Various GW emission mechanisms from CCSNe

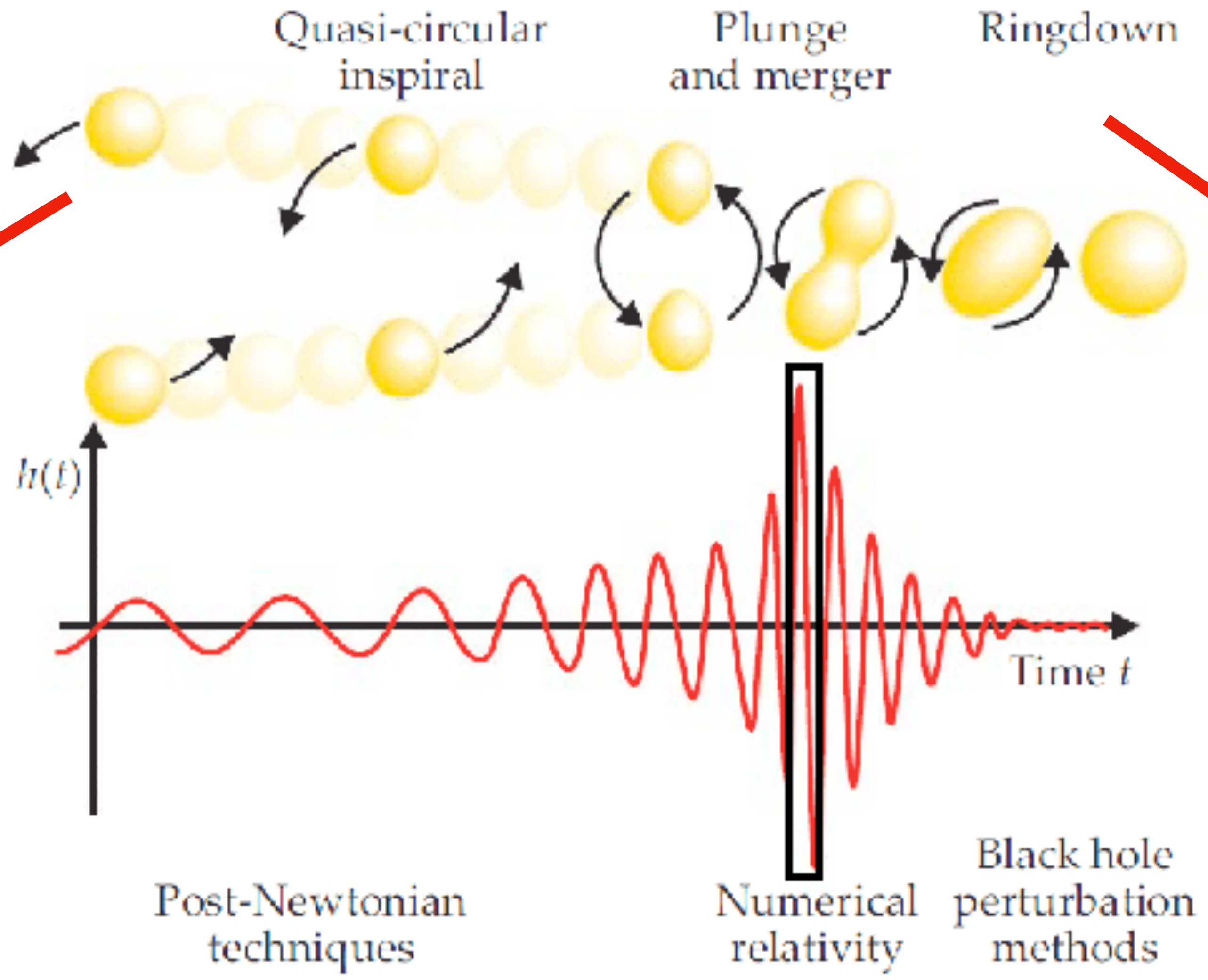
Max-Planck-Institut
für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

Takami Kuroda (MPI for Gravitational Physics)

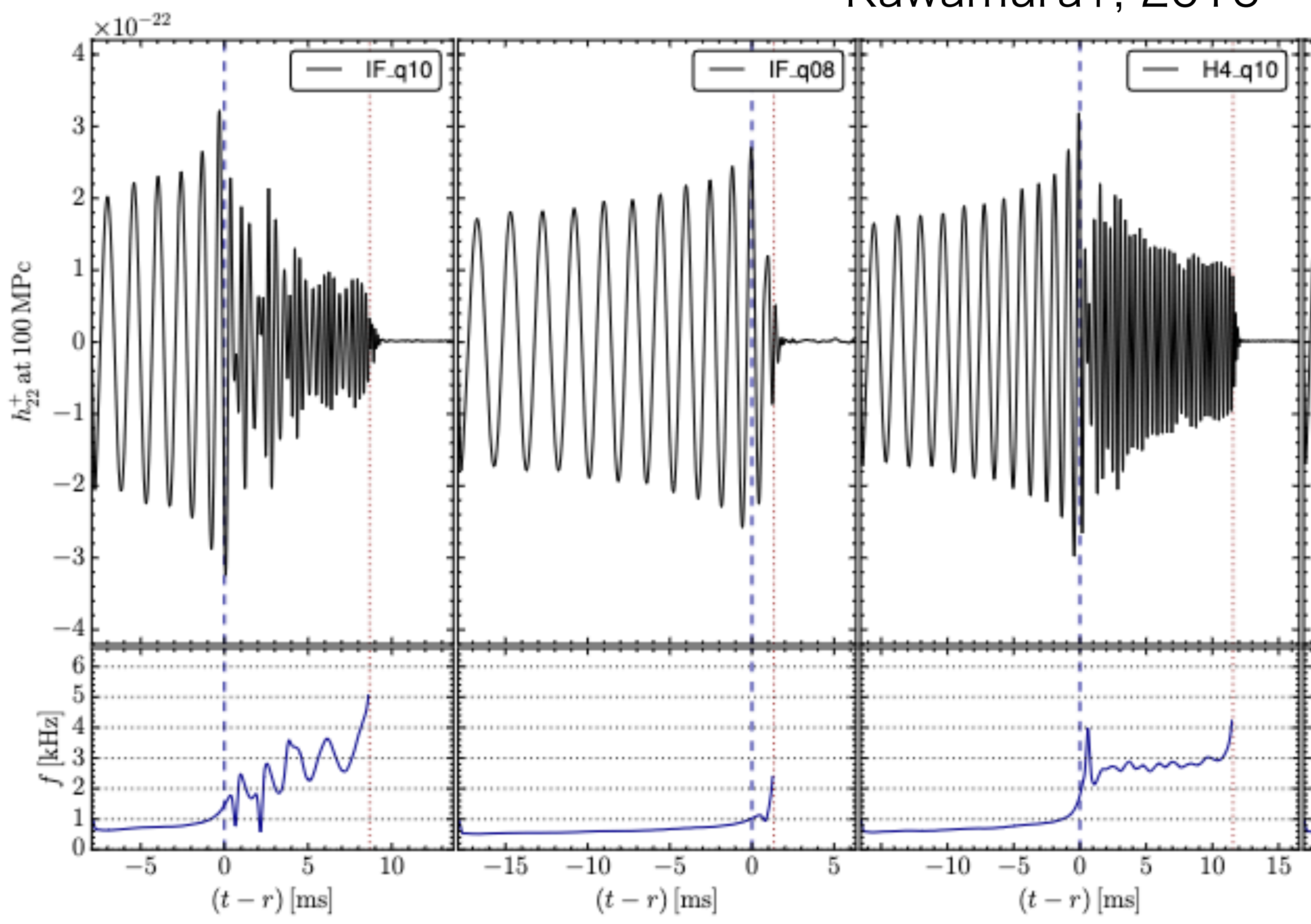
Brainstorming workshop: Deciphering the equation of state using gravitational waves from BNS(/BBH).

Kawamura+, 2016

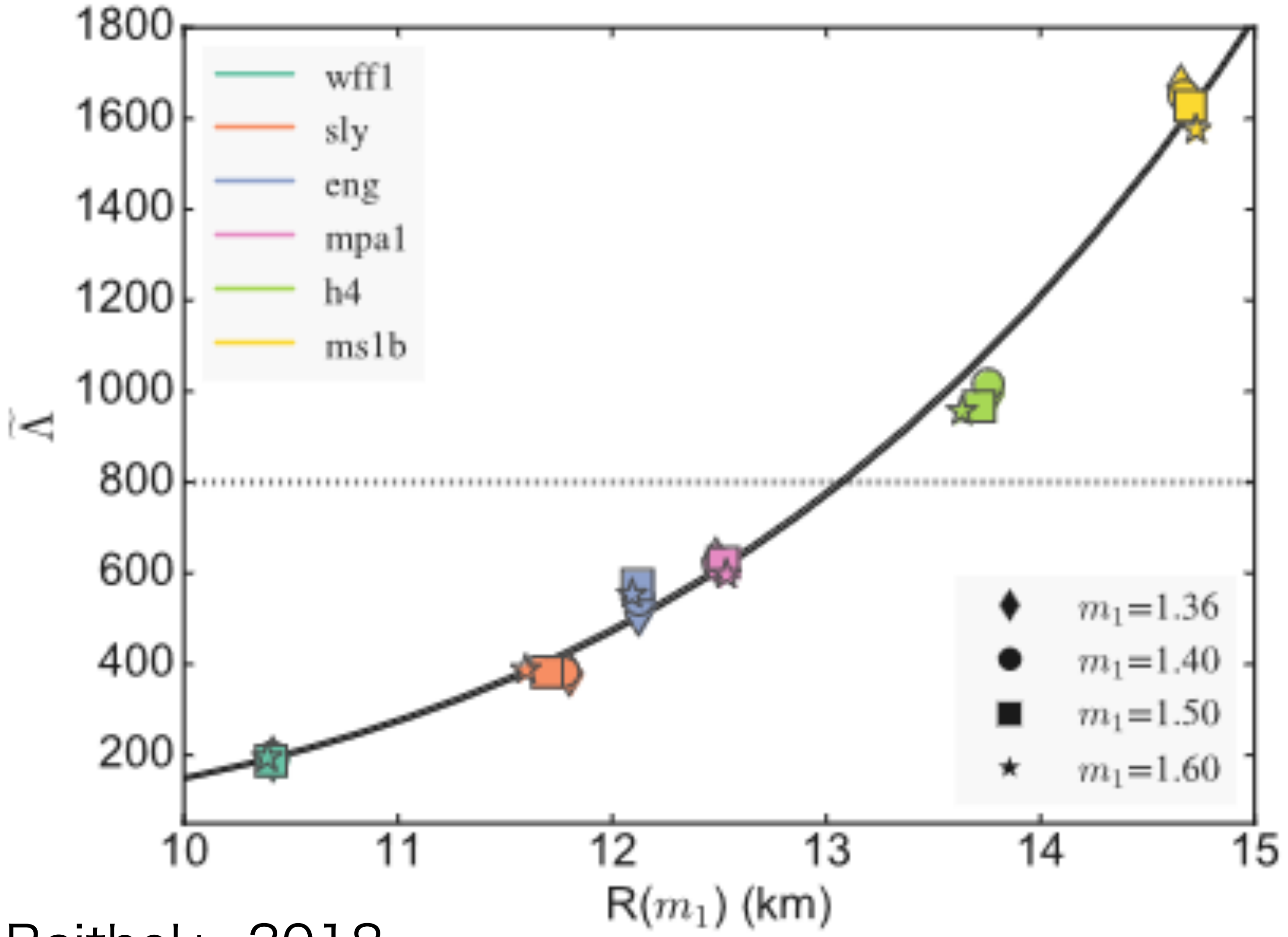
$$h^{ij}(t,\mathbf{x}) = \frac{2Gm}{Rc^4}\left\{ Q^{ij} + \frac{1}{c} Q^{ij}_{0.5\mathrm{PN}} + \frac{1}{c^2} Q^{ij}_{1\mathrm{PN}} + \frac{1}{c^3} Q^{ij}_{1.5\mathrm{PN}} + \frac{1}{c^4} Q^{ij}_{2\mathrm{PN}} + \frac{1}{c^5} Q^{ij}_{2.5\mathrm{PN}} + \dots \right\},$$



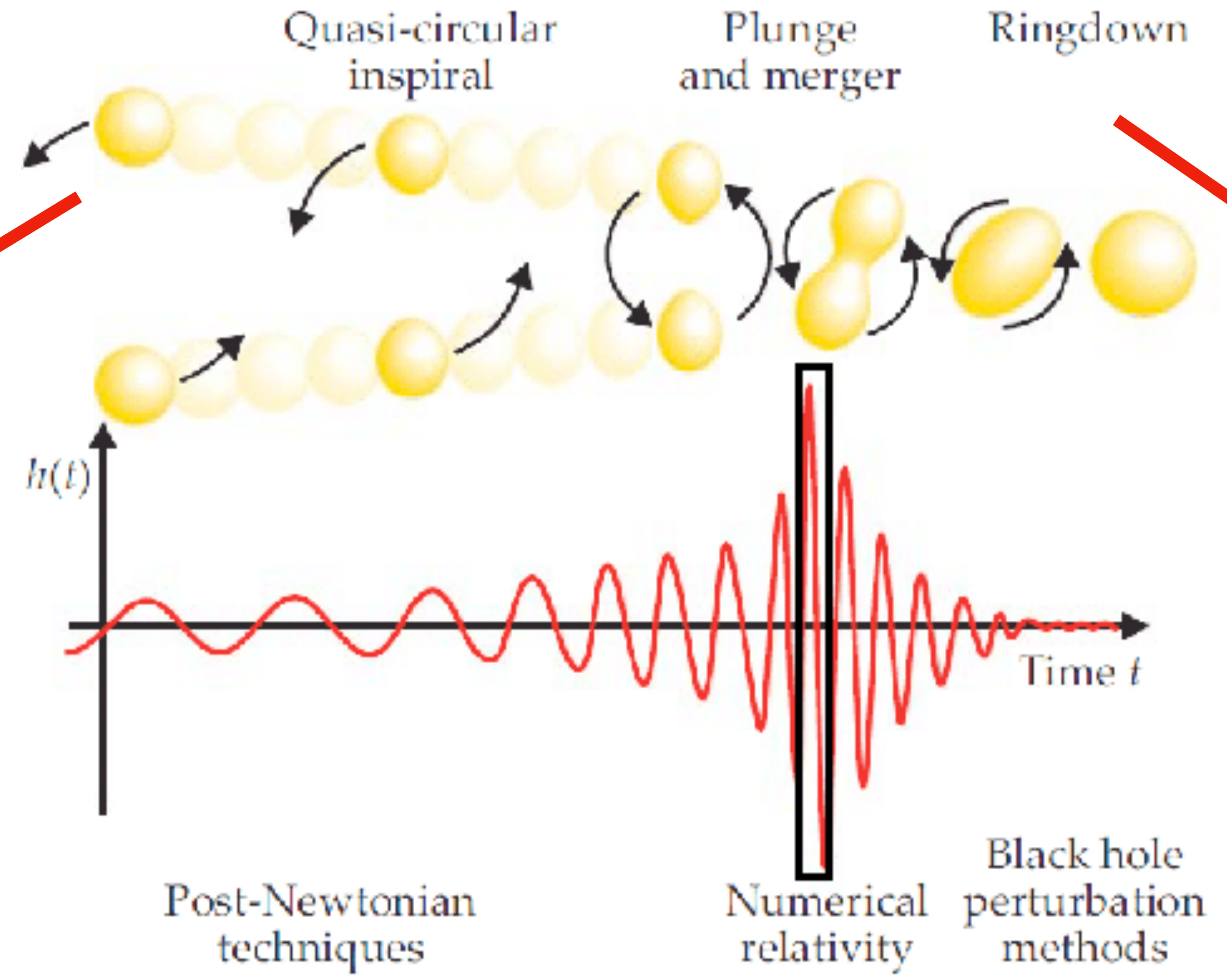
Baumgarte, T. Shapiro, S. Numerical Relativity (2010).



Brainstorming workshop: Deciphering the equation of state using gravitational waves from BNS(/BBH).

