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Neutrinos in supernovae and binary neutron star mergers

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MOST 科技部
Ministry of Science and Technology

Outline

- Core-collapse supernovae and neutrinos
  - neutrino emission
  - neutrino interaction and flavor oscillations
  - what can we probe with SN neutrinos?

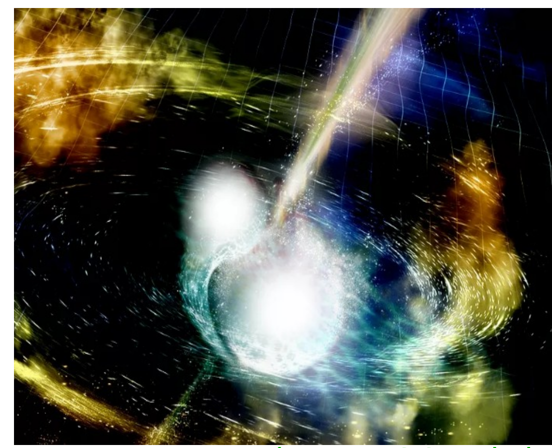
(From AAO website)

core-collapse supernovae

[see yeterday (June 2)'s talk on DSNB by Andrew Mastbaum]

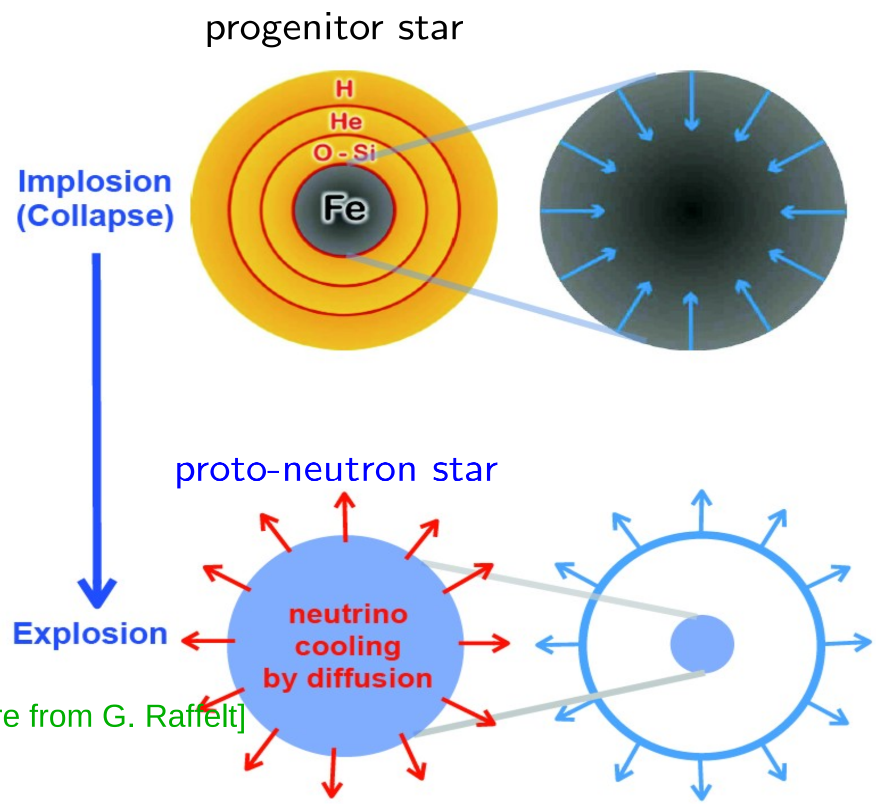
- Neutrinos in binary neutron star mergers
  - flavor oscillations and their impact

- Summary


(From LIGO website)

NS–NS (BH) mergers

Core-collapse supernovae – 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

$E_{\text{grav}} \sim \frac{G M_{\text{PNS}}^2}{R_{\text{PNS}}} \sim 10^{53}$ erg, radiated mostly by $\sim 10^{58}$ ν's in ~ 10 seconds

$\rightarrow \sim 20$ events from SN1987a at LMC

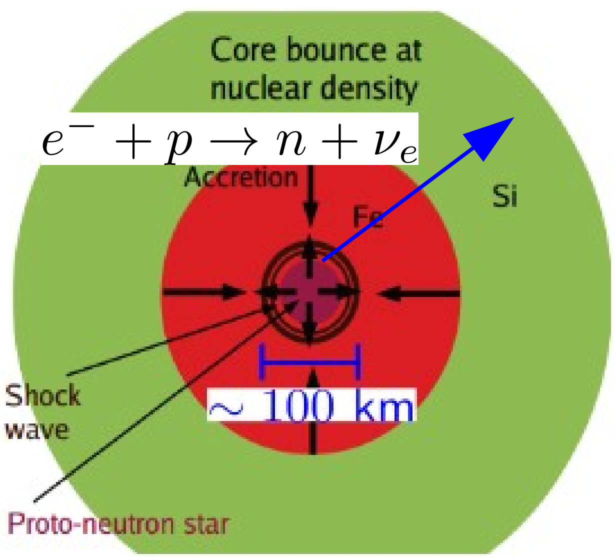
thousands of events in ALL FLAVORs expected from the next Galactic SN

General feature of supernova neutrino emission

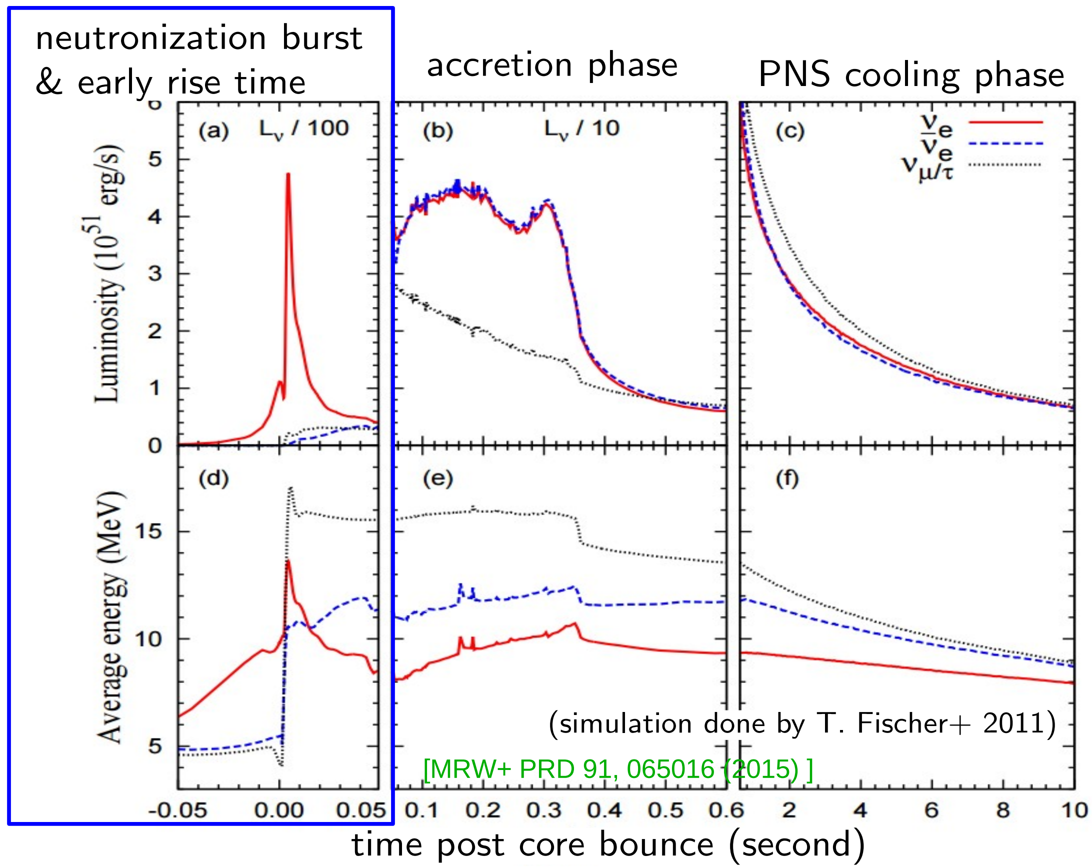
- neutronization burst: dominant ν_e emission for ~ 30 ms from shock-breakout off neutrinosphere; robust theory prediction

- accretion phase: powered by accreting material for $\mathcal{O}(100)$ ms; neutrinos play key role in reviving the shock

- cooling phase: $\mathcal{O}(10)$ s emission from PNS; ν-driven wind for nucleosynthesis



[Janka+, PTEP 01A309, 2012]



(simulation done by T. Fischer+ 2011)

[MRW+ PRD 91, 065016 (2015)]

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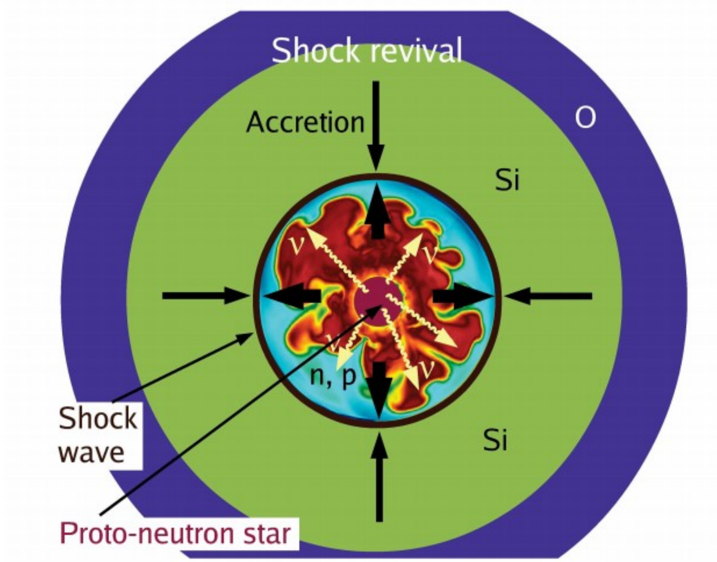
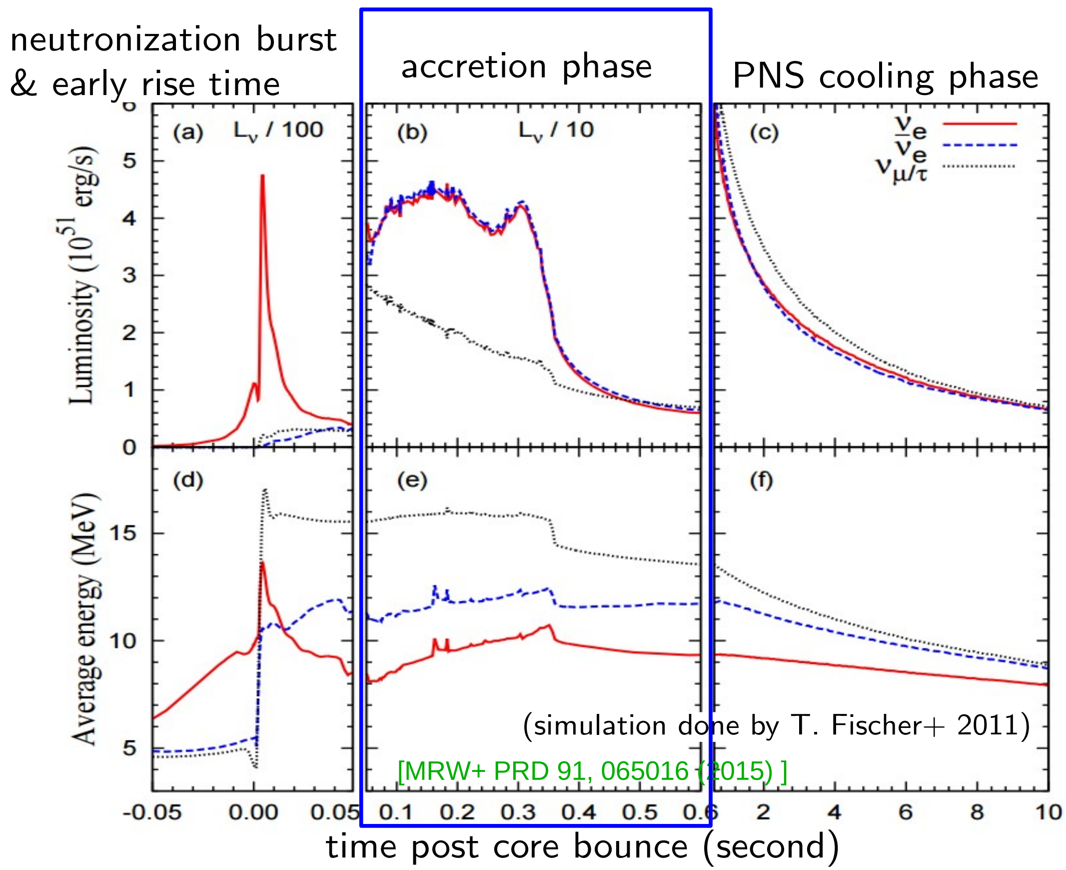


