Boosted Dark Matter at the Deep Underground Neutrino Experiment

Haider Alhazmi
University of Kansas

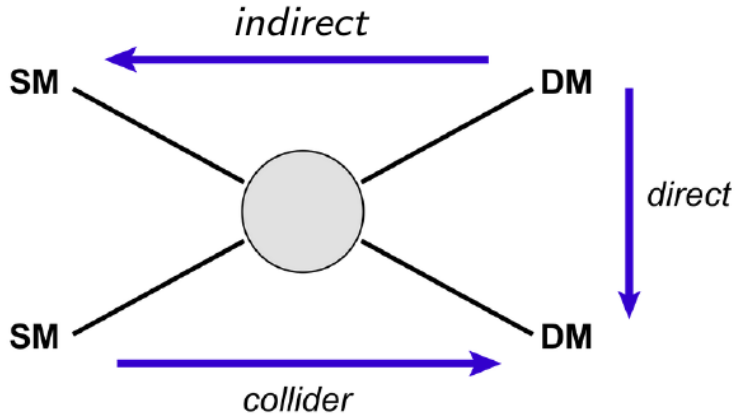
with K. Kong, G. Mohlabeng and J. C. Park

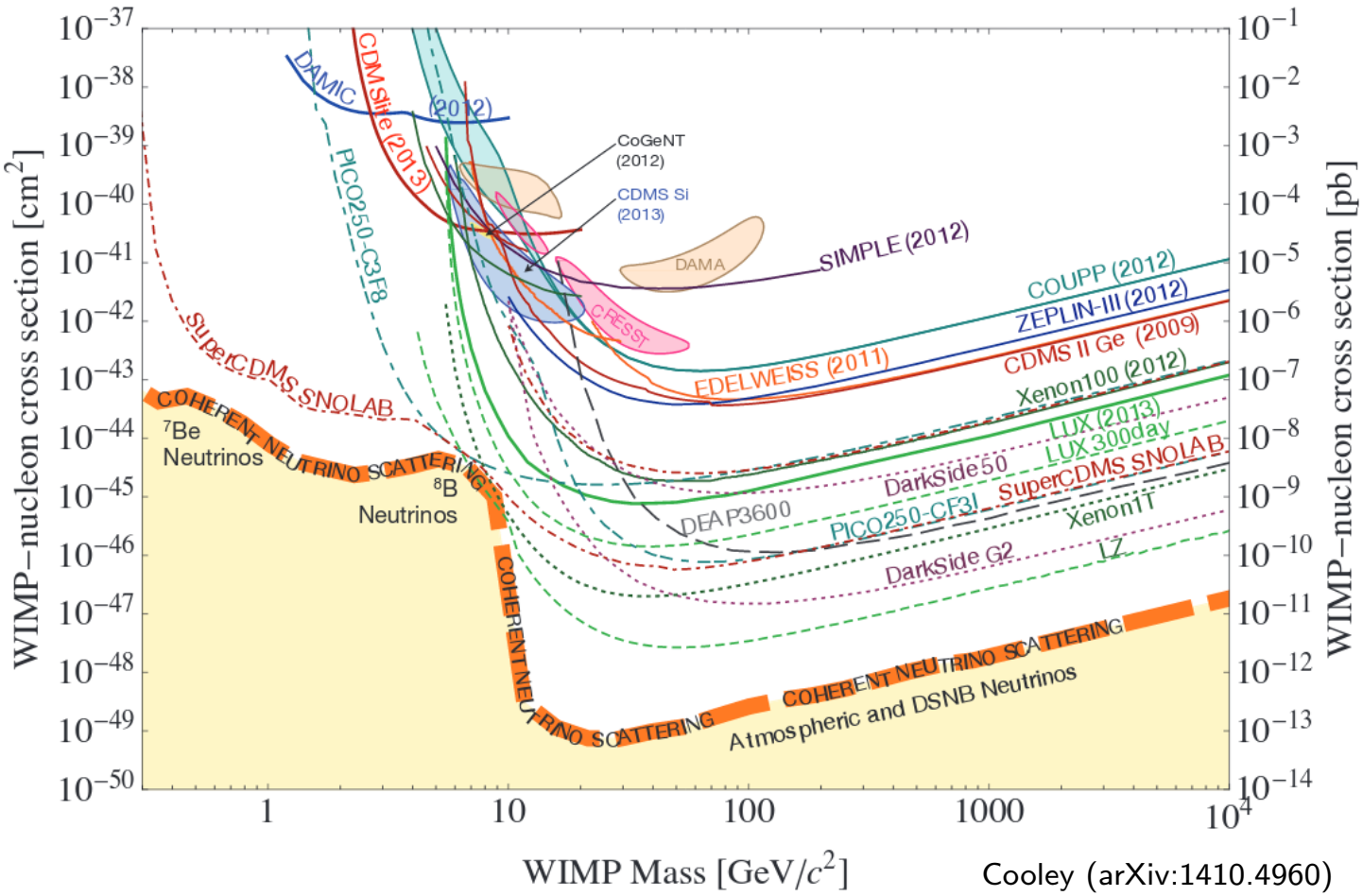
May 10, 2017

JHEP 1704 (2017) 158, (arXiv:1611.09866)

What is Dark Matter?

How to detect Dark Matter?

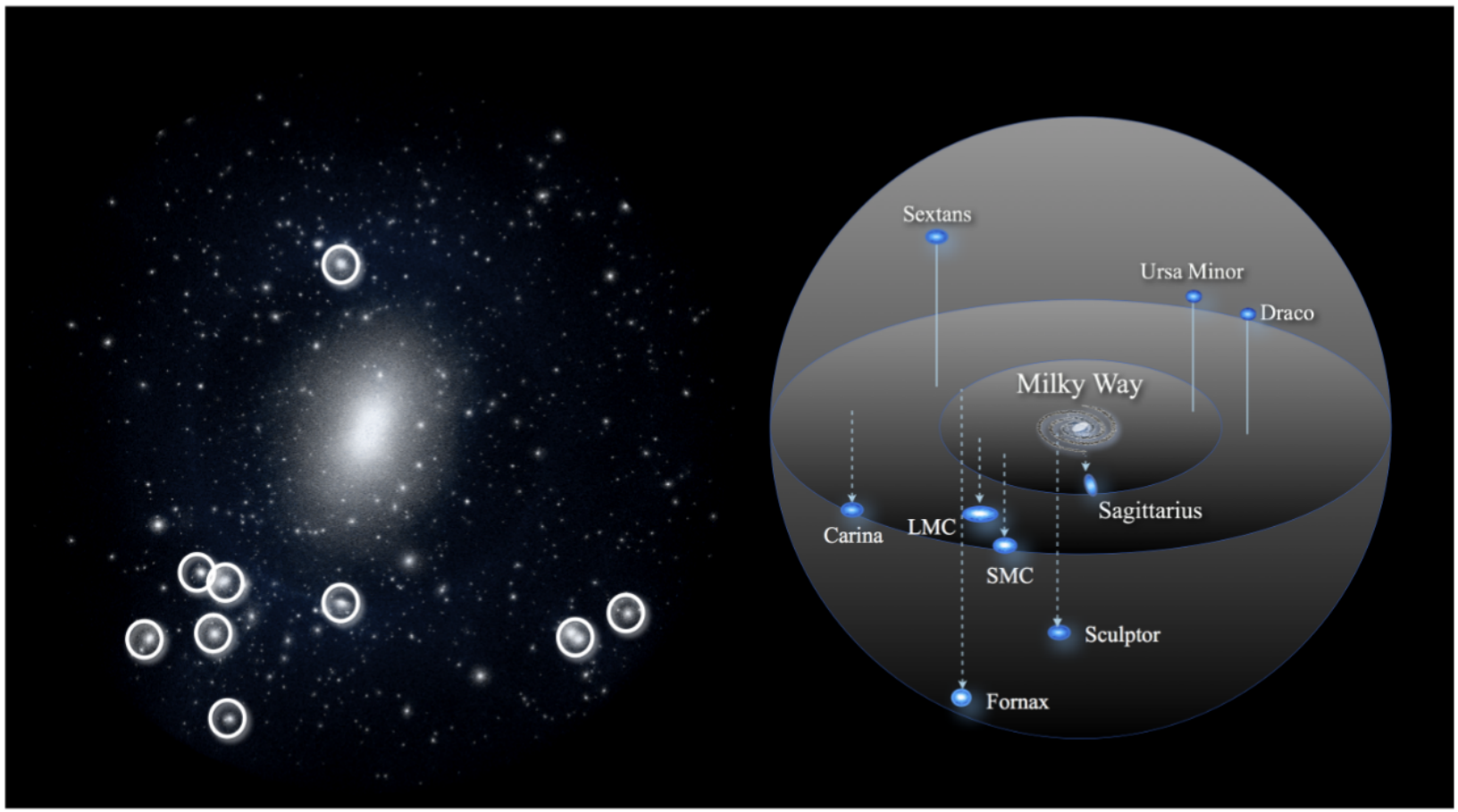




Cooley (arXiv:1410.4960)

