Searches for "Relativistic" Inelastic Dark Matter [redacted]

Doojin Kim

INFN LNF Autumn Institute II, Frascati, Italy

November 28th, 2017

Based on DK, J.-C. Park, S. Shin, PRL119, 161801 (2017)
G. Giudice, DK, J.-C. Park, S. Shin, 1711. xxxxx

Searches for "Relativistic" Inelastic Dark Matter at WIMP Detectors

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- Direct detection experiment current status, boosted dark matter search, …

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- Benchmark models, expected signatures, …

III. Signal Detection

- Benchmark detectors, detection technology, expected signal features, …

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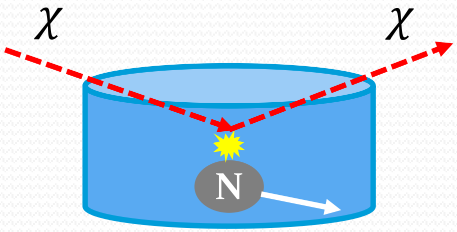

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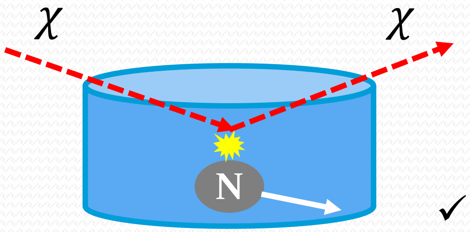

<u>Non-relativistic</u>, <u>elastic</u> scattering of <u>weak-scale</u> DM with <u>nuclei</u>

- ✓ $E_{\text{recoil}} \sim 1 - 100$ keV
- ✓ Detectors designed to be sensitive to this energy scale

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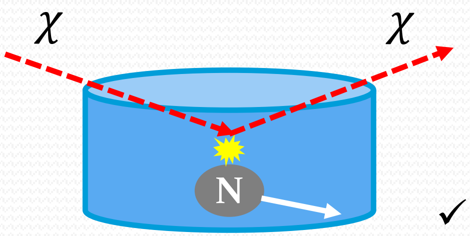

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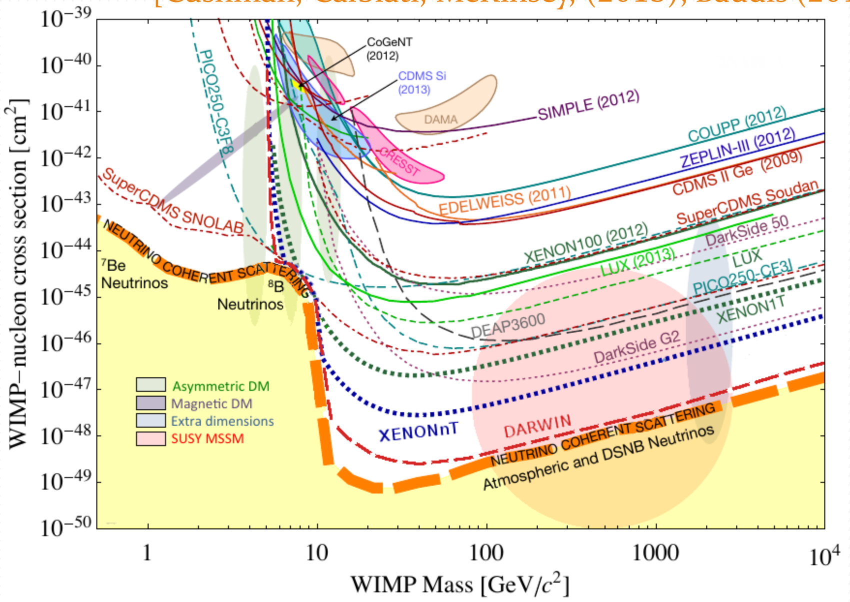
[Cushman, Calbiati, McKinsey, (2013); Baudis (2014)]



- ✓ Null observation of WIMP signals
- ✓ A wide range of parameter space already excluded
- ✓ Close to the neutrino "floor"
- ✓ **Need new ideas!**

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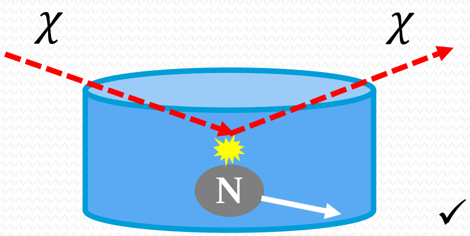

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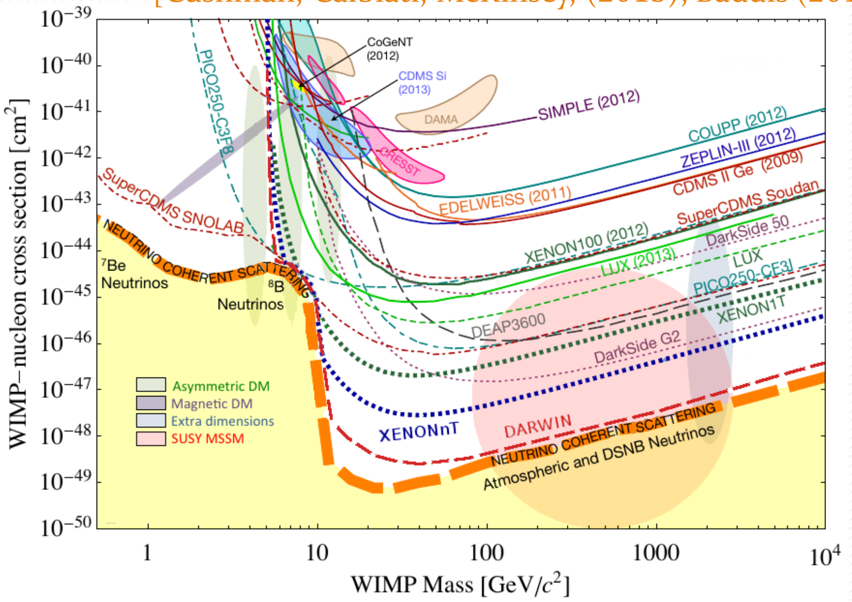

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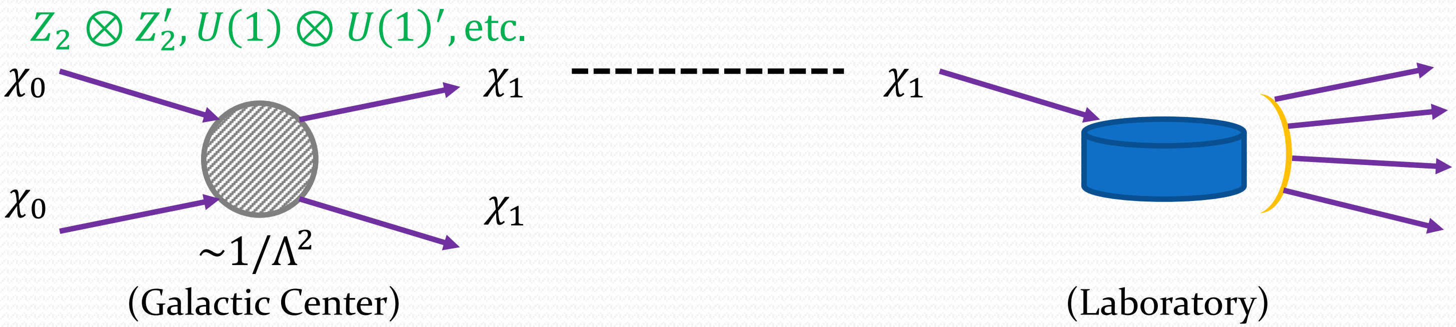

- ❖ Overall relic determined by “Assisted” Freeze-out mechanism [Belanger, Park (2011)]
- ❖ Heavier DM χ_0: dominant relic, non-relativistic, not directly communicating with SM (hard to detect them due to tiny coupling to SM)
- ❖ Lighter DM χ_1: directly communicating with SM, subdominant relic (hard to detect them due to small amount)

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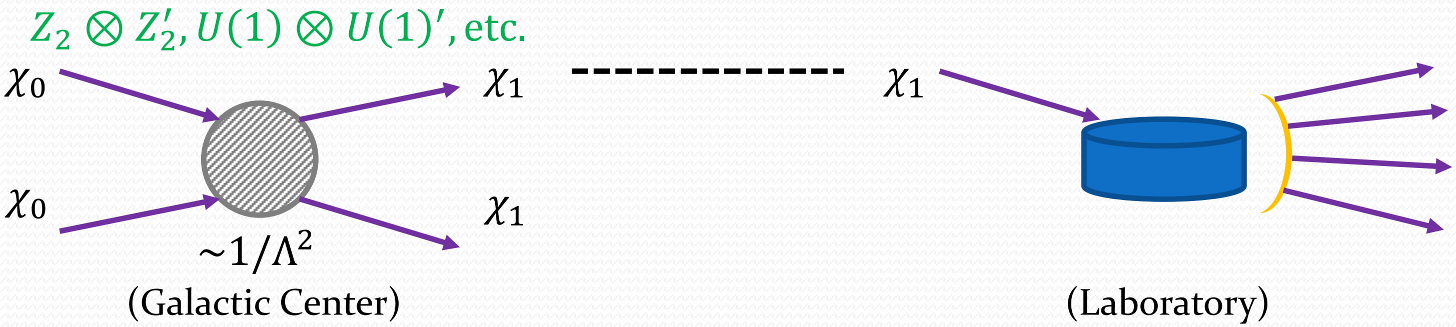

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  - ❖ Lighter DM χ_1: directly communicating with SM, subdominant relic (hard to detect them due to small amount)
- ☐ χ_1 can be relativistic at the current universe (non-relativistic as a relic): relativistic DM search

Light Boosted DM Detection

☐ Flux of boosted χ_1 near the earth

$$\mathcal{F}_{\chi_1} \sim \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$$

← from DM number density

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- ❑ Setting $\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}$ to be $\sim 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$ and assuming NFW DM halo profile, one finds

$\mathcal{F}_{\chi_1} \sim 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for WIMP mass-range χ_0

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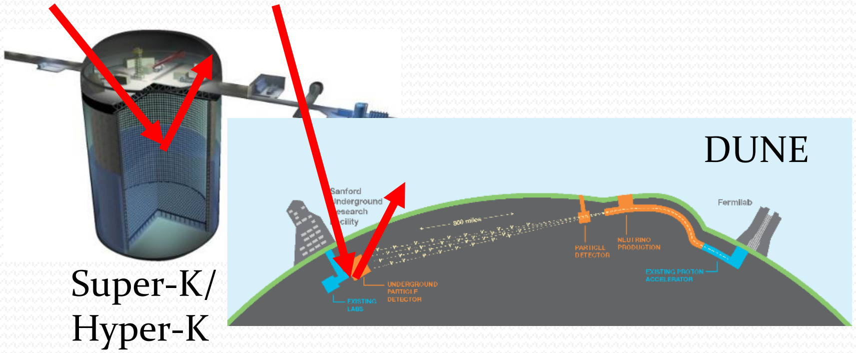
- No sensitivity in conventional dark matter direct detection experiments ⇒ large-volume (neutrino) detectors are motivated, e.g., Super-K/Hyper-K, DUNE



  - ✓ Elastic scattering [Agashe et al (2014); Berger et al (2014); Kong et al. (2014); Alhazmi et al. (2016)]
  - ✓ Inelastic scattering [**DK**, Park, Shin (2016)]

Pumping up Light DM Flux

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- Elastic nucleon scattering in the context of gauged baryon number/higgs portal models

  [Cherry, Frandsen, Shoemaker (2015)]: recoil nucleon ***NON***-relativistic

Why NOT Electron Scattering!

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e-scattering will be excellent in search for (boosted) light dark matter particles!

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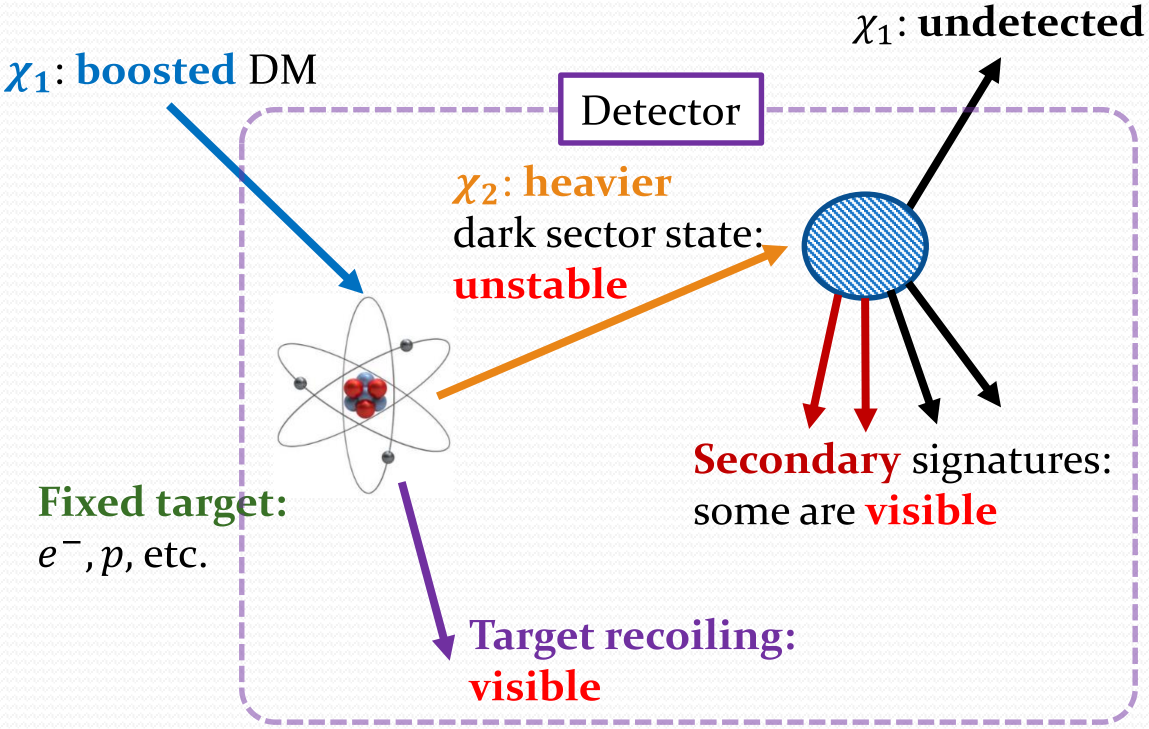
*In*elastic BDM



χ_1: **boosted** DM

Detector

χ_1: **undetected**

χ_2: **heavier**
dark sector state:
unstable

Fixed target:
e^-, p, etc.

