Upscattering light components of dark matter by cosmic rays and neutrinos

Yongsoo Jho (Weizmann Inst.)

Based on

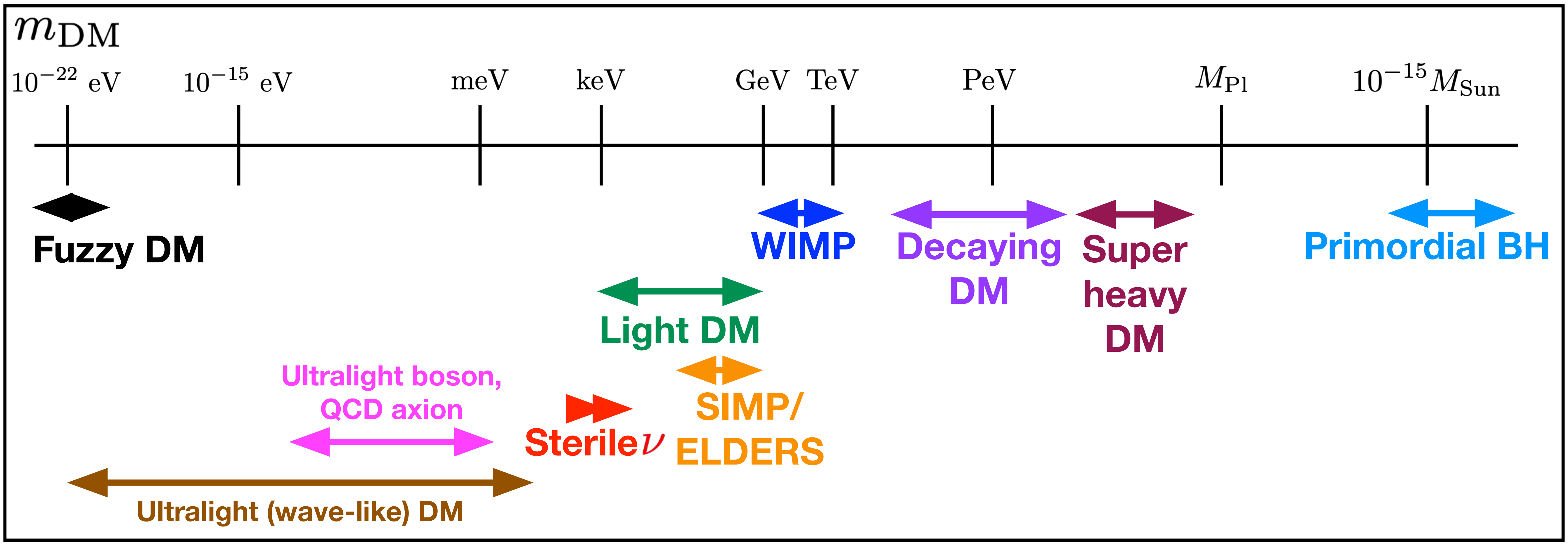
arXiv:2101.11262 [hep-ph] and work to be appear soon

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

PPC 2023: XVI International Conference on Interactions
between Particle Physics and Cosmology

DM candidates

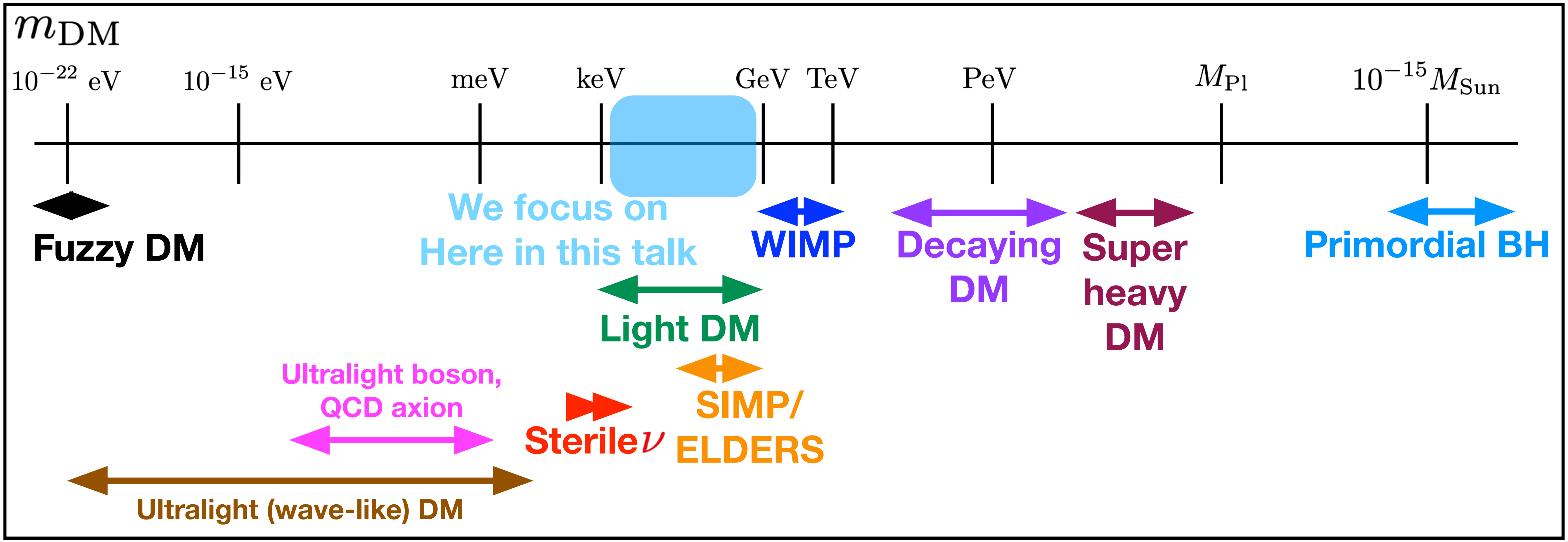
in a point of view of particle physics



In a wide range of Dark Matter mass ,
Various DM candidates has been suggested.

DM candidates

in a point of view of particle physics

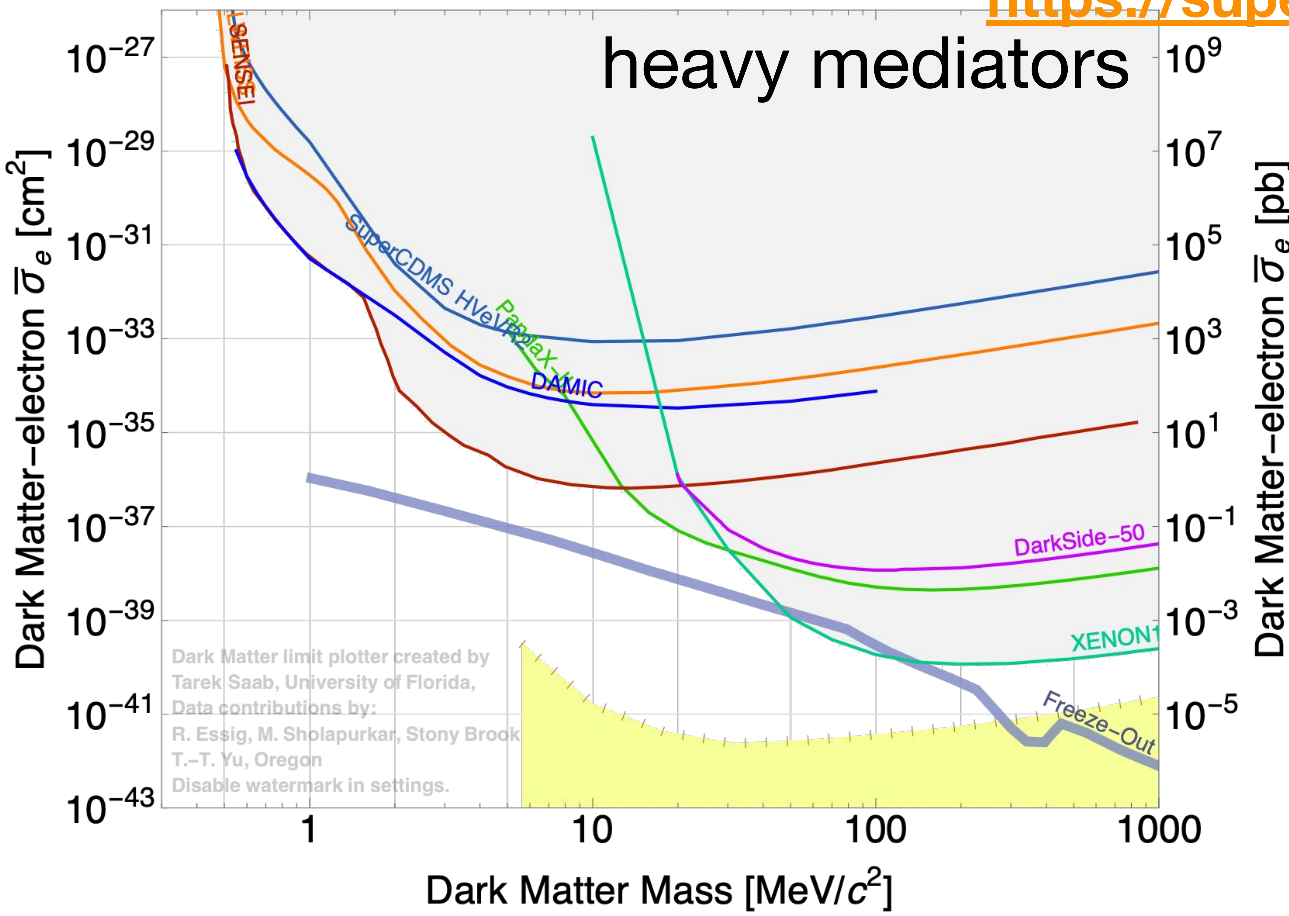


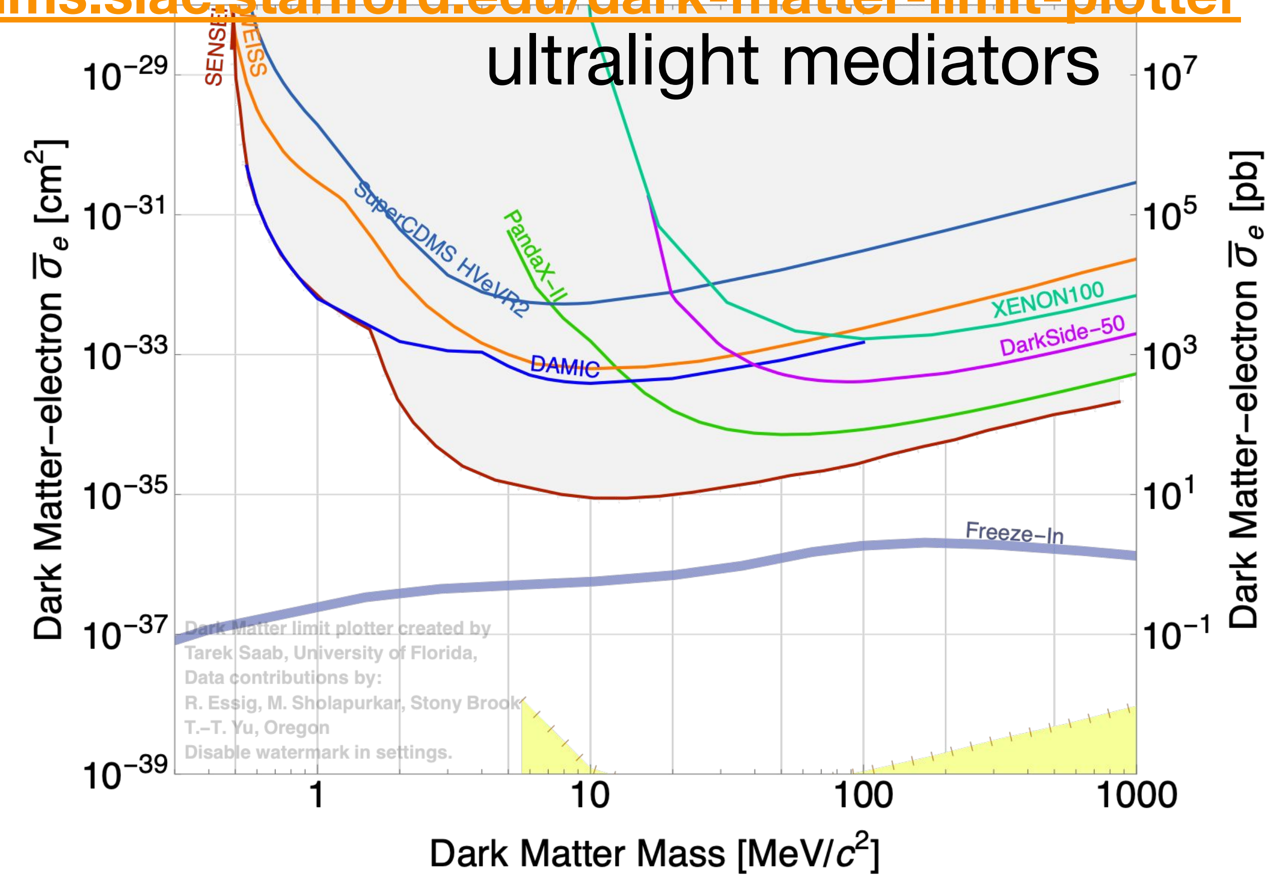
In a wide range of Dark Matter mass
Various DM candidates has been suggested.

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

Current Status 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 cliffs around 10-100 MeV,
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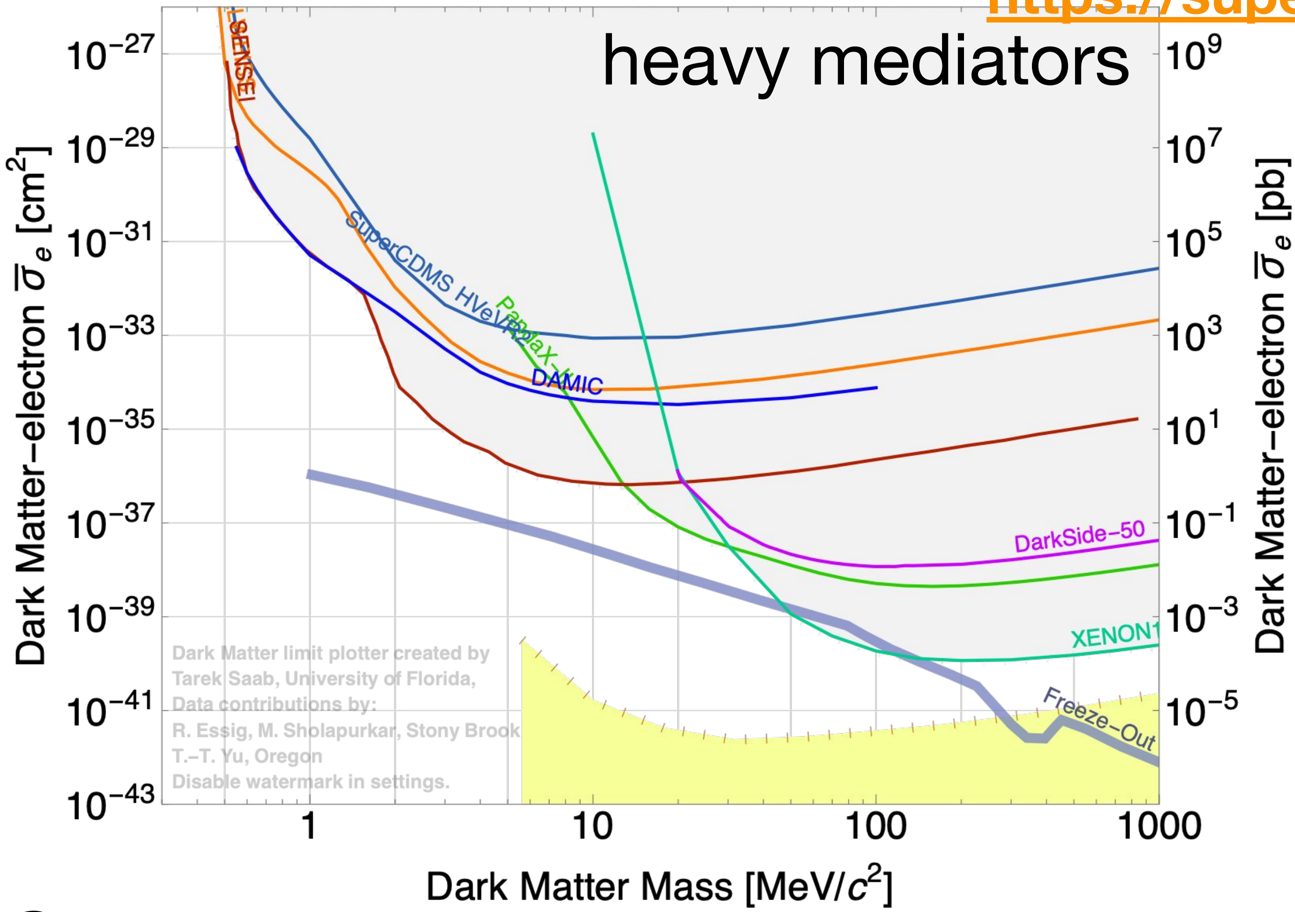

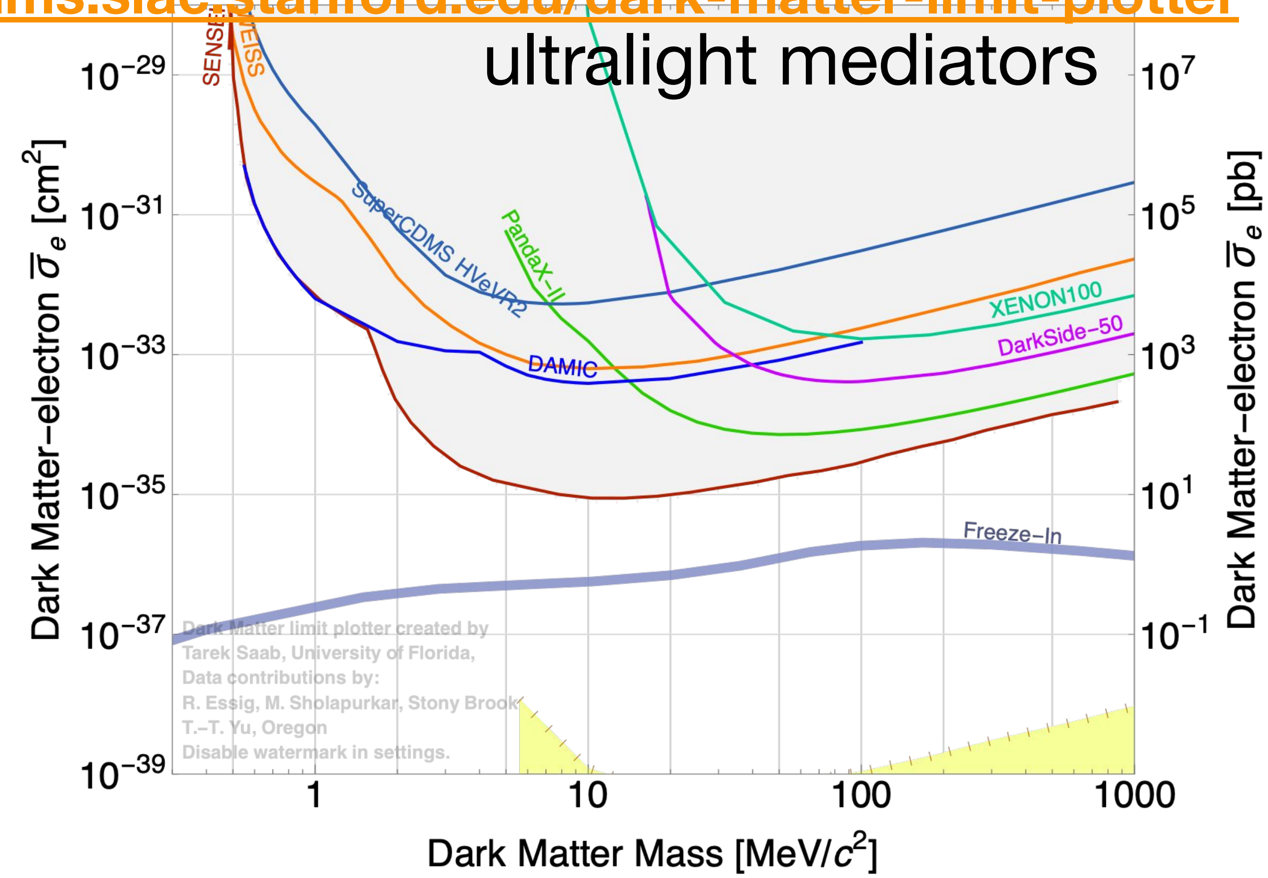

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One way to probe light DM (< MeV-GeV, depending on interaction strength) ==> is to find the boosted DM?