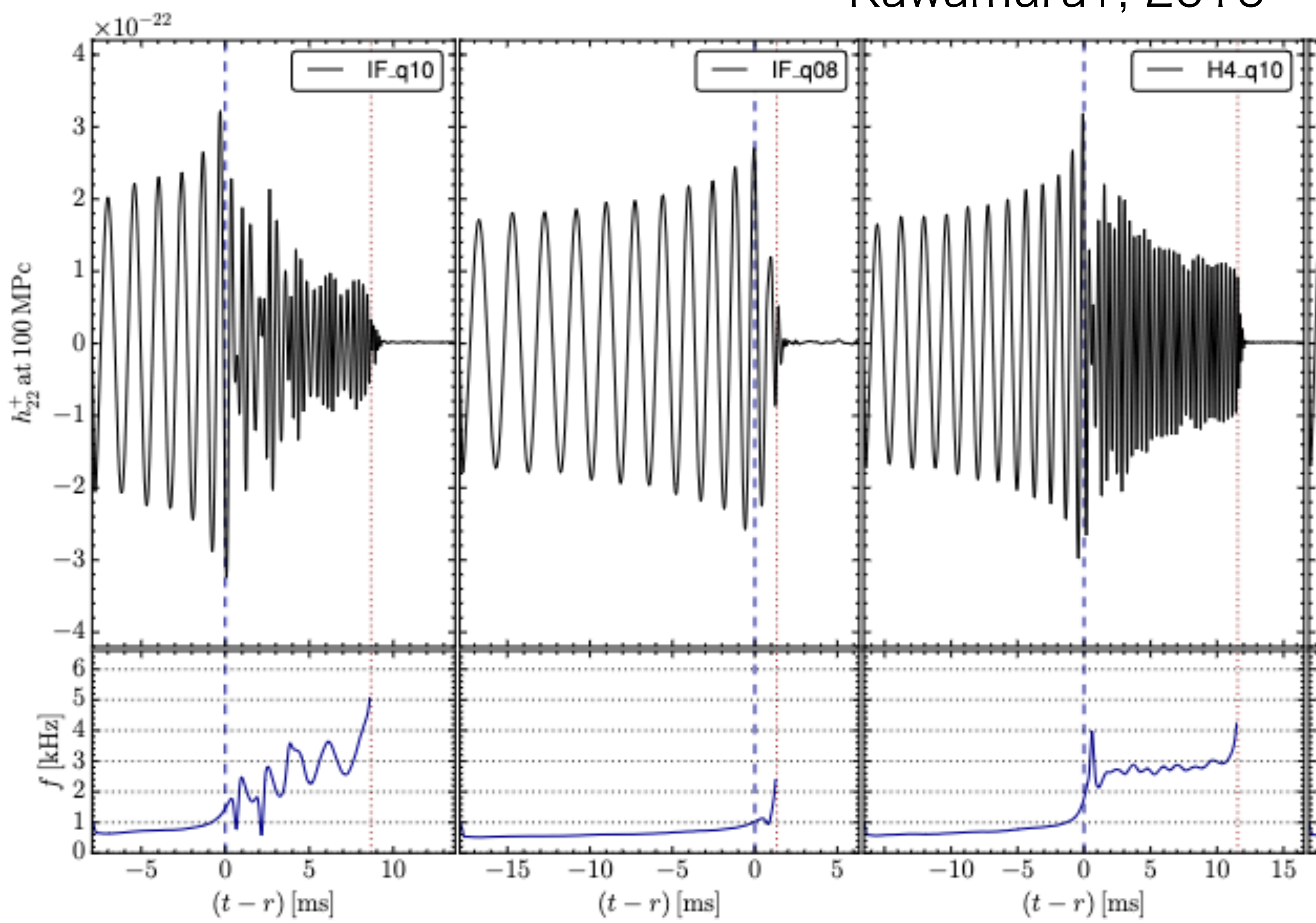


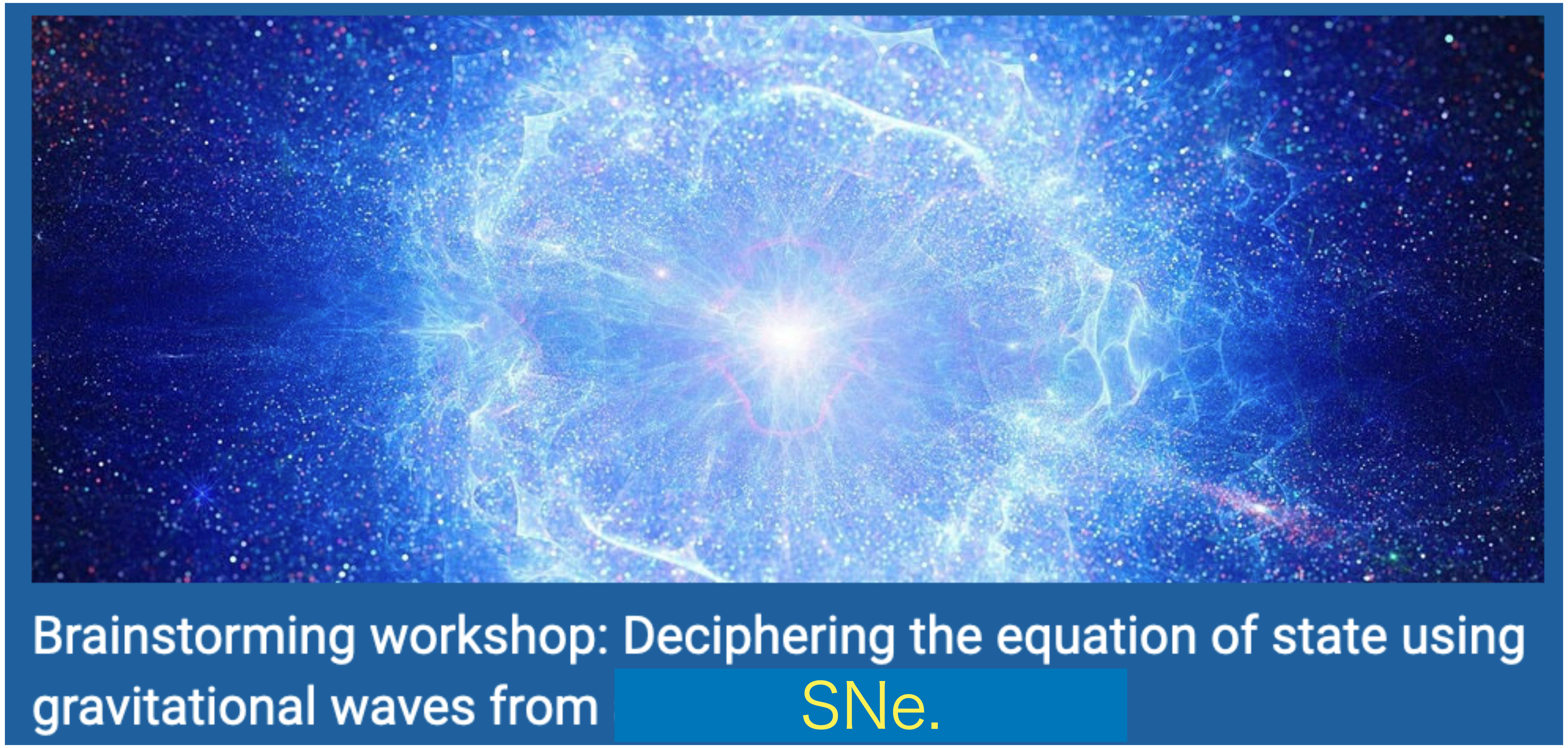
Raithel+, 2018

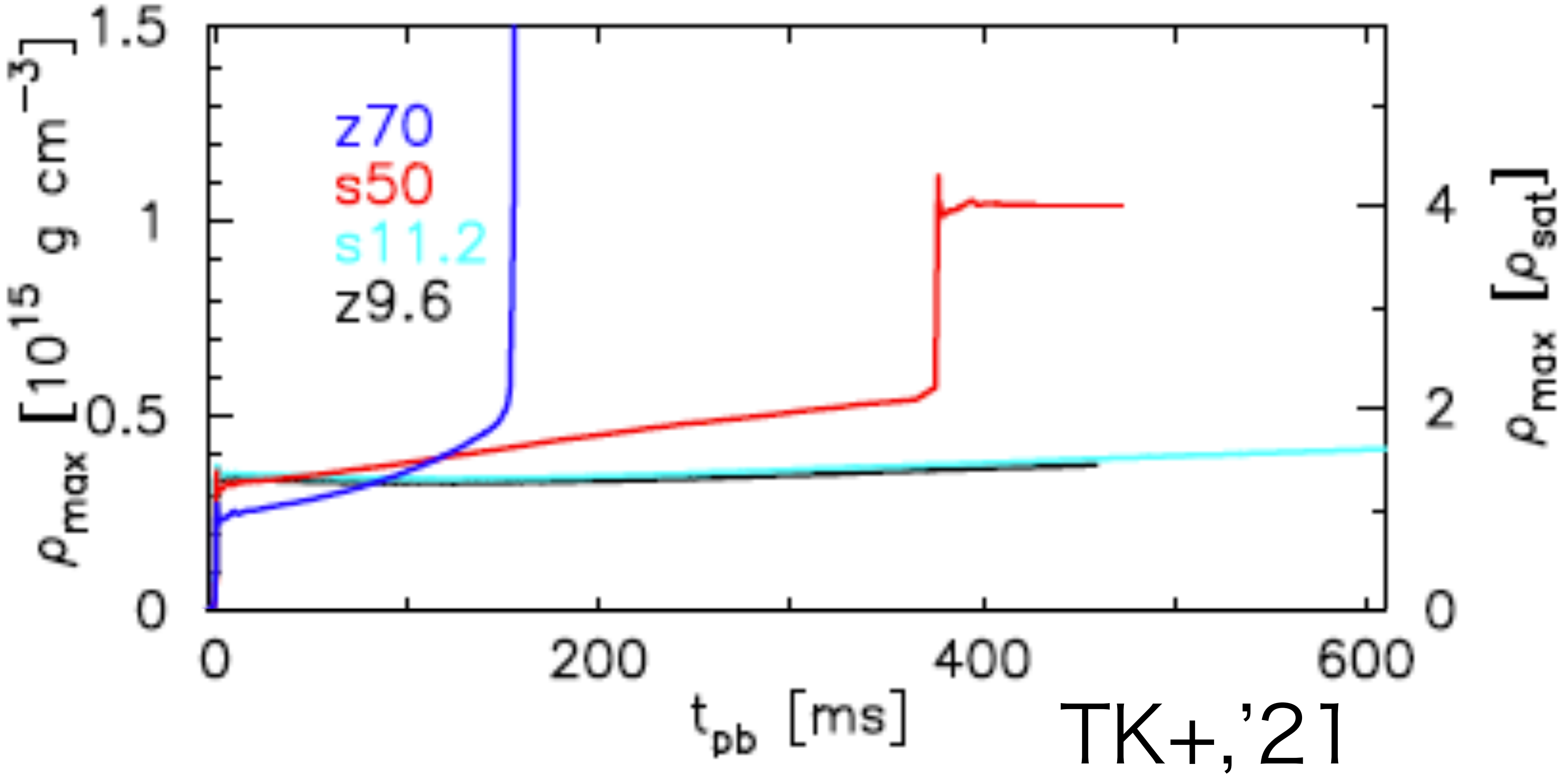


Baumgarte, T. Shapiro, S. Numerical Relativity (2010).

Kawamura+, 2016







TK+,'21

Three major phases in SN

- Collapse and bounce
- PNS contraction
- Either explosion or BH

Comparison of Multi-Messenger signals between BNS/BBH and CCSN in terms of GWs

Order-of-magnitude estimation of GW amplitude

$$h_{ij} = \frac{2G}{c^4 D}\ddot{I}_{ij} \sim \epsilon \frac{R_s}{D}\left(\frac{v}{c}\right)^2$$

ε: asphericity
R_s: size
D: source distance
v: velocity

or in terms of detection horizon D

	CCSN	BNS/BBH
ε:	~0.01-0.1	~10-100(?)
R_s:	~10km	~km
v:	~0.1c	~0.1-0.3c
$D \sim \epsilon \frac{R_s}{h}\left(\frac{v}{c}\right)^2$	~a few 10 kpc	~100Mpc (for $h \sim 10^{-21}$)

We can detect only the Galactic SNe (or SMC/LMC ~50kpc)

Comparison of Multi-Messenger signals between BNS/BBH and CCSN in terms of GWs

	CCSN (D~10kpc)	BNS/BBH (D~100Mpc)
Rate	~0.01/galaxy/yr	~several /(100Mpc)^3/yr
EM waves	✔	(✔)
Neutrinos ($D_{neutrino}$~800kpc with SK)	✔	✖

The chance of GW detection from SN is still low, <one event/(10yr).
So it is important to explore their GWs/neutrinos/EM waves emission mechanisms not to miss once-in-a-lifetime event.

Sophisticated SN modeling and GW prediction are essential

GW emissions from SN

3 major phases in SN

- Collapse and bounce
- PNS contraction
- Either explosion or BH

3 major emission mechanisms

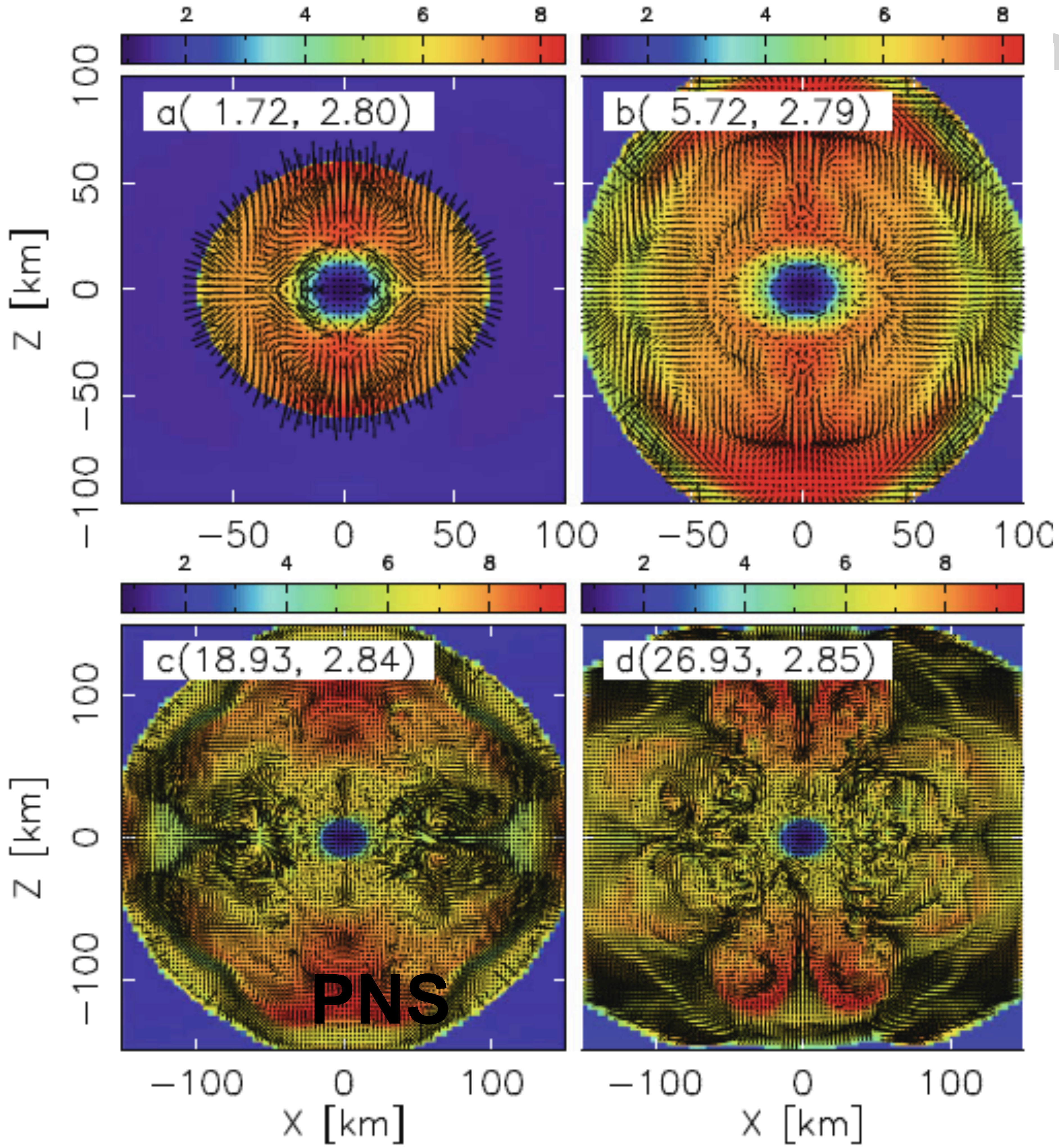
1. **Rotational bounce** —>Dh~100cm
2. **g/f-mode oscillation of PNS** —>Dh~10cm
3. **SASI motion** —>Dh~10cm

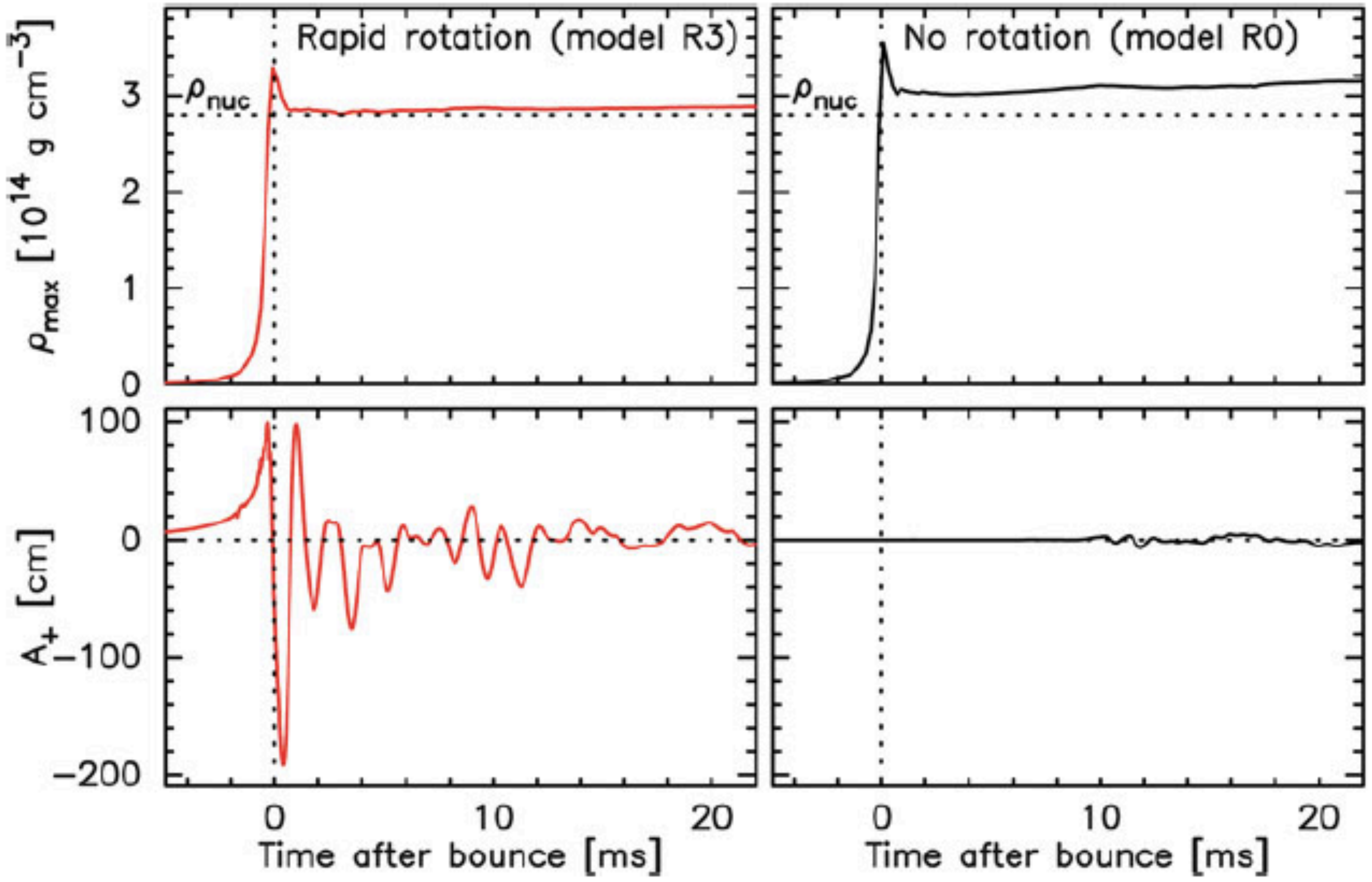
GW emissions from SN

3 major emission mechanisms

1. **Rotational bounce**
2. g/f-mode oscillation of PNS

notion





Kotake&Kuroda,'16

This component is one of promising SN GWs (for detection)