Secondary signatures:
some are **visible**

Target recoiling:
visible

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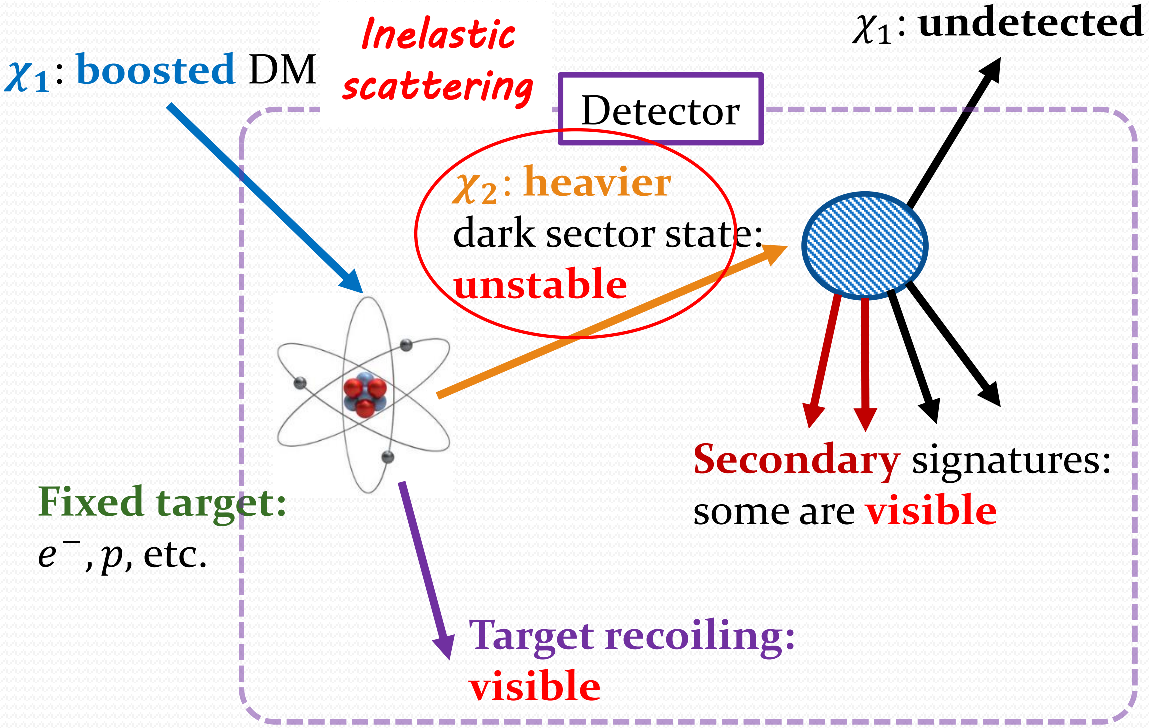

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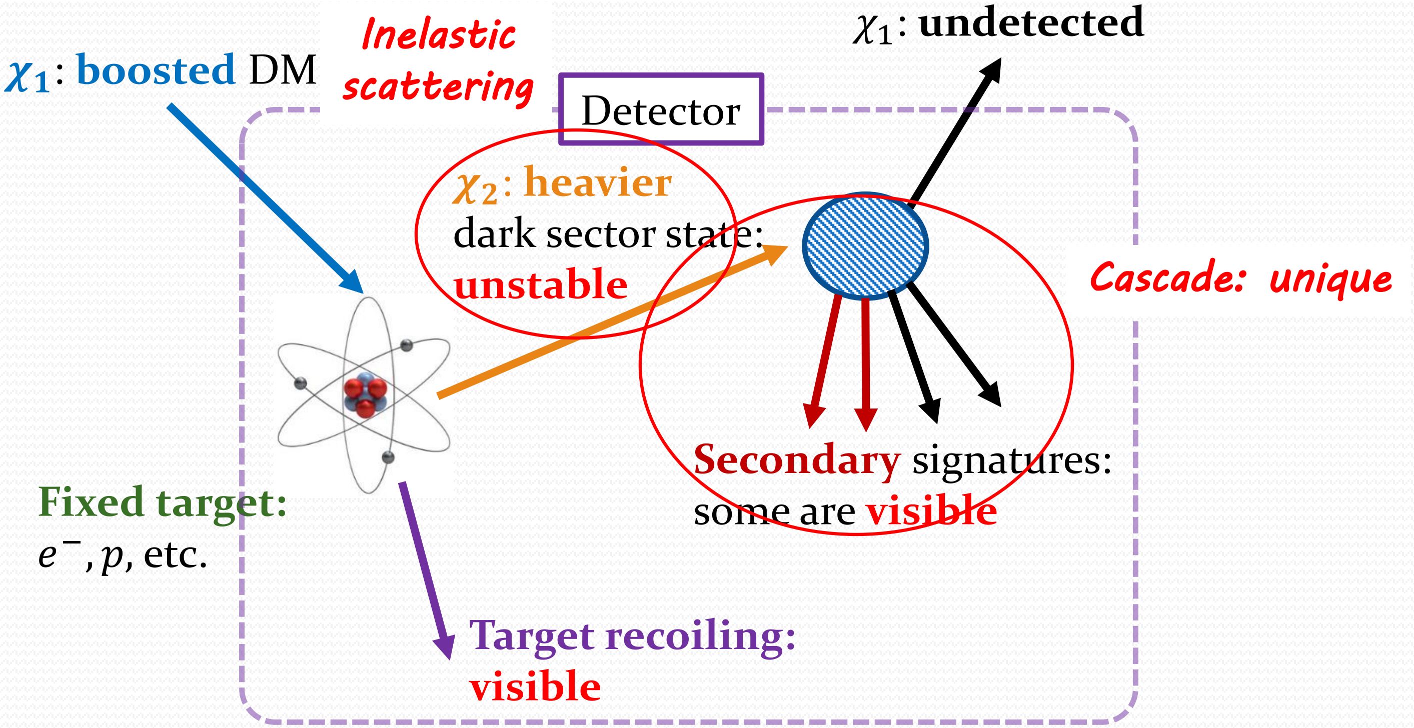

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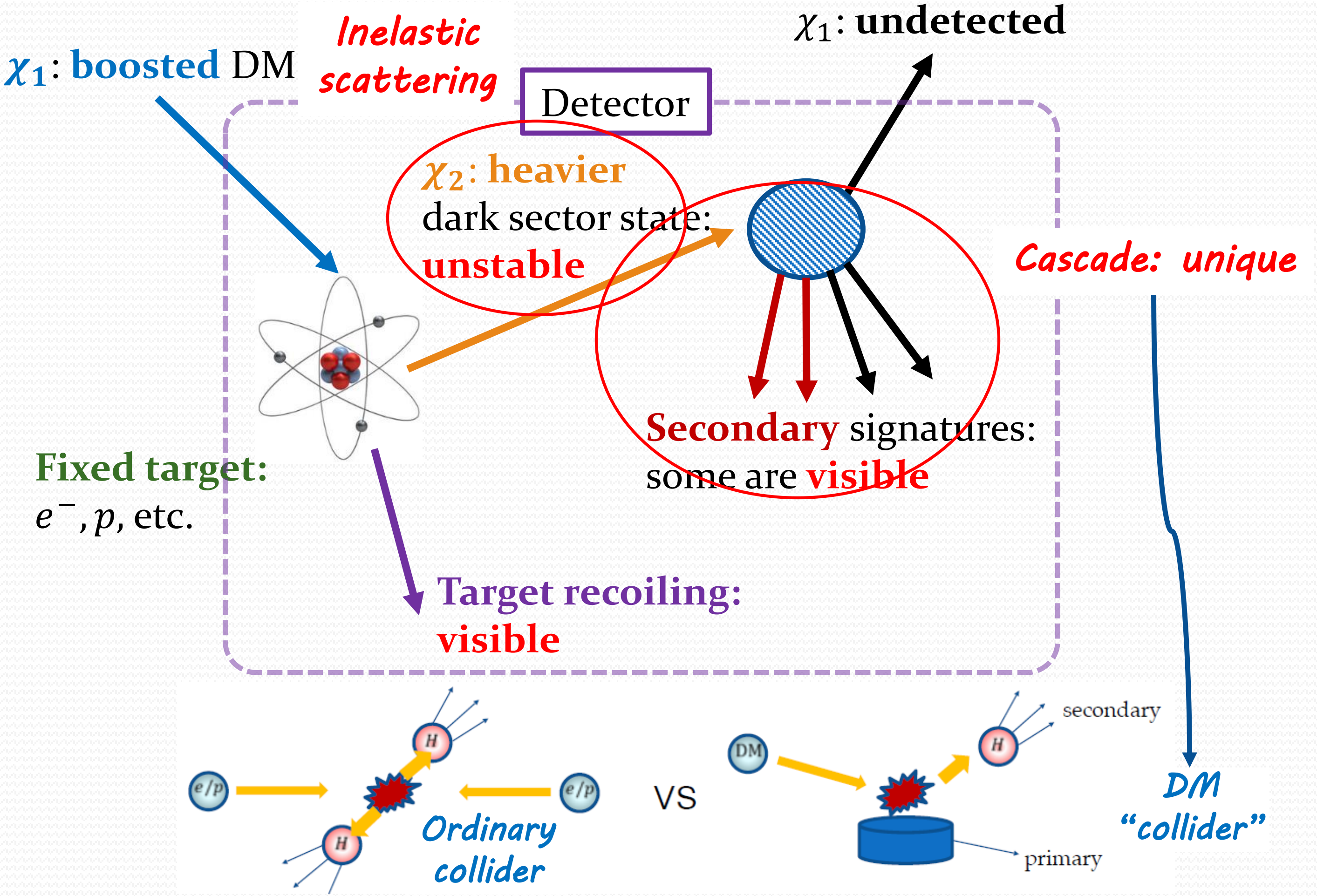

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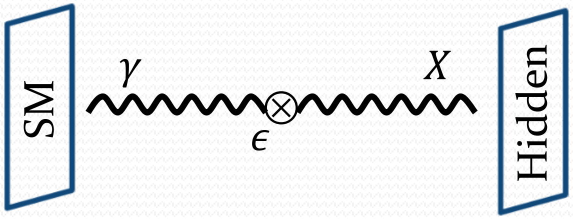
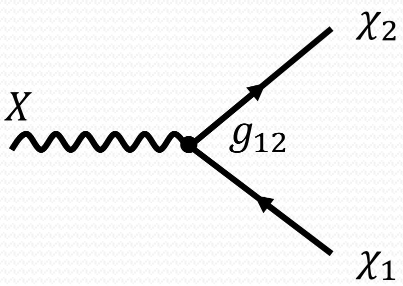
Benchmark Model

$$\mathcal{L}_{\mathrm{int}} \ni -\frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^{\mu}\chi_1 X_{\mu} + g_{12}\bar{\chi}_2\gamma^{\mu}\chi_1 X_{\mu} + \mathrm{h.c.} + (\mathrm{others})$$



- Vector portal (e.g., dark gauge boson scenario) [Holdom (1986)]
- Fermionic DM
  - χ_2: a heavier (unstable) dark-sector state
  - Flavor-conserving neutral current ⇒ elastic scattering
  - Flavor-changing neutral current ⇒ **inelastic scattering** [Tucker-Smith, Weiner (2001); Kim, Seo, Shin (2012)]



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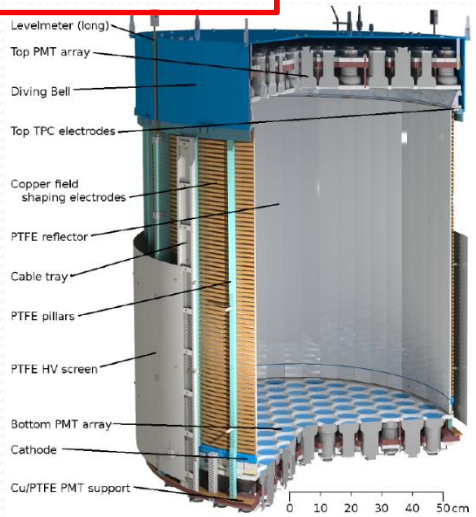
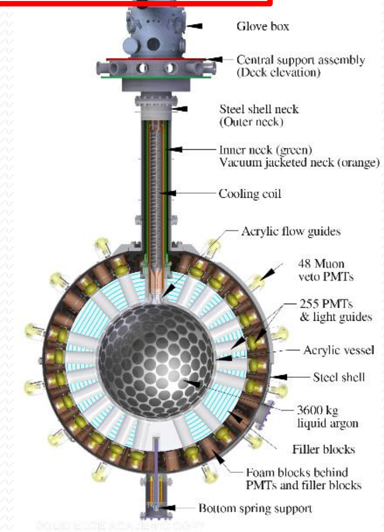
Benchmark Detectors

Xenon1T

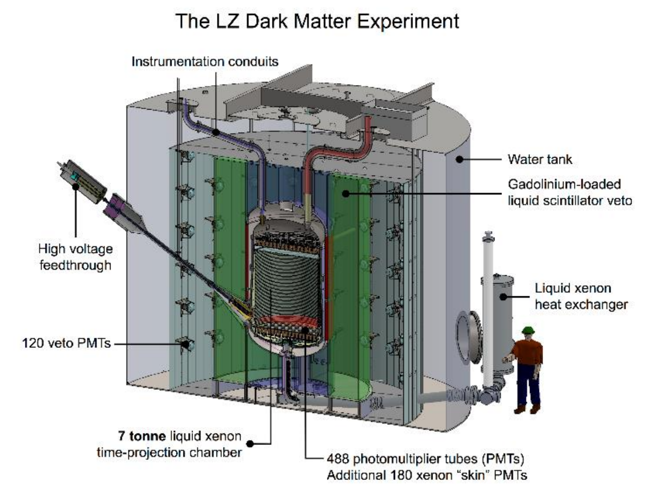


DEAP3600

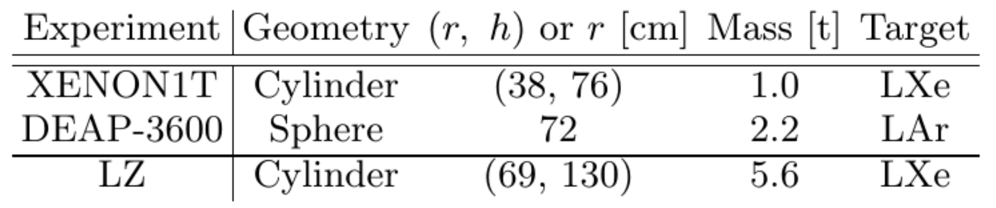


ongoing

LUX-ZEPLIN(LZ)



projected

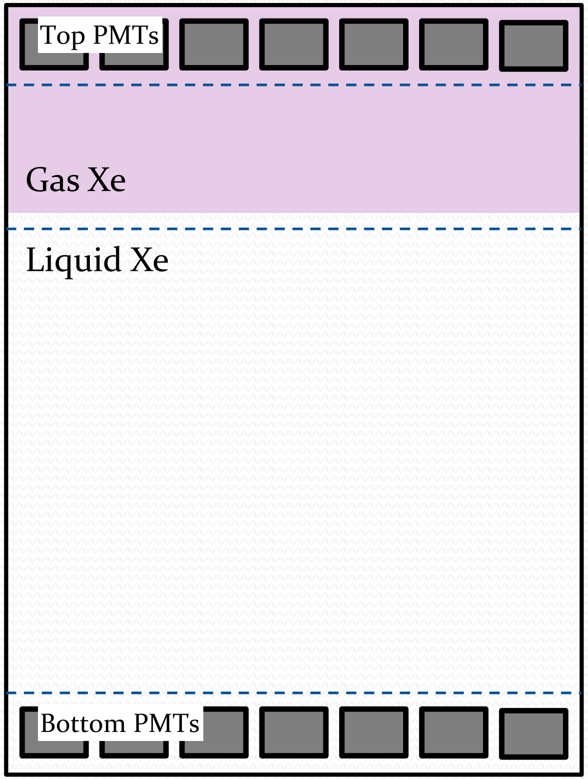


Experiment	Geometry	$(r,\ h)$ or r [cm]	Mass [t]	Target
XENON1T	Cylinder	(38, 76)	1.0	LXe
DEAP-3600	Sphere	72	2.2	LAr
LZ	Cylinder	(69, 130)	5.6	LXe

[Numbers are for fiducial volumes.]

