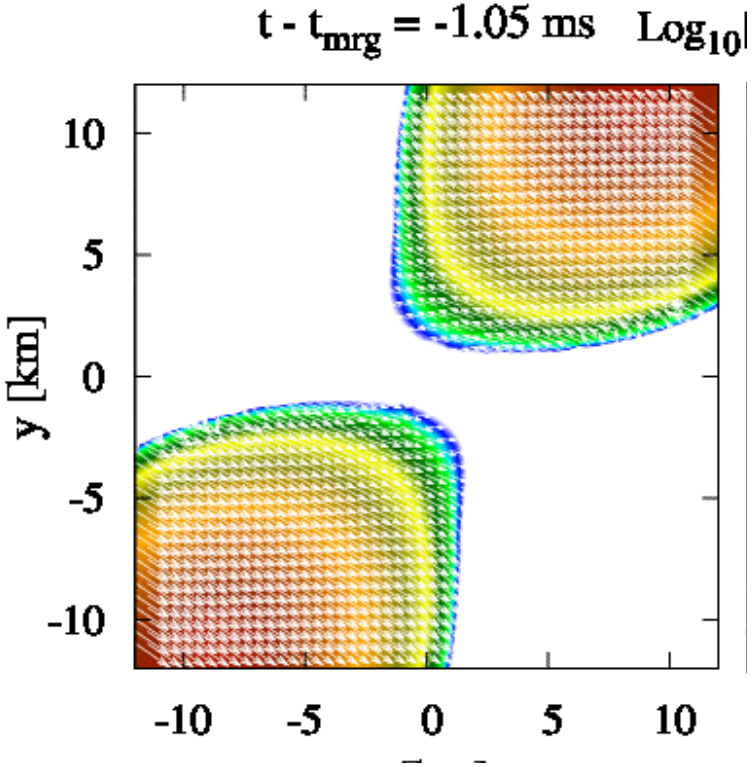
Discussion

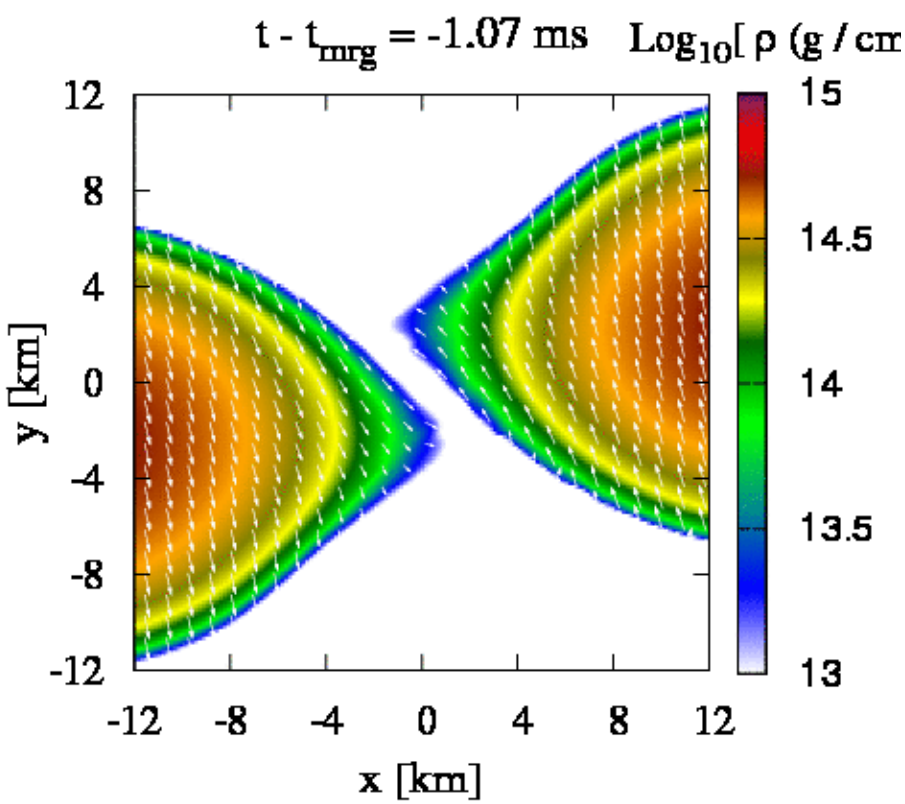
- Needed physics for post merger evolution:
  Neutrino transport & high-res MHD (later)
- Accurate modeling of kilonova/macronova to interpret optical-infrared observation
  → Kawaguchi (20 min)

