Searches for *Boosted* DM

H. Alhazmi, KC Kong, G. Mohlabeng & **JCP**
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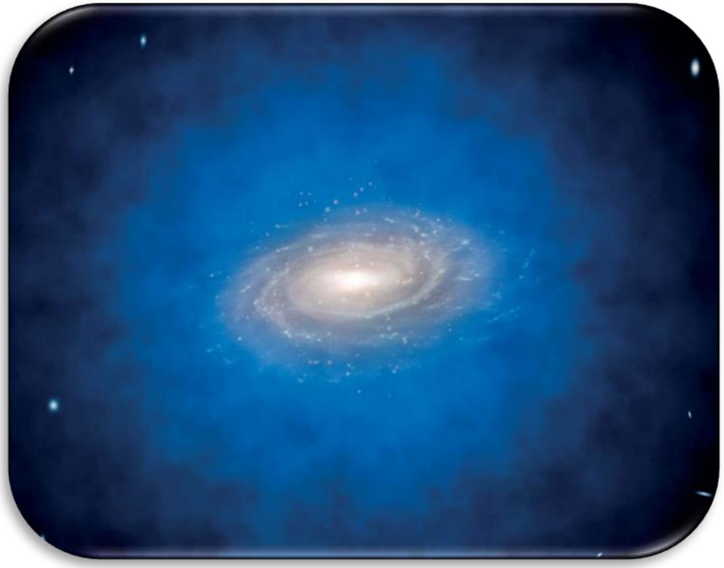

Jong-Chul Park

CHUNGNAM NATIONAL UNIVERSITY

IBS-KIAS Joint Workshop
February 07 (2017)

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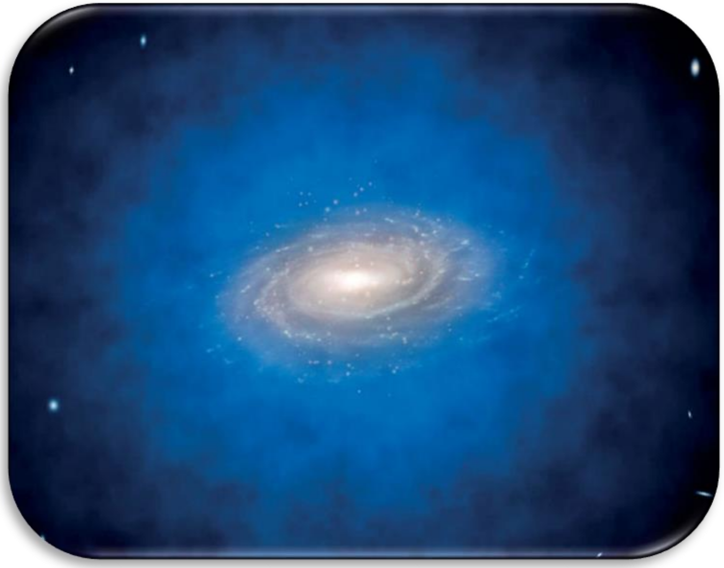
S. Shin's Talk Cosmic ray



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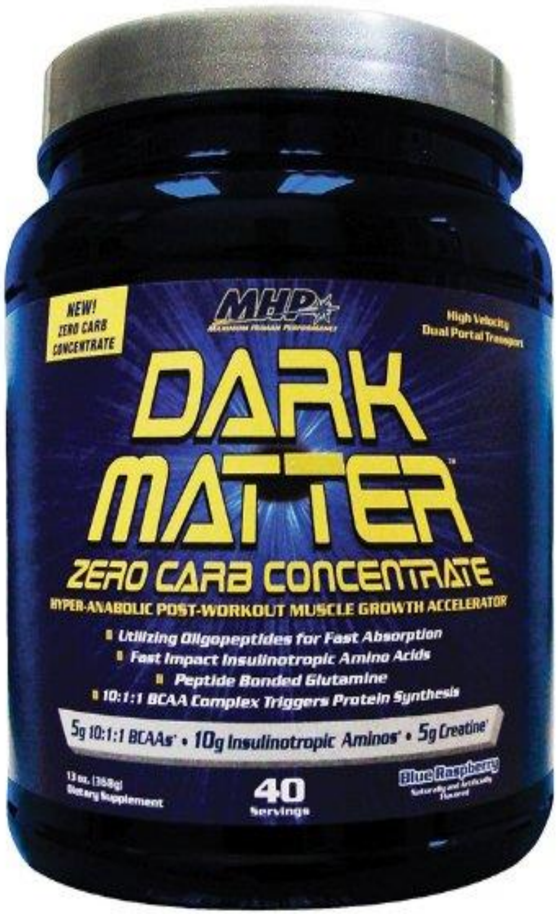
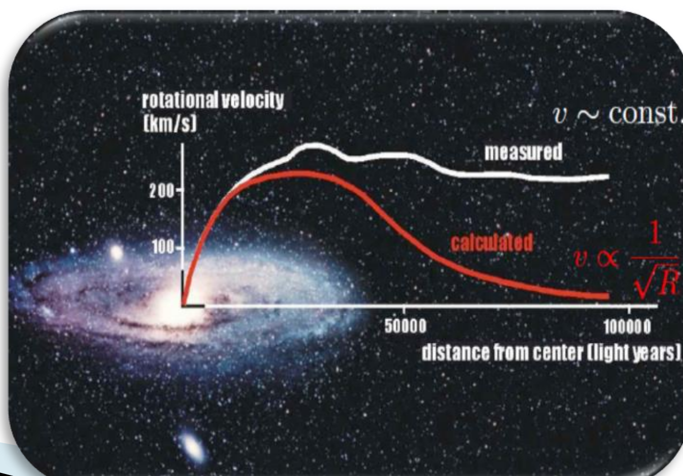


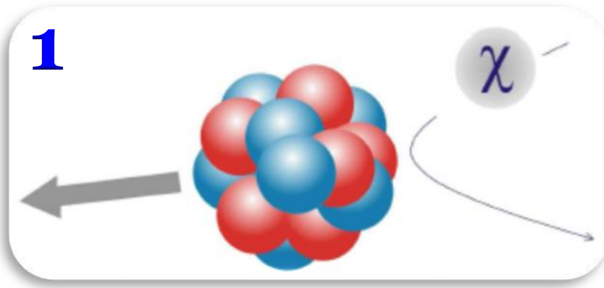
What's Dark Matter?

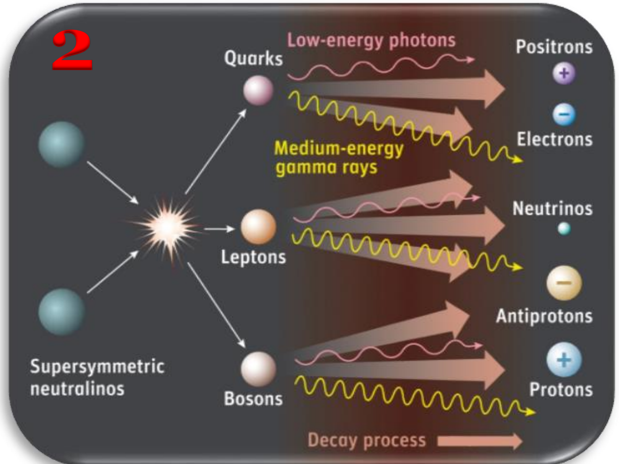
Dark Matter (DM)