Detection Technology

- Dual phase detection technology



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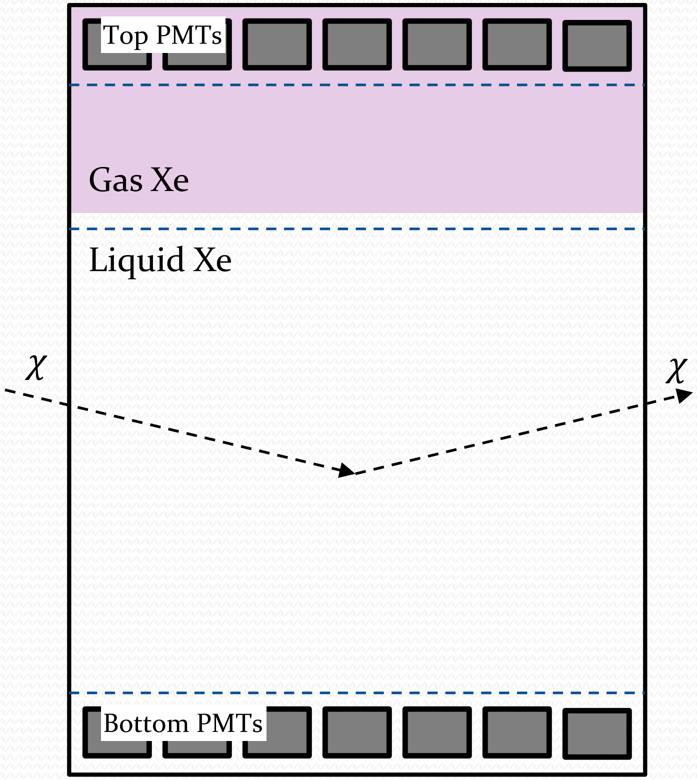

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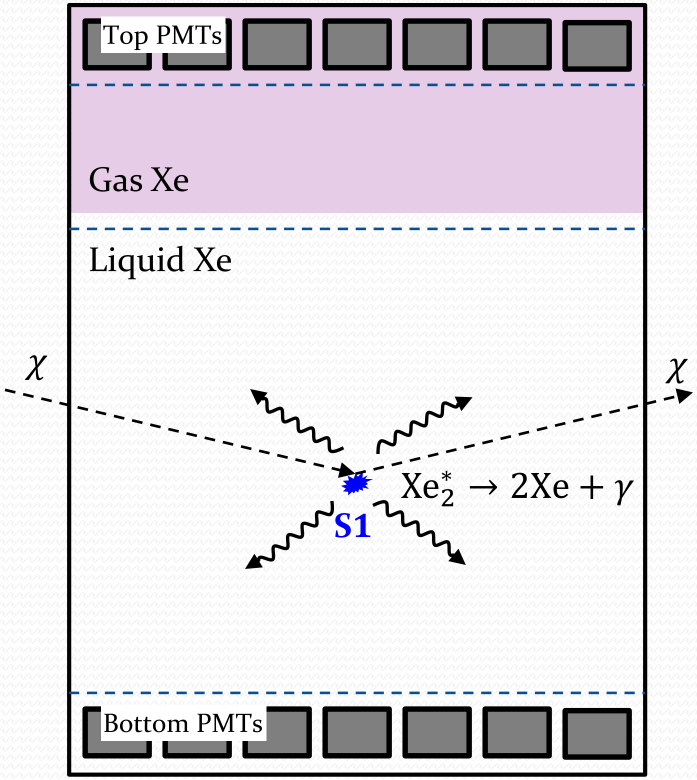

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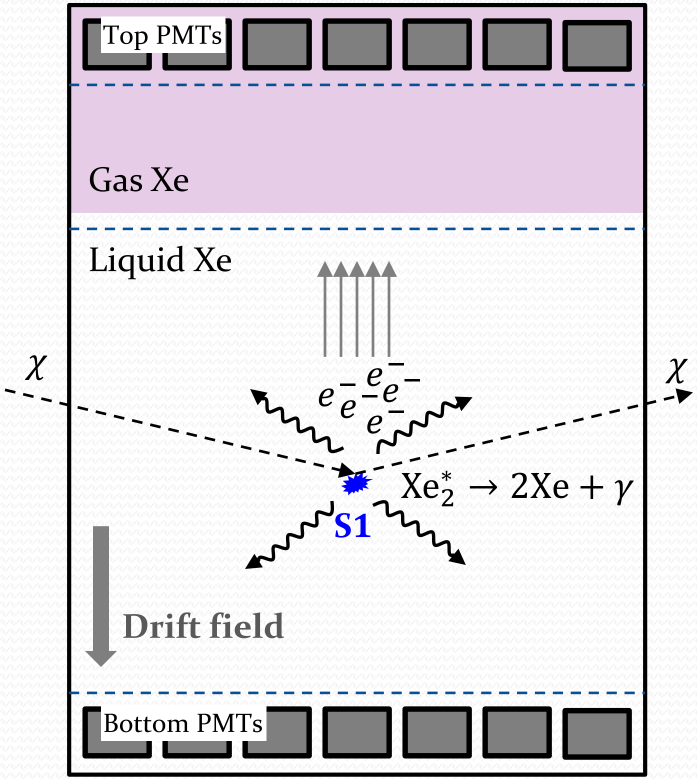

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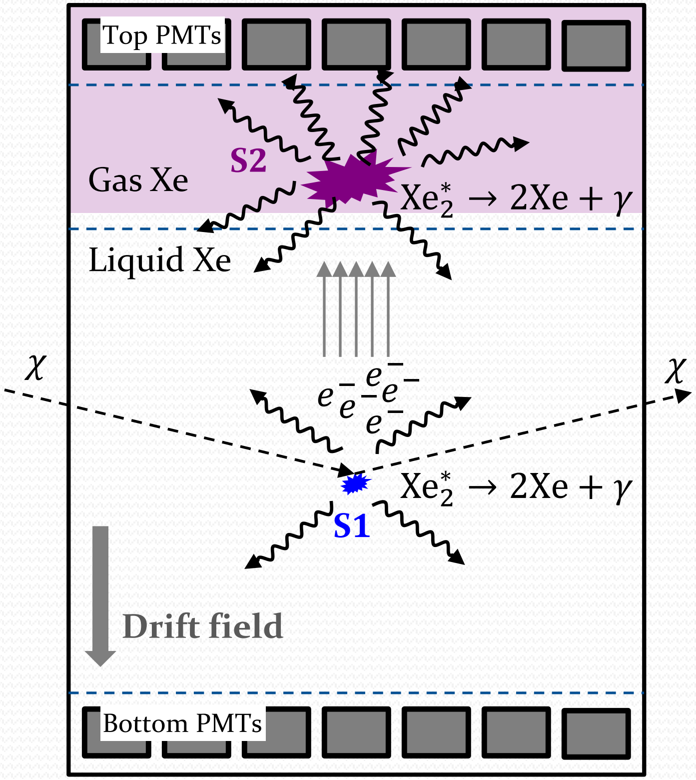

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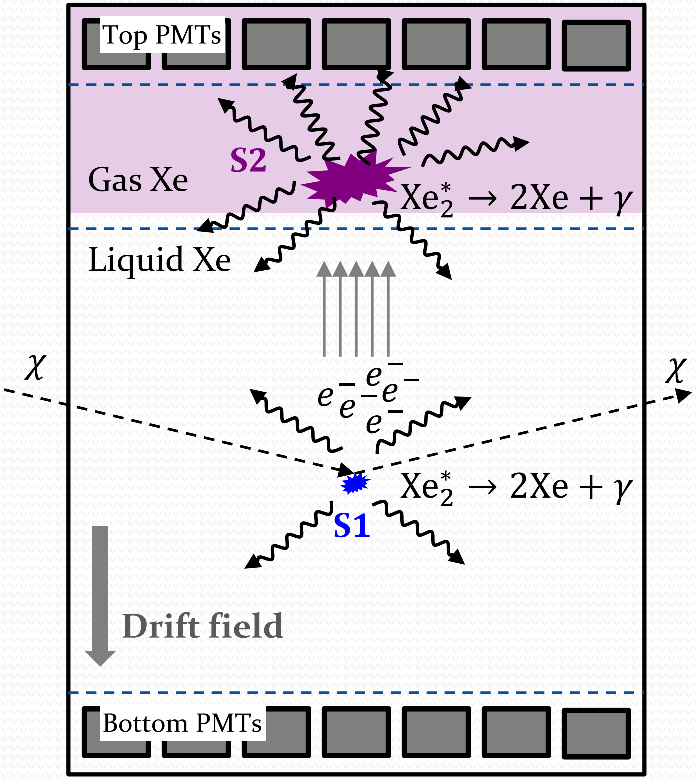

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❑ Time difference between S1 and S2 giving the depth of the scattering point (~0.1mm resolution)

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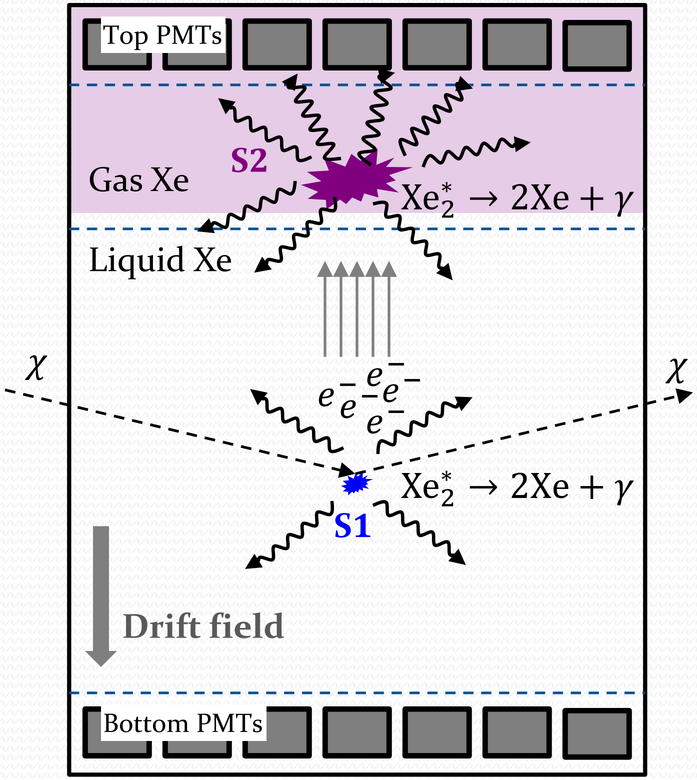

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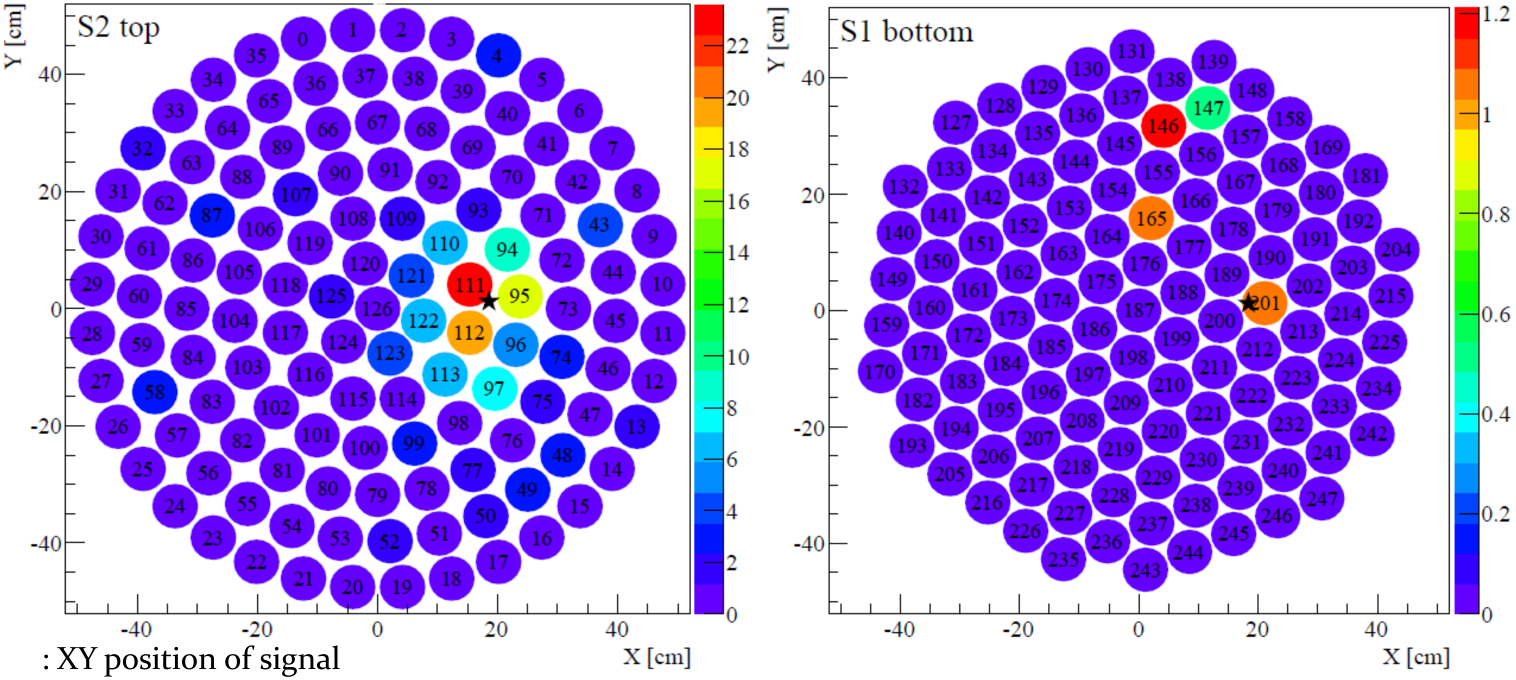
Cf.) S2 not available at DEAP3600

