Neutrino flavor oscillations in astrophysical explosions – understanding and implications

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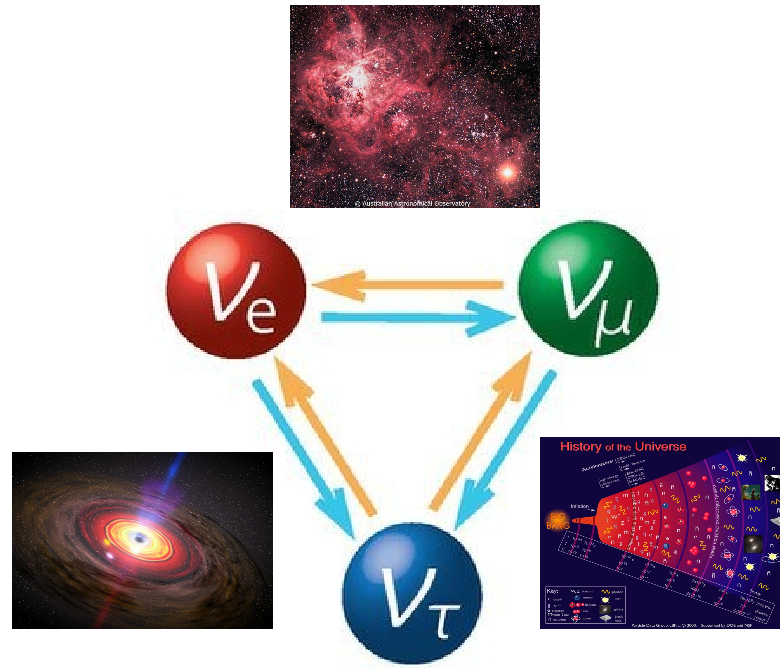
Outline

- Toy models of neutrino oscillations in dense neutrino gas
- Core-collapse supernovae and neutron star mergers
- Numerical results and prospects

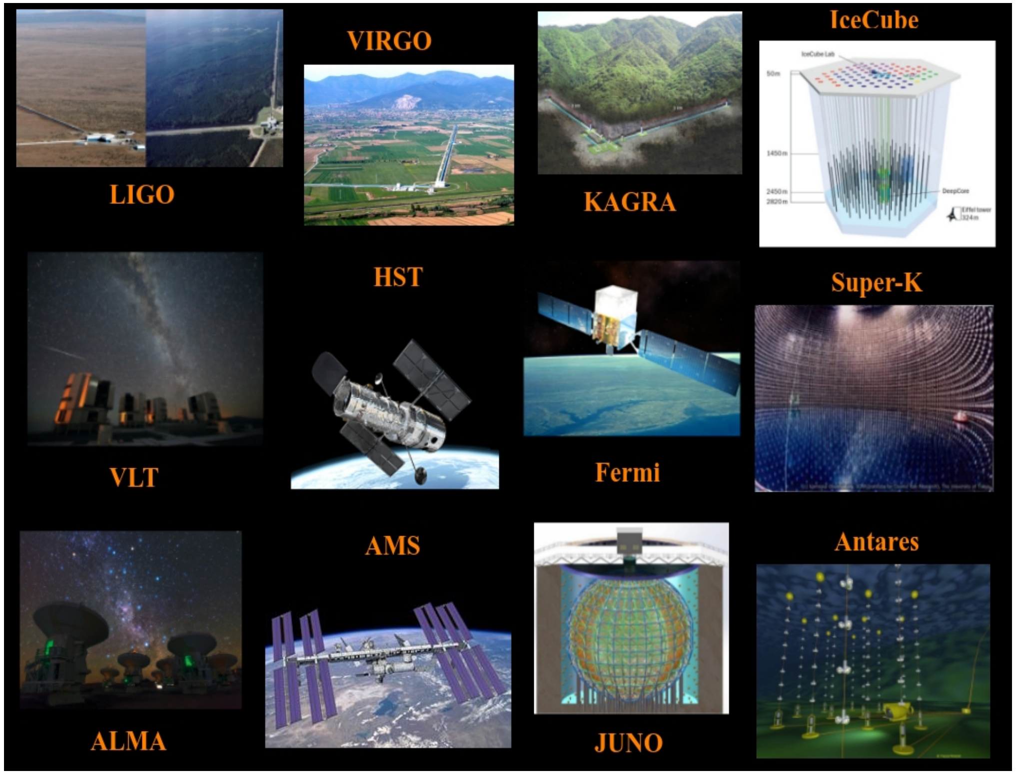


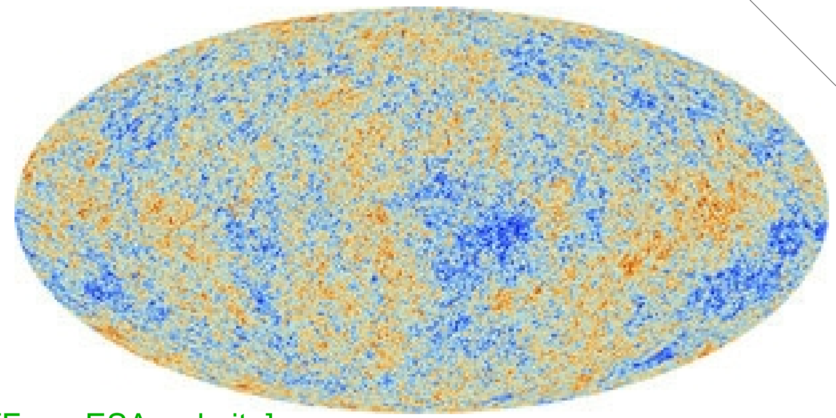
collaborators:
Tobias Fischer (U Wroclaw), G. Martínez-Pinedo (GSI & TUD), Y.-Z. Qian (UMN), I. Tamborra (NBIA) Thomas Janka (MPA Garching), Oliver Just (RIKEN).

Multi-messenger astronomy and precision cosmology

We have entered a very exciting era of utilizing different detectors to uncover the mystery of the Universe

- EM signal: from radiowaves to gamma rays
- cosmic rays
- neutrinos: from sub-MeV to PeV
- gravitational waves

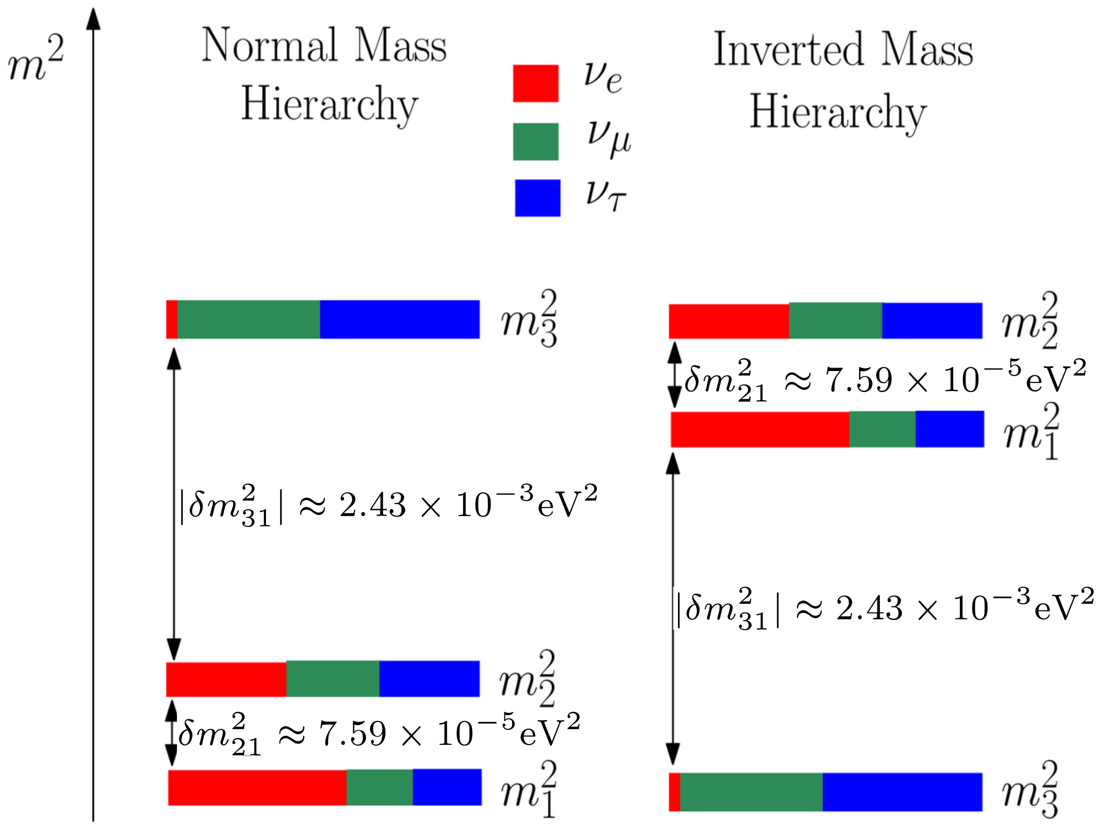




[From ESA website]

understanding of fundamental physics and (chemical) evolution of the Universe

Neutrino masses and mixing



mixing angles:

$\theta_{12} \approx 34^\circ$

$\theta_{13} \approx 9^\circ$

$\theta_{23} \approx 45^\circ$

mass hierarchy?
CP phases?
absolute neutrino mass?
Majorana or Dirac?
sterile neutrinos?

– What are the roles of neutrinos in astrophysical/cosmological environments?
– Can we explore the unknown properties of neutrinos?

How do neutrinos oscillate

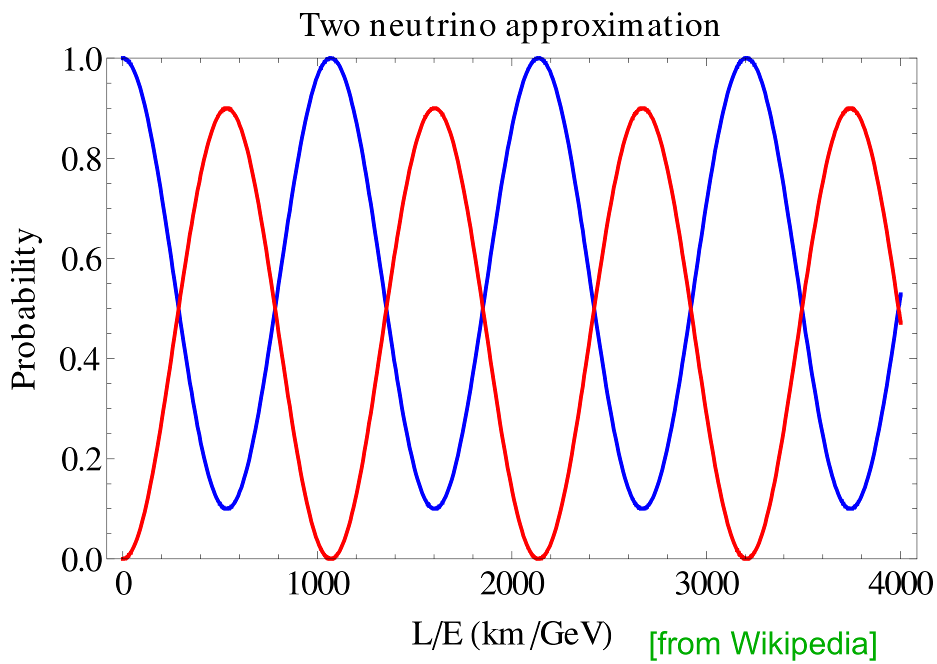
in vacuum: $$i\frac{d}{dt}\begin{bmatrix}a_e\\a_\mu\end{bmatrix} = H_{\rm vac}\begin{bmatrix}a_e\\a_\mu\end{bmatrix}$$

$$H_{\rm vac} \approx U^\dagger \frac{m^2}{2p} U + \mathbb{I}\times(sth.) \approx \frac{\delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \mathbb{I}\times(sth.)$$

survival probability:

$$P(\nu_e \to \nu_e) = |a_e|^2$$

$$= 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2}{4E_\nu}t\right)$$



[from Wikipedia]

How do neutrinos oscillate

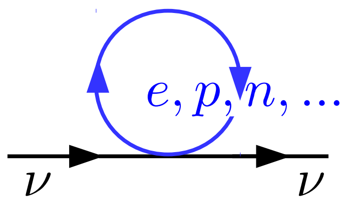
when neutrinos propagate through matter:

$$i\frac{d}{dt}\begin{bmatrix} a_e \\ a_\mu \end{bmatrix} = (H_{\rm vac} + H_{\rm m})\begin{bmatrix} a_e \\ a_\mu \end{bmatrix}$$

$$H_{\rm vac} \approx \frac{\delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$$H_{\rm m} \approx \pm\sqrt{2}G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

[Wolfenstein 1978, Mikheyev & Smirnov, 1985]



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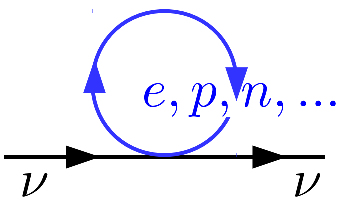


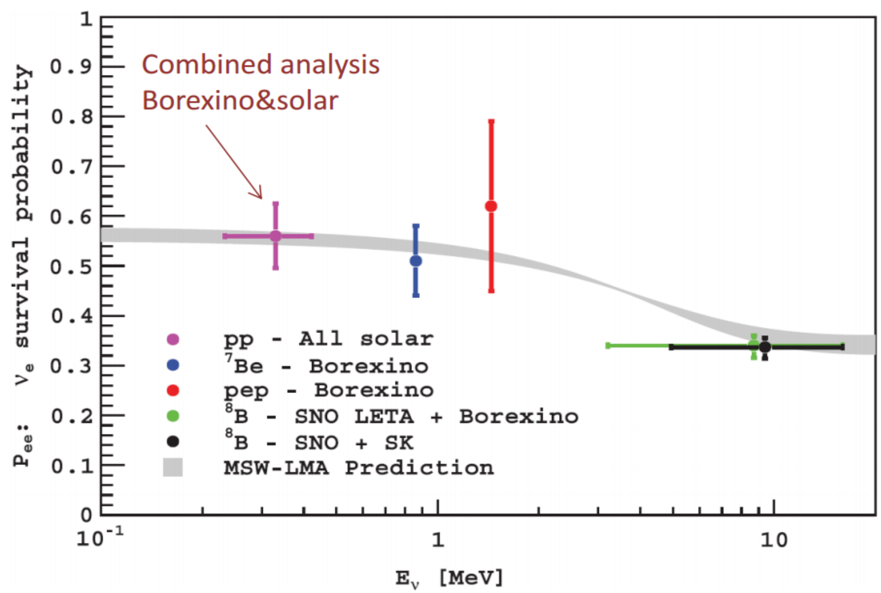
MSW resonances:

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

for density $\sim O(10^2)$ g/cm^3

$E_\nu \gtrsim 1.5$ MeV$\rightarrow$ matter dominance

$E_\nu \lesssim 1.5$ MeV$\rightarrow$ vacuum oscillations



[Bellini, et. al., PRD 89, 112007, 2014]

How do neutrinos oscillate

for solar neutrinos, $n_\nu \sim 10^6$ cm^{-3} $\ll n_e \sim 10^{25}$ cm^{-3}, MSW mechanism works fine.

