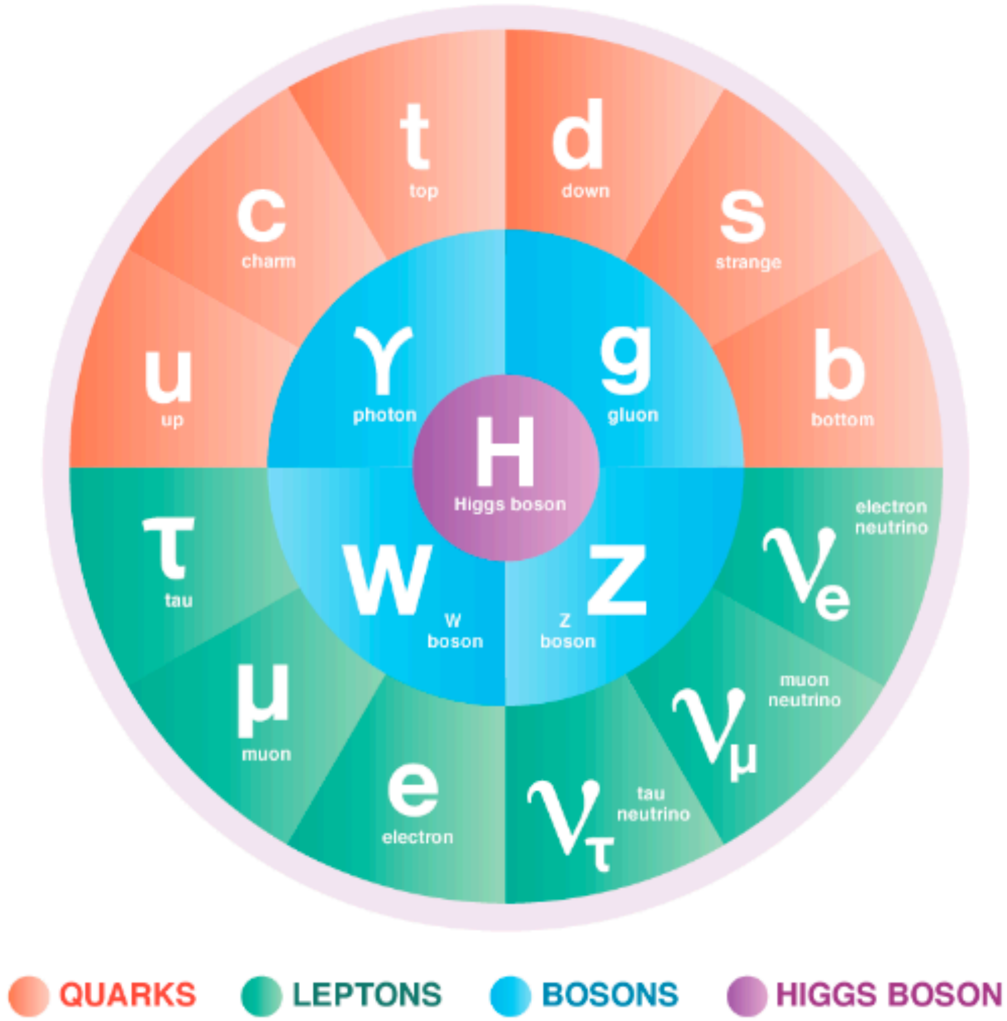
First EuCAPT Annual Symposium
05/05-07/05

BSM Searches with supernova neutrinos

Manibrata Sen
UC Berkeley & Northwestern University
Network for Neutrinos, Nuclear Astrophysics and Symmetries

What is "beyond" the SM (in this talk)?



Artwork courtesy of Sandbox Studio, Chicago for Symmetry

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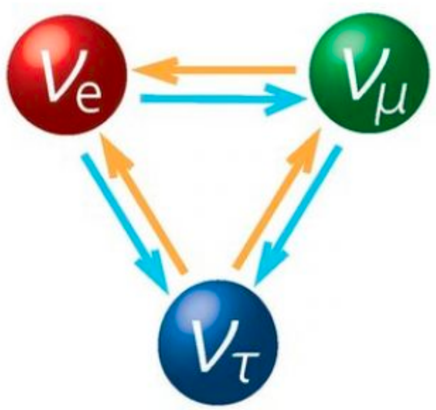

Credit: BBC

The Standard Model

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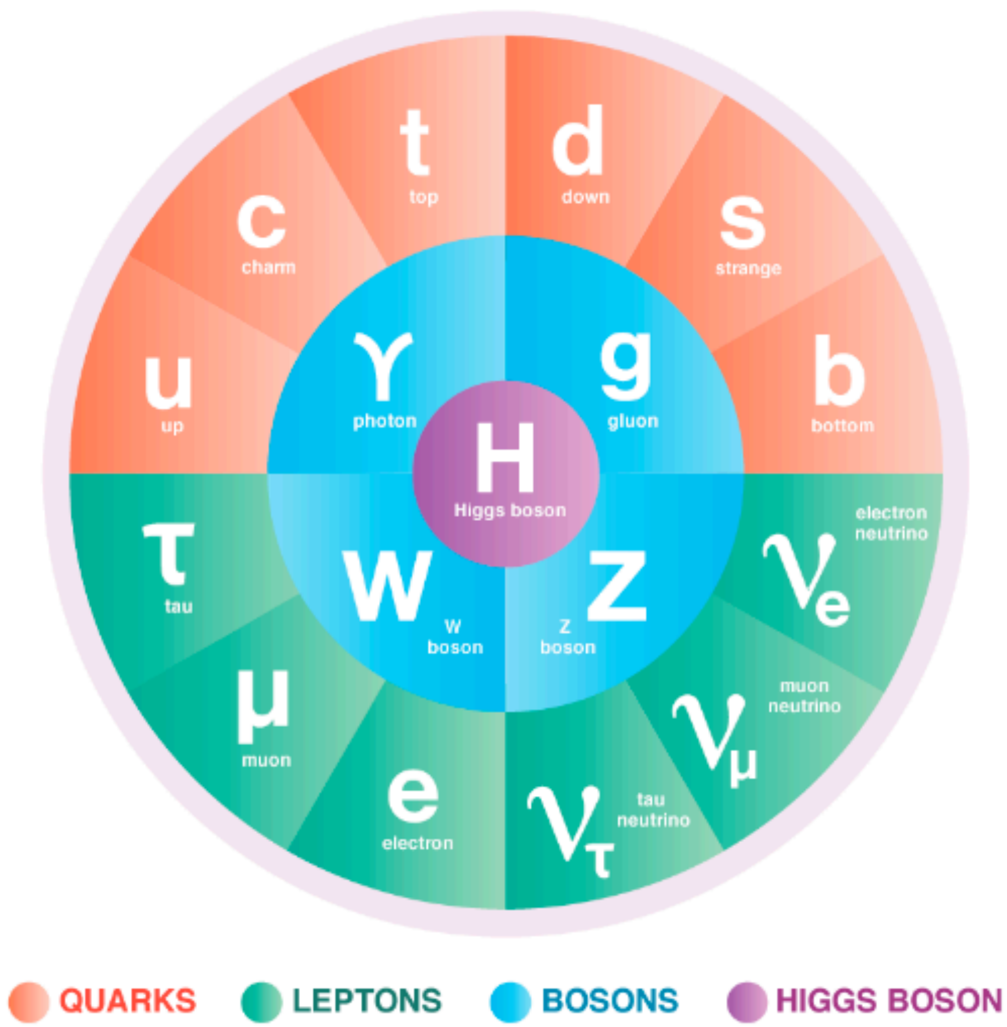

Artwork courtesy of Sandbox Studio, Chicago for Symmetry

The Standard Model

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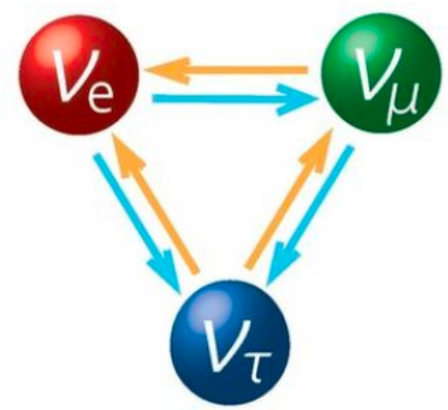
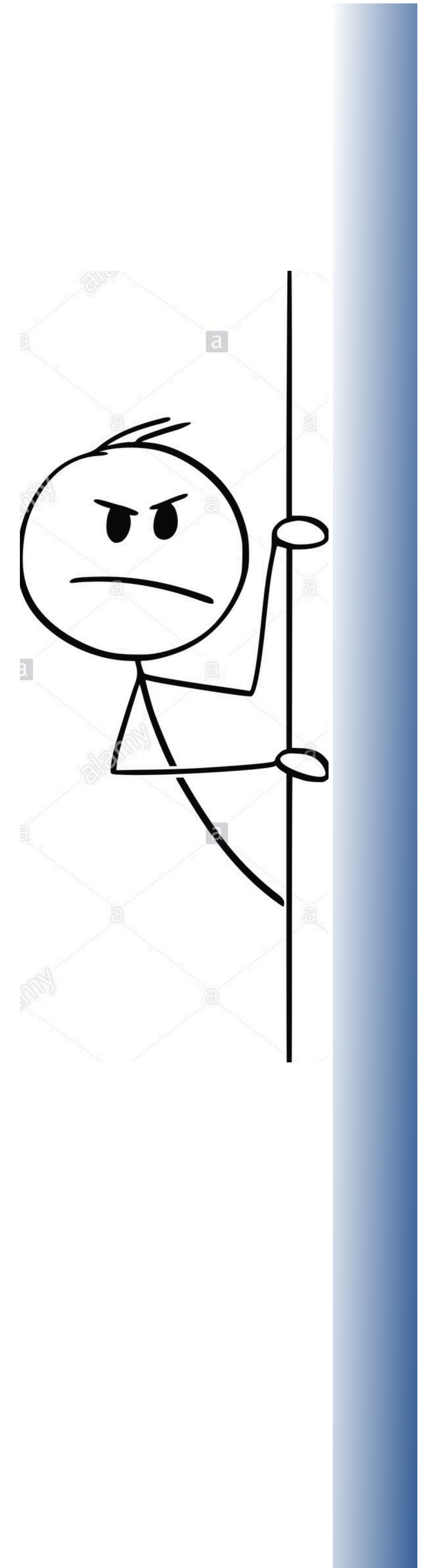