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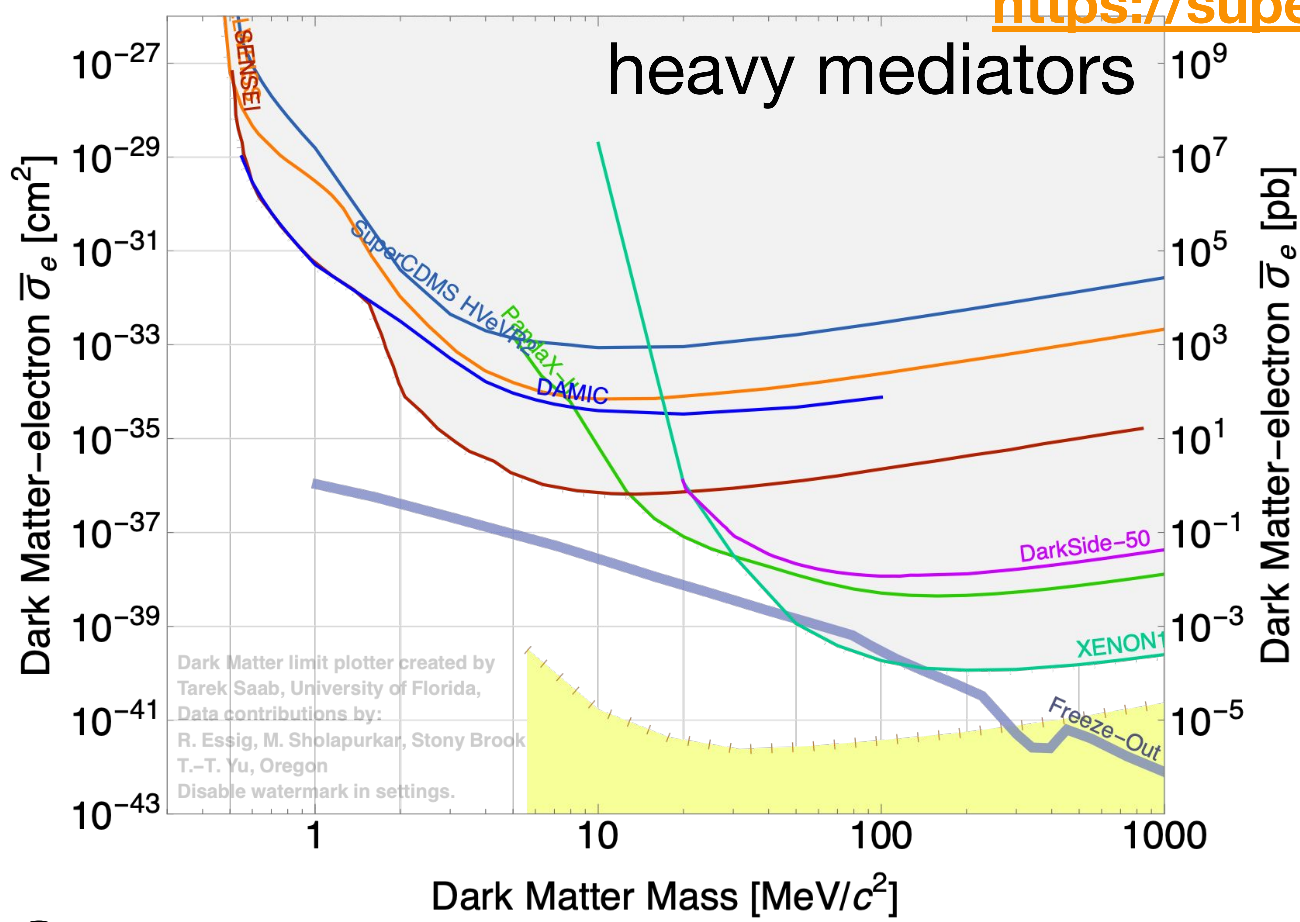

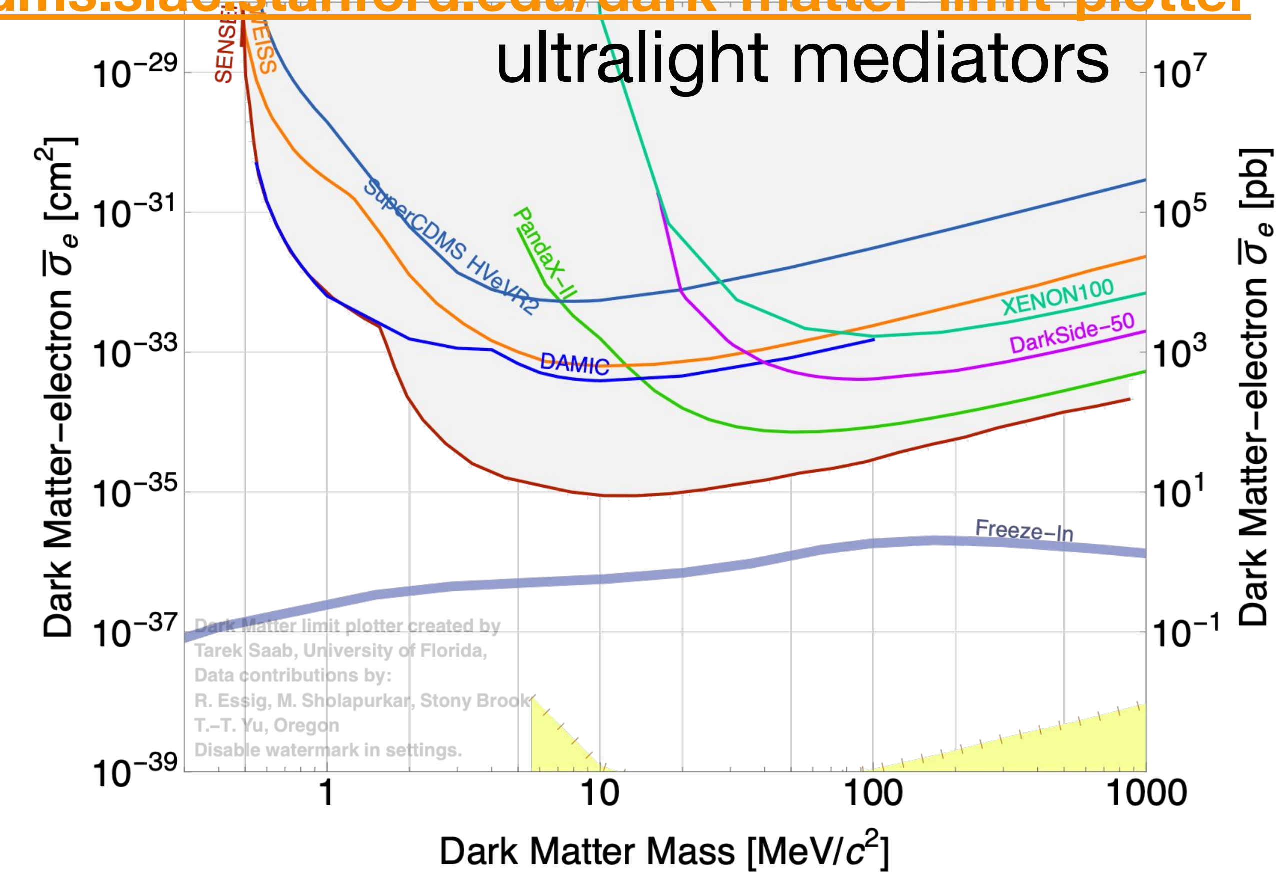

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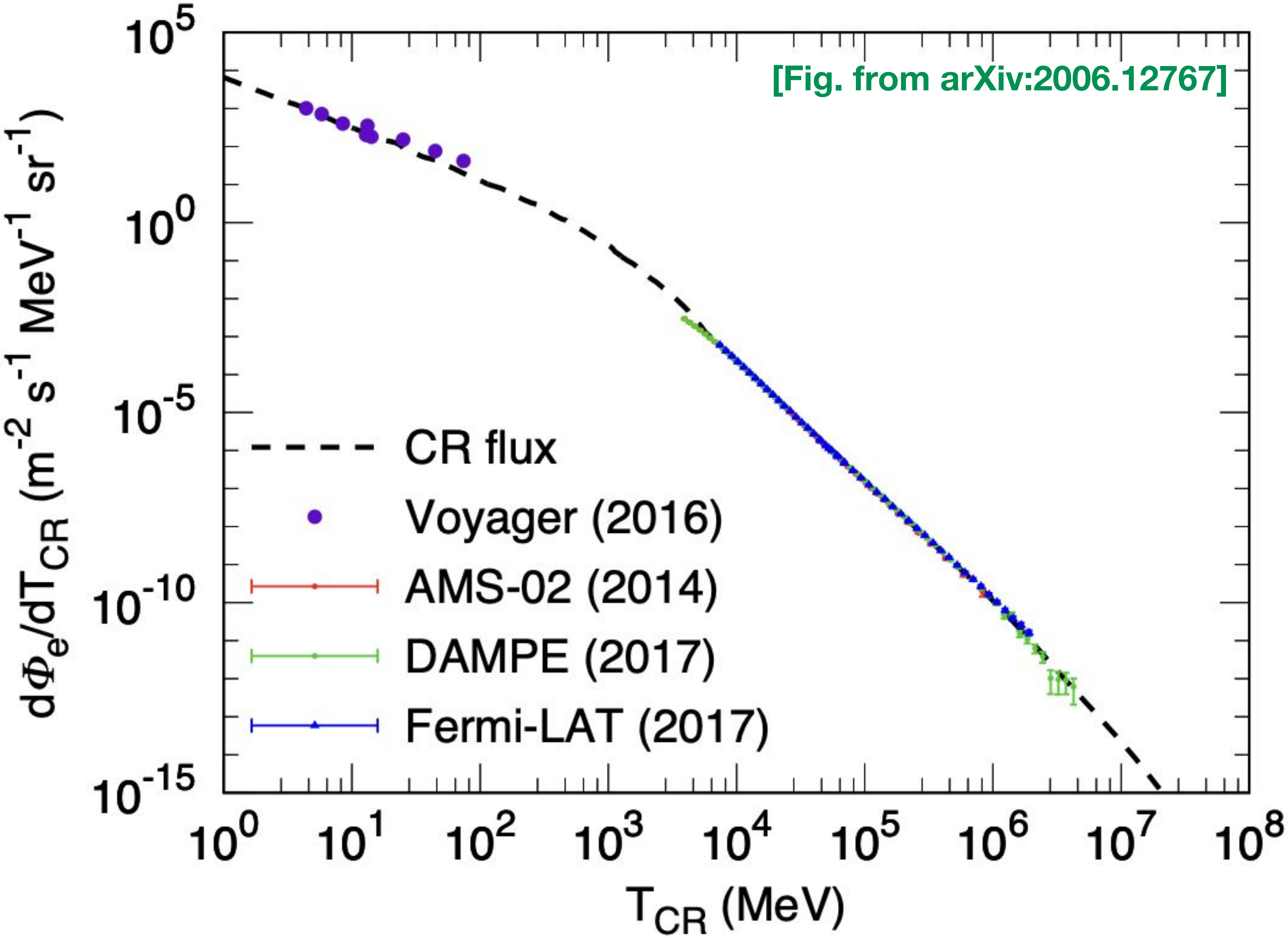
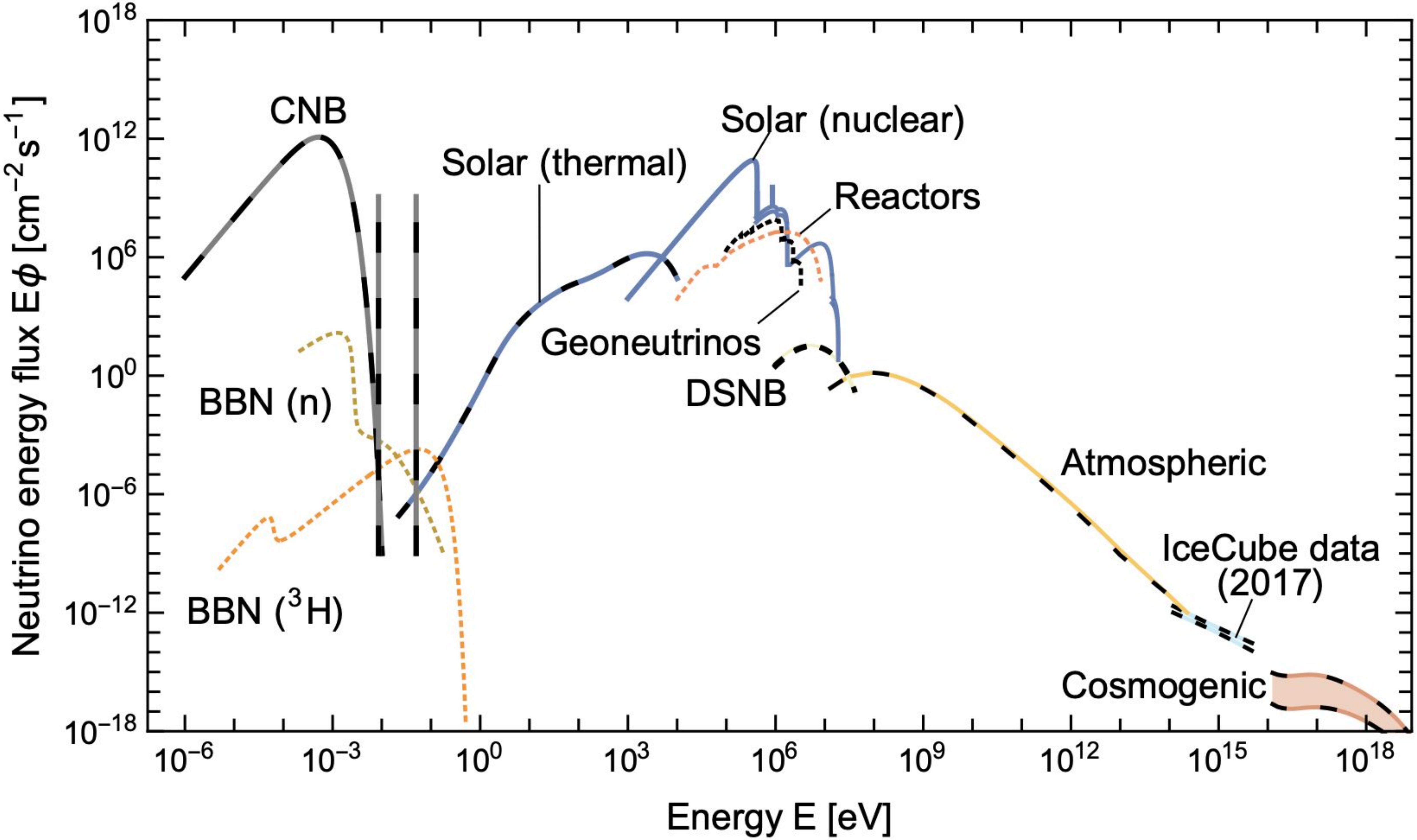
by energetic cosmic rays and neutrinos

How many electrons?: Observed spectrum of electron CR



(*) A caveat: All of these observation has been performed in the local region.

How many neutrinos?: Spectrum of neutrinos in our universe



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

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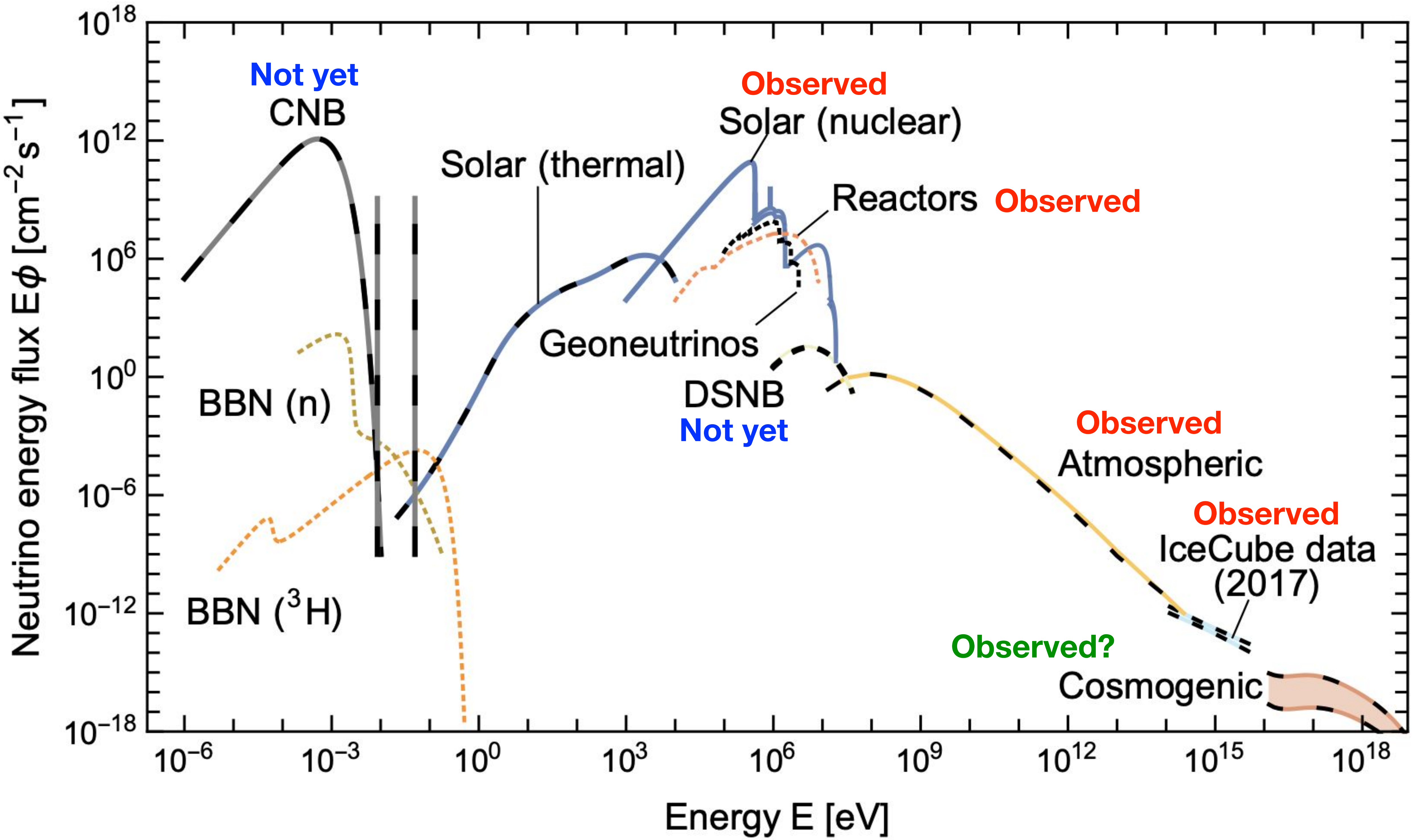

