# Neutrino flavor conversion in binary neutron star mergers

MRW, I. Tamborra, 1701.06580
MRW, I. Tamborra, O. Just, H.-T. Janka, 1711.00477

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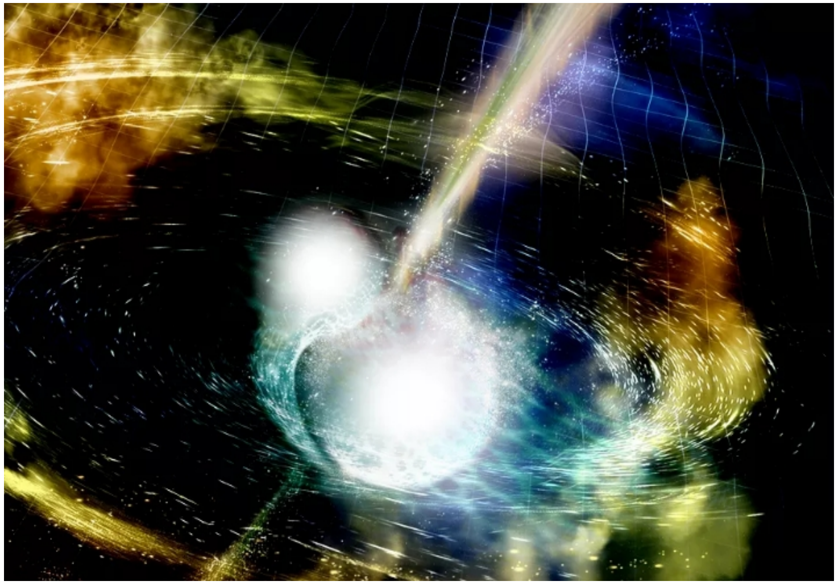
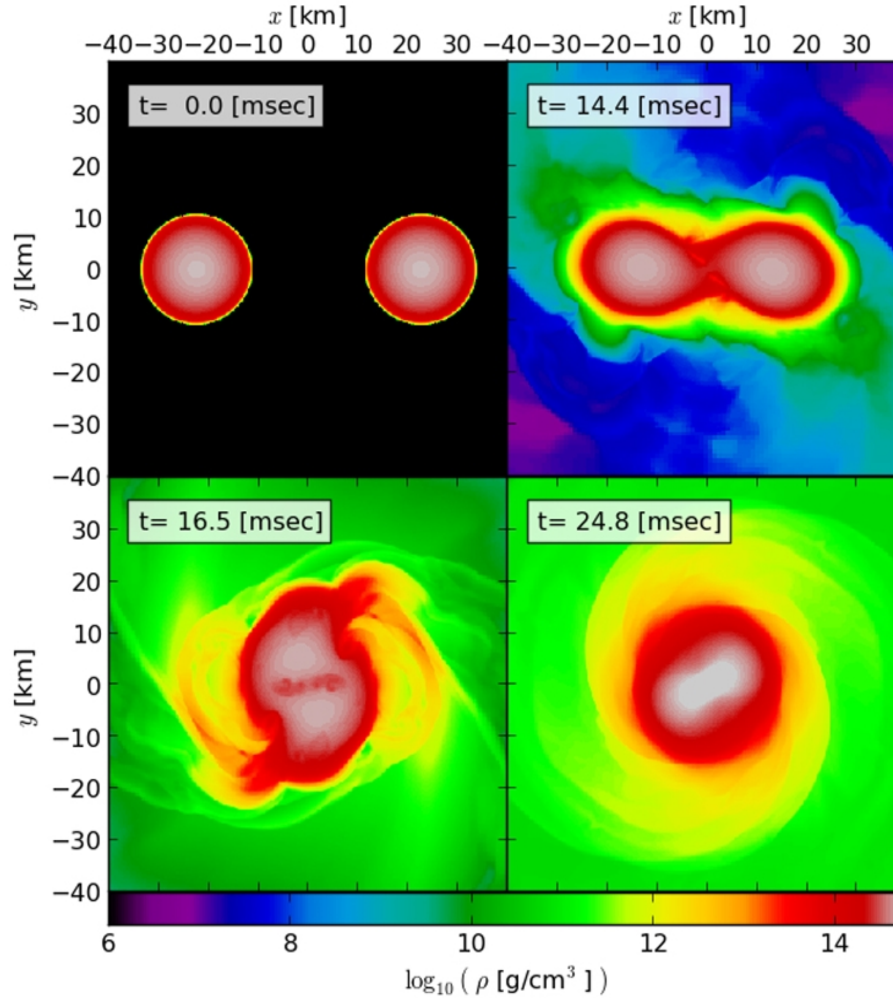
International Symposium on Cosmology and Particle Astrophysics, CosPA 2017
YITP, Kyoto, Japan, Dec 11–15, 2017

# Binary neutron star mergers






[From L. Rezzolla]

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

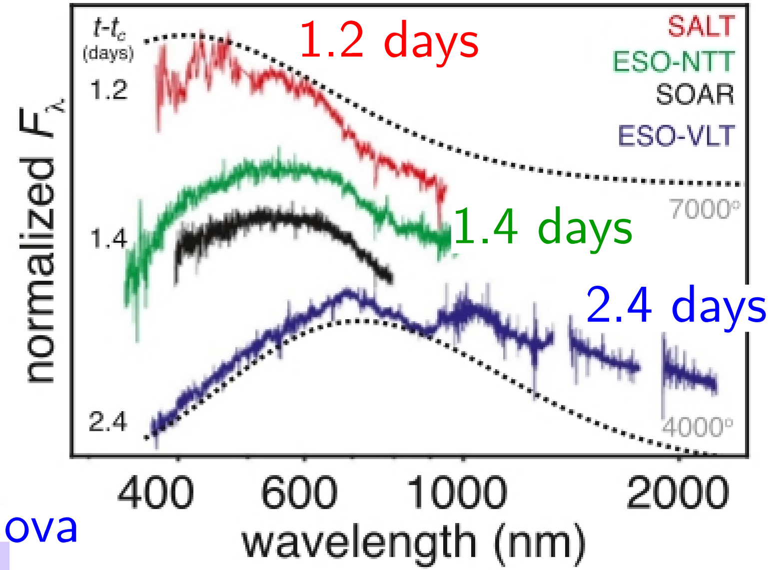
finally confirmed by the recent detection of GW170817/GRB 170817A/AT2017gfo