[Janka+, PTEP 01A309, 2012]



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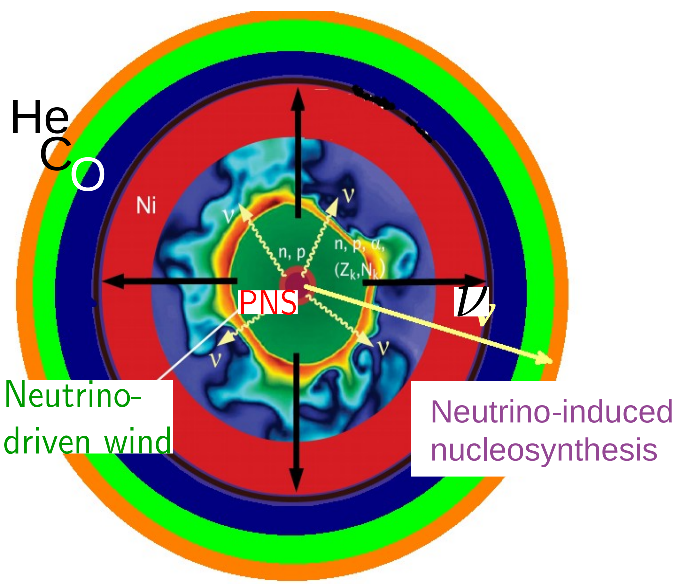
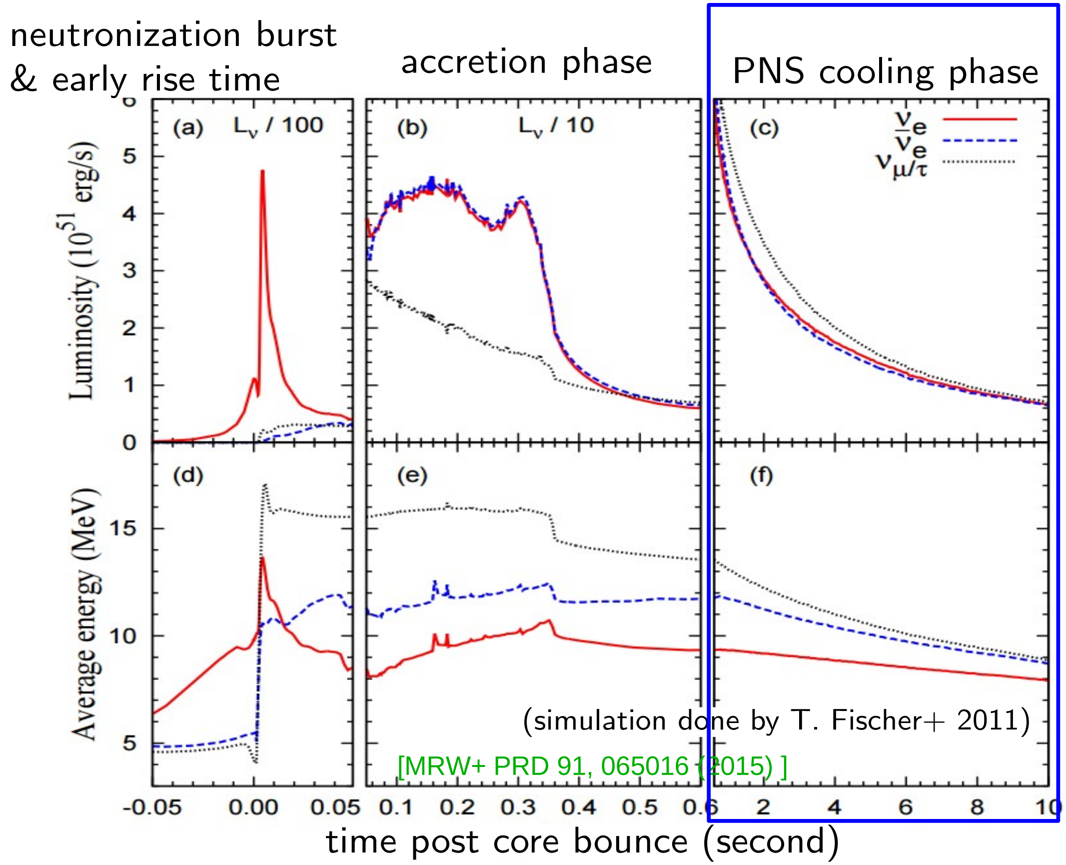


[Modified from Janka+, PTEP 01A309, 2012]



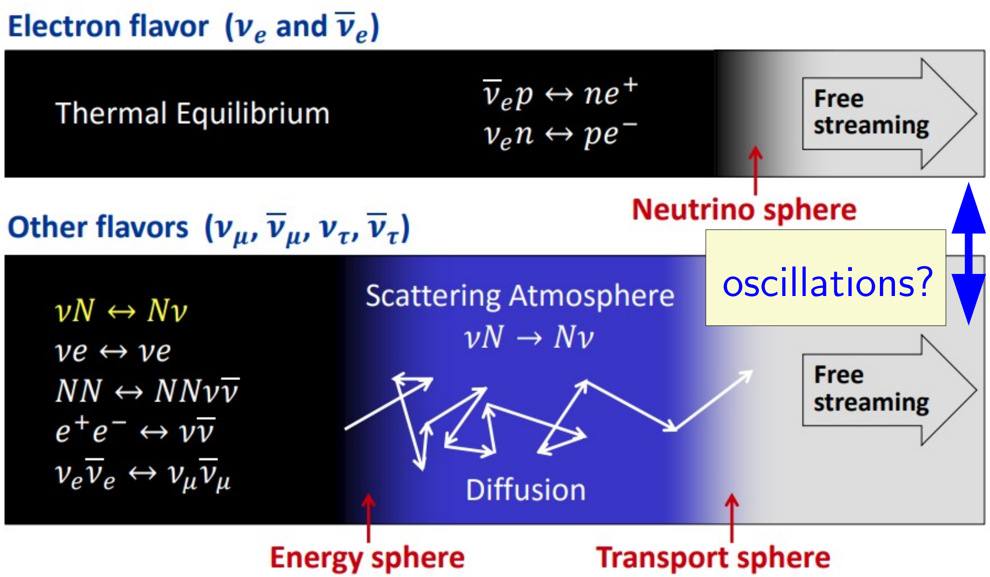
(simulation done by T. Fischer+ 2011)

[MRW+ PRD 91, 065016 (2015)]

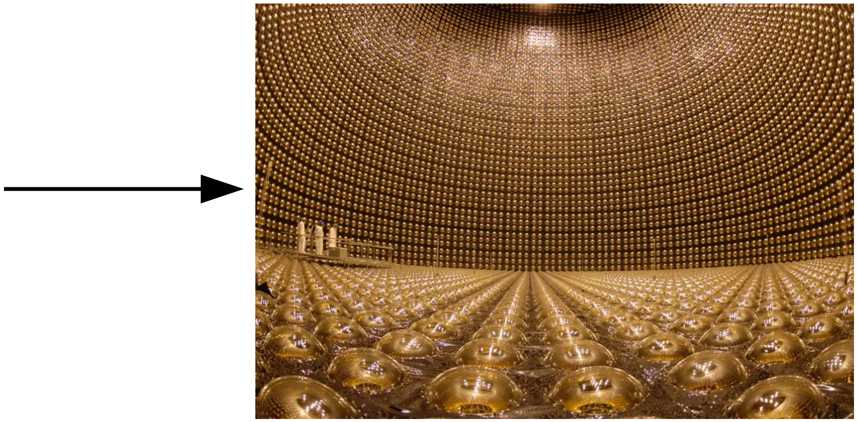
Fore-front (neutrino-related) theory issues in supernovae

• neutrino nuclear matter interaction: uncertainty can be large (a factor of a few) at high densities; impacts the neutrino luminosities at level of $\sim$ tens percents; affects shock revival dynamics and nucleosynthesis [Burrows+, Fischer+, Guo+, Horowitz+, Lin+, Martinez-Pinedo+, Oertel+ Reddy+, Roberts+, Schwenk+,...]

• neutrino flavor oscillations: new and exciting effects every few years, but no consistent and trustable global impact yet;
[Abbar+, Balantekin+, Capozzi+, Cervia+, Chakraborty+, Dasgupta+, Duan+, Fuller+, Friedland+, Johns+, Kato+, Kajino+, Kneller+, Martin+, Manibrata+, Mclaughlin+, Mirizzi+, Morigana+, Nagakura+, Raffelt+, Richers+, Rogerro+, Rrapaj+, Sawyer+, Shalgar+, Tamborra+, Volpe+, MRW+, Xiong+, Yamada+...]



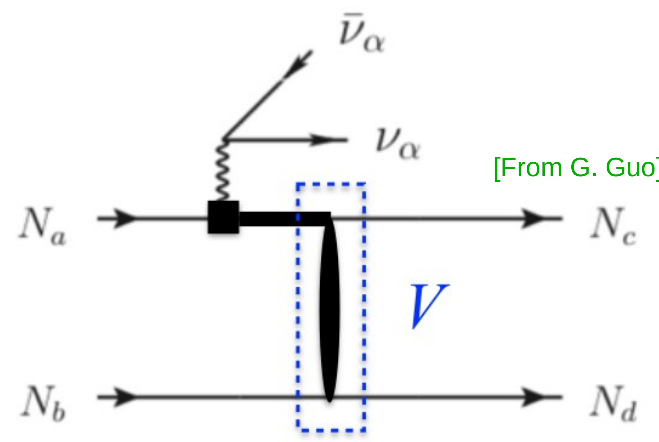
[Janka 1702.08713, Raffelt 2012]



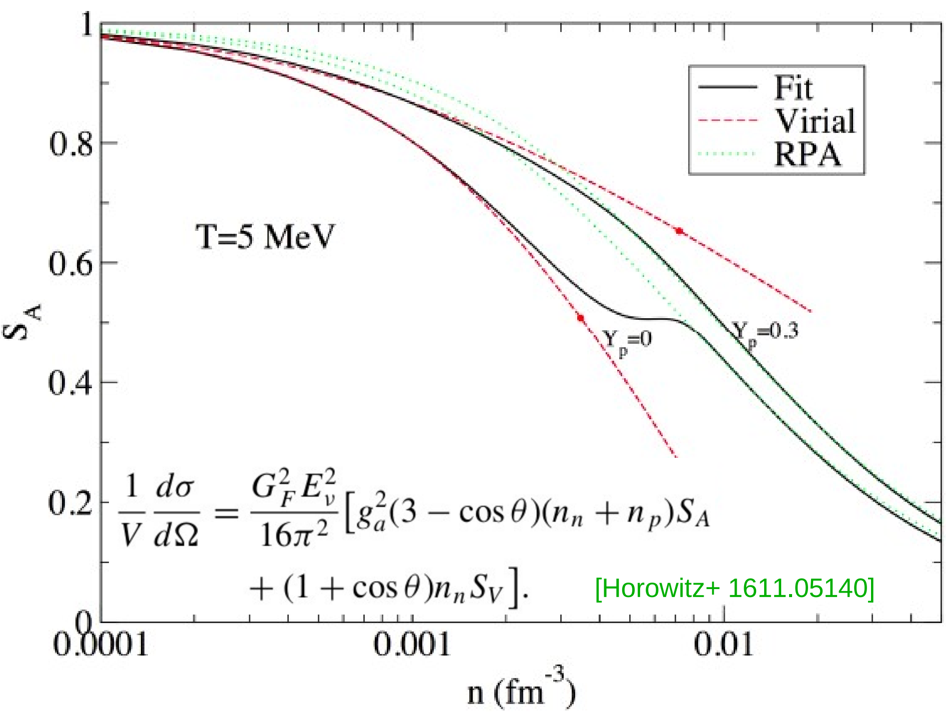
[from Super-K]

