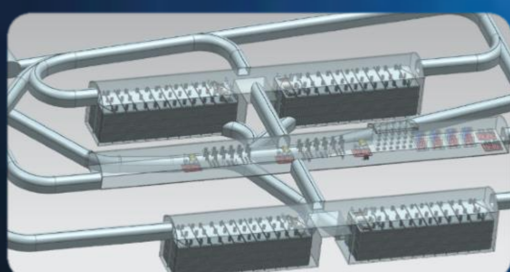
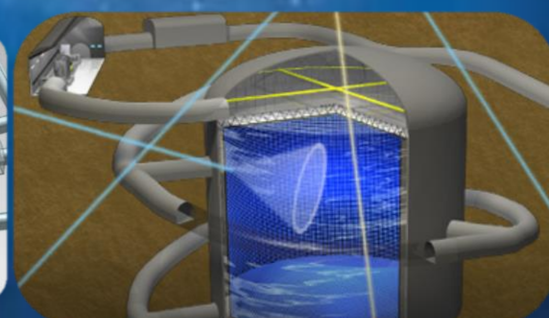
Boosted DM & its Search

Jong-Chul Park





CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

2019.02.27

YuCHE 2019 Workshop

Boosted DM & its Search

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1112.4491, 1411.6632, 1611.09866, 1612.06867, 1712.07126, 1803.03264, 1804.07302, more in progress,
In collaboration with H. Alhazmi, G. Belanger, A. Chatterjee, A. De Roeck, G. Giudice, D. Kim, KC. Kong, P. Machado, G. Mohlabeng, Z. Moghaddam, S. Shin, L. Whitehead, J. Yu

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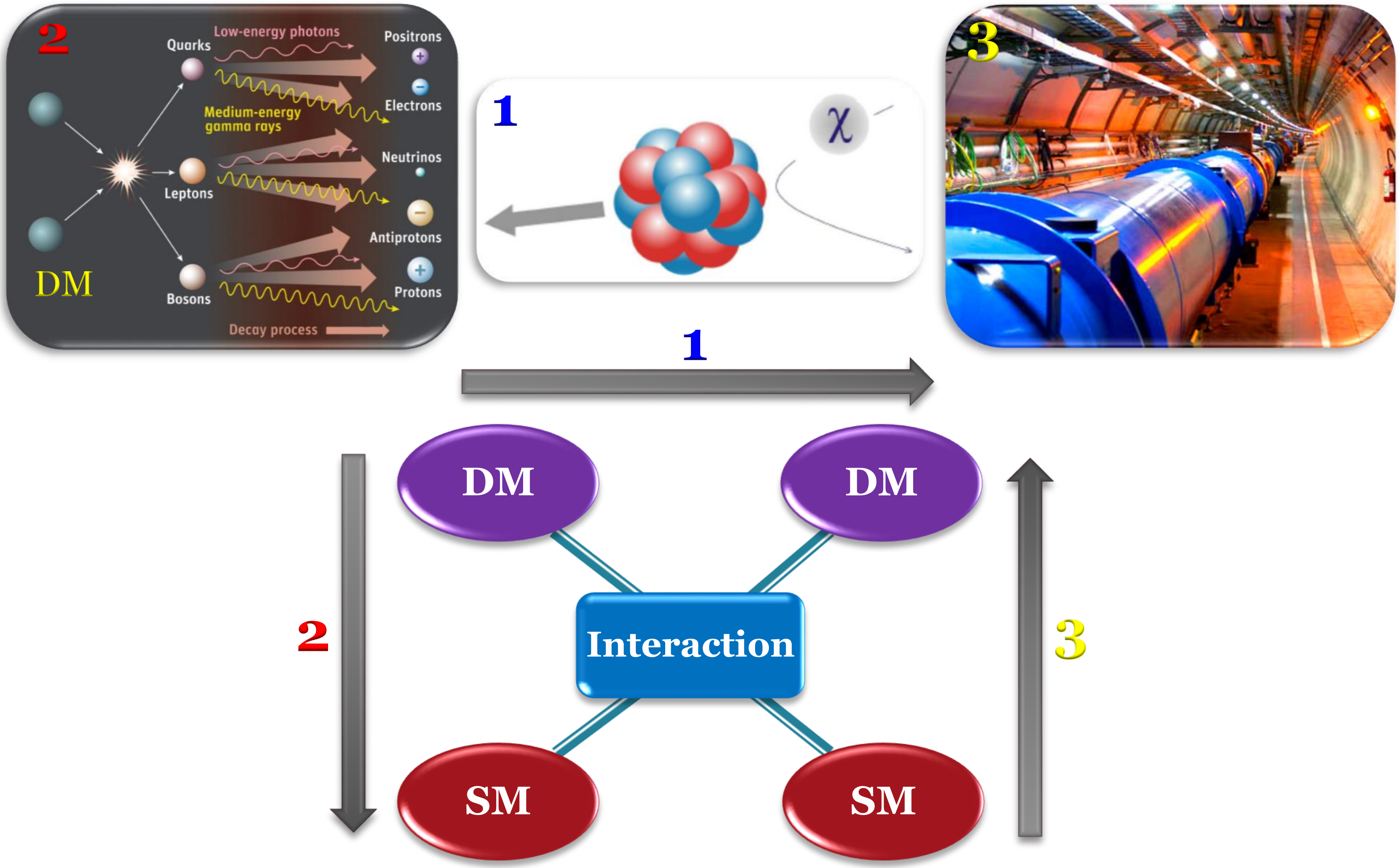
Conventional DM Search Strategies

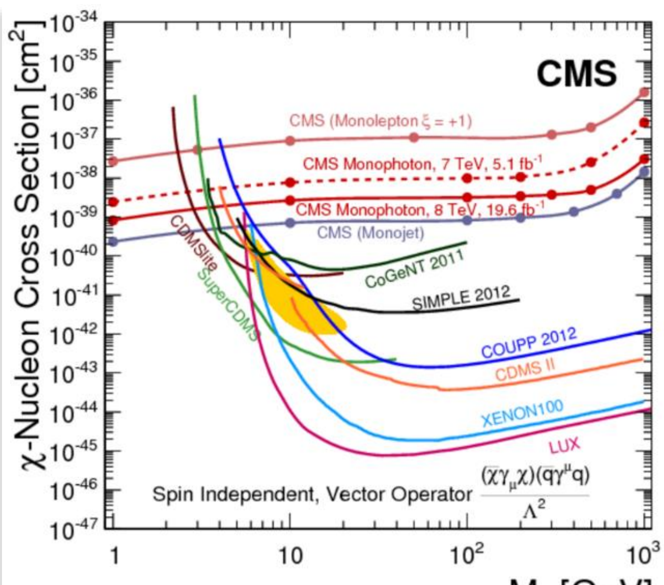


Current Status of Conventional DM Searches

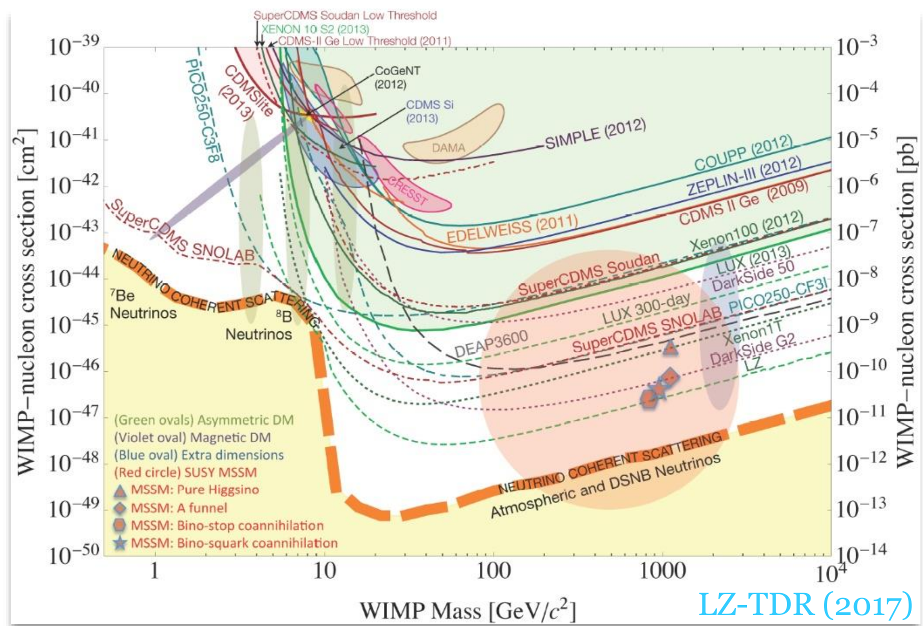
❖ No (solid) observation of DM signatures via non-gravitational interactions

❖ Many searches designed under WIMP/minimal dark sector scenarios

➔ Just excluding more parameter space in DM models



CMS (2014)



LZ-TDR (2017)

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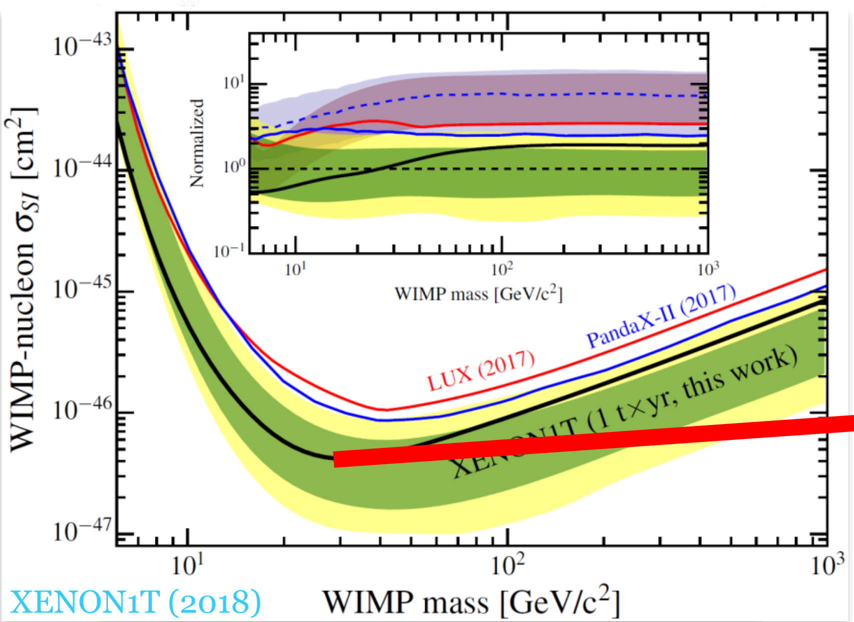

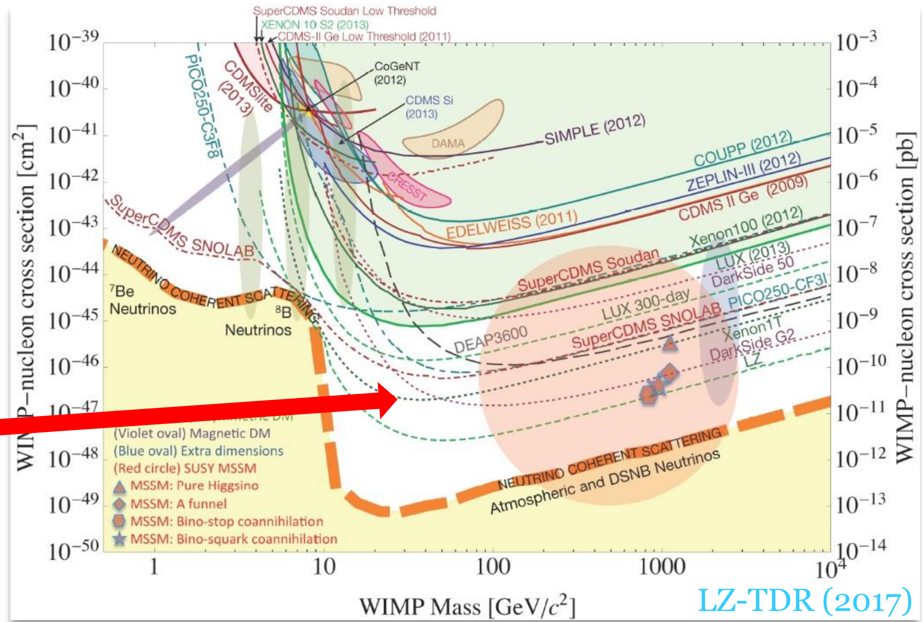

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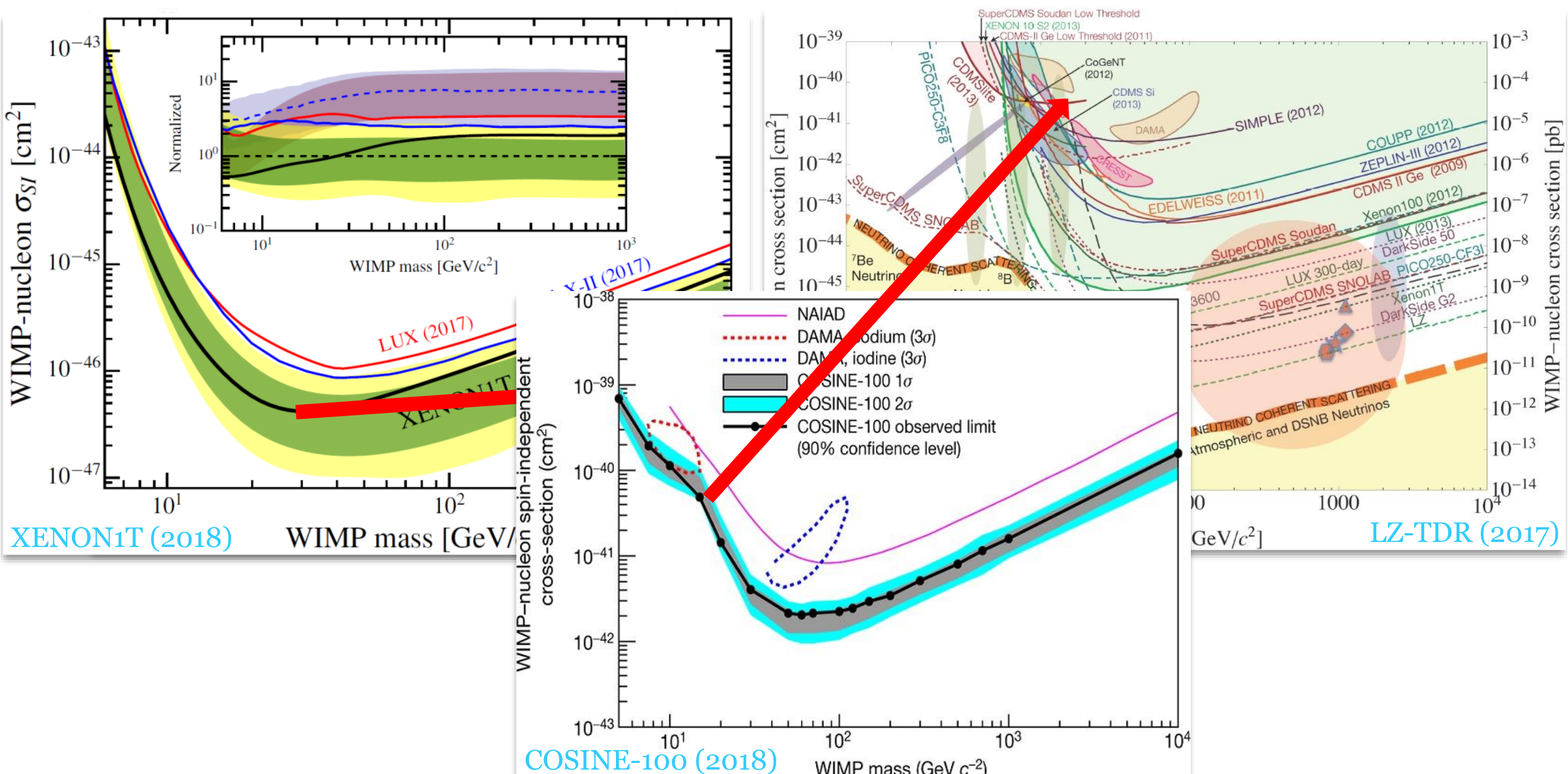
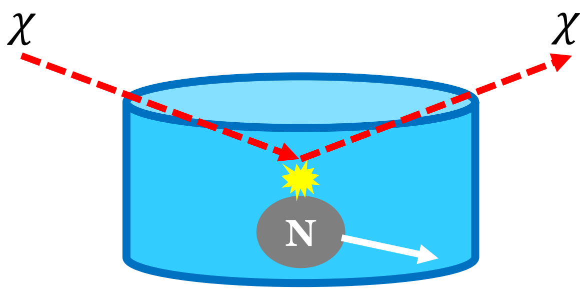