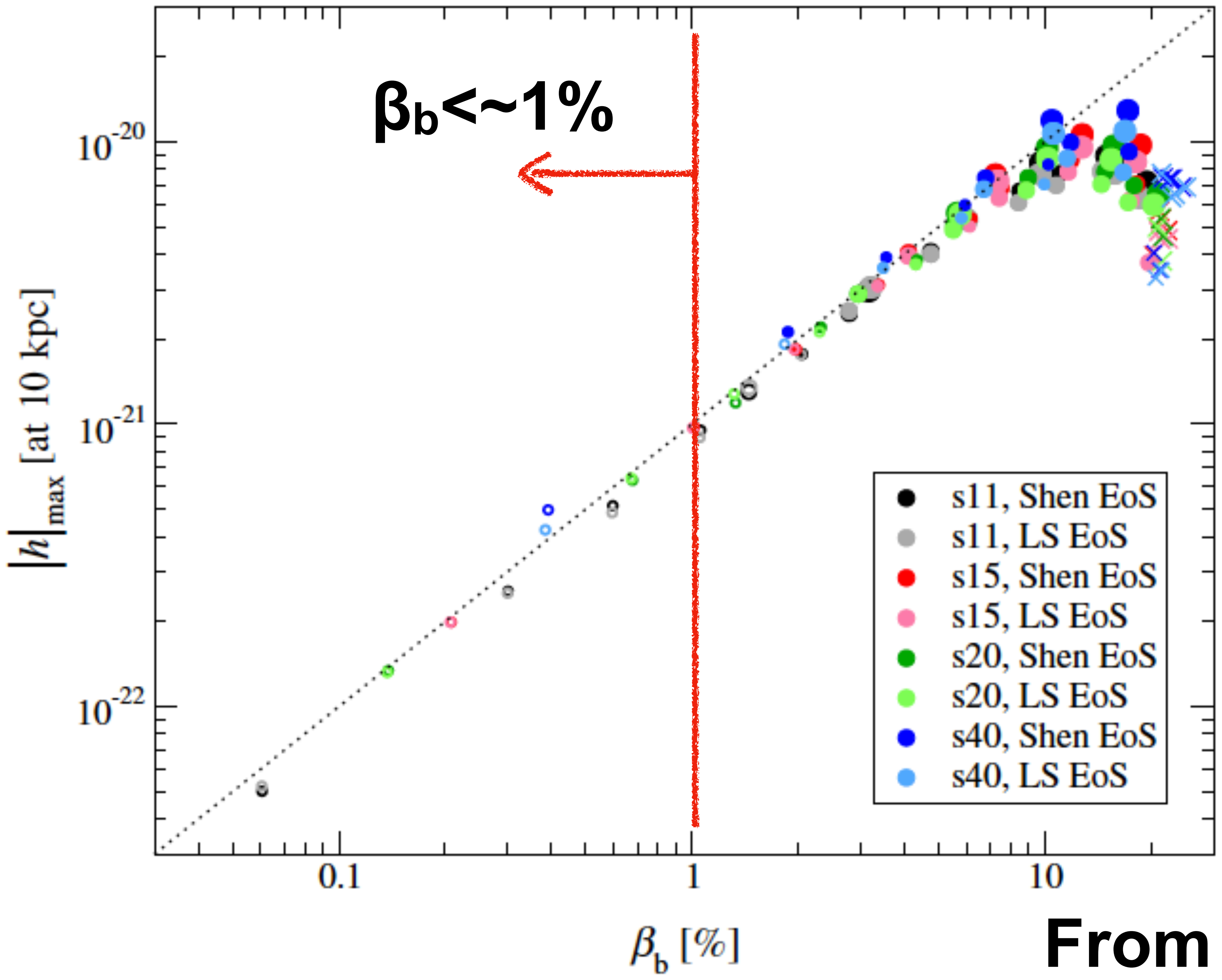
GW emissions from SN

3 major emission mechanisms

1. Rotational bounce

Type I signal —> Linear correlation between $|h|_{max}$ and β_b

3. SASI motion



Dimmelmeier+,’08

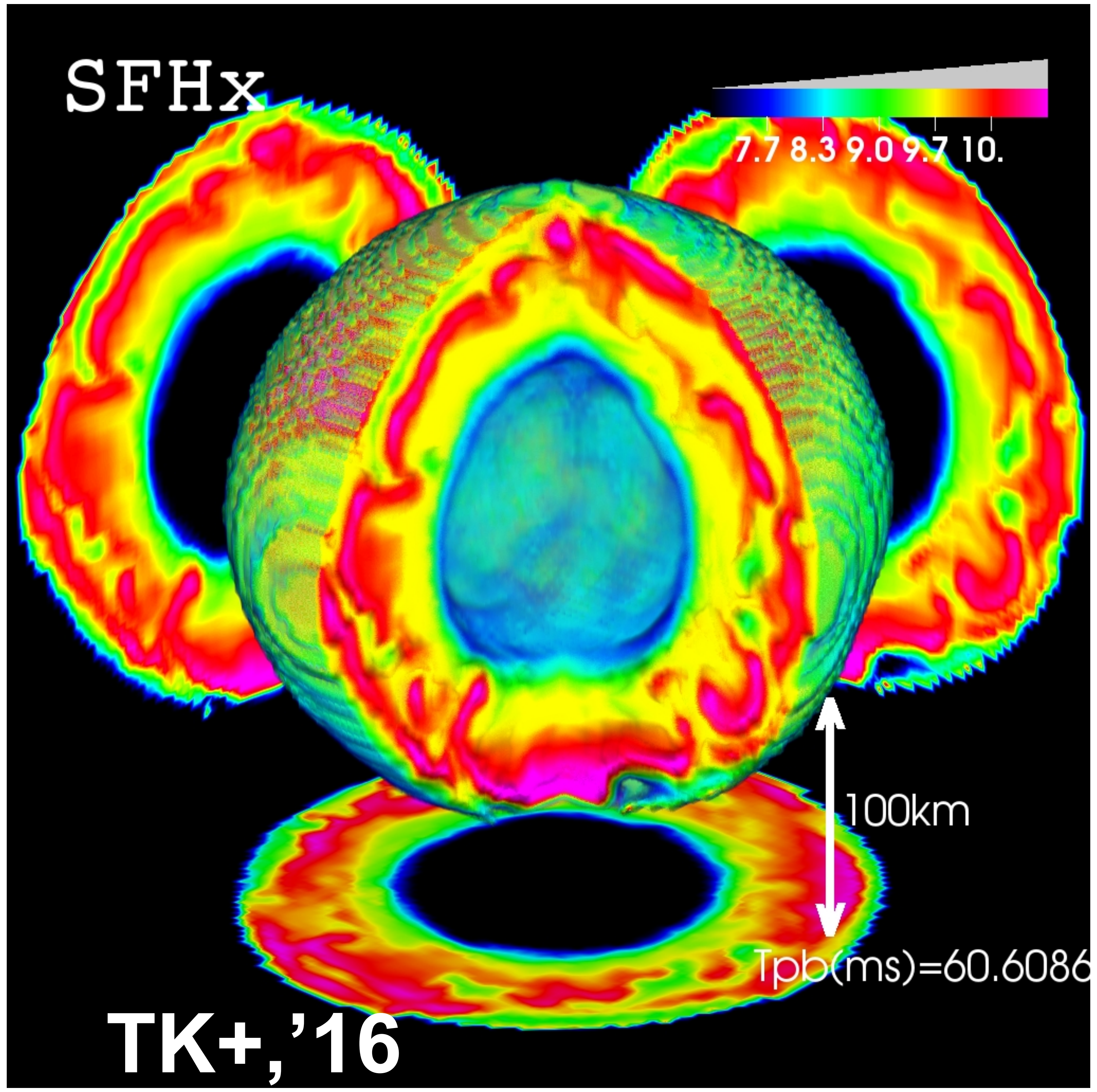
From modern stellar evolution,
β_i<~0.1% (Heger+,’05,Yoon&Langer,’08)
—>β_b<~1%

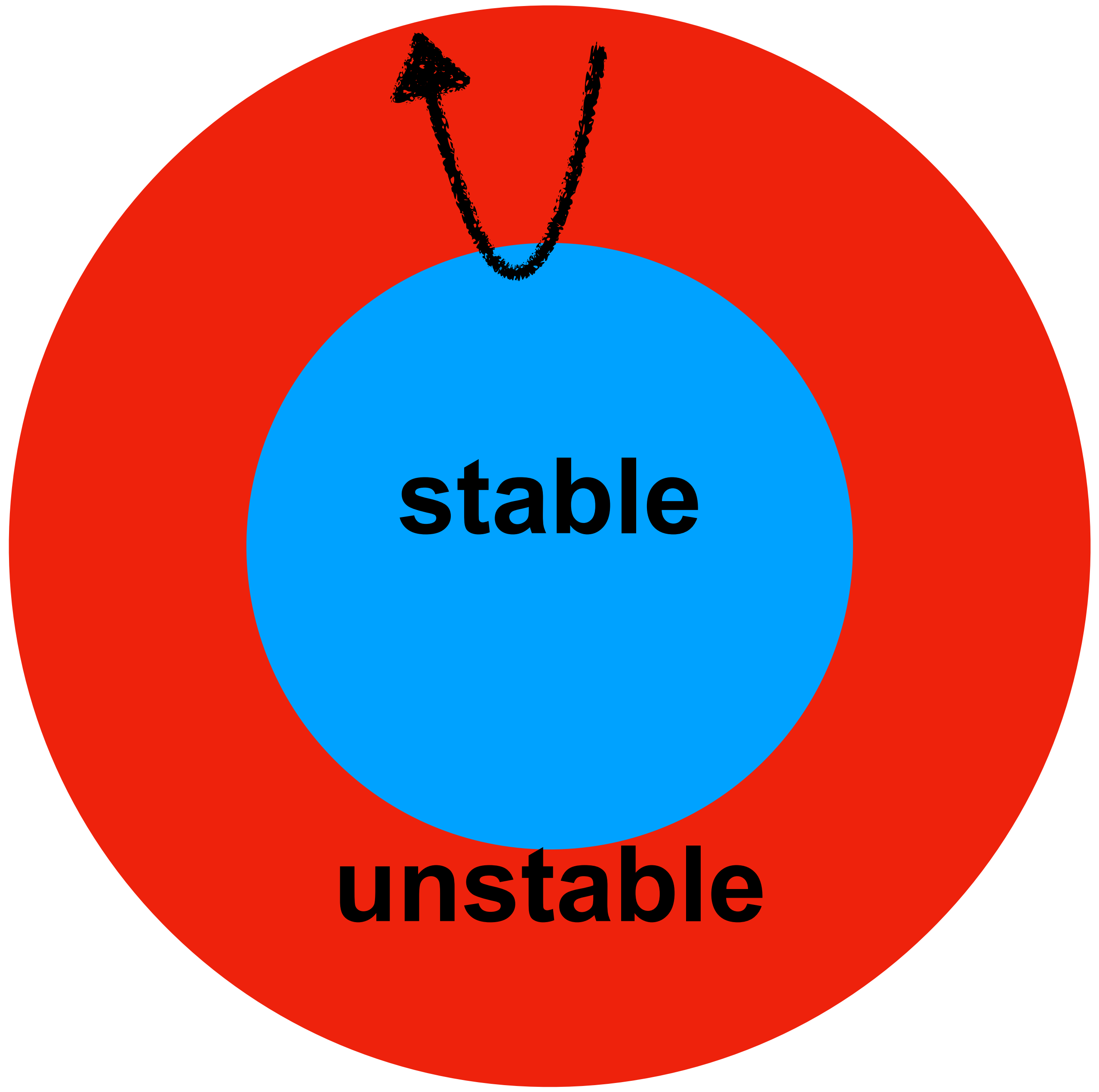
GW emissions from SN

3 major emission mechanisms

1. Rotational bounce
2. g/f-mode oscillation of PNS
3. SASI motion

Asteroseismology may identify the excited mode.
E.g., Morozova+2018,
Torres-Forne+2017,2019, Sotani, Kuroda+2017





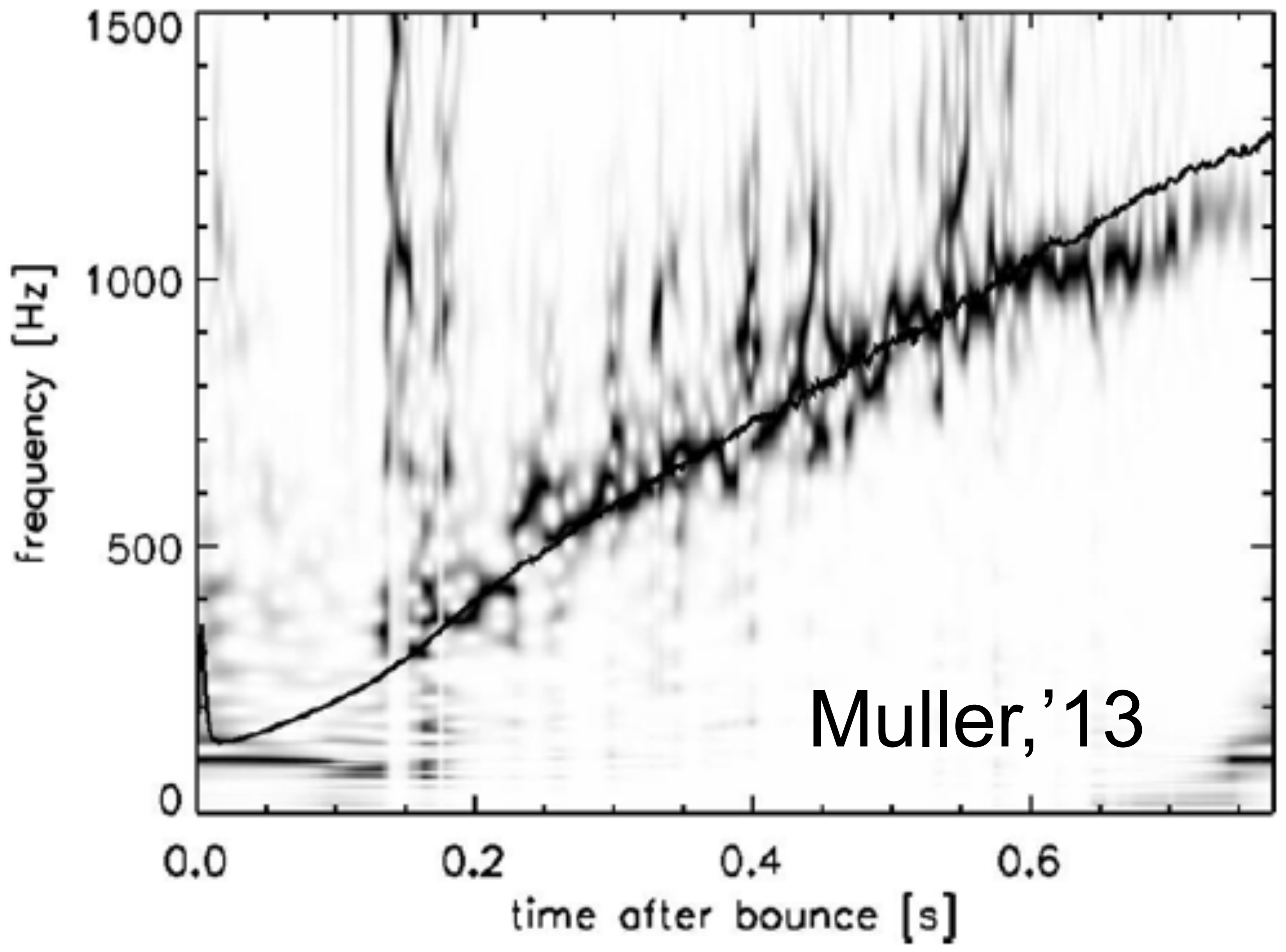
$$F_{\rm peak} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\rm n}}{\langle \varepsilon_{\bar{\nu}_e}\rangle}\frac{GM}{R^2}\left(1-\frac{GM}{Rc^2}\right)^{3/2}}$$

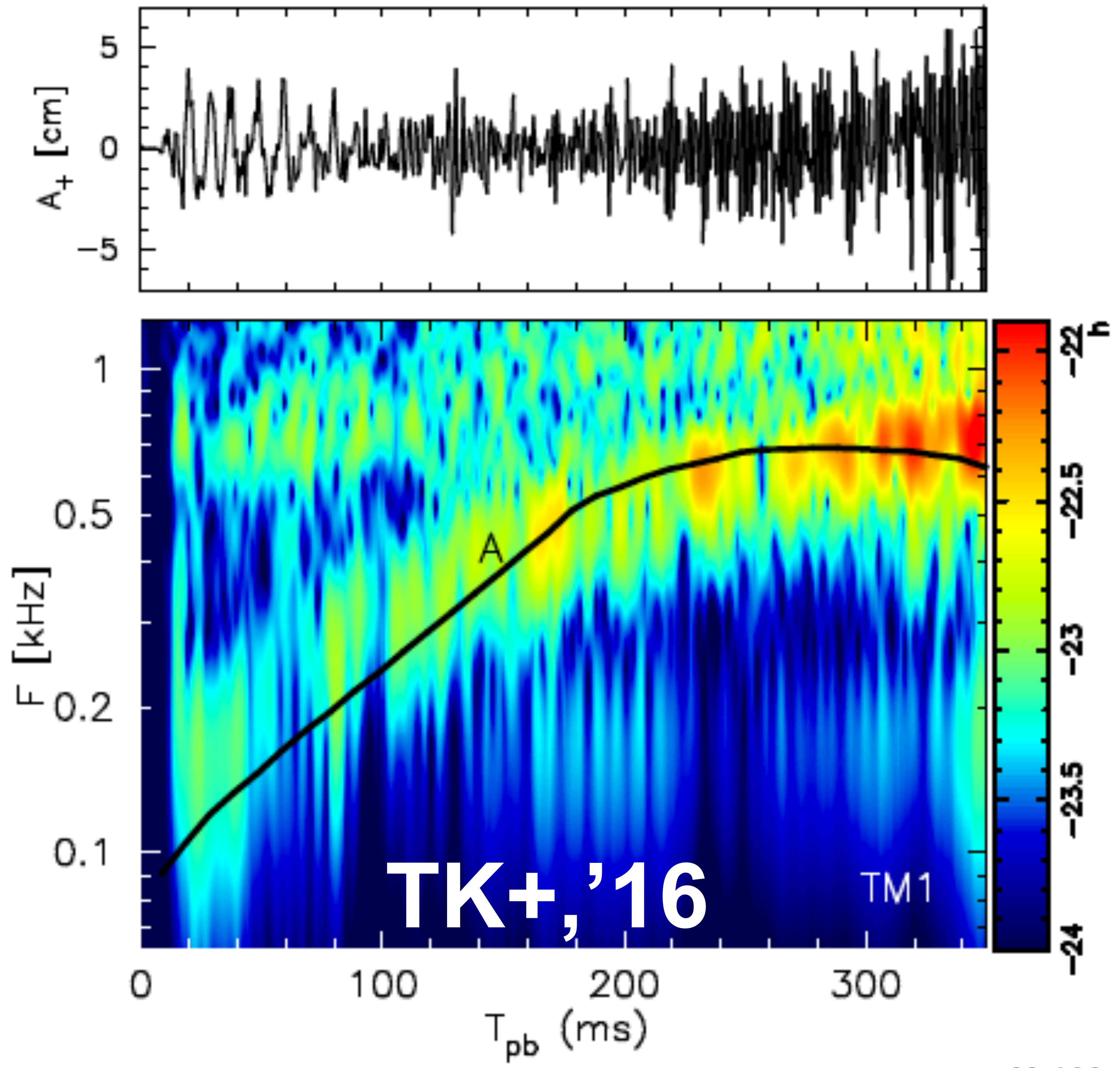
e.g. Muller,'13, Murphy+,'09

GW emissions from SN

3 major emission mechanisms

1. Rotational bounce
2. **g/f-mode oscillation of PNS**
3. SASI motion





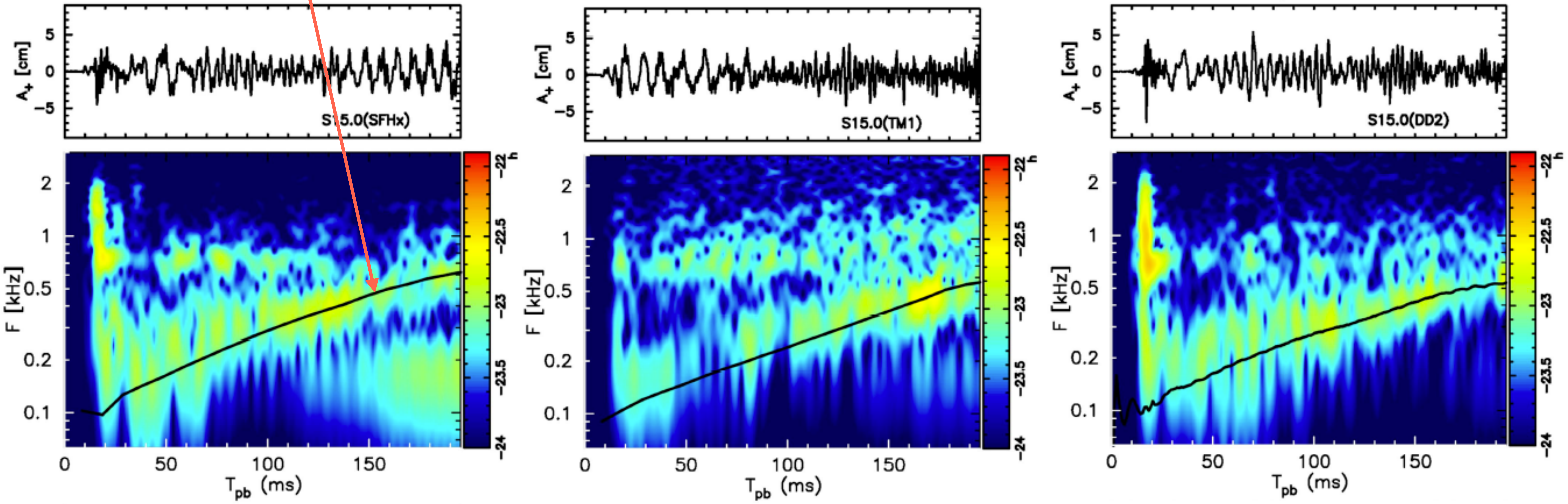
$$F_{\rm peak} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\rm n}}{\langle \varepsilon_{\bar{\nu}_e}\rangle}}\frac{GM}{R^2}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

