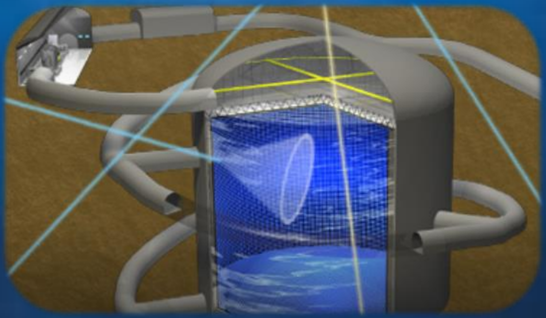
DM Search @ Neutrino Detectors



Jong-Chul Park

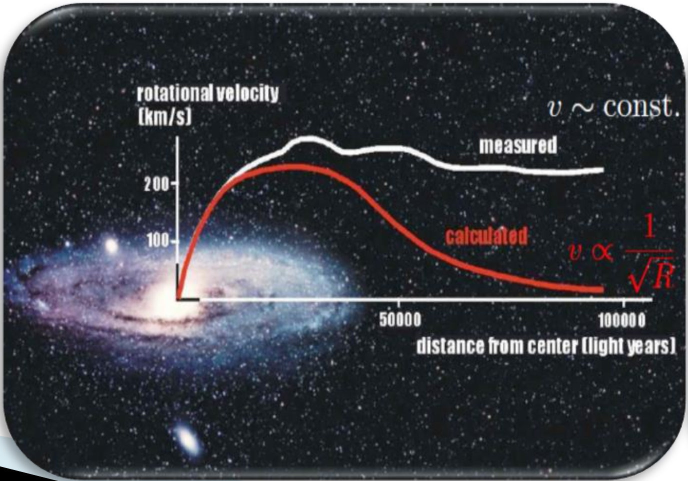
CHUNGNAM NATIONAL UNIVERSITY

2018.11.02

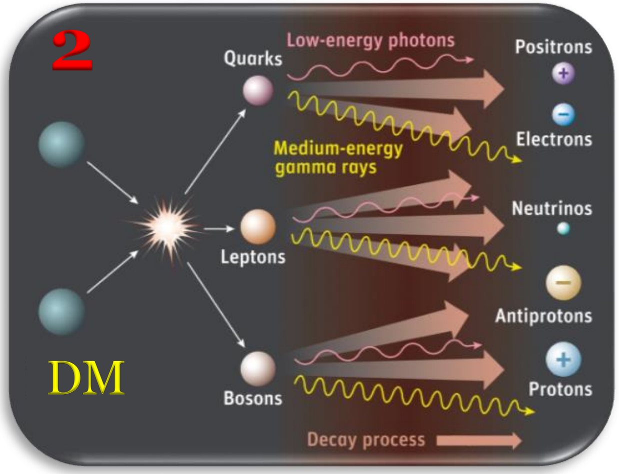
3rd KNO Workshop

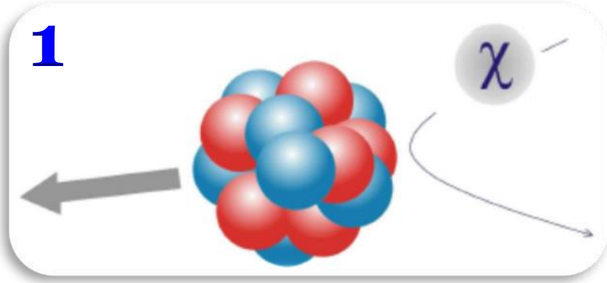
Dark Matter (DM)

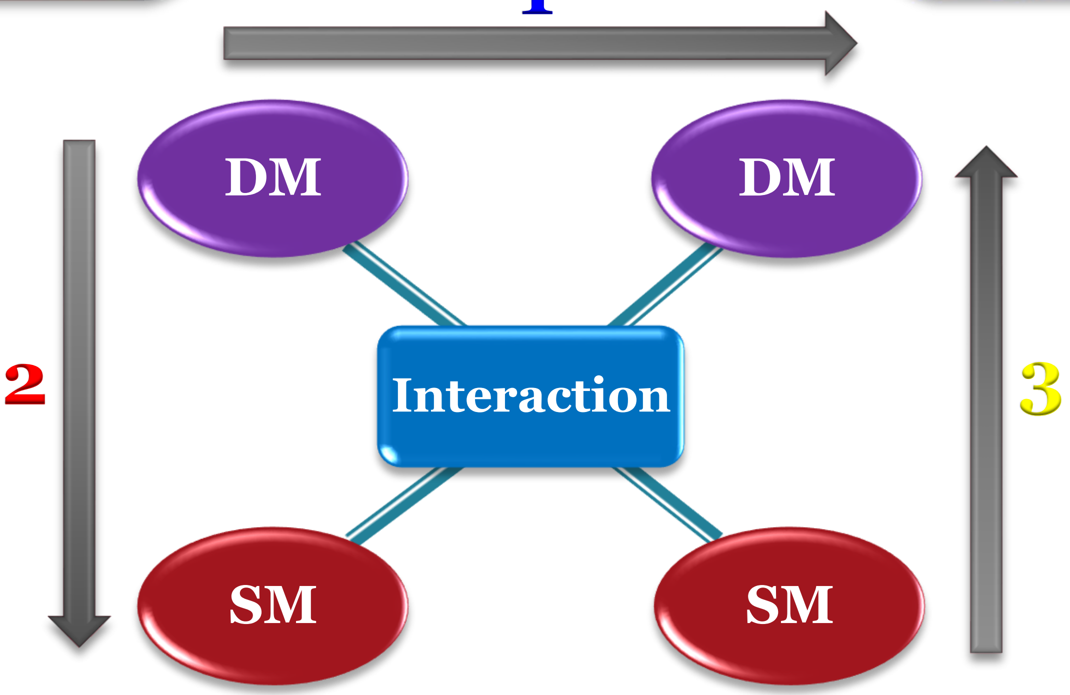
- **DM**: ~25% of our Universe
- **Compelling paradigm**:
  massive, non-luminous & stable particles
- **Evidence**
  - ✓ Galaxy rotation curve
  - ✓ Bullet cluster
  - ✓ Gravitational lensing
  - ✓ Structure formation
  - ✓ CMB
  - ✓ Coma Cluster
  - ✓ Sky surveys
  - ✓ …



