Multi-messenger predictions from 3D-GR Core-Collapse Supernova Models : Correlation *beyond*

Kei Kotake
(Fukuoka University)

with Takami Kuroda (TU. Darmstadt), Ko Nakamura (Fukuoka Univ.),
Tomoya Takiwaki (NAOJ), Kazuhiro Hayama (ICRR),
Shunsaku Horiuchi (Virginia Tech), Tobias Fischer (Univ. Wroclaw)

Ringberg Supernova Workshop, July 26th June 2017

Celebrating 30th Anniversary of SN1987A and Ewald !

Looking back ~30 ye
in both theory and o

10^{-18}

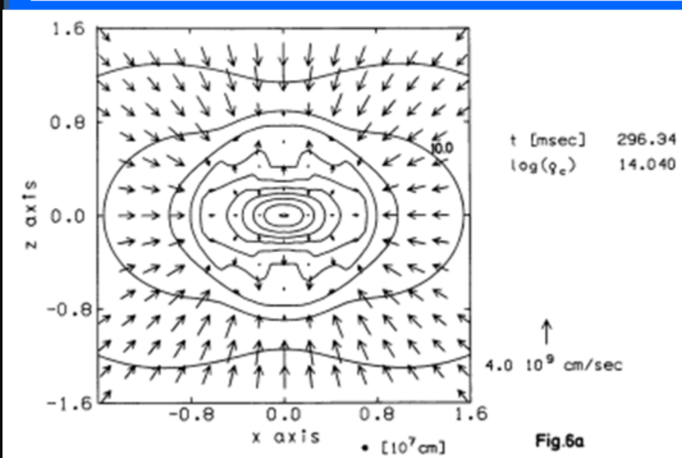
Typical thresholds of proto-types in 1989

(MIT, Garching, Caltech, Glasgow and Tokyo)

Astron. Astrophys. 114, 53–59 (1982)

Gravitational Radiation from Collapsing Rotating Stellar Cores

E. Müller



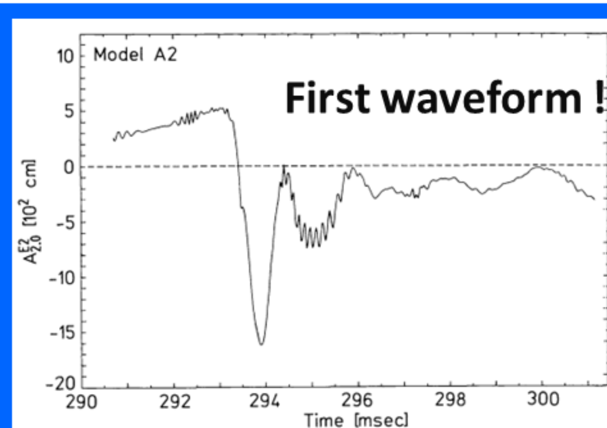


Fig. 1a. Quadrupole waveform for model A2

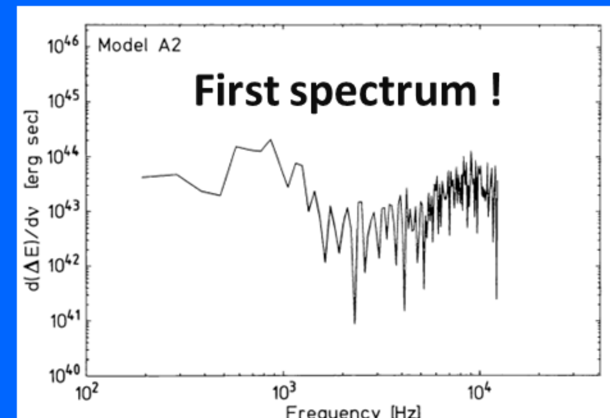


Fig. 2a. Energy spectrum corresponding to the quadrupole amplitude given in Fig. 1a

Müller & Hillebrandt (1981), A&A

could operate ~2035.

GW astronomy of CCSNe, no more a dream !

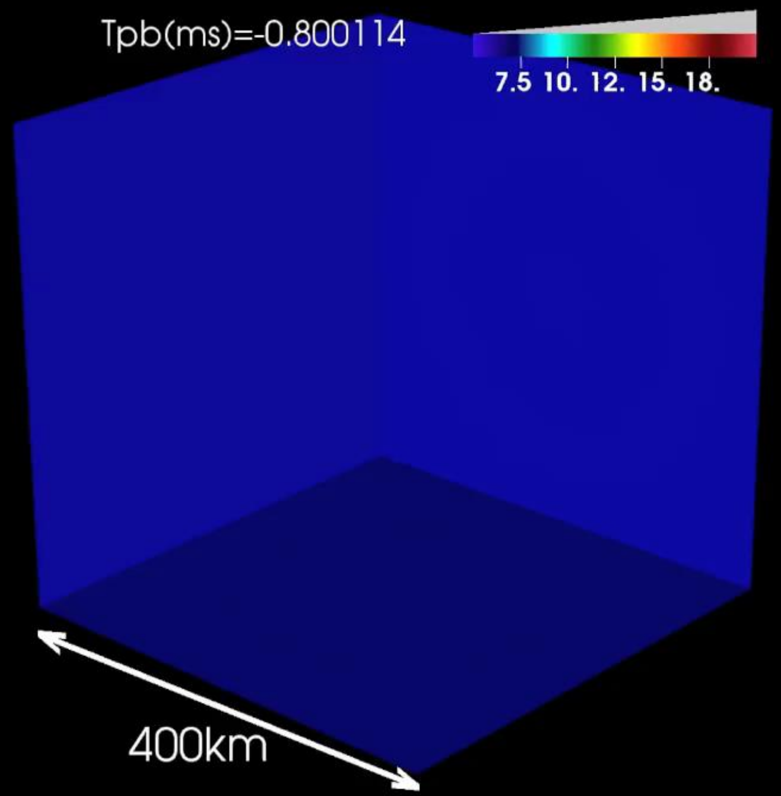
GW signautures from 3D-GR models with strong SASI vs. weak SASI activity

