Fast Neutrino Oscillations and Their Impact in Neutron Star Mergers

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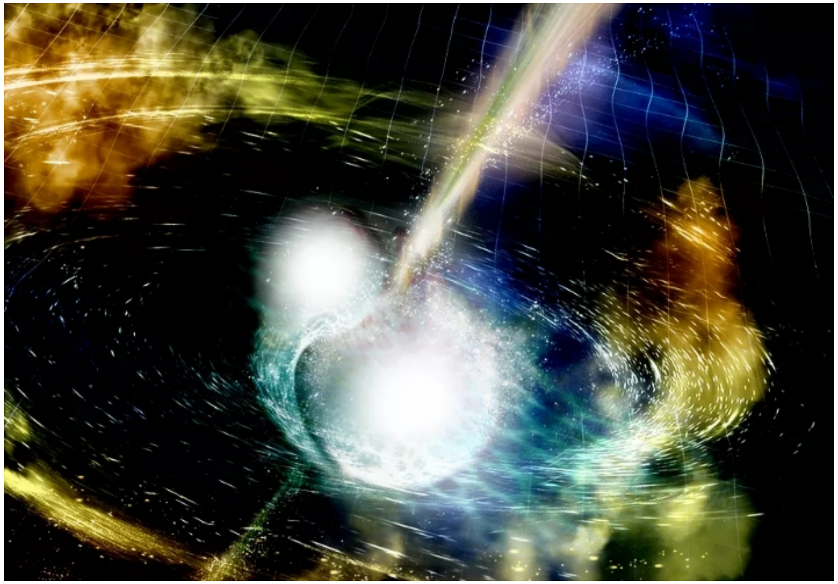
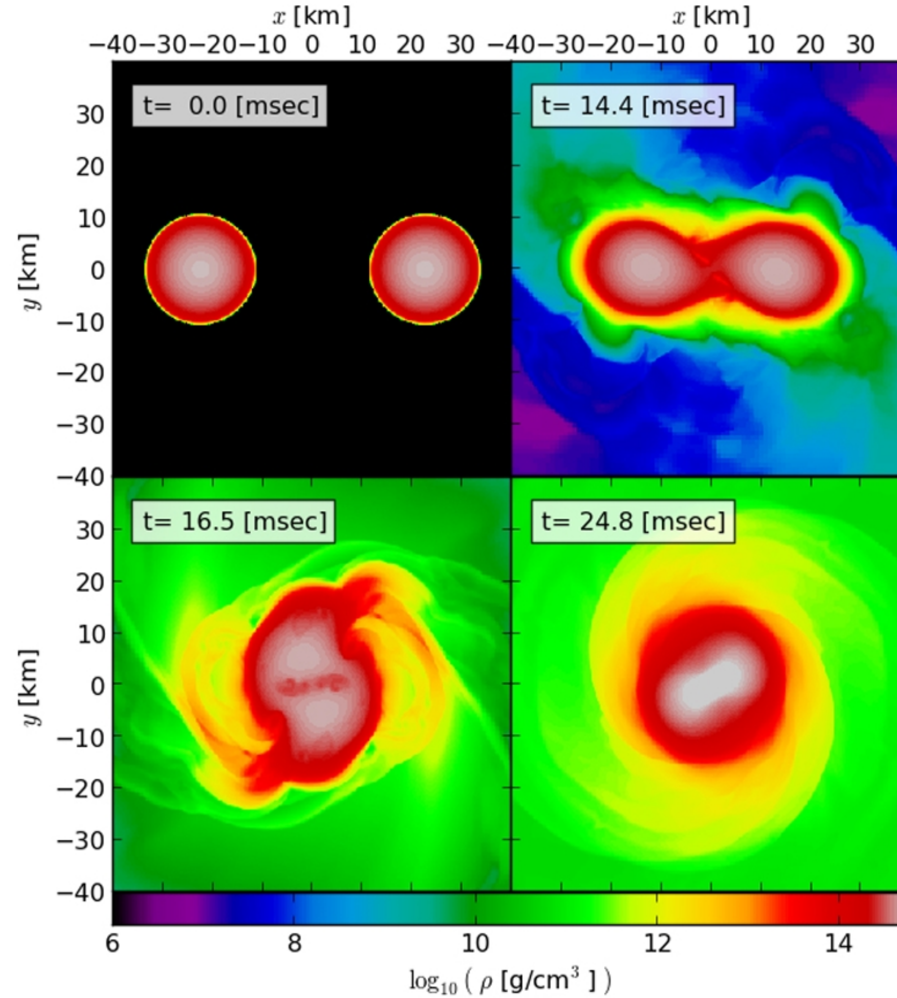
Binary neutron star mergers





[From L. Rezzolla]

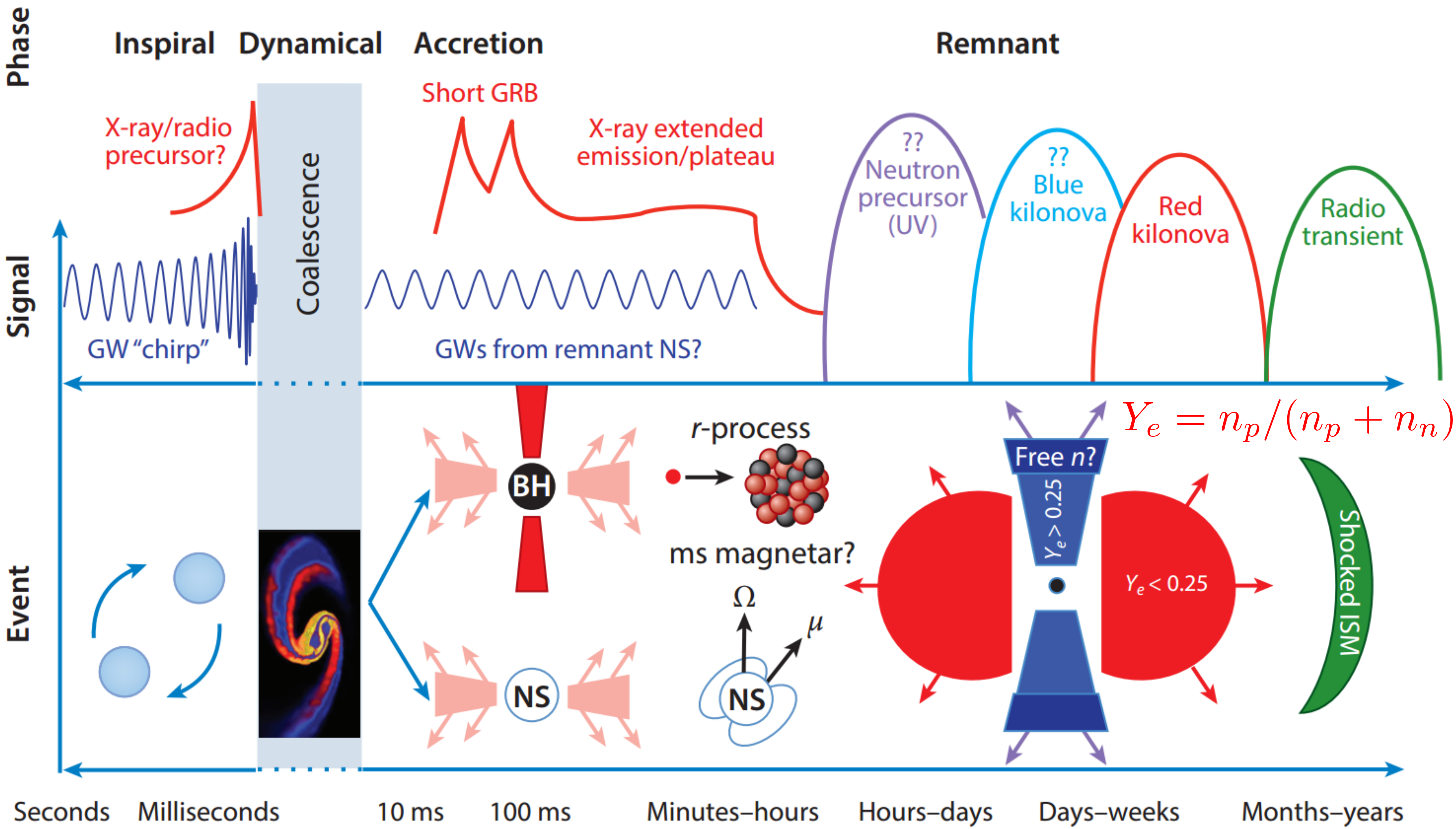
- gravitational wave sources
- origin of short γ-ray bursts
- origin of heavy elements (the r-process)$\rightarrow$ kilonovae

