Many Thanks
CoCoNuT's people
for huge efforts !!

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


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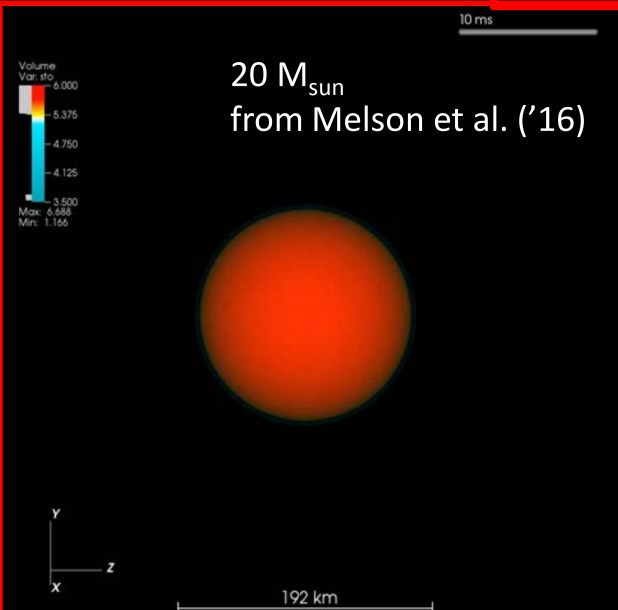
CoCoNuT meeting 2017, 27th October 2017

# 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))

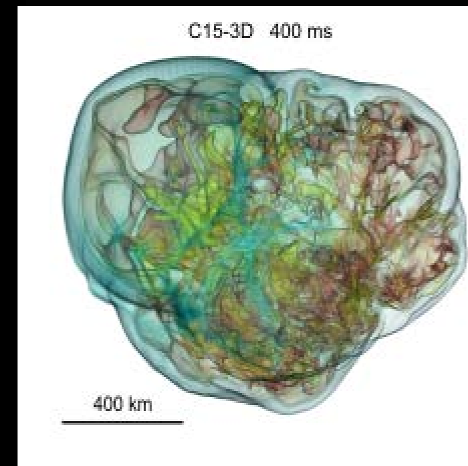
| | **Neutrino mechanism** | **MHD mechanism** |
|---|---|---|
| Progenitor | Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s) | Rapidly rotation with strong B ($\Omega_0 > \sim\pi$ rad/s, $B_0 > \sim 10^{11}$ G) |
| Key ingredients | ✓**Turbulent Convection and SASI** (e.g., Kazeroni, Guilet, 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 in prep**

(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 **BSSNOK 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