However, this does not apply to "hot and dense" explosive astrophysical & cosmological environments, where neutrinos dominate the dynamics/composition

ex: the early Universe, core-collapse supernovae, neutron star merger remnants,...

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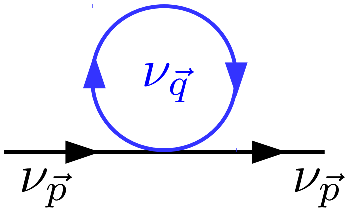
$$i\frac{d}{dt}\begin{bmatrix} a_{e,\vec{p}} \\ a_{\mu,\vec{p}} \end{bmatrix} = (H_{\rm vac} + H_{\rm m} + H_{\nu,\vec{p}})\begin{bmatrix} a_{e,\vec{p}} \\ a_{\mu,\vec{p}} \end{bmatrix}$$



$$H_{\nu,\vec{p}} \approx \sqrt{2}G_F \int (1-\hat{p}\cdot\hat{q})(dn_{\nu,\vec{q}}\rho_{\nu,\vec{q}} - dn_{\bar{\nu},\vec{q}}\bar{\rho}^*_{\nu,\vec{q}}) \quad \varrho_{\nu,\vec{p}} = \begin{pmatrix} |a_{e,\vec{p}}|^2 & a_{e,\vec{p}}a^*_{\mu,\vec{p}} \\ a^*_{e,\vec{p}}a_{\mu,\vec{p}} & |a_{\mu,\vec{p}}|^2 \end{pmatrix}$$

[Fuller+ 1987, Pantaleone 1992, Sigl & Raffelt, 1992]

$\rightarrow$ flavor evolution of neutrinos with different momenta coupled non-linearly.

("strong coupling system driven by the weak interaction")

Geometrical representation of ν oscillations

[Kim+ 1987, Pastor+ 2002, Duan+ 2005,...]

assuming the environment is isotropic, expanding traceless H and ρ_ν in terms of Pauli matrices, (e.g., $\rho_\nu \equiv \vec{s}_\nu \cdot \vec{\sigma}$...), neutrino flavor oscillations obtain a geometrical meaning:

$$\frac{d\vec{s}_i}{dt} = \vec{s}_i \times (\omega_i \vec{H}_{\rm vac} - \vec{H}_m - \sum_j \mu_j \vec{s}_j)$$

$$\vec{s}_\nu = [{\rm Re}(a_e^* a_\mu), {\rm Im}(a_e^* a_\mu), (|a_e^2| - |a_\mu^2|)/2]^T$$
$$\vec{s}_{\bar\nu} = -[{\rm Re}(a_e a_\mu^*), {\rm Im}(a_e a_\mu^*), (|a_e^2| - |a_\mu^2|)/2]^T$$

$$\omega_i = \pm \frac{\delta m^2}{2E_\nu}, \qquad \mu_i = 2\sqrt{2} G_F n_{\nu,i},$$

$$\vec{H}_{\rm vac} = (-\sin 2\theta, 0, \cos 2\theta)^T,$$
$$\vec{H}_{\rm m} = (0, 0, \sqrt{2} G_F n_e)^T$$

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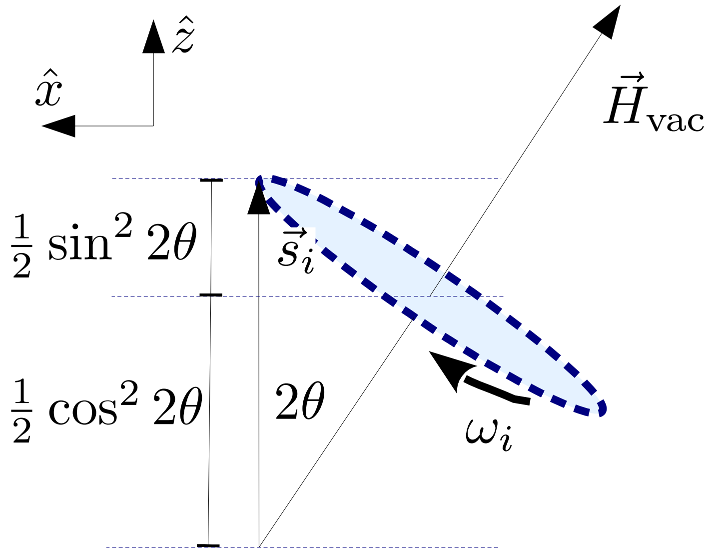
vacuum oscillations:



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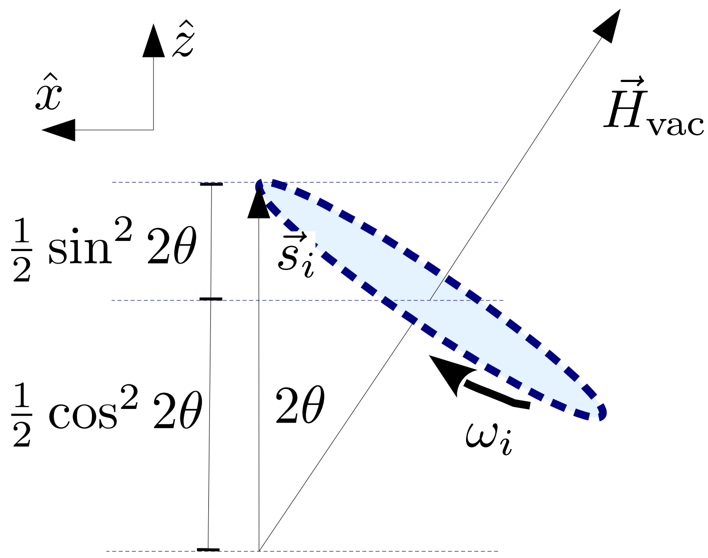


adiabatic MSW flavor transformation for ν:

angle between $\vec{s}_i$ and $\omega_i \vec{H}_{\rm vac} - \vec{H}_m$ conserved

at t_0, $|\vec{H}_{\rm m}| \gg \omega_i$, $\rightarrow$ $\vec{s}_i(t_0) \propto \vec{H}_{\rm m}$

at t_f, $|\vec{H}_{\rm m}| \ll \omega_i$, $\rightarrow$ $\vec{s}_i(t_f) \propto -\vec{H}_{\rm vac}$

if $\vec{H}_{\rm m}$ changes slowly (adiabatically)

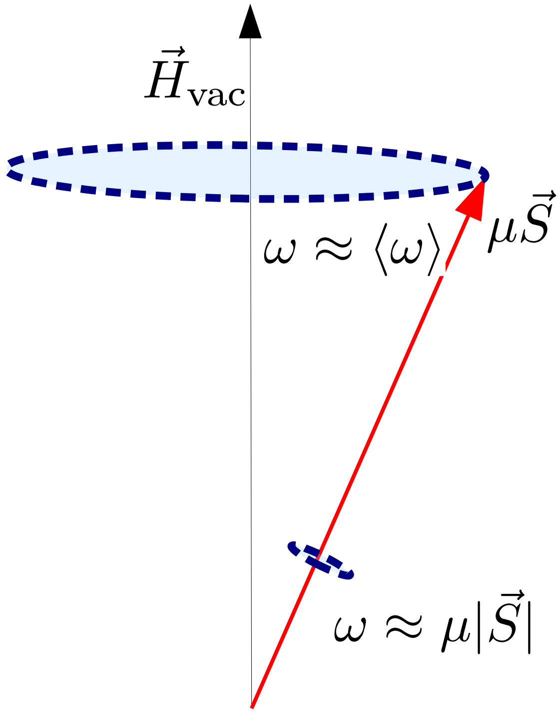
$$\left(\left| \frac{d}{dt} \frac{\vec{H}_{\rm tot}}{|\vec{H}_{\rm tot}|} \right| \ll |\vec{H}_{\rm tot}| \right)$$

Collective neutrino oscillations

[Samuel+, Raffelt+, Duan+, Mirizzi+, Volpe+...]

Let's consider a pure neutrino gas consists of N neutrinos with different energies, uniform energy spectrum, and constant density $N\mu_i = \mu \gg \omega_i$

$$\frac{d\vec{s}_i}{dt} \approx -\mu\vec{s}_i \times \sum_j \frac{\vec{s}_j}{N} \equiv -\mu\vec{s}_i \times \vec{S}$$



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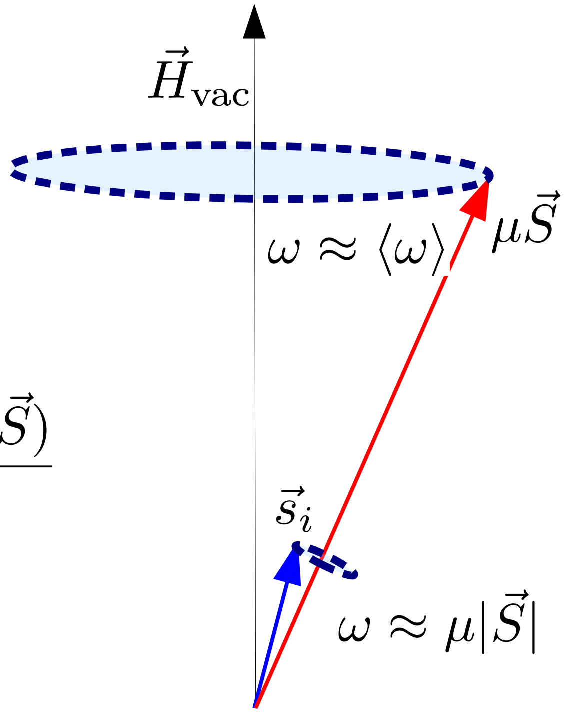
neutrinos with different energy stay in $\sim$ the same direction as $\vec{S}$, while

$$\frac{d\vec{S}}{dt} \approx \langle\omega\rangle\vec{S} \times \vec{H}_{\rm vac}, \qquad \langle\omega\rangle = \sum_i \frac{2\omega_i(\vec{s}_i \cdot \vec{S})}{N\vec{S}^2}$$

$\vec{S}$ slowly rotates around $\vec{H}_{\rm vac}$



$\rightarrow$ all neutrinos oscillate coherently with a collective frequency.

[Pastor, Raffelt, Semikoz, PRD 2002]

Spectral splits/swaps

Now, let the neutrino density parameter μ slowly decreases to zero, assuming $\theta \ll 1$, what will happen?

$\rightarrow$ neutrinos with $\omega_i > \omega_c$ undergo complete flavor transformation, while neutrinos with $\omega_i < \omega_c$ remain their initial flavor.

$\rightarrow$ spectral split/swap [Duan, Fuller, Carlson, Qian, PRD 2006, ...]

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It is actually similar to the MSW phenomenon, if we always switch to an instantaneously co-rotating frame of $\vec{S}$:

$$\frac{d\vec{s}_i'}{dt} = \vec{s}_i' \times [(\omega_i - \langle\omega\rangle)\vec{H}_{\rm vac} - \mu\vec{S}']$$

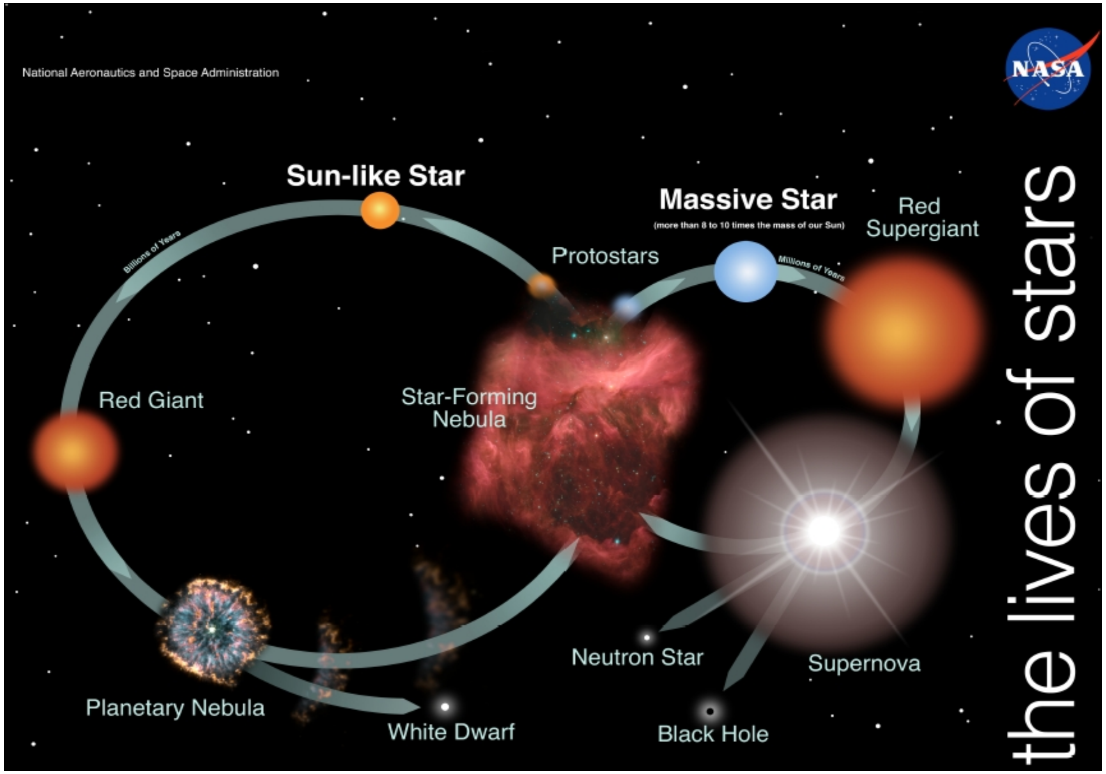
$$\omega_c = \langle\omega\rangle(\mu \rightarrow 0)$$

$\rightarrow$ collective mode(s) determines the outcome of the flavor transformation.

