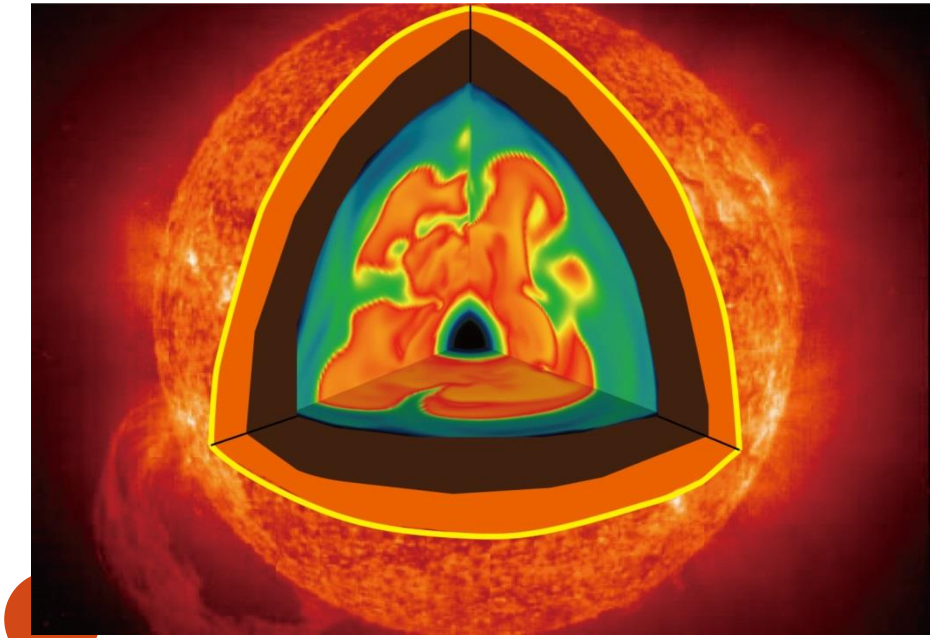
4th DTA Symposium on
Compact stars and gravitational wave astronomy
2016/05/13 at NAOJ

Gravitational Signals from Core-collapse Supernovae:
Cutting-edge samples



Tomoya Takiwaki

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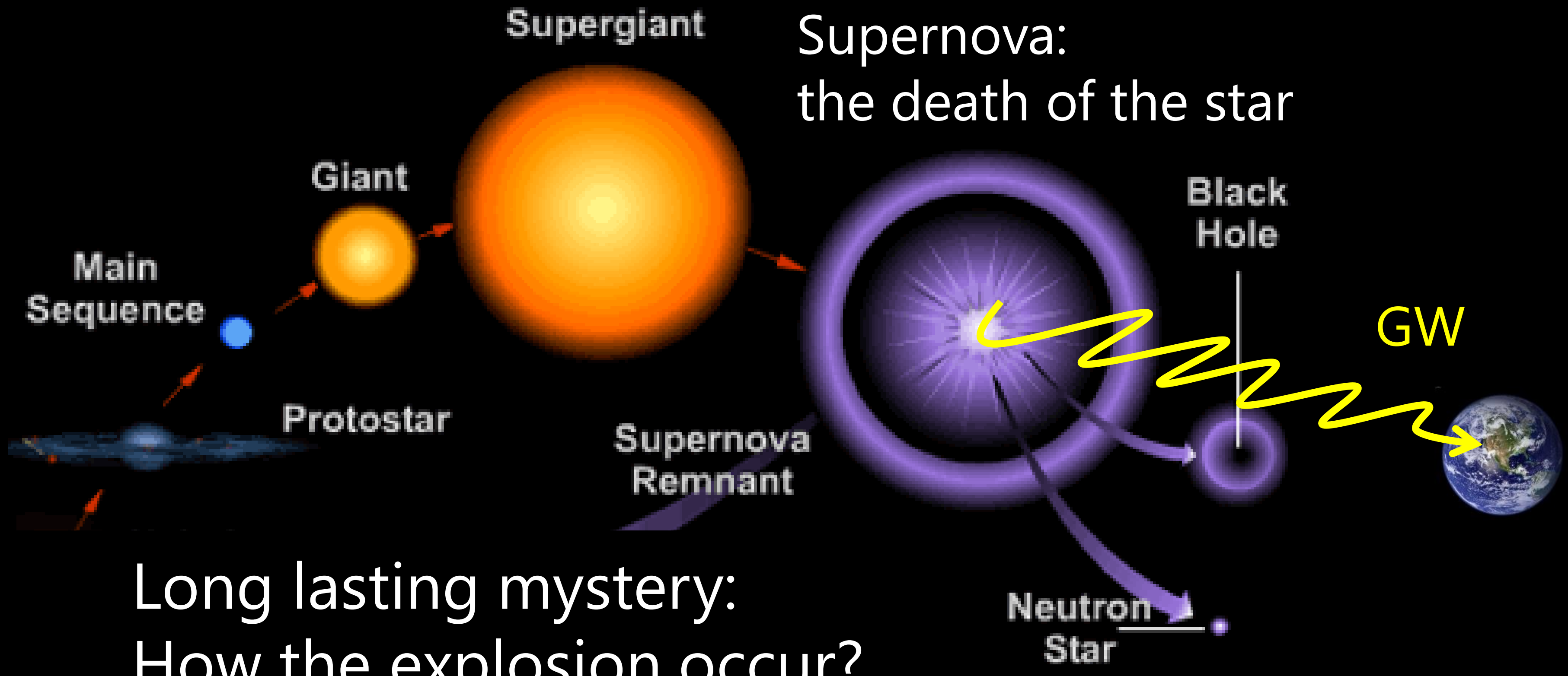
Collaborators:
Takami Kuroda,
Kazuhiro Hayama and
Kei Kotake

GW from Supernova

Purpose:

- Signal gives information of deep inside of the star

GWs is the key to understand the mystery of SNe



Supernova:
the death of the star

Long lasting mystery:
How the explosion occur?

GW from Supernovae

Purpose:

- Signal gives information of deep inside of the star

GWs is the key to understand the mystery of SNe

Difficulty:

- Rare event: 1-3 /(100 year) /(1 galaxy)
  =>I believe our luck. e.g. 1987a
- Complicated waveform.
  => Spectrogram overcomes this weak point.

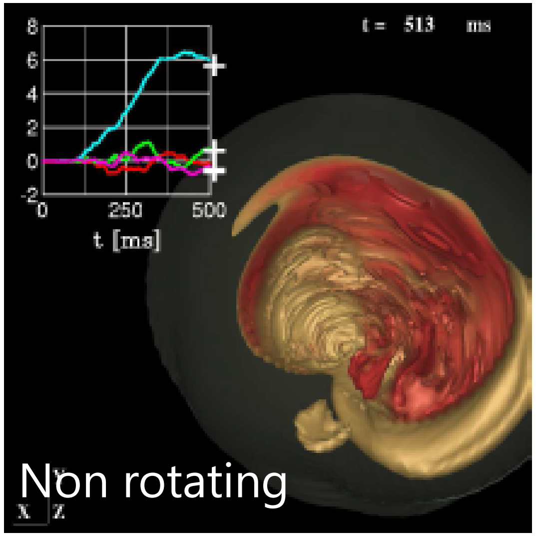
Advantage:

- ν is simultaneously detected. That helps the interpretation of the signals.
- Optical counter part is obvious

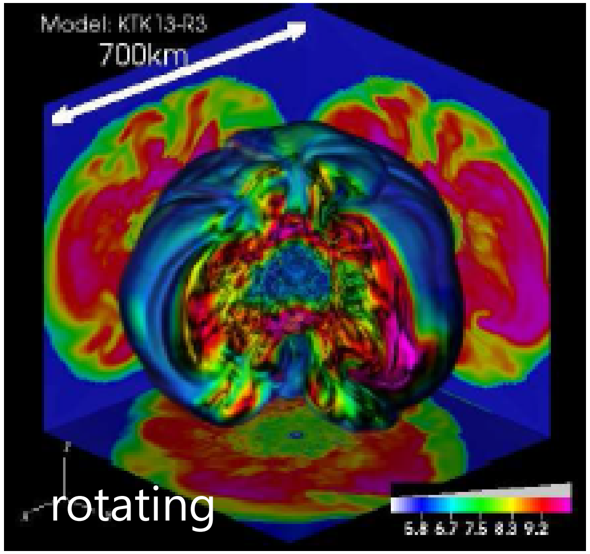
Several typical situations

Explosion mechanism depends on the profile of the progenitor

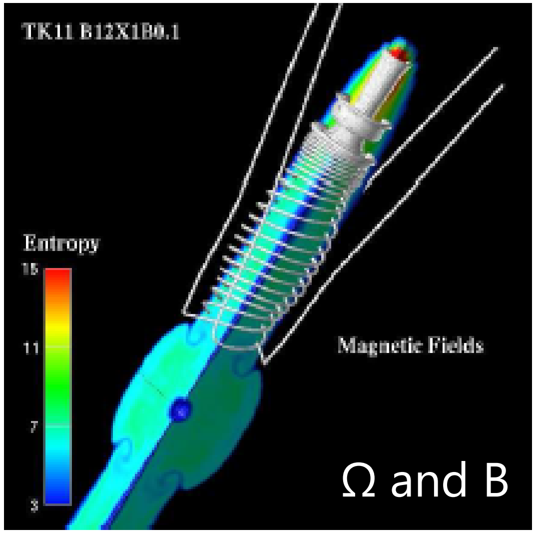
Hayama+2015



Non rotating



rotating



Ω and B

We consider three typical situations.

(1) No rotating no magnetic progenitors

(2) Rotating no magnetic progenitors

(3) Rotating magnetic progenitors

Like BHs?

Schwarzschild

Kerr

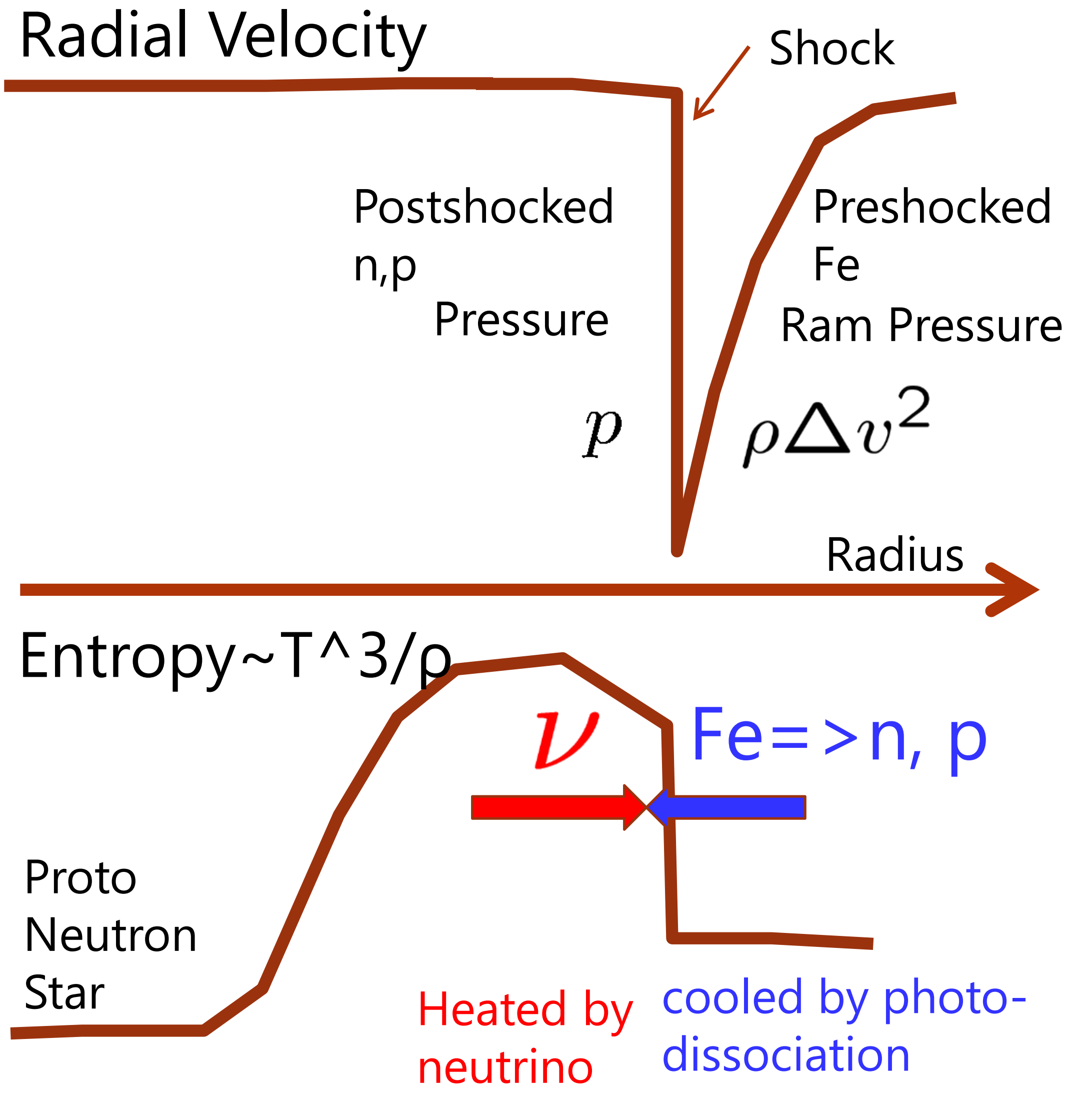
Kerr-Newman

Two typical cases

- Non rotating progenitor
  1. Explosion Mechanism
  2. 2D simulations
  3. 3D simulations
- Rapidly rotating progenitor
  1. Axisymmetric simulations
  2. Non Axisymmetric simulations

Typical 1D simulation

Key aspects of Neutrino Mechanism



Radial Velocity

Shock

Postshocked n,p Pressure

p

Preshocked Fe Ram Pressure

$\rho \Delta v^2$

Radius

Entropy~T^3/ρ

ν

Fe=>n, p

Proto Neutron Star

Heated by neutrino

cooled by photo-dissociation

When the shock is stalling, Pressure inside and ram pressure out side balances.

$$p \sim \rho \Delta v^2$$

RHS is determined by stellar structure(density profile).

LHS is determined by two ingredients.

