BOOSTING DARK MATTER WITH RELIC SUPERNOVA NEUTRINOS

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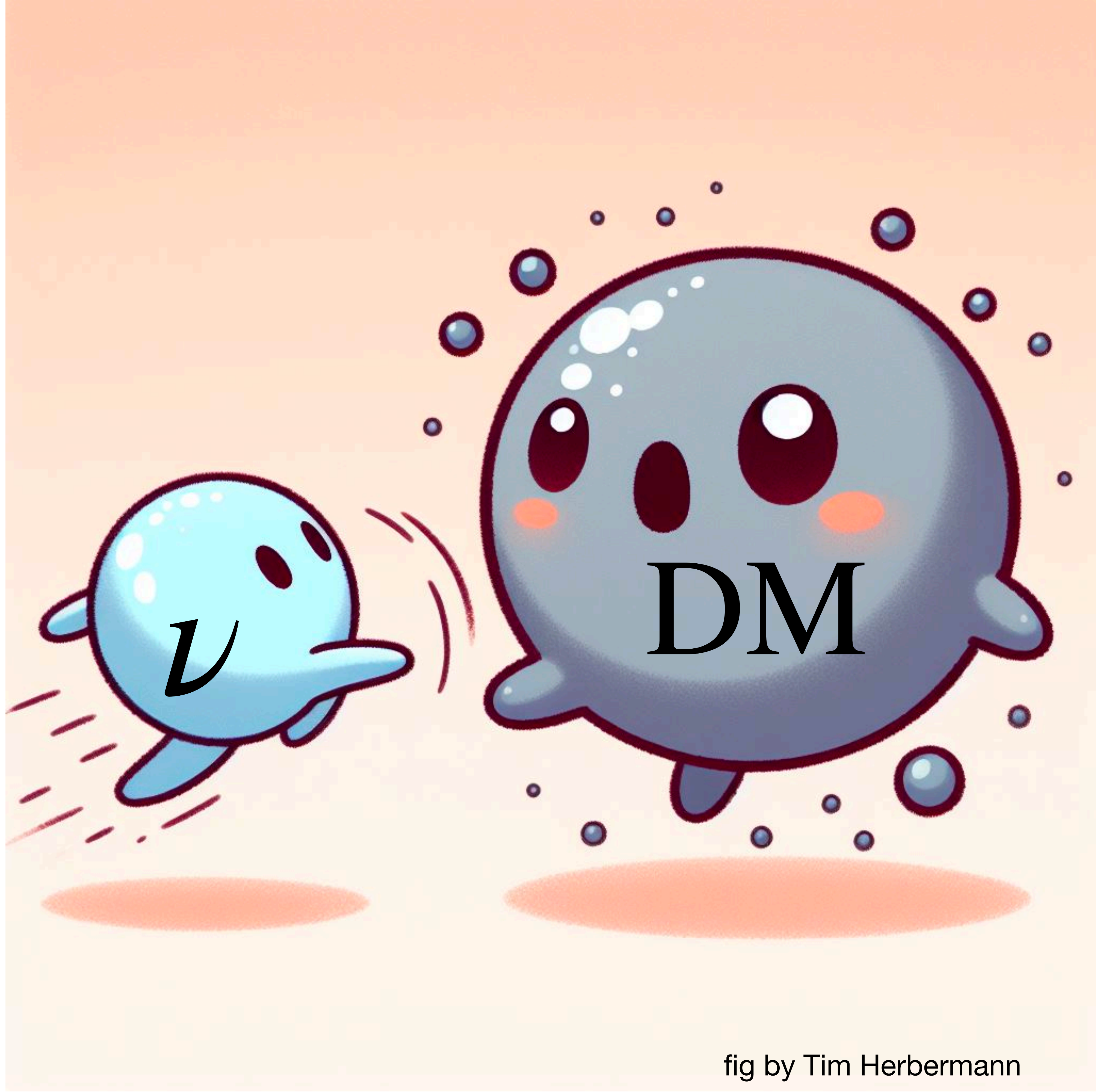
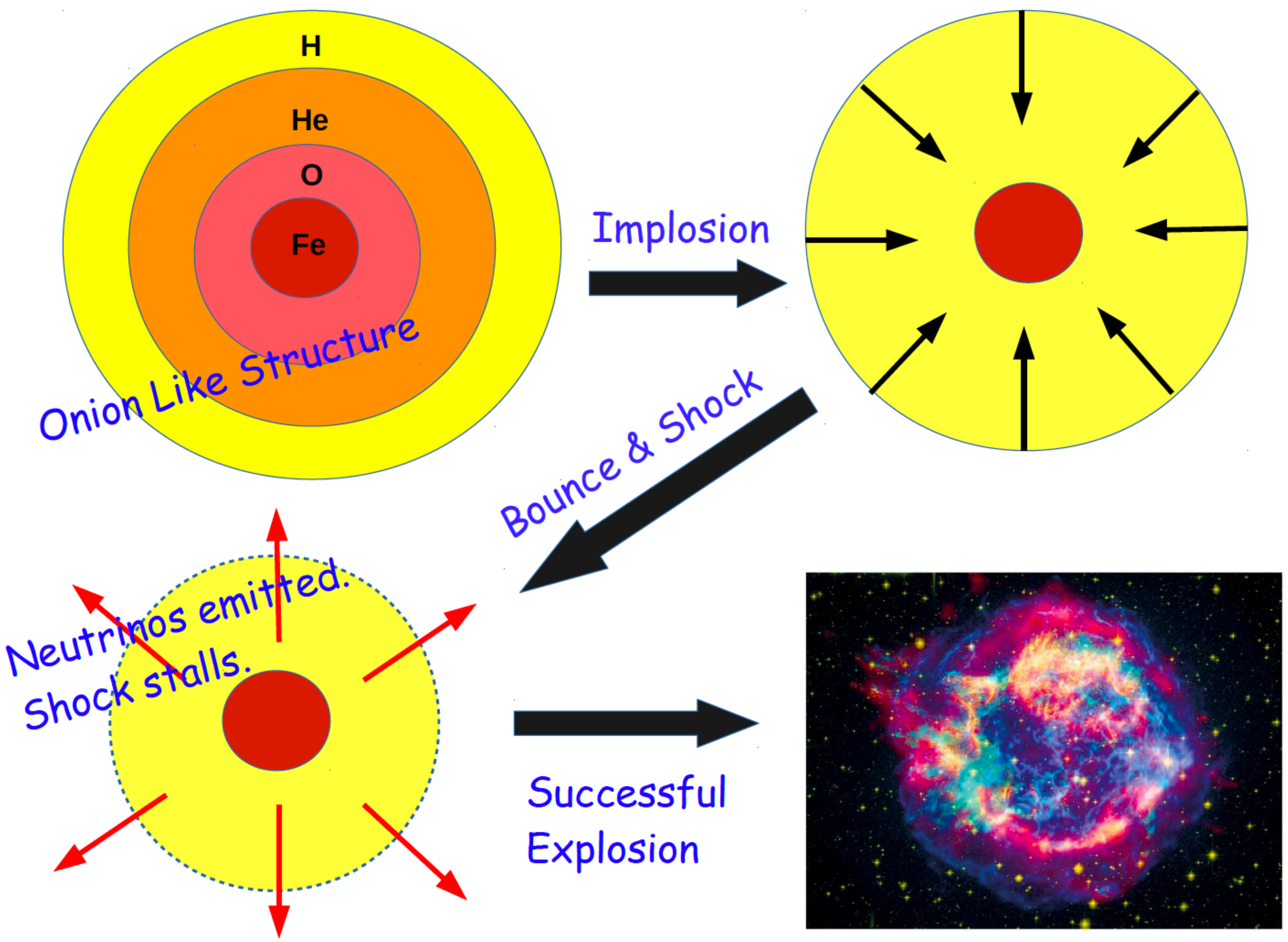


