Detection of *Boosted* DM

K.C. Kong, G. Mohlabeng & **JCP**

[arXiv: 1411.6632]

Jong-Chul Park

성균관대학교
SUNG KYUN KWAN UNIVERSITY

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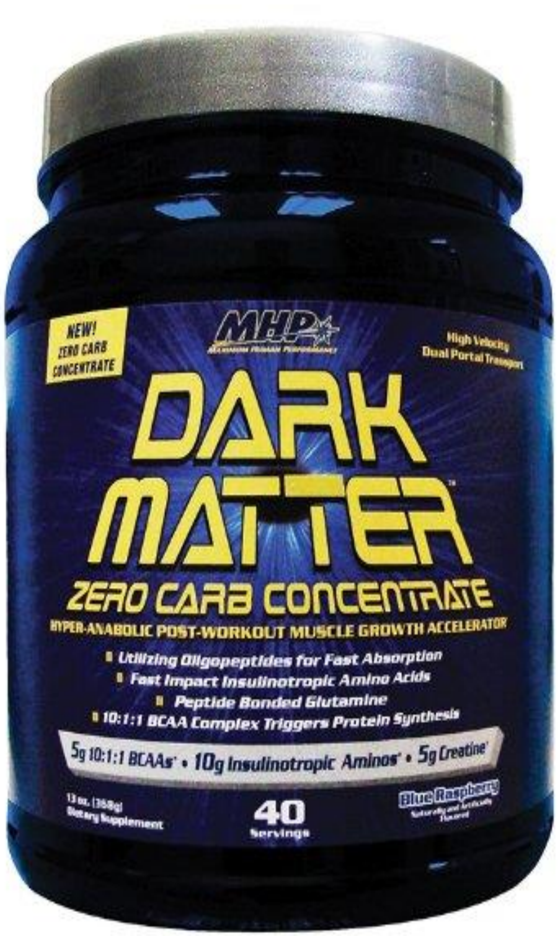
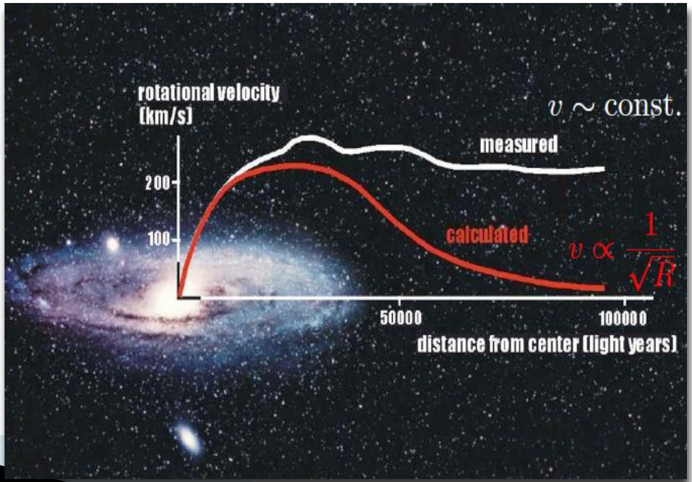


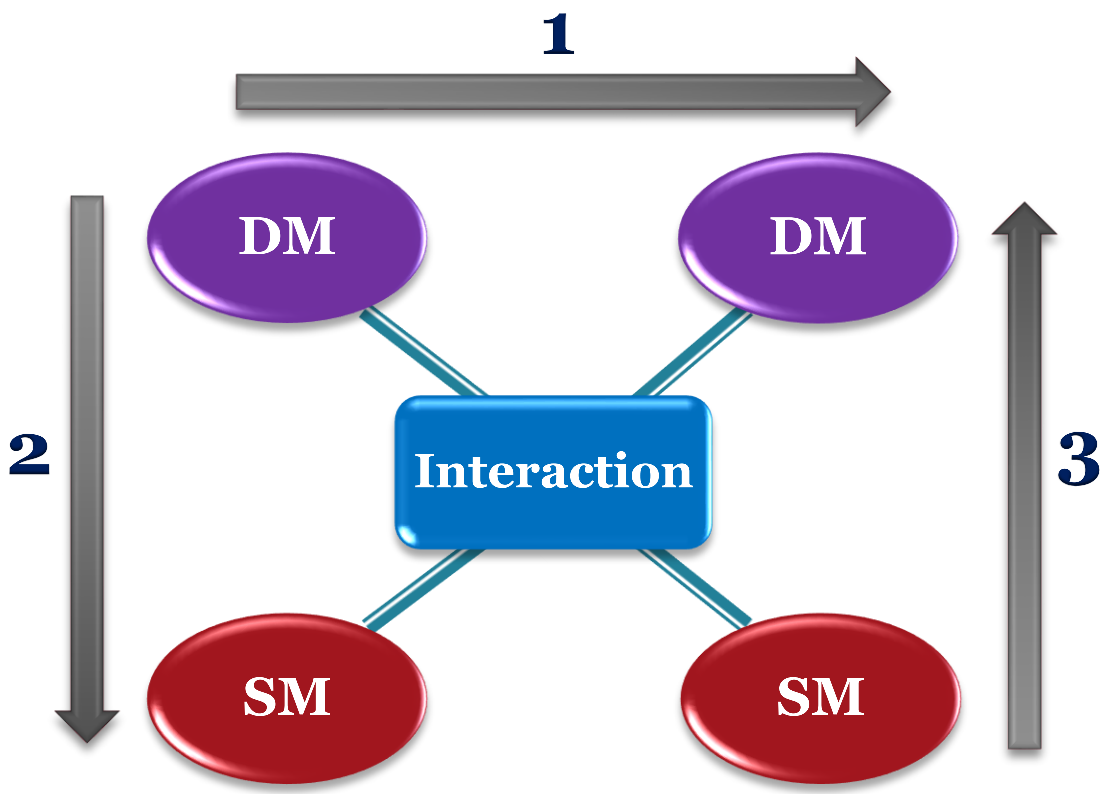
What's Dark Matter?

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
  - ✓ ...