(1) Photo-dissociation

$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p} + \Delta Q$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} + \Delta Q$$

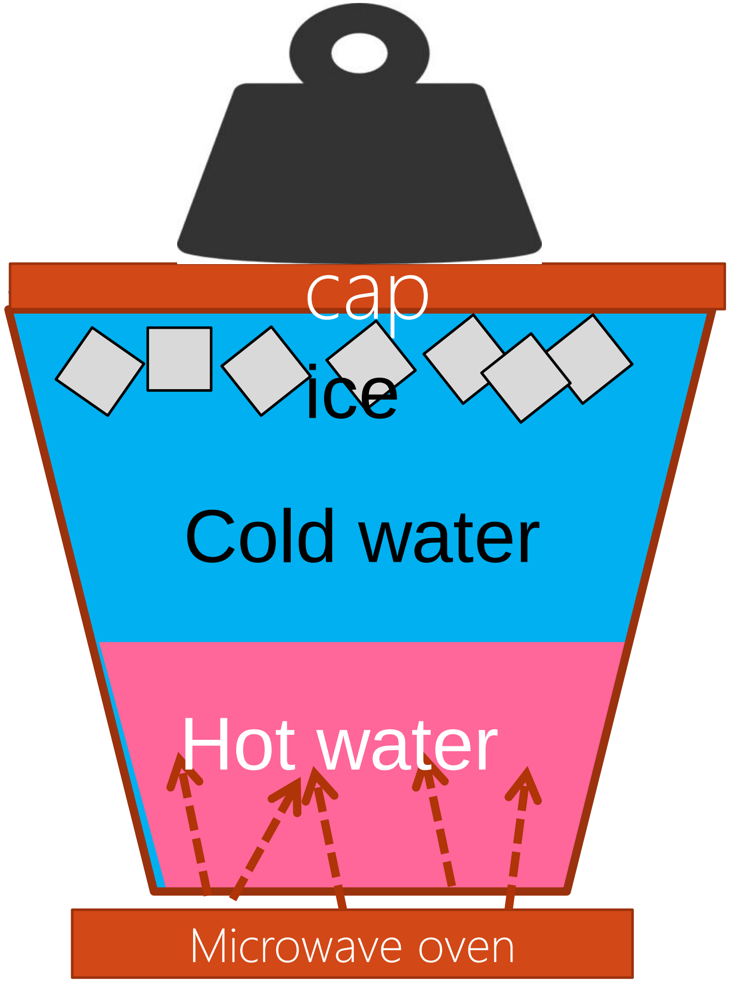
Problem

Supernova shock in simulation
tends to stall and
does NOT explode.

Long-lasting Problem ~1980.

In 2000-2005, state-of-the-art simulations with detailed neutrino transport confirm that!

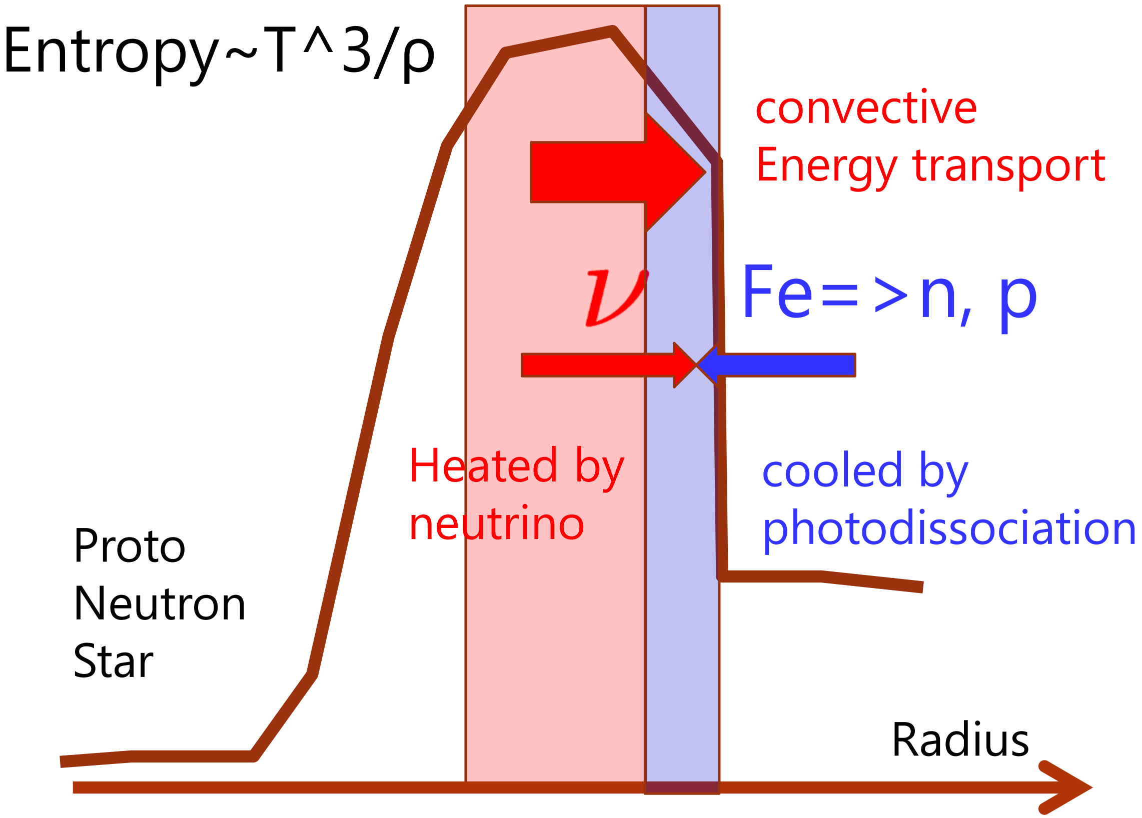
(Liebendoerfer+2001, Rampp+2002, Thompson+2003 and Sumiyoshi+2005)



(in 1D)Neutrino heating < ram pressure
=> fails to explode!

From 1D to 3D

Key aspects of Neutrino Mechanism



Entropy~T^3/ρ

convective
Energy transport

ν

Fe=>n, p

Heated by
neutrino

cooled by
photodissociation

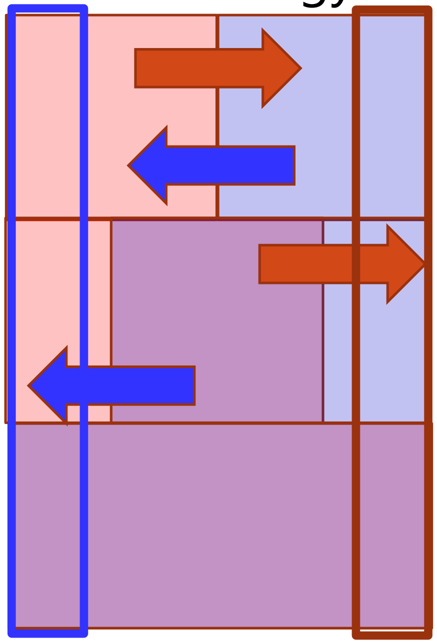
Proto
Neutron
Star

Radius

Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

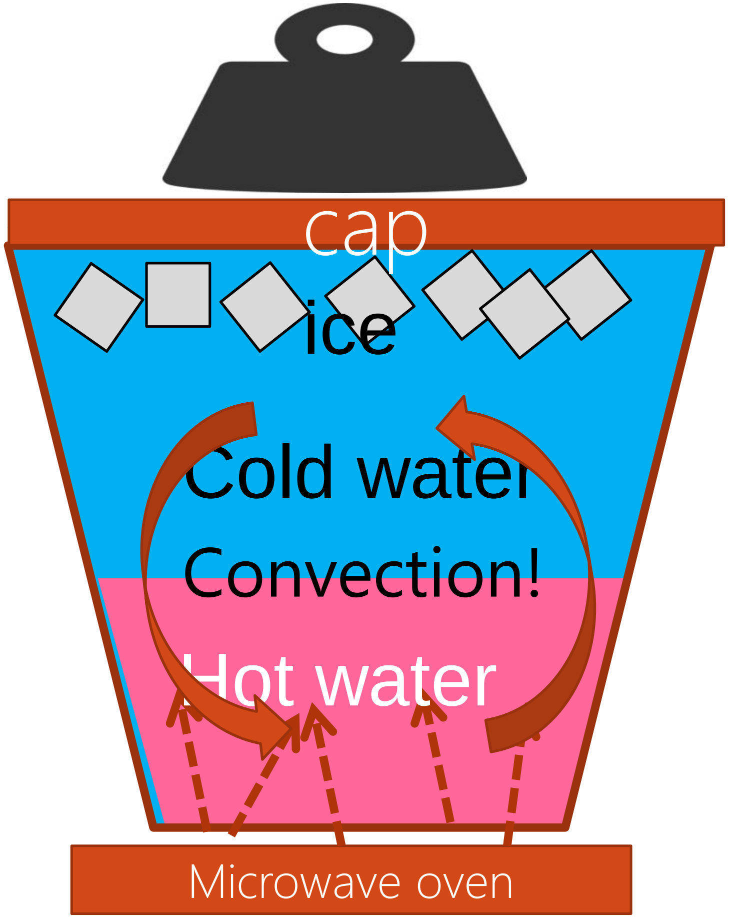
Rayleigh-Taylor convection transfer energy outward.

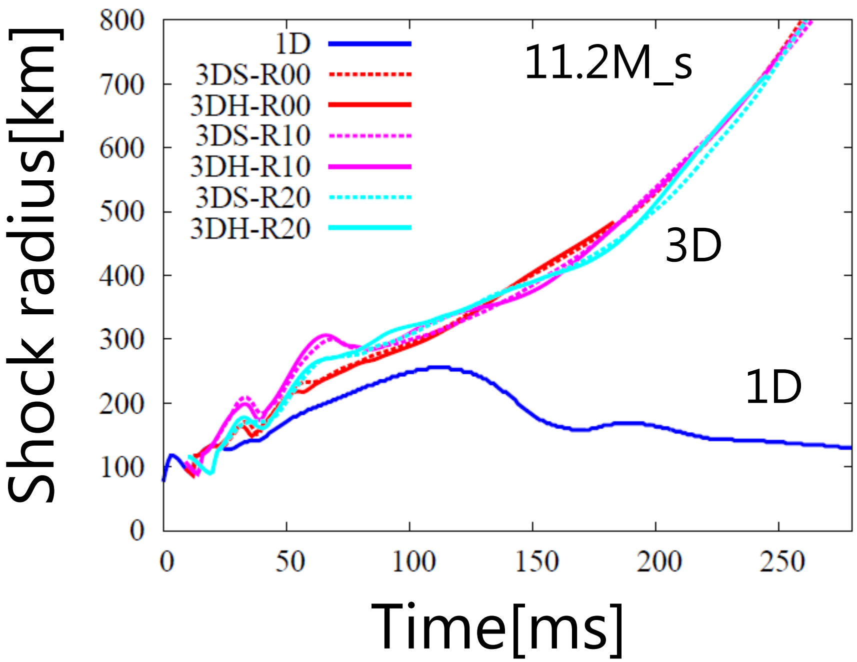


Cooler than
the initial
state but ν
heat is active

Hotter than
the initial
state

Successful 3D simulation





2 month times 16,000 cores are used in K computer

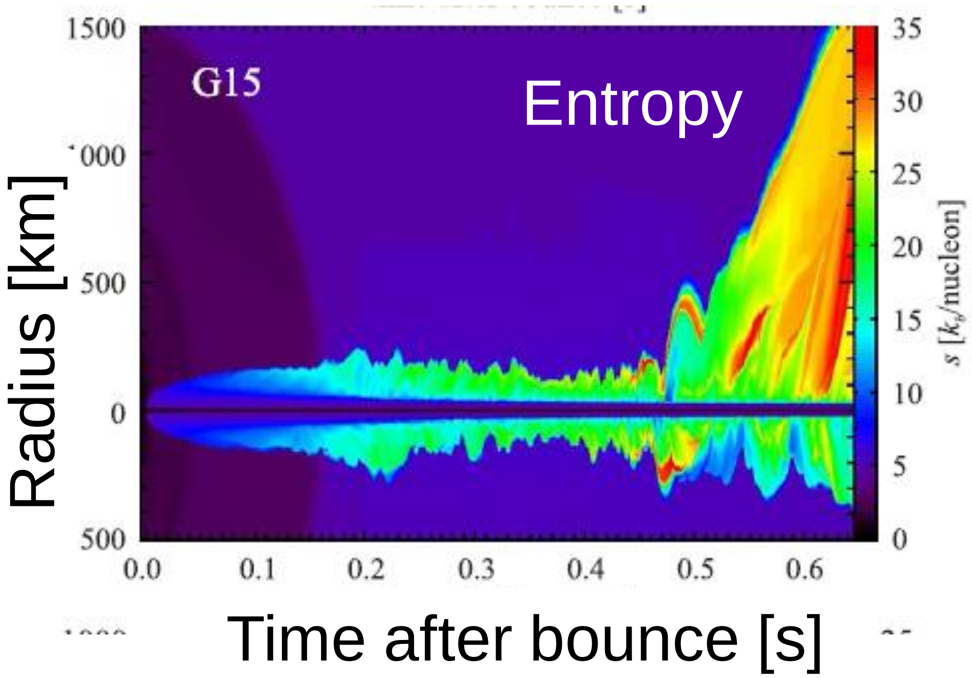
With convection hot water at the bottom is transported near the cap. The pressure at the cap become higher. Explosion occurs with the process.

