PROBING DYNAMIC NEUTRINO MASSES WITH THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

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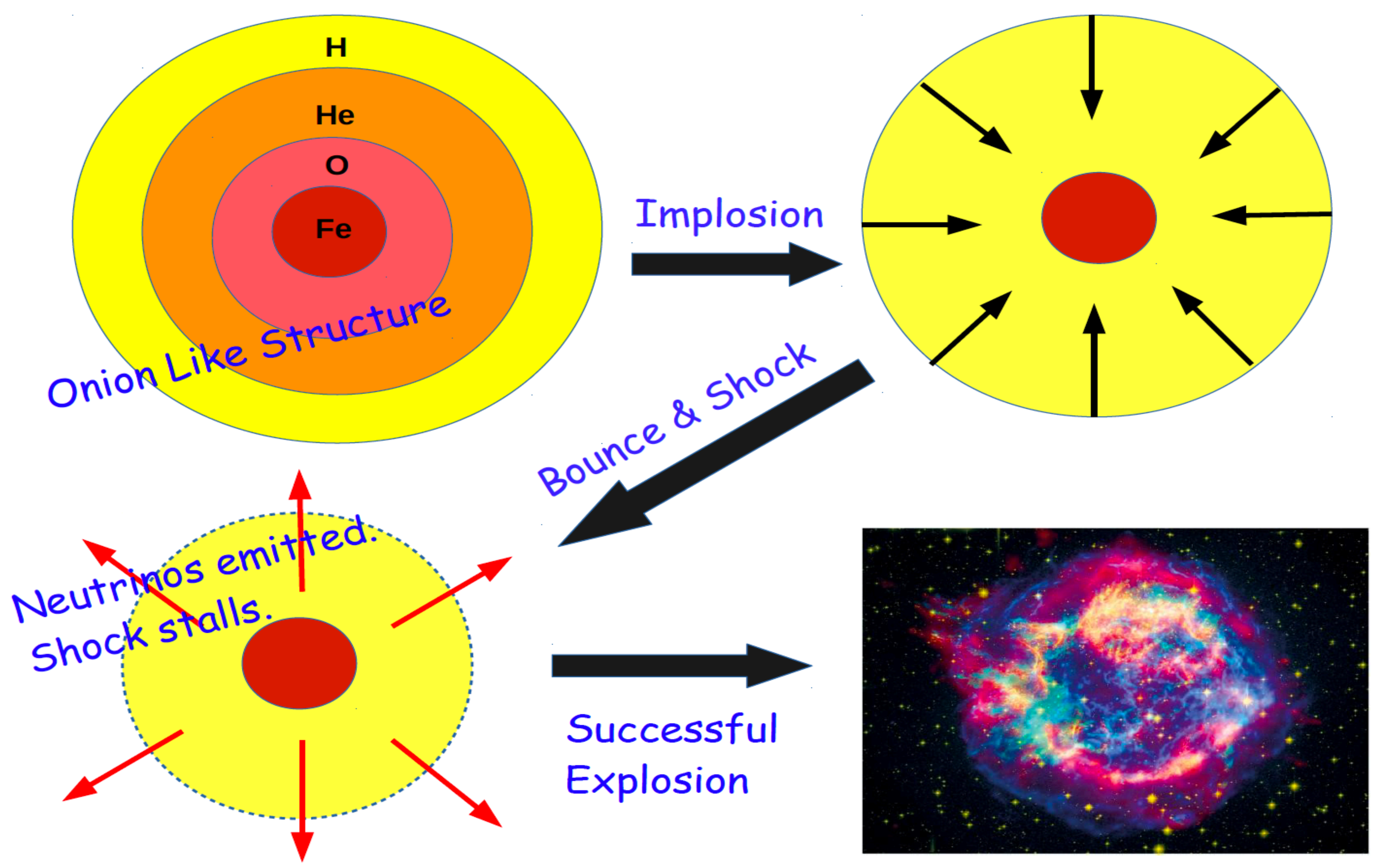
IIT Bombay

HET@BNL Seminar, 23.01.25

Core-collapse SNe: Mechanism



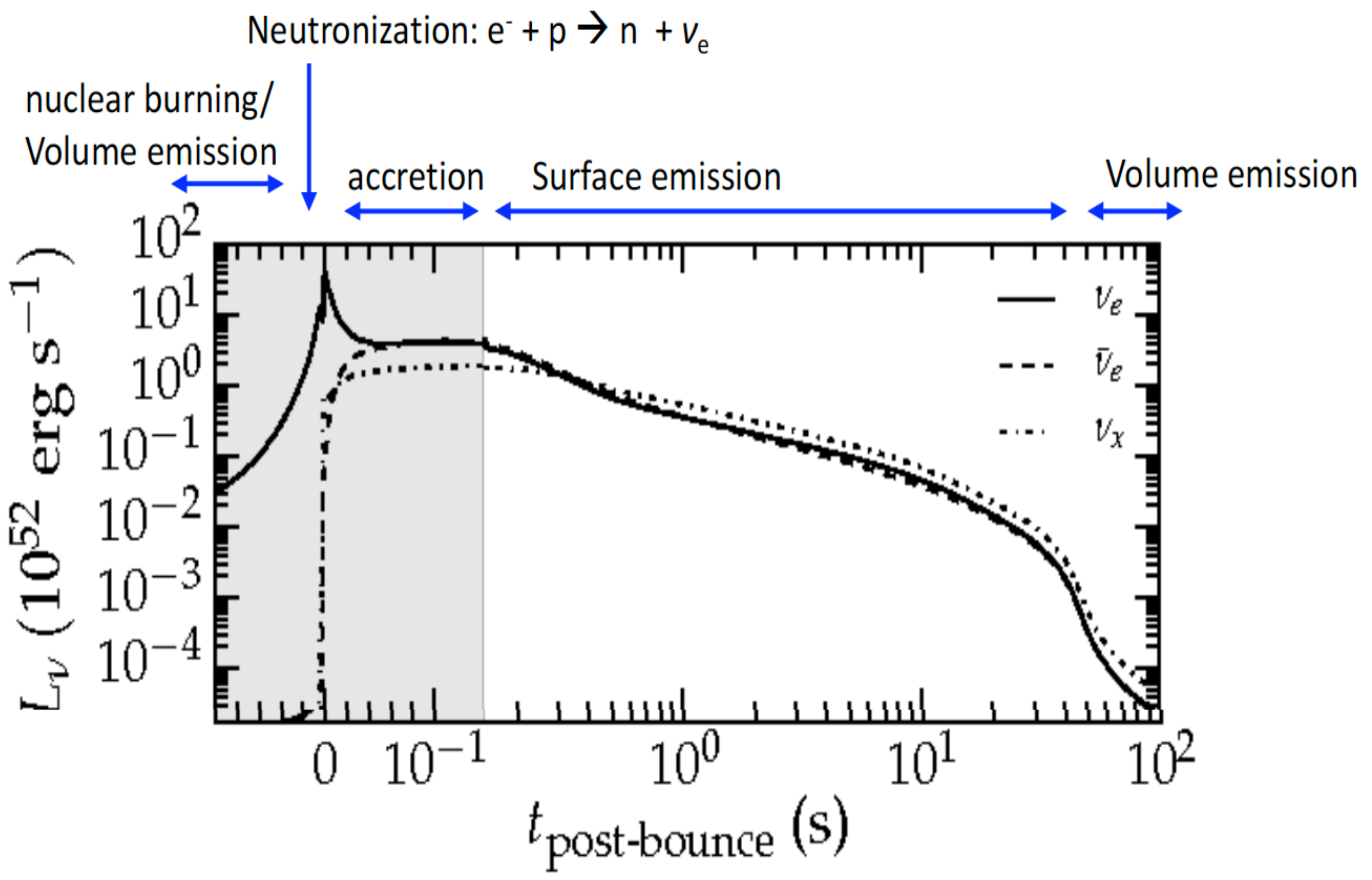
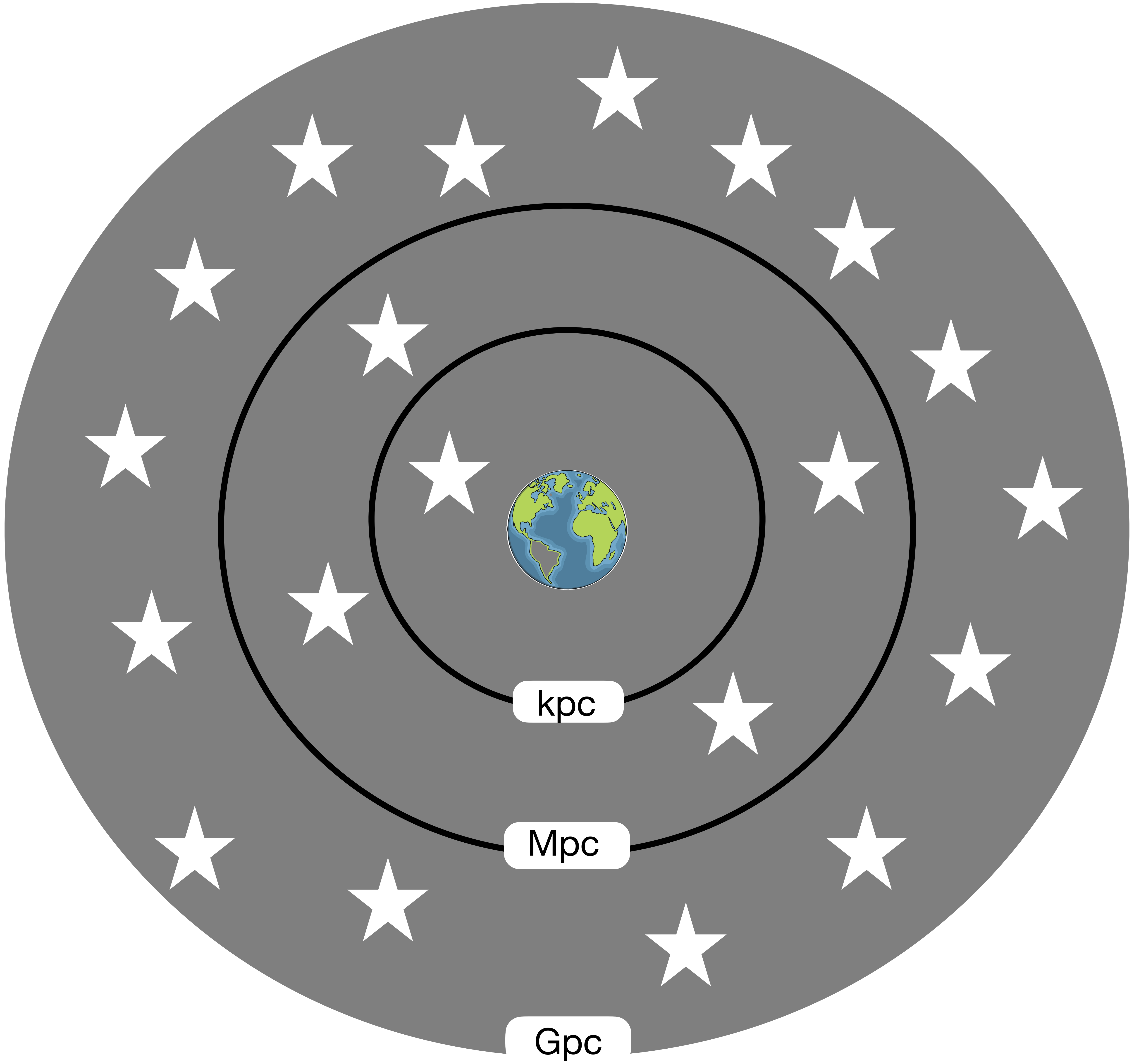


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

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



How to estimate the DSNB?

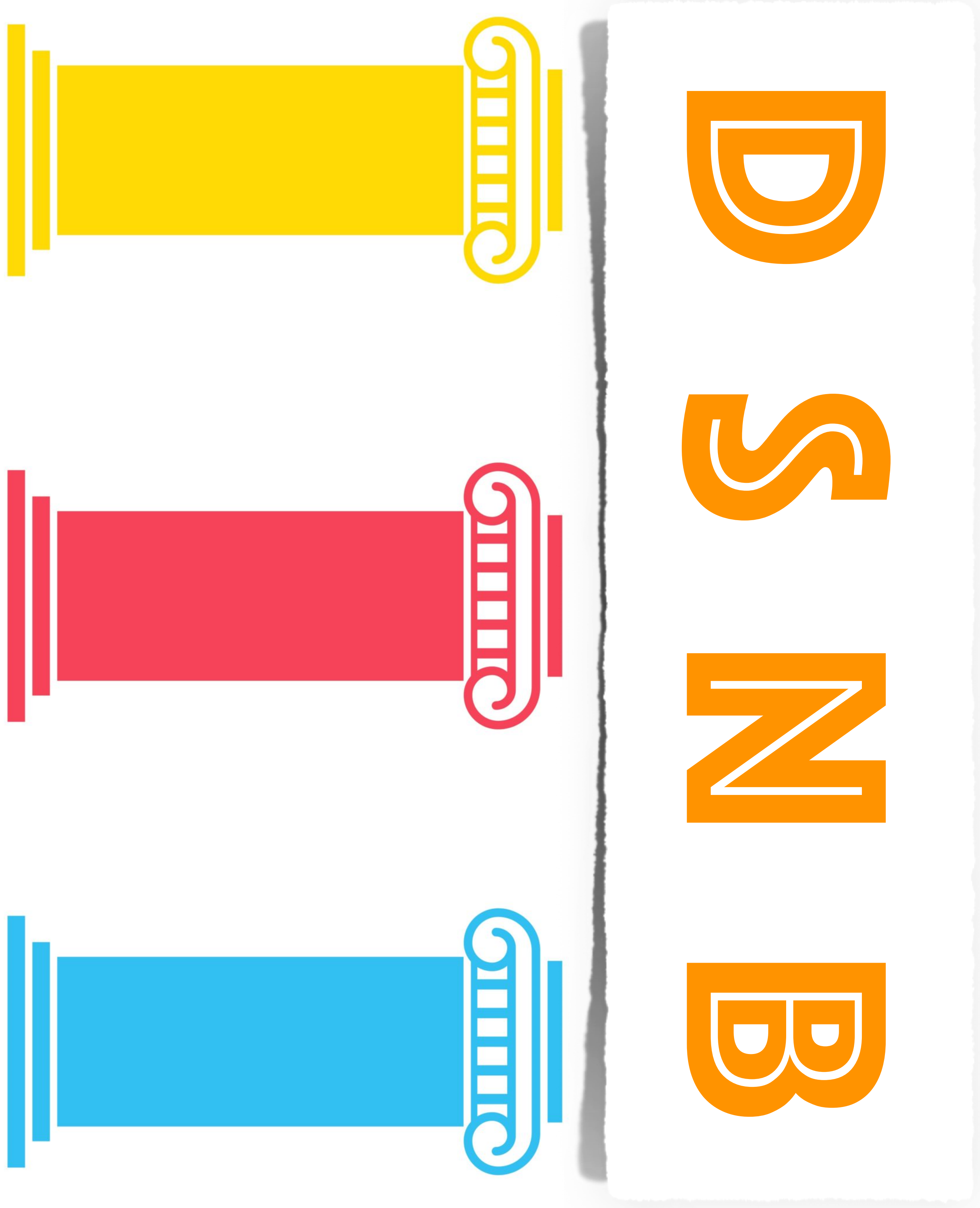
$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)}\, R_{\mathrm{CCSN}}(z)\, F_\nu\big(E(1+z)\big)$$

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

SN Neutrino spectra

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 [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

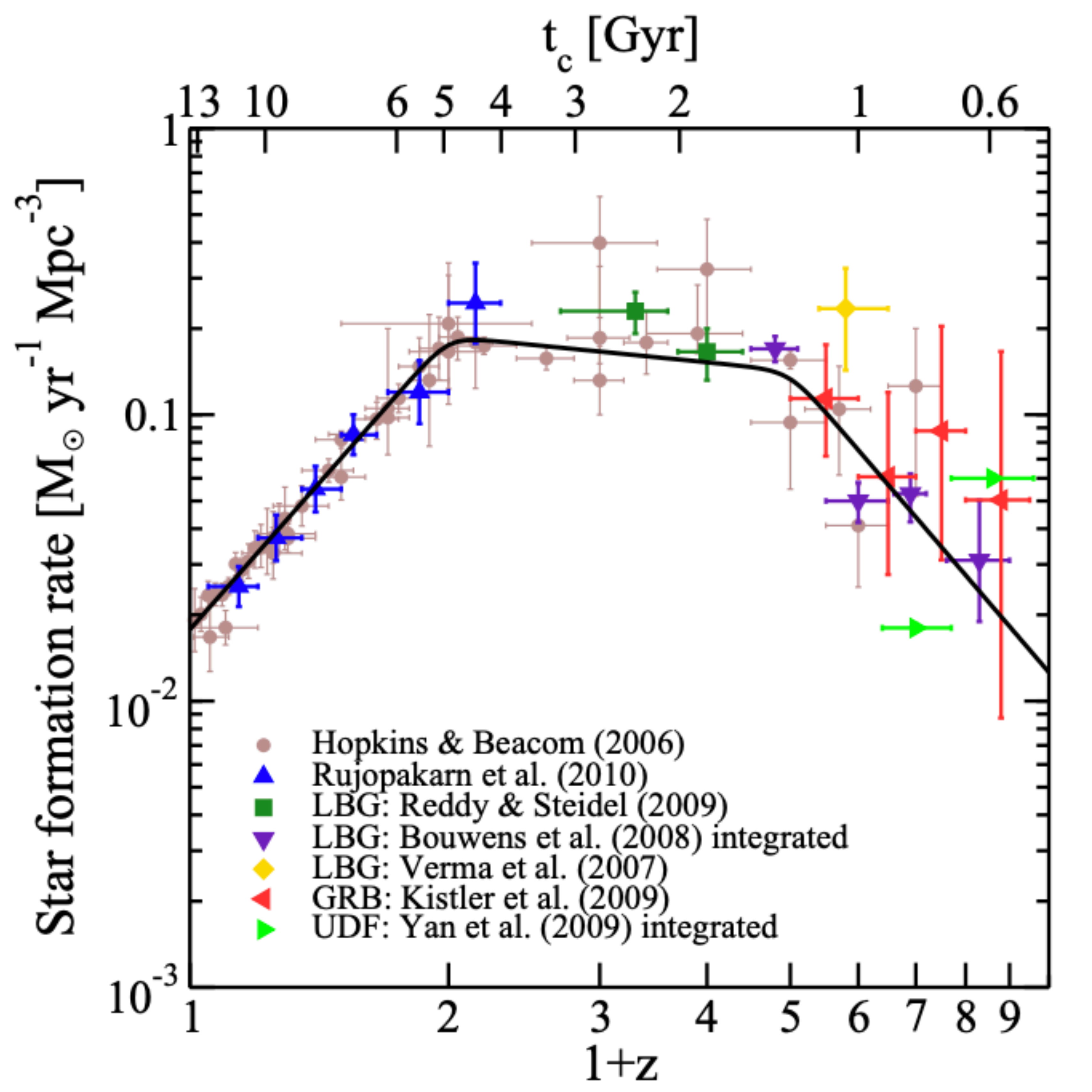
$$\dot{\rho}_*(z) = \dot{\rho}_0 \left[(1+z)^{-10\alpha} + \left(\frac{1+z}{B}\right)^{-10\beta} + \left(\frac{1+z}{C}\right)^{-10\gamma} \right]^{-1/10}$$

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

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

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

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

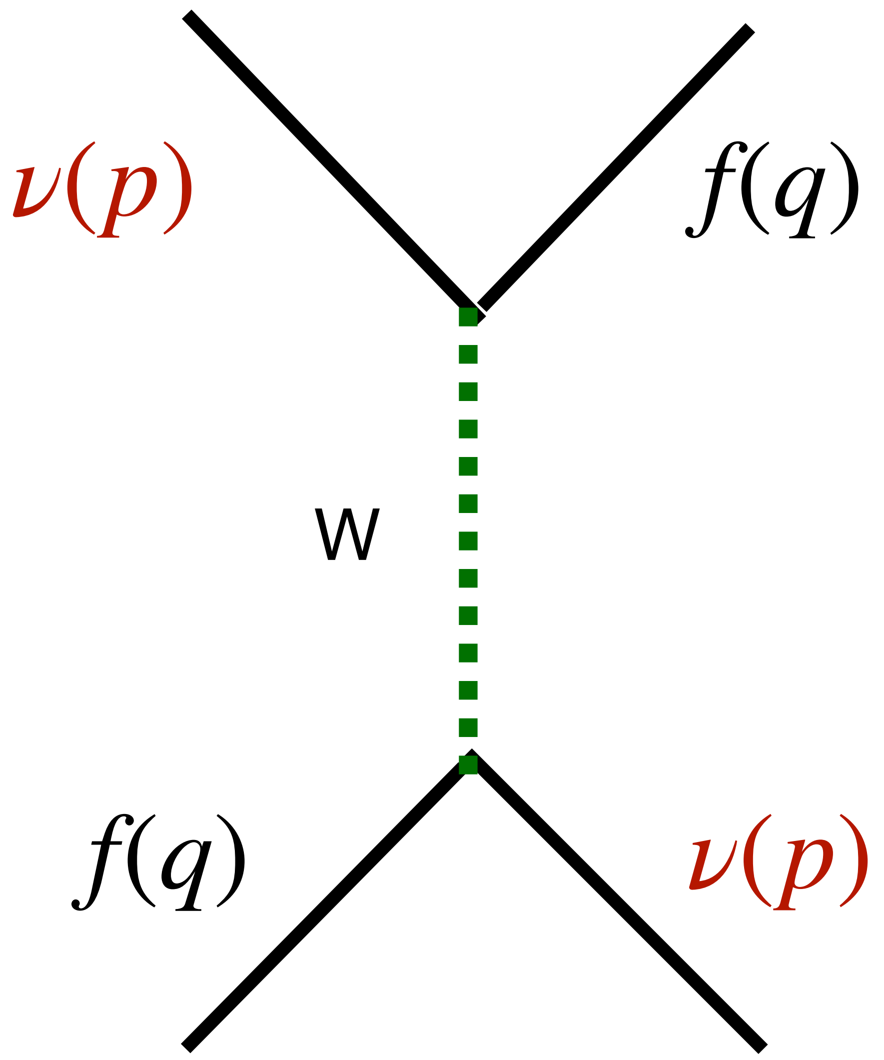
Hopkins, Beacom, ApJ2006
Yuksel, Kistler, Beacom, Hopkins, ApJ2008
Horiuchi, Beacom, Dwek, PRD2009