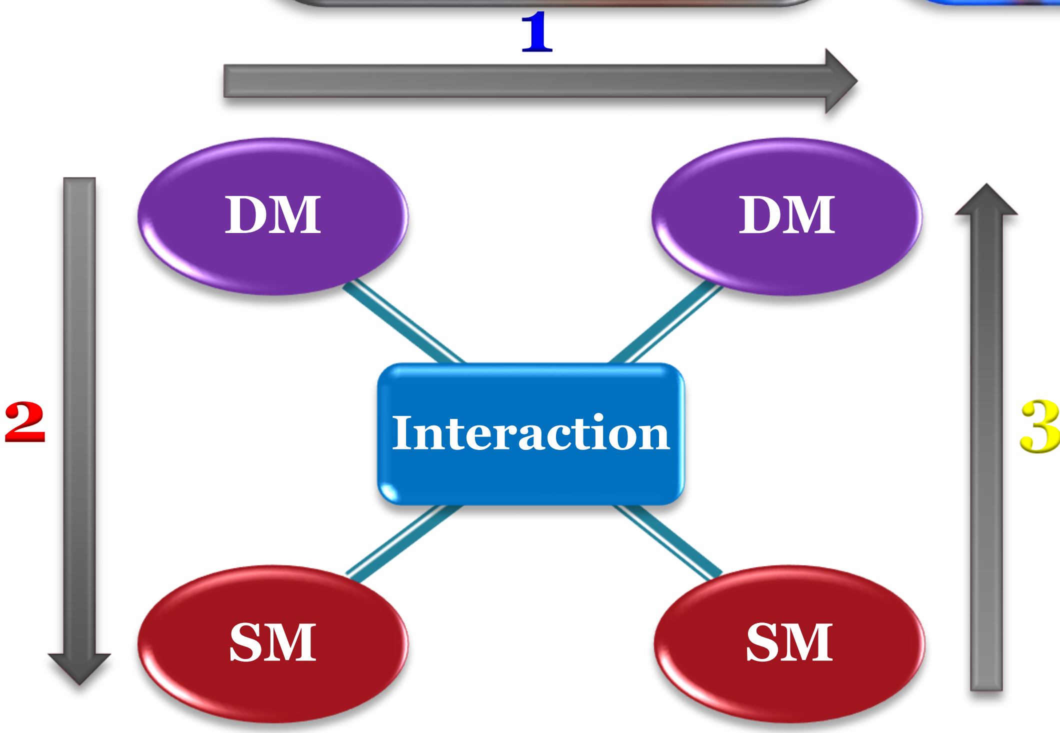
- **DM**: ~25% of our Universe
- **Compelling paradigm**:
  massive, non-luminous & stable particles
- **Evidence**
  - ✓ Galaxy rotation curve
  - ✓ Bullet cluster
  - ✓ Gravitational lensing
  - ✓ Structure formation
  - ✓ CMB
  - ✓ Coma Cluster
  - ✓ Sky surveys
  - ✓ ...



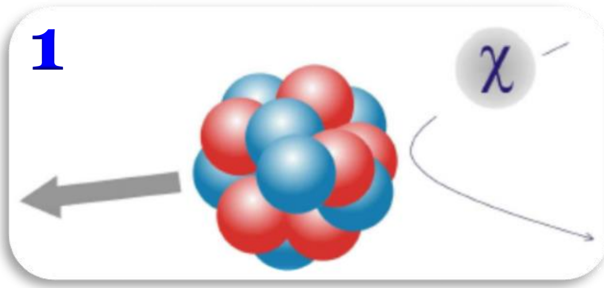
DM Search Strategies

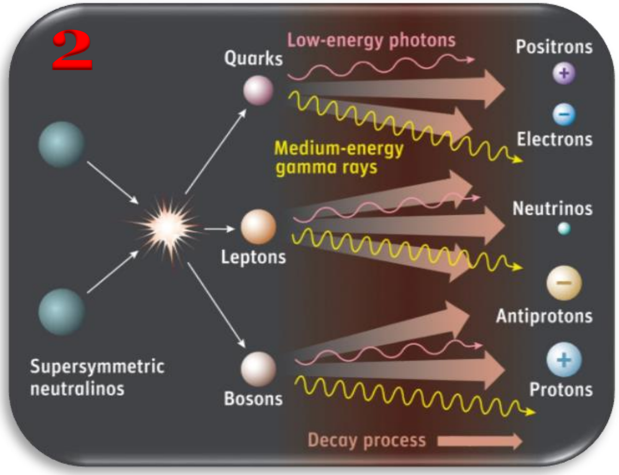


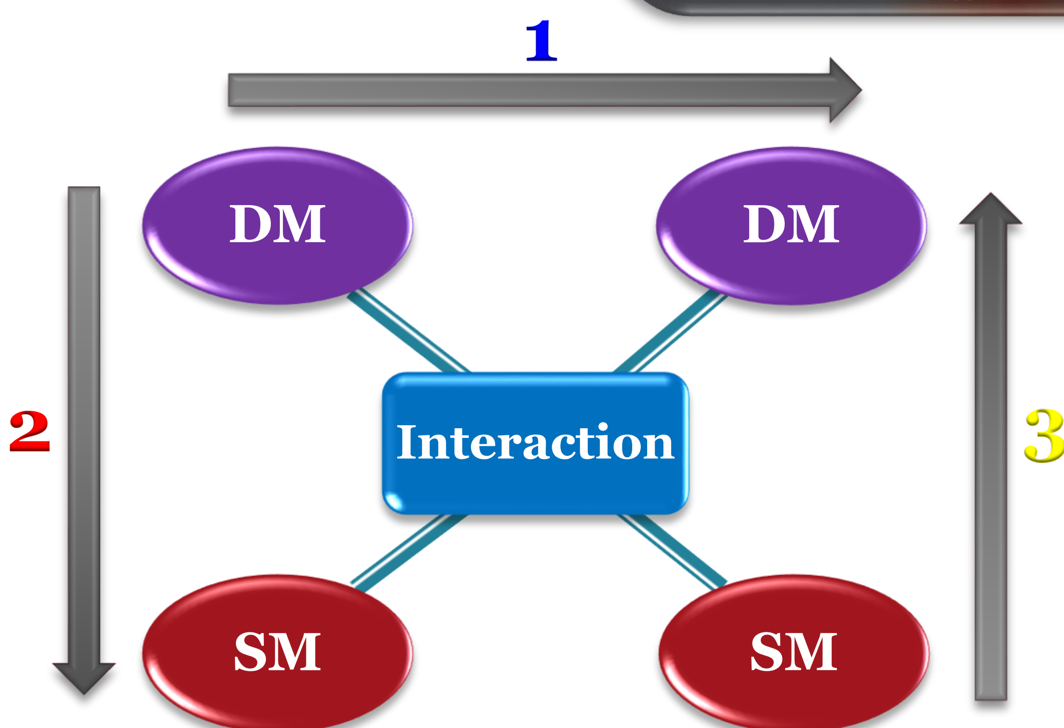




DM Search Strategies







- Current day DM: $v/c \sim 10^{-3}$

  1: Small nuclear recoil energy

  2: Annihilation to SM states

  nearly at rest

Minimal vs Non-minimal

❖ Scenario with a **single DM species**

✓ Simplest & well-motivated scenario

✓ Stability of DM ensured (typically) by a discrete symmetry

✓ Popular models having a single type of DM candidate:

- SUSY models with R-parity

- Extra-D models with KK-parity

❖ Scenario with **multiple DM species**

✓ Nothing stops from having more stable particles

- Visible sector (SM) has many stable particles: p, e, ν, γ

- Rising (theoretical) interest in non-minimal scenarios

Detection
of
Boosted DM

What's Boosted DM?