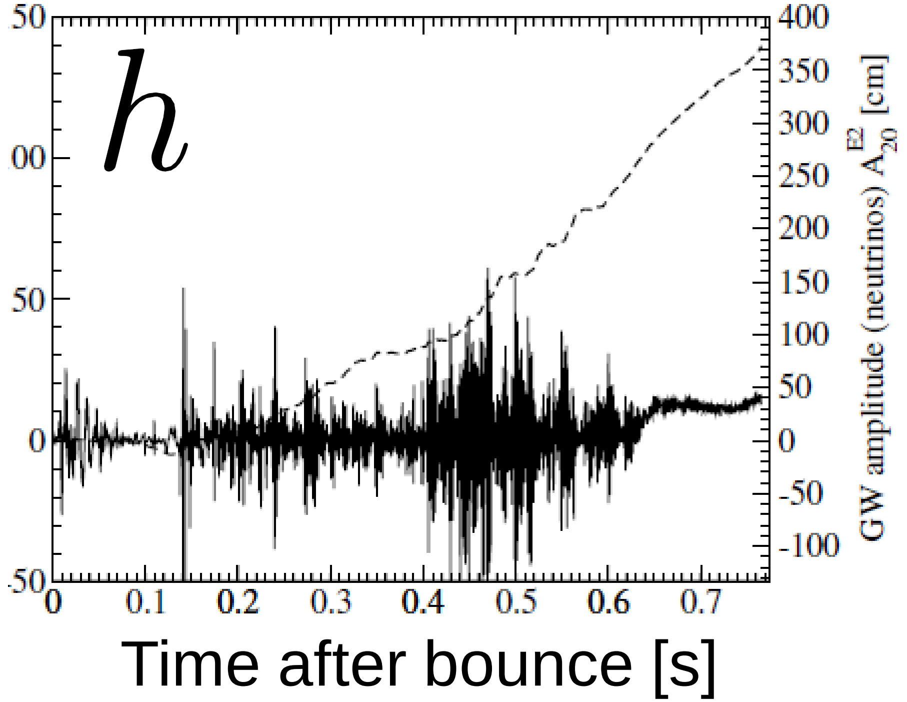
Takiwaki+2012,2014, in prep

Two typical cases

- Non rotating progenitor
  1. Explosion Mechanism
  2. GWs from 2D simulations
  3. GWs from 3D simulations
- Rapidly rotating progenitor
  1. GWs from Axisymmetric simulations
  2. GWs from Non Axisymmetric simulations

Typical Models in 2D sim.

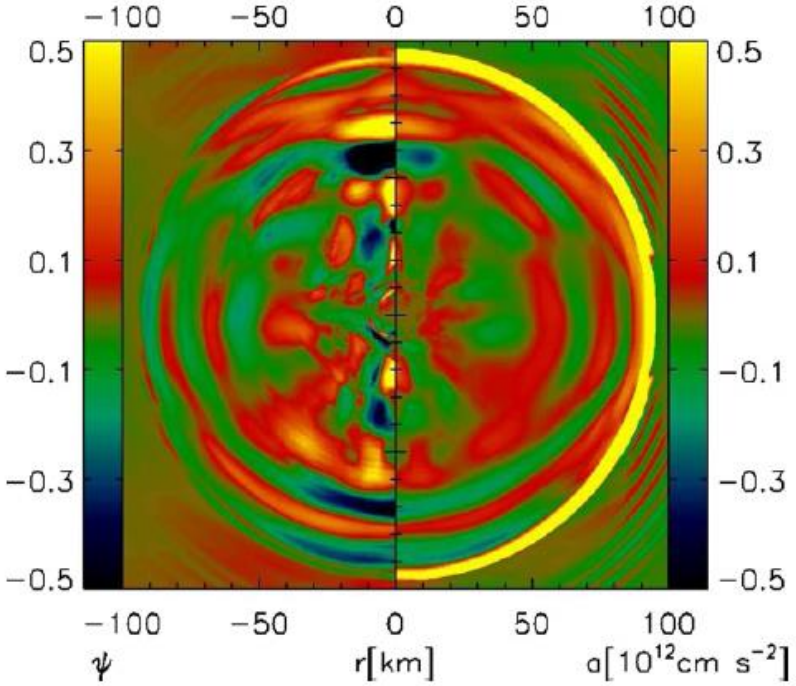


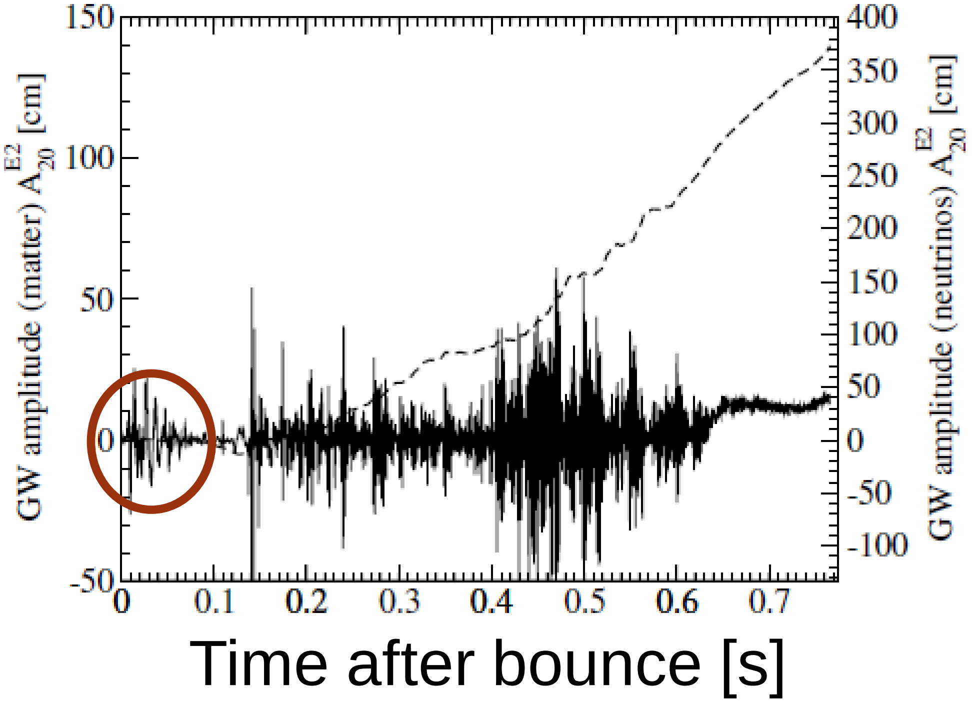


1. Early Quasi periodic signals
2. Quiescent phase
3. Stochastic GW signal (before and after the shock revival)
4. low-frequency tail signal

Mueller+2013

Typical Models in 2D sim.



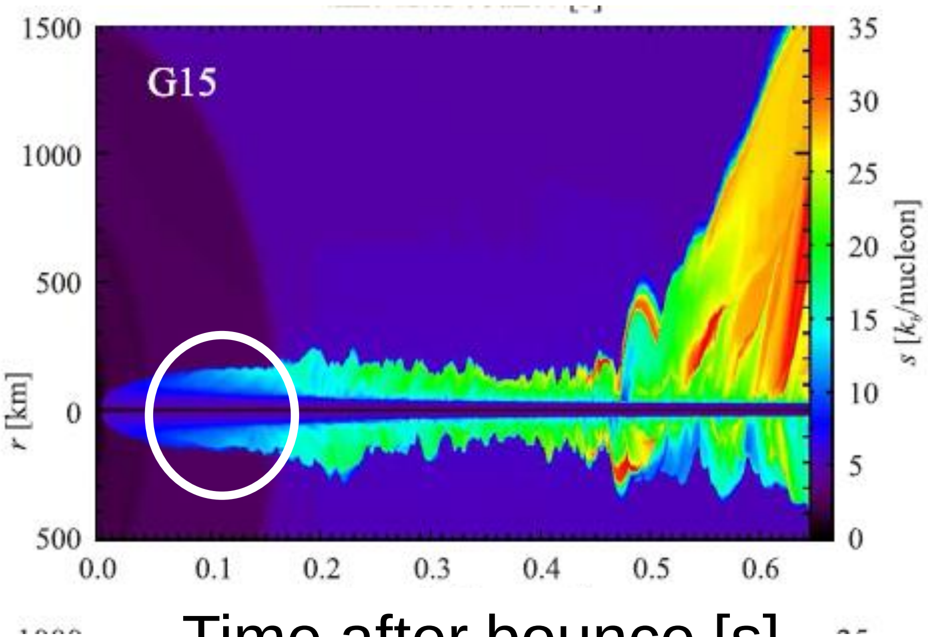


1. Early Quasi periodic signals
2. 25-50 km, anisotropic motion and
3. acoustic waves
4. low−frequency tail signal

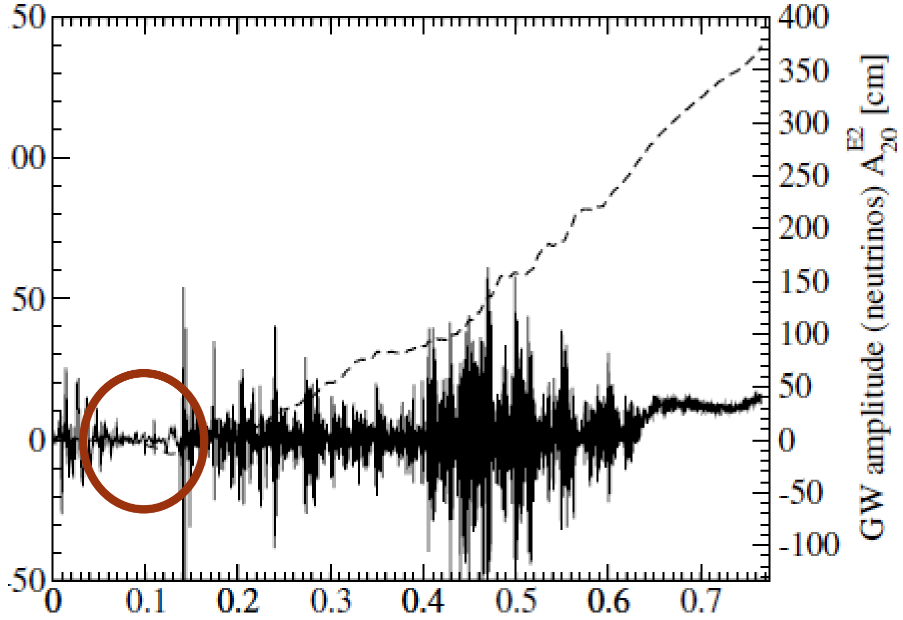
$$h = \int \psi \mathrm{d}V$$

Mueller+2013

Typical Models in 2D sim.



Time after bounce [s]



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Mueller+2013

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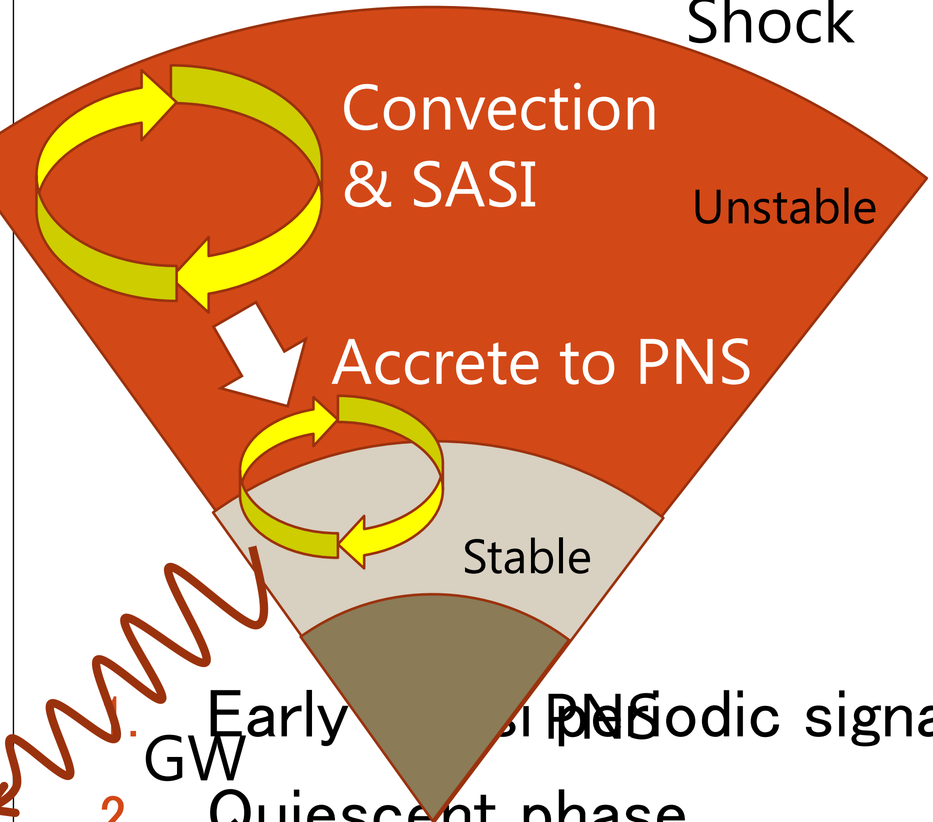