fig by Tim Herbermann

Core-collapse SNe: Mechanism



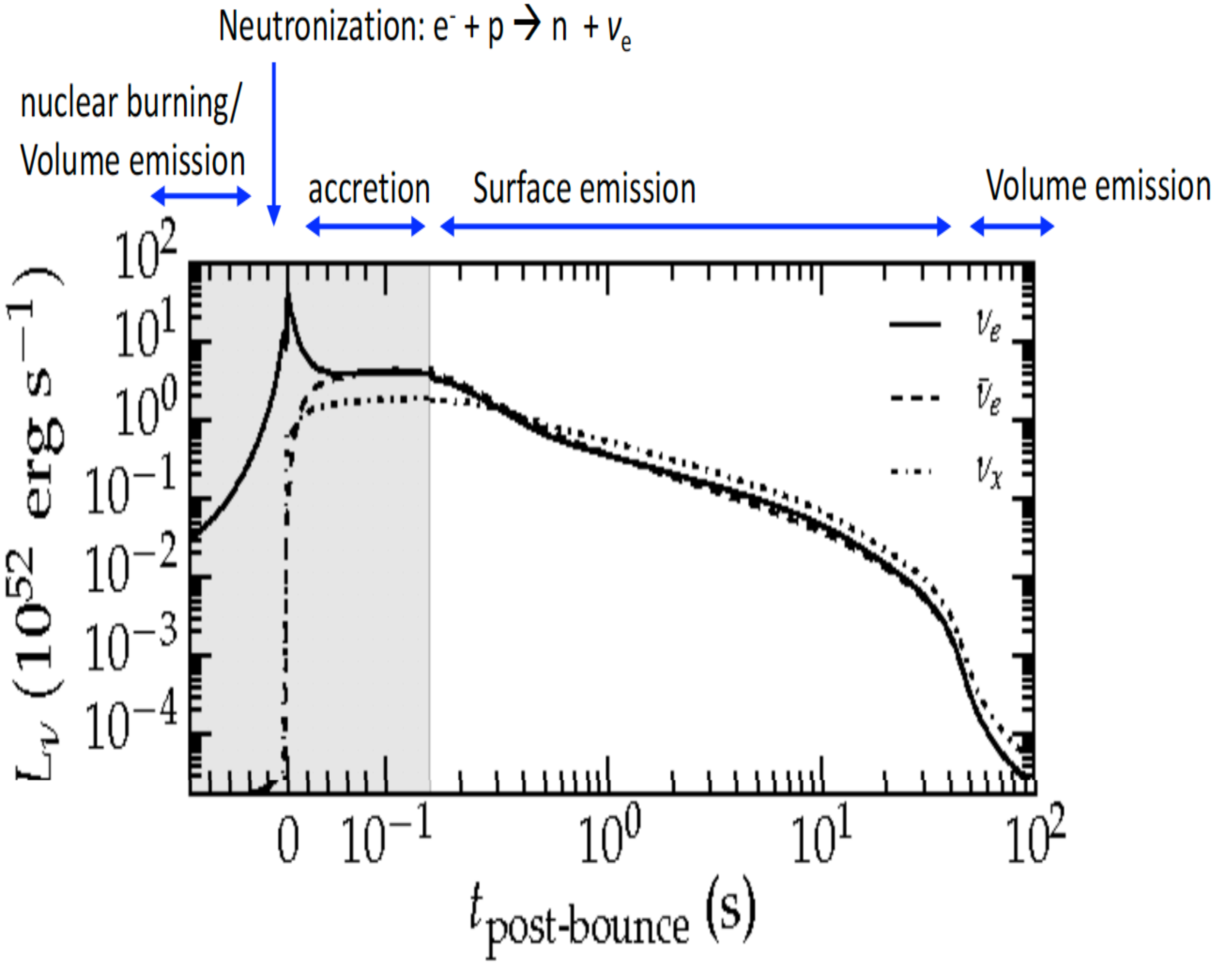


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

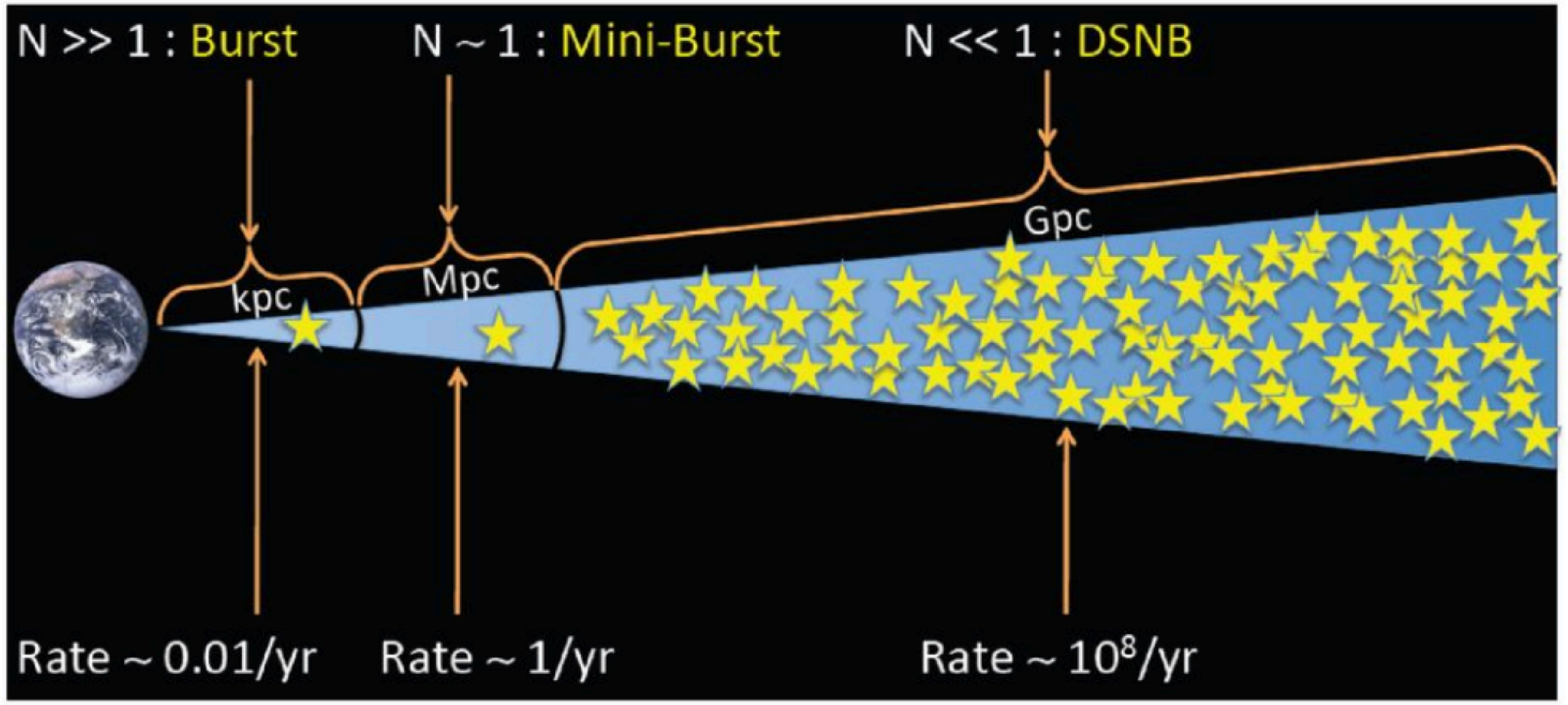
- Core-collapse SNe leading to MeV neutrino emission.

- Almost entire energy of the SN emitted in neutrinos. $\sim 10^{58}$ neutrinos in 10 seconds.

The Diffuse Supernova Neutrino Background

- A galactic SN is very rare. So, should we wait a lifetime?
- We can be more inclusive, and look to the distant Universe for more SNe.
- Not that rare. On an average, there is 1 SN going off per second. The neutrino emission produces the DSNB.
- Detectable neutrino flux, mostly from stars upto redshift z~1, but extends upto z~6.
- Opens up a new frontier in neutrino astronomy.

John Beacom, TAUP2011



DSNB=Diffuse Supernova Neutrino Background

How to estimate the DSNB?

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)}\, R_{\mathrm{CCSN}}(z)\, F_\nu\big(E(1+z)\big)$$

Beacom, Ann.Rev.Nucl.Part.Sci. 2010
Lunardini, Astropart. Phys 2016

SN Neutrino spectra

$$F_{\nu_\beta}(E_\nu) = \frac{1}{E_{0\beta}}\,\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{E_{0\beta}}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{E_{0\beta}}}$$

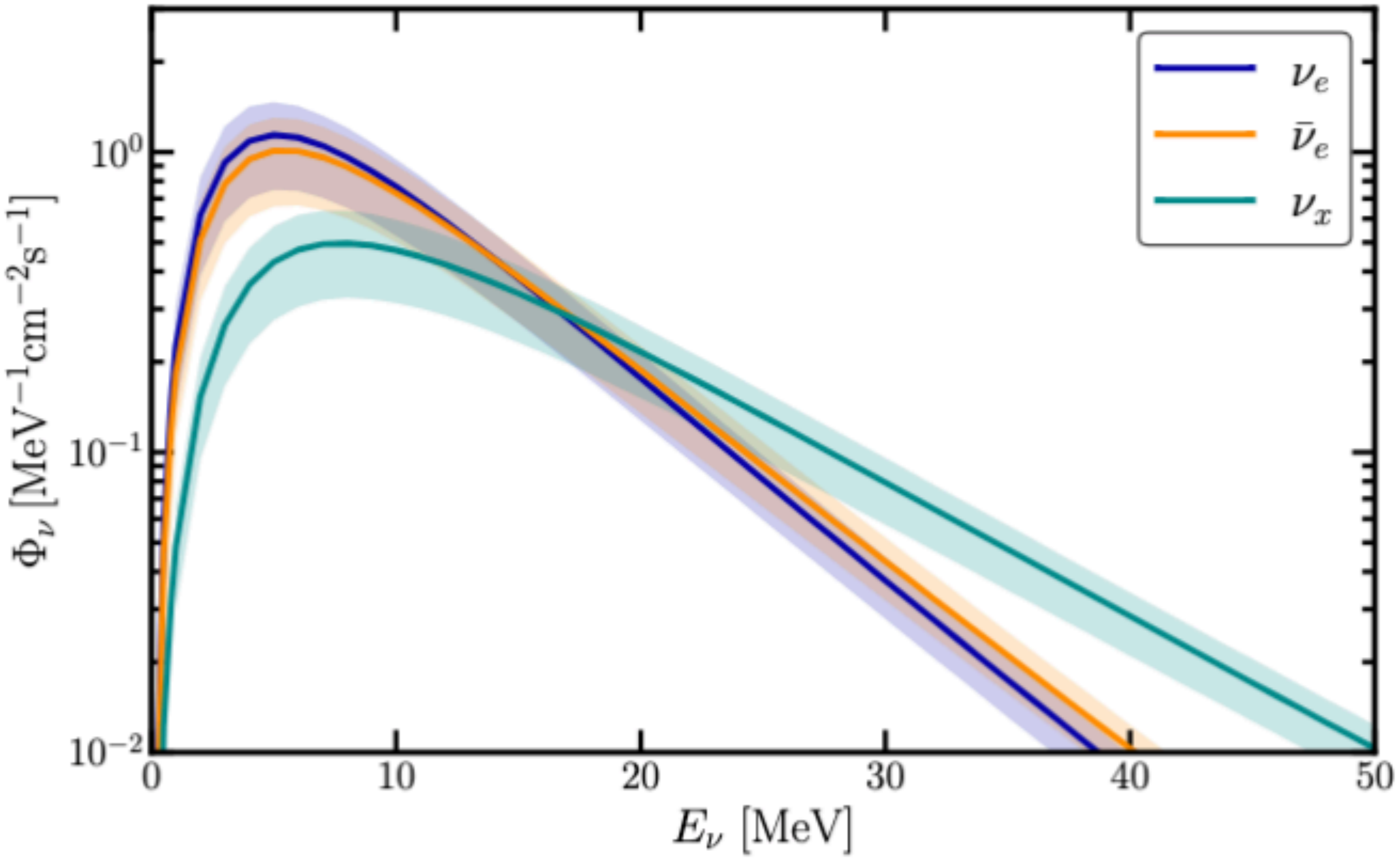
Cosmological SN rate

$$R_{\mathrm{CCSN}}(z) = \dot{\rho}_{\mathrm{SFR}}(z)\,\frac{\int_8^{50} \psi_{\mathrm{IMF}}(M)\, dM}{\int_{0.1}^{100} M\psi_{\mathrm{IMF}}(M)\, dM}\,.$$

Cosmology

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$$

Putting all ingredients together



- The DSNB - isotropic flux of neutrinos of all flavour.
- Uncertainties from lack of knowledge of star-formation rate.
- Universe filled with MeV energy neutrinos.

A. Das, T. Herbermann, **MS**, V. Takhistov (arXiv: 2403.15367)
A. Das, **MS,** (PRD 2021)

The Basic Idea

- Neutrino-Dark Matter interactions can allow neutrinos to scatter off DM.
- Upscatter a fraction of cold DM to neutrino-like energies.
- Can leave observable signature in DM direct detection experiments.

A. Das, T. Herbermann, **MS**, V. Takhistov (arXiv: 2403.15367)
A. Das, **MS**, (PRD 2021)

How to estimate Boosted Dark Matter flux?

- The flux of boosted DM at the Earth is given by

$$\frac{d\Phi_\chi}{dT_\chi} = \underbrace{\int \frac{d\Omega}{4\pi} \int dl \, \frac{\rho_\chi(l)}{m_\chi}}_{D_{\rm halo}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} dE_\nu \, \underset{\substack{\Big\downarrow \\ \textbf{DSNB}}}{\frac{d\Phi_\nu}{dE_\nu}} \, \underset{\substack{\Big\downarrow \\ \textbf{DM-}\nu\ \textbf{cross-section}}}{\frac{d\sigma_{\nu\chi}}{dT_\chi}}$$

