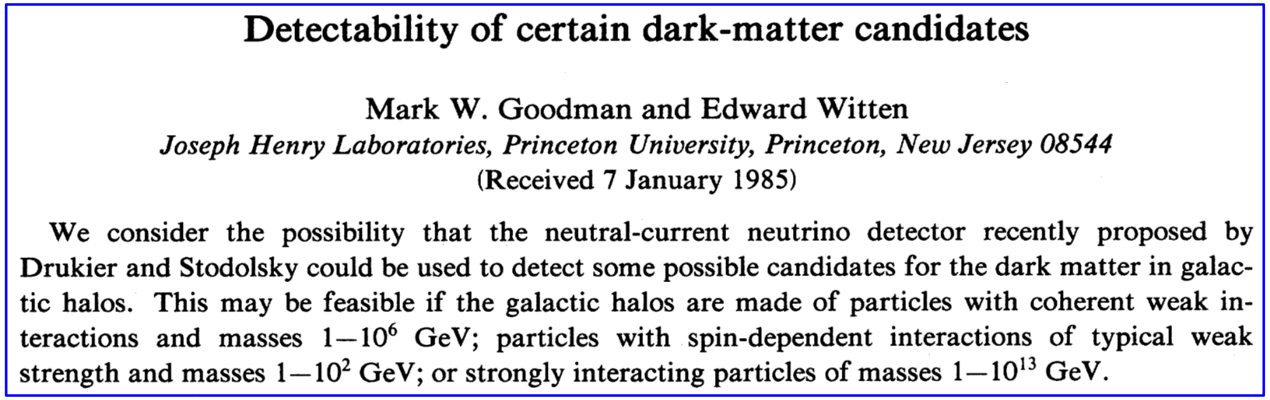


134 ± 22 events observed! ➔ The absence of CEνNS events is rejected at 6.7 σ.

COHERENT [1708.01294]

Nuclear Scattering: Elastic DM

❖ Coherent Elastic DM Nucleus Scattering ➔ DM Direct Detection

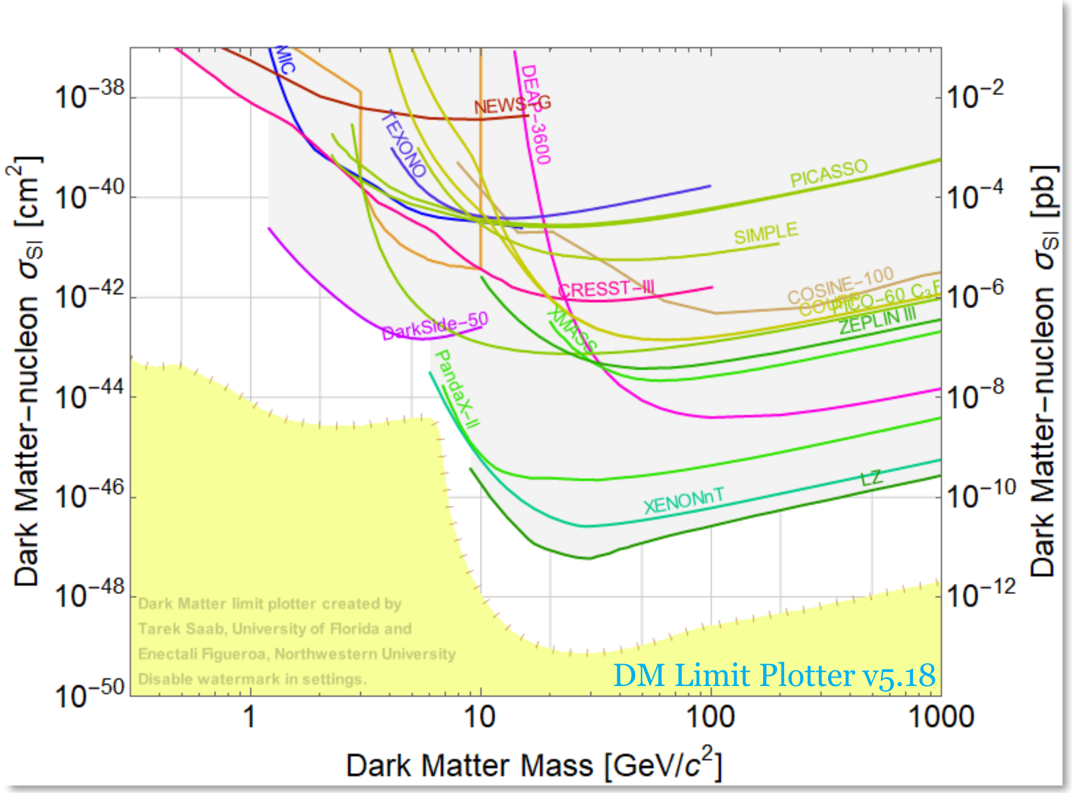


Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

PRD (1985)

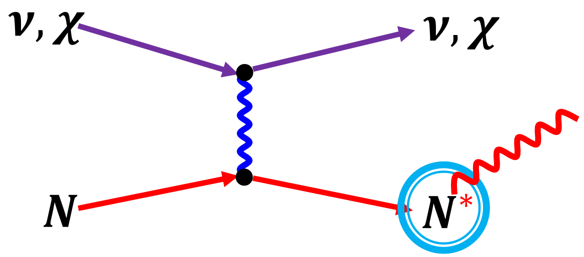


DM Limit Plotter v5.18

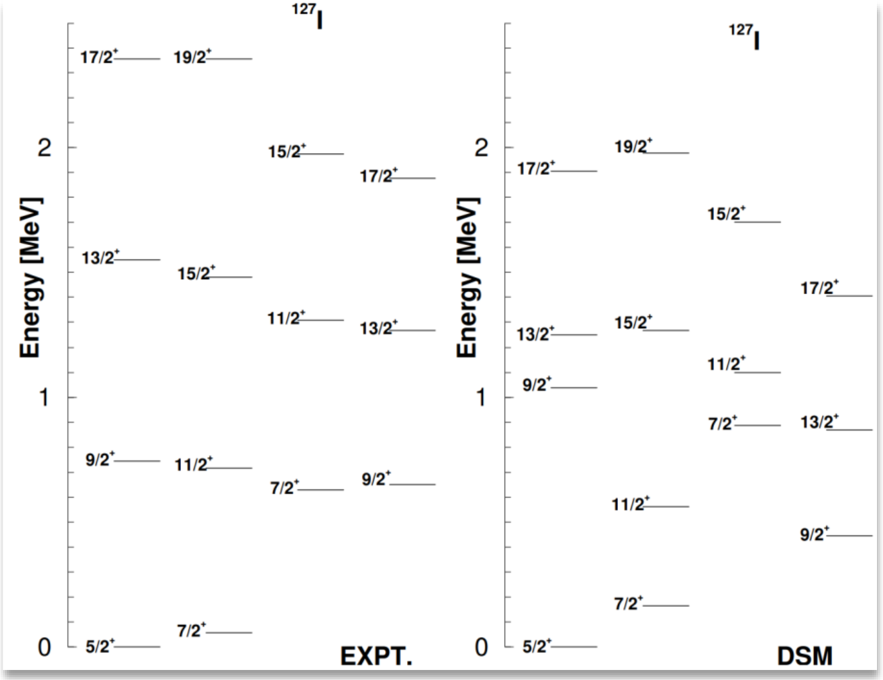
No solid observation yet.

Nuclear Scattering: *In*elastic

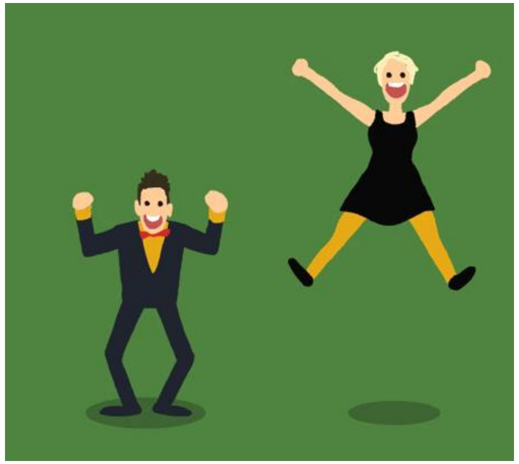
❖ Why **inelastic** channel?



$E_{in} \lesssim 50$ MeV



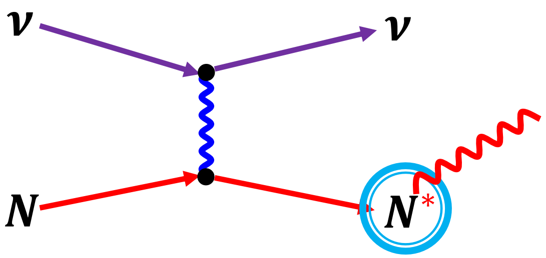
Sahu et al., [2004.04055]

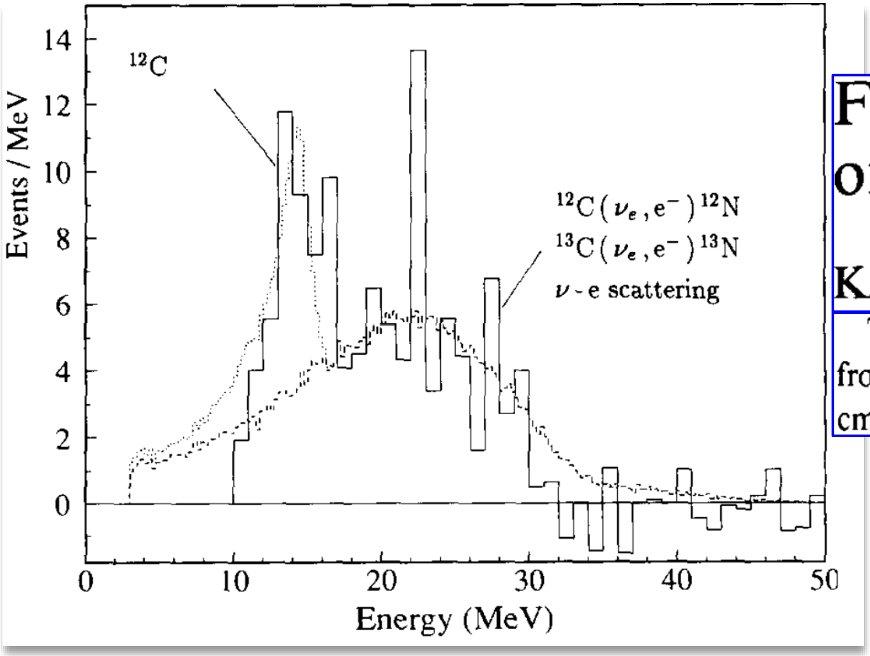


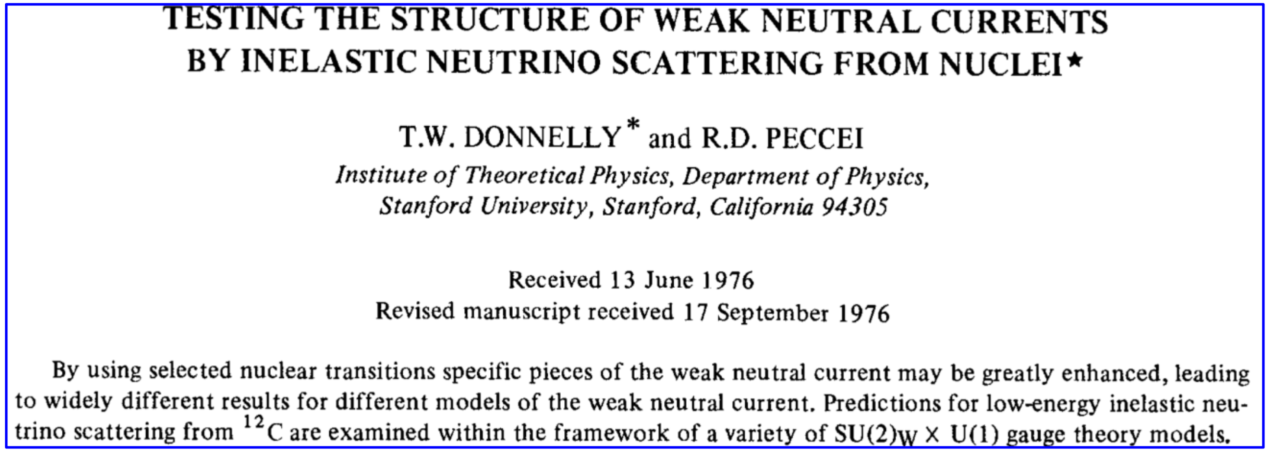
- Signatures
  - ✓ **Elastic**: low energy nuclear recoil
  - ✓ **Inelastic**: γ cascade ($\Delta E \lesssim 10$ MeV), γ cascade + nucleons ($\Delta E \gtrsim 10$ MeV)
- Motivation
  - ✓ A new channel to study
  - ✓ Larger energy $\sim O(1-10)$ MeV
  - ✓ Better S/B ratio

Nuclear Scattering: *In*elastic Neutrino

❖ **Inelastic** ν Nucleus Scattering (IνNS)







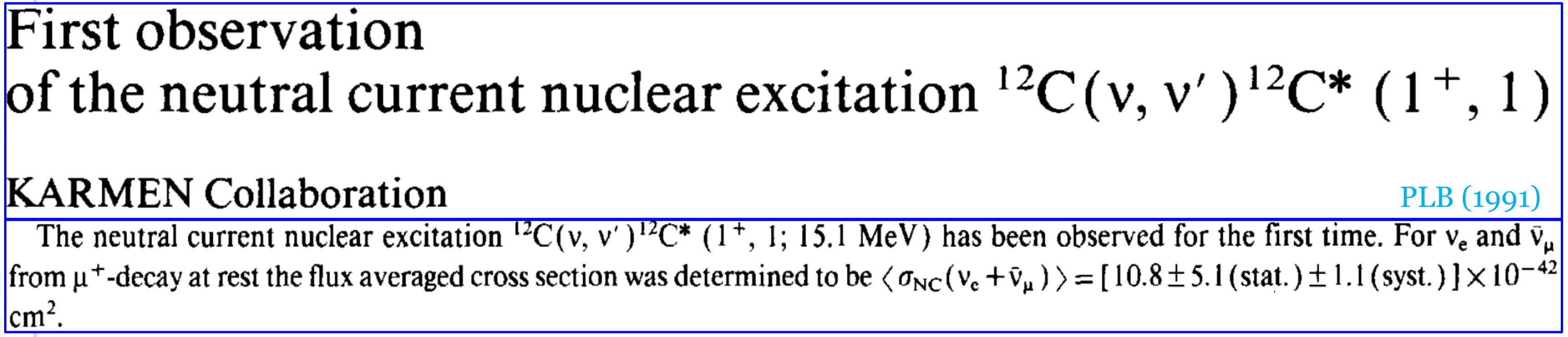
TESTING THE STRUCTURE OF WEAK NEUTRAL CURRENTS
BY INELASTIC NEUTRINO SCATTERING FROM NUCLEI*

T.W. DONNELLY* and R.D. PECCEI
Institute of Theoretical Physics, Department of Physics,
Stanford University, Stanford, California 94305

Received 13 June 1976
Revised manuscript received 17 September 1976

By using selected nuclear transitions specific pieces of the weak neutral current may be greatly enhanced, leading to widely different results for different models of the weak neutral current. Predictions for low-energy inelastic neutrino scattering from ^{12}C are examined within the framework of a variety of $SU(2)_W \times U(1)$ gauge theory models.

