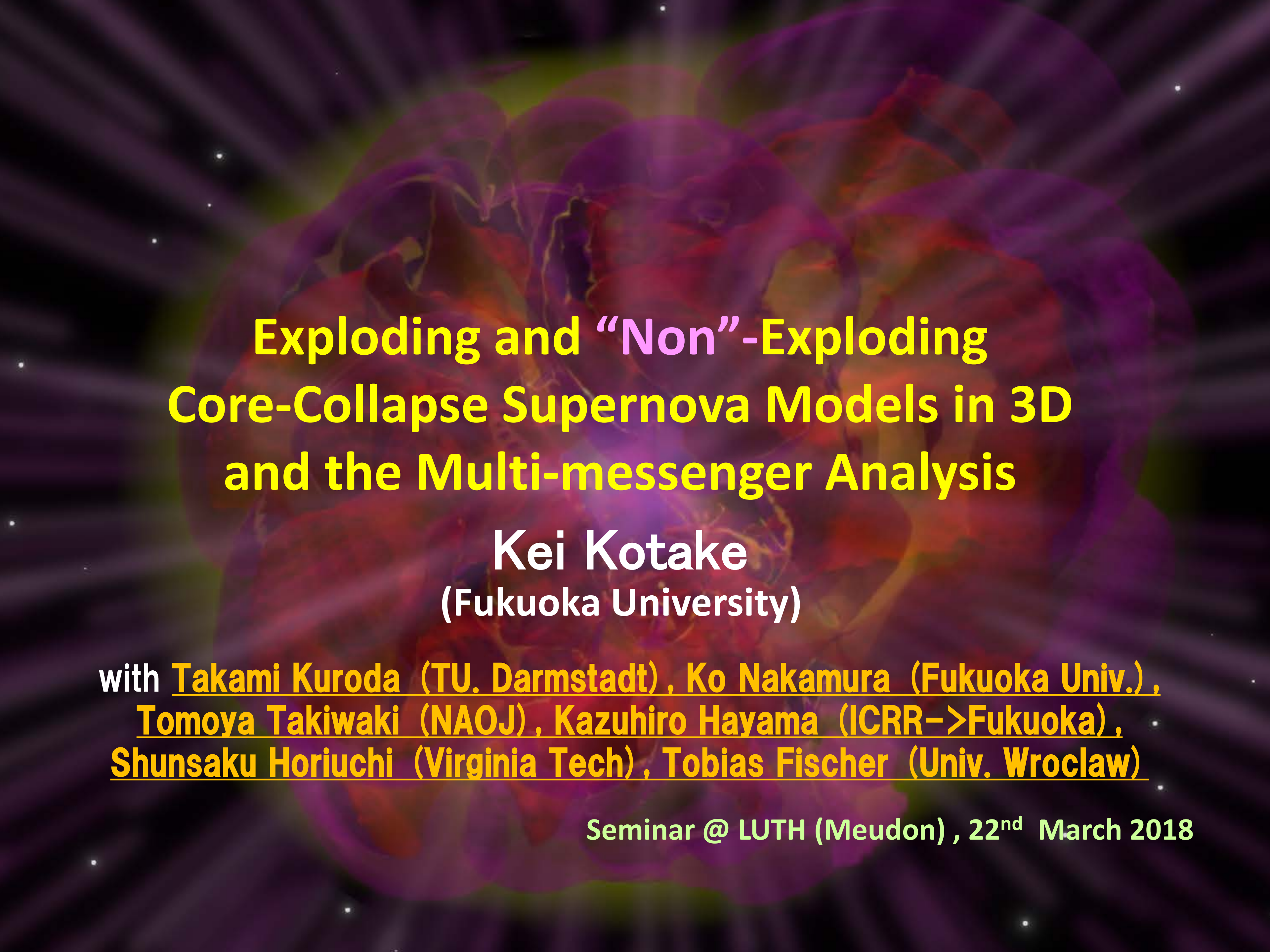

Exploding and "Non"-Exploding Core-Collapse Supernova Models in 3D and the Multi-messenger Analysis

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

Seminar @ LUTH (Meudon), 22nd March 2018

The supernova shock reaches to the stellar surface somehow… with its kinetic E of 10^{51} erg ($\equiv$1 Bethe) !

SN 1987A

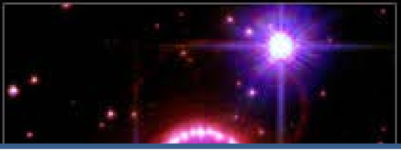
Progenitor:

$\sim 20M_{\rm sun}$

H. Bethe

Then, how do massive stars blow up ?!

Looking back ~30 years, significant progress made in GW oservation !



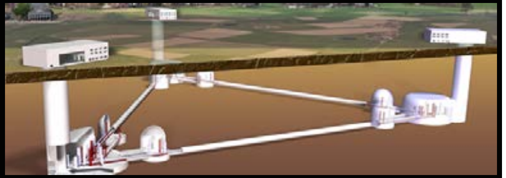
10^{-18}

Typical thresholds of proto-types in 1989

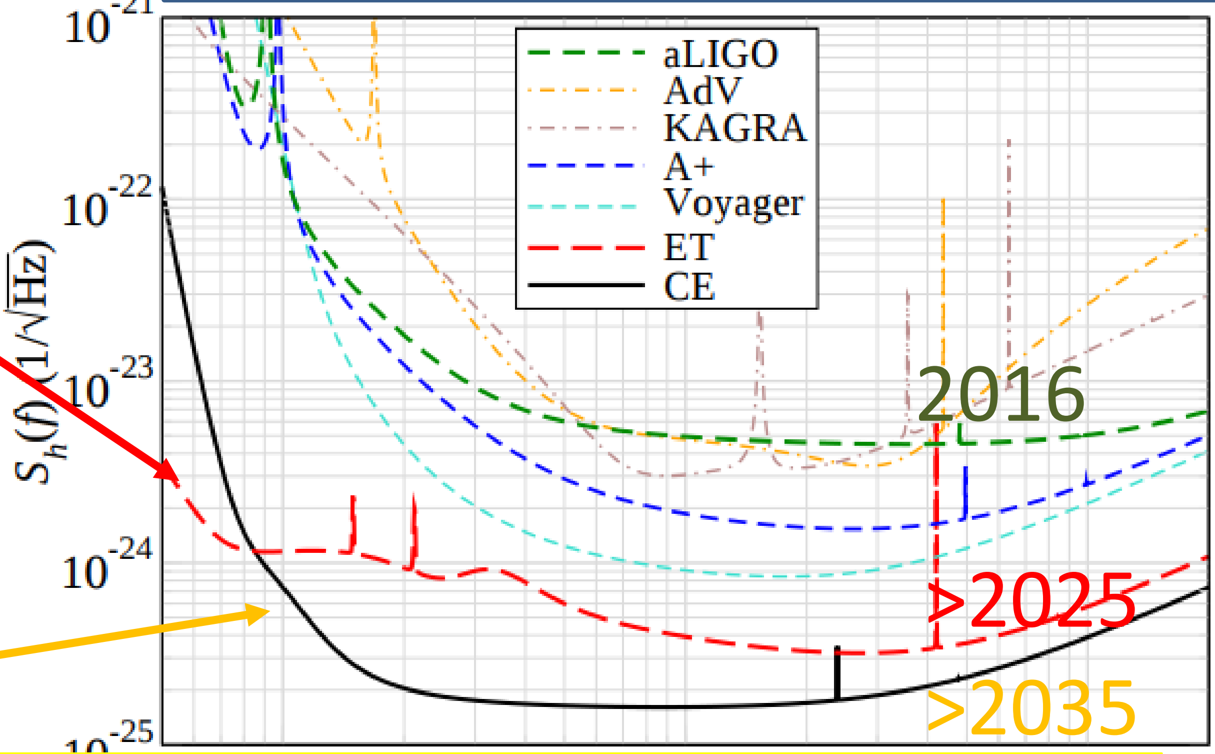
(MIT, Garching, Caltech, Glasgow and Tokyo)

Sensitivity curves of laser interferometers

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



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



2016

>2025

>2035

GW astronomy is no more a dream !

The base-line and final goal (s)

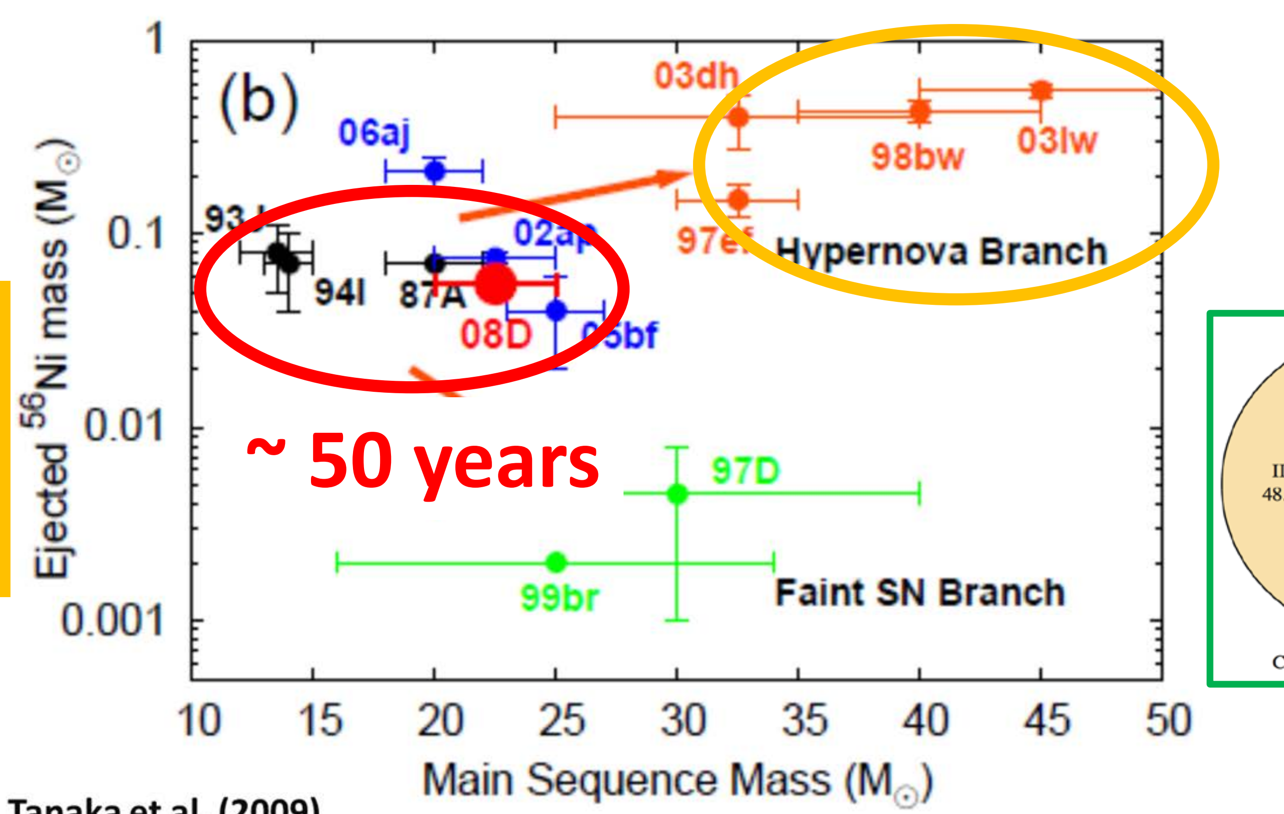
What is the physics for exploding massive stars?

~ 10FOE

~ 1 FOE

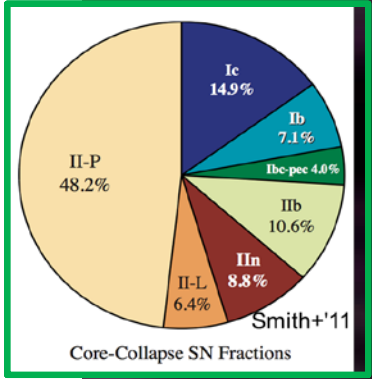
FOE: Fifty-one-erg
10^{51} erg
= 1 Bethe

Numerical study:
Colgate & White
(1966)



~ 50 years

Tanaka et al. (2009)



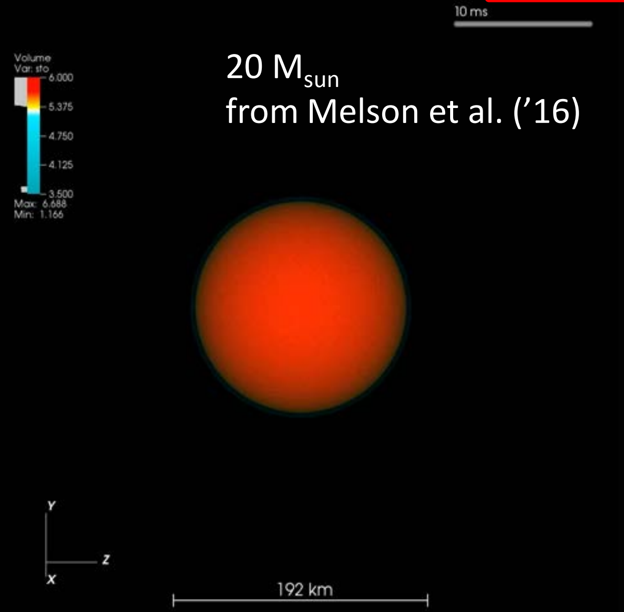
Core-Collapse SN Fractions

1). For which types of the progenitors (IIp, Ib/Ic, IIn) is rotation/B field most important ?
2). and 3). If important, why and how ?
4). Collapsar, Magnetar scenarios: Which one successful (or other) ? why ?
5). How long will it take before first-principles doable ? Strategies ?

