DM Search @ Neutrino Detectors

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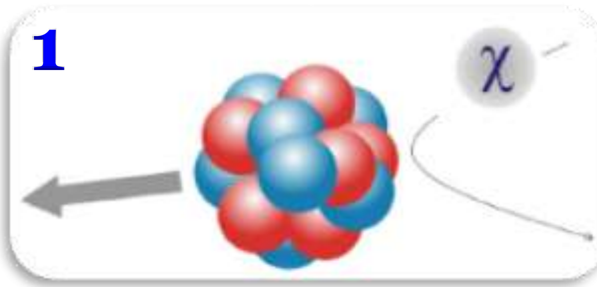
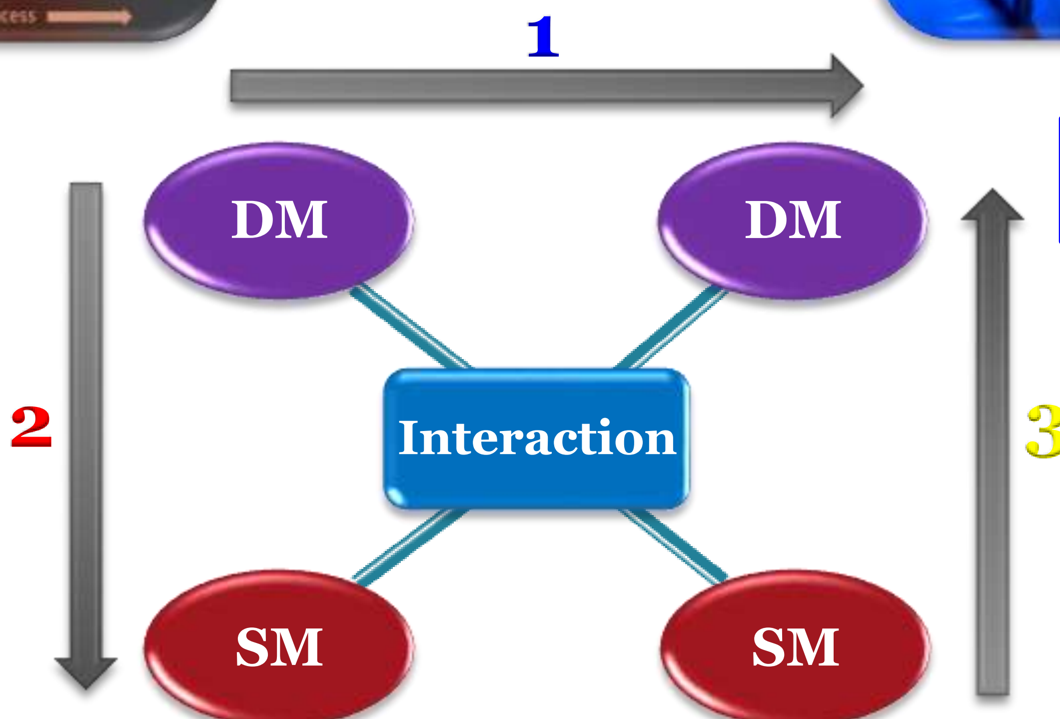
2018.12.06