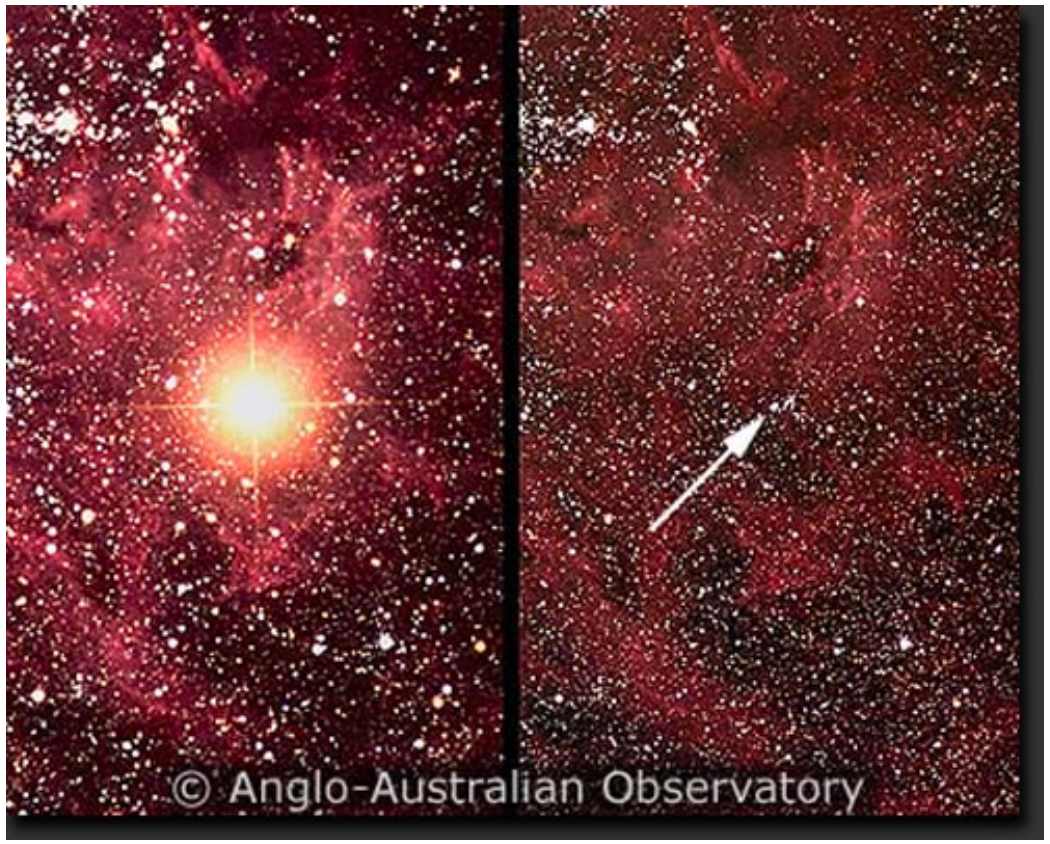
Credit: BBC

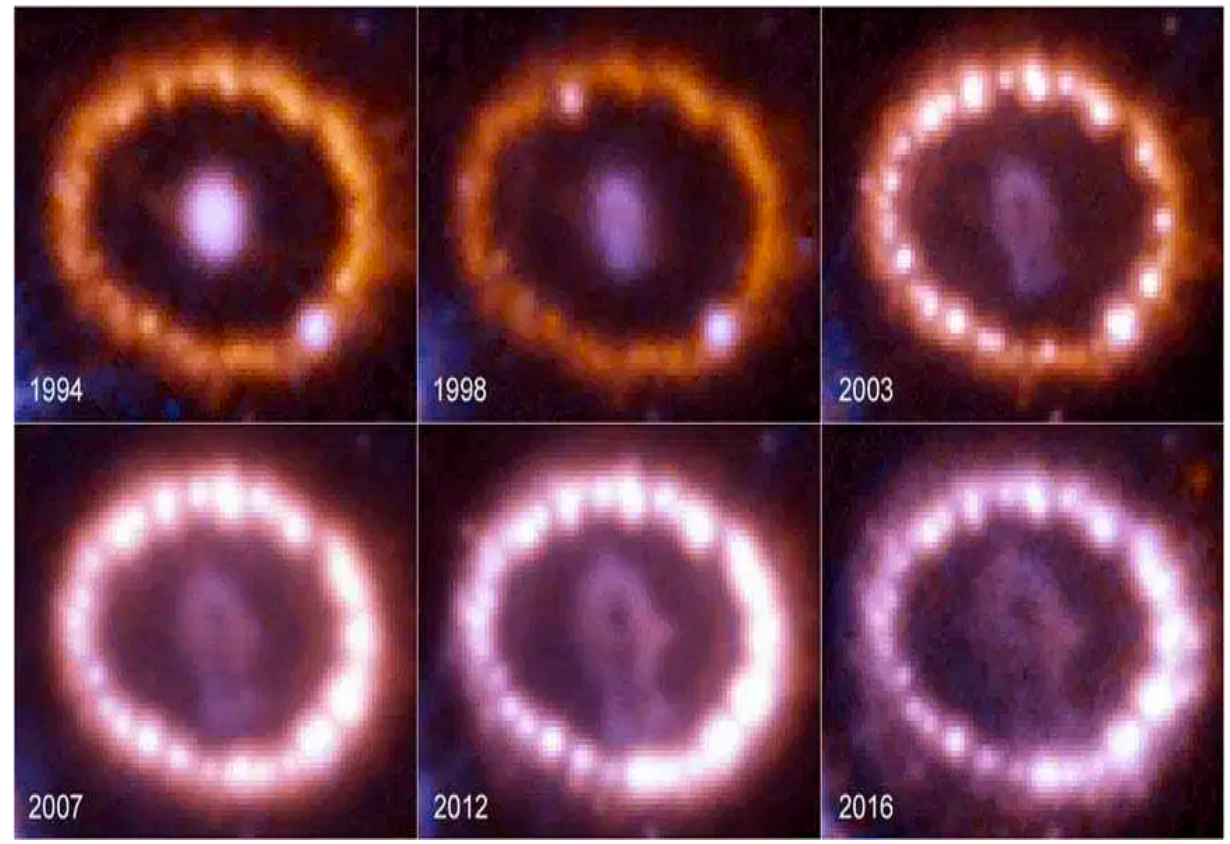


Beyond

SN1987A: the marvel of the last century

Feb 23, 1987

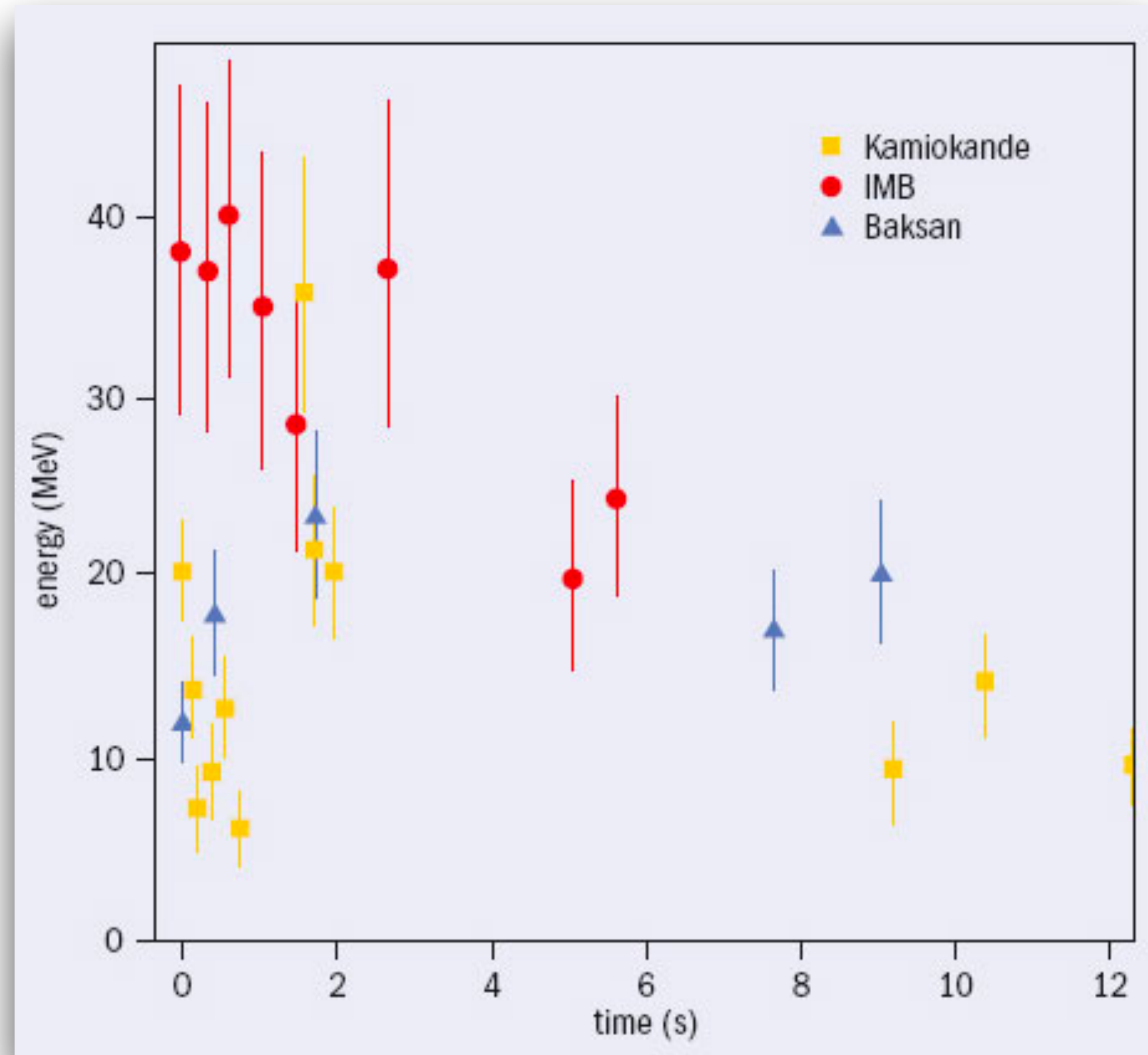




- Took place 168,000 years ago

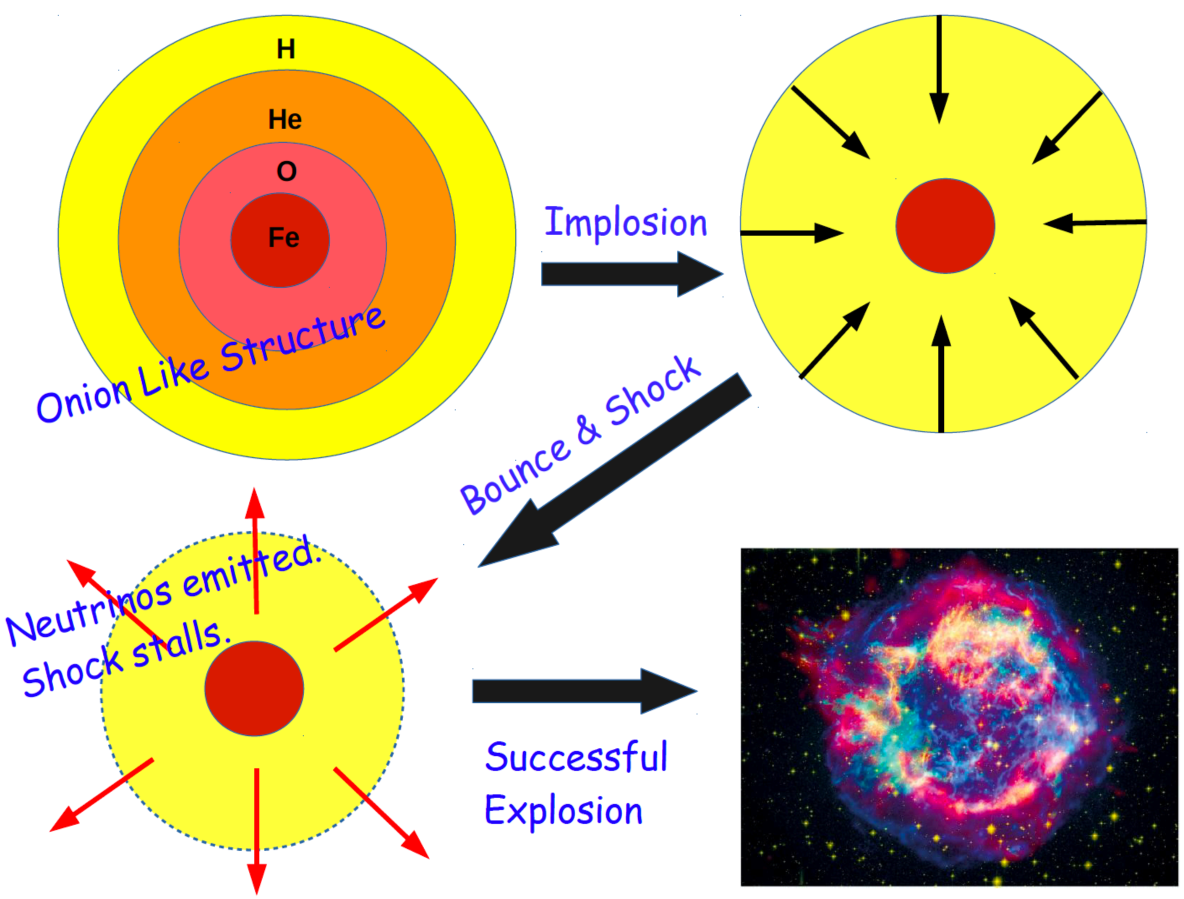
- In the Large Magellanic Cloud, 50 kpc away. $18M_\odot$ star.

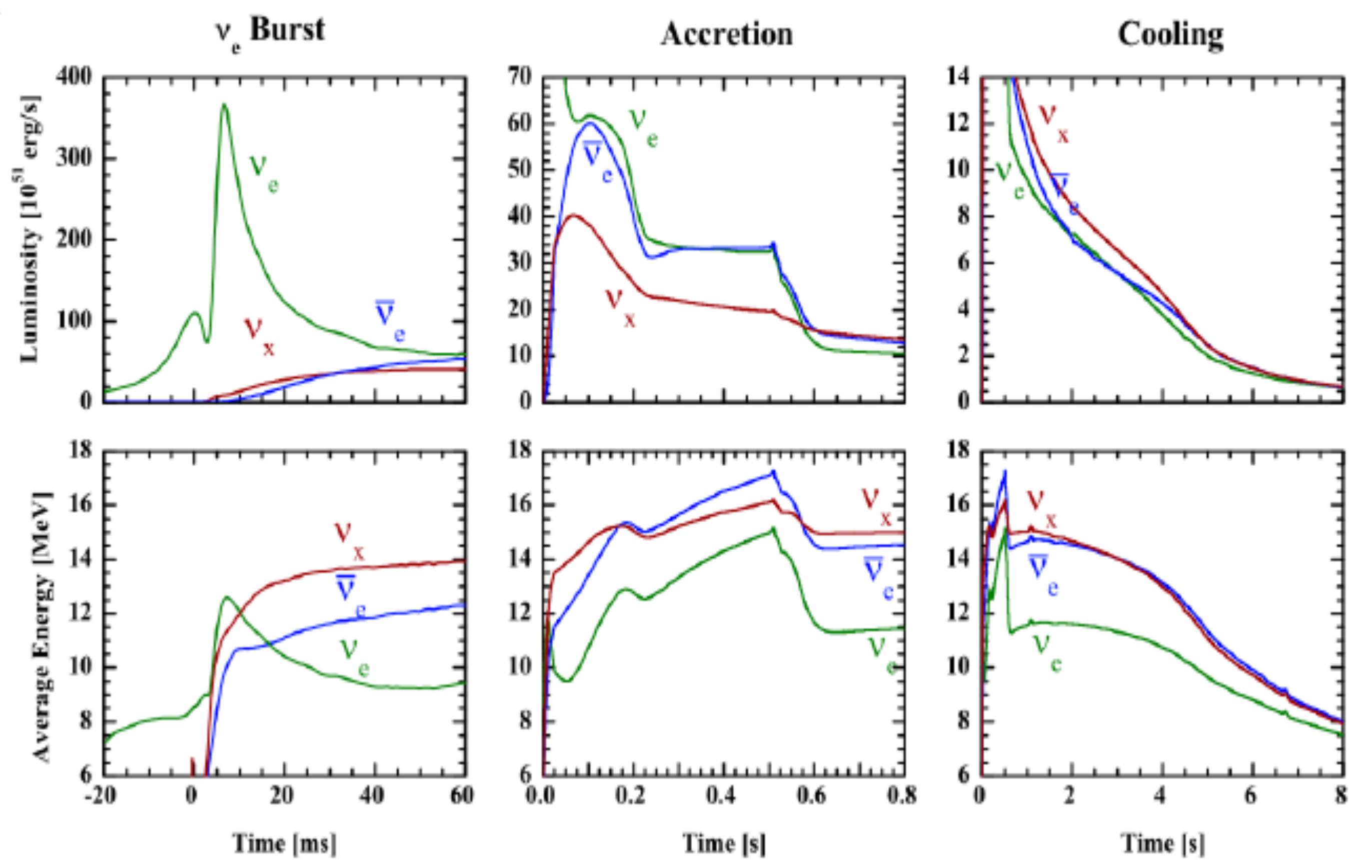
“Many” neutrinos were observed



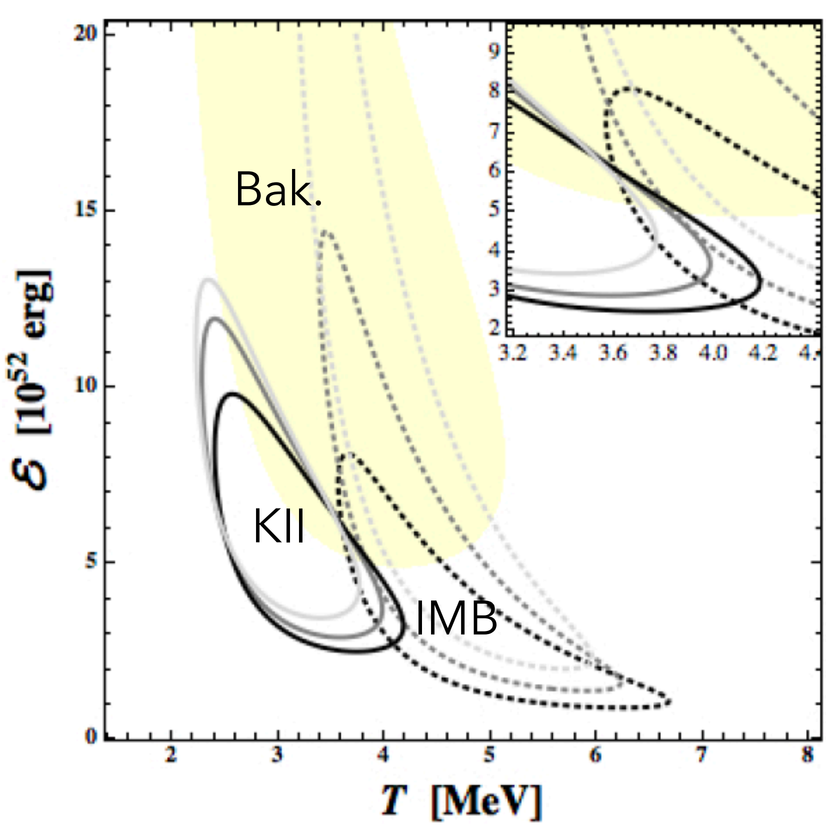
- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Neutrinos before photons.
- Not enough statistics, still a coherent picture can be formed!

A supernova engine





Garching simulations

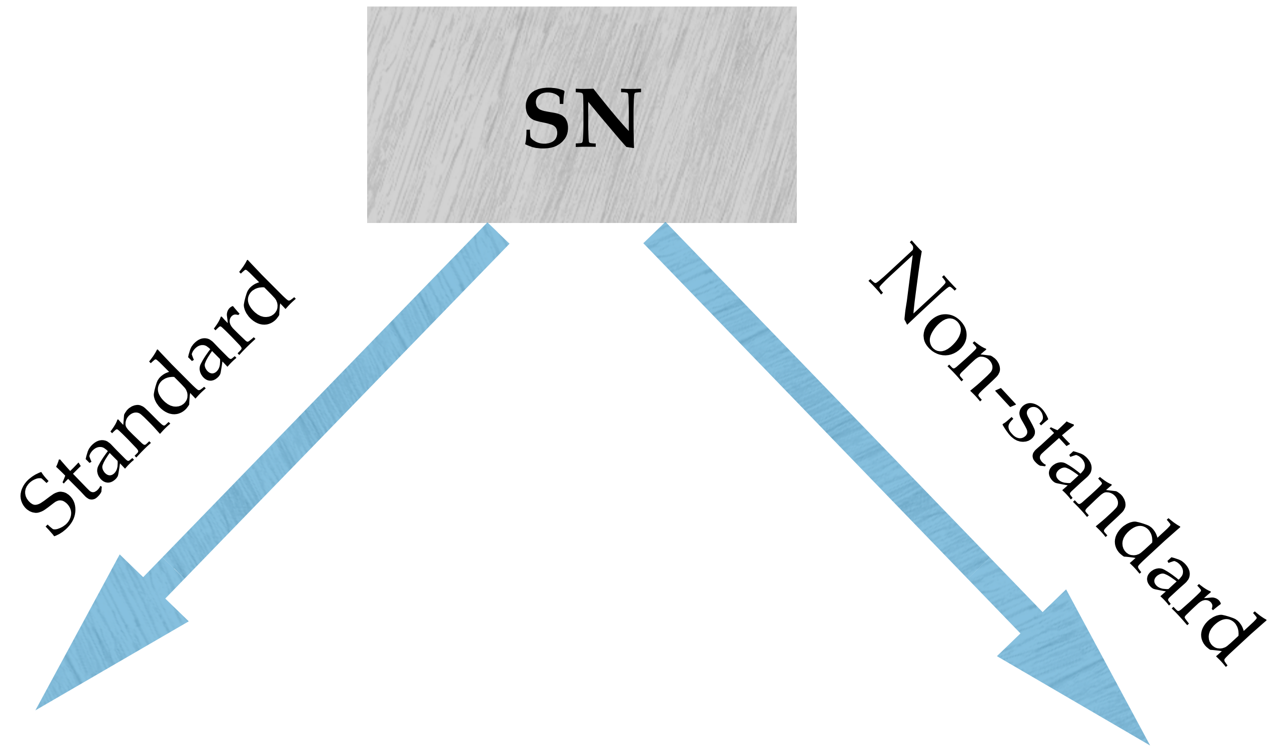


Rough agreement
with simulations

F. Vissani, J. Phys. G: Nucl. Part. Phys. (2014)

What sort of a laboratory is the SN?

Advent of multi-messenger astronomy



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

- Non-standard (self)interactions, decay, magnetic moment, millicharge, etc.
- New particles: sterile neutrinos, axions, majorons, etc.
- Any crazy stuff that theorists can think about.

Category of bounds from SN neutrinos

New Physics can

1. Impact on the neutrino luminosity, and average energy, and duration of neutrino burst

2. Impact on the neutrino spectra/ flux

Impact on the neutrino luminosity, and average energy

SN cooling bound

- New modes of energy loss due to weakly coupled particles.

- If $\mathscr{L}_x > \mathscr{L}_\nu \sim 10^{52}\,\mathrm{erg/s}$, then duration of neutrino burst is reduced.

- $g < g_{\min}$: not efficiently produced.
  $g > g_{\max}$: efficiently trapped and reabsorbed (trapping mechanism needs to be well understood)

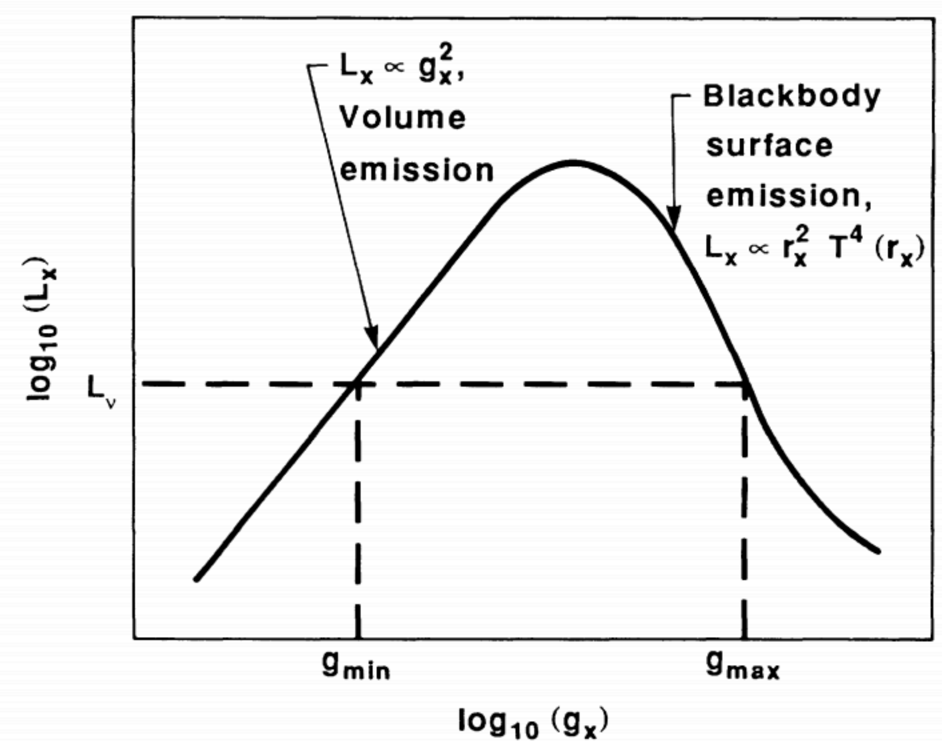


FIG. 1. Schematic dependence of L_x on the coupling strength g_x. The horizontal line denotes the neutrino luminosity L_ν. In the range $g_{\min} < g < g_{\max}$ the LEP emission L_x would exceed L_ν.

G. Raffelt and D. Seckel, PRL (1998)
G.Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

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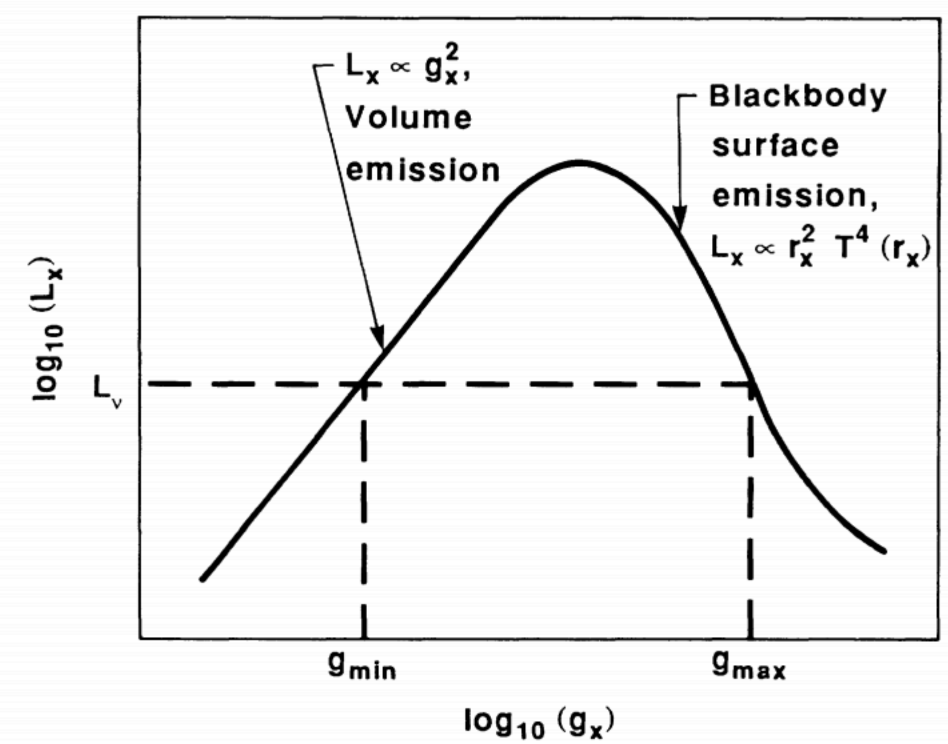

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G. Raffelt and D. Seckel, PRL (1998)
G.Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

- The impact of a new particle is optimum when m.f.p ~ stellar radius.