Boosted DM (BDM)

Agashe et al. (2014)

- ❖ Generic phenomena in non-minimal DM sector:

  Late-time processes ➔ Small fraction of DM today is relativistic: **BDM**

- ❖ Sources of boosted DM: non-minimal/extended DM sector
  - ✓ **Assisted Freeze-Out**: $\psi_i \, \psi_j \rightarrow \psi_k \, \psi_l$; ψ_k, ψ_l lighter (G. Belanger & **JCP**, 2011)
  - ✓ **Semi-annihilation**: $\psi_i \, \psi_j \rightarrow \psi_k \, \varphi$; Z_N DM symmetry (D'Eramo & Thaler, 2010)
  - ✓ **Decay**: $\psi_i \rightarrow \psi_j + \varphi$
  - ✓ …

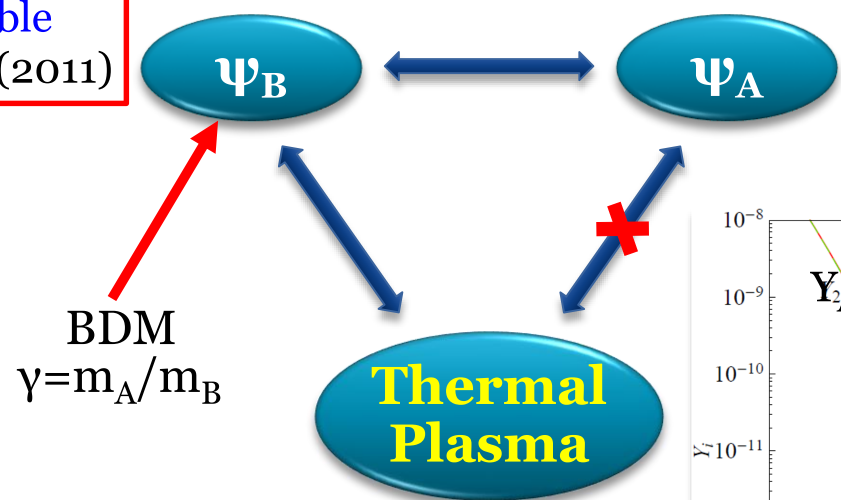
- ❖ Detection of BDM: $\boldsymbol{v} \sim \mathbf{c}$
  - ✓ Reveal non-minimal features of DM sector
  - ✓ Conventional DM searches ➔ Unsuitable ➔ New Search Strategies!

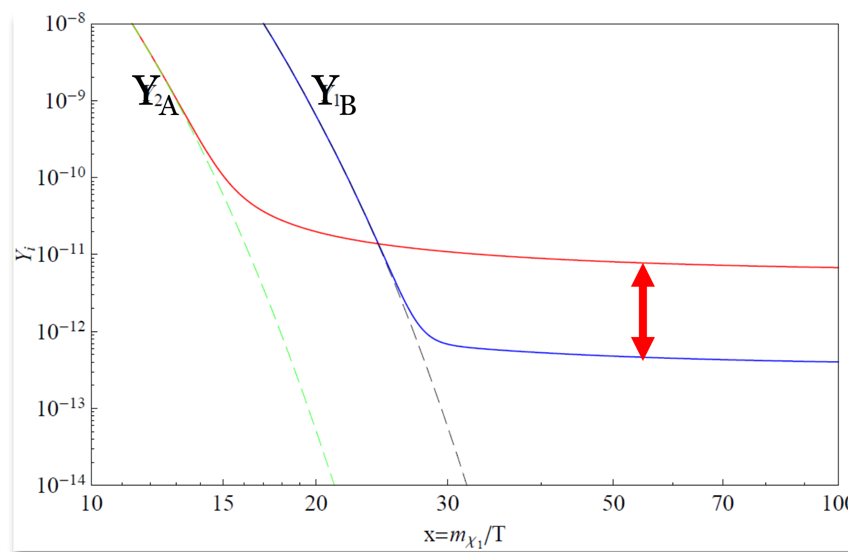
Basic Set-up: Assisted Freeze-Out

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

- Two species of DM: ψ_A, ψ_B with $m_A > m_B$ (e.g. $U(1)' \otimes U(1)''$, $Z_2' \otimes Z_2''$)
- ψ_A : dominant DM component, no direct coupling to the SM
  - ➔ Assisted Freeze-Out Mechanism: required!
- ψ_B : sub-dominant, direct coupling to the SM ($\mathcal{L} \supset -\frac{1}{2}\sin\epsilon X_{\mu\nu}F^{\mu\nu}$)

can be metastable
E. J. Chun & JCP (2011)





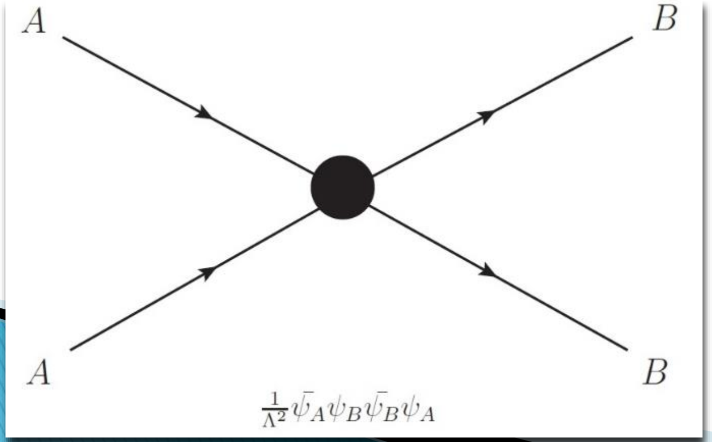
Basic Features

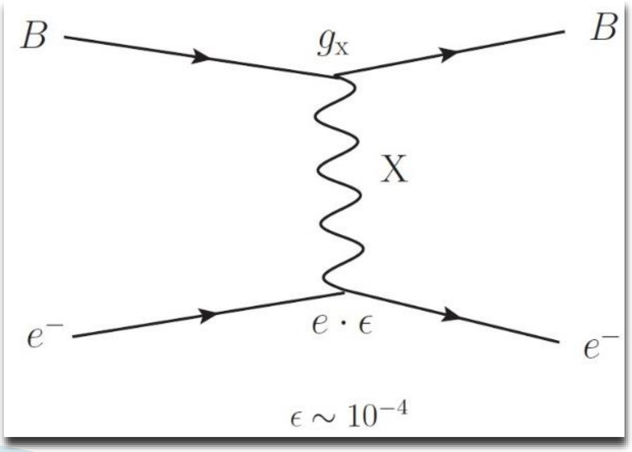
- Relic density of ψ_A is controlled by $\psi_A \overline{\psi}_A \to \psi_B \overline{\psi}_B$
- Detection of ψ_A: no-direct coupling to the SM ➔ No
- Detection of relic ψ_B: small relic ➔ No

New detection Method!

- ψ_B from annihilation of ψ_A: **Boosted DM** with $\gamma = m_A/m_B$
- **Direct** detection of **boosted ψ_B** ➔ **Indirect** detection of ψ_A

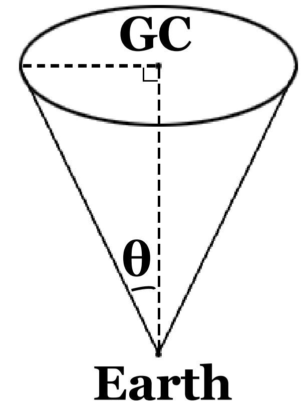
➔ Smoking-gun for non-minimal DM sector!