IBS Particle Physics & Cosmology Workshop

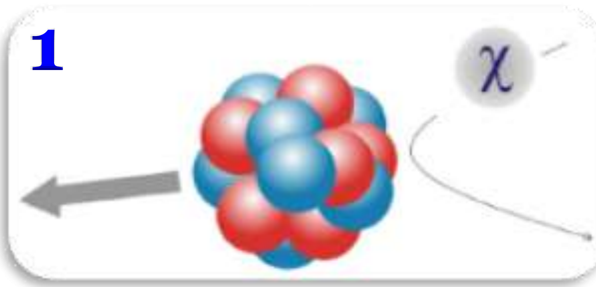
DM Search Strategies

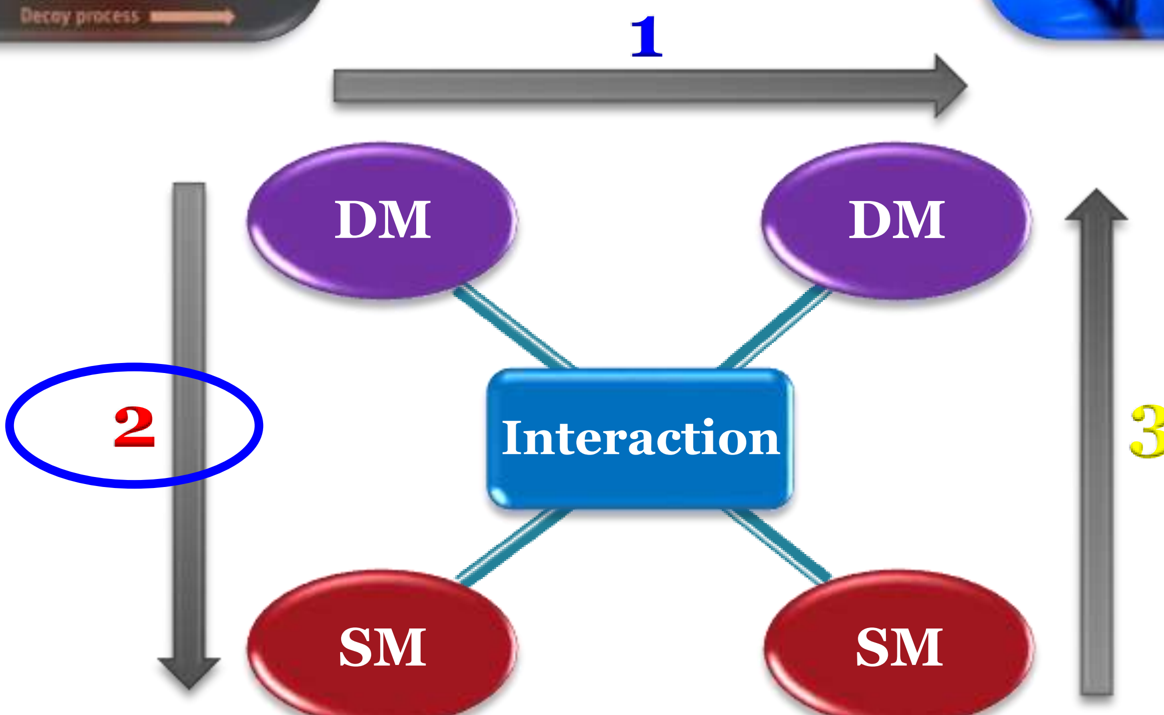




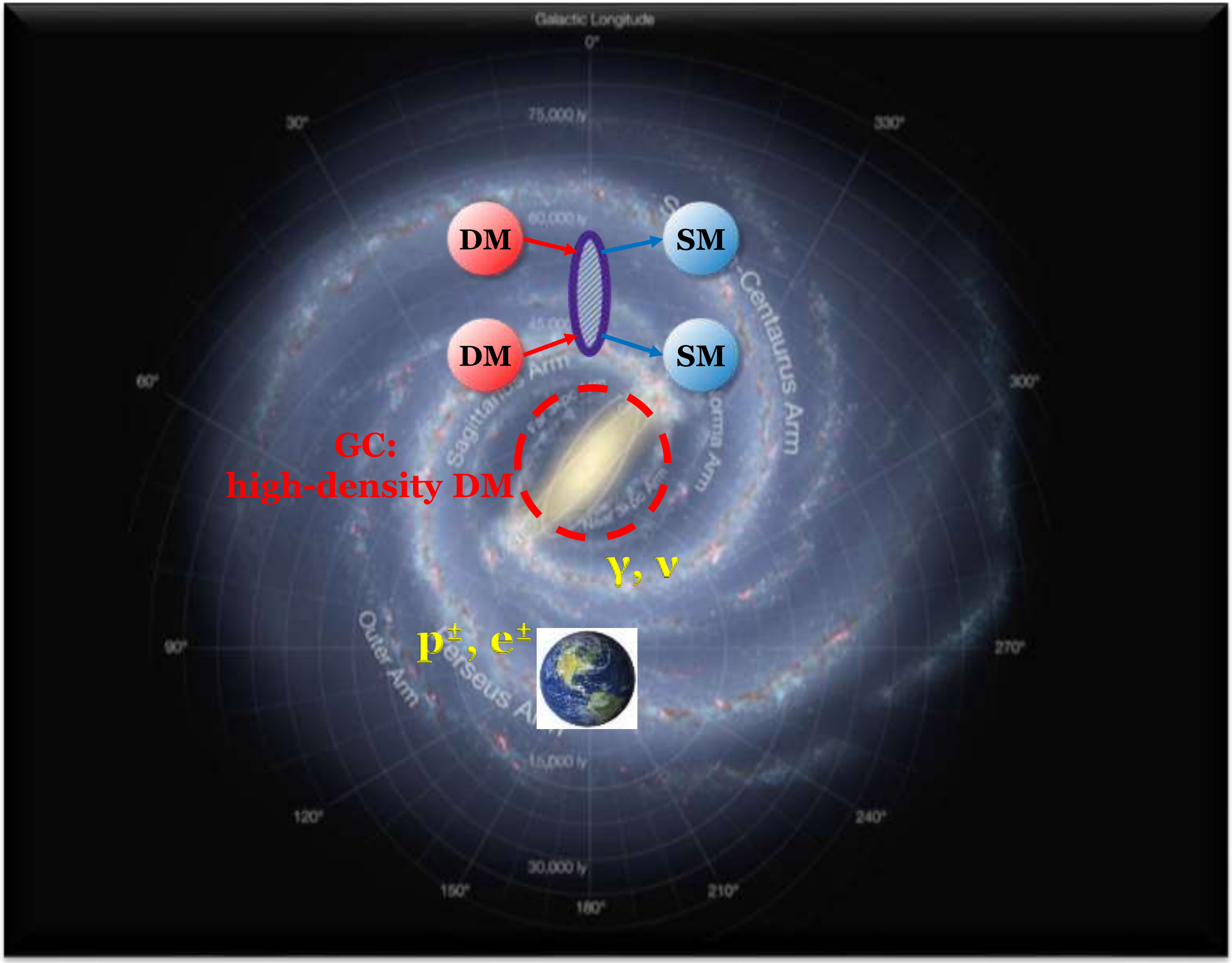
Well-introduced
by P. deNiverville

DM Indirect Detection

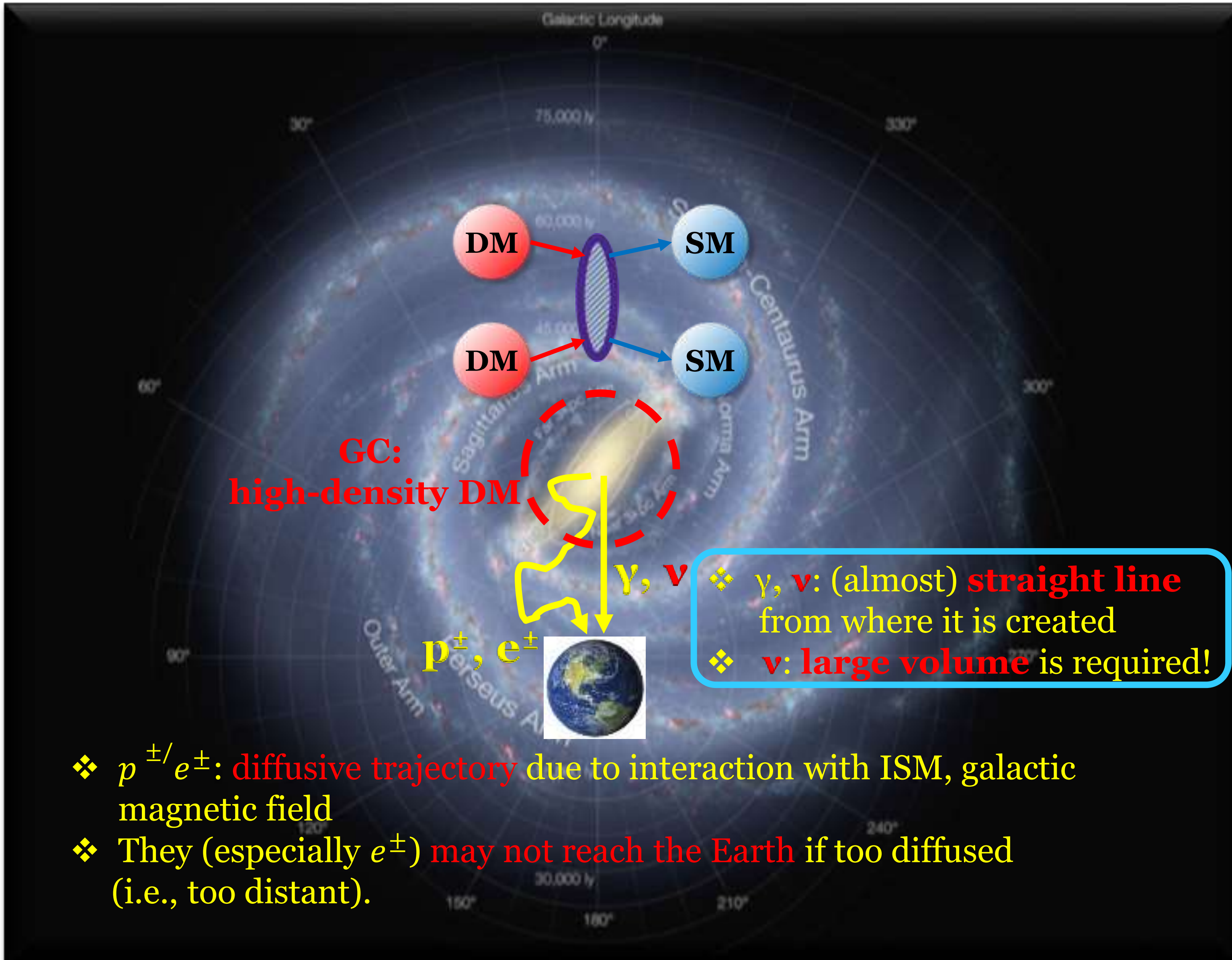




Indirect Detection: Cosmic-Rays



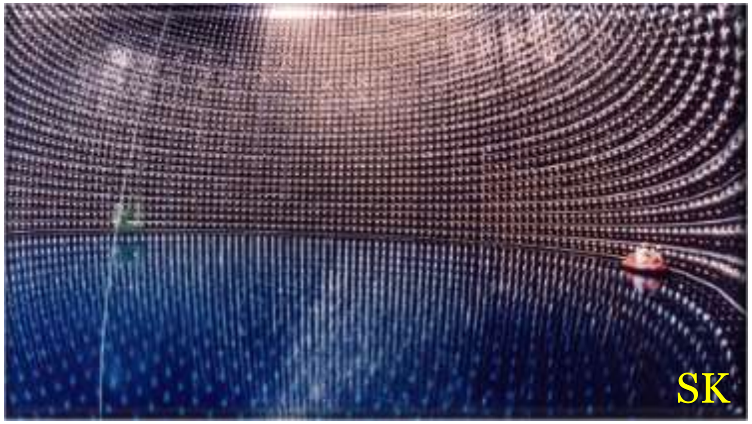
Indirect Detection: Cosmic-Rays

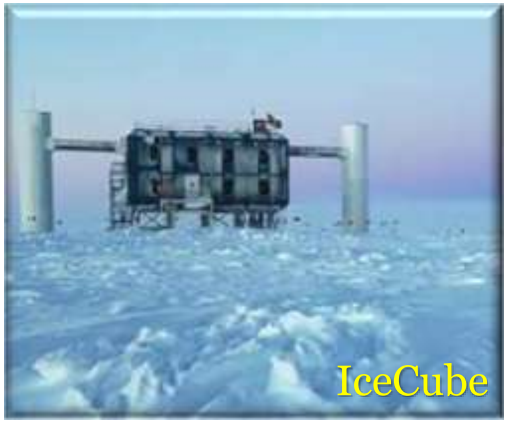


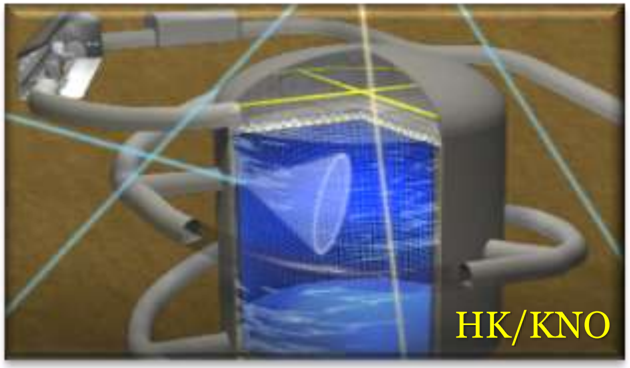
- γ, **ν**: (almost) **straight line** from where it is created
- **ν**: **large volume** is required!

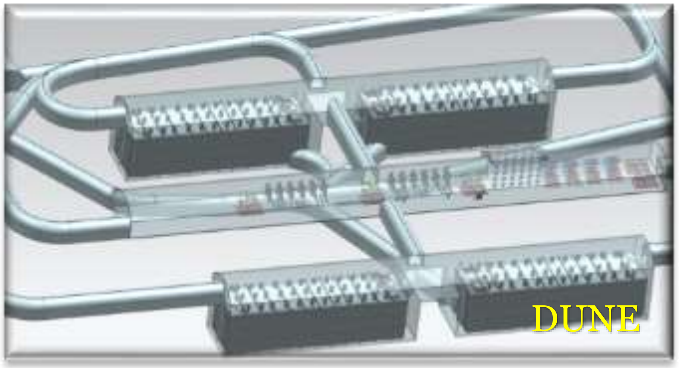
- $p^{\pm}/e^{\pm}$: diffusive trajectory due to interaction with ISM, galactic magnetic field
- They (especially $e^{\pm}$) may not reach the Earth if too diffused (i.e., too distant).

Large Volume Neutrino Experiments







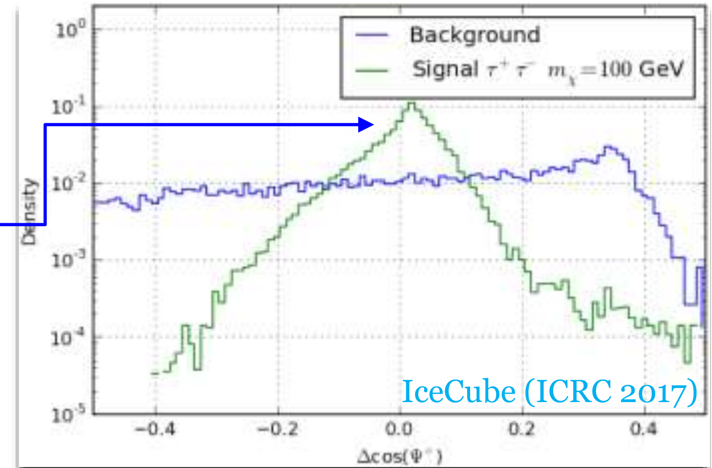


- ✓ Improved sensitivity to neutrino signals & large volume
- ✓ Better chance to have the information for extracting DM properties

ν Signals from DM Annihilation

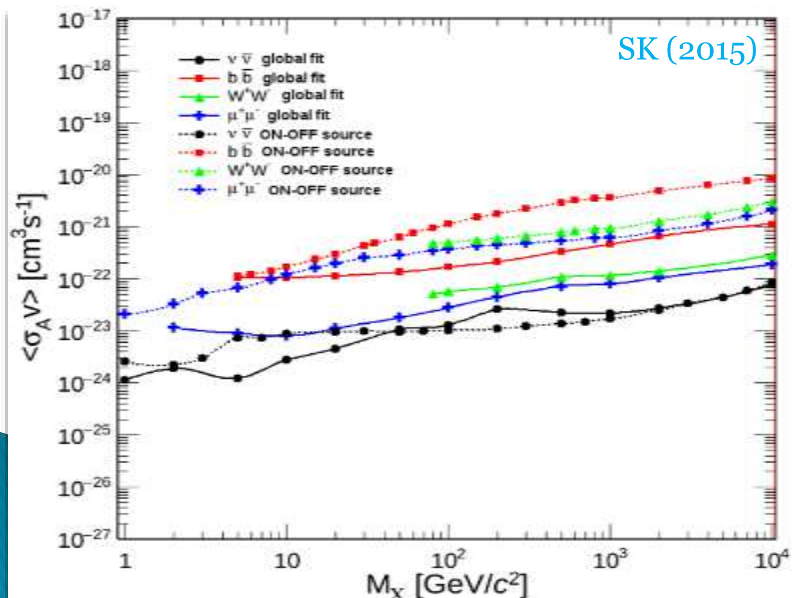
- The expected ν flux from DM annihilation

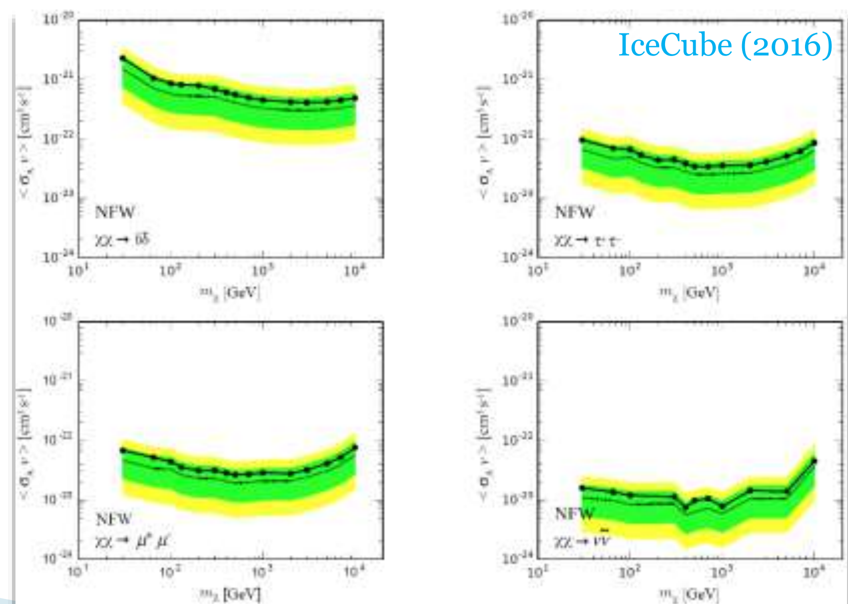
$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a(\psi) \frac{dN_\nu}{dE}$$



- Search for an excess of ν's from the GC direction compared to the expected atmospheric ν BG

- So far, no excess of ν's ➔ upper limit on $<\sigma_A v>$





DM Signals from the Sun

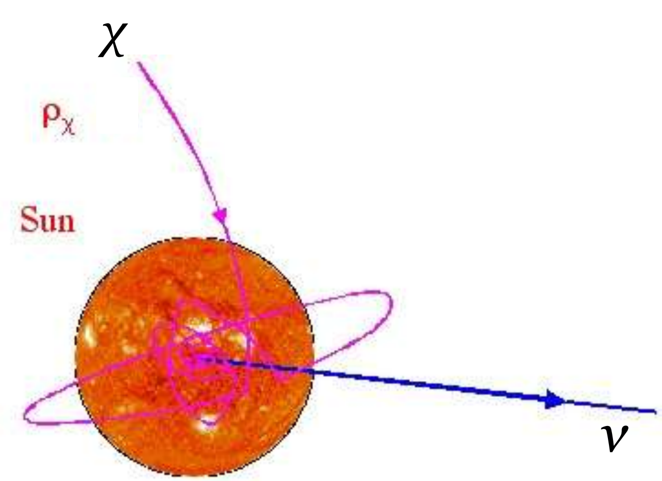
- ❖ DM χ can be captured by DM-nuclei/DM-DM scattering in the Sun
  - ➔ The Sun becomes a point-like source of DM signal.

Gould (1988),
Damour & Krauss (1999),
Chen, Lee, Lin & Lin (2014)

- ❖ Time evolution of DM number in the Sun

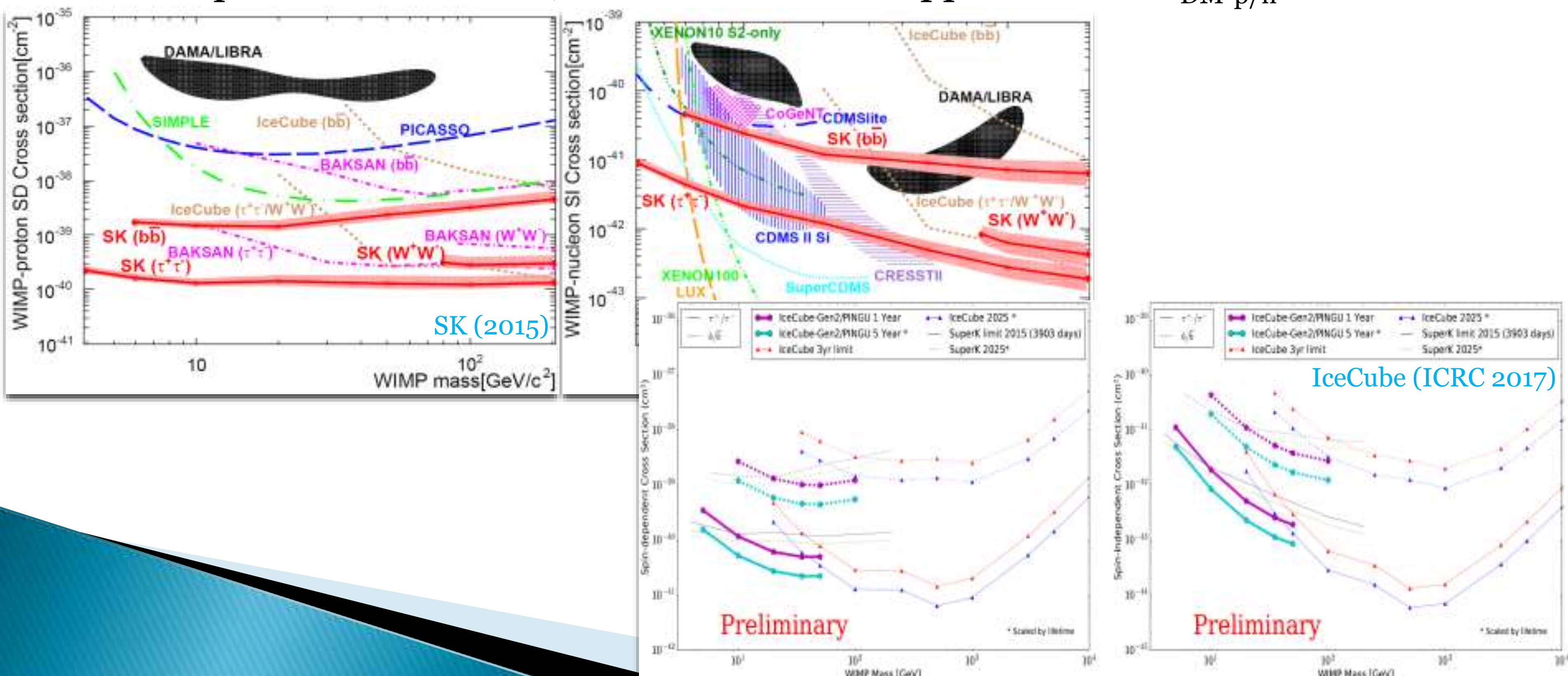
$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2$$