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

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

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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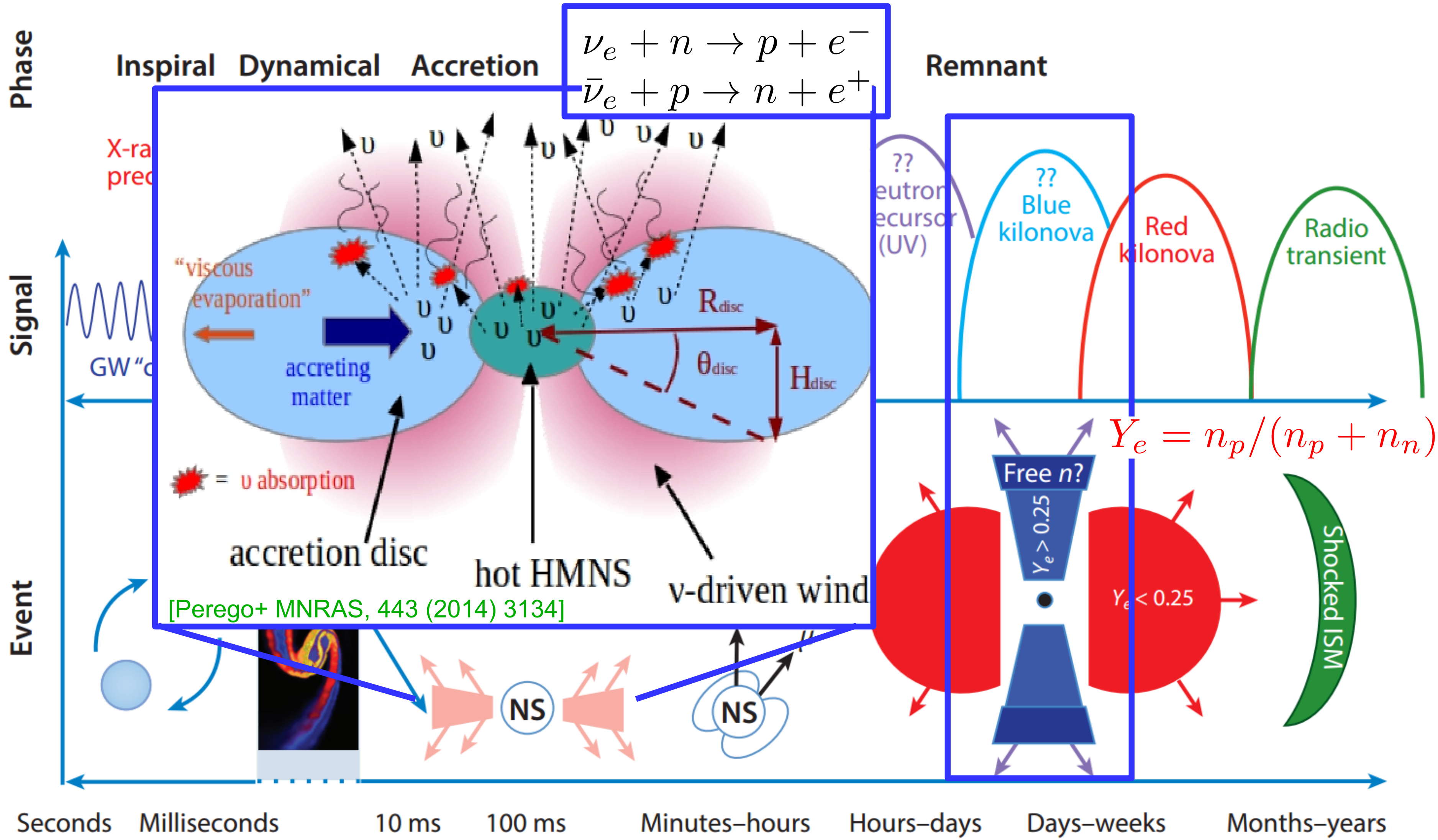
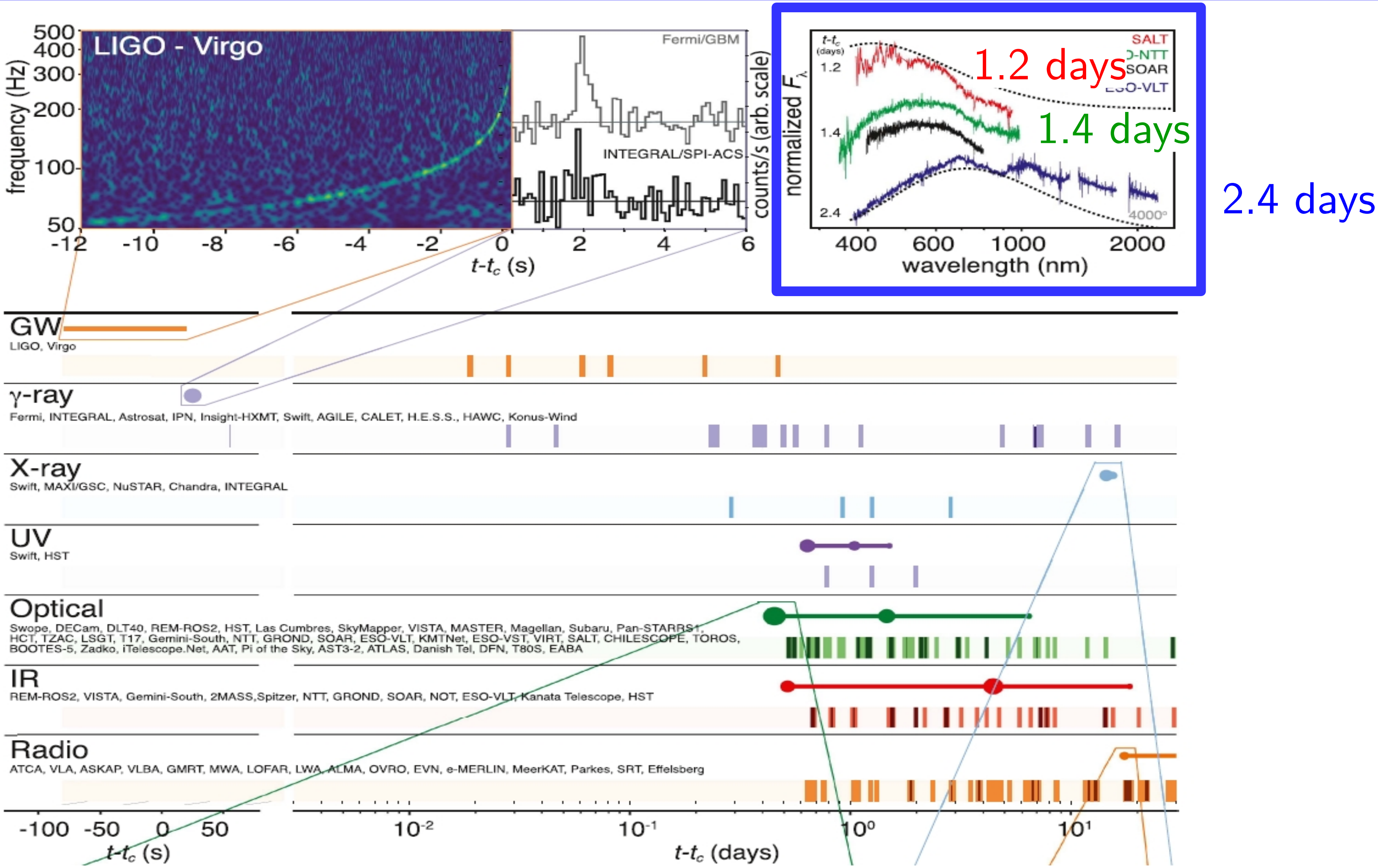