Shock

Convection & SASI

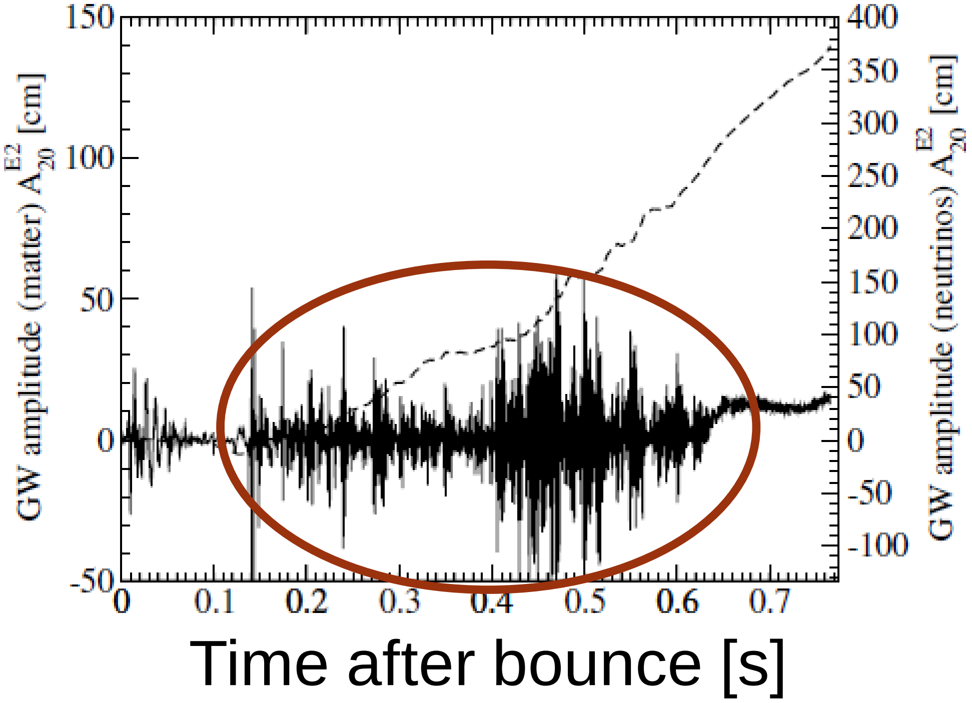
Unstable

Accrete to PNS

Stable

PNS

GW



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Mueller+2013

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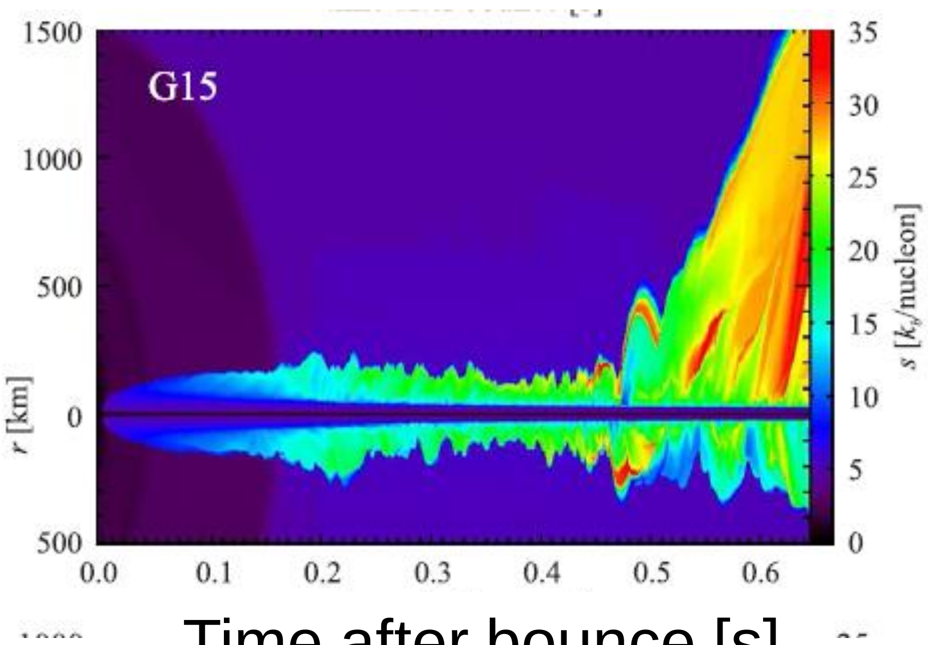
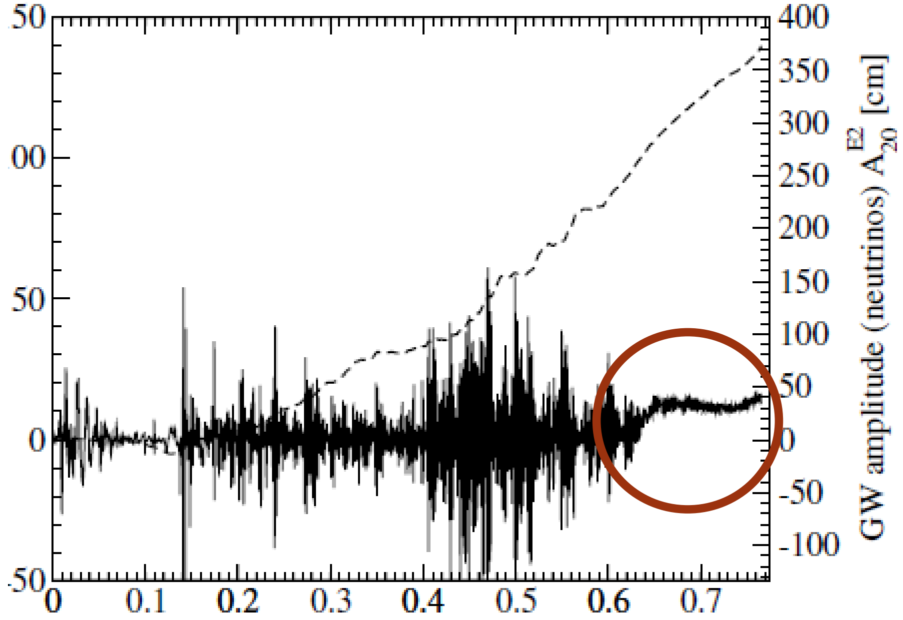


Time after bounce [s]



Time after bounce [s]

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4. low-frequency tail signal

Mueller+2013

Two typical cases

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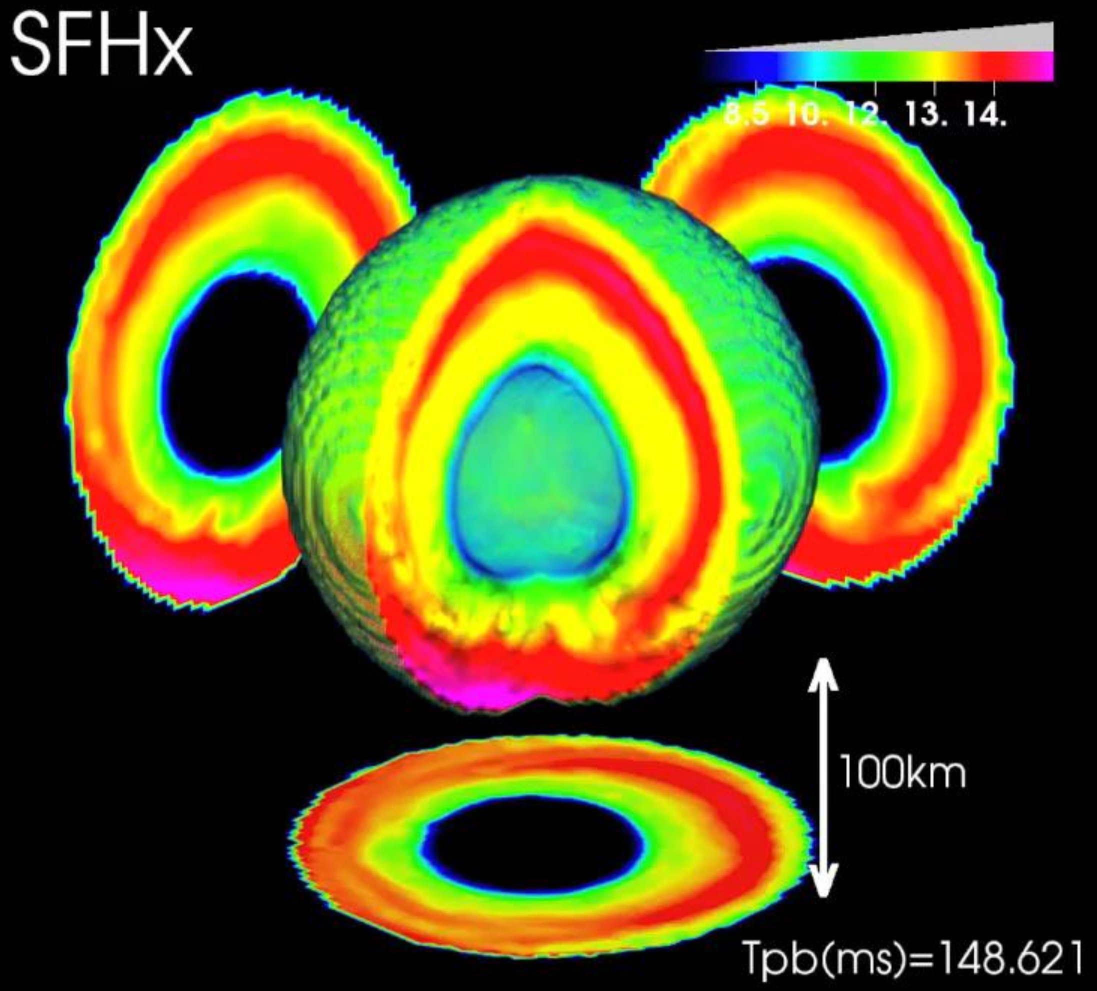
    3. GWs from 3D simulations
- Rapidly rotating progenitor
    1. GWs from Axisymmetric simulations
    2. GWs from Non Axisymmetric simulations

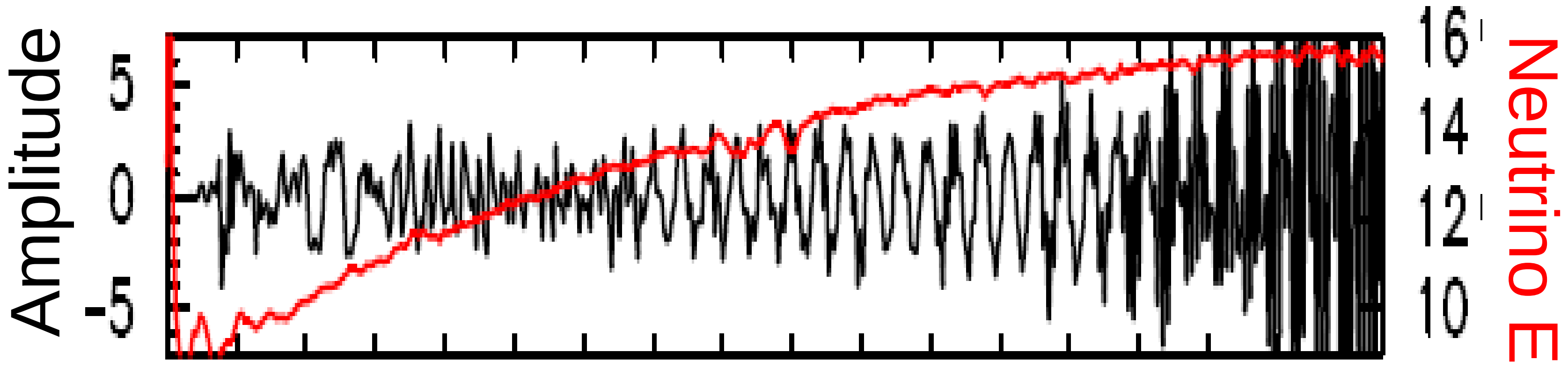
3D simulation

Kuroda et al. in prep

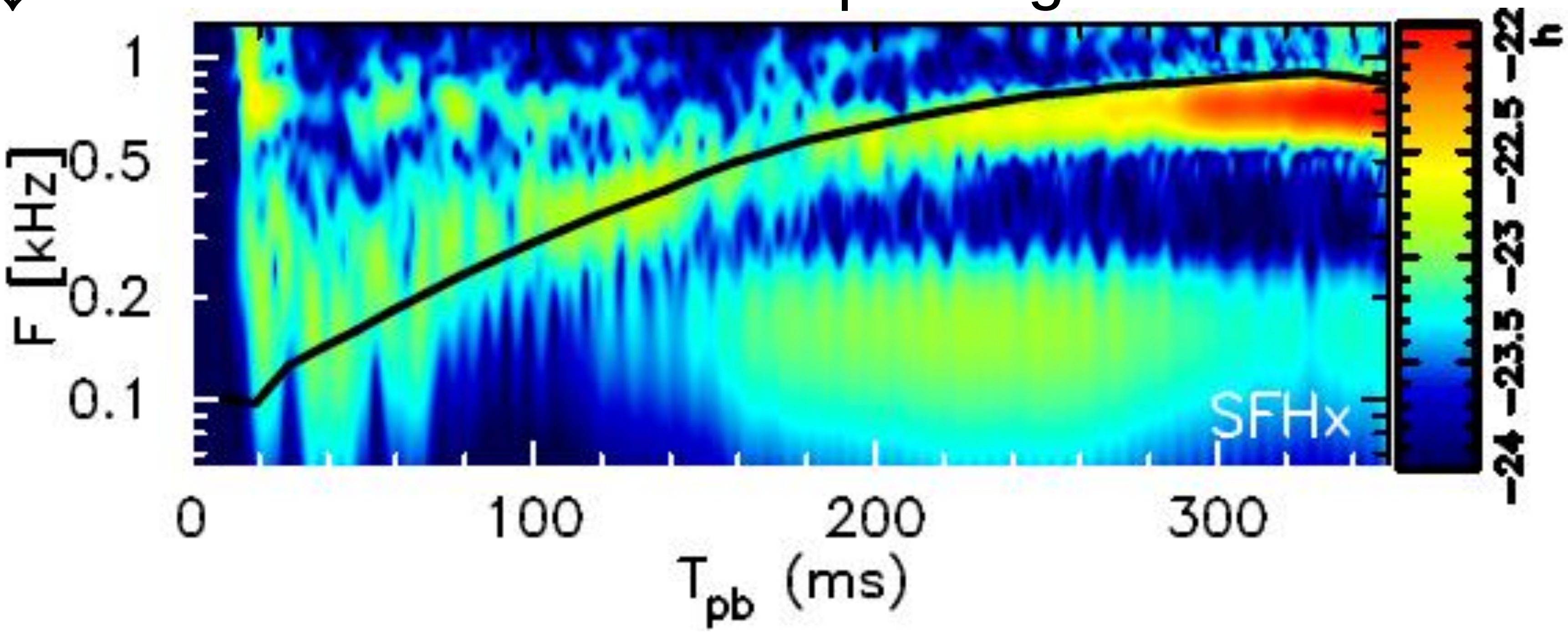


15M_s
GR
Leakage

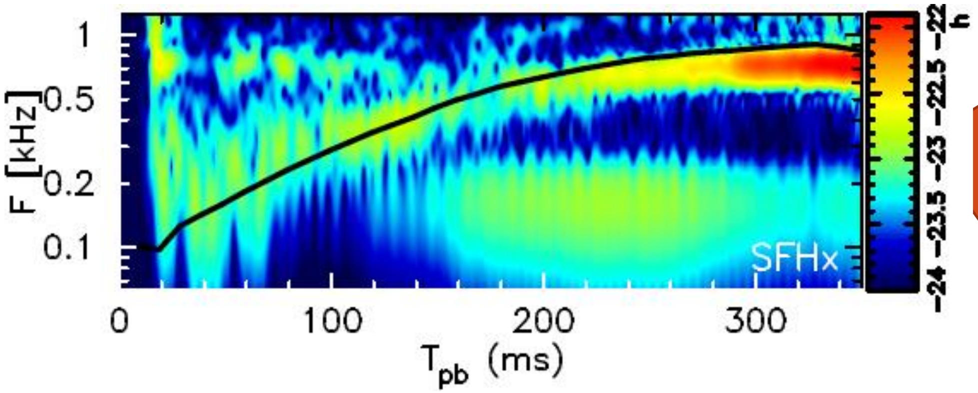
GW from 3D simulations



↓Fourier Transformations. Spectrogram.



