Multi-Messenger Signals from Magnetorotational Stellar Core Collapse

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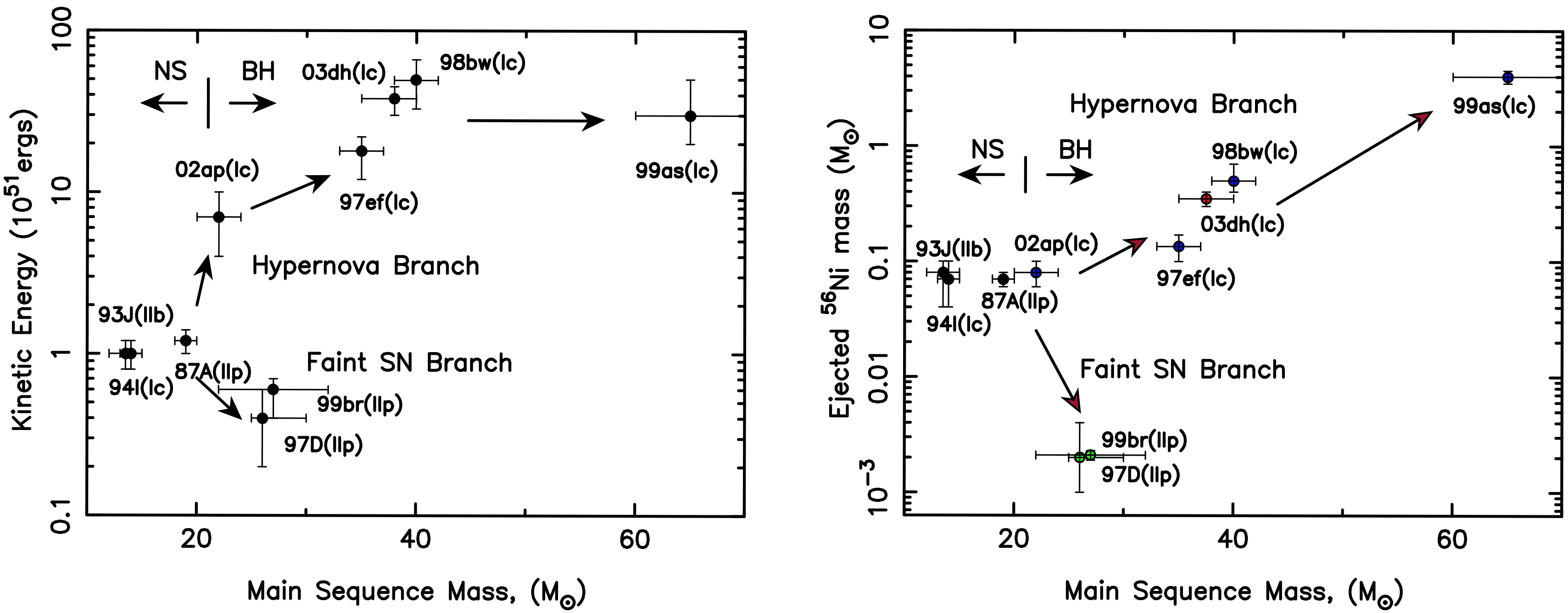
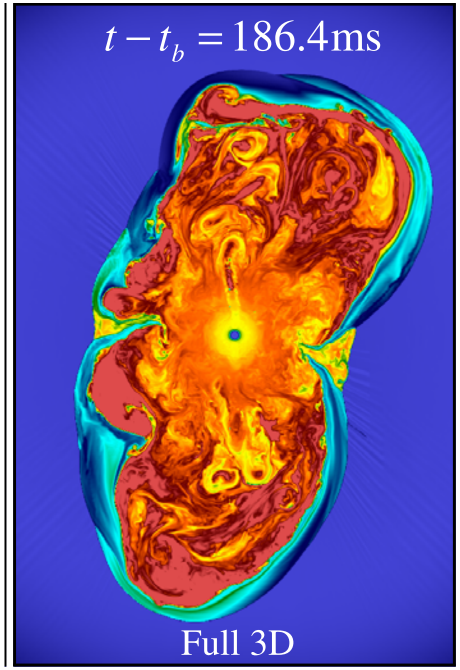
Energetic supernova