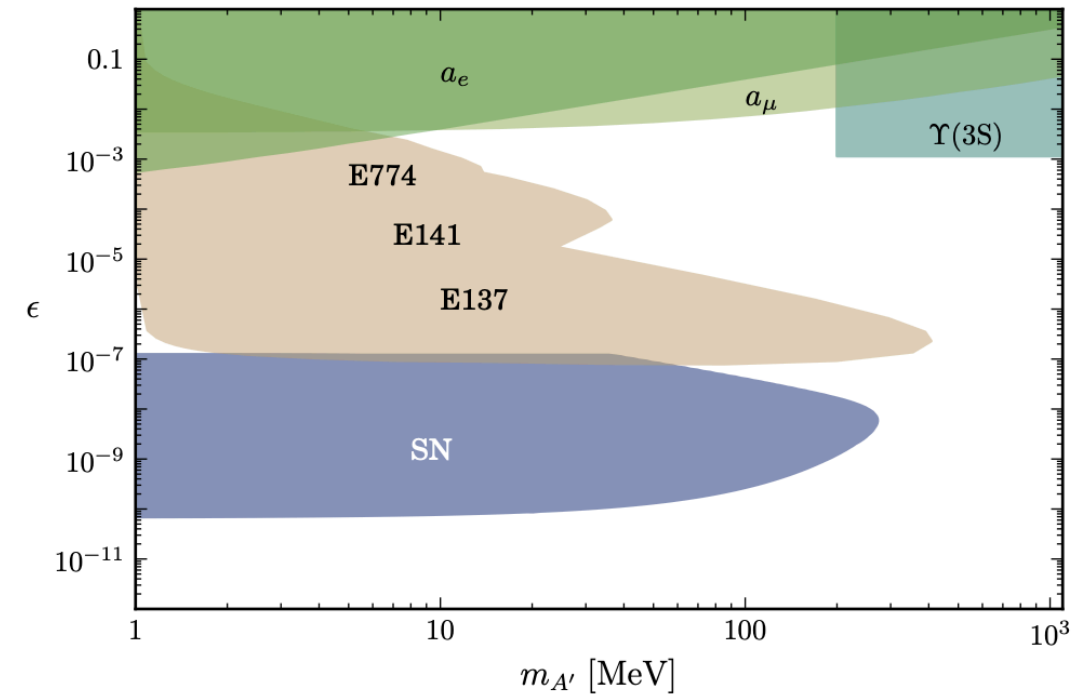
1. The dark photon, and friends in SN

Different dark photon models

1. Vanilla Dark photon ~ $\mathscr{L} \supset \frac{1}{4}F'F' + \frac{\epsilon}{2}FF'$

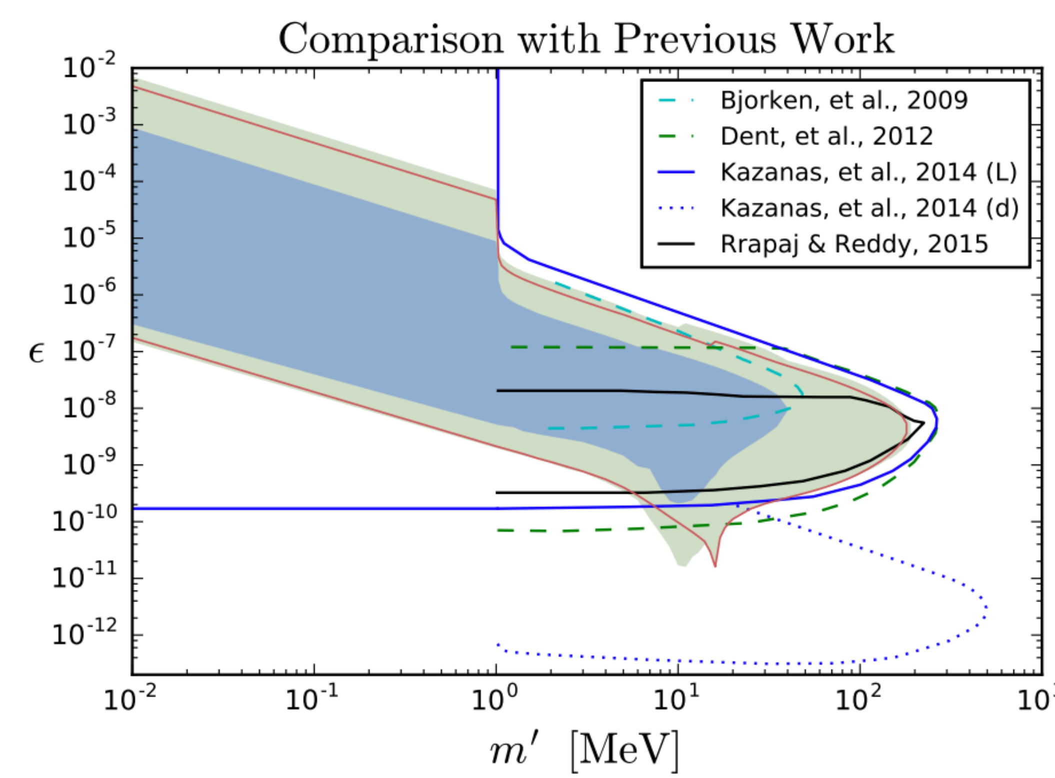
- Consider free-streaming and trapping limit. Main production from $pp \to ppA'$, $np \to npA'$.

J. Dent, F. Ferrer, L.Krauss, arXiv 1201.2683



- Include finite temperature and density effects in A′ production.

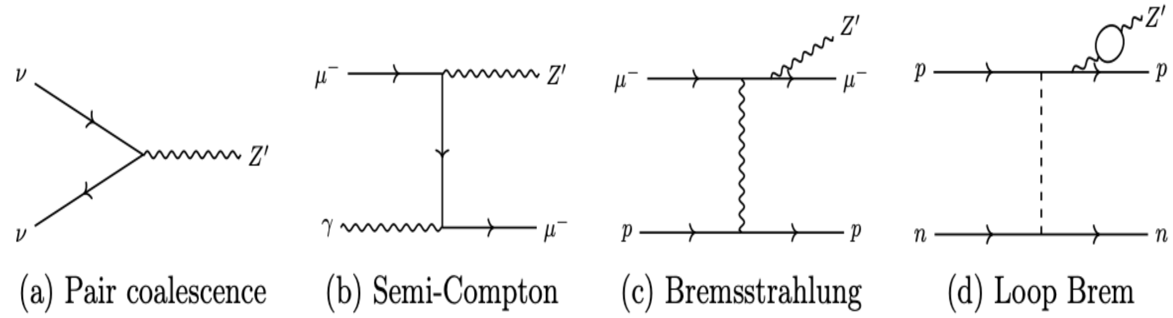
J. Chang, R. Essig, S. McDermott, JHEP (2017)



- Bounds can be further strengthened by considering decay to e^+e^-, γ, both in the mantle, and near the progenitor surface.

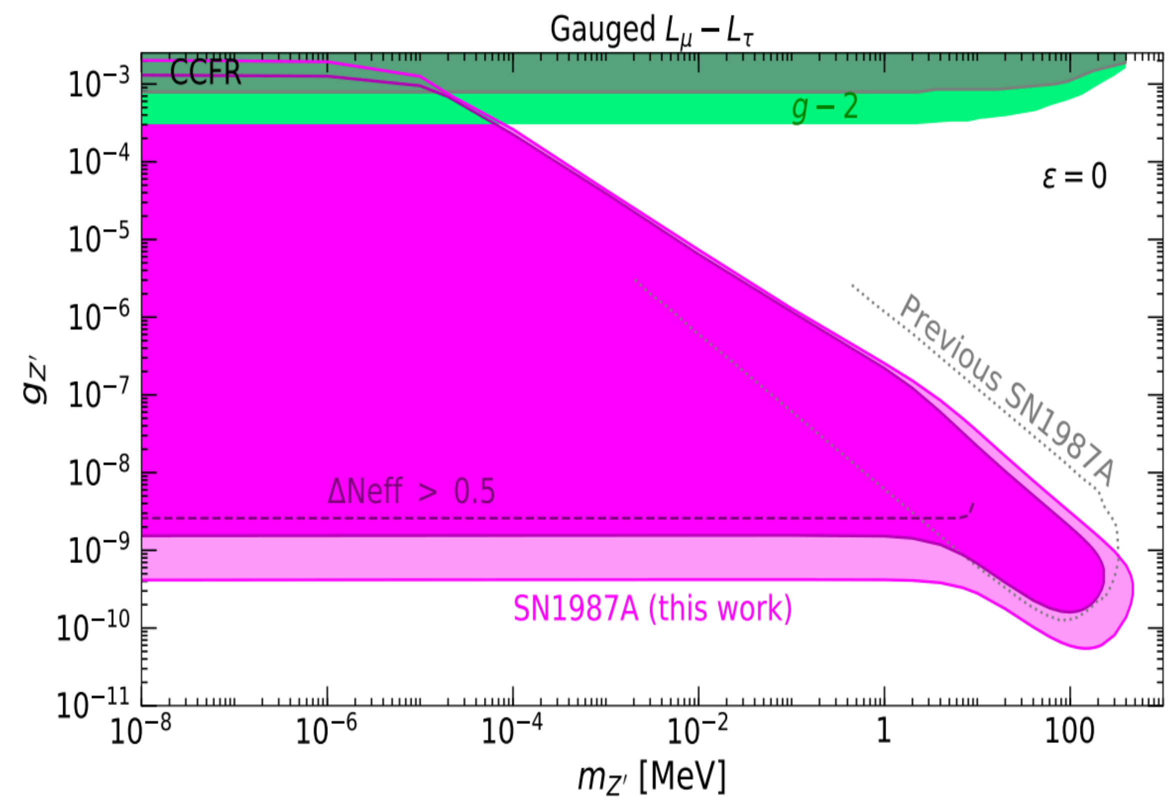
D. Kazanas, R. Mohapatra, S. Nussinov, et al. , NPB (2015)
W. DeRocco, P. Graham, D. Kasen, et al., JHEP (2019)

Inclusion of muons from simulations



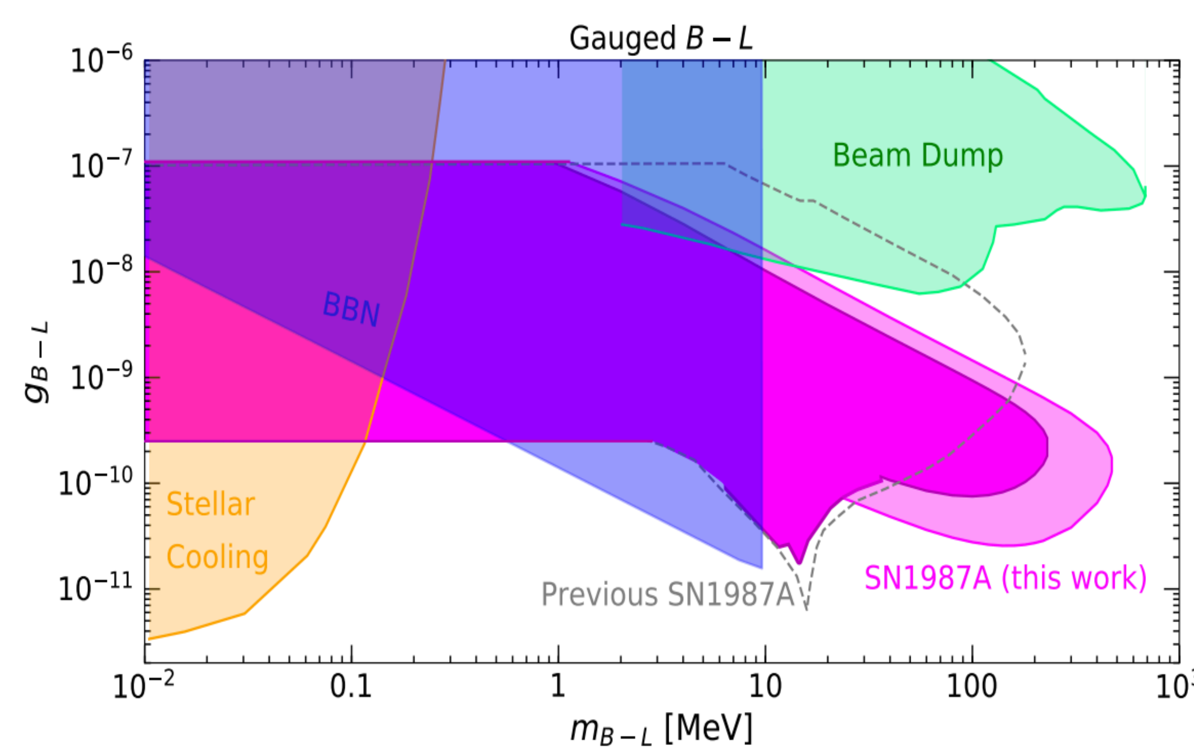
2. $L_\mu - L_\tau$ gauge boson.

- For lower Z′ masses, semi-Compton process relevant.
- Upper bound fixed by trapping arguments.



3. $B - L$ gauge boson.

- Peak due to kinetic mixing, which opens up $np \to npZ'$



D. Croon, G. Ellor, R. Leane, S. McDermott, JHEP (2021)

2. Sterile neutrinos in SN

Sterile neutrinos in supernova

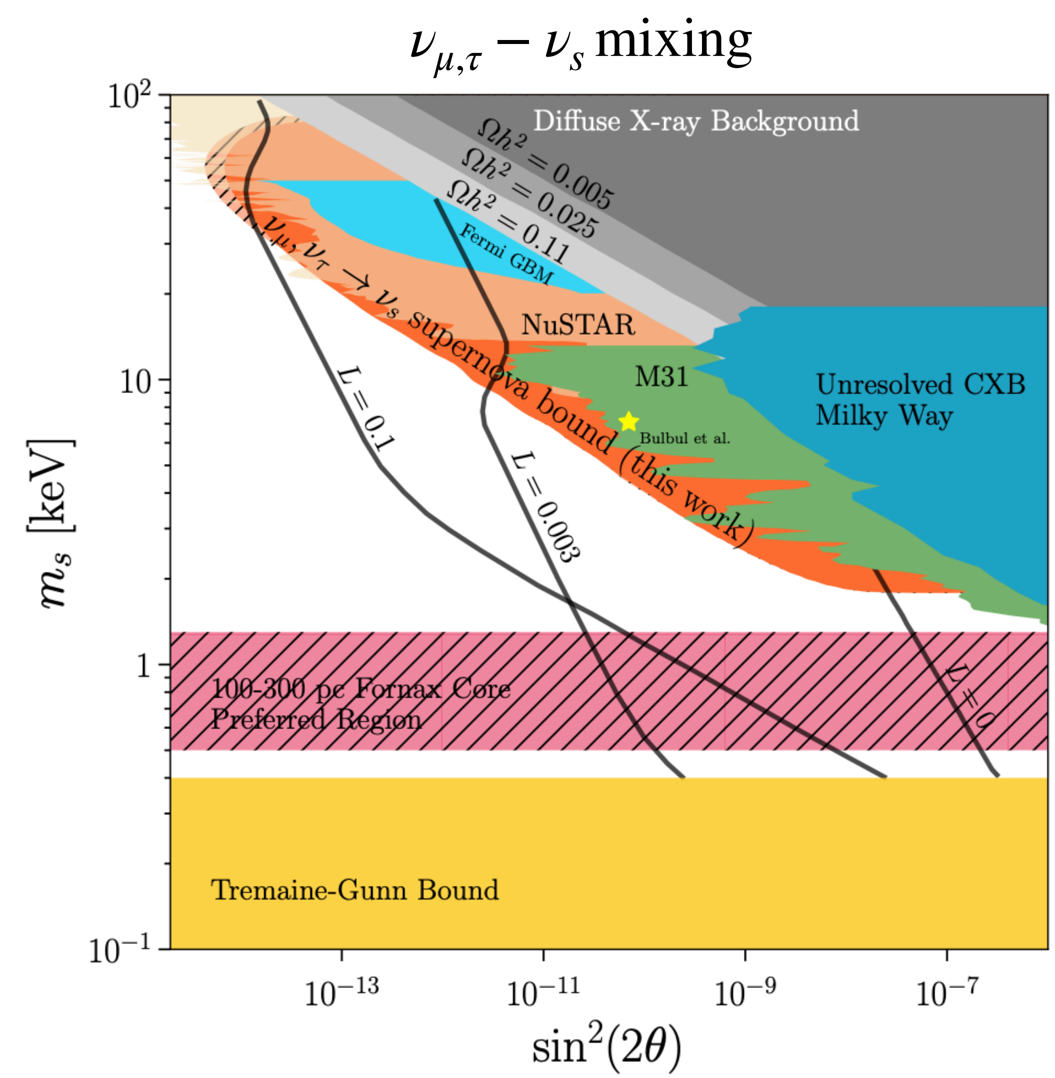
- Sterile neutrino production in SN, through
  (i) adiabatic MSW conversion at radii 10-15 km inside neutrinosphere.

  (ii) collisional production due to $\nu_{\mu,\tau} - n$ scattering.

- Interplay of two main parameters: width of the resonance region and the oscillation length, and m.f.p.

- Constraint from

$$R(\sin^2 2\theta, m_s) = \frac{\varepsilon_s}{\varepsilon_{\text{grav}}} < 1$$



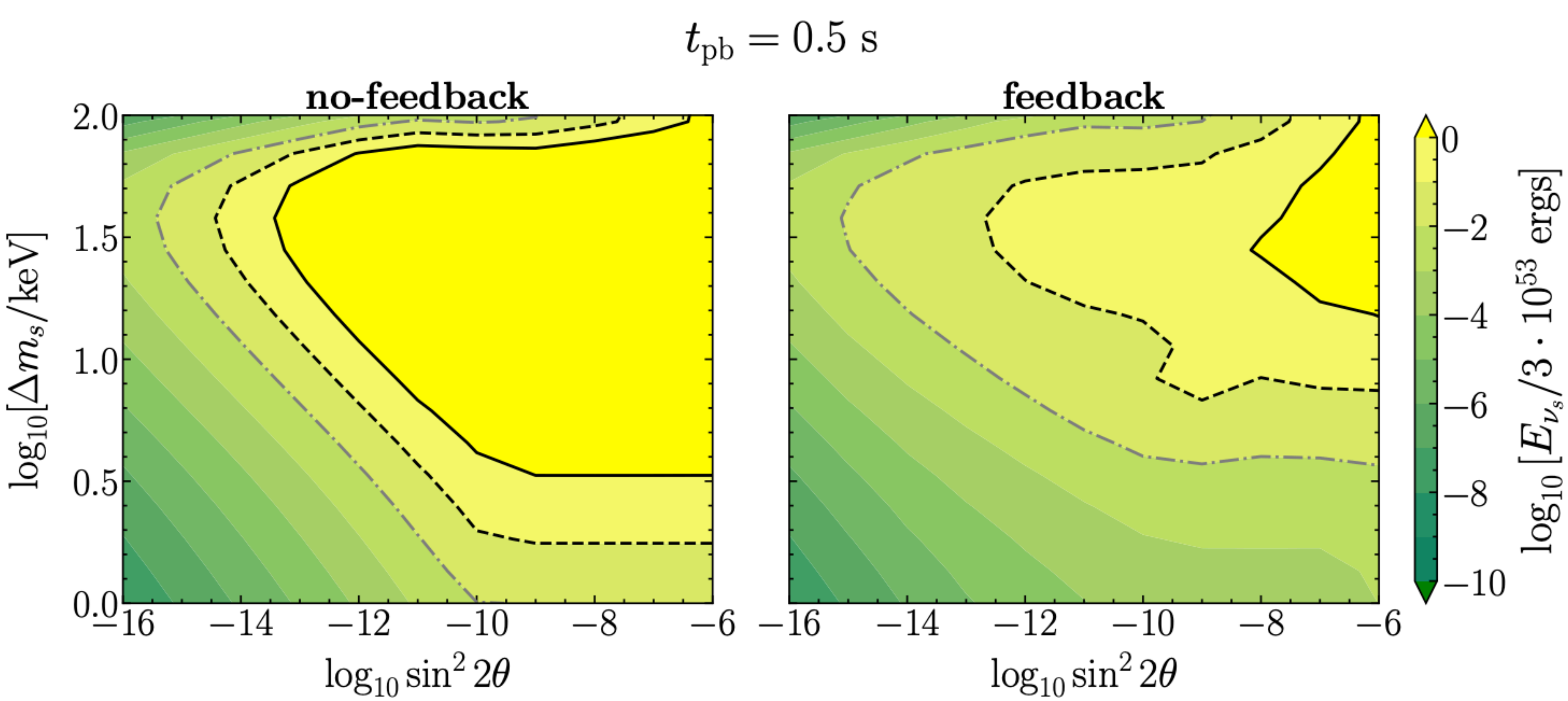
C. Arguelles, V. Brdar, J. Kopp, PRD 2019

But…feedback is important

- ν_s is produced from ν_a. This affects the V_{eff}, which again affects flavor conversions: feedback.