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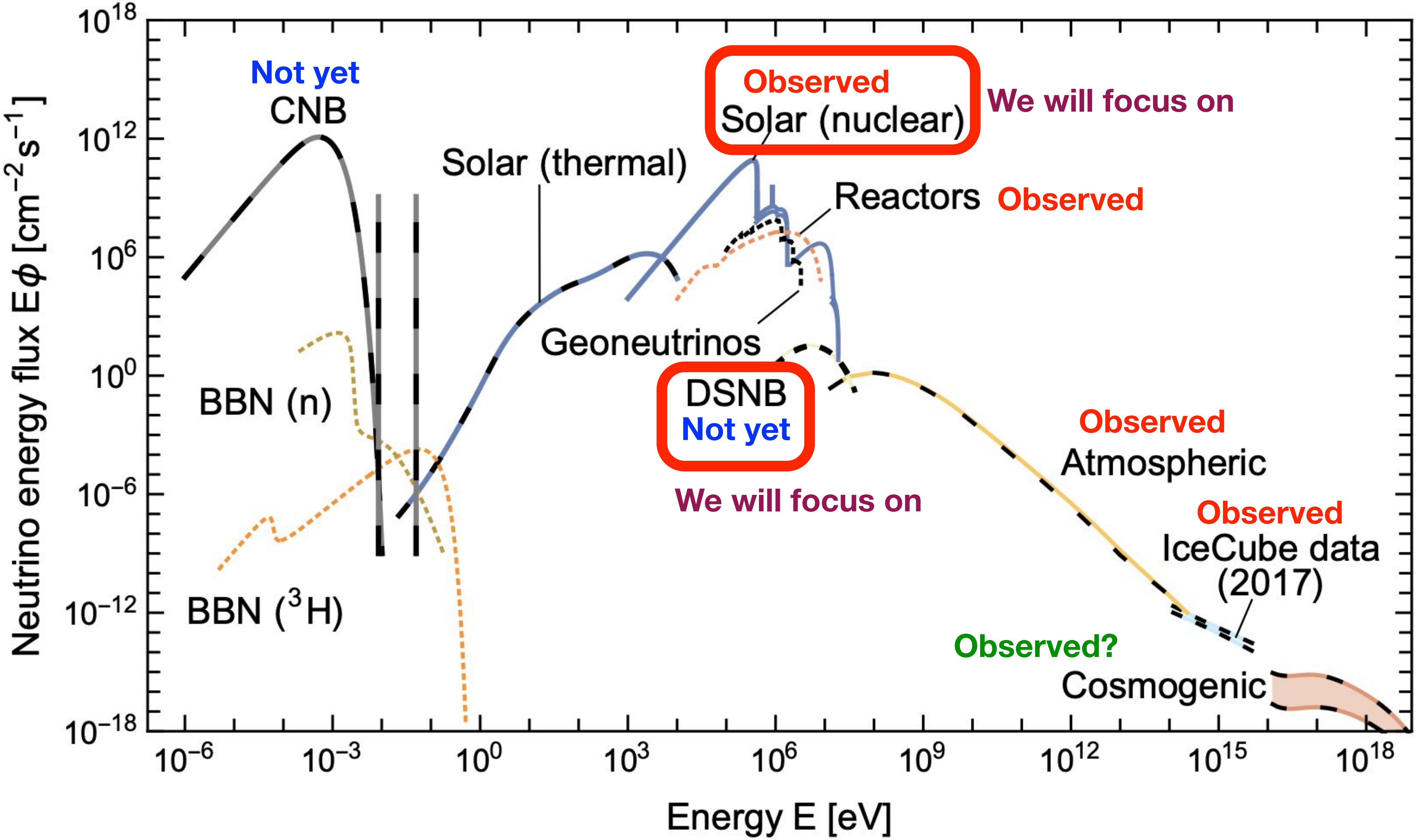
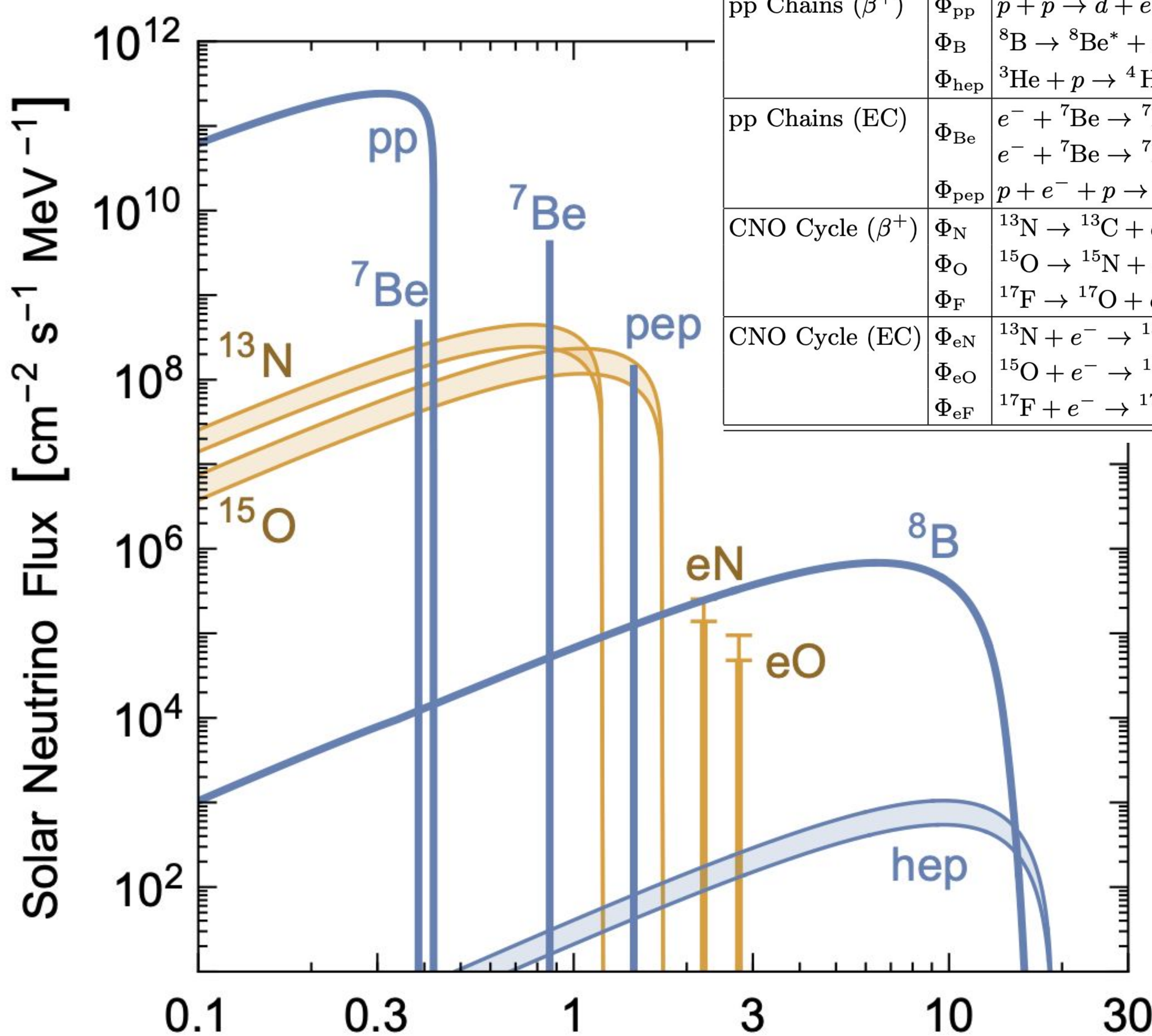


[Raffelt, Tamborra, Vitagliano et al. 19']

How many neutrinos?: Spectrum of neutrinos in our universe

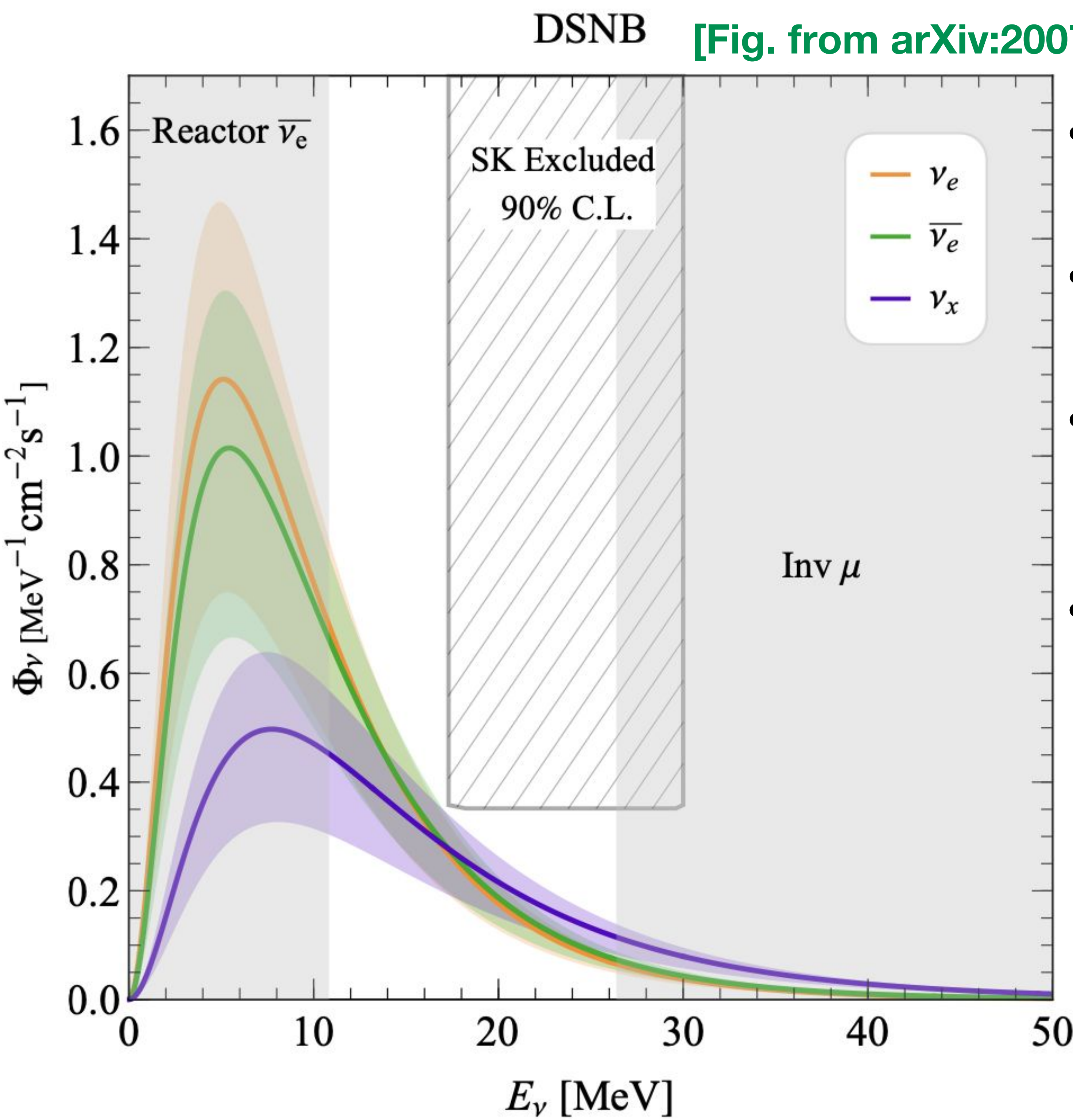
Channel	Flux	Reaction	E_{av} MeV	E_{max} MeV	Flux at Earth GS98	AGSS09	Observed	Units
pp Chains (β^+)	Φ_{pp}	$p + p \to d + e^+ + \nu_e$	0.267	0.423	5.98 $\pm0.6\%$	6.03 $\pm0.5\%$	$5.971^{+0.62\%}_{-0.55\%}$	10^{10} cm^{-2} s^{-1}
	Φ_B	$^8B \to {}^8Be^* + e^+ + \nu_e$	6.735 ± 0.036	~ 15	5.46 $\pm12\%$	4.50 $\pm12\%$	$5.16^{+2.5\%}_{-1.7\%}$	10^6 cm^{-2} s^{-1}
	Φ_{hep}	$^3He + p \to {}^4He + e^+ + \nu_e$	9.628	18.778	0.80 $\pm30\%$	0.83 $\pm30\%$	$1.9^{+63\%}_{-47\%}$	10^4 cm^{-2} s^{-1}
pp Chains (EC)	Φ_{Be}	$e^- + {}^7Be \to {}^7Li + \nu_e$ $e^- + {}^7Be \to {}^7Li^* + \nu_e$	0.863 (89.7%) 0.386 (10.3%)		4.93 $\pm6\%$	4.50 $\pm6\%$	$4.80^{+5.9\%}_{-4.6\%}$	10^9 cm^{-2} s^{-1}
	Φ_{pep}	$p + e^- + p \to d + \nu_e$	1.445		1.44 $\pm1\%$	1.46 $\pm0.9\%$	$1.448^{+0.90\%}_{-0.90\%}$	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 $\pm15\%$	2.04 $\pm14\%$	< 13.7	10^8 cm^{-2} s^{-1}
	Φ_O	$^{15}O \to {}^{15}N + e^+ + \nu_e$	0.996	1.732	2.05 $\pm17\%$	1.44 $\pm16\%$	< 2.8	10^8 cm^{-2} s^{-1}
	Φ_F	$^{17}F \to {}^{17}O + e^+ + \nu_e$	0.998	1.736	5.29 $\pm20\%$	3.26 $\pm18\%$	< 8.5	10^6 cm^{-2} s^{-1}
CNO Cycle (EC)	Φ_{eN}	$^{13}N + e^- \to {}^{13}C + \nu_e$	2.220		2.20 $\pm15\%$	1.61 $\pm14\%$	—	10^5 cm^{-2} s^{-1}
	Φ_{eO}	$^{15}O + e^- \to {}^{15}N + \nu_e$	2.754		0.81 $\pm17\%$	0.57 $\pm16\%$	—	10^5 cm^{-2} s^{-1}
	Φ_{eF}	$^{17}F + e^- \to {}^{17}O + \nu_e$	2.758		3.11 $\pm20\%$	1.91 $\pm18\%$	—	10^3 cm^{-2} s^{-1}



- **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)**

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

How many neutrinos?: Spectrum of neutrinos in our universe



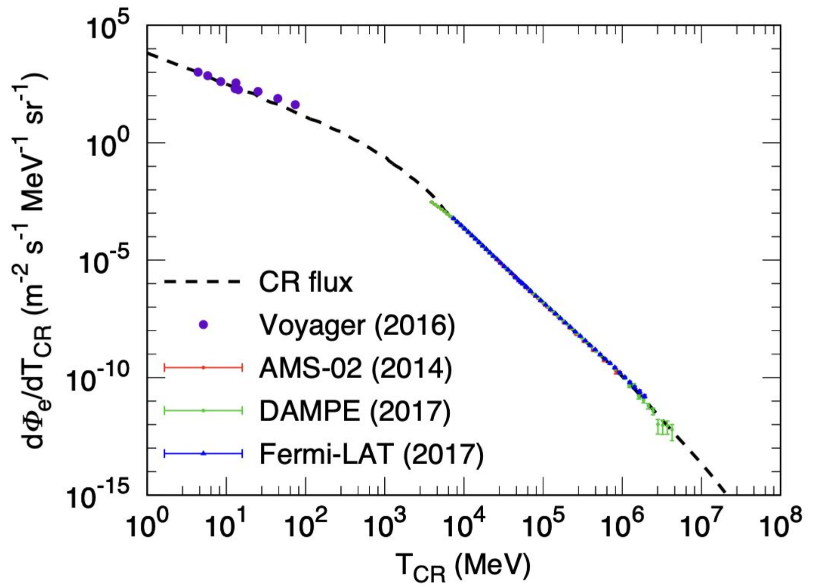
[Fig. from arXiv:2007.13748 [hep-ph]]

- **Thermally produced from neutronization in proto-neutron stars**
- **Usually has Boltzmann peaks around 5-10 MeV (depending on flavor**
- **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)



Boosting keV-GeV DM with

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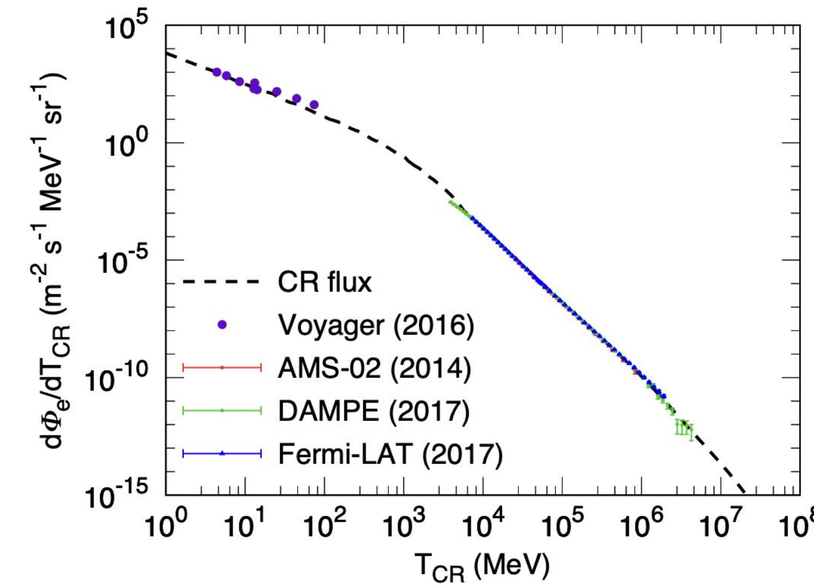
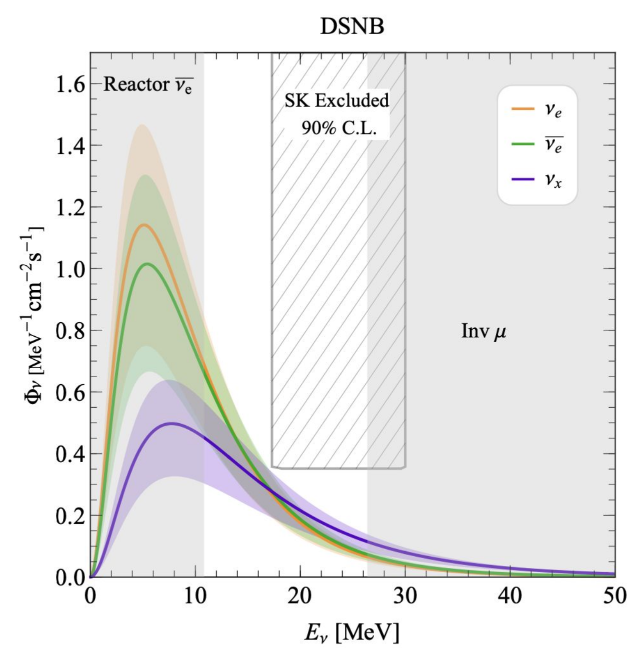
- DSNB (extragalactic origin)