- ✓ C_c: capture rate by nuclei inside the Sun
- ✓ C_s: DM self-capture rate
- ✓ C_e: evaporation rate due to DM-nuclei interaction
- ✓ C_a: annihilation rate
- ✓ C_{se}: evaporation rate due to DM self-interaction

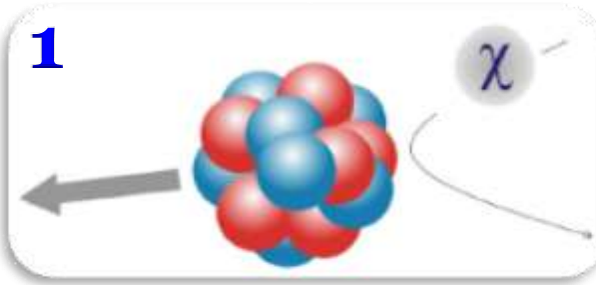


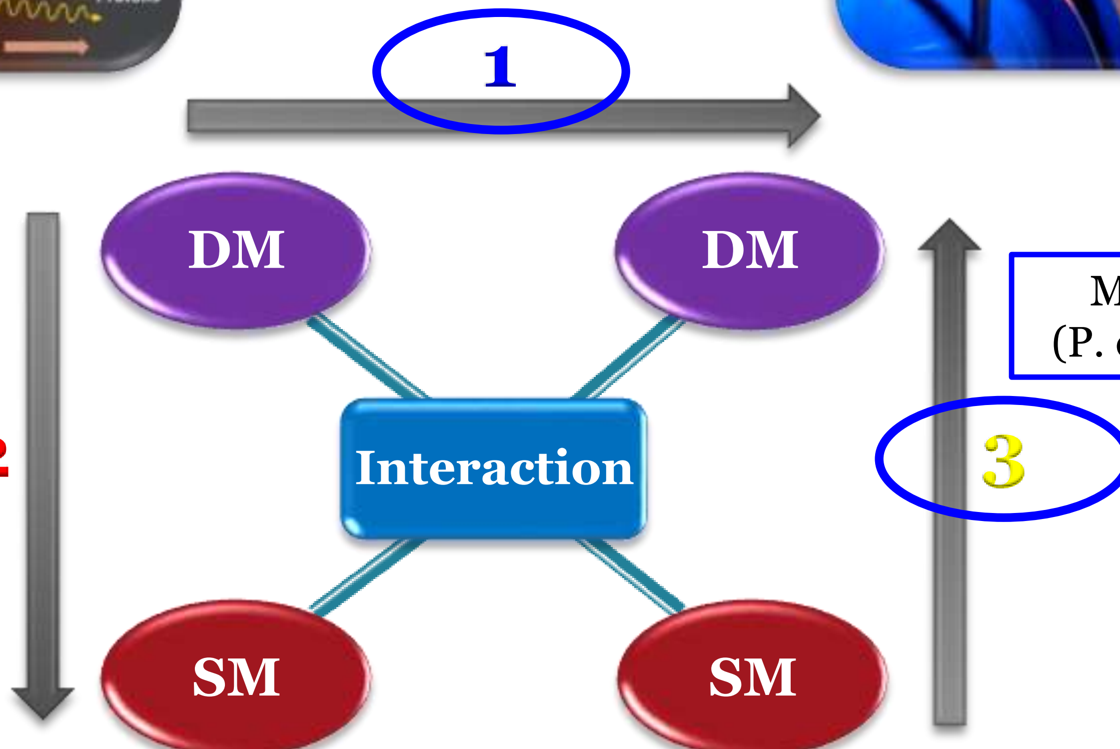
ν Signals from the Sun

- The Sun can be a good source of ν flux from DM annihilation due to the solar capture & relatively short distance compared to the GC.
- Search for an excess of ν's from the Sun direction compared to the expected atmospheric ν BG: So far, no excess of ν's ➔ upper limit on $\sigma_{DM\text{-}p/n}$



DM Direct Detection & Production



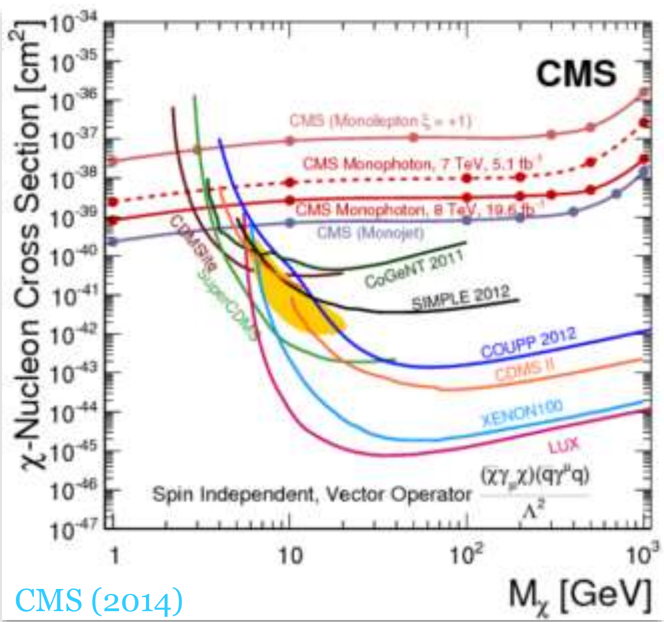


M. Park's talk
(P. deNiverville's)

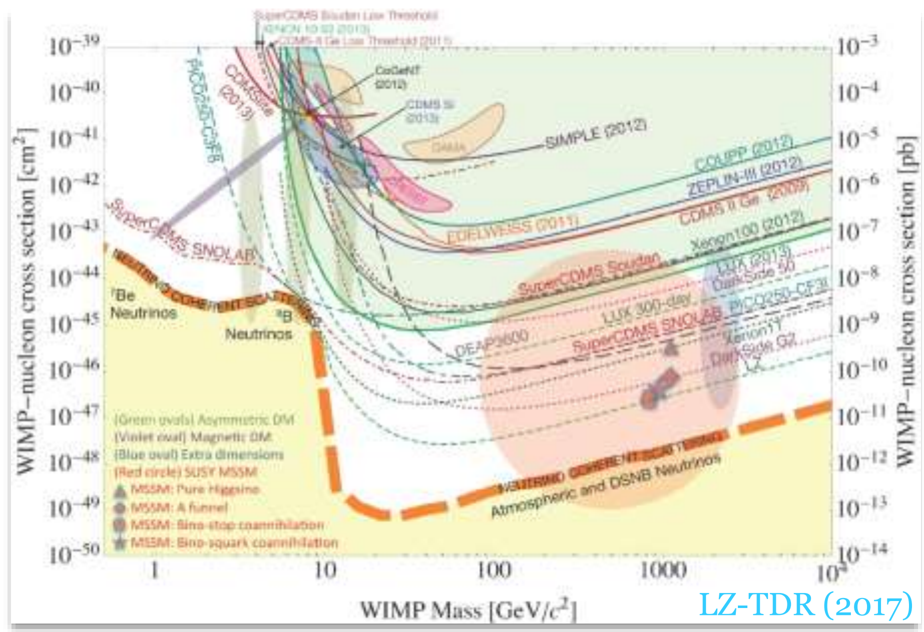
Current Status of DM Searches

❖ 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



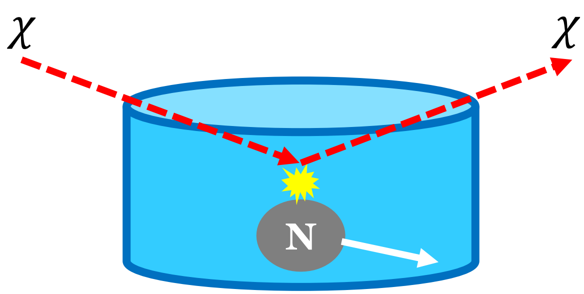
CMS (2014)



LZ-TDR (2017)

Typical DM Direct Searches

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



[Goodman, Witten (1985)]

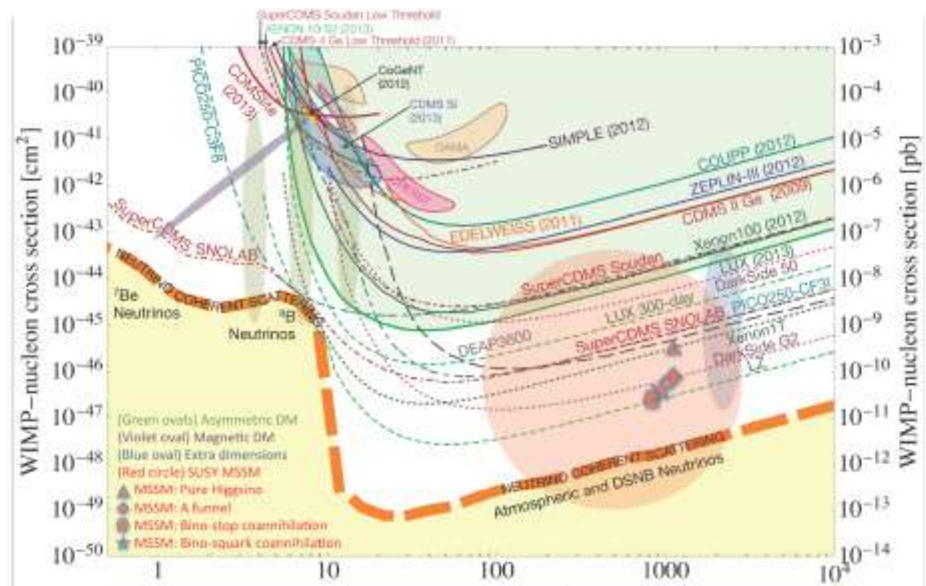
- ✓ Elastic scattering of
- ✓ Non-relativistic
- ✓ Weak-scale DM
- ✓ with nuclei

✓ $E_{\text{recoil}} \sim mv^2$

$\sim 1 - 100$ keV

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

✓ Detectors designed to be sensitive to this E range



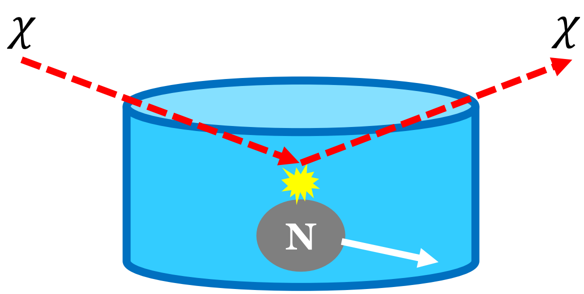
LZ-TDR (2017)

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

Time to change our point of view?!

Typical DM Direct Searches

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



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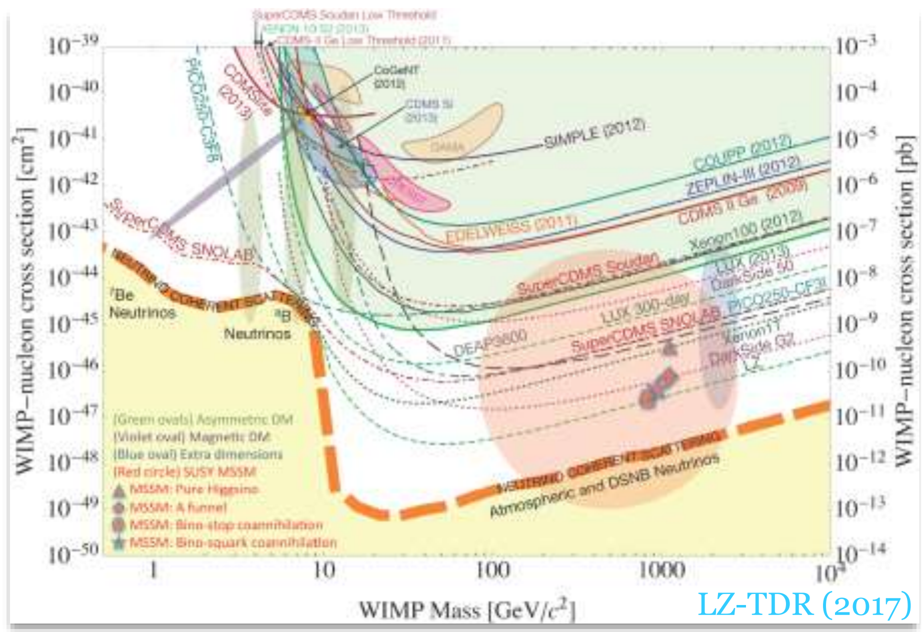


LZ-TDR (2017)

(in) ✓ Elastic scattering of

✓ ~~Non~~-relativistic

Other

✓ ~~Weak~~-scale DM

✓ with nuclei *or electron*

✓ No solid observation of WIMP signals

✓ A wide parameter respace already excluded

✓ Close to the neutrino "floor"

✓ Need new ideas!