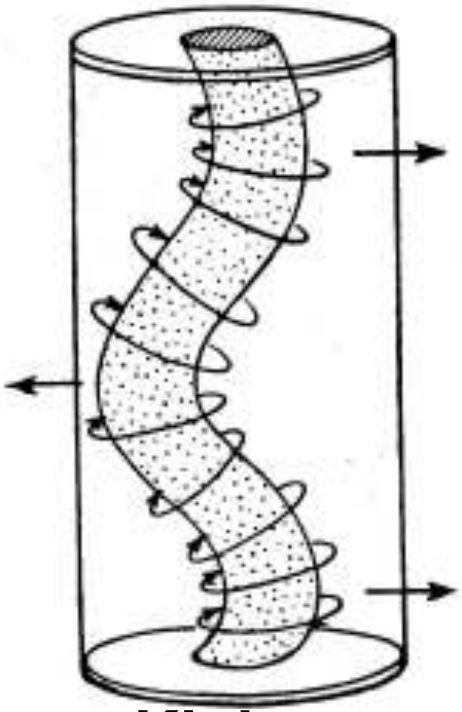


Nomoto et al. 2005

3D MHD Jet SN

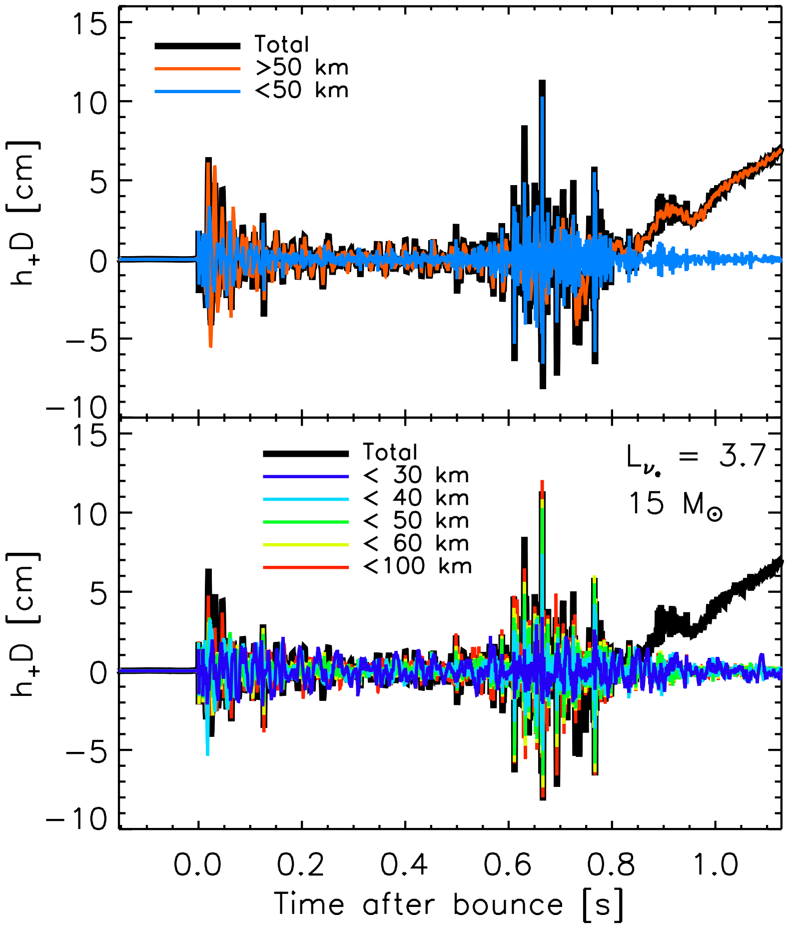


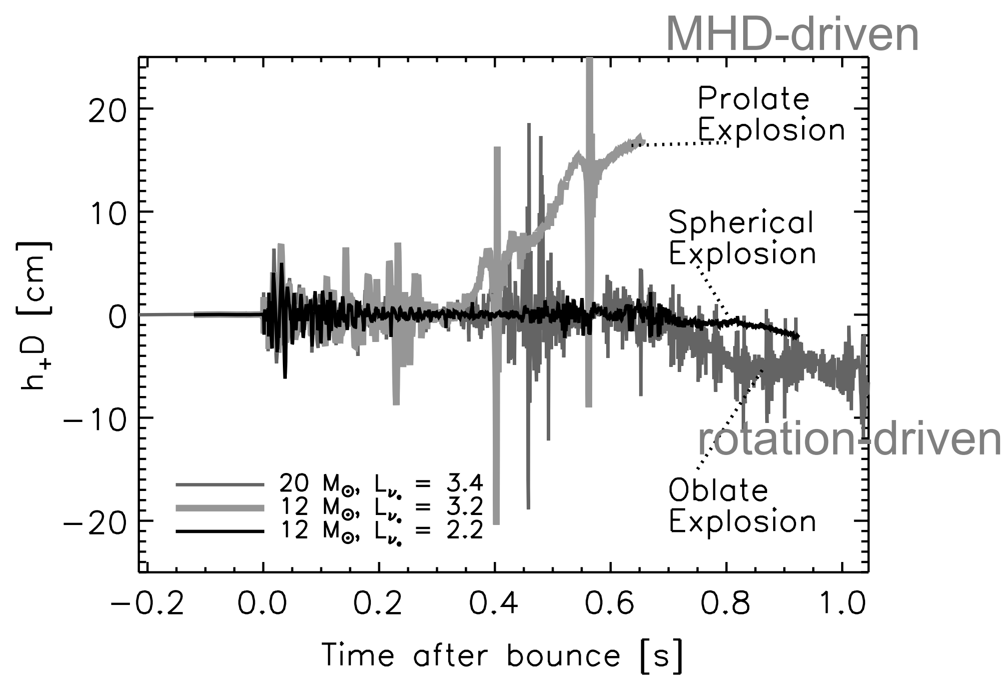
Moesta et al. 2014



Kink instability

GW from Aspherical Explosion



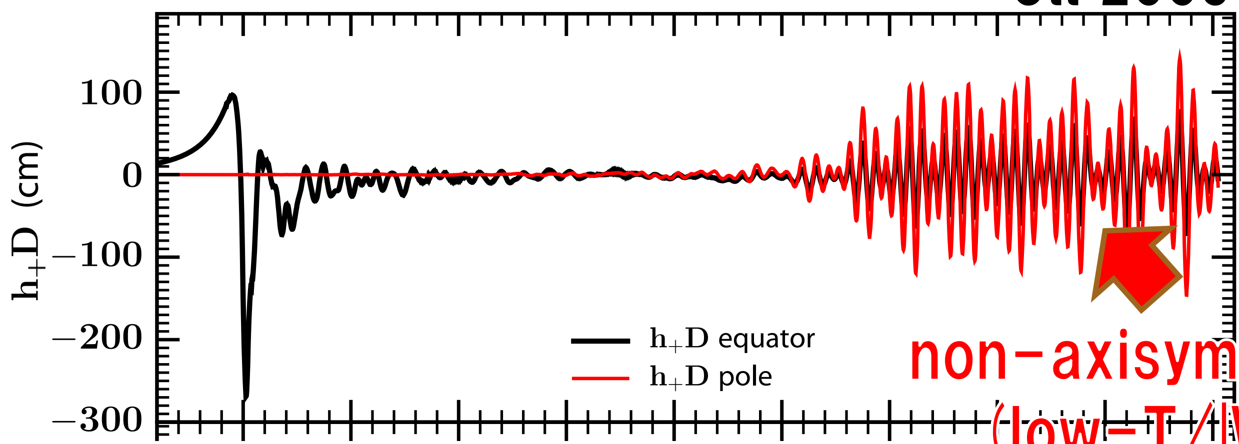


Murphy et al. 2009

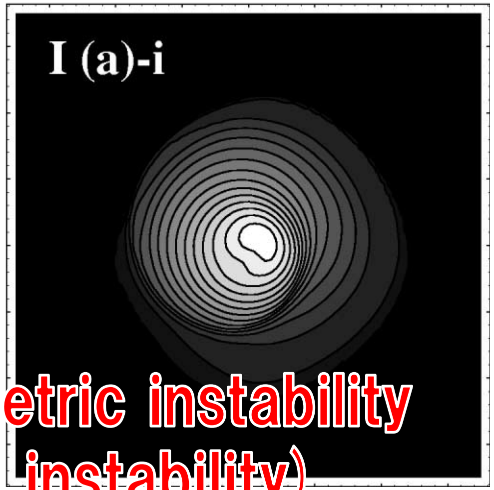
Rapidly rotating core collapse

Larger quasi-periodic GW

Ott 2009



Saijo et al. 2003



non-axisymmetric instability
(low-T/|W| instability)

Previous 3D simulations:

- Ott et al. 2005 Newtonian+no neutrino, 2007 full GR+Ye prescription
- Scheidegger et al. 2008, 2010 effective GR+leakage
- Kuroda et al. 2014 full GR+M1 (grey), 2025 full GR+M1
- Takiwaki et al. 2016, 2018 Newtonian+IDSA, 2021 effective GR+IDSA
- Pan et al. 2021, Hsieh et al. 2024 effective GR+IDSA
- Longo Micchi et al. 2023 full GR+M1 (grey)

Full GR + M1 ν radiation simulations

Method

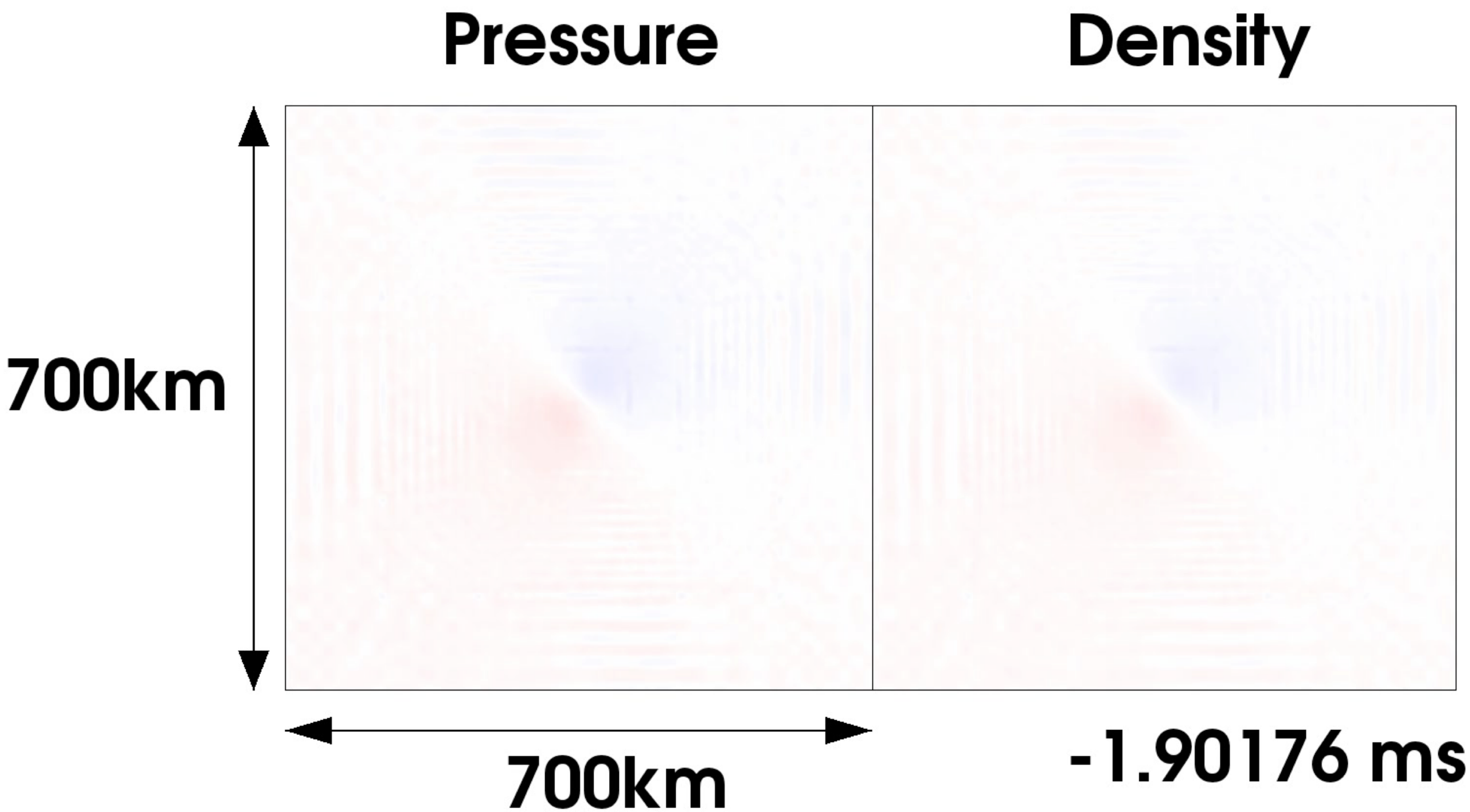
- Fully general relativistic neutrino radiation hydrodynamics code (Kuroda et al. 2016)
  - BSSN formalism for general relativity
  - Multi-energy neutrino transport with M1 scheme
  - Lattimer & Swesty EOS (K = 220 MeV)
  - 70 M_{sun} zero-metallicity star (Takahashi et al. 2014)
  - initial central rotation rate: Ω_0 = **2**, 1, 0 rad/sec

  c.f.) non rot. sim. showed BH formation at t_{pb}～230ms

Shibagaki, Kuroda, Kotake, Takiwaki, MNRAS (2020, 2021)