Self Interacting DM SIDM

- too big to fail or missing satellites problem



Weinberg et al (arXiv:1306.0913)

Self Interacting DM SIDM

- core vs cusp problem

Weinberg et al (arXiv:1306.0913)

Self Interacting DM SIDM

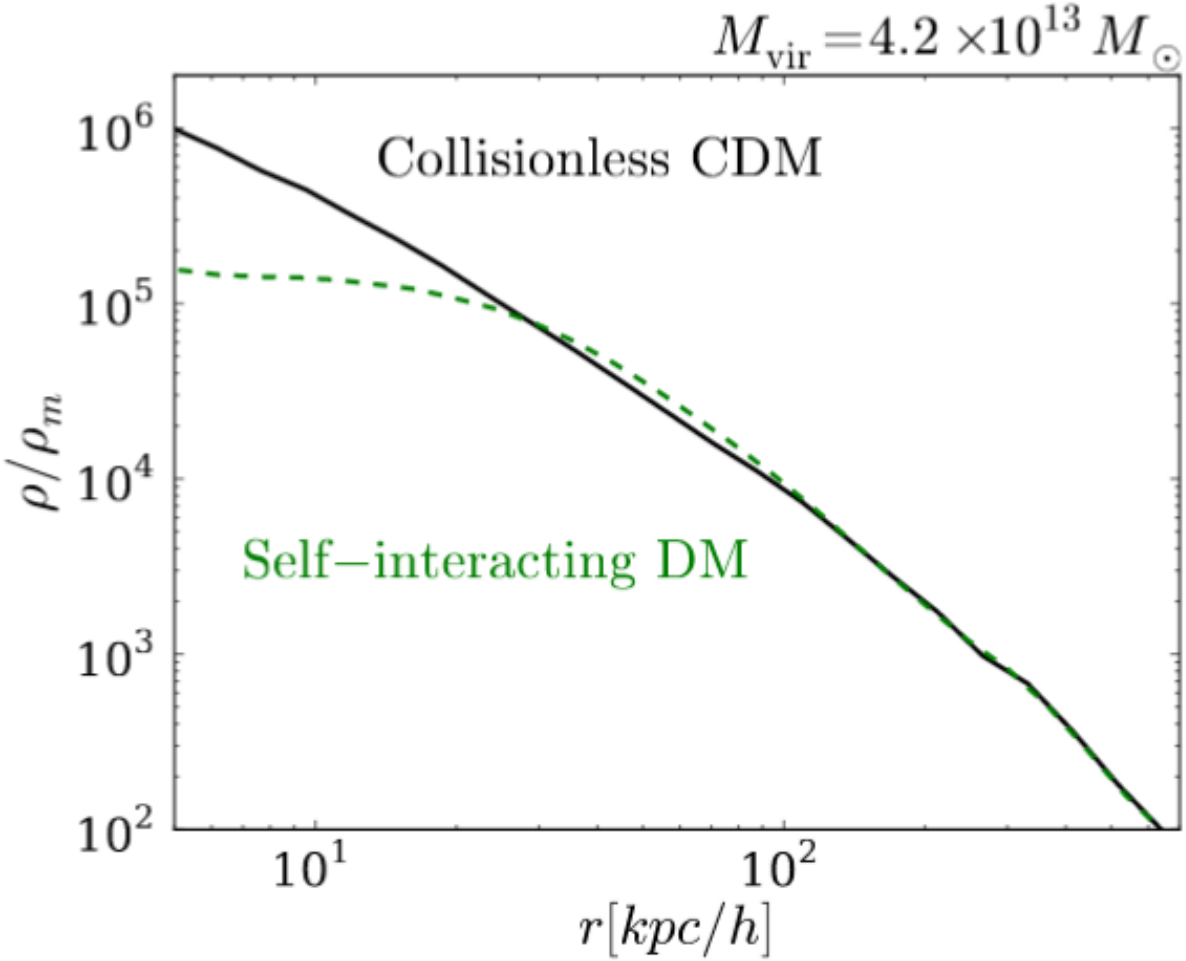
- Introducing SIDM as a solution

Upper Limit:

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 1.25 \ \frac{\text{cm}^2}{\text{g}}$$

Lower Limit:

$$\frac{\sigma_{\chi\chi}}{m_\chi} \gtrsim 0.1 \frac{\text{cm}^2}{\text{g}}$$



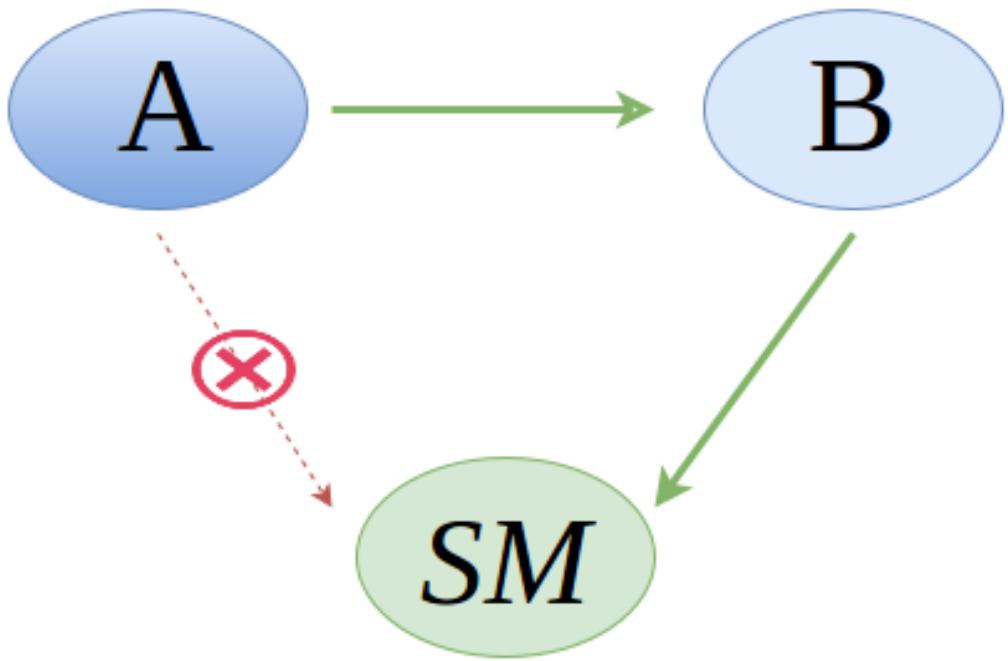
Randall et al (arXiv:0704.0261)

Zavala Vogelsberger and Walker (arXiv:1211.6426)

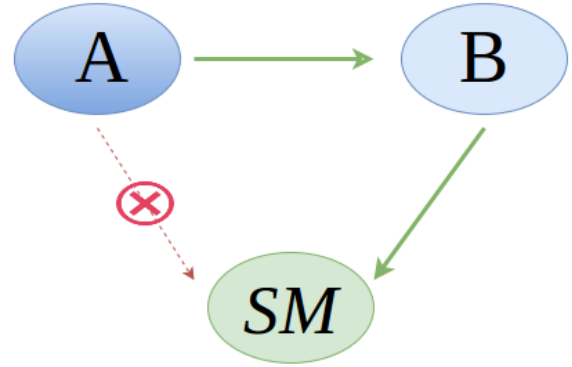
Weinberg et al (arXiv:1306.0913)

BDM Model

- Typical DM model.
- The simplest scenario.
- Multi-component DM model.
- Preserving relic abundance.