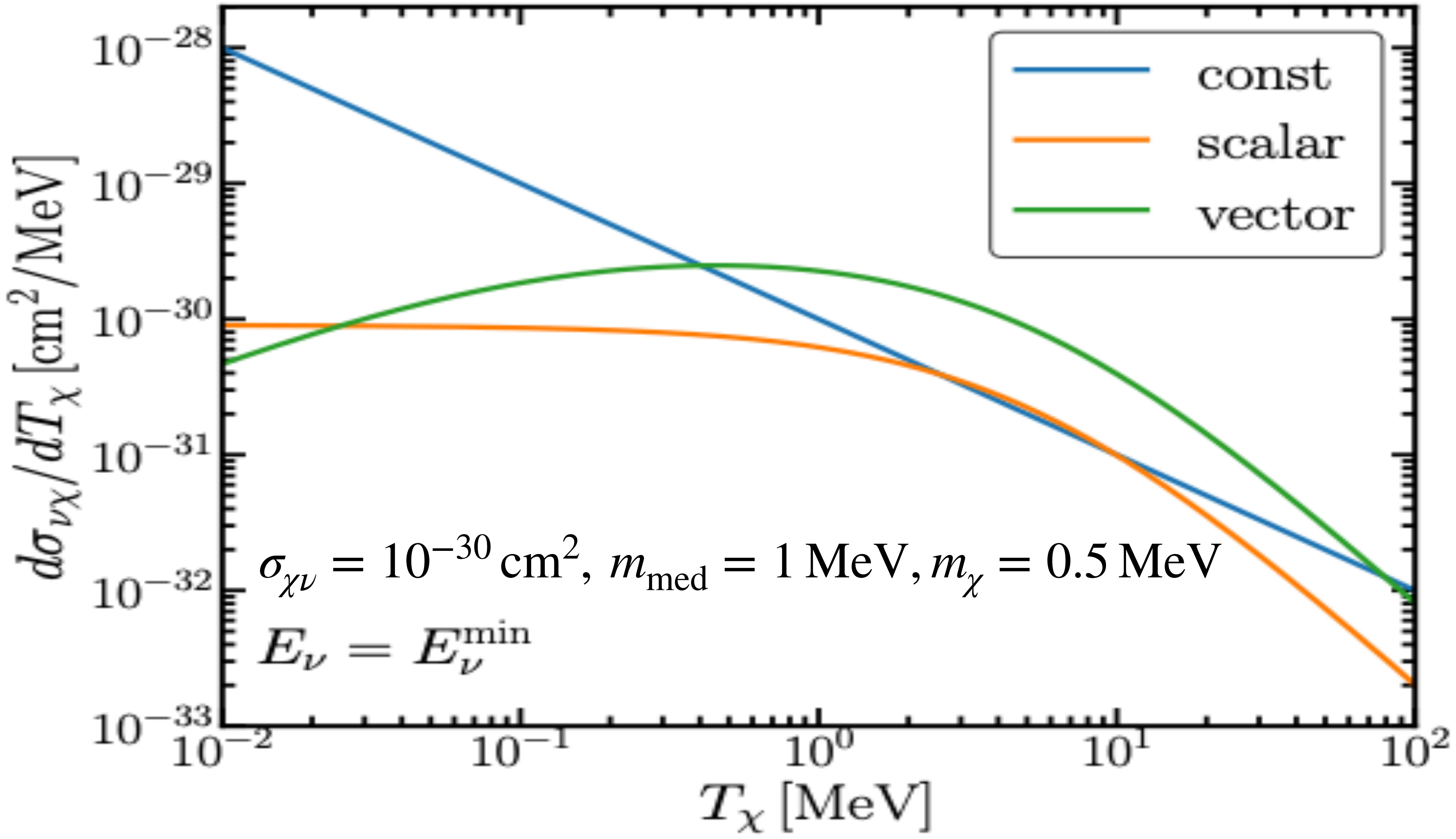
- Previous works on cosmic ray - boosted dark matter assumed $\frac{d\sigma_{\nu\chi}}{dT_\chi} = \frac{\sigma}{T_\chi^{\rm max}}$.

- Parametric assumption. Is it correct?

Inaccuracy of a constant cross-section assumption

- The assumption $\frac{d\sigma_{\nu\chi}}{dT_\chi} = \frac{\sigma}{T_\chi^{\max}}$ can lead to erroneous results.

- Consider two examples:
  1. Scalar mediated interaction: $\mathscr{L} \supset g\,\bar{L}\,\Phi\,\chi_{\rm DM}$
  2. Vector mediated interaction: $\mathscr{L} \supset (g\,\bar{L}\gamma_\mu L + g_\chi\,\bar{\chi}\gamma_\mu\chi)\,Z'^\mu$



Max. kinetic energy for a given neutrino energy

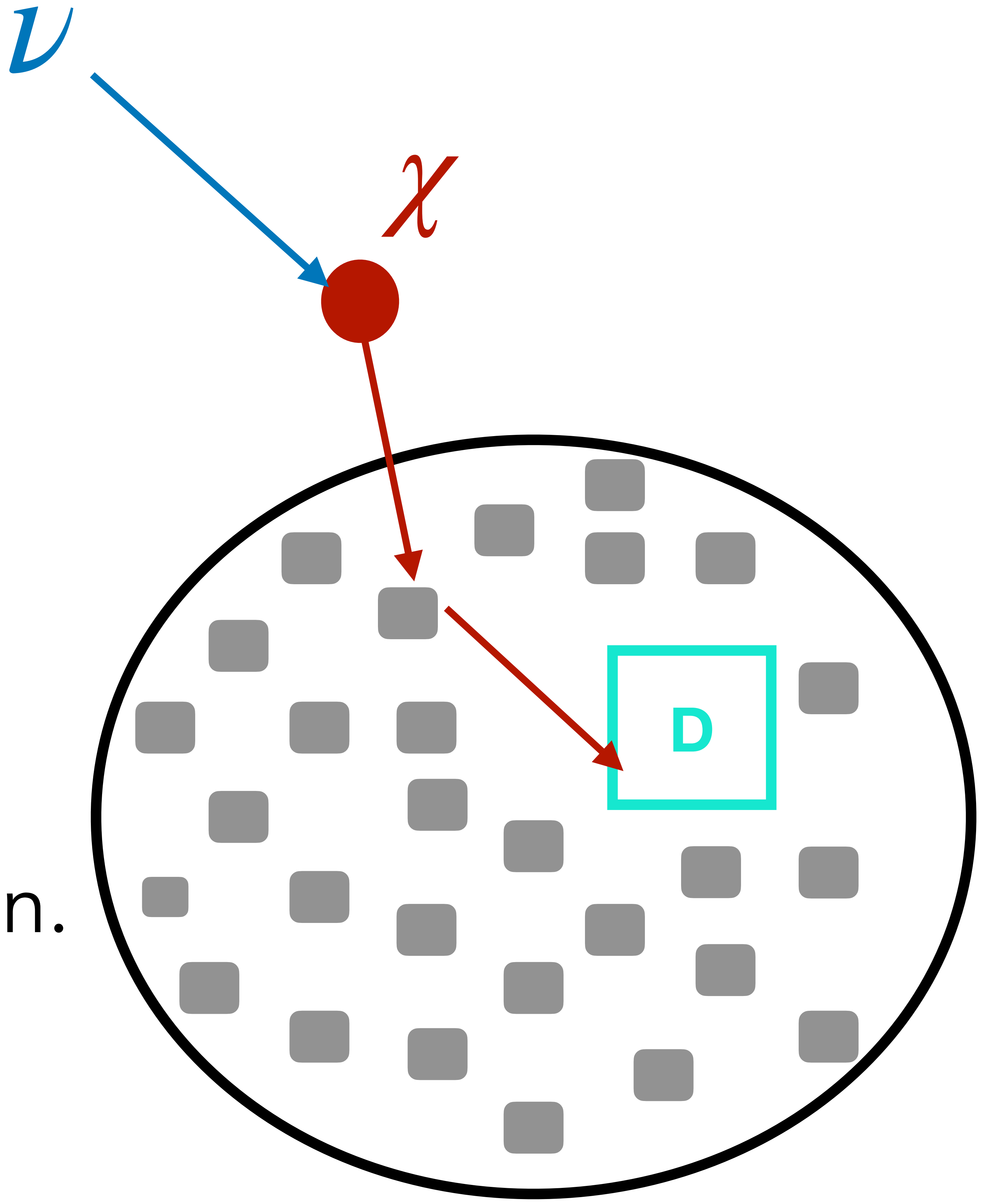
$$T_\chi^{\max} = \frac{E_\nu^2}{E_\nu + m_\chi/2}$$

Attentuation effect

- Attenuation due to interaction with particles in the Earth and atmosphere.

- Mean energy loss of a single DM particle due to scattering with particle i

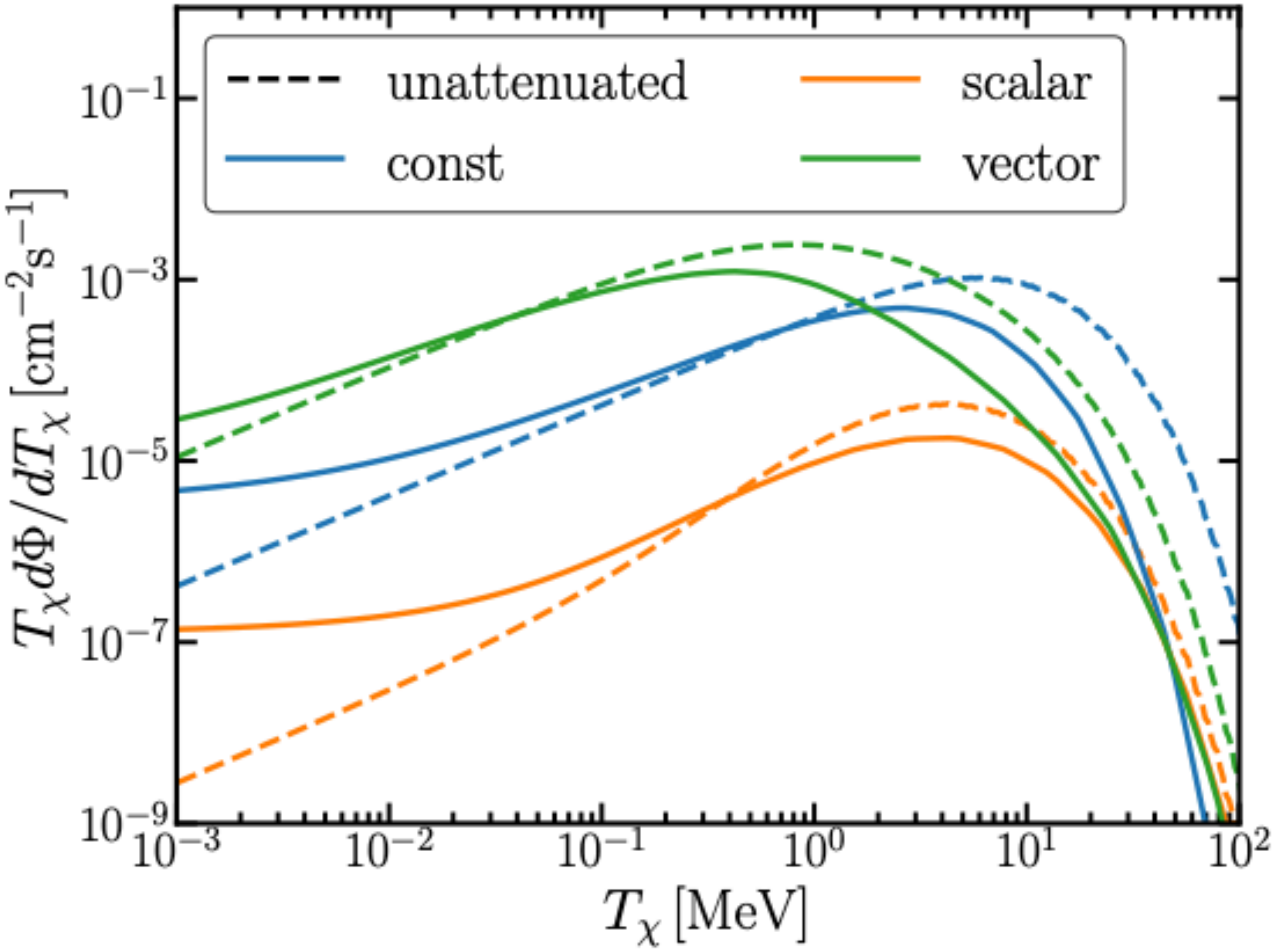
$$\frac{dT_\chi}{dx}(x) = -\sum_i n_i(x) \int_0^{T_i^{\max}} dT_i\, T_i \frac{d\sigma_{i\chi}}{dT_i}\,.$$



- Analytical solution under constant cross-section assumption. Can give inaccurate results!

- We perform a fully numerical computation of the attenuation.

