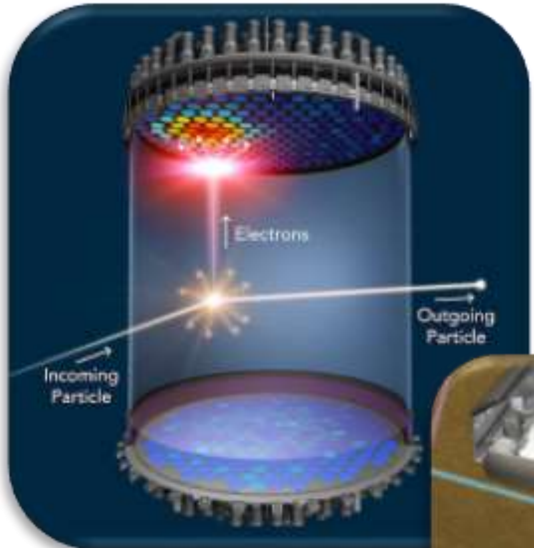
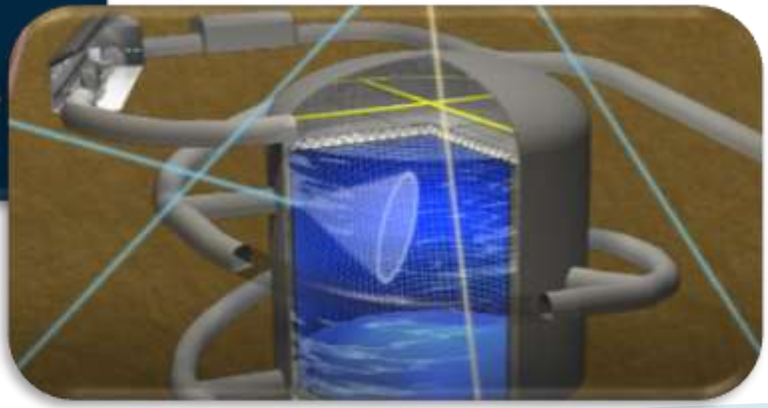
A New DM (in)Direct Search Strategy

K. Kong, G. Mohlabeng, JCP, arXiv:1411.6632
H. Alhazmi, K. Kong, G. Mohlabeng, JCP, arXiv: 1611.09866
D. Kim, JCP, S. Shin, arXiv:1612.06867
G. Giudice, D. Kim, JCP, S. Shin, to appear soon





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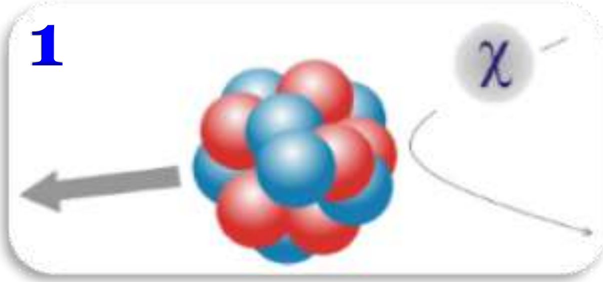
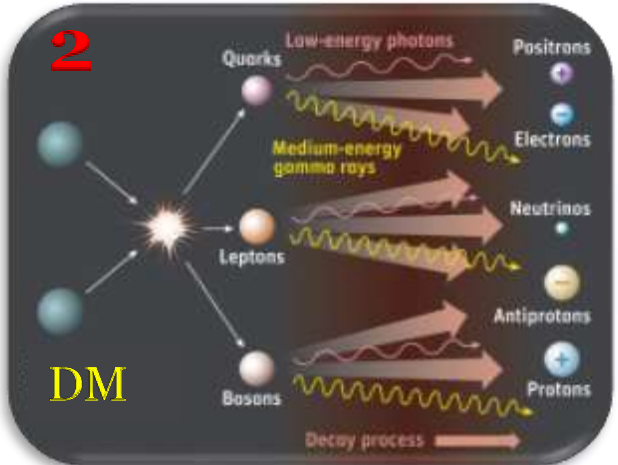
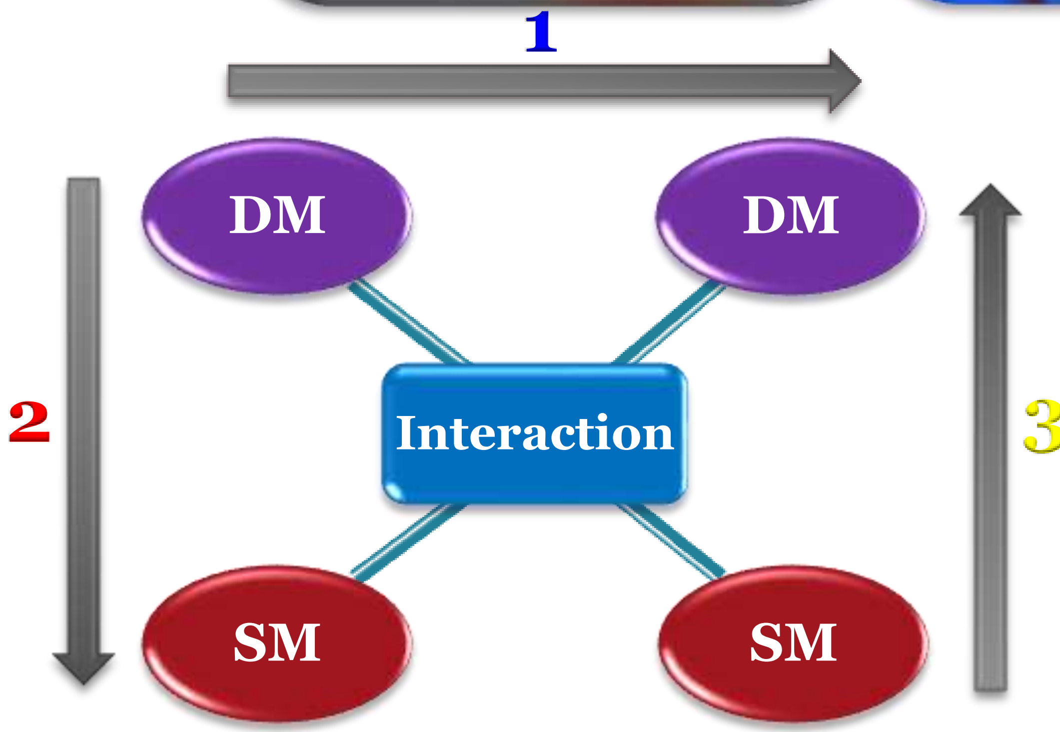
CHUNGNAM NATIONAL UNIVERSITY

IBS Conference on Dark World **November 01 (2017)**

Typical DM Search Strategies



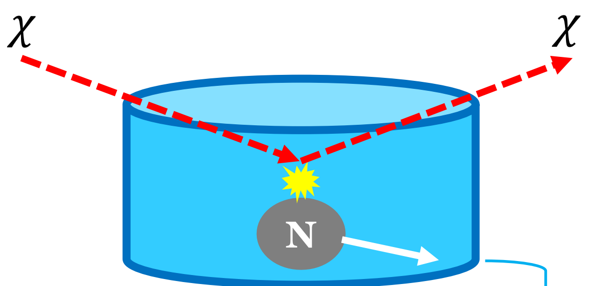




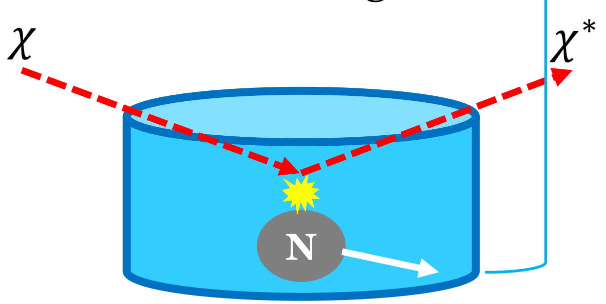
Typical DM Direct Searches

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

- Elastic scattering

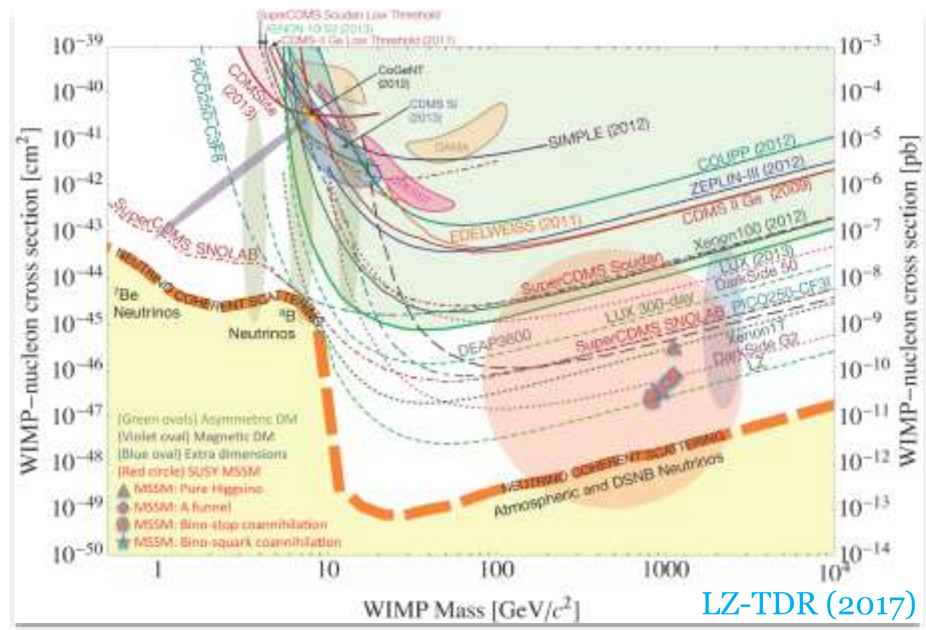


- Inelastic scattering (iDM)