BDM Model



- Assisted freeze-out scenario: $\psi_A\psi_A \to \psi_B\psi_B$.
- where both ψ_A and ψ_B are stable DM particles.
- Achieved by separate symmetry e.g. $U(1)' \otimes U(1)''$ or $Z_2 \otimes Z_2'$.
- ψ_A and ψ_B interact via contact operator:

$$\mathcal{L}_{AB} = \frac{1}{\Lambda^2}\overline{\psi}_A\psi_B\overline{\psi}_B\psi_A.$$

- ψ_B is charged under hidden $U(1)_X$ symmetry, $Q_X^B = 1$.
- $U(1)_X$ is spontaneously broken leading to gauge boson mass m_X.
- Mass hierarchy $m_A > m_B > m_X$.

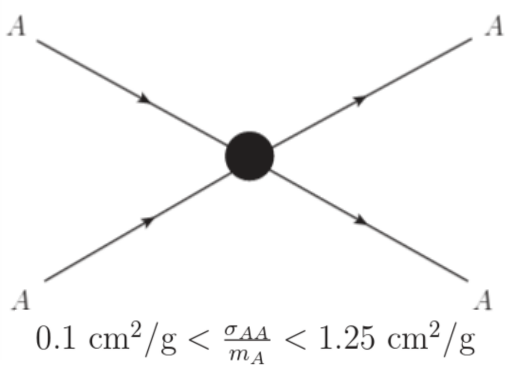
D'Eramo and Thaler (arXiv:1003.5912)
Belanger, Park (arXiv:1112.4491)

BDM Model

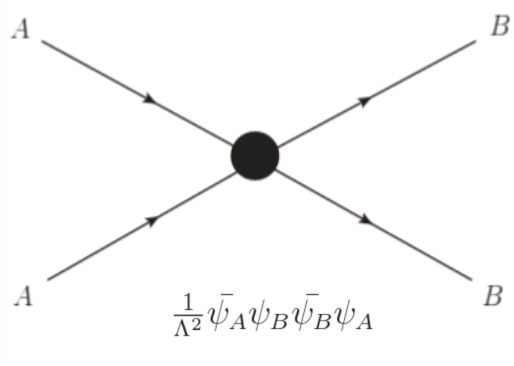
- Large $g_X \implies$ small $\Omega_B \implies$ large $\sigma(\psi_B \overline{\psi}_B \to X\,X)$.
- Assuming coupling of DM sector to SM sector occurs only via kinetic mixing between $U(1)_X$ and $U(1)_{EM}$.

$$\mathcal{L} \supset -\sin\epsilon\, X_{\mu\nu} F^{\mu\nu}.$$

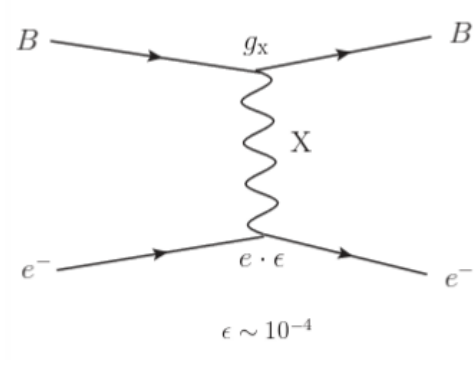
- ψ_B scatters off SM via t-channel X boson exchange.
- $(m_A,\ m_B,\ m_X,\ \Lambda,\ g_X,\ \epsilon,\ \sigma_{AA})$ to $(m_A,\ m_B,\ m_X,\ g_X \cdot \epsilon,\ \sigma_{AA})$



$0.1\ \mathrm{cm}^2/\mathrm{g} < \frac{\sigma_{AA}}{m_A} < 1.25\ \mathrm{cm}^2/\mathrm{g}$



$\frac{1}{\Lambda^2}\bar{\psi}_A\psi_B\bar{\psi}_B\psi_A$



$\epsilon \sim 10^{-4}$

Kong, Mohlabeng, Park (arXiv:1411.6632)
Necib, Moon, Wongjirad, and Conrad (arXiv:1610.03486)

BDM in the Sun

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

- C_c is the capture rate of DM particles.
- C_s is the capture rate due to self interaction.
- C_e is the evaporation rate due to interaction with nuclei.
- C_a is the annihilation rate $\psi_A\psi_A \to \psi_B\psi_B$.
- C_{se} is the evaporation particles due to self interaction.

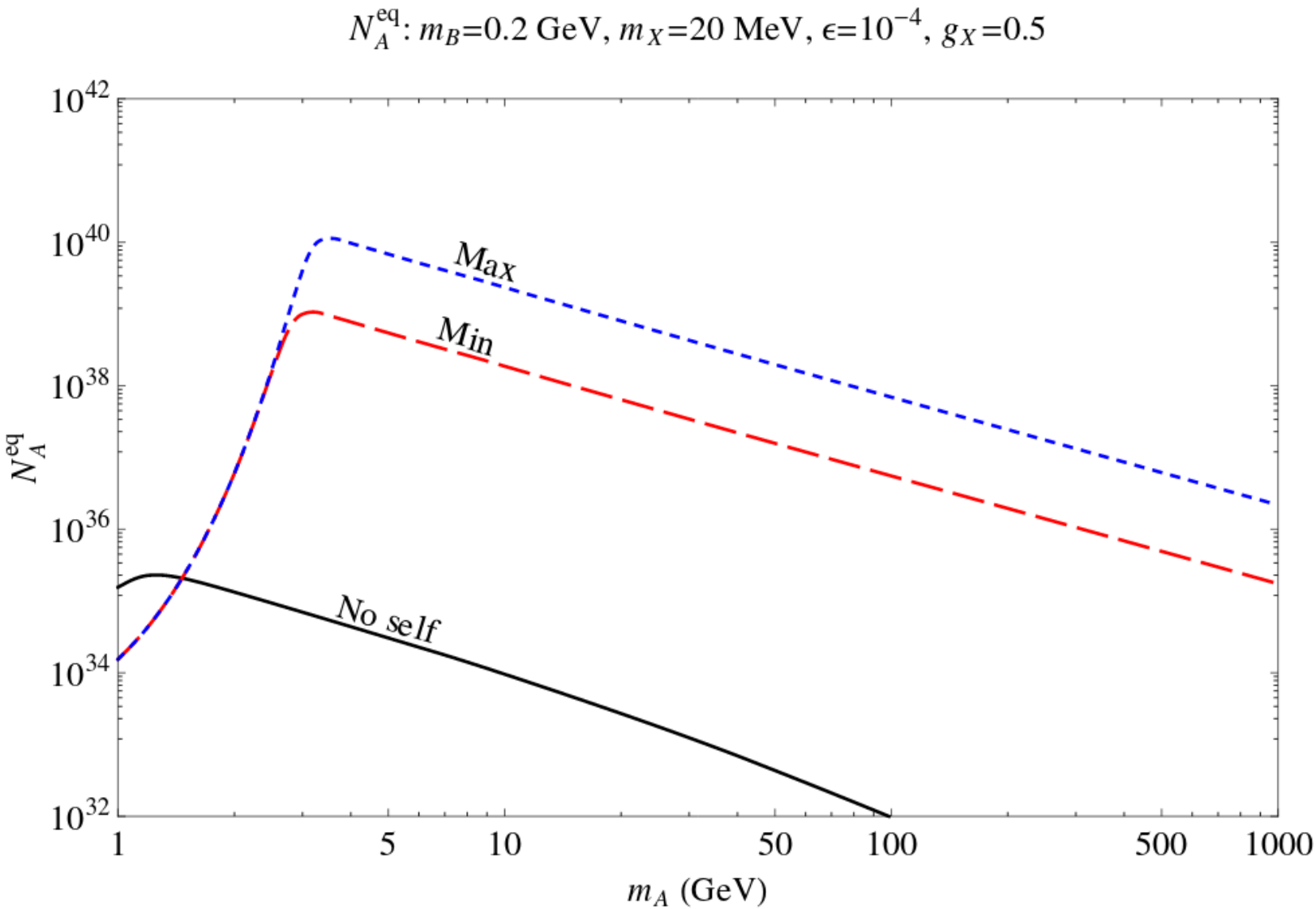
- Analytical solution:

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_{\text{eq}})}{\tau_{\text{eq}}^{-1} - (C_s - C_e)\tanh(t/\tau_{\text{eq}})/2},$$

where τ_{eq} is the constant of integration and can be calculated using initial condition: $N_\chi(0) = 0$.