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

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

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

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

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

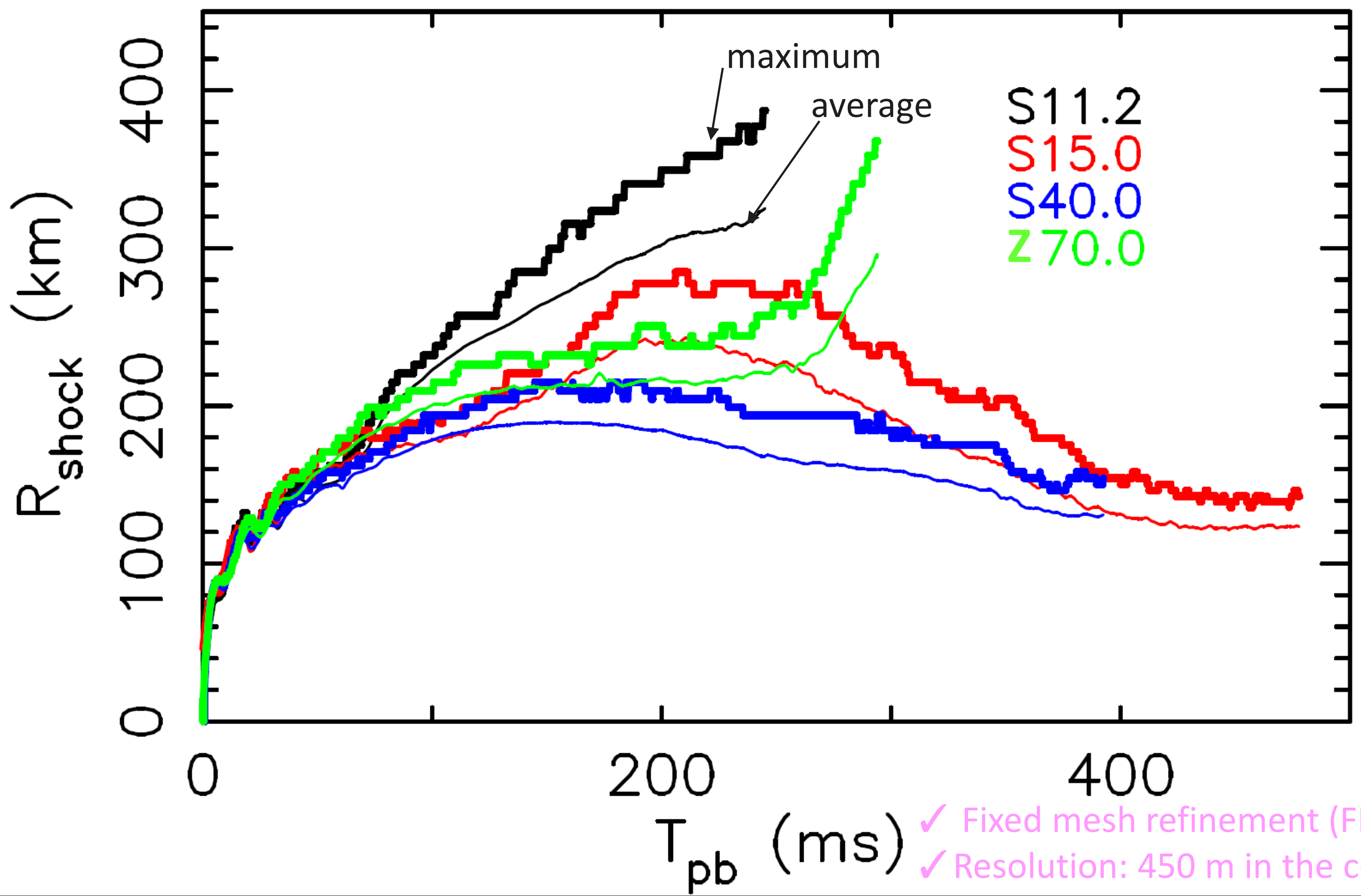
| Process | Reference |
|---|---|
| $n\nu_e \leftrightarrow e^- p$ | Bruenn (1985), Rampp & Janka (2002) |
| $p\bar{\nu}_e \leftrightarrow e^+ n$ | Bruenn (1985), Rampp & Janka (2002) |
| $\nu_e A \leftrightarrow e^- A'$ | Bruenn (1985), Rampp & Janka (2002) |
| $\nu p \leftrightarrow \nu p$ | Bruenn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

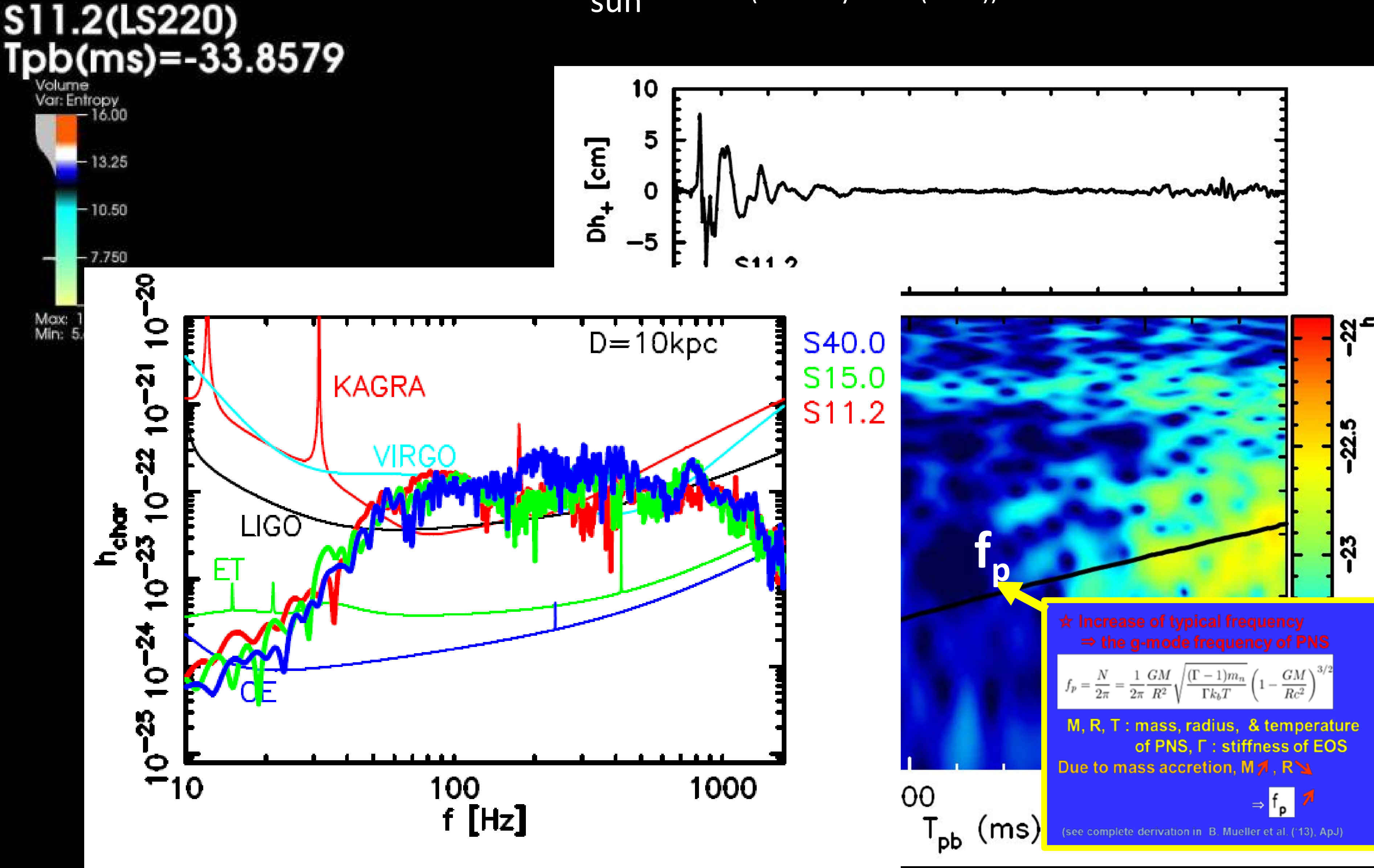
# Preliminary FUGRA results for 4 progenitors: Kuroda, KK, Takiwaki, Thielemann in prep

