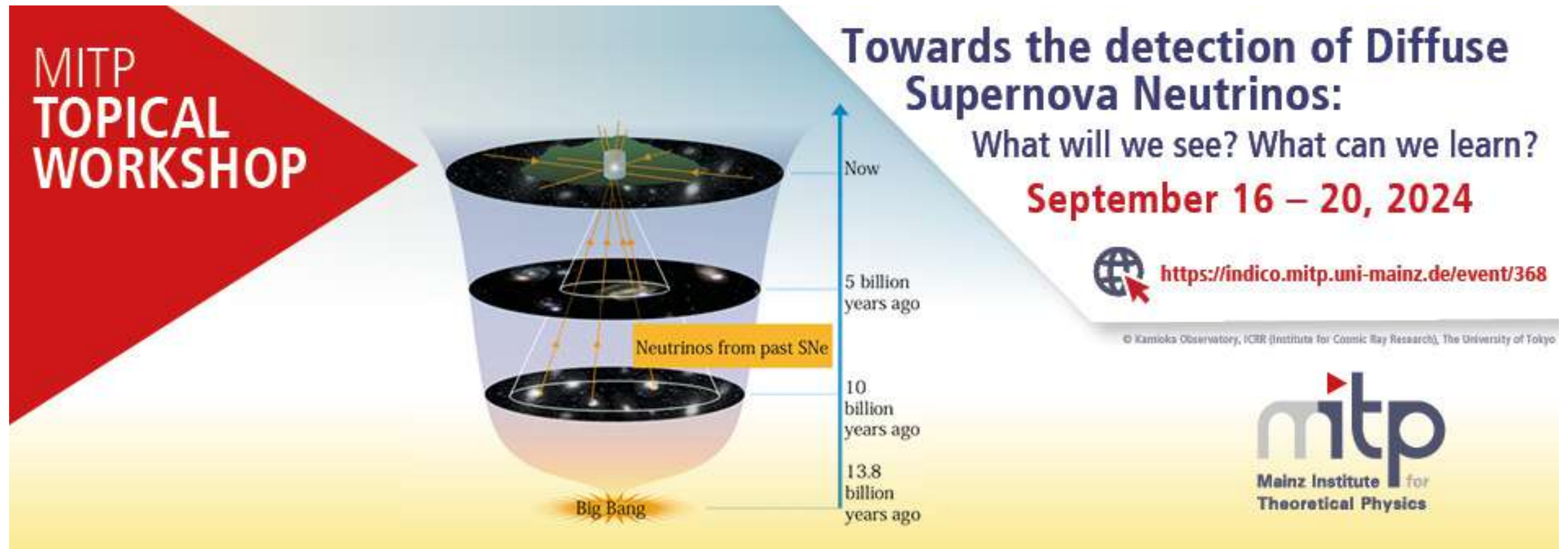
OVERVIEW OF BSM PHYSICS WITH THE DSNB

Manibrata Sen

MPIK Heidelberg

18/09/24



MITP
TOPICAL
WORKSHOP

Towards the detection of Diffuse Supernova Neutrinos:
What will we see? What can we learn?

September 16 – 20, 2024

https://indico.mitp.uni-mainz.de/event/368

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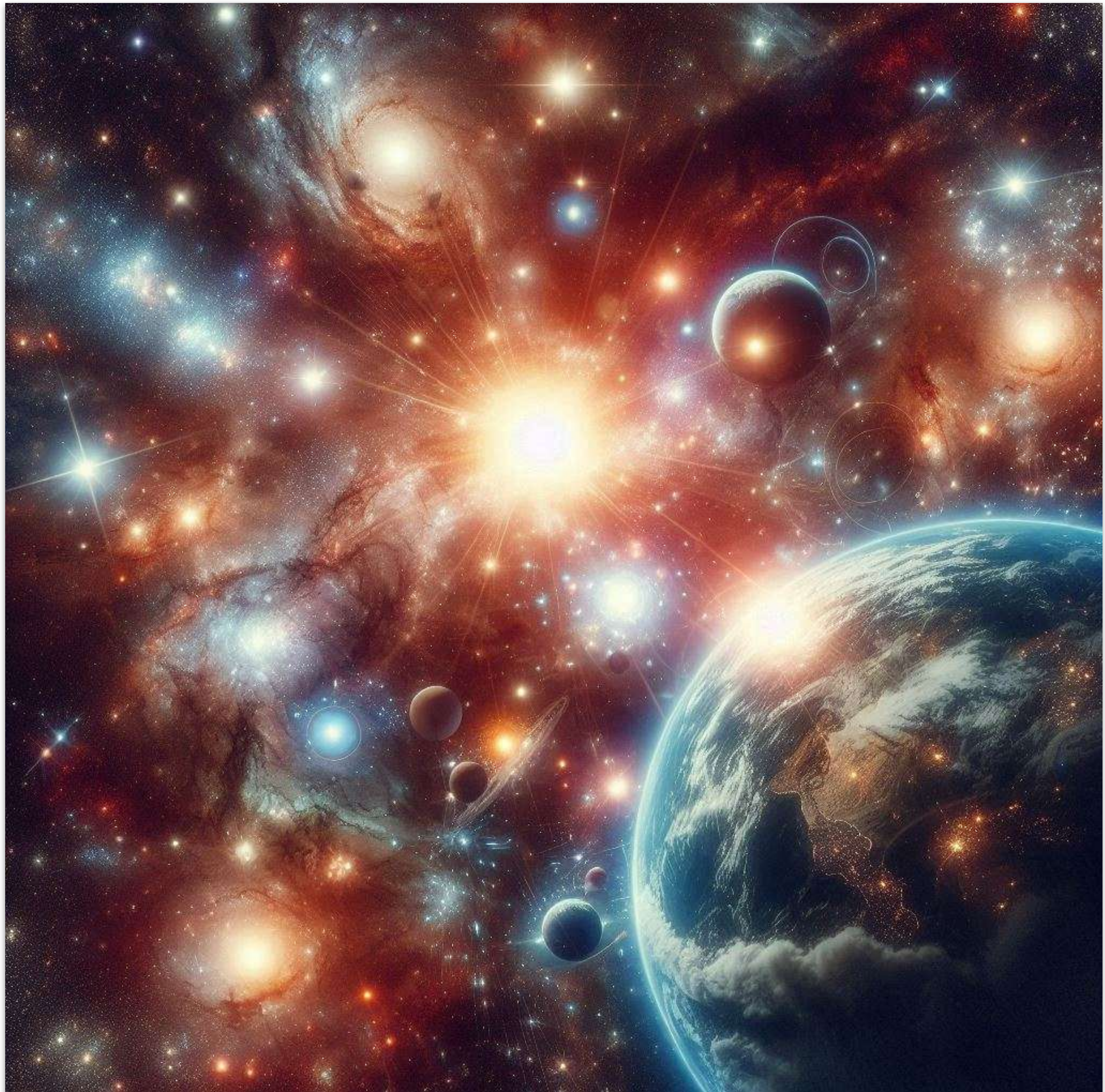
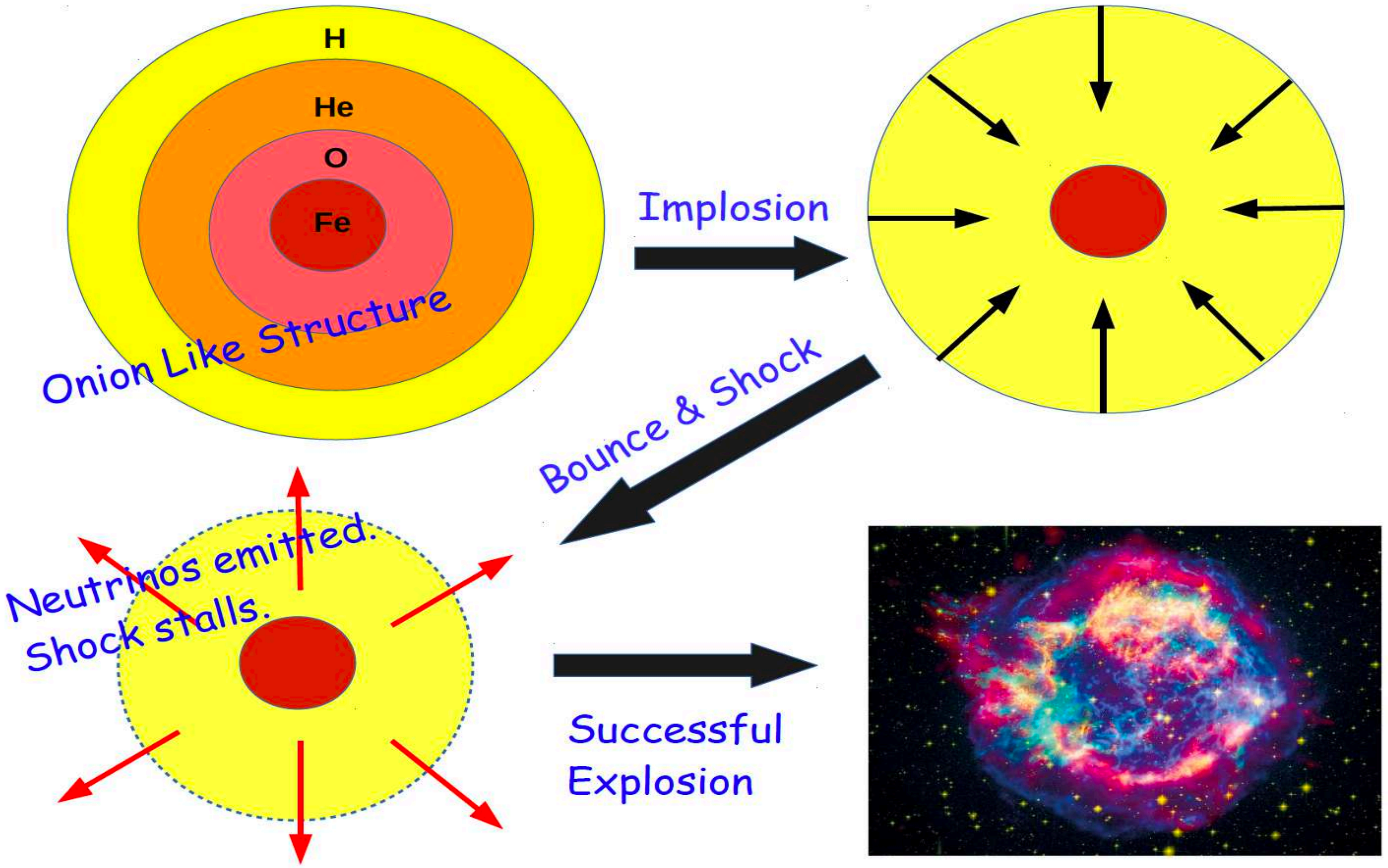


Core-collapse SNe: Mechanism



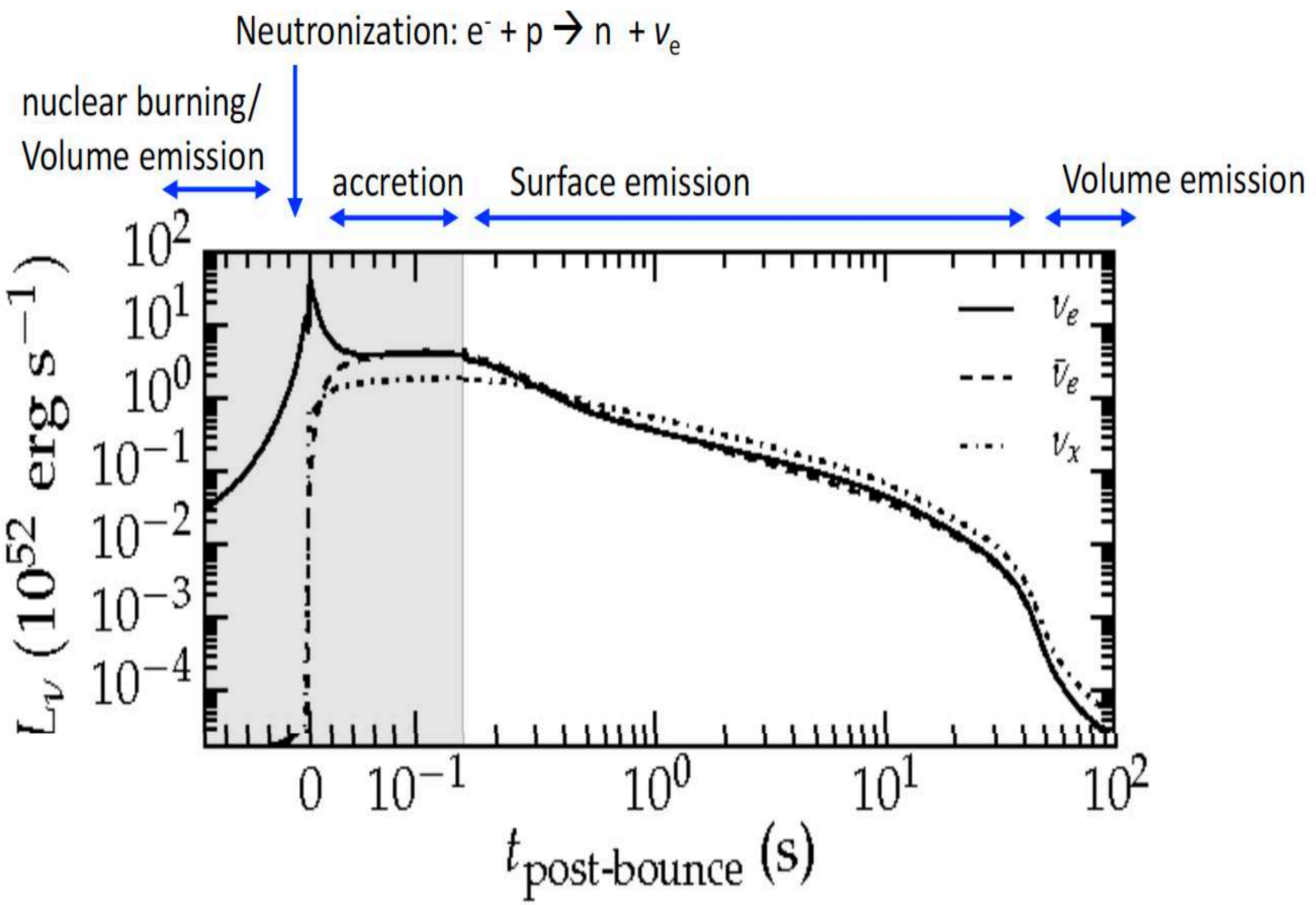
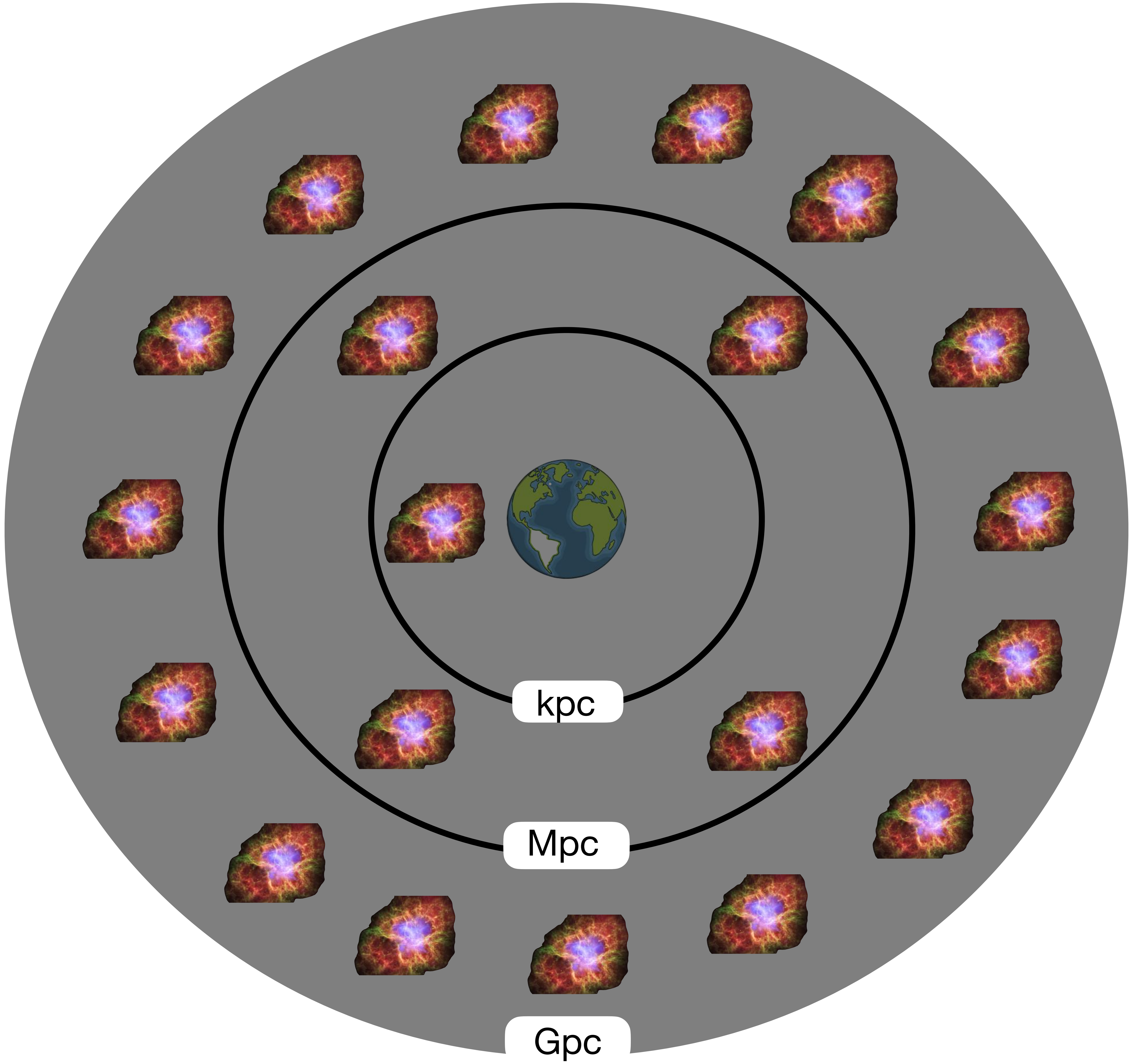


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

- Core-collapse SNe leading to MeV neutrino emission.
- Almost thermal spectra for different flavors.
- SN1987A: some of the strongest bounds on neutrino properties!

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, dominantly from stars upto redshift z~1, but extends upto z~6.
- Opens up a new frontier in neutrino astronomy.



How to estimate the DSNB?

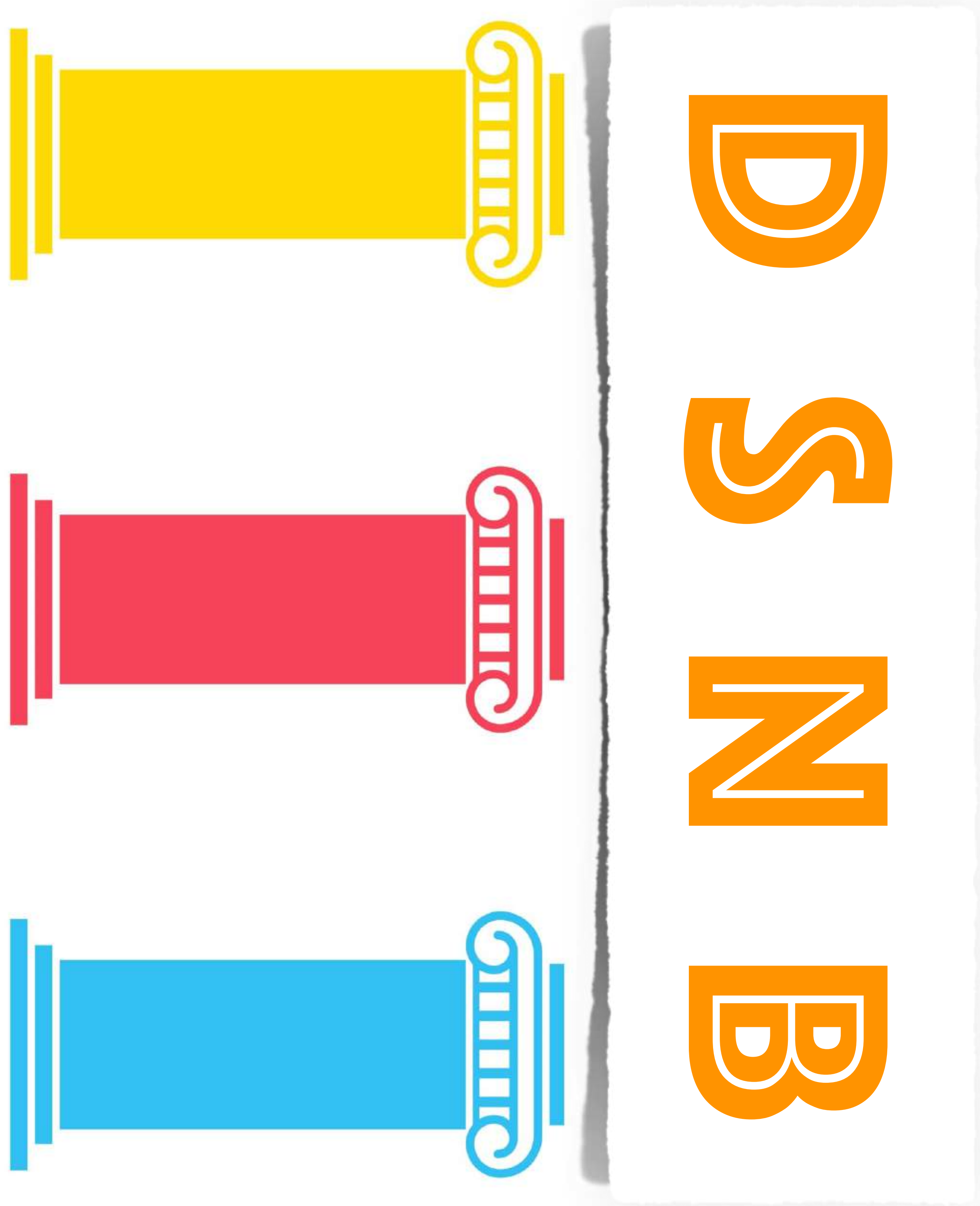
$$\Phi_\nu(E) = \int_0^{z_{\rm max}} \frac{dz}{H(z)}\, R_{\rm CCSN}(z)\; F_\nu\big(E(1+z)\big)$$

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

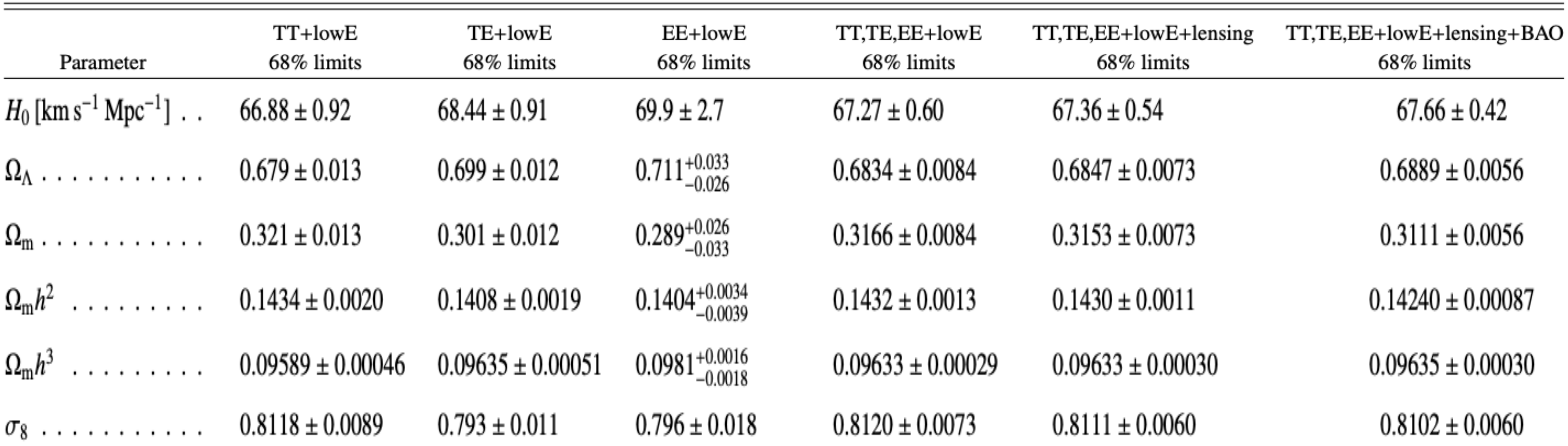
SN Neutrino spectra

Cosmological SN rate

Cosmology



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 data.
- Parameters provide a normalisation to the spectra

PLANCK 2018

Ingredient 2: Core-collapse SNe Rate

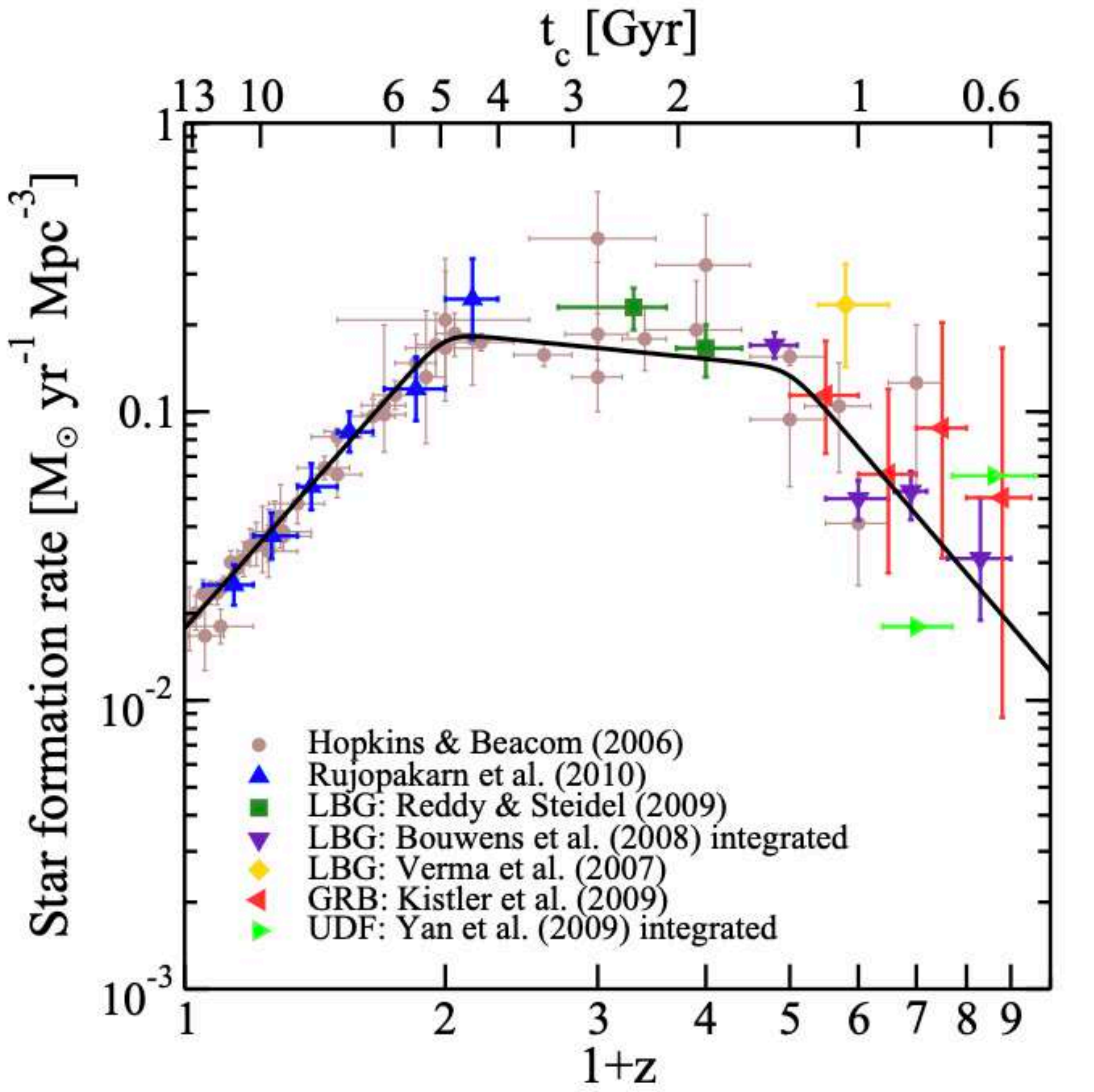
$$R_{\rm CCSN}(z) = \dot{\rho}_*(z)\frac{\int_8^{50}\psi(M)\,dM}{\int_{0.1}^{100}M\psi(M)\,dM}\,.$$

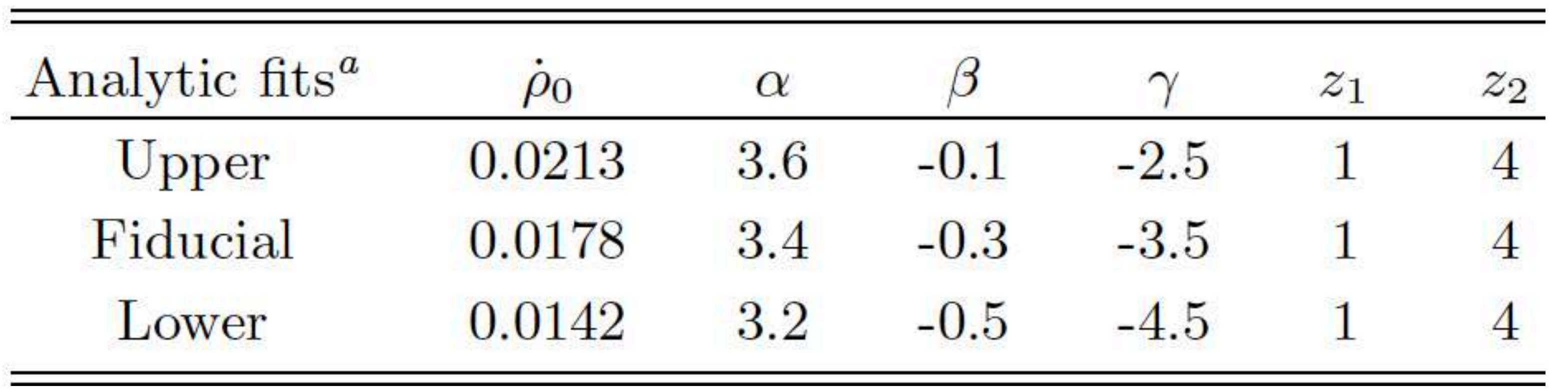
Cosmic SFR pretty well known from data in the UV and the far-infrared

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

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

$\psi(M)$ is the initial mass distribution





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
Ekanger et al. PRD 2024

Non trivial contribution from failed BHs and Mrot driven SNe.
We neglect for this talk!

Talks on Day 2

Ingredient 3: Neutrino spectra

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

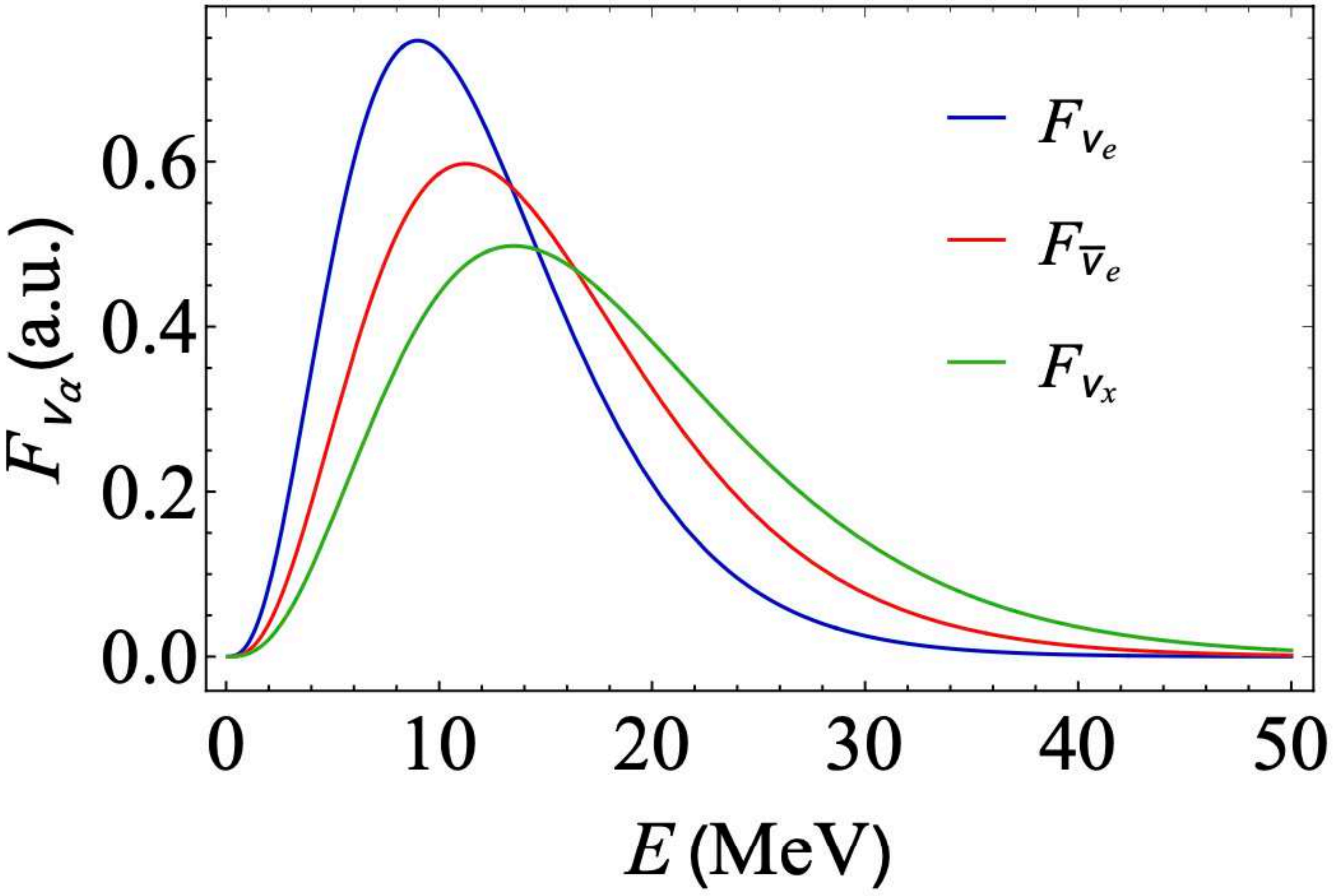
$$F_{\nu_\beta}(E_\nu) = \frac{1}{\langle E_\beta \rangle} \frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)} \left(\frac{E_\nu}{\langle E_\beta \rangle} \right)^{\alpha} e^{-(1+\alpha)\frac{E_\nu}{\langle E_\beta \rangle}}$$

Tamborra, Mueller,Huedepohl, Janka, Raffelt (PRD 2012)

- Could be processed by collective neutrino oscillations, however effect is subleading. Hence ignore.

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

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



How to estimate the DSNB?

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

Beacom, Ann.Rev.Nucl.Part.Sci. 2010
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SN Neutrino spectra

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

Cosmological SN rate

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

Cosmology

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

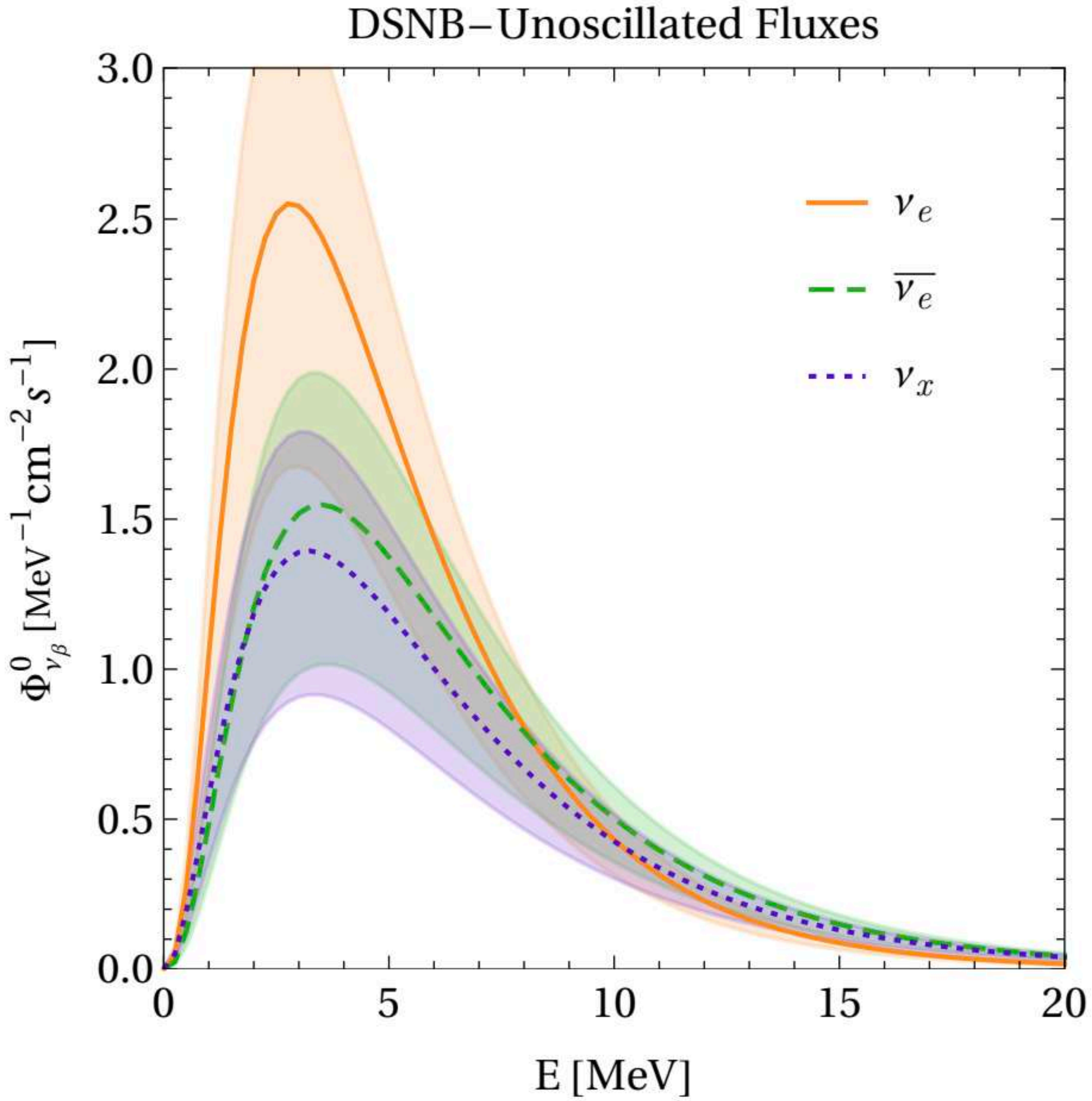
Putting all ingredients together

- The DSNB window ~10-26 MeV.
- Main backgrounds to keep in mind:

Solar ν_e: extends upto ~20 MeV.
Geo $\bar{\nu}_e$: Mostly dominates low energy ~ 4 MeV background.
Reactor $\bar{\nu}_e$: extends upto ~10 MeV.
Atmospheric ν: Low energy tails of ν_e and $\bar{\nu}_e$. Exceeds the DSNB at E~30 MeV.