PLB (1976)



First observation
of the neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*\ (1^+, 1)$

KARMEN Collaboration

The neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*\ (1^+, 1; 15.1\ \text{MeV})$ has been observed for the first time. For ν_e and $\bar{\nu}_\mu$ from μ^+-decay at rest the flux averaged cross section was determined to be $\langle \sigma_{NC}(\nu_e + \bar{\nu}_\mu) \rangle = [10.8 \pm 5.1(\text{stat.}) \pm 1.1(\text{syst.})] \times 10^{-42}$ cm^2.

PLB (1991)

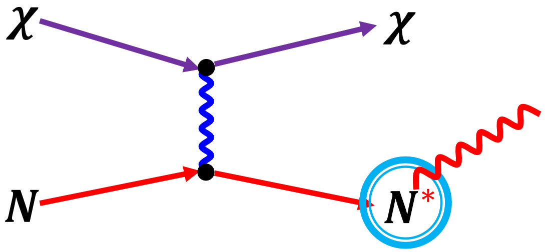
➢ Recent improvements

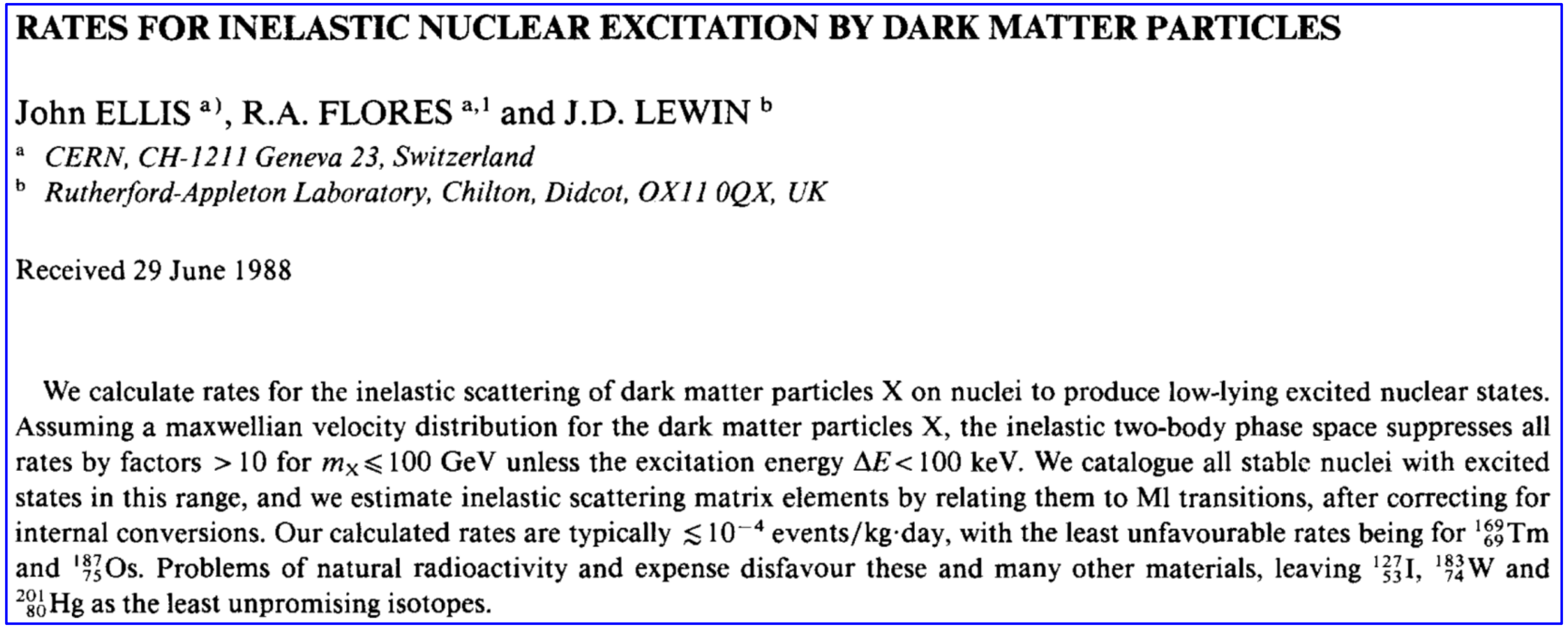
Dutta, Newstead et al., [2206.08590]

- ✓ Inclusion of multiple excited states
- ✓ Consistent handling of hadronic currents
- ✓ Exclusive cross sections for each state

Nuclear Scattering: *In*elastic DM @ Direct Exps.

❖ **Inelastic** DM Nucleus Scattering




RATES FOR INELASTIC NUCLEAR EXCITATION BY DARK MATTER PARTICLES

John ELLIS [a)], R.A. FLORES [a,1] and J.D. LEWIN [b]

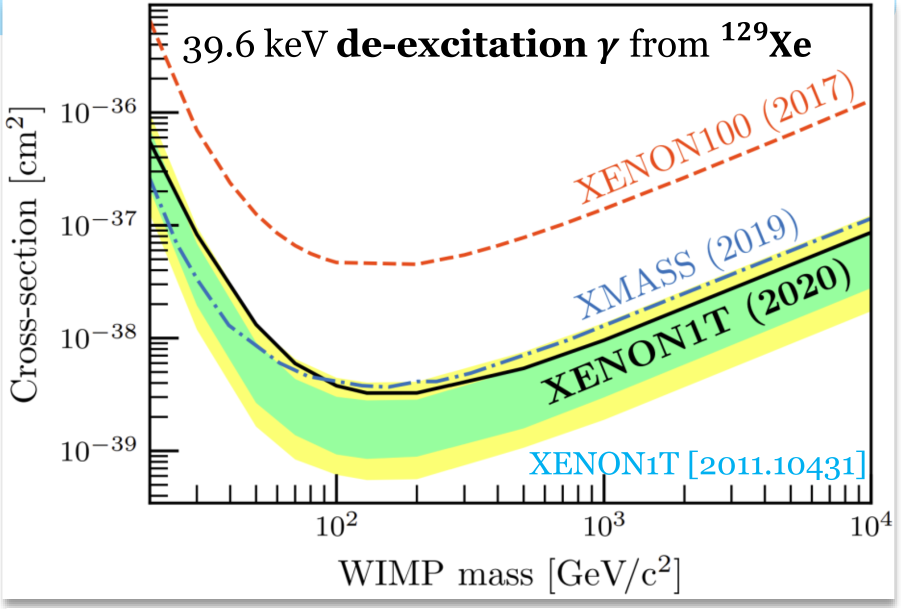
[a] *CERN, CH-1211 Geneva 23, Switzerland*

[b] *Rutherford-Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK*

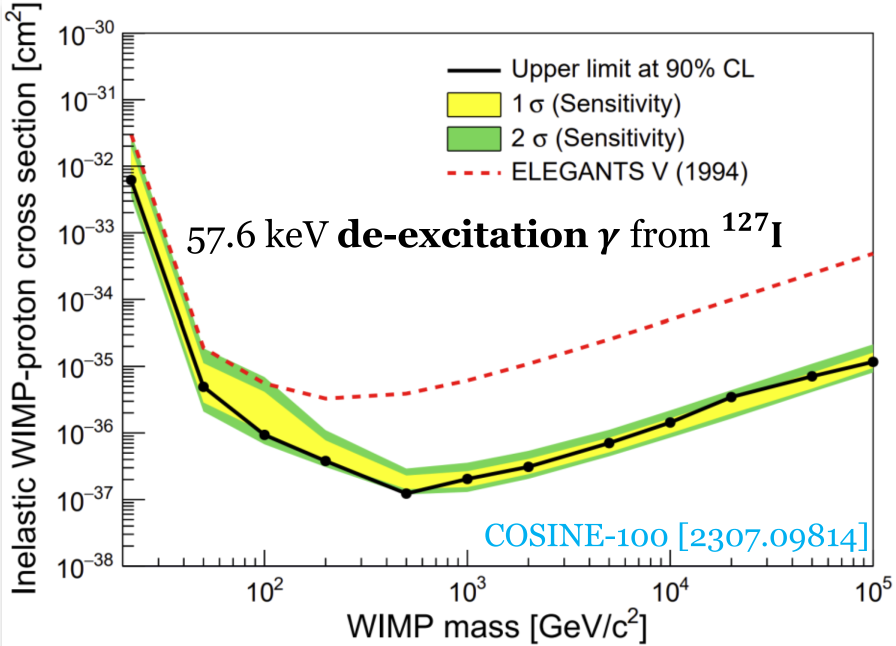
Received 29 June 1988

We calculate rates for the inelastic scattering of dark matter particles X on nuclei to produce low-lying excited nuclear states. Assuming a maxwellian velocity distribution for the dark matter particles X, the inelastic two-body phase space suppresses all rates by factors >10 for $m_X \leqslant 100$ GeV unless the excitation energy $\Delta E < 100$ keV. We catalogue all stable nuclei with excited states in this range, and we estimate inelastic scattering matrix elements by relating them to Ml transitions, after correcting for internal conversions. Our calculated rates are typically $\lesssim 10^{-4}$ events/kg·day, with the least unfavourable rates being for $^{169}_{69}$Tm and $^{187}_{75}$Os. Problems of natural radioactivity and expense disfavour these and many other materials, leaving $^{127}_{53}$I, $^{183}_{74}$W and $^{201}_{80}$Hg as the least unpromising isotopes.

PLB (1988)


39.6 keV **de-excitation γ** from ^{129}**Xe**

XENON1T [2011.10431]


57.6 keV **de-excitation γ** from ^{127}**I**

COSINE-100 [2307.09814]

Is it possible to search for *inelastic* nuclear scatterings by DM in neutrino detectors?

Kinematically impossible for the ambient DM
to leave detectable MeV-range signatures
through the inelastic channel: $\boldsymbol{E_R \sim \mu_{\chi N} v^2 < \mathrm{MeV}}$

Is it possible to search for *inelastic* nuclear scatterings by DM in neutrino detectors?

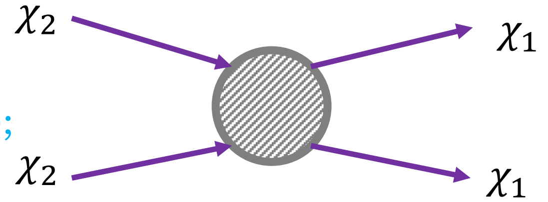
Kinematically impossible for the ambient DM
to leave detectable MeV-range signatures
through the inelastic channel: $E_R \sim \mu_{\chi N} v^2 < \mathrm{MeV}$

Boosted Dark Matter (BDM)

DM Boosting Mechanisms: Dark Sector

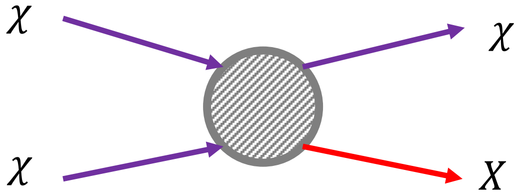
Boosted DM (BDM) coming from the Universe

[Belanger & **JCP**, JCAP (2012);
Agashe et al., JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015);
Berger et al., JCAP (2015);
Kim, **JCP**, Shin, PRL (2017);
more]



✓ Multi-component model

$m_2 \gg m_1$



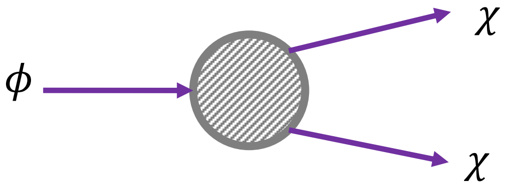
[D’Eramo & Thaler, JHEP (2010);
Berger et al., JCAP (2015)]

✓ Semi-annihilation model

$m_\chi \gg m_X$

Large E_k^{DM} (monochromatic) due to **mass gap**

- Relic component DM:
  Non-relativistic!