GW emissions from SN

3 major emission mechanisms

1. Rotational bounce
2. **g/f-mode oscillation of PNS** ← This might reflect the EOS most clearly.
3. SASI motion

$$F_{\mathrm{peak}} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\mathrm{n}}}{\langle \varepsilon_{\bar{\nu}_e} \rangle}\frac{GM}{R^2}\left(1 - \frac{GM}{Rc^2}\right)^{3/2}}$$



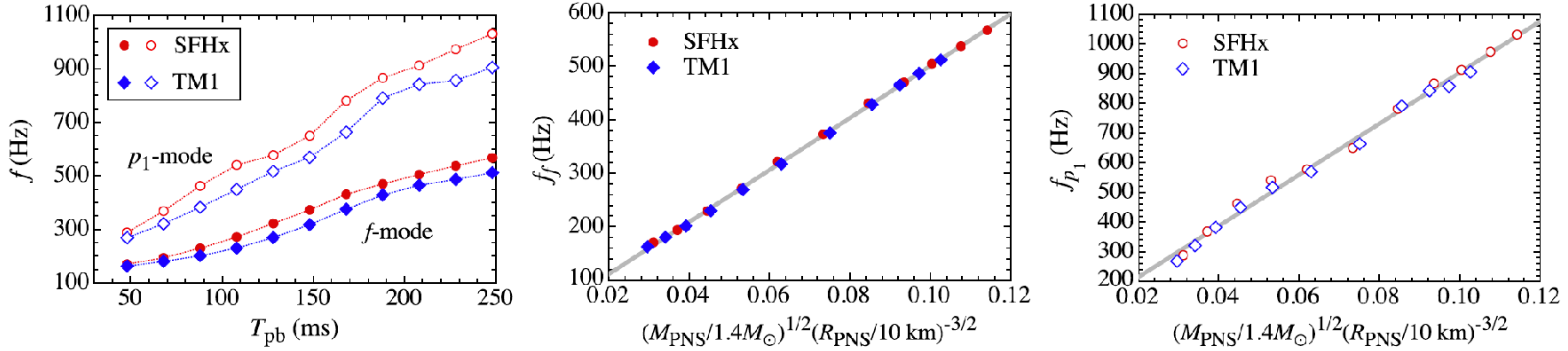
Softer EOS ⟷ Stiffer EOS

Softer EOS <——> Stiffer EOS

F_{peak} ~600Hz ~540Hz ~500Hz

(@t_{pb}=175ms)

$$F_{\rm peak} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\rm n}}{\langle \varepsilon_{\bar{\nu}_e}\rangle}\frac{GM}{R^2}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$



Sotani, Kuroda+, '17

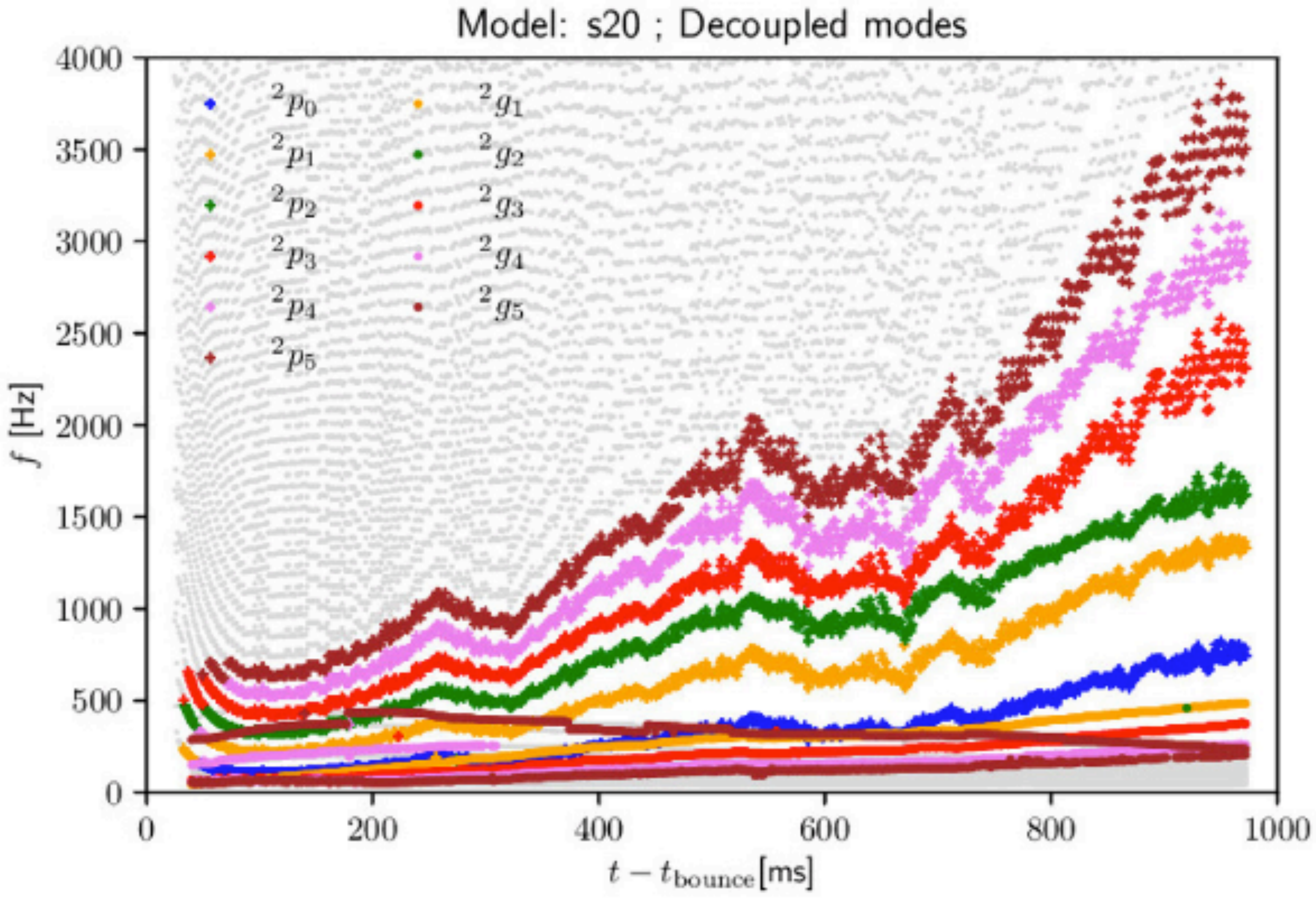
Softer EOS leads to more compact PNS (i.e. smaller R).

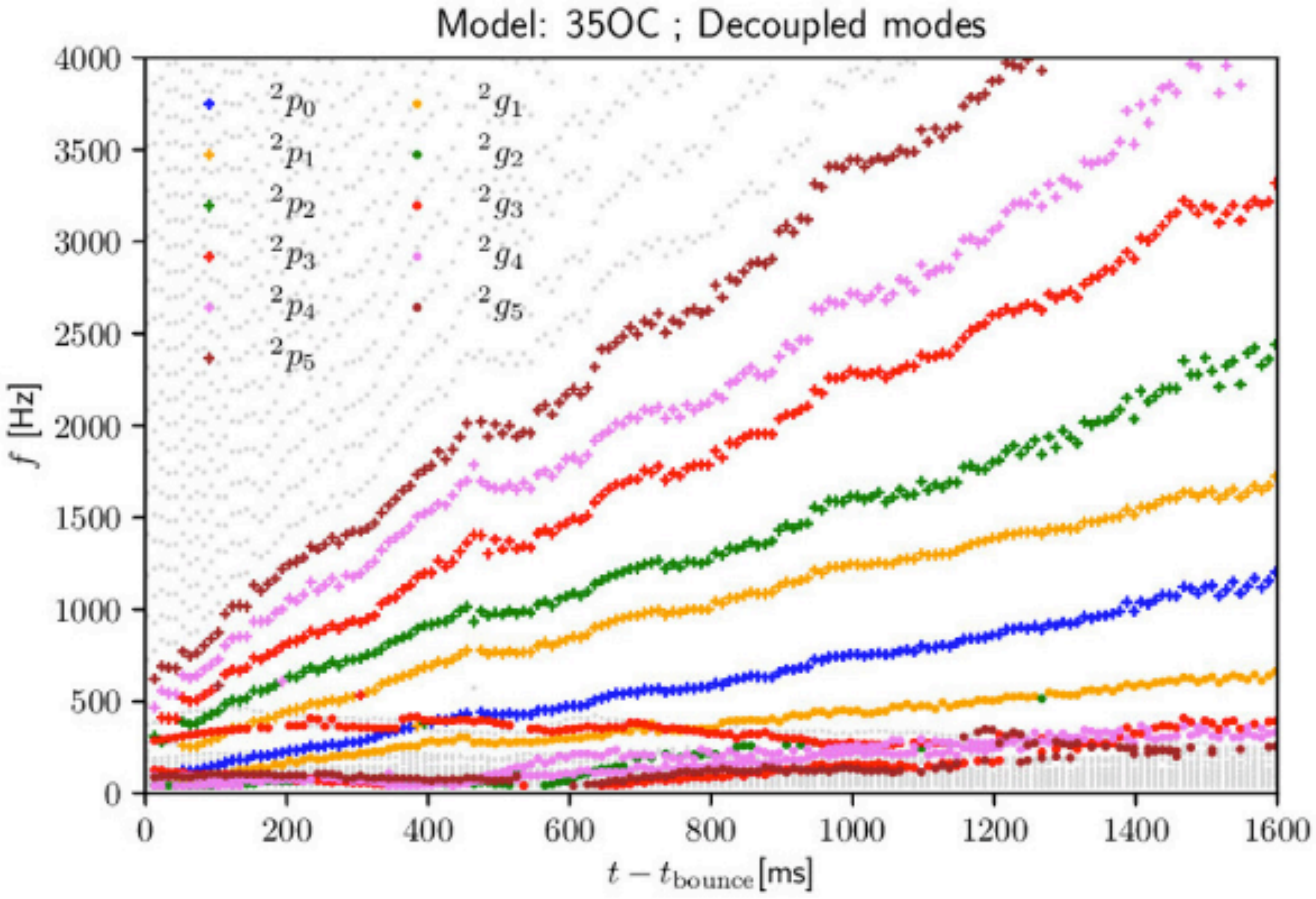
Thus higher $f_{\{f/g/p\}}$.

I.e. $f_{\{f/p\}} \propto \mathrm{sqrt}(M/R^3) \sim \mathrm{sqrt}\langle\rho\rangle$

$$f_{\{g\}} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\mathrm{n}}}{\langle\varepsilon_{\bar{\nu}_e}\rangle}}\frac{GM}{R^2}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

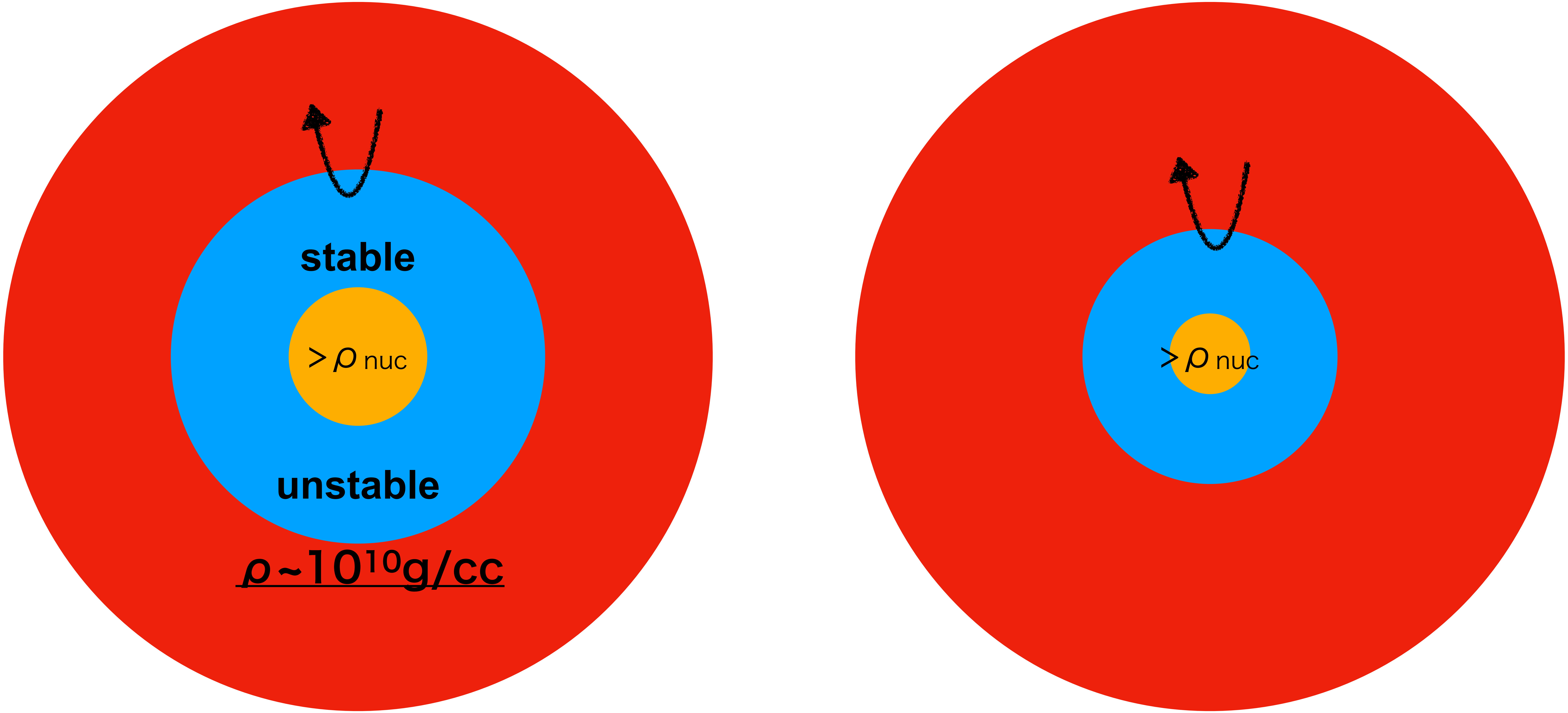
From asteroseismology, the actual GWs are expected to be contaminated by many modes (e.g. f/g/p/w=modes).





Torres-Forne+,'19

Not only the nuclear EOS but also **low-density EOS** can affect on the F_{peak}.

