Multimessenger signals from core collapse of massive stars

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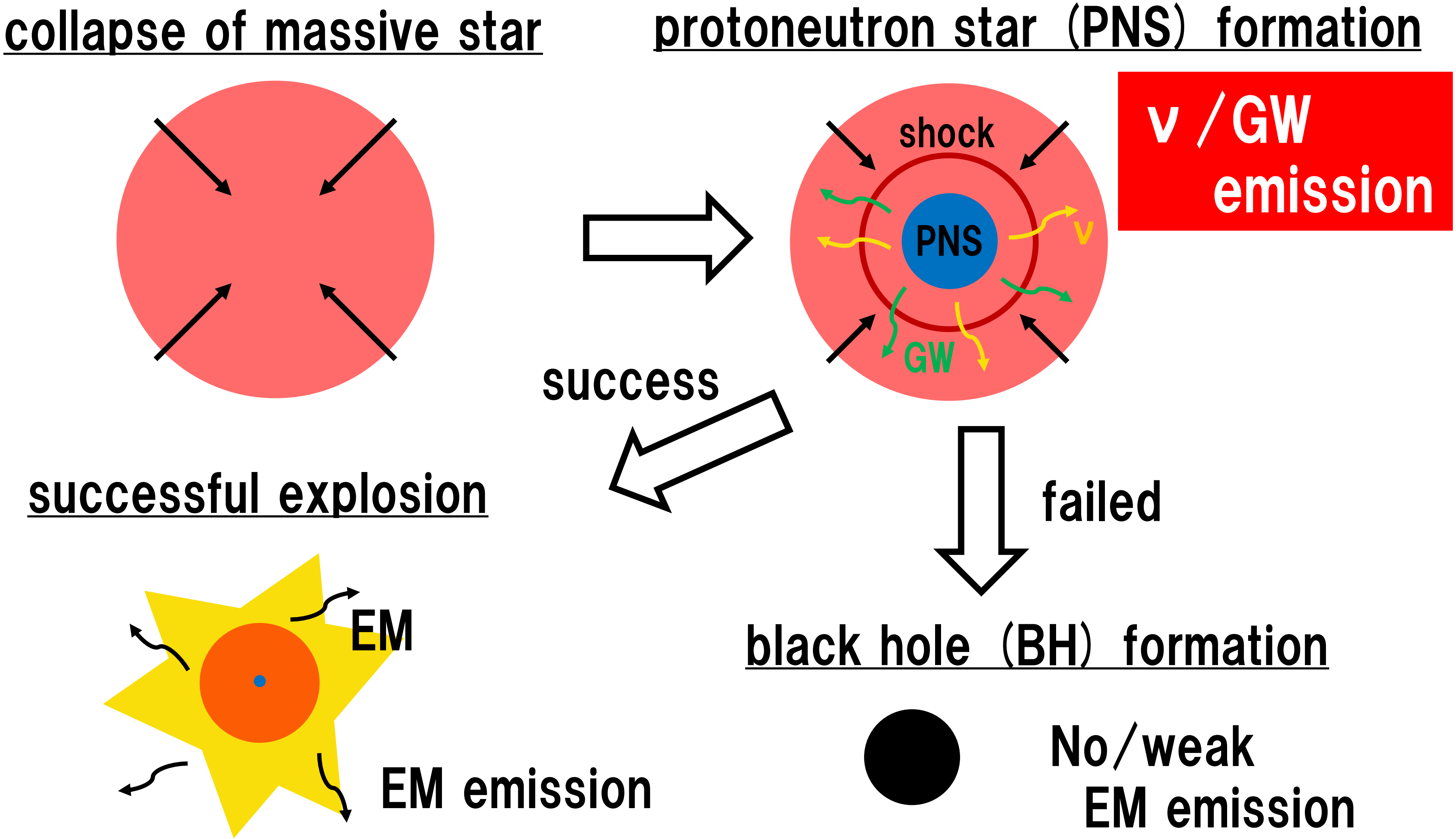
Fate of massive stars



collapse of massive star

protoneutron star （PNS） formation

shock

PNS

ν

GW

ν / GW emission

success

failed

successful explosion

EM

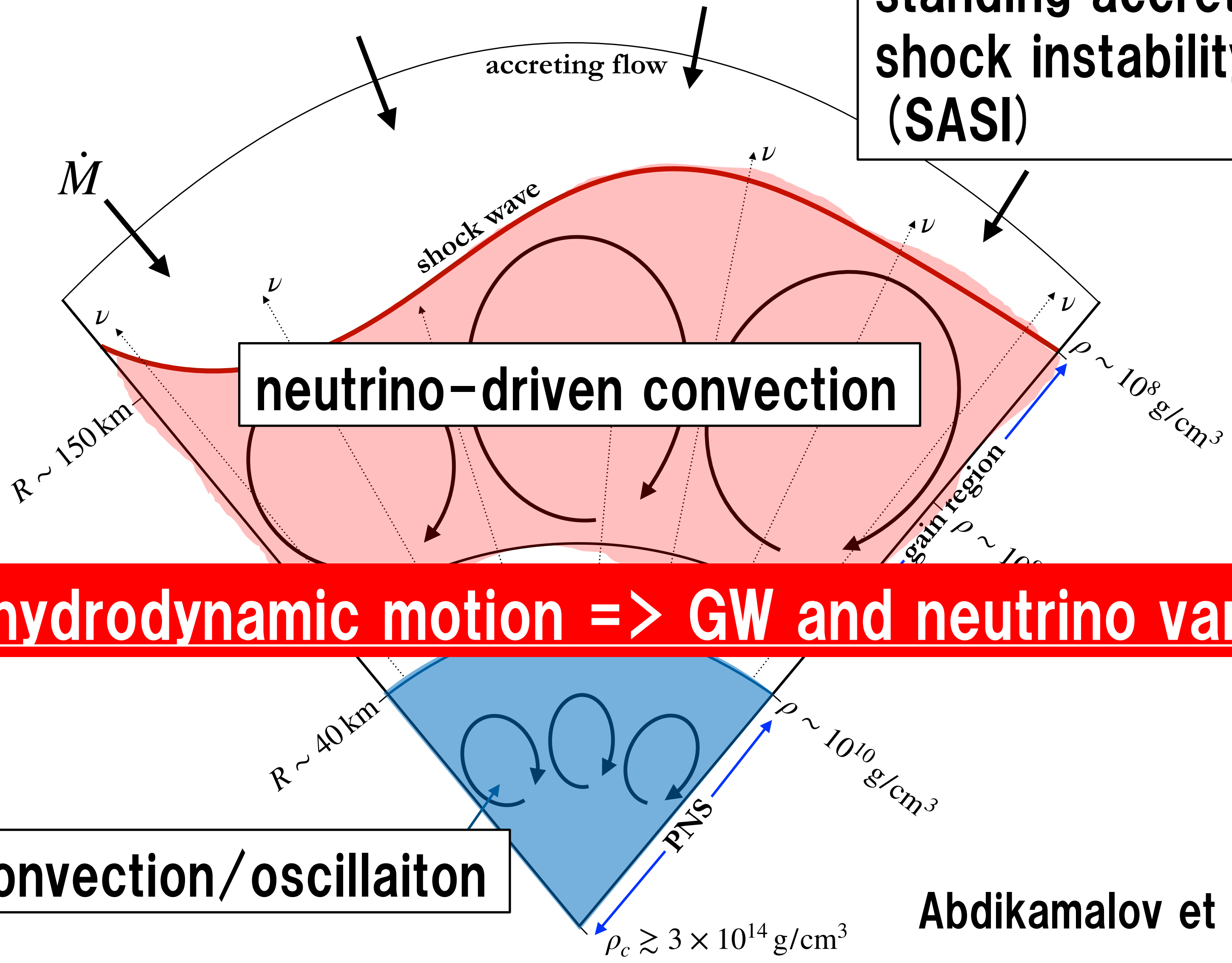
EM emission

black hole （BH） formation

No / weak EM emission

GW and neutrinos: Unique probes of supernovae core

Multidimensional hydrodynamic phenomena in SN core



standing accretion shock instability (SASI)

neutrino-driven convection

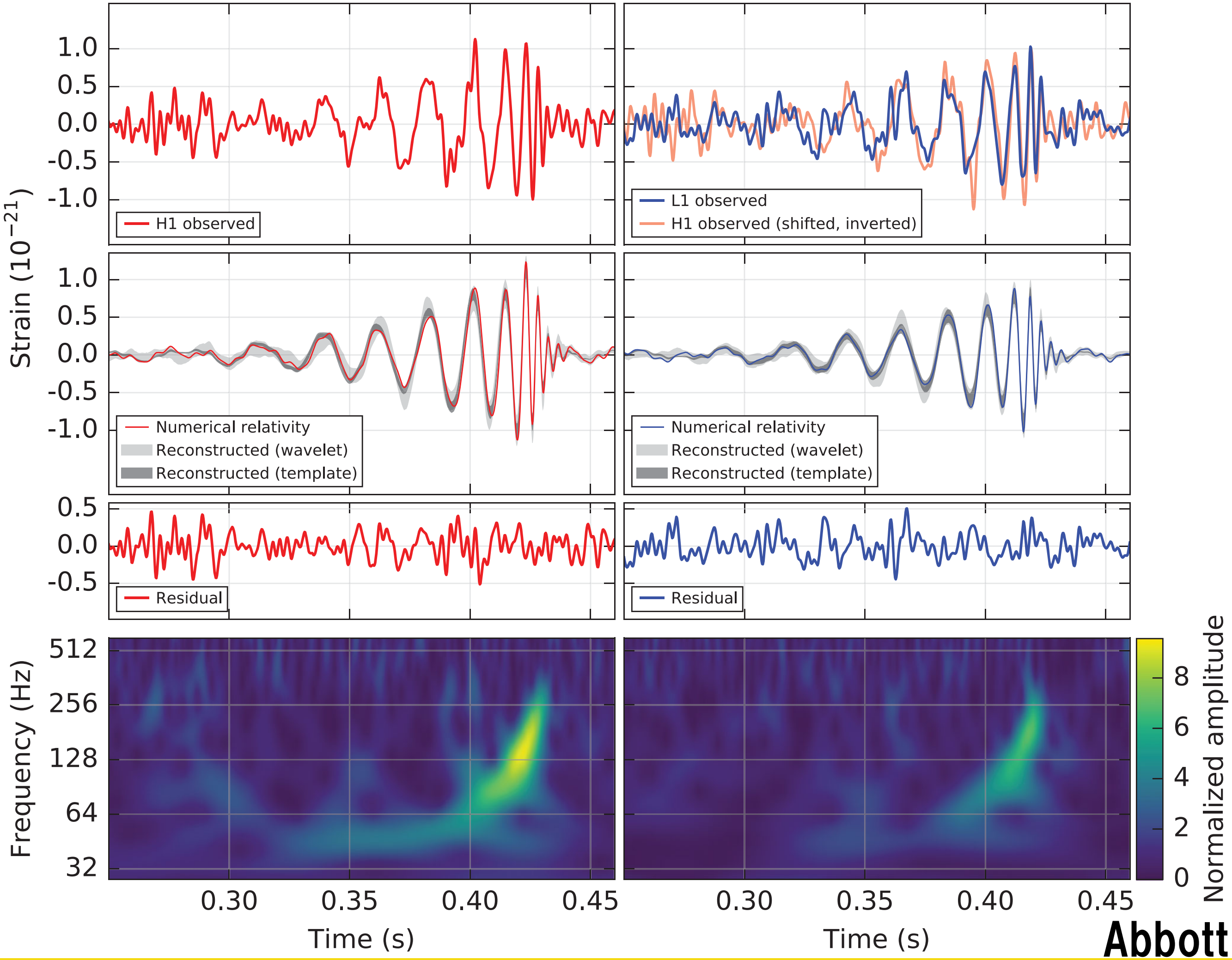
3D hydrodynamic motion => GW and neutrino variation

PNS convection/oscillaiton

Abdikamalov et al. 2020

Short-Term Fourier Transform

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



Abbott et al. 2016

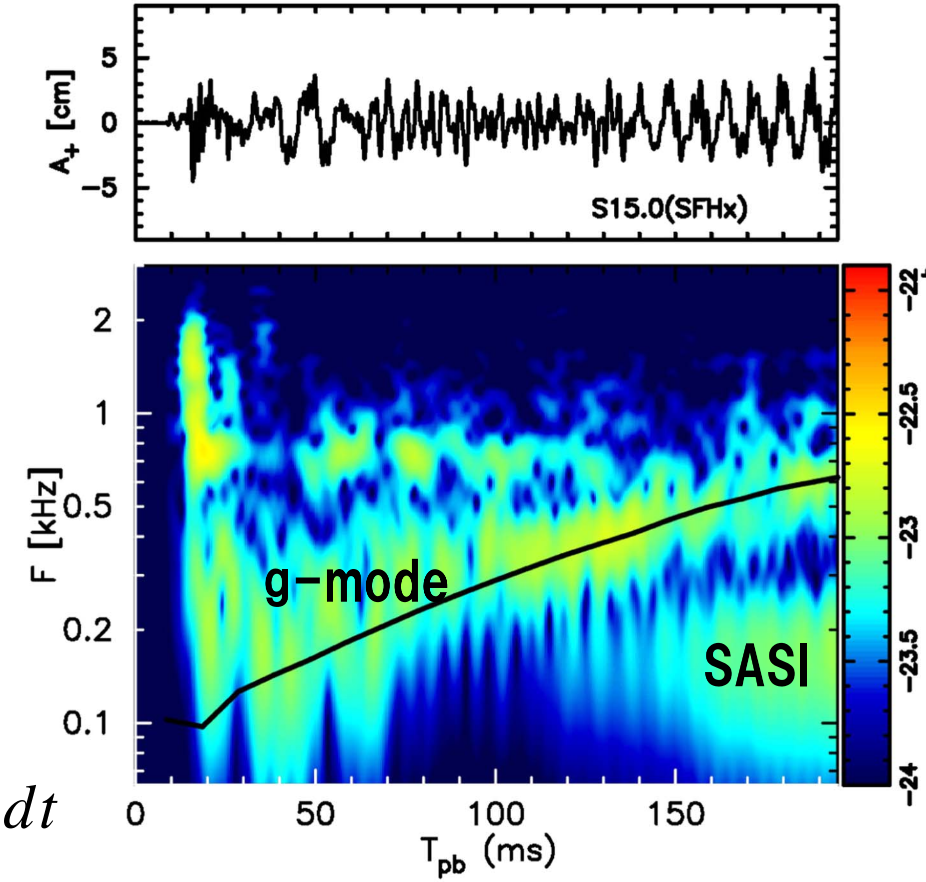
Multi-messengers from SNe: GW

- Imprints of standing accretion shock instability (SASI) & g-mode of protoneutron star may be found in observed GW.

ex.) Kuroda et al. 2017
Andresen et al. 2017, 2019
O’Connor et al. 2018
Vartanyan et al. 2019
Powell & Muller 2020
Mezzacappa et al. 2020

Short term Fourier trans.

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

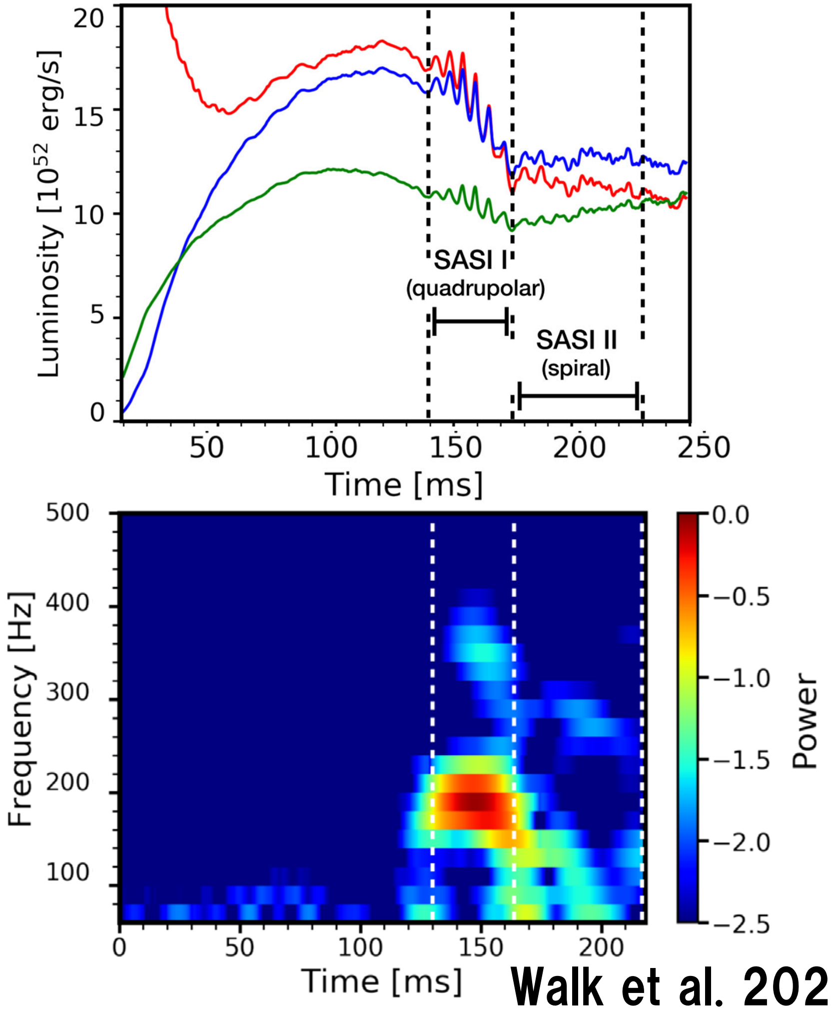


Kuroda et al. 2017

Multi-messengers from SNe: ν

- Imprints of standing accretion shock instability (SASI) may be found in observed neutrinos.

ex.) Tamborra et al. 2014
Kuroda et al. 2017
O’Connor et al. 2018
Walk et al. 2018, 2020
Vartanyan et al. 2019
Nagakura et al. 2020



Walk et al. 2020

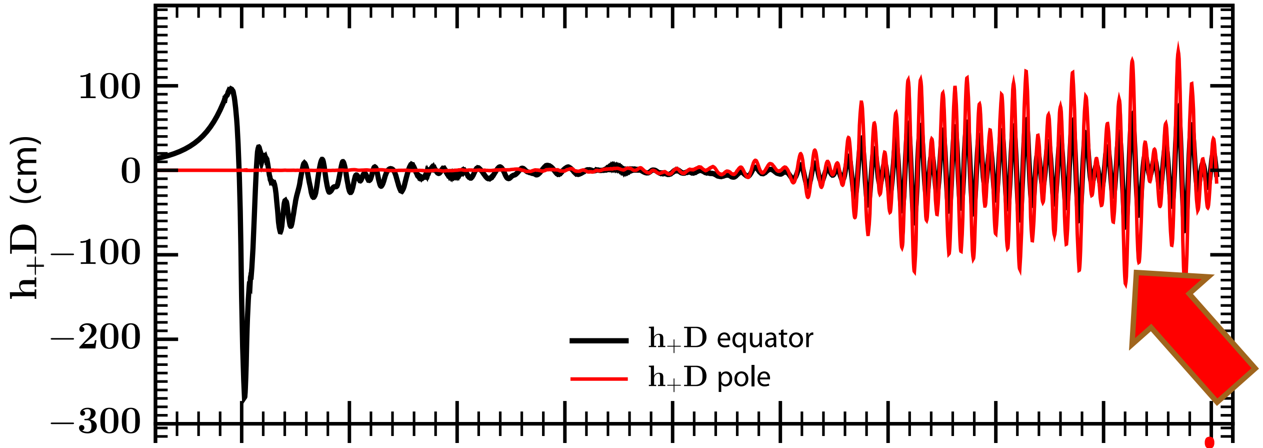
Short term Fourier trans.