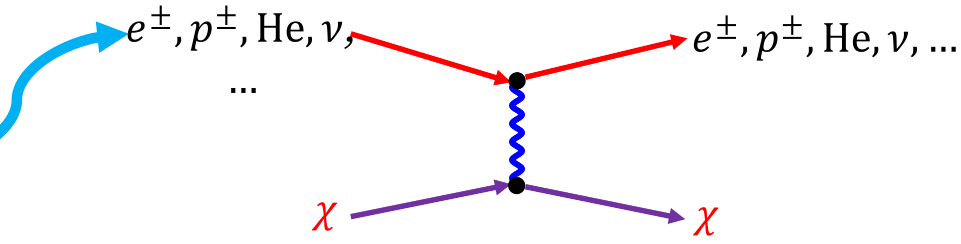
[Bhattacharya et al., JCAP (2015);
Kopp et al., JHEP (2015);
Cline et al., PRD (2019);
Heurtier, Kim, **JCP**, Shin, PRD (2019);
more]

✓ Decaying multi-component DM

$m_\phi \gg m_\chi$

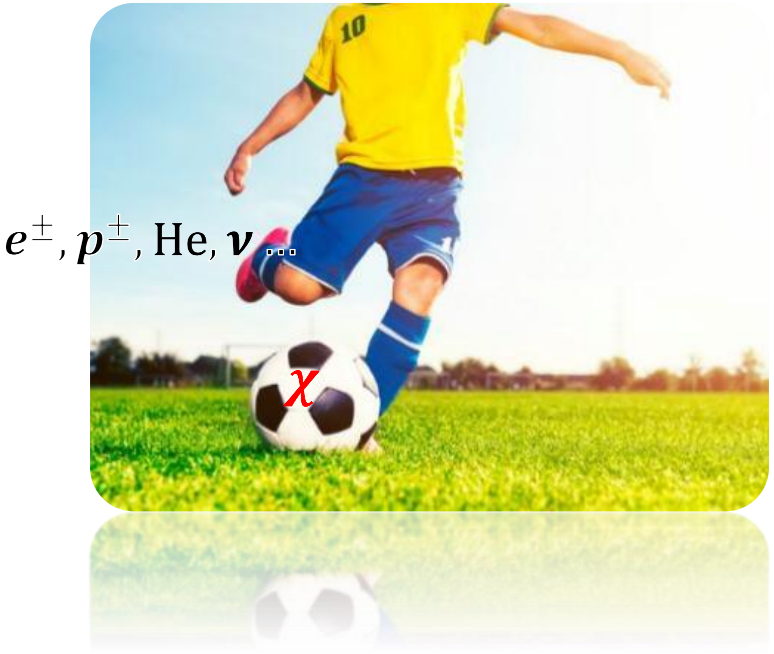
DM Boosting Mechanisms: Cosmic-Rays (CRs)

Cosmic-Ray-Induced BDM



- Energetic cosmic-ray-induced BDM: energetic cosmic-rays kick DM (large $E_{e^\pm,p^\pm,\mathrm{He},\boldsymbol{\nu},\dots}$ ➔ large E_χ)

  ➔ Efficient for Light DM



- **Charged** CRs: [Bringmann & Pospelov, PRL (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent & Dutta et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho et al., PRD (2020); more]
- CR $\boldsymbol{\nu}$ (**$\boldsymbol{\nu}$BDM**): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; Chao, Li, Liao, 2108.05608; Lin, Wu, Wu, Wong, 2206.06864; more]

- BDM from astrophysical processes:

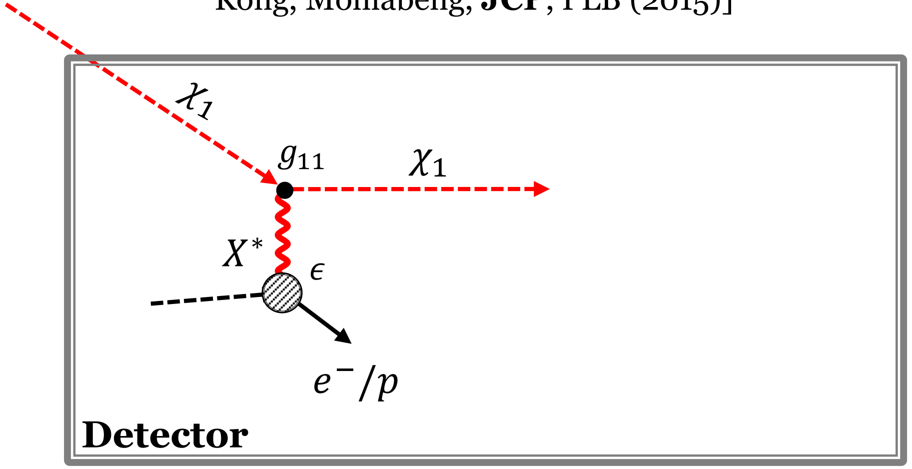
Solar evaporation - Kouvaris, PRD (2015)
Dark cosmic rays - Hu +, PLB (2017)
Solar reflection - An +, PRL (2018)
Solar acceleration - Emken +, PRD (2018)
Atmospheric collider – Alvey+, PRL (2019)
PBH evaporation - Calabrese +, PRD (2022)
Blazar jets - Wang +, PRL (2022)
Supernova shocks – Cappiello
more

BDM Signatures: Elastic or Inelastic DM

- BDM signal: detectable at **large volume** detectors

elastic scattering (eBDM)

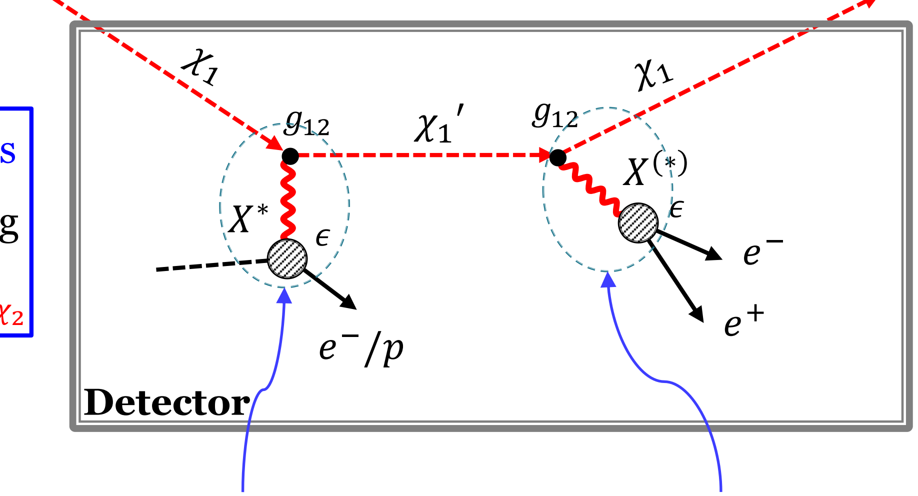
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]



1~3 tracks depending on $E_{\rm th}$ & l_{χ_2}

inelastic scattering (*i*BDM)

[D. Kim, **JCP**, S. Shin, PRL (2017);
G. Giudice, D. Kim, **JCP**, S. Shin, PLB (2018)]

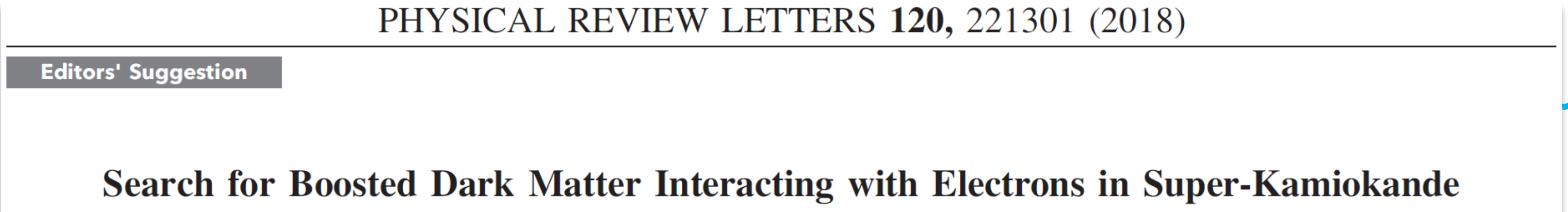


p- or e-scattering (primary)

Decay (secondary)

BDM Searches @ Neutrino Experiments

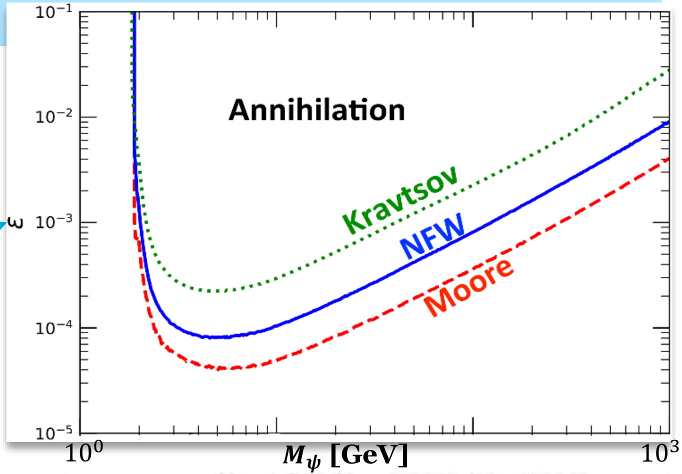
Boosted DM (BDM) scenarios:
Receiving rising attention