DM Search Strategies







1

DM

DM

2

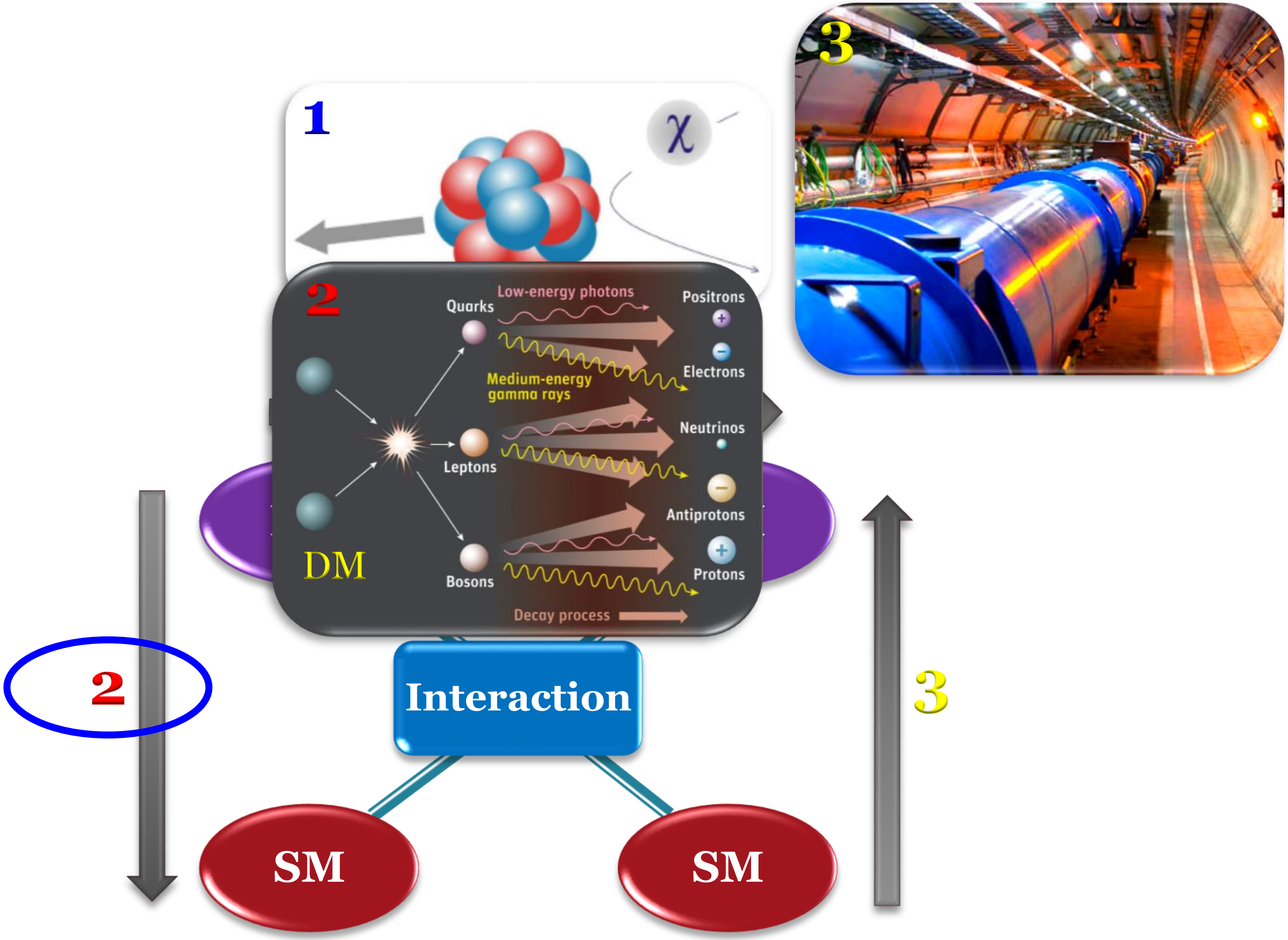
Interaction

3

SM

SM

DM Indirect Detection



2

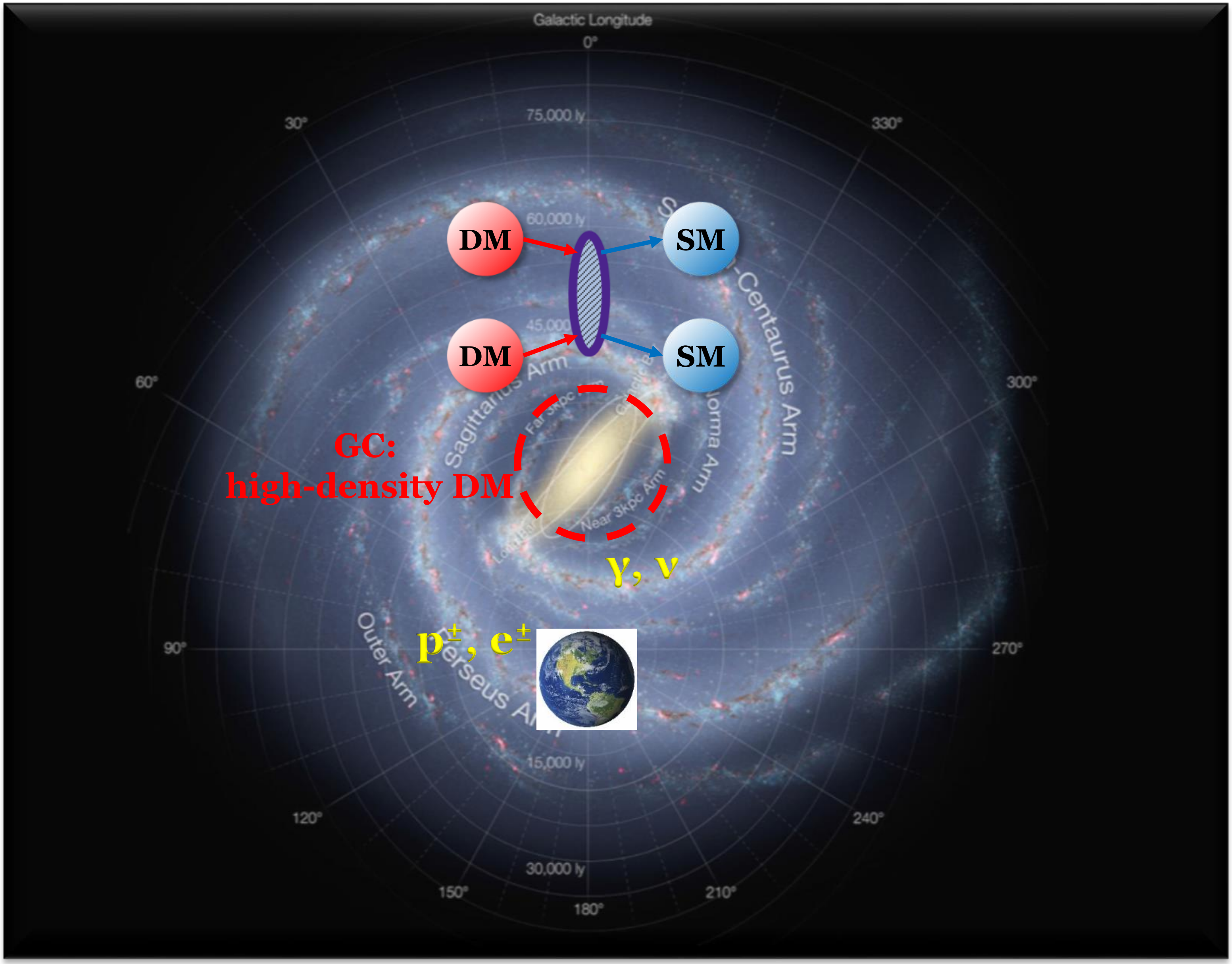
Interaction

SM

SM

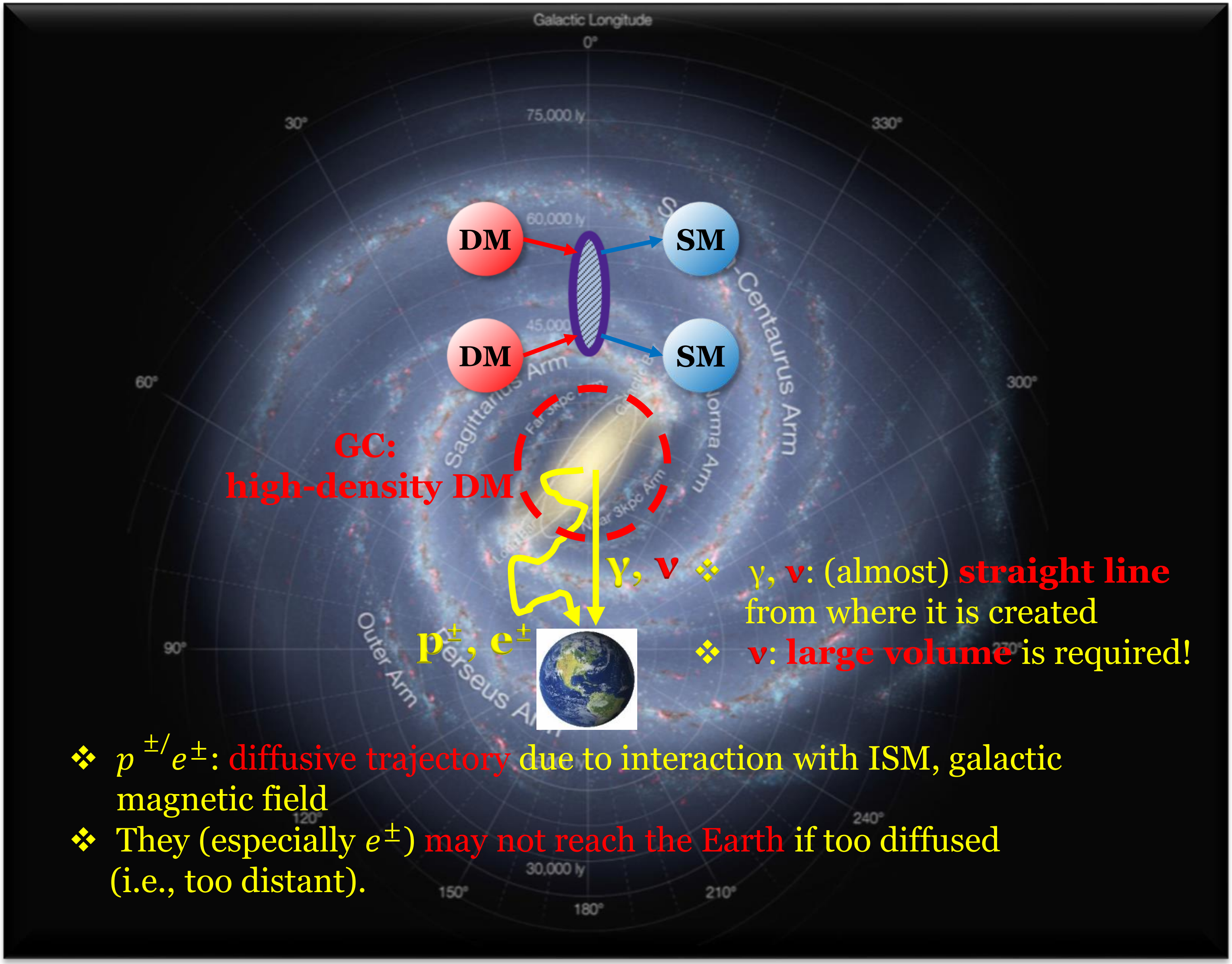
3

Indirect Detection: Cosmic-Rays



GC:
high-density DM

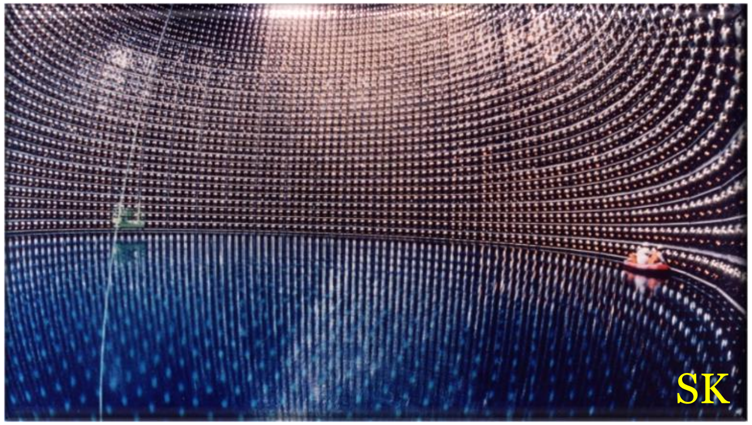
Indirect Detection: Cosmic-Rays



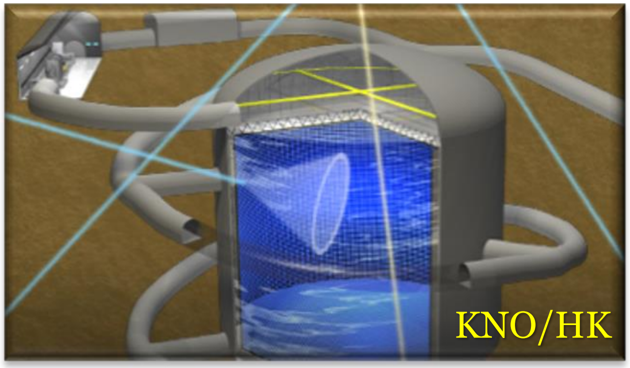
- γ, ν: (almost) **straight line** from where it is created
- ν: **large volume** is required!

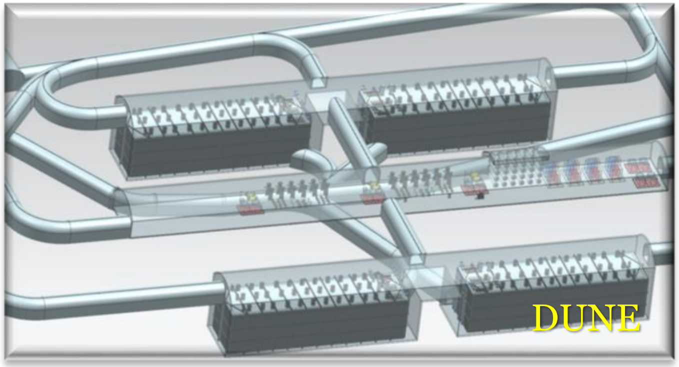
- $p^{\pm}/e^{\pm}$: diffusive trajectory due to interaction with ISM, galactic magnetic field
- They (especially $e^{\pm}$) may not reach the Earth if too diffused (i.e., too distant).

Large Volume Neutrino Experiments


SK


IceCube


KNO/HK

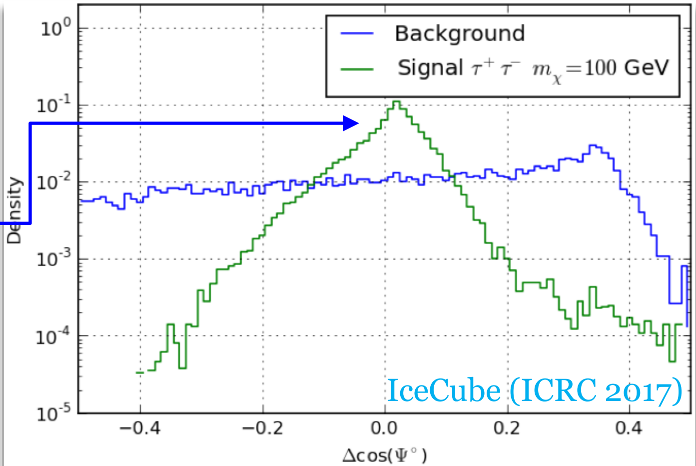

DUNE

- ✓ Great sensitivity to neutrino signals
- ✓ Better chance to have the information for extracting DM properties

ν Signals from DM Annihilation

- The expected ν flux from DM annihilation

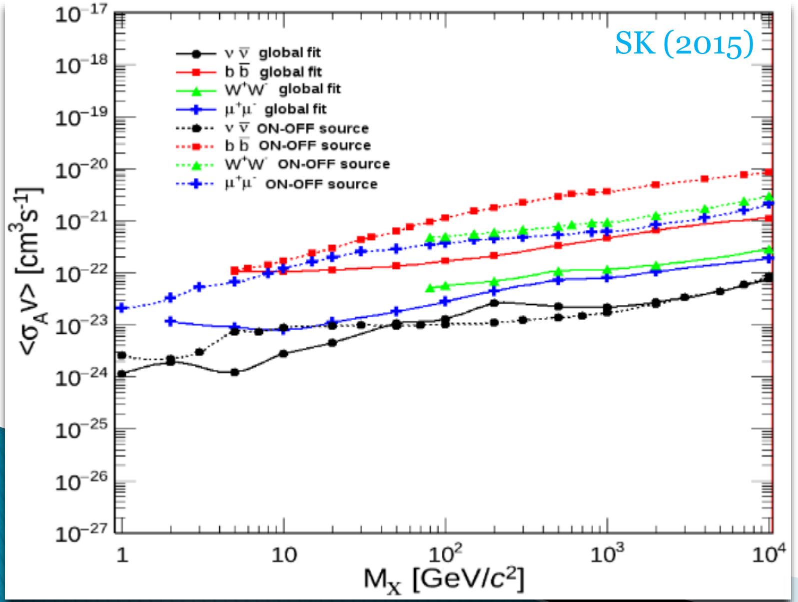
$$\frac{d\phi_\nu}{dE} = \frac{\langle\sigma_A v\rangle}{2}\,\frac{1}{4\pi m_\chi^2}\,\boxed{J_a(\psi)}\,\frac{dN_\nu}{dE}$$



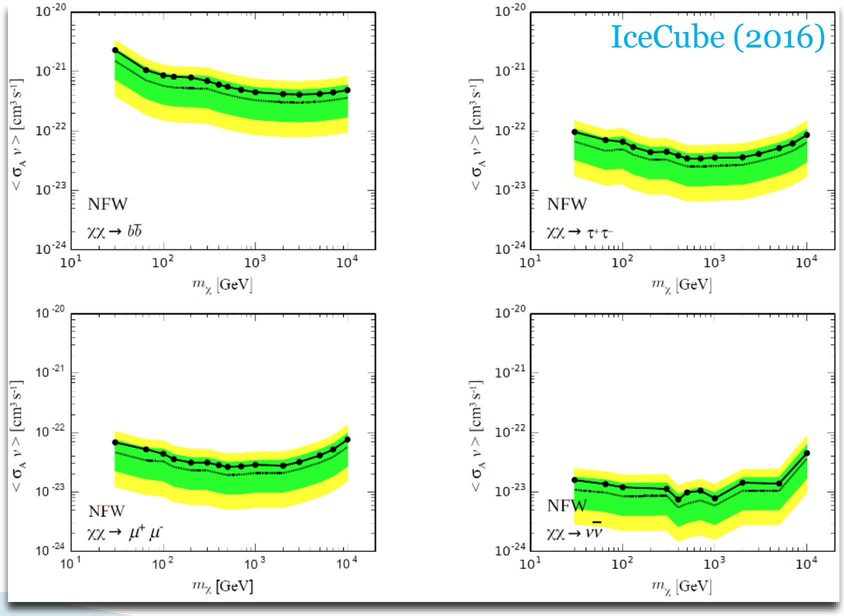
IceCube (ICRC 2017)

- 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 $<\sigma_A v>$



SK (2015)



IceCube (2016)

DM Signals from the Sun

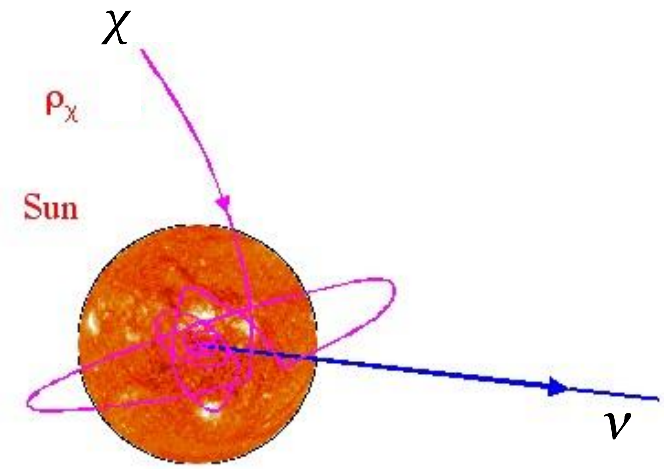
- DM χ can be captured by DM-nuclei/DM-DM scattering in the Sun
  - ➔ The Sun becomes a point-like source of DM signal.

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

- Time evolution of DM number in the Sun

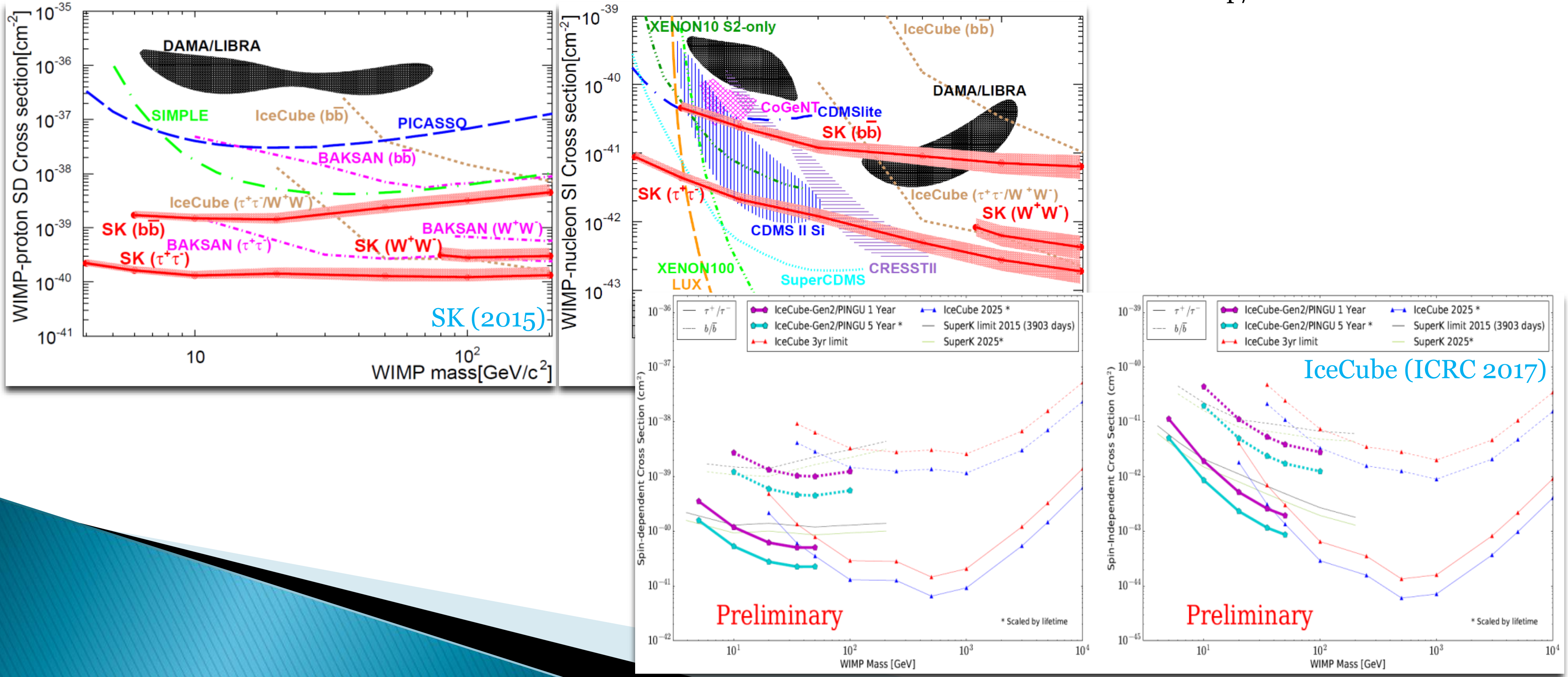
$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2$$

