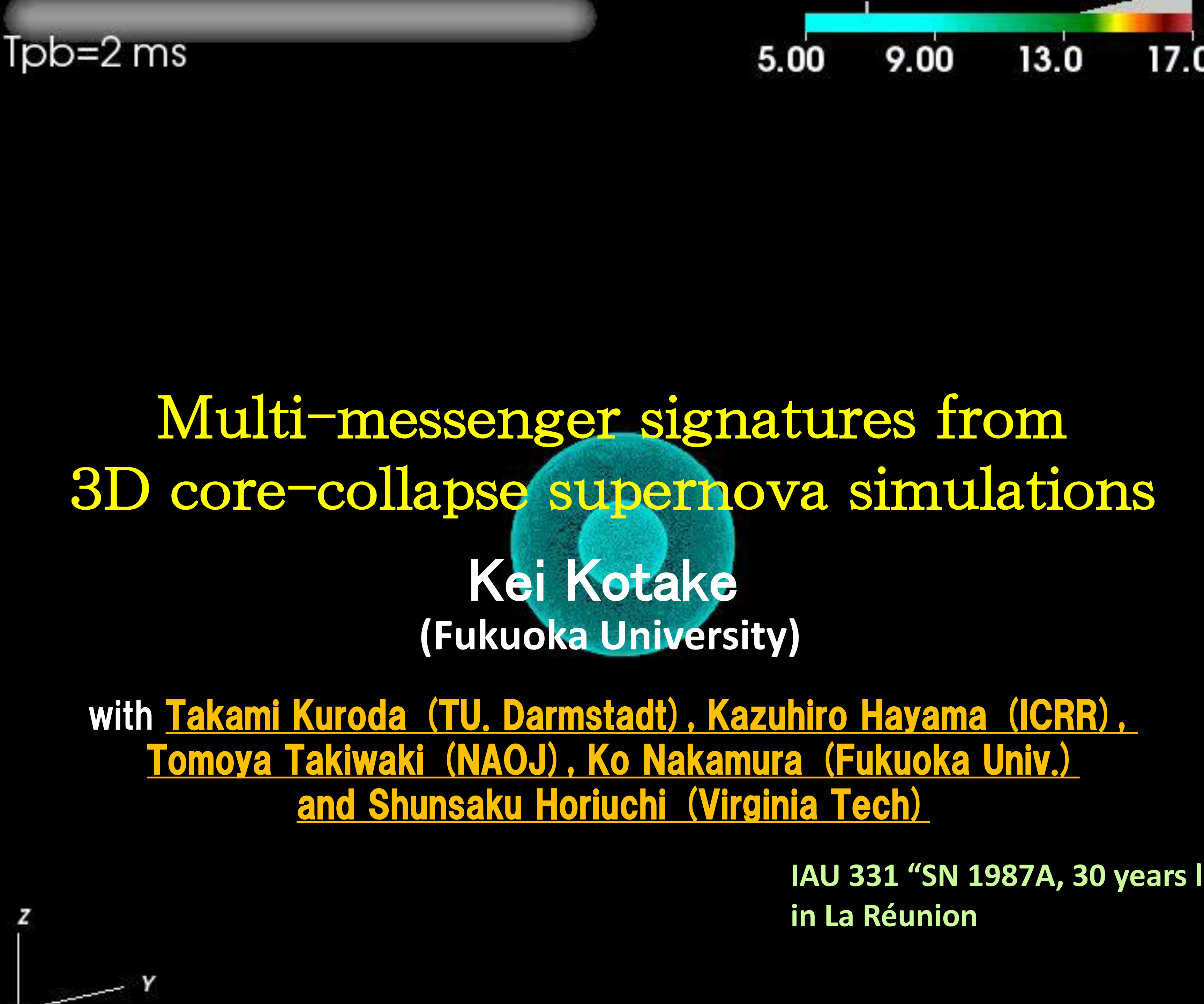


Multi-messenger signatures from 3D core-collapse supernova simulations

Kei Kotake
(Fukuoka University)

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

IAU 331 “SN 1987A, 30 years later
in La Réunion

Celebrating 30th Anniversary of SN1987A !

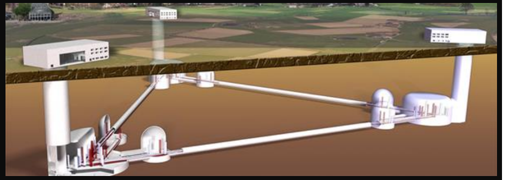
Looking back ~30 ye... in both theory and o...

10^-18

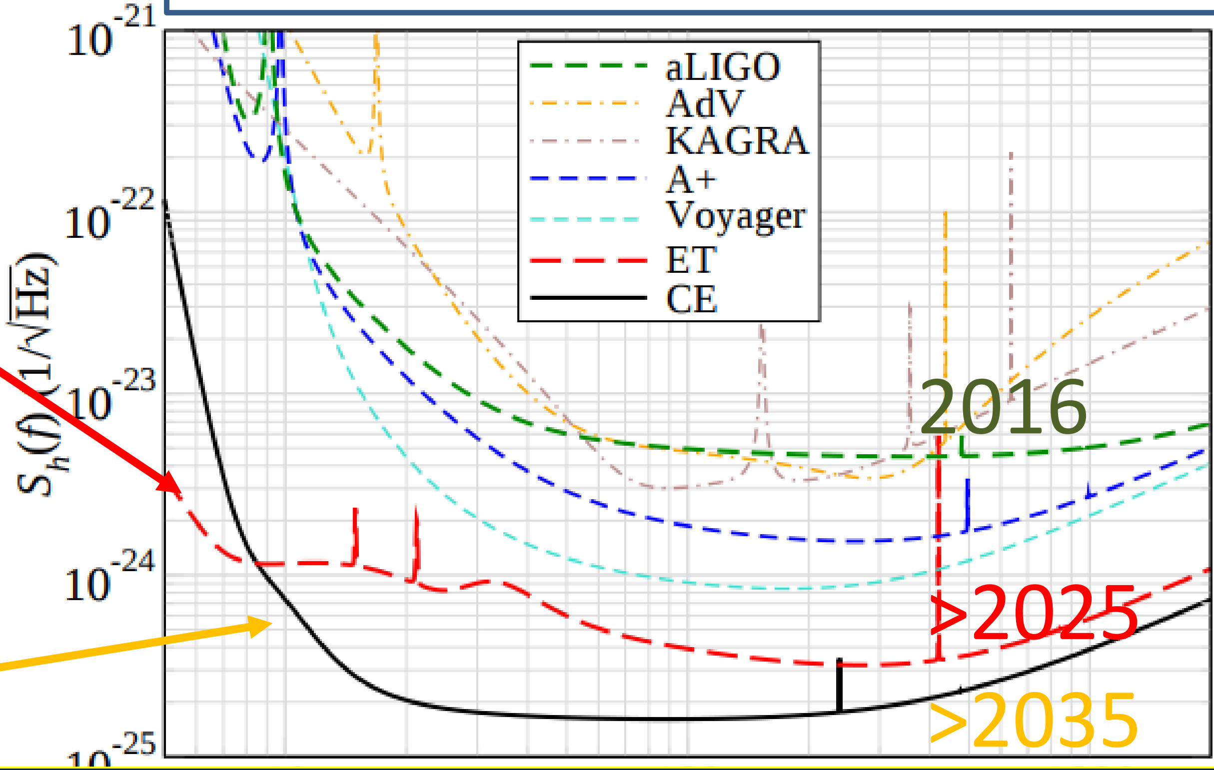
Typical thresholds of proto-types in 1989
(MIT, Garching, Caltech, Glasgow and Tokyo)