Two candidates : **The key** is "initial rotation rate and B" of the iron core

(See reviews in Janka ('17), Mezzacappa et al. ('15), Foglizzo et al. ('15), Burrows ('13), Kotake et al. ('12))

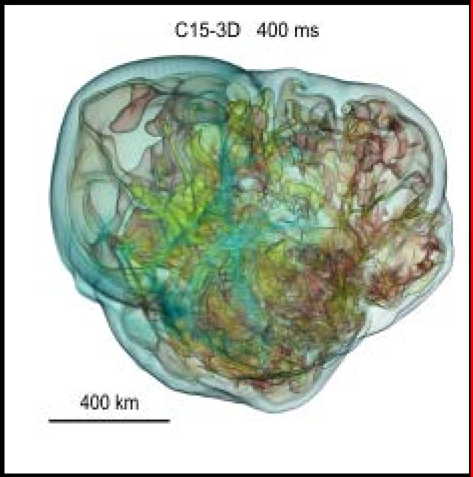
	Neutrino mechanism	**MHD mechanism**
Progenitor	Non- or slowing- rotating star $(\Omega_0 < \sim 0.1\ \mathrm{rad/s})$	Rapidly rotation with strong B $(\Omega_0 > \sim\pi\ \mathrm{rad/s}, B_0 > \sim 10^{11}\ \mathrm{G})$
Key ingredients	✓**Turbulent Convection and SASI** (e.g., Kazeroni, Guilet, Foglizzo, (2017)) ✓**Progenitor Inhomogenities** (e.g., B.Mueller, Melson, Heger, Janka, (2017)) ✓**Novel neutrino microphysics:** Bollig+(2017)	✓**Field winding and the MRI** (e.g., Obergaulinger & Aloy (2017), Rembiasz et al. (2016), Moesta et al. (2016), Masada + (2015)) ✓ **Non-Axisymmetric instabilities** (e.g., Takiwaki, et al. (2016), Summa et al. (2017))
Progenitor fraction	~99% : Main players	~1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)



20 M_{sun}
from Melson et al. ('16)

11.2 M_{sun} from
Nakamura et al. in prep.

15 M_{sun} star
from Lentz et al. ('15)



(see also, Burrows et al. ('17), Melson et al. ('15), Lentz et al. ('15), Roberts et al. ('16), B. Mueller ('15), Takiwaki et al. ('16))

First full-3D-GR simulations with multi-energy neutrino transport (M1)

Kuroda, KK, Takiwaki, Thielemann submitted MNRAS

(see also,GR models using the CoCoNuT code (CFC(+) by Cerda-Duran+2011, Obergaulinger and Aloy (2017): 2D by Dimmelmeier et al. (2007), B. Mueller (2015), B. Mueller et al. (2017):3D)

✓ "FUGRA" : FUlly General Relativistic code with multi-energy neutrino trAnsport

Kuroda, Takiwaki, and KK, ApJS. (2016)

The marriage of **BSSN formalism** (3D GR code, Kuroda & Umeda (2010, ApJS))

$$G = \{\tilde{\gamma}_{ij},\ \tilde{A}_{ij},\ \phi,\ K,\ \tilde{\Gamma}^i,\ \alpha,\ \beta^i\}$$

+ **M1 scheme**; Shibata+2011, Thorne 1981, (see also, Just et al. (2015), O'Connor (2015) for recent work)

✓ Evolution equation of neutrino radiation energy

$$\partial_t\sqrt{\gamma}E_{(\varepsilon)} + \partial_i\sqrt{\gamma}(\alpha F^i_{(\varepsilon)} - \beta^i E_{(\varepsilon)}) + \sqrt{\gamma}\alpha\partial_\varepsilon(\varepsilon\tilde{M}^\mu_{(\varepsilon)}n_\mu) = \sqrt{\gamma}(\alpha P^{ij}_{(\varepsilon)}K_{ij} - F^i_{(\varepsilon)}\partial_i\alpha - \alpha S^\mu_{(\varepsilon)}n_\mu),$$

✓ Evolution equation of radiation flux

$$\partial_t\sqrt{\gamma}F_{(\varepsilon)i} + \partial_j\sqrt{\gamma}(\alpha P_{(\varepsilon)}{}_i{}^j - \beta^j F_{(\varepsilon)i}) - \sqrt{\gamma}\alpha\partial_\varepsilon(\varepsilon\tilde{M}^\mu_{(\varepsilon)}\gamma_{i\mu}) = \sqrt{\gamma}[-E_{(\varepsilon)}\partial_i\alpha + F_{(\varepsilon)j}\partial_i\beta^j + (\alpha/2)P^{jk}_{(\varepsilon)}\partial_i\gamma_{jk} + \alpha S^\mu_{(\varepsilon)}\gamma_{i\mu}]$$

✓ Analytic Closure with the use of Minerbo-type Eddington factor **(Murchikova, Abdikamalov + (2017))**

$$P^{ij}_{(\varepsilon)} = \frac{3\chi_{(\varepsilon)} - 1}{2}P^{ij}_{\mathrm{thin}(\varepsilon)} + \frac{3(1-\chi_{(\varepsilon)})}{2}P^{ij}_{\mathrm{thick}(\varepsilon)}$$

$$\chi_{(\varepsilon)} = \frac{5 + 6\bar{F}^2_{(\varepsilon)} - 2\bar{F}^3_{(\varepsilon)} + 6\bar{F}^4_{(\varepsilon)}}{15}$$

Closed set of rad-hydro equations

$$\partial_t\rho_* + \partial_i(\rho_* v^i) = 0,$$

$$\partial_t\sqrt{\gamma}S_i + \partial_j\sqrt{\gamma}(S_i v^j + \alpha P\delta^j_i) = -\sqrt{\gamma}[S_0\partial_i\alpha - S_k\partial_i\beta^k - 2\alpha S^k_k\partial_i\phi + \alpha e^{-4\phi}(S_{jk} - P\gamma_{jk})\partial_i\tilde{\gamma}^{jk}/2 + \alpha\int d\varepsilon S^\mu_{(\varepsilon)}\gamma_{i\mu}],$$

$$\partial_t\sqrt{\gamma}\tau + \partial_i\sqrt{\gamma}(\tau v^i + P(v^i + \beta^i)) = \sqrt{\gamma}[\alpha K S^k_k/3 + \alpha e^{-4\phi}(S_{ij} - P\gamma_{ij})\tilde{A}^{ij} - S_i D^i\alpha + \alpha\int d\varepsilon S^\mu_{(\varepsilon)}n_\mu],$$

$$\partial_t(\rho_* Y_e) + \partial_i(\rho_* Y_e v^i) = \sqrt{\gamma}\alpha m_u\int\frac{d\varepsilon}{\varepsilon}(S^\mu_{(\nu_e,\varepsilon)} - S^\mu_{(\bar{\nu}_e,\varepsilon)})u_\mu$$

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

Process	Reference
$n\nu_e \leftrightarrow e^- p$	Bruenn (1985), Rampp & Janka (2002)
$p\bar{\nu}_e \leftrightarrow e^+ n$	Bruenn (1985), Rampp & Janka (2002)
$\nu_e A \leftrightarrow e^- A'$	Bruenn (1985), Rampp & Janka (2002)
$\nu p \leftrightarrow \nu p$	Bruenn (1985), Rampp & Janka (2002)
$\nu n \leftrightarrow \nu n$	Bruenn (1985), Rampp & Janka (2002)
$\nu A \leftrightarrow \nu A$	Bruenn (1985), Rampp & Janka (2002)
$\nu e^\pm \leftrightarrow \nu e^\pm$	Bruenn (1985)
$e^- e^+ \leftrightarrow \nu\bar{\nu}$	Bruenn (1985)
$NN \leftrightarrow \nu\bar{\nu}NN$	Hannestad & Raffelt (1998)

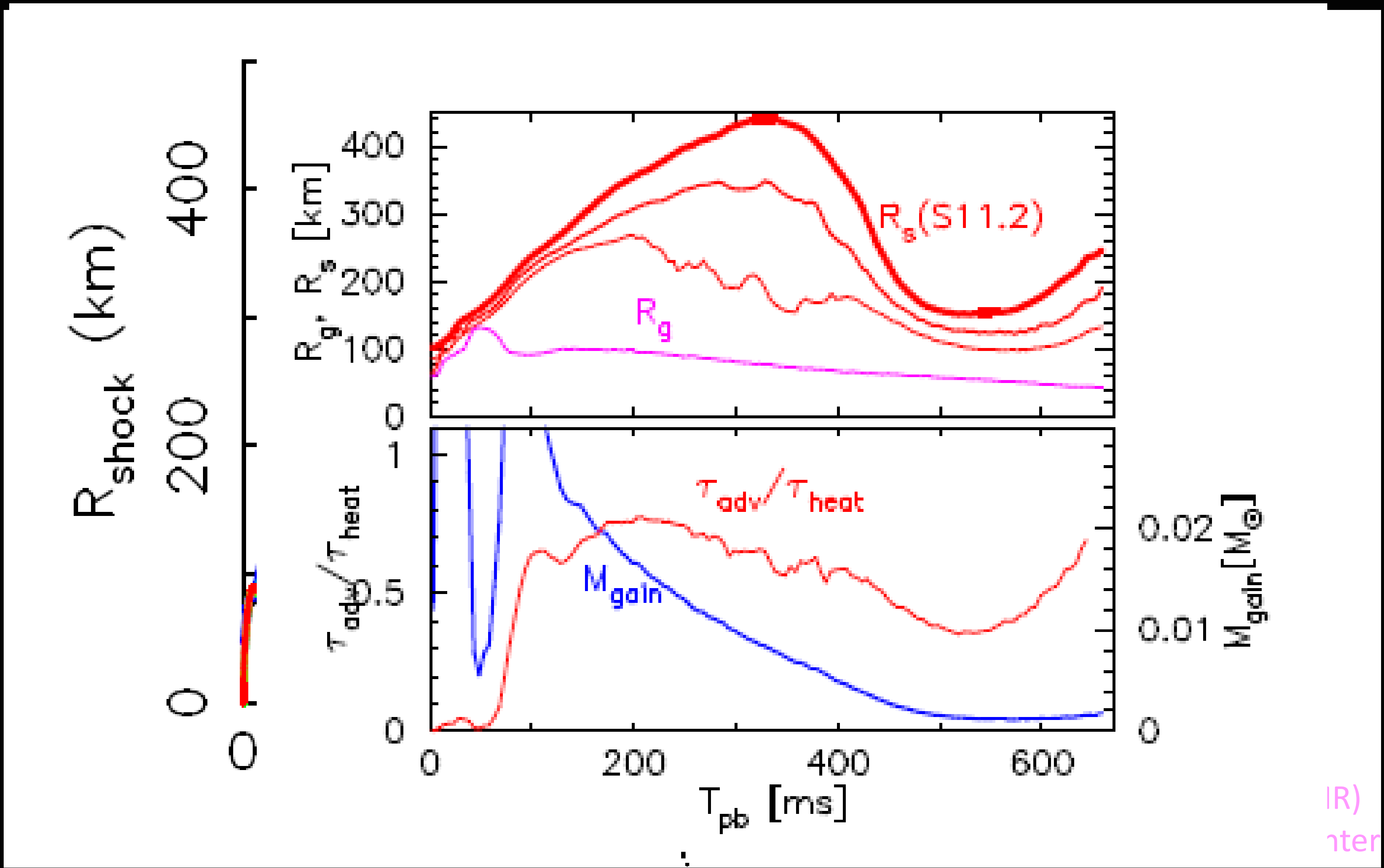
✓3 flavor neutrino transport

✓Base-line opacity

(t.b.updated)