Matter Distribution

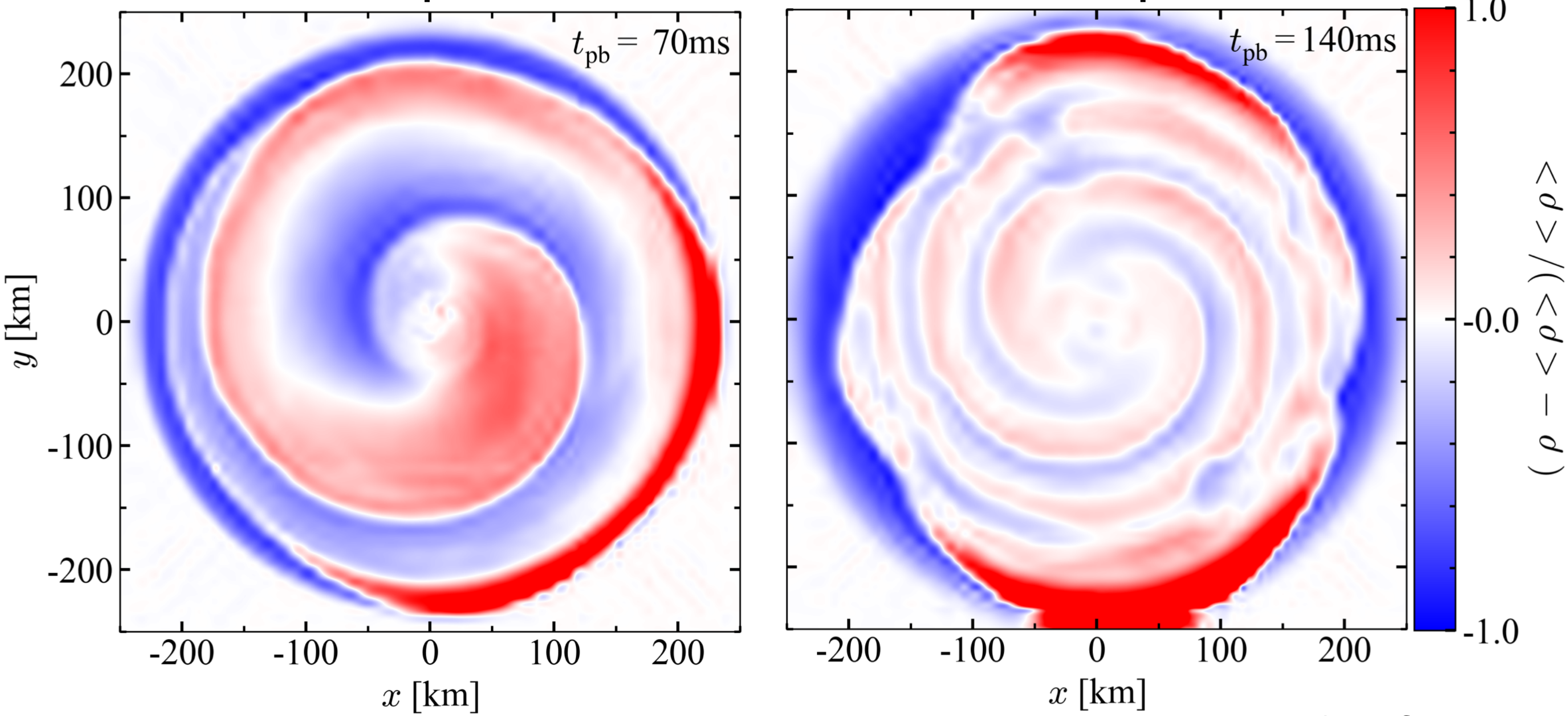
$\Omega_0 = 2\mathrm{rad/sec}$



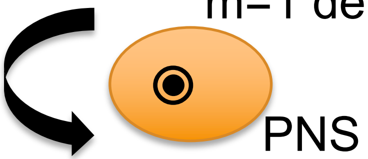
Density Distribution

Ω_0=2rad/sec

one arm (t_{pb}=70ms) two arms (t_{pb}=140ms)

