Neutrino Fast Flavor Conversions in Neutron-star Post-Merger Accretion Disks

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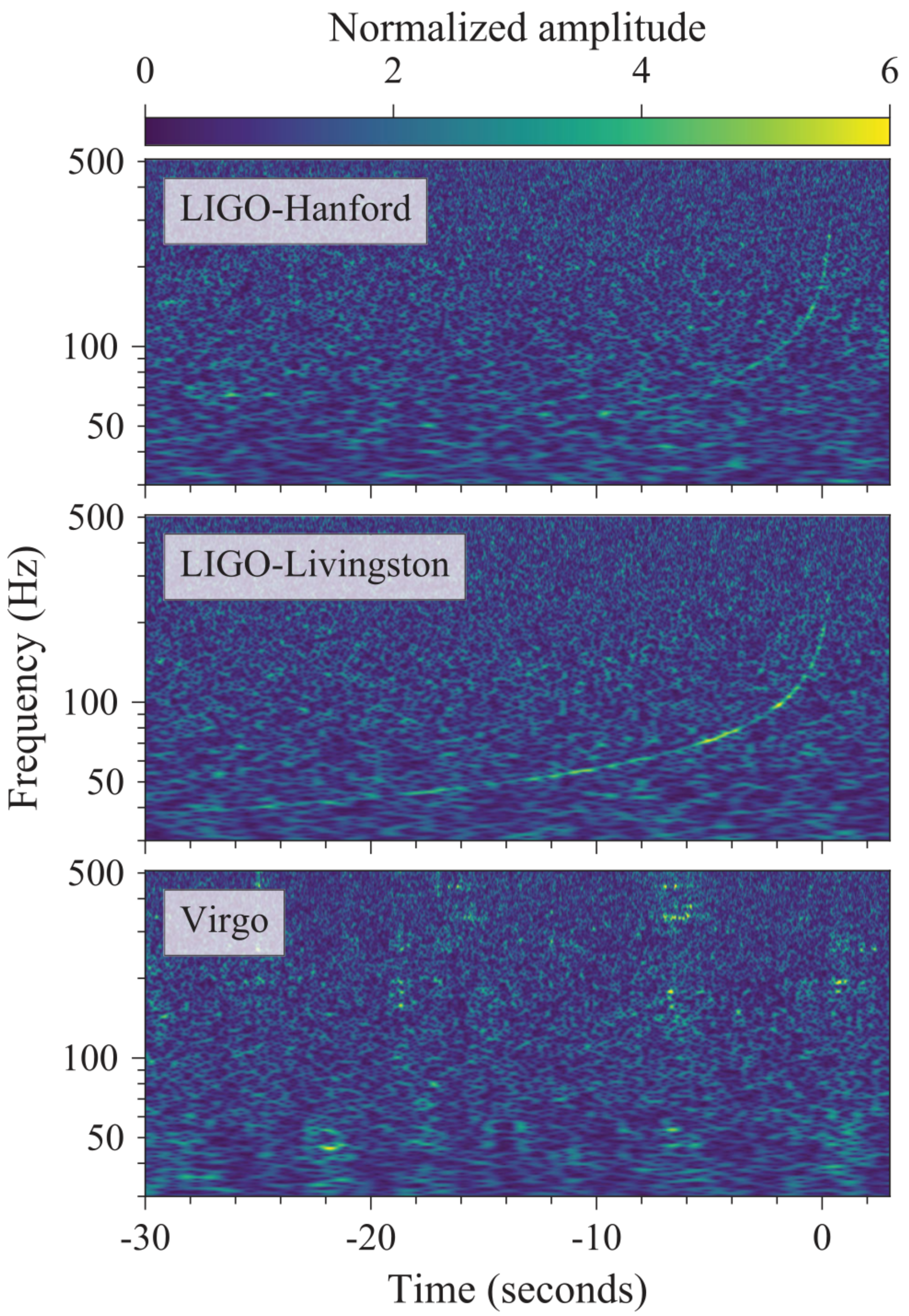
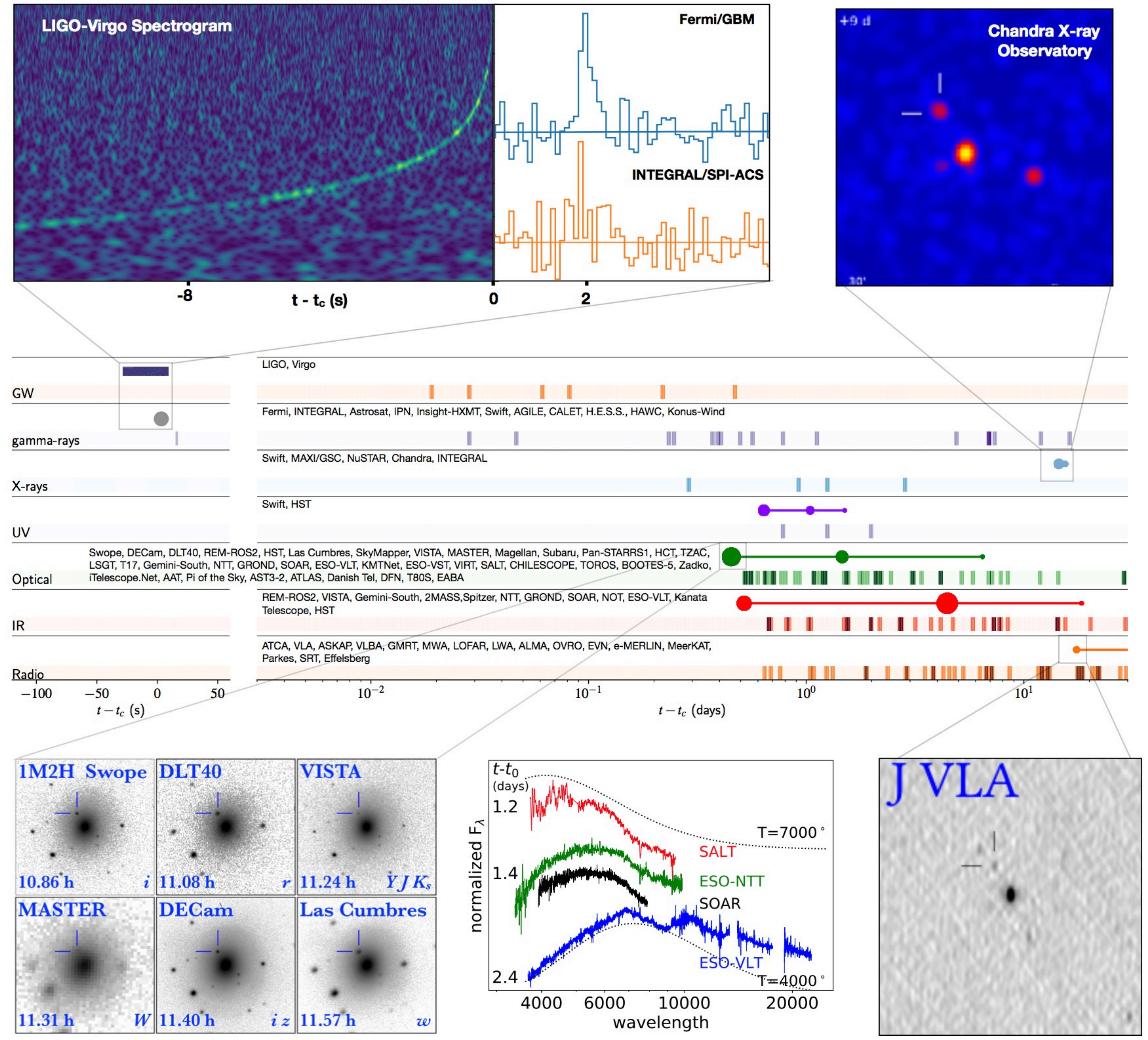
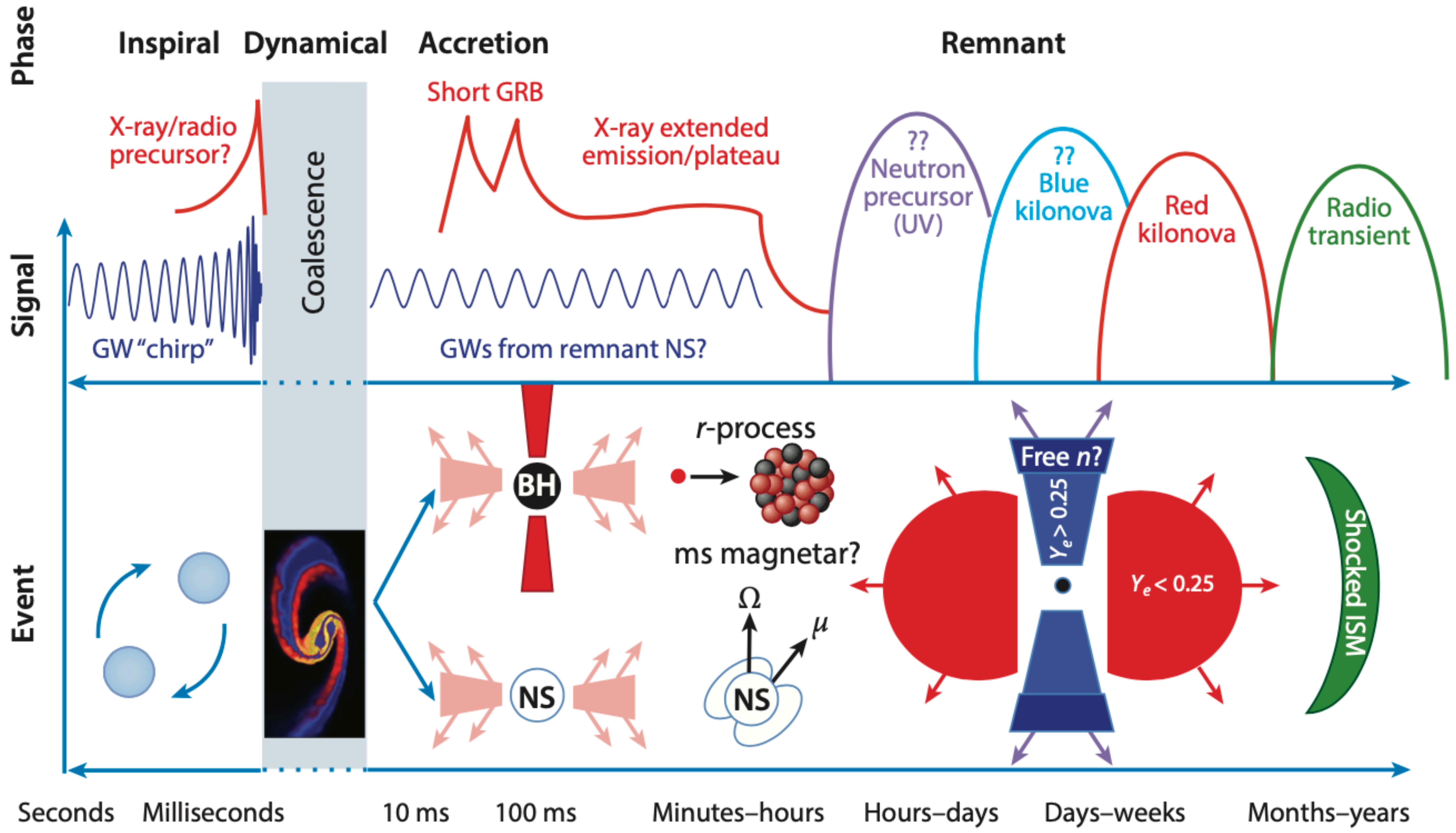
GW170817: The first multimessenger observation with gravitational wave





