2019/10/21

4M-COCOS @Fukuoka University

Status report of group C01

Neutrino and Gravitational Wave Signatures of Core-Collapse Supernovae

Tomoya Takiwaki

(National Astronomical Observatory of Japan)

Purpose of C01

Goal:

Deciphering mechanism of core−collapse supernovae via gravitational waves

Sub-goals:

1. Theoretical investigation by 3D simulations
   This talk
2. Proposing new data-analysis methods
3. Burst search using LIGO-VIRGO and KAGRA
   Kazuhiro Hayama will talk about it on 23rd

Collaboration among theory, data-analysis and experiments should be important.

Core Members of C01

Theory

Project Research

PI:
Kei Kotake
(Fukuoka University)

CI: (This talk)
Tomoya Takiwaki
(NAOJ)

PD: (Talk on 24th)
Shota Shibagaki
(Fukuoka University)

Data-Analysis

Project Research

CI:
Nobuyuki Kanda
(Osaka City University)

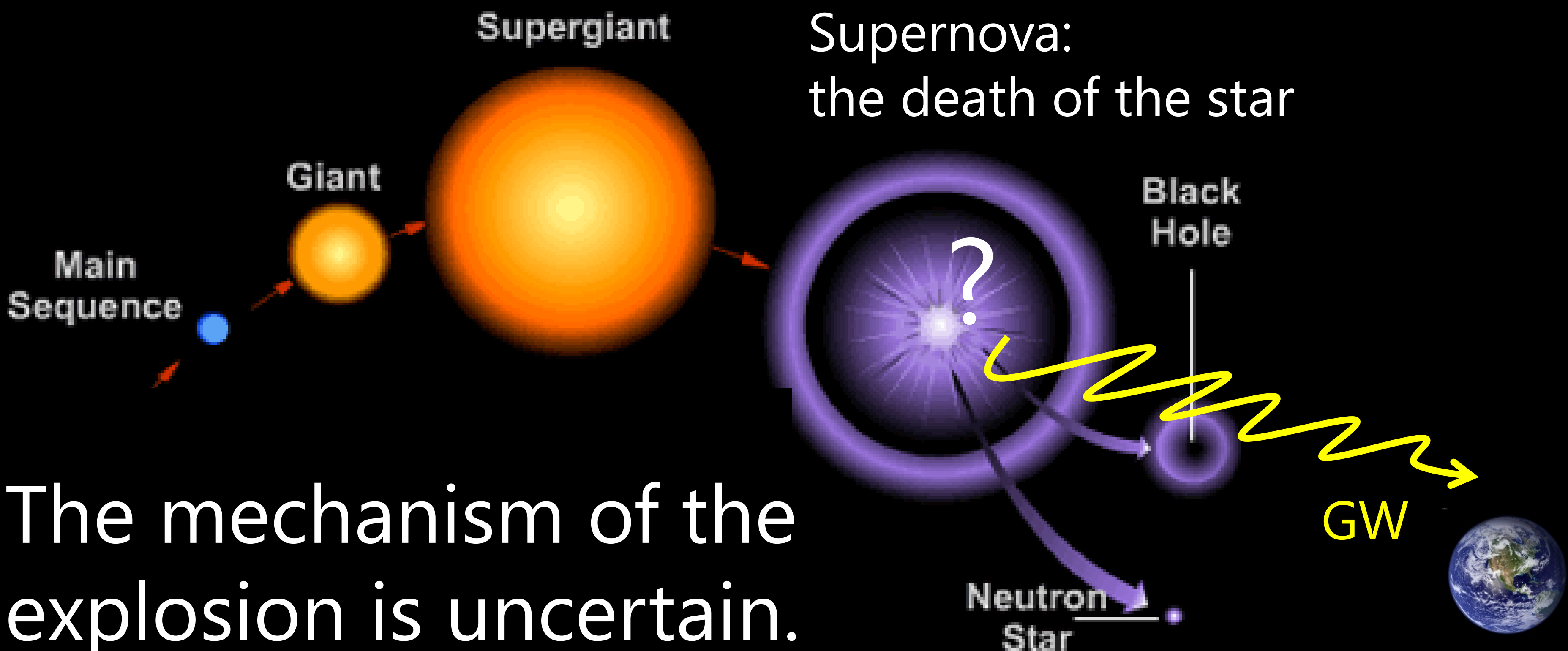
CI: (Talk on 23rd)
Kazuhiro Hayama
(Fukuoka University)

PD:
Man Leong Chan
(Fukuoka University)

Subscription research

Hajime Kawahara
(University of Tokyo)

Gravitational wave from Supernova

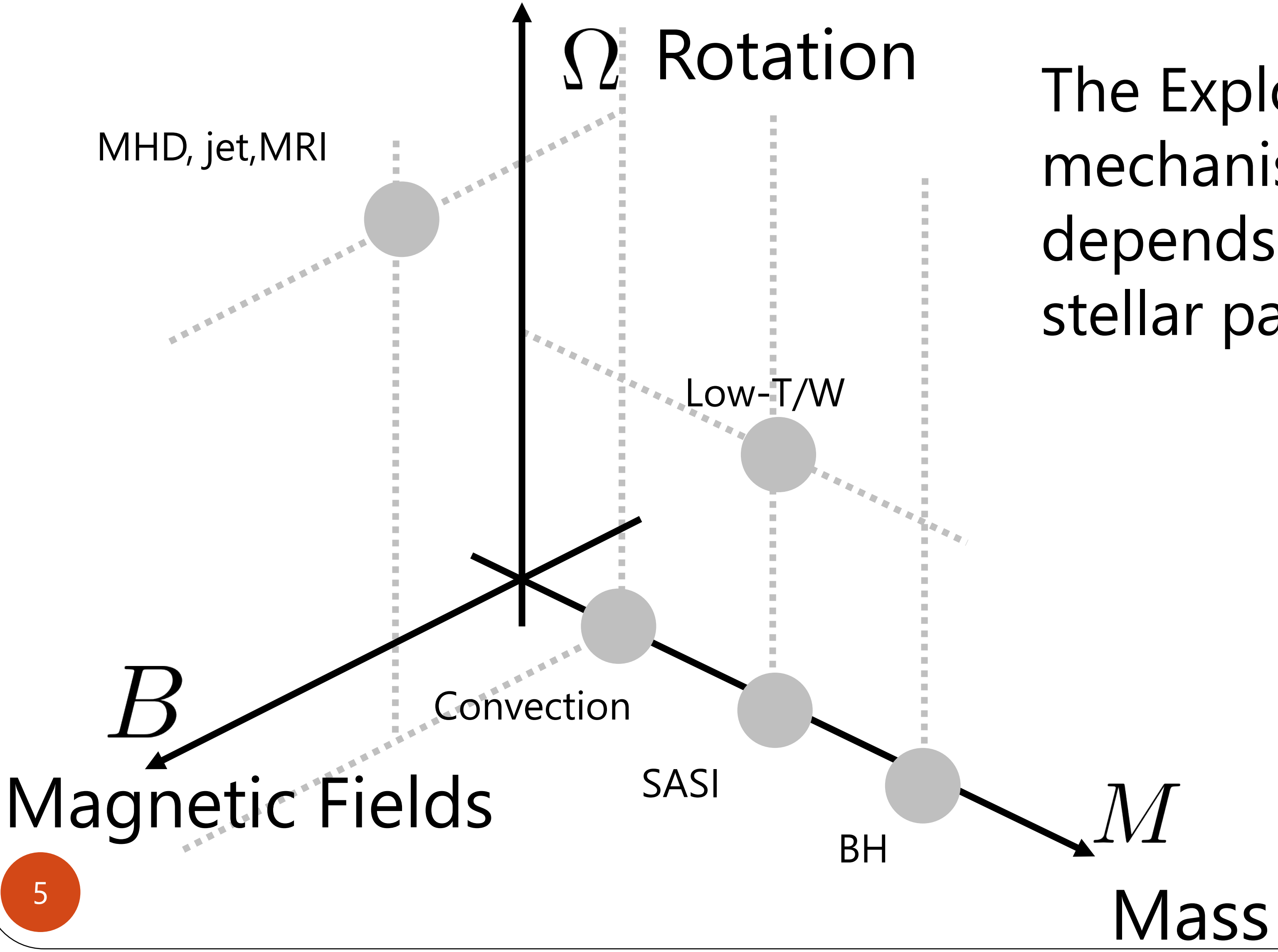


Supernova:
the death of the star

The mechanism of the explosion is uncertain.

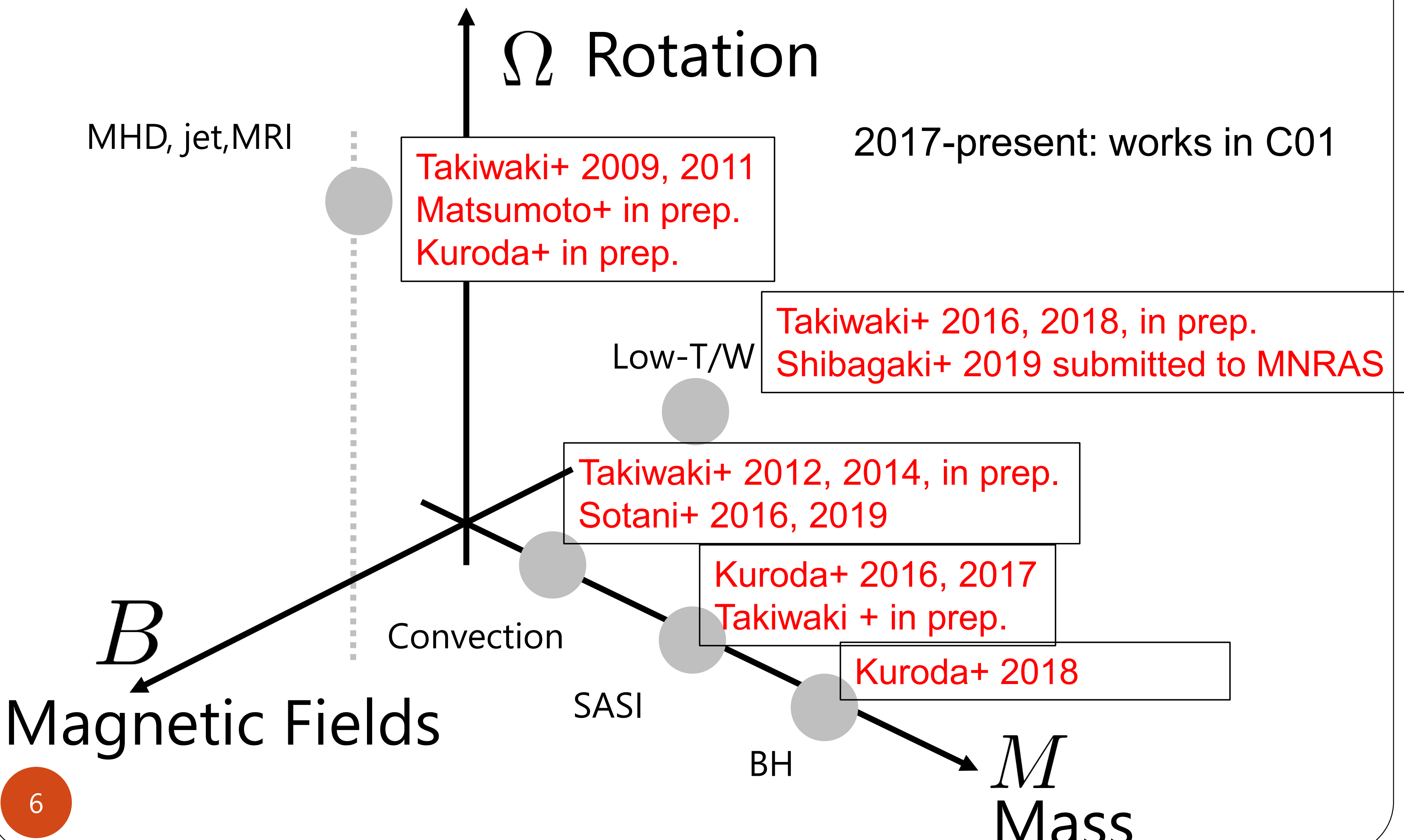
GW propagates through the star.
GW provides the direct info. of the explosion mechanism.