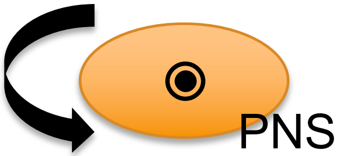


m=1 deformation



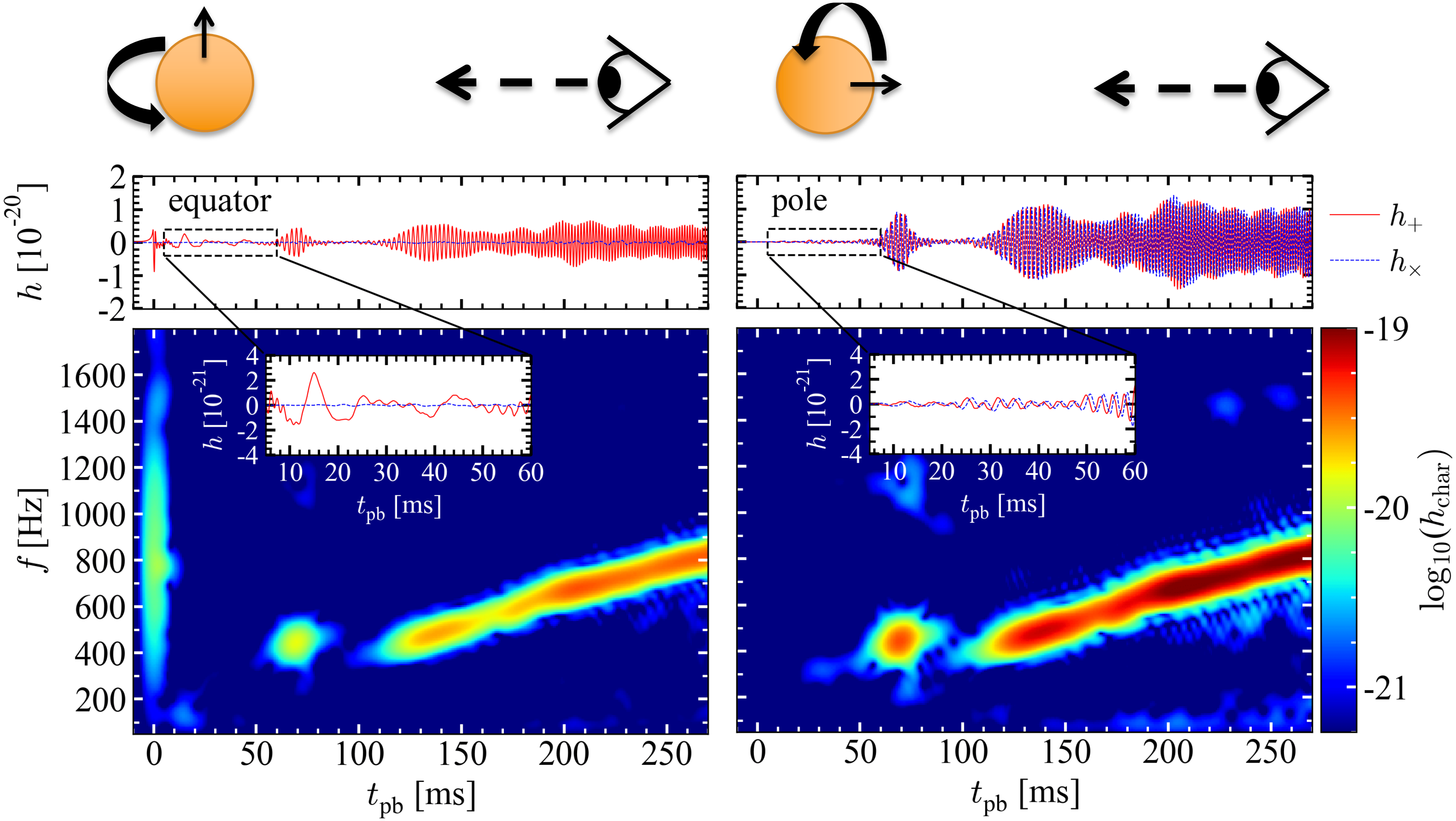
low T/|W| instability

m=2 deformation



GW Spectrogram

Ω_0=2rad/sec

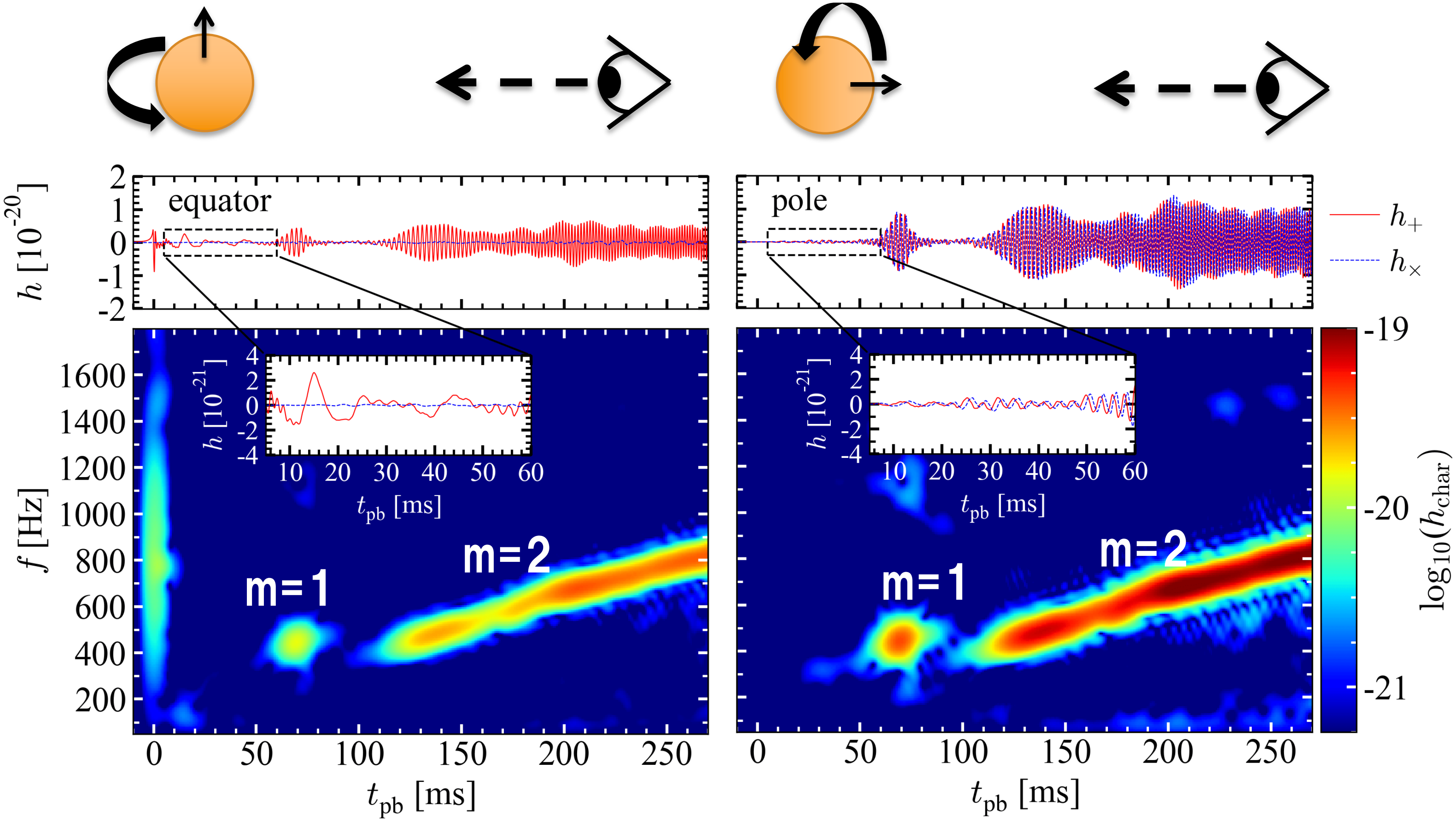


Short term Fourier trans.

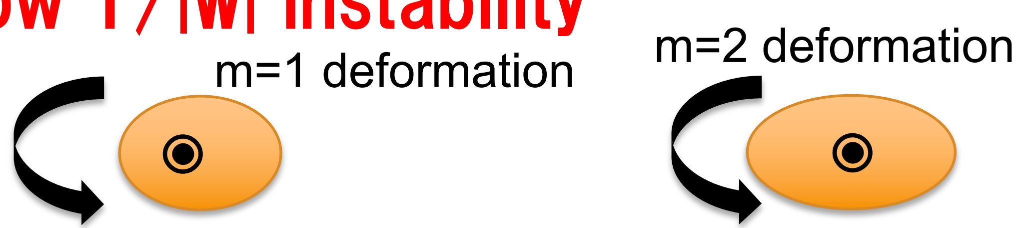
$$\tilde{S}(f,\tau) = \int_{-\infty}^{\infty} \underbrace{A(t)}_{\text{GW}}\, \underbrace{H(t-\tau)}_{\text{window function}}\, e^{-2\pi i f t} dt$$