The boosted DM flux

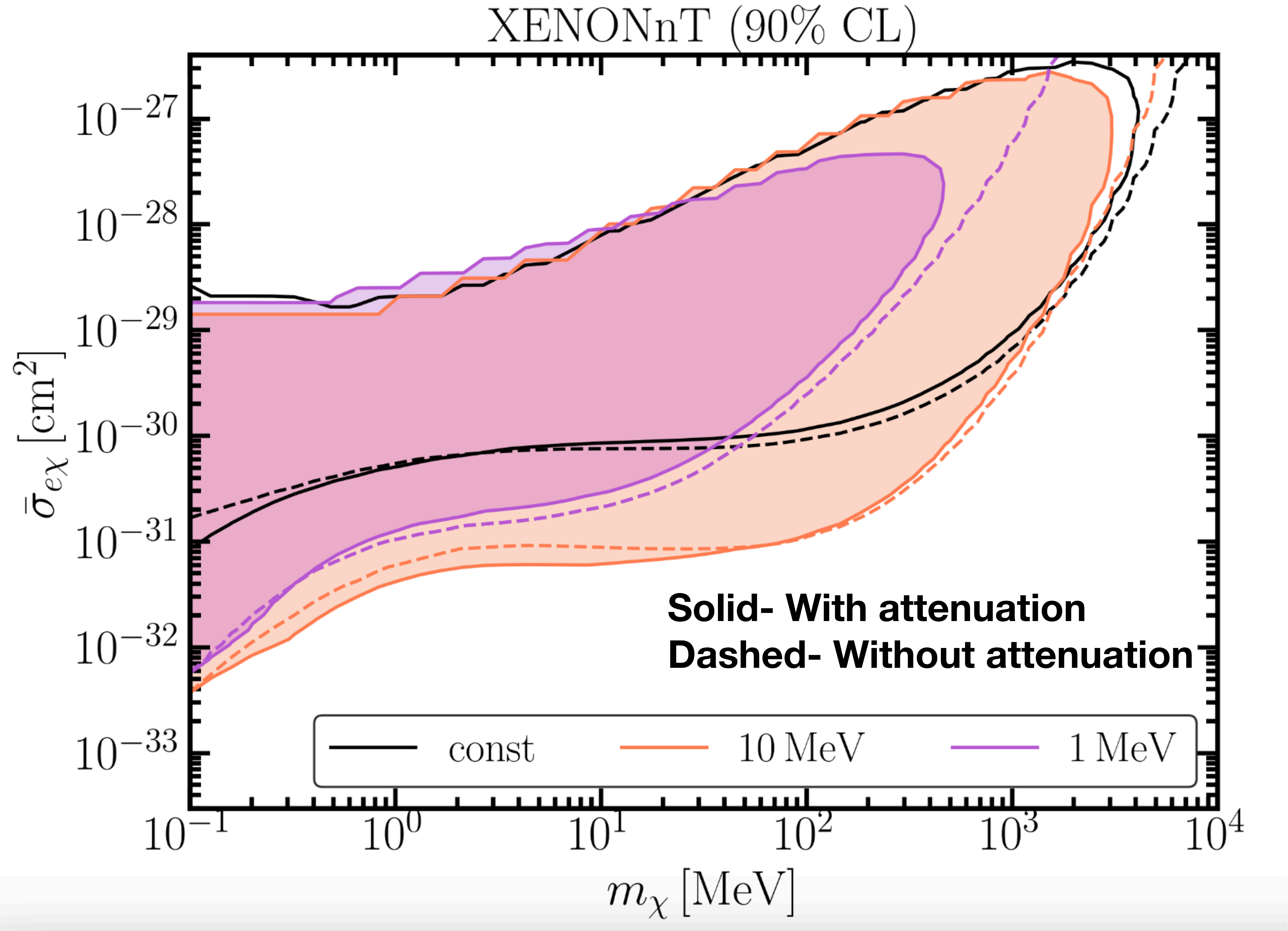


- Significant difference with results from constant case with same effective cross-section!!

- Attenuation:
  - (i) Suppression
  - (ii) Down scattering of high energy BDM.

A. Das, T. Herbermann, **MS**, V. Takhistov (arXiv: 2403.15367)

How does this affect signals in DD experiments?



Solid- With attenuation
Dashed- Without attenuation

- Consider the example of vector mediator and XENONnT.
- Here

$$\bar{\sigma}_{e\chi} = \frac{g^4}{\pi} \frac{\mu_{e\chi}^2}{(q_{\text{ref}}^2 + m_{\text{med}}^2)^2}$$

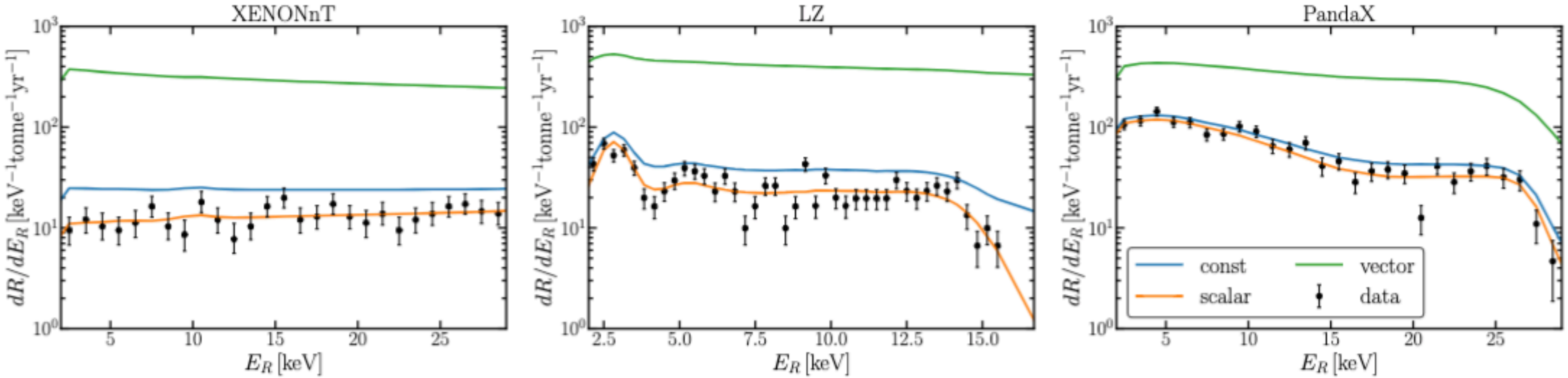
- Attenuation:
  (i) Upper ceiling constraint.

  (ii) Down scattering - stronger constraints at lower m_χ.
- Strong differences with constant cross-section assumption.

A. Das, T. Herbermann, **MS**, V. Takhistov (arXiv: 2403.15367)

Signals in different experiments

- Differential electron scattering rate $\frac{dR}{dT_e} = N_e \int dT_\chi \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{e\chi}}{dT_e}$



$$\bar{\sigma}_{e\chi} = 10^{-30}\,\mathrm{cm}^2,\ m_\chi = 0.5\,\mathrm{MeV},\ \ m_{\mathrm{med}} = 1\,\mathrm{MeV}$$

A. Das, T. Herbermann, **MS**, V. Takhistov (arXiv: 2403.15367)

Constraints on parameter space

- Constraints from Xenon and LZ are similar.
- PandaX has weaker constraints due to location at larger depth.
- Highlights the necessity of energy-dependent cross-section as well as attenuation effects.

Conclusions

- The DSNB- an isotropic, ever-present flux of supernova neutrinos. Opens up a plethora of avenues for multi-messenger astroparticle physics, next giant leap from the Sun and SN1987A.

- Neutrino-dark matter interactions allow the DSNB to boost DM to MeV energies. Can have observational sigantures.

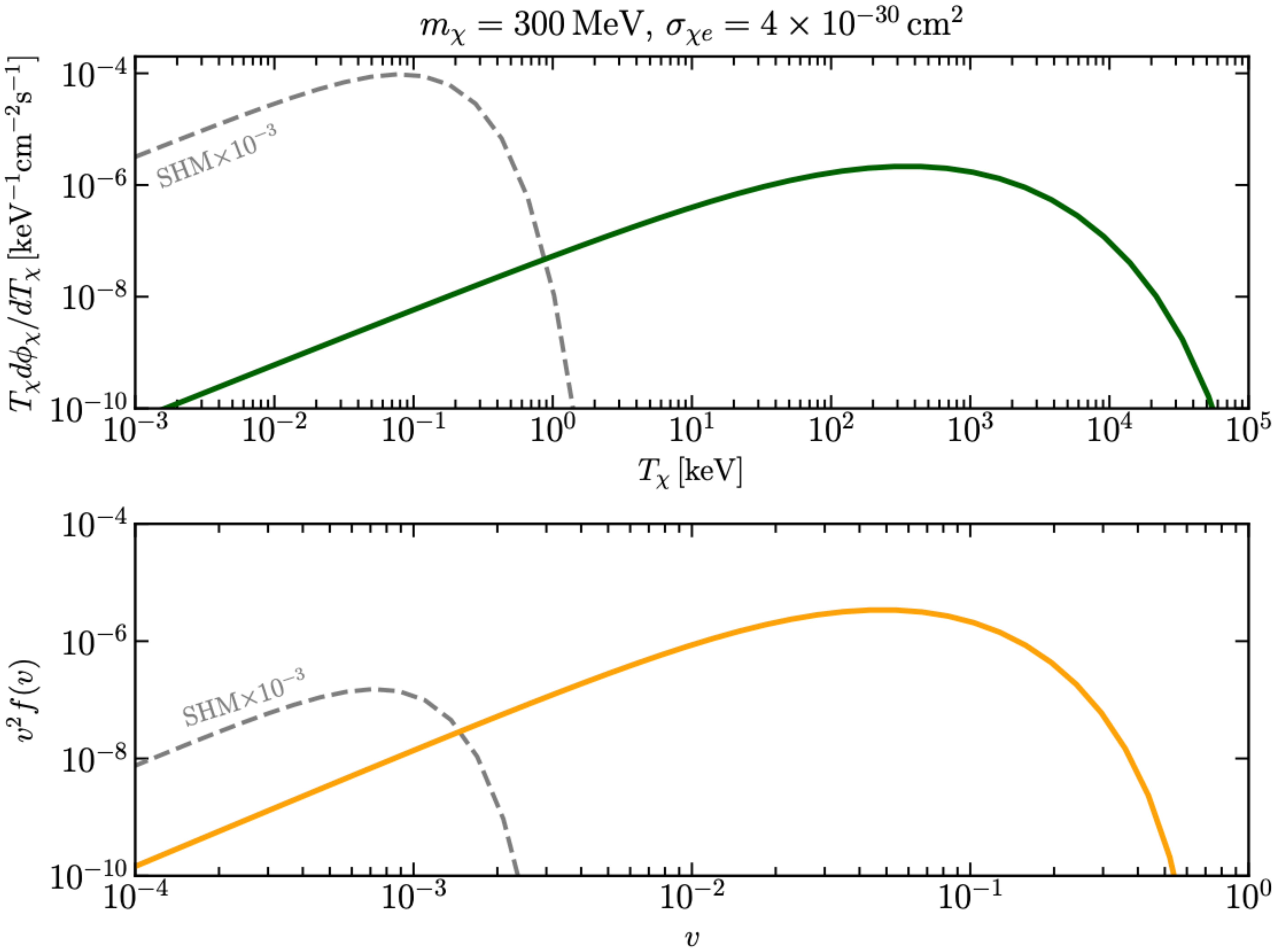
- Discard the assumption of constant interaction cross-section. This is not valid for light mass particles. Can alter limits drastically!

