Probing Neutrino Decays with SN Neutrinos

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(N3AS)

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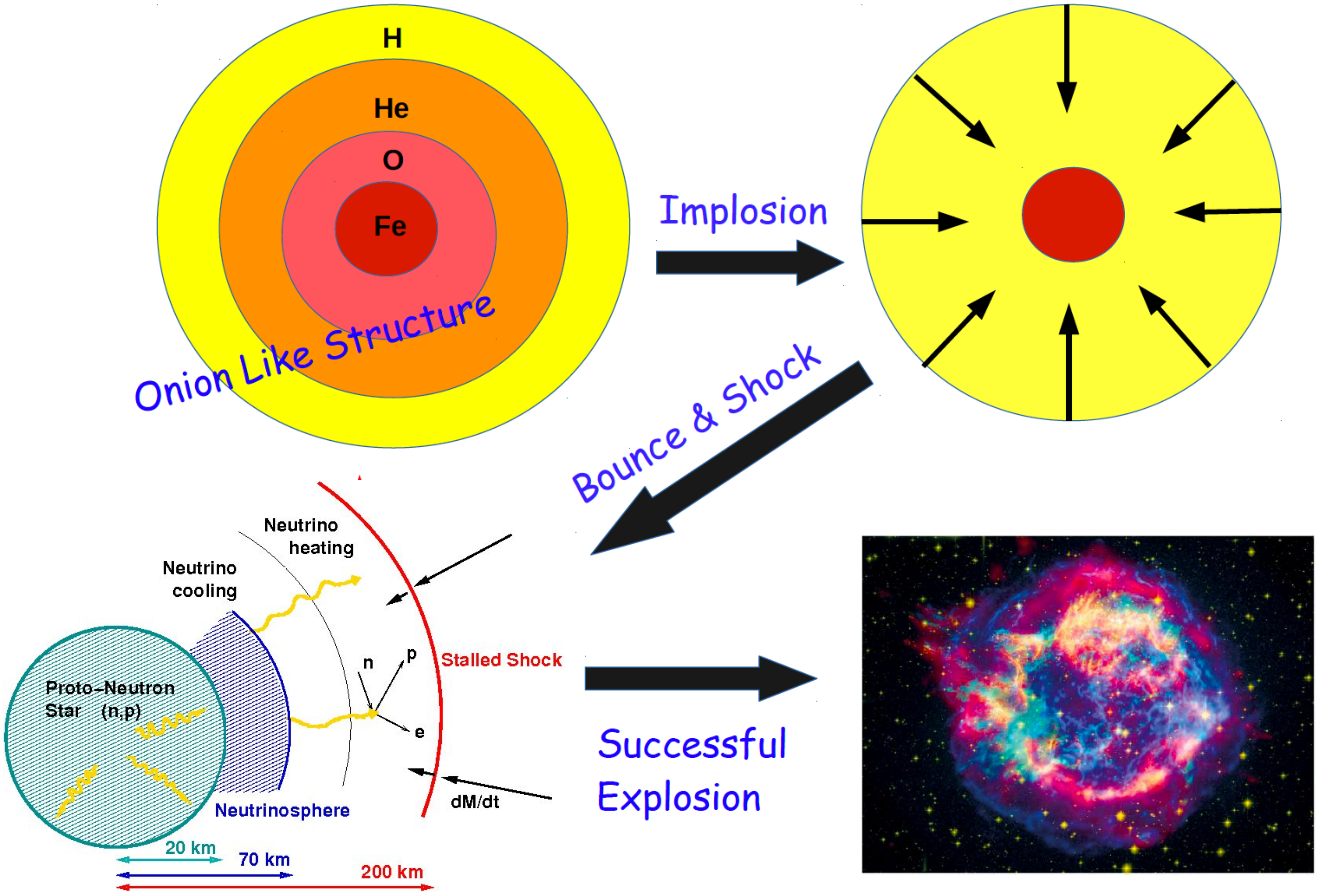
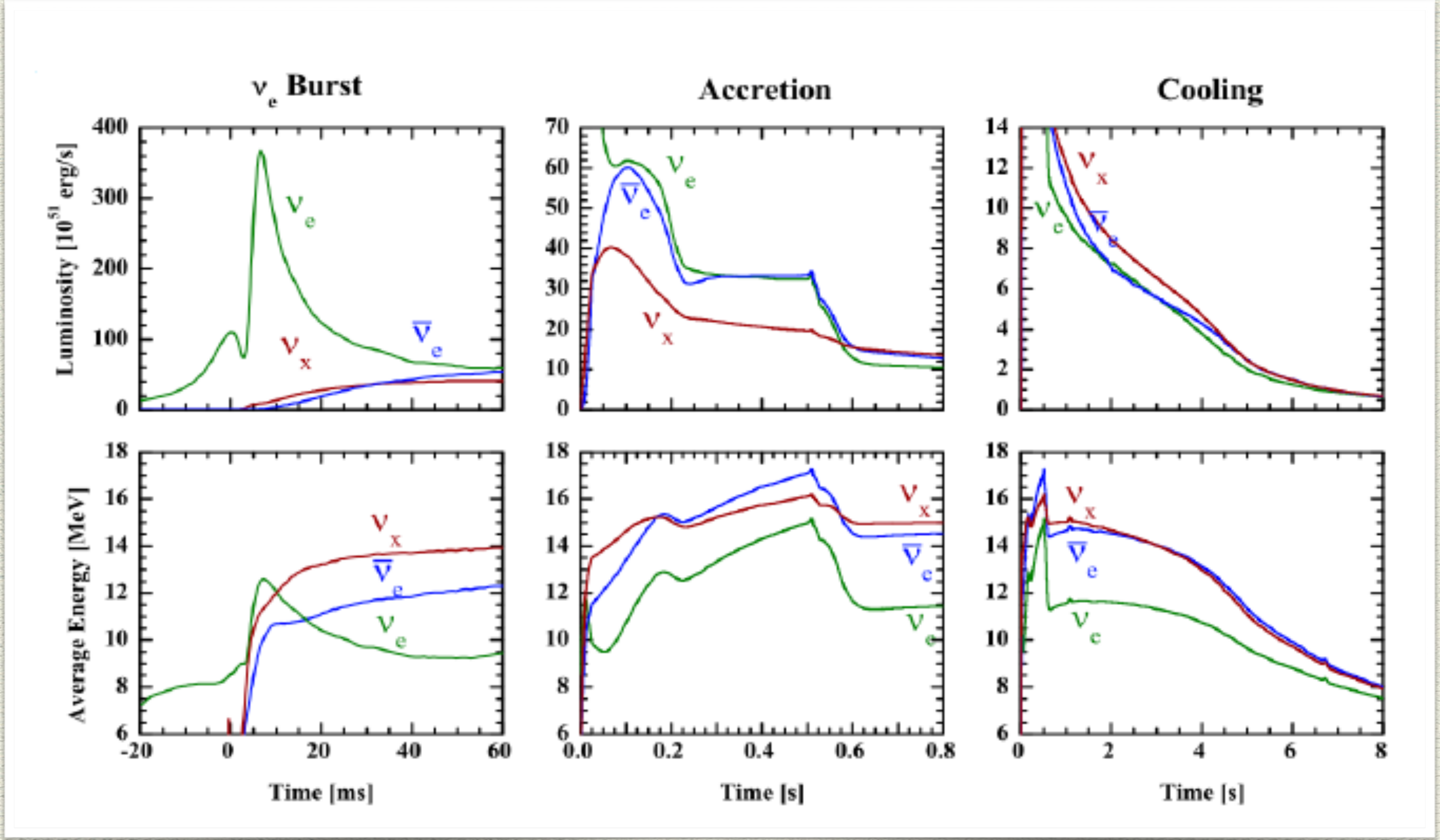
CCSN Odyssey