Parameter Plane & Explosion Mechanism

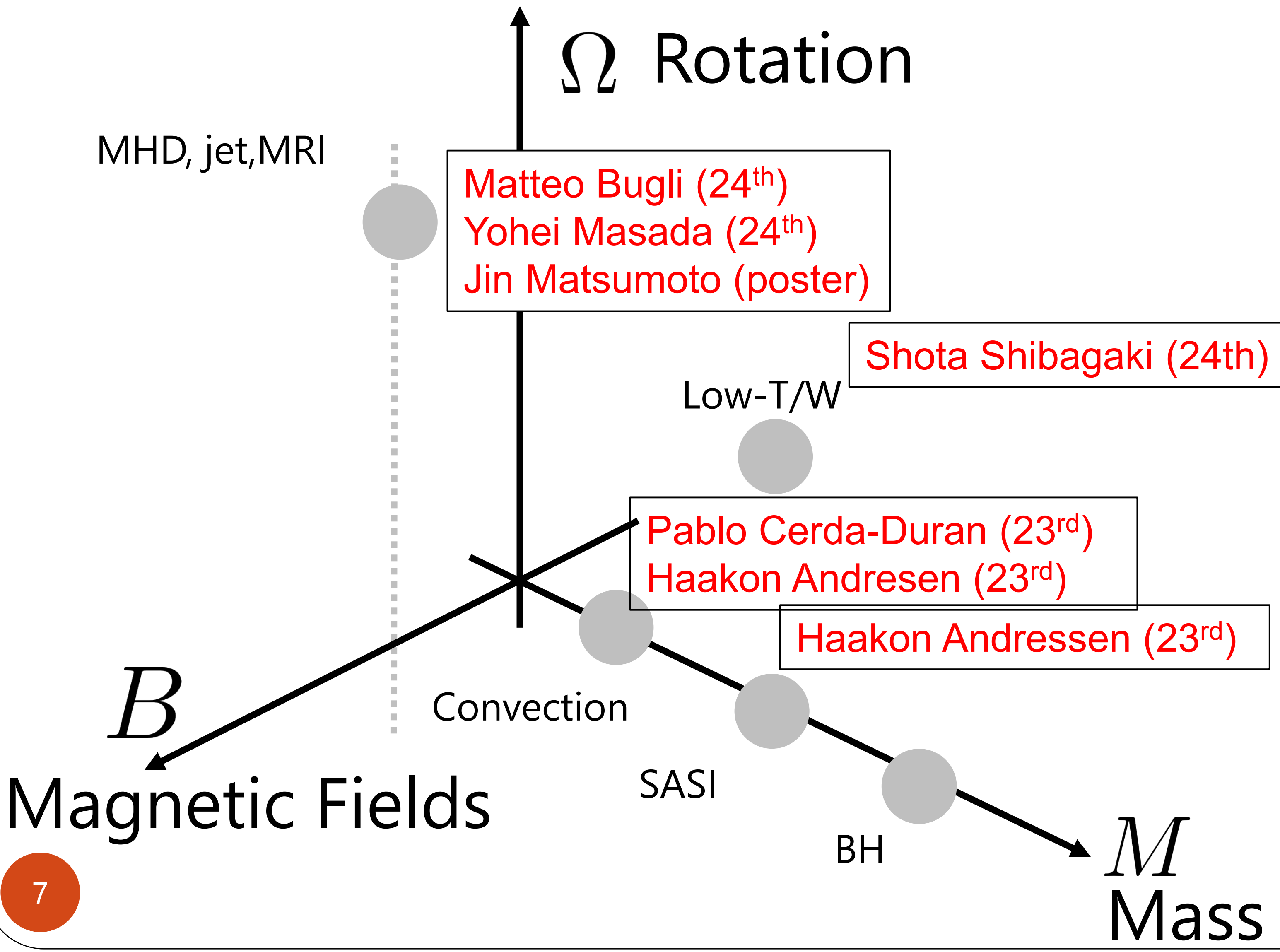


The Explosion mechanism depends on the stellar parameter.

