PROBING ν PHYSICS WITH SUPERNOVA NEUTRINOS

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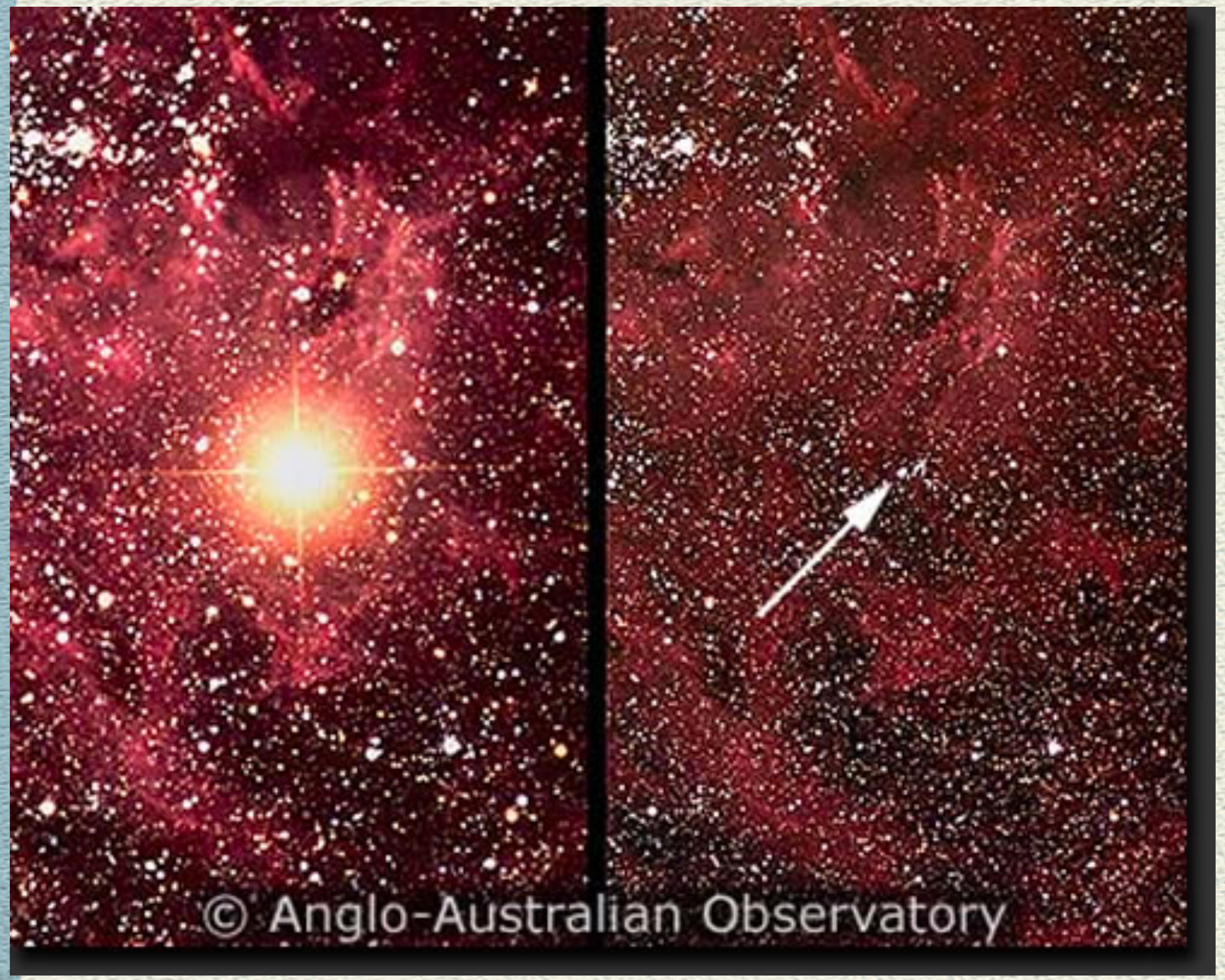
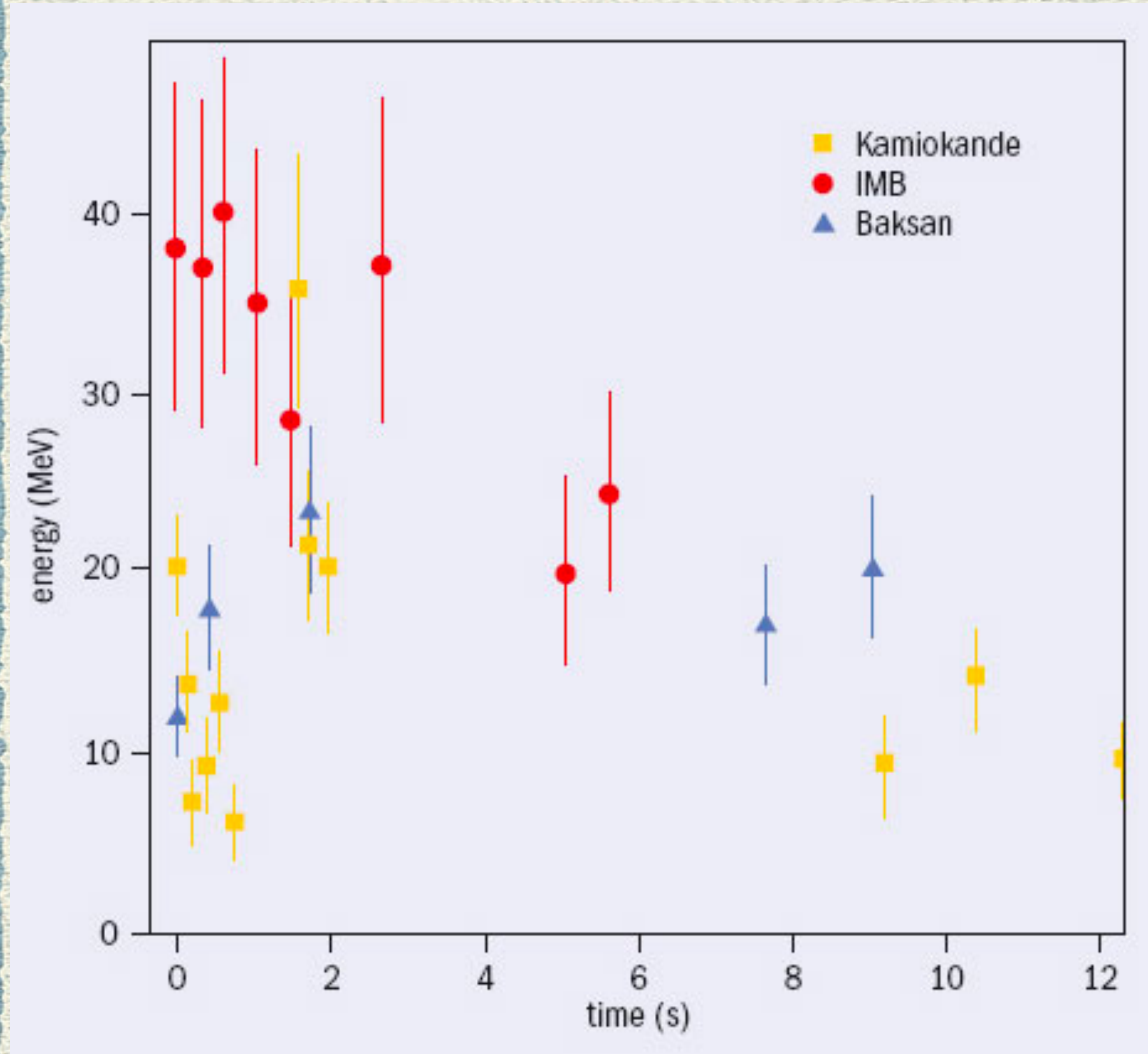
UC Berkeley & Northwestern University

Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

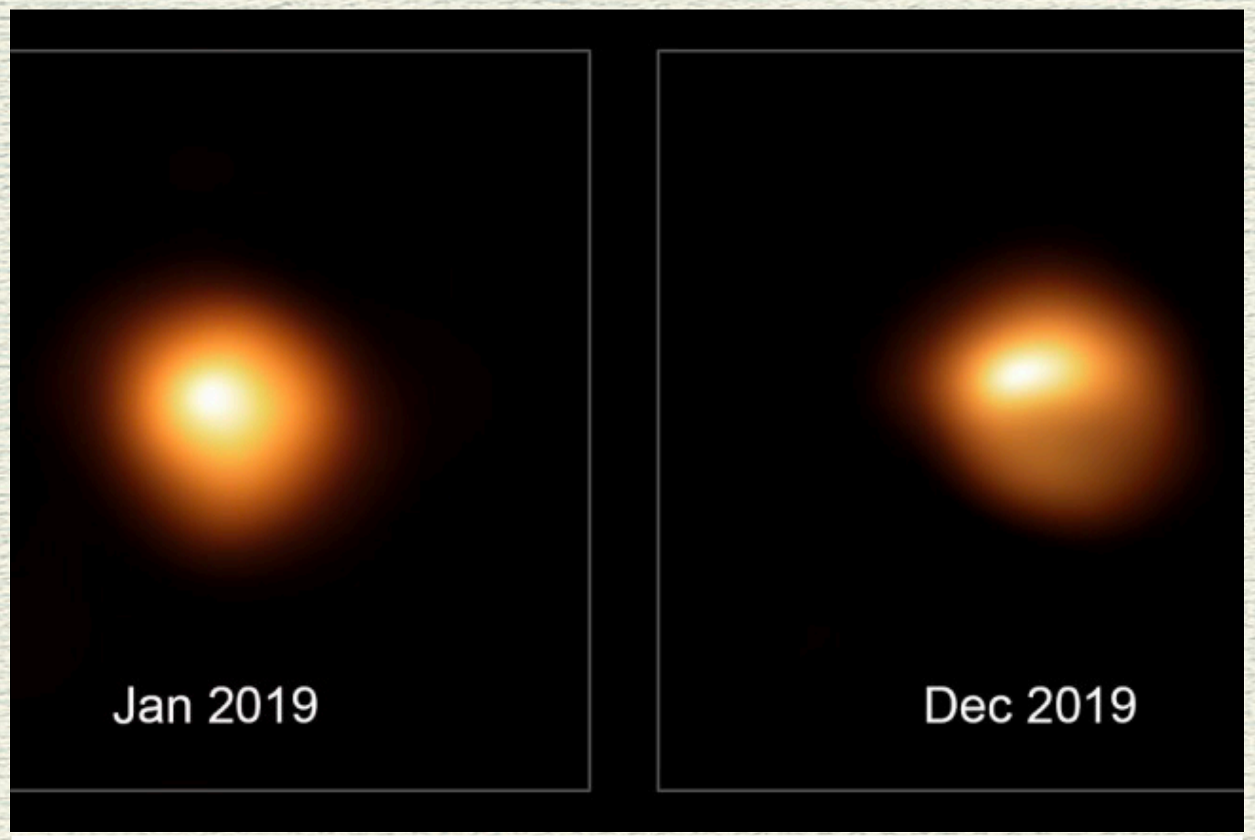
BNTVS seminar
07-20-2020

SN 1987A: "Many" neutrinos were observed





- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Not enough statistics, still some of the strongest bounds on neutrino properties!
- A future galactic SN will have O(10k) events in detectors! Surely, we can capitalize on that!

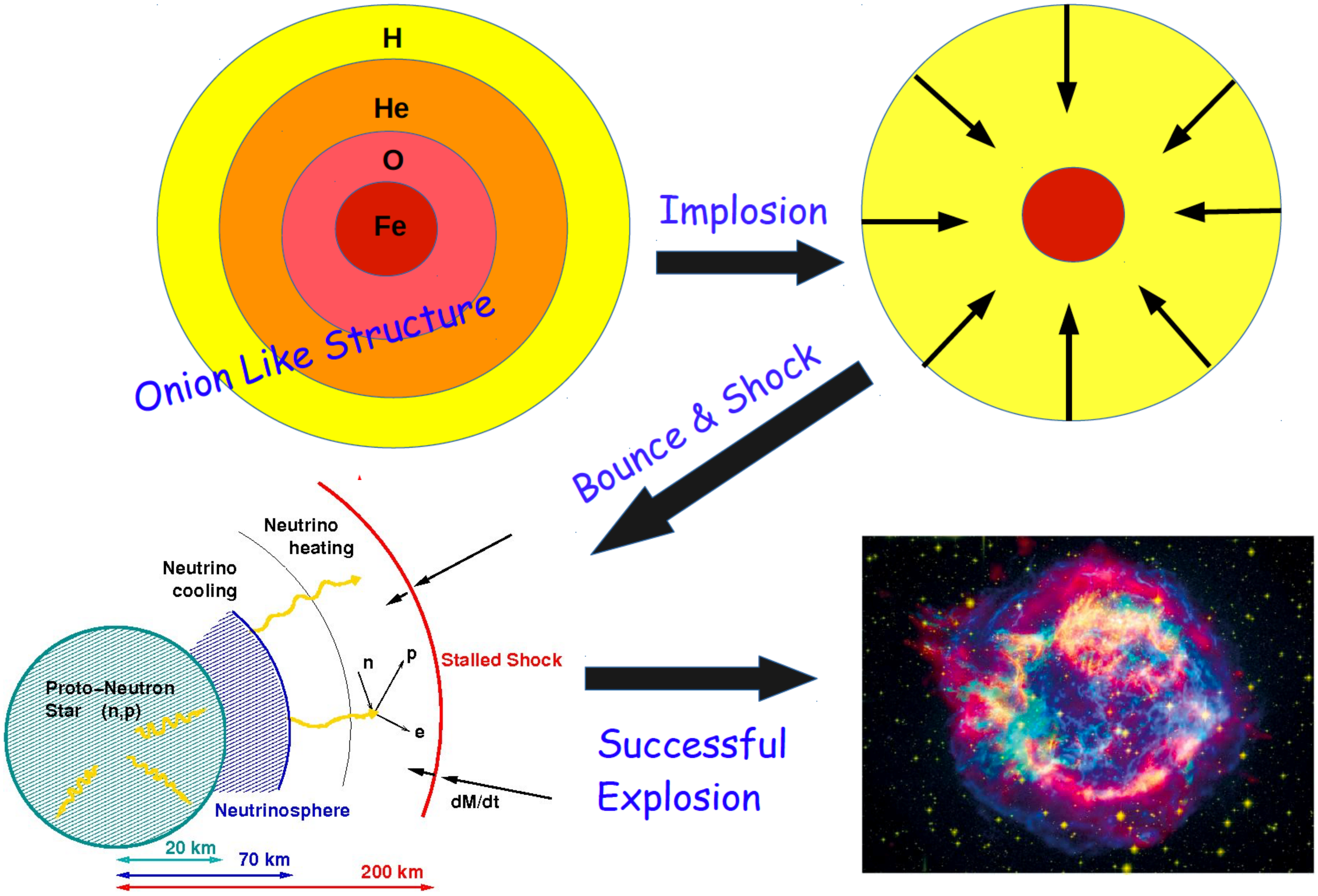


Will Bright Star Betelgeuse Finally Explode? A Look at the Dimming Red Giant in Orion's Shoulder

By Chelsea Gohd January 03, 2020

It can't hurt to look up at the night sky just in case.

CCSN Odyssey



Phases of neutrino emission

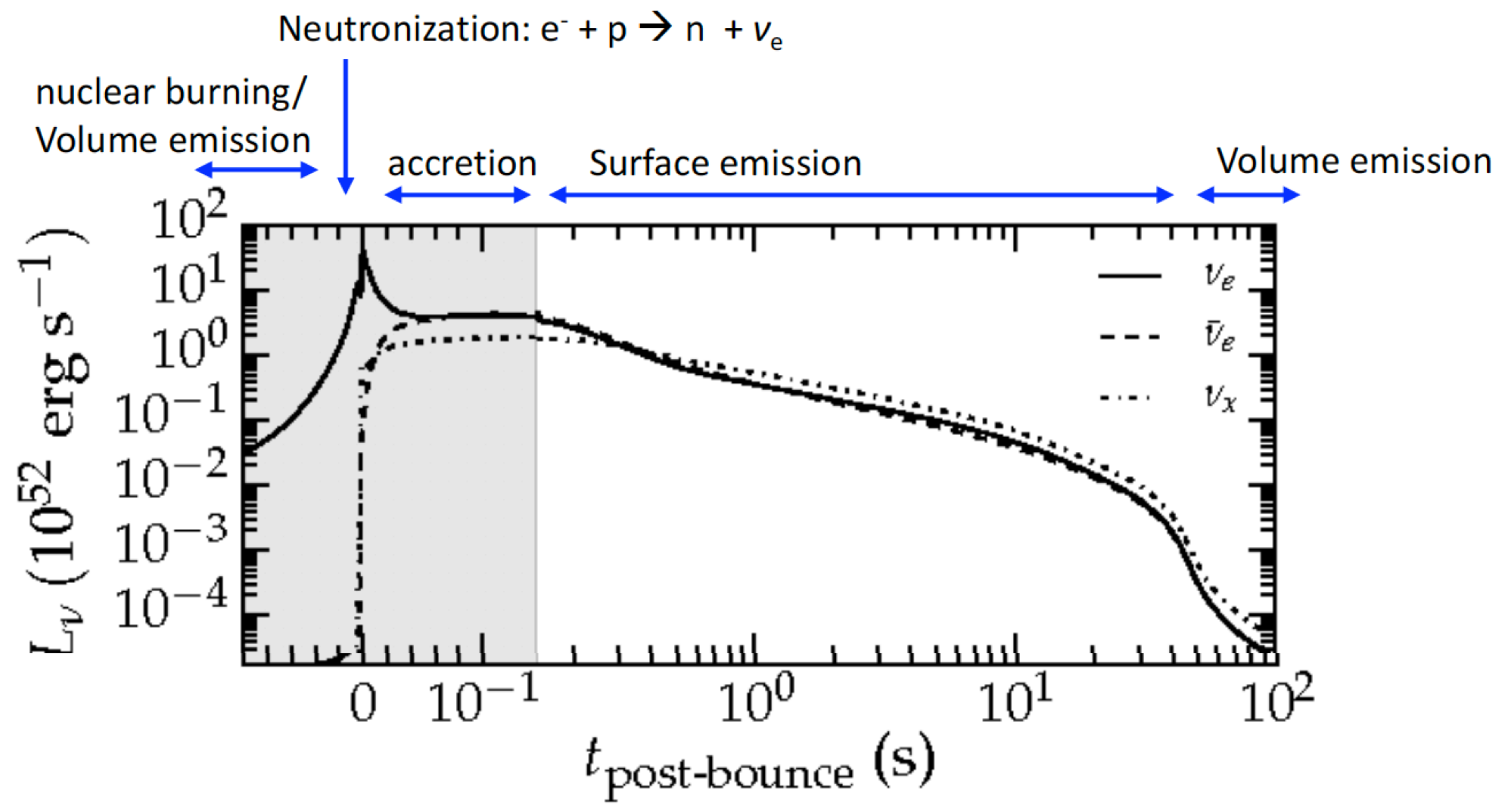
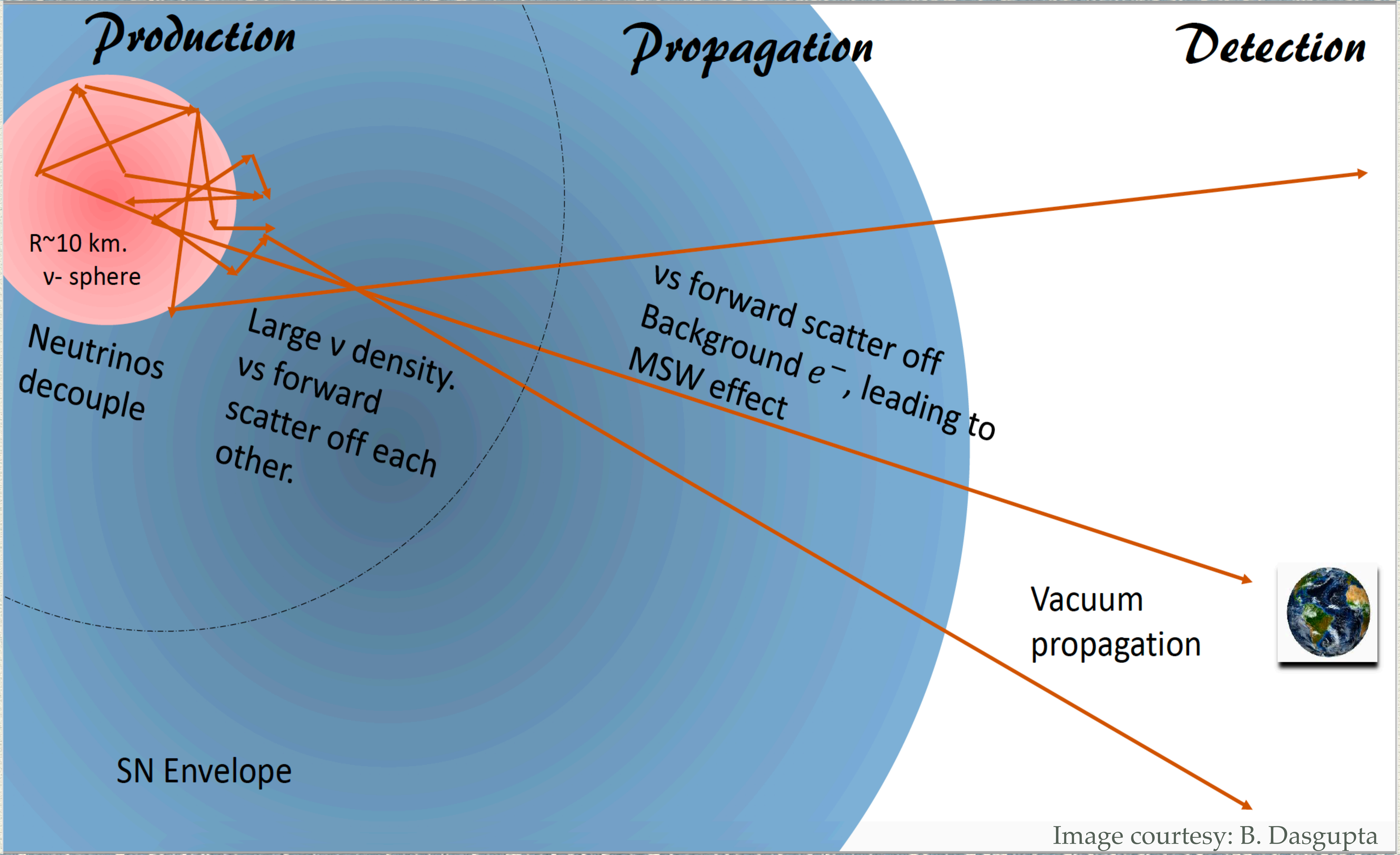