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

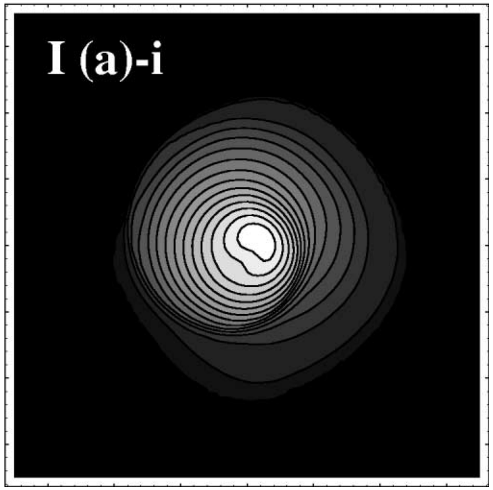
Rapidly rotating cases

- Larger GW amplitude

Ott 2009



Saijo et al. 2003



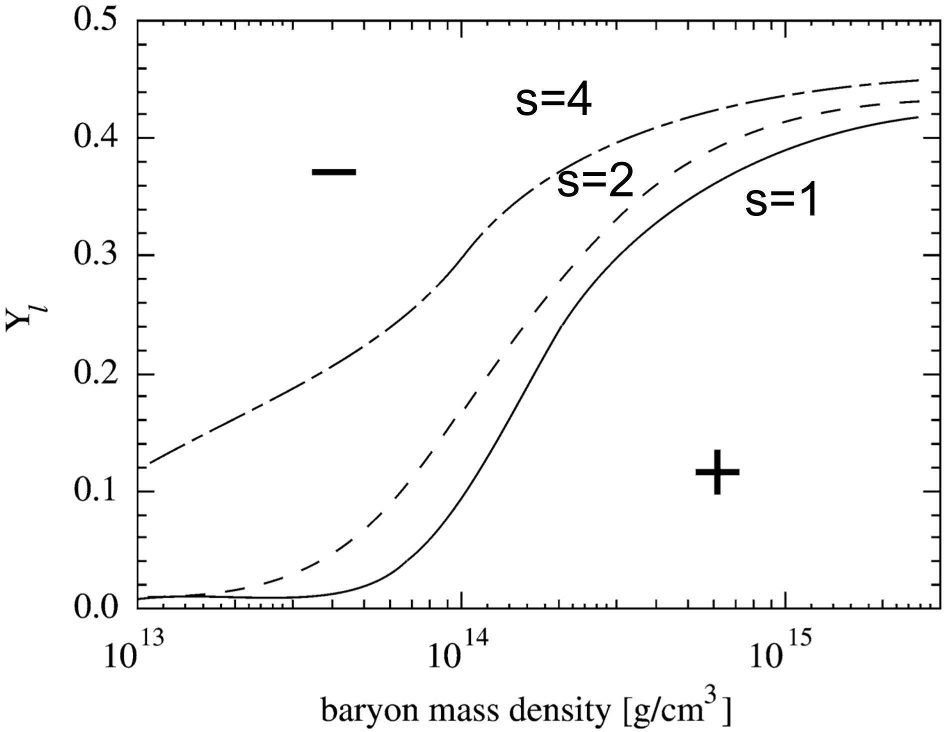
non-axisymmetric instability
(low-T/|W| instability)

Previous 3D simulations:

- Ott et al. 2005 Newtonian + no neutrino
- Ott et al. 2007 full GR + Ye prescription
- Scheidegger et al. 2008, 2010 effective GR + leakage
- Takiwaki et al. 2016, 2018 Newtonian + IDSA

➡ Full GR ν radiation-hydrodynamics simulations

PNS Convection



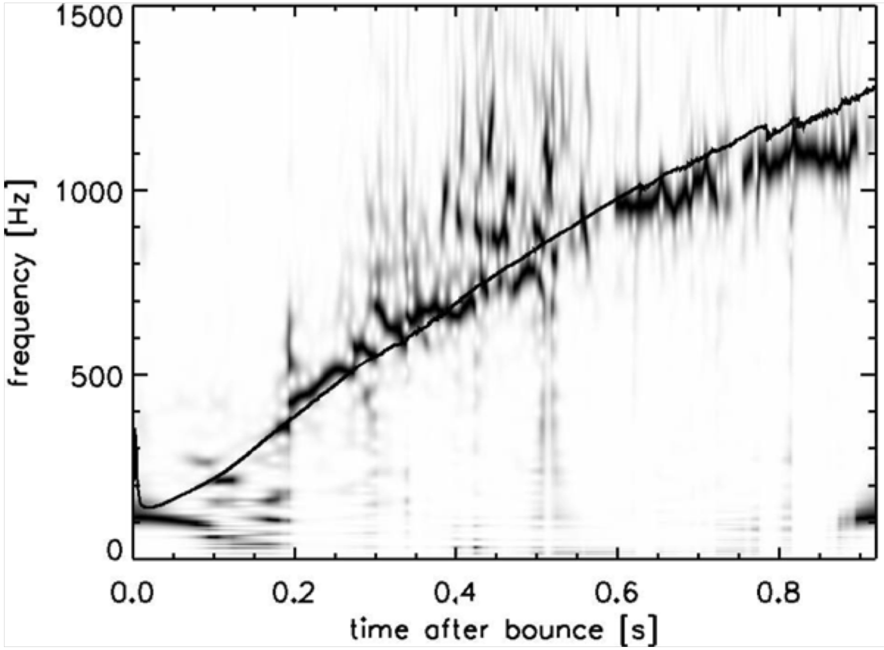
The Ledoux criterion depends on the property of EOS:

$$\left(\frac{\partial\rho}{\partial Y_l}\right)_{P,S}\left(\frac{dY_l}{dr}\right)+\left(\frac{\partial\rho}{\partial S}\right)_{P,Y_l}\left(\frac{dS}{dr}\right)\geqslant 0$$

stable against convection

Sumiyoshi et al. 2004

GW from PNS Oscillation



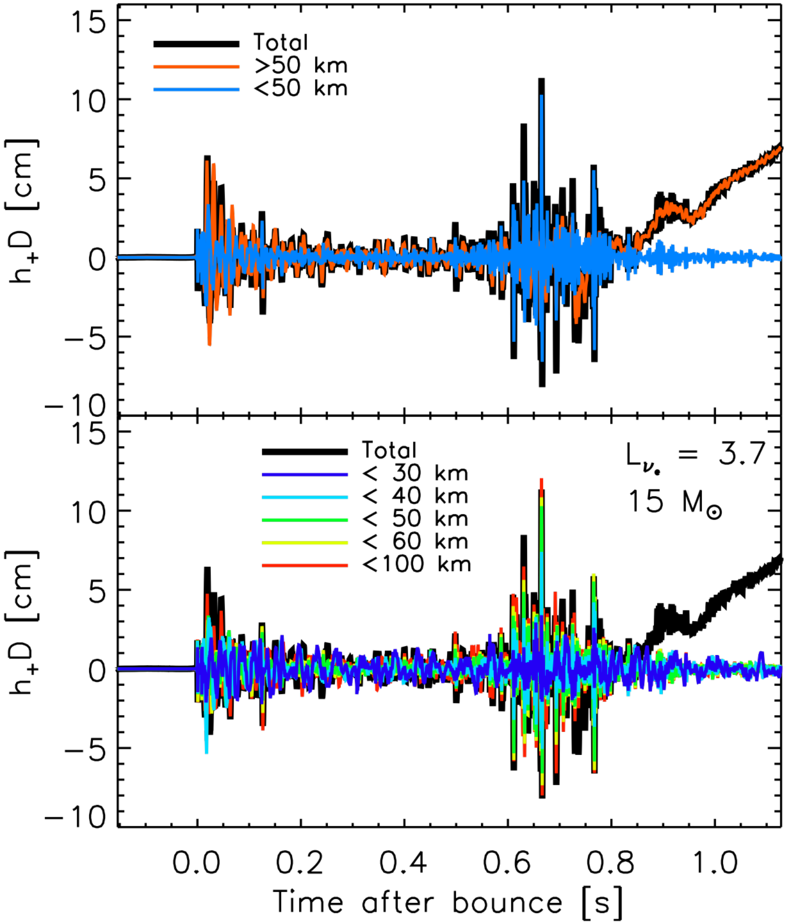
$$f_p = \frac{N}{2\pi} \approx \frac{1}{2\pi} \frac{GM}{R^2} \sqrt{1.1 \frac{m_n}{\langle E_{\bar{\nu}_e} \rangle}} \left(1 - \frac{GM}{Rc^2}\right)^2$$

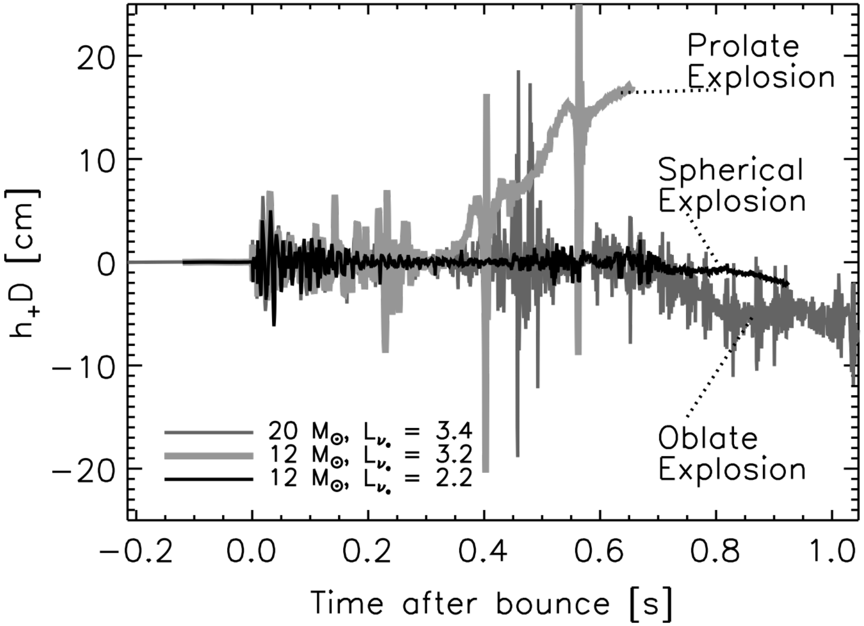
$$N^2 = \frac{\alpha C_{\mathrm{L}}}{\rho h \phi^4} \frac{\partial \alpha}{\partial r} \qquad C_{\mathrm{L}} = \frac{\partial \rho(1+\epsilon)}{\partial r} - \left(\frac{d\rho(1+\epsilon)}{dP}\right)_{s, Y_e = \mathrm{const.}} \frac{\partial P}{\partial r}$$

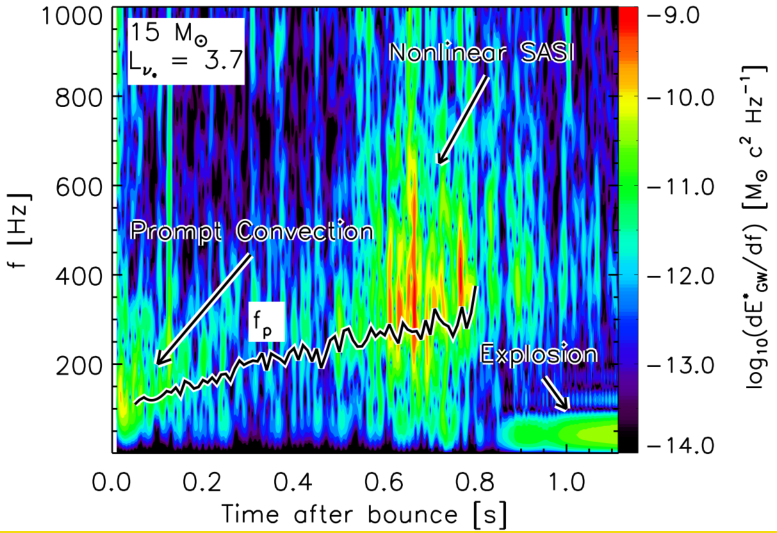
Brunt-Vaisala frequency

Muller et al. 2013

GW from Aspherical Explosion

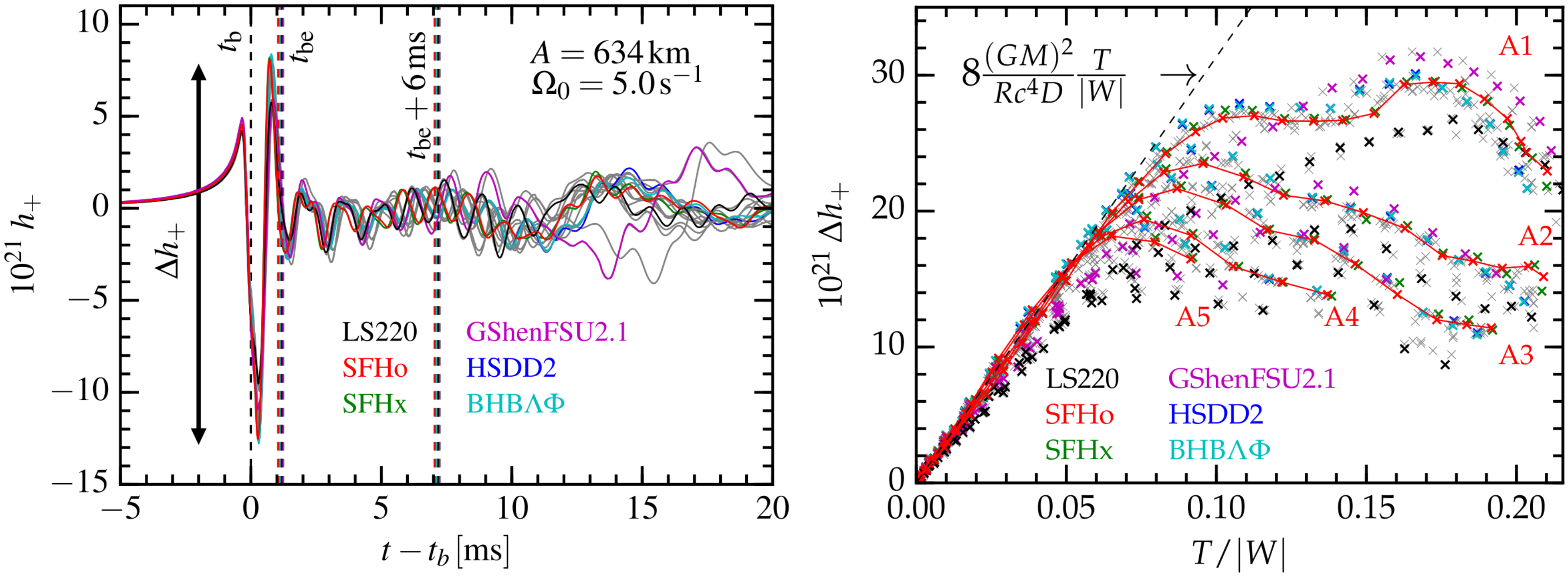






Murphy et al. 2009

Effect of EOS on GW（rot. case)