✓ 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)




✓ Fixed mesh refinement (FMR)
✓ Resolution: 450 m in the center

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




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

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

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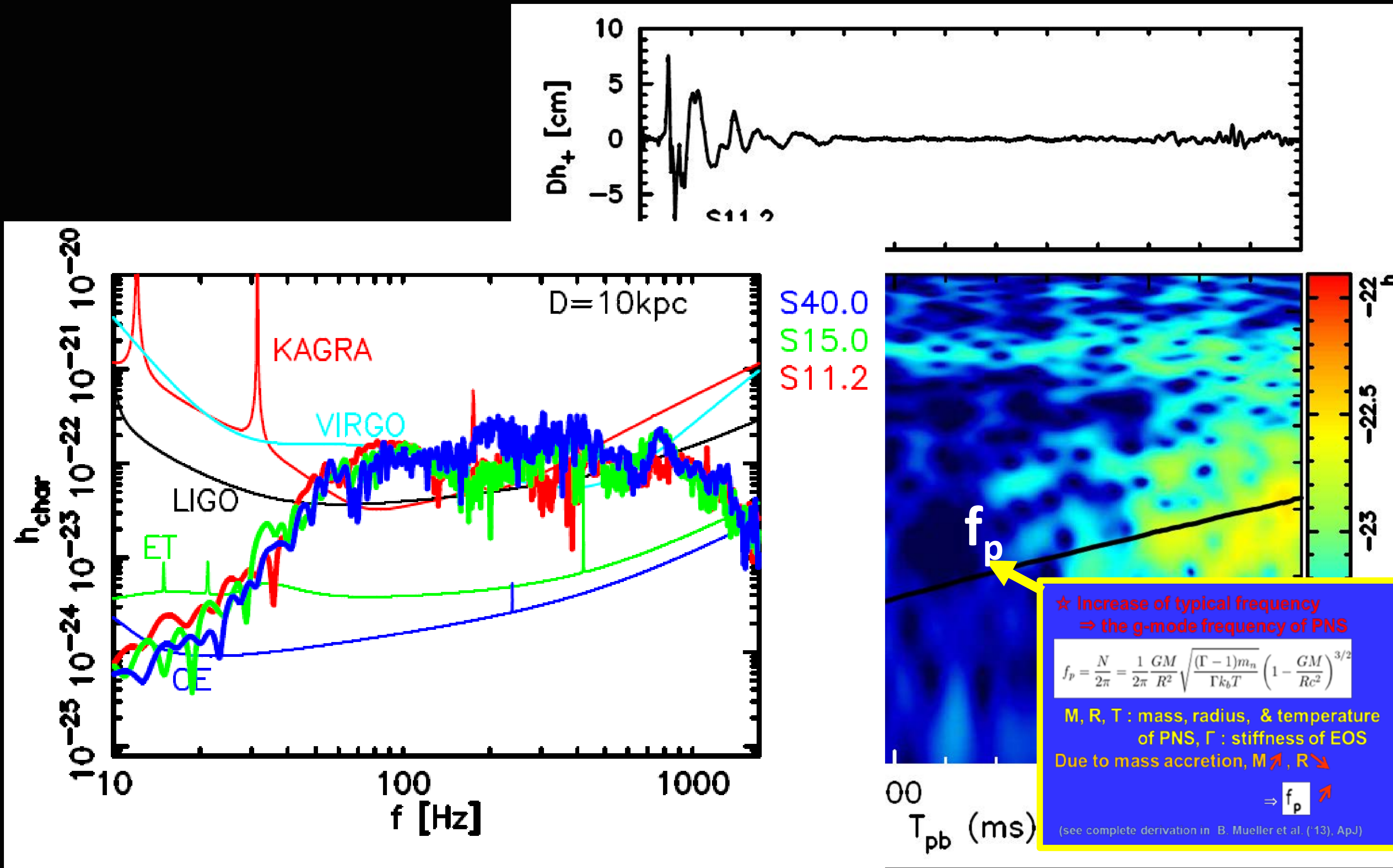
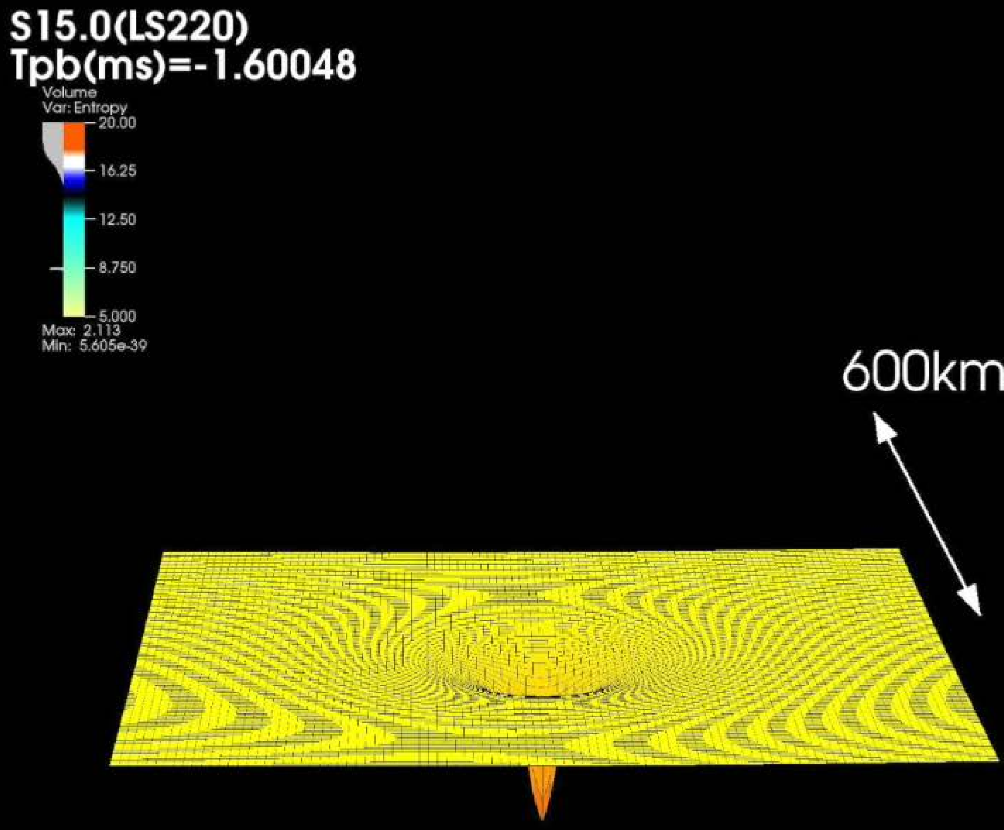
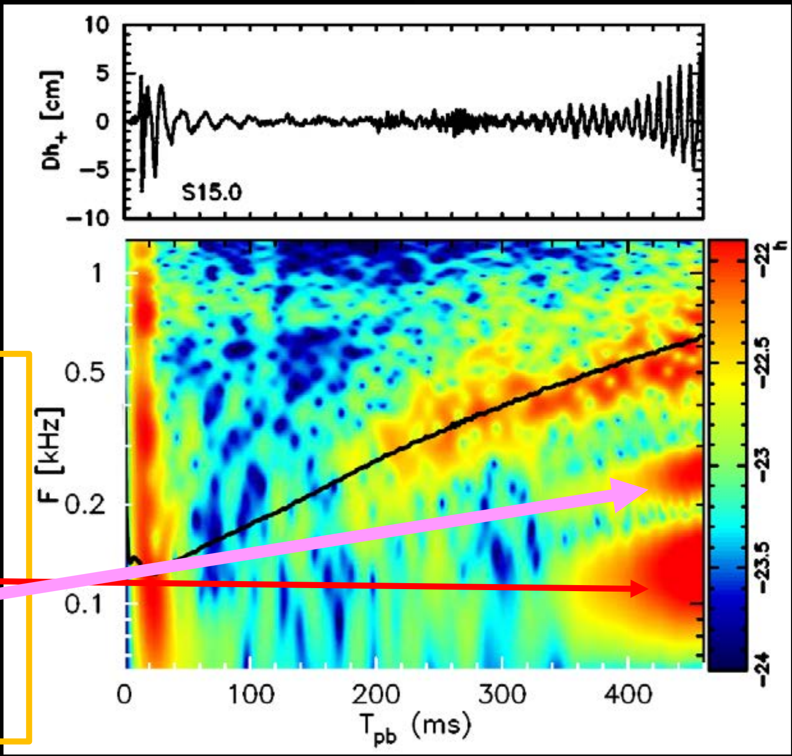