High-resolution GRMHD for NS-NS

Kiuchi et al. 2015



Δx=17.5m



Δx=70m

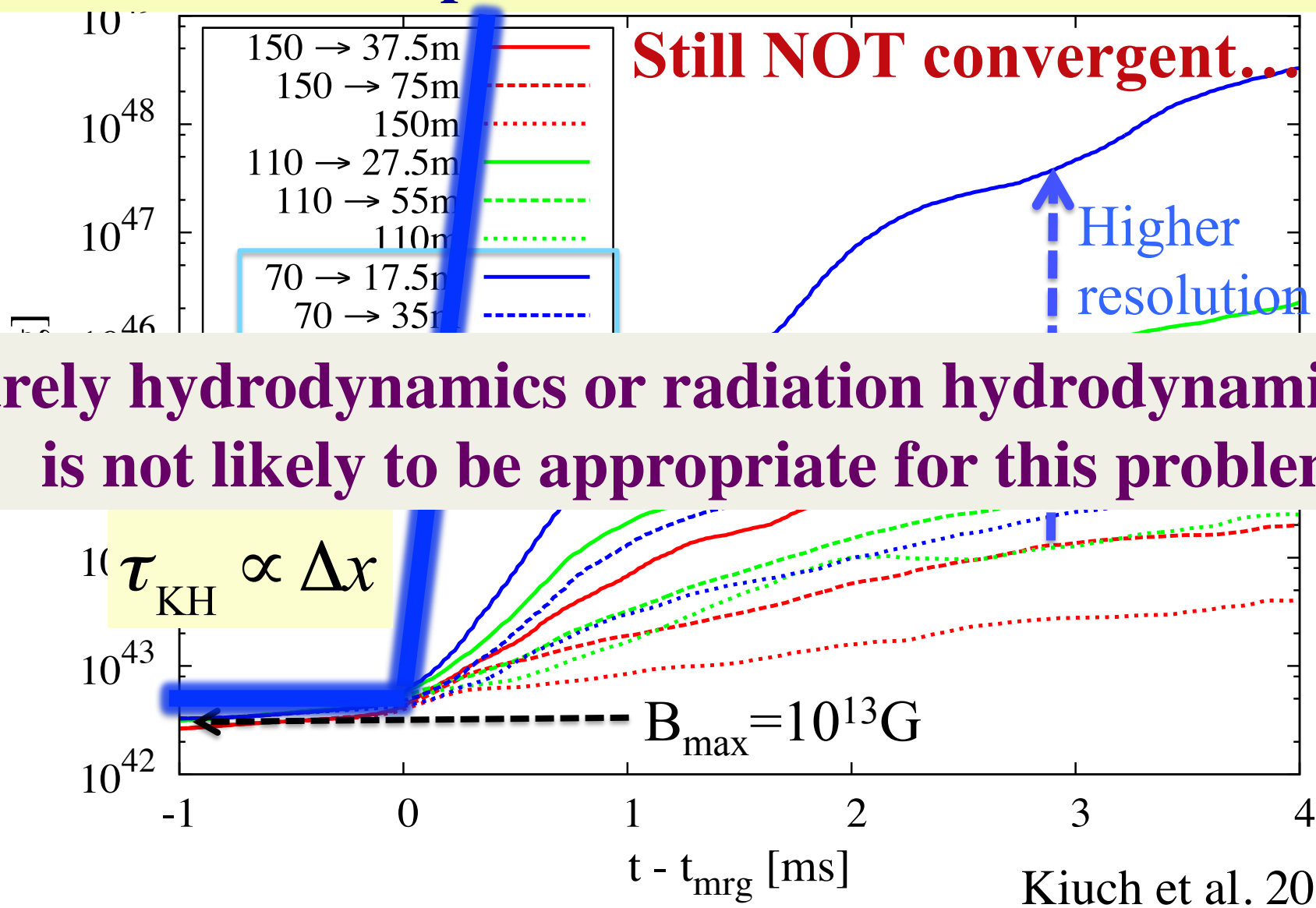
Kelvin-Helmholtz instability:

→ Magnetic field should be amplified by winding

→ Quick angular momentum transport ? (not yet seen)

Magnetic energy: Resolution dependence

B field would be amplified in $\Delta t \ll 1$ ms → turbulence ?



Purely hydrodynamics or radiation hydrodynamics is not likely to be appropriate for this problem