Ingredient 3:Neutrino spectra

Ingredient 3: Neutrino oscillations in a media

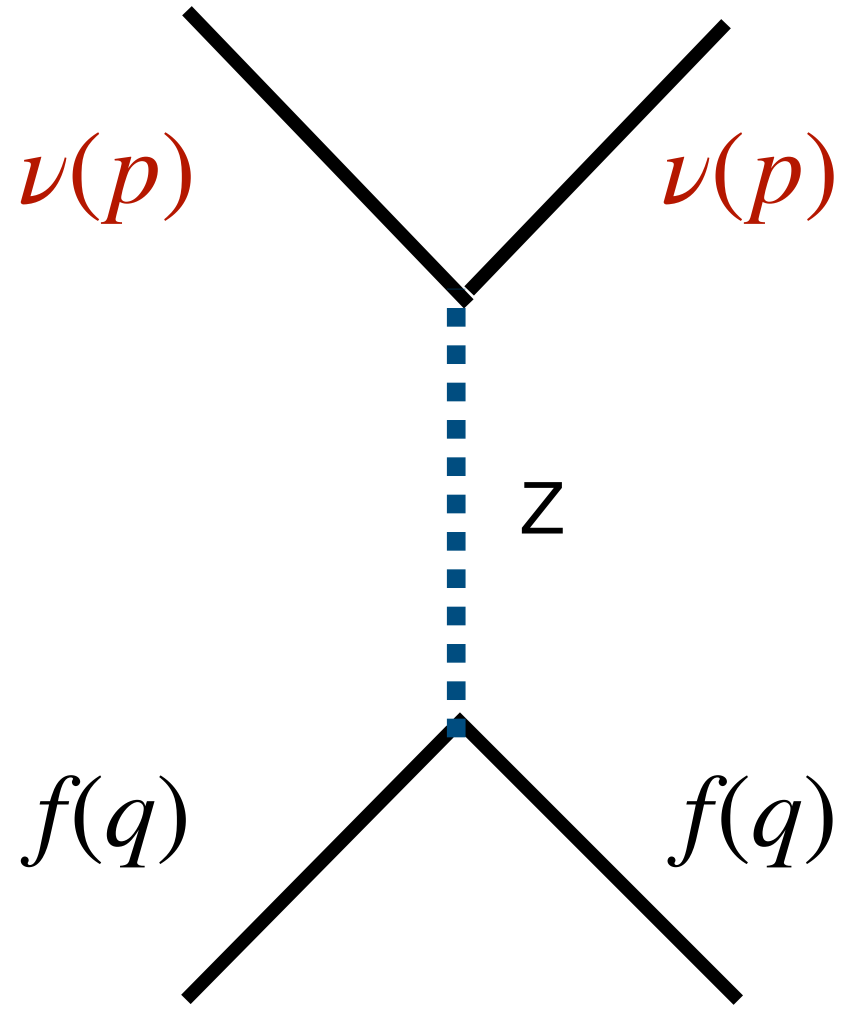
- Evolution in vacuum can be described by

$$H_{\mathrm{vac}} = \frac{1}{2E_\nu} U(\theta) \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U(\theta)^\dagger$$



- In the medium, neutrinos "feel" a potential due to scattering with the particles.

- Potential is proportional to the number density (n) of background scatters.



- This effect can be computed as

$$H_{\mathrm{mat}} = \sqrt{2} G_F \begin{pmatrix} n_e & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F \begin{pmatrix} -n_n/2 & 0 \\ 0 & -n_n/2 \end{pmatrix}$$

$$G_F \propto g^2/M_W^2$$

MSW resonance

- Net evolution in medium:

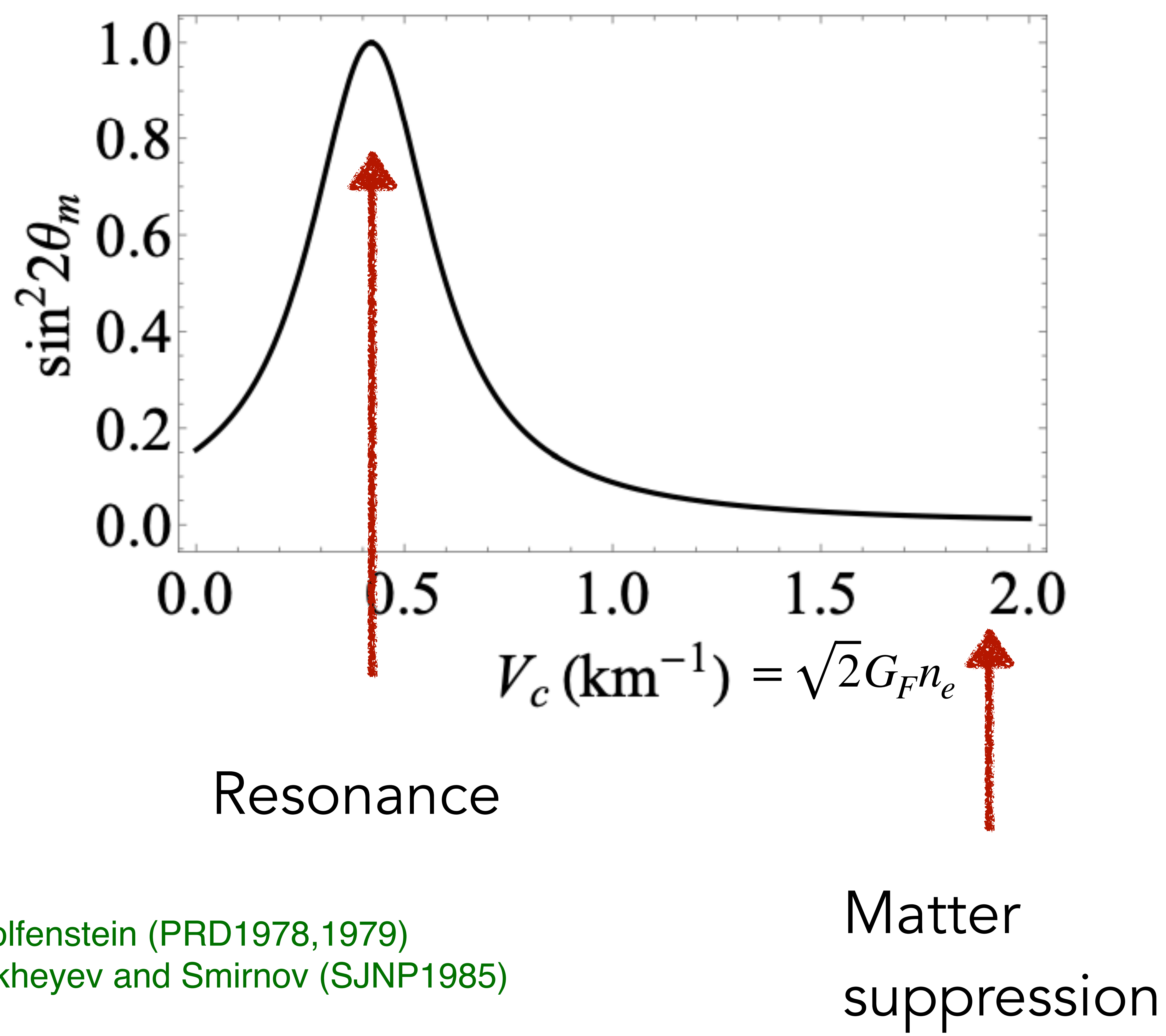
$$H = \frac{1}{2E_\nu} U(\theta) \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U(\theta)^\dagger + \sqrt{2} G_F \begin{pmatrix} n_e & 0 \\ 0 & 0 \end{pmatrix}$$

- Diagonalise using effective in-medium mixing angle $\sin 2\theta_m$.

- Enhanced flavour conversions when

$$\frac{\Delta m^2}{2E_\nu} \cos 2\theta = \sqrt{2} G_F n_e$$

- This is the MSW resonance.



Wolfenstein (PRD1978,1979)
Mikheyev and Smirnov (SJNP1985)

Adiabaticity of Resonance

- Evolution in terms of matter eigenstates: $\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = U(\theta_m)^\dagger \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$

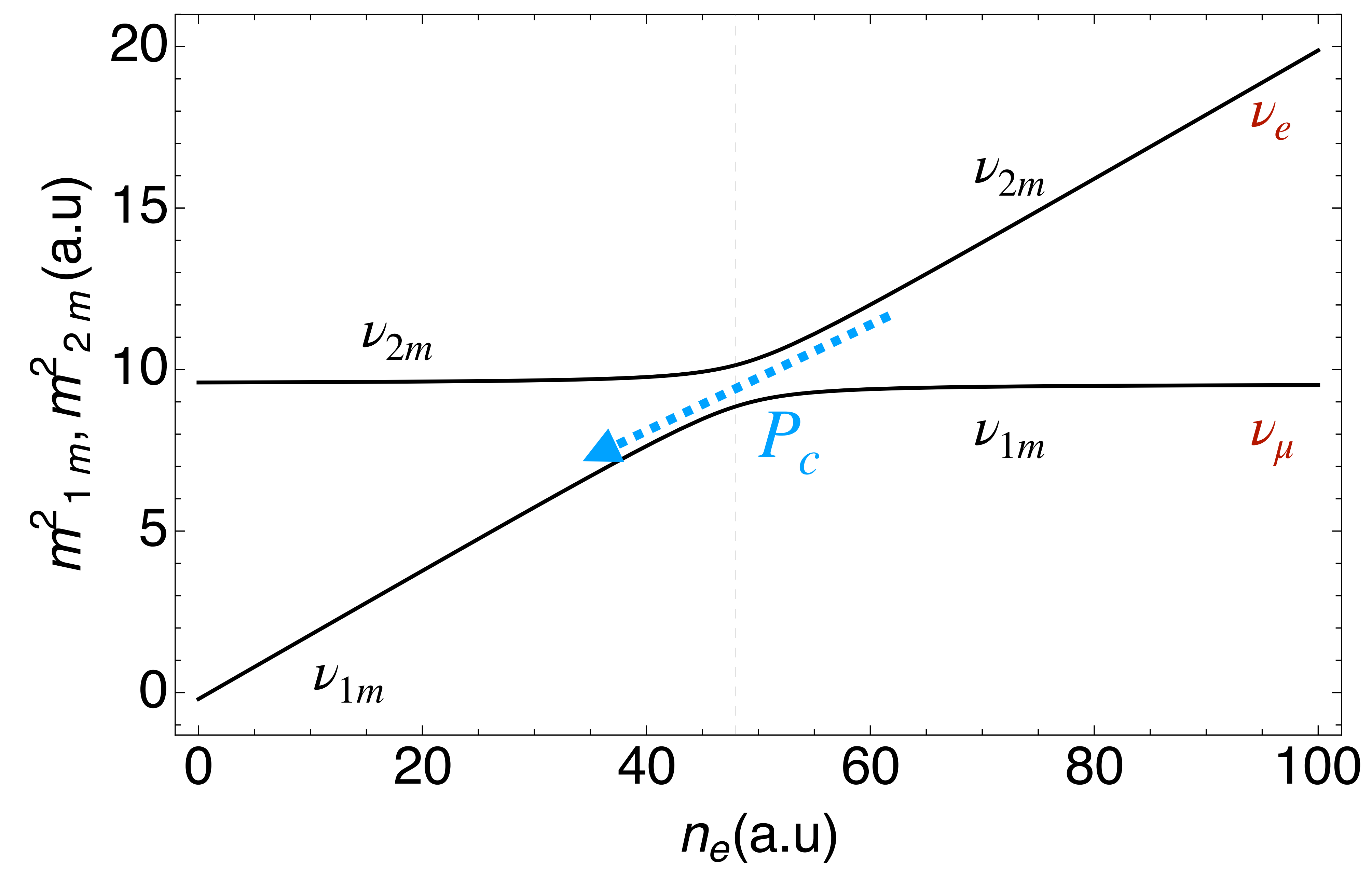
- Flip probability P_c if propagation is non- adiabatic, $\dot{\theta}_m \gg m_m^2$

- Landau Zener probability $P_c \simeq \exp\left(-\frac{\pi}{2}\gamma\right)$

  where $\gamma = \frac{\Delta m^2}{2E}\frac{\sin^2 2\theta}{\cos 2\theta}\frac{n_e}{\dot{n}_e}$.

- Adiabaticity corresponds to $\gamma \gg 1$.

- Current parameters imply adiabaticity.



Wolfenstein (PRD1978,1979)
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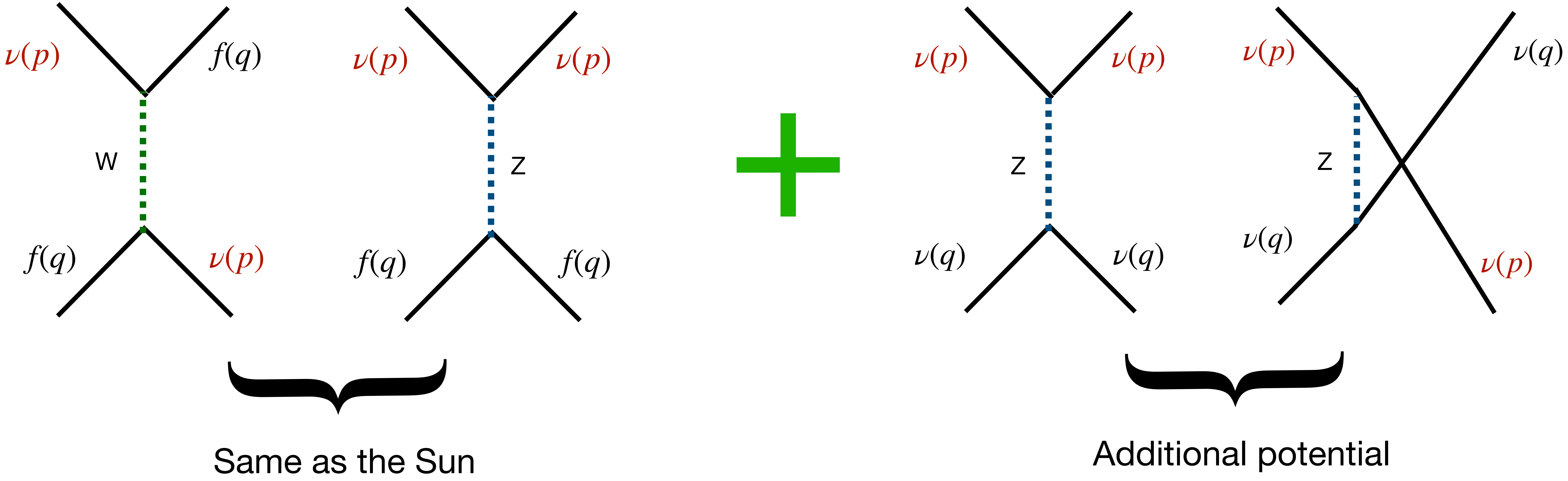
Neutrino self-interactions in dense media



- Neutrino density so high that they feel additional potential due to neutrinos. This potential can be between different neutrino flavours.

- Only lab where neutrino self-interactions become important.

Wolfenstein (PRD1978,1979)
Mikheyev and Smirnov (SJNP1985)
Pantaleone (PRD 1992)
Duan, Fuller, Carlson and Qian (PRD 2006,200
Hannestad, Raffelt, Sigland Wong (2006)

Ingredient 3: Neutrino spectra

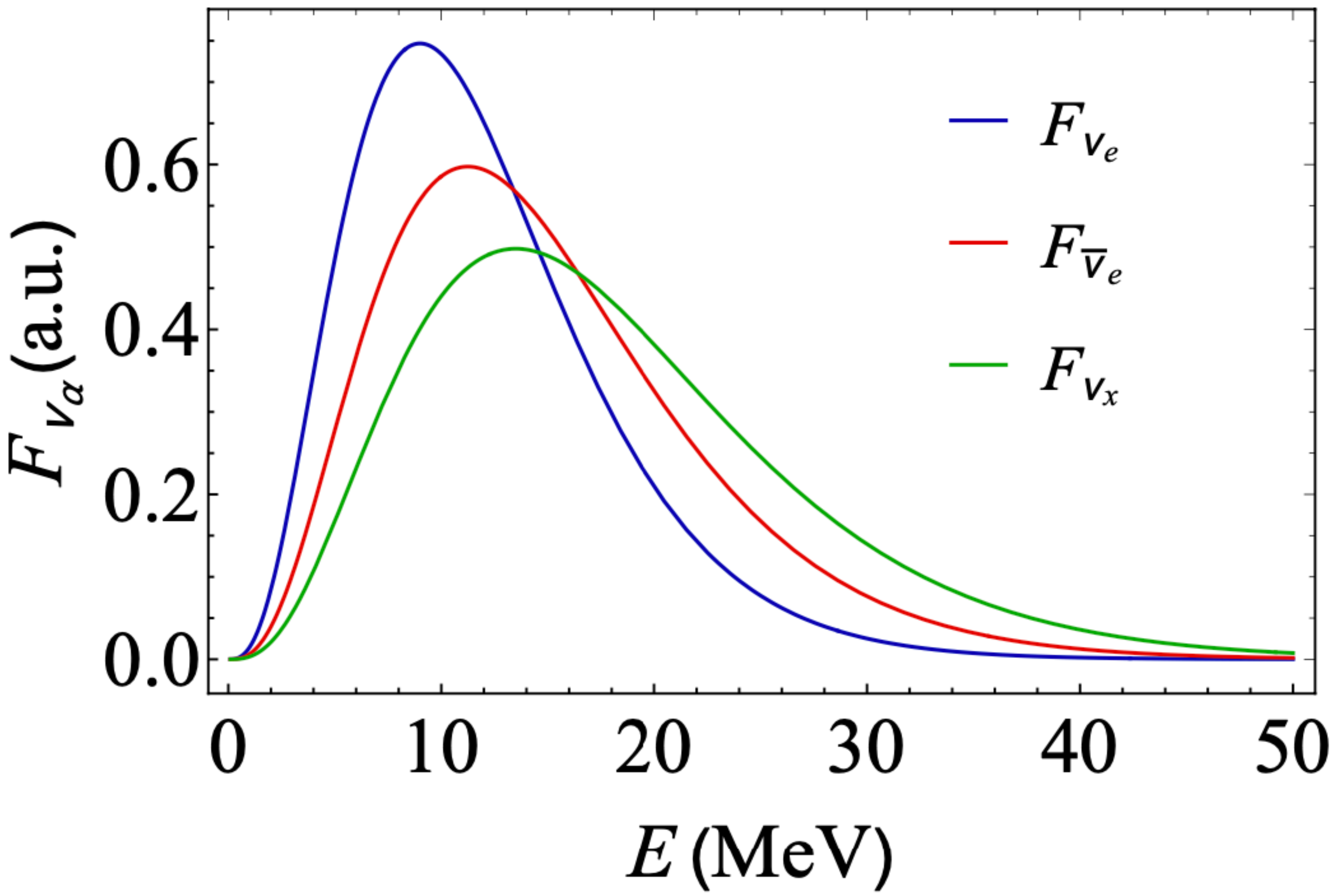
- Assume an approximately thermal spectra, characteristic of late-time phase.

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

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



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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

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

Cosmology

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

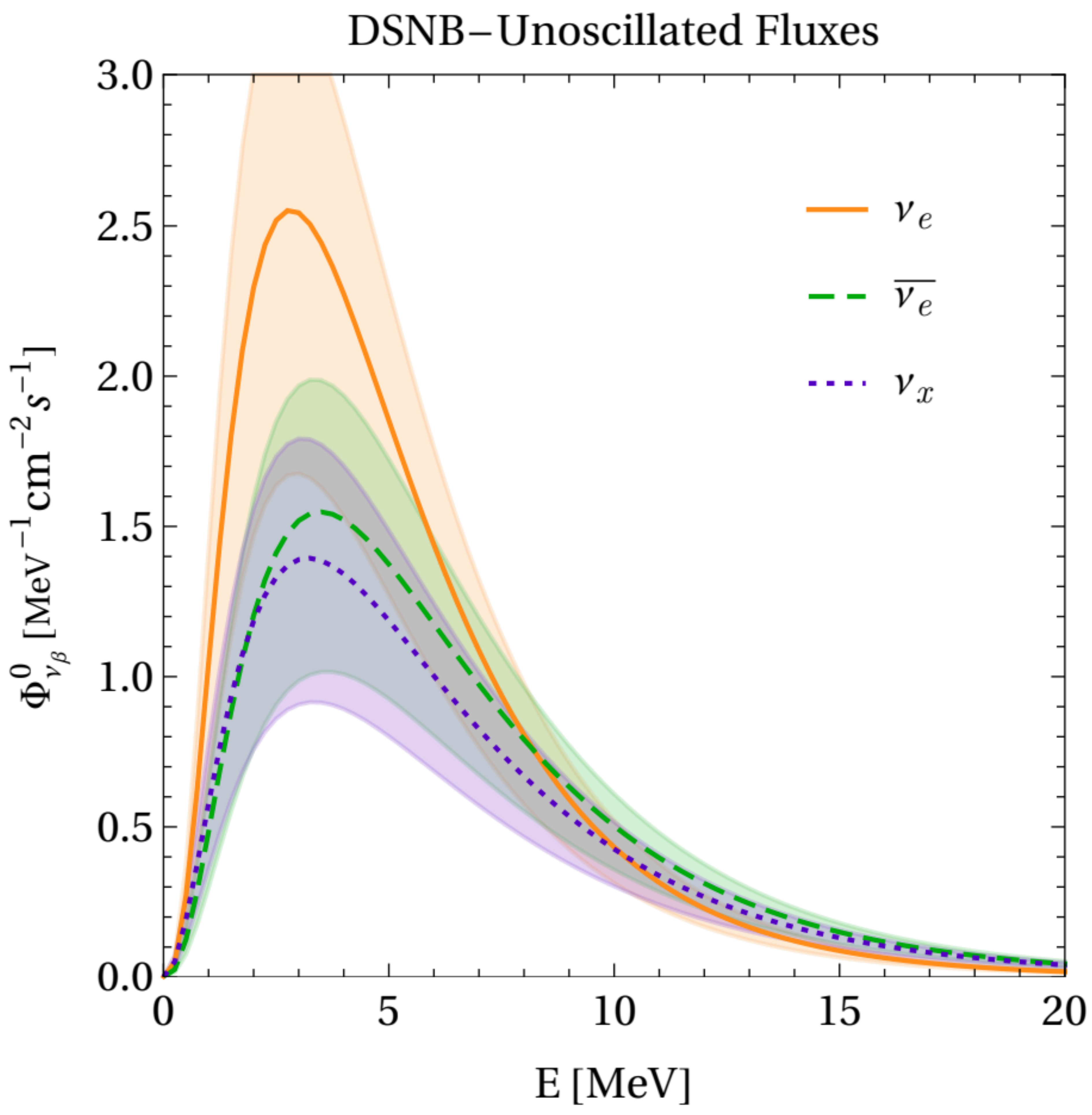
Putting all ingredients together

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

  Solar ν_e: extends upto ~20 MeV (can be reduced by directional information).
  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.