- Set new limits on DM-neutrino and electron interactions for DM masses in the range $m_{\rm DM} \sim (0.1, 10^4)\,{\rm MeV}$, using recent data from XENONnT, LUX-ZEPLIN, and PandaX-4T.

THANK YOU!

Backup

Flux and velocity distribution



Cross-section dependence

Scalar

Vector

Heavy Mediator Limit:

$$\frac{d\sigma_{\nu\chi}}{dT_\chi} \propto \begin{cases} \frac{m_\chi}{m_\Phi^4}\,, & \text{for } E_\nu \gg m_\chi \\ \frac{m_\chi}{m_\Phi^4}\left(1 - \frac{4 m_\chi T_\chi}{m_\Phi^2}\right)\,, & \text{for } m_\chi \gg E_\nu\,. \end{cases}$$

$$\frac{d\sigma_{\nu\chi}}{dT_\chi} \propto \begin{cases} \frac{m_\chi}{m_{Z'}^4}\,, & \text{for } E_\nu \gg m_\chi \\ \frac{T_\chi}{m_{Z'}^4}\,, & \text{for } m_\chi \gg E_\nu\,. \end{cases}$$

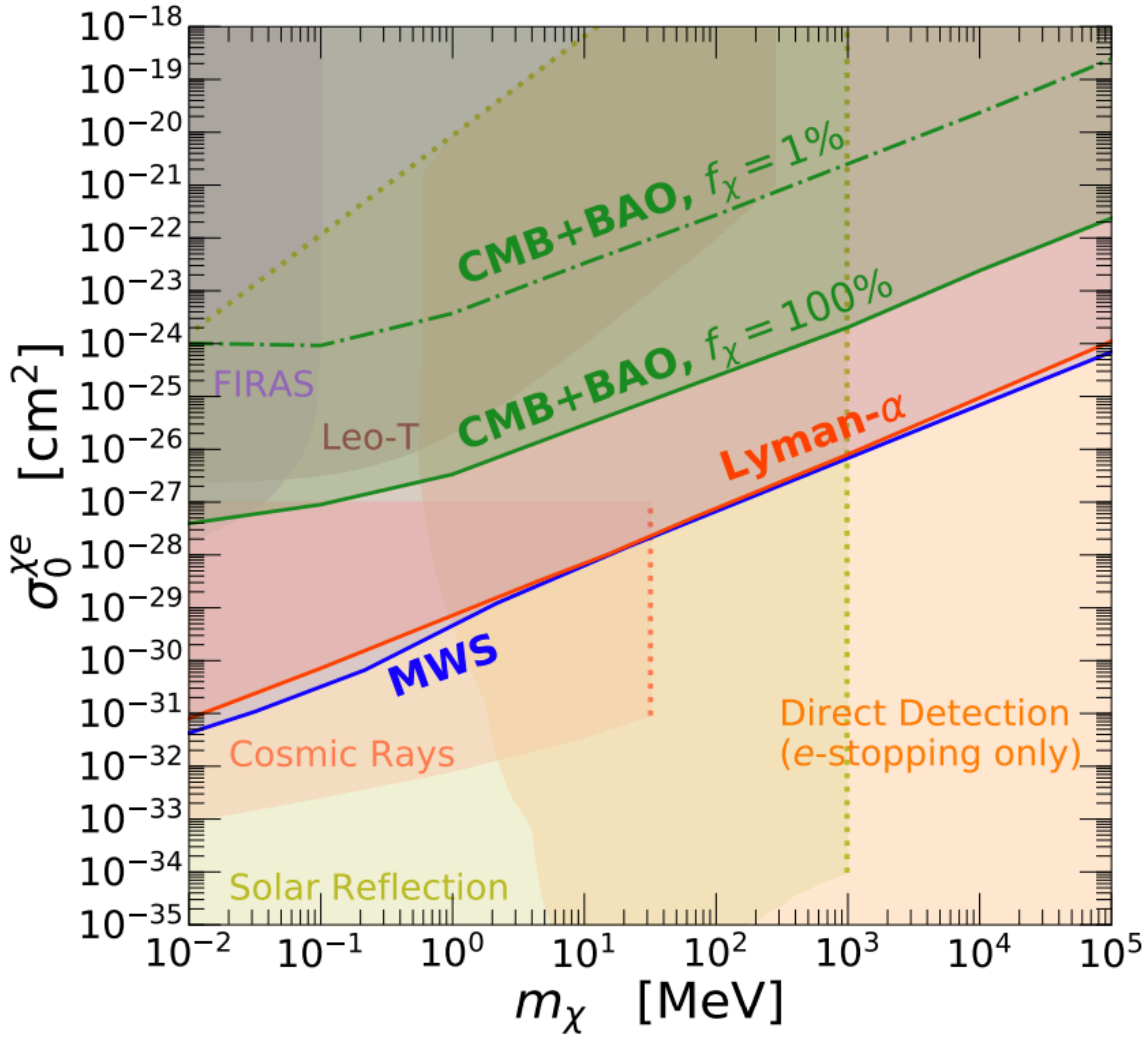
Light Mediator Limit:

$$\frac{d\sigma_{\nu\chi}}{dT_\chi} \propto \begin{cases} \frac{1}{T_\chi^2 m_\chi}\,, & \text{for } E_\nu \gg m_\chi \\ \frac{1}{m_\chi^3}\,, & \text{for } m_\chi \gg E_\nu\,. \end{cases}$$

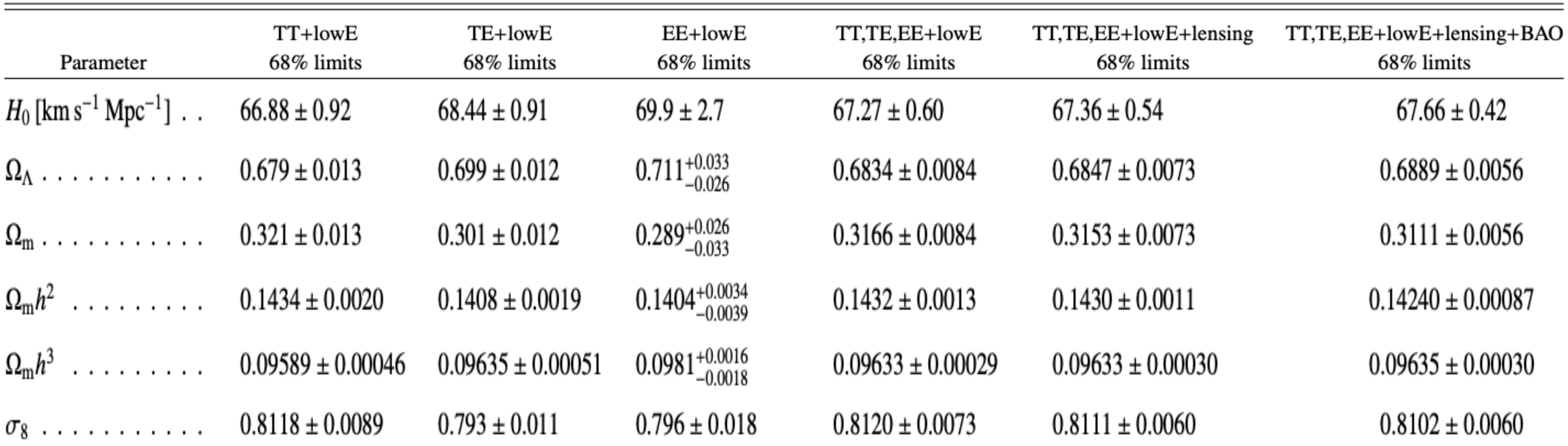
$$\frac{d\sigma_{\nu\chi}}{dT_\chi} \propto \begin{cases} \frac{1}{T_\chi^2 m_\chi}\,, & \text{for } E_\nu \gg m_\chi \\ \frac{1}{T_\chi m_\chi^2}\,, & \text{for } m_\chi \gg E_\nu\,. \end{cases}$$

Constraints on parameter space

Other constraints



Ingredient 1: Cosmology



Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$ . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_\mathrm{m}h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_\mathrm{m}h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$$

- Underlying cosmology is well constrained from Planck 2018 data.
- Parameters provide a normalisation to the spectra

PLANCK 2018

Ingredient 2: Star formation Rate

Cosmic SFR pretty well known from data in the UV and the far-infrared

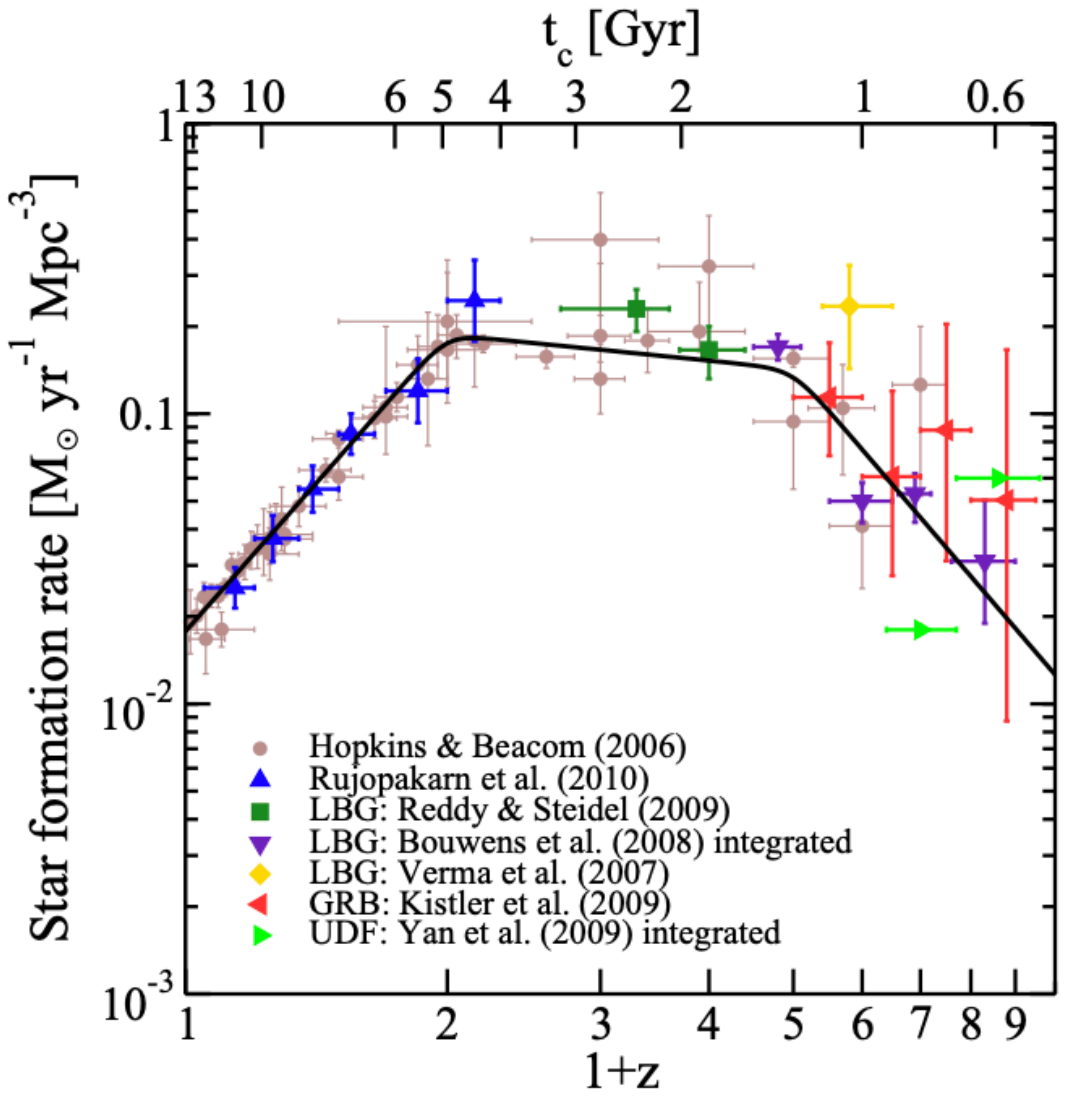
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\,\alpha} + \left(\frac{1+z}{B} \right)^{-10\,\beta} + \left(\frac{1+z}{C} \right)^{-10\,\gamma} \right]^{-1/10}$$