Sensitivity curves of laser interferometers

10 km long:
Einstein Telescope (ET)
could start ~2025.



40 km long:
Cosmic Explore (CE)
could operate ~2035.



GW astronomy of CCSNe, no more a dream !

Quiz :Depending on (a) , supernova dynamics deviates from spherical symmetry.

⇒ Essential for understanding the GW emission mechanism!

(Pioneered by E. Müller (1982), Reviews, Fryer and New (2003), Ott (2009), KK (2013)

Recent work by Andresen, B & E Muller and Janka. (2016), Yakunin + (2017)

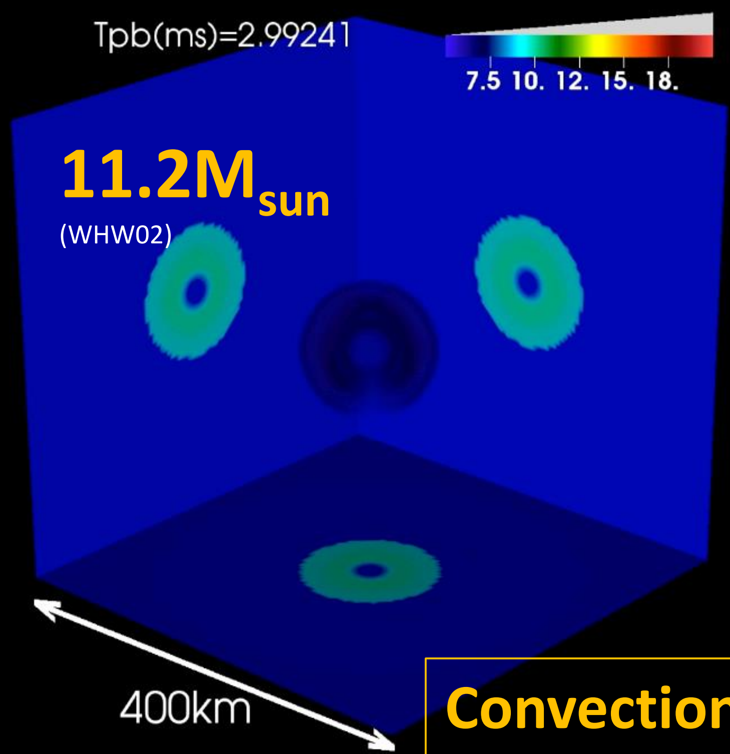
See a chapter about GW from CCSNe in "Handbook of Supernovae" by Kotake and Kuroda (2016))

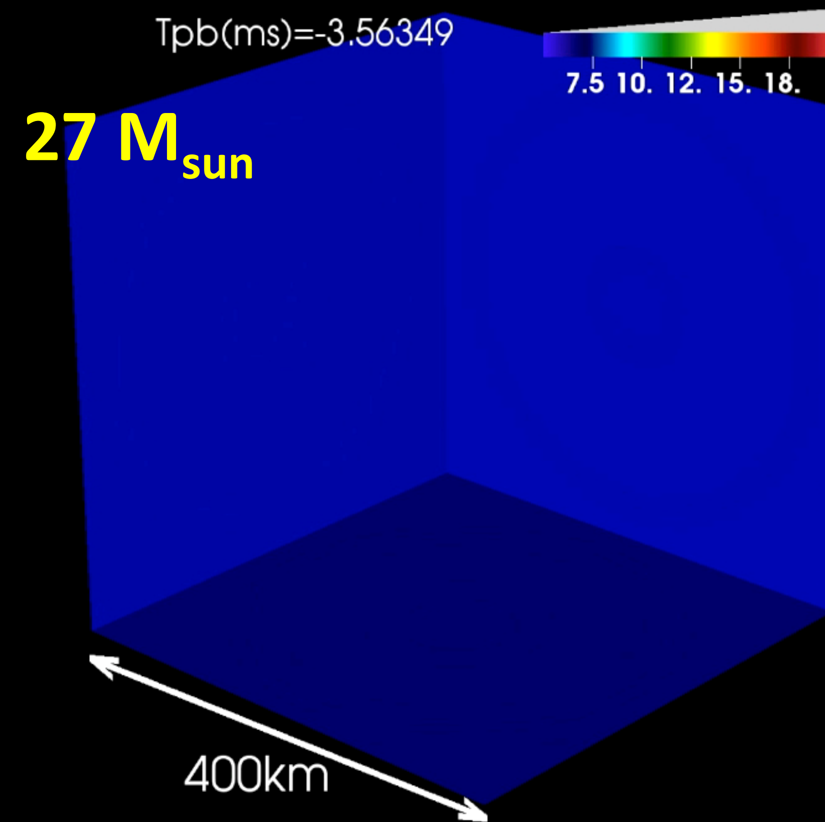
Choice (1) Progenitor mass / compactness

Quiz :Depending on (a) , supernova dynamics deviates from spherical symmetry.
⇒ Essential for understanding the GW emission mechanism!