Typical DM Direct Searches

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



[Goodman, Witten (1985)]

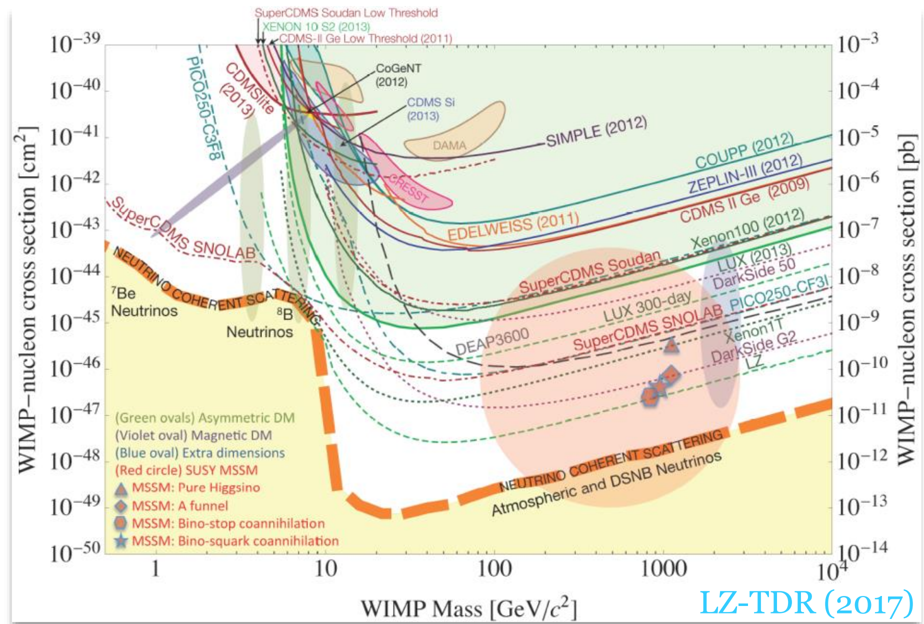
- ✓ Elastic scattering of
- ✓ Non-relativistic
- ✓ Weak-scale DM
- ✓ with nuclei

✓ $E_{\mathrm{recoil}} \sim mv^2$

$\sim 1 - 100$ keV

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

✓ Detectors designed to be sensitive to this E range



- ✓ No solid observation of WIMP signals
- ✓ A wide parameter respace already excluded
- ✓ Close to the neutrino "floor"
- ✓ Need new ideas!

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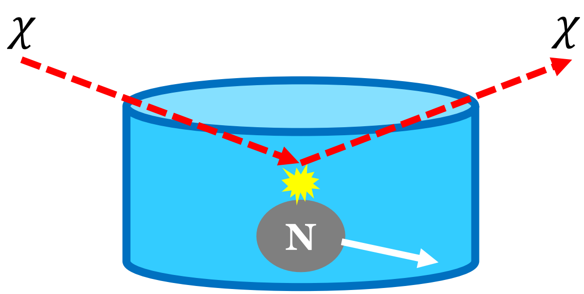

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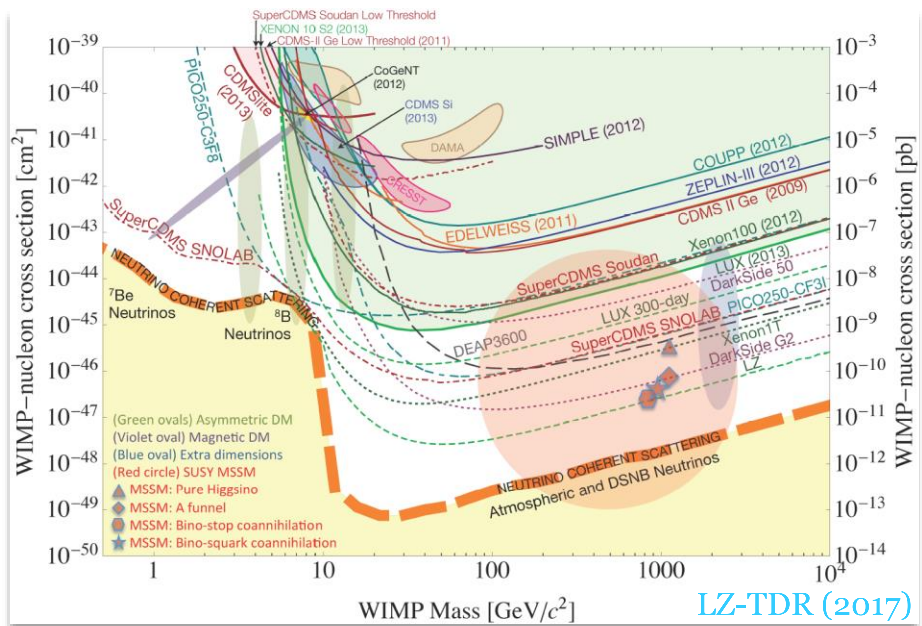

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Time to change our point of view?!

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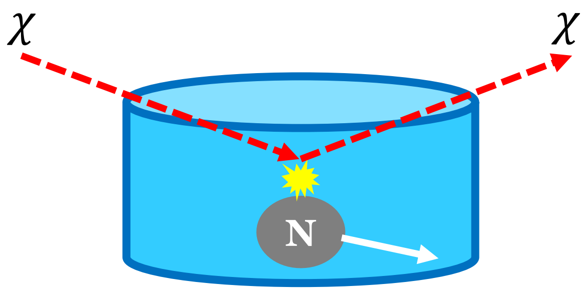


[Goodman, Witten (1985)]

✓ $E_{\rm recoil} \sim mv^2$

$\sim 1 - 100$ keV

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

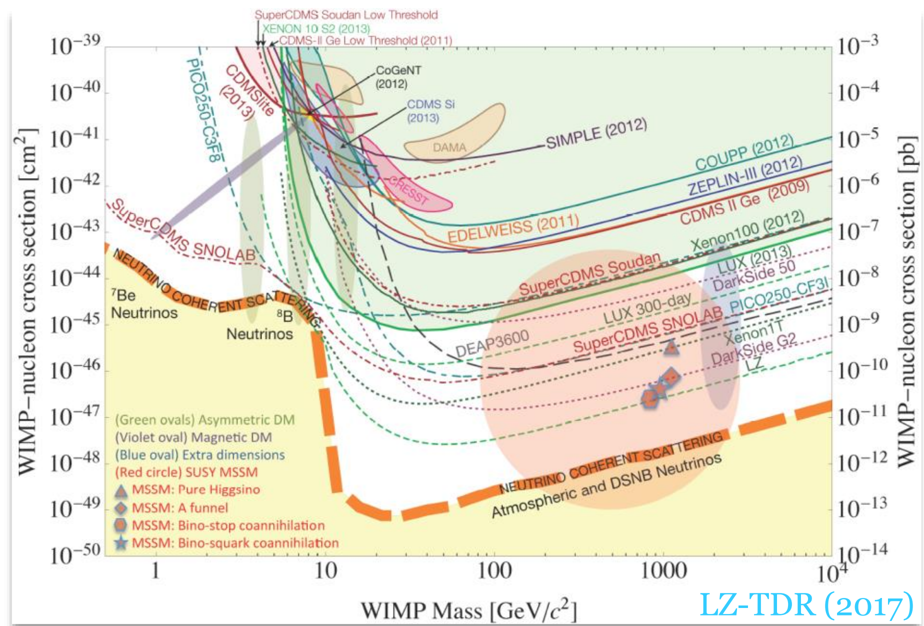
✓ Detectors designed to be sensitive to this E range

(in) Elastic scattering of

✓ ~~Non~~-relativistic

✓ ~~Weak~~ Other-scale DM

✓ with nuclei *or electron*



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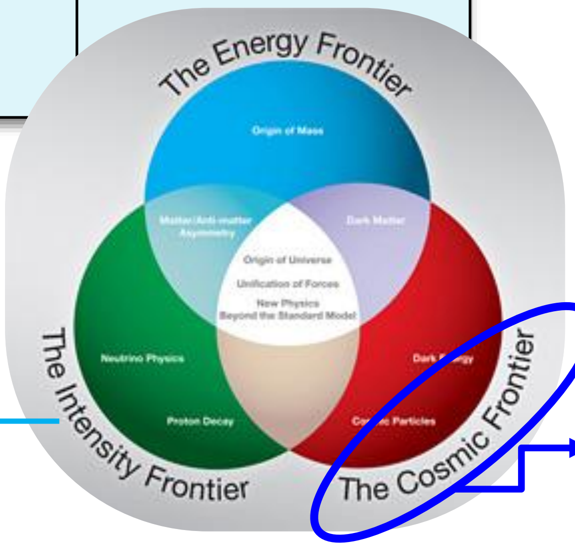
DM Search Schemes (via Scattering)

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

Very well-studied

DM Search Schemes (via Scattering)

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



Beam dump Experiments

This Talk

Boosted Dark Matter (BDM)

What if DM has a relativistic velocity?

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

- DM coming from the universe with $E > E_{th}$ in ν-detectors
- Model building: right DM relic abundance & DM boosting mechanism

Boosted Dark Matter (BDM)

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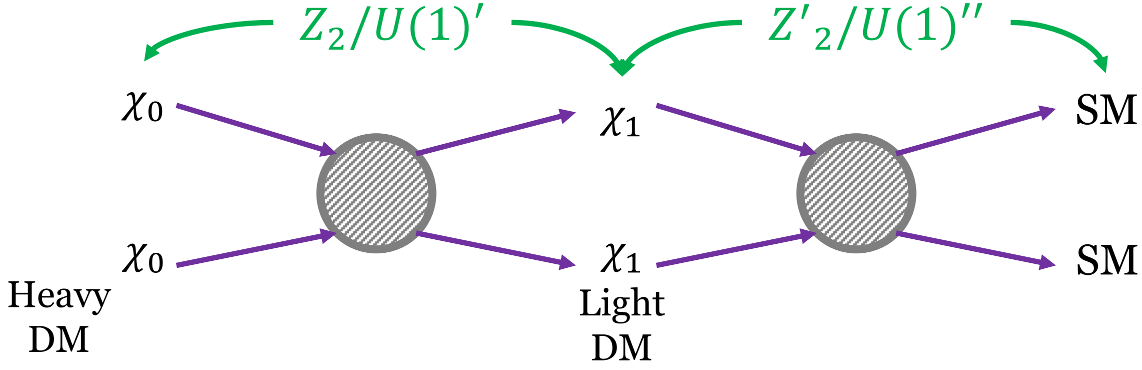
[Agashe, Cui, Necib, Thaler (2014)]

- DM coming from the universe with $E > E_{th}$ in ν-detectors
- Model building: right DM relic abundance & DM boosting mechanism
  - ✓ Multi-component model: [Belanger & **JCP**, 1112.4491; Kong, Mohlabeng, **JCP**, 1411.6632; Kim, **JCP**, Shin, 1702.02944; Aoki & Toma, 1806.09154; etc.]
  - ✓ Semi-annihilation model: [D'Eramo & Thaler, 1003.5912]
  - ✓ Decaying multi-component DM: [Bhattacharya et al., 1407.3280; Kopp, Liu, Wang, 1503.02669]
  - ✓ High velocity (semi-relativistic) DM
    - Anti-DM from DM-induced nucleon decay in the Sun: [Huang & Zhao, 1312.0011]
    - Energetic cosmic-ray induced DM: [Yin, 1809.08610; Bringmann & Pospelov, 1810.10543; Ema, Sala, Sato, 1811.00520]

Two-component BDM Scenario

G. Belanger, **JCP** (2011)



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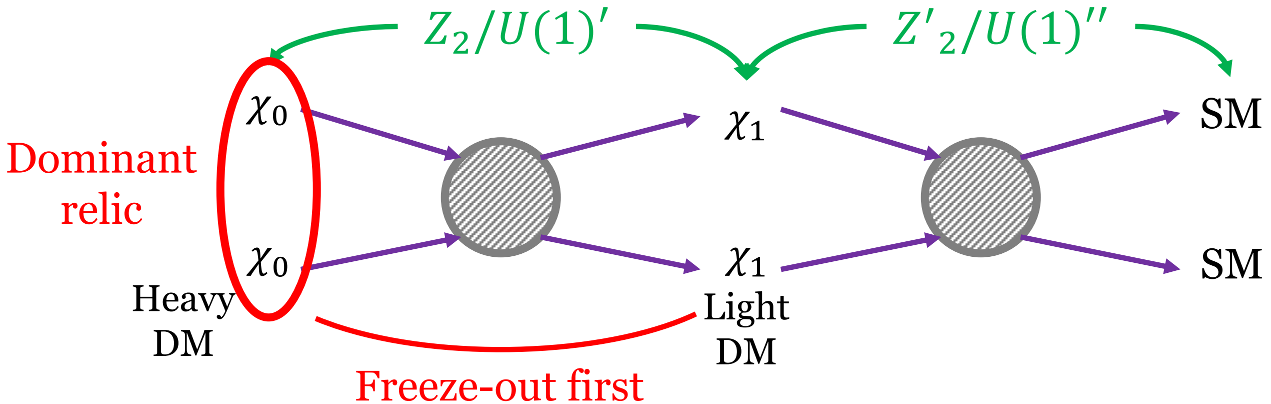