[Fernandez & Metzger, ARNPS 66 (2016) 23]

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

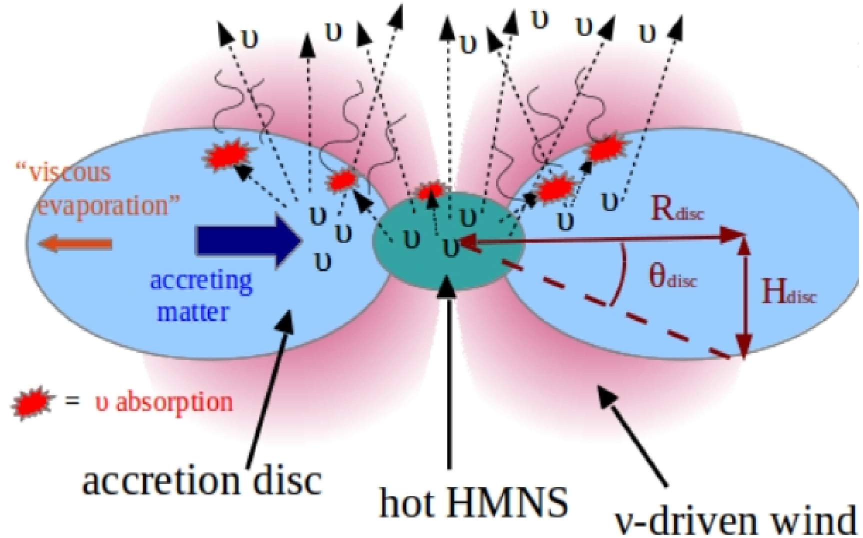


[LIGO/Virgo collaboration, Fermi...... Aboott+, ApJL 848:L12 (2017)]

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

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.

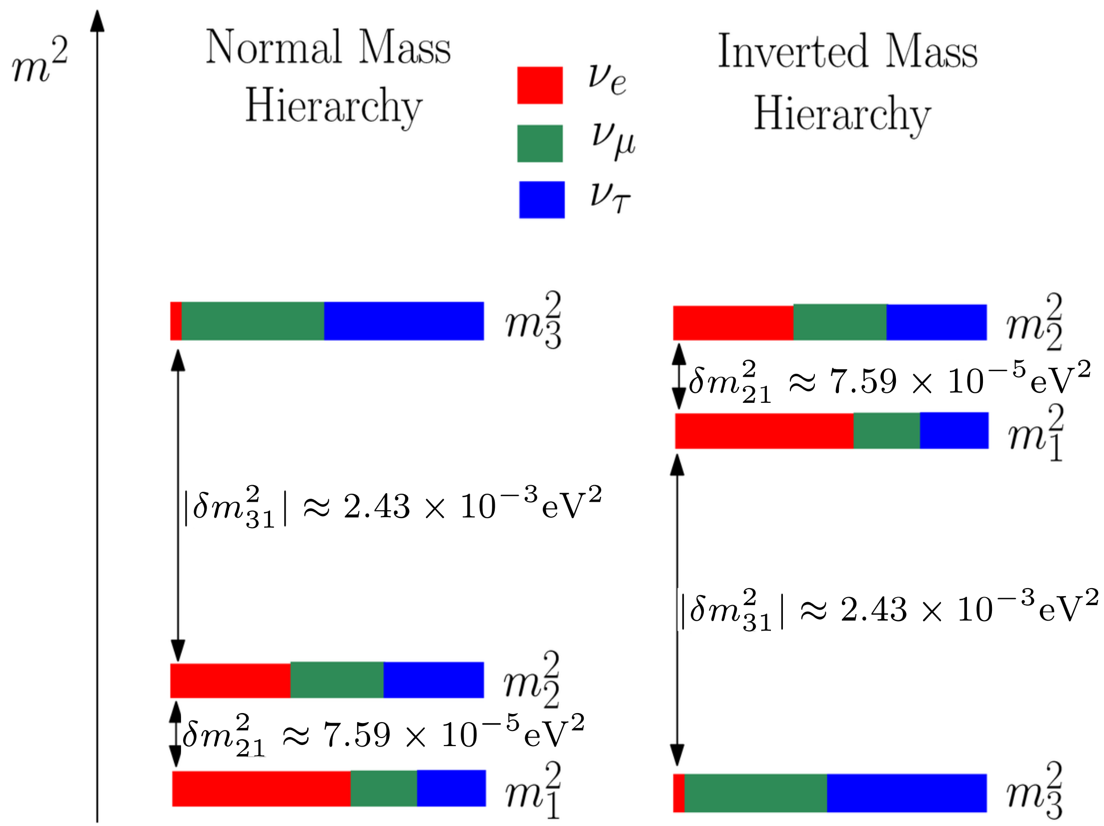
Table III. Emission parameters with $\nu_x \in \{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau\}$.

	$\langle E_\nu \rangle$ [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

[Perego+ MNRAS, 443 (2014) 3134]

→ need to understand better their transport and flavor oscillations

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...