BDM from Galactic Center

❖ Flux of boosted ψ_B from the GC by the annihilation of ψ_A:



NFW profile (ρ_{sun}=0.3 GeV/cm^3) + 10° cone around GC

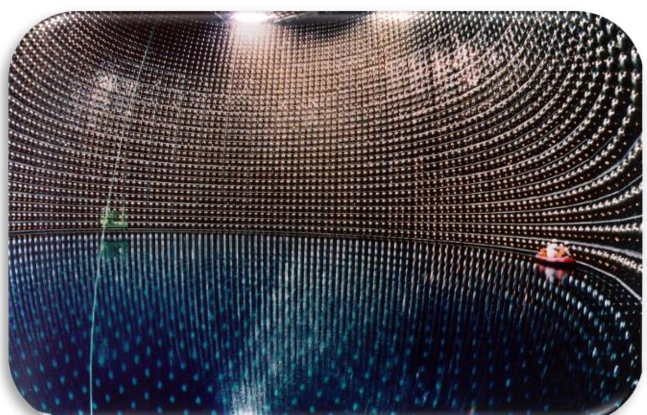
$$\Phi_{GC}^{10^\circ} = 9.9 \times 10^{-8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \left(\frac{\langle \sigma_{A\bar{A}\to B\bar{B}} v \rangle}{5 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right) \left(\frac{20\ \mathrm{GeV}}{m_A} \right)^2$$

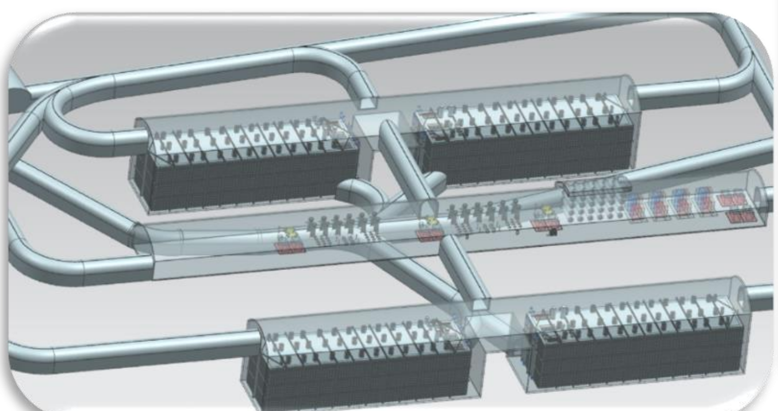
Agashe et al. (2014)

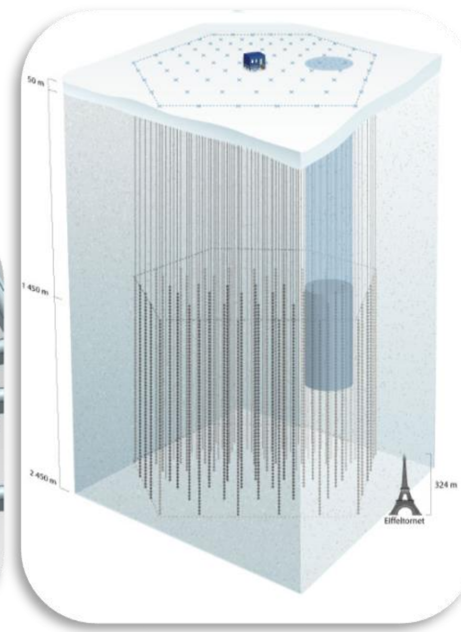
❖ Low flux ➔ Large volume detector to see ψ_B+SM → ψ_B+SM scattering

➔ Neutrino detectors: Super-K, IceCube, ...

Future: Hyper-K, DUNE, PINGU, ...