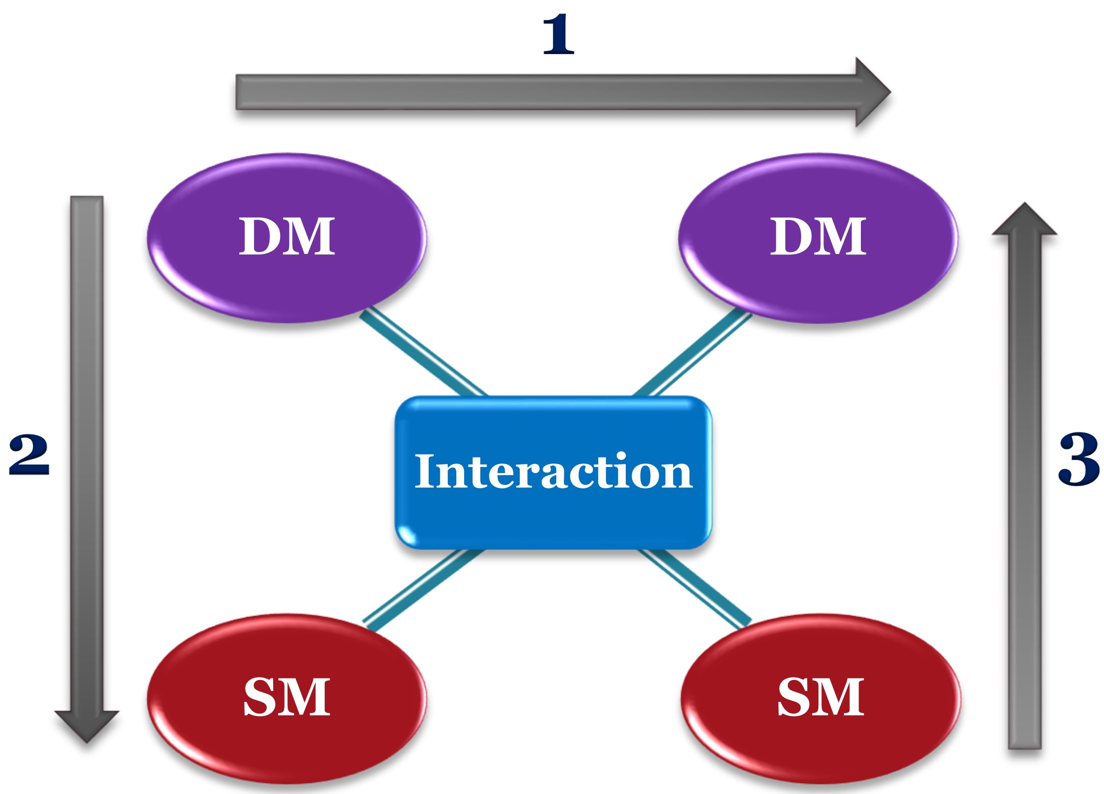


DM Search Strategies



- **1**: Direct detection
- **2**: Indirect detection
- **3**: Production at colliders

DM Search Strategies



- **1**: Direct detection
- **2**: Indirect detection
- **3**: Production at colliders

- Current day DM: non-relativistic, $v/c \sim 10^{-3}$
  - ✓ **1**: small nuclear recoil energy
  - ✓ **2**: nearly at rest annihilation to SM states

What’s Boosted DM?

Boosted DM (BDM)

Agashe et al. (2014)

- ❖ Generic phenomena in non-minimal DM sector:

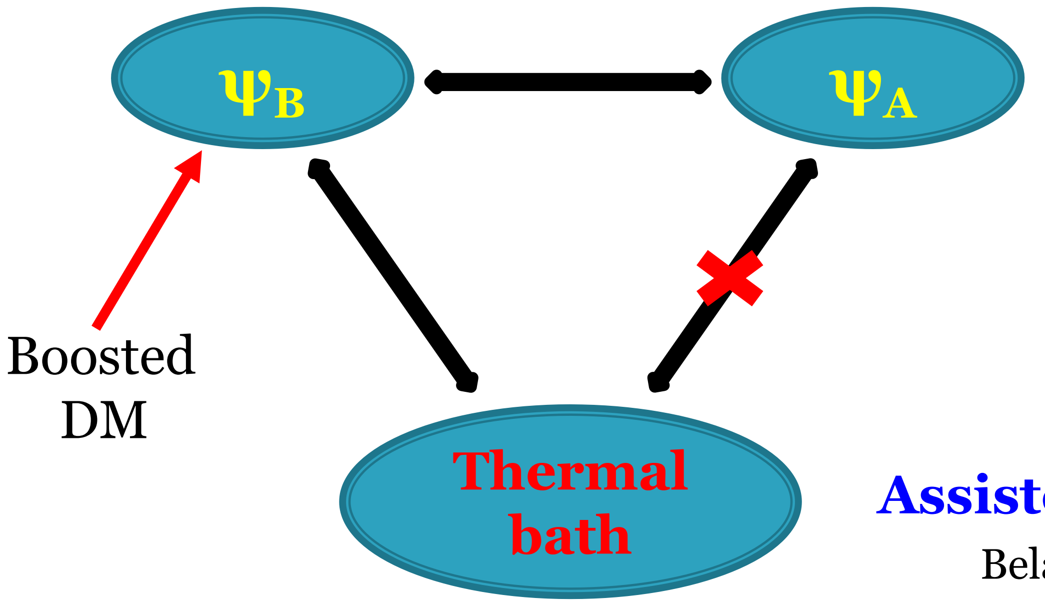
  Late-time processes ➔ Small fraction of DM today is relativistic.

- ❖ 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 (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:
  - ✓ Reveal non-minimal features of DM sector
  - ✓ Conventional DM searches ➔ Unsuitable ➔ New Search Strategies!

Basic Set-up

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



Assisted Freeze-out

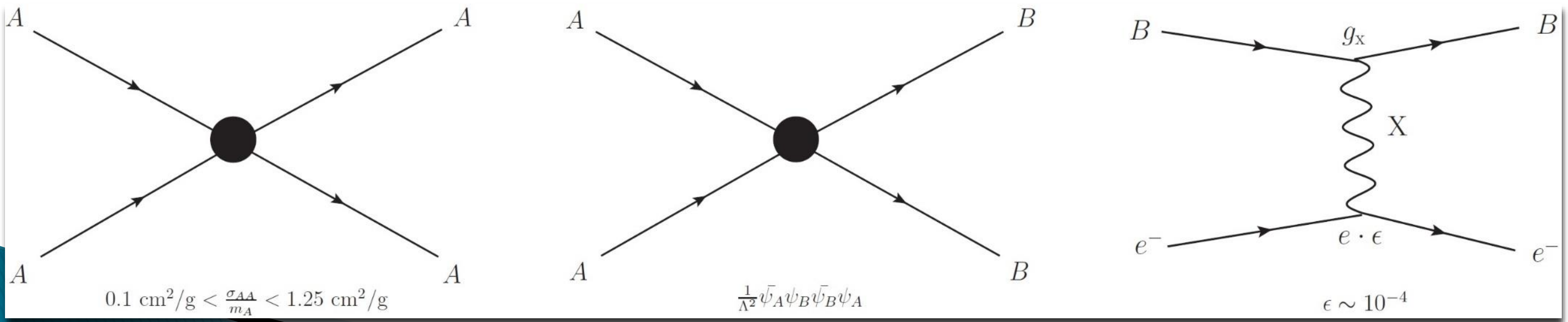
Belanger & **JCP** (2011)

Basic Features

- Relic density of ψ_A is set by $\psi_A\overline{\psi}_A \rightarrow \psi_B\overline{\psi}_B$
- Detection of ψ_A: no-direct coupling to the SM ➔ X
- Detection of relic ψ_B: small relic ➔ X
- Annihilation products ψ_B: boosted with Lorentz factor $\gamma=m_A/m_B$

  ➔ Boosted DM!
- Detection of boosted ψ_B ➔ Indirect detection of ψ_A

  ➔ Smoking-gun of DM sector!