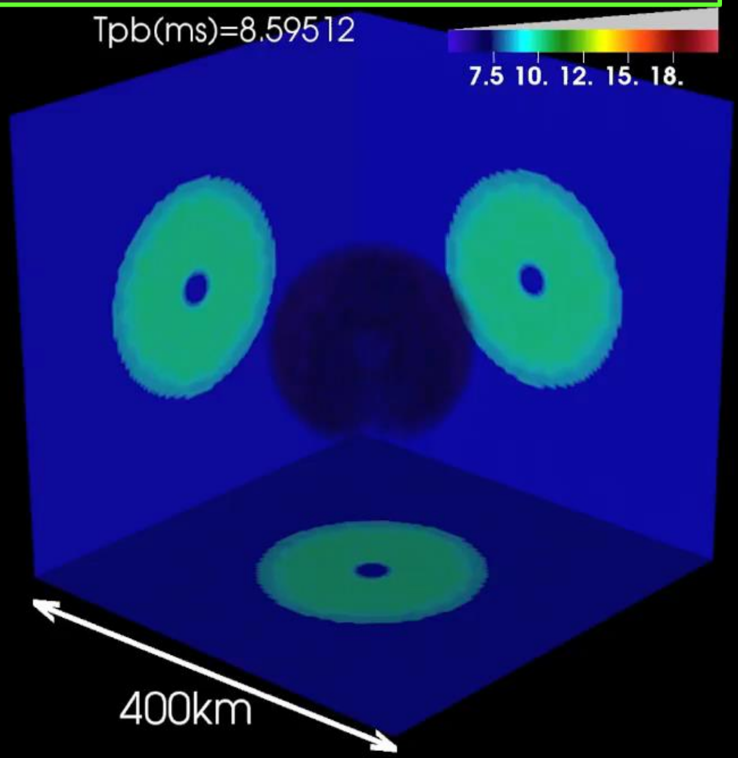
(from **Kuroda, KK, & Takiwaki ApJL (2016), see also Andresen, B, E Müller and Janka (2017))**

- ✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)), **HS(TM1)** (Shen et al. (1998)).
- ✓ 15 M_{sun} star (Woosley & Weaver (1995))

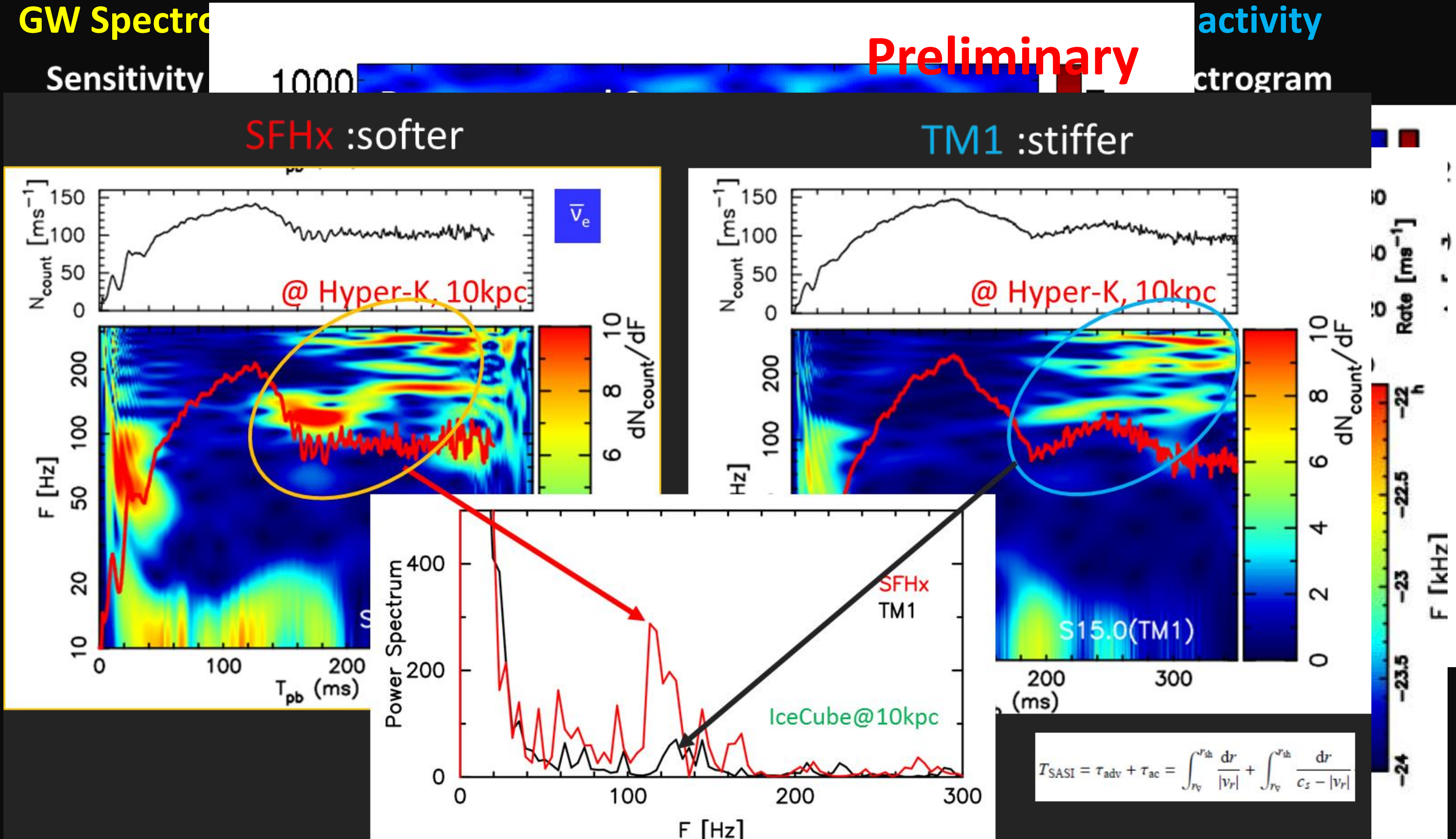
✓ 3D GR simulations (BSSN) with neutrino transport (gray, M1 scheme)
(Kuroda, KK, and Takiwaki 2012, ApJ, 2014, PRD)
see **multi-energy version available !**
in Kuroda,Takiwaki, & KK. ApJS (2016))

SFHx :softer





✓ **SASI activity higher for softer EOS** (due to shorter growth rate, e.g., Foglizzo et al. ('06)).