Detection Technology: XY Plane

- **LOW** energy source (^{241}AmBe)



[★ : XY position of signal
Color : uncorrected photoelectrons]

[Xenon Collaboration (2017)]

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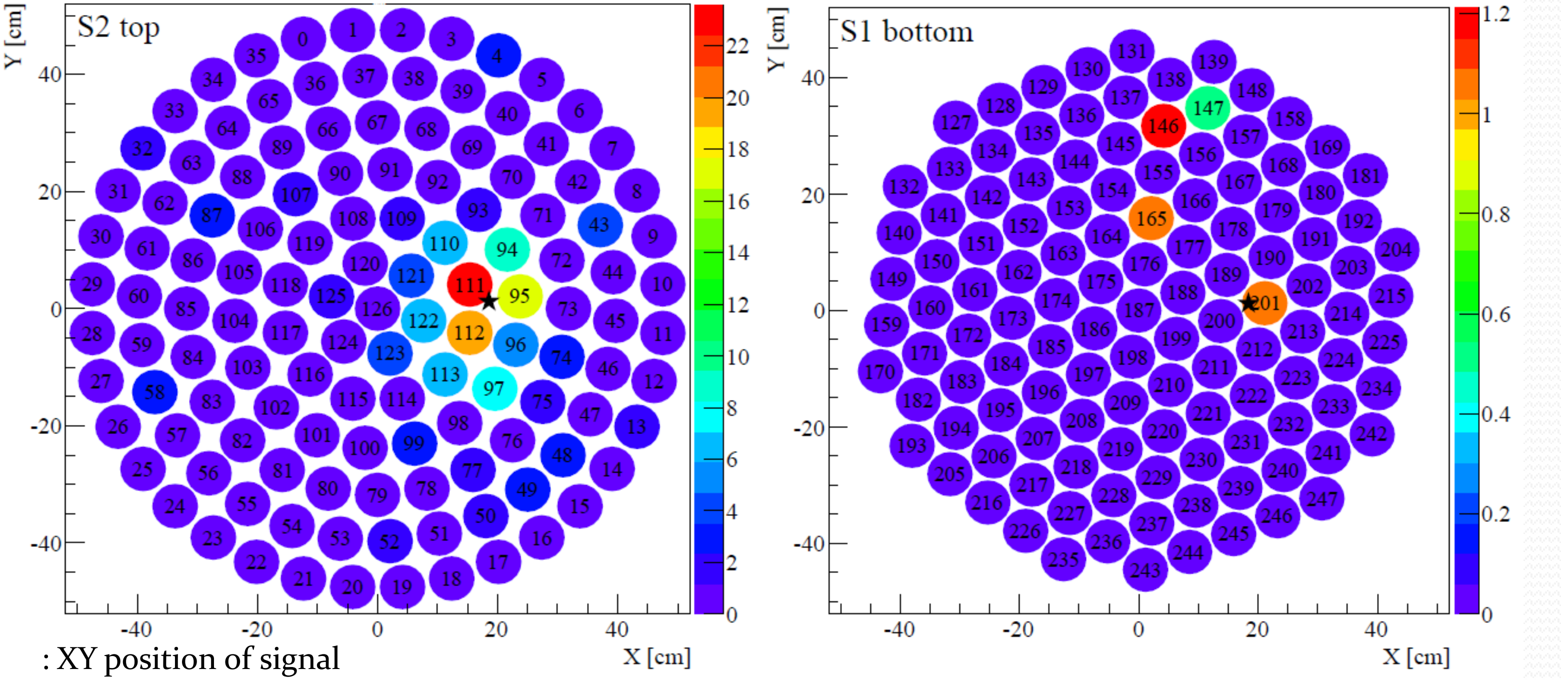

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[Xenon Collaboration (2017)]

- ❑ Likelihood analysis allowing position resolution in XY plane as good as < 2 cm (may be better with high energy source [LUX collaboration (2017)])

“Disclaimer”

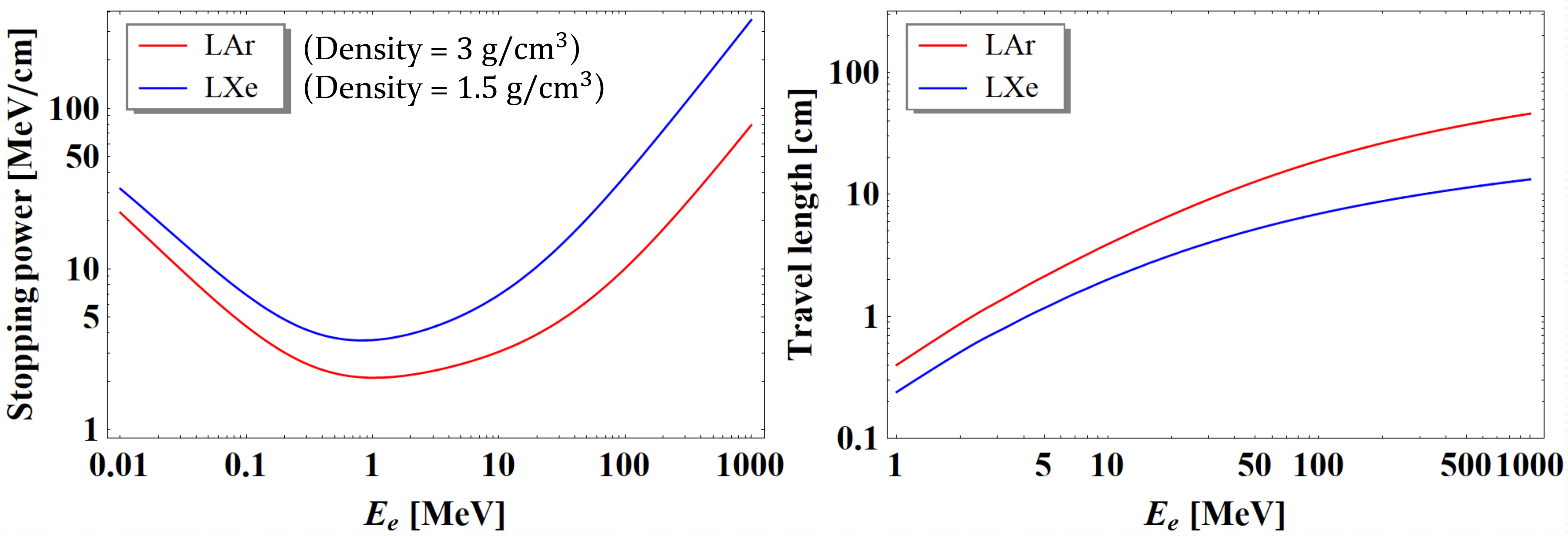
- ☐ No dedicated detector studies with high-energetic recoil signals
- ☐ Doing our best to make as reasonable estimate and expectation as possible

High-energetic DM Signal Detection

- ☐ Point-like scattering position?

High-energetic DM Signal Detection

☐ Point-like scattering position? → Expect a **sizable track**!



[Material property available at NIST (https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html)]

High-energetic DM Signal Detection

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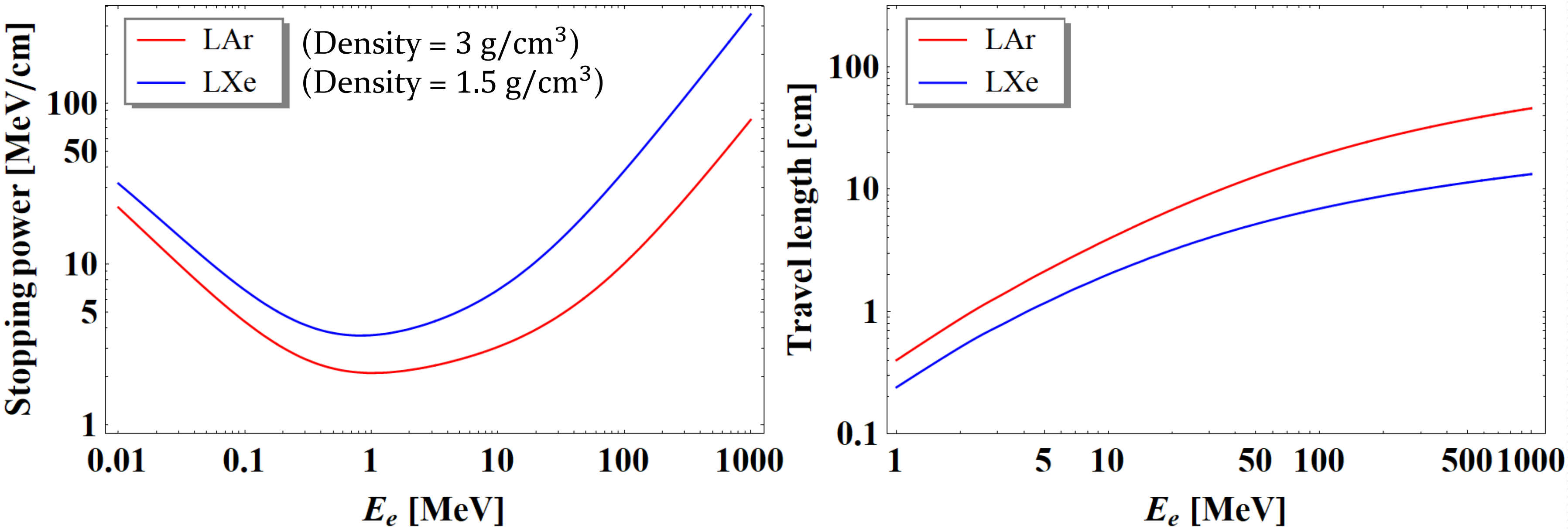

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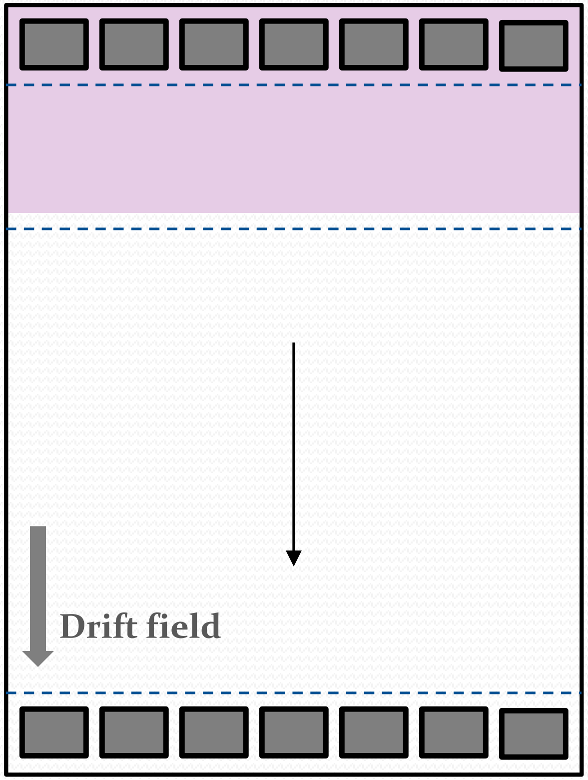
- ☐ Expect tracks of **2 – 10 cm** (with LXe) for energy regime of interest

Expected Pattern: Vertical Track

- ❑ A given vertical track



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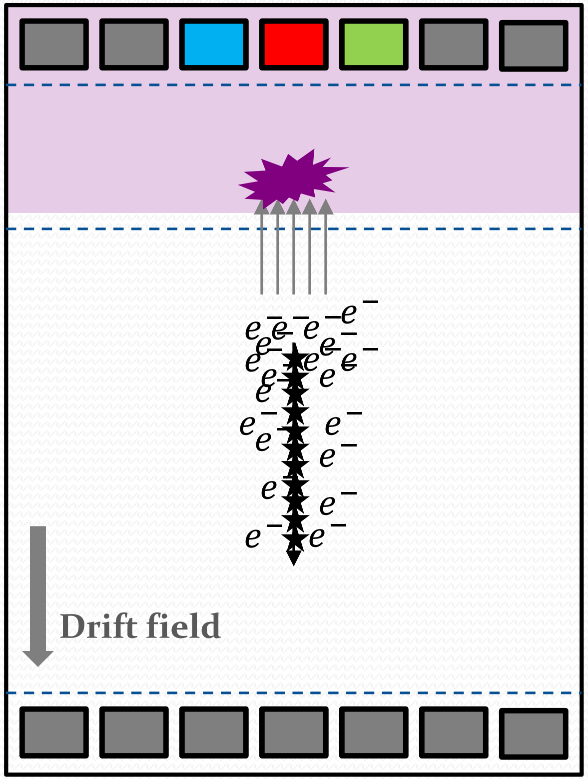

1) can be considered as an array of scattering points,
2) Free electrons released at each point: more (less) electrons at the starting (ending) point,
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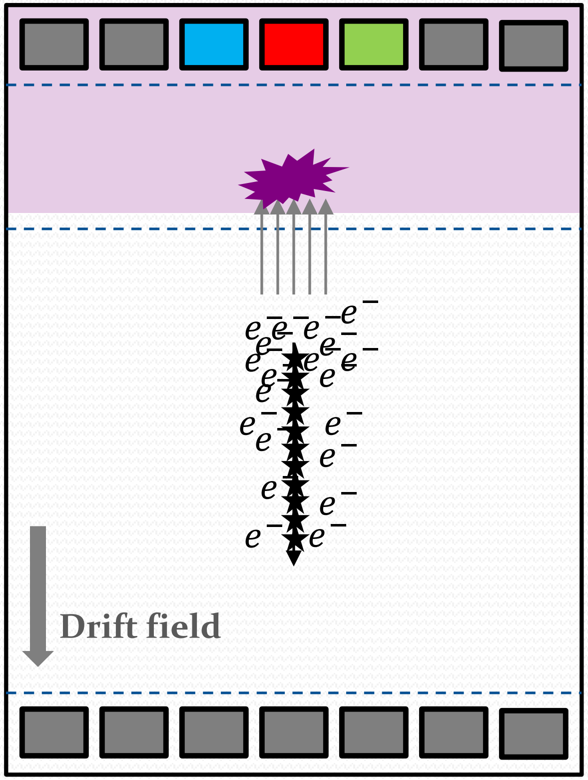