[multiple splits/swaps can happen if more then one mode exists.
e.g., MRW & Y.-Z. Qian, PRD (2011), G. Raffelt, PRD (2011)]

Some astrophysics...

Core-collapse supernova explosion – the death of massive stars



(From NASA website)

The Tarantula Nebula and supernova 1987a in the LMC

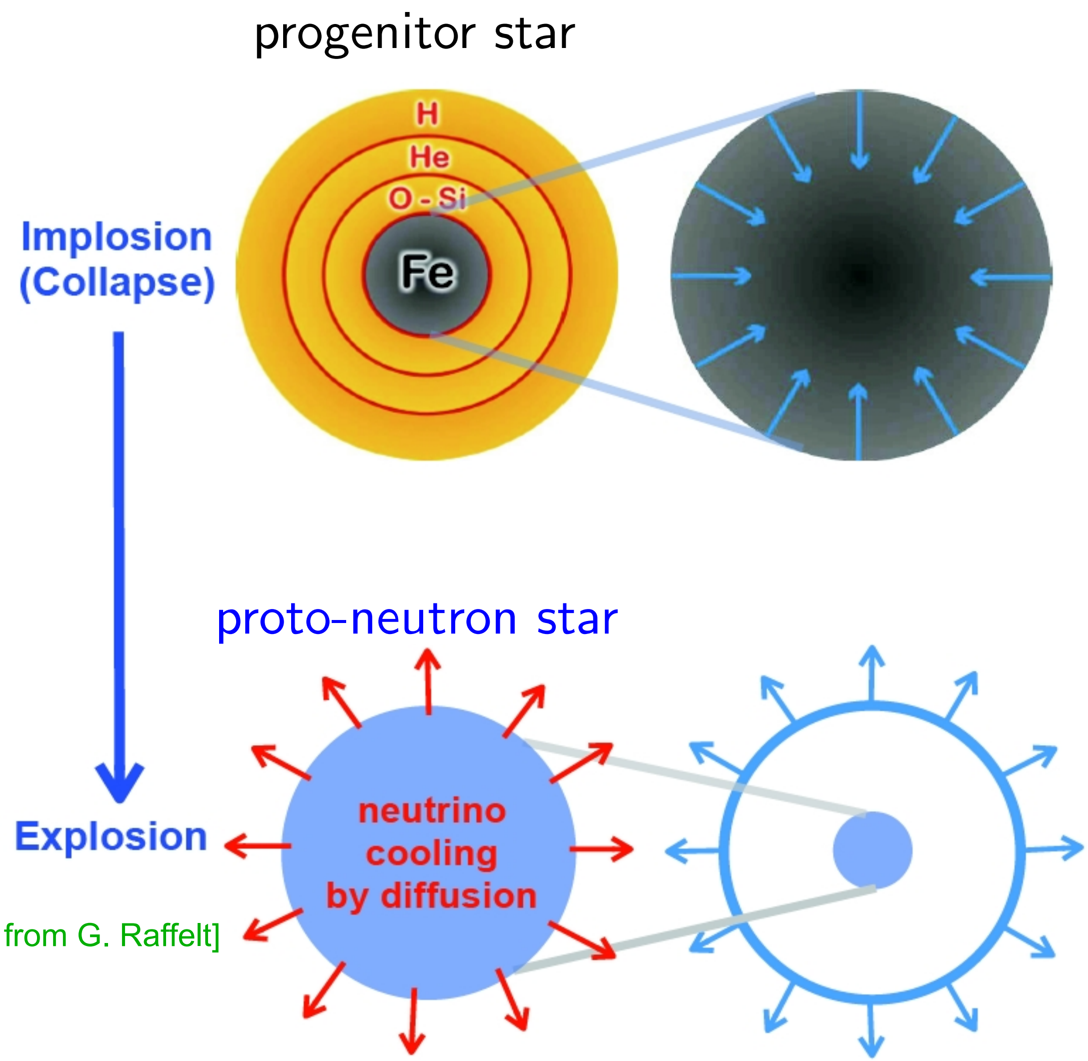
(From AAO website)

- explosive death of stars heavier than $\sim 8\ M_{\odot}$
- progenitors of neutron stars & black holes
- star formation & galaxy formation ("baryonic" feedback)
- galactic chemical enrichment

the released energy:

$E_{\gamma} \sim 10^{49}$ erg, $E_{GW} \sim 10^{46}$ erg, $E_{\text{kinetic}} \sim 10^{51}$ erg, $E_{\nu} \sim 10^{53}$ erg.

Turning implosion into explosion



[Figure from G. Raffelt]

$M_{\text{Fe,core}} \approx 1.4 M_\odot$

$R_{\text{Fe,core}} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

$M_{\text{PNS}} \approx 1.4 M_\odot$

$R_{\text{PNS}} \approx 15$–$50$ km

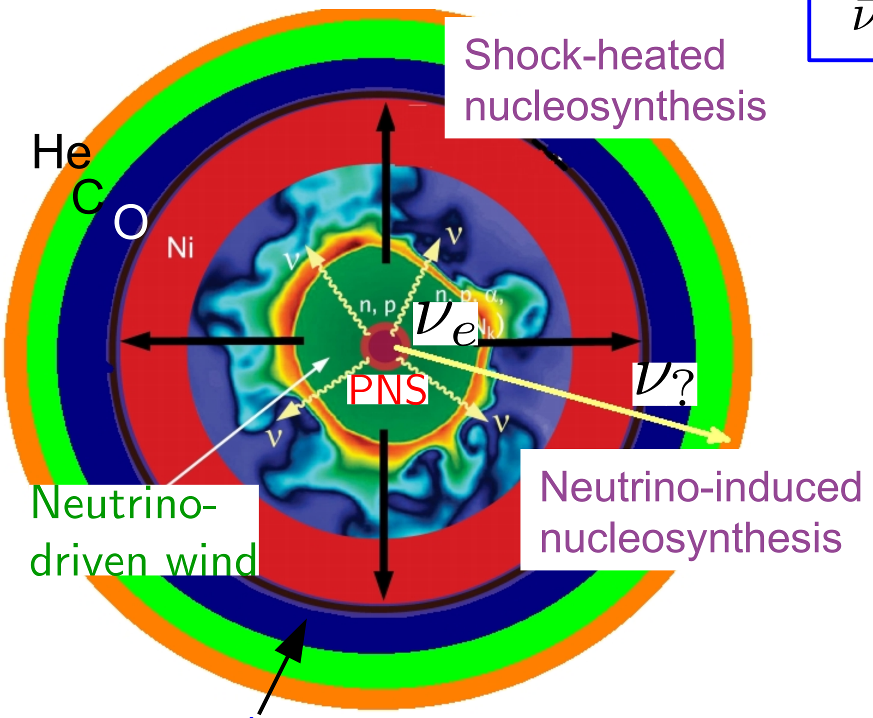
$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

$T_c \approx 30$ MeV

neutrinos dominate the available energy budget and therefore the core-collapse physics

Neutrinos in supernovae

[Modified from Janka+, PTEP 01A309, 2012]



$$\nu_e + n \to p + e^-$$
$$\bar{\nu}_e + p \to n + e^+$$

shockwave (revived mainly by ν-heating but not a settled issue yet)

$\sim 10^{58}$ neutrinos of different flavors in ~ 10 seconds

$$\langle E_\nu \rangle \sim 7 - 20 \text{ MeV}$$

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$$

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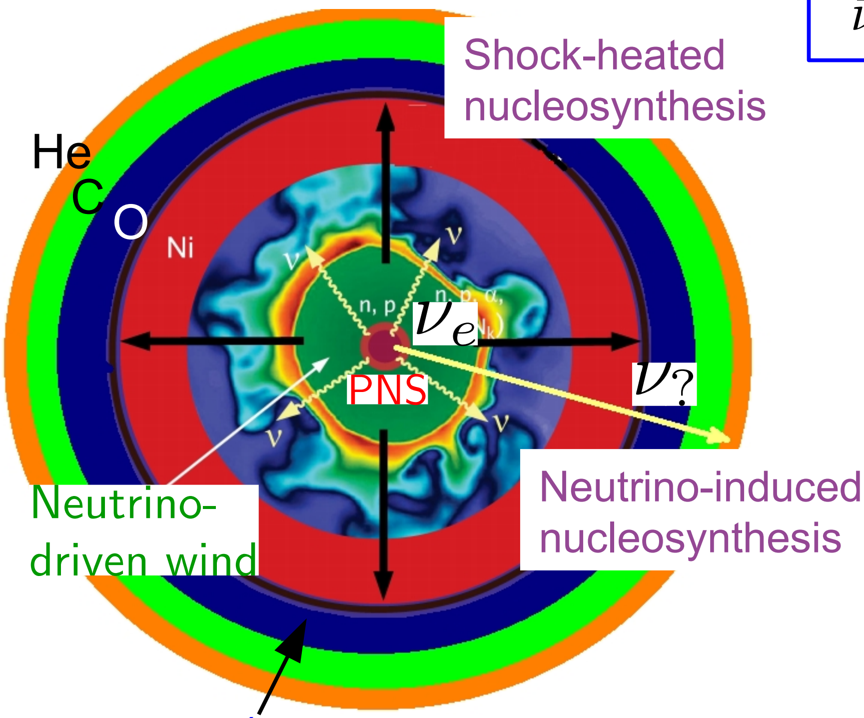

$$\nu_e + n \to p + e^-$$
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- neutrino (induced) nucleosynthesis
  - $\to$ light elements : Li, Be, B, F
  - $\to$ radioactive nuclei : ^{22}Na, ^{26}Al
    rare isotopes : ^{138}La, ^{180}Ta

- neutrino-driven wind
  - $\to$ determine initial condition of the ejecta

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$\langle E_\nu \rangle \sim 7 - 20$ MeV

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neutrino flavor oscillations

$\nu_e \leftrightarrow \nu_{\mu,\tau}$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$

$\nu_e \leftrightarrow \nu_s$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_s$

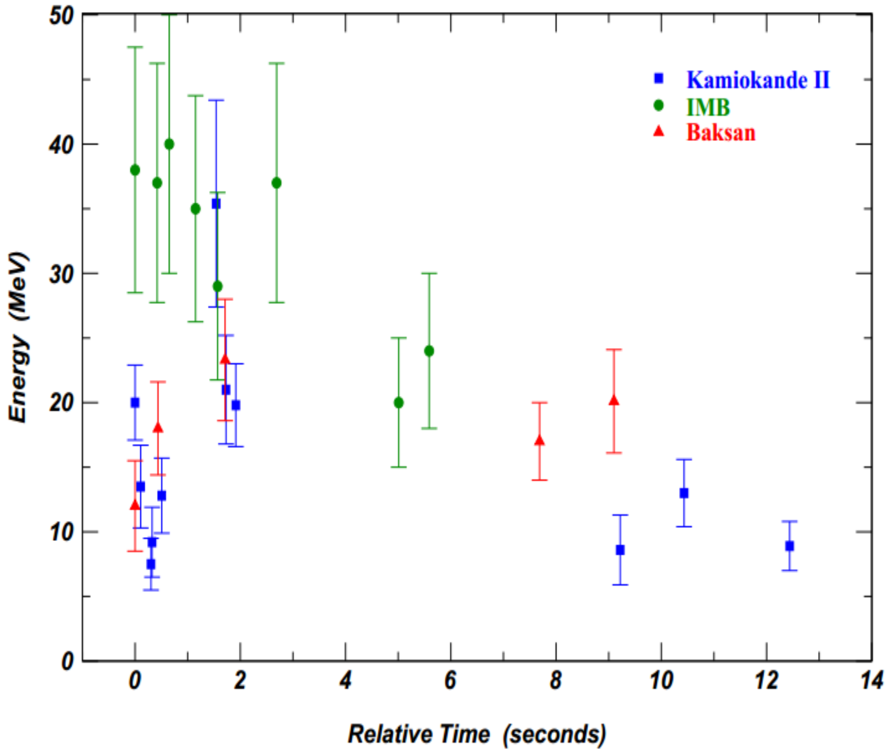
when? where? how (much)?

Supernova neutrino signals

~ 20 SN $\bar{\nu}_e$ detected from SN1987a

- confirms the basic picture of the core-collapse SN model.

- sets limit on the absolute neutrino mass from the time-of-flight.



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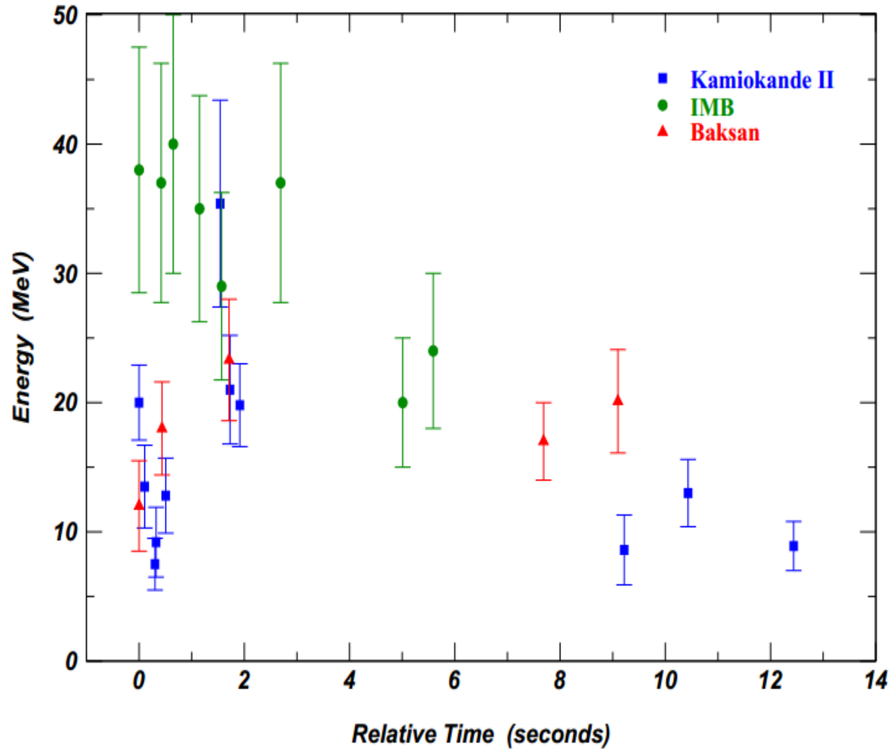
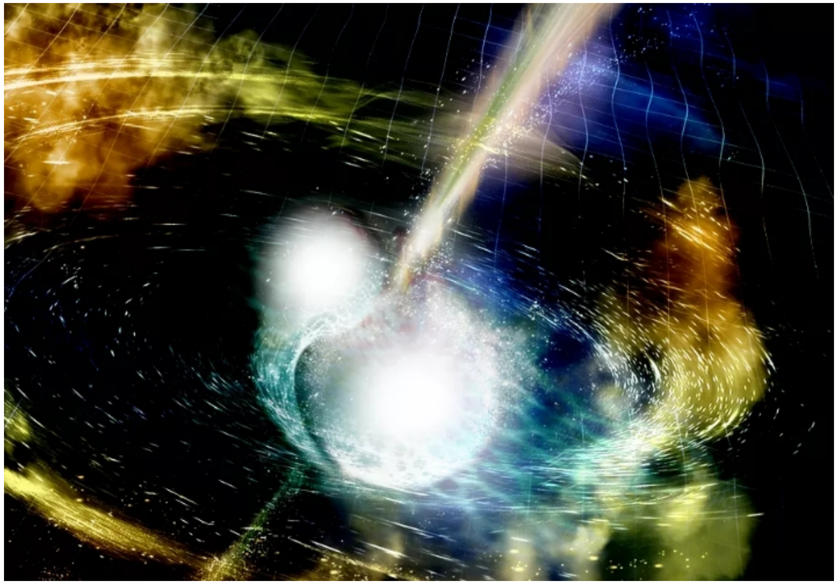


thousands of events in the multi-kiloton detector expected for the next Galactic supernova ($\sim$ 0.5–3 per century).