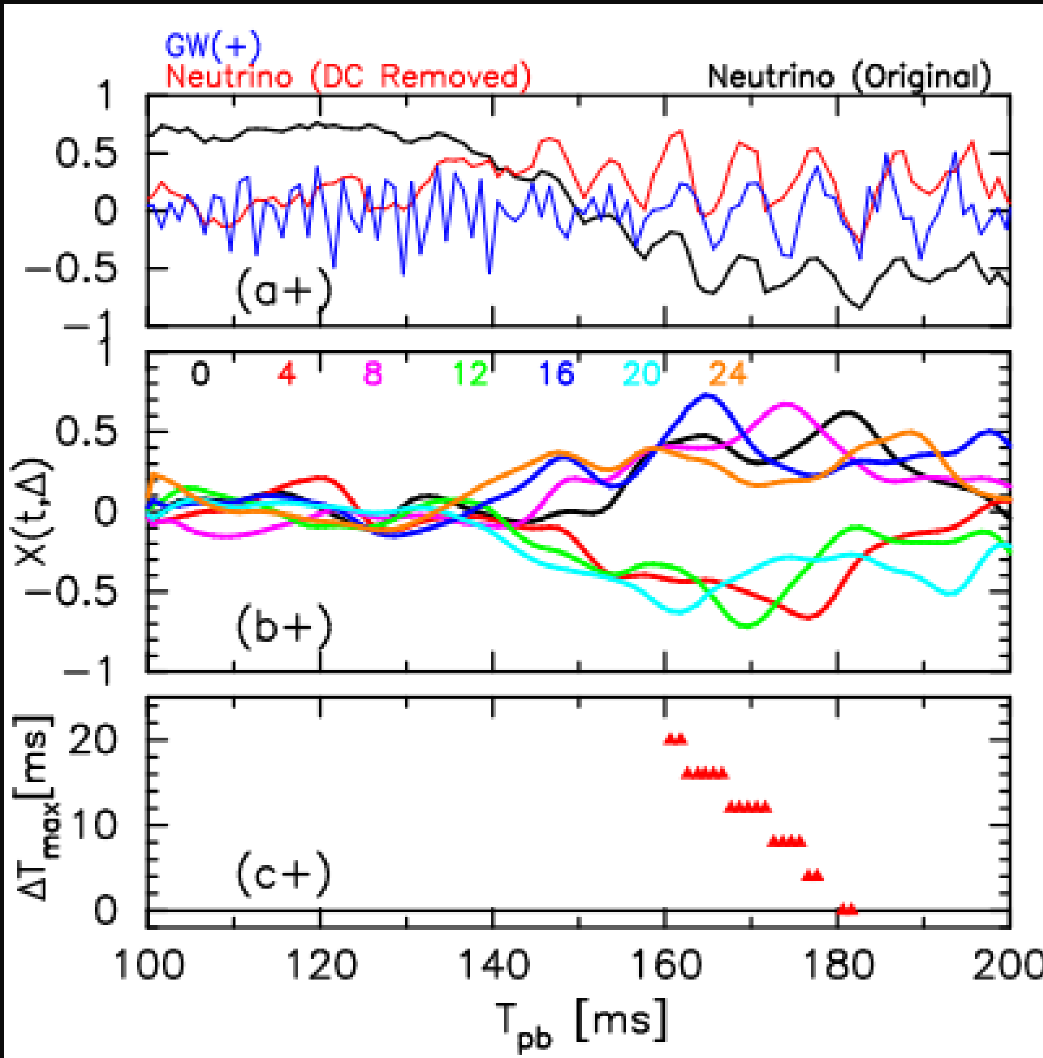


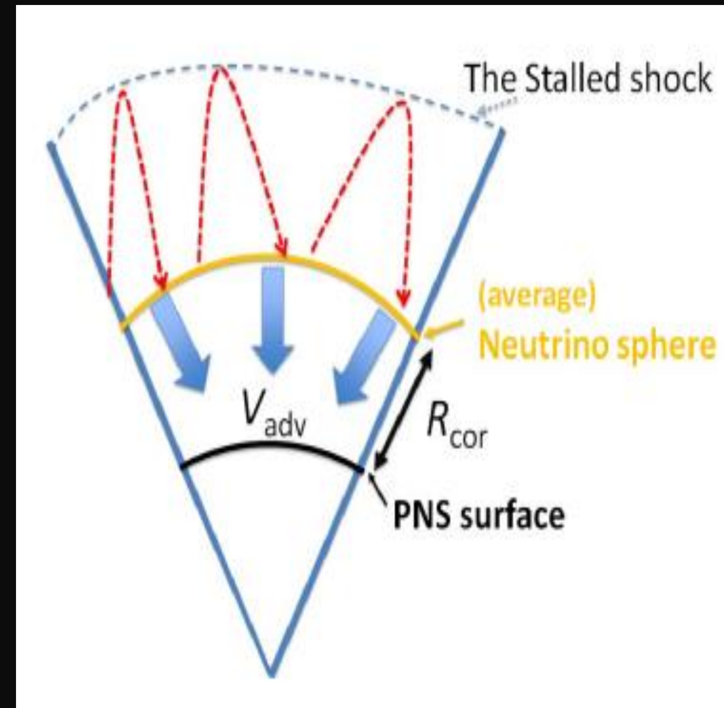
- ✓ By **coherent network analysis** of LIGO, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc, but could extend out to 100 kpc when **ET and CE are on-line (>2035).**
- ✓ **Detection of neutrinos (Super-K, IceCube) important to get timestamp of GW detection.**
- ✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (e.g., Tamborra et al. (2012) for SASI-induced neutrino signals).