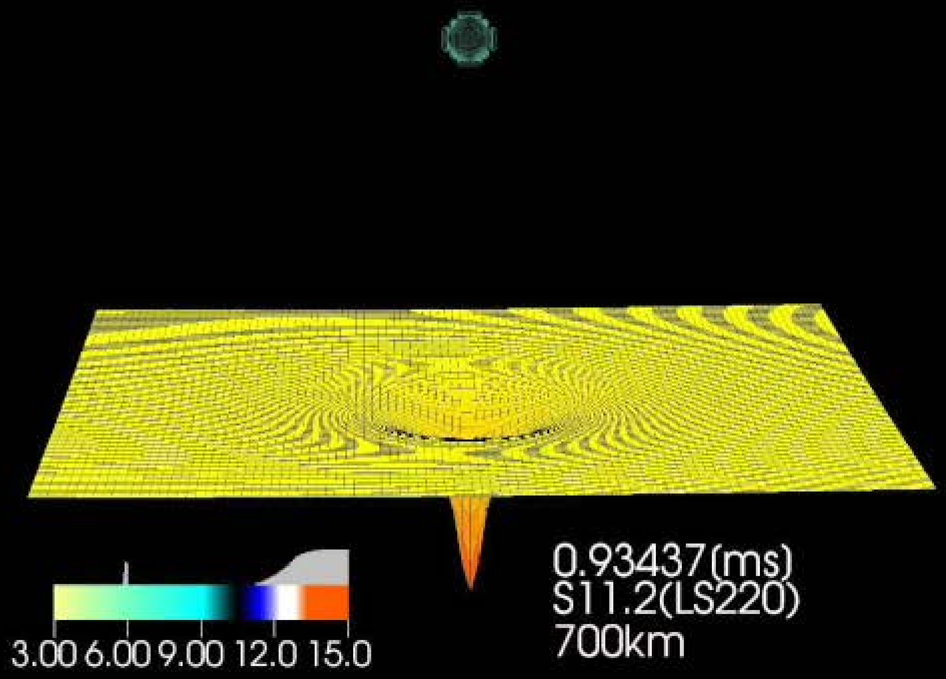
Preliminary FUGRA results for 4 progenitors: Kuroda, KK, Takiwaki, Thielemann submitted

- ✓ Three Solar-metallicity stars of 11.2 and 40 M_{sun} from Woosley+(2002) and 15 M_{sun} of WW95, One Zero-metal 70 M_{sun} star of Takahashi, Umeda, et al. (2014, ApJ)

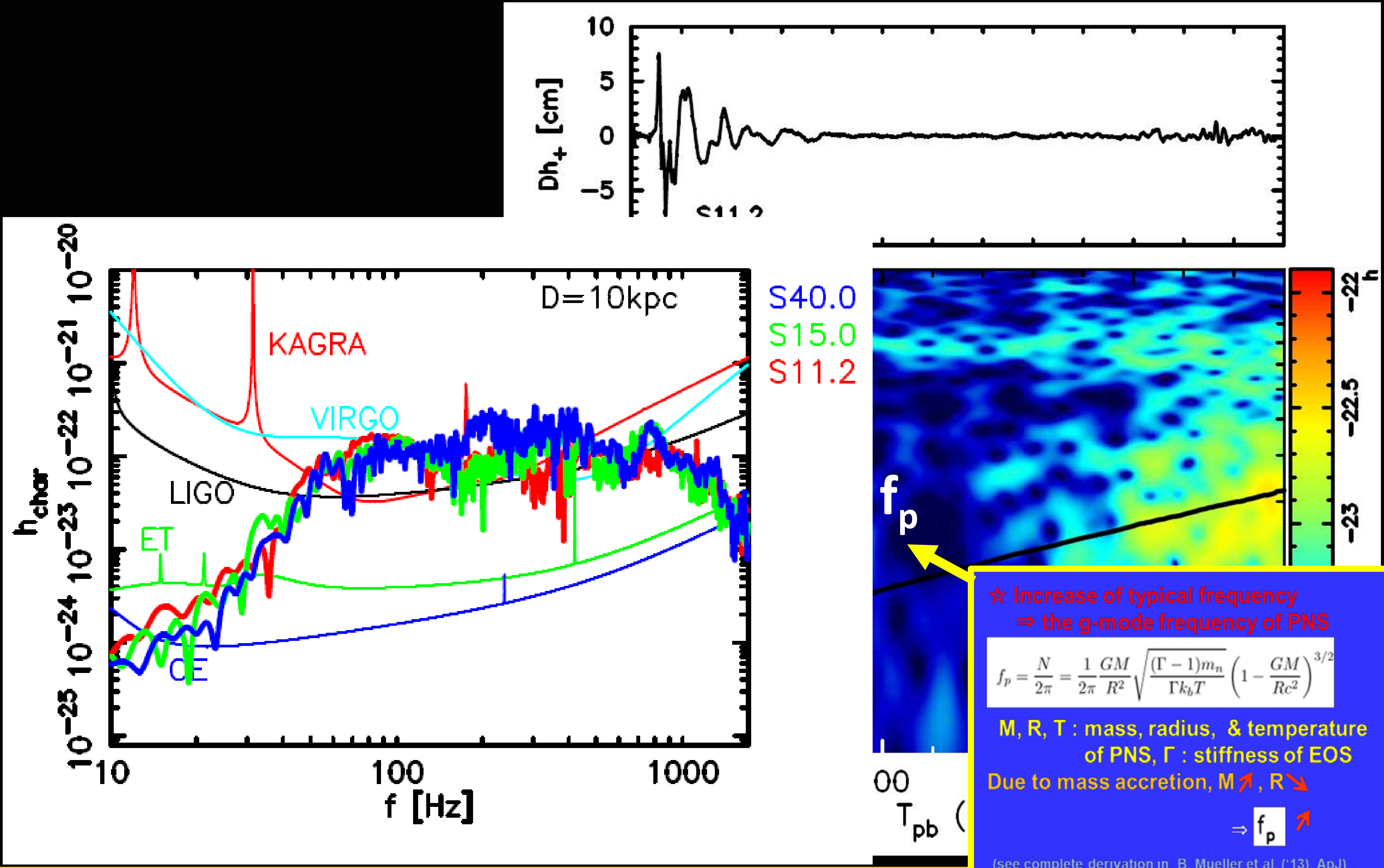


✓FUGRA results of 11.2 M_{sun} star (Woosley et al. (2002))

Kuroda+ in prep



✓FUGRA results of 11.2 M_{sun} star (Woosley et al. (2002))



☆ Increase of typical frequency
⇒ the g-mode frequency of PNS

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

M, R, T : mass, radius, & temperature of PNS, Γ : stiffness of EOS

Due to mass accretion, M↗, R↘

⇒ $\boxed{f_p}$ ↗

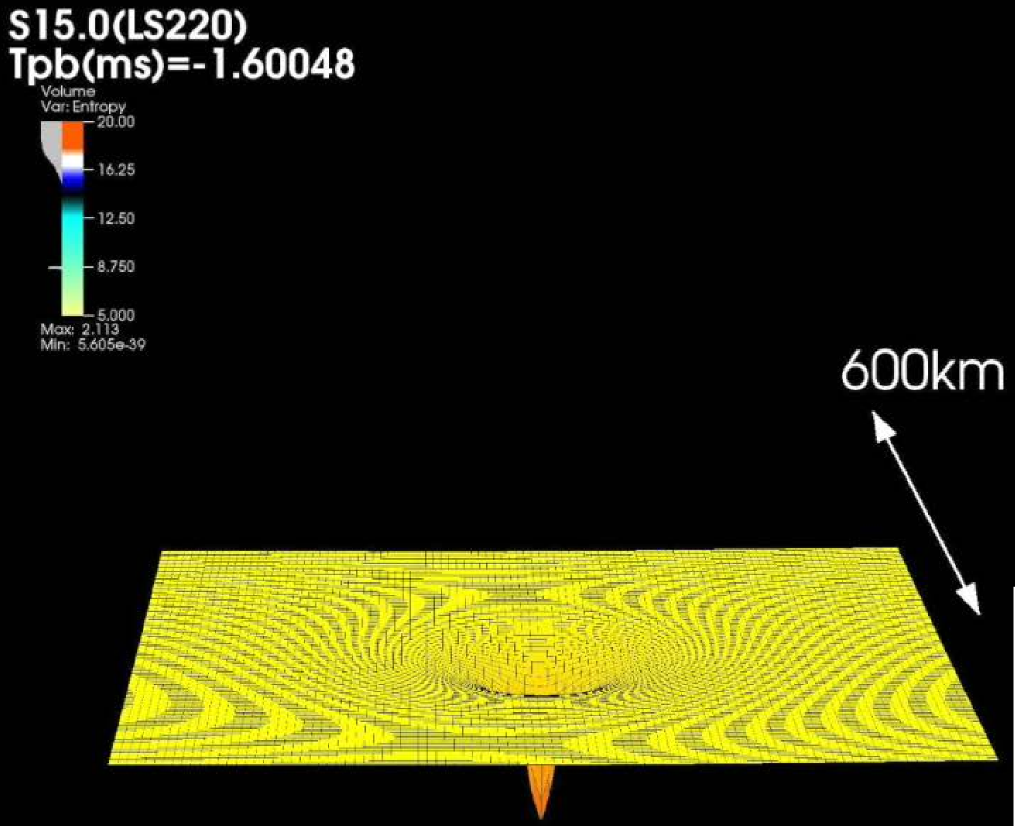
(see complete derivation in B. Mueller et al. ('13), ApJ)

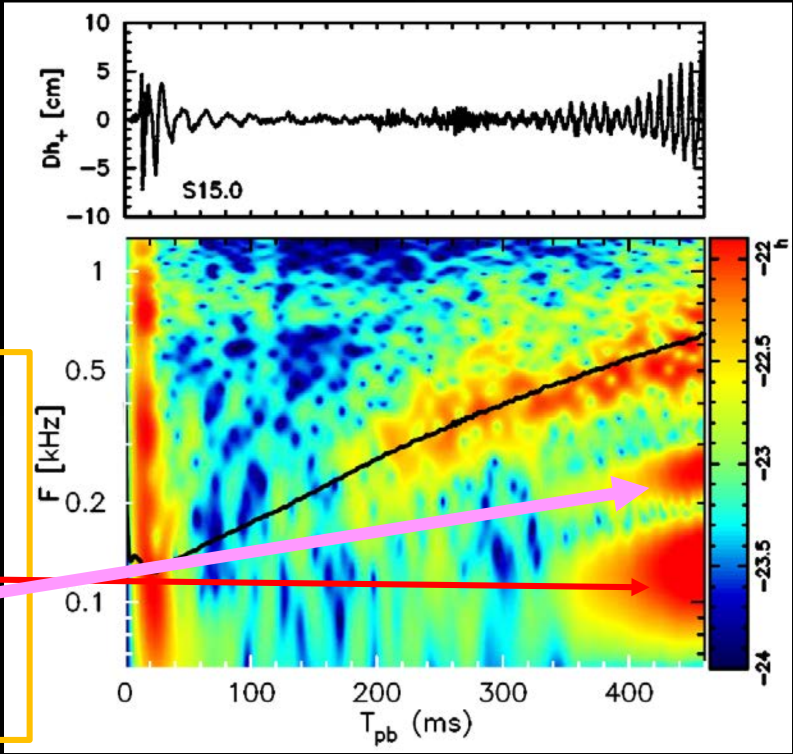
✓ 11.2 M_{sun} star is likely to explode very weakly ! (long-term simulation is needed …)

✓ Weak GW/neutrino emission due to short explosion timescale.