✓ $E_{\text{recoil}} \sim mv^2$ ~ 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)

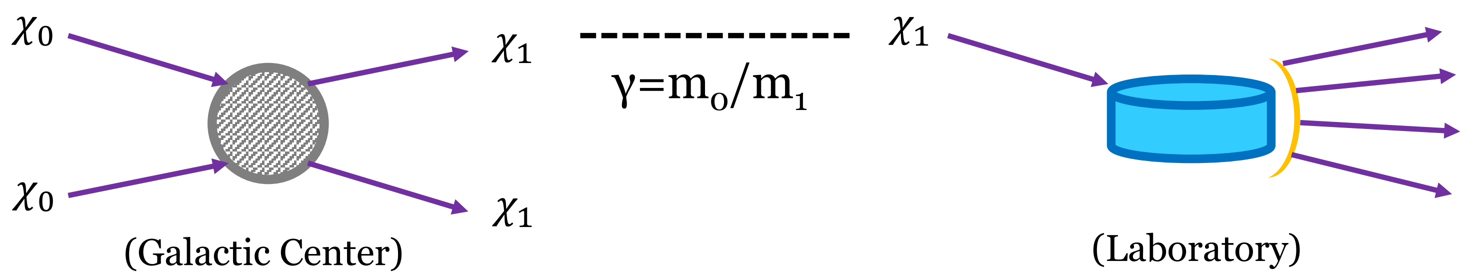
Very well-studied

DM Search Schemes (Scattering)

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

"Relativistic" DM (BDM)

❖ Need for alternative approaches



$Z_2 \otimes Z_2', U(1)' \otimes U(1)'', \ldots$

✓ χ_0: heavier DM, dominant relic, no direct coupling to SM

✓ χ_1: lighter DM, subdominant relic, direct coupling to SM,

can be relativistic at the current universe (non-relativistic as a relic!!)

✓ Overall relic determined by "**<u>Assisted Freeze-out</u>**" mechanism [Belanger, JCP (2011)]

A $U(1)' \otimes U(1)''$ model proposed

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 DM number density

❖ 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 $\mathcal{F}_{\chi_1} \sim 10^{-7} \mathrm{cm^{-2} s^{-1}}$ 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

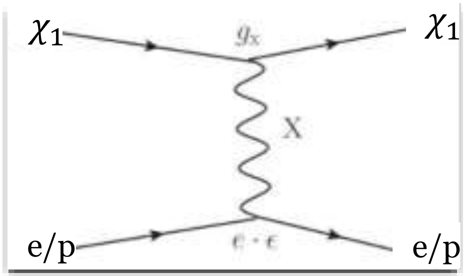
✓ GC: Agashe et al (2014); Necib et al (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016)

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

✓ Dwarf galaxies: Necib et al (2016)

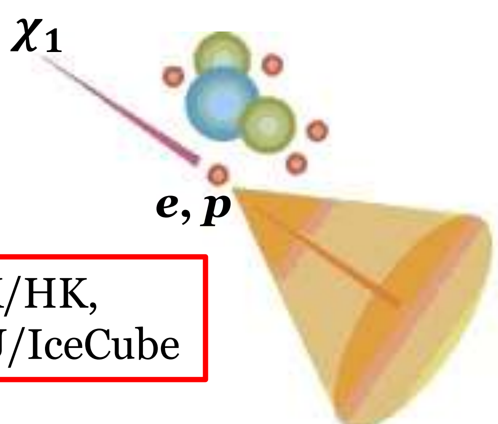
Detection of BDM

❖ Large volume ν detectors detect energetic charged particles from ν-matter collisions, e.g. $\nu_e n \to e^- p$



❖ Boosted DM: energetic e's/p's resulting from $\chi_1 e/p \rightarrow \chi_1 e/p$

❖ Energetic e's/p's ➔ Cherenkov light / charged particle track

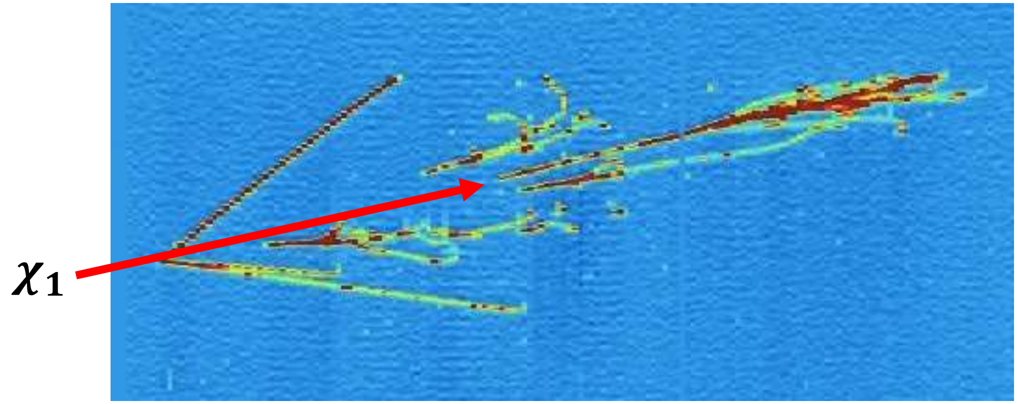


SK/HK, PINGU/IceCube

Cherenkov light

$$E_e^{\min} = E_e^{\text{thresh}} > \gamma_{\text{Cherenkov}} m_e$$

> 1.5

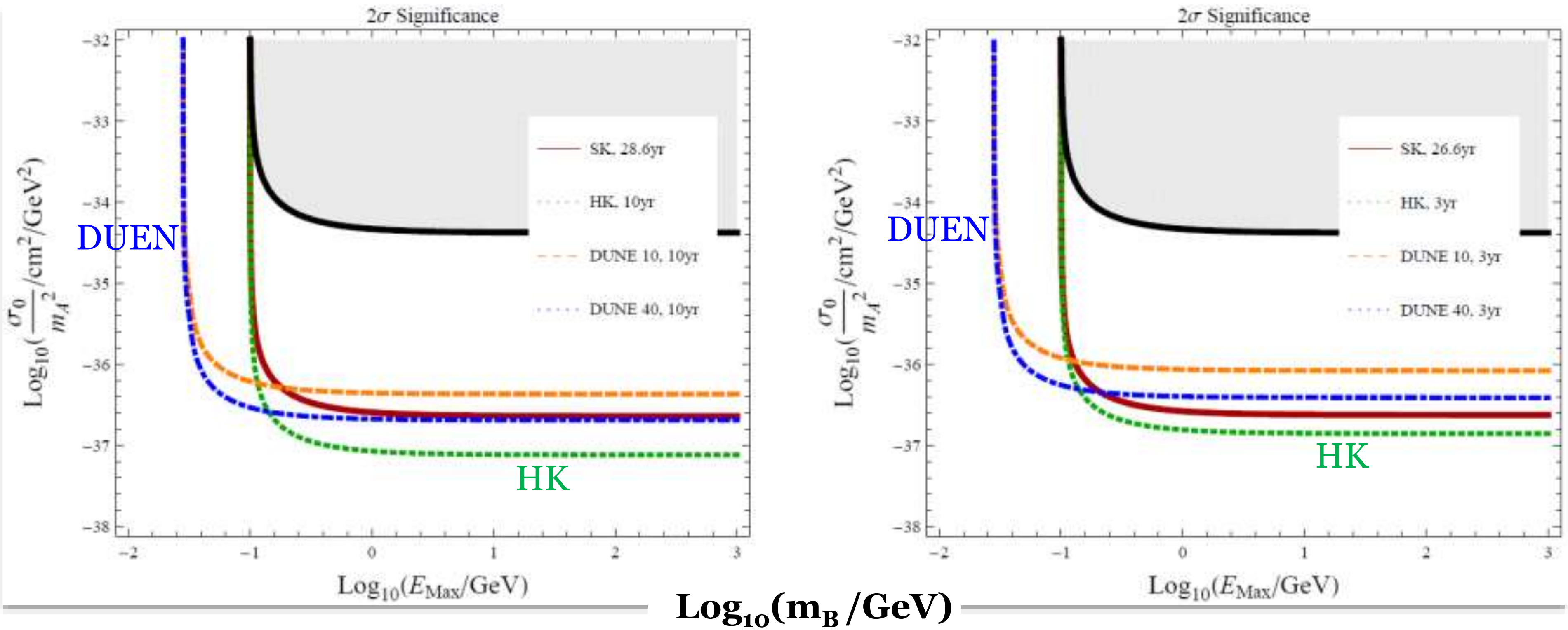


DUNE: LArTPC

Experimental Reach (GC)