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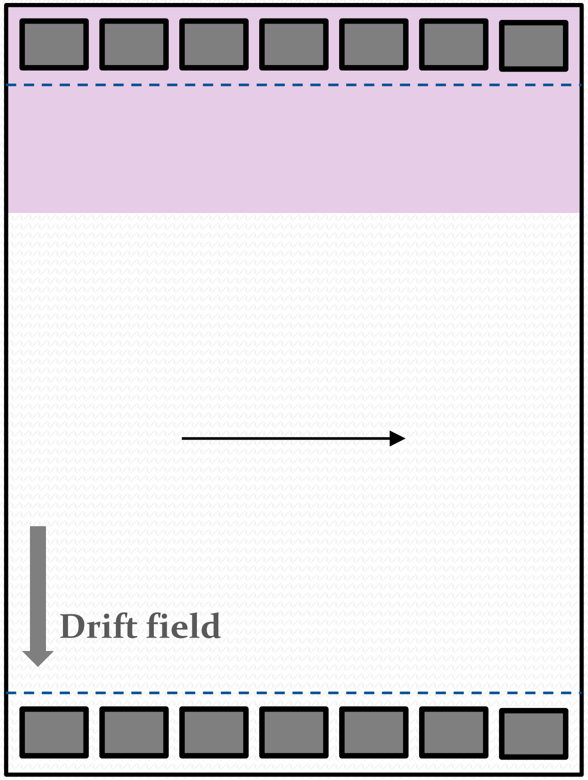
✓ Expect (relatively) **easy identification of a lengthy track** plus **more precise track/energy reconstruction** (than the horizontal track in the next slide)

Expected Pattern: Horizontal Track

- ❑ For a given horizontal track



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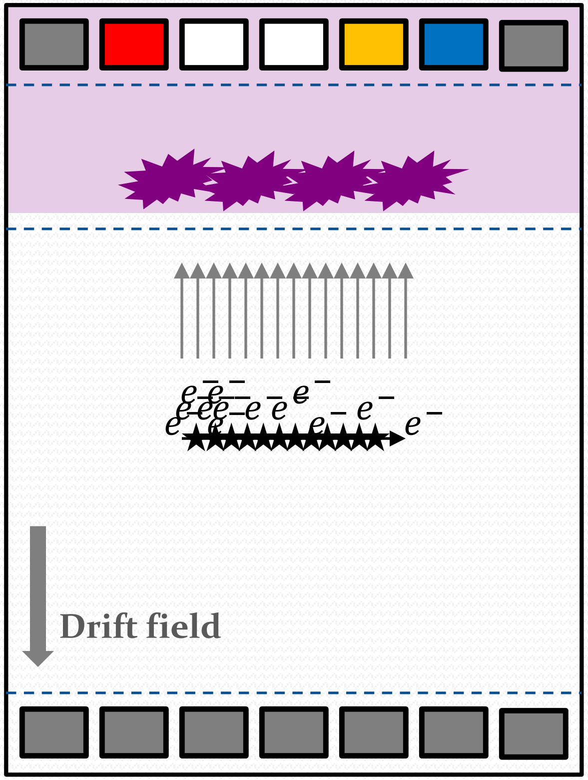
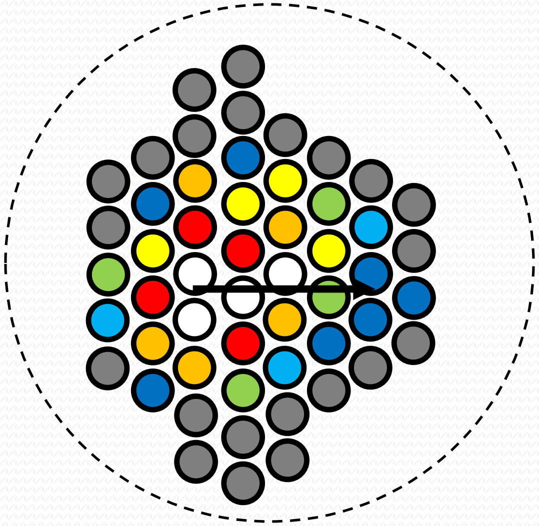


1) Expect (almost) simultaneous charging of several PMTs, some of which may saturate



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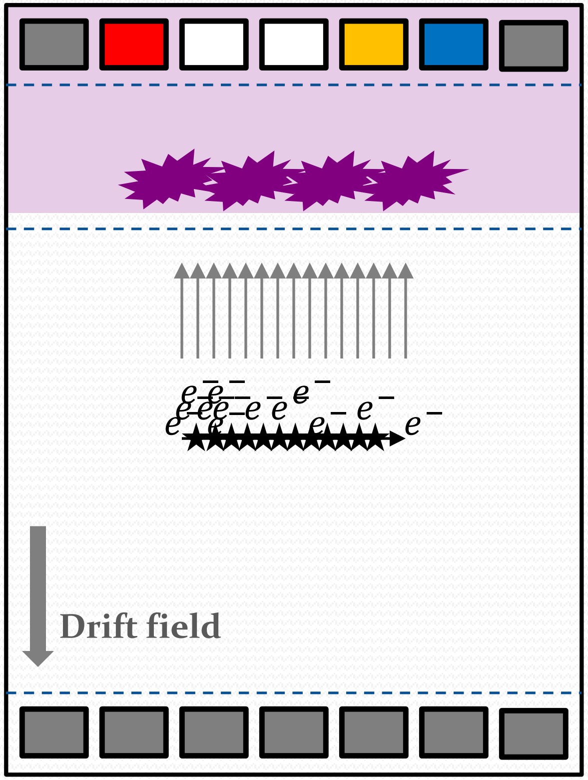

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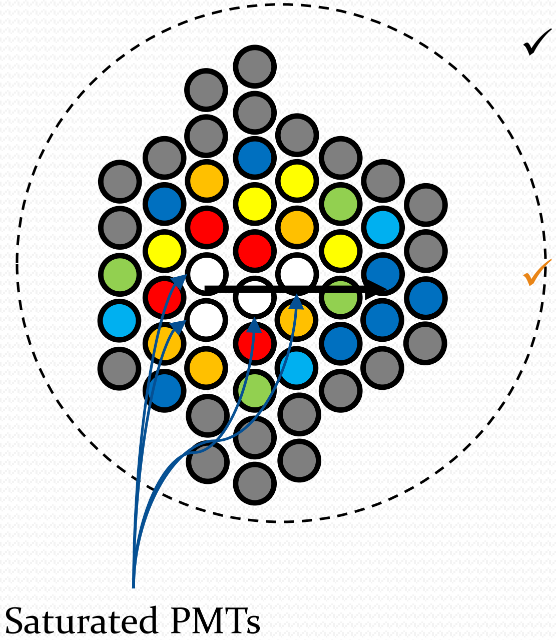

- ✓ Expect **identification of a lengthy track** is doable/ achievable
- ✓ **Track/energy recon.** may require likelihood analysis with unsaturated PMTs

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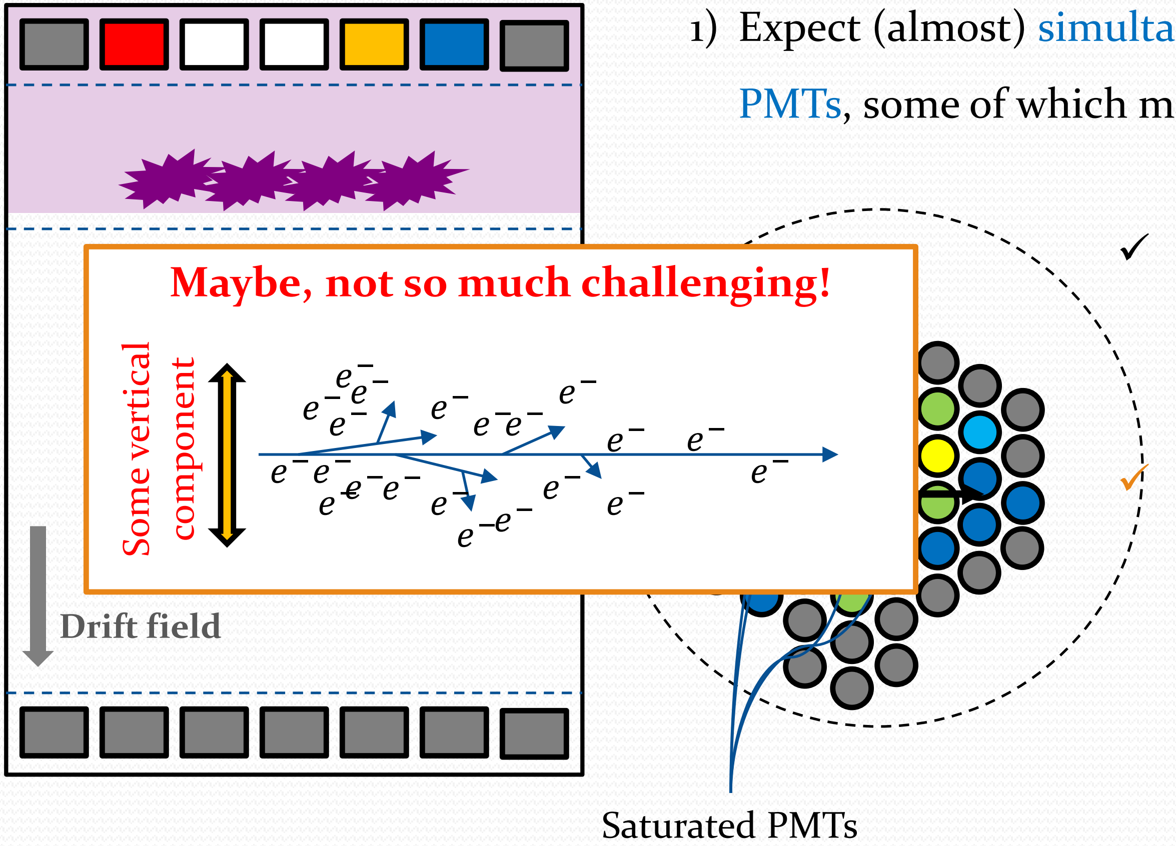

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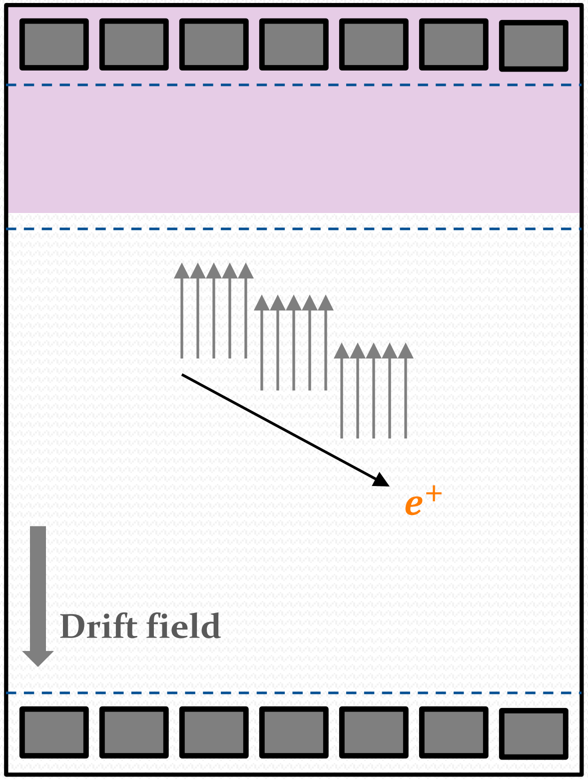
Positron Signature: Bragg Peak

- ☐ A given positron track



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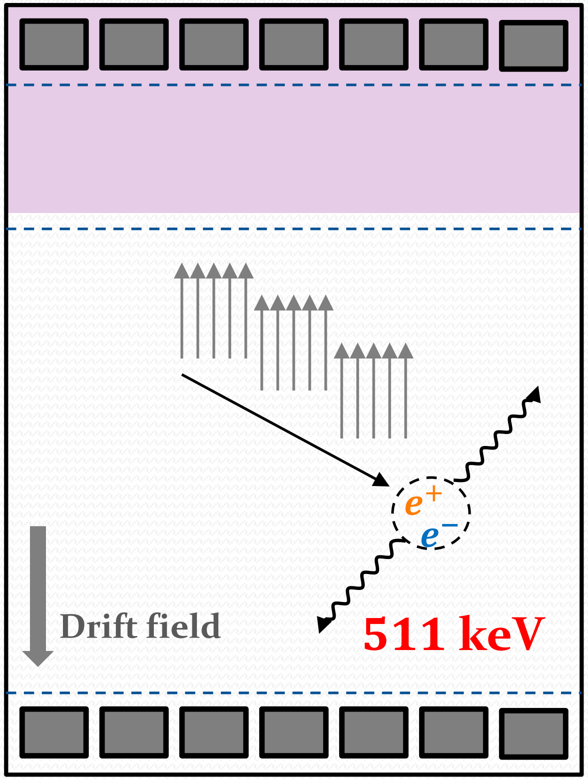


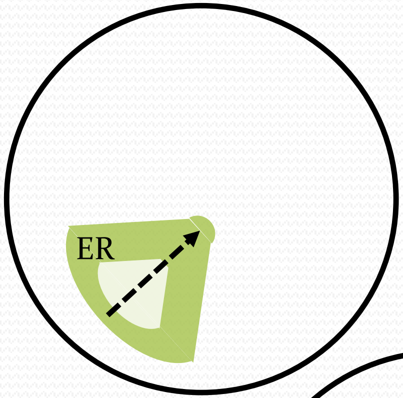
1) stops and gets annihilated with a (nearby) electron, creating **a characteristic signature of Bragg Peak**!!!

   ⇒ Additional handle to identify positrons (or positron tracks)

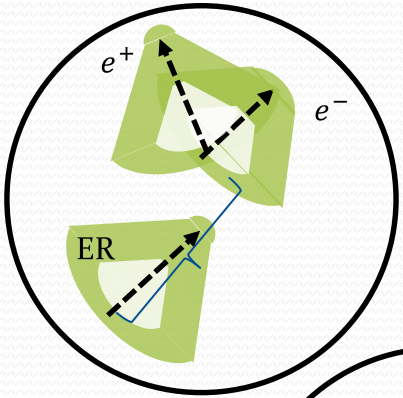
   ⇒ Cf.) DEAP having better acceptance for the Bragg peak due to its spherical geometry

Expected DM Signals: XY Plane-view

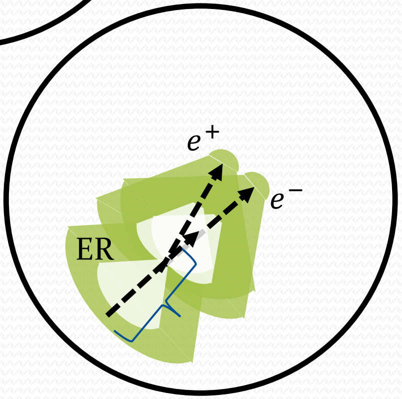
☐ Tracks **POP UP** inside the fiducial volume, **NOT** from outside!