✓ FUGRA results of 15 M_{sun} star (progenitor from Woosley & Weaver 1995)

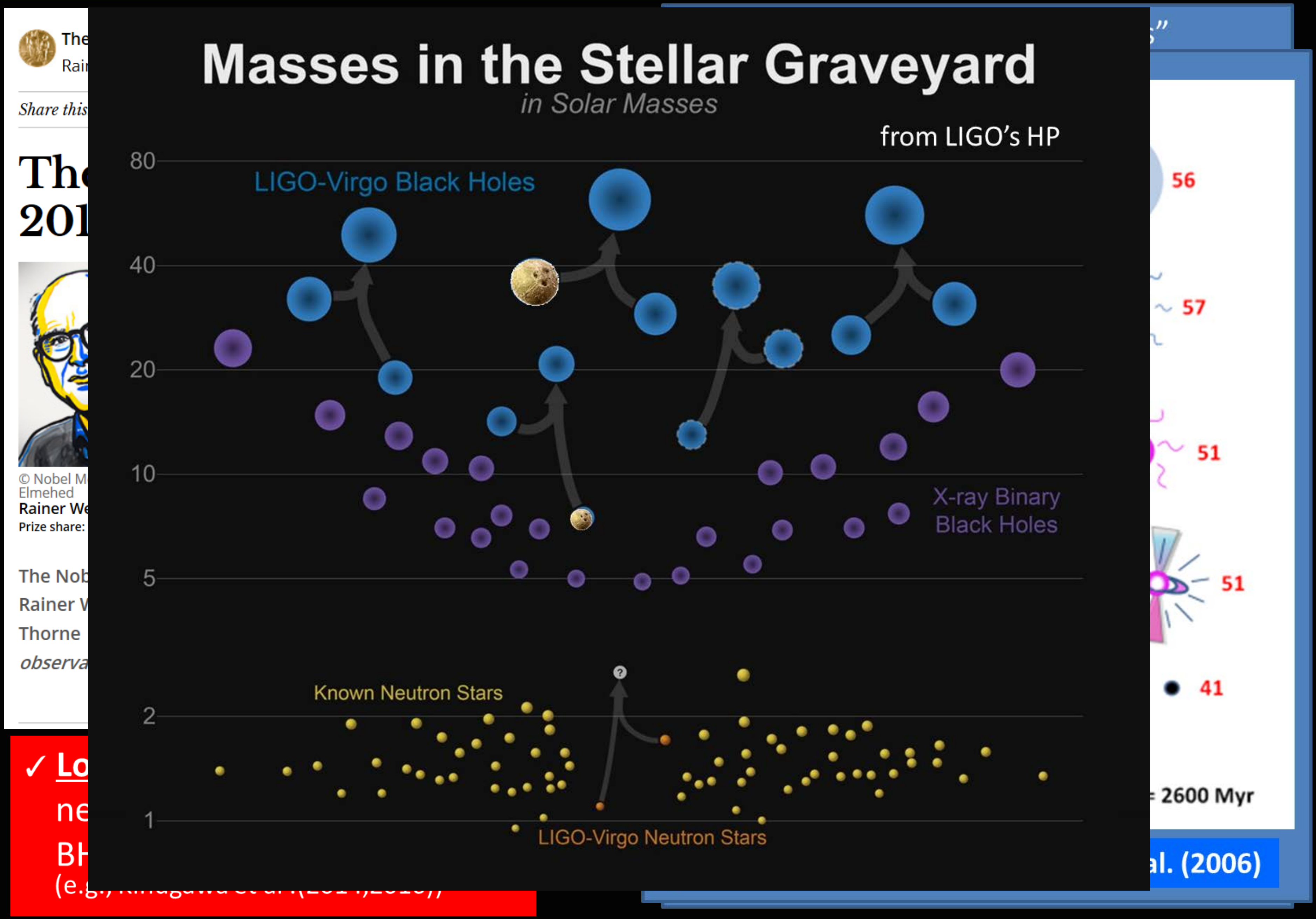
Kuroda+ in prep





- ✓ The 15 M_{sun} star unexplodes bef. 450 ms pb. (e.g., Marek & Janka (2009)).
- ✓ After 400 ms after bounce, a weak SASI activity observed.
- ✓ ⇒ **Low-frequency (100Hz) excess in the GW spectrogram** as in Kuroda,KK et al.(2016) using SFHx EOS + gray transport. (see Andresen et al. (2017)).
- ✓ **Daughter mode (overtone)** of the PNS core-oscillation !

The Origin of the Nobel-Prize-winning BHs (7 ~40 M_{sun}) ?



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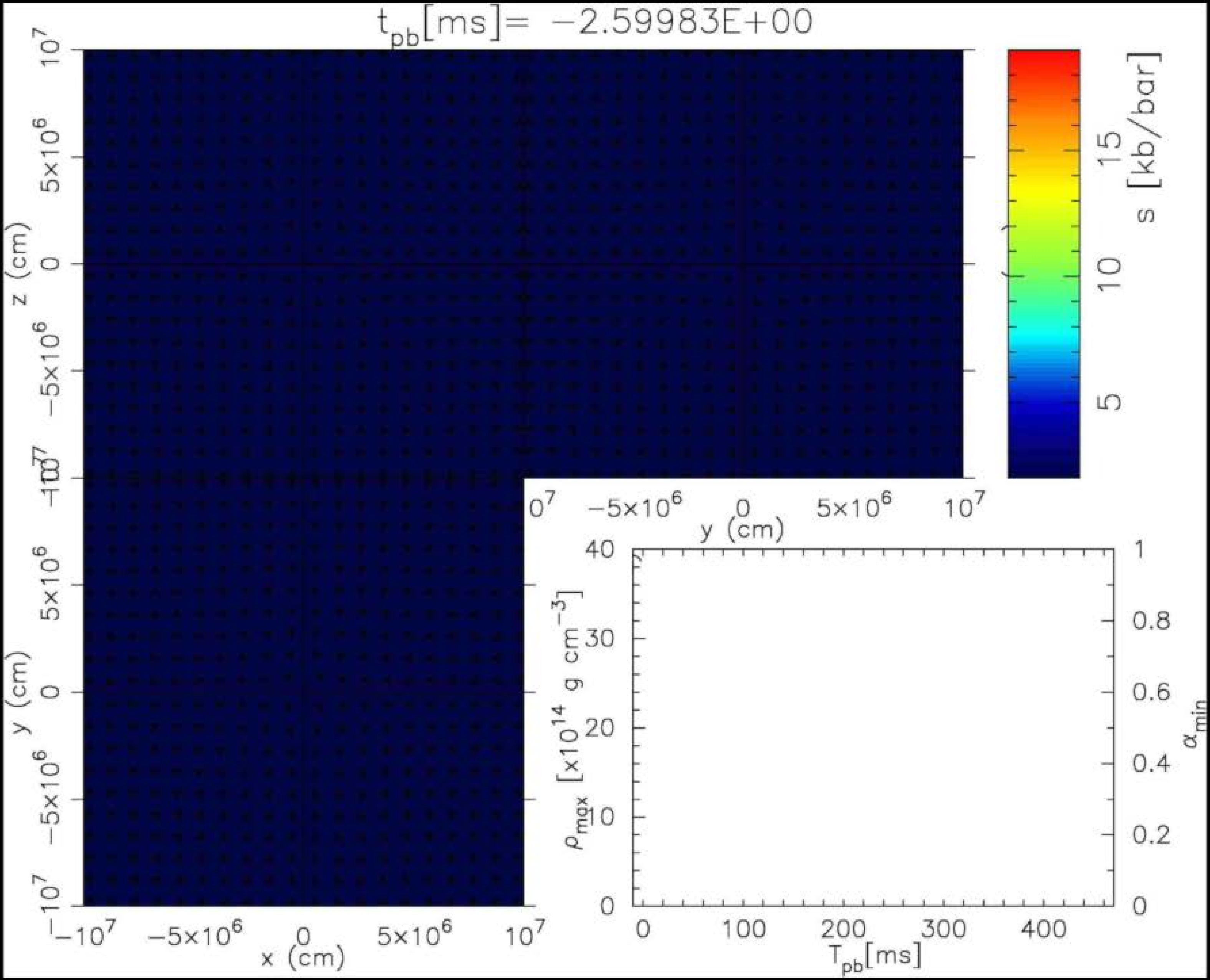
✓ **Lo**
ne
BH
(e.g.) Kinugawa et al.(2014,2016))

al. (2006)

✓FUGRA results of 70 M_{sun} (M_{CO} ~ 28.5 M_{sun}) (progenitor from Takahashi et al. (2014))



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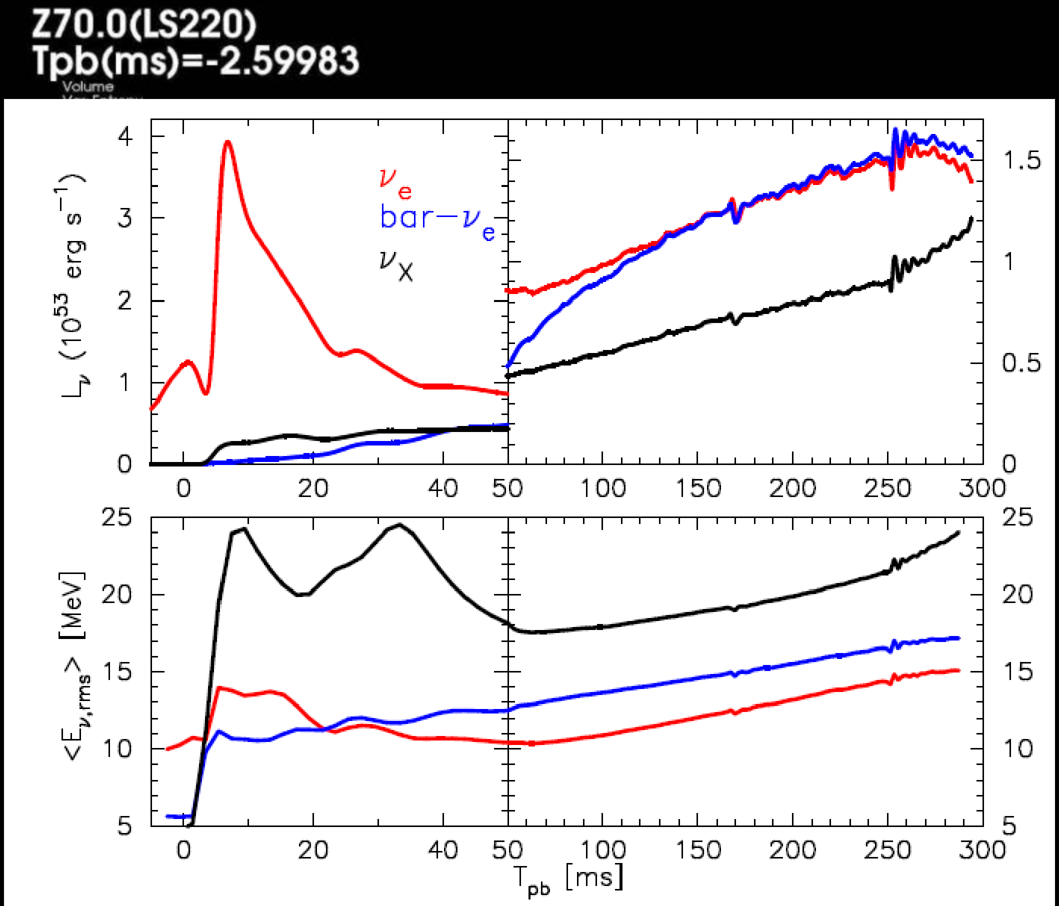
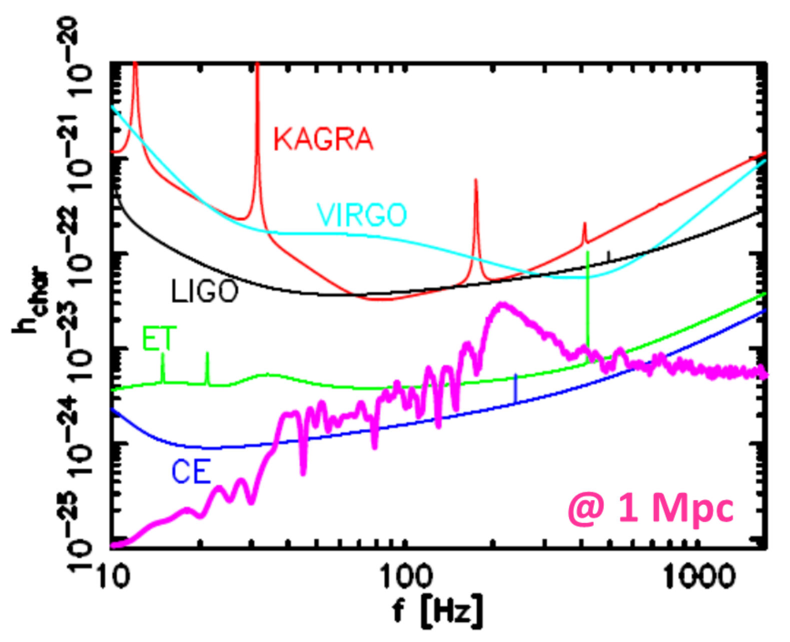