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

Choice (1) Progenitor mass / compactness



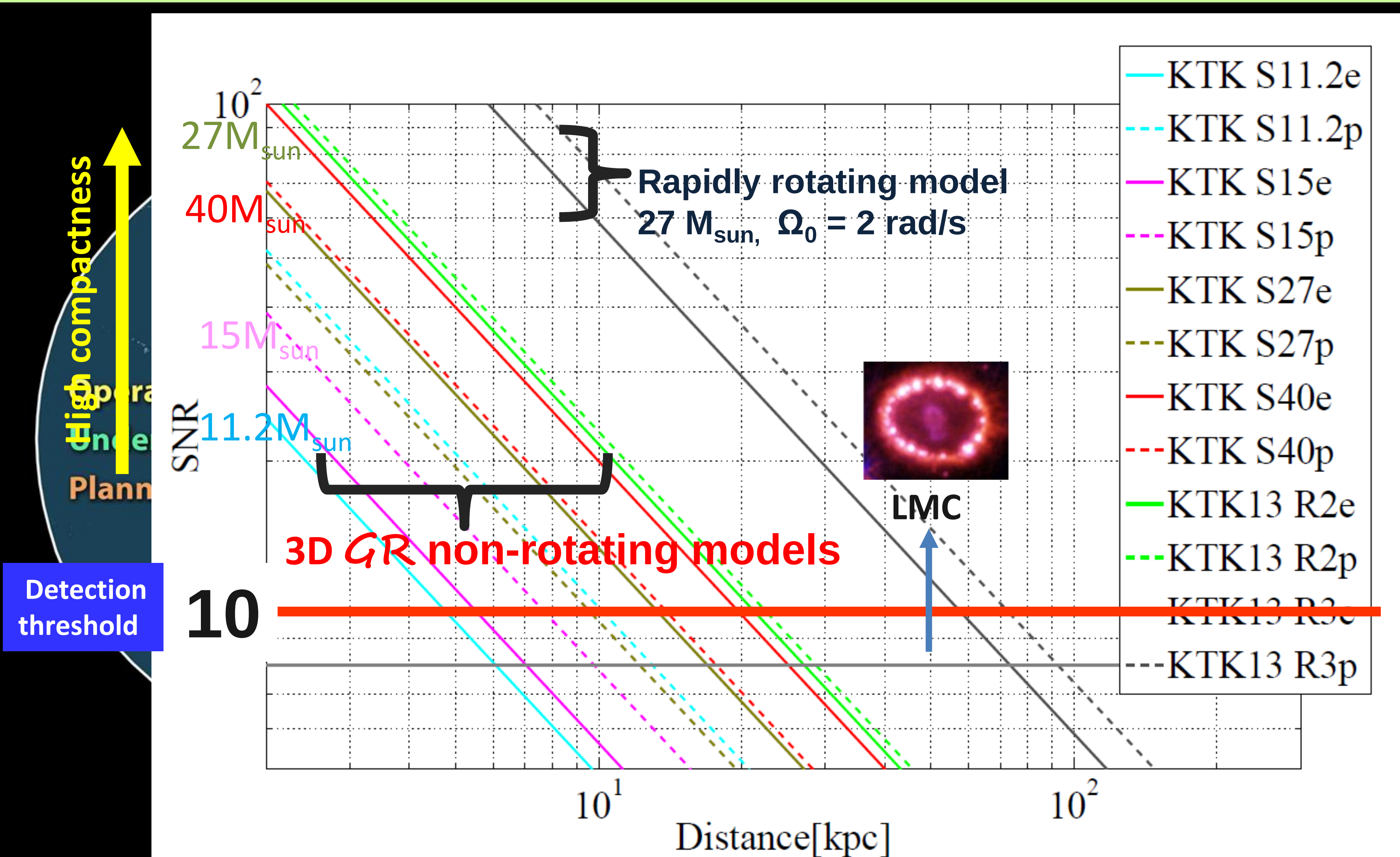


SASI-dominant ⇒ Global deformation with low (l,m).

Convection-dominant ⇒ Smaller-scale anisotropy with high (l,m).

Detectability of 3D-GR models: ***Signal-to-Noise (SNR)***

✓Coherent Network analysis between LIGO-(H/L), VIRGO, KAGRA. (Hayama et al. (2015), PRD)



✓High progenitor's compactness (ξ) ⇒ high mass accretion to PNS ⇒ violent SASI/convection, efficient GW emission.

✓This method can reach beyond Galactic Center (8.5 kpc) for high ξ (non-rotating) progenitors.

Quiz :Depending on (a) , supernova dynamics deviates from spherical symmetry.
⇒ Essential for understanding the GW emission mechanism!

Choice (1) Progenitor mass / compactness

Ans: Yes !
⇒ high progenitor compactness leads to efficient GW emission.
Caveat:
Need more 3D-GR models (with better transport and hopefully with explosions!) for quantitative GW predictions.