Abbot et al. 2017

Kilonova emission



- Blue component: neutron-poor (Ye>0.3) ejecta.
- Red component: low velocity (0.1-0.2c) neutron rich (Ye<0.3) ejecta.

Neutron-star post-merger disk

- Hot dense environment with density up to 10^{12} g/cc.
- Neutrinos are produced and are optically thick close to the central object with luminosity up to 10^{52-53} erg/s.
- Neutrinos can change nucleosynthesis through weak interactions.
- Previous simulations use simple approximation, e.g. leakage scheme (Siegel 2018).
- Only Monte-Carlo transport by Miller et al. (2019).

Neutrino fast flavour conversion

- Neutrino density matrix with flavour eigenstates as the bases

$$\varrho_\nu = \frac{f_{\nu_e} + f_{\nu_X}}{2} I + \frac{f_{\nu_e} - f_{\nu_X}}{2} \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

- Hamiltonian

$$H = \frac{M^2}{2E} - v^\nu \Lambda_\nu \frac{\sigma_3}{2} - \frac{\sqrt{2}}{(2\pi)^3} G_F \int v^\nu v_\nu \rho_\nu E^2 \, \mathrm{d}E \mathrm{d}\Omega$$

- Equation of Motion

$$i v^\mu \partial_\mu \rho_\nu = [H, \rho_\nu]$$

Evolution of the off-diagonal term

- Linearized evolution with $S_{\boldsymbol{v}}(t,\boldsymbol{r}) = Q_{\boldsymbol{v}}(\tilde{\varpi},\boldsymbol{k})\exp[-i(\tilde{\varpi}t - \boldsymbol{k}\cdot\boldsymbol{r})]$

$$v^\mu k_\mu Q_{\boldsymbol{v}} + \int \mathrm{d}\Omega'\, v^\mu v'_\mu G_{\boldsymbol{v}'} Q_{\boldsymbol{v}'} = 0. \qquad G_{\boldsymbol{v}} = \frac{\sqrt{2}}{(2\pi)^3} G_F \int \mathrm{d}E\, E^2\, [f_{\nu_e}(E,\boldsymbol{v}) - f_{\bar{\nu}_e}(E,\boldsymbol{v})]$$

- The coherence $S \propto exp(i\varpi t)$ develops runaway instability when ϖ is complex, and the imaginary part $\omega \equiv Im\varpi$ gives the growth rate.

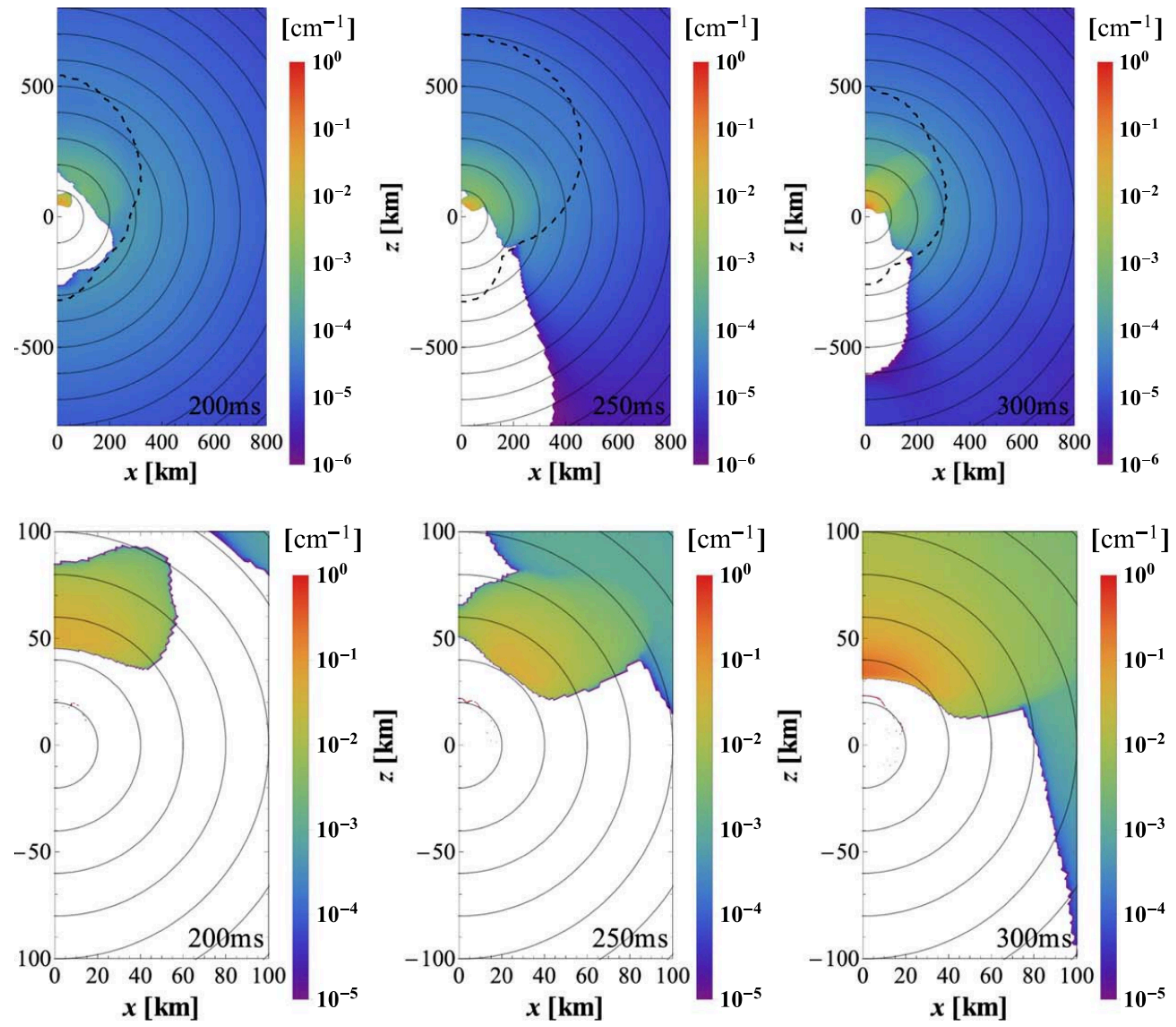
- The self-interaction term induces the exponential growth of the off-diagonal term (flavour conversion) with growth rate

$$\Phi_0 = \sqrt{2} G_F n_\nu/\hbar = 1.92 \times 10^9 \left(\tfrac{n_\nu}{10^{31}\mathrm{cm}^{-3}}\right) \mathrm{s}^{-1}$$