- ✓ **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

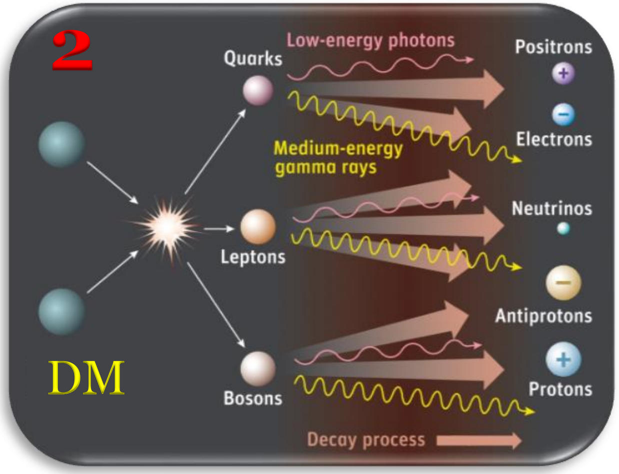


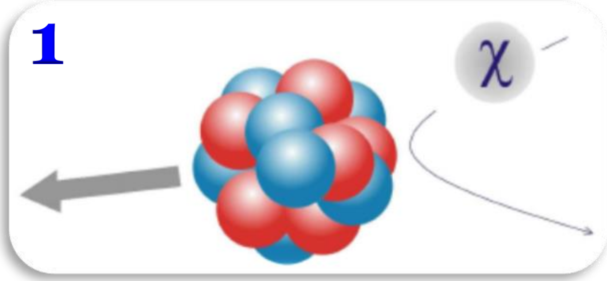
ν Signals from the Sun

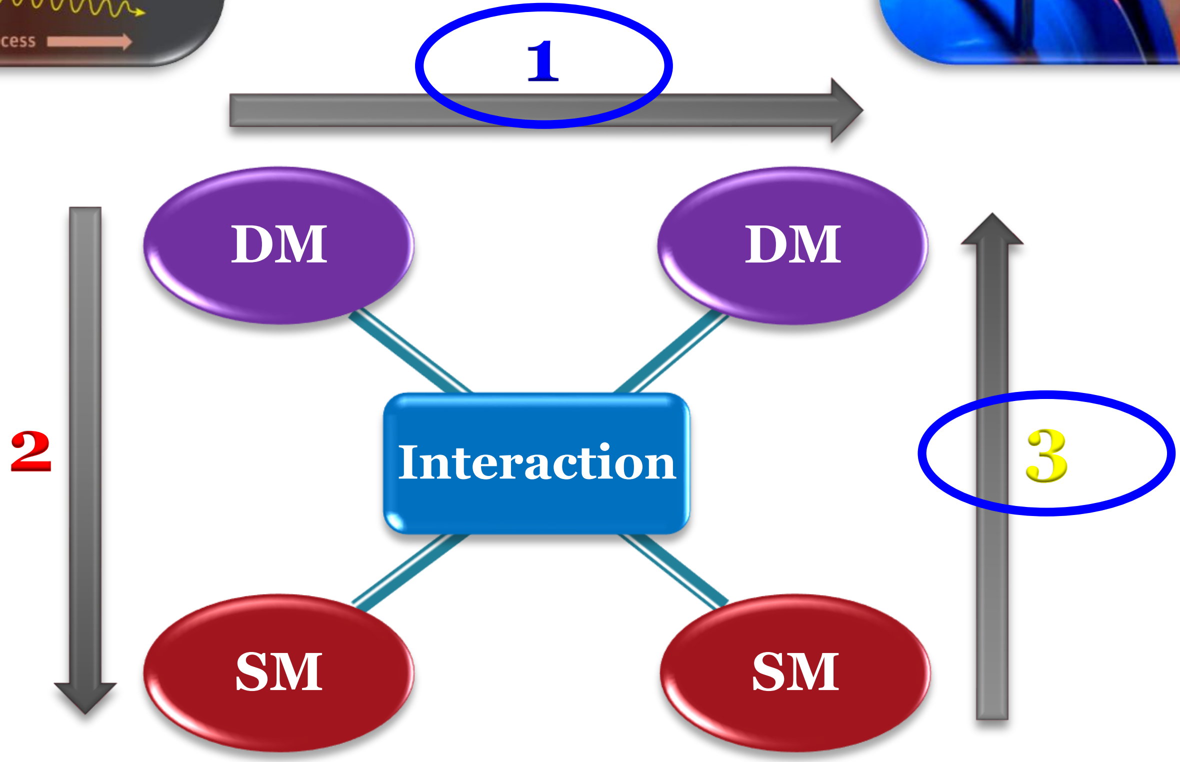
- The Sun can be a good source of ν flux from DM annihilation due to the solar capture & relatively short distance compared to the GC.
- Search for an excess of ν's from the Sun direction compared to the expected atmospheric ν BG: So far, no excess of ν's ➔ upper limit on $\sigma_{\text{DM-p/n}}$



DM Direct Detection & Production



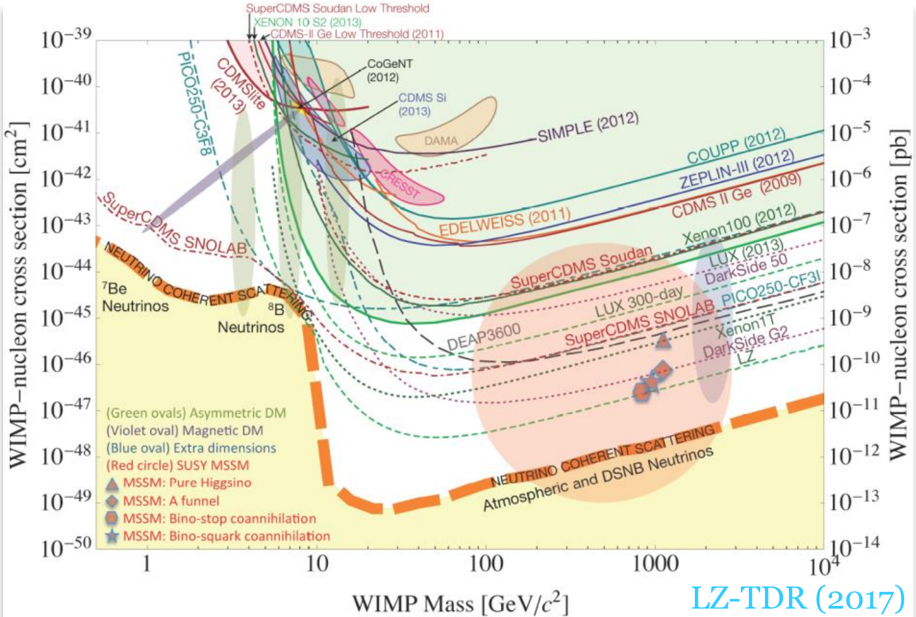




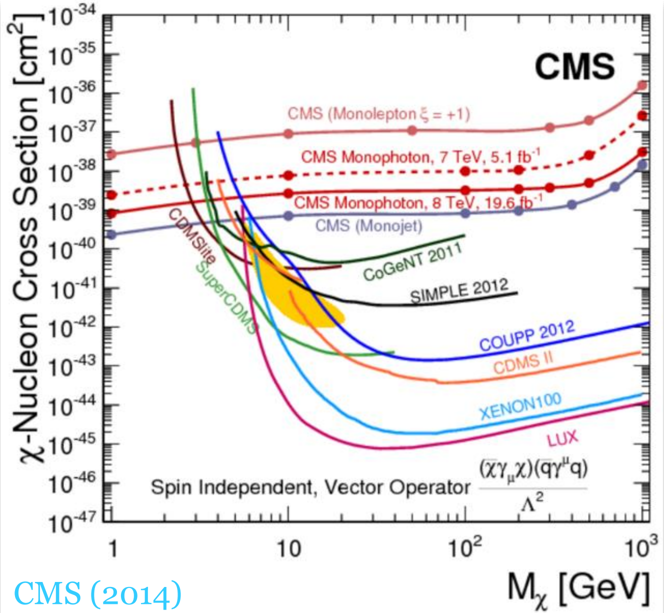
Current Status of DM Searches

❖ 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



LZ-TDR (2017)



CMS (2014)

Time to change our approach?!

Conventional vs Nonconventional

❖ Traditional approaches for DM searches:

  - ✓ Weak-scale mass
  - ✓ Weakly-coupled
  - ✓ Minimal dark sector
  - ✓ Elastic scattering
  - ✓ Non-relativistic

Conventional vs Nonconventional

❖ Traditional approaches for DM searches:

- ✓ ~~Weak-scale mass~~
- ✓ ~~Weakly coupled~~
- ✓ ~~Minimal dark~~ sector
- ✓ ~~Elastic scattering~~
- ✓ ~~Non-relativistic~~

❖ Modified approaches for DM searches:

- ✓ Other mass scale: e.g. PeV, sub-GeV, MeV, keV, meV, …
- ✓ Various couplings to the SM: e.g. vector portal (dark photon), scalar portal, axion portal, …
- ✓ “Flavorful” dark sector: e.g. more DM species, unstable heavier dark-sector states, …
- ✓ Inelastic scattering
- ✓ Relativistic

Conventional vs Nonconventional

❖ Traditional approaches for DM searches:

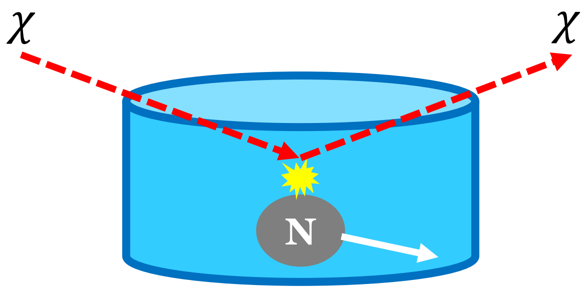
- ✓ ~~Weak-scale mass~~
- ✓ ~~Weakly coupled~~
- ✓ ~~Minimal dark sector~~
- ✓ ~~Elastic scattering~~
- ✓ ~~Non-relativistic~~

❖ Modified approaches for DM searches:

- ✓ Other mass scale: e.g. PeV, sub-GeV, MeV, keV, meV, …
- ✓ Various couplings to the SM: e.g. vector portal (dark photon), scalar portal, axion portal, …
- ✓ “Flavorful” dark sector: e.g. more DM species, unstable heavier dark-sector states, …
- ✓ Inelastic scattering
- ✓ Relativistic

Typical DM Direct Searches

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



[Goodman, Witten (1985)]

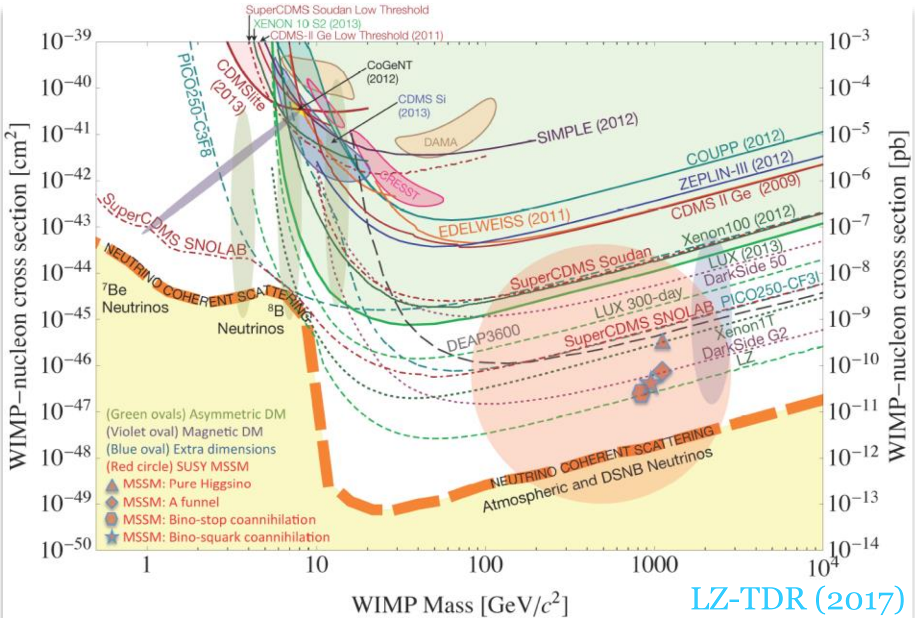
- ✓ Elastic scattering of
- ✓ Non-relativistic
- ✓ Weak-scale DM
- ✓ with nuclei

✓ $E_{\text{recoil}} \sim mv^2$

$\sim 1 - 100$ keV

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

✓ Detectors designed to be sensitive to this E range

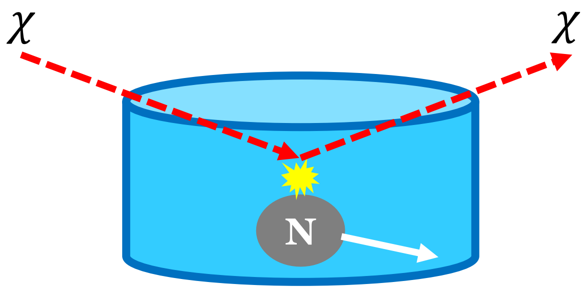


LZ-TDR (2017)

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

Typical DM Direct Searches

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



[Goodman, Witten (1985)]

(in)Elastic scattering of

✓ ~~Non~~-relativistic

Other

✓ ~~Weak~~-scale DM

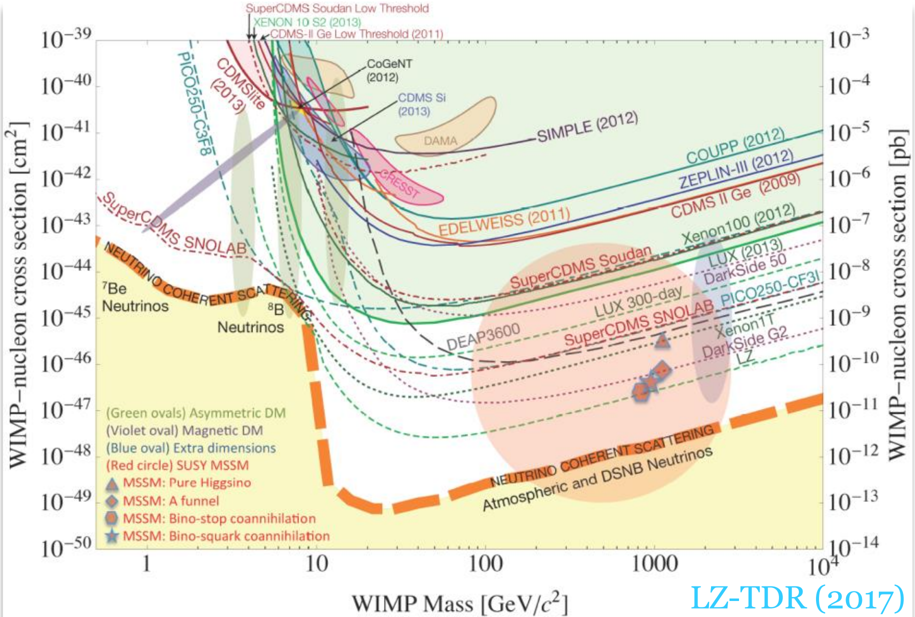
✓ with nuclei or electron

✓ $E_{\text{recoil}} \sim mv^2$

$\sim 1 - 100$ 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!

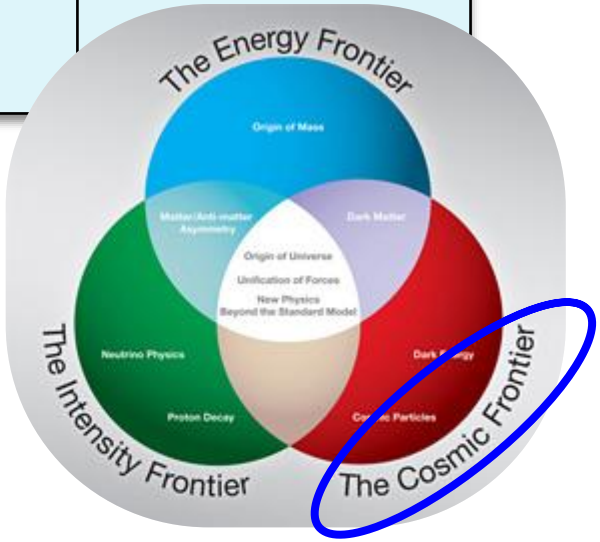
DM Search Schemes (Scattering)

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

Very well-studied

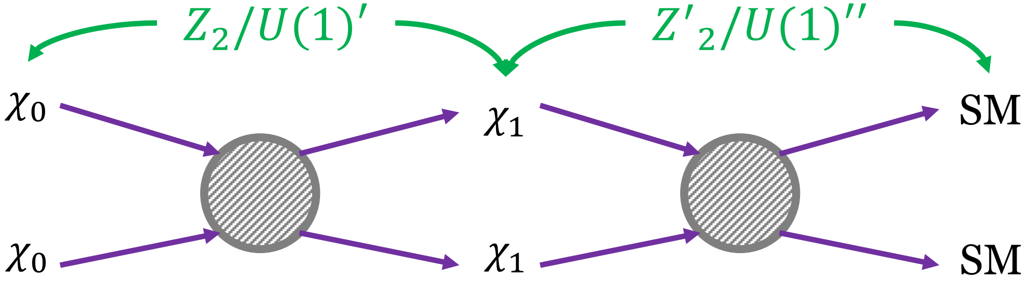
DM Search Schemes (Scattering)