Kiuch et al. 2015

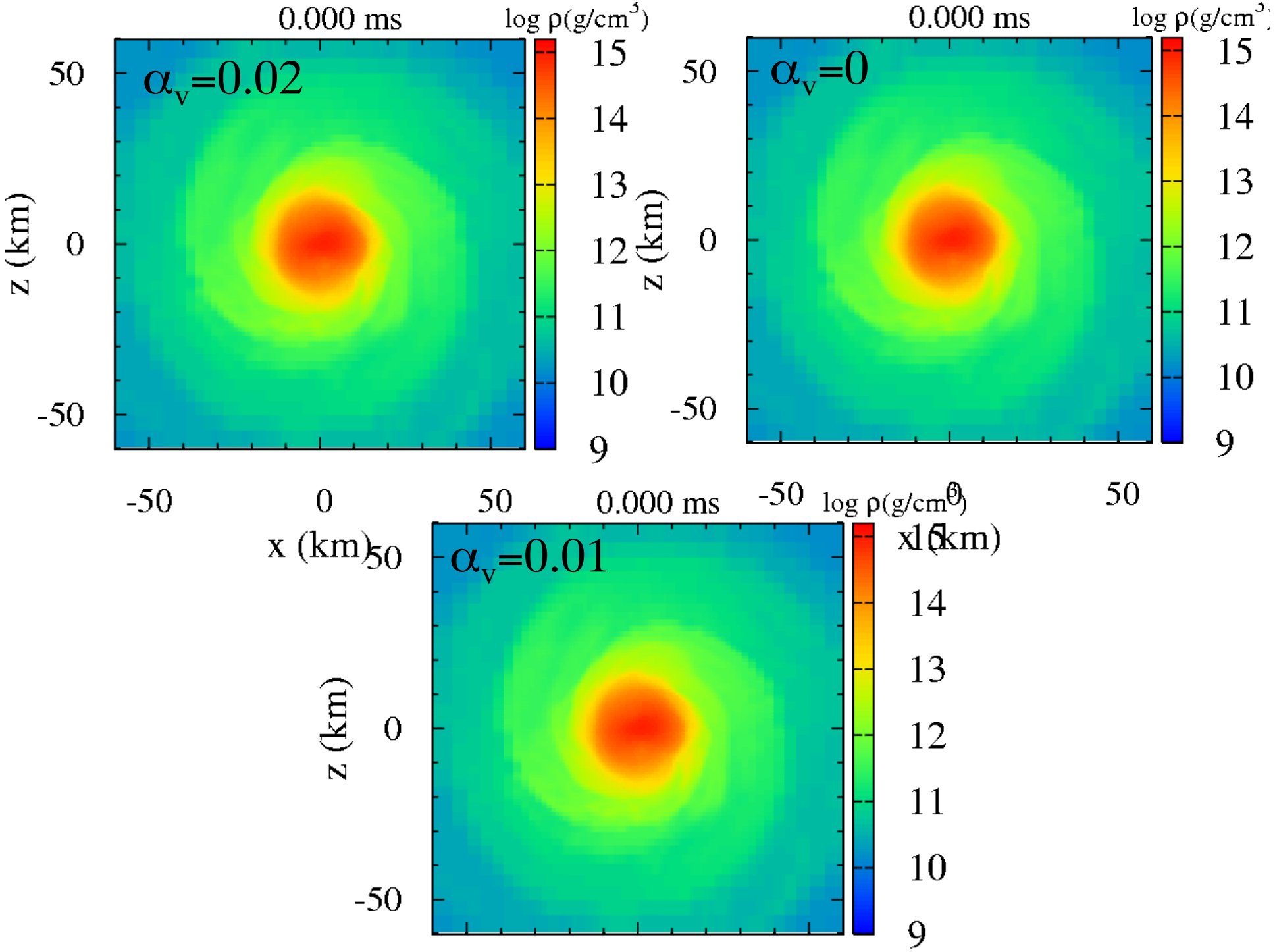
Viscous hydrodynamics for post-merger of NS-NS (MS-Kiuchi '17)

