Cosmic-Neutrino-Boosted Dark Matter

Yongsoo Jho (Yonsei U.)

Based on
PLB 811 (2020) 135863 (arXiv:2006.13910 [hep-ph]),
arXiv:2101.11262 [hep-ph], and a work in preparation

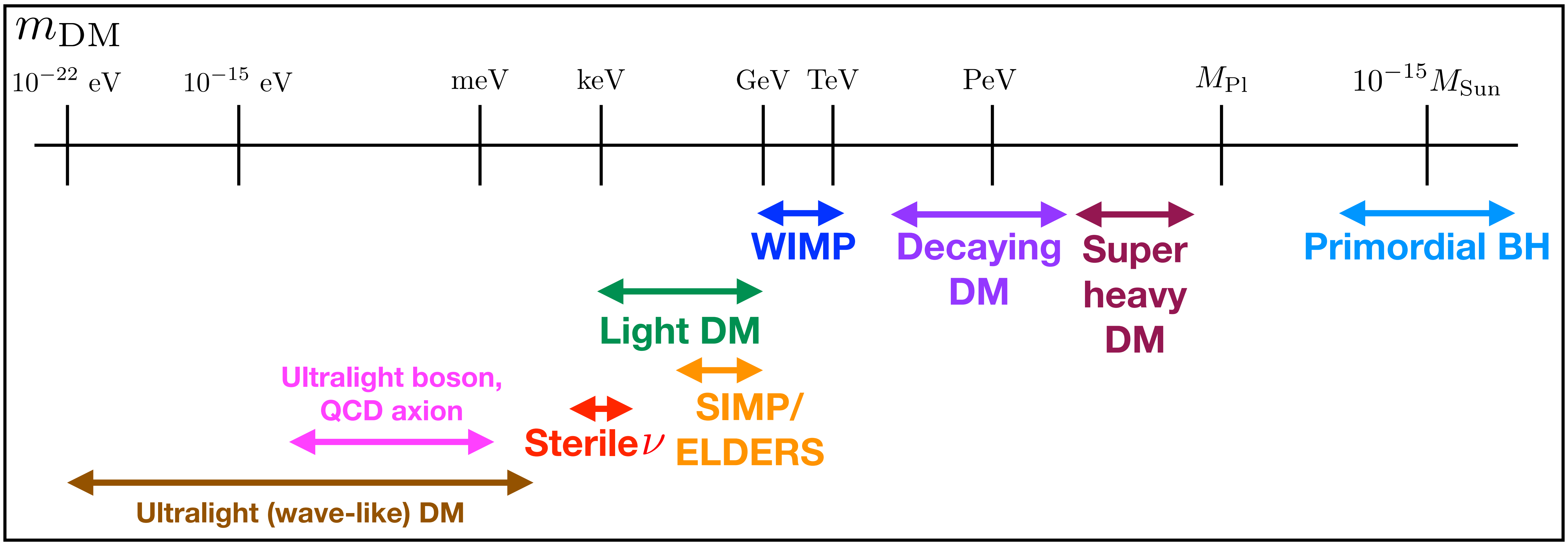
Collaboration with
Jong-Chul Park (Chungnam Natl. U.), Seong Chan Park (IPAP, Seoul and Yonsei U.),
and Po-Yan Tseng (IPAP, Seoul and Yonsei U. and Natl. Tsing Hua U.)

June 22, 2022

LIO International Conference and France-Korea STAR Workshop
on "Fundamental Forces from Colliders to Gravitational Waves"

DM candidates

in a point of view of particle physics



In a wide range of Dark Matter mass 10^{-22} eV $- 10^{-12} M_{\rm Sun}$ **,**
Various DM candidates has been suggested.

DM candidates

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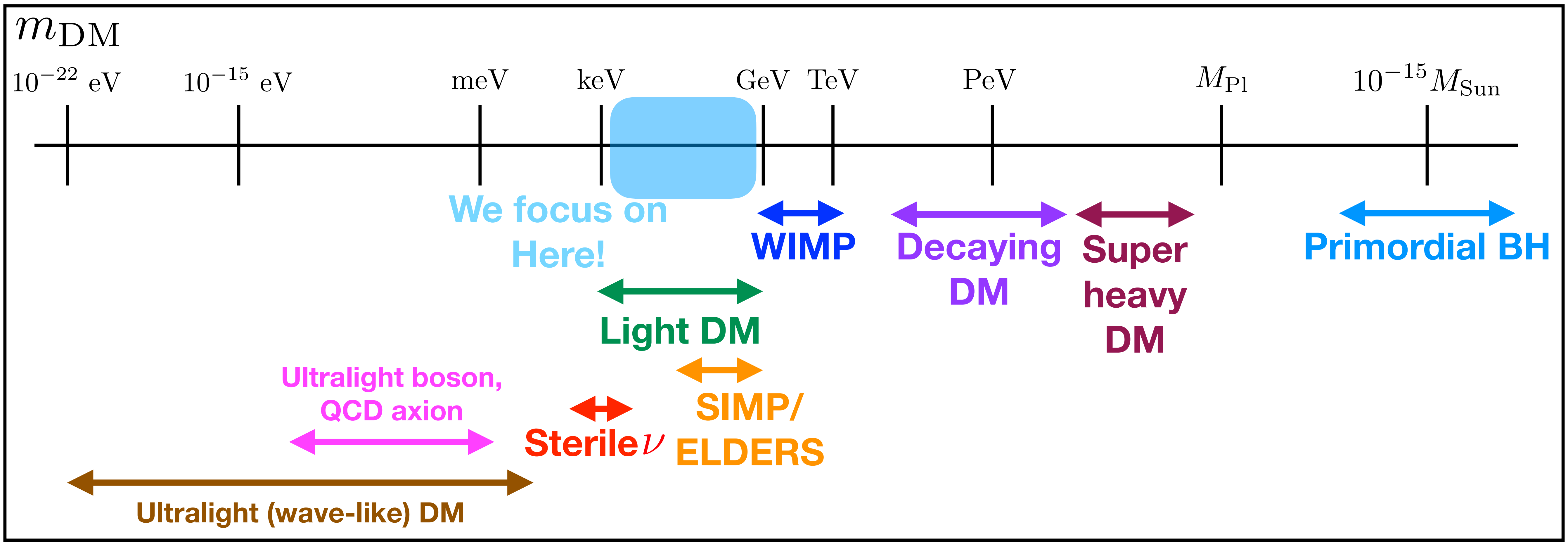
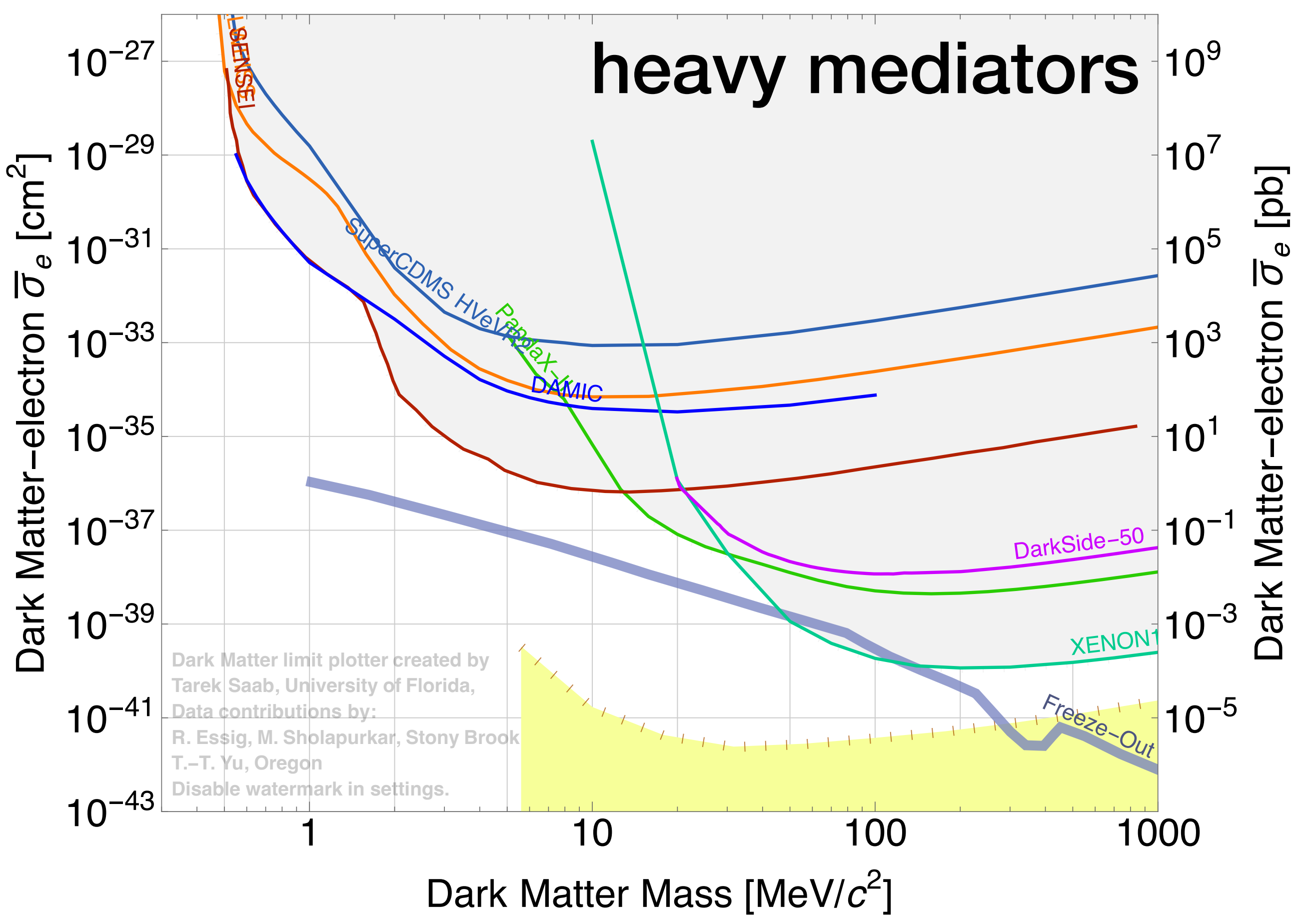


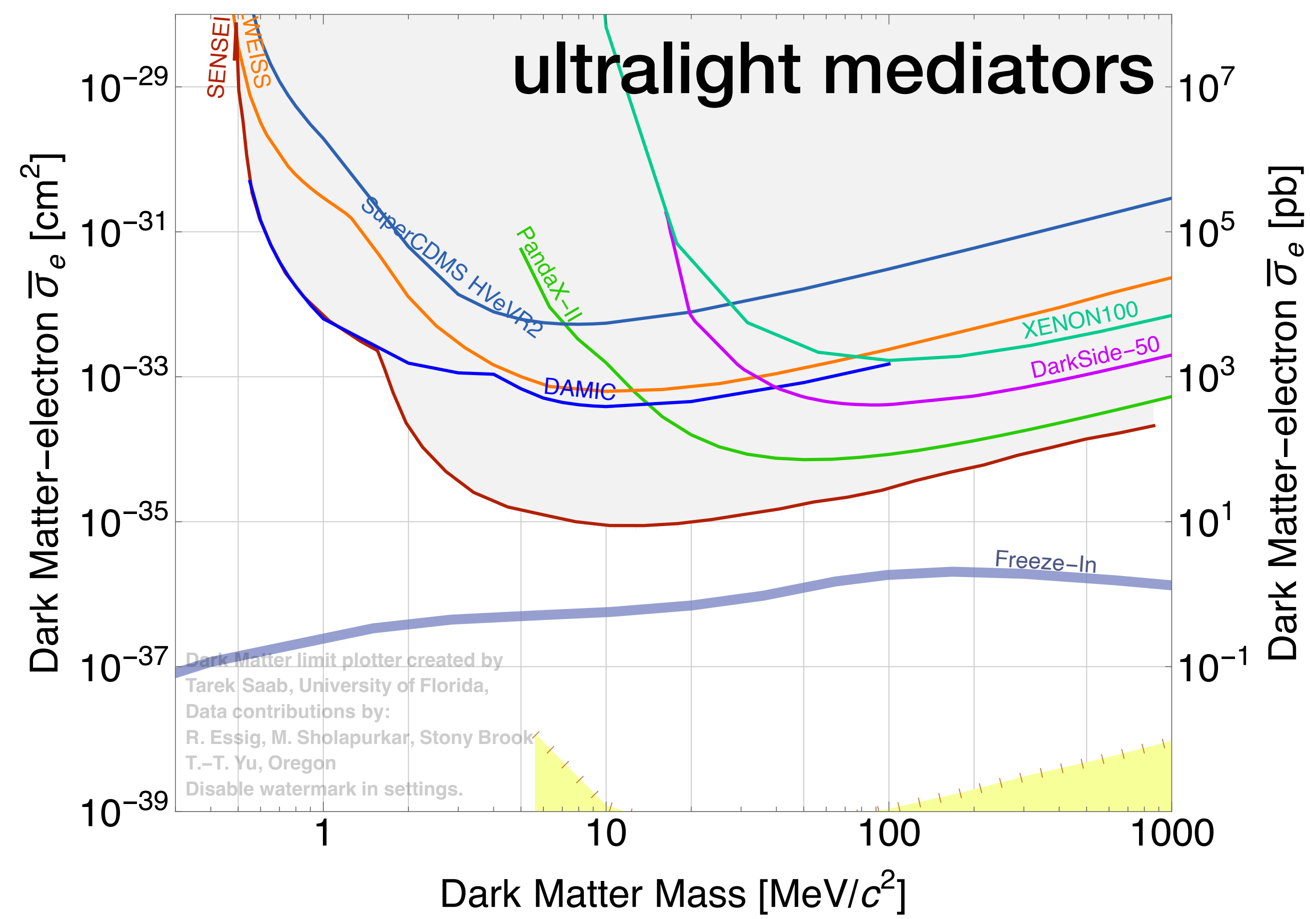
In a wide range of Dark Matter mass $10^{-22}\ \mathrm{eV} - 10^{-12} M_{\rm Sun}$ **,**
Various DM candidates has been suggested.

In the ranges of keV-GeV masses, DM can be actively upscattered by energetic cosmic rays and neutrinos in our universe.

The limits on light DM direct detection

https://supercdms.slac.stanford.edu/dark-matter-limit-plotter





Conventional searches on halo DM using nuclear/electron recoils usually have the cliffs around 10-100 MeV,
due to tiny kinetic energies which are lower than E thresholds.

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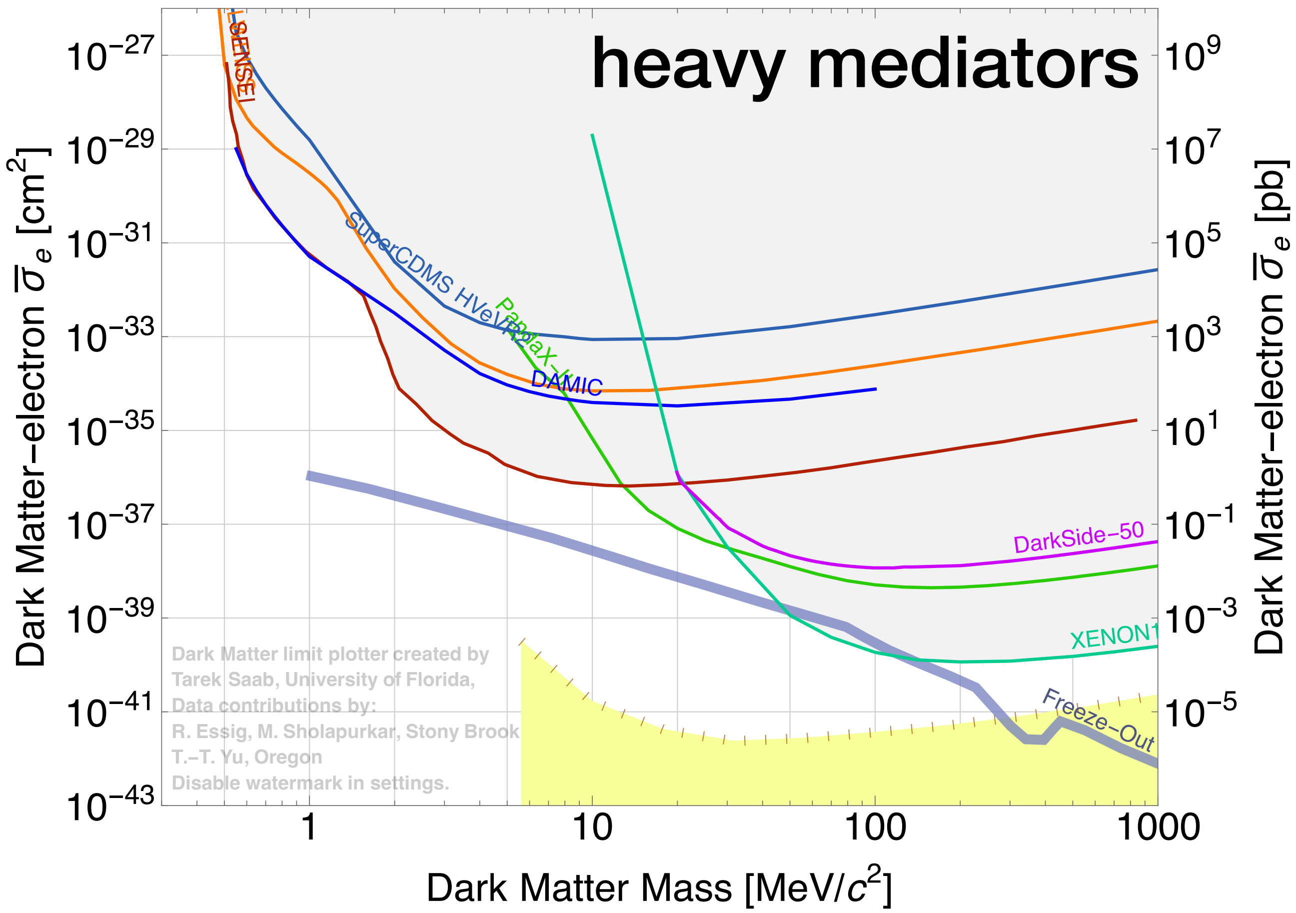

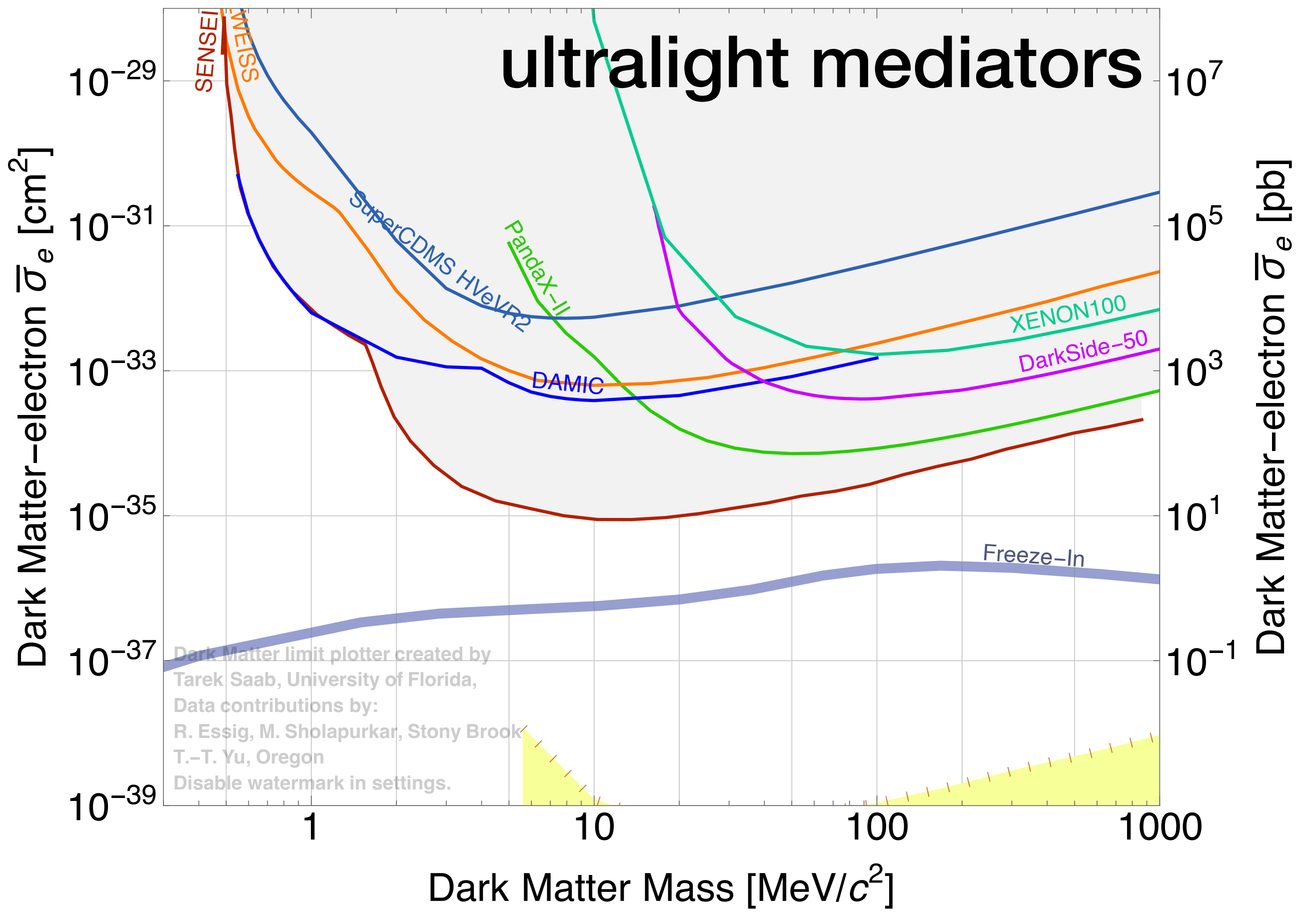

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One way to probe light DM (< MeV-GeV, depending on interaction strength) ==> is to find the boosted DM?

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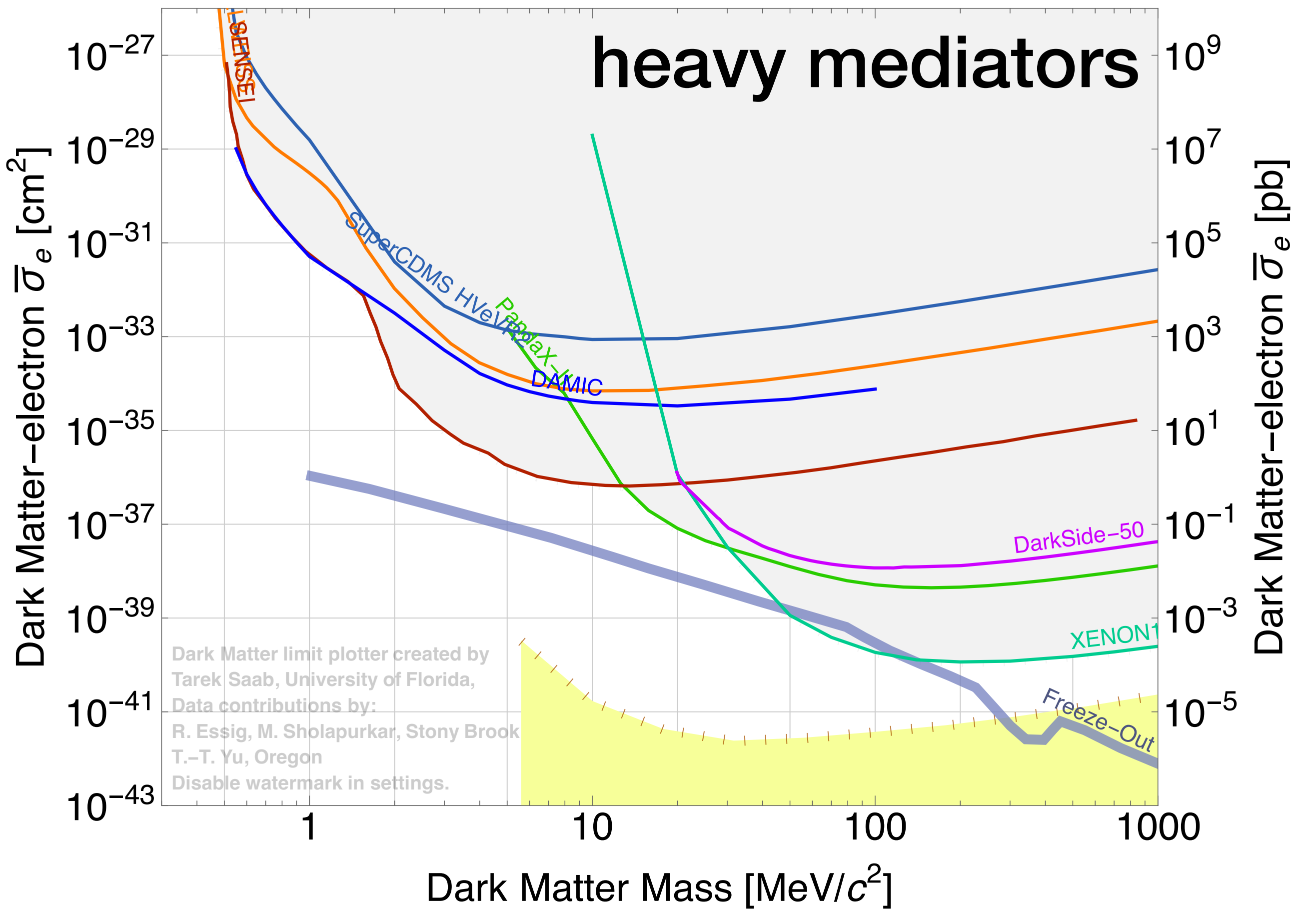

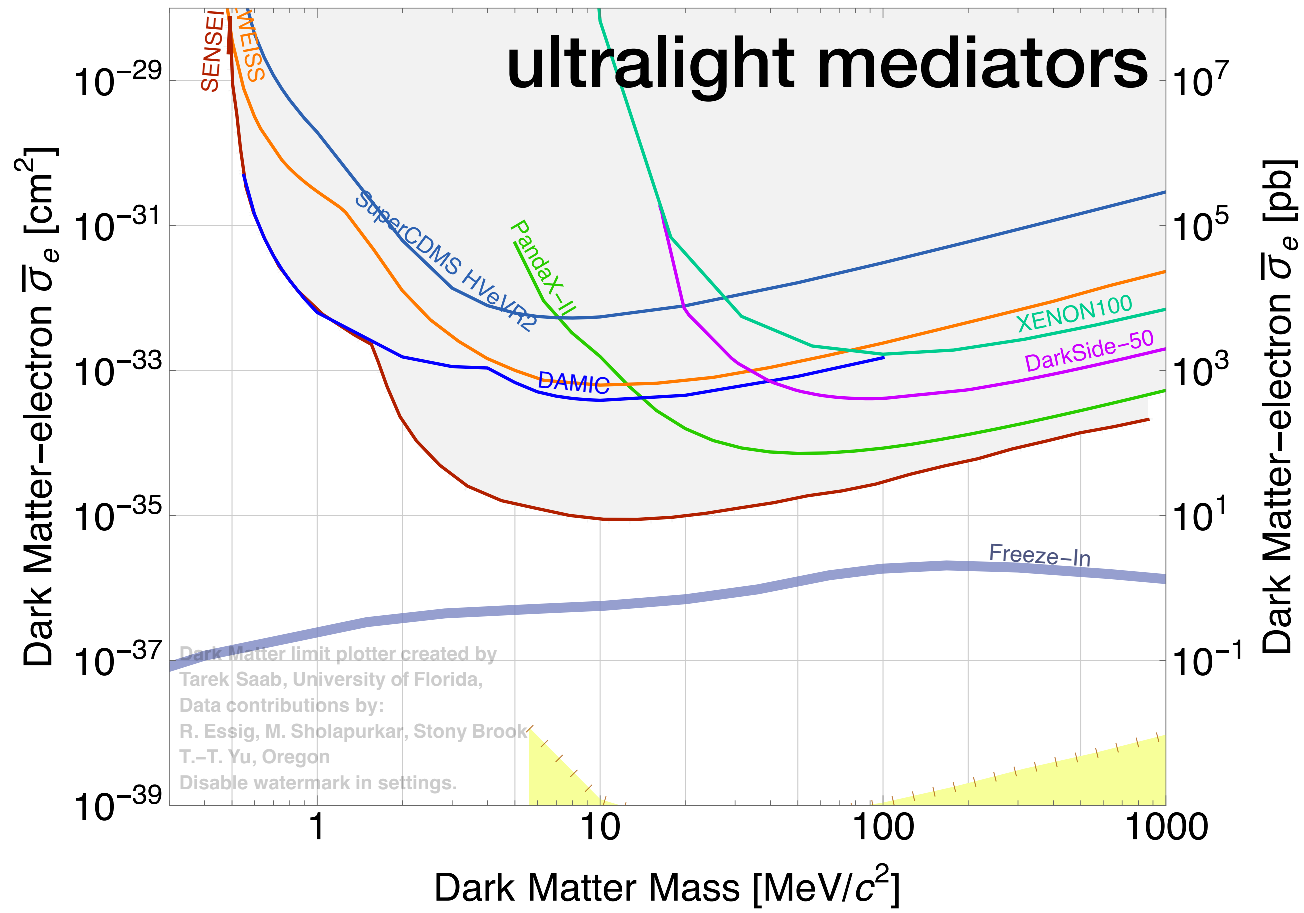

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by energetic cosmic rays and neutrinos

Accelerating DM with energetic CRs and neutrinos!