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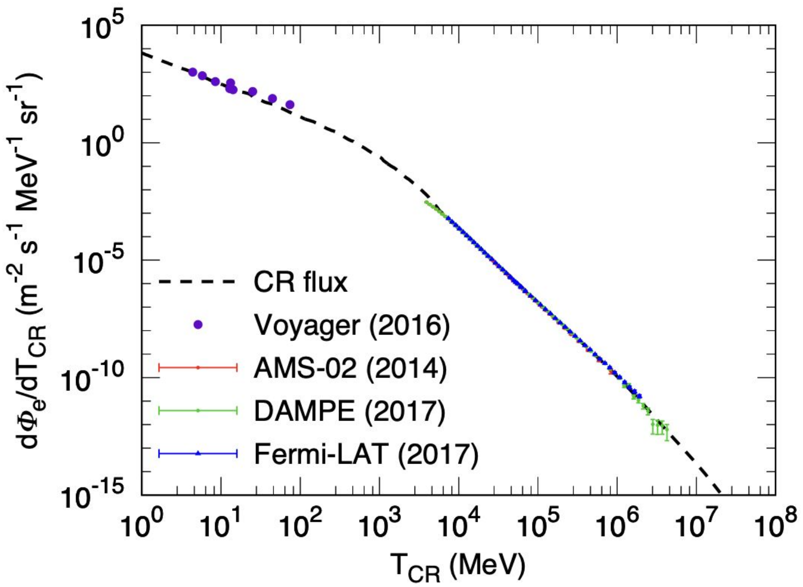
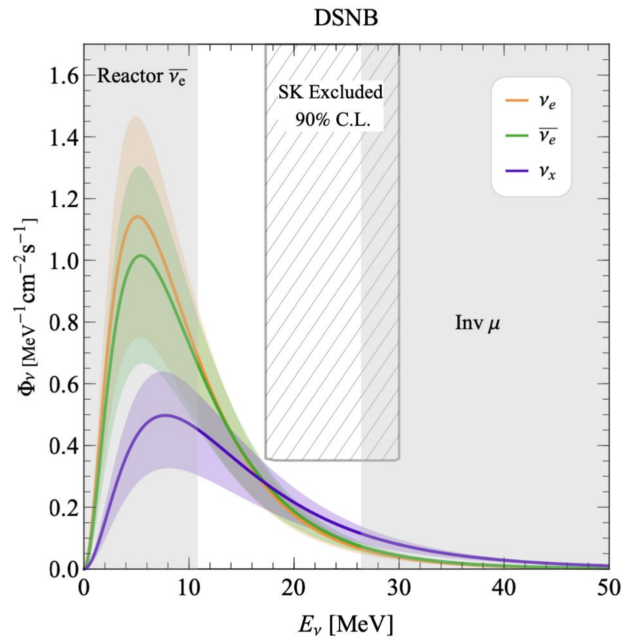
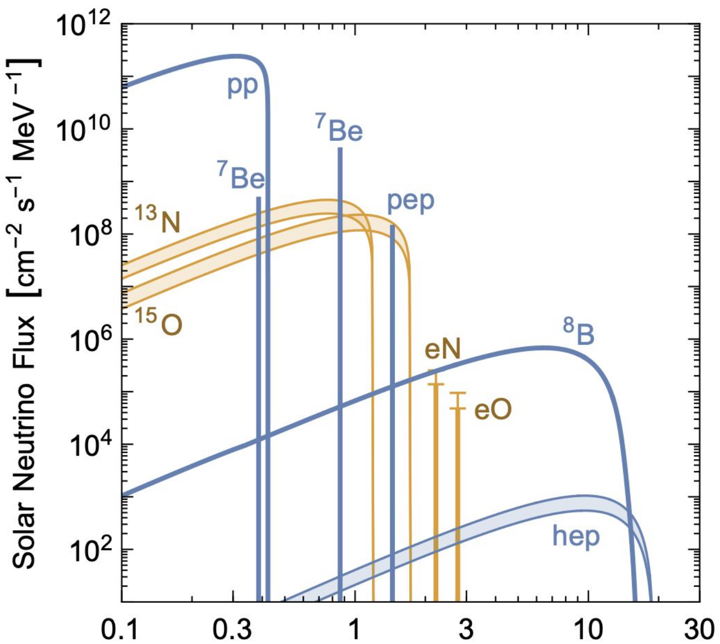


- DSNB (extragalactic origin)



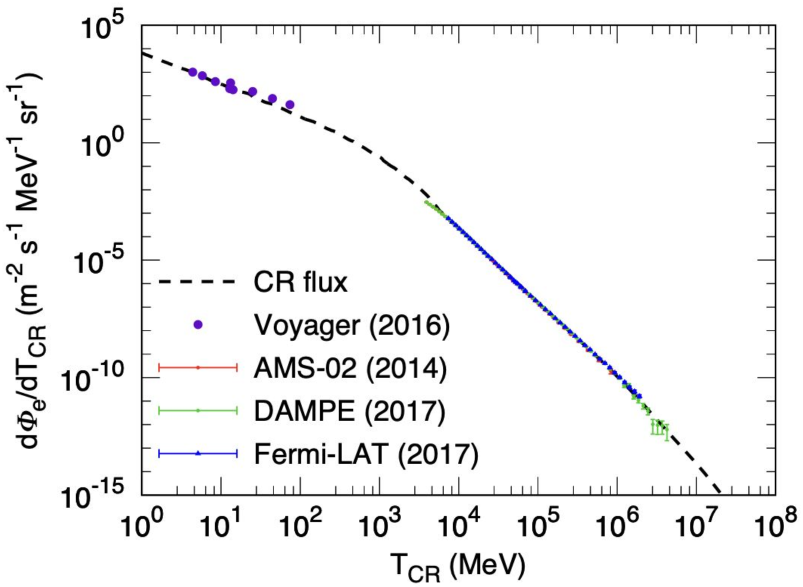


- Stellar neutrinos (Galactic/Extragalactic origin, This work)

Boosting keV-GeV DM with

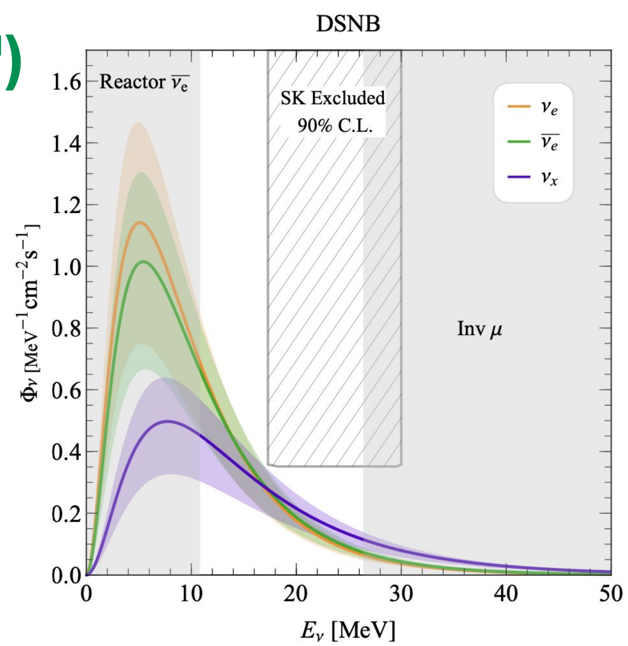
Y. Ema et al. (18')
C. V. Cappiello et al. (19')

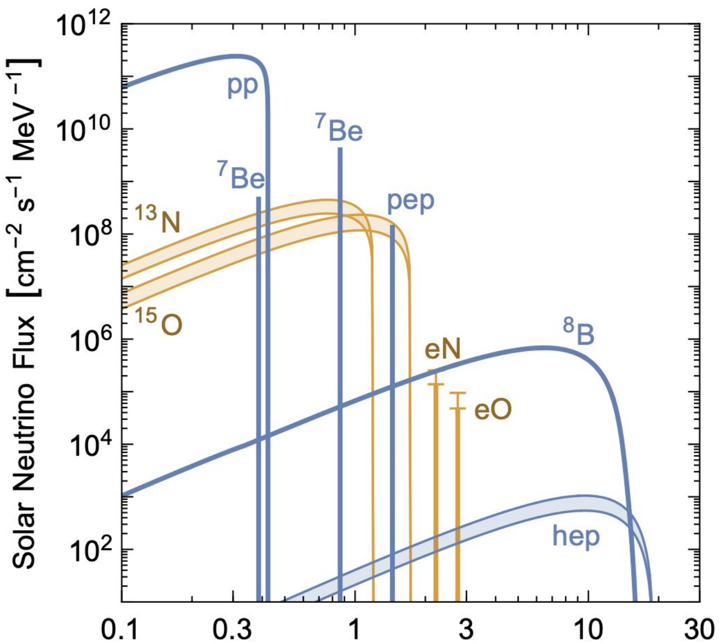
- Electron Cosmic rays (based on observed data)
  Electron CR (2 MeV - 90 GeV for the observed data)



- DSNB (extragalactic origin)
  Neutrino (O(1)-O(100) MeV) & normalization predicted by SFR

first suggested by A. Das et al. (21')

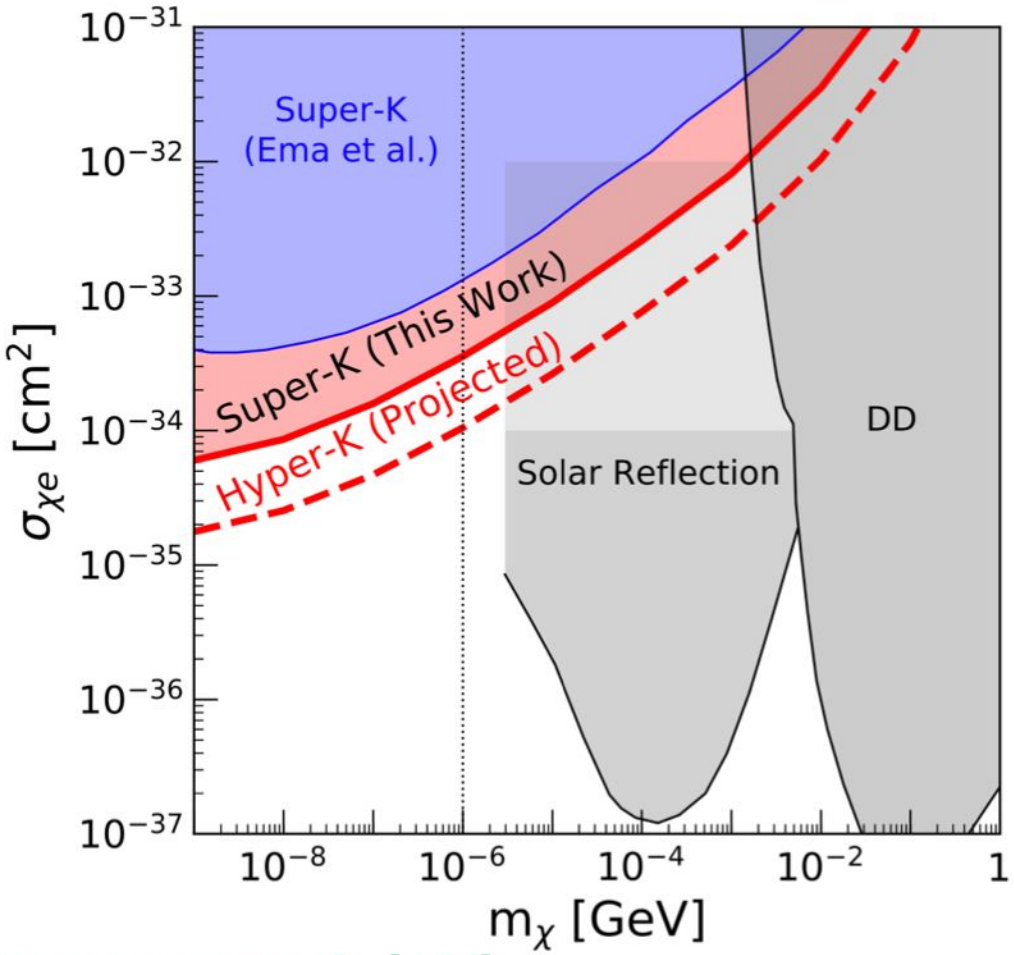




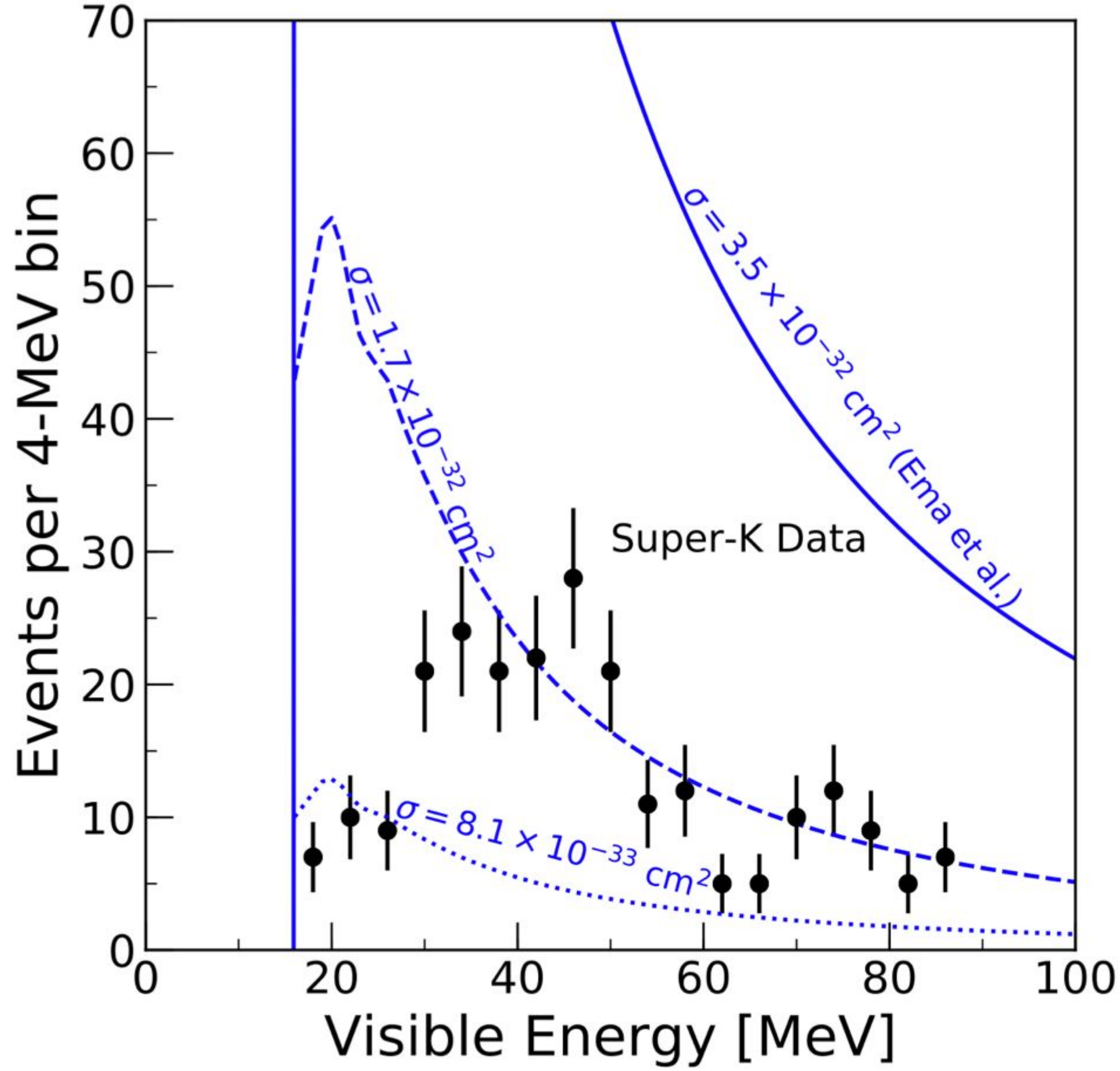
- Stellar neutrinos (Galactic/Extragalactic origin, Our work)
  Neutrino (O(100) keV - 20 MeV) & precisely measured by solar neutrino detection exp.

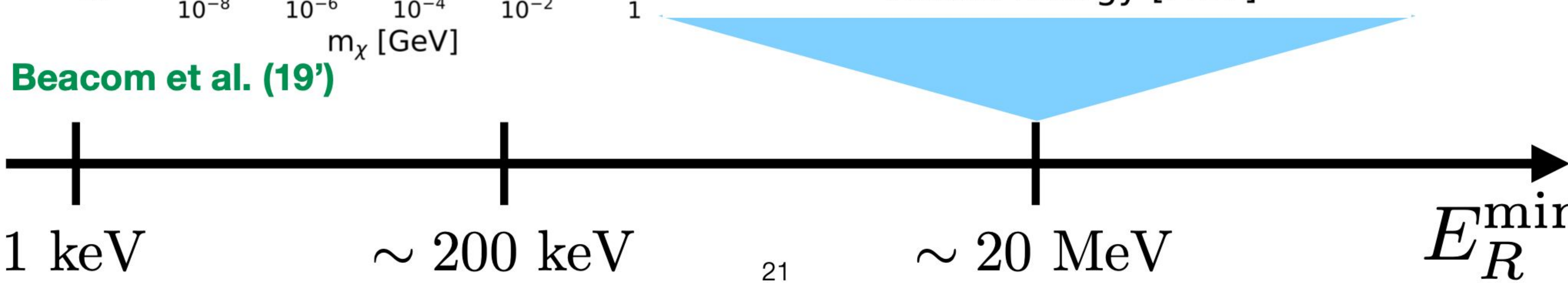
How to detect them?: The low threshold frontier of electron recoils in DM/neutrino exp.

SN neutrino searches (SK- I/II/III/IV)
- **E threshold ~ 5-10 MeV (Super-K)**
- **Typical Exposure ~ 300 kton-yr**



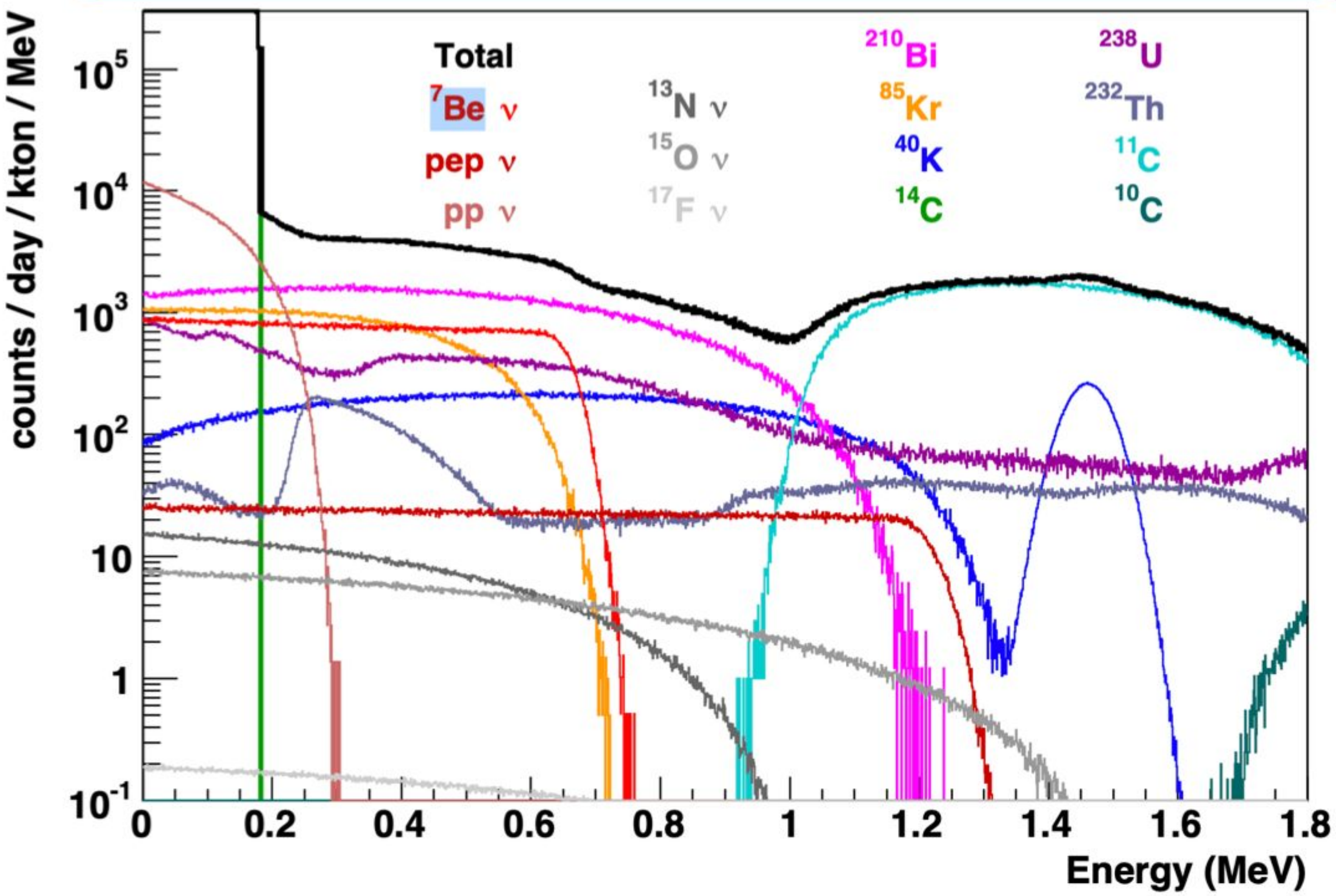
J. Beacom et al. (19')