Correlation between GWs and neutrinos with strong SASI activity (15 M_{sun} + SFHx)

$$X(t,\Delta T) = \frac{\int d\tau H(t-\tau) A_\nu(\tau+\Delta T) A_{\rm GW}(\tau)}{\sqrt{\int d\tau H(t-\tau)(A_\nu(\tau+\Delta T))^2}\sqrt{\int d\tau H(t-\tau)(A_{\rm GW}(\tau))^2}}$$

Kuroda, KK, Hayama, Takiwaki
(soon to be submitted)





$\Delta T_{max} \sim R_{cor} / V_{adv}$
$\sim$ O(10) km/($10^{7\text{~}8}$ cm/s)
$\sim$ O(10) ms

✓ **The simultaneous detection potentially tells the distance between the neutrino sphere and PNS radius !** (Need to follow long-term 3D evolution how long this continues..)

"New" GW messenger is Circular Polarization of GW) :Non-axisymmetric instabilities (incl. low T/|W|, spiral SASI

Stokes Parameters:

Hayama et al. (2016), PRL (see also Klimenko et al. (2015) PRD)

$$\begin{pmatrix} \langle h_R(f,\hat{n}) h_R(f',\hat{n}')^* \rangle & \langle h_L(f,\hat{n}) h_R(f',\hat{n}')^* \rangle \\ \langle h_R(f,\hat{n}) h_L(f',\hat{n}')^* \rangle & \langle h_L(f,\hat{n}) h_L(f',\hat{n}')^* \rangle \end{pmatrix} = \frac{1}{4\pi} \delta_D^2(\hat{n}-\hat{n}') \delta_D(f-f') \times \begin{pmatrix} I(f,\hat{n}) + \underline{V(f,\hat{n})} & Q(f,\hat{n}) - iU(f,\hat{n}) \\ Q(f,\hat{n}) + iU(f,\hat{n}) & I(f,\hat{n}) - \underline{V(f,\hat{n})} \end{pmatrix}$$

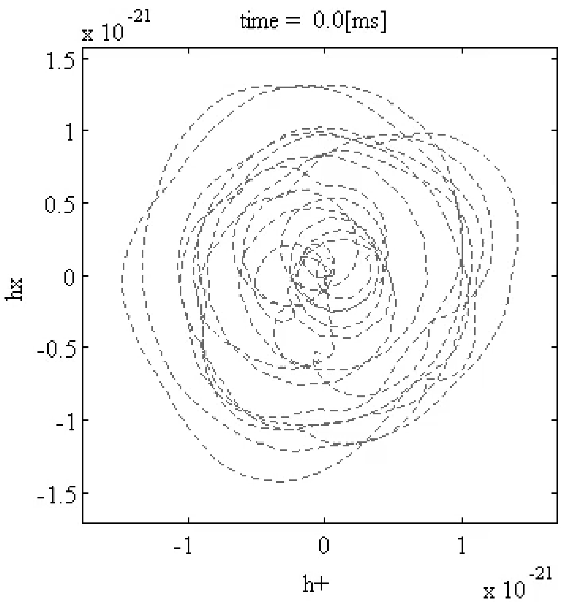
V parameter = Asymmetry of right and left modes

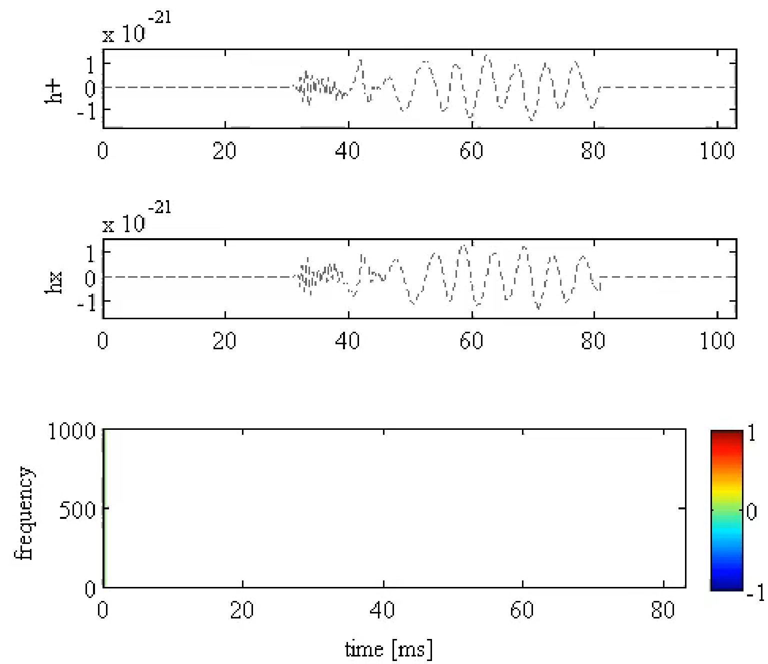
$$h_R := (h_+ - i h_\times)/\sqrt{2} \qquad h_L := (h_+ + i h_\times)/\sqrt{2}$$

(See definitions in Seto and Taruya (2007), PRL)

Rapidly rotating 15 M_{sun} (early postbounce phase)
from Kuroda, Takiwaki, KK (2014) PRD)

@10kpc





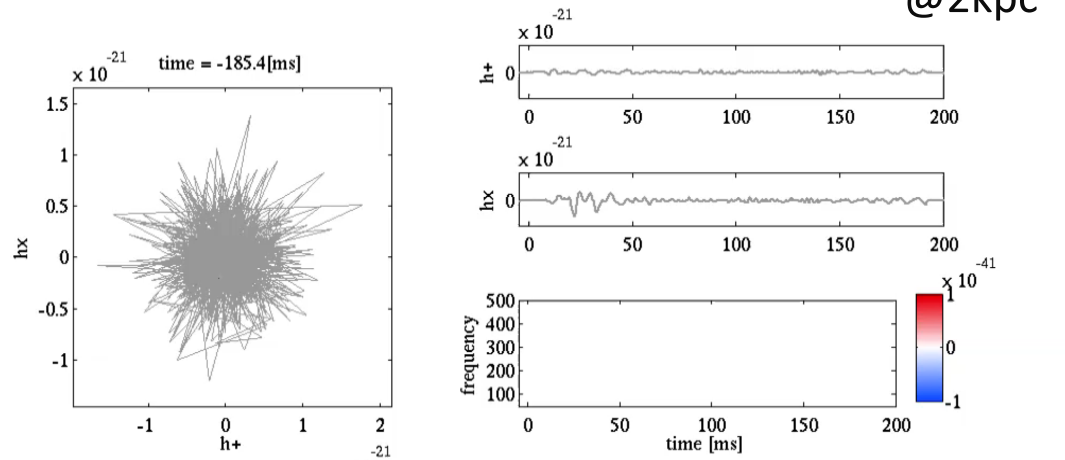
CP (if seen from the spin axis) :evidence of "rapid rotation".