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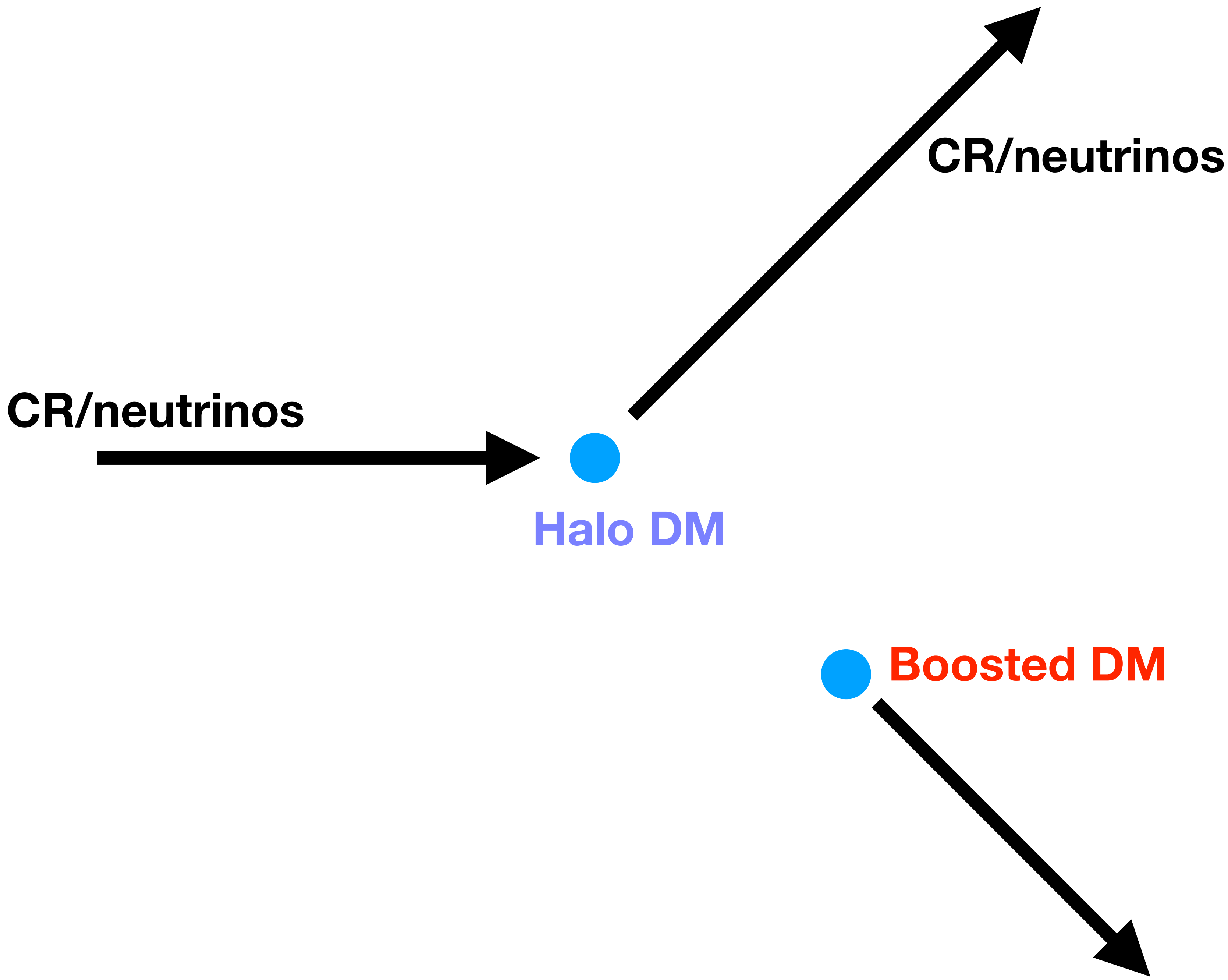
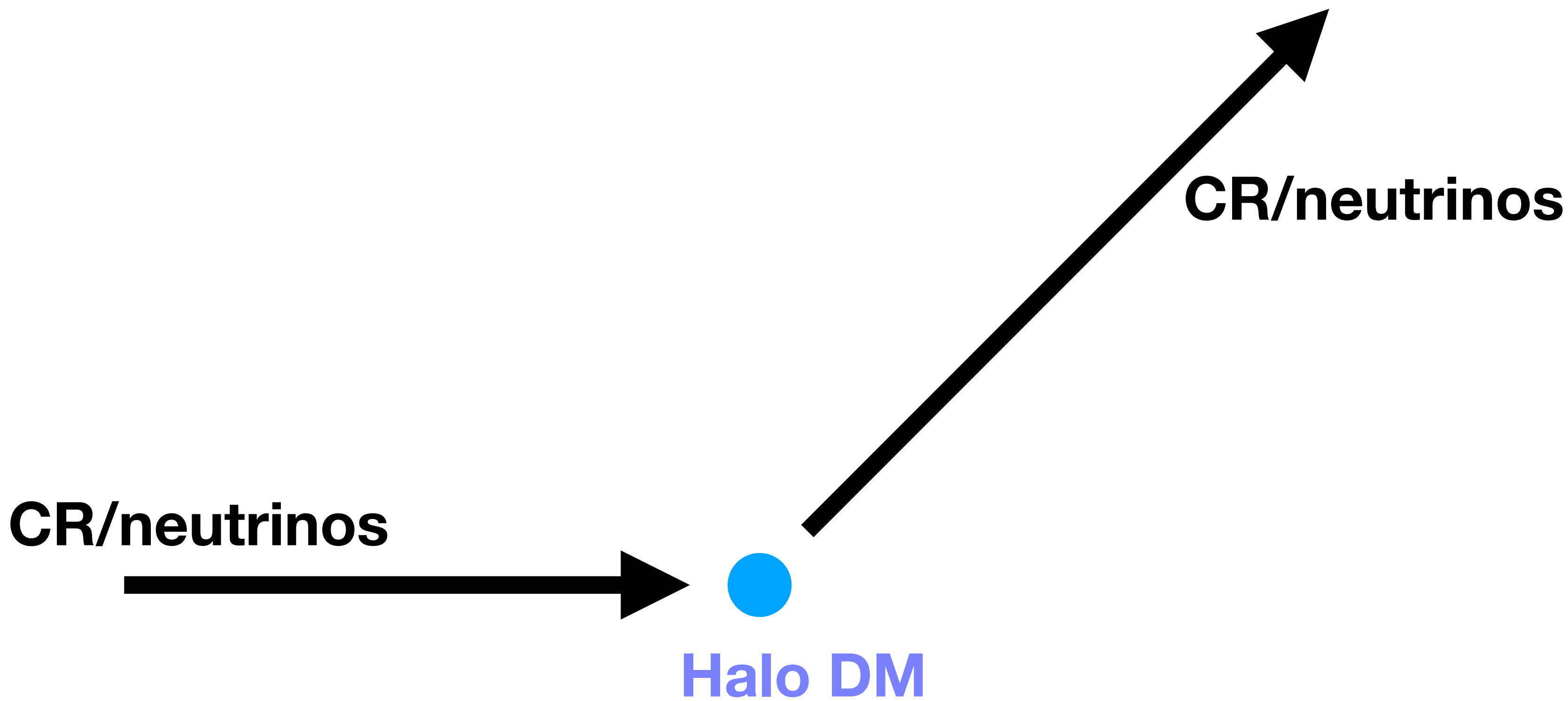
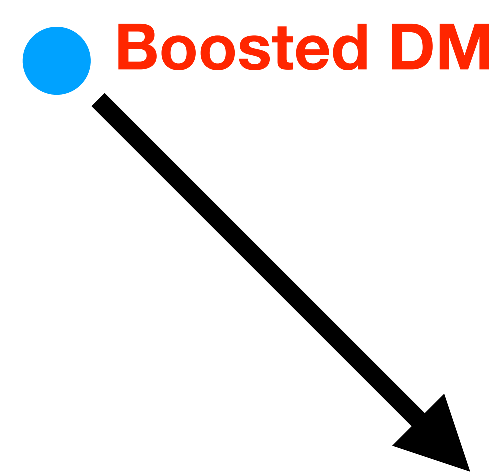


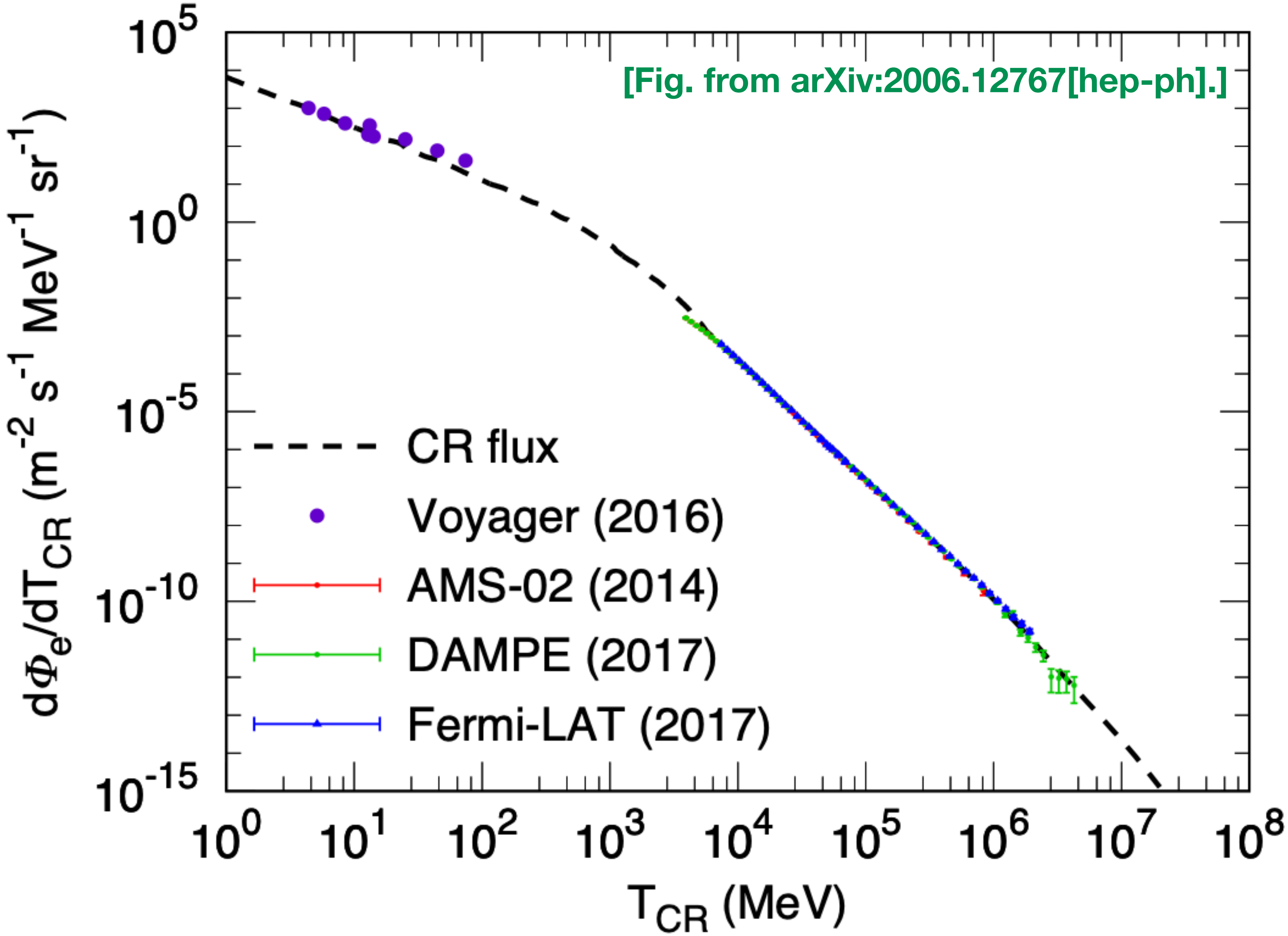
Accelerating DM with energetic CRs and neutrinos!





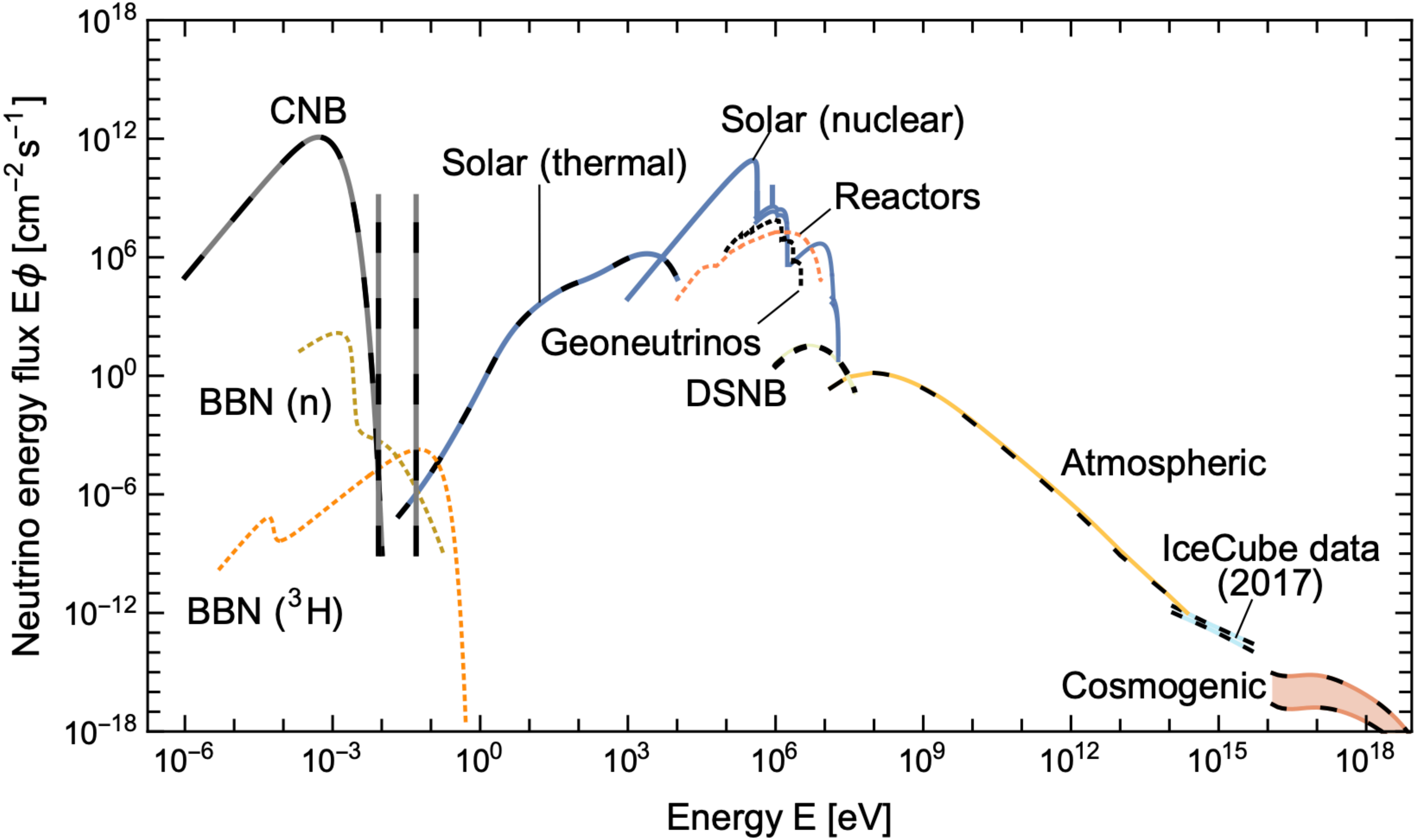
How many CR/neutrinos (in the universe) to boost halo DM?

How many electrons?: Observed spectrum of electron CR



A caveat: All of these observation is in the local region.

How many neutrinos?:
Spectrum of neutrinos in our universe



[Raffelt, Tamborra, Vitagliano et al. 19']

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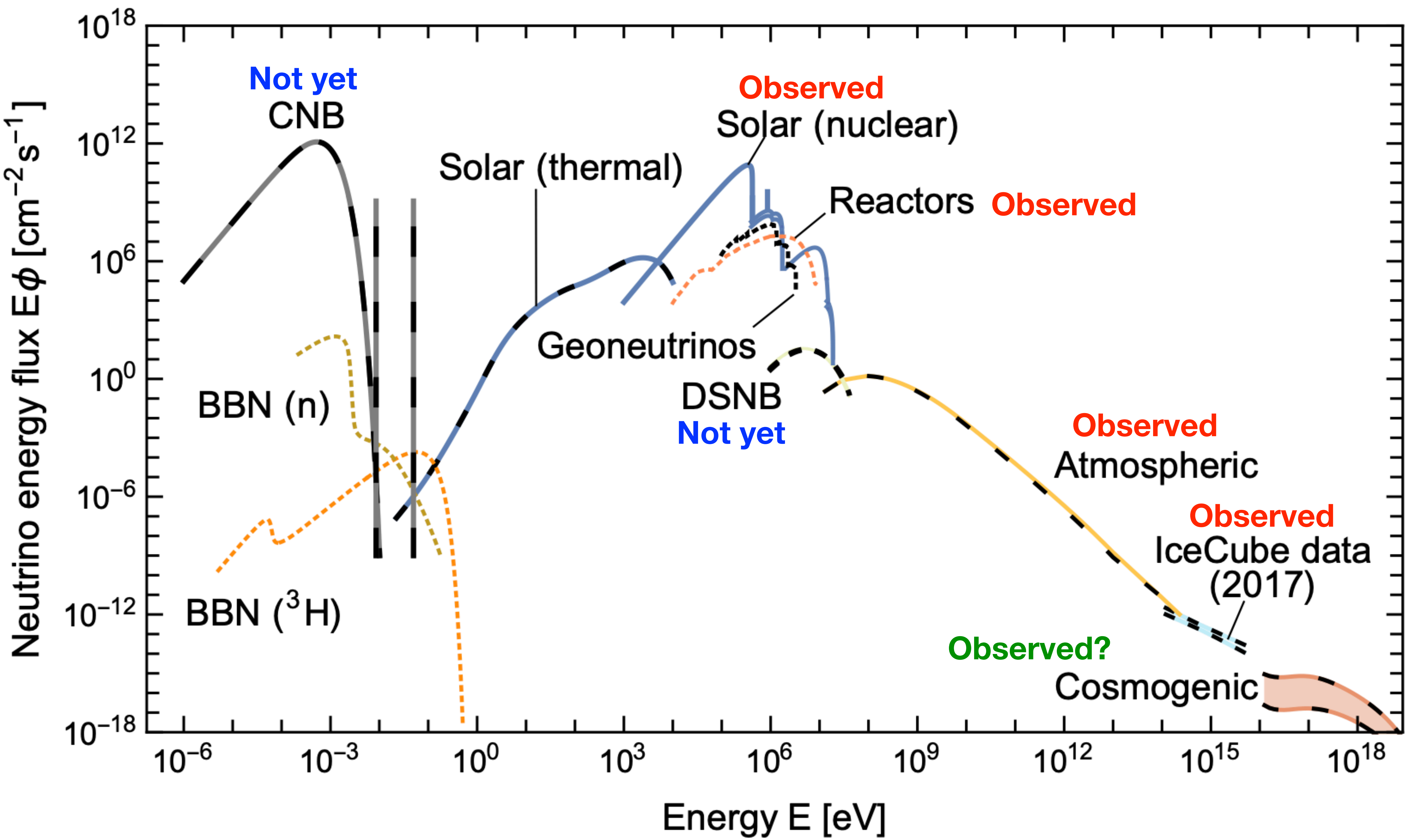

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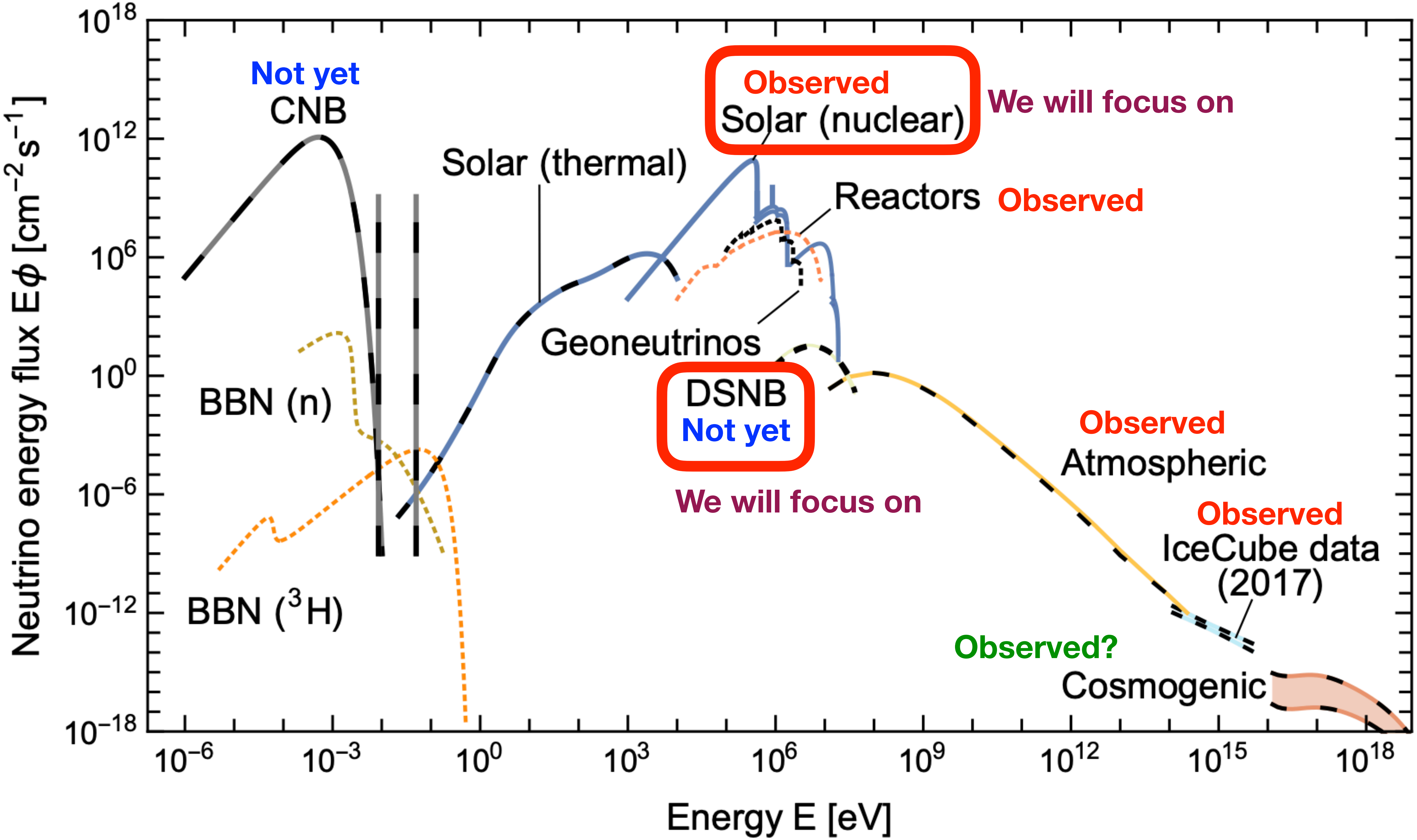

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How many neutrinos?: Spectrum of neutrinos in our universe

Channel	Flux	Reaction	E_{av} MeV	E_{max} MeV	Flux at Earth GS98	AGSS09	Observed	Units
pp Chains (β^+)	Φ_{pp}	$p + p \to d + e^+ + \nu_e$	0.267	0.423	5.98 ±0.6%	6.03 ±0.5%	$5.971^{+0.62\%}_{-0.55\%}$	10^{10} cm^{-2} s^{-1}
	Φ_B	$^8B \to {}^8Be^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15	5.46 ±12%	4.50 ±12%	$5.16^{+2.5\%}_{-1.7\%}$	10^6 cm^{-2} s^{-1}
	Φ_{hep}	$^3He + p \to {}^4He + e^+ + \nu_e$	9.628	18.778	0.80 ±30%	0.83 ±30%	$1.9^{+63\%}_{-47\%}$	10^4 cm^{-2} s^{-1}
pp Chains (EC)	Φ_{Be}	$e^- + {}^7Be \to {}^7Li + \nu_e$	0.863 (89.7%)		4.93 ±6%	4.50 ±6%	$4.80^{+5.9\%}_{-4.6\%}$	10^9 cm^{-2} s^{-1}
		$e^- + {}^7Be \to {}^7Li^* + \nu_e$	0.386 (10.3%)					
	Φ_{pep}	$p + e^- + p \to d + \nu_e$	1.445		1.44 ±1%	1.46 ±0.9%	$1.448^{+0.90\%}_{-0.90\%}$	10^8 cm^{-2} s^{-1}
CNO Cycle (β^+)	Φ_N	$^{13}N \to {}^{13}C + e^+ + \nu_e$	0.706	1.198	2.78 ±15%	2.04 ±14%	< 13.7	10^8 cm^{-2} s^{-1}
	Φ_O	$^{15}O \to {}^{15}N + e^+ + \nu_e$	0.996	1.732	2.05 ±17%	1.44 ±16%	< 2.8	10^8 cm^{-2} s^{-1}
	Φ_F	$^{17}F \to {}^{17}O + e^+ + \nu_e$	0.998	1.736	5.29 ±20%	3.26 ±18%	< 8.5	10^6 cm^{-2} s^{-1}
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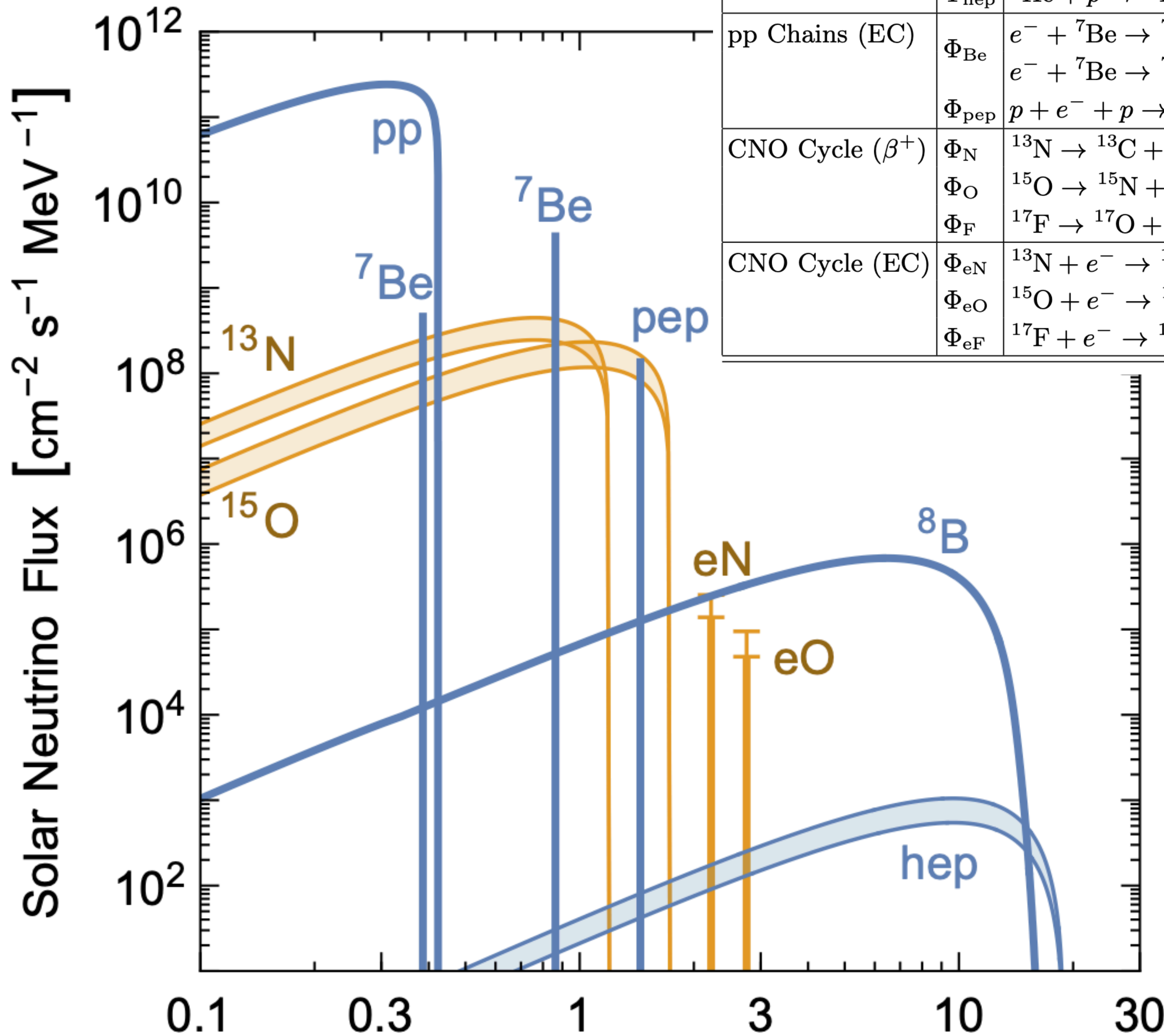

- The solar neutrino spectrum has maximum around 300 keV
- & Includes several bumps/peaks from each nuclear channels.
- Dominant contributions to fluxes are very well measured by experiments (e.g. Borexino, Gemma)