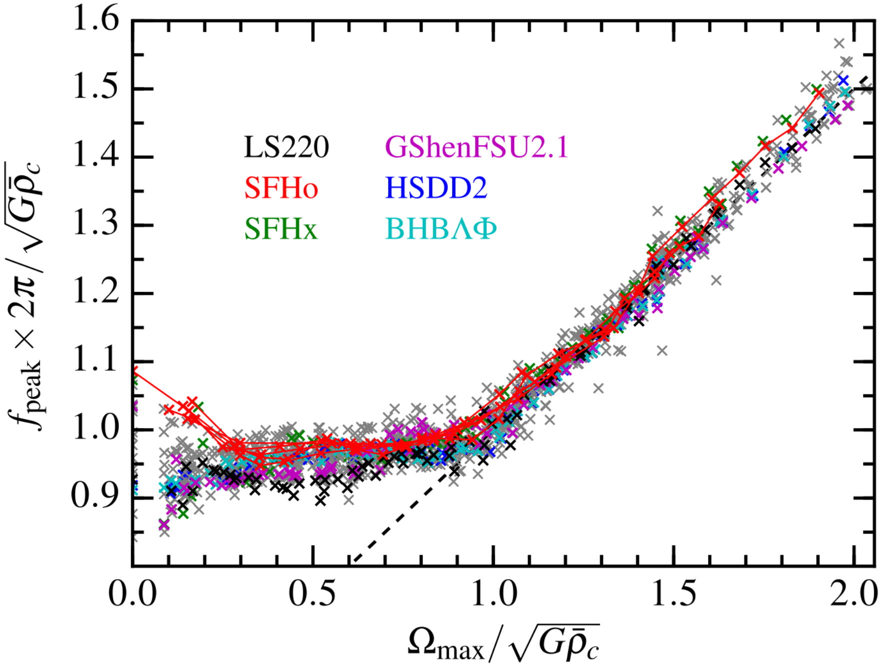


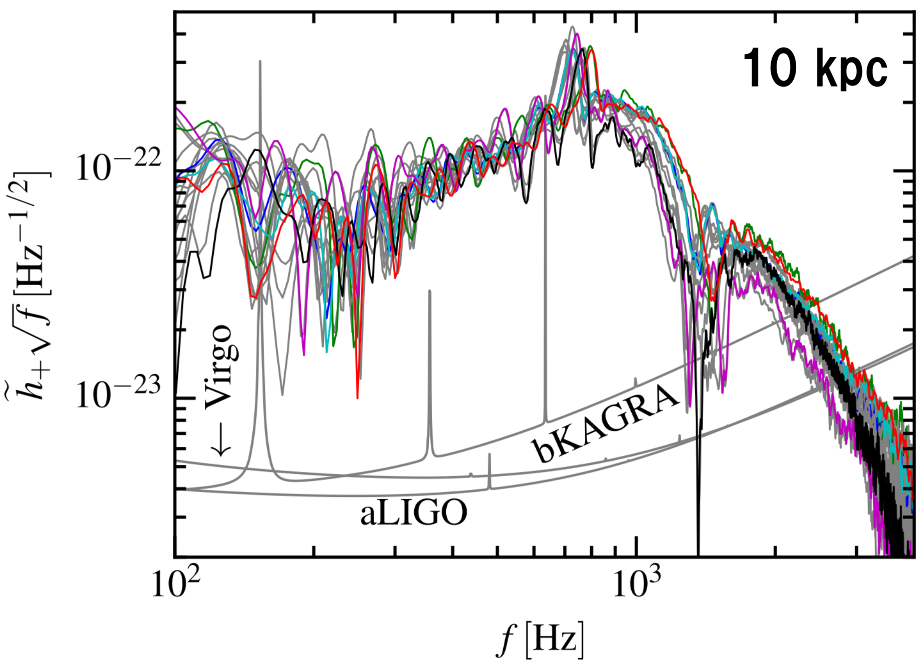
Systematic 2D simulations（1824 models）revealed the two universal relationships.

$$h_+ \sim \frac{GM\Omega^2R^2}{c^4D} \sim \frac{T}{|W|}\frac{(GM)^2}{Rc^4D}$$

Abdikamalov et al. 2014, Richers et al. 2017

Effect of EOS on GW（rot. case）





Systematic 2D simulations（1824 models）revealed the two universal relationships.

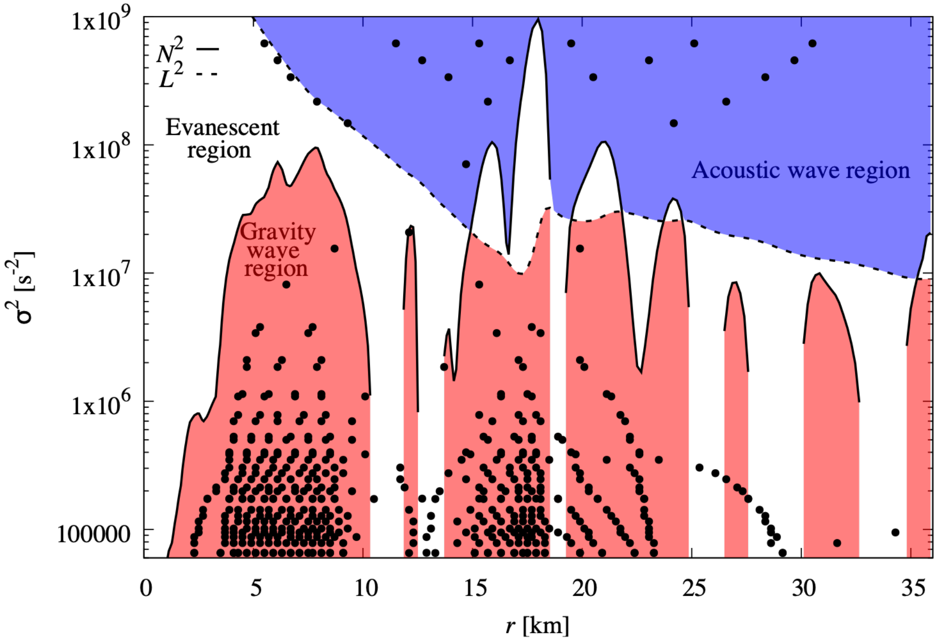
$$2\pi f_{\rm peak}/\sqrt{G\bar{\rho}_c} = 0.5(1+\Omega_{\rm max}/\sqrt{G\bar{\rho}_c})$$

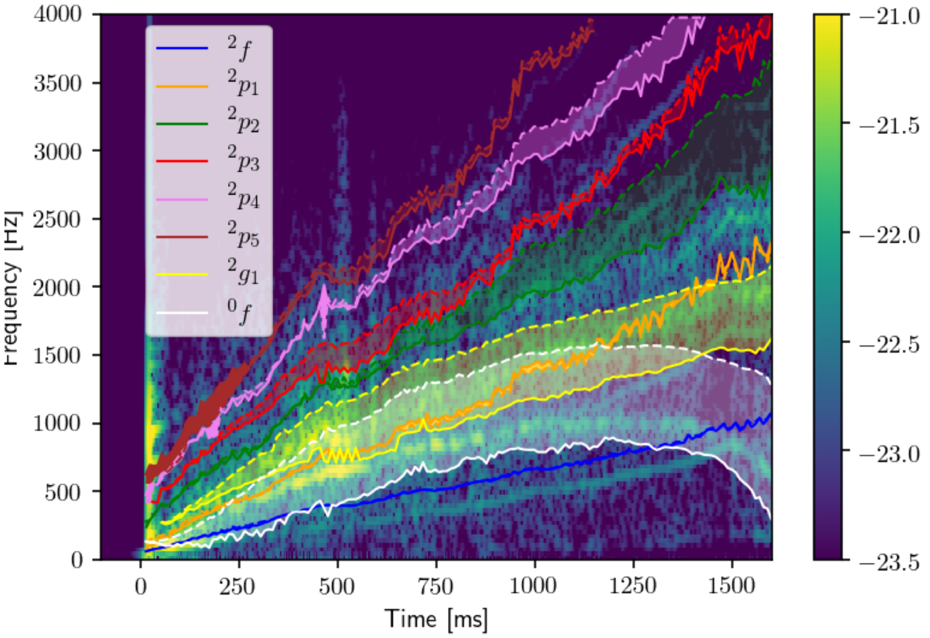
Abdikamalov et al. 2014, Richers et al. 2017

Mode analysis

$$\mathcal{L}^2 \equiv \frac{\alpha^2}{\psi^4} c_s^2 \frac{l\,(l+1)}{r^2}$$ Lamb freq.

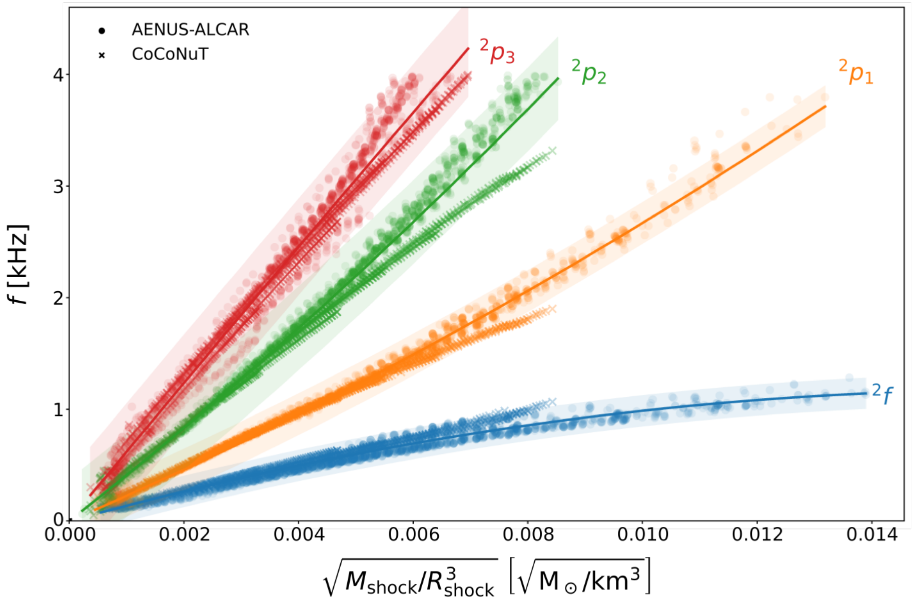
$$\mathcal{N}^2 \equiv \frac{\alpha^2}{\psi^4} \mathcal{G}^i \mathcal{B}_i$$ Brunt-Vaisala freq.

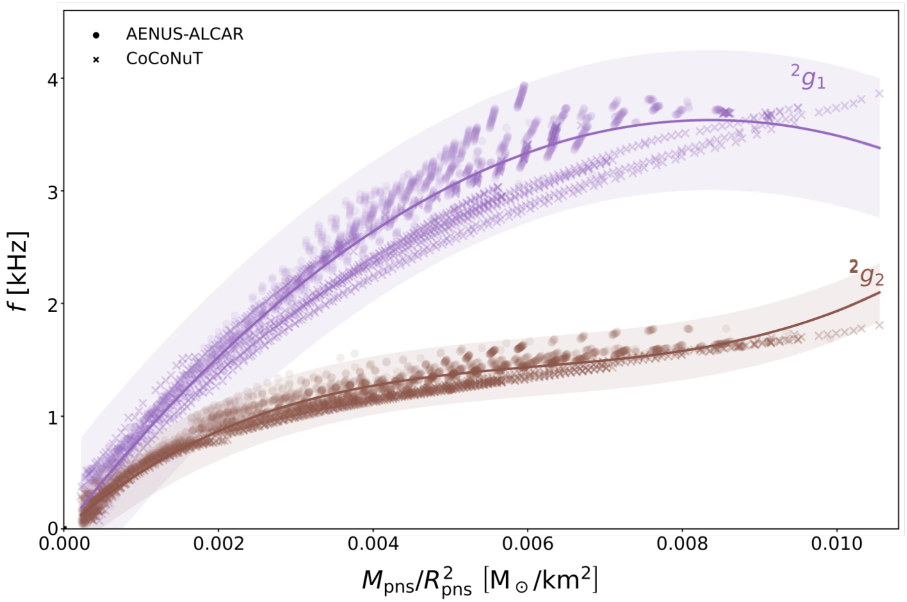


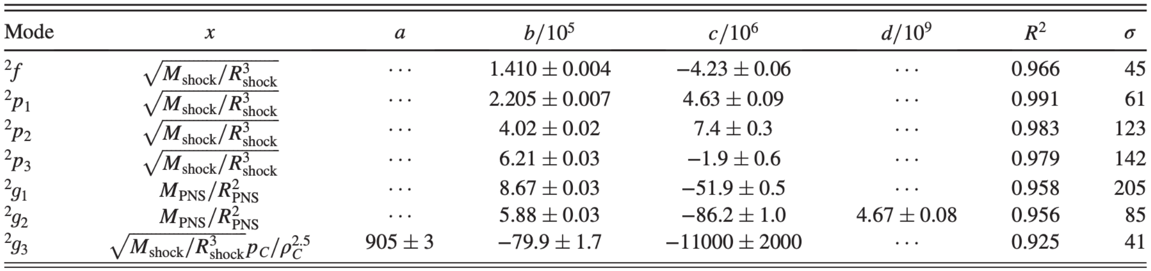


Torres-Forne et al. 2018, 2019a, 2019b

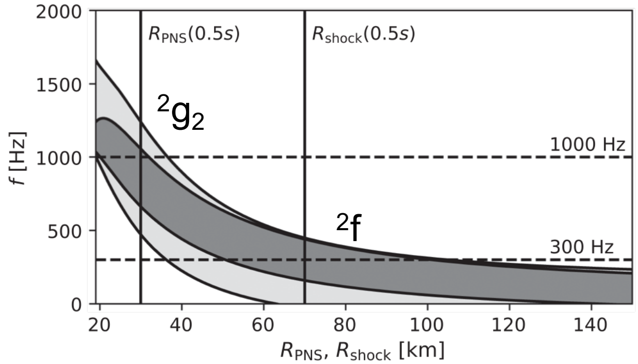
Universal Relation







Mode	x	a	$b/10^5$	$c/10^6$	$d/10^9$	R^2	σ
^2f	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	···	1.410 ± 0.004	-4.23 ± 0.06	···	0.966	45
$^2p_1$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	···	2.205 ± 0.007	4.63 ± 0.09	···	0.991	61
$^2p_2$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	···	4.02 ± 0.02	7.4 ± 0.3	···	0.983	123
$^2p_3$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}$	···	6.21 ± 0.03	-1.9 ± 0.6	···	0.979	142
$^2g_1$	$M_{\rm PNS}/R^2_{\rm PNS}$	···	8.67 ± 0.03	-51.9 ± 0.5	···	0.958	205
$^2g_2$	$M_{\rm PNS}/R^2_{\rm PNS}$	···	5.88 ± 0.03	-86.2 ± 1.0	4.67 ± 0.08	0.956	85
$^2g_3$	$\sqrt{M_{\rm shock}/R^3_{\rm shock}}p_C/\rho_C^{2.5}$	905 ± 3	-79.9 ± 1.7	-11000 ± 2000	···	0.925	41