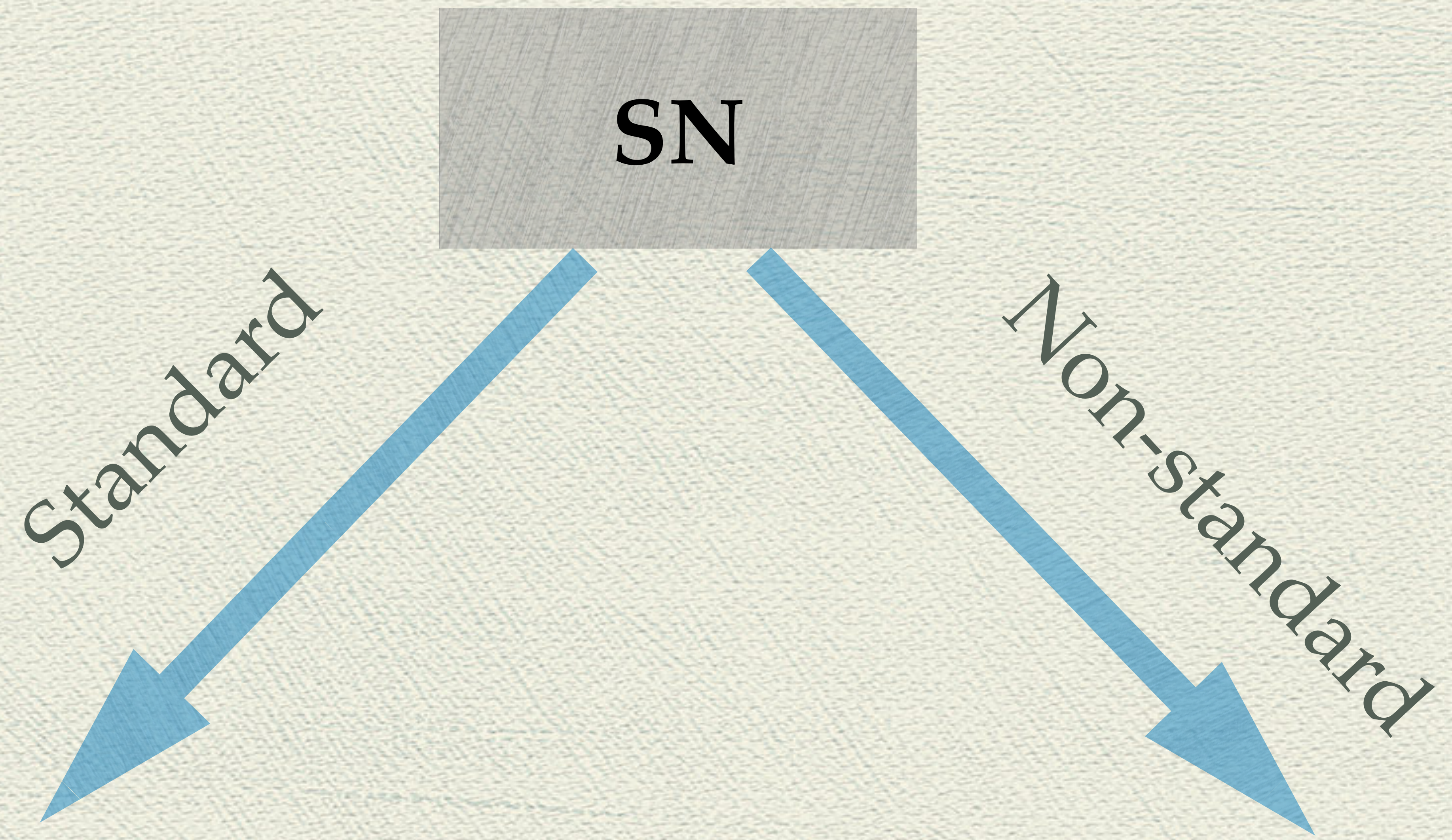
Phases of neutrino emission

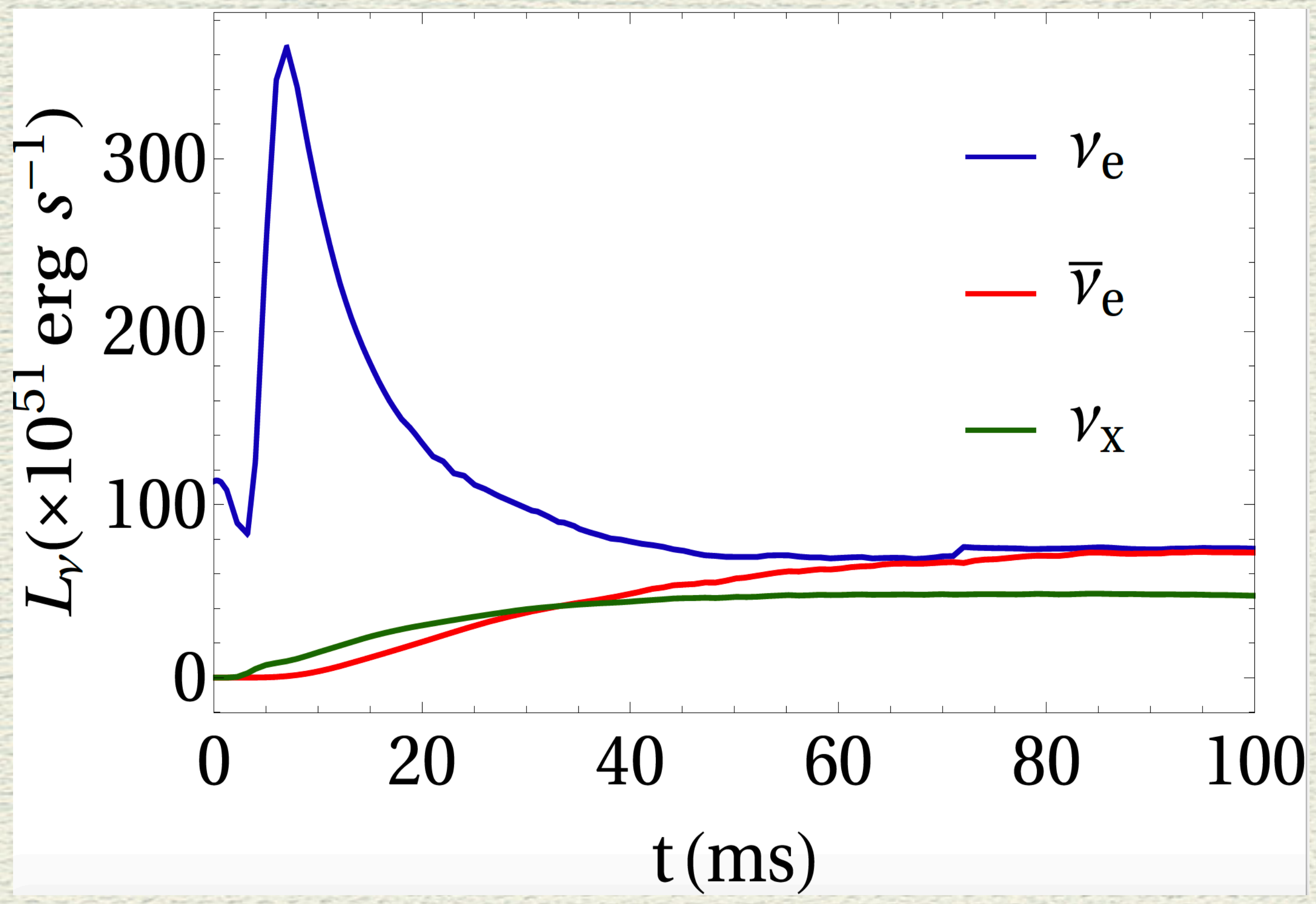


- $\sim 10^{58}$ neutrinos emitted.
- 99% energy of the star carried away.

1D simulation of a 27 solar mass star by the Garching group

What sort of a laboratory is the SN?

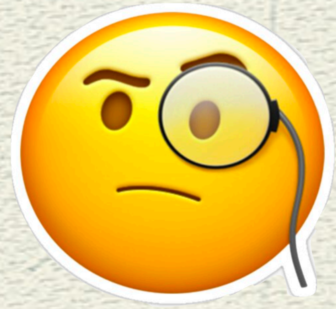




- νs probe stellar interiors.
- Relevant information about supernova dynamics, shockwave propagation, turbulence.
- Physics of dense neutrino streams. Can lead to “collective oscillations”!

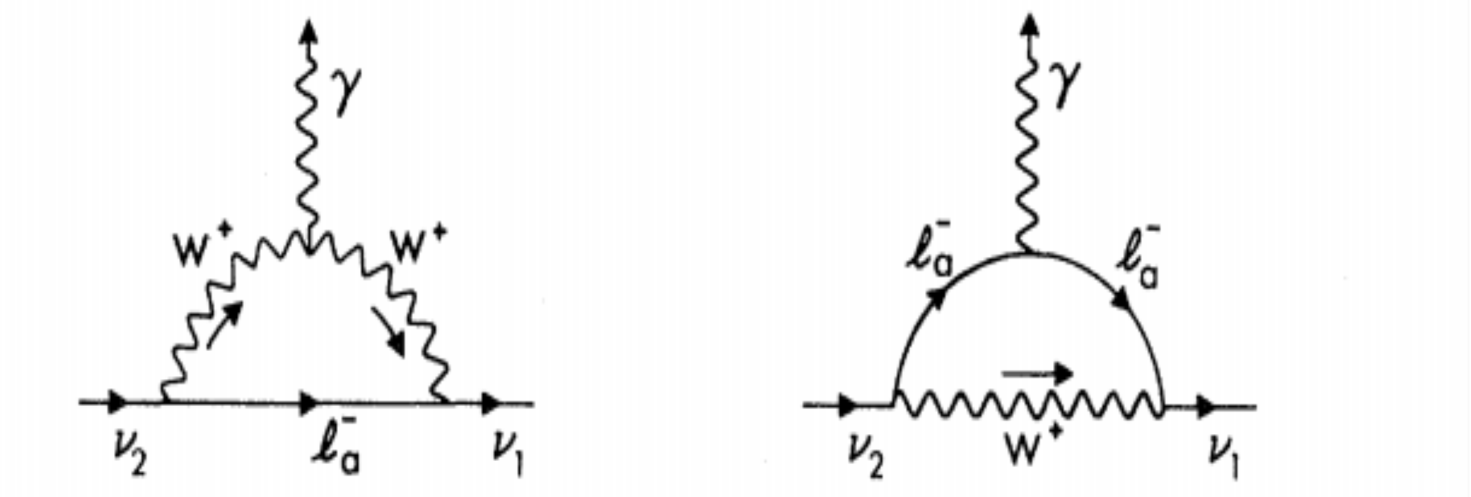
- Non-standard neutrino properties: decay, self-interactions, magnetic moment, Dirac-Majorana nature, etc.
- New particles.
- Any crazy stuff that theorists can think about.

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



2. Neutrino-decay

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



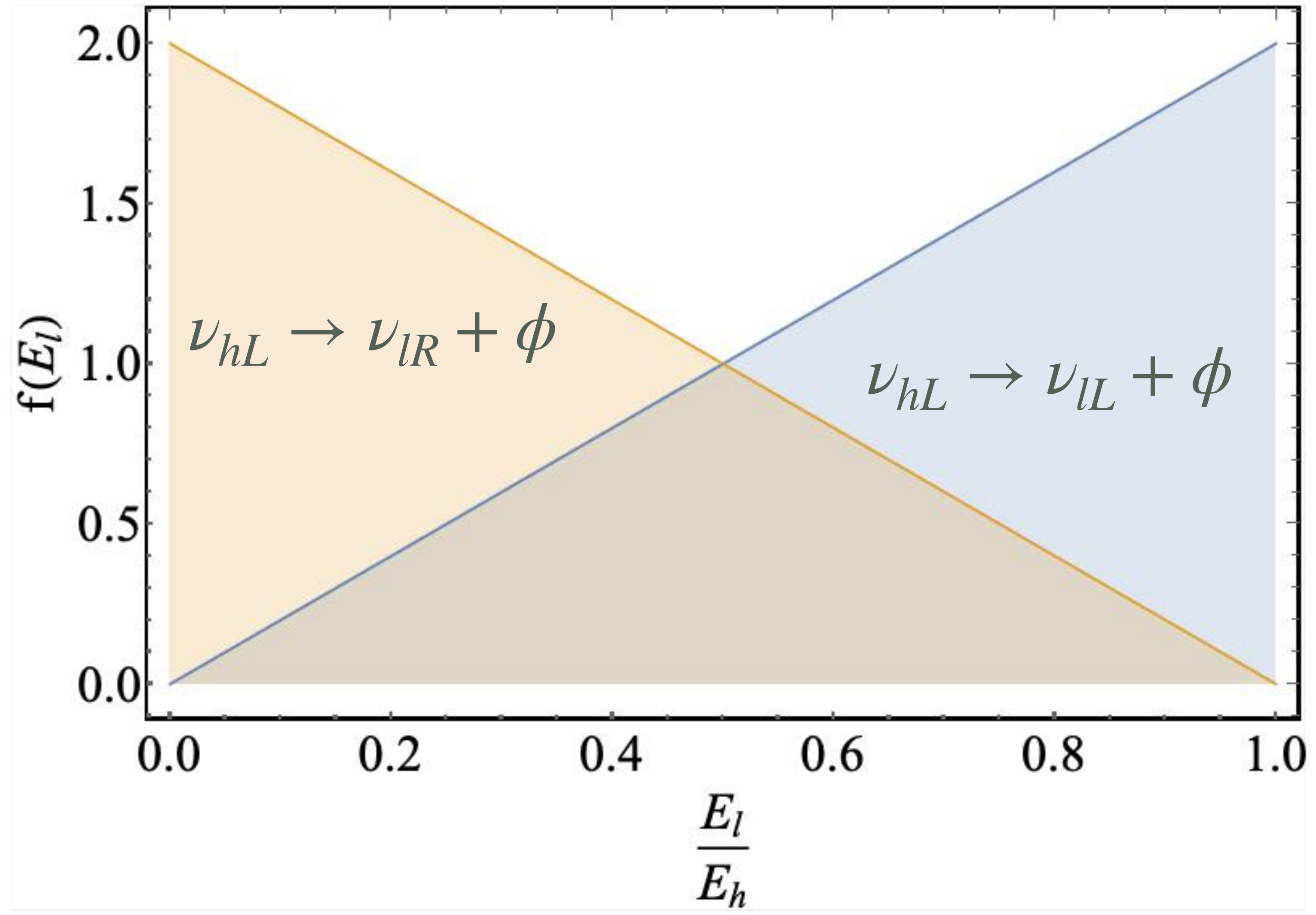
Pal and Wolfenstein (PRD1982)

- New physics can mediate faster decay.