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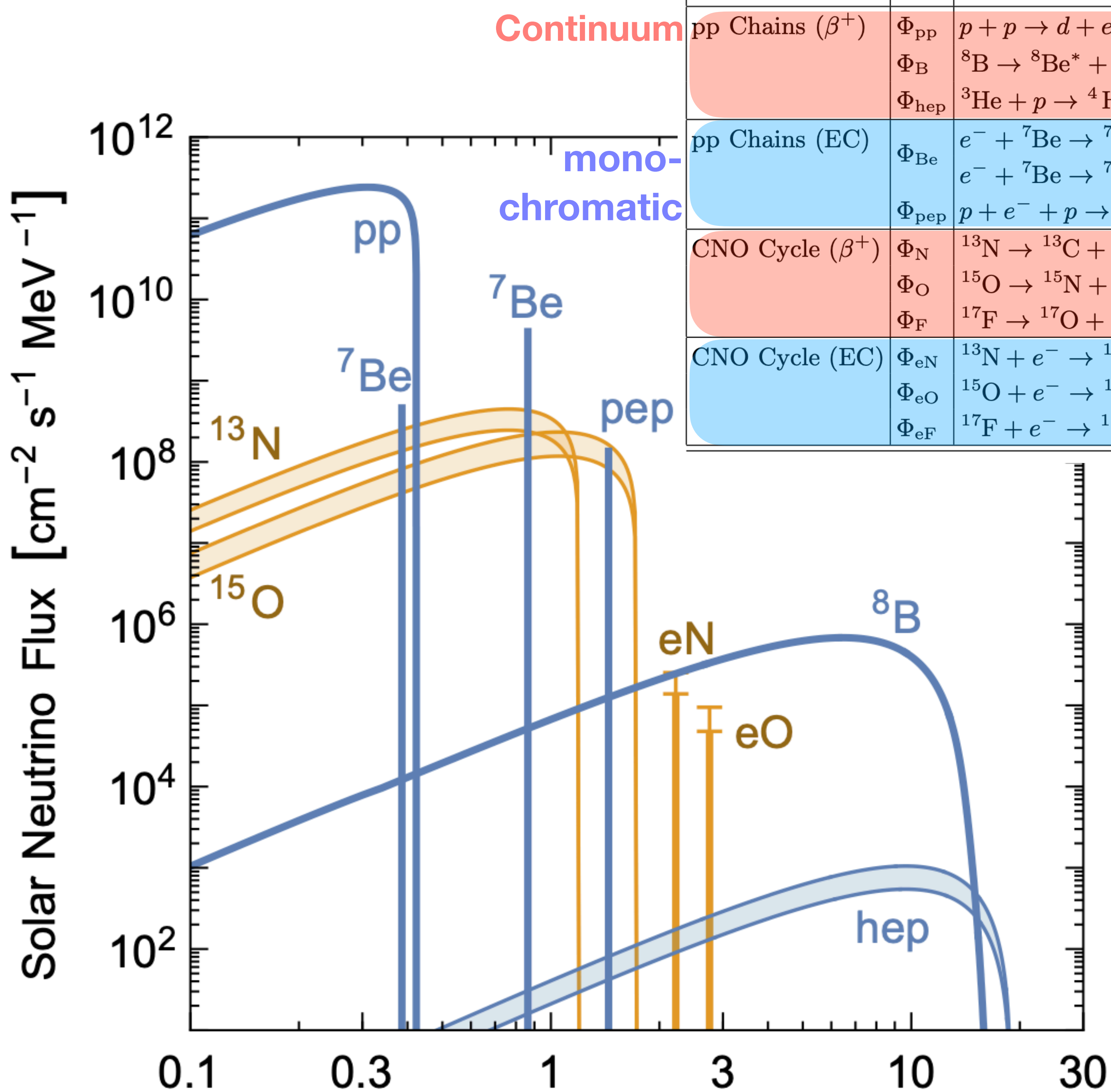

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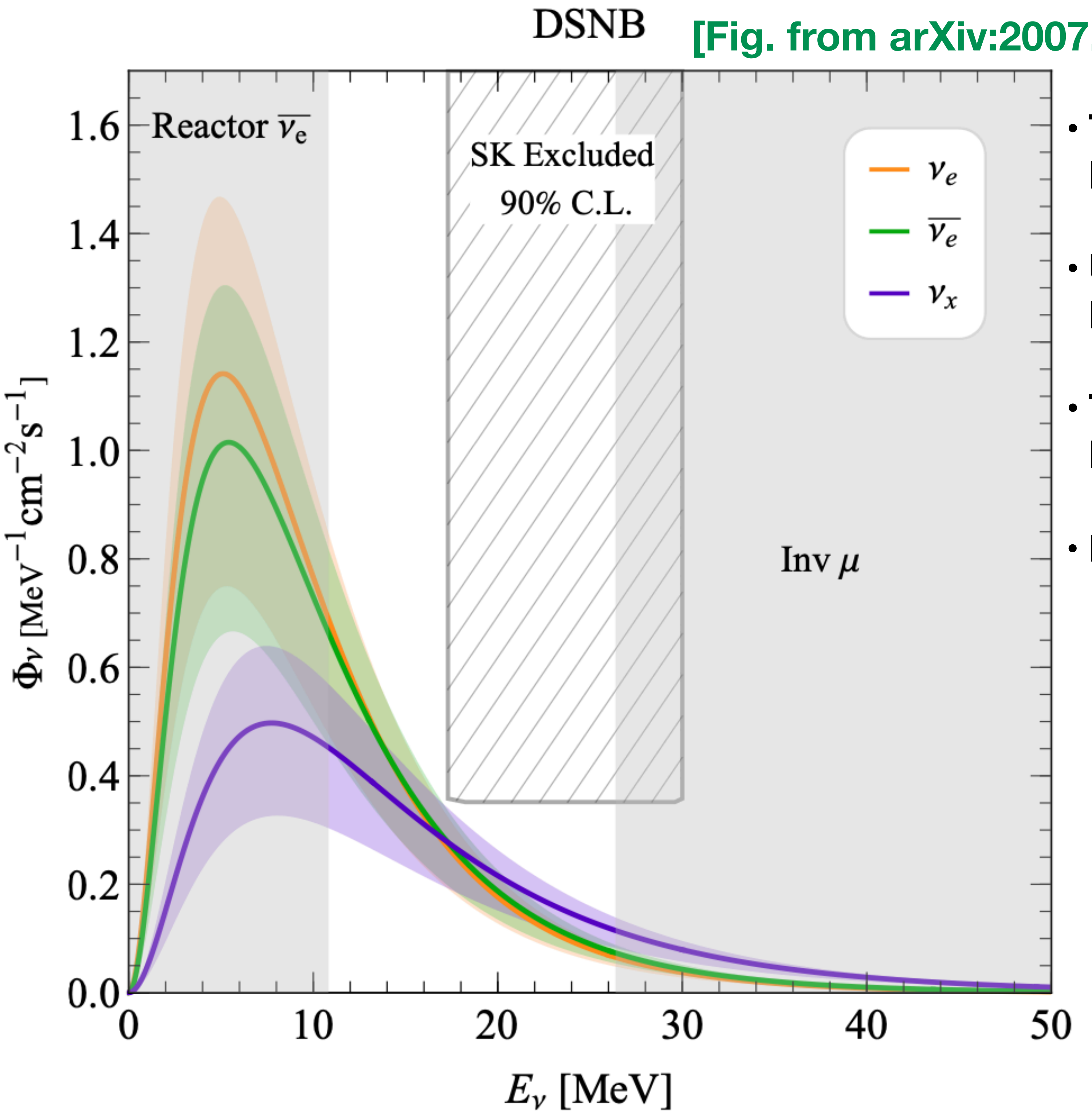
[Raffelt, Tamborra, Vitagliano et al. 19']

How many neutrinos?: Spectrum of neutrinos in our universe

[Fig. from arXiv:2007.13748 [hep-ph]]

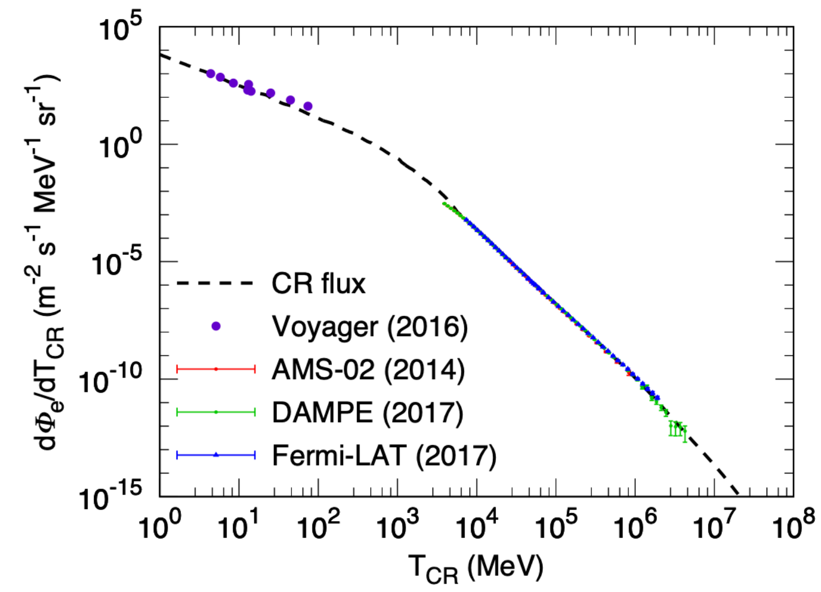


- Thermally produced from neutronization in Proto-Neutron Stars (PNS)
- Usually has Boltzmann peaks around 5-10 MeV (depending on flavor of neutrinos)
- The amount of flux is determined by Star-Formation-Rate (SFR) including high redshift.
- Extragalactic origin & almost isotropic

A direct detection of DSNB suggested by [Beacom. 10']

Boosting keV-GeV DM with

- Electron Cosmic rays (based on observed data)



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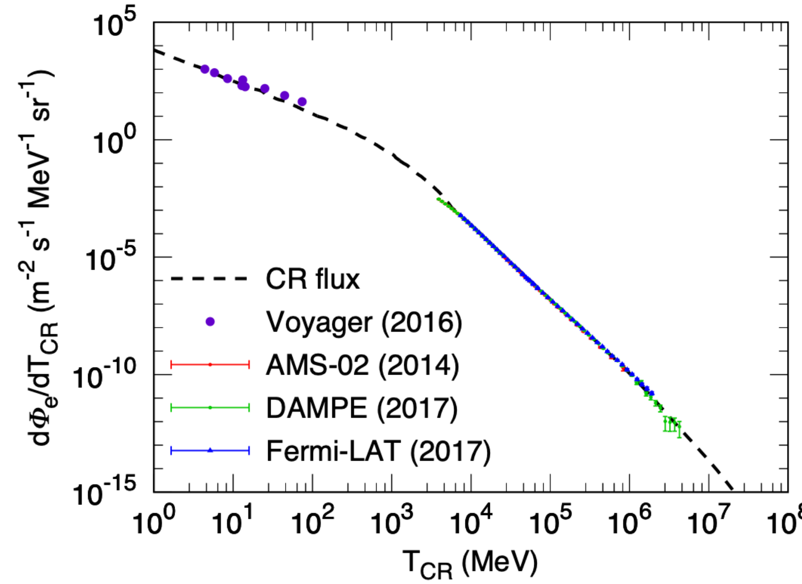
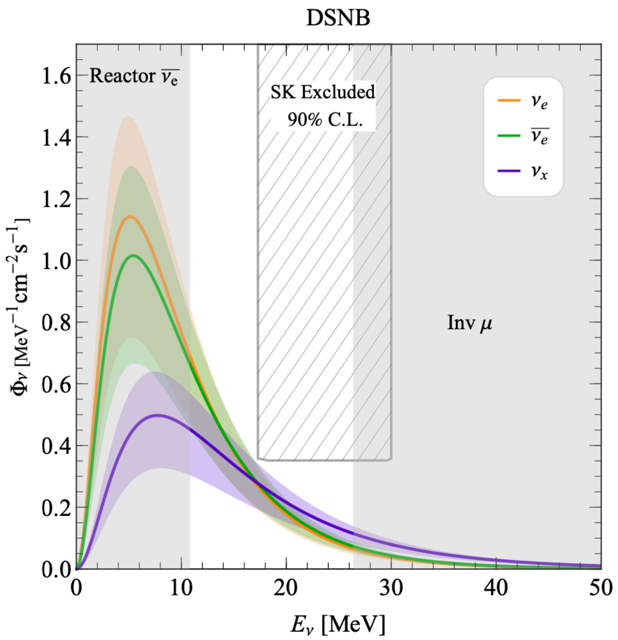


- DSNB (extragalactic origin)



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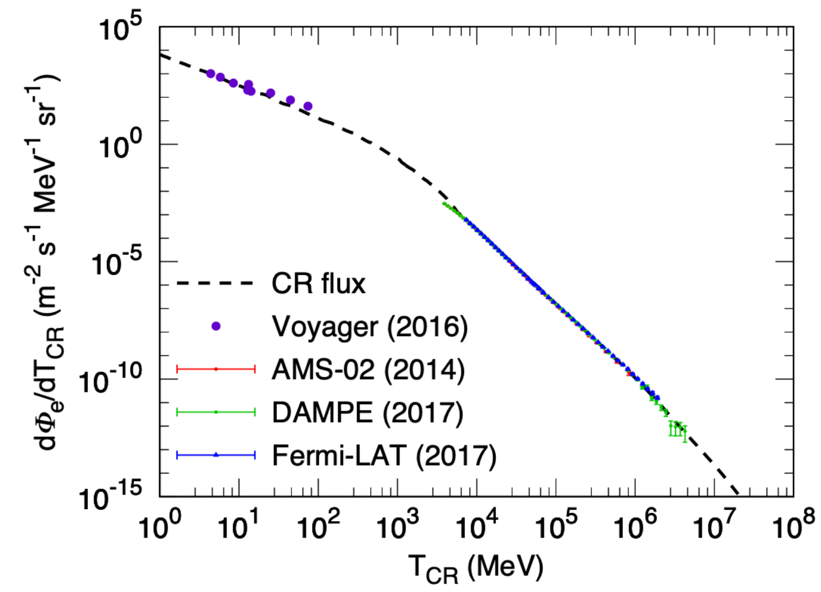

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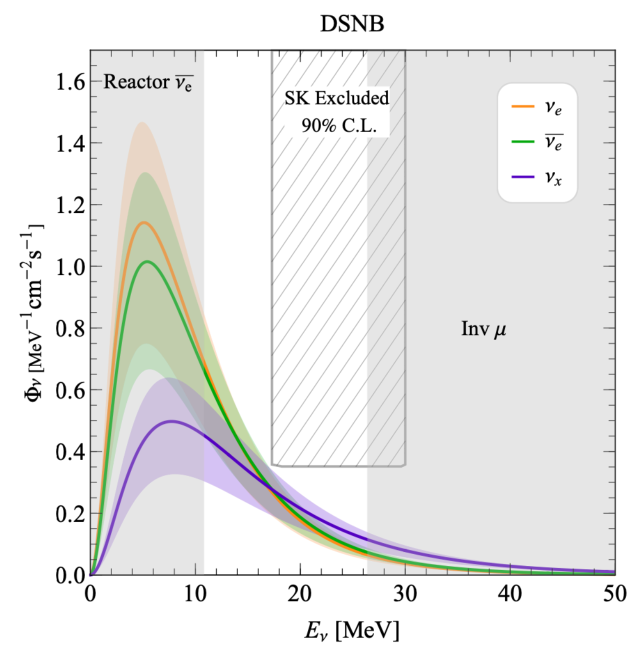
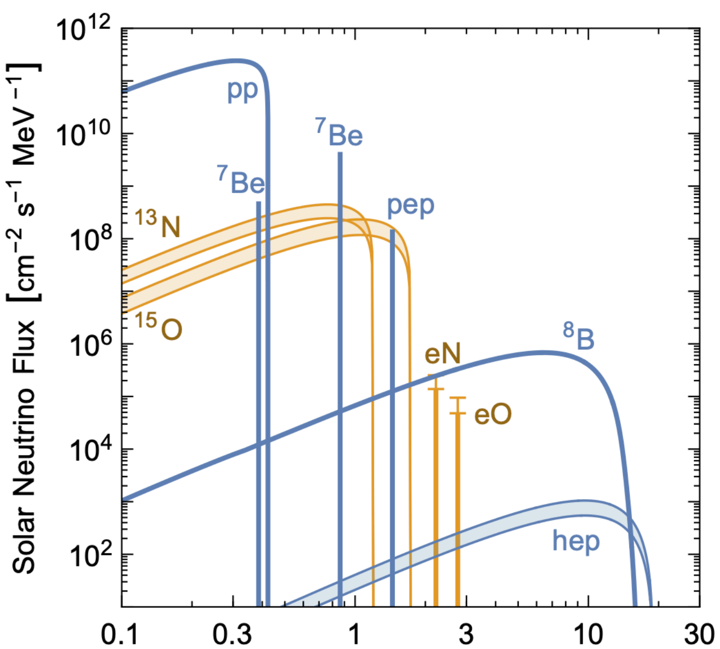
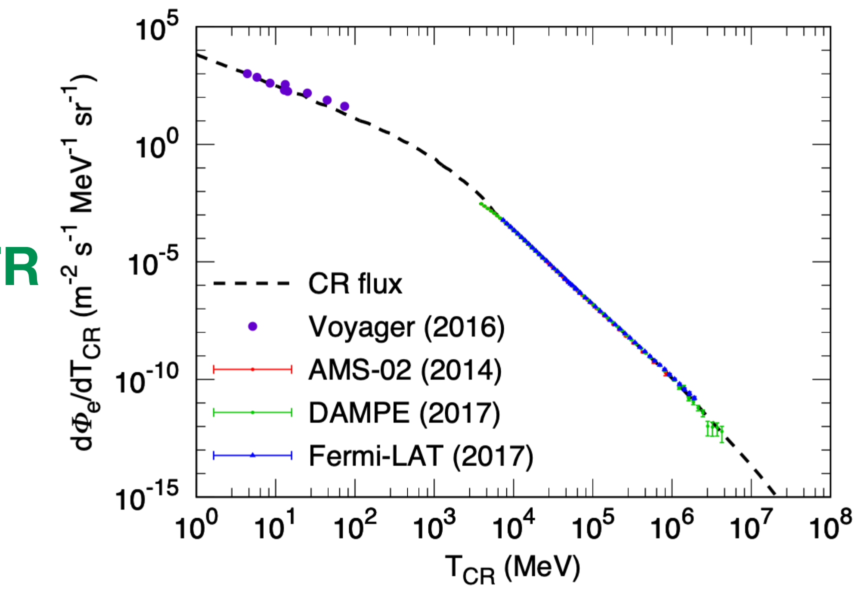




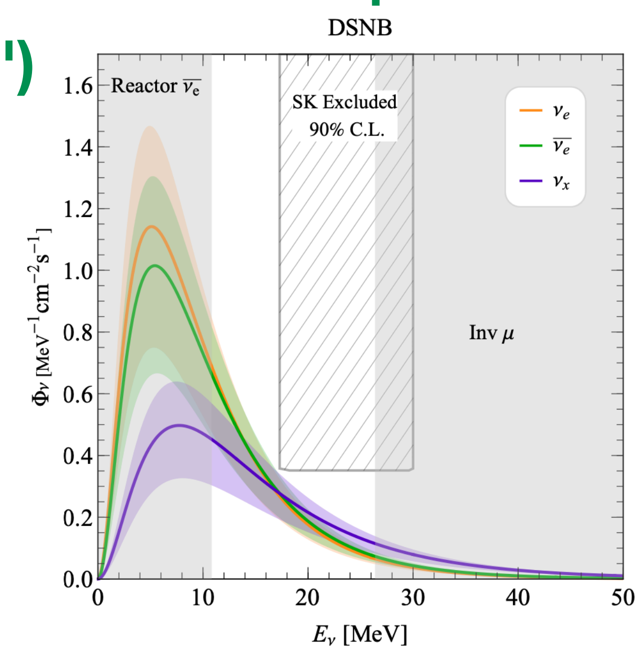
- Stellar neutrinos (Galactic/Extragalactic origin, This work)

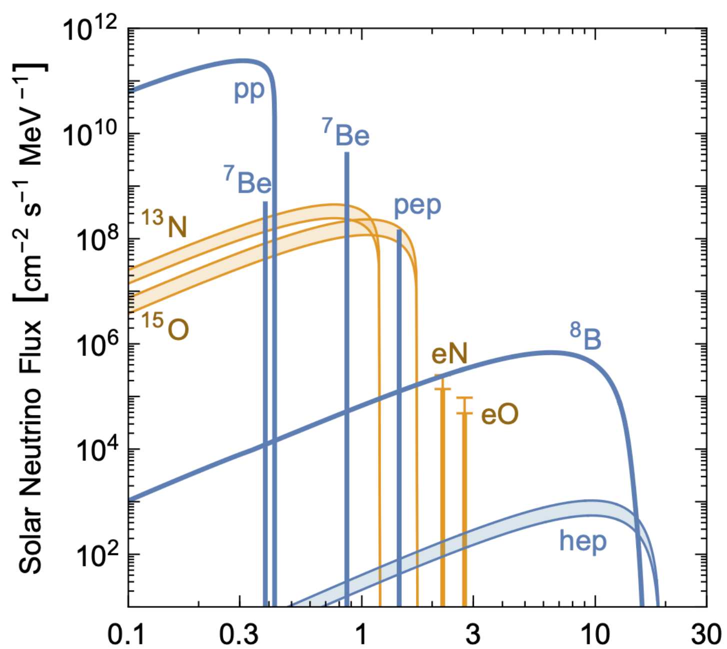
Boosting keV-GeV DM with

- Electron Cosmic rays (based on observed data)
  first suggested by Y. Ema et al. (18')
  Electron CR (2 MeV - 90 GeV for the observed data)



- DSNB (extragalactic origin)
  Neutrino (O(1)-O(100) MeV) & normalization predicted by SFR
  first suggested by A. Das et al. (21')

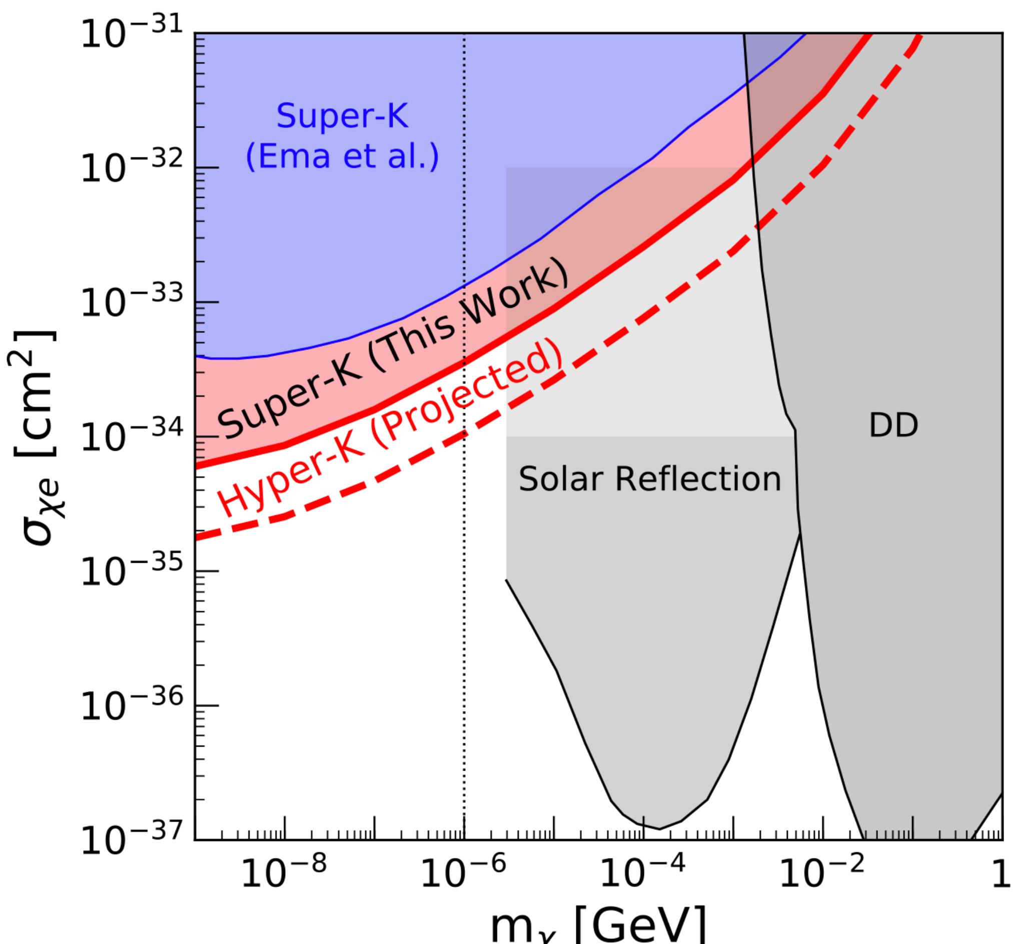




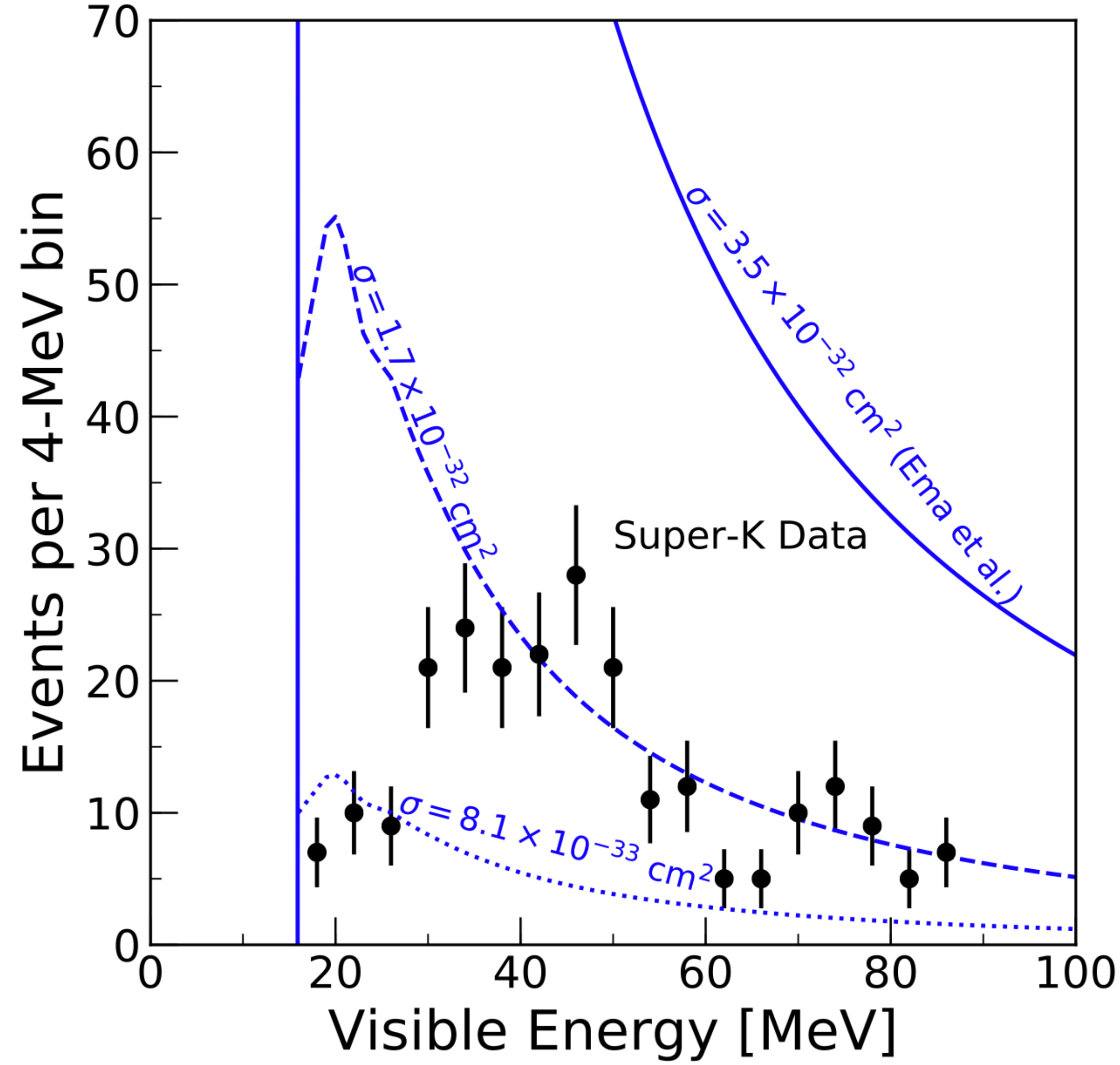
- Stellar neutrinos (Galactic/Extragalactic origin, Our work)
  Neutrino (~100 keV - 20 MeV) & precisely measured by solar neutrino detection exp.

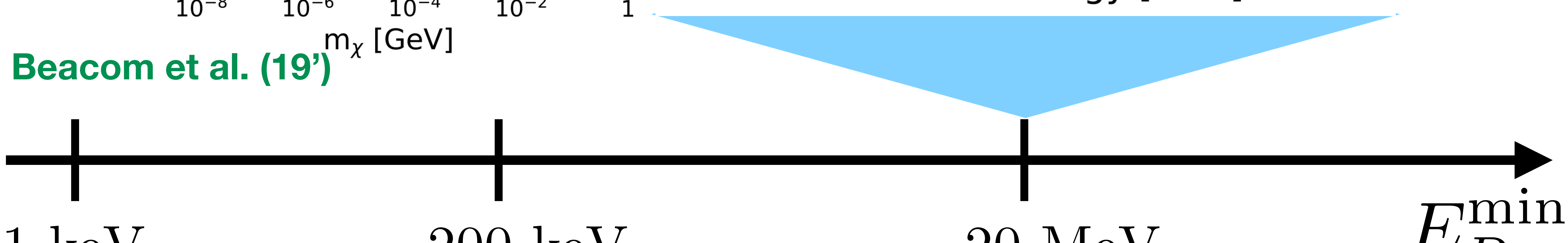
How to detect them?: The low threshold frontier of electron recoils in DM/neutrino exp.