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- Detection of ψ_A: no-direct coupling to the SM ➔ X
- Detection of relic ψ_B: small relic ➔ X

New detection Method!

- Annihilation products ψ_B: boosted with Lorentz factor $\gamma = m_A/m_B$

  ➔ Boosted DM!

- Detection of boosted ψ_B ➔ Indirect detection of ψ_A

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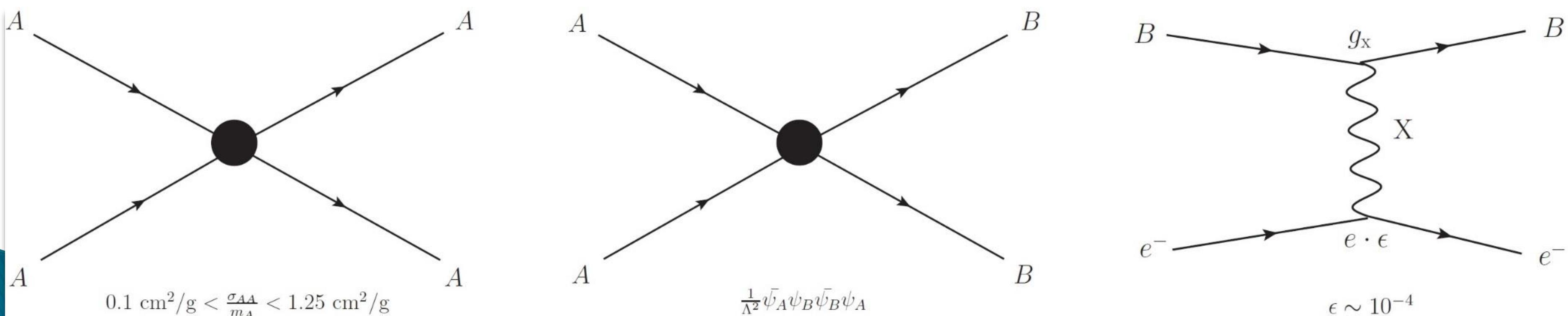
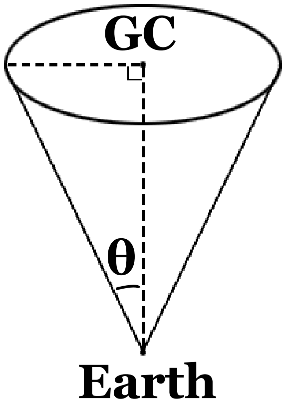


BDM from Galactic Center

❖ Agashe et al. (arXiv:1405.7370) examined flux of boosted ψ_B by the annihilation of ψ_A from the Galactic Center (GC).

❖ Flux: NFW profile + 10° cone around GC

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



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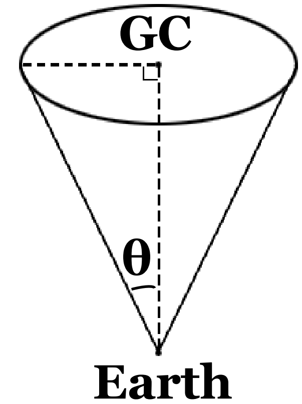

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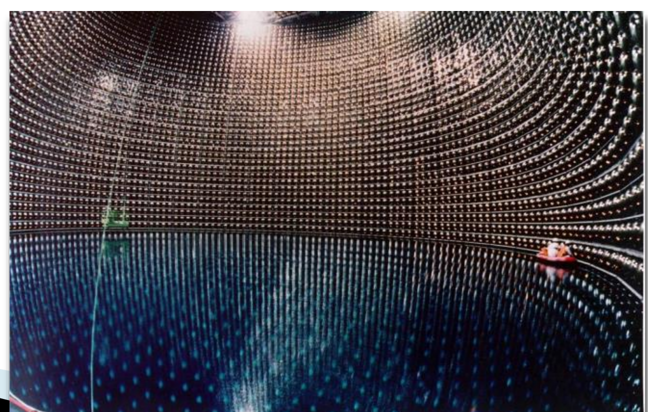
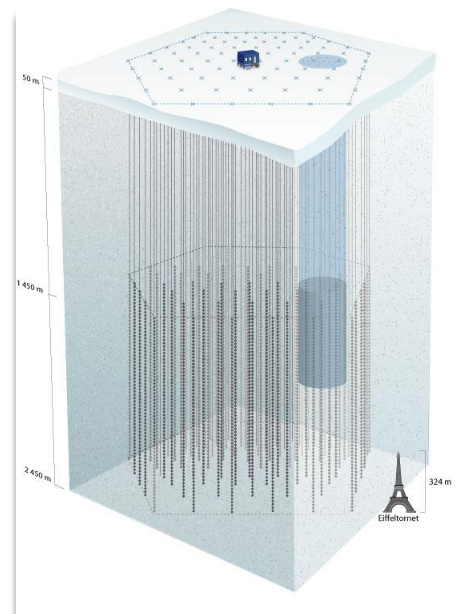
- Small flux ➔ Large volume detector sensitive to ψ_B +SM → ψ_B +SM

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

  Future: Hyper-K, PINGU, ...

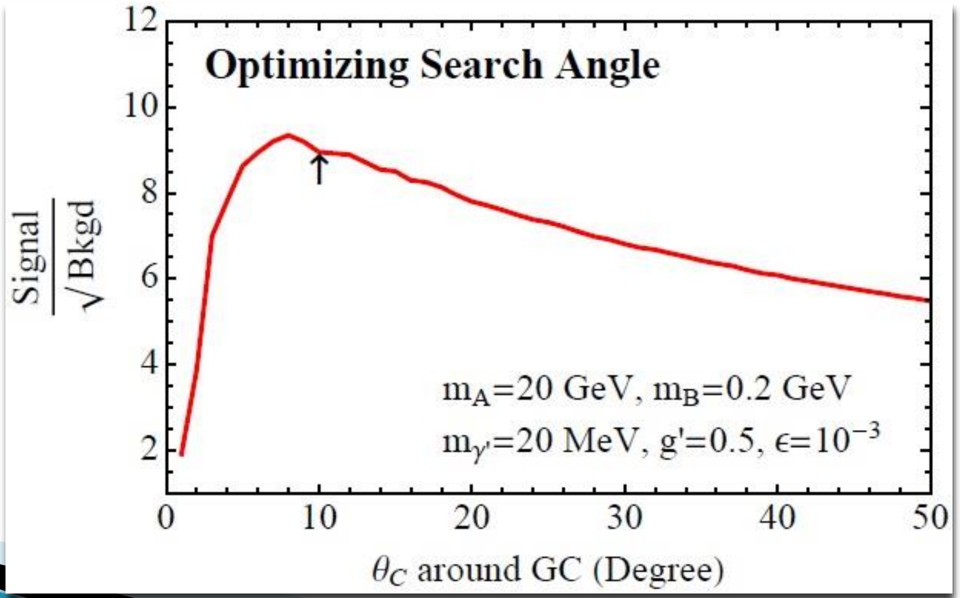




Background & its Rejection

- Major background: atmospheric neutrinos $\nu_e n \rightarrow e^- p$
  - ➔ Almost uniform in the entire sky!
- Background reduction: governed by angular resolution of an experiment
- θ_{min} ~ 10° : optimal angle for S/√B due to the DM halo distribution

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



Agashe et al. (2014)


Point-like Source?