- Experiments: SK, JUNO, DUNE, HK, Theia, Resnova, many others being considered.

Talks on Day 1

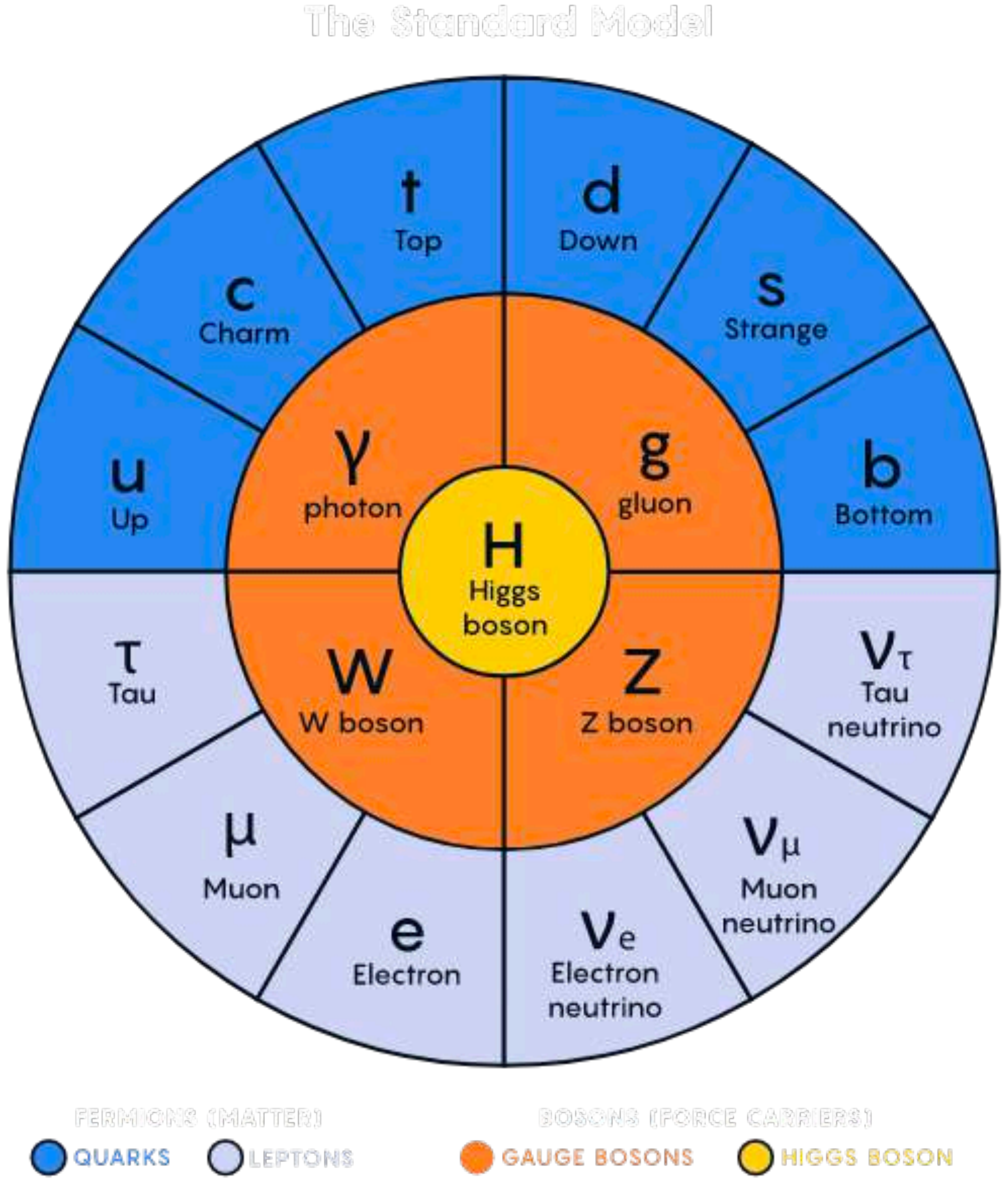


The DSNB as a late Universe laboratory

Multidisciplinary aspects of understanding the supernova neutrinos:

- Particle physics aspects: Neutrino physics in dense media, neutrino properties (this talk), anomalous cooling mechanism due to new physics,…
- Astrophysics: Star formation rates, including life and birth cycles, constraints on new sources, neutron star equation of state, nucleosynthesis…
- Cosmology: SN distance indicators, fundamental cosmology parameters, dark matter physics,..
- Multi-messenger aspect: adds to information from photons and gravity waves. All these channels can open up with a future detection of the DSNB…

Sensitive to BSM physics



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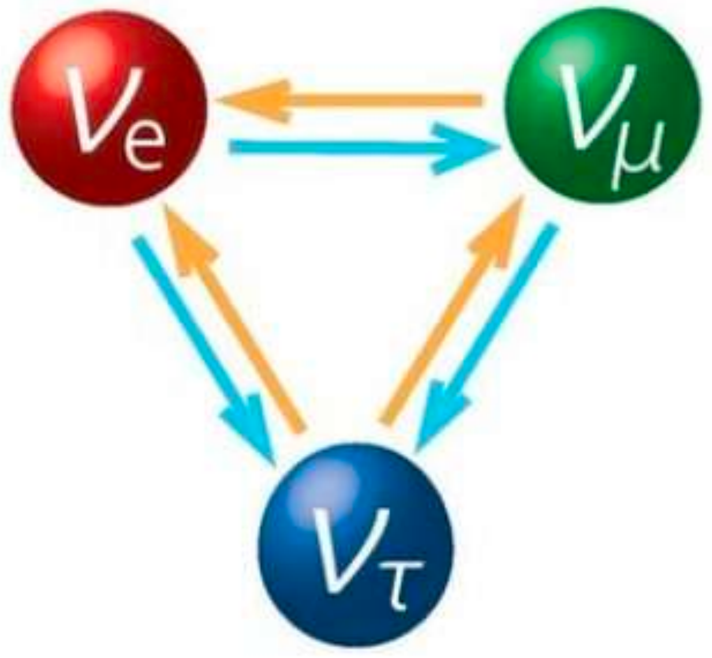
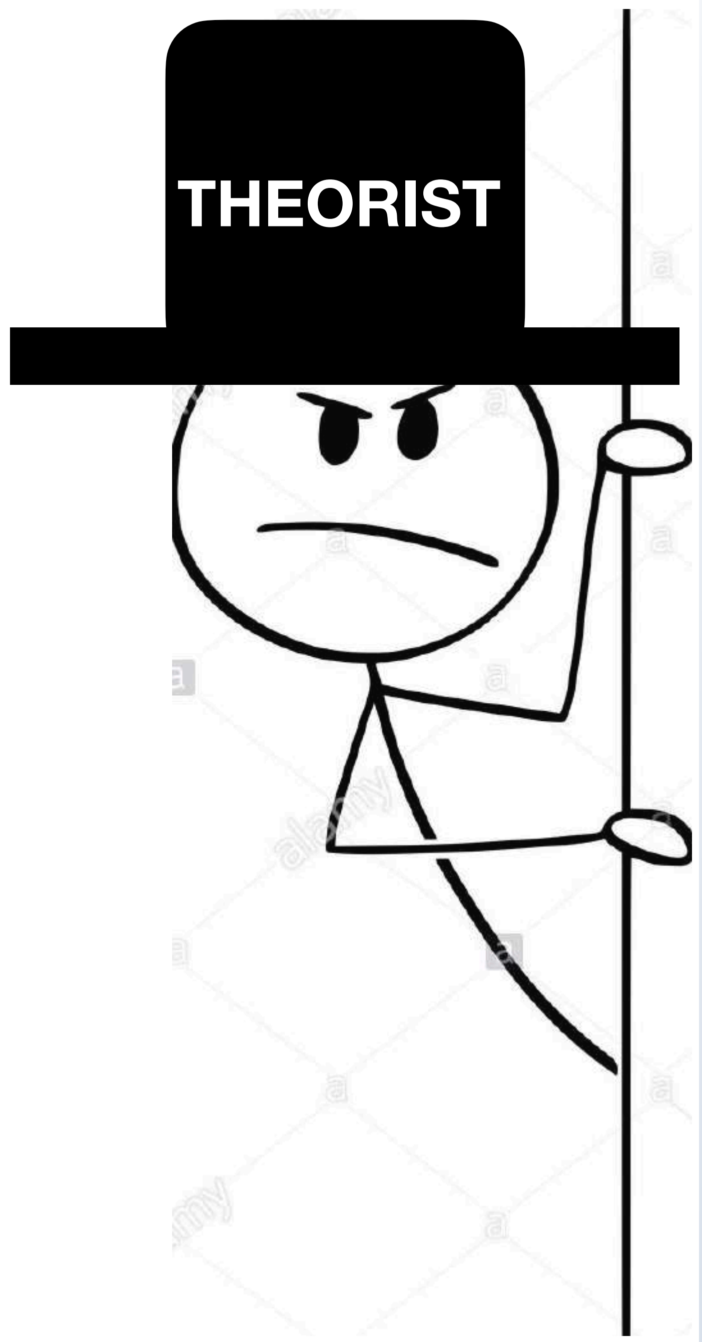


Credit: BBC



Beyond

The Standard Model

How can new physics affect neutrinos?

A brief list of non-standard neutrino physics:

Mass and Mixing, Decay,

Non-SM interactions,

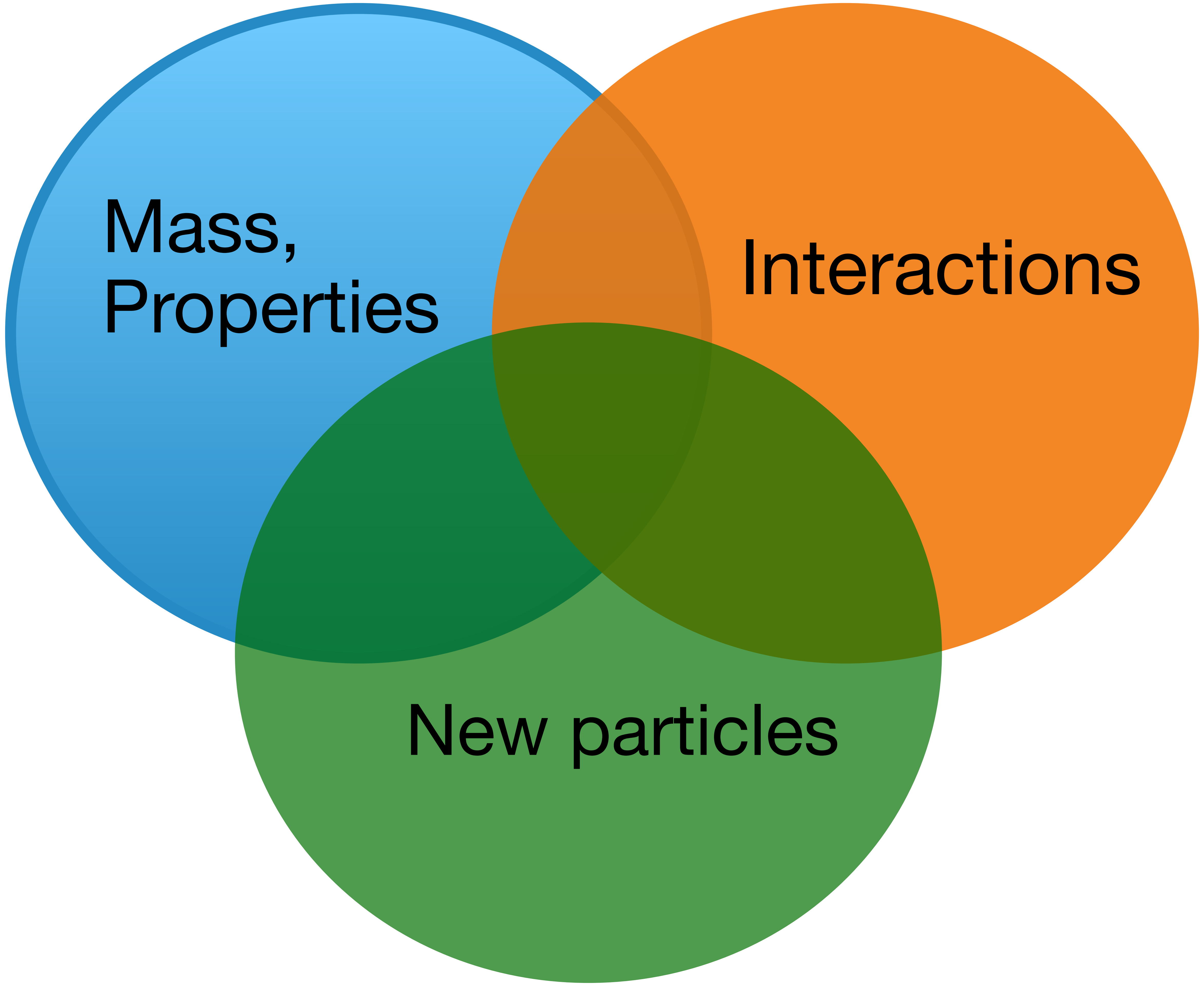
New particles,

Dirac or Majorana nature (L-violation),

Electromagnetic properties, CPT-properties and Lorenz invariance,

Quantum Decoherence,

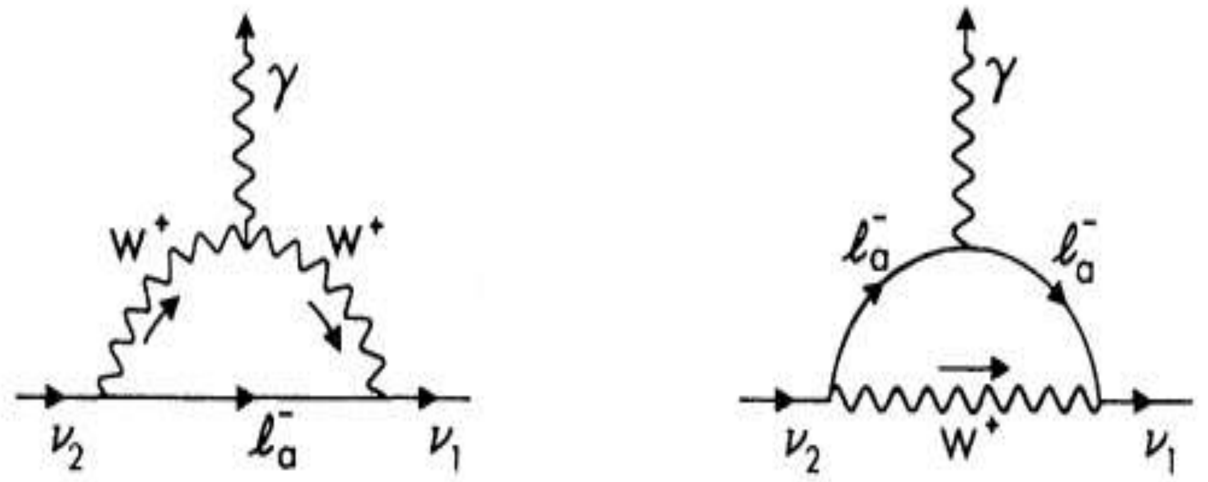
…….



1. Neutrino Decay

Neutrino Properties: Decay

- Massive neutrinos can decay to lighter ones even within the SM. Age longer than universe.



Smirnov and Zatsepin (Yad. Phy. 1978),
Pal and Wolfenstein (PRD1982)

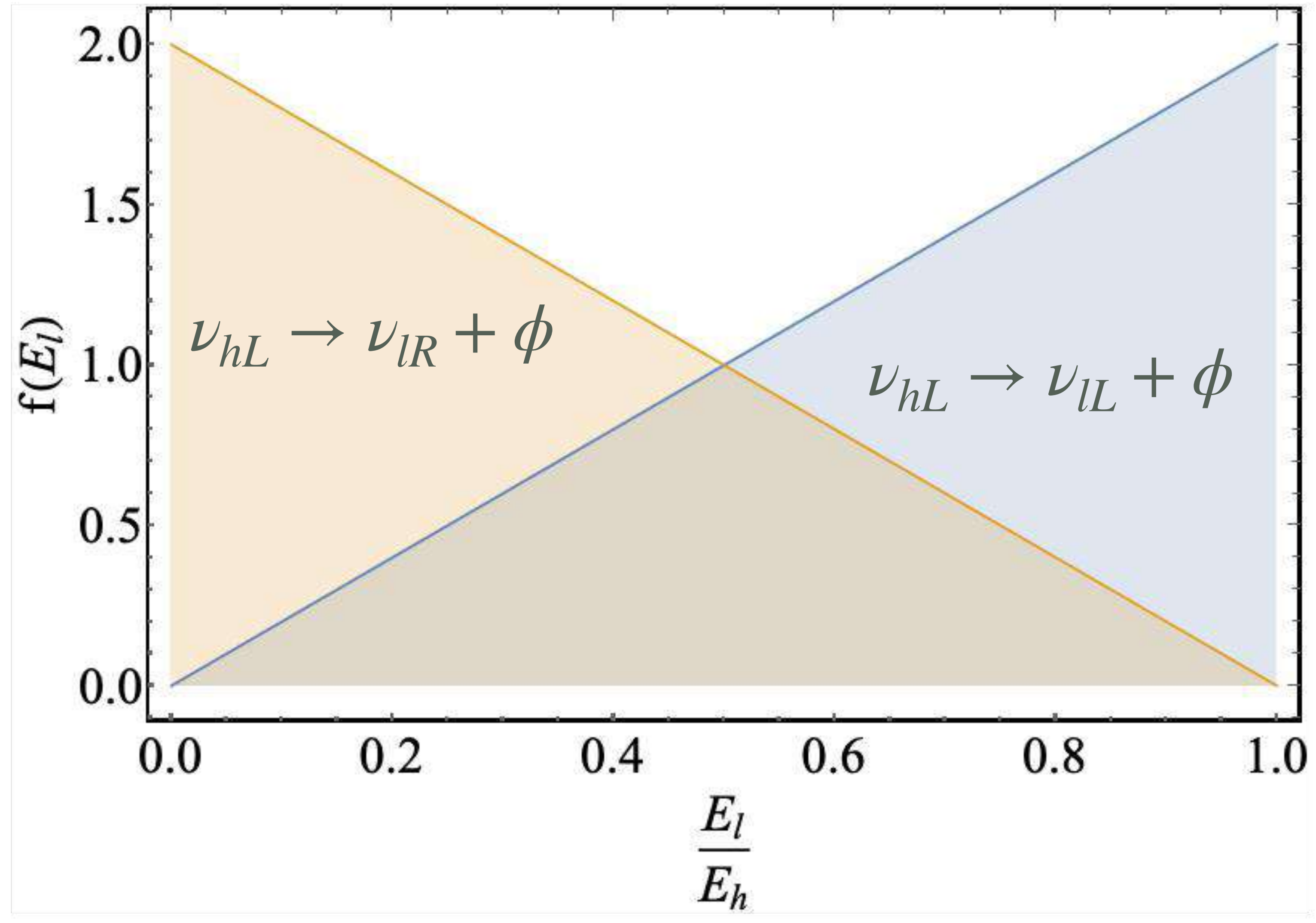
- New physics can mediate faster decay.

$$\mathscr{L} \supset \bar{\nu}_l \nu_h \, \varphi + \mathrm{H.c.}$$

$\nu_{hL} \to \nu_{lL} + \varphi$ …. Helicity cons. (h.c.)

$\nu_{hL} \to \nu_{lR} + \varphi$ …. Helicity flip. (h.f.)

- In ν_h rest frame, the daughter that shares the same helicity as the parent is emitted preferrentially along the parent helicity direction.

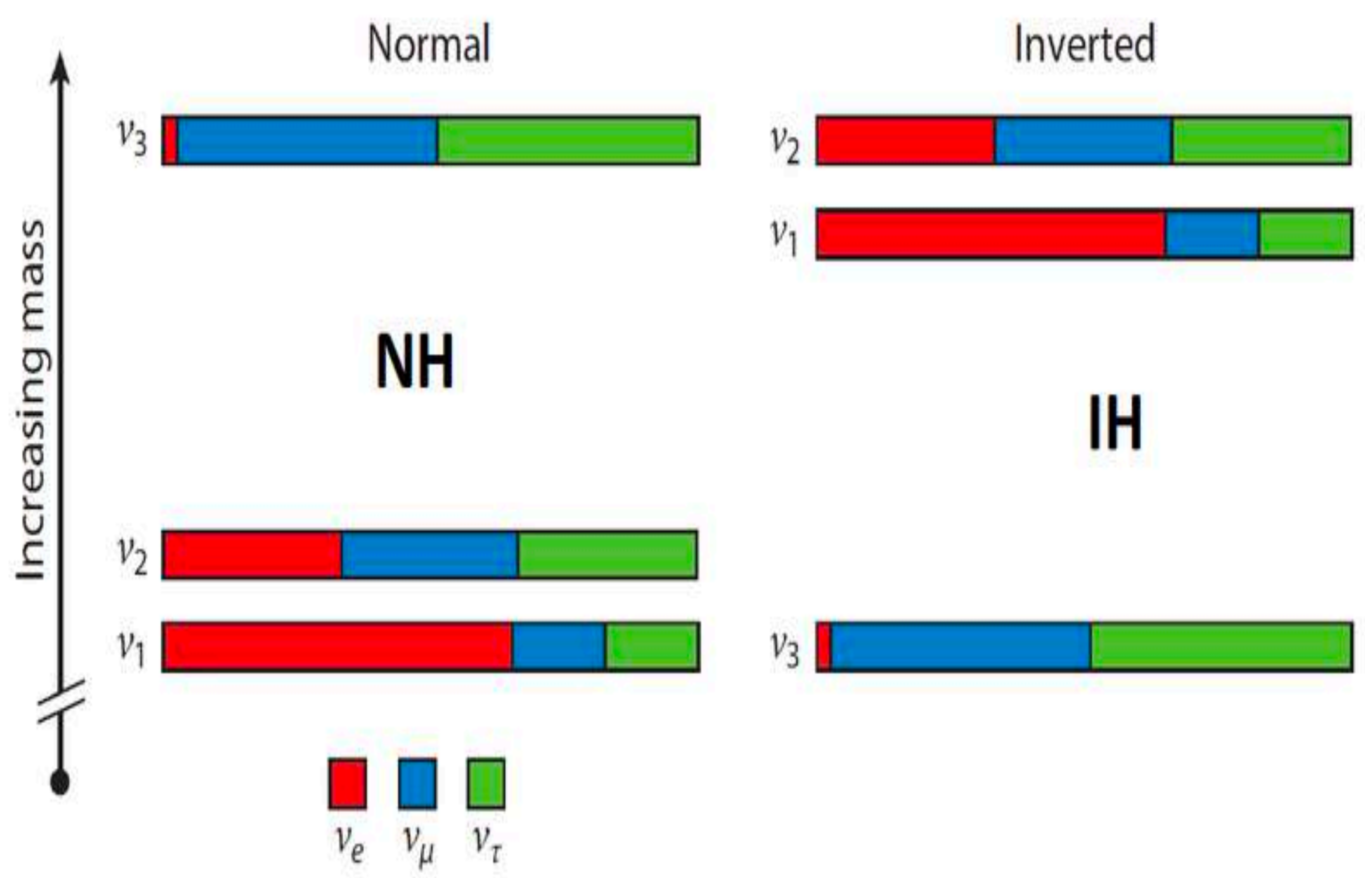


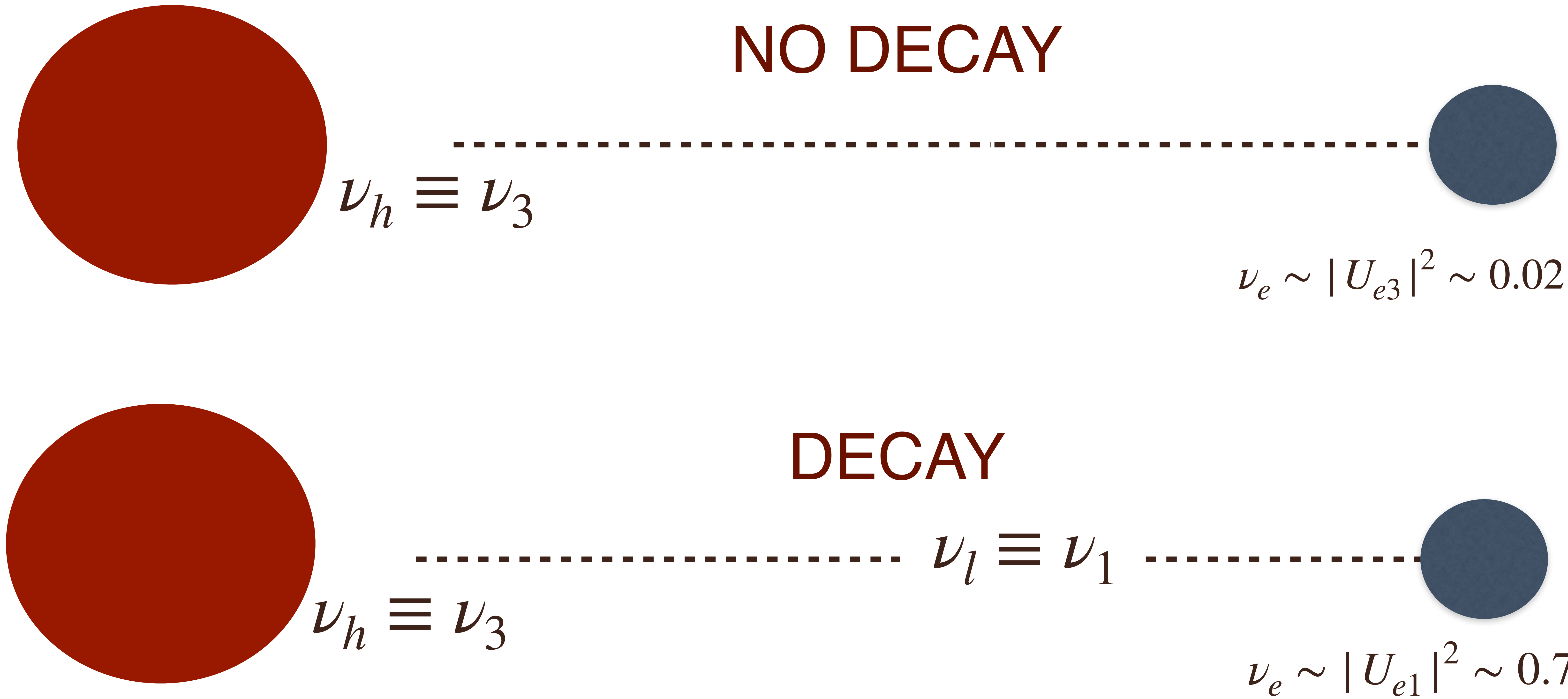
de Gouvea, Martinez-Soler, **MS** (PRD 2020)

How does neutrino decay work?

Normal Ordering

$\nu_3 \to \nu_1 \varphi$





NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim |U_{e3}|^2 \sim 0.02\, \nu_3$

Enhancement in spectra

DECAY

$\nu_l \equiv \nu_1$

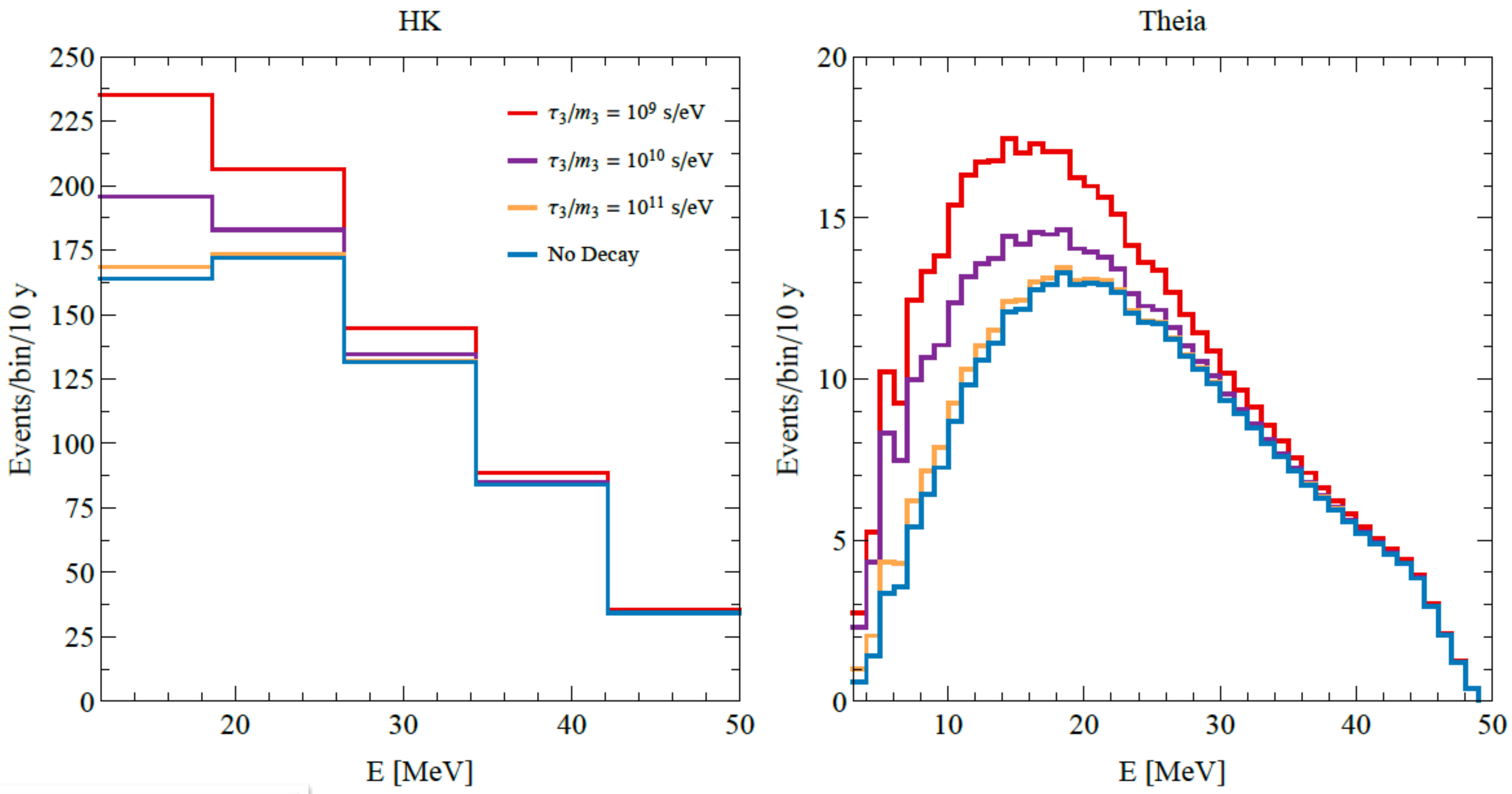
$\nu_h \equiv \nu_3$

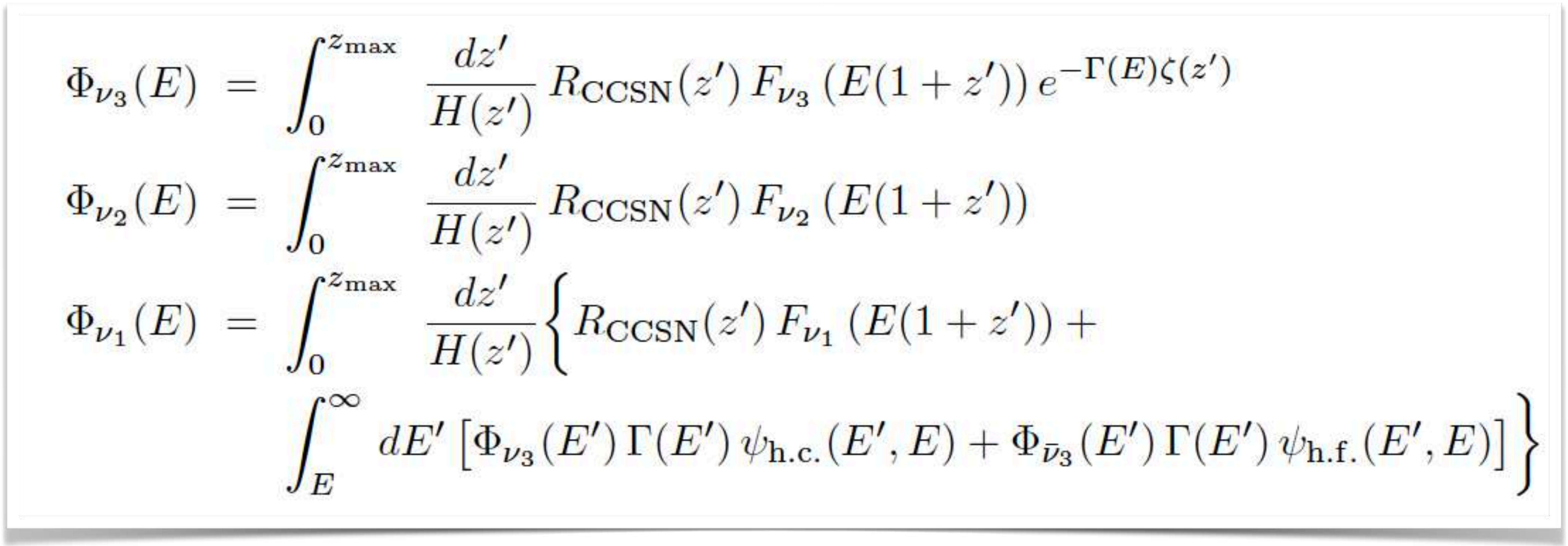
$\nu_e \sim |U_{e1}|^2 \sim 0.7\, \nu_e^{\text{in}}$

Simulated data at HK & Theia

- Consider Majorana neutrinos for maximum impact.
  Two channels:
  1. $\nu_{3L} \to \nu_{1L} + \varphi$
  2. $\nu_{3L} \to \nu_{1R}\, (\bar{\nu}_{1R}) + \varphi$

- ν_{1R} acts as anti-neutrinos, and detected as well.





$$\Phi_{\nu_3}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} R_{\rm CCSN}(z')\, F_{\nu_3}\,(E(1+z'))\, e^{-\Gamma(E)\zeta(z')}$$