SN neutrino searches (SK- I/II/III/IV)
- **E threshold ~ 10-20 MeV (Super-K)**
- **Typical Exposure ~ O(200) kton-yr**



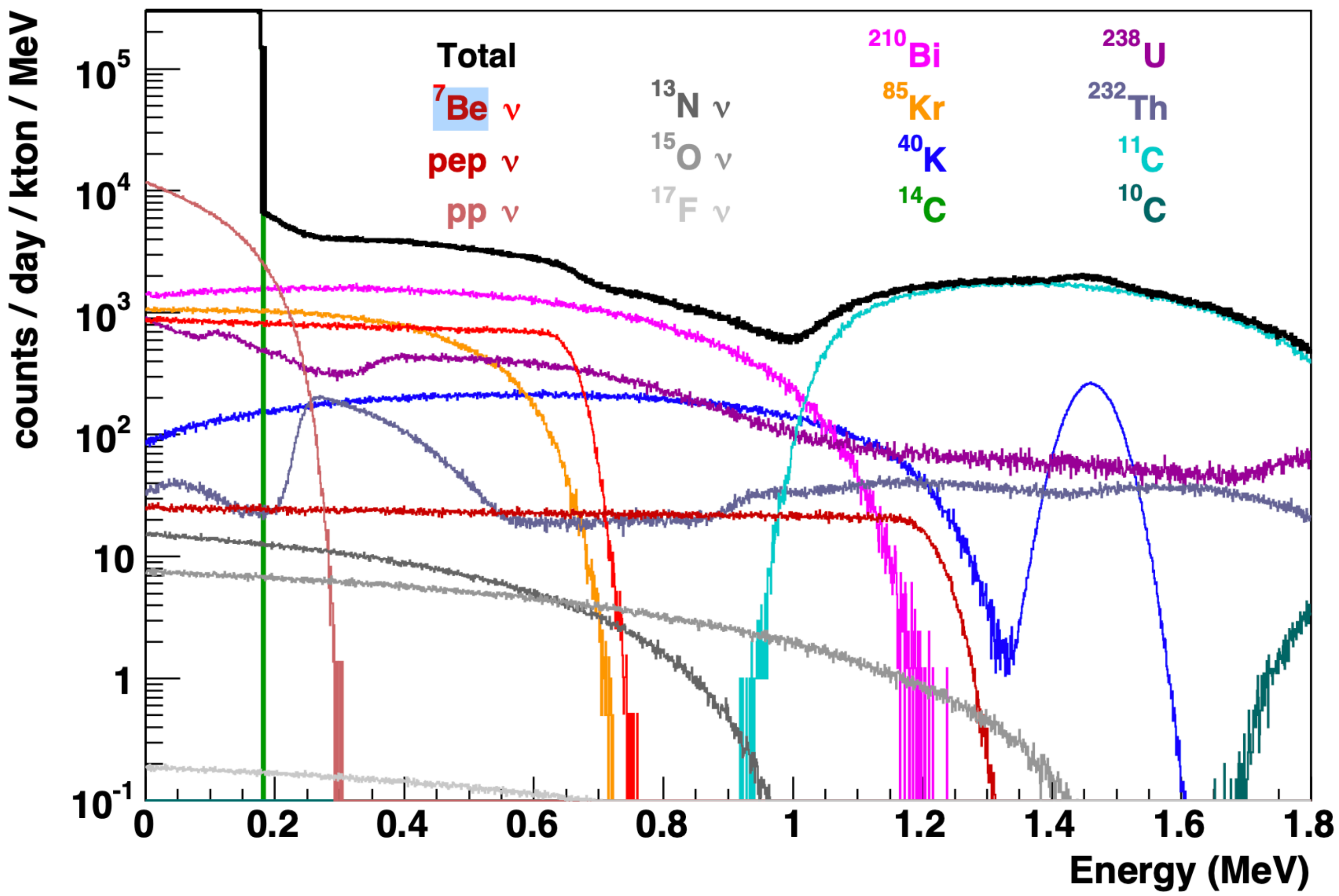
J. Beacom et al. (19')

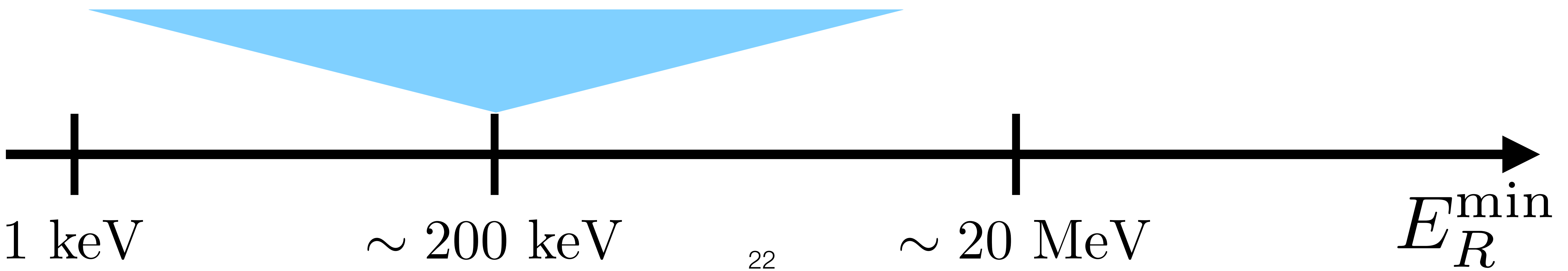




How to detect them?: The low threshold frontier of electron recoils in DM/neutrino exp.

Low-E solar neutrinos (e.g. 7Be neutrino)
- E threshold ~ 200-300 keV (JUNO/Borexino)
- Typical Exposure ~ O(10) kton-yr





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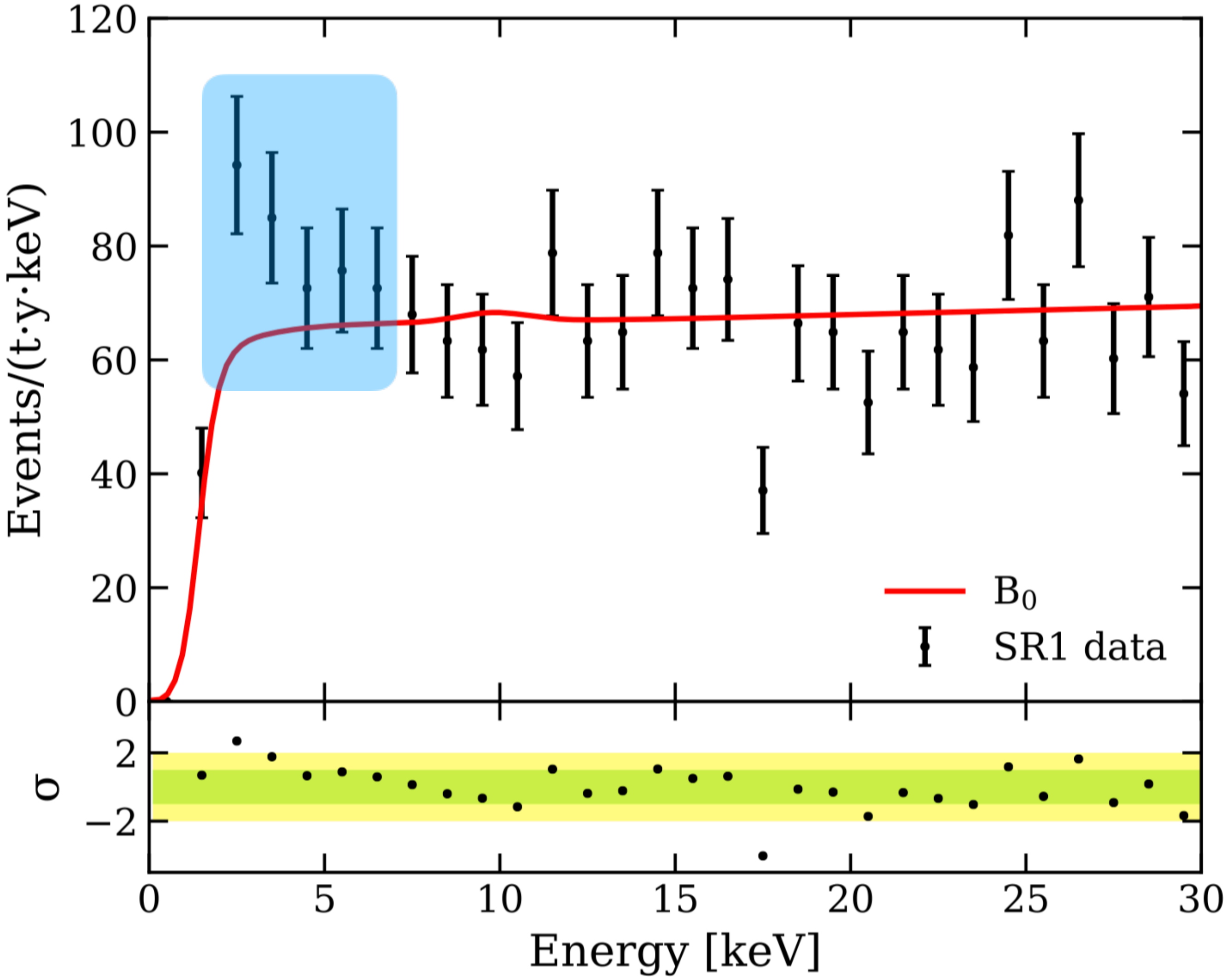
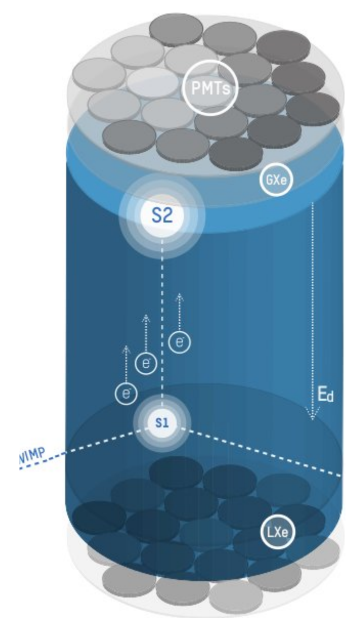
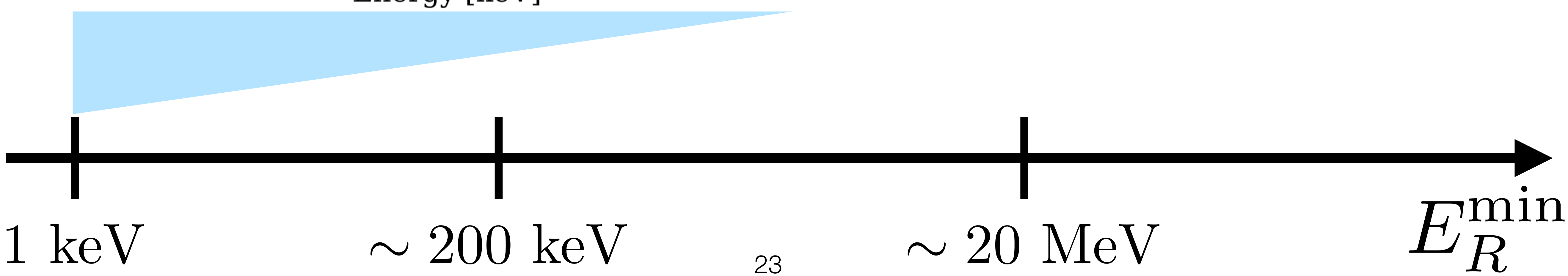
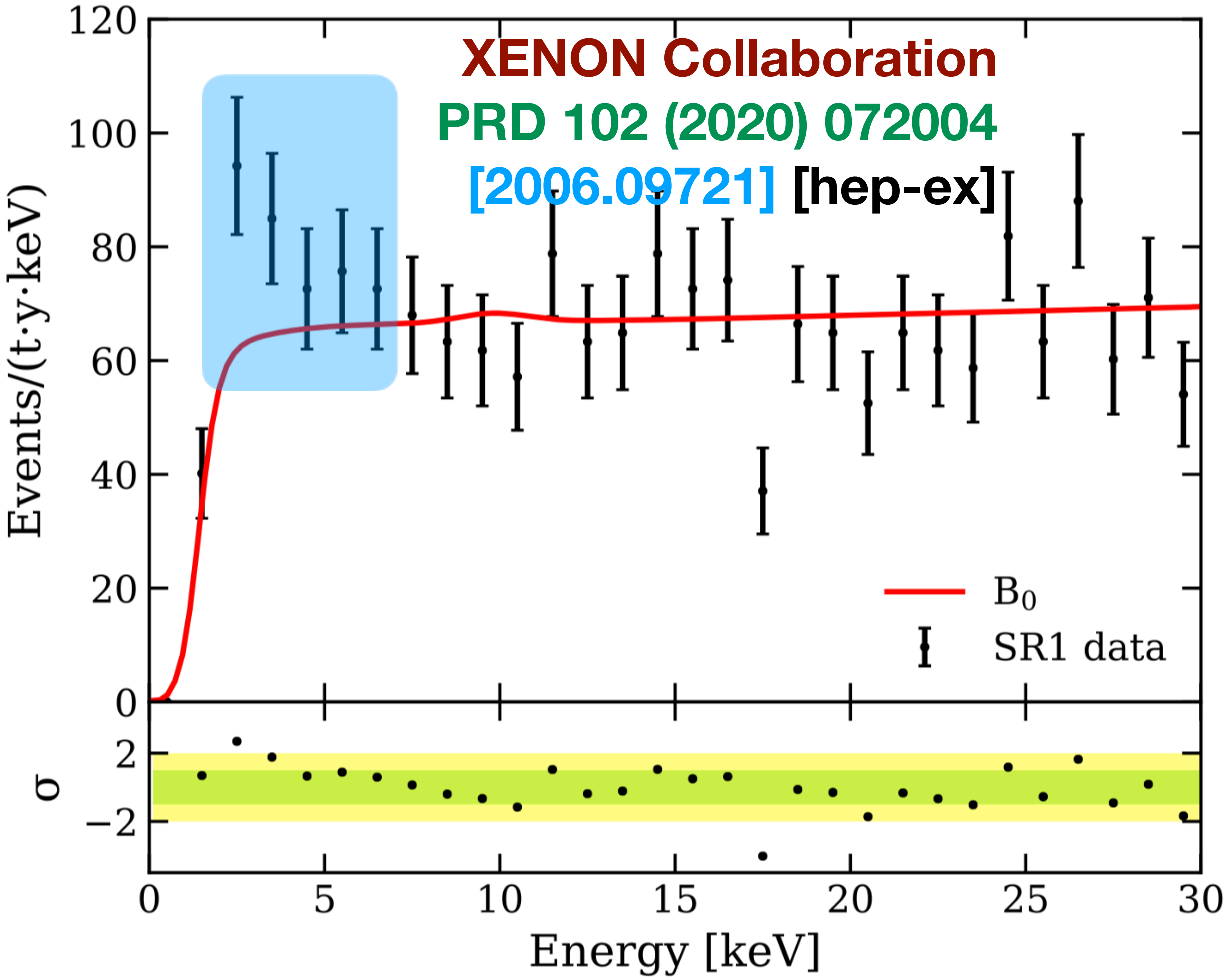


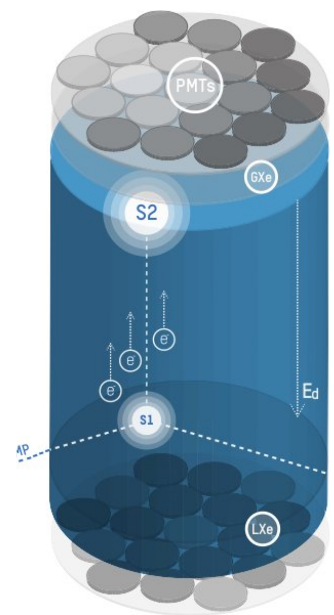
DM direct detections
- E threshold ~ 1 keV (XENON, LZ, PandaX)
- Typical Exposure ~ O(1-10) ton-yr

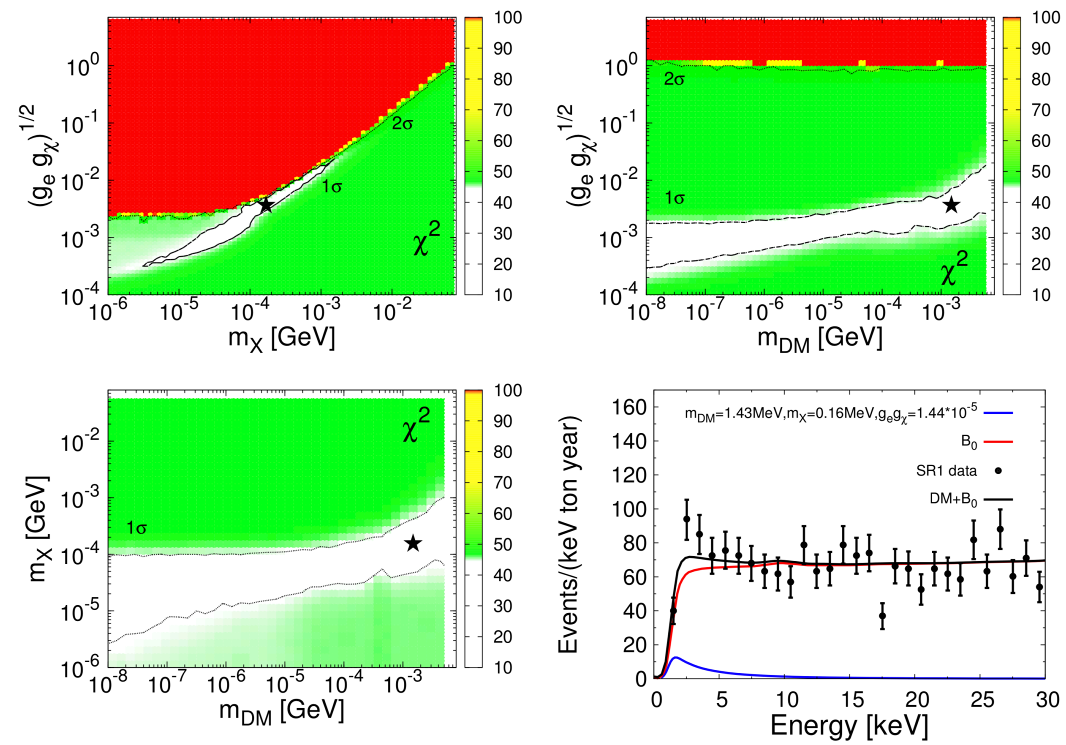




eCR-Boosted Dark Matter (BDM) & Observation of BDM at DM Direct detection





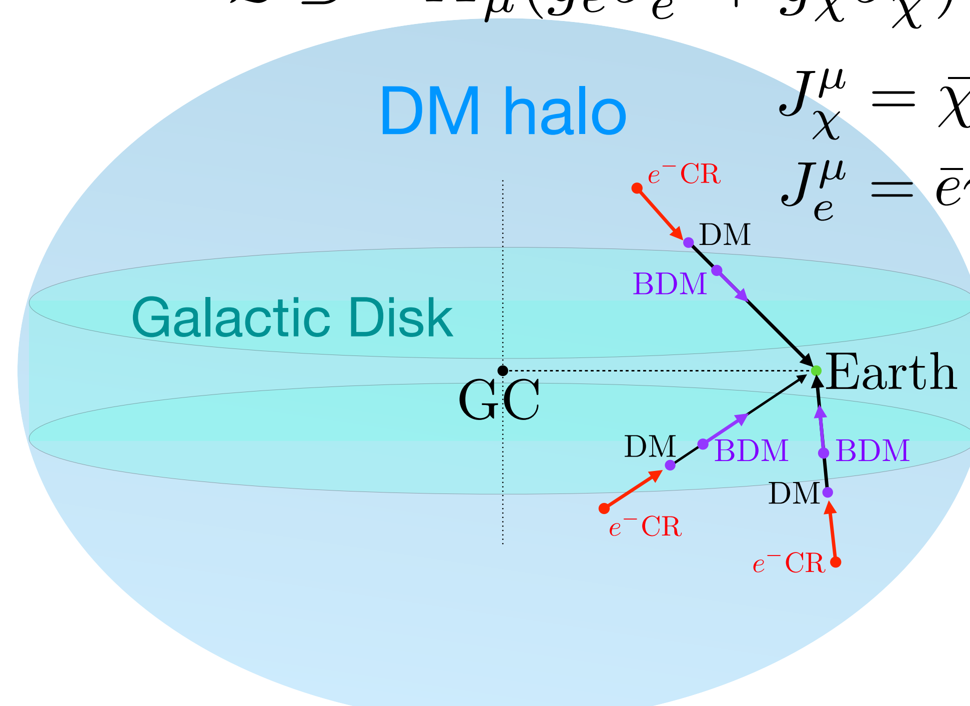


YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng, PLB 811 (2020) 135863 [2006.13910] [hep-ph]

$$\mathcal{L} \supset -X_\mu (g_e J_e^\mu + g_\chi J_\chi^\mu) + \ldots$$

$$J_\chi^\mu = \bar{\chi}\gamma^\mu\chi$$

$$J_e^\mu = \bar{e}\gamma^\mu e$$



Charged Cosmic ray (electron) BDM provides an interesting possibility in DM direct detection/neutrino observatories.

Caveat) Large e-DM interaction can be suffered from the constraints by cosmology and SN.

eCR-Boosted Dark Matter (BDM) & Observation of BDM at DM Direct detection

- The flux of DM, boosted by CR electron

$$\frac{d\Phi_{\rm DM}}{d\Omega}(K_{\rm DM}, b, l) = \frac{J(b,l)}{m_{\rm DM}} \int dK_e \underbrace{\frac{d\Phi_e}{d\Omega}}_{\text{electron CR flux}} \underbrace{\frac{d\sigma_{{\rm DM}e\to{\rm DM}e}}{dK_{\rm DM}}}_{e^-_{\rm CR}+\chi_{\rm halo}\to e^- + \chi_{\rm Boosted}}$$

$$J(b,l) = \int_{l.o.s} d\ell \rho_{\rm DM}$$

- Boosted DM-target electron (in the detector) cross section with light mediator X

$$\frac{d\sigma_X({\rm DM}e \to {\rm DM}e)}{dK_e} = \frac{(g_e g_\chi)^2}{4\pi} \frac{2m_e(m_{\rm DM}+K_{\rm DM})^2 - K_e\left((m_e+m_{\rm DM})^2 + 2m_e K_{\rm DM}\right) + m_e K_e^2}{(2m_{\rm DM}K_{\rm DM}+K_{\rm DM}^2)(2m_e K_e + m_X^2)^2}$$

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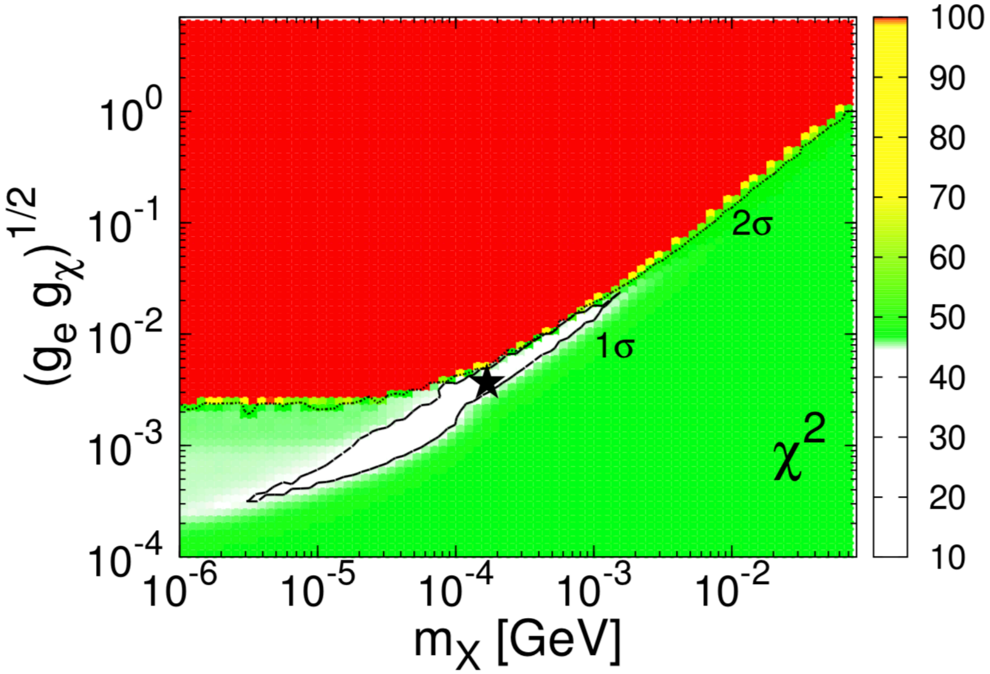
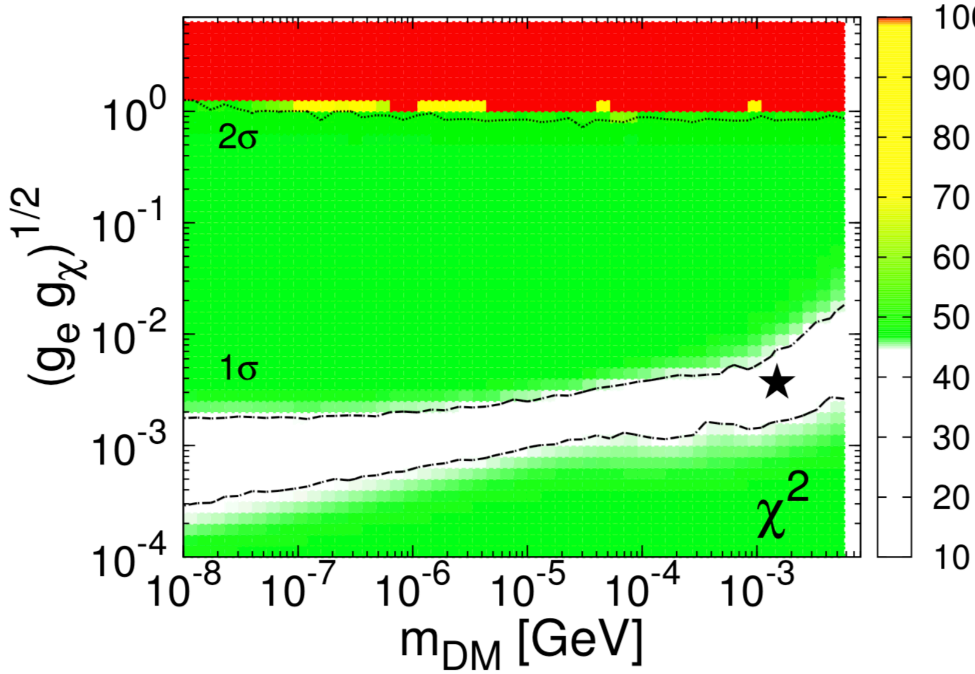
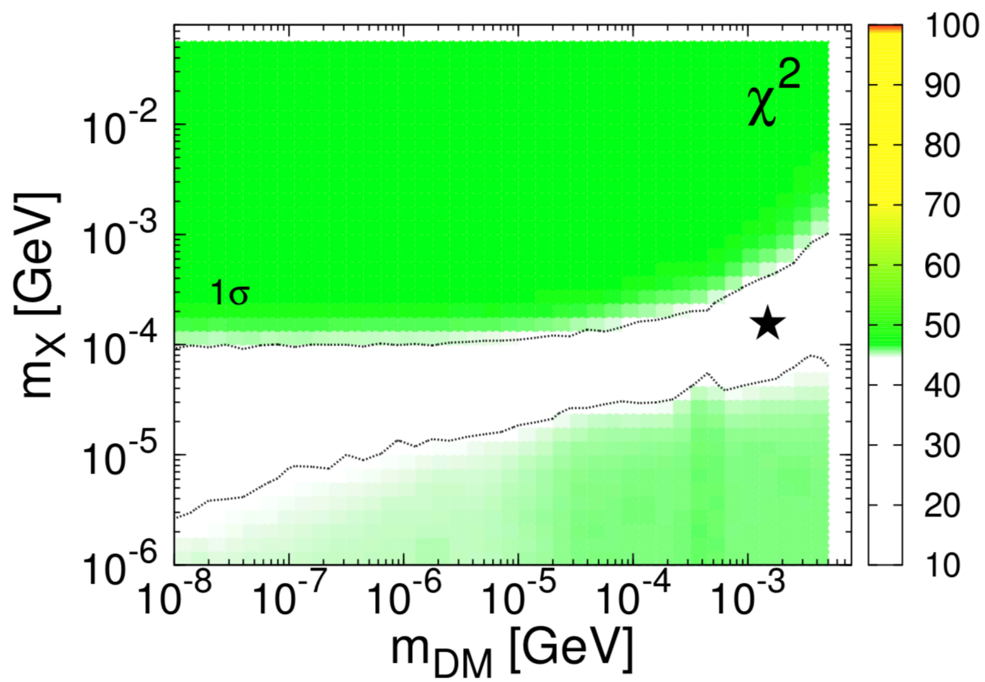
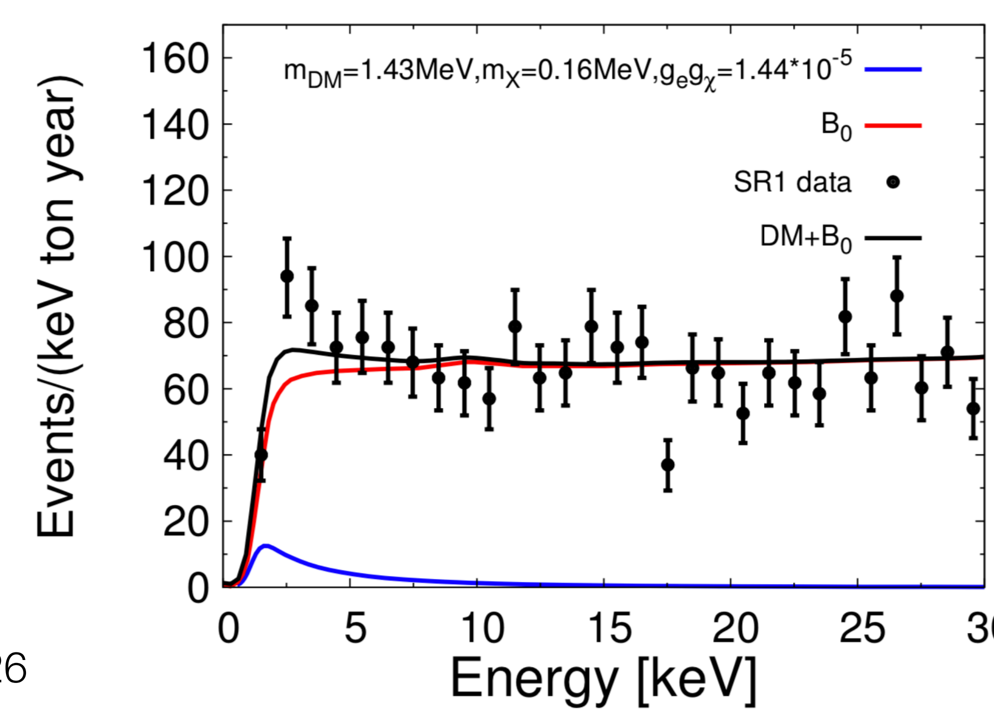
- Favored parameters





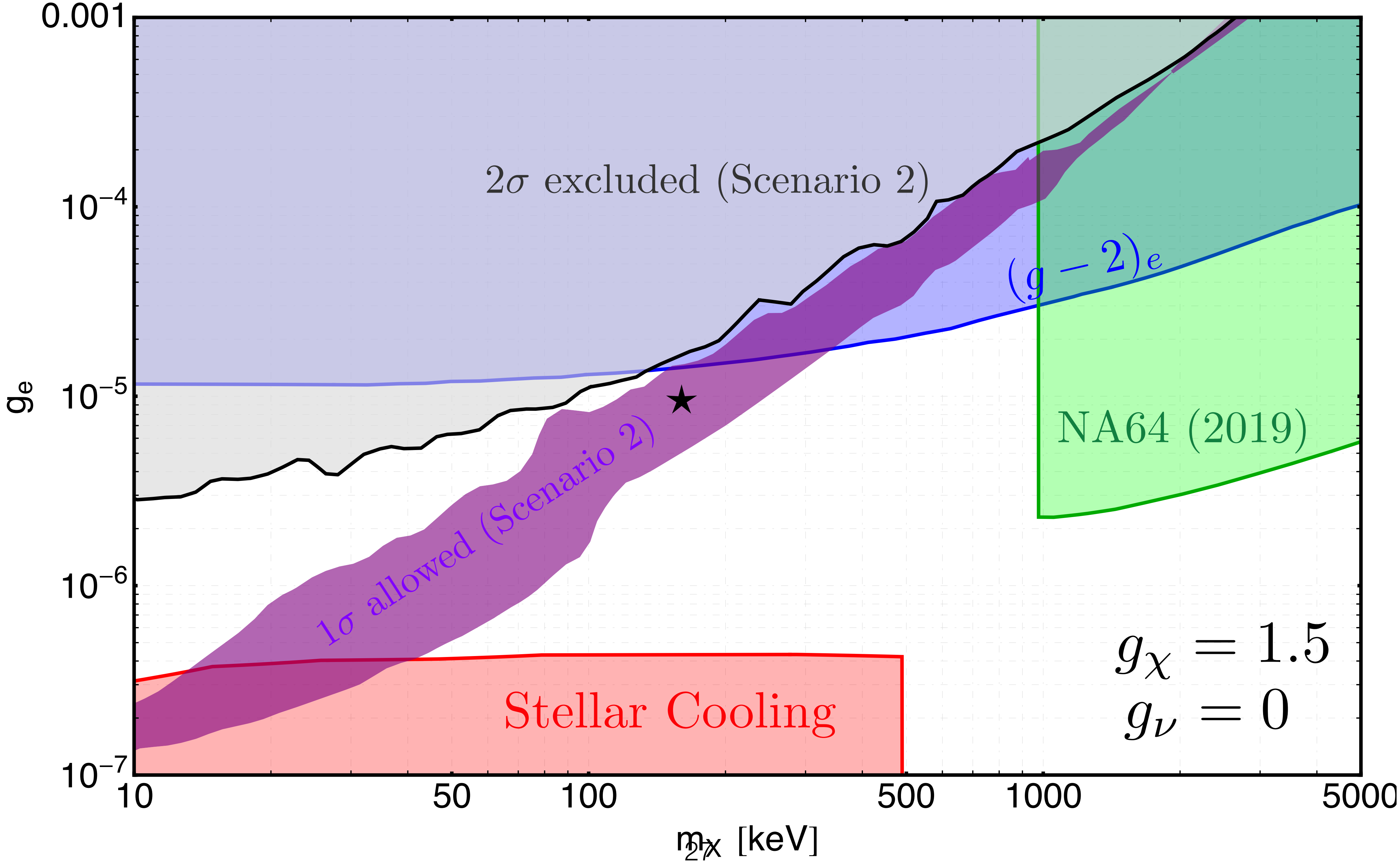




eCR-Boosted Dark Matter (BDM) & Observation of BDM at DM Direct detection

- Constraints (mediator mass/coupling)

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
PLB 811 (2020) 135863 [2006.13910] [hep-ph]



Then, How about neutrinos?