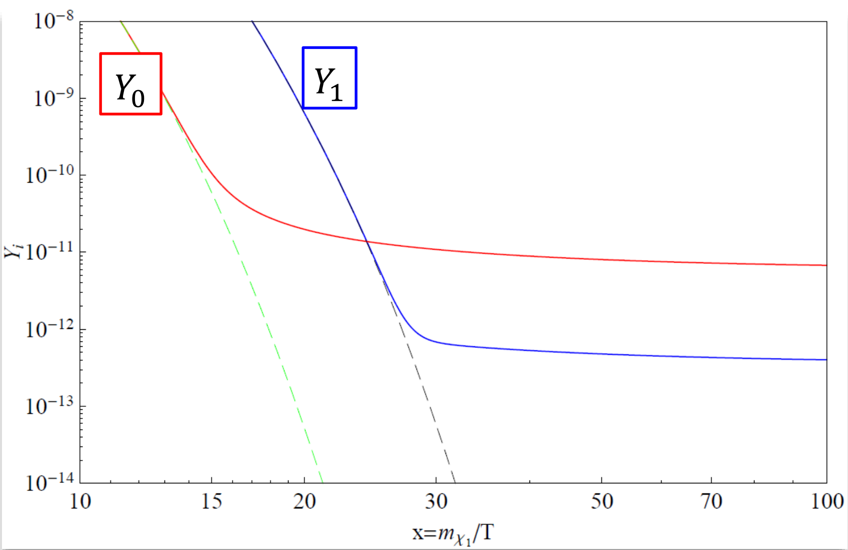

"**<u>Assisted Freeze-out</u>**" Mechanism

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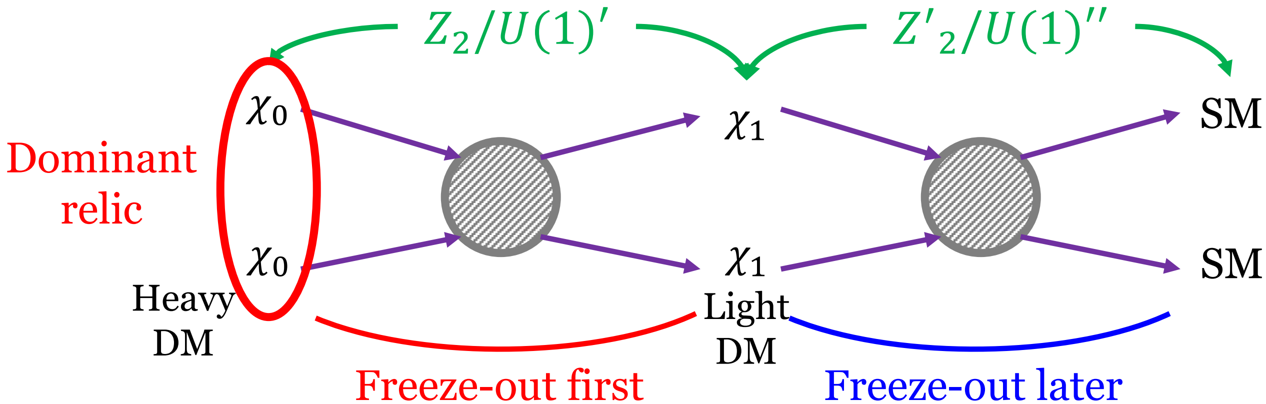
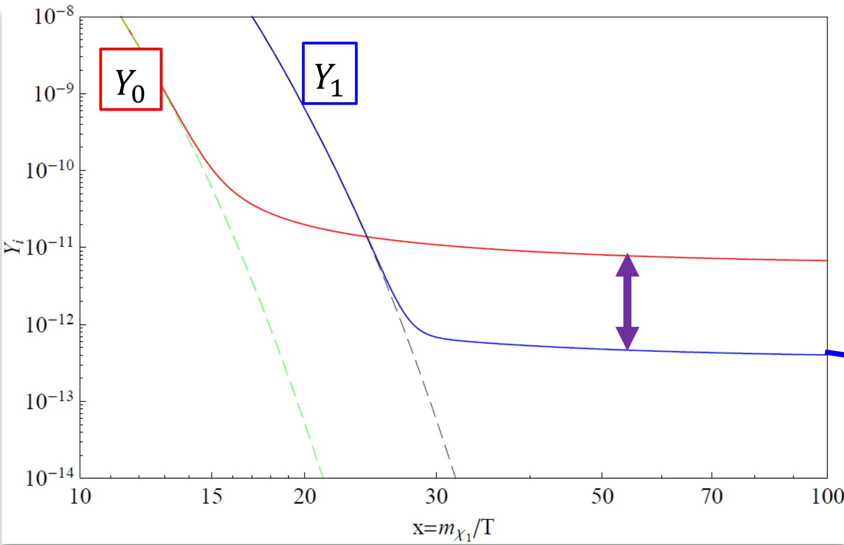


"**Assisted Freeze-out**" Mechanism



χ_1: Negligible, Non-relativistic thermal relic

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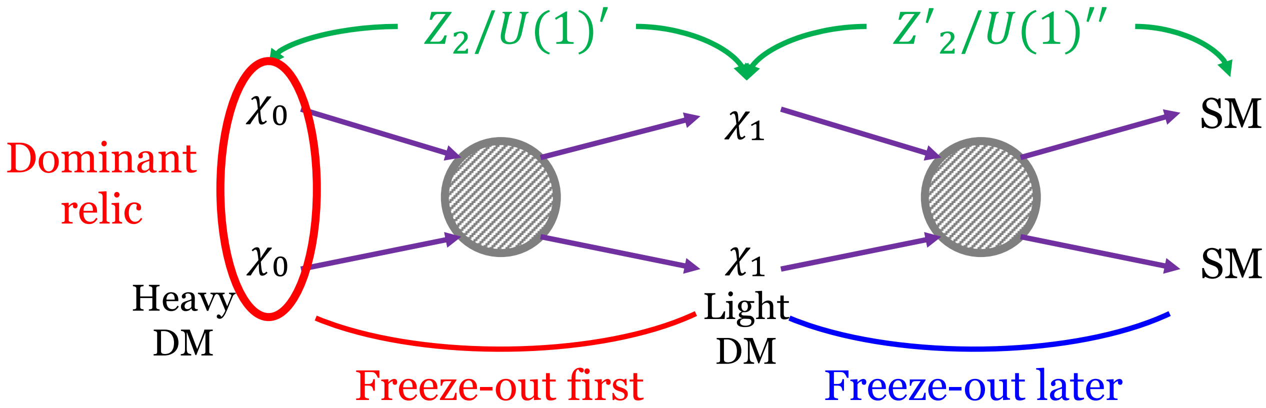

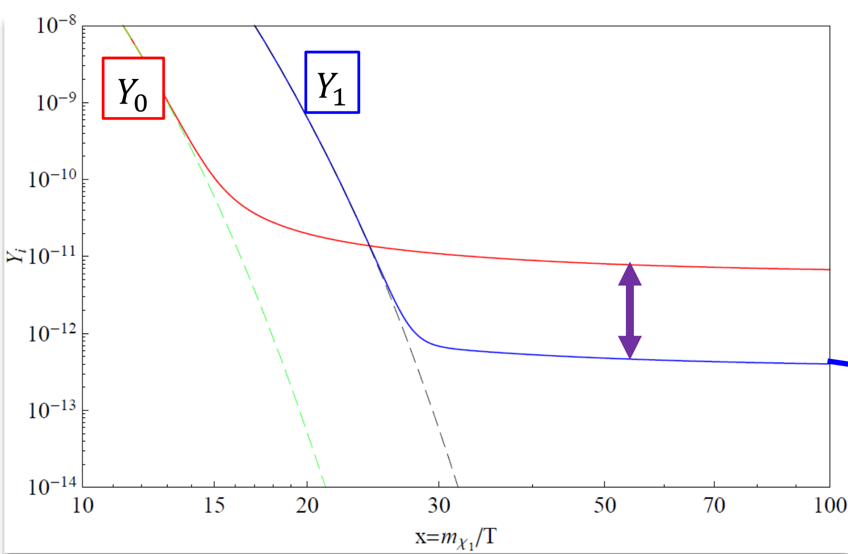

<u>"**Assisted Freeze-out**"</u> Mechanism

✓ Heavier relic χ_0: hard to detect it due to tiny coupling to SM

✓ Lighter relic χ_1: hard to detect it due to small relic

χ_1: Negligible, Non-relativistic thermal relic

Two-component BDM Scenario

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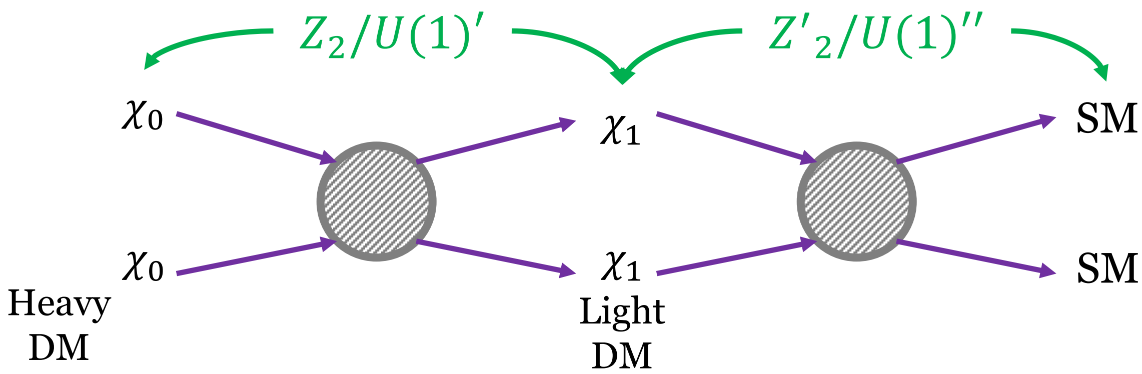
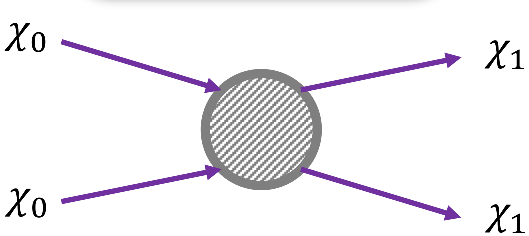


$\chi_0\chi_0 \rightarrow \chi_1\chi_1$ (**Current** universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

(Note that thermal relic χ_1 is non-relativistic.)

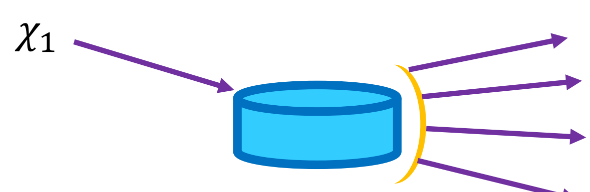
(cf. $\chi\chi \rightarrow \gamma\gamma,\ \nu\nu$)



(Galactic Center)

becomes boosted

($\gamma_1 = m_0/m_1$)



(Laboratory)

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

Detection of BDM

❖ Flux of boosted χ_1 near the earth (cf. $\chi\chi \to \gamma\gamma,\ \nu\nu$)

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

from the number density of DM χ_0, $n_0 = \rho_0 / m_0$

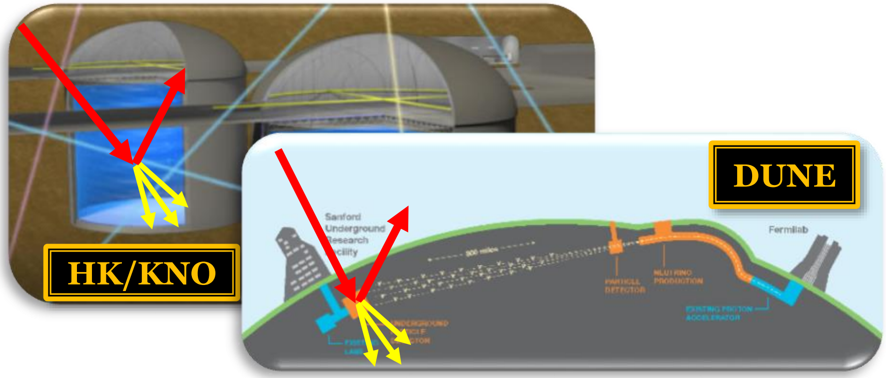
❖ Setting $\langle \sigma v \rangle_{\chi_0\chi_0\to\chi_1\chi_1} \sim 10^{-26}\ \text{cm}^3\text{s}^{-1}$ and assuming the NFW DM halo profile,

one can obtain $\mathcal{F}_{\chi_1} \sim 10^{-6\sim 8}\text{cm}^{-2}\text{s}^{-1}$ 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: SK/HK/KNO, DUNE, IceCube, …



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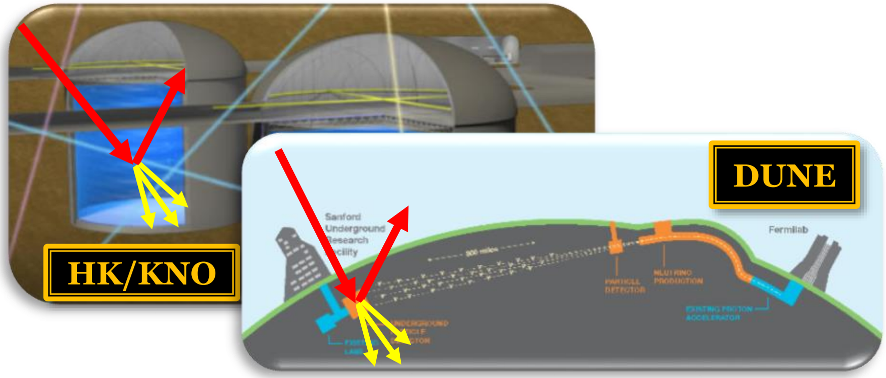


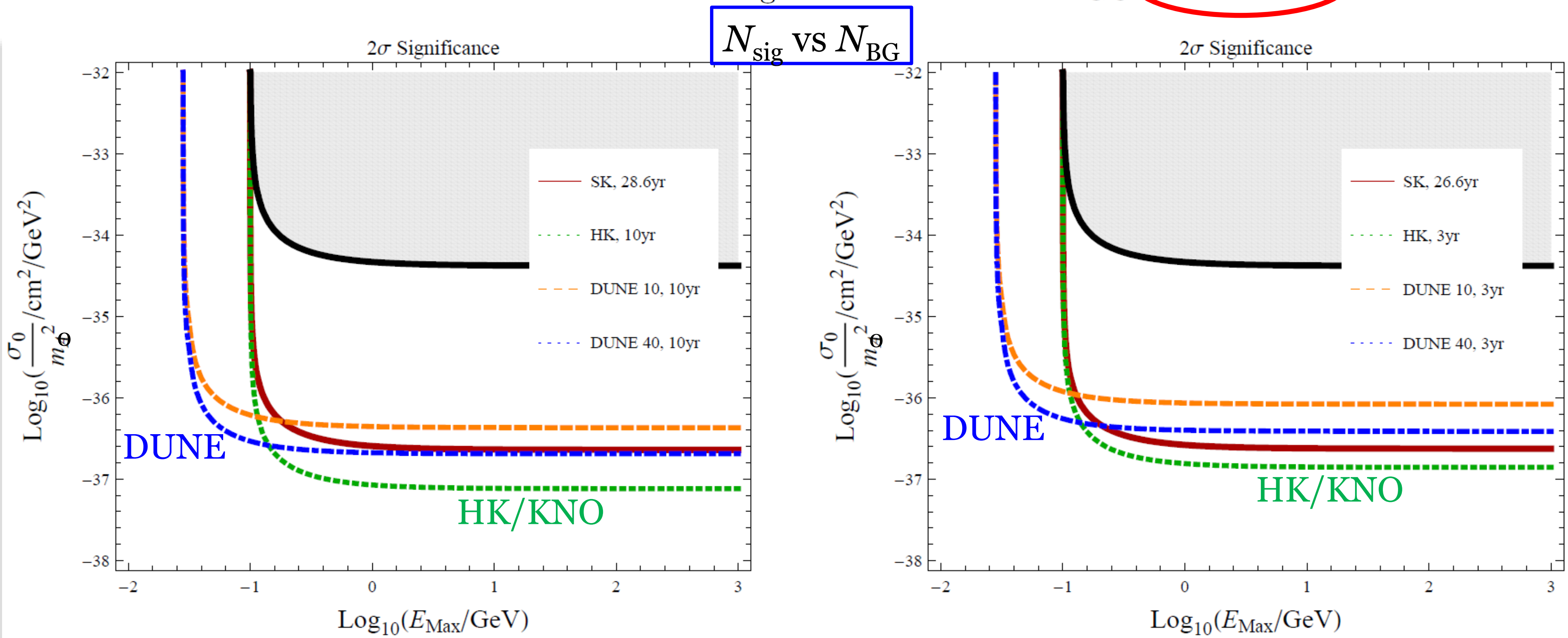
❖ Sources

- ✓ GC: Agashe et al. (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Sun: Berger et al. (2014); Kong, Mohlabeng, **JCP** (2014); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Dwarf galaxies: Necib et al (2016)