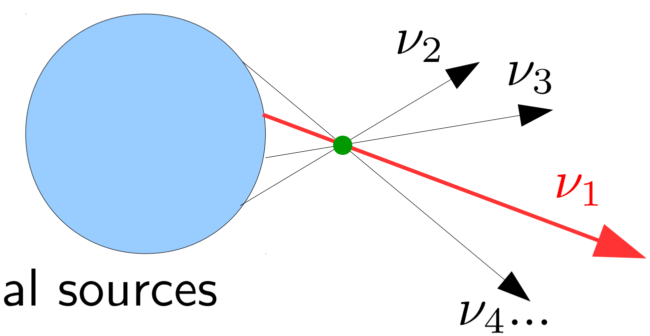
Neutrino oscillations in neutrino-dense environment

In the regime where neutrinos nearly free-stream

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

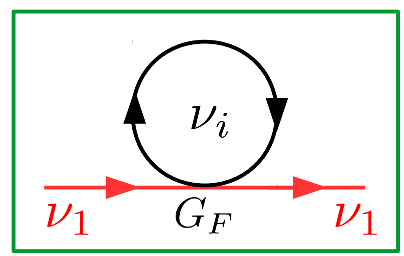
ϱ: Wigner-transformed flavor density matrix, $= \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{pmatrix}$

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



astrophysical sources

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



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

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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 ϱ evolves in linear regime. [Izaguirre+ 2017, Capozzi+ 2017]

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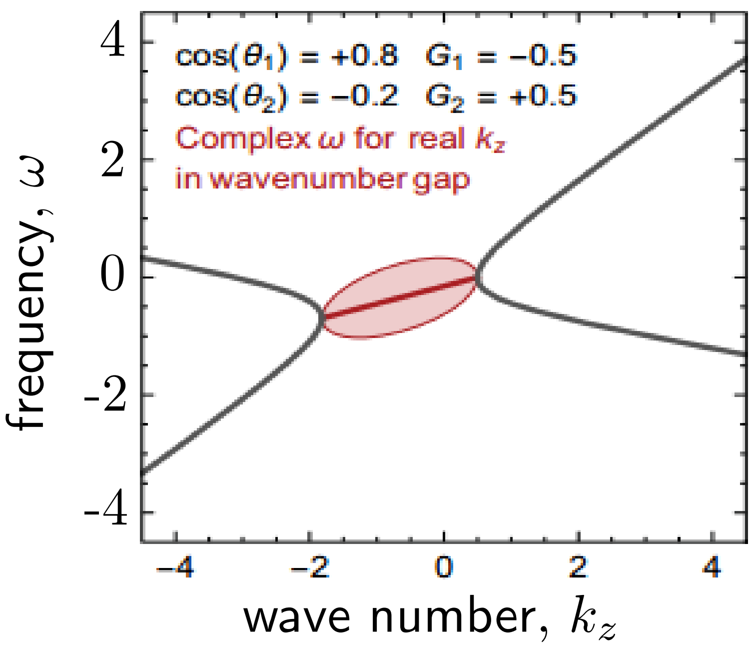
Complex frequency solution in the dispersion relation of the plane-wave $\leftrightarrow$ "flavor instability" leads to flavor conversion

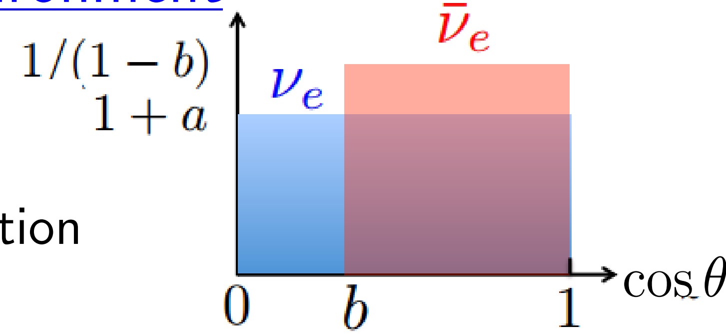


[Izaguirre+, PRL 118, 021101 (2017)]

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

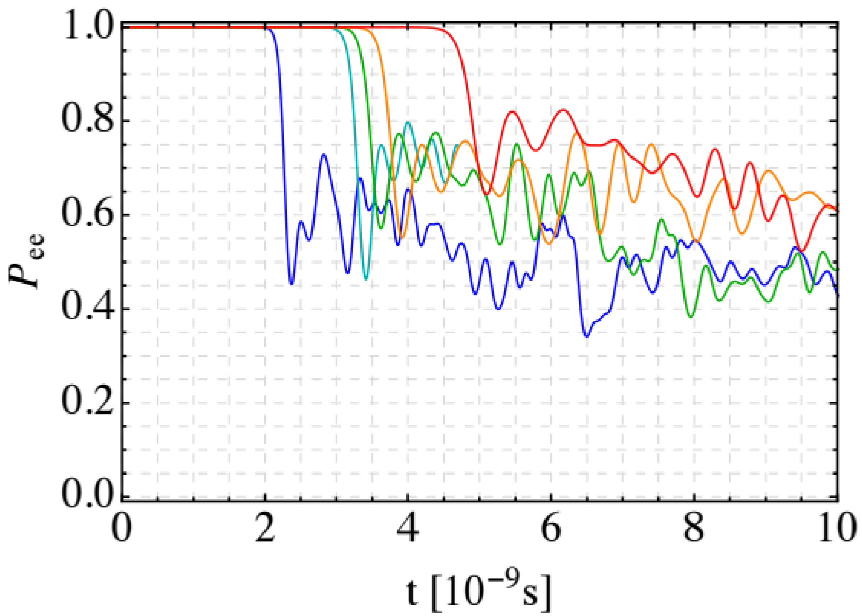
[Sawyer+ 2005, 2009, 2016, Izaguirre+ 2016-17, Dasgupta+ 2016]

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...]



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

$a = 0.1, b = 0.6$

$a = 0.2, b = 0.6$

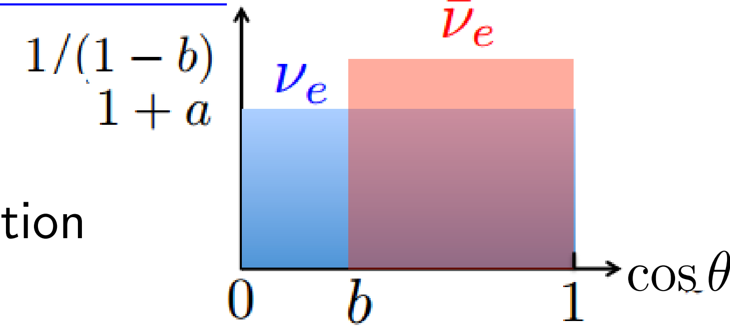
$a = 0.1, b = 0.4$

$a = 0.1, b = 0.35$

$a = 0.1, b = 0.3$

[Dasgupta+ JCAP 1702, 019 (2017]

Neutrino oscillations in neutrino-dense environment



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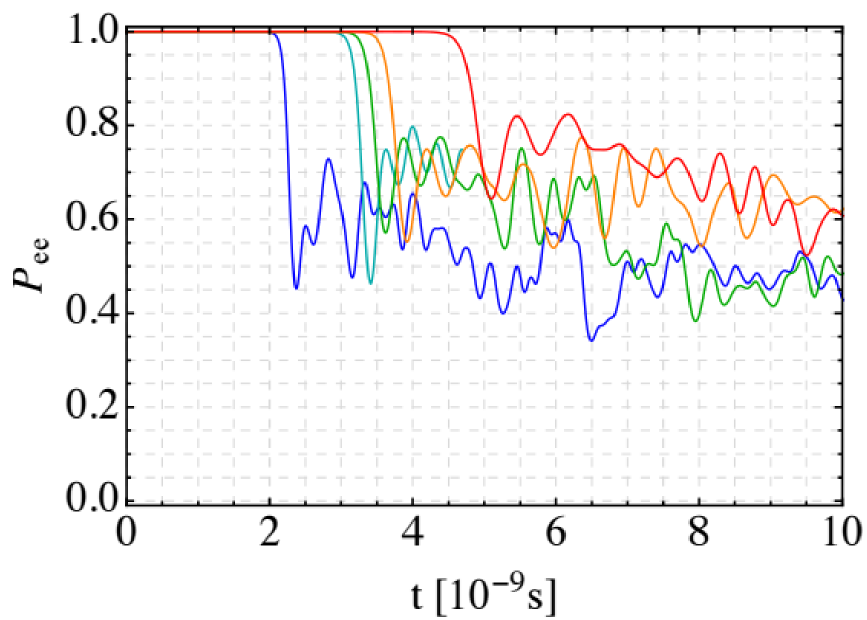

