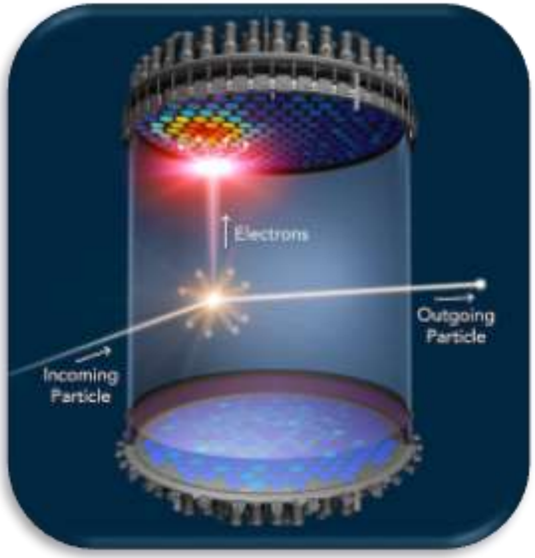
Boosted DM @ Direct Detection Experiments

In collaboration w/ G. Giudice, D. Kim, **JCP**, S. Shin
arXiv: 1712.07126



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CHUNGNAM NATIONAL UNIVERSITY

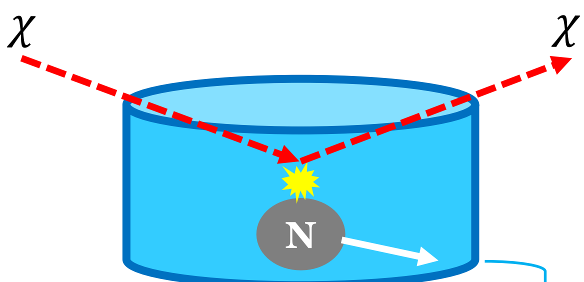
2nd IBS-KIAS Joint Workshop @ High1

January 08 (2018)

Typical DM Direct Searches

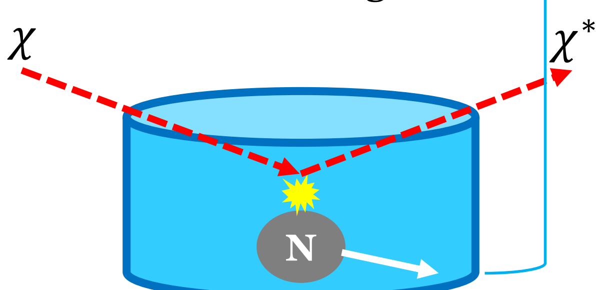
❖ (Mainly) focusing on “*Non-relativistic*” weakly interacting massive particles (WIMPs) searches

- Elastic scattering



[Goodman, Witten (1985)]

- Inelastic scattering (iDM)



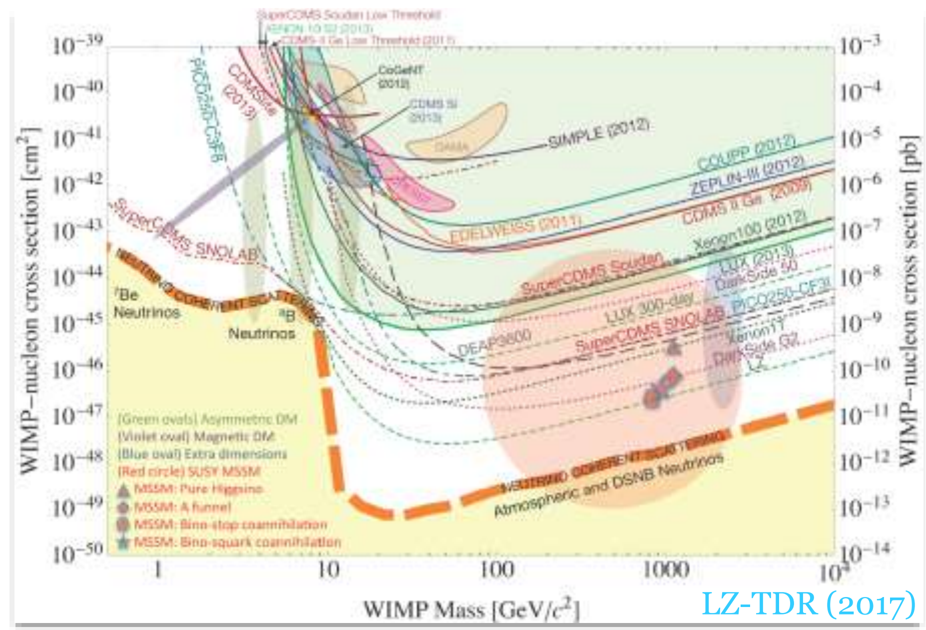
[Tucker-Smith, Weiner (2001)]

✓ $E_{\rm recoil} \sim mv^2$

$\sim 1 - 100$ keV

$(v/c \sim 10^{-3})$

✓ Detectors designed to be sensitive to this E scale



LZ-TDR (2017)

✓ No solid observation of WIMP signals

✓ A wide parameter respace already excluded

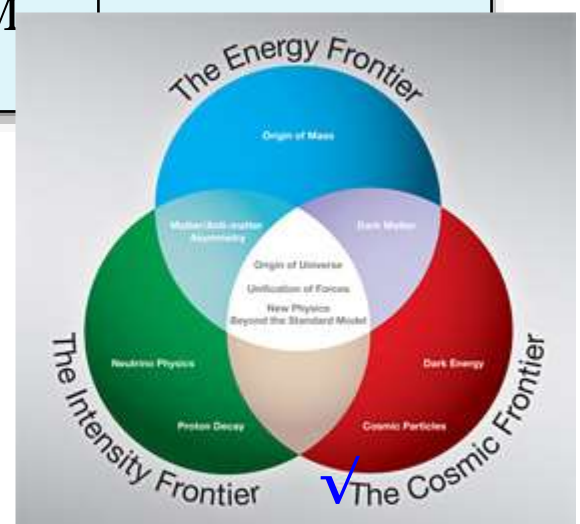
DM Search Schemes (Scattering)

Scattering \ v_{DM}	***non*-relativistic (<< c)**
elastic	Direct detection
***in*elastic**	inelastic DM (iDM)

Very well-studied

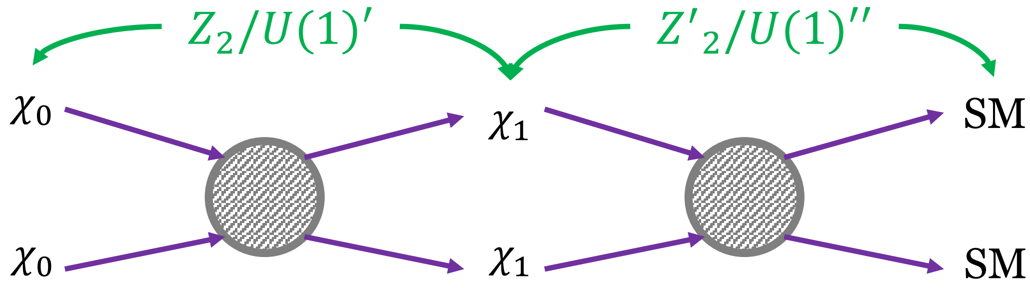
DM Search Schemes (Scattering)

v_{DM} / **Scattering**	***non*-relativistic (<< c)**	**relativistic (~c)**
elastic	Direct detection	Boosted DM (BDM)
***in*elastic**	inelastic DM (iDM)	



Two-component BDM Scenario

Belanger, **JCP** (2011)



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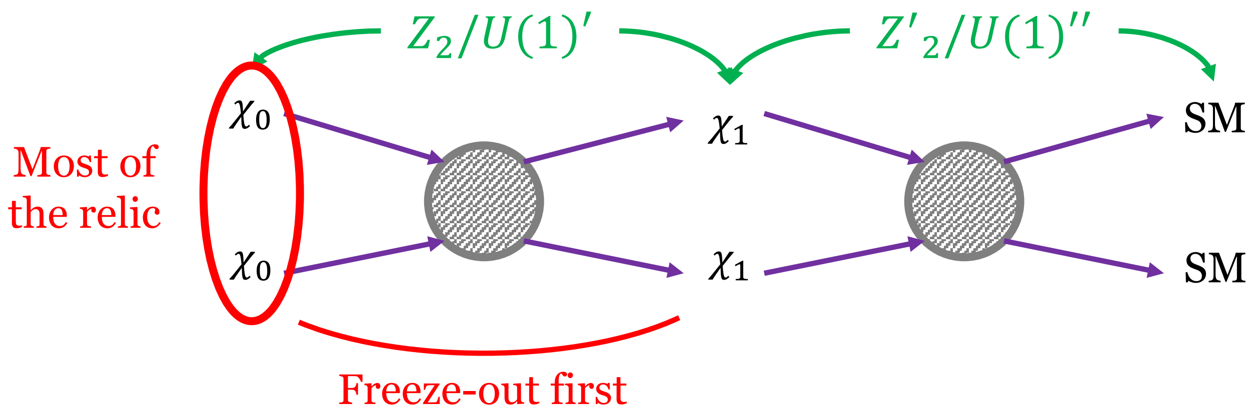