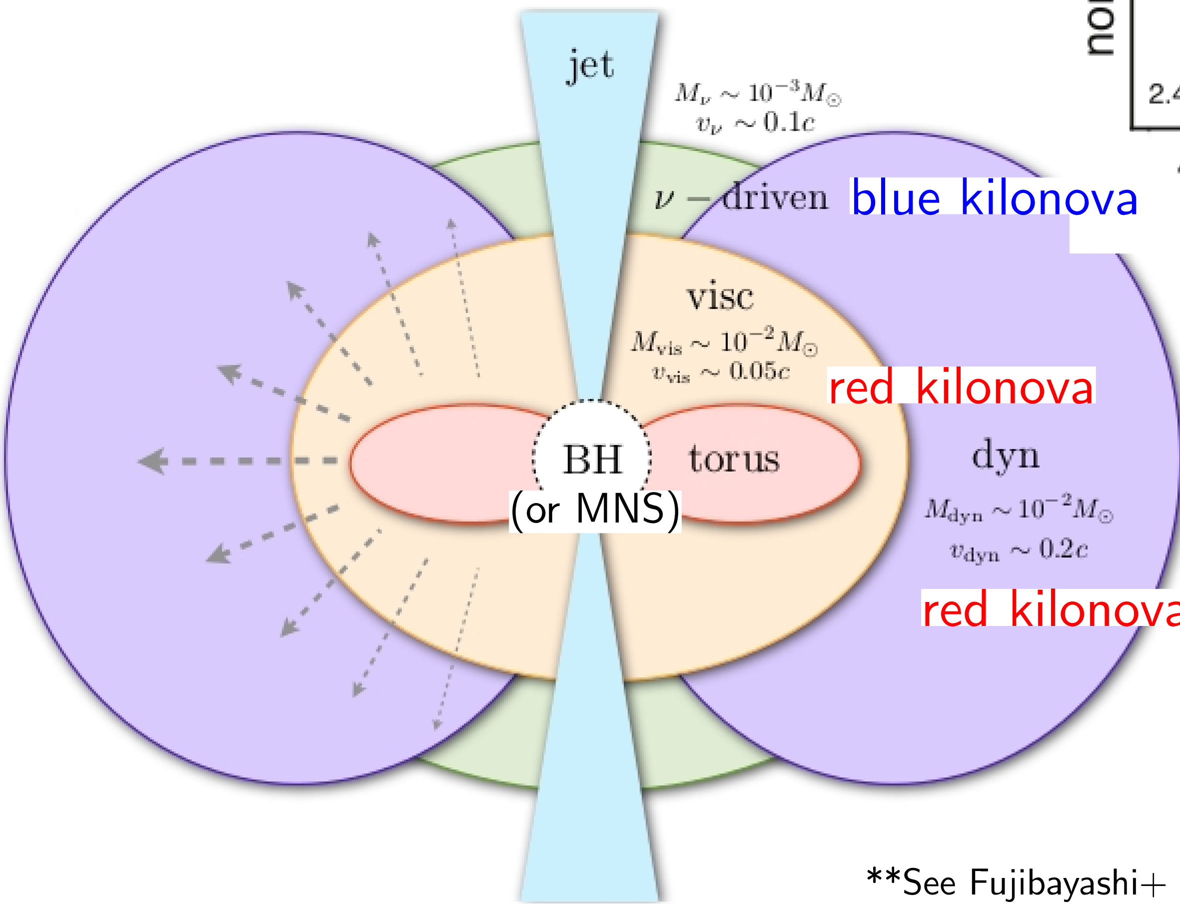
expected to see $\gtrsim 10$ per year at full advanced LIGO sensitivity

# Neutrinos and kilonovae

higher proton-to-neutron ratio
$\leftrightarrow$ more $f$-shell elements (Lanthanides)
$\leftrightarrow$ bluer photon spectrum

early kilonova optical spectrum



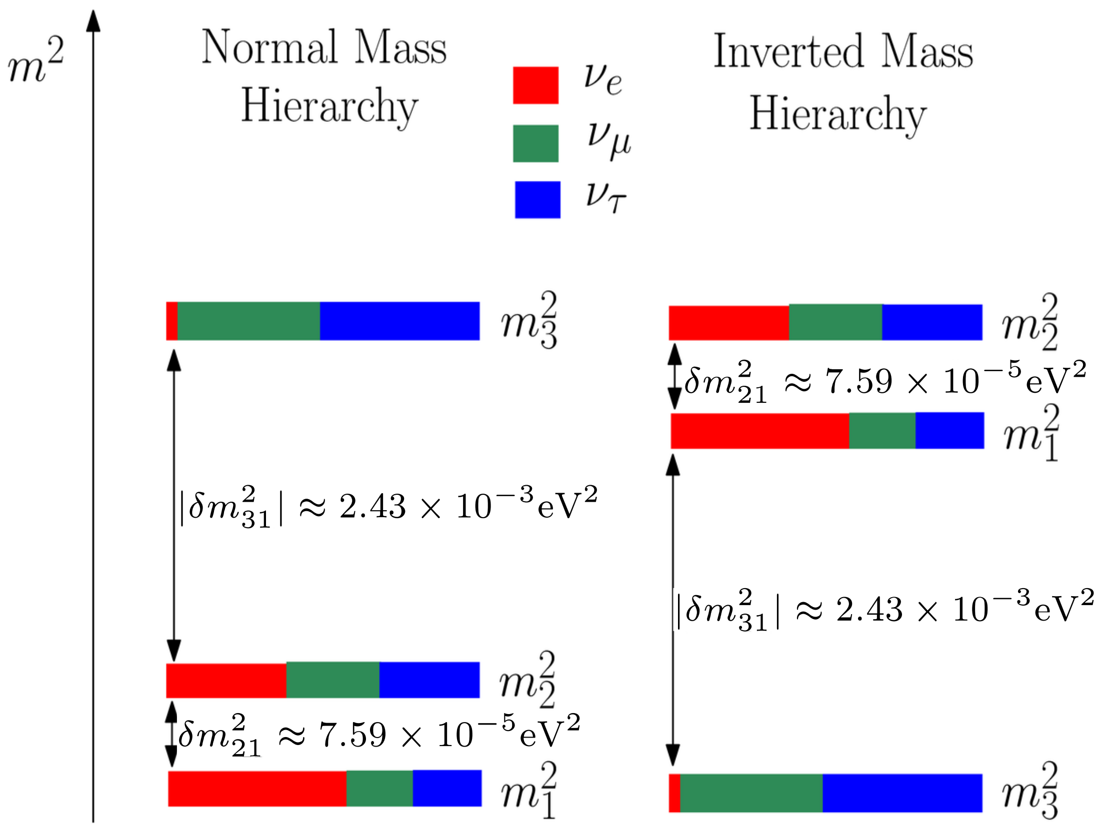

[MRW, Tamborra, Just, Janka, arXiv: 1711.00477]