Q1: Can Cosmic "Neutrinos"
boost light Dark Matter in the halo?

Q2: Cosmic-Neutrino-Boosted Dark Matter
can be probed at
various ground experiments/observatories?

Then, How about neutrinos?

Q1: Can Cosmic "Neutrinos" boost light Dark Matter in the halo?

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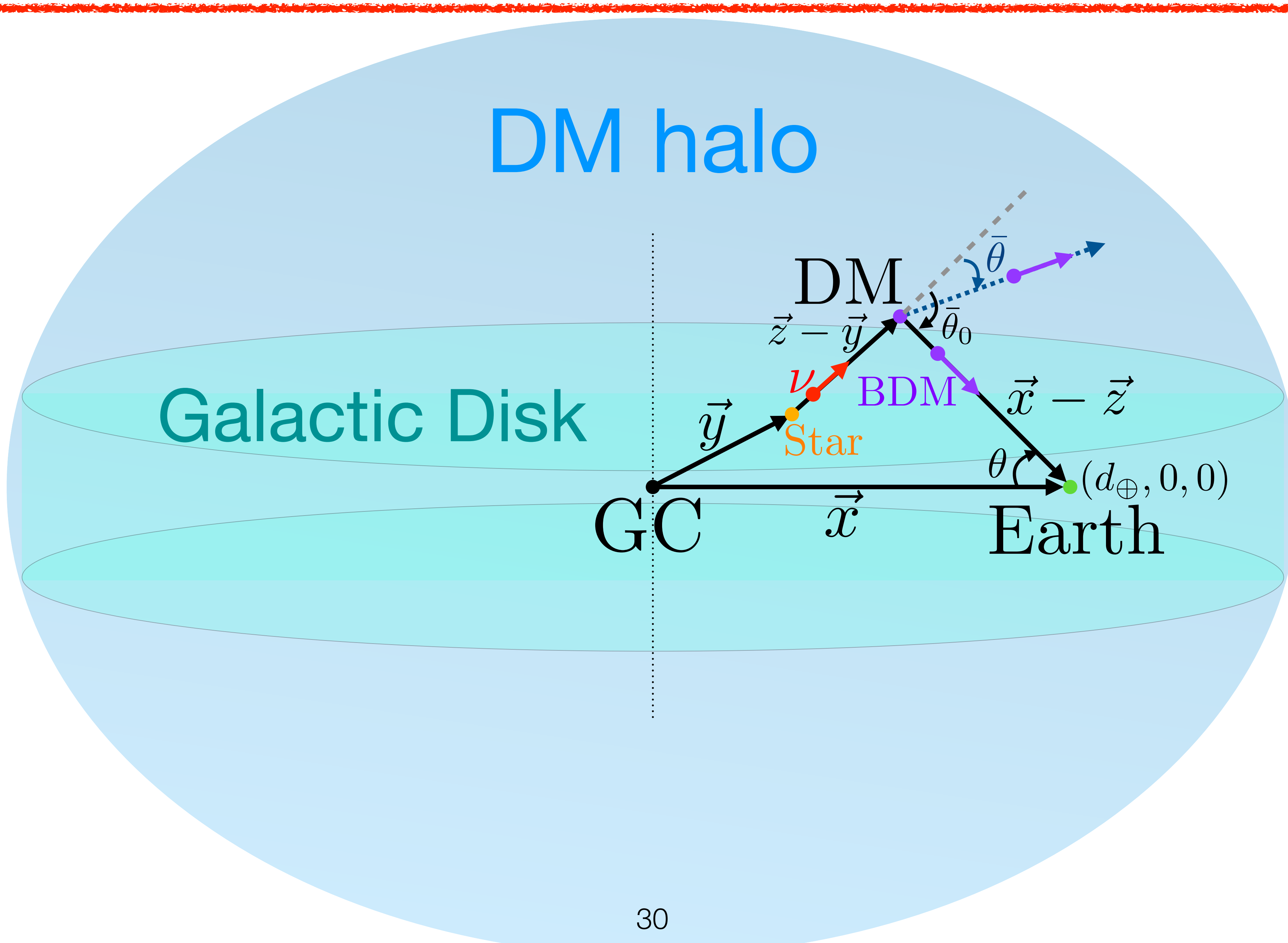
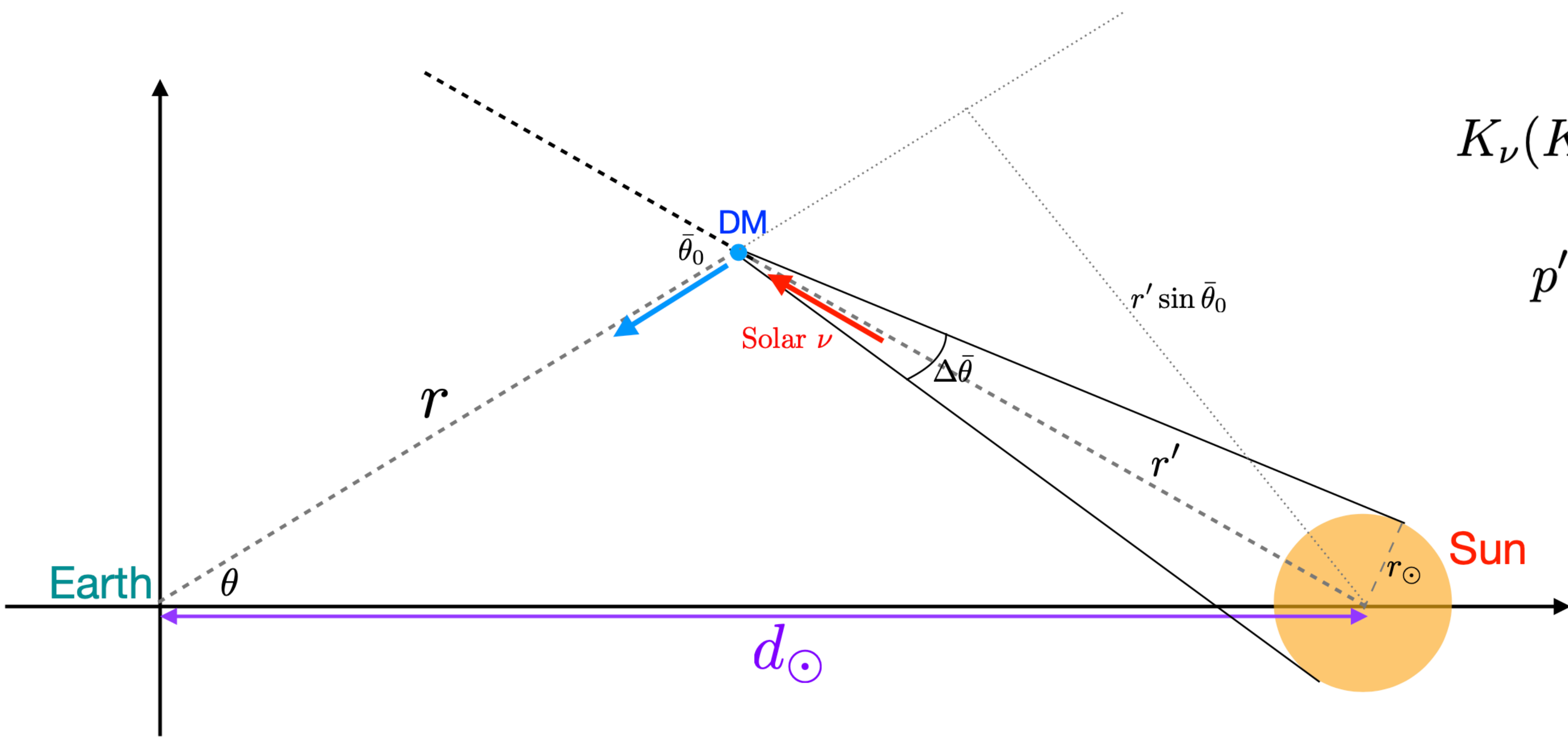
Q1: Can Cosmic "Neutrinos" boost light Dark Matter in the halo?



Galactic Neutrino-Boosted Dark Matter

Dark Matter boosted by neutrinos emitted from the Sun



$$K_\nu(K_{\rm DM},\bar{\theta}) = \frac{K_{\rm DM}^2 - p'^2}{2(K_{\rm DM} - p'\cos\bar{\theta})},$$

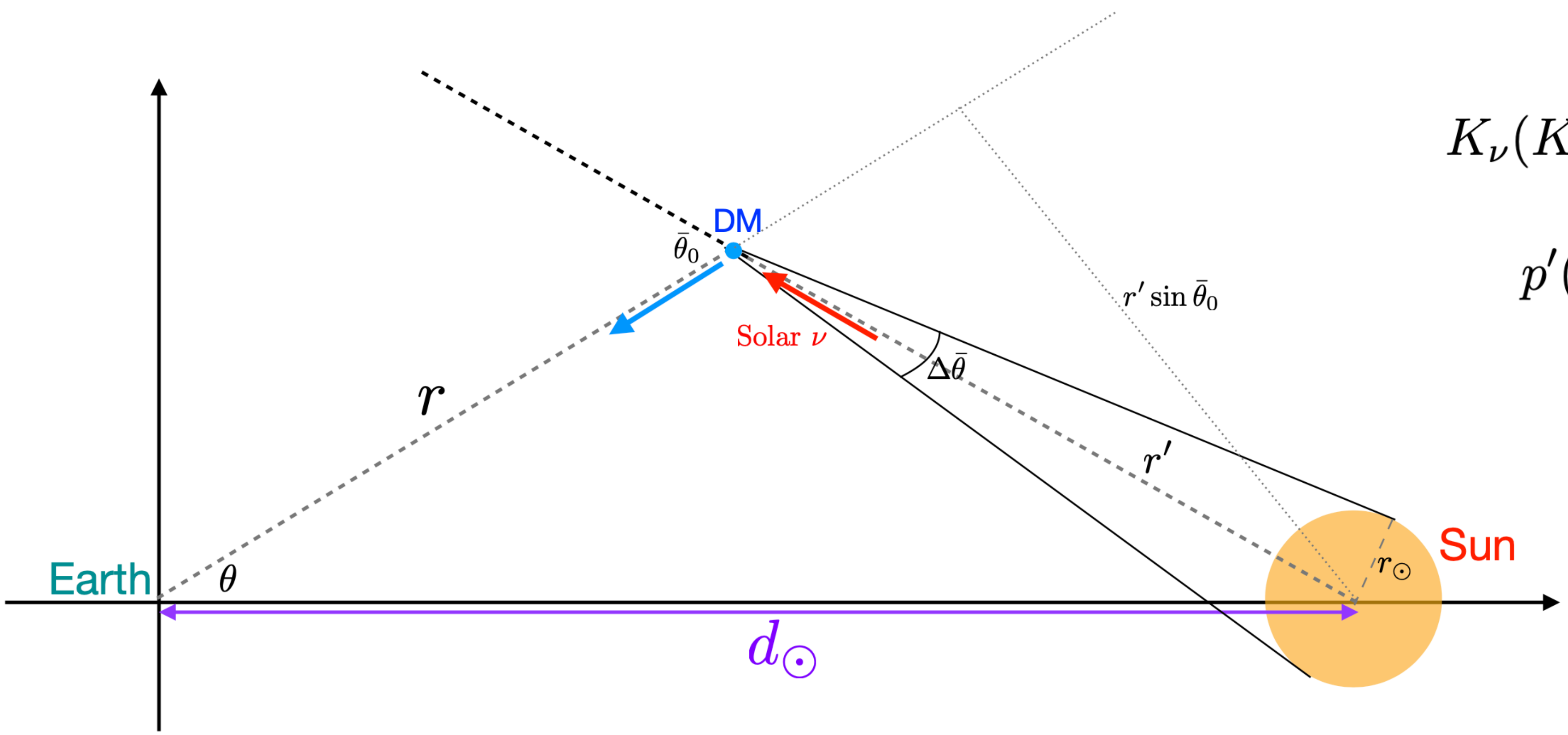
$$p'(K_{\rm DM}) = \sqrt{2m_{\rm DM}K_{\rm DM} + K_{\rm DM}^2}.$$

$$\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} = \int dV \frac{\rho_{\rm DM}}{m_{\rm DM}} \frac{1}{r^2} \int_{K_\nu^{\rm min}}^{K_\nu^{\rm max}} \underset{\propto r_\odot}{dK_\nu} \frac{d\sigma_{\nu-{\rm DM}}(K_{\rm DM},\bar{\theta})}{dK_{\rm DM}} \cdot \left(\frac{r_\odot}{4r'\sin\bar{\theta}}\right) \cdot \underbrace{\left(\frac{d^2\Phi^{{\rm Solar}\ \nu}}{d\Omega dK_\nu}\right) \cdot \left(\frac{d_\odot}{r'}\right)^2}_{\frac{\dot{N}_\nu}{4\pi r_\odot^2}}$$

(It is valid in the point source limit, $r_\odot \to 0$)

Galactic Neutrino-Boosted Dark Matter

Dark Matter boosted by neutrinos emitted from the Sun



$$K_\nu(K_{\rm DM},\bar{\theta}) = \frac{K_{\rm DM}^2 - p'^2}{2(K_{\rm DM} - p'\cos\bar{\theta})},$$
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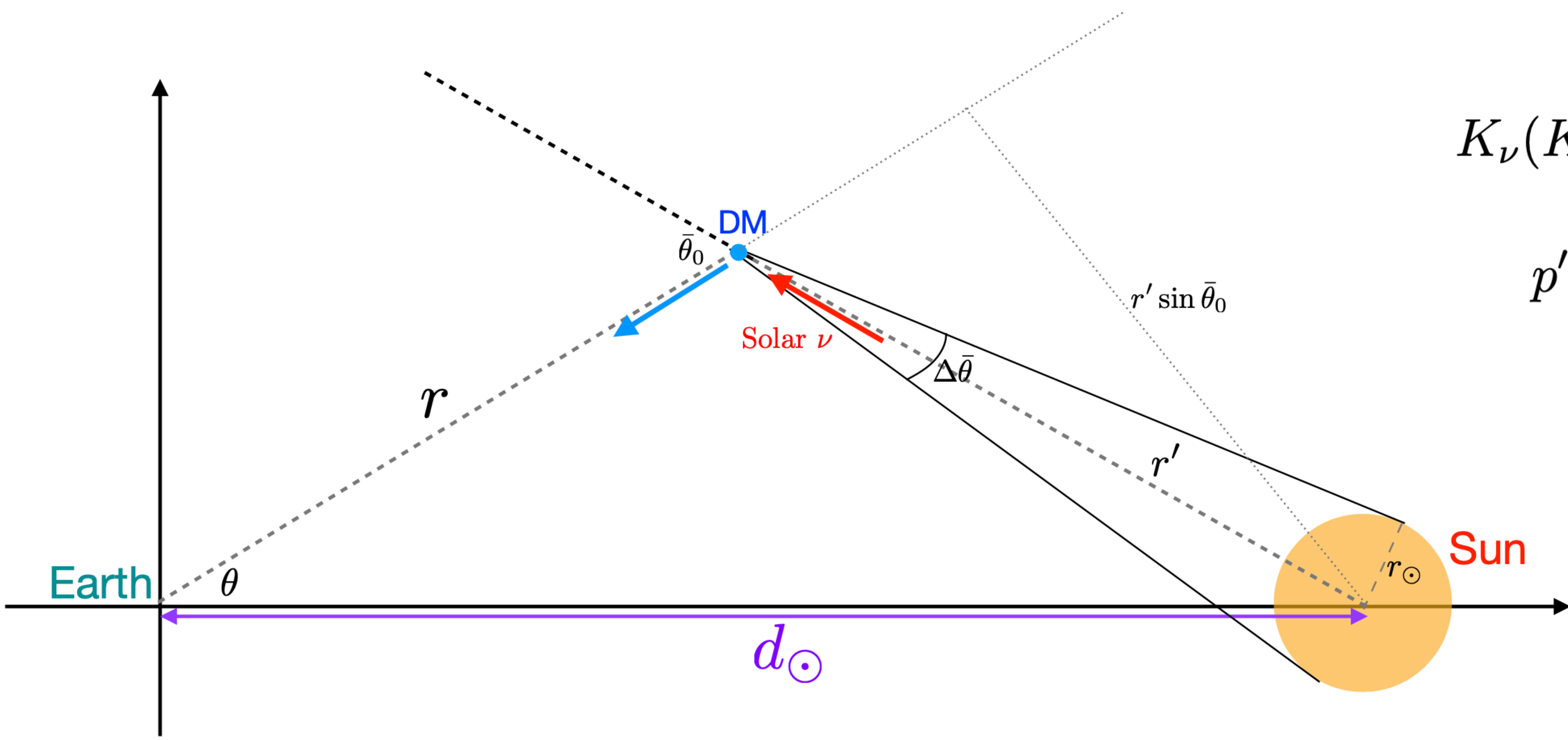
$$\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} = \int dV \frac{\rho_{\rm DM}}{m_{\rm DM}} \frac{1}{r^2} \int_{K_\nu^{\rm min}}^{K_\nu^{\rm max}} \underbrace{dK_\nu}_{\propto r_\odot} \frac{d\sigma_{\nu-{\rm DM}}(K_{\rm DM},\bar{\theta})}{dK_{\rm DM}} \cdot \left(\frac{r_\odot}{4r'\sin\bar{\theta}}\right) \cdot \underbrace{\left(\frac{d^2\Phi^{\text{Solar }\nu}}{d\Omega dK_\nu}\right) \cdot \left(\frac{d_\odot}{r'}\right)^2}_{\frac{\dot{N}_\nu}{4\pi r_\odot^2}}$$

(It is valid in the point source limit, $r_\odot \to 0$**)**

Galactic Neutrino-Boosted Dark Matter

Dark Matter boosted by neutrinos emitted from the Sun



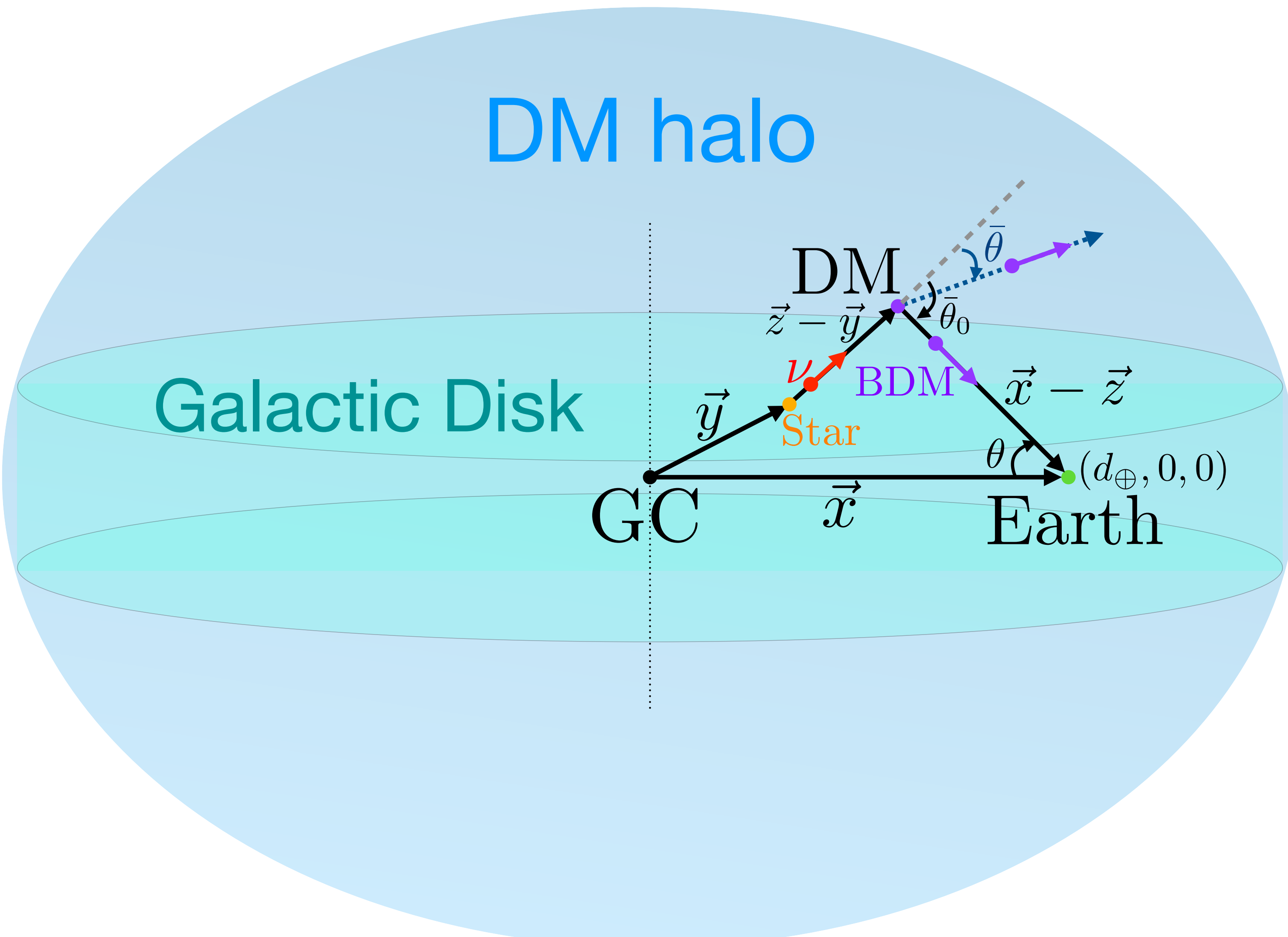
$$K_\nu(K_{\rm DM},\bar\theta) = \frac{K_{\rm DM}^2 - p'^2}{2(K_{\rm DM} - p'\cos\bar\theta)},$$
$$p'(K_{\rm DM}) = \sqrt{2m_{\rm DM}K_{\rm DM} + K_{\rm DM}^2}.$$

$$\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} \approx \frac{\dot N_\nu}{8\pi}\frac{\rho_{\rm DM}}{m_{\rm DM}}\int dV \frac{1}{r^2} \times \left(\frac{dK_\nu}{d\bar\theta}\bigg|_{\bar\theta=\bar\theta_0}\right) \times \left(\frac{d\sigma_{\nu-{\rm DM}}}{dK_{\rm DM}}\bigg|_{\bar\theta=\bar\theta_0}\right) \times \frac{1}{r'^2 \sin\bar\theta_0}$$

For a single neutrino source (here, our Sun) contribution!
(The volume integration for DM coordinates)

Galactic Neutrino-Boosted Dark Matter

The expectation of total Galactic Star neutrino BDM



Individual star contribution

$$\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}} \simeq \frac{1}{8\pi^2}\left(\tilde{f}_1 \frac{d\dot{N}^{\rm Sun}_\nu}{dK_\nu}\right)\int d^3\vec{z}\, \frac{\rho_{\rm DM}(|\vec{z}|)}{m_{\rm DM}} \frac{1}{|\vec{x}-\vec{z}|^2} \times \left(\frac{dK_\nu}{d\bar{\theta}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right)\left(\frac{d\sigma_{\nu\rm DM}}{dK_{\rm DM}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right) \times \frac{1}{\sin\bar{\theta}_0}\frac{1}{|\vec{z}-\vec{y}|^2}\times \exp\left(-\frac{|\vec{z}-\vec{y}|}{d_\nu}\right),$$

Total Galaxy contribution

$$\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} = \int d^3\vec{y}\, n_{\rm star}(\vec{y})\, \frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}}$$

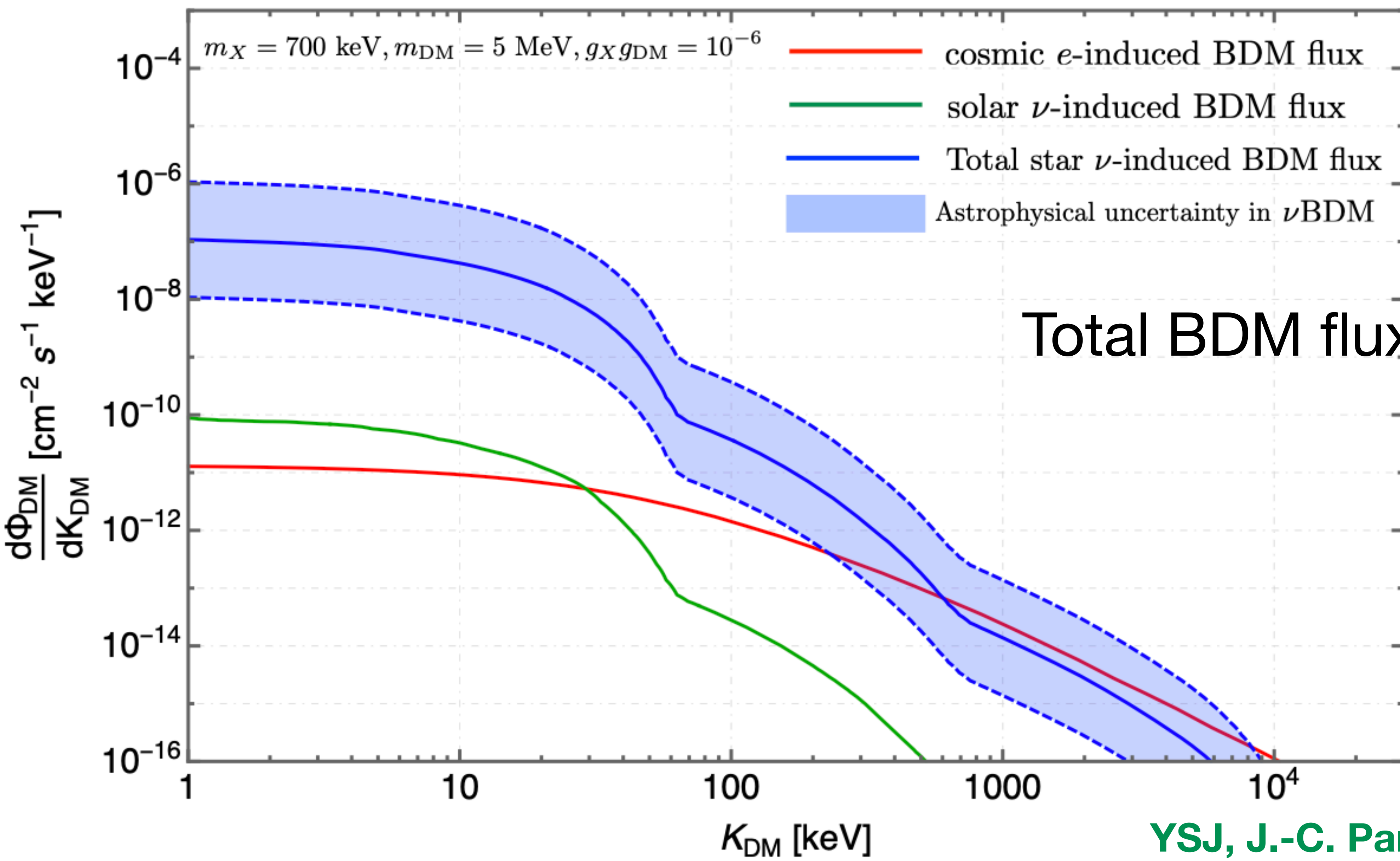
We conservatively assume
1. Symmetric population of Stars
2. All stars have the same luminosity as the Sun

In a realistic estimation, Production of BDM is highly anisotropic, and depends on spectrum of injected neutrinos.