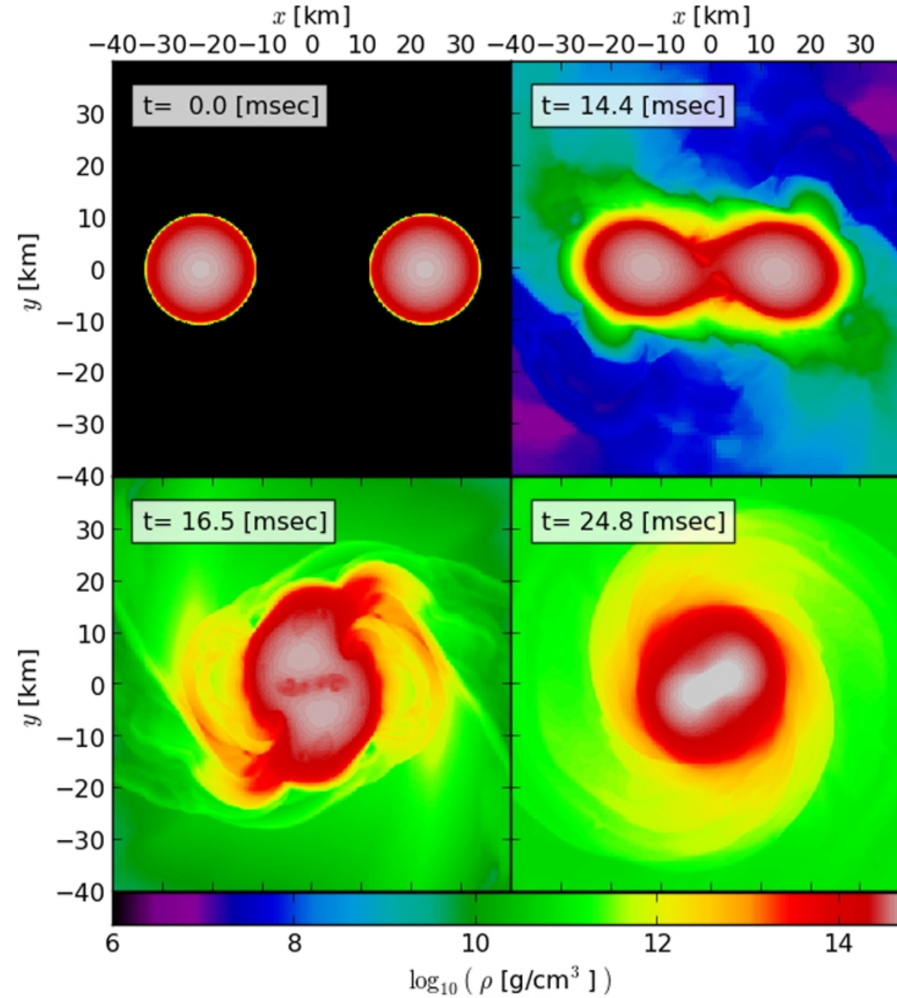
moreover, there exist supernova relic neutrinos that are expected to be detected a few per year with Gd doping in SuperK.

$\rightarrow$ unique opportunities to understand questions related to supernova explosion, the properties of neutron star, and the properties of neutrinos.

Binary neutron star mergers



- gravitational wave sources
- origin of short γ-ray bursts
- origin of heavy elements (the r-process)$\rightarrow$ kilonovae



[From L. Rezzolla]

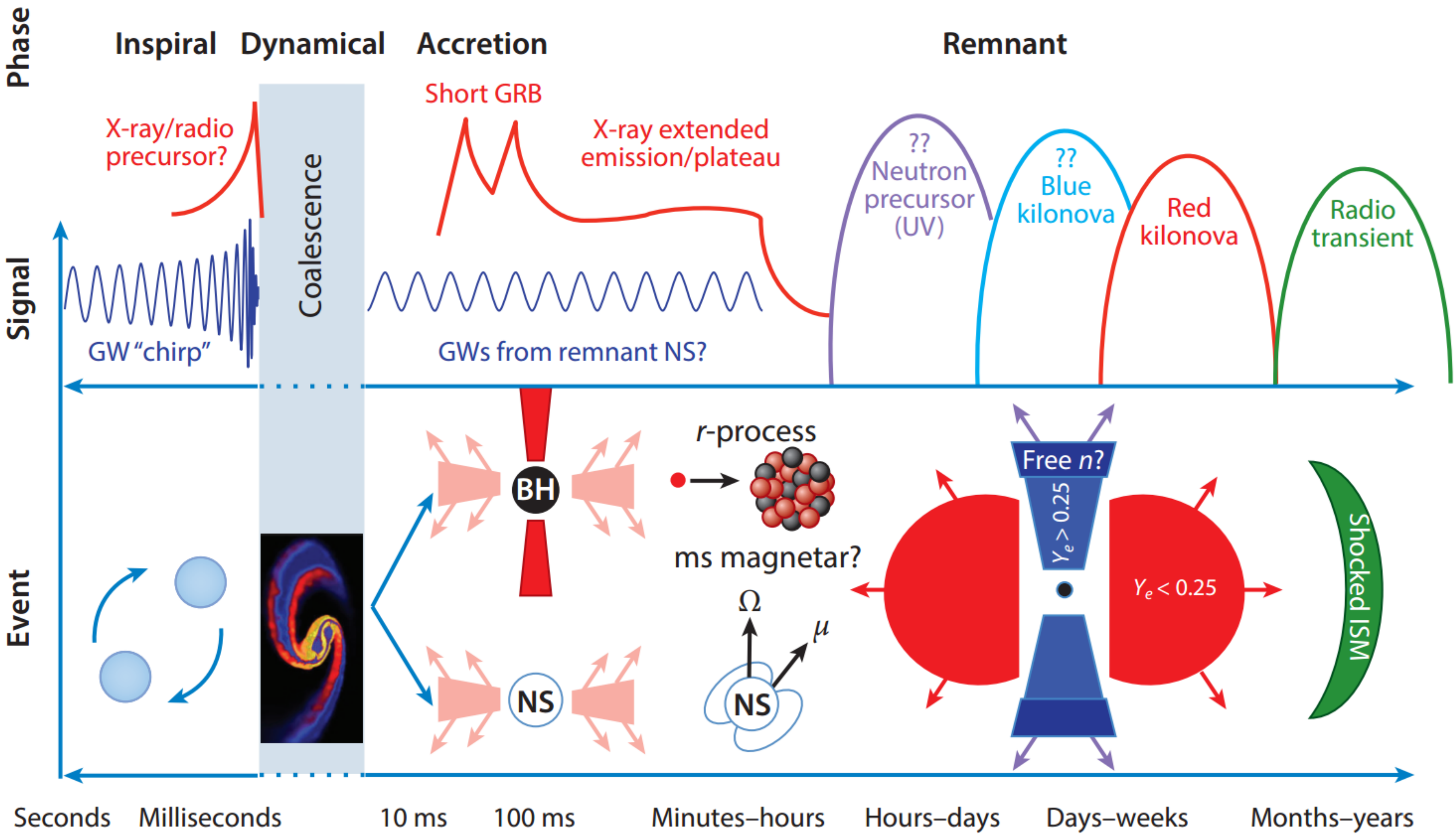
finally confirmed by the recent detection of GW170817/GRB 170817A/AT2017gfo

expected to see $\gtrsim 10$ per year at full advanced LIGO sensitivity

The multi-messenger of binary neutron star mergers

Expected signals:

1. GW, 2. sGRB (gamma ray, x-ray...) 3. kilonovae/macronovae (optical, infrared)



[Fernandez & Metzger, ARNPS 66 (2016) 23]

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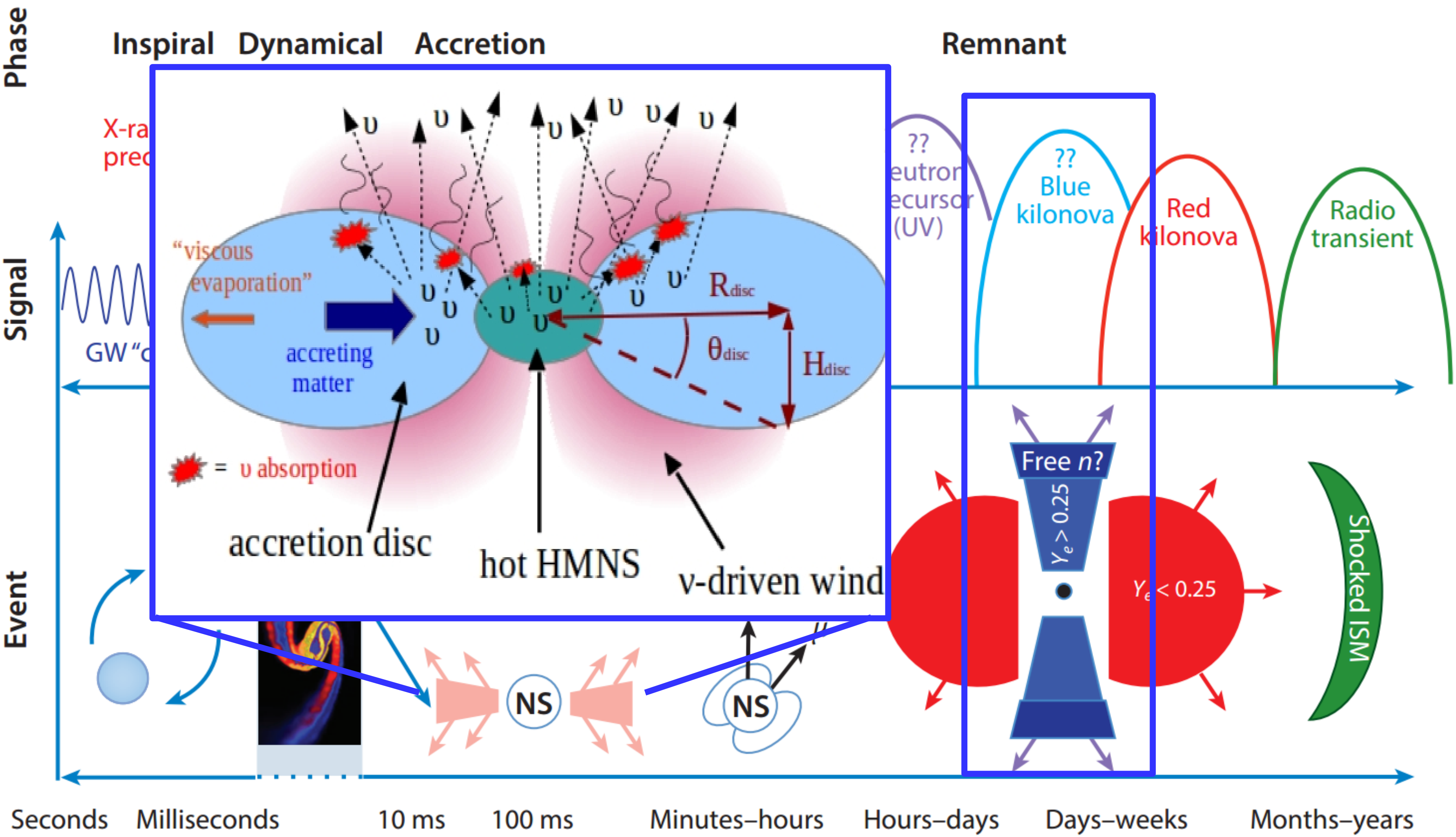
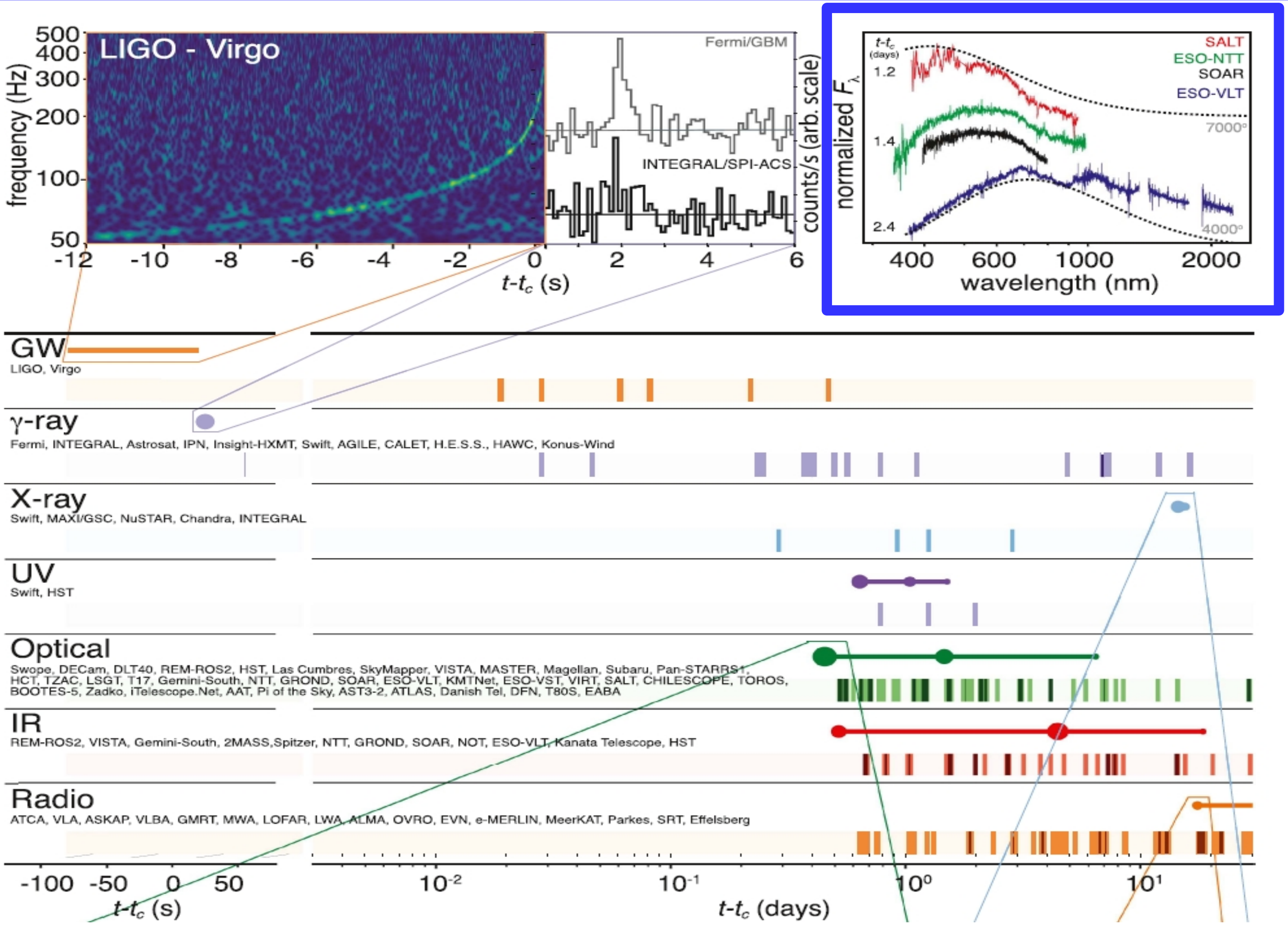