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

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

Dirac vs Majorana

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

$\nu_{hL} \to \nu_{lL} + \varphi$

$\nu_{hL} \to \nu_{lR} + \varphi$

acts as an "inert" neutrino and cannot be observed.

$$\mathscr{L}_{\rm Maj} \supset \bar{\nu_l^c} \nu_h \phi + \mathrm{H.c.}$$

$\nu_{hL} \to \nu_{lL} + \varphi$

$\nu_{hL} \to \nu_{lR} + \varphi$

acts as the "antineutrino" - produces an e^+ on interaction—observable

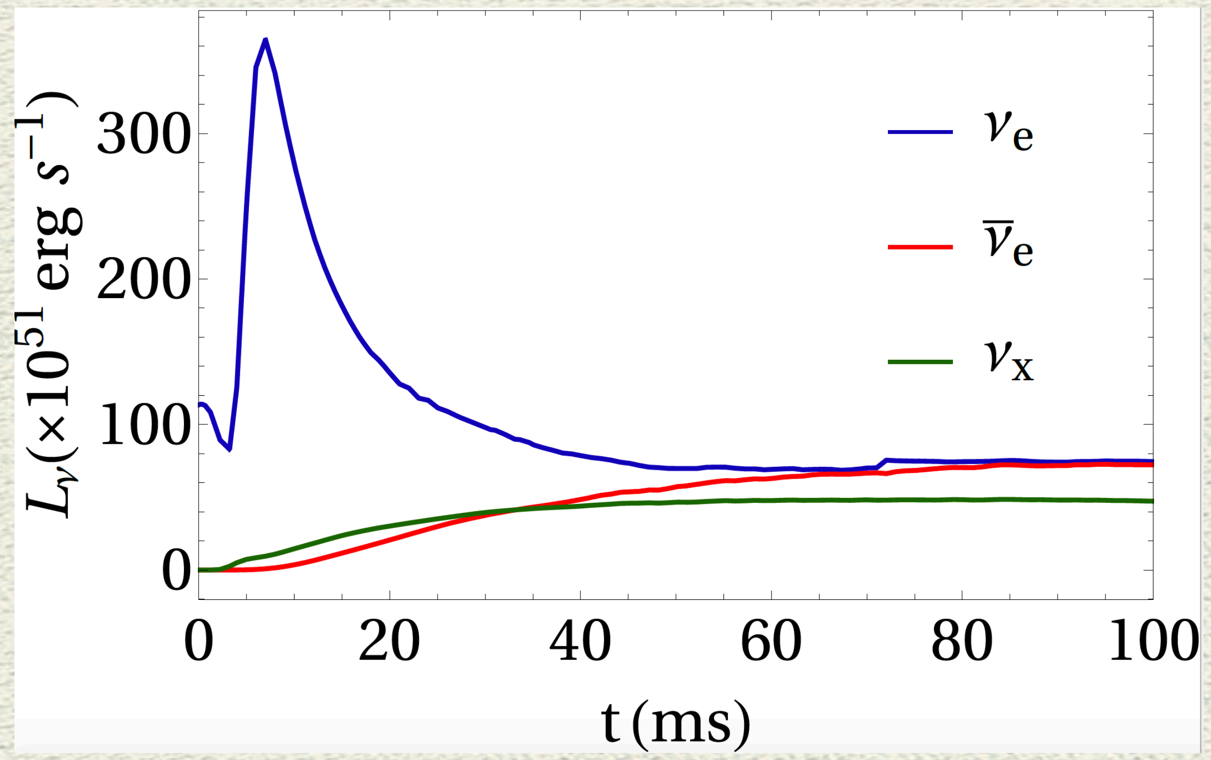
Use the ν-burst flux to

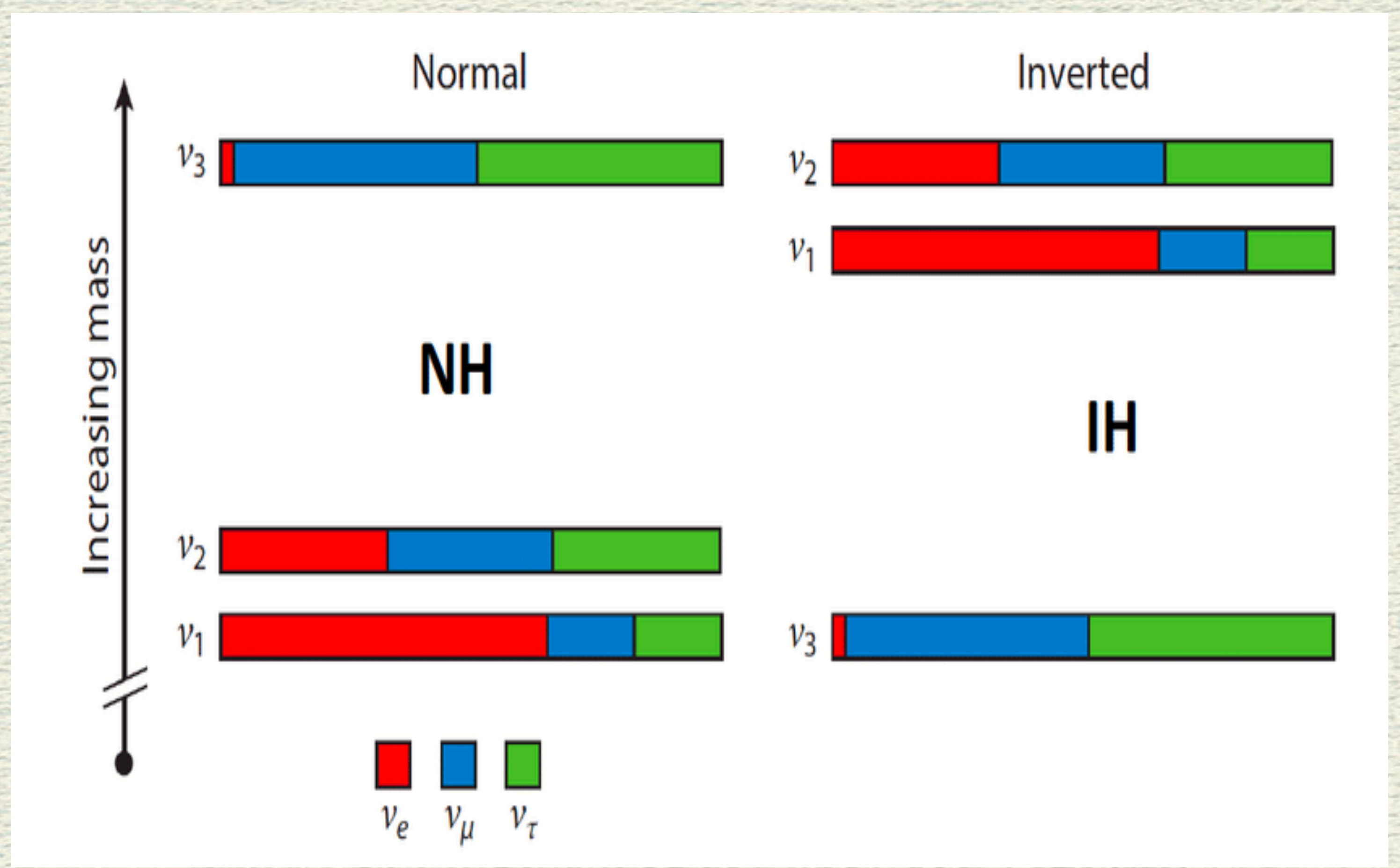
(i) Put some of the tightest bound on this decay.

(ii) Check if finite lifetime can hinder mass-ordering identification

(iii) Distinguish between Dirac and Majorana nature.

How to play this game?