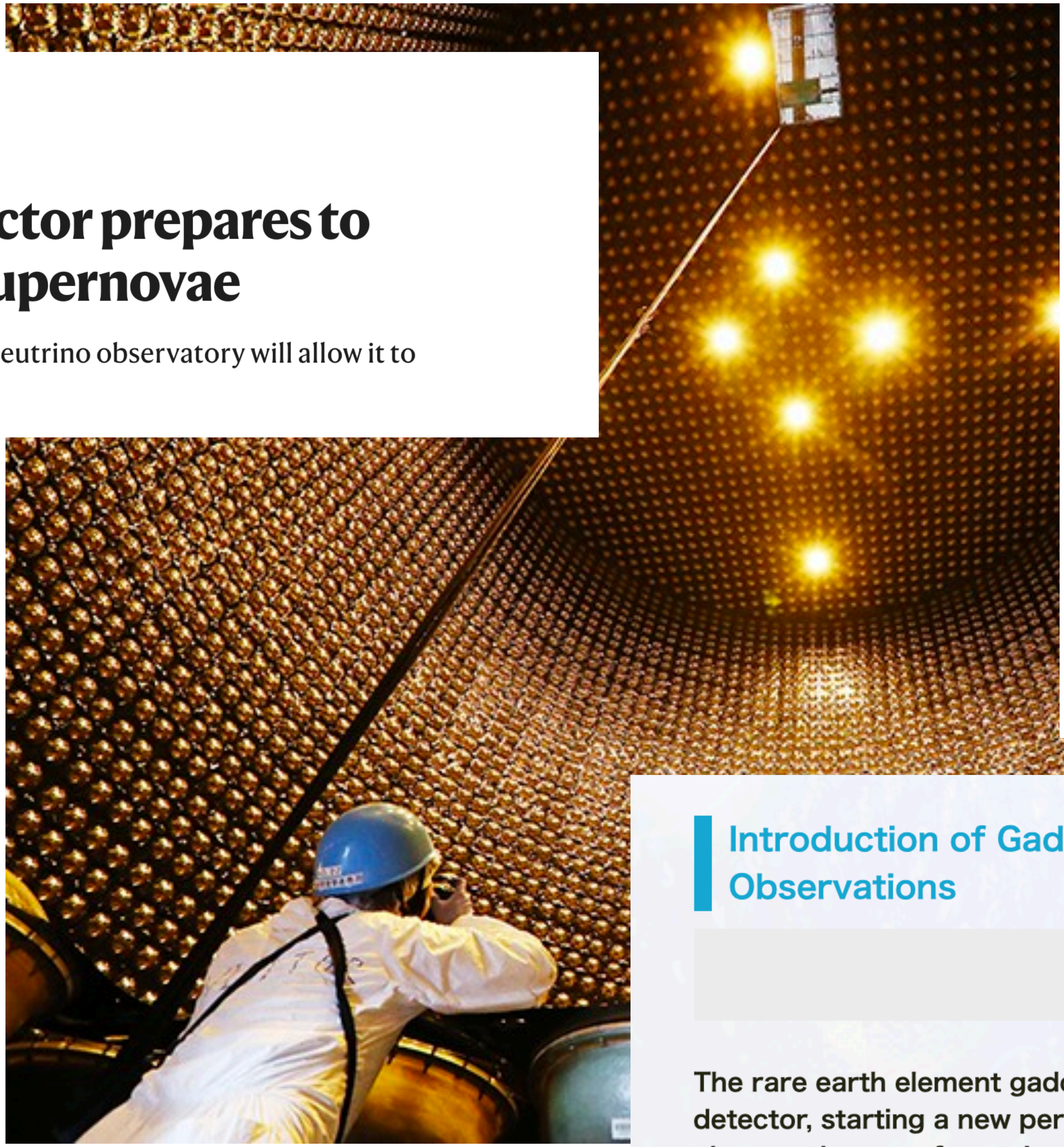
The Diffuse Supernova Neutrino Background

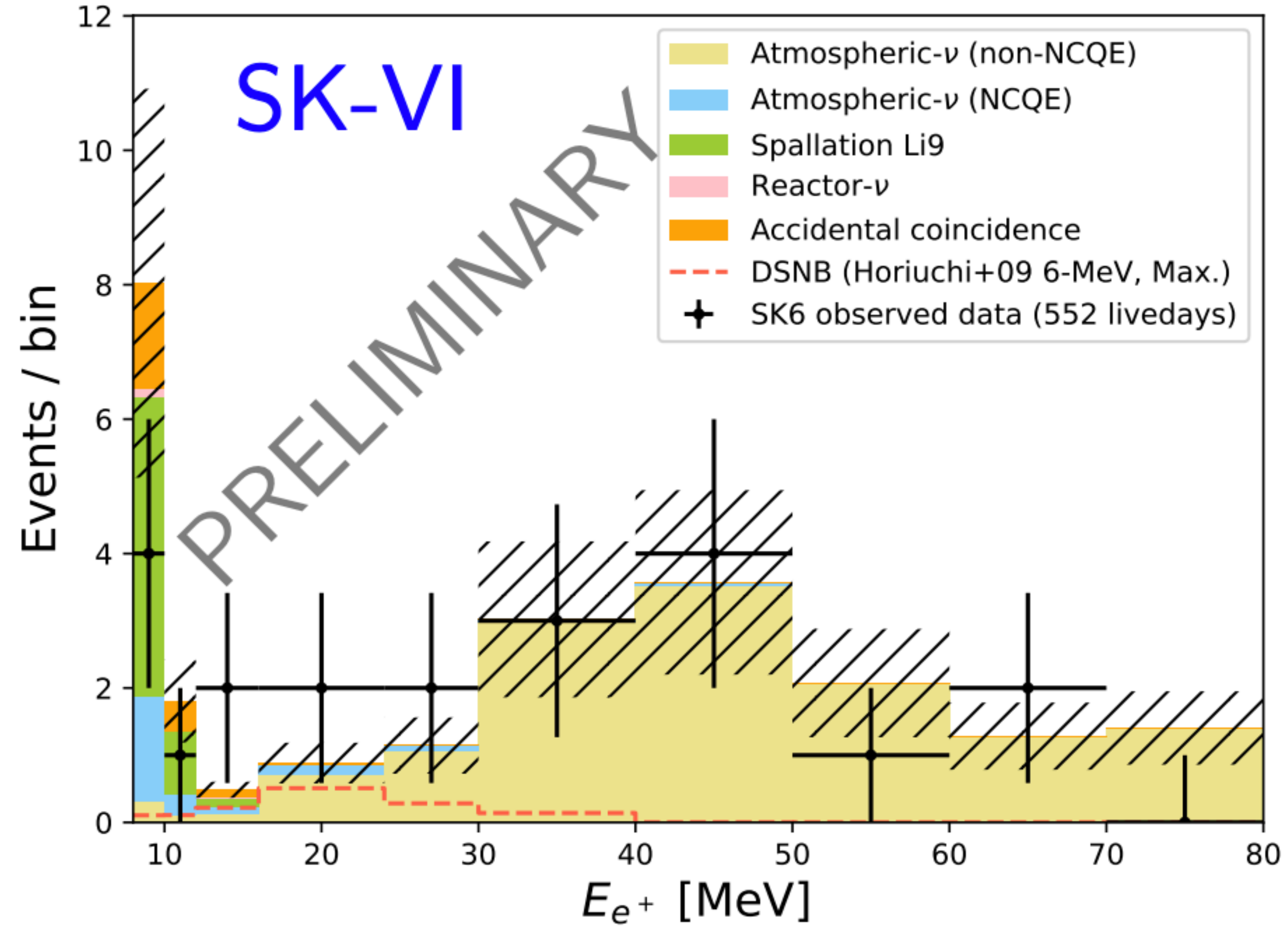
news > article

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?

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…

Origin of neutrino mass

Neutrino mass in particle physics

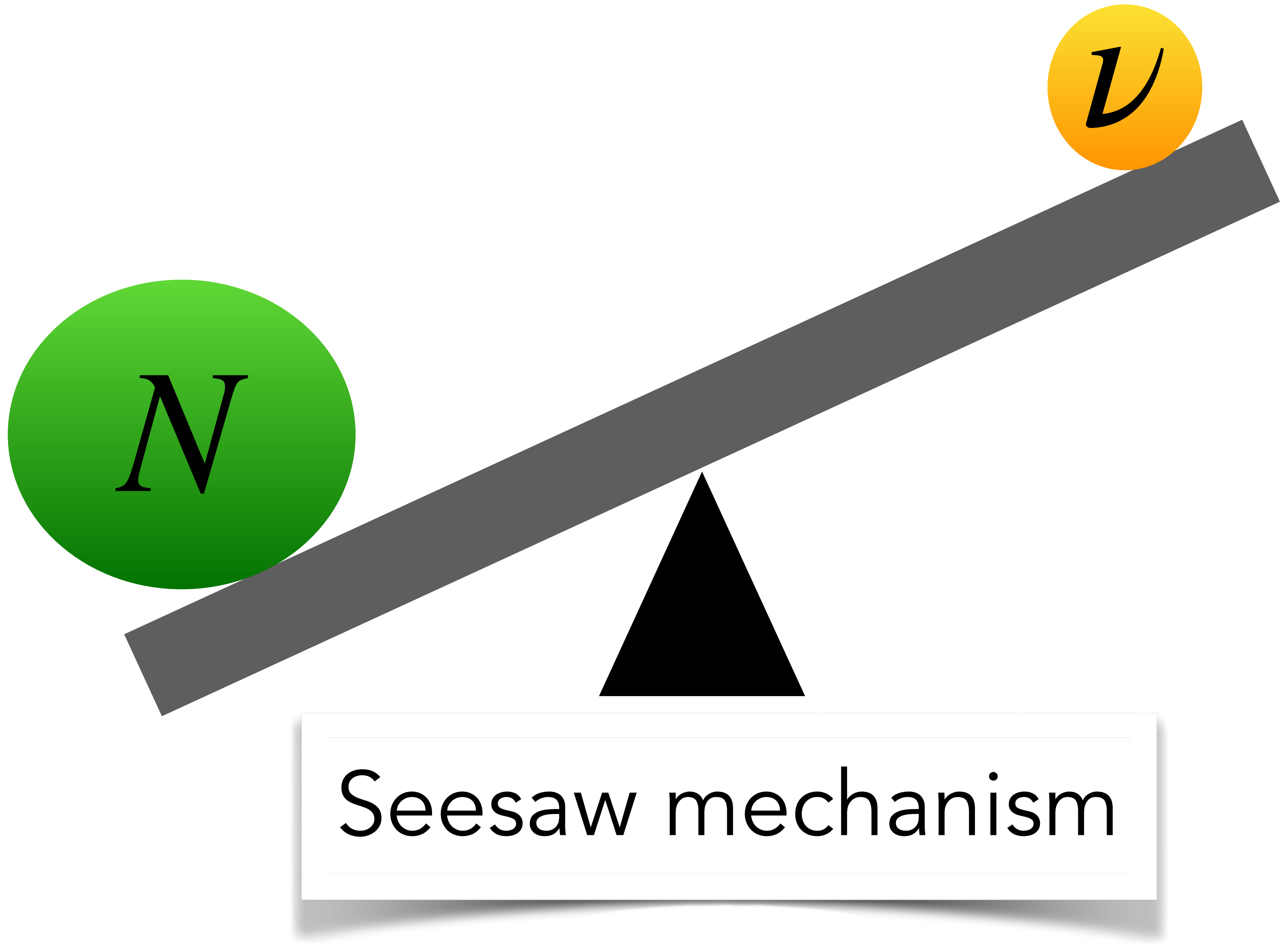
- Can be simple Dirac type $\mathscr{L}_{\text{Dirac}} = y\bar{L}H^cN$

- Or can be generated through the LNV Weinberg operator
$\mathscr{L}_{\text{Maj}} \supset \frac{c}{\Lambda}(LH)^2$

- Leads to Majorana neutrino mass $m_\nu \simeq \frac{cv^2}{\Lambda}$.

  Different UV completions available.

- Rely on vacuum expectation values of a scalar (like Higgs, etc.)



Dynamic Neutrino masses

- Or neutrino masses can be dynamic - not originating from vev.
- For e.g., massless neutrinos scattering off ultralight scalar DM ϕ. Refractive mass through an MSW-like effect.
- Multiple models where neutrino mass is generated through some interaction.
- Or through some unknown phase transition in the early Universe.
- Neutrino mass can be redshift-dependent!

Dark Origin of neutrino mass

Redshift dependent neutrino mass

- Can the neutrino mass be redshift dependent?

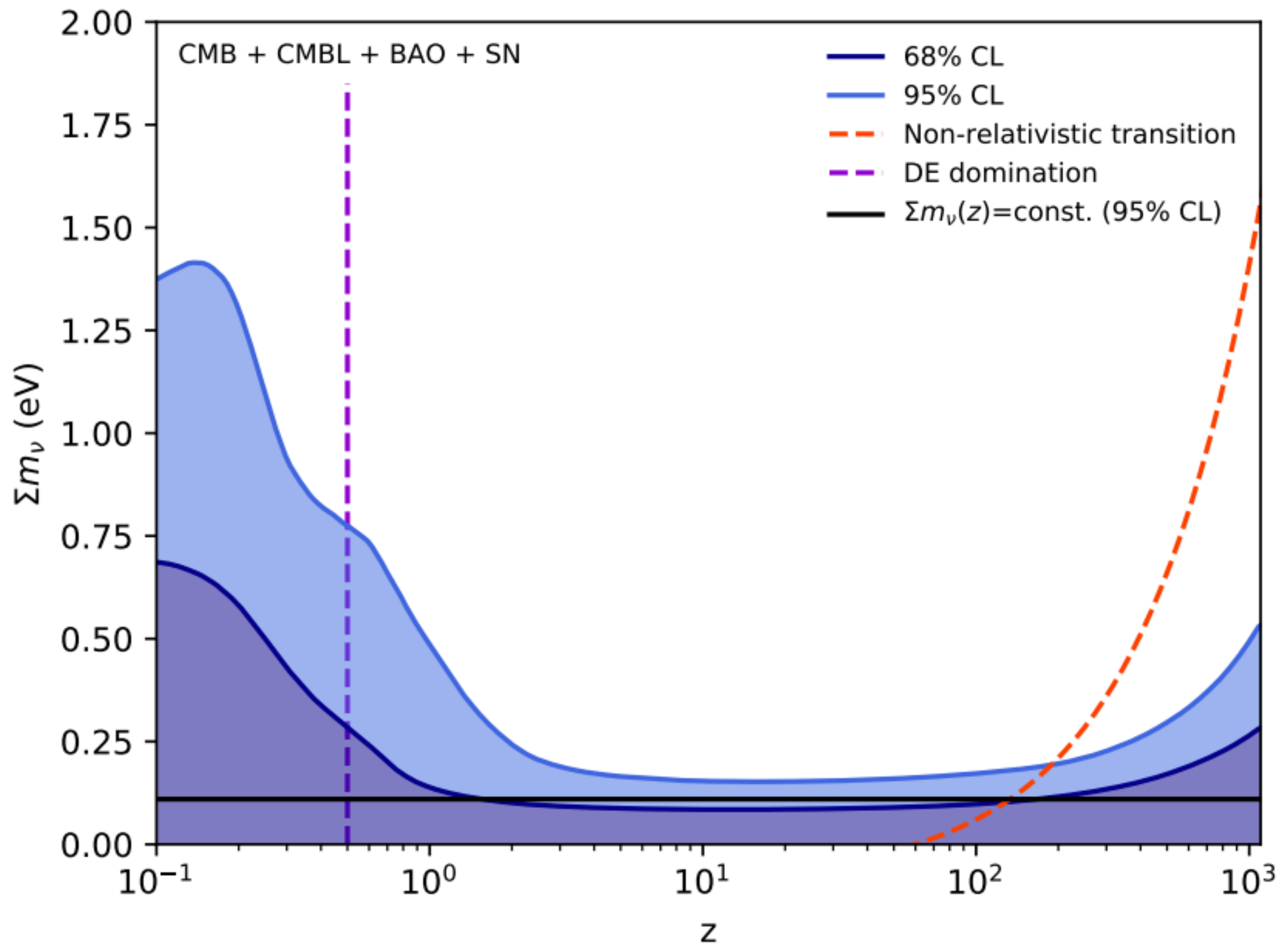
- Use $\sum m_\nu$ as a function of redshift.

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

  2. BAO from 6dF, SDSS, BOSS,…

  3. Type Ia SN from Pantheon.

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



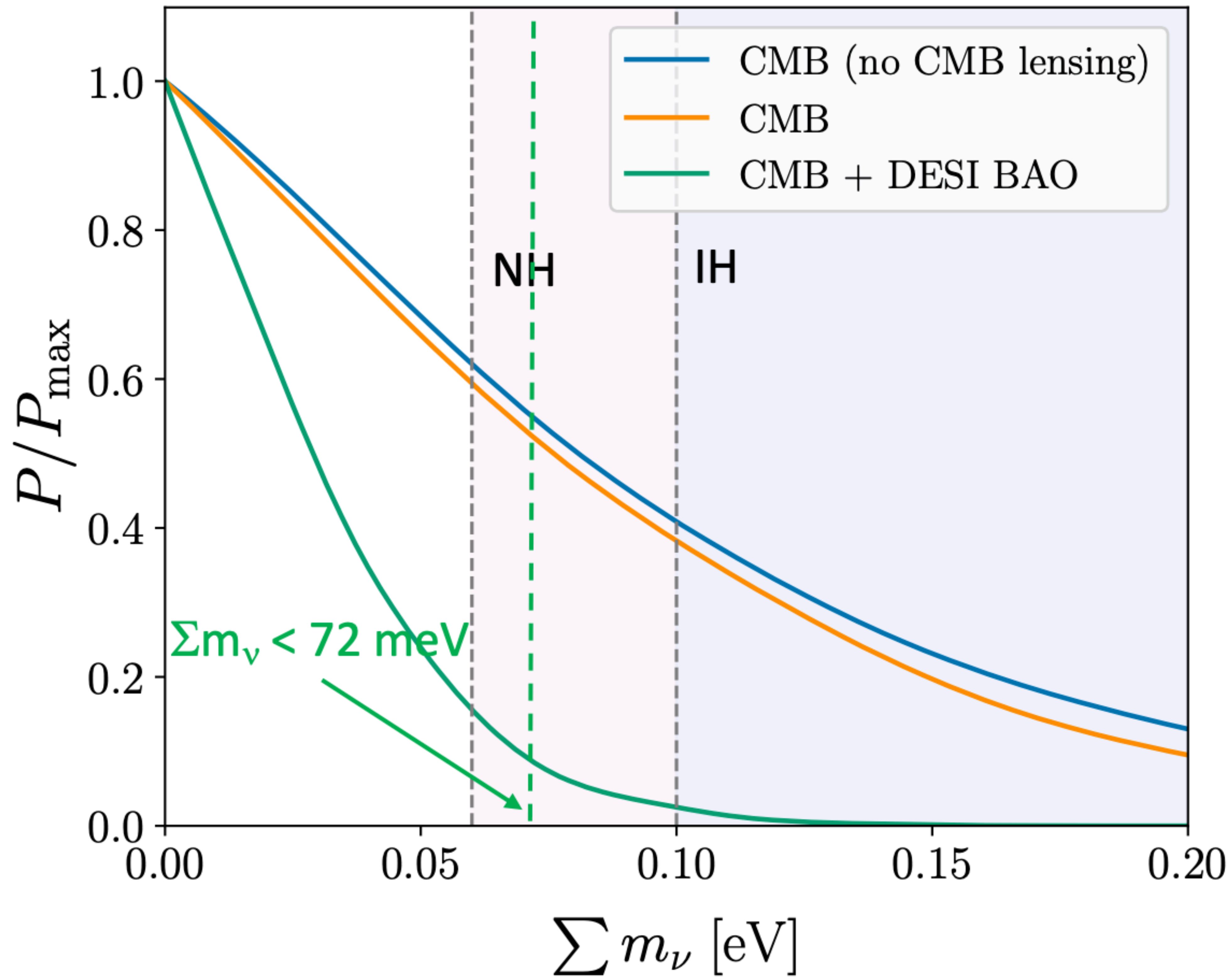
Dvali, Funcke, PRD 2016
Lorenz,Funcke,Löffler, Calabrese, PRD 2021
Lorenz,Funcke,Calabrese,Hannestad PRD 2019

Neutrino masses in cosmology

- Recent DESI results indicate some tension in $\sum m_\nu$ with oscillation results.