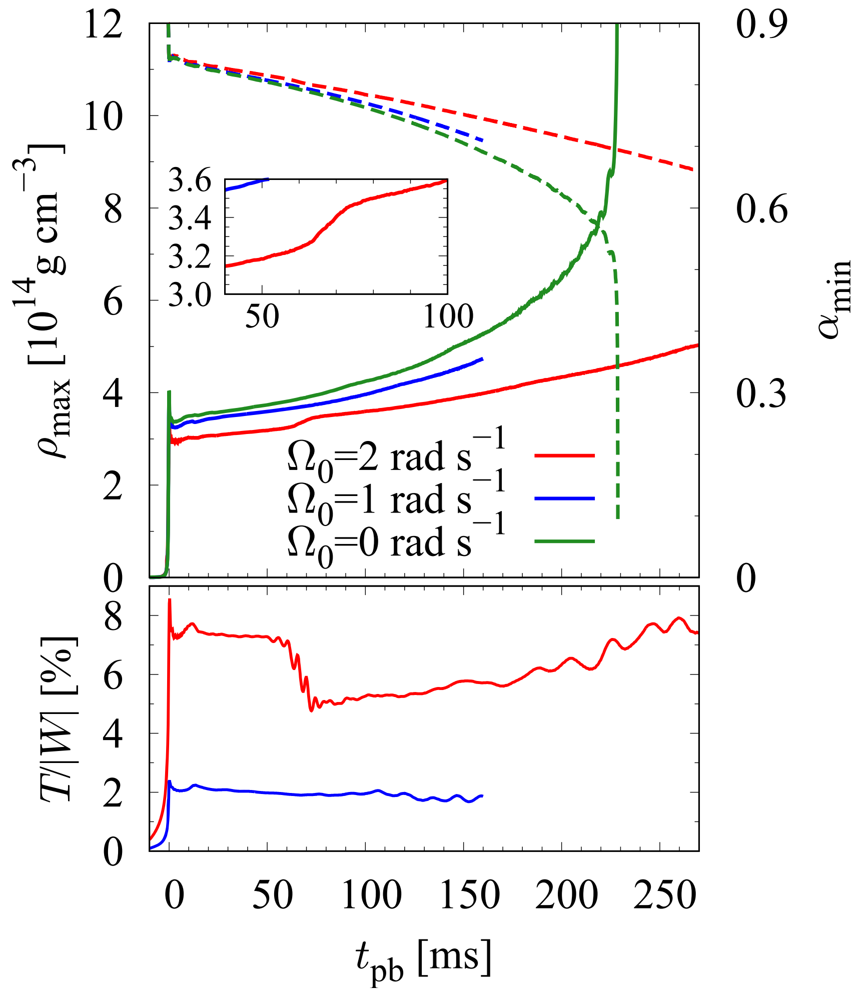
Torres-Forne et al. 2018, 2019a, 2019b

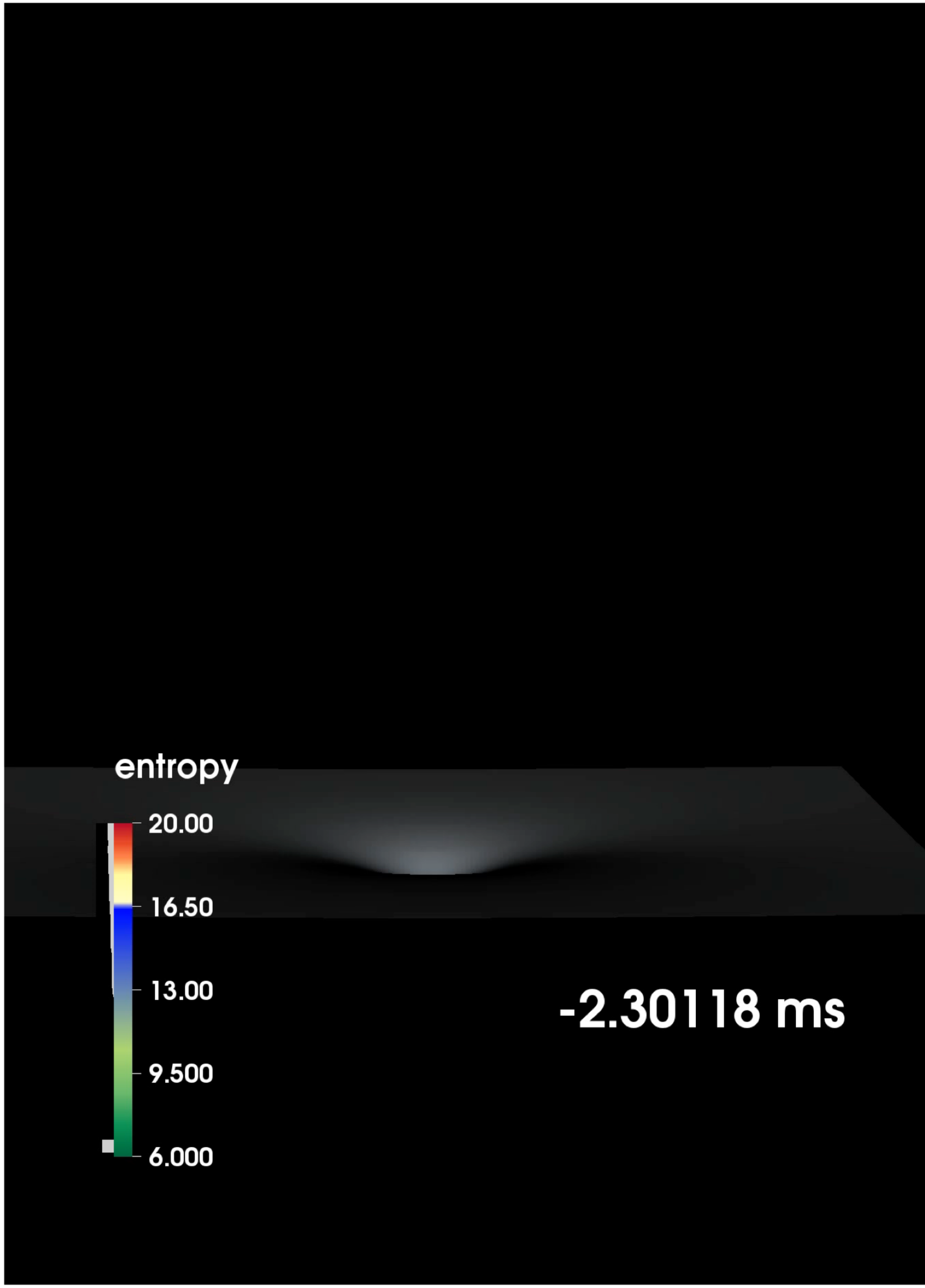
Method

- 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

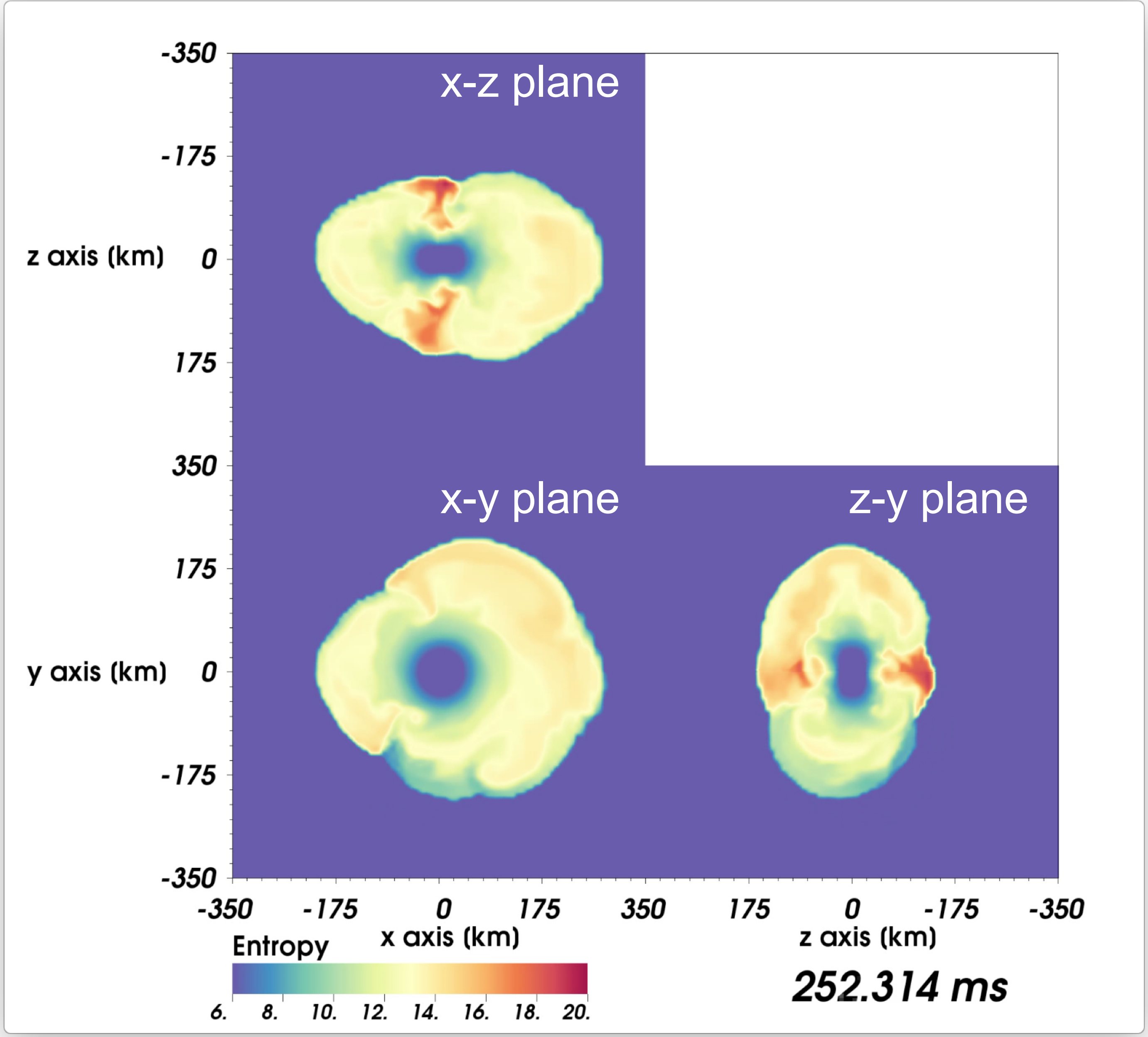
Ω_0=0rad/sec model





Entropy Evolution

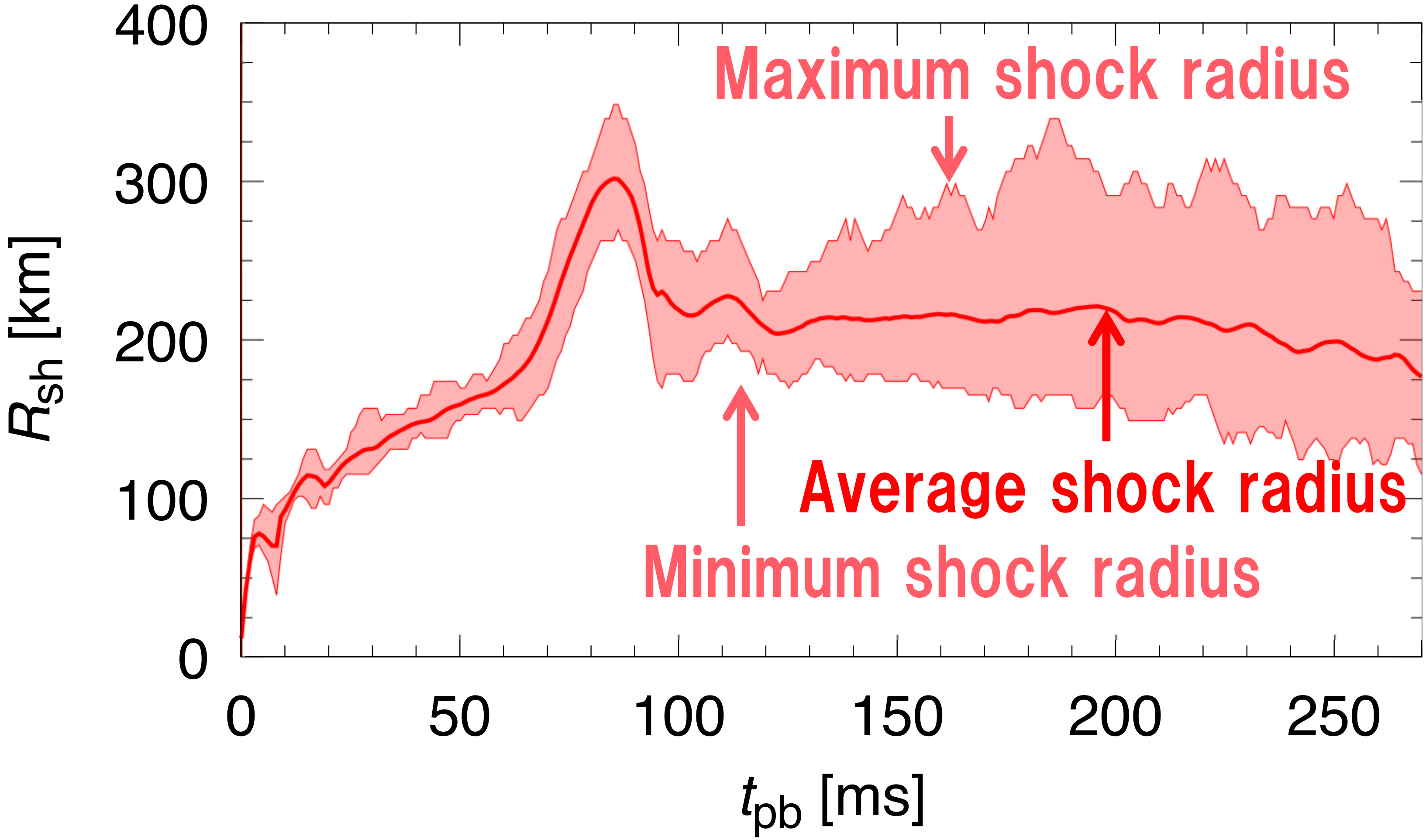
Ω_0=2rad/sec



Shock Radius

Ω_0=2rad/sec

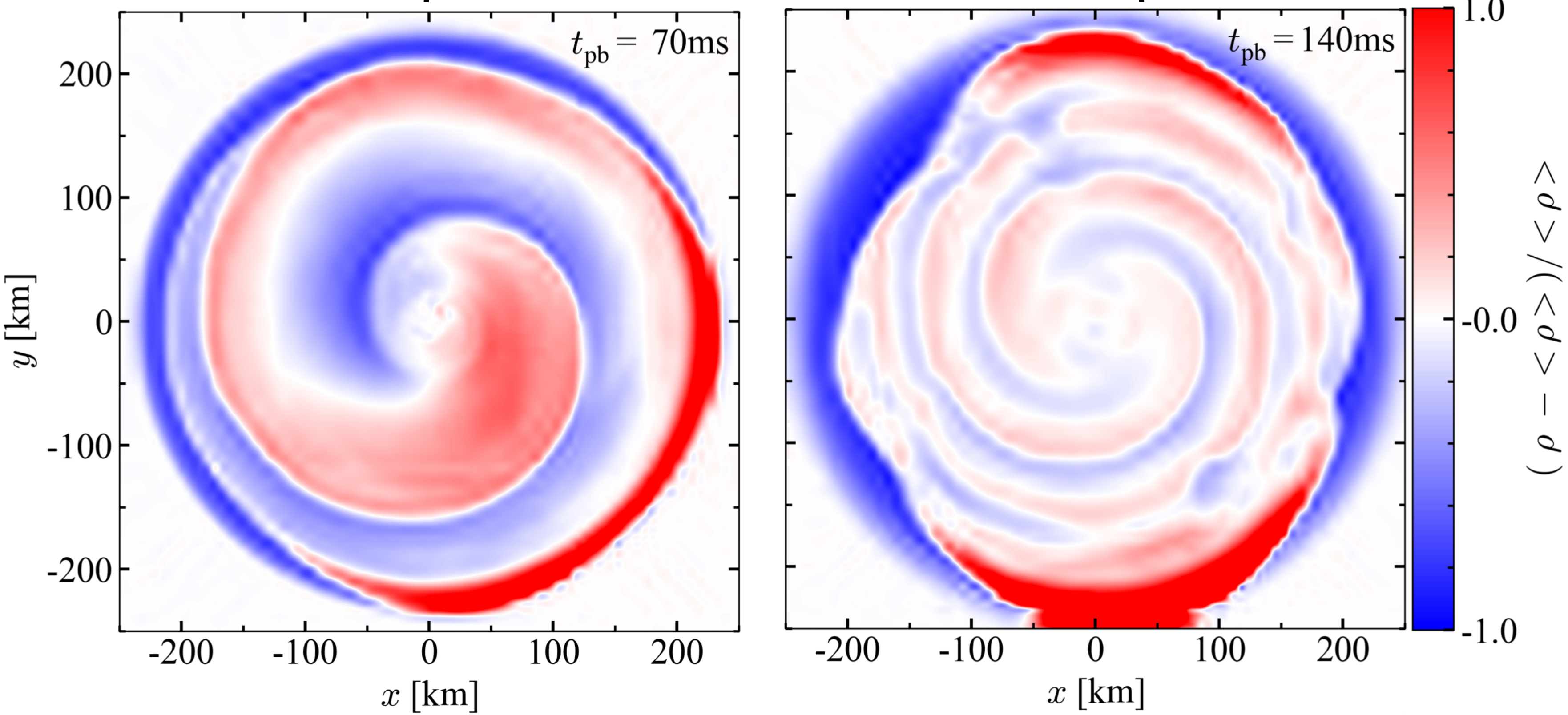
What is happening?