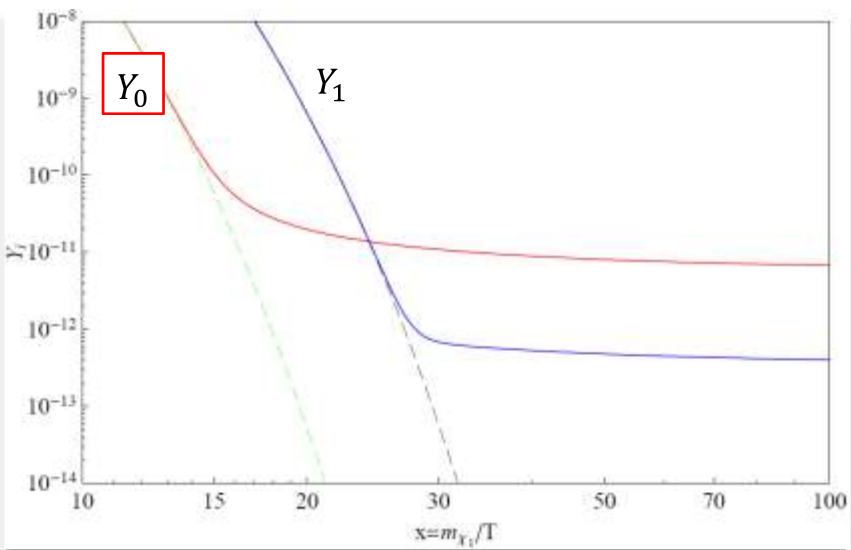

"**Assisted Freeze-out**" mechanism

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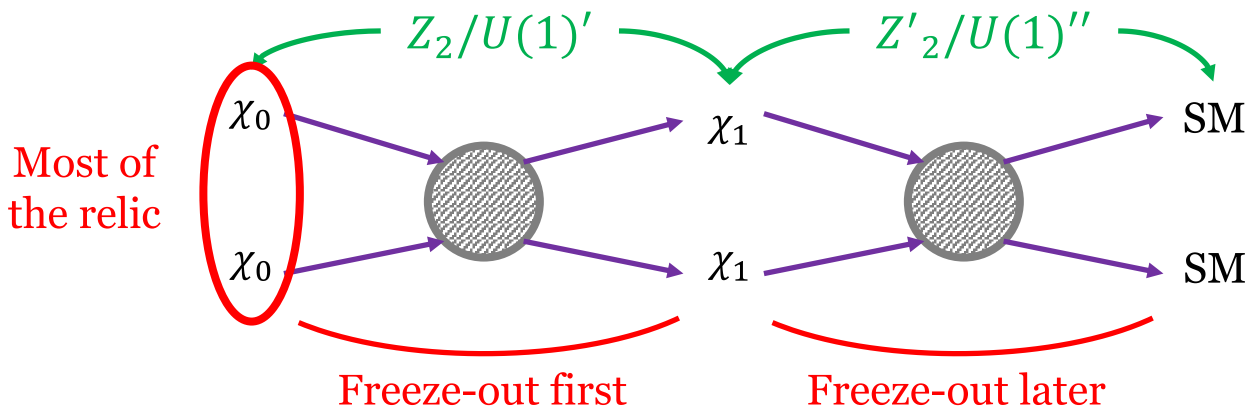

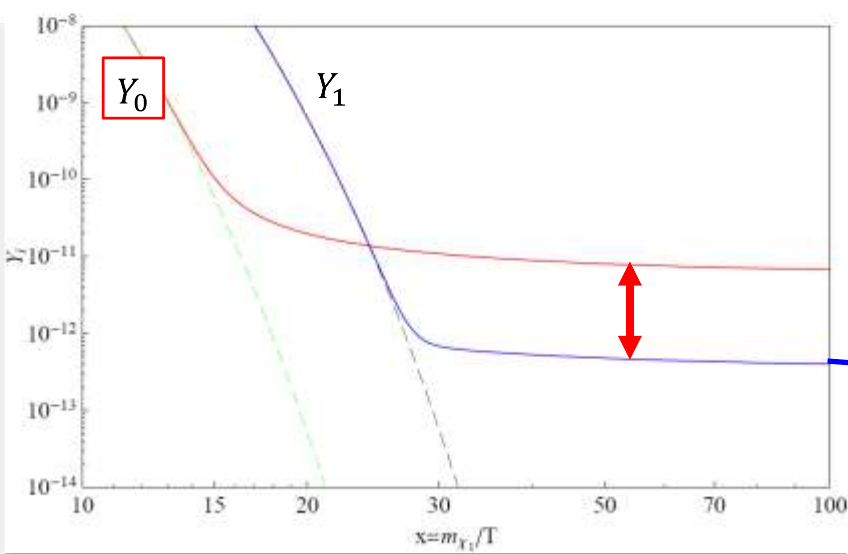

"**<u>Assisted Freeze-out</u>**" mechanism

Non-relativistic relic χ_1

Two-component BDM Scenario

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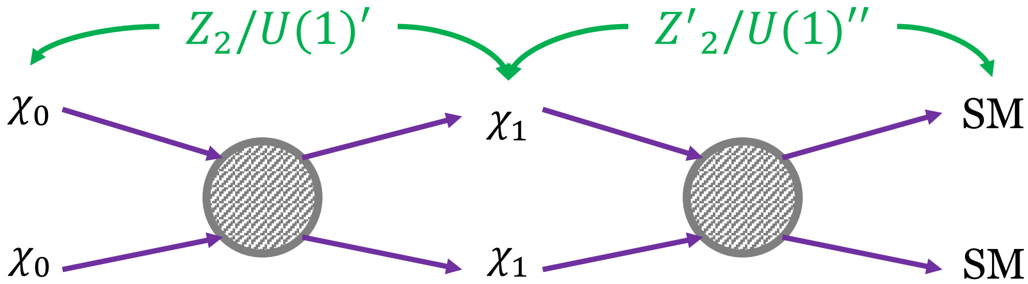

$\chi_0\chi_0 \to \chi_1\chi_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

(Note that relic χ_1 is non-relativistic.)

(Galactic Center) (Laboratory)

[Agashe, Cui, Necib, Thaler (2014)]

Detection of BDM

❖ Flux of boosted χ_1 near the earth

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

from the number density of DM χ_0, $n_o = \rho_o / m_o$

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

one can obtain $\mathcal{F}_{\chi_1} \sim 10^{-6\sim 8} \mathrm{cm^{-2} s^{-1}}$ for χ_0 of weak-scale mass, $m_0 \sim$O(10-100 GeV).

❖ Low flux ➔ No sensitivity in conventional DM direct detection experiments

➔ Large volume (neutrino) detectors motivated: Super-/Hyper-K, DUNE, …

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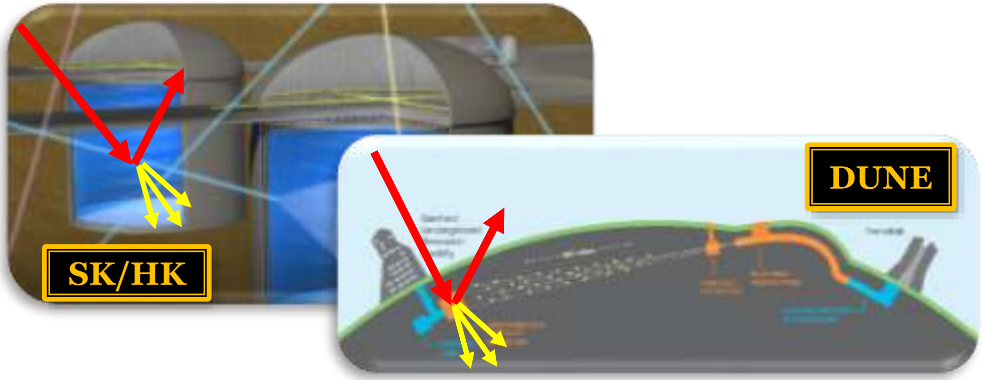


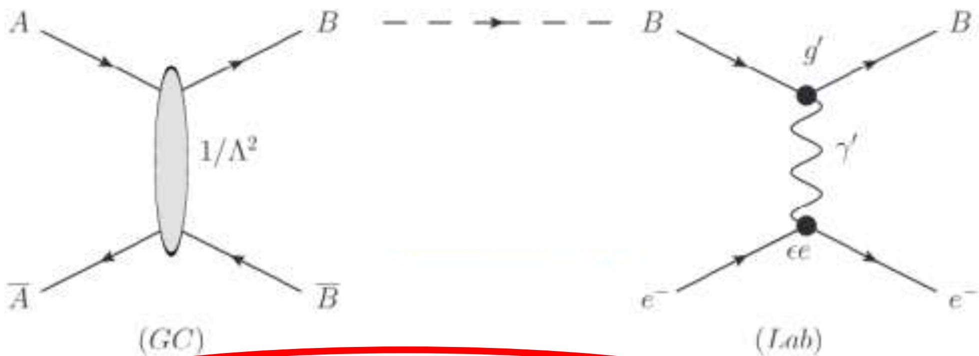
❖ Sources

✓ GC: Agashe et al (2014); Necib et al (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016)

✓ Sun: Berger et al (2014); Kong, Mohlabeng, **JCP** (2014); Alhazmi, Kong, Mohlabeng, **JCP** (2016)

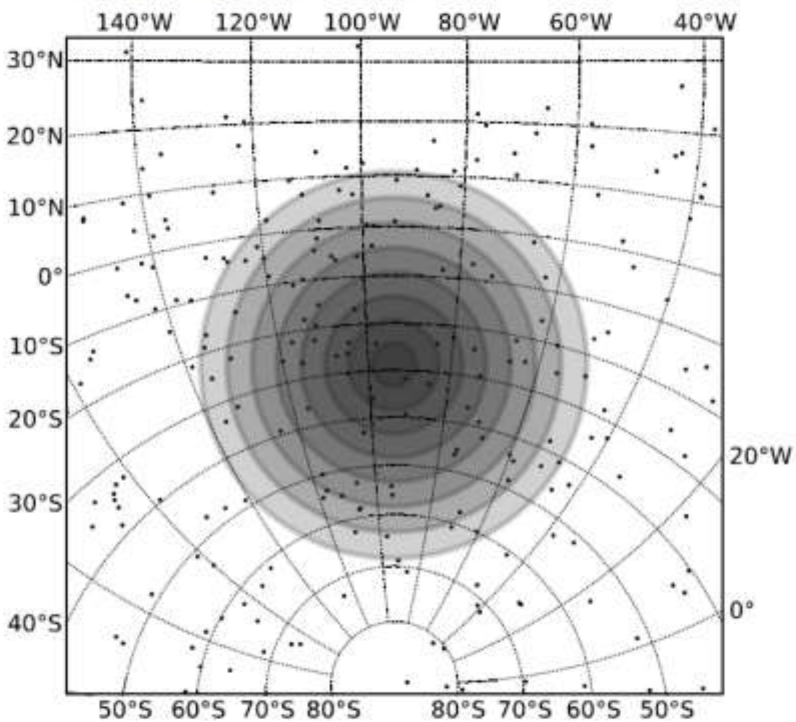
✓ Dwarf galaxies: Necib et al (2016)

(In)direct dark matter detection?