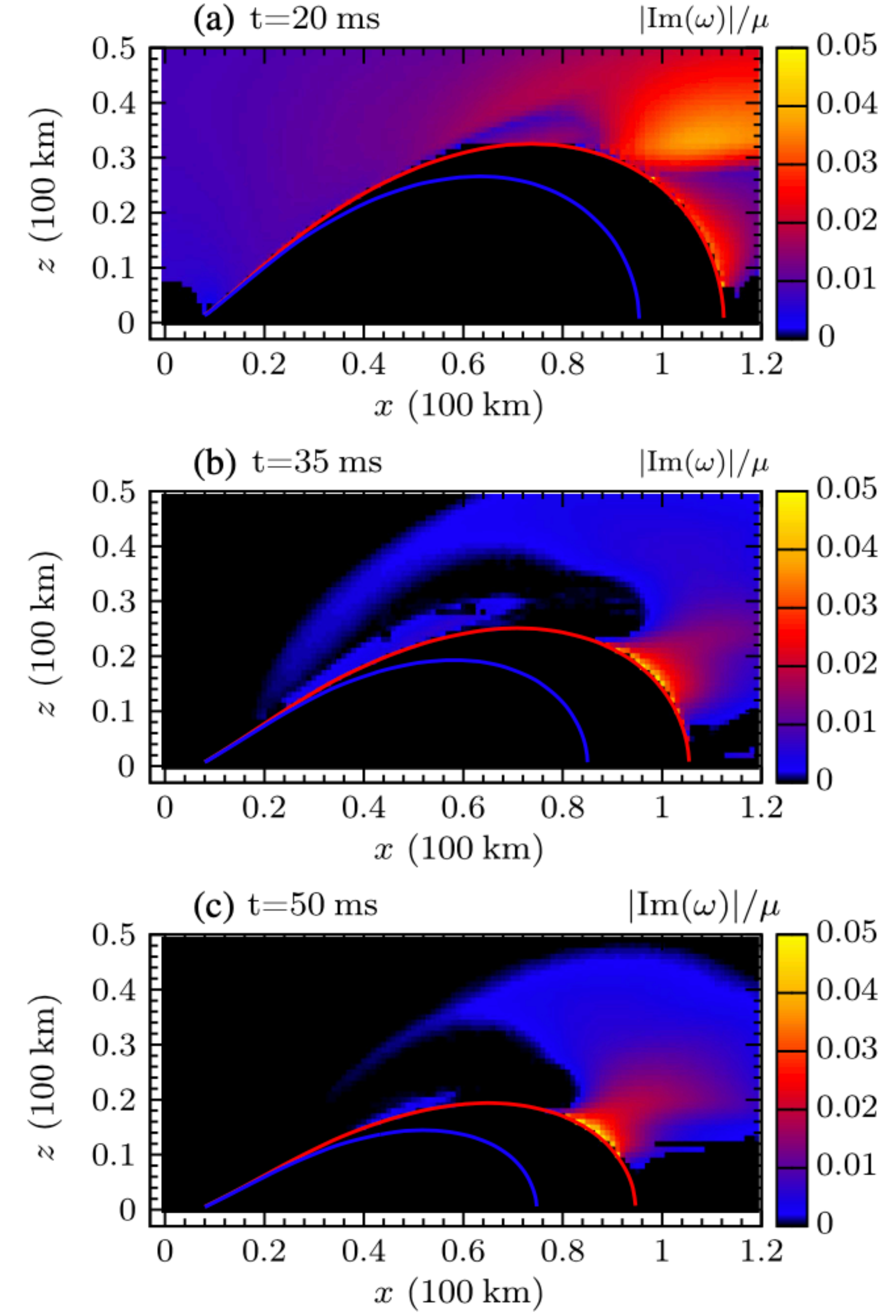
- ~ns time in the neutron star post-merger disk!

Method of Dispersion Relation (Izaguirre 2017)

- Define $a_\mu \equiv -\int \mathrm{d}\Omega\, v_\mu G_{\boldsymbol{v}} Q_{\boldsymbol{v}}$
- Equation of Motion $\Pi^{\mu\nu} a_\mu = 0$ $\quad \Pi^{\mu\nu} = \eta^{\mu\nu} - \int \mathrm{d}\Omega\, G_{\boldsymbol{v}} \frac{v^\mu v^\nu}{\varpi - \boldsymbol{k}\cdot\boldsymbol{v}},$
- To have nontrivial solution $\det \Pi^{\mu\nu} = 0$
- Fast conversion happens when the above equation admits complex roots
- We are solely interested in the $k = 0$ case, the second term is proportional to the 2-moment of the radiation field.
- For the GR case $\det\left[\varpi g^{\mu\nu} - \sqrt{2} G_F \left(M^{\mu\nu}_{\nu_e} - M^{\mu\nu}_{\bar{\nu}_e}\right)\right] = 0, \quad M^{\mu\nu}_s \equiv \frac{1}{(2\pi)^3}\int E^2 \mathrm{d}E \mathrm{d}\Omega\, f_s v^\mu v^\nu$



Collapsar (Nagakura et al. 2019)

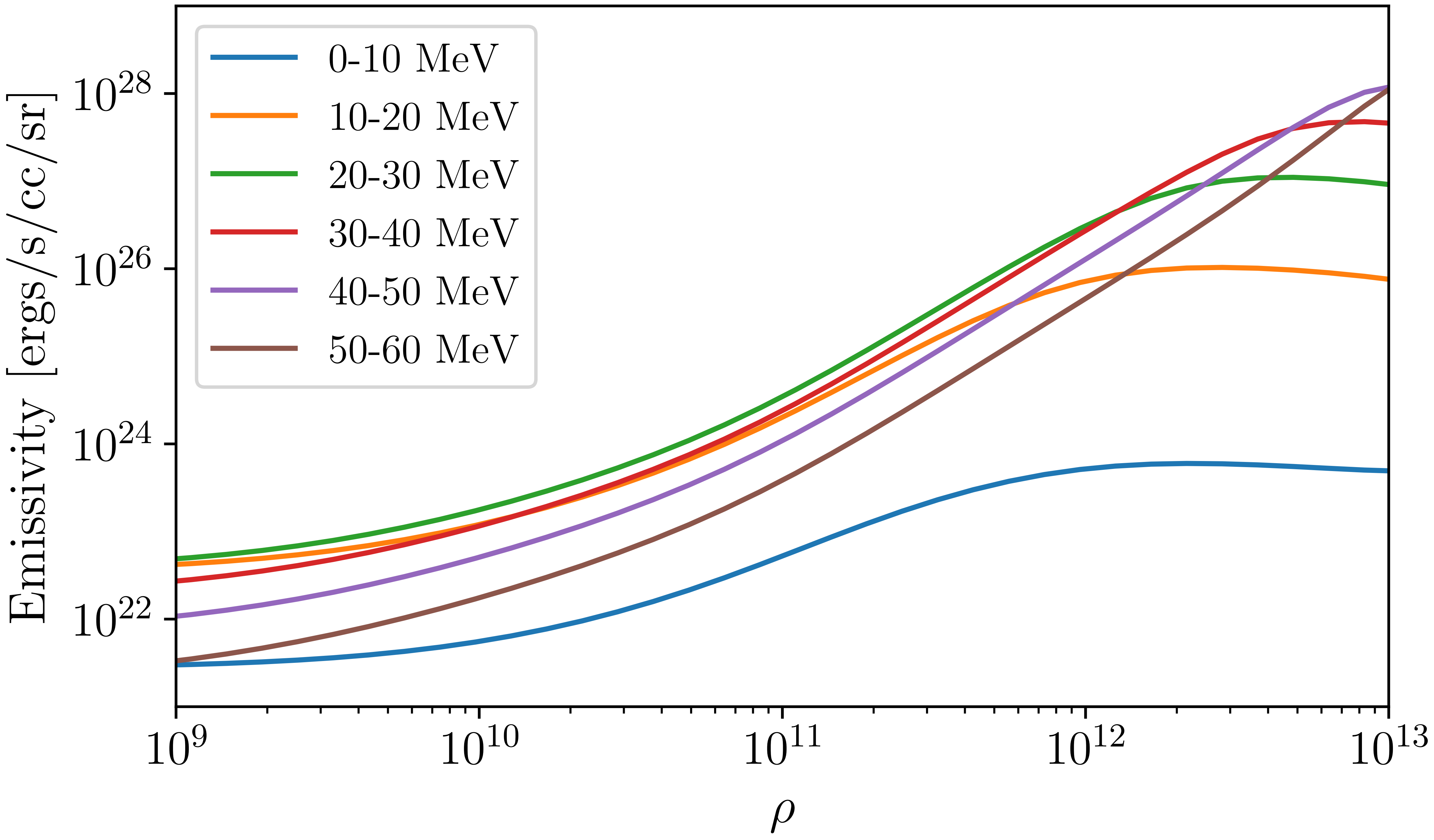


NS merger remnants (Wu et al. 2017)

GRMHD simulation: neutrino radiation transport

- Include neutrino transport using the general relativistic M1 method (Shibata et al. 2011, Roberts et al. 2016).
- We trace 4 species with 6 energy bins between 0-60MeV.
- In the fluid dynamics equations, the evolution of the nth moment depends on the (n+1)-th moment (closure problem).
- The M1 scheme treats the radiation field as a fluid and assumes the second moments given by a proposed analytical relation from the first moments.