What about Circular GW polarization in "Non-rotating" progenitors ?

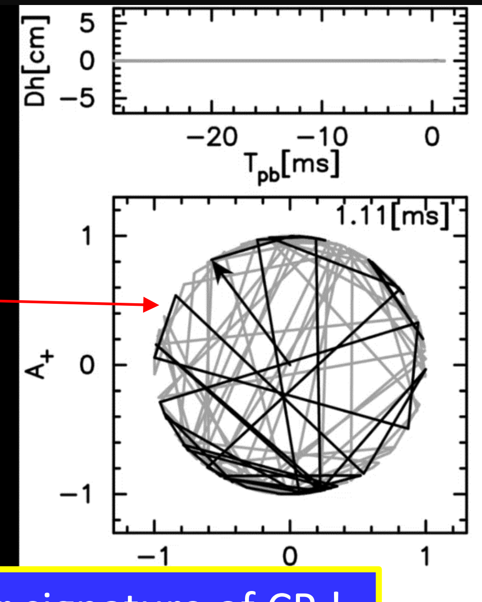
Hayama, KK et al. in prep

Non-rotating 11.2 M_{sun} star ; Convection dominant

@2kpc



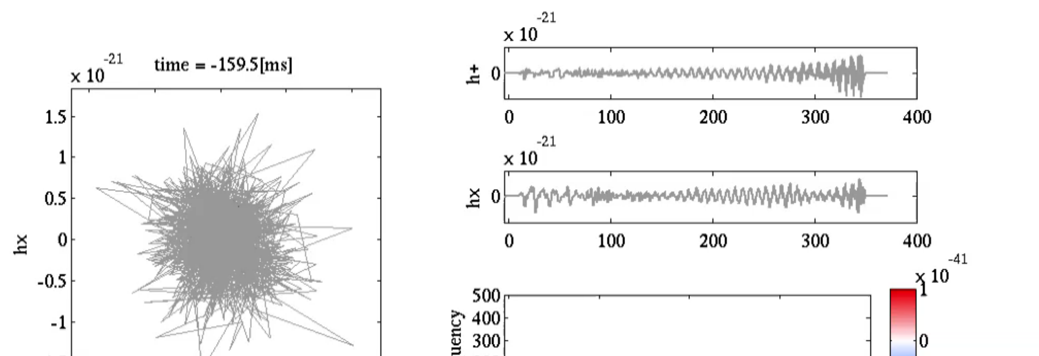
Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_x$)

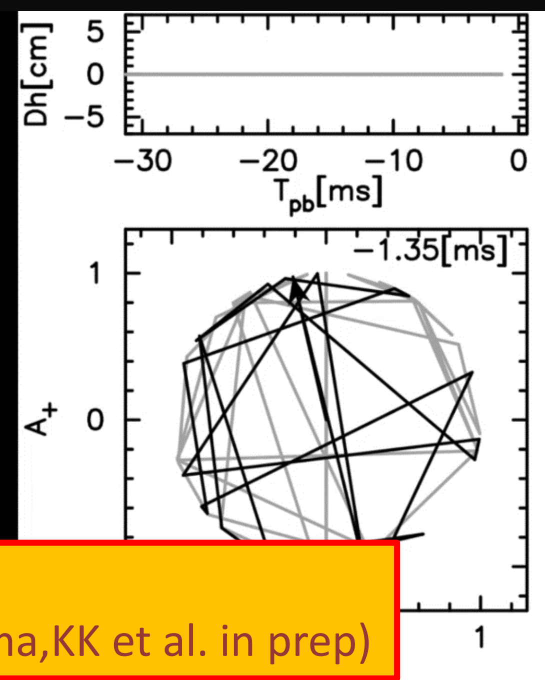


If the core is convection-dominant (likely for low ξ stars), no clear signature of CP !