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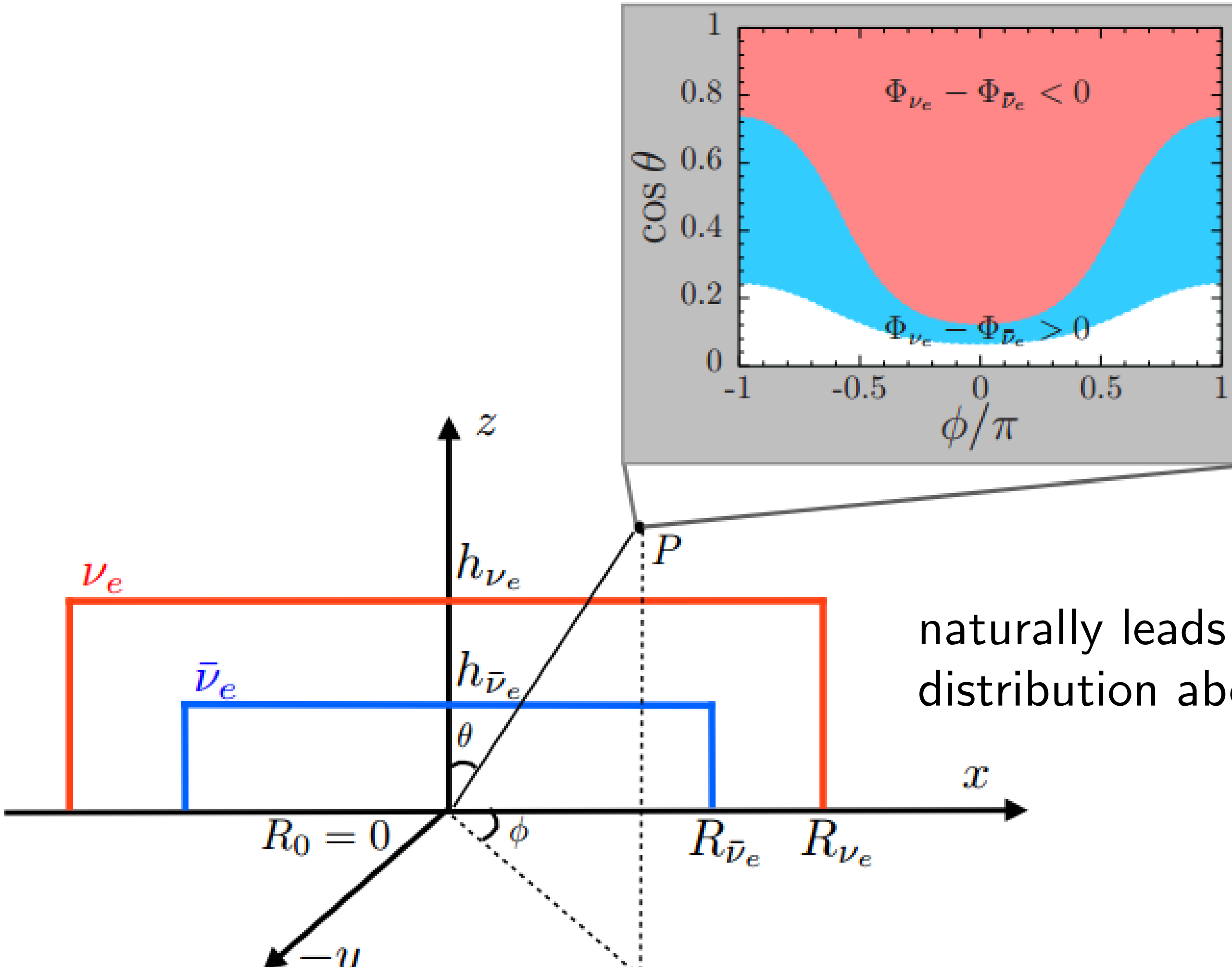
[Dasgupta+ JCAP 1702, 019 (2017)]

- 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 ν 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 ν_e [Foucart+, Perego+, Janka+,...]

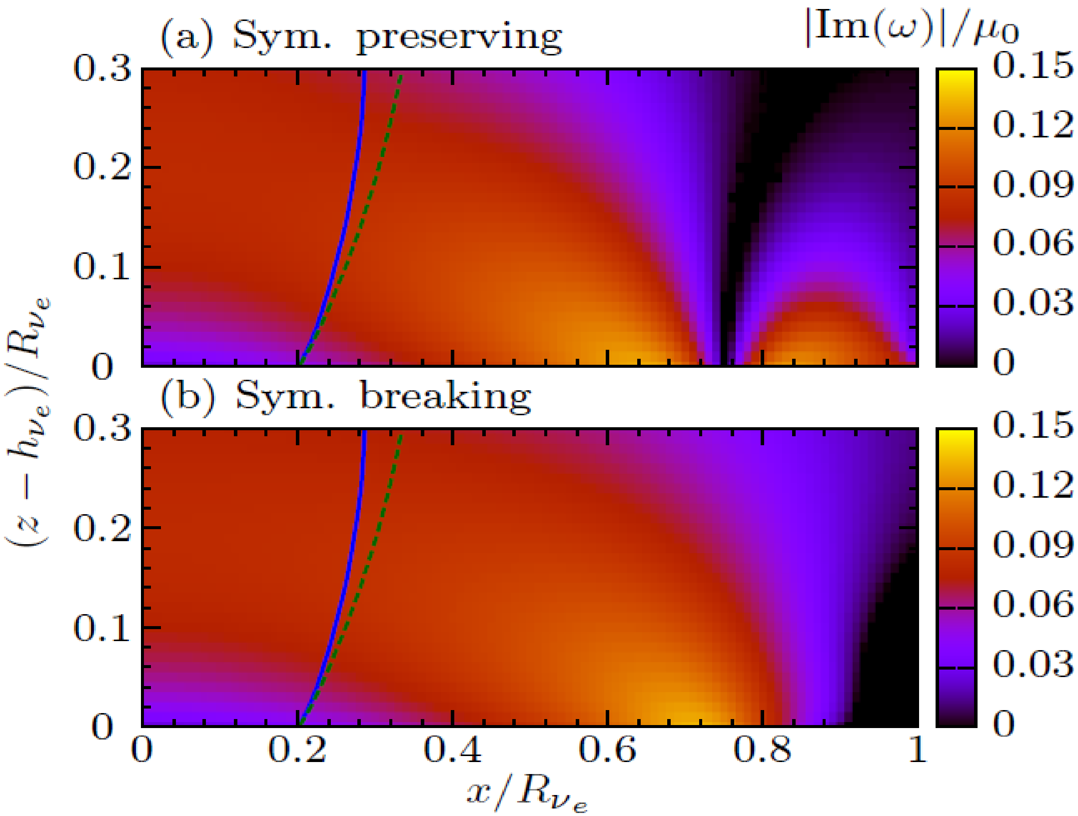


naturally leads to crossing in angular distribution above the merger remnant

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

Fast ν oscillations in merger remnants – parametrized model

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



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$\mathrm{Im}(\omega)$: 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