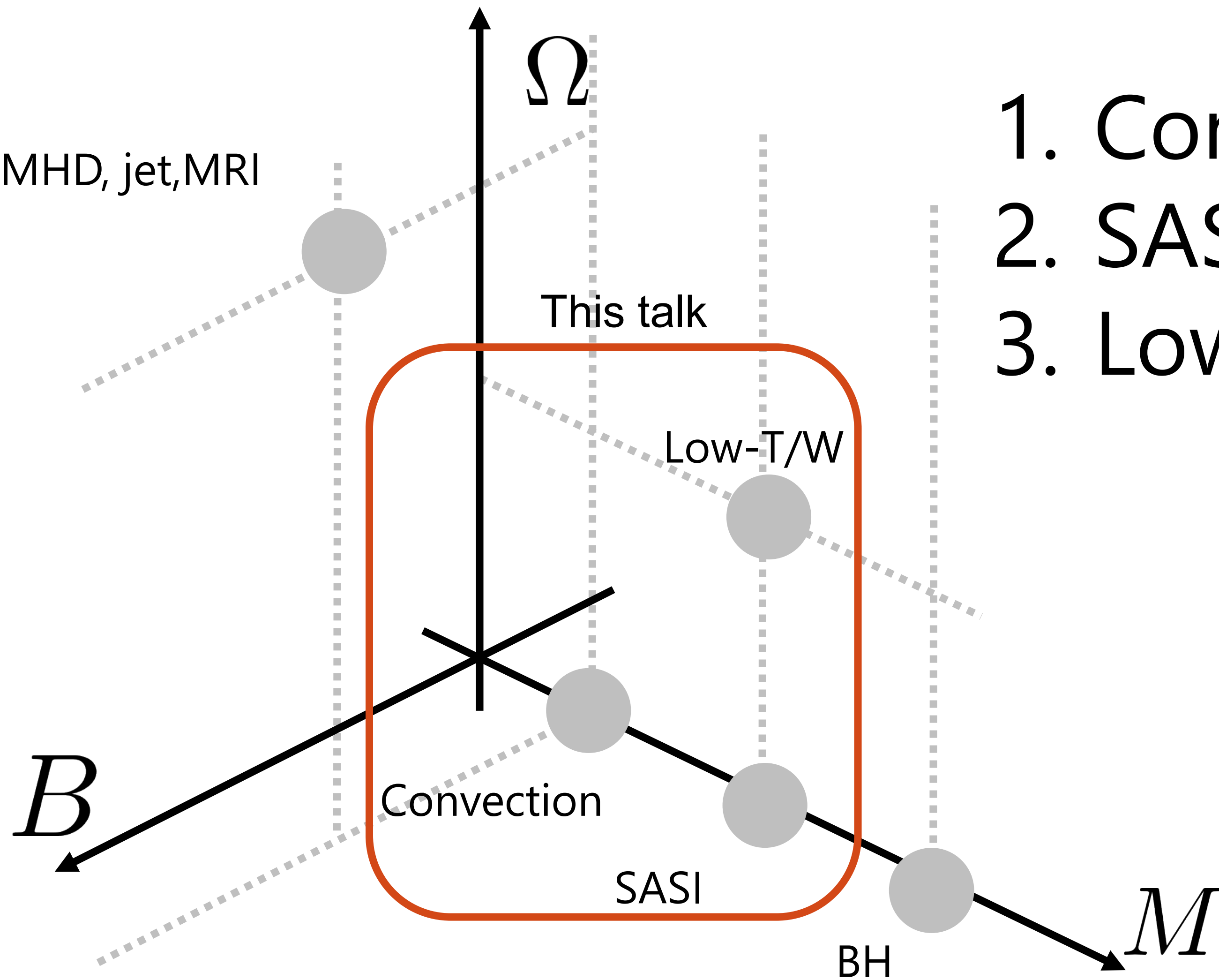
Selected Publication List



Connection to talk in this workshop

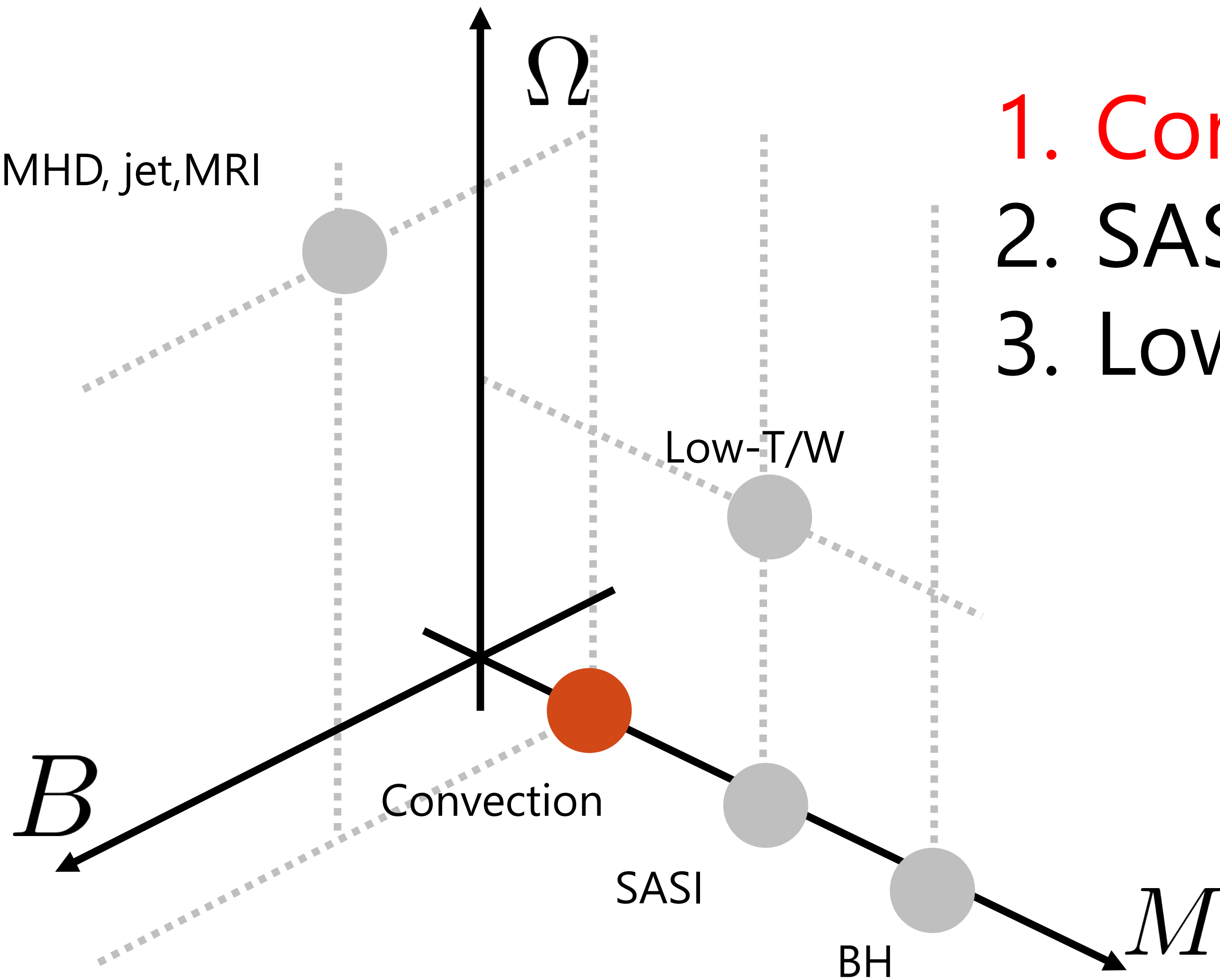


Parameter Plane & Explosion Mechanism



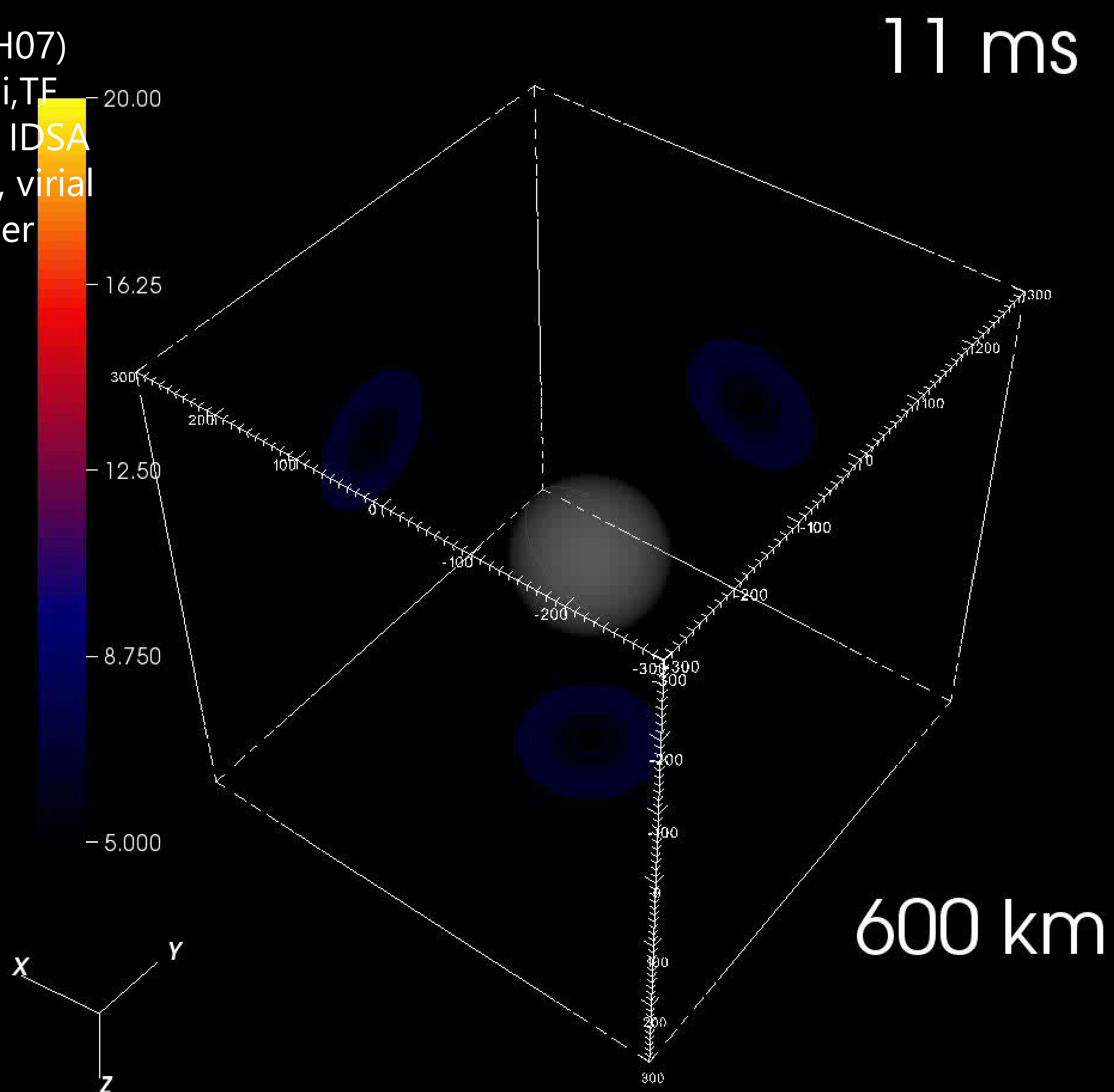
1. Convection
2. SASI
3. Low-T/W

Parameter Plane & Explosion Mechanism

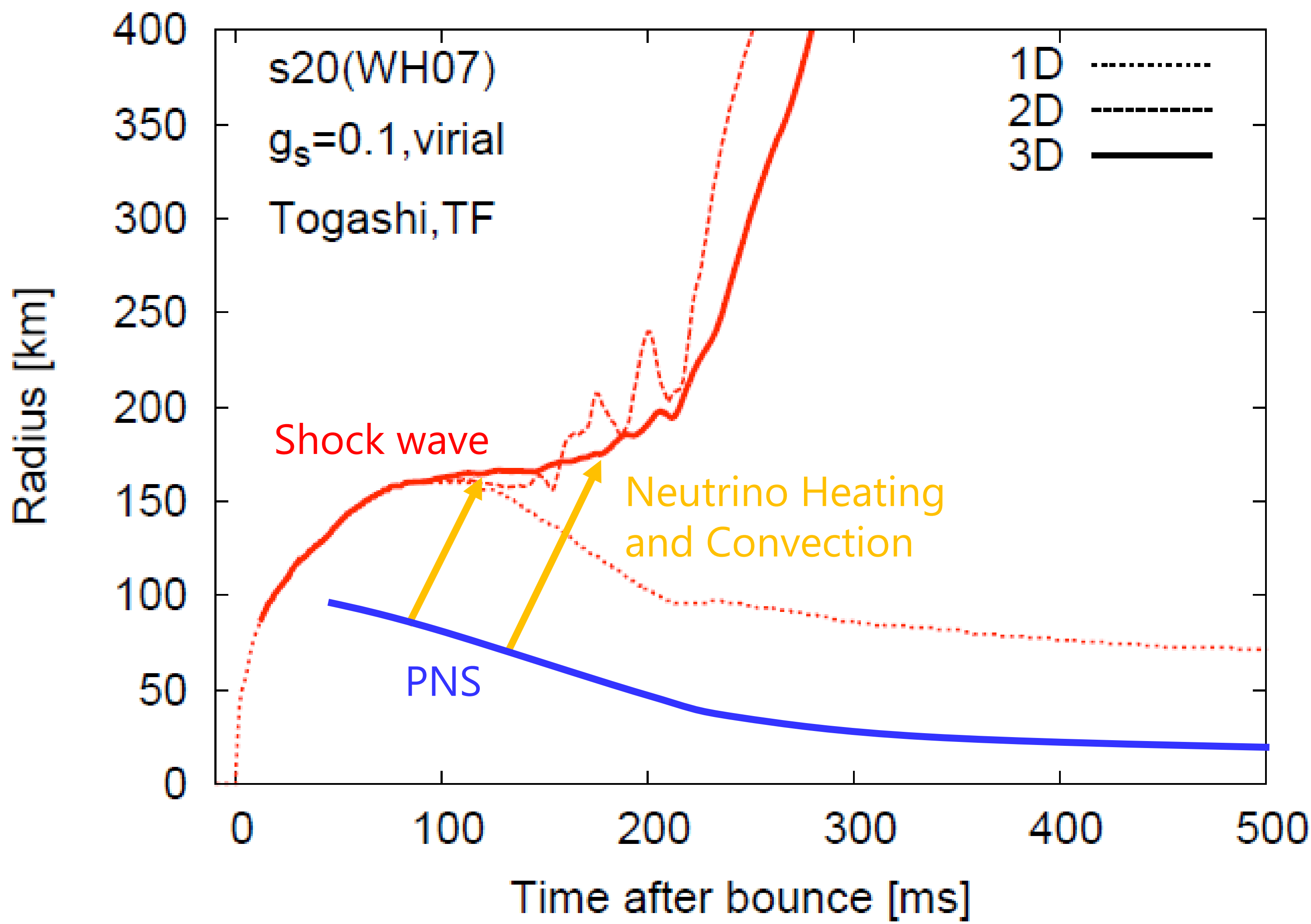


1. Convection
2. SASI
3. Low-T/W

s20(WH07)
Togashi,TF
3flavor IDSA
gs=0.1, virial
2^{nd} order
HLLC



Explosion Mechanism for non-rotating model

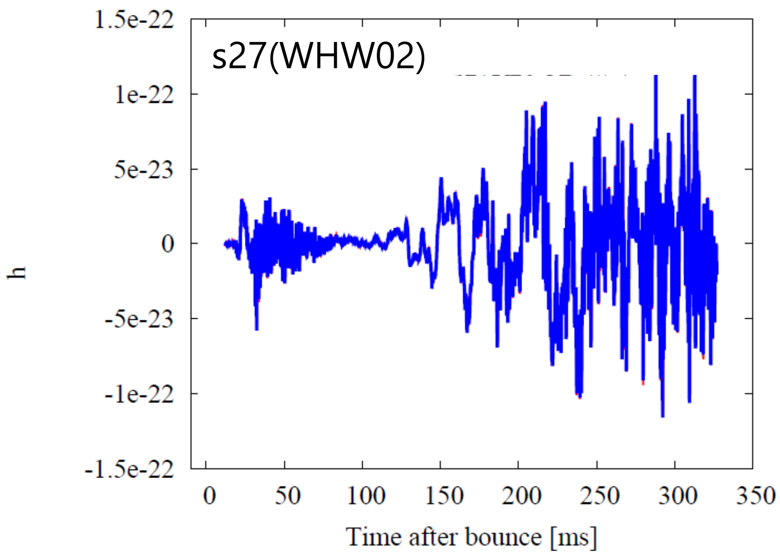


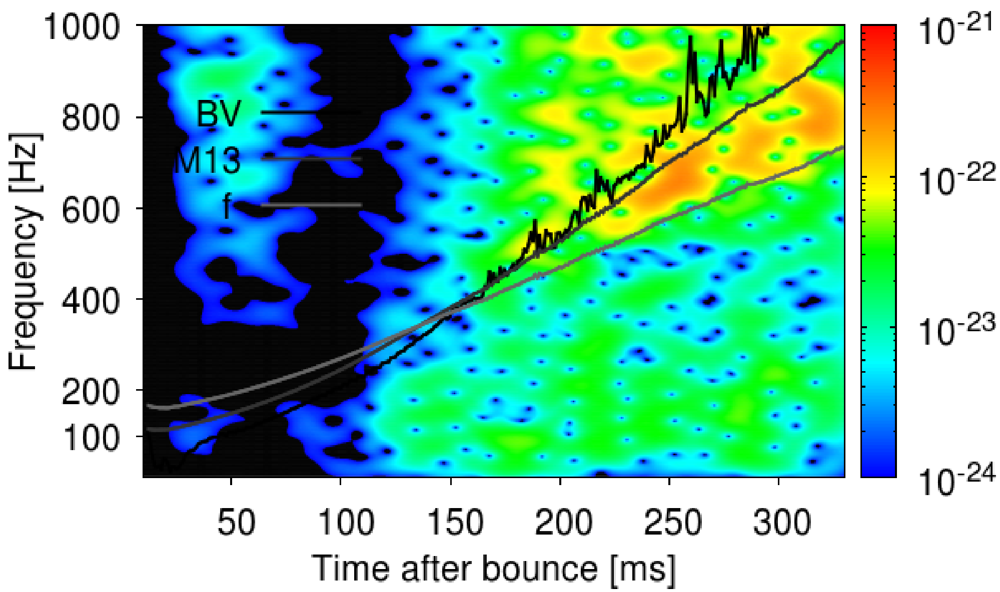
Convective activity is imprinted in GW

Quadrupole Formula: (Mueller, E. +2012)

$$h \sim \frac{G}{c^4} \int \mathrm{d}V \rho \left(2v_i v_j \boxed{- x_i \partial_j \Phi - x_j \partial_i \Phi)}$$

Amplitude Density velocity Gravitational Potential





Wave form → Spectrogram

Fourier transformation

Origin of GW(1): GW from PNS surface

(A) Surface g-mode

$$f_{\rm g} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_B T}}\left(1-\frac{GM}{R^2c^2}\right)^{\frac{3}{2}}$$

Mueller+13

M: Mass of PNS

R: Radius of PNS

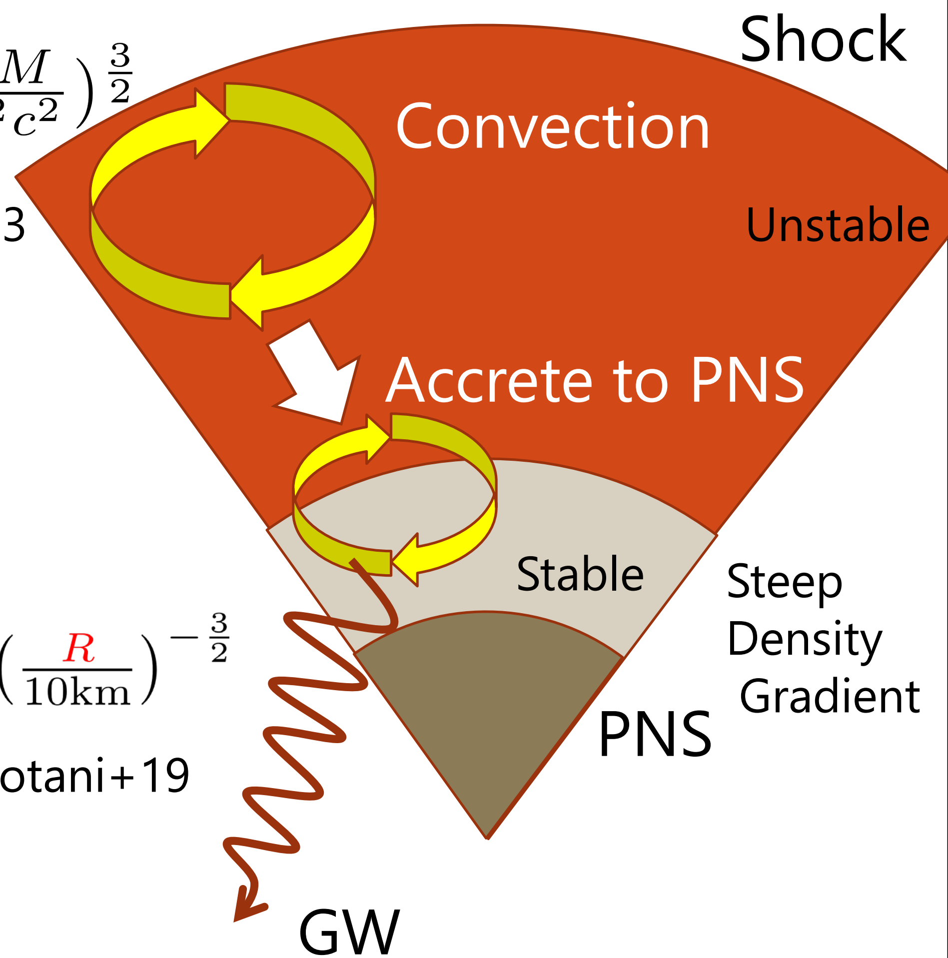
T: Temperature of PNS surface

or

(B) f-mode

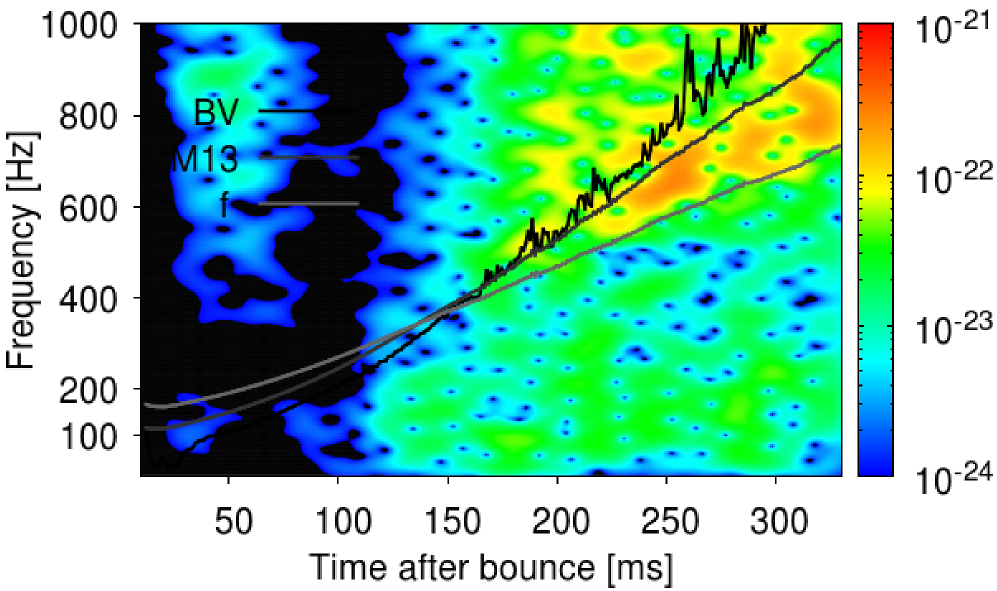
$$f_{\rm f} = -87.34 + 4080.78\left(\frac{M}{1.4M_\odot}\right)^{\frac{1}{2}}\left(\frac{R}{10\mathrm{km}}\right)^{-\frac{3}{2}}$$

Sotani+19



The frequency rises as the radius, R, decreases.