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



Two-component BDM Scenario

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



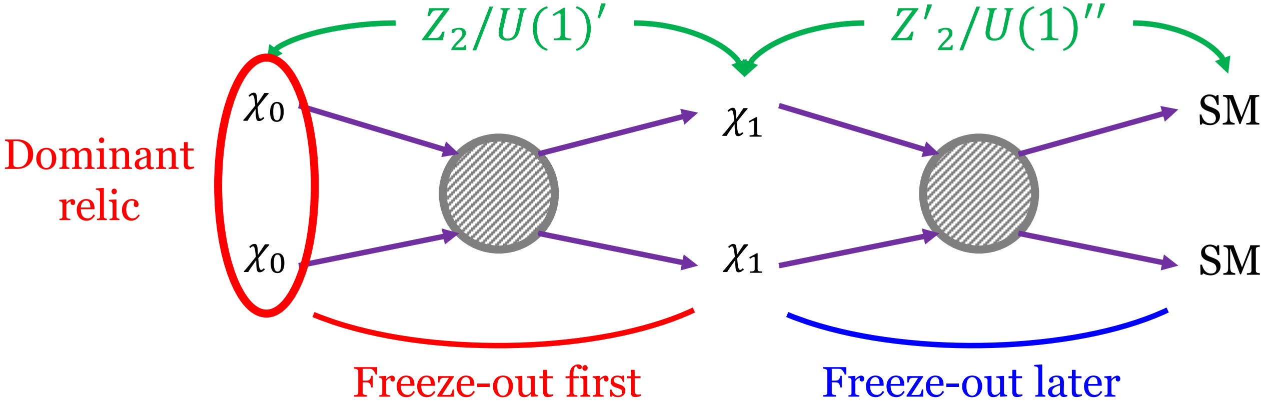
$Z_2/U(1)'$ $Z'_2/U(1)''$

χ_0 χ_1 SM

χ_0 χ_1 SM

Two-component BDM Scenario

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



$Z_2/U(1)'$

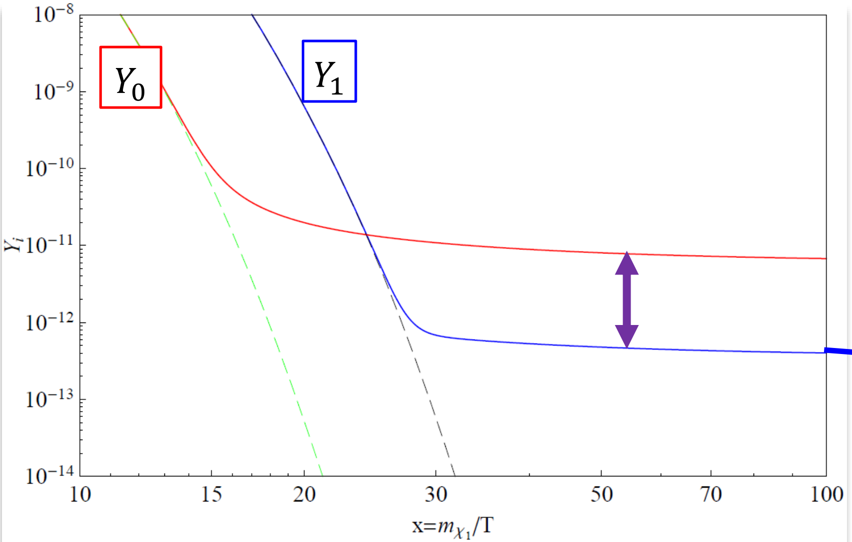
$Z'_2/U(1)''$

Dominant relic

χ_0 χ_0 → χ_1 χ_1 → SM SM

Freeze-out first

Freeze-out later



"**Assisted Freeze-out**" Mechanism

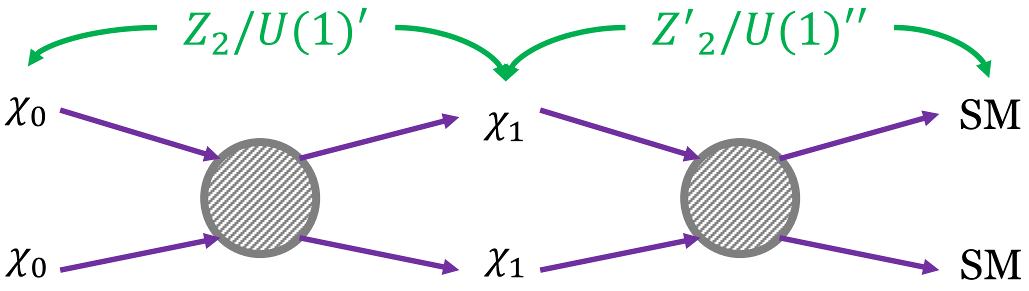
✓ Heavier relic χ_0: hard to detect it due to tiny coupling to SM

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

χ_1: Negligible, Non-relativistic relic

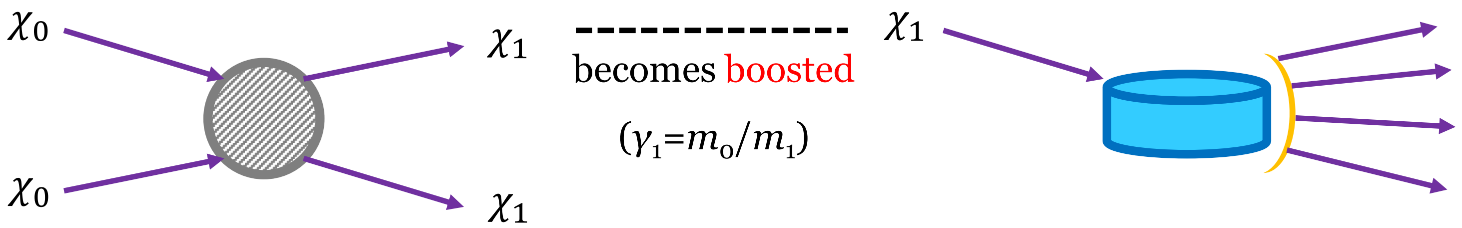
Two-component BDM Scenario

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



$\chi_0\chi_0 \rightarrow \chi_1\chi_1$ (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, $n_0 = \rho_0 / m_0$

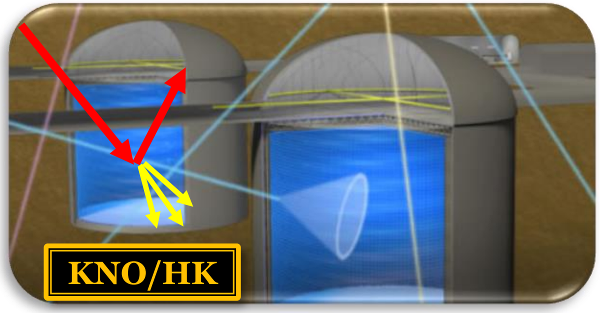
- Setting $\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1} \sim 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}$ and assuming the NFW DM halo profile,

  one can obtain $\mathcal{F}_{\chi_1} \sim 10^{-4\sim 8} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ for χ_0 of weak-scale mass, m_0~O(1-100 GeV).

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

  ➔ Large volume (neutrino) detectors motivated:

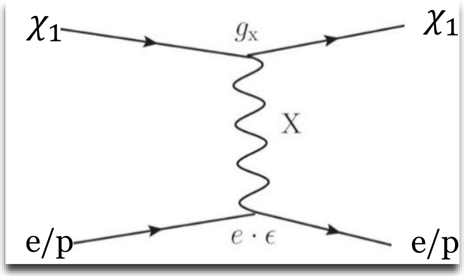
  SK/HK/KNO, DUNE, IceCube, …



Detection of BDM

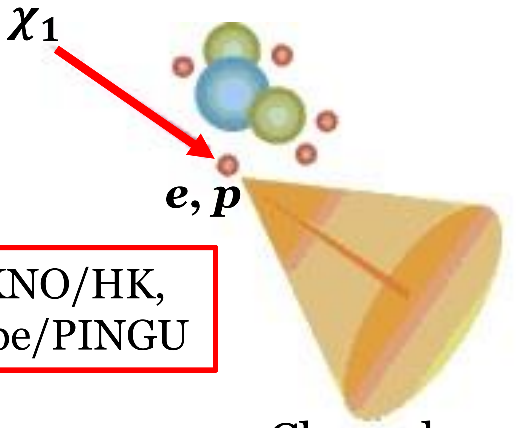
- ❖ Large volume ν detectors are designed to detect energetic charged particles

  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

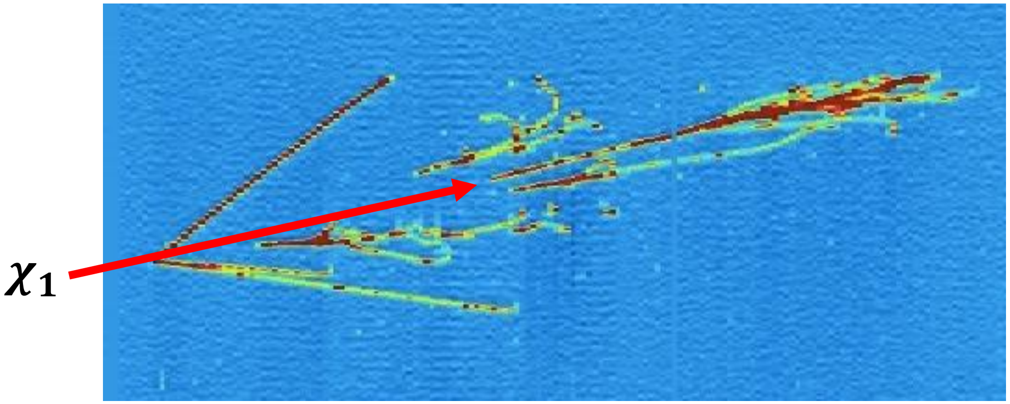


SK, KNO/HK,
IceCube/PINGU

Cherenkov light

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

> 1.5



DUNE: LArTPC

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, $n_0=\rho_0/m_0$

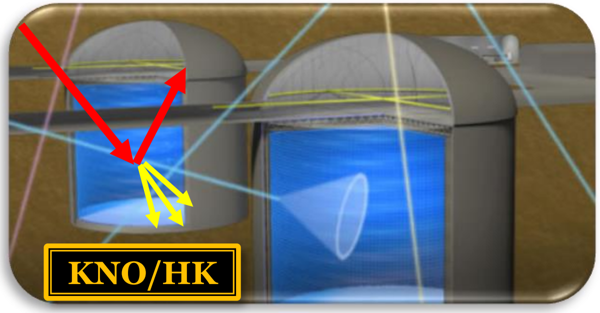
- ❖ Setting $\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}\sim10^{-26}\ \mathrm{cm^3 s^{-1}}$ and assuming the NFW DM halo profile,

  one can obtain $\mathcal{F}_{\chi_1}\sim10^{-4\sim8}\mathrm{cm^{-2}s^{-1}}$ for χ_0 of weak-scale mass, m_0~O(1-100 GeV).

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

  ➔ Large volume (neutrino) detectors motivated:

  SK/HK/KNO, DUNE, IceCube, …



- ❖ 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)

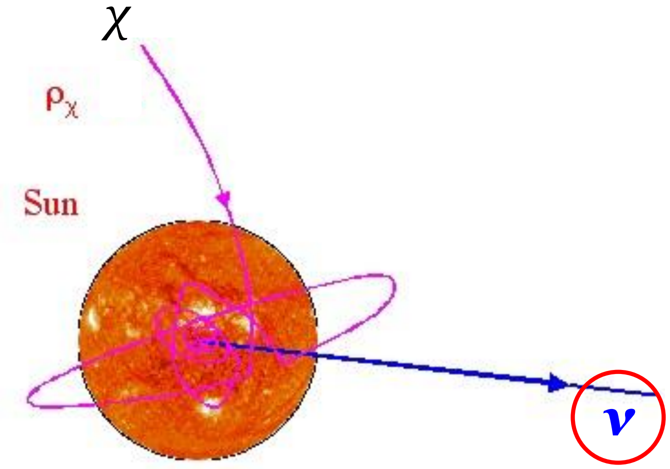
DM Signals from the Sun

- ❖ 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)

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

- ✓ 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



BDM from the Sun

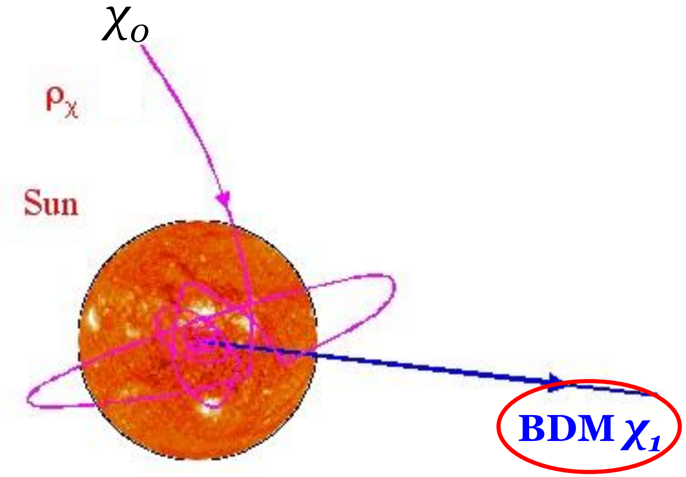
KC Kong, G. Mohlabeng & **JCP** (2014)

- 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)

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

- ✓ **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

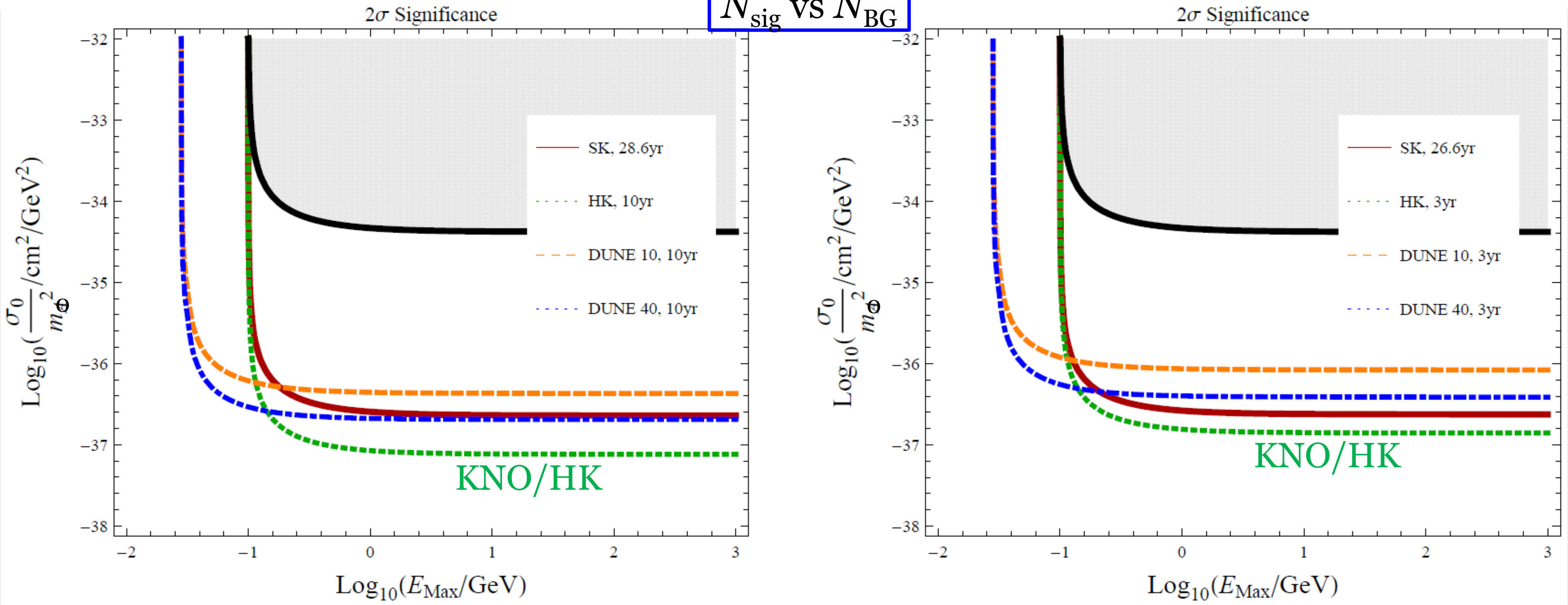


Experimental Reach (GC)