Galactic Neutrino-Boosted Dark Matter

The expectation of total Galactic Star neutrino BDM

At the Earth, one can expect $\sim 10^{-15} - 10^{-16} \cdot \frac{d\Phi_{Solar\nu}}{dE_\nu}$

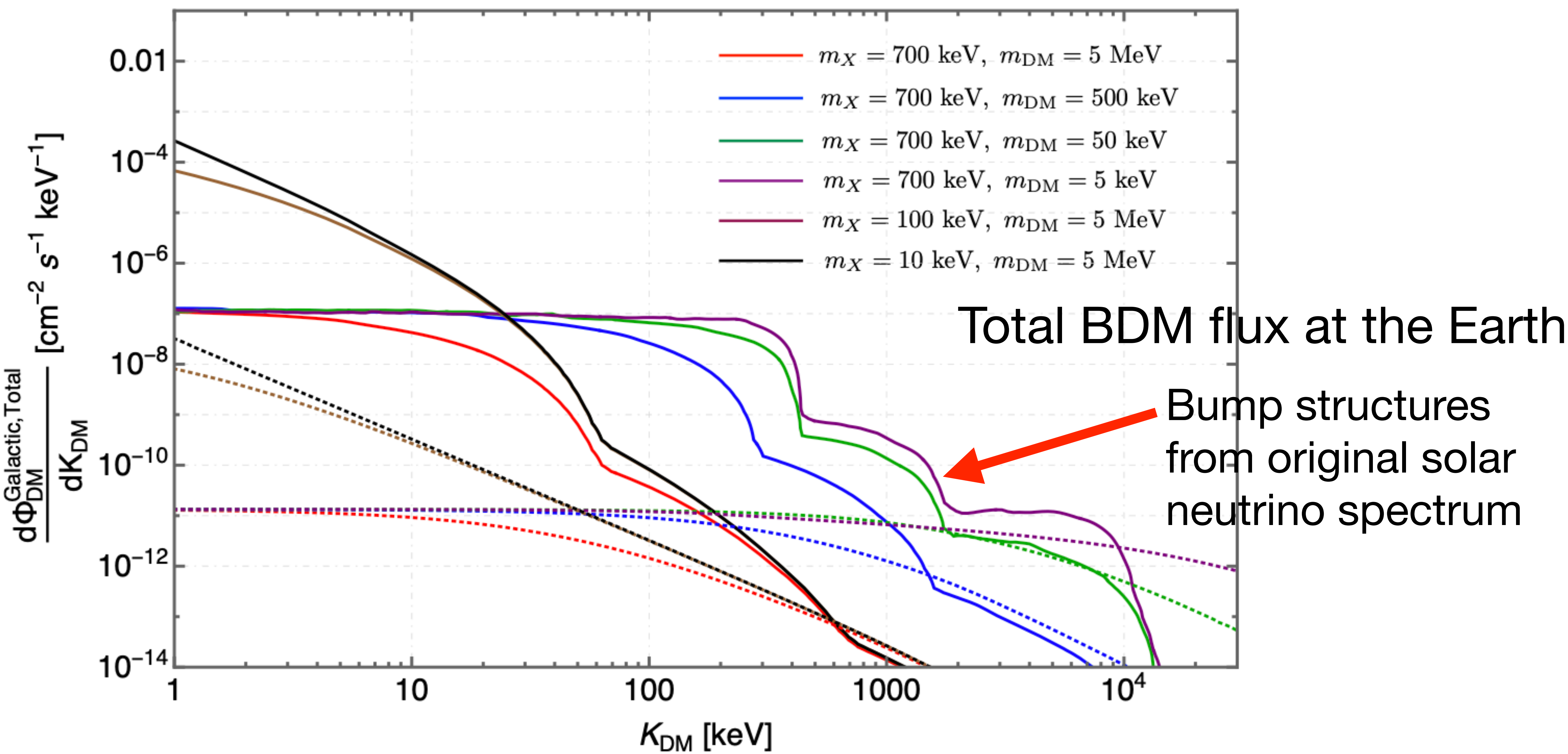


Total BDM flux at the Earth

YSJ, J.-C. Park, S.-C. Park, P.-Y. Tseng [2101.11262] [hep-ph]

Galactic Neutrino-Boosted Dark Matter

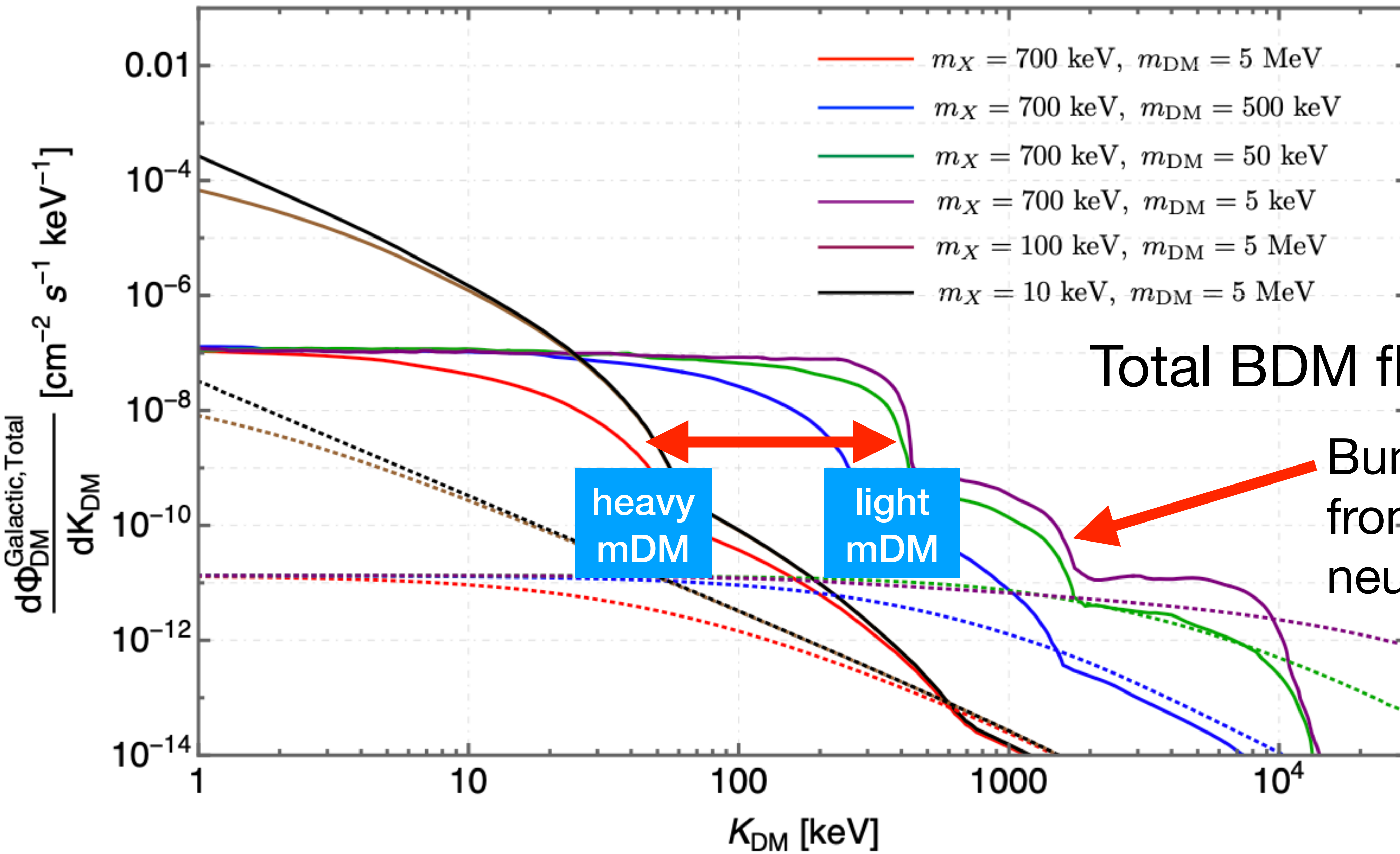
The expectation of total Galactic Star neutrino BDM



YSJ, J.-C. Park, S.-C. Park, P.-Y. Tseng [2101.11262] [hep-ph]

Galactic Neutrino-Boosted Dark Matter

The expectation of total Galactic Star neutrino BDM



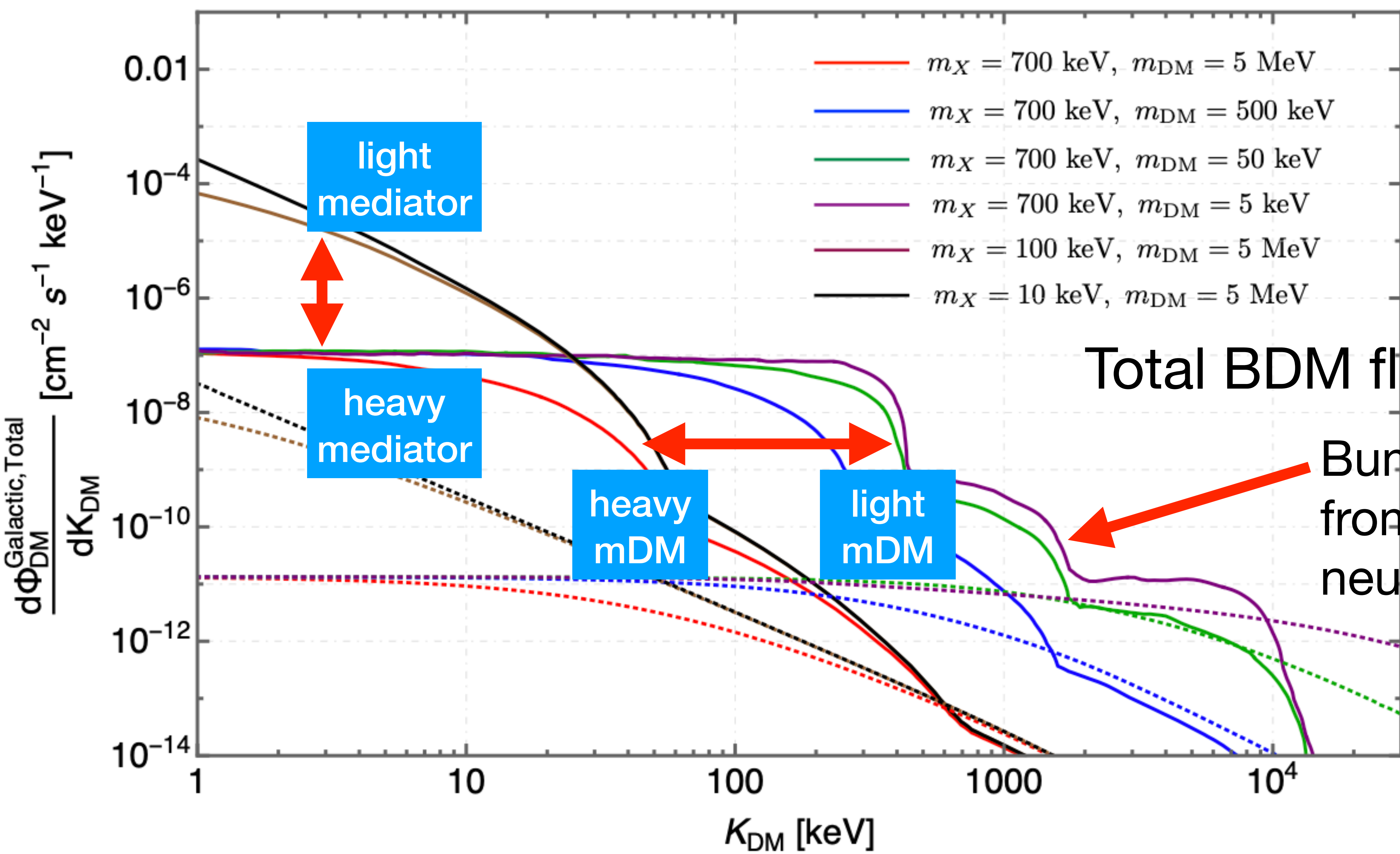
Total BDM flux at the Earth

Bump structures from original solar neutrino spectrum

YSJ, J.-C. Park, S.-C. Park, P.-Y. Tseng
[2101.11262] [hep-ph]

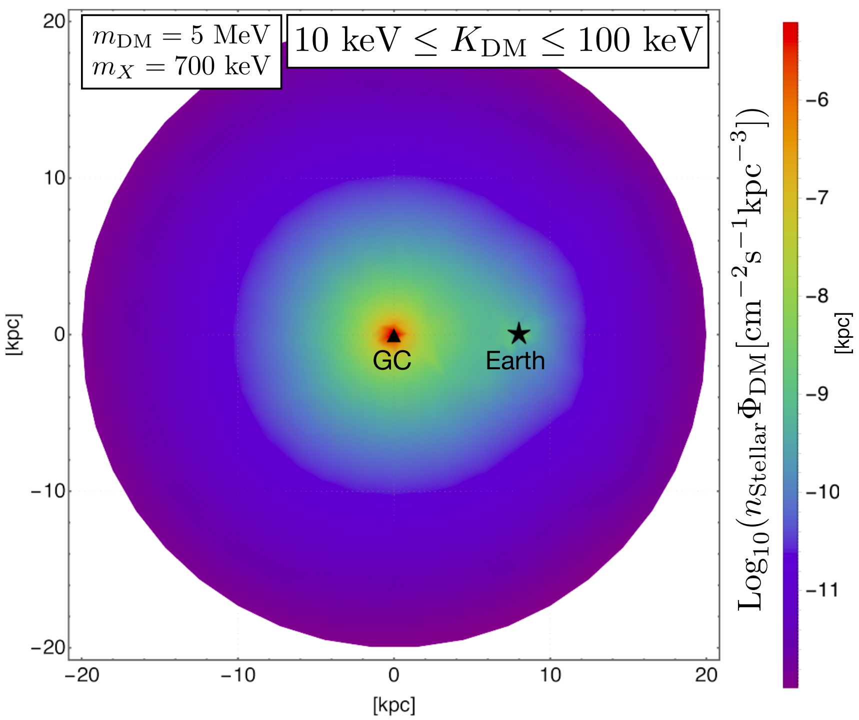
Galactic Neutrino-Boosted Dark Matter

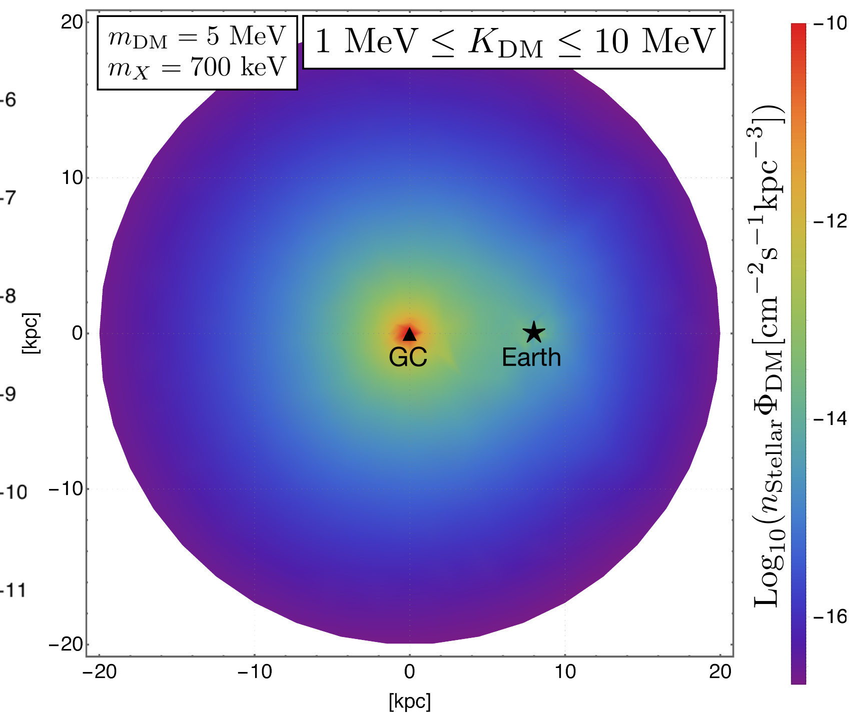
The expectation of total Galactic Star neutrino BDM



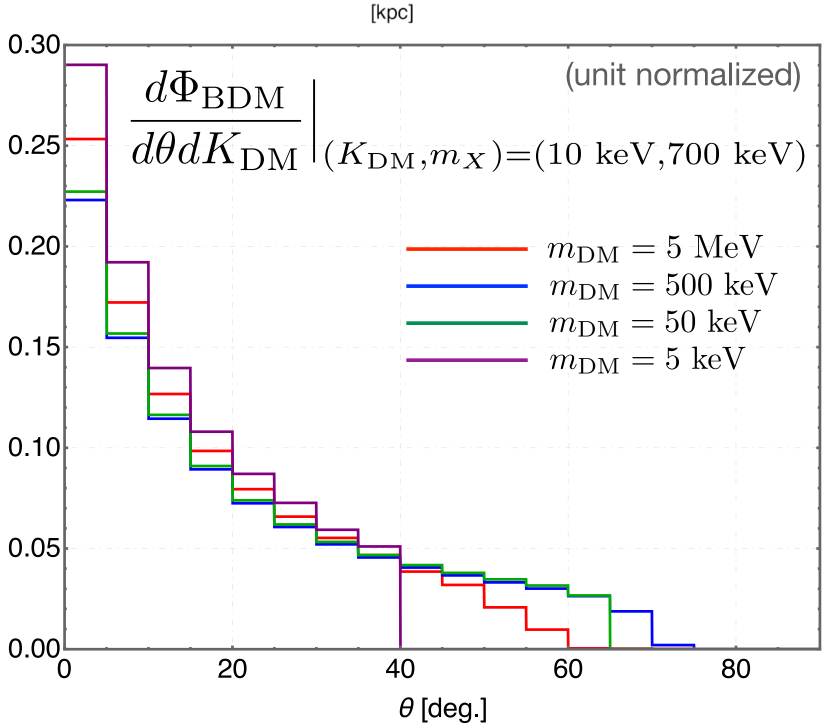
YSJ, J.-C. Park, S.-C. Park, P.-Y. Tseng
[2101.11262] [hep-ph]

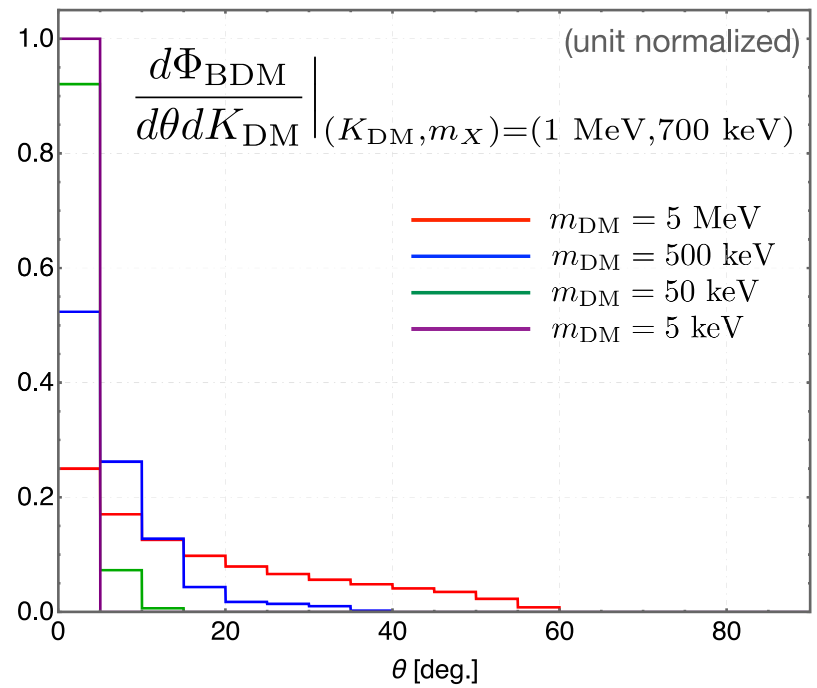
Expectation of Galactic neutrino BDM distribution





Galactic Disk distribution





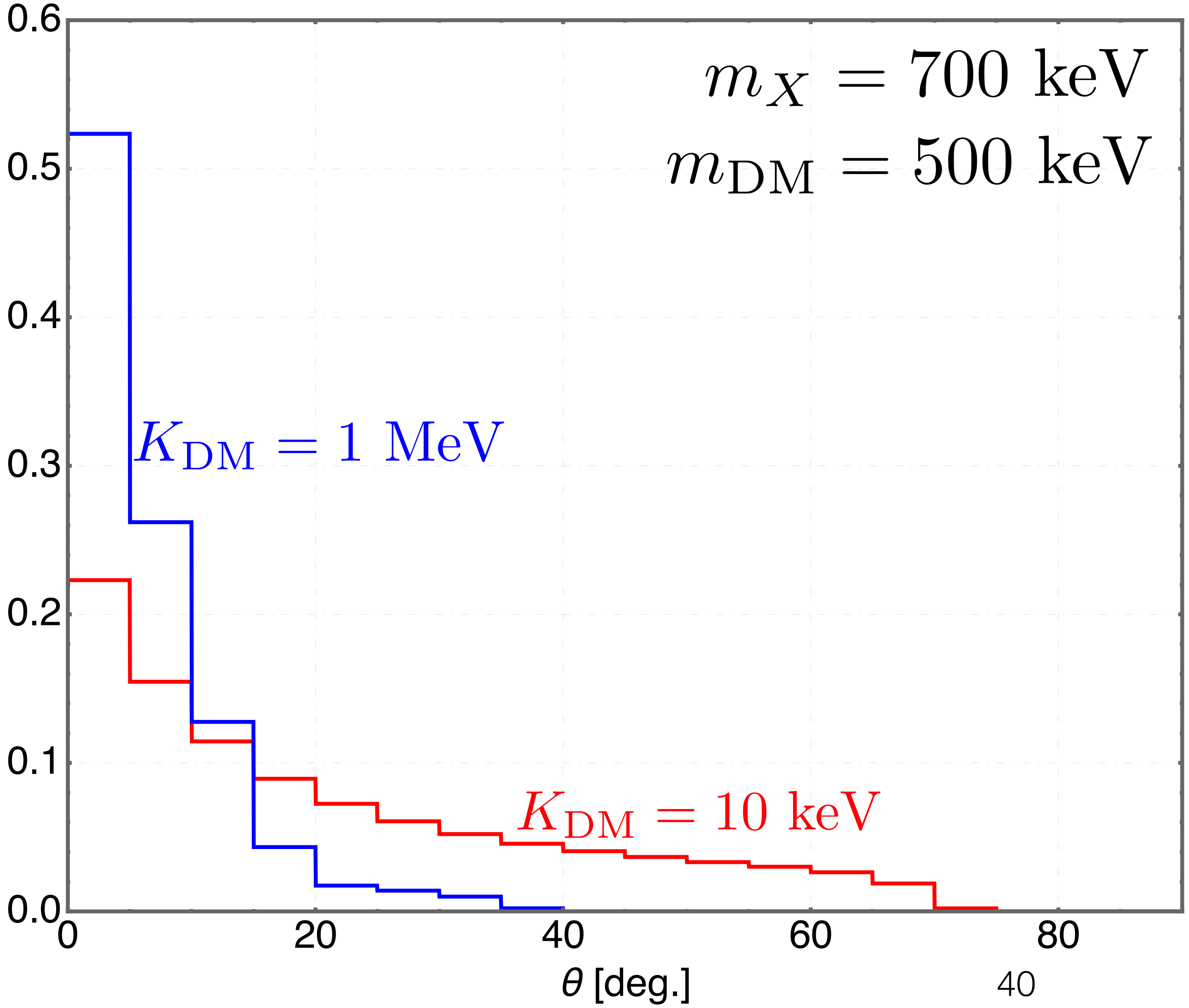
Arrival direction distribution of BDM

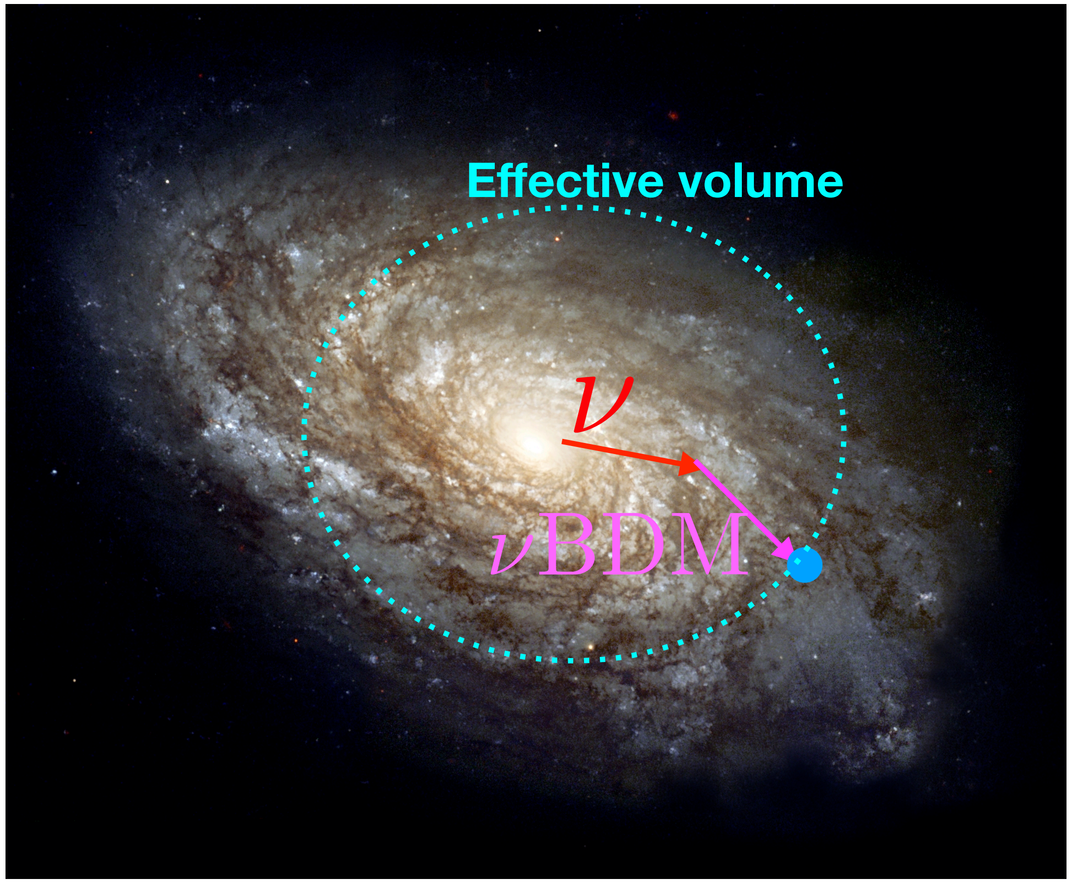
Non-trivial distribution of BDM arrival direction could help to probe nuBDM scenario.

YSJ, J.-C. Park, S.-C. Park, P.-Y. Tseng
[2101.11262] [hep-ph]

Arrival direction distribution of Galactic Neutrino-BDM

- $K_{\rm DM} \gg m_{\rm DM}$: Forward scattering is dominant (small effective volume)
- $K_{\rm DM} \ll m_{\rm DM}$: Large-angle scatterings are allowed (large effective volume)





Extragalactic contribution to Neutrino-BDM

- Main contribution to EG-nuBDM

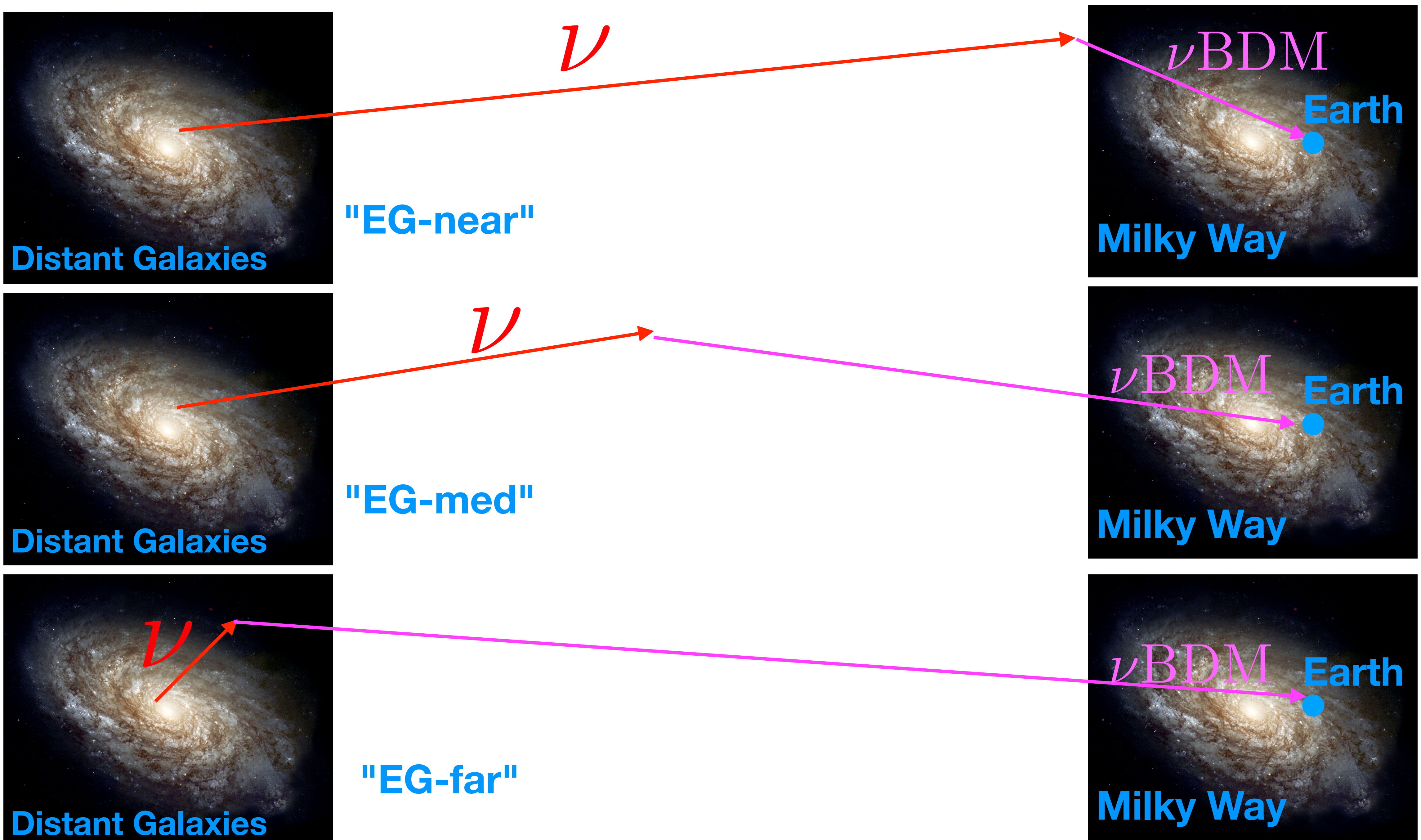
YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)

Dominant contributions coming from the regions in which both neutrino and DM are populated.