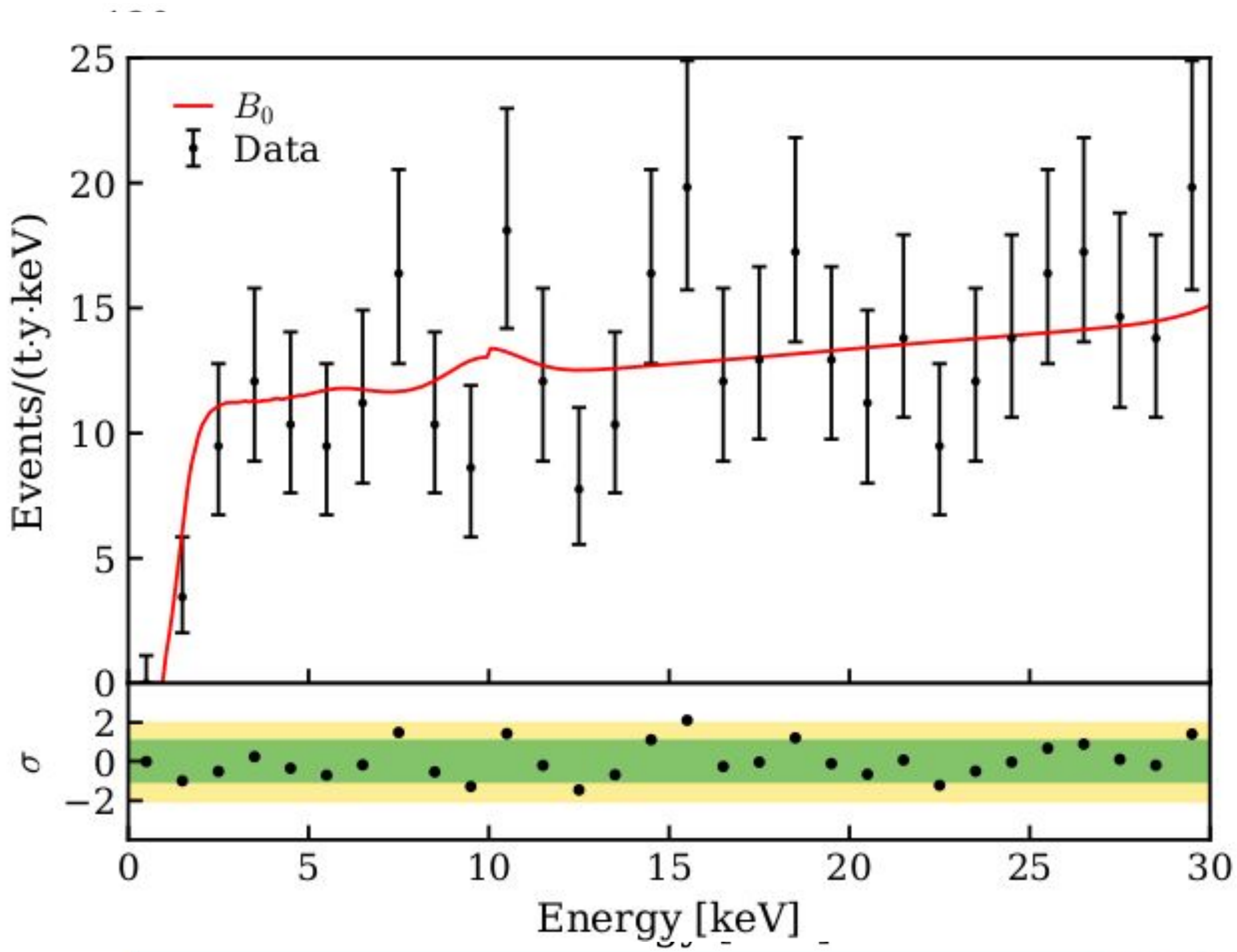
How to detect them?: The low threshold frontier of electron recoils in DM/neutrino exp.

Low-E solar neutrinos (e.g. 7Be neutrino)
- E threshold ~ 200-300 keV (JUNO/Borexino)
- Typical Exposure ~ O(20) kton-yr

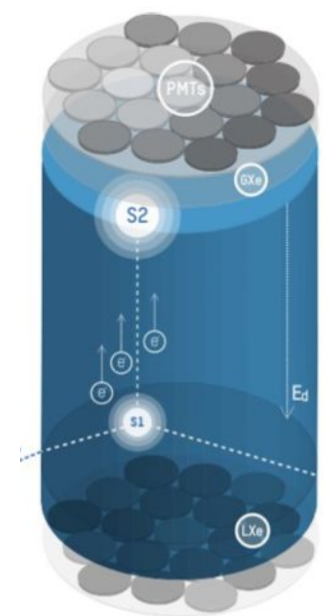


$1\ \mathrm{keV}$ — $\sim 200\ \mathrm{keV}$ — $\sim 20\ \mathrm{MeV}$ — E_R^{min}

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



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



$1\ \text{keV}$ $\sim 200\ \text{keV}$ $\sim 20\ \text{MeV}$ E_R^{min}

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?

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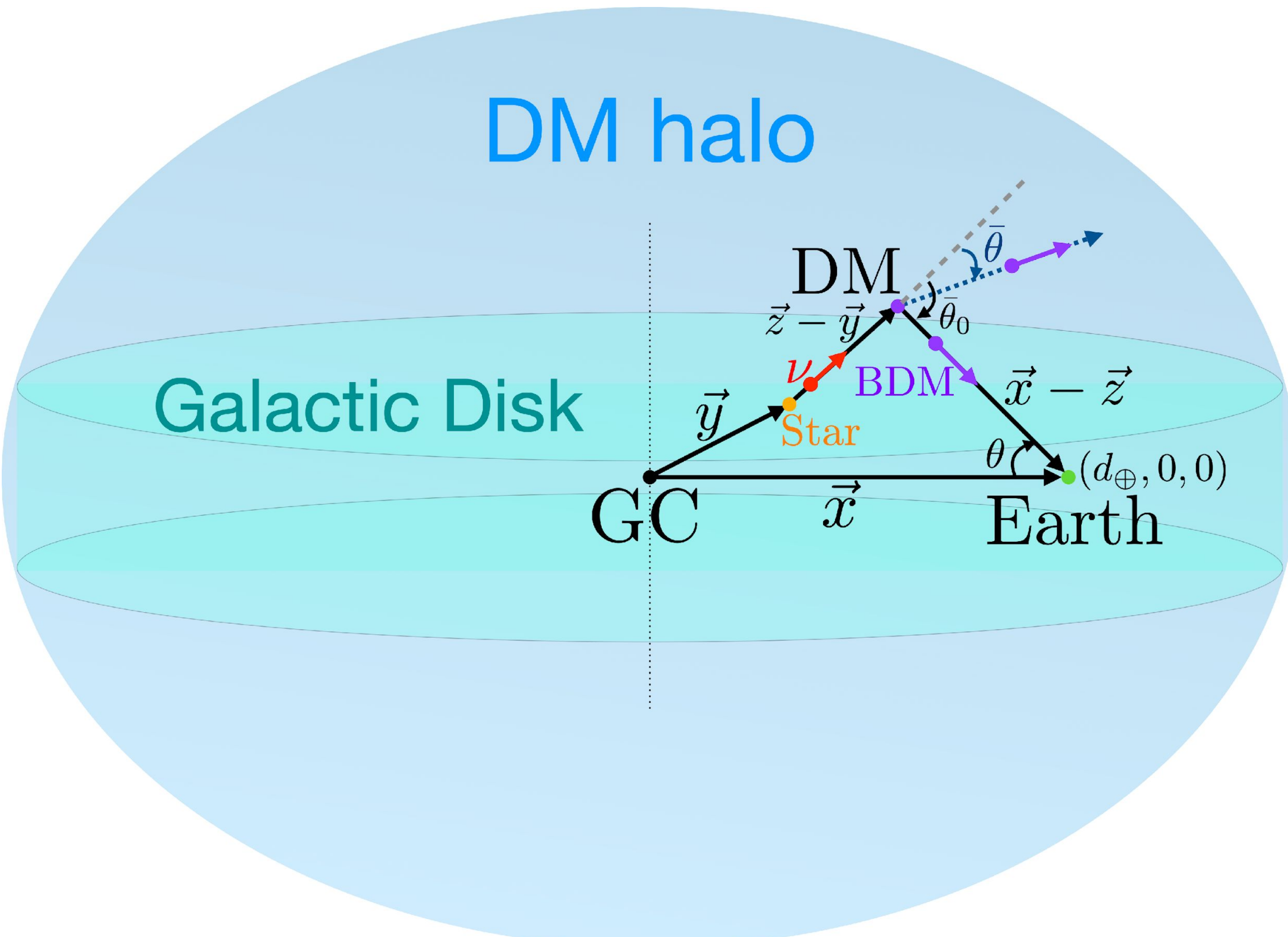
Galactic Neutrino-Boosted Dark Matter