Time to change our point of view?!

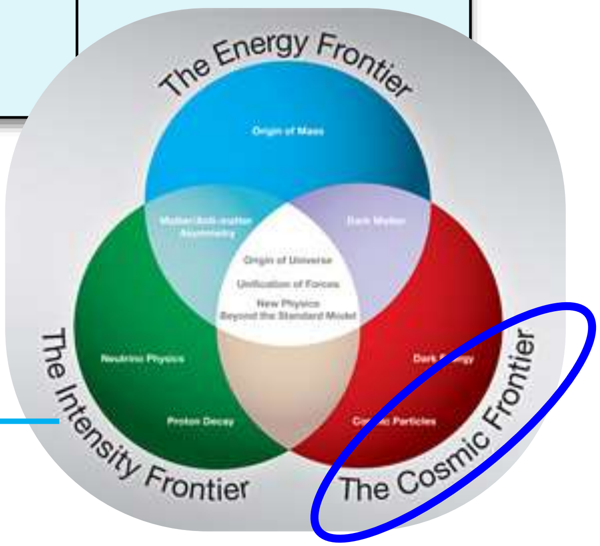
DM Search Schemes (Scattering)

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

Very well-studied

DM Search Schemes (Scattering)

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



P. deNiverville's talk

Boosted Dark Matter (BDM)

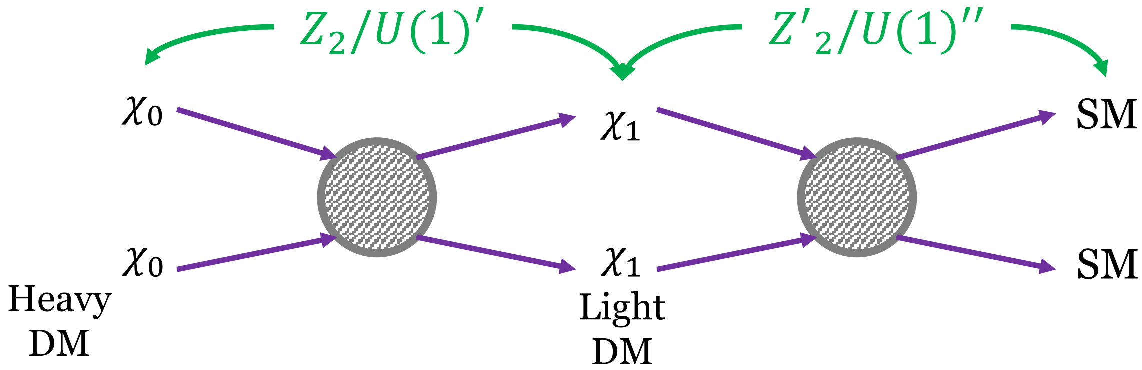
What if DM has a relativistic velocity?

[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
  - ✓ Multi-component model: [Belanger & **JCP**, 1112.4491; Kong, Mohlabeng, **JCP**, 1411.6632; Kim, **JCP**, Shin, 1702.02944; Aoki & Toma, 1806.09154]
  - ✓ 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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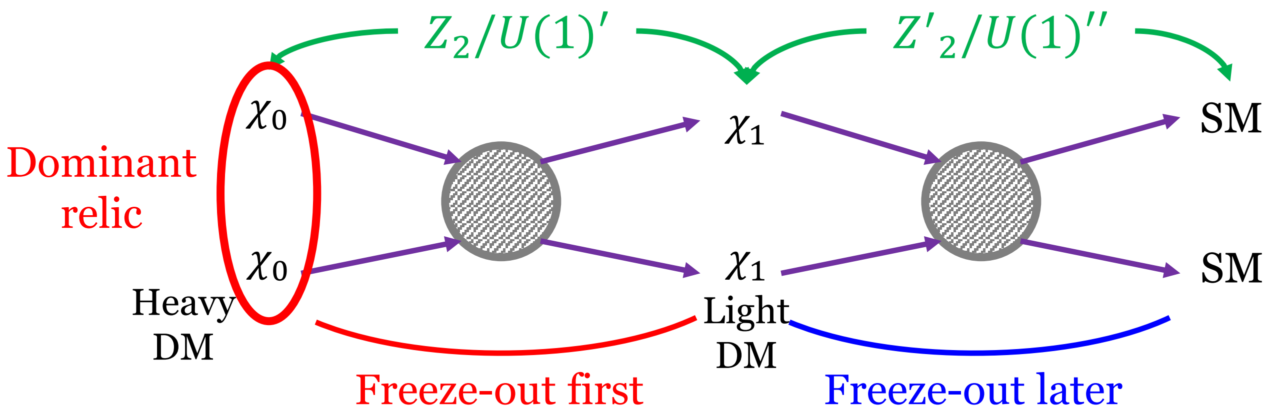

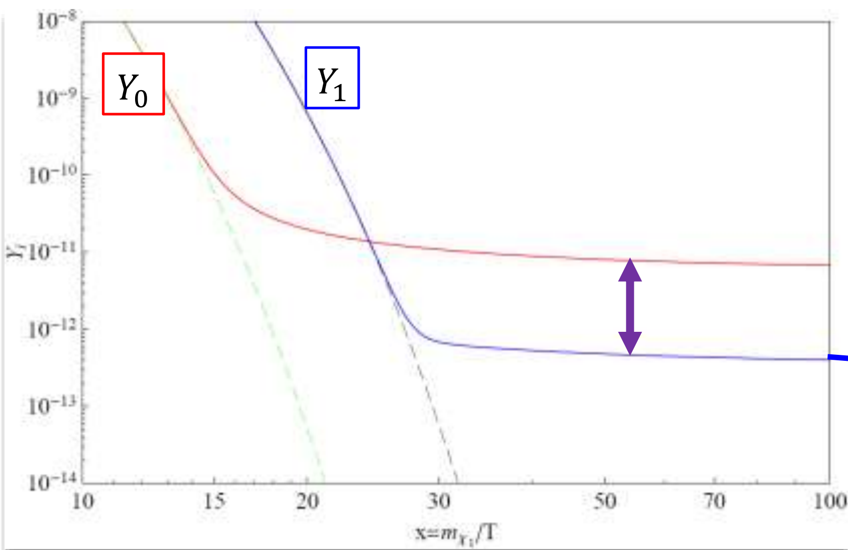

"**Assisted Freeze-out**" Mechanism

- ✓ 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 relic

Two-component BDM Scenario

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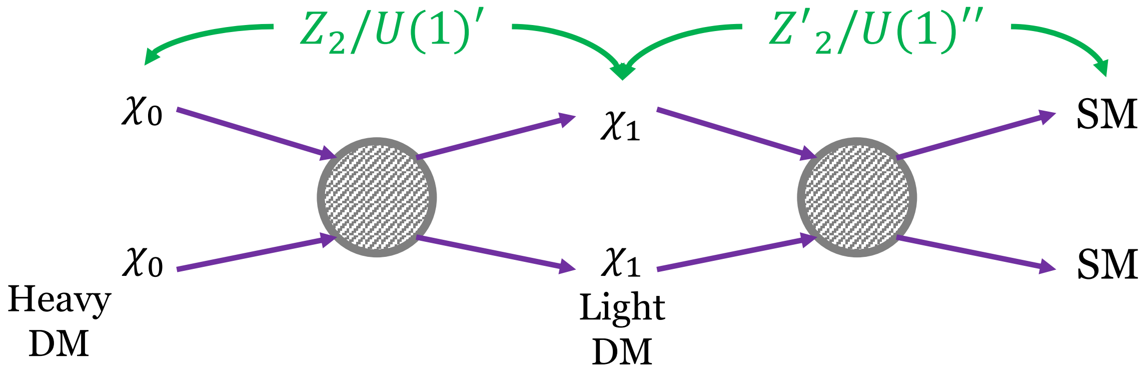
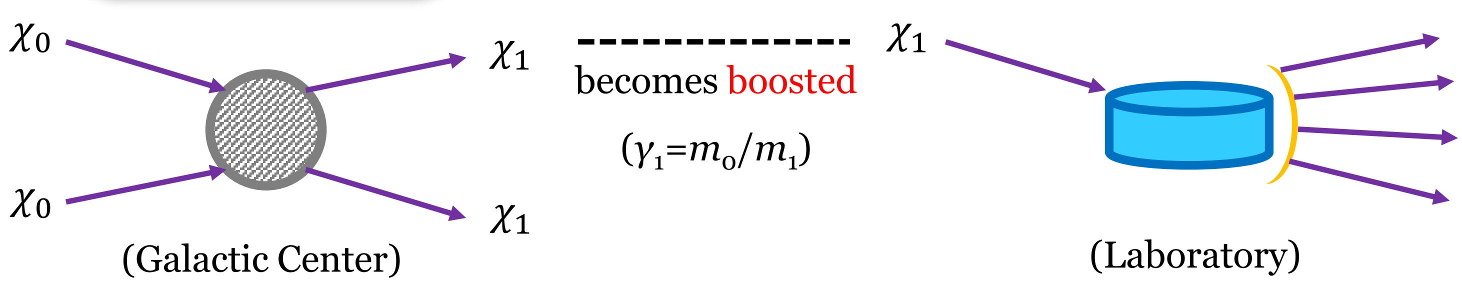


$\chi_0\chi_0 \to \chi_1\chi_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

(Note that relic χ_1 is non-relativistic.)

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



[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, $n_o = \rho_o / m_o$

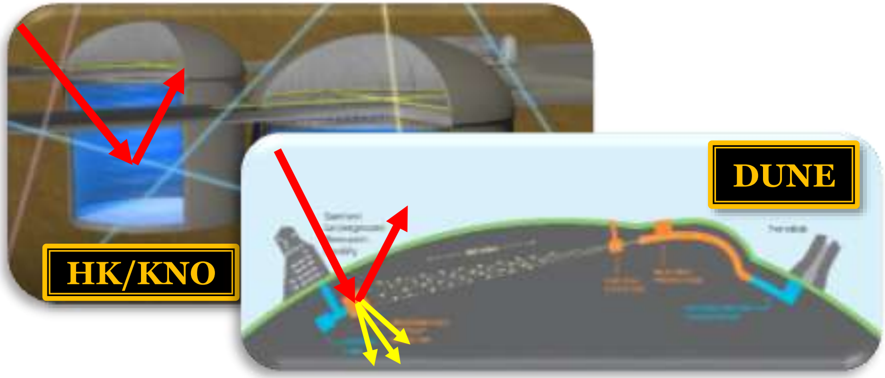
❖ Setting $\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$ and assuming the NFW DM halo profile,

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~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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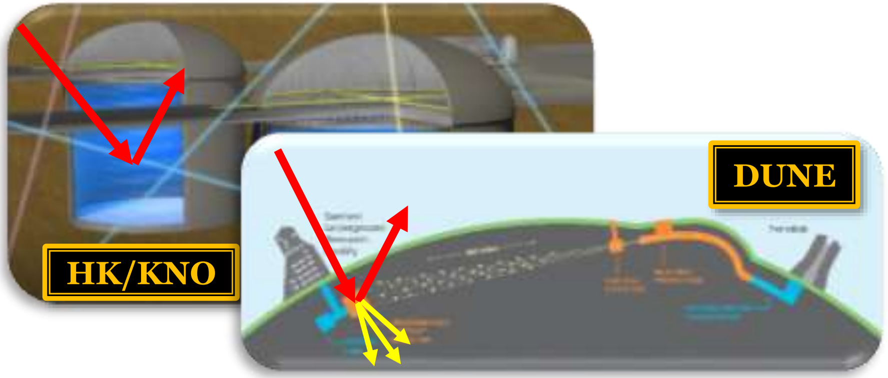

❖ Sources

✓ 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)

DM Signals from the Sun

❖ DM χ can be captured by DM-nuclei/DM-DM scattering in the Sun

➔ The Sun becomes a point-like source of **DM signal (ν)**.