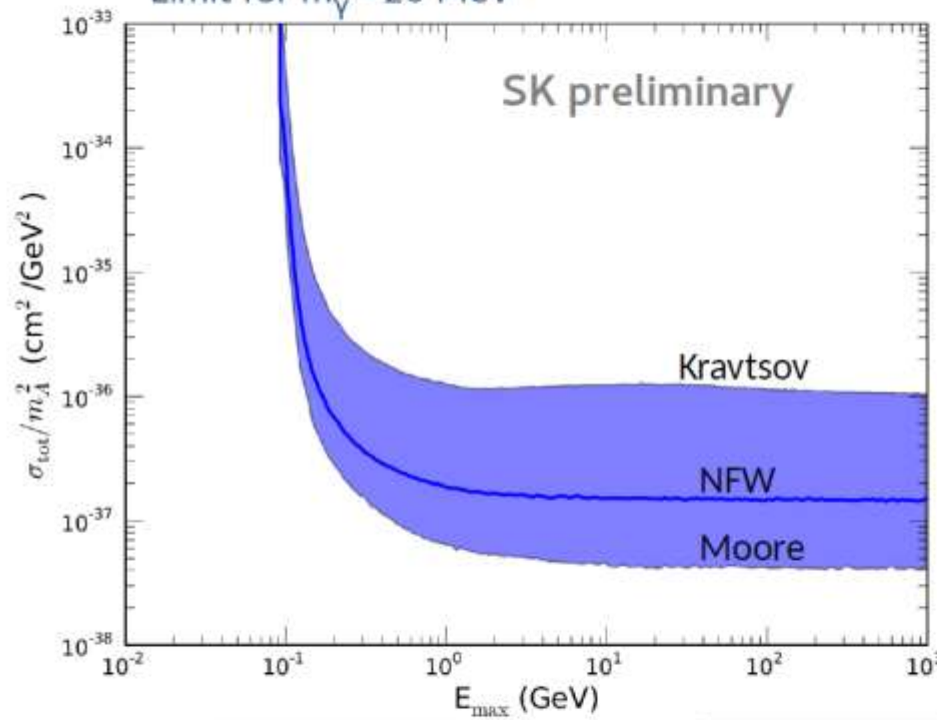


- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC
→ **No clusters visible**



Limit for m_{γ}'=20 MeV



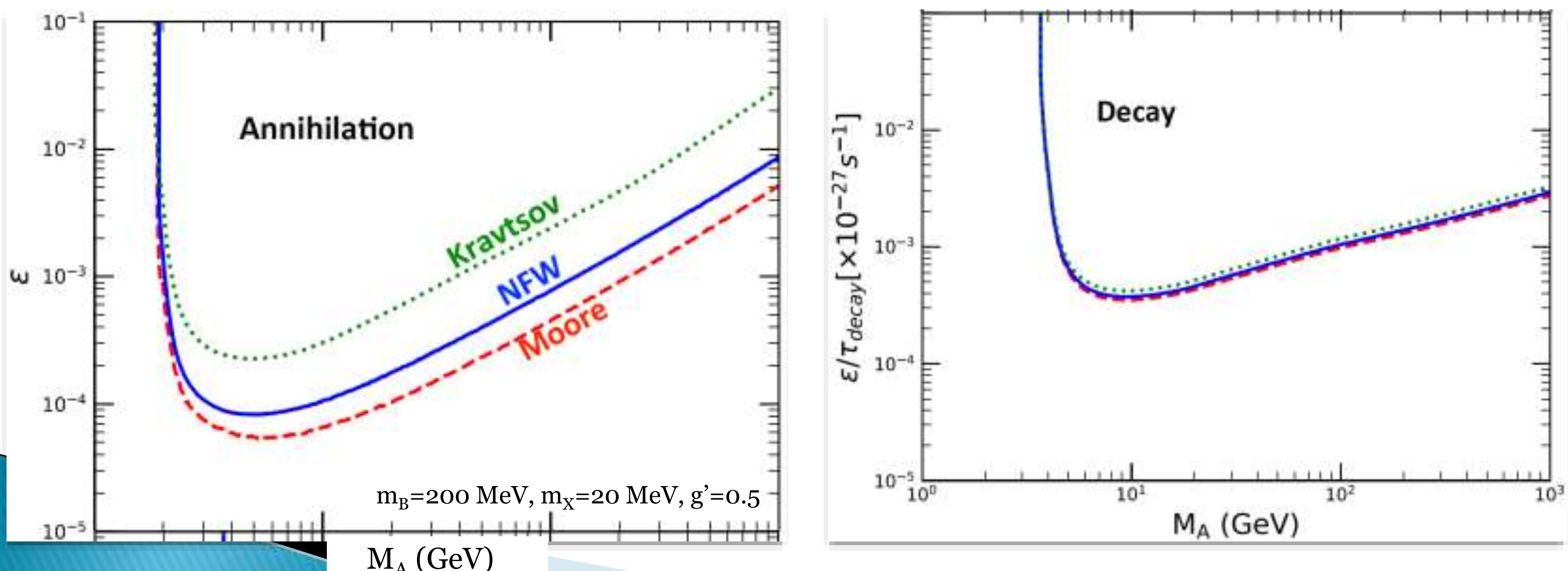
SK Official Results for BDM Search

SK Collaboration, arXiv:1711.05278

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

(Dated: November 16, 2017)

A search for boosted dark matter using 161.9 kiloton-years of Super-Kamiokande IV data is presented. We search for an excess of elastically scattered electrons above the atmospheric neutrino background, with a visible energy between 100 MeV and 1 TeV, pointing back to the Galactic Center or the Sun. No such excess is observed. Limits on boosted dark matter event rates in multiple angular cones around the Galactic Center and Sun are calculated. Limits are also calculated for a baseline model of boosted dark matter produced from cold dark matter annihilation or decay.



DM Search Schemes (Scattering)

Scattering \ $v_{\rm DM}$	***non*-relativistic (<< c)**	**relativistic (~c)**
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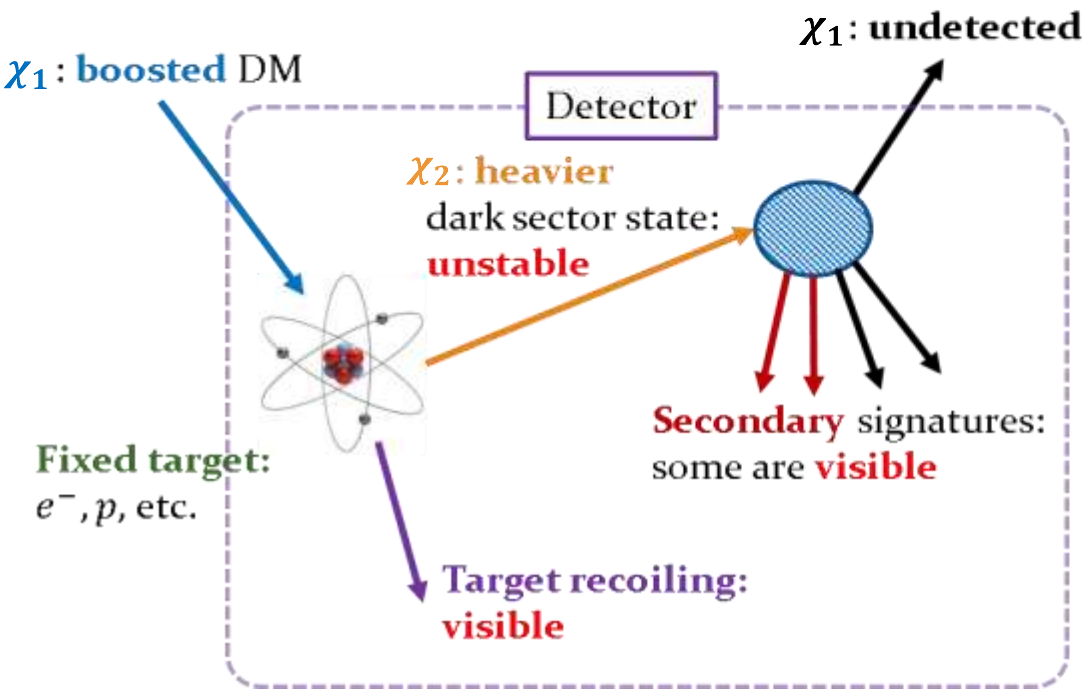
iBDM: DM "Colliders"