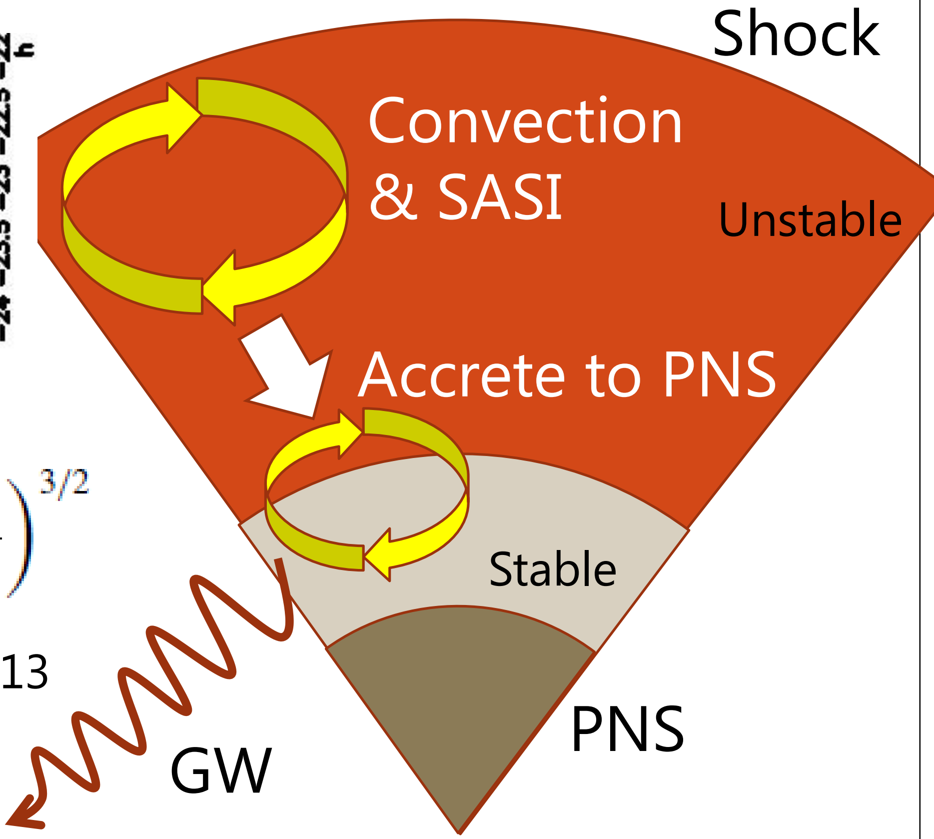
Origin of GW(1): g-mode oscillation at PNS surface



$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

Mueller+13

M: Mass of PNS
R: Radius of PNS
T: Temperature of PNS surface

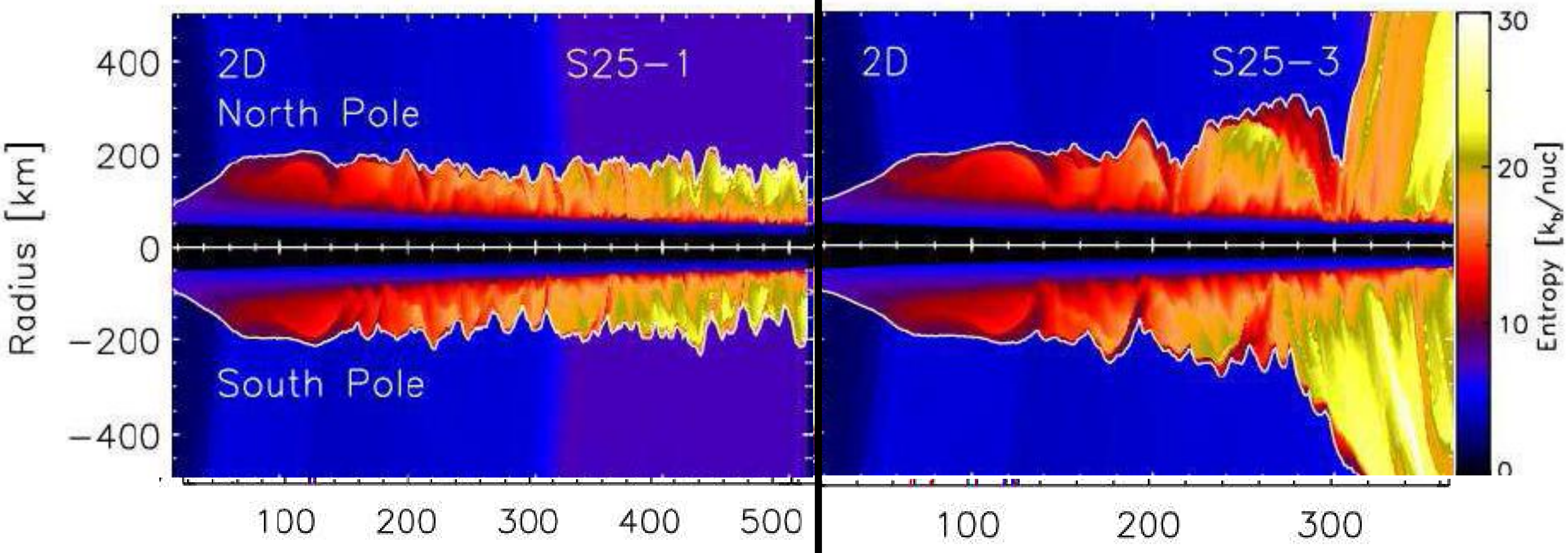


Frequency of GW tells us the evolution of PNS.

Why is Evolution of PNS important?

Hanke+13

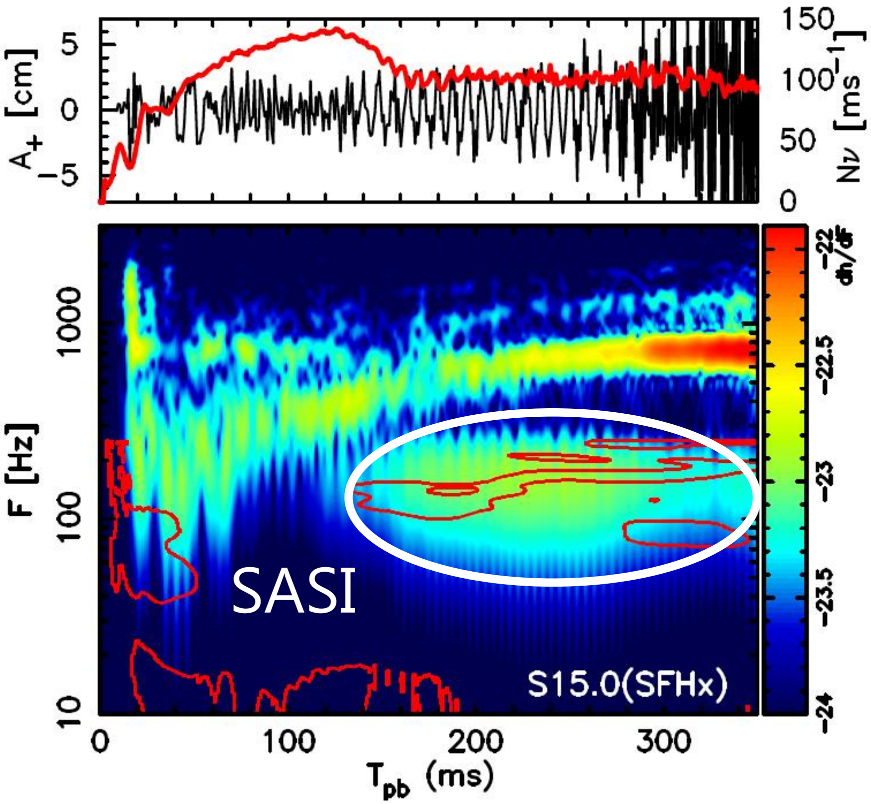
PNS shrinks slowly. | PNS shrinks fast.

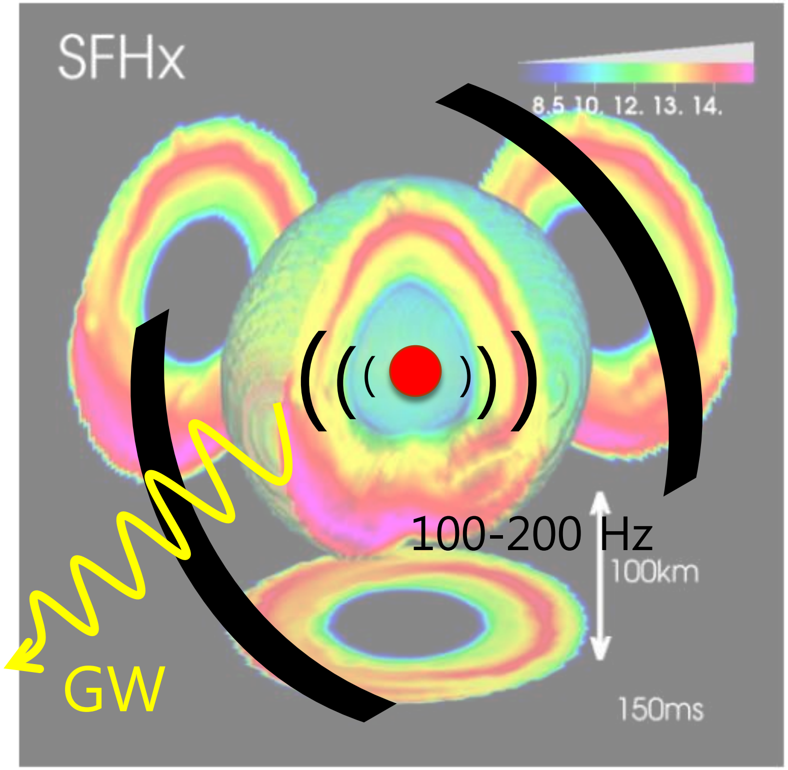


$$R_{\rm PNS}\downarrow,\ E_{\rm grav}\uparrow,\ L_\nu\uparrow,\ R_{\rm shock}\uparrow$$

The evolution of PNS is important gradient for the explosion mechanism.

Origin of GW(2):
SASI(Standing Accretion Shock Instability)



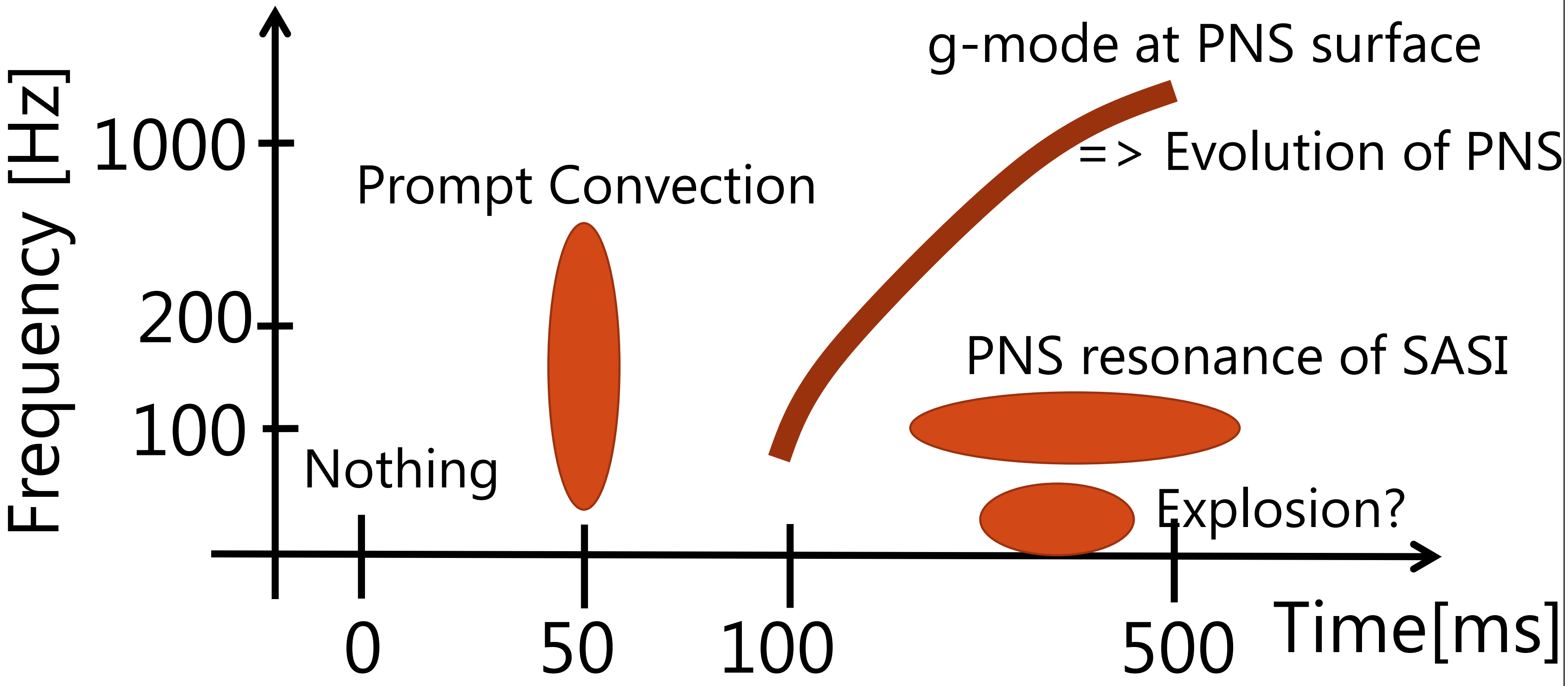


Due to SASI, the shock oscillate at 100-200Hz.
After that, PNS begins to oscillate at the same frequency.