❖ Time evolution of DM number in the Sun

Chen, Lee, Lin & Lin (2014)

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2$$

- ✓ $\mathbf{C_c}$: capture rate by nuclei inside the Sun
- ✓ $\mathbf{C_s}$: DM self-capture rate
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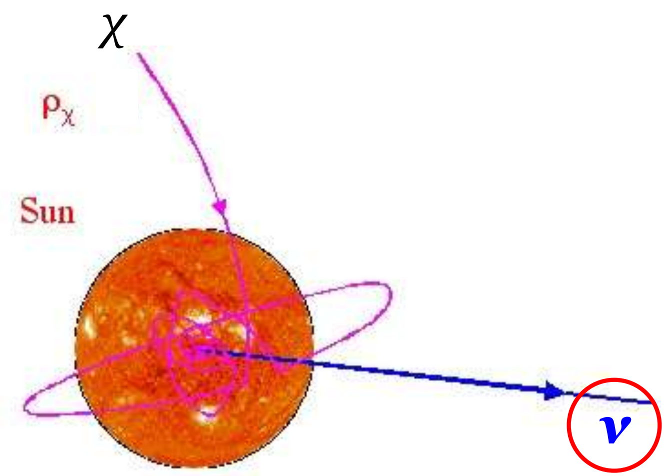

BDM from the Sun

KC Kong, G. Mohlabeng & **JCP** (2014)

- DM χ_o can be captured by DM-nuclei/DM-DM scattering in the Sun
  - ➔ The Sun becomes a point-like source of **BDM**.
- Time evolution of DM number in the Sun

Chen, Lee, Lin & Lin (2014)

$$\frac{dN_{\chi_o}}{dt} = C_c + (C_s - C_e)N_{\chi_o} - (C_a + C_{se})N_{\chi_o}^2$$

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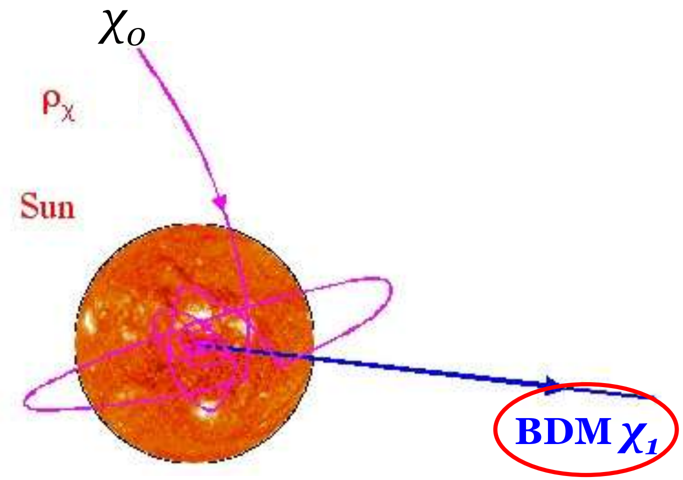
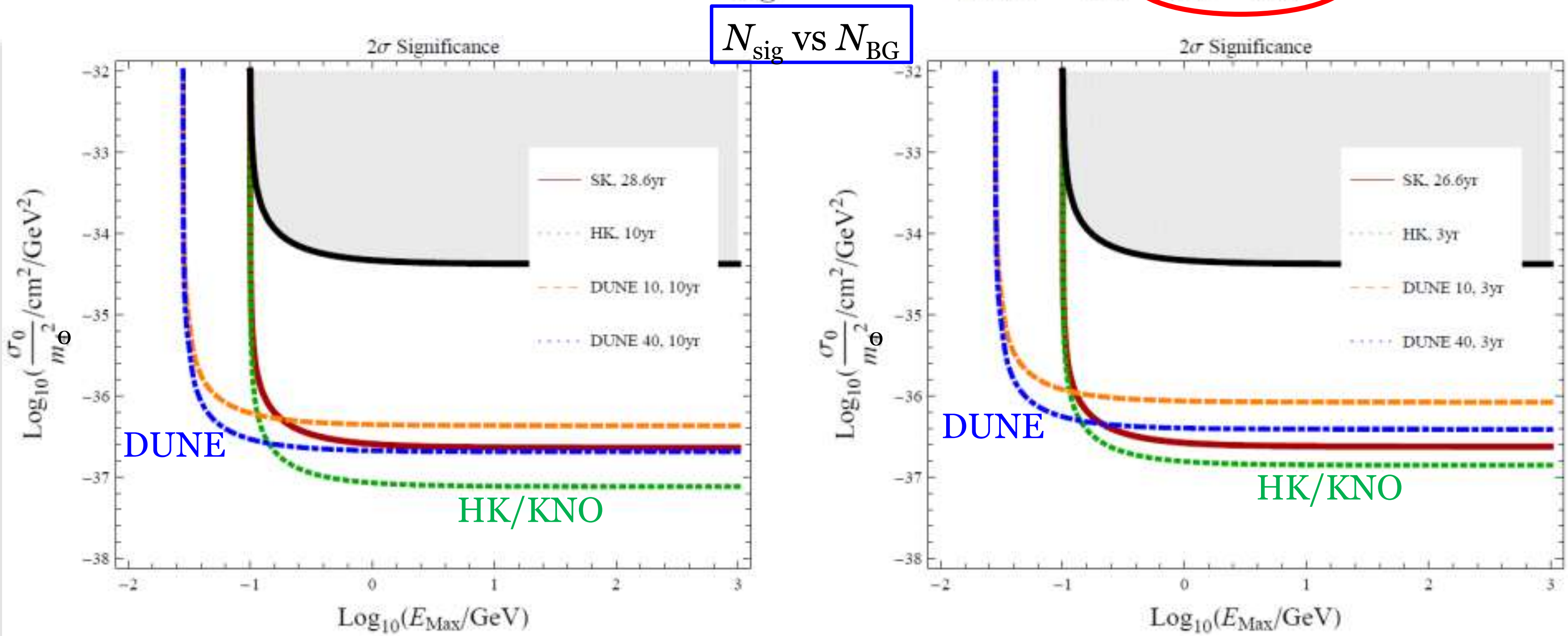


Experimental Reach (GC)

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

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



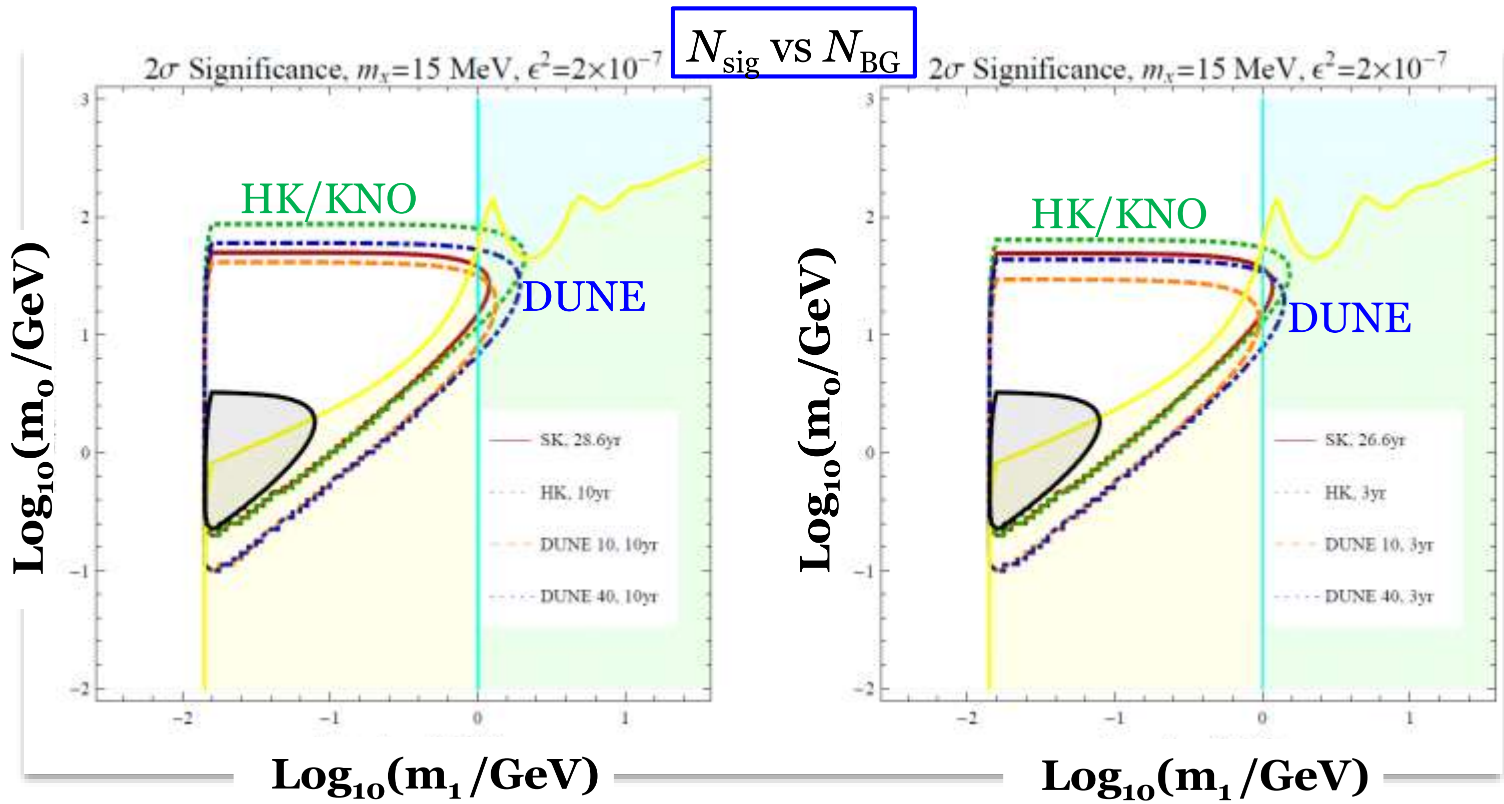
5 year construction + 10 year running vs 10 year construction + 3 year running

✓ 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 (GC)

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

❖ Experimental coverage in the mass plane



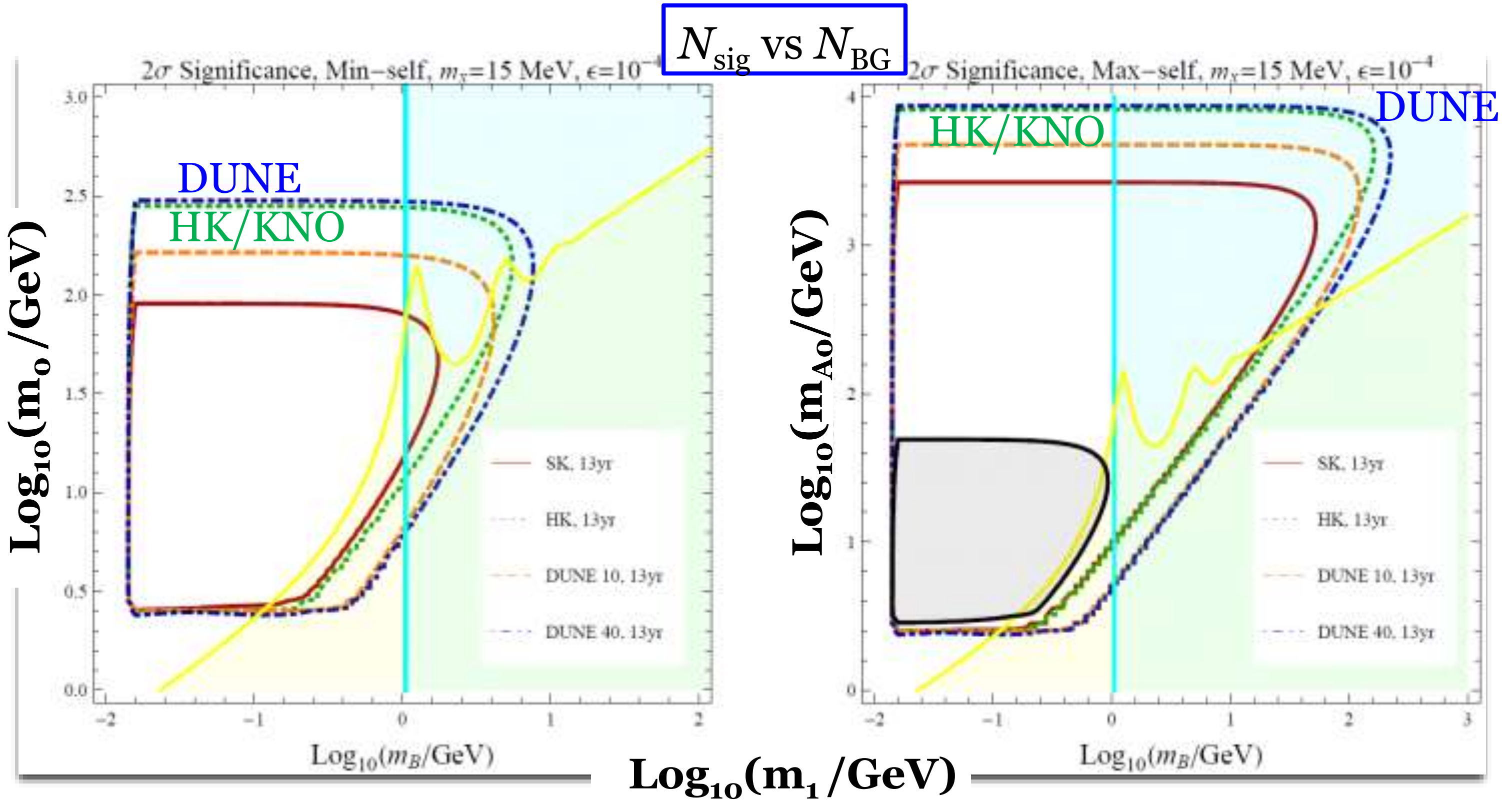
5 year construction + 10 year running vs 10 year construction + 3 year running