Chen, Lee, Guey-Lin Lin, Yen-Hsun Lin (arXiv:1408.5471)

The Significance of Self Interaction



Kong, Mohlabeng, Park (arXiv:1411.6632)

BDM Detection

- Our benchmark: $m_X = 15\,MeV$, $g_X = 0.5$, and $\epsilon = 10^{-4}$

- Experiments in summary:

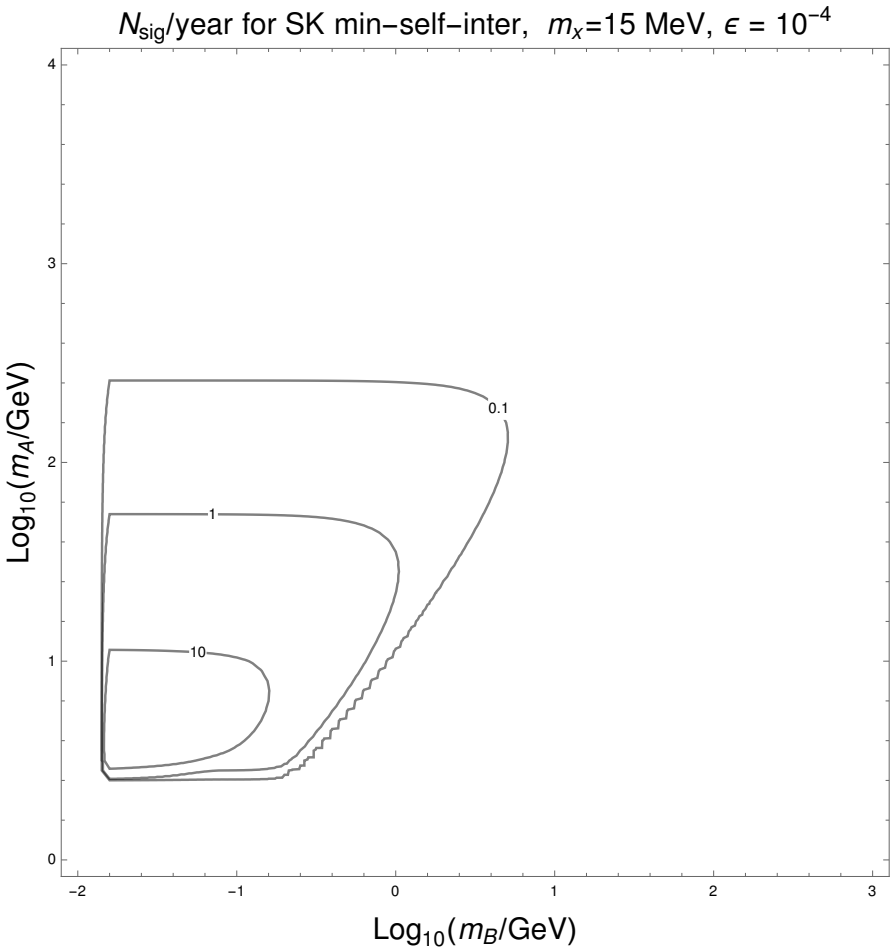
	θ_{res}[deg.]	V_{eff} [kTons]	E_{thr}[MeV]
SK	3	22.5	100 (10)
HK	3	560	100 (10)
DUNE10	1	10	30
DUNE40	1	40	30

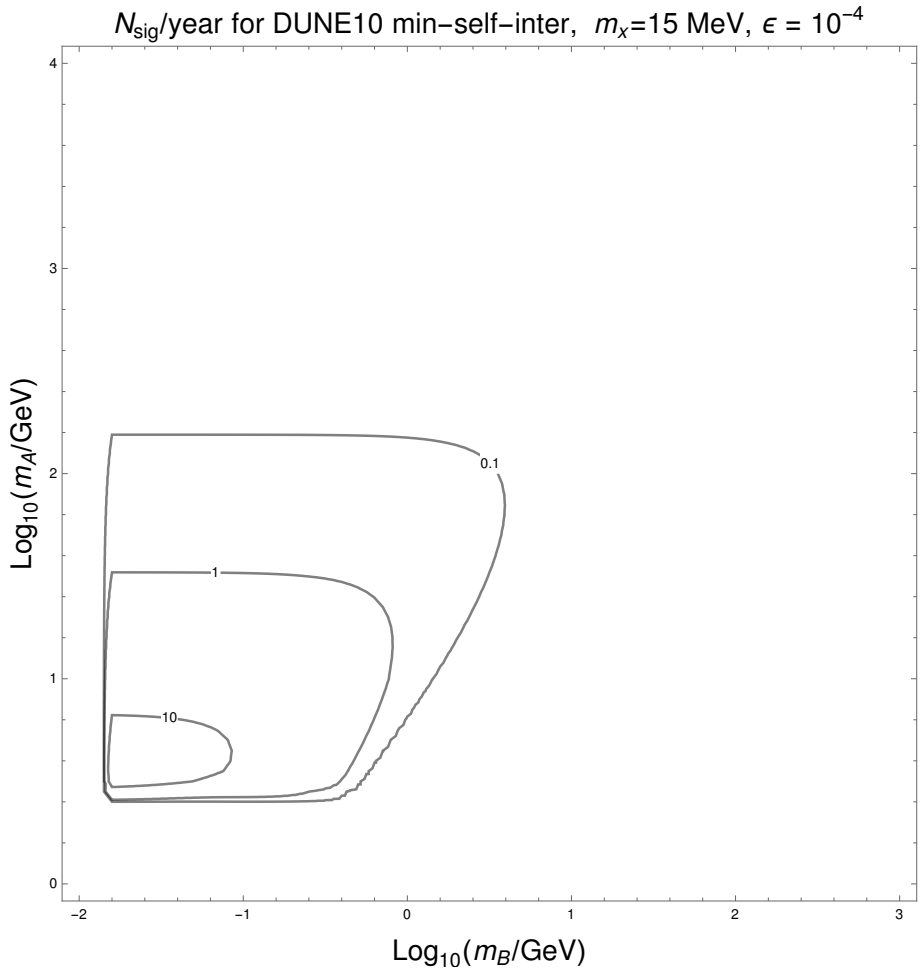
- Signal of BDM:

$$N_{\text{sig}}^{\text{Sun}} = T\ N_{\text{target}}\ \Phi_B^{\text{Sun}}\ \sigma_{Be^- \to Be^-}$$

Super-Kamiokande (arXiv:1510.08127)
DUNE (arXiv:1601.05823)