- Neglecting feedback drastically over-estimates the ν_a lepton number.

- Including feedback in multi-zone models relaxes SN bounds.



I. Tamborra, M.Wu, A. Suliga, JCAP (2019)

See also G. Raffelt and S. Zhou PRD (2011), for an earlier discussion of feedback in one-zone models.

Consider $\nu_e - \nu_s$ mixing

- Possibility of multiple MSW resonances inside core. Important for shock-reheating?

- Sophisticated analysis including feedback suggests possible parameter space.

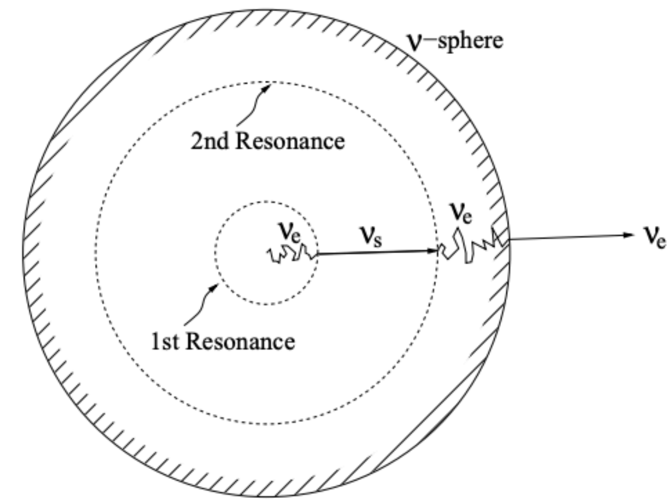
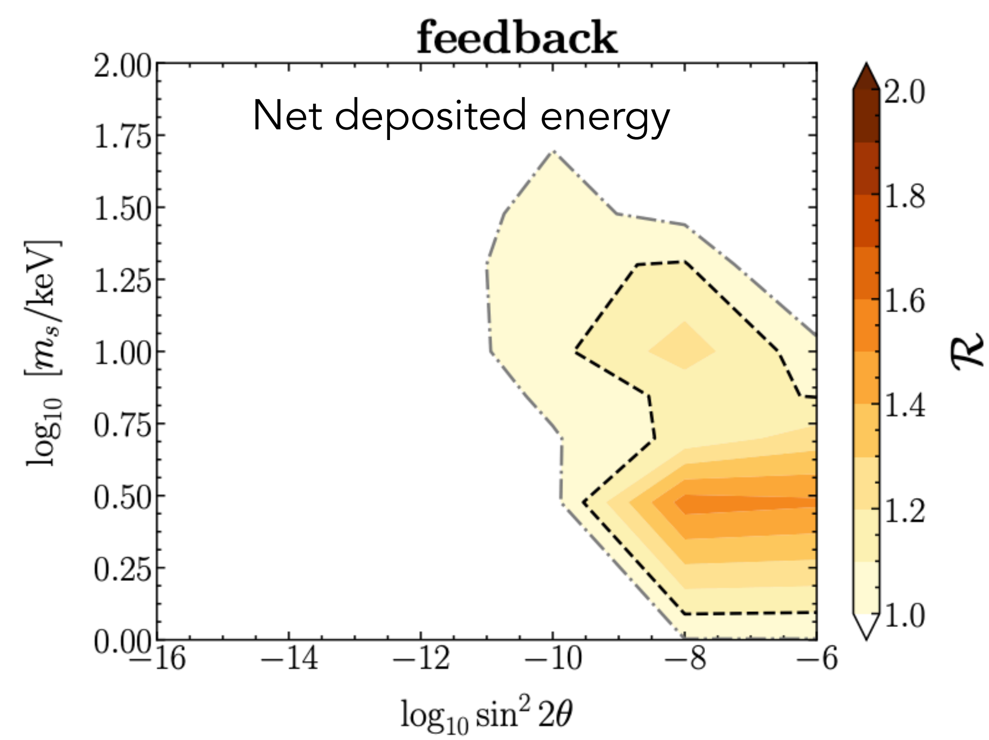


FIG. 8: High energy ν_e's could be converted to sterile neutrinos deep in the core and then re-generated as ν_e further out, nearer the neutrino sphere (edge of core).

J. Hidaka, G. Fuller, PRD (2007)



I. Tamborra, M.Wu, A. Suliga, JCAP (2020)

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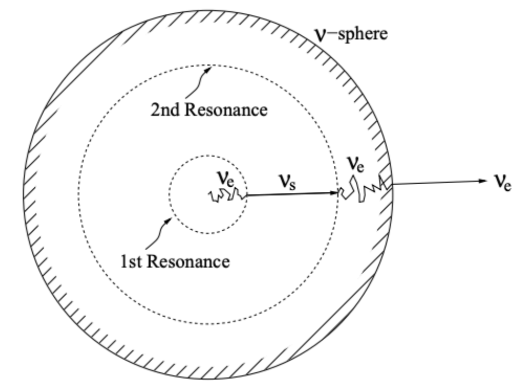

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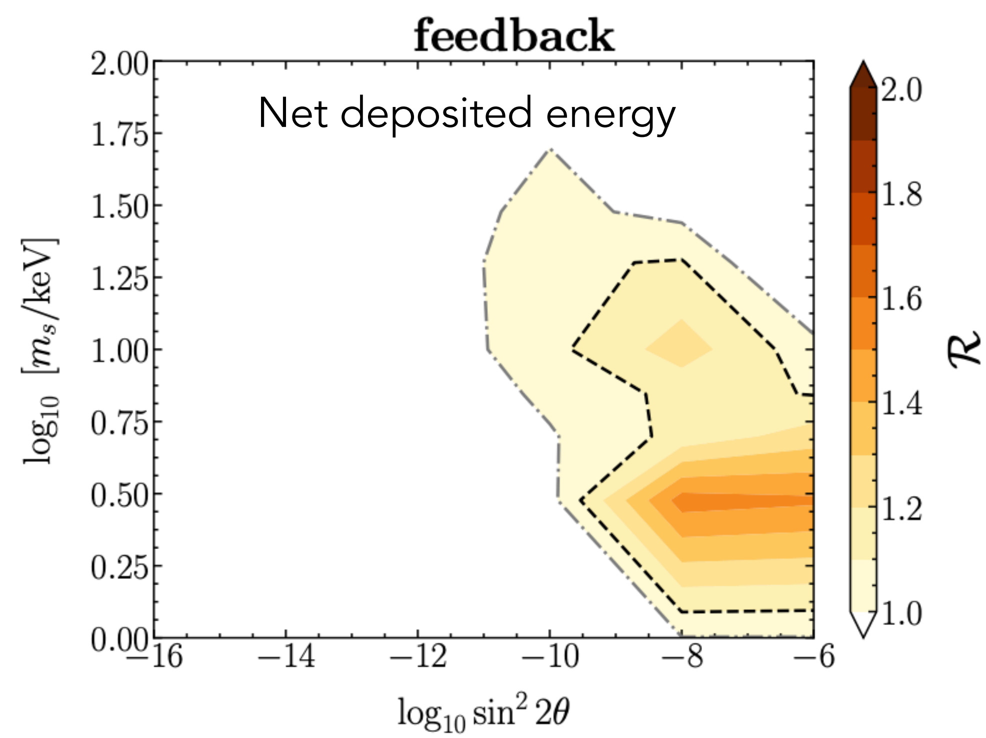
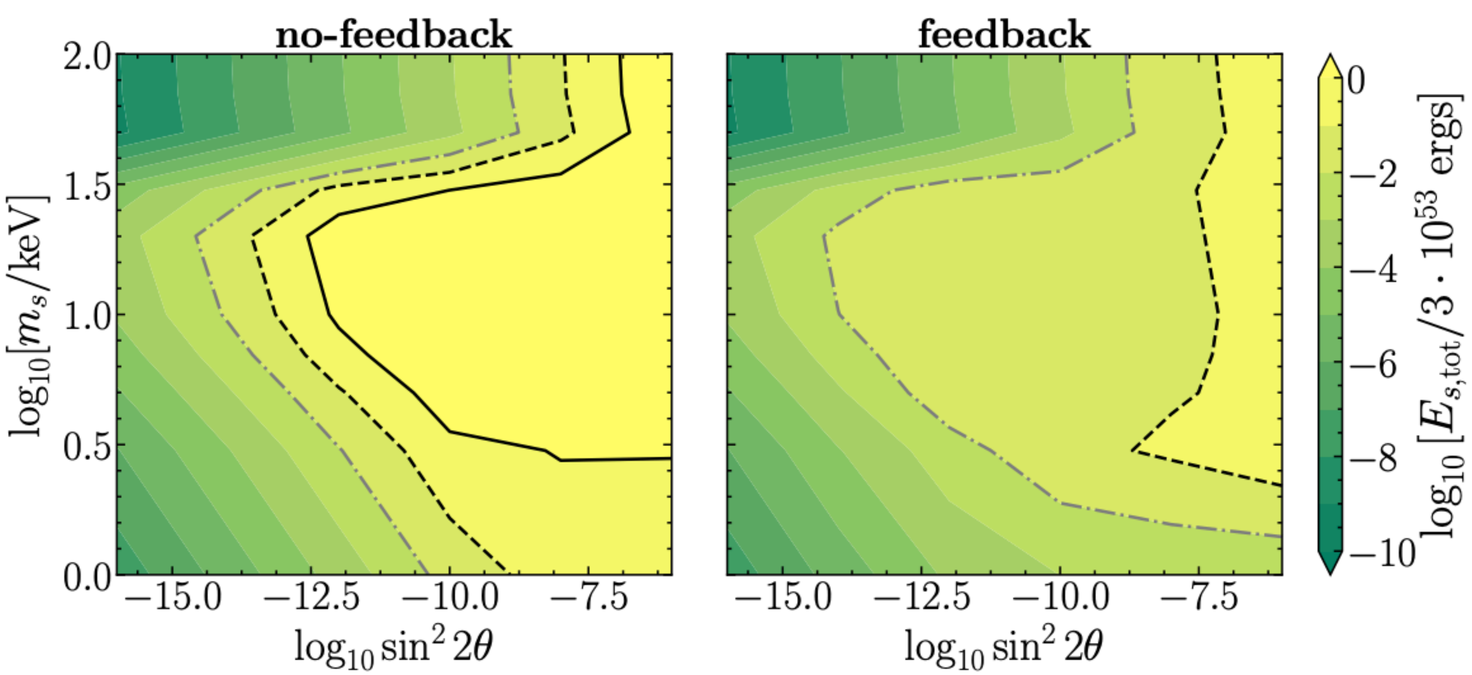
J. Hidaka, G. Fuller, PRD (2007)

- Sophisticated analysis including feedback suggests possible parameter space.

- No such cooling bounds once feedback is included.

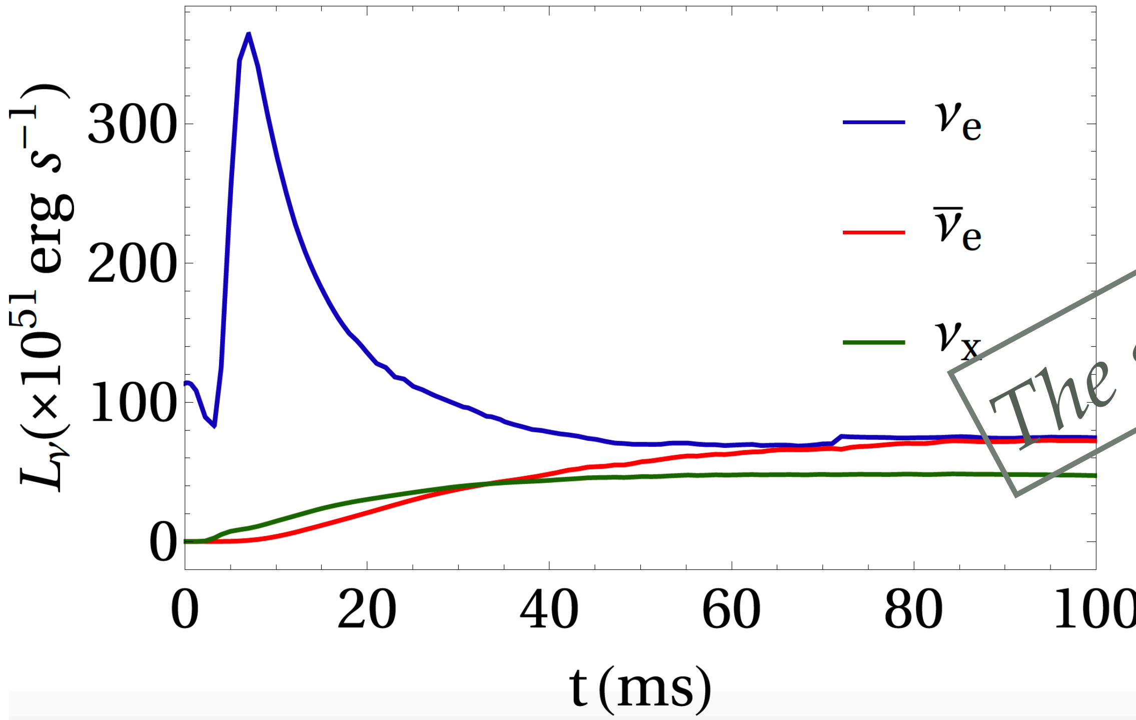




I. Tamborra, M.Wu, A. Suliga, JCAP (2020)

Impact on the neutrino spectra/flux

The neutronization burst: a foreward

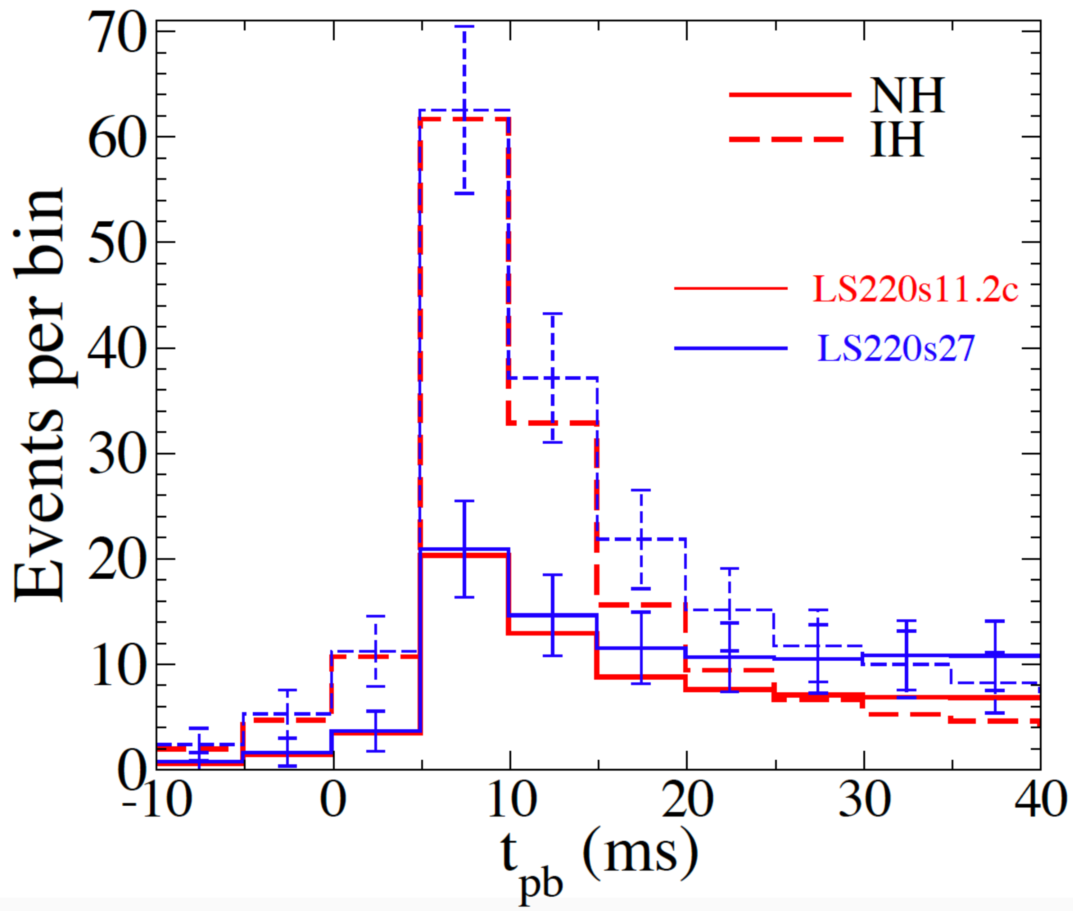


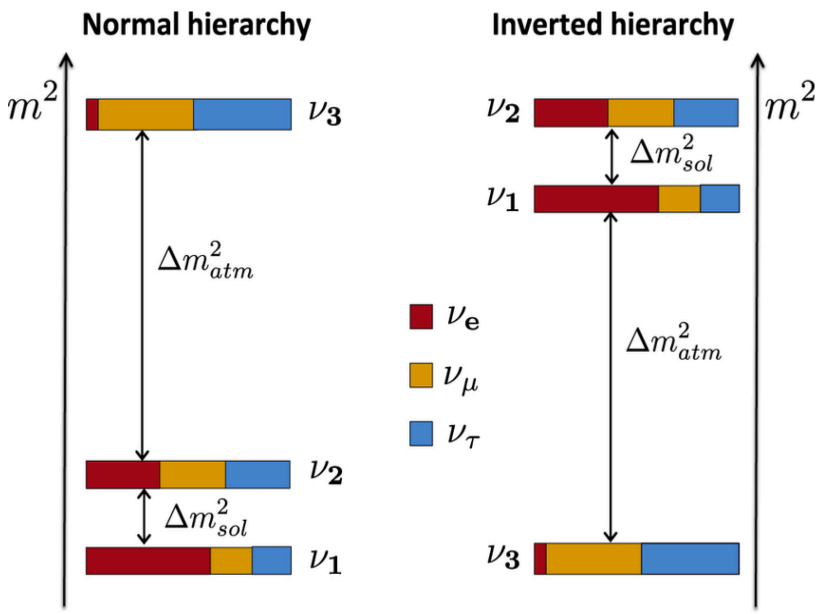
The shock-breakout burst

- Large burst of ν_e in the first ~30 ms post bounce.
- Robust feature of all simulations.
- Large ν_e excess, *hence no collective oscillations within the SM*. (Remember $\nu_e\overline{\nu}_e \leftrightarrow \nu_\mu\overline{\nu}_\mu$!)

See talk by Francesco for further details

Sensitivity to neutrino mass ordering





ν_e is produced as ν_3 (ν_2) in NH (IH).