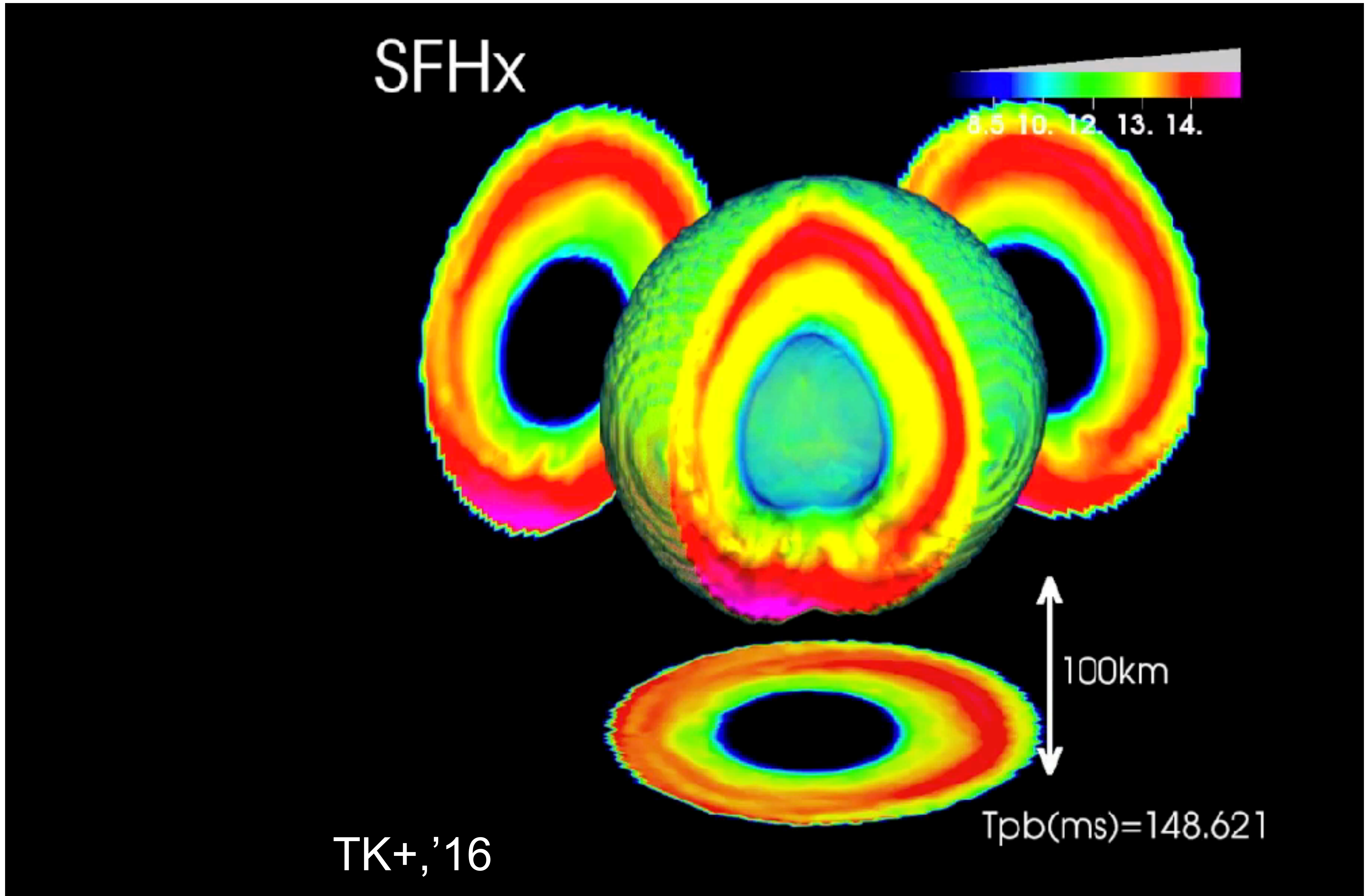


$$F_{\rm peak} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\rm n}}{\langle \varepsilon_{\bar{\nu}_e} \rangle}\frac{GM}{R^2}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$ at $\rho \sim 10^{10}$g/cc

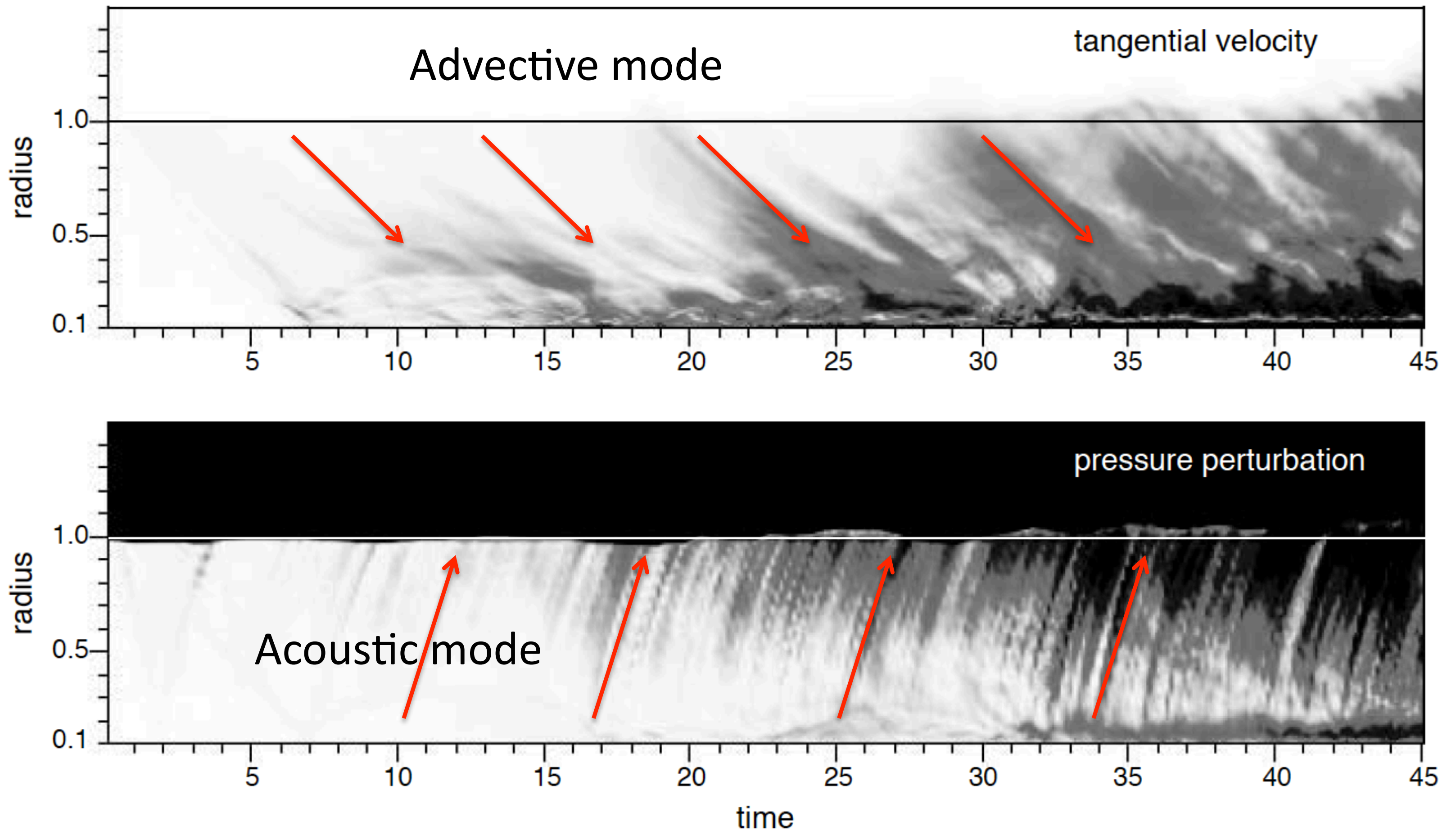
GW emissions from SN

3 major emission mechanisms

1. Rotational bounce
2. g/f-mode oscillation of PNS
3. SASI motion



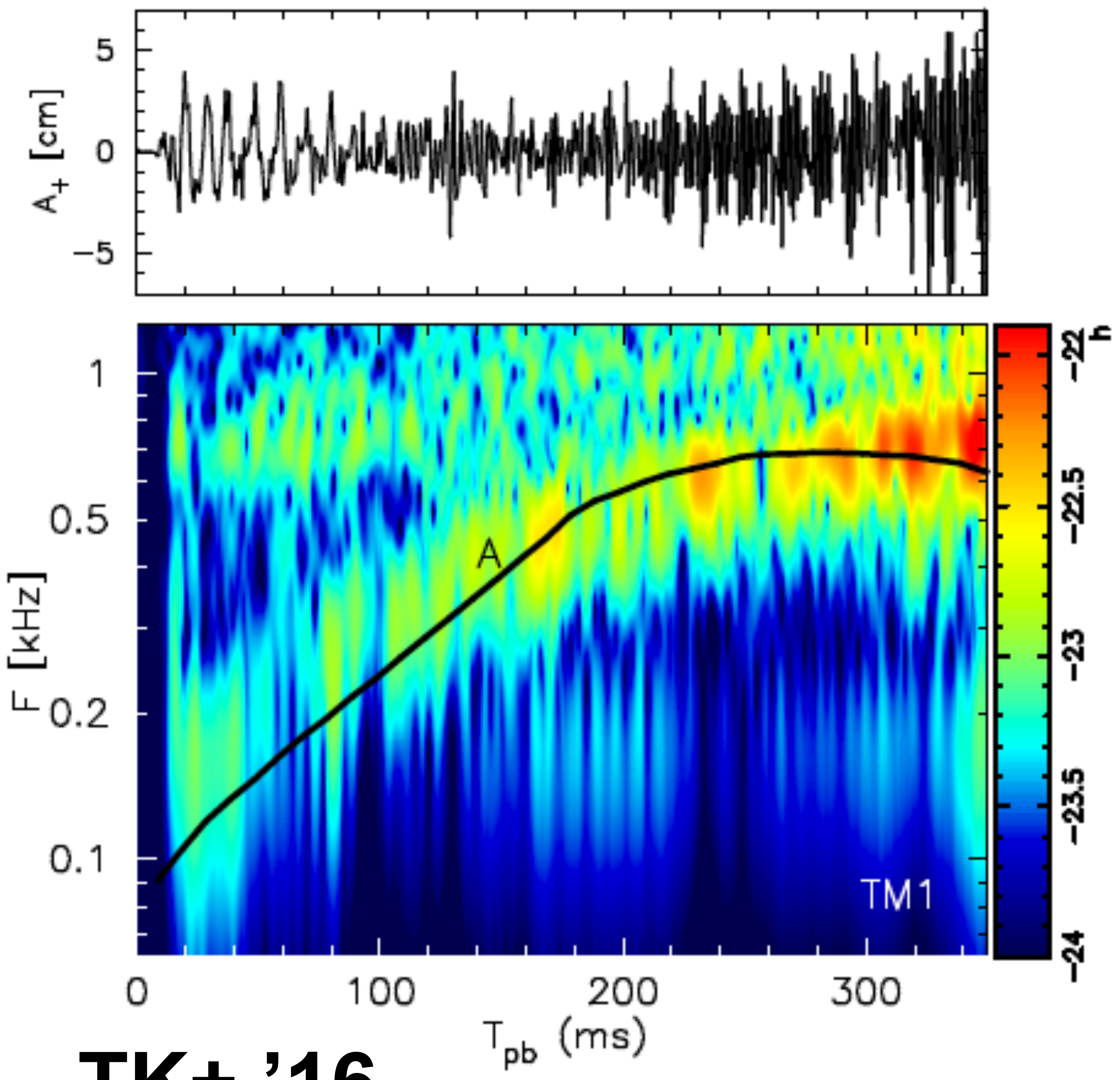
Standing Accretion Shock Instability



Blondin+,'03

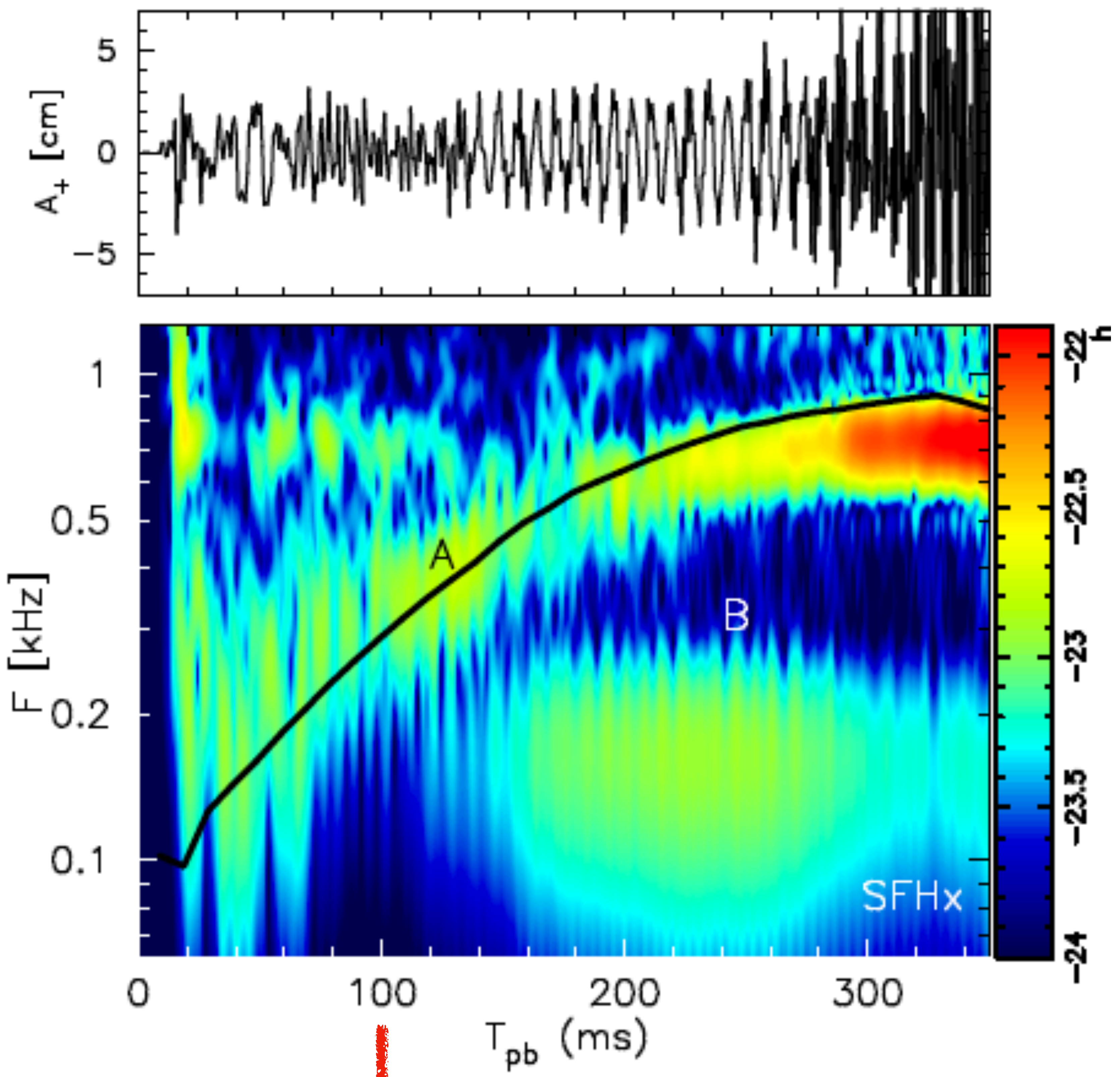
SASI-indued low-frequency GWs

SASI is inactive



TK+,'16

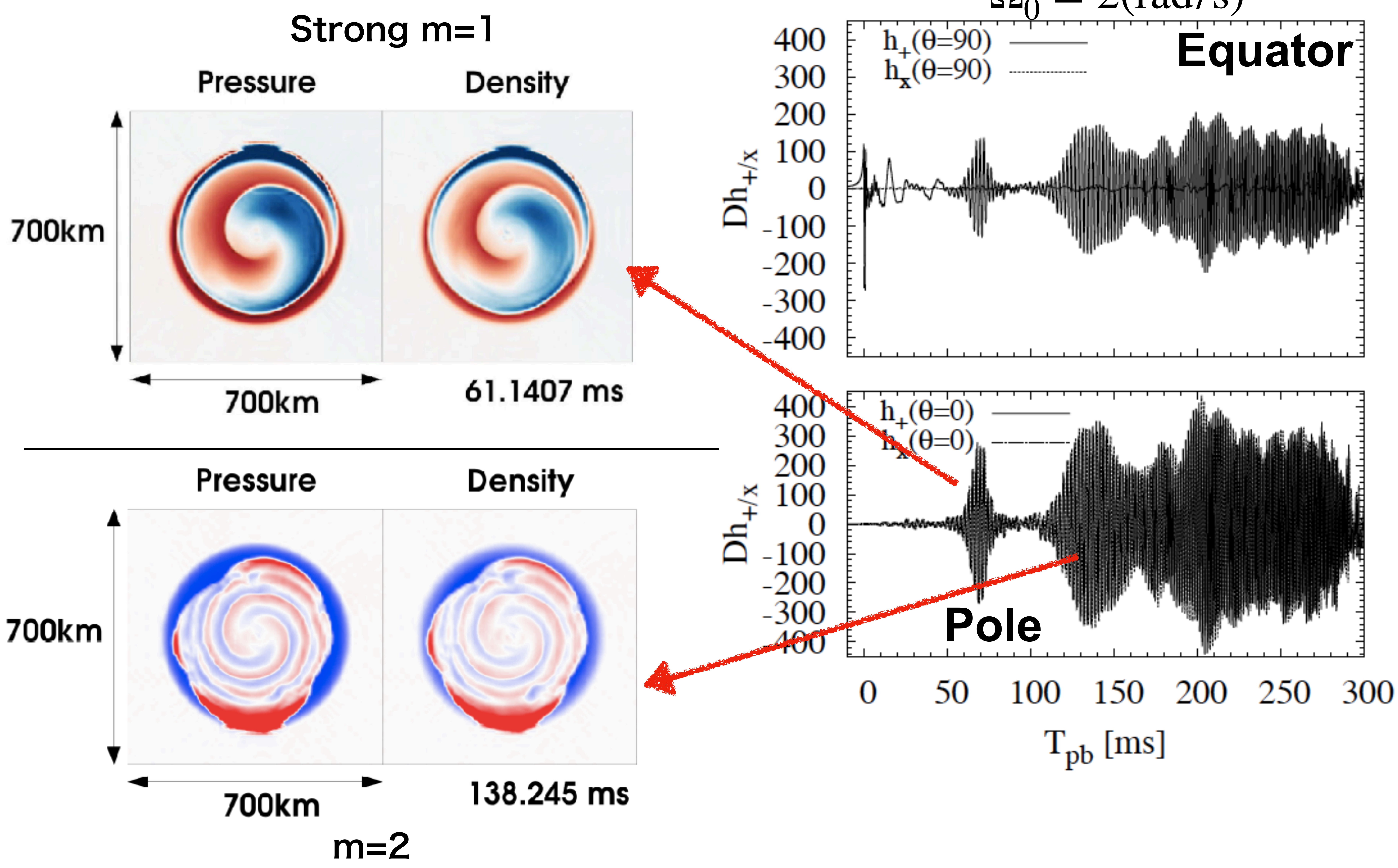
SASI is active



SASI nonlinear phase

TM1 (Hempel&Schaffner-Bielichi,'10): **stiffer EOS, less SASI activity**
SFHx (Steiner,'13) : **softer EOS, more SASI activity**