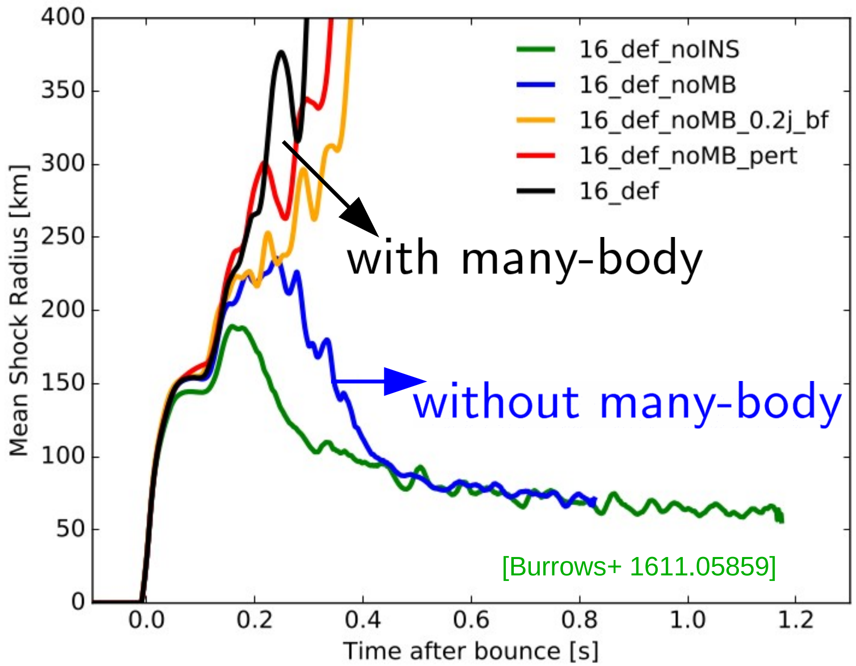
Role of neutrino interaction

Accurate description of neutrino interaction with nuclear matter, better than $\sim 20-30\%$ is needed, especially near the neutrinosphere



Modification on the axial-current response for neutrino-nucleon scattering:

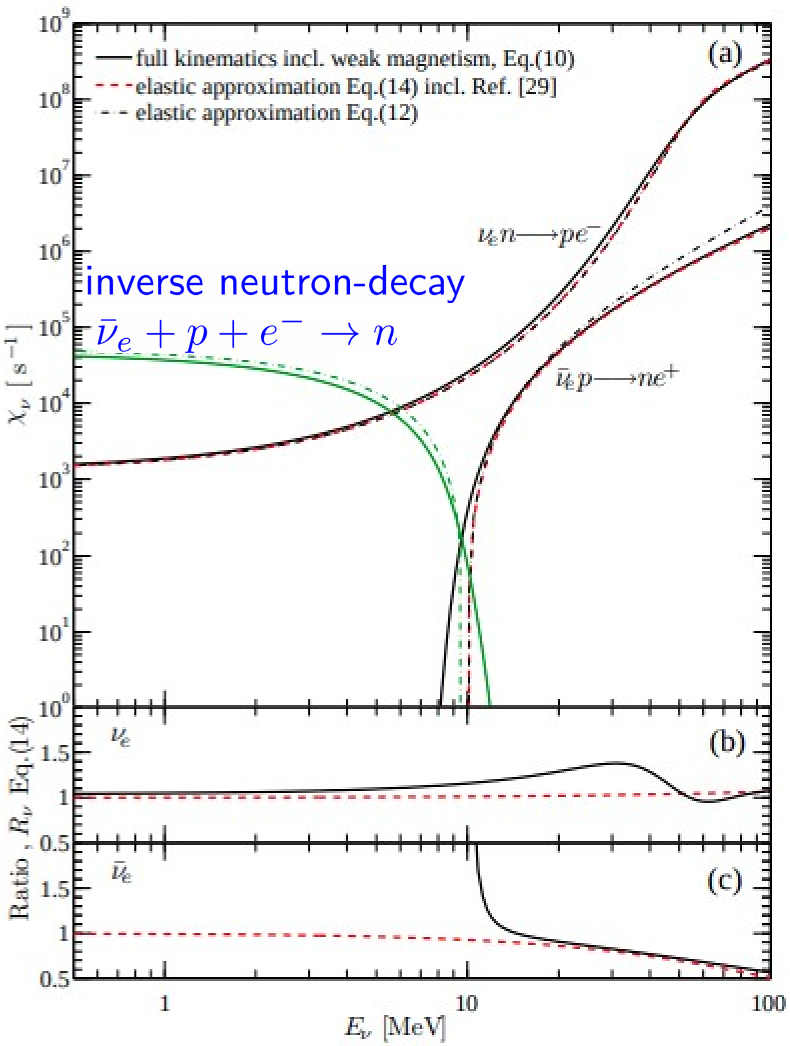


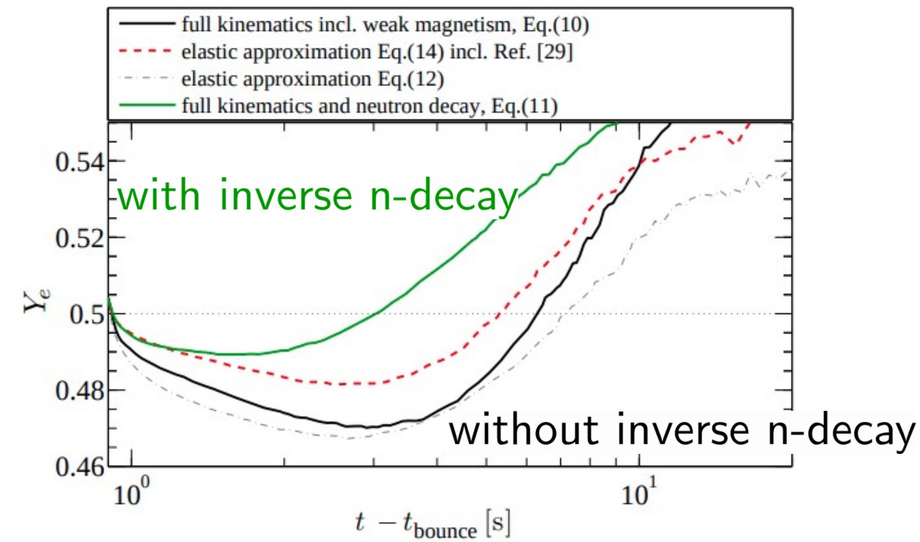


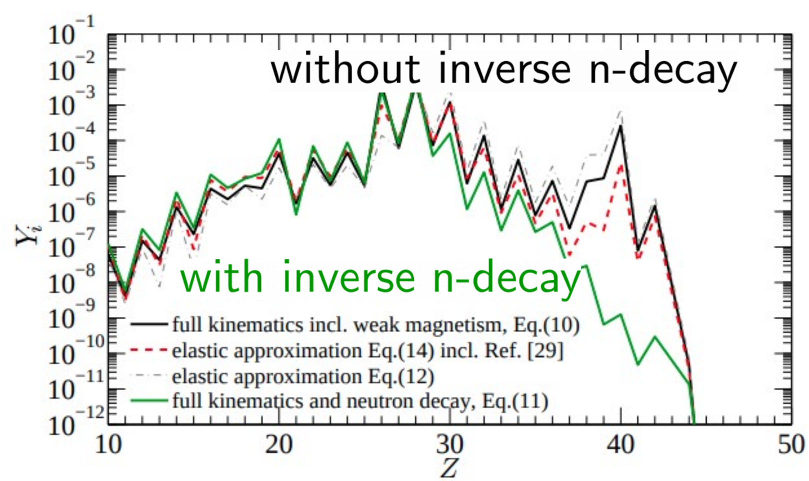
[See also: Burrows+ 9801082, Reddy+ 9811294, Horowitz+ 9908219, Burrows+ 0404432, Martinez-Pinedo+ 1205.2793, Roberts+ 1205.4066, Horowitz+ 1209.3173, Becca+ 1112.5185, Bartl+ 1403.4114, Melson+ 1504.07631, Fischer 1608.05004, Roberts+ 1612.02764, Lin+ 1708.01788, Bedaque+ 1801.07077, Fischer+ 1804.10890, Guo+ 1905.13634, Oertel+ 2003.02152, Betranhandy+ 2010.02261,...]

Role of neutrino interaction

Accurate description and inclusion of rates also affects heavy element production in neutrino-driven wind

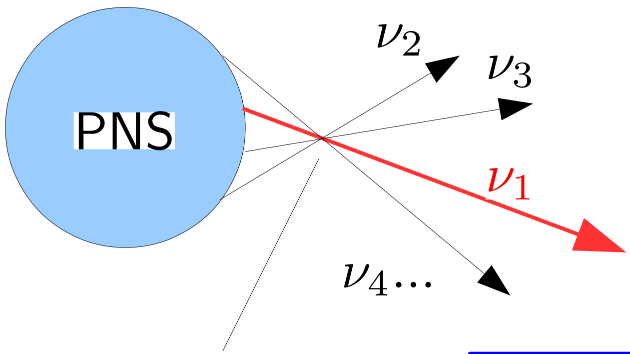






[Fischer+ 1804.10890]

Collective neutrino oscillations

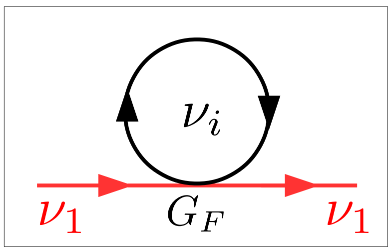


flavor evolution for ν with different momenta are coupled

→ many-body quamtum system

→ "strong" coupling system $(G_F n_\nu \gg \frac{\delta m^2}{2E_\nu})$

→ collective phenomenon



$$\partial_t \varrho(\mathbf{x},\mathbf{p},t) + \mathbf{v}\cdot\nabla_{\mathbf{x}}\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm MSW} + H_{\nu\nu}, \varrho]$$

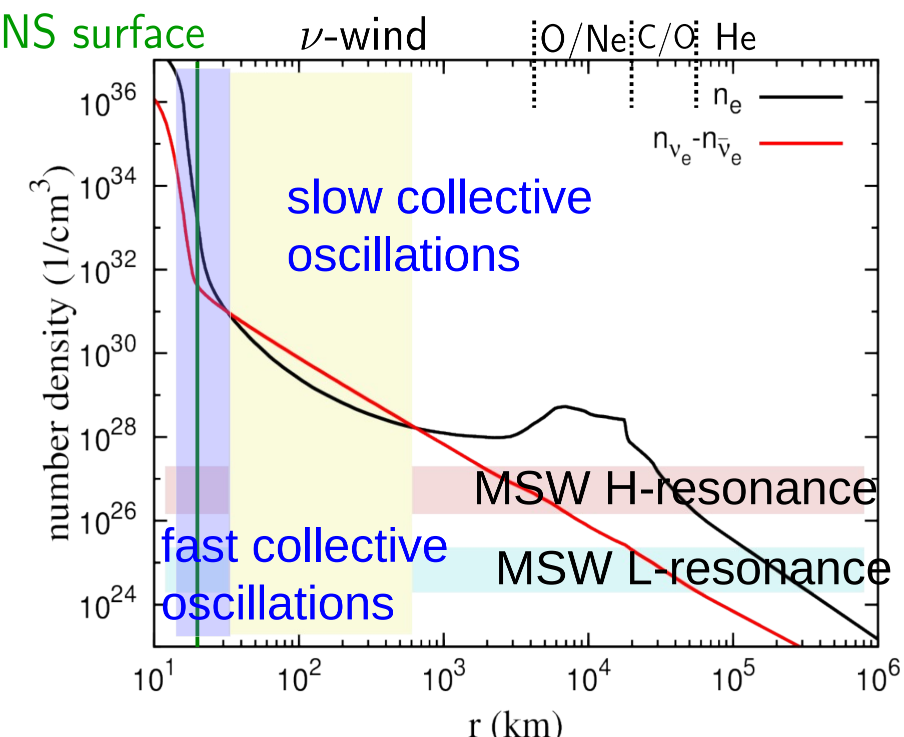
$$H_{\rm vac}(p) = UM^2U^\dagger/(2|\mathbf{p}|),$$

$$H_{\rm MSW}(\mathbf{x},t) = \sqrt{2}G_F n_e \times {\rm diag}(1,0,0)$$

$$H_{\nu\nu}(\mathbf{x},\mathbf{p},t) = \frac{\sqrt{2}G_F}{(2\pi)^3}\int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho - \bar{\varrho}^*]$$

$$\varrho(t,\mathbf{x},\mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{bmatrix}$$

flavor density matrix of the neutrino ensemble



Fast ν oscillations

The angular crossing of electron-neutrino lepton number (ELN crossing)

(the ELN function $G^0_{\mathbf{v}_\nu} \propto \int E_\nu^2 dE_\nu [f^0_{\nu_e}(\mathbf{p}_\nu) - f^0_{\bar{\nu}_e}(\mathbf{p}_\nu)]$ has $+$ and $-$ values)

$\rightarrow$ flavor instability with growth rate $\sim G_F n_\nu \sim \mathcal{O}(\mathrm{ns}^{-1})$ [Sawyer+, Izaguirre+, Dasgupta+, Morinaga+...]