Experimental Reach (GC)

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

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



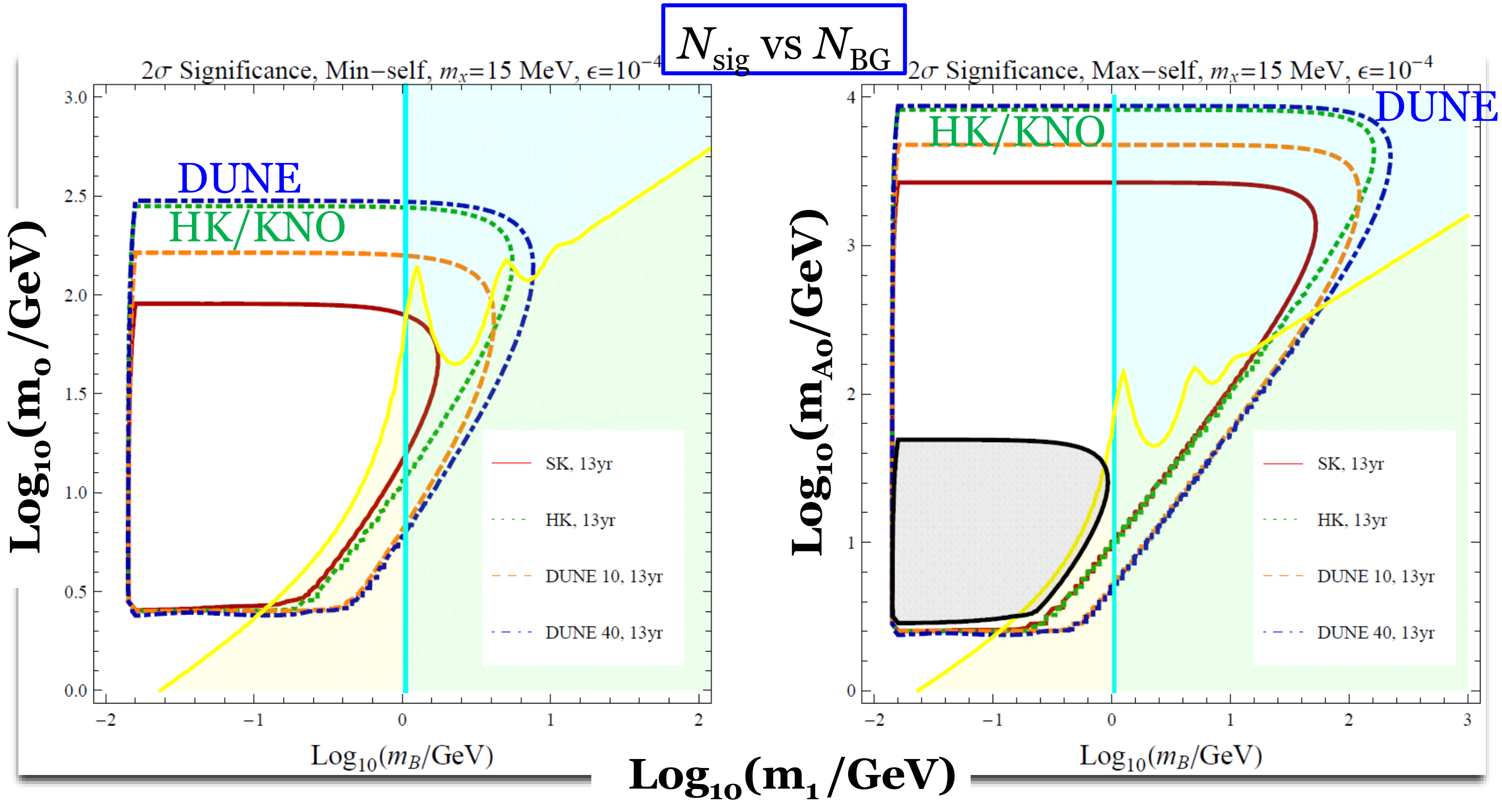
5 year construction + 10 year running vs 10 year construction + 3 year running

✓ Vertical edge: $E_{\rm Max} > E_{\rm th}$, Horizontal edge: $N_{\rm sig} \sim N_{\rm target} \Delta T$ & $n_{\rm DM} \sim \rho_{\rm DM}/m_{\rm DM}$

Experimental Reach (Sun)

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

❖ 2σ sensitivities for 13 years of data



❖ **Point-like** source ➔ Efficient background reduction!

❖ $\theta_C \sim \theta_{res}$ (cf. GC: $\theta_C \sim \max\{10^o, \theta_{res}\}$) $N_{BG}^{\theta_C} = \frac{1-\cos\theta_{res}}{2} N_{BG} \sim \theta_{res}^2$

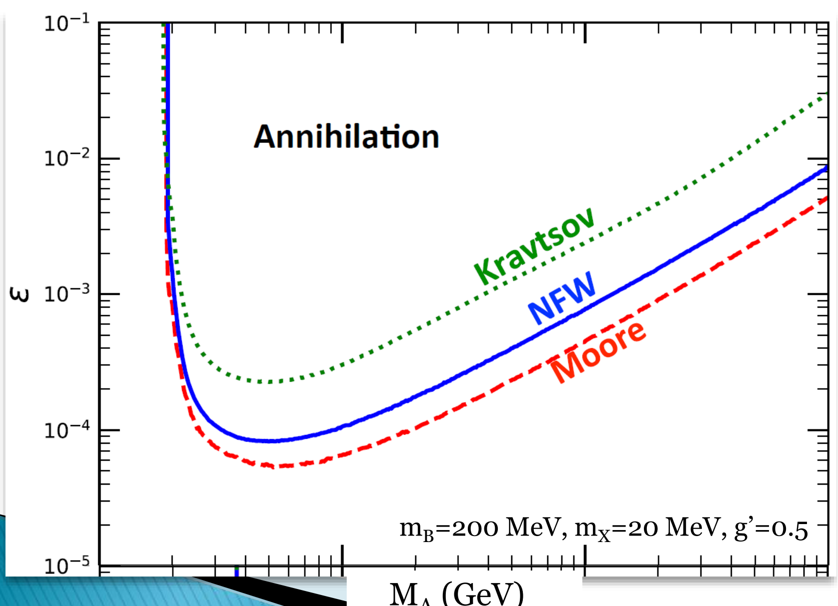
SK Official Results for BDM Search

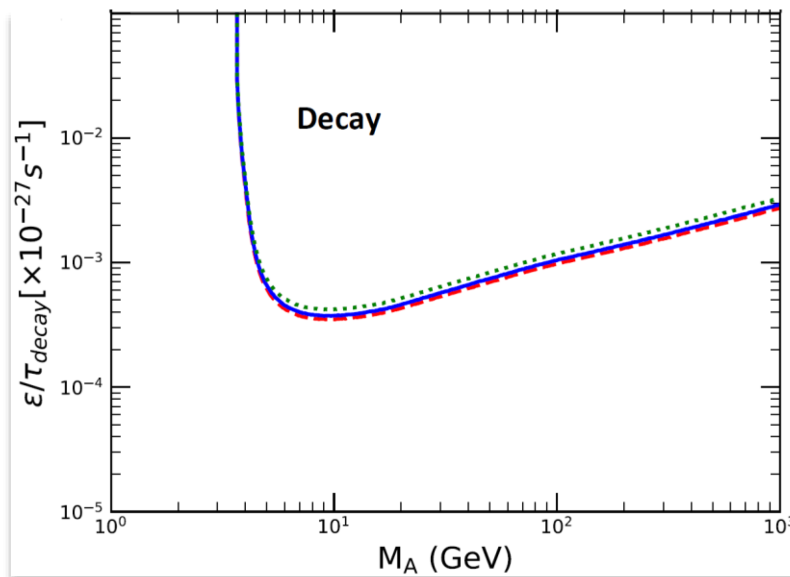
Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande

(Dated: November 16, 2017)

No more SF of Theorists!

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.





SK Collaboration, PRL (2018)

DM Search Schemes (via Scattering)

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

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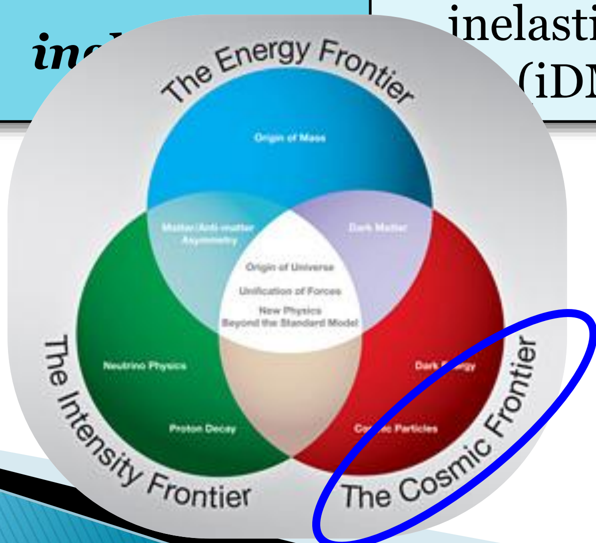
Scattering \ v_{DM}	***non*-relativistic** **(<< c)**	**relativistic** **(~c)**
elastic	Direct detection	Boosted DM (eBDM)
in	inelastic DM (iDM)	inelastic BDM (*i*BDM)

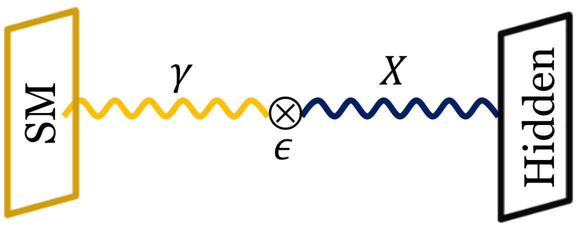


BDM Models

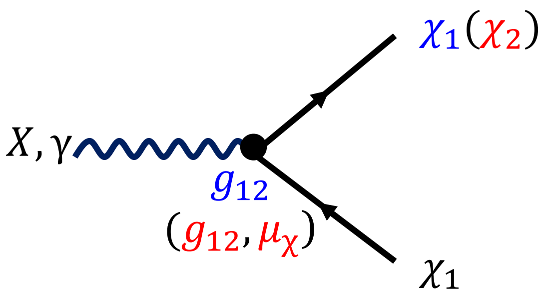
$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 X_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + h.c.$$

$$\mathcal{L}_{\rm int} \ni (\mu_\chi/2)\bar{\chi}_2\sigma^{\mu\nu}\chi_1 F_{\mu\nu} + h.c.$$

Kim, **JCP** & Shin, PRL (2017)
Giudice, **JCP**, et al., PLB (2018)



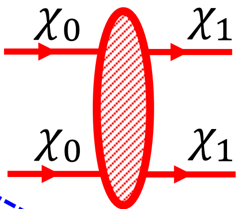
- ✓ χ_2: a heavier (unstable) dark-sector state
- ✓ Flavor-conserving ➔ elastic scattering (eBDM)
- ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)



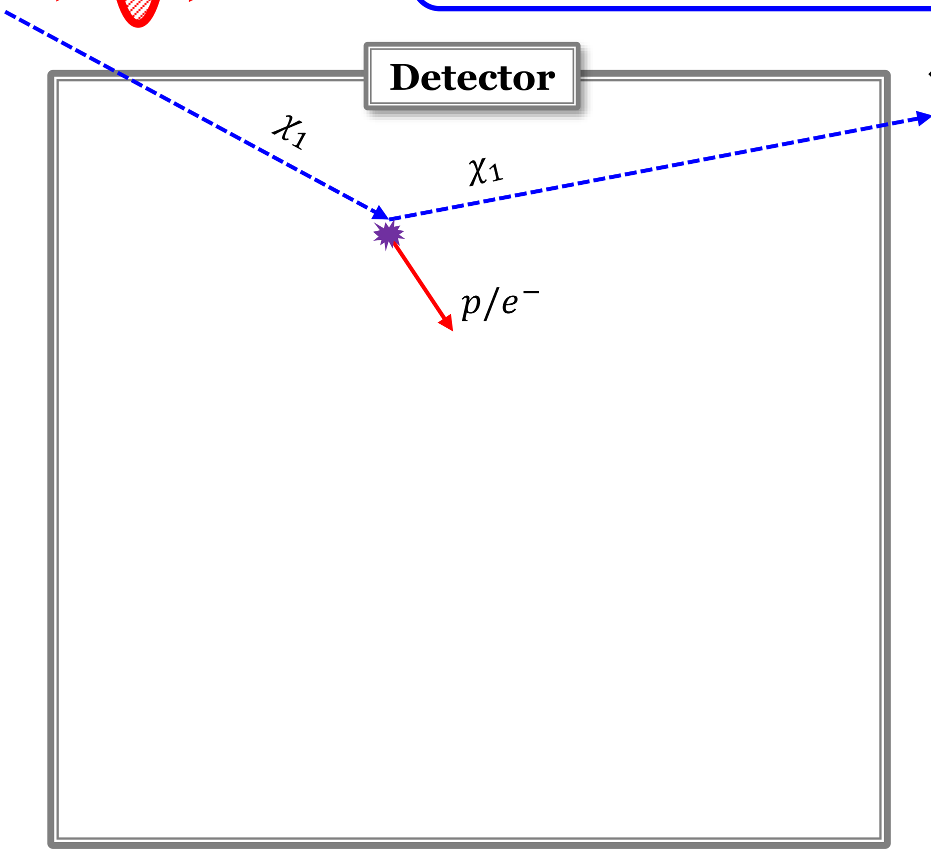
❖ Various models conceiving BDM signatures

- ✓ Source: GC, Sun (capture), dwarf galaxies, etc.
- ✓ Mechanism: assisted freeze-out, semi-annihilation, decaying, cosmic-ray induced DM, etc.
- ✓ Portal: vector portal, scalar portal, etc.
- ✓ DM spin: fermionic DM, scalar DM, etc.
- ✓ *i*BDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Expected Signatures: eBDM



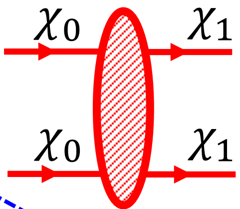
Primary signature: (quasi-elastic) e/p-scattering (& DIS)