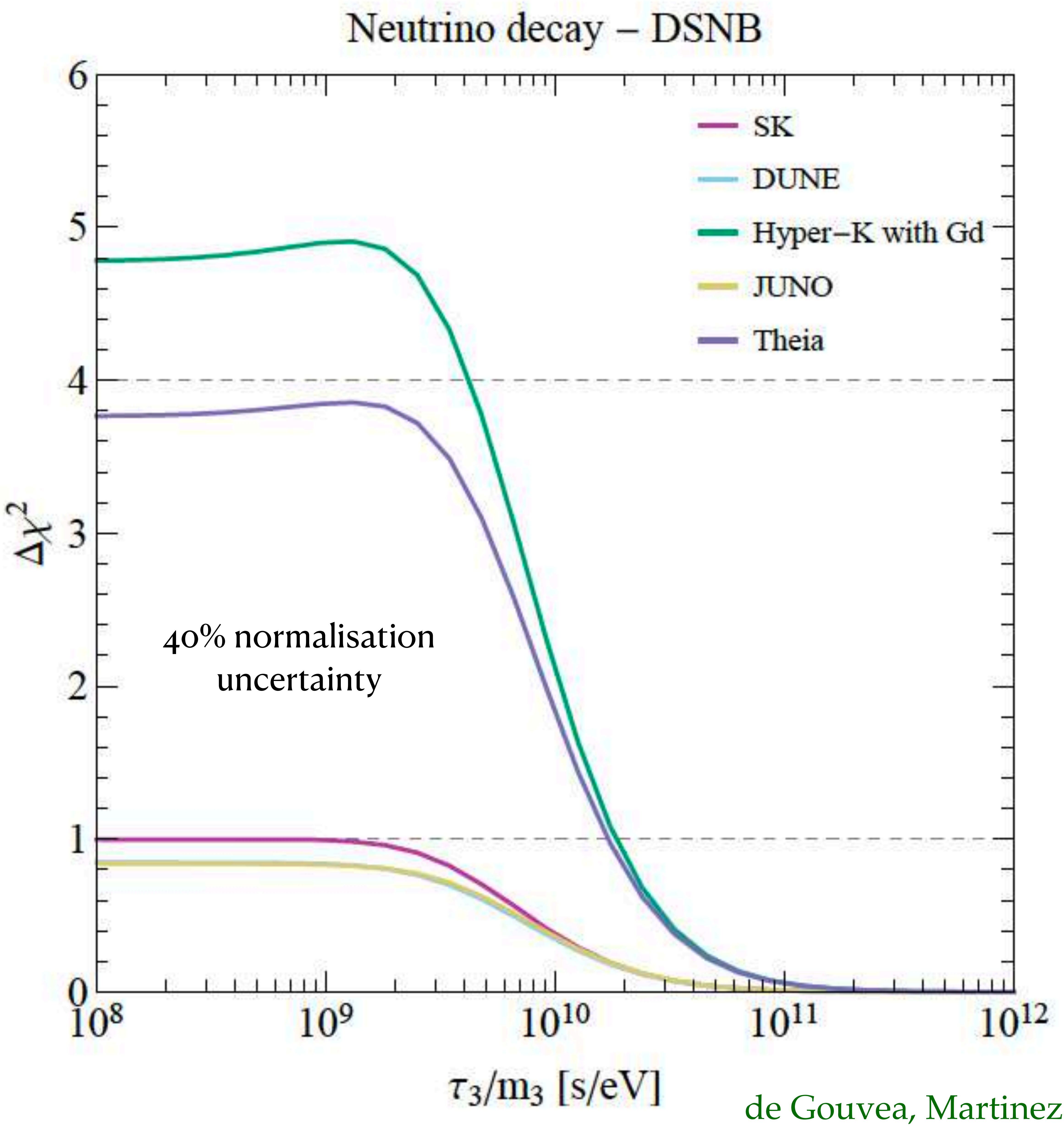
$$\Phi_{\nu_2}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} R_{\rm CCSN}(z')\, F_{\nu_2}\,(E(1+z'))$$

$$\Phi_{\nu_1}(E) = \int_0^{z_{\max}} \frac{dz'}{H(z')} \Big\{ R_{\rm CCSN}(z')\, F_{\nu_1}\,(E(1+z')) + \int_E^{\infty} dE' \left[\Phi_{\nu_3}(E')\,\Gamma(E')\,\psi_{\rm h.c.}(E',E) + \Phi_{\bar{\nu}_3}(E')\,\Gamma(E')\,\psi_{\rm h.f.}(E',E)\right] \Big\}$$

Ando (PLB 2003)
Fogli, Lisi, Mirizzi, Montanino (PRD 2004)

de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

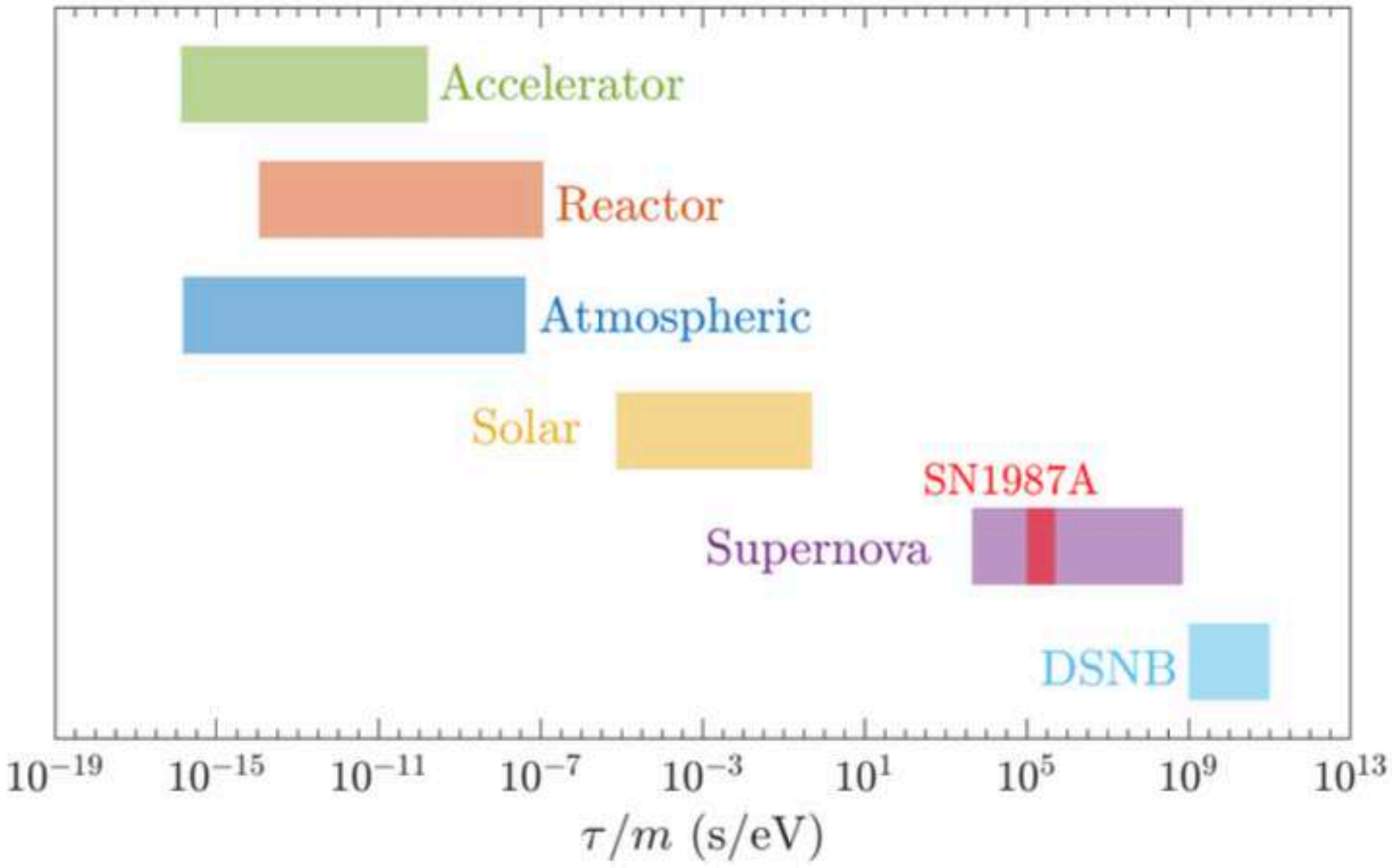
Constraints on neutrino lifetime



40% normalisation uncertainty

de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

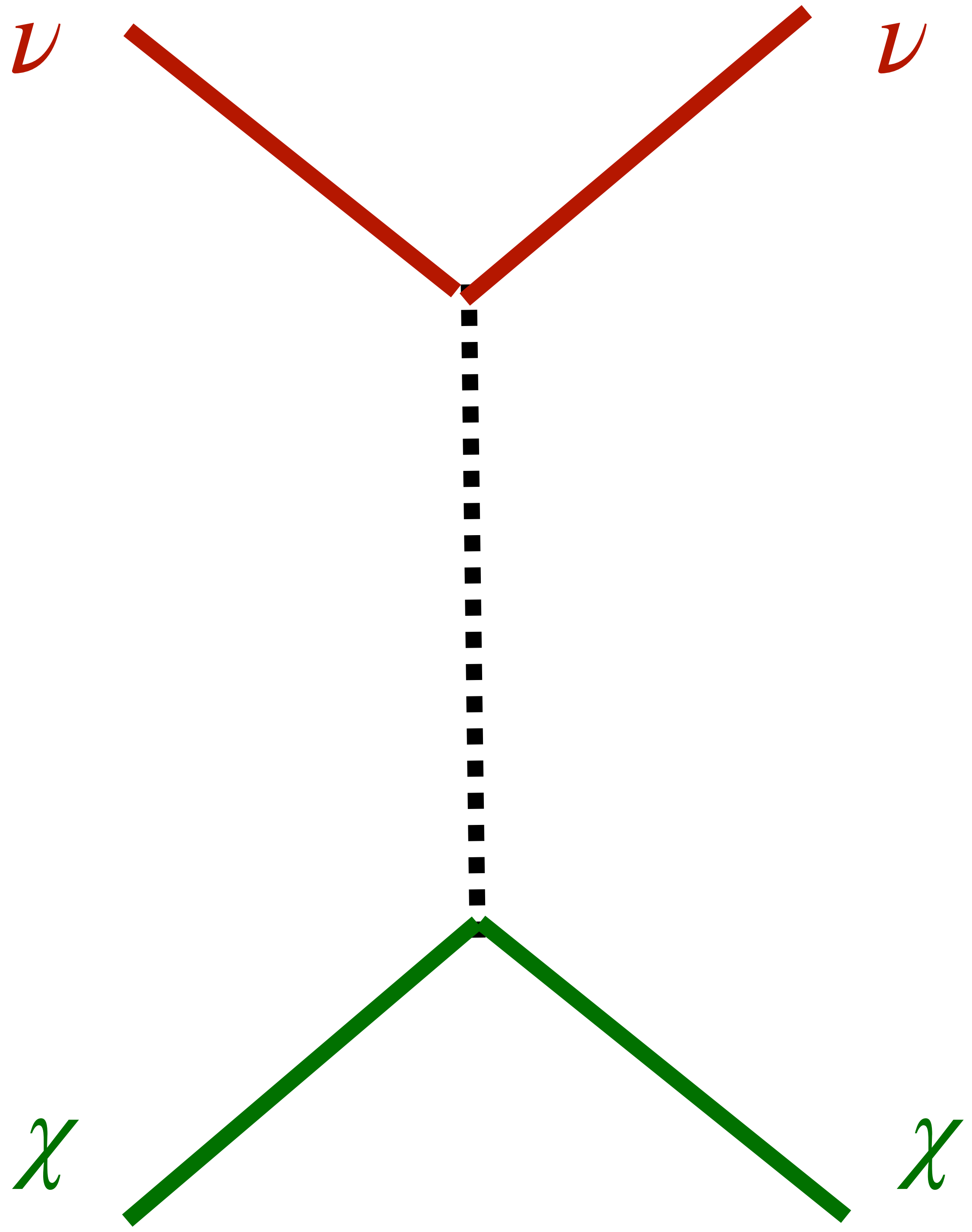
Ivanez-Ballesteros, Volpe (PLB 2023)



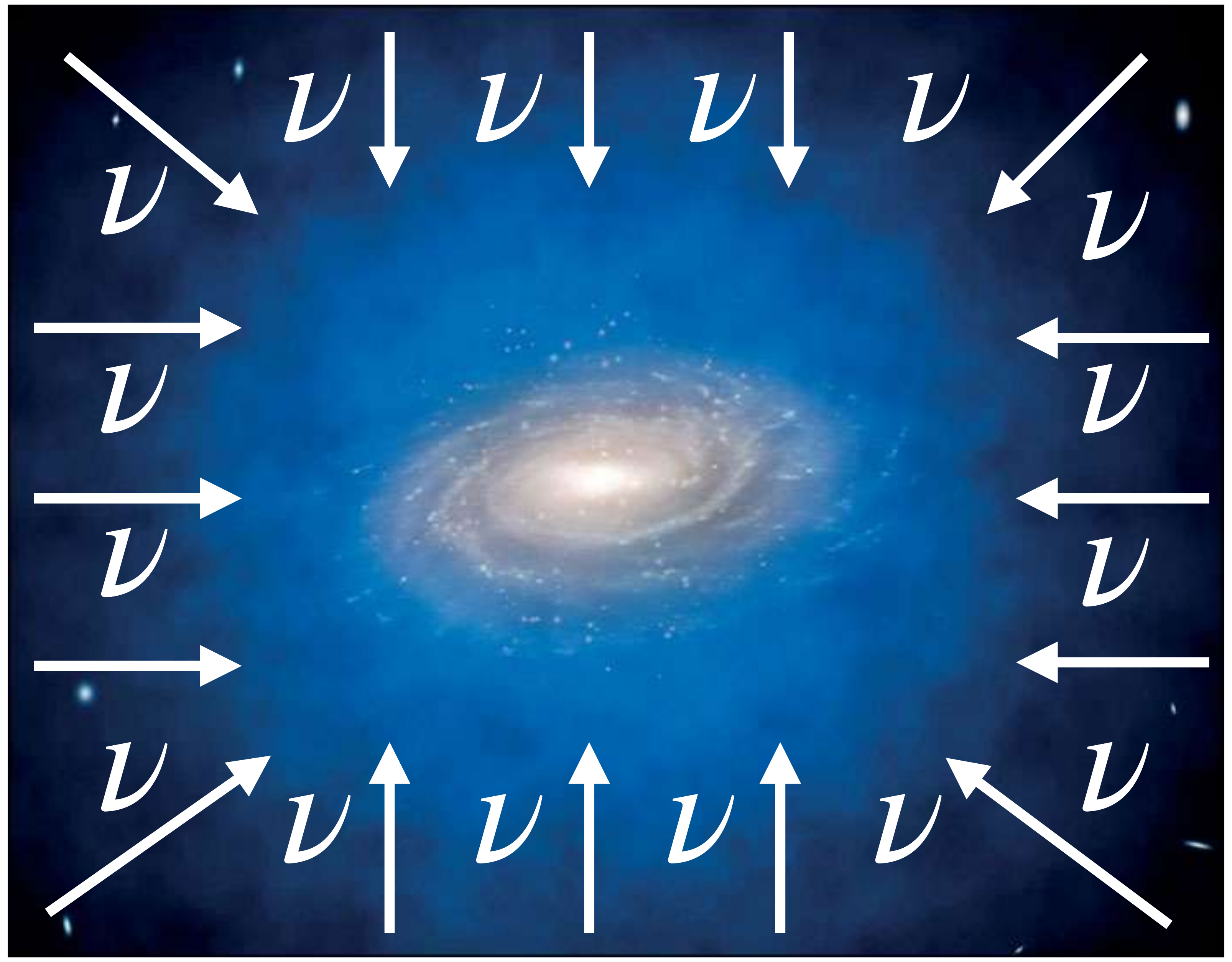
See also

1) Tabrizi and Horiuchi (JCAP 2021)
2) Ivanez-Ballesteros, Volpe (PRD 2023)
3) Martinez-Mirave, Tamborra, Tortola (JCAP 2024)

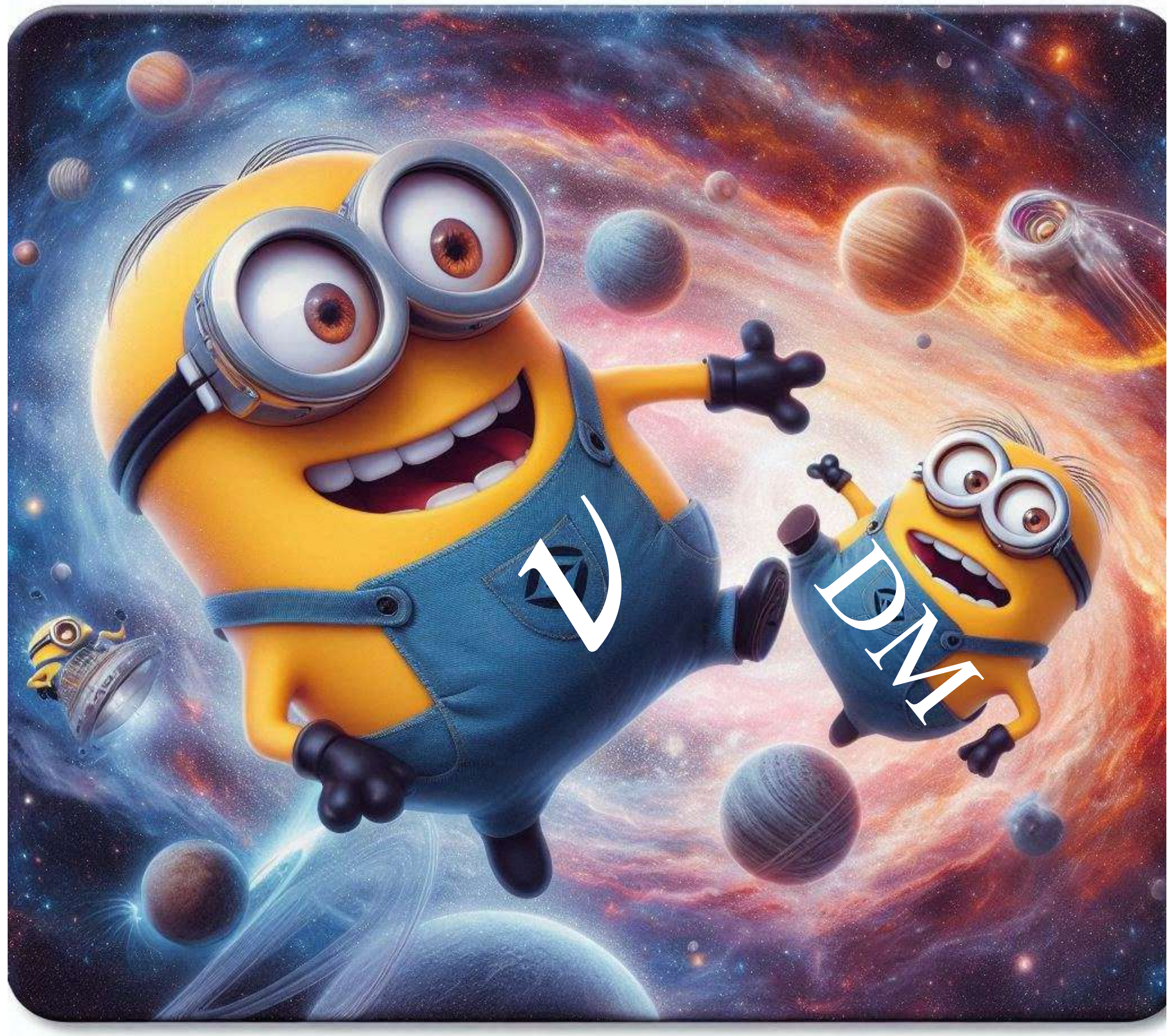
2. Neutrino-dark matter interactions



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 for sub GeV DM particles.



Das, Herbermann, **MS**, Takhistov (JCAP 2024)
Das, **MS** (PRD 2021)

How to estimate Boosted Dark Matter flux?

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

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

- Simplification $\frac{d\sigma_{\nu\chi}}{dT_\chi} = \frac{\sigma}{T_\chi^{\text{max}}}$, where $T_\chi^{\text{max}} = \frac{E_\nu^2}{E_\nu + m_\chi/2}$

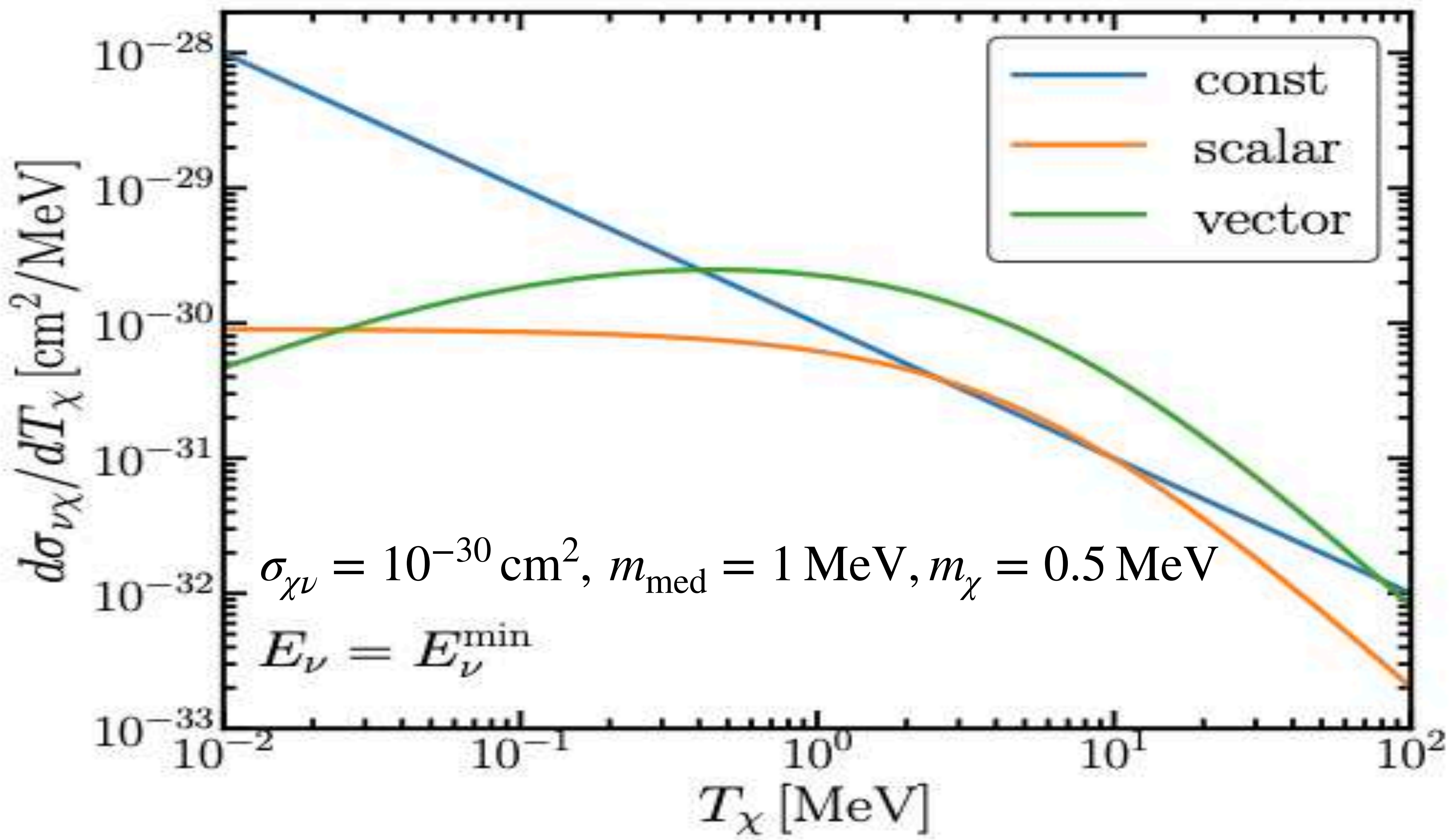
- Or over-simplification?

Inaccuracy of a constant cross-section assumption

- The assumption $\dfrac{d\sigma_{\nu\chi}}{dT_\chi} = \dfrac{\sigma}{T_\chi^{\max}}$ can sometimes 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: $\mathscr{L} \supset (g\,\bar{L}\gamma_\mu L + g_\chi\,\bar{\chi}\gamma_\mu\chi)\,Z'^{\mu}$

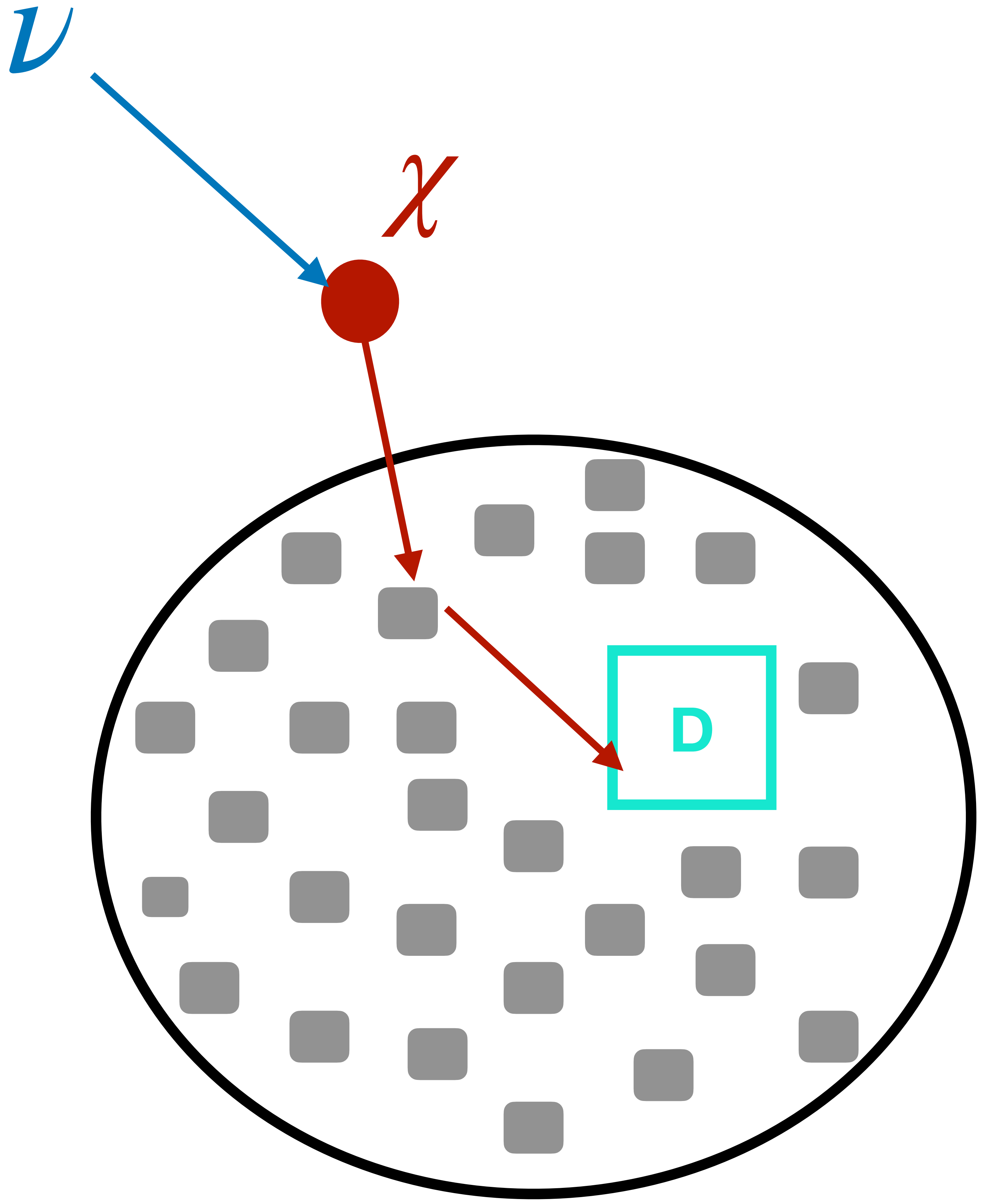


Attentuation effect

- 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

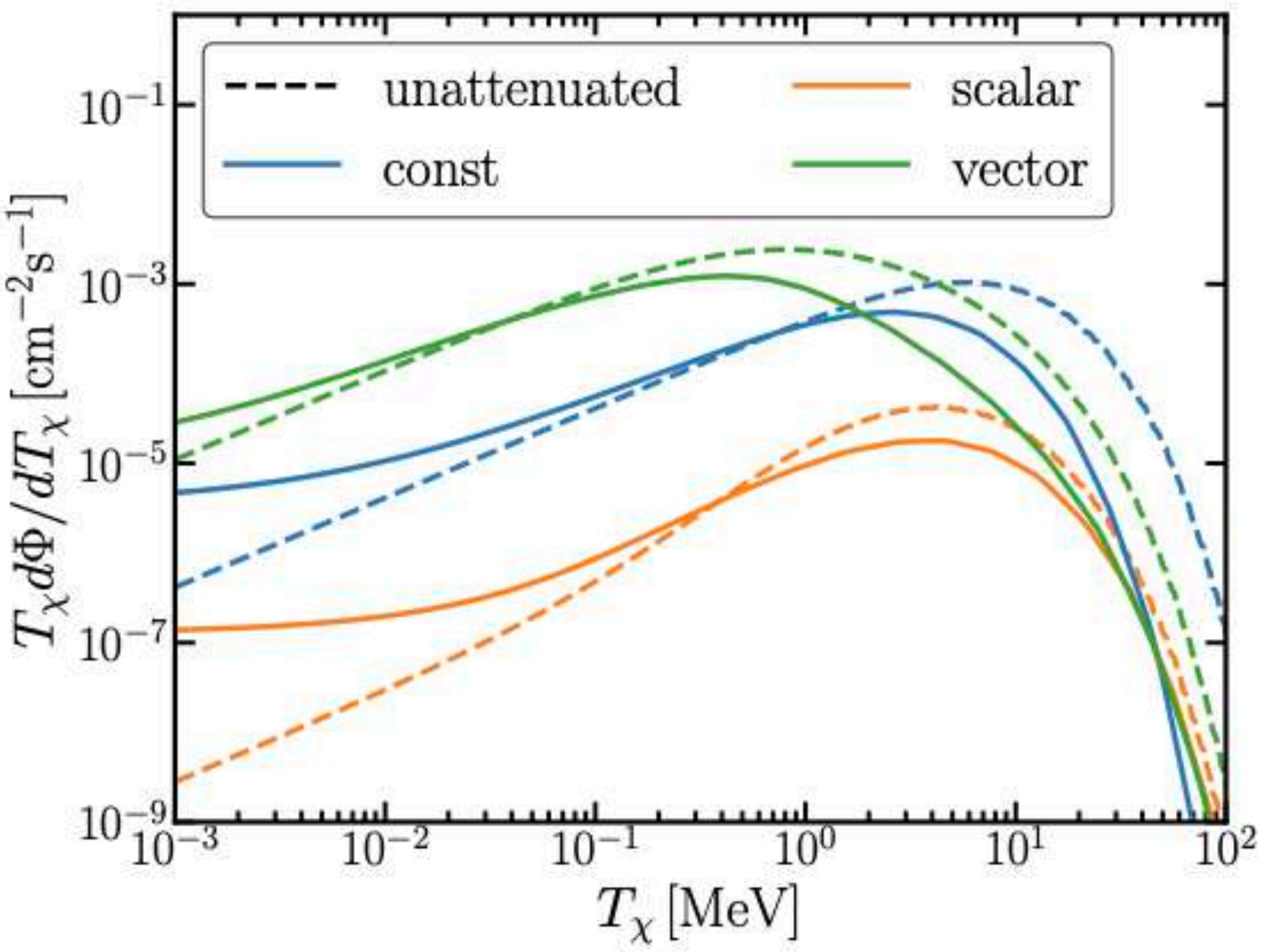
$$\frac{dT_\chi}{dx}(x) = -\sum_i n_i(x) \int_0^{T_i^{\max}} dT_i\, T_i \frac{d\sigma_{i\chi}}{dT_i}\,.$$



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

- Perform a fully numerical computation of the attenuation.

The boosted DM flux



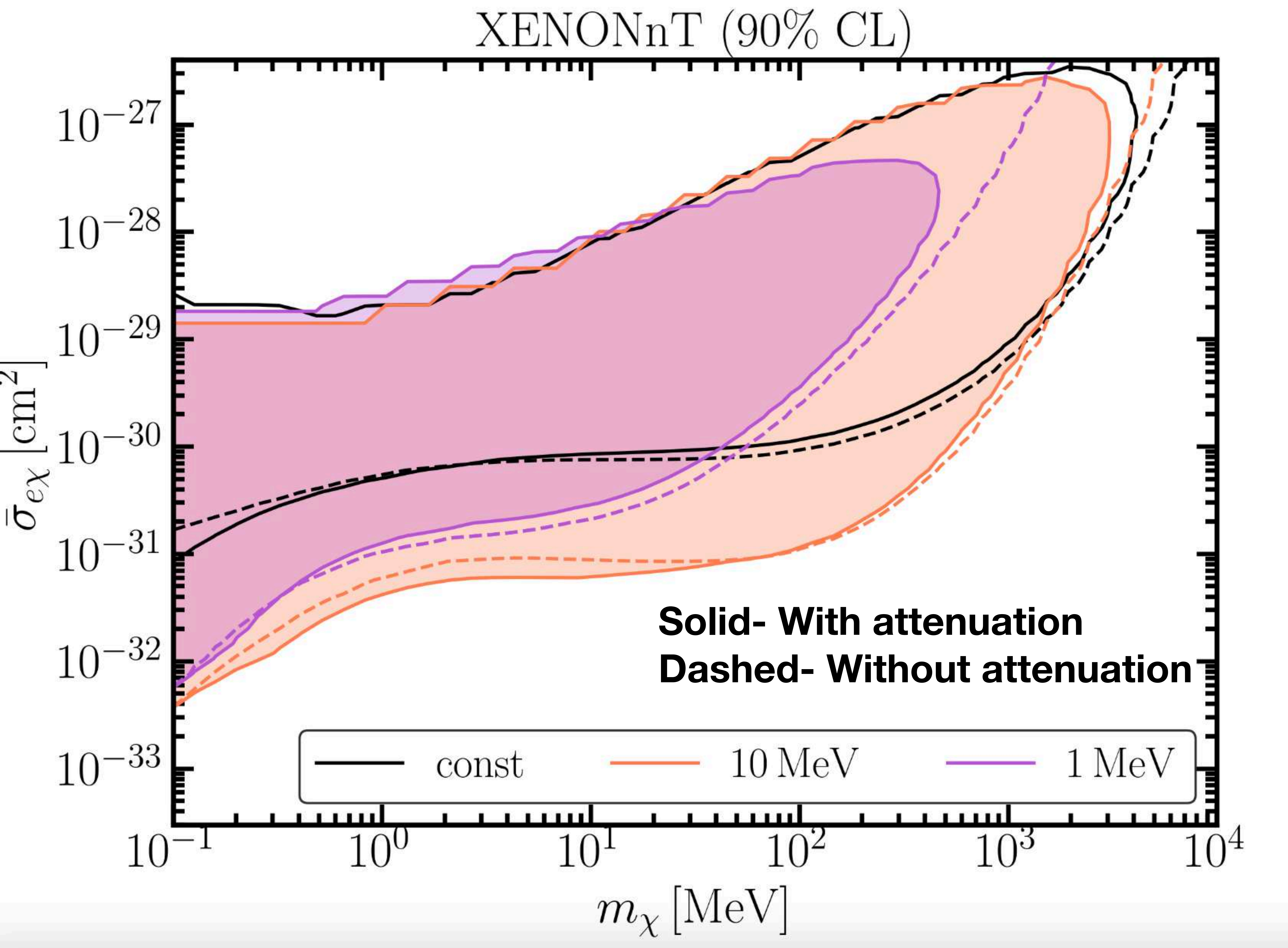
- Significant difference with results from constant case with same effective cross-section!!

- Attenuation:
  (i) Suppression

  (ii) Down scattering of high energy BDM.

Das, Herbermann, **MS**, Takhistov (JCAP 2024)

How does this affect signals in DD experiments?



Das, Herbermann, **MS**, Takhistov (JCAP 2024)

- Consider the example of vector mediator and XENONnT.

- Here

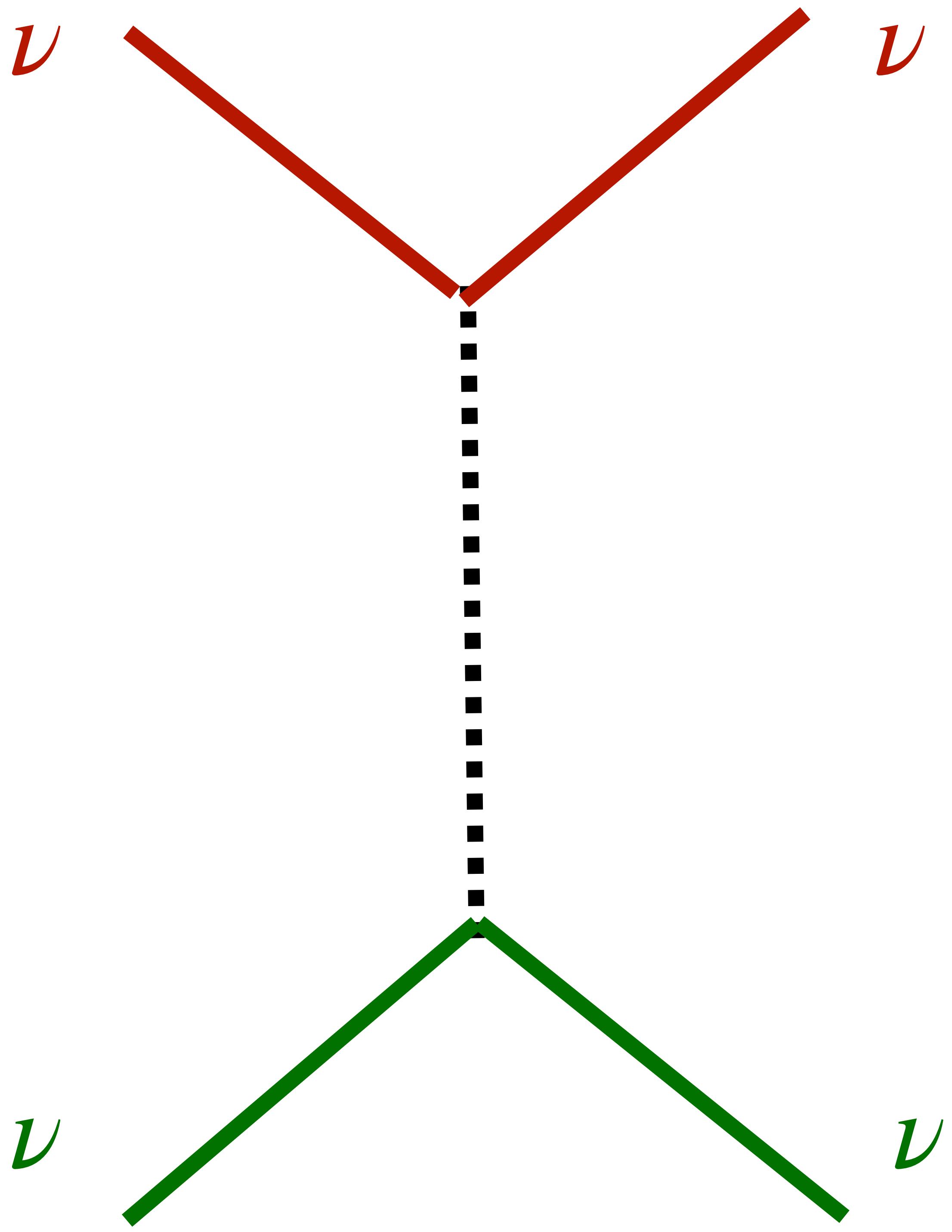
$$\bar{\sigma}_{e\chi} = \frac{g^4}{\pi} \frac{\mu_{e\chi}^2}{(q_{\rm ref}^2 + m_{\rm med}^2)^2}$$

- Attenuation:
  (i) Upper ceiling constraint.