[Fernandez & Metzger, ARNPS 66 (2016) 23]

First GW+EM detection from BNS merger (GW170817+AT2017gfo)

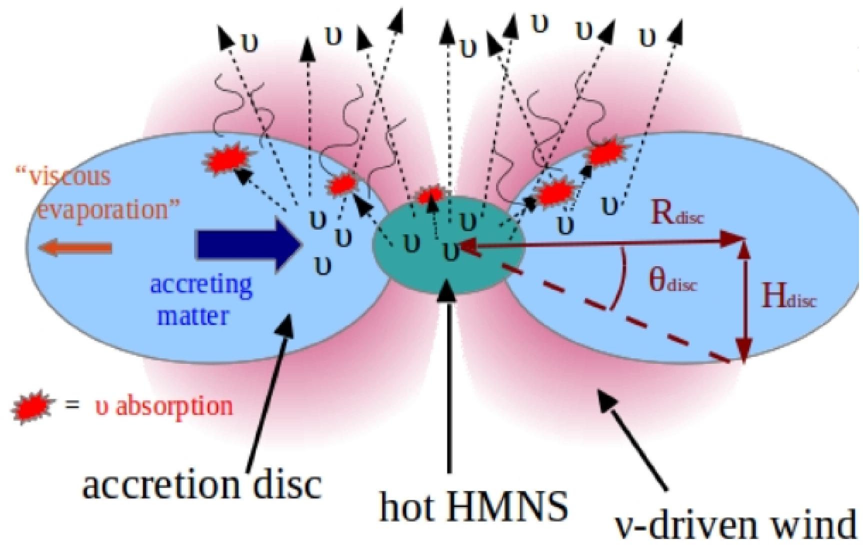


[LIGO/Virgo collaboration, Fermi...... Aboott+, ApJL 848:L12 (2017)]

The initial blue color of the kilonova lightcurve strongly suggest that early ejecta were reshaped by thermal neutrinos

→ need to understand better their transport and flavor oscillations

Neutrinos from NS merger remnant



due to the initial neutron richness,
and the self-regulating semi-degeneracy,
neutrino emission go through the phase
of "protonization".

→ dominant $\bar{\nu}_e$ emission compared to ν_e.

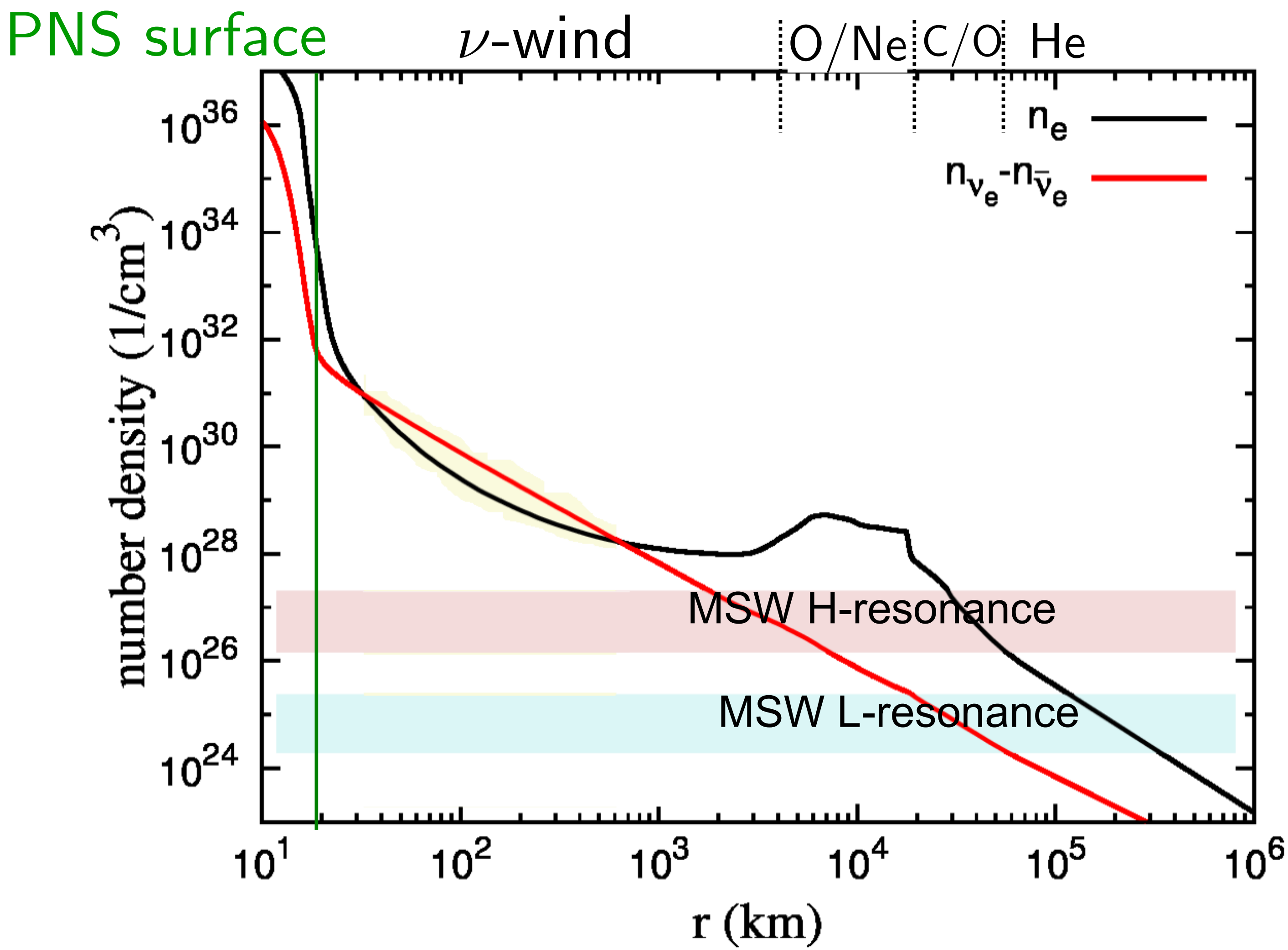
Table III. Emission parameters with $\nu_x \in \{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau\}$.

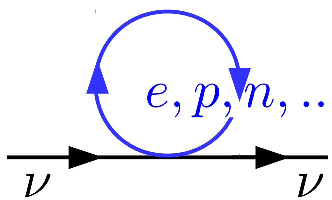
	$\langle E_\nu \rangle$ [MeV]	$T_\nu = \frac{F_2(0)}{F_3(0)} \langle E_\nu \rangle$ [MeV]	$(L_\nu/10^{51})$ [erg/s]
ν_e	10.6	3.4	15
$\bar{\nu}_e$	15.3	4.9	30
ν_x	17.3	5.5	8

very asymmetric and dynamic environment, more difficult to model than in supernovae

Neutrino oscillations in core-collapse supernovae and neutron star mergers

MSW flavor conversion in supernovae





$$\sqrt{2} G_F n_e \approx \frac{\delta m^2}{2E_\nu}$$

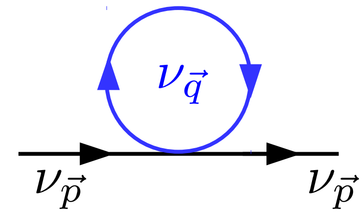
[Wolfenstein 1978, Mikheyev & Smirnov, 1985]

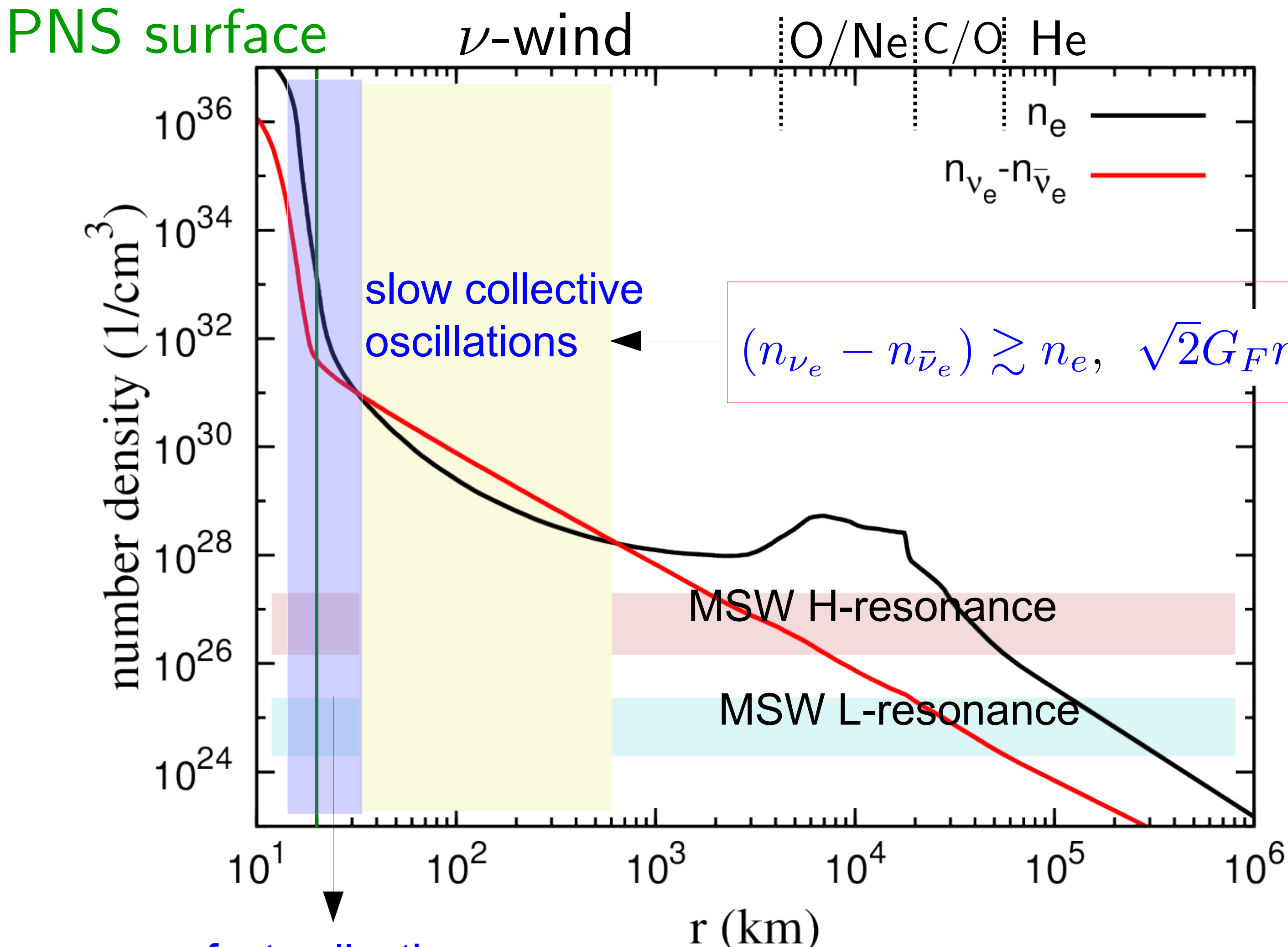
– little impact on supernova physics, except for neutrino-nucleosynthesis

– signature in neutrino detection when SN shock crosses the MSW region

Collective neutrino flavor conversion in supernovae

[Fuller+ 1987, Pantaleone 1992, Sigl & Raffelt, 1992]





$$(n_{\nu_e} - n_{\bar{\nu}_e}) \gtrsim n_e, \quad \sqrt{2} G_F n_{\nu_e} \times \frac{R_\nu^2}{r^2} \gtrsim \frac{\delta m^2}{2E_\nu}$$

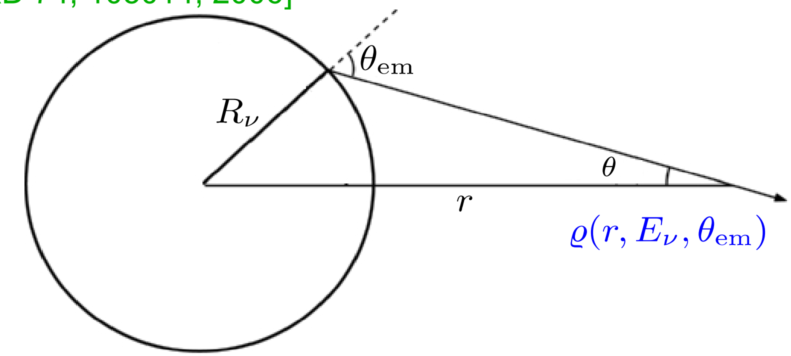
fast collective oscillations?