- CMB + BAO + Lensing : 2.8σ

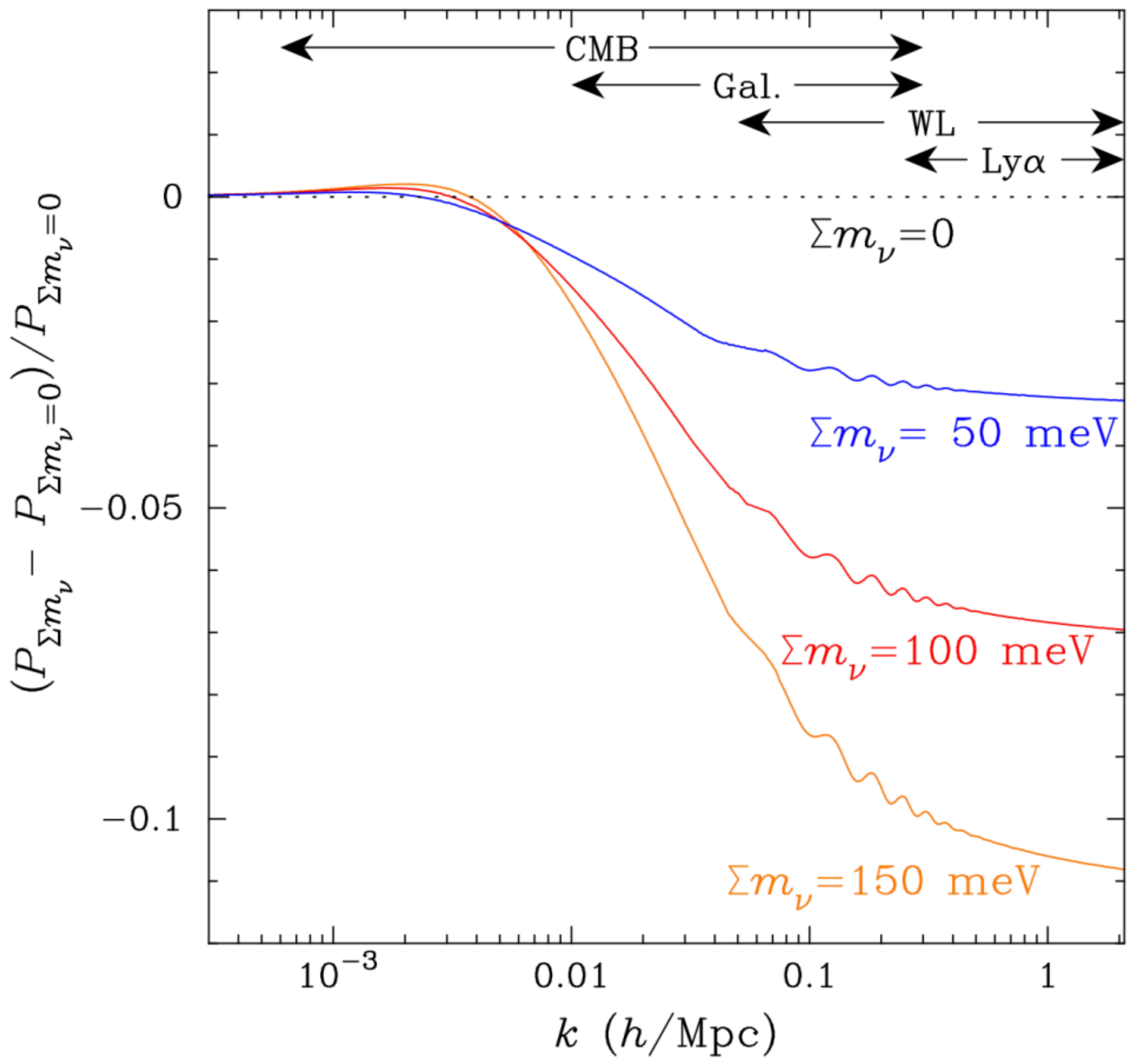
- Can this tension be explained using dynamical neutrino mass-models?



DESI Collaboration, 2024

How is neutrino mass in cosmology constrained?

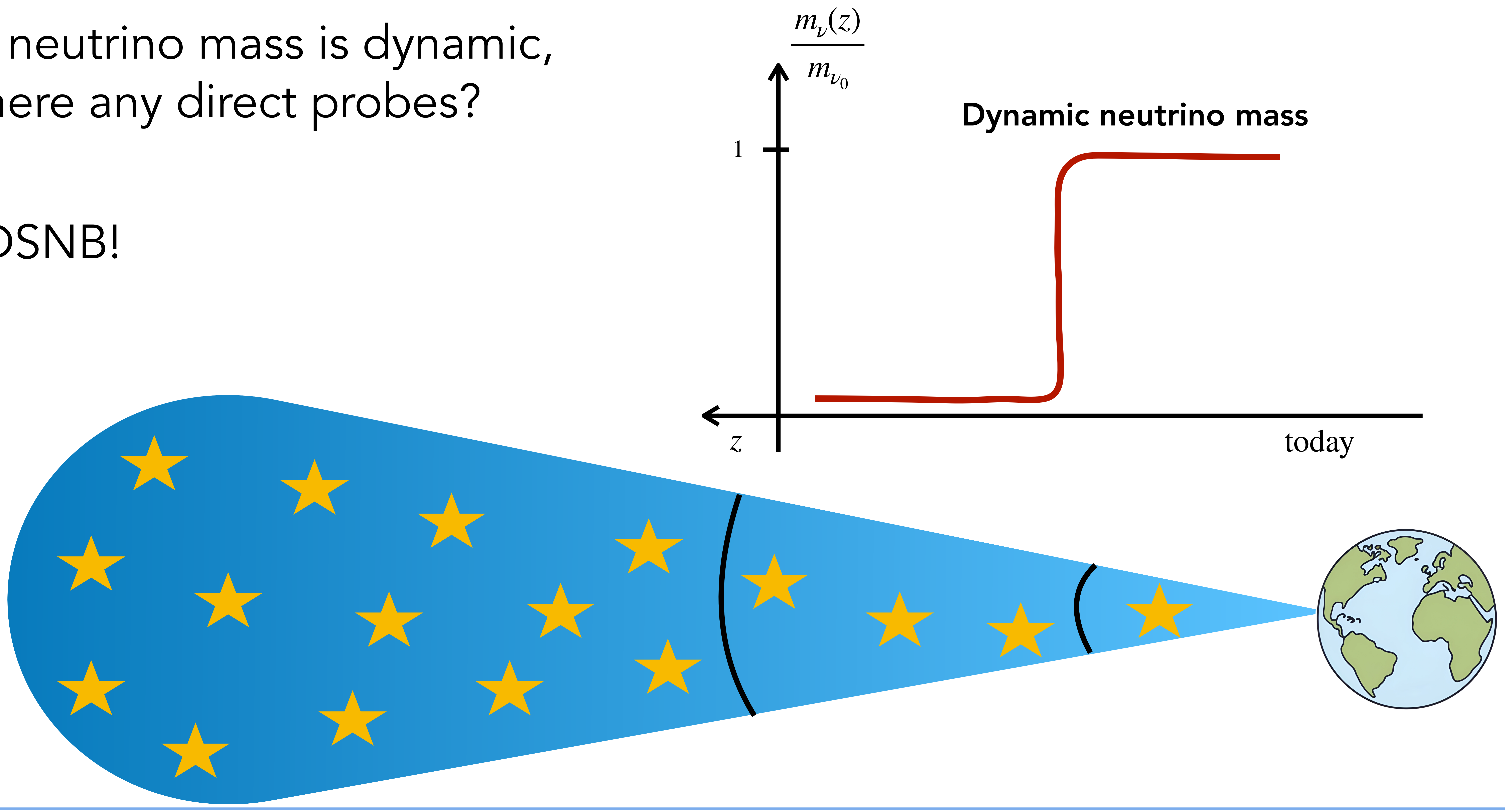
- Relativistic neutrinos contribute to the radiation content of the Universe.
- As neutrinos become non-relativistic, they start to cluster.
- Do not cluster for length scales smaller than free-streaming scale $\lambda_{FS} \sim v/H$.
- Suppress power at small scales (or large k)
- But cosmology is mainly sensitive to neutrino energy density, and through it, to neutrino mass!



Abazajian et al., Astropart.Phys, (2015)

How to probe dynamic neutrino masses?

- Cosmology does not directly measure neutrino mass!
- If the neutrino mass is dynamic, are there any direct probes?
- The DSNB!

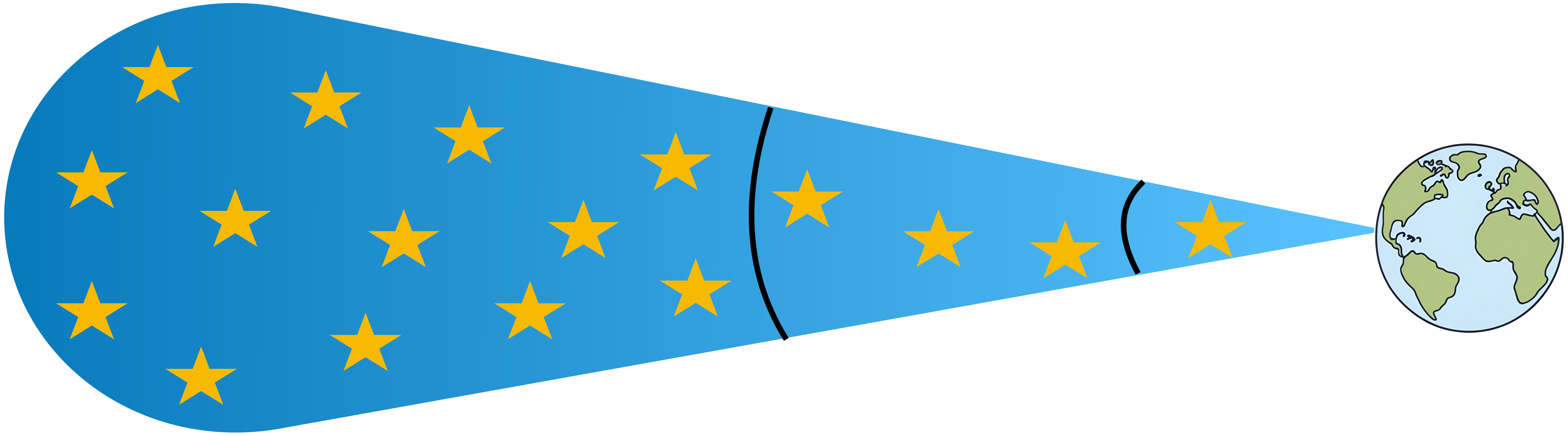


Using the DSNB to probe dynamic neutrino masses

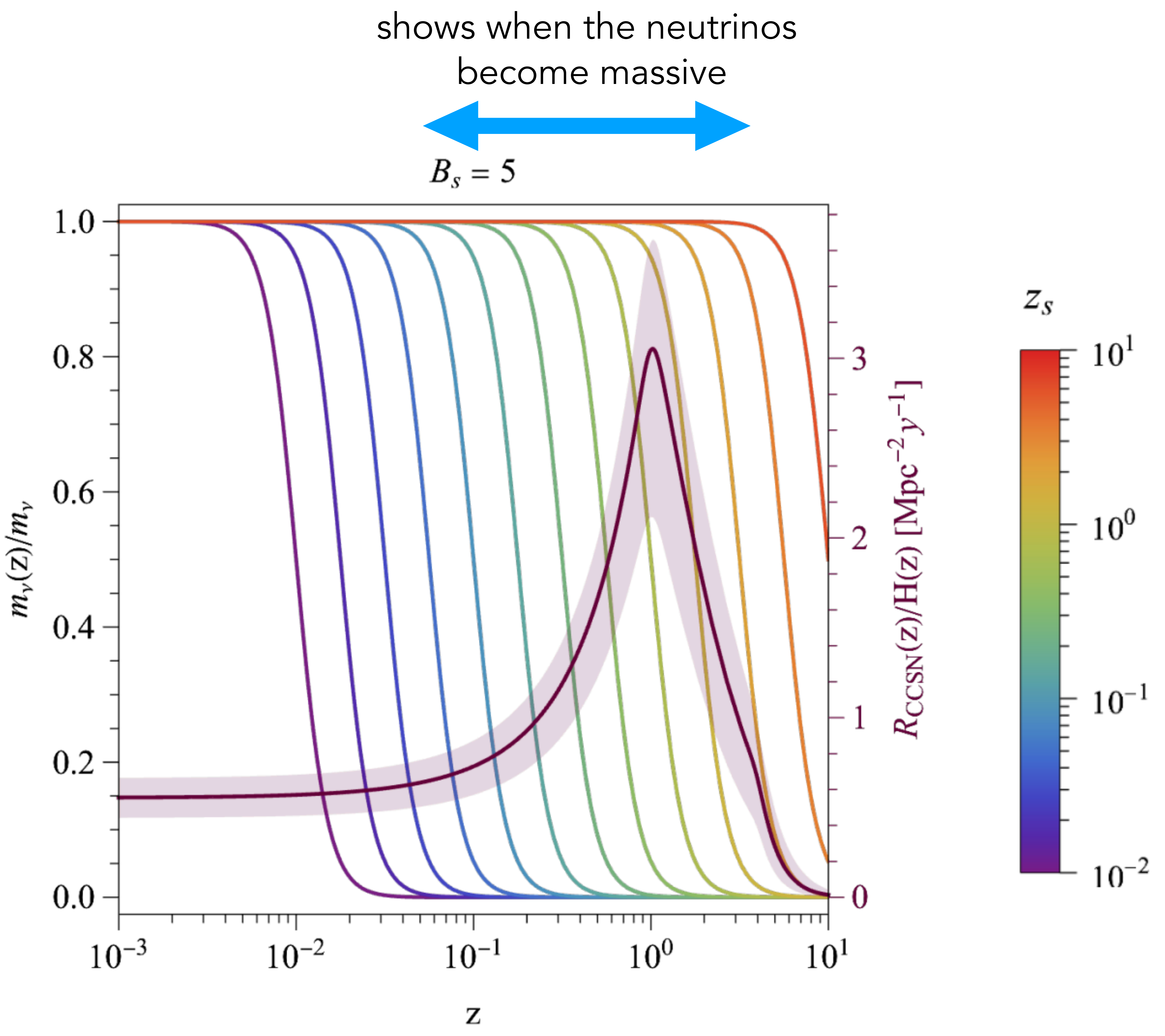
Redshift dependent neutrino masses can affect the DSNB in 2 ways:

1) Smaller masses and hence mass-squared difference can cause neutrino propagation during resonance to be non-adiabatic.

2) Change in sign of mass-squared differences can affect whether neutrinos or antineutrinos encounter a resonance.



1) Smaller neutrino masses in higher redshifts



de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2022

- We stay agnostic of the mechanism causing mass variation.

- The mass variation, same for all eigenstates

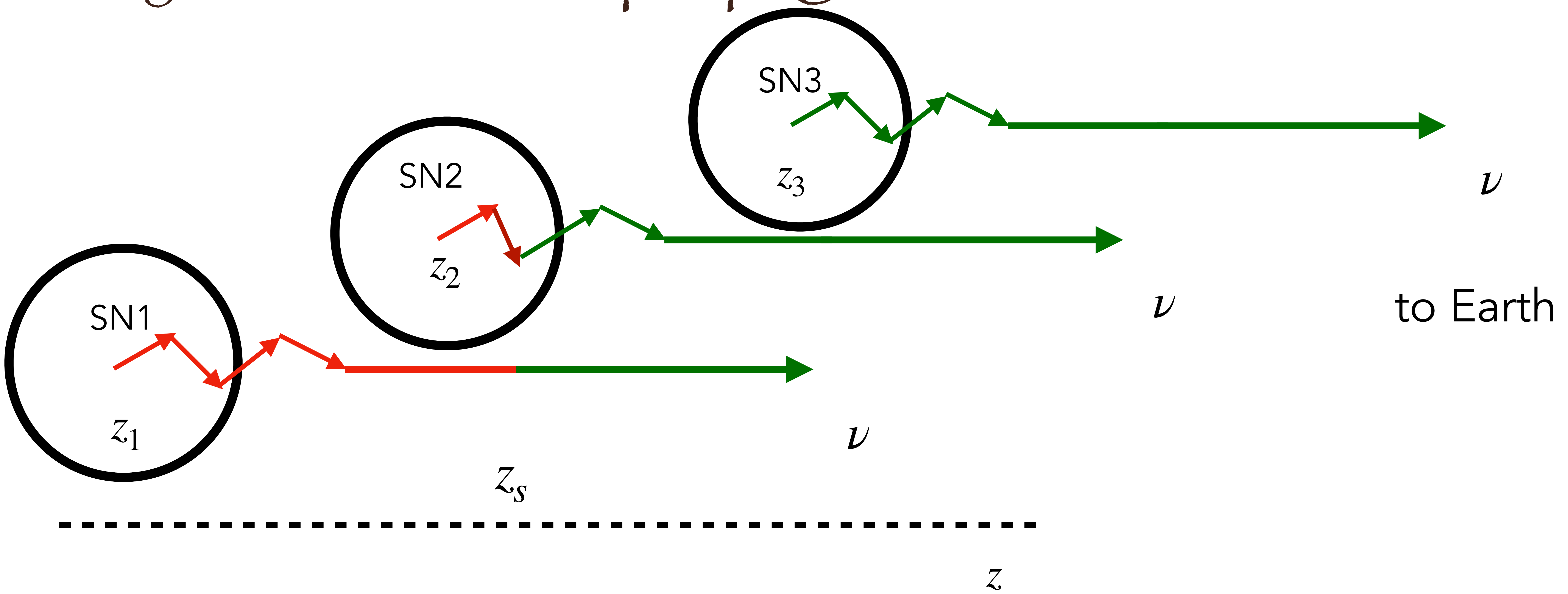
$$m_\nu(z) = \frac{m_\nu}{1 + (z/z_s)^{B_s}}.$$

z_S indicates redshift when mass switches on.

B_s governs the width of transition.

- Effect on DSNB is stronger if m_ν switches on when the R_{CCSN} peaks, i.e., around $z_S \sim 1$

Physics of neutrio propagation as mass varies



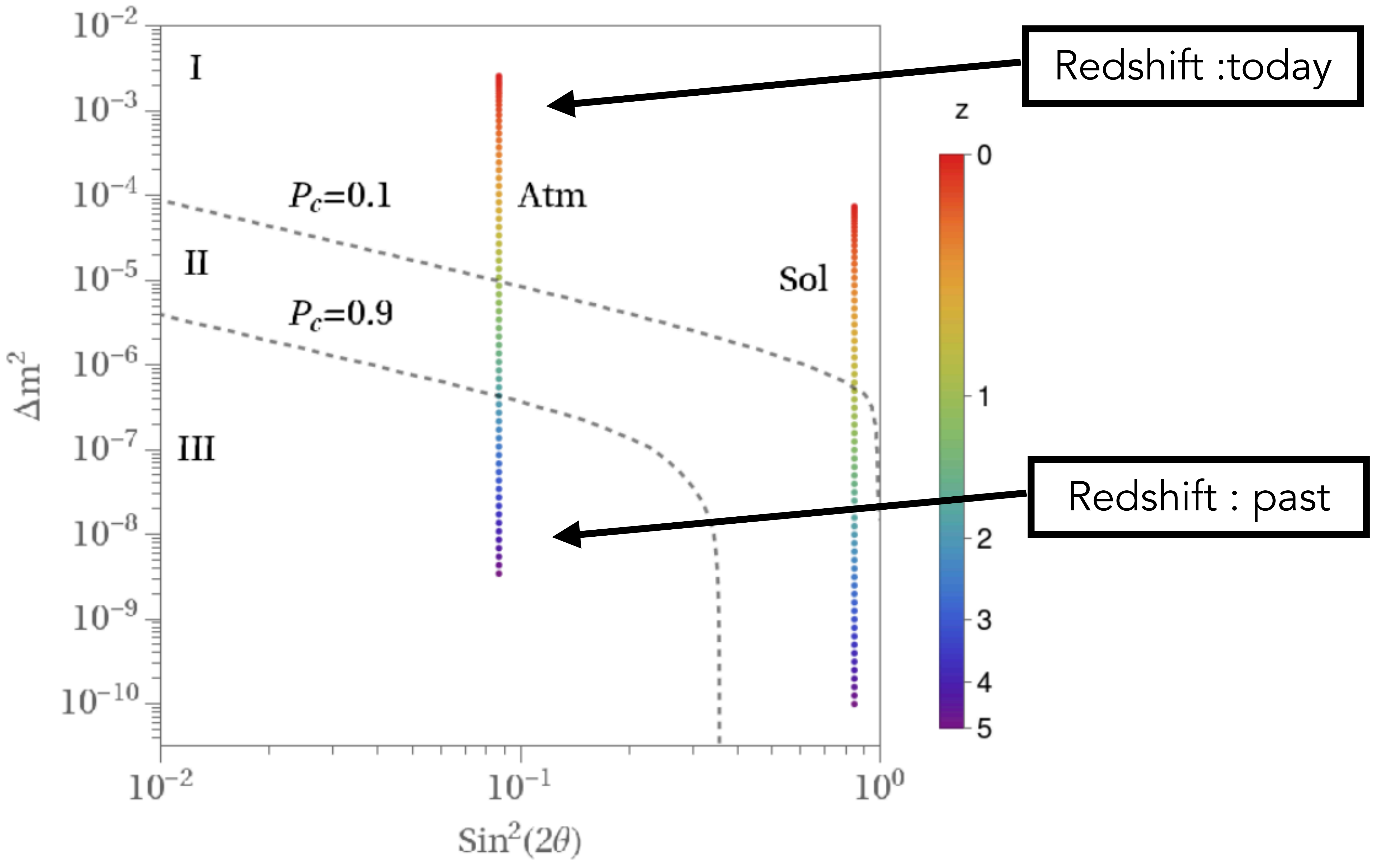
- For tiny mass neutrinos, non-adiabaticity of propagation becomes important.

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

- 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.