BDM from the Sun

Kong, Mohlabeng & **JCP** (2014)

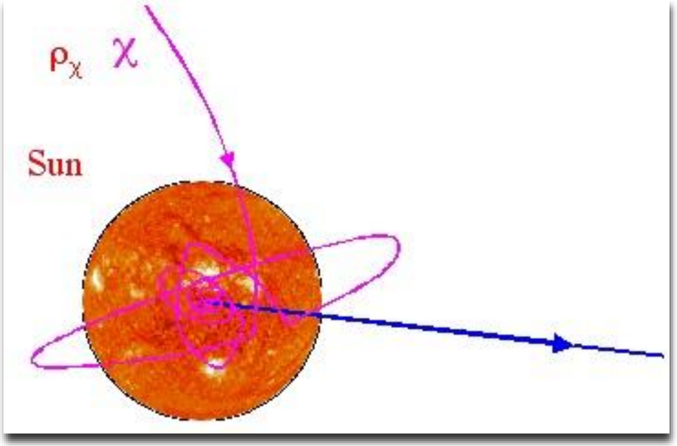
❖ Self-interaction of the secluded DM greatly enhances the capture rate in the Sun ➔ The Sun becomes a point-like source of BDM

❖ 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
- ✓ $\mathbf{C_s}$: self-capture rate
- ✓ $\mathbf{C_e}$: evaporation rate due to the self-interaction
- ✓ $\mathbf{C_a}$: annihilation rate
- ✓ $\mathbf{C_{se}}$: evaporation rate due to the self-interaction



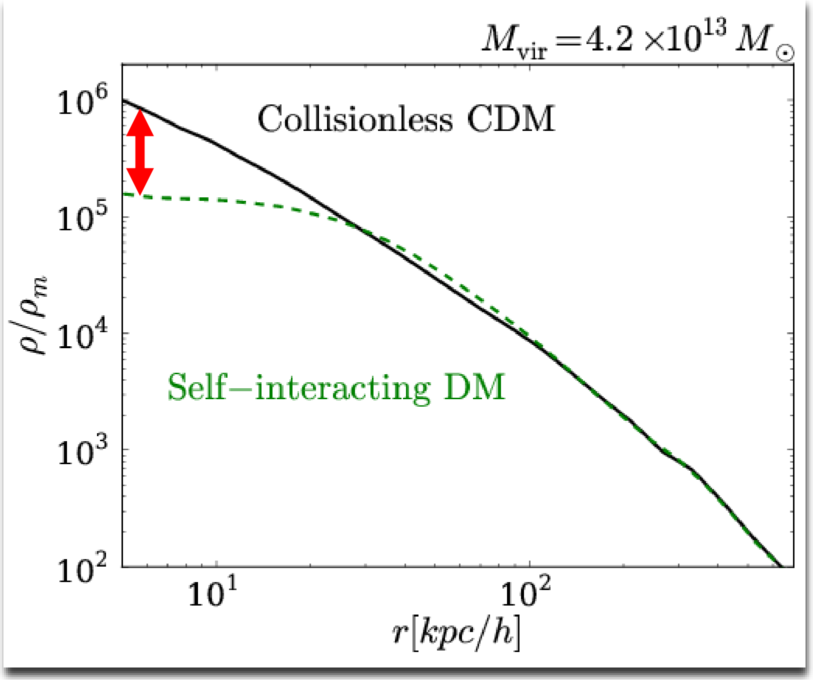
For BDM from the Sun, see also Berger et al. (arXiv:1410.2246)

Self-Interacting DM (SIDM)

- Simulations with SIDM show that SIDM with $\sigma_{\chi\chi}/m_\chi \sim \mathcal{O}(0.1 - 1\,\mathrm{cm}^2/\mathrm{g})$ can reconcile simulations & observations at small scales while not changing CDM behavior at large scales.

Upper limit

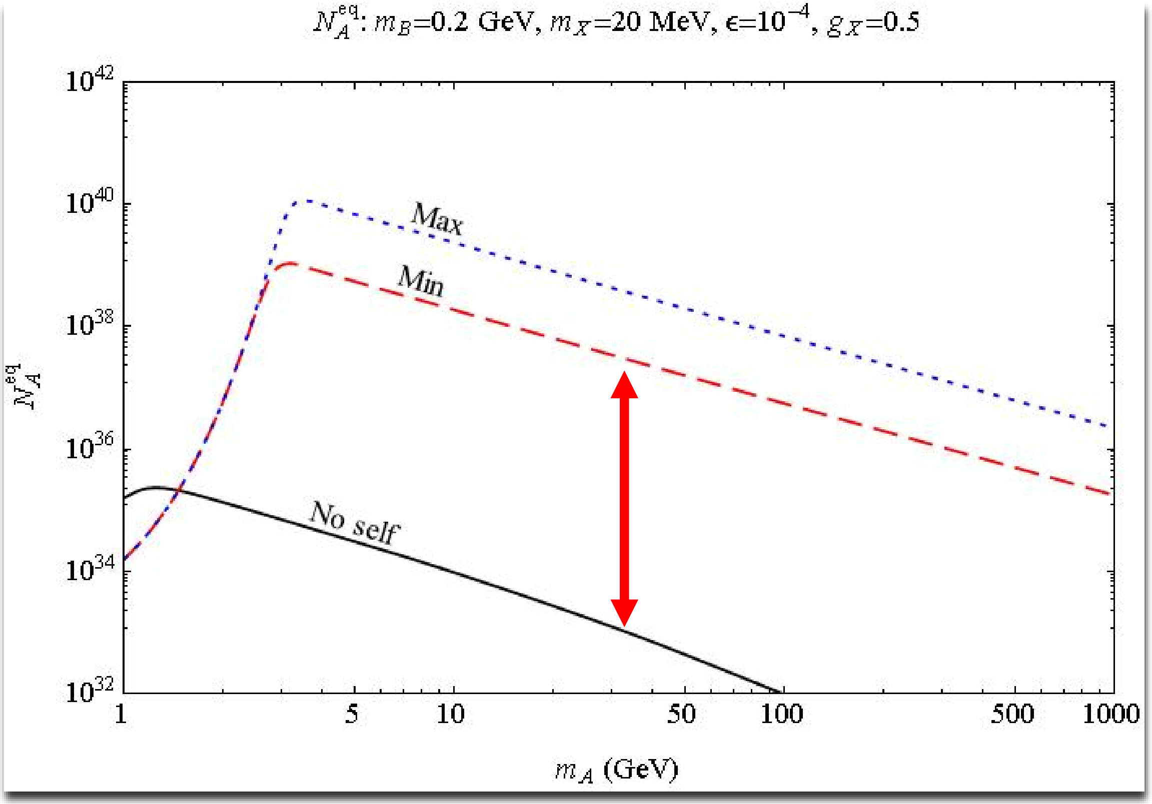
- "Cusp vs Cored" problem:
  - CDM N-body simulations present steep cusp profile.
  - Dwarf galaxies indicate cored profile.
- "Too big to fail" problem:
  Satellites of Milky-way type galaxies have less DM than N-body simulations.