GW Spectrogram

Ω_0=2rad/sec

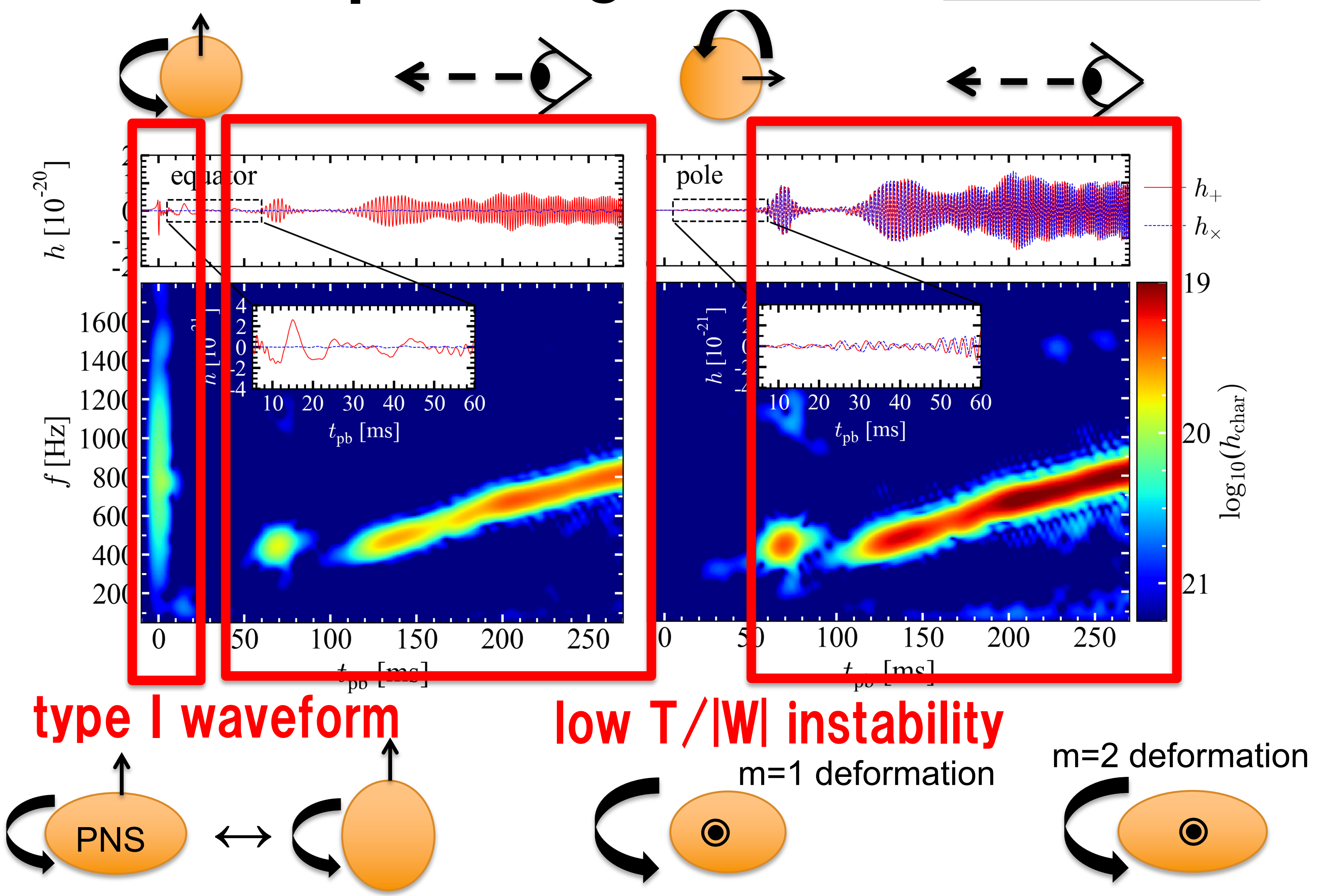


low T/|W| instability



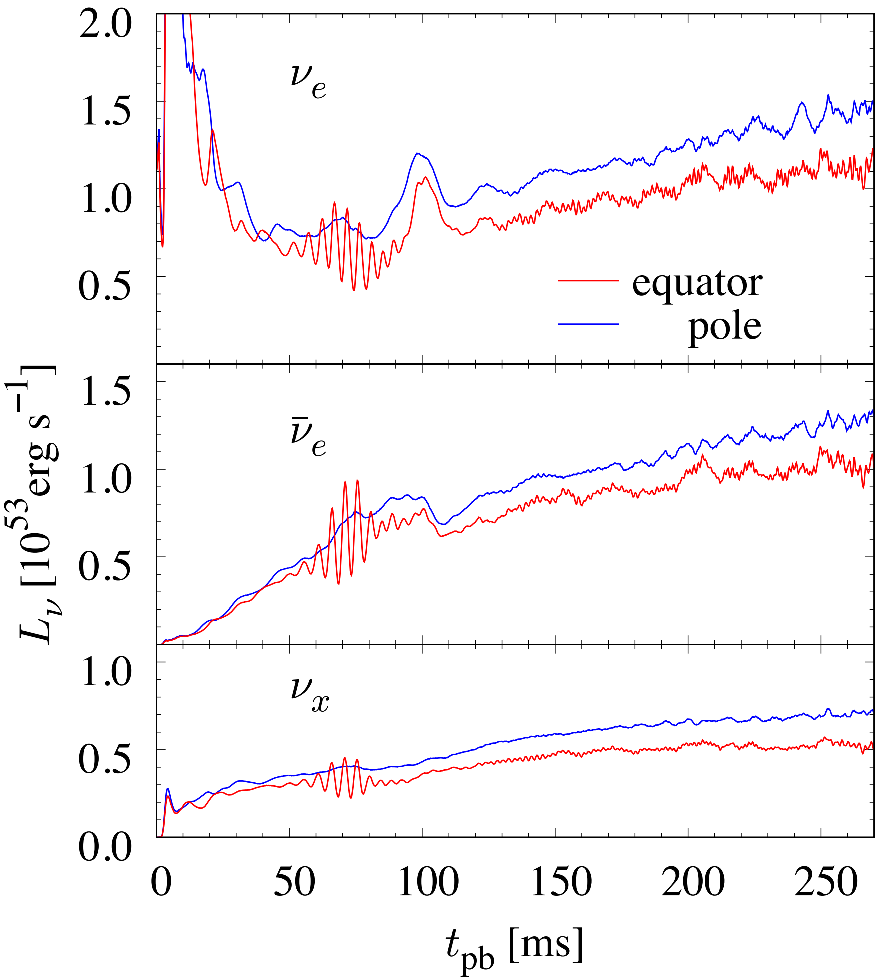
GW Spectrogram

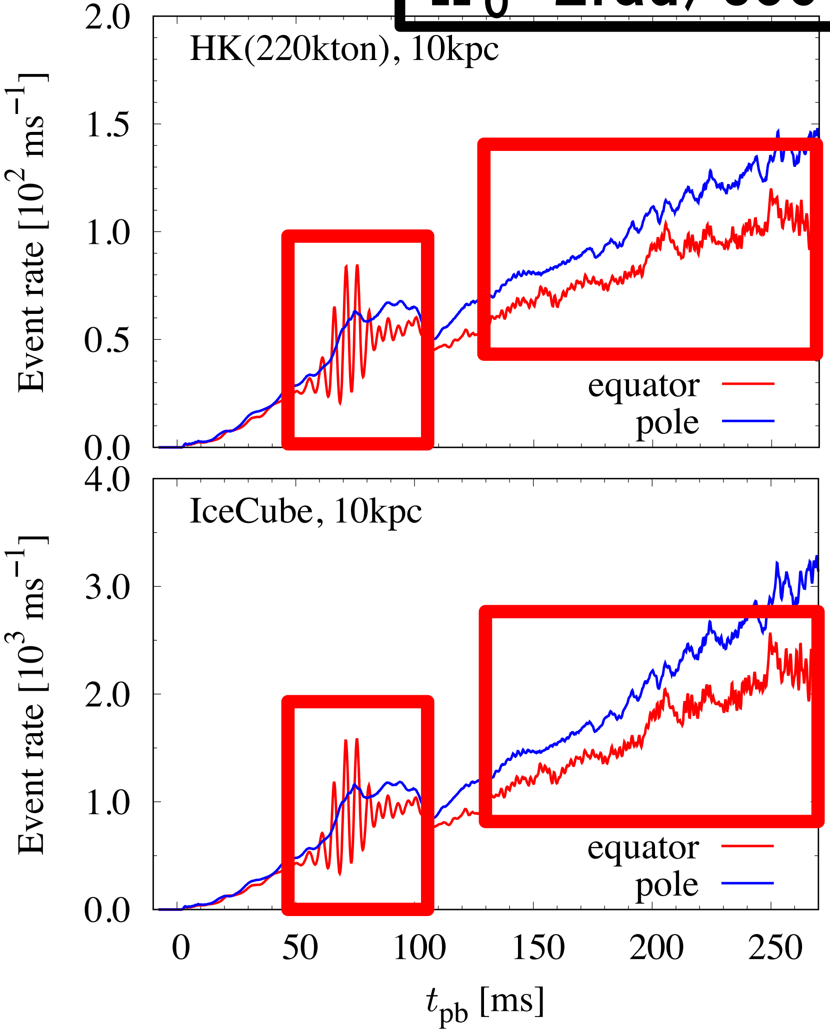
Ω_0=2rad/sec



Neutrino luminosity and event rate

Ω_0=2rad/sec

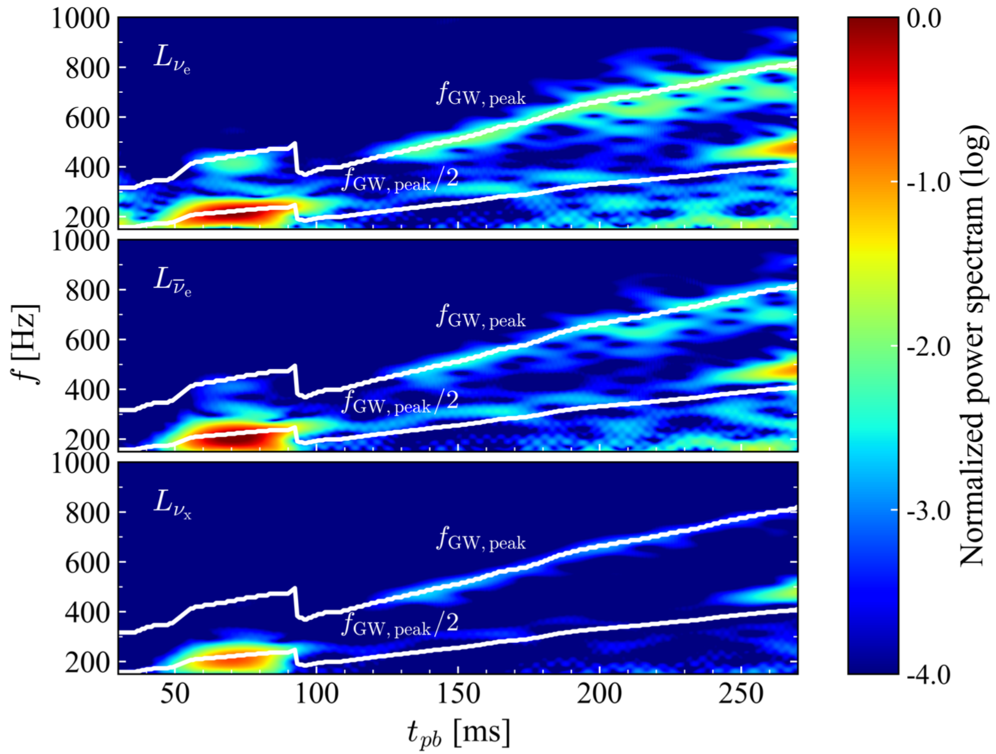


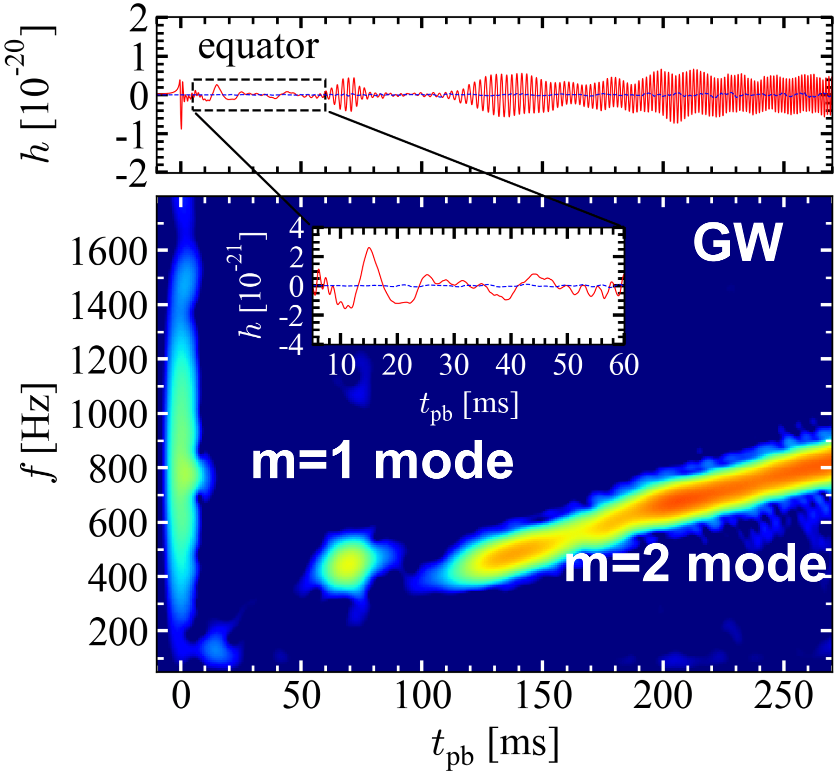


Oscillation in event rate found for equatorial observer

Neutrino spectrogram（equator）

Ω_0=2rad/sec