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

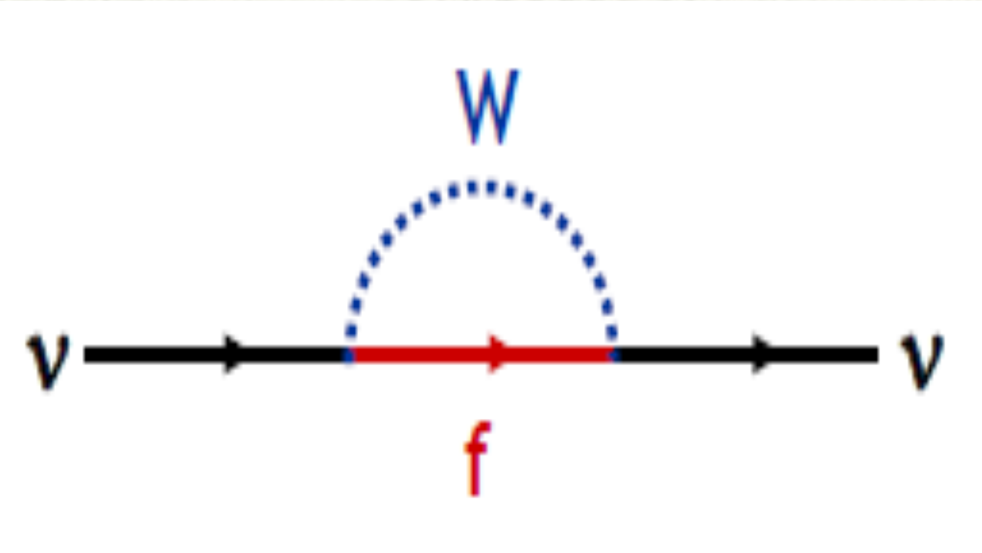
Slide from Cecilia Lunardini, BNTVS, July 2020

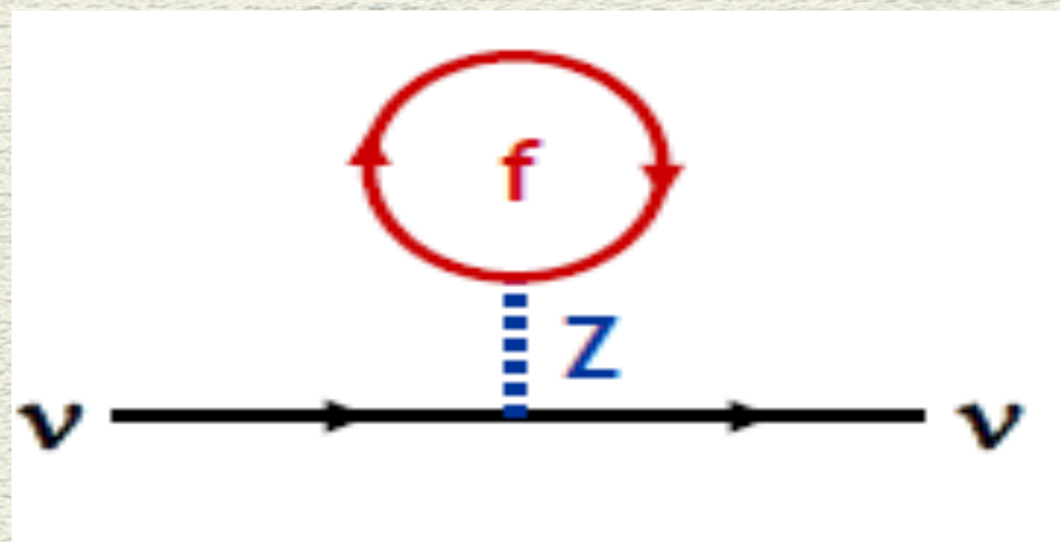
- ~10^{58} neutrinos emitted. Lots of neutrinos on target (νot)

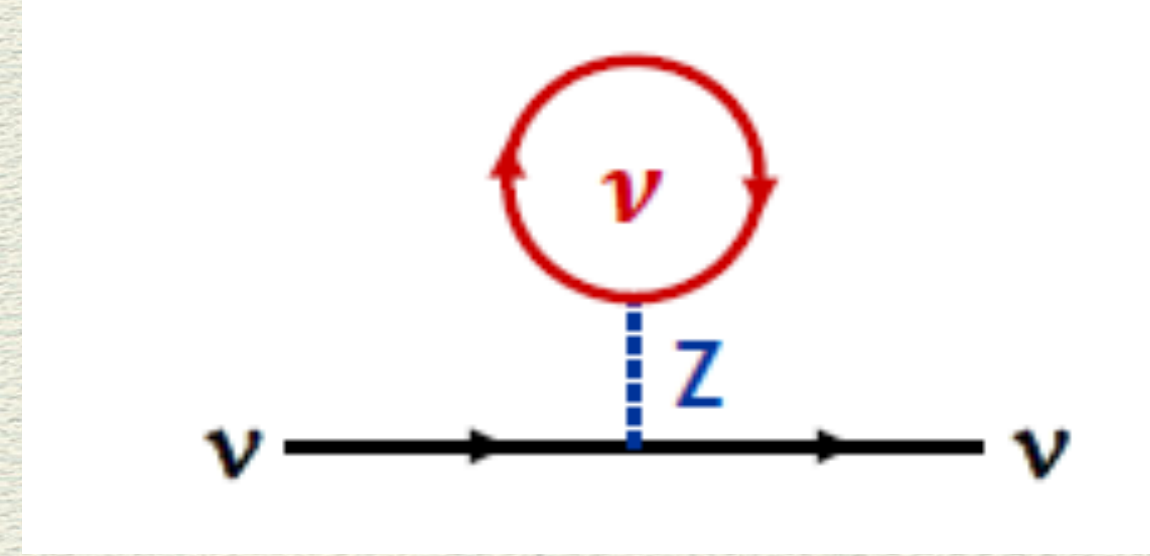
- 99% energy of the star carried away.


Production
Propagation
Detection
R~10 km.
ν- sphere
Neutrinos decouple
Large ν density. νs forward scatter off each other.
νs forward scatter off Background e^-, leading to MSW effect
Vacuum propagation
SN Envelope
Image courtesy: B. Dasgupta

Neutrino propagation inside a SN?







- Neutrino density so high that they feel additional potential. *Only lab where neutrino self-interactions become important.*

- This makes flavor evolution a complicated non-linear problem.

$$H = \frac{M^2}{2E} + \sqrt{2}G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix} + \sqrt{2}G_F \begin{pmatrix} N_{\nu_e} & N_{\langle \nu_e | \nu_\mu \rangle} \\ N_{\langle \nu_\mu | \nu_e \rangle} & N_{\nu_\mu} \end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

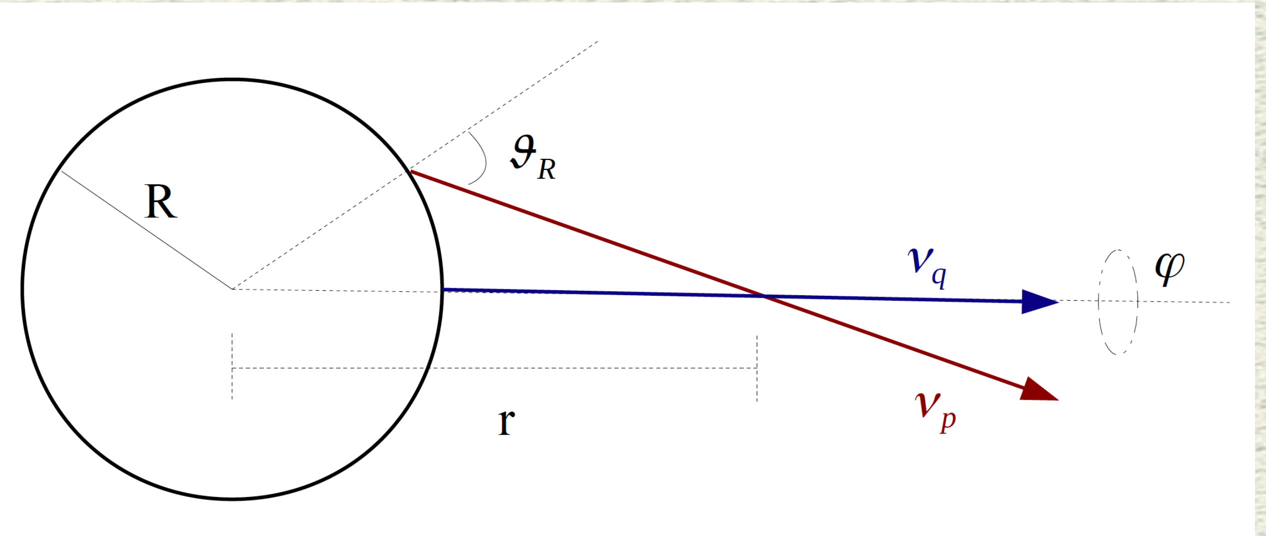
Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Raffelt, Seattle 2015

The matrix of densities: (3+3+1) dim

$$\varrho = \begin{bmatrix} \langle \nu_e | \nu_e \rangle & \langle \nu_e | \nu_x \rangle \\ \langle \nu_x | \nu_e \rangle & \langle \nu_x | \nu_x \rangle \end{bmatrix}$$



EoM: $d_t \varrho_p(r,p,t) = -i[H_p, \varrho_p] + C[\varrho_p]$

$$H_p = \omega_p \quad + \quad \lambda \quad + \quad \mu \int d\Gamma' (1 - v_p \cdot v_{p'}) \varrho_{p'}$$

ω_p: $\dfrac{\mathrm{M}^2}{2\mathrm{E_p}}$

λ: Matter (MSW) term $\propto \sqrt{2} G_F n_e$

μ: $\nu - \nu$ interaction term $\propto n_\nu$

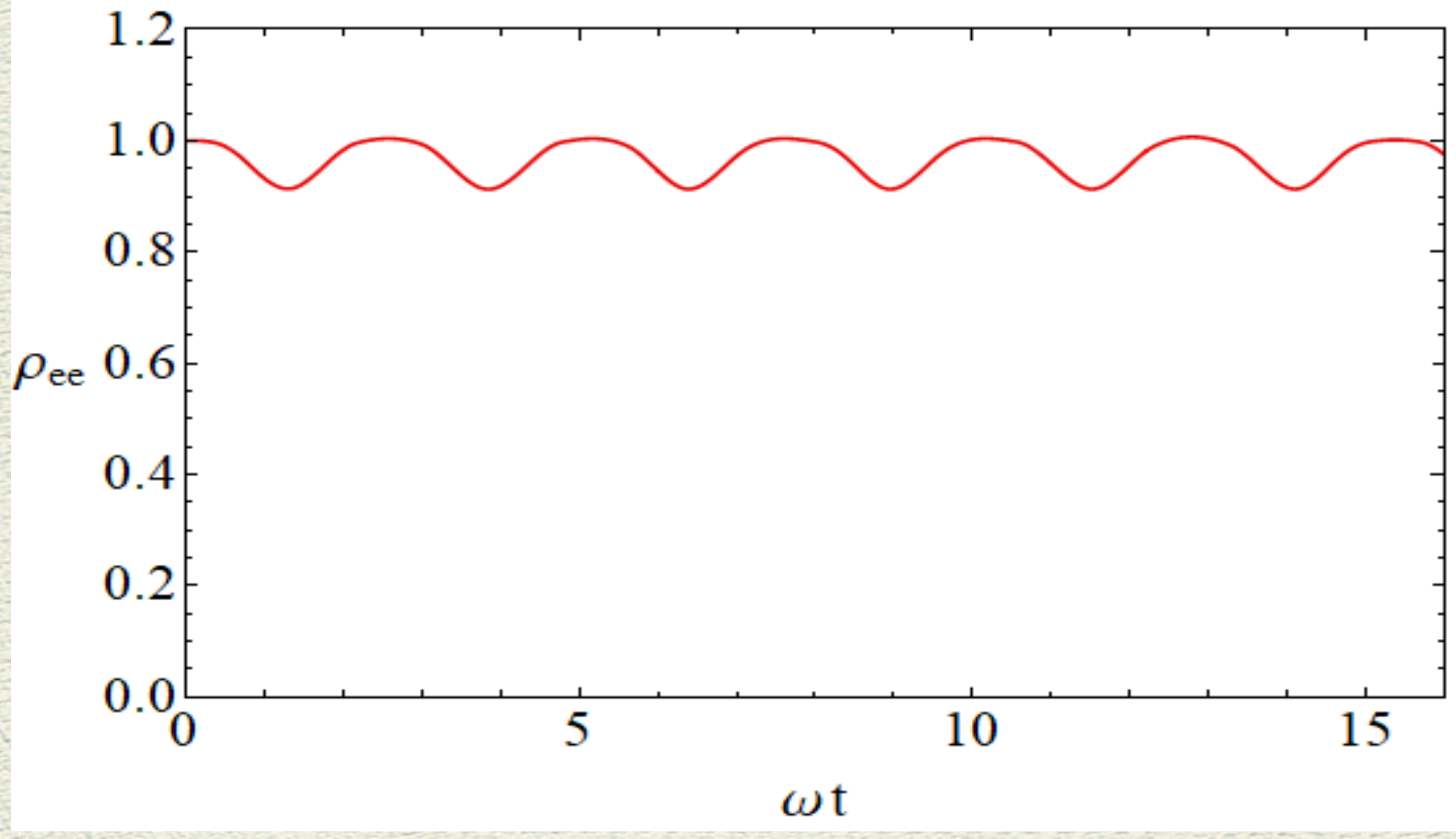
Kim, Kim and Sze (PRD 1988)

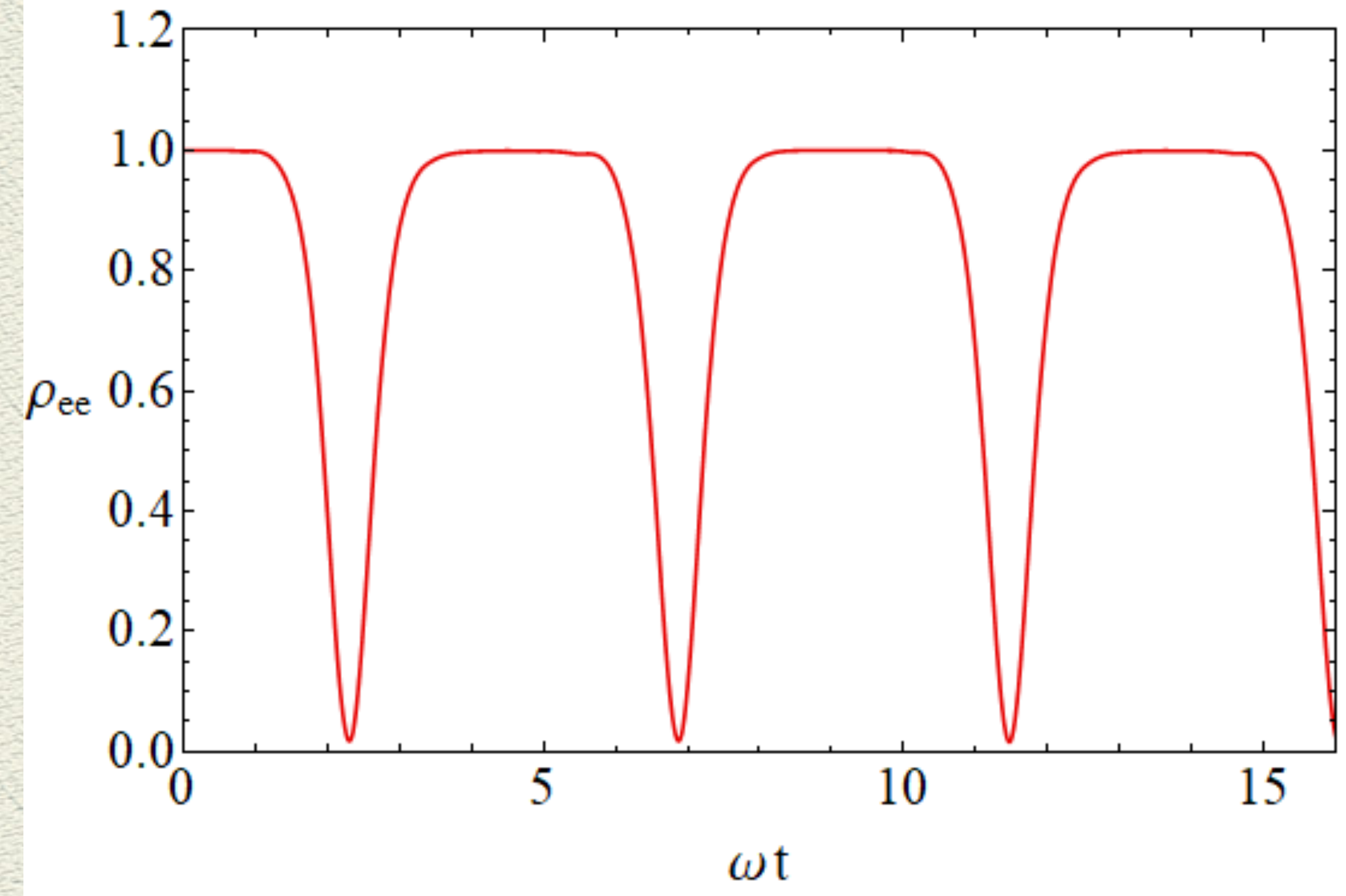
$\mu \sim \lambda \gg \omega$

Wolfenstein (PRD1978,1979)
Mikheyev and Smirnov (SJNP1985)
Pantaleone (PRD 1992)
Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Hannestad, Raffelt, Sigl and Wong (2006)

Collective oscillations: effect of non-linearity

- If $\mu \propto n_\nu \gg \omega$, oscillations are synchronized.
- As n_ν decreases, bipolar oscillations $\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$ take place.
- Can lead to complete flavor conversions deep inside the SN.
- Bipolar conversions can be "fast" or "not-so-fast", yet way larger than MSW rate.