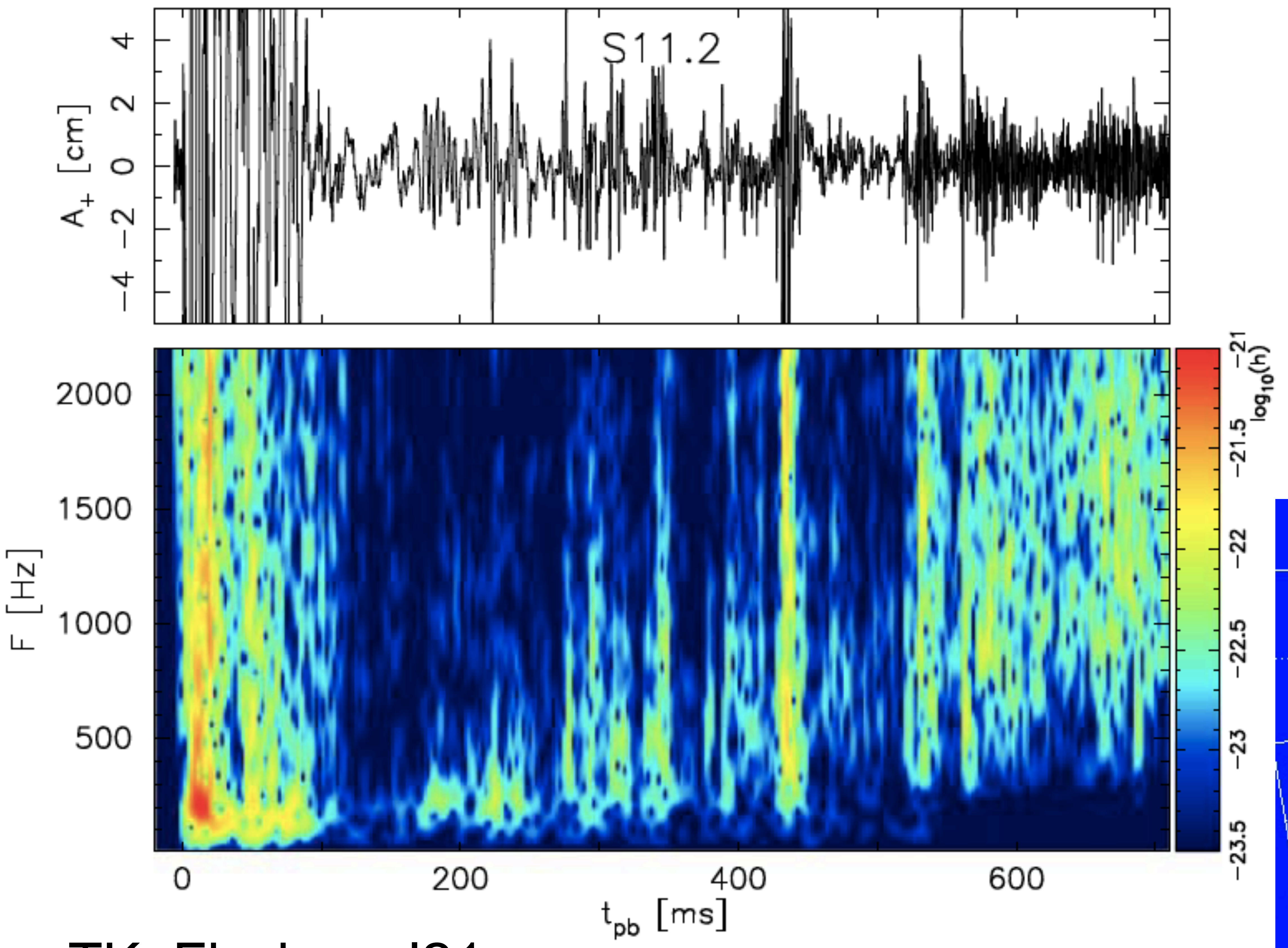
Deviations from cylindrical average



Shibagaki, TK, Takiwaki, Kotake, arXiv:1909.09730

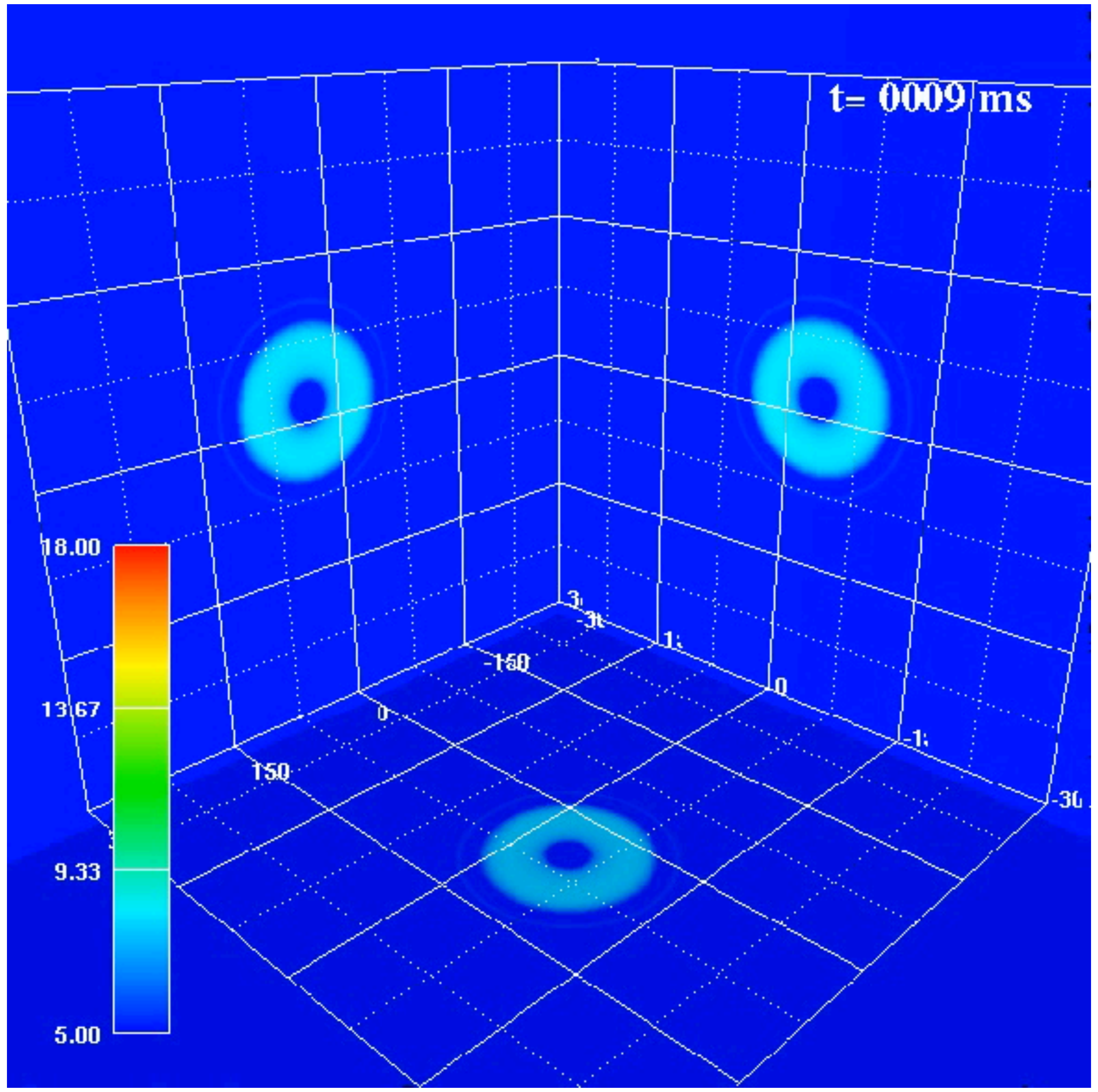
Another example of EOS dependence: QCD phase transition

GW signals (canonical case: $11.2M_{sun}$)



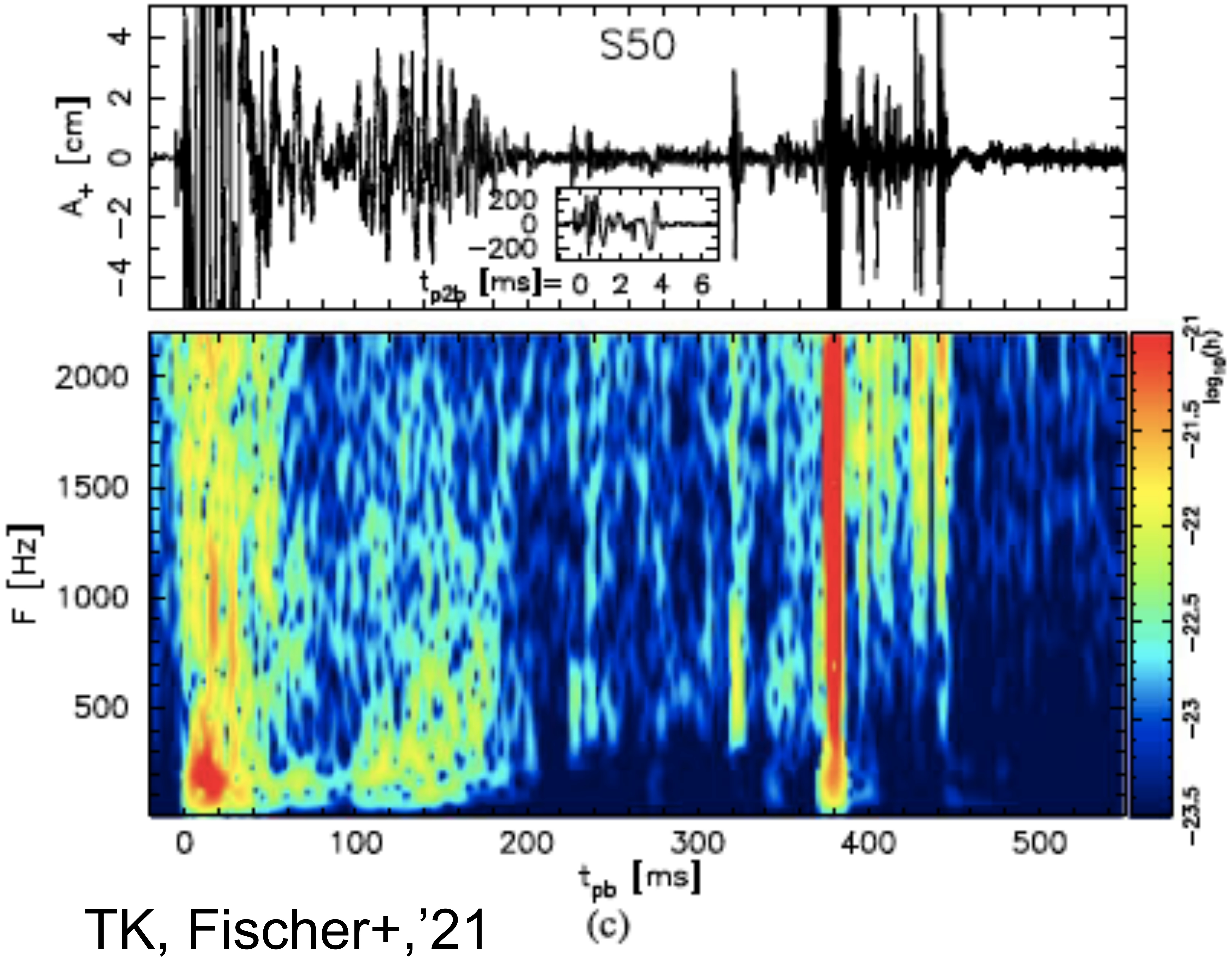
TK, Fischer+,'21

Takiwaki+,'18

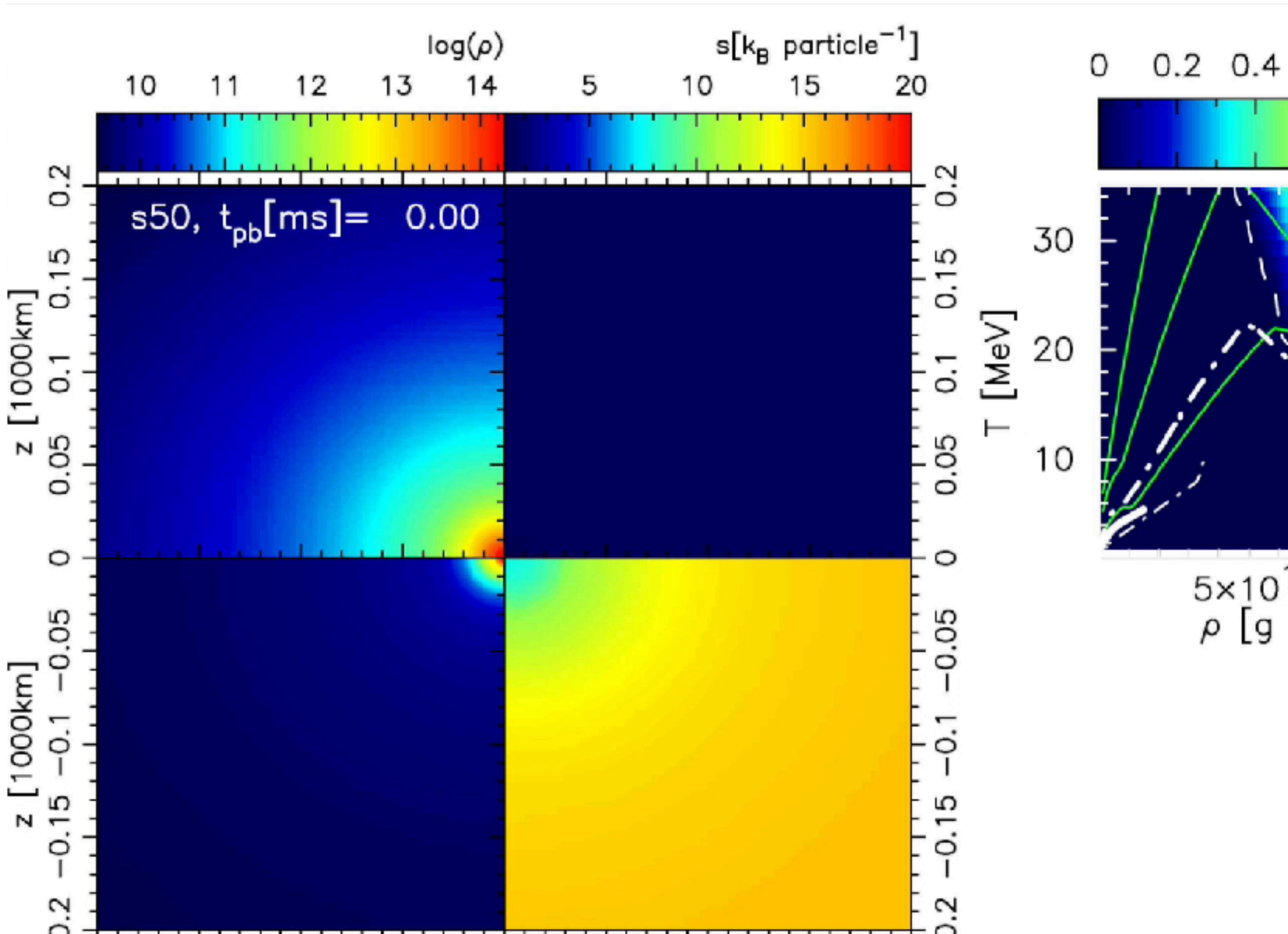


Another example of EOS dependence: QCD phase transition

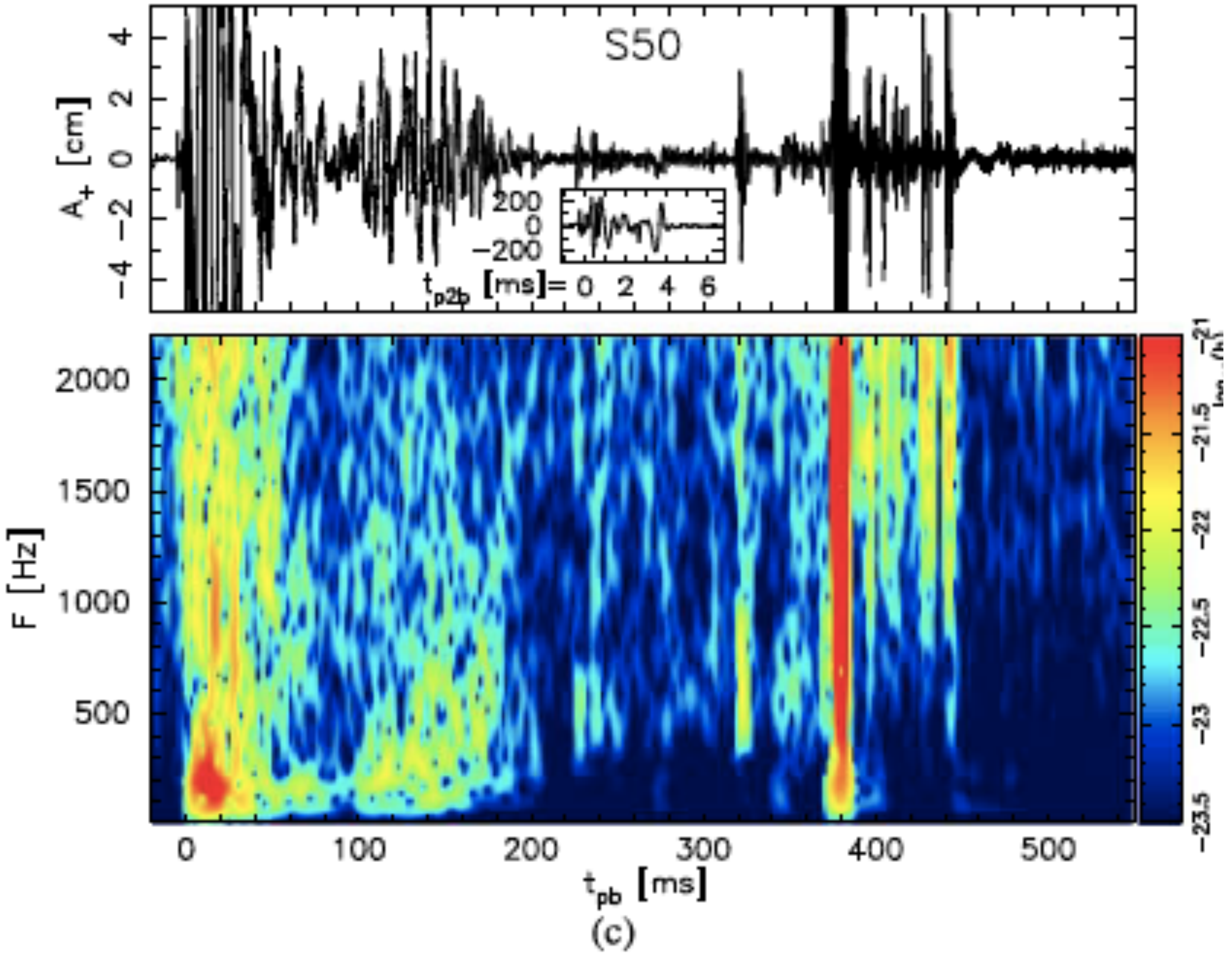
GW signals (PT case: 50M_{sun})