Captured Heavy DM ψ_A

Kong, Mohlabeng & **JCP** (2014)

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



Flux of BDM ψ_B from the Sun

Kong, Mohlabeng & **JCP** (2014)

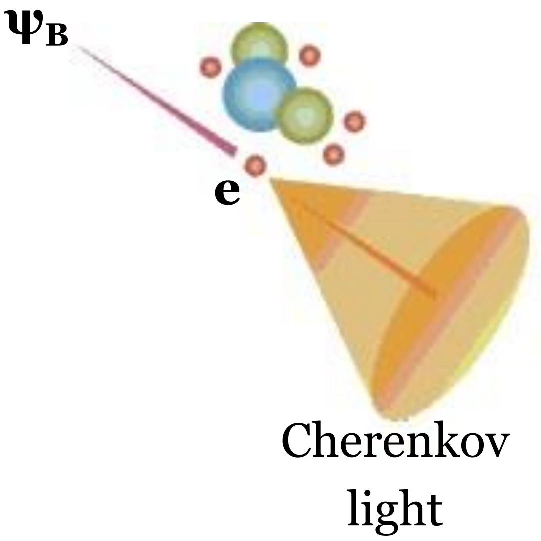
$$\frac{d\Phi_B^{\rm Sun}}{dE_B} = \frac{\Gamma_A^{\psi_A}}{4\pi R_{\rm Sun}^2} \frac{dN_B}{dE_B}$$

$$\frac{dN_B}{dE_B} = 2\delta(E_B - m_A)$$

- ❖ Annihilation of ψ_A produces 2 mono-energetic boosted ψ_B's.
- ❖ We have to take into account other factors, e.g. E loss of ψ_B during propagation through the Sun ~ O(1-10 GeV).

Detection of BDM

- ❖ Large volume ν detectors can detect energetic charged particles from ν-matter collisions.
- ❖ Boosted DM: energetic e's resulting from $\psi_B e^- \to \psi_B e^-$
- ❖ Energetic e's would emit Cherenkov light



Background Reduction

Kong, Mohlabeng & **JCP** (2014)

- Sun: Point-like source ➔ Efficient background reduction! (GC: θ_{min} ~ 10°)

$$N_{\rm BG}^{\theta_{\rm res}} = \frac{1-\cos\theta_{\rm res}}{2} N_{\rm BG}$$

$$\text{Super-K}: \frac{N_{\rm BG}^{3^\circ}}{\Delta T} = 0.63/\text{year}$$

$$\text{Hyper-K}: \frac{N_{\rm BG}^{3^\circ}}{\Delta T} = 15.8/\text{year}$$

$$\text{PINGU}: \frac{N_{\rm BG}^{23^\circ}}{\Delta T} = 562/\text{year}$$

- Good angular resolution is very important.

Experiment	Volume (MTon)	$E_e^{\rm thresh}$ (GeV)	$\theta_e^{\rm res}$ (degree)
Super-K	2.24×10^{-2}	0.01	3°
Hyper-K	0.56	0.01	3°
IceCube	10^3	100	30°
PINGU	0.5	1	23° (at GeV scale)

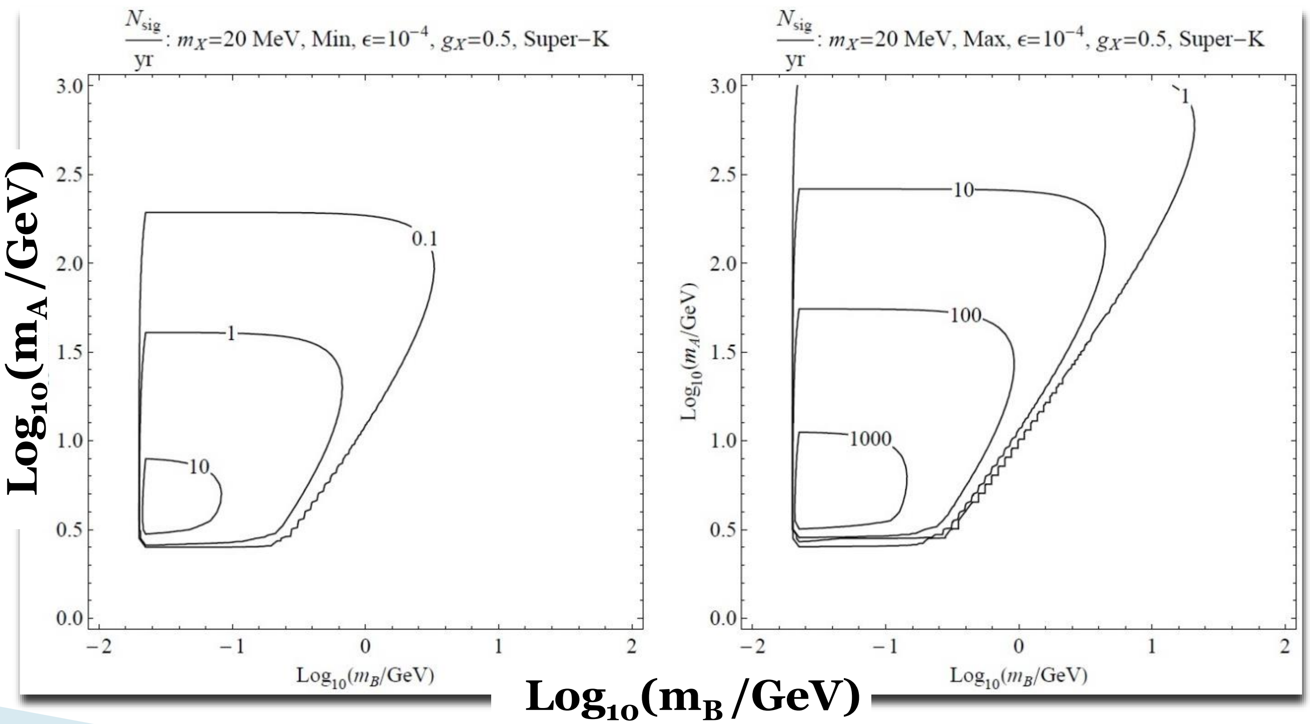
Signal Rates

Kong, Mohlabeng & **JCP** (2014)