Non-rotating 15 M_{sun} star (SFHx EOS); SASI dominant

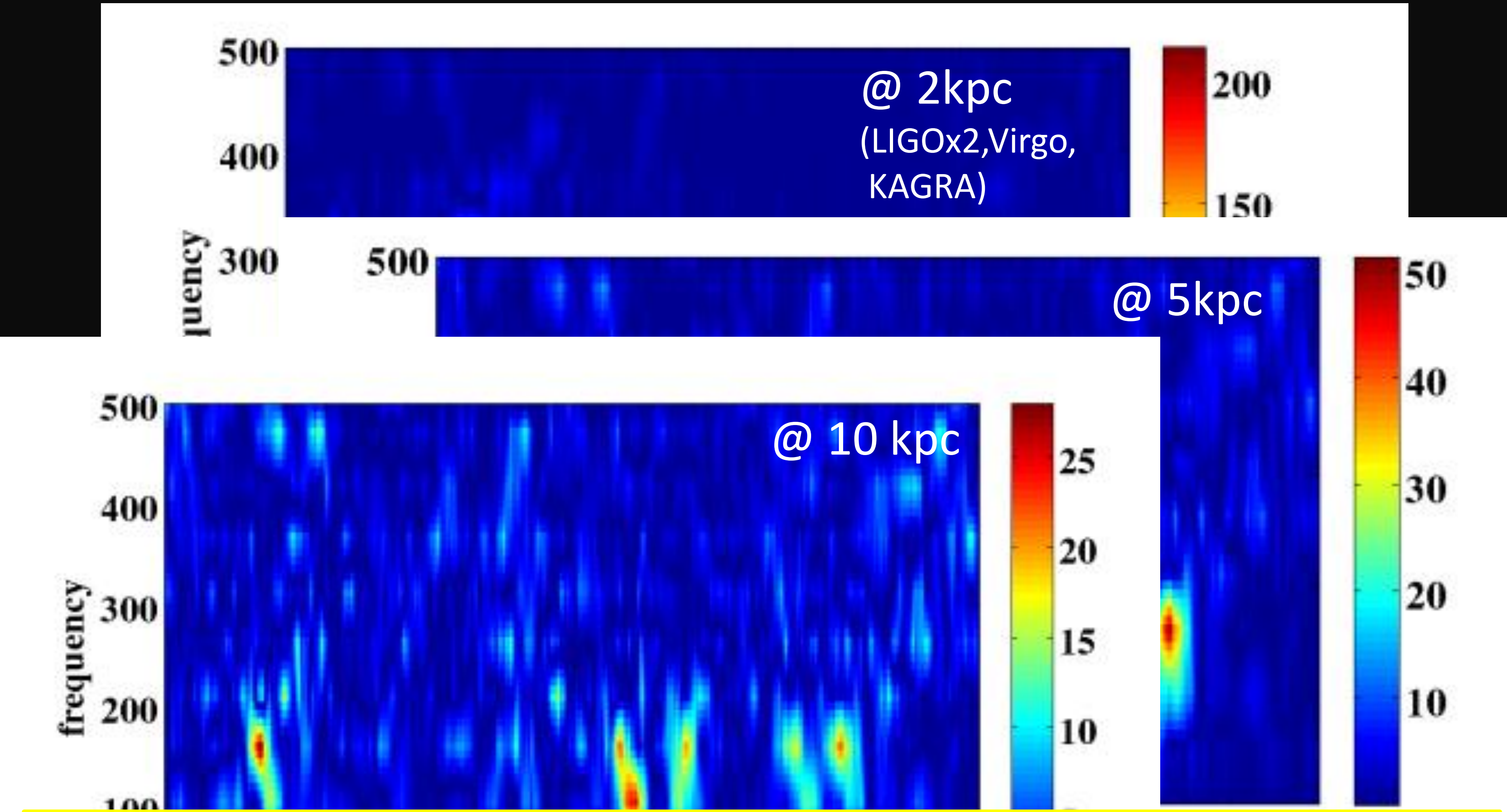
@5kpc





If the SASI dominant (likely for high ξ stars), clear signature of CP !
⇒ indication of SASI motions non-spherical mass accretion (Hayama,KK et al. in prep)

SNR of Circular Polarization of GW relative to background



✓ The detection of GW amplitude is within several kpc using LIGO (e.g.,Andresen et al. (2017))

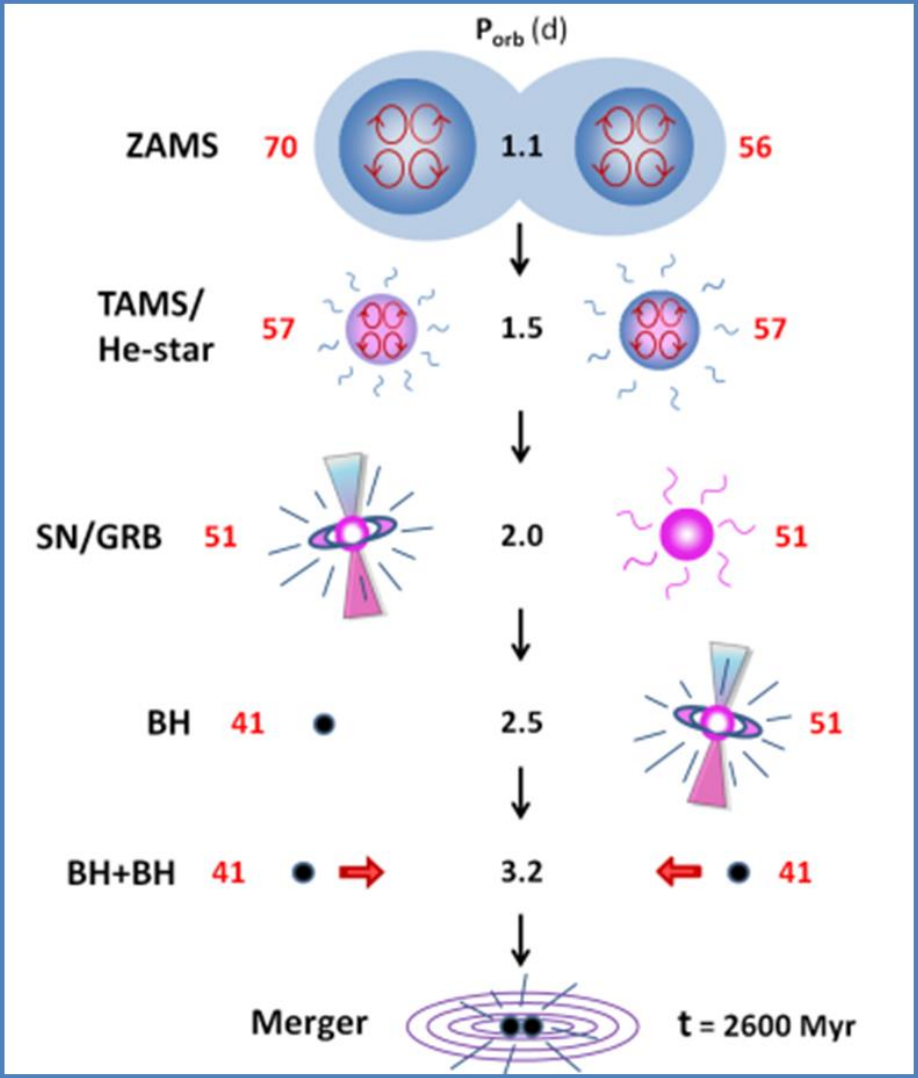
✓ The detection of CP could extend (far) beyond the detection horizon of GW waveform !

✓ The CP would provide new window to detect GW signals !