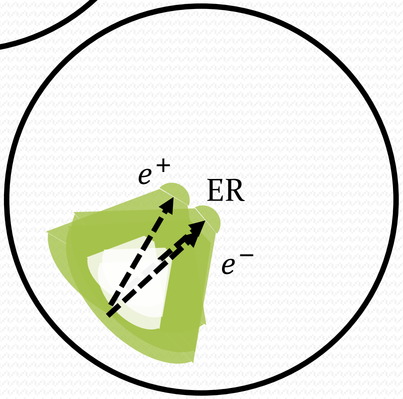
- Ordinary elastic scattering: one track



- Three distinguishable tracks
- May show a displaced secondary vertex



- Three overlaid tracks
- Density pattern different from that is the elastic scattering
- Displaced vertex identifiable



- (Relatively) prompt secondary process
- Three overlaid tracks
- Density pattern different from that is the elastic scattering
- Displaced vertex non-identifiable

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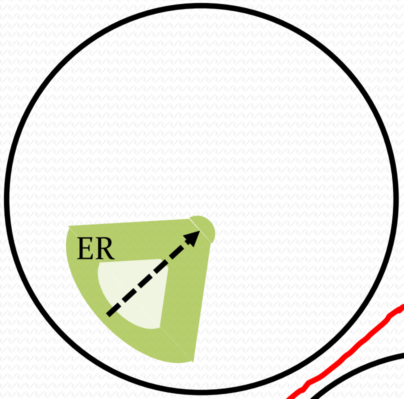

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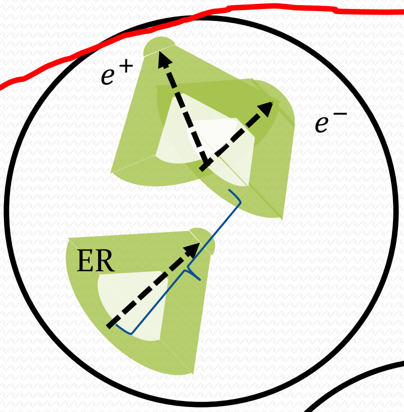

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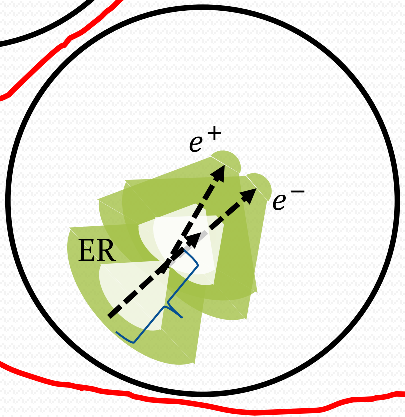

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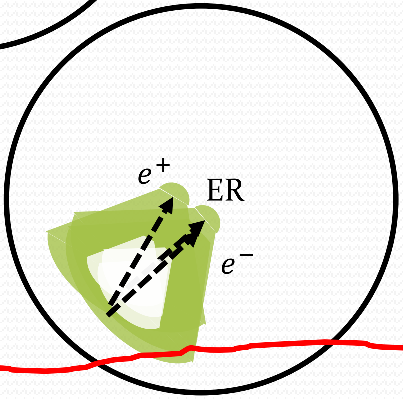

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- Three overlaid tracks
- Density pattern different from that is the elastic scattering
- Displaced vertex non-identifiable

❑ Multiple tracks/displaced vertex necessary only for post-discovery (e.g., elastic vs. inelastic)

Cf.) DEAP3600: displaced vertex $\gtrsim$ 6.5 cm identifiable with S1 only by likelihood methods

Potential Backgrounds

☐ Any SM backgrounds creating an electron recoil track appearing inside the fiducial volume?

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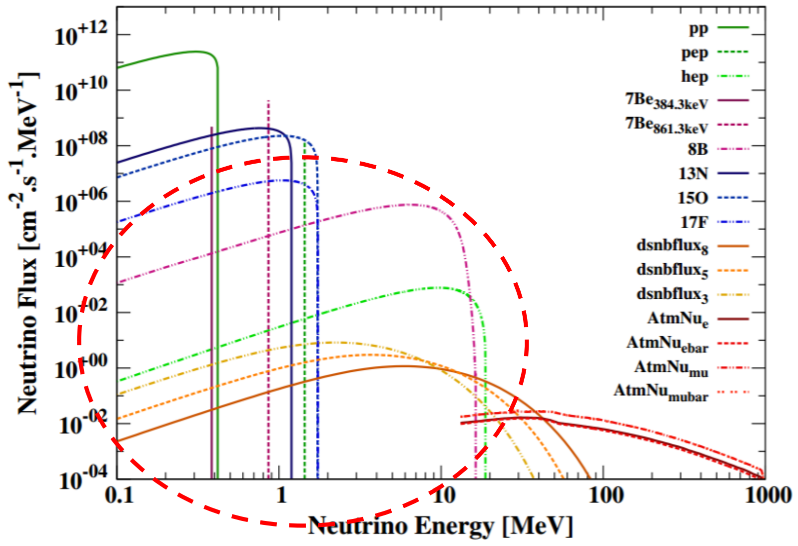

[Ruppin et al., (2014)]

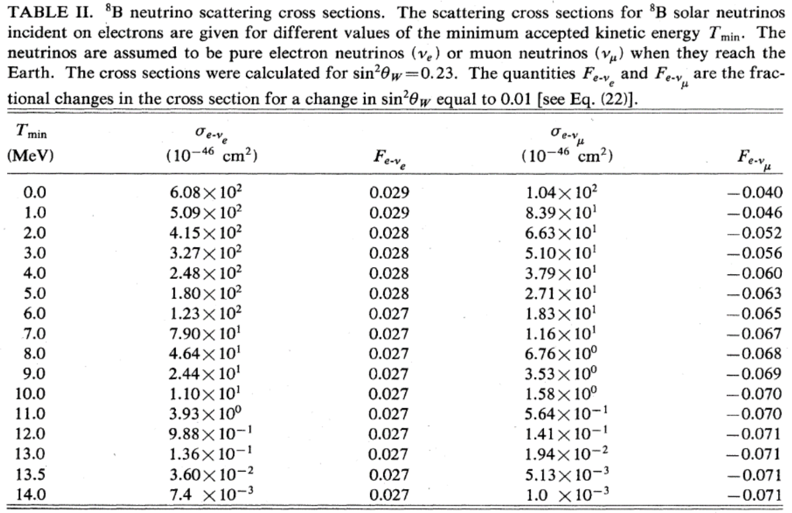

TABLE II. ^{8}B neutrino scattering cross sections. The scattering cross sections for ^{8}B solar neutrinos incident on electrons are given for different values of the minimum accepted kinetic energy $T_{\min}$. The neutrinos are assumed to be pure electron neutrinos (ν_e) or muon neutrinos (ν_μ) when they reach the Earth. The cross sections were calculated for $\sin^2\theta_W = 0.23$. The quantities $F_{e\text{-}\nu_e}$ and $F_{e\text{-}\nu_\mu}$ are the fractional changes in the cross section for a change in $\sin^2\theta_W$ equal to 0.01 [see Eq. (22)].

$T_{\min}$ (MeV)	$\sigma_{e\text{-}\nu_e}$ (10^{-46} cm^2)	$F_{e\text{-}\nu_e}$	$\sigma_{e\text{-}\nu_\mu}$ (10^{-46} cm^2)	$F_{e\text{-}\nu_\mu}$
0.0	6.08×10^{2}	0.029	1.04×10^{2}	−0.040
1.0	5.09×10^{2}	0.029	8.39×10^{1}	−0.046
2.0	4.15×10^{2}	0.028	6.63×10^{1}	−0.052
3.0	3.27×10^{2}	0.028	5.10×10^{1}	−0.056
4.0	2.48×10^{2}	0.028	3.79×10^{1}	−0.060
5.0	1.80×10^{2}	0.028	2.71×10^{1}	−0.063
6.0	1.23×10^{2}	0.027	1.83×10^{1}	−0.065
7.0	7.90×10^{1}	0.027	1.16×10^{1}	−0.067
8.0	4.64×10^{1}	0.027	6.76×10^{0}	−0.068
9.0	2.44×10^{1}	0.027	3.53×10^{0}	−0.069
10.0	1.10×10^{1}	0.027	1.58×10^{0}	−0.070
11.0	3.93×10^{0}	0.027	5.64×10^{-1}	−0.070
12.0	9.88×10^{-1}	0.027	1.41×10^{-1}	−0.071
13.0	1.36×10^{-1}	0.027	1.94×10^{-2}	−0.071
13.5	3.60×10^{-2}	0.027	5.13×10^{-3}	−0.071
14.0	$7.4\ \times10^{-3}$	0.027	$1.0\ \times10^{-3}$	−0.071

[Rev. Mod. Phys., Vol. 59, No. 2, April 1987]

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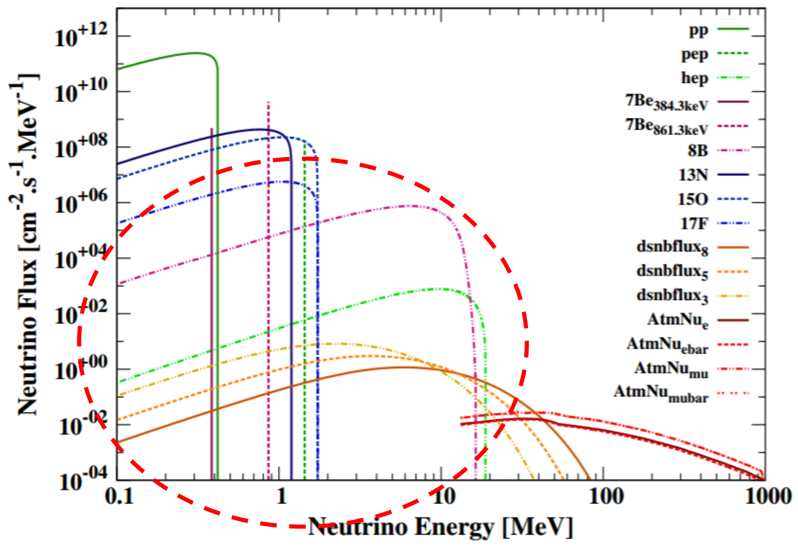

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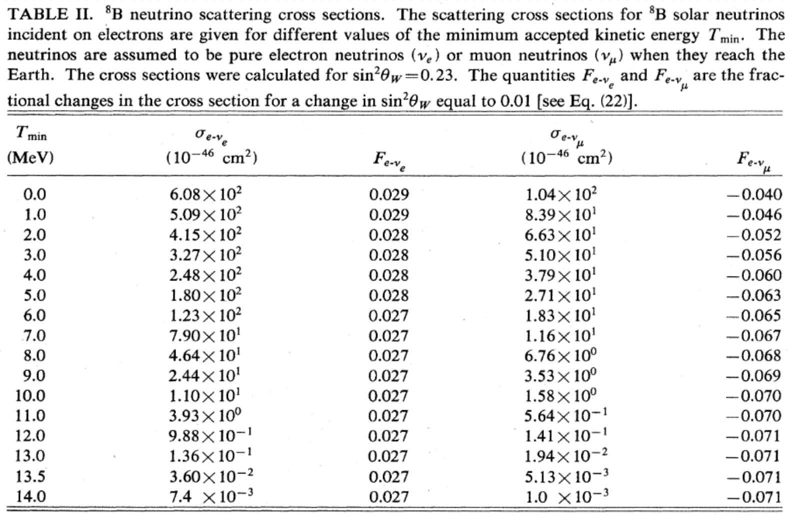

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- ❑ Estimate only ~0.1 events even at LZ-5yr with an energy cut of ≥ 10 MeV (Energy resolution at $E_{\text{recoil}} = 10$ MeV is expected to be $\mathcal{O}(10\%)$ [private communications with experimentalists].)

Outline

I. Introduction/Motivation

- Direct detection experiment current status, boosted dark matter search, …

II. Model

- Benchmark models, expected signatures, …

III. Signal Detection

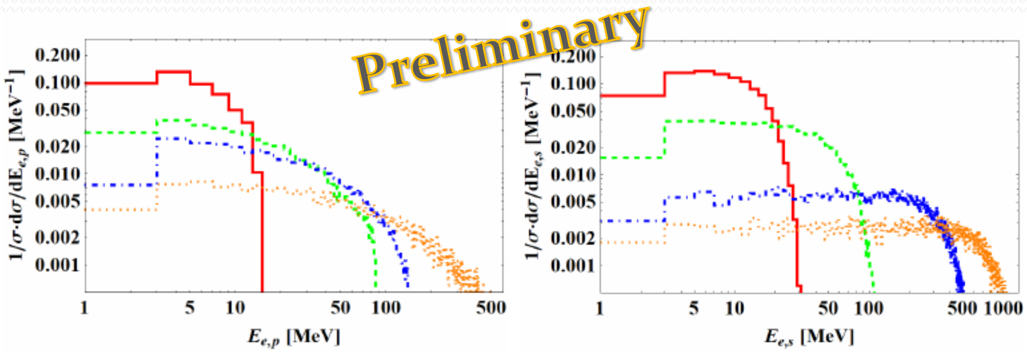
- Benchmark detectors, detection technology, expected signal features, …

IV. Phenomenology

- Detection prospects, model-independent reach, …

V. Conclusions

Benchmark Studies



	m_1	m_2	m_X	γ_1	ϵ
ref1 (red solid)	2	5.5	5	20	4.5×10^{-5}
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ref3 (blue dot-dashed)	20	35	11	50	7×10^{-4}
ref4 (orange dotted)	20	40	15	100	6×10^{-4}

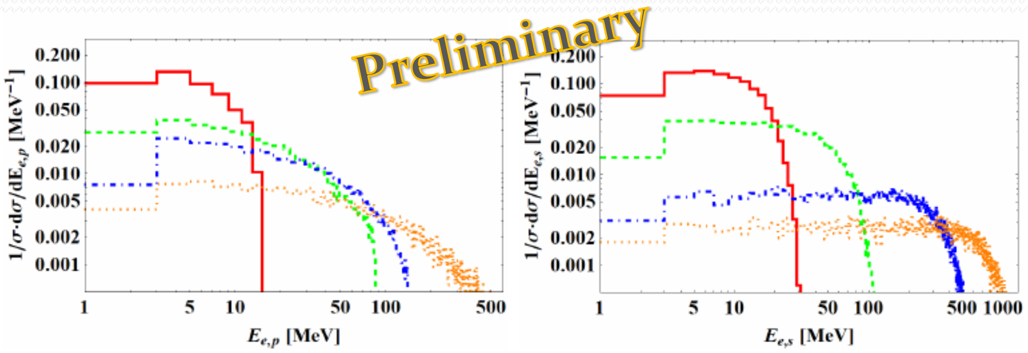
FIG. 2: Expected energy spectra of the primary (upper-left panel) and secondary (upper-right panel) e^- and/or e^+ for four reference points whose details are tabulated in the lower panel. g_{12} is set to be unity and all mass quantities are in MeV.