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

neutrinos raise the proton-to-neutron ratio

**See Fujibayashi+ 2017 for larger amount of high $Y_e$ ejecta in the polar region due to the viscous effect in the HMNS**

# Neutrino masses and mixing

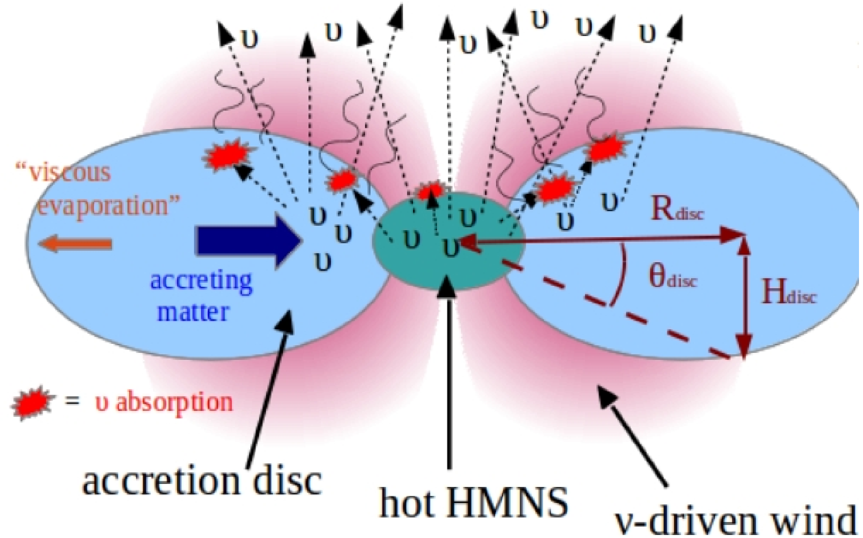



mixing angles:
$\theta_{12} \approx 34^\circ$
$\theta_{13} \approx 9^\circ$
$\theta_{23} \approx 45^\circ$

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

Neutrino oscillations in vacuum and in the solar interior well-understood, but not inside the astrophysical system where neutrinos are abundantly present...

# 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 $\nu_e$.

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] |
|---|---|---|---|
| $\nu_e$ | 10.6 | 3.4 | 15 |
| $\bar{\nu}_e$ | 15.3 | 4.9 | 30 |
| $\nu_x$ | 17.3 | 5.5 | 8 |

[Perego+ MNRAS, 443 (2014) 3134]

→ need to understand better their flavor oscillations

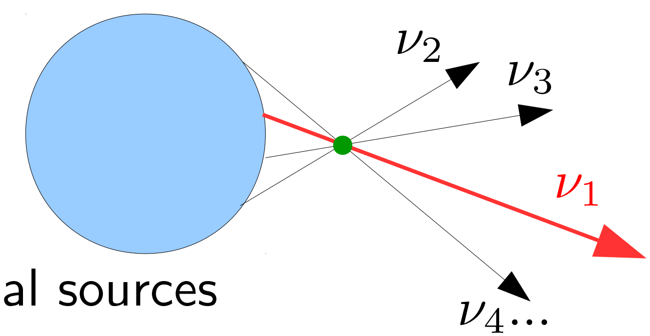
# Neutrino oscillations in neutrino-dense environment

In the regime where neutrinos nearly free-stream

Equation of Motion: $(\partial_t + \mathbf{v}\cdot\partial_\mathbf{x})\varrho(\mathbf{x},\mathbf{p},t) = -i[H(\mathbf{x},\mathbf{p},t),\varrho(\mathbf{x},\mathbf{p},t)] + \cancel{\mathcal{C}(\varrho)}$

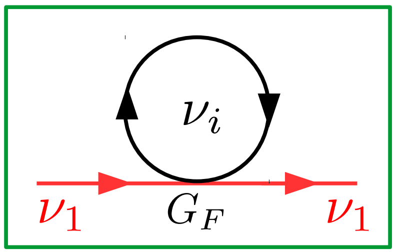
$\varrho$: Wigner-transformed flavor density matrix, $= \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{pmatrix}$

$H(\mathbf{x},\mathbf{p},t) \supset \sum_{\mathbf{p}'}(\varrho(\mathbf{x},\mathbf{p}',t) - \bar{\varrho}^*(\mathbf{x},\mathbf{p}',t))(1-\mathbf{v}\cdot\mathbf{v}') \rightarrow$ non-linear coupling




astrophysical sources

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




$\rightarrow$ many-body quamtum system in "strong" coupling regime ($G_F n_\nu \gg \frac{\delta m^2}{2E_\nu}$), leading to "collective" oscillations, extensively studied in the context of core-collapse supernovae [Duan+, Raffelt+, Mirizzi+, Volpe+, Balantekin+, Qian+, MRW+, Tamborra+, Lisi+,...]

# Neutrino oscillations in neutrino-dense environment

EoM: $(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H(\mathbf{x},\mathbf{p},t), \varrho(\mathbf{x},\mathbf{p},t)]$

$H(\mathbf{x},\mathbf{p},t) \supset \sum_{\mathbf{p}'}(\varrho(\mathbf{x},\mathbf{p}',t) - \bar{\varrho}^*(\mathbf{x},\mathbf{p}',t))(1-\mathbf{v}\cdot\mathbf{v}') \rightarrow \text{non-linear coupling}$

Solving the full EoM is cubersome, but one can linearize the EoM and analyze locally how the plane-wave (Fourier) mode of the off-diagonal term in $\varrho$ evolves in linear regime. [Izaguirre+ 2017, Capozzi+ 2017]