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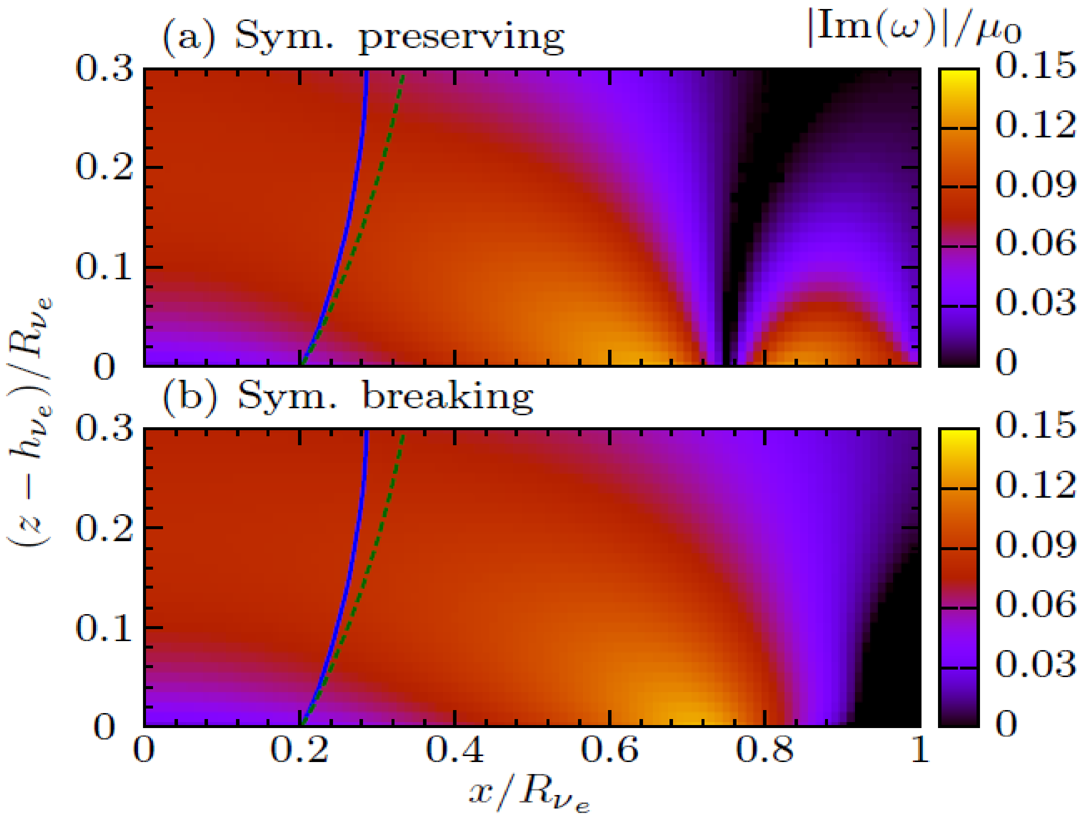

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fast flavor conversion condition exists everywhere above the remnant, with any reasonable parameters

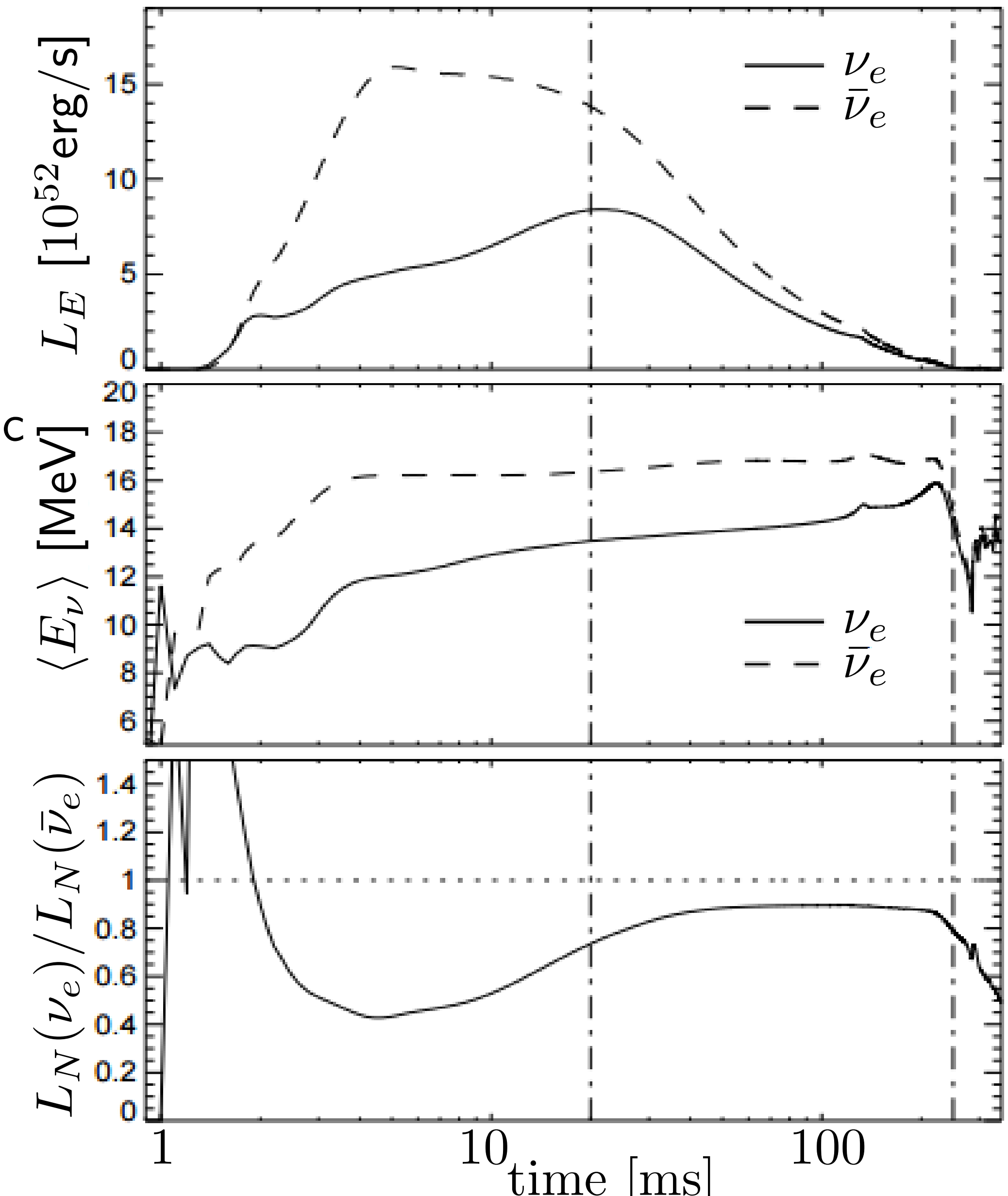
- does the picture remain beyond the parametrized model?
- impact on nucleosynthesis and the kilonova EM observables?