Extragalactic contribution to Cosmic-Neutrino-BDM

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)

- Schematic pictures for main contribution to EG-nuBDM



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YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
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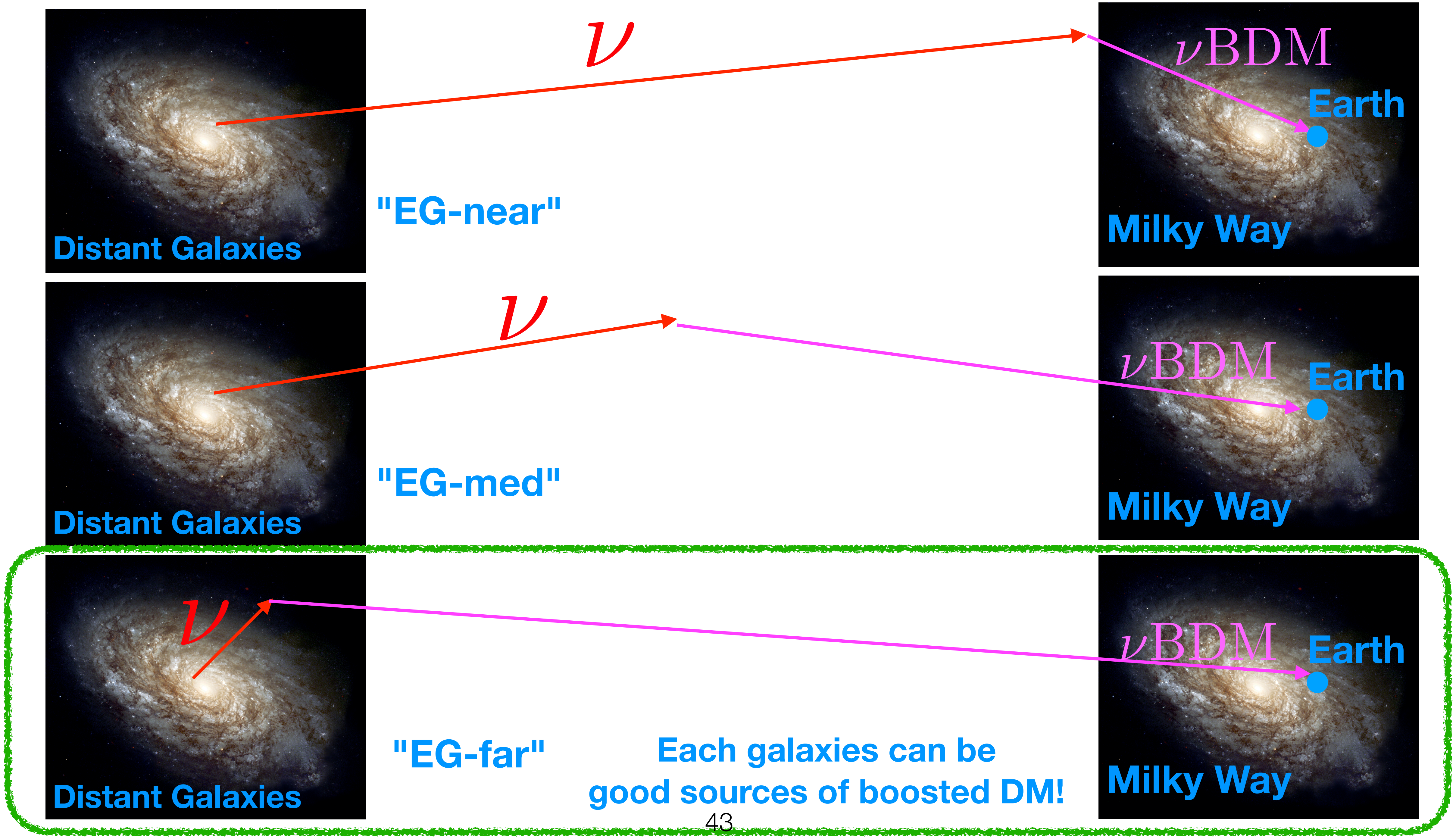
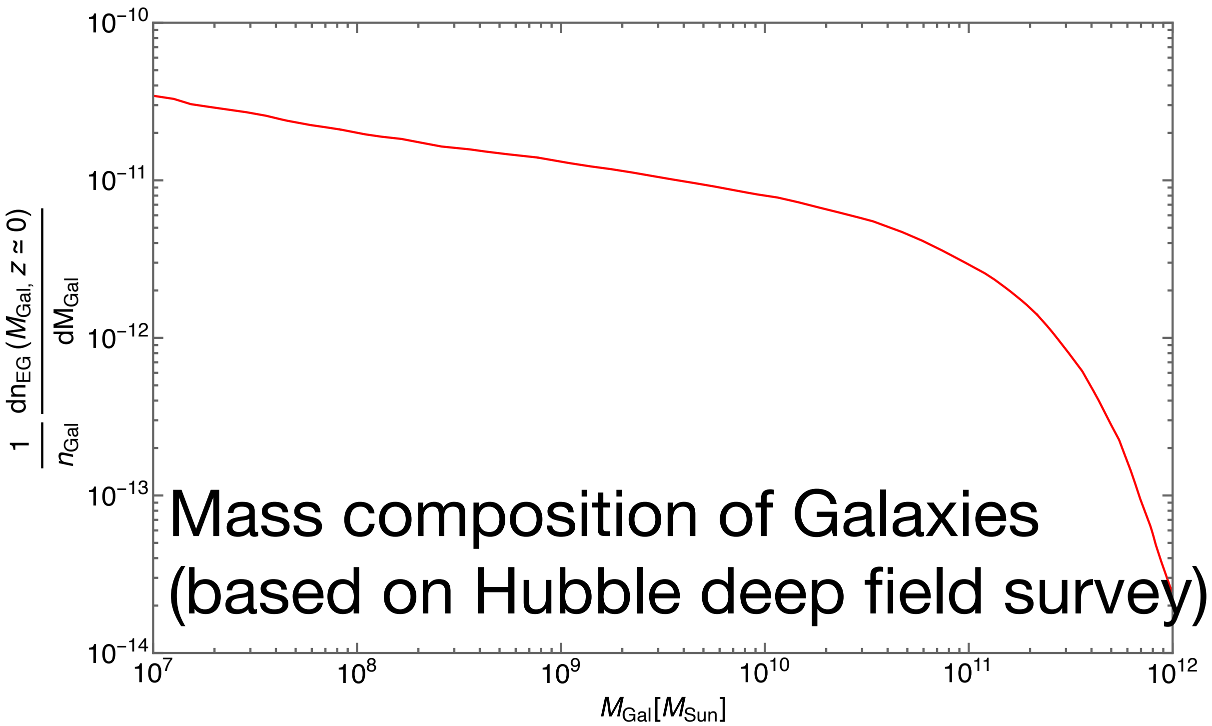
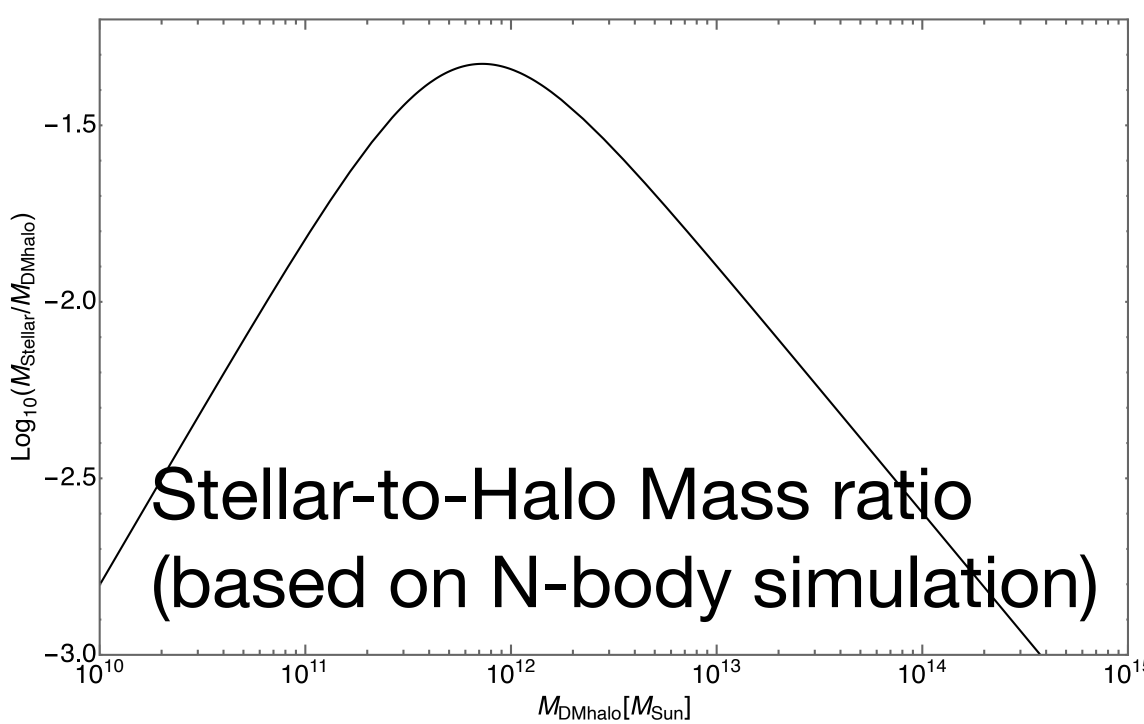


How to estimate Massive galaxy contributions?

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)

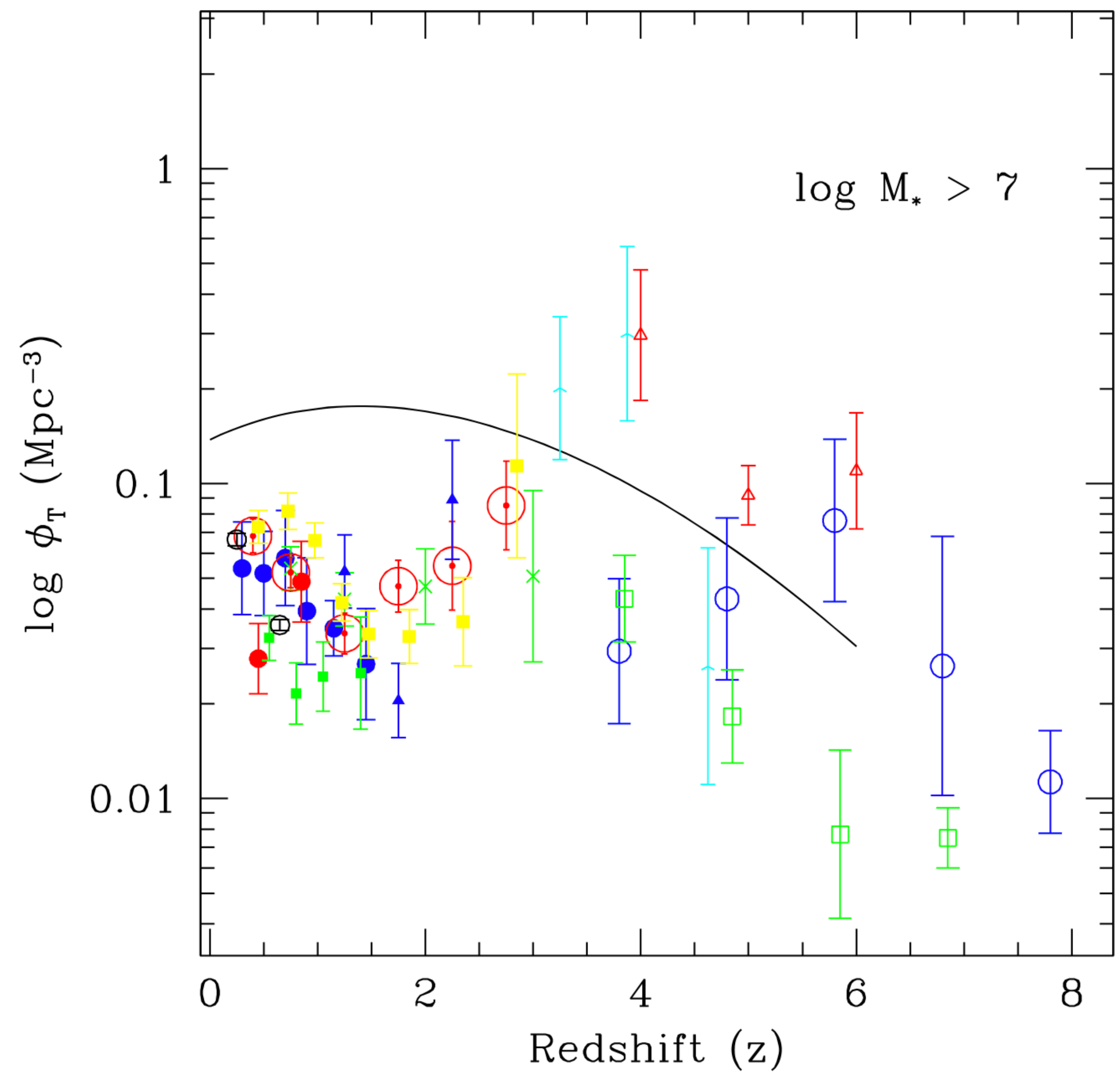


Mass composition of Galaxies
(based on Hubble deep field survey)



Stellar-to-Halo Mass ratio
(based on N-body simulation)

The estimation of Halo/Stellar Mass ratio, Size of Halo/Disk are mostly based on observation data.



Mass composition of Galaxies
(based on Hubble deep field survey)

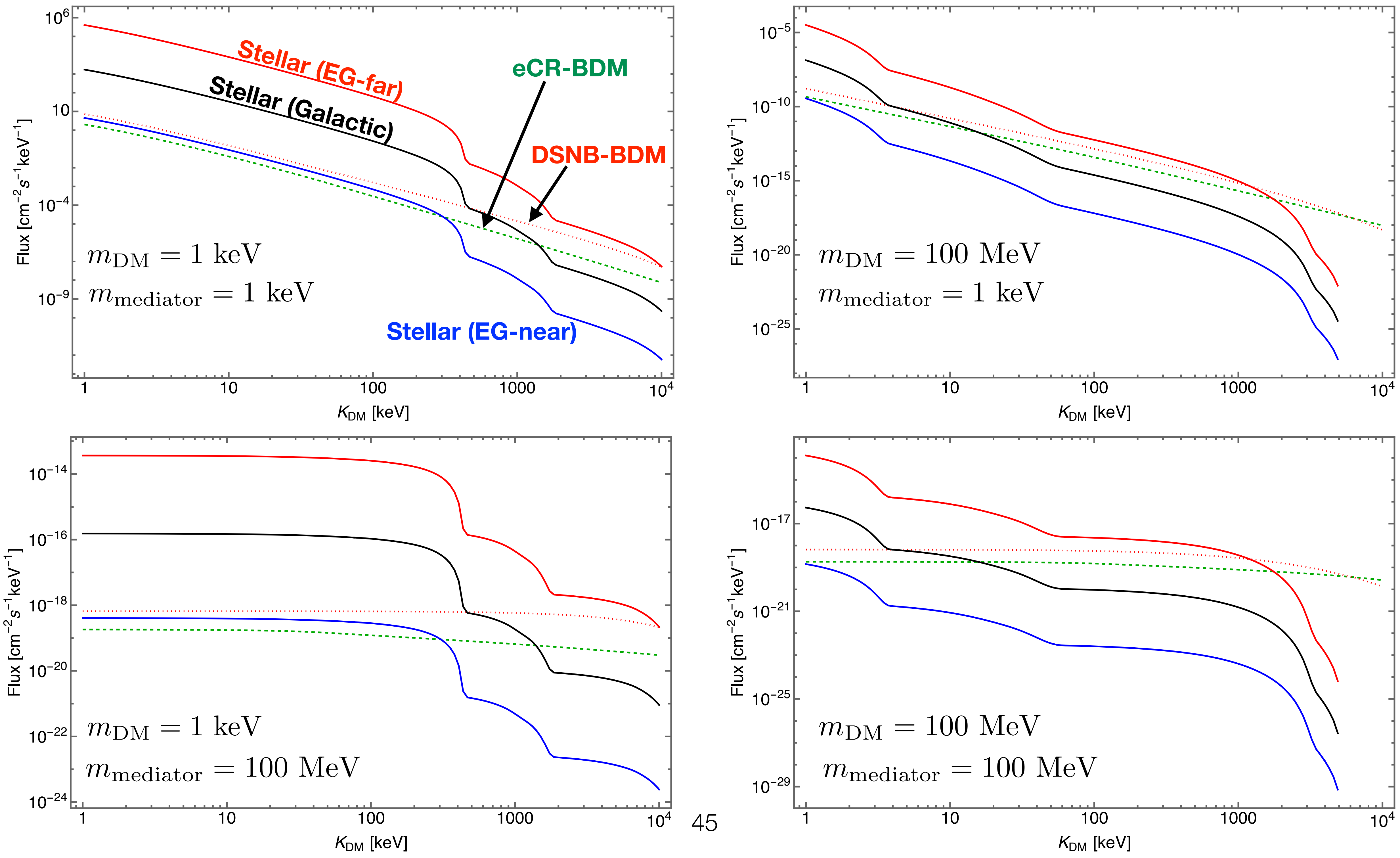
Extragalactic contribution of neutrino-BDM flux

$0 \leq z \leq 1$

$\mathcal{L}_{\text{eff.}} \supset -g_e \bar{e}\gamma^\mu e X_\mu - g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_{\text{DM}} \bar{\chi}\gamma^\mu \chi X_\mu$

$g_e g_{\text{DM}} = g_\nu g_{\text{DM}} = 10^{-6}$

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)



Then, How about neutrinos?

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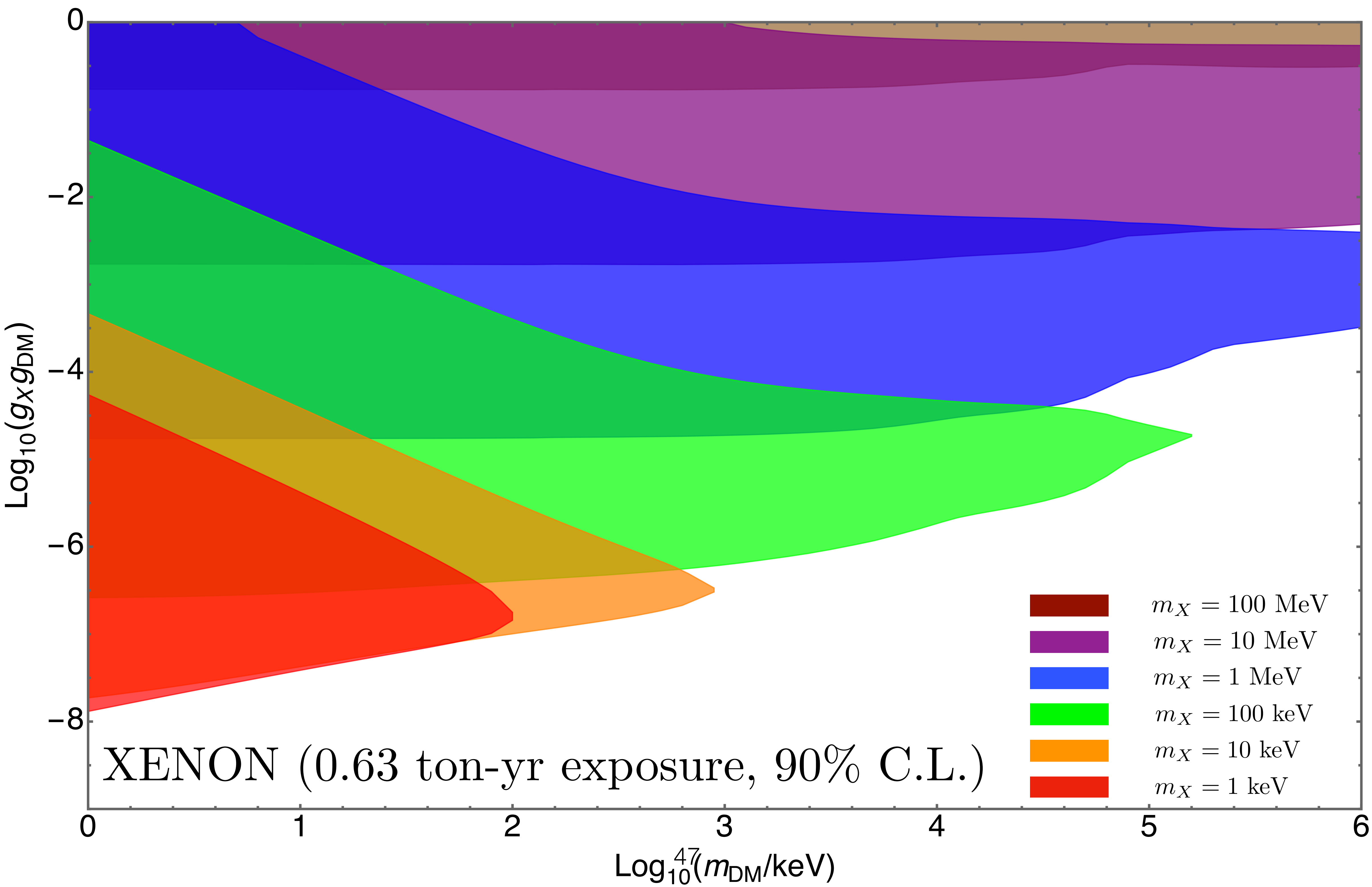
can be probed at
various ground experiments/observatories?

Constraints from XENON1T

$$\mathcal{L}_{\rm eff.} \supset -g_e \bar{e}\gamma^\mu e X_\mu - g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$$

$$g_e = g_\nu = g_X$$

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)

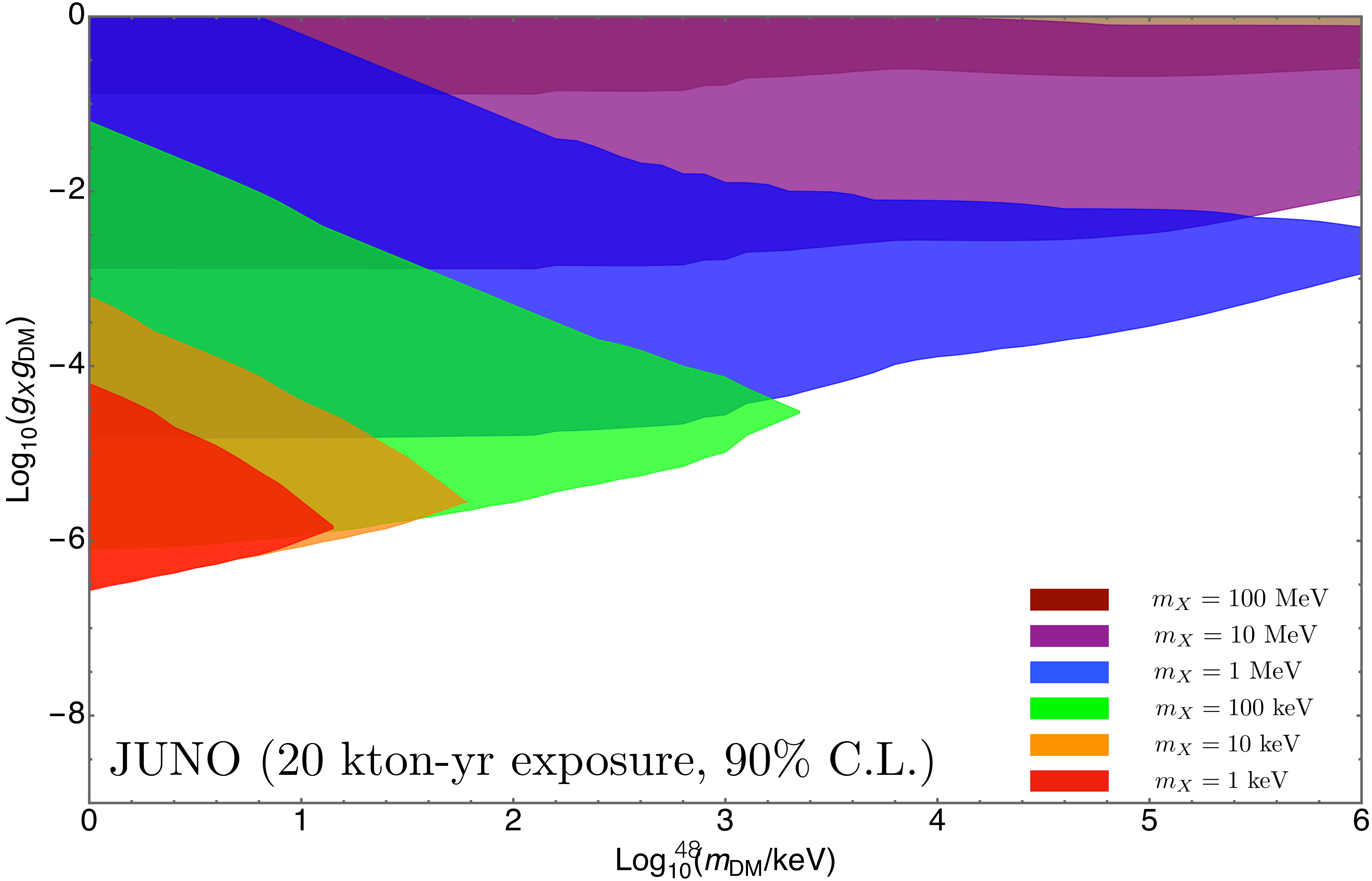


Expected limit from JUNO

$$\mathcal{L}_{\rm eff.} \supset -g_e \bar{e}\gamma^\mu e X_\mu - g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$$

$$g_e = g_\nu = g_X$$

YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)



Direct detection (XENON1T) vs. Neutrino telescope (JUNO)

$\mathcal{L}_{\rm eff.} \supset -g_e \bar{e}\gamma^\mu e X_\mu - g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$

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YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
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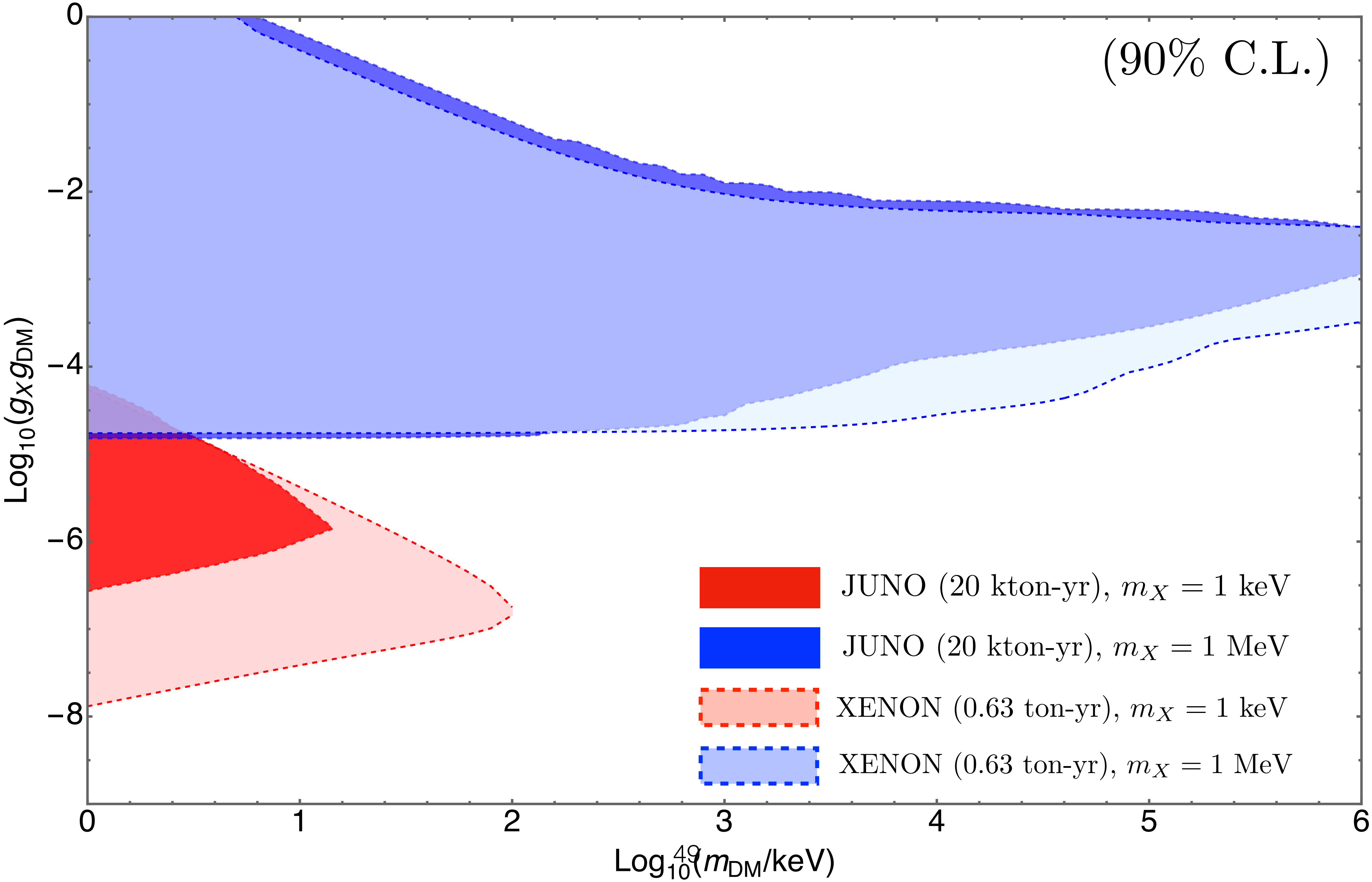