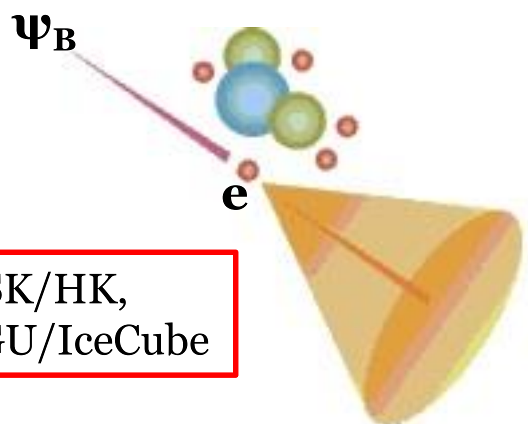
Detection of BDM

- **Large volume ν detectors** detect energetic charged particles

  from ν-matter collisions, i.e. $\nu_e n \to e^- p$

- Boosted DM: energetic e's resulting from $\psi_B e^- \to \psi_B e^-$

- Energetic e's ➔ Cherenkov light / charged particle track

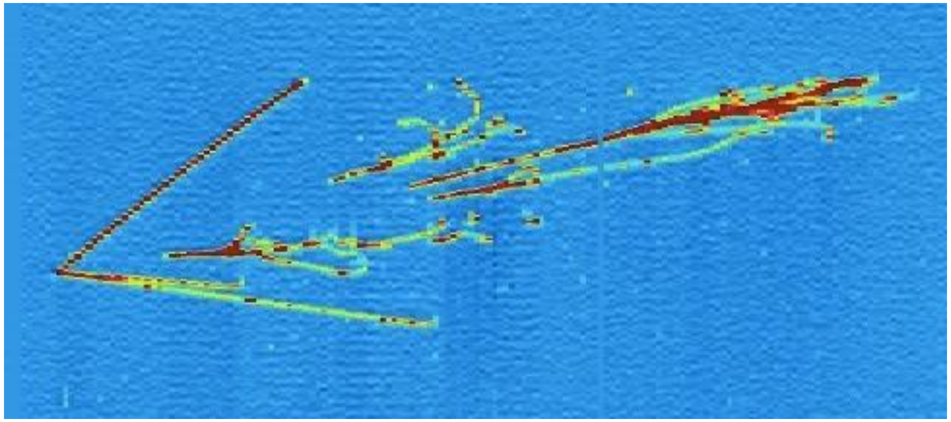


SK/HK, PINGU/IceCube

Cherenkov light

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

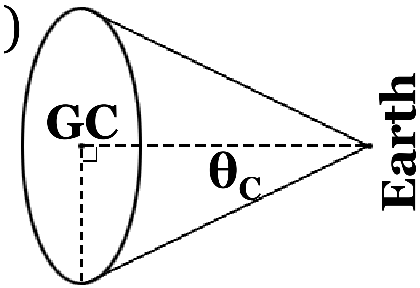
> 1.5



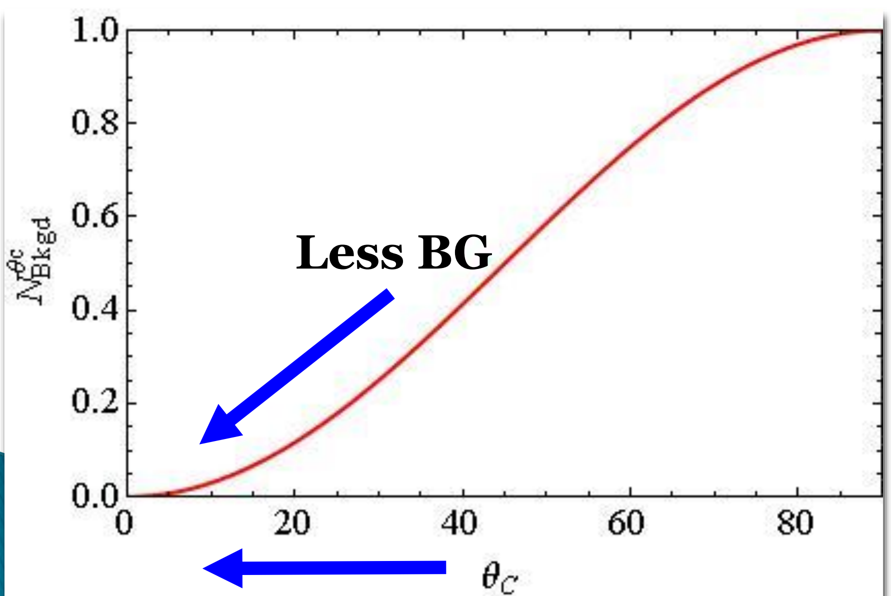
DUNE: LArTPC

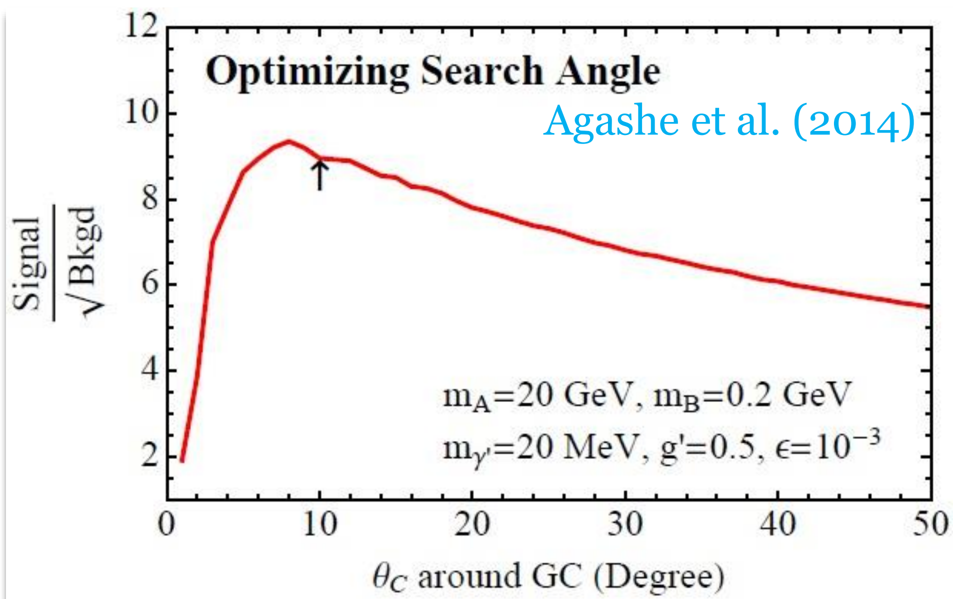
Background & its Rejection

- Major background: atmospheric neutrinos ($\nu_e n \to e^- p$)
  - ➔ Almost uniform in the entire sky!
- Background reduction: directionality ➔ governed by θ_C
- θ_{min} ~ 10° : optimal angle for $S/\sqrt{B}$ due to the DM halo distribution



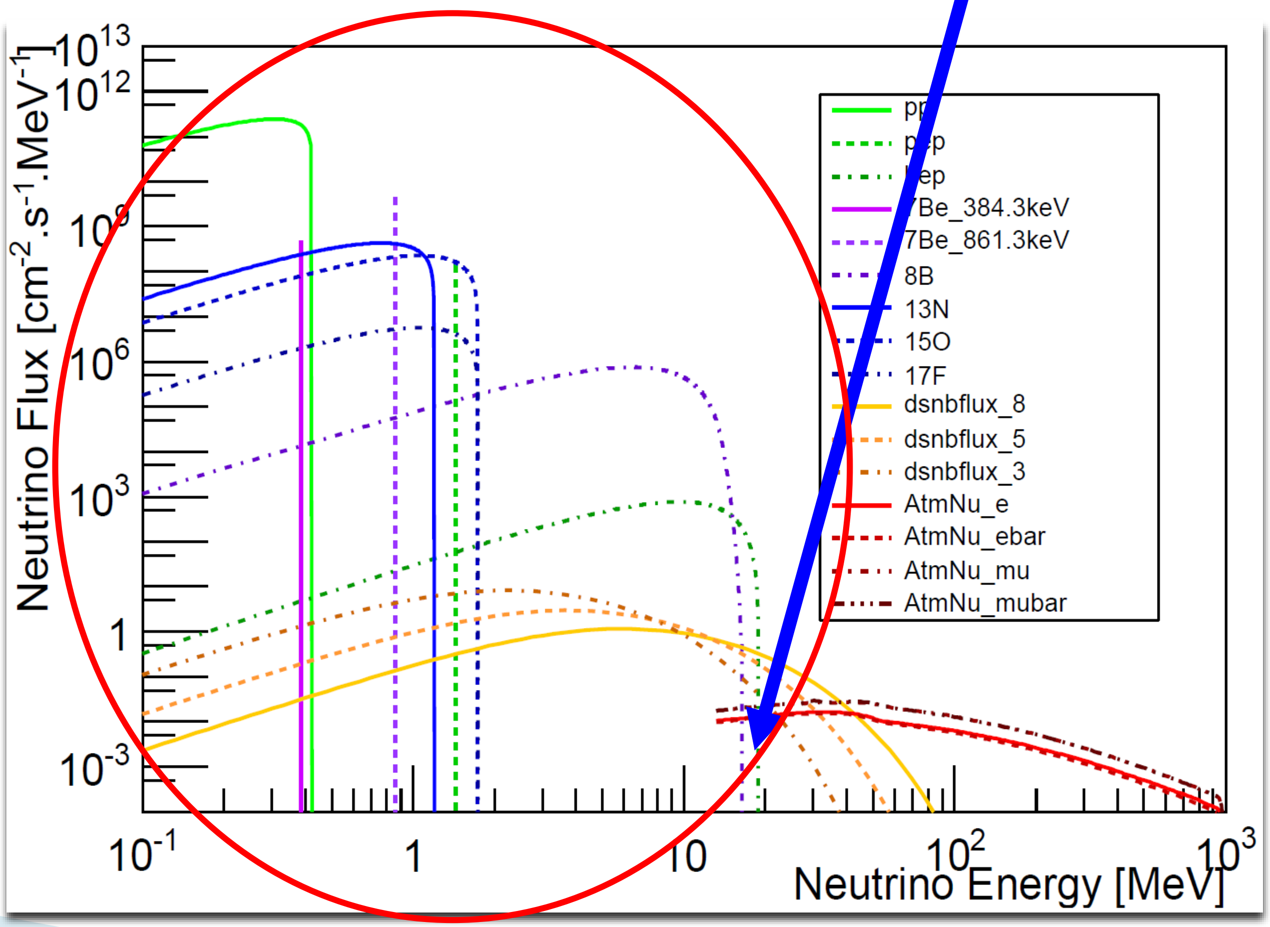
$$N_{\rm bkgd}^{\theta_C} = \frac{1-\cos\theta_C}{2} N_{\rm bkgd}^{\rm all\ sky} \sim \theta_C^2 \qquad \theta_C = \max\{10^\circ, \theta_e^{\rm res}\}$$





Neutrino Fluxes

❖ For efficient rejection of solar ν BGs → E^{min}≈20~30 MeV



Billard et al. (2013)

Summary of Experiments

❖ Experimental details

Rejection of BGs from muon decays

	Volume (kTon)	$E_{\rm th}$ (MeV)	$\theta_{\rm res}$ (°)	Running Time (years)
SK [37]	22.5	100	3°	> 13.6
HK [38]	560	100	3°	
DUNE [22]	40-50	30	1°	
PINGU/IceCube:	500/10^6,	a fev GeV/100 GeV,	23^{o} at ~GeV	

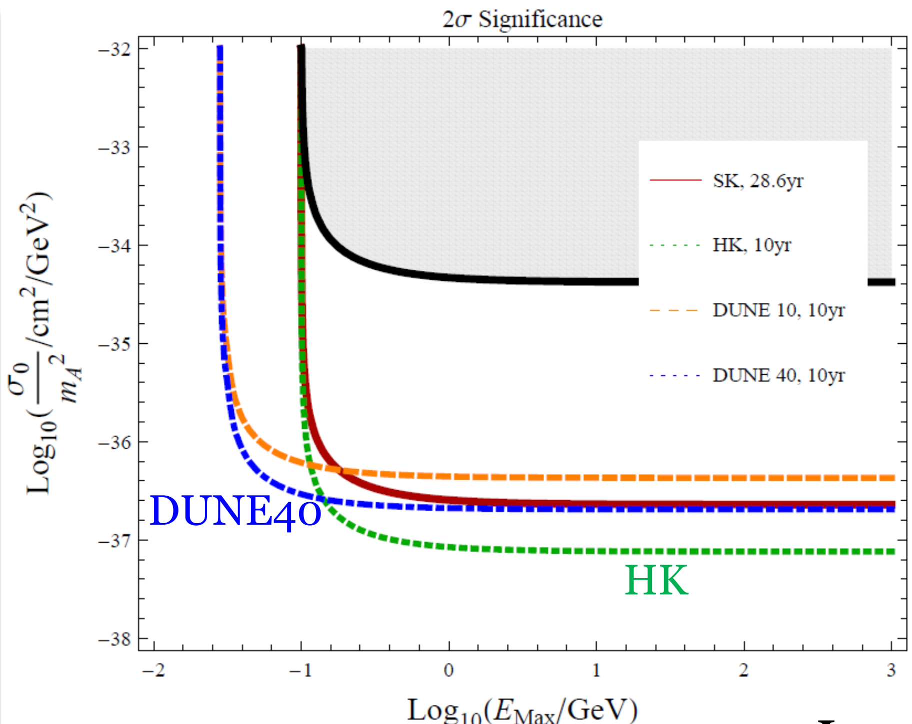
❖ Expected number of background events (/year) $\sim V \cdot \theta_C^2$