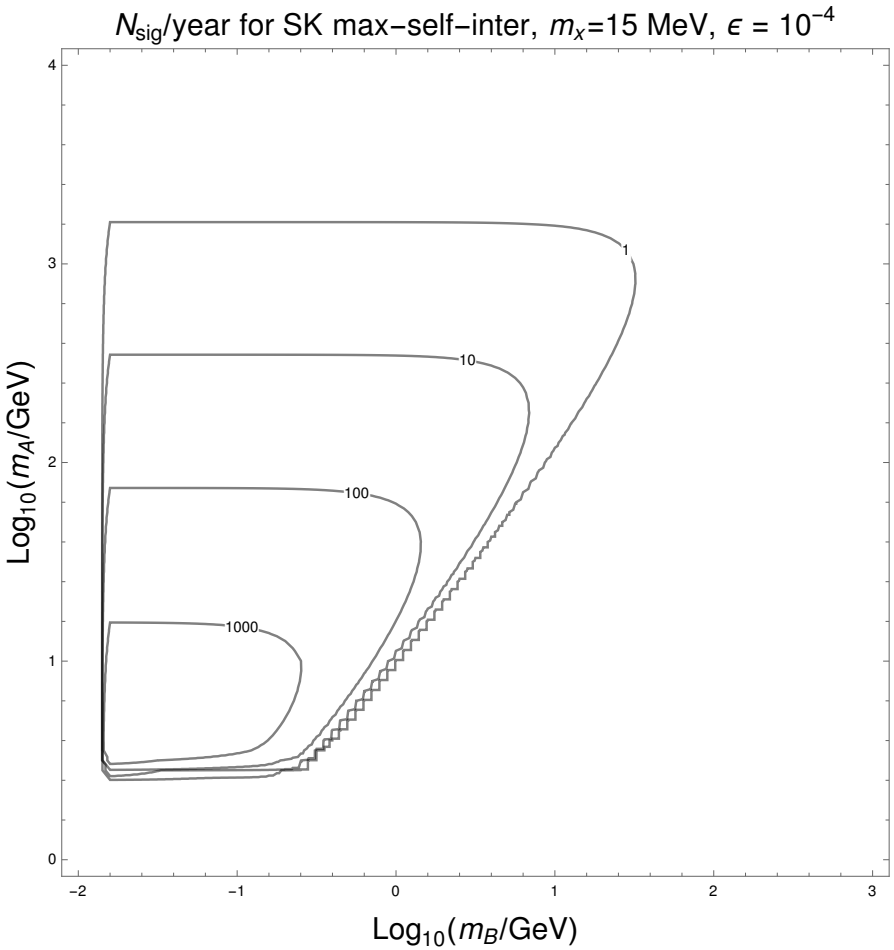
Signal at SK and DUNE

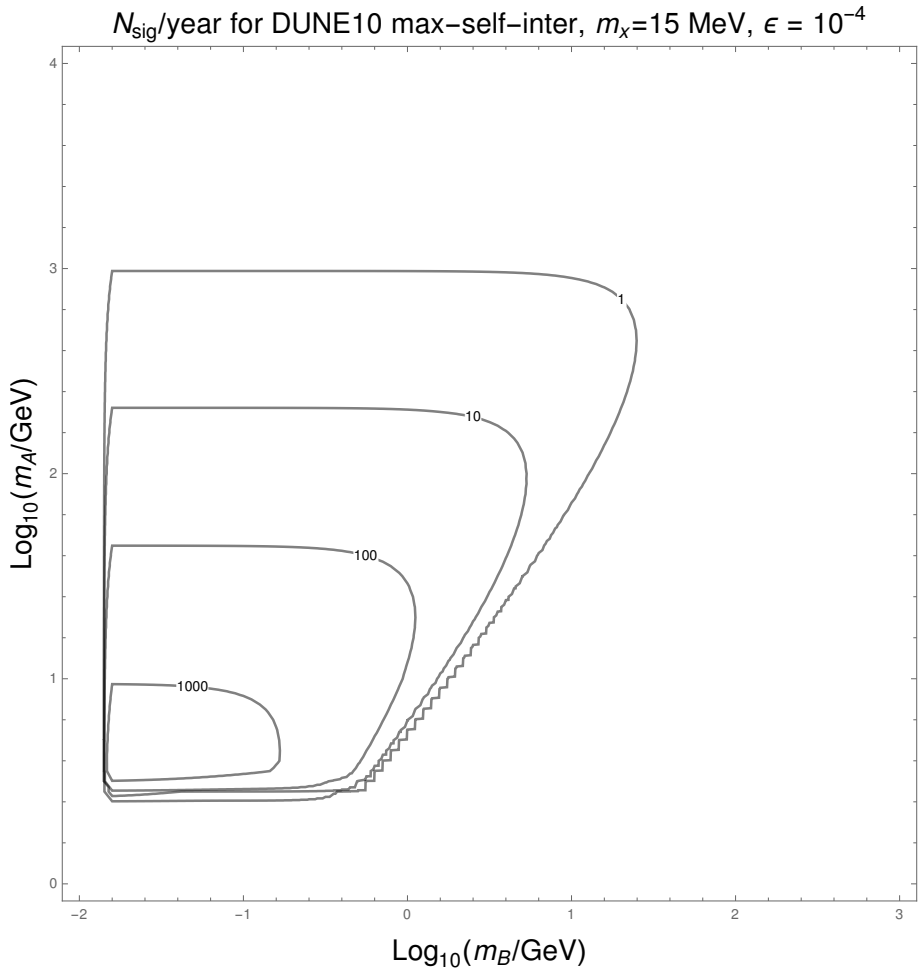




Alhazmi, Kong, Mohlabeng, Park (arXiv:1611.09866)

Signal at SK and DUNE





Alhazmi, Kong, Mohlabeng, Park (arXiv:1611.09866)

Background

- Solar Neutrinos.
- Atmospheric Neutrinos.
- Reduction due to angular resolution.
- DUNE has better particle ID.

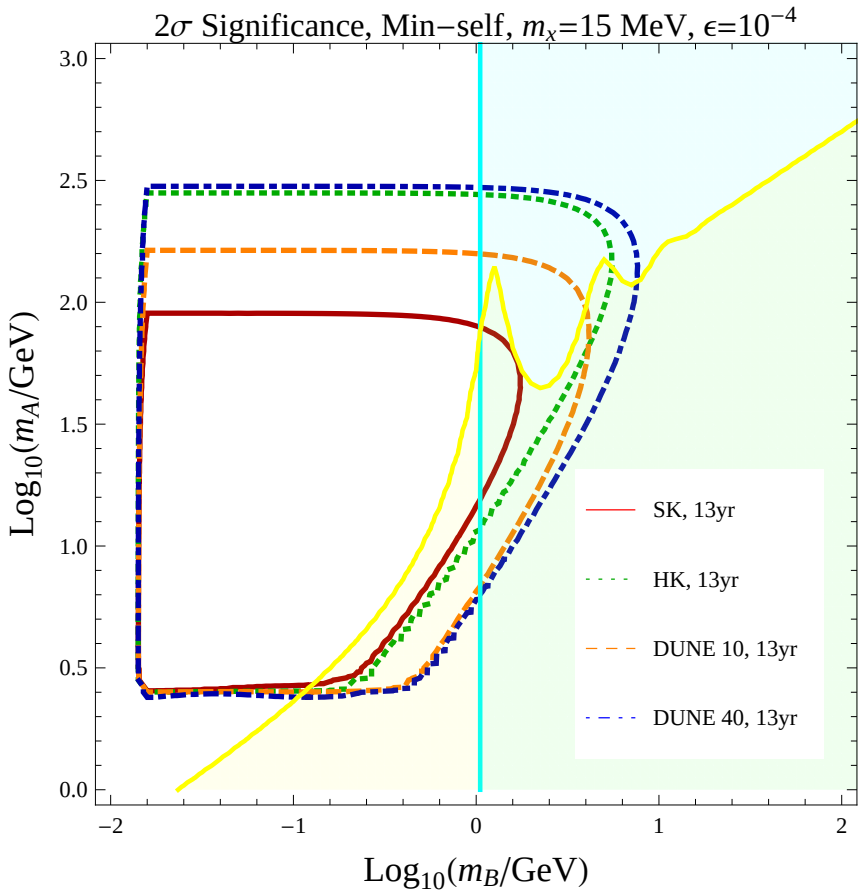
$$N_{BG}^{\theta_{res}} = \frac{1-cos\,\theta_{res}}{2} N_{BG}.$$

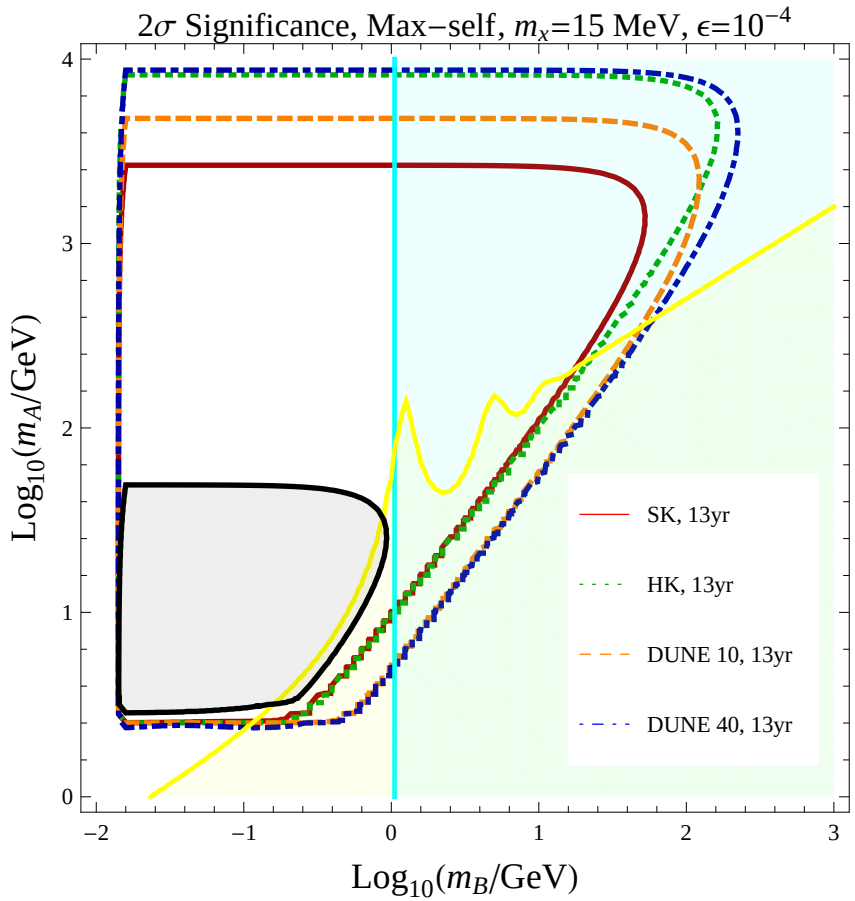
	$N_{BG}^{\text{all sky}}$/year	$N_{BG}^{\theta_{res}}$/year
SK	923	0.63
HK	22972	15.8
DUNE10	128	0.01
DUNE40	512	0.04