- Total number of signal events:

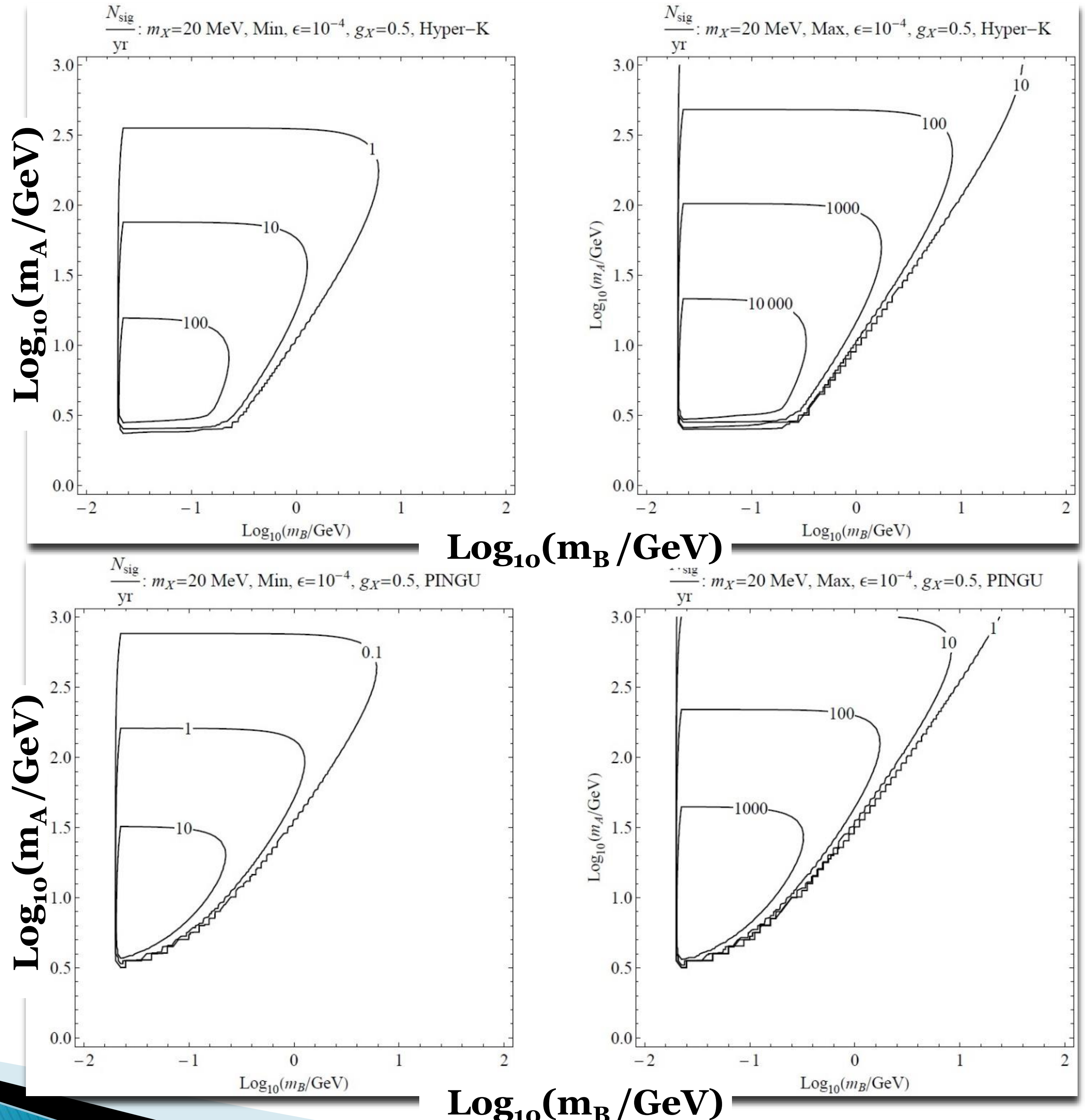
$$N_{\rm sig} = \Delta T\, N_{\rm target}\, \Phi_B^{\rm Sun}\, \sigma_{Be^- \to Be^-}$$
$$= \Delta T\, \frac{10\,\rho_{\rm target}\, V_{\rm exp}}{m_{\rm H_2O}}\, \frac{2\Gamma_A^{\psi_A}}{4\pi R_{\rm Sun}^2} \int_{E_e^{\rm min}}^{E_e^{\rm max}} dE_e\, \frac{d\sigma_{Be^- \to Be^-}}{dE_e}$$