D. Kim, **JCP** & S. Shin, PRL (2017)



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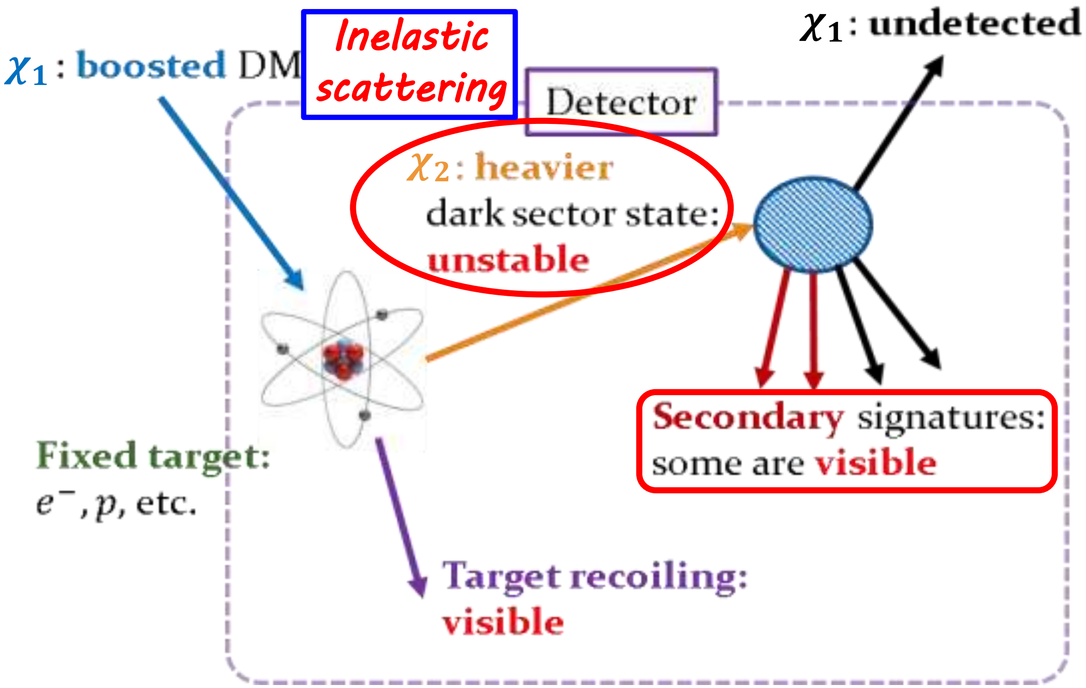

- Target recoil (like in typical DM direct detection exp.) + secondary visible signatures ➔ **more** handles, (relatively) **background-free**
- **Complementary** to standard DM direct searches
- **Boosted DM sources** needed: BDM scenarios, fixed target experiments, etc.

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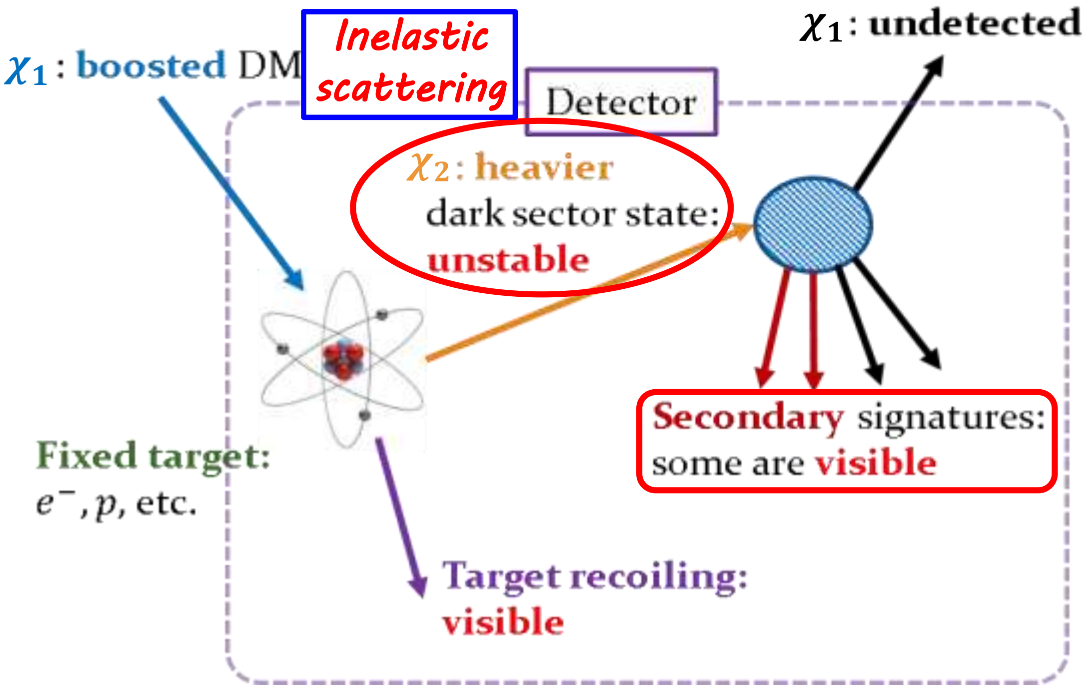

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- **Complementary** to standard DM direct searches
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Follow-ups in collaborations with experimentalists (DUNE, HK, SHiP, ...)

Amplifying BDM Flux

❖ Flux of boosted χ_1

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

Reducing by 2-3 orders of magnitude

➔ Flux increased by 4-6 orders of magnitude!

GeV/sub-GeV m_0 ➔ MeV-range m_1 motivated

Conventional DM direct detection Exps.

may have MeV-range (boosted) DM signal!

❖ Elastic scattering off nucleus in the context of quark-philic scenarios, e.g. gauged baryon number/Higgs portal models ➔ non-energetic [Cherry, Frandsen, Shoemaker (2015)]

Electron Scattering?

- Conventional DM direct detection experiments: *e*-recoil (ER) events are rejected (mostly, E ~ keV – sub-MeV)
- Boosted MeV-range DM
  - ✓ Energetic ER expected (efficient E transfer) ➔ E ~ MeV – sub-GeV
  - ✓ May leave an appreciable track:

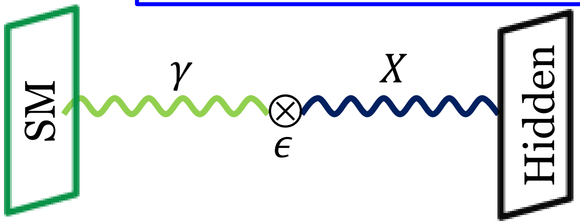
    2-10 cm @ LXe (4-20 cm @LAr) for *e* of E~O(10-100 MeV)
  - ✓ *e*-scattering cross section can be larger than *p*/*N*-scattering (depending on parameter choice)

***e*-scattering will be excellent in search for MeV-range (boosted) DM particles!**

Benchmark Model

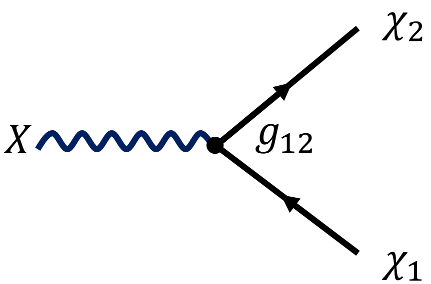
$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 X_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + h.c.$$

Based on
Assisted FO set-up
[Belanger, **JCP** (2011)]



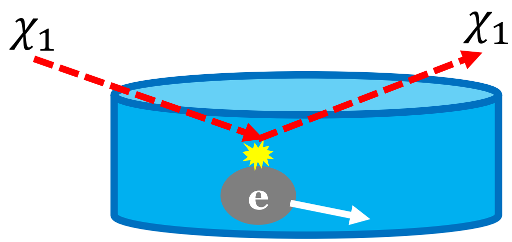
- ❖ Vector portal (kinetic mixing) [Holdom (1986)]
- ❖ Fermionic DM
  - ✓ χ_2: a heavier (unstable) dark-sector state
  - ✓ Flavor-conserving ➔ elastic scattering
  - ✓ Flavor-changing ➔ inelastic scattering

  [Tucker-Smith, Weiner (2001); Kim, Seo, Shin (2012)]

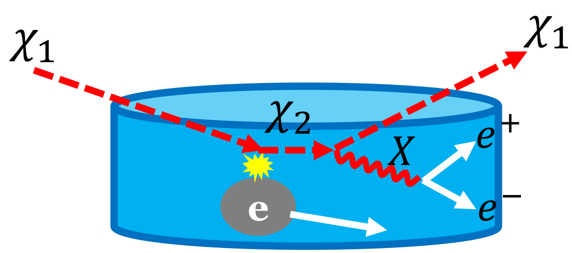


- ❖ Diagonal coupling may be highly suppressed, even vanishing.
- ❖ Scalar DM also possible

Types of Expected Signatures

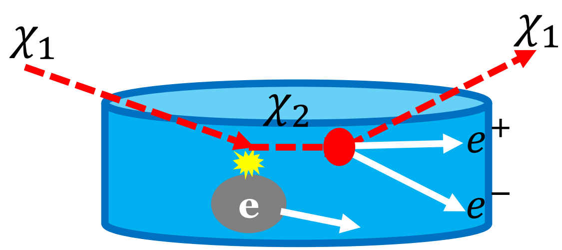


: ER ➔ ordinary but energetic elastic scattering



: ER + e^+e^- pair (from the decay of on-shell X)

$(m_2 > m_1 + m_X)$

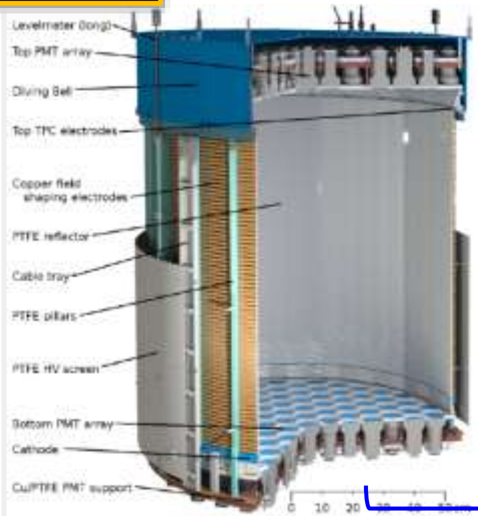


: ER + e^+e^- pair (from the decay of off-shell X 🡐 three-body decay of χ_2) ➔ secondary signal may be displaced.