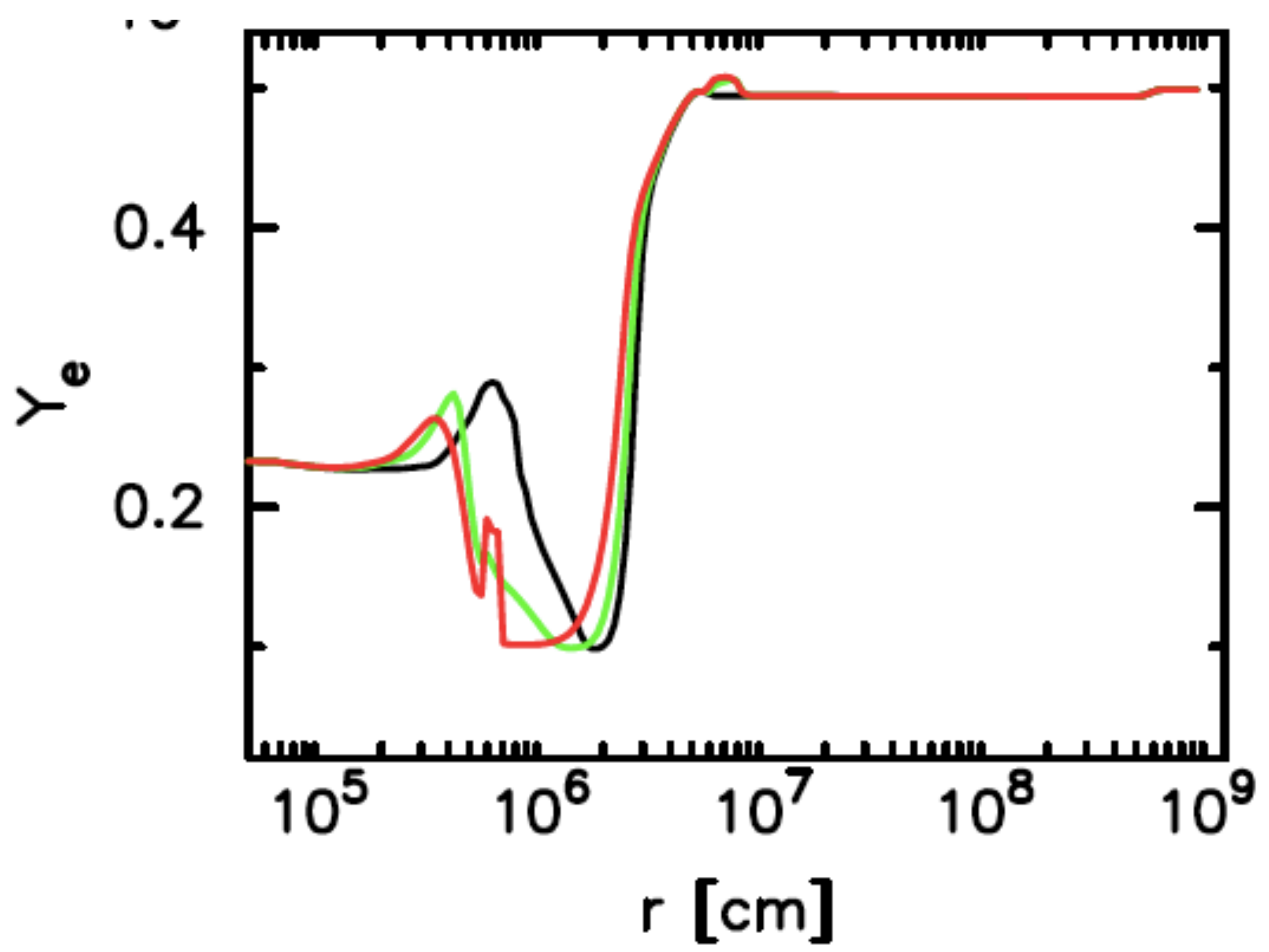


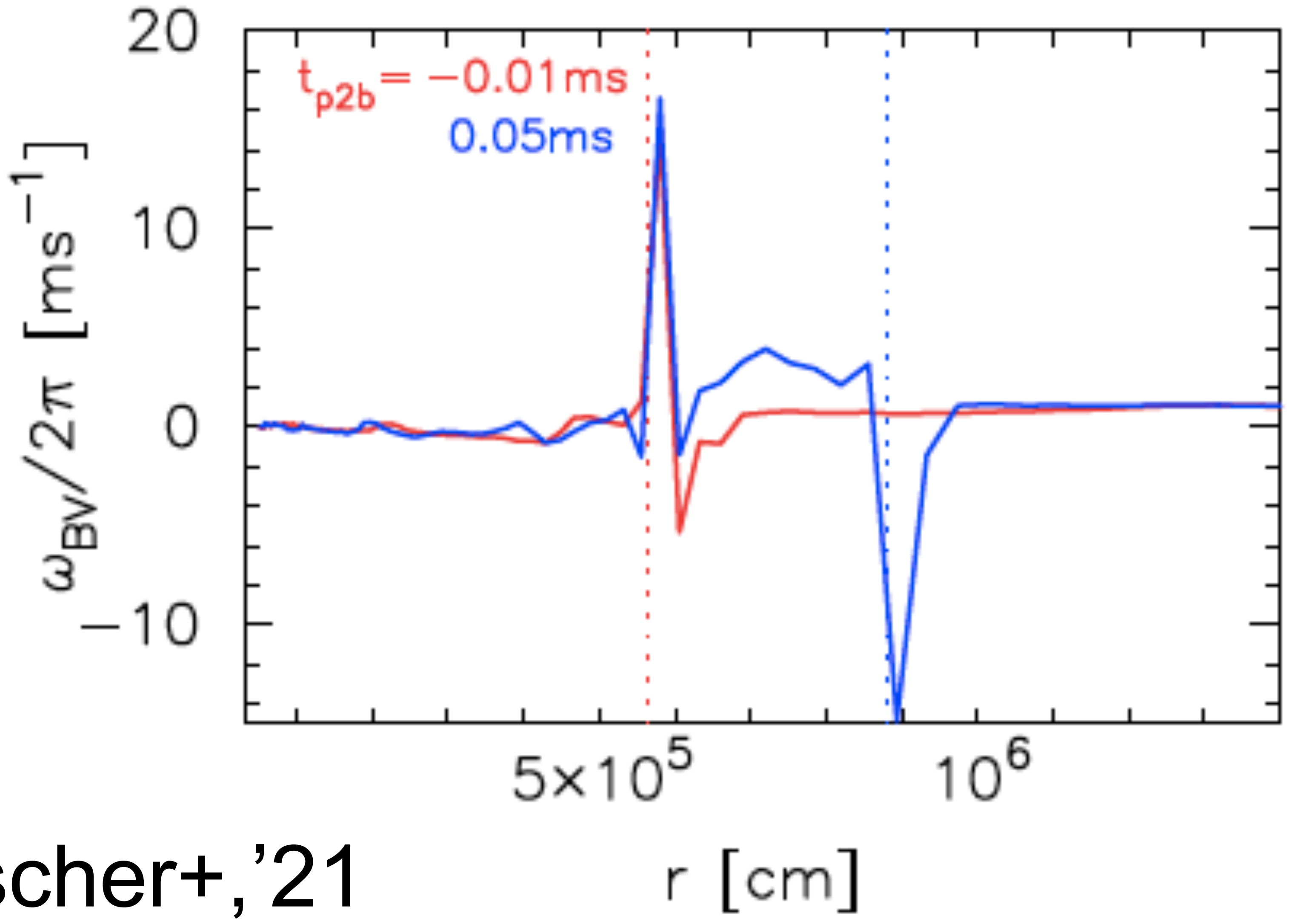
TK, Fischer+,'21
(see also Zha+,'20)



Another example of EOS dependence: QCD phase transition
GW signals (PT case: $50M_{sun}$)





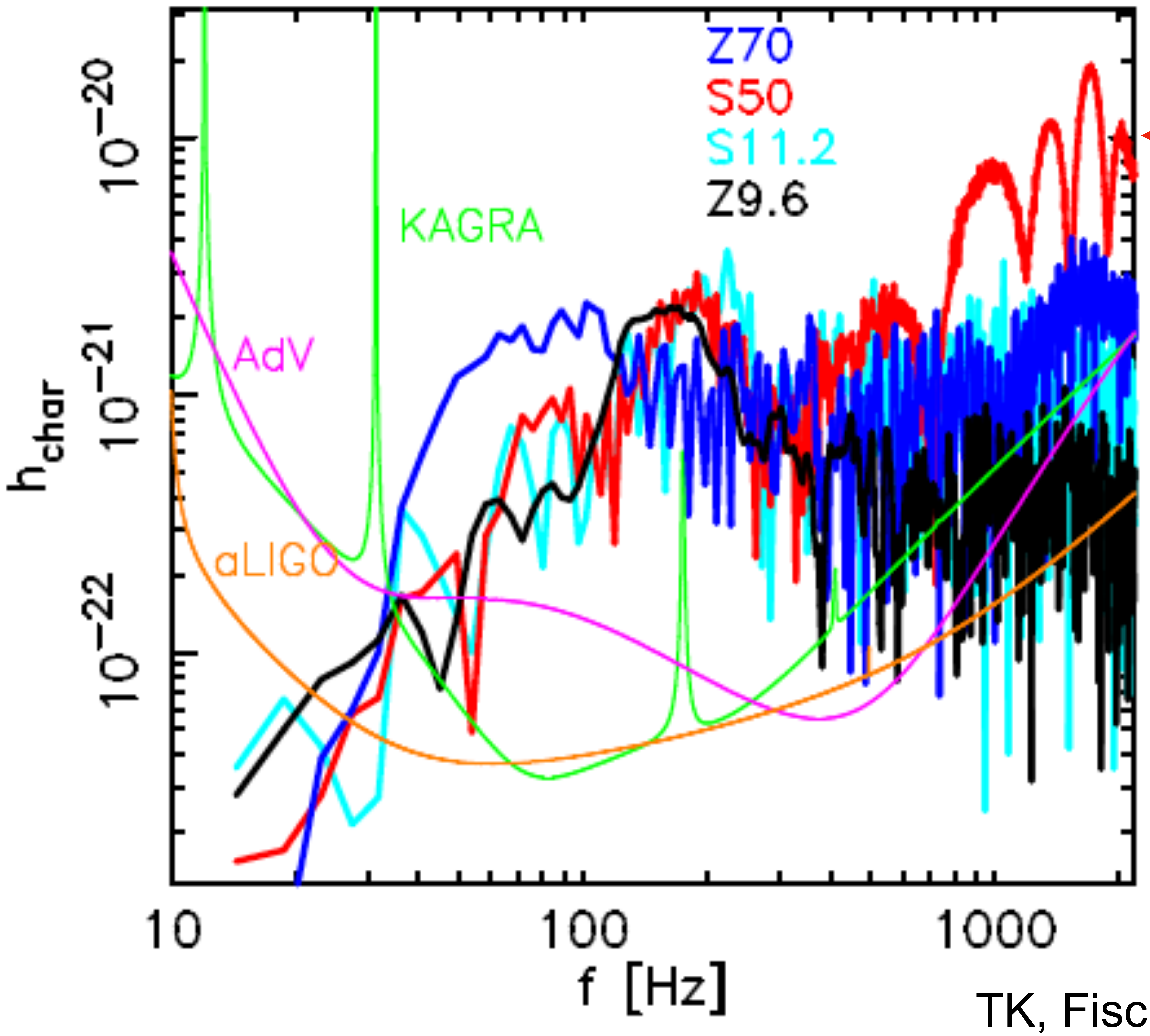


<u>Strong convection motions are generated via the shock passage similar to the 1st core bounce.</u>

TK, Fischer+,'21

Another example of EOS dependence: QCD phase transition

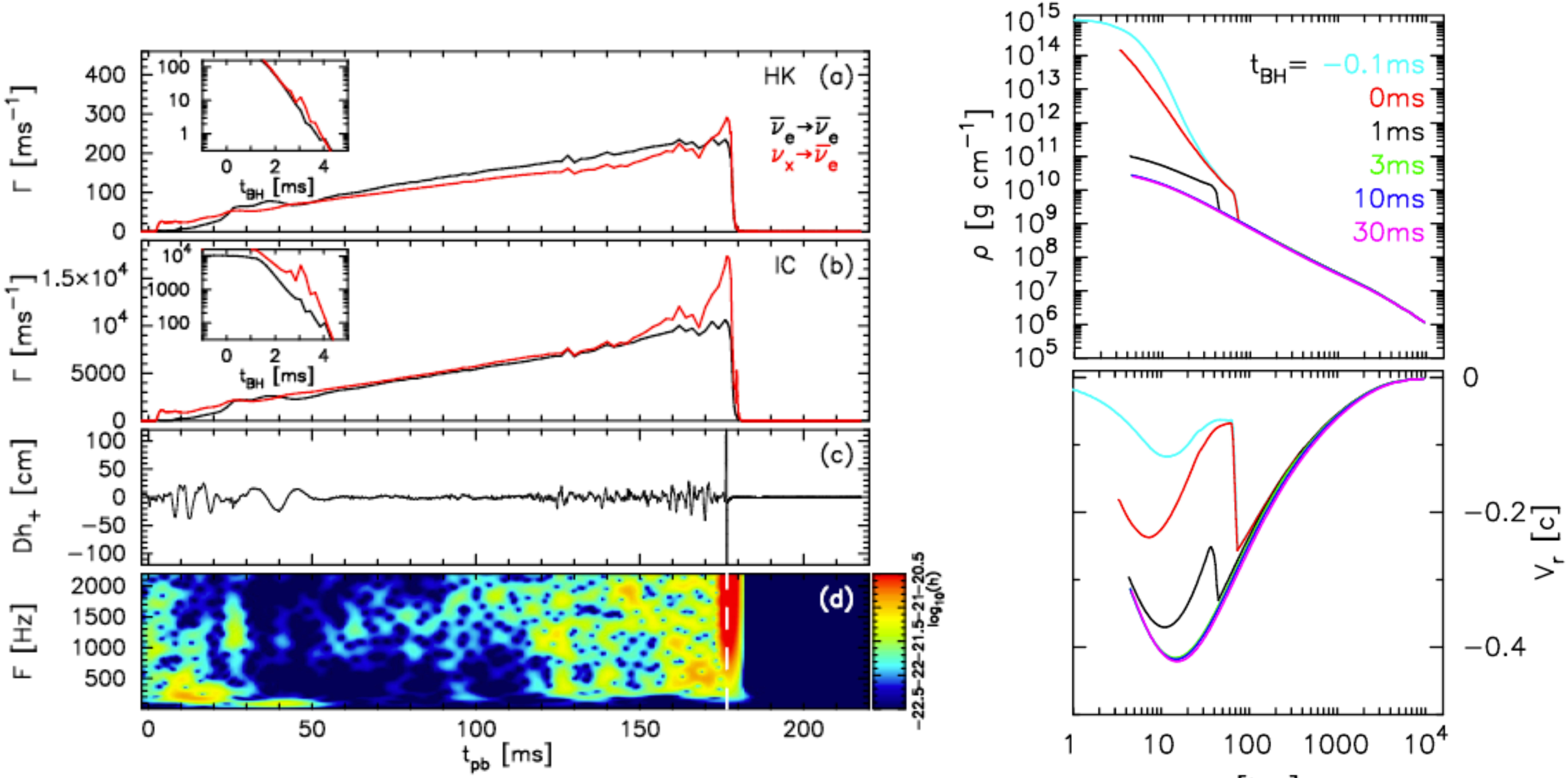
GW signals



Such loud signals at high frequency might be one of signatures of QCD PT

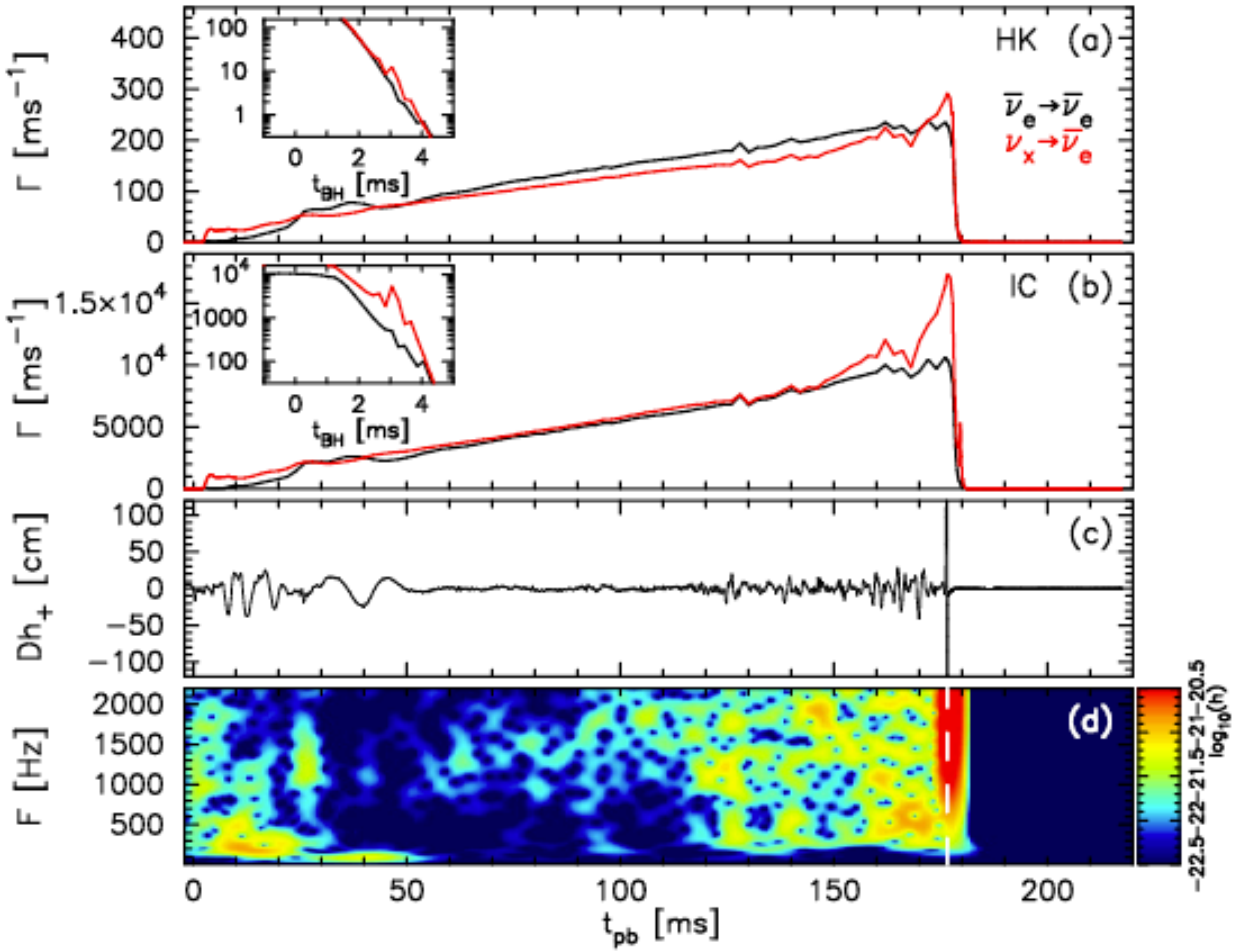
TK, Fischer+,'21

Deciphering the EOS via BH formation

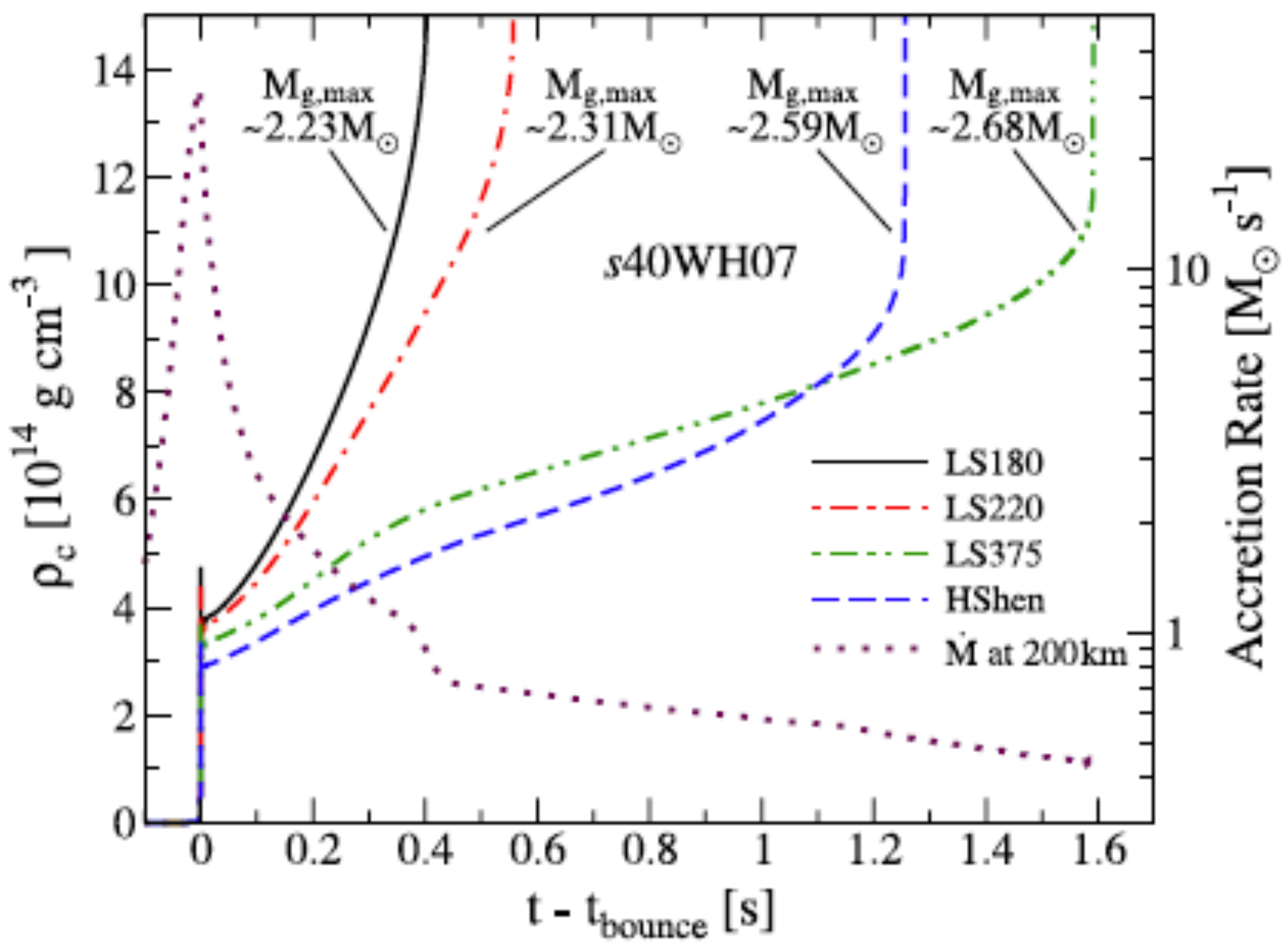


TK & Shibata, ‘23

Deciphering the EOS via BH formation



O'Connor & Ott, '13



BH formation time sensitively depends on the EOS (i.e. maximum NS mass).