✓ Left edge: $m_B > m_X$, Top edge: $n_{DM} \sim \rho_{DM}/m_{DM}$, Diagonal edge: $E_{max} > E_{th}$

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

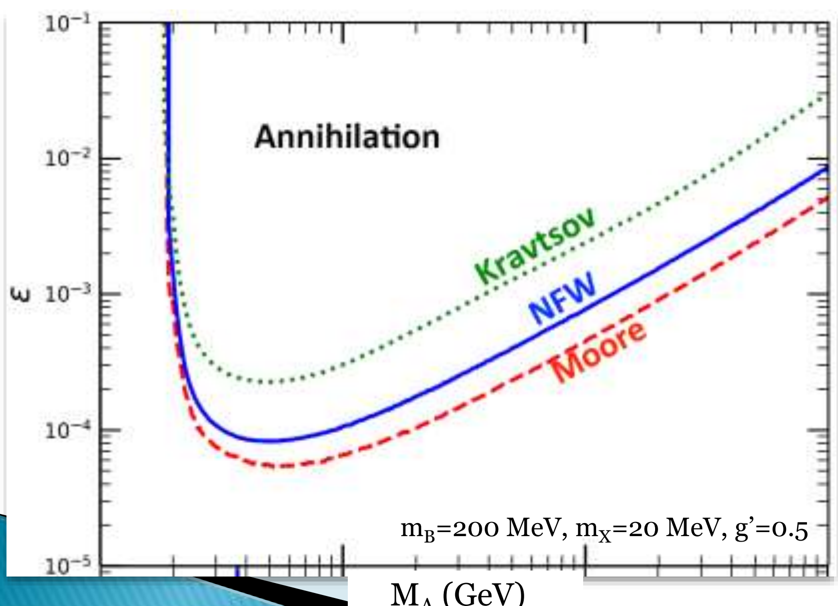
SK Official Results for BDM Search

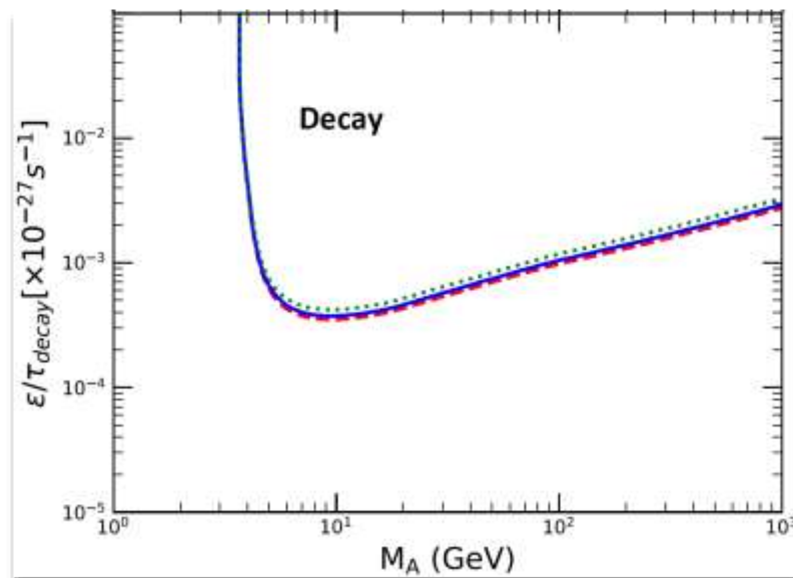
Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande

(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.





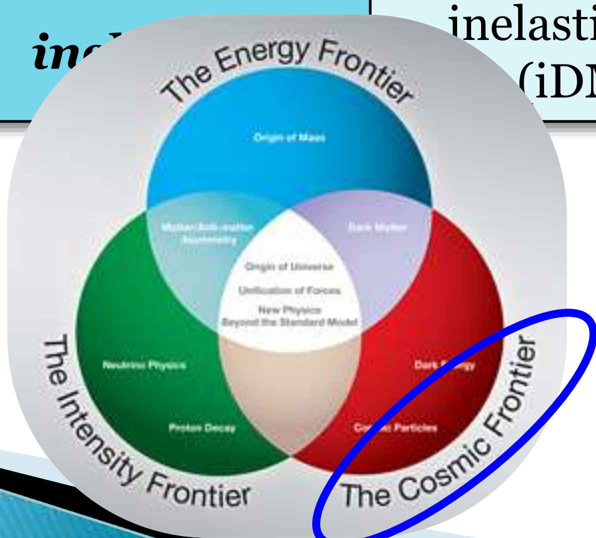
SK Collaboration, PRL (2018)

DM Search Schemes (Scattering)

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

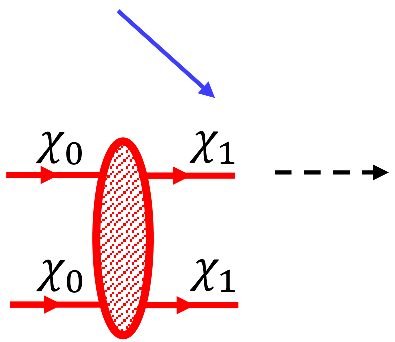
DM Search Schemes (Scattering)

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



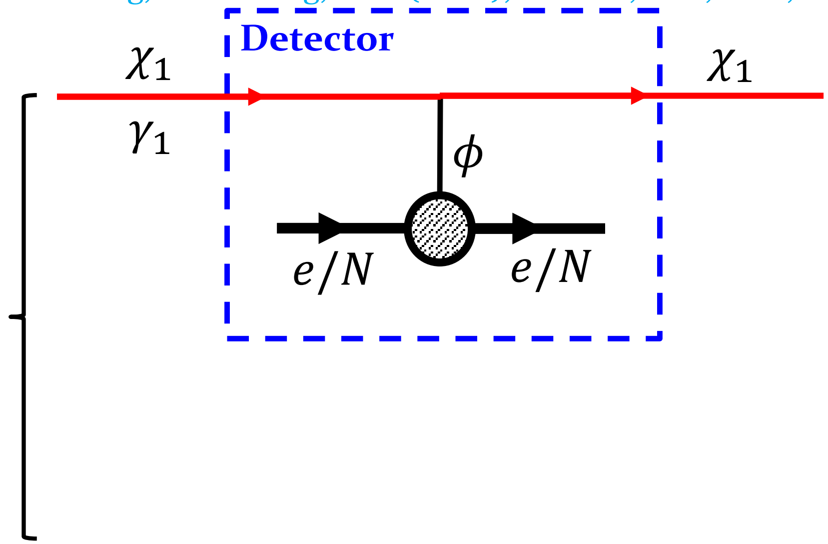
BDM Signatures

$\mathcal{F}_{\chi_1} = \sim 10^{-4} - 10^{-8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
with $m_0 = E_1 = \sim 1\ \mathrm{GeV} - 100\ \mathrm{GeV}$



Galactic Center

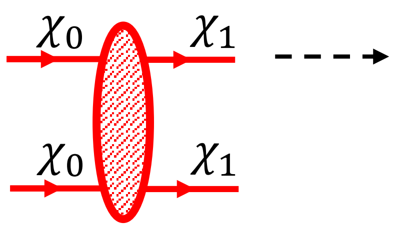
(a) Elastic scattering (**eBDM**) (cf. eBDM at HK/DUNE/PINGU/Xenon1T/…
[Agashe et al. (2014); Kong, Mohlabeng, **JCP** (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); Giudice, Kim, **JCP**, Shin (2017); Kim, Kong, **JCP**, Shin (2018); many more])



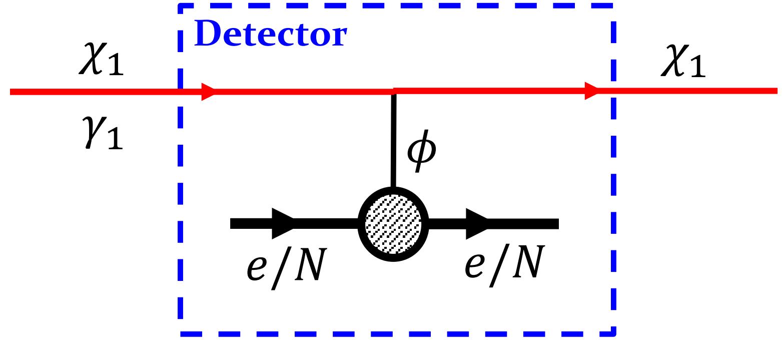
- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

BDM Signatures

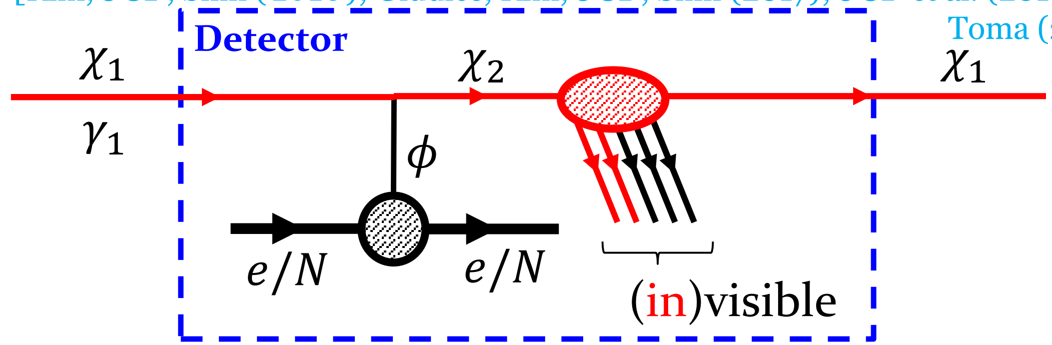
$\mathcal{F}_{\chi_1} = \sim 10^{-4} - 10^{-8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
with $m_0 = E_1 = \sim 1\ \mathrm{GeV} - 100\ \mathrm{GeV}$



(a) Elastic scattering (**eBDM**) (cf. eBDM at HK/DUNE/PINGU/Xenon1T/…
[Agashe et al. (2014); Kong, Mohlabeng, **JCP** (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); Giudice, Kim, **JCP**, Shin (2017); Kim, Kong, **JCP**, Shin (2018); many more])



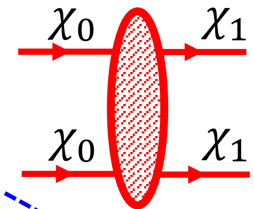
(b) Inelastic scattering (***i*BDM**) (cf. iBDM at HK/DUNE/Xenon1T/…
[Kim, **JCP**, Shin (2016); Giudice, Kim, **JCP**, Shin (2017); **JCP** et al. (2018); Aoki, Toma (2018)])



- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

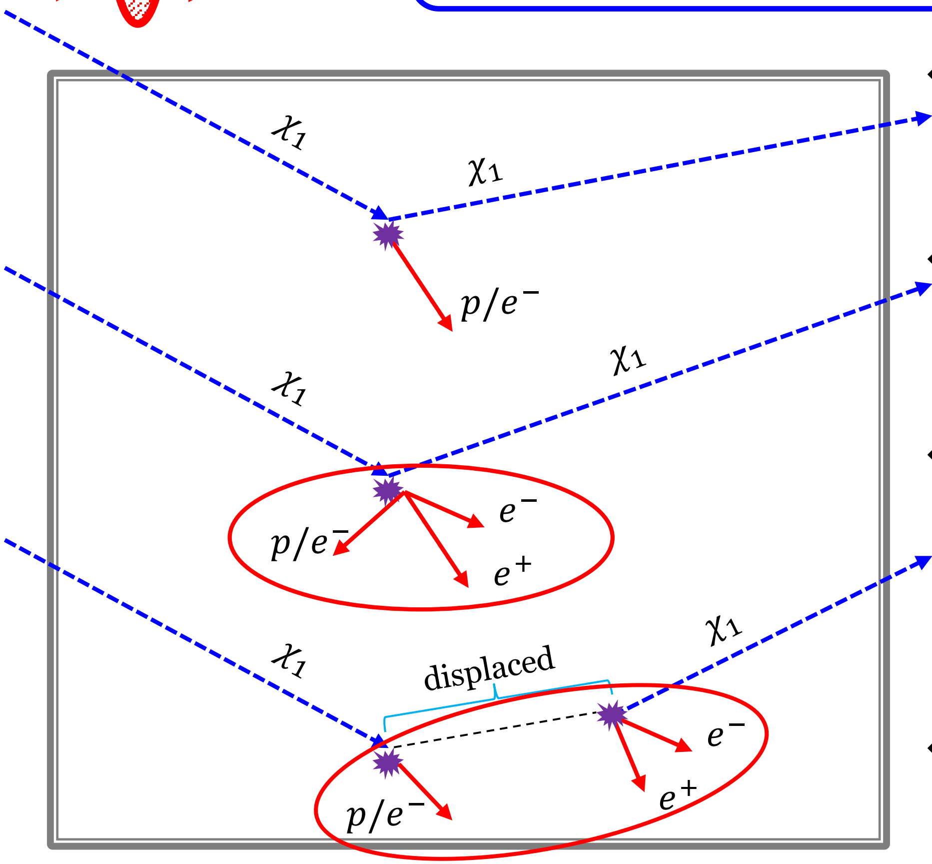
D. Kim, **JCP**, S. Shin, 1612.06867
G. Giudice, D. Kim, **JCP**, S. Shin, 1712.07126