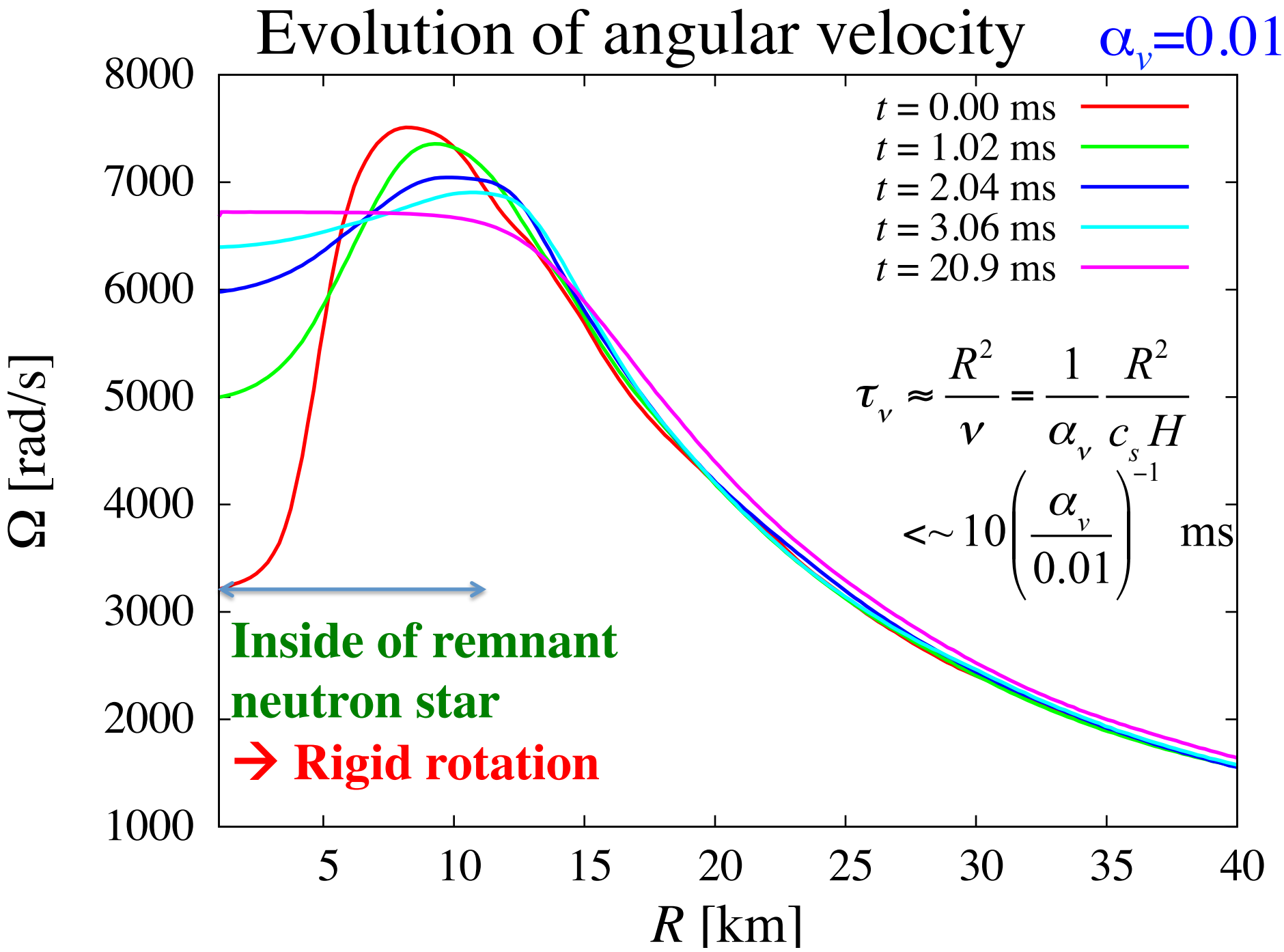
❖ **Massive neutron stars (MNS) are typical remnants**

- MHD simulations indicate that **magnetic fields would be significantly amplified by Kelvin-Helmholtz instability and subsequent quick winding** (e.g., Price & Rosswog, '06, Kiuchi et al. '14, '15, '17)

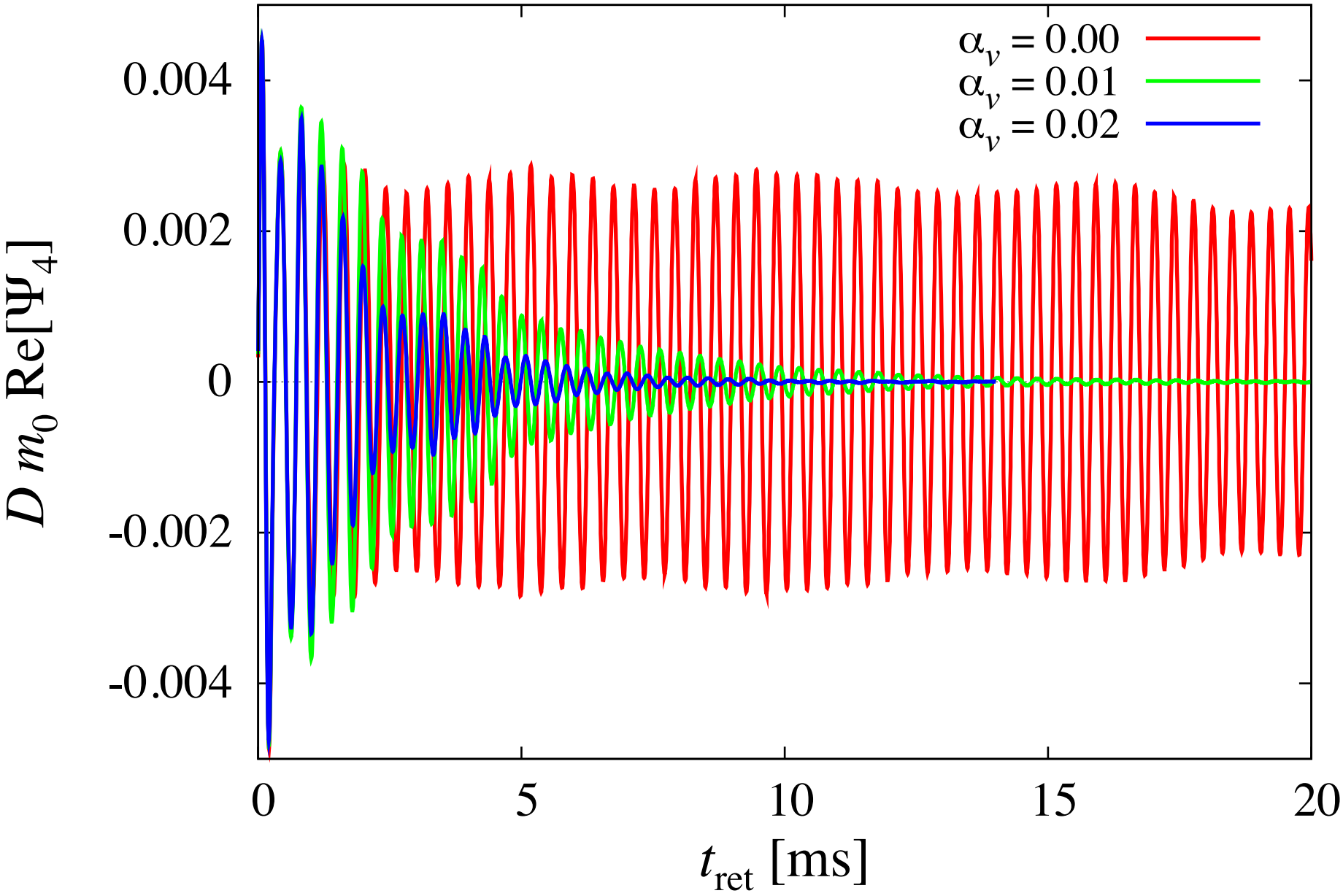
→Turbulence & **turbulent viscosity** could be induced