# Neutrino oscillations in neutrino-dense environment

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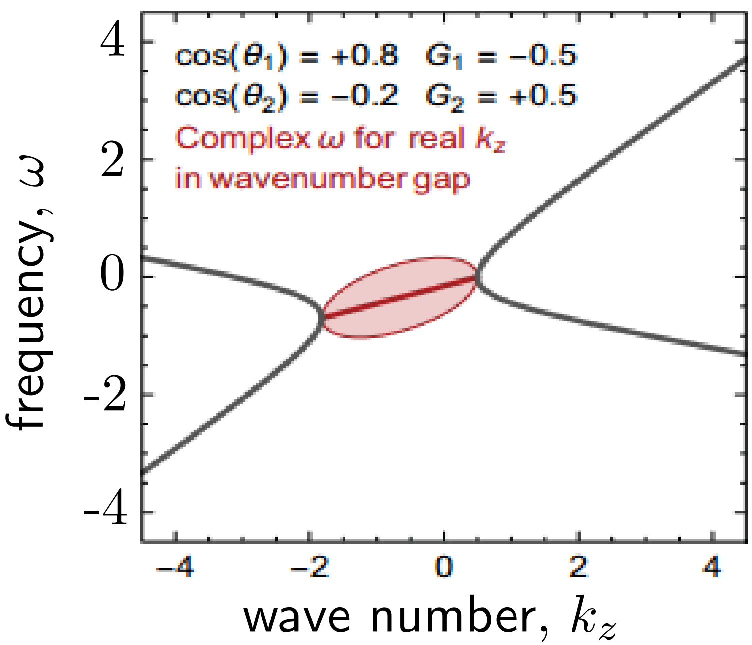
Complex frequency solution in the dispersion relation of the plane-wave $\leftrightarrow$ "flavor instability" leads to flavor conversion




[Izaguirre+, PRL 118, 021101 (2017) ]

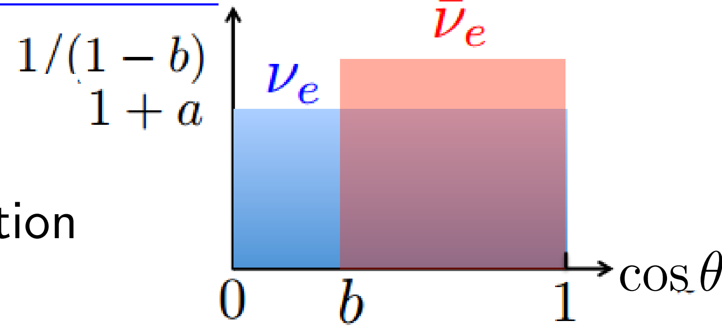
"fast" conversion can happen extremely close to the $\nu$ surfaces, provided that local angular distribution of neutrino lepton number has a "crossing" (more $\bar{\nu}_e$ than $\nu_e$ in some solid angle range, while more $\nu_e$ than $\bar{\nu}_e$ in other range)

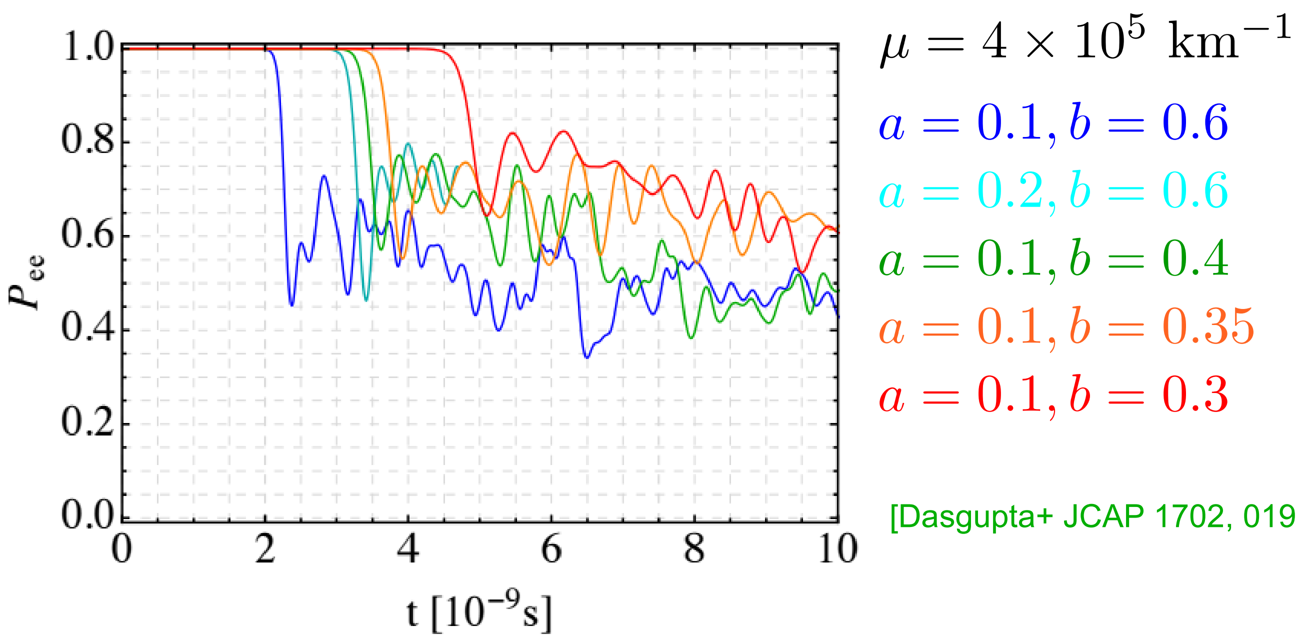
[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016 ]

# Neutrino oscillations in neutrino-dense environment

The local angular crossing in the neutrino lepton number leads to flavor instability of time scale $\tau \lesssim \mu^{-1} = (\sqrt{2} G_F n_\nu)^{-1}$, which implies an oscillation length scale of $\sim$ centimeters!