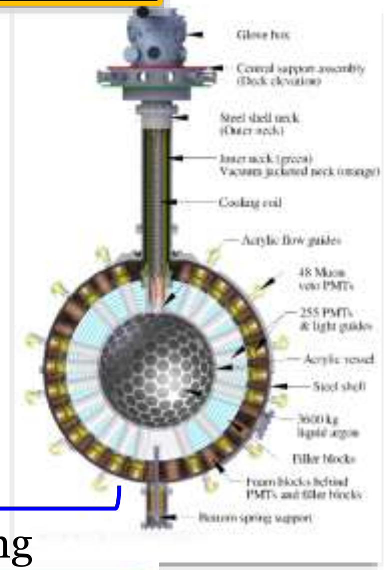
$(m_2 < m_1 + m_X)$

Benchmark Detectors

XENON1T



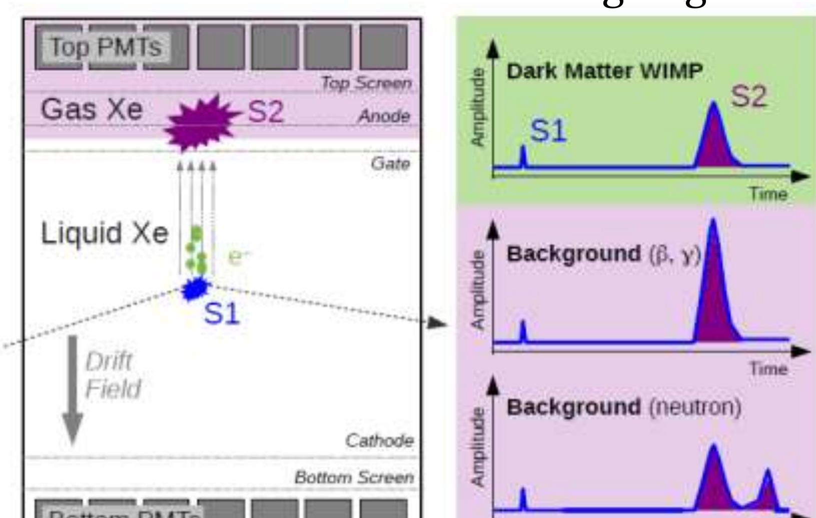
DEAP-3600



Ongoing

LUX-ZEPLIN(LZ)

Future



XENON (2017)

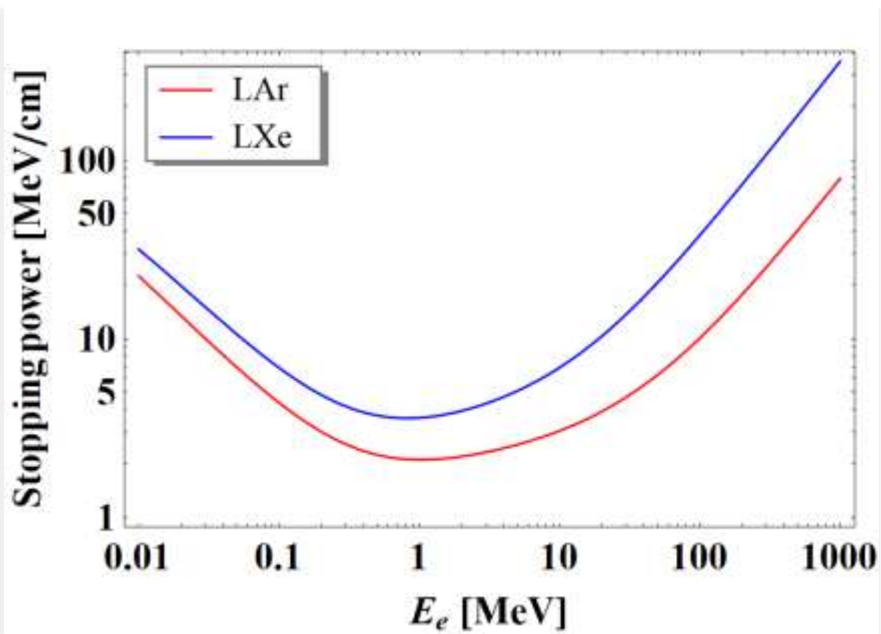
Experiment	Geometry	$(r,\ h)$ or r [cm]	Mass [t]	Target
XENON1T	Cylinder	(38, 76)	1.0	LXe
DEAP-3600	Sphere	72	2.2	LAr
LZ	Cylinder	(69, 130)	5.6	LXe

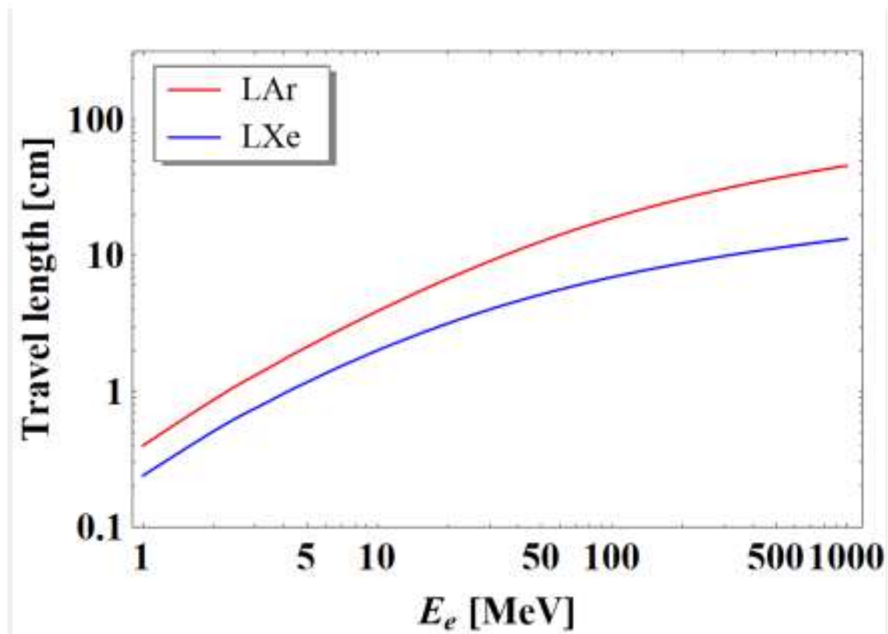
[Numbers are for fiducial volumes.]

- XENON1T & LZ: S1(scintillation) + S2(ionization)
- DEAP-3600: S1 only

Very Energetic DM Signal: Track

- A sizable track is expected!
- Tracks of 2-10 cm @ LXe / 4-20 cm @LAr for electrons of E~O(10-100 MeV)

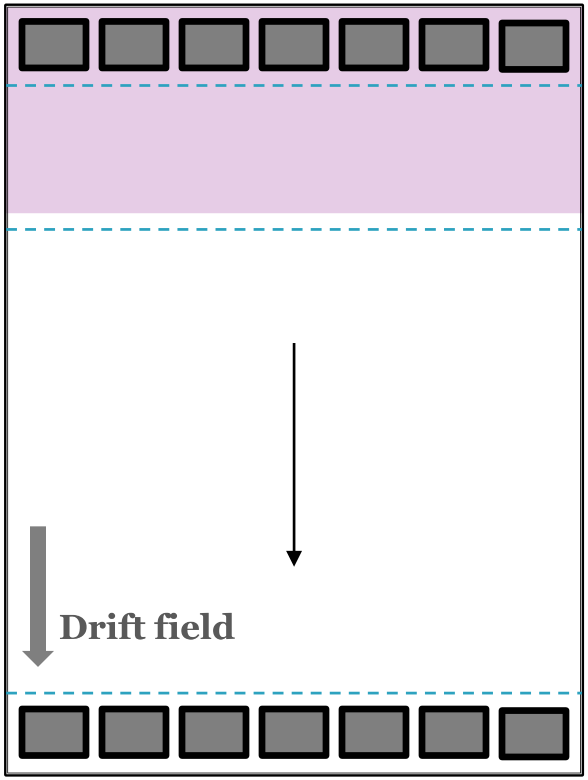




[Material property available at NIST
https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html]

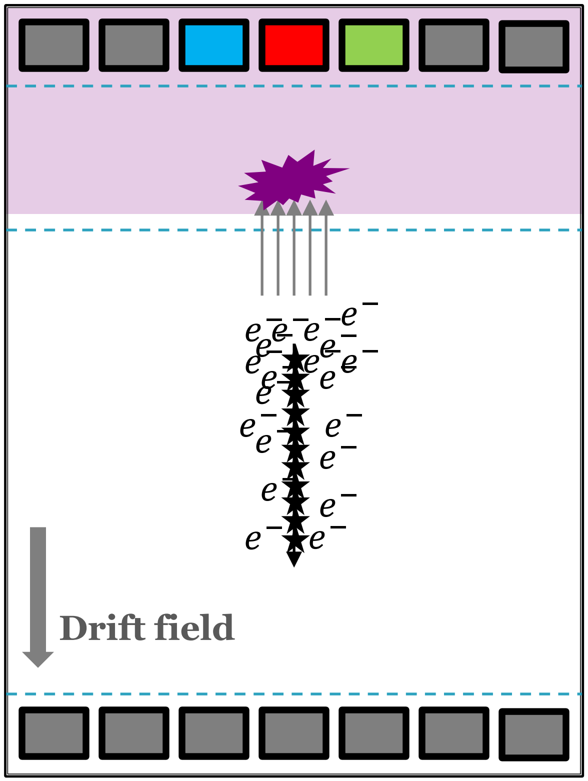
Expected Pattern: Vertical Track

- A given vertical track



Expected Pattern: Vertical Track

- A given vertical track

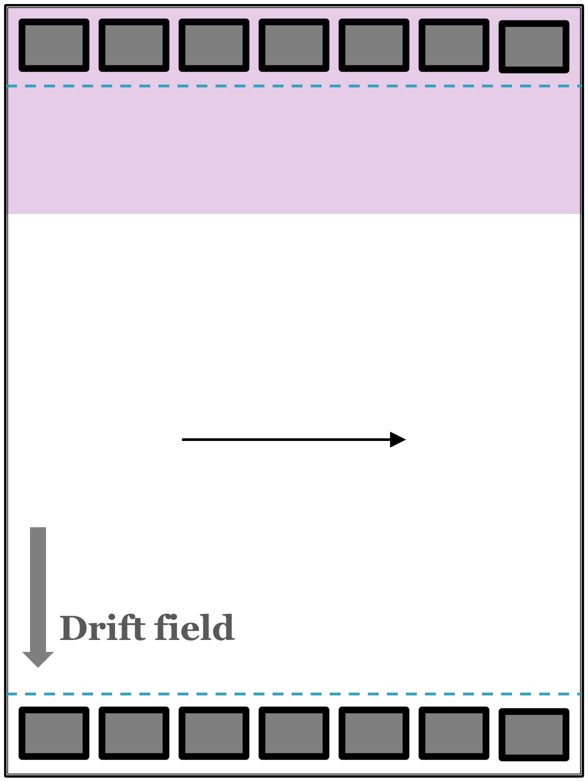


- ✓ can be considered as an array of scattering points.
- ✓ free electrons released at each point: more (less) electrons at the scattering (ending) point
- ✓ expect a series of flickers of several PMTs by an interval of ~10 ns (1 cycle of charge – discharge)