Electron Neutrino Emissivity for Each Energy Bin

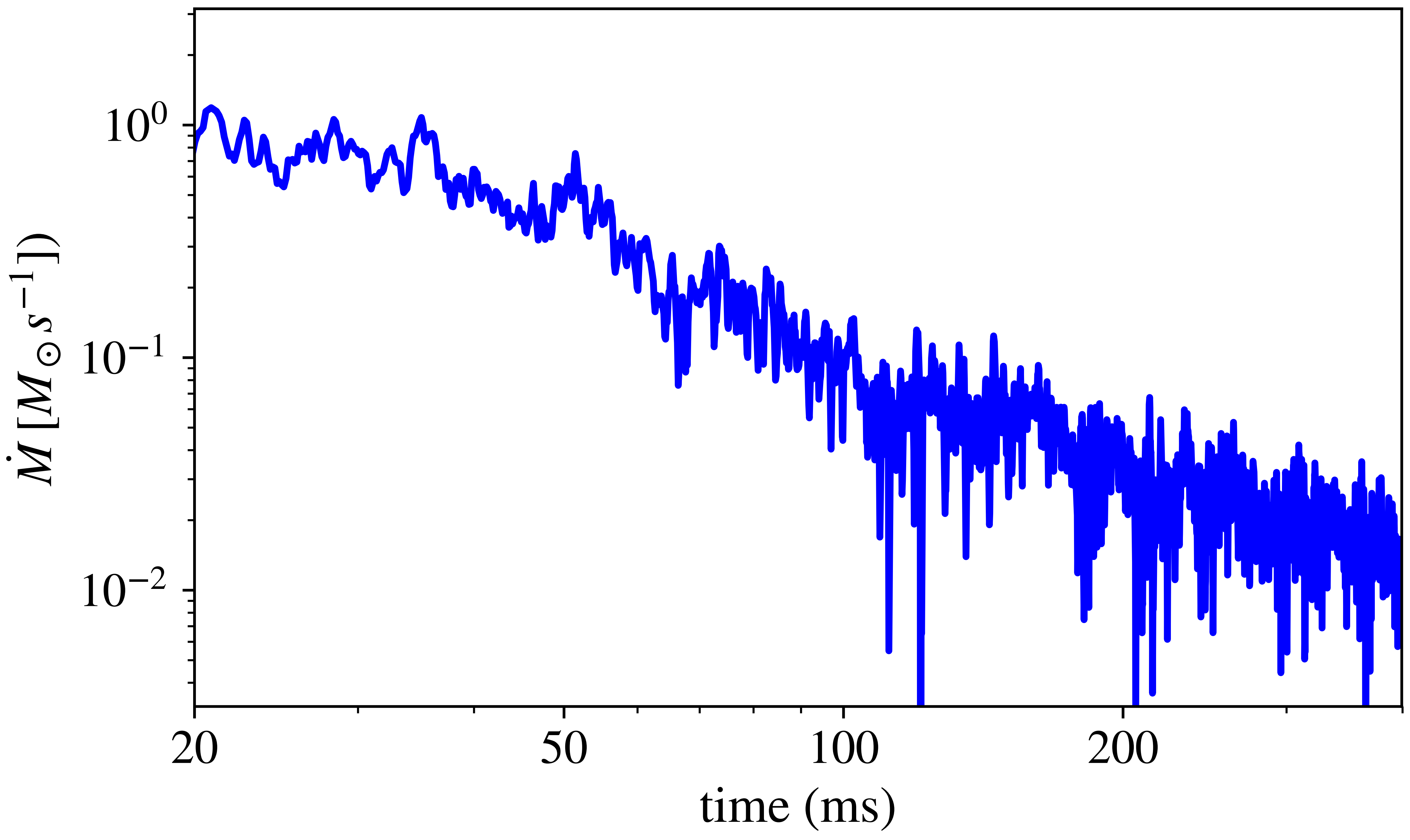


GRMHD simulation: fast flavour conversion

- Start with an equilibrium torus of 0.07Msun around a 3Msun black hole with spin 0.8, Ye=0.1 and evolve to 400ms.
- The disk relaxes to a quasi-steady state after ~20ms, which serves as the effective initial condition.
- Calculate the maximum growth rate ω for each grid: set flavour equipartition among neutrinos and anti-neutrinos separately if $1/\omega < 10^{-7}$s.
- This timescale is much smaller than our time step, which is much smaller than the weak interaction timescale. (For equipartition, see discussion in Padilla-Gay 2021, Bhattacharyya 2021 and Richers 2021.)
- We compare two simulations with (FC) and without (NFC) fast flavour conversion.

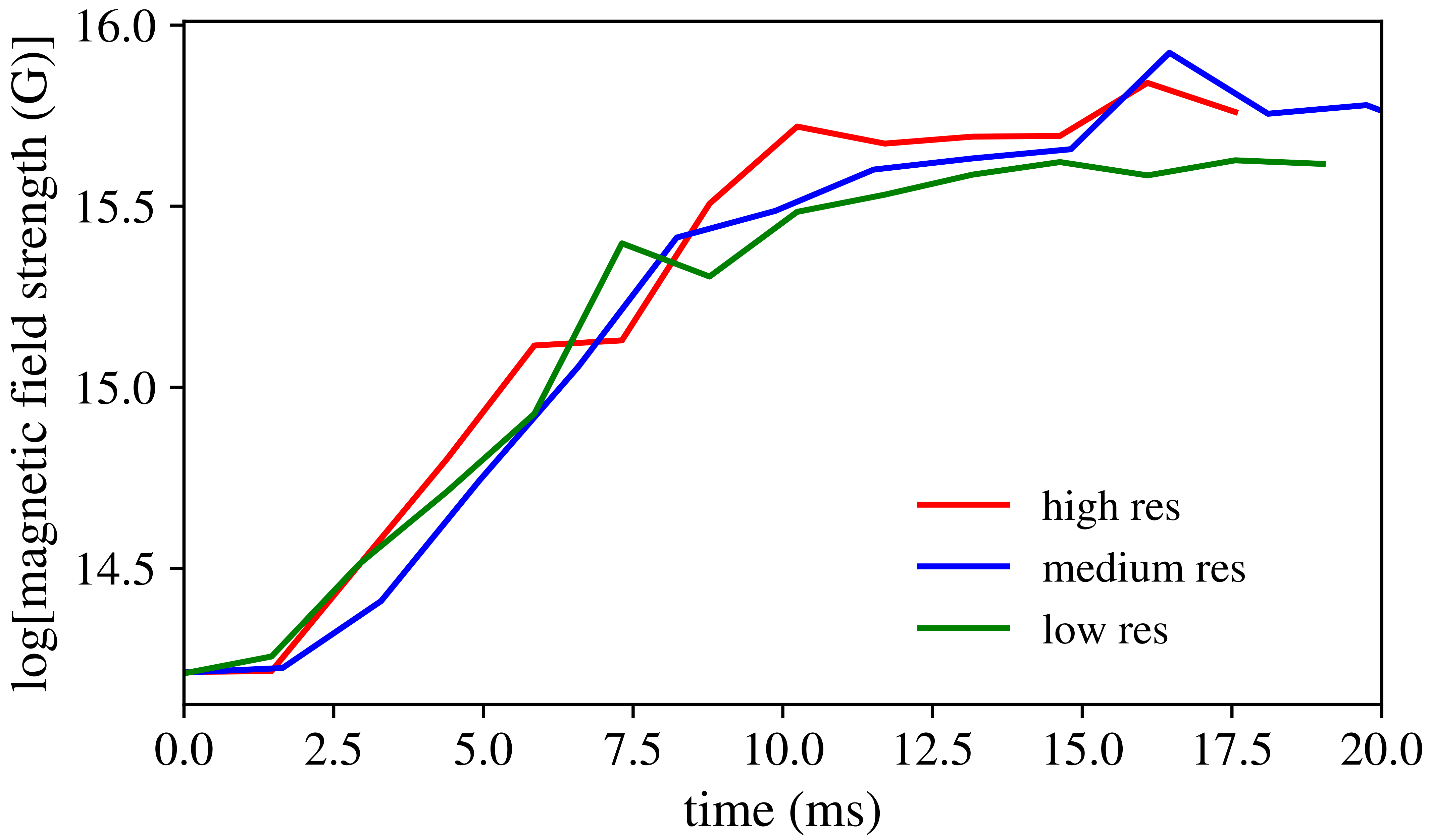
Disk evolution

- After an initial stage of relaxation, the disk relaxes into a quasi-steady turbulent state with accretion rate ~1Msun/s above the r-process threshold (1e-3).