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



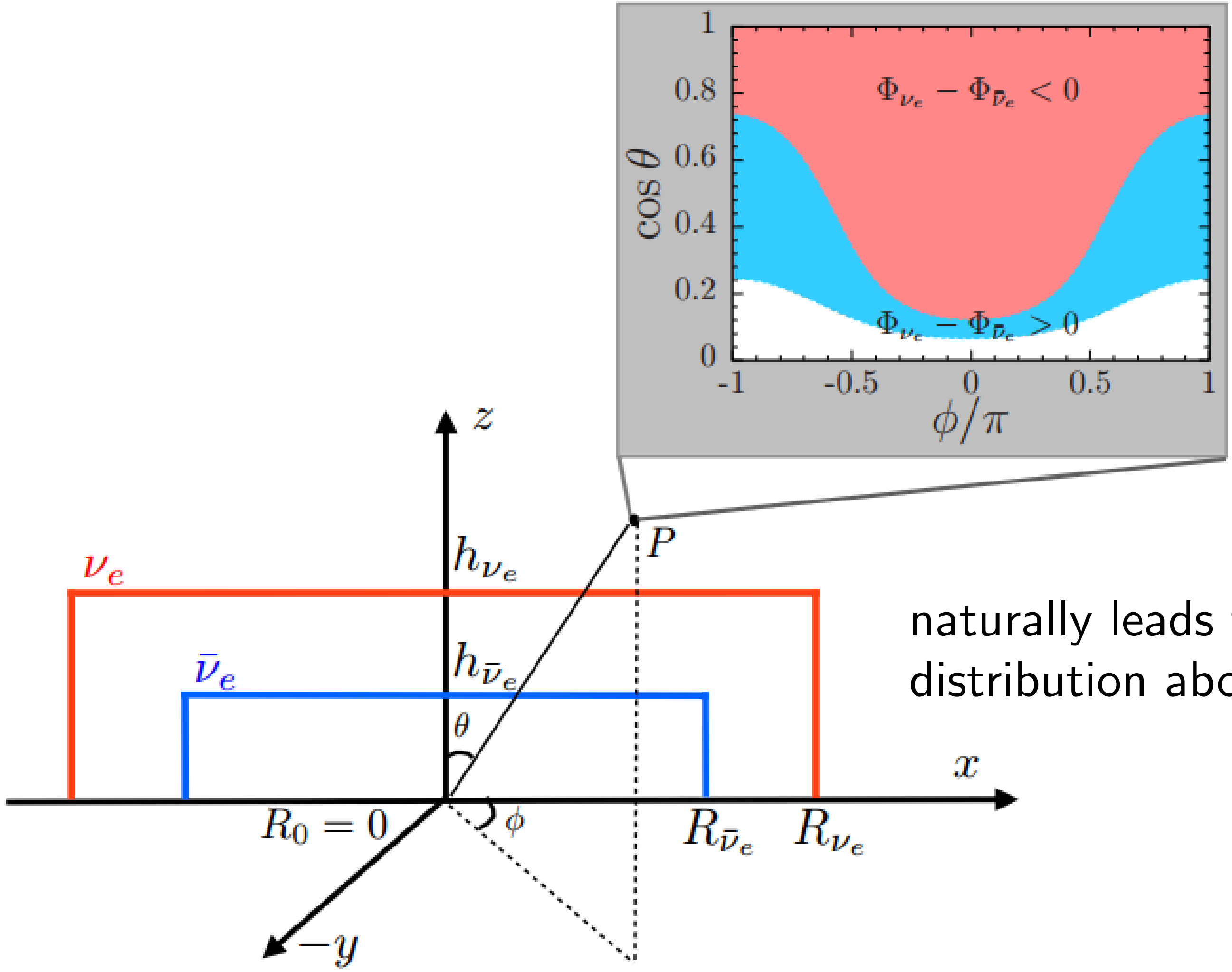

[Dasgupta+ JCAP 1702, 019 (2017)]

- very different from the typical "slow" collective neutrino oscillations studied extensively during the past decade in core-collapse supernovae.
- whether supernovae can provide such a condition remain uncertain as the proto-neutron star deleptonizes (neutronizes)

# Fast $\nu$ oscillations in merger remnants – parametrized model

Why is this particularly revelant for merger remnants?

Becuse they protonize, i.e., more $\bar{\nu}_e$ emission than $\nu_e$ [Foucart+, Perego+, Janka+,...]



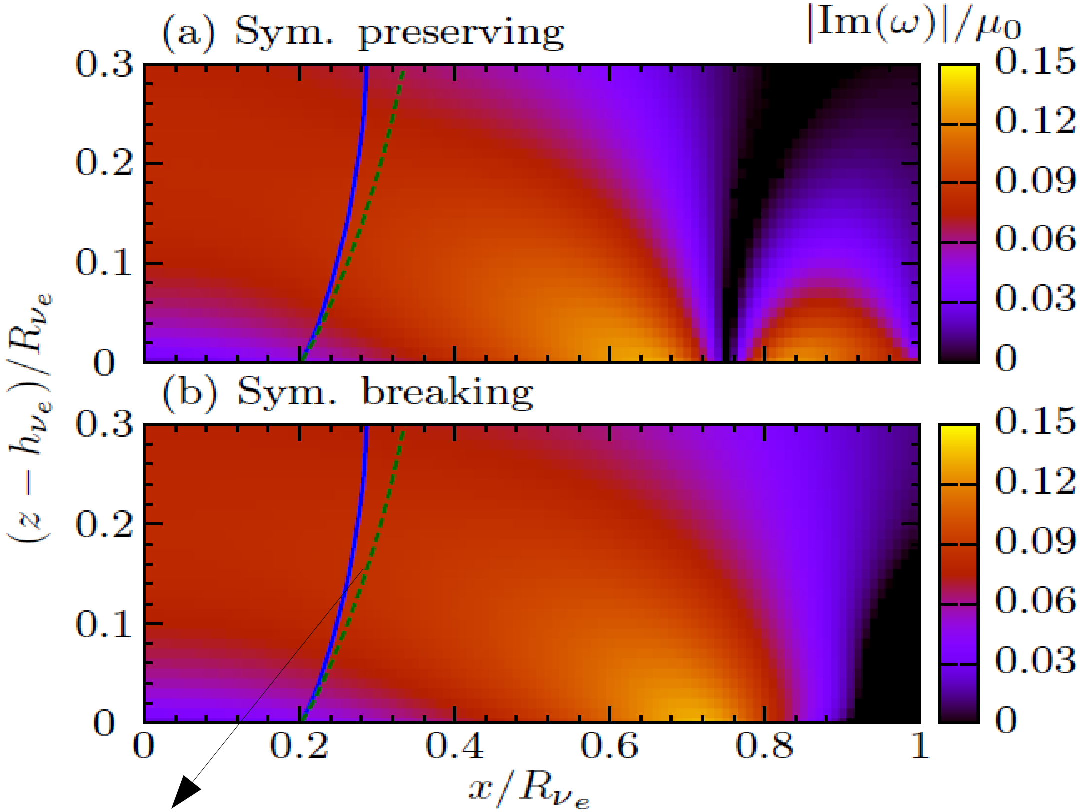

naturally leads to crossing in angular distribution above the merger remnant

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

# Fast $\nu$ oscillations in merger remnants – parametrized model

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

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




Matter-neutrino resonances [McLaughlin+, MRW+,...]