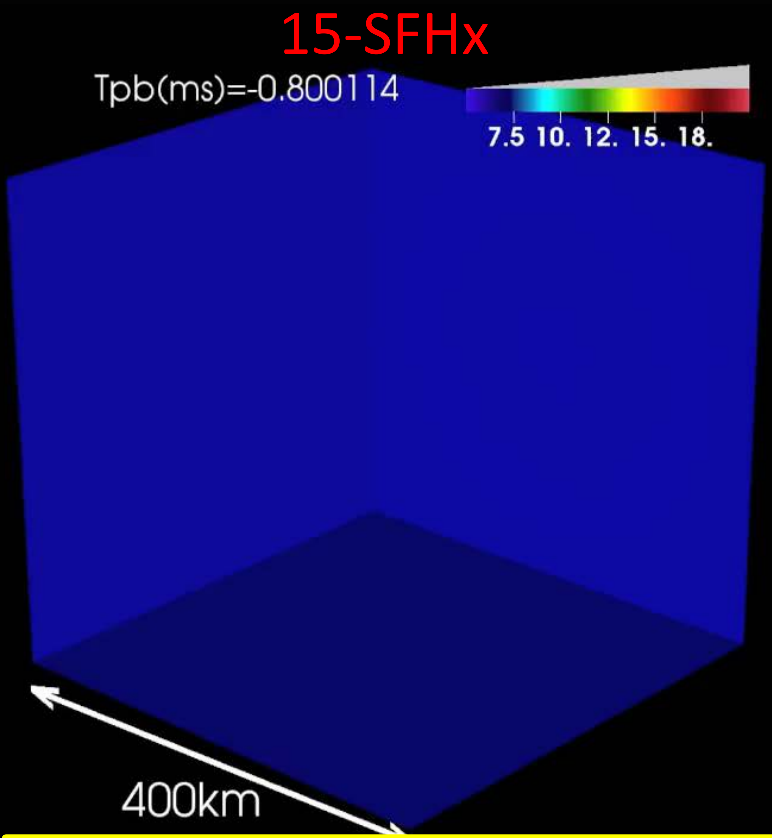


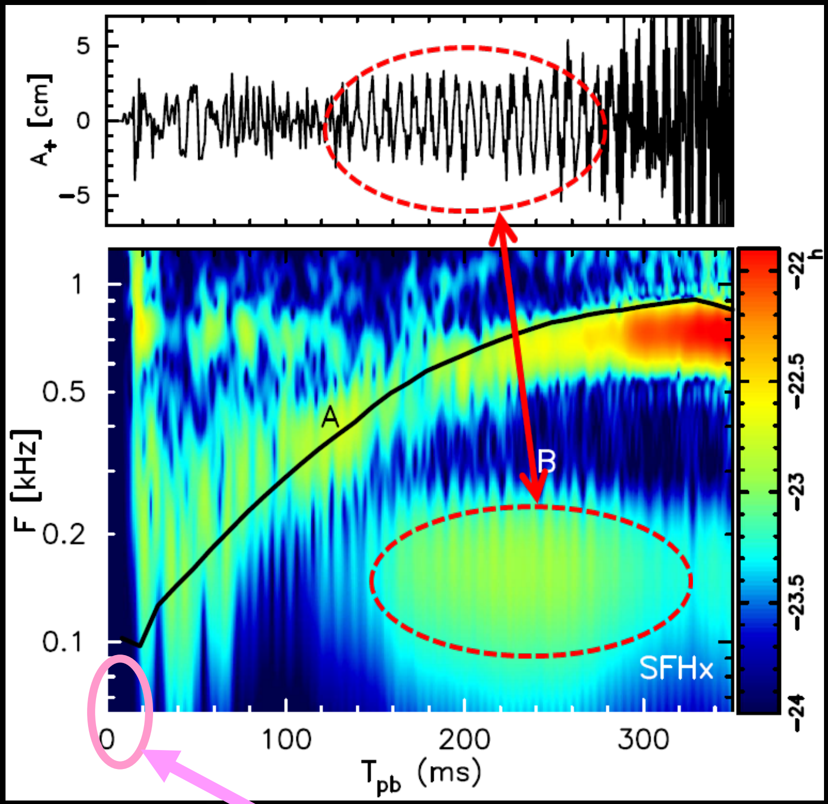
- ✓ **Earliest BH formation** after bounce (～300 ms postbouce) ！
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.
  (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Fischer+ (2009), Huedepohl+(2016))
- ✓ Strong GW emission is visible to 1 Mpc, **but not** O(100) Mpc…
- ✓ Our code needs upgrade to follow long after BH formation…

FUGRA-gray results of 15 M_{sun} star (WW95) using SFHx EOS ⇒ strong SASI activity

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

✓ **SFHx EOS**(Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011))





- ✓ **The quasi-periodic modulation is associated with SASI, clearly visible with softer EOS.**
- ✓ By **coherent network analysis** of LIGO, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc, but could miss every Galactic events 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. (2013,2014), Kuroda, KK et al. (2017, submitted)).

“New” GW messenger is Circular Polarization of GW) :Non-axisymmetric instabilities

Stokes Parameters:

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

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

V parameter =
Asymmetry of right and left modes

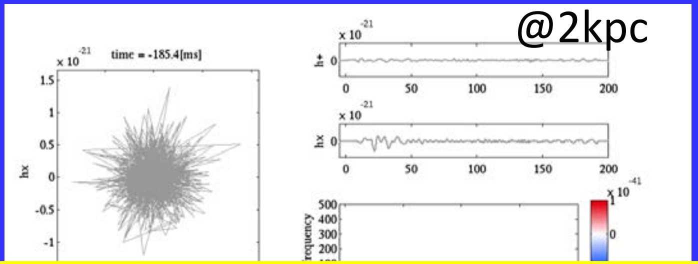
$$h_R := (h_+ - ih_\times)/\sqrt{2}$$

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

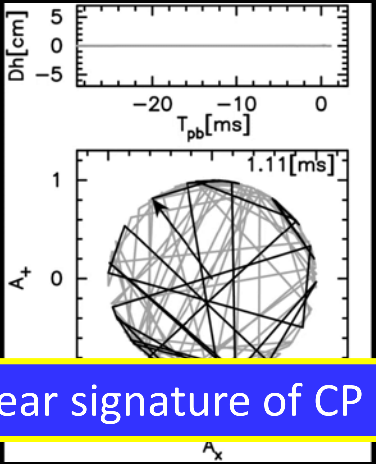
(See definitions in Seto and Taruya (2007), PRL)

Non-rotating 11.2 M_{sun} (gray) ; Convection dominant

@2kpc



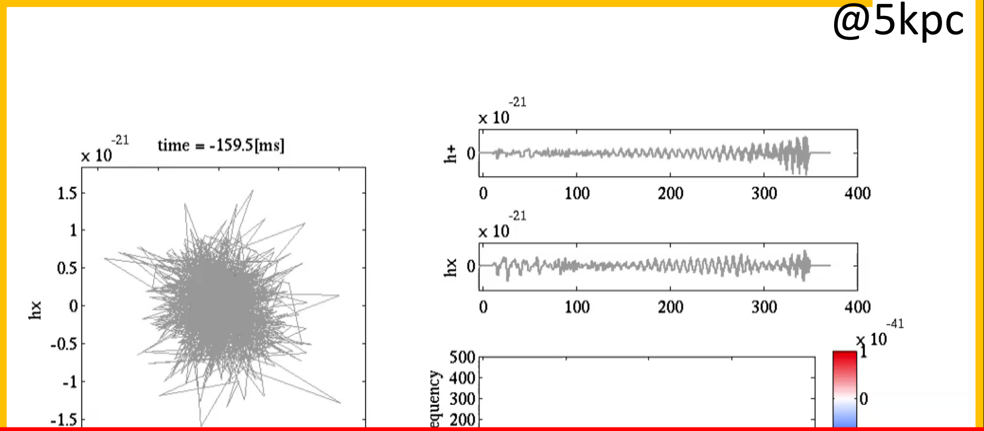
Normalized polarization (e.g.,
$$\frac{x}{\sqrt{x^2+y^2}},$$
$x = h_+, h_x$)

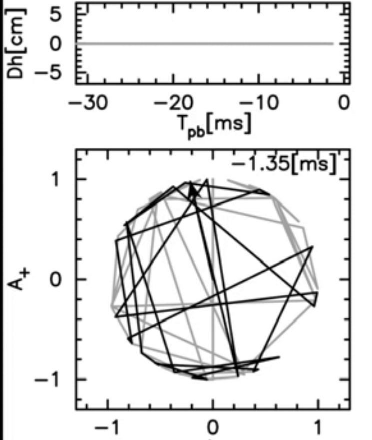


If the core is convection-dominant (likely for low ξ stars), no clear signature of CP !

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

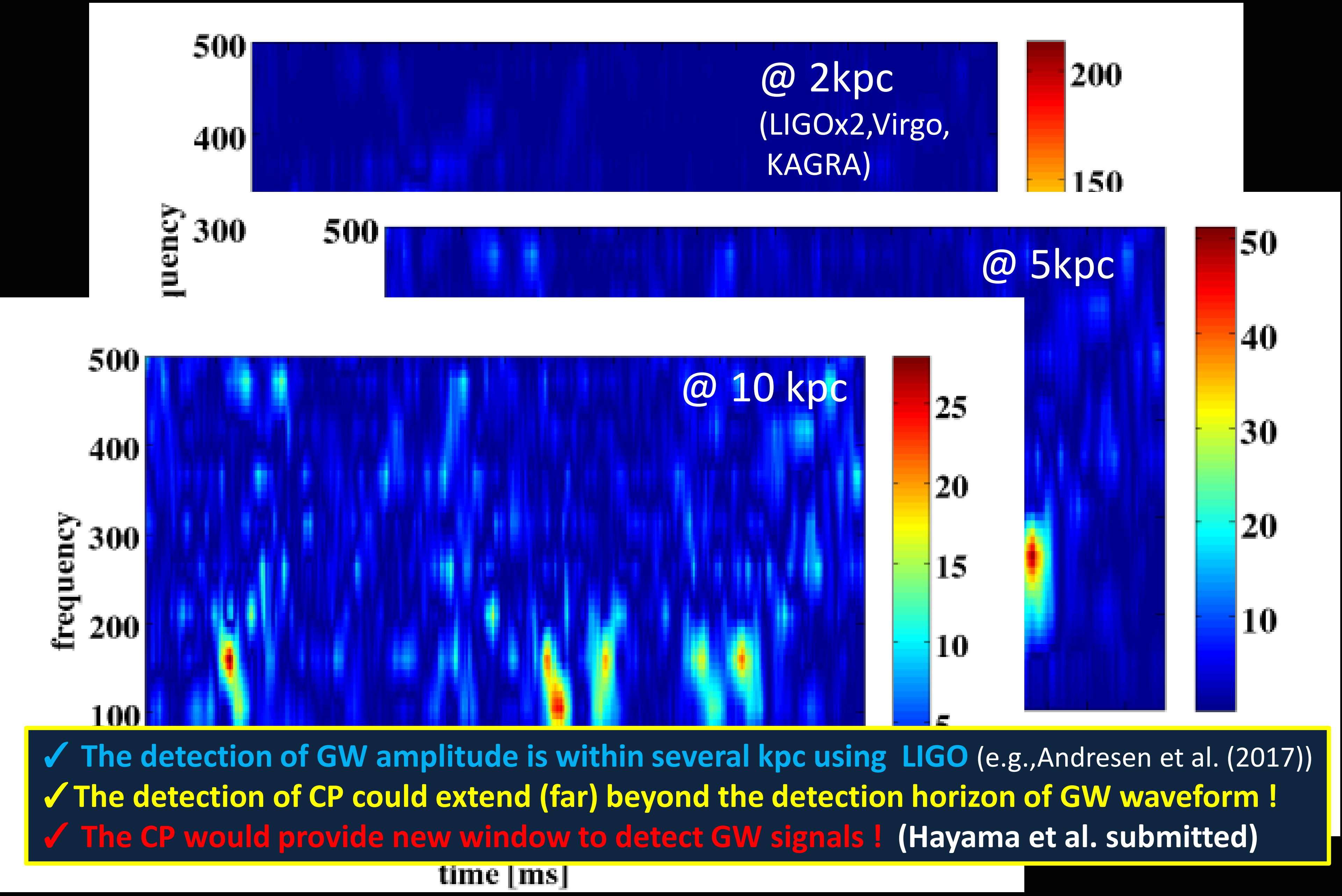
@5kpc





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



@ 2kpc
(LIGOx2,Virgo,
KAGRA)