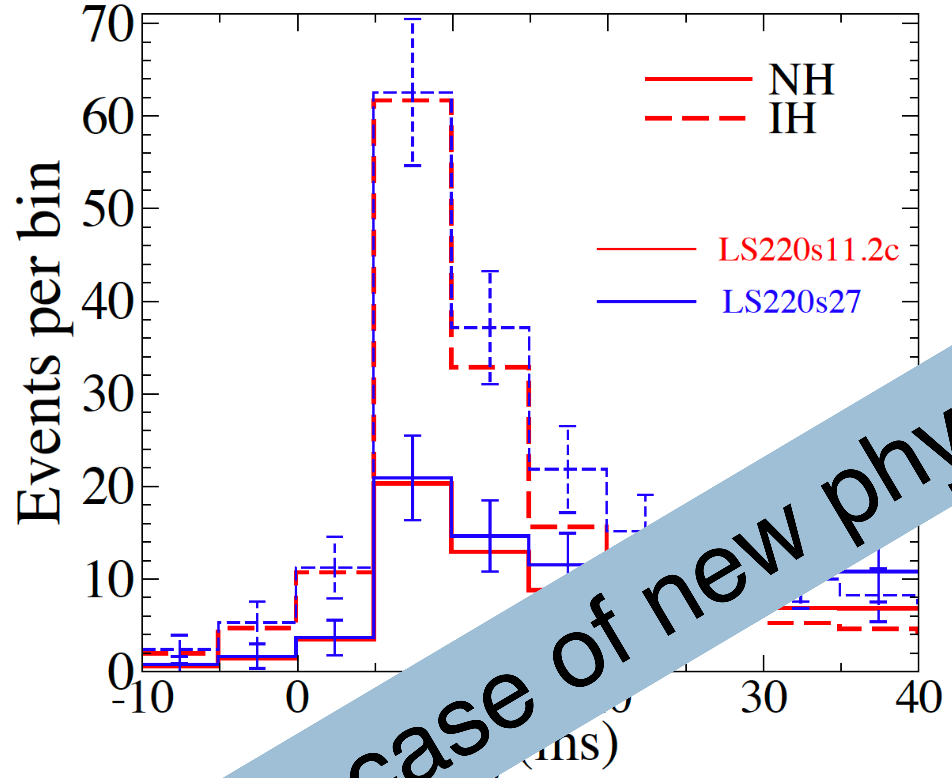
$L_{\nu_e}(R_E) \simeq |U_{e2}|^2 \, L^0_{\nu_e} = 0.2 \, L^0_{\nu_e}$ IH

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

A. Dighe, A. Smirnov, PRD (2000)

Independent probe of mass ordering!

Sensitivity to neutrino mass ordering



What happens in case of new physics?

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

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

Independent probe of mass ordering!

3. Non-standard (self)interactions

Non-standard interactions

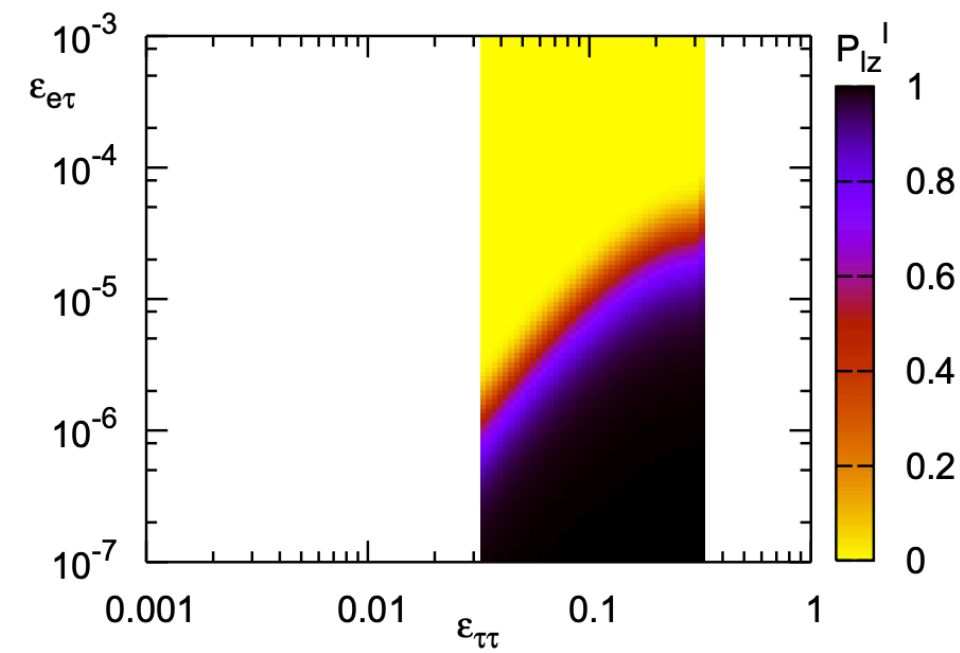
- Presence of NSI can lead to important consequences in dense core
$\mathscr{L} \supset \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F \, (\bar{\nu}^{\alpha} \gamma^{\mu} L \, \nu^{\beta}) \, (\bar{f} \gamma_{\mu} P f)$

- Extra potential $V = \sqrt{2} G_F N_f \, \varepsilon^{fP}_{\alpha\beta}$

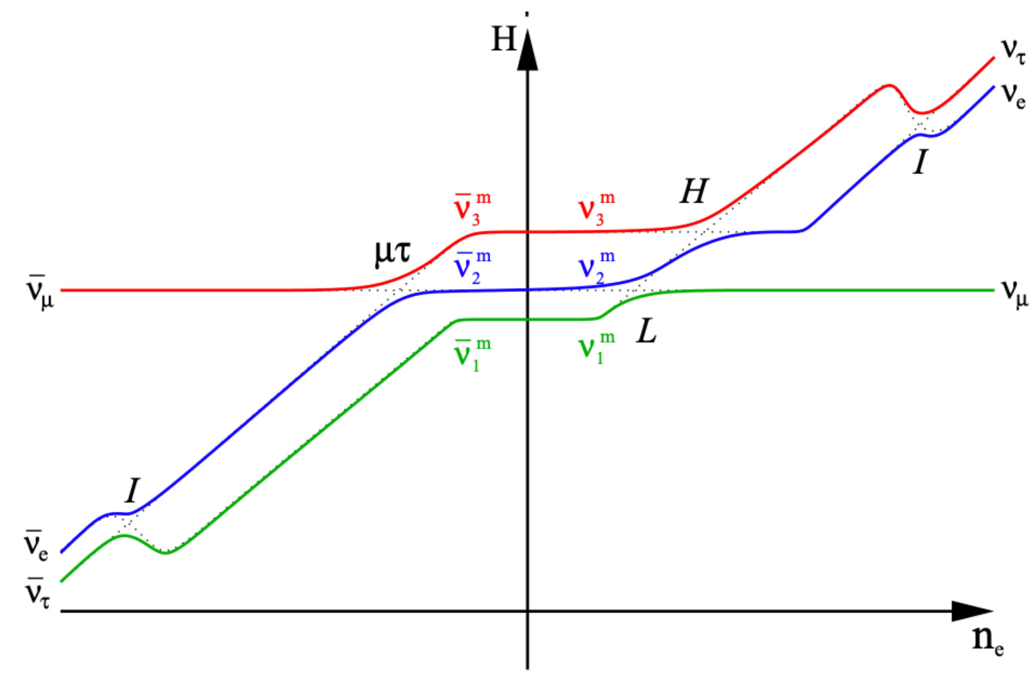
- Leads to an extra resonance ('I' resonance) if $H_{ee} = H_{\mu\mu}, H_{\tau\tau}$. Changes flavor content deep inside the SN.

- Can reduce Y_e during collapse, leading to lower shock energy.

P. Amanik, G. Fuller, PRD (2007)
See also P. Amanik, G. Fuller, B. Grinstein, Astropart. Phys (2005)



A. Esteban-Pretel, R. Tomas, J. Valle, PRD (2007)



A neutrinophilic ϕ

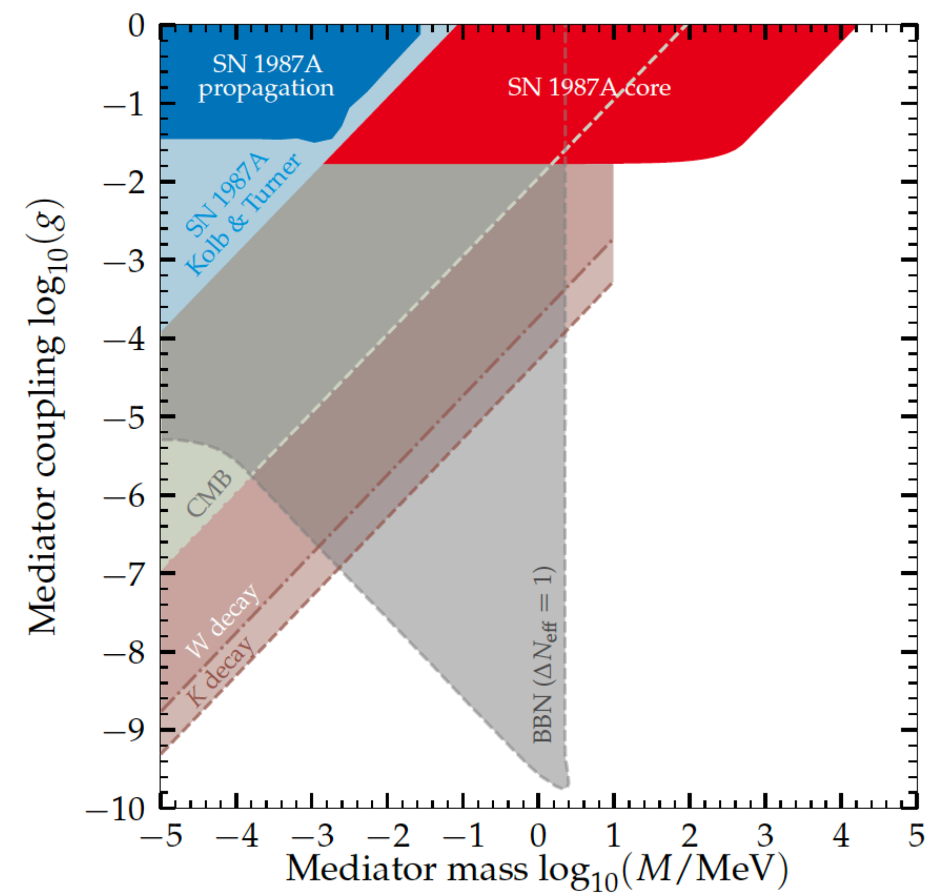
- Consider a neutrinophilic scalar
  $\mathscr{L} \supset g\,\nu\nu\phi$

- Leads to $\nu\bar{\nu} \to 2\nu 2\bar{\nu}$. Doubles ν number density, but energy is halved.
  Cannot transfer enough energy to stalled shock (red region).

- Additional bounds from scattering with CνB, and losing energy (blue region).

- Additional bounds due to modification of stellar physics.

G. Fuller, R. Mayle, J. Wilson, Astrophys. J. (1988)
M. Kachelreiss, R. Tomas, J. Valle, PRD. (2000)
Y. Farzan PRD (2000)



S. Shalgar, I. Tamborra, M. Bustamante, arXiv:1912.09115

Non-standard self-interactions

- Consider $\mathscr{L} \supset G_F\, (G_{\alpha\beta}\,\bar{\nu}^{\alpha}\,\gamma^{\mu} L\, \nu^{\beta})\; (G_{\eta\delta}\;\bar{\nu}^{\eta}\,\gamma^{\mu} L\, \nu^{\delta})$,

$$\boxed{x = \mu, \tau}$$

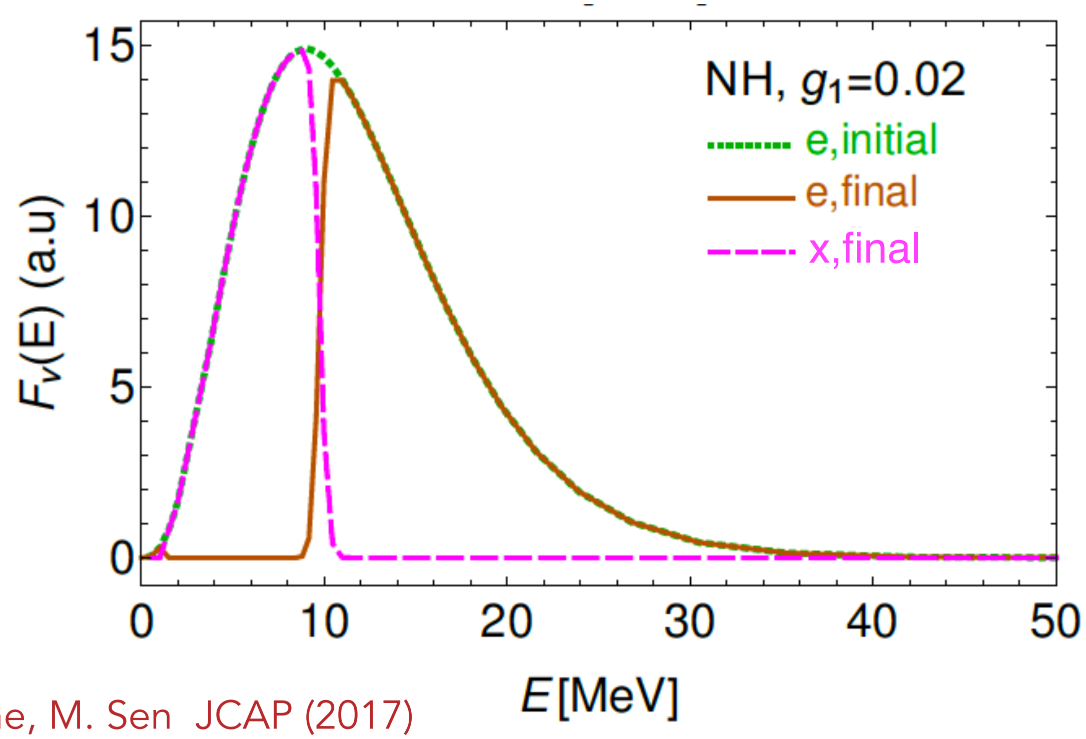
where most generally, $G = \begin{pmatrix} 1 + g_{ee} & g_{ex} \\ g_{ex} & 1 + g_{xx} \end{pmatrix}.$

- Non-linear EoMs, extremely sensitive to νSI.

G. Raffelt, G. Sigl NPB (1993)
M. Blennow, A. Mirizzi, P. Serpico, PRD (2008)

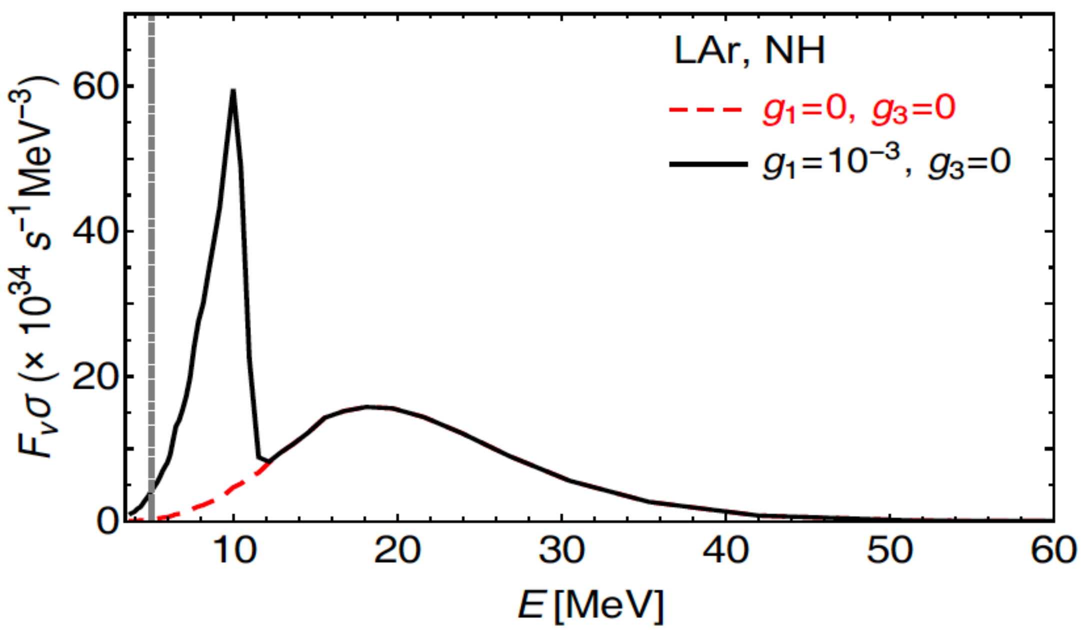
$$i\, d_t\, \varrho_p = \left[H_{\rm vac} + H_{\rm mat} + \sqrt{2} G_F \int d\mathbf{q}\, G\, \varrho_q\, G\,, \varrho_p \right],$$

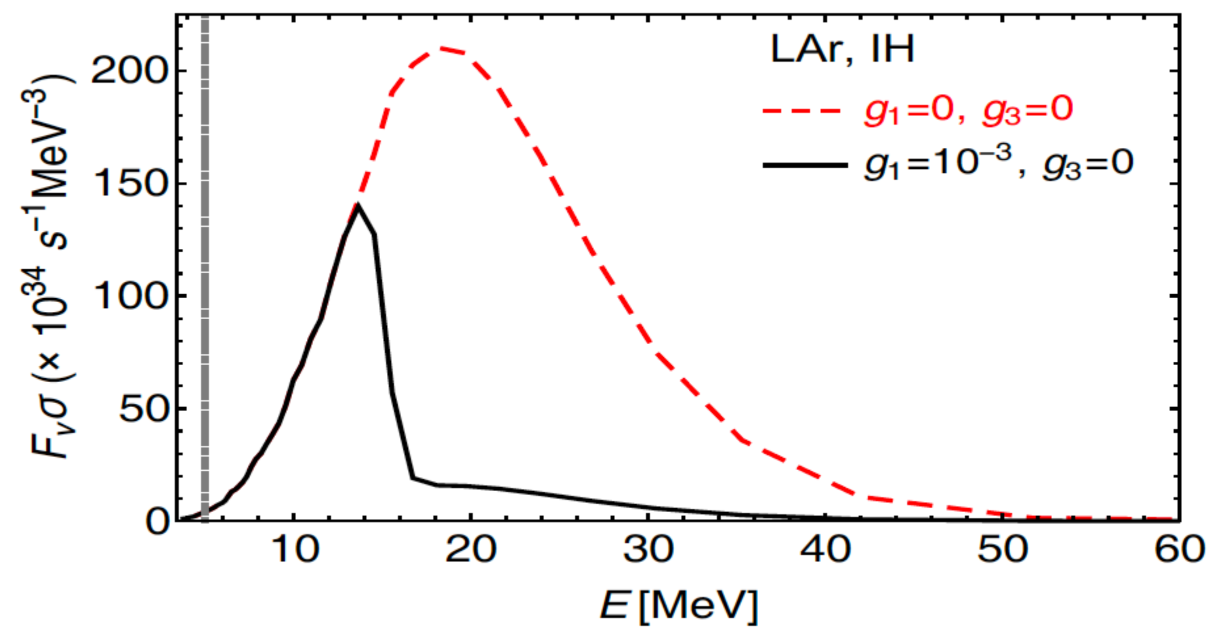
- $g_{ex} \neq 0$ can populate ν_x from ν_e during neutronization. Cause collective oscillations now, giving distinct spectral splits in neutronization spectra.



A. Das, A. Dighe, M. Sen JCAP (2017)

Smoking-gun signal of NSSI





A. Das, A. Dighe, M. Sen JCAP (2017)

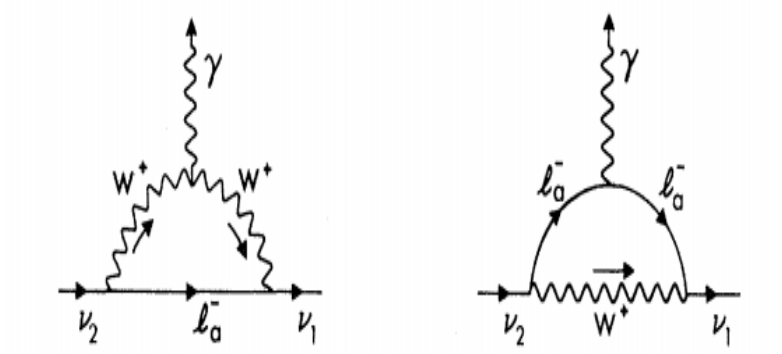
- Due to collective oscillations in the neutronization phase, distinct splits can be detected at DUNE.
- Put flux dependent constraints on NSSI.
- Caveat: sensitive to details of collective oscillations! Should be explored in more details.