SK



HK

PINGU



$\frac{N_{sig}}{yr}$: m_X=20 MeV, Min, $\epsilon=10^{-4}$, g_X=0.5, Hyper–K
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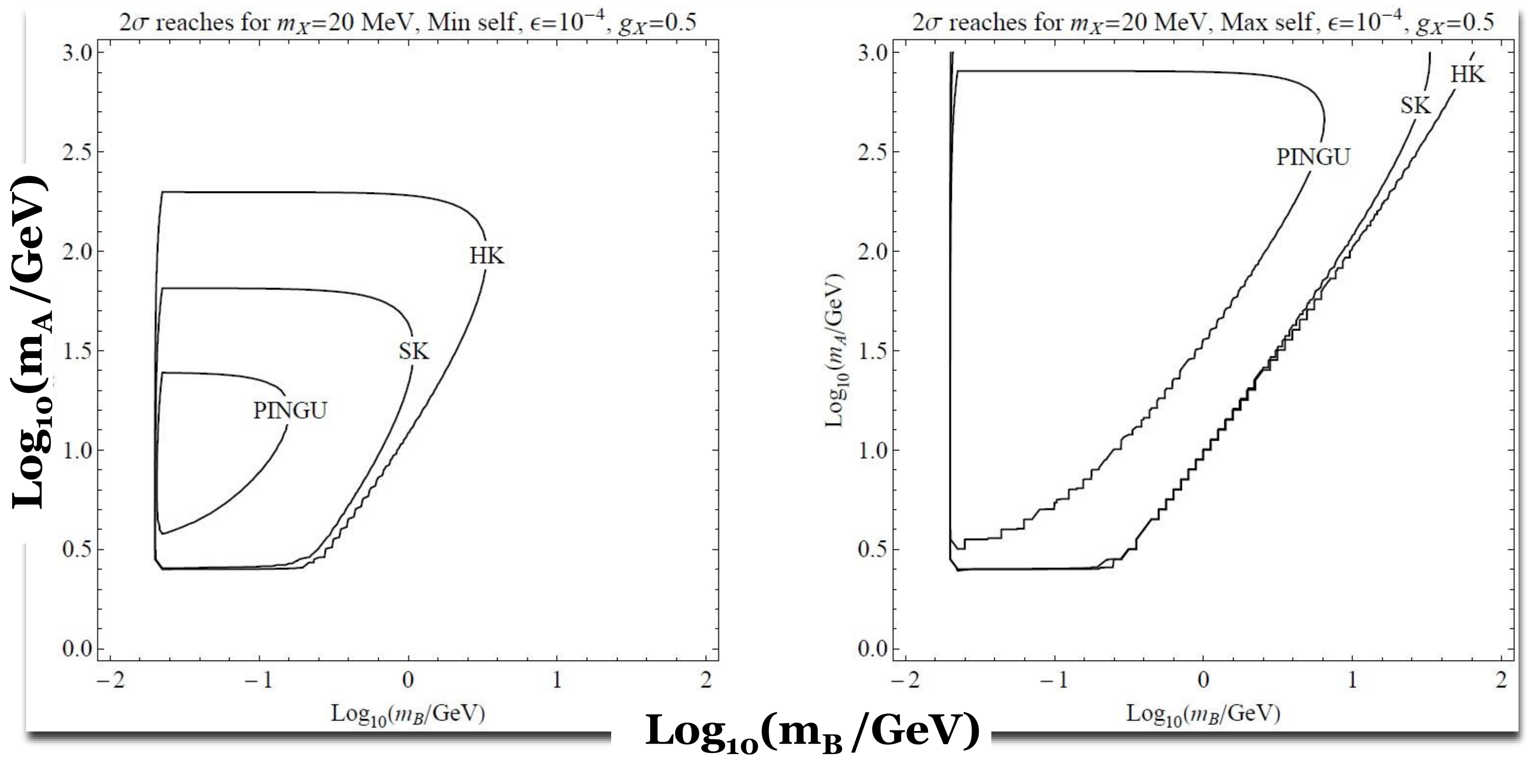
$\frac{N_{sig}}{yr}$: m_X=20 MeV, Max, $\epsilon=10^{-4}$, g_X=0.5, PINGU
$Log_{10}(m_A/GeV)$
$Log_{10}(m_B/GeV)$

Experimental Reach

❖ 2σ sensitivities for ~10 years of data

Kong, Mohlabeng & **JCP** (2014)

$$S^{\theta_{\rm res}} \equiv \frac{N_{\rm sig}}{\sqrt{N_{\rm BG}^{\theta_{\rm res}}}}$$



✓ 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}

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_{eff})
- Reduction of ν background ➔ **smaller** angular resolution (θ_{res})
- **Hyper-K** is so far the best experiment for BDM detection.
- **IceCube/PINGU** with $V_{eff}(E)$ & $\theta_{res}(E)$ ➔ Improving $S/\sqrt{B}$

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Thank you

Back-Up

Model Parameter Space

- Defined by 7 parameters $\{m_A, m_B, m_X, \Lambda, g_X, \epsilon, \sigma_{AA}\}$
- Λ: adjusted to yield $\Omega_A \approx \Omega_{DM} \approx 0.2$
- ψ_B +SM → ψ_B +SM: scales homogeneously with g_X & ε

  → Dominant phenomenology depends on mass parameters

Boosted DM from GC

Agashe et al. (2014)

❖ Flux of boosted ψ_B from the Galactic center (GC)

$$\frac{d\Phi_{\rm GC}}{d\Omega\, dE_B} = \frac{1}{4}\frac{r_{\rm Sun}}{4\pi}\left(\frac{\rho_{\rm local}}{m_A}\right)^2 J \, \langle \sigma_{A\overline{A}\to B\overline{B}} v\rangle_{v\to 0}\frac{dN_B}{dE_B}$$

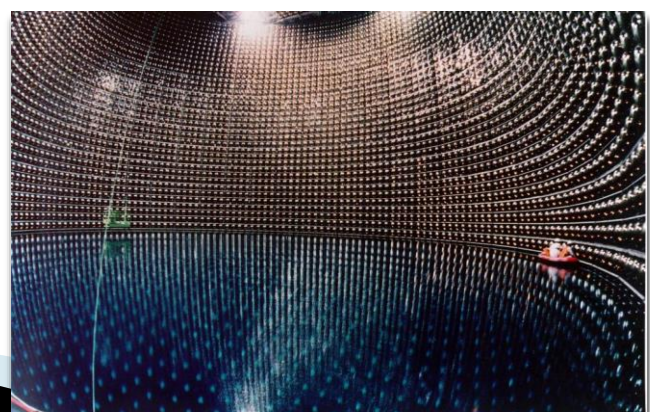
❖ Assuming NFW profile, integrate over 10° cone around GC

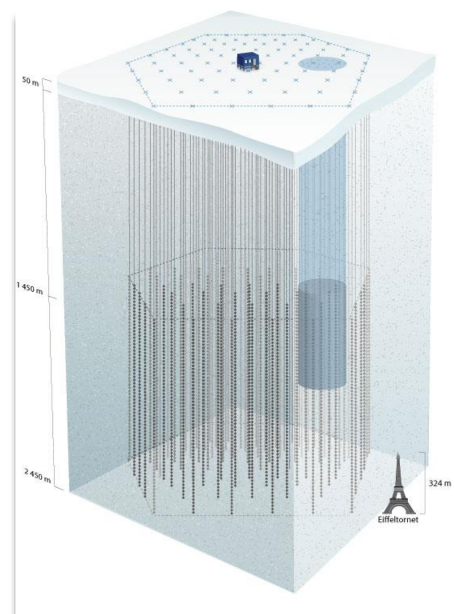
$$\Phi_{\rm GC}^{10^\circ} = 9.9\times 10^{-8}\ {\rm cm^{-2}s^{-1}}\left(\frac{\langle\sigma_{A\overline{A}\to B\overline{B}} v\rangle}{5\times 10^{-26}\ {\rm cm^3/s}}\right)\left(\frac{20\ {\rm GeV}}{m_A}\right)^2$$