Super-Kamiokande, (arXiv:1510.08127)

Agashe, Cui, Necib, Thaler, (arxiv: 1405.7370)

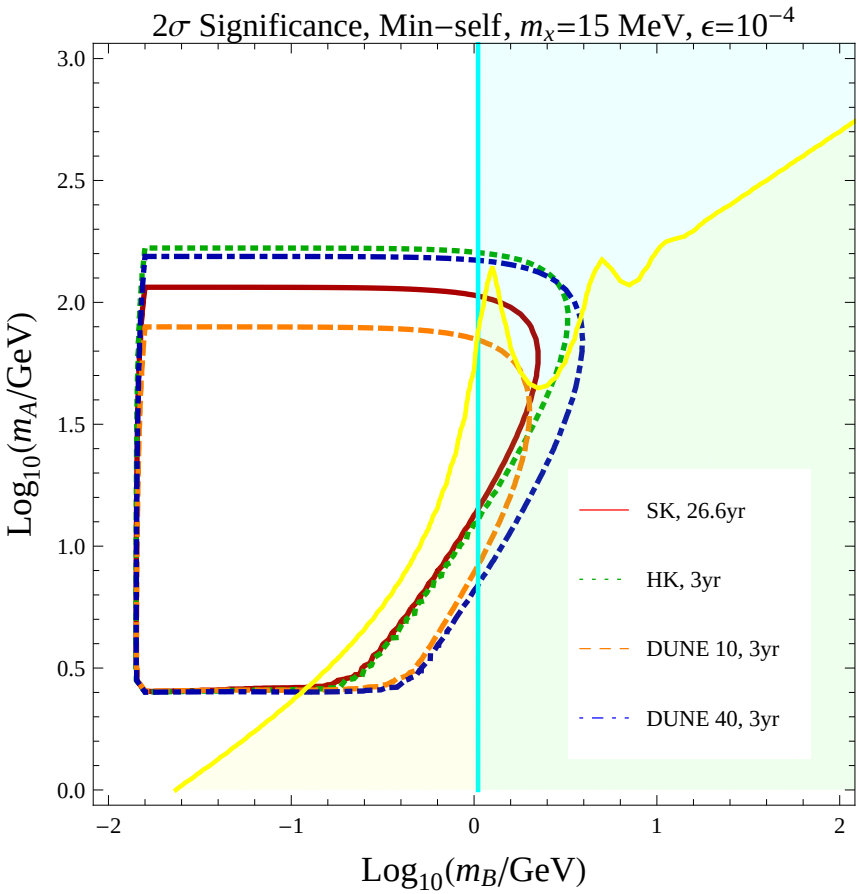
Significance



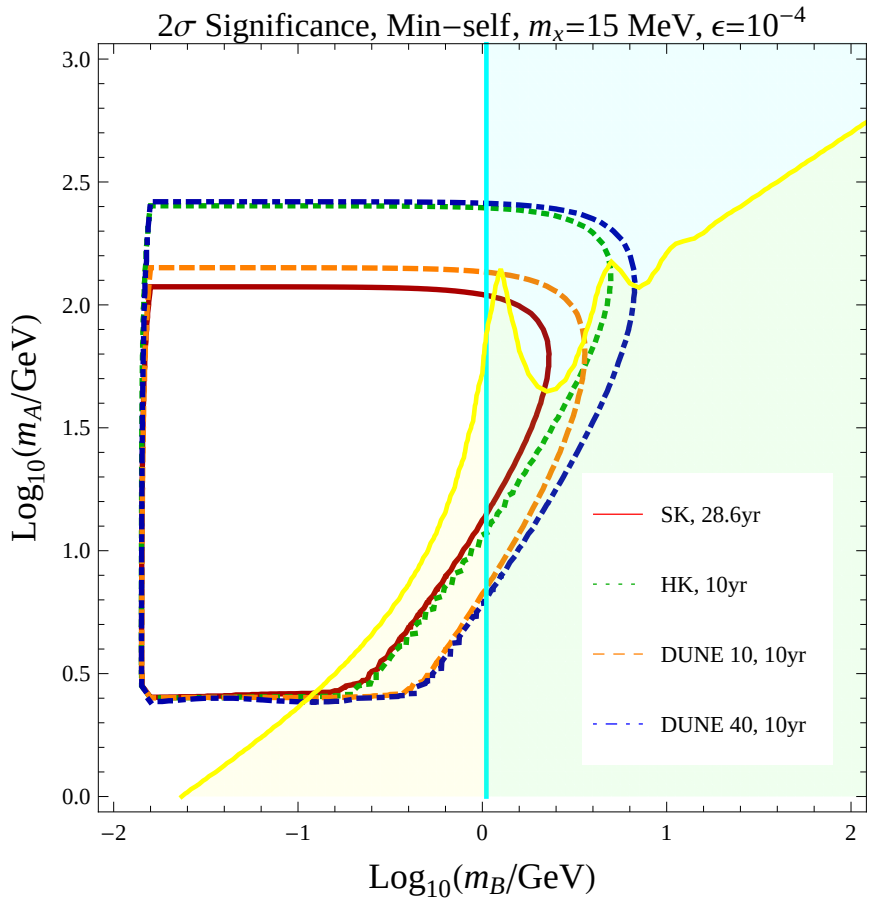


Alhazmi, Kong, Mohlabeng, Park (arXiv:1611.09866)

Significance



10 years of construction and 3 years of running



5 years of construction and 10 years of running

Alhazmi, Kong, Mohlabeng, Park (arXiv:1611.09866)

Conclusion

- Multi-component is well motivated.
- Introducing SIDM reconciles simulation vs observation problems.
- SIDM helps enhancing number of DM in the Sun.
- Terrestrial neutrino experiments can detect BDM.
- DUNE with its smaller volume shows a comparable performance to SK when detecting BDM signals.
- DUNE also shows a better significance comparing to SK, even for less exposure time.
- The parameter space of BDM still can be probed with the presence of the existing limits.

Thank You

backup slides

BDM in the Sun

DM evolution in the Sun is described by:

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

- C_c represents the capture rate of DM particles due to gravity and kinetic energy loss while traveling inside the Sun. Number of DM particles increases in this process.

- C_s: capture rate of DM particles in the Sun due to self interacting, DM number increases as long as the velocity of scattered particles is smaller than $V_{\text{esc}}(r)$.

- C_e: evaporation rate of DM particles from the sun due to interaction with nuclei, DM number decreases when the velocity of scattered particles is larger than $V_{esc}(r)$. It is effective for $m_A \lesssim 5\,GeV$ and totally negligible otherwise.

BDM in the Sun

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

- C_a: is the annihilation rate of two DM particles trapped in the Sun. Described by: $\psi_A\psi_A \to \psi_B\psi_B$, and also governs the production of DM ψ_B particles inside the Sun.

- C_{se}: is the evaporation rate of DM particles due to self interaction. DM number density decreases when the velocity of the scattered particles is smaller than $V_{esc}(r)$.