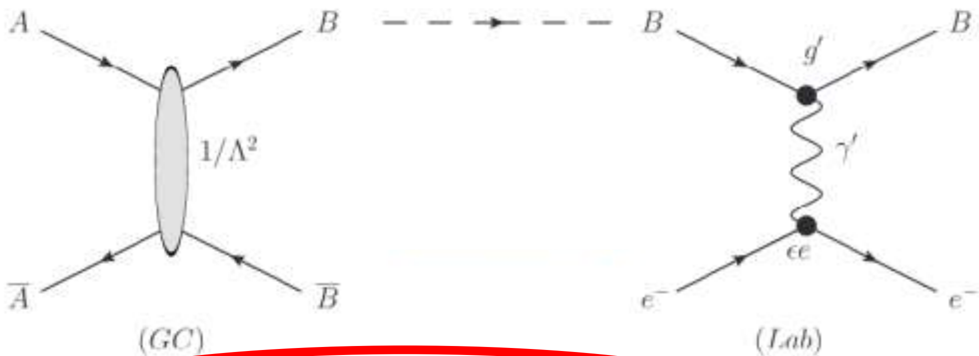
H. Alhazmi, KC Kong, G. Mohlabeng & **JCP** (2016)

❖ Total number of signal events: $N_{\rm sig}^{\rm GC} = \Delta T \; N_{\rm target} \; \Phi_{\rm GC}^{\theta_C} \; \sigma_{Be^- \to Be^-}$



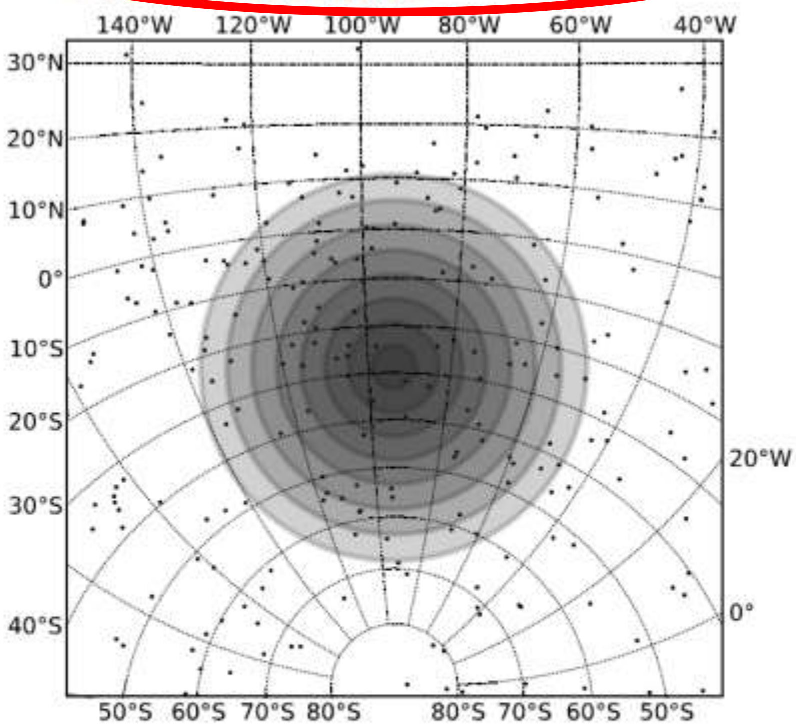
5 year construction+10 year running vs 3 year construction+3 year running

(In)direct dark matter detection?

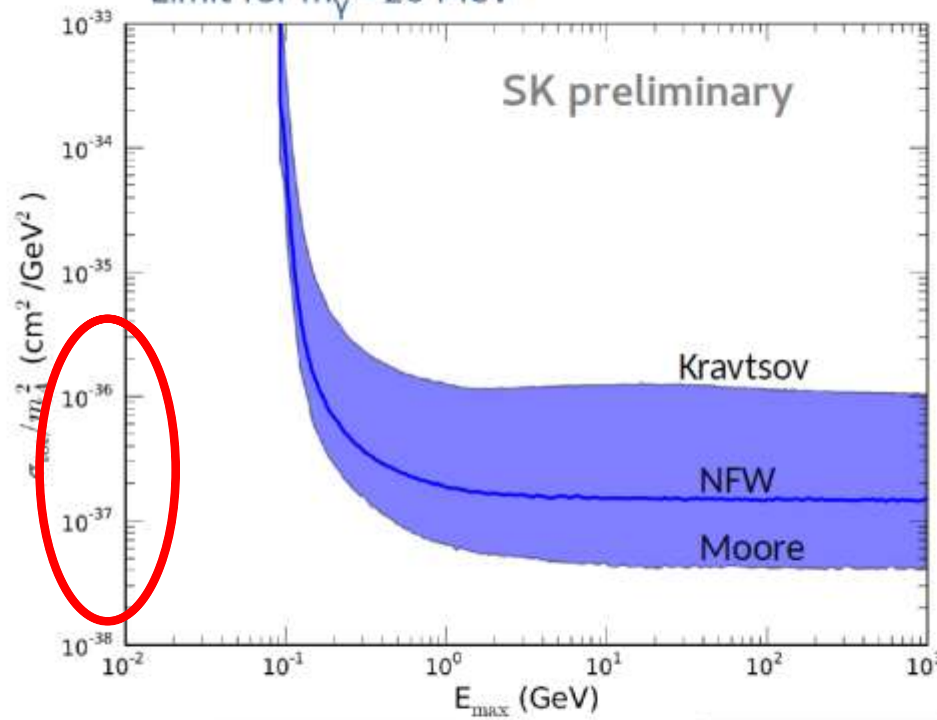


- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

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



Limit for m_{γ}'=20 MeV



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elastic	Direct detection	Boosted DM (BDM)
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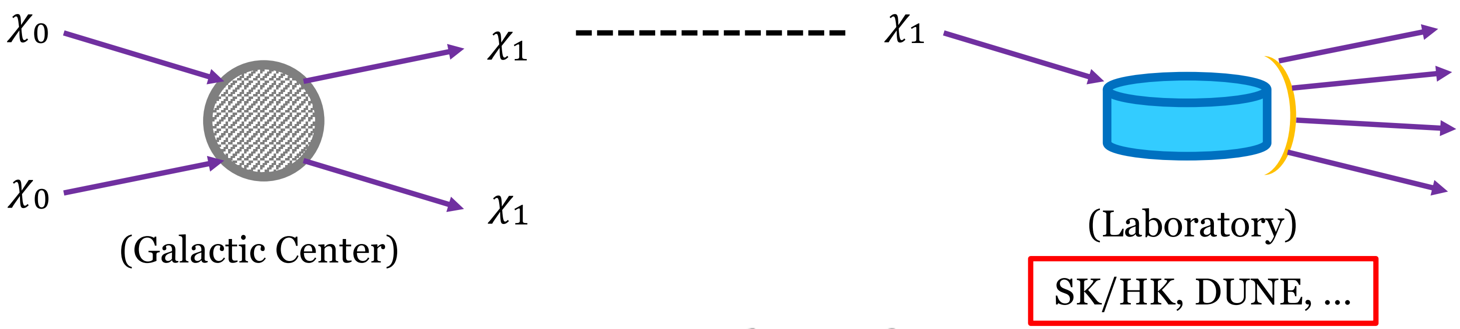
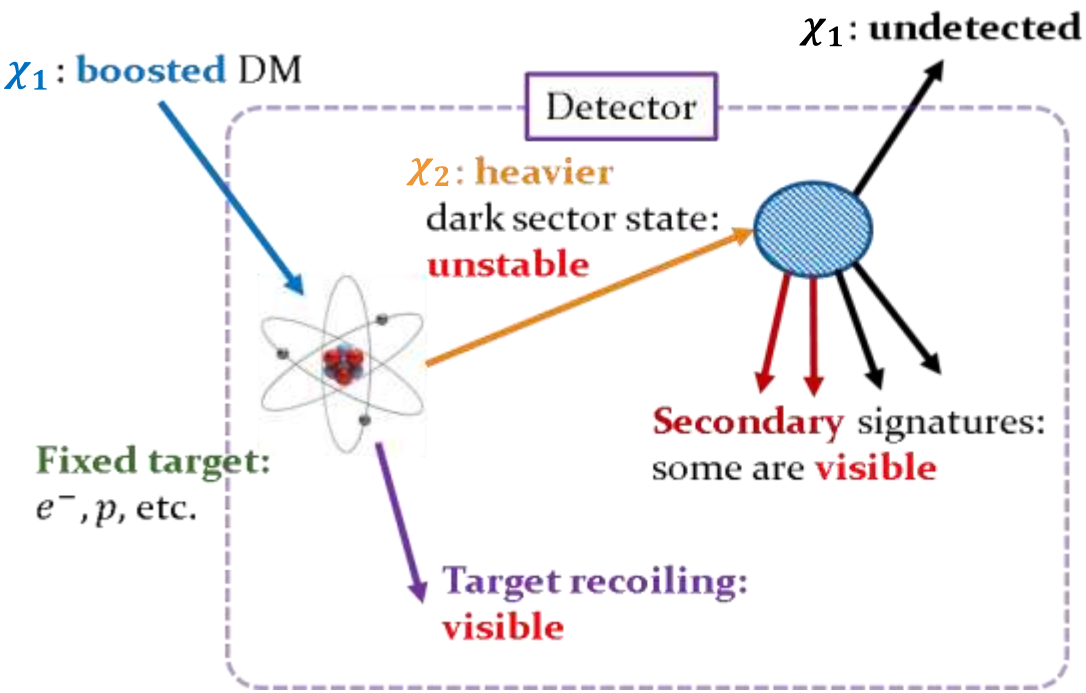
iBDM: DM "Colliders"