Convective activity is imprinted in GW



BV: Stabilization of the Pressure
M13: Empirical Formula for BV
(Mueller, B.+2013)

$$\frac{1}{2\pi}\frac{GM}{R^2}\sqrt{1.1\frac{m_n}{E_{\bar{\nu}_e}}}\mathrm{Hz}$$

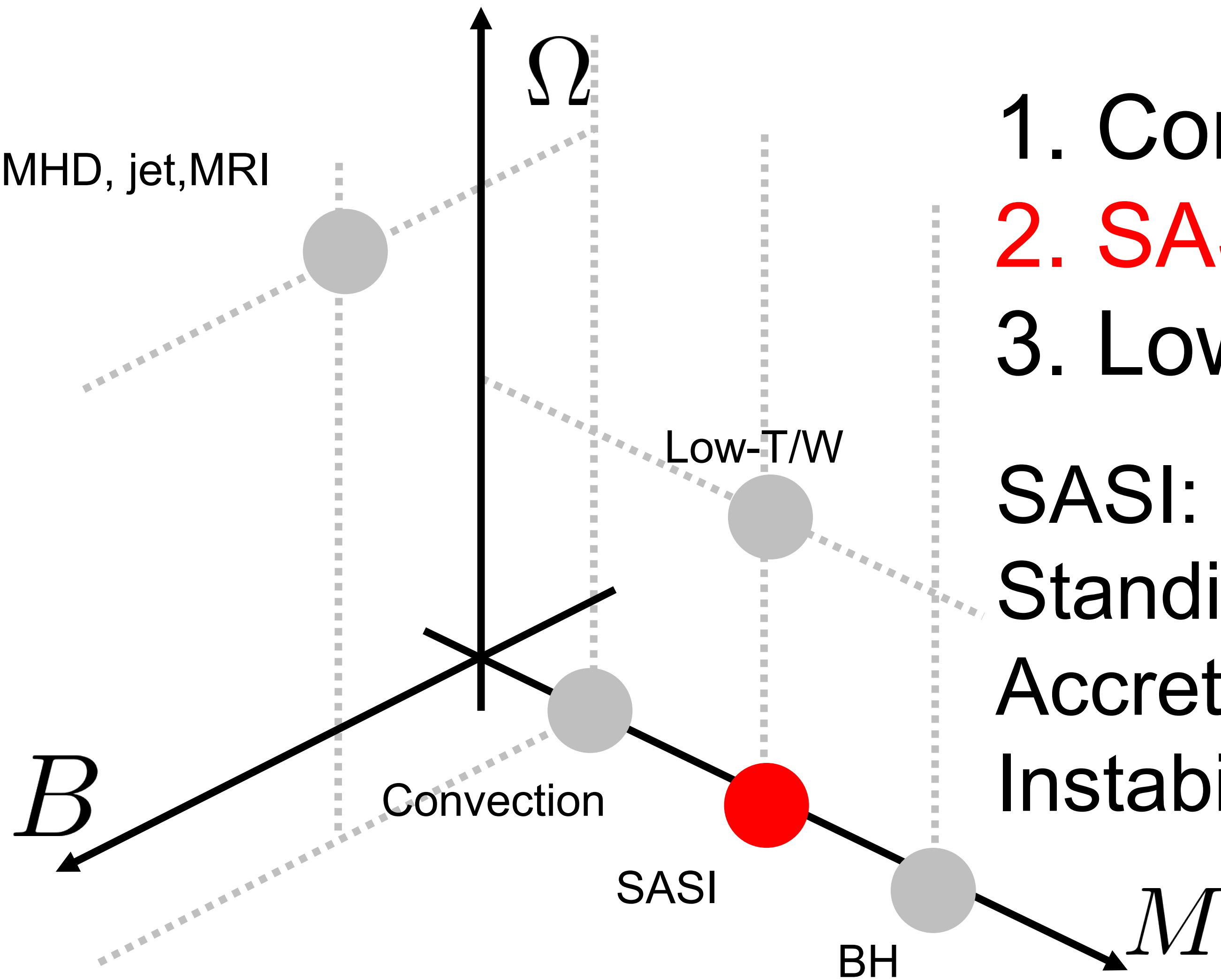
f-mode: (Sotani+ 2019)

$$4000\ \left(\frac{R}{10\mathrm{km}}\right)^{-3/2}\left(\frac{M}{1.4M_\odot}\right)^{1/2}\mathrm{Hz}$$

These formulae provide good estimation of the mode.

From the frequency of GW, we can know the evolution of radius of PNS.

Parameter Plane & Explosion Mechanism



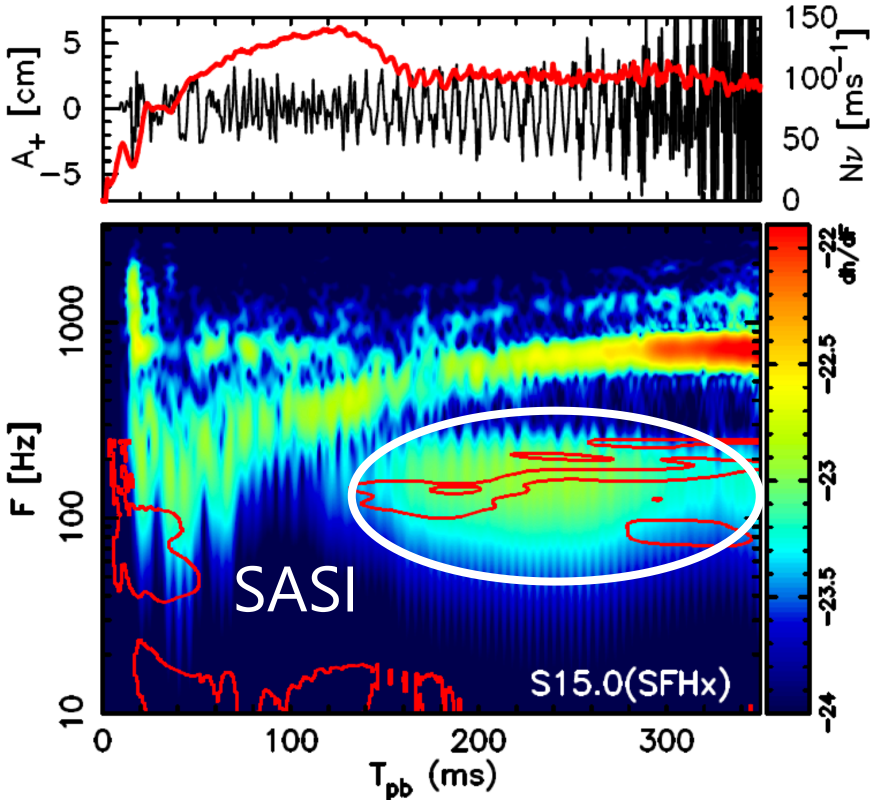
1. Convection
2. SASI
3. Low-T/W

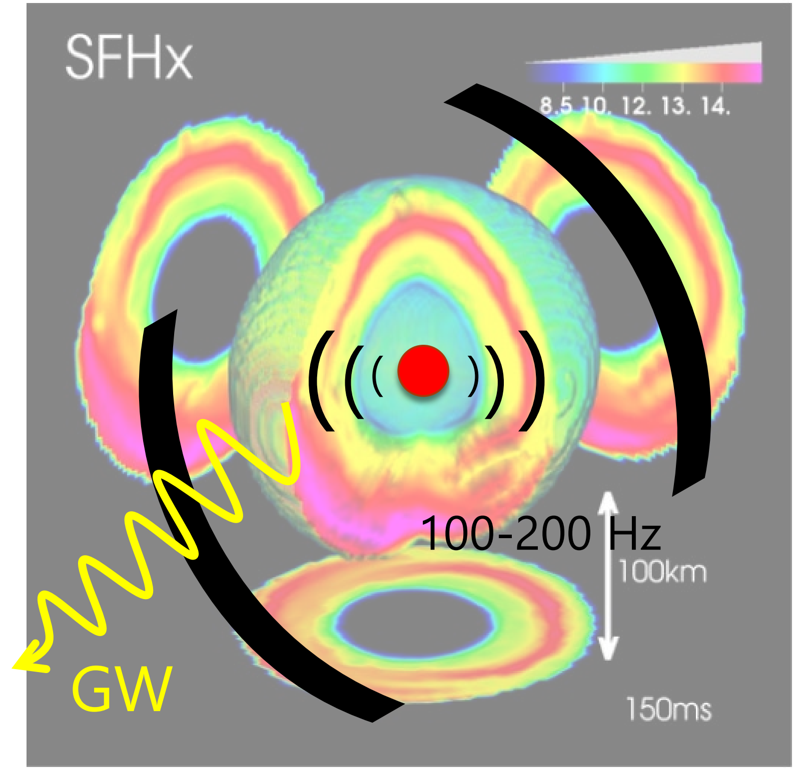
SASI:
Standing
Accretion Shock
Instability