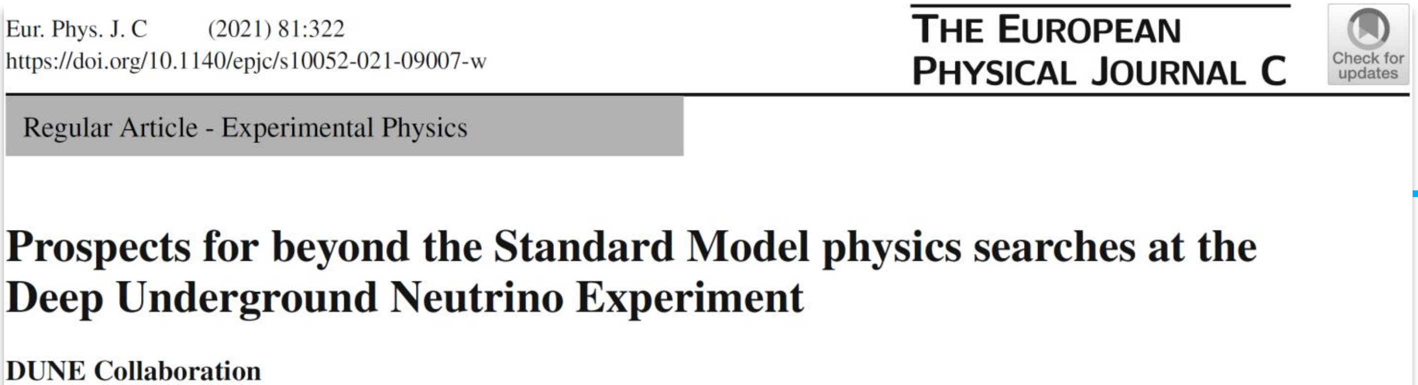


PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande





Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

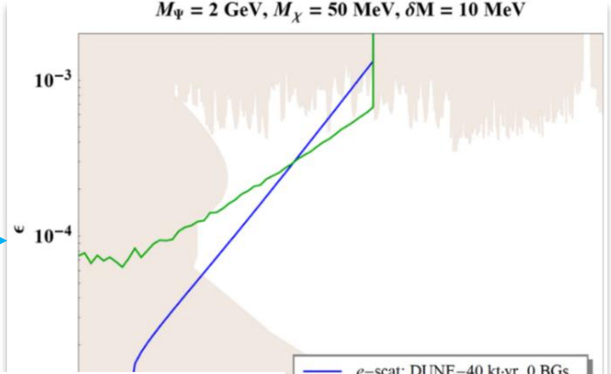
THE EUROPEAN PHYSICAL JOURNAL C

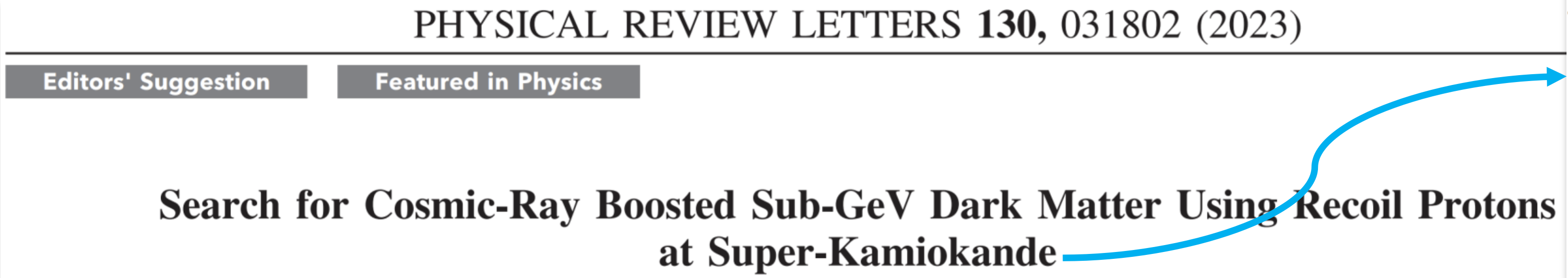
Check for updates

Regular Article - Experimental Physics

Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment

DUNE Collaboration

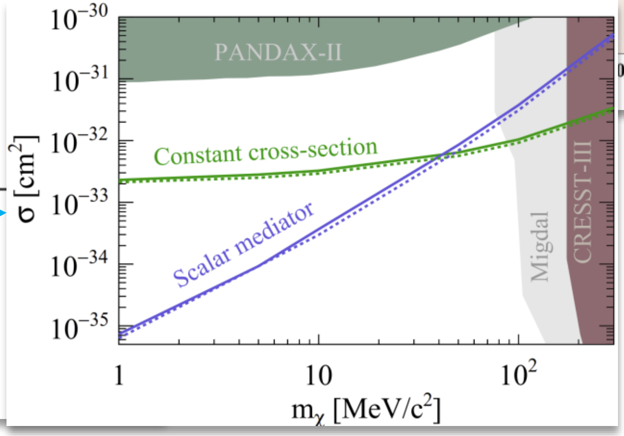




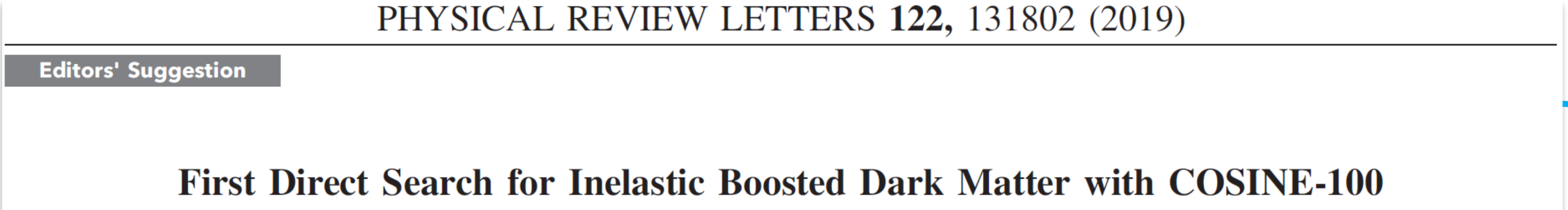
PHYSICAL REVIEW LETTERS **130,** 031802 (2023)

Editors' Suggestion **Featured in Physics**

Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande



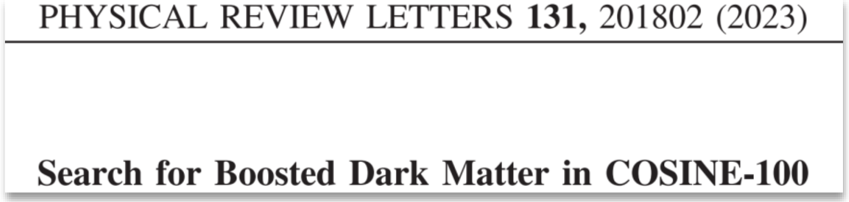
BDM Searches @ DM Experiments



PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

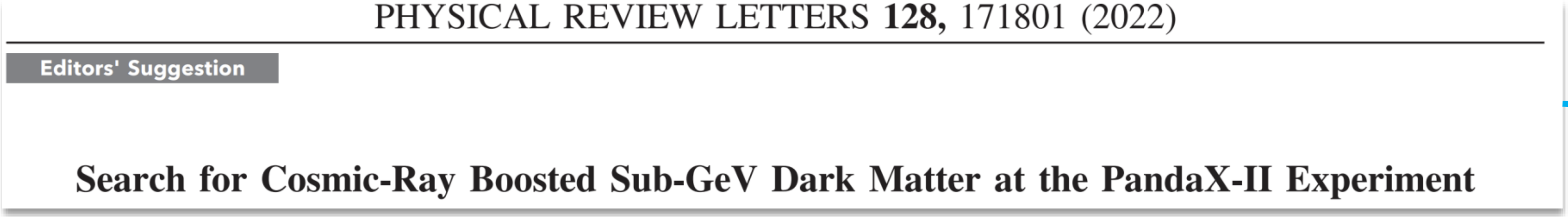
Editors' Suggestion

First Direct Search for Inelastic Boosted Dark Matter with COSINE-100



PHYSICAL REVIEW LETTERS **131,** 201802 (2023)

Search for Boosted Dark Matter in COSINE-100



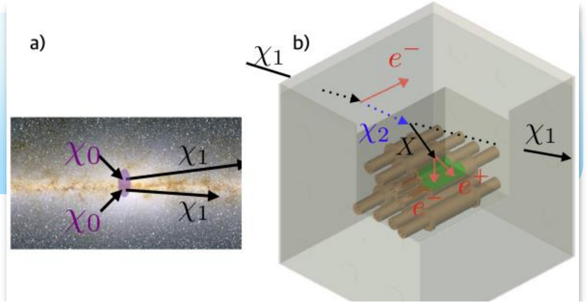
PHYSICAL REVIEW LETTERS **128,** 171801 (2022)

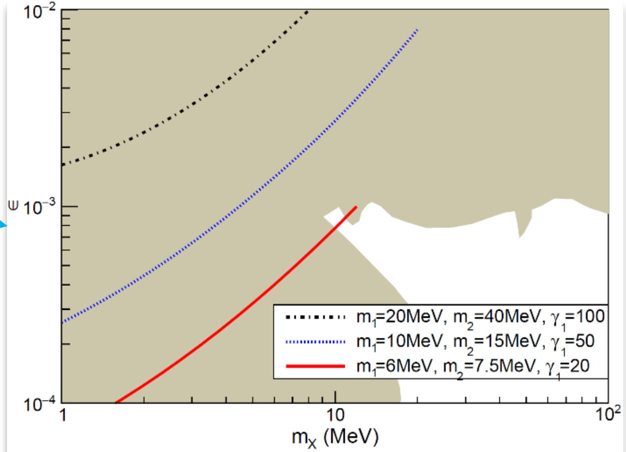
Editors' Suggestion

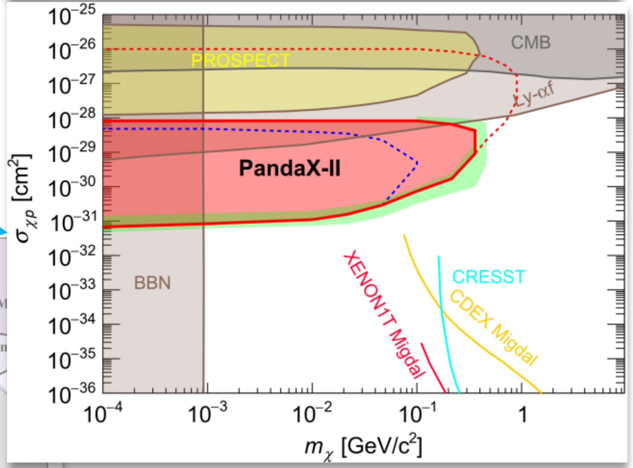
Search for Cosmic-Ray Boosted Sub-GeV Dark Matter at the PandaX-II Experiment

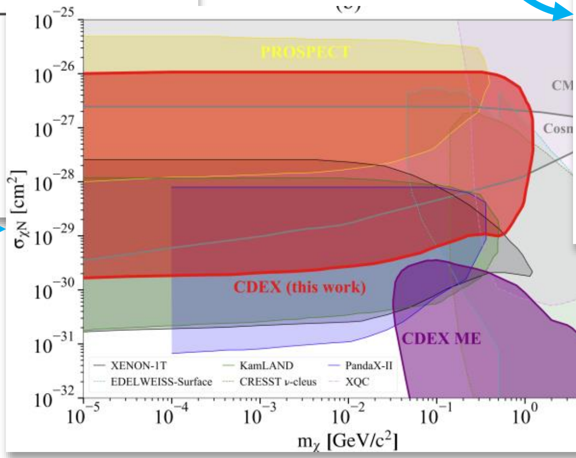
PHYSICAL REVIEW D **106,** 052008 (2022)

Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory









✓ Searches for e/p/N **elastic** scattering signals

Exciting Prospects for DM

Benchmark: BDM by Cosmic Rays

- **Focus**: the interaction between DM & quark

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu \chi + \epsilon Q_b A'_\mu \bar{q}\gamma^\mu q$$

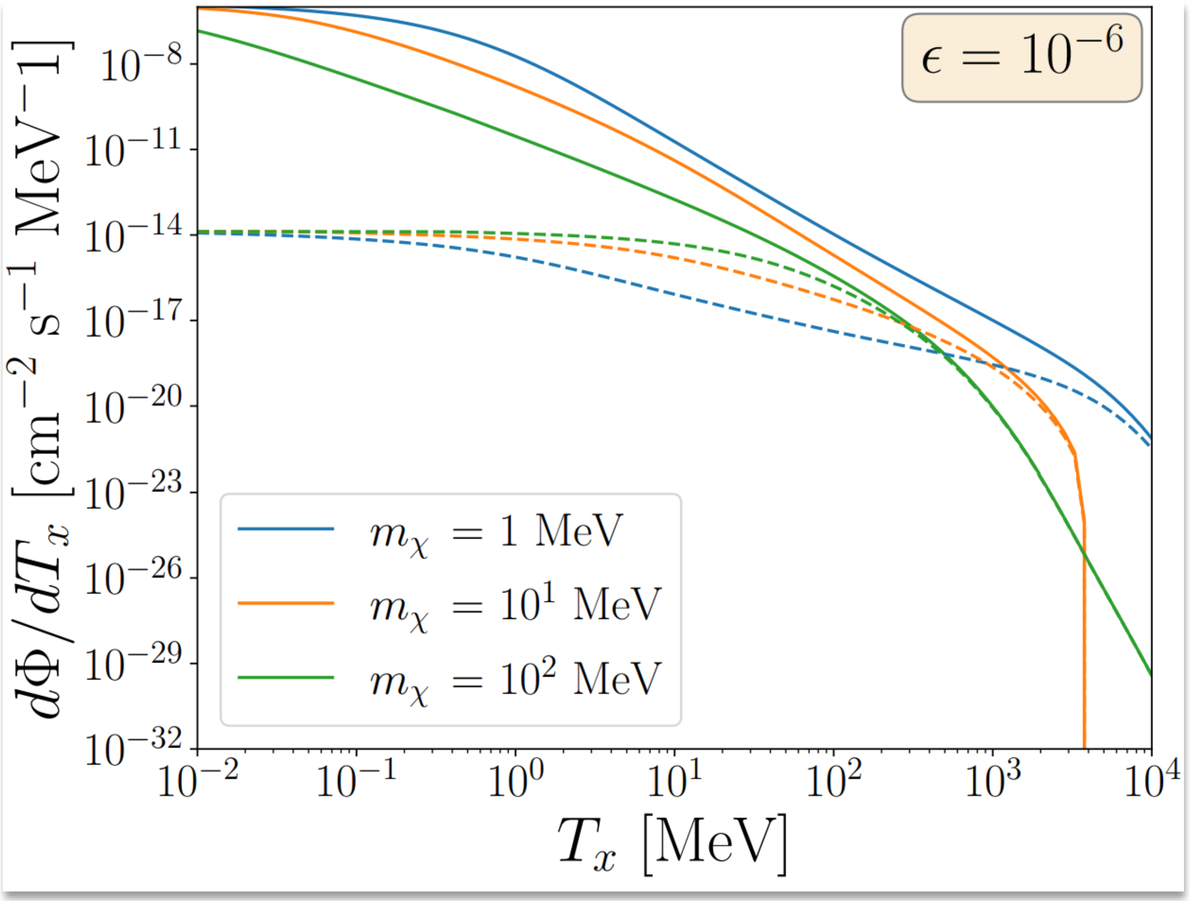
➔ **DM** can be boosted by energetic cosmic rays (p, He) throughout the galaxy.