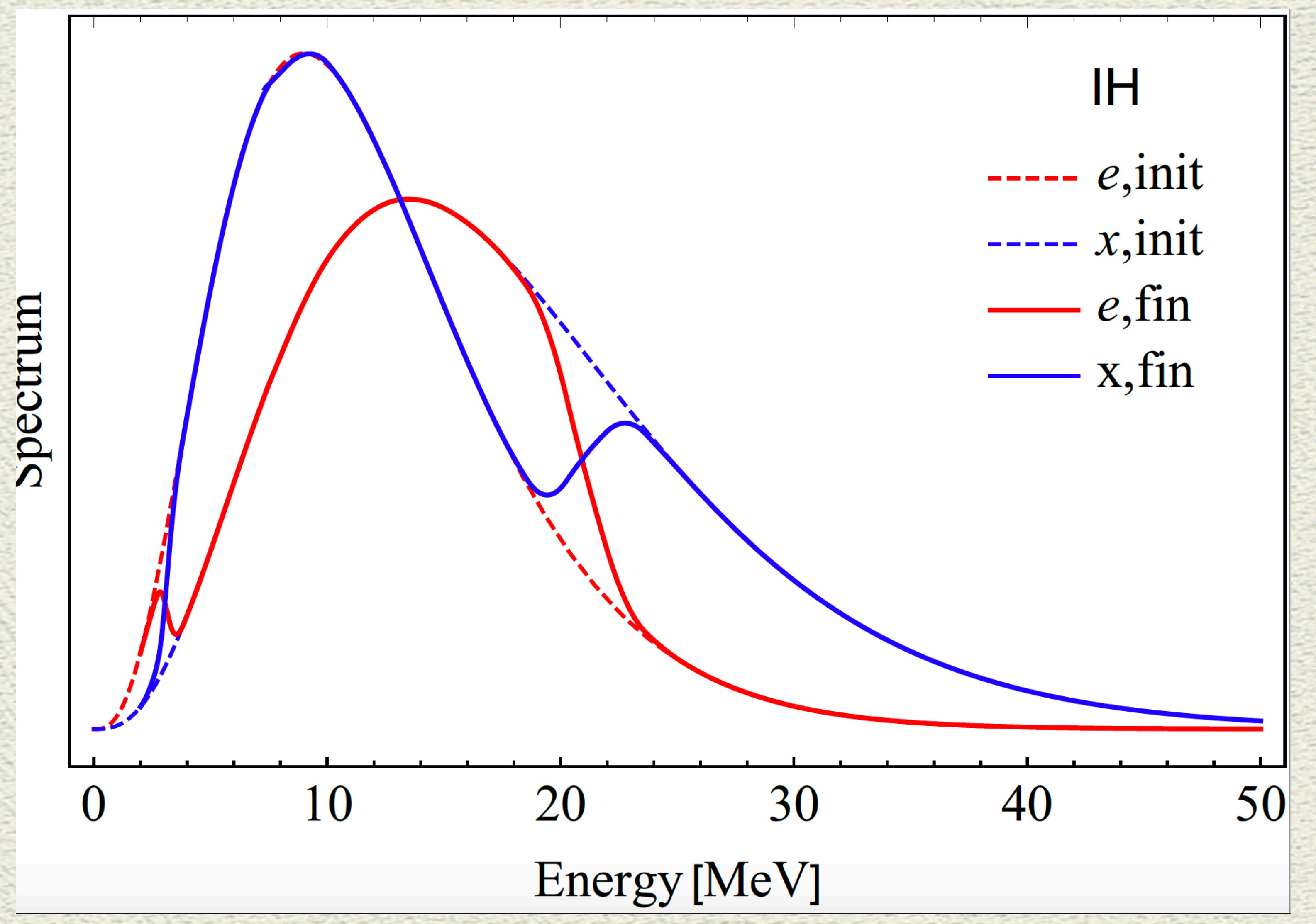


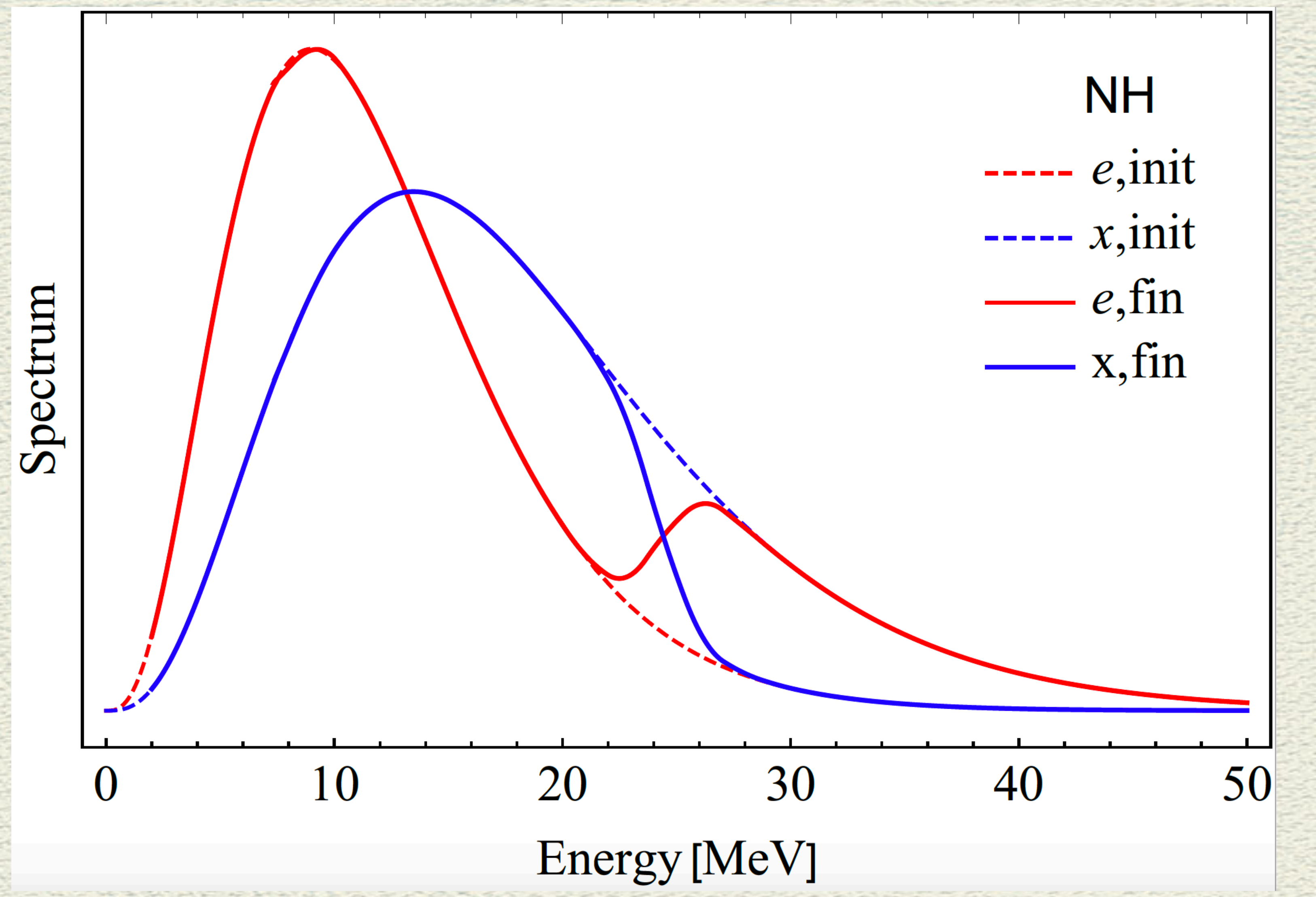


Chakraborty, Hansen, Izagguire and Raffelt (JCAP 2016)
Dasgupta, Mirizzi and MS (JCAP 2017)
Izagguire, Raffelt and Tamborra (PRL 2017)

Duan, Fuller, Carlson and Qian (PRD 2006,2007; PRL 2006)
Hannestad, Raffelt, Sigl and Wong (PRD 2006)

Spectral swaps: formation of splits





e= electron
x=muon or tau

Bipolar oscillations lead to large 'spectral swaps':
smoking gun signal of collective oscillations. Can be detected!

Duan, Fuller, Carlson and Qian (PRL 2006)
Dasgupta, Dighe, Mirizzi and Raffelt (PRD 2008)
Friedland (PRL 2010)

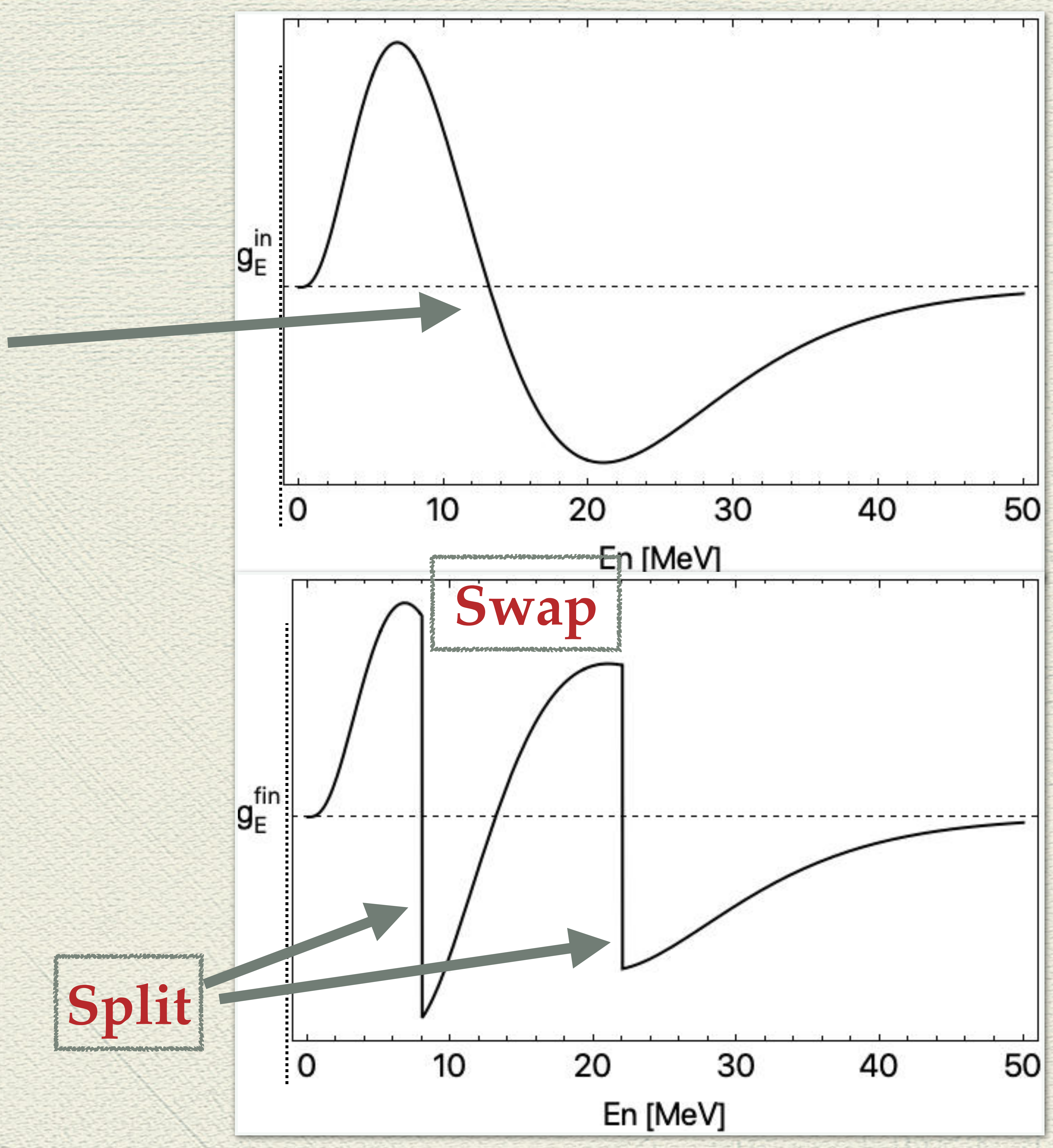
Spectral swaps: formation of splits

- Empirical explanation in terms of "spectrum"
  $g(E) = f_{\nu_e}(E) - f_{\nu_x}(E)$

- If g(E) has a zero-crossing, system is unstable and there is flavor conversion.

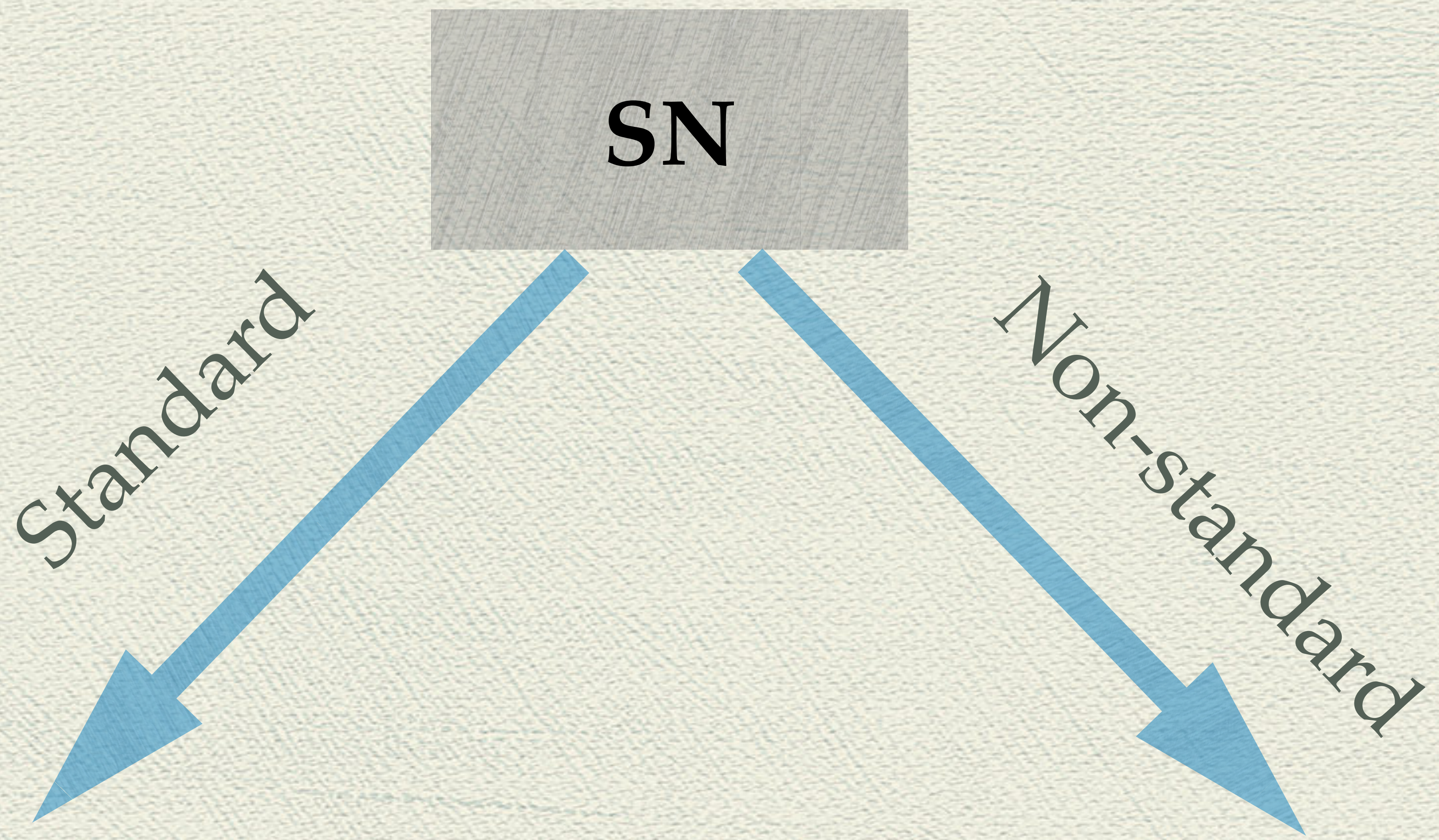
- Leads to spectral *swaps* with distinct *splits*.

- Width of swap governed by *flavor-lepton number conservation*. Within a swapped region,
  $$\int dE\, g(E) = 0$$
  i.e., initial lepton flavor asymmetry is conserved.



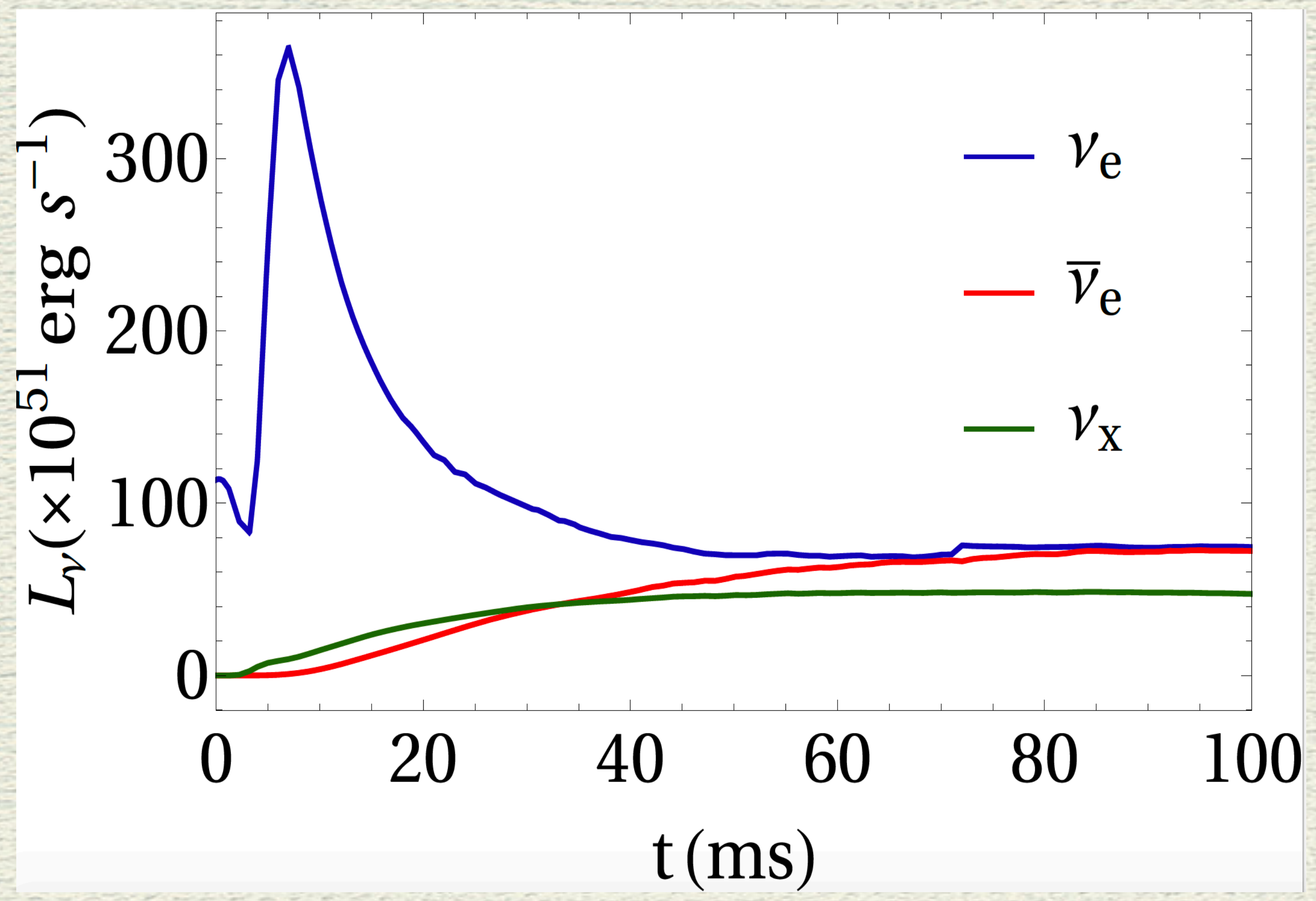
Dasgupta, Dighe, Raffelt and Smirnov (PRL 2009)
+ many others

What sort of a laboratory is the SN?

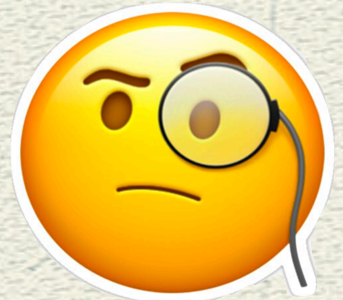


- νs probe stellar interiors.
- Relevant information about supernova dynamics, shockwave propagation, turbulence.
- Physics of dense neutrino streams. Can lead to "collective oscillations"!

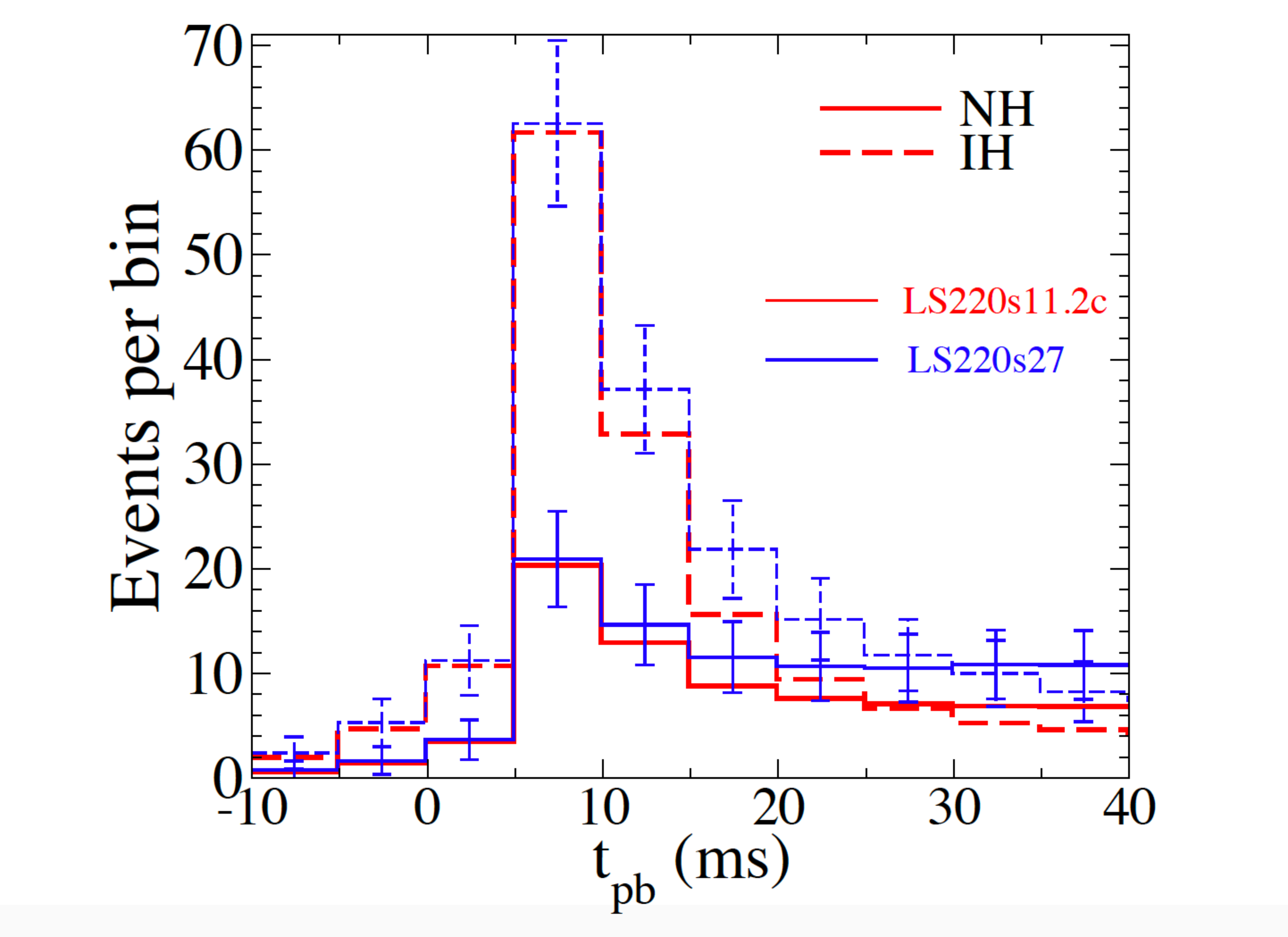
- Non-standard neutrino properties: decay, self-interactions, magnetic moment, Dirac-Majorana nature, etc.
- New particles.
- Any crazy stuff that theorists can think about.