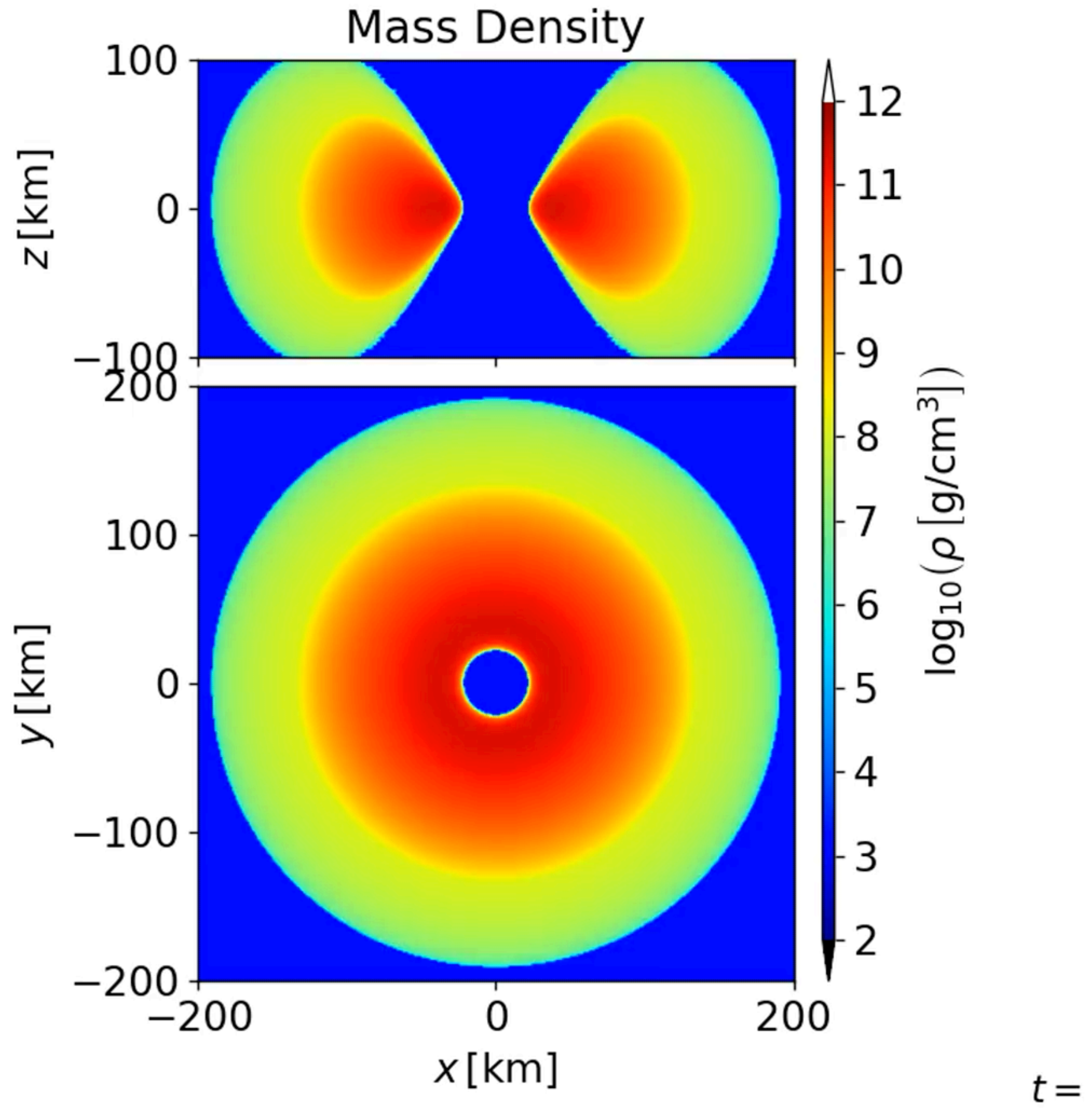


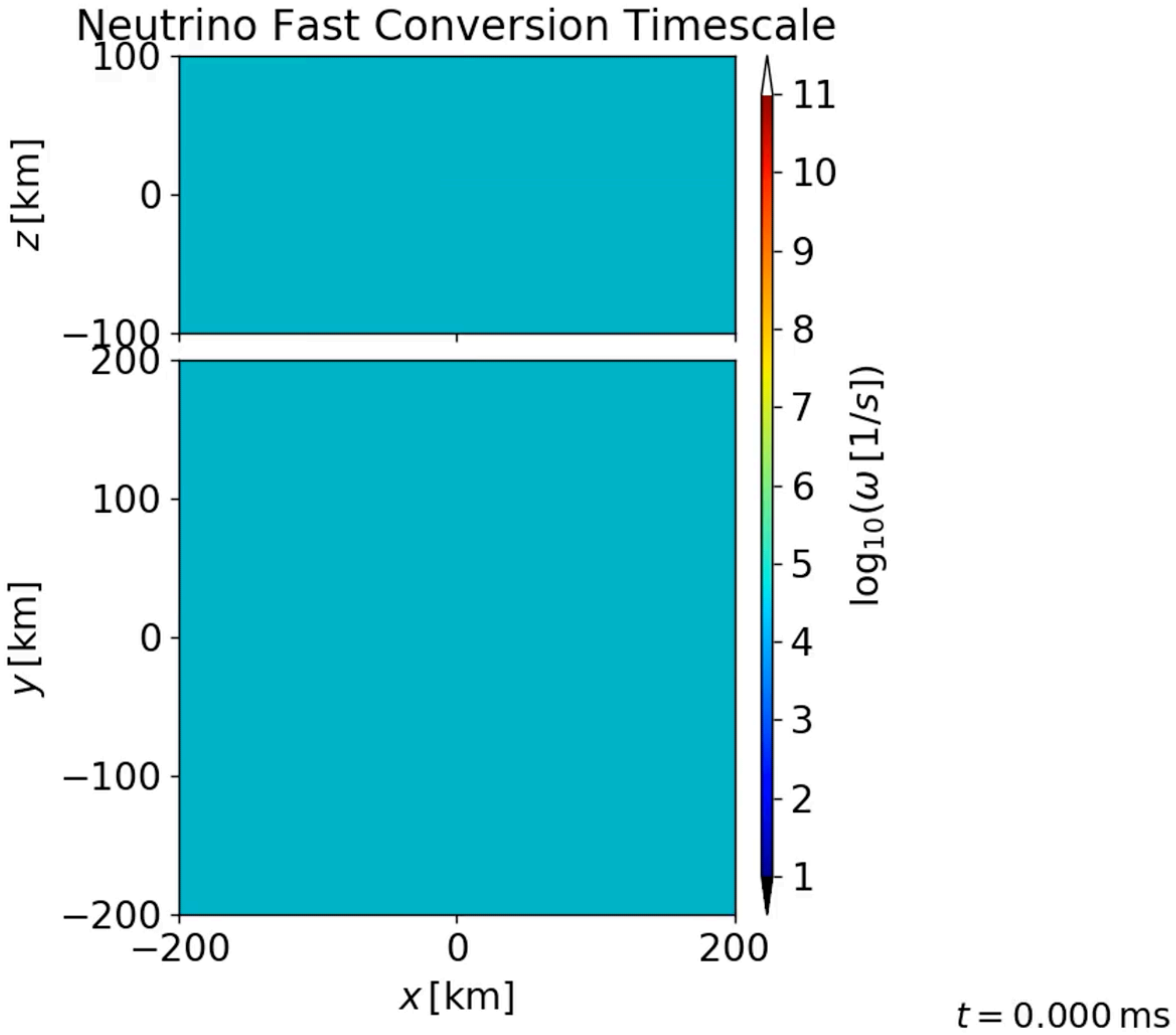
Convergence Test for MRI Growth

- High res: 0.85km; Medium res: 1.3km; Low res: 1.7km.