– difficult problem, but may greatly affect the supernova theory

Neutrino bulb model:

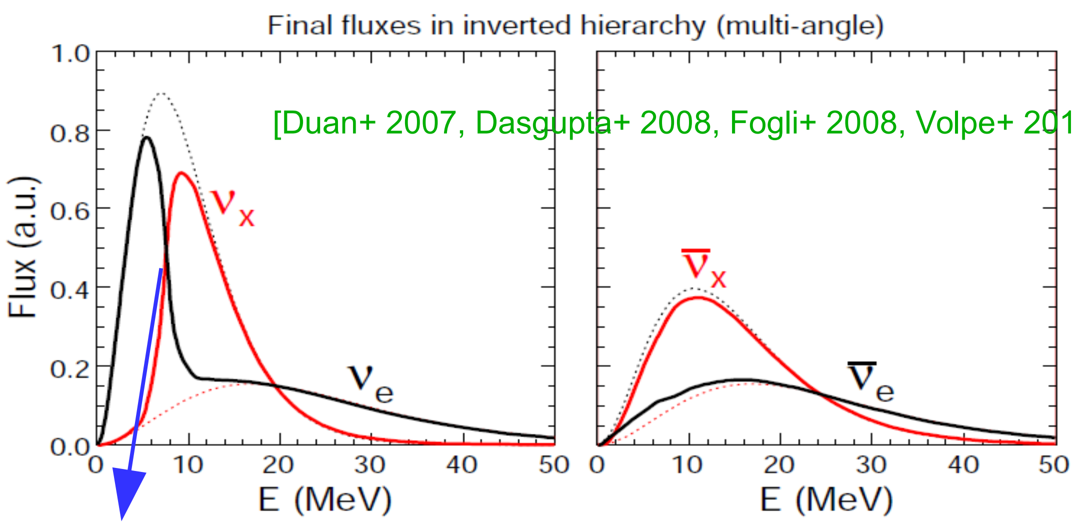
[Duan, Fuller, Carlson, Qian, PRD 74, 105014, 2006]

- stationary during ν propagation
- a sharp ν-emitting spheres, R_ν
- all neutrinos in pure flavor eigenstates at R_ν
- axial-symmetry of ν flavor evolution



$$i \cos\theta \frac{d}{dr} \varrho_\nu(r, E_\nu, \theta_{\rm em}) = [H_{\rm vac}(E_\nu) + H_m(r) + H_\nu(r, \theta_{\rm em}), \varrho_\nu]$$

$\rightarrow$ numerically ray-tracing $\sim$ thousands to millions of coupled ODEs from the strong coupling regime to the vacuum regime

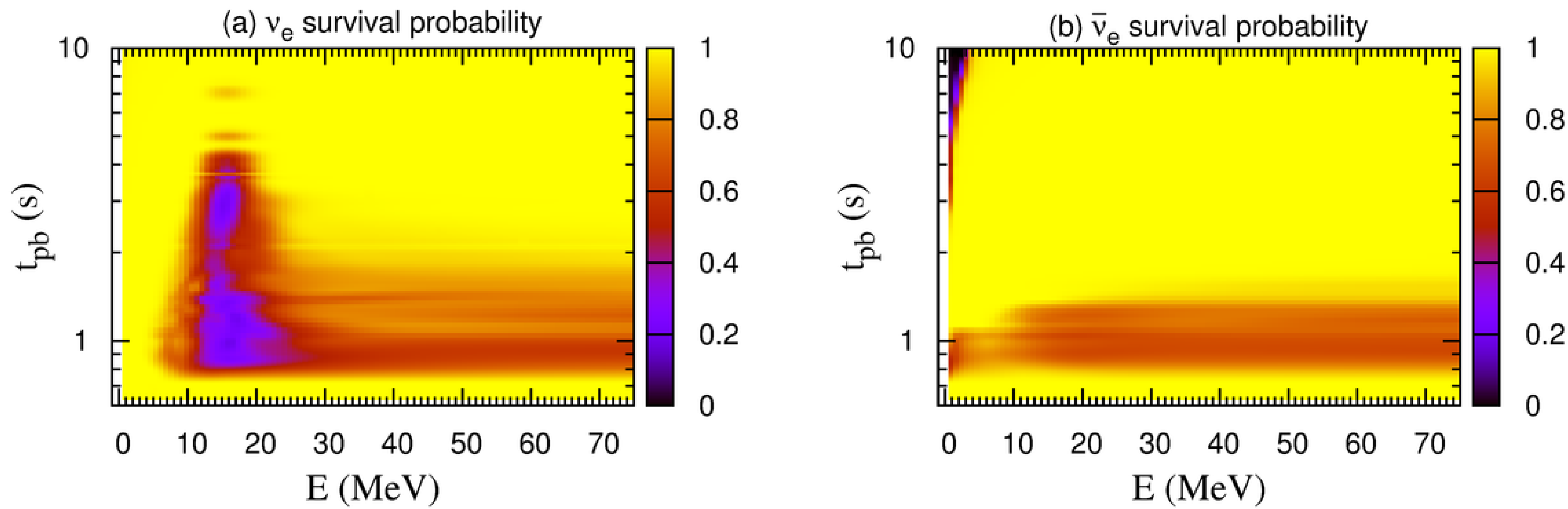


[Duan+ 2007, Dasgupta+ 2008, Fogli+ 2008, Volpe+ 2011, Raffelt 2011, MRW+2011]

spectral split at E_c (corresponds to a collective frequency)

Approach consistent with the underlying astrophysical model

ex: using full time-dependent neutrino energy/angular spectra and the matter density profile from an 18 $M_\odot$ spherically-symmetric supernova model:

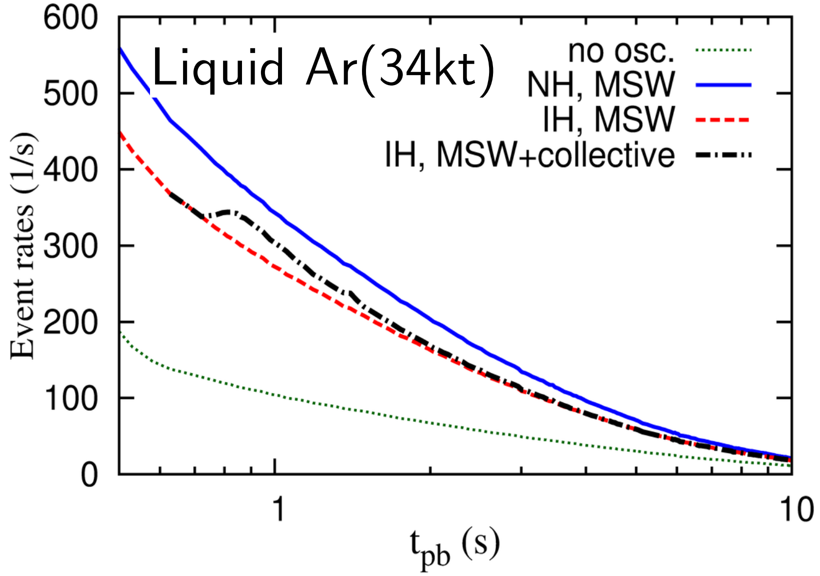


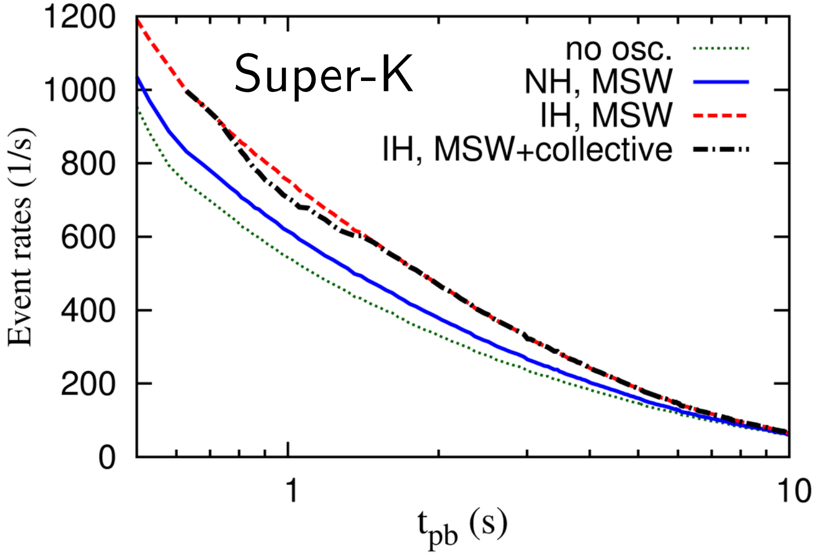
[MRW, Qian, Martinez-Pinedo, Fischer, Huther, PRD 91, 065016 (2015)]

- detail outcome sensitive to the time-evolution of supernovae
- anisotropic effect can "smooth" the spectral splits
- do not affect the shock revival
- can affect the nuclei production at outer SN shell but not in the ν-driven wind

Neutrino signals - cooling phase

Assuming a supernova explodes at 10 kpc:





Bump and dip in the time profile may signal the occurrence of collective oscillations

(Can we define an ultimate evidence of neutrino forming a strong coupling system?)

“symmetry breaking”?

Although non-linear flavor equations introduce complicated results that can only be obtained by numerical simulations, recent development of “flavor instability” analysis gives us a handle to probe whether new suprises may appear when symmetry constraints are removed.

$\rightarrow$ neutrino flavor evolution does not necessarily preserve the initial approximate-symmetry of the system [Duan+ 2015, 2016, Mirizzi+ 2015, 2016...]

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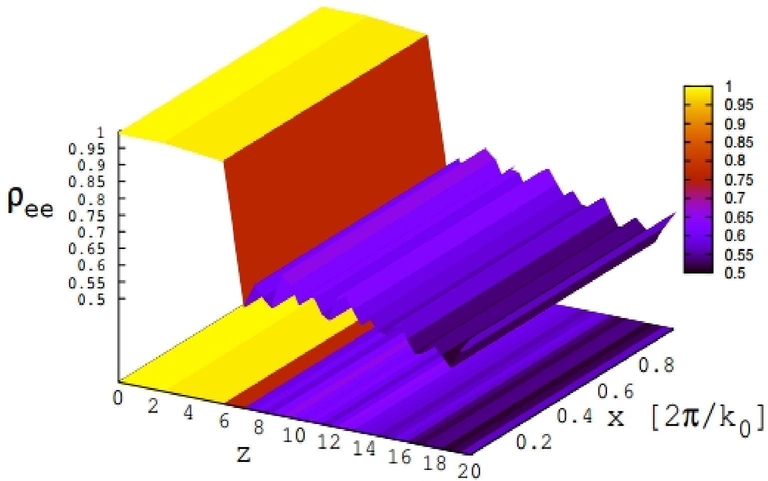
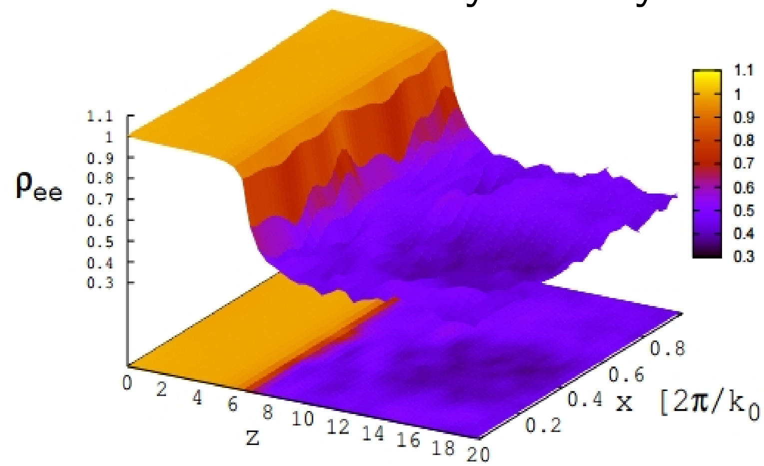
ex: “neutrino line model”:

with translation symmetry in x



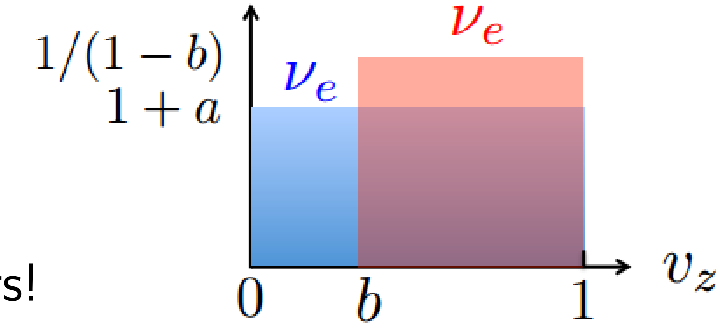
without translation symmetry in x



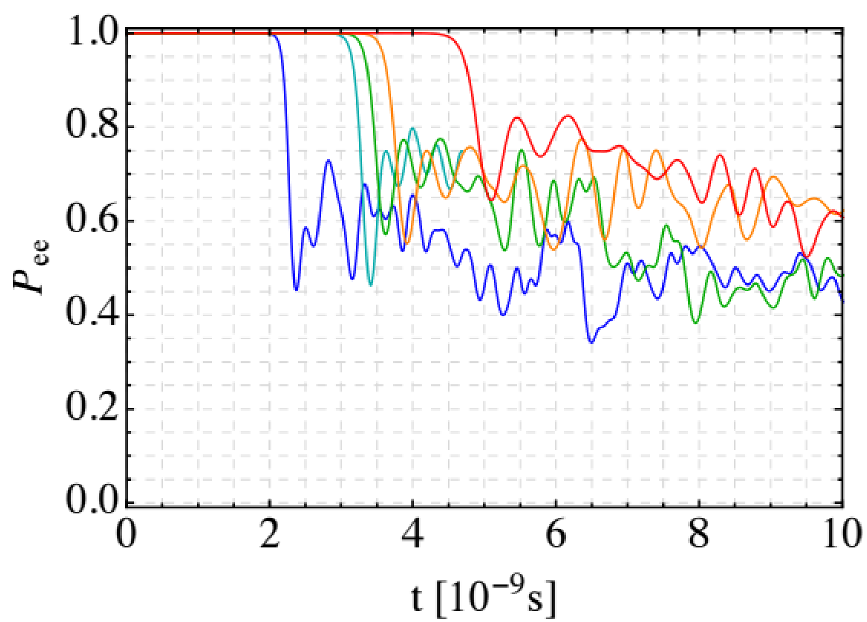
[Mirizzi, Mangano, Saviano, PRD 92, 021702, 2015]

“fast ν oscillations”?