✓ 11.2 $M_{sun}$ star is likely to explode ! (long-term simulation is needed …)

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

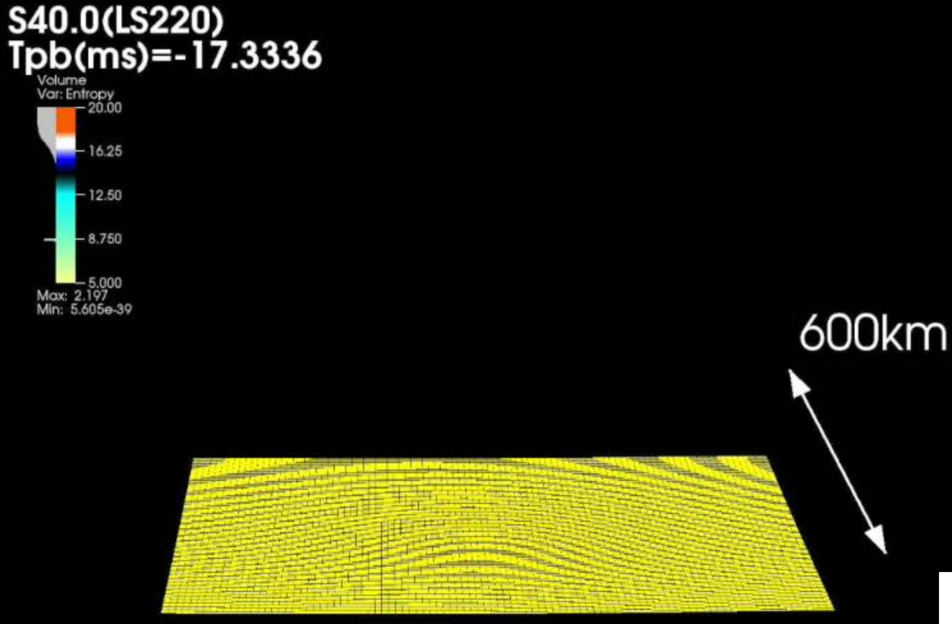
# ✓ FUGRA results of 15 $M_{sun}$ star (progenitor from Woosley & Weaver 1995)