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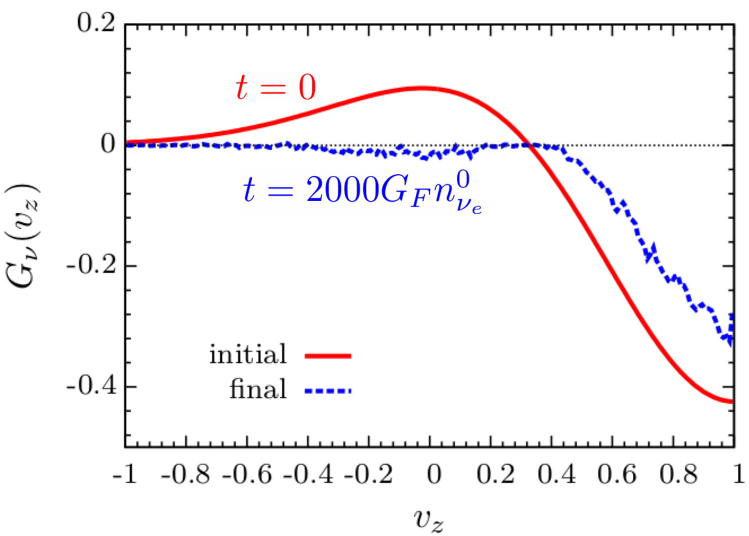
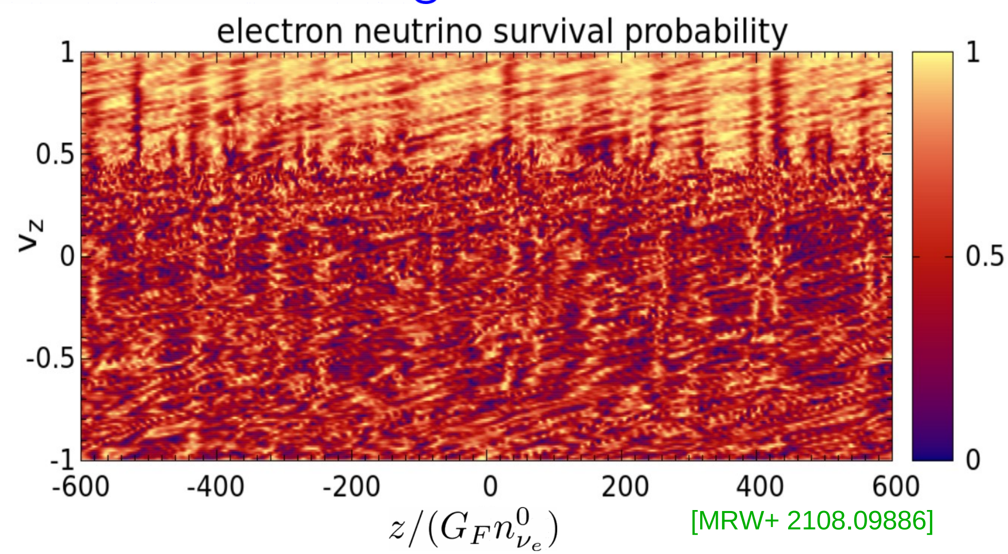
Several groups started to develop multidimensional simulation code to solve the quantum kinetic equation numerically [See Richers+ 2205.06282 for detailed comparison of simulation results]

$\rightarrow$ fast oscillations that tend to erase the ELN crossing [Bhattacharyya+, Richers+, MRW+]





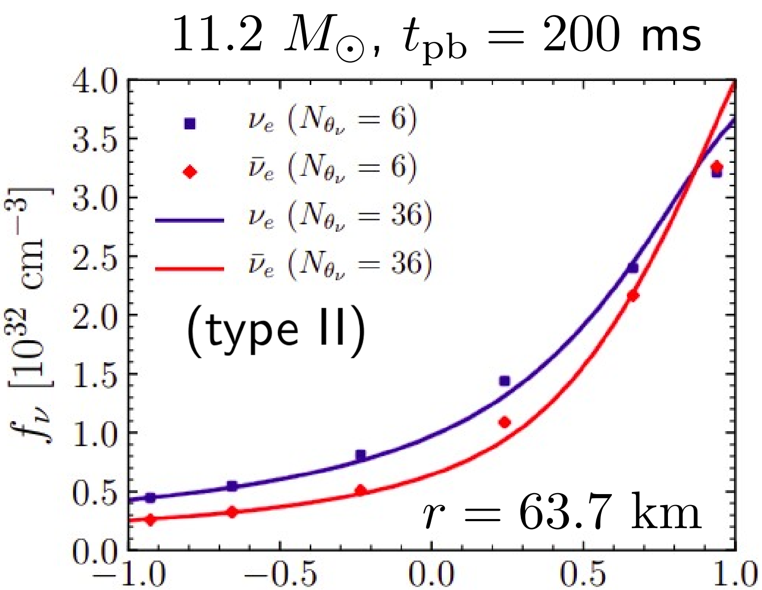
[MRW+ 2108.09886]

Can the final shape of ELN be estimated (semi-)analytically?

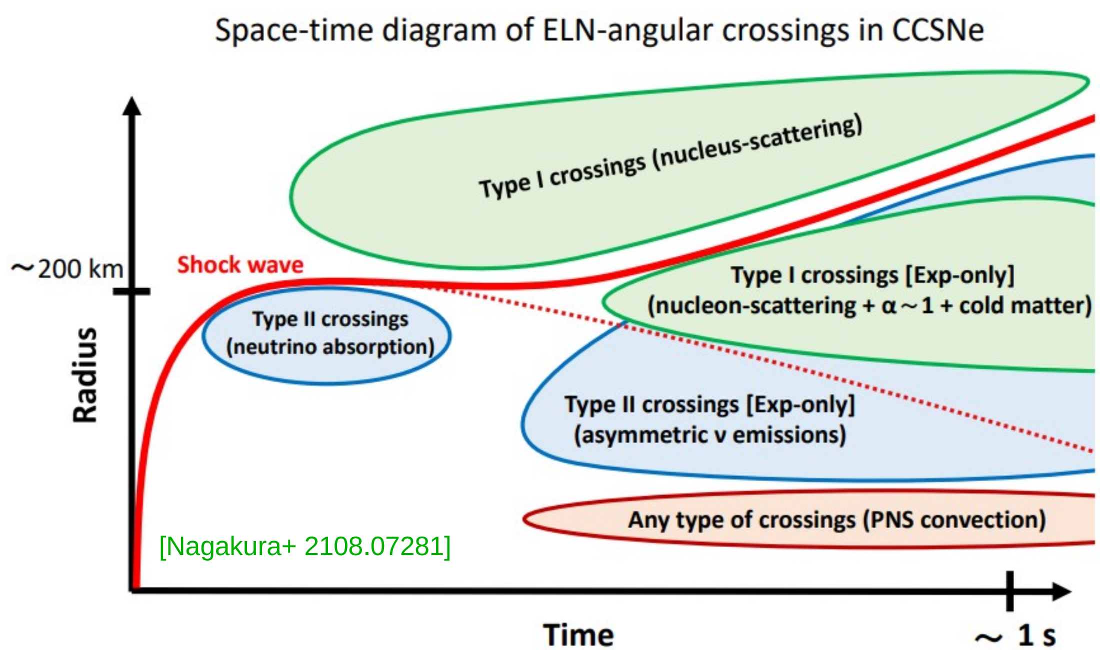
$\rightarrow$ see Bhattacharyya+ 2009.03337, 2205.05129 for nice attempts

Fast ν oscillations in supernovae

1D supernova models do not show ELN crossing, but the ELN crossing are found in multi-D supernova simulations



[Abbar+ 1911.01983]



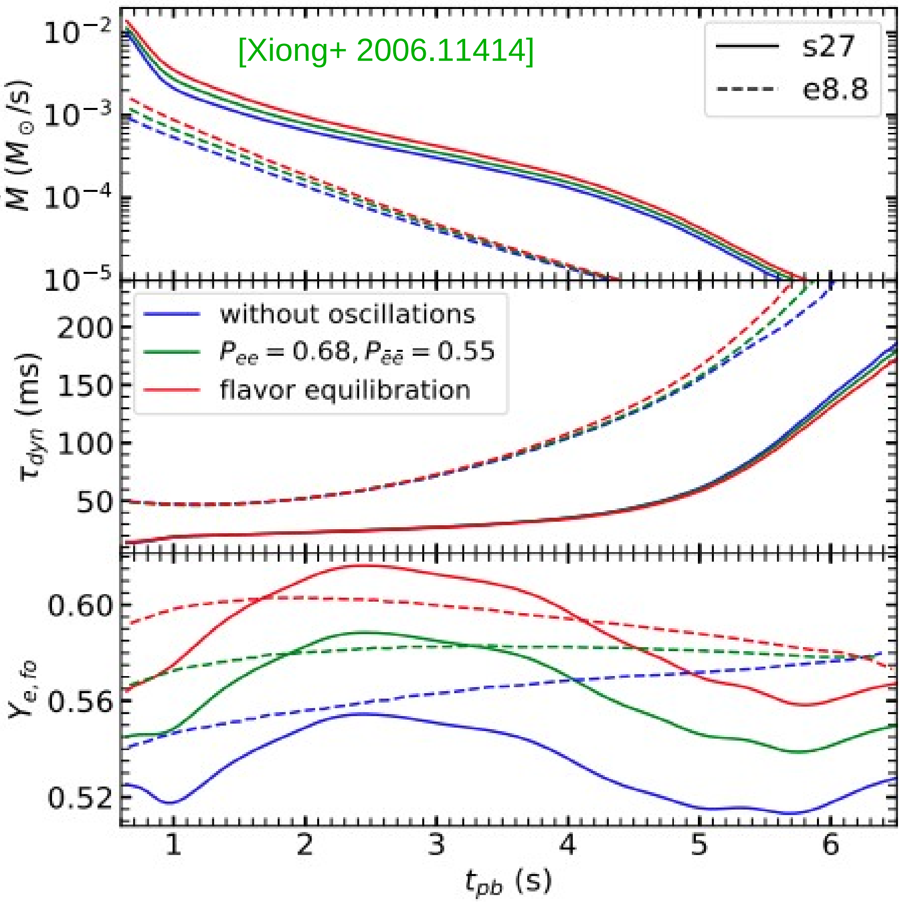
[Nagakura+ 2108.07281]

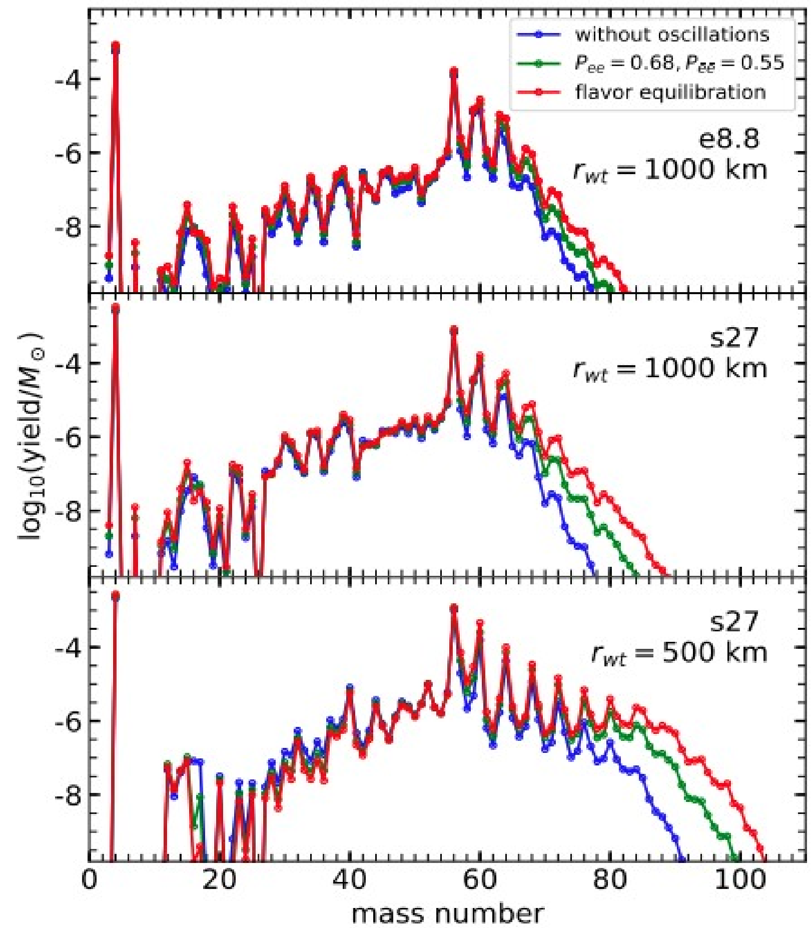
[See also Morigana+ 1909.13131, Nagakura+ 1910.04288, Johns+ 1910.05682, Delfan Azari+ 1910.06176, Glas+ 1912.00274, Abbar+ 2003.00969, Capozzi+ 2005.14204, Abbar+ 2012.06594, Capozzi+ 2012.08525, Johns+ 2104.04106, Nagakura+ 2106.02650, Harada+ 2110.08291]

What is the exact outcome and impact? (If flavor equipartition occurs globally, heating rate during the accretion phase can be substantially enhanced)

Role of neutrino flavor oscillations

If fast flavor oscillations happen for neutrinos in cooling phase, they can also affect the nucleosynthesis outcome





[See also Duan+ 1012.0532, MRW+ 1412.8587, Pllumbi+ 1406.2596, Sasaki+ 1707.09111, Kusakabe+ 1907.01715, Ko+ 1903.02086, Ko+ 2203.13365 for other oscillation effects on nucleosynthesis]

More on collective oscillations

Several other interesting new effects or understandings:

- 3-flavor and $\mu - \tau$ asymmetry effect

  [Chakraborty+ 1909.10420, Shalgar+ 2103.12743, Capozzi+ 2005.14204, Capozzi+ 2012.08525, ...]