3D simulation

Kuroda et al. 2016

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





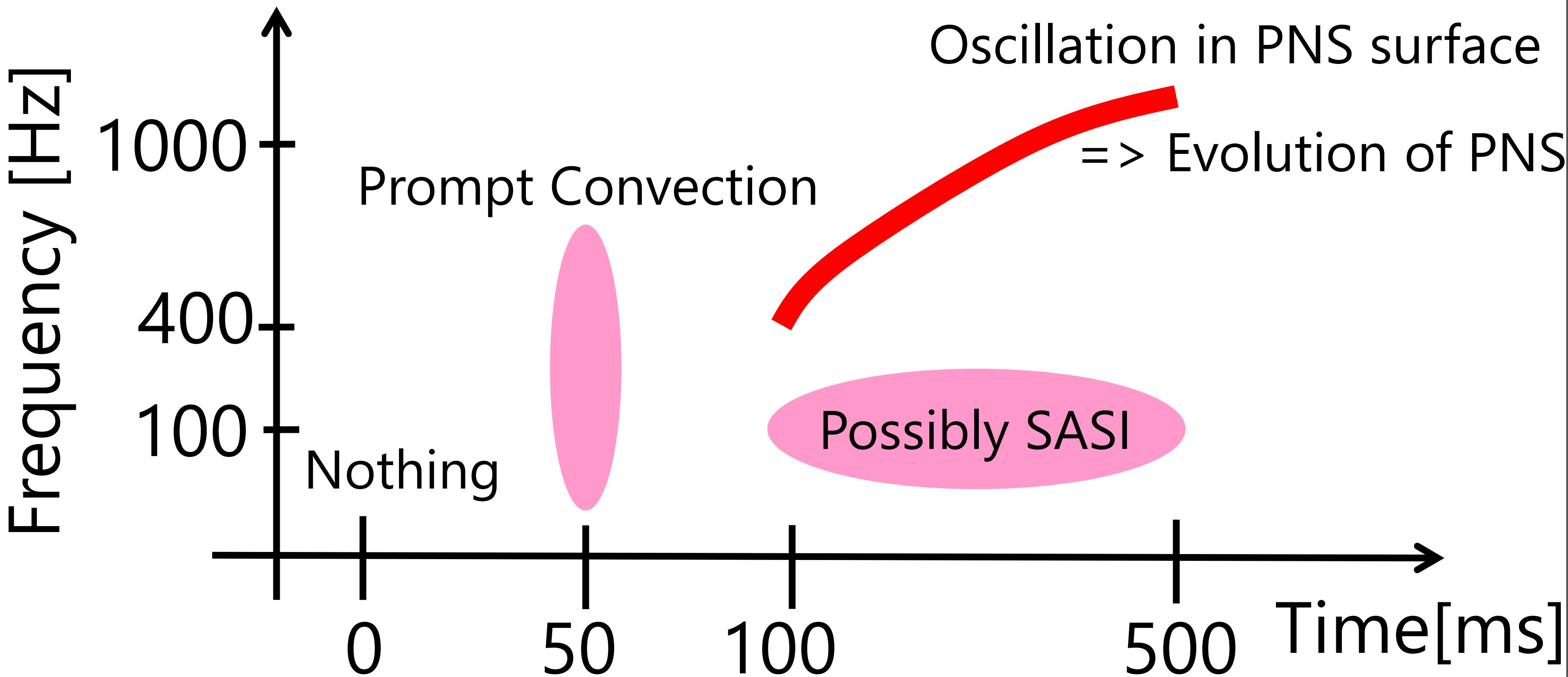
Kuroda et al. 2016

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

From GW signals (~200Hz), we can get evidence of SASI

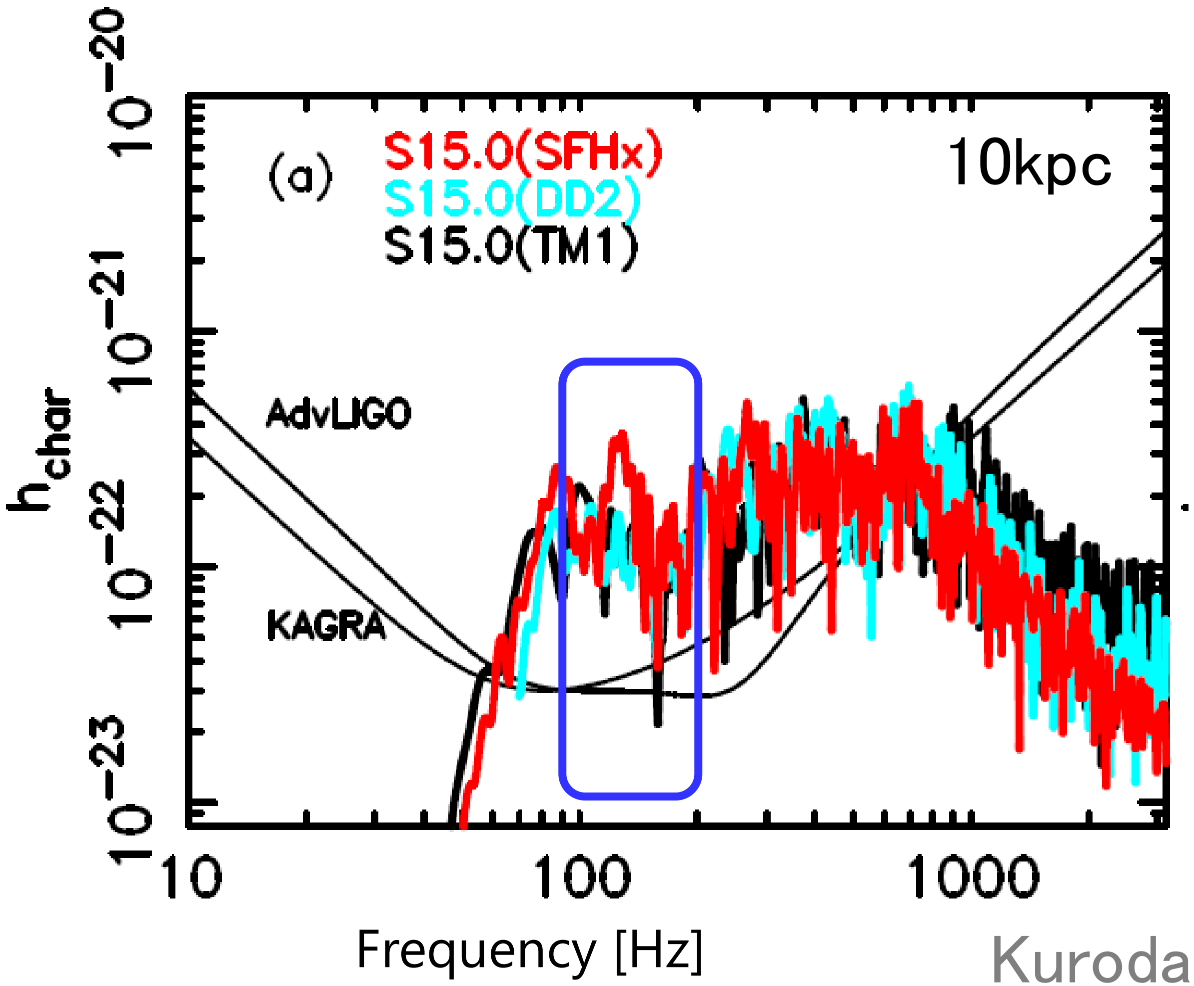
Summary of no rotating model

Non rotating progenitor



↑ Bounce time will be determined by ν observation

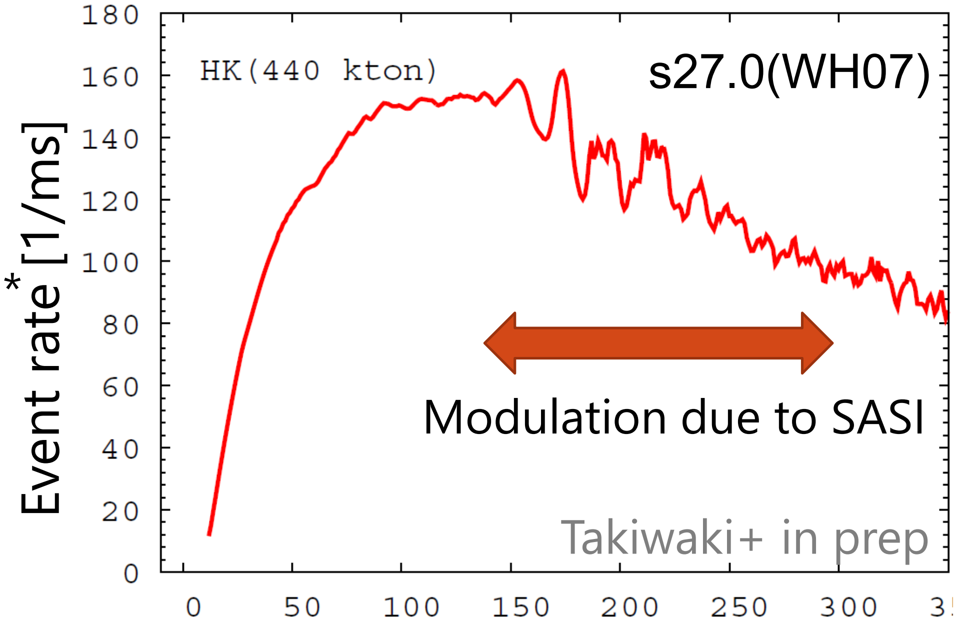
Detectability



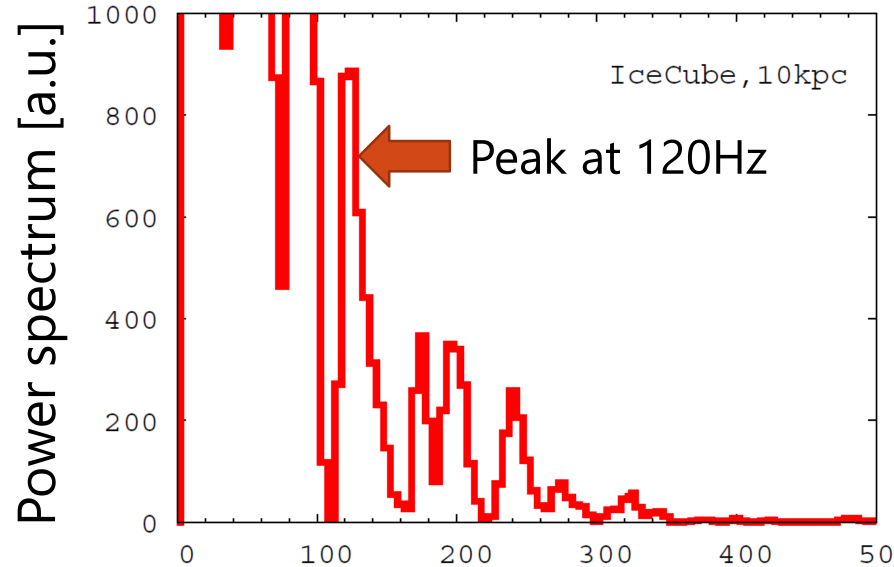
Kuroda+2017

With optimistic evaluation, S/N~10.

SASI Modulation imprinted in ν-signal



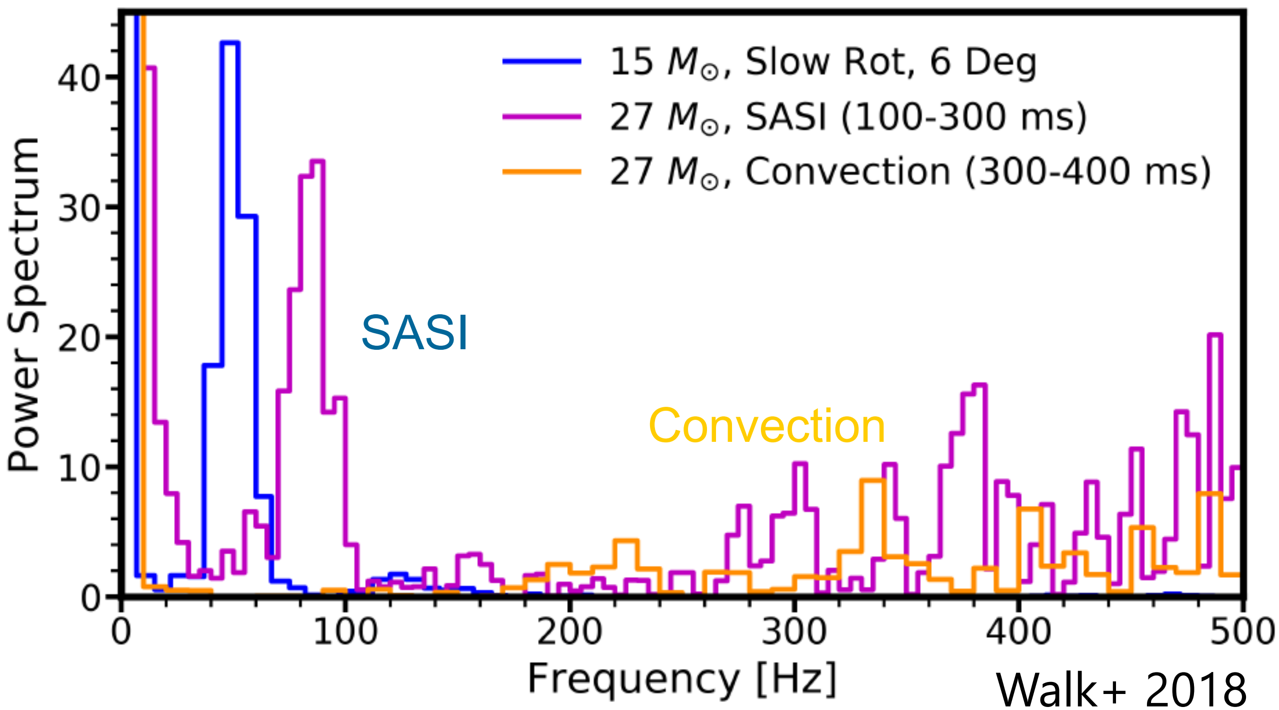
* Event is 5 times larger in IceCube



Modulation due to SASI

The results are consistent with Tamborra+ 2013,2014, Walk+ 2018

From Fourier Spectrum

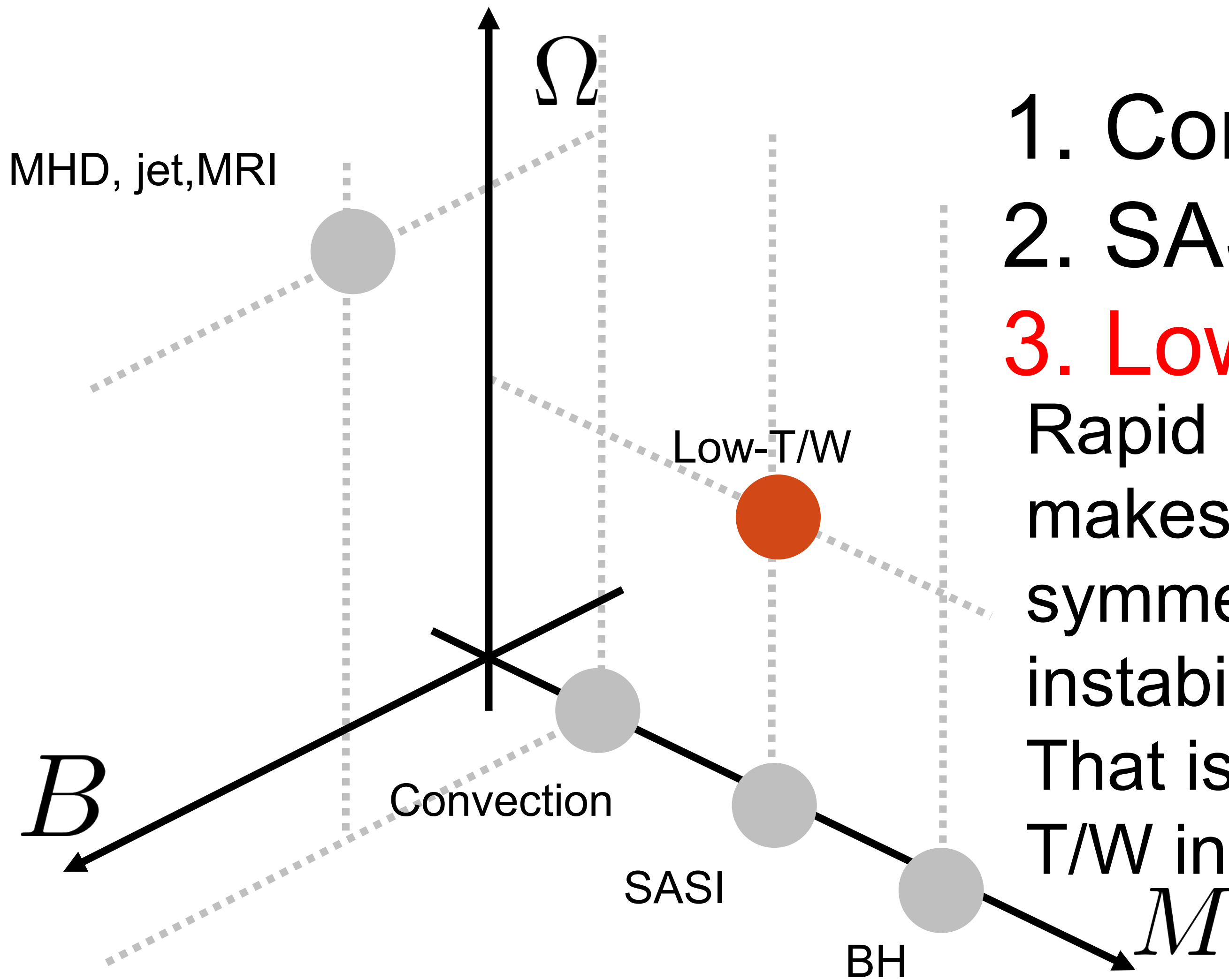


Walk+ 2018

FT of ν signal in SASI–dominant era -> ~100Hz

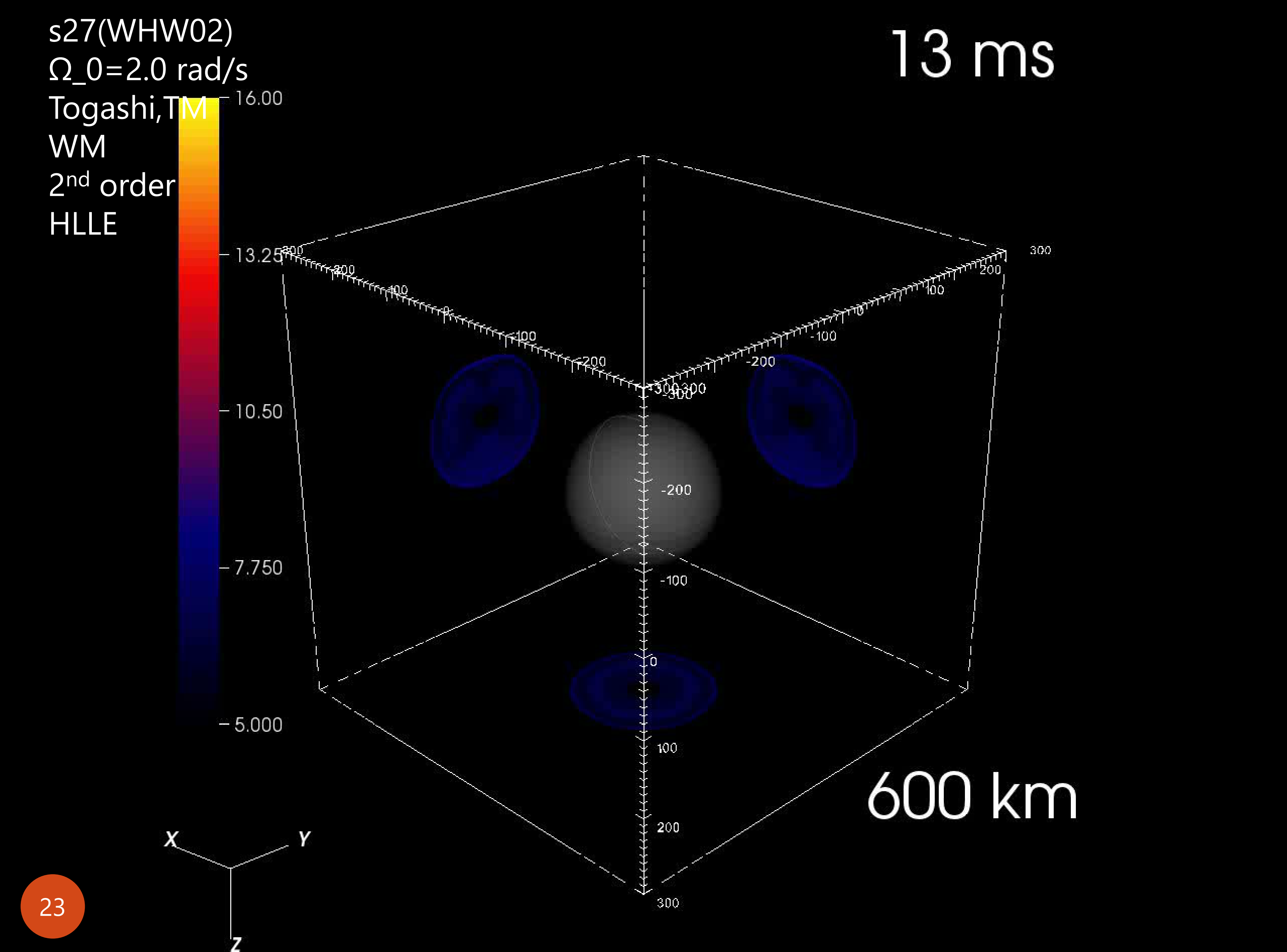
FT of ν signal in convection–dominant era -> high frequency