Fast ν 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



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

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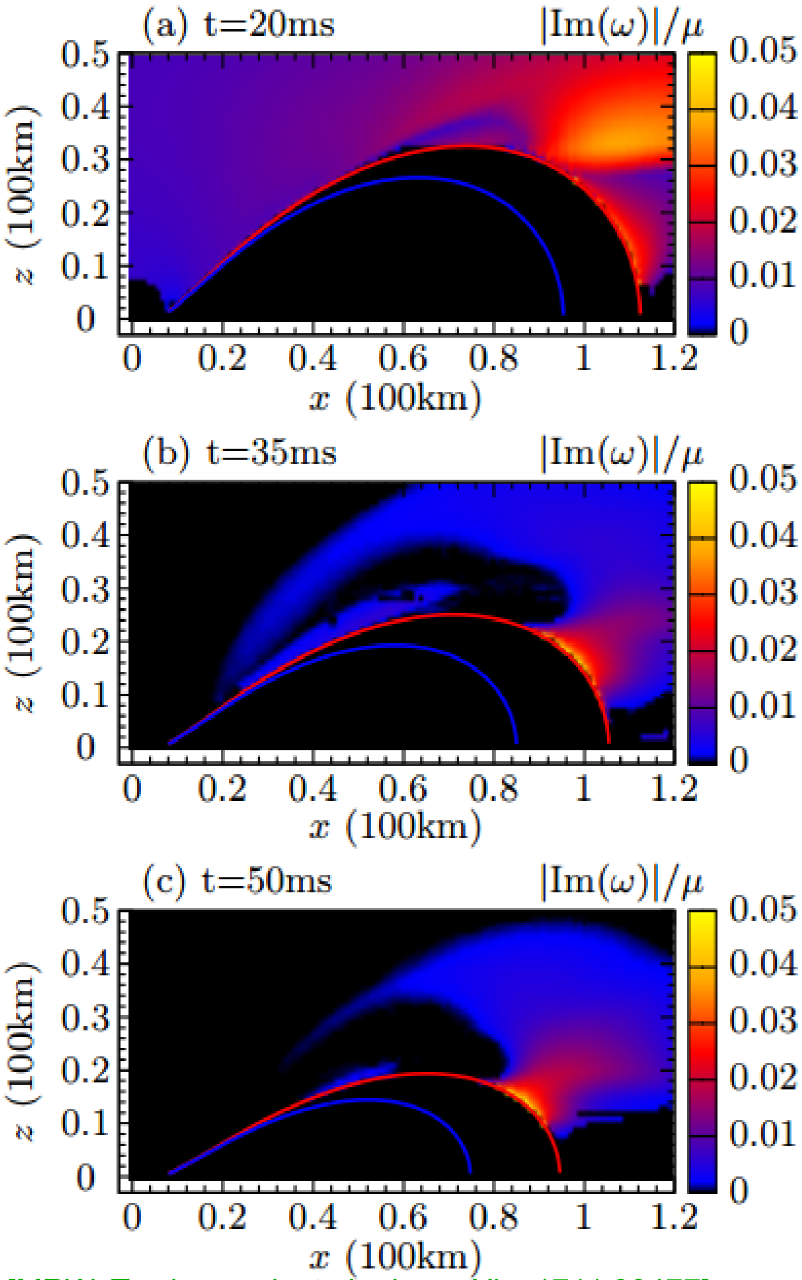

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– again, flavor instability seeding fast conversion found above the remnant

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

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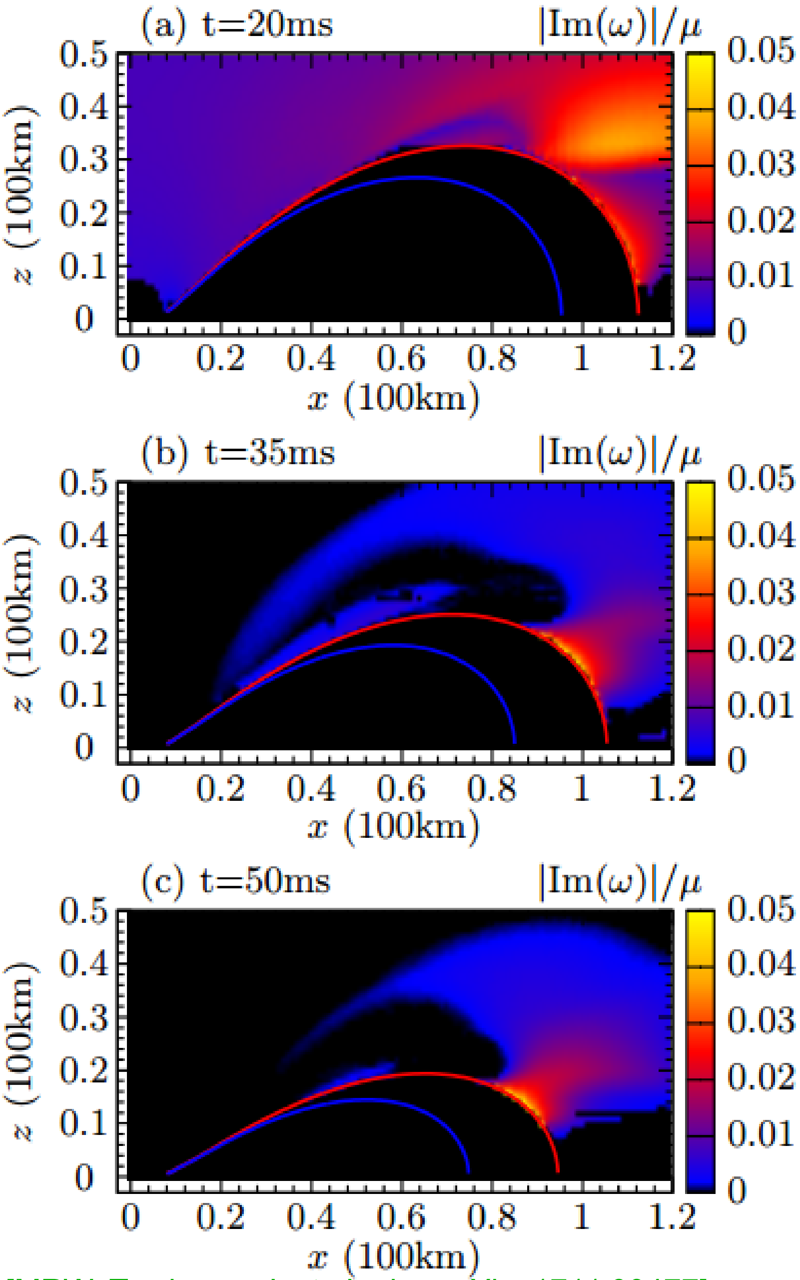