- interplay of collisions and oscillations

  [Shalgar+ 2011.00004, Martin+ 2101.01278, Johns 2104.11369, Sasaki+ 2109.14011, Sigl 2109.00091, ...]

- impact of turbulence

  [Abbar+ 2007.13655 for turbulence coupling on collective oscillations;
  (see also Kneller+ 1202.0776, Lund+ 1304.6372, Borriello+ 1310.7488, Patton+ 1407.7835, Yang+ 1510.01998, Kneller+ 1702.06591, Yang+ 1706.01339… for other turbulence effect)]

- many-body (beyond the mean-field)

  [Friedland+ 0304055, 0307140, Birol+ 1805.11767, Patwardhan+ 1905.04386, Rrapaj 1905.13335, Roggero 2102.10188, 2103.11497, Patwardhan+ 2109.08995, Xiong 2111.00437, Martin+ 2112.12686, Cervia+ 2202.01865, Lacroix+ 2205.09384,...]

- analytical understanding of toy models

  [Johns+ 2009.09024, Xiong+ 2104.05618, Bhattacharyya+ 2101.01226, Padilla-Gay+ 2109.14627, ...]

- attemps of global simulations

  [Richers+ 1903.00022, Stapleford+ 1910.04172, Myers+ 2111.13722, ...]

What can we learn from detecting supernova neutrinos?

What can we learn from detecting supernova neutrinos?

- neutronization burst:
  - neutrino mass ordering
  - light (eV) sterile neutrinos

NO: $\nu_e^{\text{final,MSW}} \approx \nu_x^{\text{initial}}$

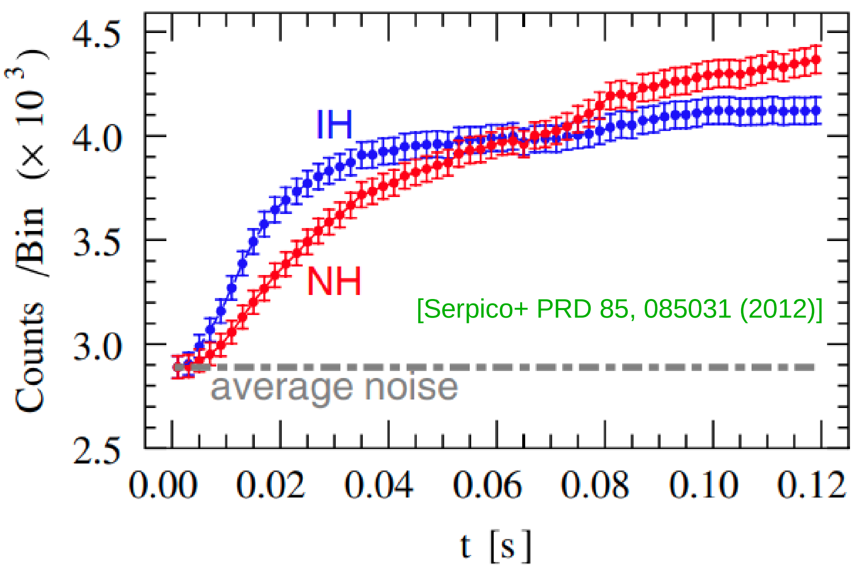
IO: $\nu_e^{\text{final,MSW}} \approx 0.3\nu_e^{\text{initial}} + 0.7\nu_x^{\text{initial}}$

- accretion phase:
  - explosion mechanism

  (SASI? phase-transition? thermonuclear?)

- cooling phase:
  - nuclear property or progenitor
  - new physics

for a SN at 10 kpc, counts at IceCube



[See also Kachelriess+ 0412082, MRW+ 1412.8587, Vale+ 1509.07342, Scholberg 1707.06384 Jia+ 1709.09453, Lai+ 2001.08543, Brdar & Xu 2204.13135, ...]

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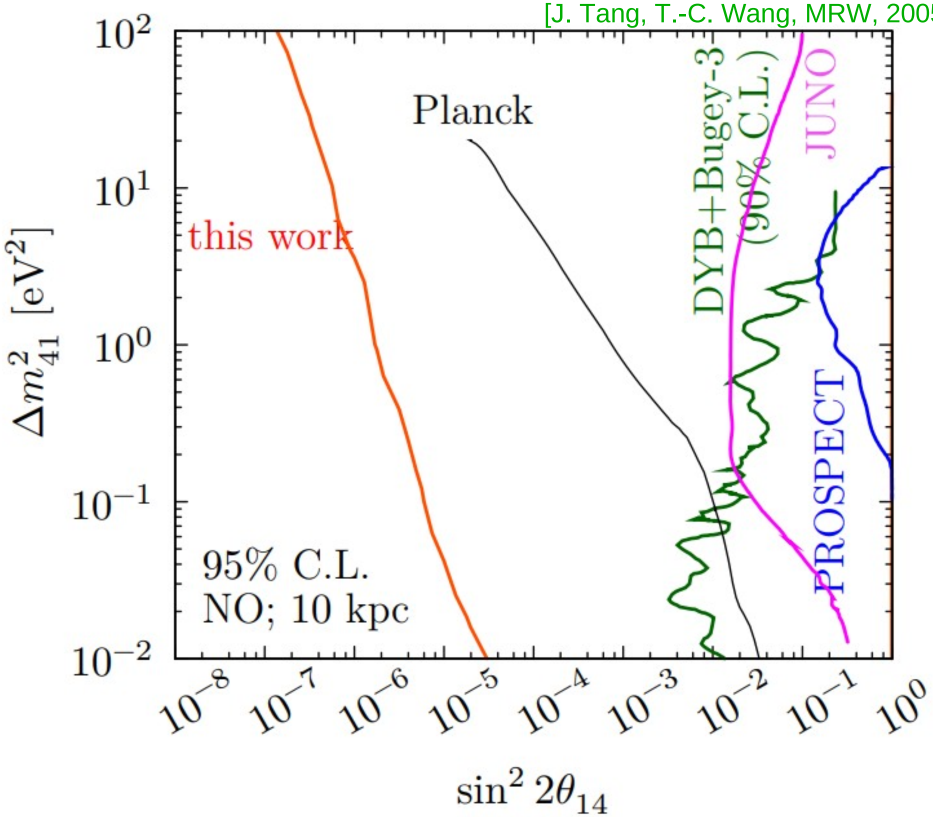
much lowered overall event numbers in all detectors

[J. Tang, T.-C. Wang, MRW, 2005.09168]



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[see also: Esmaili+ 1402.1453, Franarin+ 1712.03836 on neutrino signals and Tamborra+ 1110.2104, MRW+,1305.2382, Pllumbi+ 1406.2596, Xiong+ 1904.09371, Ko+1910.04984 for other impacts]

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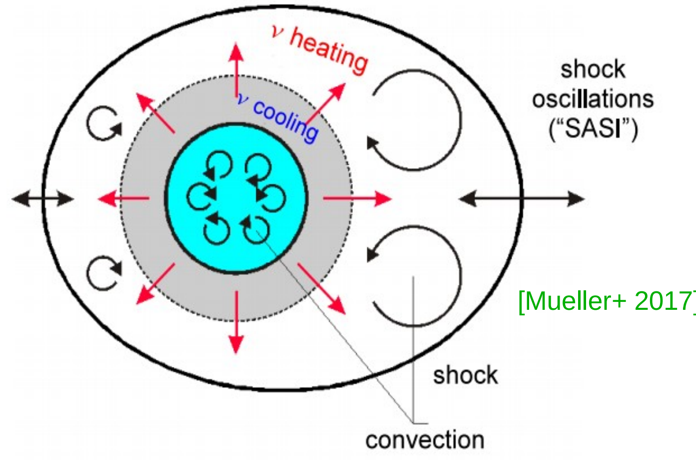

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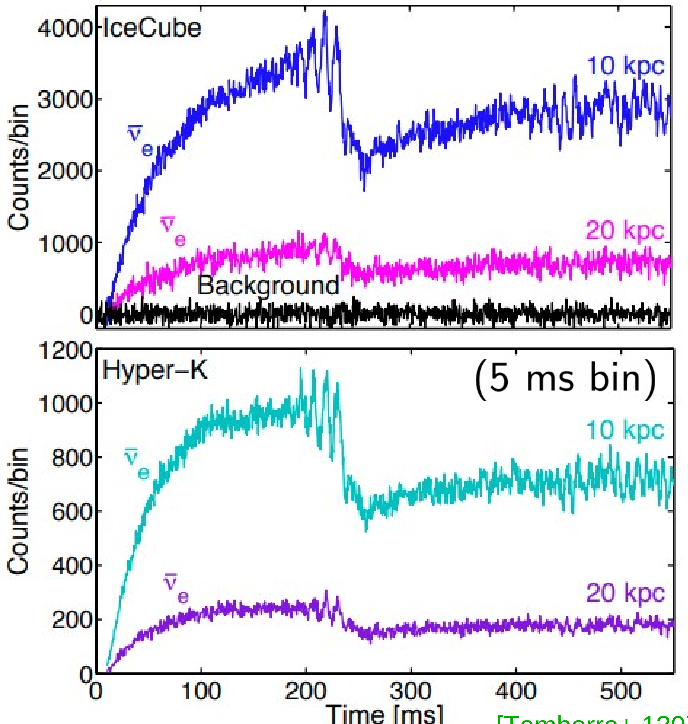
[see also:
Takiwiki+ 1308.5755
Mueller+ 1402.3415
Tamborra+ 1406.0006
Brueen+ 1409.5779
Kuroda+ 1708.05252
Takiwiki+ 1711.01905
Seadrow+ 1804.00689
Walk+ 1807.02366
Walk+ 1901.06235
Lin+ 1911.10656...]



[Tamborra+ 1307.7936]

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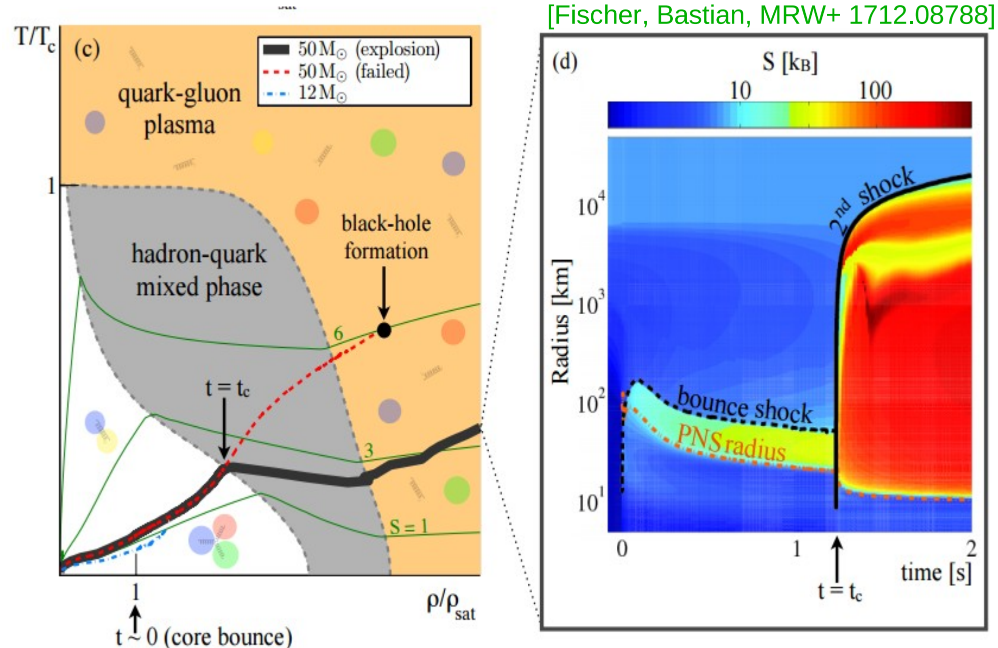
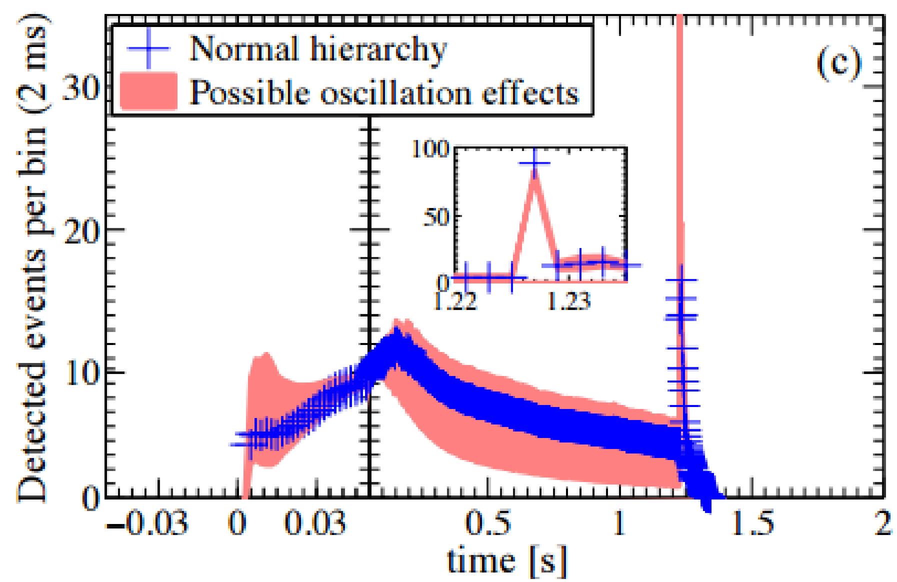
[Fischer, Bastian, MRW+ 1712.08788]



a millisecond neutrino burst!