Normal Ordering

NO DECAY

$\nu_h \equiv \nu_3$

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

DECAY

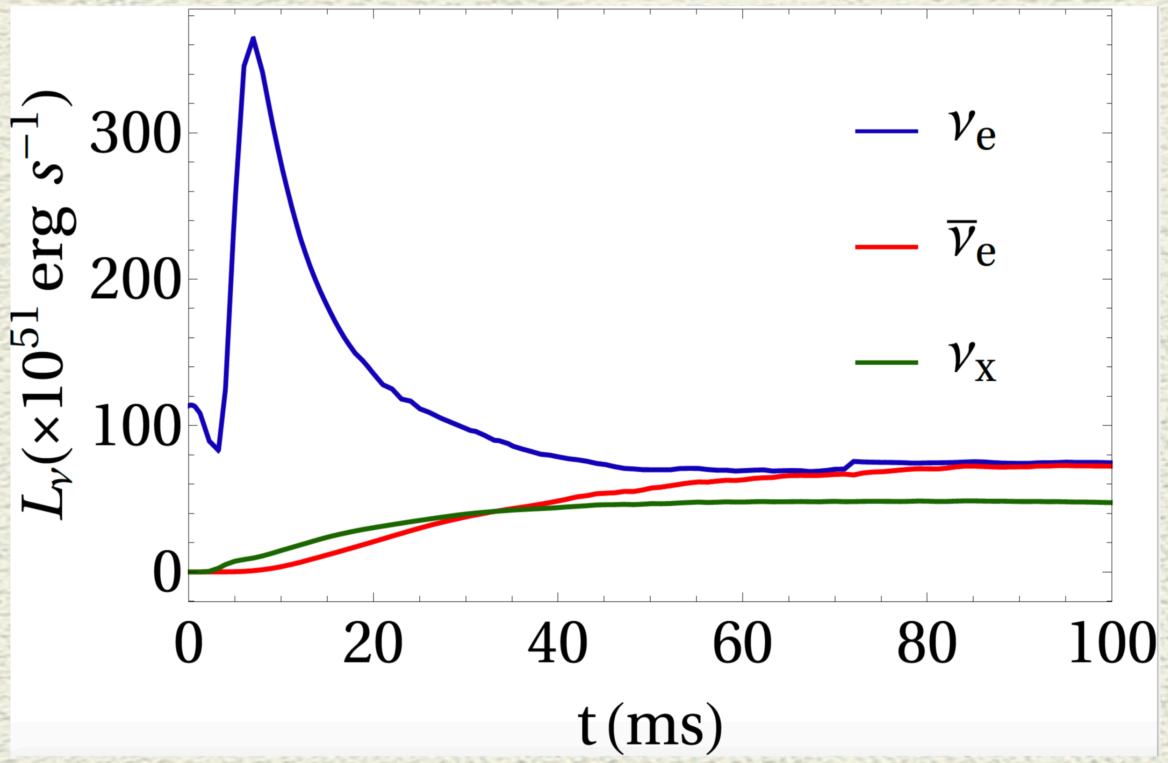
$\nu_h \equiv \nu_3$

$\nu_l \equiv \nu_1$

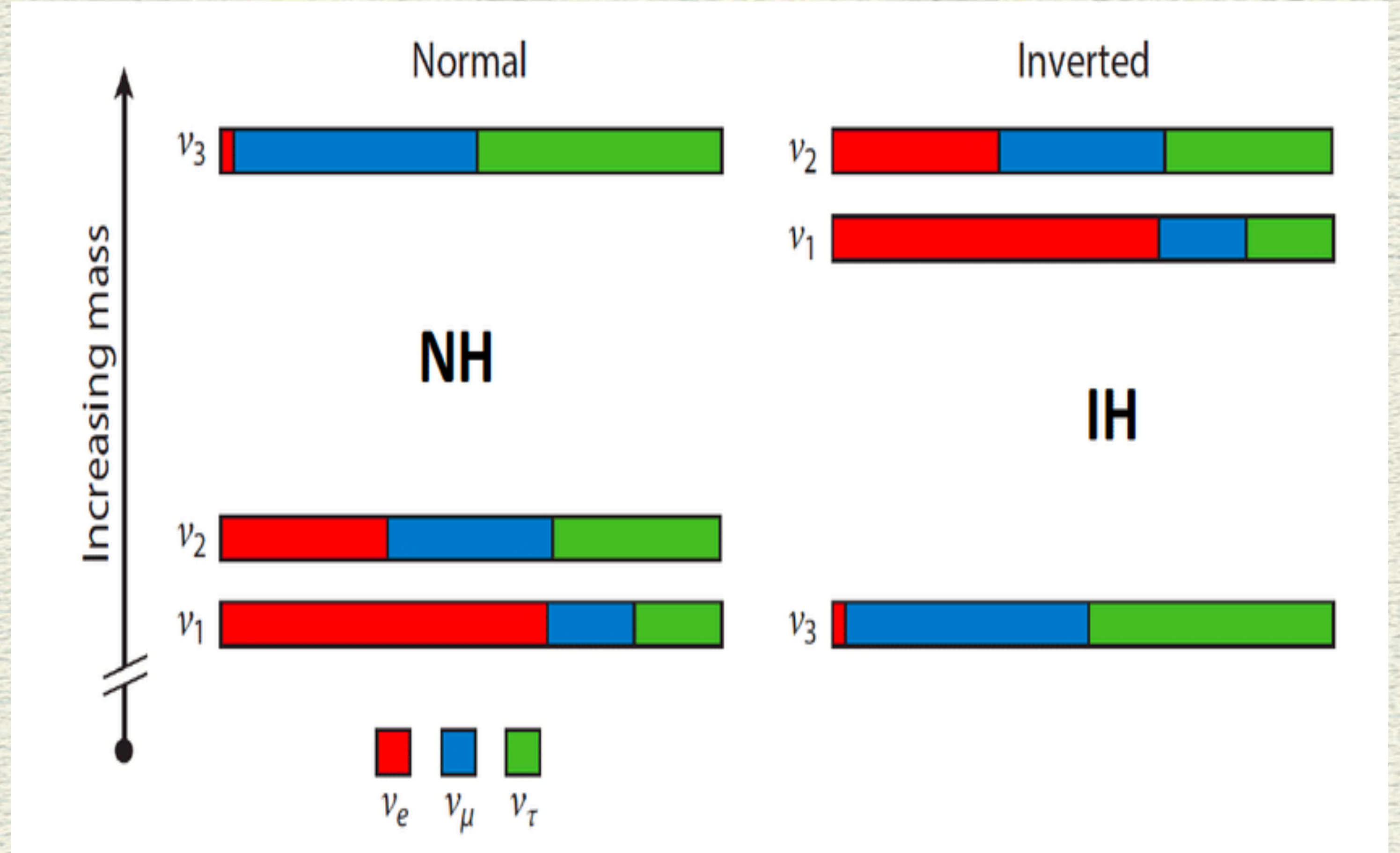
$\nu_e \sim |U_{e1}|^2 \sim 0.7\,\nu_e^{\mathrm{in}}$

Enhancement in spectra

How to play this game?