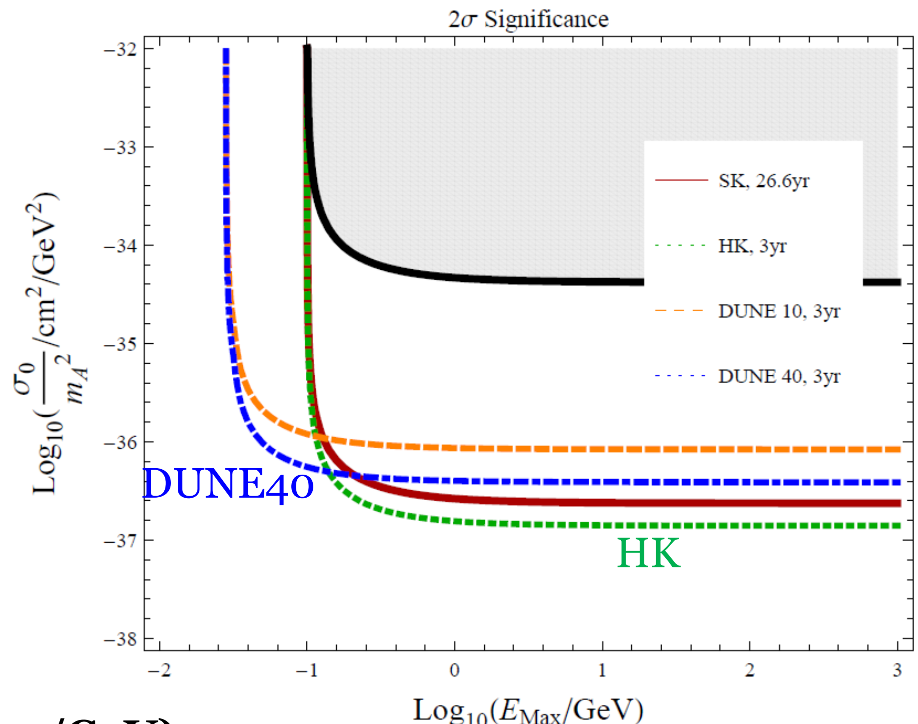
	DUNE 10	DUNE 40	SK	HK
GC	1 with 10°	4 with 10°	7.01 with 10°	174 with 10°
Point	0.01 with 1°	0.04 with 1°	0.632 with 3°	15.7 with 3°

➢ Single-ring 0-decay e-like events

Experimental Reach (GC)

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





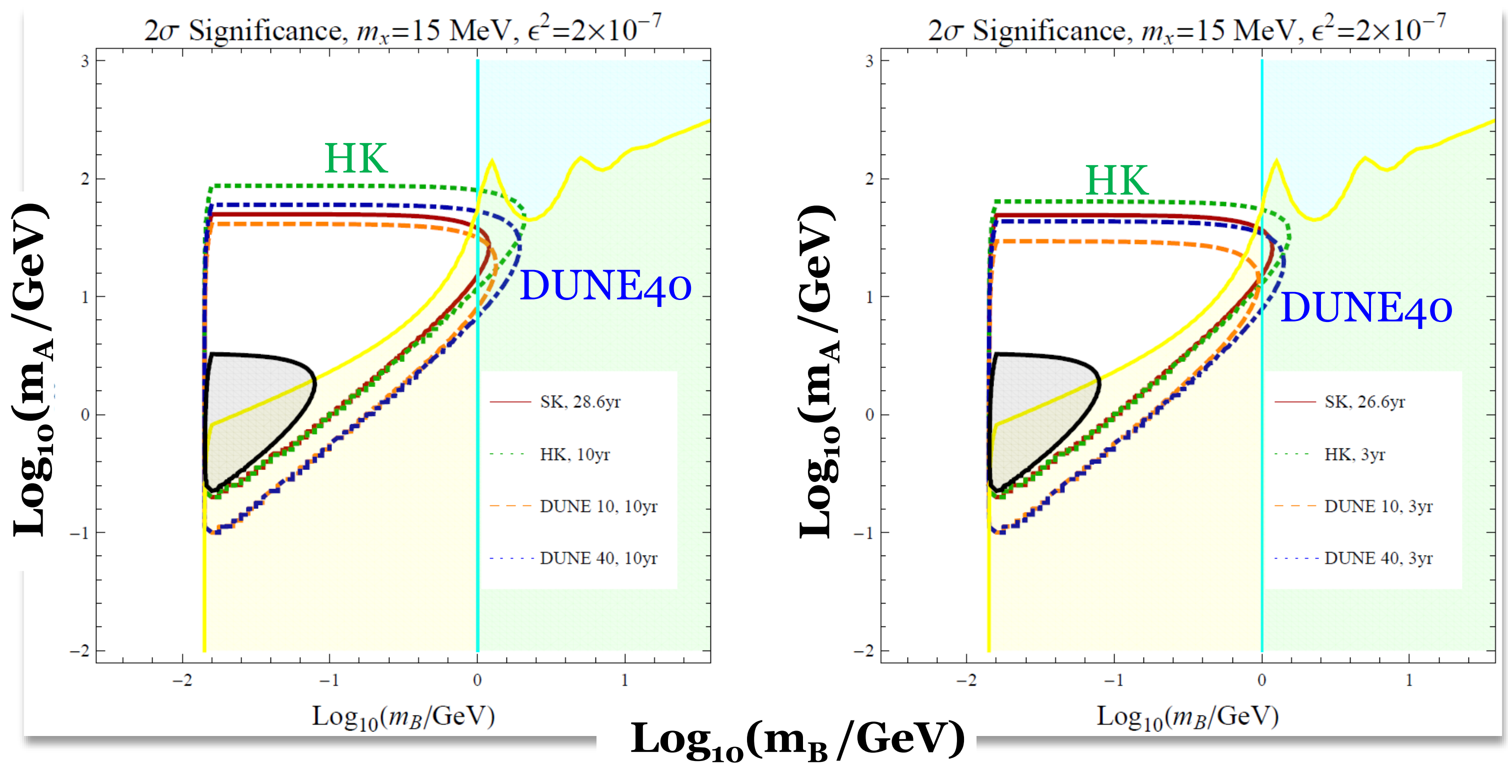
$\mathbf{Log_{10}(m_B\,/GeV)}$

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

$$\sigma = \sqrt{2(N_{\rm sig}+N_{\rm BG})\log\left(1+\frac{N_{\rm sig}}{N_{\rm BG}}\right) - 2N_{\rm sig}}$$

Experimental Reach (GC)

❖ Experimental coverage in the mass plane



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

Background Reduction

- **Point-like** source ➔ Efficient background reduction!
- $\theta_C \sim \theta_{res}$ (cf. GC: $\theta_C \sim \max\{10^o, \theta_{res}\}$) $N_{BG}^{\theta_C} = \frac{1-\cos\theta_{res}}{2} N_{BG}$ $\sim\theta_{res}^2$
- Good angular resolution is very important.

	Volume (kTon)	E_{th} (MeV)	θ_{res} (°)	Running Time (years)
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Point	0.01 with 1°	0.04 with 1°	0.632 with 3°	15.7 with 3°


Point-like Source?