- eBDM: elastic scattering

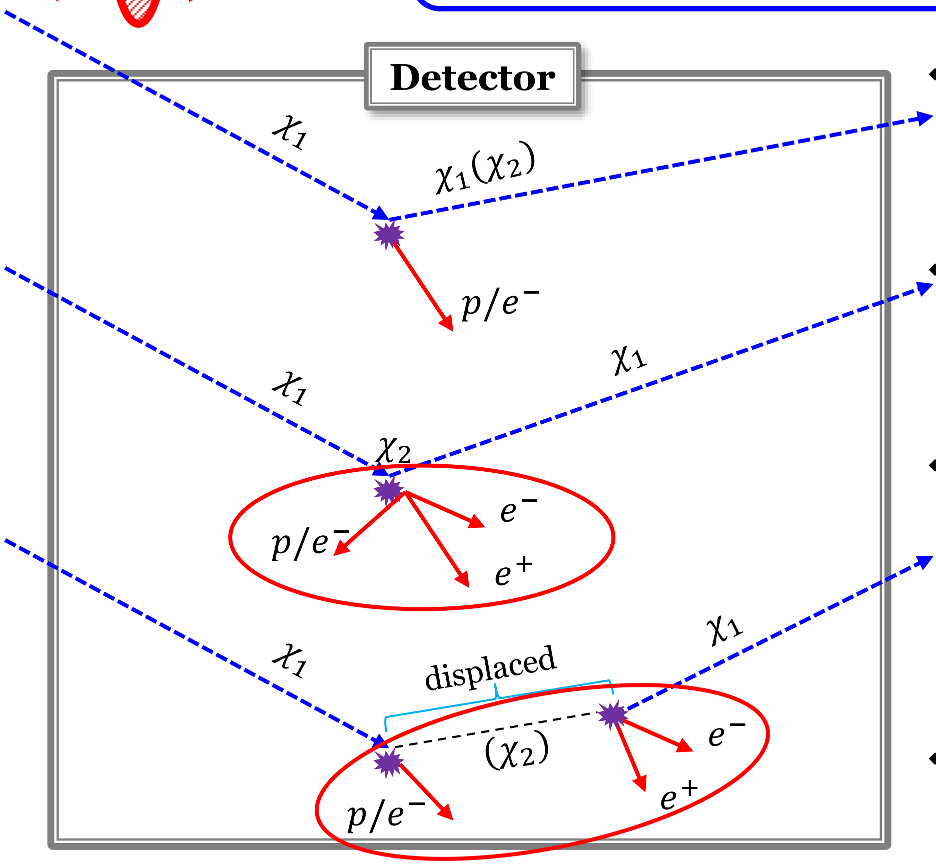
➔ only e/p-recoil ➔ single track

Expected Signatures: *i*BDM



Primary signature: (quasi-elastic) e/p-scattering (& DIS)

Secondary signatures: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma, \ldots$ (by δm)



- eBDM: elastic scattering or loose 2nd signature
  ➔ only e/p-recoil ➔ single track
- *i*BDM: "Prompt" inelastic scattering
  ➔ e/p-recoil + e^+e^- pair ➔ three tracks
- *i*BDM: "Displaced" inelastic scattering
  ➔ e/p-recoil + e^+e^- pair (typically from a three-body decay of χ_2) ➔ three tracks
- **Tracks** will **pop-up** inside the fiducial volume

Experimental Efforts

- ❖ DM direct detection experiments: by pumping up the BDM flux with sub-GeV m_0
  - ✓ Theoretical study: [G. Giudice, D. Kim, **JCP**, S. Shin, 1712.07126]

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✓ COSINE-100: [COSINE-100 Collaboration, 1811.09344]

First official direct search for *i*BDM

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

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(COSINE-100 Collaboration)

Experimental Efforts

❖ DM direct detection experiments: by pumping up the BDM flux with sub-GeV m_0

- ✓ Theoretical study: [G. Giudice, D. Kim, **JCP**, S. Shin, 1712.07126]
- ✓ COSINE-100: [COSINE-100 Collaboration, 1811.09344]

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

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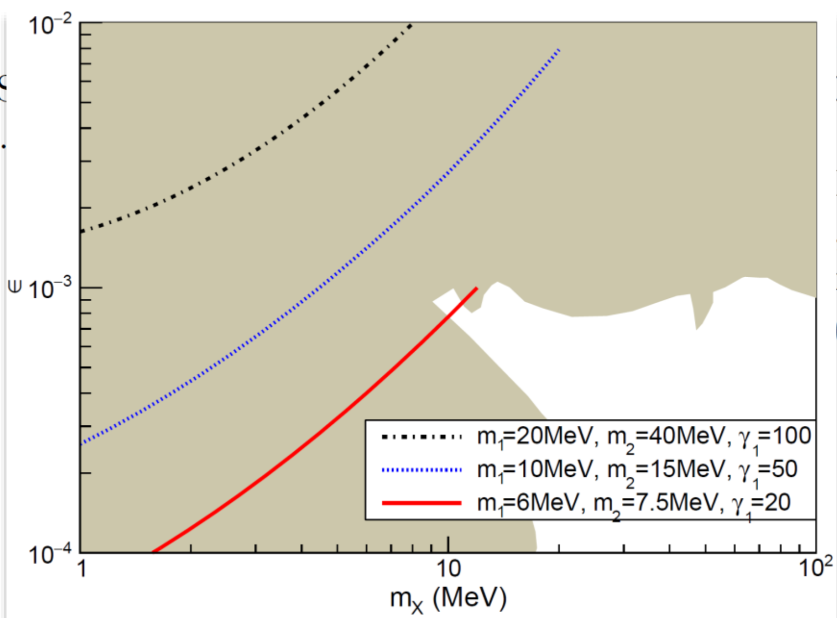
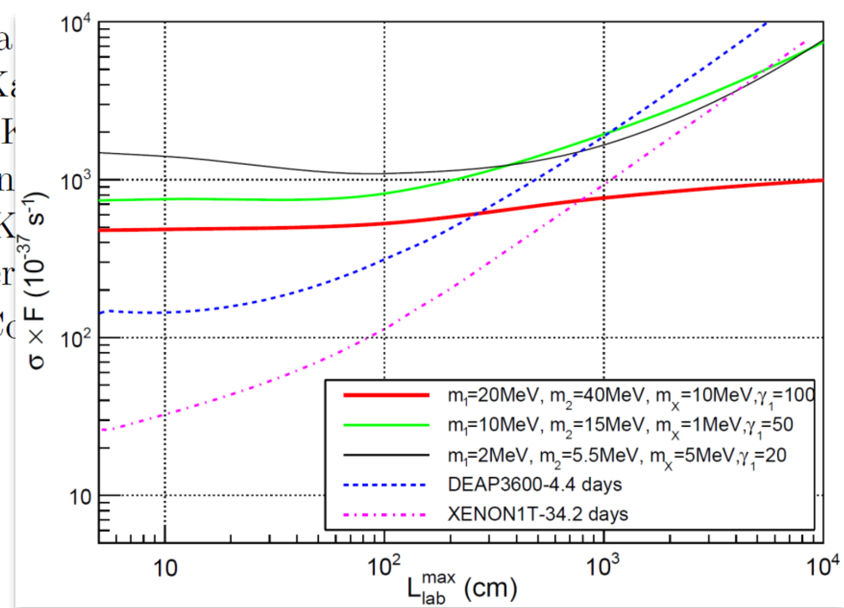




Experimental Efforts

❖ Surface ν experiments (cosmic-ray backgrounds)

- ✓ ProtoDUNE: [Chatterjee, De Roeck, Kim, Moghaddam, **JCP**, Shin, Whitehead, Yu, 1803.03264]

  Proposal submitted to ProtoDUNE collaboration (1st new physics search @ ProtoDUNE)

- ✓ Short-Baseline Neutrino (SBN) program: ICARUS, MicroBooNE, SBND

  eBDM search using Earth Shielding @ ProtoDUNE & SBN

  [D. Kim, KC Kong, **JCP**, S. Shin, 1804.07302]

  Discussion with ICARUS for *i*BDM (Gran Sasso + Future @ SBN-Fermilab)

❖ Underground ν experiments

- ✓ DUNE: dedicated study [D. Kim, **JCP**, S. Shin, work in progress with DUNE experimentalists]

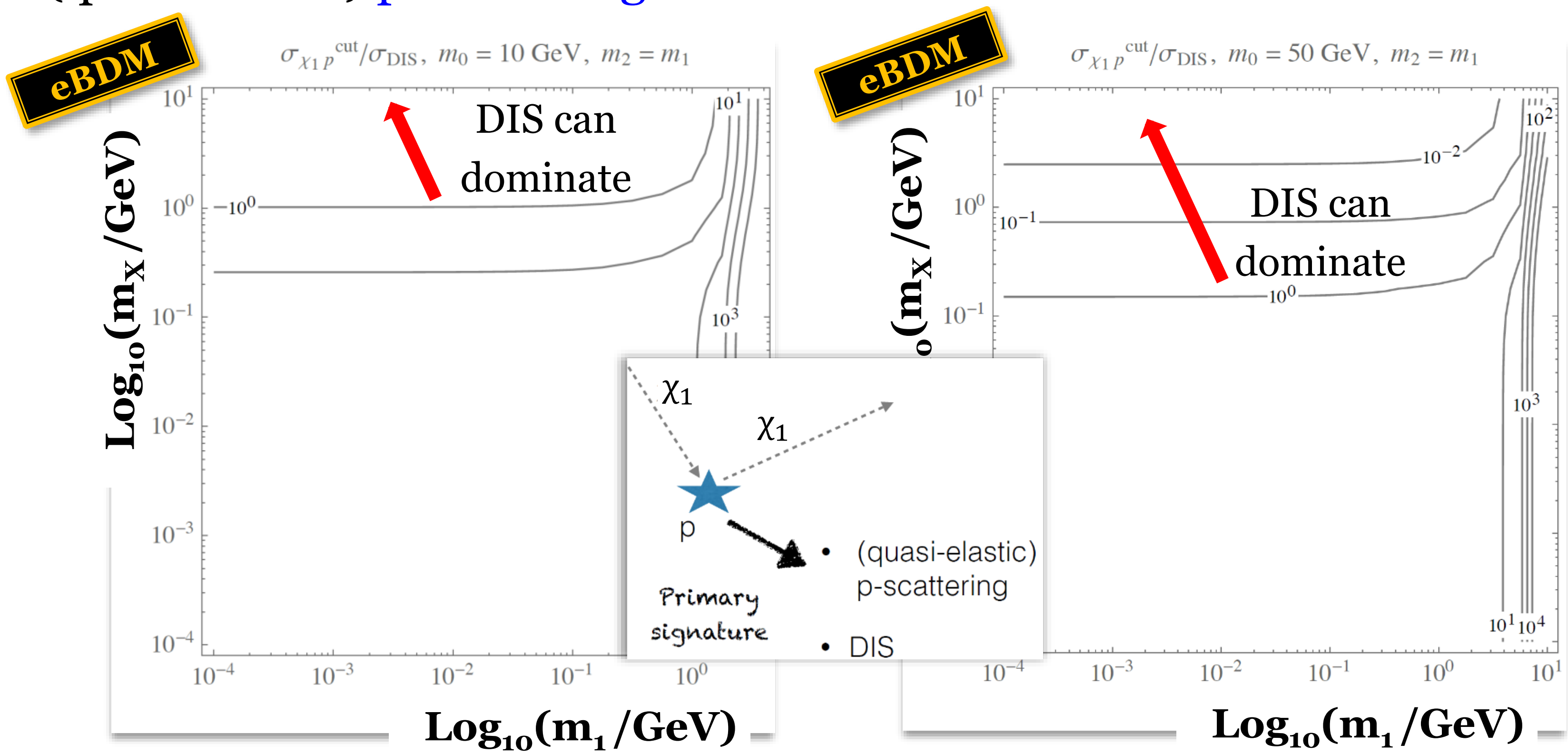
  included in DUNE TDR as new particle searches (BSM physics opportunities)

- ✓ Summary of possible phenomenology (e vs p vs DIS) in various relevant experiments such as DarkSide-20k, DUNE, Hyper-K, IceCube, … [Kim, Machado, **JCP**, Shin, 1903.xxxxx]

Signals @ DUNE: p vs DIS

P. Machado, D. Kim, **JCP** & S. Shin [1903.xxxxx]

❖ (quasi-elastic) p-scattering vs DIS



- ✓ Penalty on p-scattering $E_{\rm th}$> 21 MeV [ArgoNeuT, 1405.4261]: $\sigma_{\chi 1\, p}^{cut}$
- ✓ But, no cuts on DIS
- ✓ p-scattering still dominates over DIS for m_X < 1 GeV (cf. ν scattering via W, Z)

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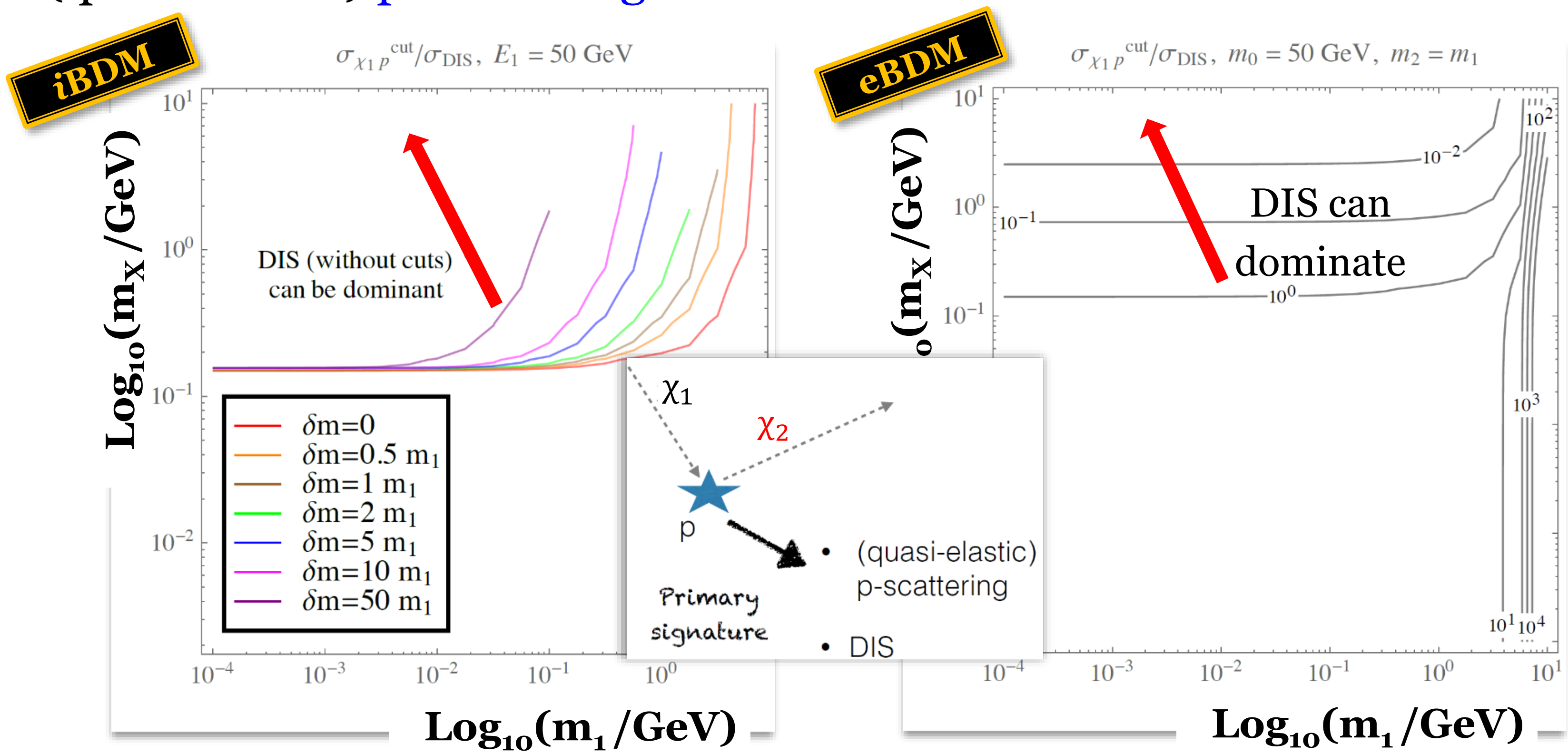