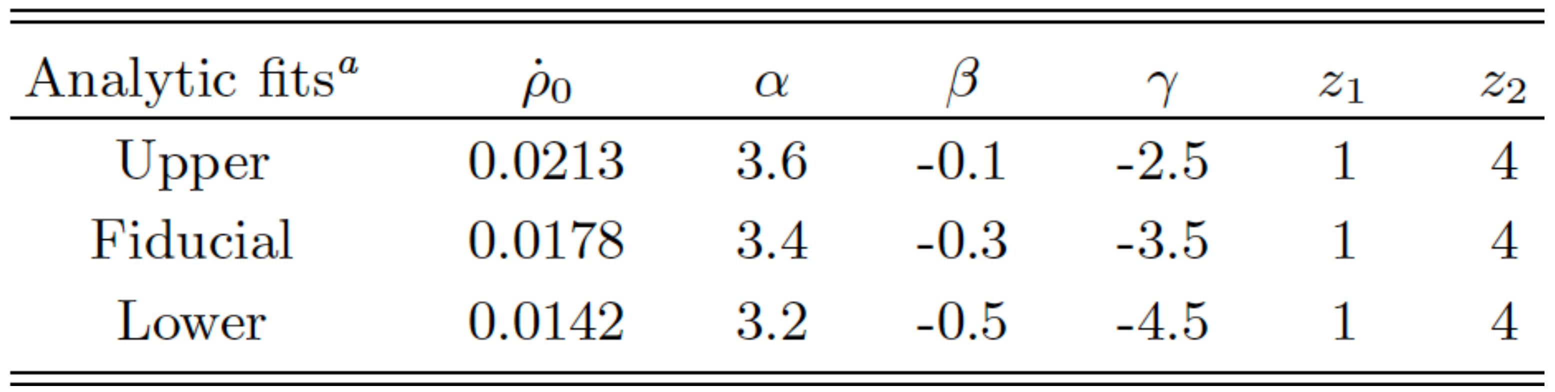
$$B = (1+z_1)^{1-\alpha/\beta}$$

$$C = (1+z_1)^{(\beta-\alpha)/\gamma}(1+z_2)^{1-\beta/\gamma}$$

$$R_{\rm CCSN}(z) = \dot{\rho}_*(z) \frac{\int_8^{50} \psi(M)\, dM}{\int_{0.1}^{100} M\psi(M)\, dM}\,.$$

Here $\psi(M) \sim M^{-2.35}$ is the initial mass distribution function





Analytic fits^a	$\dot{\rho}_0$	α	β	γ	z_1	z_2
Upper	0.0213	3.6	-0.1	-2.5	1	4
Fiducial	0.0178	3.4	-0.3	-3.5	1	4
Lower	0.0142	3.2	-0.5	-4.5	1	4

Hopkins, Beacom, ApJ2006
Yuksel, Kistler, Beacom, Hopkins, ApJ2008
Horiuchi, Beacom, Dwek, PRD2009

Ingredient 3:Neutrino spectra

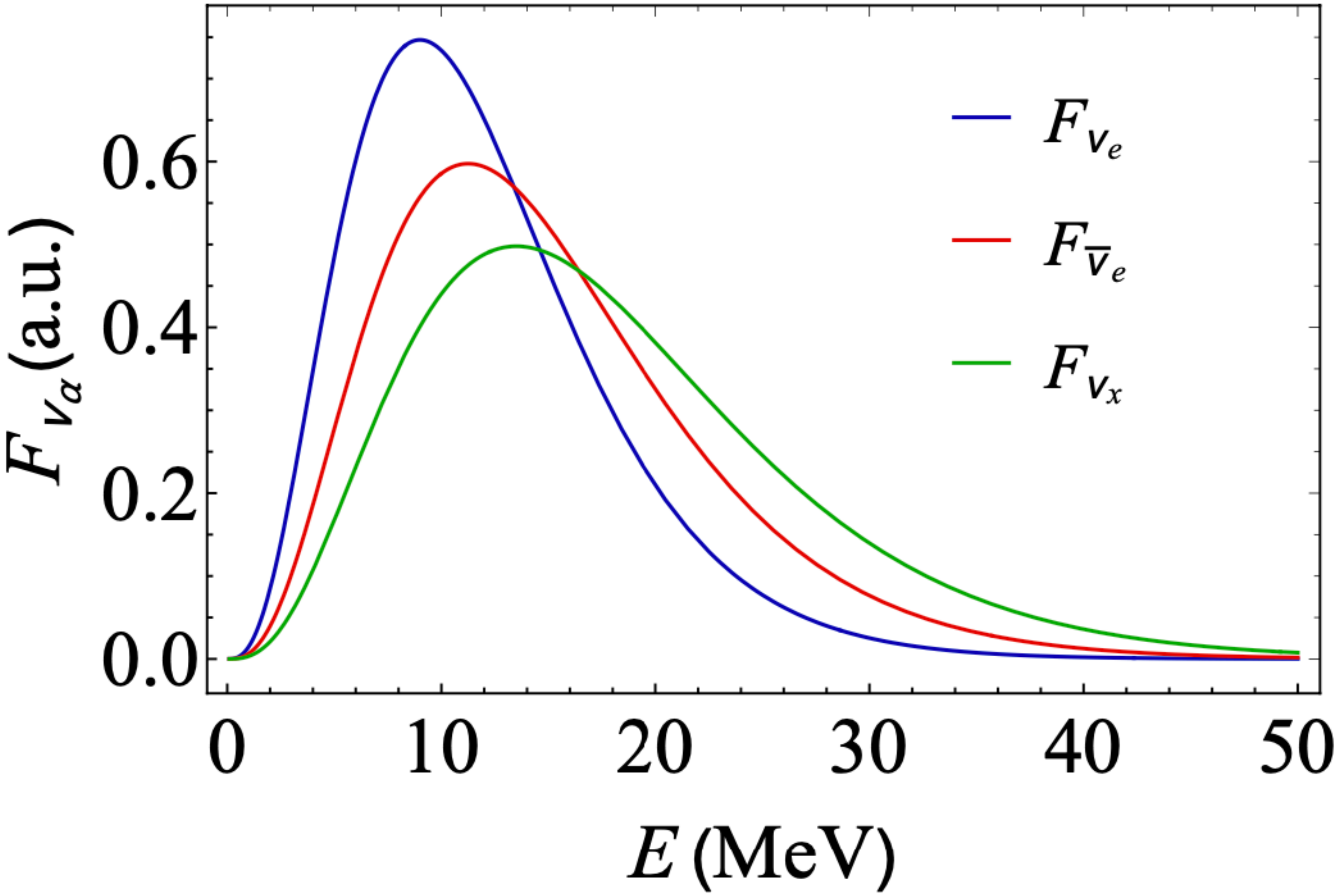
- Assume an approximately thermal spectra, characteristic of late-time phase.

$$F_{\nu_\beta}(E_\nu) = \frac{1}{E_{0\beta}}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{E_{0\beta}}\right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{E_{0\beta}}}$$

- Could be processed by collective neutrino oscillations, however effect is not very large. Hence ignore.

- Only assume adiabatic MSW transition, so
  heaviest neutrino $\leftrightarrow \nu_e$
  lightest neutrinos $\leftrightarrow \nu_x$

- Temperature hierarchy $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$



Variation with <E> and alpha

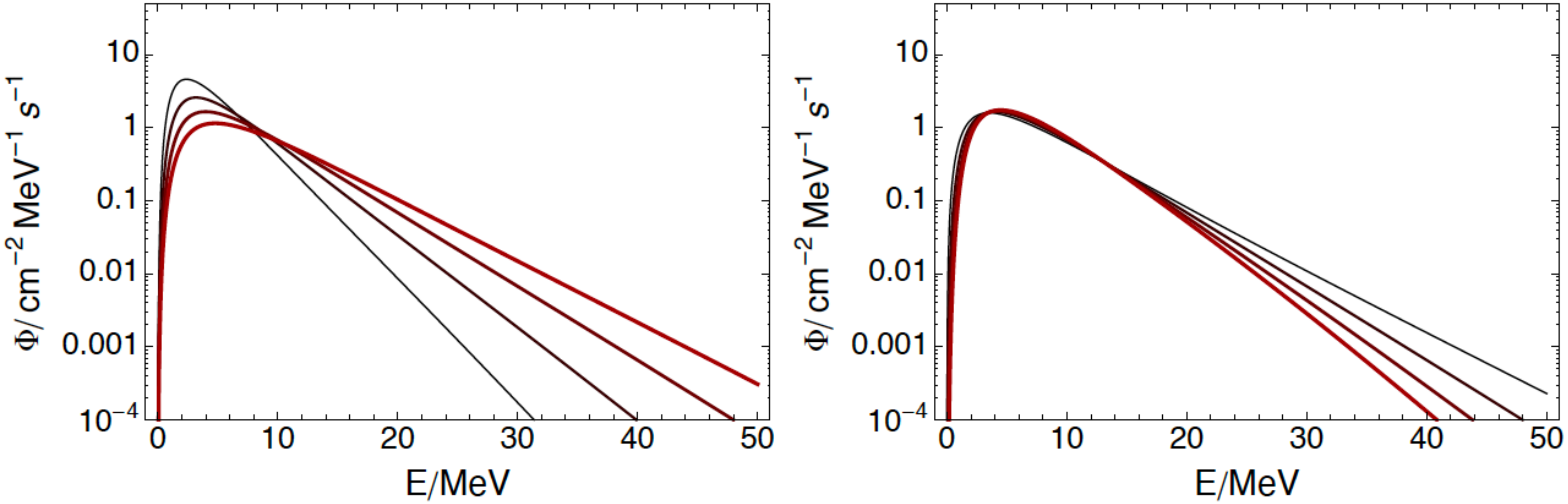


Figure 10: Examples of unoscillated flux, Φ^0_w $(w = e, \bar{e}, x)$ (Eq. (15)), for different spectral parameters E_{0w}, α_w. Left: the curves of increasing thickness (increasing color intensity) correspond to $E_{0w} = 9, 12, 15, 18$ MeV, with $\alpha_w = 3$. Right: the curves of increasing thickness (increasing color intensitiy) correspond to $\alpha_w = 2, 3, 4, 5$ with $E_{0w} = 15$ MeV.