Im($\omega$): 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

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

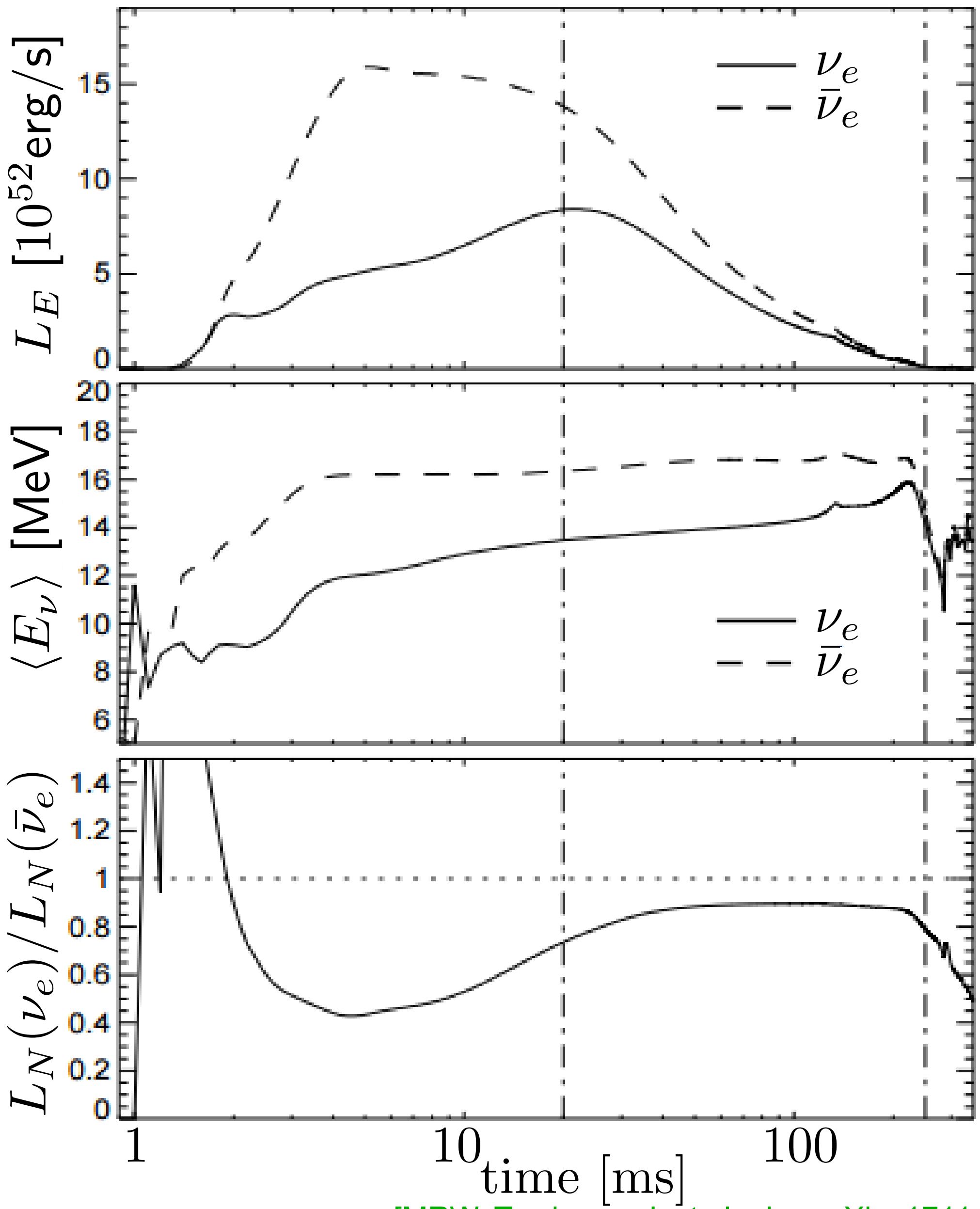
# Fast $\nu$ oscillations in merger remnants – realistic BH-disk model

– a BH-disk system with $3M_\odot$ BH, $0.3M_\odot$ disk, $\chi_{BH} = 0.8$

– axial-symmetric hydrodynamic simulation with detailed neutrino transport

[Just+, MNRAS 448 (2015) 541]

– protonization during the neutrino emission phase, particularly at earlier time

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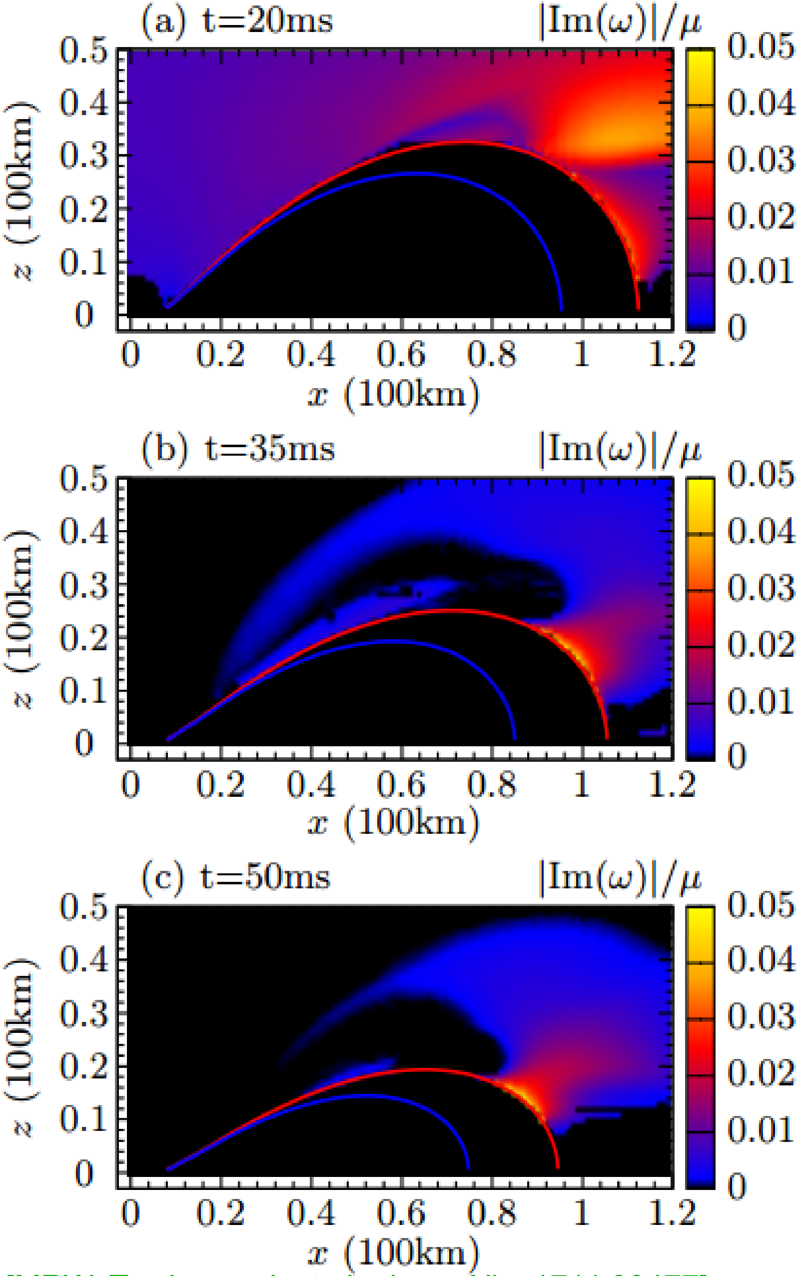