➔ Expect (relatively) easy identification of a lengthy track + more precise track/E reconstruction (than the horizontal track)

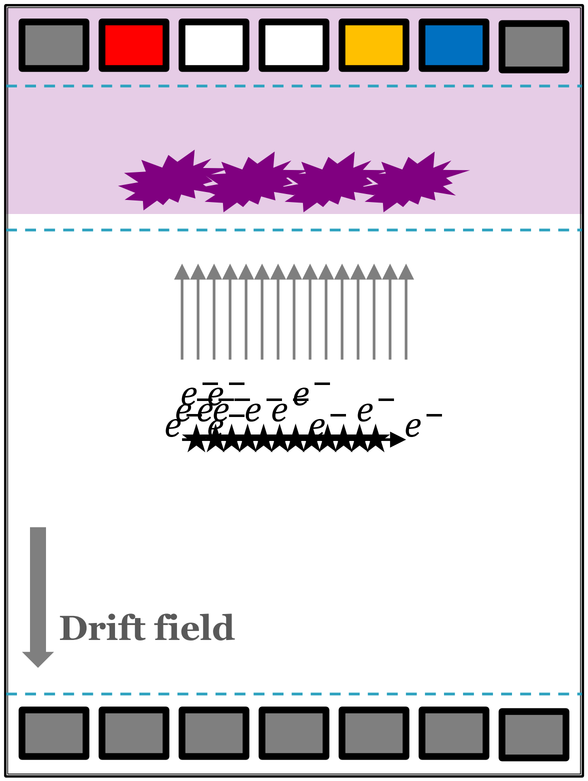
Expected Pattern: Horizontal Track

❖ A given horizontal track

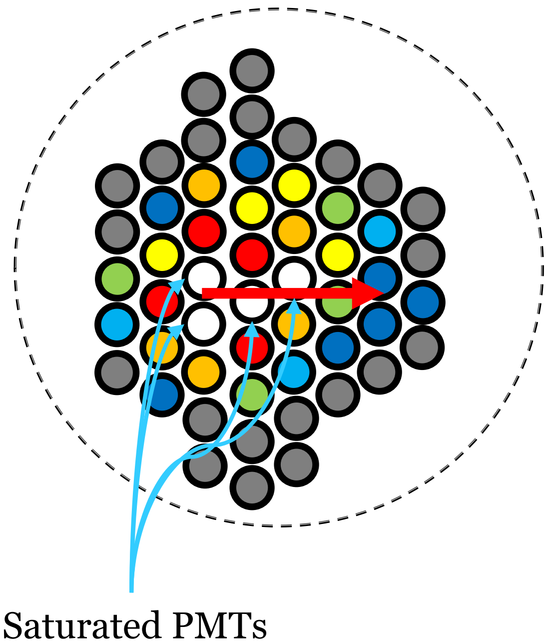


Expected Pattern: Horizontal Track

❖ A given horizontal track



✓ expect simultaneous charging of several PMTs, some of which may saturate

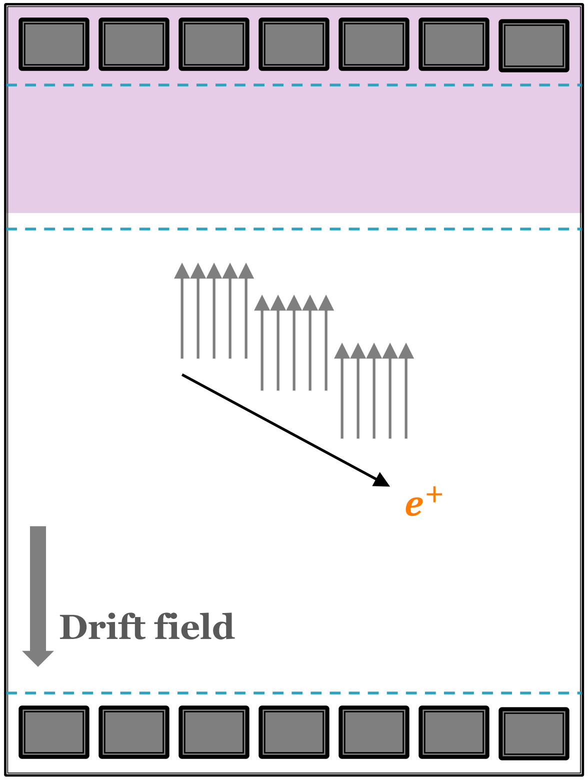


➔ Expect identification of a lengthy track is doable/achievable

➔ Track/E reconstruction may require likelihood analysis with unsaturated PMTs

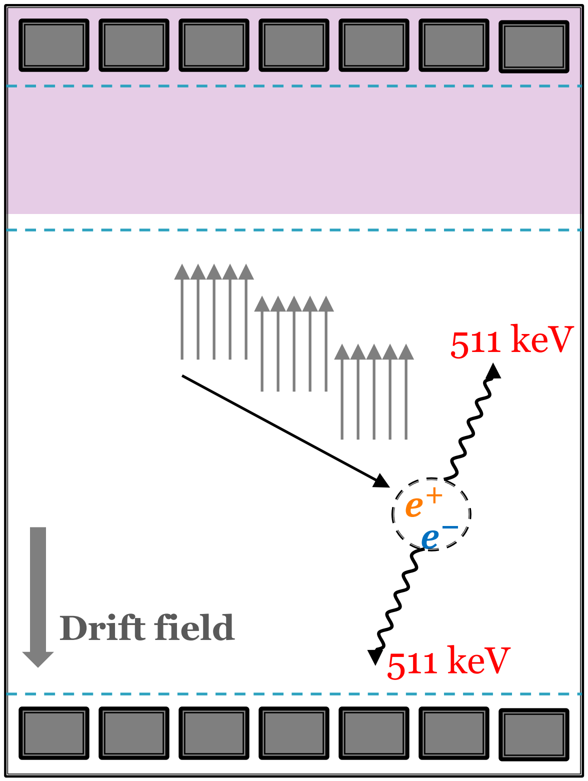
Positron Signature: Bragg Peak

❖ A given positron track



Positron Signature: 511 keV Peak

❖ A given positron track



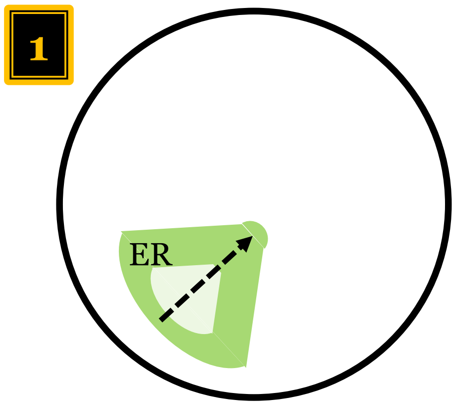
✓ stops in the detector and gets annihilated with a nearby electron, creating two characteristic 511 keV photon!

➔ Additional handle to identify positrons or positron tracks

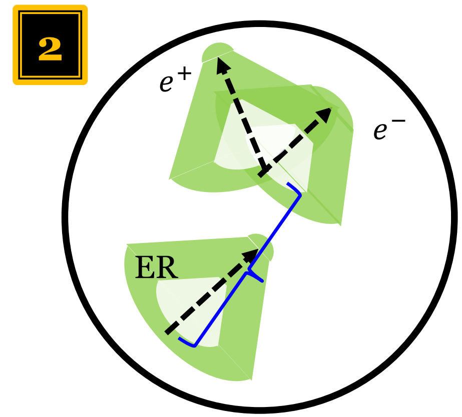
➔ This signature is particularly useful for DEAP-3600 as PMTs cover almost the entire surface of the detector.

Expected DM Signal Patterns (XY)

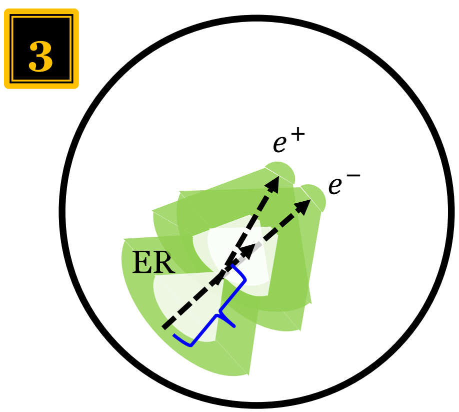
❖ Tracks Pop Up inside the fiducial volume, Not from outside!