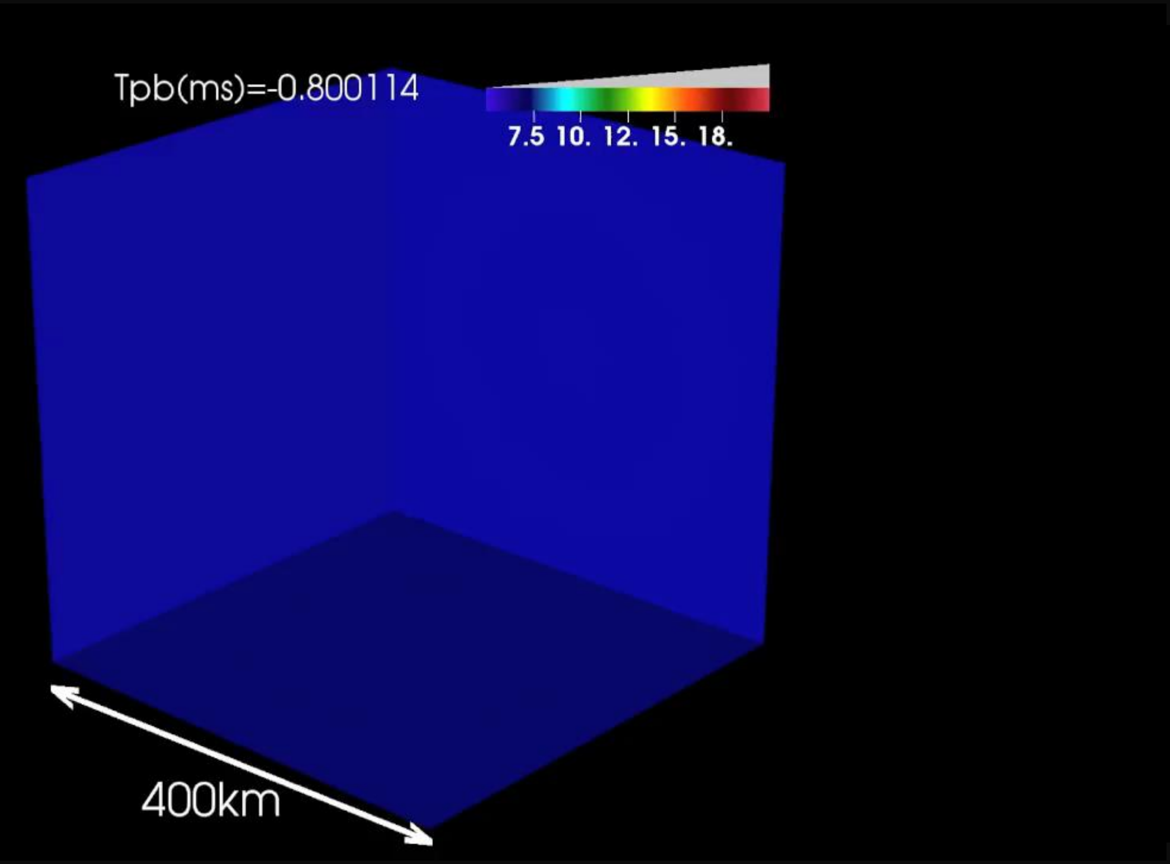
Choice (2) Equation of State

GW signals from 3D-GR models with different EOSs (1/2)

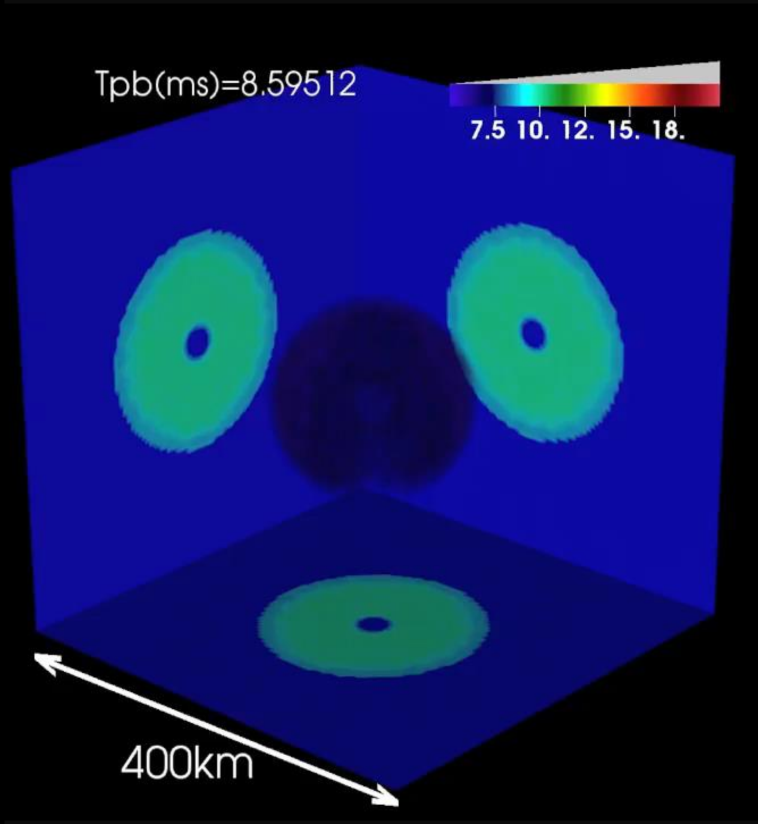
✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)),
HS(TM1) (Shen et al. (1998), Hempel & Schaffner-Bielich (2010)).

✓ 15 M_{sun} star (Woosley & Weaver (1995))