[see also:
Nakazato+ 0804.0661
Sagert+ 0809.4225
Dasgupta+ 0912.2568
Nishimura+ 1112.5684
Fischer+ 2003.00972
Zha+ 2007.04716
Zha+ 2103.02268
Fischer+ 2108.00196
Kuroda+ 2109.01508
Lin+ 2203.05141
Jakobus+ 2204.10397...]

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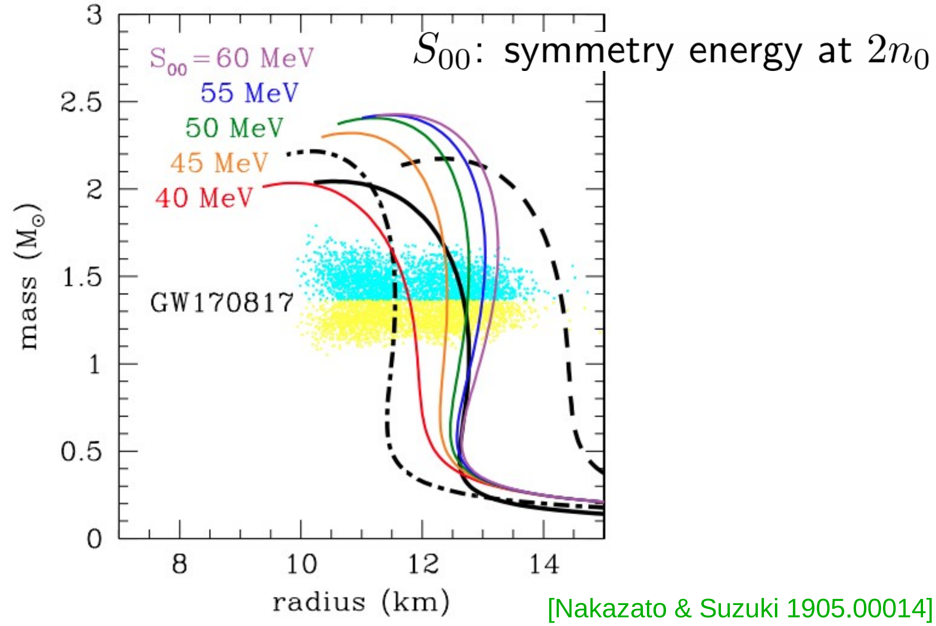
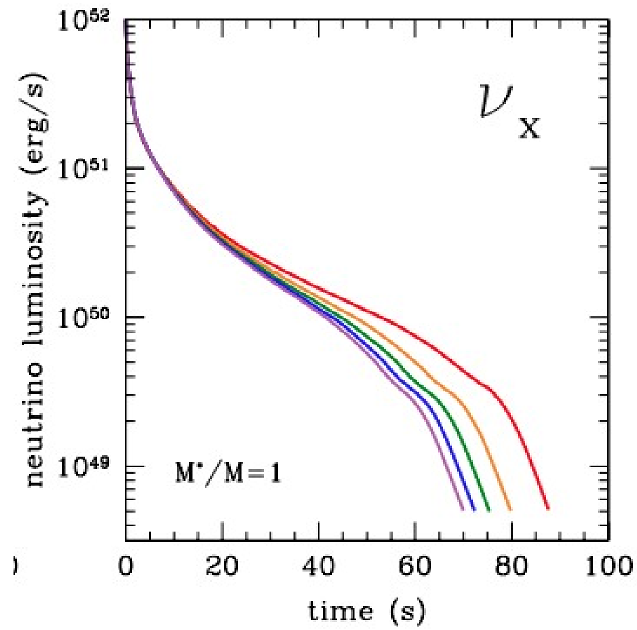


[Nakazato & Suzuki 1905.00014]



[see also:
Roberts+ 1112.0335
Horowitz+ 1611.10226
Rosso+ 1708.00760
Roggero+ 1710.10206
Nakazato+ 1710.10441
Rosso+ 1809.09074
Suwa+ 1904.09996
Nakazato+ 2002.03300
Li+ 2008.04340...]

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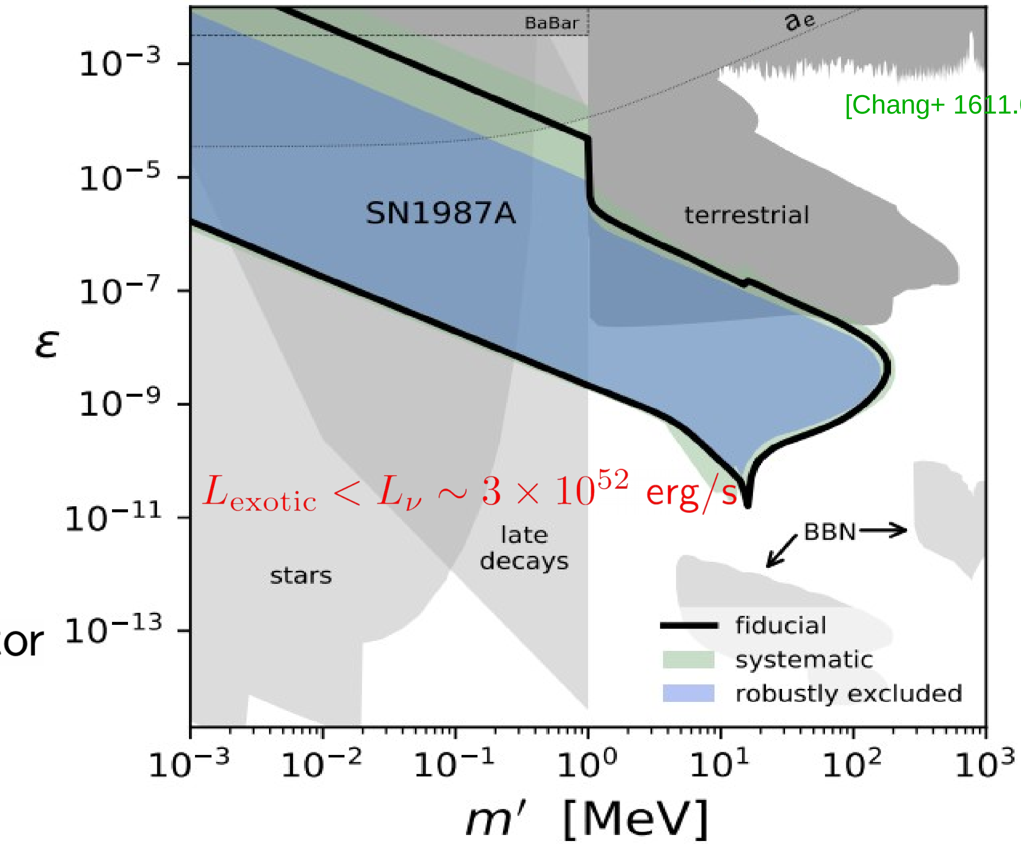
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$
$$-e\sum_f q_f(A_\mu + \epsilon A'_\mu)\,\bar{f}\gamma^\mu f\,.$$



[Chang+ 1611.03864]

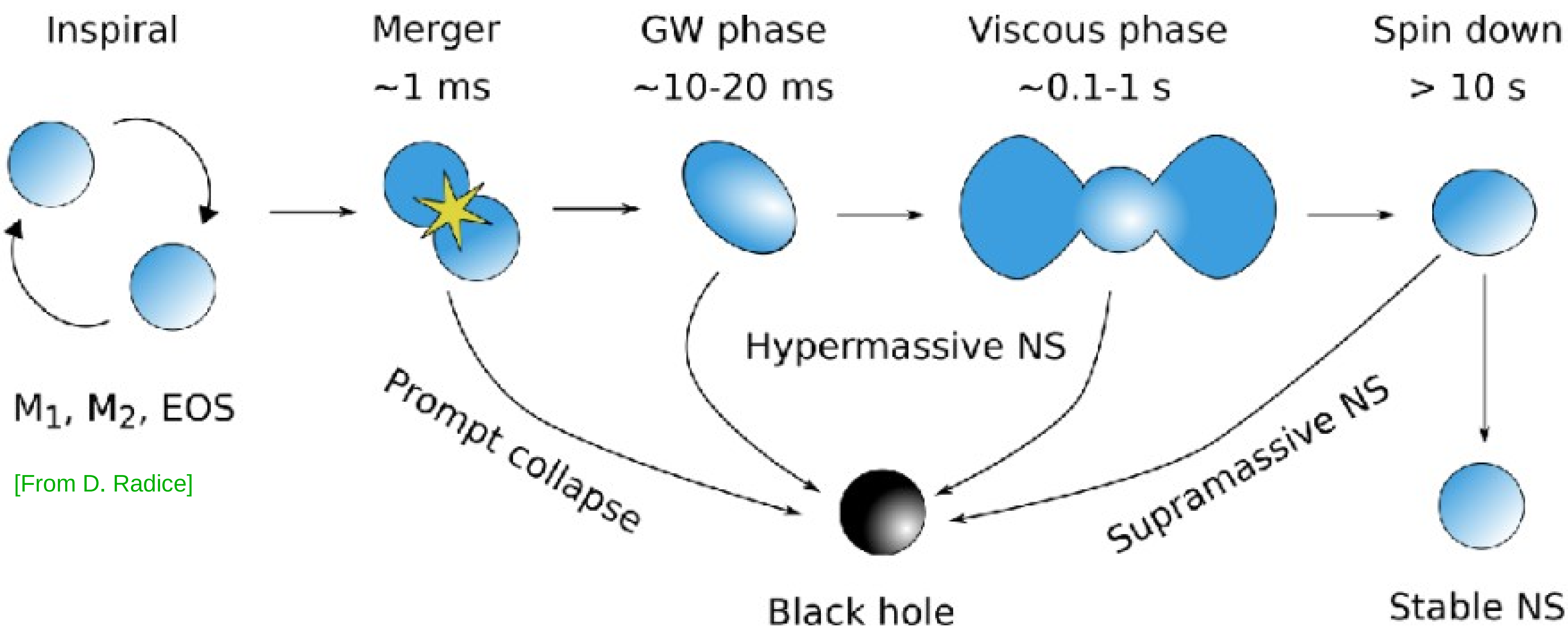
[see also:
Raffelt+ 1988, Turner+ 1988, Janka+ 9507023, Fischer+ 1605.08780, Bar+1907.05020, Lucente+ 2008.04918, Fischer+ 2108.13726, Mori+ 2112.03613, Lucente+ 2203.15812, Ferreira+ 2205.07896... for axions; Dent+ 1201.2683, Rrapaj+1511.09136, Hardy+ 1611.05852, Chang+ 1803.00993, DeRocco+1901.08596, Sung+ 1903.07923, DeRocco+ 1905.09284, Dev+ 2005.00490, Darme+ 2012.07894, Sung+ 2102.04601, Balaji+ 2205.01669, ... for dark photons (sector); Raffelt+ 1102.5124, Arguelles+ 1605.00654, Suliga+ 1908.11382, Syvolap+ 1909.06320, Suliga+ 2004.11389, ... for keV sterile neutrinos; Rembiasz+ 1806.03300, Mastrototaro+ 1910.10249, ... for MeV sterile neutrinos, ...]