  (ii) Down scattering - stronger constraints at lower m_χ.

- Allows testing low mass DM through direct detection

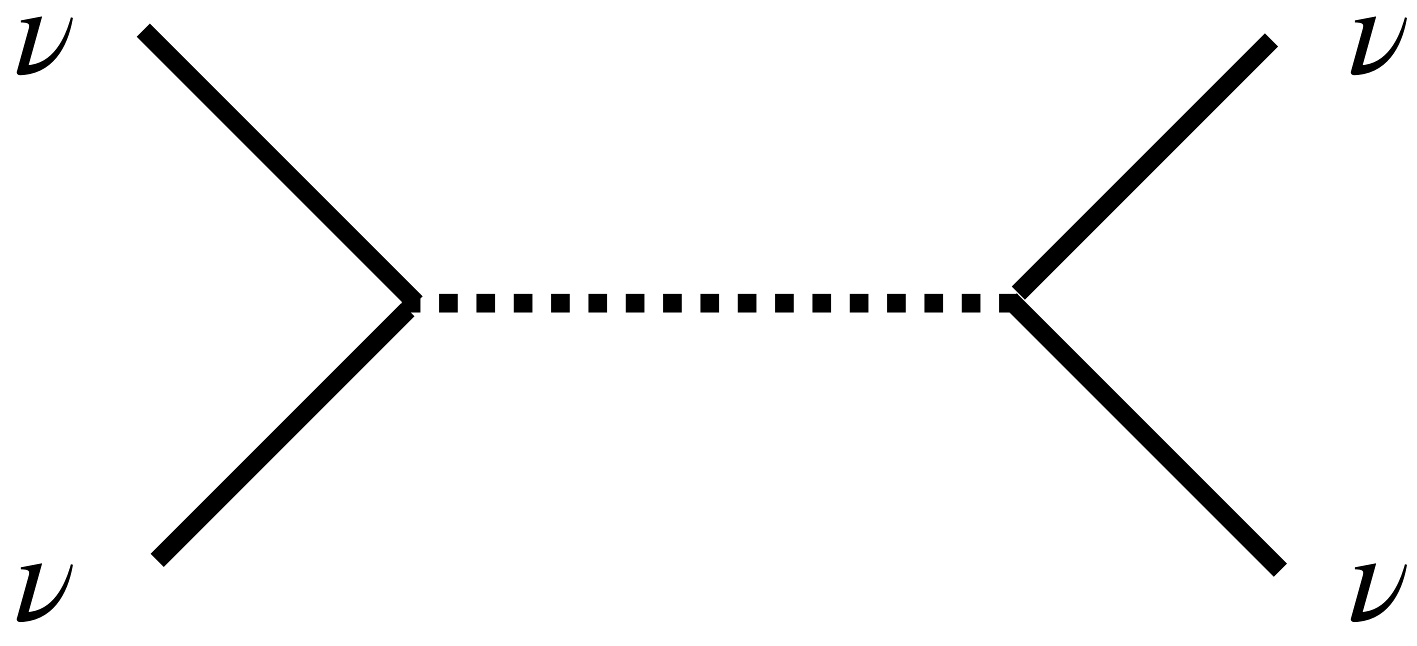
3. Neutrino self-interactions



Neutrino non-standard self-interactions

- Active neutrino secret self-interactions. Can be much stronger than ordinary weak interactions.

- Model building aspect?
  Consider
  $$\mathscr{L}_\nu = \frac{y}{\Lambda^2}(LH)^2\varphi^* \quad \xrightarrow{\text{EWSB}} \quad \lambda_\varphi \nu_a \nu_a \varphi^* \ ,$$
  φ can have lepton number



- Constraints from terrestrial experiments are loose: $G \sim (10^7 - 10^9)G_F$ cannot always be ruled out.

- However, can have strong impact in the early Universe or compact objects.

What are the different constraints?

- Invisible Higgs decays, Z decays : $H, Z \to \nu\nu\phi$. Tau decays.
- Meson decays: $K^- \to \mu^-\nu_\mu\varphi, \quad \varphi \to \nu\nu$. Bounds from $\mathrm{Br}(K^- \to \mu^- 3\nu) < 10^{-6}$.
- Neutrinoless double beta decay. $(Z, A) \to (Z+2, A)\ e^-e^-\phi$
- BBN: extra radiation

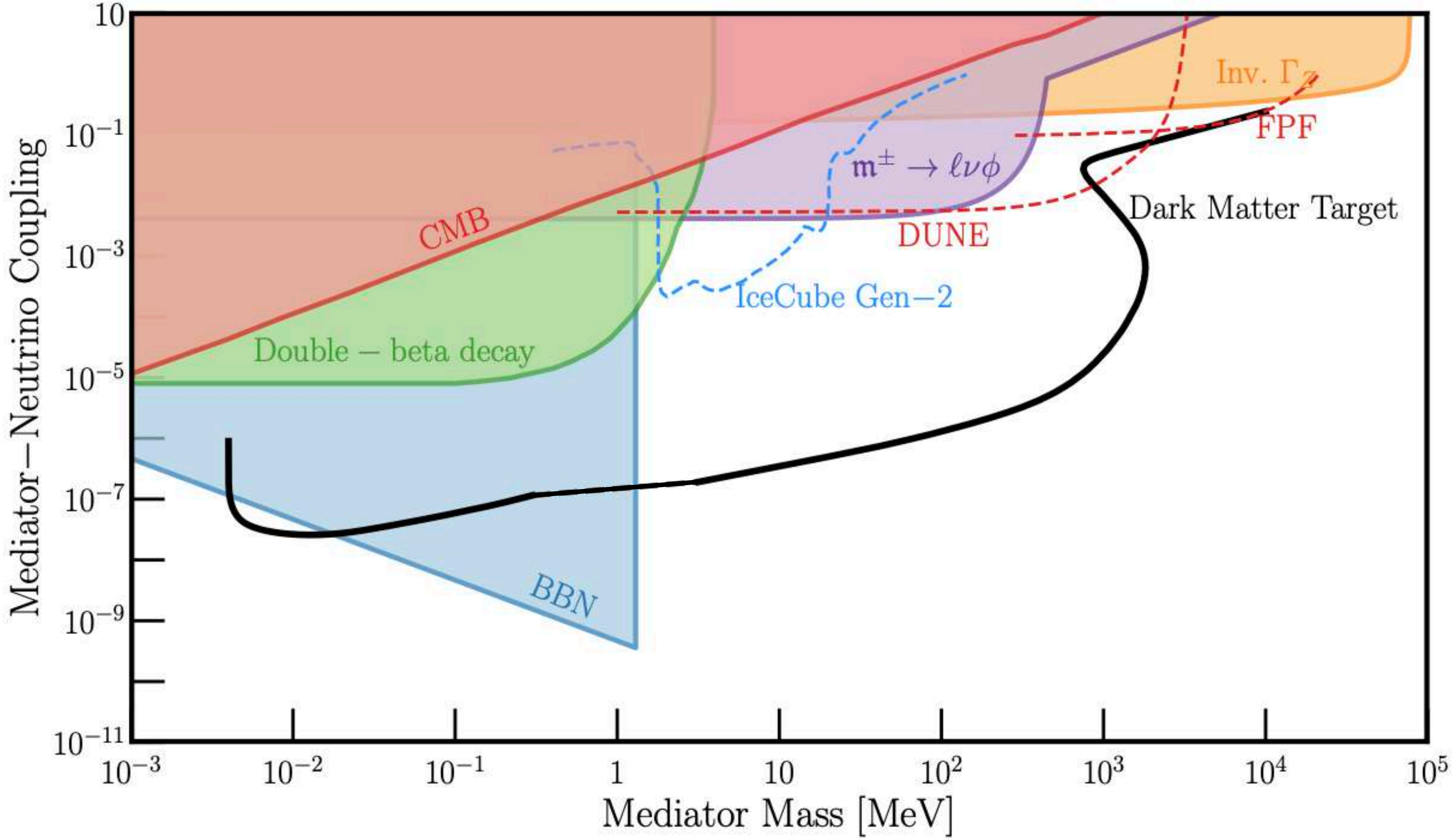
- SN1987A: cooling bounds, scattering on dense environments.
- High energy neutrinos scattering off the Cosmic Neutrino Background.
- Look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$.

Neutrino Self-Interactions: A White Paper

Jeffrey M. Berryman, Nikita Blinov, Vedran Brdar, Thejs Brinckmann, Mauricio Bustamante, Francis-Yan Cyr-Racine, Anirban Das, André de Gouvêa, Peter B. Denton, P.S. Bhupal Dev, Bhaskar Dutta, Ivan Esteban, Damiano F.G. Fiorillo, Martina Gerbino, Subhajit Ghosh, Tathagata Ghosh, Evan Grohs, Tao Han, Steen Hannestad, Matheus Hostert, Patrick Huber, Jeffrey Hyde, Kevin J. Kelly, Felix Kling, Zhen Liu, Massimiliano Lattanzi, Marilena Loverde, Sujata Pandey, Ninetta Saviano, Manibrata Sen, Ian M. Shoemaker, Walter Tangarife, Yongchao Zhang, Yue Zhang

Snowmass report (Phys. Dark. Uni., 2023)

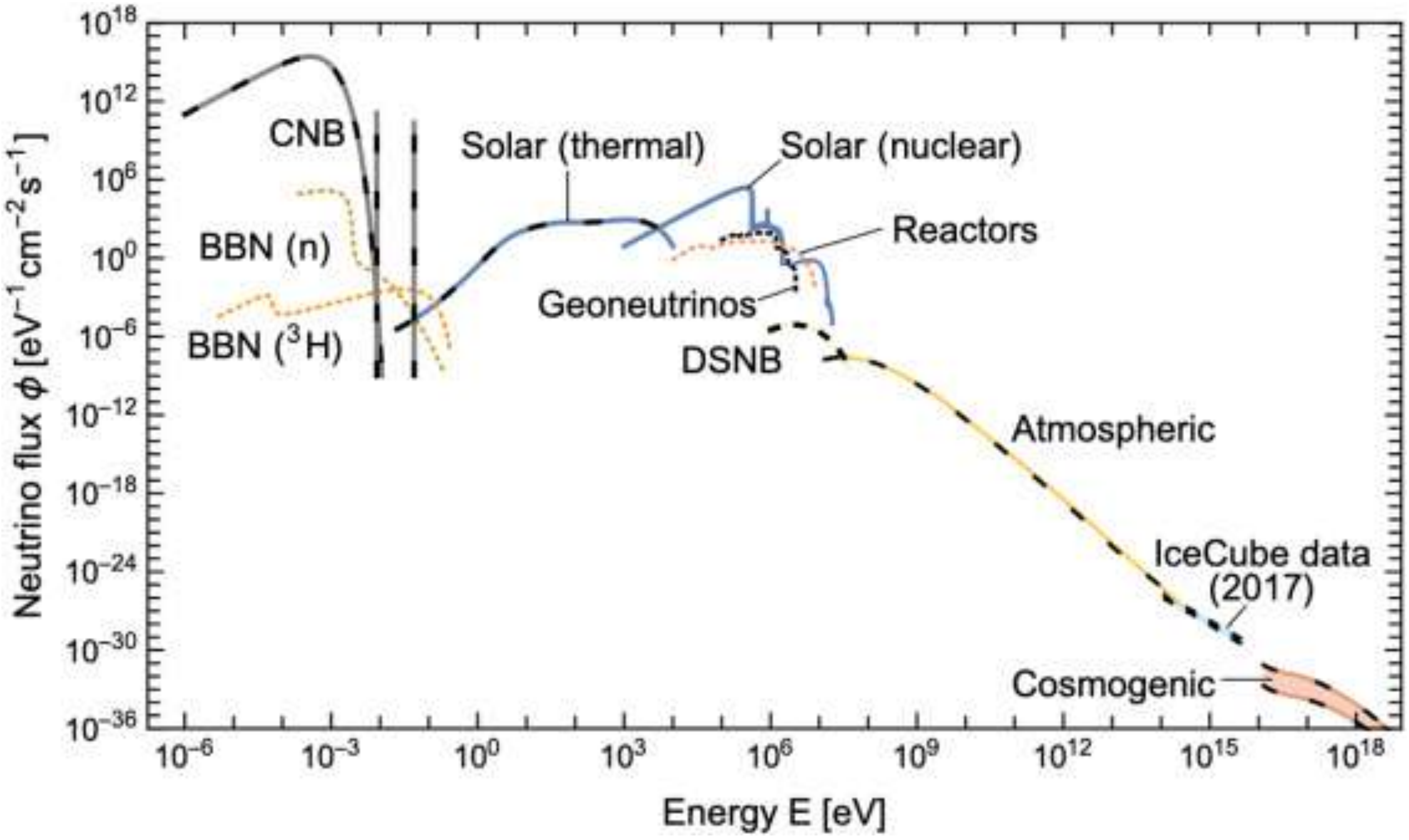
Neutrino self-interaction bounds



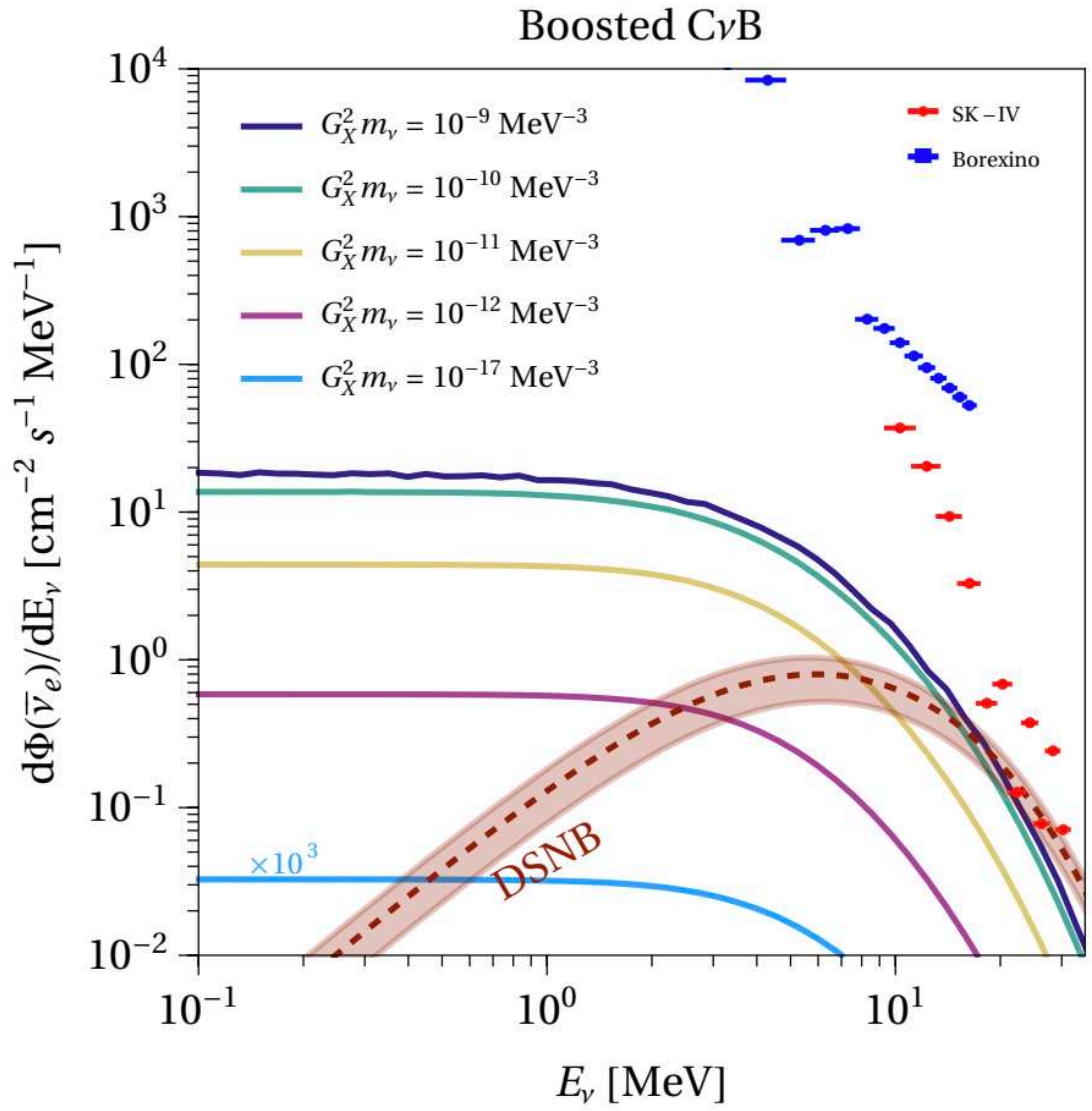
Zhang, Kelly, **MS**, (PRL 2021)

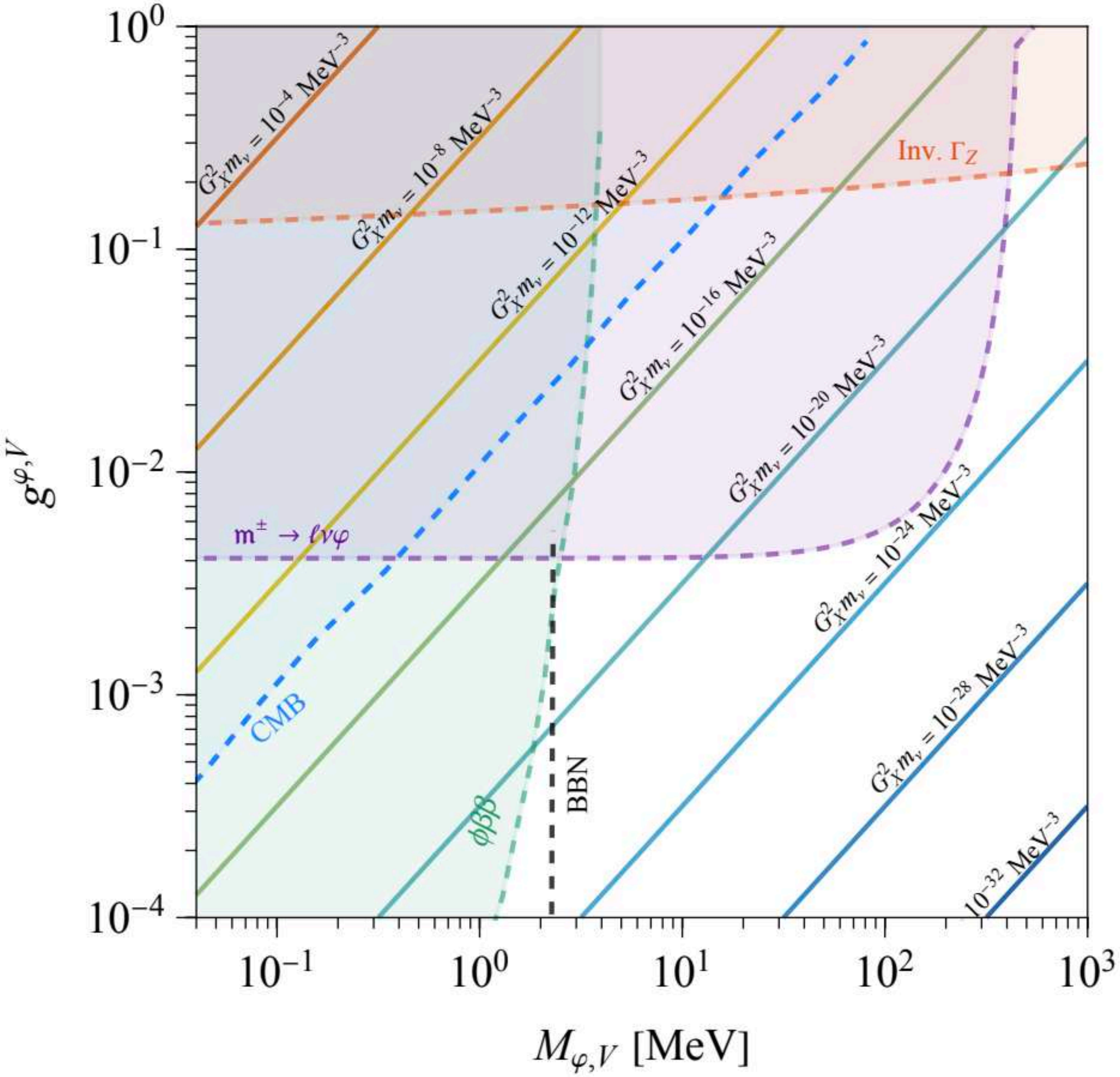
Snowmass report (Phys. Dark. Uni., 2023)

3.1) Boosting the CνB



The boosted CνB flux





The values of the self-interaction that can boost the CνB is in tension with lab bounds.

Das, Perez-Gonzalez, **MS** (PRD 2022)

3.2) Scalar production and decay into neutrinos

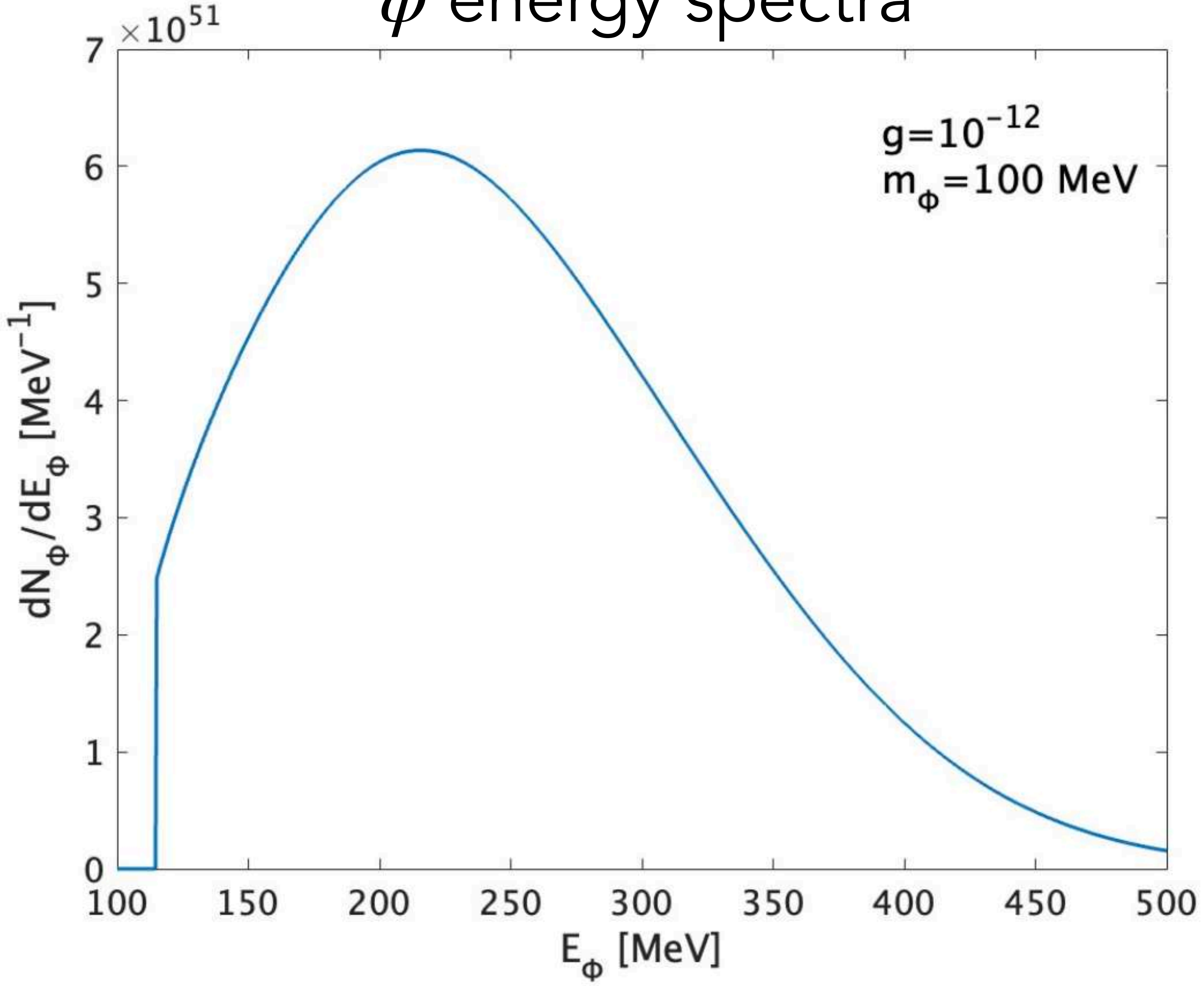
- $\mathscr{L}_\nu \supset g\, \nu_a \nu_a \varphi$,

- Allows for $\nu_a \nu_a \rightarrow \phi$ and subsequent $\phi \rightarrow \nu_a \nu_a$.

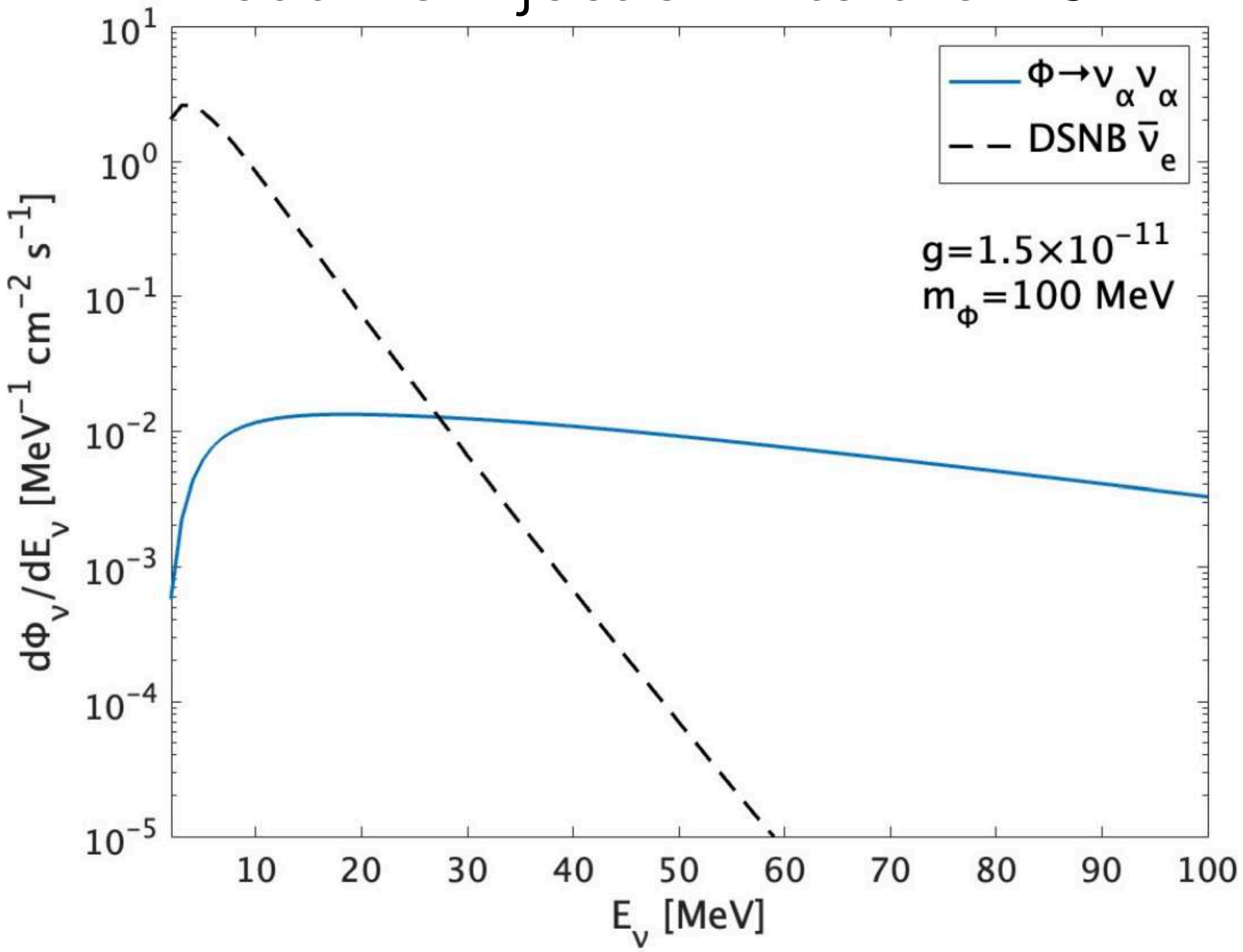
Akita, Im, Masud (JHEP 2022)

- Considered $\mu_{\nu_e} \simeq 200\,\mathrm{MeV}$, which allows large mass ϕ to be produced.