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



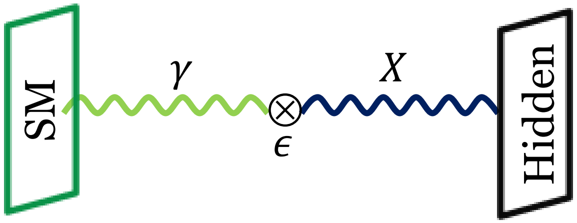


Follow-ups in collaborations with
experimentalists (DUNE, HK, SHiP, ...)

- 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.

Benchmark Model

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



❖ Vector portal (kinetic mixing) [Holdom (1986)]

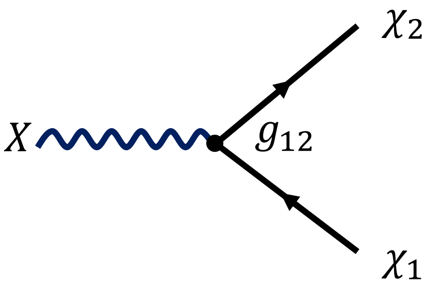
❖ Fermionic DM

✓ χ_2: a heavier (unstable) dark-sector state

✓ Flavor-conserving ➔ elastic scattering

✓ Flavor-changing ➔ inelastic scattering

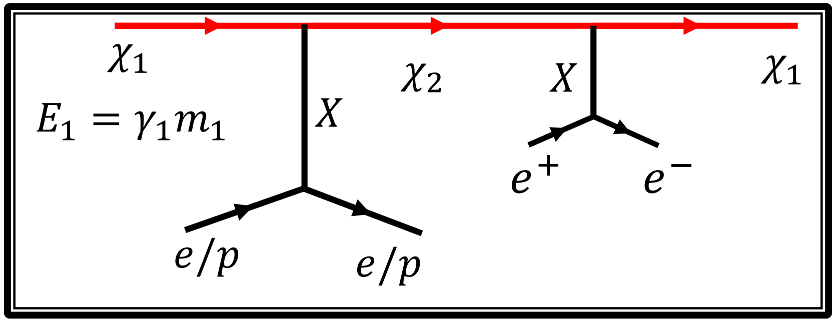
[Tucker-Smith, Weiner (2001); Kim, Seo, Shin (2012)]



❖ Diagonal coupling may be highly suppressed, even vanishing.

❖ Scalar DM also possible

Signal Attributes



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

Exp.	e-scattering	p-scattering
Energy for primary scattering	Peaking towards smaller momentum transfer	
Threshold energy	Small	Large for Cherenkov Small for LArTPC
Form factor suppression	N/A	Yes
Deep inelastic scattering	N/A	Yes
Energy for secondary process	(Typically) highly boosted	(Typically) less boosted
Object identification	Highly collimated (in preferred mass spectra) Recoil electron + single object-like e^+e^- pair (assuming θ_{res}~3°)	Reasonably separated (in preferred mass spectra) Recoil proton + well-separated e^+e^- pair

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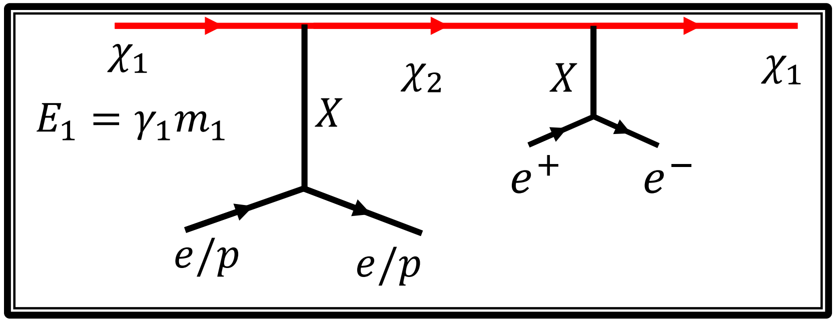

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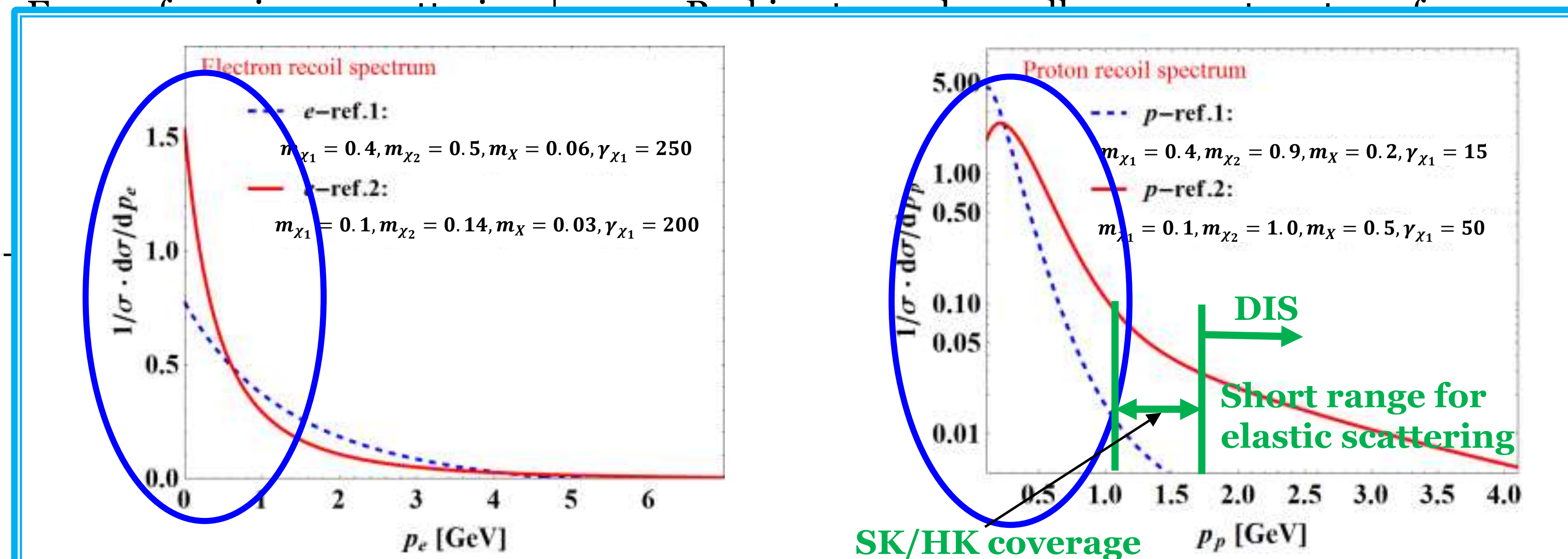

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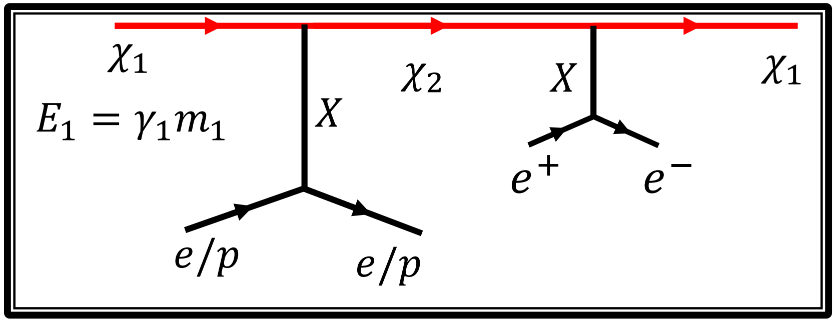

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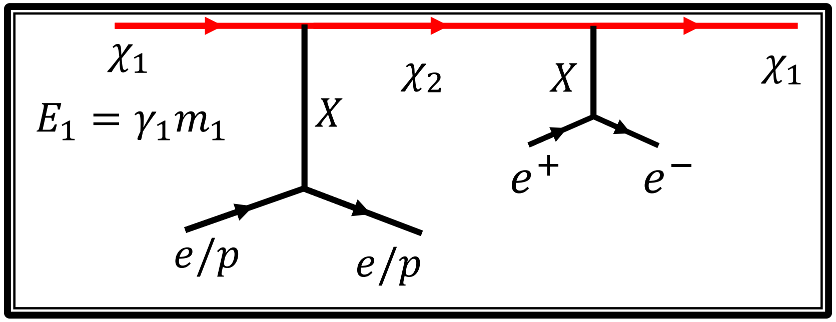