@ 5kpc

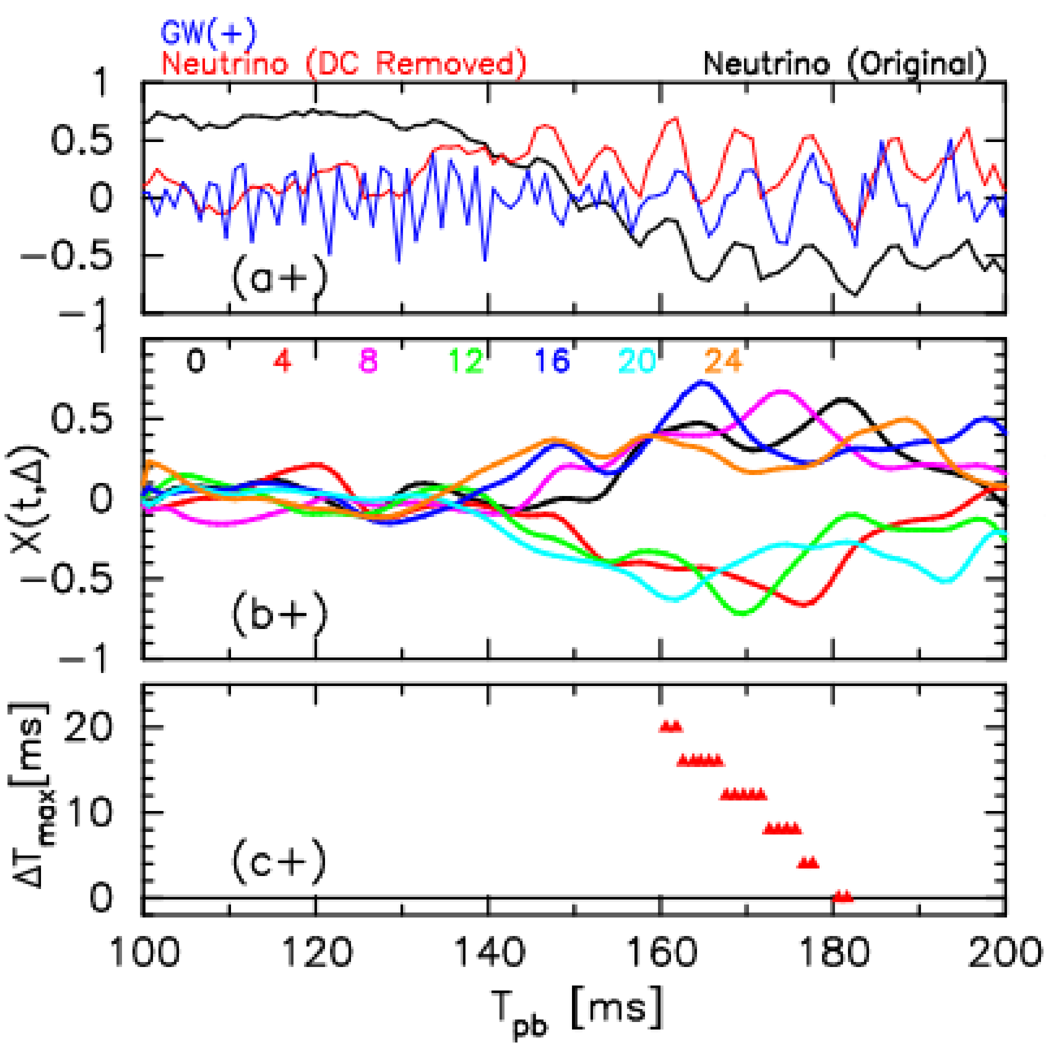
@ 10 kpc

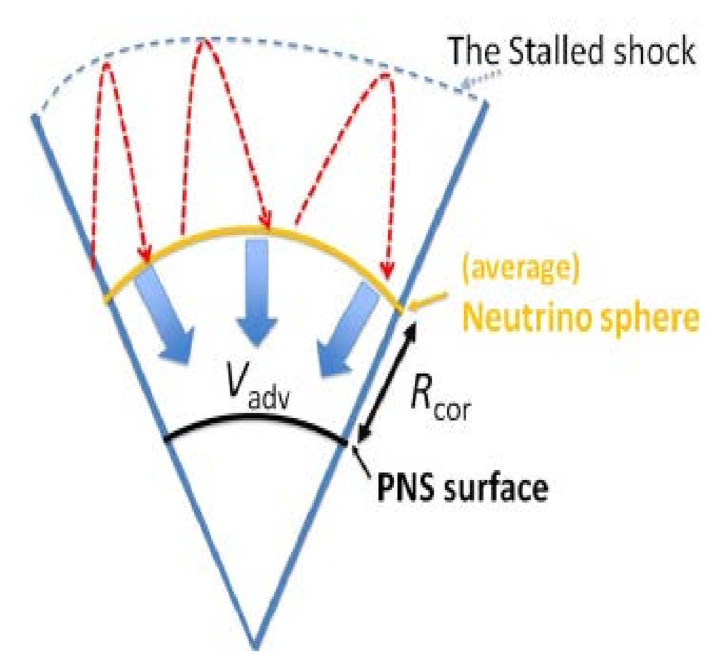
- ✓ The detection of GW amplitude is within several kpc using LIGO (e.g.,Andresen et al. (2017))
- ✓ The detection of CP could extend (far) beyond the detection horizon of GW waveform !
- ✓ The CP would provide new window to detect GW signals ! **(Hayama et al. submitted)**

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 (2017, ApJ)



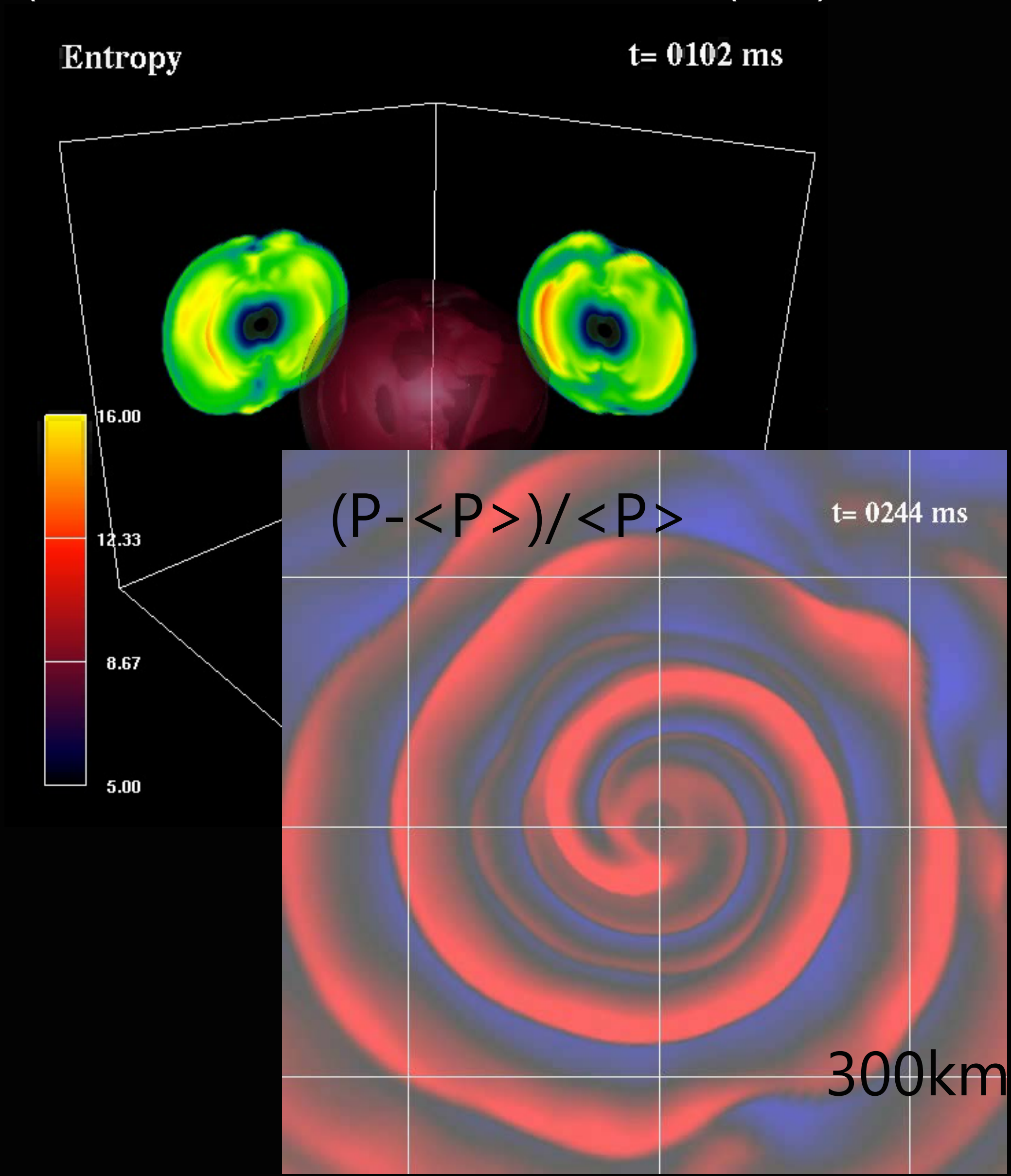


$$\Delta T_{max} \sim R_{cor} / V_{adv}$$
$$\sim O(10)\ \mathrm{km}/(10^{7\sim8}\ \mathrm{cm/s})$$
$$\sim O(10)\ \mathrm{ms}$$

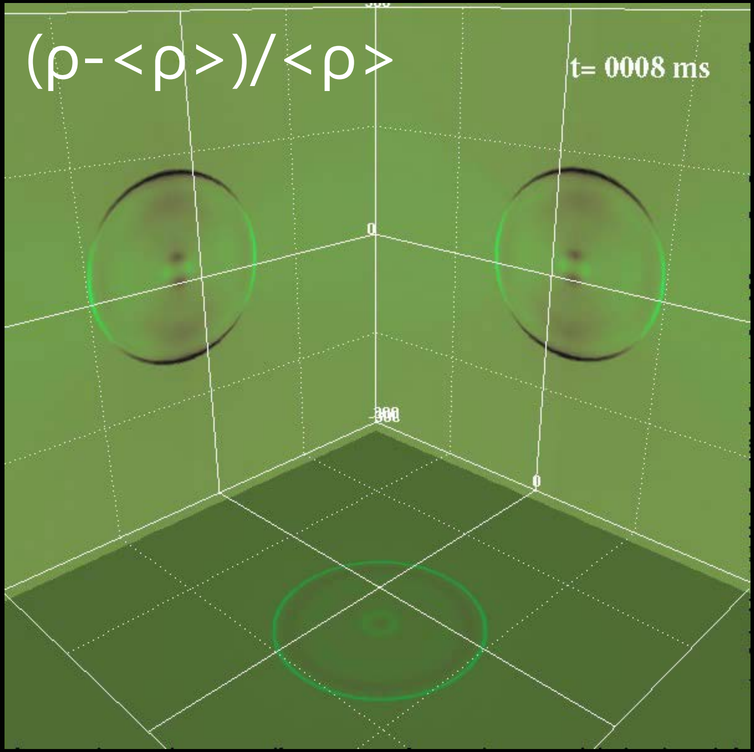
✓ The simultaneous detection potentially tells the distance between the neutrino sphere and PNS radius ! (Need to follow long-term 3D evolution how long this continues..)

Switching gears to MHD mechanism (rapid rotation required !!)

3D rotating explosion simulation of a 27 M_{sun} star (Ω_0 = 2 rad/s) with IDSA.
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016), see also Summa et al. (2017)).



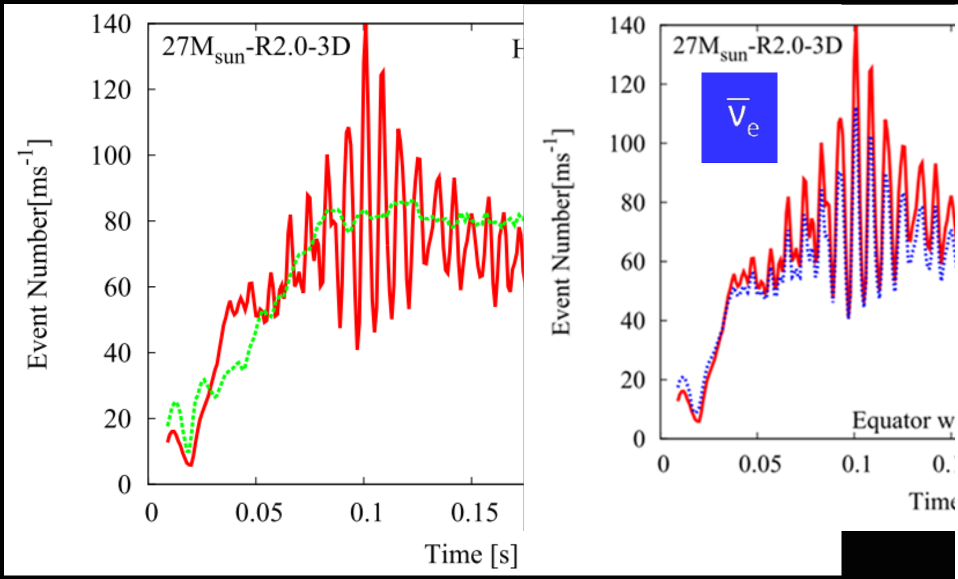
- ✓ Spiral waves enhance energy transport from PNS to gain region !