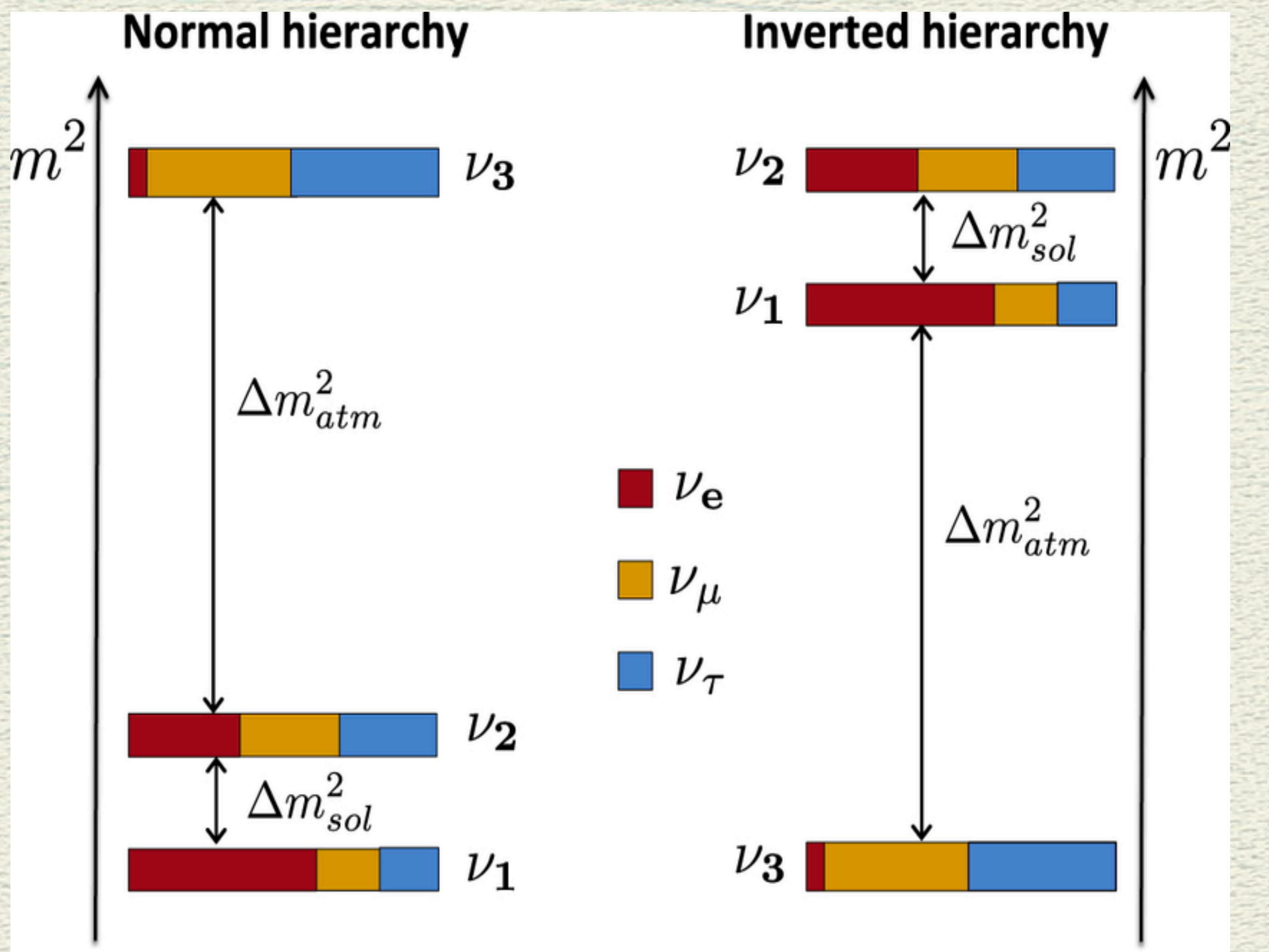


Use the neutronization flux simply because it is usually unaffected by collective oscillatons



Neutronization burst: Sensitivity to mass hierarchy





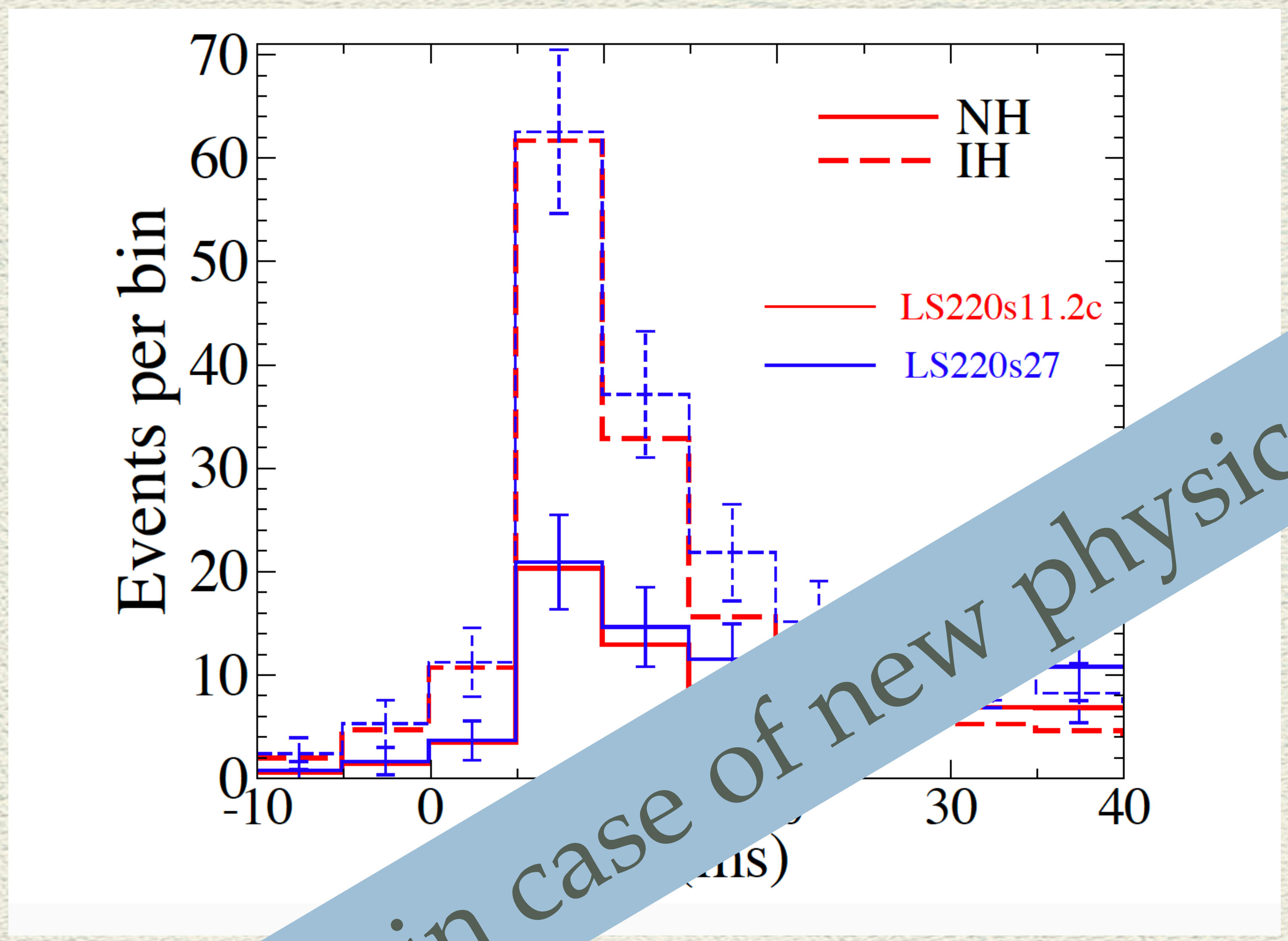
$$L_{\nu_e}(R_E) \simeq |U_{e2}|^2\, L^0_{\nu_e} = 0.2\, L^0_{\nu_e} \quad \text{IH}$$

$$L_{\nu_e}(R_E) \simeq |U_{e3}|^2\, L^0_{\nu_e} = 0.03\, L^0_{\nu_e} \quad \text{NH}$$

Dighe and Smirnov, PRD 2000

Suppression of spectra for NH.
Independent probe of mass ordering!

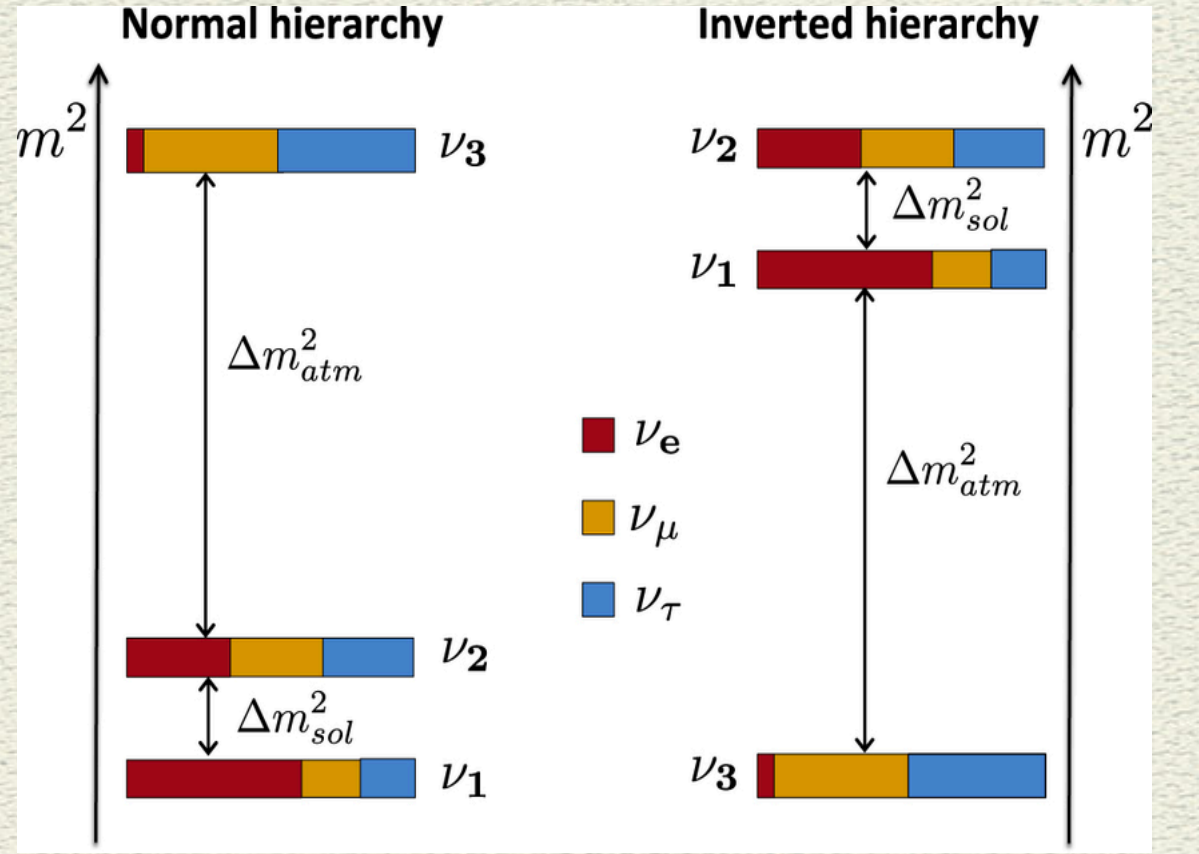
Sensitivity to mass hierarchy



What happens in case of new physics?

$|U_{e2}|^2\, L^0_{\nu_e} = 0.2\, L^0_{\nu_e}$ IH

$(R_E) \simeq |U_{e3}|^2\, L^0_{\nu_e} = 0.03\, L^0_{\nu_e}$ NH



Independent probe of mass ordering!

1. Neutrino non-standard self-interactions

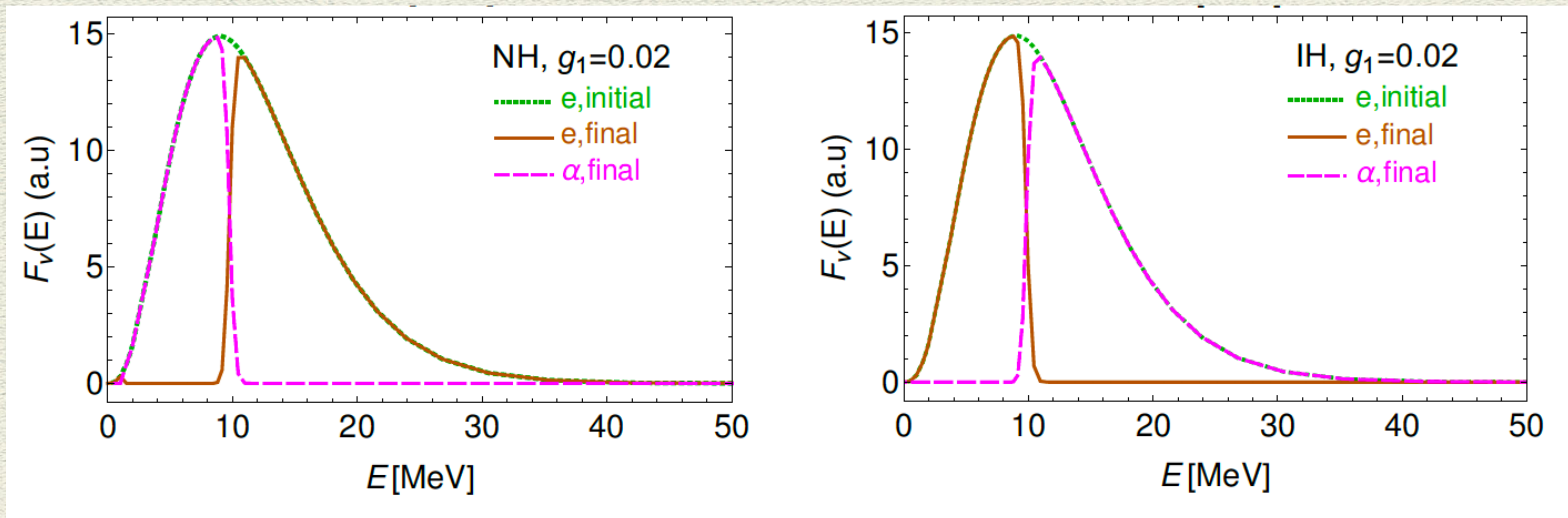
- Generalize neutrino self-interactions to $G^{ij}\, G^{km} G_F\, (\bar{\nu}_i \gamma_\mu P_L \nu_j)\, (\bar{\nu}_k \gamma^\mu P_L \nu_m)$, where

$$G = \begin{pmatrix} 1 + g_{ee} & g_{ex} \\ g_{ex} & 1 + g_{xx} \end{pmatrix}$$

- $g_{ex} \neq 0$ can populate ν_x from ν_e , causing *flavor-lepton number violation*.

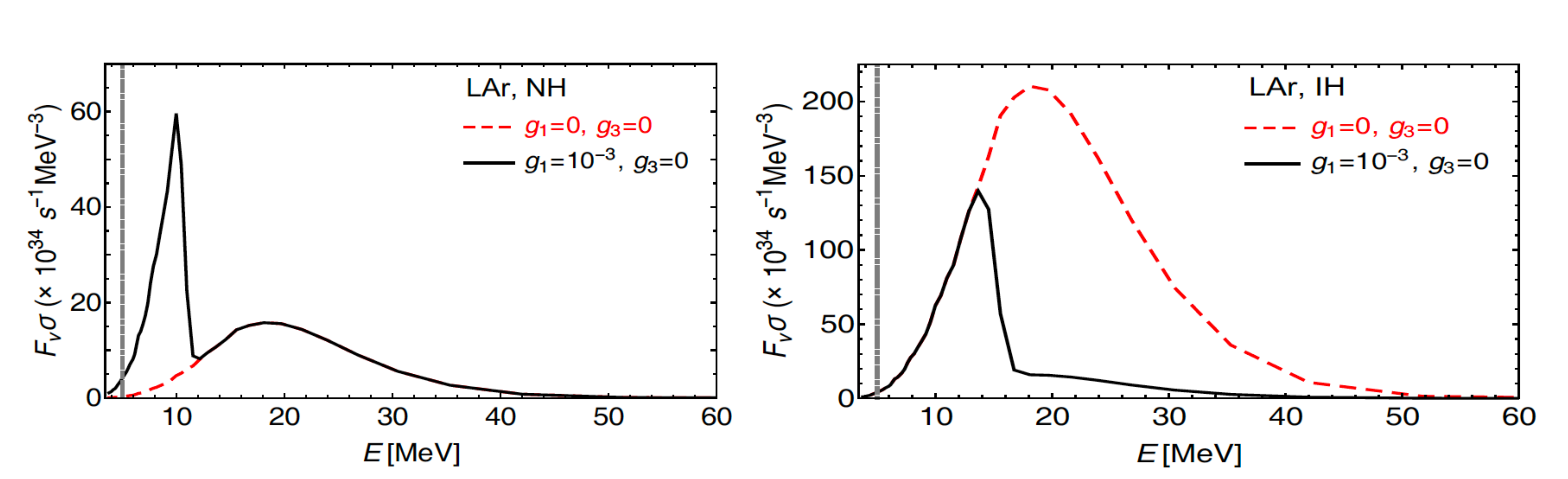
- Can cause collective oscillations *even in the absence of a spectral crossing*.

- *Distinct spectral splits in neutronization spectra? — Smoking gun signal!*



Dighe, Das and MS (JCAP 1705 (2017) 051)
Dighe and MS (PRD97 (2018))

NSSI and spectral swaps in neutronization

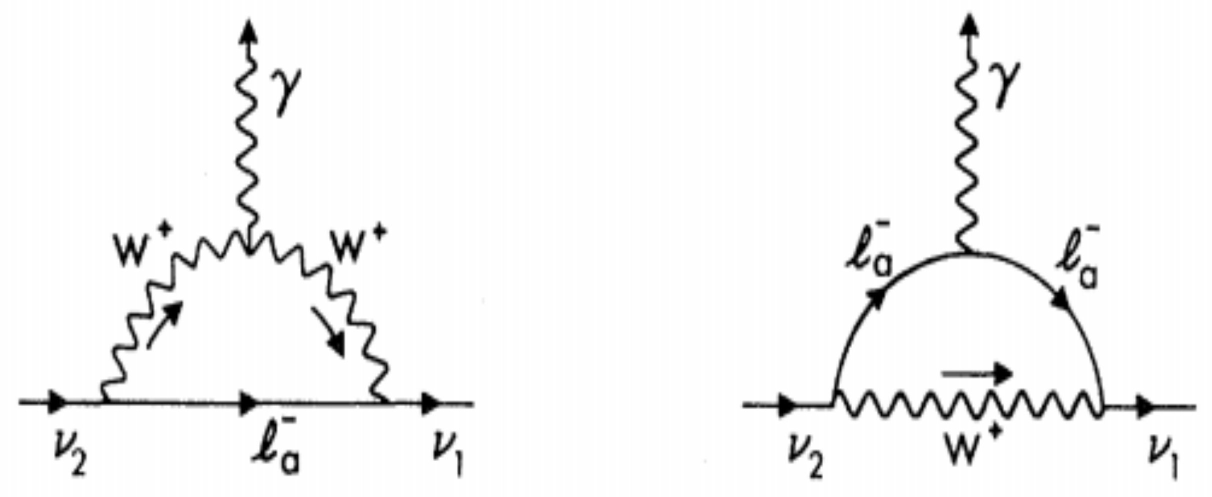


- Distinct splits can be detected at DUNE. True for both mass ordering.
- Put flux dependent constraints on NSSI.
- Caveat: sensitive to details of collective oscillations! Should be explored in more details.