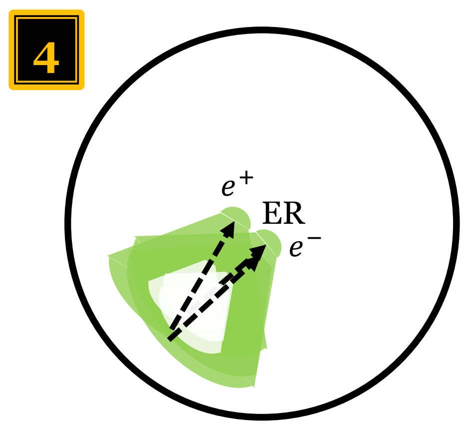
- ✓ Ordinary elastic scattering: single-track



- ✓ Three distinguishable tracks
- ✓ May leave an identifiable displaced secondary vertex



- ✓ Three overlaid tracks
- ✓ Density pattern: different from that for the elastic scattering
- ✓ Displaced vertex: maybe identifiable

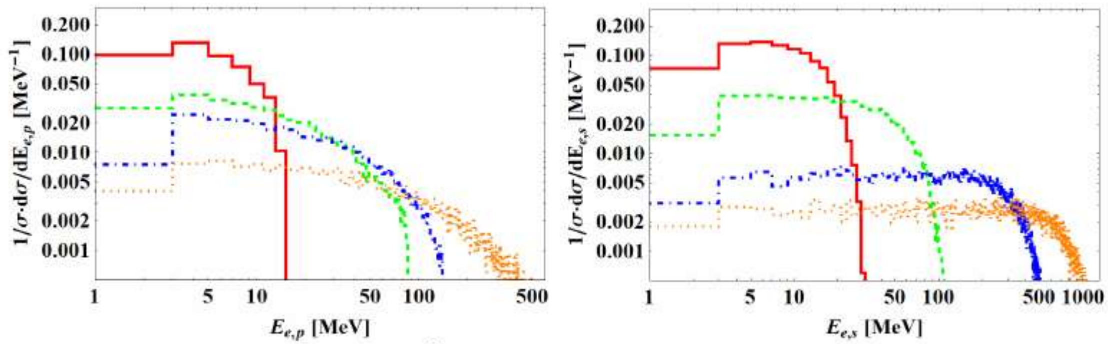


- ✓ (Relatively) prompt secondary process
- ✓ Three overlaid tracks
- ✓ Density pattern: different from that for the elastic scattering
- ✓ Displaced vertex: non-identifiable

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

❖ DEAP-3600: a displaced vertex $\gtrsim$ 6.5 cm identifiable only with S1 through a likelihood fitter

Benchmark Analysis: E-Spectrum



	m_1	m_2	m_X	γ_1	ϵ
ref1 (red solid)	2	5.5	5	20	4.5×10^{-5}
ref2 (green dashed)	3	8.5	7	50	6×10^{-5}
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.

Quite energetic ER & secondary signals

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

Three-body decay of χ_2 ➔ long-lived χ_2 ➔ a sizable vertex

$(m_2 < m_1 + m_X)$

Two-body decay of χ_2

➔ no displaced vertex < resolution

$(m_2 > m_1 + m_X)$

Analysis: Detection Prospects

		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

[Required fluxes of χ_1 in unit of 10^{-3} cm^{-2} sec^{-1}]

✓ Multi: primary & secondary tracks / Single: ≥ 1 track with E ≥ 10 MeV within the fiducial volume

❖ Requiring 3 signal events under the zero background assumption

❖ DEAP-3600 has no sensitivity to ref3 & ref4 (no displaced vertices) in "multi" channel: It is challenging to identify 3 final state particles only with S1.

However, it has sensitivity to identify just BDM even for ref3 & ref4 (not iBDM).

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

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

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

Controllable!

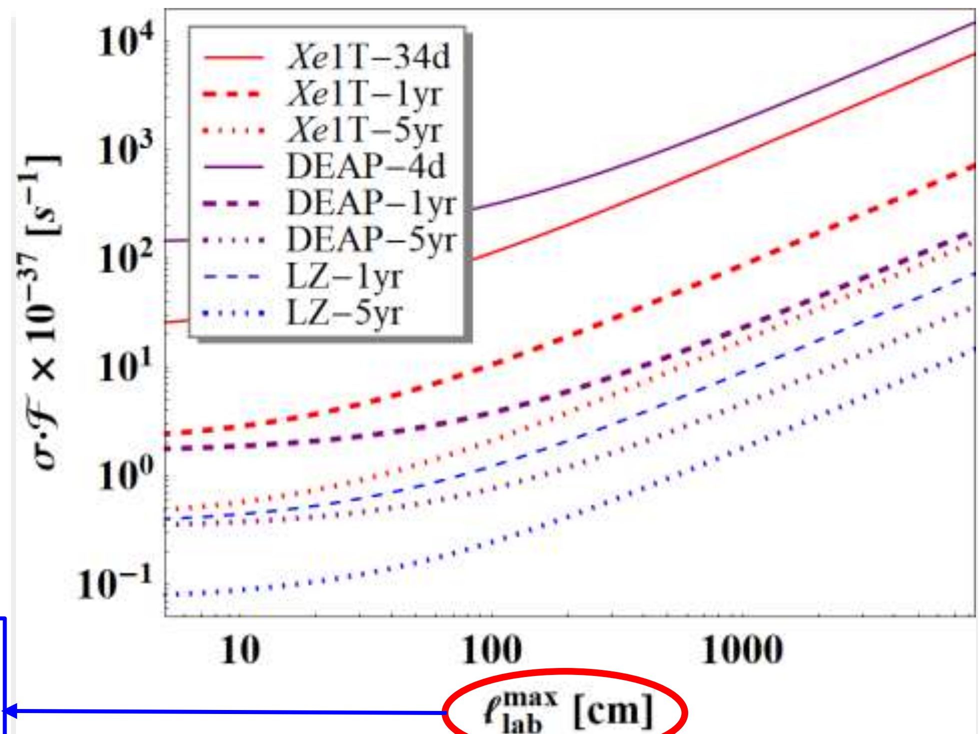
Model-independent Reach: Displaced Vertex

❖ Acceptance determined by the distance between the primary & 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

$$\sigma \cdot \mathcal{F} \geq \frac{2.3}{\underbrace{A(\ell_{\text{lab}})}_{\text{Calculable given a detector}} \cdot t_{\text{exp}} \cdot N_e}$$



ℓ_{lab}: different event-by-event taking $\ell_{\text{lab}}^{\text{max}}$ for more conservative limit

Model-independent Reach: Displaced Vertex

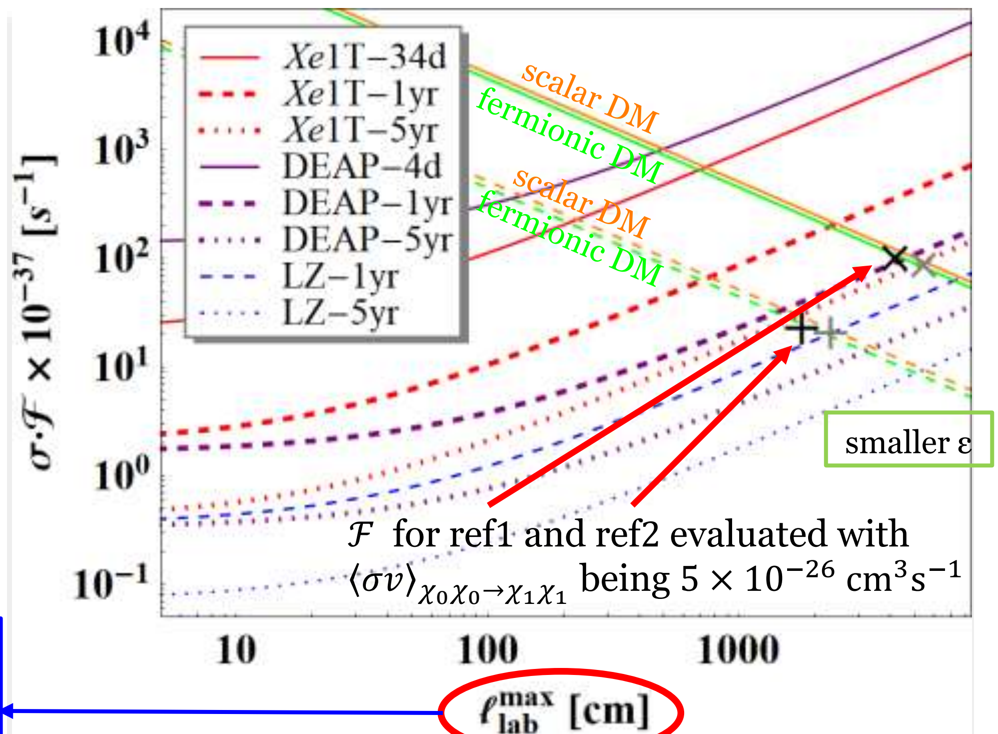
❖ Acceptance determined by the distance between the primary & the secondary vertices

➔ (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

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

Calculable given a detector



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

Model-independent Reach: Prompt Decay

❖ No (measurable) displaced vertex ➔ Acceptance ≈ 1

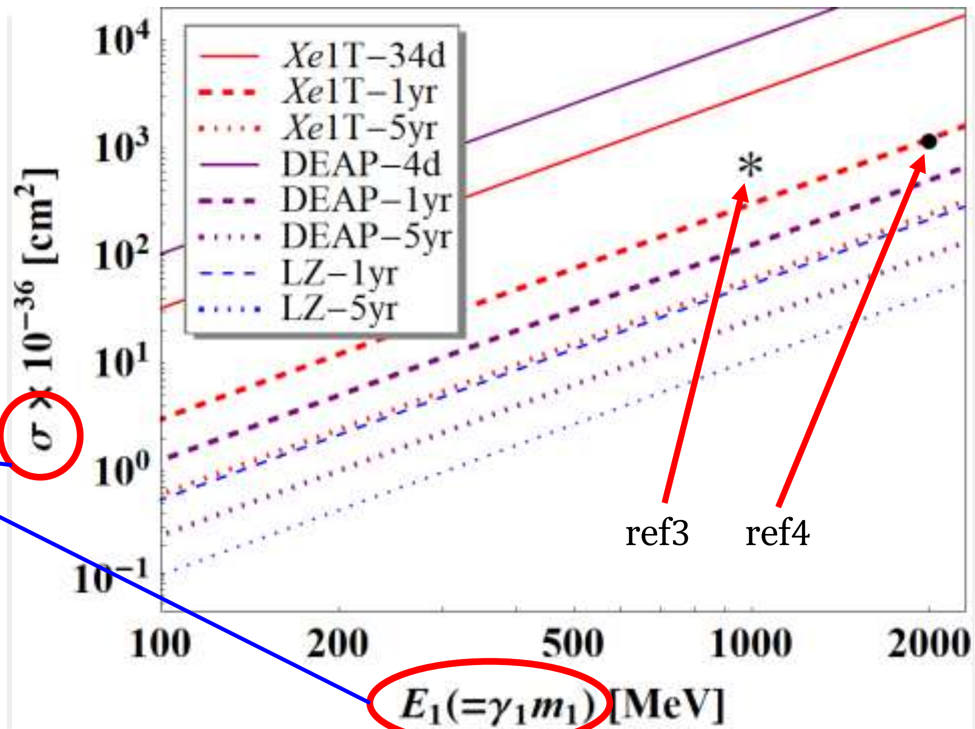
: relevant to signals with overlaid vertices or elastic scattering signals