(Hayama, Takiwaki, KK, Kuroda in prep)

First discovery ! (Announced Feb 12th (2am JST)) by LIGO

✓ One of them.. "Isolated binaries"

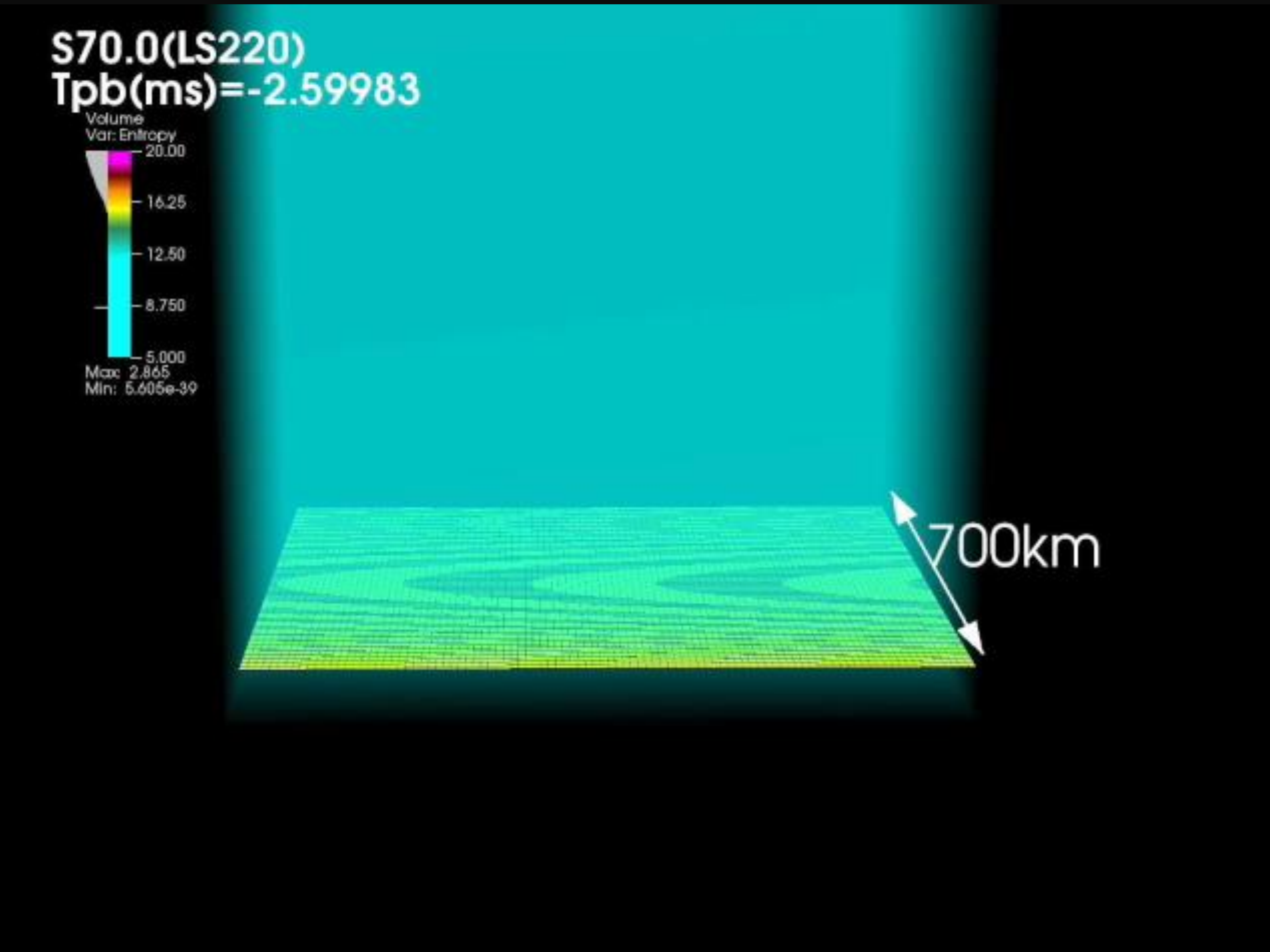


Marchant, Langer, Podsiadlowski et al. (2006)

✓ Origin of ~ 30-40 M_{sun} BH ?!

✓ **Low metallicity** environment needed for large stellar mass BH formation.

(e.g., Kinugawa et al .(2014,2016))



S70.0(LS220)
Tpb(ms)=-2.59983
Volume
Var: Entropy
20.00
16.25
12.50
8.750
5.000
Max: 2.865
Min: 5.605e-39
700km

Need improvement in opacity of our 3D-GR code (with energy transport)!

Table 1
The Opacity Set Included in this Study and their References

Process	Reference	Summarized In
$n\nu_e \leftrightarrow e^- p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$p\bar{\nu}_e \leftrightarrow e^+ n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu_e A \leftrightarrow e^- A'$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu p \leftrightarrow \nu p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu n \leftrightarrow \nu n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu A \leftrightarrow \nu A$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu e^\pm \leftrightarrow \nu e^\pm$	Bruenn (1985)	Appendix A.3
$e^- e^+ \leftrightarrow \nu\bar{\nu}$	Bruenn (1985)	Appendix A.4
$NN \leftrightarrow \nu\bar{\nu}NN$	Hannestad & Raffelt (1998)	Appendix A.5

KTK (2016), ApJS (essentially, Bruenn rates + Bremsstrahlung)

Most advanced set (e.g., Fischer(2016), Bollig et al. (2017))