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

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

$N_{\rm sig}$ vs $N_{\rm BG}$



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

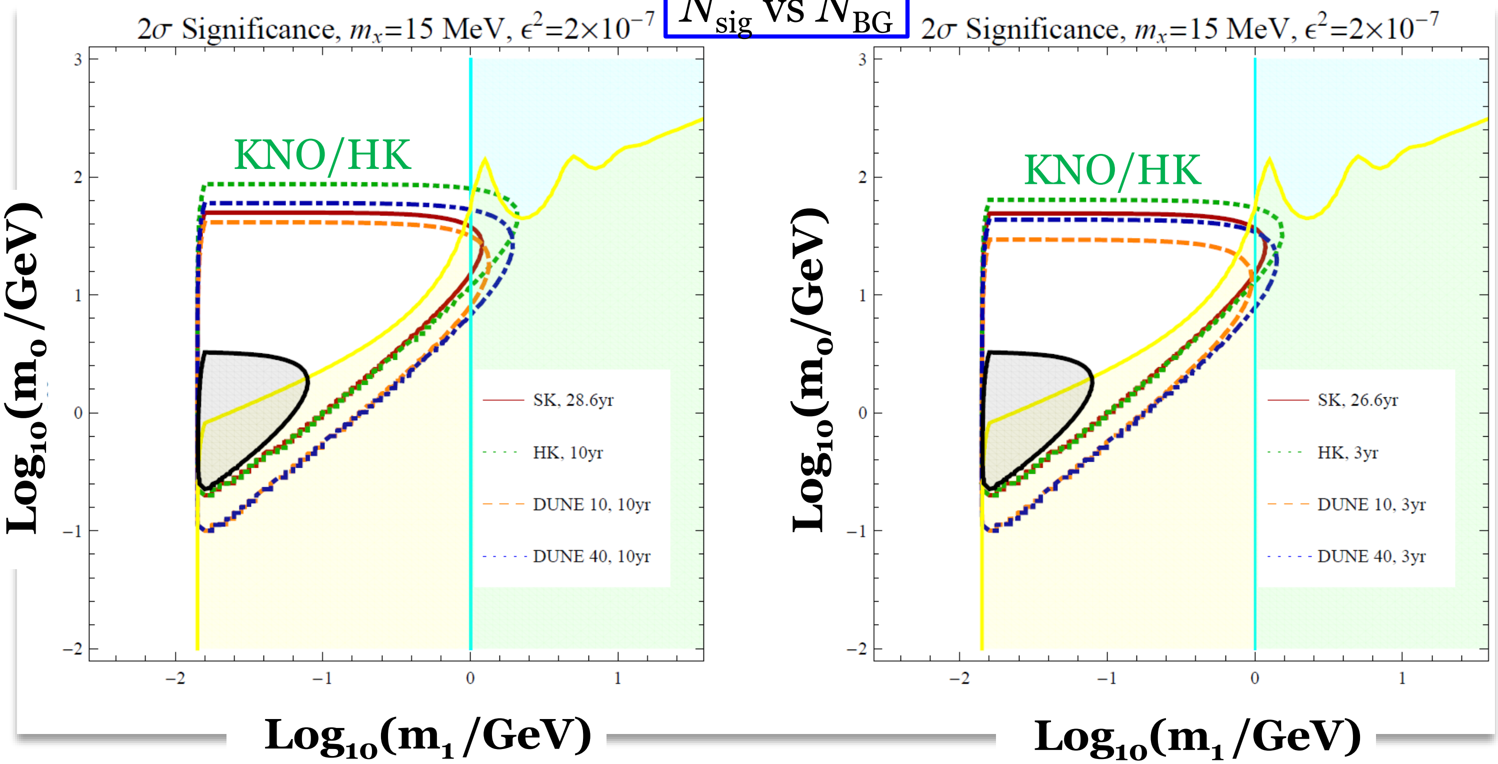
✓ Vertical edge: $E_{\rm Max} > E_{\rm th}$, Horizontal edge: $N_{\rm sig} \sim N_{\rm target} \Delta T$ & $n_{\rm DM} \sim \rho_{\rm DM}/m_{\rm DM}$

Experimental Reach (GC)

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

- Experimental coverage in the mass plane

N_{sig} vs N_{BG}



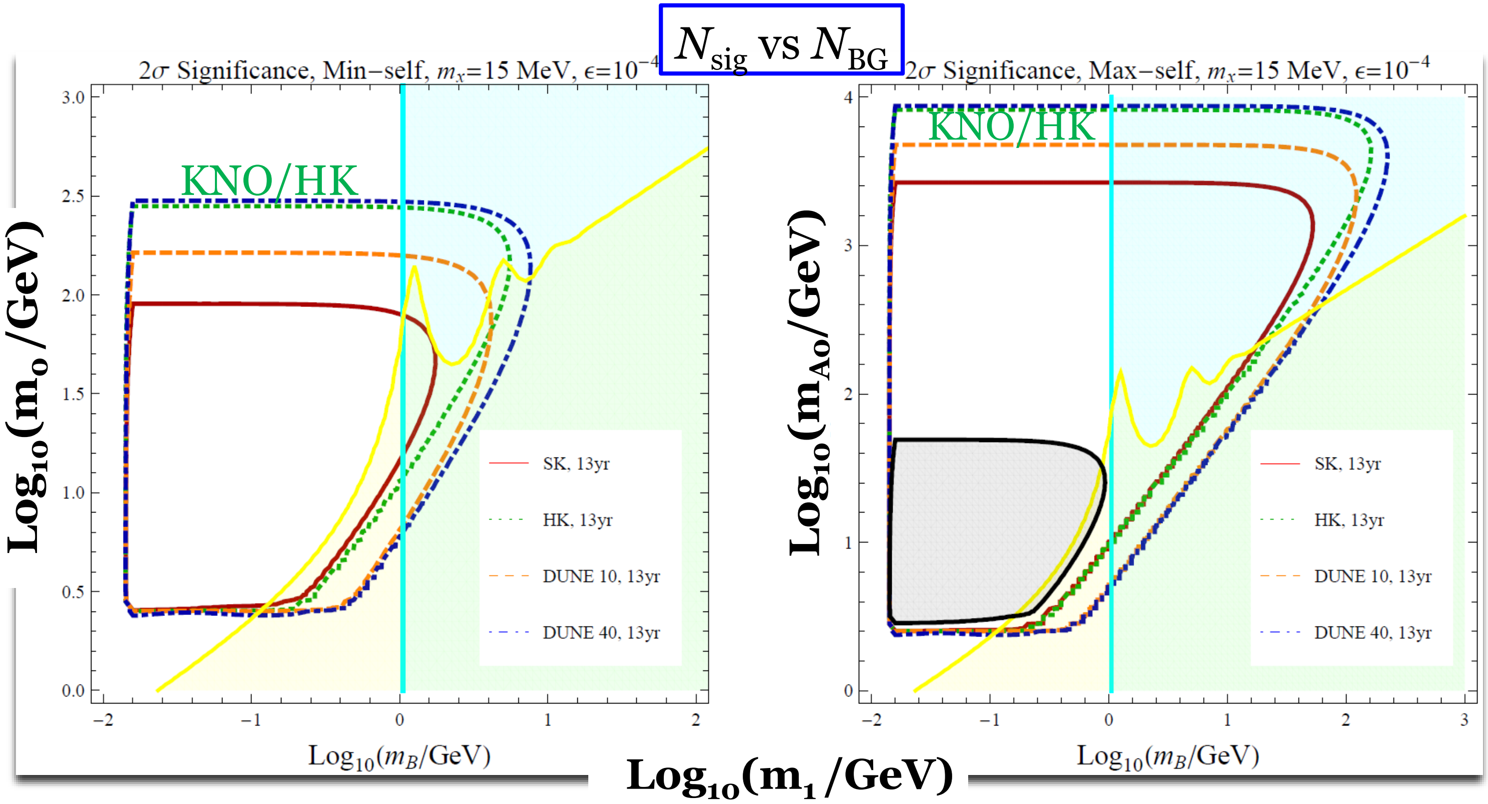
5 year construction + 10 year running vs 10 year construction + 3 year running

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

Experimental Reach (Sun)

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

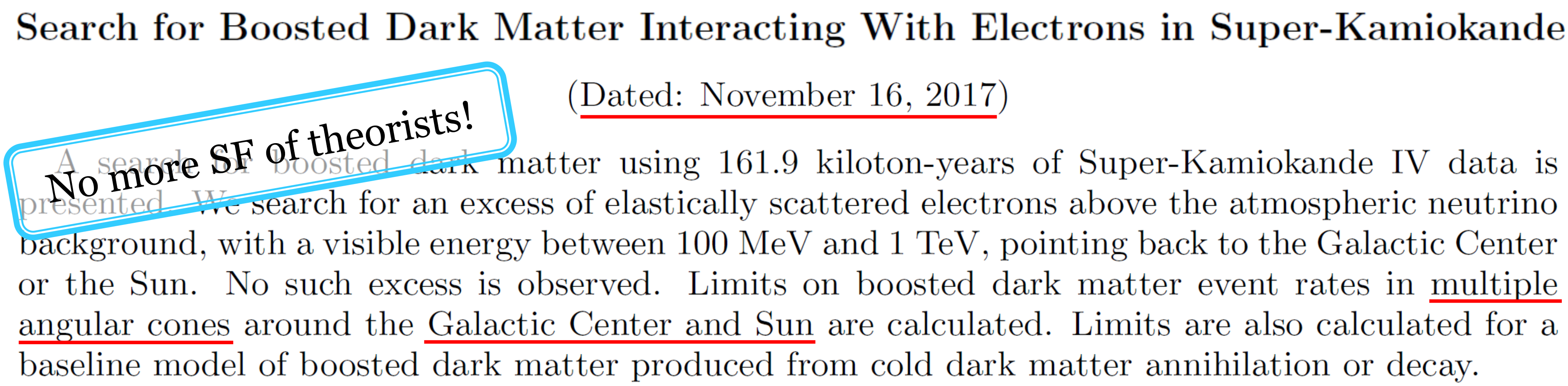
❖ 2σ sensitivities for 13 years of data



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

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

SK Official Results for BDM Search

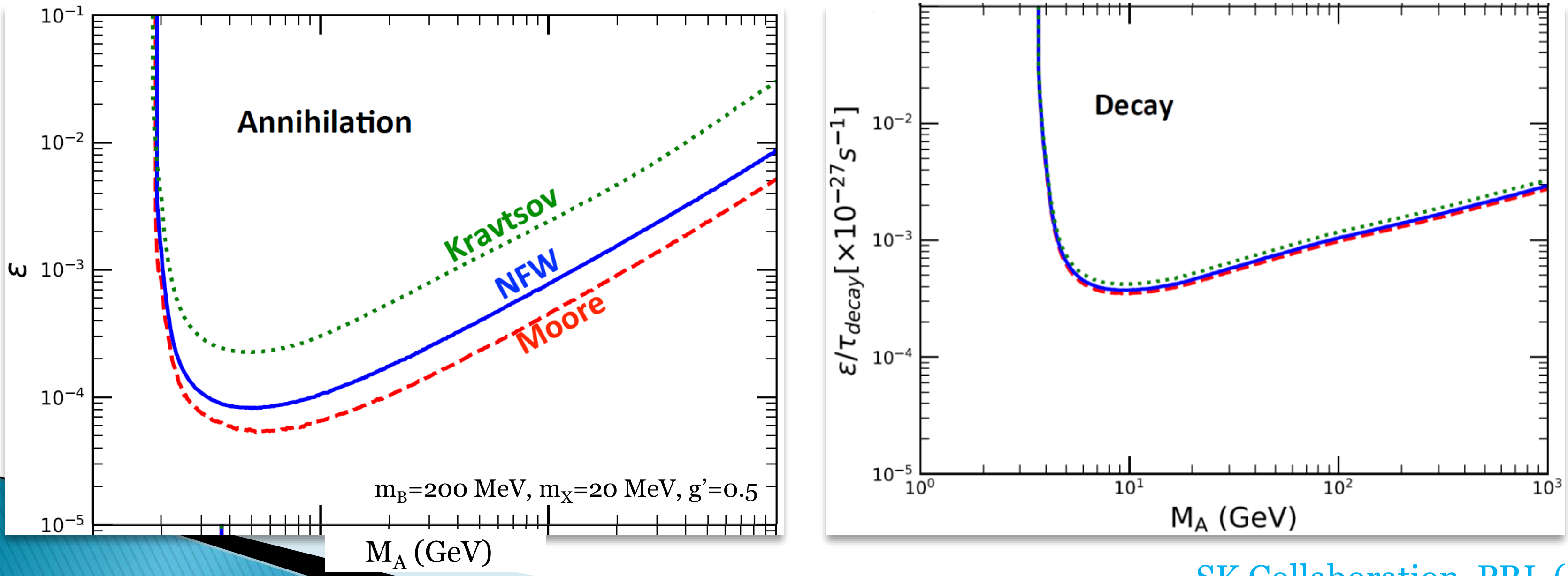


Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande

(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.

No more SF of theorists!



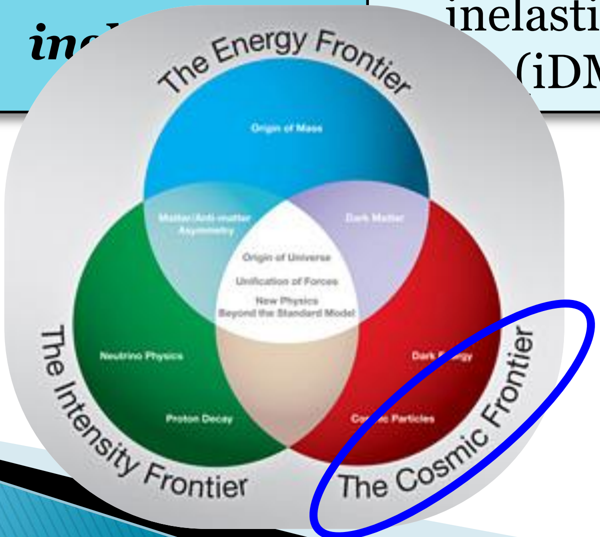
SK Collaboration, PRL (2018)

DM Search Schemes (Scattering)

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

DM Search Schemes (Scattering)

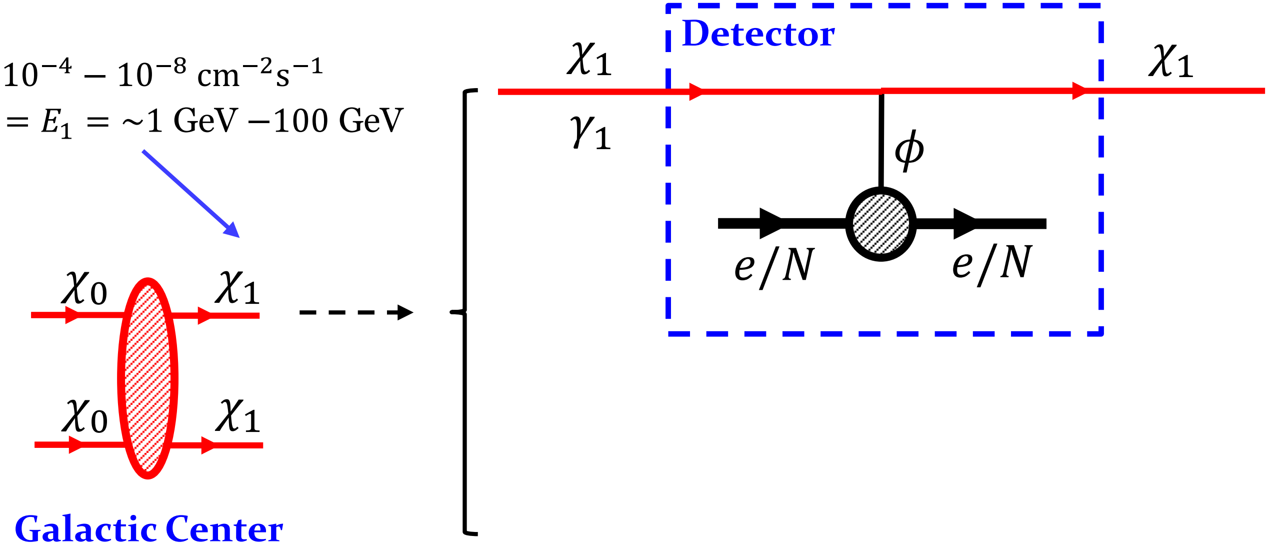
v_{DM} **Scattering**	***non*-relativistic** **(<< c)**	**relativistic** **(~c)**
elastic	Direct detection	Boosted DM (eBDM)
in	inelastic DM (iDM)	inelastic BDM (*i*BDM)



BDM Signatures

(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])

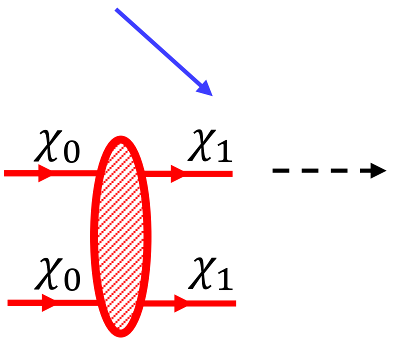
$\mathcal{F}_{\chi_1} = \sim 10^{-4} - 10^{-8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
with $m_0 = E_1 = \sim 1$ GeV -100 GeV