SFHx :softer



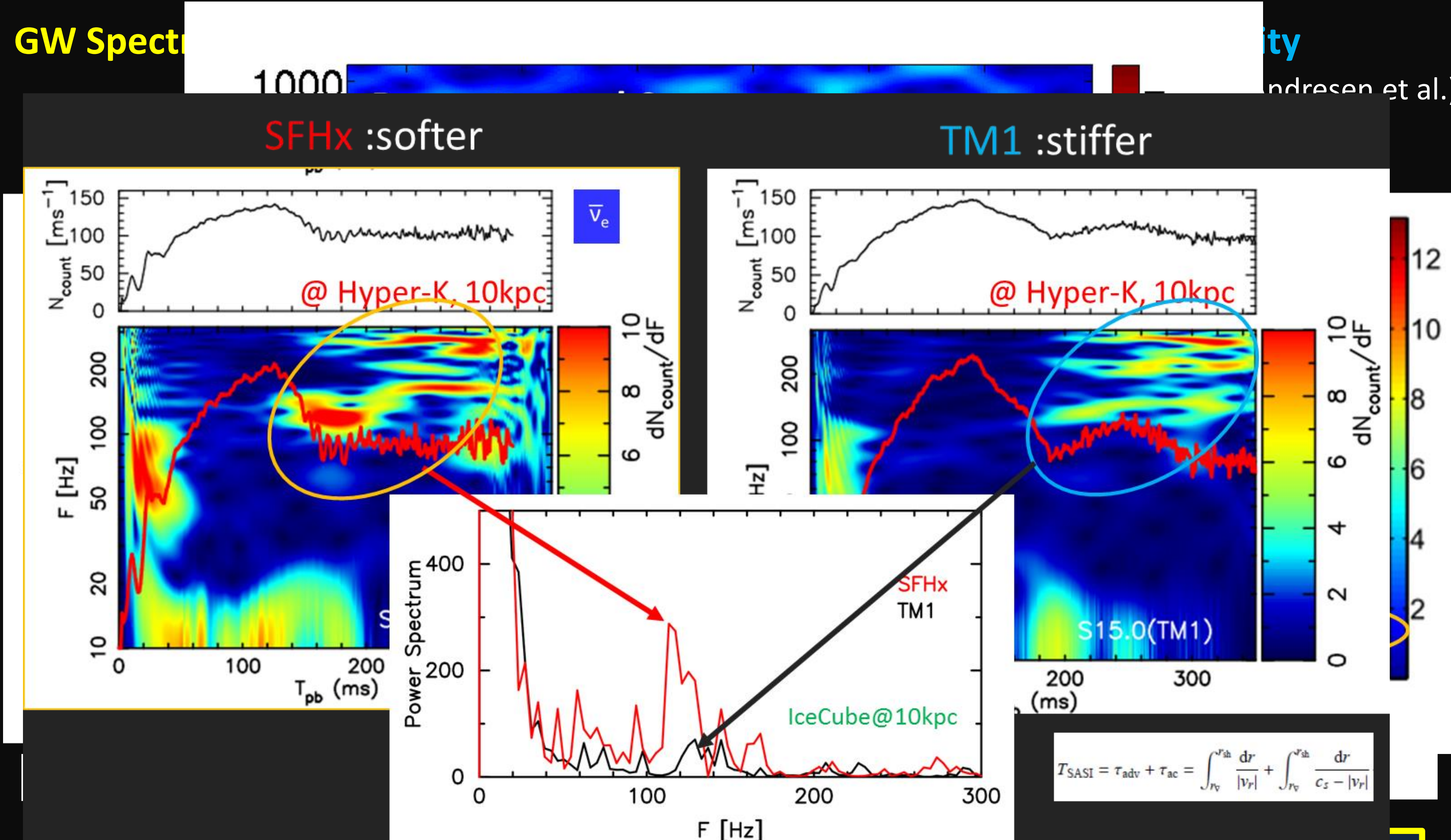
TM1 :stiffer



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

GW Spectr ... **ity**

...ndresen et al.)



- ✓ **The quasi-periodic modulation is associated with SASI, clearly visible with soft EOS.**
- ✓ By **coherent network analysis** of LIGOx2, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc, but could extend out to 100 kpc when **CE and ET are on-line. (2035~)**
- ✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (**see talks by Raffelt and Tamborra**).

Quiz :Depending on (a) , supernova dynamics deviates from spherical symmetry.
⇒ Essential for understanding the GW emission mechanism!

Choice (3) Precollapse rotation rate

Kuroda, Takiwaki, Kotake (2014), PRD.

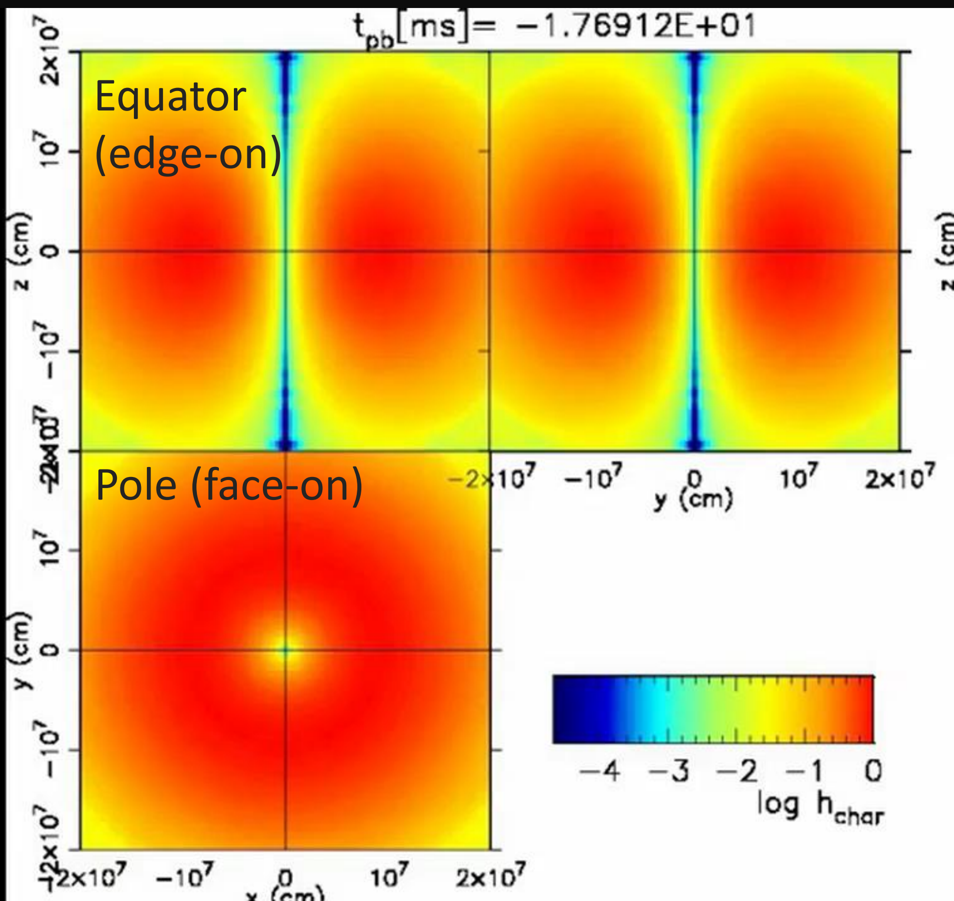
✓Very rapidly rotating ($\Omega_0 = \pi$ rad/s) 3D-GR model of 15 M_{sun} with M1-gray transport.

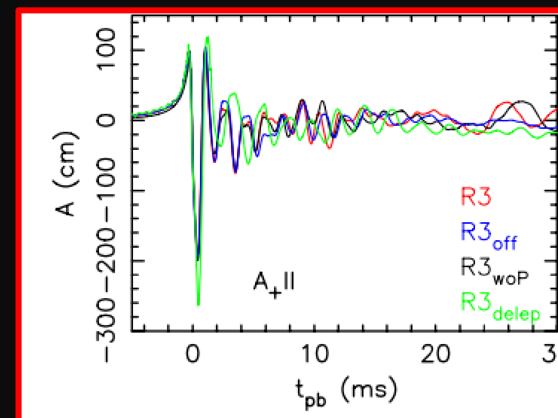
✓ Seen from **Equator**

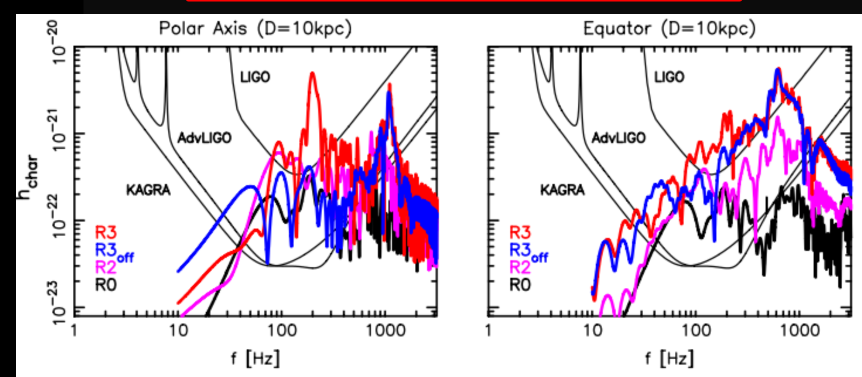
GW emissivity: $\psi \equiv (A_+ I)^2 + (A_\times I)^2 = (\ddot{I}_{xx} - \ddot{I}_{yy})^2 + (2\ddot{I}_{xy})^2$