❖ Small flux → Large volume detector sensitive to ψ_B +SM → ψ_B +SM

→ Neutrino detectors: Super-K, IceCube, …

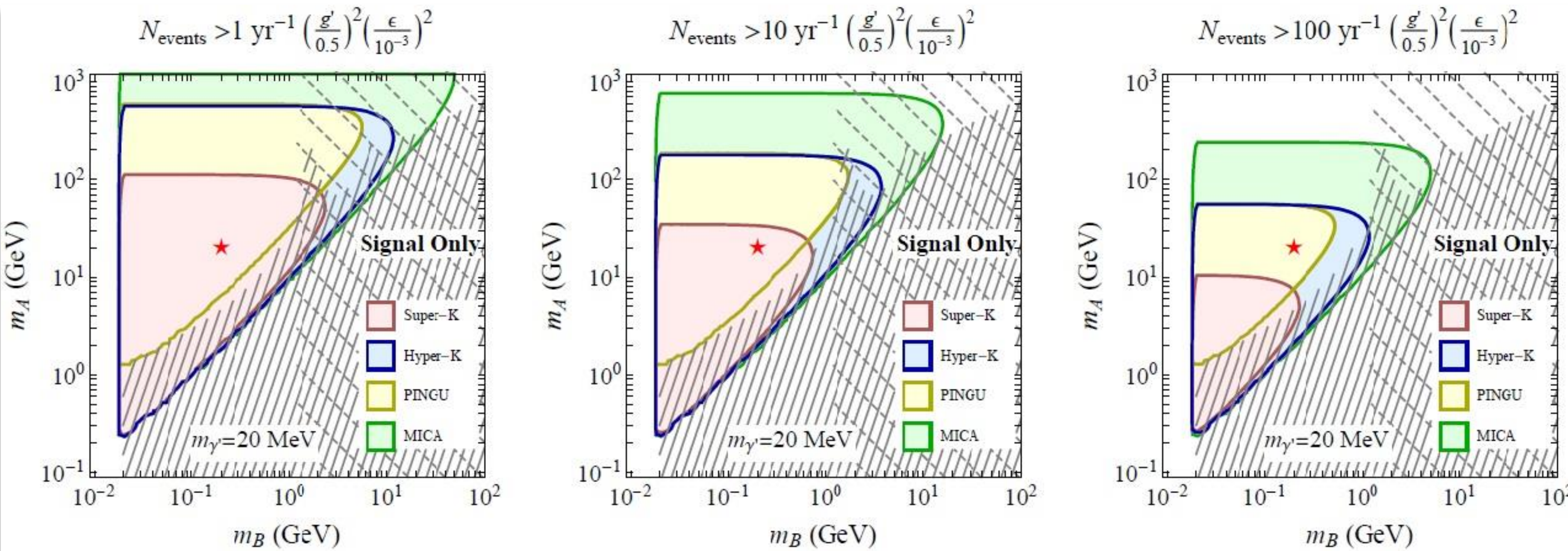
Future: Hyper-K, PINGU, …





Signal Rates

❖ Total number of signal events: $N^{\theta_C}_{\text{signal}} = \Delta T\, N_{\text{target}} \left(\Phi_{\text{GC}} \otimes \sigma_{Be^- \to Be^-}\right)\big|_{\theta_C}$



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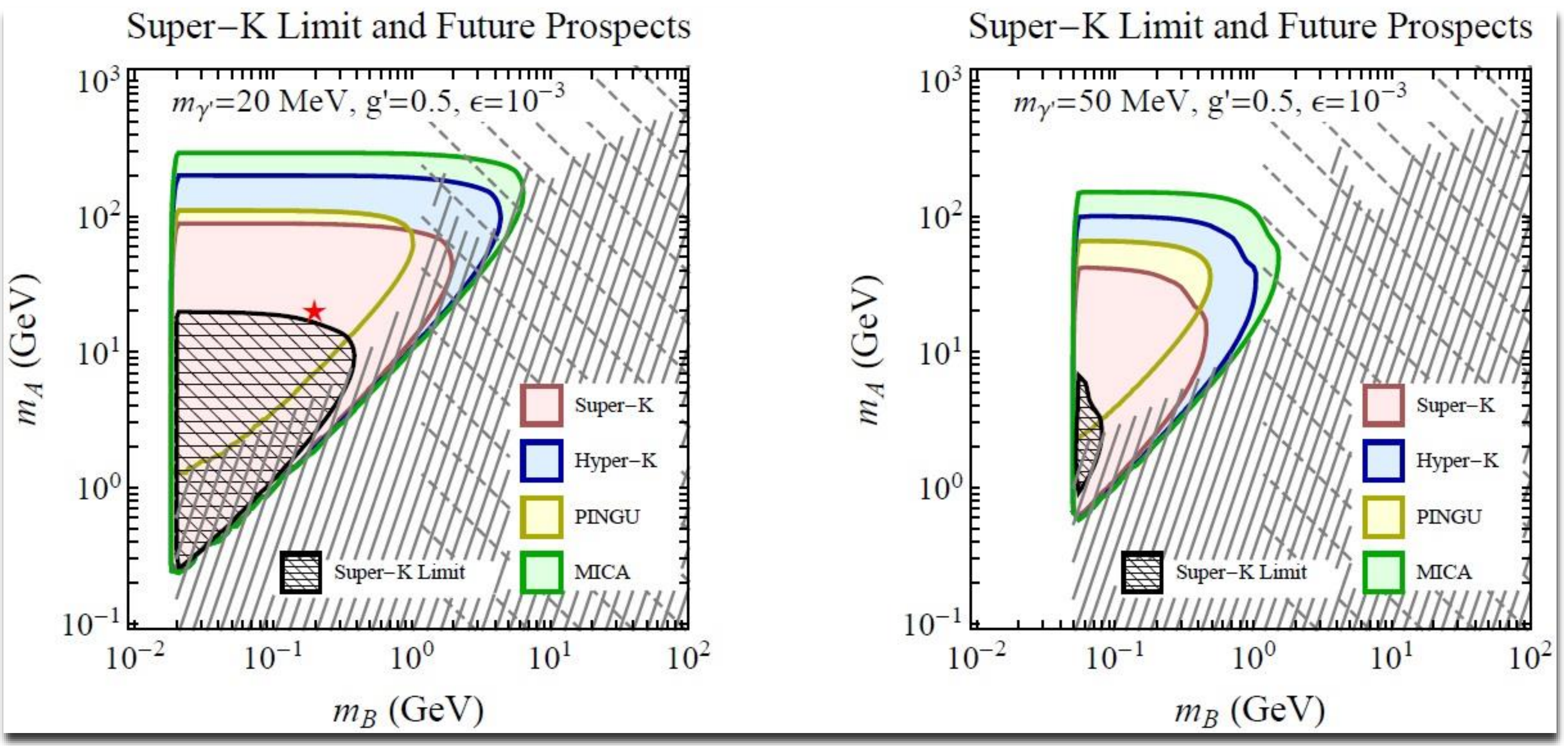
IceCube	10^3	100	30°
PINGU	0.5	1	23°(at GeV scale)
MICA	5	0.01	30°(at 10 MeV scale)

Agashe et al. (2014)

Experimental Reach

❖ 2σ exclusion limit using Super-K ~10-year all-sky data



Agashe et al. (2014)