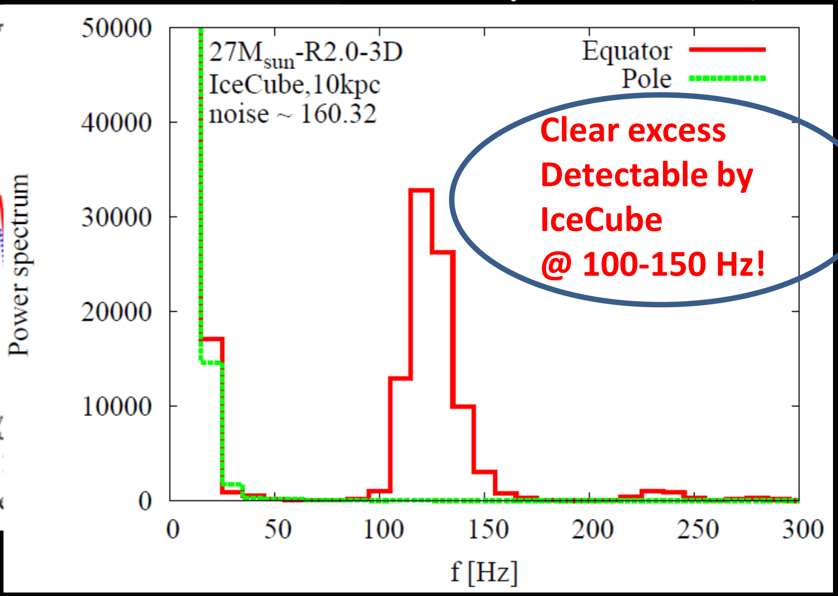


Neutrino signatures from rapidly rotating explosion of 27 M_{sun} star

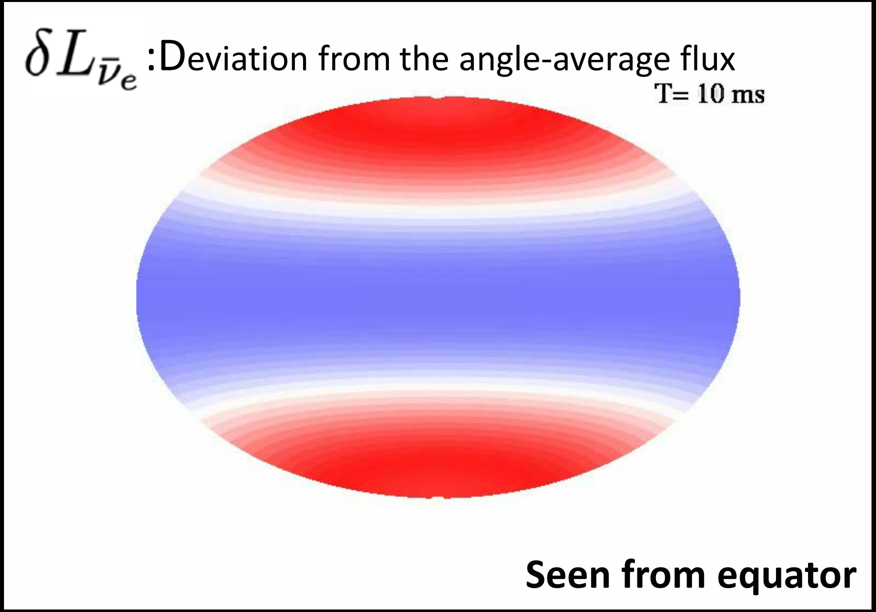
Takiwaki and KK
(MNRAS Letters, 2018)

Quasi-periodic variation ! May survive with coll. oscillation





Clear excess Detectable by IceCube @ 100-150 Hz!

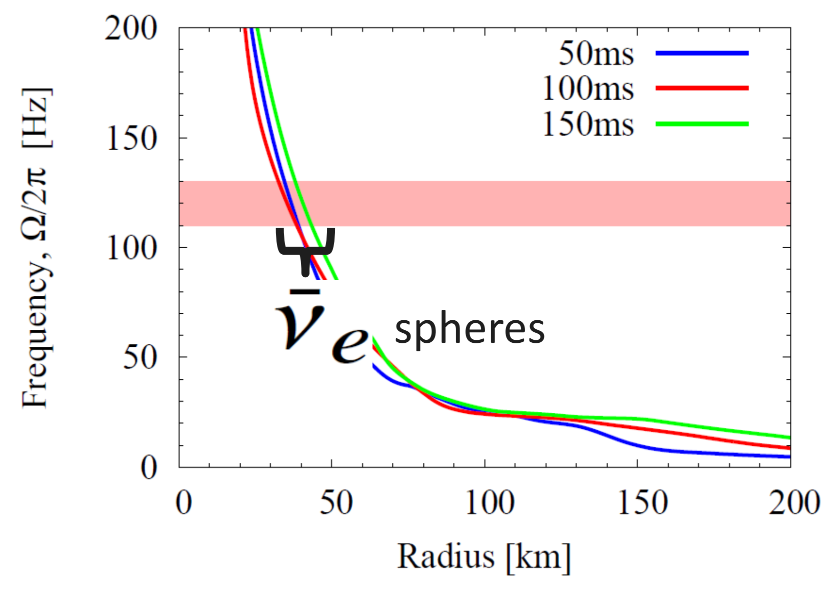


$\delta L_{\bar{\nu}_e}$:Deviation from the angle-average flux

T= 10 ms

Seen from equator

"Lighthouse effect"

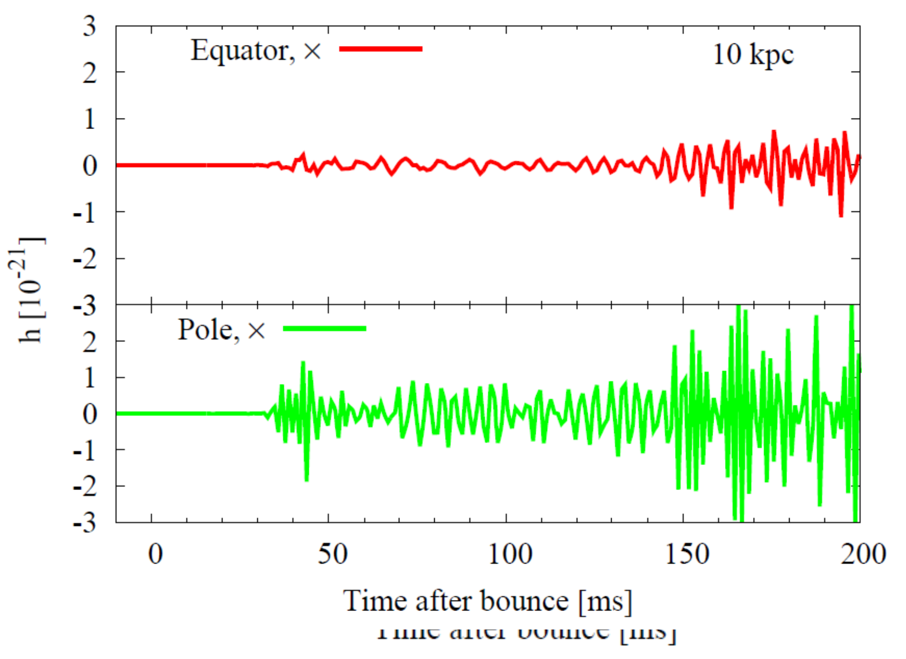


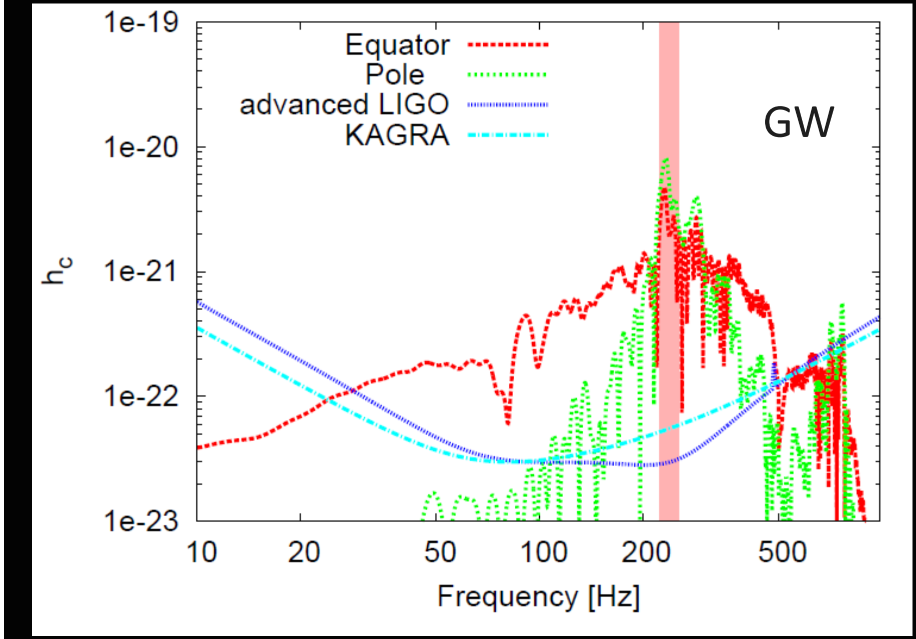
$\bar{\nu}_e$ spheres

Correlation of GW and neutrino signatures from the 3D rotating model,

Gravitational waveform (27 M_{sun}, Ω_0 = 2rad/s)

Takiwaki and KK (MNRAS Letters, 2018)

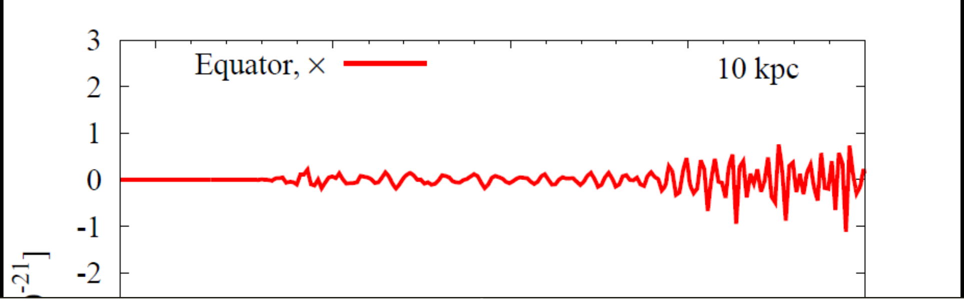


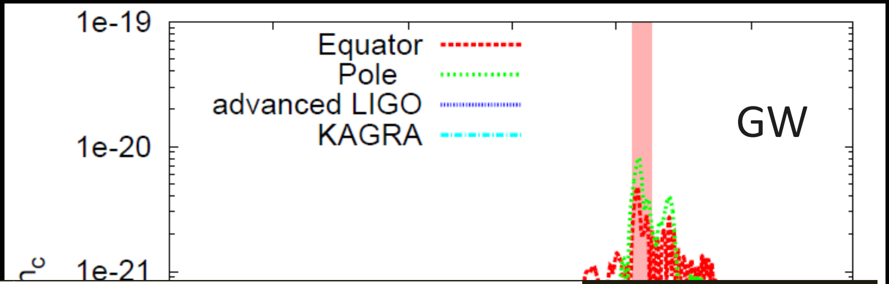


Correlation of GW and neutrino signatures from the 3D rotating model,

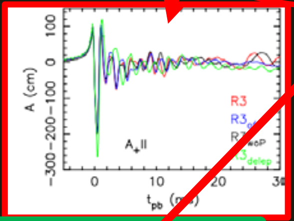
Gravitational waveform (27 M_{sun}, Ω_0 = 2rad/s)

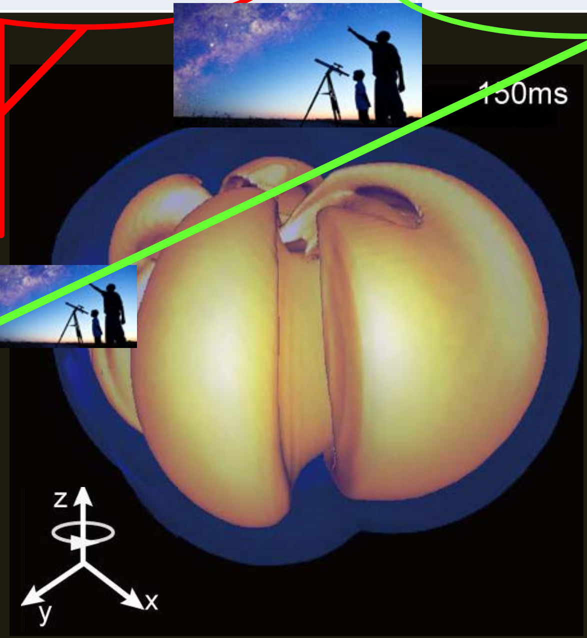
Takiwaki and KK (MNRAS Letters, 2018)