– again, flavor instability seeding fast conversion found above the remnant

– region of flavor instability changes as the system evolves, still large enough to affect most neutrinos influencing the ejecta

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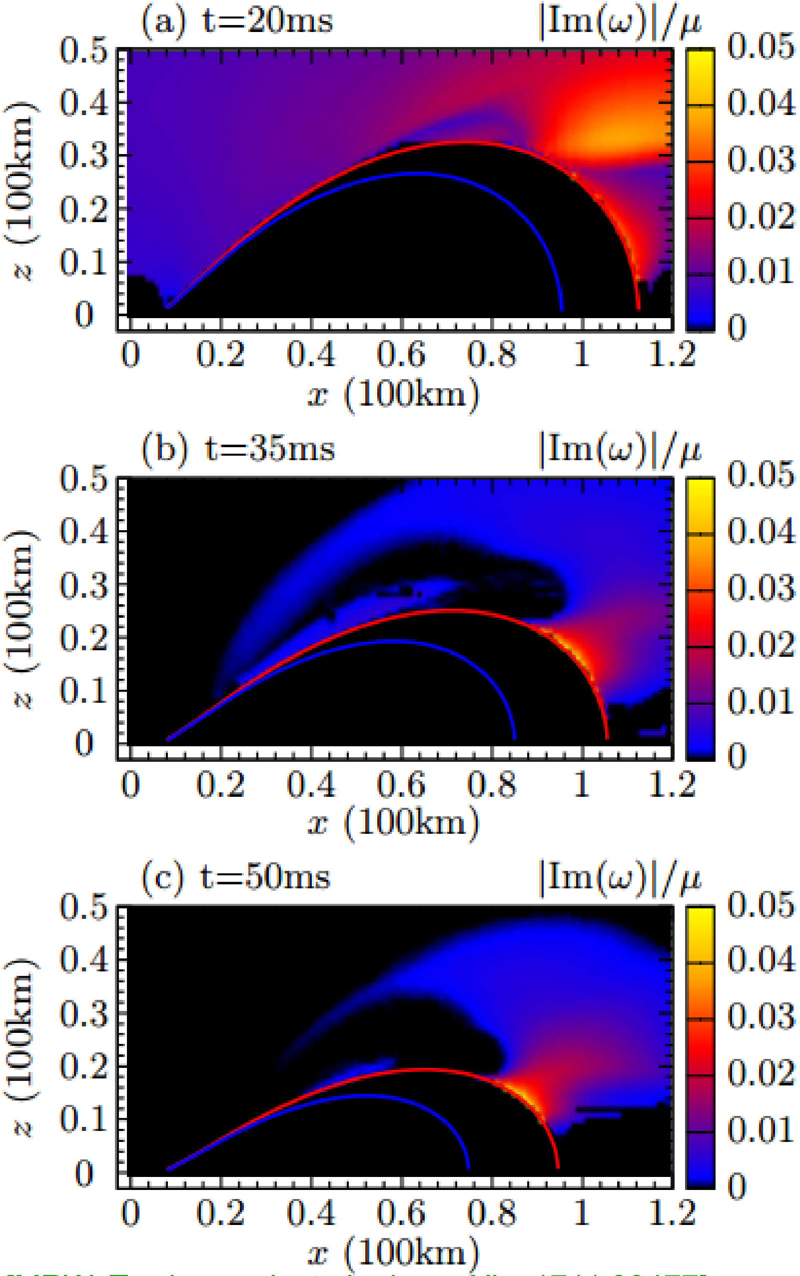


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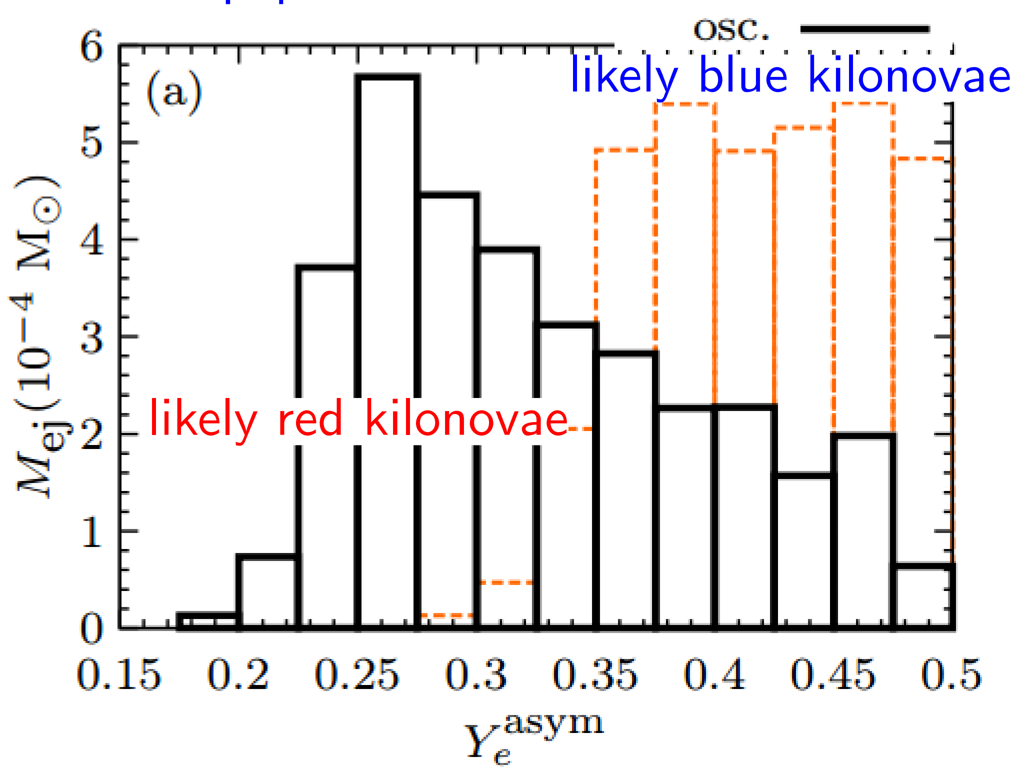
- assuming fast conversions lead to full flavor equipartition