- Analytical solution can be easily achieved:

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_{\text{eq}})}{\tau_{\text{eq}}^{-1} - (C_s - C_e)\tanh(t/\tau_{\text{eq}})/2},$$

where τ_{eq} is the constant of integration and can be calculated using initial condition: $N_\chi(0) = 0$.

$$\tau_{\rm eq} = \frac{1}{\sqrt{C_c\left(C_a + C_{se}\right) + \left(C_s - C_e\right)^2/4}}$$

• The production of DM particle ψ_B in the Sun is controlled by the annihilation rate of DM particle ψ_A which is given by: $\Gamma_A^{\chi} = \frac{C_a}{2} N_{\chi}^2$.
• The current number and annihilation rate of DM in the Sun can be achieved by setting the time to be the age of the sun. When $t/\tau_{\rm eq} > 1$, One can write:

$$N_{\chi}^{eq} = \sqrt{\frac{C_c}{C_a + C_{se}}}\left(\sqrt{\frac{R}{4} + 1} \pm \sqrt{\frac{R}{4}}\right)$$

and

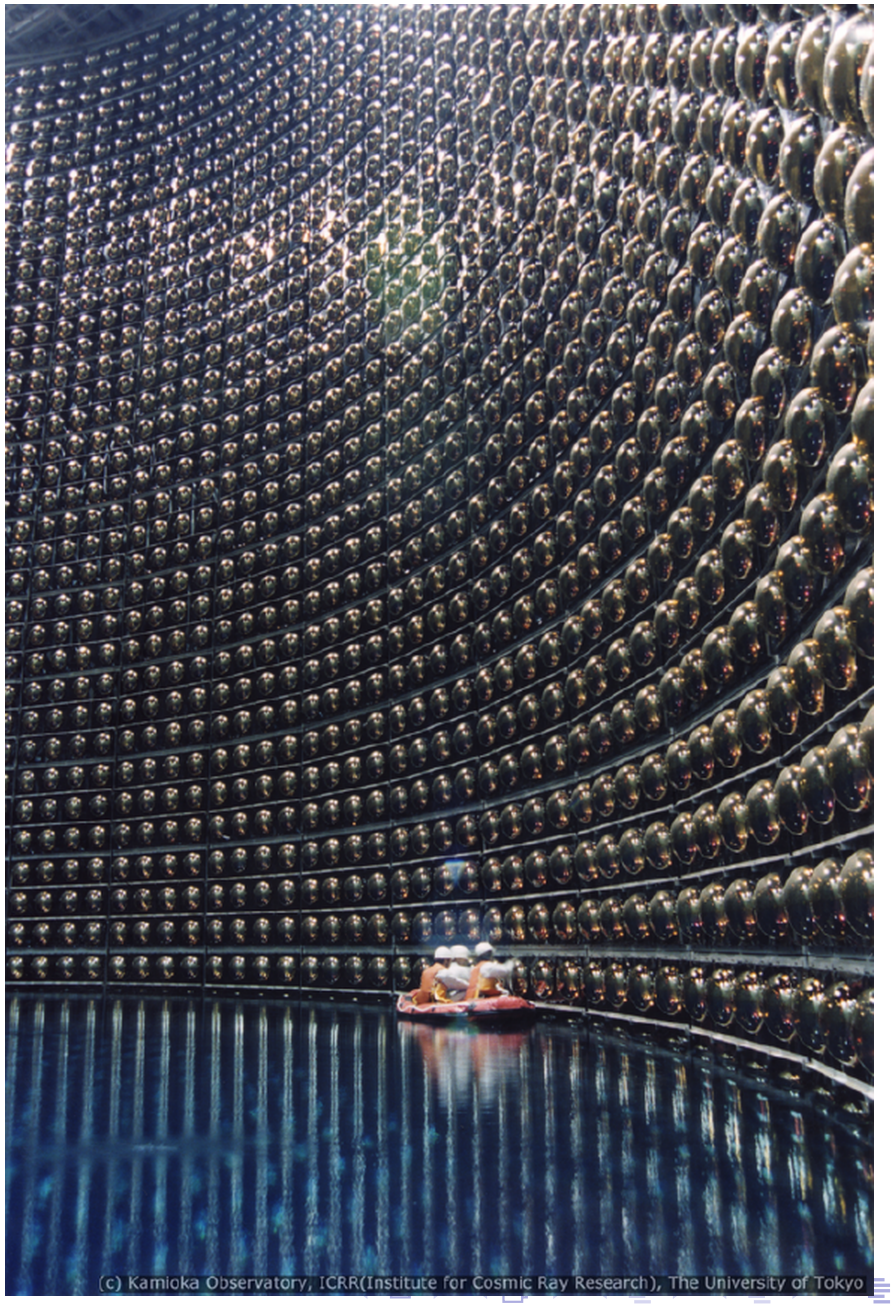
$$\Gamma_A^{\chi} = \frac{C_a C_c}{C_a + C_{se}}\left(\sqrt{\frac{R}{4} + 1} \pm \sqrt{\frac{R}{4}}\right)^2,$$

where $R \equiv \left(C_s - C_e\right)^2 / \left[C_c\left(C_a + C_{se}\right)\right]$.

Experiments

Super-Kamiokande:

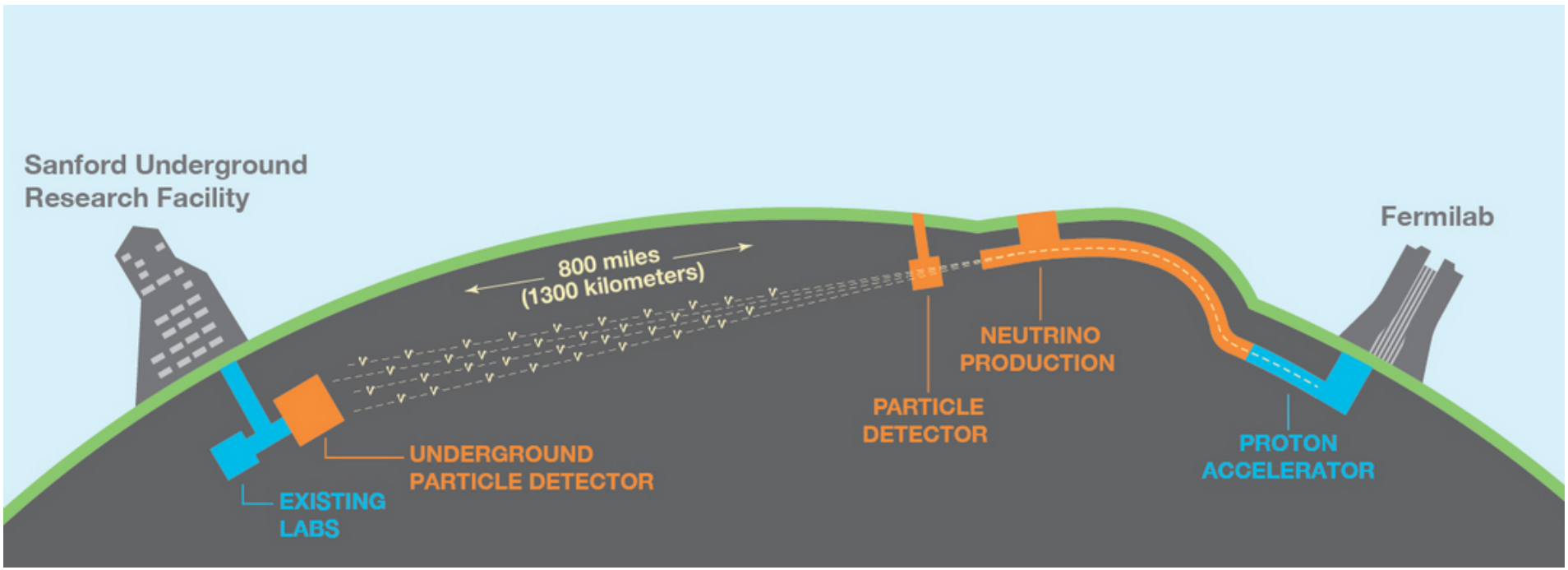
- 22.5 kTon of water.
- Cherenkov Radiation.
- 39.3m diameter and 41.4m tall.
- 13,000 photo-multipliers.
- It has been collecting data for more than 13 years.



Experiments

DUNE:

- Future experiment.
- LAr Detector.
- Far Detector.
- Can detect BDM.