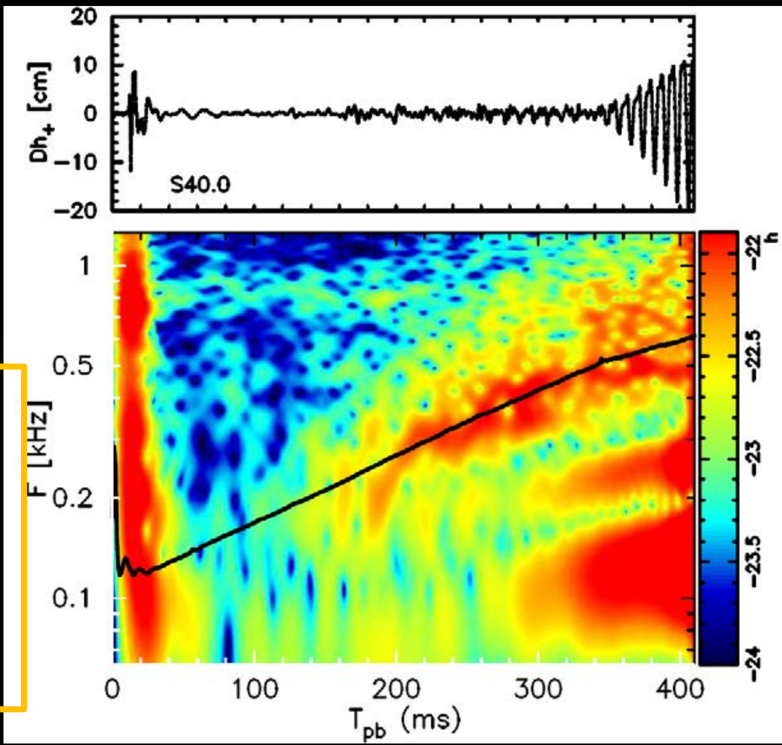



- ✓ The 15 $M_{sun}$ star unexplodes bef. 450 ms pb. (e.g., Marek & Janka (2009)).
- ✓ After 400 ms after bounce, a weak SASI activity observed.
- ✓ ⇒ Low-frequency (100Hz) excess in the GW spectrogram as in Kuroda,KK et al.(2016) using SFHx EOS + gray transport. (see Andresen et al. (2017)).
- ✓ Daughter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

# ✓ FUGRA results of 40 $M_{sun}$ star (progenitor from Woosley et al. (2002))



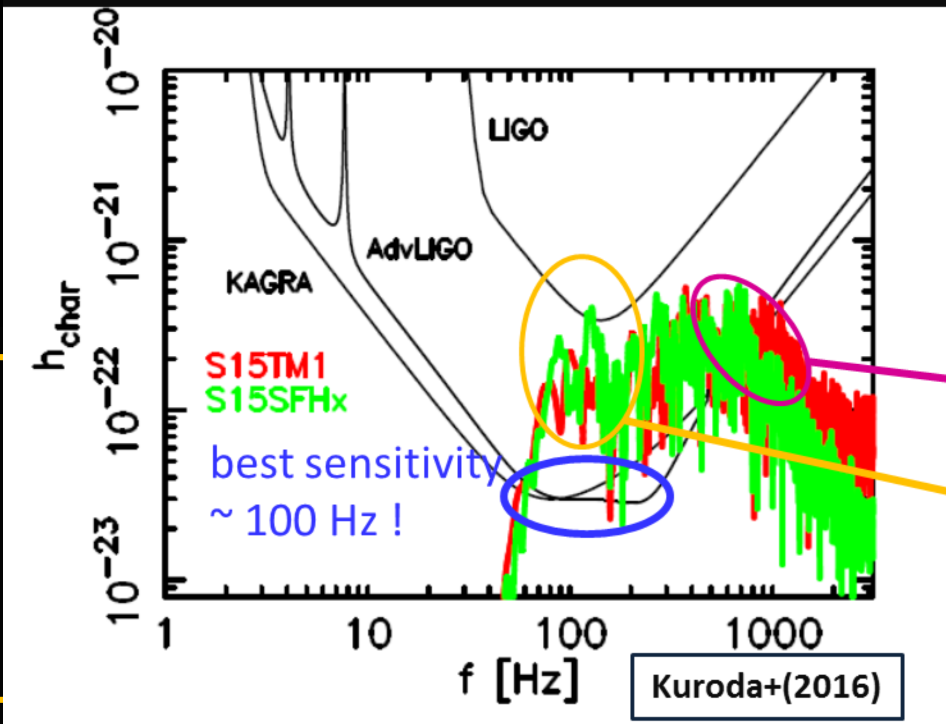




- ✓ The 40 $M_{sun}$ star unexplodes bef. 400 ms pb.
- ✓ After 350 ms after bounce, a weak SASI activity observed.
- ✓ ⇒ Low-frequency (100Hz) excess in the GW spectrogram (see Andresen et al. (2017)).
- ✓ Daughter mode (overtone) of the PNS core-oscillation !