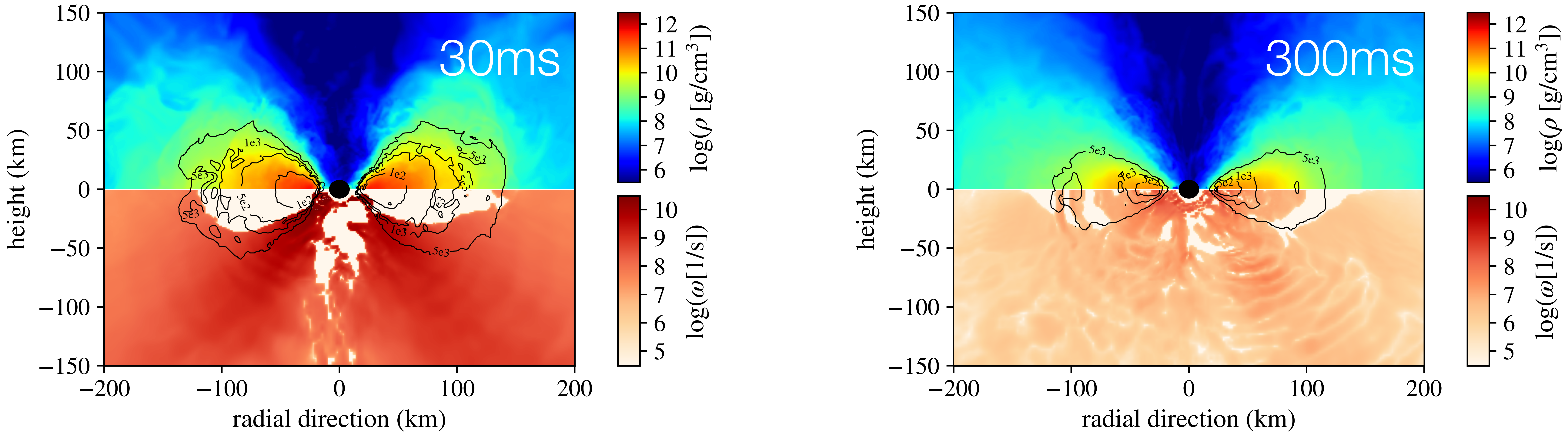
Disk Evolution





Disk Evolution

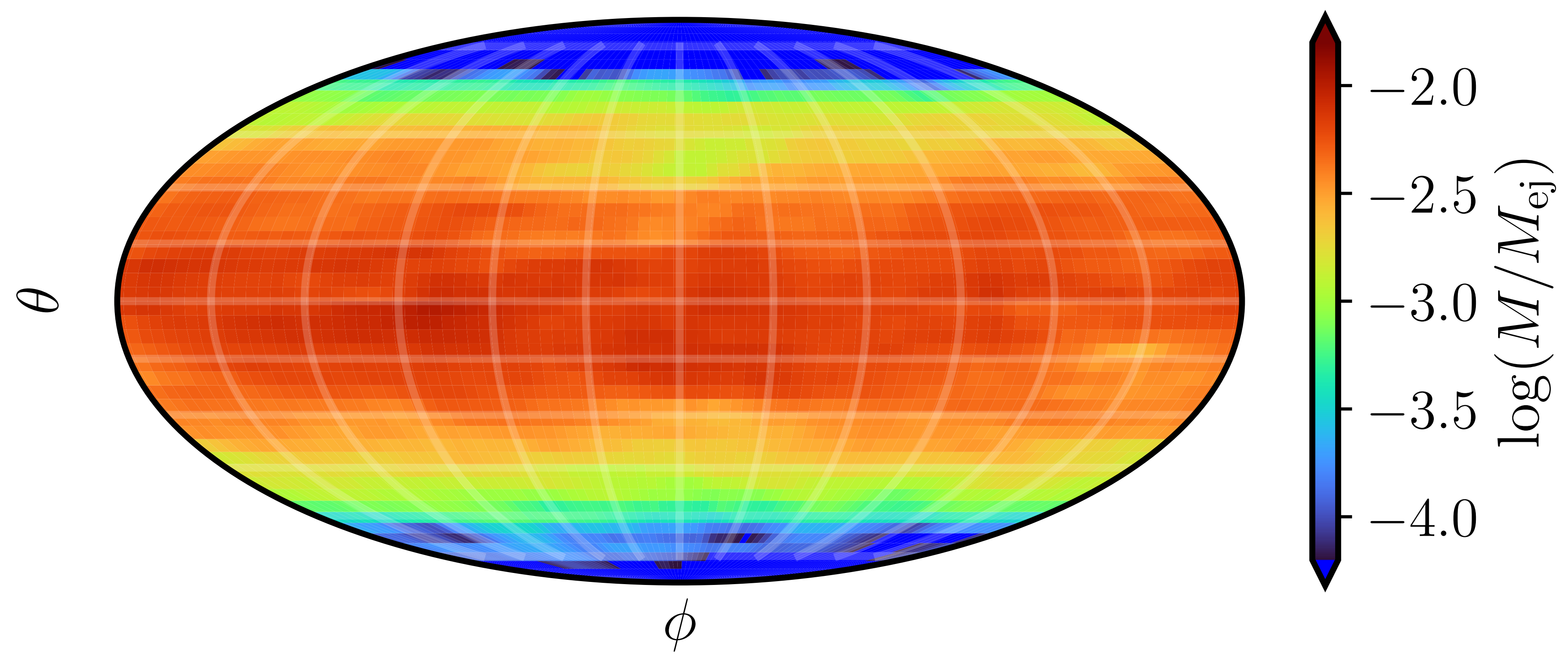
- At early stage, fast flavour conversions emerge where neutrinos stream freely. Later, fast flavour conversion becomes ubiquitous with smaller growth rate.

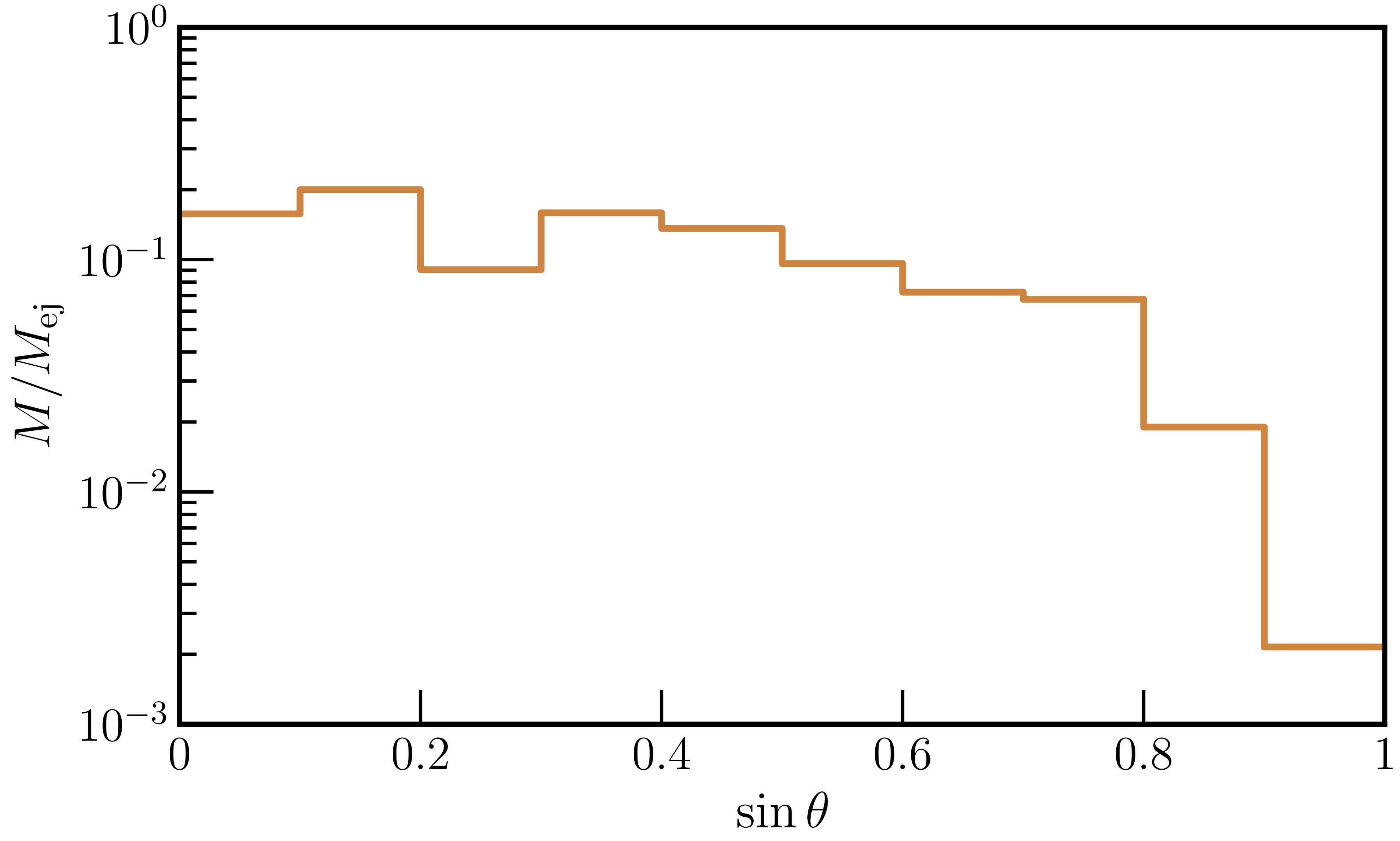


Ejecta Distribution

- Most ejecta originates close to the equatorial plane, only a tiny portion ~0.2% from the polar regions.