Expected Signatures



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

Secondary signatures: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma, \ldots$



- 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

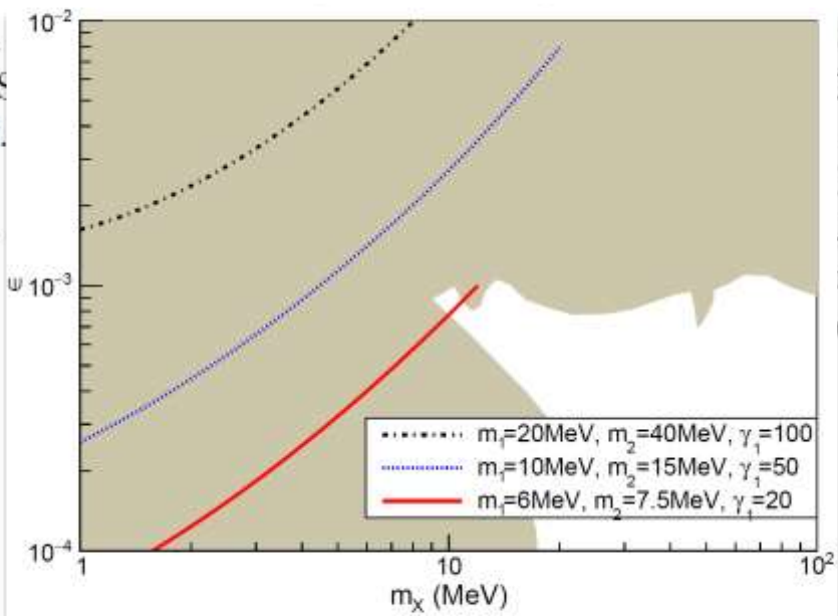
Experimental Efforts

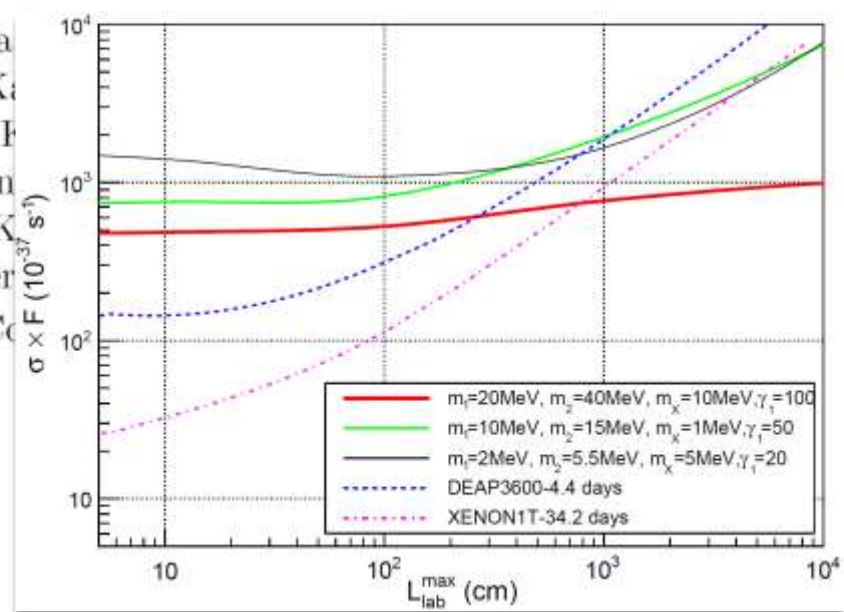
❖ DM direct detection experiments: by pumping up the BDM flux with sub-GeV m_0

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





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]

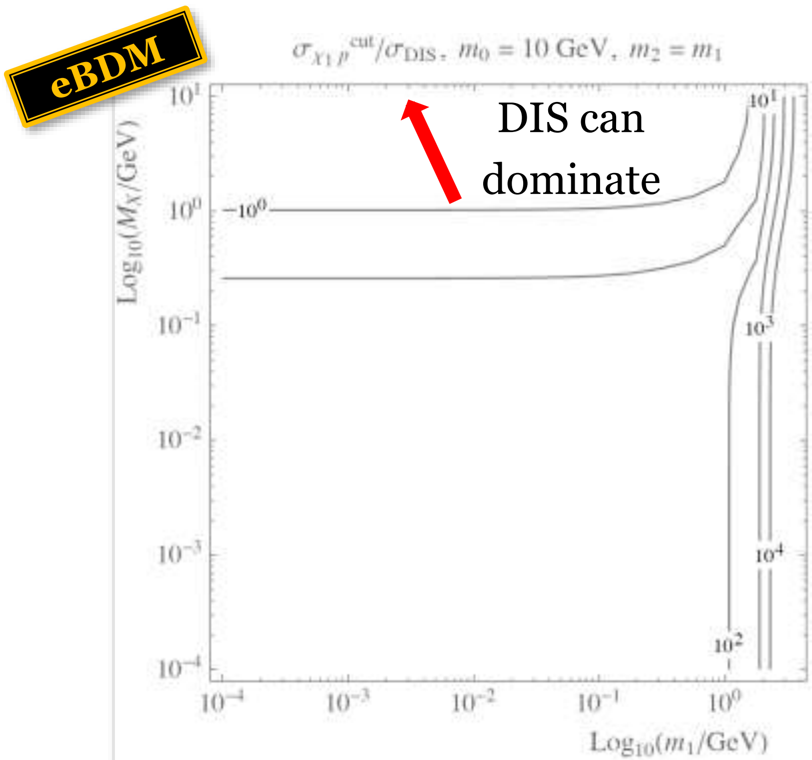
    Discussion with ICARUS for iBDM (Gran Sasso + Future @ SBN)
- ❖ Underground ν experiments
  - ✓ DUNE: dedicated study [D. Kim, **JCP**, S. Shin, work in progress with DUNE experimentalists]

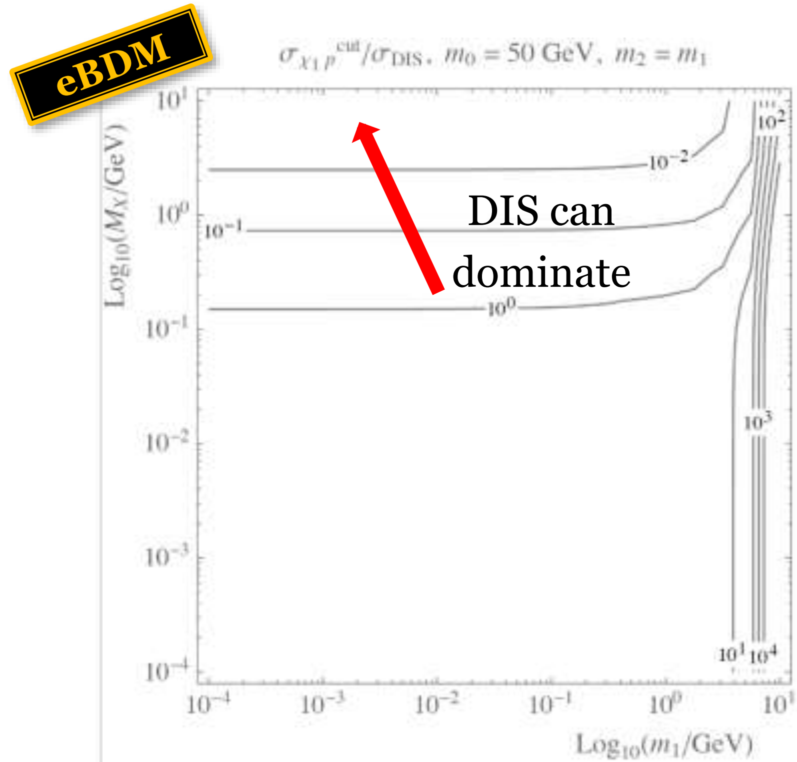
    included in DUNE TDR as new particle searches (BSM physics opportunities)
  - ✓ Summary of possible phenomenology (e vs p vs DIS) in various relevant experiments such as DarkSide-20k, DUNE, Hyper-K, IceCube, … [Kim, Machado, **JCP**, Shin, 1812.xxxxx]

Signals @ DUNE: p vs DIS

P. Machado, D. Kim, **JCP** & S. Shin [1812.xxxxx]

- ❖ (quasi-elastic) p-scattering vs DIS



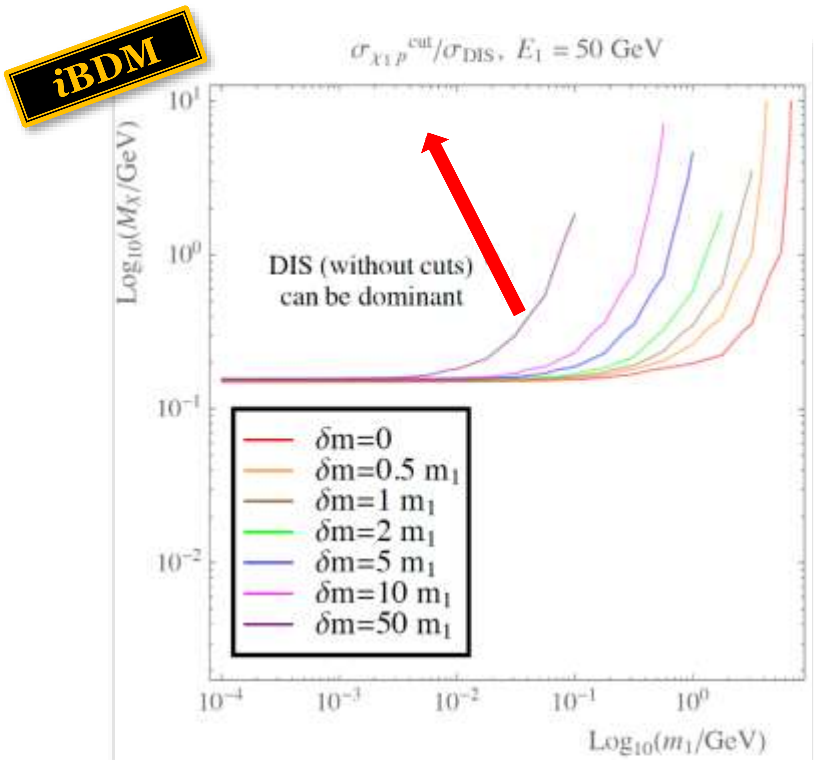


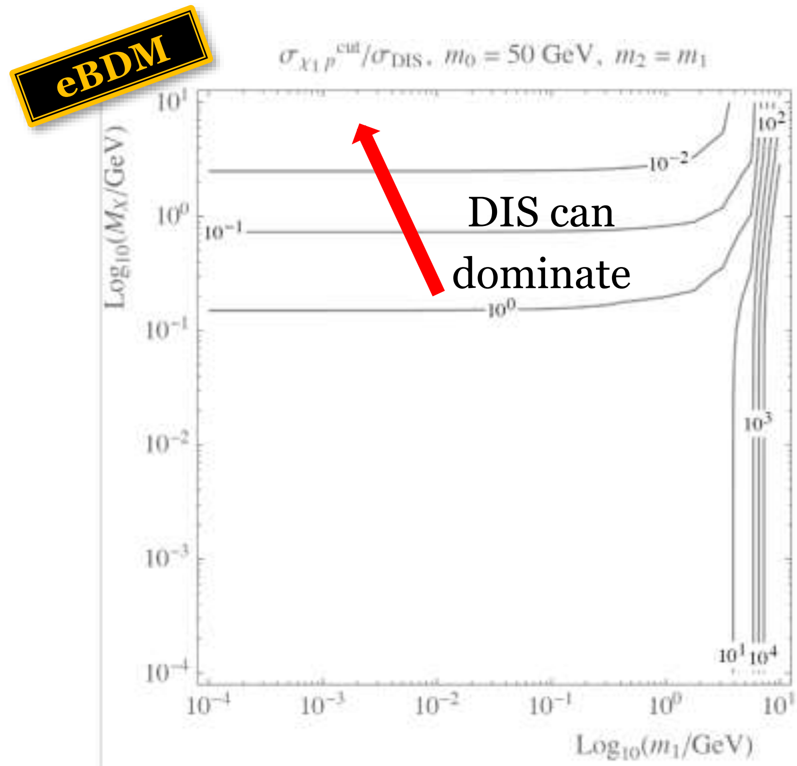
- ✓ Penalty on p-scattering $E_{\mathrm{th}} > 21$ MeV [ArgoNeuT, 1405.4261]: $\sigma^{cut}_{\chi 1\, p}$
- ✓ But, no cuts on DIS
- ✓ p-scattering still dominates for $m_X < 1$ GeV