Variation with redshift

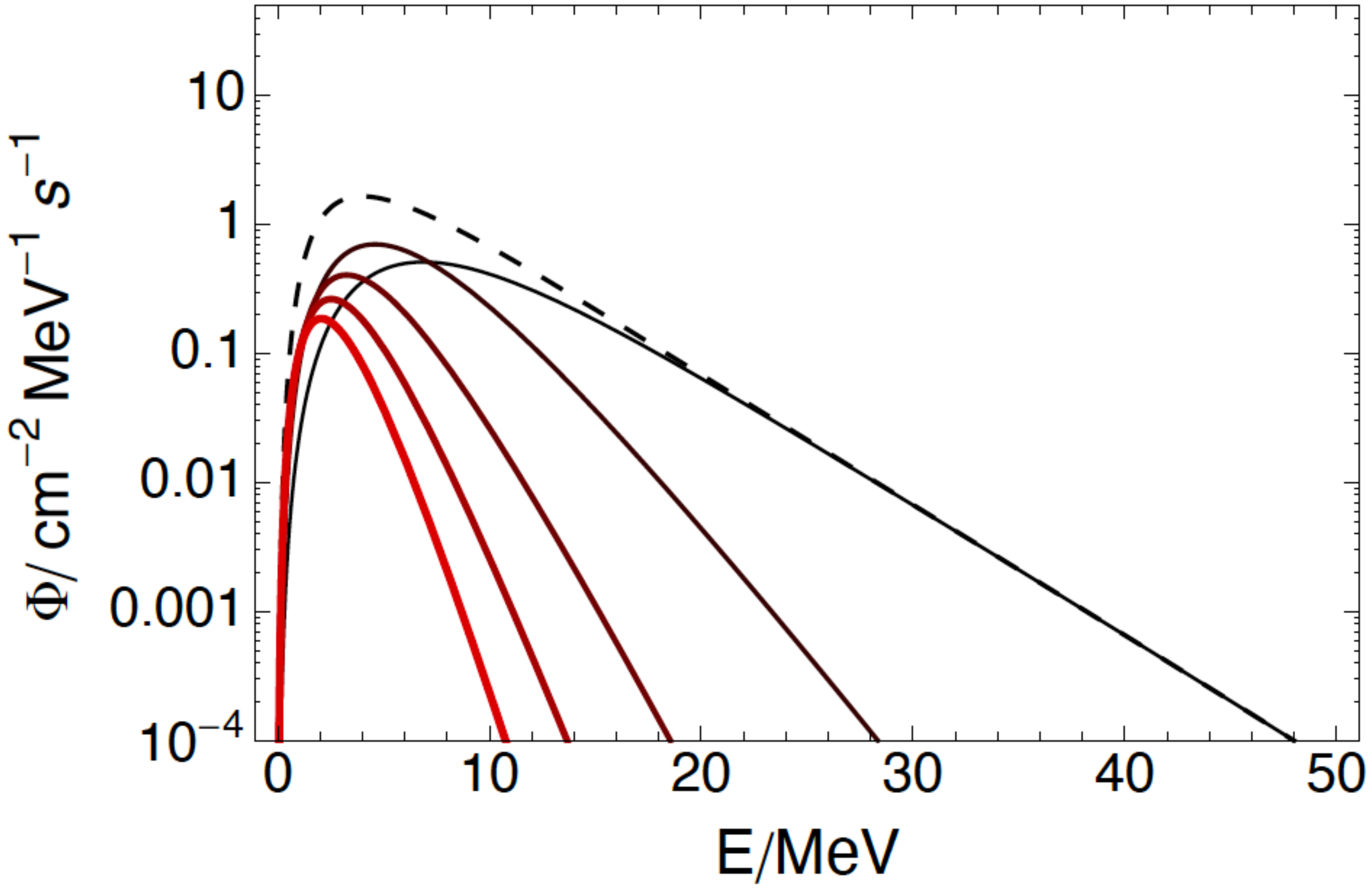
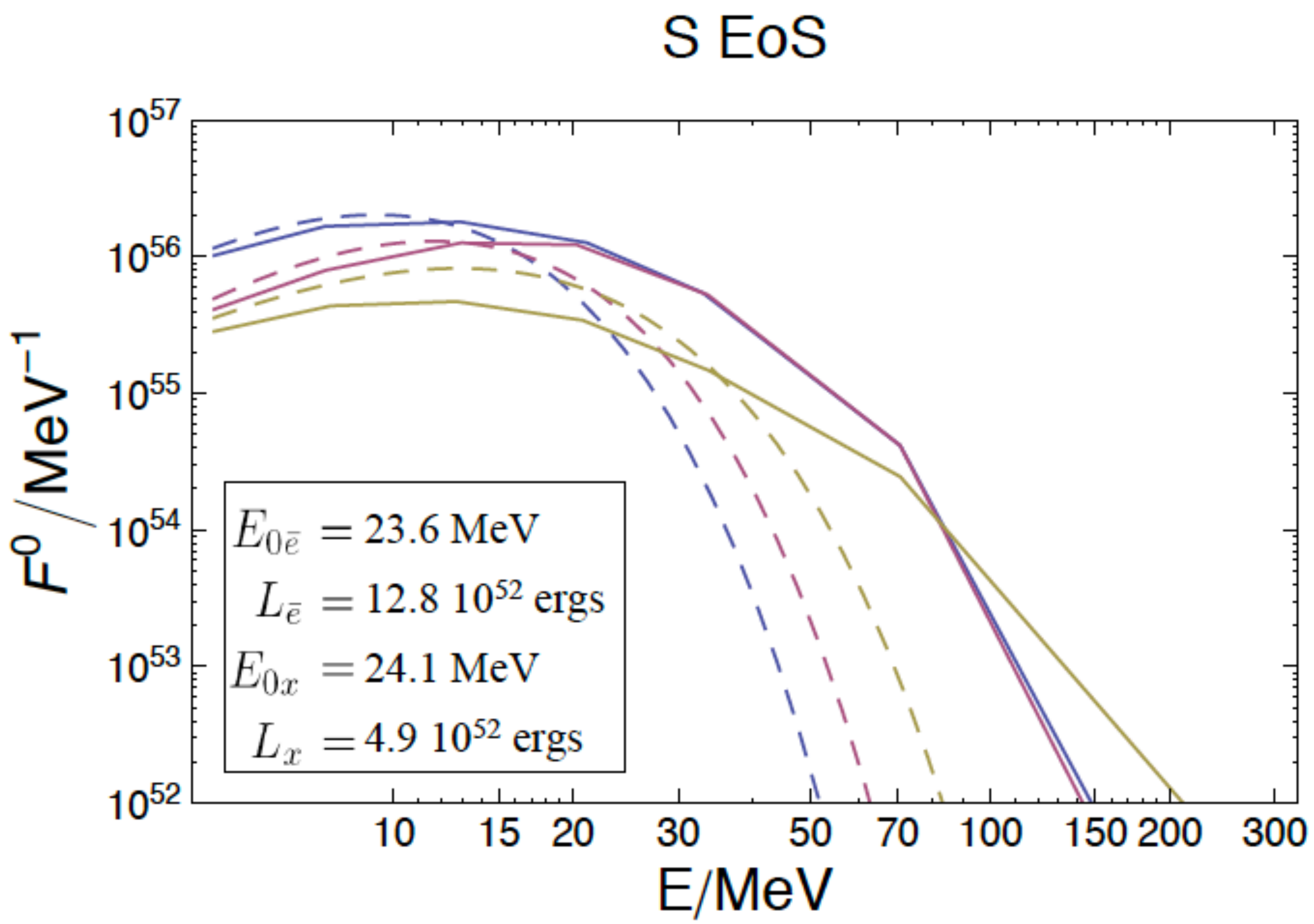
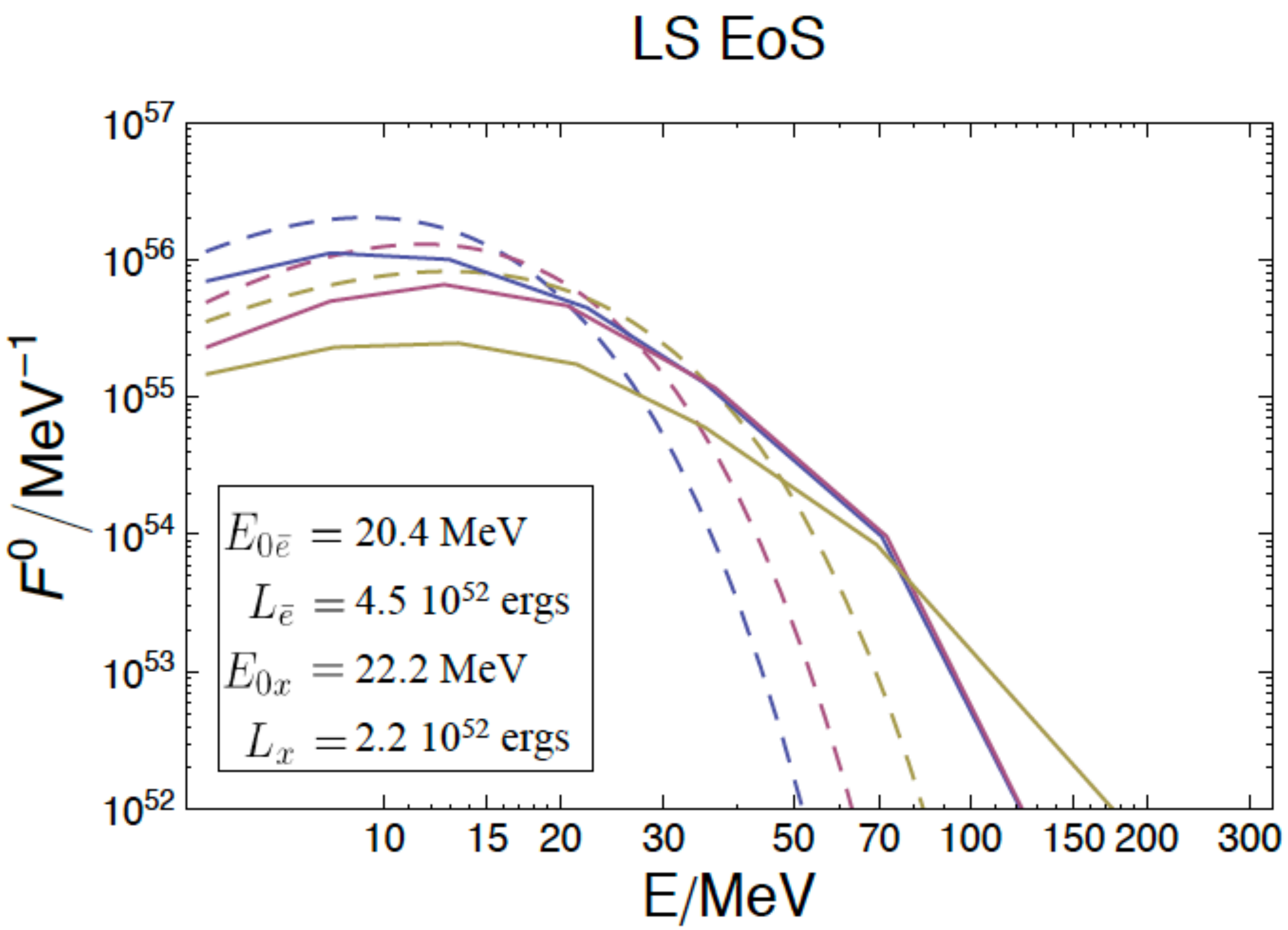


Figure 13: The contribution to the *unoscillated* $\bar{\nu}_e$ flux of sources in bins of increasing redshift, for the best fit SNR parameter $\beta = 3.28$ [59]. The solid curves from thinner to thicker (darker to lighter color) refer to the intervals: $z = 0 - 1$, $z = 1 - 2$, $z = 2 - 3$, $z = 3 - 4$ and $z = 4 - 5$. The dashed line is the total flux integrated over all redshifts. The parameters of the H case were used (Table 1).