Inverted Ordering



NO DECAY

$\nu_h \equiv \nu_2$

$\nu_e \sim 0.3\,\nu_2$

DECAY

$\nu_l \equiv \nu_3$

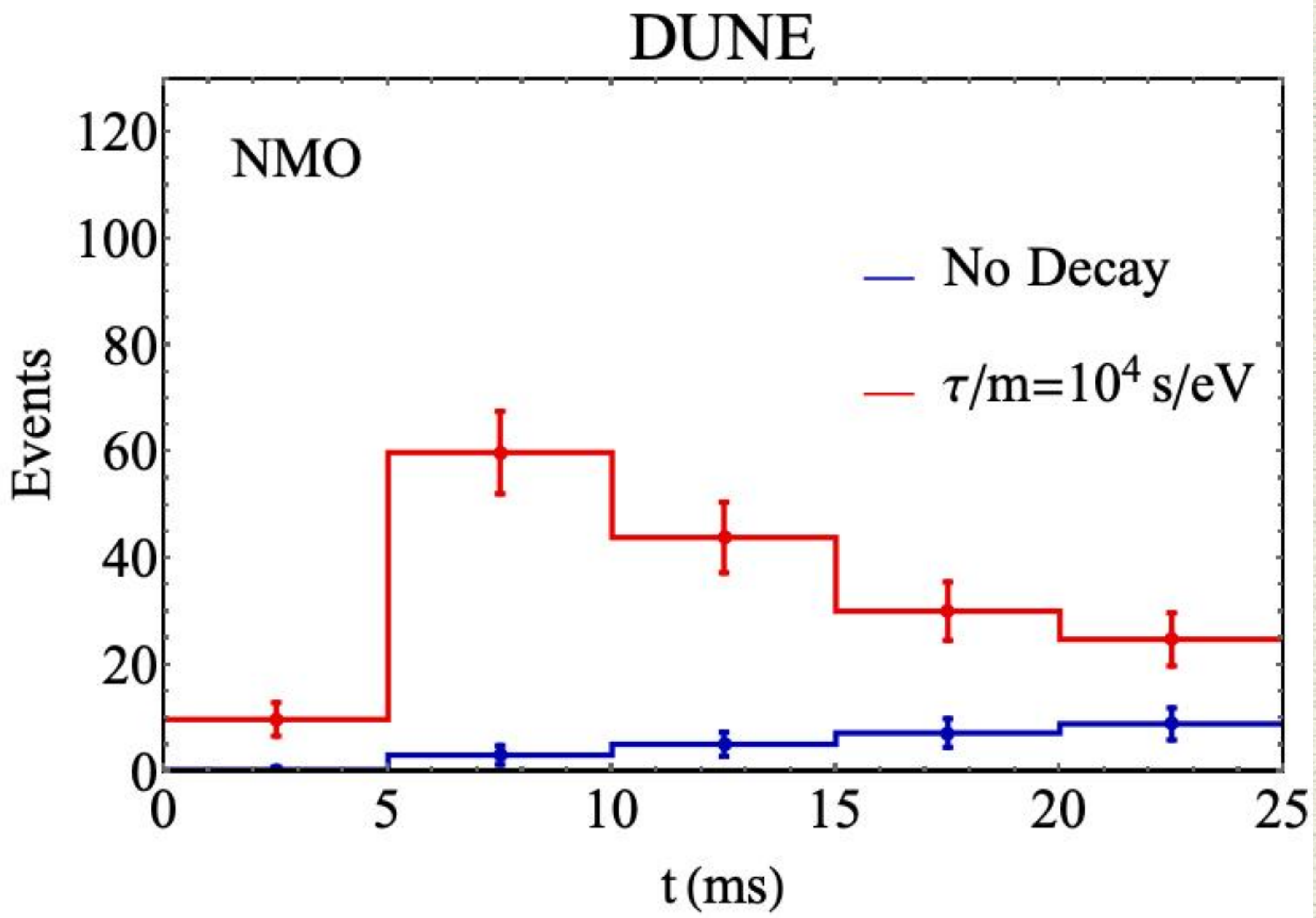
$\nu_h \equiv \nu_2$

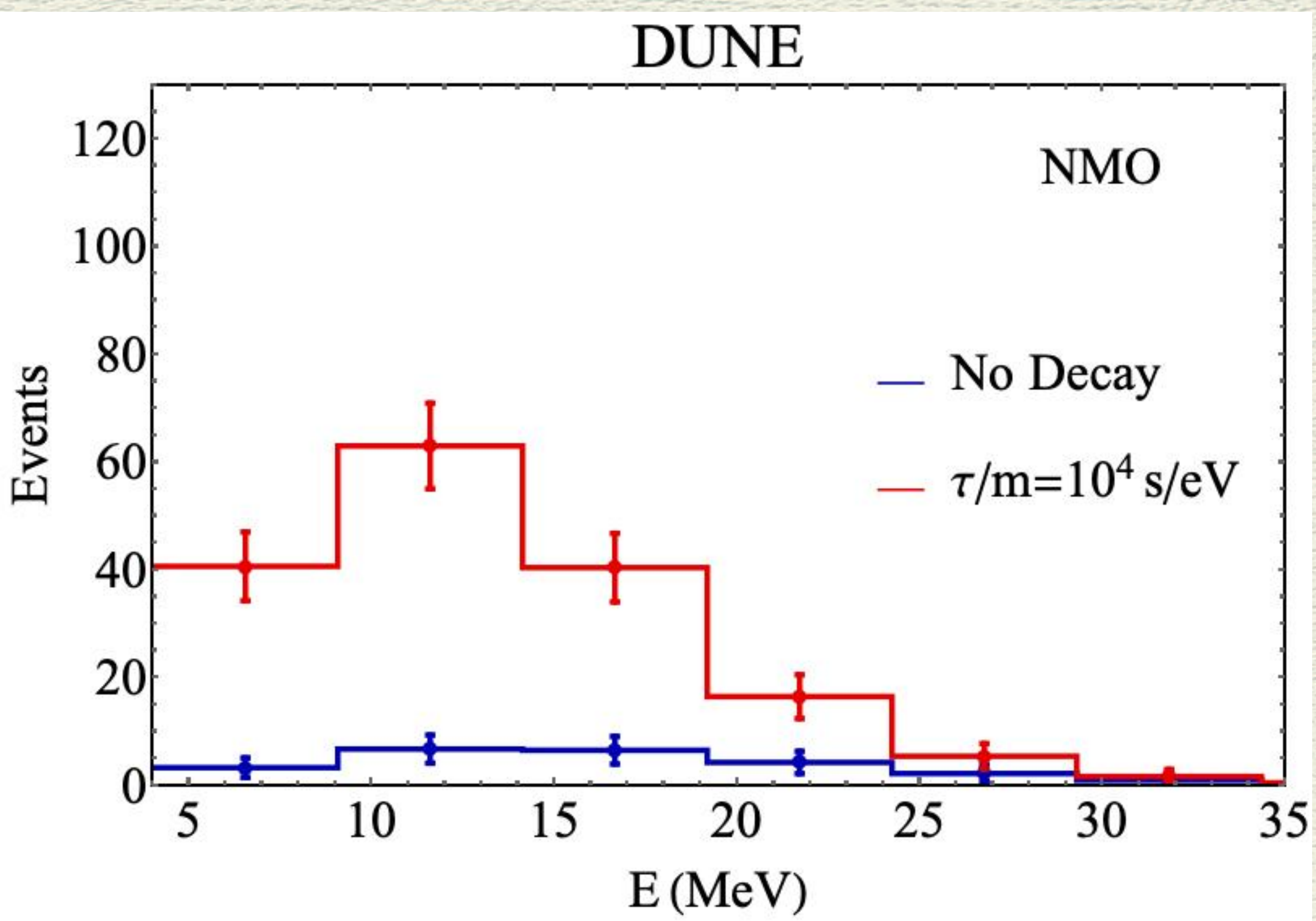
$\nu_e \sim 0.02\,\nu_e^{\mathrm{in}}$

Suppression in spectra

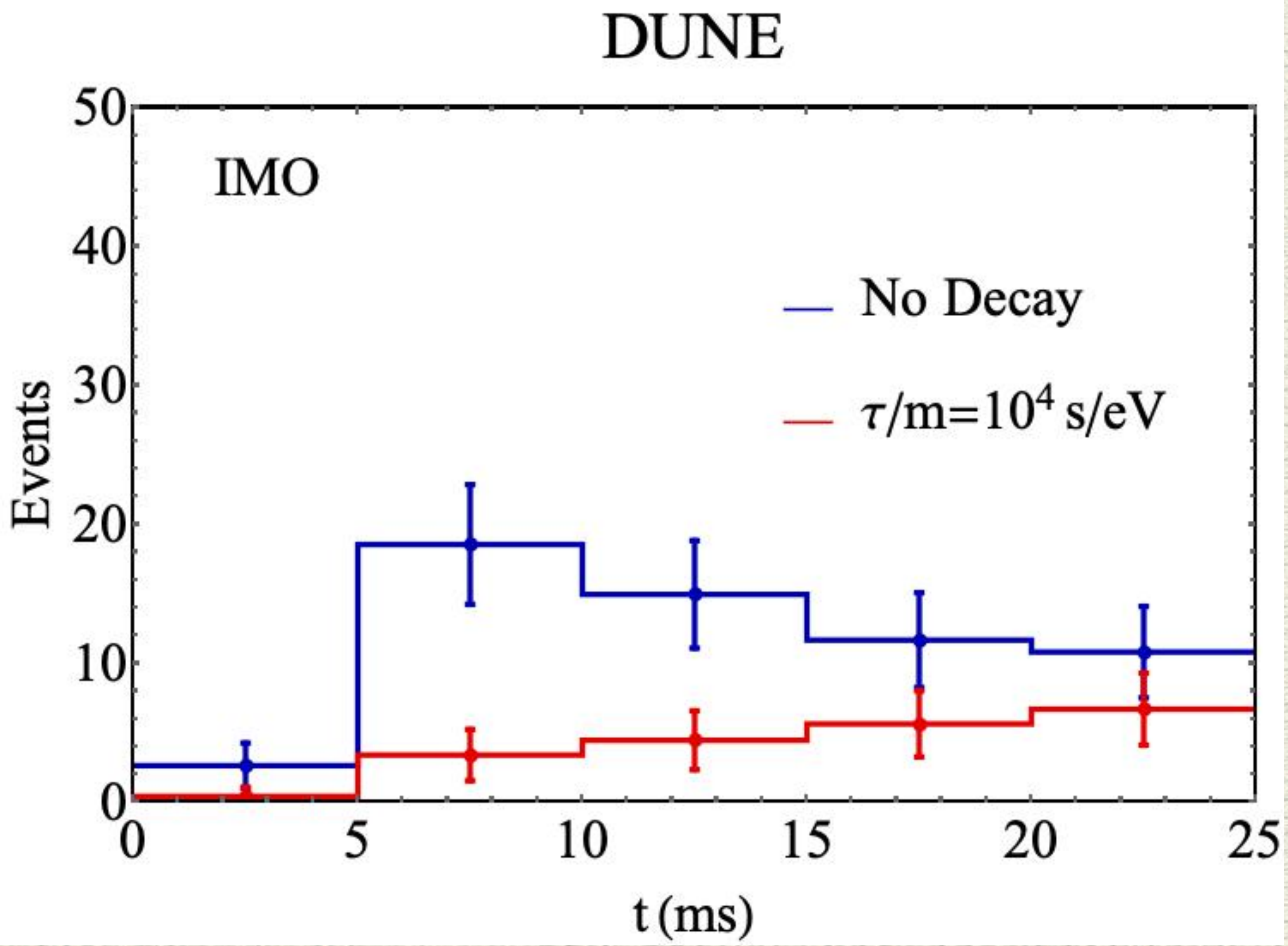