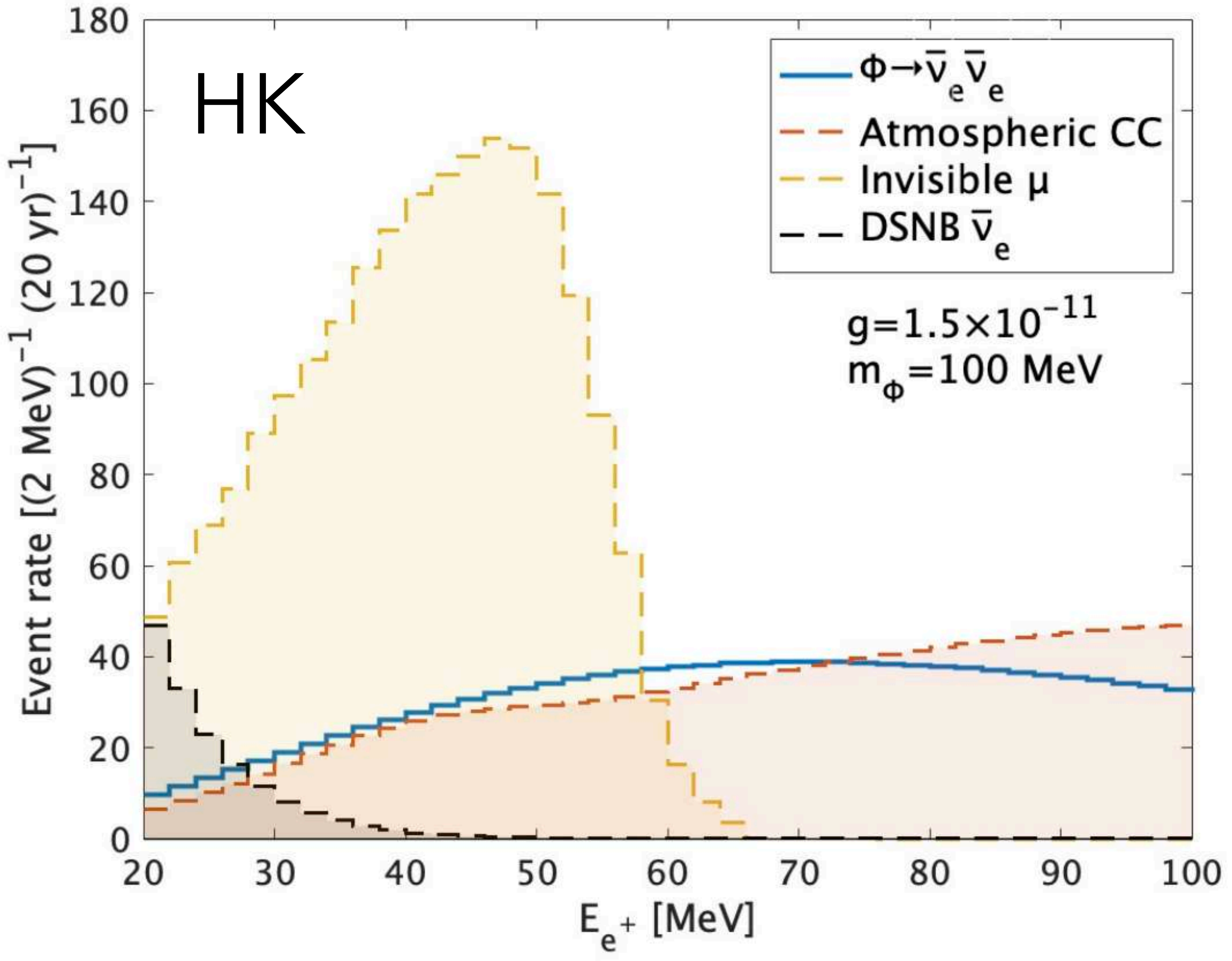
ϕ energy spectra

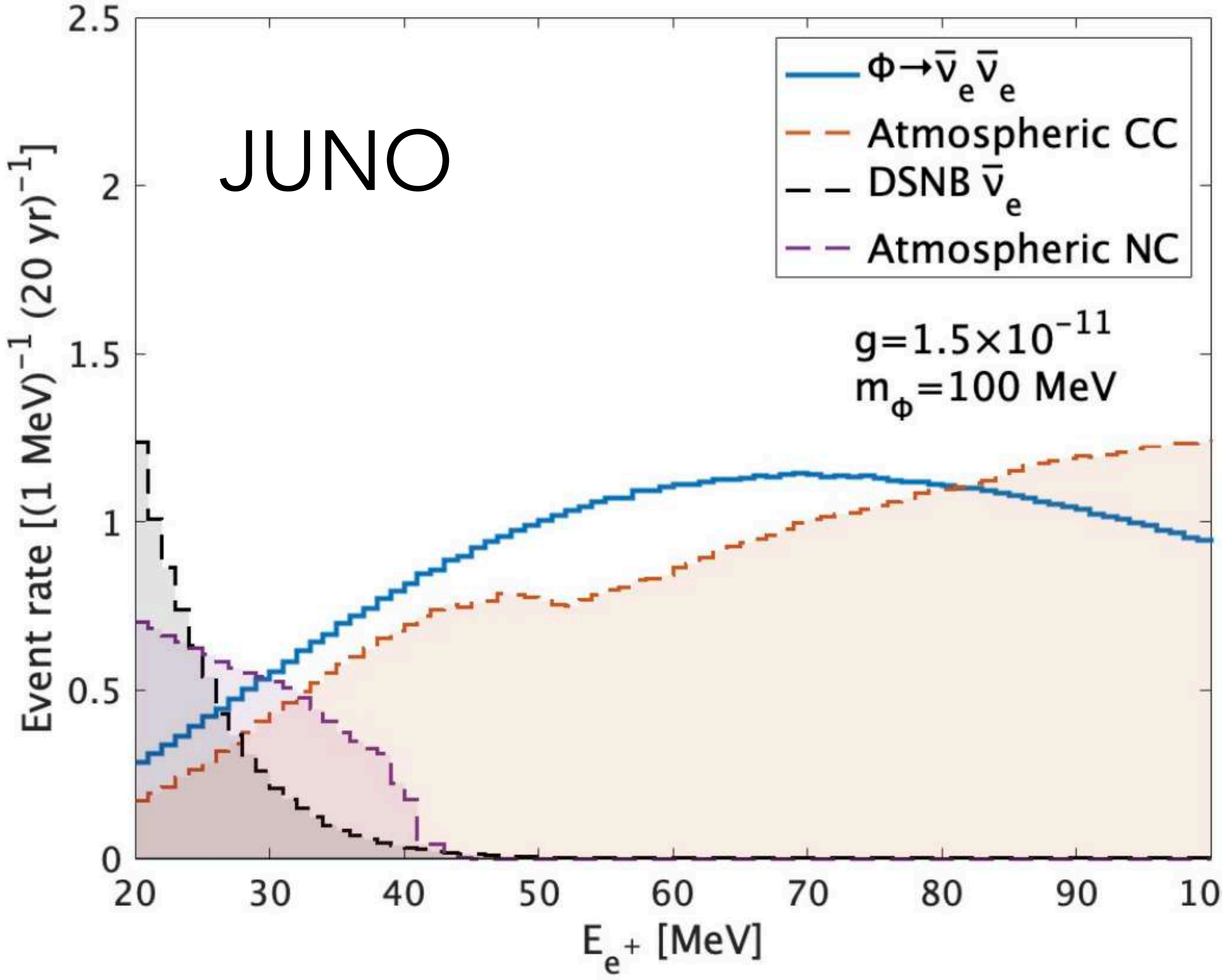


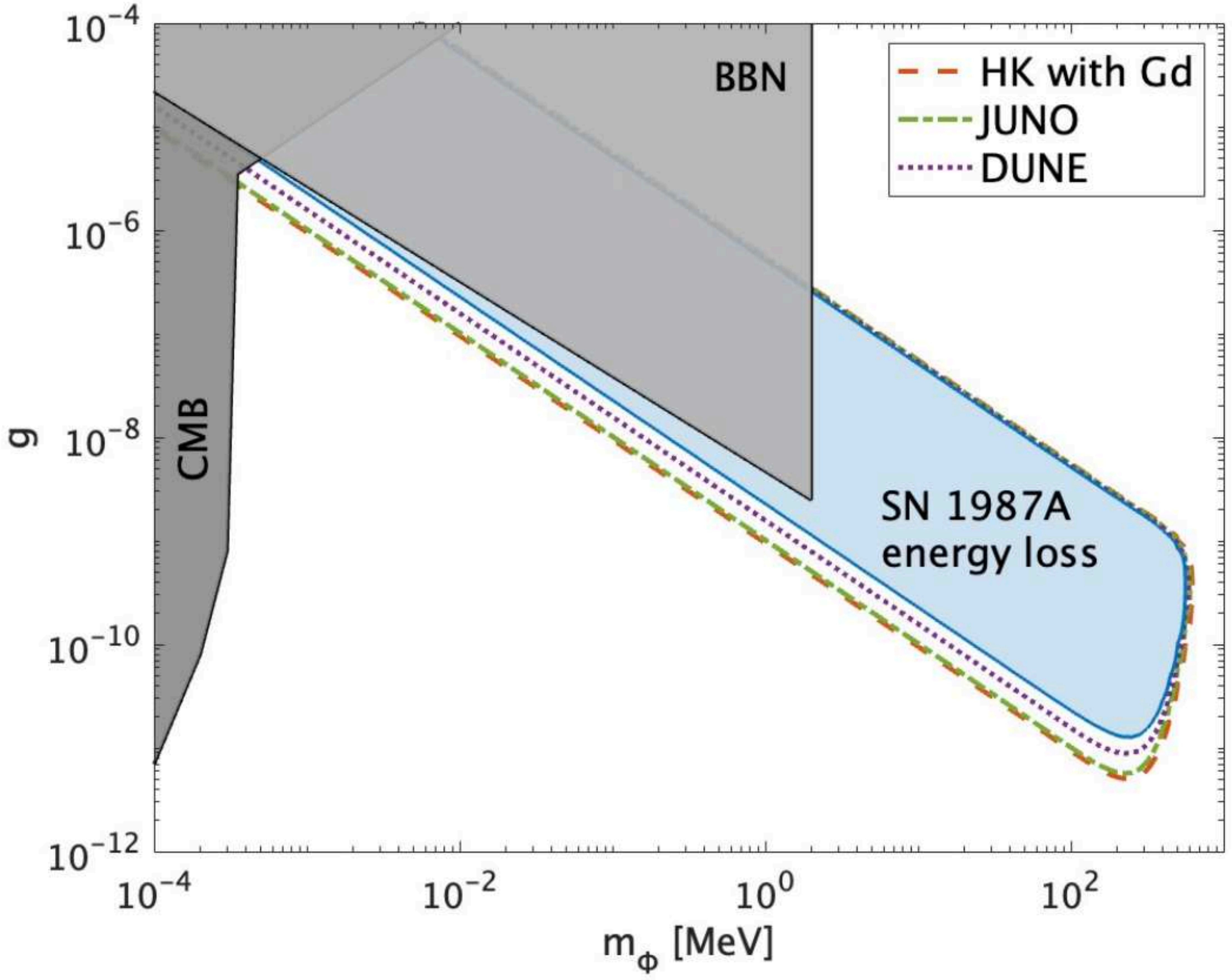
Neutrino injection into the DSNB



Scalar decays into neutrinos

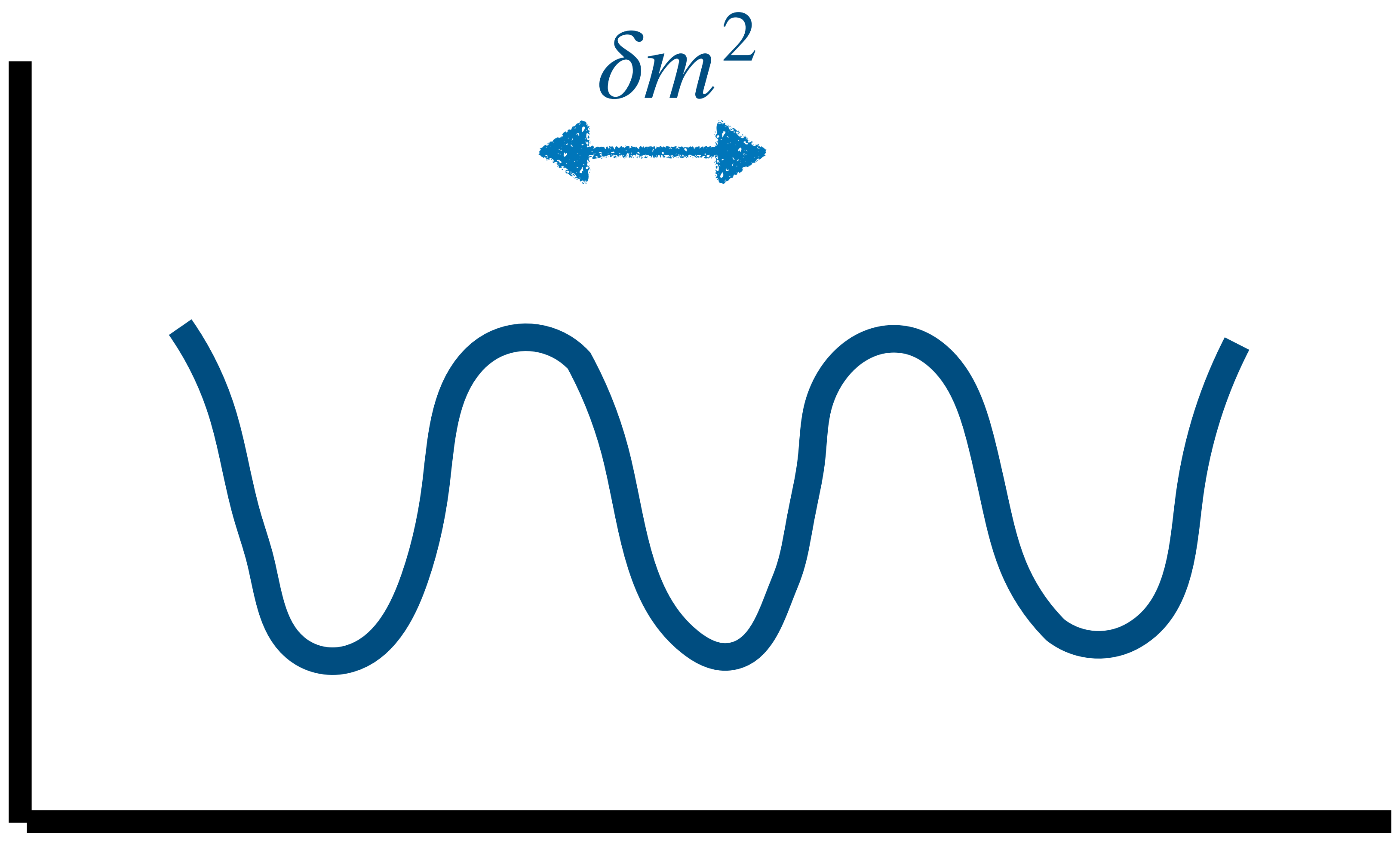






Akita, Im, Masud (JHEP 2022)

4. Pseudo-Dirac Neutrinos



Pseudo(quasi) Dirac Neutrinos

- Neutrinos have sub-dominant Majorana mass terms.

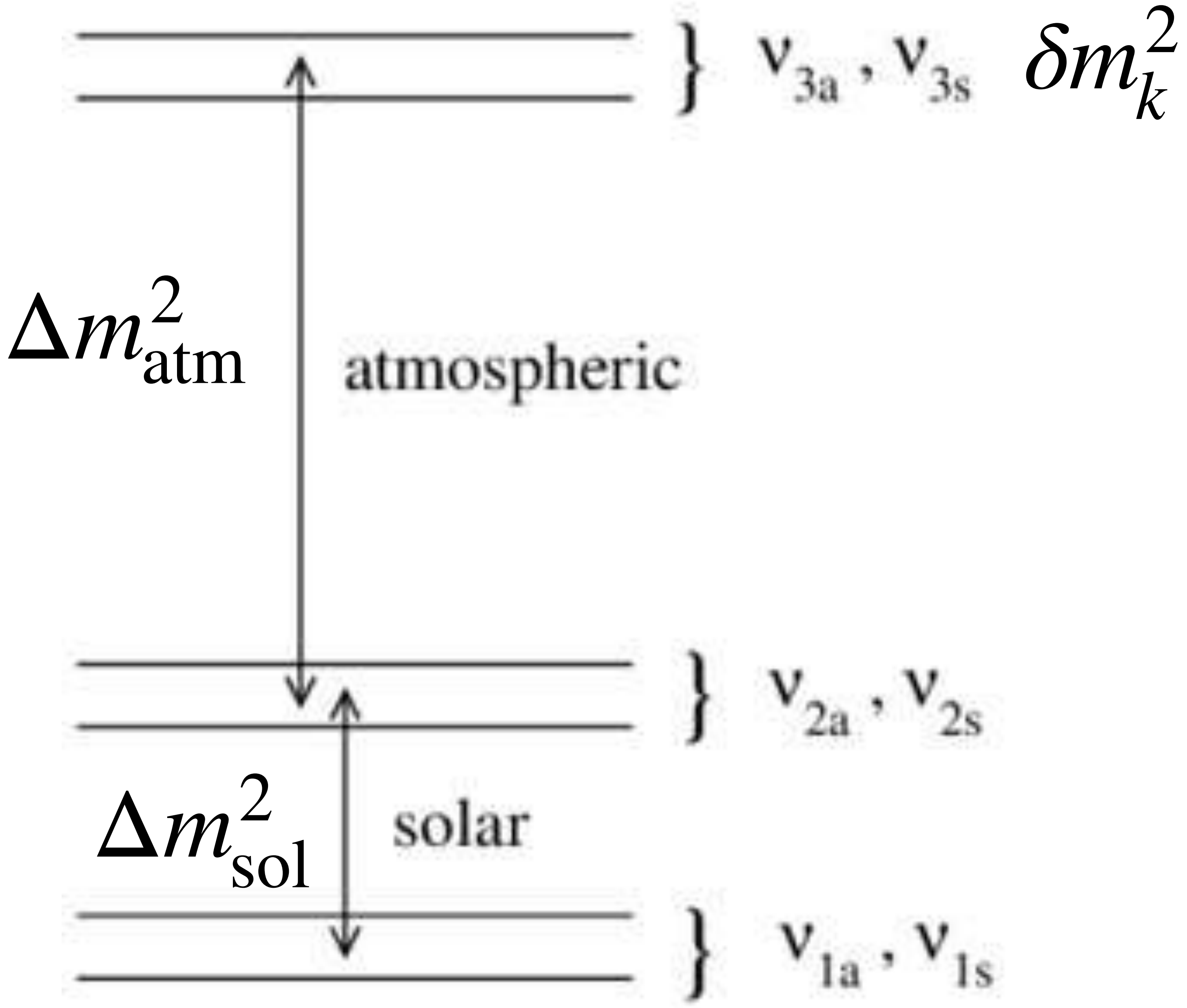
  Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

  Pseudo-Dirac limit : $m_{L,R} \ll m_D$ Kobayashi, Lim, PRD2001

- 3 pairs of quasi-degenerate states, separated by δm_k^2, which is much smaller than the usual $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$.

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_{js} + i\,\nu_{ja})$$

- Maximally mixed active and sterile states. Oscillations driven by this tiny mass.



Talk by Yuber Perez-Gonzalez

Oscillations due to pseudo Dirac Neutrinos

- δm_k^2 will lead to oscillations at very large distances.

- Flavor oscillation probability induced by $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ over a large distance gets averaged.

$$P(\nu_\beta \to \nu_\gamma) = P_{aa}(z,E)\left|U_{\beta k}\right|^2 \left|U_{\gamma k}\right|^2$$

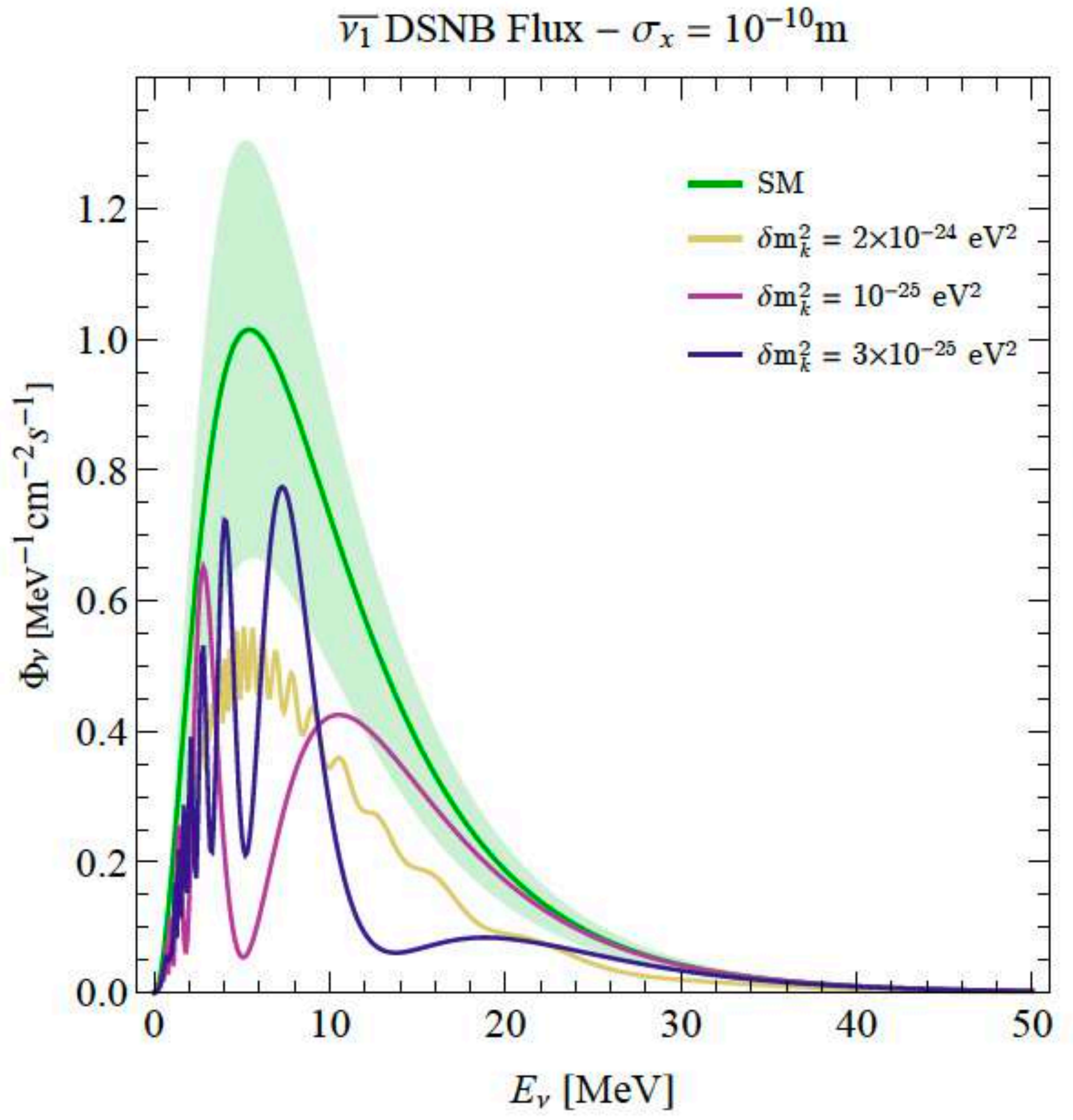
- The active-sterile probability, driven by δm_k^2 is

$$P_{aa}(z,E) = \frac{1}{2}\left(1+e^{-\left(\frac{L(z)}{L_{\rm coh}}\right)^2}\cos\left(2\pi\frac{L(z)}{L_{\rm osc}}\right)\right)$$

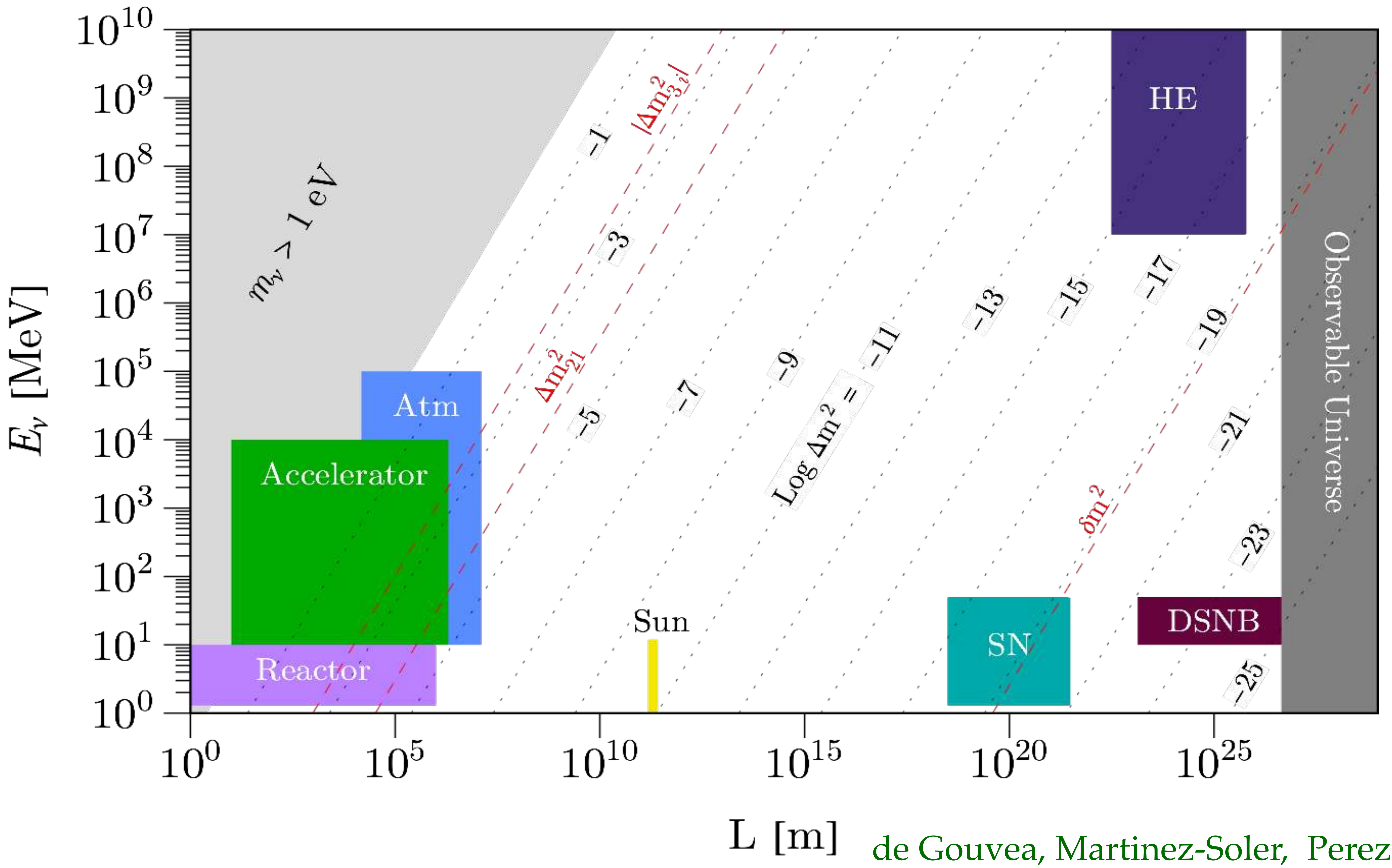
- Wave-packet separation decoherence also becomes important.

$$L_{\rm osc} = \frac{4\pi E}{\delta m_k^2} \approx 8.03\ \text{Gpc}\left(\frac{E}{10\ \text{MeV}}\right)\left(\frac{10^{-25}\ \text{eV}^2}{\delta m_k^2}\right),$$

$$L_{\rm coh} = \frac{4\sqrt{2}E^2}{|\delta m_k^2|}\sigma_x \approx 180\ \text{Gpc}\left(\frac{E}{10\ \text{MeV}}\right)^2\left(\frac{10^{-25}\ \text{eV}^2}{\delta m_k^2}\right)\left(\frac{\sigma_x}{10^{-12}\ \text{m}}\right).$$



Sensitivity to tiny mass-squared differences



de Gouvea, Martinez-Soler, Perez-Gonzalez, MS (PRD 2020)
See Beacom, Bell, Hooper, Learned, Pakvasa, Weiler (PRL 2003) for earlier version

- DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\mathrm{eV}^2)$ with a high significance - tiniest values constrained so far.

5. Origin of neutrino mass

Redshift dependent neutrino mass

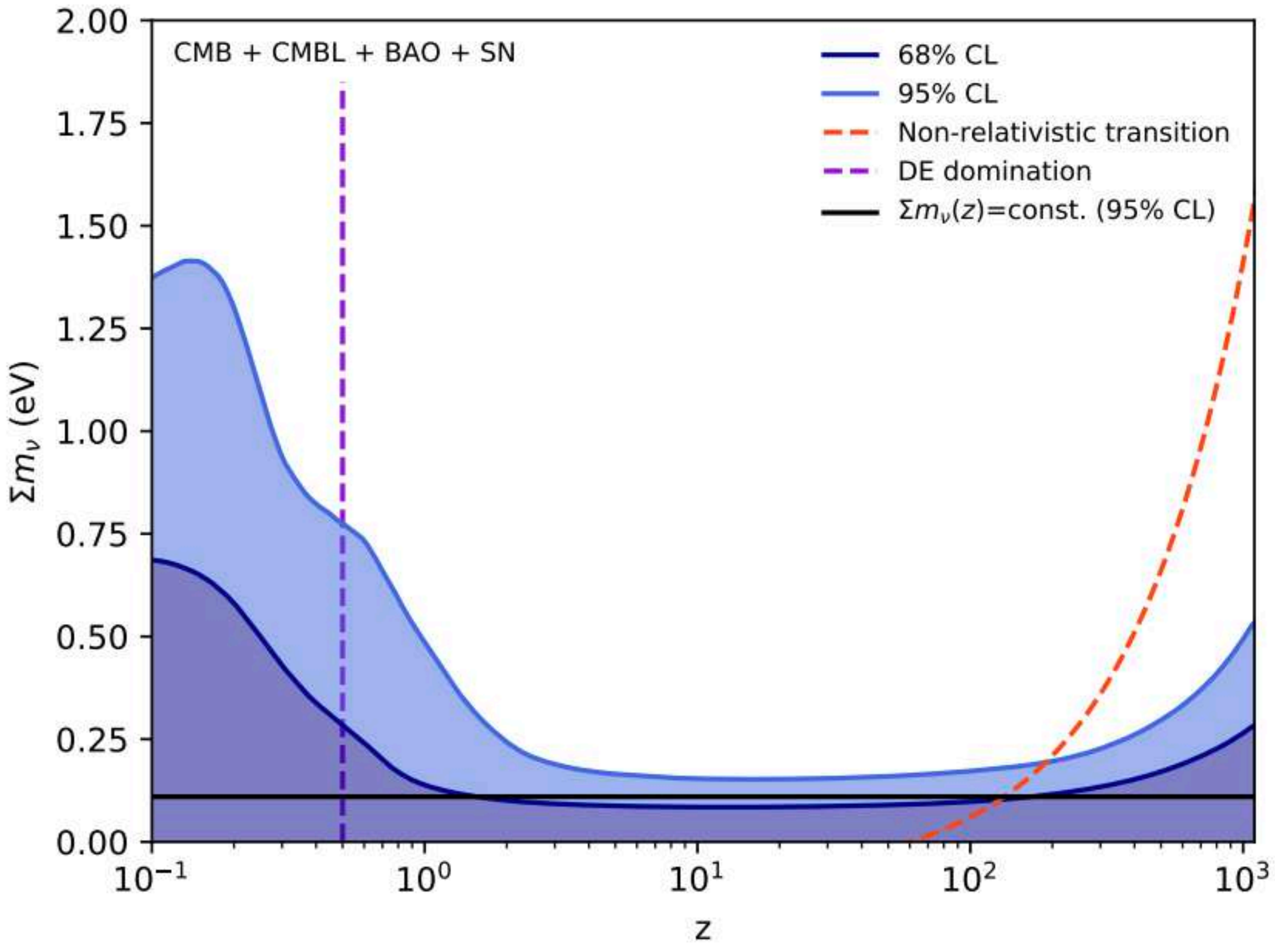
- Can the neutrino mass be redshift dependent?

- Use $\sum m_\nu$ as a function of redshift.

- Consider bounds from
  1. CMB temperature, polarization and lensing data
  Planck.

  2. BAO from 6dF, SDSS, BOSS,…

  3. Type Ia SN from Pantheon.



- Bound on $\sum m_\nu$ increases at very low redshifts.

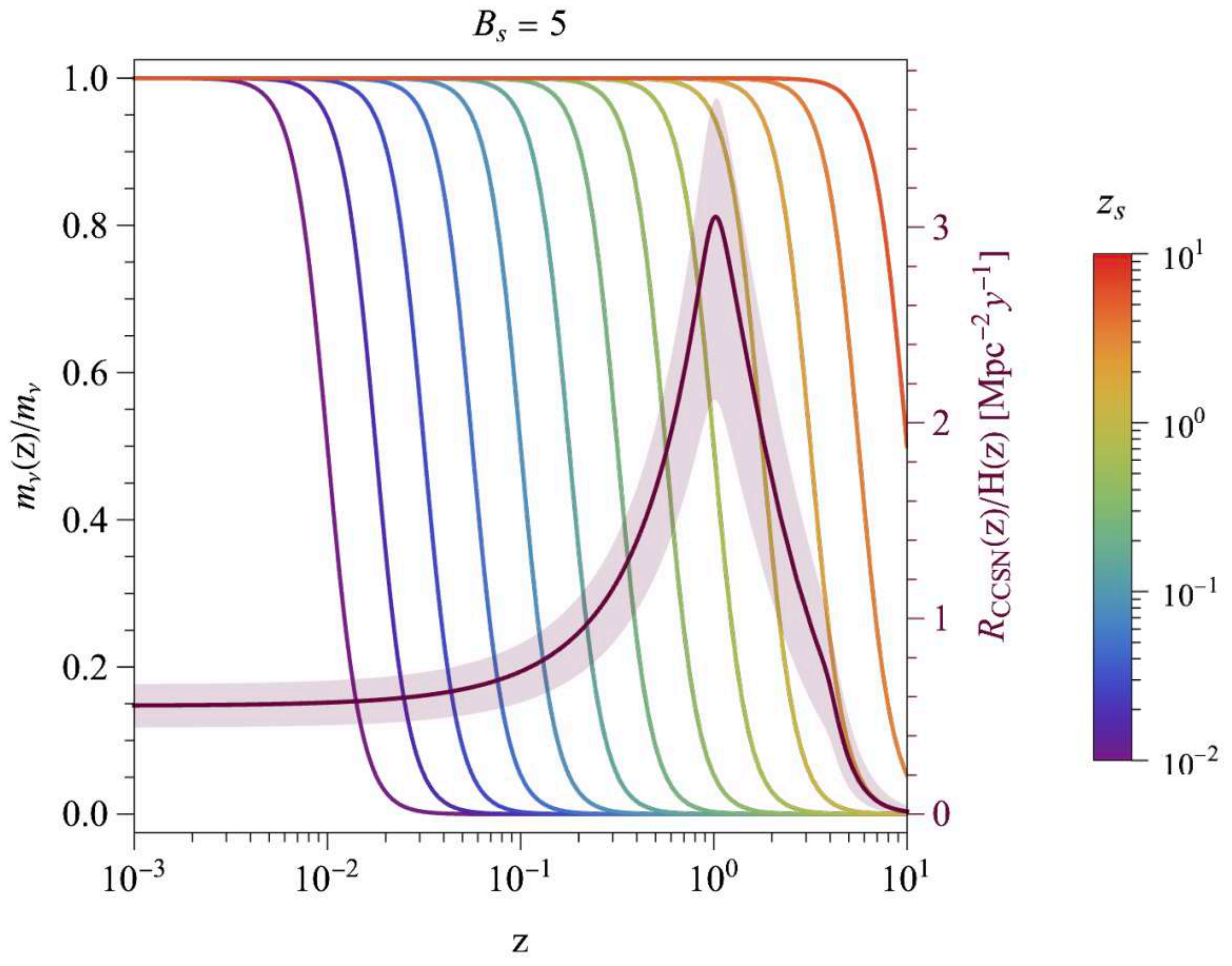
- If the neutrino mass is indeed generated at low redshifts, are there any other probes?

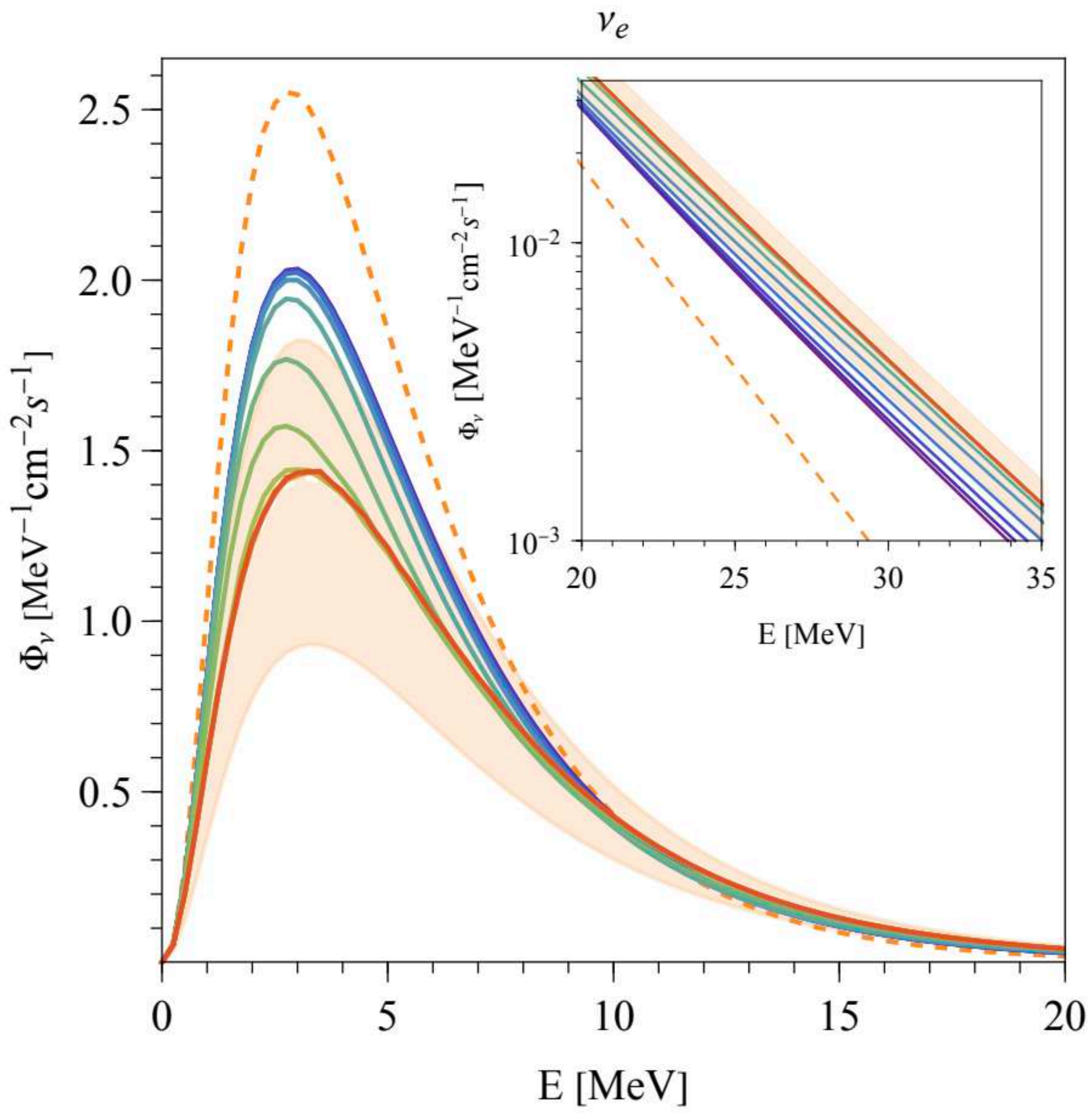
Dvali, Funcke (PRD 2016)
Lorenz,Funcke,Löffler, Calabrese (PRD 2021)
Lorenz,Funcke,Calabrese,Hannestad (PRD 2019)

Talk by Yuber Perez-Gonzalez

DSNB spectral difference due to mass variation

de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)





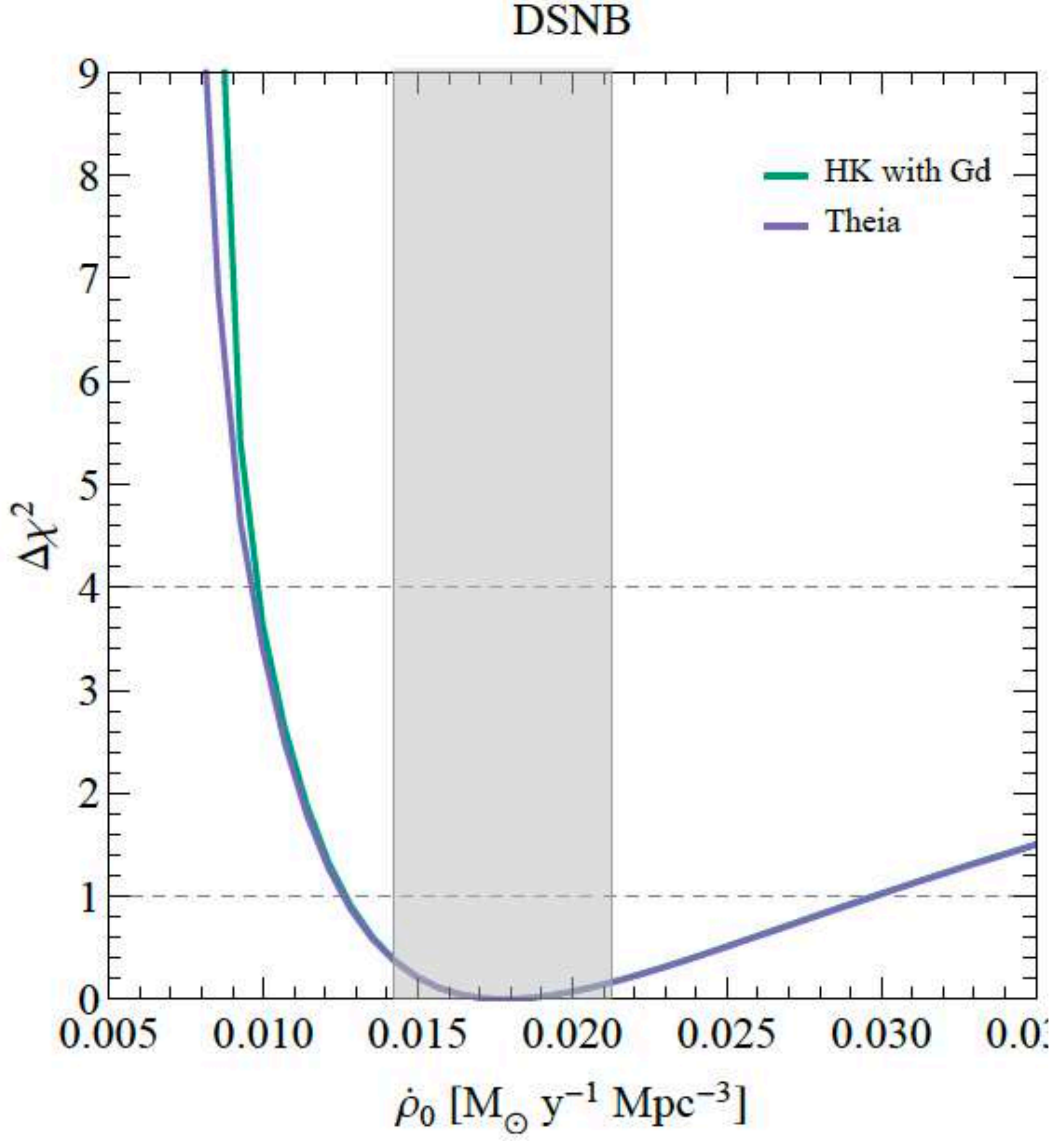
The mass variation is parameterized as

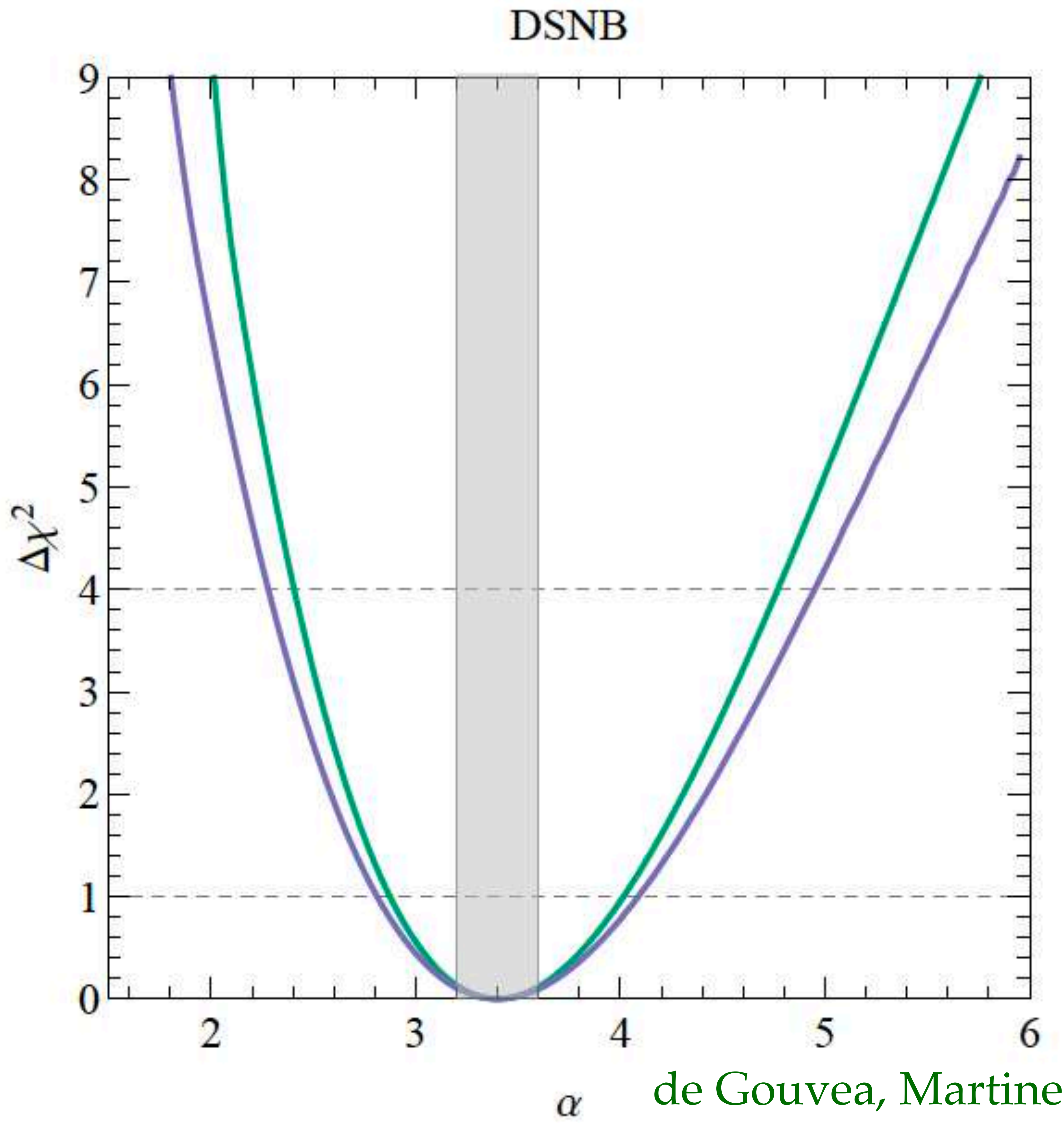
$$m_\nu(z) = \frac{m_\nu}{1+(z/z_s)^{B_s}}.$$