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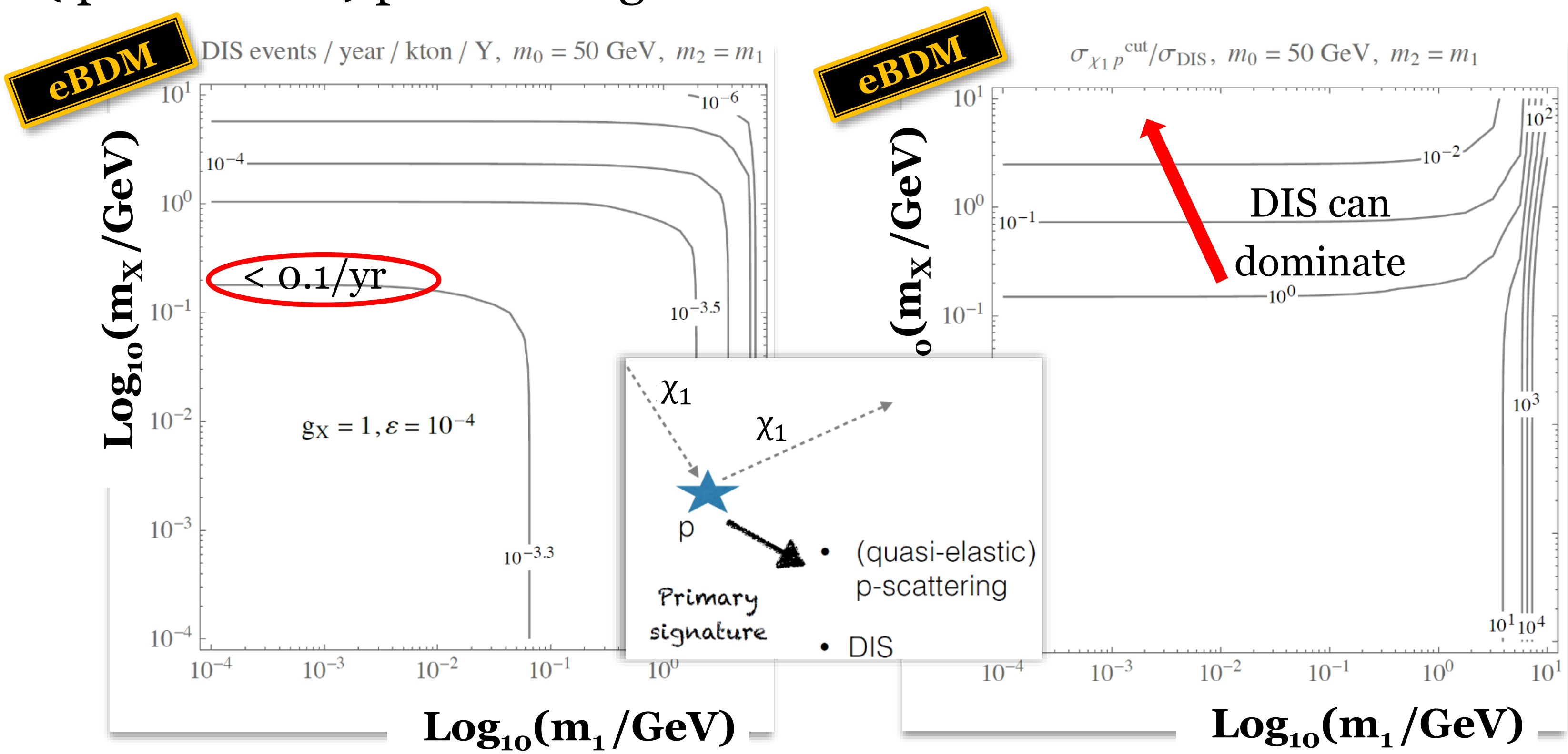


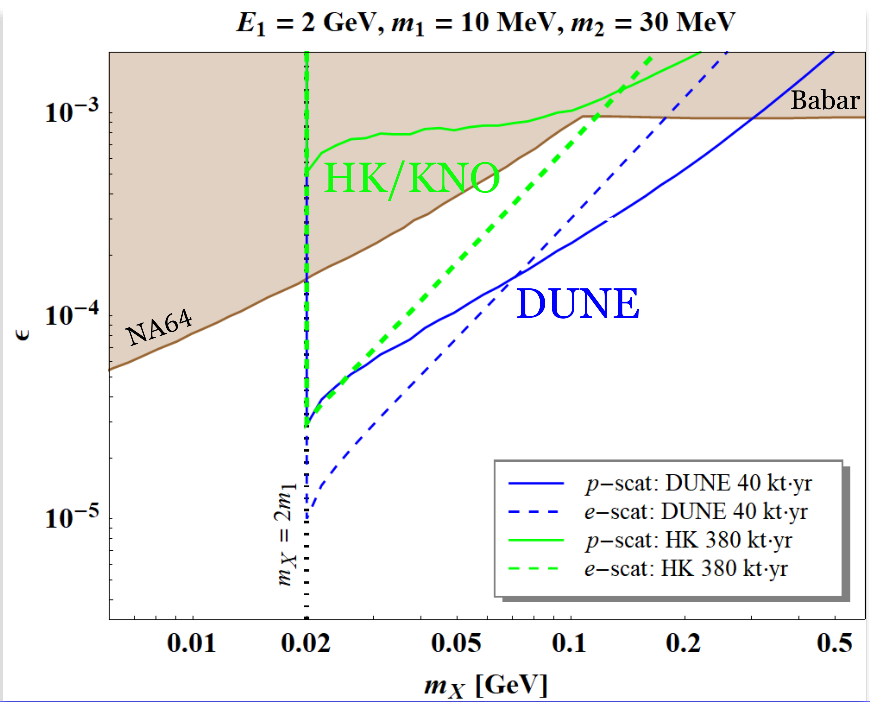
✓ Number of DIS induced events (Y=atomic number/atomic weight)

✓ Even with 380 kt water target (HK/KNO), DIS $\lesssim$ 0.1 events/yr

Dark X Parameter Space: Scenario I

P. Machado, D. Kim, **JCP** & S. Shin [1903.xxxxx]

❖ Scenario I: χ_2 decays visibly via an off-shell X exchange ($\delta m < m_X$ & $m_X > 2m_1$)



$$\chi_2 \to X^* \chi_1 \to e^+ e^- \chi_1$$

Experimental reach for 1-year of running

DUNE - cuts

i) $p_e > 30$ MeV, 200 MeV $< p_p < 2$ GeV,

ii) $\Delta\theta_{e-i} > 1^\circ$, $\Delta\theta_{p-i} > 5^\circ$ with i denoting the other visible final state particles,

iii) both primary and secondary vertices should appear in the detec

HK/KNO - cuts

i) $p_e > 100$ MeV, 1.07 GeV $< p_p < 2$ GeV,

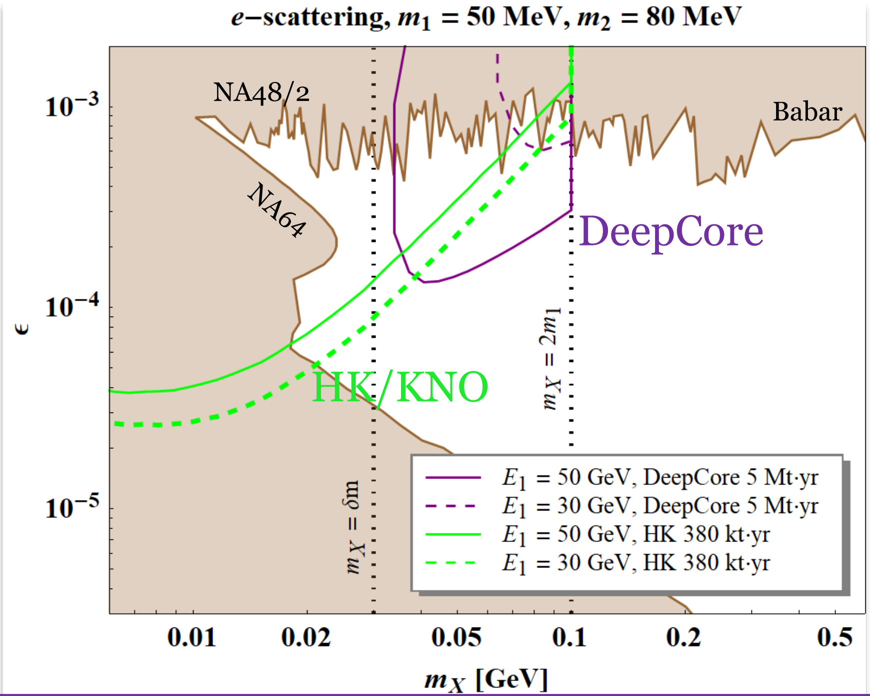
ii) $\Delta\theta_{e-i} > 3^\circ$ ($\Delta\theta_{e-i} > 1.2^\circ$) for $p_e < 1.33$ GeV ($p_e > 1.33$ GeV) and $\Delta\theta_{p-i} > 3^\circ$ for all p_p with i running over the other visible final state particles, and

iii) both primary and secondary vertices should appear in the detector fiducial volume.

Dark X Parameter Space: Scenario I

P. Machado, D. Kim, **JCP** & S. Shin [1903.xxxxx]

❖ Scenario II: χ_2 emits an on-shell X & the X decays visibly ($\delta m > m_X$ & $m_X < 2m_1$) or χ_2 decays visibly via a three-body process just like scenario I ($\delta m < m_X < 2m_1$).



$$\chi_2 \rightarrow X^{(*)}\chi_1 \rightarrow e^+e^-\chi_1$$

Experimental reach for 1-year of running

DeepCore - cuts

i) $p_e^{\rm recoil} > 10$ GeV, $p_{e^+e^-}^{\rm secondary} > 10$ GeV, and

ii) the secondary vertex should appear in the detector fiducial volume and be at least 5 meters away from the primary vertex.

HK/KNO - cuts

i) $p_e > 100$ MeV, 1.07 GeV $< p_p < 2$ GeV,

ii) $\Delta\theta_{e-i} > 3^\circ$ ($\Delta\theta_{e-i} > 1.2^\circ$) for $p_e < 1.33$ GeV ($p_e > 1.33$ GeV) and $\Delta\theta_{p-i} > 3^\circ$ for all p_p with i running over the other visible final state particles, and

iii) both primary and secondary vertices should appear in the detector fiducial volume.

e/*i*BDM Searches in Various Exps.

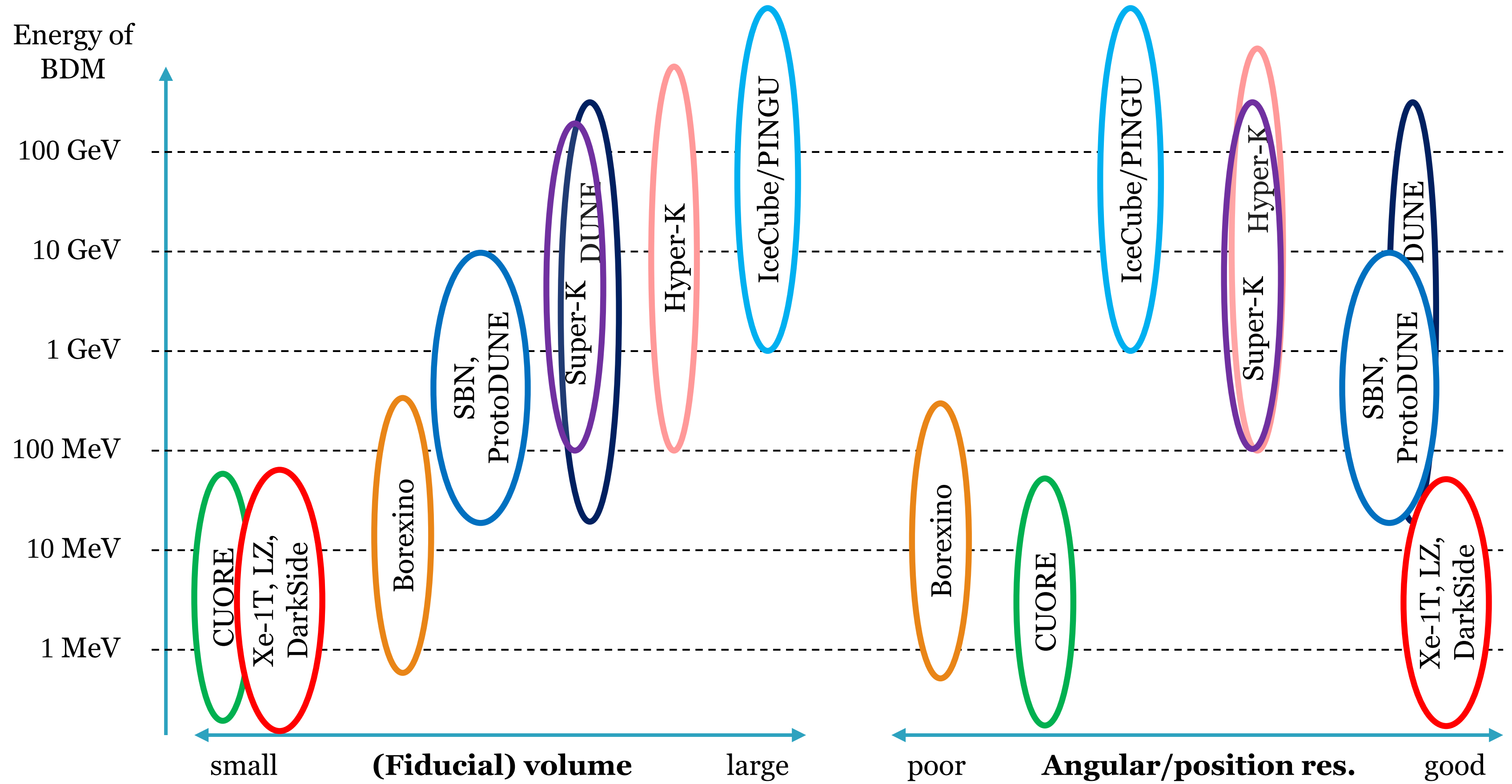
P. Machado, D. Kim, **JCP** & S. Shin [1903.xxxxx]

DM Experiment	Target Material	Volume [t] Active	Volume [t] Fiducial	Depth [m]	E_{th} [keV]	Resolution: Position [cm]	Resolution: Angular [°]	Resolution: Energy [%]	PID	Run Time	Refs.
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-	[82]
DarkSide -20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	goal: 2021-	[53]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	2016 -2018	[83, 84]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	goal: 2019-	[83]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10-20$	–	2016-	[70–72]
DEAP -50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[70]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	4,300 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	2.5 MeV: 2	–	goal: 2020-	[85]
Neutrino Experiment	**Target Material**	**Volume [kt] Active**	**Volume [kt] Fiducial**	**Depth [m]**	**E_{th} [MeV]**	**Resolution: Vertex [cm]**	**Resolution: Angular [°]**	**Resolution: Energy [%]**	**PID**	**Run Time**	**Refs.**
Borexino	organic LS	0.278	0.1	3,800 m.w.e.	~ 0.2	~9-17	–	$\frac{5}{\sqrt{E\,(\mathrm{MeV})}}$	–	> 5.6 year	[86]
KamLAND	LS	1	0.2686	1,000	0.2 - 1	$\frac{12-13}{\sqrt{E\,(\mathrm{MeV})}}$	–	$\frac{6.4-6.9}{\sqrt{E\,(\mathrm{MeV})}}$	–	~ 10 year?	[87, 88]
JUNO	LS	–	20	700	< 1, goal: 0.1	$\frac{12}{\sqrt{E\,(\mathrm{MeV})}}$	μ: $L > 5$ m: < 1, $L > 1$ m: < 10	$\frac{3}{\sqrt{E\,(\mathrm{MeV})}}$	$\mu^\pm$ vs $\pi^\pm$, $e^\pm$ vs π^0: difficult	goal: 2020-	[89]
DUNE	LArTPC	Total: 17.5 ×4	(SP: 10 + DP: 10.6) ×2	1500	$e: 30$, p: 21-50	1-2	$e, \mu, \pi^\pm: 1$, $p, n: 5$	$e: 1 \oplus \frac{15}{\sqrt{E\,(\mathrm{MeV})}}$, $p: 10\,(p < 0.4\,\mathrm{GeV})$, $5 \oplus \frac{30}{\sqrt{E\,(\mathrm{GeV})}}$ $(p > 0.4\,\mathrm{GeV})$	good $e, \mu, \pi^\pm, p$ separation	10 kt: 2025-, 20 kt: 2026-	[6, 54–56]
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	$\gtrsim 15$ year	[90–92]
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: 2026-	[57–59]
	Target Material	**Effective Volume [Mt]**		**Depth [m]**	**E_{th} [GeV]**	**Resolution: Vertex [m]**	**Resolution: Angular [°]**	**Resolution: Energy [%]**	**PID**	**Run Time**	**Refs.**
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)	[61, 93]
DeepCore	Ice Cherenkov	10 GeV: ~ 5, 100 GeV: ~ 30		2,100 Ice	~ 10	better	μ-track: ~1, shower: $\gtrsim 10$	–	only μ	2011- (2010)	[60, 61]
PINGU	Ice Cherenkov	1 GeV: ~ 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	[94]
Gen2	Ice Cherenkov	~ 10 Gt		1,360 Ice	~ 50 TeV	worse	μ-track: < 1 shower: ~ 15	–	only μ	–	[95]

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

e/*i*BDM Searches in Various Exps.