From GW signals, we can get evidence of SASI

Summary of non rotating model

Non rotating scenario



↑ Bounce time is determined by ν observation

Two typical cases

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- Rapidly rotating progenitor
  1. GWs from Axisymmetric simulations
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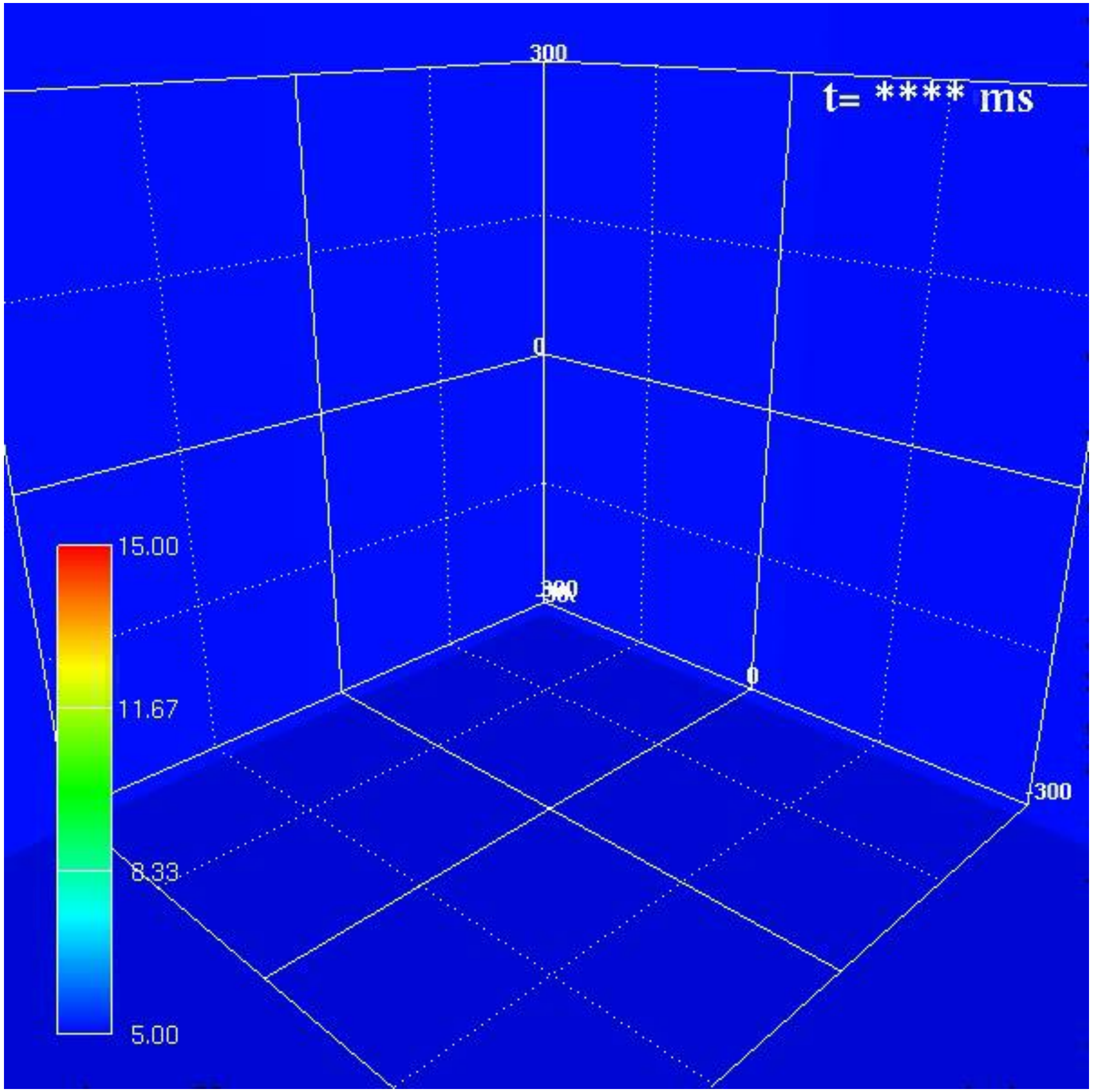
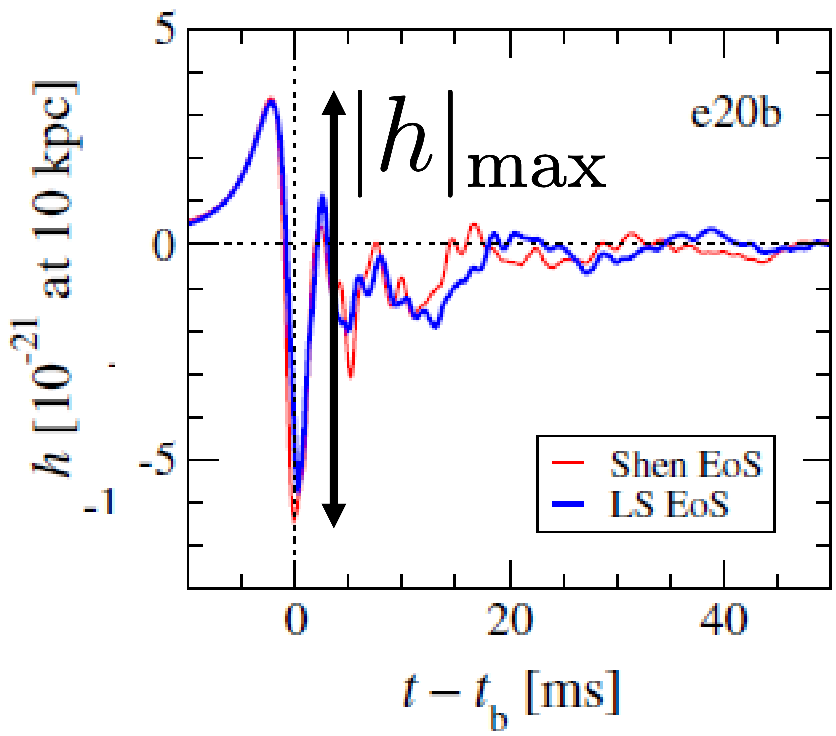
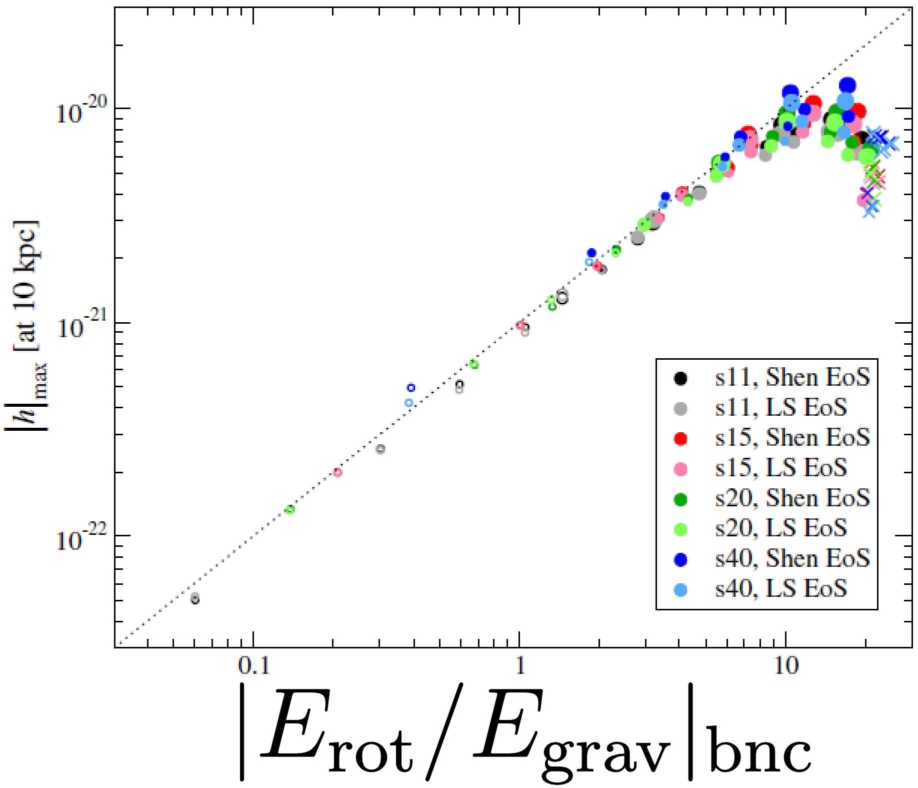
Typical Models in Axi-sym. sim.



Typical Models in Axi-sym. sim.





Bounce Signal at the rotational core-collapse
Rotation increase the GW amplitude until a limit.

Dimmelmeier+2008

Two typical cases

- Non rotating progenitor
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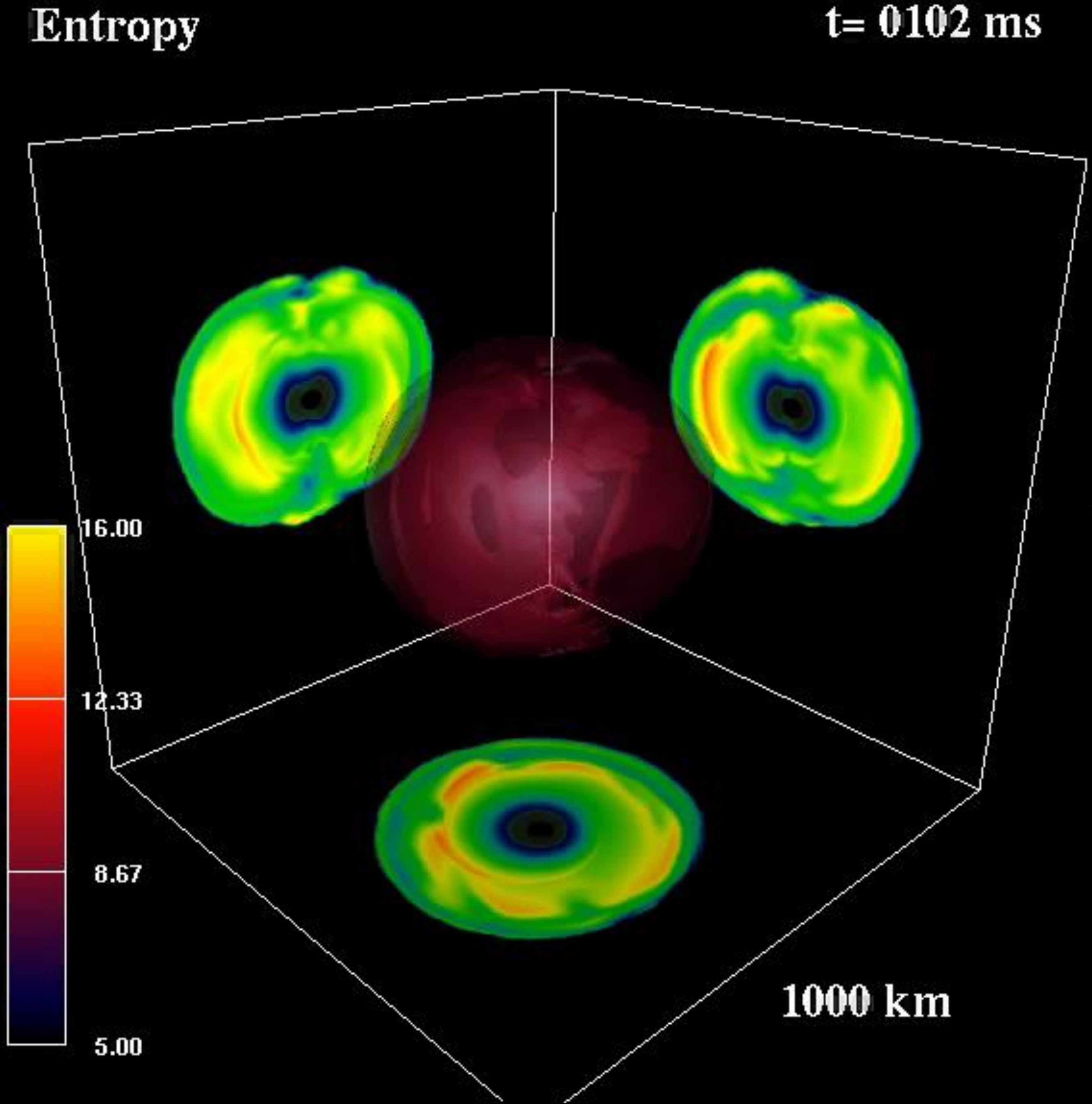
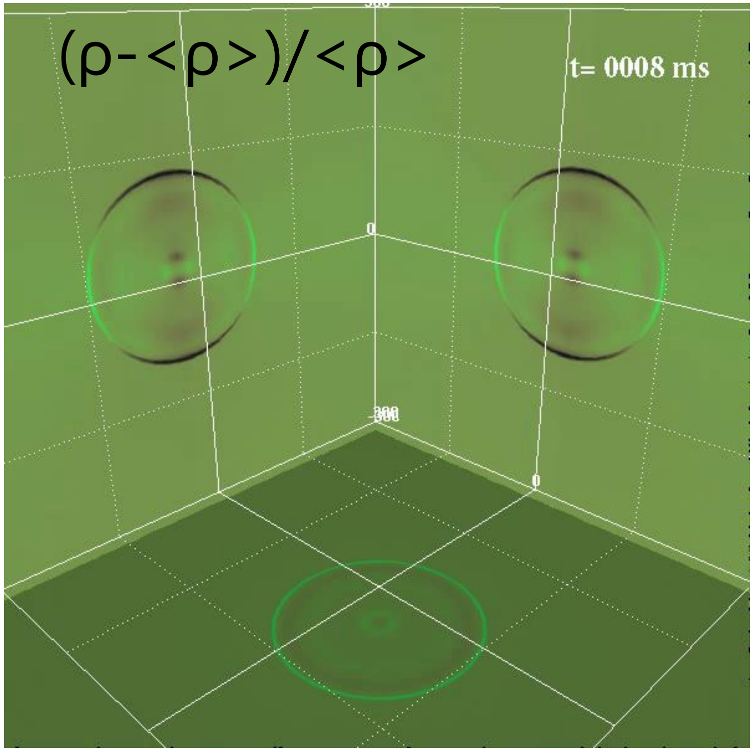
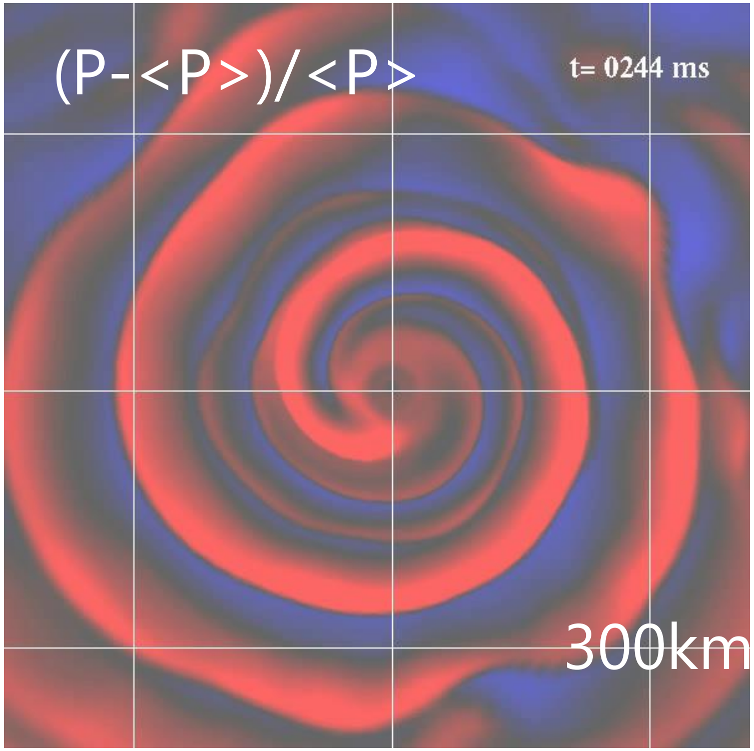
27.0M_s R2.0