: type I waveform

(e.g., Zwerger & Müller '97 in 2D Dimmelmeier+ 2007,PRL in 3D)







Non-axisymmetric instabilities (incl. low T/|W|, spiral SASI) and Circular Polarization (CP).

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

Stokes Parameters:

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

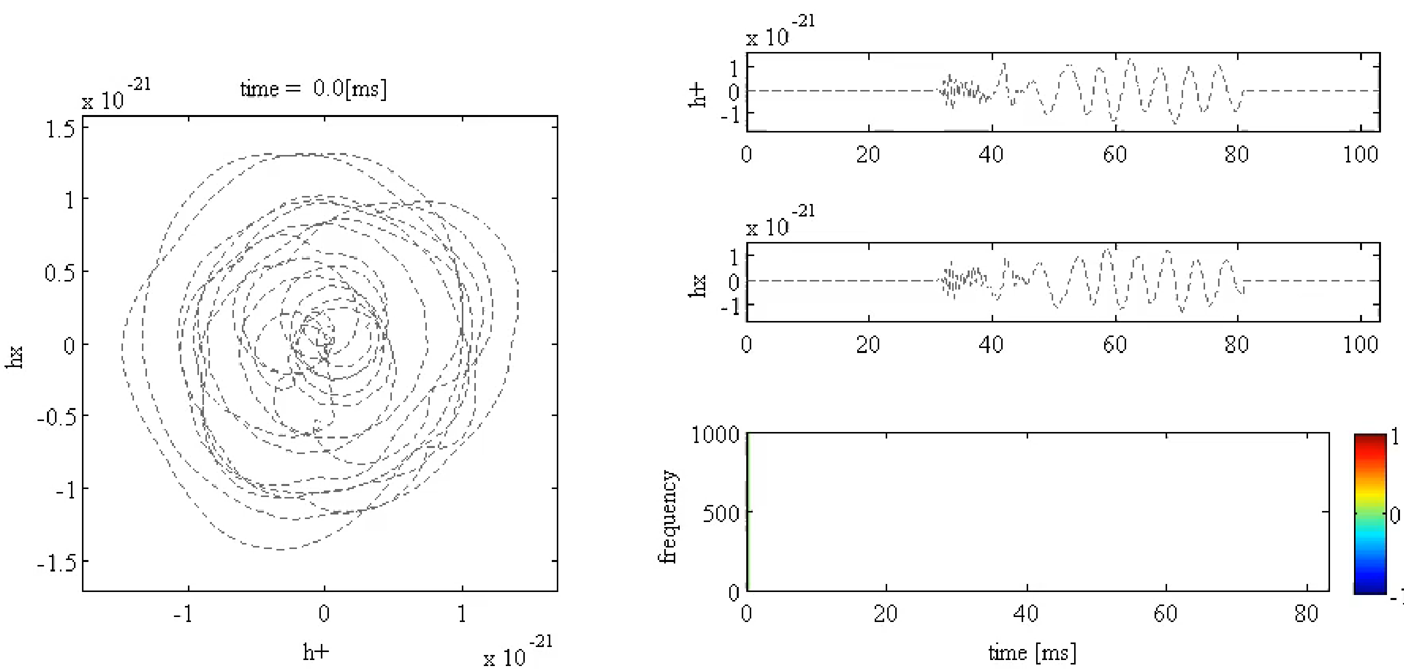
V parameter =
Asymmetry of right and left modes

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

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

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

@10kpc



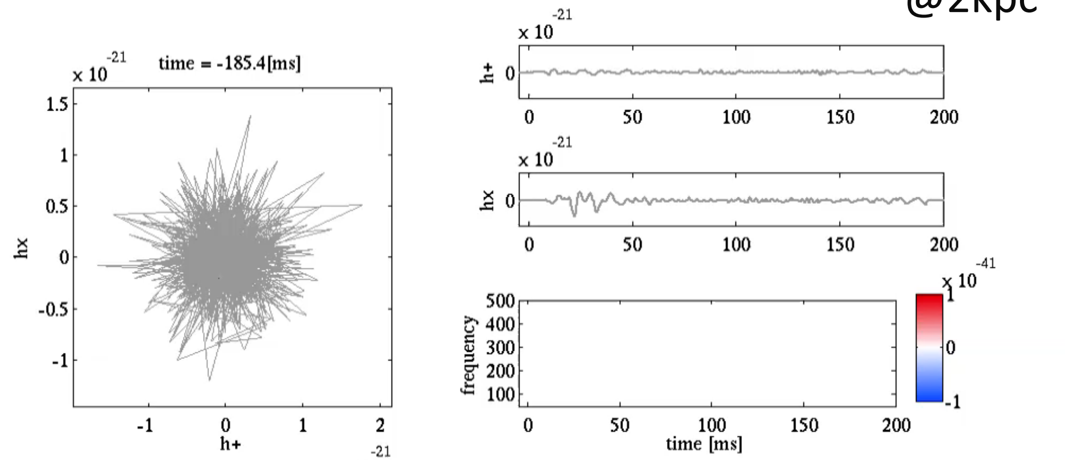
CP (if seen from the spin axis)
:evidence of "rapid rotation".