- 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

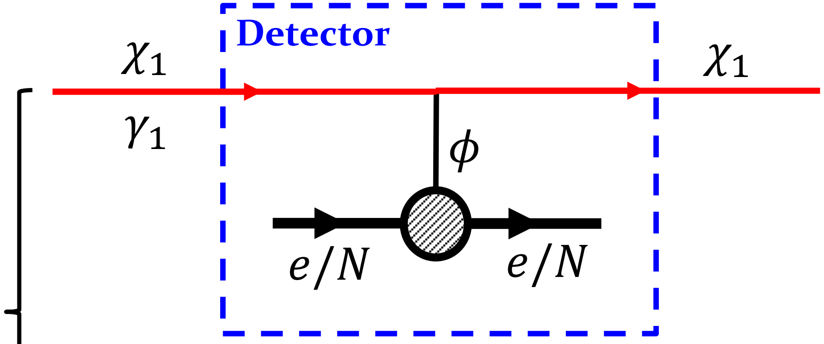
BDM Signatures

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

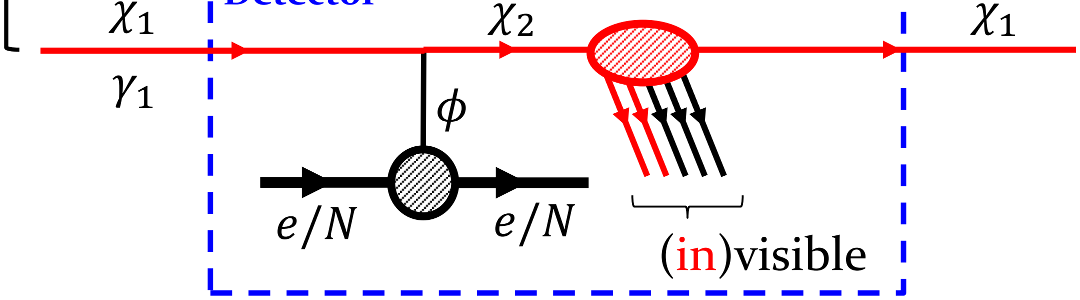


Galactic Center

(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])



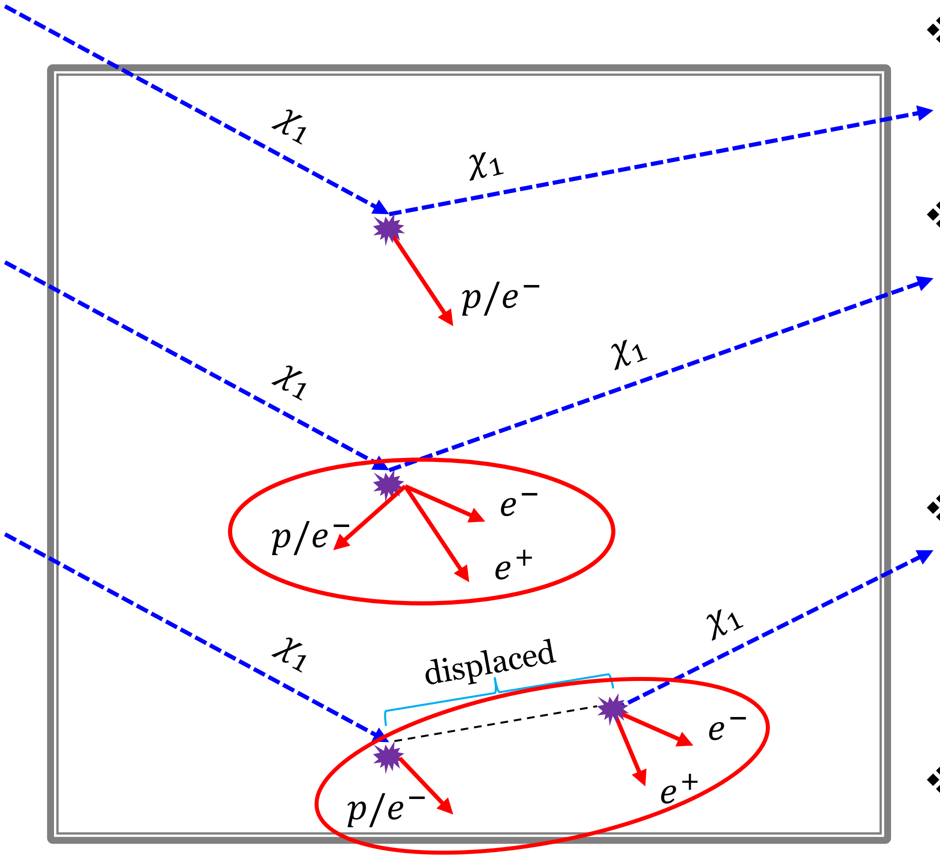
(b) Inelastic scattering (***i*BDM**) (cf. *i*BDM at HK/DUNE/Xenon1T/… [Kim, **JCP**, Shin (2016); Giudice, Kim, **JCP**, Shin (2017); **JCP** et al. (2018); Aoki, Toma (2018)])



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

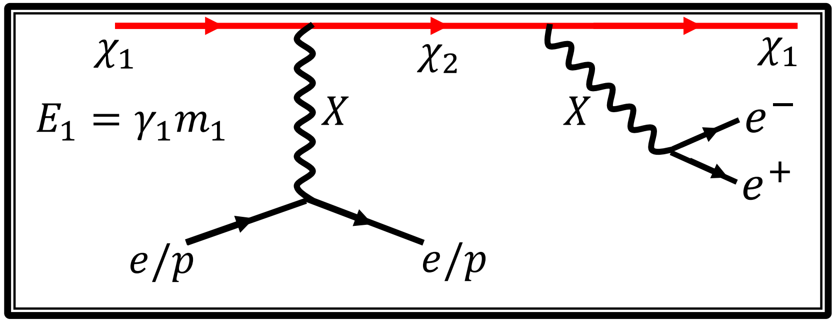
- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

Expected Signatures



- Ordinary elastic scattering (eBDM): only e/p-recoil (ER/PR) ➔ single track
- "Prompt" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (from the decay of on-shell X: $m_2 > m_1 + m_X$) ➔ three tracks
- "Displaced" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (typically from a three-body decay of χ_2) ➔ three tracks
- **Tracks** will **pop-up** inside the fiducial volume.
- Focus on ER. But, Straightforwardly applicable to PR (up to form factor, DIS, etc.)

Signal Attributes



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

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

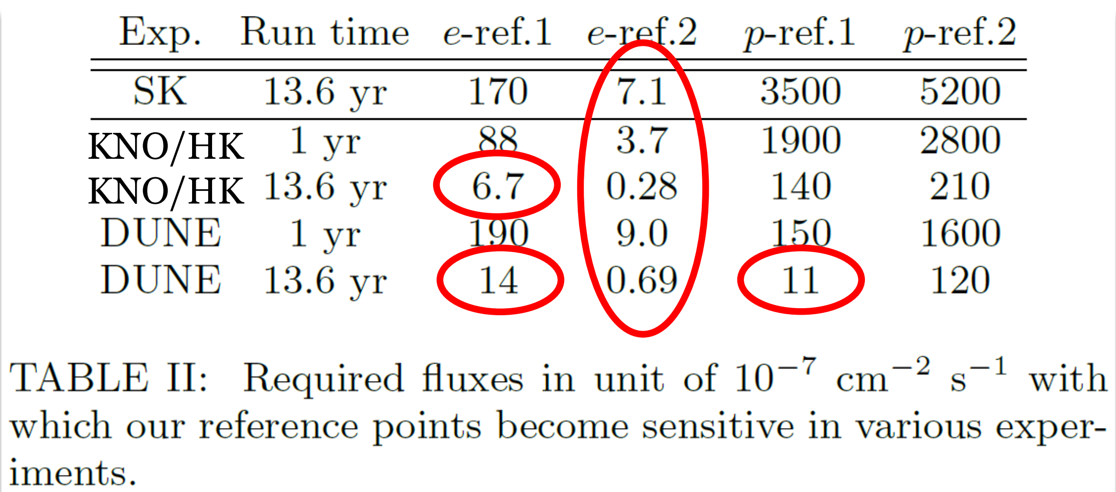
[1811.xxxxx]

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

Vs.

Discovery Potential

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



Exp.	Run time	*e*-ref.1	*e*-ref.2	*p*-ref.1	*p*-ref.2
SK	13.6 yr	170	7.1	3500	5200
KNO/HK	1 yr	88	3.7	1900	2800
KNO/HK	13.6 yr	6.7	0.28	140	210
DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

TABLE II: Required fluxes in unit of 10^{-7} cm^{-2} s^{-1} with which our reference points become sensitive in various experiments.

	m_{χ_B}	m_ψ	m_X	γ_{χ_B}
e-ref1	0.4	0.5	0.06	250
e-ref2	0.1	0.14	0.03	200
p-ref1	0.4	0.9	0.2	15
p-ref2	0.1	1.0	0.5	50

- ✓ $\varepsilon = 3 \times 10^{-4}$ & $g_B = 0.5$
- ✓ γ_{χ_B}: boost factor of boosted DM χ_B
- ✓ "Zero" background assumed
- ✓ Every mass in GeV

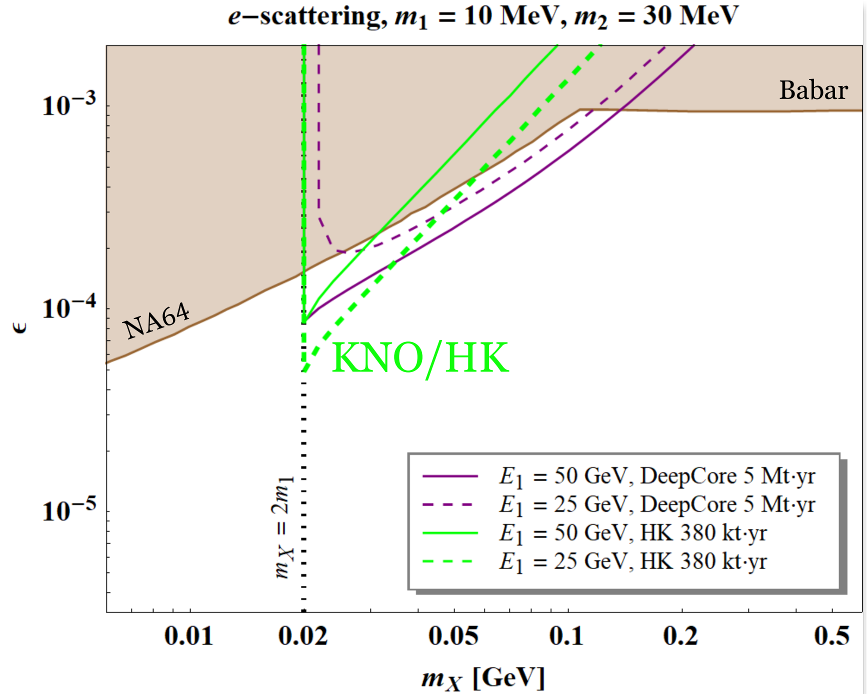
- ❖ Remind, in a minimal BDM scenario, if the BDM flux over the whole sky is $\mathcal{O}(10^{-6\sim7})$ $\text{cm}^{-2}\text{s}^{-1}$, it is promising & achievable!

Richer Phenomenology and Large Territory to Explore!

Dark X Parameter Space: Scenario I

P. Machado, D. Kim, **JCP** & S. Shin [1811.xxxxx]

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

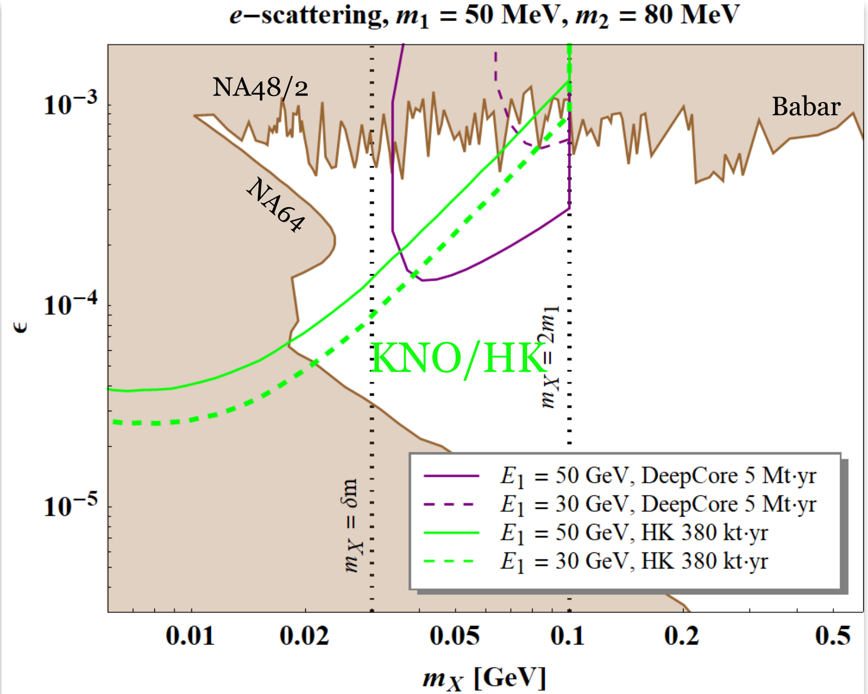


Experimental reach for 1-year of running

Dark *X* Parameter Space: Scenario II

P. Machado, D. Kim, **JCP** & S. Shin [1811.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 ($\delta m < m_X < 2m_1$).

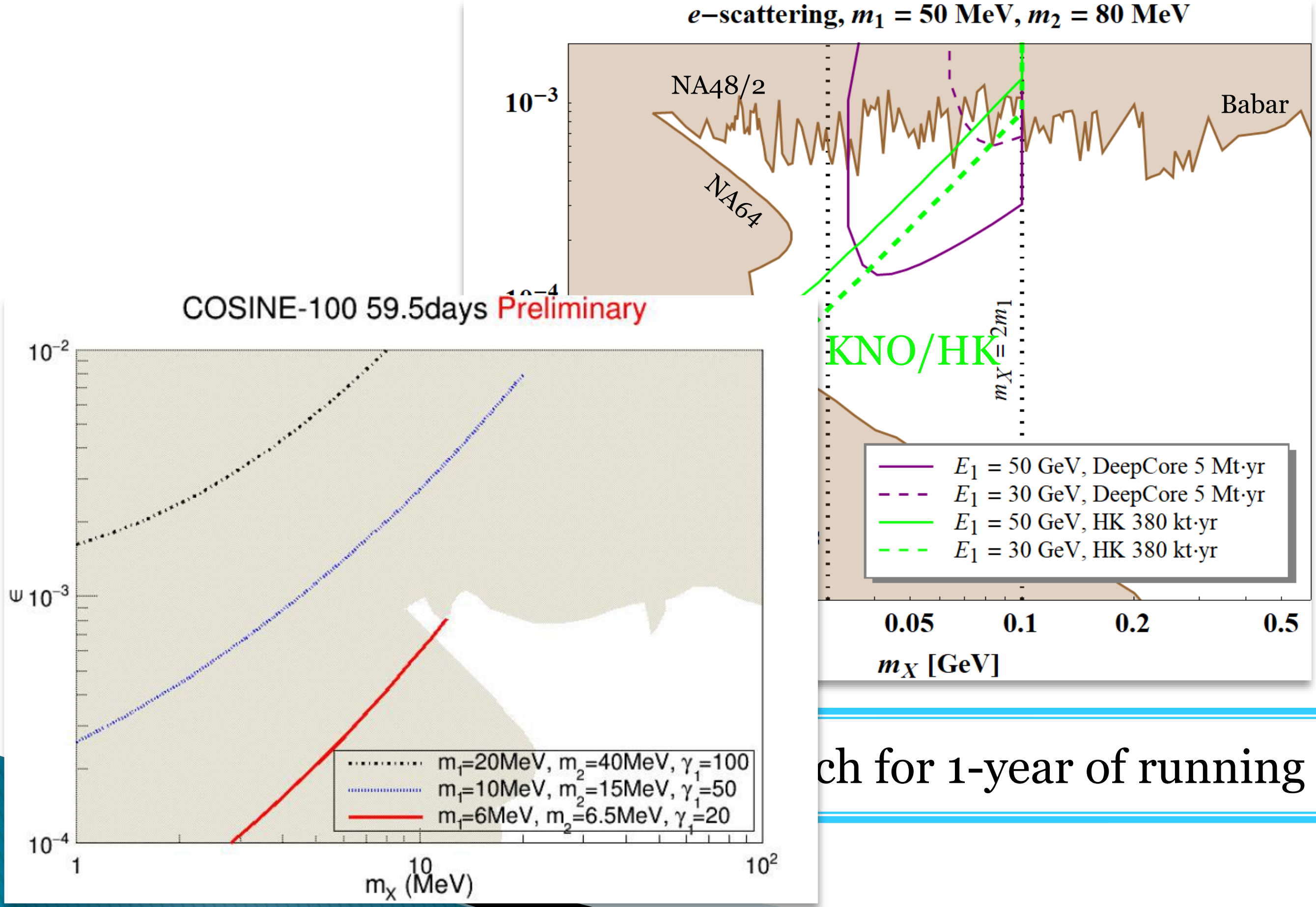


Experimental reach for 1-year of running

Dark X Parameter Space: Scenario II

P. Machado, D. Kim, **JCP** & S. Shin [1811.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 ($\delta m < m_X < 2m_1$).