Parameter Plane & Explosion Mechanism



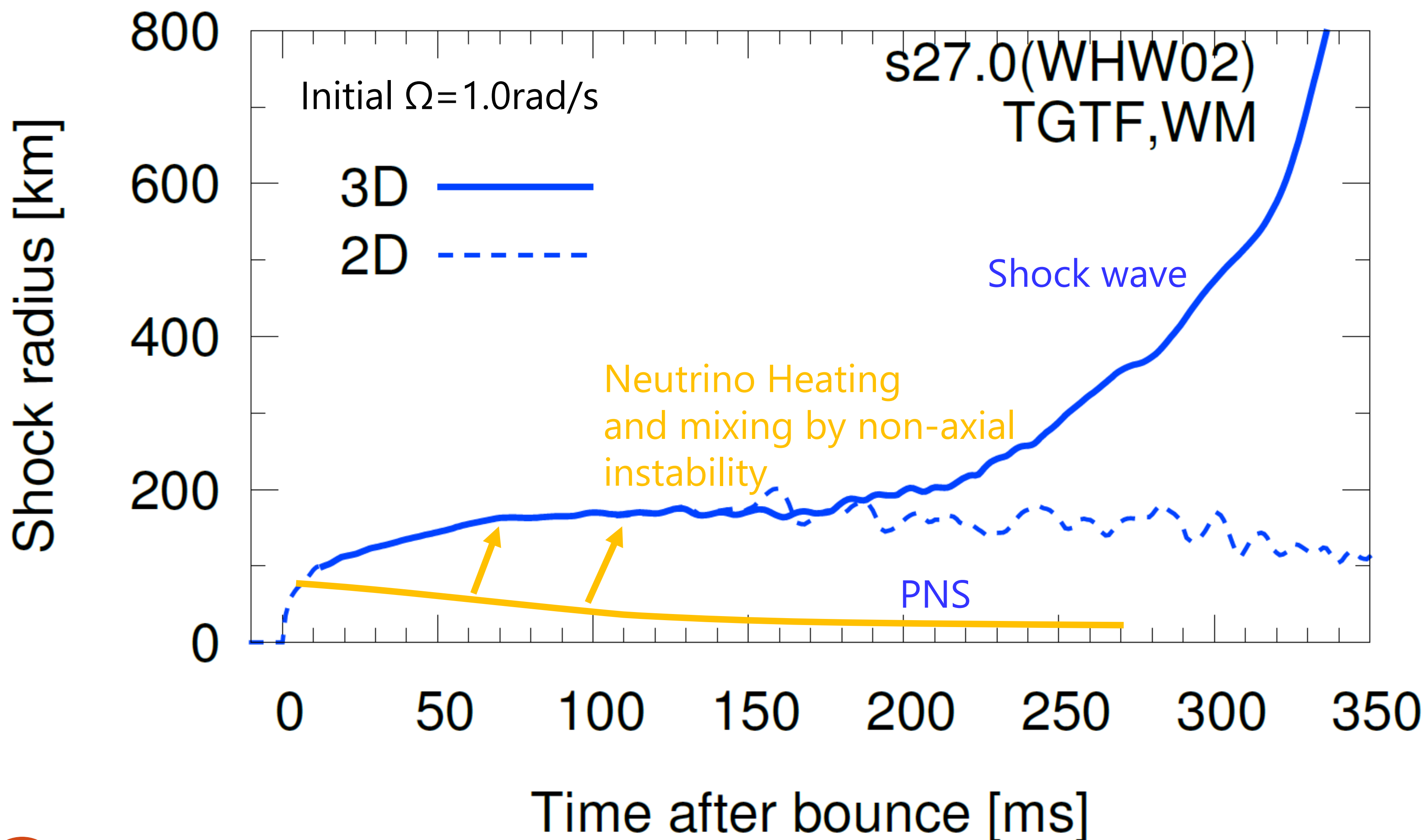
1. Convection
2. SASI
3. Low-T/W

Rapid rotation makes non-axi symmetric instability.
That is called low T/W instability.



s27(WHW02)
Ω_0=2.0 rad/s
Togashi,TM
WM
2nd order
HLLE
13 ms
16.00
13.25
10.50
7.750
5.000
600 km
X
Y
Z

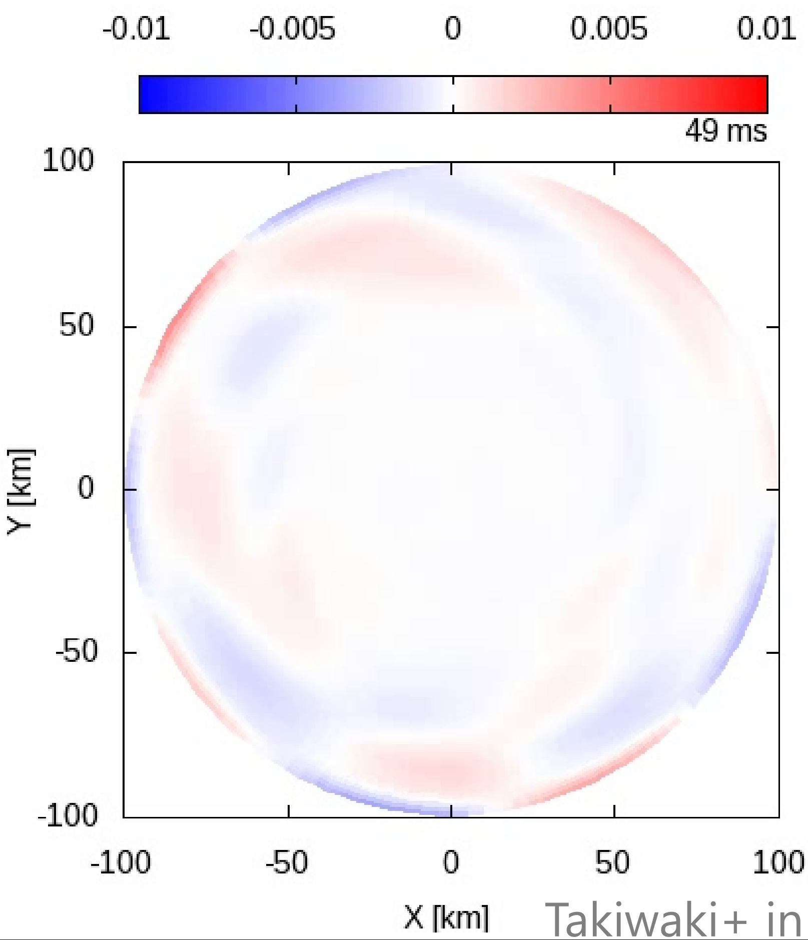
Explosion Mechanism for rotating model



Low T/W instability

$$\Delta\rho = \frac{\rho - \langle\rho\rangle}{\rho}$$

z=0 plane



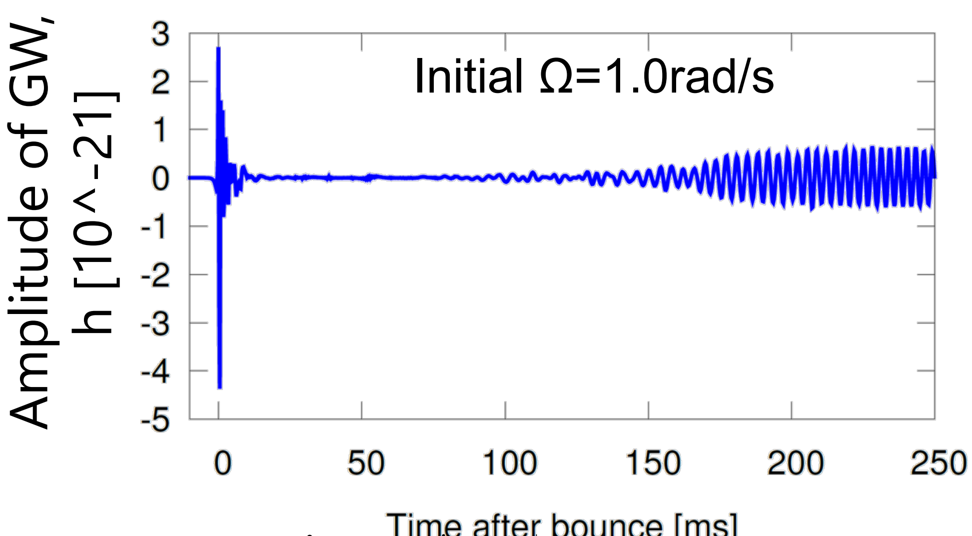
Takiwaki+ in prep

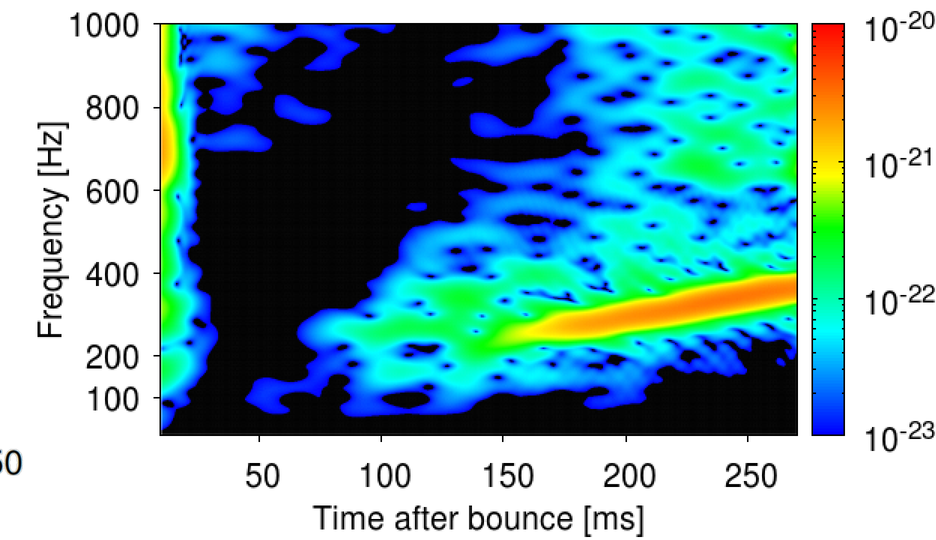
When the rotation energy exceeds a threshold.

Perturbation of low mode (m=1 or m=2) become unstable.

The threshold value depends on rate of differential rotation.
In this case, typically ~6% of gravitational binding energy.

GW Emission in rotating model





Time after bounce [ms]

Wave form

Fourier transformation

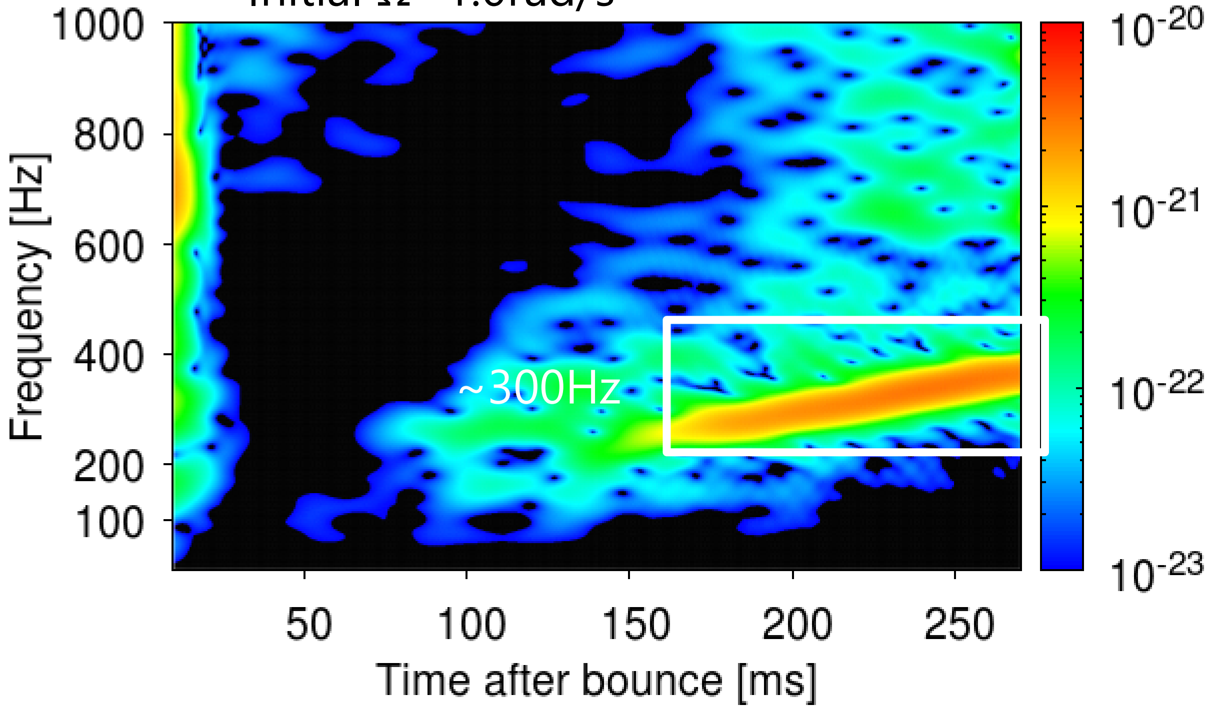
Spectrogram

Large amplitude of Gravitational wave is emitted.