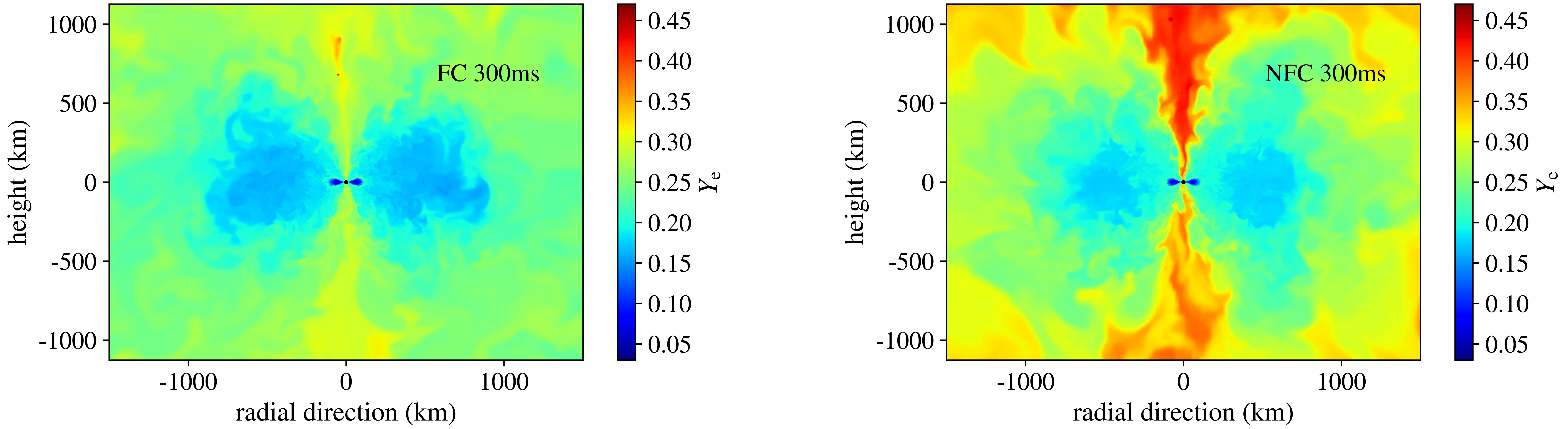
- Though M1 schemes tend to somewhat overenhance Ye compared to Monte-Carlo based approaches in polar regions, it is not an issue here. Neutrino annihilation in the polar regions can also be safely neglected.





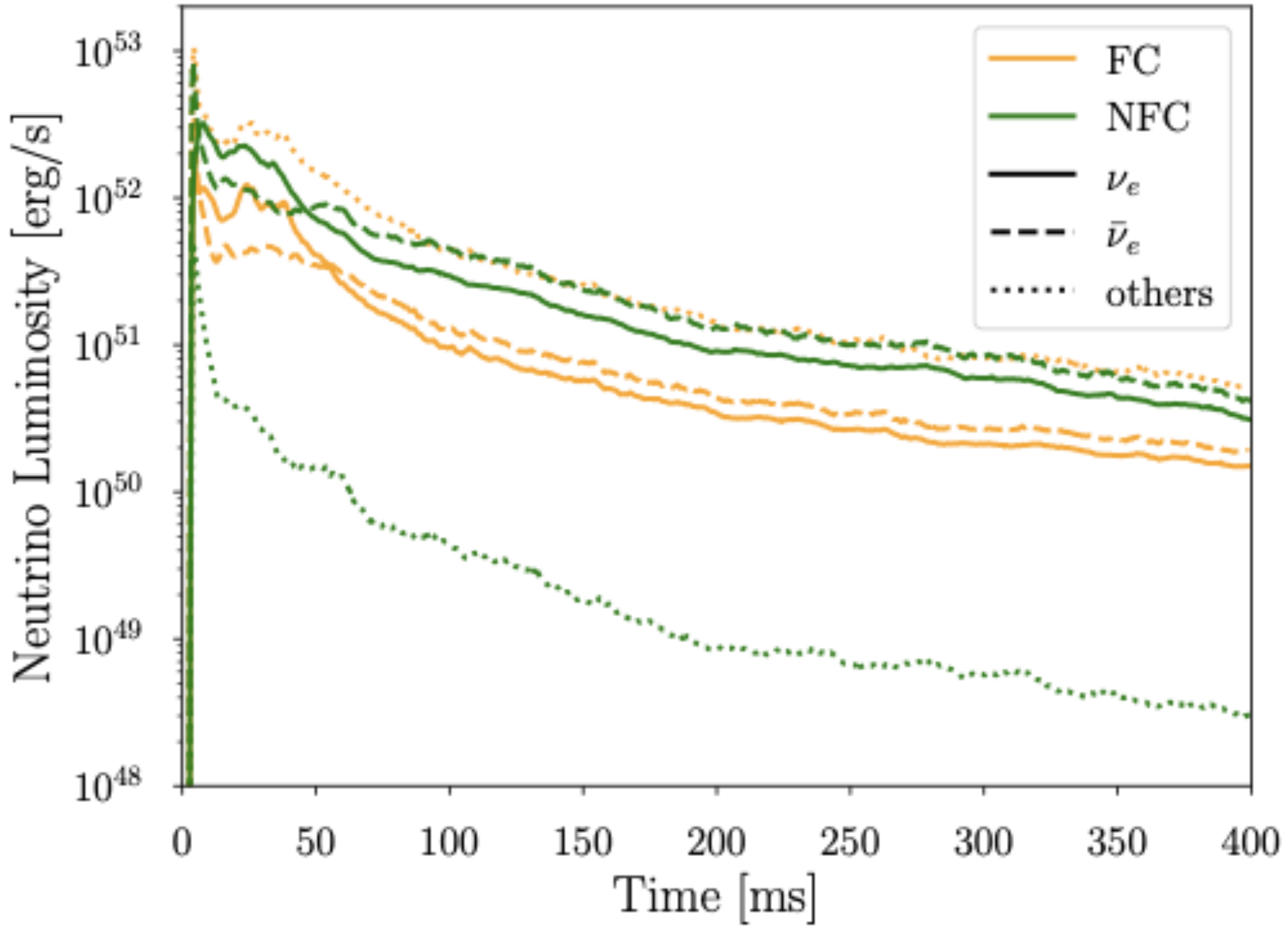
Comparison between with and without fast flavour conversion

- With fast conversion, the ejecta are more neutron rich.
- Radial dependences of Ye are observed in both cases. The Ye gradient is more prominent without fast conversion.
- Corresponds to a radial lanthanide gradient of the r-process.



Comparison between with and without fast flavour conversion

- Electron and anti-electron neutrinos are more copiously emitted than other species.
- Fast flavour conversion essentially reduce their densities.