- CR-BDM flux

$$\frac{d\Phi_\chi}{dT_\chi} = \int_V dV \int_{T_i^{\min}} dT_i \, \frac{d^2\Gamma_{i\to\chi}}{dT_i dT_\chi}$$

$$= D_{\rm eff} \frac{\rho_\chi}{m_\chi} \sum_i \int_{T_i^{\min}} dT_i \, \frac{d\sigma_{\chi i}^{\rm el}}{dT_\chi} \frac{d\Phi_i^{\rm LIS}}{dT_i}$$

[Bringmann & Pospelov, PRL (2019)]



✓ $m_{A'}$ = 1 MeV (solid) & 100 MeV (dashed)

Inelastic Nuclear Scattering of DM

- Gamow-Teller (GT) transitions are the dominant contribution to the inelastic cross section.

$$\frac{d\sigma^{\rm inel}_{\chi N}}{d\cos\theta} = \frac{2\epsilon^2 g_D^2 {E'}_\chi {p'}_\chi}{(2m_T E_R + m_{A'}^2 - \Delta E^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1}$$

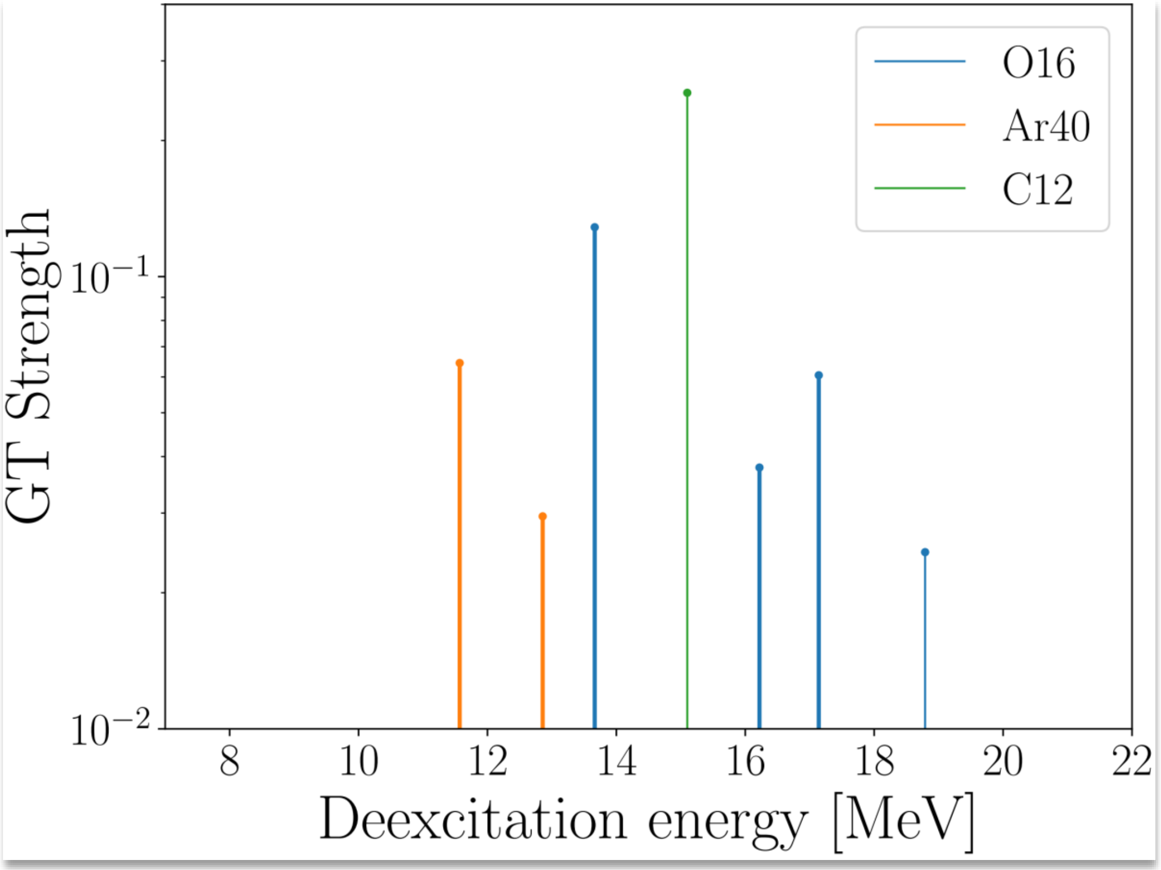
$$\times \sum_{s_i,s_f} \vec{l}\cdot\vec{l}^* \frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A} \frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2 \,,$$

$$\sum_{s_i,s_f} \vec{l}\cdot\vec{l}^* = 3 - \frac{1}{E_\chi E'_\chi}\left[\frac{1}{2}\left({p_\chi}^2 + {p'_\chi}^2 - 2m_T E_R\right) + \frac{3m_\chi^2}{4}\right]$$

* For more details, See e.g. Dutta et al., [2206.08590].

- The expected # of signal events

$$N_\chi = N_T \Delta t \int \sigma^{\rm inel}_{\chi N}(E_\chi)\frac{d\Phi_\chi}{dE_\chi} dE_\chi \cdot \frac{\Gamma_{N^*\to N\gamma}}{\Gamma_{\rm total}}$$

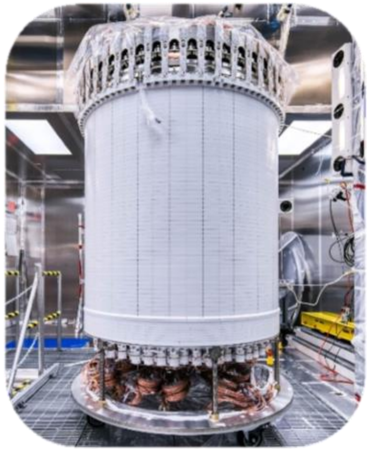


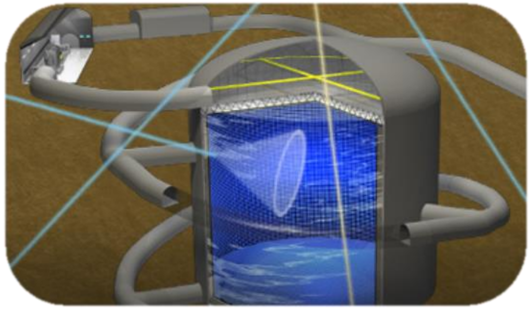
The GT strengths are derived from experimental results & the large-scale shell model code BIGSTICK.

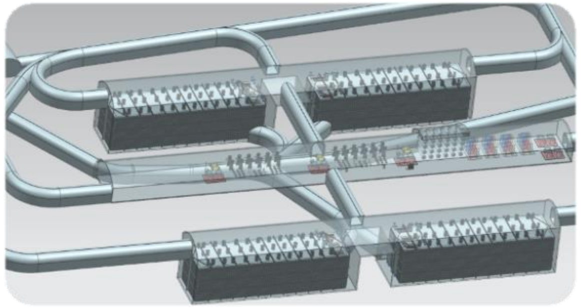
Benchmark Detectors

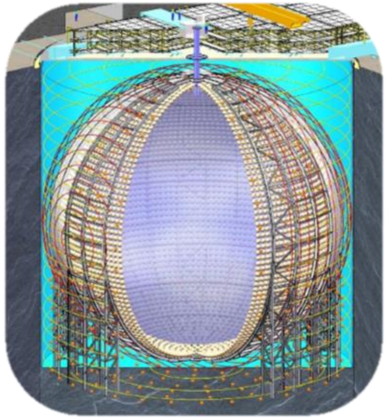
- Key specifications of the benchmark detectors

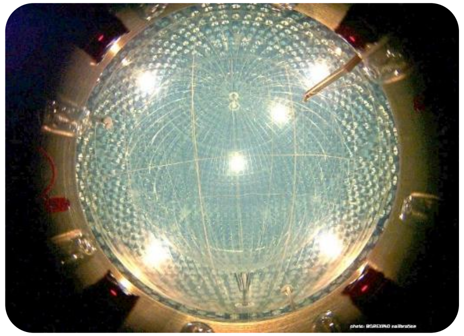
	Experiment	Target	Mass (kton)	Time (year)	E_{res} (MeV)	E_{range} (MeV)	Background
inelastic	Super-K	water	22.5	20	2	10 - 22	2.9×10^{-3}
	Hyper-K	water	188	10	2	10 - 22	1.2×10^{-2}
	DUNE	Ar	40	10	2	7 - 15	167.5
	JUNO	CH_2	20	10	-	15.1	47
	Borexino	CH_2	0.1	5.6	-	15.1	0.13
elastic	DUNE	p,n	40	10	-	50 - 1270	550
	JUNO	p	20	10	-	15 - 100	1420
	Borexino	p	0.1	1.22	-	12.3 - 24.6	84
	LZ	Xe	0.0055	0.167	-	$(1-68)\cdot10^{-3}$	1.4
	DarkSide	Ar	0.02	5	-	0.03 - 0.1	1.6