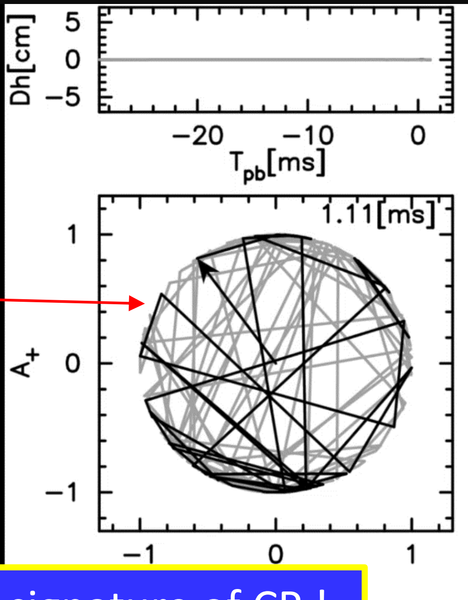
What about Circular GW polarization in "Non-rotating" progenitors ?

Hayama, KK+ in prep

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

@2kpc



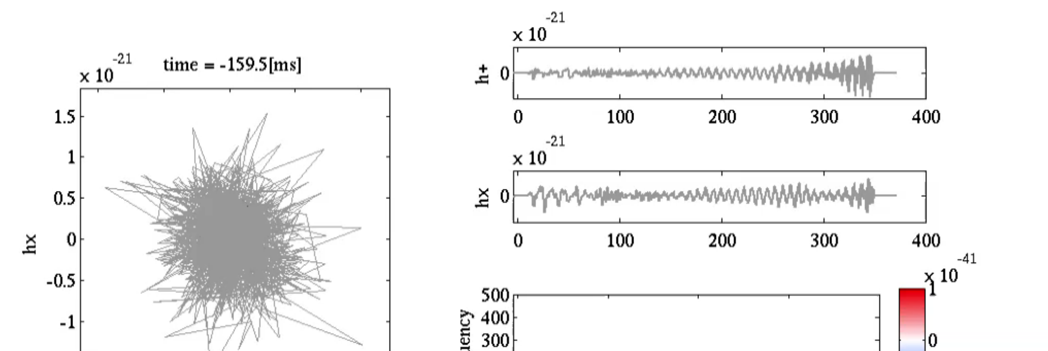


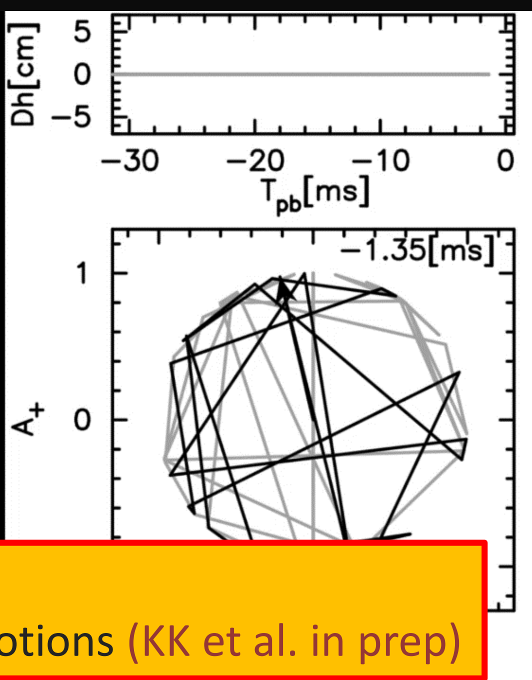
Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_x$)

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



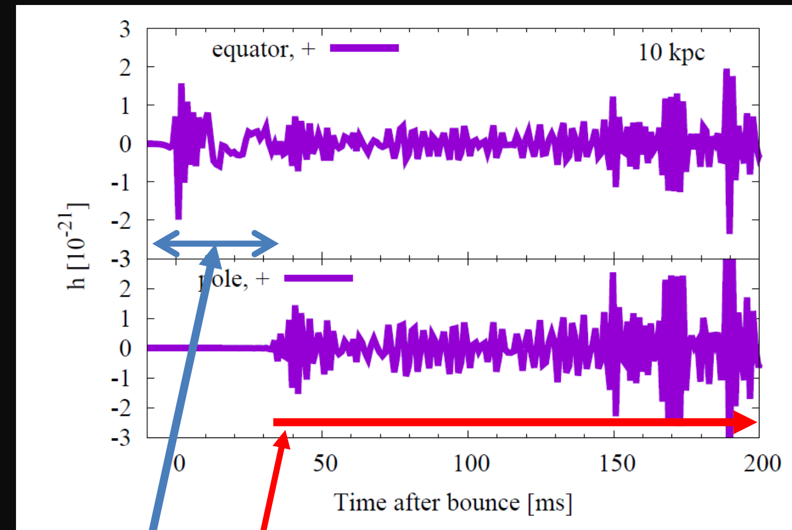


If the SASI dominant (likely for high ξ stars), clear signature of CP !
(albeit chaotically change with time) ⇒ indication of SASI's spiral motions (KK et al. in prep)

GW and neutrino signatures from 3D "exploding" model,

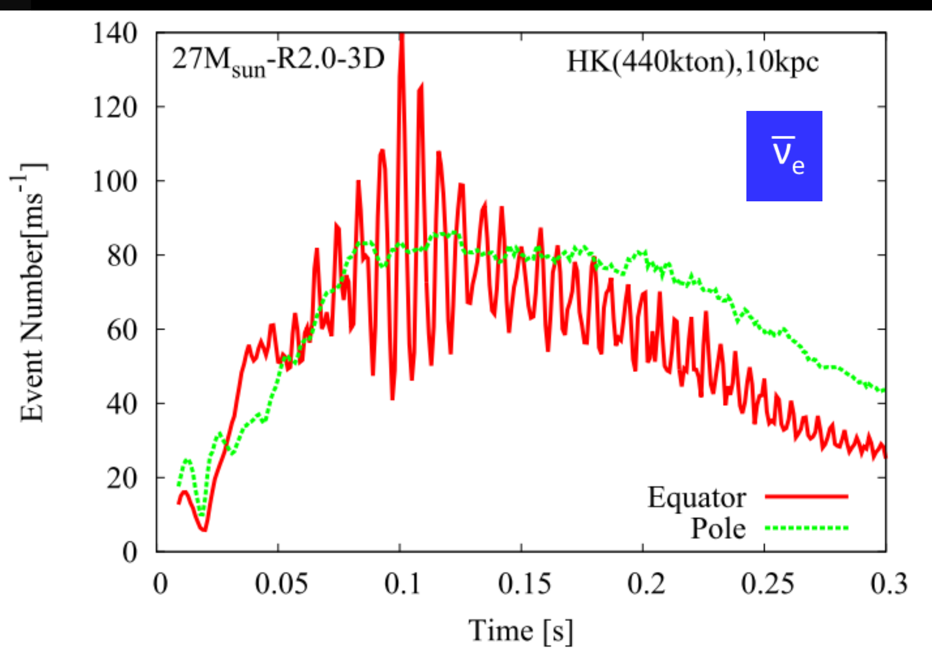
3D Newtonian model of rapidly rotating
27 M_{sun} star (Ω_0 = 2 rad/s) with IDSA transport.
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016)).