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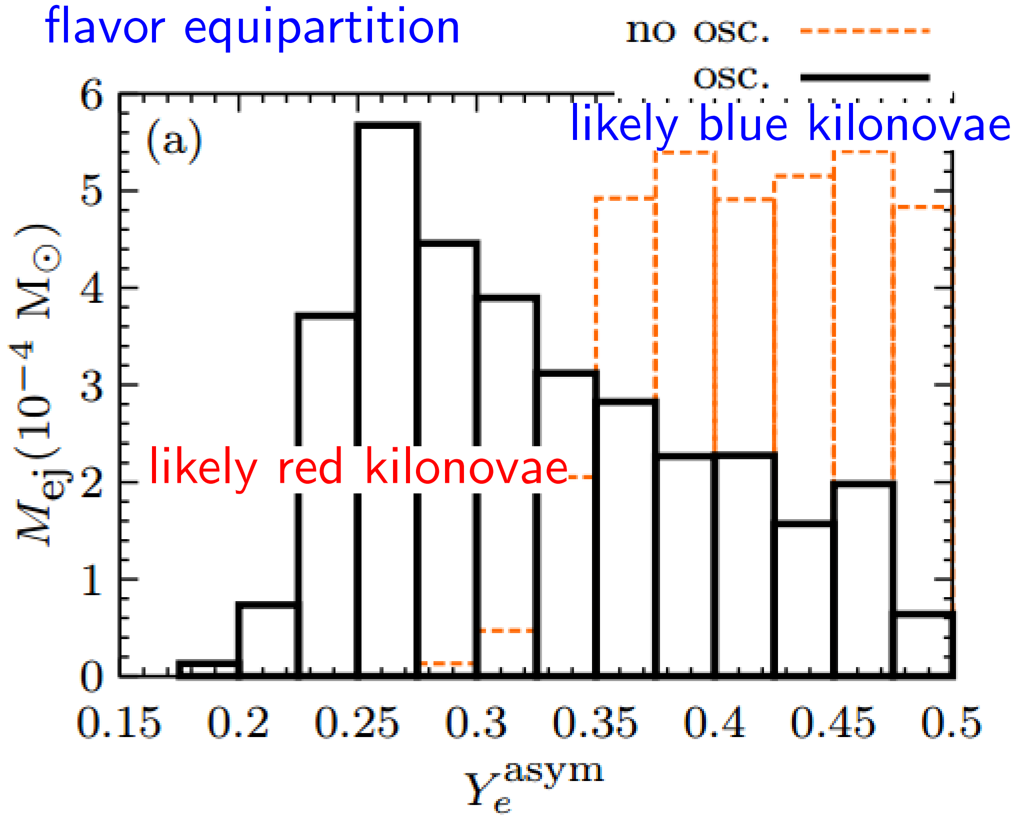

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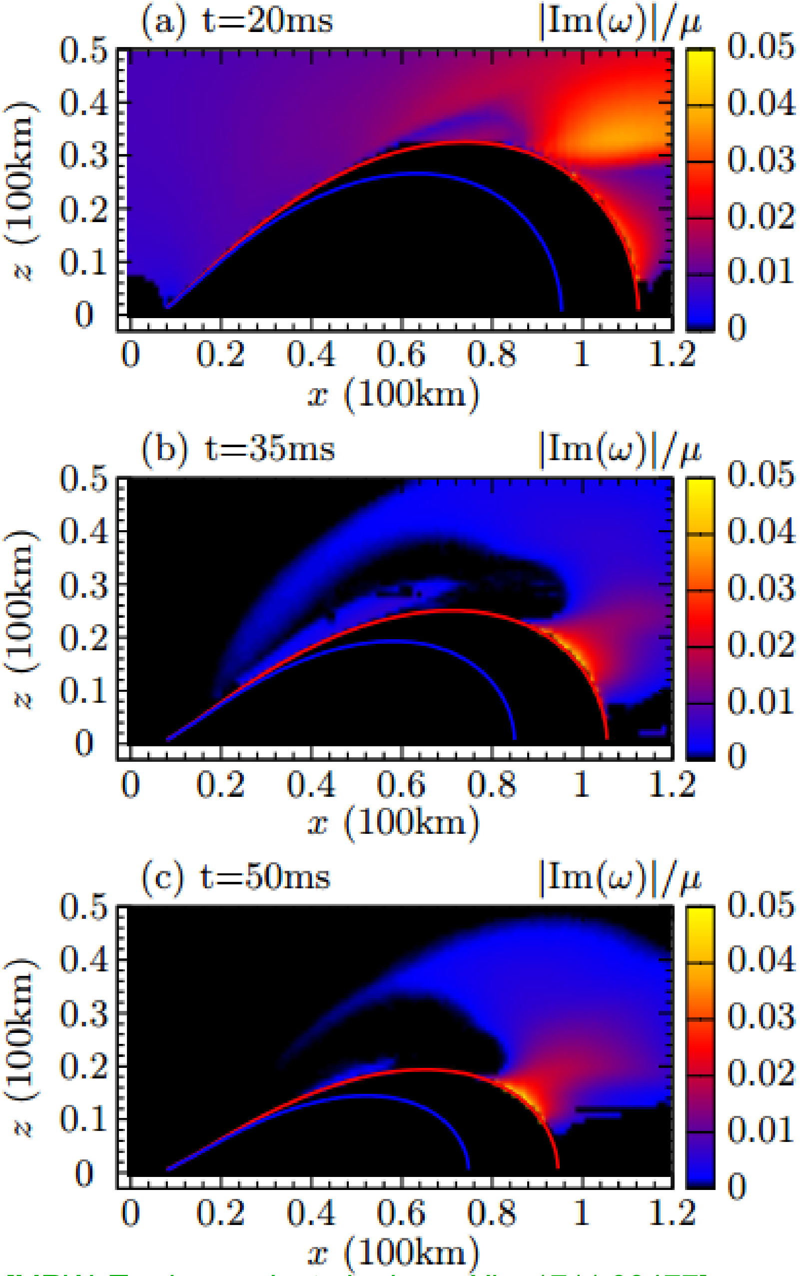

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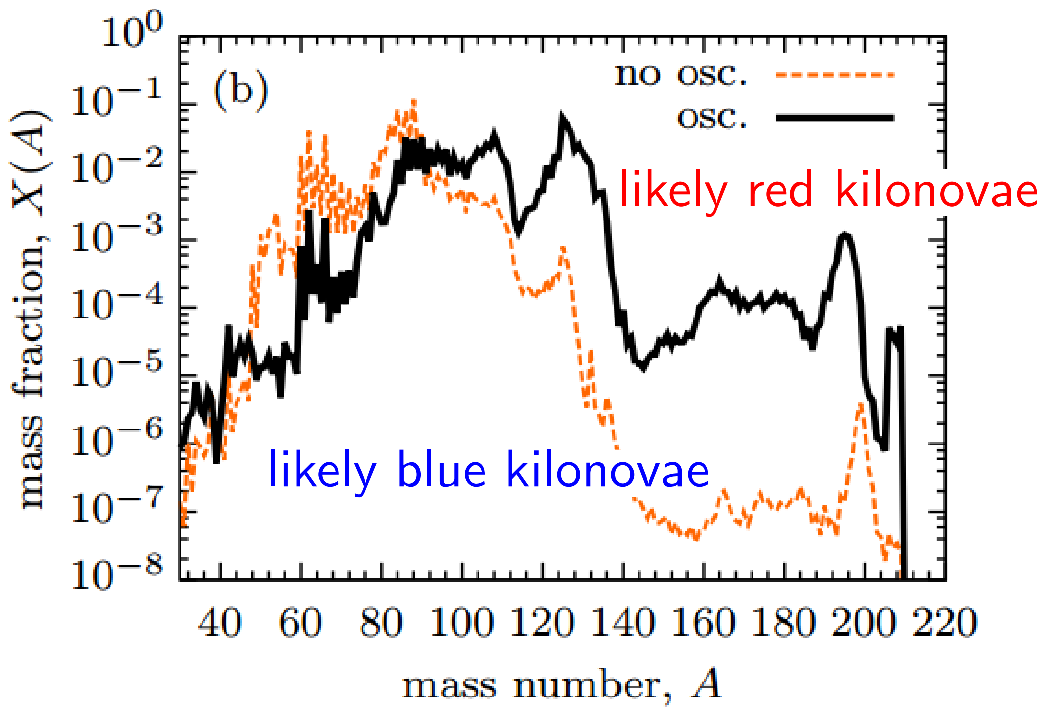

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Summary

- 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.