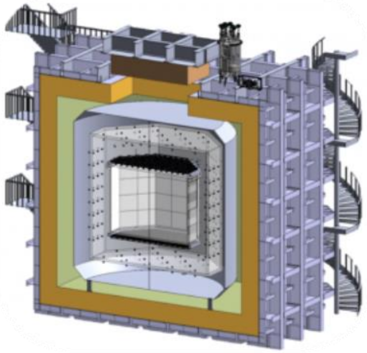






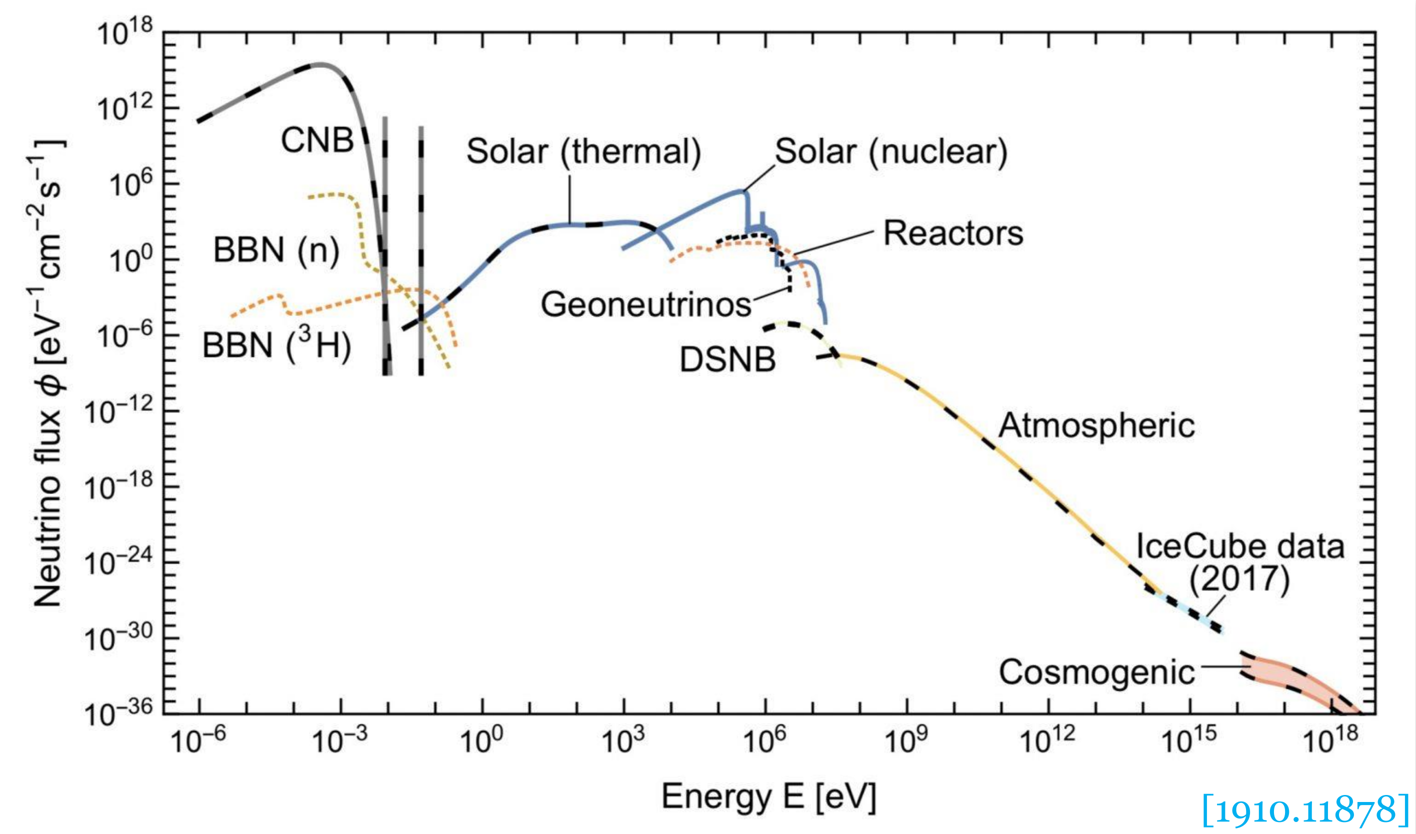




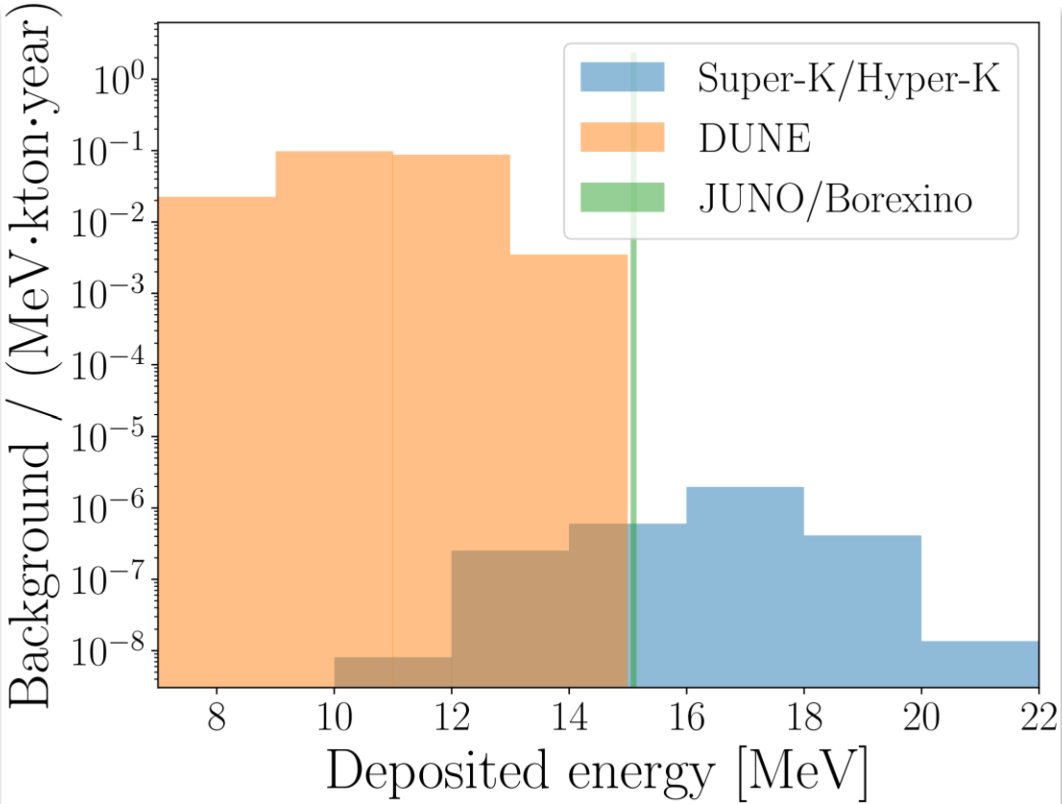


Estimated Background Rates

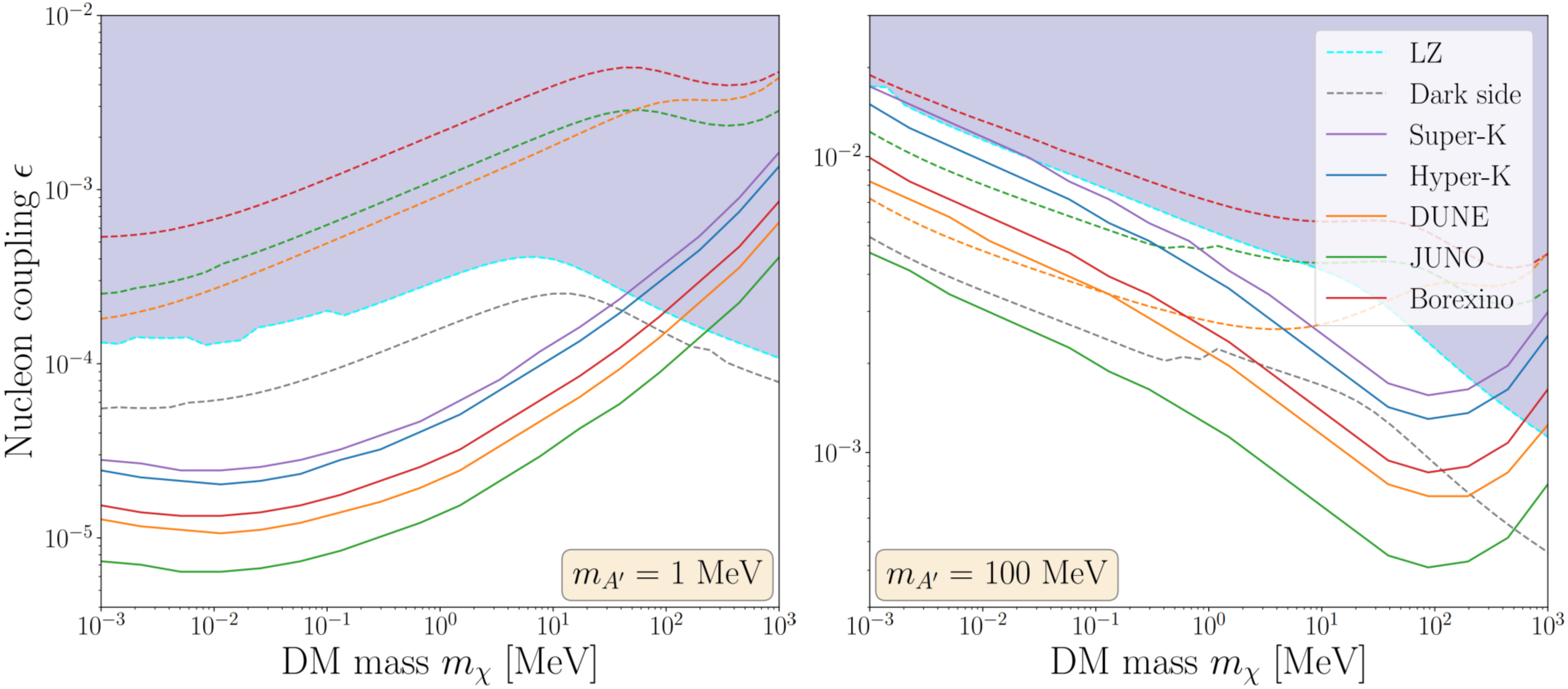
- The main irreducible background: the elastic & inelastic neutral-current scattering of solar & atmospheric neutrinos.



[1910.11878]

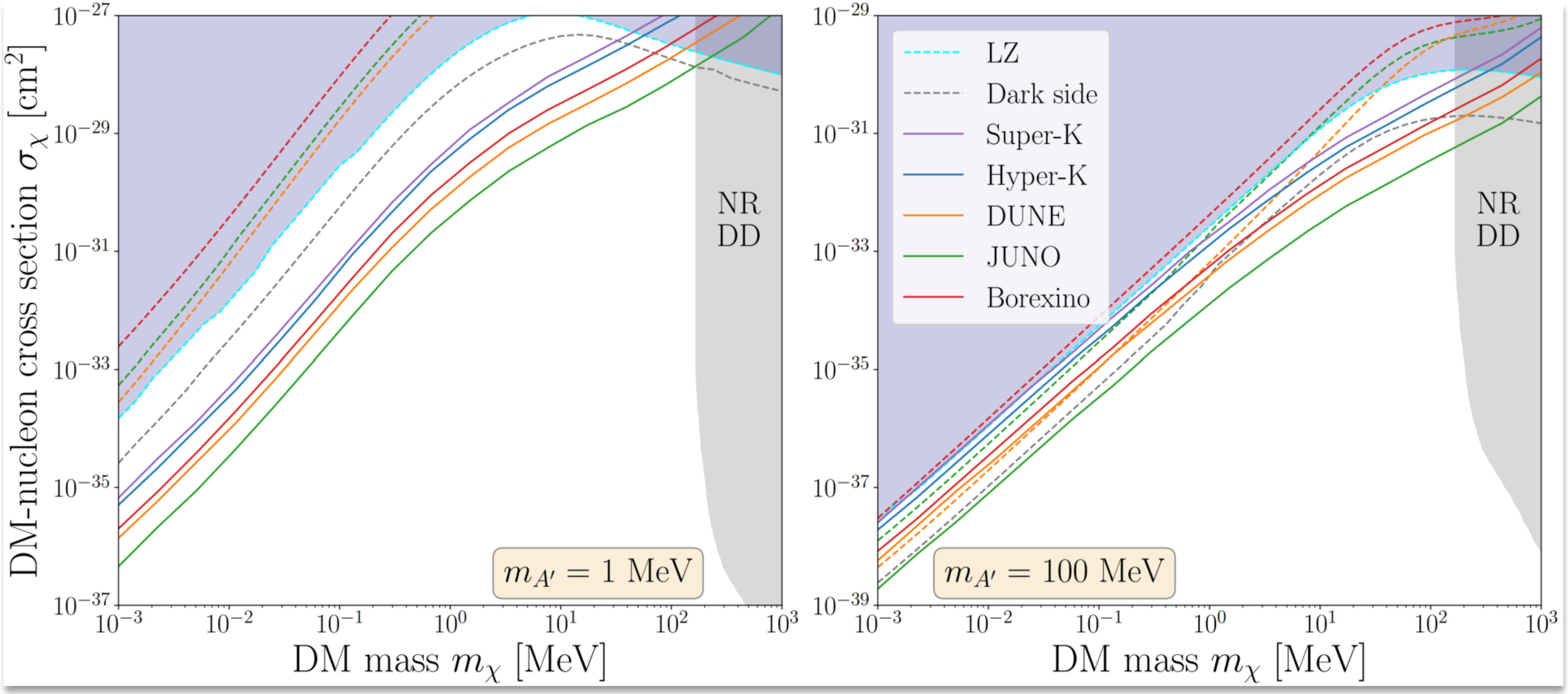


Projected/Attainable Sensitivity Reaches



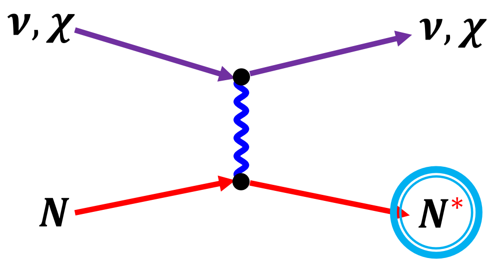
❖ Inelastic channels (solid) better than elastic channels (dashed: LZ & Borexino – data, others - future)

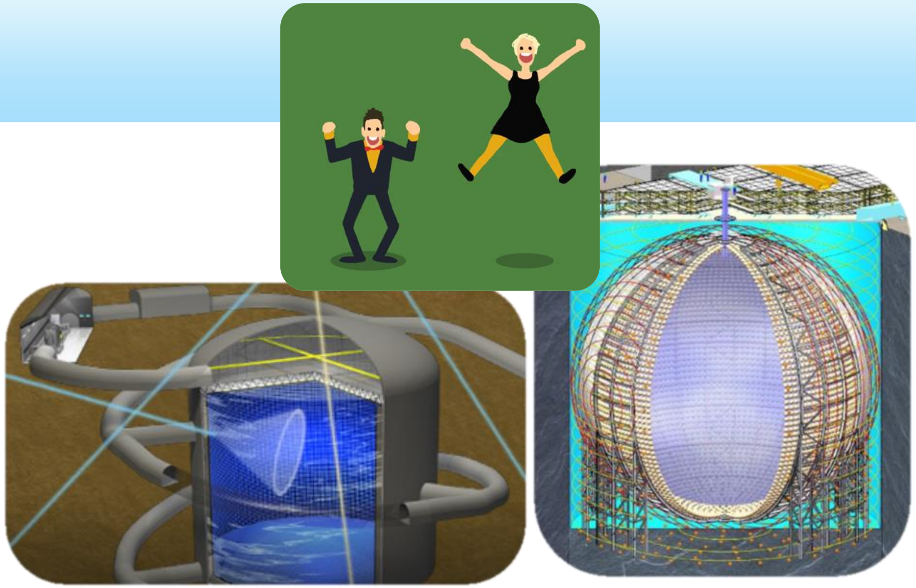
Projected/Attainable Sensitivity Reaches - σ_χ



- ❖ Inelastic channels (solid) better than elastic channels (dashed: LZ & Borexino – data, others - future)

Summary



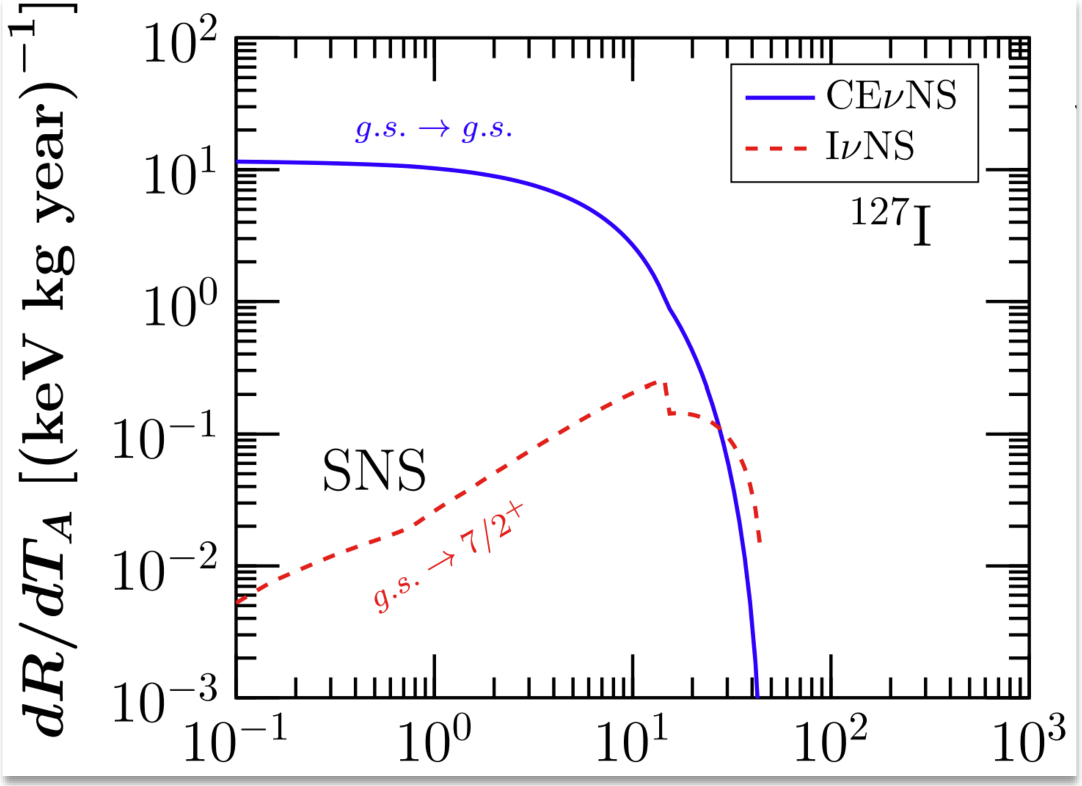


- ❖ **DM-quark interactions** ➔ cosmic-ray boosting of DM & DM-nuclear scattering.
- ❖ ***Inelastic*** **nuclear scattering**:
  - ✓ **Nuclear line: E ~$\mathcal{O}(10)$ MeV** ➔ No need for low threshold detectors.
  - ✓ **Lower background** ➔ Statistical advantage.
- ❖ Large volume neutrino detectors: wonderful to probe light DM.
- ❖ Inelastic channels: better than elastic channels in keV – GeV range.