→Alpha viscosity: $\nu = \alpha_v c_s H$ with α_v= O(0.01) and H=10 km for neutron star (this is reasonable approximation for accretion disks around BH/NS)

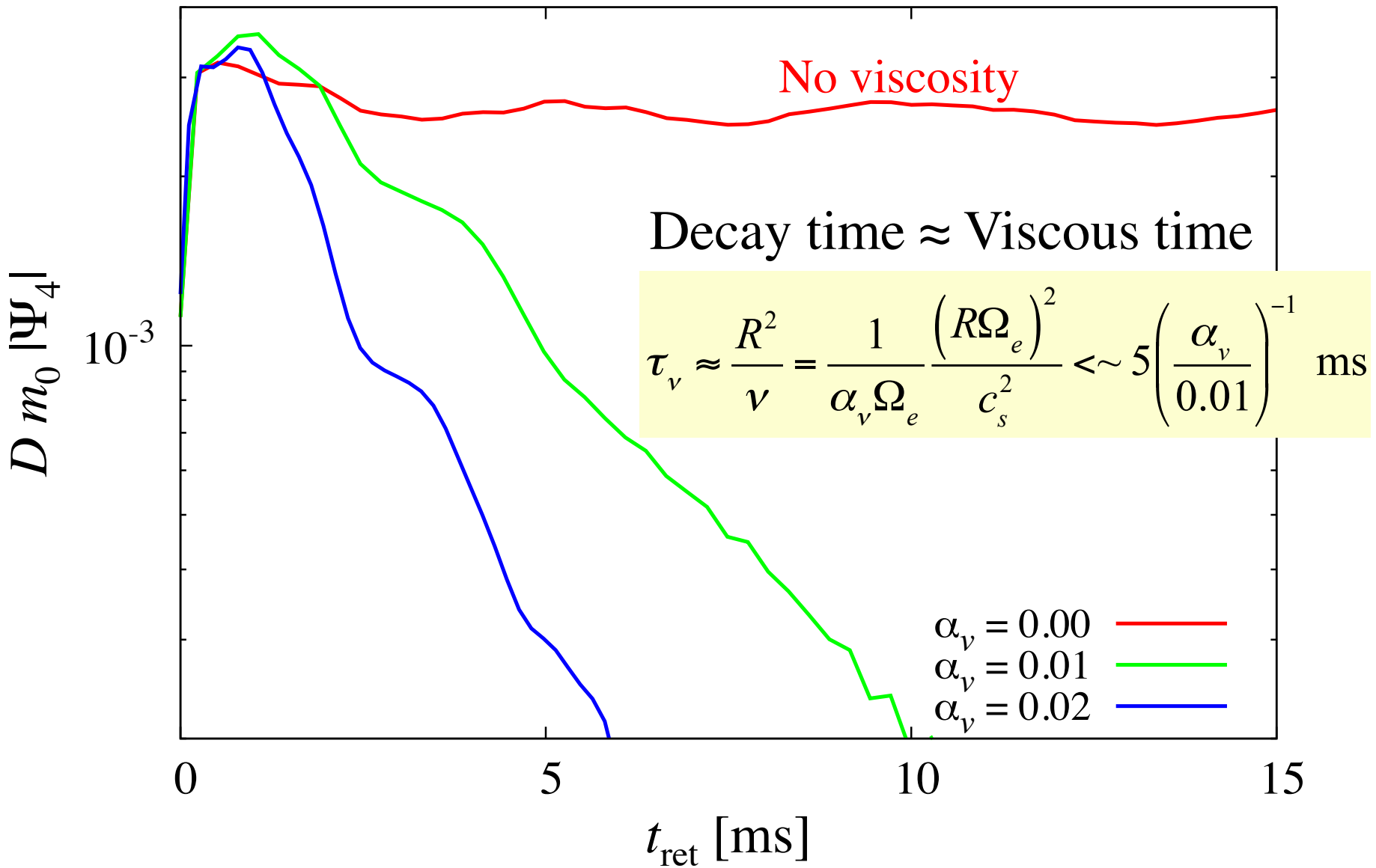

0.000 ms
log ρ(g/cm³)
α_v=0.02
α_v=0
α_v=0.01
z (km)
x (km)
50
0
-50
15
14
13
12
11
10
9


Evolution of angular velocity
α_v=0.01
8000
7000
6000
5000
4000
3000
2000
1000
Ω [rad/s]
5
10
15
20
25
30
35
40
R [km]
t = 0.00 ms
t = 1.02 ms
t = 2.04 ms
t = 3.06 ms
t = 20.9 ms
$\tau_\nu \approx \frac{R^2}{\nu} = \frac{1}{\alpha_\nu} \frac{R^2}{c_s H}$
$<\sim 10 \left(\frac{\alpha_\nu}{0.01} \right)^{-1}$ ms
Inside of remnant neutron star
→ Rigid rotation