ch for 1-year of running

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, KNO/HK, DUNE, IceCube, …).
- Experimental studies have already begun, e.g. SK, COSINE-100, ProtoDUNE, …

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

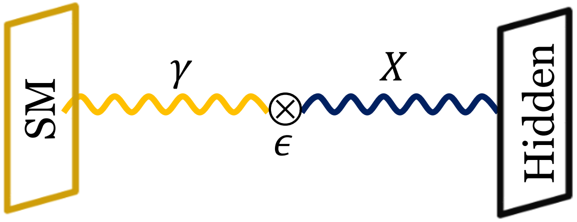
Thank you

Back-Up

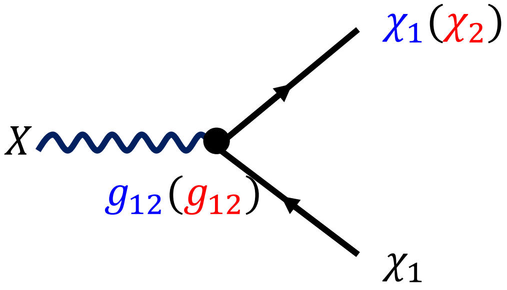
Benchmark Model

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

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 (eBDM)
  - ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)



- Various models conceiving BDM signatures
  - ✓ BDM source: GC, Sun (capture), dwarf galaxies/assisted freeze-out, semi-annihilation, decaying, etc.
  - ✓ Portal: vector portal, scalar portal, etc.
  - ✓ DM spin: fermionic DM, scalar DM, etc.
  - ✓ iBDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Summary of Experiments

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

- Experimental details

Rejection of BGs from non-energetic μ decays

	Volume (kTon)	$E_{\rm th}$ (MeV)	$\theta_{\rm res}$ (°)	Running Time (years)
SK [37]	22.5	100	3°	> 13.6
KNO/HK	560	100	3°	
DUNE [22]	40-50	30	1°	
PINGU/IceCube	500/10^6	~GeV/~100 GeV	23° at ~GeV	

- Expected number of background events (/year) ~$V \cdot \theta_C^2$

	DUNE 10	DUNE 40	SK	KNO/HK
GC	1 with 10°	4 with 10°	7.01 with 10°	174 with 10°
Point	0.01 with 1°	0.04 with 1°	0.632 with 3°	15.7 with 3°

- Single-ring 0-decay e-like events

- Major background: atmospheric neutrinos ($\nu_e n \to e^- p$)

Potential BGs: Neutrinos

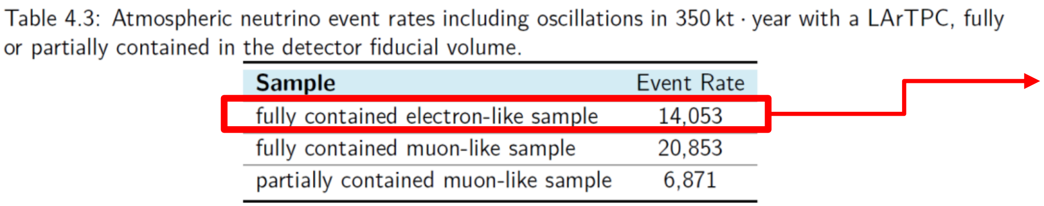
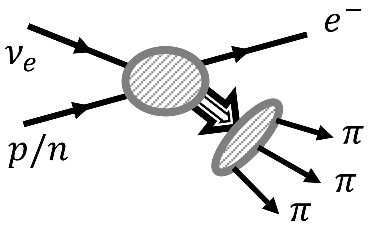


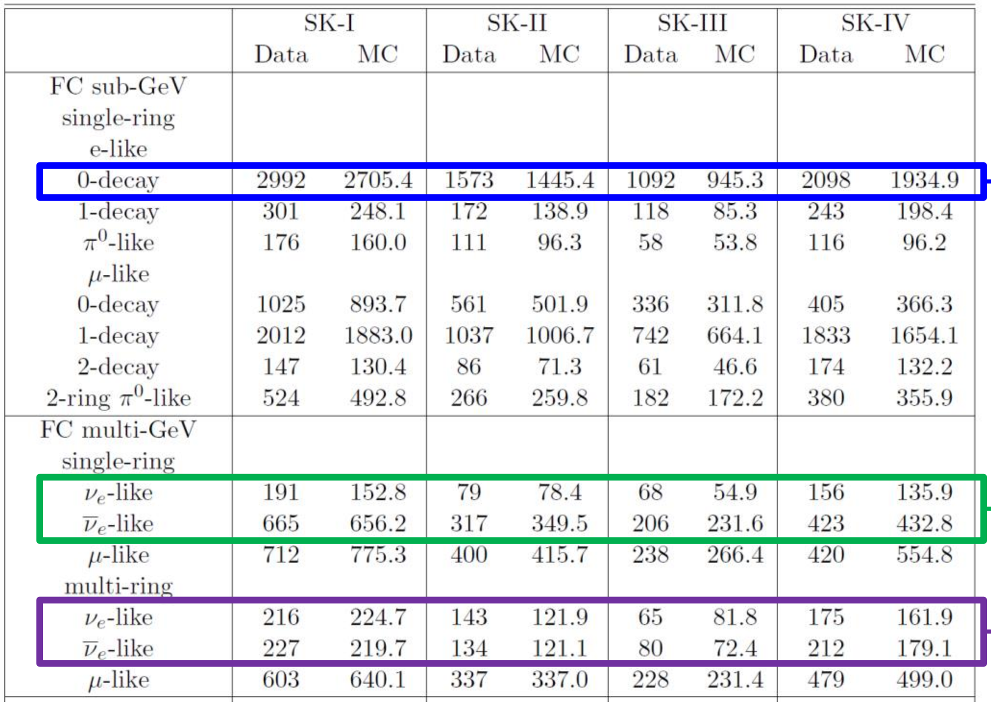
Table 4.3: Atmospheric neutrino event rates including oscillations in 350 kt · year with a LArTPC, fully or partially contained in the detector fiducial volume.

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)]

$\sim\mathbf{40.2}$/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
$\bar{\nu}_e$-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
$\bar{\nu}_e$-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: $\mathbf{32.4} + \mathbf{8.8} = \mathbf{41.2}$ /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

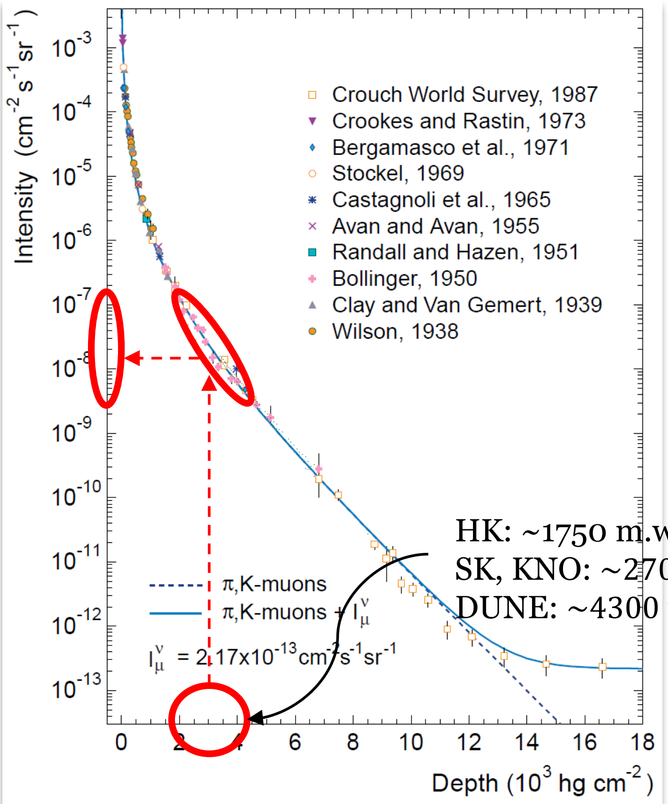
Multi-track candidates: $\mathbf{5.2}$ /yr/kt

$\Rightarrow$ 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

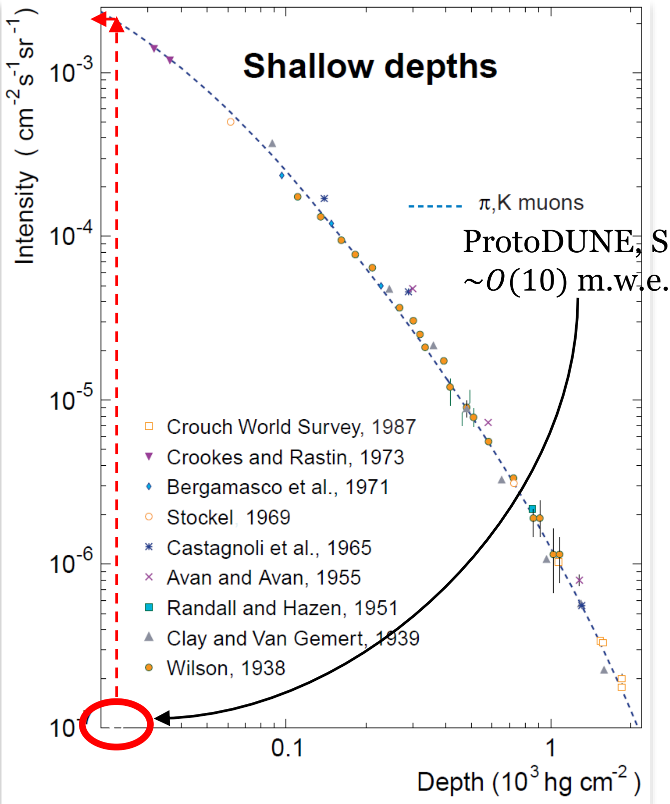
Potential BGs: High E Muons

- ❖ Expecting $\sim 10^{4-6}$ more muon flux at ProtoDUNE/SBN than that at HK, SK/KNO, DUNE.
- ❖ Expecting $\sim 5-50$ more muon flux at HK than that at SK/KNO, DUNE.



HK: ~1750 m.w.e.
SK, KNO: ~2700 m.w.e.
DUNE: ~4300 m.w.e.

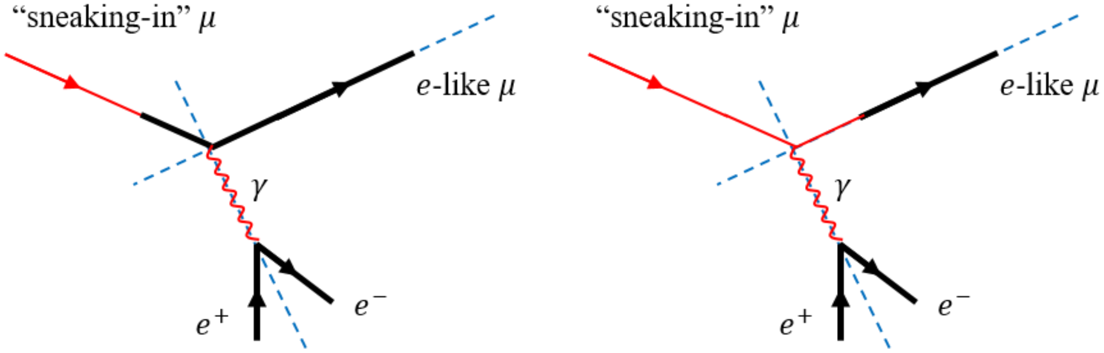
[Bugaev et al. (1998)]



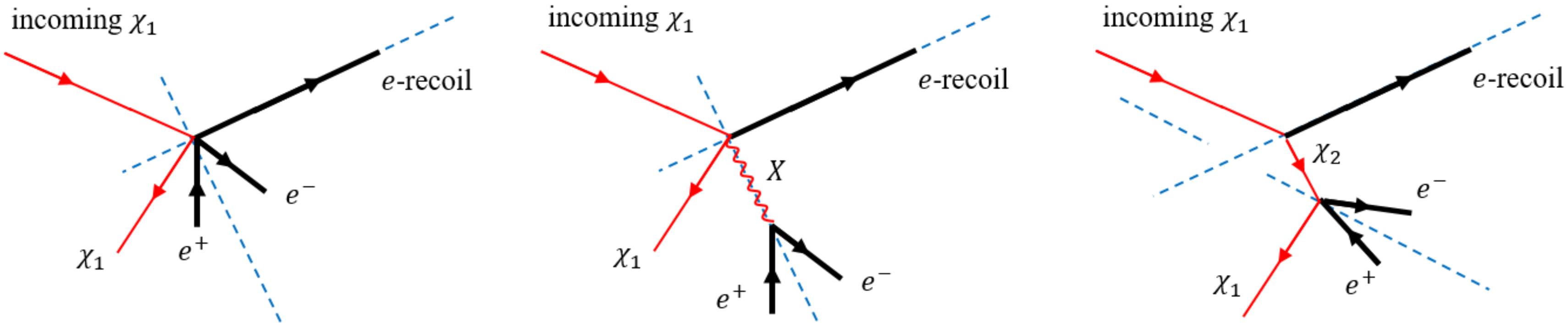
ProtoDUNE, SBN:
$\sim O(10)$ m.w.e.

Possible Event Shapes (*i*BDM)

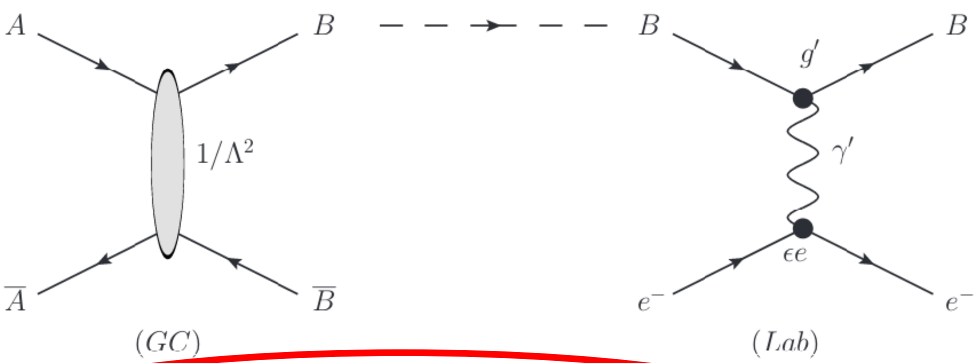
(a) μ-induced background event shapes

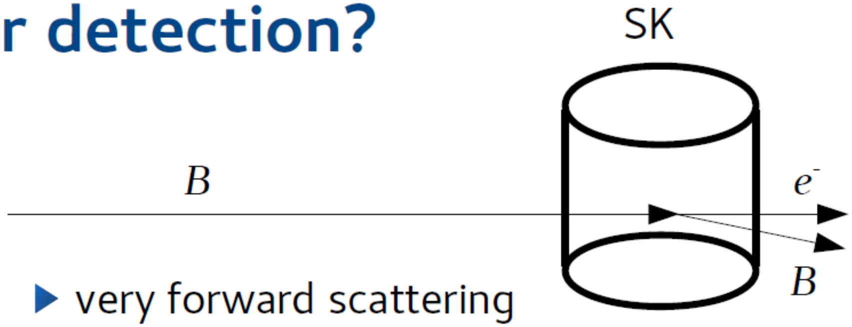


(b) Signal event shapes



(In)direct dark matter detection?