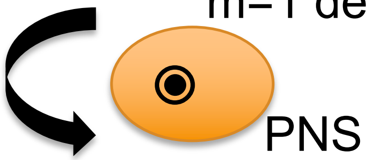


Density Distribution

Ω_0=2rad/sec

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

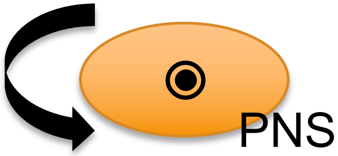




m=1 deformation

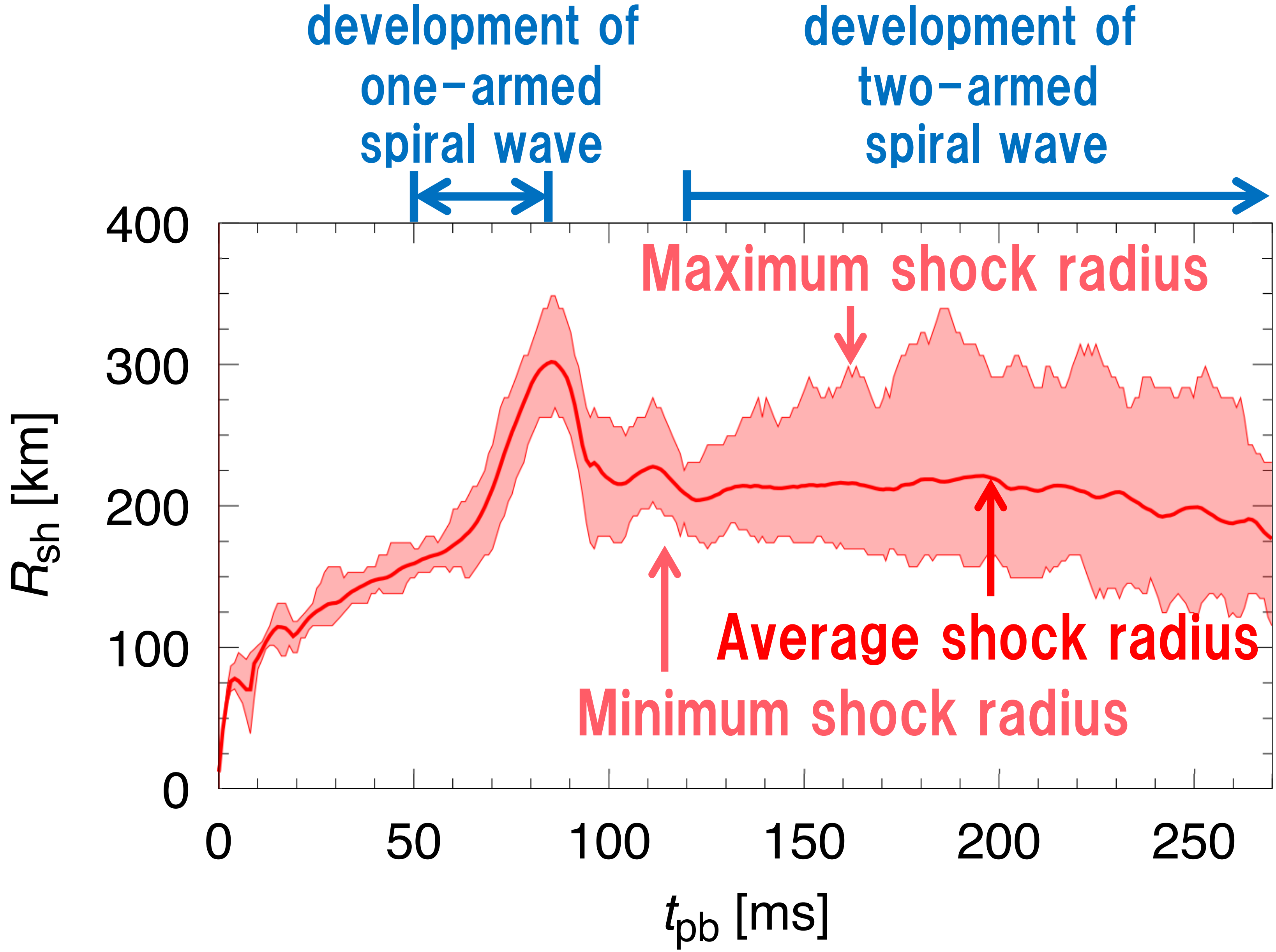
low T/|W| instability

m=2 deformation



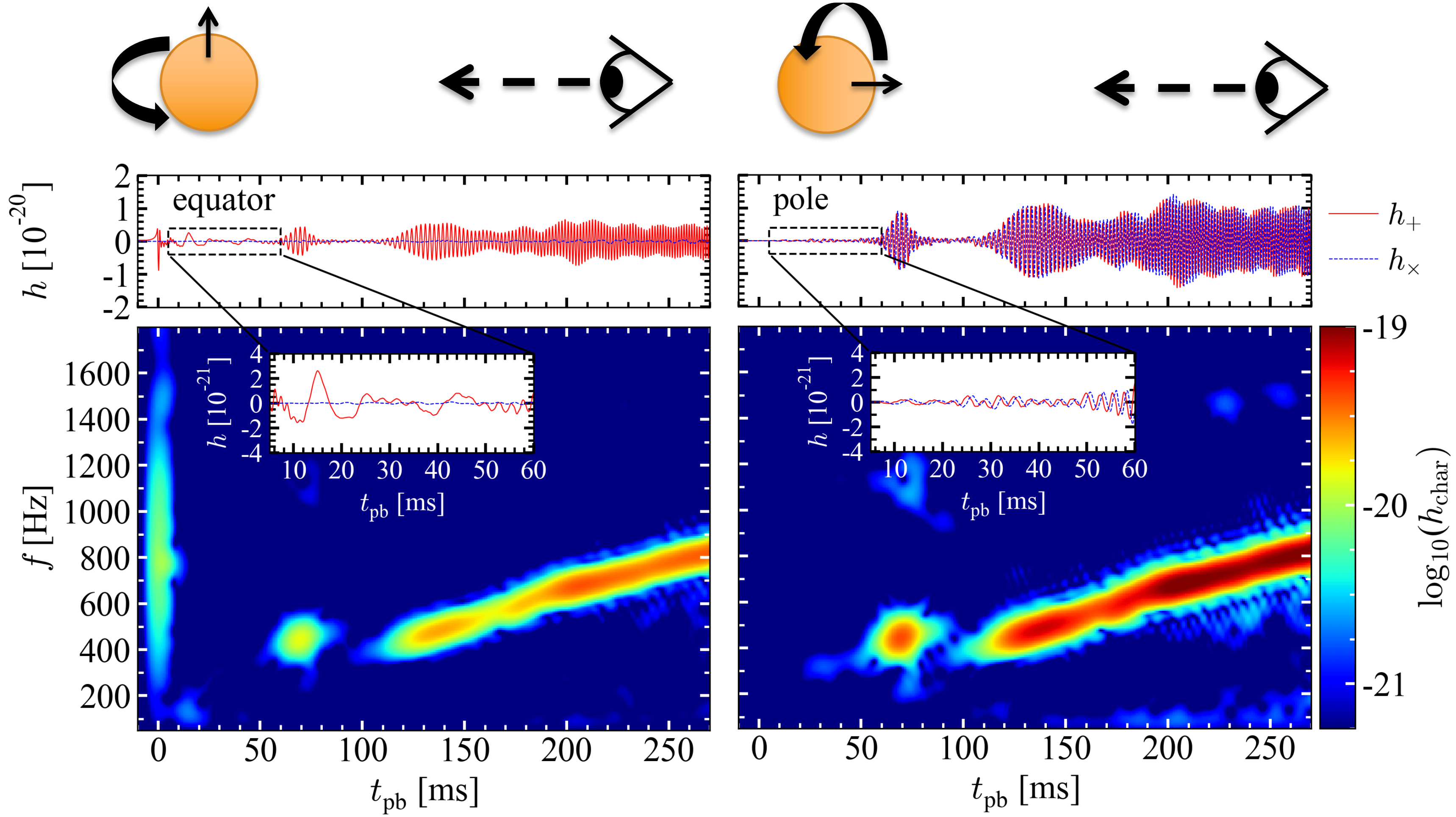
Shock Radius

Ω_0=2rad/sec



GW Spectrogram

Ω_0=2rad/sec

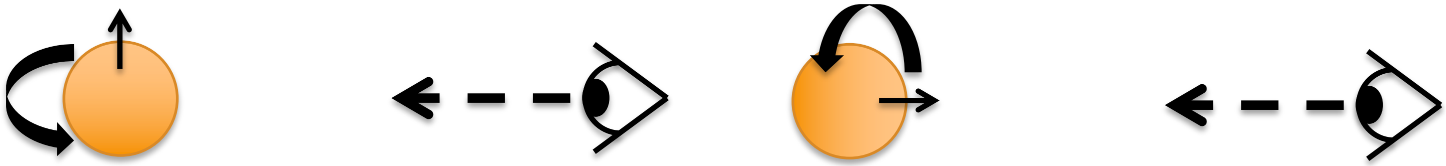


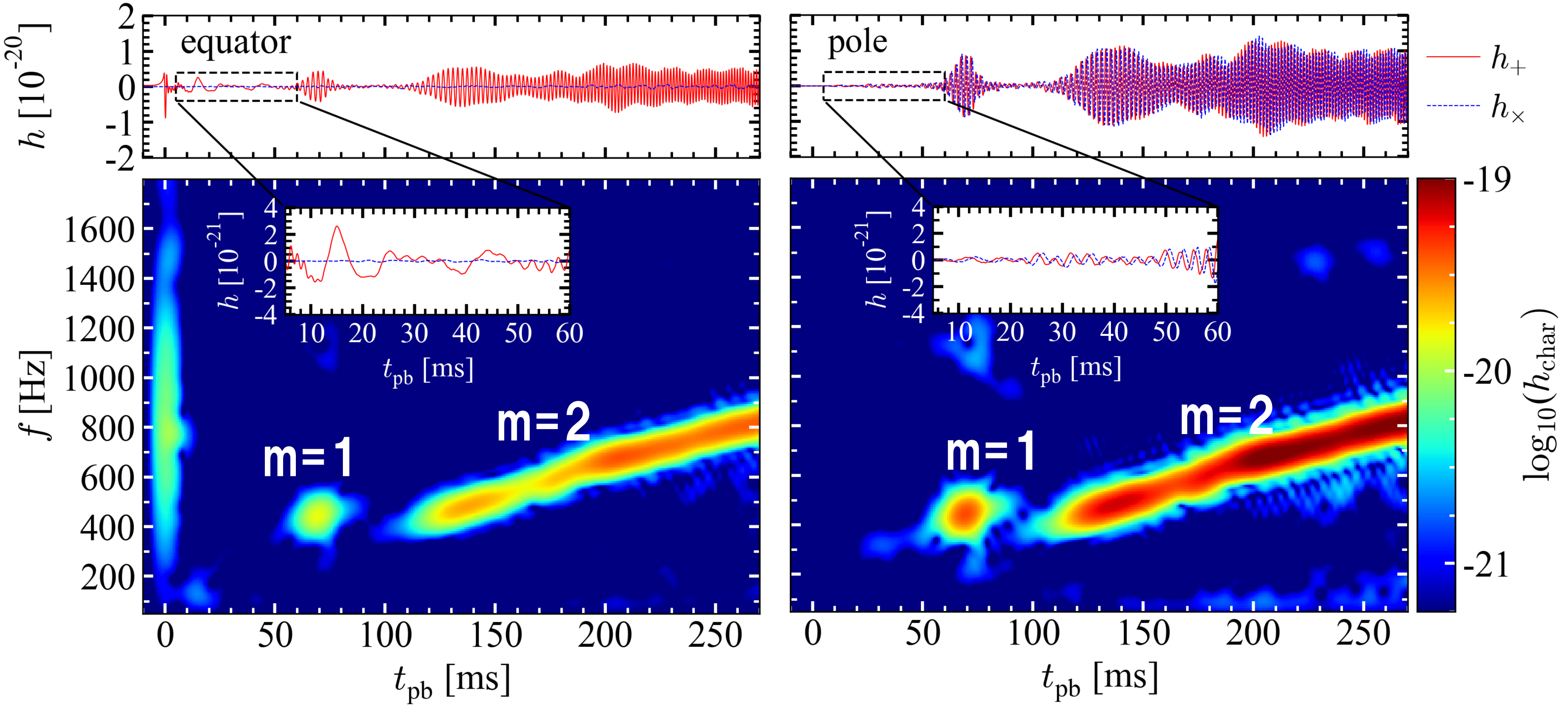
Short term Fourier trans.