Dighe, Das and MS (JCAP 1705 (2017) 051)
Dighe and MS (PRD97 (2018))

2. Neutrino-decay

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



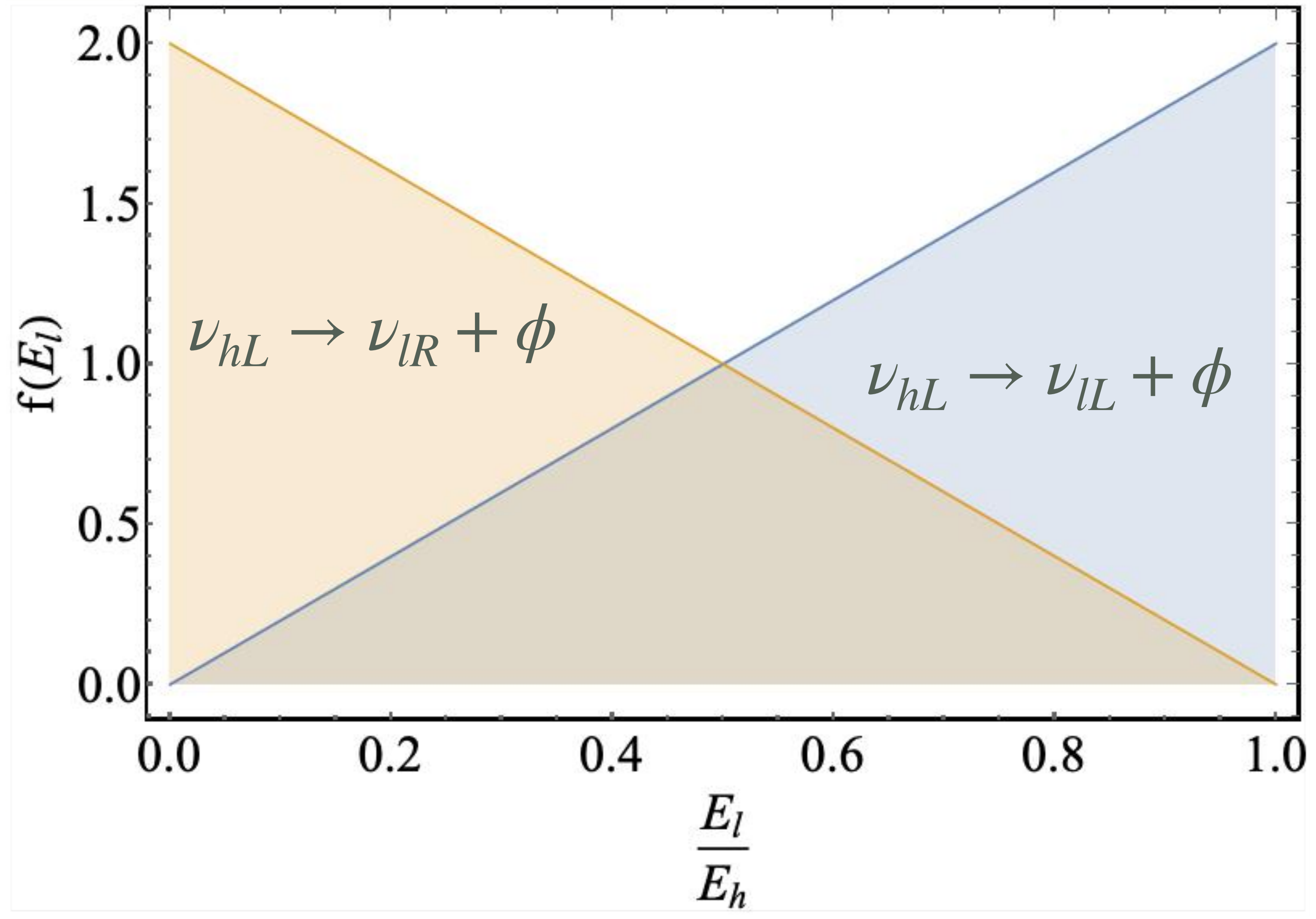
Pal and Wolfenstein (PRD1982)

- New physics can mediate faster decay.

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

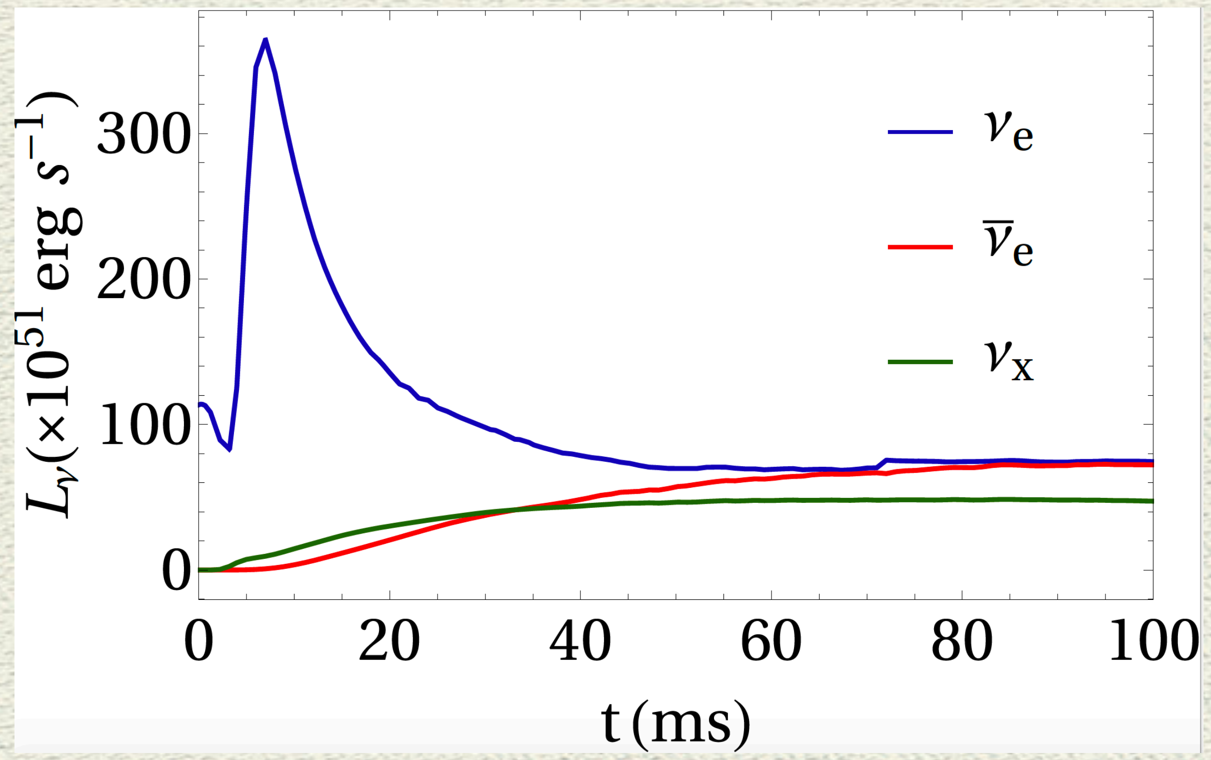
$\nu_{hL} \to \nu_{lL} + \varphi$ .... Helicity cons. (h.c.)
$\nu_{hL} \to \nu_{lR} + \varphi$ .... Helicity flip. (h.f.)

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



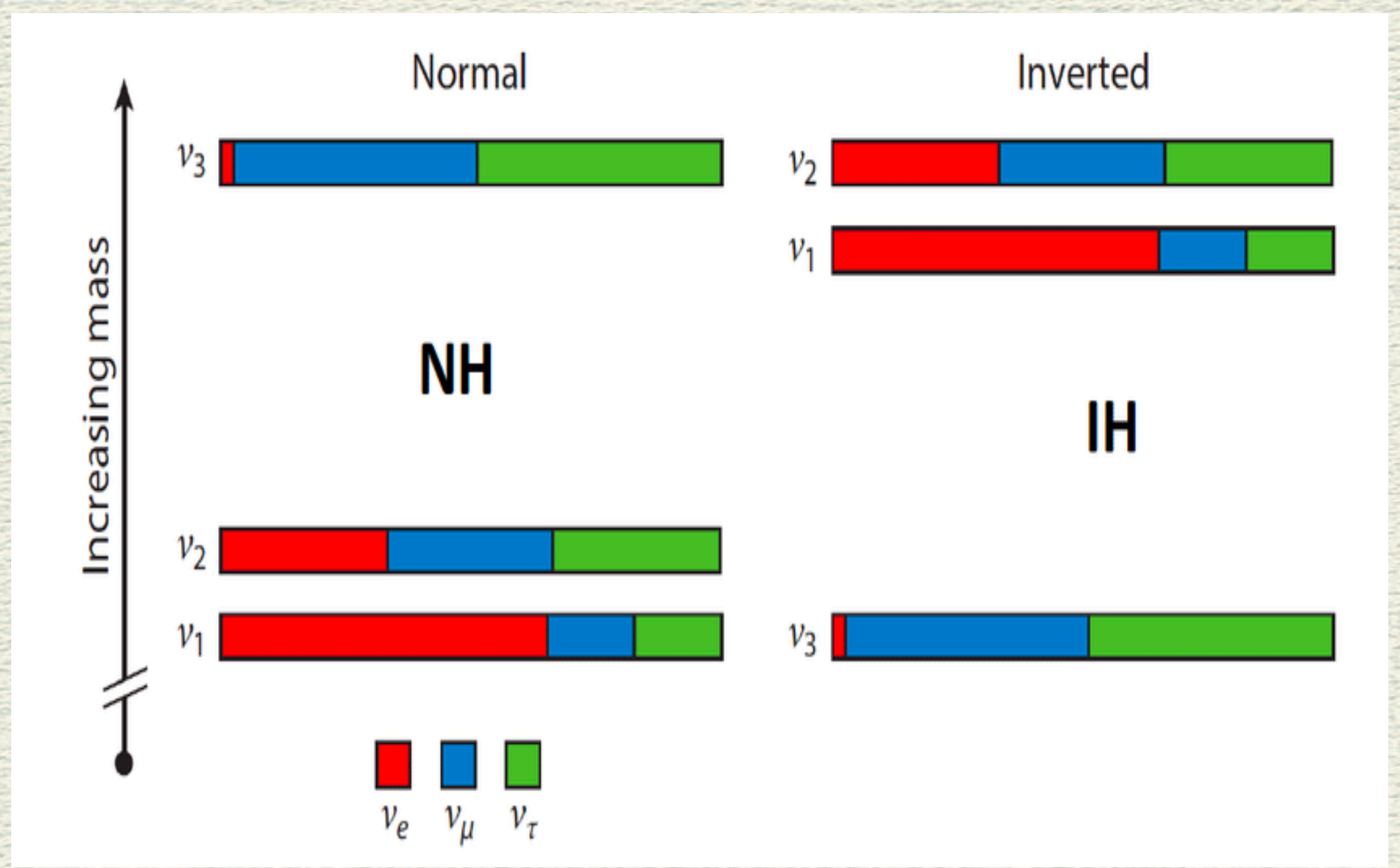
Daughter neutrinos have a harder spectra in the h.c. channel

How to play this game?



Normal Ordering

$$\nu_3 \rightarrow \nu_1 \varphi$$



NO DECAY

$\nu_h \equiv \nu_3$

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

DECAY

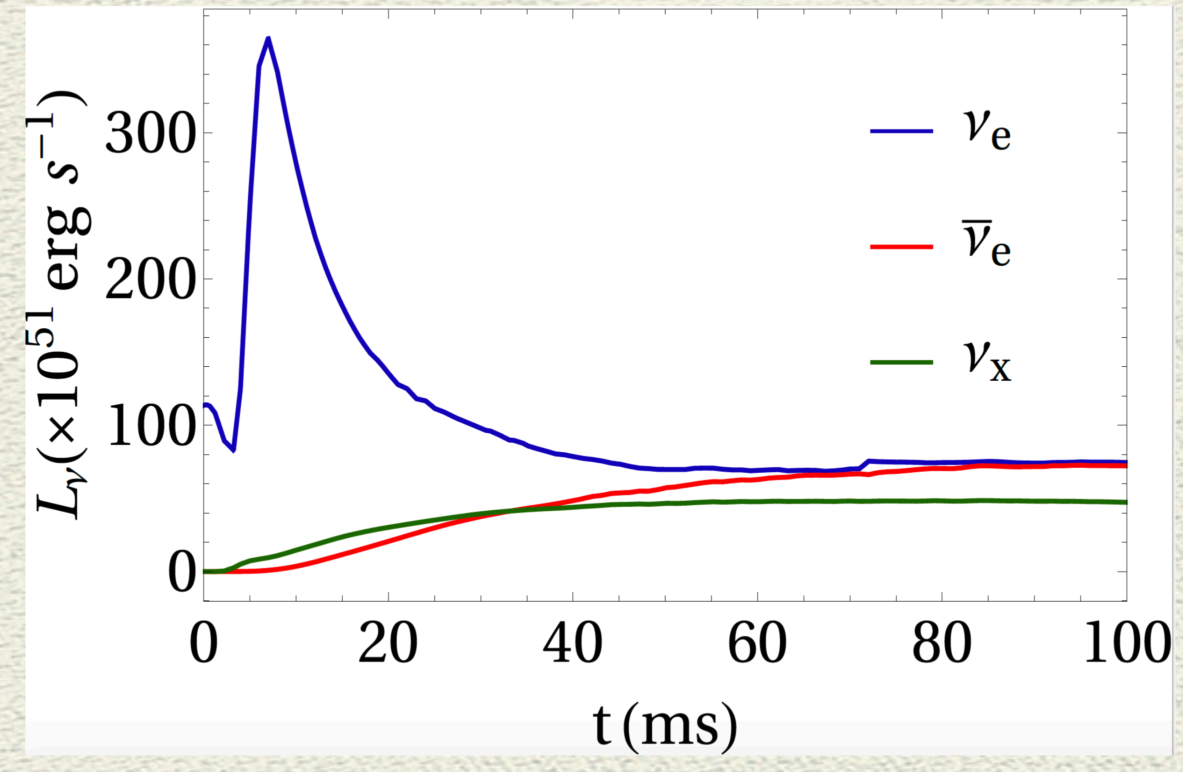
$\nu_l \equiv \nu_1$

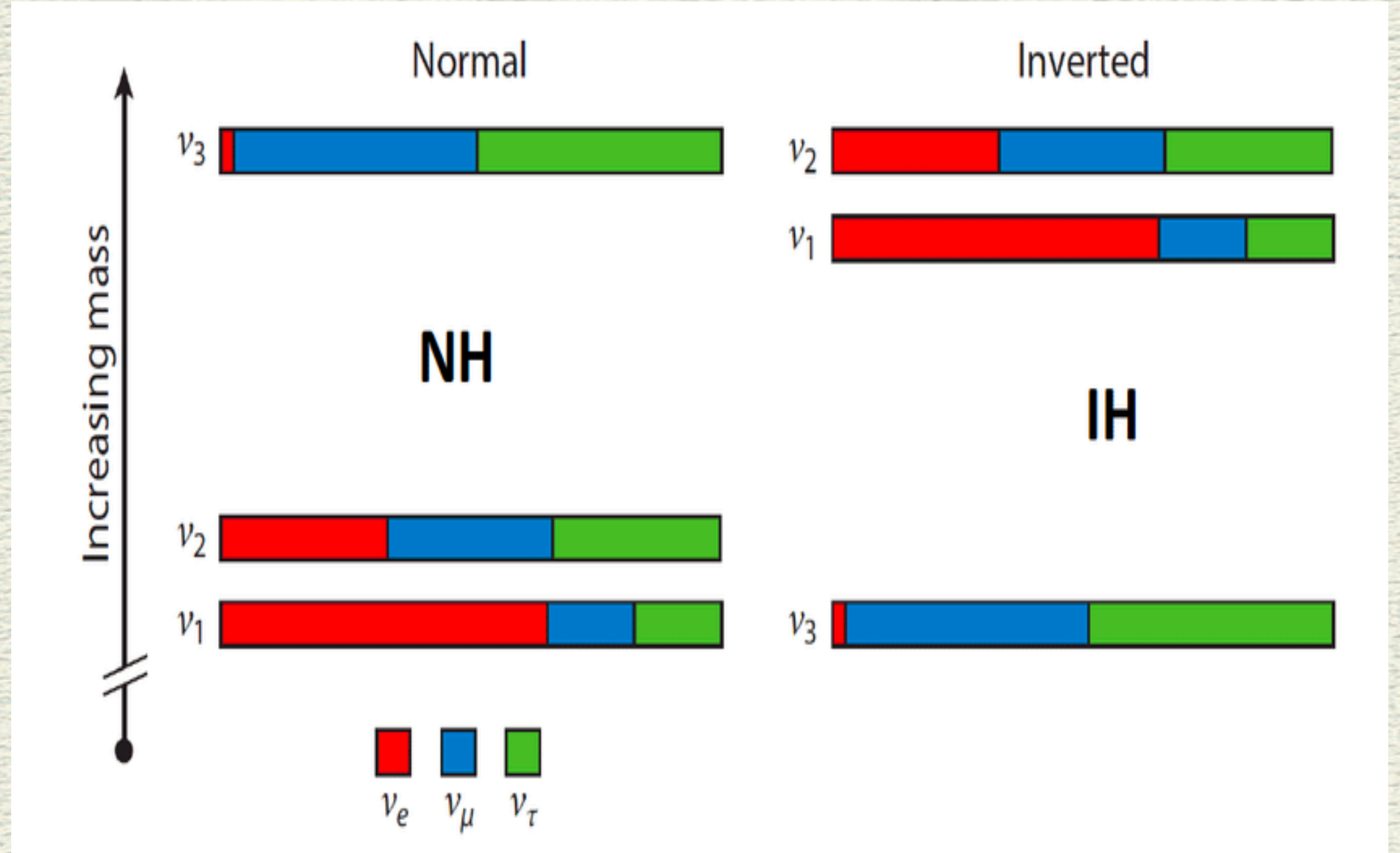
$\nu_h \equiv \nu_3$

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

Enhancement in spectra

How to play this game?