χ_2 long-lived

$$\ell_{2,\text{lab}} = \frac{c\gamma_2}{\Gamma_2} \sim 16.2\text{ cm} \times \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \left(\frac{1}{g_{12}}\right)^2 \times \left(\frac{m_X}{30\text{ MeV}}\right)^4 \times \left(\frac{10\text{ MeV}}{\delta m}\right)^5 \times \frac{\gamma_2}{10}$$

Two-body decay of χ_2 (no displaced vertex)

Benchmark Studies



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Quite energetic ER and secondary signals as expected

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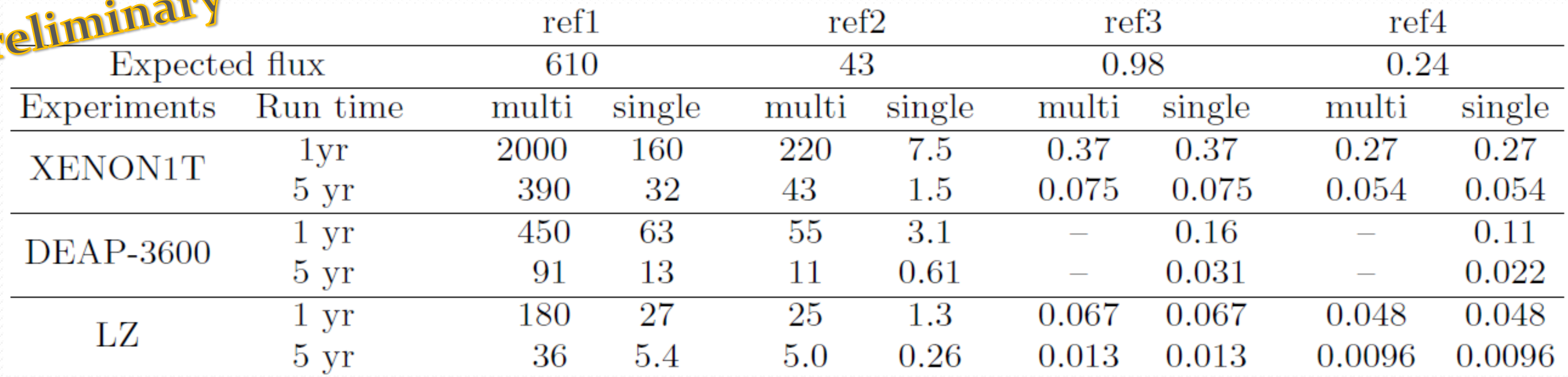
Benchmark Studies: Detection Prospects

Preliminary



		ref1		ref2		ref3		ref4	
Expected flux		610		43		0.98		0.24	
Experiments	Run time	multi	single	multi	single	multi	single	multi	single
XENON1T	1yr	2000	160	220	7.5	0.37	0.37	0.27	0.27
	5 yr	390	32	43	1.5	0.075	0.075	0.054	0.054
DEAP-3600	1 yr	450	63	55	3.1	–	0.16	–	0.11
	5 yr	91	13	11	0.61	–	0.031	–	0.022
LZ	1 yr	180	27	25	1.3	0.067	0.067	0.048	0.048
	5 yr	36	5.4	5.0	0.26	0.013	0.013	0.0096	0.0096

TABLE II: Required fluxes of χ_1 in unit of $10^{-3}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with which our reference points get sensitive to the benchmark experiments. For comparison expected fluxes are shown under the assumptions of $\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1} = 5\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$and the NFW DM halo profile.

- ❑ 3 signal events under the zero background assumption.
- ❑ Selection criteria: "multi" channel – multiple tracks, "single" channel - > 1 track or a single track with $E_{\mathrm{recoil}} \geq 10$ MeV.
- ❑ DEAP3600 having no sensitivity to ref3 and ref4 in the "multi" channel: no displaced vertices in ref3 and ref4, it is challenging to identify 3 final state particles with S1 only.

Model-independent Reach

- ☐ Non-trivial to find appropriate parameterizations for providing model-independent reaches due to many parameters involved in the model
- ☐ Number of signal events N_{sig} is

$$N_{\text{sig}} = \sigma \cdot \mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_e$$

  - σ: scattering cross section between χ_1 and (target) electron
  - $\mathcal{F}$: flux of incoming (boosted) χ_1
  - A: acceptance
  - t_{exp}: exposure time
  - N_e: total number of target electrons

$\left.\begin{array}{l} t_{\text{exp}} \\ N_e \end{array}\right\}$ **Controllable!**

Model-independent Reach: Displaced Vertex

❑ Acceptance determined by the distance between the primary (ER) and the secondary vertices

⇒ (relatively) conservative limit to require two correlated vertices in the fiducial volumes

(also to be distinguished from elastic scattering)

90% C.L. with
zero background

$$\sigma \cdot \mathcal{F} \geq \frac{2.3}{A(\ell_{\rm lab}) \cdot \underbrace{t_{\rm exp} \cdot N_e}}$$

Calculable given
a detector

Evaluated under the assumption
of cumulatively isotropic χ_1 flux

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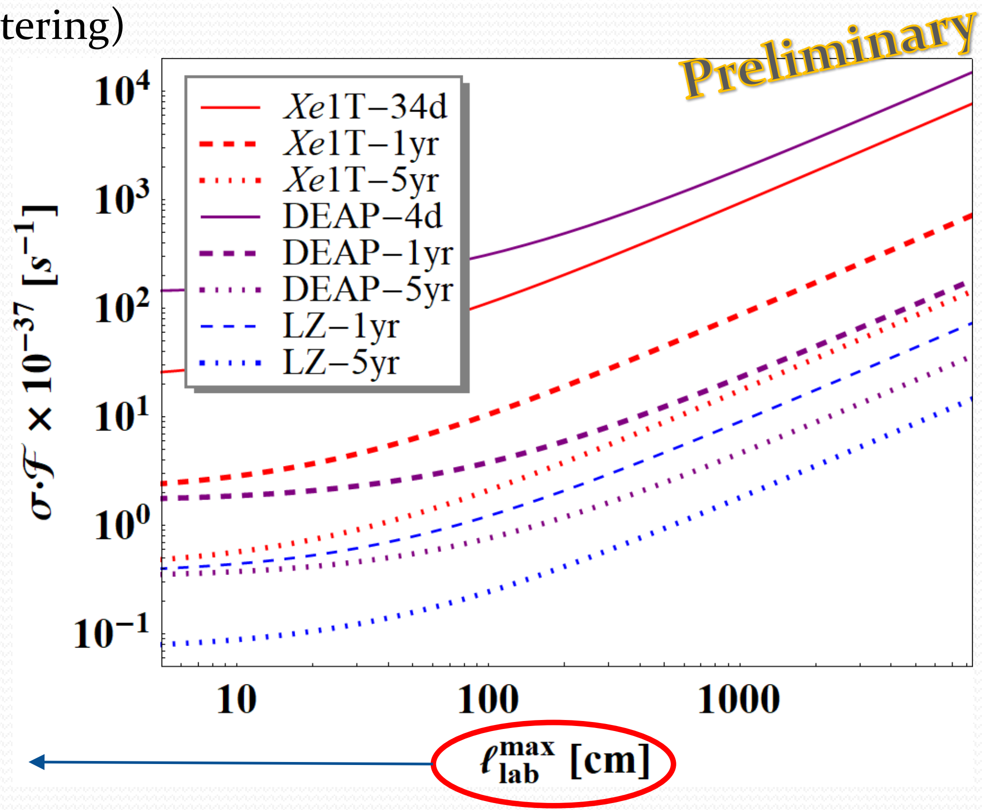
$\ell_{\rm lab}$ different event-by-event, so taking $\ell_{\rm lab}^{\rm max}$ for more conservative limit



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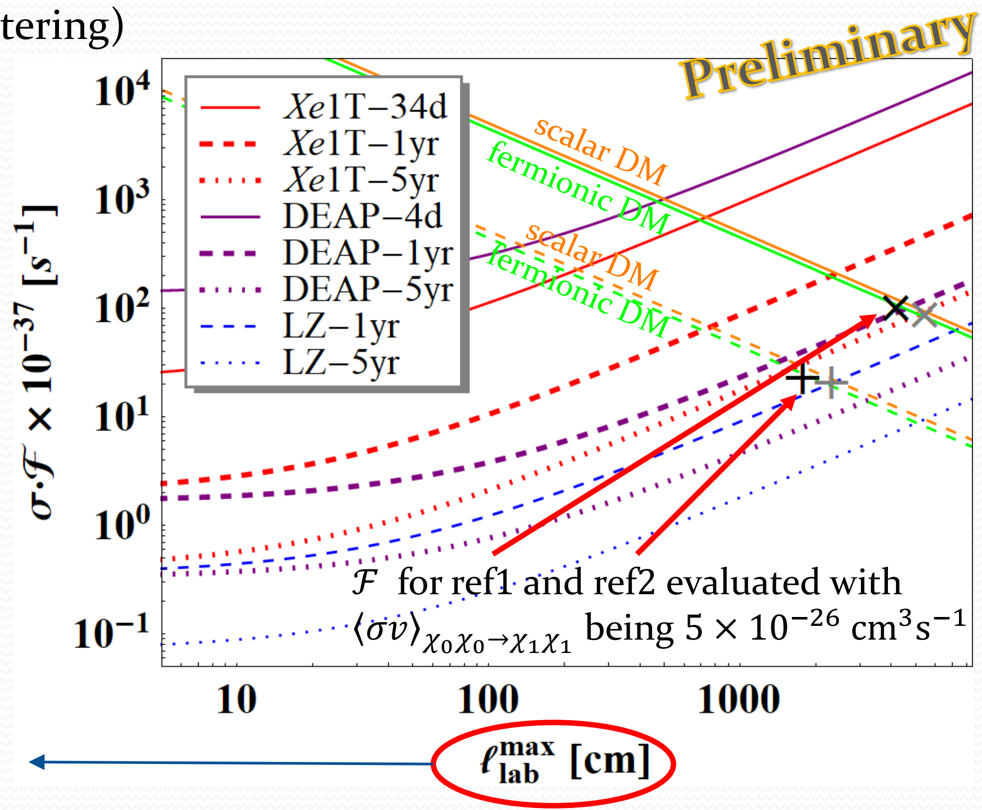

$\mathcal{F}$ for ref1 and ref2 evaluated with $\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}$ being 5×10^{-26} cm^{3}s^{-1}

Model-independent Reach: “Prompt” Decay

☐ No measurable/appreciable displaced vertex ⇒ $A \approx 1$, limit relevant to signals with overlaid vertices or elastic scattering signals

$$\sigma \geq \frac{2.3}{\mathcal{F} \cdot A \cdot t_{\rm exp} \cdot N_e}$$ with

$$\mathcal{F} \sim \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$$

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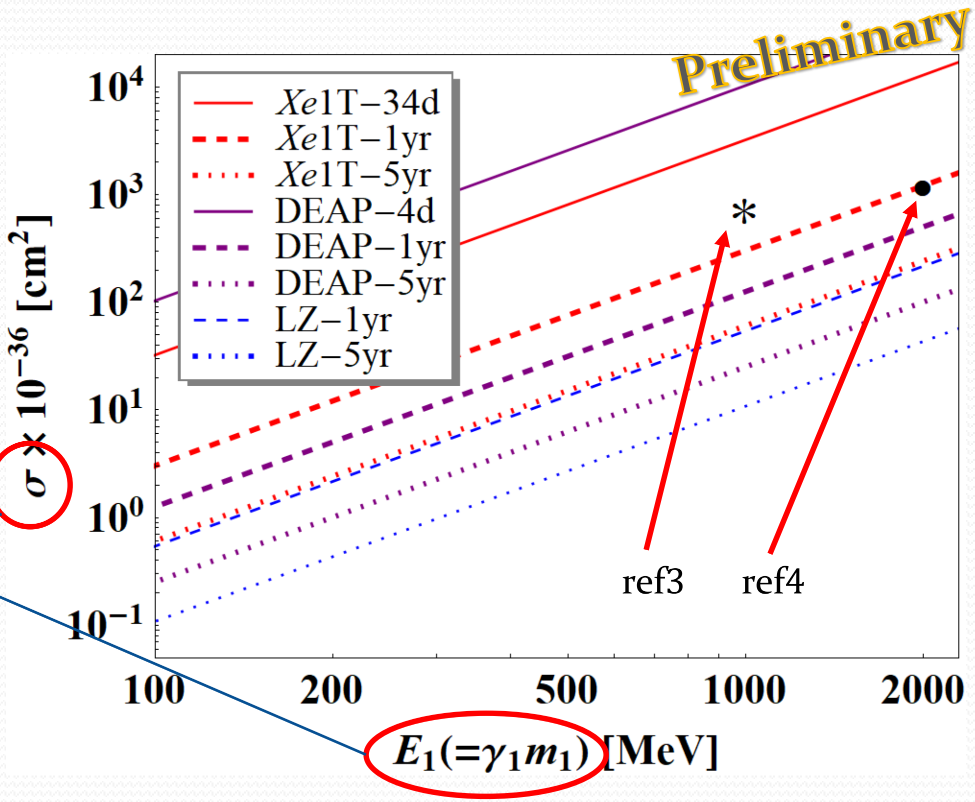
Experimental sensitivity can be represented by σ vs. m_0 $(= E_1)$.

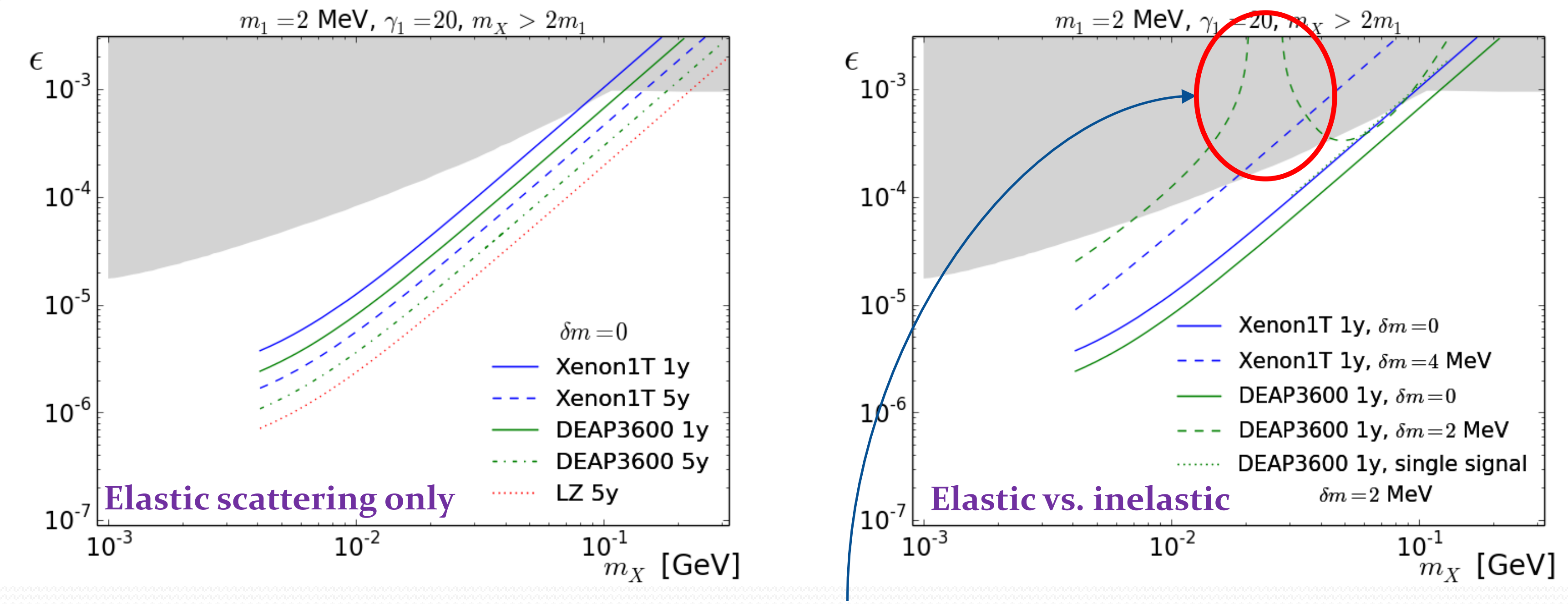


[Note that DEAP may not tell apart inelastic scattering from elastic scattering.]