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

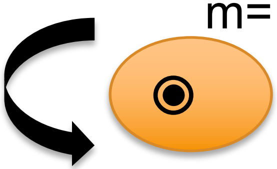
GW Spectrogram

Ω_0=2rad/sec

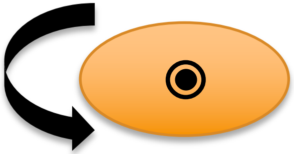




low T/|W| instability



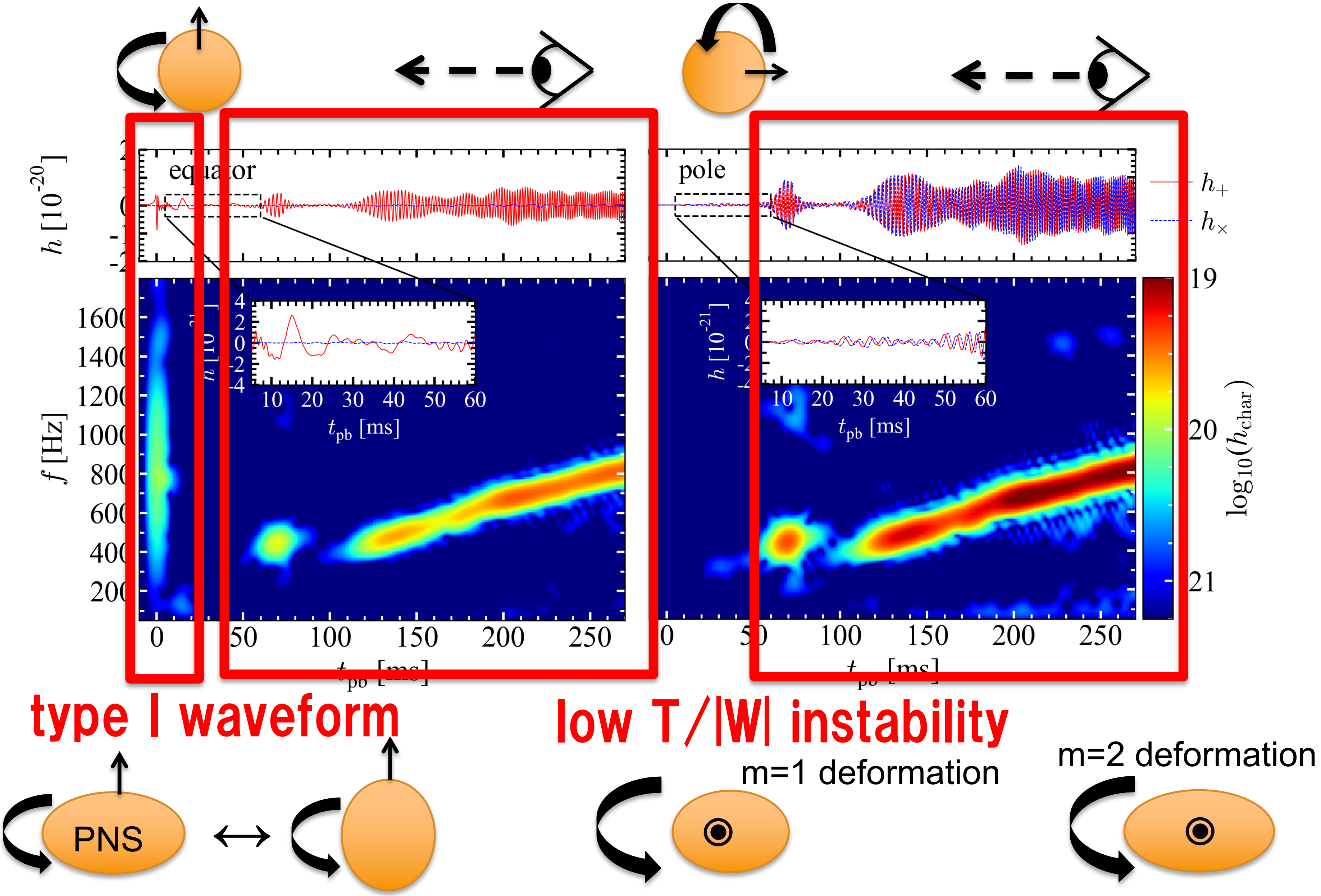
m=1 deformation



m=2 deformation

GW Spectrogram

Ω_0=2rad/sec



type I waveform

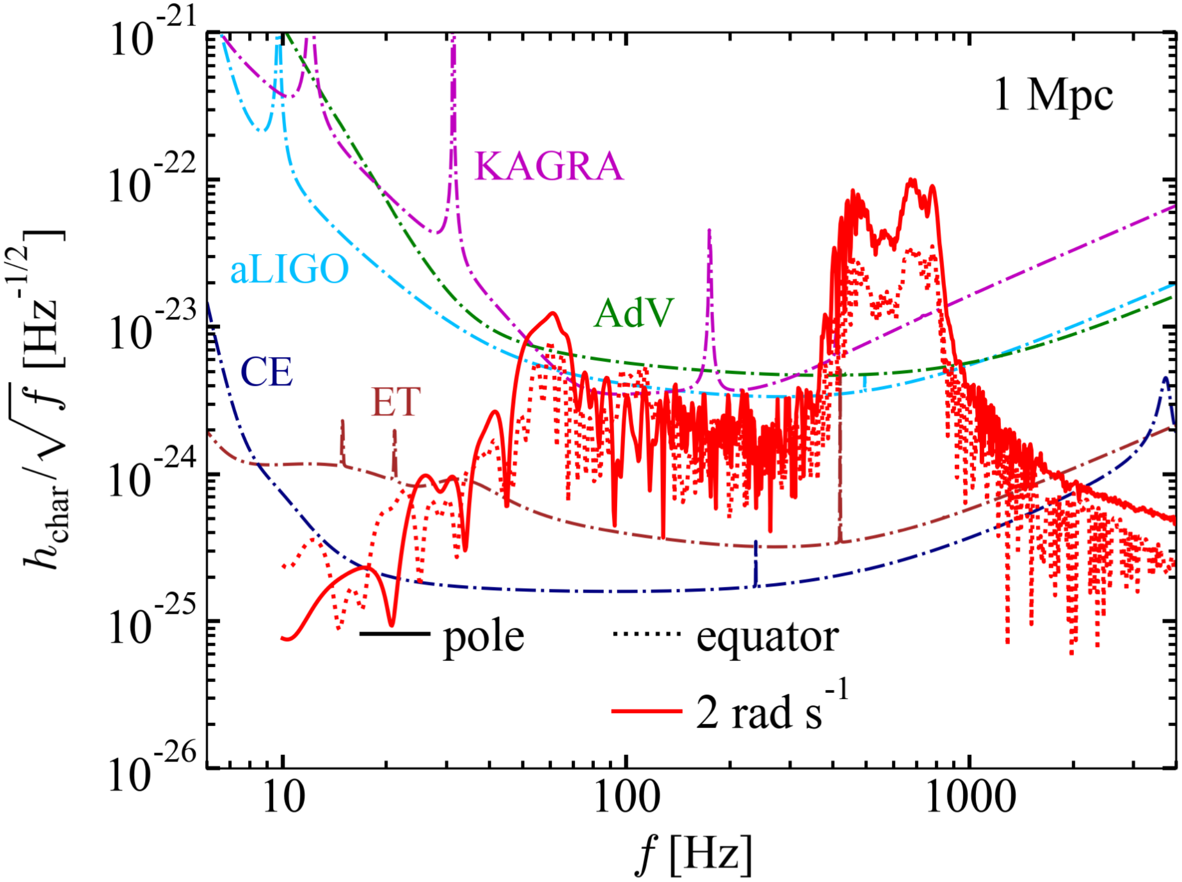
low T/|W| instability

m=1 deformation

m=2 deformation

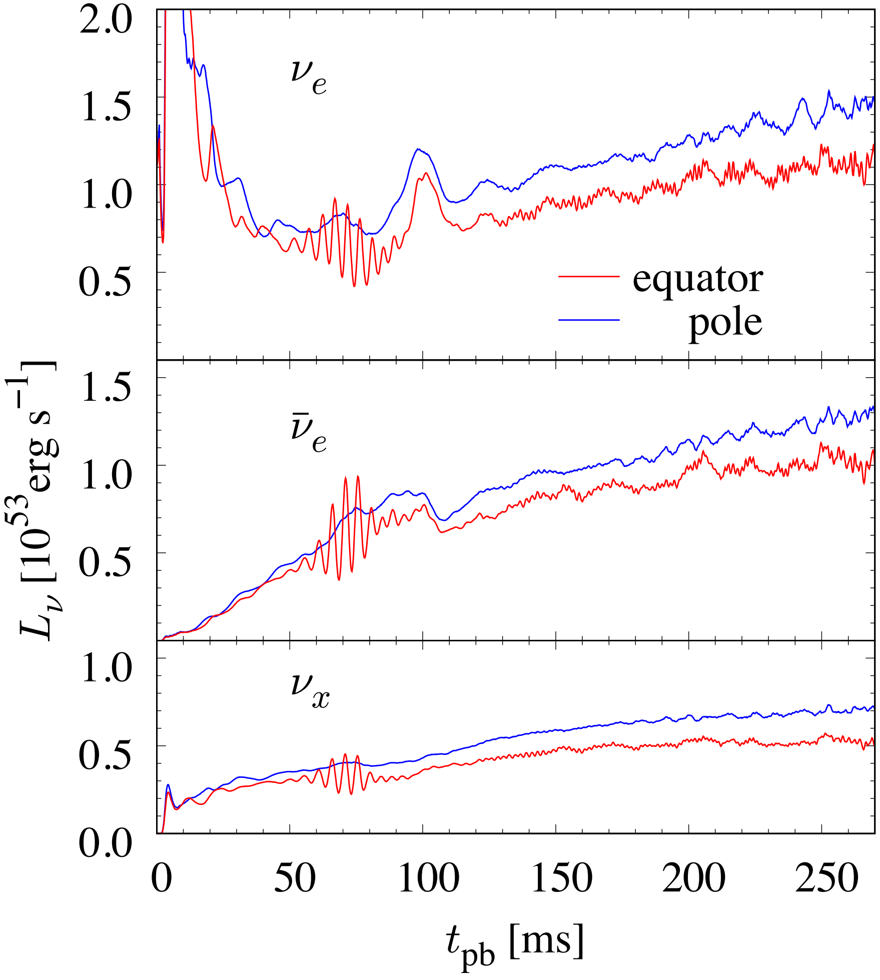
GW Detectability

Ω_0=2rad/sec

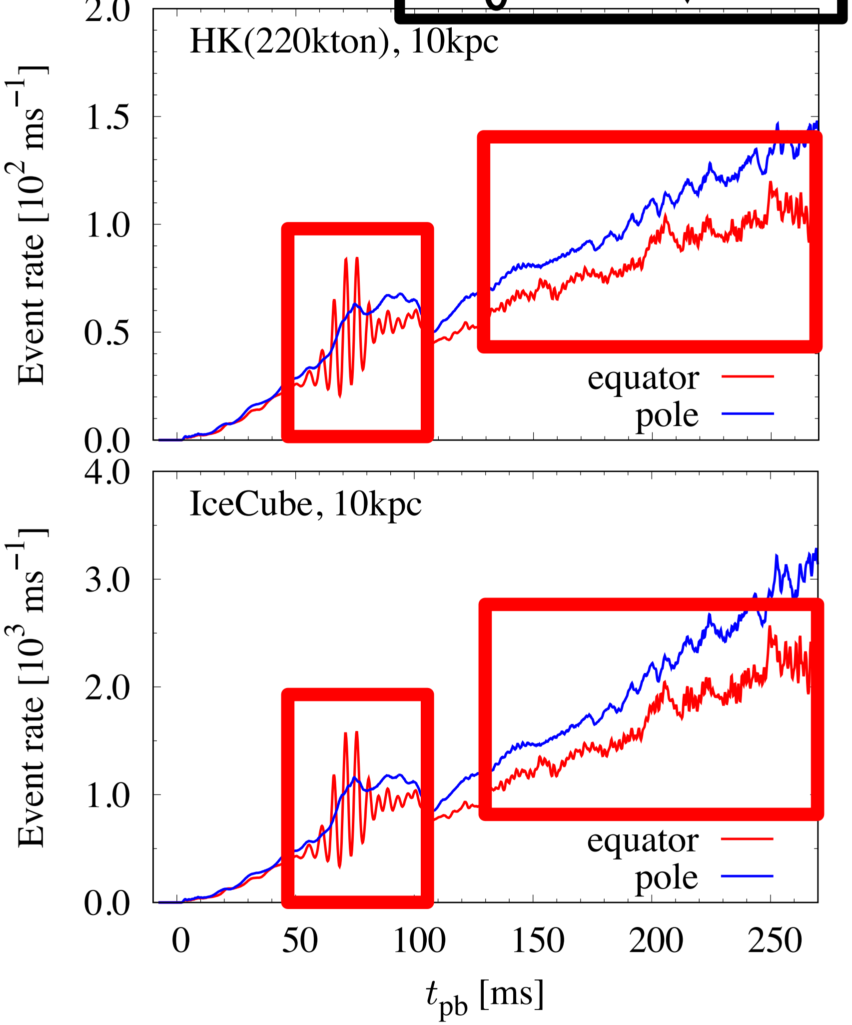


Current GW detectors have a potential to detect this GW up to ~Mpc scale!!

Neutrino luminosity and event rate



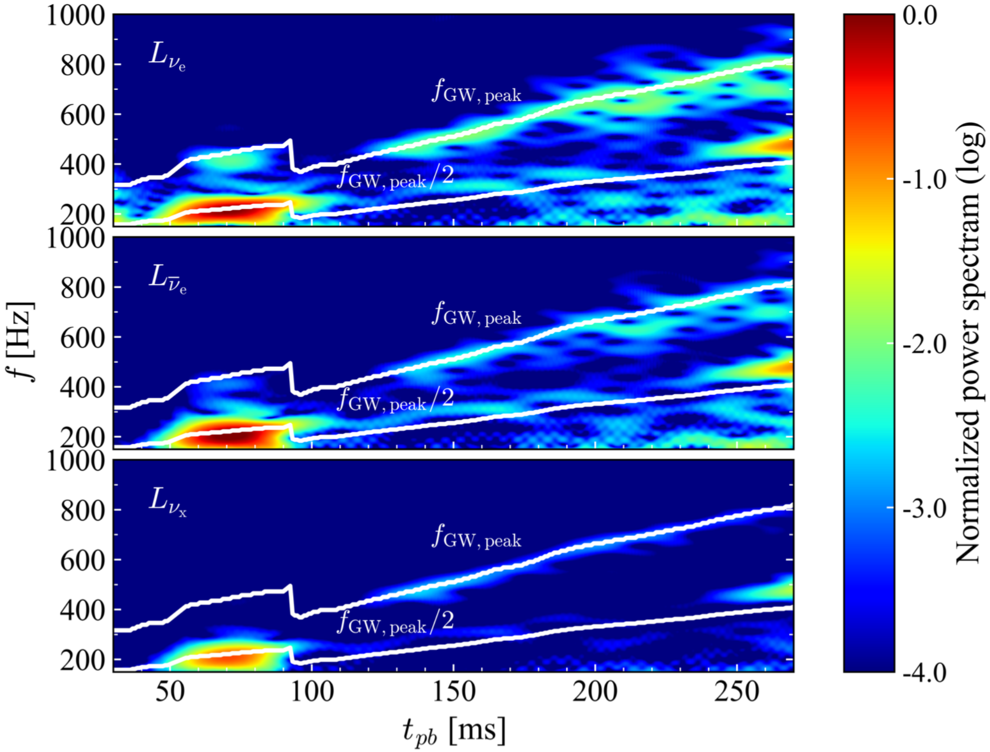
Ω_0=2rad/sec

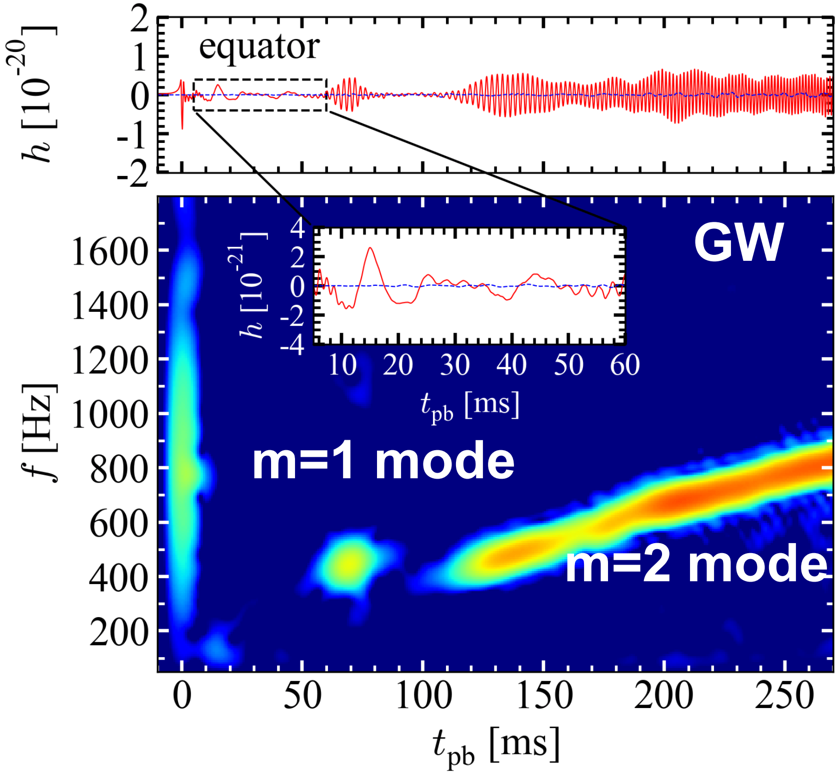


Oscillation in event rate found for equatorial observer

Neutrino spectrogram（equator）

Ω_0=2rad/sec



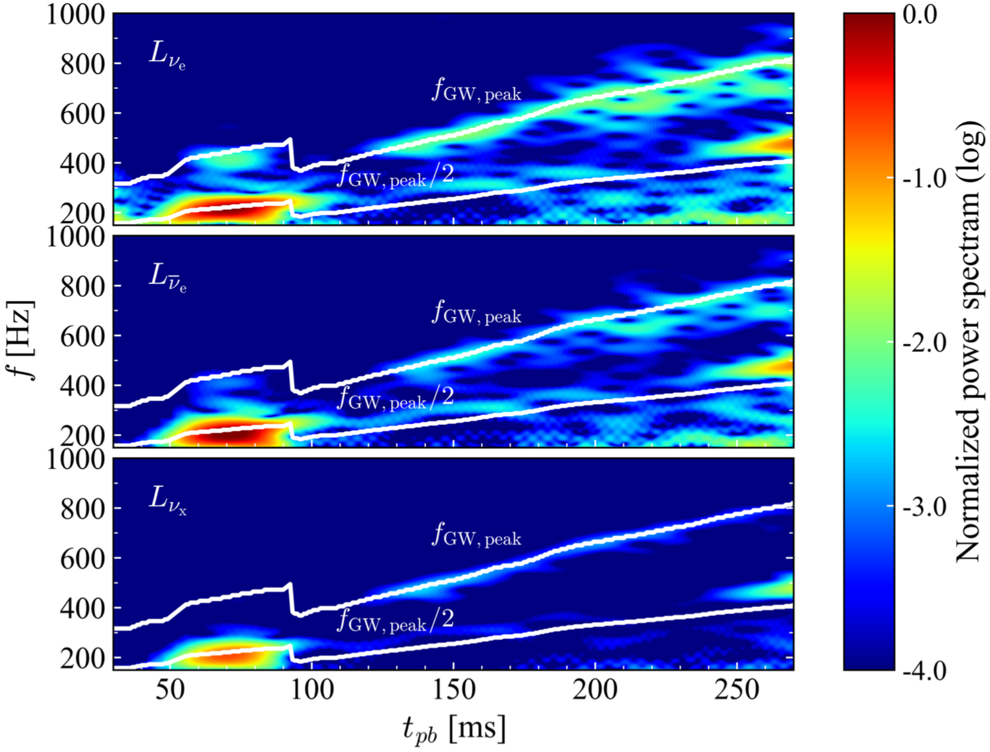


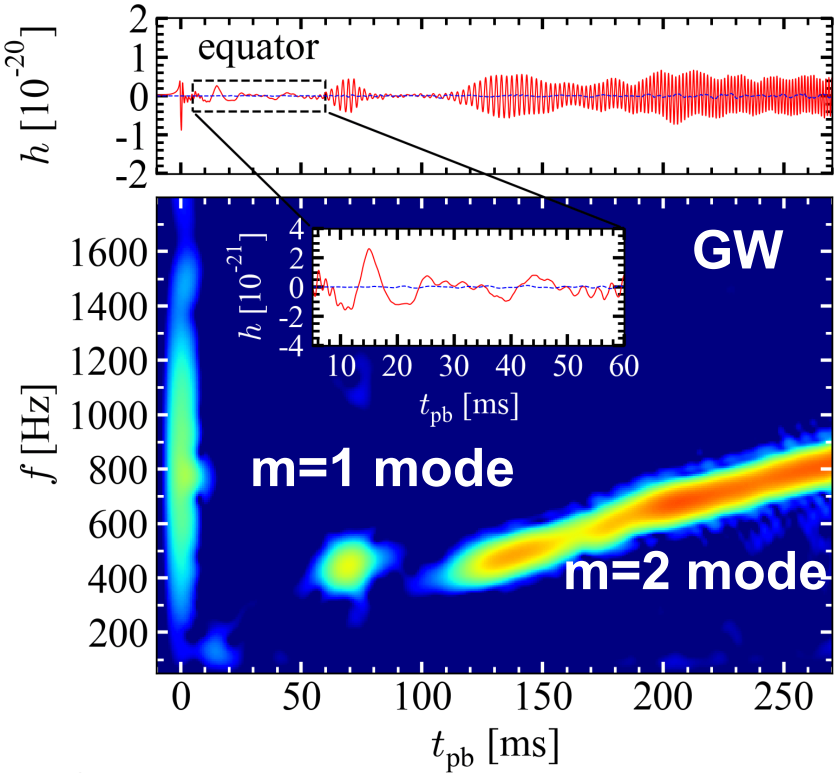
Correlation between GW and neutrino!!