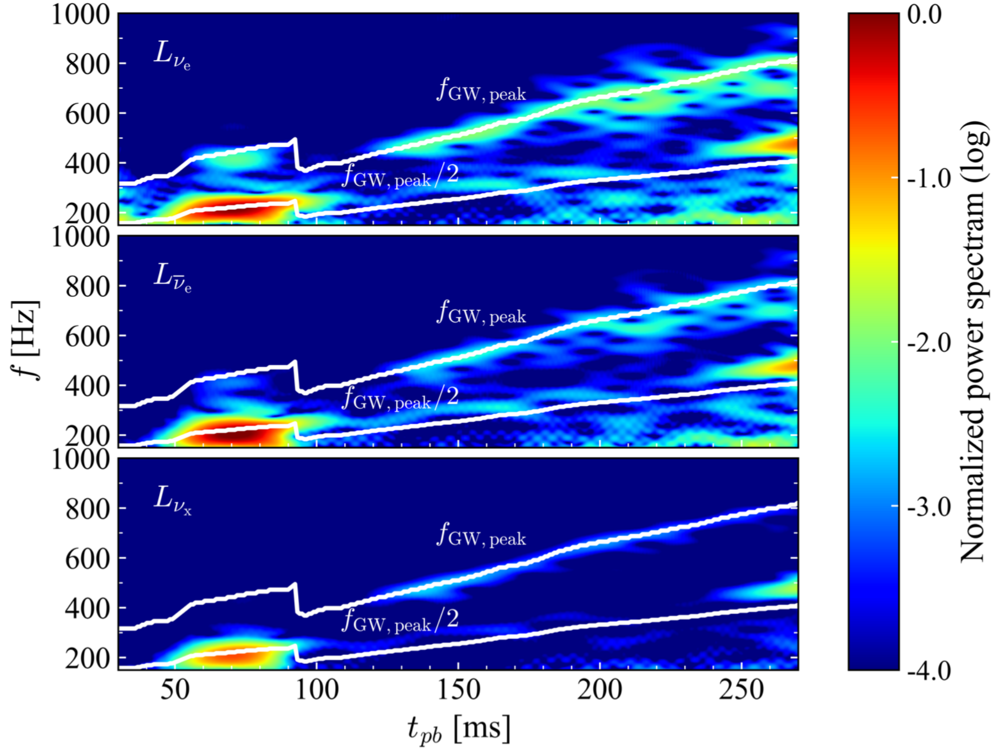


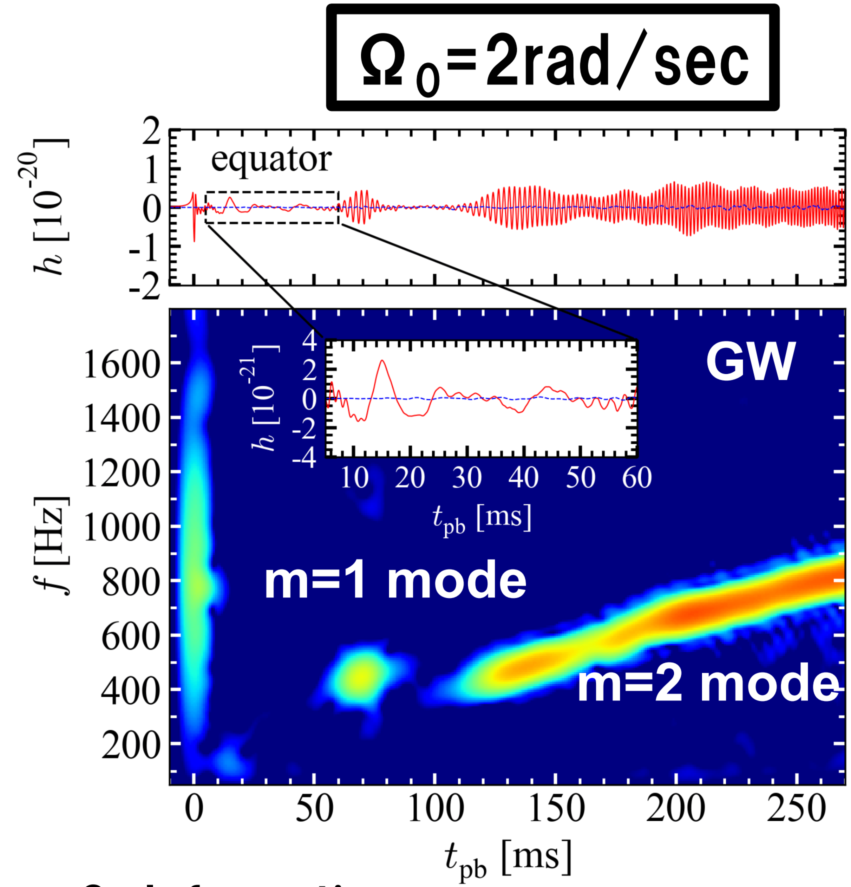


Correlation between GW and neutrino!!

m=1 spiral arm（ $50<t_{pb}<100$ ms）: $f_\nu \sim f_{GW}/2$
m=2 spiral arm（$120<t_{pb}<270$ ms）: $f_\nu \sim f_{GW}$

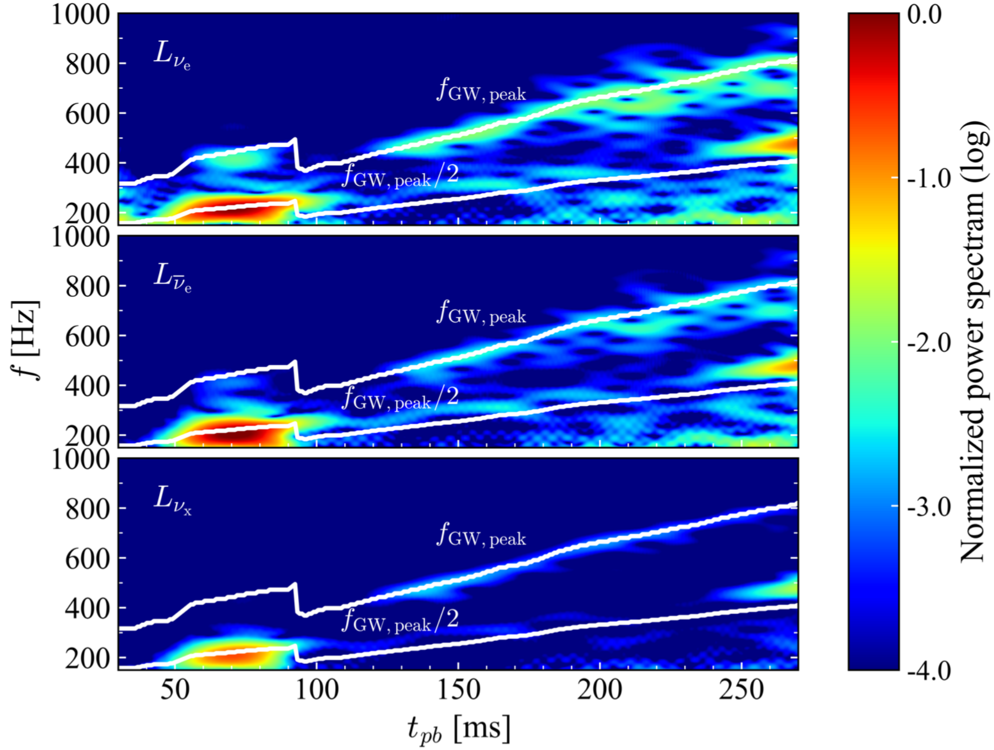
Neutrino spectrogram (equator)

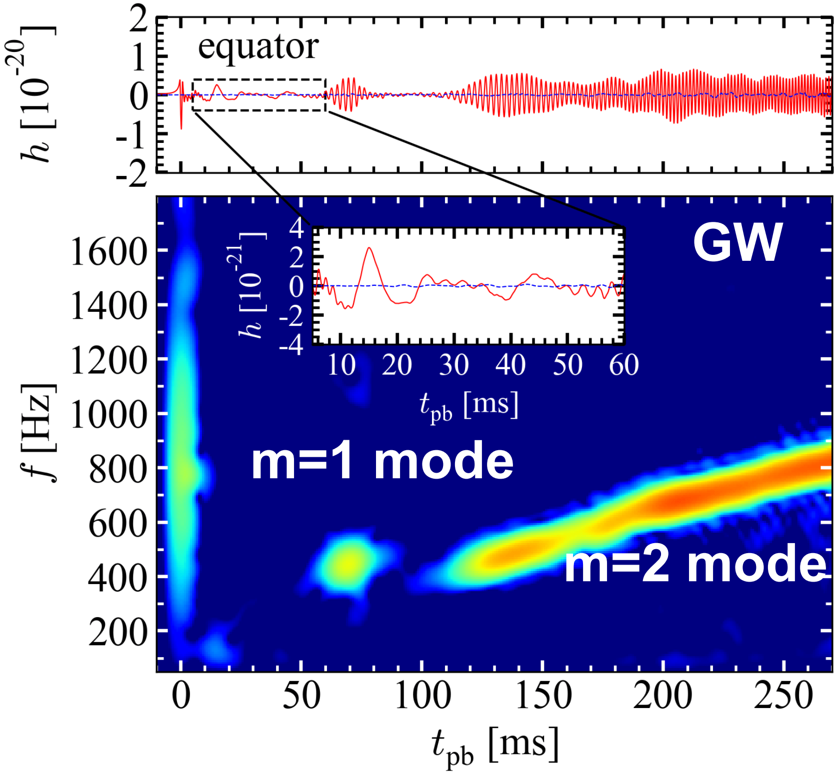




Neutrino spectrogram (equator)

Ω_0=2rad/sec





Correlation between GW and neutrino!!