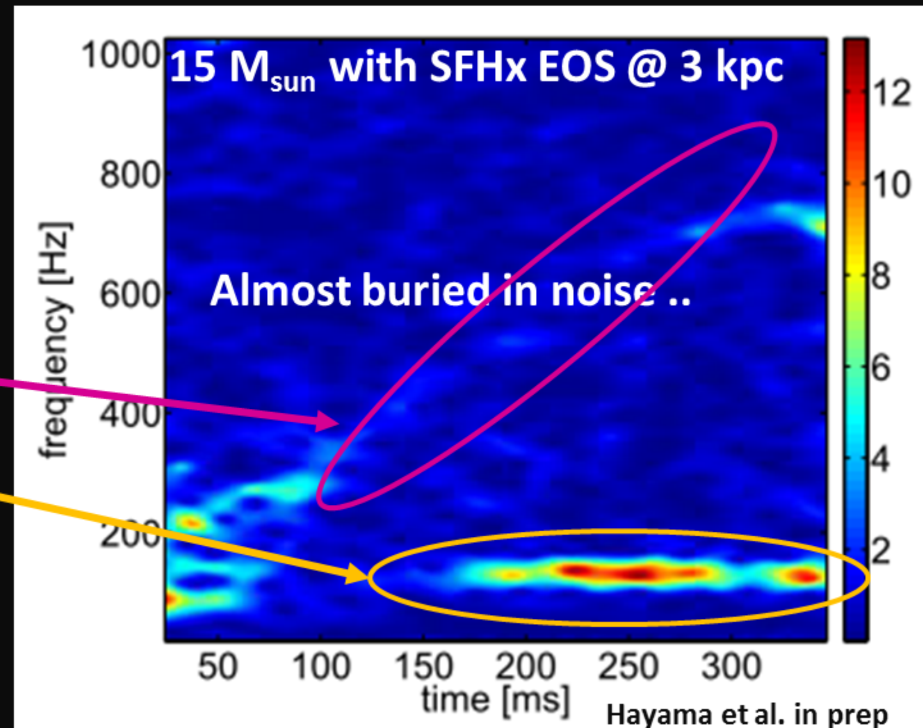
**⇒ Low frequency component is in the best sensitivity range !**