Spiral Mode





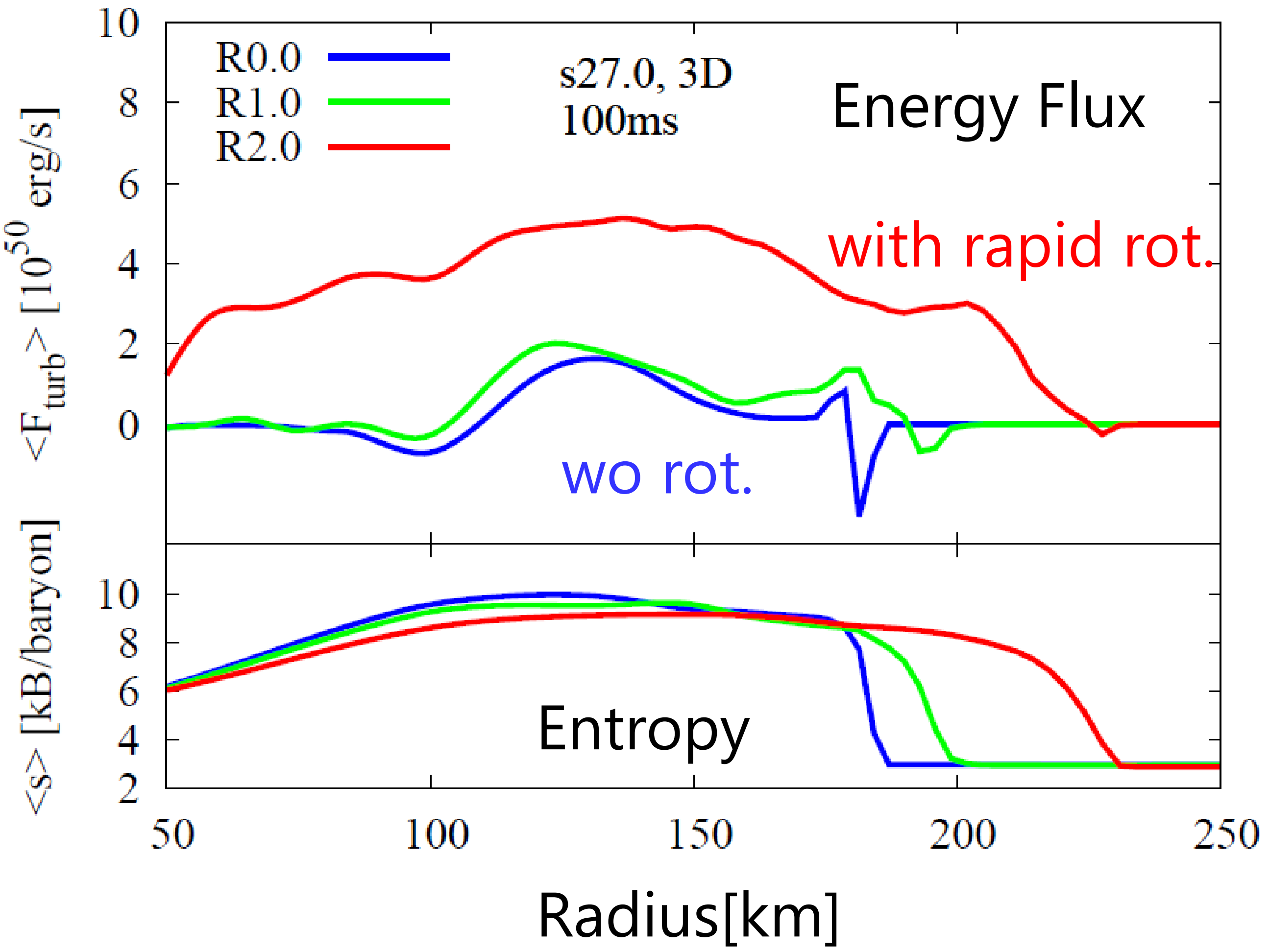
Rotational energy(T)/gravitational energy(W) reach some criteria => Spiral mode arises

In the rigid ball: 14%

Ott+ 2005

In SNe case: ~ 6% (Called low-T/W instability)

Energy Transport by spiral mode

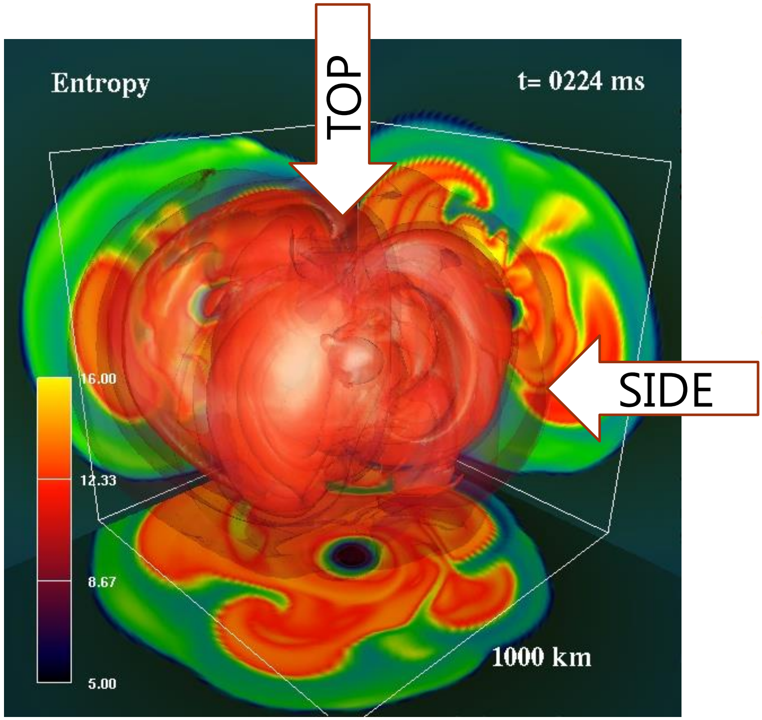


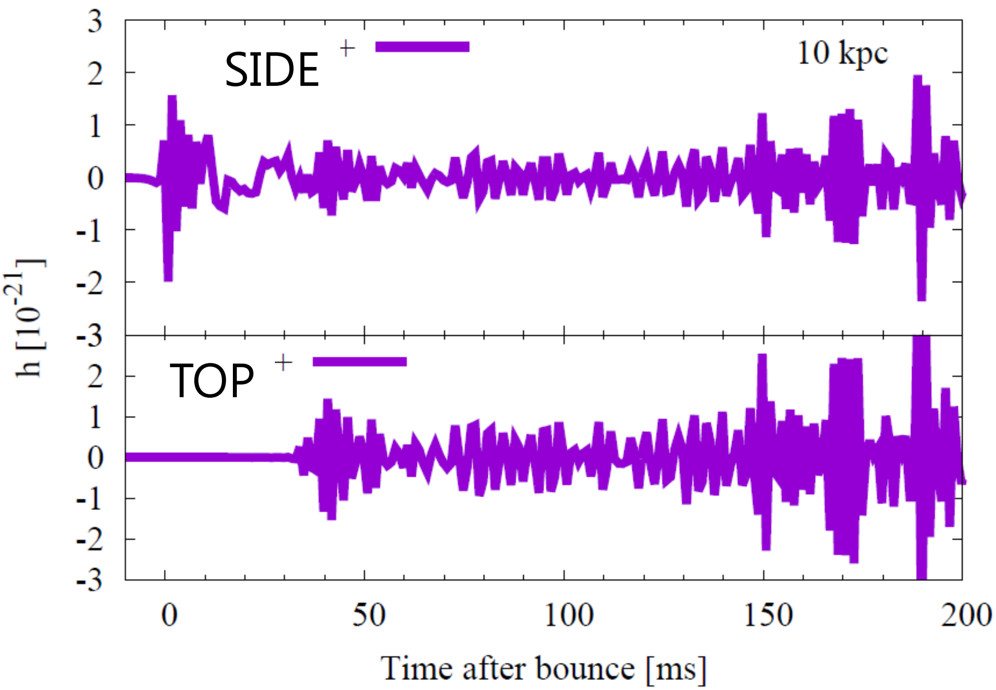
Power of ν heating = 10ˆ52 erg/s

Power of Spiral mode = 0.5 x 10ˆ52 erg/s

Spiral mode transport energy from center to outer region and helps explosion.

GW signals from rotating model



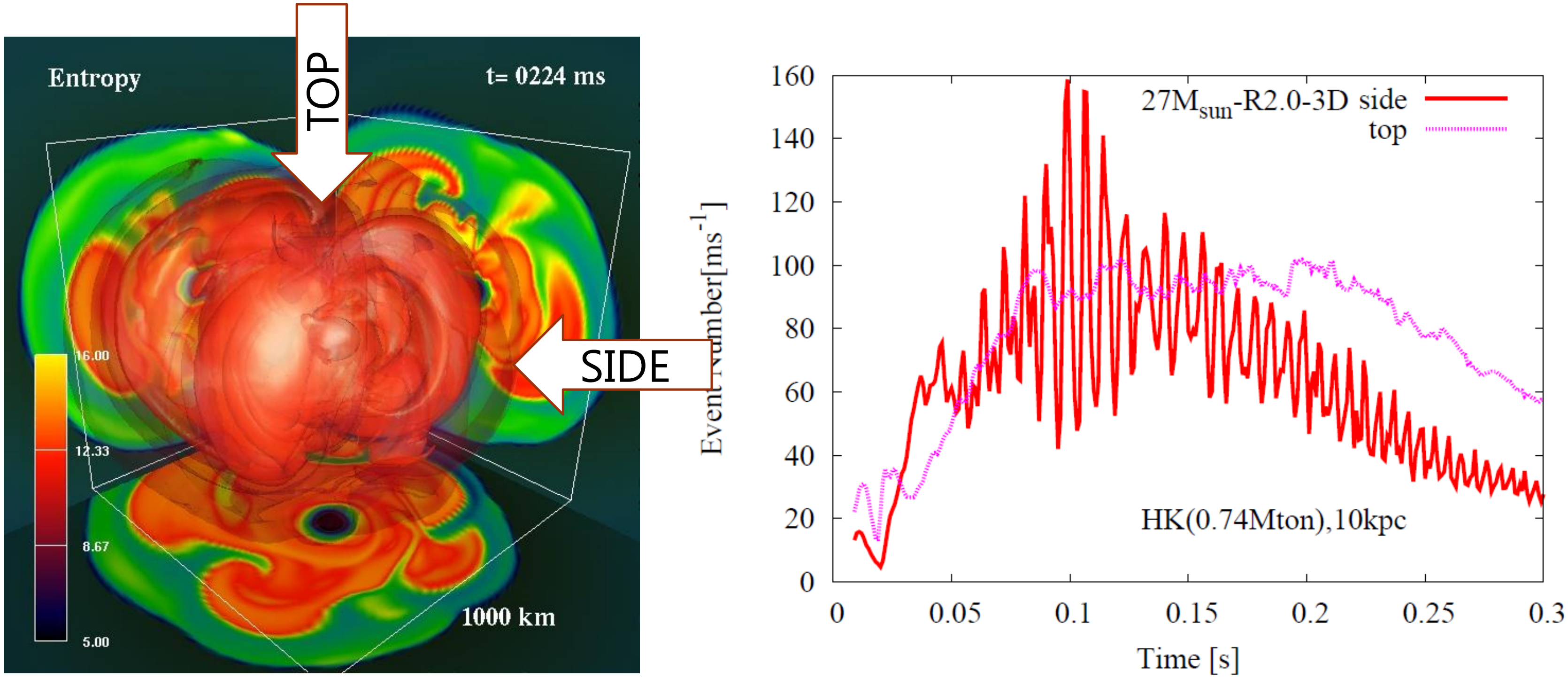


Takiwaki+ in prep

Bounce signal can be observed from side view.

Non-axisymmetric motion emits GWs at later phase.