waveform

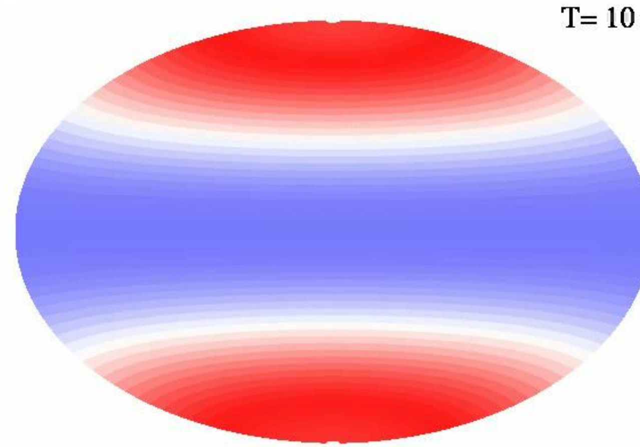


Type I signal (visible to ~Mpc by CE or ET),
Non-axisymmetric instabilities appear.

Quasi-periodic variation in neutrino signals !



$\delta L_{\bar{\nu}_e}$: RMS deviation from the angle-average luminosity



"Lighthouse effect"

Seen from equator

Quiz :Depending on (a) , supernova dynamics deviates from spherical symmetry.

⇒ Essential for understanding the GW emission mechanism!

Choice (3) Precollapse rotation rate

Choice (1) Progenitor mass / compactness

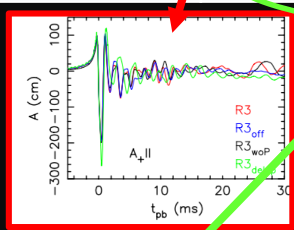
Ans: Yes

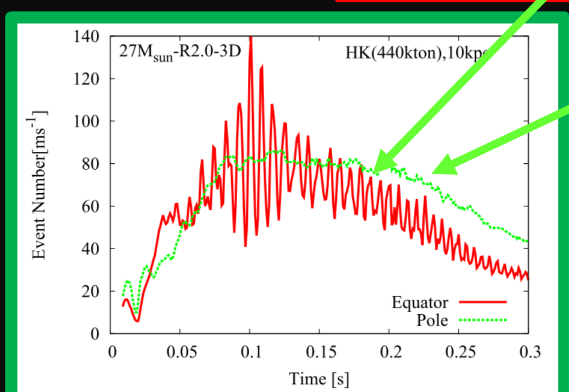
For rapidly rotating core (Ω_0 = 2~3 rad/s, maybe plausible in CH evolution see, e.g., Yoon & Langer (2008))

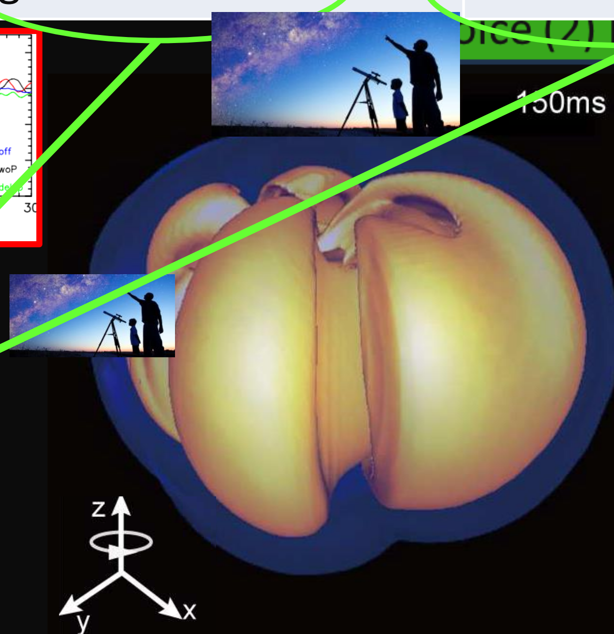
Several interesting features !

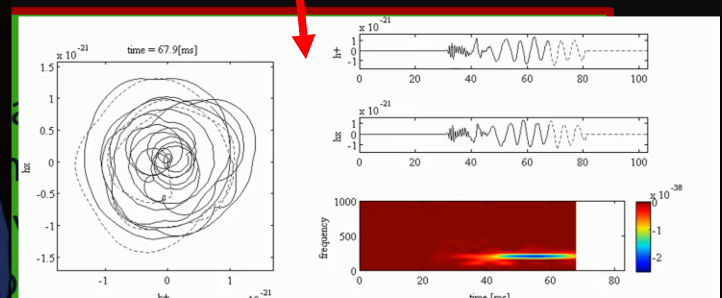
Key words	Equator	Pole
Gravitational Wave	Type I signal	✓ Quasi-periodic signals from non-axis. instability ✓ Circular polarization
Neutrinos	Light-house effect	No surprise …

...oice (2) Equation of State









...modulation in both GWs and ...os is smoking-gun of ...g of the shock (SASI).

Summary

Quiz: Depending on (a), supernova dynamics deviates from spherical symmetry.
⇒ Essential for understanding the MM signatures !

Choice (1) Progenitor mass / compactness

Ans: Yes !
⇒ high progenitor compactness leads to efficient GW/neutrino emission.

Choice (2) Equation of State

Ans: Yes !
⇒ The SASI modulation **more clearly visible in 3D-GR model with soft EOS**
⇒ **smoking-gun GW/neutrino signature of the SASI**.

✓ *In order to break the degeneracy…*
of these multiple physical elements (all of which impact GW signatures !),

✓ **Correlation analysis of MMs needed !**
(lots of work …….)

Choice (3) Precollapse rotation rate

Answer(3): Yes !

Key words	Equator	Pole
Gravitational Wave	Type I signal	✓ Quasi-periodic signals from non-axis. instability ✓ Circular polarization
Neutrinos	Light-house effect	No surprise …

Many thanks!