m=1 spiral arm ($50<t_{pb}<100$ ms): $f_{\nu} \sim f_{GW}/2 \sim f_{rot}$

m=2 spiral arm ($120<t_{pb}<270$ ms): $f_{\nu} \sim f_{GW} \sim 2f_{rot}$

Setup

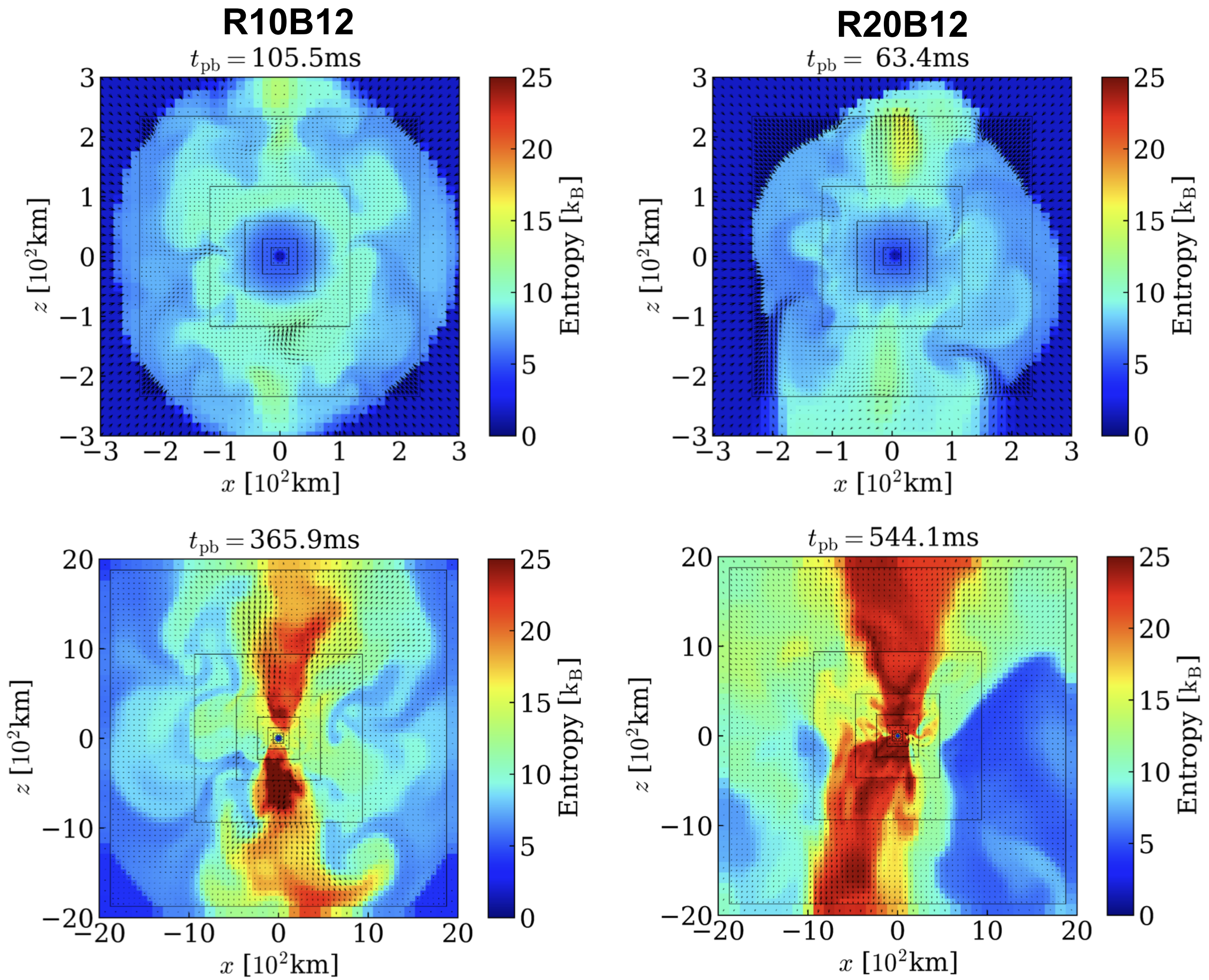
- Progenitor: s20 (Woosley & Heger2007)
- full GR RMHD code (Kuroda et al. 2020, 2021)
- neutrino transport: M1 scheme (Shibata et al. 2011)
- nuclear EOS: SFHo (Steiner et al. 2013)
- cylindrical rotation
- dipole magnetic field

Model	Ω_0 [rad s^{-1}]	$\frac{B_0}{\sqrt{4\pi}}$ [10^{12}G]
R05B12	0.5	1
R10B12	1.0	1
R10B13	1.0	10
R20B12	2.0	1

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

Entropy

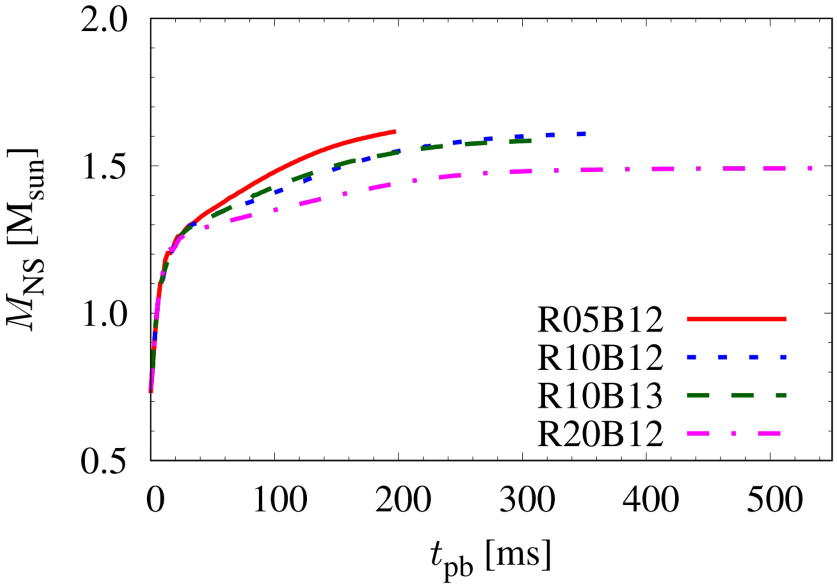
Model	Ω_0 [rad s^{-1}]	$\frac{B_0}{\sqrt{4\pi}}$ [10^{12}G]
R10B12	1.0	1
R20B12	2.0	1