Signals @ DUNE: p vs DIS

P. Machado, D. Kim, **JCP** & S. Shin [1812.xxxxx]

❖ (quasi-elastic) p-scattering vs DIS





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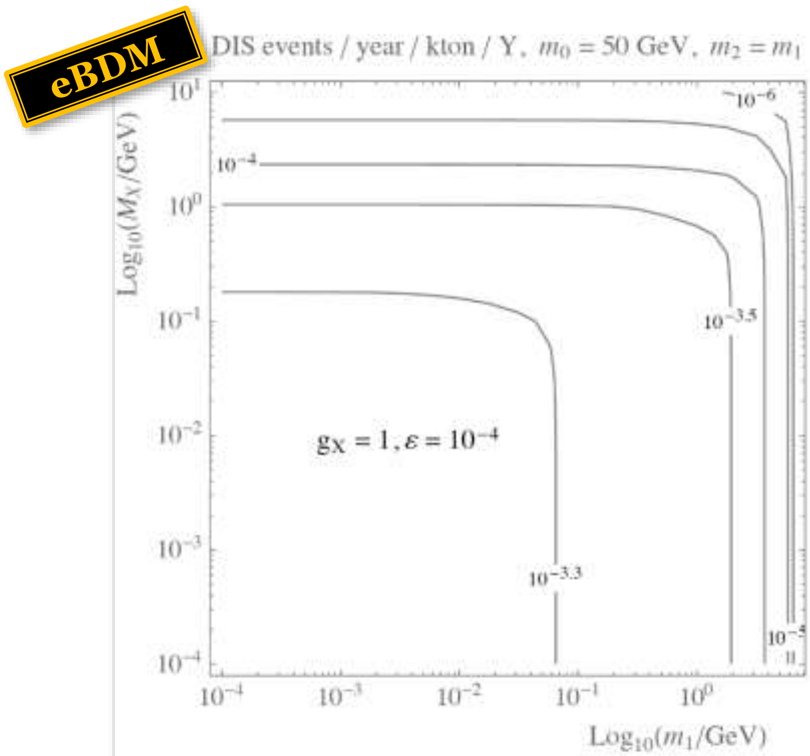
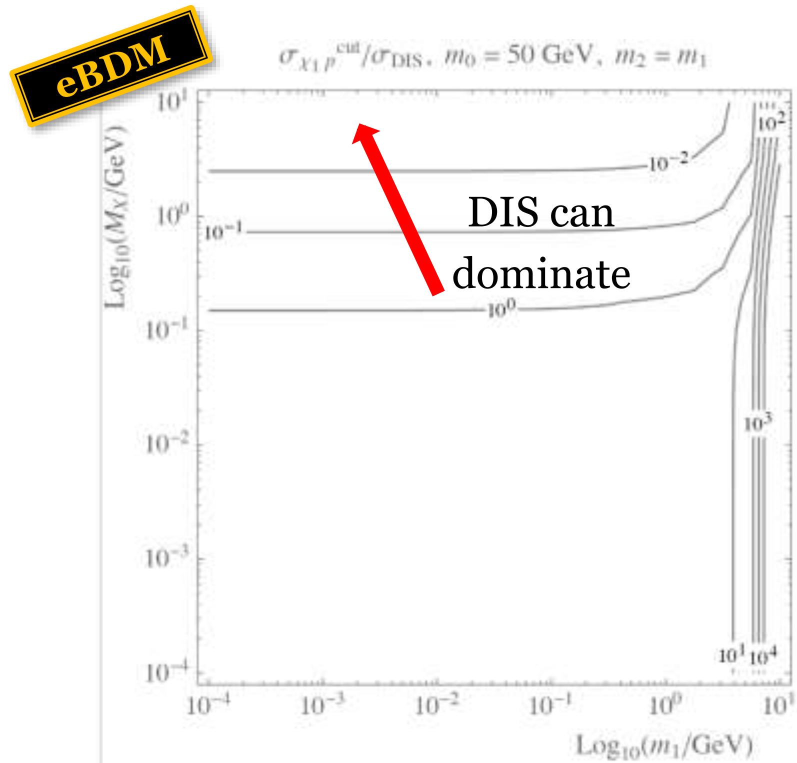




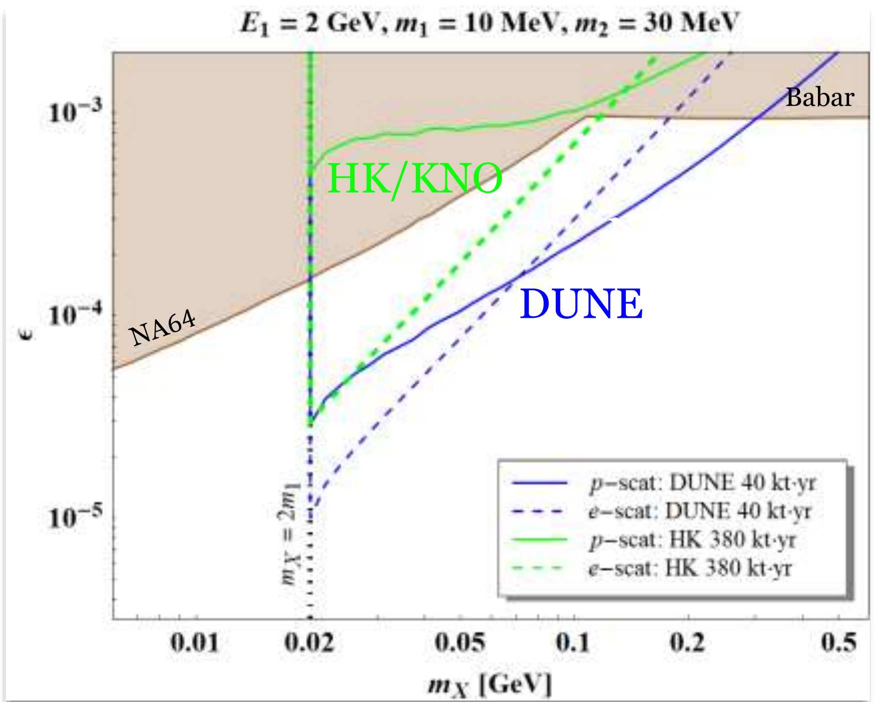
✓ Number of DIS induced events (Y=atomic number/atomic weight)

✓ 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 [1812.xxxxx]

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



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

Experimental reach for 1-year of running

DUNE - cuts

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

ii) $\Delta\theta_{e-i} > 1°$, $\Delta\theta_{p-i} > 5°$ 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,

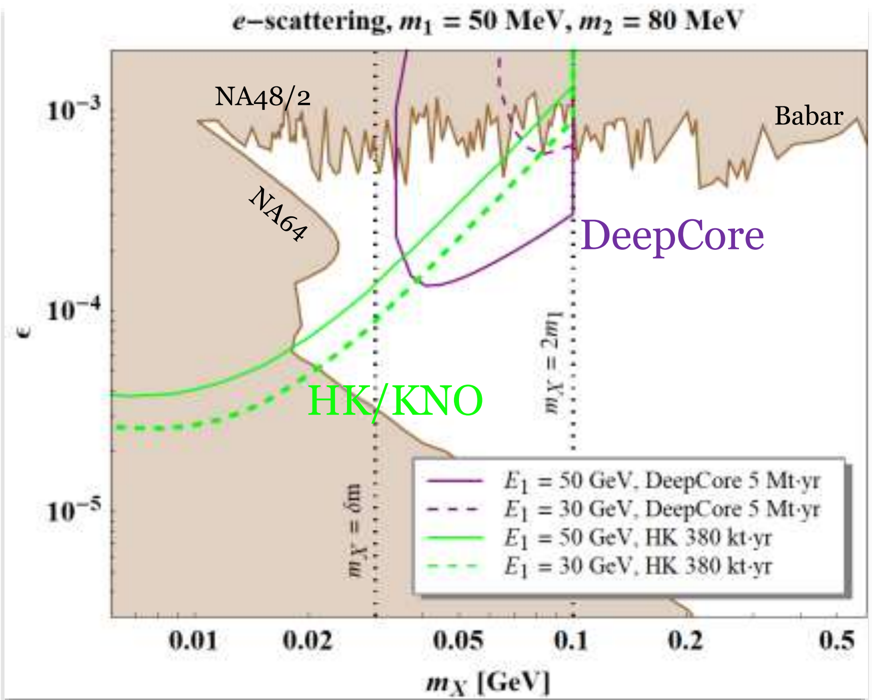
ii) $\Delta\theta_{e-i} > 3°$ ($\Delta\theta_{e-i} > 1.2°$) for $p_e < 1.33$ GeV ($p_e > 1.33$ GeV) and $\Delta\theta_{p-i} > 3°$ for all p_p with i running over the other visible final state particles, and

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 [1812.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 ($\delta m < m_X < 2m_1$).



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

Experimental reach for 1-year of running

DeepCore - cuts

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

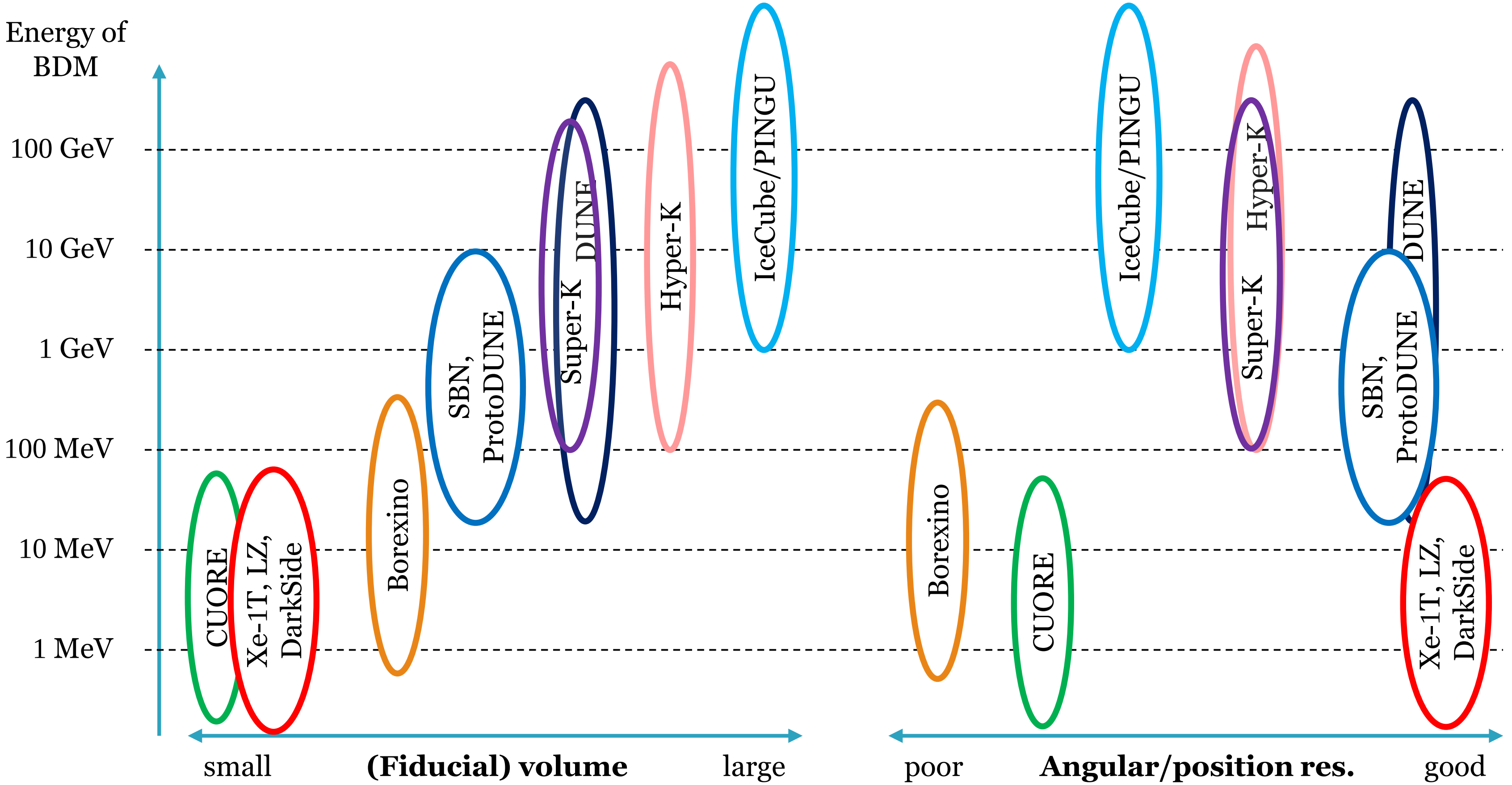
i) $p_e > 100$ MeV, 1.07 GeV $< p_p < 2$ GeV,

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 [1812.xxxxx]



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

Conclusion

- Neutrino experiments can indirectly search for DM by detecting ν's from DM.
- BDM (relativistic DM) 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)

Thank you