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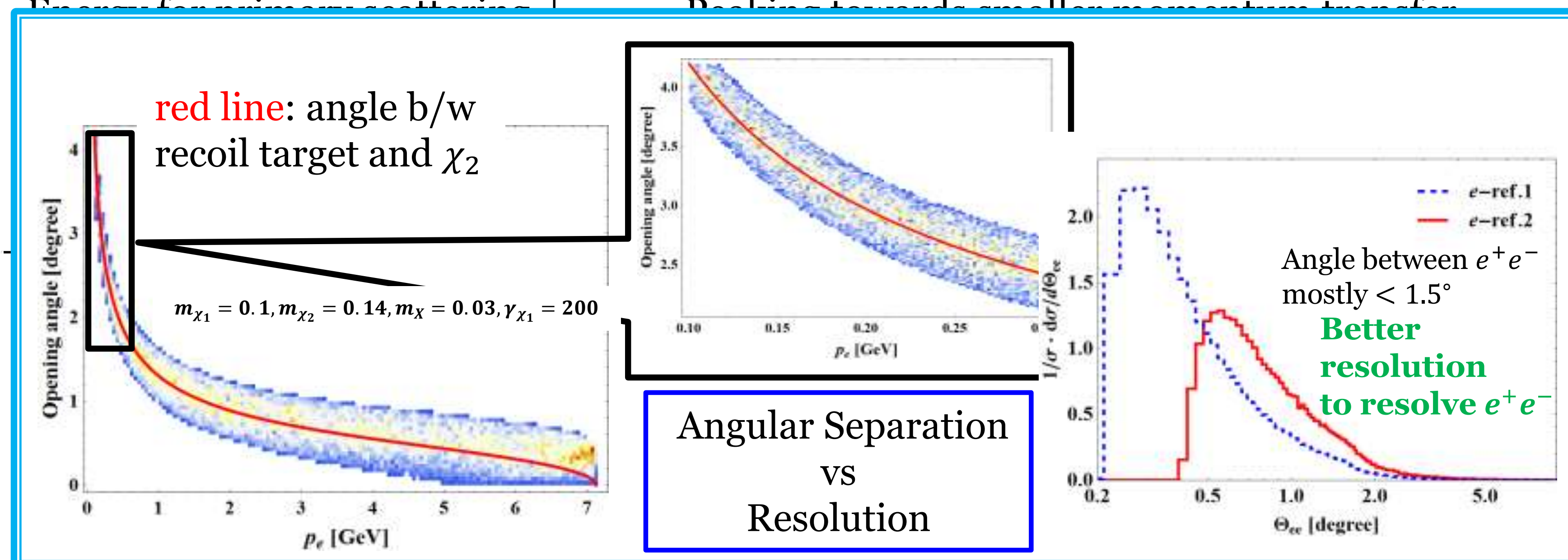

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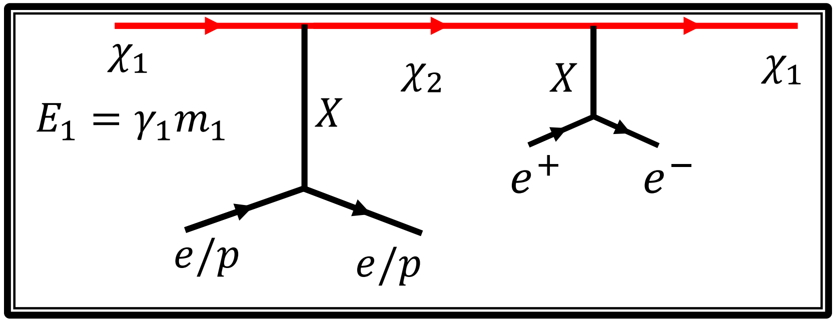

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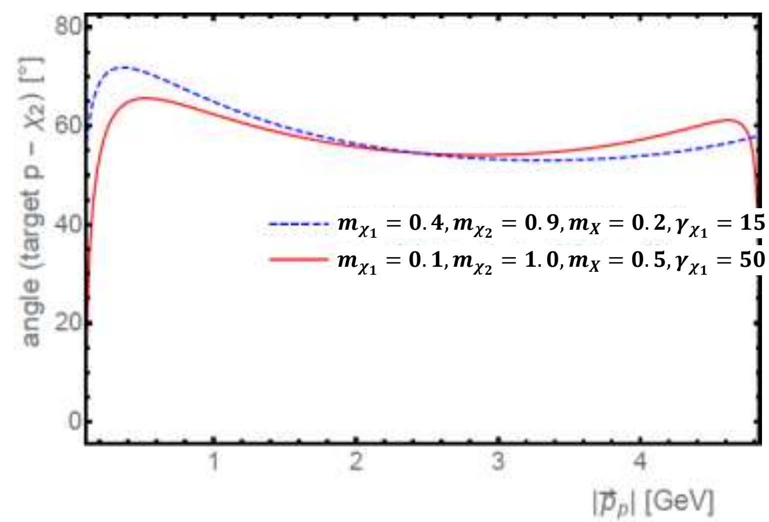
Angular Separation
vs
Resolution



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 [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 (stopping power of *e* of E~O(10 MeV) @ LXe: ~4 MeV/cm [Aprile, Doke (2009)])
  - ✓ *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!**

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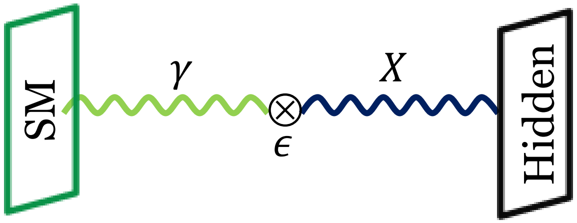

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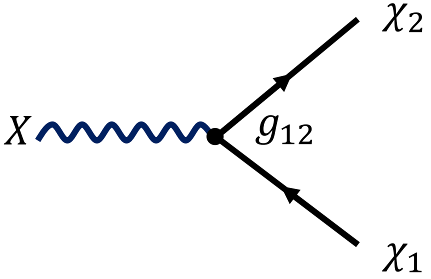

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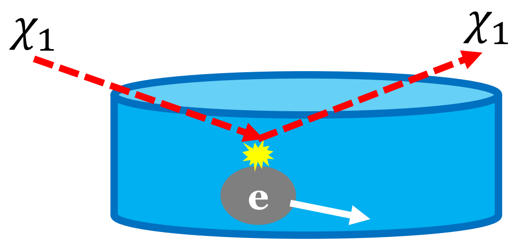
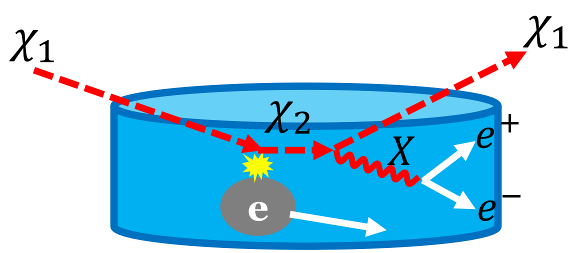
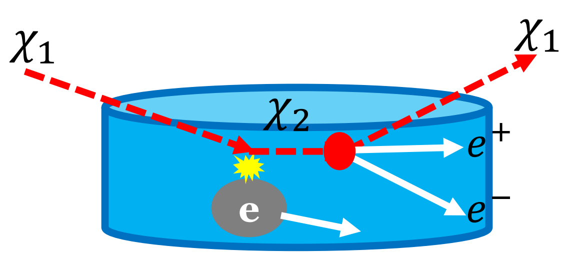
Expected Signatures



: ER ➔ ordinary but energetic elastic scattering



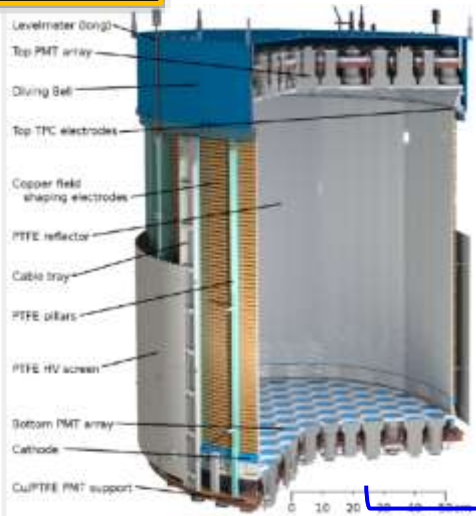
: ER + e^+e^- pair (from the decay of on-shell X)



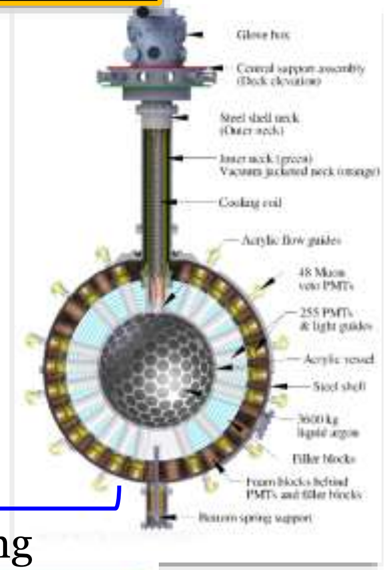
: ER + e^+e^- pair (from the decay of off-shell X ← three-body decay of χ_2) ➔ secondary signal may be displaced.