Limit on total cross sections

$$\mathcal{L}_{\text{eff.}} \supset -g_e \bar{e}\gamma^\mu e X_\mu - g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_{\text{DM}} \bar{\chi}\gamma^\mu \chi X_\mu$$

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YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
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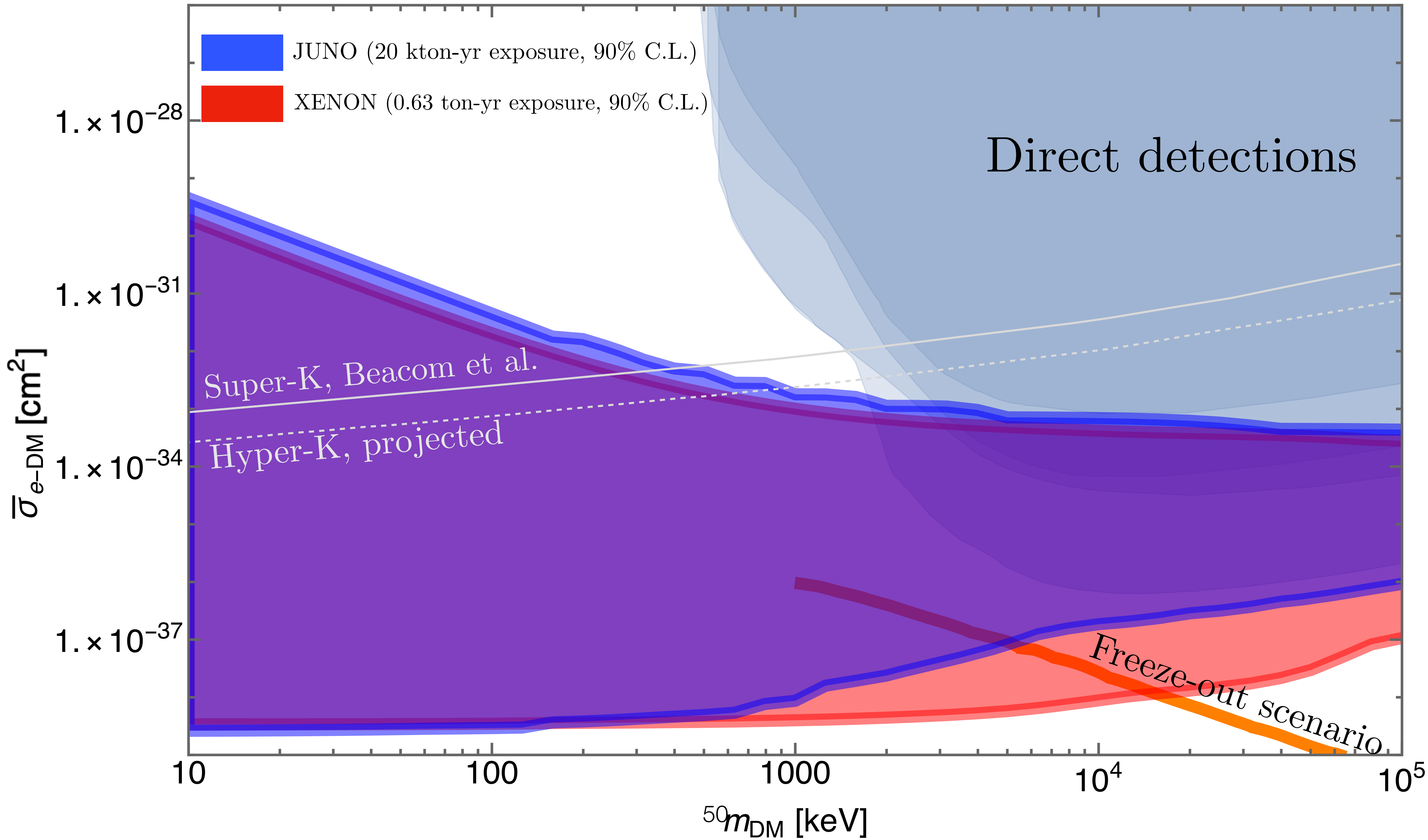

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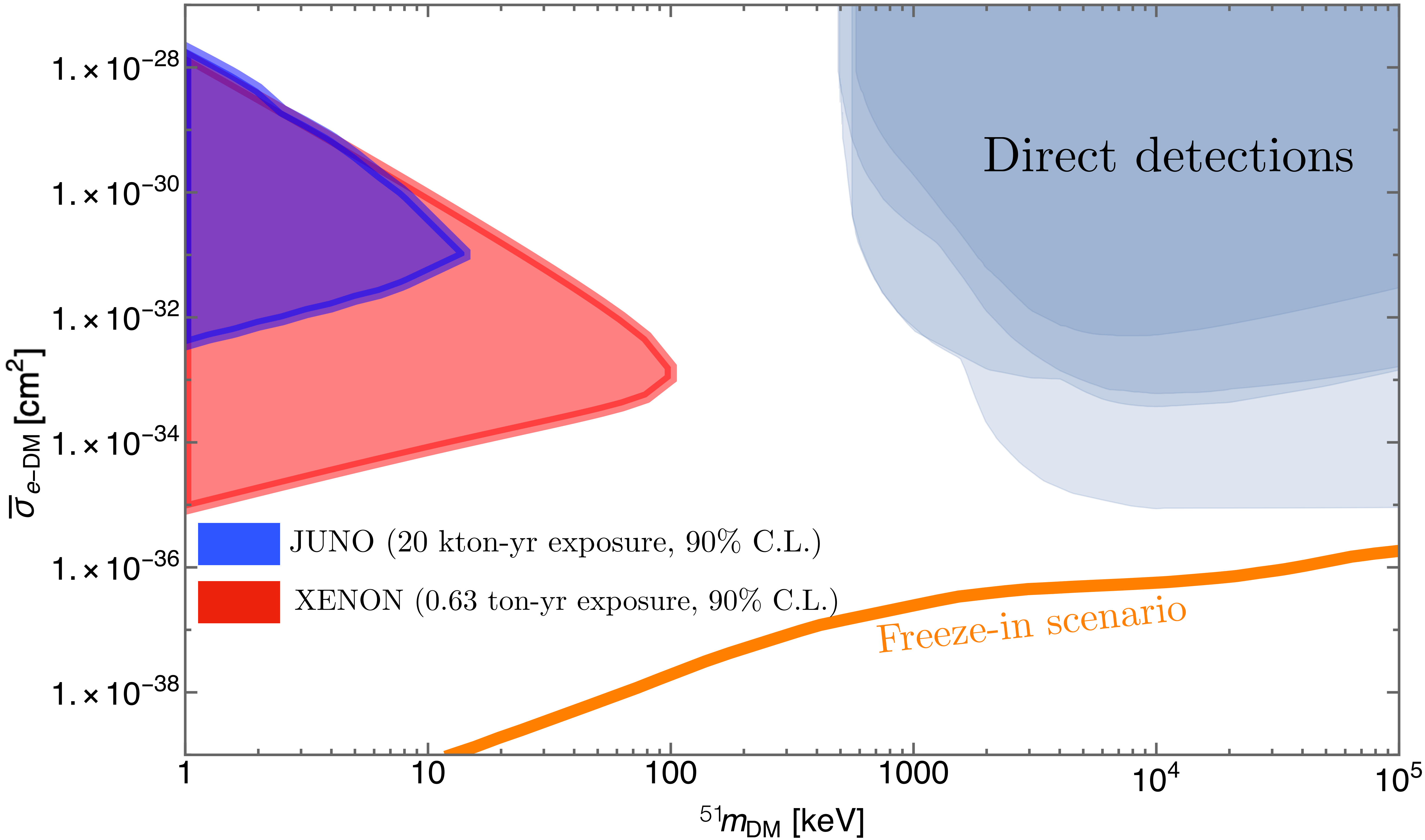
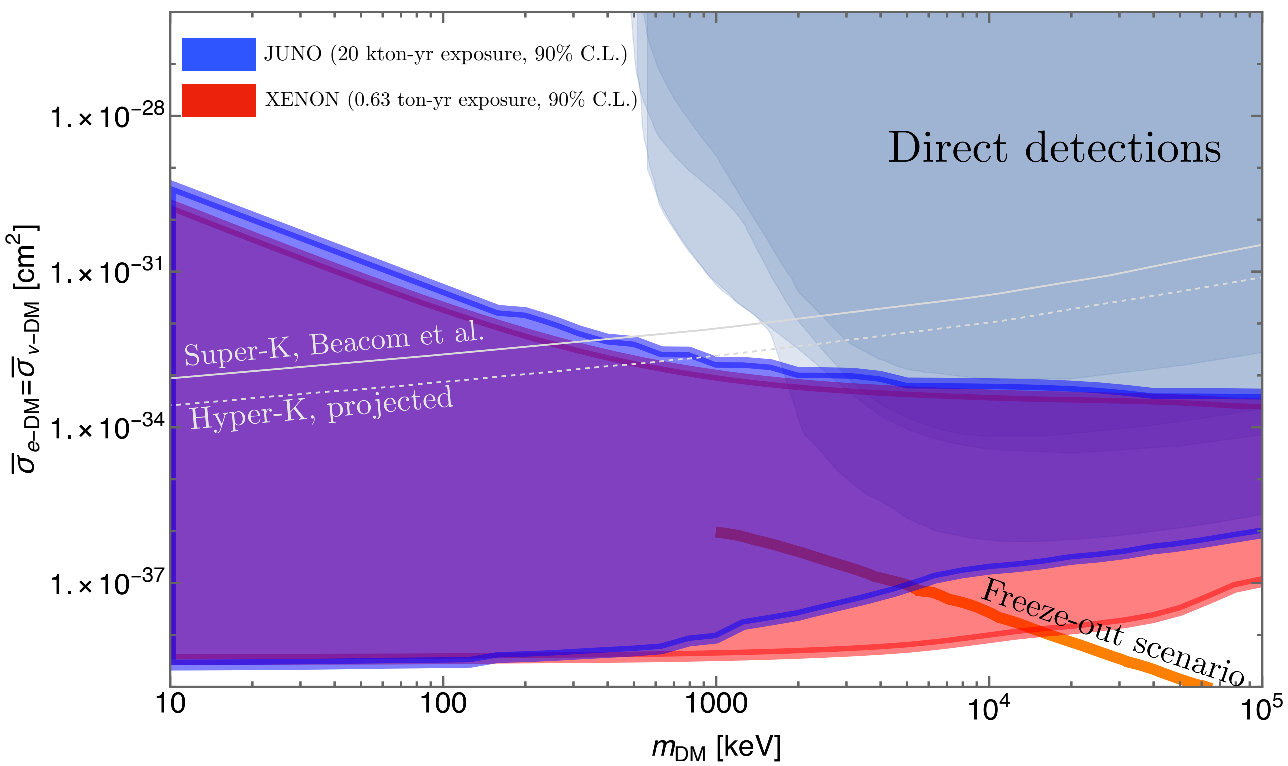
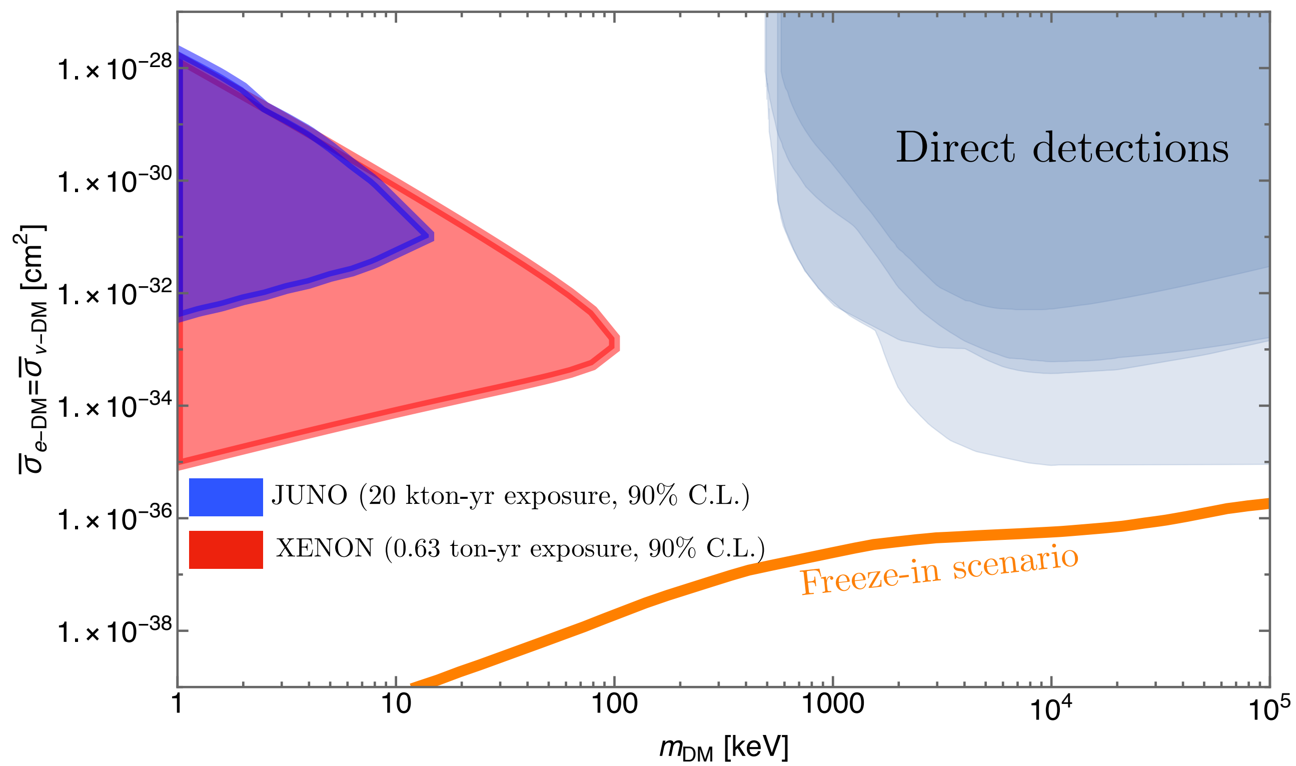
YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)



Conclusion

- A noble mechanism to boost light DM by neutrinos emitted from stars in our/distant galaxies is proposed.
- Future neutrino exp (JUNO) and Direct detection (XENON/LUX) & distribution of arrival direction will help to probe neutrino-BDM scenario in near future.
- Extragalactic contribution to neutrino-BDM also has interesting features and depends on DM/mediator masses.

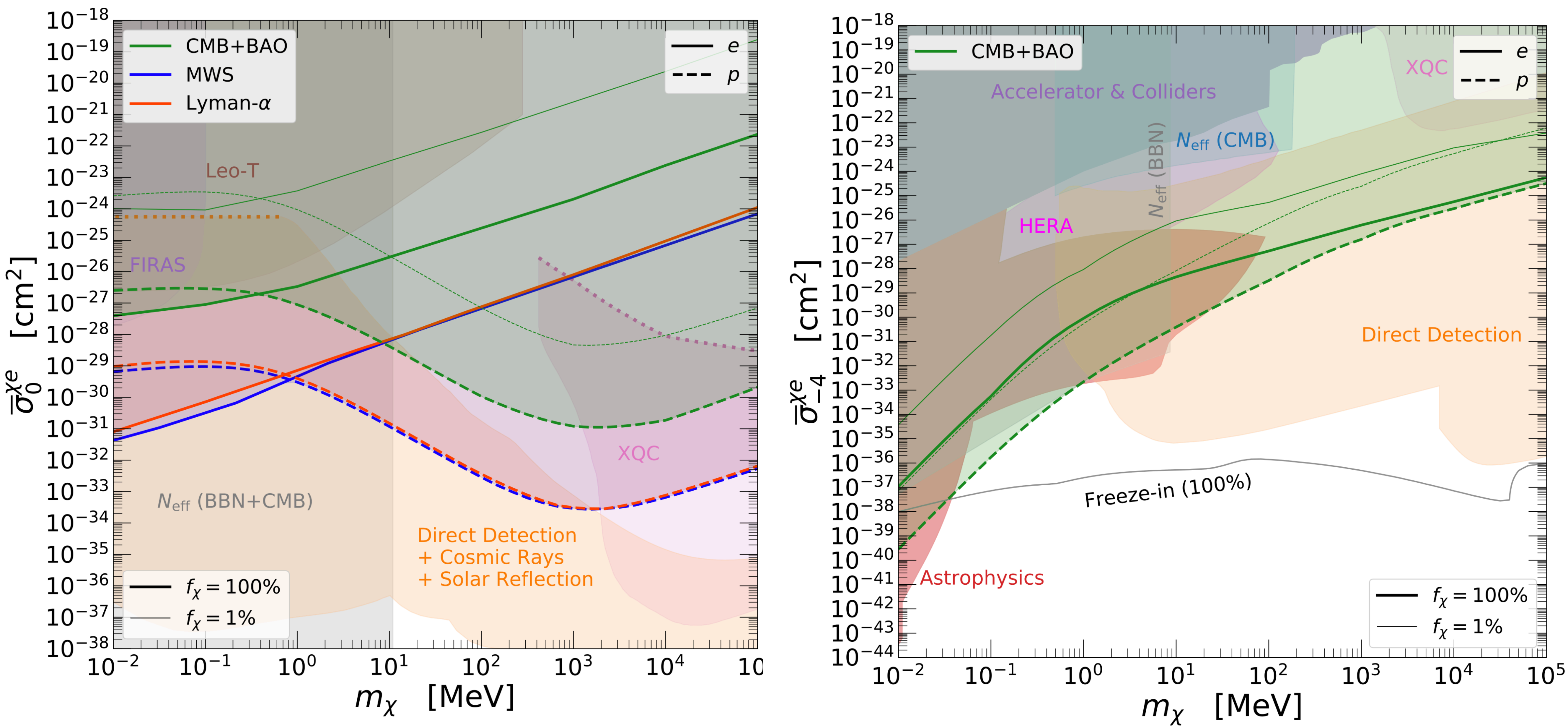




Thank you for your attention

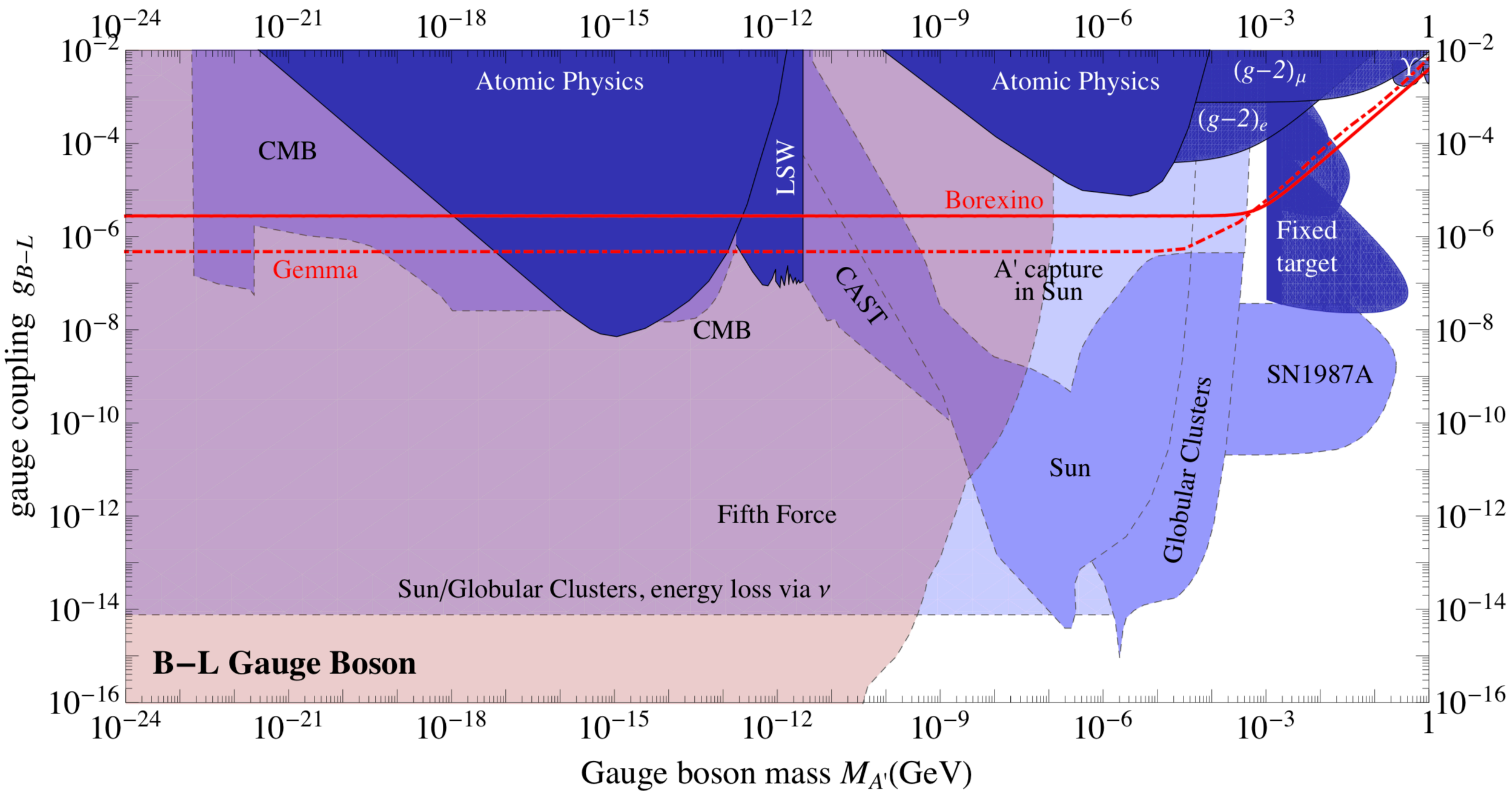
Other constraints

R. Essig et al. (21')



Constraints on light mediator

R. Harnik et al. [JCAP 07 (2012) 026] [1202.6073] [hep-ph]



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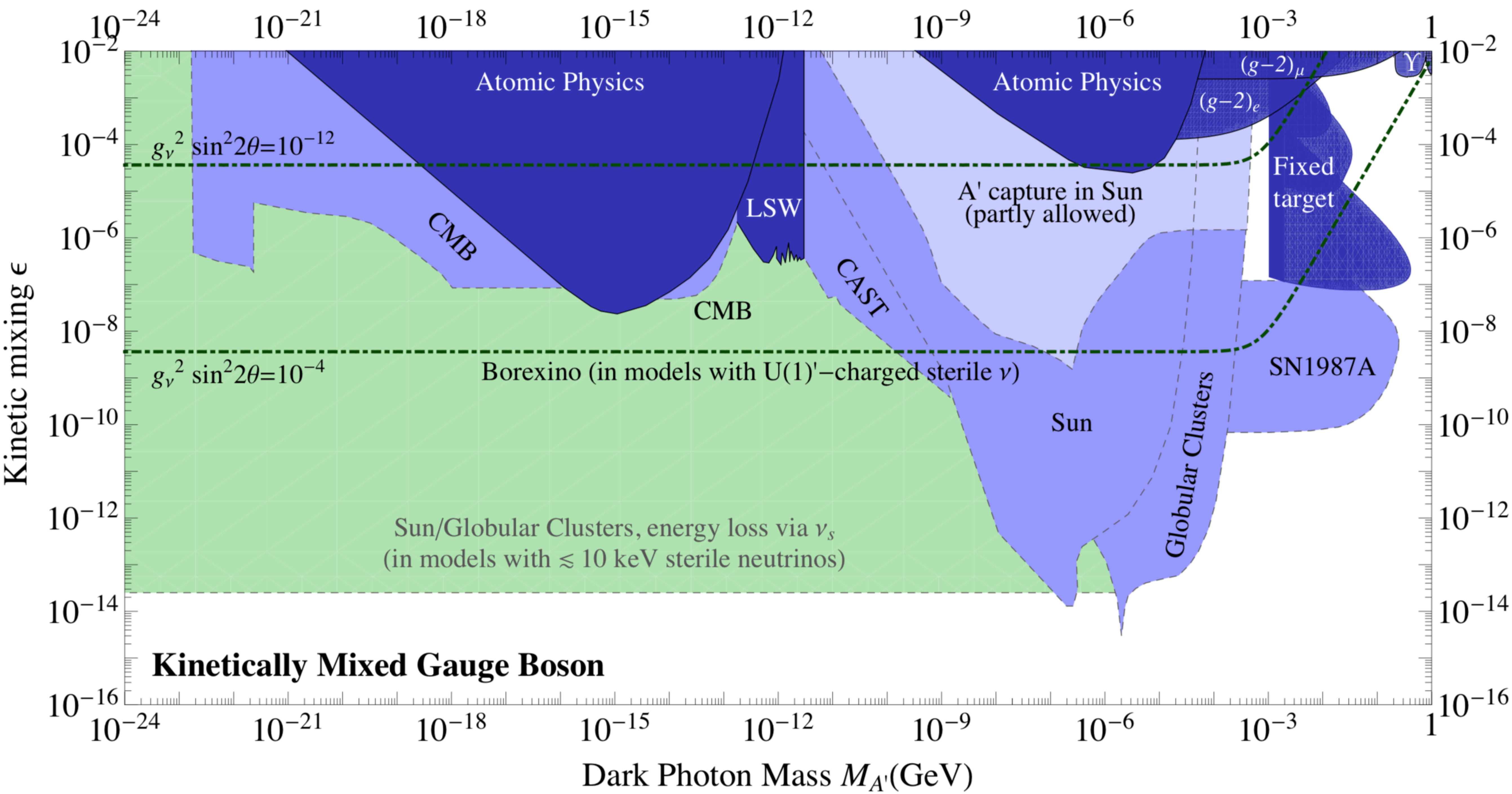
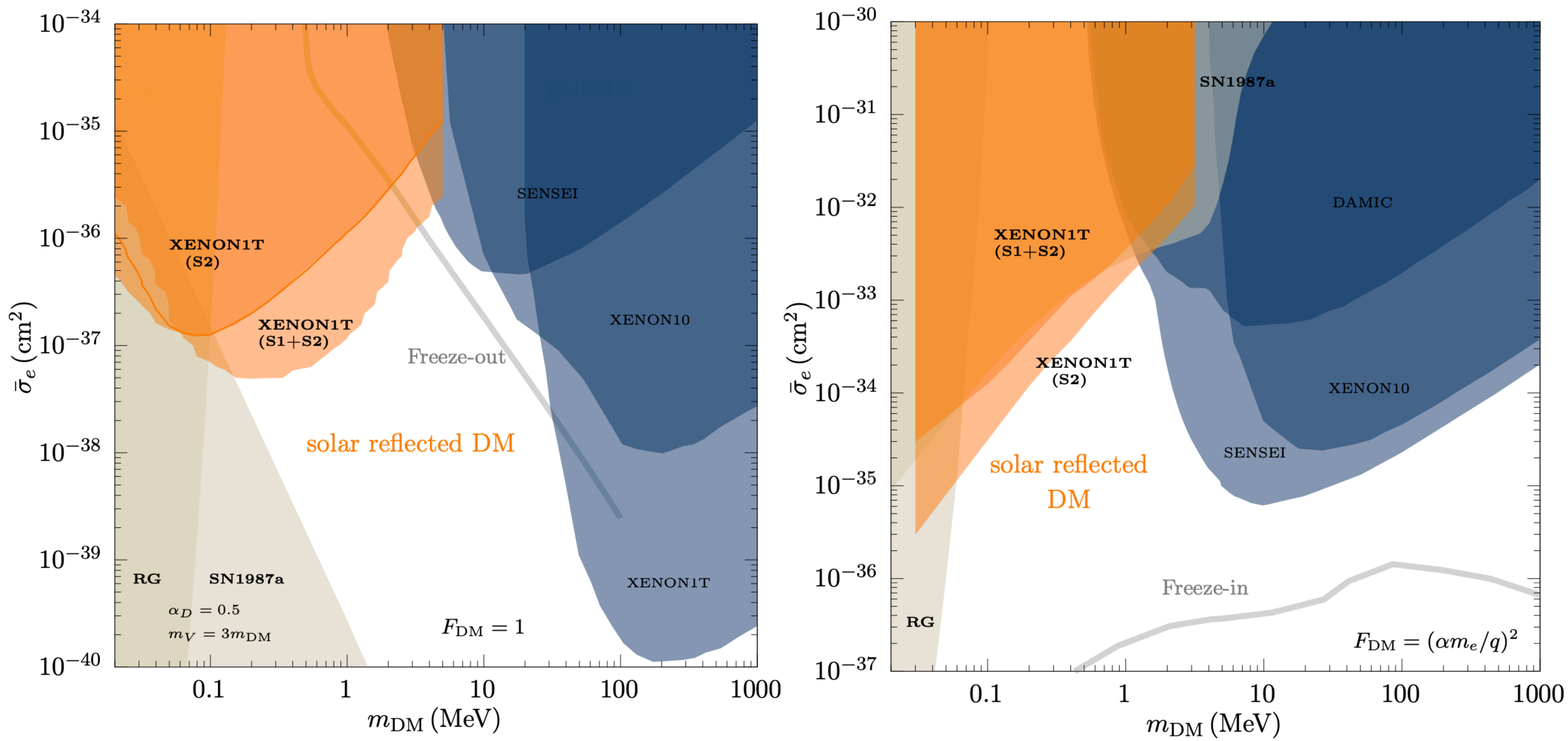


Solar Reflection of DM

Pospelov et al. (19' and 21')



Galaxy number distribution up to z<8