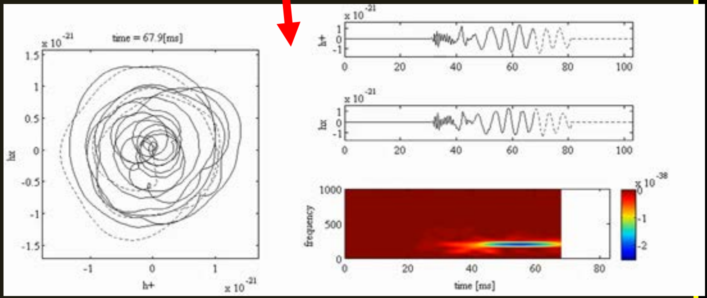


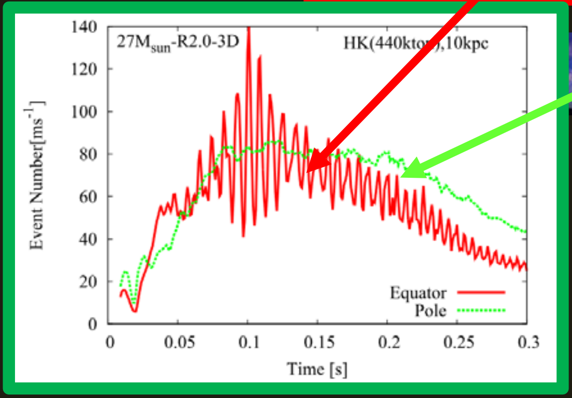


Directionality	Equator	Pole
Gravitational Wave	Type I signal	✓Quasi-periodic signals from non-axis. instability ✓Circular polarization
Neutrinos	Light-house effect	No surprise …









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

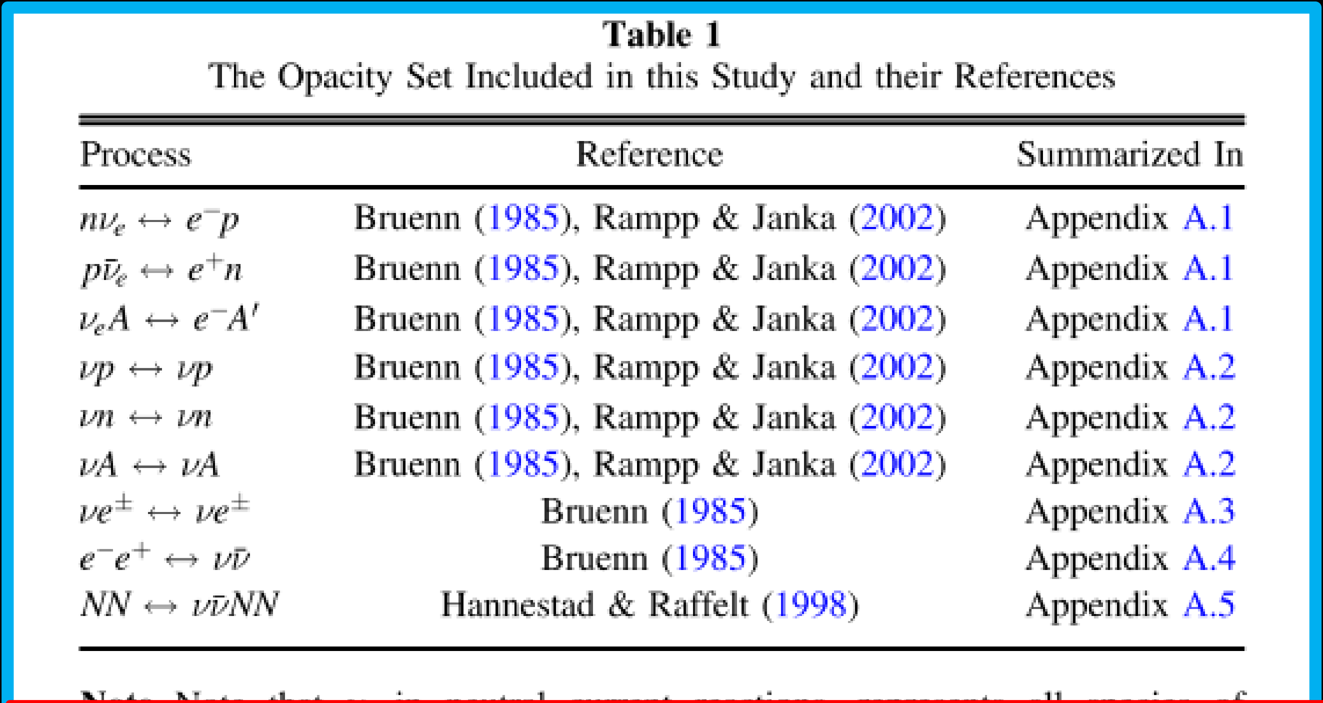


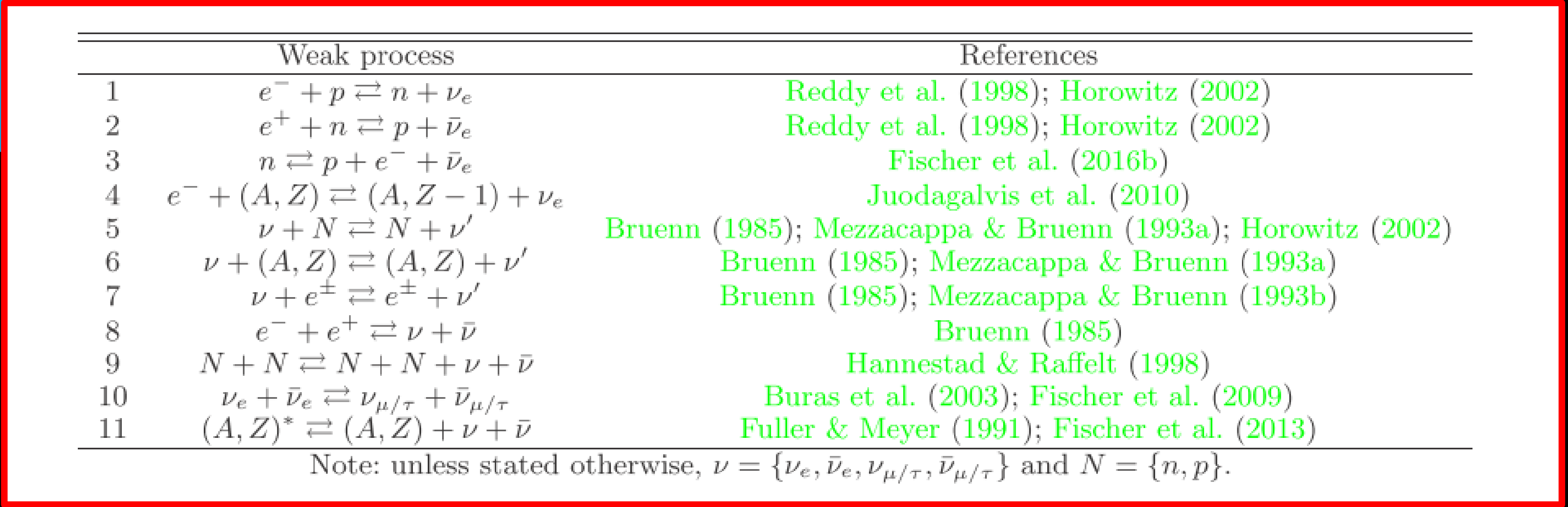
Table 1

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))

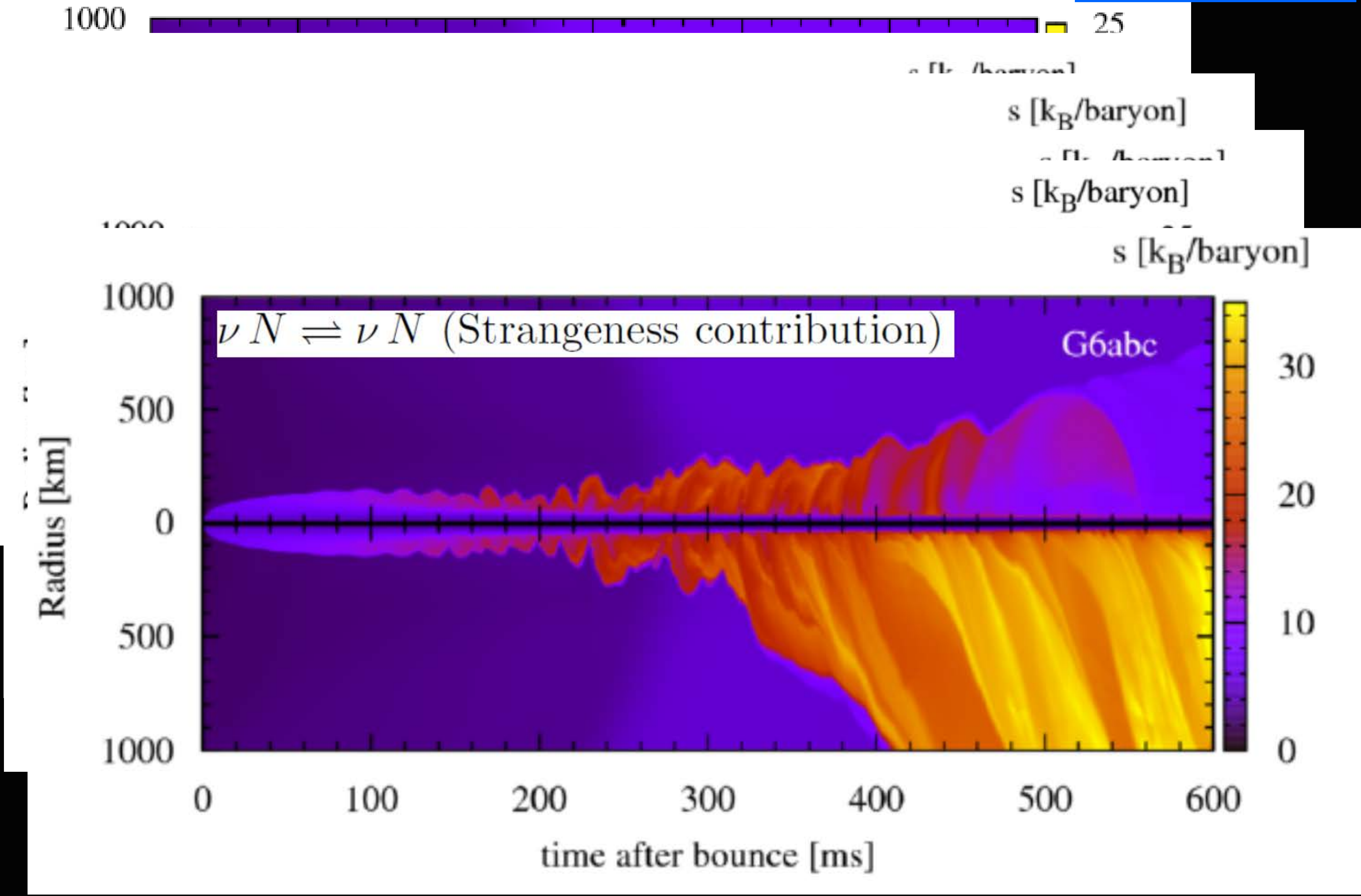


	Weak process	References
1	$e^- + p \rightleftarrows n + \nu_e$	Reddy et al. (1998); Horowitz (2002)
2	$e^+ + n \rightleftarrows p + \bar{\nu}_e$	Reddy et al. (1998); Horowitz (2002)
3	$n \rightleftarrows p + e^- + \bar{\nu}_e$	Fischer et al. (2016b)
4	$e^- + (A,Z) \rightleftarrows (A,Z-1) + \nu_e$	Juodagalvis 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 $N = \{n, p\}$.

2D IDSA simulation of 20 M_{sun} (Woosley and Heger (2007)

KK et al. (2018), ApJ



✓Quantitative GW･neutrino signal prediction, the updates in opacities mandatory!

Summary

✓ **First 3D-GR simulation** with multi-energy transport where we've followed the hydrodynamics up to **BH formation.**
(Kuroda, KK, Takiwaki, Thielemann, submitted to MNRAS Letters)
- 11.2 M_{sun} star is trending toward an explosion.

✓ Circular Polarization could be a new tool to detect GWs.
- The Stokes "V" parameter can be a measure of SASI's motions.
- We need KAGRA for detecting CP !

(Hayama, Kuroda, KK, Takiwaki, submitted to MNRAS Letters)

✓ **From rapidly rotating CCSNe**, the GWs from non-axisymmetric instabilities are **detectable** for a Galactic source. If detected, the peak GW frequency **should be twice** of the neutrino modulation frequency, which is surely visible to IceCube.

(Takiwaki and KK, MNRAS Letters (2018))

✓ **All above results need "upgrade"** quantitatively (at least) with elaborate neutrino opacities.
(e.g., KK, Takiwaki, Fischer, Nakamura, G.M. Pinedo ApJ, (2018))

Thanks!