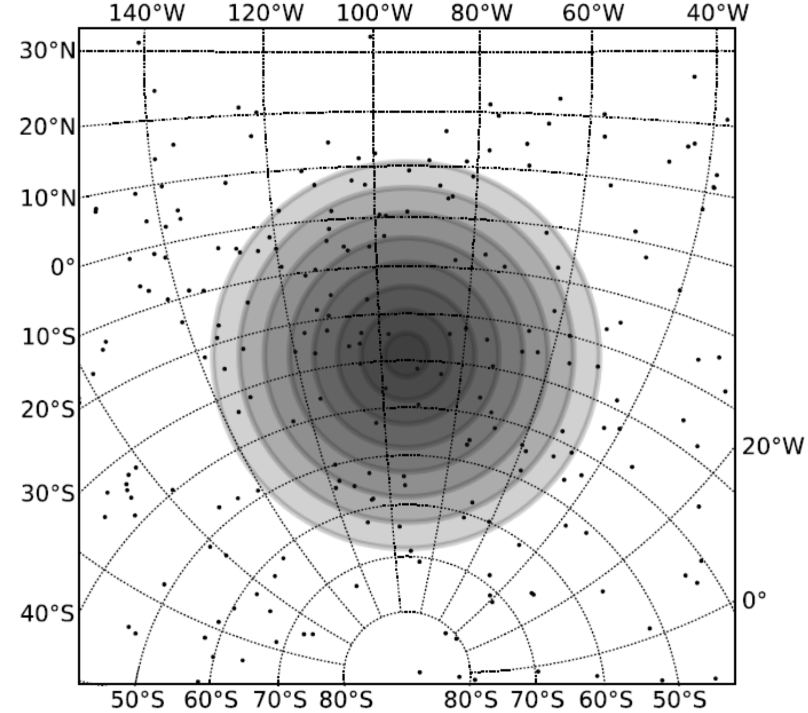




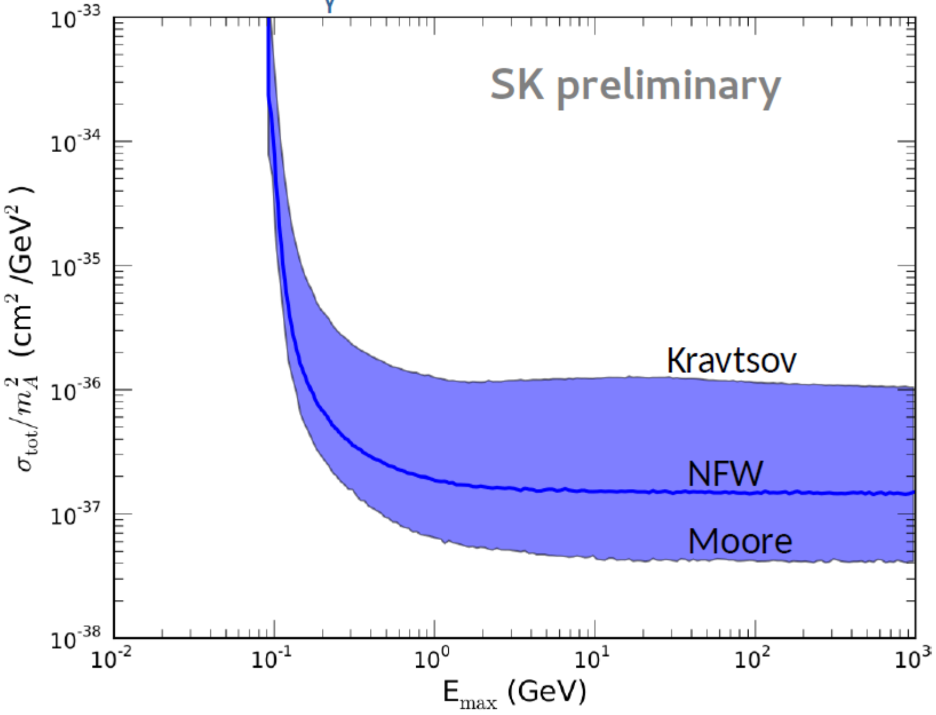
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC

→ **No clusters visible**

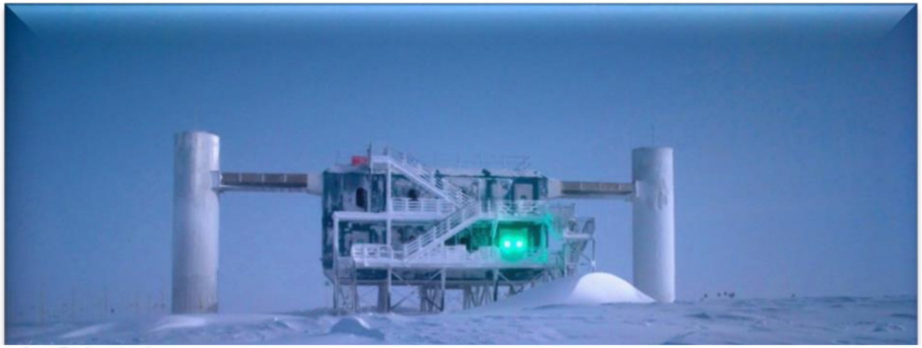


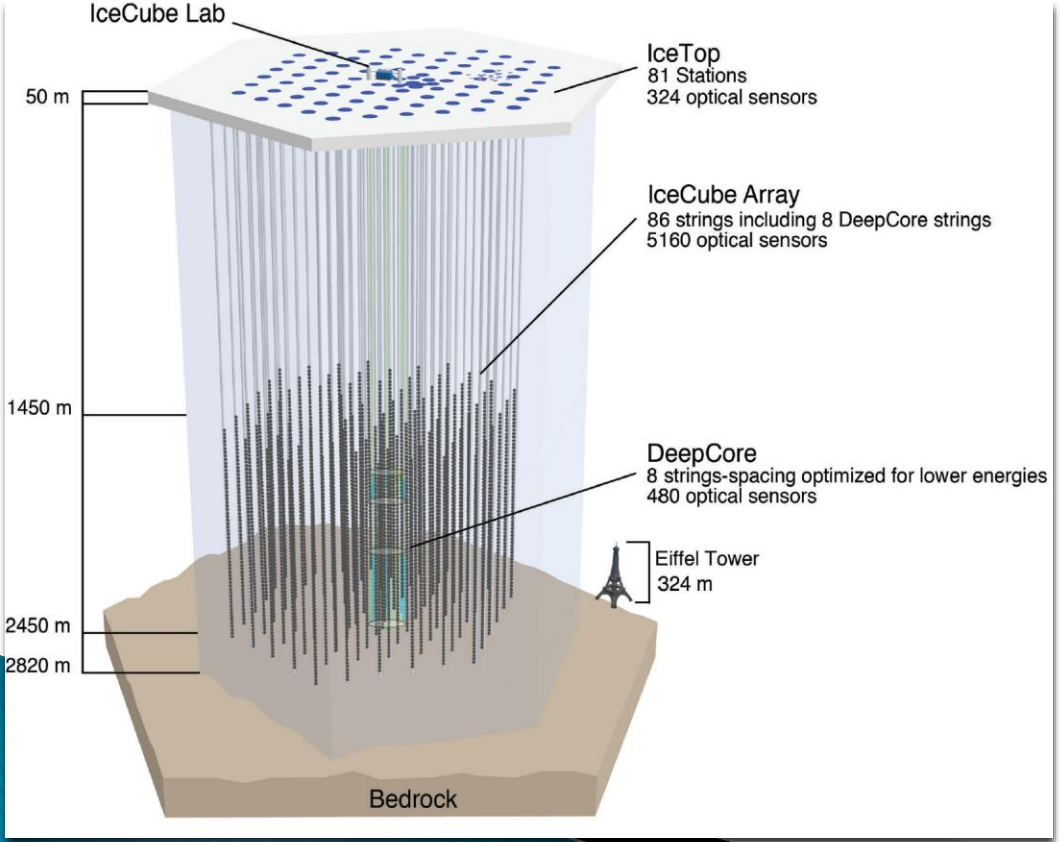
Limit for m_{γ}'=20 MeV

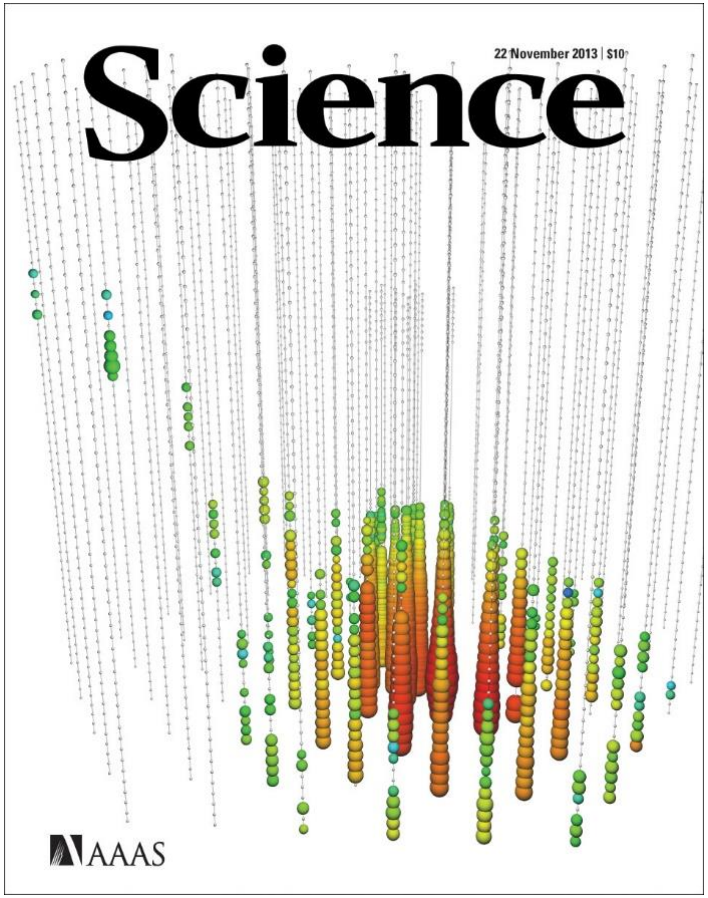


IceCube: PeV Signals by BDM?

Kopp et al (2015); Bhattacharya et al (2016)

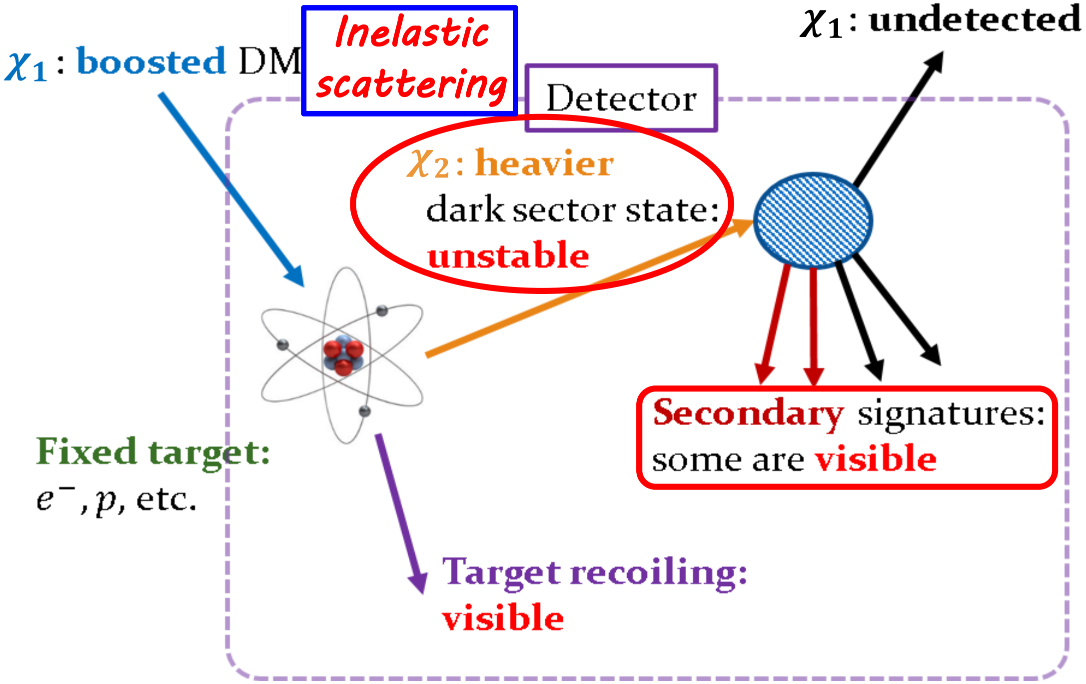






*i*BDM: DM "Colliders"

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



χ_1 : **boosted** DM

Inelastic scattering

Detector

χ_1 : **undetected**

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

Secondary signatures: some are **visible**

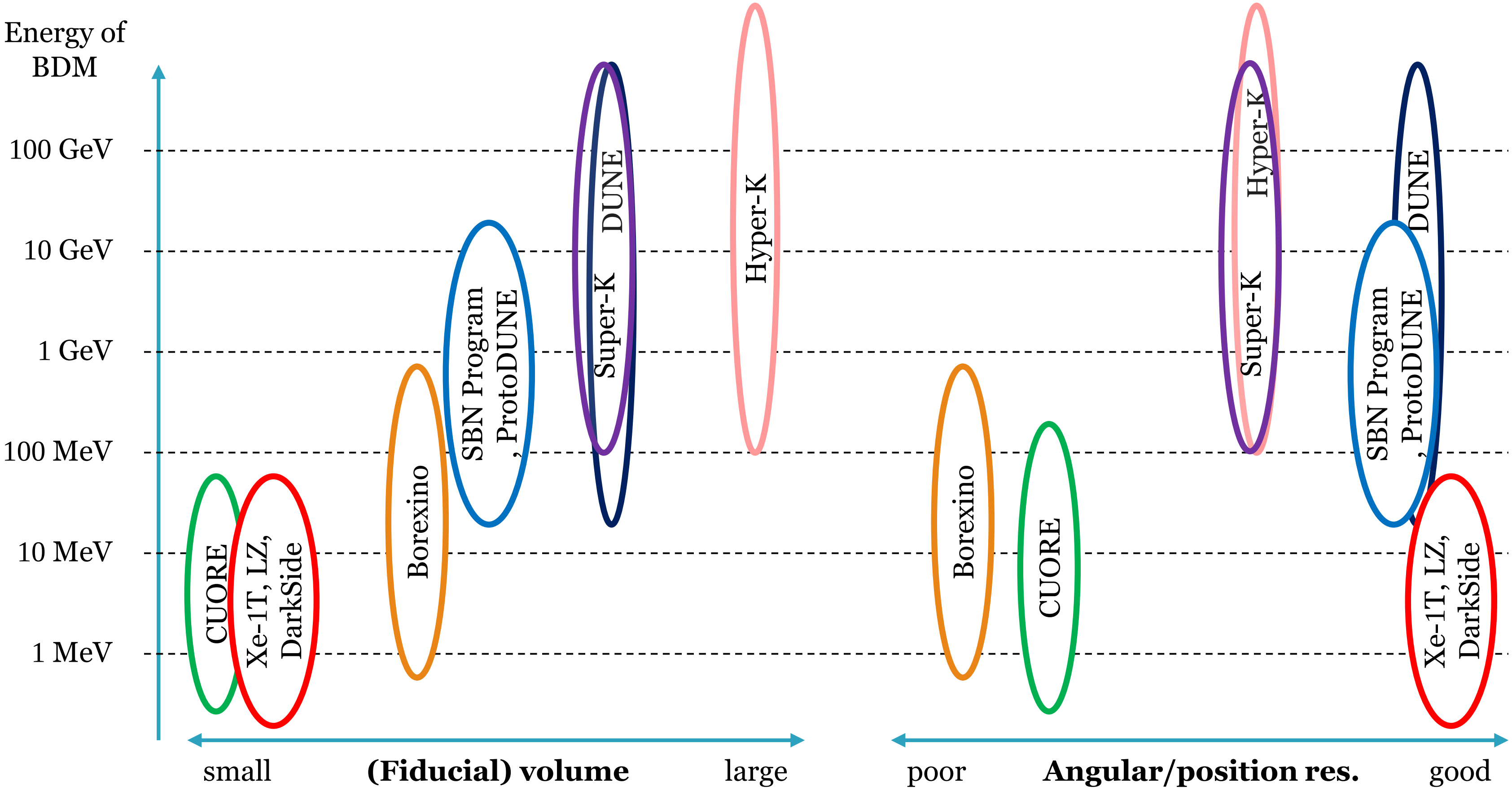
Fixed target: e^-, p, etc.

Target recoiling: visible

- ❖ 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.

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

e/*i*BDM Searches in Various Exps.



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