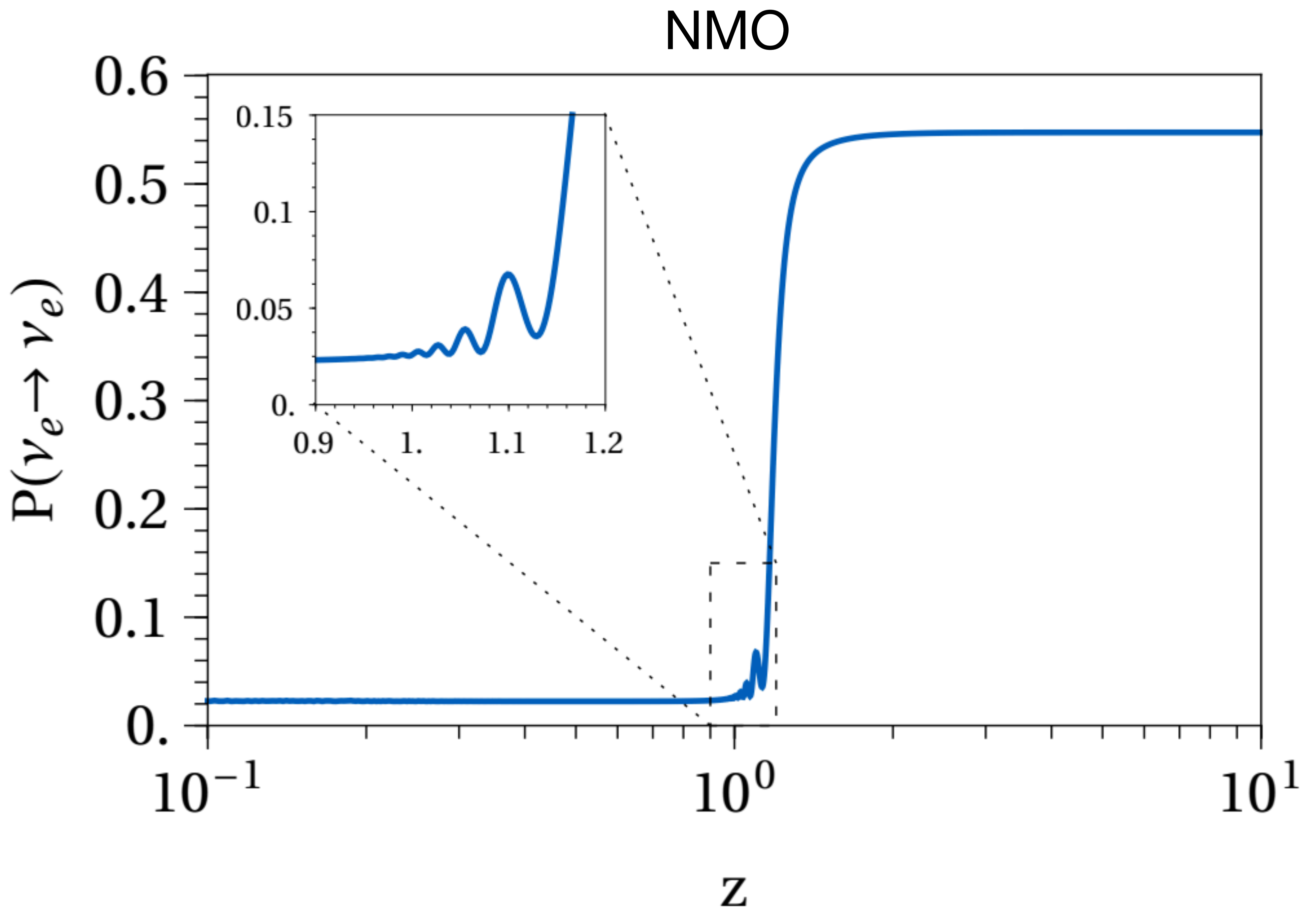
Redshift dependent mass: adiabaticity



Shows how P_c varies as the Δm^2 changes with redshift

Neutrino probability calculation

- Solve the neutrino propagation inside a SN to obtain probability



Neutrino probability calculation

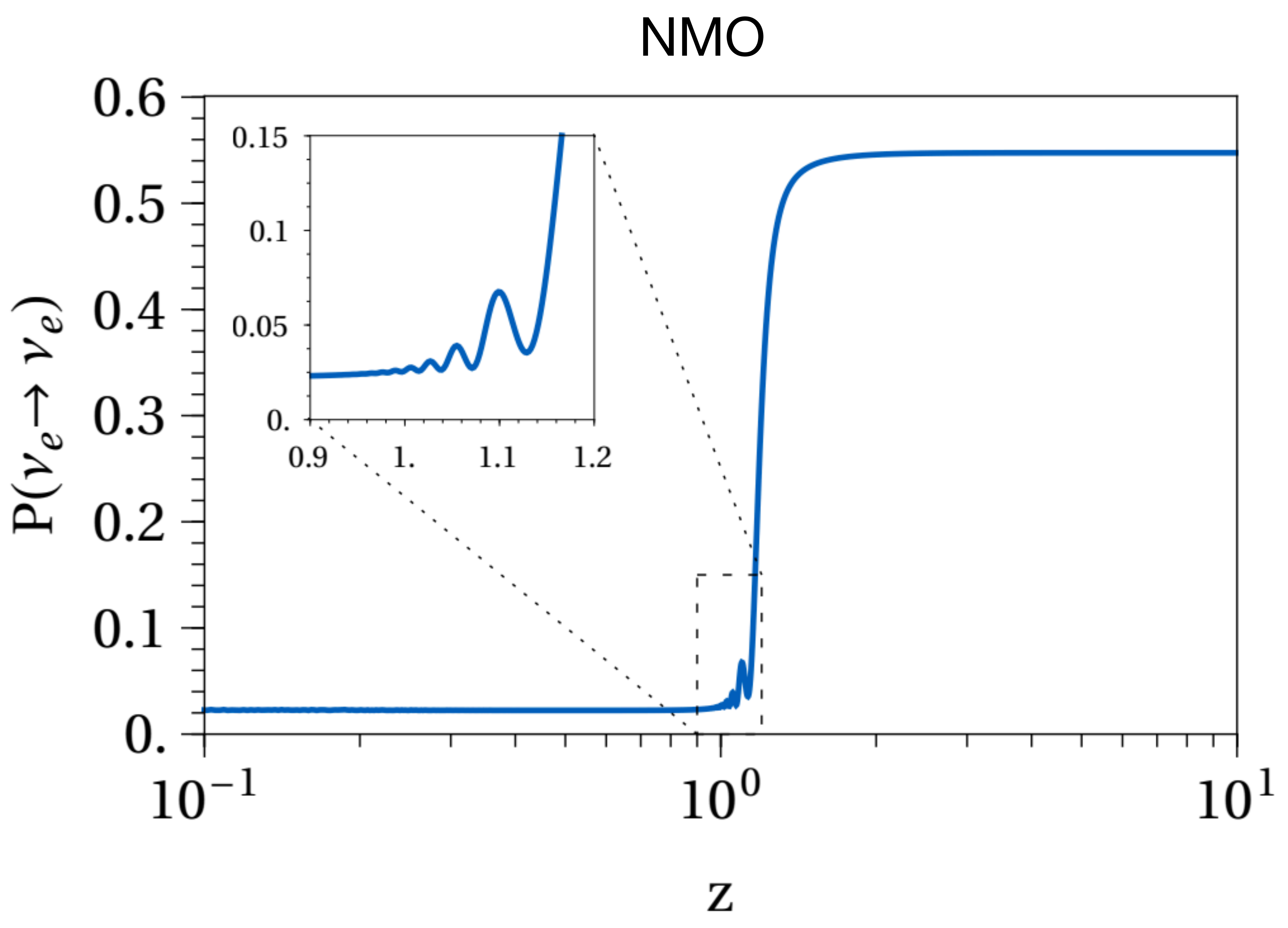
- Solve the neutrino propagation inside a SN to obtain probability

- As neutrino mass switches on while in vacuum, propagation simil 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 $P_{ee}(\bar{\nu}_e) \sim |U_{e1}|^2 = 0.67$

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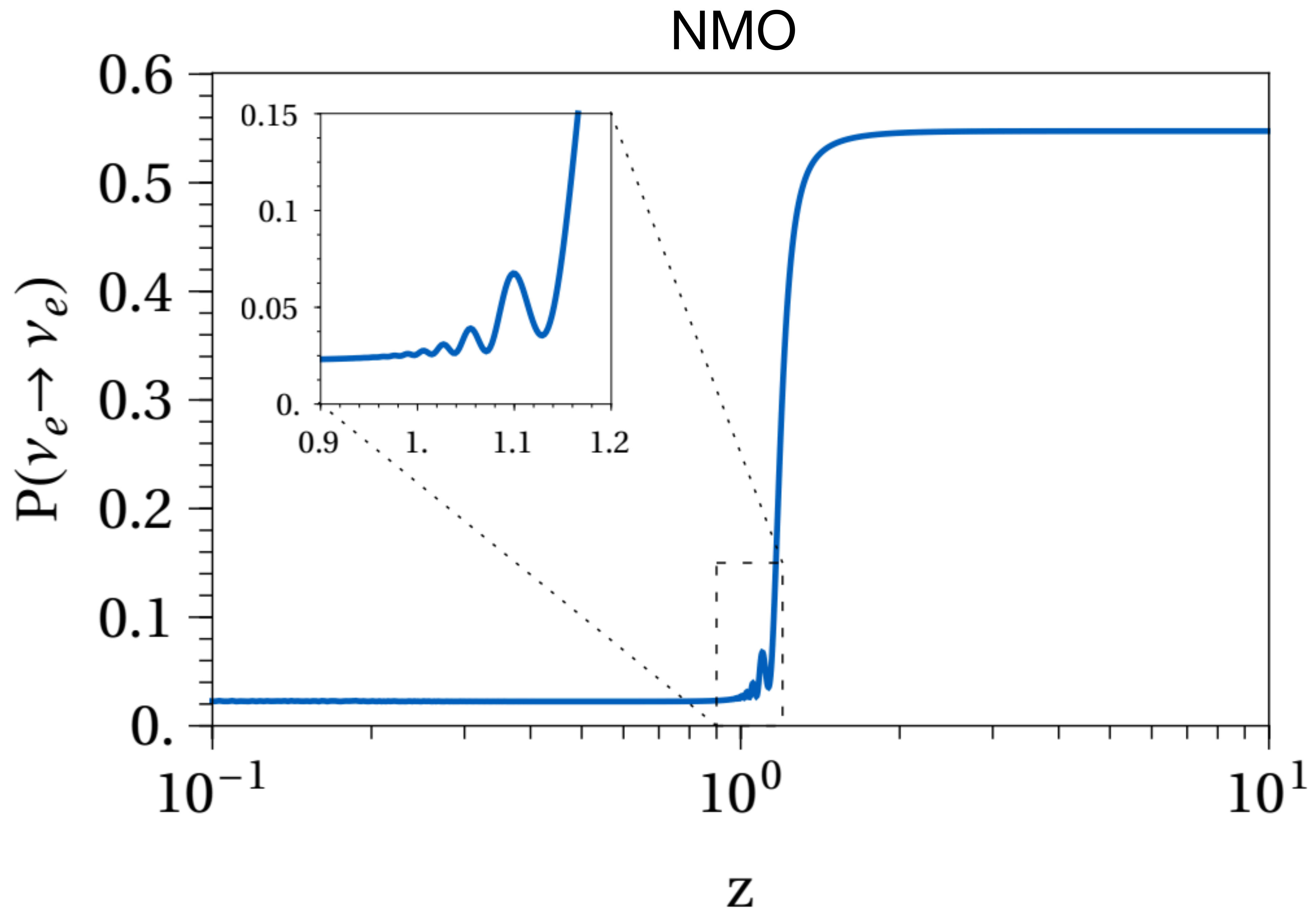


- The net DSNB flux at Earth

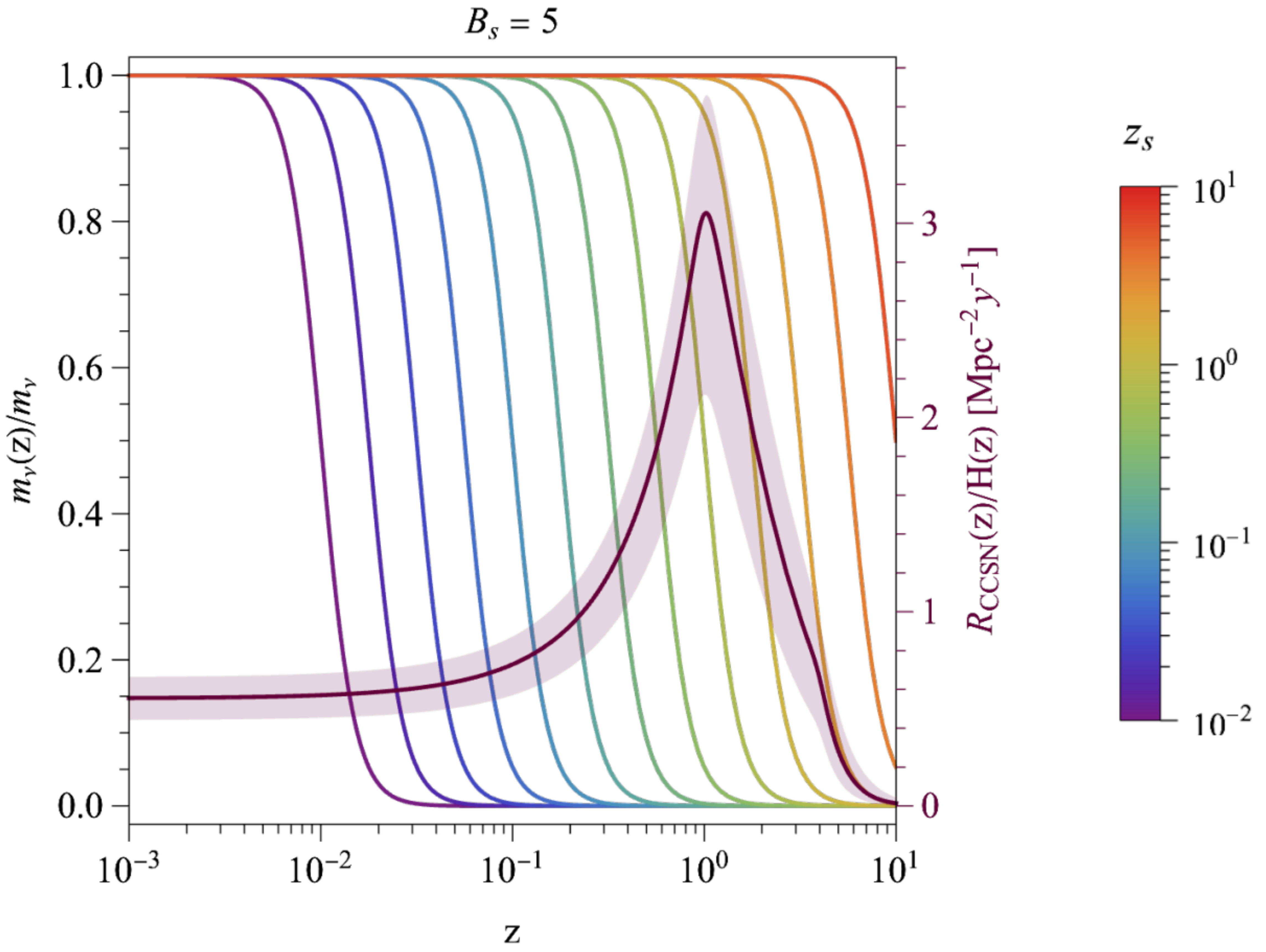
$$\Phi_{\nu_e}(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm CCSN}(z) \left\{ P_{ee}(z)\phi^0_{\nu_e} + (1 - P_{ee}(z))\phi^0_{\nu_x} \right\}$$

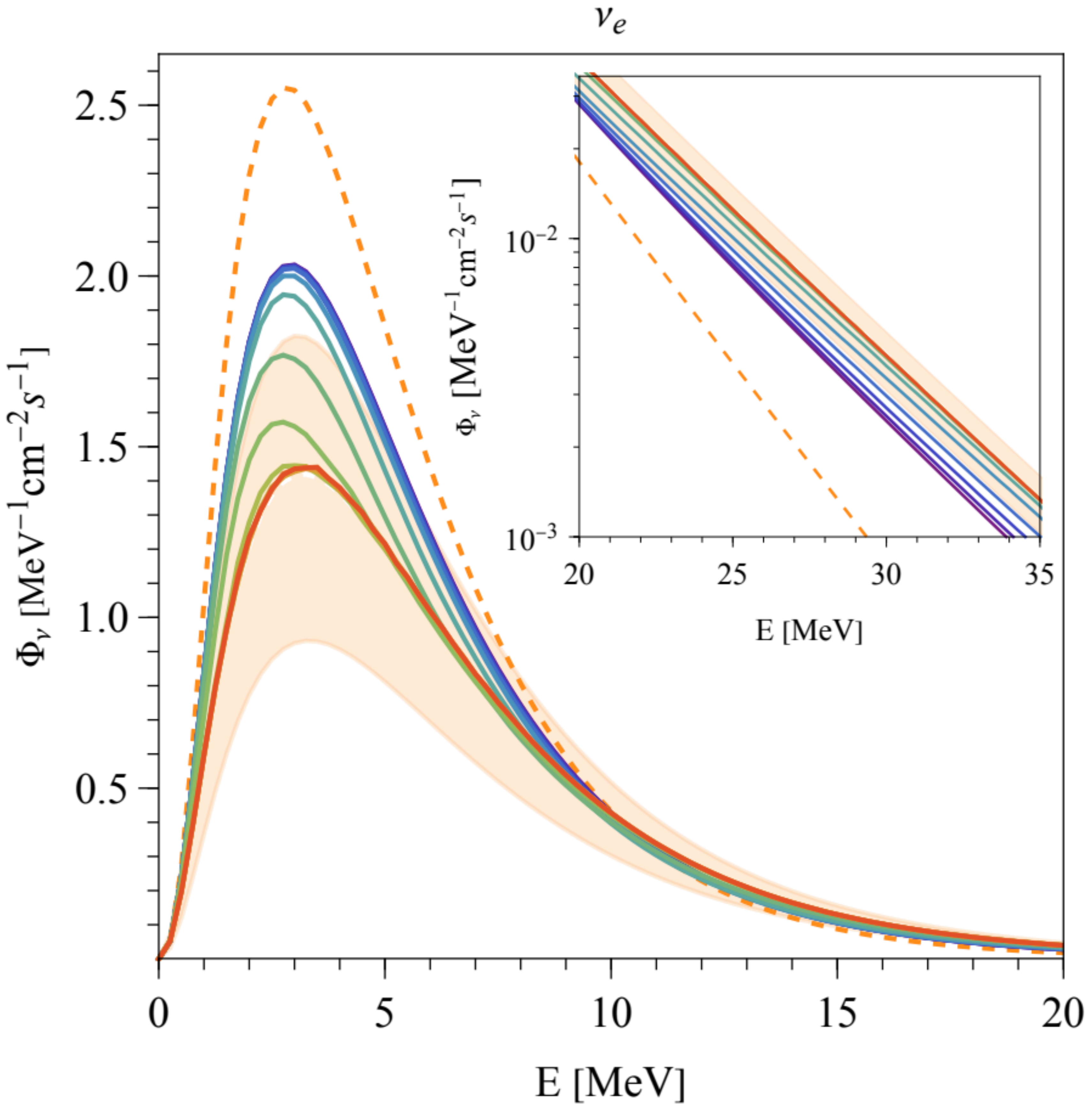
→ Impact strongest for ν_e at NMO

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

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

DSNB spectral difference due to mass variation



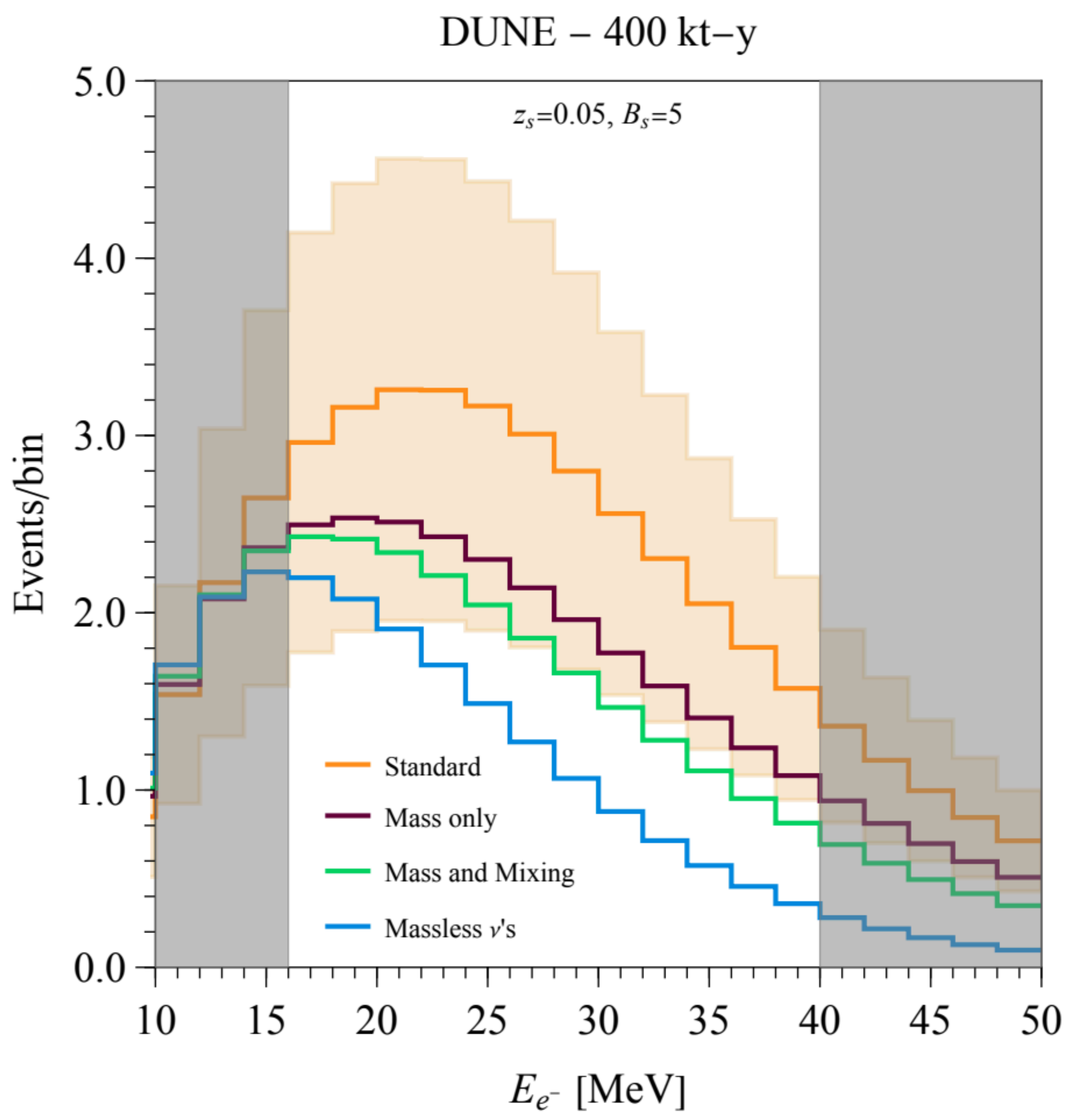


- Effect is strongest when mass switches on at low redshift, since maximum contribution comes from massless neutrinos.