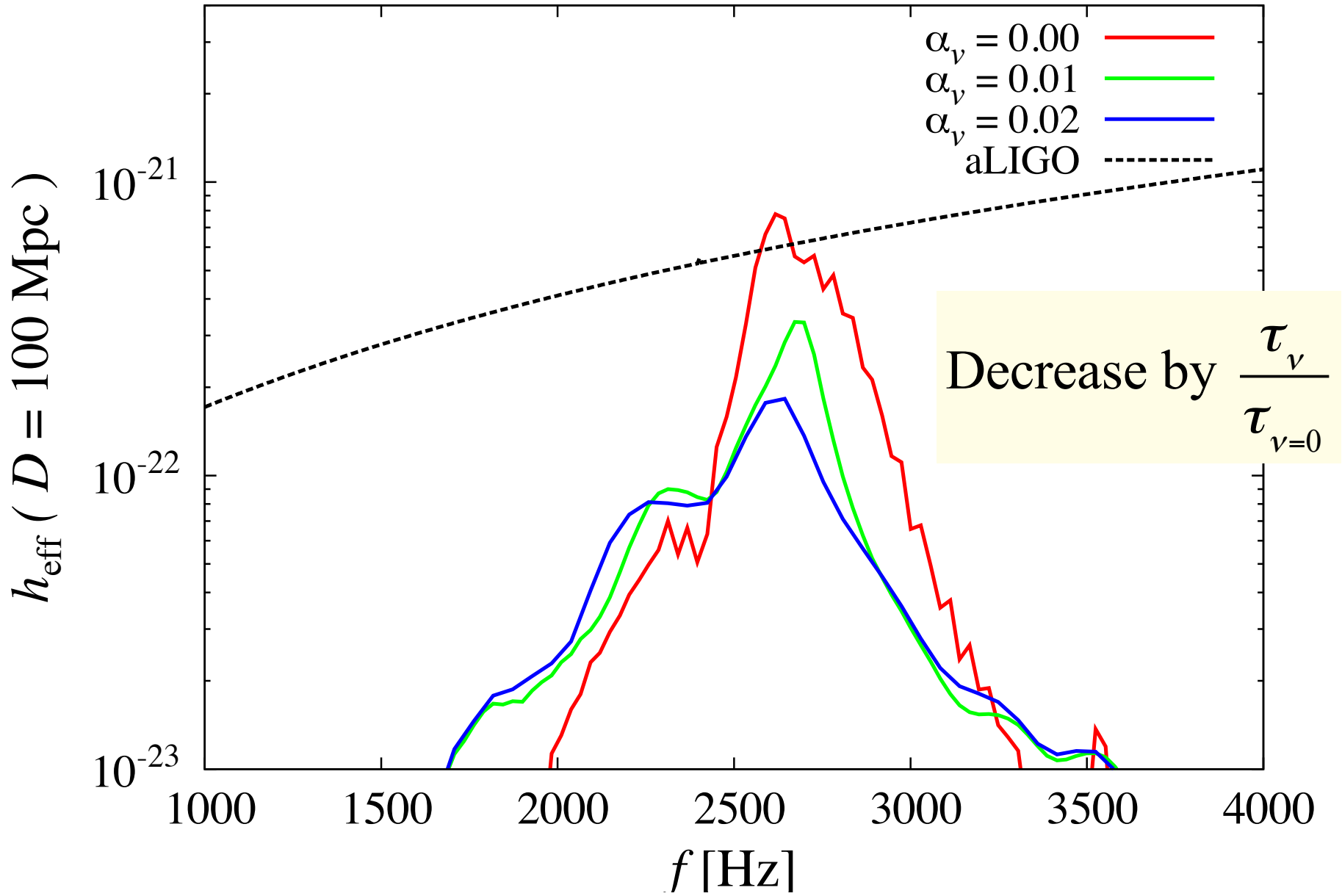
Gravitational waveforms



Amplitude of gravitational waves



Spectrum


$\alpha_\nu = 0.00$
$\alpha_\nu = 0.01$
$\alpha_\nu = 0.02$
aLIGO
Decrease by $\frac{\tau_\nu}{\tau_{\nu=0}}$
$h_{\rm eff}$ (D = 100 Mpc)
10^{-21}
10^{-22}
10^{-23}
1000
1500
2000
2500
3000
3500
4000
f [Hz]

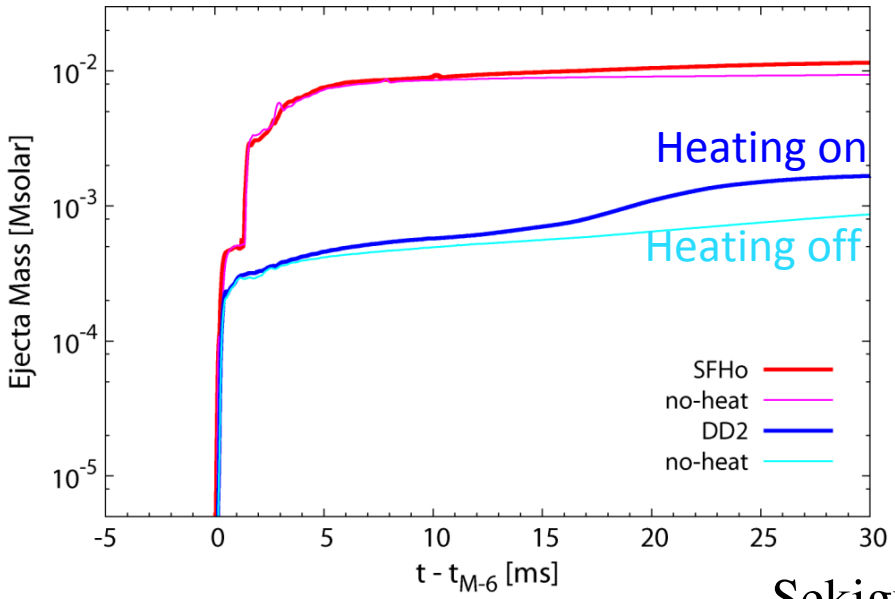
Short summary