Inverted Ordering

$$\nu_2 \rightarrow \nu_3 \varphi$$

NO DECAY

$\nu_h \equiv \nu_2$

$\nu_e \sim 0.3\, \nu_2$

DECAY

$\nu_l \equiv \nu_3$

$\nu_h \equiv \nu_2$

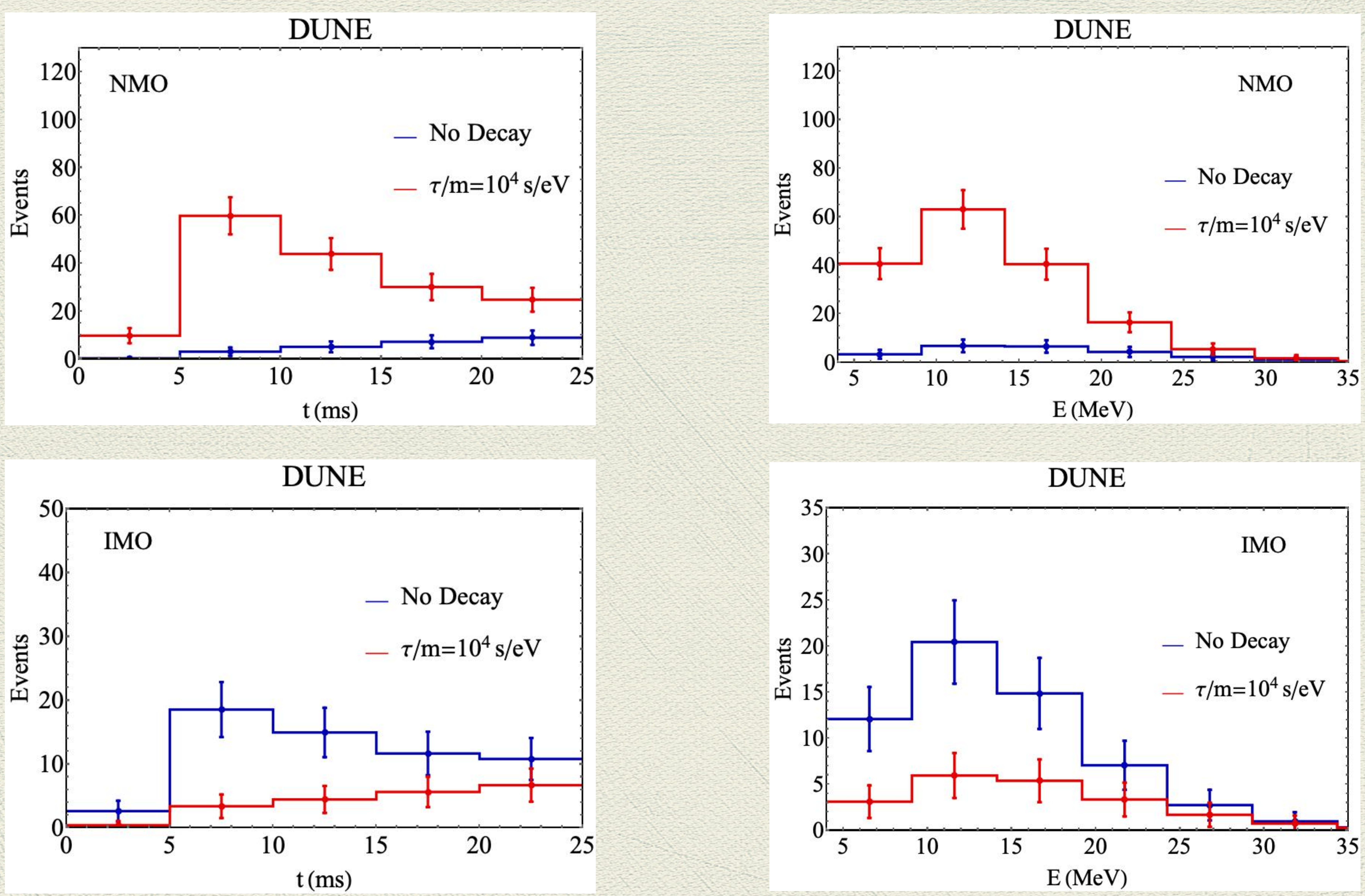
$\nu_e \sim 0.02\, \nu_e^{\mathrm{in}}$

Suppression in spectra

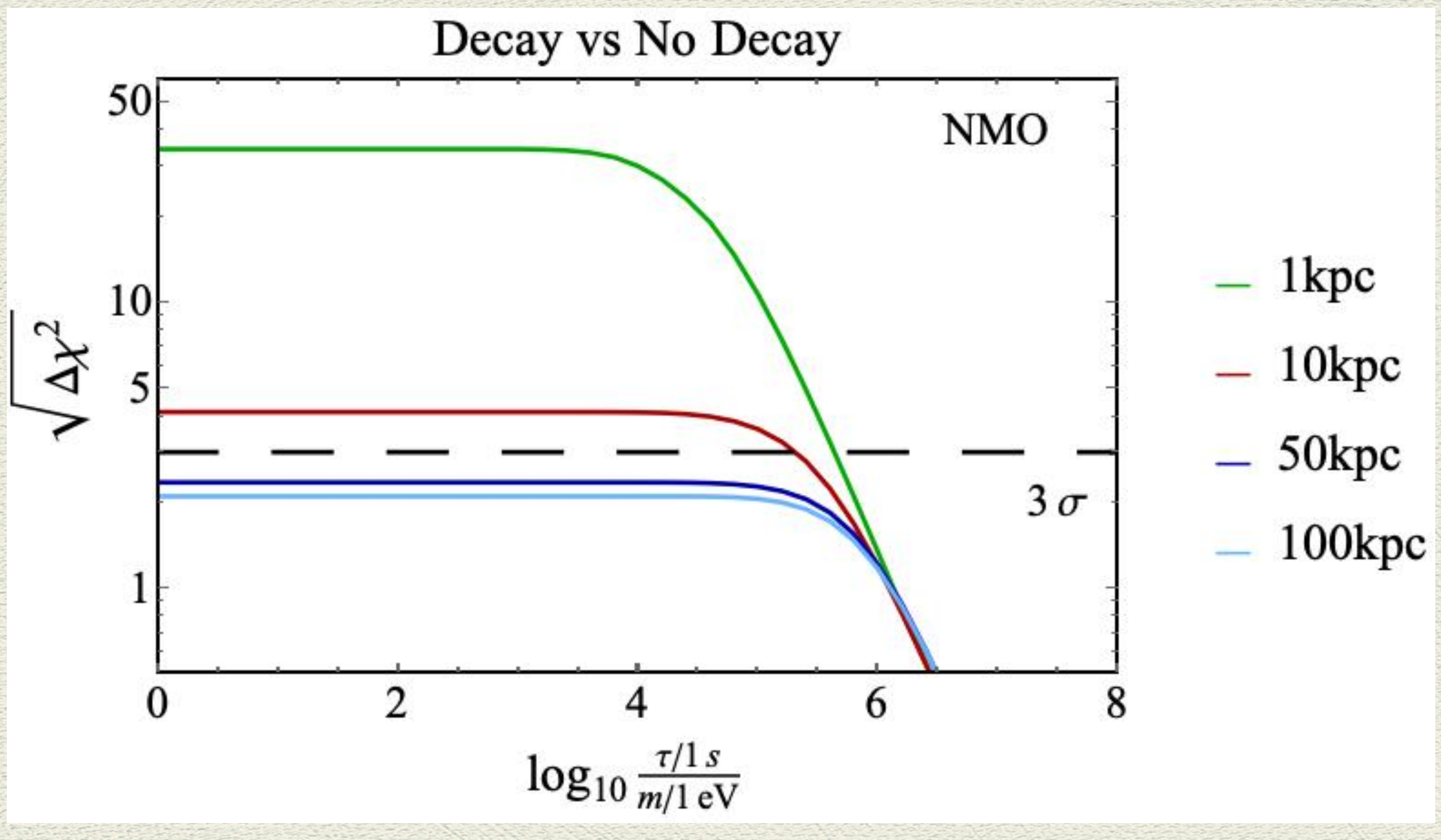
Simulate data in DUNE

Enhancement

Suppression



Bounds on neutrino life-time



solar bounds: $\tau_2/m_2 > 10^{-3}\,\mathrm{s/eV}$.
$\tau_3/m_3 > 10^{-5}\,\mathrm{s/eV}$.

Berryman, de Gouvea, Hernandez, PRD2015
Funcke, Vitagliano, Raffelt PRD2020 + …

long baseline: $\tau_3/m_3 > 10^{-10}\,\mathrm{s/eV}$.

Gonzalez-Garcia, Maltoni, PLB2008 + …

IceCube: $\tau_3/m_3 \sim 10^{2}\,\mathrm{s/eV}$

Denton, Tamborra PRL2018

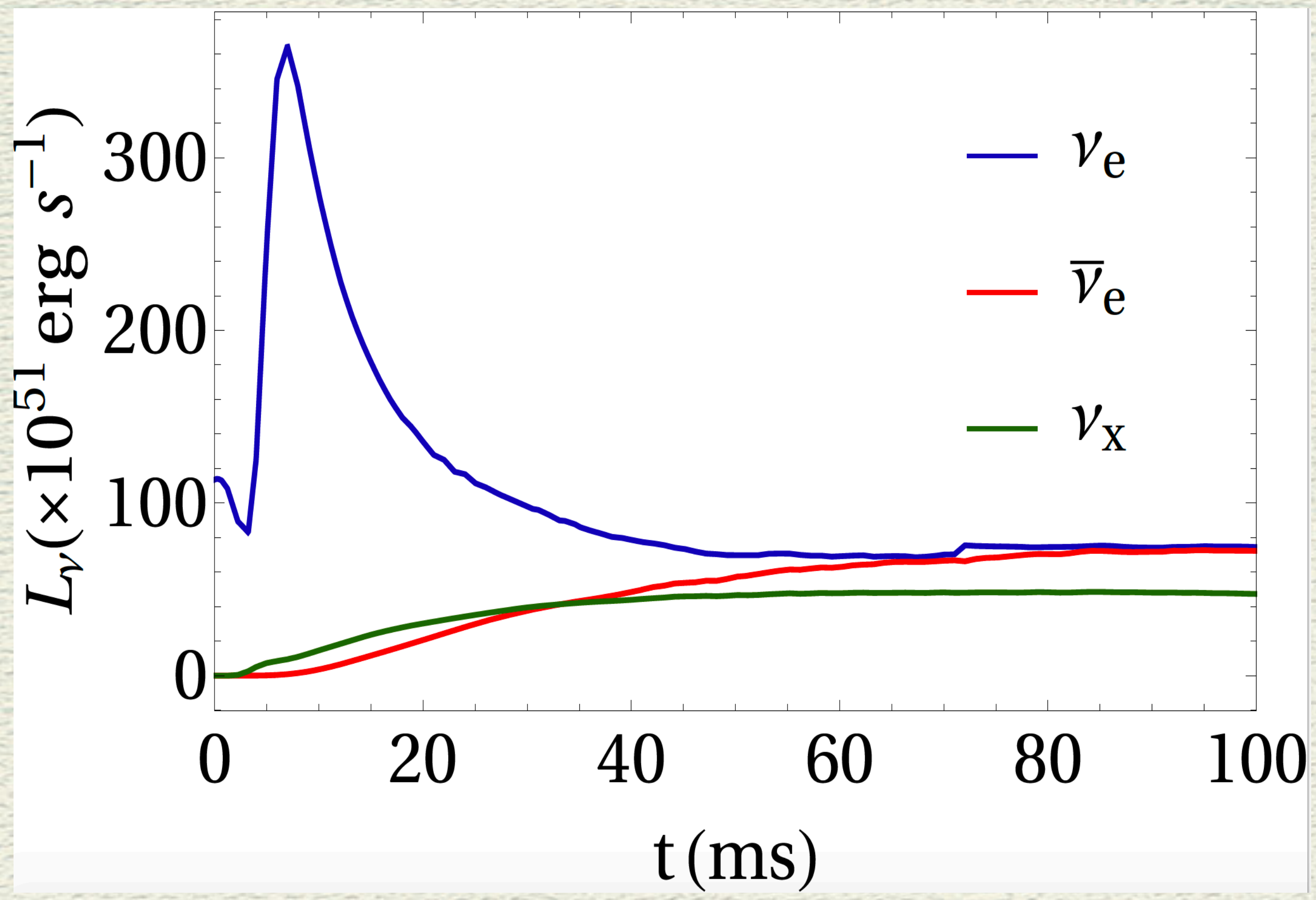
CMB: $\tau/m \sim 10^{9}\,\mathrm{s/eV}$

Escudero, Fairbairn PRD2019

$$\tau_3/m_3 \sim 10^5\,\mathrm{s/eV}\left(\frac{L}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E}\right) \Rightarrow |g| \sim 10^{-9}\left(\frac{E}{10\,\mathrm{MeV}}\right)^{1/2}\left(\frac{10\,\mathrm{kpc}}{L}\right)^{1/2}\left(\frac{0.5\,\mathrm{eV}}{m_3}\right)$$

de Gouvea, Martinez-Soler, MS, PRD2020

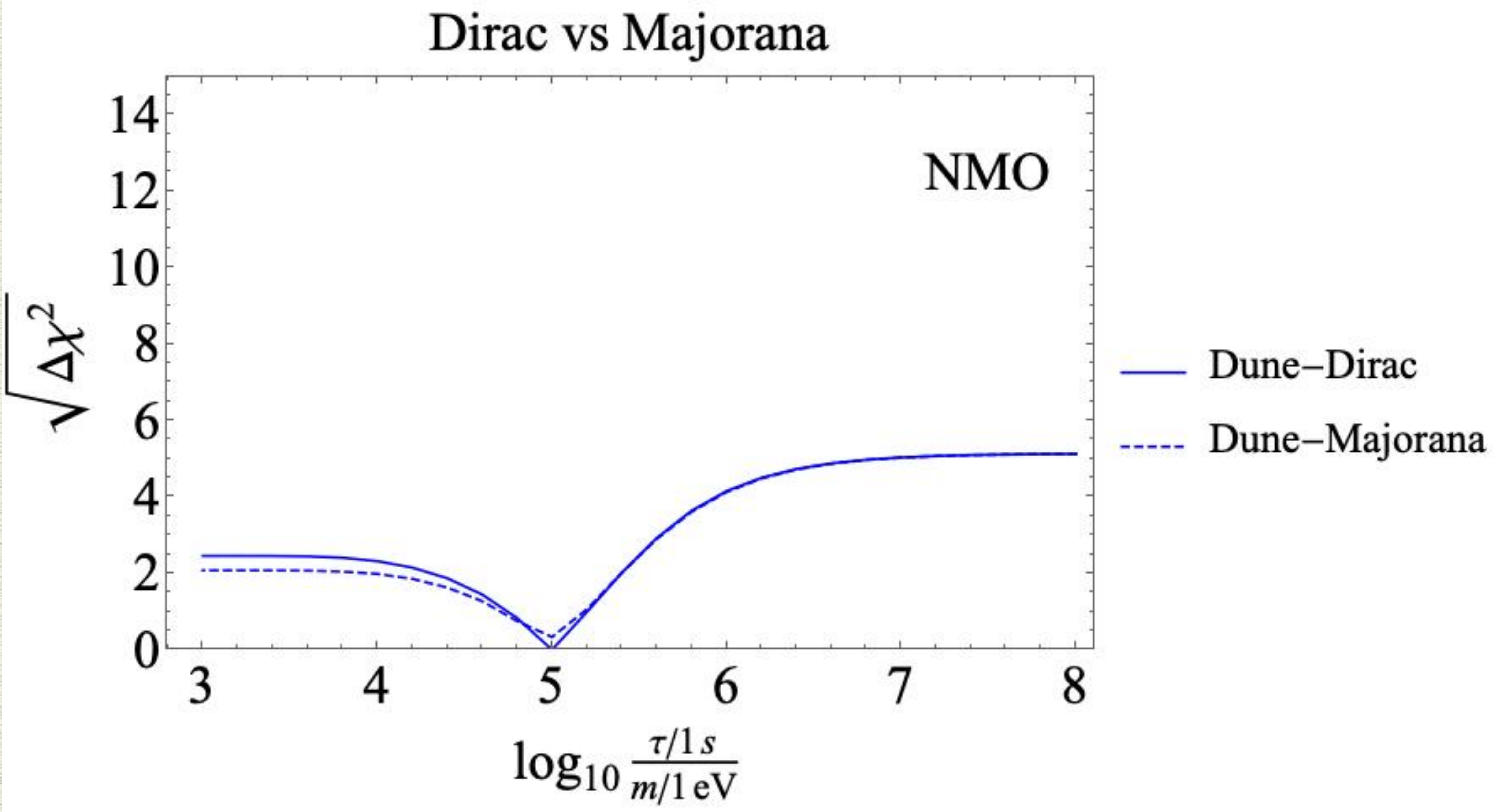
Dirac vs Majorana



Dirac neutrinos	Majorana neutrinos
$\nu_{3L} \to \nu_{1L} + \varphi$	$\nu_{3L} \to \nu_{1L} + \varphi$
$\nu_{3L} \to \nu_{1R}\,(\nu_s) + \varphi$	$\nu_{3L} \to \nu_{1R}\,(\bar{\nu}_{1R}) + \varphi$

- The h.f. channel becomes important.
- DUNE only sensitive to ν_e , so it does not detect the daughter produced from h.f. channel for both Dirac and Majorana.
- HK can detect the daughter $\bar{\nu}_e$ from the h.f channel if neutrinos are Majorana.

Dirac(D) vs Majorana(M): DUNE

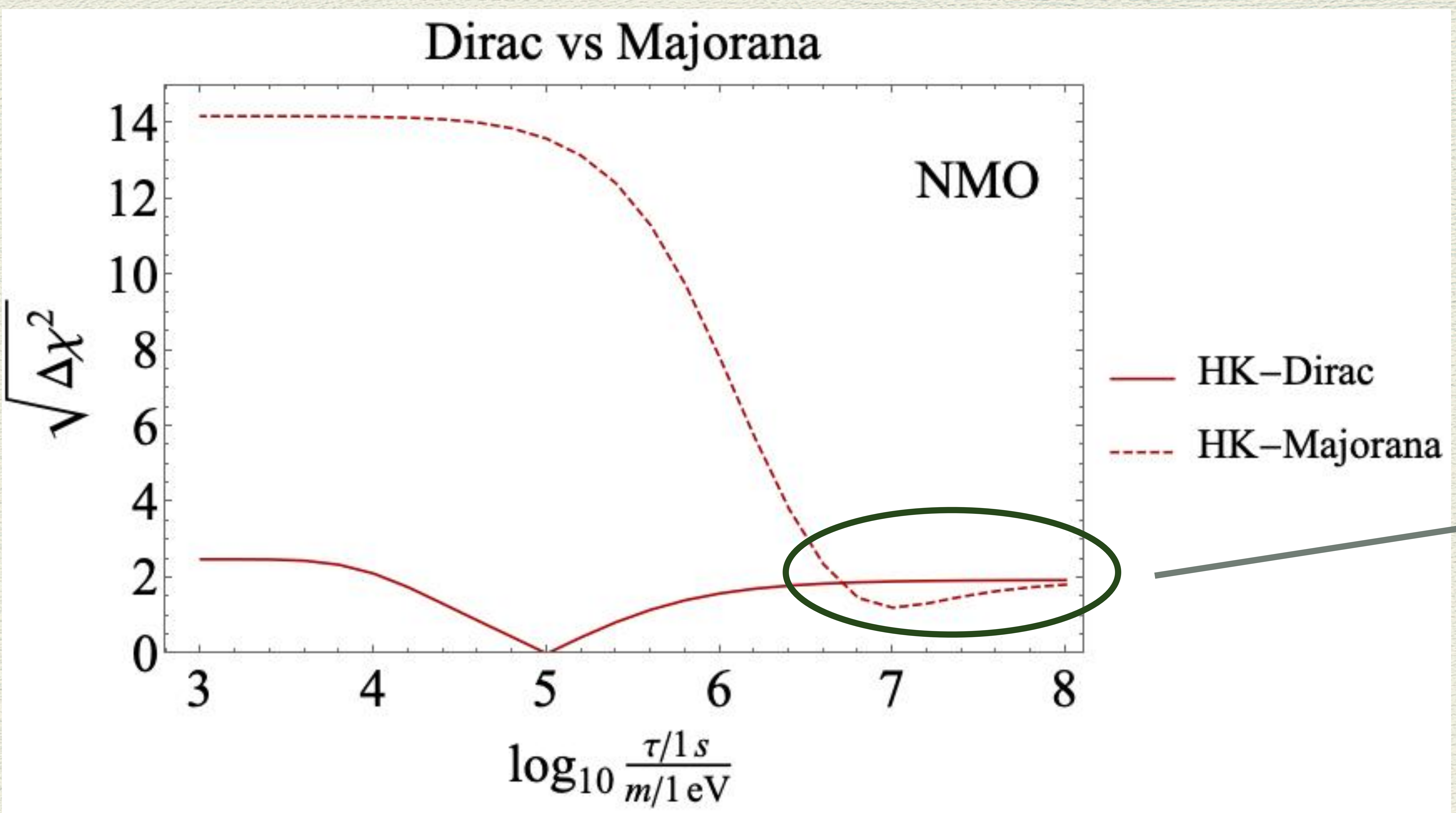


DUNE sensitive to ν_e, hence it cannot distinguish between Dirac and Majorana

Test hypothesis: νs are Dirac, $\tau/m = 10^5$ s/eV

de Gouvea, Martinez-Soler, MS, PRD2020

Dirac (D) vs Majorana (M): Hyper-Kamiokande



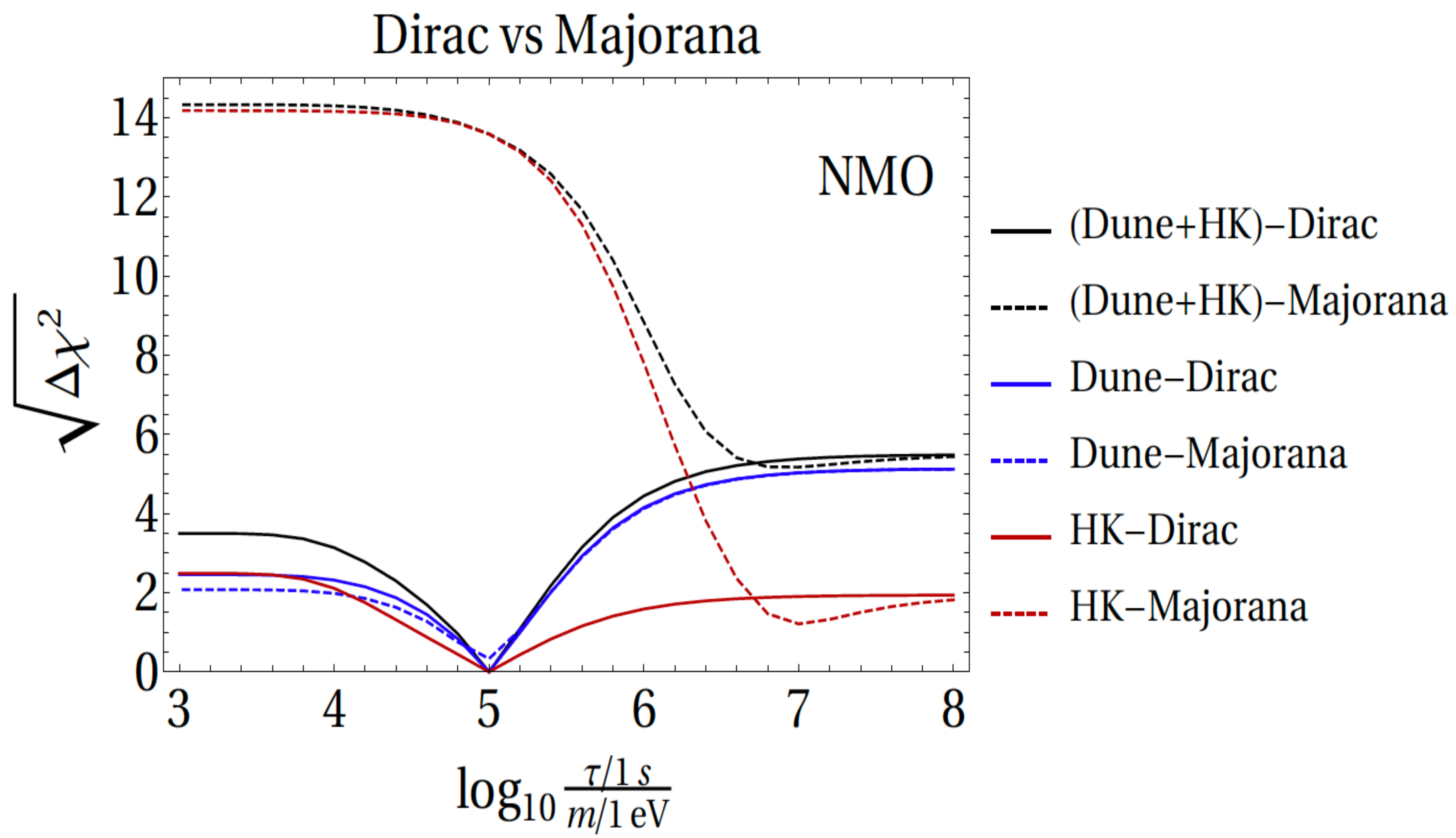
HK fails to distinguish a long-lived Majorana from a decaying Dirac.

Since ν_e is the dominant flux, this lifetime leads to a comparable flux of $\bar{\nu}_e$ from decay.

Test hypothesis: $\bar{\nu}$s are Dirac, $\tau/m = 10^5$ s/eV

de Gouvea, Martinez-Soler, MS, PRD2020

Dirac (D) vs Majorana (M) : DUNE+ Hyper-K



Test hypothesis: νs are Dirac, $\tau/m \sim 10^5$s/eV

A combination of DUNE and HK can always distinguish between a decaying Dirac and a decaying Majorana neutrino.

de Gouvea, Martinez-Soler, MS, PRD2020

Conclusion

- Core-collapse SNe are one of the very few places where $\nu - \nu$ interactions are relevant. Need better understanding of neutrino flavor propagation in dense media to appreciate its effect.

- Can be used to put some of the best bounds on $\nu - \nu$ non-standard interactions. Non-linear effects amplify tiny effects.