Comparison between with and without fast flavour conversion

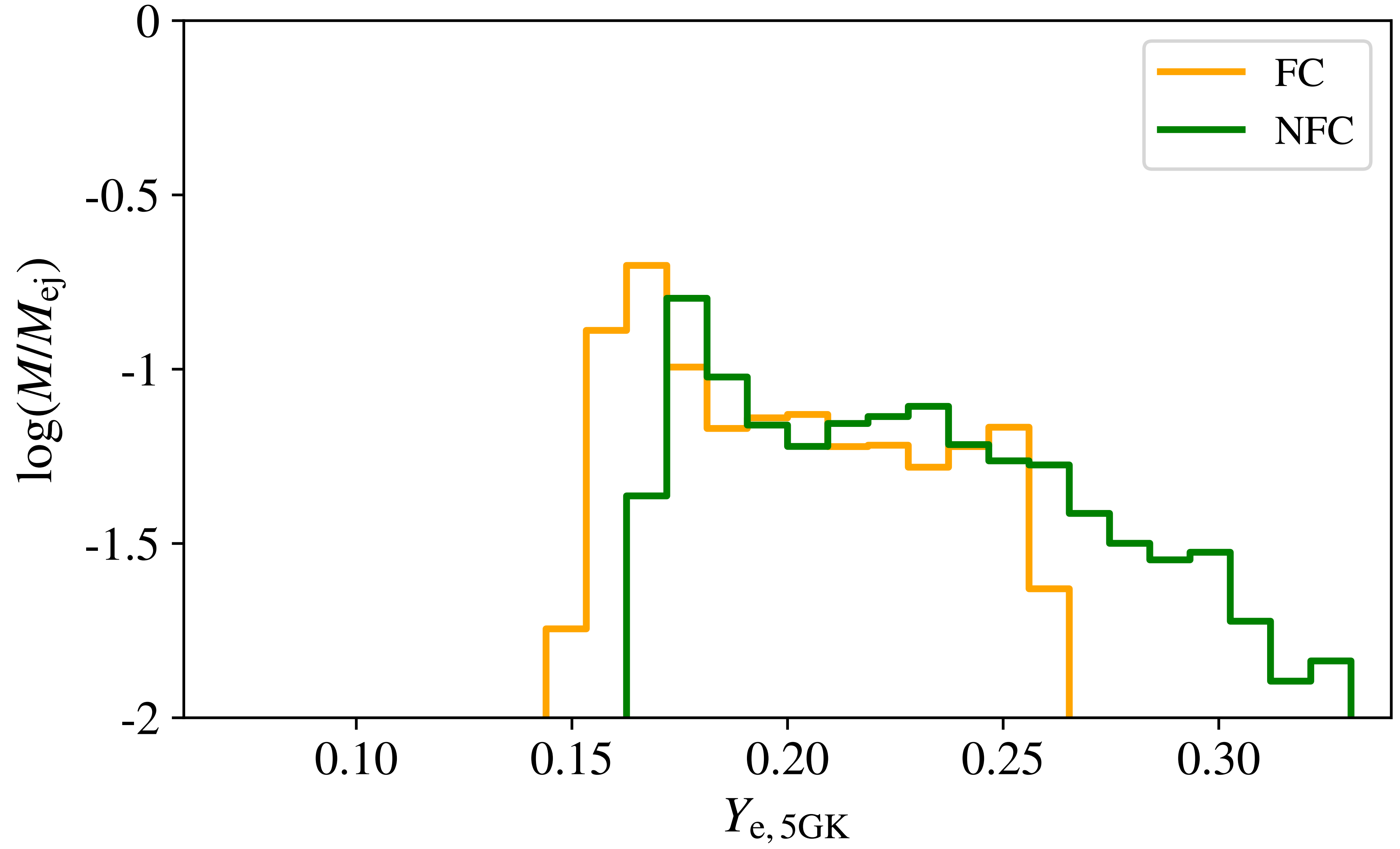
- We initially put 100K passive tracer particles in the disk. The unbounded tracer particles reaching 700km at the end are input into SkyNet (Lipunner 2015) for r-process calculation.

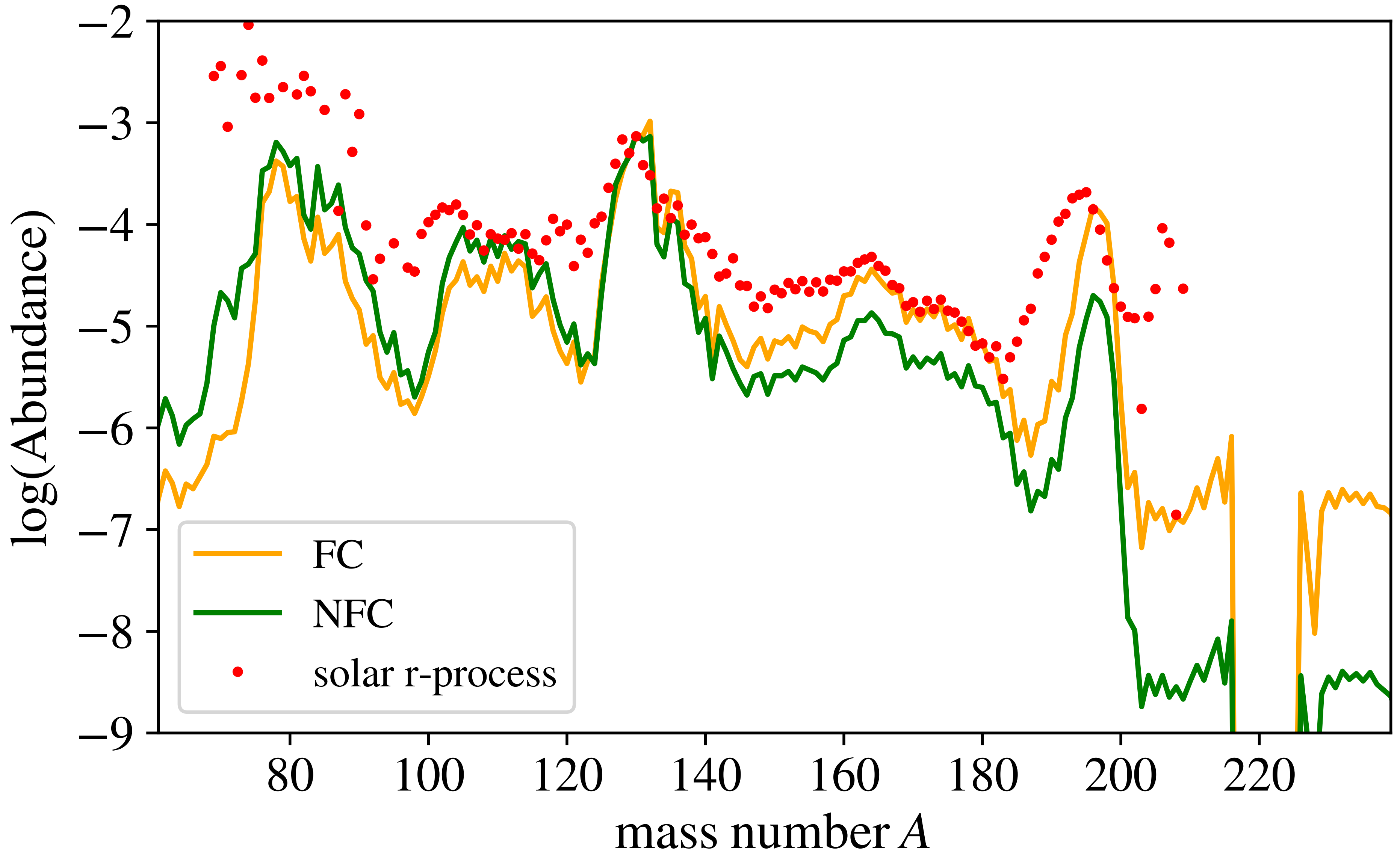
- Neutrino fluxes for absorption are obtained from the simulations by fitting a Dirac-Fermi distribution and are extrapolated beyond the evolution time by power laws.

- The projected total unbound mass of $\approx$ 0.026 M (FC) and $\approx$0.03 M (NFC) as well as the mass-averaged velocity of $\approx$0.1c of the ejecta only mildly differ between the two runs, since neutrinos play a minor role in setting the outflow energetics for these disk winds.

Comparison between with and without fast flavour conversion

- High energy neutrinos reduce the lanthanide production. Fast conversion can restore the abundance close to solar values.





SkyNet run	$X_{2\mathrm{nd}}$	$X_{3\mathrm{rd}}$	X_{La}
FC	0.631	0.134	0.097
NFC	0.709	0.023	0.049
solar r-process	0.347	0.183	0.139

Table I. Mass fractions of the 2nd ($125 \leq A \leq 135$) and 3rd ($186 \leq A \leq 203$) r-process peak as well as of lathanides in the disk outflows simulated with and without accounting for fast conversions. Solar abundances are also listed [84].

Conclusion

- We performed GRMHD simulations with neutrino fast flavour conversion included dynamically.

- The post-merger disk has high initial accretion rate ~1Msun/s and shows clear radial gradient of Ye indicating early bluer kilonova emissions turning into redder emissions, similar to GW170817.

- Fast flavour conversion is found to boost the r-process lanthanide abundance close to the solar values.

Future Work

- Collapsar disk simulation.
- Include the fast conversion in the merger simulation.
- More study on the assumption of flavour equipartition.
- Include instability when k is nonzero.

Thank you for your attention!

Fast Conversion Instability

- The coherence $S \propto exp(i\varpi t)$ develops runaway instability when ϖ is complex, and the imaginary part $\omega \equiv Im\varpi$ gives the growth rate.

- Dispersion measure approach (Izaguirre et al. 2017): ϖ is given by $\det \Pi = 0$.

$$\Pi^{\mu\nu} = \eta^{\mu\nu} - \int \mathrm{d}\Omega\, G_{\boldsymbol{v}} \frac{v^{\mu}v^{\nu}}{\varpi - \boldsymbol{k}\cdot\boldsymbol{v}}$$

- In GR, for k=0,

$$\det\left[\varpi g^{\mu\nu} - \sqrt{2}G_F\left(M^{\mu\nu}_{\nu_e} - M^{\mu\nu}_{\bar{\nu}_e}\right)\right] = 0,$$

$$M^{\alpha\beta} = \int \frac{\mathrm{d}\nu}{E}\left(E_{(\nu)}n^{\alpha}n^{\beta} + F^{(\alpha}_{(\nu)}n^{\beta)} + P^{\alpha\beta}_{(\nu)}\right)$$