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

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

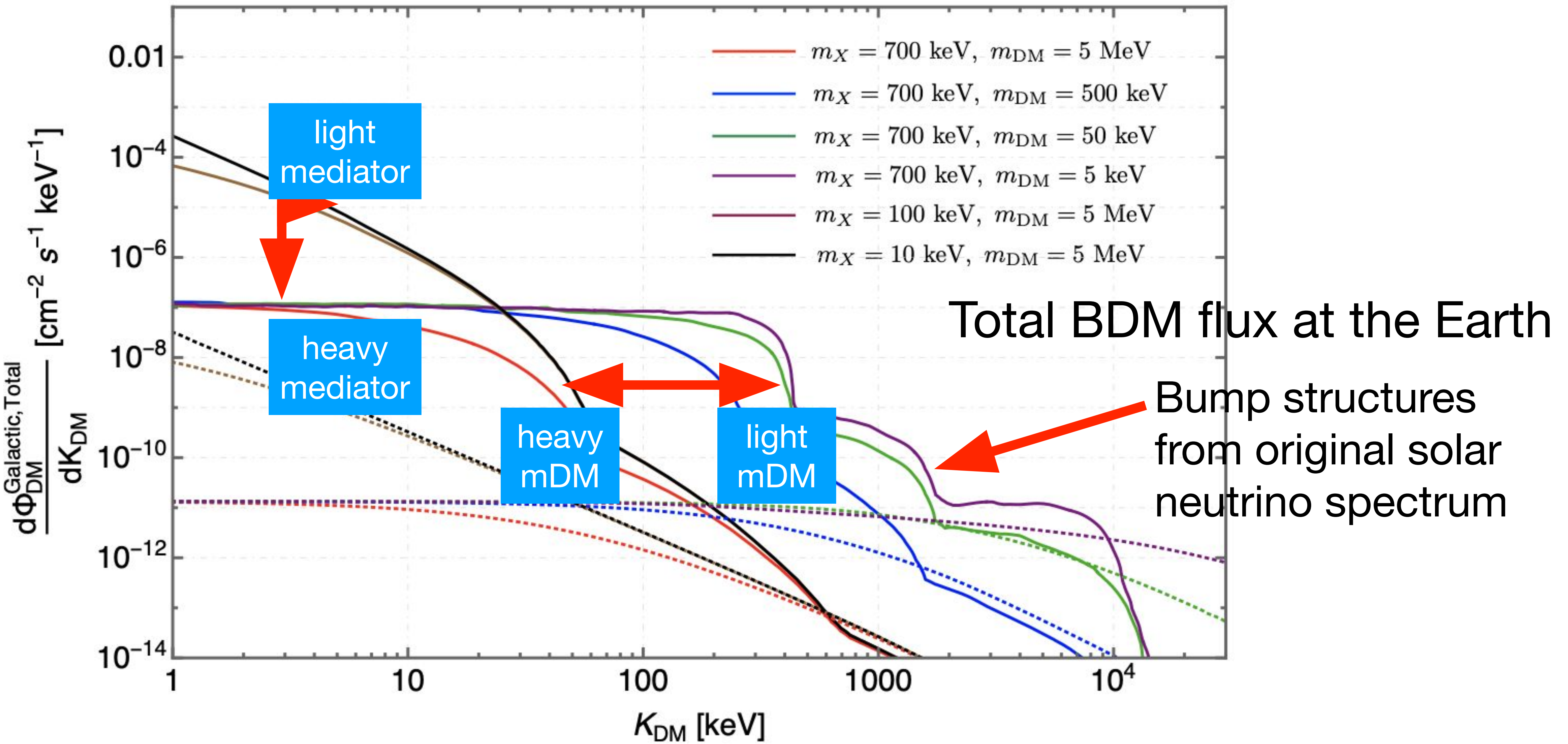
-Assumption in the evaluation-

1. Symmetric population of Stars&DM
2. All stars have 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



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

Extragalactic contribution to Neutrino-BDM

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

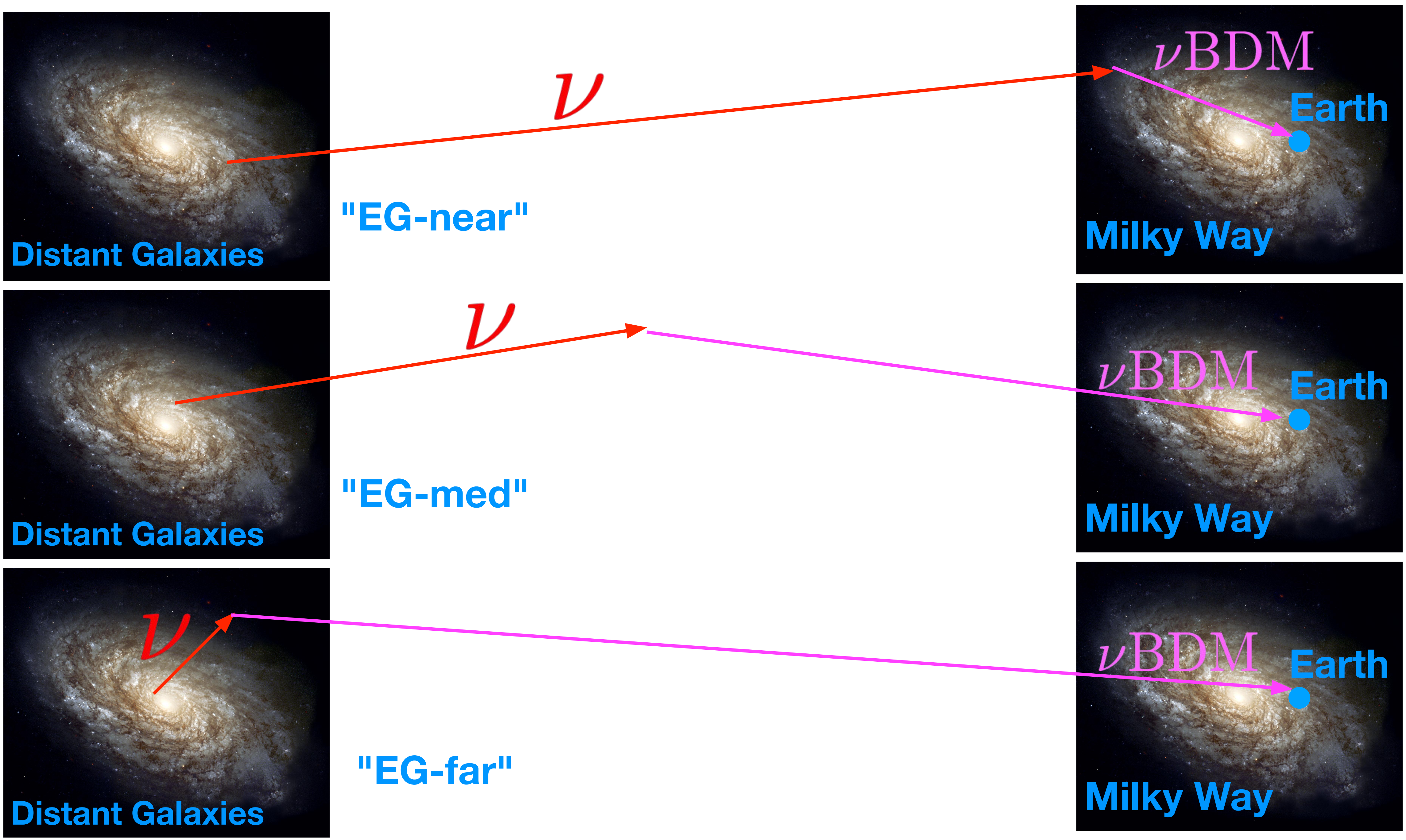
- Main contribution to EG-nuBDM

Dominant contributions coming from the region 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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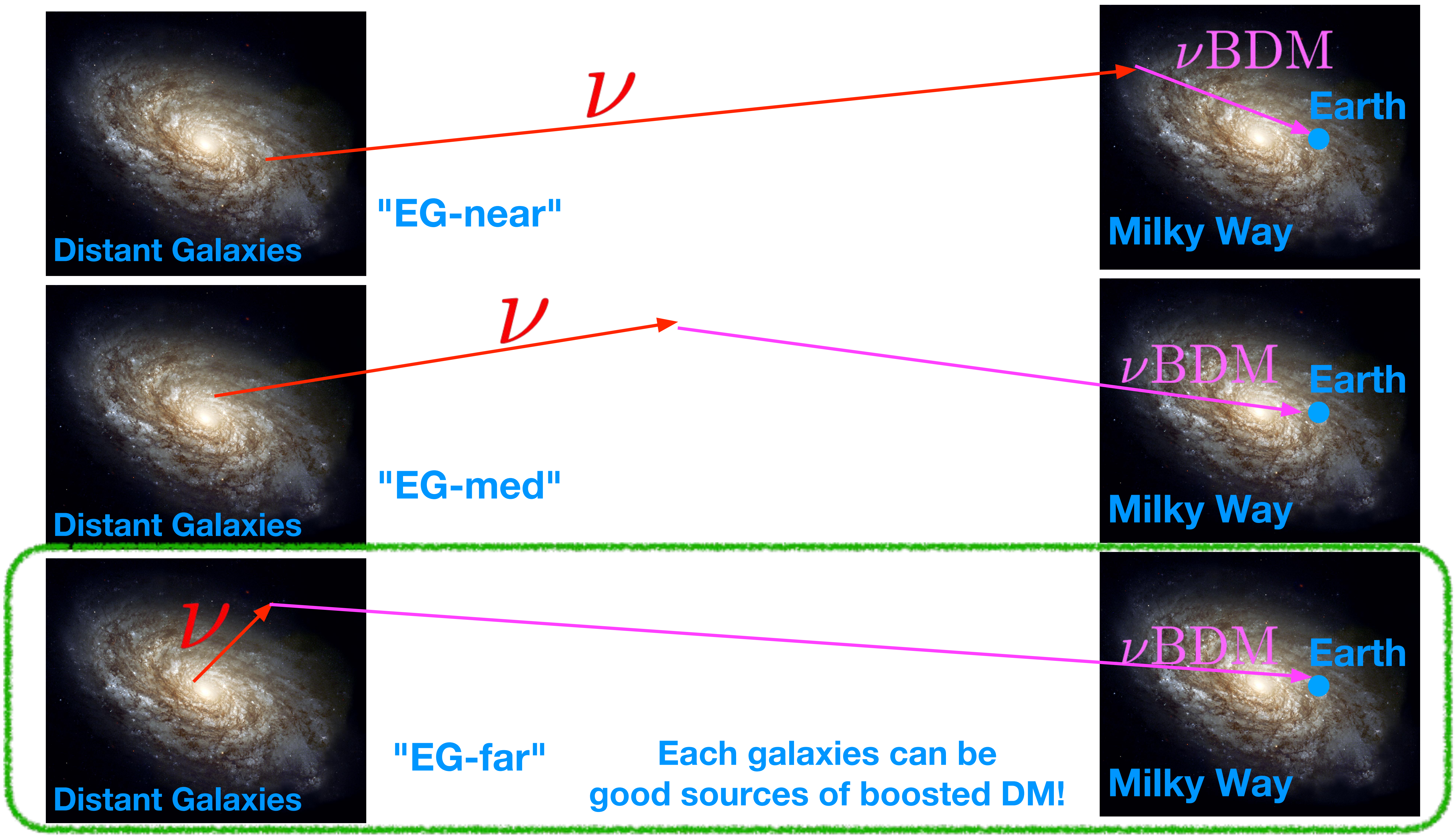
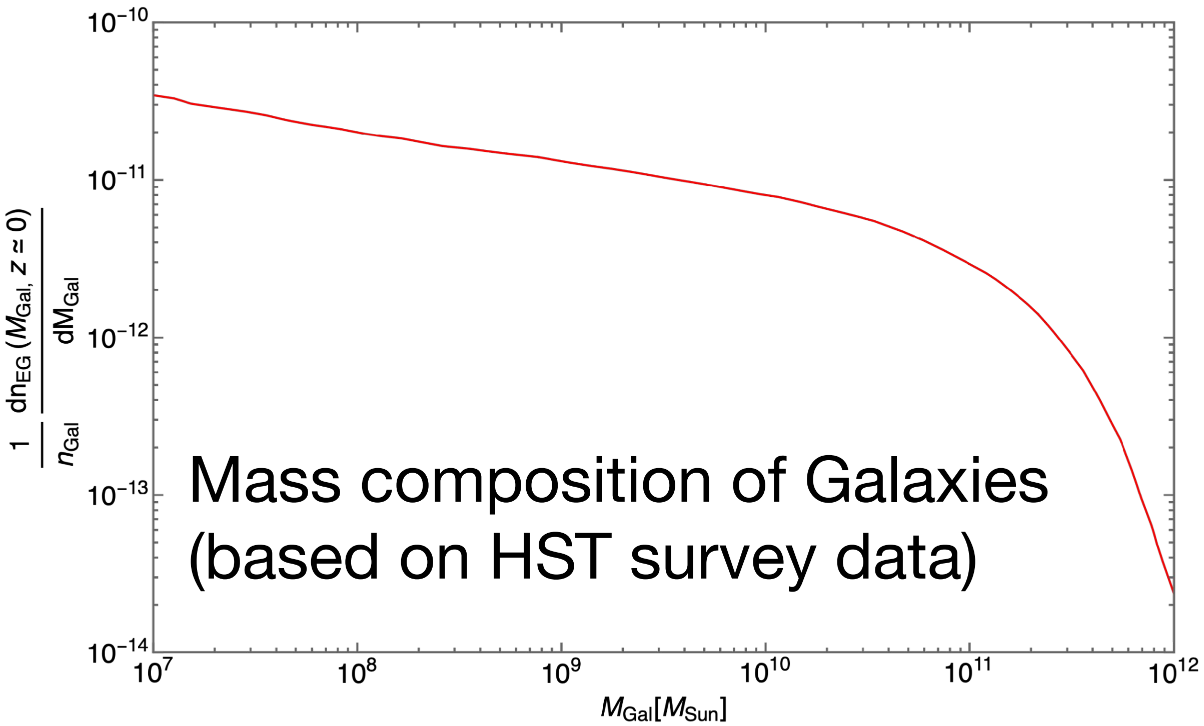
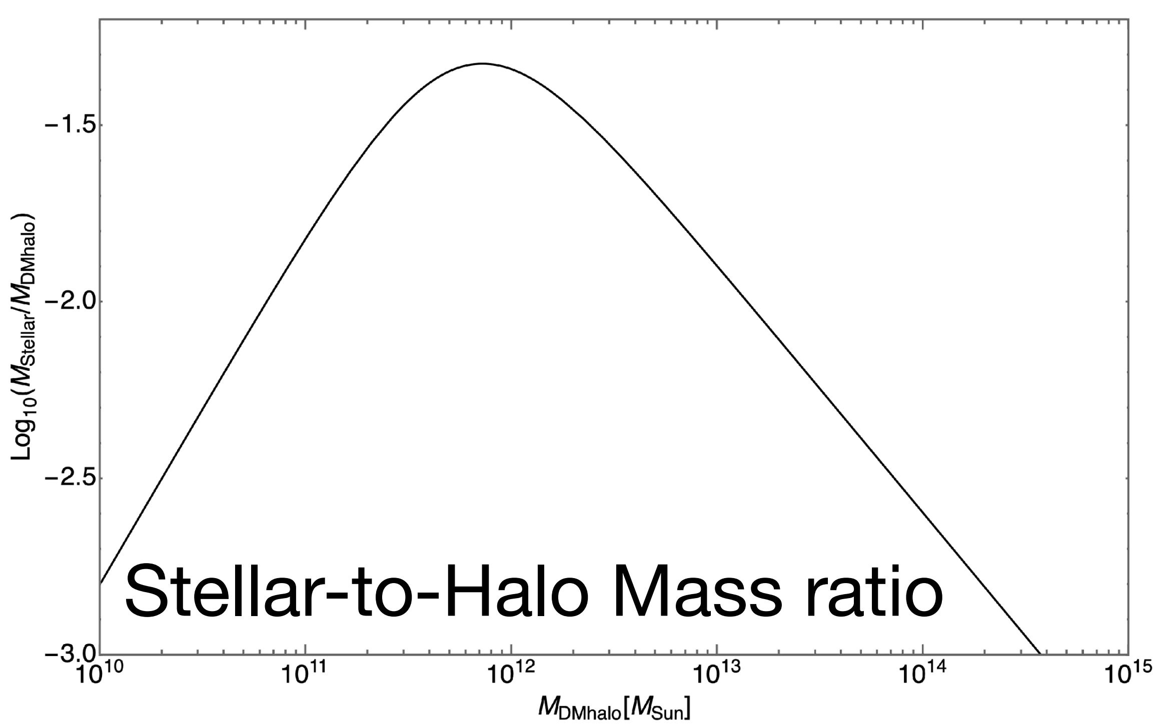


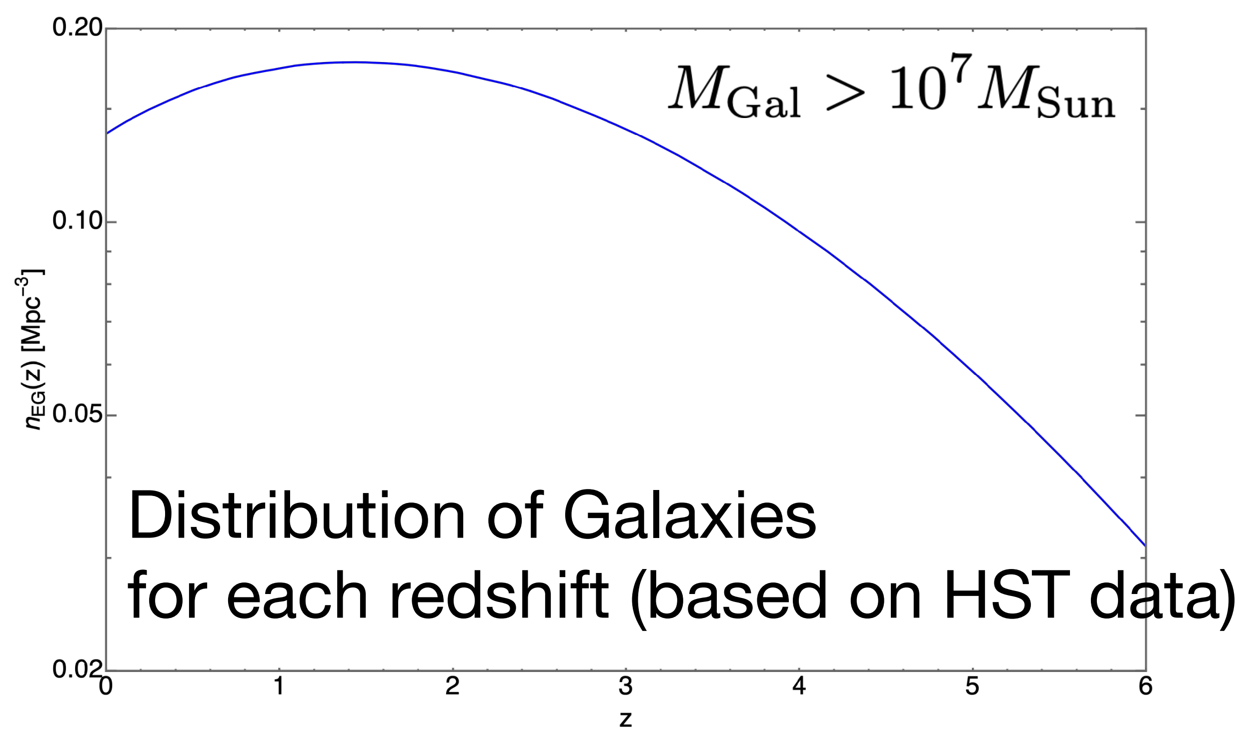
Recipes to evaluate Extragalactic contribution

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



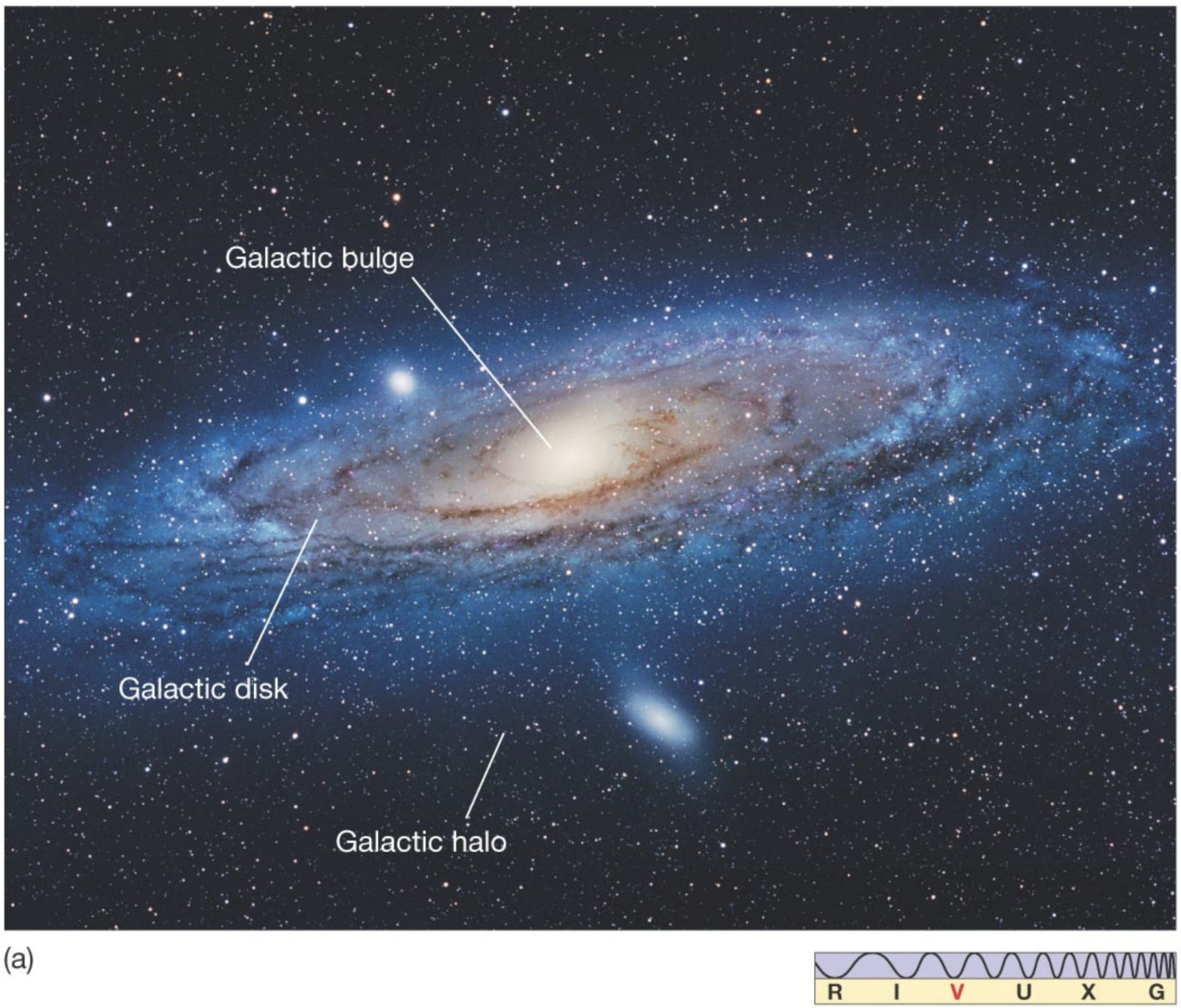
The estimation of Halo/Stellar Mass ratio, Size of Halo/Disk are mostly based on observation data.



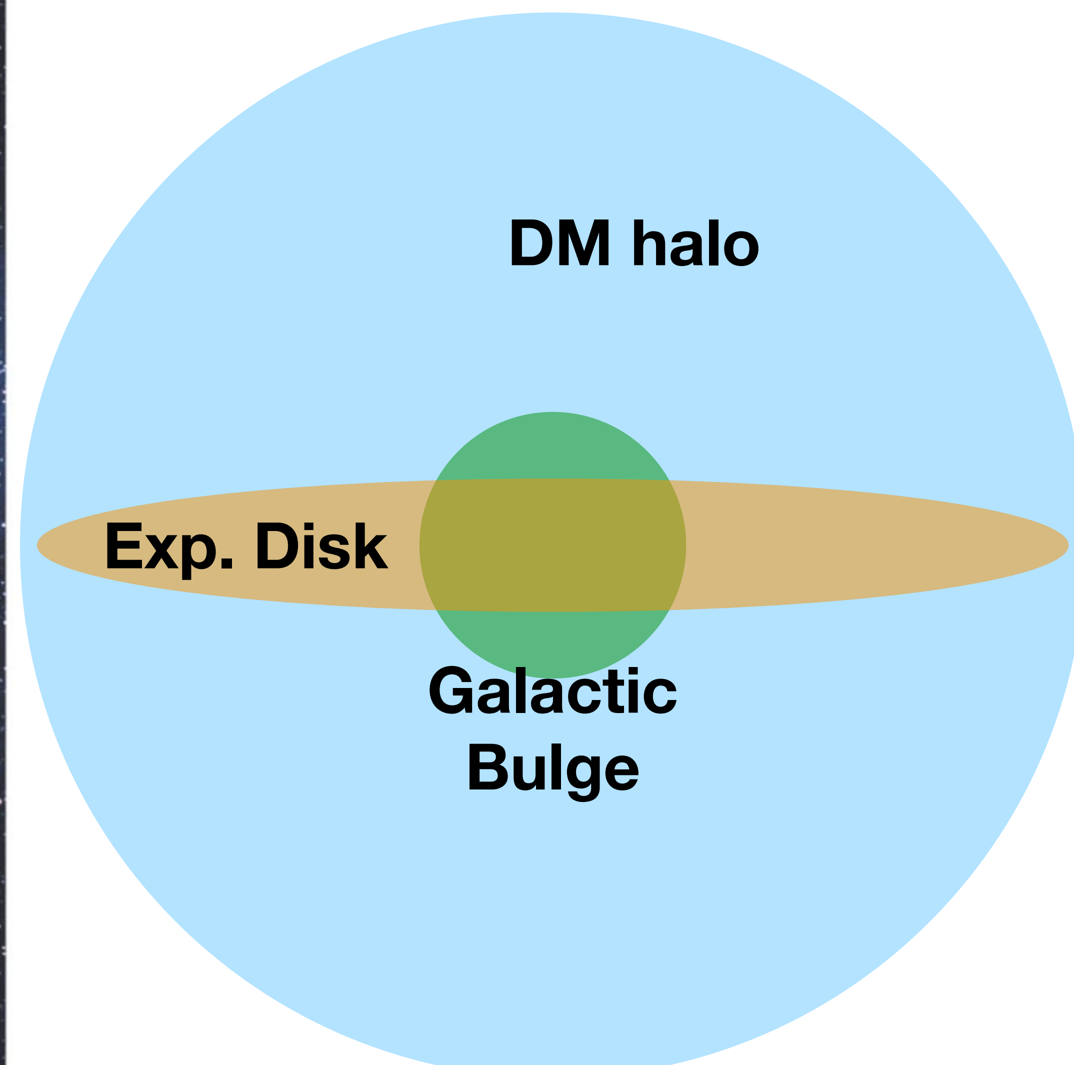


Estimation of BDM flux

Most typical (spiral) galaxy = (Sersic Bulge + Exponential Disk + Spherical Halo)



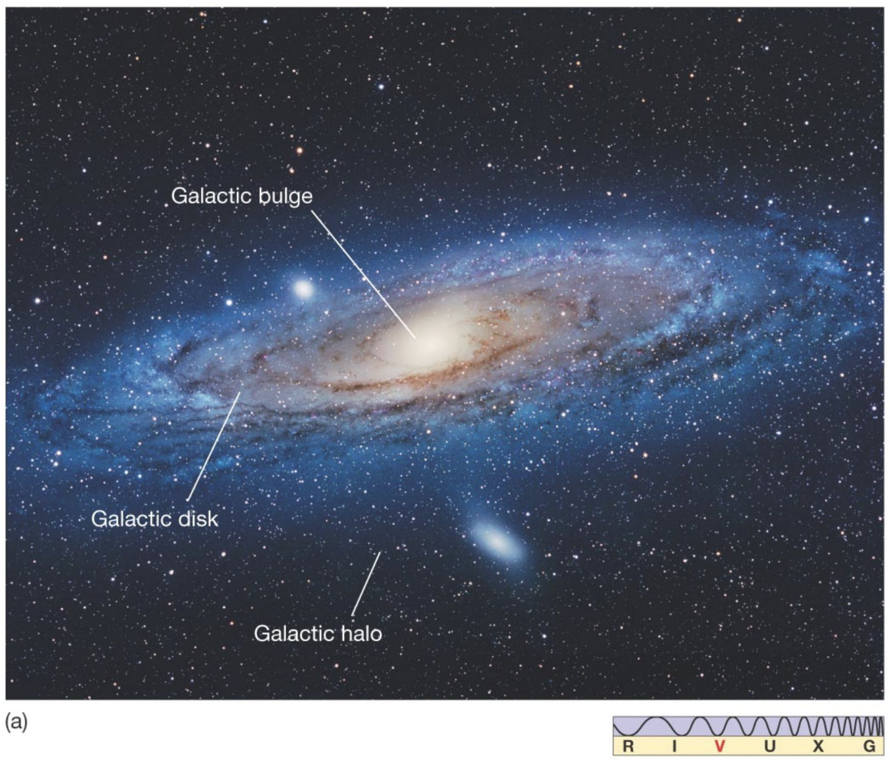
(a)



Estimation of BDM flux

Most typical (spiral) galaxy = (Sersic Bulge + Exponential Disk + Spherical Halo)

$$\underbrace{\text{Sersic Bulge + Exponential Disk}}_{\text{Stellar}} + \underbrace{\text{Spherical Halo}}_{\text{DM}}$$



e.g.) For the Milky Way,
a representative density profile choice gives

Parameter	Value
Bulge	
$M_{\rm b}$	$2.6 \times 10^{10}\,{\rm M_\odot}$
$r_{\rm b}$	$0.5\,{\rm kpc}$
$r_{\rm b,max}$	$3\,{\rm kpc}$
Stellar disc	
$M_{\rm d}$	$5 \times 10^{10}\,{\rm M_\odot}$
$R_{\rm d}$	$2.5\,{\rm kpc}$
$R_{\rm d,max}$	$19\,{\rm kpc}$
$Z_{\rm d}$	$0.3\,{\rm kpc}$
DM halo	
ρ_h	$0.5 \times 10^7\,{\rm M_\odot kpc^{-3}}$
$M_{\rm h}$	$4.8 \times 10^{11}\,{\rm M_\odot}$
$r_{\rm h}$	$20\,{\rm kpc}$
$r_{\rm h,max}$	$100\,{\rm kpc}$

$$\rho_{\rm bulge}(r_s) = \frac{M_b}{(\sqrt{2\pi}r_h)^3} e^{-r_s^2/2r_b^2}\ [M_\odot\ {\rm kpc}^{-3}]$$

$$\rho_{\rm disc}(r_s, z_s) = \rho_0 \cdot e^{-r_s/r_d} \cdot {\rm sech}^2\left(\frac{z_s}{z_d}\right)\ [M_\odot\ {\rm kpc}^{-3}]$$

$$\rho_{\rm halo}(r_\chi) = \frac{\rho_h}{\left(\frac{r_\chi}{r_h}\right)\left(1 + \frac{r_\chi}{r_h}\right)^2} [M_\odot\ {\rm kpc}^{-3}]$$