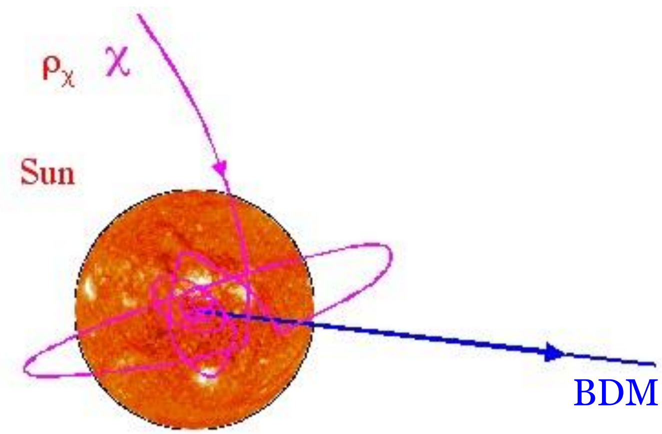
BDM from the Sun

- ❖ Self-interaction of the secluded DM ψ_A greatly enhances the capture rate 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)

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

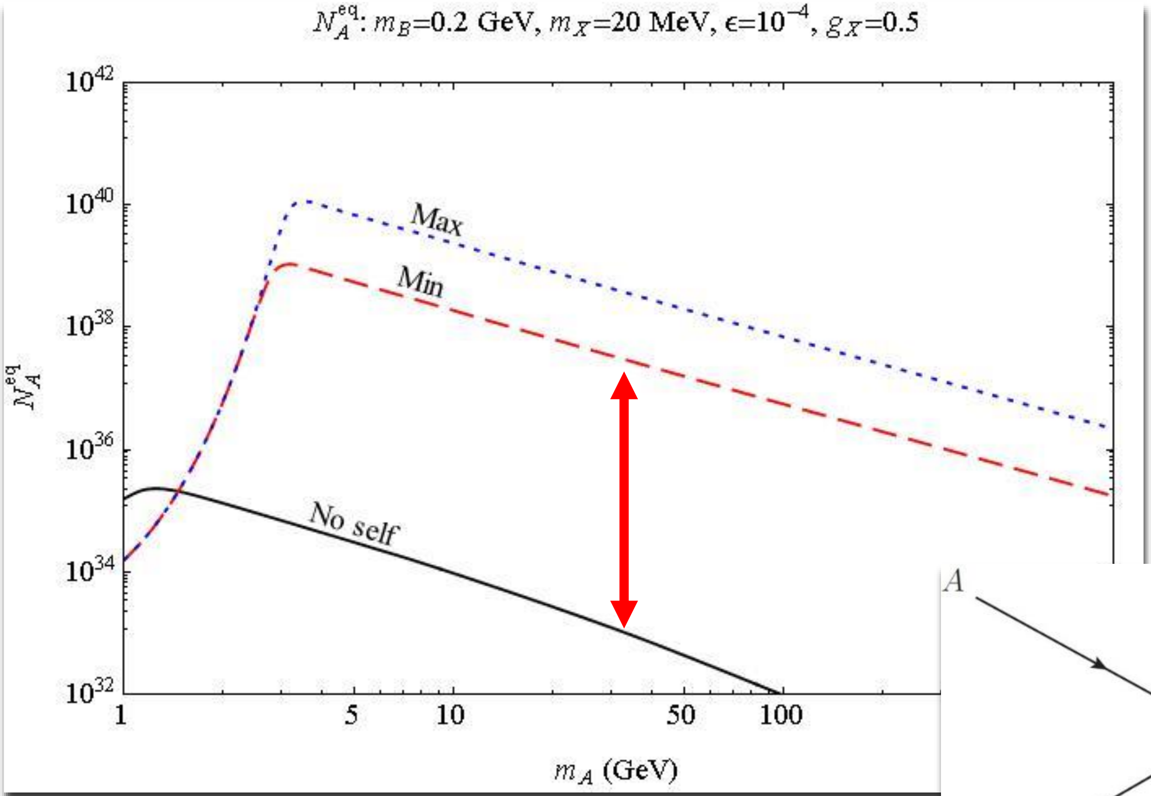
- ✓ $\mathbf{C_c}$: capture rate by nuclei inside the Sun
- ✓ $\mathbf{C_s}$: DM self-capture rate
- ✓ $\mathbf{C_e}$: evaporation rate due to DM-nuclei interaction
- ✓ $\mathbf{C_a}$: annihilation rate
- ✓ $\mathbf{C_{se}}$: evaporation rate due to DM self-interaction

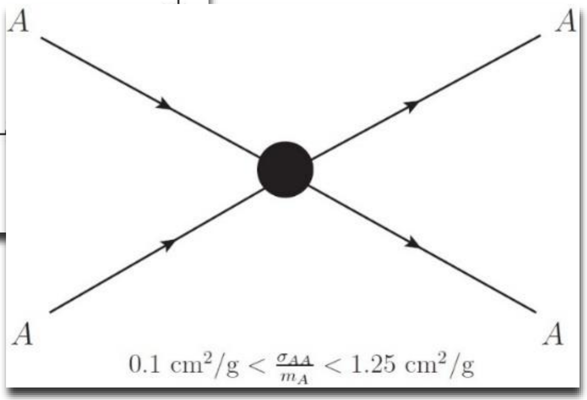


For BDM from the Sun, see also Berger et al. (arXiv:1410.2246)

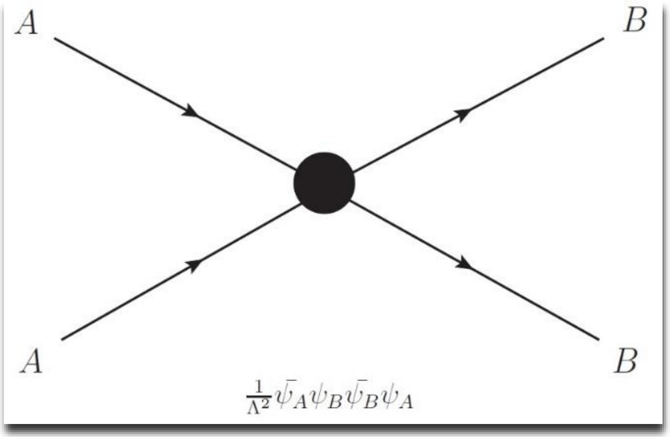
Captured Heavy DM ψ_A

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_{\rm eq})}{\tau_{\rm eq}^{-1} - (C_s - C_e)\tanh(t/\tau_{\rm eq})/2} \qquad \tau_{\rm eq} = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}}$$