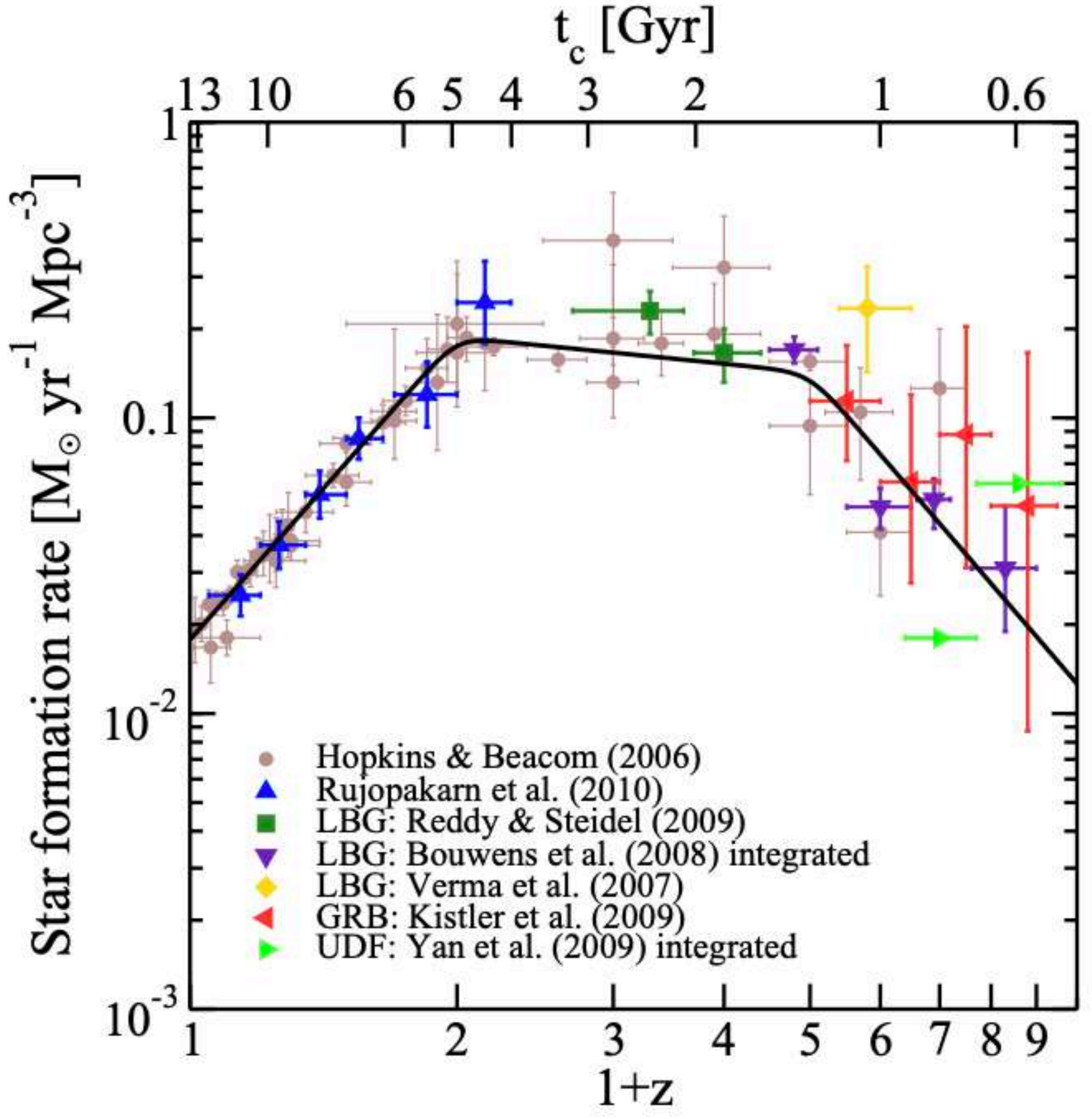
Non-trivial effect on the DSNB

Astrophysical Probes

Cosmic star formation rate







de Gouvea, Martinez-Soler, Perez-Gonzalez, MS (PRD 2020)

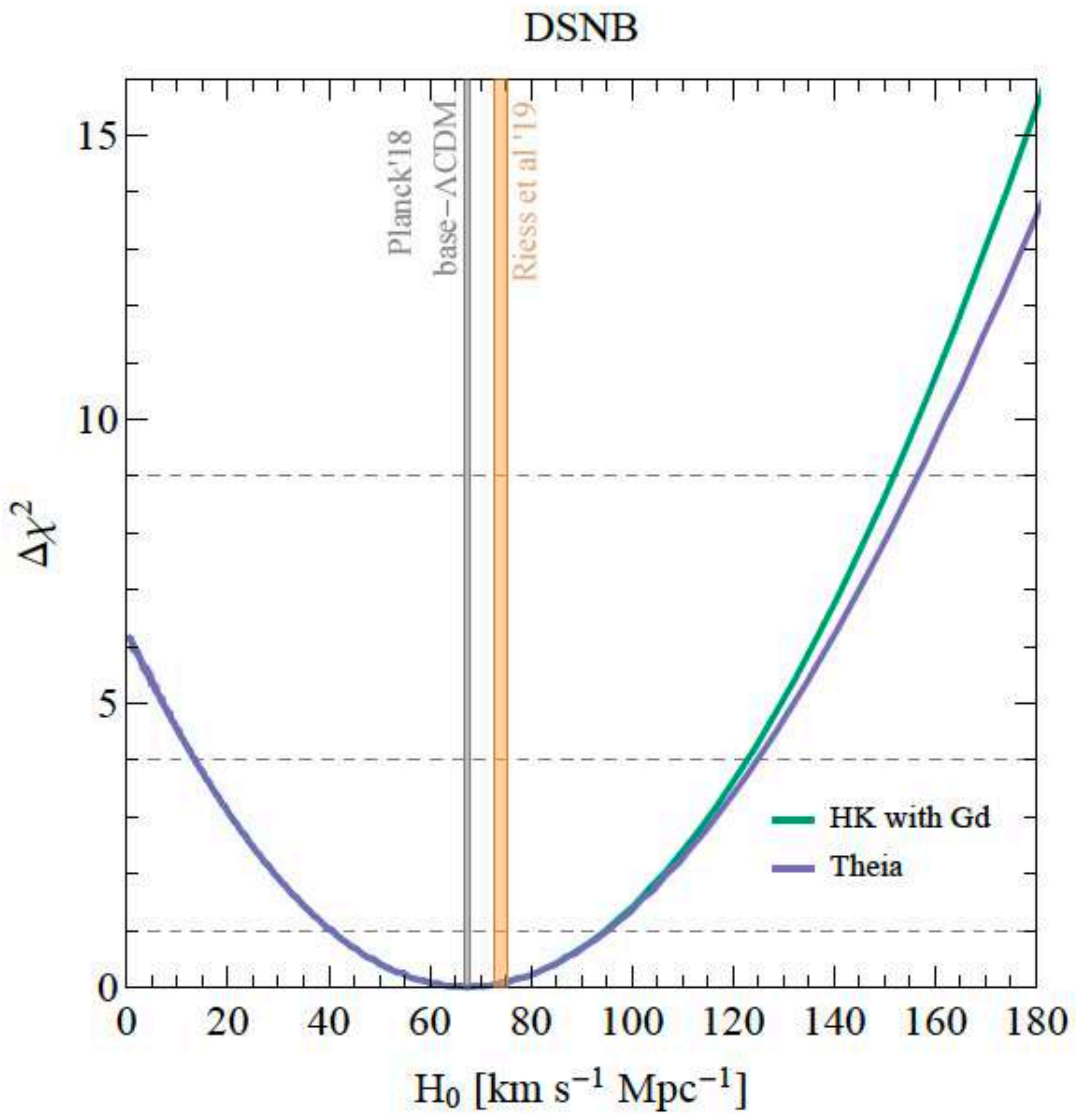
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\alpha} + \left(\frac{1+z}{B}\right)^{-10\beta} + \left(\frac{1+z}{C}\right)^{-10\gamma} \right]^{-1/10}$$

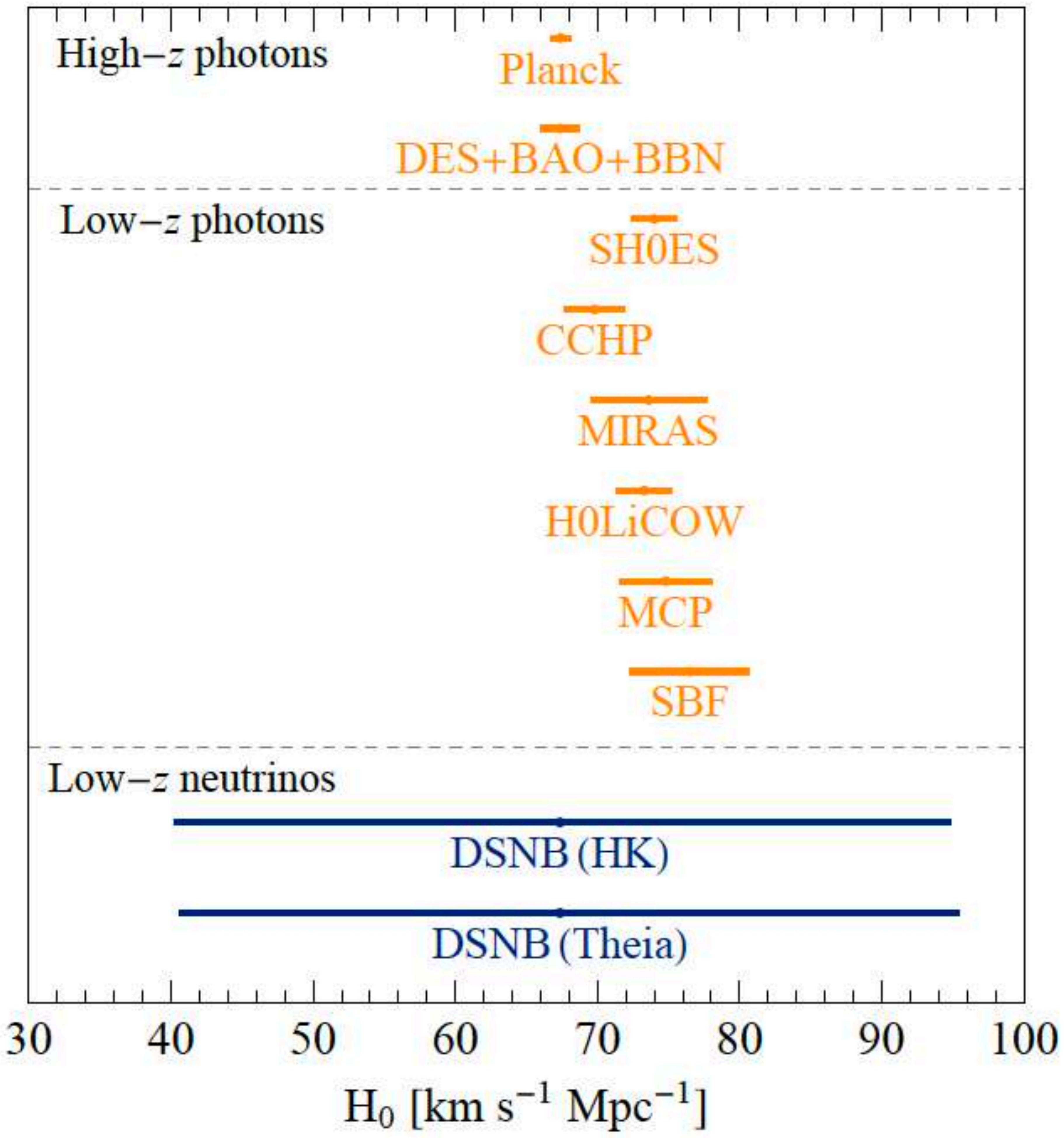
At the 2σ level, the results obtained from the DSNB are almost competetive with those obtained from decades of astronomical surveys.

see also, Møller, Suliga, Tamborra, Denton (JCAP 2018)

Cosmological Distance Ladder

Cosmology: Hubble Parameter





de Gouvea, Martinez-Soler, Perez-Gonzalez, MS (PRD 2020)

- Distance yardstick using neutrinos.
- Measure H_0 at 40% level, which is the systematic uncertainty.

Conclusions

The DSNB opens up a plethora of avenues for neutrino physics, next giant leap from the Sun and SN1987A.

Crucial for testing extreme neutrino properties, which cannot be tested otherwise.

Probable constraints on cosmological star formation rate, and hence the rate of core-collapse SNe in the Universe.

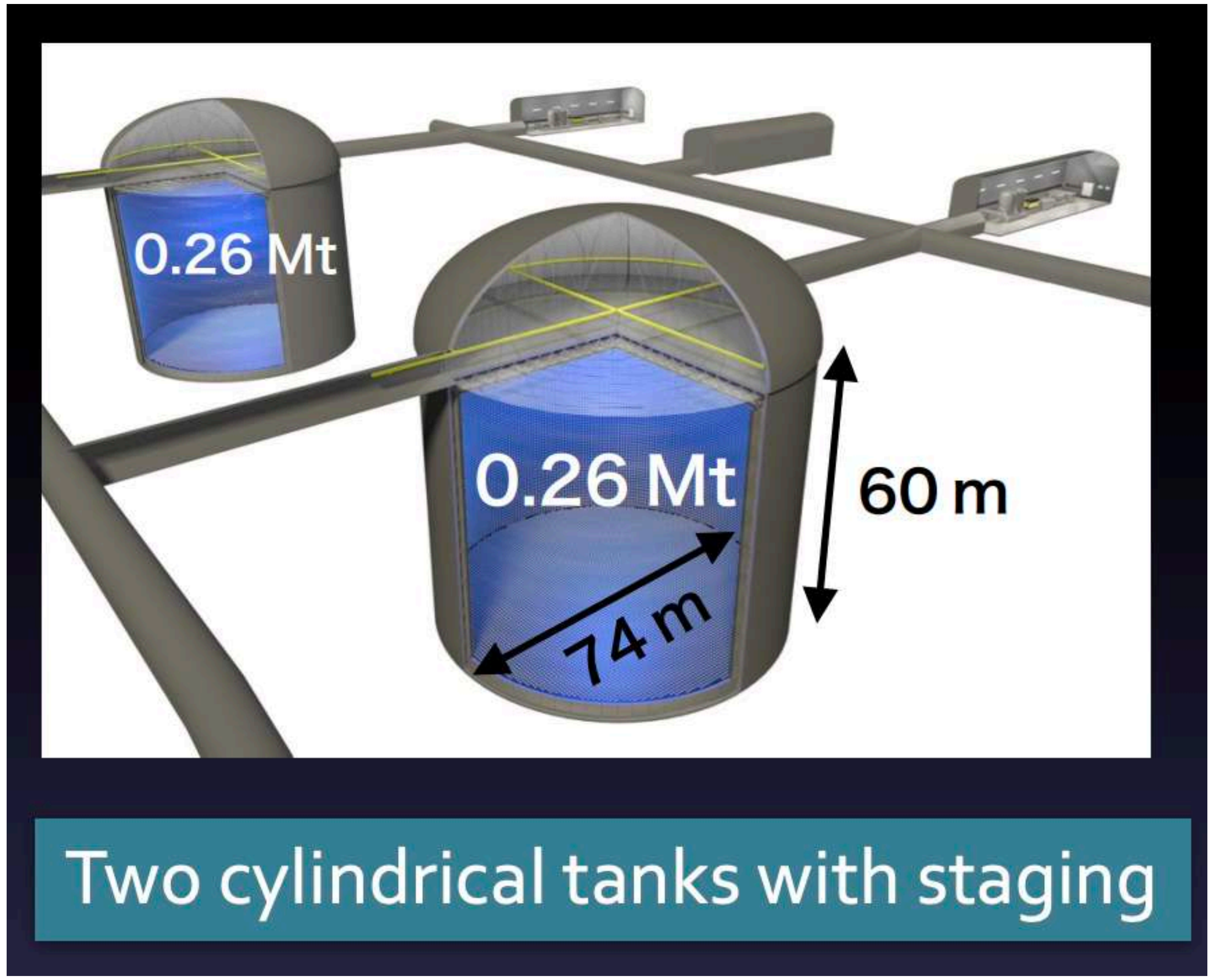
Other constraints discussed in the literature: black-hole fraction (primordial as well as astrophysical), alternate cosmological models, models of neutrino emission, and propagation, any new exotic physics in the neutrino sector.

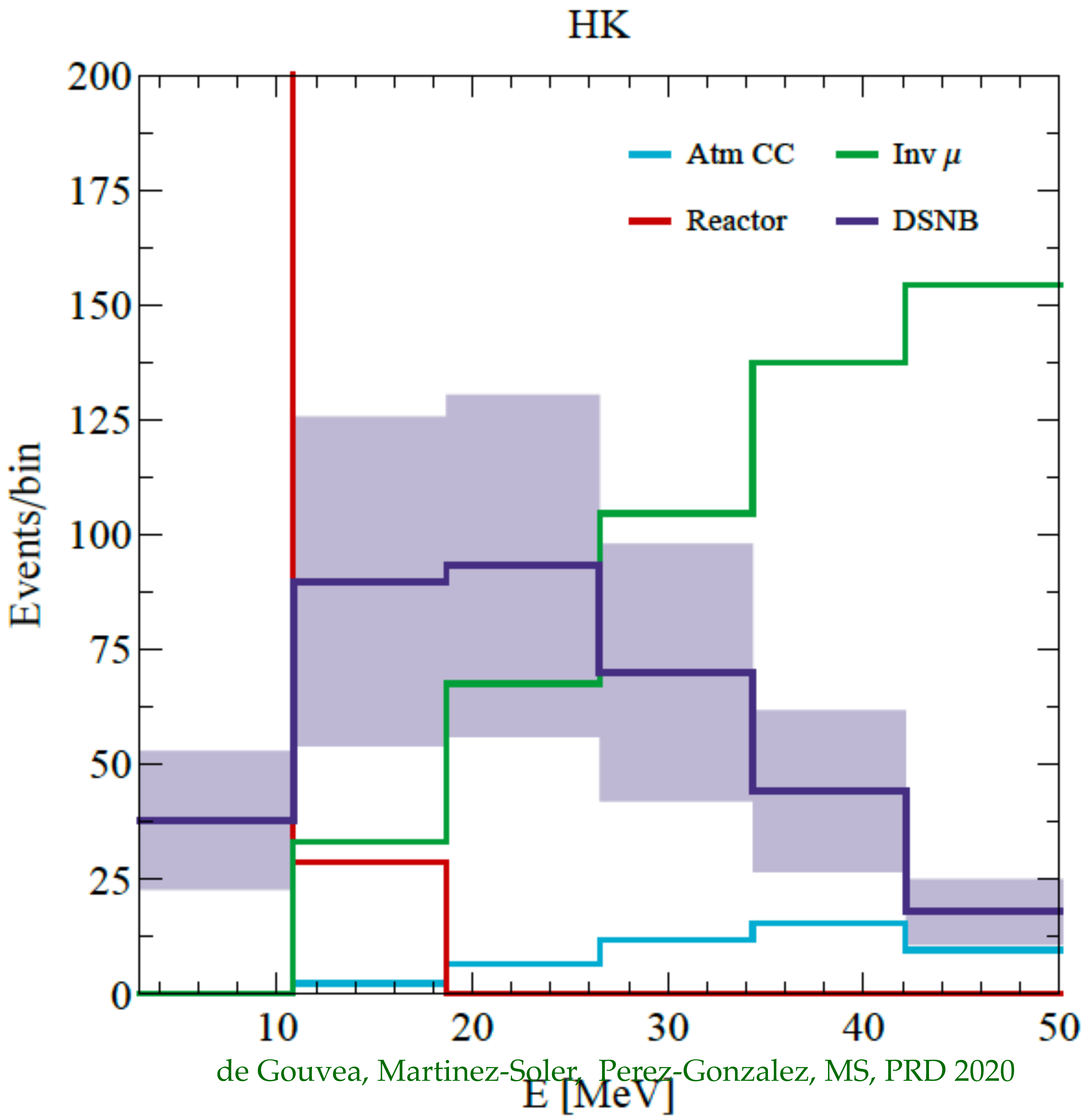
A future detection can provide neutrino only measurement of expansion rate of the Universe, complementary to measurement with photons and gravity waves.

THANK YOU

Backup

Future Detection: Hyper-Kamiokande + Gd

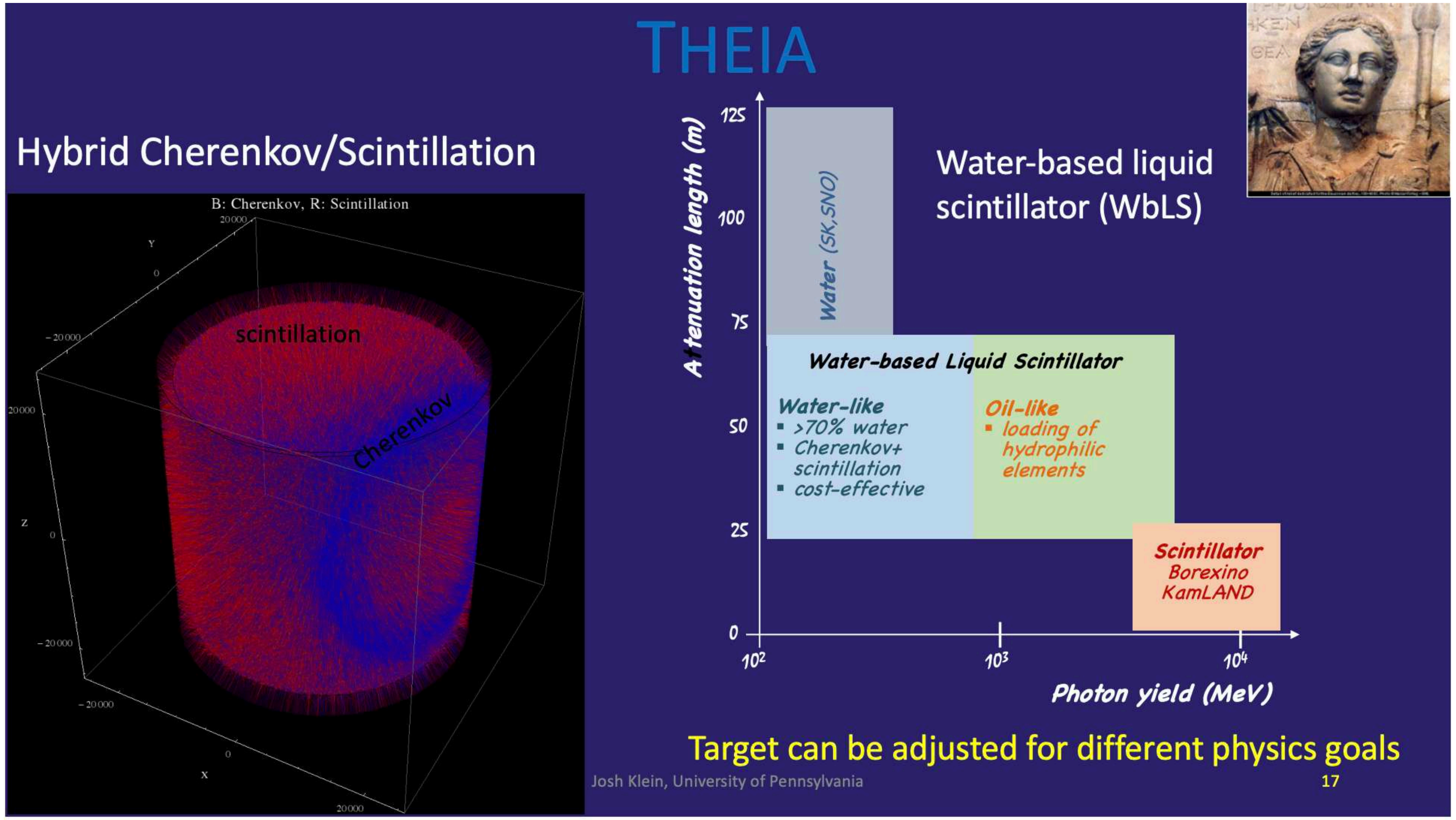




de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

- HK enriched with Gd provides excellent detec
- Results with 1 tank with 10 years of data takin
- Backgrounds same as SK.

Future Detection: Theia



THEIA

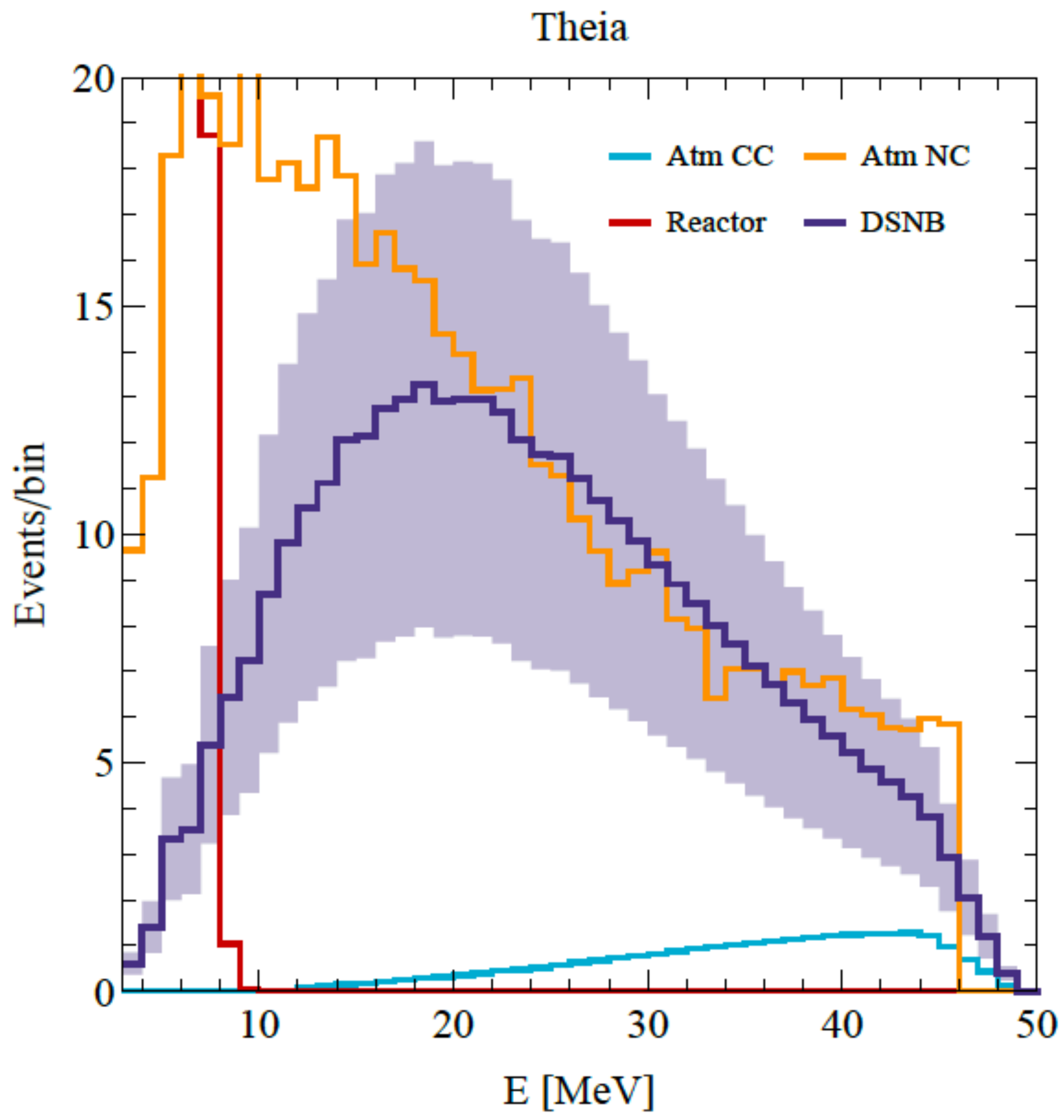
Hybrid Cherenkov/Scintillation

Water-based liquid scintillator (WbLS)

Target can be adjusted for different physics goals

Josh Klein, University of Pennsylvania

17



de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

- 100 kT detector, with 10 years of data-taking
- Low energy resolution of scintillator, and high-energy reconstruction techniques for Cherenkov detector.
- Major background: NC interactions of ν on C nuclei. Prompt signal in recoil + delayed signal due to absorption of emitted neutron. Can be reduced using Cherenkov/Scintillation ratio.

Variation with <E> and alpha

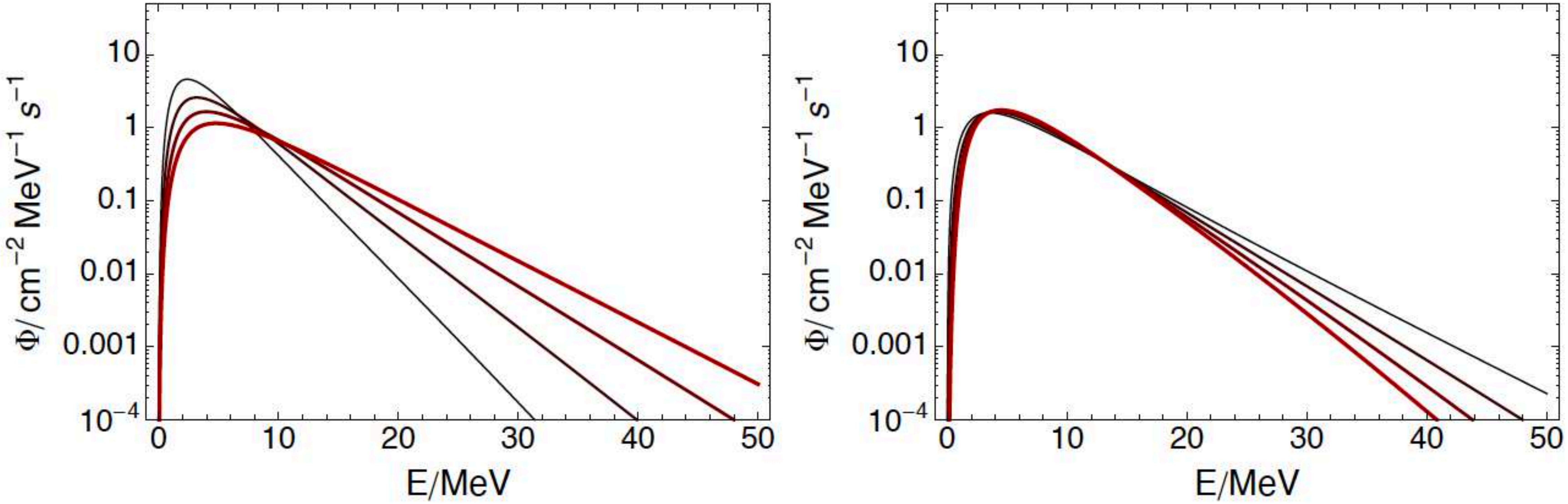


Figure 10: Examples of unoscillated flux, Φ^0_w $(w = e, \bar{e}, x)$ (Eq. (15)), for different spectral parameters E_{0w}, α_w. Left: the curves of increasing thickness (increasing color intensity) correspond to $E_{0w} = 9, 12, 15, 18$ MeV, with $\alpha_w = 3$. Right: the curves of increasing thickness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