Neutrino signals from rotating model



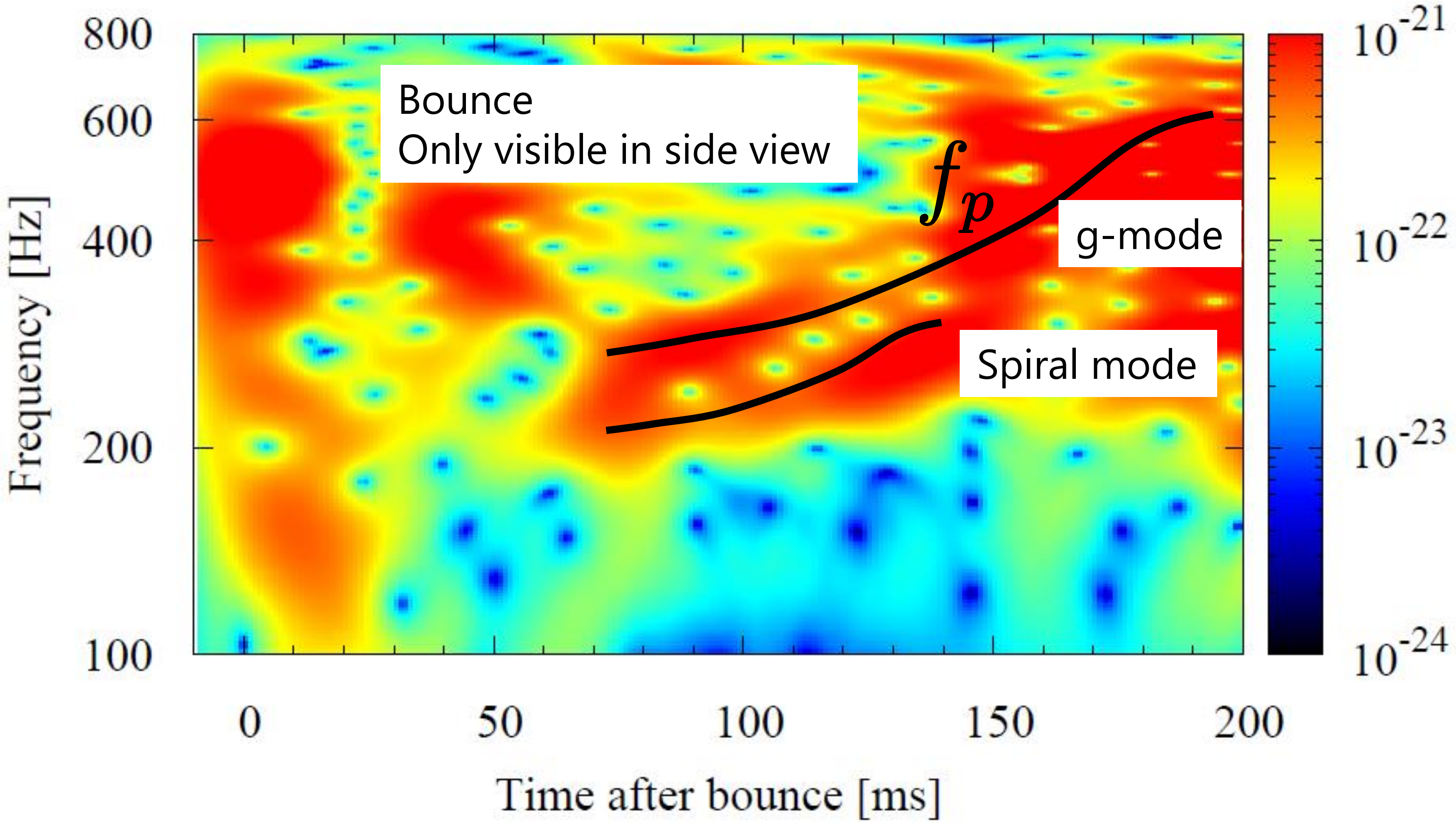
Takiwaki+ in prep

Period of spiral mode is extracted by ν-signal

Feature of GWs from Rotational Explosion

Viewing from side direction

Takiwaki+ in prep



Bounce
Only visible in side view

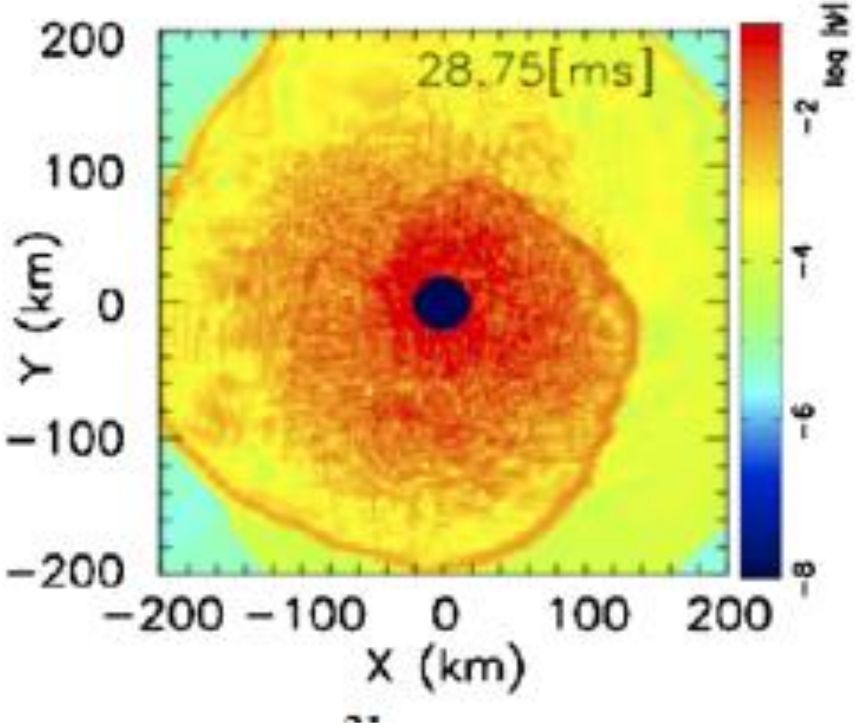
g-mode

Spiral mode

In addition to g-mode signal, GW from spiral mode arises and spin period of PNS surface can be extracted.

Circular Polarization?

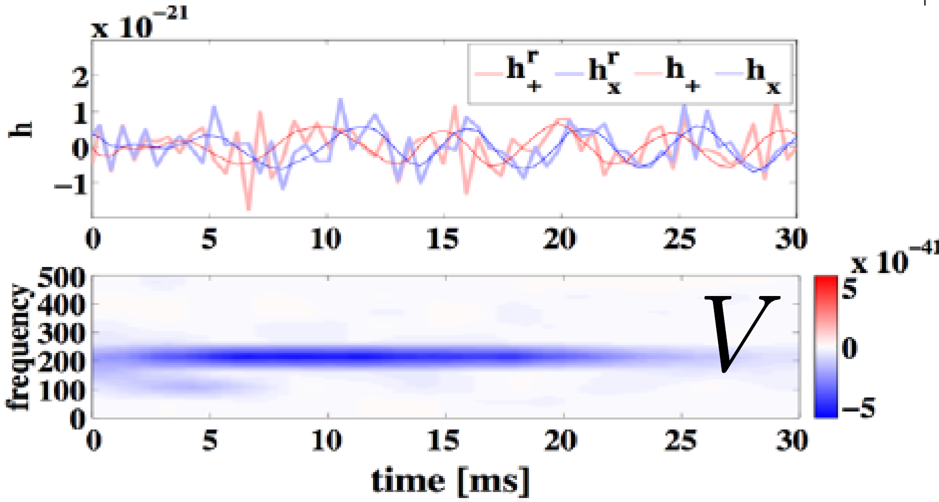
Hayama+2016



$$h_+, h_\times$$

=Data analysis=>

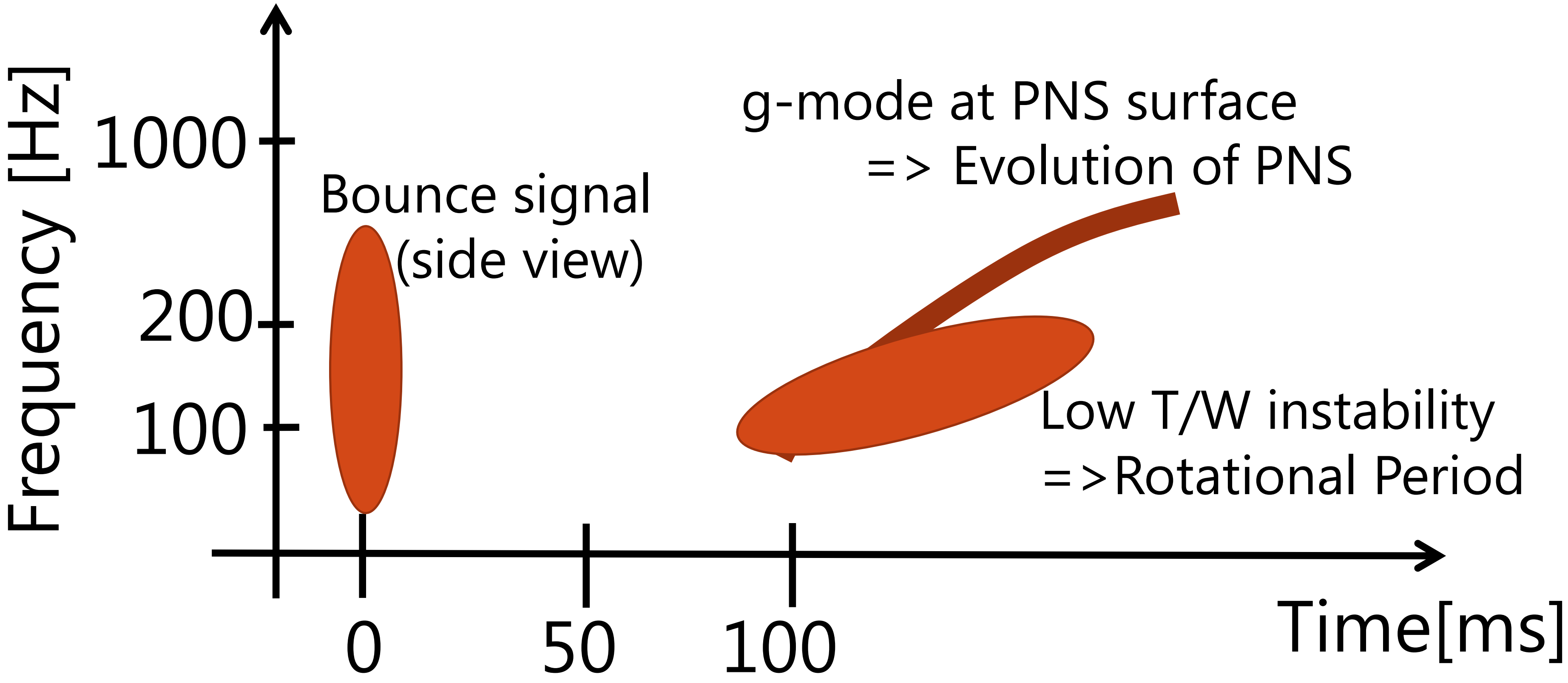
Circular Polarization Parameter, V



With the analysis we can extract circular polarizations.
We can distinguish Spiral mode from SASI-mode.

Summary of rotating model

Rapidly rotating scenario



Bounce signal
(side view)

g-mode at PNS surface
=> Evolution of PNS

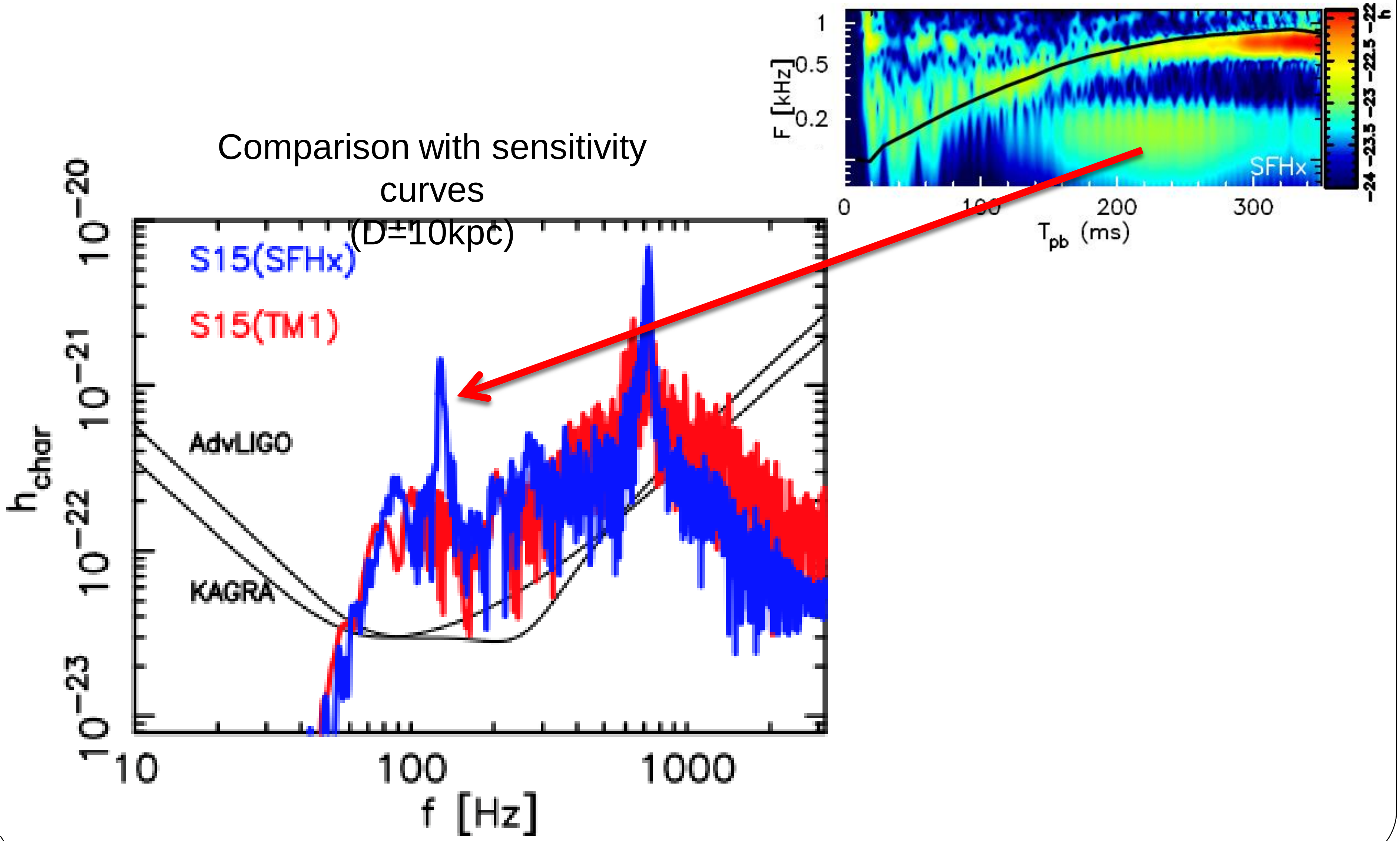
Low T/W instability
=>Rotational Period

↑ Bounce time is determined by ν observation

Summary

1. GW from SN gives the information on what happen in the Fe core. Although the waveform is complicated, spectrogram gives hints on the physical processes.
2. For non-rotating case, FOUR types of GWs is emitted.
   From these, we can know the evolution of PNS and whether strong SASI happens or not.
3. For rotating case, strong bounce signal is the evidence for the rotation. From the GWs, the information of spin period could be extracted.

Gravitational Wave Emission in 3DGR Models


Comparison with sensitivity curves (D=10kpc)