- *If* MHD turbulence ≈ viscous hydrodynamics with $\alpha_\nu \geq 0.01$, evolution of merger remnant of NS-NS would be **highly different from that by ideal fluid dynamics**
- Viscous hydrodynamics suggests that **post-merger gravitational waves could be quite weak**
- **How large is α_ν in reality ?**

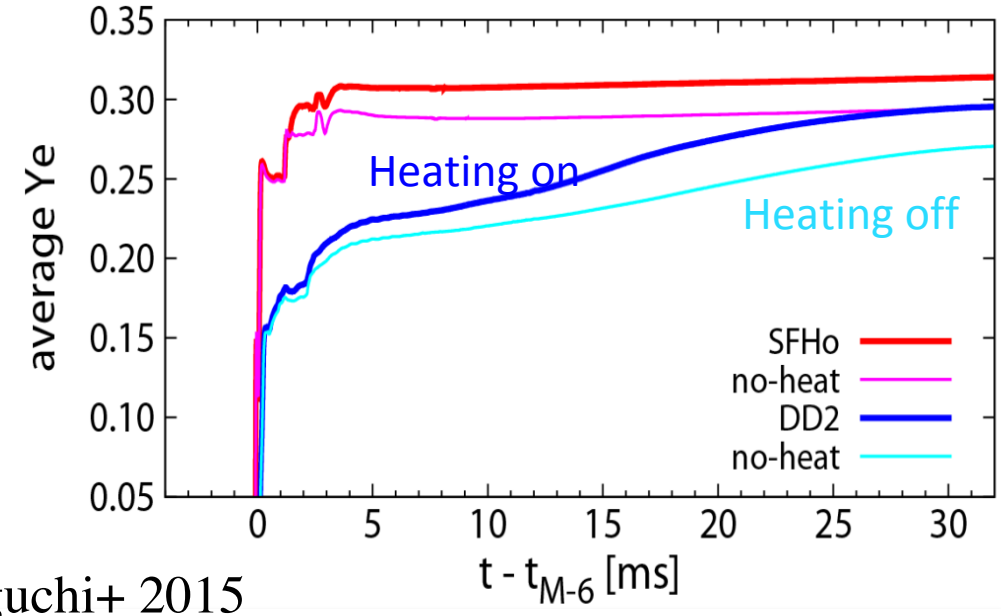
➢ **High-resolution MHD is obviously required or some other prescription ??**