Background

- Solar Neutrinos.
- Atmospheric Neutrinos.
- Reduction due to angular resolution.
- DUNE has better particle ID.

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

	$N_{BG}^{\text{all sky}}$/year	$N_{BG}^{\theta_{res}}$/year
SK	923	0.63
HK	22972	15.8
DUNE10	128	0.01
DUNE40	512	0.04

Super-Kamiokande, (arXiv:1510.08127)

Agashe, Cui, Necib, Thaler, (arxiv: 1405.7370)

Significance and Limits

- Define significance as:

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

- Current SK limit.
- CMB limit.
- Limit from DD of non-relativistic ψ_{B}.

Galactic Center

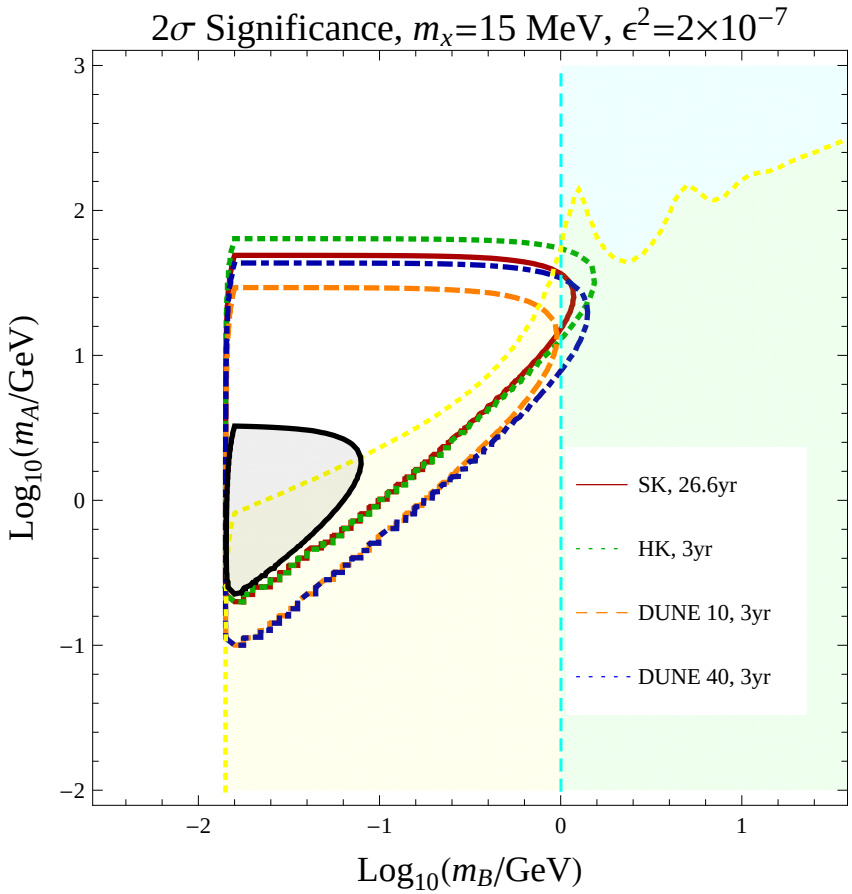
$$N_{\text{sig}}^{\text{GC}} = T \; N_{\text{target}} \; \Phi_B^{\theta_C} \; \sigma_{Be^- \to Be^-}$$

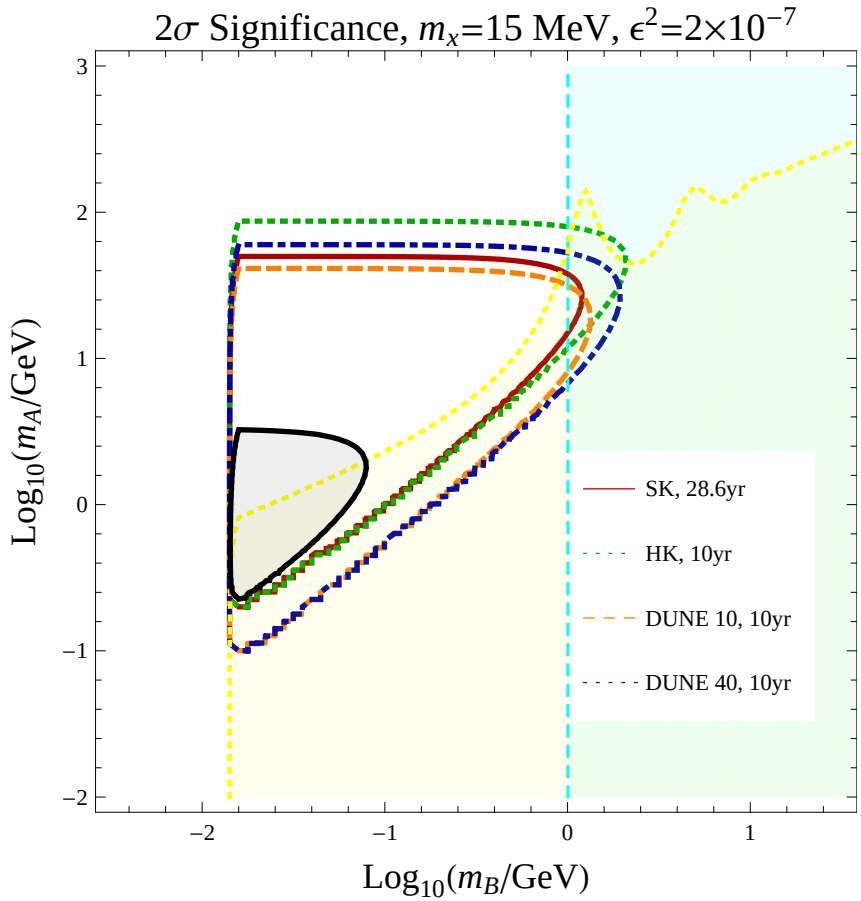
$$\frac{d\Phi_{\text{GC}}}{d\Omega dE_{\text{B}}} = \frac{r_{\text{Sun}}}{16\pi} \left(\frac{\rho_0}{m_A} \right)^2 \langle \sigma_{A\bar{A} \to B\bar{B}} v \rangle \; J \, \frac{dN_{\text{B}}}{dE_{\text{B}}}$$

$$J(\theta) = \int_{\text{l.o.s}} \frac{ds}{r_{\text{Sun}}} \left(\frac{\rho(r(s,\theta))}{\rho_0} \right)$$

$$\frac{dN_{\text{B}}}{dE_{\text{B}}} = 2\delta(E_{\text{B}} - m_{\text{A}})$$

Significance





1612.xxxx, Alhazmi, Kong, Mohlabeng, Park

Discussion

- Energy Loss in the Sun:
  - Bethe-Bloch Formula.
  - General treatment based on cross section calculation.
  - Simulation.

- Future Work.
  - Angular resolution as a function of energy.
  - Volume as a function of energy.
  - Interaction with nucleons.

References

K. Kong, G. Mohlabeng and J. C. Park, Phys. Lett. B **743**, 256 (2015) doi:10.1016/j.physletb.2015.02.057 [arXiv:1411.6632 [hep-ph]].

K. Agashe, Y. Cui, L. Necib and J. Thaler, JCAP **1410**, no. 10, 062 (2014) doi:10.1088/1475-7516/2014/10/062 [arXiv:1405.7370 [hep-ph]].

D. Clowe, M. Bradac, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones and D. Zaritsky, Astrophys. J. **648**, L109 (2006) doi:10.1086/508162 [astro-ph/0608407].

G. Bertone and D. Hooper, [arXiv:1605.04909 [astro-ph.CO]].

M. A. Deliyergiyev, Open Physics Volume 14 Issue 1 (2016) 281-303 doi:10.1515/phys-2016-0034 [arXiv:1510.06927 [hep-ph]].

J. Cooley, Phys. Dark Univ. **4**, 92 (2014) doi:10.1016/j.dark.2014.10.005 [arXiv:1410.4960 [astro-ph.IM]].

D. H. Weinberg, J. S. Bullock, F. Governato, R. Kuzio de Naray and A. H. G. Peter, Proc. Nat. Acad. Sci. **112**, 12249 (2014) doi:10.1073/pnas.1308716112 [arXiv:1306.0913 [astro-ph.CO]].