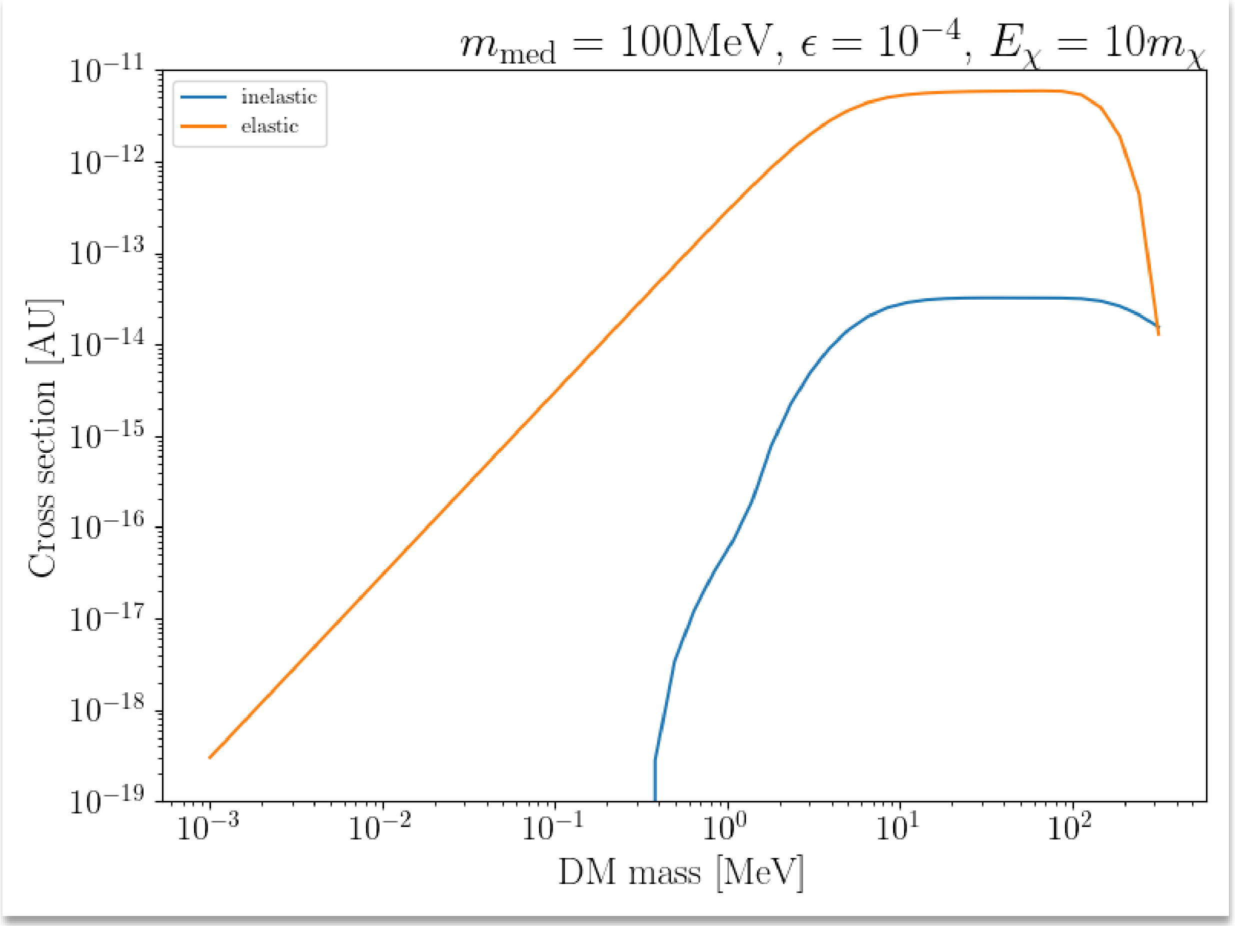
Thank you

Supplemental

Elastic vs. Inelastic

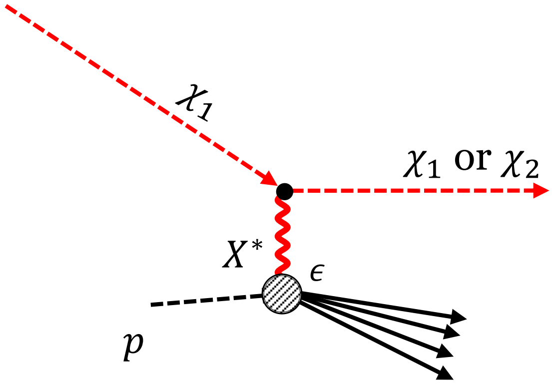


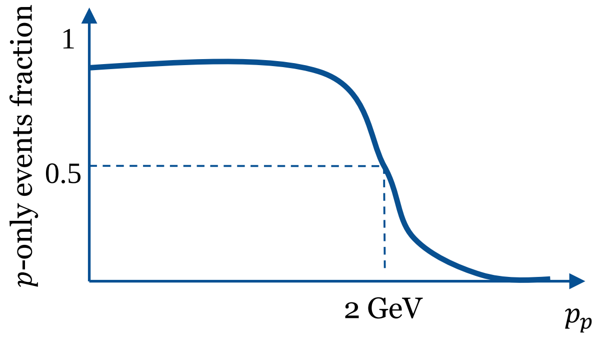
Sahu et al., [2004.04055]



p-Scattering vs. DIS

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

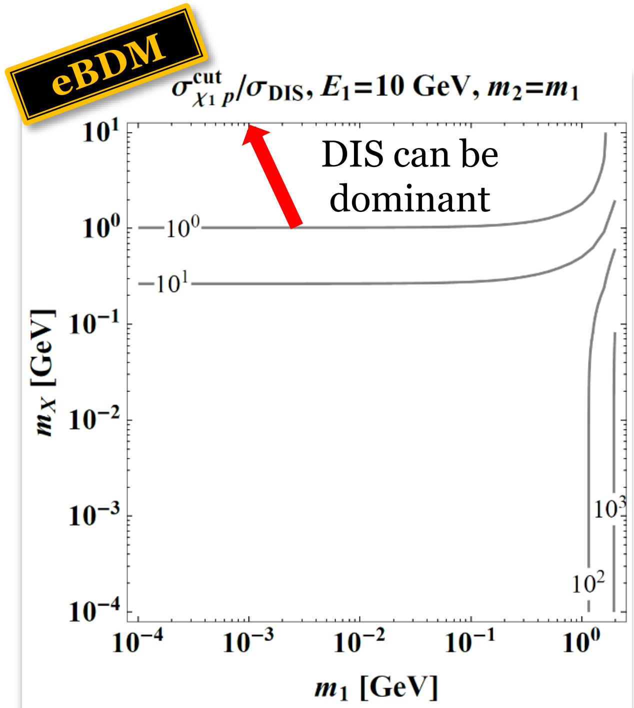


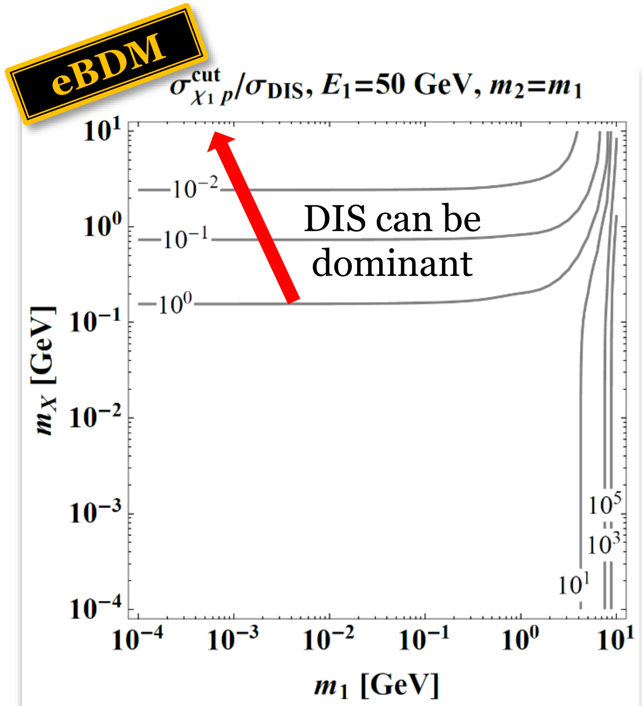


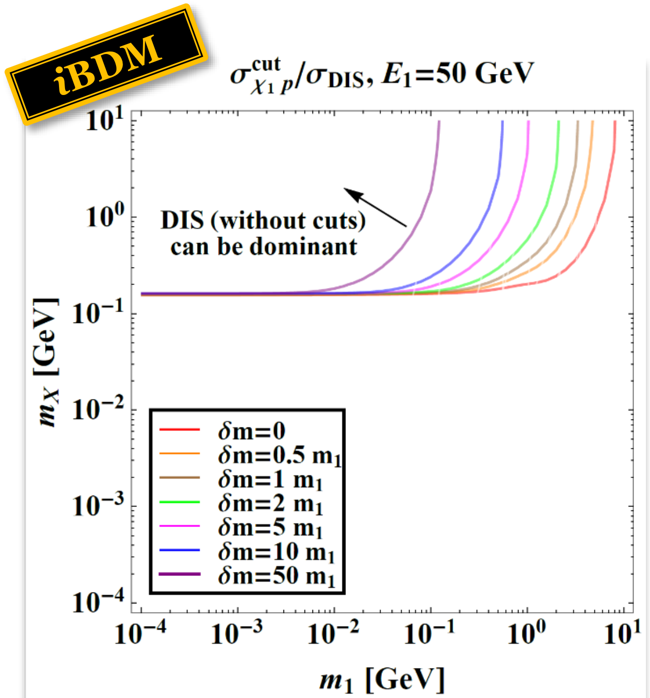
- If a momentum transfer is too large, a proton may break apart.
- What is large? ➔ A SK simulation study [Fechner et al, PRD (2009)] showed about 50 % events accompany (at least) a pion or a secondary particle for $p_p \approx 2$ GeV.
- We categorize any event with $p_p < 2$ GeV as the p-scattering (i.e., simplified step-function-like transition).

p-Scattering vs. DIS: Numerical Study

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]



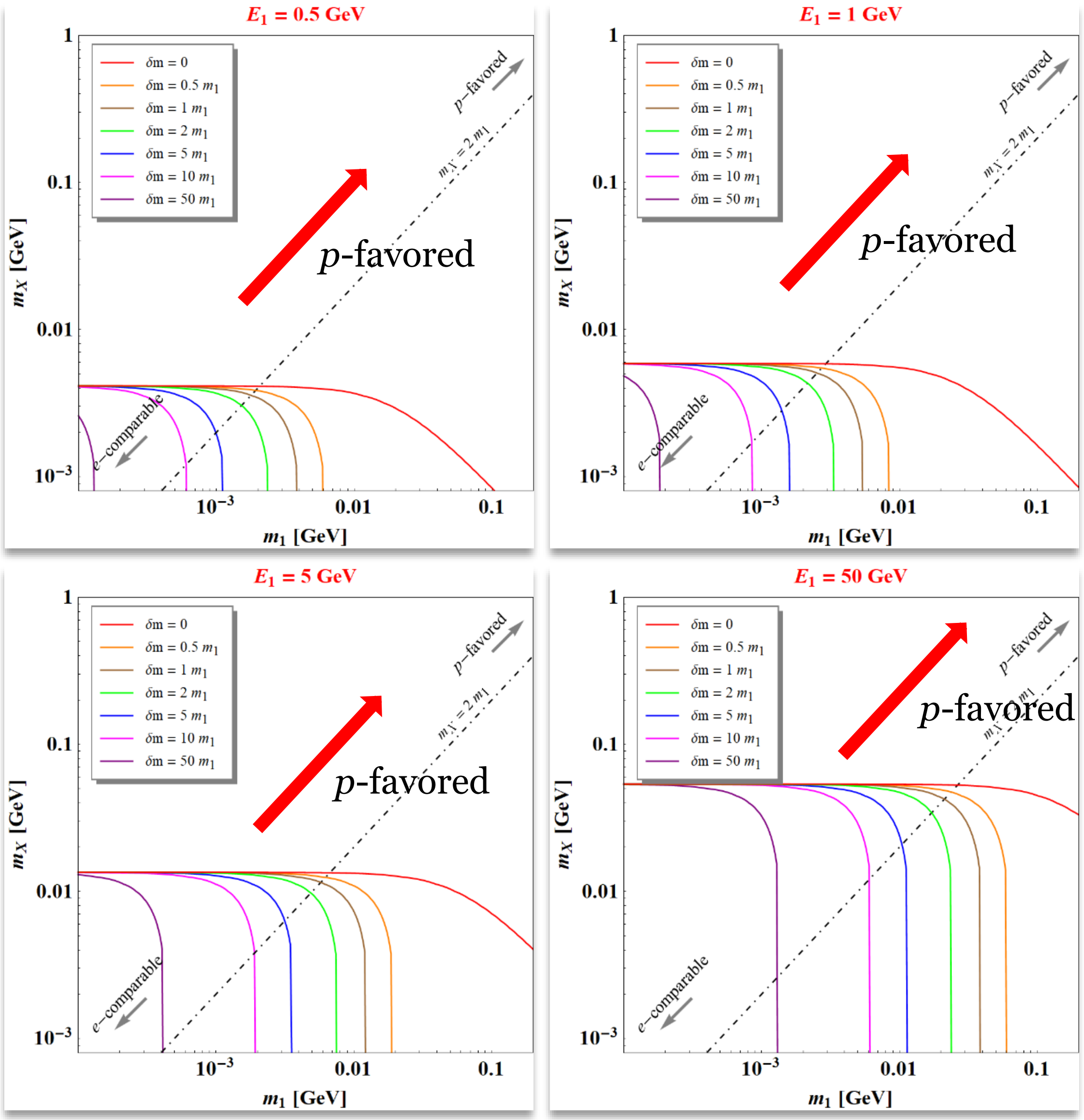




- ✓ We study $\sigma^{\rm cut}_{\chi_1 p}/\sigma_{\rm DIS}$ where 200 MeV $< p_p <$ 2 GeV is applied to $\sigma_{\chi_1 p}$ while no cuts are imposed to $\sigma_{\rm DIS}$.
- ✓ p-scattering dominates over DIS for m_X < O(GeV) (cf. ν scattering via W, Z).
- ✓ As the process becomes more “inelastic”, p-scattering dominates over DIS for a given E_1.
- ✓ DIS-preferred region expands in increasing E_1.