GW Emission in rotating model

$$h \sim \frac{G}{c^4} \int \mathrm{d}V \boxed{\rho \left(v_z v_z - v_x v_x \right.} \left. - z \partial_z \Phi + x \partial_x \Phi \right)$$

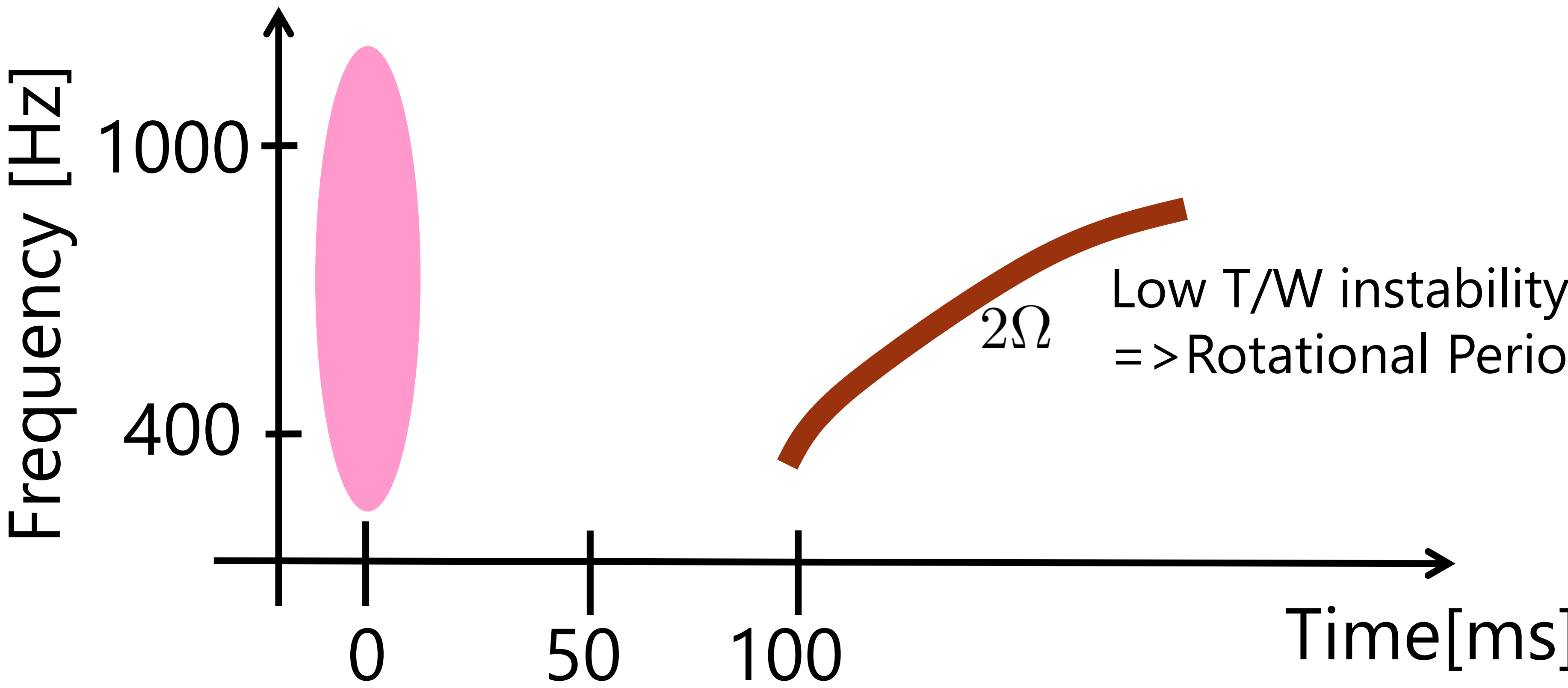
Initial Ω=1.0rad/s



This frequency is twice as large as the rotational frequency of PNS.

Summary of rotating model

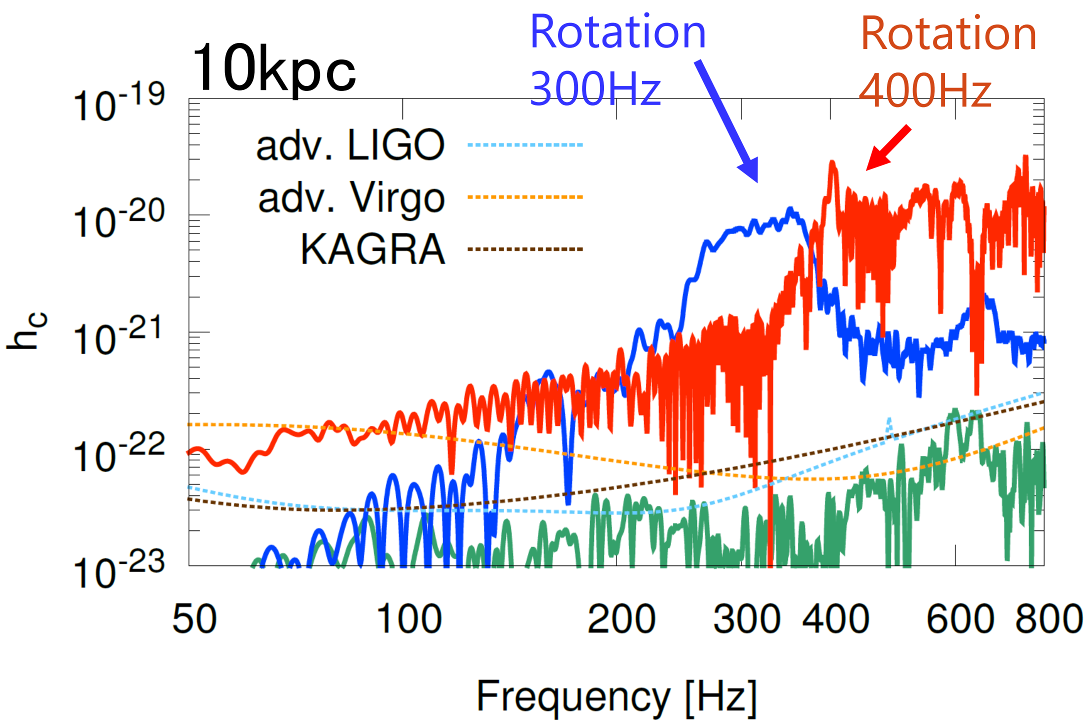
Rapidly rotating progenitor



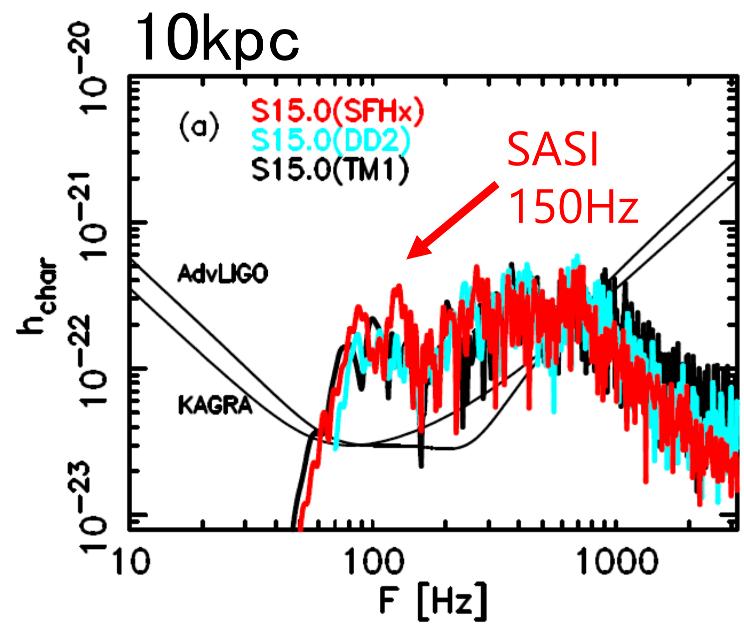
↑ Bounce time is determined by ν observation

Detectability

Rotating Model



Non-Rotating Model



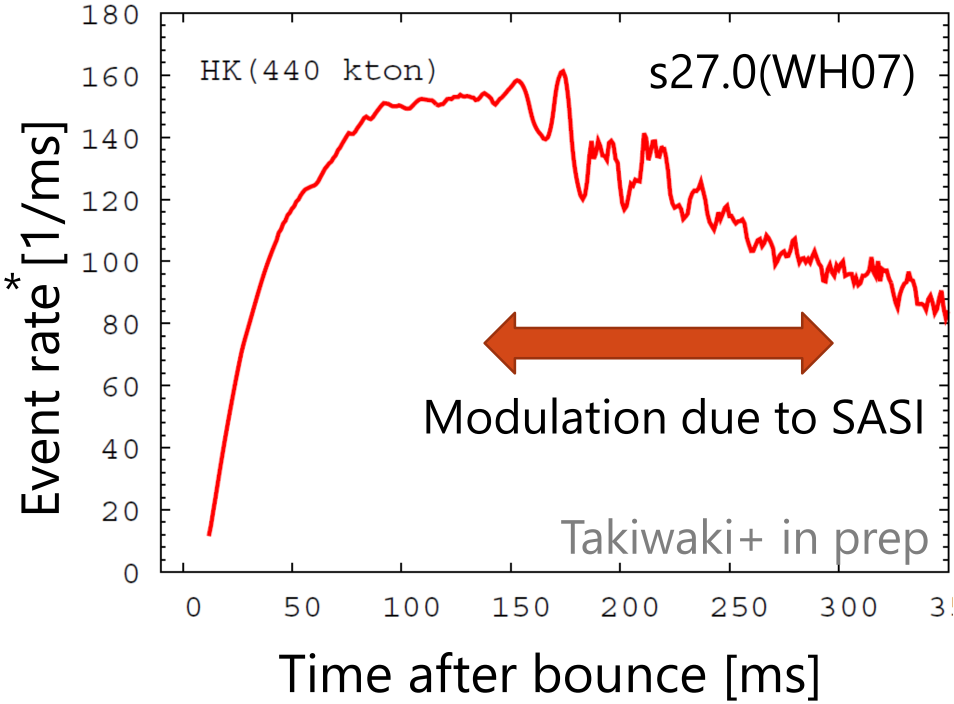
Kuroda+2017

S/N~100.

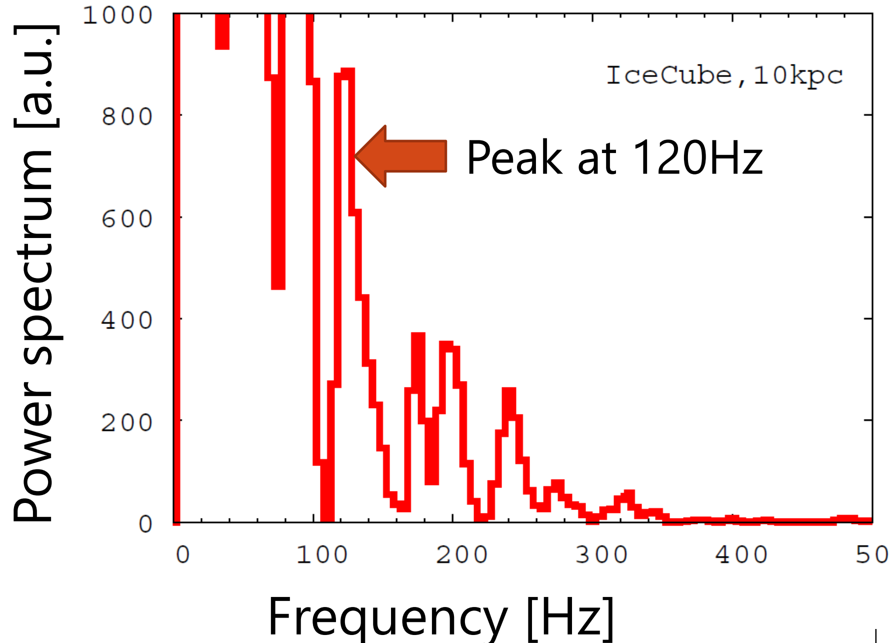
Takiwaki+ in prep.

SASI and Rotation provide gravitational waves that has typical frequencies. Polarization analysis of LIGO-VIRGO-KAGRA network can help us to distinguish those.