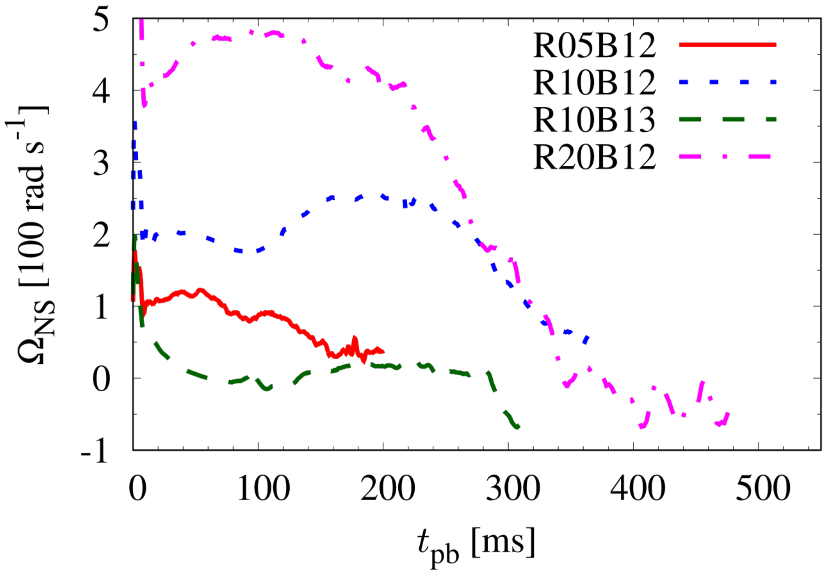


Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

PNS evolution

Model	Ω_0 [rad s^{-1}]	$\frac{B_0}{\sqrt{4\pi}}$ [10^{12}G]
R20B12	2.0	1



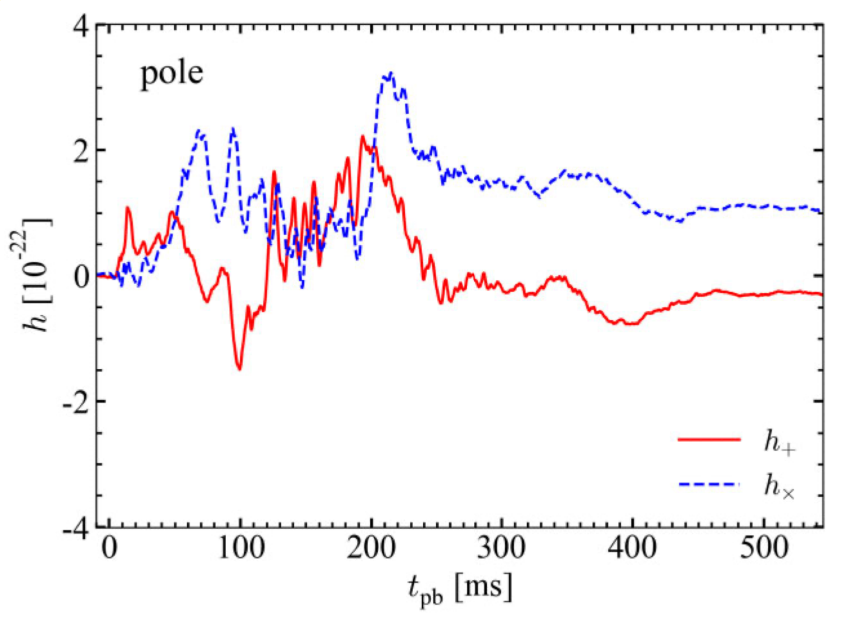


Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

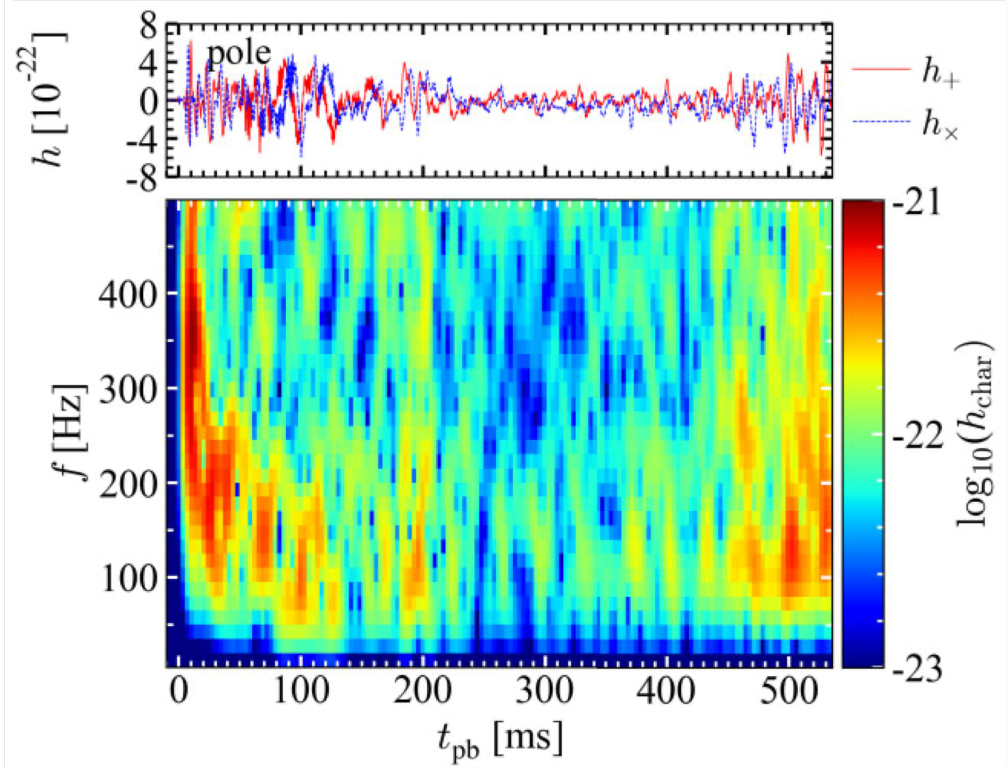
GW Spectrogram

R20B12
polar observer@10kpc

neutrino



matter



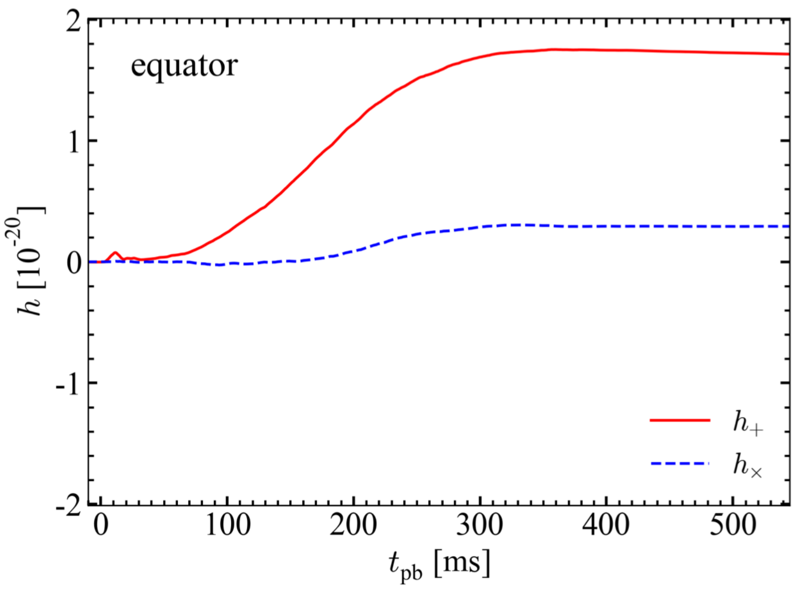
The amplitudes of GWs from matter and neutrinos are comparable.

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

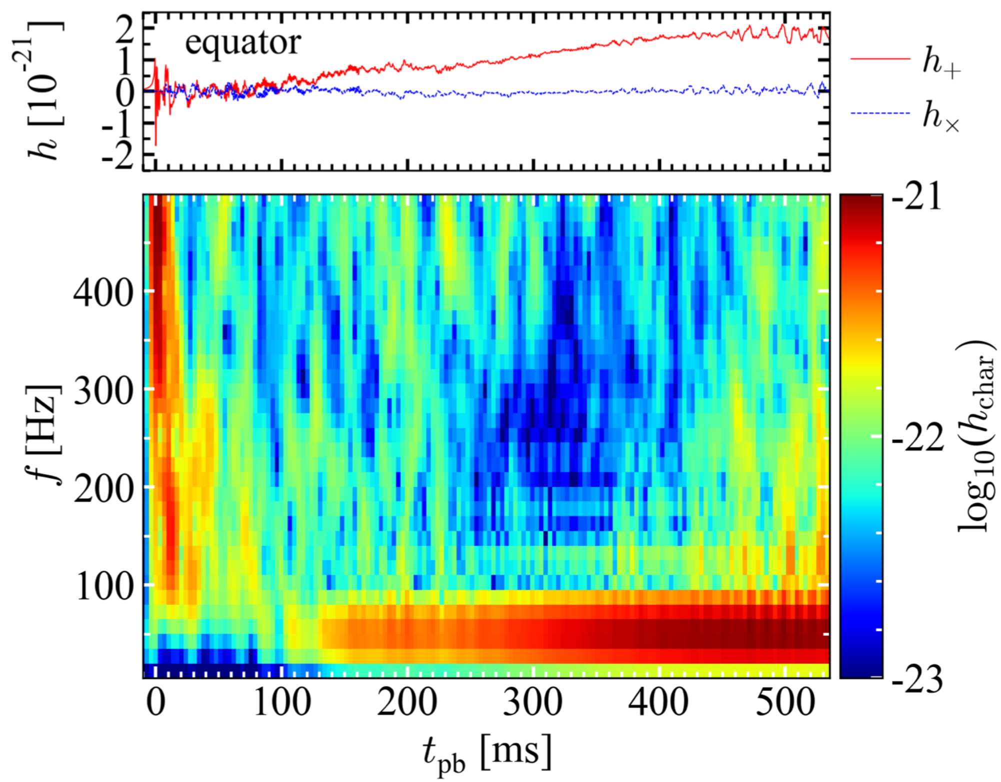
GW Spectrogram

R20B12
equatorial observer@10kpc

neutrino



matter

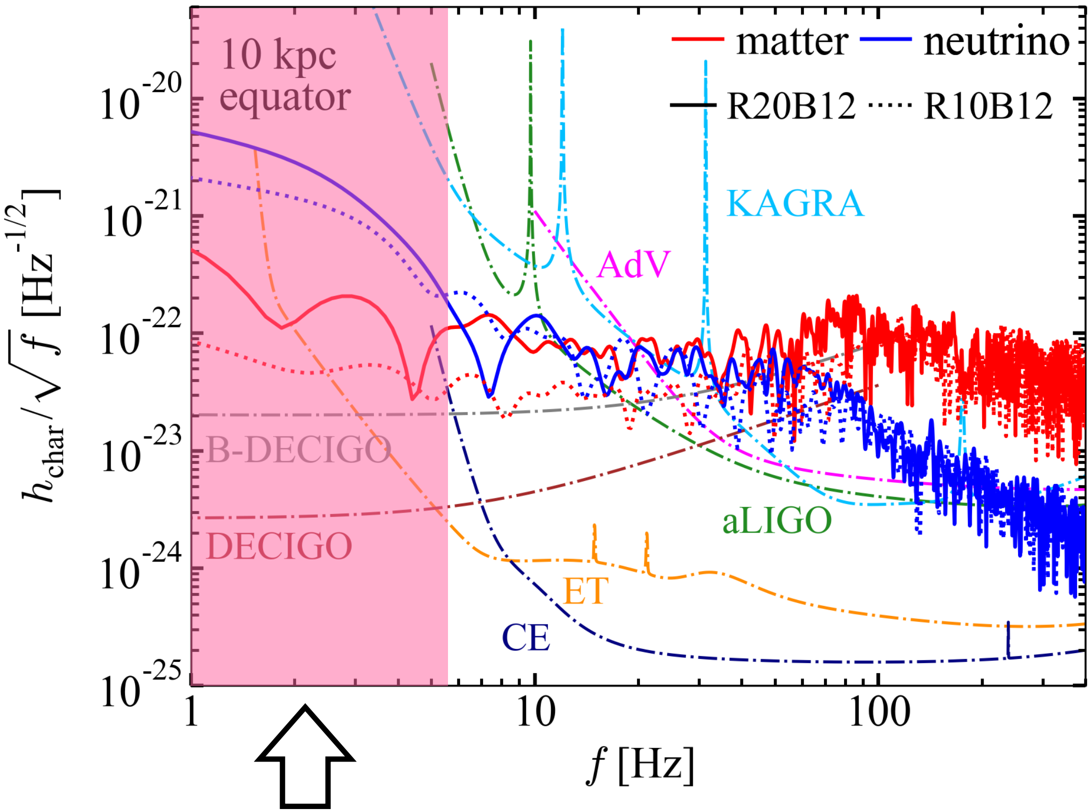


Both MHD jets and asymmetric neutrino emissions contribute to the generation of low-frequency GW.

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

GW Detectability

equatorial observer



The neutrino component is dominated over the jet component at low frequencies.

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)

Summary

- 3D GR ν-radiation hydrodynamics simulation of 70 solar mass rapidly rotating stellar core collapse
- The protoneutron star deformation due to rotation changes relationship between GW and neutrinos on their spectrograms. Shibagaki, Kuroda, Kotake, Takiwaki, MNRAS (2020, 2021)
  - m=1 deformation： $f_\nu \sim f_{GW}/2$
  - m=2 deformation： $f_\nu \sim f_{GW}$
- This indicates that joint observation of GW and neutrino could give us a hint of the protoneutron star deformation as well as its rotation.
- Fully general relativistic 3D neutrino radiation-magnetohydrodynamics simulations of rotating magnetized core collapse
- GW from anisotropic neutrino emission may hide GW from aspherical explosion.

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, MNRAS (2024)