Summary

- The nuclear EOS, which sensitively affects on the SN explosion, imprints its various features into the emergent GWs.
- The low-density EOS is a key factor as well.
- From those features (if detected), one might be able to decipher the EOS via SN core dynamics.
- One of noteworthy features is that we would detect higher frequency GWs for softer EOS. (Notice the same tendency for mass and rotation)
- The emergence of active SASI favors softer EOSs —> stronger GWs.
- BH formation time, which is influenced by EOS, also tells us about the EOS.

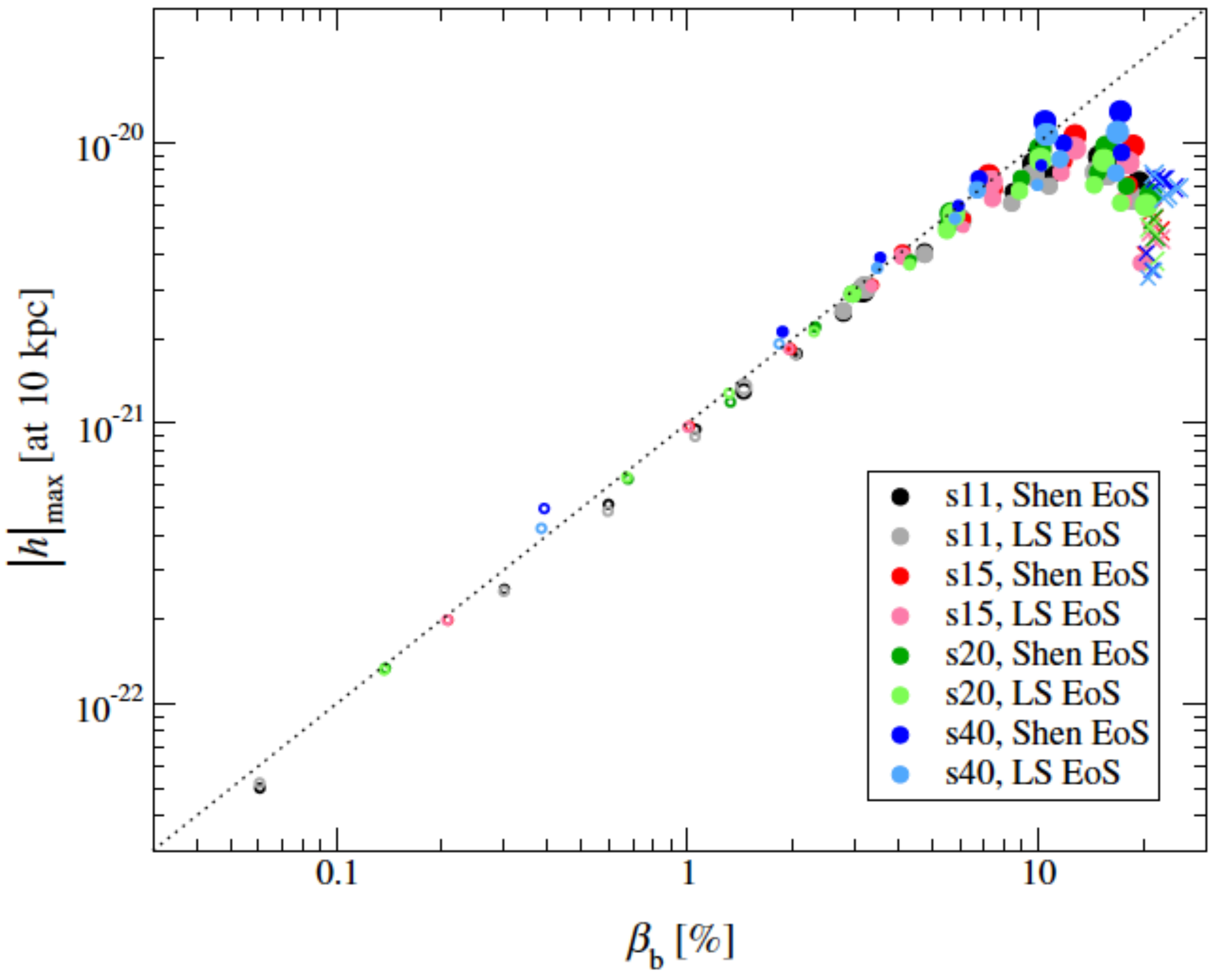
Discussion

3 major phases in SN

- Collapse and bounce
- PNS contraction
- Either explosion or BH

3 major emission mechanisms

1. **Rotational bounce**
2. **g/f-mode oscillation of PNS**
3. **SASI motion**



The biggest uncertainty is the observational angle

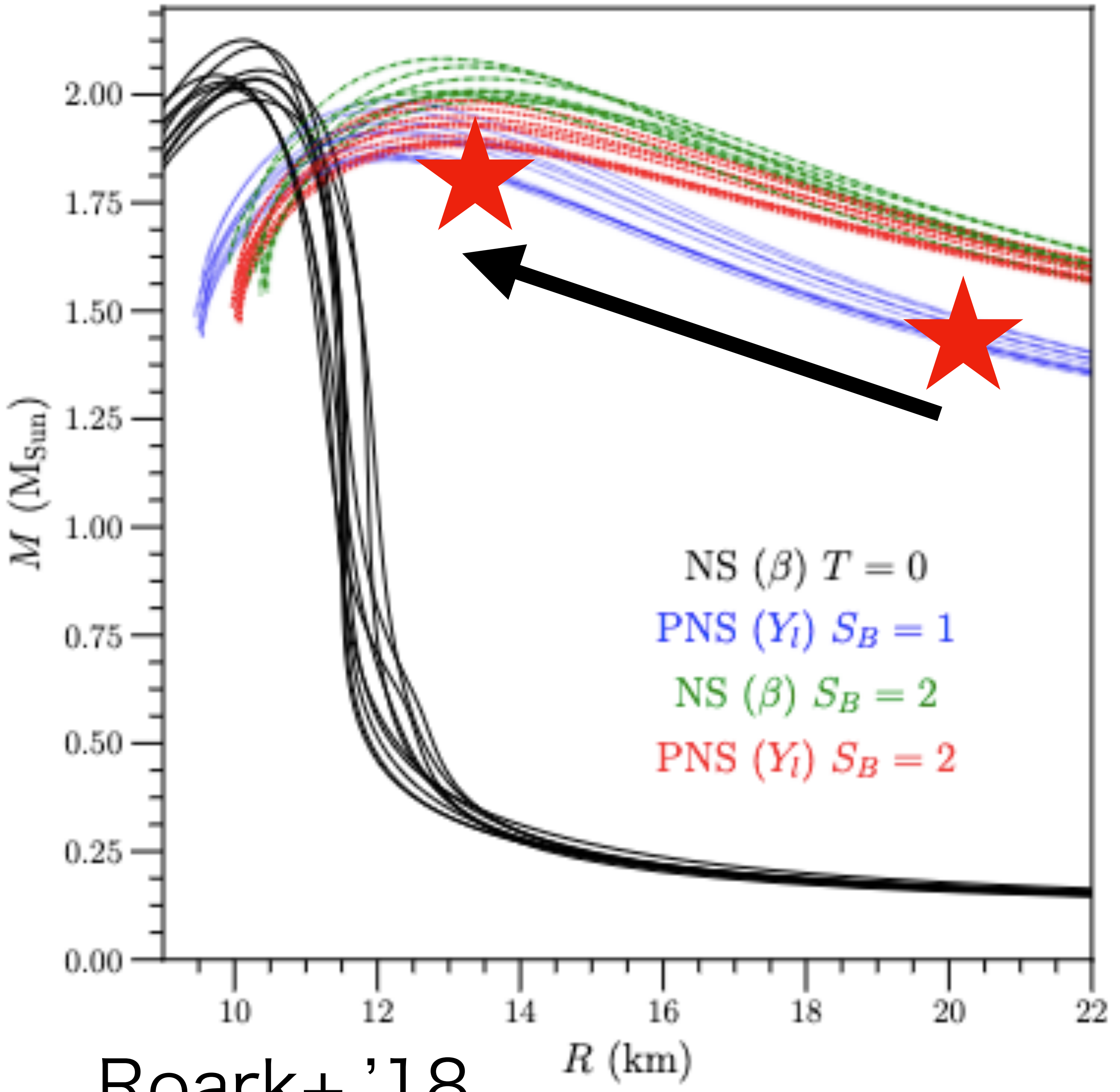
Discussion

3 major phases in SN

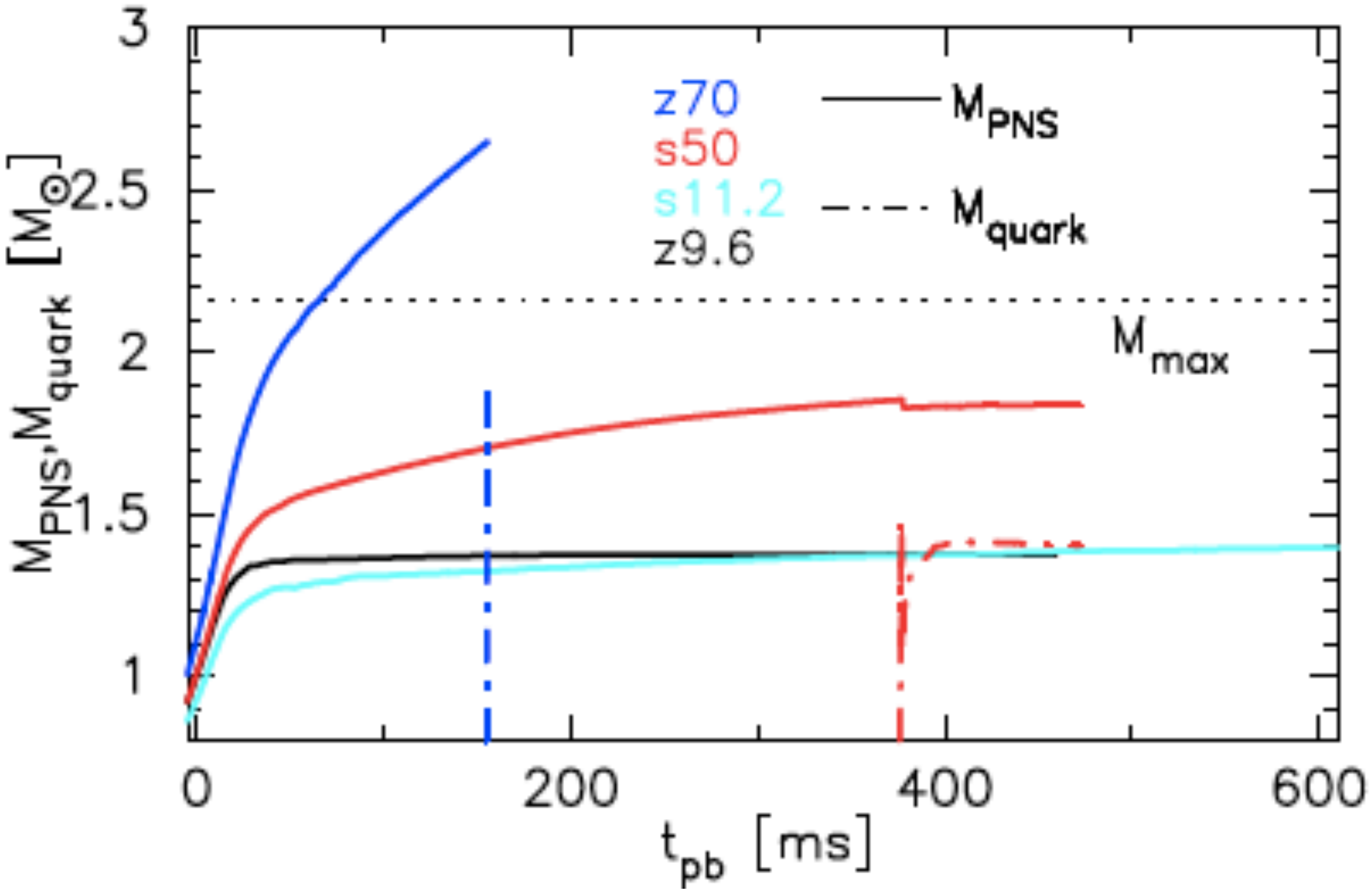
- Collapse and bounce
- PNS contraction
- Either explosion or BH

3 major emission mechanisms

1. **Rotational bounce**
2. **g/f-mode oscillation of PNS**
3. **SASI motion**



Roark+,'18



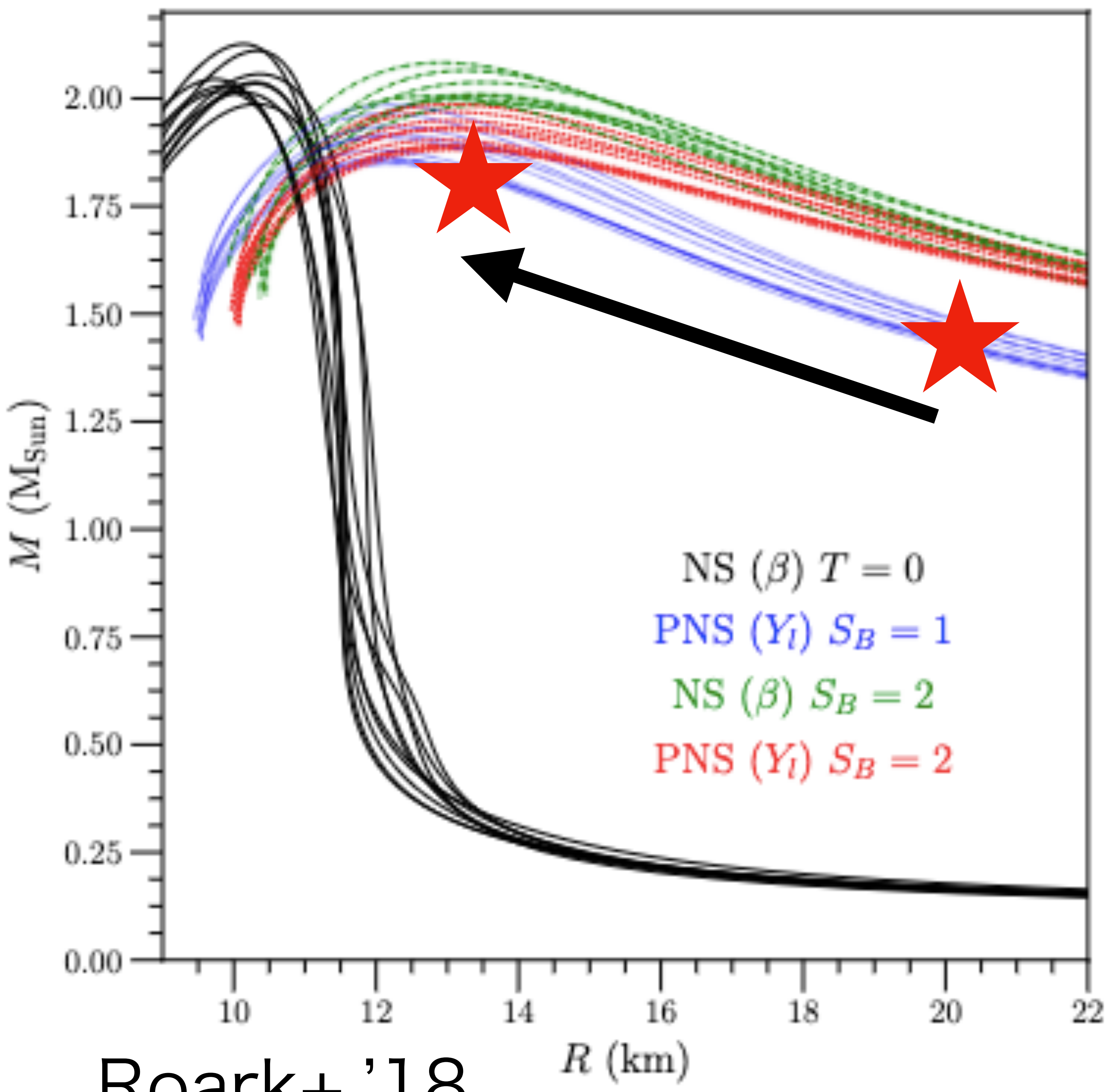
Discussion

3 major phases in SN

- Collapse and bounce
- PNS contraction
- Either explosion or BH

3 major emission mechanisms

1. **Rotational bounce**
2. **g/f-mode oscillation of PNS**
3. **SASI motion**



Roark+,'18

E.g. from (M,R)=(1.4Msun,20km)

to (M,R)=(1.75Msun,12km)

the frequency can be increased

by a factor of ~2.4 for $f_f(\propto \sqrt{M/R^3})$

and of ~3.3 for $f_g(\propto M/R^2)$