If there exists asymmetric angular distribution between ν_e and $\bar{\nu}_e$, flavor instability may develope at time scale $\lesssim (\sqrt{2}G_F n_\nu)^{-1}$, which implies an oscillation length scale of $\sim$ centimeters!



[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016-17...]



$\mu = 4 \times 10^5\ \mathrm{km}^{-1}$

$a = 0.1, b = 0.6$

$a = 0.2, b = 0.6$

$a = 0.1, b = 0.4$

$a = 0.1, b = 0.35$

$a = 0.1, b = 0.3$

[Dasgupta+ JCAP 1702, 019 (2017]

whether supernovae can provide such a condition remain uncertain as the proto-neutron star deleptonizes (neutronizes)

“fast ν oscillations” in merger remnants

recall that the NS–NS merger remnant leptonizes (protonizes) : prominent site for fast flavor conversion!

$$L_{n,\bar{\nu}_e}/L_{n,\nu_e} = 1.35,\ R_{\bar{\nu}_e} = 0.75 R_{\nu_e},\ h_{\nu_e}/R_{\nu_e} = h_{\bar{\nu}_e}/R_{\bar{\nu}_e} = 0.25,\ \vec{k} = 0.$$

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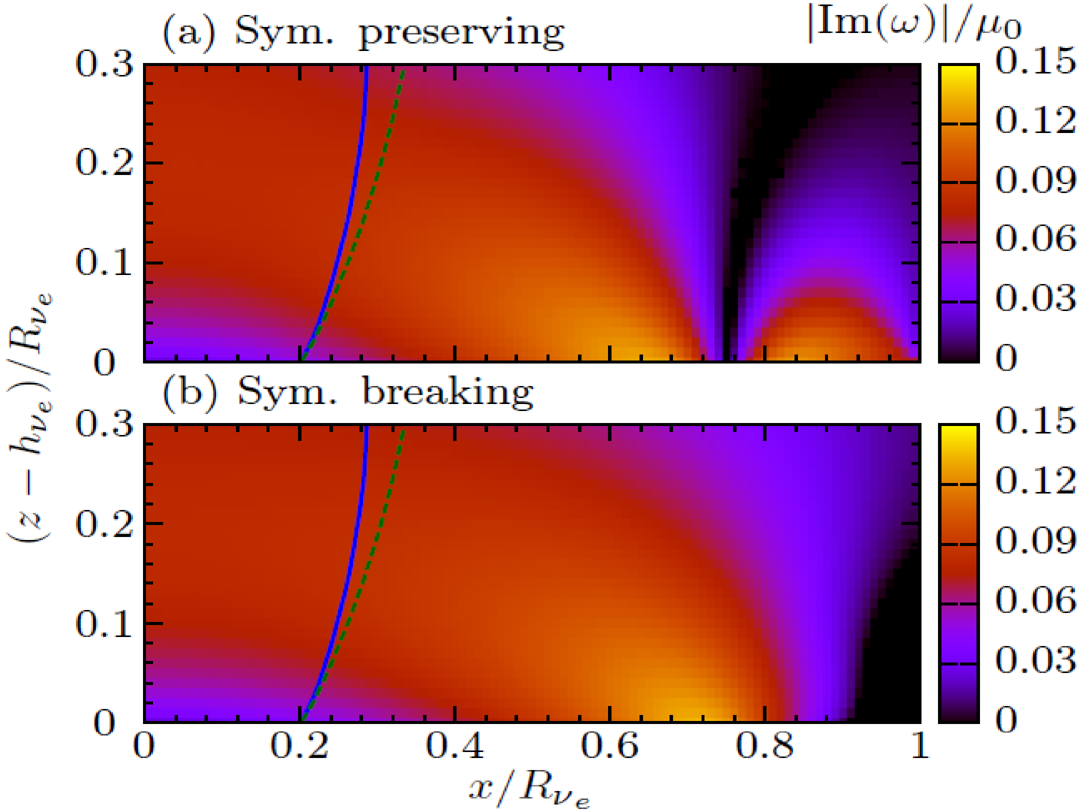


Im(ω): growth rate of flavor mixing in the linear regime

$$\mu_0 \approx 4.25\ \mathrm{cm}^{-1} \times \left(\frac{L_{\nu_e}}{10^{53}\mathrm{erg/s}}\right)\left(\frac{10\mathrm{MeV}}{\langle E_{\nu_e}\rangle}\right)\left(\frac{100\mathrm{km}}{R_{\nu_e}}\right)^2$$

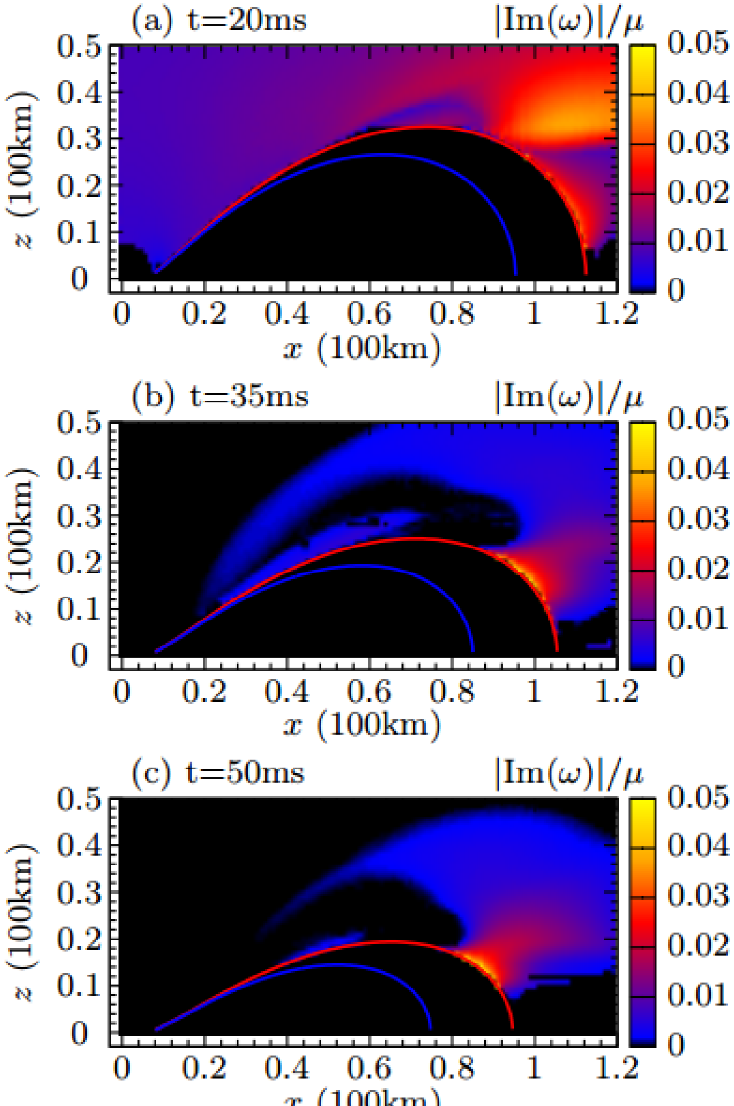
fast flavor conversion condition exists everywhere above the remnant

[MRW & Tamborra, PRD 95, 103007, 2017]

- does the picture remain beyond the toy model?
- impact on nucleosynthesis and the kilonova EM observables?

“fast ν oscillations” in merger remnants

We recently examine the condition using inputs from state-of-the-art BH-disk system



[MRW, Tamborra, Just, Janka, arXiv: 1711.00477]

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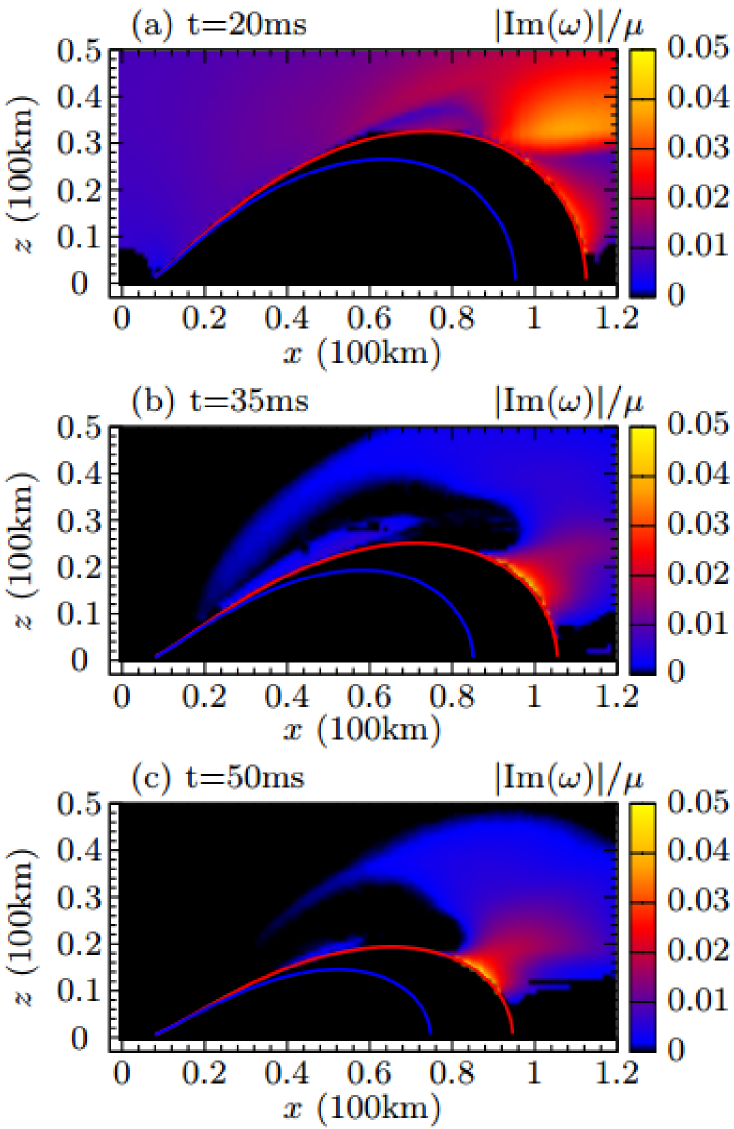
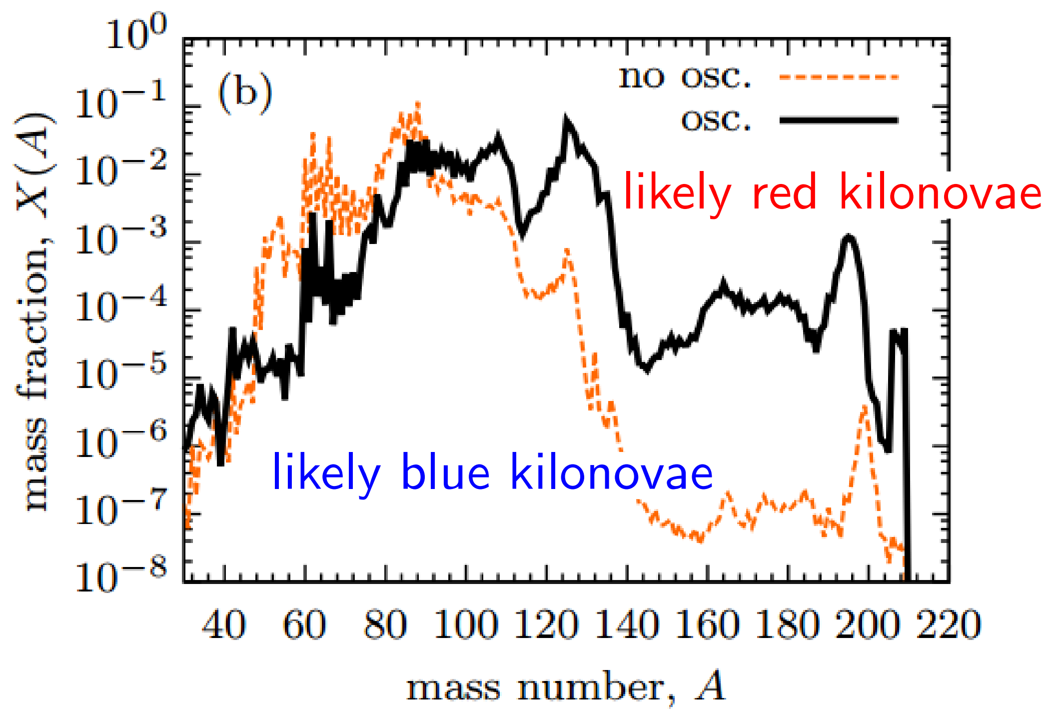


assume fast conversions lead to full flavor equipartition



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Summary

- Neutrino oscillations in explosive astrophysical transients present rich phenomena due to the "strong" non-linear coupling among neutrinos.
- In core-collapse supernovae and the remants of neutron star mergers, non-linear neutrino oscillations can affect several observables – neutrinos detection from a Galactic supernova or EM signals from neutron star mergers.
- Further improved numerical modeling taking into account the asymmetry of the astrophysical systems is needed, particularly for the fast oscillations.