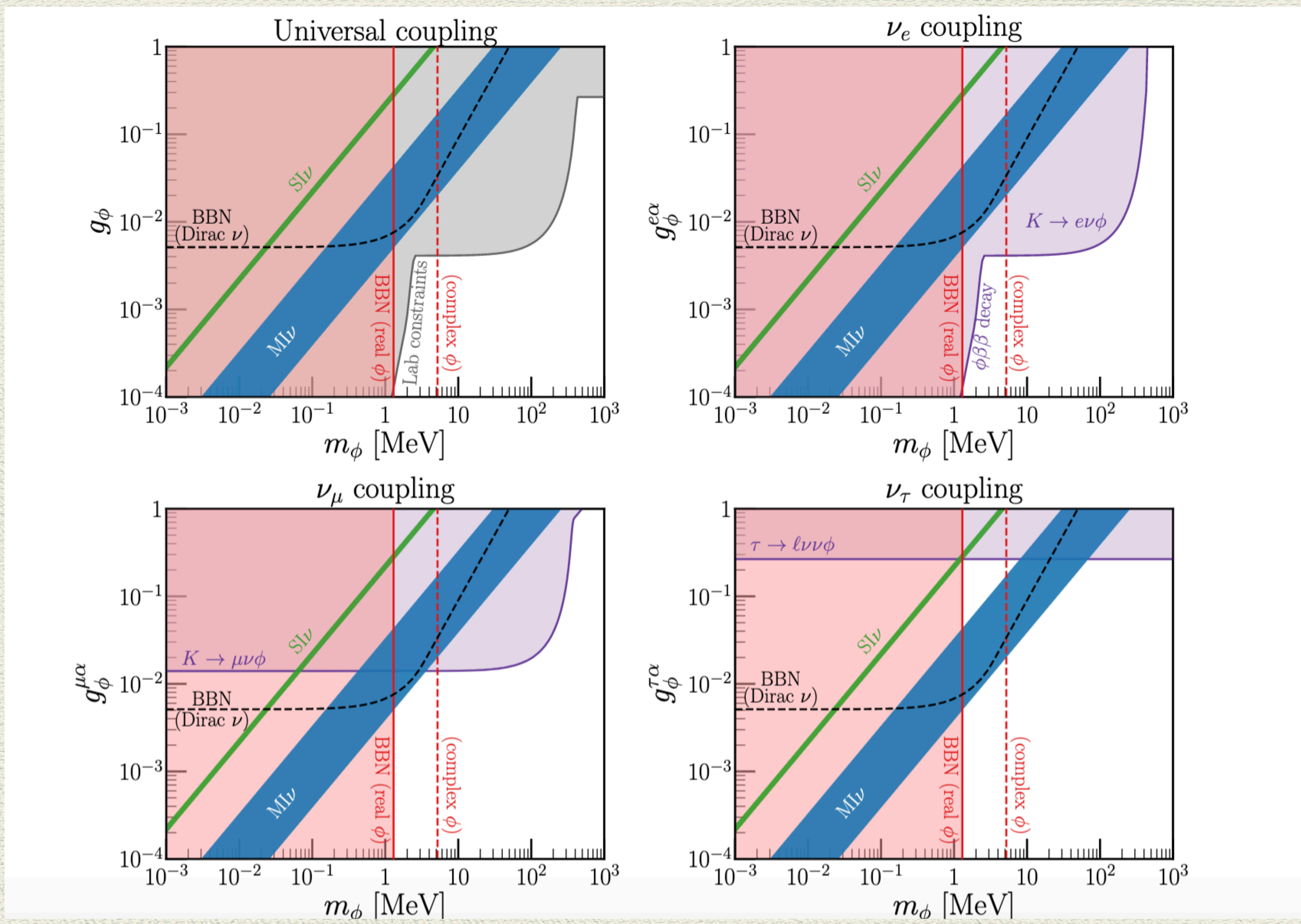
- Naturally long baseline provided can be used to constrain non-standard neutrino decays, and determine the Dirac-Majorana nature.

- Probes of other BSM physics.

Thank you!

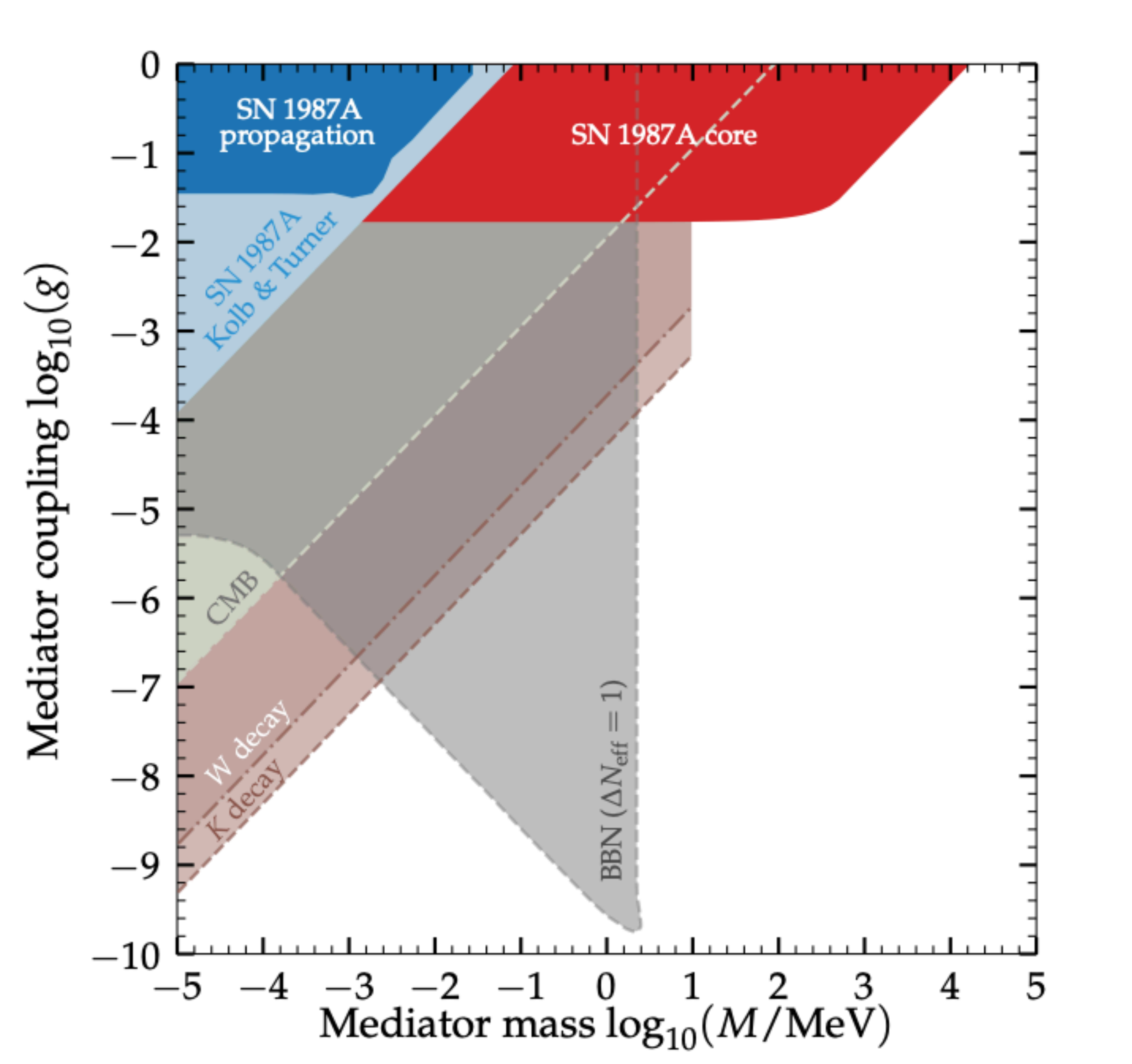
Backup

Bounds on neutrino self-interactions



Blinov, Kelly, Krnjaic, McDermott, PRL 2019

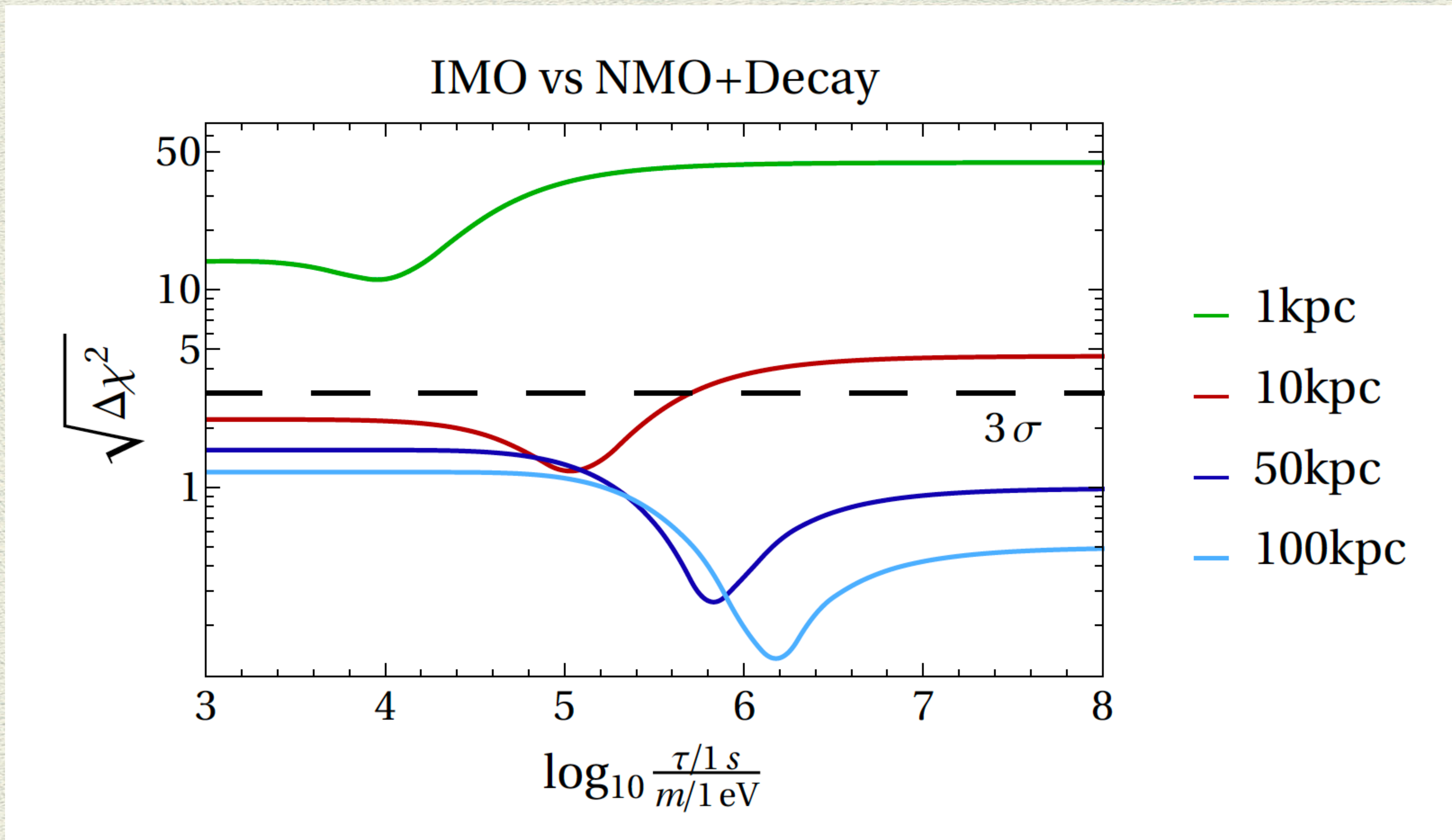
SN bounds on neutrino self-interactions



- 2->4 processes increase neutrino number density, but reduces energy in half. Might be difficult to re-energise shockwave.
- Downscatter in energy with the CnuB.

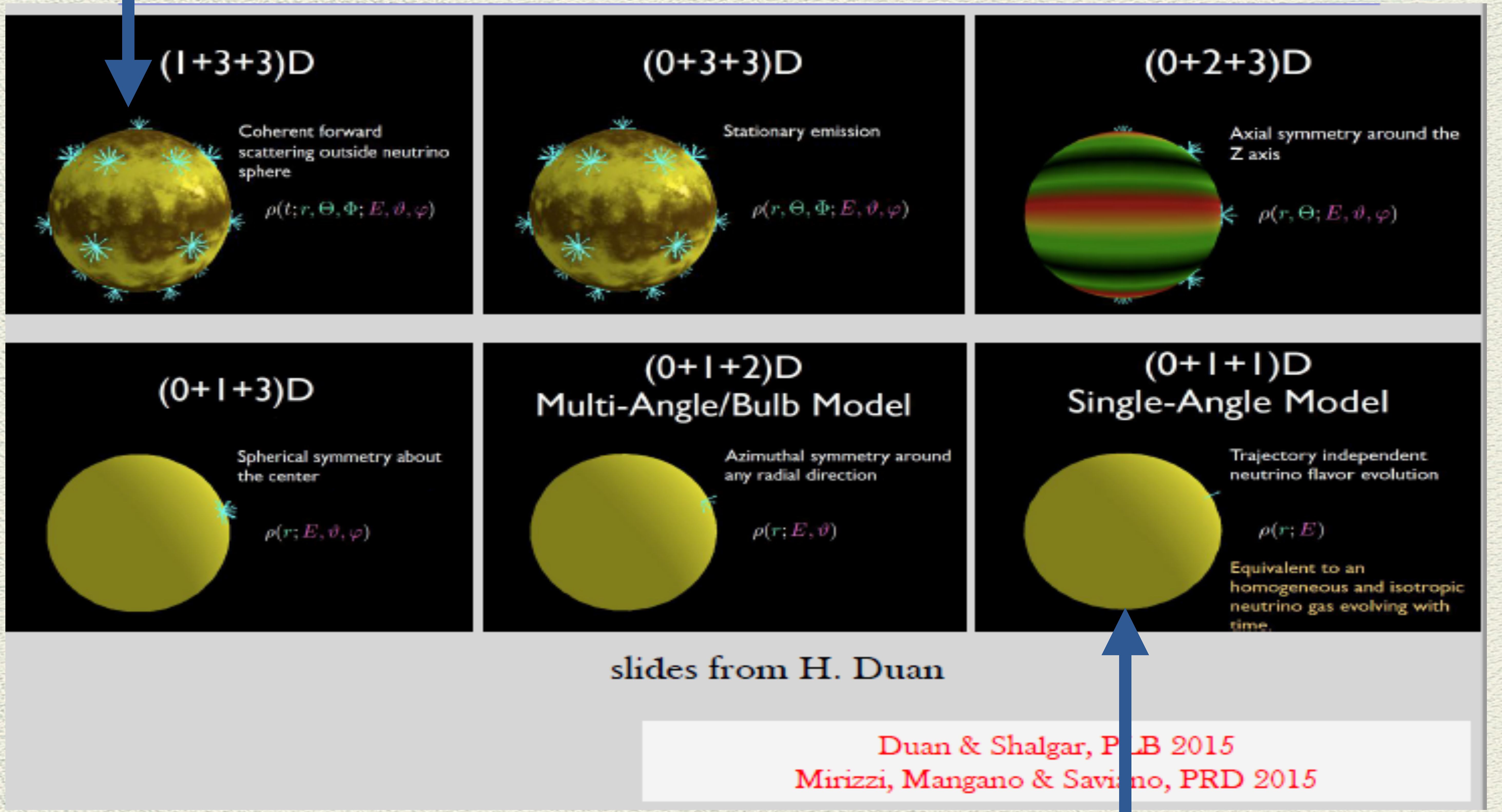
Bustamante, Shalgar, Tamborra, 1912.09115