M. Sen, I. Tamborra, M.Wu, in prep

4. Neutrino decay & properties

Non-standard neutrino decay

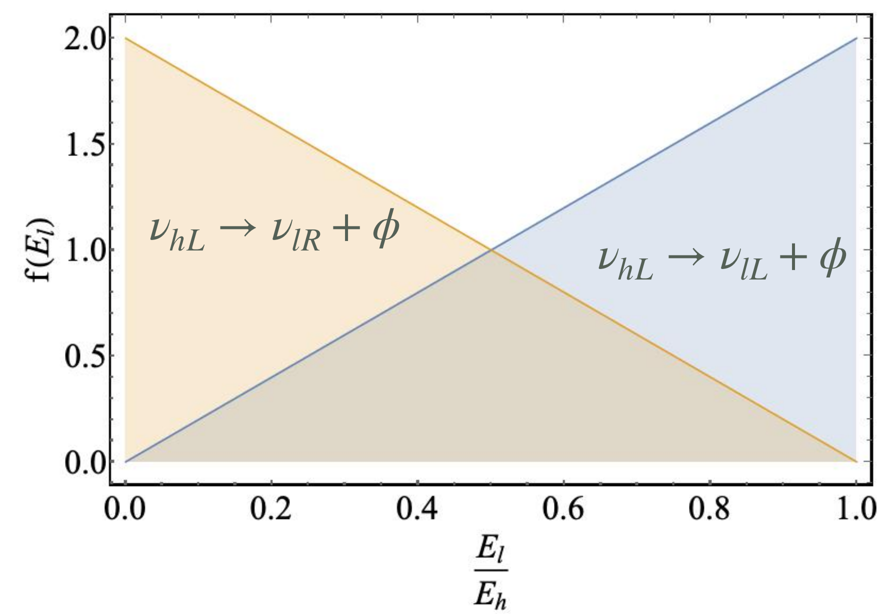
- Massive neutrinos can decay to lighter ones even within the SM. Age longer than universe.



Pal and Wolfenstein PRD (1982)

- New physics can mediate faster decay.

$$\mathscr{L} \supset \nu_h \nu_l \phi + \mathrm{H.c.}$$



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

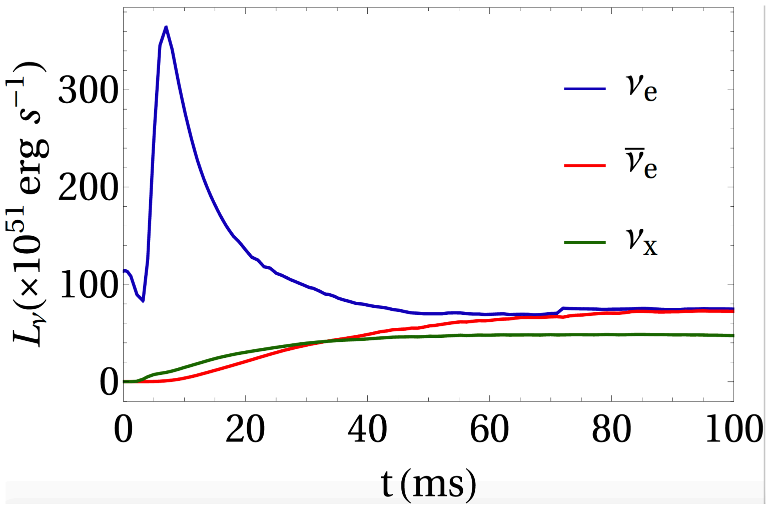
$\nu_{hL} \to \nu_{lR} + \phi$ .... Helicity flip. (h.f.)

Use the neutronization flux to

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

(ii) Distinguish between Dirac and Majorana nature.

The game plan



Normal Ordering

S. Ando PRD (2004)
A. de Gouvea, I. Martinez-Soler, M. Sen PRD (2019)

For a detailed theoretical framework of neutrino decay, see
M. Lindner, T. Ohlsson, W. Winter, NPB (2002)

NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim 0.02\, \nu_3$

DECAY

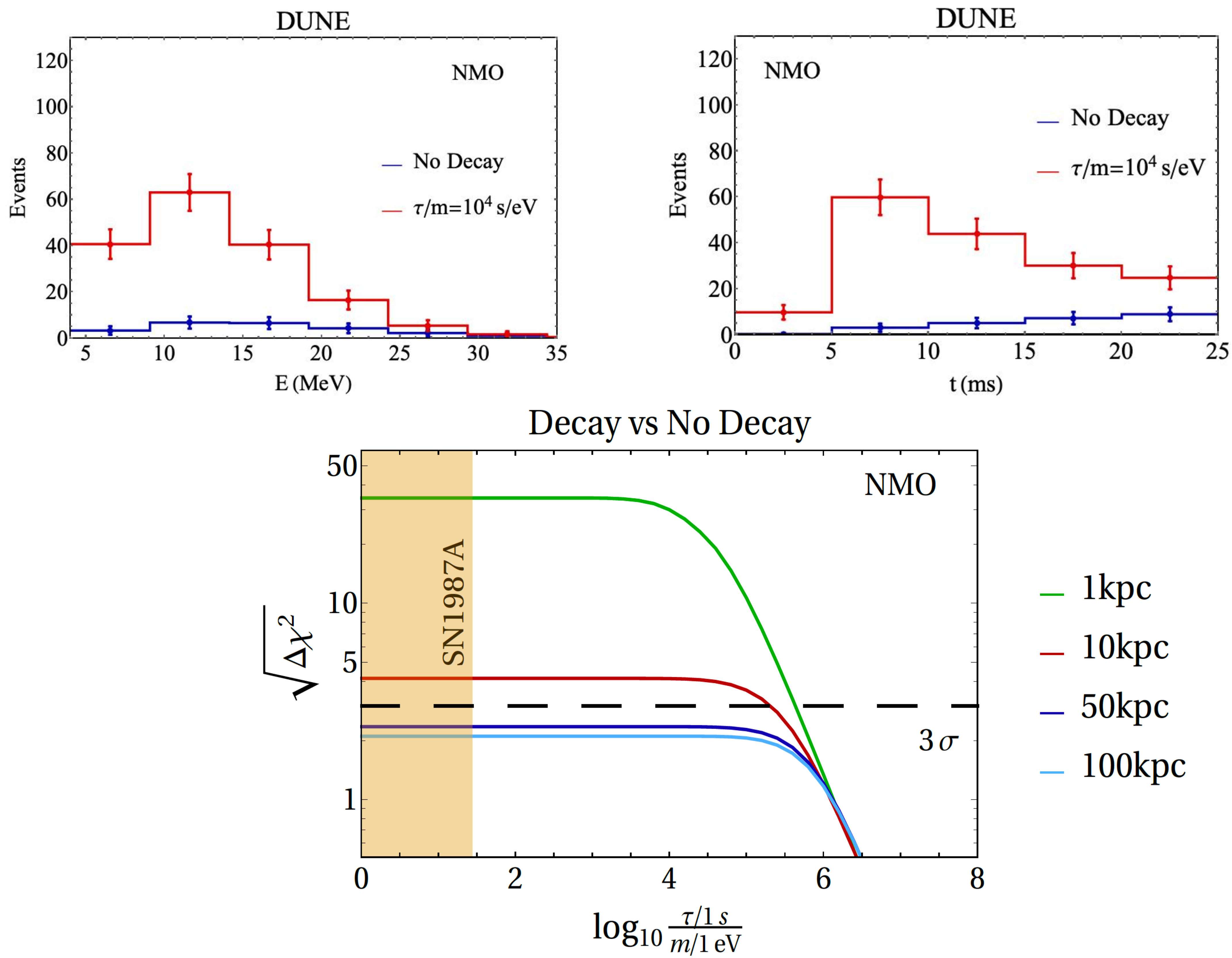
$\nu_l \equiv \nu_1$

$\nu_h \equiv \nu_3$

$\nu_e \sim 0.7\, \nu_e^{\mathrm{in}}$

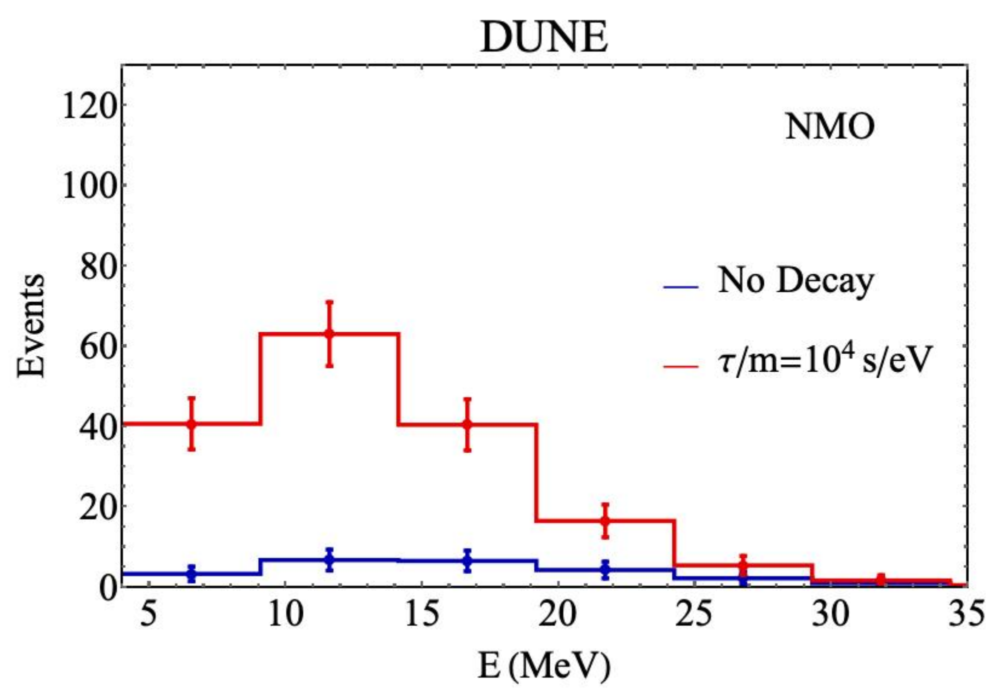
Enhancement in spectra

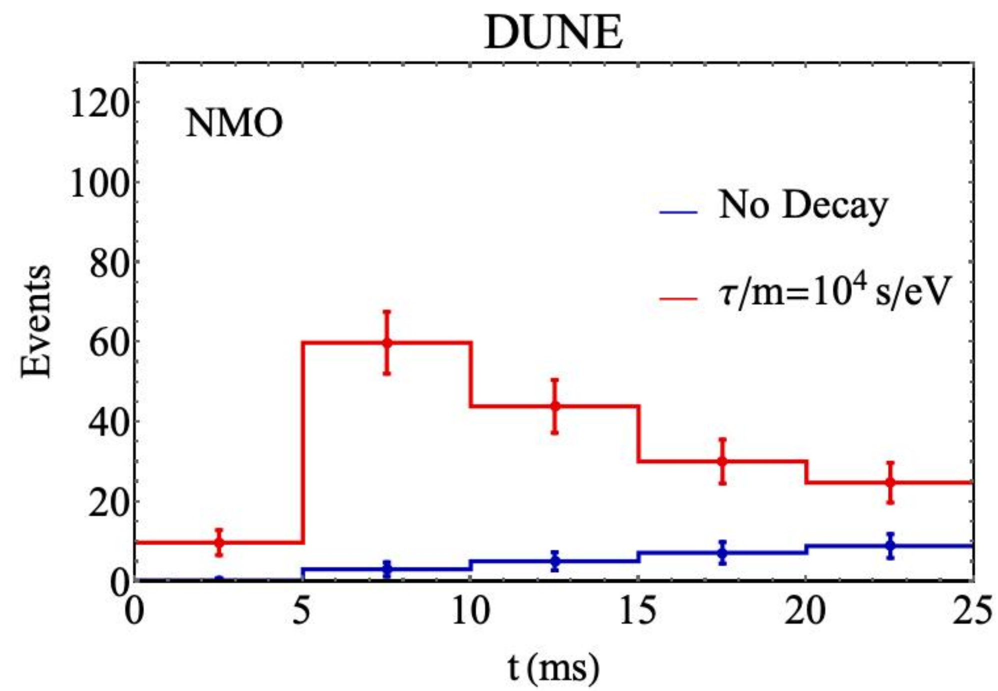
Simulated data in DUNE

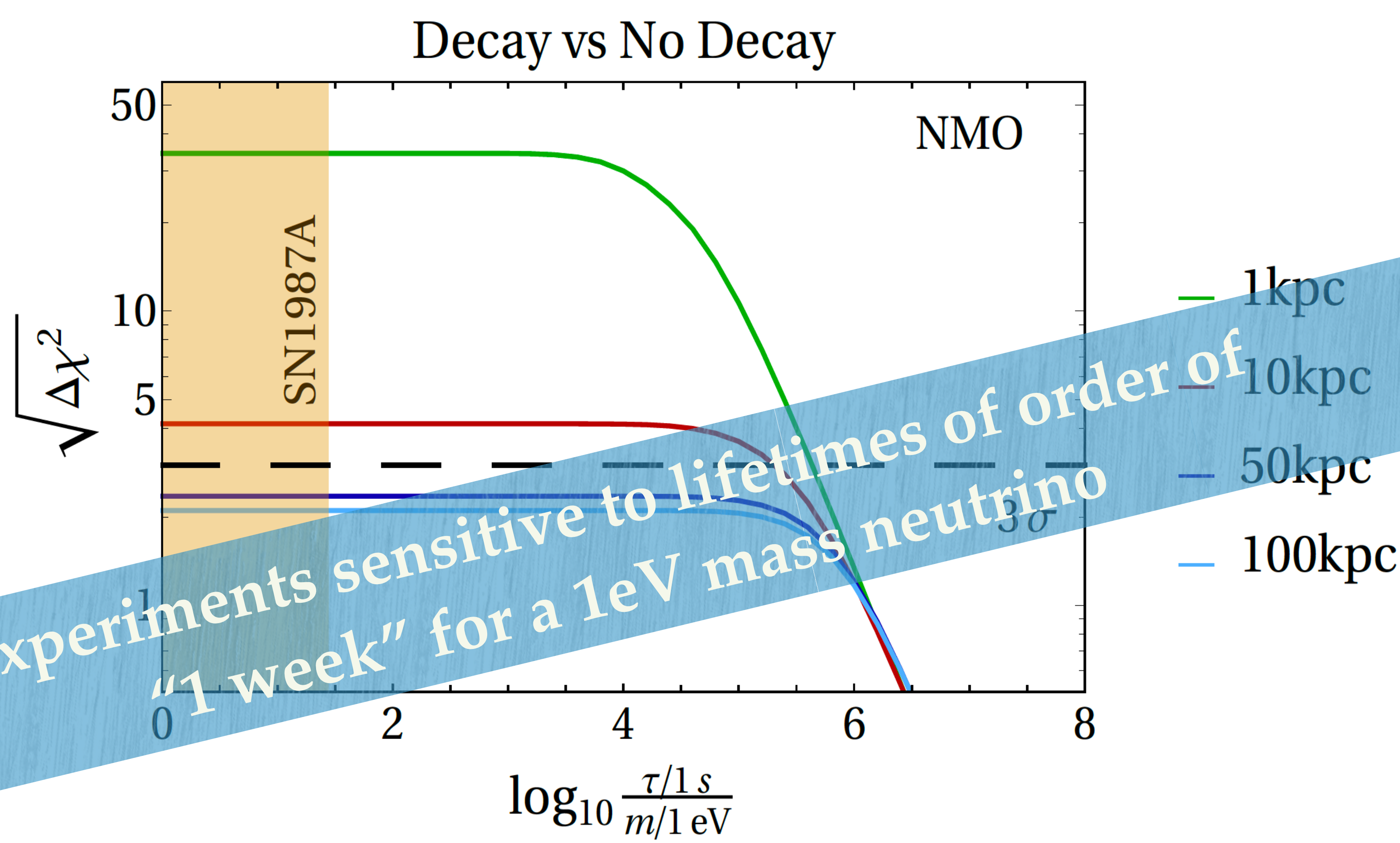


A. de Gouvea, I. Martinez-Soler, M. Sen PRD (2019)

Simulated data in DUNE







Experiments sensitive to lifetimes of order of "1 week" for a 1eV mass neutrino

A. de Gouvea, I. Martinez-Soler, M. Sen PRD (2019)

Dirac vs Majorana

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

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

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

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

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

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

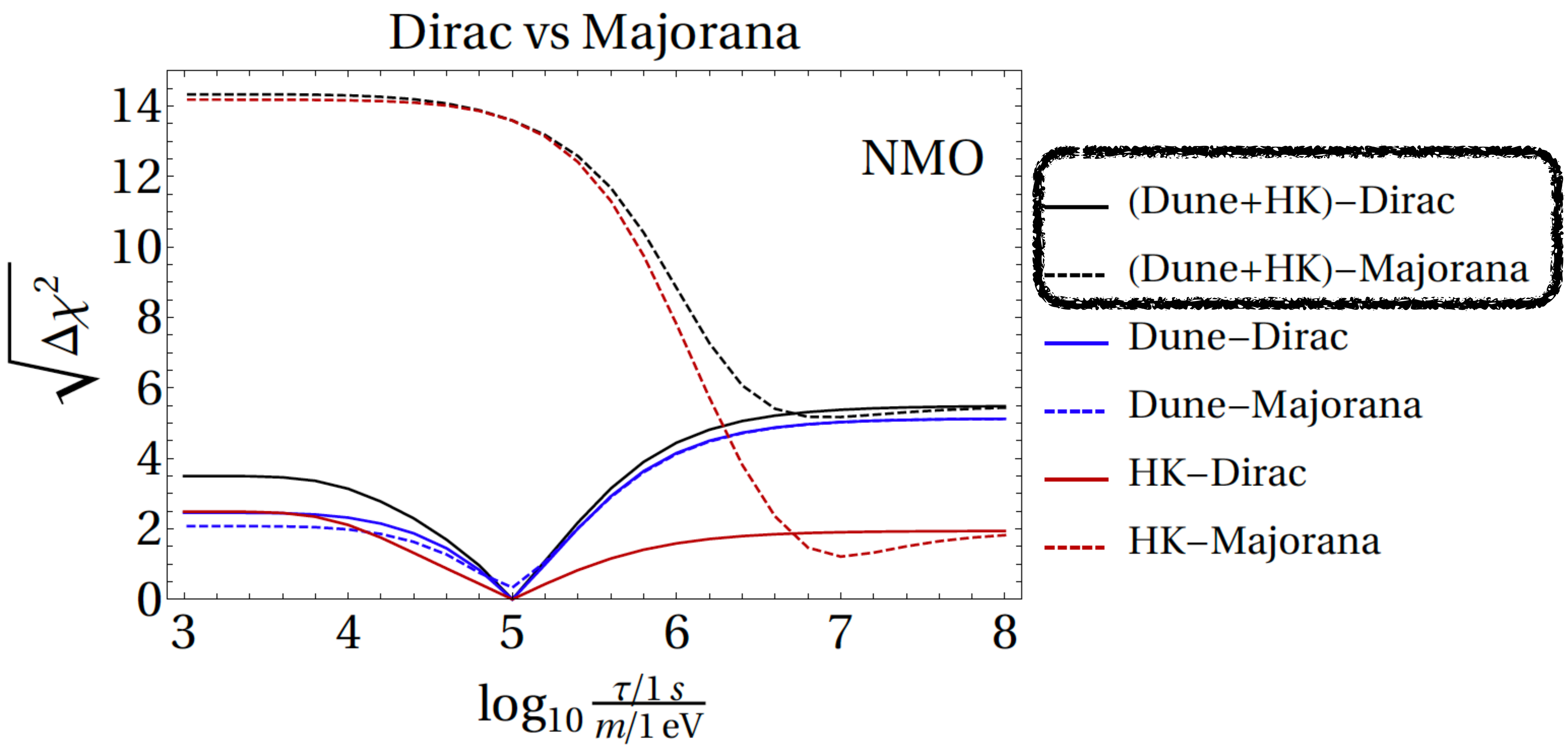
$$\nu_{hL} \to \nu_{lR} + \phi$$

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

Different signatures in detectors sensitive to ν_e and $\overline{\nu}_e$.