Summary

- Neutrino oscillations in explosive astrophysical transients present rich phenomena due to the "strong" non-linear coupling among neutrinos.
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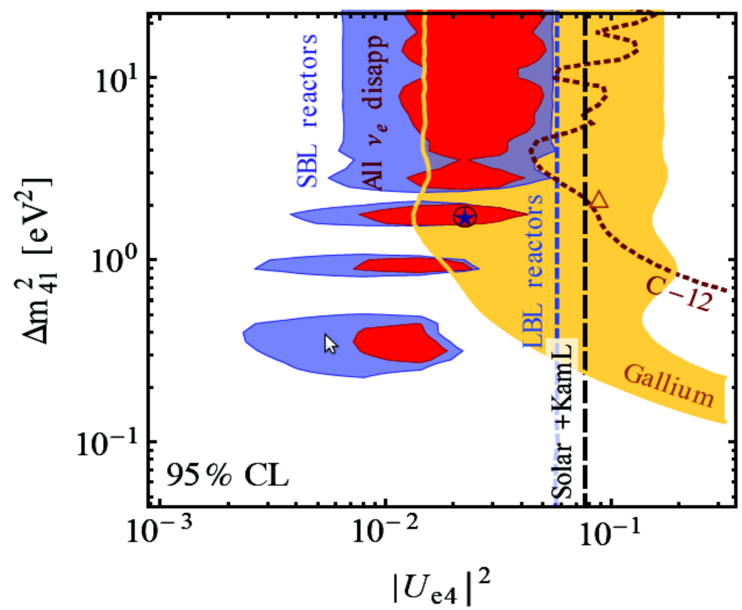
– Other impact such as the role of sub-leading order terms in the flavor evolution equations (ν mass term, higher order correlations...), uncertainties from astrophysical modeling, the presence of large magnetic field, etc., remain to be explored.

– With the advances of multi-dimensional astrophysical simulations, the anticipation of future galactic supernova neutrinos, and coming merger observations, it is now a good time to take this problem to the next level of sophistication, both from theory and from observation point of view.

eV sterile neutrinos?

Active - sterile (mainly eV) ν mixing

[Kopp et.al, JHEP05 (2013) 050]



Reactor ν anomaly + Gallium anomaly:

[Mention+ 2011] [Giunti+ 2011-2013]

$$\delta m^2_{41} \sim O(\mathrm{eV}^2)$$
$$\sin^2 2\theta_{14} = \sin^2 2\theta_{ee} \sim 0.1$$

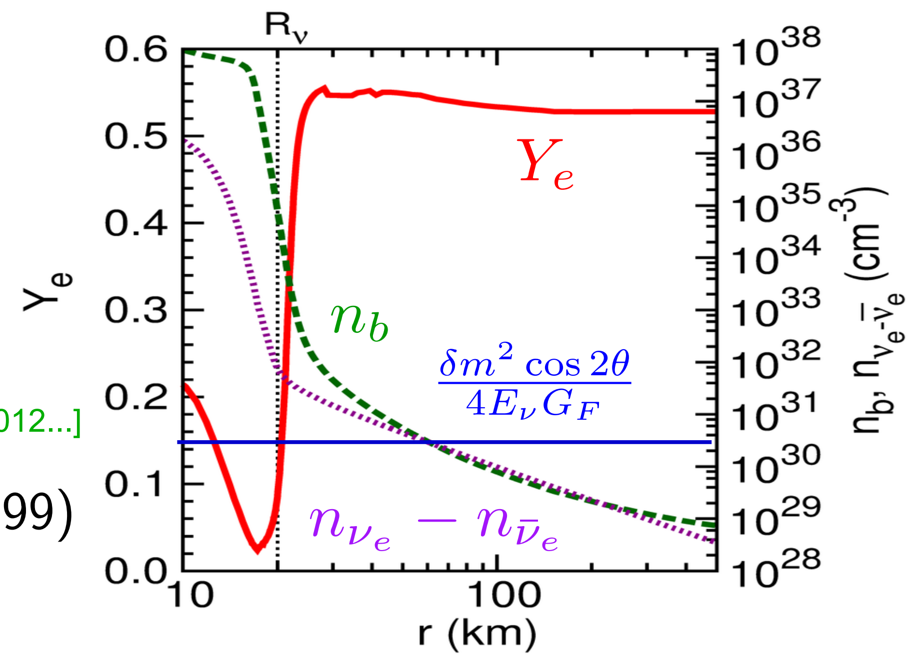
MSW-like resonances occur at

(i) $Y_e \approx 1/3$

(ii) $G_F n_b Y_e \sim \frac{\delta m^2_{41}}{2E_\nu}$

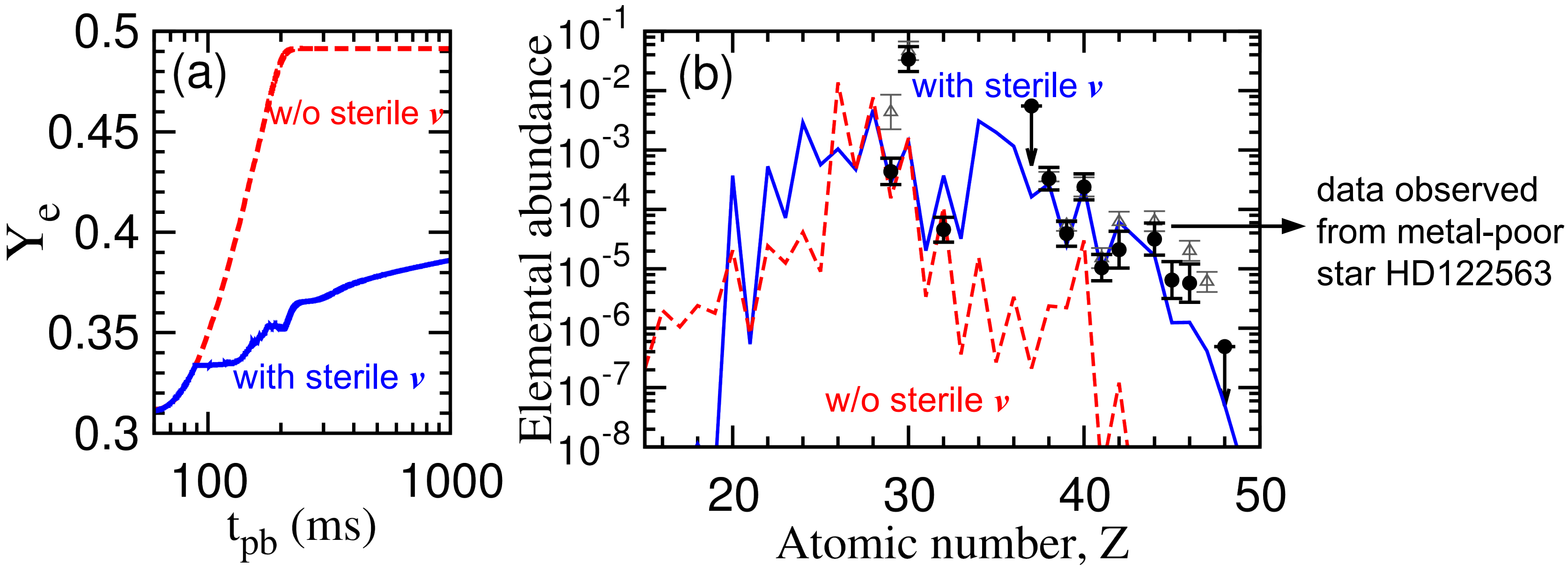
[Pastor+ 1995, Nunokawa+1997, McLaughlin+1999, Tamborra+ 2012...]

may enable an r-process (McLaughlin+1999) or weak r-process (Wu+2014)



Impact on nucleosynthesis

[MRW, Fischer, Huther, Martinez-Pinedo, Qian, PRD 89, 061303, 2014]



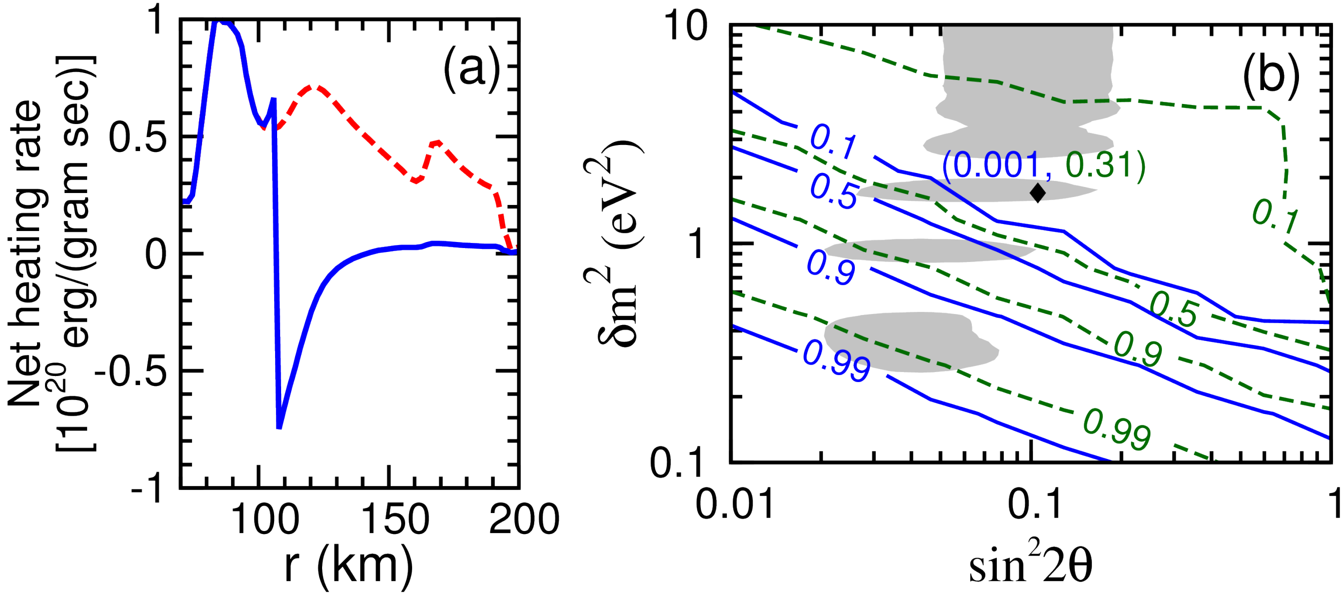
- Y_e is lowered from ~ 0.48 to ~ 0.37 for the ejecta
- produces neutron-rich isotopes
- results insensitive to the mixing parameters

$\rightarrow$ a viable option for the weak-r process?

Impact on SN explosions?

ν heating rates may be greatly reduced with light sterile neutrinos

[MRW, Fischer, Huther, Martinez-Pinedo, Qian, PRD 89, 061303, 2014]

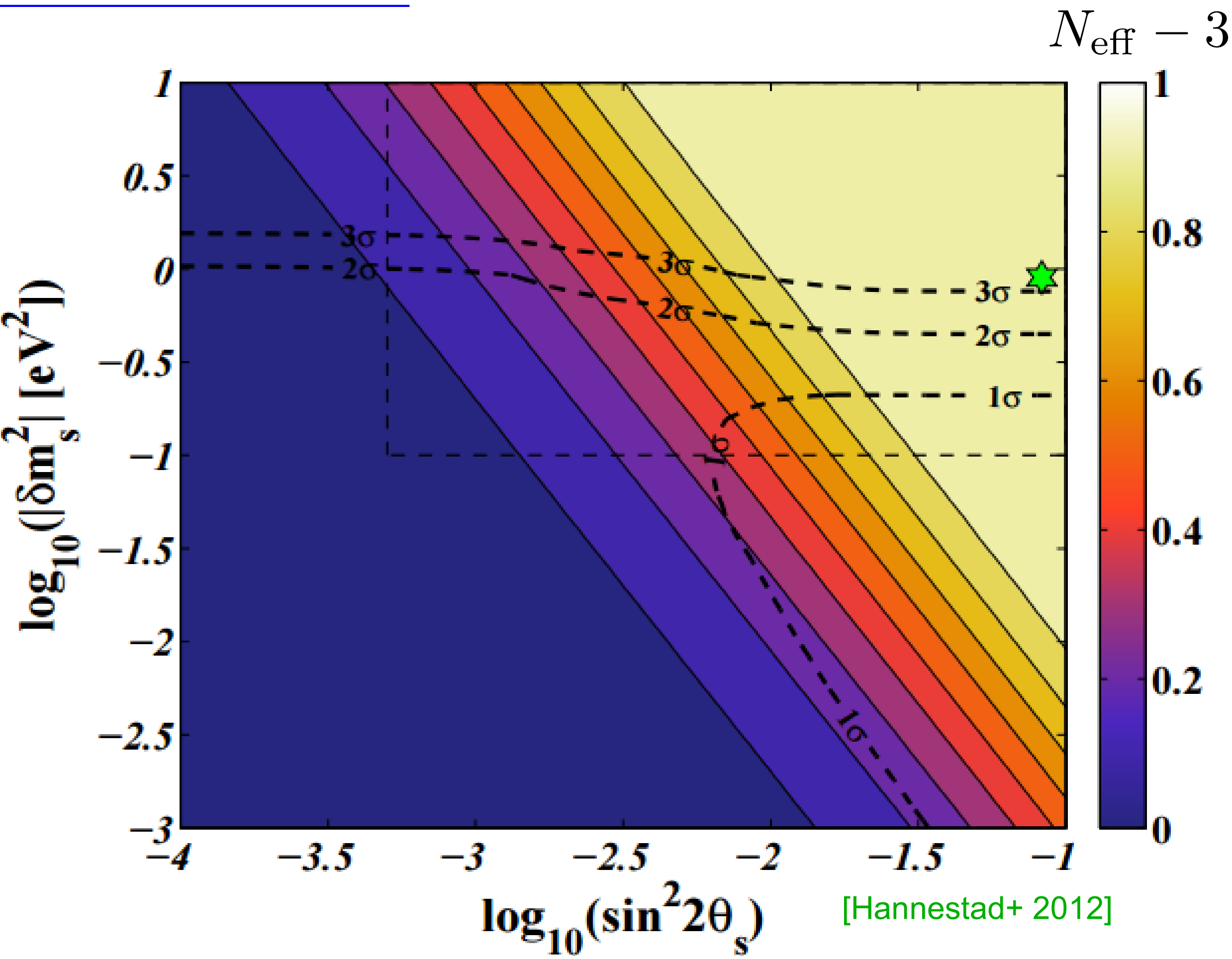


are eV sterile neutrinos consistent with SN explosion?

KeV or even MeV sterile neutrinos?

[Hidaka+ 2006, Warren+ 2014, Fuller+ 2008, Albertus+ 2015]

Constraint from cosmology



[Hannestad+ 2012]

reactor anomaly value probably gives too large $N_{\rm eff}$ for CMB but there are some other ways to reconcile:
e.g., impose large lepton asymmetry, $[(n_\nu - n_{\bar{\nu}})/n_\gamma \sim 10^{-2}]$,
or introduce interaction among sterile neutrino themselves...

[Hannestad+ 2013, Dasgupta+ 2013]