Simulate data in DUNE

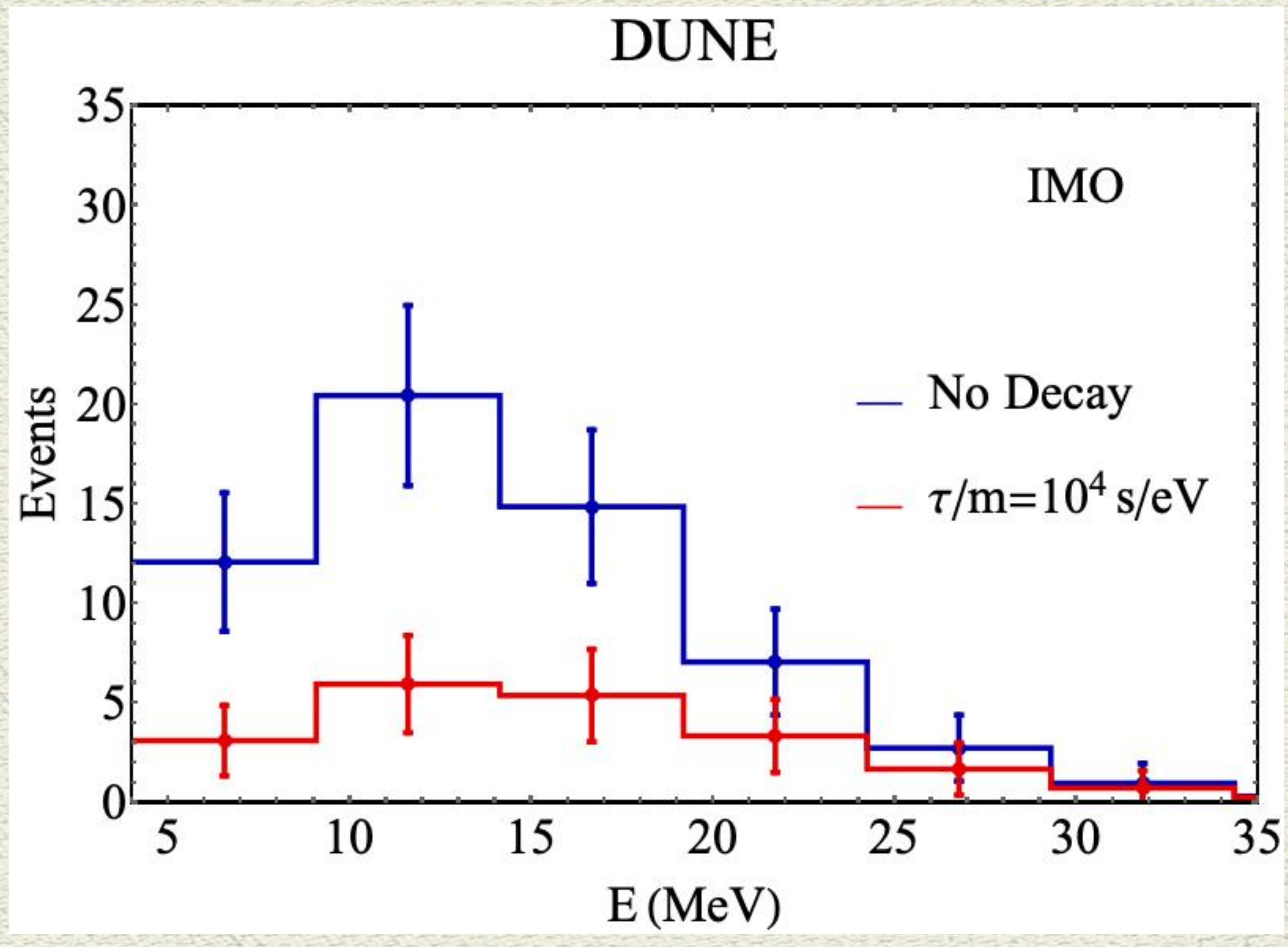
Enhancement



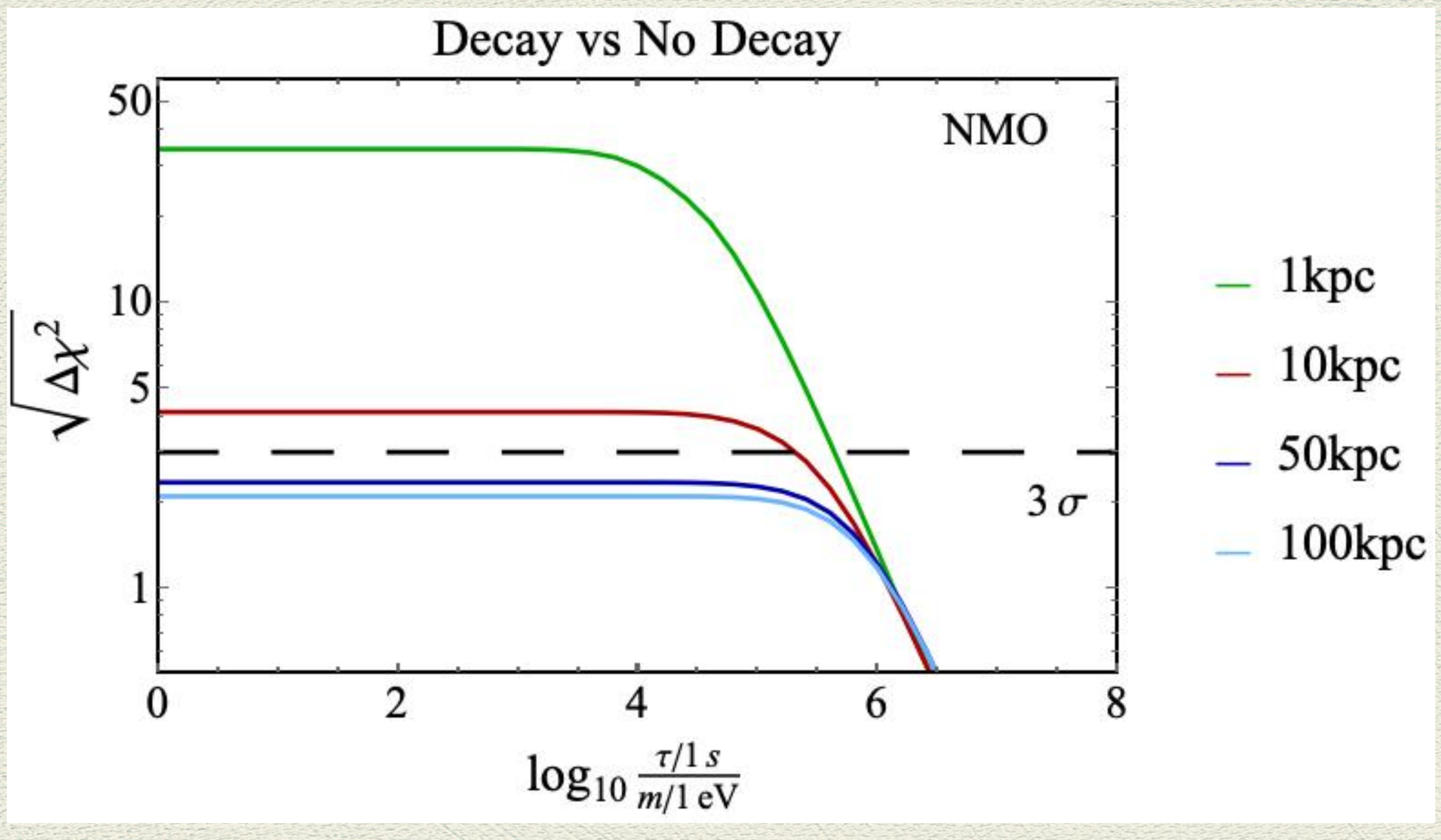


Suppression





Q1: 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

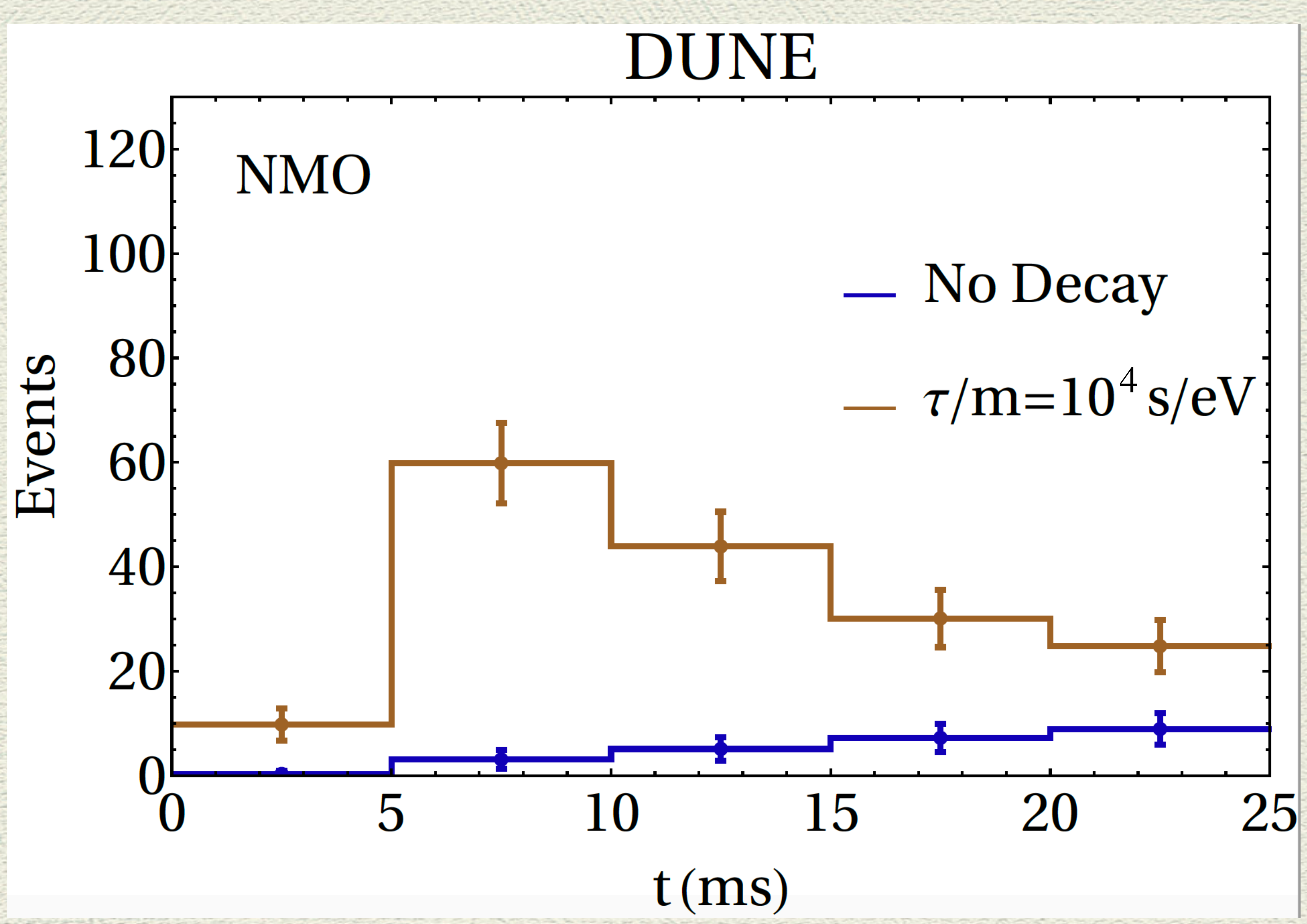
IceCube: $\tau_3/m_3 \sim 10^2\,\mathrm{s/eV}$