P. Machado, D. Kim, **JCP** & S. Shin [1903.xxxxx]



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

Conclusion

- Rising interest in non-minimal dark sector scenarios & BDM (relativistic DM)
- BDM searches at the cosmic frontier are promising & provide a new direction to explore dark sector physics.
- Weak interaction/Small flux ➔ Large V is required (e.g. SK, HK/KNO, DUNE, IceCube, …).
- Experimental studies have already begun, e.g. SK, COSINE-100, ICARUS, ProtoDUNE, …

Scattering \ v_{DM}	***non*-relativistic ($v_{DM} \ll c$)**	**relativistic ($v_{DM} \sim c$)**
elastic	Direct detection	Boosted DM (eBDM)
***in*elastic**	inelastic DM (*i*DM)	inelastic BDM (*i*BDM)

New Opportunities at the Next Generation Neutrino Experiments

12-13 April 2019
University of Texas, Arlington
US/Central timezone

Search...

- Overview
- Timetable
- Registration
- Participant List
- Local Information

This event is a 2-day workshop to explore new opportunities at the next generation neutrino experiments, e.g. DUNE, SBN and IceCube, on the campus of the University of Texas at Arlington on Friday April 12 and Saturday April 13, 2019. The participants of the workshop will be a well-balanced mixture of theorists and experimentalists to promote exchanging ideas for various physics opportunities and to discuss necessary tasks demanded to support timely exploitation of the opportunities.

Speakers

- Joushua Berger
- Bhaskar Dutta
- Doojin Kim
- More to confirm..

Organizing Committee:

- **Conference committee**

  Jaehoon Yu (Chair)
  Doojin Kim (Co-chair)

- **Program committee**

  Andre de Gouvea (Chair)
  Alexandre Sousa (Co-chair)
  Animesh Chatterjee
  Pedro A.N. Machado
  Jong-Chul Park
  Seodong Shin
  Yun-Tse Tsai

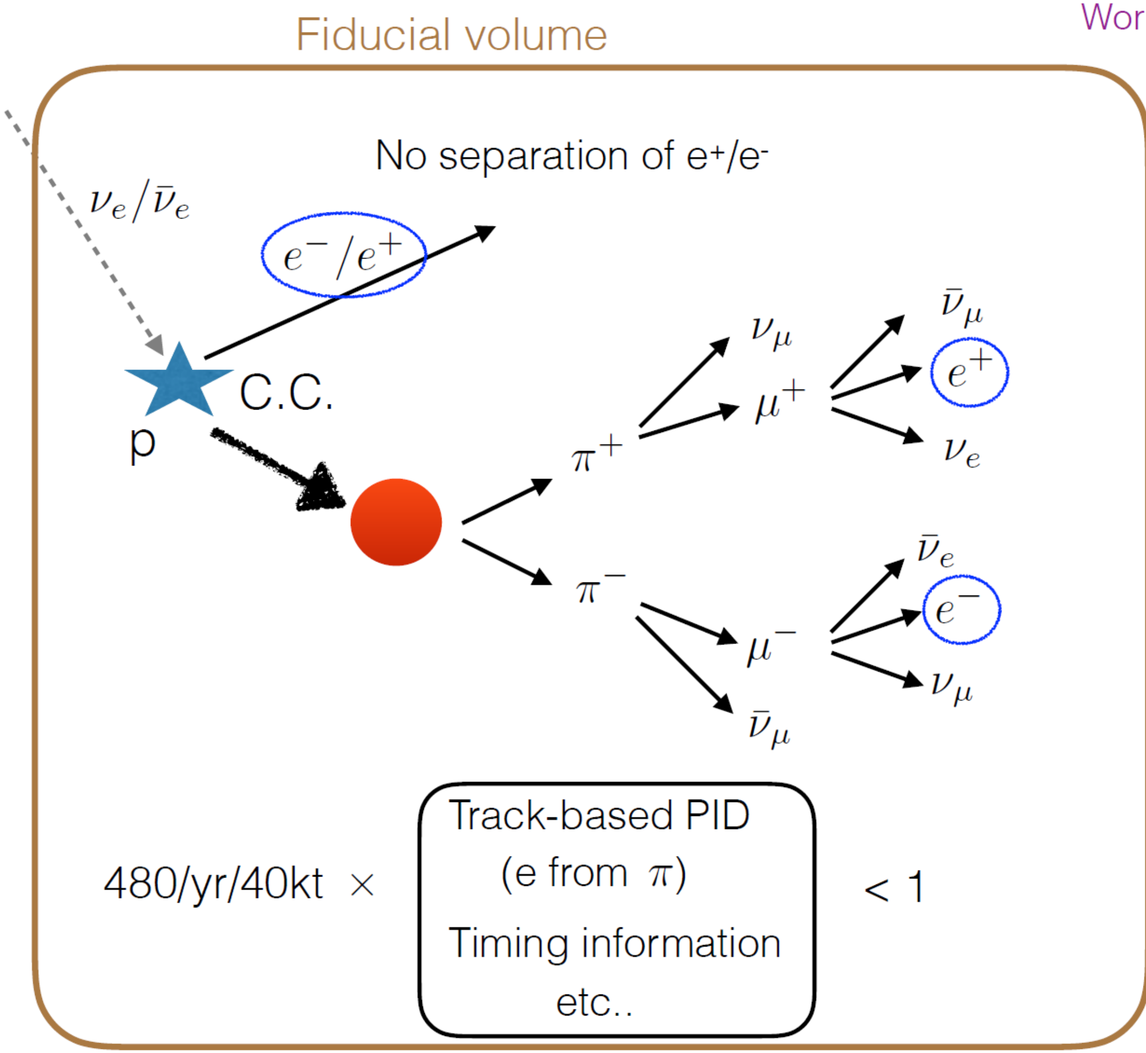
Supported by DOE

Back-Up

Potential BGs: Neutrino-induced

e.g., primary: e-scattering, secondary e^+ e^-

Work in progress



- Other subdominant bkg. negligible

  N.C. events (smaller)

  ν_μ: accompanying μ

  ν_τ: too small flux

- Zero-bkg. is easily achievable

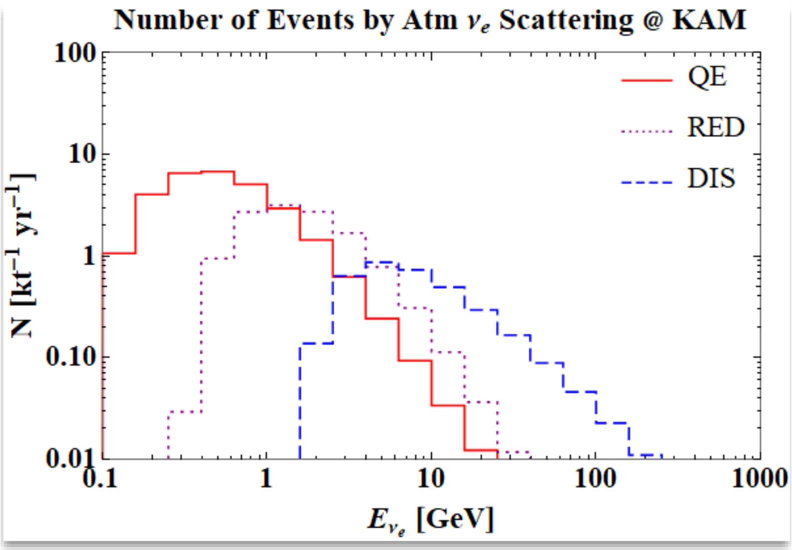
- (quasi-elastic) proton scattering: less bkg.

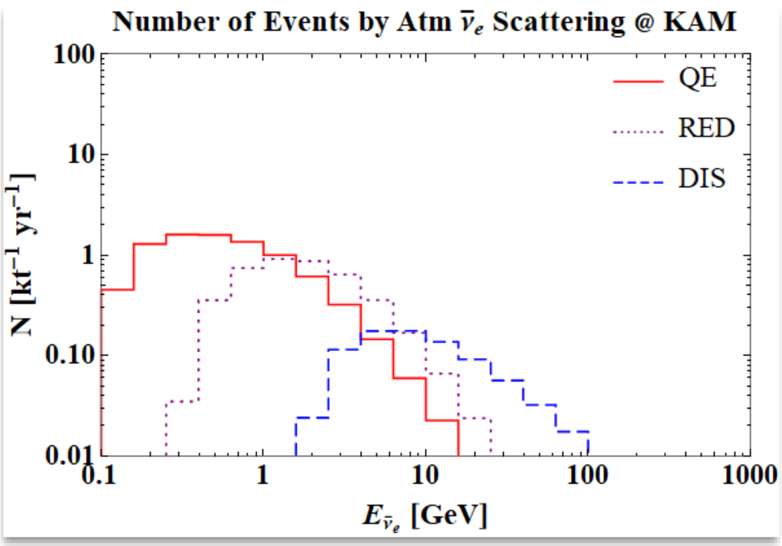
Dedicated study in progress

[S. Shin's talk @ PONDD 2018]

Expected Number of ν-induced Events

❖ ν_e flux [SK, 1502.03916] ⊗ ν_e cross section [Formaggio, Zeller, 1305.7513]





✓ Most DIS events result in messy final states, not mimicking signal events &

A majority of resonance event may create a few mesons in the final state

[Formaggio, Zeller, 1305.7513]

➔ 12.2 events/kt/yr are potentially relevant.

✓ PID, timing information, vertex resolution, etc. can suppress such events significantly. ➔ Zero-BG is achievable!

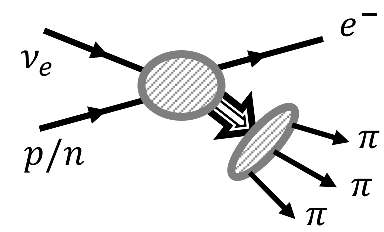
Potential BGs: Neutrinos

Table 4.3: Atmospheric neutrino event rates including oscillations in 350 kt · year with a LArTPC, fully or partially contained in the detector fiducial volume.

Sample	Event Rate
fully contained electron-like sample	14,053
fully contained muon-like sample	20,853
partially contained muon-like sample	6,871

[DUNE CDR-Vol.2 (2015)]

$\sim$**40.2**/yr/kt: may contain multi-track events



	SK-I		SK-II		SK-III		SK-IV	
	Data	MC	Data	MC	Data	MC	Data	MC
FC sub-GeV single-ring e-like								
0-decay	2992	2705.4	1573	1445.4	1092	945.3	2098	1934.9
1-decay	301	248.1	172	138.9	118	85.3	243	198.4
π^0-like	176	160.0	111	96.3	58	53.8	116	96.2
μ-like								
0-decay	1025	893.7	561	501.9	336	311.8	405	366.3
1-decay	2012	1883.0	1037	1006.7	742	664.1	1833	1654.1
2-decay	147	130.4	86	71.3	61	46.6	174	132.2
2-ring π^0-like	524	492.8	266	259.8	182	172.2	380	355.9
FC multi-GeV single-ring								
ν_e-like	191	152.8	79	78.4	68	54.9	156	135.9
$\overline{\nu}_e$-like	665	656.2	317	349.5	206	231.6	423	432.8
μ-like	712	775.3	400	415.7	238	266.4	420	554.8
multi-ring								
ν_e-like	216	224.7	143	121.9	65	81.8	175	161.9
$\overline{\nu}_e$-like	227	219.7	134	121.1	80	72.4	212	179.1
μ-like	603	640.1	337	337.0	228	231.4	479	499.0

[Super-Kamiokande (2012)]

Single-track candidates: **32.4** + **8.8** = **41.2** /yr/kt, while total e-like events are 49.9 /yr/kt. (Note that SK takes e-like events with $E > \sim$10 MeV.)

$\Rightarrow$ Potential BGs for elastic scattering signal (eBDM) events

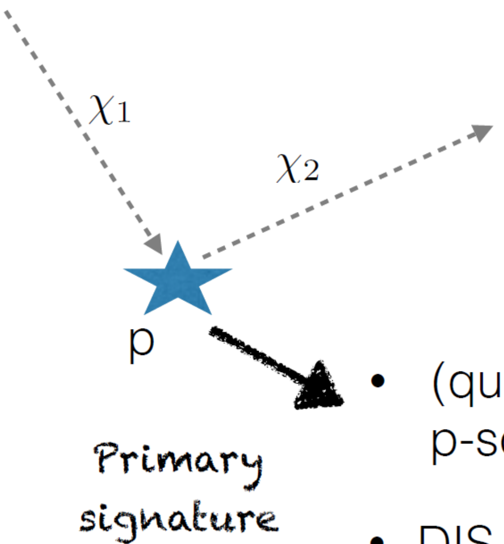
Multi-track candidates: **5.2** /yr/kt

$\Rightarrow$ Most extra tracks come from mesons which can be identified at LArTPC.