Failed Supernovae

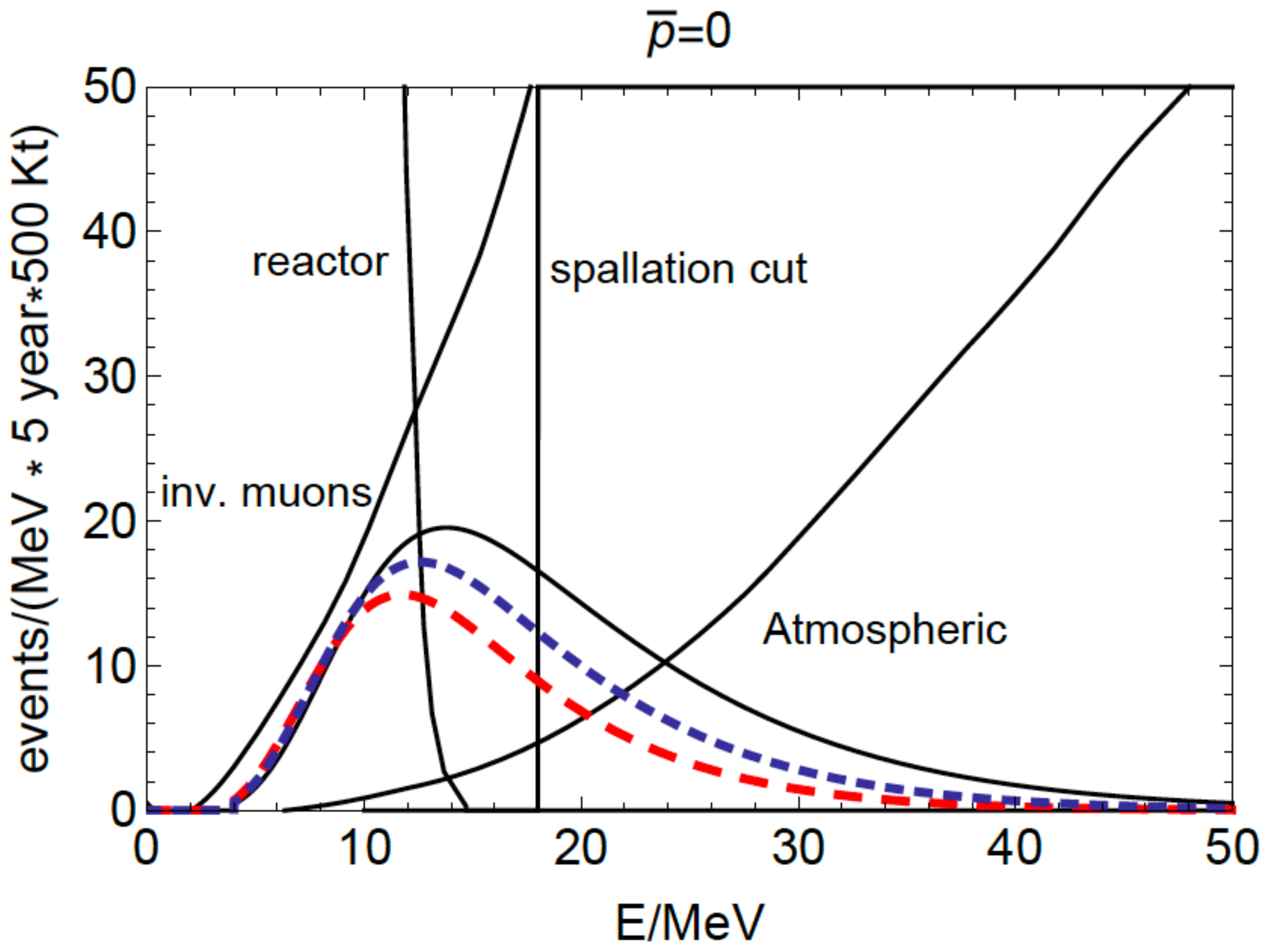




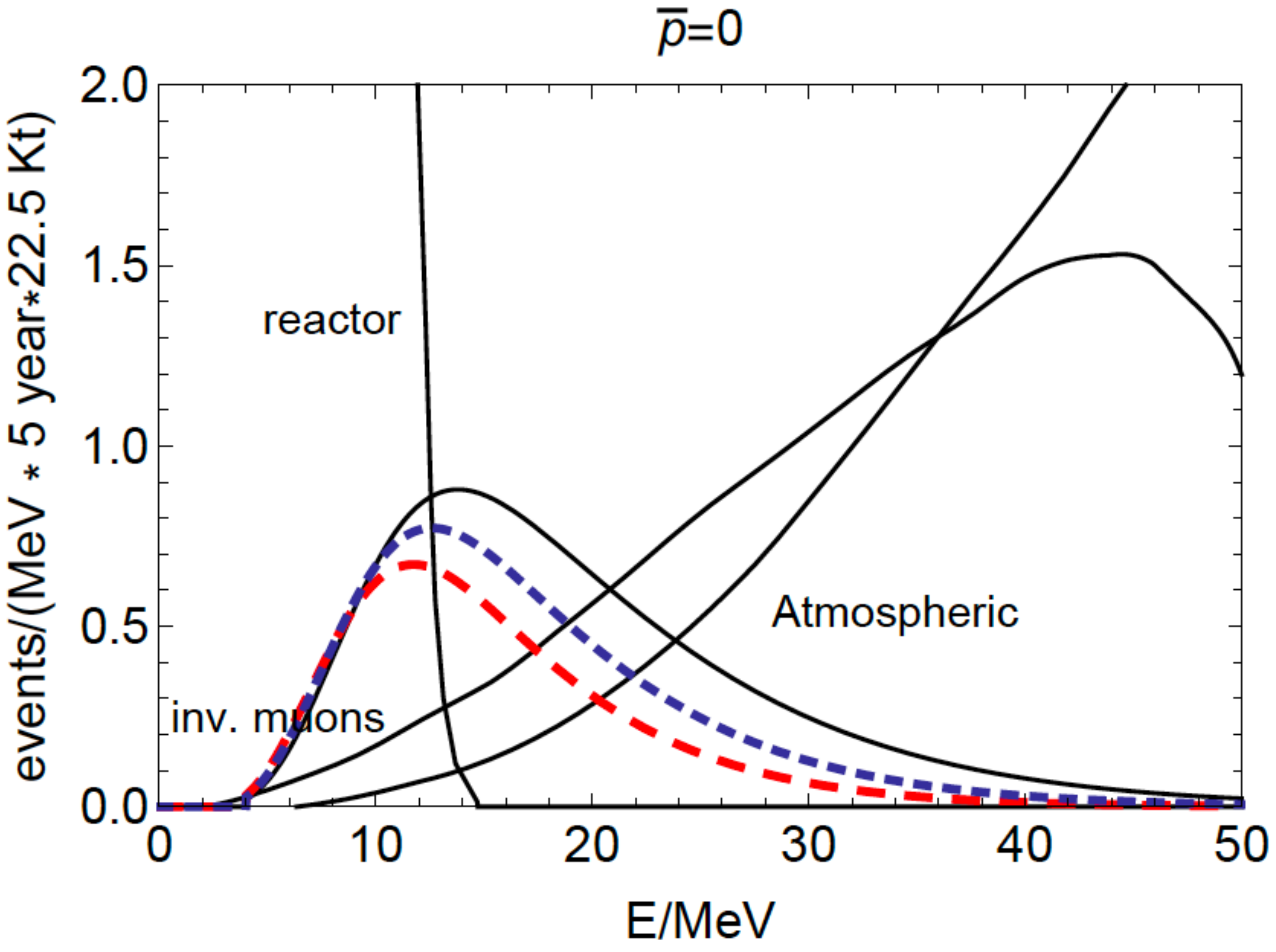
- Stars with $M > 25 - 40\,M_{\odot}$ can end up forming a failed SN. (Dashed - SN, solid- BH).
- Neutrino spectra can be more energetic due to rapid contraction of the PNS before collapse.
- ’S’ EoS is stiffer, so stronger core-bounce and hence more energetic neutrinos.

Gd doping: GADZOOKS!

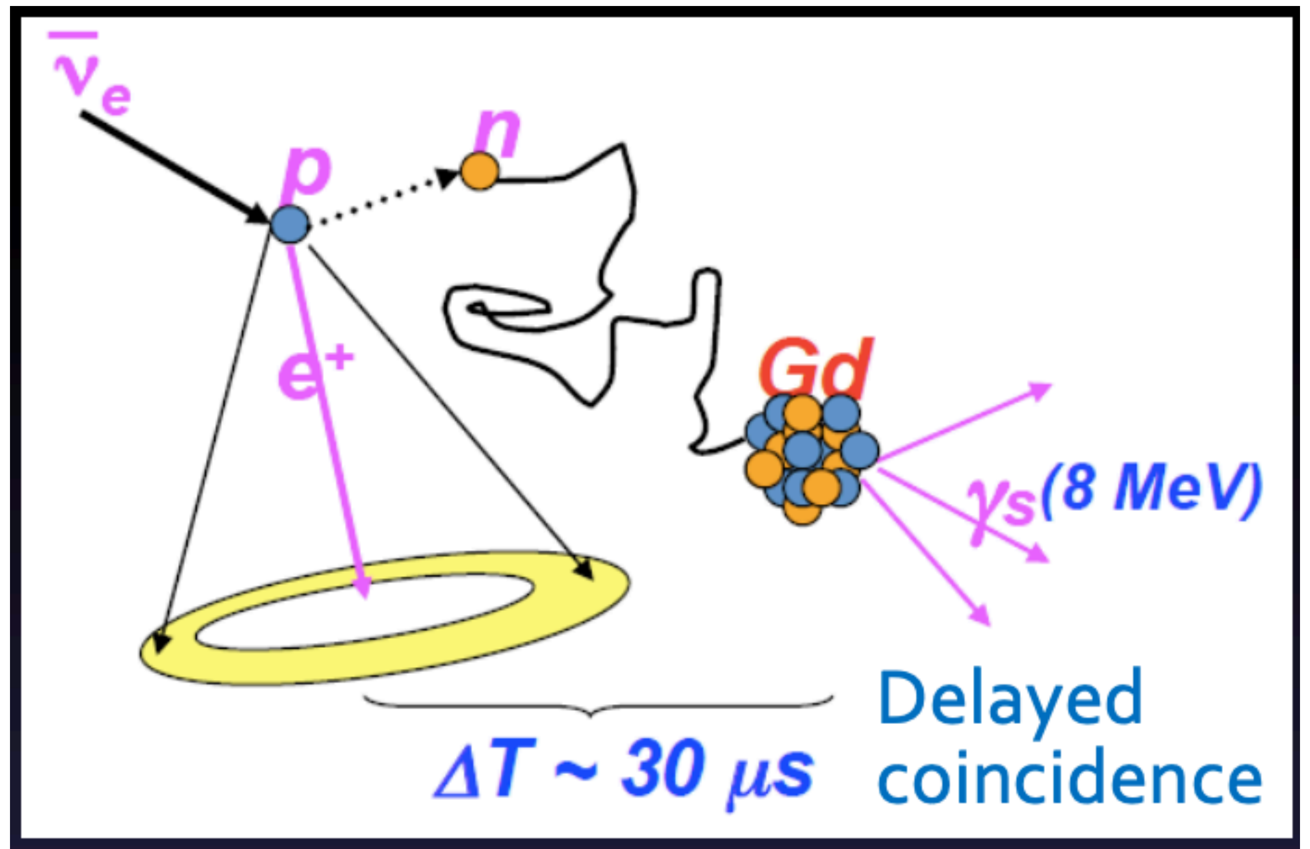
Beacom, Vagins, PRL2004



Lunardini, Astropart. Phys2016



- Solution: Gd doping.
- Reduces energy threshold.
- Background due to spallation will be subtracted almost completely and the one due to invisible muons will be reduced by a factor of 5.



ΔT~30 μs, Vertices within 50 cm