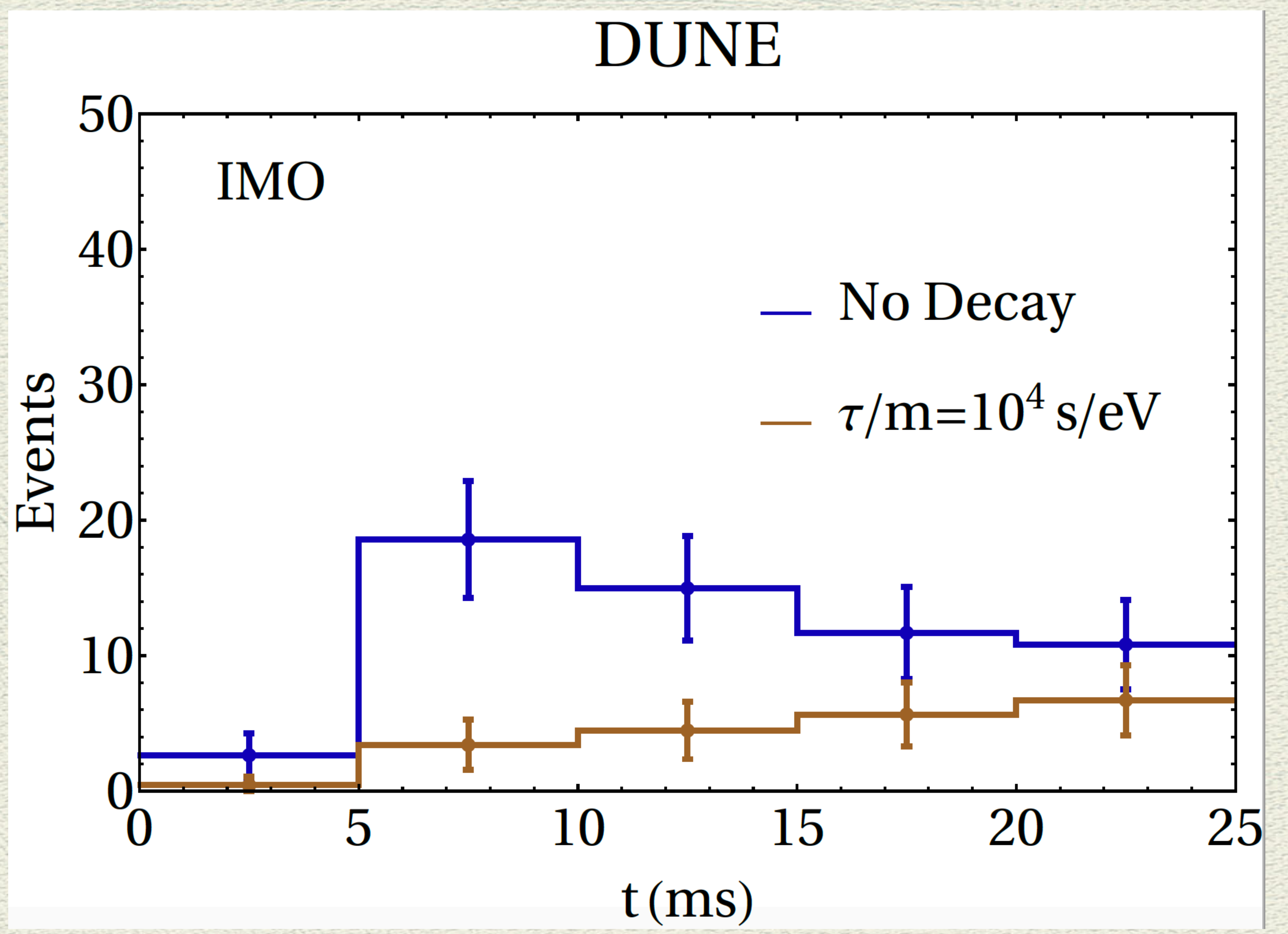
Denton, Tamborra PRL2018

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

de Gouvea, Martinez-Soler, MS, PRD2020

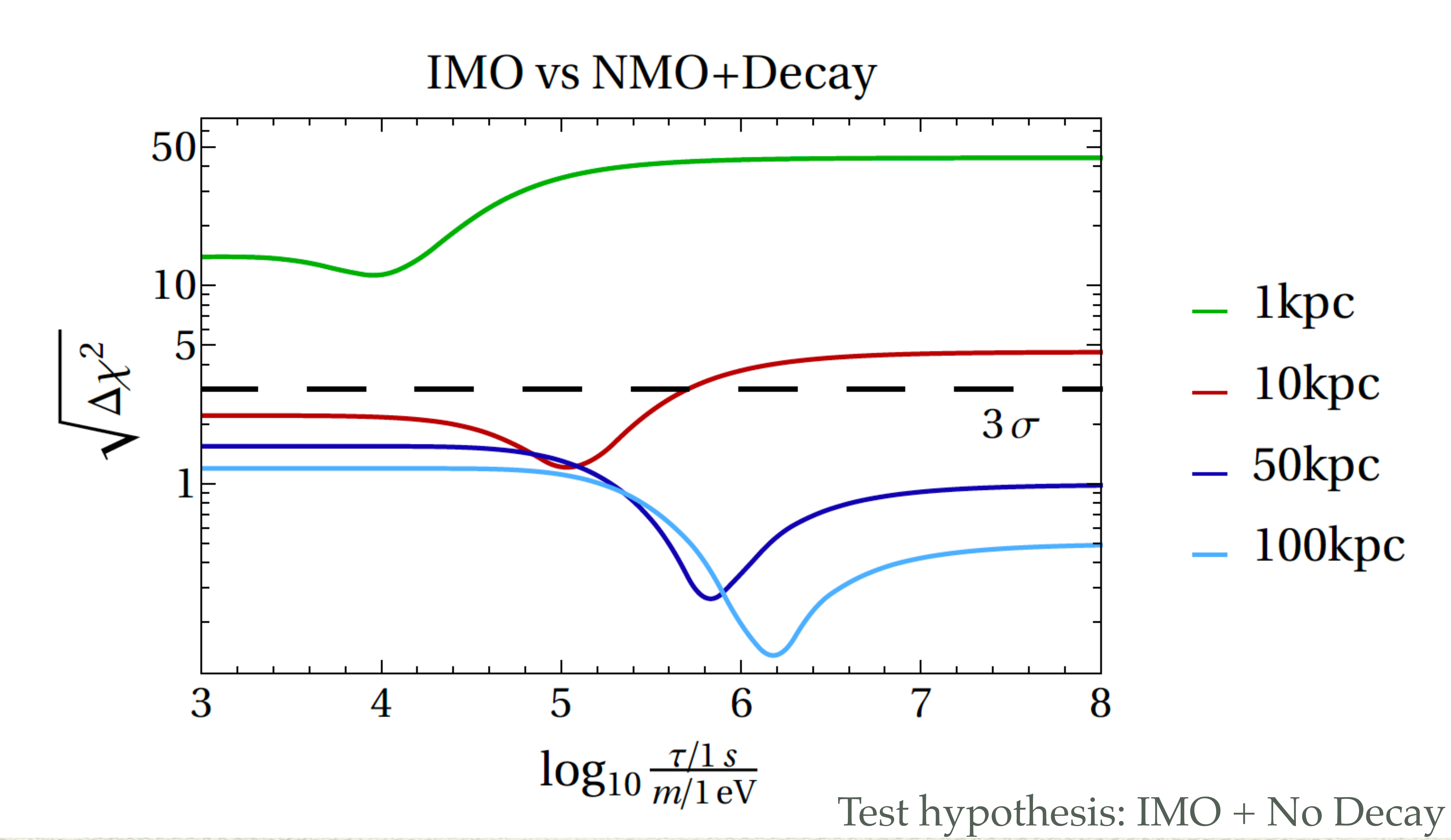
Q2: Mimicking another mass ordering





- NMO or IMO + decay?
- IMO or NMO + decay?

Q2: Mimicking another mass ordering

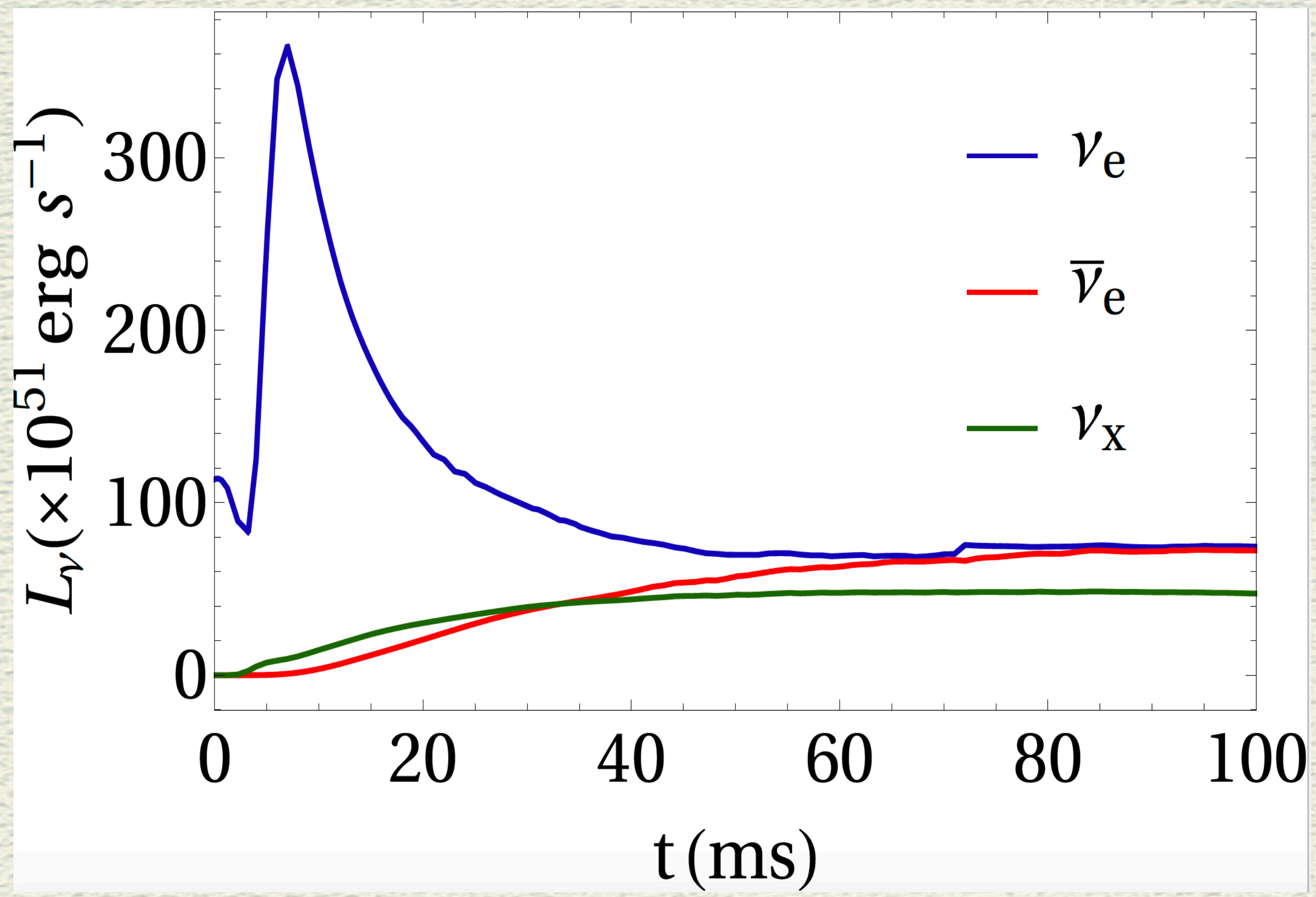


Test hypothesis: IMO + No Decay

DUNE can distinguish between two scenarios if neutrinos sufficiently long-lived, or SN takes place close enough.