Impact of neutrinos in binary neutron star mergers

Binary neutron star mergers: diversity

Mergers of two neutron stars can result in a variety of outcomes, depending on the initial state of the system and the yet-unknown nuclear EoS

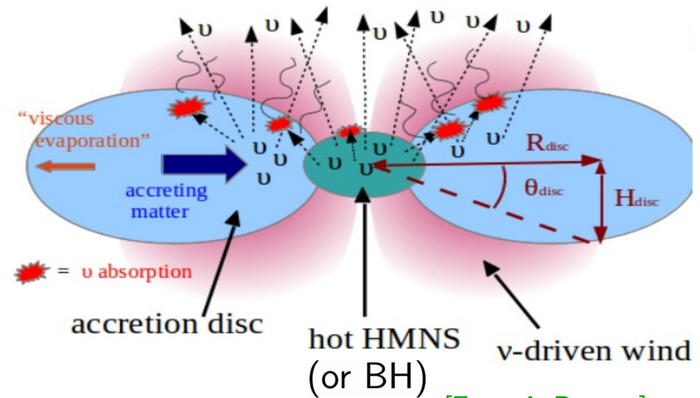
$\rightarrow$ different post-merger GW signals, EM, and neutrino emissions



[From D. Radice]

Neutrinos from the merger remnants

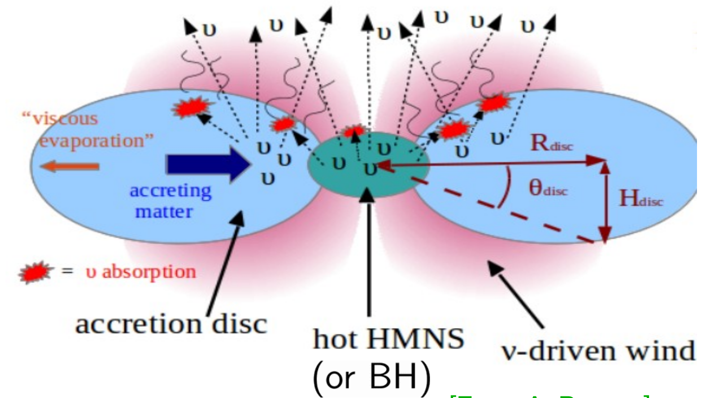
After the merger, large amount of neutrinos will be emitted from the central remnant before it collapsing to a BH, as well as from the accretion disk.



[From A. Perego]

Their energy luminosity can reach $\sim 10^{52} - 10^{53}$ erg/s, similar to supernovae.

Neutrinos from the merger remnants



[From A. Perego]

After the merger, large amount of neutrinos will be emitted from the central remnant before it collapsing to a BH, as well as from the accretion disk.

Their energy luminosity can reach $\sim 10^{52} - 10^{53}$ erg/s, similar to supernovae.

However, merger remnants must protonizes for some periods, differently from the proto-neutron star

[Foucart+, Perego+, Janka+, Sekiguchi, Radice, ...]

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

[Perego+ 1405.6730]

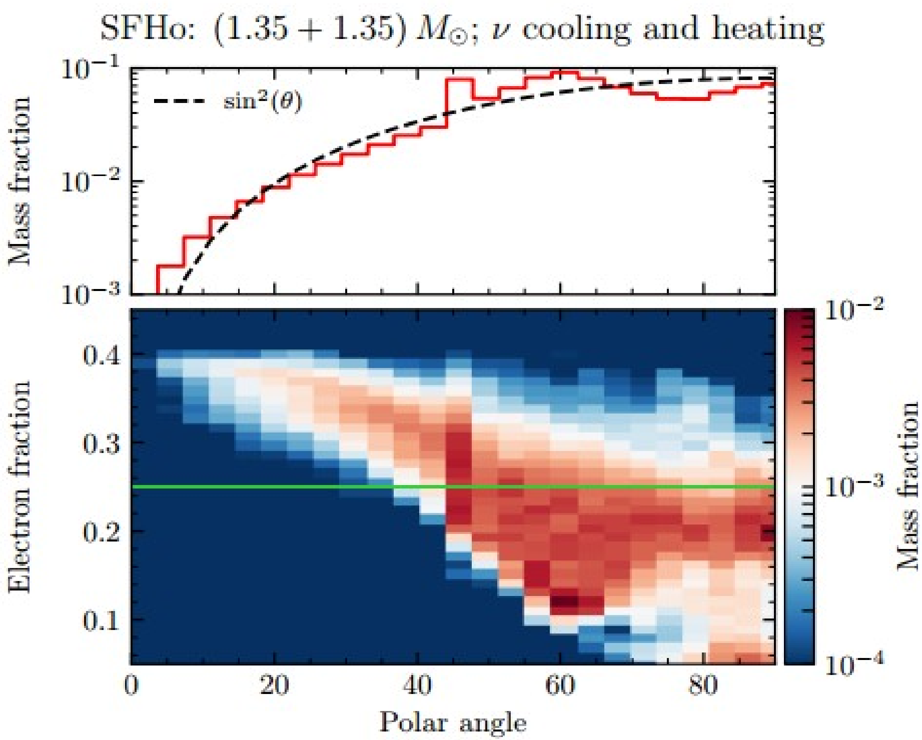
How important are the neutrinos in merger ejecta?

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

Neutrinos raise the proton-to-neutron ratio of the ejecta and thereby affecting the kilonova “color”

$Y_e \gtrsim 0.25 \leftrightarrow$ blue $\qquad Y_e \lesssim 0.25 \leftrightarrow$ red

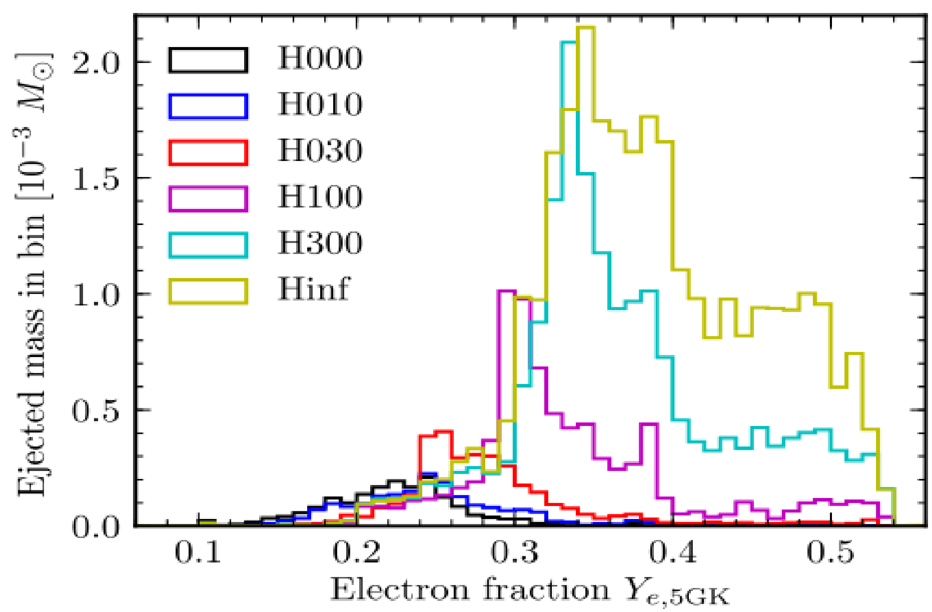
BNS dynamical ejecta: [Radice+ 1601.02426]



[See also Wanajo+ 1402.7317, Sekiguchi+ 1502.06660, Foucart+ 1607.07450, Ardevol-Pulpillo+ 1808.00006, Miller+ 1905.07477, Vincent+ 1908.00655, George+ 2009.04046, Kullmann+ 2109.02509,...]

disk ejecta:

[Lippuner+ 1703.06216]



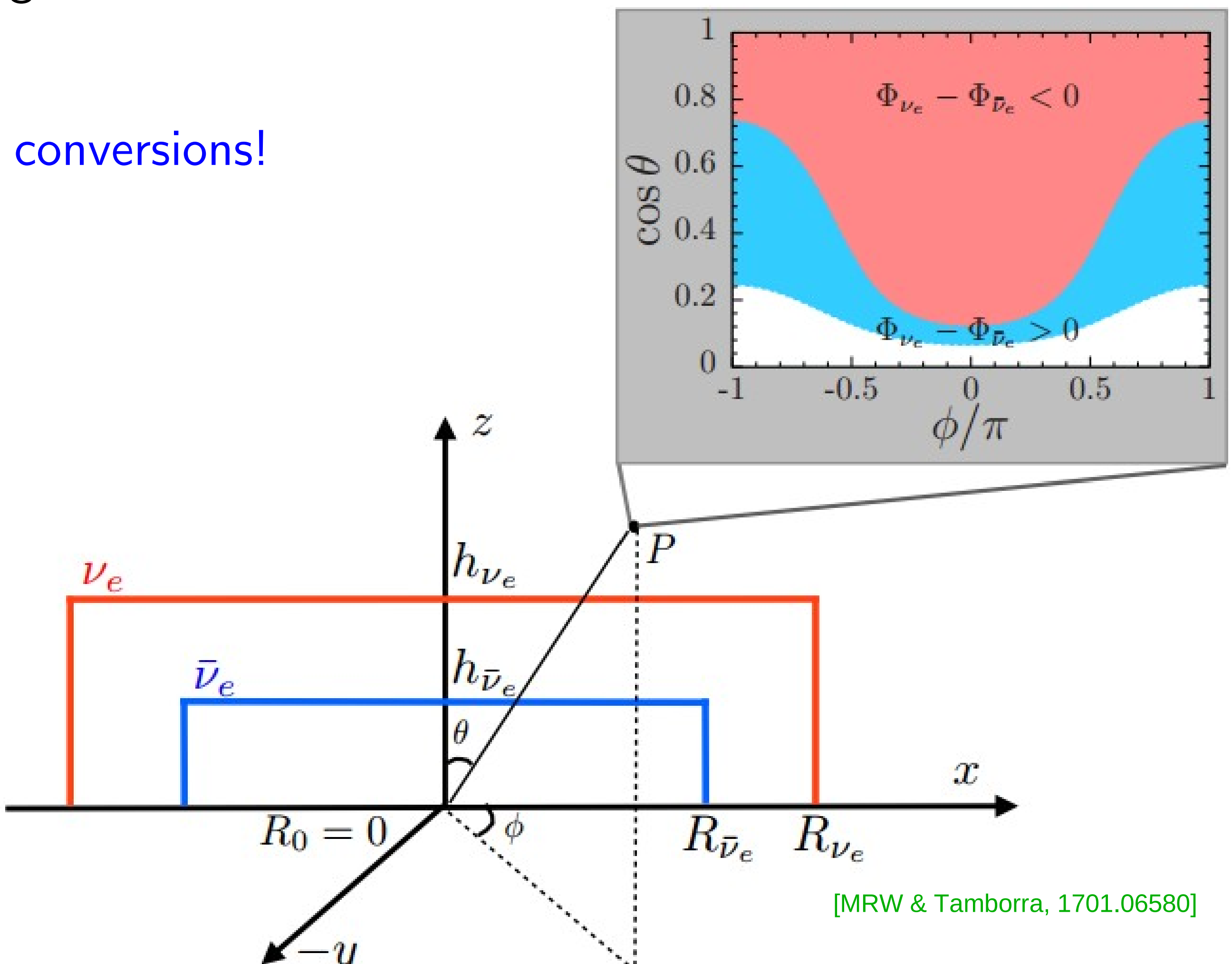
[See also Fernandez+ 1304.6720, Perego+ 1405.6730, Just+ 2015, MRW+ 1607.05290, Siegel+ 1705.05473, Fujibayashi+ 1711.02093, Fahlman+ 1811.08906, Just+ 2102.08387, Fahlman+ 2204.03005, Fujibayashi+ 2205.05557 ...]

observation of GW170817 kilonova implies neutrinos play some roles

Fast ν oscillations in merger remnants

The protonization of the merger remnant, i.e., more $\bar{\nu}_e$ emission than ν_e, plus the smaller $\bar{\nu}_e$ emission surface, naturally leads to crossing in angular distribution above the merger remnants

$\rightarrow$ fast flavor conversions!