Variation with redshift

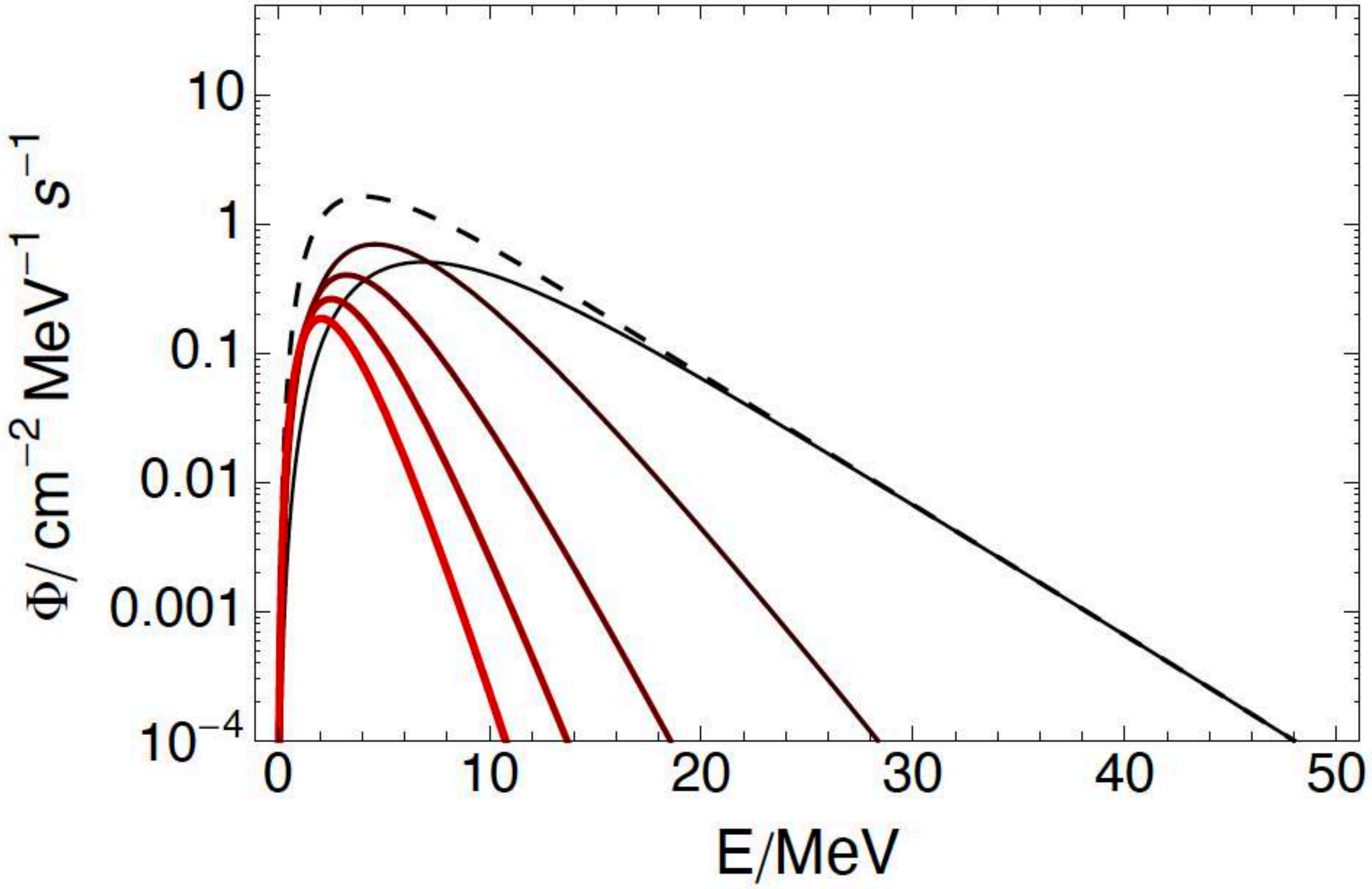
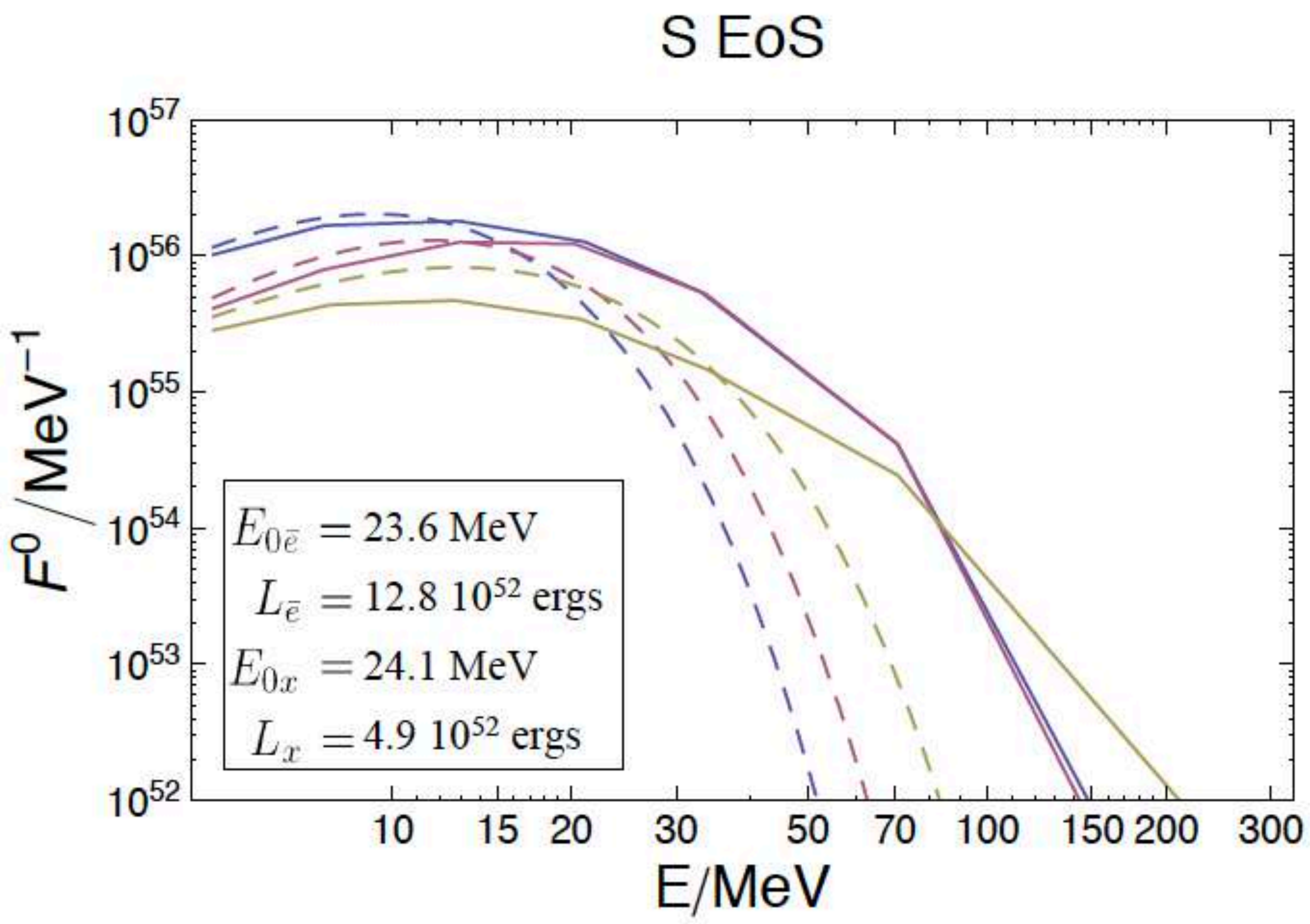
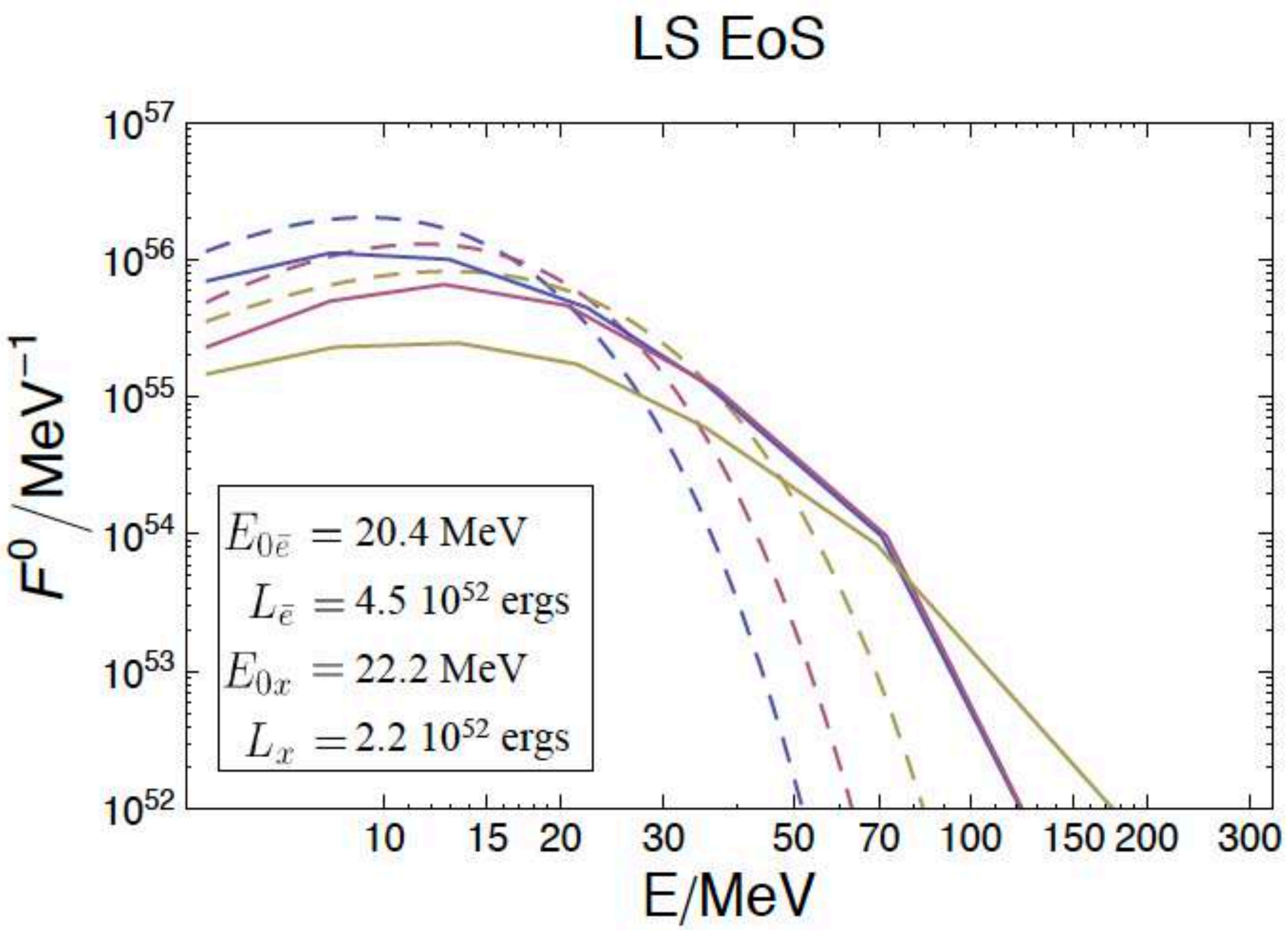


Figure 13: The contribution to the *unoscillated* $\bar{\nu}_e$ flux of sources in bins of increasing redshift, for the best fit SNR parameter $\beta = 3.28$ [59]. The solid curves from thinner to thicker (darker to lighter color) refer to the intervals: $z = 0 - 1$, $z = 1 - 2$, $z = 2 - 3$, $z = 3 - 4$ 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.

Redshift dependent mass: adiabaticity

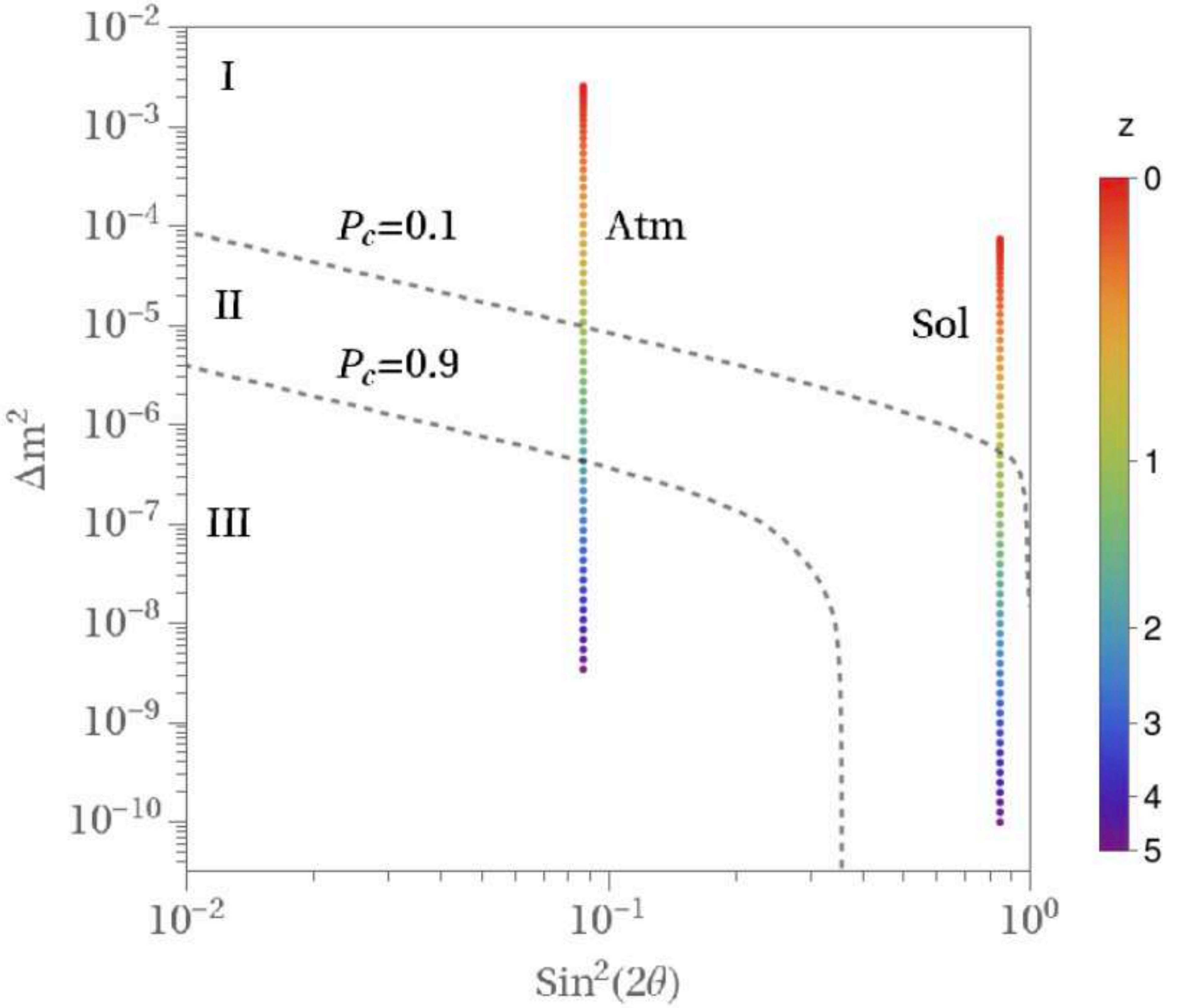
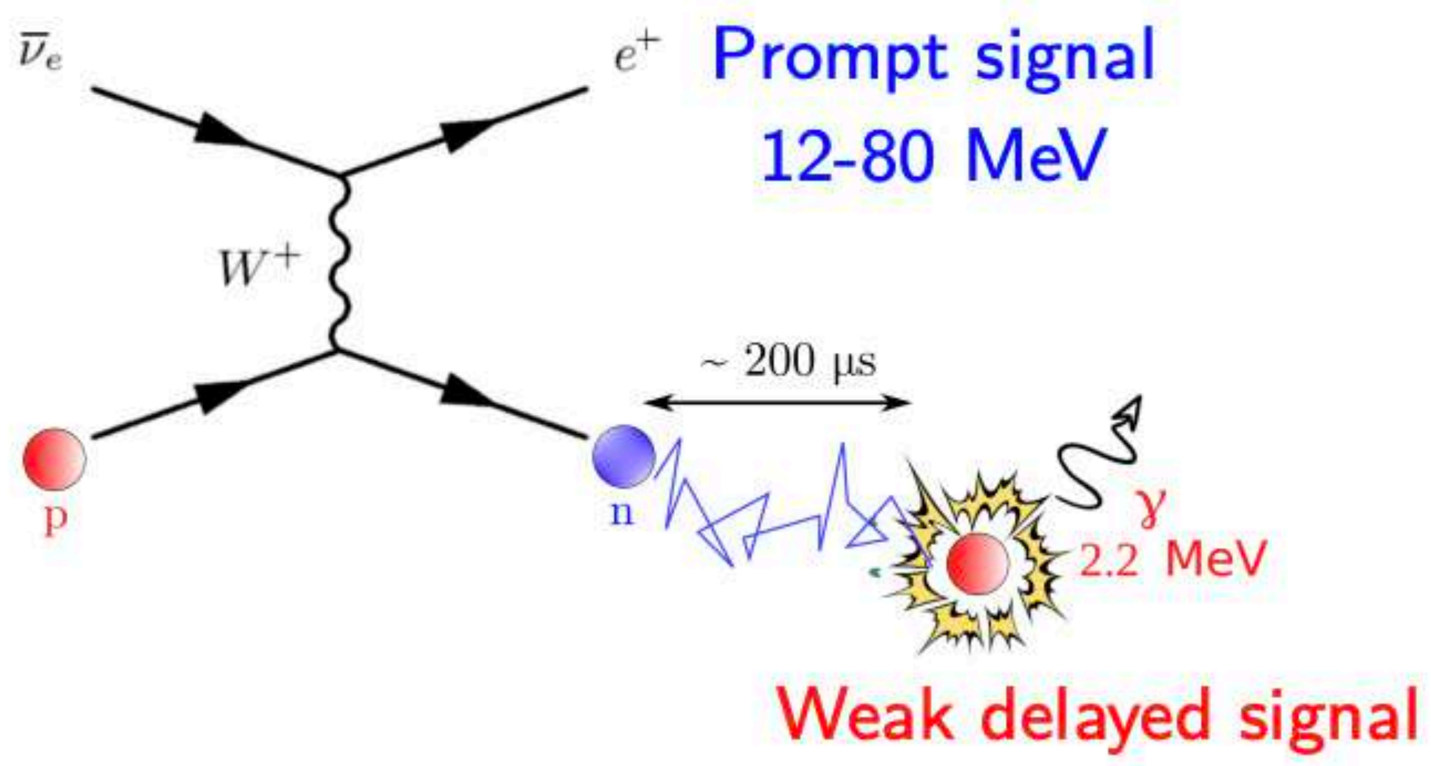


FIG. 2: Constant crossing probability contours in the $\sin^2 2\theta \times \Delta m^2$–plane. These define three regions: (I) $P_c < 0.1$, (II) $0.1 < P_c < 0.9$, and (III) $P_c > 0.9$. The color scale indicates the values of the two independent mass-squared differences as a function of the redshift of neutrino production. For the mass variation, we make use of Eq. (III.1) with $z_s = 0.32$ and $B_s = 5$.

Detecting the DSNB + backgrounds: Super-K

- Event rate $N_i = N_{\mathrm{tar}}(\Delta\, t)\int_{\mathrm{bin\,i}} dE^{\mathrm{rec}} \int_{\mathrm{all}} dE^{\mathrm{true}}\, \Phi_\nu\, \sigma_\nu\, \epsilon(E^{\mathrm{true}}, E^{\mathrm{rec}})$

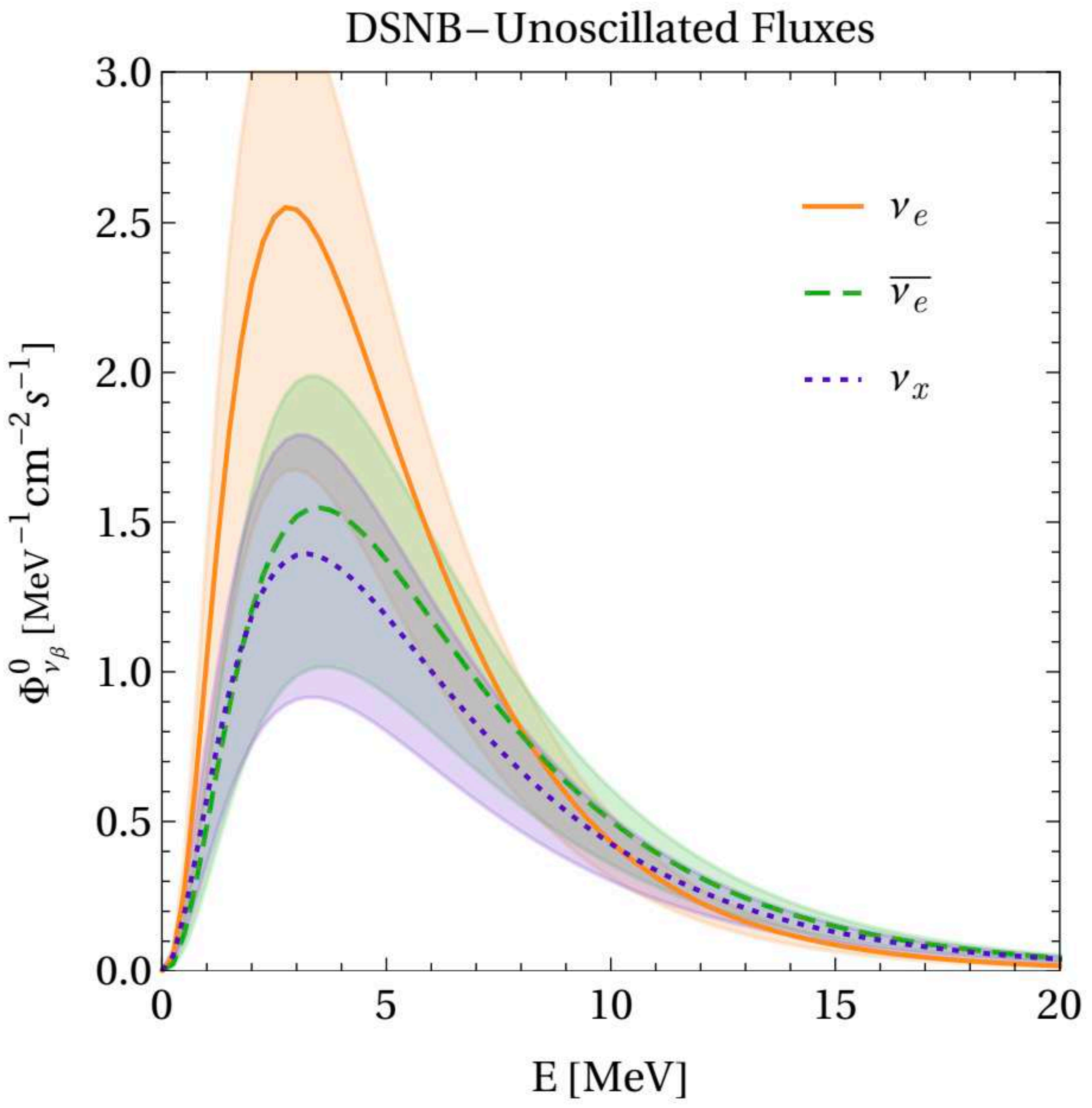


- Main channel is IBD: $\bar{\nu}_e + p \to e^+ + n$

- Spallation backgrounds: radioactivity induced by cosmic muon spallation in water: $\mu + O \to \mu + X$. Substantial background ~ 20 MeV.

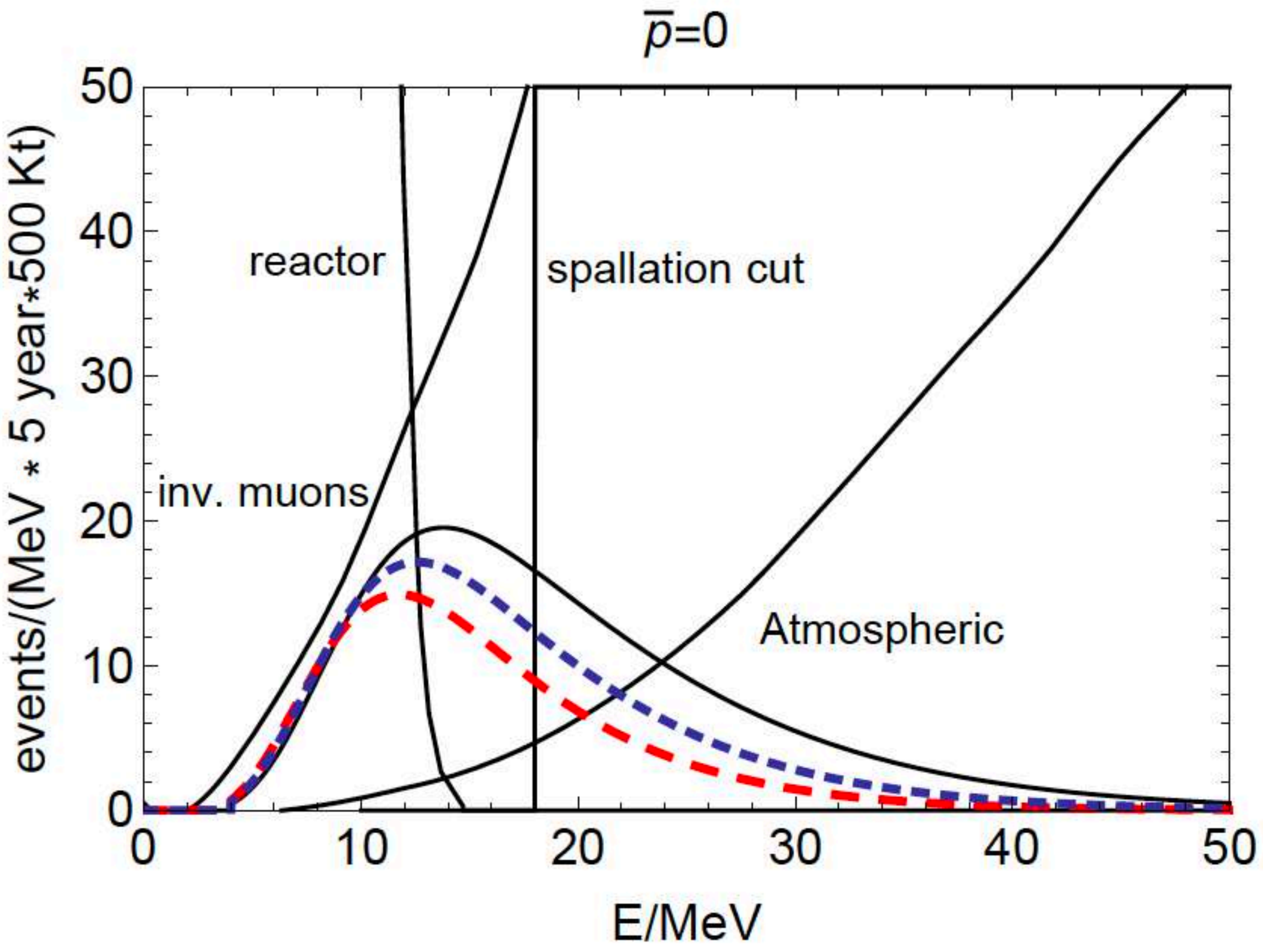
- Invisible muons: $\nu_\mu + N \to \mu + N'$. If muon energy is below Cherenkov threshold, it can only be detected through decay.

- Low energy atmospheric neutrinos. Isotropic background.

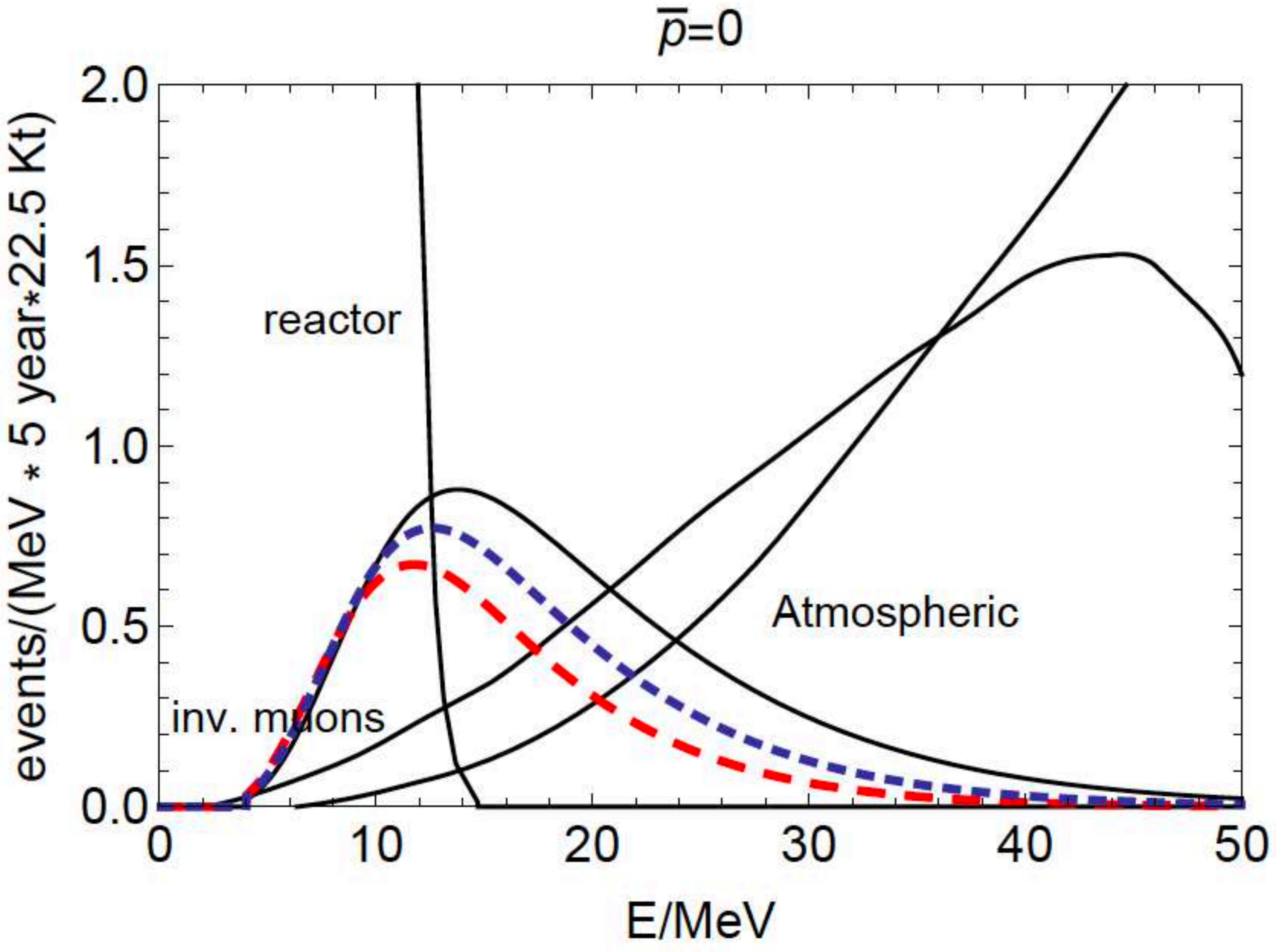


Gd doping: GADZOOKS!

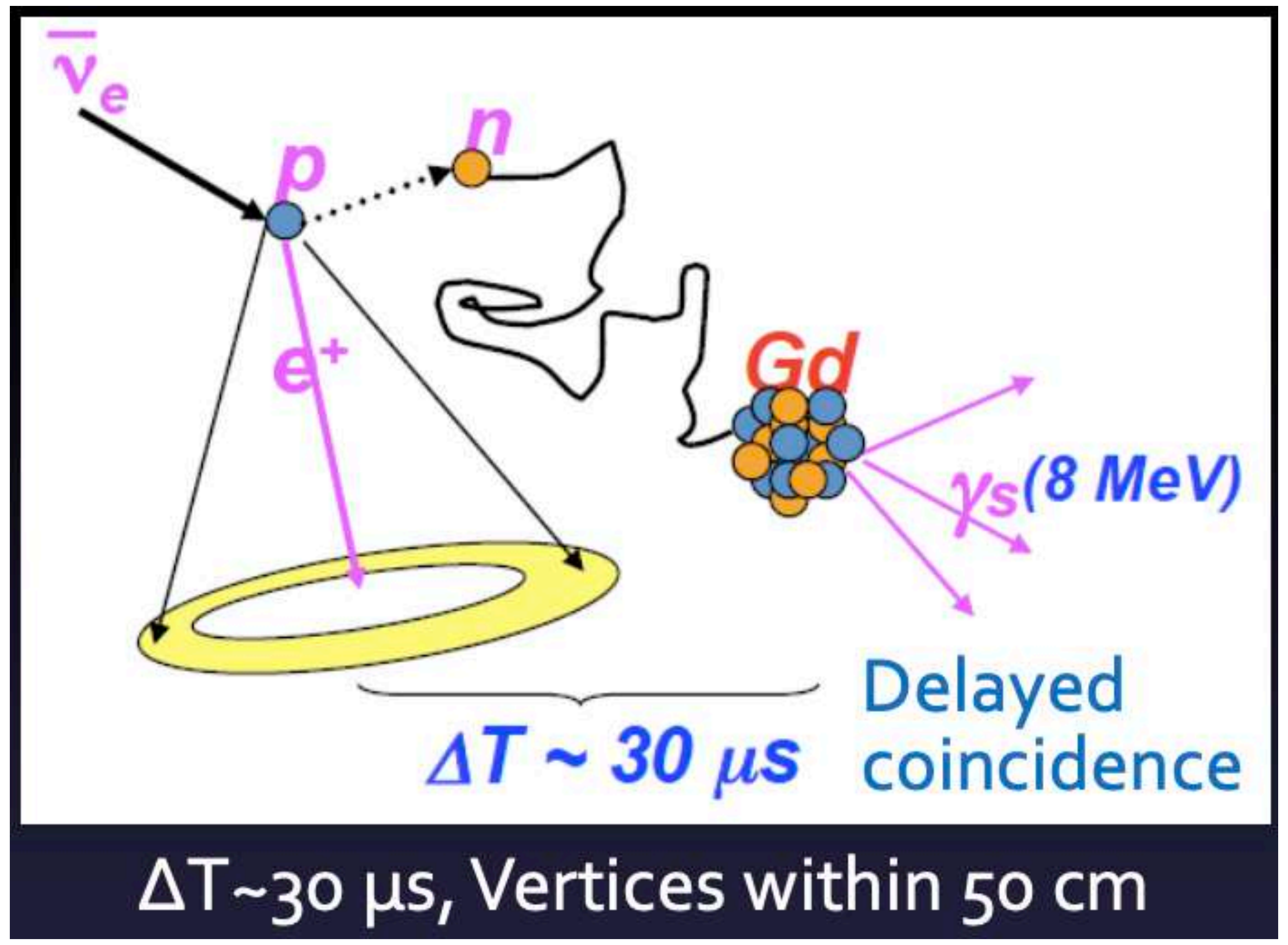
Beacom, Vagins, PRL2004



Lunardini, Astropart. Phys2016

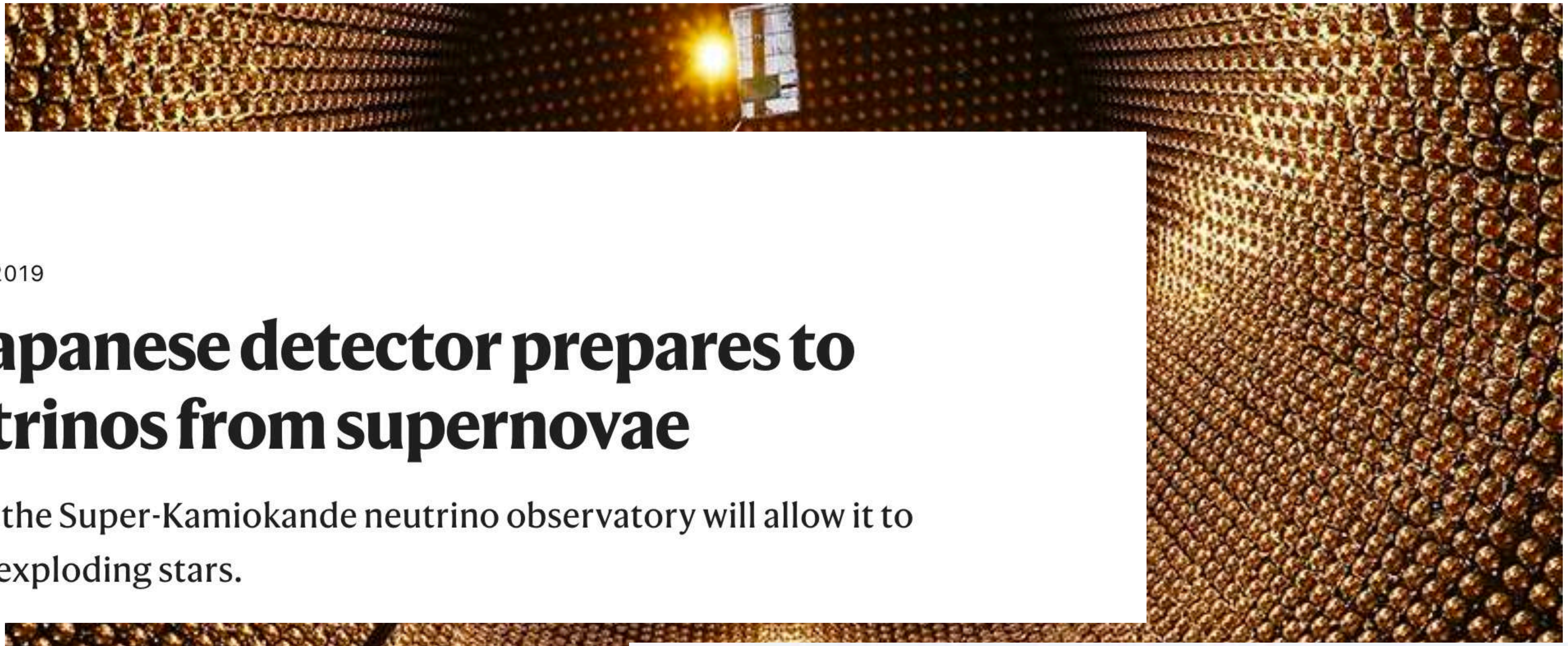


- Solution: Gd doping.
- Reduces energy threshold.
- Background due to spallation will be subtracted almost completely and the one due to invisible muons will be reduced by a factor of 5.



ΔT~30 μs, Vertices within 50 cm

The Diffuse Supernova Neutrino Background

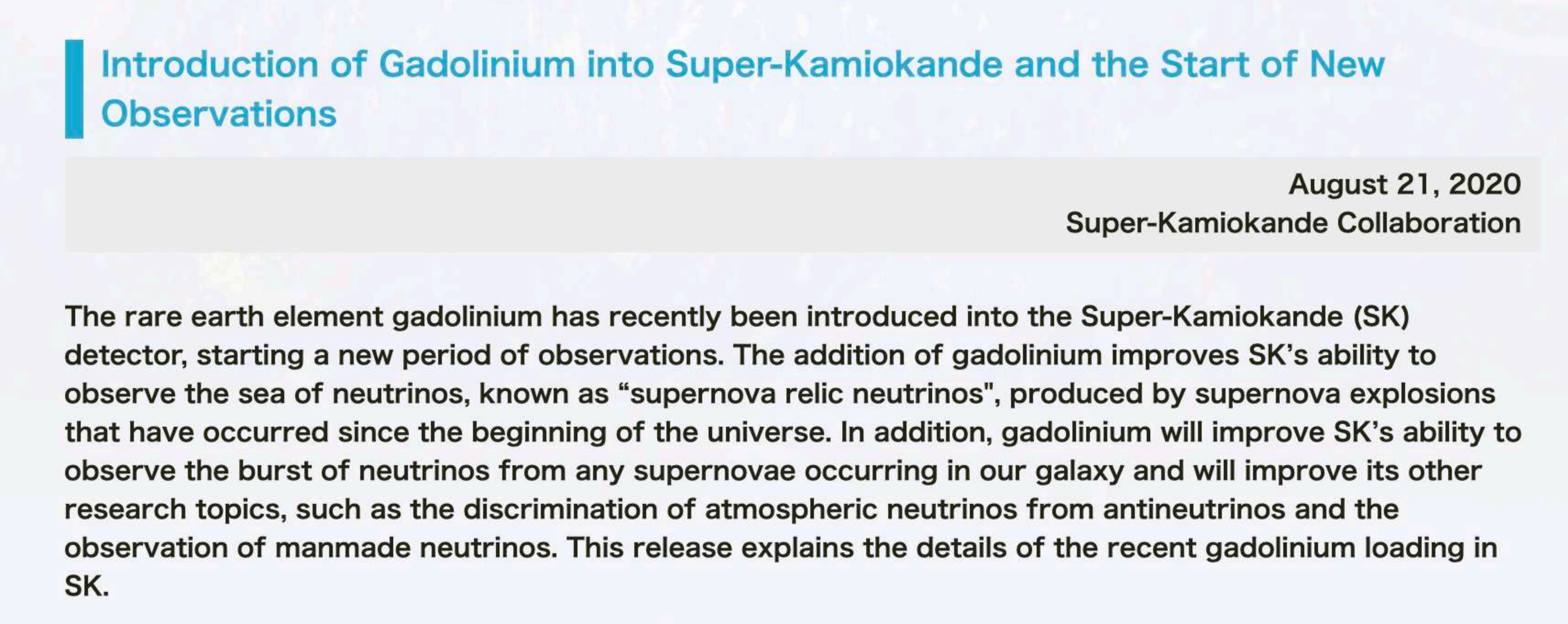


nature > news > article

NEWS · 27 FEBRUARY 2019

Gigantic Japanese detector prepares to catch neutrinos from supernovae

Recent upgrades to the Super-Kamiokande neutrino observatory will allow it to trace the history of exploding stars.



Introduction of Gadolinium into Super-Kamiokande and the Start of New Observations

August 21, 2020
Super-Kamiokande Collaboration

The rare earth element gadolinium has recently been introduced into the Super-Kamiokande (SK) detector, starting a new period of observations. The addition of gadolinium improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos", produced by supernova explosions that have occurred since the beginning of the universe. In addition, gadolinium will improve SK's ability to observe the burst of neutrinos from any supernovae occurring in our galaxy and will improve its other research topics, such as the discrimination of atmospheric neutrinos from antineutrinos and the observation of manmade neutrinos. This release explains the details of the recent gadolinium loading in SK.