Benchmark Detectors

XENON1T



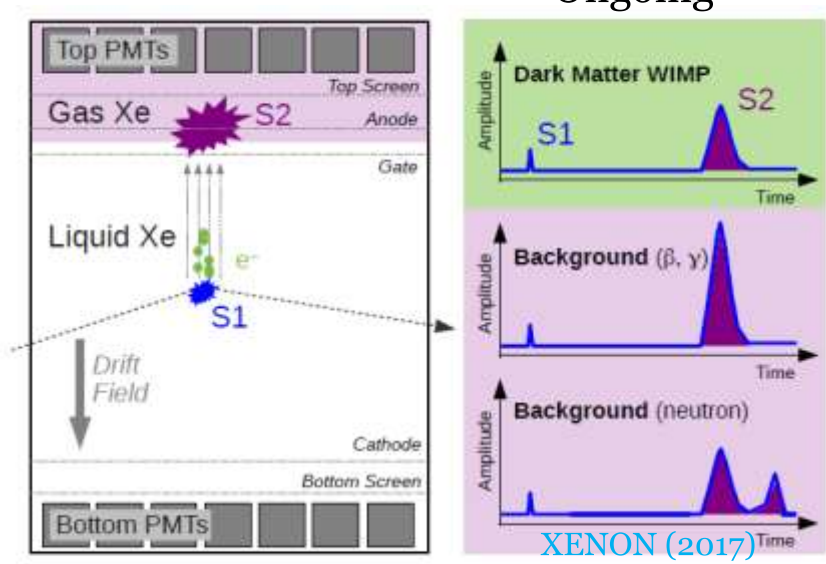
DEAP-3600



Ongoing

LUX-ZEPLIN(LZ)

Future

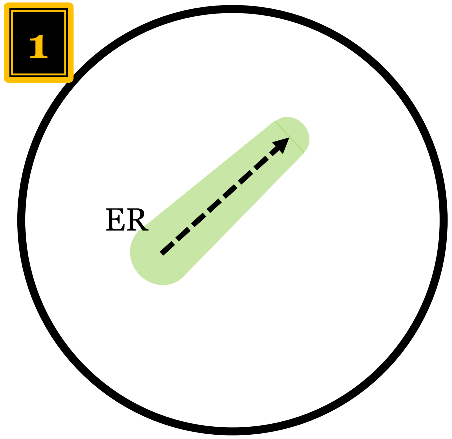


Experiment	Geometry $(r,\ h)$ or r [cm]		Mass [t]	Target
XENON1T	Cylinder	(38, 76)	1.0	LXe
DEAP-3600	Sphere	72	2.2	LAr
LZ	Cylinder	(69, 130)	5.6	LXe

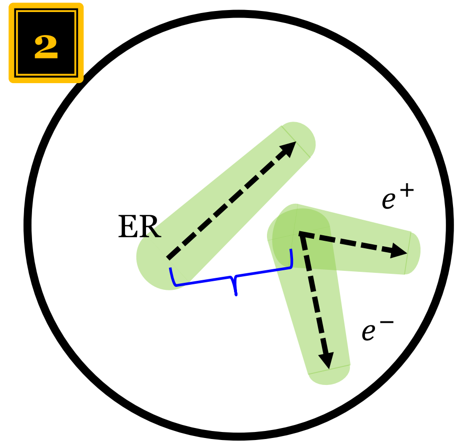
[Numbers are for fiducial volumes.]

- ❖ XENON1T & LZ: S1 + S2
- ❖ DEAP-3600: S1 only

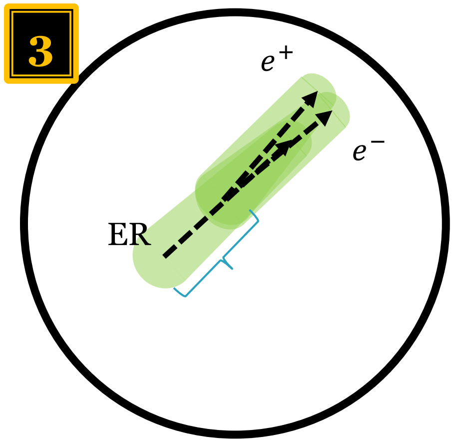
Expected DM Signal Patterns



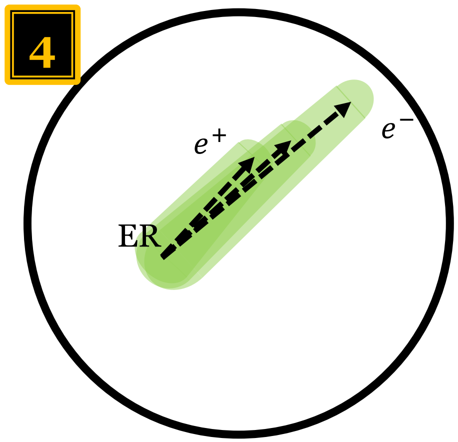
- ✓ Ordinary elastic scattering: single-track



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



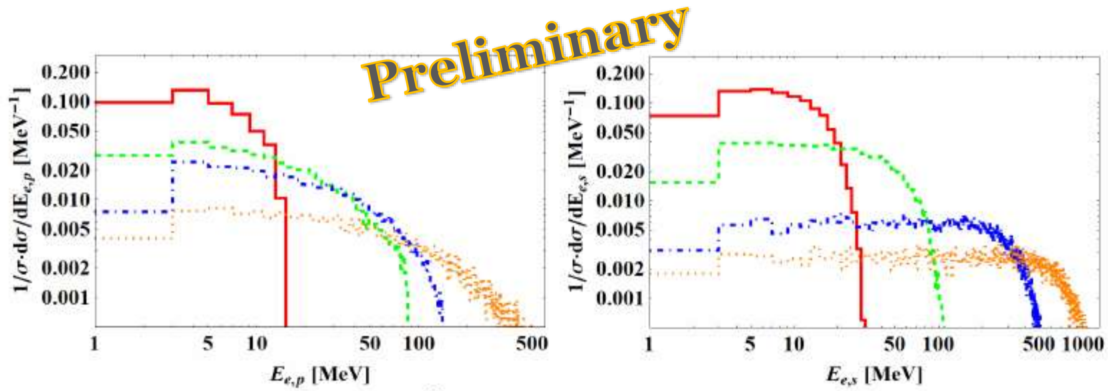
- ✓ Three overlaid tracks
- ✓ Density pattern: different from that for the elastic scattering
- ✓ Displaced vertex: maybe identifiable



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

❖ DEAP-3600: a displaced vertex $\gtrsim$ 6.5 cm identifiable only with S1 (scintillation) through a maximum 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

Two-body decay of χ_2

➔ no displaced vertex < resolution

Analysis: 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	17	220	5.1	0.37	0.37	0.27	0.27
	5 yr	390	3.3	43	1.0	0.075	0.075	0.054	0.054
DEAP-3600	1 yr	450	6.9	55	2.1	–	0.16	–	0.11
	5 yr	91	1.4	11	0.42	–	0.031	–	0.022
LZ	1 yr	180	3.0	25	0.91	0.067	0.067	0.048	0.048
	5 yr	36	0.59	5.0	0.18	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 events / Single: only primary event within the fiducial volume

❖ Requiring 3 signal events with 3 *e*'s under the zero background assumption

❖ DEAP-3600 has no sensitivity to ref3 & ref4: no displaced vertices in ref3 & ref4

🡐 It is challenging to identify 3 final state particles only with S1.