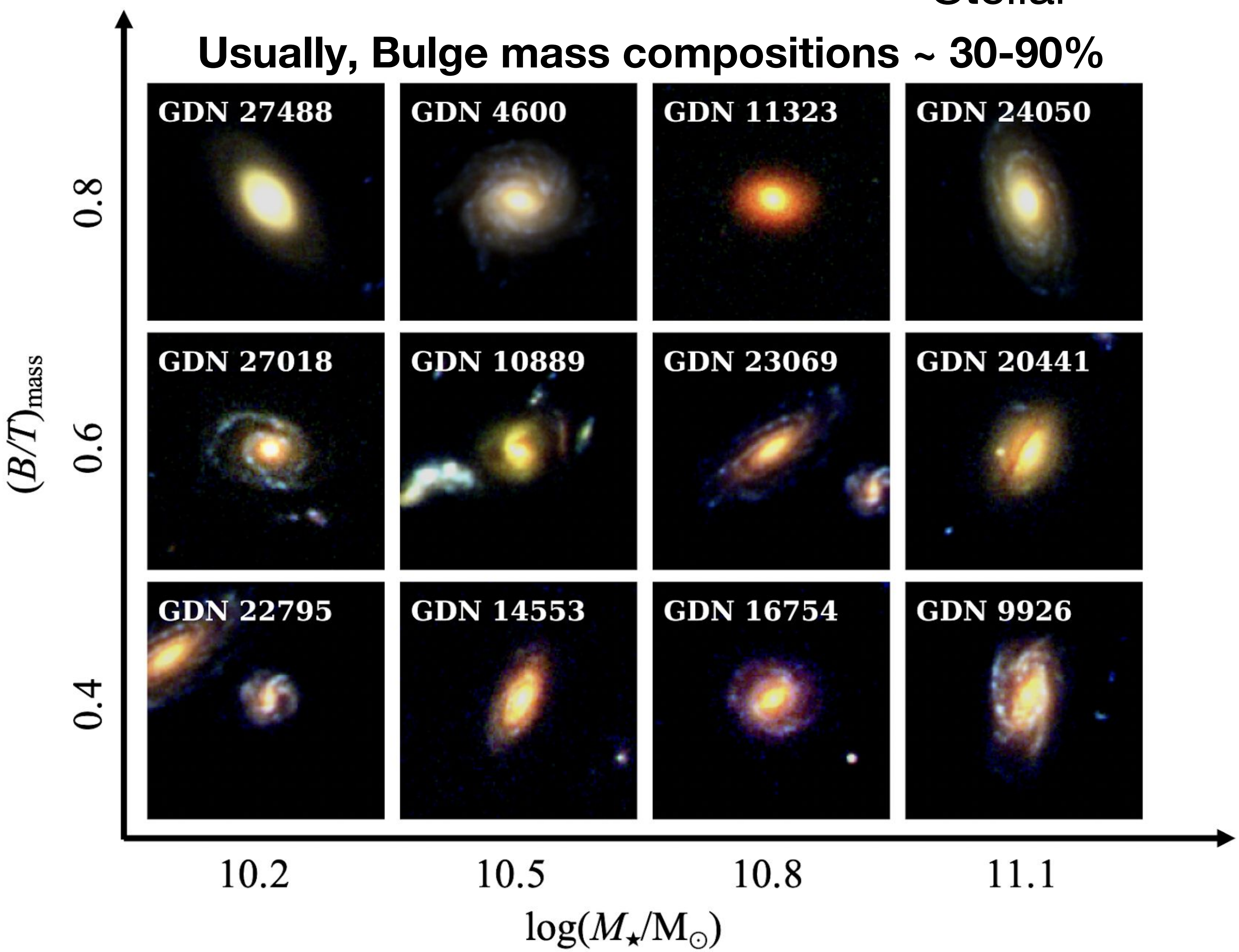
arXiv:1806.03306 [astro-ph.GA]

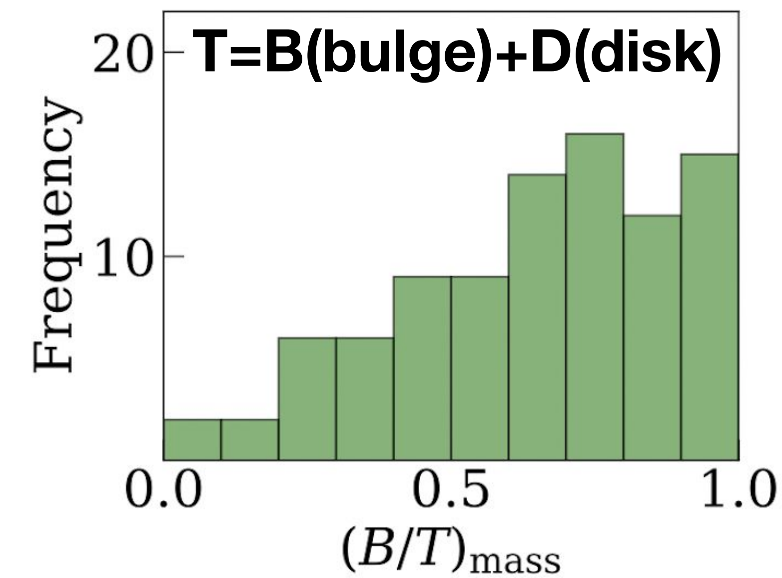
Estimation of BDM flux

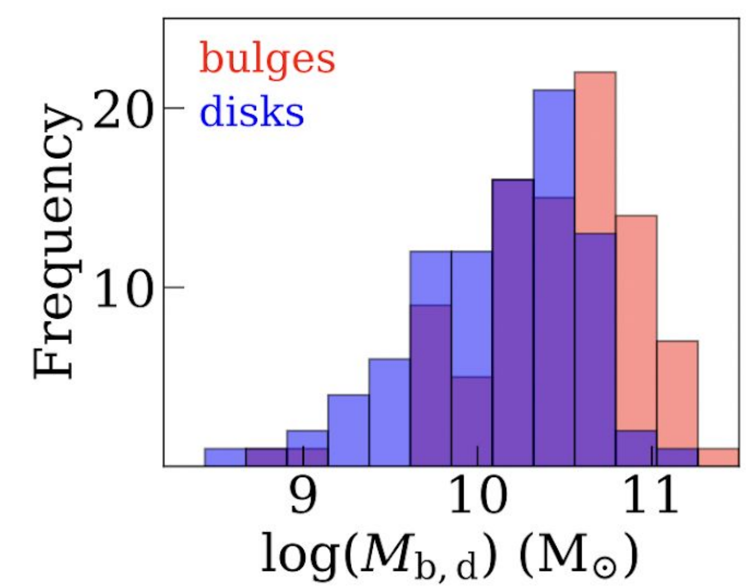
Most typical (spiral) galaxy = (Sersic Bulge + Exponential Disk + Spherical Halo)

Stellar DM

Usually, Bulge mass compositions ~ 30-90%







Based on HST survey data in 0.14 < z < 1.0

arXiv:2202.02332 [astro-ph.GA]

Estimation of BDM flux

- Extragalactic BDM flux

$$\frac{d\Phi_\chi^{\text{EG-I}}}{dK_\chi} = \int dM_{\text{Gal}} \int dr \left[\frac{dK'_\chi(z)}{dK_\chi}\frac{d\Phi_\chi^{\text{Gal}}(M_{\text{Gal}})}{dK'_\chi}\right]\left[\frac{d^2 n_{\text{Gal}}(z, M_{\text{Gal}})}{dM_{\text{Gal}}\, dz}\right] \cdot 4\pi[r(z)]^2 \cdot \left(\frac{r_{\text{Gal}}(M_{\text{Gal}})}{r(z)}\right)^2$$

$$= \int dM_{\text{Gal}} \int dz \, \frac{dr}{dz} \left[\frac{dK'_\chi(z)}{dK_\chi}\frac{d\Phi_\chi^{\text{Gal}}(M_{\text{Gal}})}{dK'_\chi}\right]\left[\frac{d^2 n_{\text{Gal}}(z, M_{\text{Gal}})}{dM_{\text{Gal}}\, dz}\right] \cdot 4\pi[r_{\text{Gal}}(M_{\text{Gal}})]^2$$

$$= \int_0^{z_{\max}} dz \int_{M_{\text{Gal}}^{\min}}^{M_{\text{Gal}}^{\max}} dM_{\text{Gal}} \left[\frac{dK'_\chi(z)}{dK_\chi}\frac{d\Phi_\chi^{\text{Gal}}(M_{\text{Gal}})}{dK'_\chi}\right]\left[\frac{d^2 n_{\text{Gal}}(z, M_{\text{Gal}})}{dM_{\text{Gal}}\, dz}\right] \frac{4\pi[r_{\text{Gal}}(M_{\text{Gal}})]^2}{H_0(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

- BDM flux contribution from each individual galaxies

$$\frac{d\Phi_\chi^{\text{Gal}}(M_{\text{Gal}})}{dK'_\chi} = \frac{\mathcal{J}_2(M_{\text{Gal}})}{m_\chi} \int dK_\nu \frac{d\Phi_\nu^{\text{Solar}}}{dK_\nu}\frac{d\sigma_{\nu\chi}}{dK'_\chi}$$

Estimation of BDM flux

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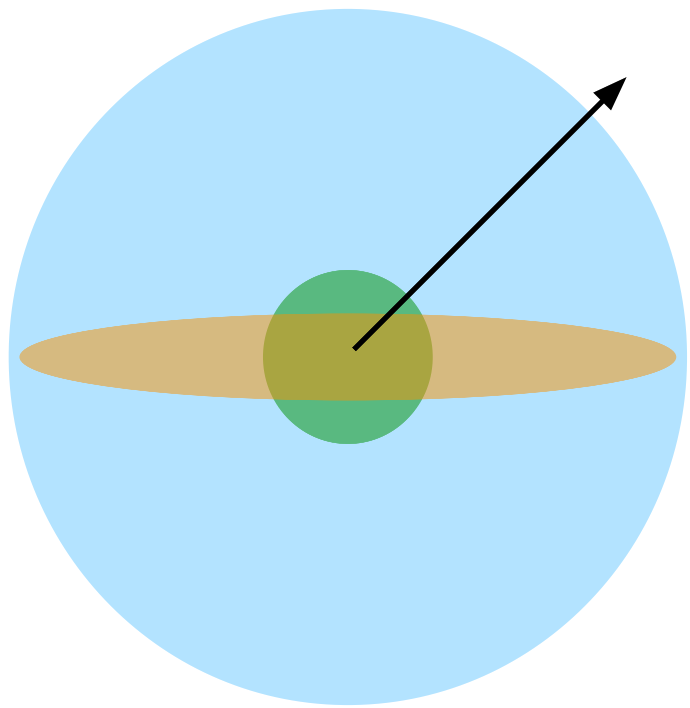
- “Outward” Line-of-sight integral (approximated to isotropic limit)

$$\mathcal{J}_2(M_{\text{Gal}}) \equiv \mathcal{J}_2^{(\text{bulge})}(M_{\text{Gal}}) + \mathcal{J}_2^{(\text{disc})}(M_{\text{Gal}}),$$

$$\mathcal{J}_2^{(\text{bulge})}(M_{\text{Gal}}) \sim \int_{r_{\chi,\min}}^{\infty} dr_\chi \int_0^{r_\chi} dr_s\; 2\pi r_s^2 \int_0^{\pi} d\theta_s\; \sin\theta_s \times\left[n_{\text{bulge}}(M_{\text{Gal}}, r_s)\times\rho_{\text{halo}}(M_{\text{Halo}}(M_{\text{Gal}}), r_\chi)\times\left(\frac{1\text{AU}}{L_{\chi s}^{(\text{bulge})}}\right)^2\right],$$

$$\mathcal{J}_2^{(\text{disc})}(M_{\text{Gal}}) \sim \int_{r_{\chi,\min}}^{\infty} dr_\chi \int_0^{r_\chi} dr_s\; 2\pi r_s \int_0^{\infty} 2\; dz_s \times\left[n_{\text{disc}}(M_{\text{Gal}}, r_s, z_s)\times\rho_{\text{halo}}(M_{\text{Halo}}(M_{\text{Gal}}), r_\chi)\times\left(\frac{1\text{AU}}{L_{\chi s}^{(disc)}}\right)^2\right].$$

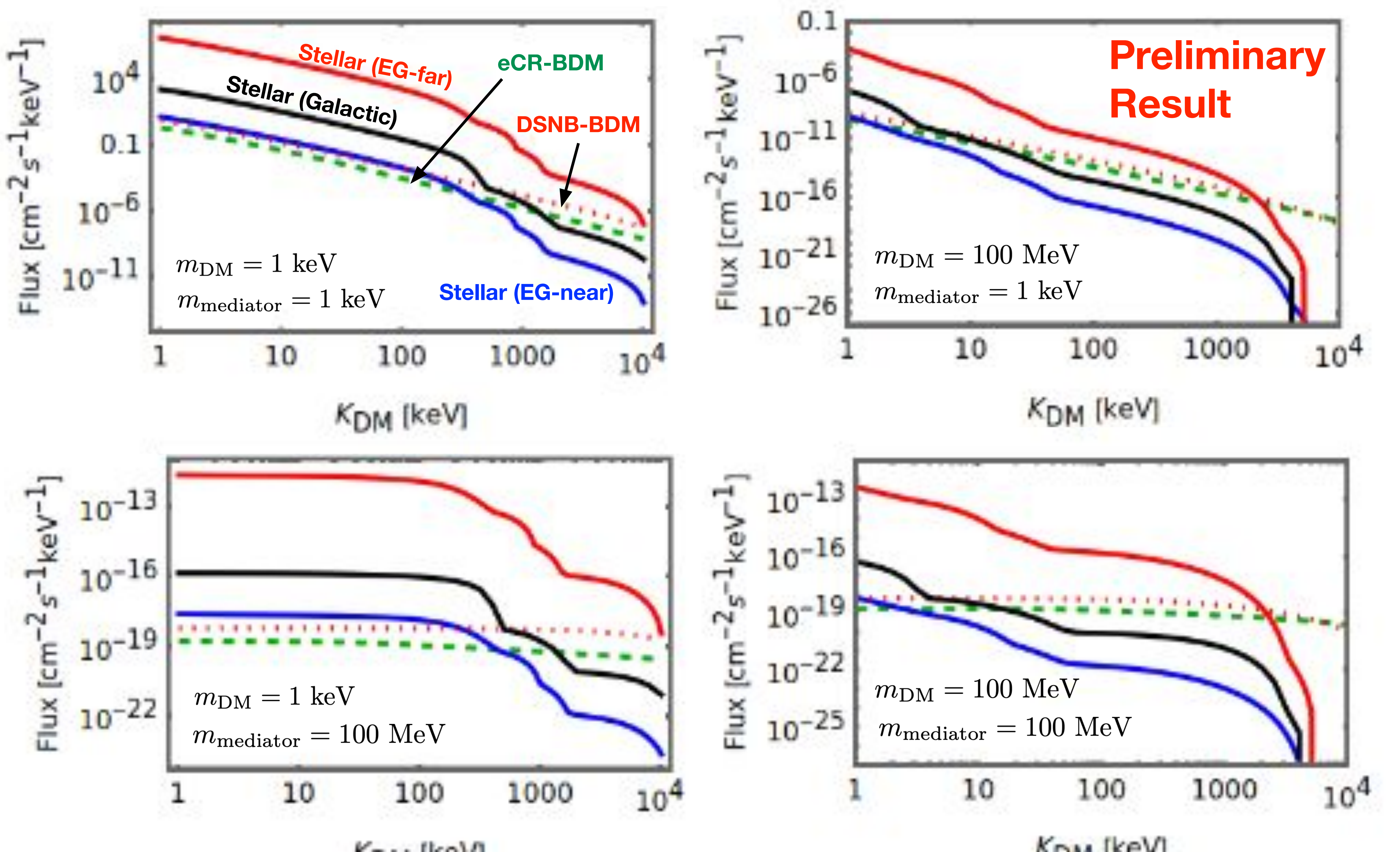


Extragalactic contribution of nu-BDM

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

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

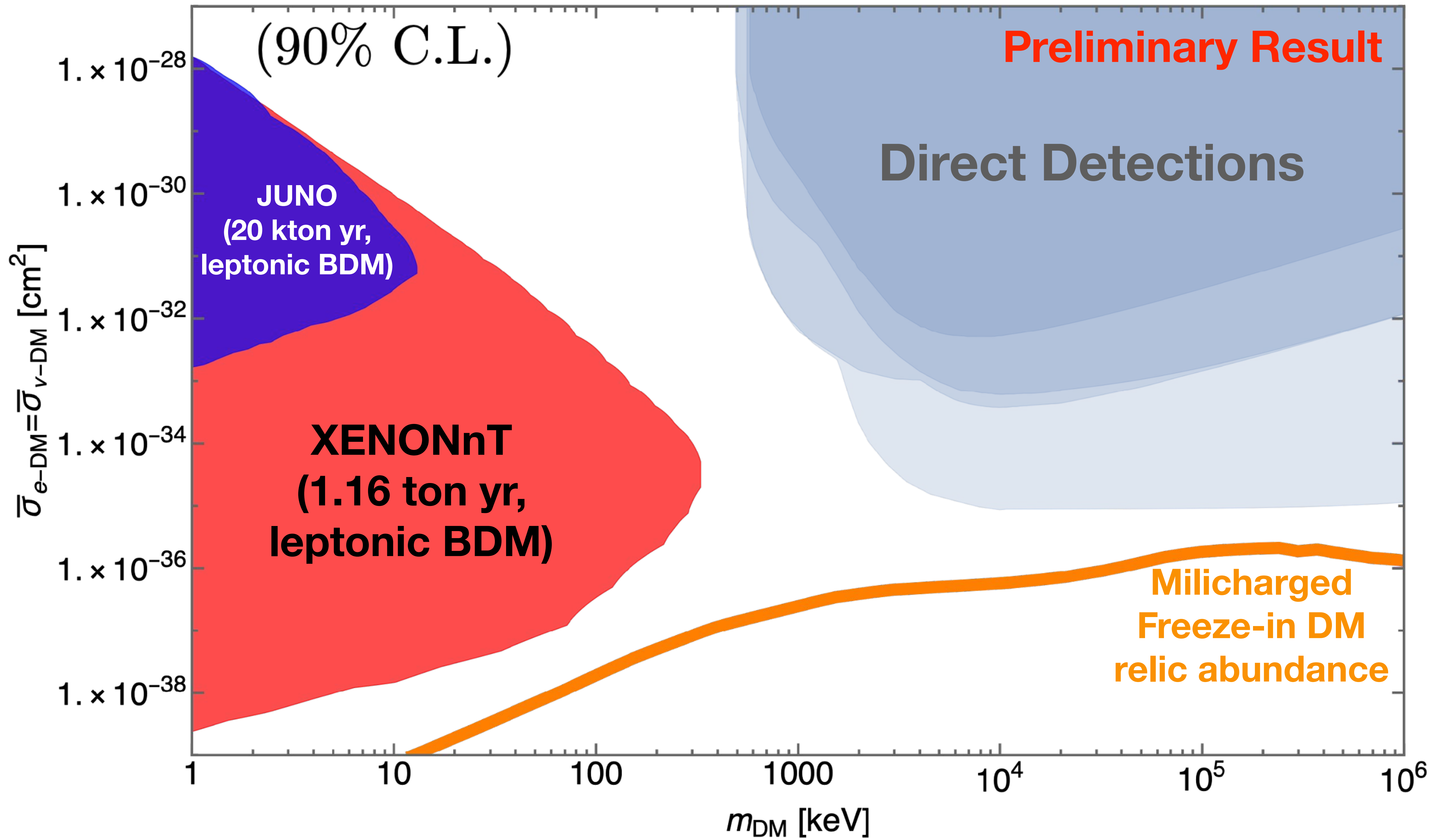
YJ, J.-C. Park, S.-C. Park, P.-Y. Tseng,
(work in preparation)