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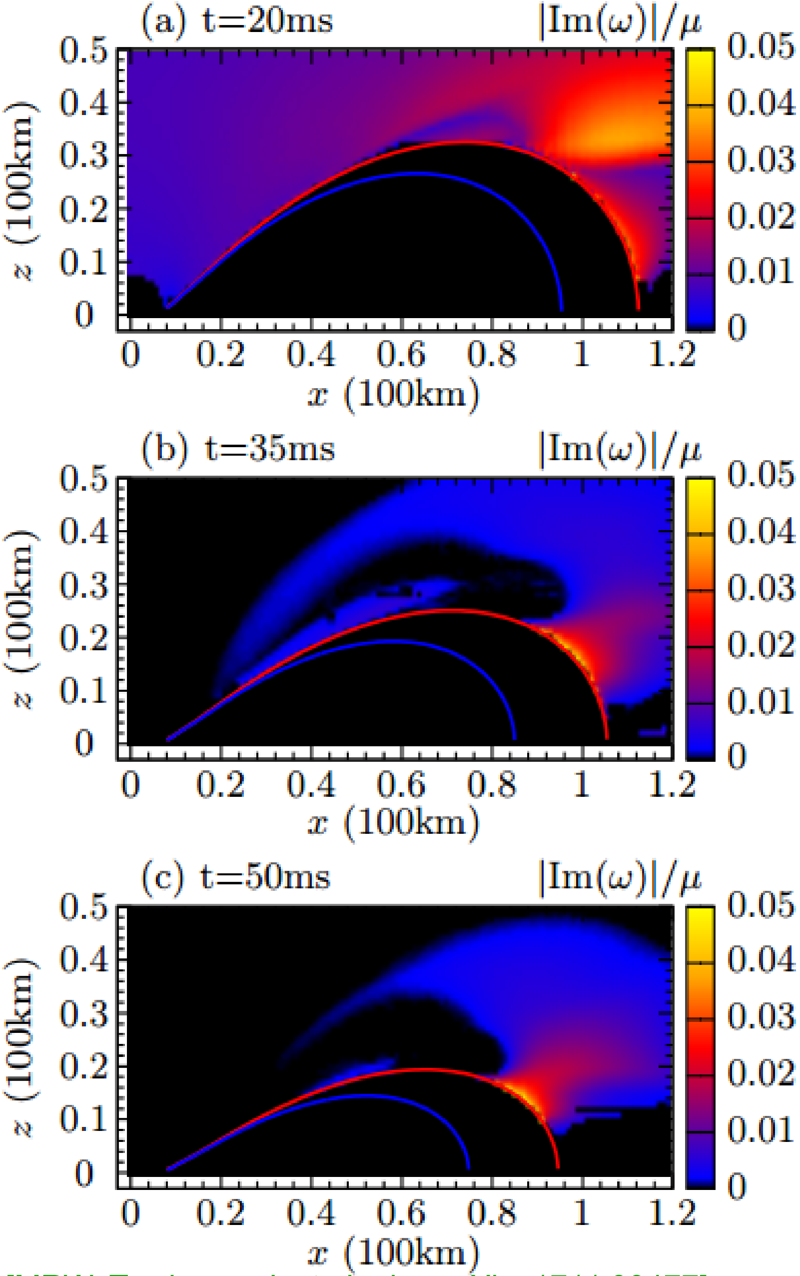


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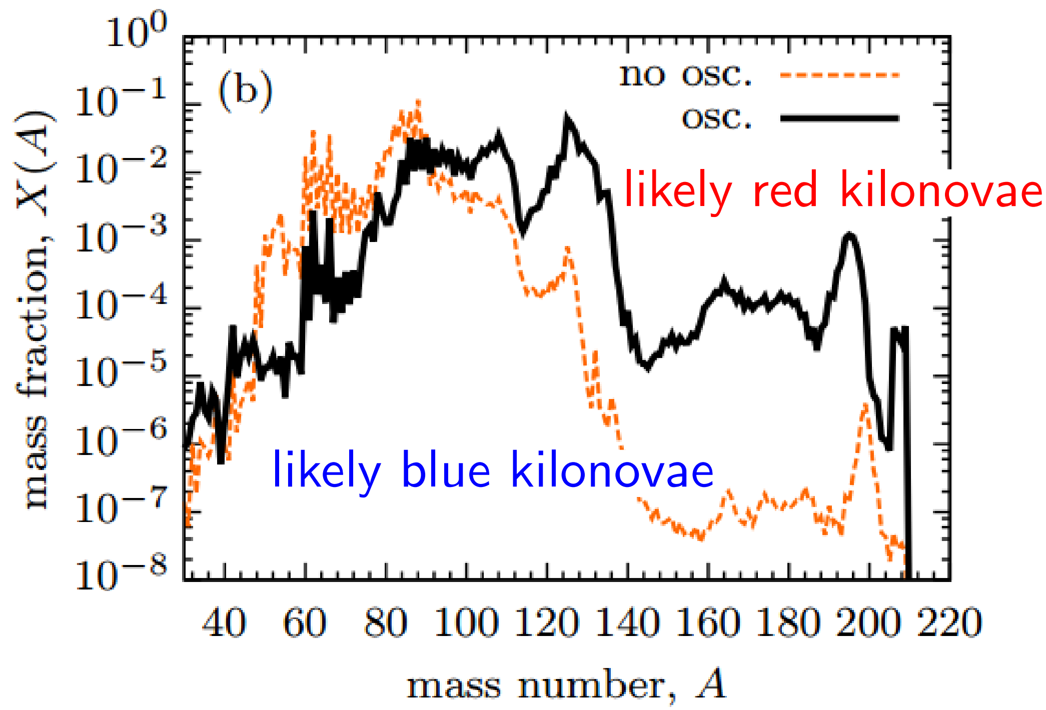

## Summary

- Recent electromagnetic follow-up kilonova observation of GW170817 suggests important role of neutrinos in the binary neutron star mergers.
- In a merger system, condition for fast neutrino flavor oscillations – a consequence of "strong" coupling among neutrinos – to occur is favored, due to the protonization of the remnant.
- The nucleosynthesis outcome and the kilonova color may be affected by fast oscillations. Further work in NS–disk system and detailed numerical modeling in the non-linear regime is needed to clarify this issue and to have reliable interpretation of the observation.