It may have 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

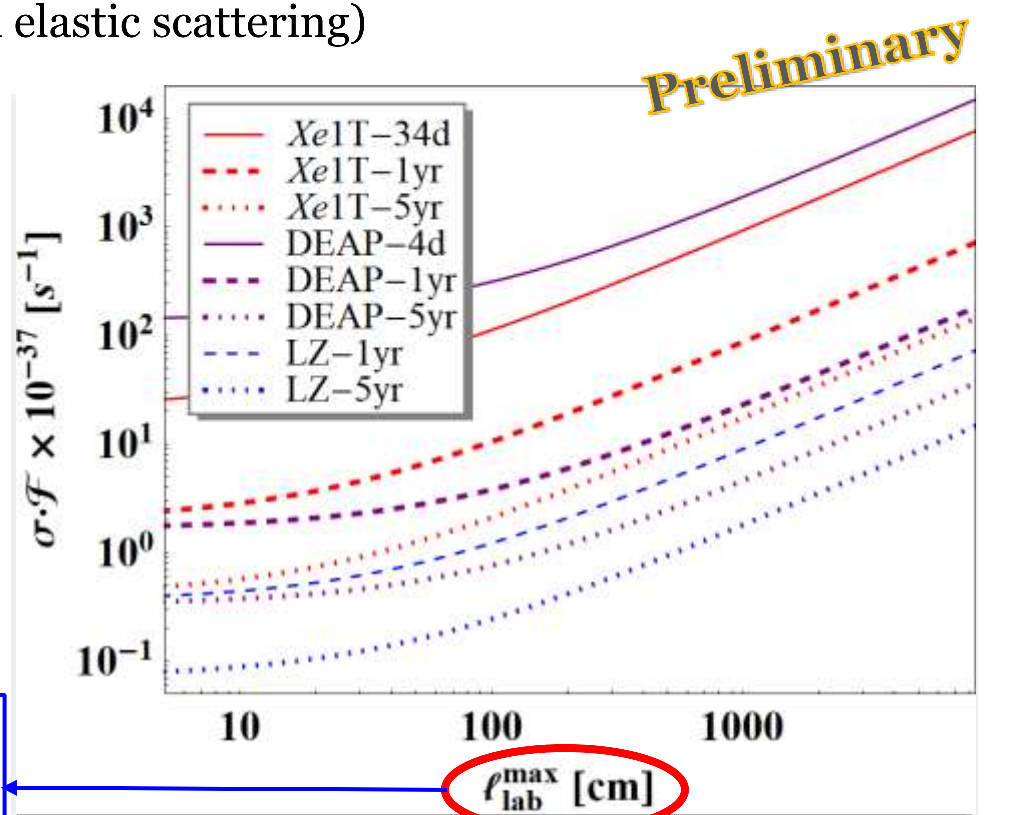
- ❖ Acceptance determined by the distance between the primary & the secondary vertices

  ➔ (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

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

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



Model-independent Reach: Displaced Vertex

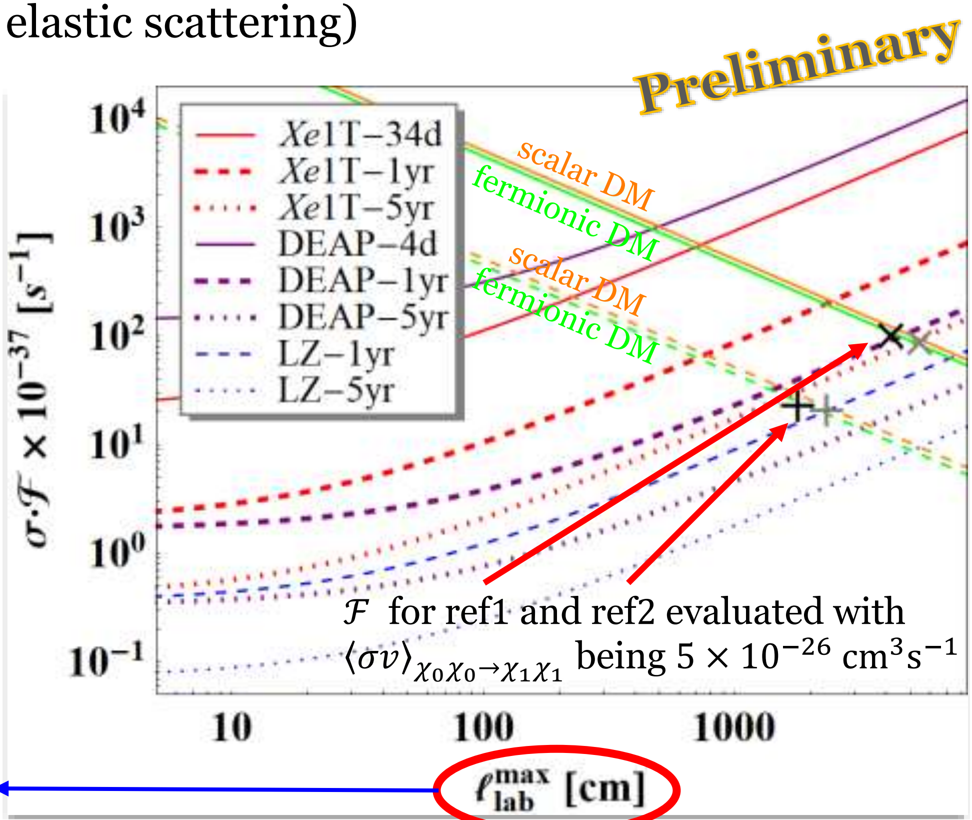
❖ Acceptance determined by the distance between the primary & the secondary vertices

➔ (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

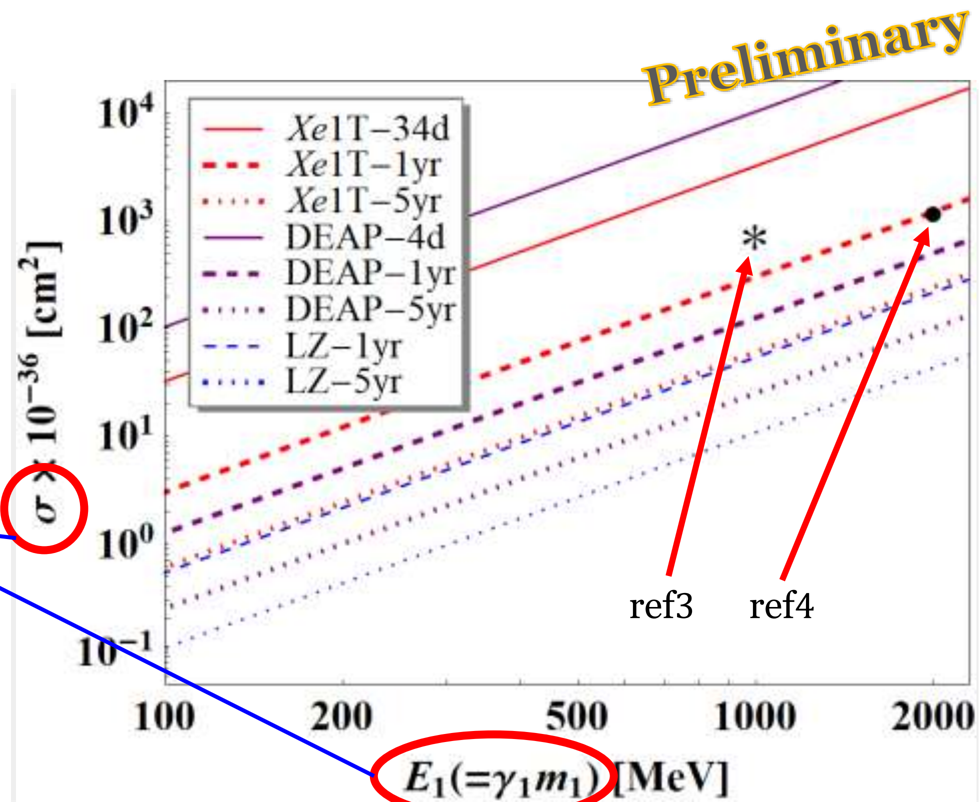
$$\sigma \geq \frac{2.3}{\mathcal{F} \cdot A \cdot t_{\rm exp} \cdot N_e}$$

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

set to be 5×10^{-26} cm^{3}s^{-1}

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

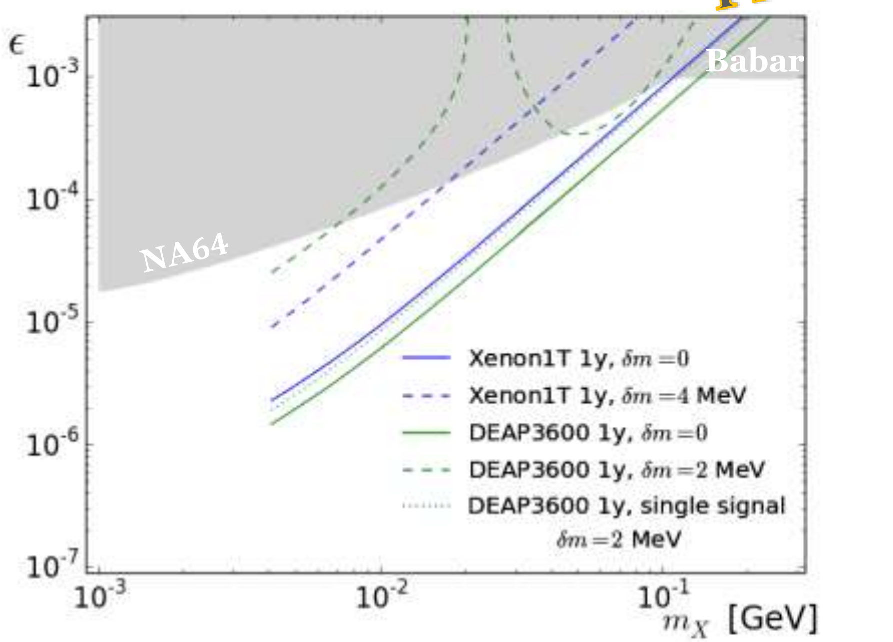
[Note that DEAP-3600 may not tell apart inelastic scattering from elastic scattering.]