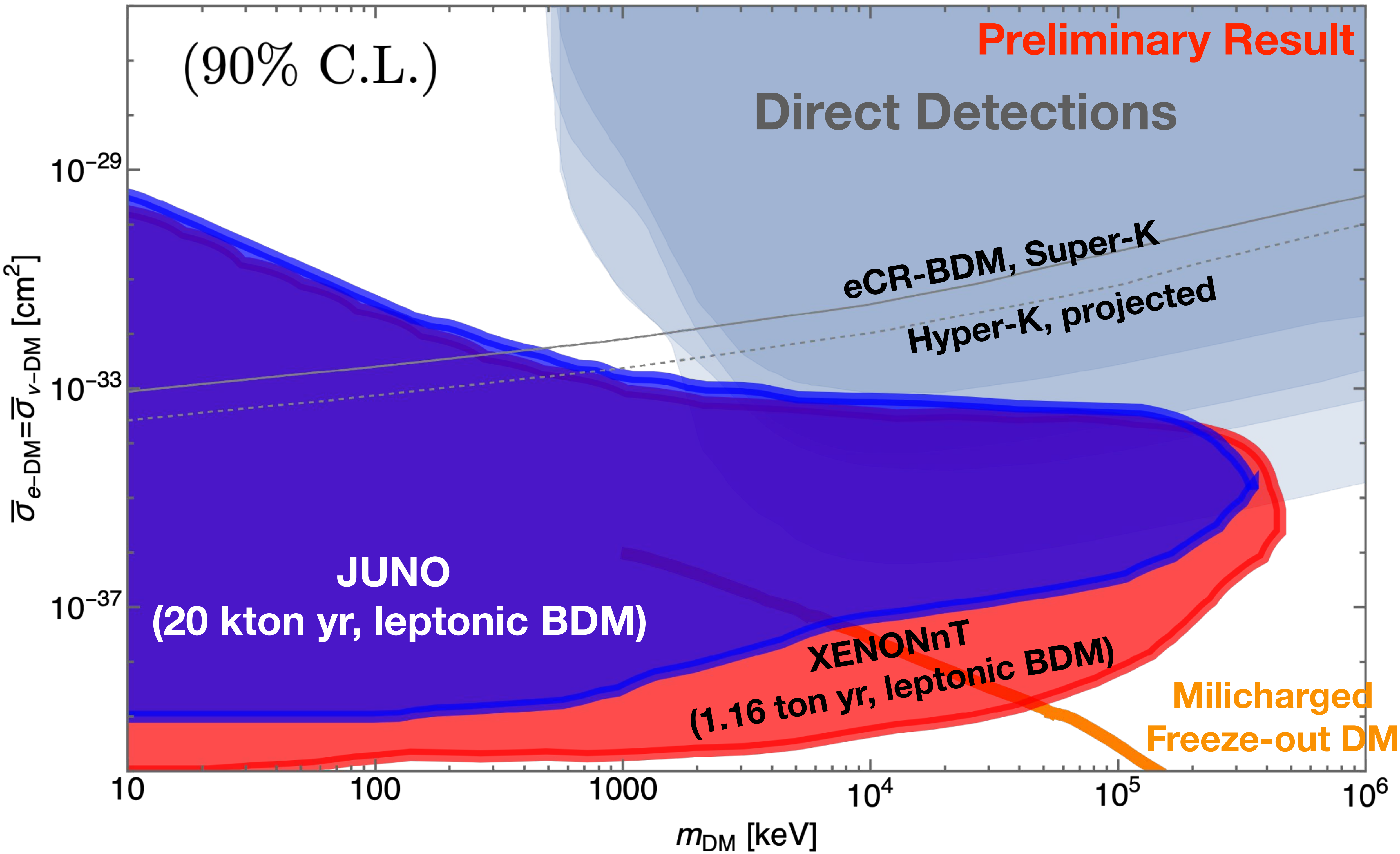
Q1: Can Cosmic "Neutrinos" boost light Dark Matter in the halo?

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

Sensitivity limits on DM/neutrino experiments



Sensitivity limits on DM/neutrino experiments



Conclusion

- A new mechanism to boost light DM by neutrinos emitted from stars in our/distant galaxies is proposed. Extragalactic contributions are especially important as we can treat each massive galaxies as a gigantic source of boosted dark matter.

- Future neutrino exp (JUNO) and Direct detection (XENON/LUX) will have excellent sensitivity to probe neutrino-DM interactions in near future.

Thank you for your attention

Backup slides

Boosted DM flux

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

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

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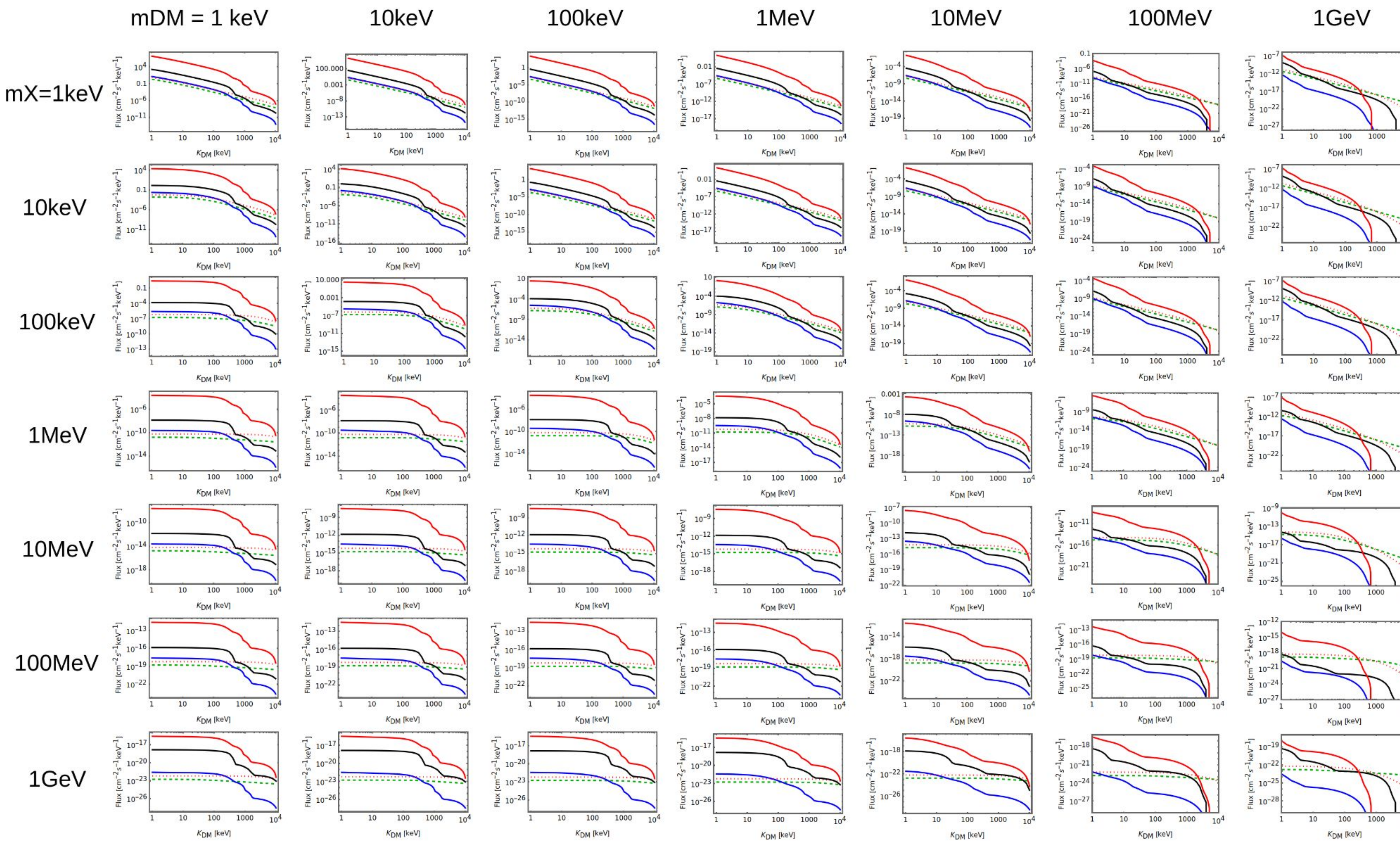
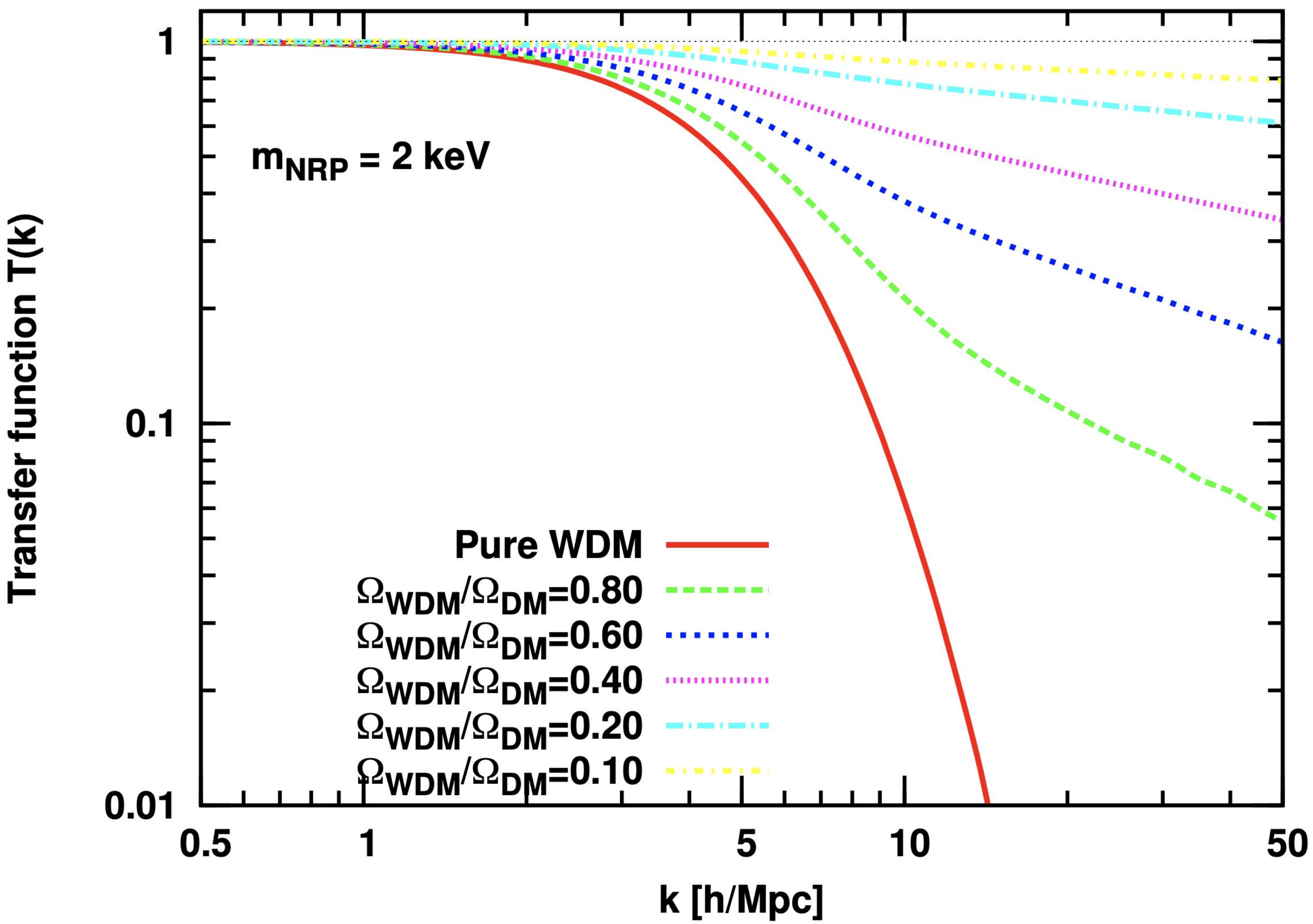


Ly-alpha constraints on neutrino-DM interactions

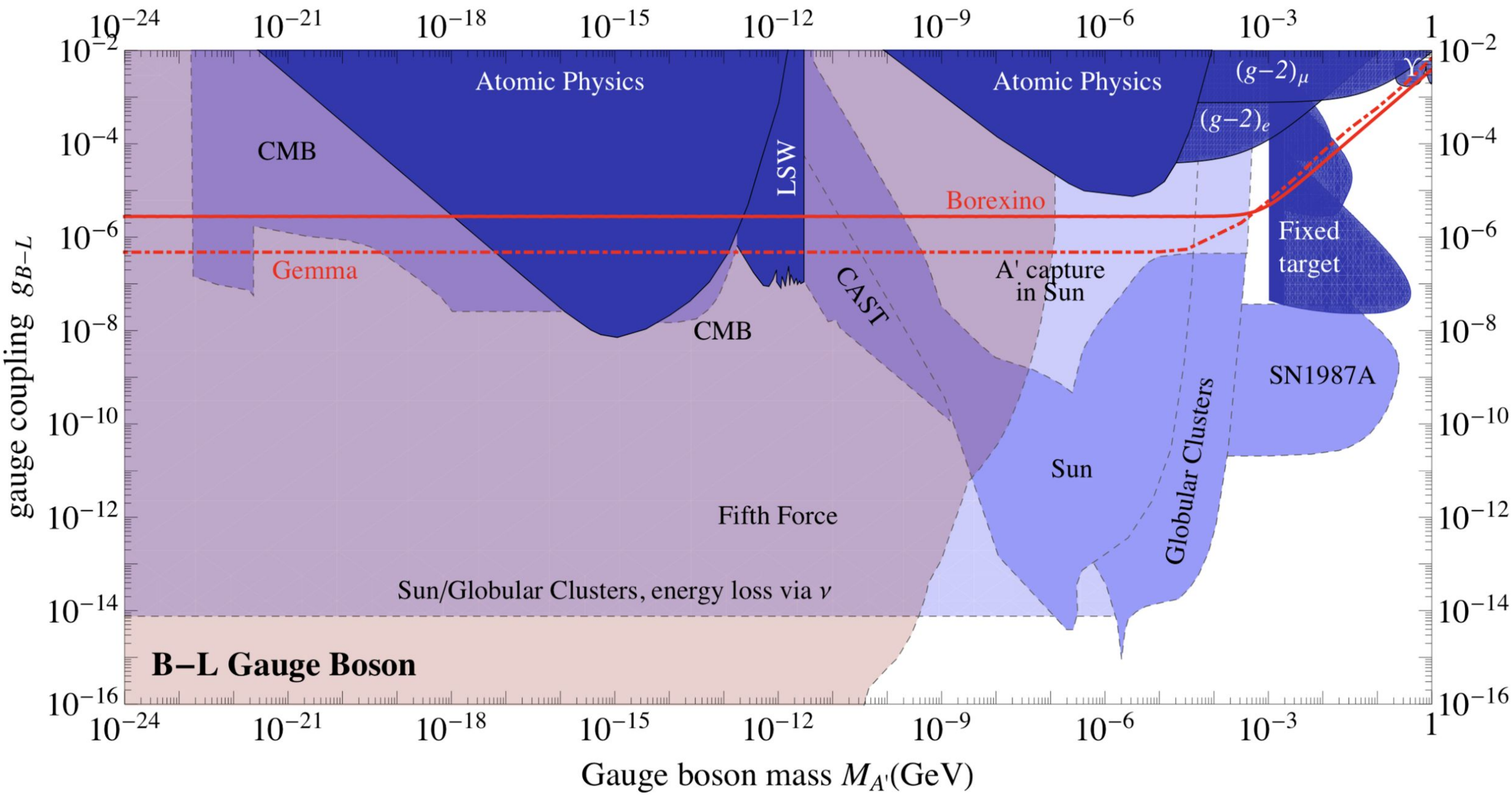


[0812.0010] [hep-ph]

- >~10% fraction of light DM component can be constrained by Ly-alpha.

Constraints on light mediator

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



Constraints on light mediator

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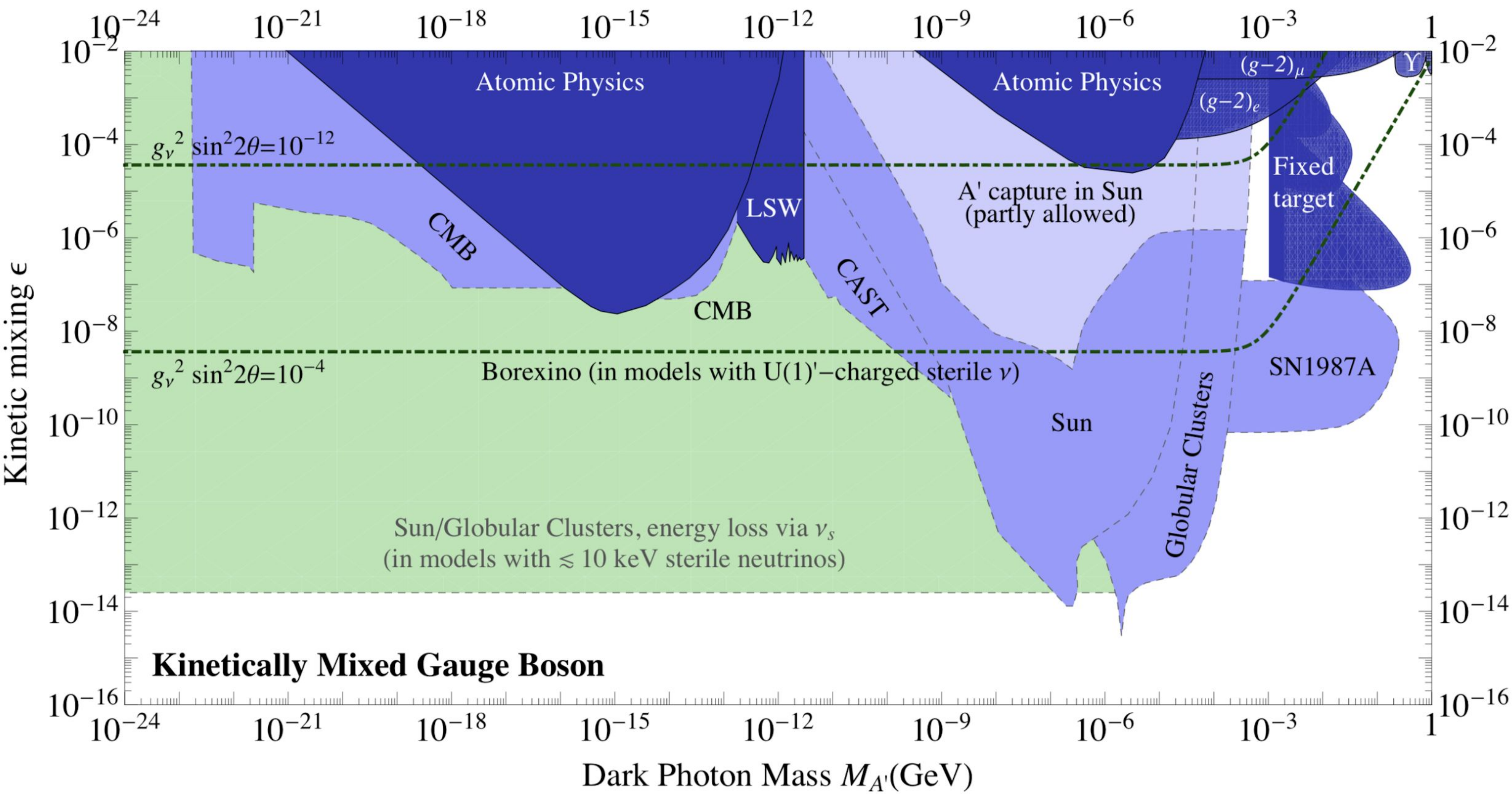

End of Slides