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）

Ω_0=2rad/sec





m=1 deformation

m=2 deformation

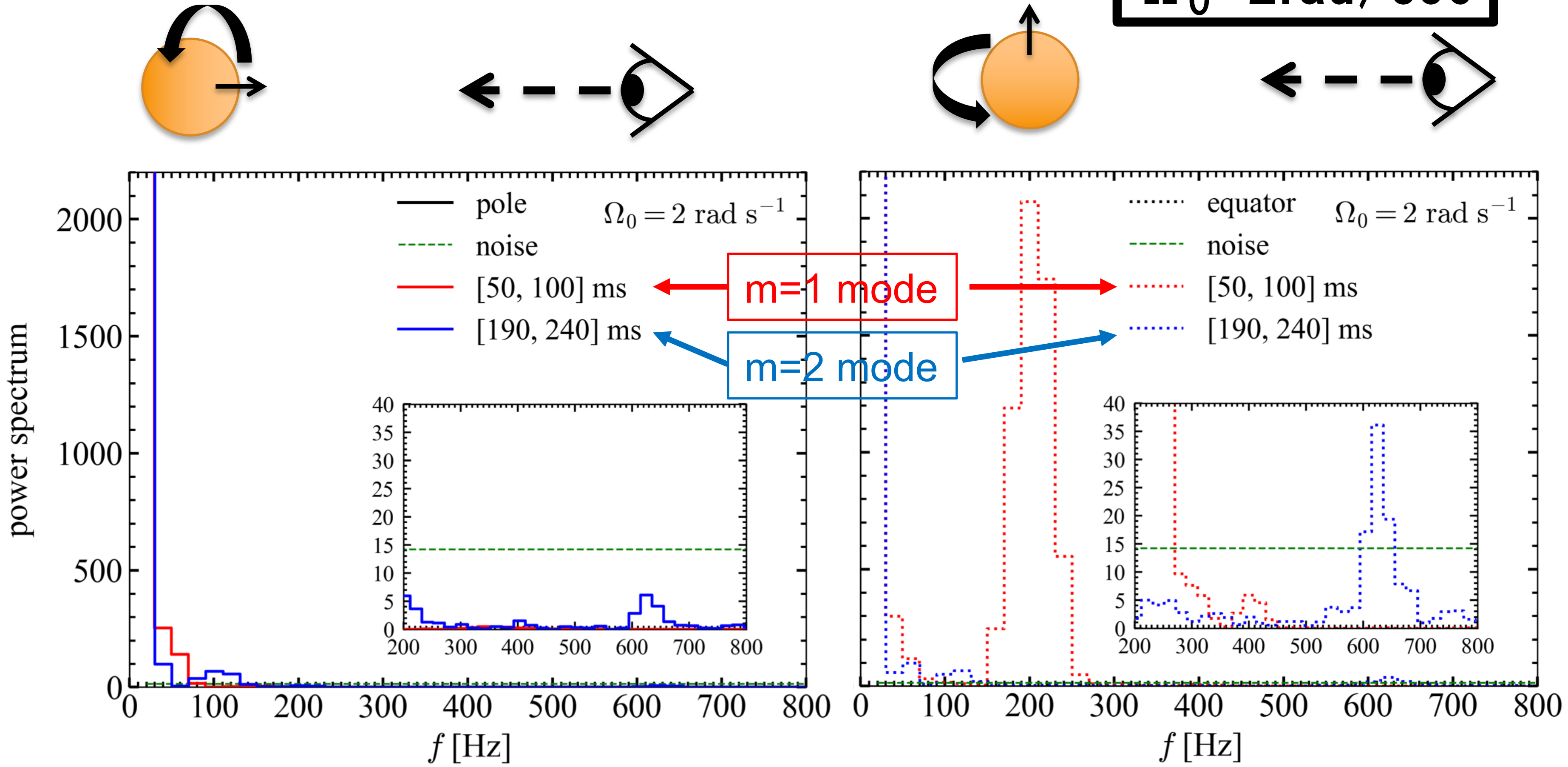
hot spot (s)

neutrino sphere

Neutrino event rate（spectrum)

IceCube @10kpc

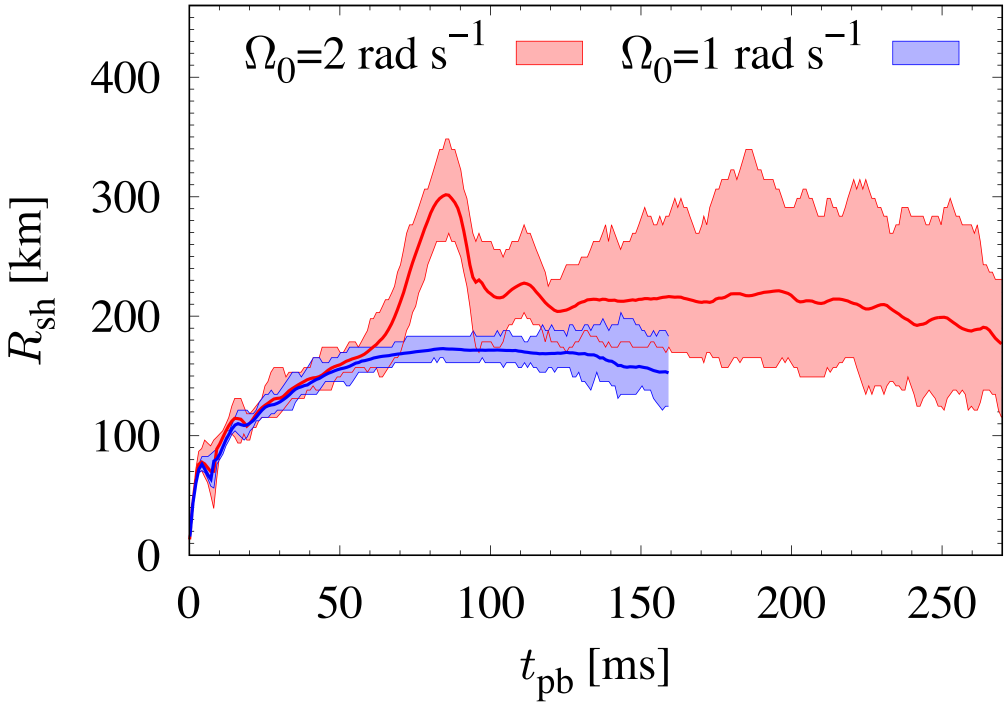
Ω_0=2rad/sec



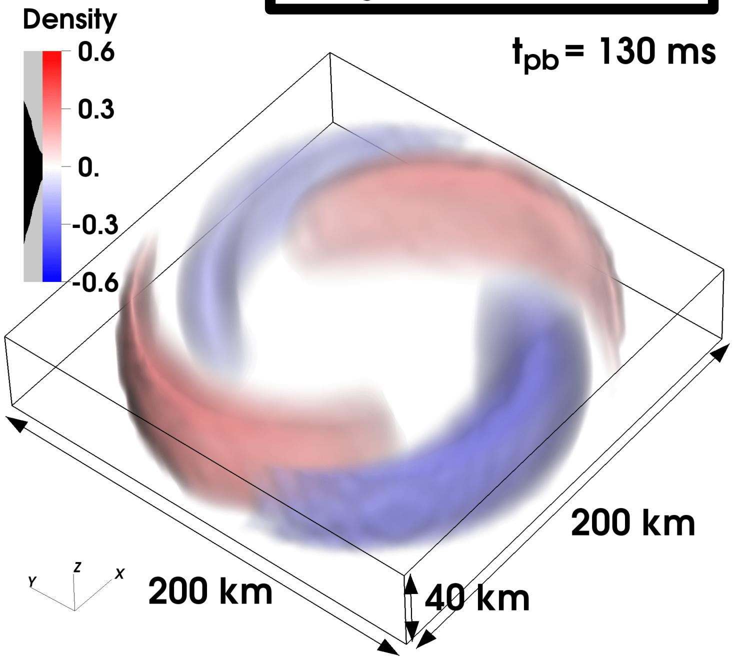
Polar observer:
no clear oscillation

Equatorial observer:
oscillation observed

Comparison with Ω_0=1rad/sec model



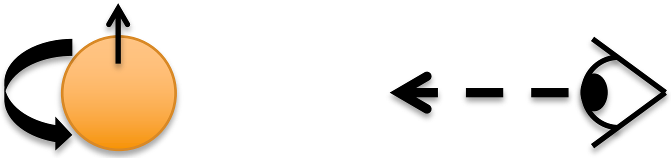
Ω_0=1rad/sec



Shock is stalled like normal non-rotating core-collapse.
Two spiral arms are generated (m=2 mode).

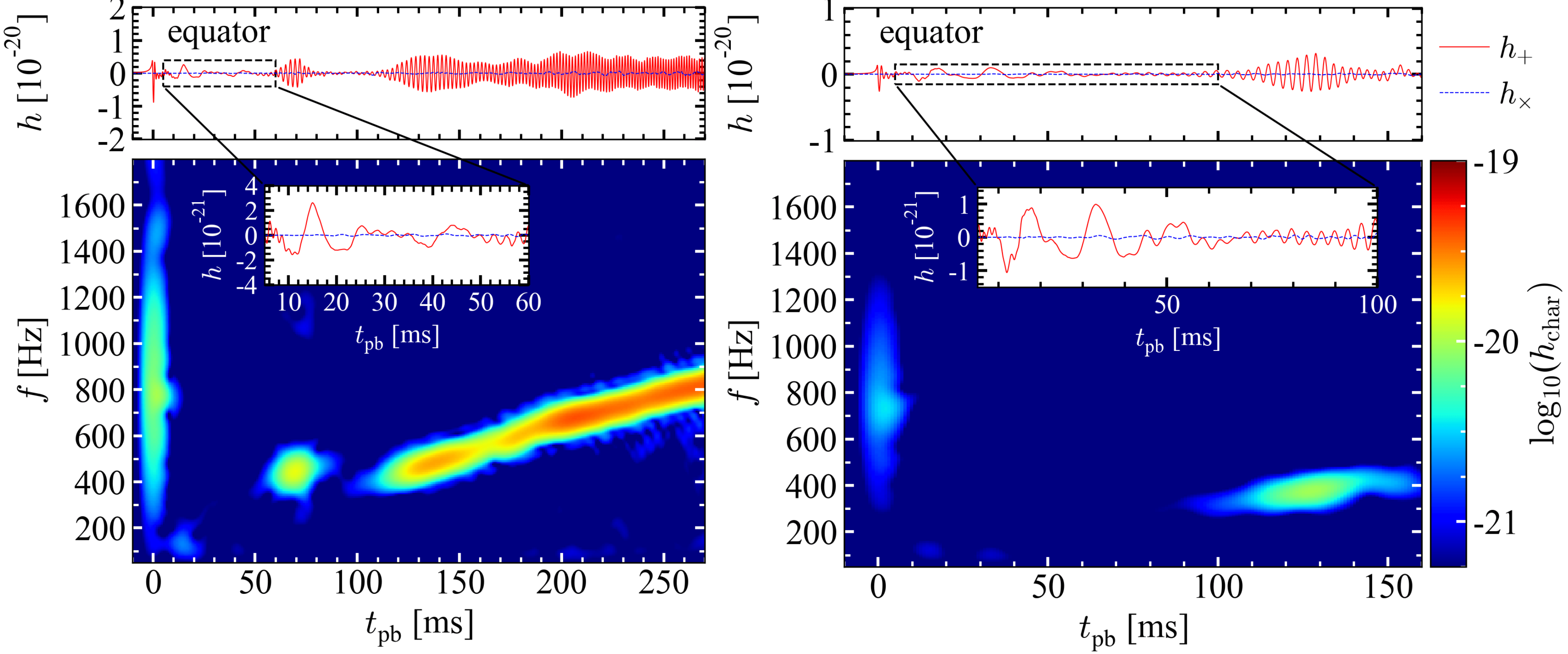
Comparison with Ω_0=1rad/sec model

@10kpc



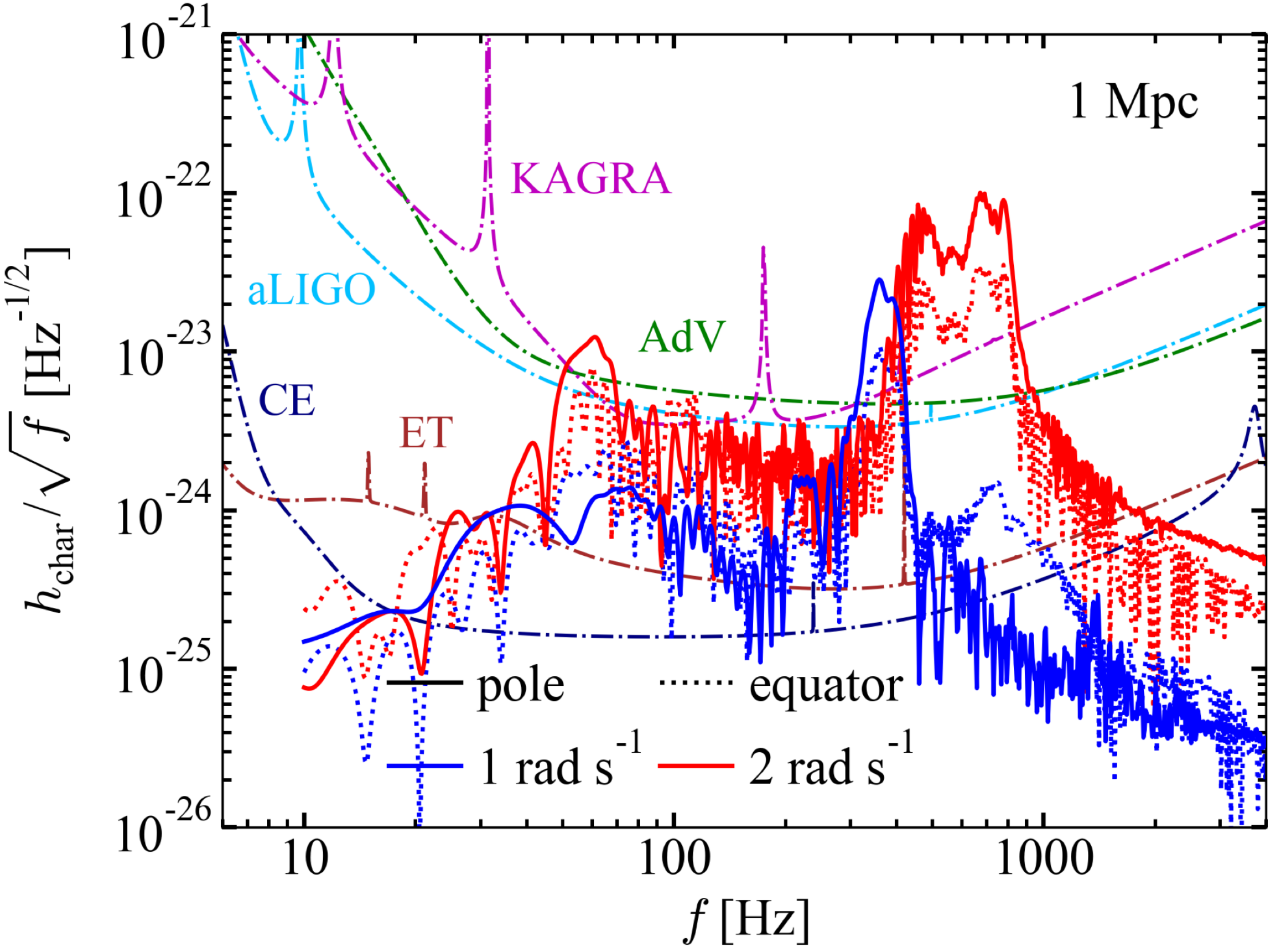
Ω_0=2rad/sec

Ω_0=1rad/sec



Weaker low-frequency GW signal in Ω_0=1rad/sec model

GW Detectability

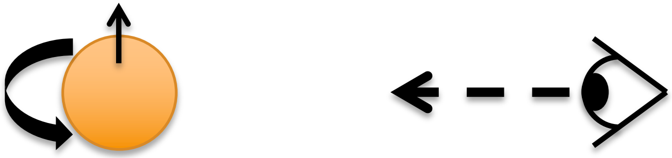


Current GW detectors have a potential to detect these GWs up to ~Mpc scale!!