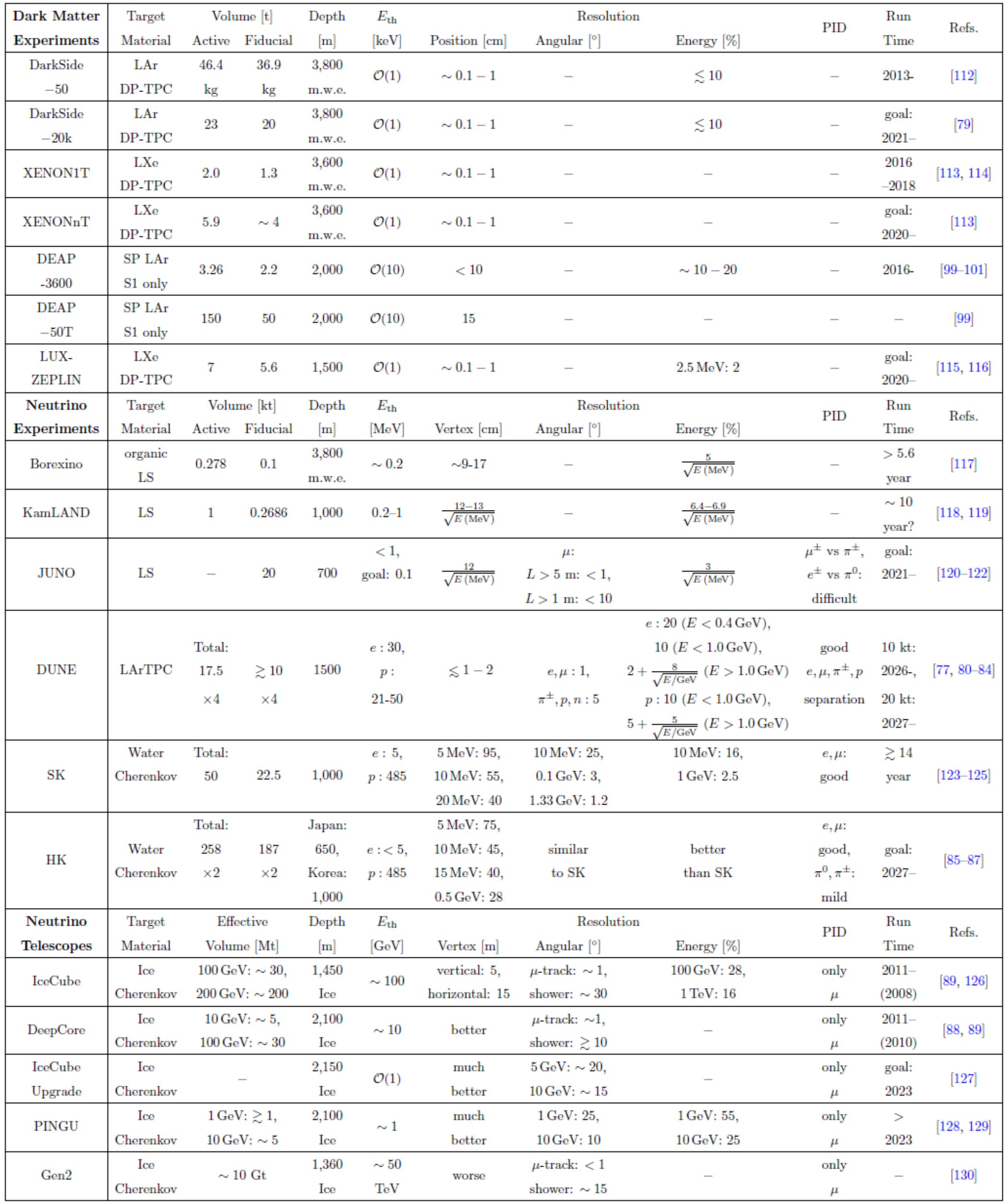
p-Scattering vs. *e*-Scattering

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]



- ✓ If a BDM search hypothesizes a heavy dark photon (say, sub-GeV range), the *p*-channel may expedite discovery.
- ✓ If a model conceiving iBDM signals allows for large mass gaps between χ_1 and χ_2, the *p*-channel is more advantageous.
- ✓ The *e*-channel becomes comparable in probing the parameter regions with smaller m_1 and m_X.
- ✓ As the boosted χ_1 comes with more energy, more parameter space where the *e*-channel is comparable opens up.
- ✓ With cuts, more e-channel favored region.

Many More Well-Motivated Exps.



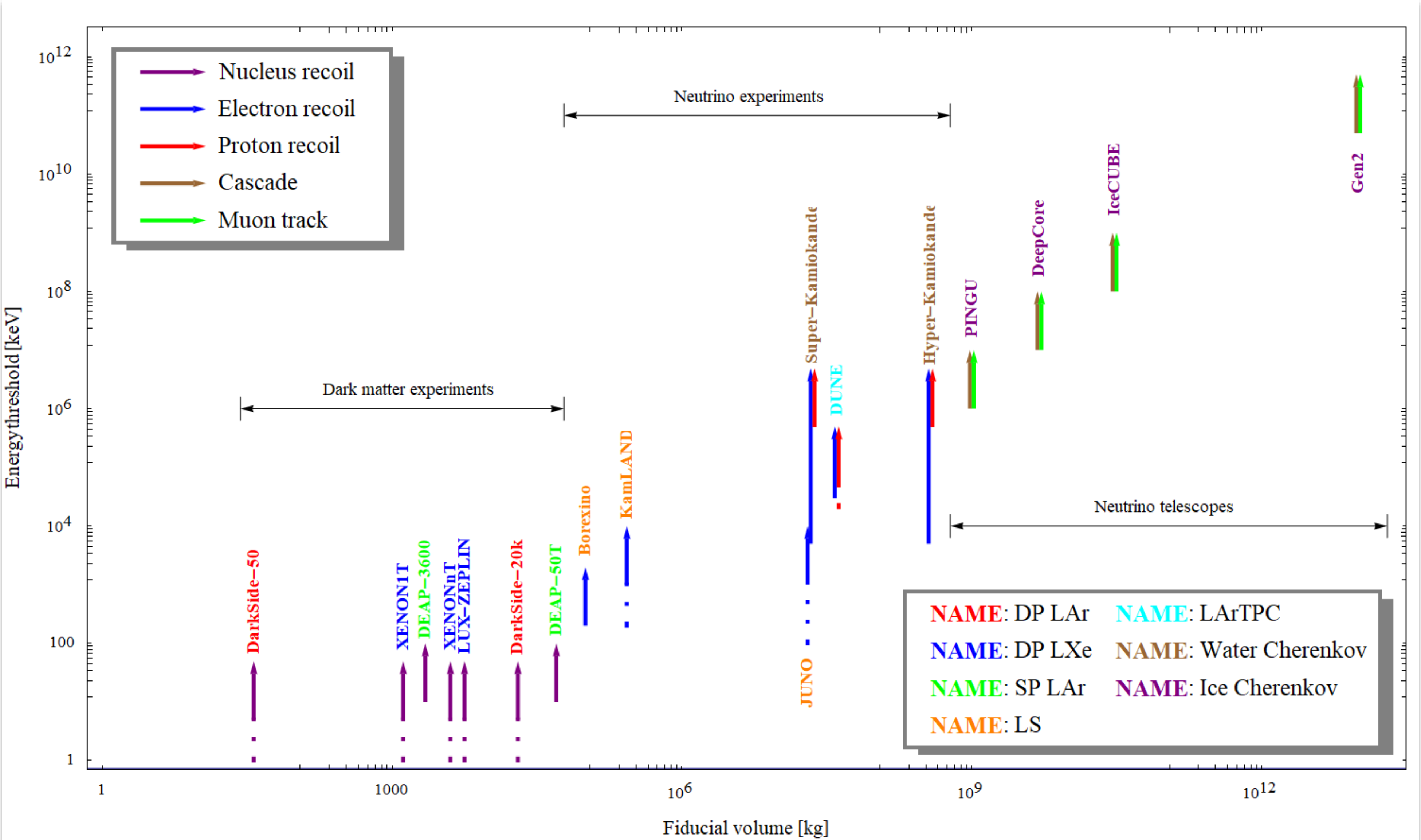
Dark Matter Experiments	Target Material	Volume [t]		Depth [m]	E_{th} [keV]	Resolution			PID	Run Time	Refs.
		Active	Fiducial			Position [cm]	Angular [°]	Energy [%]			
DarkSide –50	LAr DP-TPC	46.4 kg	36.9 kg	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	$\lesssim 10$	–	2013-	[112]
DarkSide –20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	$\lesssim 10$	–	goal: 2021–	[79]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	–	–	2016 –2018	[113, 114]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	–	–	goal: 2020–	[113]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10 - 20$	–	2016-	[99–101]
DEAP –50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[99]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	1,500	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	2.5 MeV: 2	–	goal: 2020–	[115, 116]
Neutrino Experiments	Target Material	Volume [kt]		Depth [m]	E_{th} [MeV]	Resolution			PID	Run Time	Refs.
		Active	Fiducial			Vertex [cm]	Angular [°]	Energy [%]			
Borexino	organic LS	0.278	0.1	3,800 m.w.e.	~ 0.2	~9-17	–	$\frac{5}{\sqrt{E\,(\text{MeV})}}$	–	> 5.6 year	[117]
KamLAND	LS	1	0.2686	1,000	0.2–1	$\frac{12\text{–}13}{\sqrt{E\,(\text{MeV})}}$	–	$\frac{6.4\text{–}6.9}{\sqrt{E\,(\text{MeV})}}$	–	~ 10 year?	[118, 119]
JUNO	LS	–	20	700	< 1, goal: 0.1	$\frac{12}{\sqrt{E\,(\text{MeV})}}$	μ: $L > 5$ m: < 1, $L > 1$ m: < 10	$\frac{3}{\sqrt{E\,(\text{MeV})}}$	$\mu^\pm$ vs $\pi^\pm$, $e^\pm$ vs π^0: difficult	goal: 2021–	[120–122]
DUNE	LArTPC	Total: 17.5 ×4	$\gtrsim 10$ ×4	1500	$e: 30$, p: 21-50	$\lesssim 1 - 2$	$e, \mu: 1$, $\pi^\pm, p, n: 5$	$e: 20$ ($E < 0.4$ GeV), 10 ($E < 1.0$ GeV), $2 + \frac{8}{\sqrt{E/\text{GeV}}}$ ($E > 1.0$ GeV) $p: 10$ ($E < 1.0$ GeV), $5 + \frac{5}{\sqrt{E/\text{GeV}}}$ ($E > 1.0$ GeV)	good $e, \mu, \pi^\pm, p$ separation	10 kt: 2026-, 20 kt: 2027–	[77, 80–84]
SK	Water Cherenkov	Total: 50	22.5	1,000	e: 5, $p: 485$	5 MeV: 95, 10 MeV: 55, 20 MeV: 40	10 MeV: 25, 0.1 GeV: 3, 1.33 GeV: 1.2	10 MeV: 16, 1 GeV: 2.5	e, μ: good	$\gtrsim 14$ year	[123–125]
HK	Water Cherenkov	Total: 258 ×2	187 ×2	Japan: 650, Korea: 1,000	$e: < 5$, $p: 485$	5 MeV: 75, 10 MeV: 45, 15 MeV: 40, 0.5 GeV: 28	similar to SK	better than SK	e, μ: good, $\pi^0, \pi^\pm$: mild	goal: 2027–	[85–87]
Neutrino Telescopes	Target Material	Effective Volume [Mt]		Depth [m]	E_{th} [GeV]	Resolution			PID	Run Time	Refs.
						Vertex [m]	Angular [°]	Energy [%]			
IceCube	Ice Cherenkov	100 GeV: ~ 30, 200 GeV: ~ 200		1,450 Ice	~ 100	vertical: 5, horizontal: 15	μ-track: ~ 1, shower: ~ 30	100 GeV: 28, 1 TeV: 16	only μ	2011– (2008)	[89, 126]
DeepCore	Ice Cherenkov	10 GeV: ~ 5, 100 GeV: ~ 30		2,100 Ice	~ 10	better	μ-track: $\sim$1, shower: $\gtrsim 10$	–	only μ	2011– (2010)	[88, 89]
IceCube Upgrade	Ice Cherenkov	–		2,150 Ice	$\mathcal{O}(1)$	much better	5 GeV: ~ 20, 10 GeV: ~ 15	–	only μ	goal: 2023	[127]
PINGU	Ice Cherenkov	1 GeV: $\gtrsim 1$, 10 GeV: ~ 5		2,100 Ice	~ 1	much better	1 GeV: 25, 10 GeV: 10	1 GeV: 55, 10 GeV: 25	only μ	$>$ 2023	[128, 129]
Gen2	Ice Cherenkov	~ 10 Gt		1,360 Ice	~ 50 TeV	worse	μ-track: < 1 shower: ~ 15	–	only μ	–	[130]

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

- Many existing/upcoming experiments are potentially capable of testing models conceiving BDM signals.
- Additional physics opportunity on top of the main mission of each experiment.

Many More Well-Motivated Exps.

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]



Detectors are complementary to one another rather than superior to the other!