- For $z_s \sim 0.01$, DSNB spectra can be a factor of 1.5 or so larger.

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2022

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:

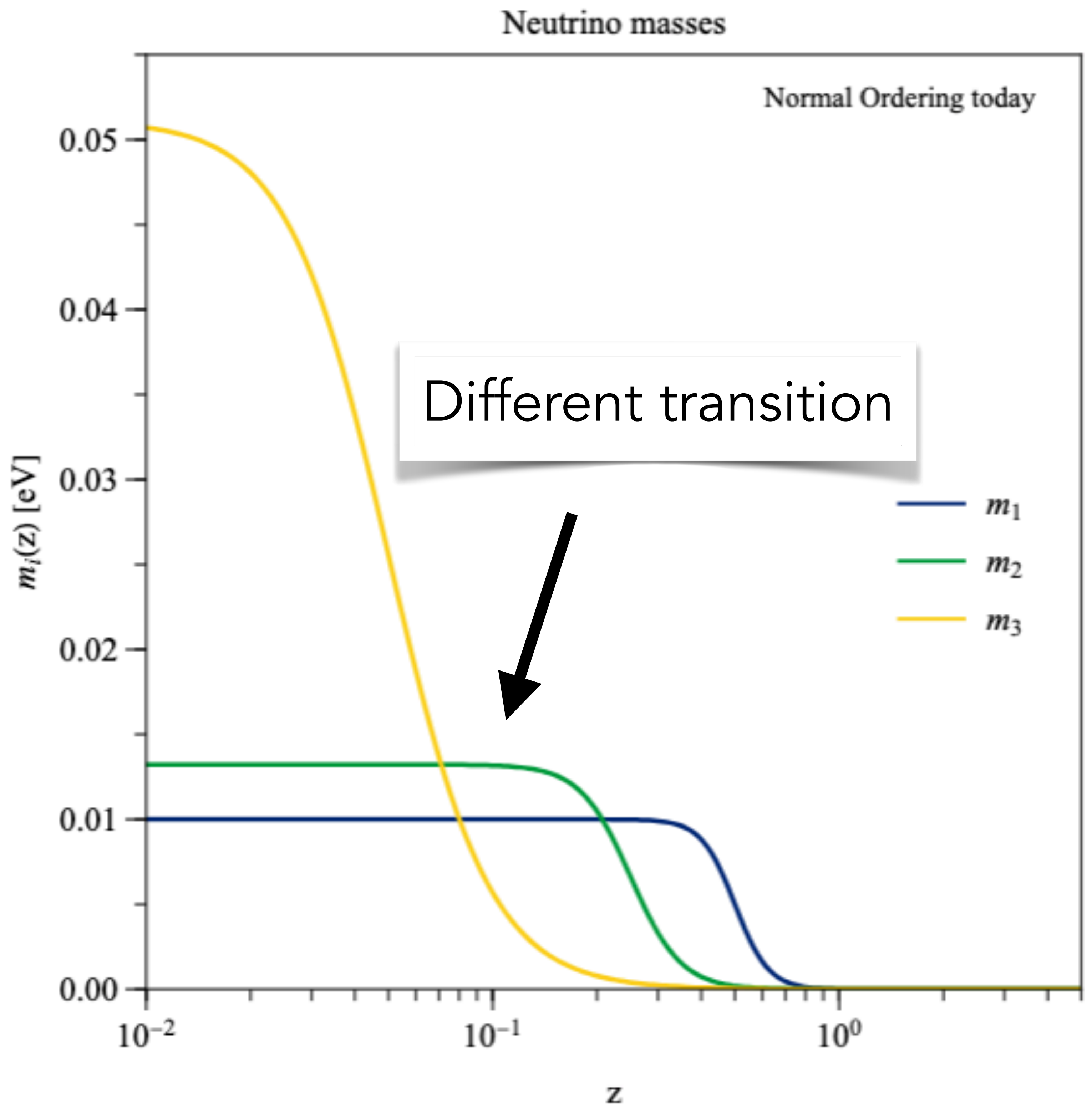
  1. Expect a reduction in number of ν_e events in a DUNE like detector, in energy above 20-sh MeV.

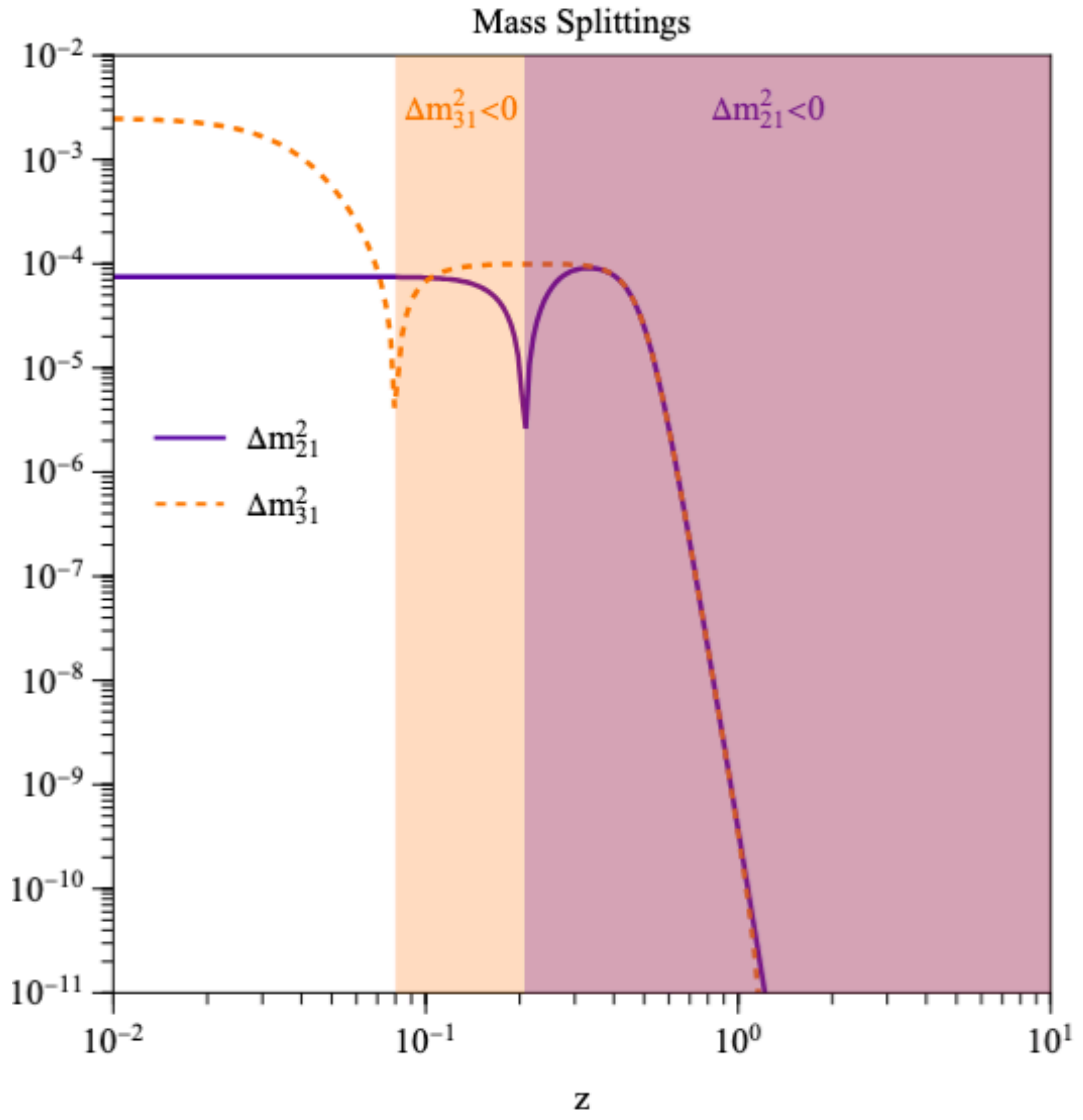
  2. In parallel, there would be no change in the $\bar{\nu}_e$ event rate in a HK/JUNO like detector.

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

de Gouvea, Martinez-Soler, Perez-Gonzalez, MS, PRD 2022

2) Different mass-squared differences

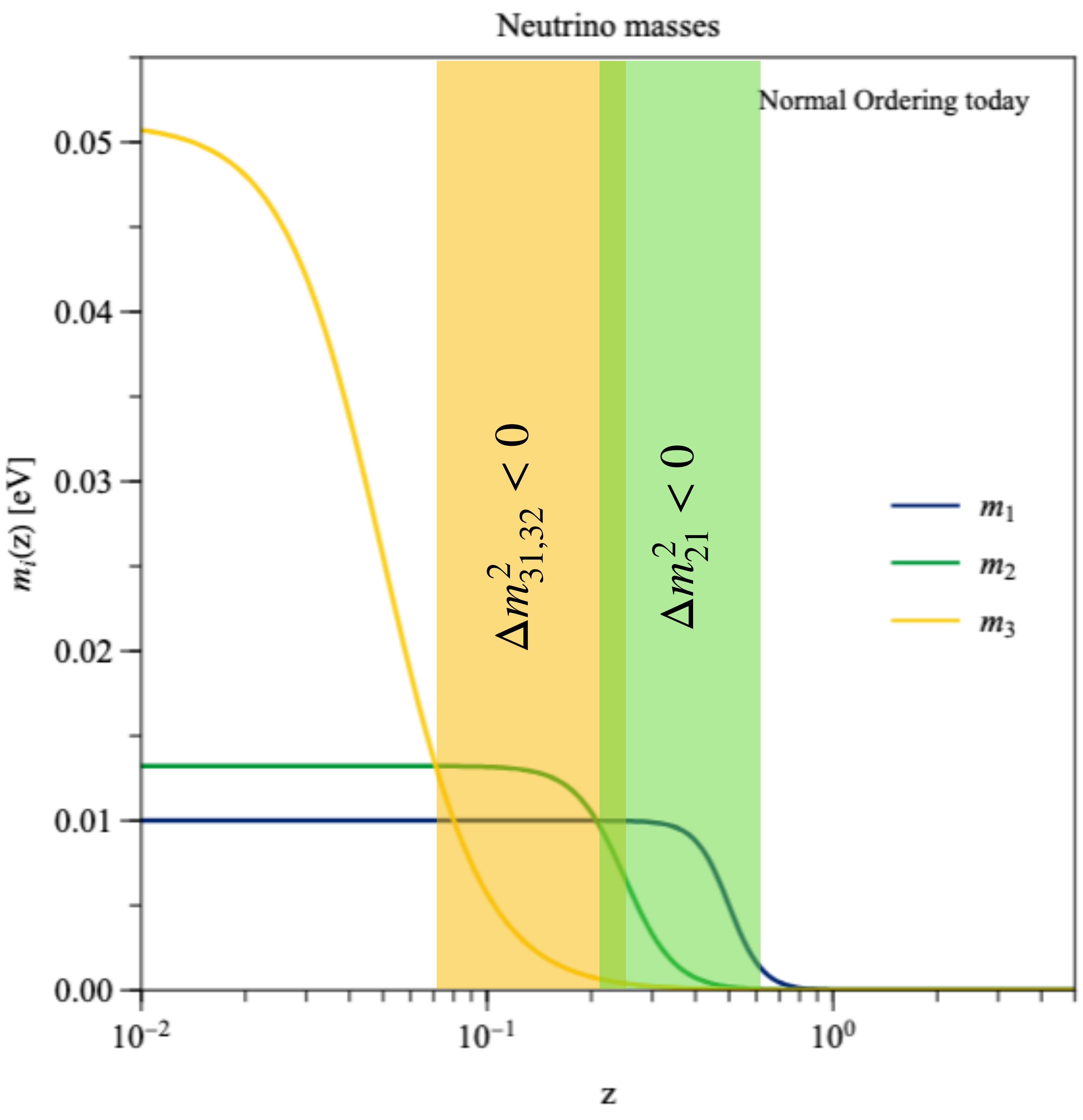


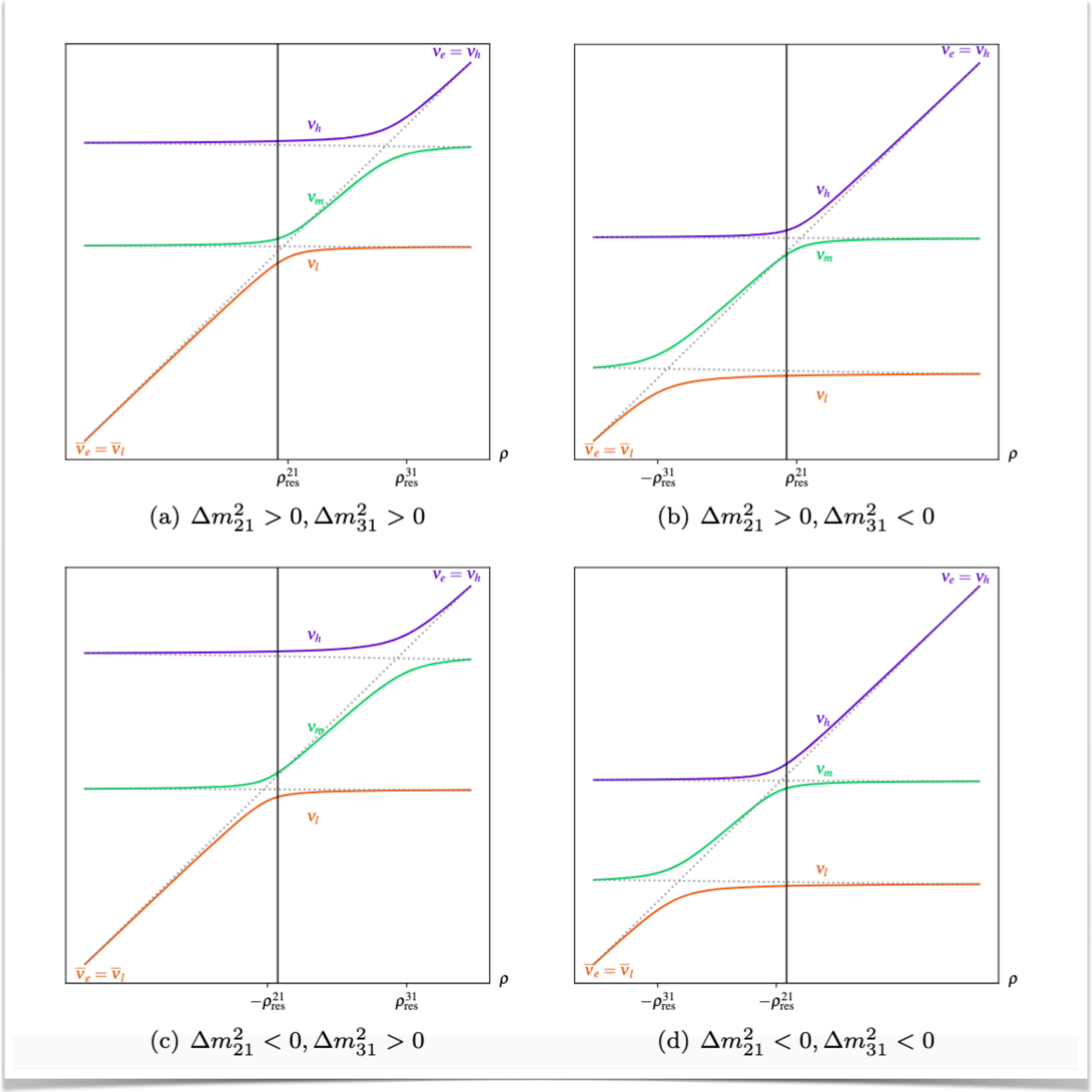


- If each mass eigenstate has a different transition point, the Δm^2 can change value and sign.
- This determines whether neutrinos or antineutrinos have resonances.

Perez-Gonzalez, MS, (250X.XXXX)

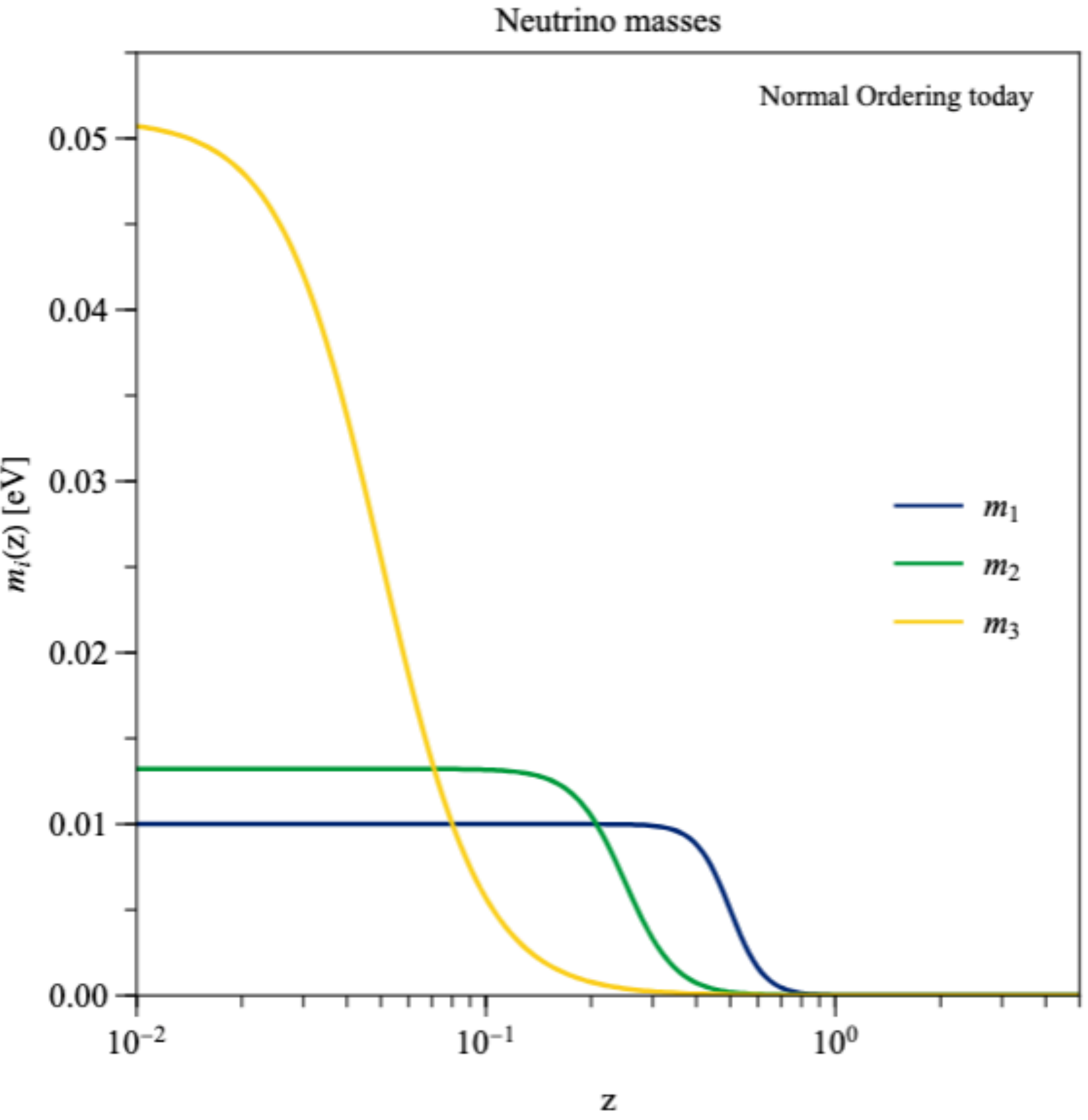
2) Different mass-squared differences determine resonances