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

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

set to be $5 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$

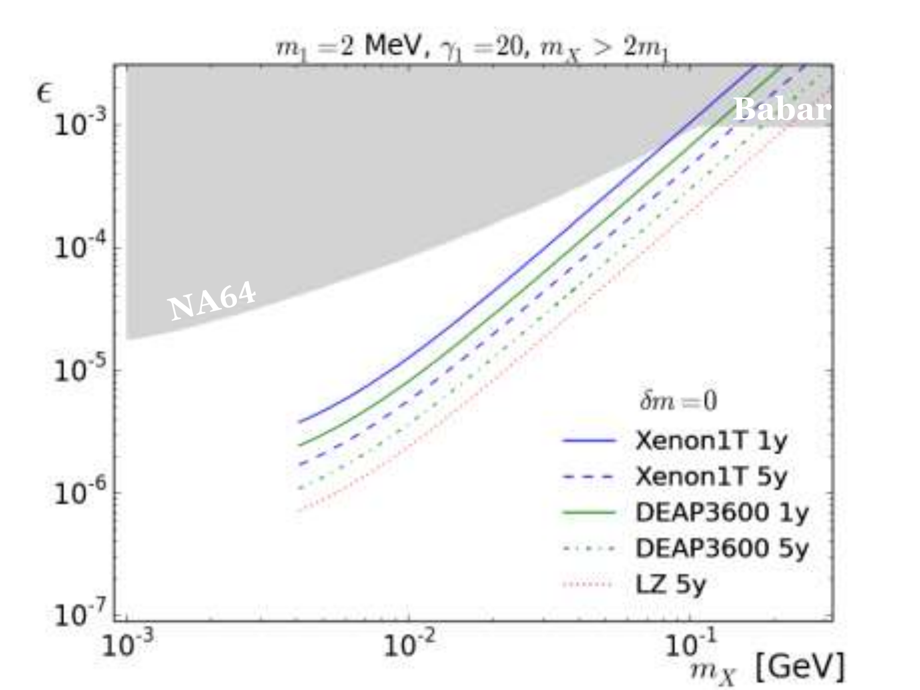
Experimental sensitivity can be represented by σ vs. $m_0 (= E_1)$.

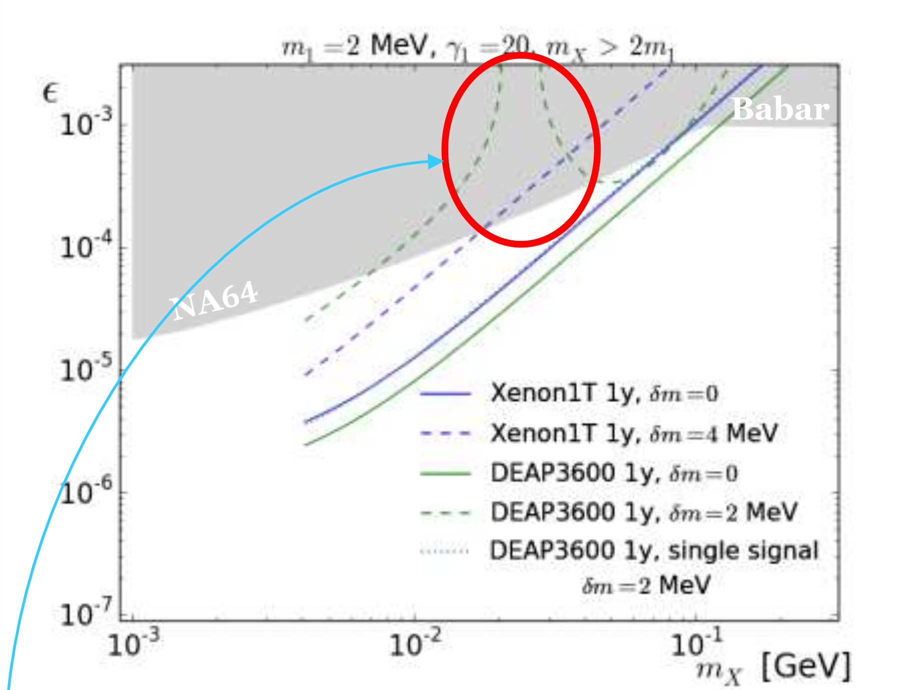


[Note that DEAP-3600 may not tell apart inelastic scattering from elastic scattering.]

Parameter Space: Invisible X Decay

❖ Dark X invisibly decays into DM pairs ($m_X > 2m_1$)

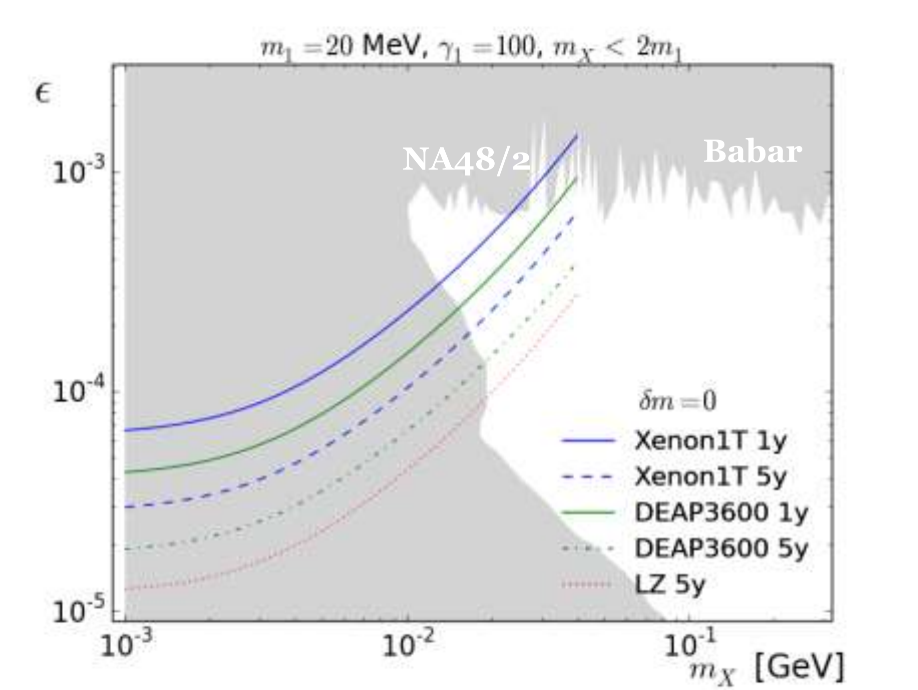


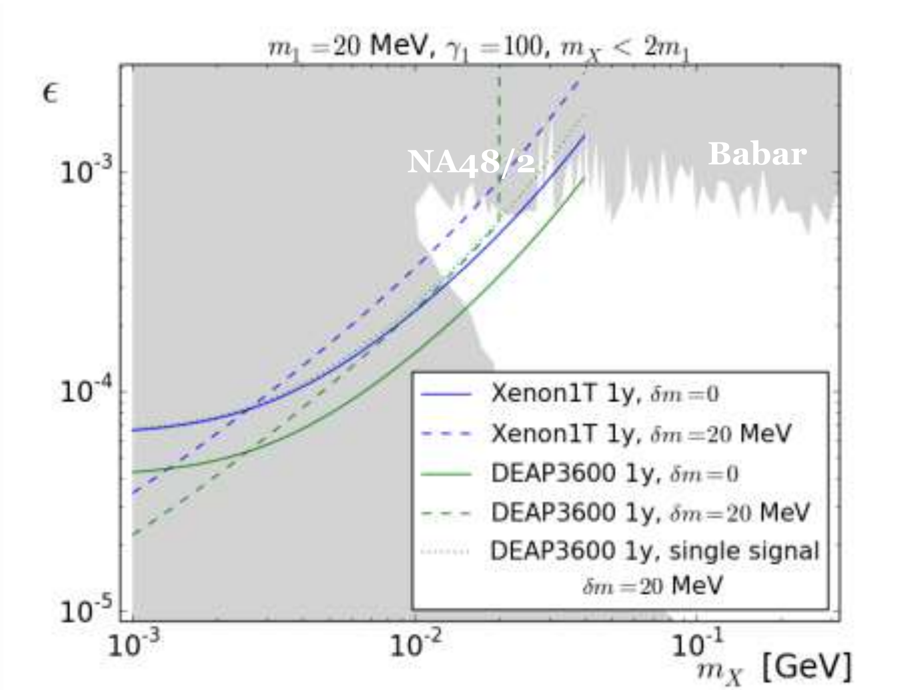


Caused by the position resolution of 6.5 cm
@ DEAP-3600

Parameter Space: Visible *X* Decay

❖ Dark *X* decays into SM pairs, i.e. e^+e^- ($m_X < 2m_1$)





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Conclusion

v_{DM} / **Scattering**	***non*-relativistic (<< c)**	**relativistic (~c)**
elastic	Direct detection	Boosted DM (BDM)
inelastic	inelastic DM (iDM)	inelastic BDM (iBDM)

- **Direct** detection of lighter BDM ➔ **Indirect** detection of heavier DM
- **Small** flux ➔ **Large** volume required (e.g. SK/HK, DUNE, …)
- Conventional DM direct detection Exps. have sensitivities to MeV-range DM.
- Provide alternative avenue to probe dark photon parameter space.

Thank you