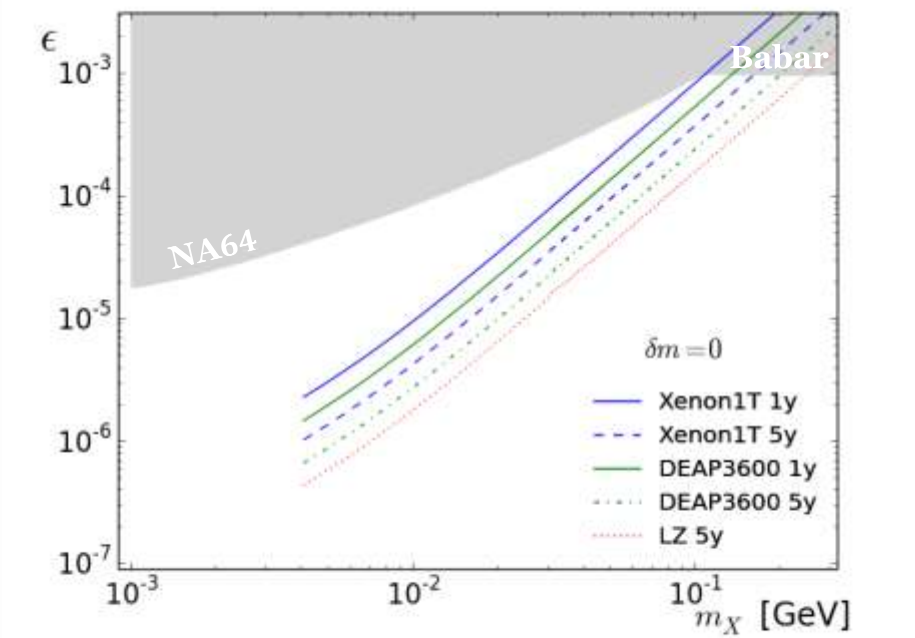


Parameter Space: Invisible X Decay

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

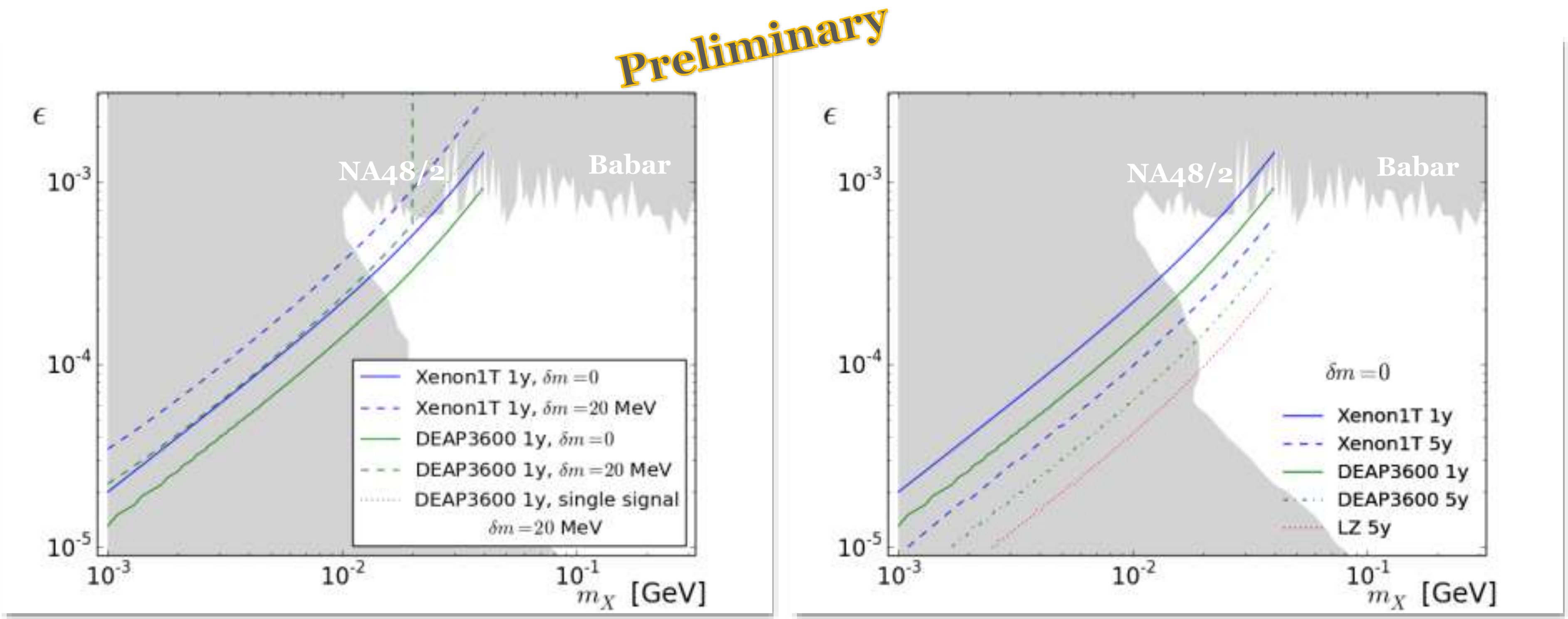
Preliminary

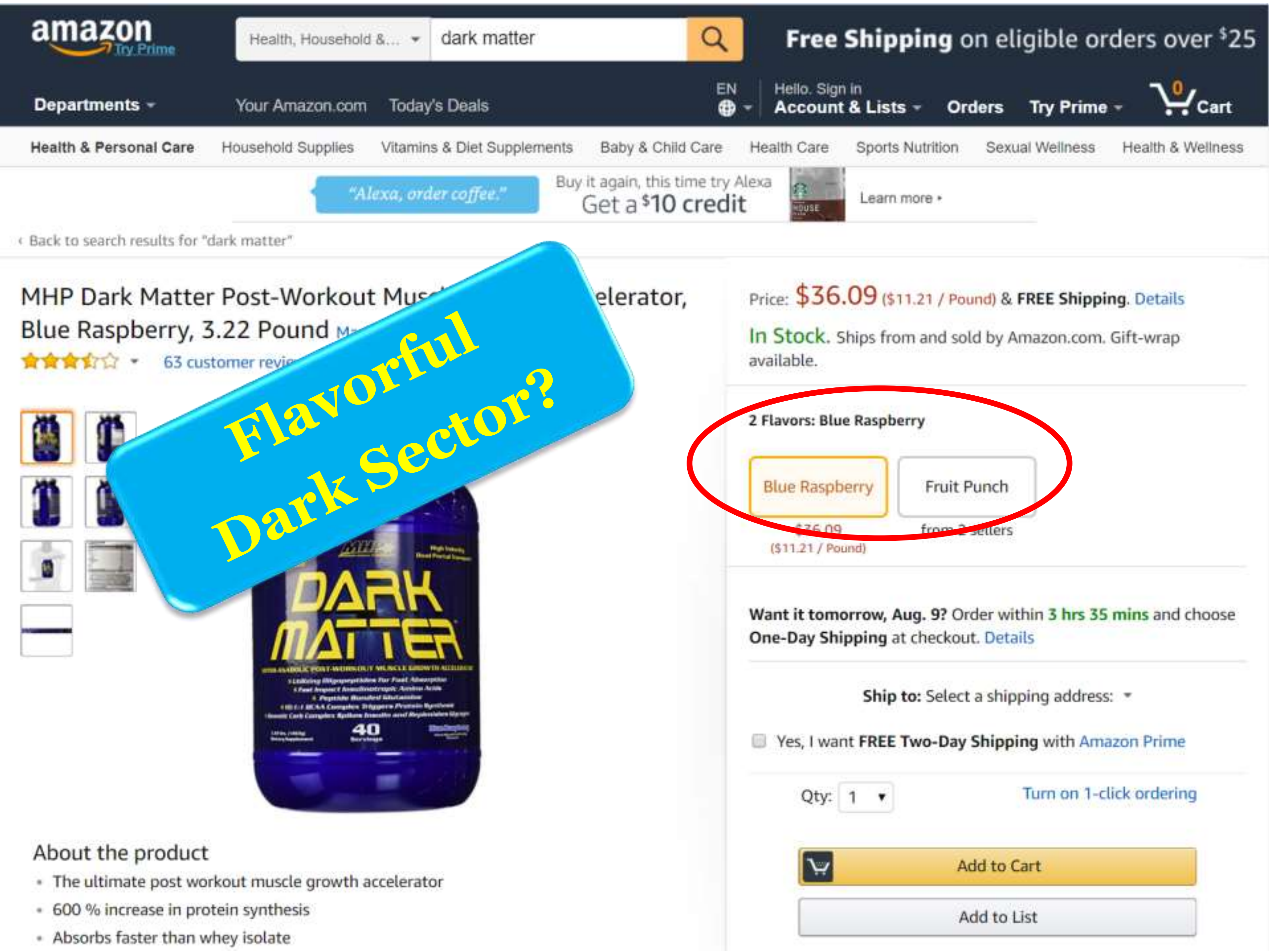




Parameter Space: Visible X Decay

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

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Conclusion

Scattering \ v_{DM}	***non*-relativistic (<< c)**	**relativistic (~c)**
elastic	Direct detection	Boosted DM (BDMP
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