Neutrino irradiation is important for Y_e

Ejecta mass



Electron fraction

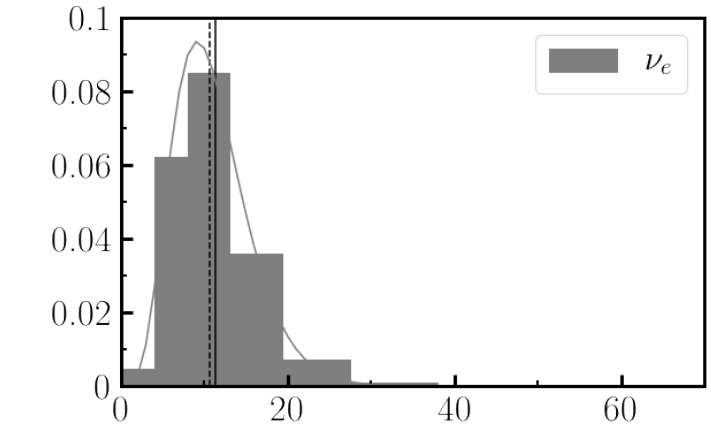


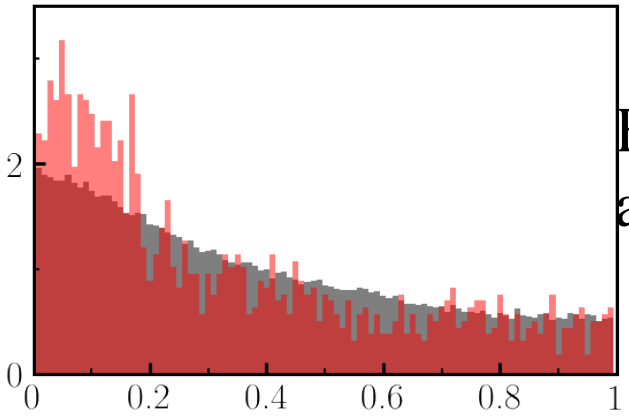
Sekiguchi+ 2015

- Neutrino irradiation from MNS increases **average value of Y_e by ~ 0.03 in a few 10ms**

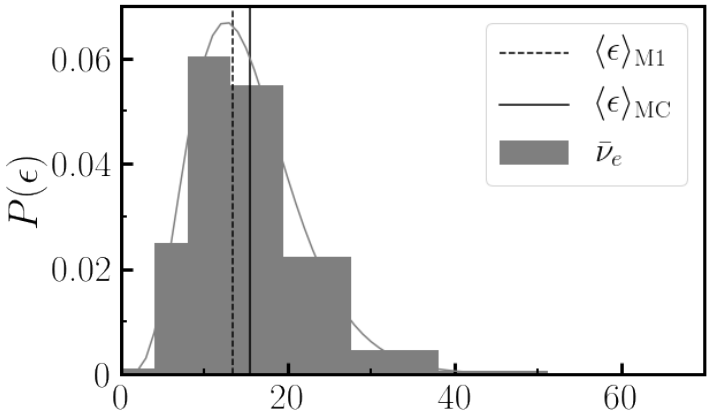
→ **Sophisticated treatment for neutrino transfer would be needed**

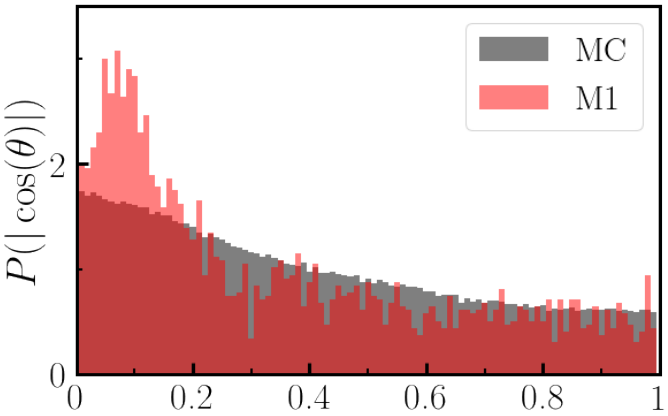
See, e.g., Perego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016





Foucart et al.
arXiv: 1806.02349





M1 is OK,
but need more