Flux of BDM ψ_B from the Sun



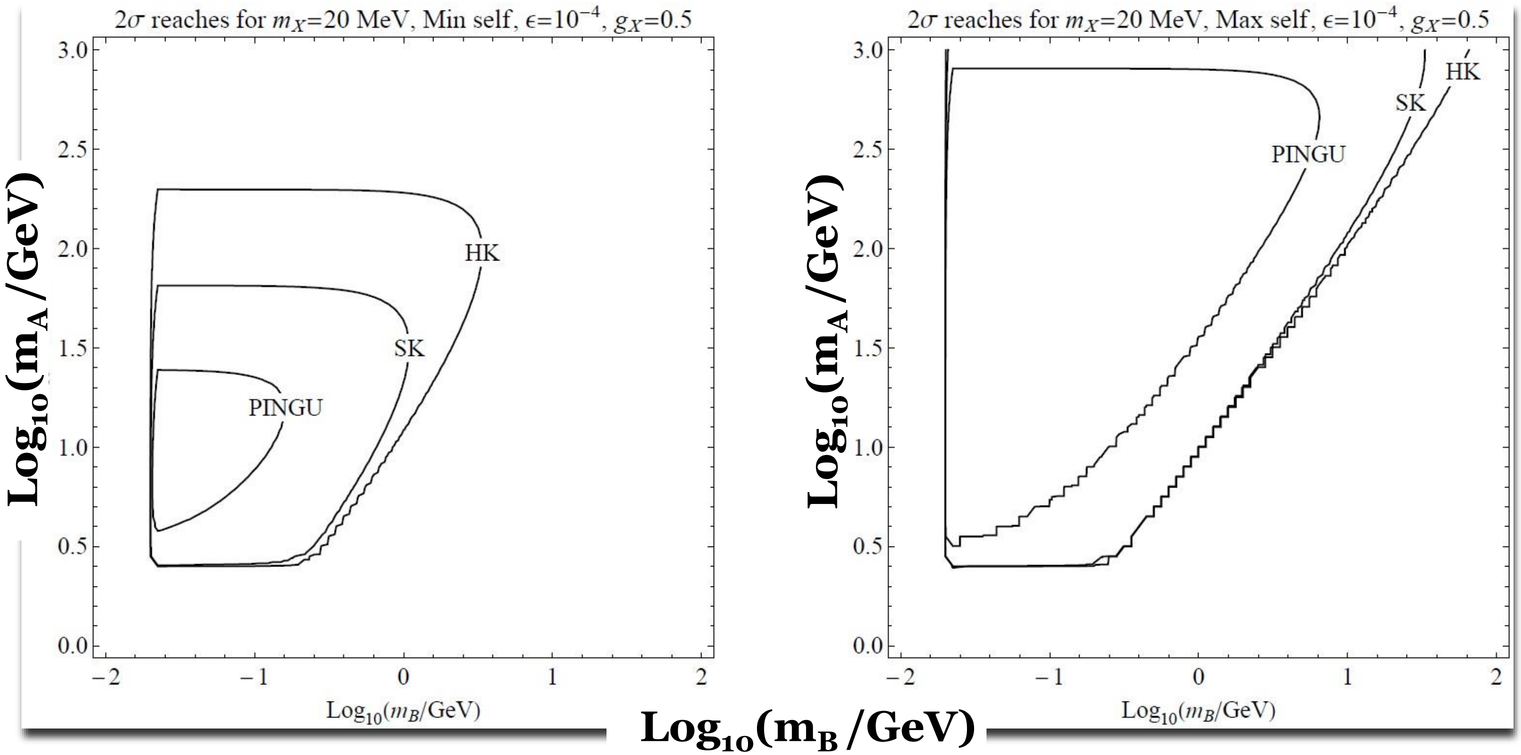
$$\frac{d\Phi_B^{\rm Sun}}{dE_B} = \frac{\Gamma_A^{\psi_A}}{4\pi R_{\rm Sun}^2}\frac{dN_B}{dE_B}$$

$$\frac{dN_B}{dE_B} = 2\delta(E_B - m_A) \qquad \Gamma_A^{\psi_A} = \frac{C_a}{2}N_{\psi_A}^2$$

- ❖ Annihilation of ψ_A produces 2 mono-energetic boosted ψ_B's.
- ❖ $\Phi_B^{\rm Sun}$ can be **comparable or even larger** than $\Phi_B^{\rm GC}$.
- ❖ We have to take into account other factors, e.g. E loss of ψ_B during propagation through the Sun ~ O(1-10 GeV).

Experimental Reach

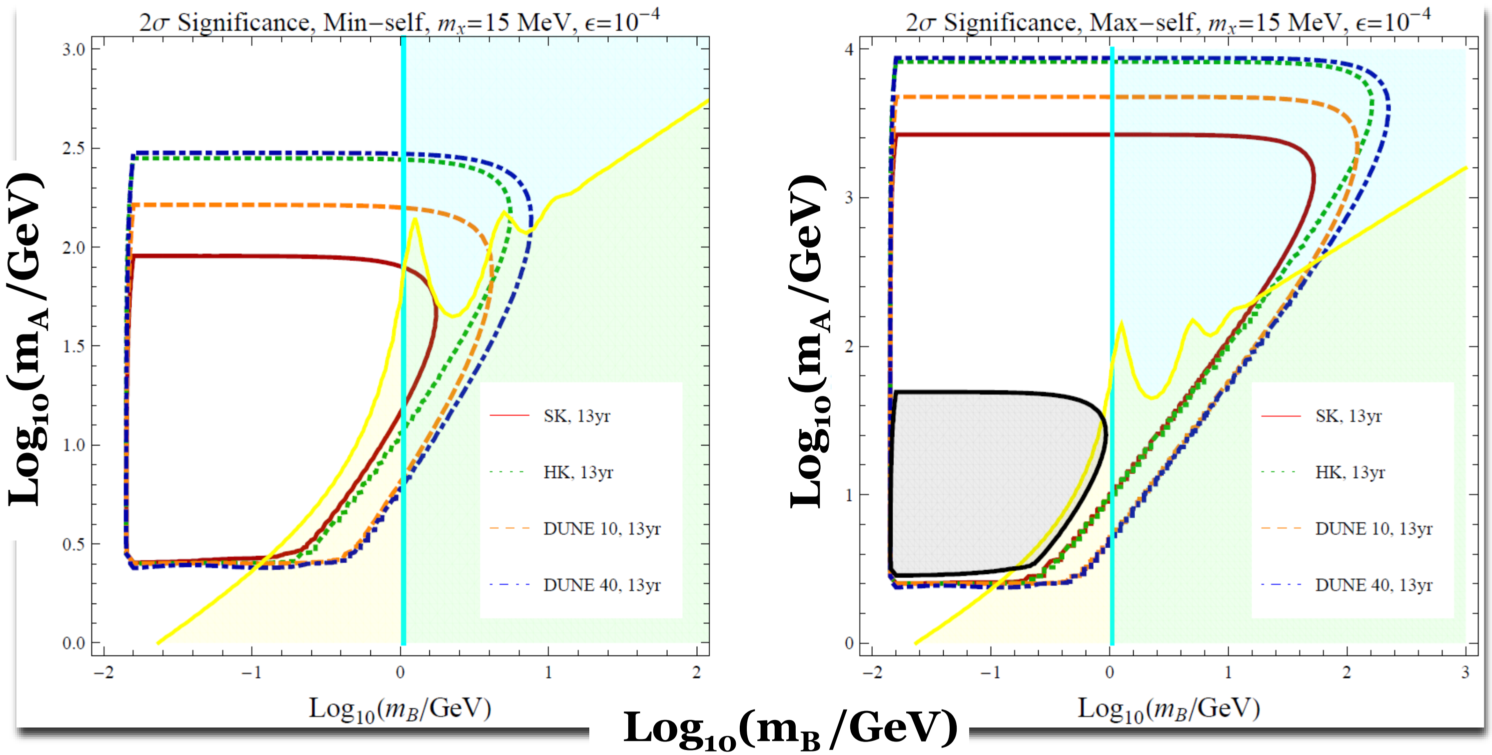
- 2σ sensitivities for ~10 years of data $N_{\rm sig} = \Delta T \, N_{\rm target} \, \Phi_B^{\rm Sun} \, \sigma_{Be^- \to Be^-}$



- ✓ Left edge: $m_B > m_X$, Top edge: $n_{DM} \sim \rho_{DM}/m_{DM}$
- ✓ Right edge: $E_{max} > E_{min}$, Bottom edge: drop in N_{ψ_A}

Experimental Reach

❖ 2σ sensitivities for 13 years of data for SK, HK, DUNE10/40



$$\sigma = \sqrt{2(N_{\text{sig}} + N_{\text{BG}}) \log\left(1 + \frac{N_{\text{sig}}}{N_{\text{BG}}}\right) - 2N_{\text{sig}}}$$

Conclusion & Future

- **Boosted DM(BDM)** ($v \sim c$): Generic in non-minimal DM sector
- **Direct** detection of light BDM ➔ **Indirect** detection of heavy DM
- Small flux ➔ **Larger** volume ($V_{\rm eff}$)
- Reduction of ν background ➔ **smaller** angular resolution ($\theta_{\rm res}$)
- **Hyper-K/DUNE40** are so far the best experiments for BDM detection.
- **IceCube/PINGU** with $V_{\rm eff}(E)$ & $\theta_{\rm res}(E)$ ➔ Improving $S/\sqrt{B}$

Thank you