Dark Photon Parameter Space: Invisible X Decay

- ❑ Case study 1: mass spectra for which dark photon decays into DM pairs, i.e., $m_X > 2m_1$
- ❑ Same selection criteria imposed

Preliminary

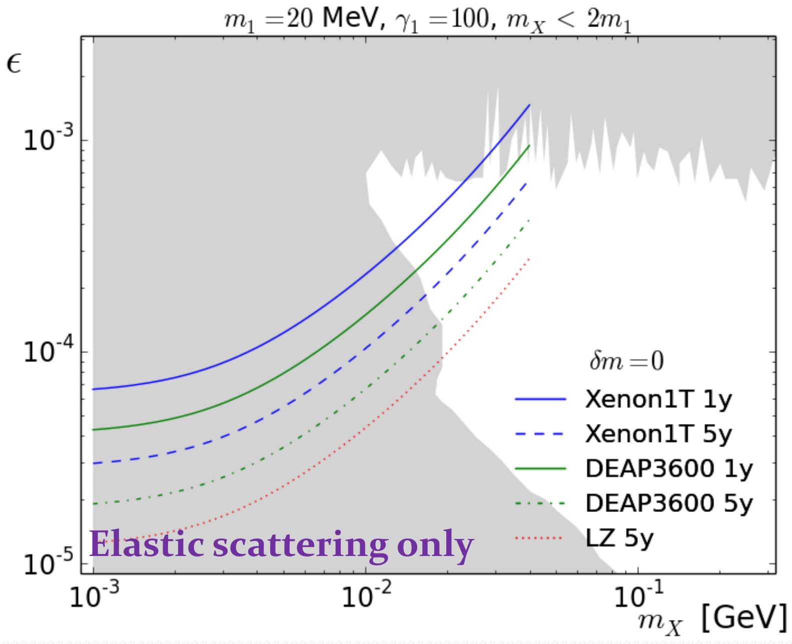


Caused by the position resolution of 6.5 cm at DEAP

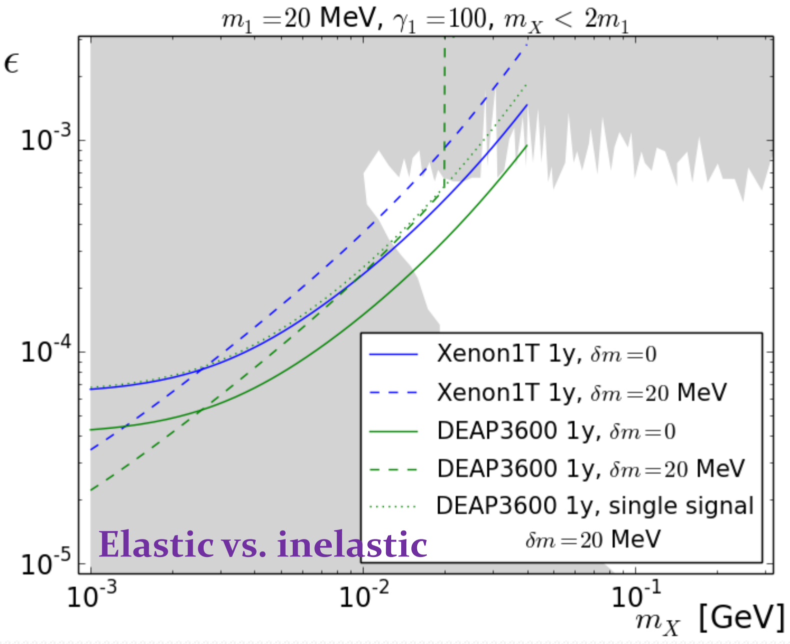
Dark Photon Parameter Space: Visible X decay

- Case study 2: mass spectra for which dark photon decays into lepton pairs, i.e., $m_X < 2m_1$
- Same selection criteria imposed

Preliminary



Elastic scattering only



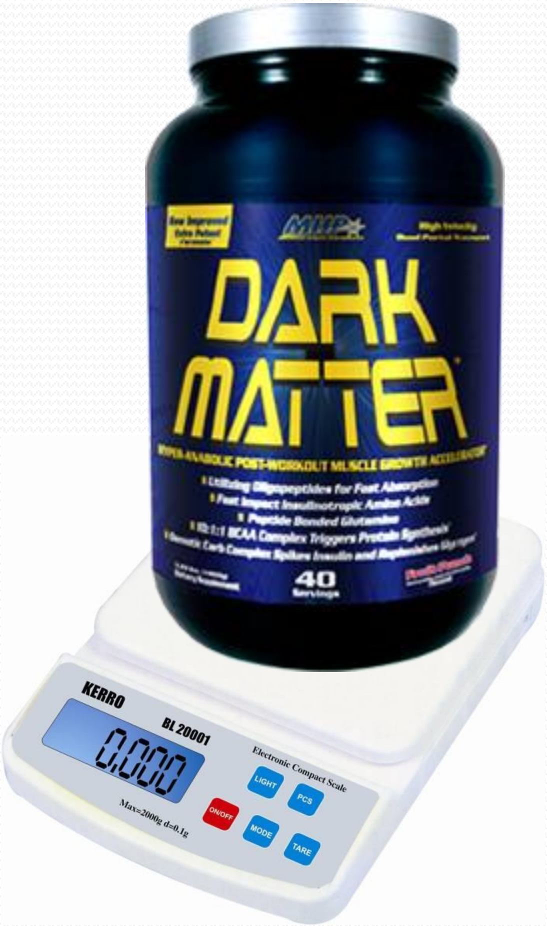
Elastic vs. inelastic

Final Remark: Detector Comparison

Experiments		Fiducial volume	Pros	Cons
Liquid Xe/Ar	Xenon1T, DEAP, LZ, etc.	1 – 5 tons	• (Relatively) good angular/position resolution • Decent size of fiducial volume, hence less suffering from background	• Relatively poor energy resolution (due to the saturation issue)
Neutrino-related	Borexino, KamLAND, etc.	~100 tons	• Good energy resolution (in the range of interest) • Larger fiducial volume	• Relatively poor at identifying the secondary vertex (S1 only) • More background
Array-type	CUORE, COSINE, etc.	< 1 ton	• Better for signal events with displaced vertices • Essentially no background	• Smaller fiducial volume (i.e., probing less parameter space)

Conclusions

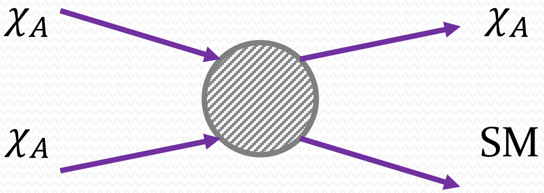
- Boosted light dark matter searches are **promising**.
- Conventional dark matter direct detection experiments possess **sensitivities to MeV-range** (heaviest light?) DM.
- They can provide an **alternative avenue** to probe dark photon parameter space.



Back-up

Boosted DM from the Sky: Semi-annihilation

- ☐ In DM models where relevant DM is stabilized by e.g., Z_3 symmetry, one may have a process like

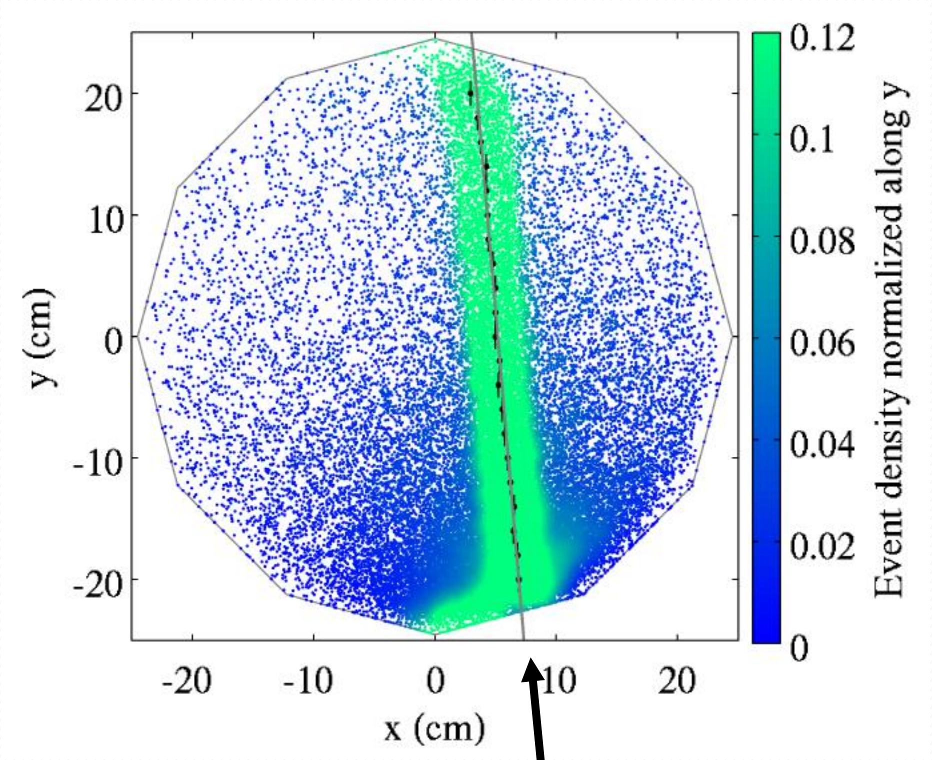


- ☐ Under the circumstance in which the mass of SM here is lighter (i.e., $m_A > m_{\text{SM}}$), the outgoing χ_A can be boosted and its boost factor is given by

$$\gamma_A = \frac{5m_A^2 - m_{\text{SM}}^2}{4m_A^2}$$

Boosted DM Signal Detection

[LUX Collaboration (2017)]



Expecting a long track by an energetic electron/positron

[Points: reconstructed S2 positions]

2.45 MeV neutron beam source

Backgrounds for Xenon1T

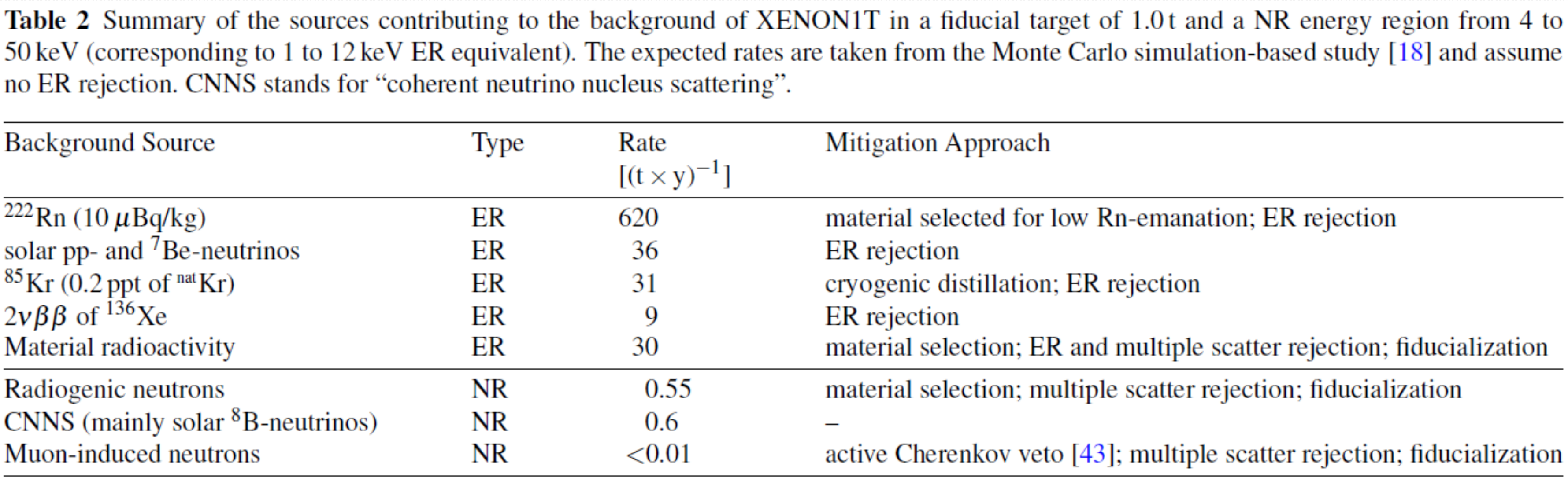


Table 2 Summary of the sources contributing to the background of XENON1T in a fiducial target of 1.0 t and a NR energy region from 4 to 50 keV (corresponding to 1 to 12 keV ER equivalent). The expected rates are taken from the Monte Carlo simulation-based study [18] and assume no ER rejection. CNNS stands for "coherent neutrino nucleus scattering".

Background Source	Type	Rate $[(\mathrm{t} \times \mathrm{y})^{-1}]$	Mitigation Approach
^{222}Rn (10 μBq/kg)	ER	620	material selected for low Rn-emanation; ER rejection
solar pp- and ^{7}Be-neutrinos	ER	36	ER rejection
^{85}Kr (0.2 ppt of $^{\mathrm{nat}}$Kr)	ER	31	cryogenic distillation; ER rejection
$2\nu\beta\beta$ of ^{136}Xe	ER	9	ER rejection
Material radioactivity	ER	30	material selection; ER and multiple scatter rejection; fiducialization
Radiogenic neutrons	NR	0.55	material selection; multiple scatter rejection; fiducialization
CNNS (mainly solar ^{8}B-neutrinos)	NR	0.6	–
Muon-induced neutrons	NR	<0.01	active Cherenkov veto [43]; multiple scatter rejection; fiducialization

[Xenon Collaboration (2017)]

All are smaller than ~100 keV, hence irrelevant to our signals