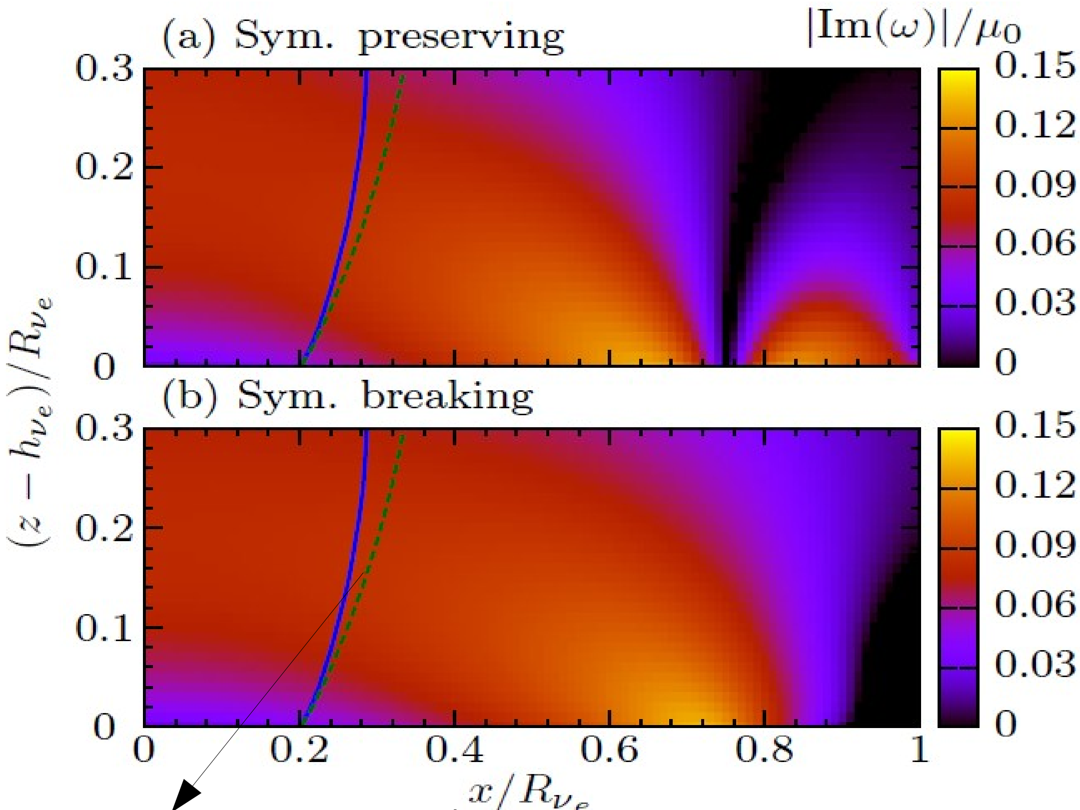


[MRW & Tamborra, 1701.06580]

Fast ν oscillations in merger remnants

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

[MRW & Tamborra, 1701.06580]



(matter-neutrino resonances)

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, with any reasonable parameters

potenally affects the nucleosynthesis outcome in the merger outflows

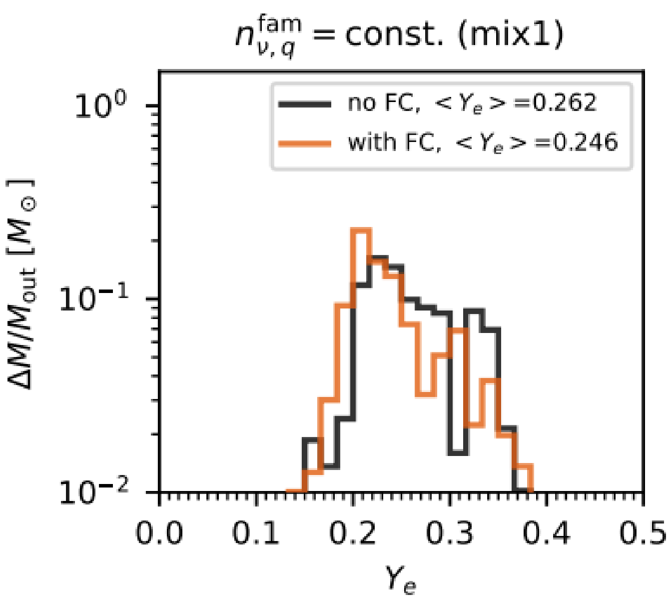
[MRW, Tamborra, Just, Janka, 1711.00477 for BH-torus cases and
M. George, MRW, I. Tamborra et al, 2009.04046 for NS–disk cases]

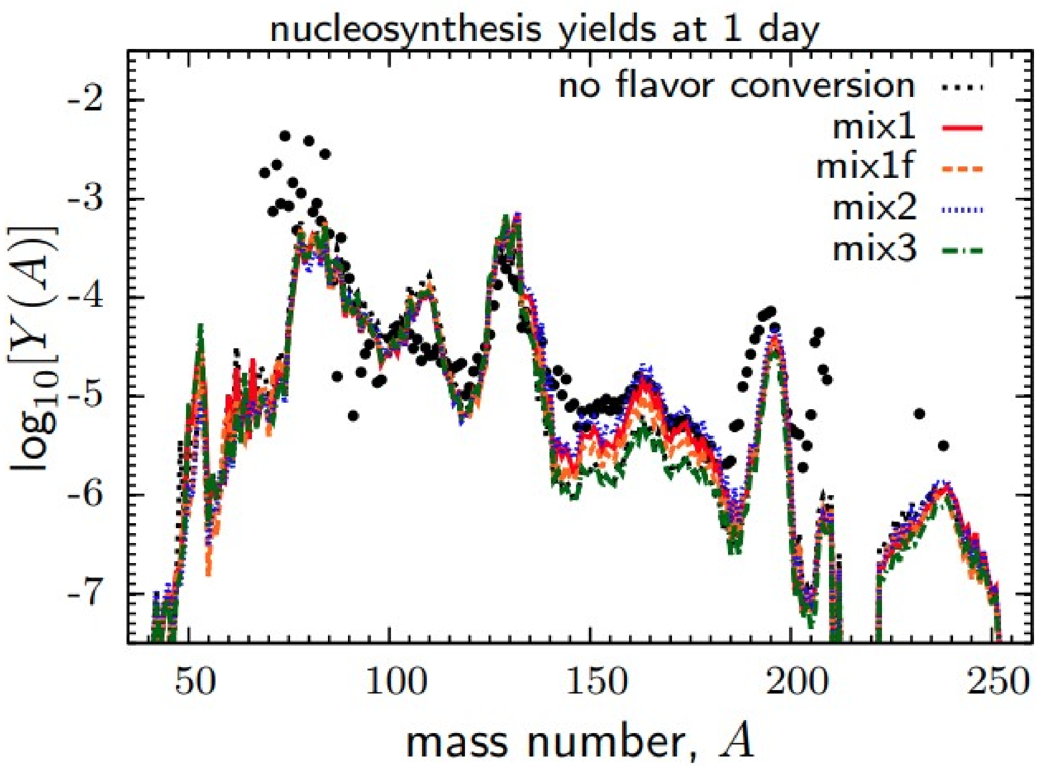
Fast ν oscillations in merger remnants

Recently, we include the fast conversions (in a parametrized fashion) for BH-disk simulations [See also Li & Siegel 2103.02616]

$\rightarrow$ flavor conversions can occur inside the neutrino-trapped regime, affect the disk cooling, and lower Y_e in the ejecta by $\sim 0.02 - 0.03$

$\rightarrow$ enhance production of lanthanides $(150 \lesssim A \lesssim 180)$ by a factor of $\sim 2-3$



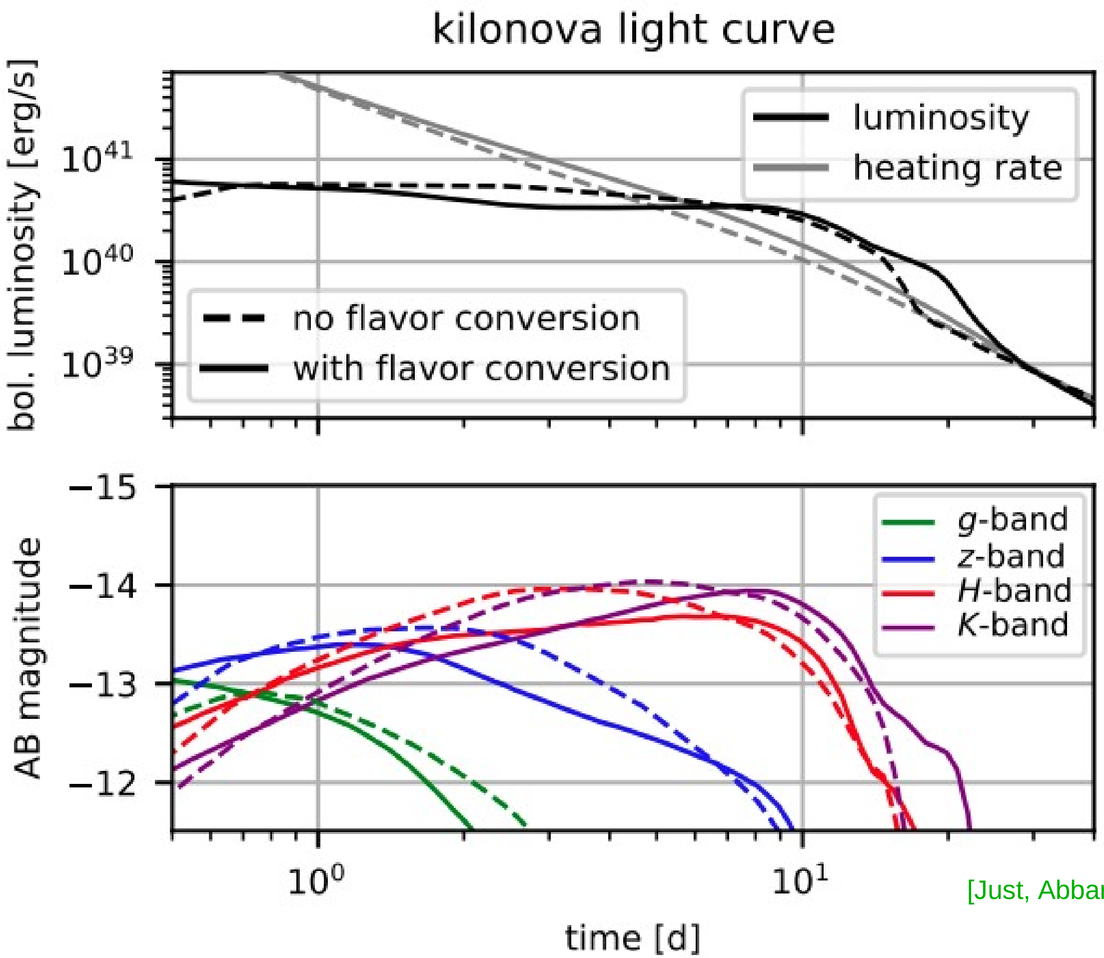


[Just, Abbar, MRW+ 2203.16559]

Fast ν oscillations in merger remnants

– large atomic opacity for kilonova's thermal photons

– prolonged "diffusion" bumps in bolometric lightcurve



[Just, Abbar, MRW+ 2203.16559]

Summary

- Neutrinos play crucial roles in core-collapse supernovae and the merger of two neutron stars in determining their dynamics and observables.
- Improvement of both the theoretical modeling for neutrino interaction with nuclear matters and their flavor oscillations are important to make robust understanding of these events.
- The detection of the next Galactic supernova may help reveal the ellusive nature of core-collapse supernovae, constrain exotic physics, and will be able to provide useful guidance for further theoretical modeling.

See excellent posters on SN neutrino related topics:

Lolian Shtembari (MT12-926), Joseph Smolsky (MT12-785)
Ali Kheirandish (MT12-747), Fumi Nakanishi (MT12-746)
Yago P Porto Silva (MT12-732), Nora Valtonen-Mattila (MT12-624)
Godefroy Vannoye (MT12-574), Andrea Molinario (MT12-541)
Huang Xin (MT12-499), Masamitsu Mori (MT12-498)
Marta Colomer Molla (MT12-491 and MT12-490)
Meriem Bendahman (MT12-434), Mainak Mukhopadhyay (MT12-433)
Huiyou Chen (MT12-432), Akira Harada (MT12-412)
Spencer Griswold (MT12-278), Pablo Barham Alzs (MT12-245)
Ziping Ye (MT12-239), Guillaume Pronost (MT12-236), Jim Kneller (MT12-227)
Lucas Nascimento Machado (MT12-222), Minori Eizuka (MT12-168)
Marcos Vinicius Dos Santos (MT12-114), Amanda Baxter (MT12-081)
Spencer Axani (MT12-053), John LoSecco (MT12-019), Artem Popov (DT02-270)
Darcy Newmark (MT05-403), Jose Carpio Dumler (DT15-402)
Amol Patwardhan (MT05-947), Melih Kara (MT17-040)

Thank you!