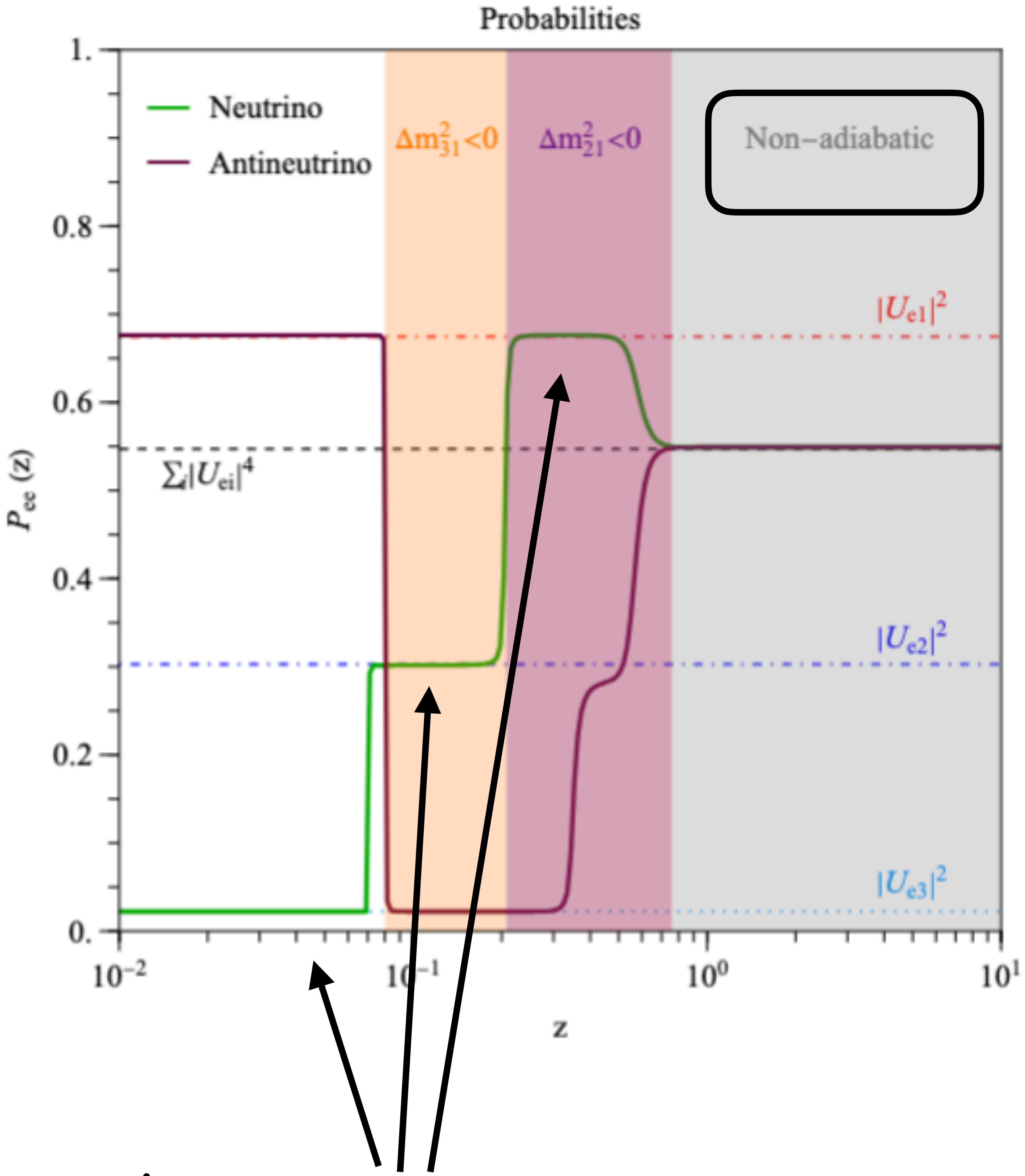


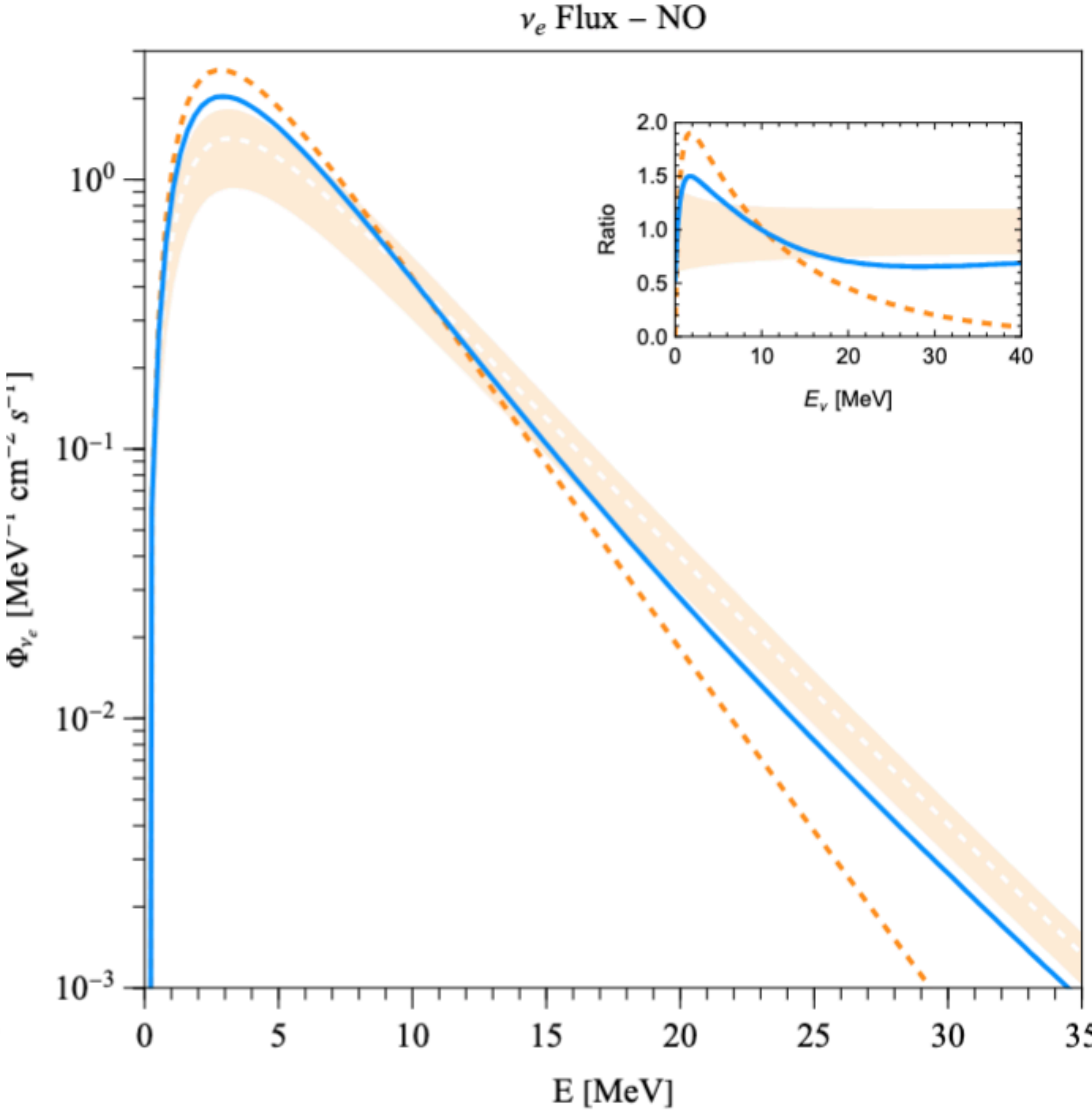


Perez-Gonzalez, MS, (250X.XXXX)

2) Impact on the DSNB







- Adiabatic propagation ensures $\nu_e \equiv \nu_h$.

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- Changes imprinted on the DSNB

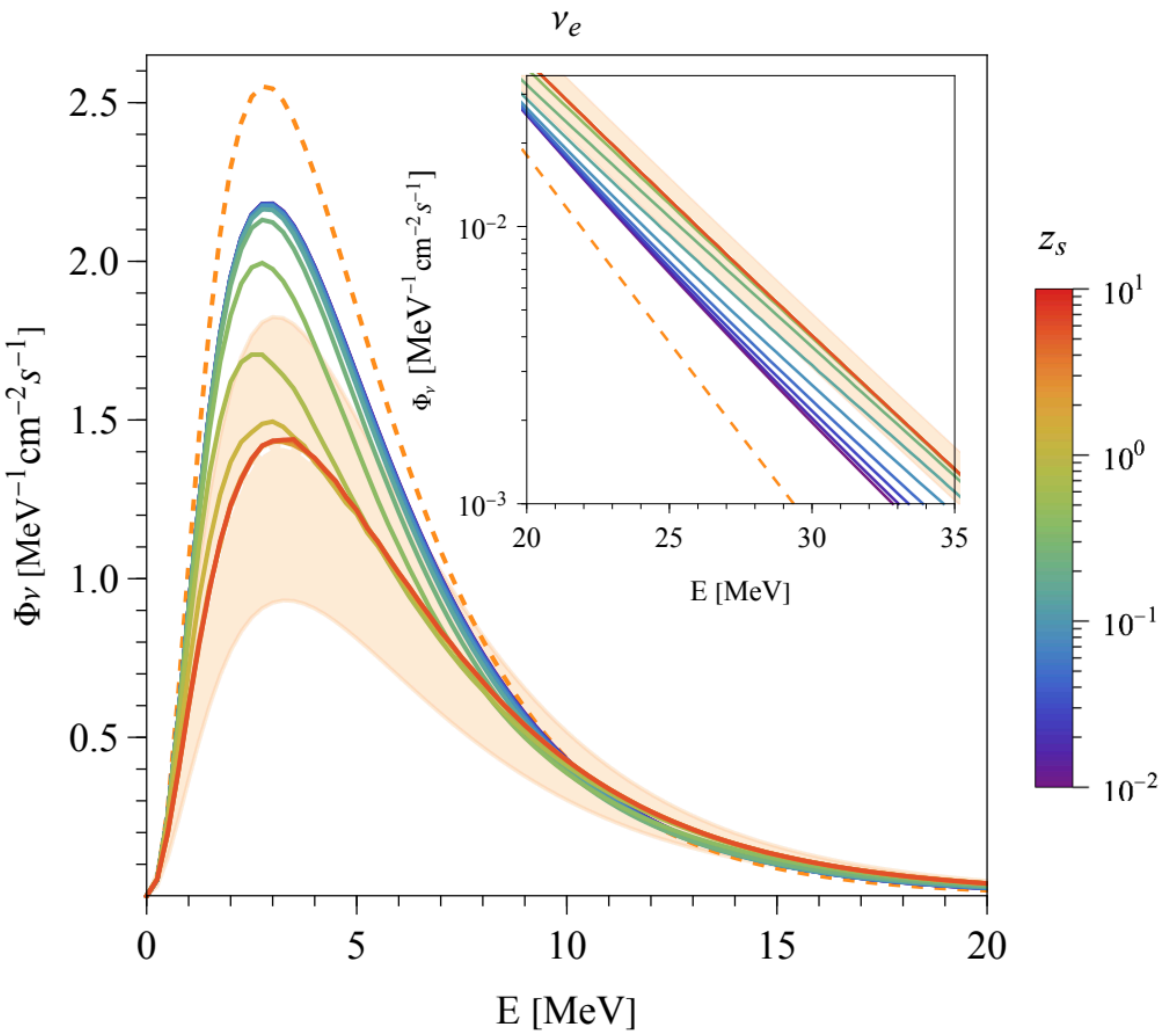
Conclusions

- The DSNB opens up a plethora of avenues for neutrino physics, next giant leap from the Sun and SN1987A.
- A core-collapse SN is extremely rare, so this is currently our best bet to measure SN neutrinos.
- Crucial for testing extreme neutrino properties, which cannot be tested otherwise.
- In particular, this will provide one of the rare opportunities to directly probe dynamic neutrino masses in the early Universe.
- Will be complementary to probes from cosmology.

THANK YOU

Backup

What happens if the mixing angles vary similarly?



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

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

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

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

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Variation with <E> and alpha

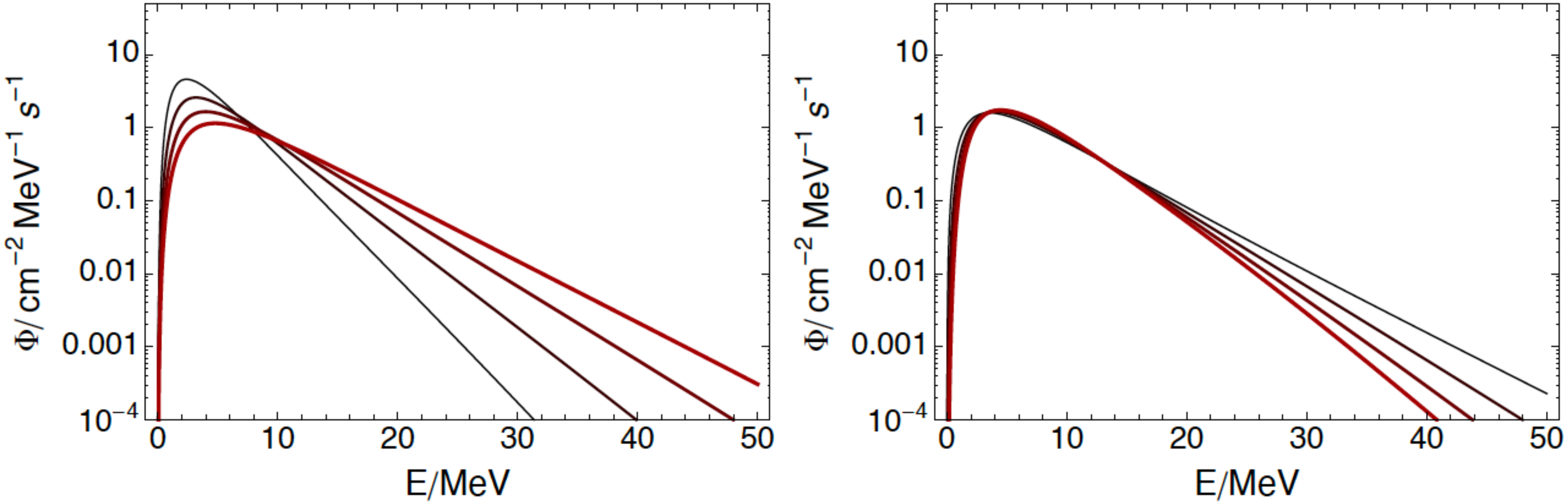


Figure 10: Examples of unoscillated flux, Φ^0_w ($w = e, \bar{e}, x$) (Eq. (15)), for different spectral parameters E_{0w}, α_w. Left: the curves of increasing thickness (increasing color intensity) correspond to $E_{0w} = 9, 12, 15, 18$ MeV, with $\alpha_w = 3$. Right: the curves of increasing thickness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

Variation with redshift

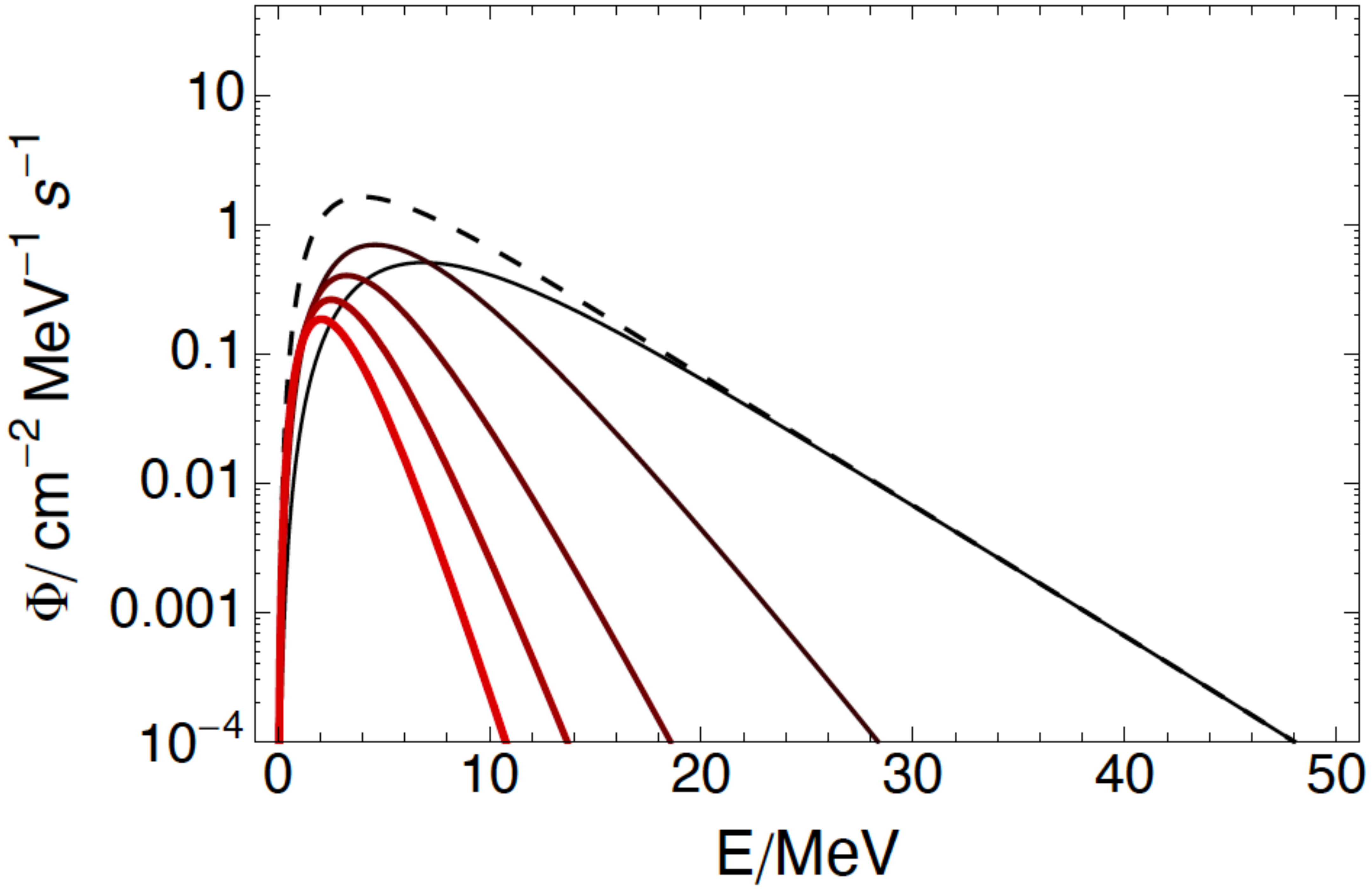
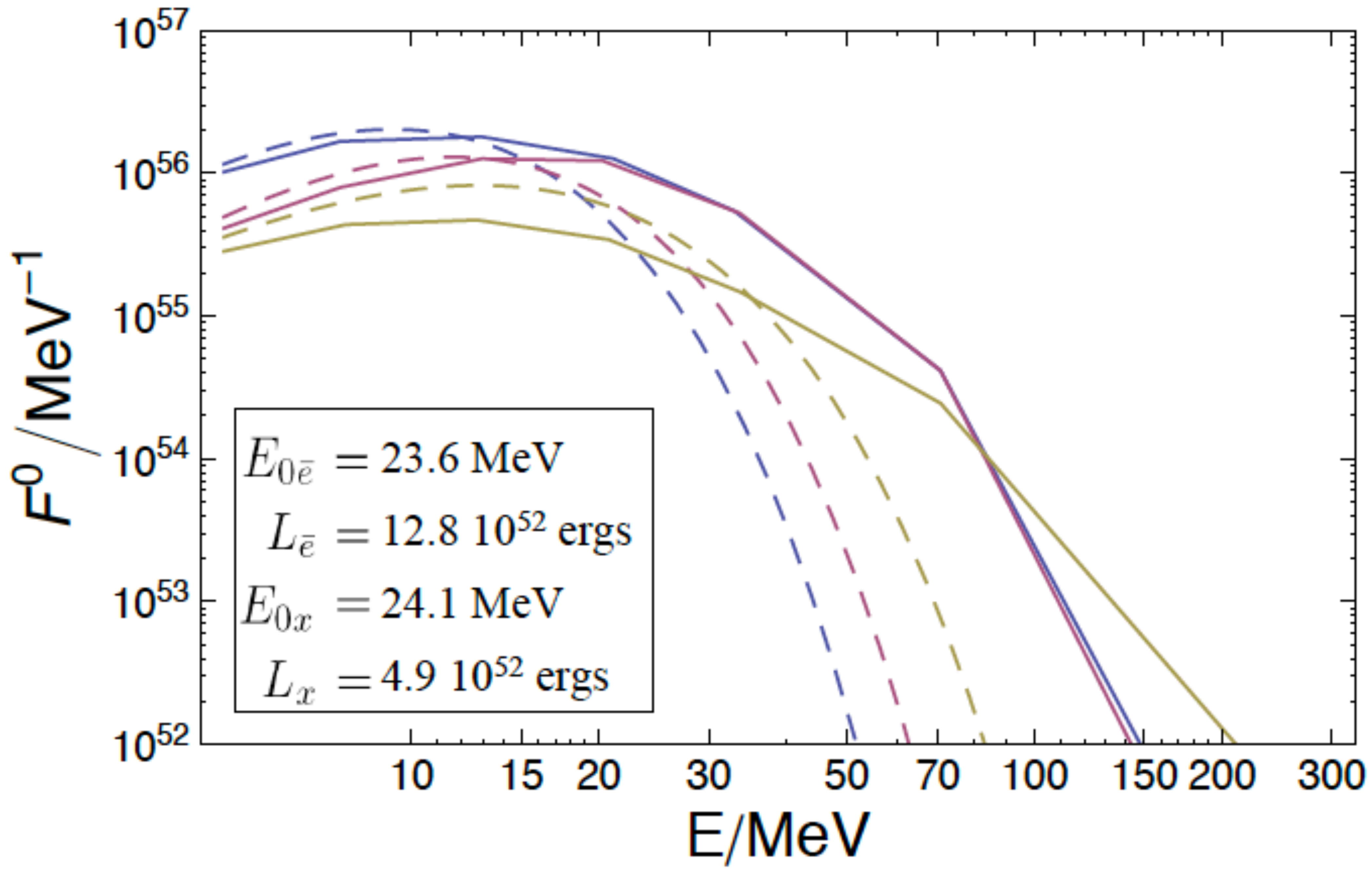