Neutrino Observation



* Event is 5 times larger in IceCube



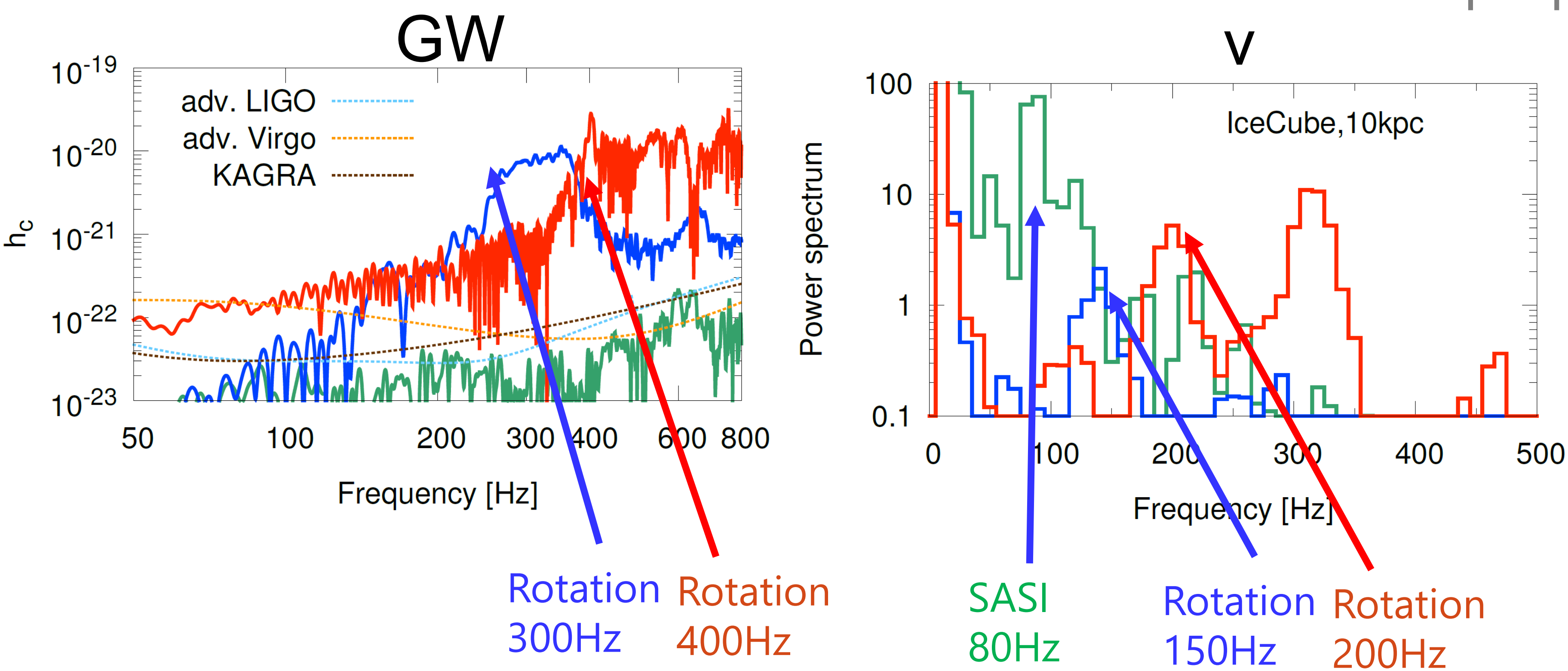
Modulation due to SASI

Fourier analysis of neutrino signal also provides an interesting probe to identify the explosion mechanism.

The results are consistent with Tamborra+ 2013,2014, Walk+ 2018

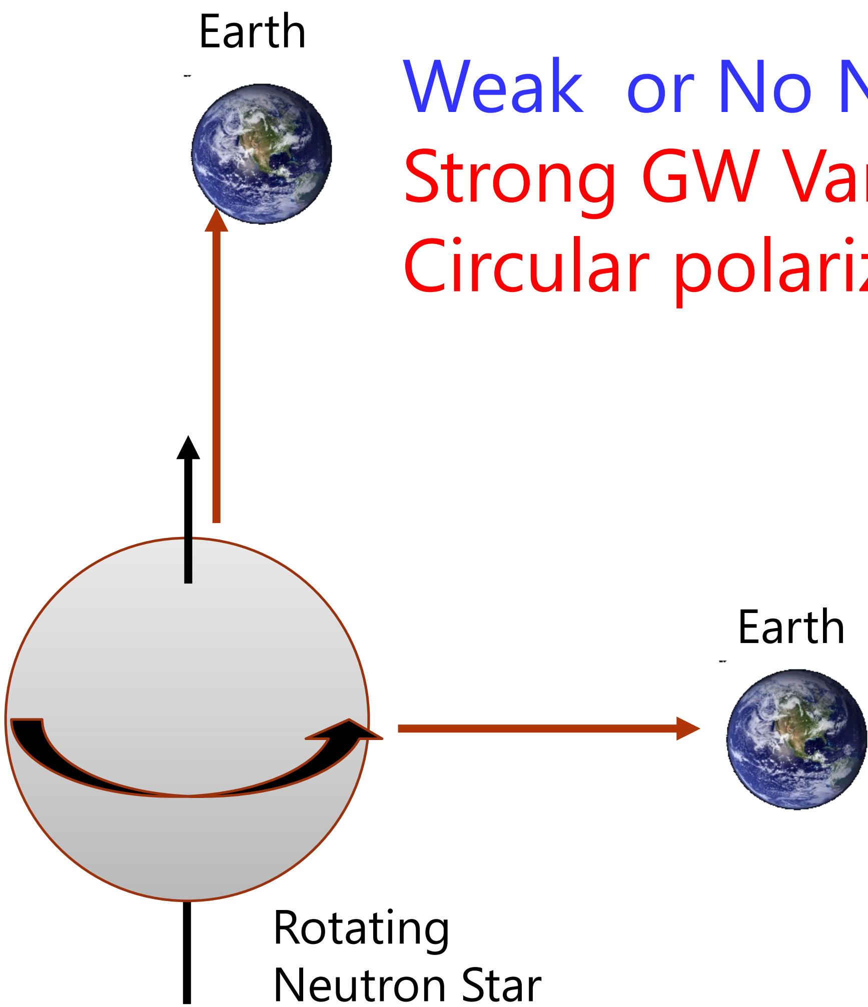
Multi-messenger Astronomy

Takiwaki+ in prep.



Joint observation of Hyper Kamiokande and IceCube will give indispensable opportunity to identify the explosion mechanism.

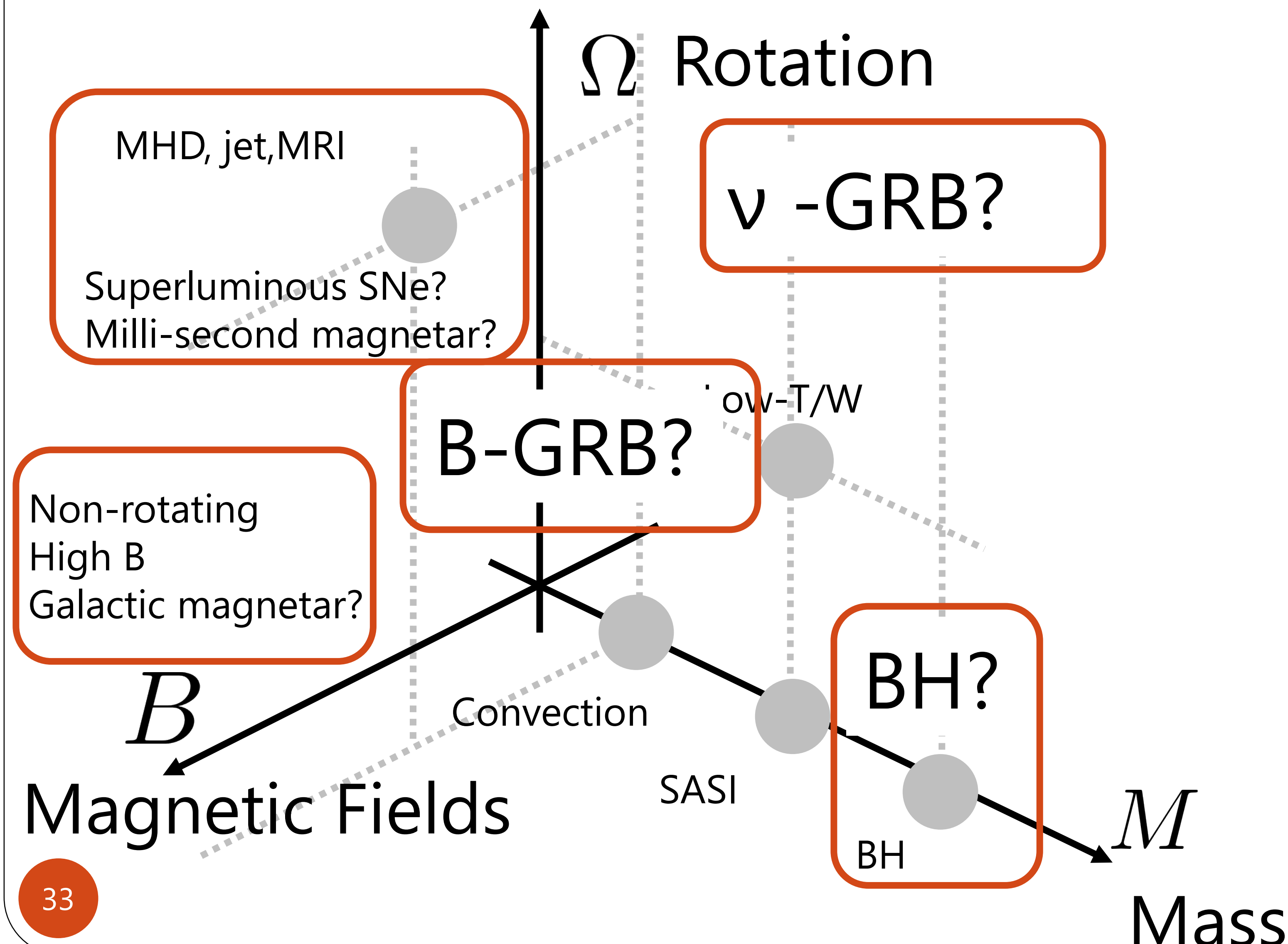
Direction dependence in Rotating model



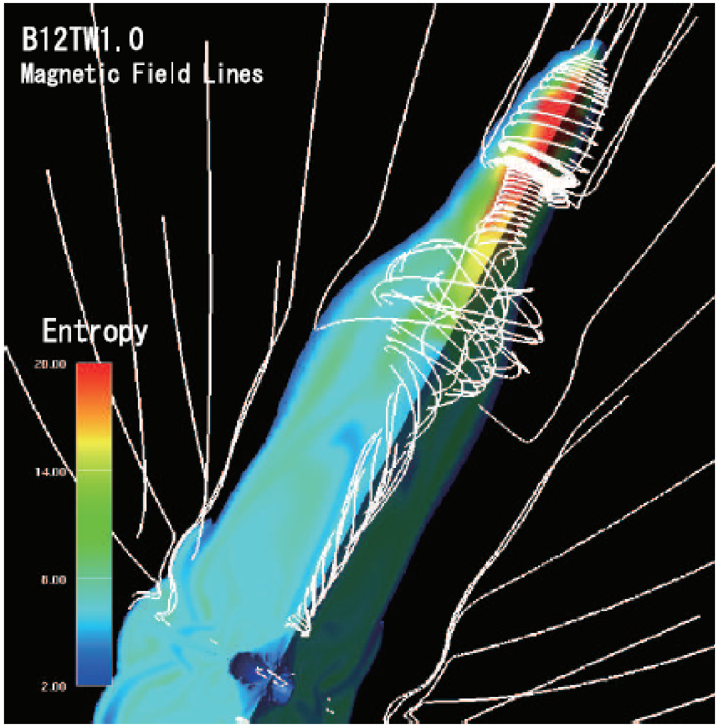
Weak or No Neutrino Variability
Strong GW Variability
Circular polarization

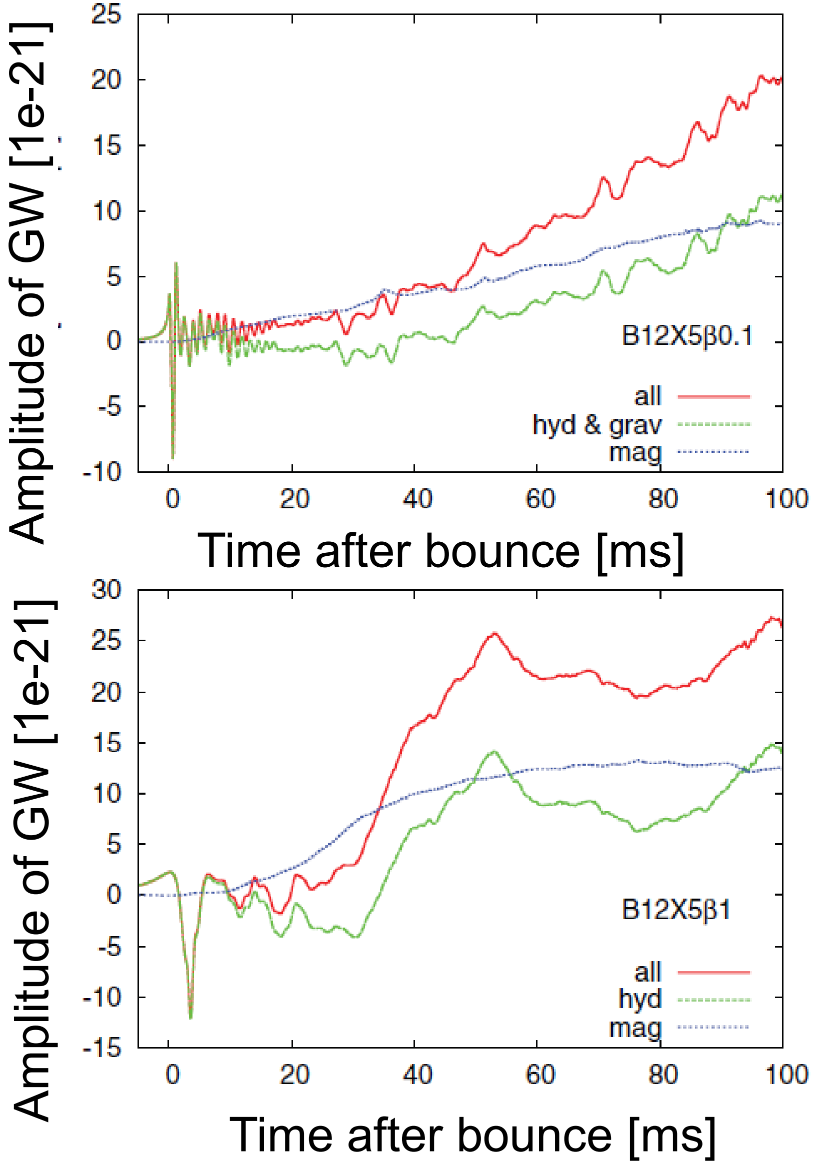
Strong Neutrino Variability
Moderate GW Variability
Liner polarization

Lots of Open Questions !!!



Jet-like Explosion and low frequency GW





Takiwaki+2009, 2011 discussed low-frequency GW signal from jet-like Explosion of strongly magnetized core-collapse.

Looking forward to seeing the update!

Summary

Supernova explosion mechanism has diversity.
GW would be powerful tool to identity it.

Convection: Ramp-up ~200-1000Hz in GW
SASI: ~150Hz, S/N~10 of GW and 75Hz ν
Rotation: ~300Hz, S/N~100 of GW and 150Hz ν

For detailed analysis, joint observation of LIGO-VIRGO-KAGRA and Hyper-K, IceCube would be indispensable.