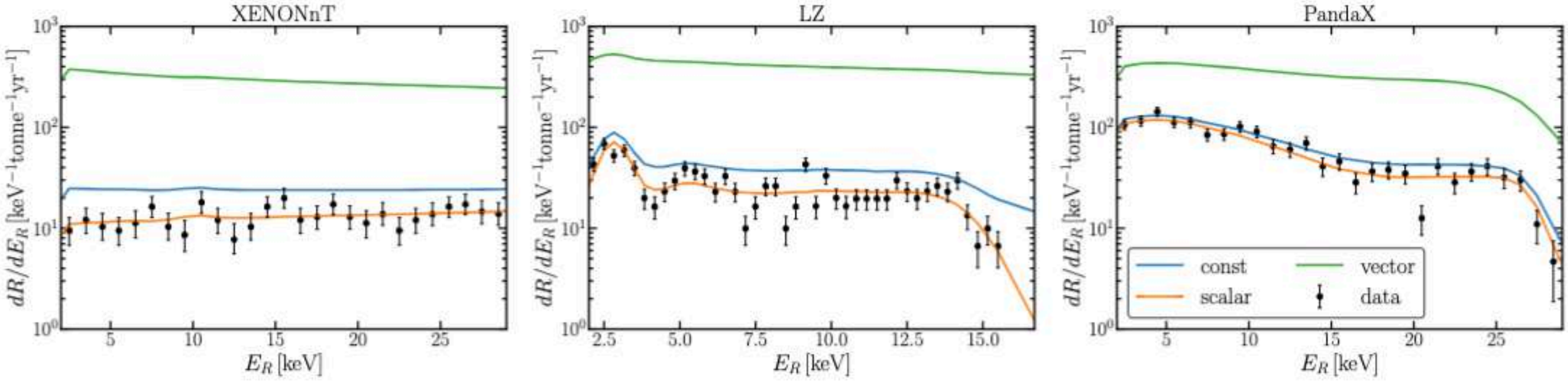
What about the future?

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.

Signals in different experiments

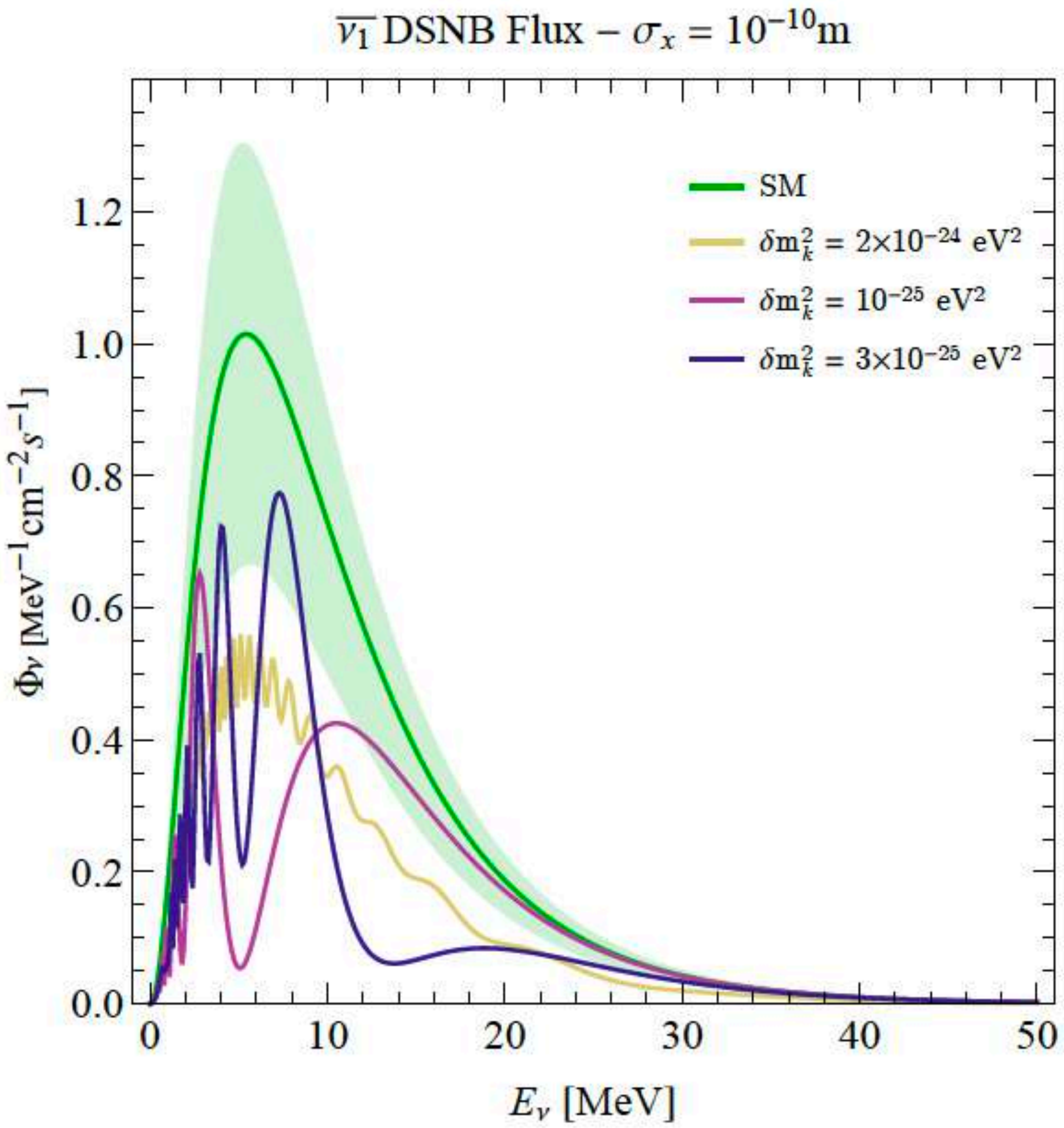
- Differential electron scattering rate $\dfrac{dR}{dT_e} = N_e \int dT_\chi \dfrac{d\Phi_\chi}{dT_\chi^z} \dfrac{d\sigma_{e\chi}}{dT_e}$

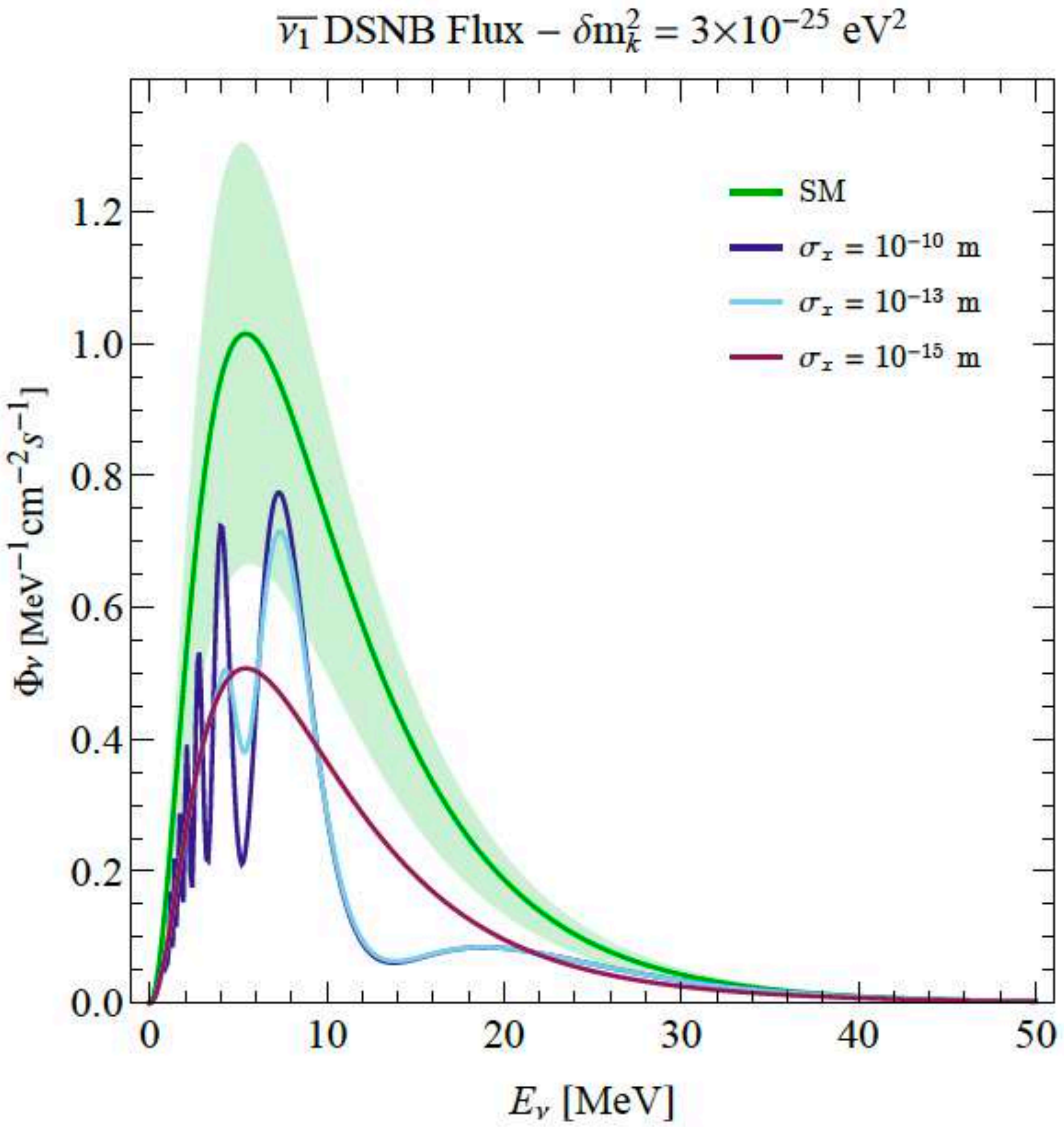


$$\bar{\sigma}_{e\chi} = 10^{-30}\,\mathrm{cm}^2,\ m_\chi = 0.5\,\mathrm{MeV},\ \ m_{\mathrm{med}} = 1\,\mathrm{MeV}$$

Das, Herbermann, **MS**, Takhistov (JCAP 2024)

Oscillations due to pseudo-Dirac nature

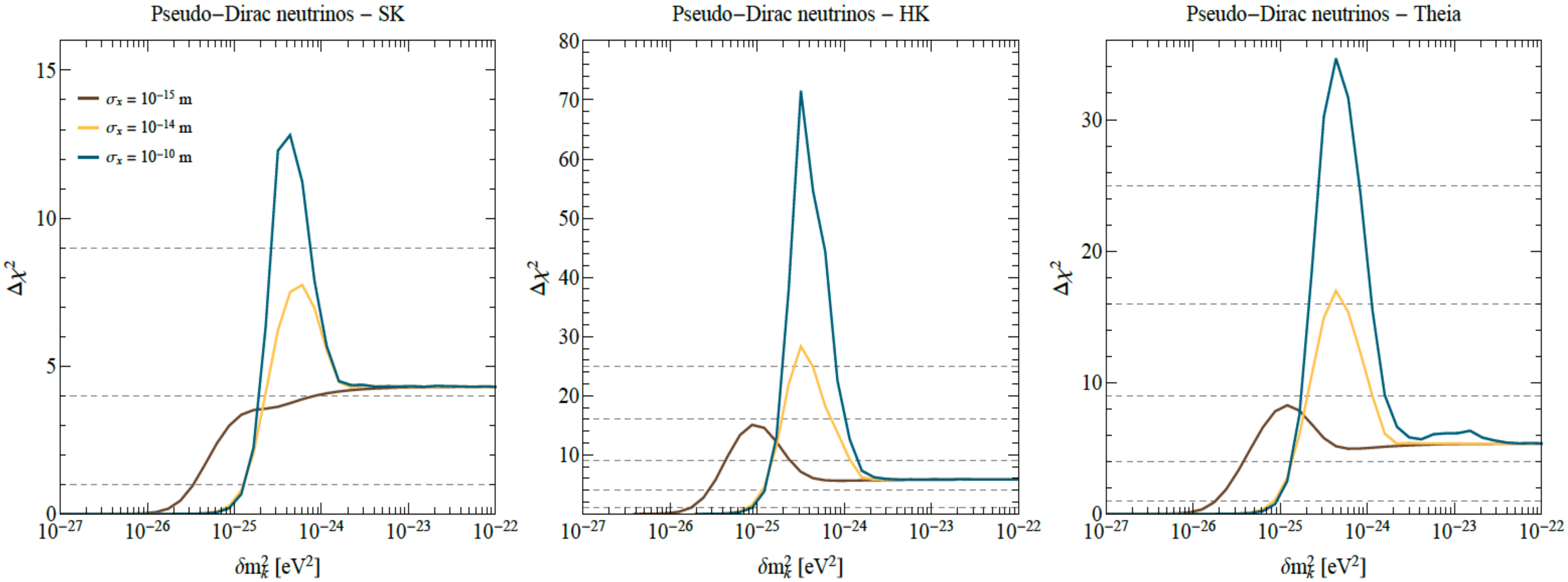

$\overline{\nu_1}$ DSNB Flux – $\sigma_x = 10^{-10}$m


$\overline{\nu_1}$ DSNB Flux – $\delta m_k^2 = 3\times10^{-25}$ eV^2

Increasing δm^2 reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

Decreasing σ_x reduces $L_{\rm coh}$, and causes more decoherence

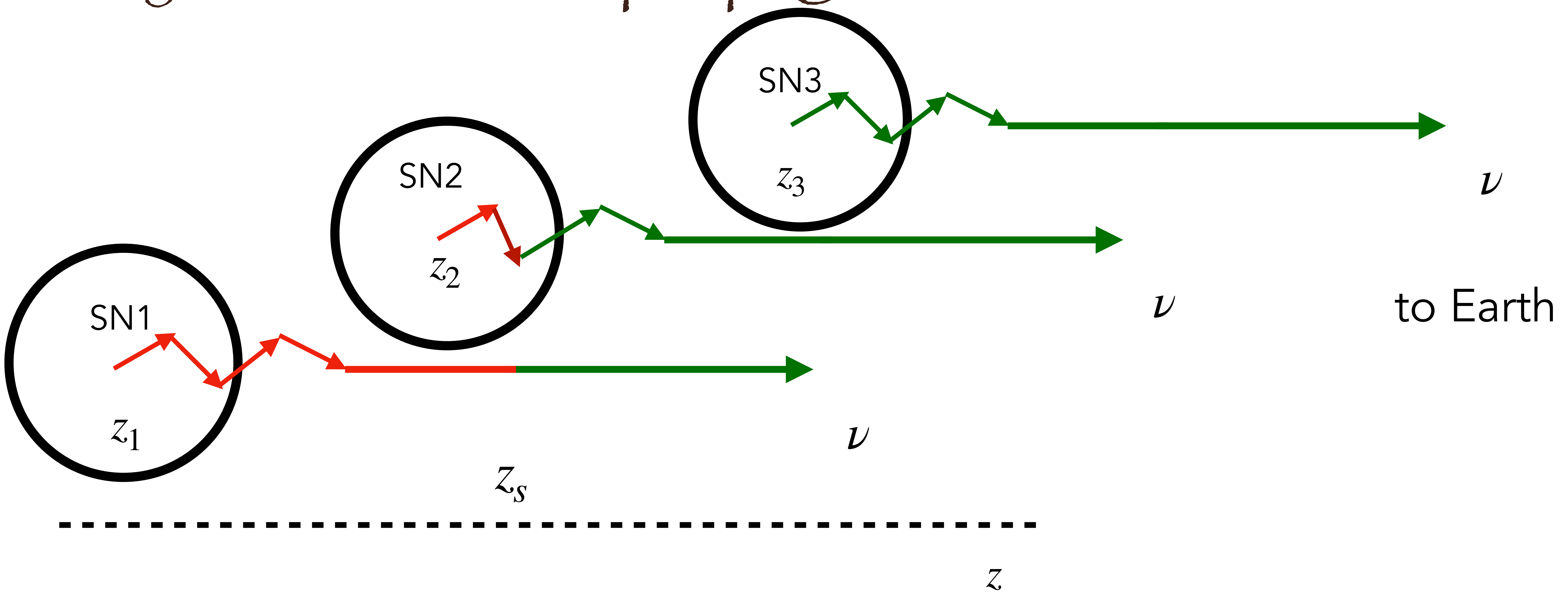
Sensitivity to tiny mass-squared differences



- DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\mathrm{eV}^2)$ with a high significance - tiniest values constrained so far.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2020

Physics of neutrio propagation as mass varies



- For tiny mass neutrinos, non-adiabaticity of propagation becomes important.

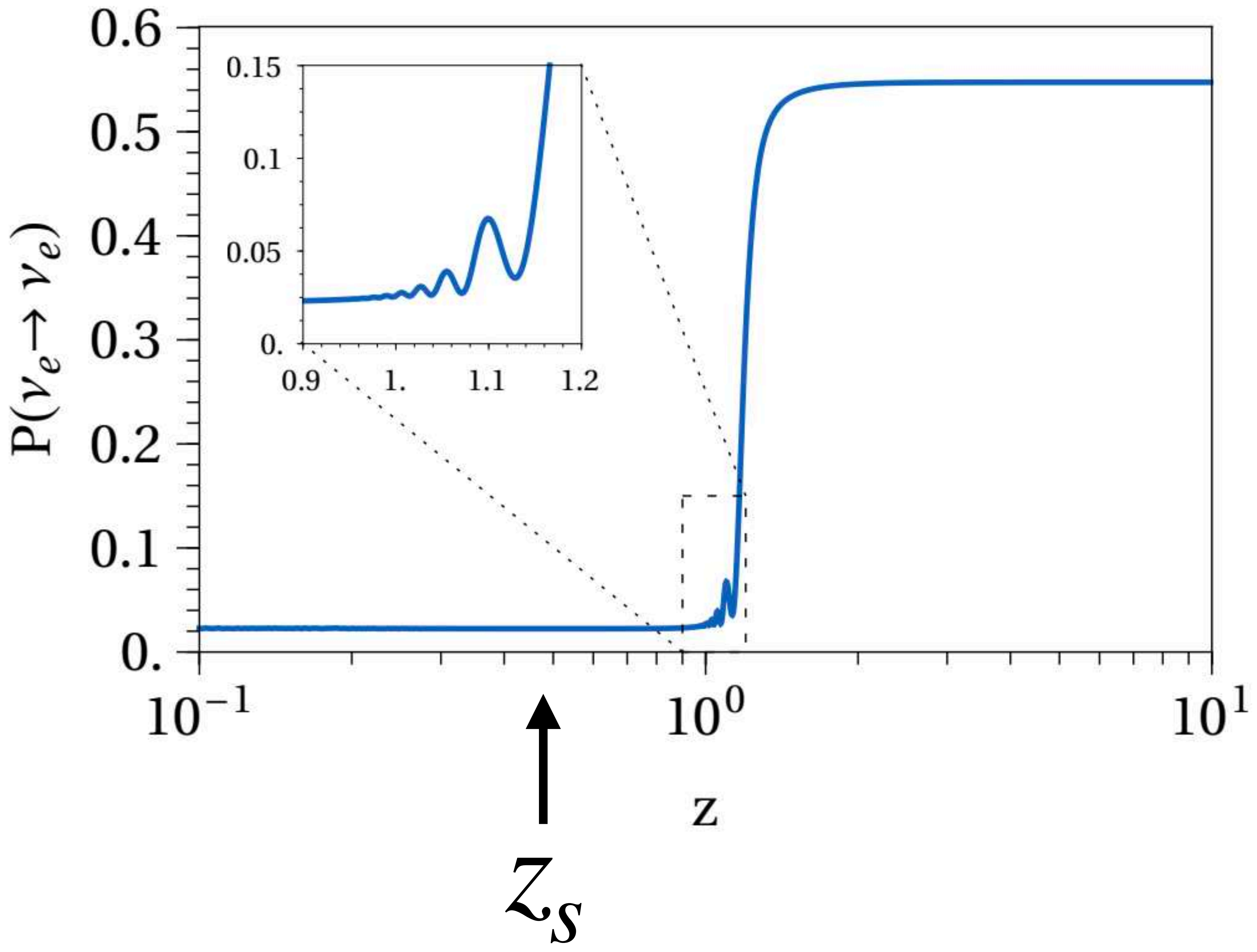
$$P_{ee} = |U_{e1}|^2 P_c^H P_c^L + |U_{e2}|^2 (P_c^H - P_c^H P_c^L) + |U_{e3}|^2 (1 - P_c^H)\,.$$

- As neutrino mass switches on while in vacuum, propagation changes depending on what the neutrino encounters: matter effects, vacuum, etc.

- This changes the probability of a certain flavor arriving at Earth, leading to enhancement.

Neutrino probability calculation

- Solve the neutrino propagation inside a SN to obtain probability

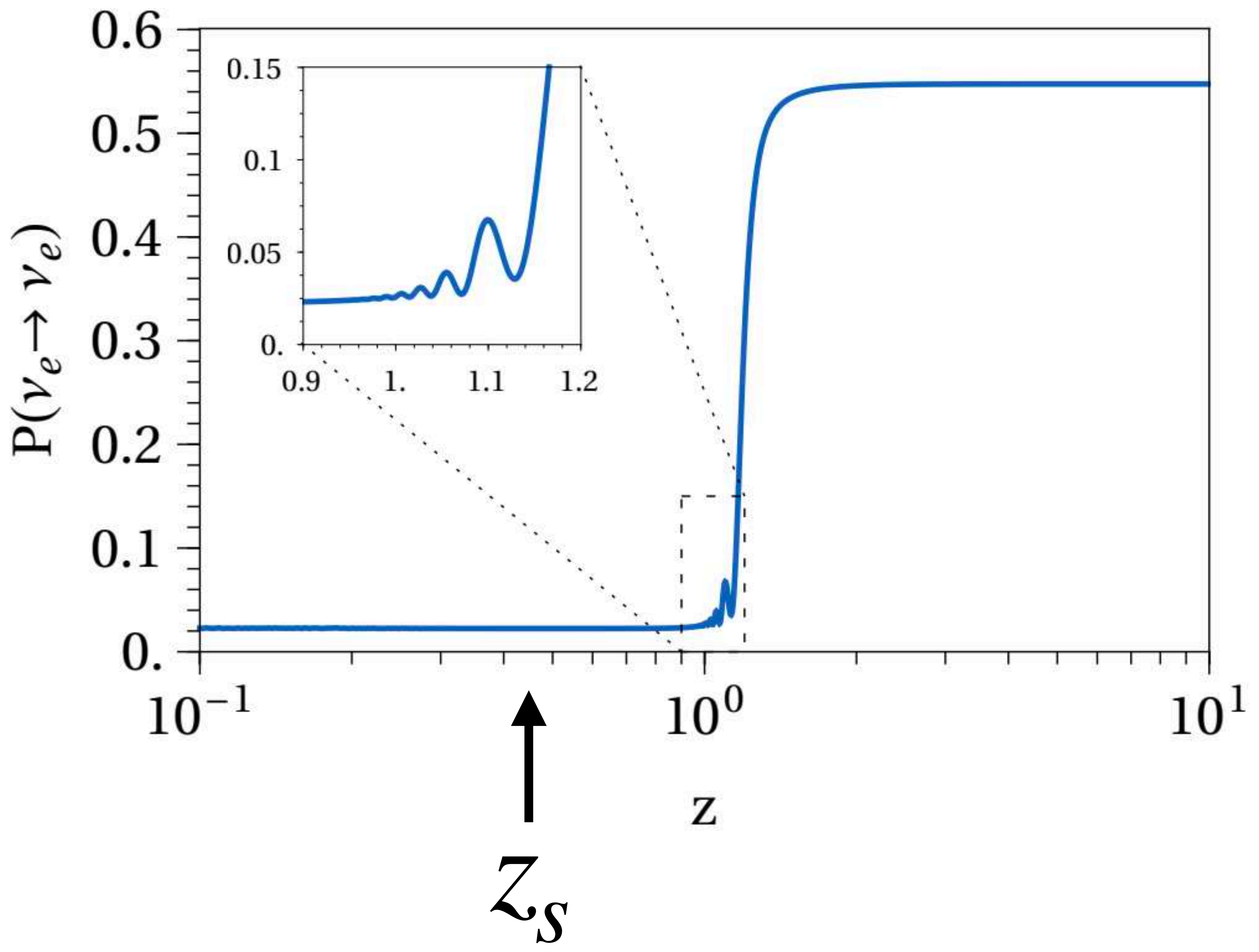


Neutrino probability calculation

- Solve the neutrino propagation inside a SN to obtain probability
- As neutrino mass switches on while in vacuum, propagation similar to vacuum, hence $P_{ee}(\nu_e) = \sum_k |U_{ek}|^4 = 0.57$
- Contrast with MSW matter propagation:

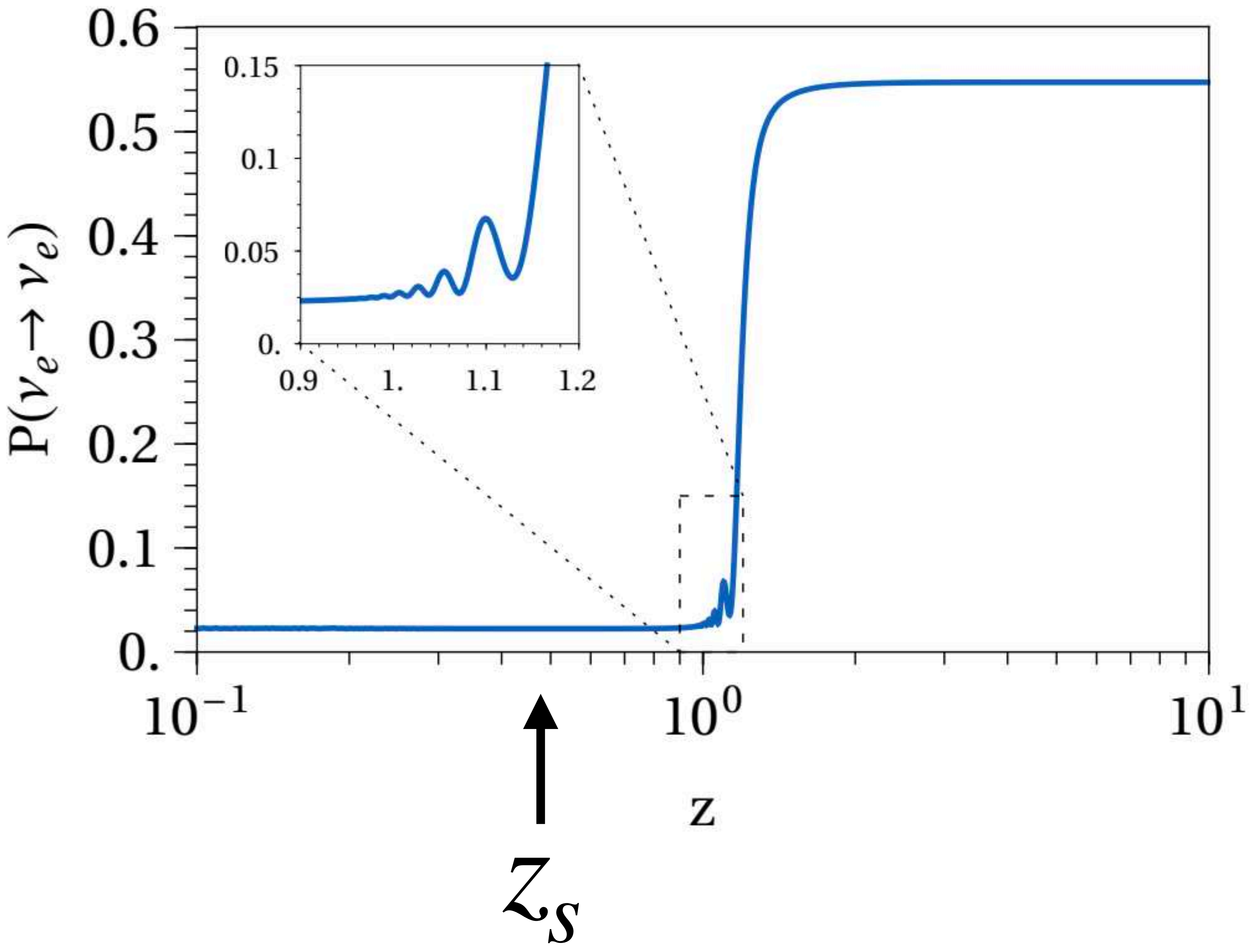
For massive neutrinos, in NMO,
$P_{ee}(\nu_e) \sim |U_{e3}|^2 = 0.02$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e1}|^2 = 0.67$

For massive neutrinos, in IMO,
$P_{ee}(\nu_e) \sim |U_{e2}|^2 = 0.3$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e3}|^2 = 0.03$



Neutrino probability calculation

- Solve the neutrino propagation inside a SN to obtain probability



- As neutrino mass switches on while in vacuum, propagation similar to vacuum, hence $P_{ee}(\nu_e) = \sum_k |U_{ek}|^4 = 0.57$
- Contrast with MSW matter propagation:

For massive neutrinos, in NMO,
$P_{ee}(\nu_e) \sim |U_{e3}|^2 = 0.02$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e1}|^2 = 0.67$

For massive neutrinos, in IMO,
$P_{ee}(\nu_e) \sim |U_{e2}|^2 = 0.3$ and $P_{ee}(\bar{\nu}_e) \sim |U_{e3}|^2 = 0.03$

- The net DSNB flux at Earth

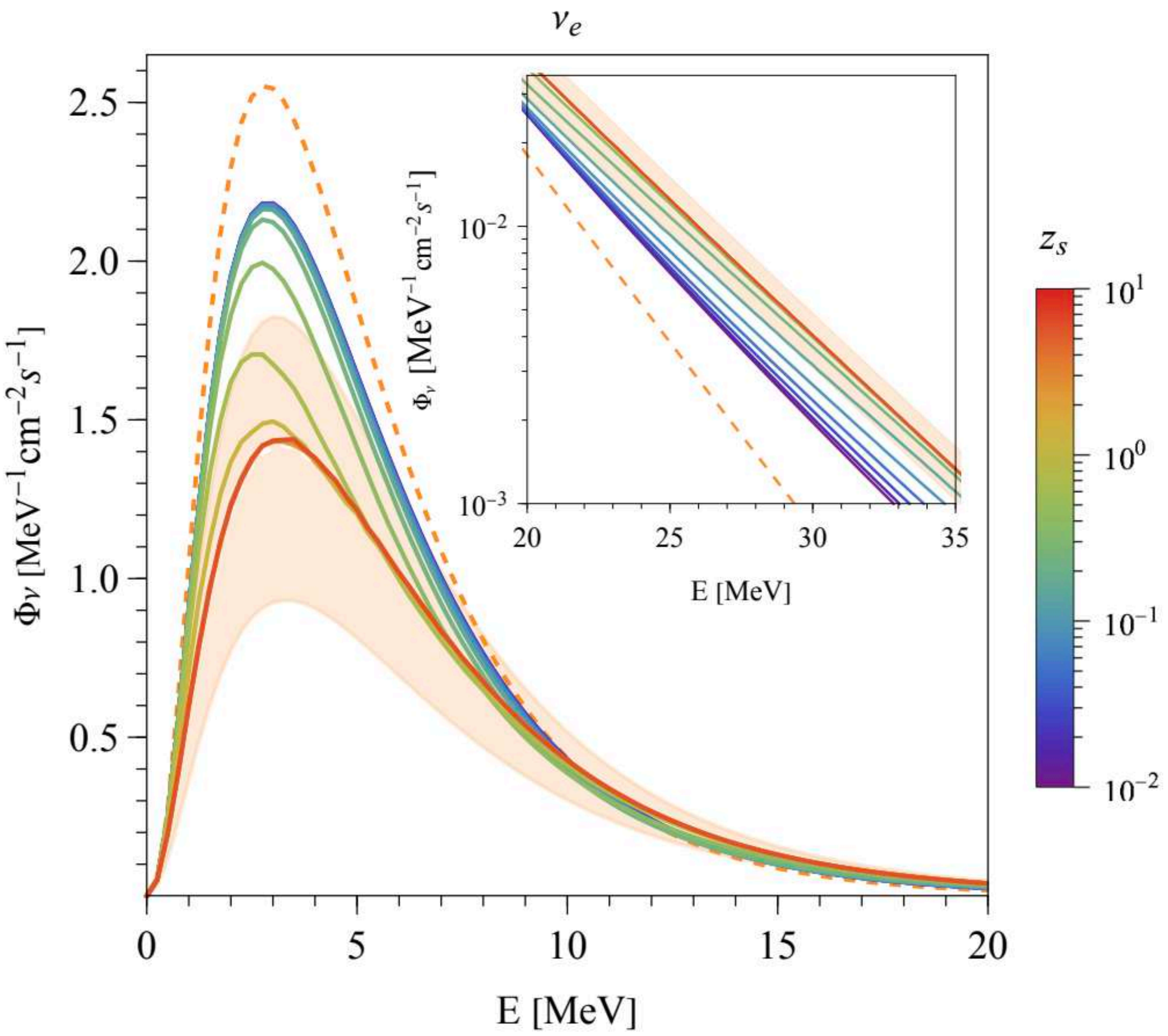
$$\Phi_{\nu_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}}(z) \left\{ P_{ee}(z)\phi^0_{\nu_e} + (1 - P_{ee}(z))\phi^0_{\nu_x} \right\} \longrightarrow$$

Impact strongest for ν_e at NMO

$$\Phi_{\bar{\nu}_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\mathrm{CCSN}} \left\{ \overline{P_{ee}}(z)\phi^0_{\bar{\nu}_e} + (1 - \overline{P_{ee}}(z))\phi^0_{\nu_x} \right\} \longrightarrow$$

Almost null effect in both orderings, since $\bar{\phi}_{\nu_e} \sim \phi_{\nu_x}$

What happens if the mixing angles vary similarly?



- A similar variation can be induced in mixing angles as well,

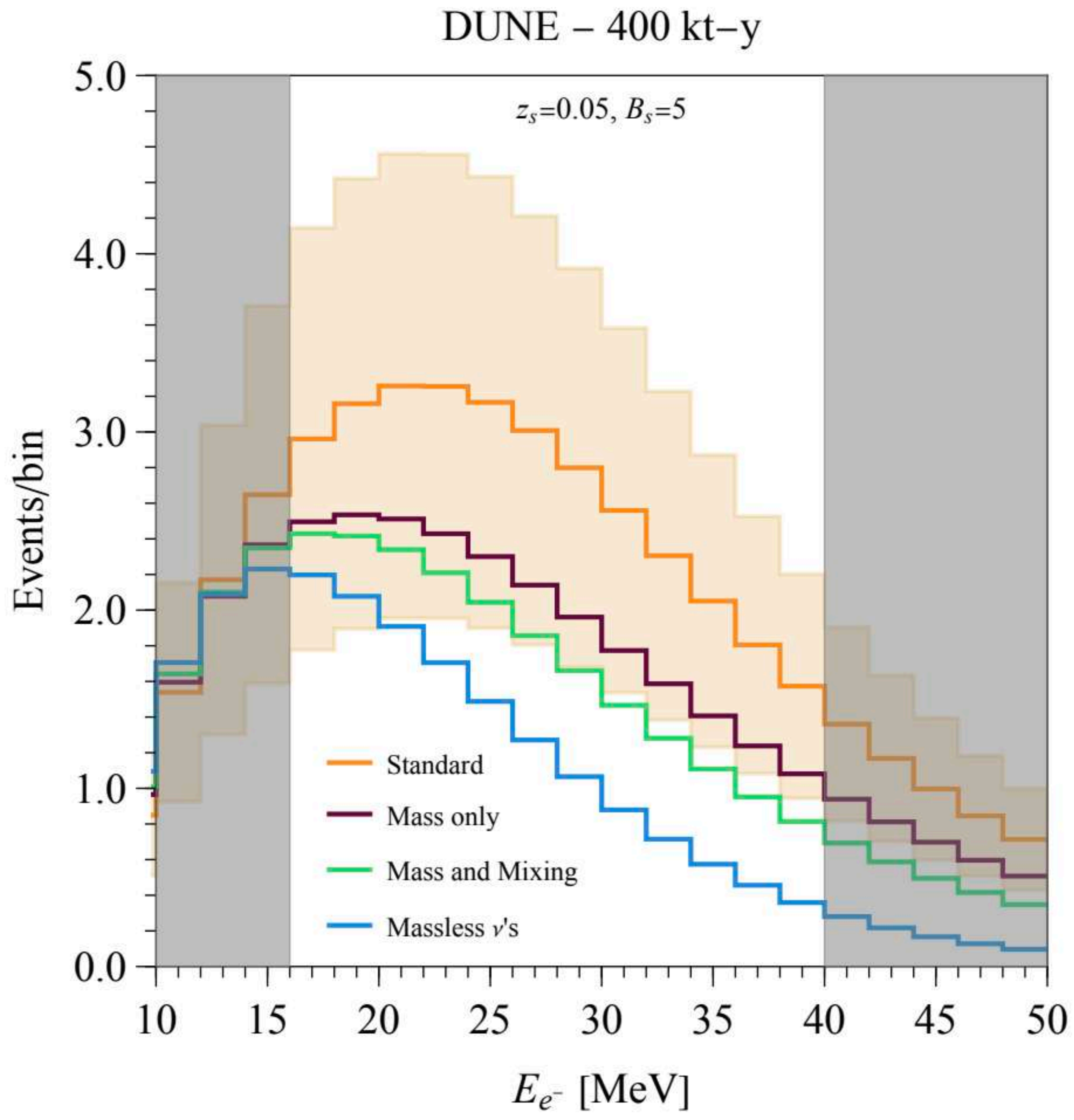
$$\theta_{ij}(z) = \frac{\theta_{ij}}{1 + (z/z_s)^{\mathrm{B}_s}}\,.$$

- As θ is small, the ν_e exits as a ν_1 .

- Combined effect of mass, and mixing variation is stronger.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102

Event spectra in a DUNE like detector



- Currently, one needs to be very "optimistic" for this effect to show up.

- But, there is a correlation:

  1. Expect a reduction in number of ν_e events in a DUNE like detector, in energy above 20-sh MeV.

  2. In parallel, there would be no change in the $\bar{\nu}_e$ event rate in a HK/JUNO like detector.

- With better astrophysical modelling, and improved detectors, this will become a possibility. So, stay tuned.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, arXiv:2205.01102