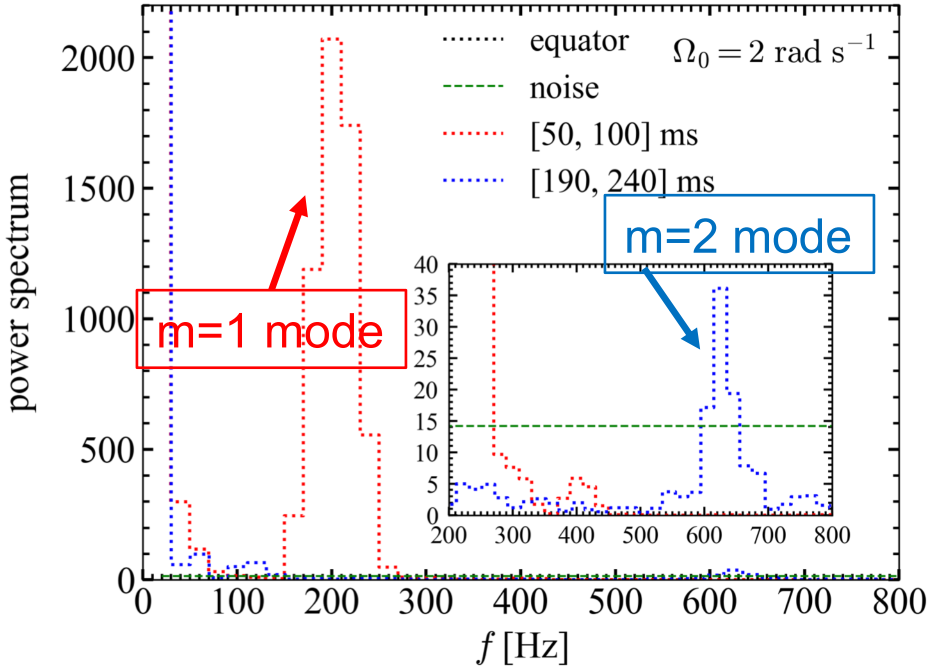
Neutrino event rate（spectrum）

@10kpc

Ω_0=2rad/sec

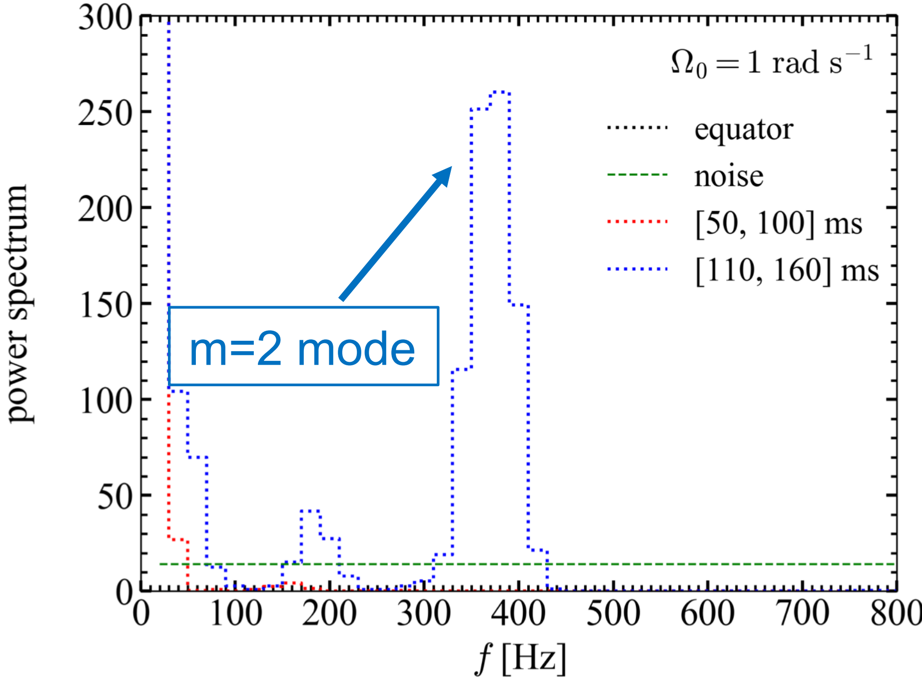


Ω_0=1rad/sec



m=1 mode

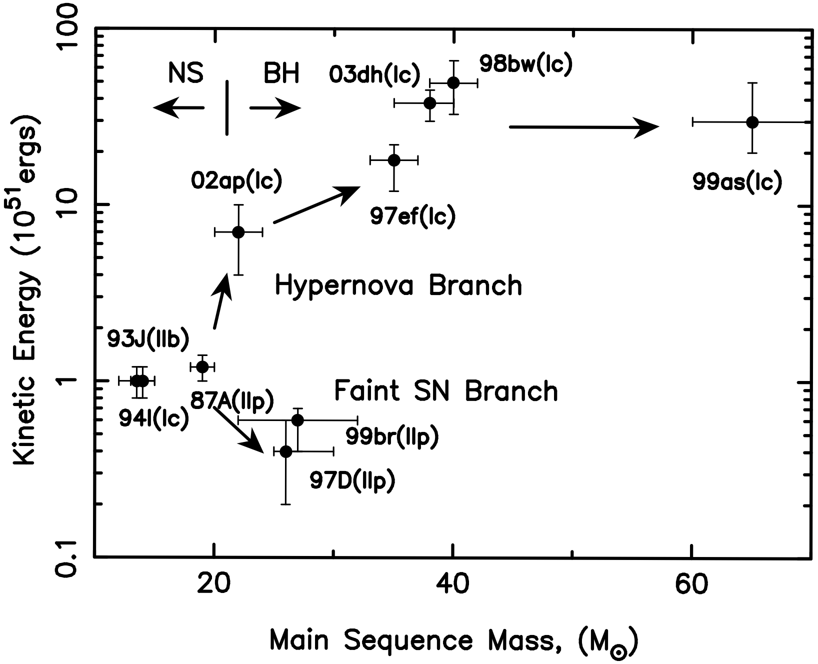
m=2 mode

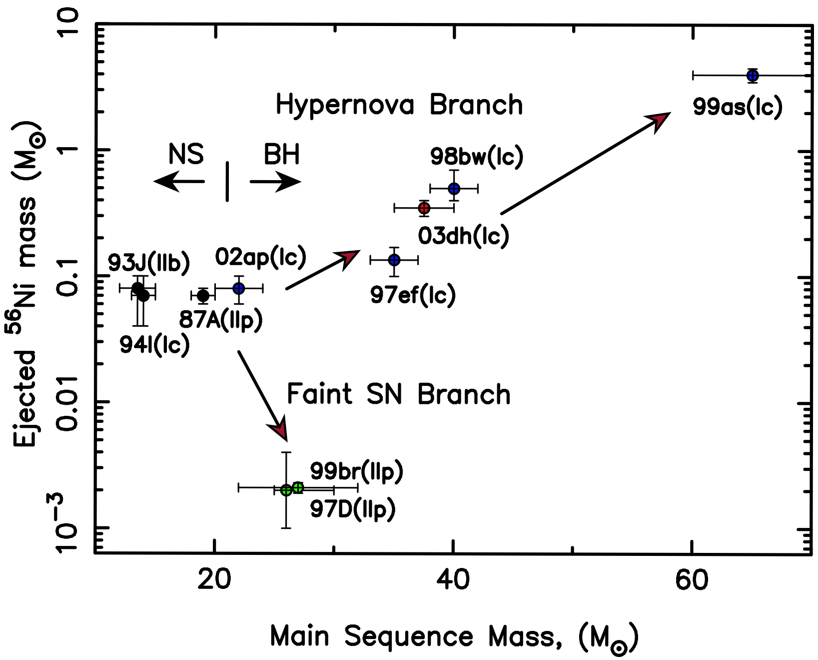


m=2 mode

Lower peak amplitude in Ω_0=1rad/sec,
but it still exceeds the noise level!!

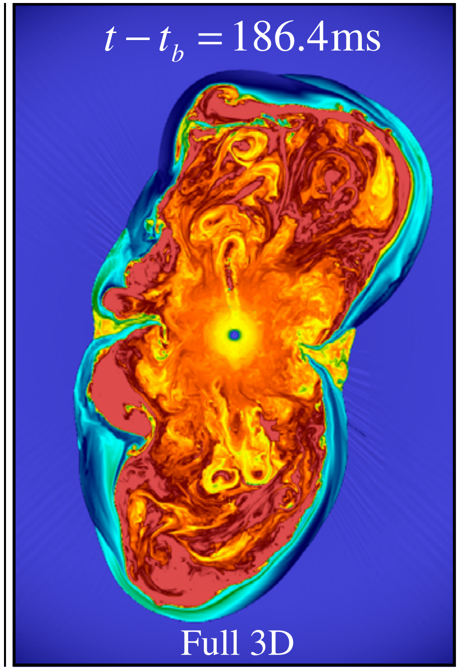
Energetic supernova



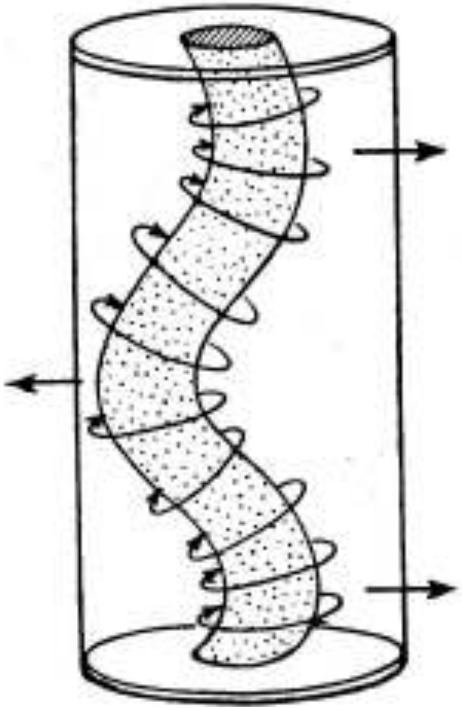


Nomoto et al. 2005

3D MHD Jet SN



Moesta et al. 2014



Kink instability

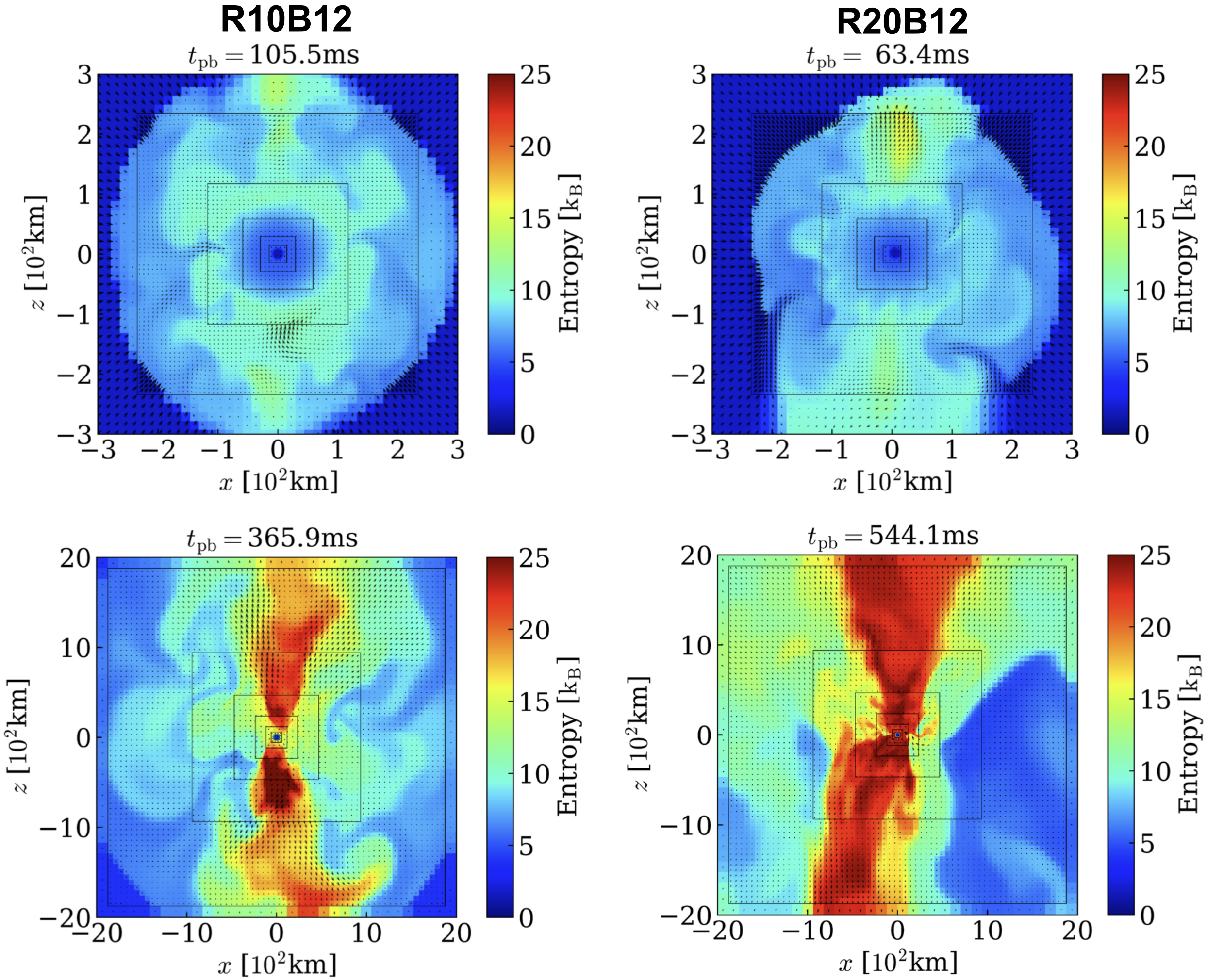
Setup

- Progenitor: s20（Woosley & Heger2007）
- full GR RMHD code（Kuroda et al. 2020, 2021）
- neutrino transport: M1 scheme
- 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

Entropy

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

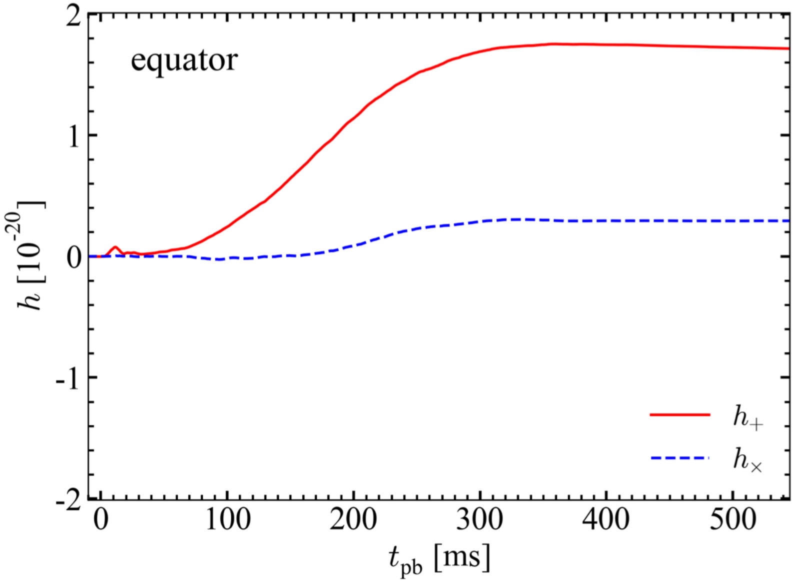


Shibagaki, Kuroda, Kotake, Takiwaki, Fischer (2024)

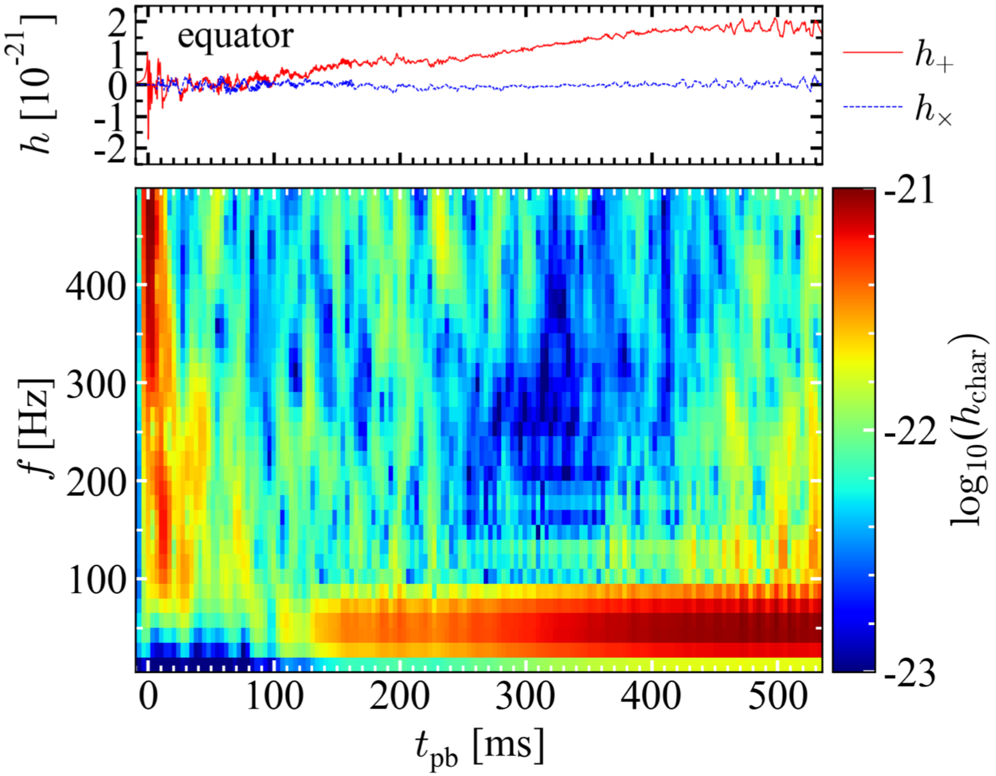
GW Spectrogram

R20B12
equatorial observer

neutrino



matter

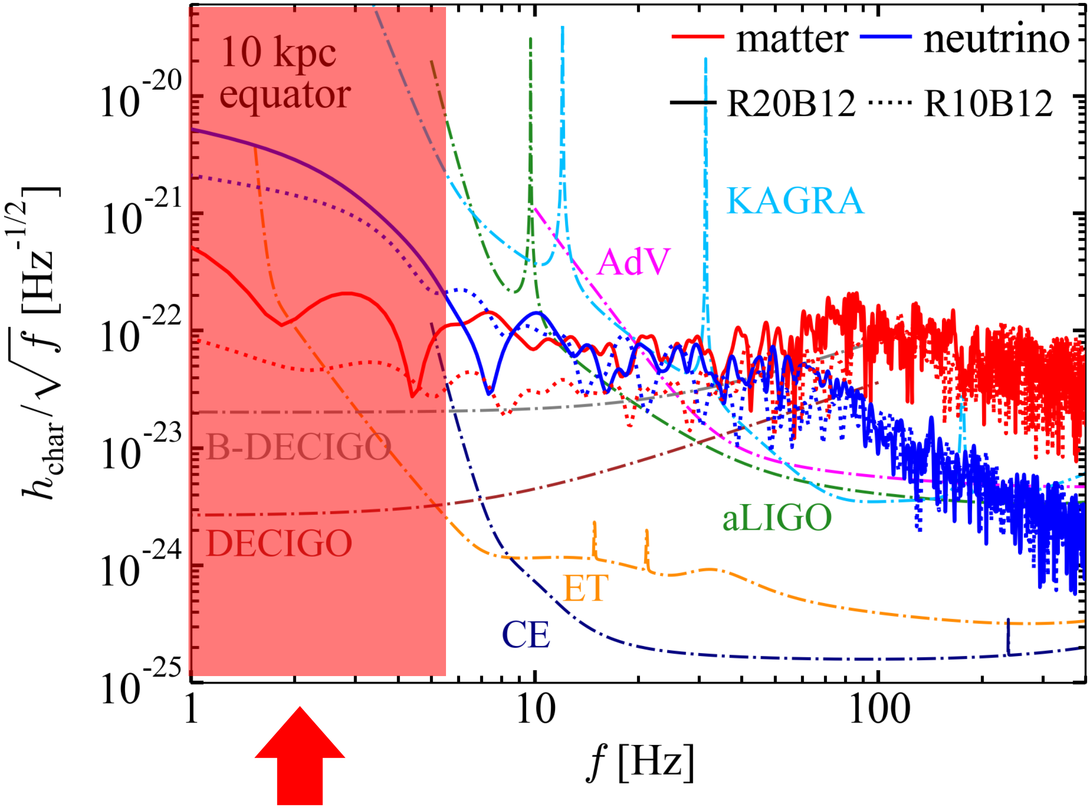


Both MHD jets and asymmetric neutrino emissions contribute to the generation of low-frequency GW.

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

GW Detectability

equatorial observer



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

Shibagaki, Kuroda, Kotake, Takiwaki, Fischer, accepted (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.
    - 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.
- Fully general relativistic 3D neutrino radiation-magnetohydrodynamics simulations of rotating magnetized core collapse
- GW from anisotropic neutrino emission may hide GW from hydrodynamic motion.