Look at DUNE and HK

Distinguishing capacity: Dirac(D) vs Majorana (M)



- Simulate data consistent with Dirac neutrinos and $\tau/m = 10^5\mathrm{s/eV}$.

- A combination of DUNE+ HK can distinguish between Dirac and Majorana neutrinos at 5σ.

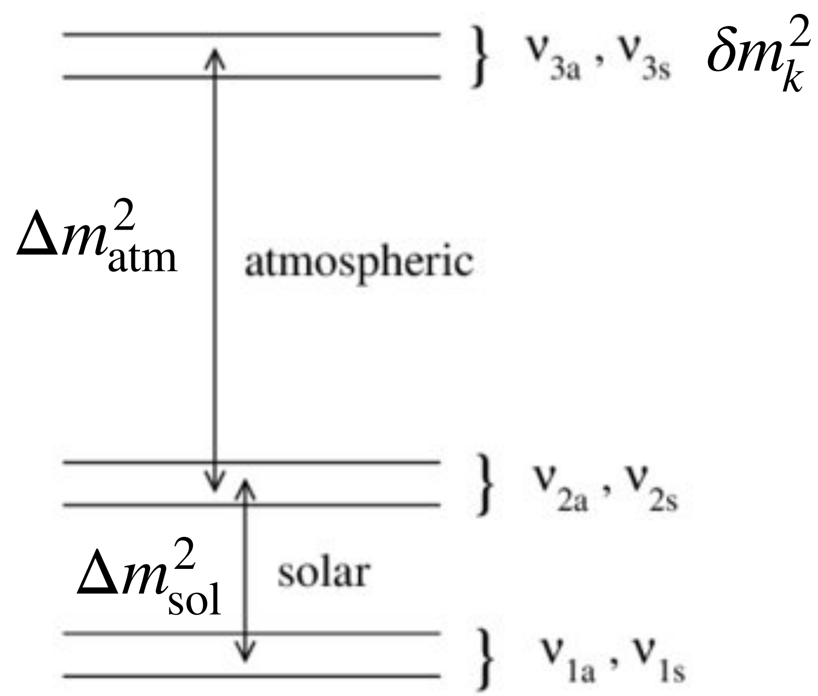
A. de Gouvea, I. Martinez-Soler, M. Sen PRD (2019)

Pseudo-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 : $m_{L,R} \ll m_D$



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

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

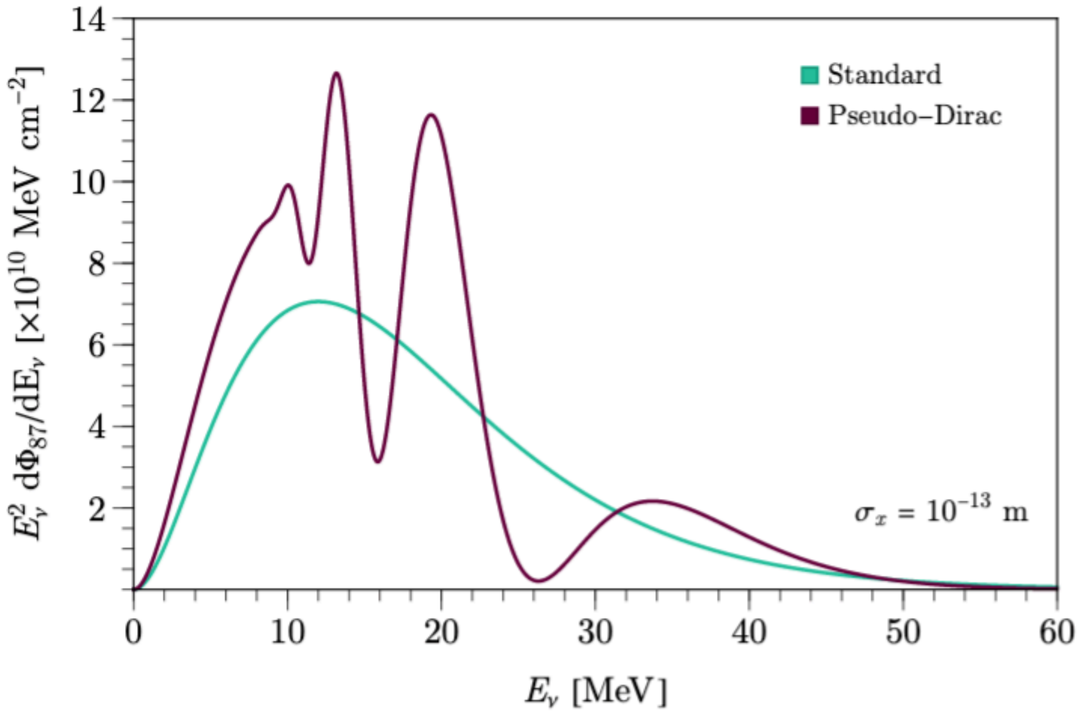
- Maximally mixed active and sterile states. Oscillations driven by this tiny mass.

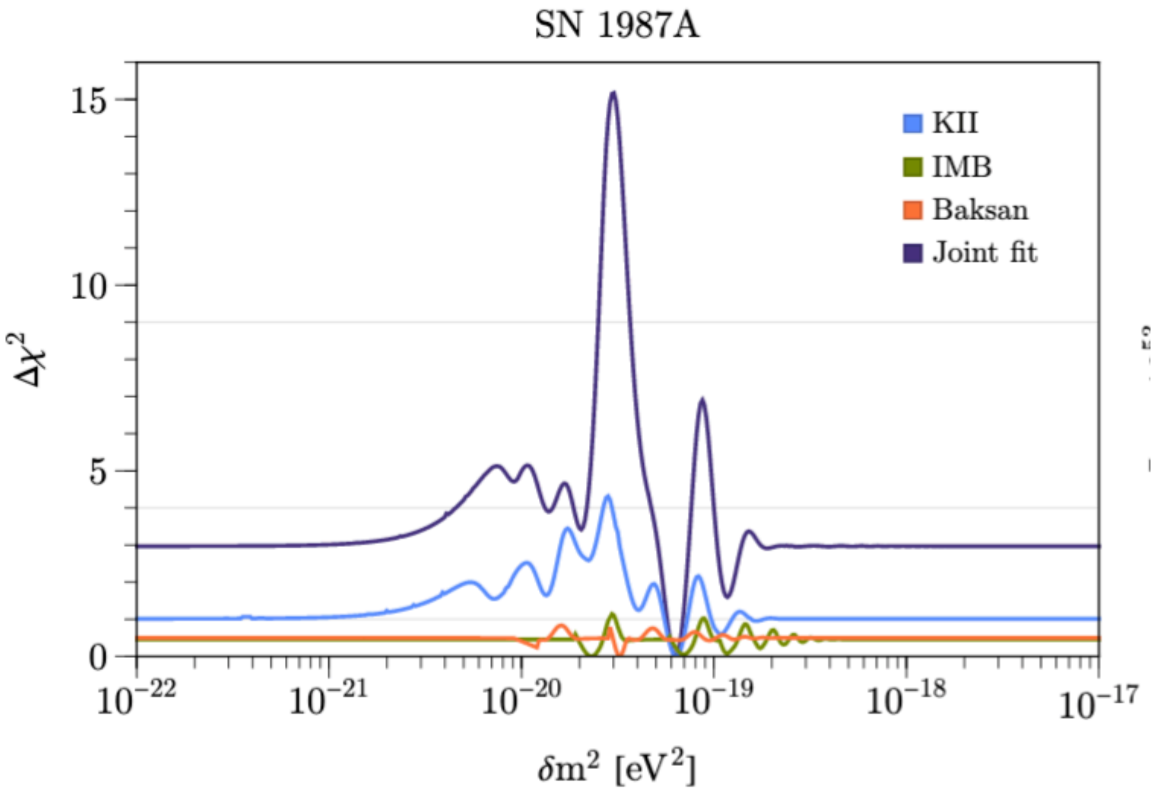
I. Martinez-Soler, Y. Perez-Gonzalez, M. Sen, in prep

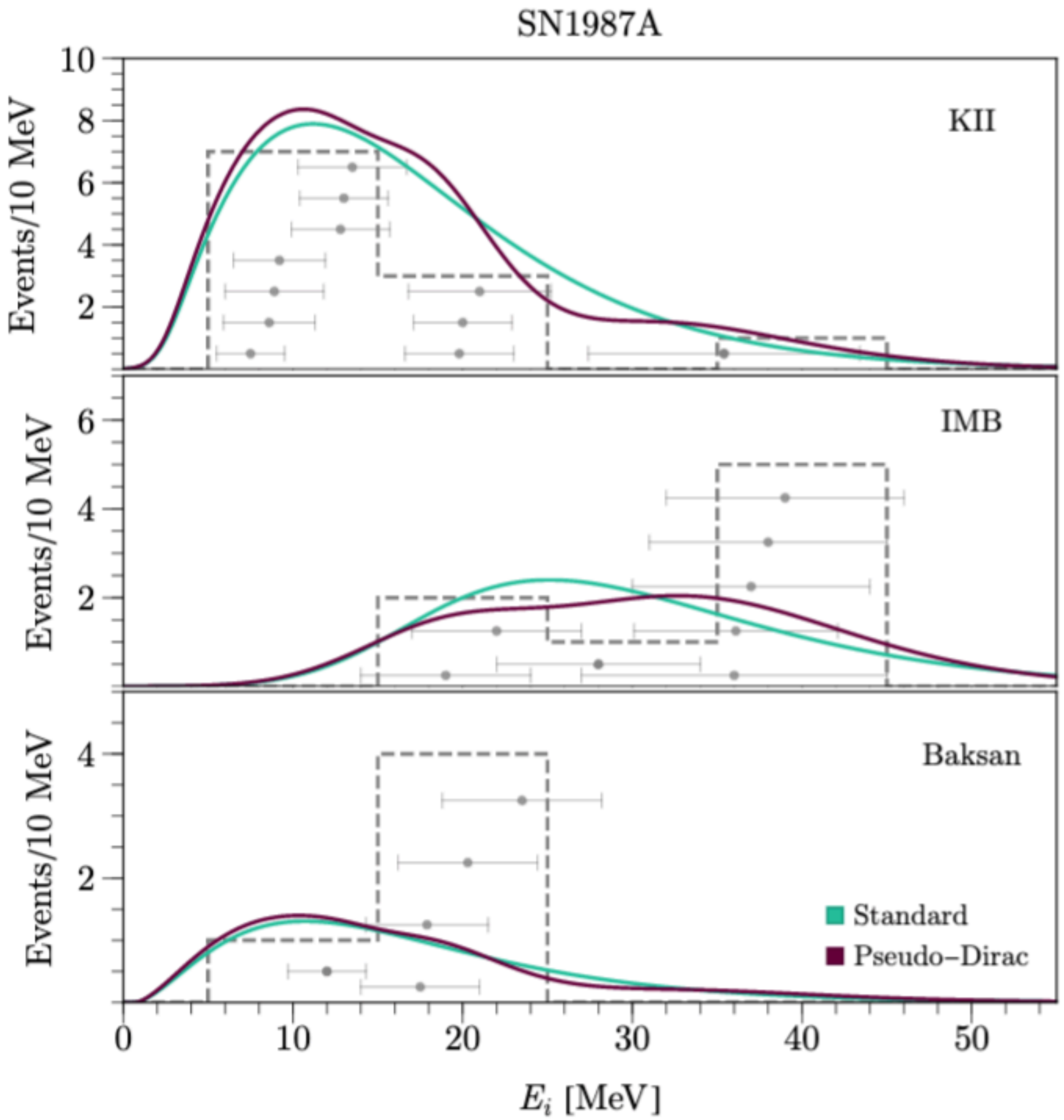
Bounds:

1. Solar neutrinos $\delta m^2 = 10^{-12}\,{\rm eV}^2$
   de Gouvea, Huang, Jenkins, PRD2009
2. Atmospheric neutrinos
   $\delta m^2 > 10^{-4}\,{\rm eV}^2$
   Beacom, Bell, et al., PRL2004
3. High energy astrophysical neutrinos
   $10^{-18}\,{\rm eV}^2 < \delta m^2 < 10^{-12}\,{\rm eV}^2$
   Esmaili, Farzan, JCAP2012

Pseudo-Dirac neutrinos: SN1987A





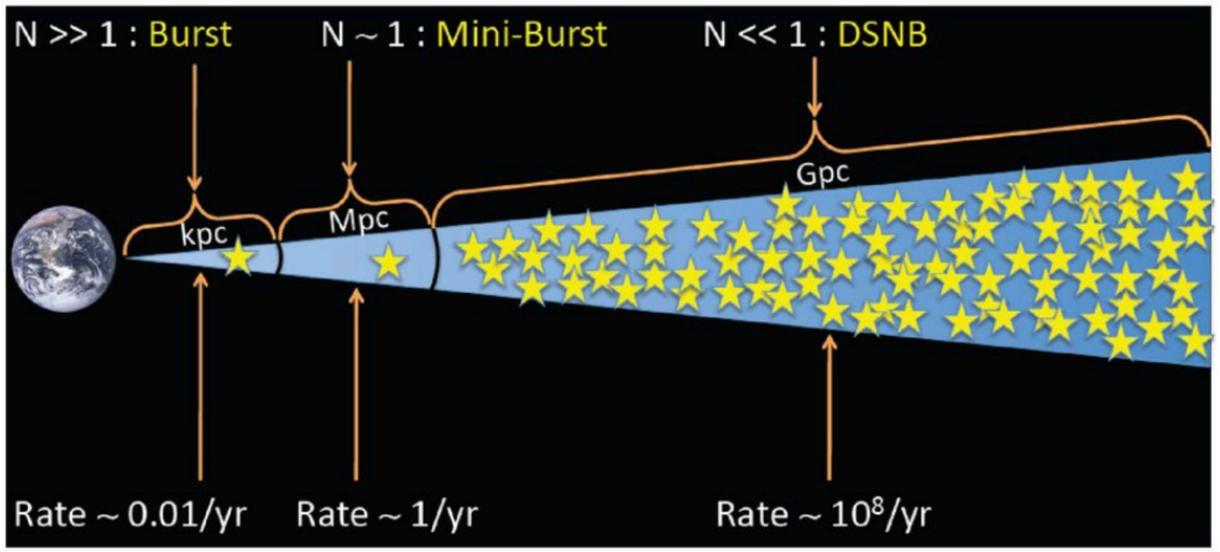


Preference for $\delta m^2 = 6.31 \times 10^{-20} \mathrm{eV}^2$ over the un-oscillated scenario by $\Delta\chi^2 \approx 3$.

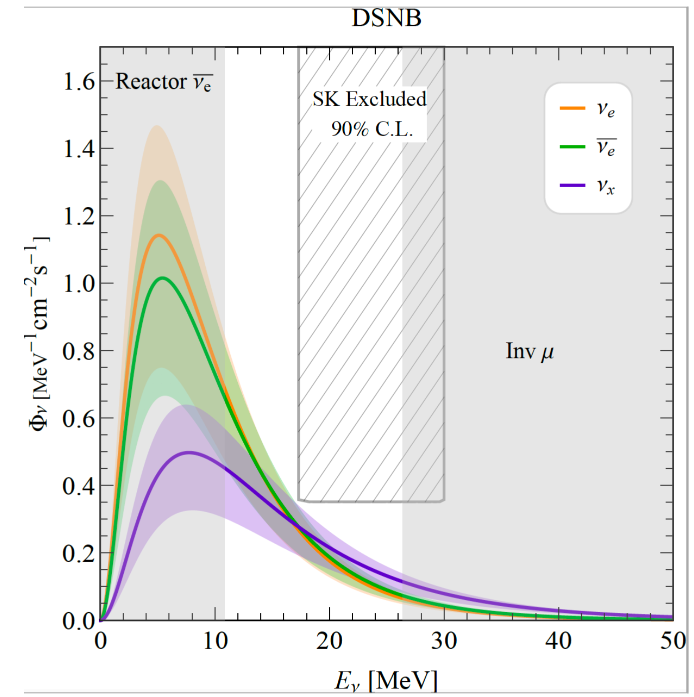
I. Martinez-Soler, Y. Perez-Gonzalez, M. Sen, in prep

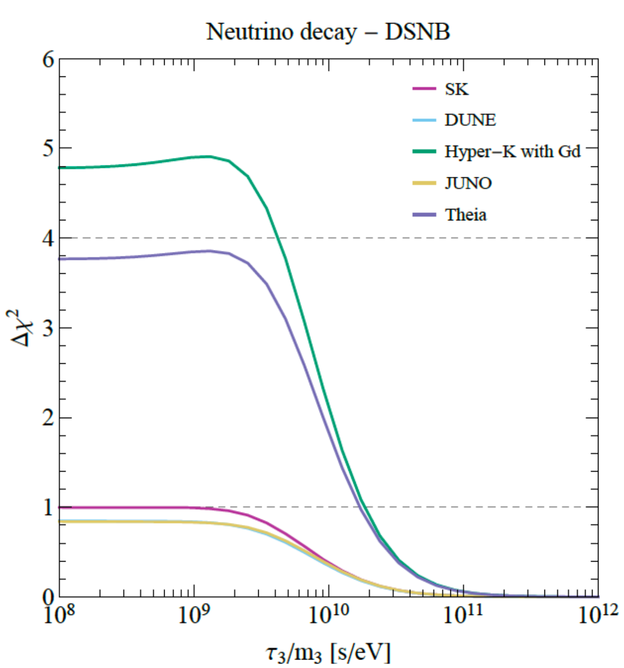
Finally, the DSNB: an omnipresent laboratory

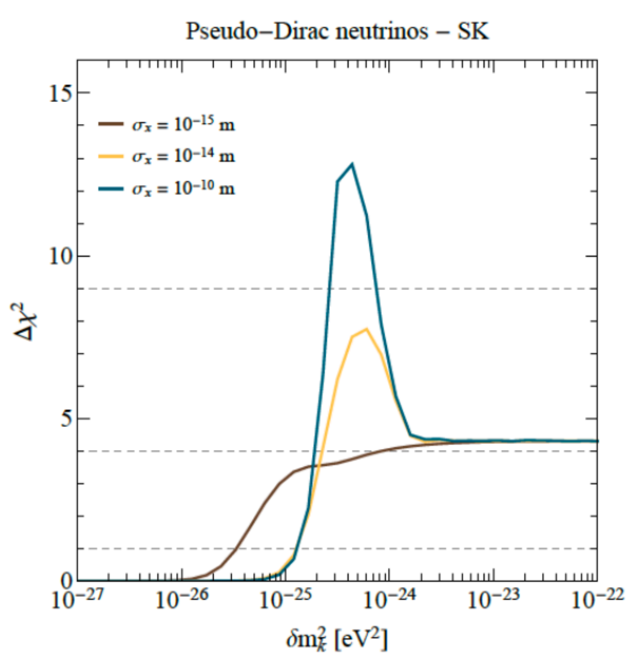
John Beacom, TAUP2011

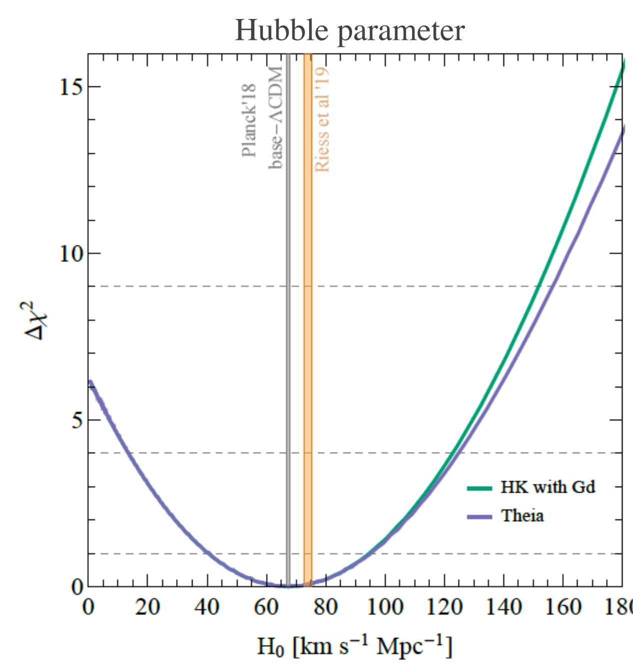


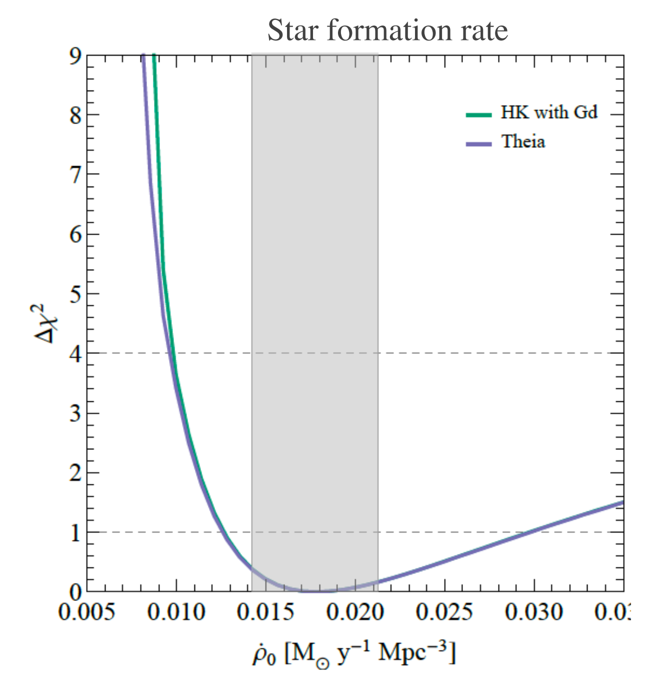
DSNB=Diffuse Supernova Neutrino Background











A. de Gouvea, I. Martinez-Soler, Y. Perez-Gonzalez ,M. Sen PRD (2020)

Other kind of new physics

- Axions, and axion-like particles.