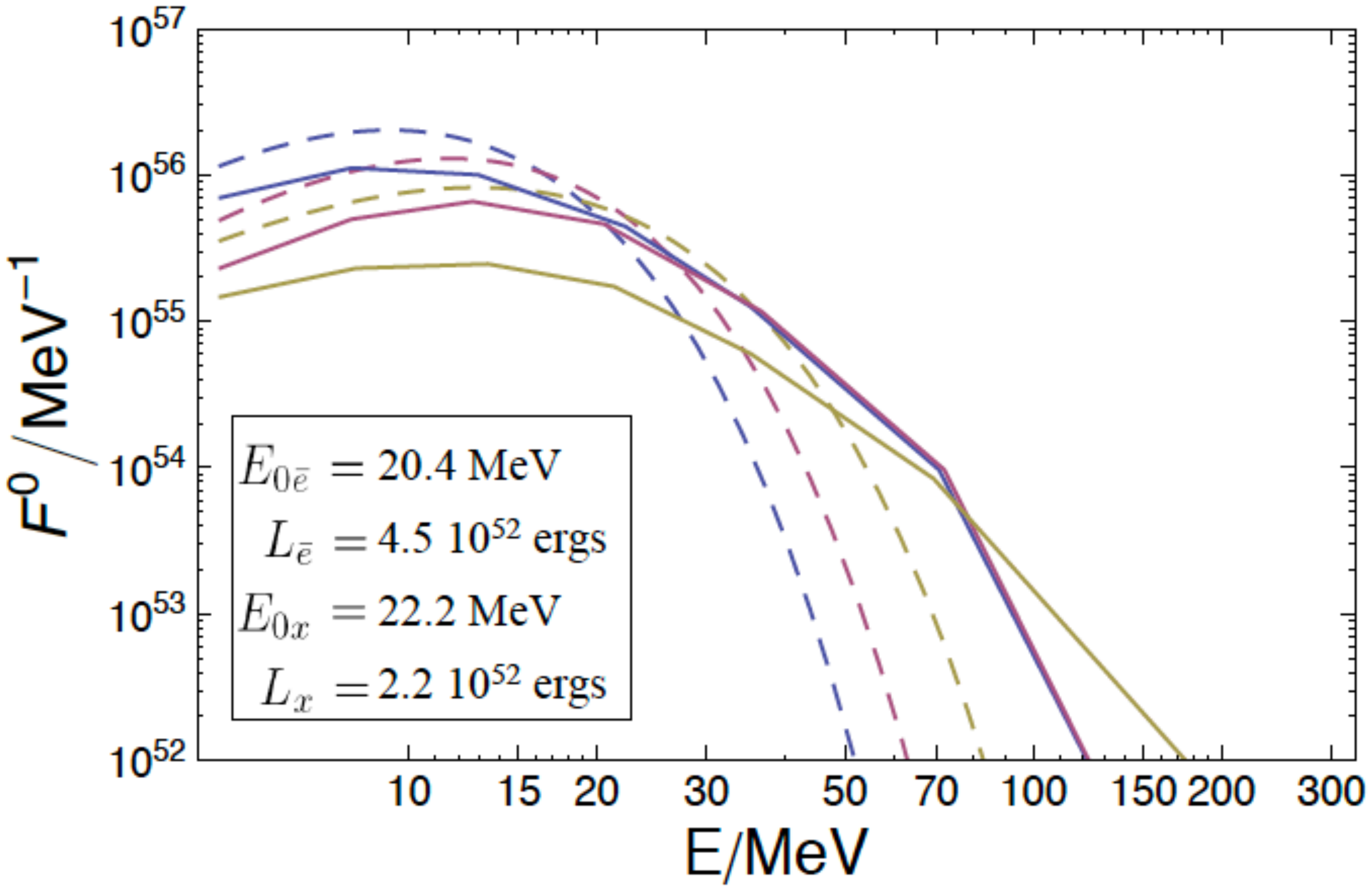
Figure 13: The contribution to the *unoscillated* $\bar{\nu}_e$ flux of sources in bins of increasing redshift, for the best fit SNR parameter $\beta = 3.28$ [59]. The solid curves from thinner to thicker (darker to lighter color) refer to the intervals: $z = 0 - 1$, $z = 1 - 2$, $z = 2 - 3$, $z = 3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

S EoS



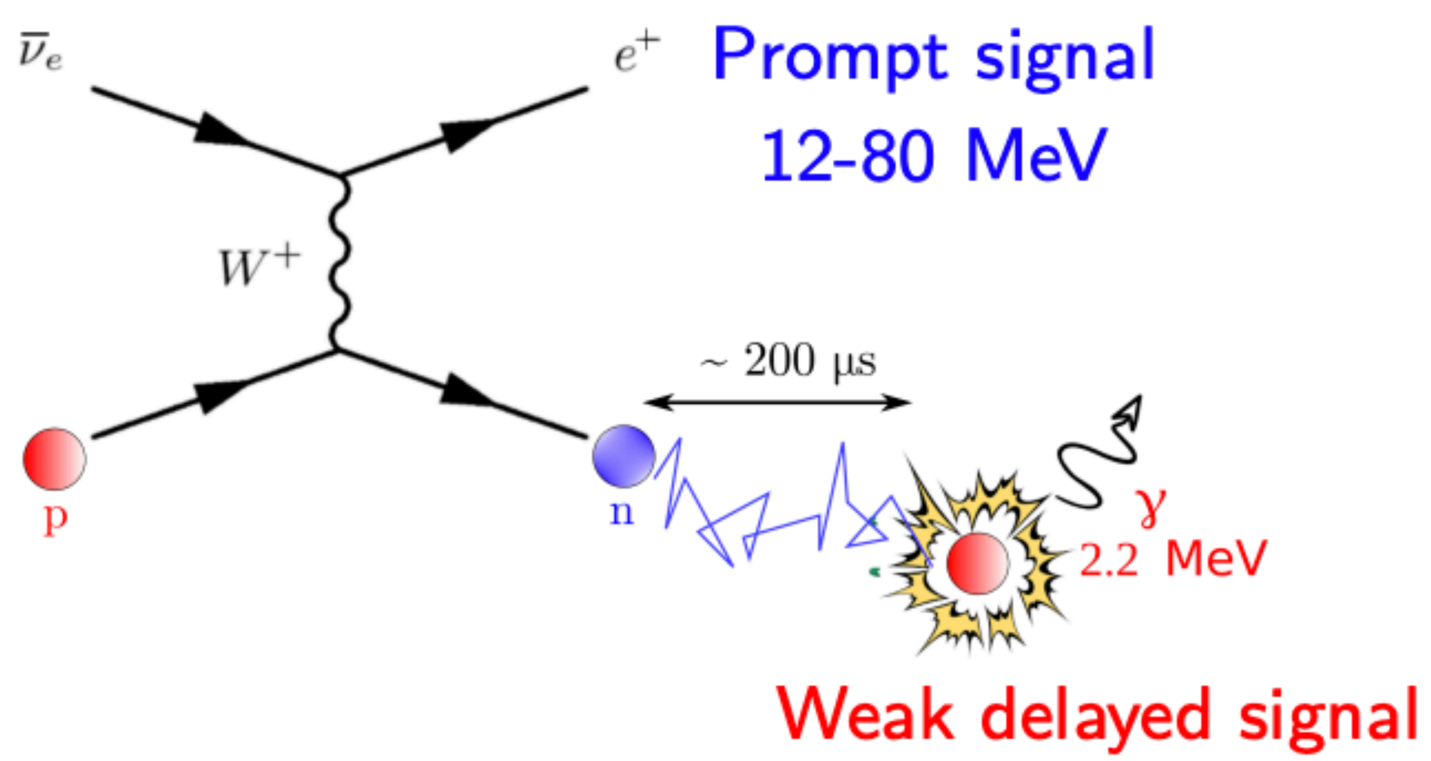
LS EoS



- 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.

Detecting the DSNB + backgrounds: Super-K

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

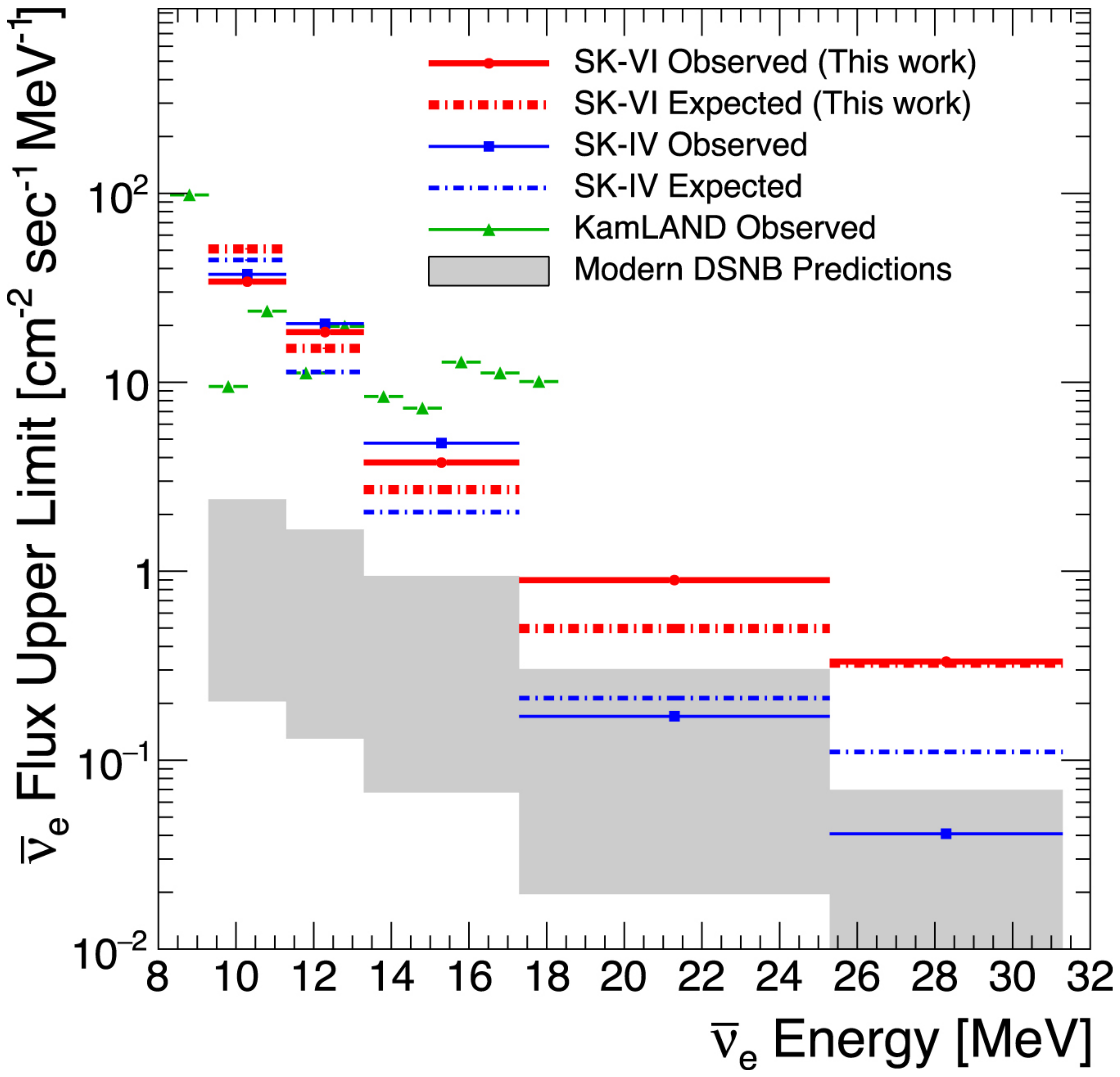


- Main channel is IBD: $\bar{\nu}_e + p \to e^+ + n$

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

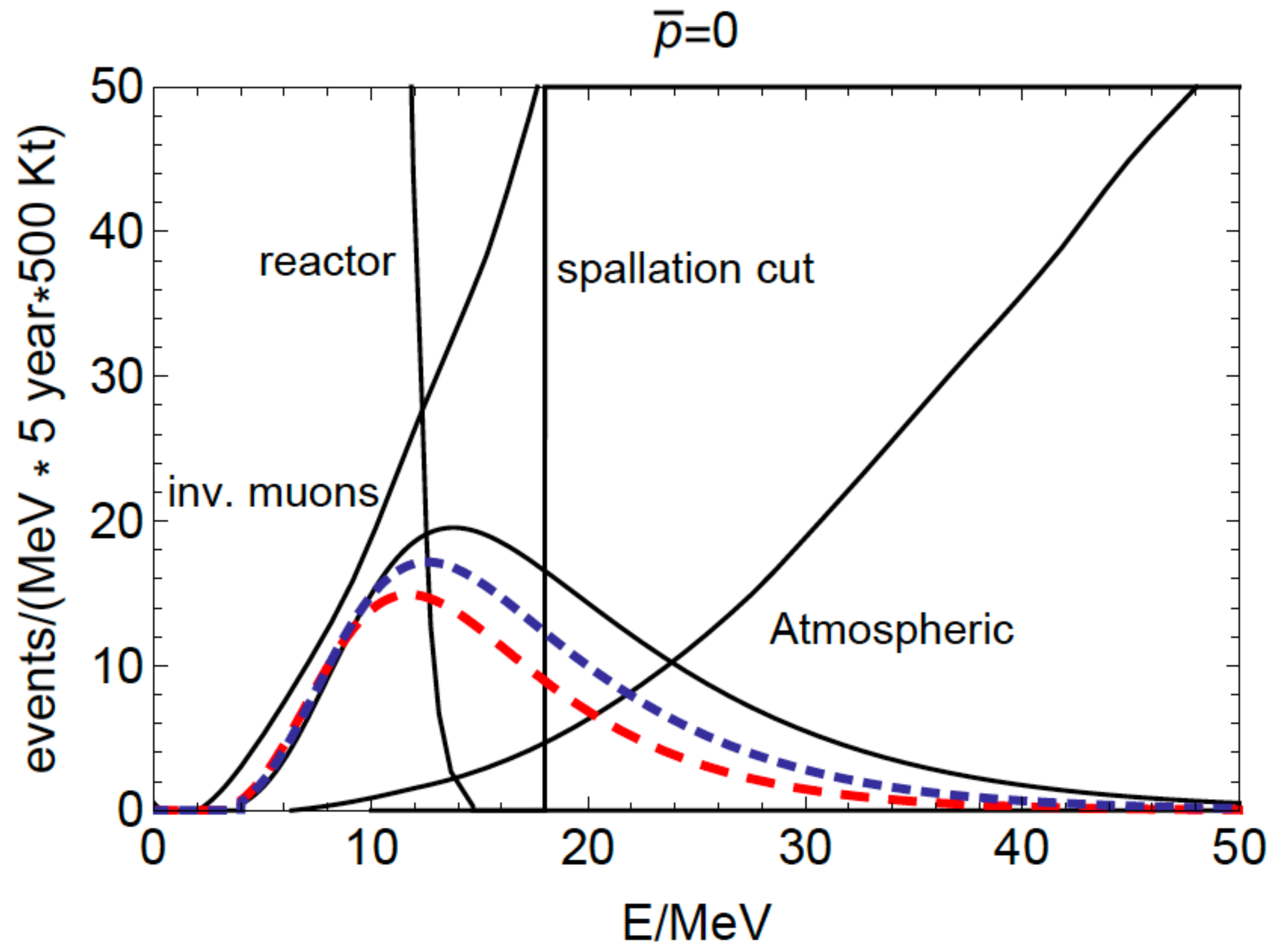
- Invisible muons: $\nu_\mu + N \to \mu + N'$. If muon energy is below Cherenkov threshold, it can only be detected through decay.

- Low energy atmospheric neutrinos. Isotropic background.

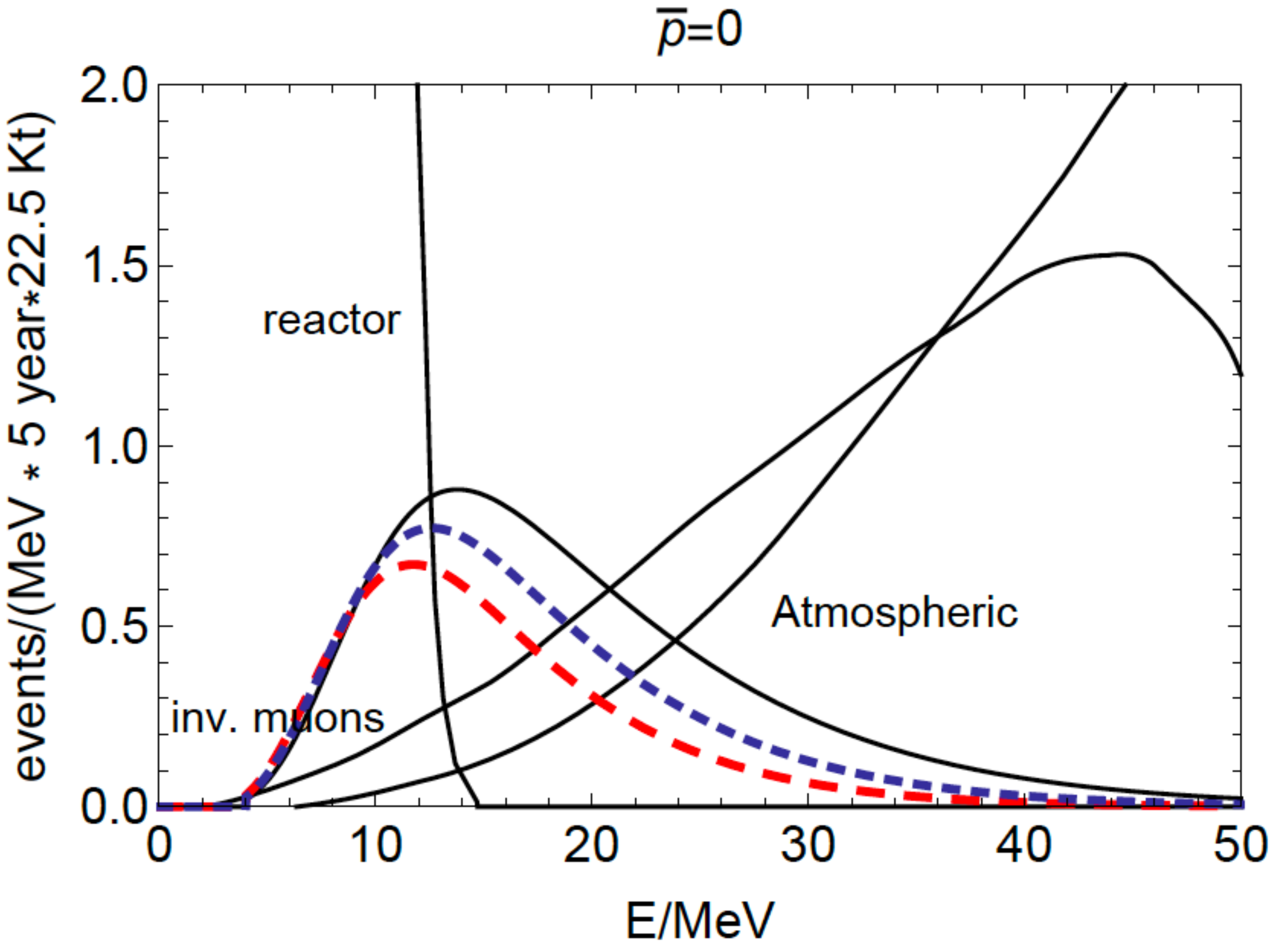


Gd doping: GADZOOKS!

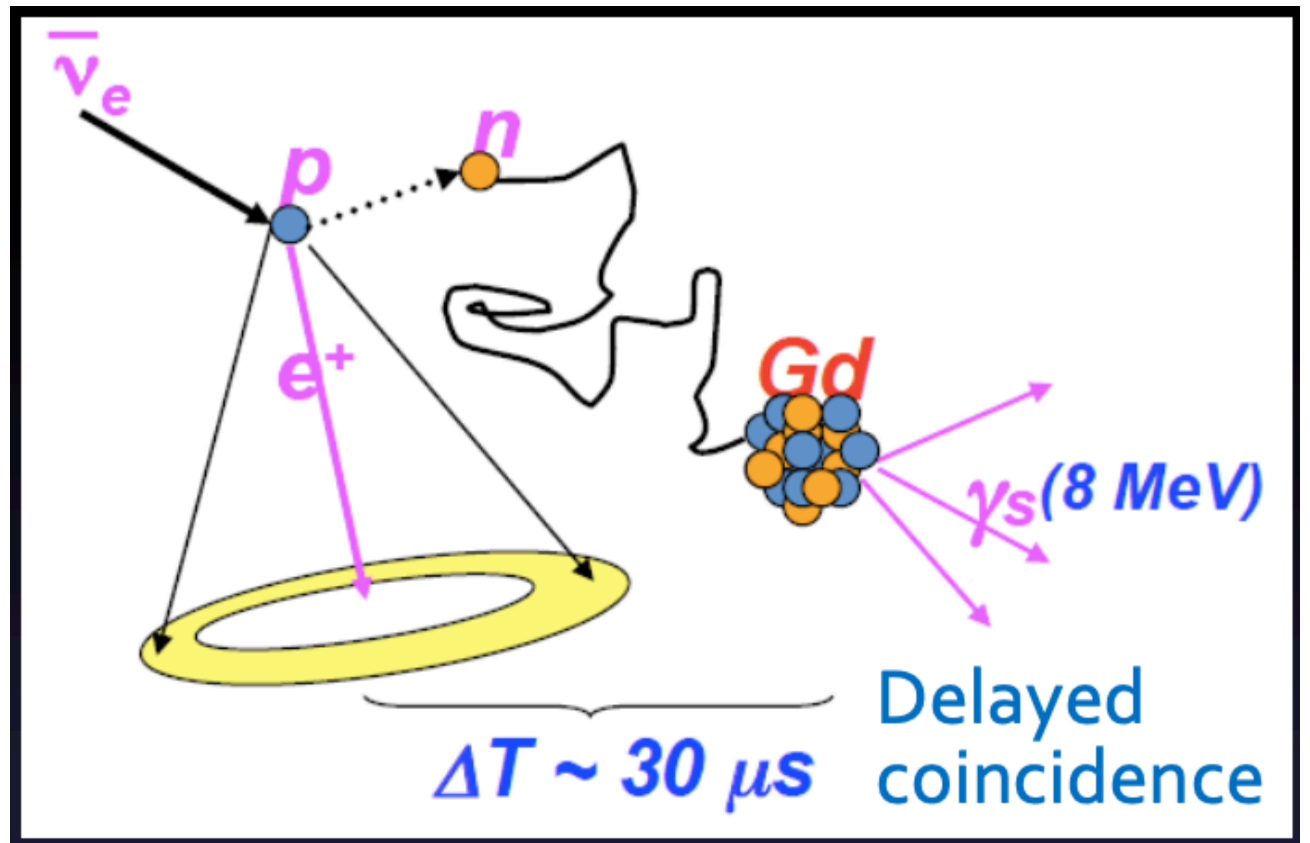
Beacom, Vagins, PRL2004



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