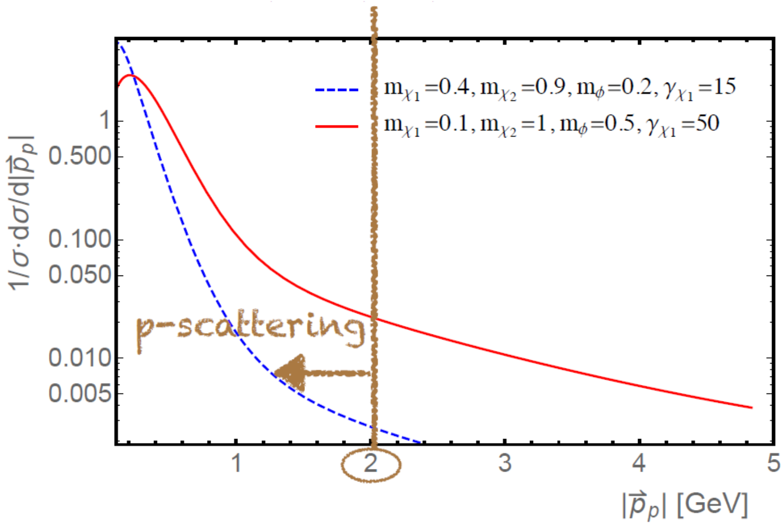
$\Rightarrow$ Very likely to be background-free for inelastic scattering signal (*i*BDM) events

BDM Signals: p-scattering vs DIS

D. Kim, **JCP** & S. Shin [1612.06867]



- (quasi-elastic) p-scattering



- DIS p-scattering dominates for smaller $m_X < 1$ GeV even for $E_1 > 50$ GeV (unlike neutrino scattering events: mediator W, Z)

$$\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \frac{1}{(p_p^2 + m_X^2)^2} \qquad \frac{d\sigma_{\rm DIS}}{dx dy} \propto \frac{1}{(Q^2 + m_X^2)^2}$$

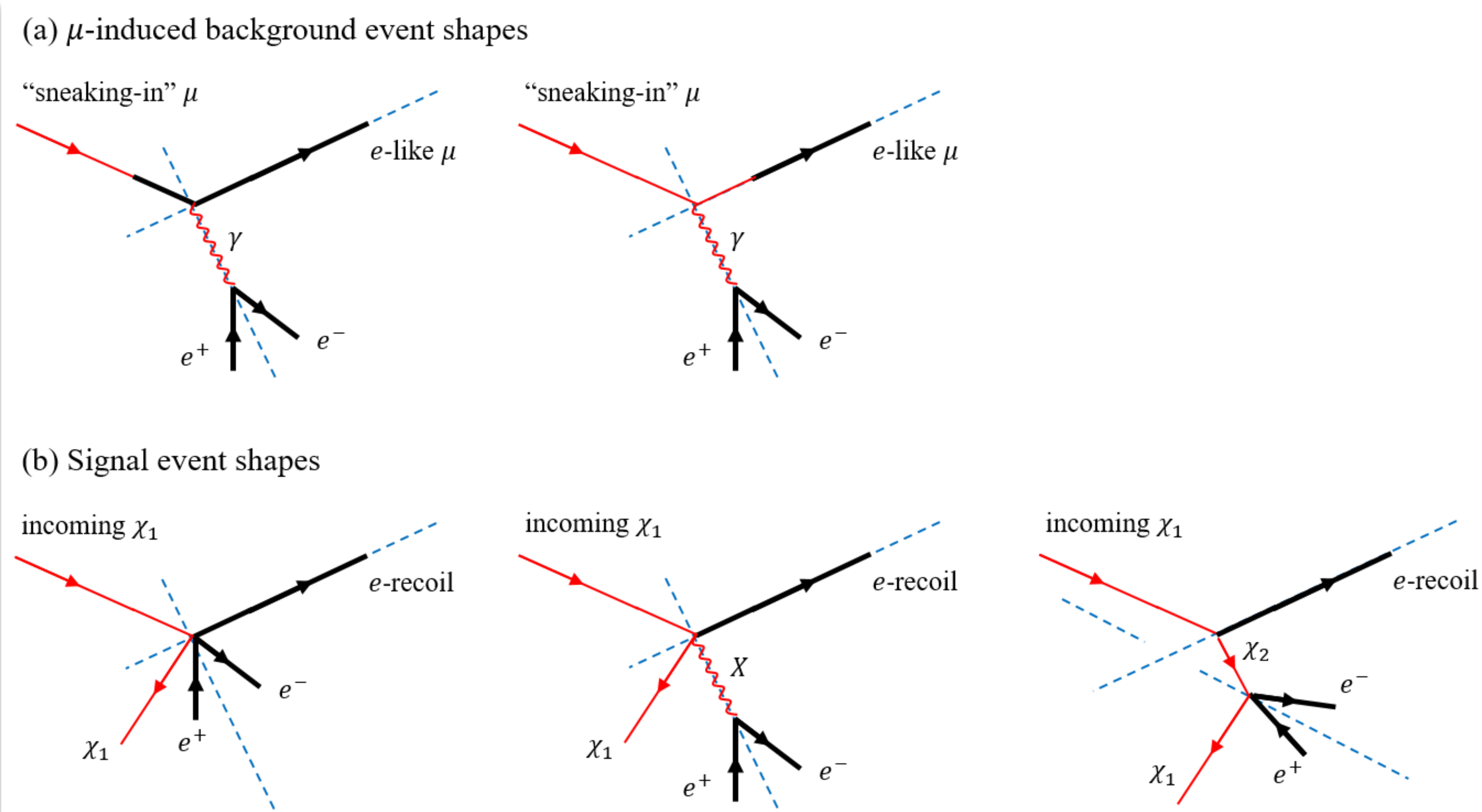
Differential cross section peaks $p_p \ll 1$ GeV

$$Q > 1.5\,\mathrm{GeV}$$

[S. Shin's talk @ PONDD 2018]

Possible Event Shapes (*i*BDM)

A. Chatterjee, **JCP** et al. [1803.03264]



Model-independent Reach

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

❖ 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 (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!**

We factored out the acceptance related to the distance between the primary (ER) & the secondary vertices, other factors such as cuts, E_{th} are absorbed into σ_ϵ.

Model-independent Reach: Displaced Vertex

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

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

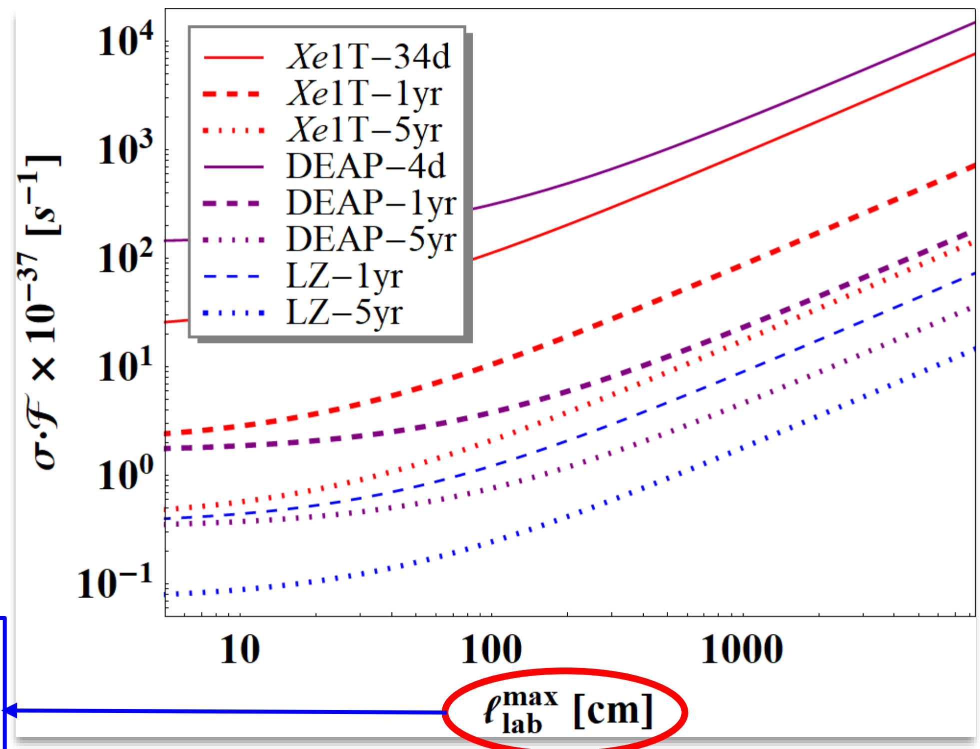
➔ (relatively) conservative limit to require two correlated vertices in the fiducial volumes (also to be distinguished from elastic scattering)

90% C.L. with zero background

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

Evaluated for each detector

Calculable given a detector



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

Model-independent Reach: Familiar Form

❖ More familiar parameterization is possible with the below modification.

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

set to be $5\times10^{-26}\ \mathrm{cm^3 s^{-1}}$

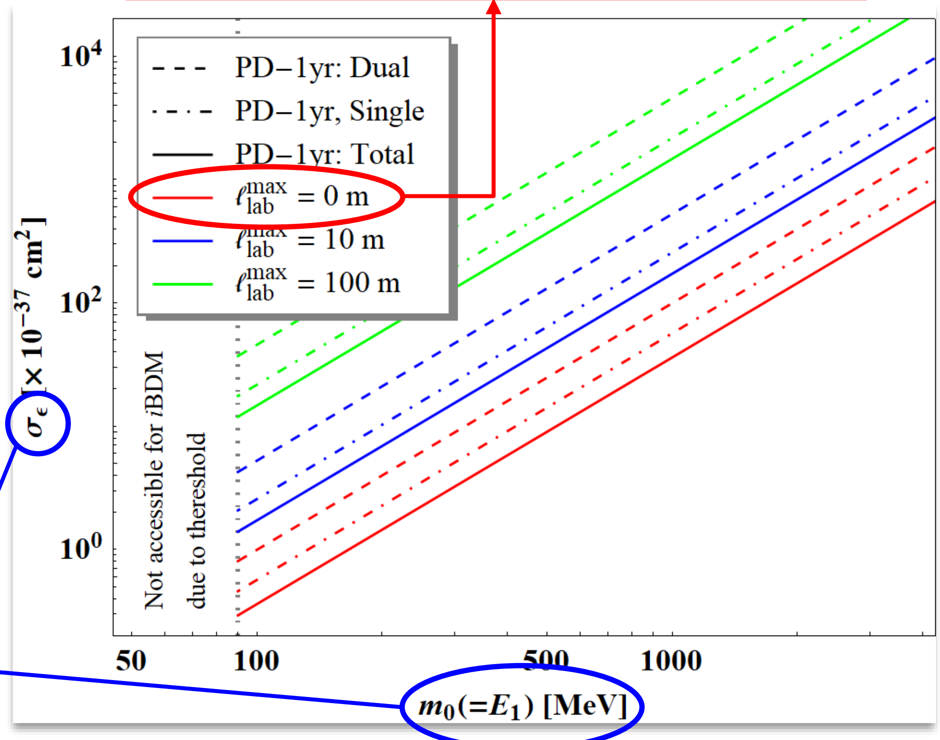
$$\mathcal{F}\sim\frac{\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{m_0^2}$$

❖ Then having

$$\sigma_\epsilon \text{ vs. } m_0(=E_1=\gamma_1 m_1)$$

cf. σ vs. $m_{\rm DM}$ in conventional WIMP searches

Relevant to signals with overlaid vertices or elastic scattering signals

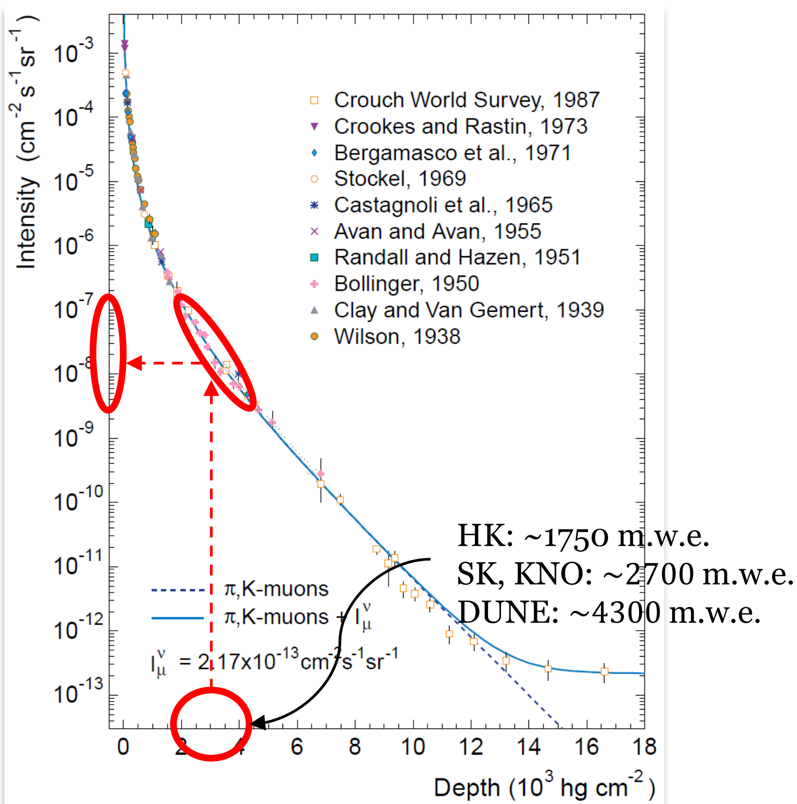


Experimental sensitivity can be represented by σ_ϵ vs. $m_0(=E_1)$.

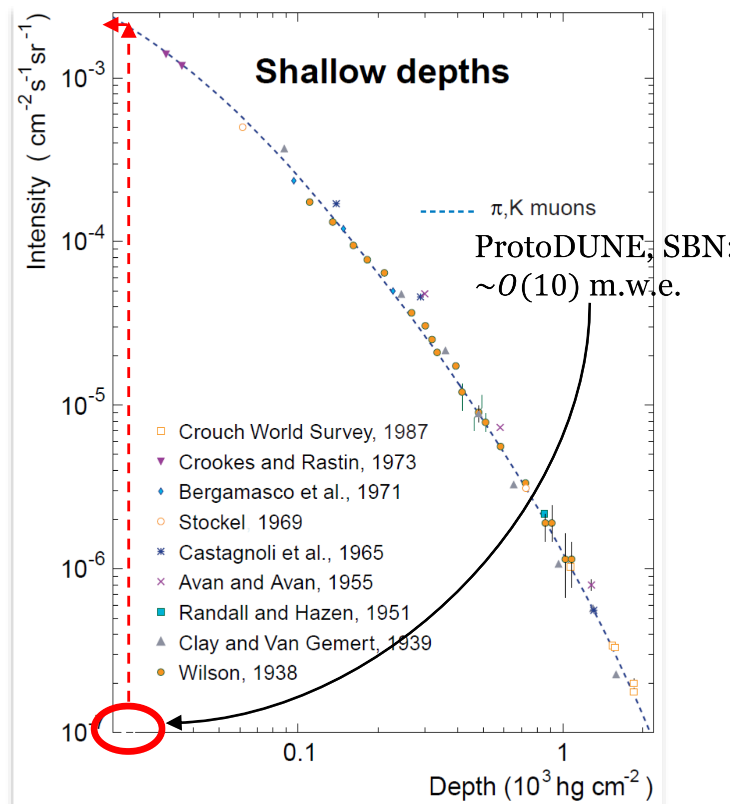
Potential BGs: High E Muons

❖ Expecting ~10^{4-6} more muon flux at ProtoDUNE/SBN than that at HK, SK/KNO, DUNE.

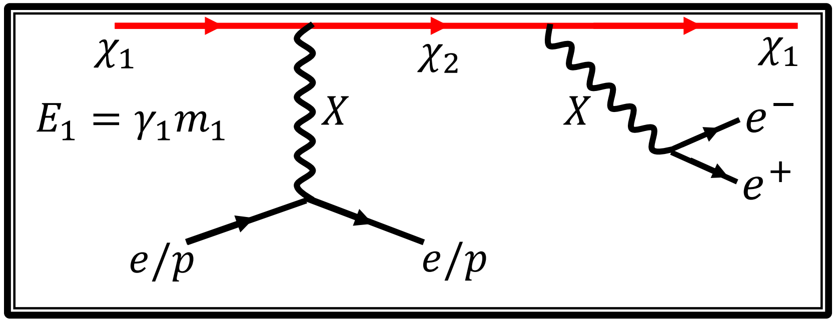
❖ Expecting ~5 – 50 more muon flux at HK than that at SK/KNO, DUNE.



[Bugaev et al. (1998)]



Signal Attributes



D. Kim, **JCP** & S. Shin (2016),

P. Machado, D. Kim, **JCP** & S. Shin

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Exp.	e-scattering **Vs.**	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 $\theta_{res}\sim 3^\circ$)	Reasonably separated (in preferred mass spectra) Recoil proton + well-separated e^+e^- pair