  G.Raffelt, Stars as laboratories for fundamental physics, UCP (1996)
  J. Jaeckel, M. Spannowsky, PLB (2016)
  G. Lucente, P. Carenza, T. Fischer, et al. JCAP (2020)

  Majorons. M. Kachelreiss, R. Tomas, J. Valle, PRD. (2000)
  Y. Farzan PRD (2000)

- Neutrino magnetic moment: within the SN, $\nu_L e \to e \nu_R$ can drain energy, bounds $\mu_D < 10^{-12} \mu_B$. R. Barbieri, R. Mohapata, PRL (1988)

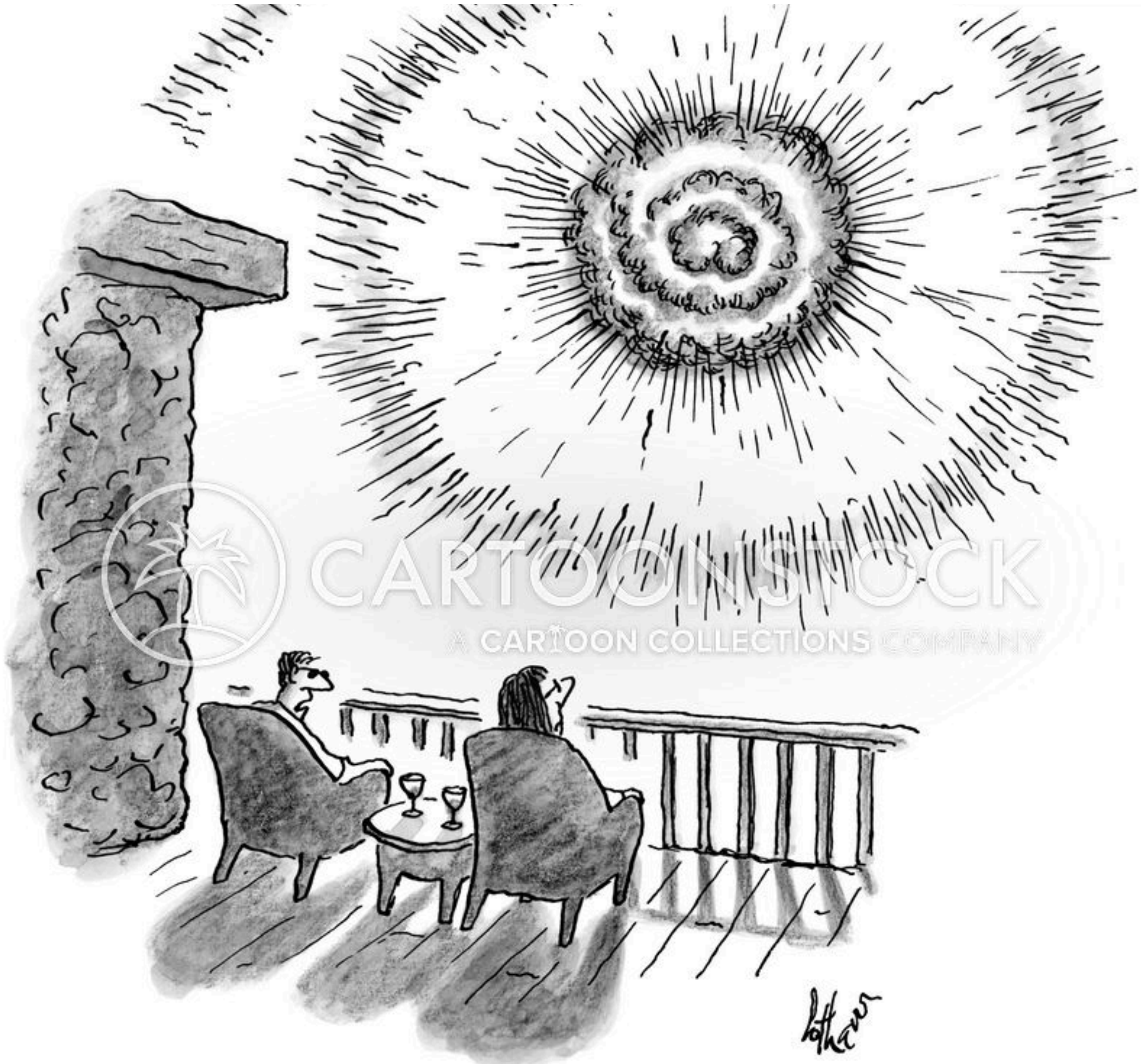
- Radiative decays: $\nu \to \nu' \gamma$, gives a coincident γ-ray flare. Bounds $\tau/m > 10^{15}\,\mathrm{s/eV}$. G.Raffelt, Stars as laboratories for fundamental physics, UCP (1996)

- Time of flight delay due to massive neutrinos: $m_\nu < 20\,\mathrm{eV}$. G. Zatsepin, JETP Lett (1968)
  More precise time measurements narrow it to O(1)eV.
  R. Hansen, M. Lindner, O. Scholer, PRD (2020)

- If ν have millicharge, their path can be bent by galactic B field, causing a time delay, $e_\nu < 10^{-17} e\,(1\mu G/B)$ G. Barbiellini, G. Cocconi, Nature (1987)

Conclusion

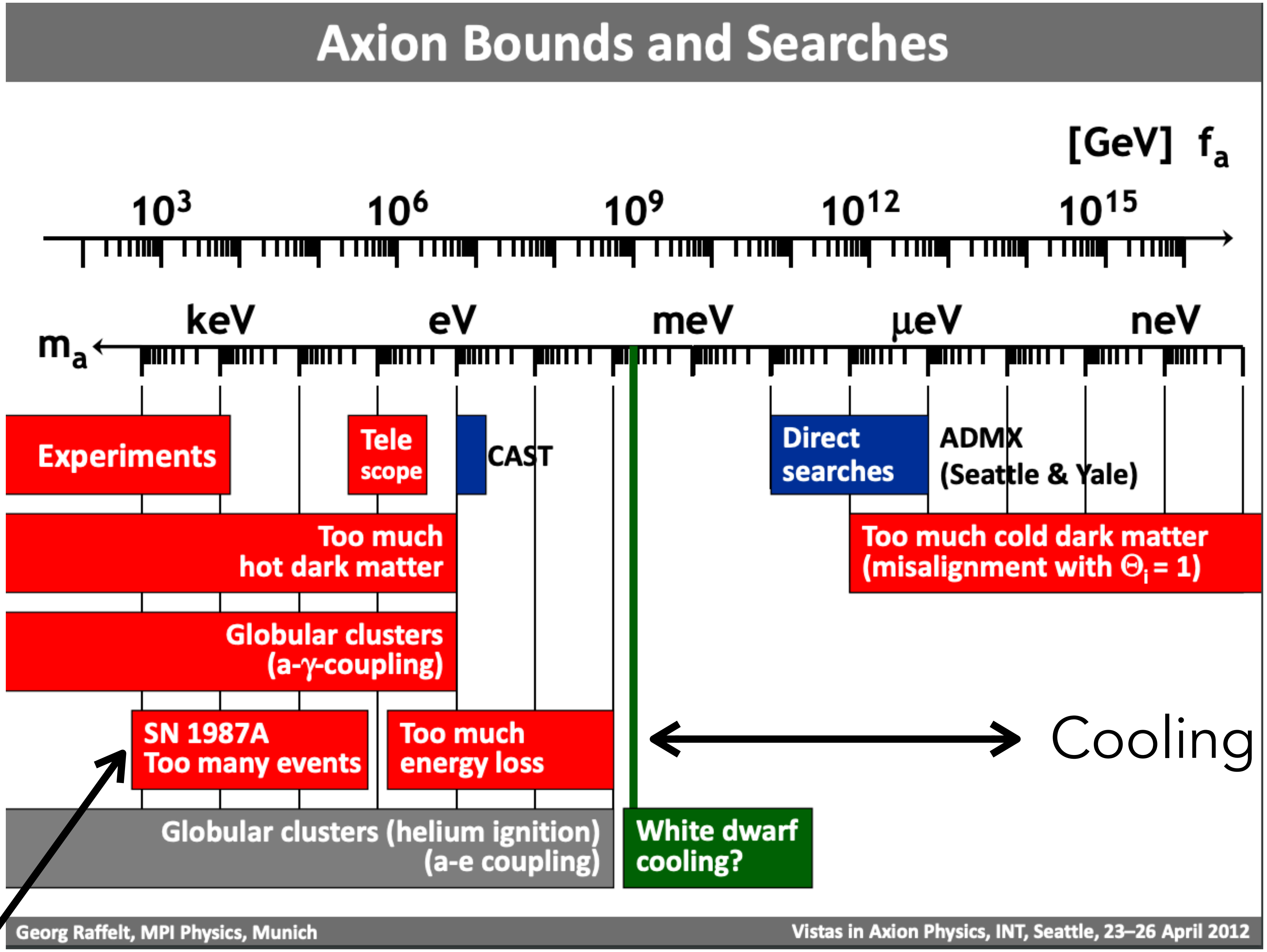
- A core-collapse SN is one of the best astrophysical laboratories for fundamental neutrino physics.
- Can use neutrino luminosity constraints to put bounds on exotic new particles.
- Better understanding of the underlying neutrino physics can be leveraged to use the signal to put some of the best bounds on non-standard neutrino properties, as well as the nature of neutrinos.
- Till a galactic SN takes place, one can utilize the constant availability of the DSNB to already probe some of these physics.



Thank you!

Backup

Axion bounds



Cooling bound

Too many events due to absorption on O, and subsequent γ emission.

Multiple resonances in $\nu_e - \nu_s$ system

- Initially, $E_{\rm res}$ decreases as density increases upto a minimum.
- As density increases further, $E_{\rm res} \sim \mu_{\nu_e}$, which implies that more neutrinos are available for conversion.
- This increases holes in the medium, which captures e, reducing the net lepton number.
- Since $E_{\rm res} \propto 1/Y_e$, this increases the resonance energy.
- This can lead to multiple MSW resonances.

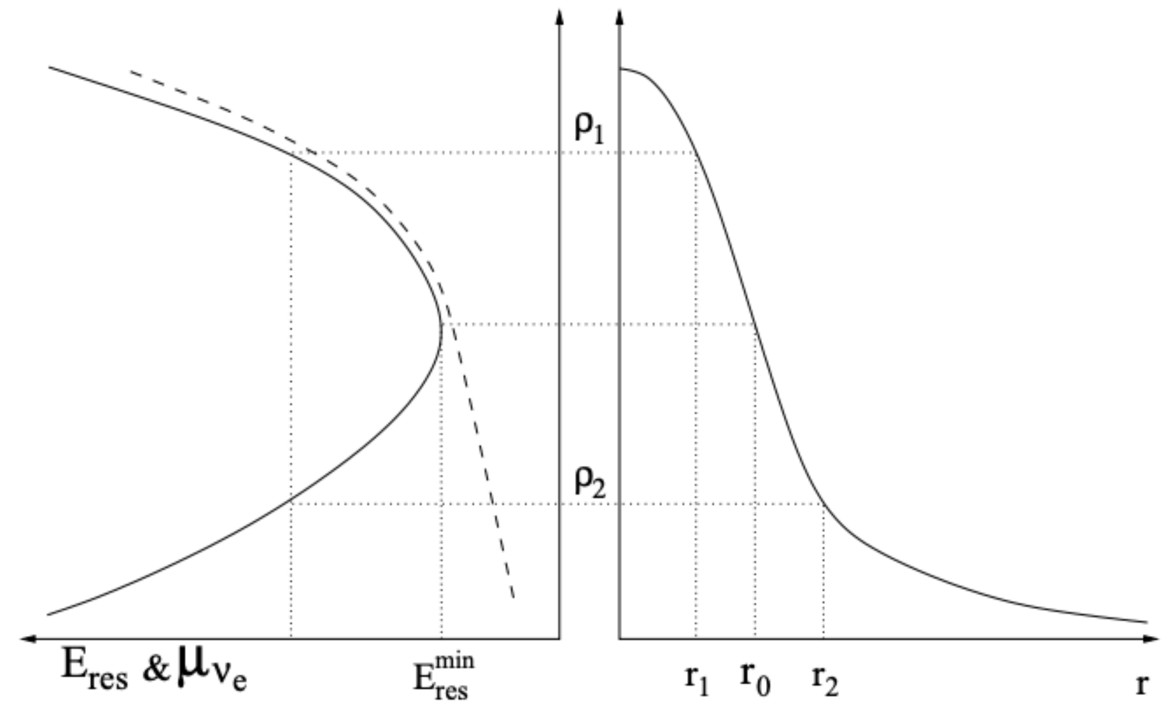
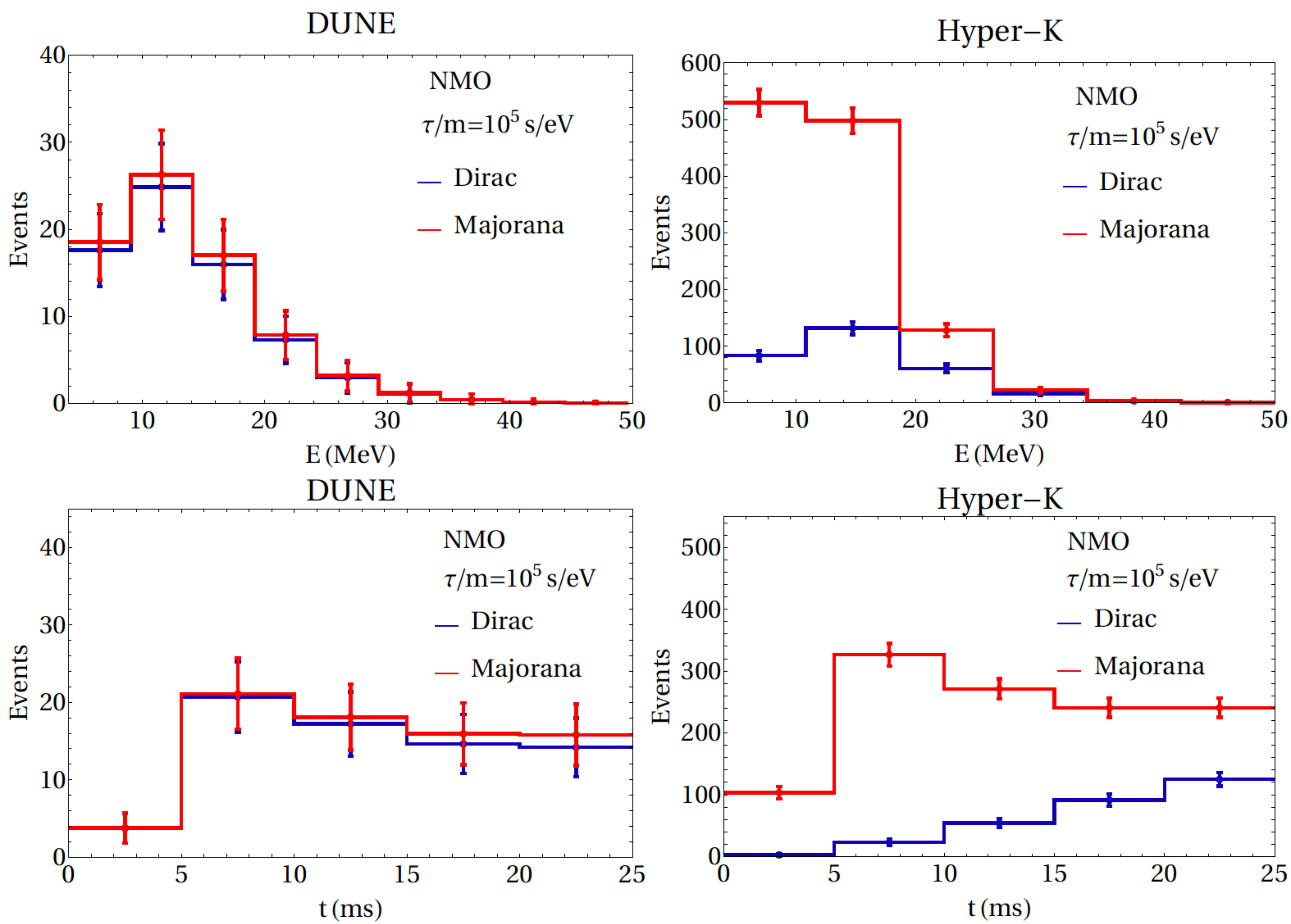


FIG. 1: Right panel shows the core density profile with radius r, while the corresponding profiles for MSW resonance energy $E_{\rm res}$ (solid) and ν_e chemical potential μ_{ν_e} (dashed) are shown in the left panel. Here $E_{\rm res}$ takes its minimum value $E_{\rm res}^{\rm min}$ at r_0. For a particular neutrino energy, an MSW resonance can occur at two locations (densities), *e.g.*, r_1 (ρ_1) and r_2 (ρ_2).

J. Hidaka, G. Fuller, PRD (2007)

Dirac vs Majorana: in DUNE and HK



A. de Gouvea, I. Martinez-Soler, M. Sen PRD (2019)