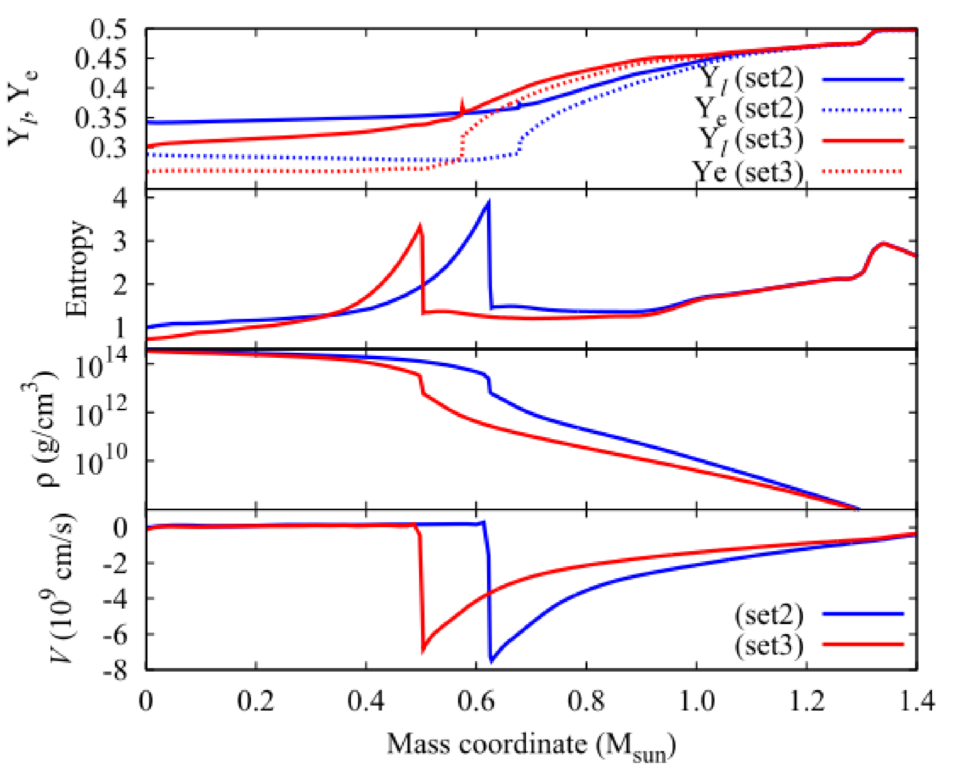
	Weak process	References
1	$e^- + p \rightleftarrows n + \nu_e$	Reddy et al. (1998); Horowitz (2002)
2	$e^+ + n \rightleftarrows p + \bar{\nu}_e$	Reddy et al. (1998); Horowitz (2002)
3	$n \rightleftarrows p + e^- + \bar{\nu}_e$	Fischer et al. (2016b)
4	$e^- + (A,Z) \rightleftarrows (A,Z-1) + \nu_e$	Juodagalvis et al. (2010)
5	$\nu + N \rightleftarrows N + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993a); Horowitz (2002)
6	$\nu + (A,Z) \rightleftarrows (A,Z) + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993a)
7	$\nu + e^\pm \rightleftarrows e^\pm + \nu'$	Bruenn (1985); Mezzacappa & Bruenn (1993b)
8	$e^- + e^+ \rightleftarrows \nu + \bar{\nu}$	Bruenn (1985)
9	$N + N \rightleftarrows N + N + \nu + \bar{\nu}$	Hannestad & Raffelt (1998)
10	$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$	Buras et al. (2003); Fischer et al. (2009)
11	$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}$	Fuller & Meyer (1991); Fischer et al. (2013)

Note: unless stated otherwise, $\nu = \{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}$ and $N = \{n, p\}$.

2. Comparison with Agile-Tobias rates

n – September)

KK et al. in prep



Hix +2003, PRL

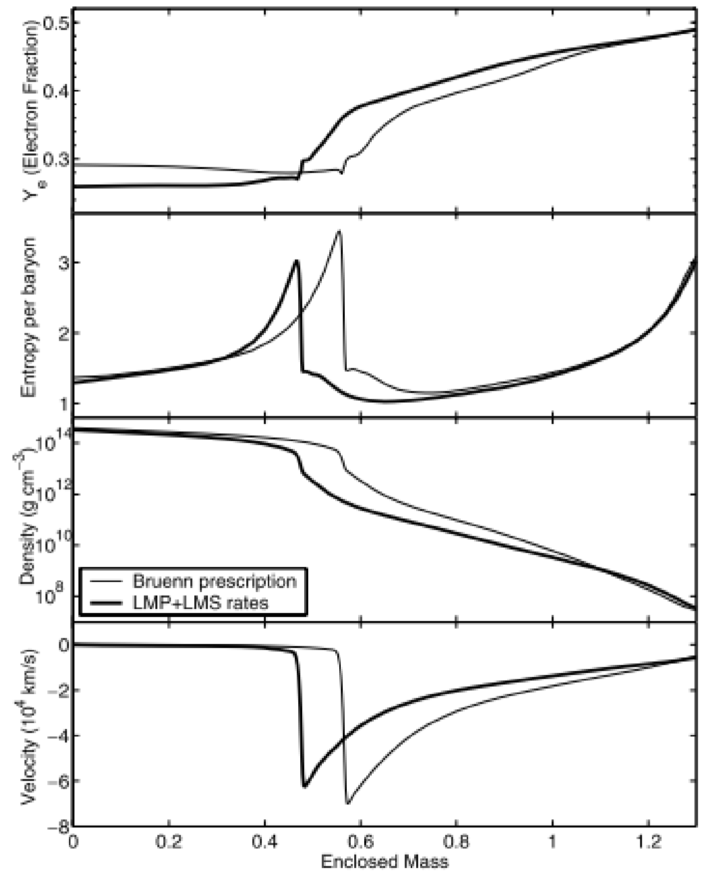


FIG. 1. The electron fraction, entropy, density, and velocity as functions of the enclosed mass at the beginning of bounce for a 15 $M_\odot$ model. The thin line is a simulation using the Bruenn parametrization, while the thick line is for a simulation using the LMP and hybrid reaction rate sets.

Consistent with previous literatures!

E_ν [MeV]

10 100

Energy [MeV]

Summary

- ✓ <u>**Simultaneous detection**</u> of SASI-induced modulation both in neutrino and GW signals is <u>**a smoking-gun signature**</u> of the <u>**violent SASI motion**</u> in the core.
  - If detected, we could get information of the relative distance between the neutrino emission region (neutrino sphere) and the PNS core.

  (Kuroda, KK, Hayama, Takiwaki, soon to be submitted)

- ✓ <u>**First 3D-GR simulation**</u> with multi-energy transport that followed the hydrodynamics up to <u>**BH formation.**</u>

  (Kuroda, Takiwaki, KK in prep)

- ✓ <u>**All above results need "upgrade"**</u> quantitatively (first) with elaborate neutrino opacities.

  (KK, Takiwaki, Fischer, Kuroda, Nakamura, G.M. Pinedo in prep)