de Gouvea, Martinez-Soler, MS, PRD2020

Q3: Dirac vs Majorana



Dirac neutrinos

$\nu_{3L} \to \nu_{1L} + \varphi$

$\nu_{3L} \to \nu_{1R}\,(\nu_s) + \varphi$

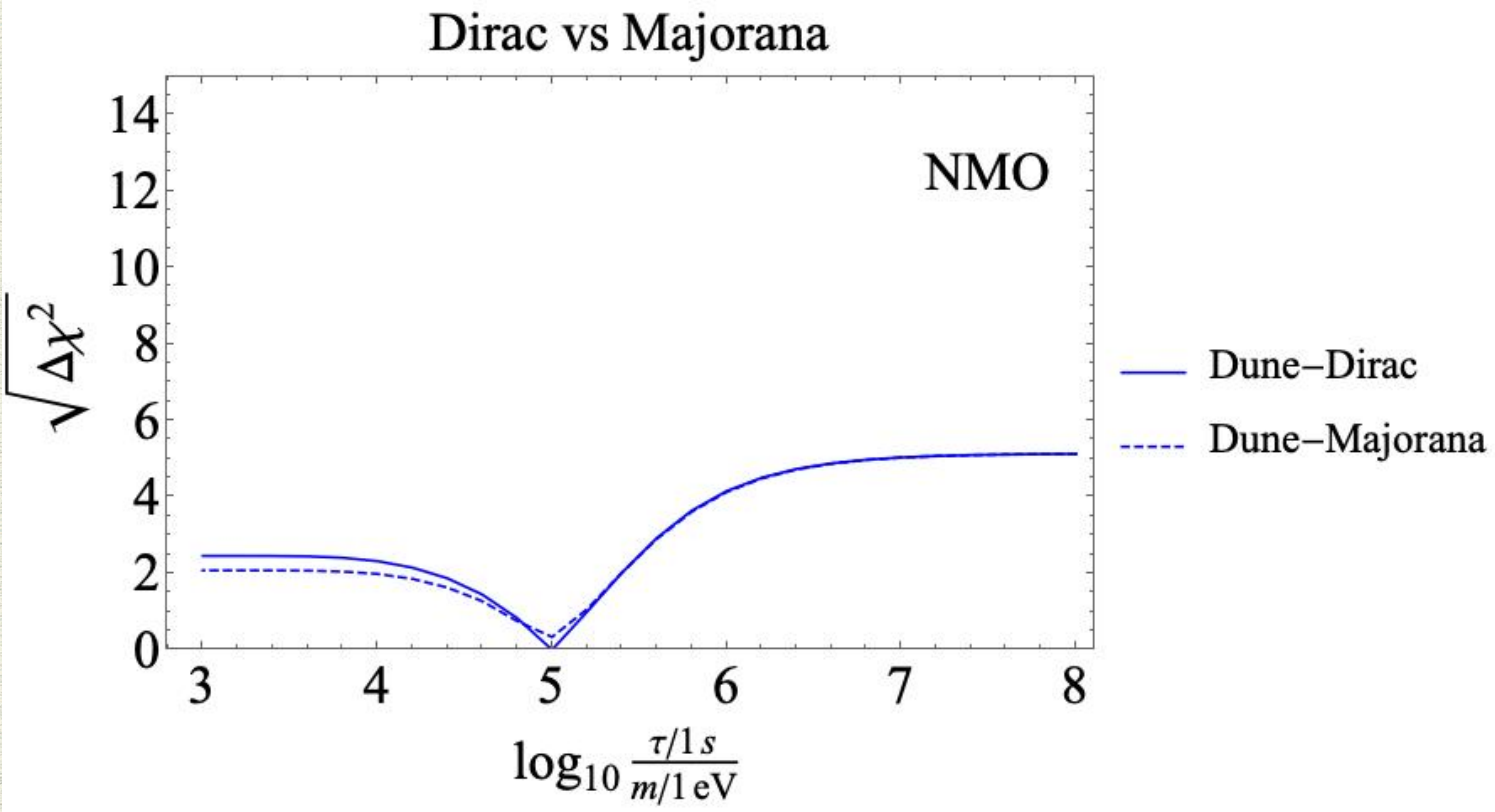
Majorana neutrinos

$\nu_{3L} \to \nu_{1L} + \varphi$

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

- 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

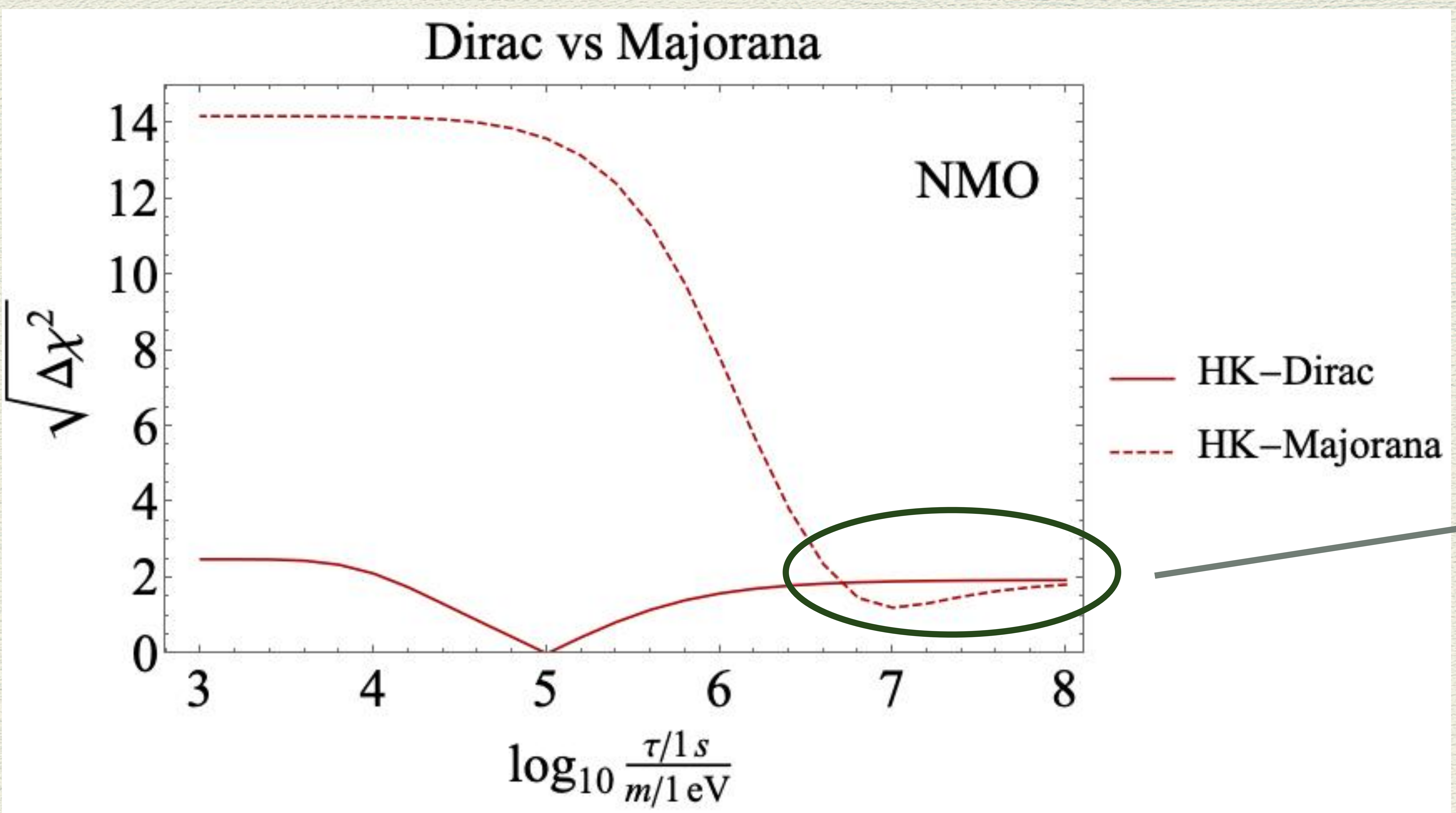


DUNE sensitive to ν_e, hence it cannot distinguish between Dirac and Majorana

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

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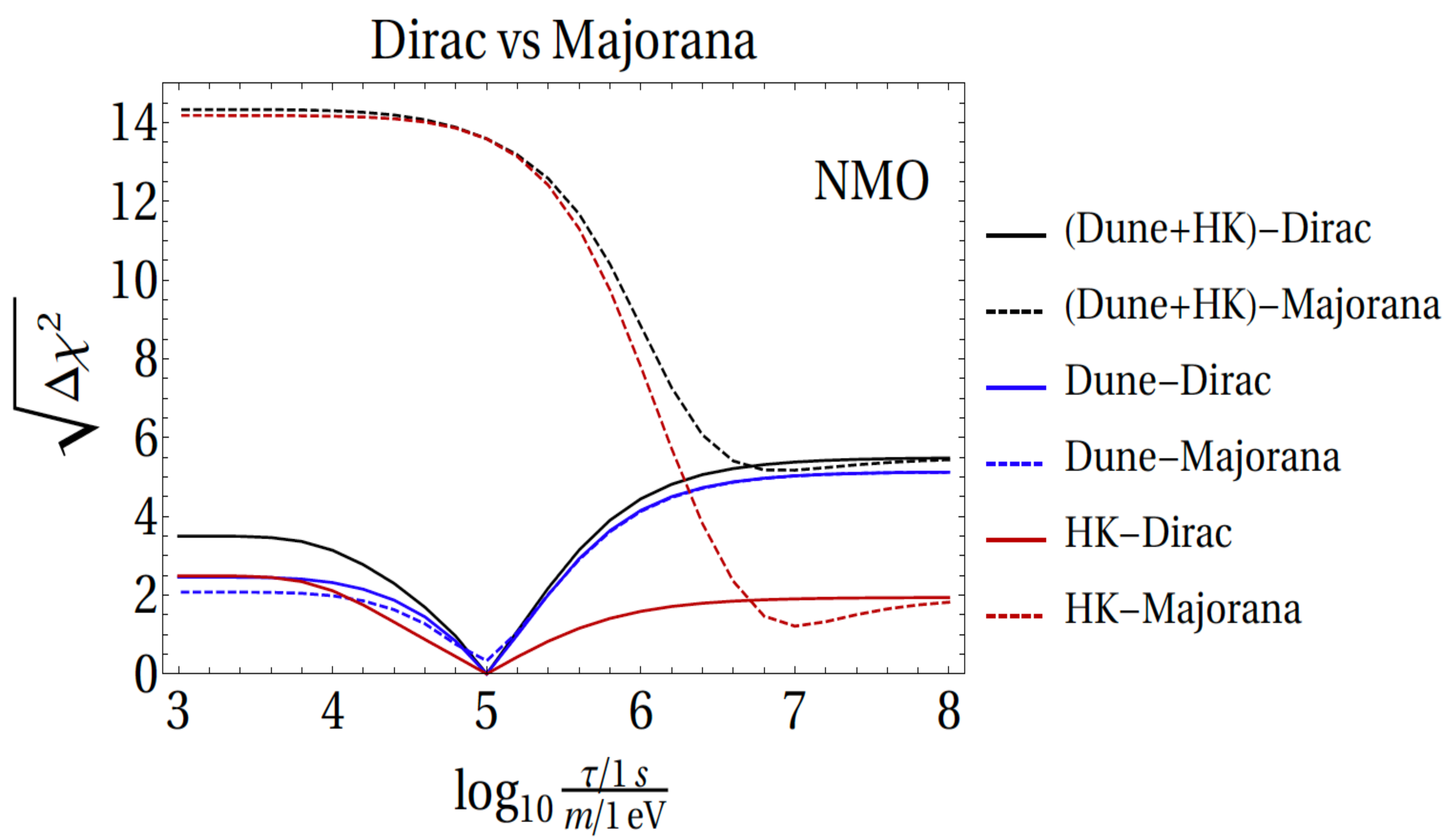
Dirac(D) vs Majorana(M): DUNE+ Hyper-K



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

- Neutrino burst phase of a Core-collapse SNe is a fantastic laboratory for testing new physics.
- Naturally long baseline provided can be used to constrain non-standard neutrino decays. Some of the strongest bounds on neutrino decays.
- Combination of DUNE and HK can be used to distinguish between a decaying Dirac neutrino and a decaying Majorana neutrino.

Thank you!

Dirac vs Majorana: Dune vs HK