Neutrino Decay: Mass ordering confusion



The pathway

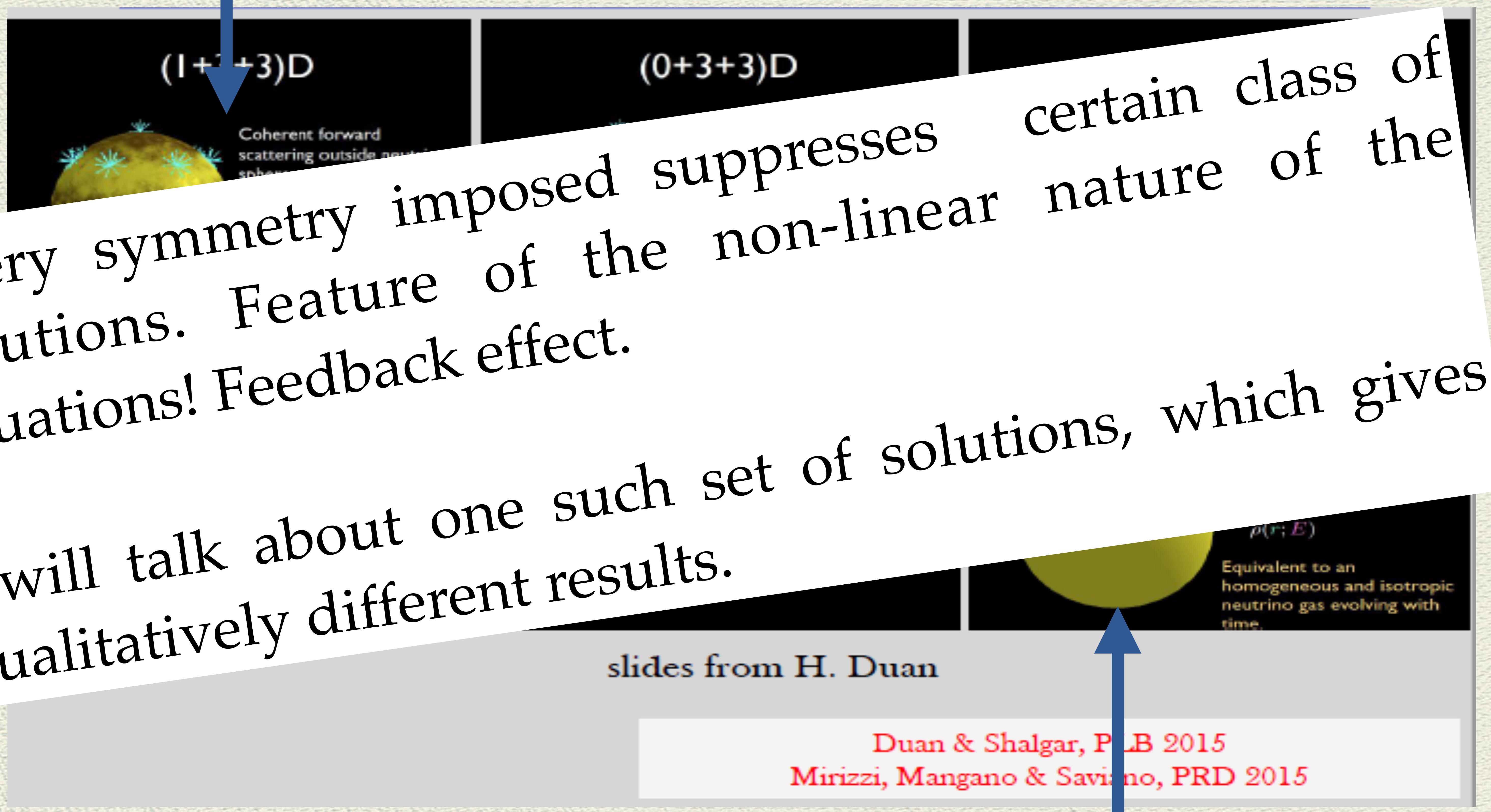
Can do this for few modes



Started here

The pathway

Can do this for few modes

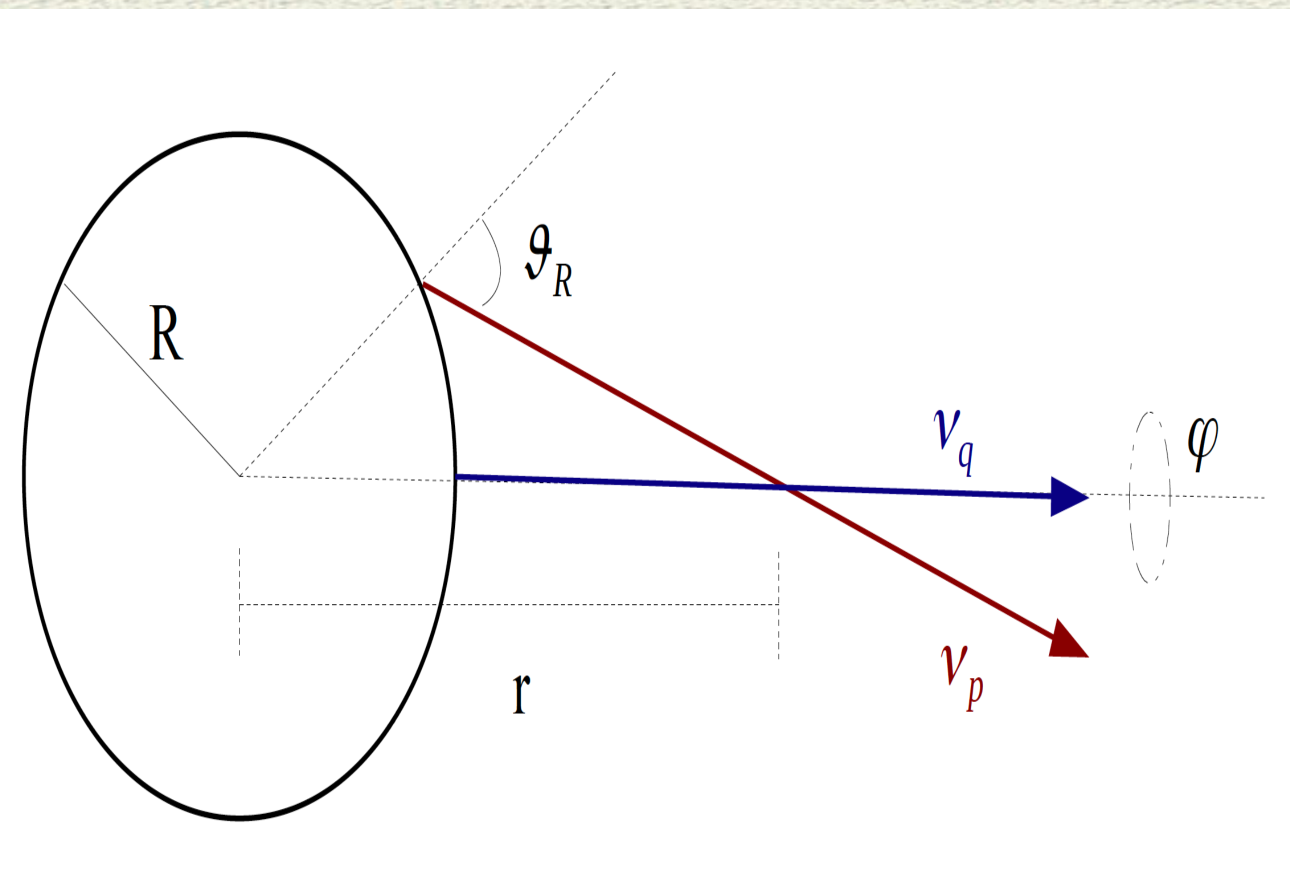


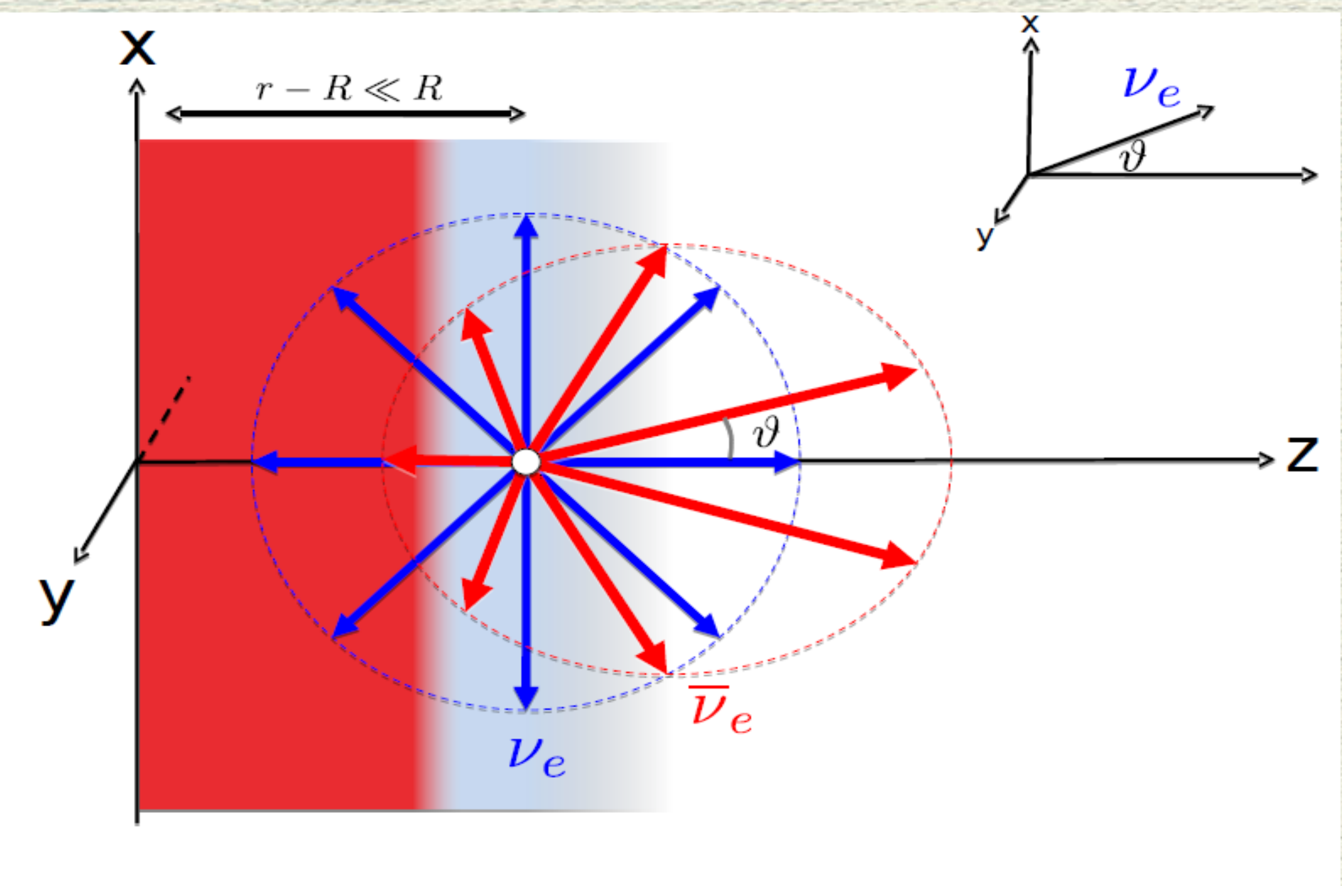
Every symmetry imposed suppresses certain class of solutions. Feature of the non-linear nature of the equations! Feedback effect.

I will talk about one such set of solutions, which gives qualitatively different results.

Started here

Fast flavor oscillations



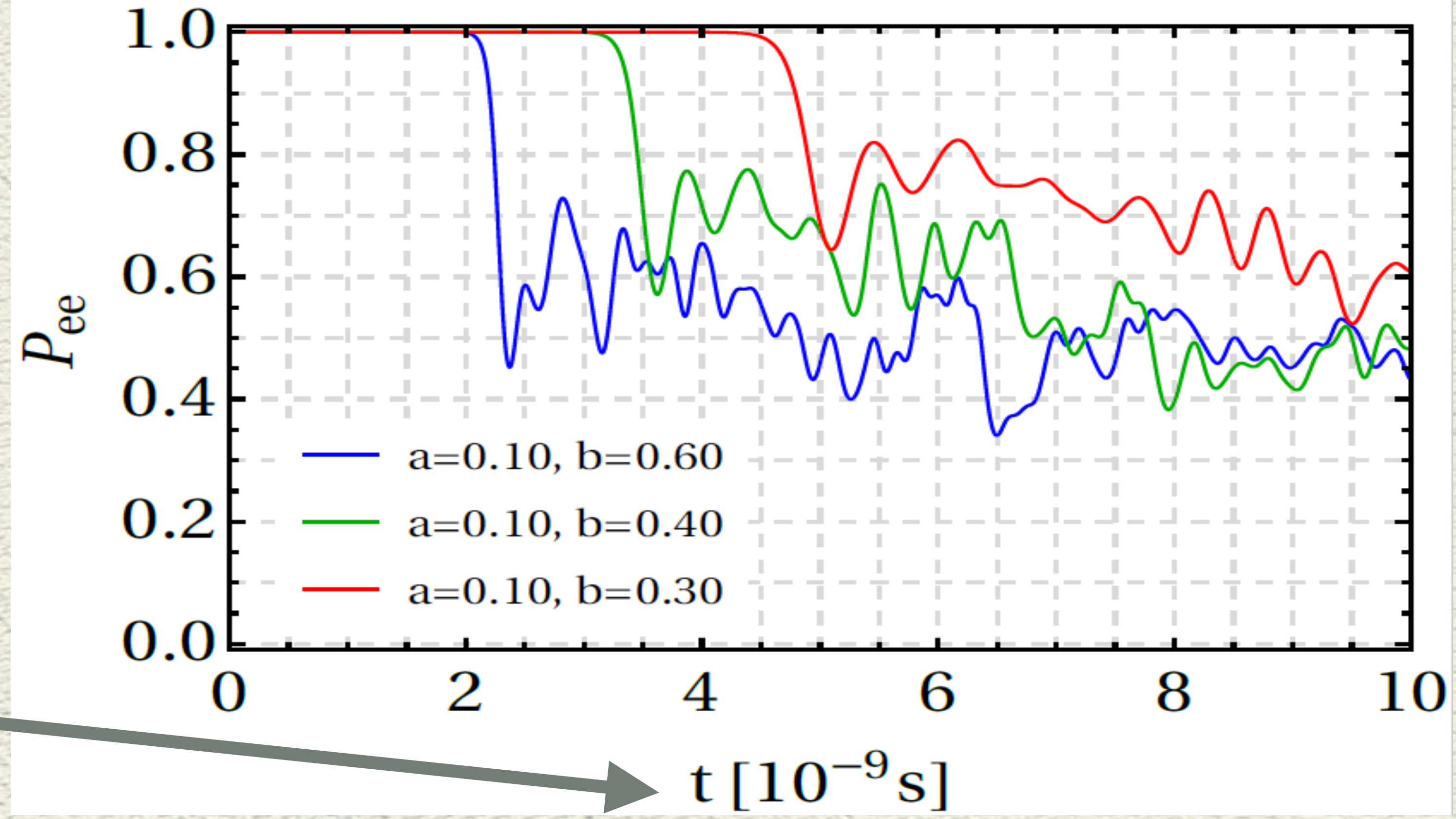


Discard the concept of a distinct neutrino-sphere

Flavor dependent free-streaming. Leads to different angular distributions.

Rapid flavor conversions, rate $\propto n_\nu$

Timescales~ nanoseconds, hence fast conversions!



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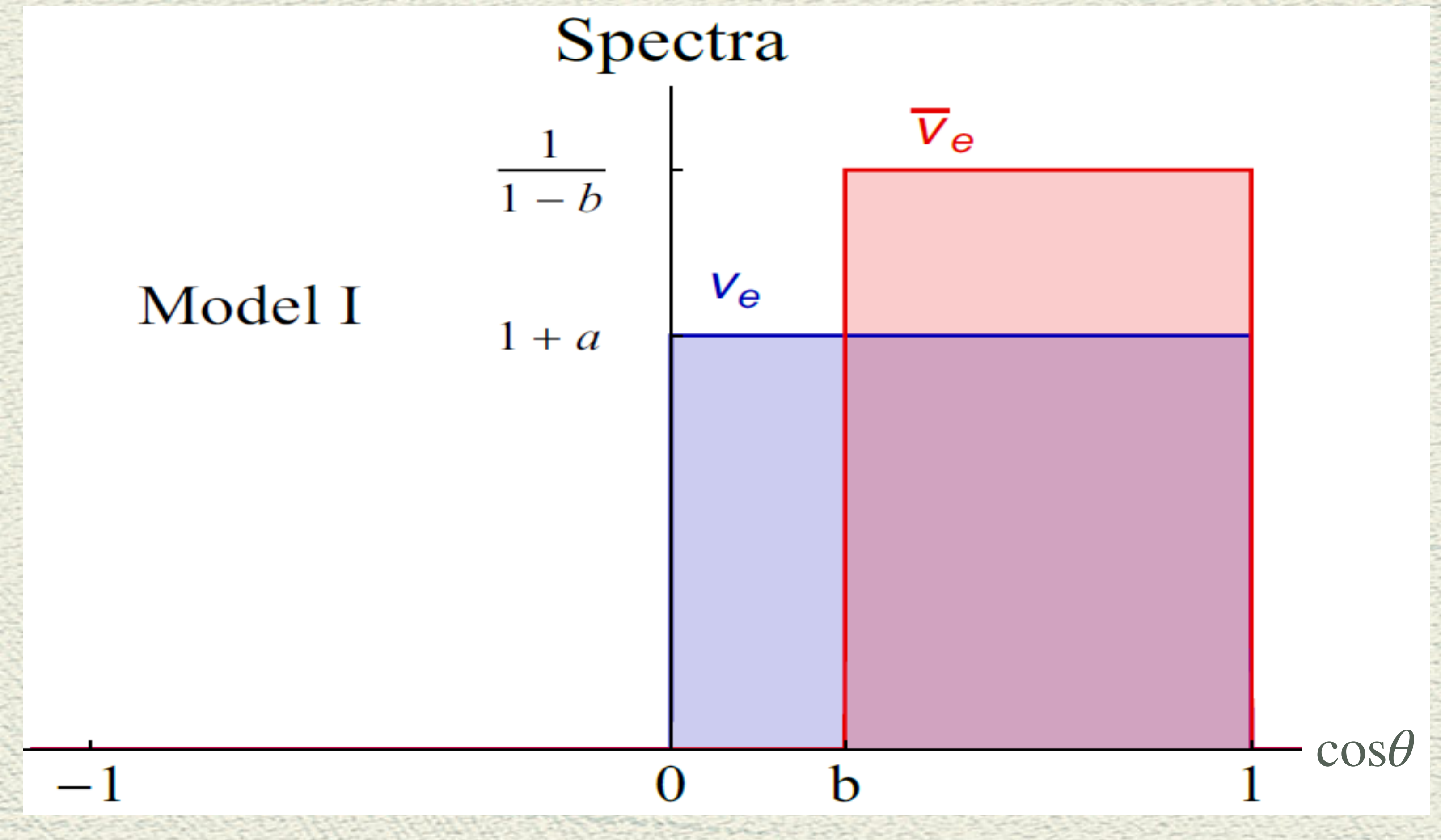
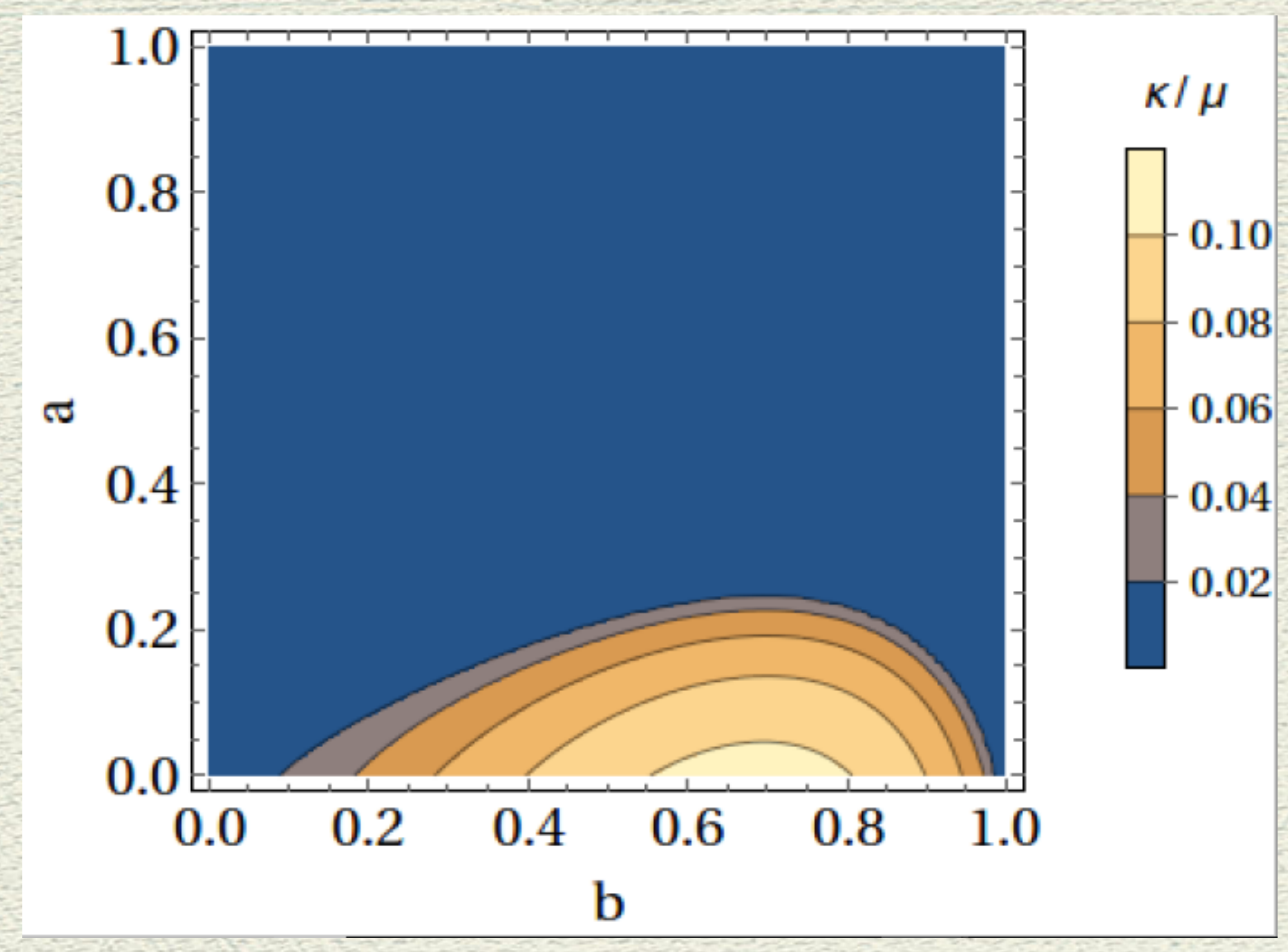
Analytical probes

Toy spectra





b = asymmetry in angular emission

$a = n_\nu - \bar{n}_\nu$

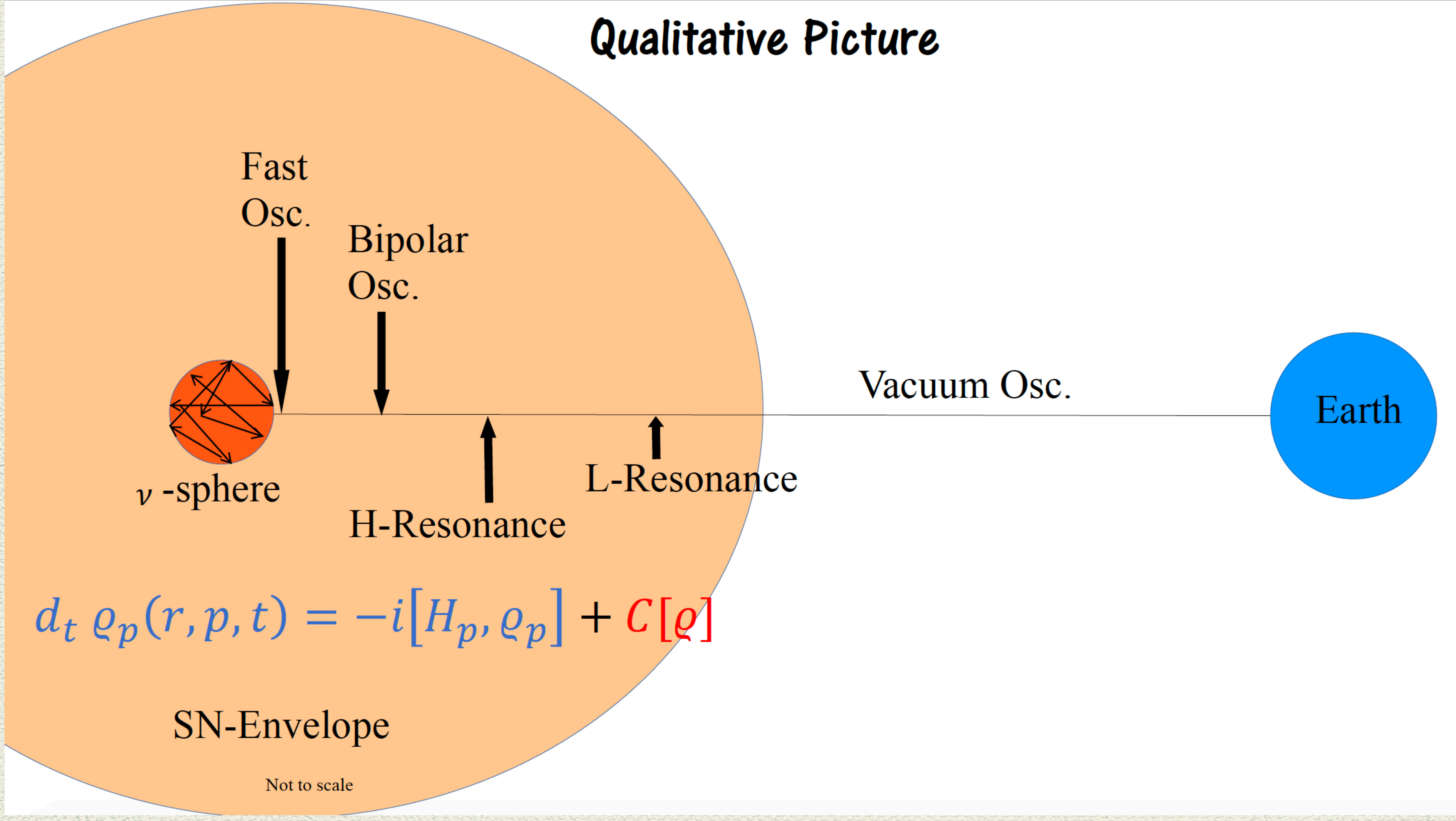
Simple criteria: $b \neq 0$, $a > 0$

1. FFC require a crossing in $h(\theta) = h_{\nu_e}(\theta) - h_{\bar{\nu}_e}(\theta)$.

2. This automatically demands $n_{\bar{\nu}} > n_\nu$ in certain directions of the SN

Dasgupta, Mirizzi and MS (JCAP 2017)

Qualitative Picture



$$d_t\, \varrho_p(r,p,t) = -i\left[H_p, \varrho_p\right] + C[\varrho]$$