# ✓ FUGRA results of 40 $M_{sun}$ star (progenitor from Woosley et al. (2002))

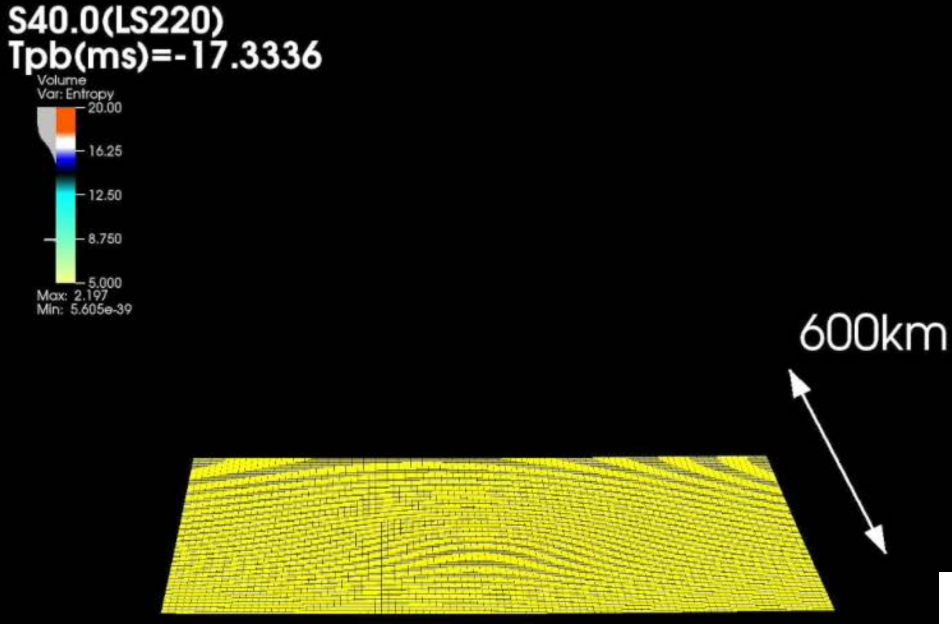

## Sensitivity curves and model predictions

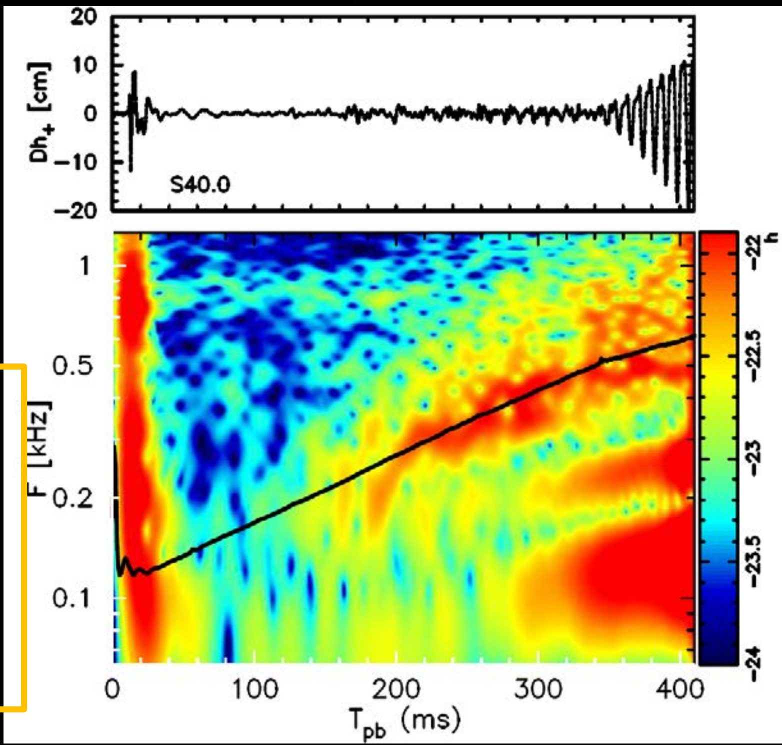



## The reconstructed GW spectrogram



# ✓ FUGRA results of 40 $M_{sun}$ star (progenitor from Woosley et al. (2002))

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**⇒ Low frequency component is in the best sensitivity range !**

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

**The Nobel Prize in Physics 2017**
Rainer Weiss, Barry C. Barish, Kip S. Thorne

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## The Nobel Prize in Physics 2017

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**Rainer Weiss**
Prize share: 1/2

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**Barry C. Barish**
Prize share: 1/4

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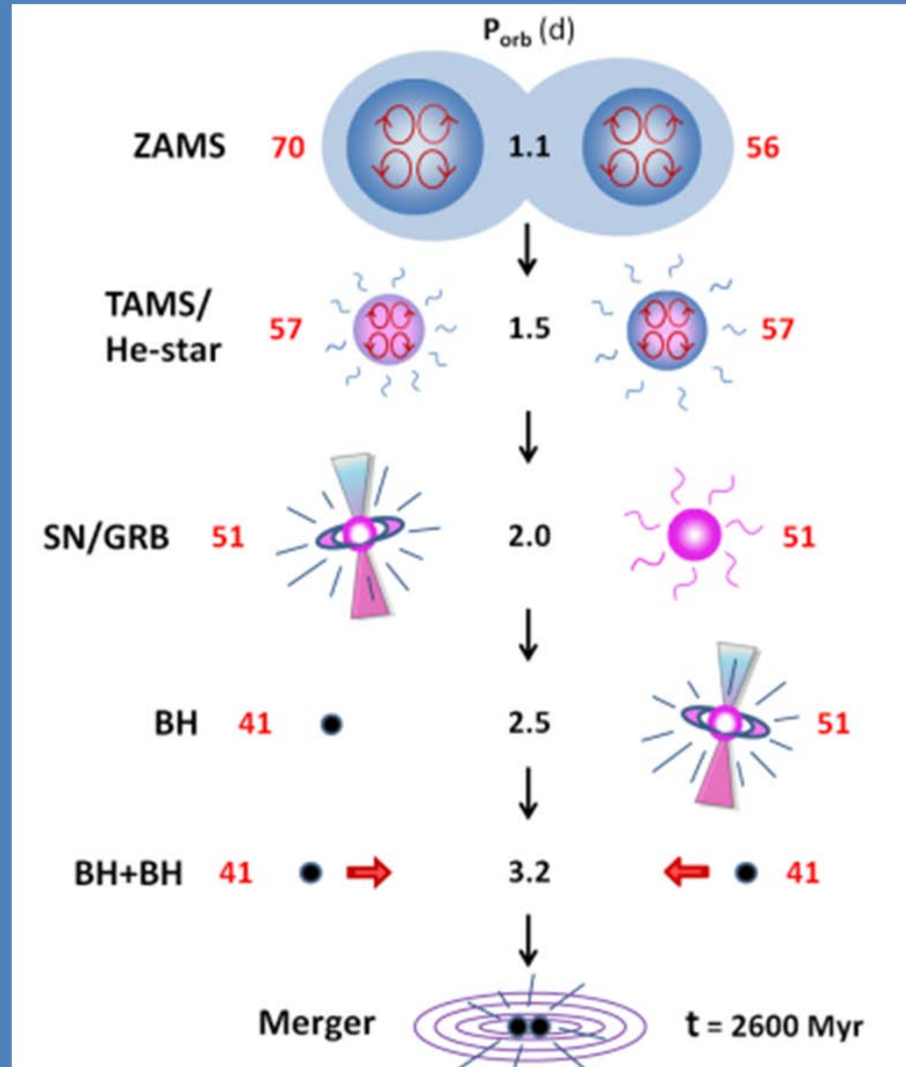
**Kip S. Thorne**
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

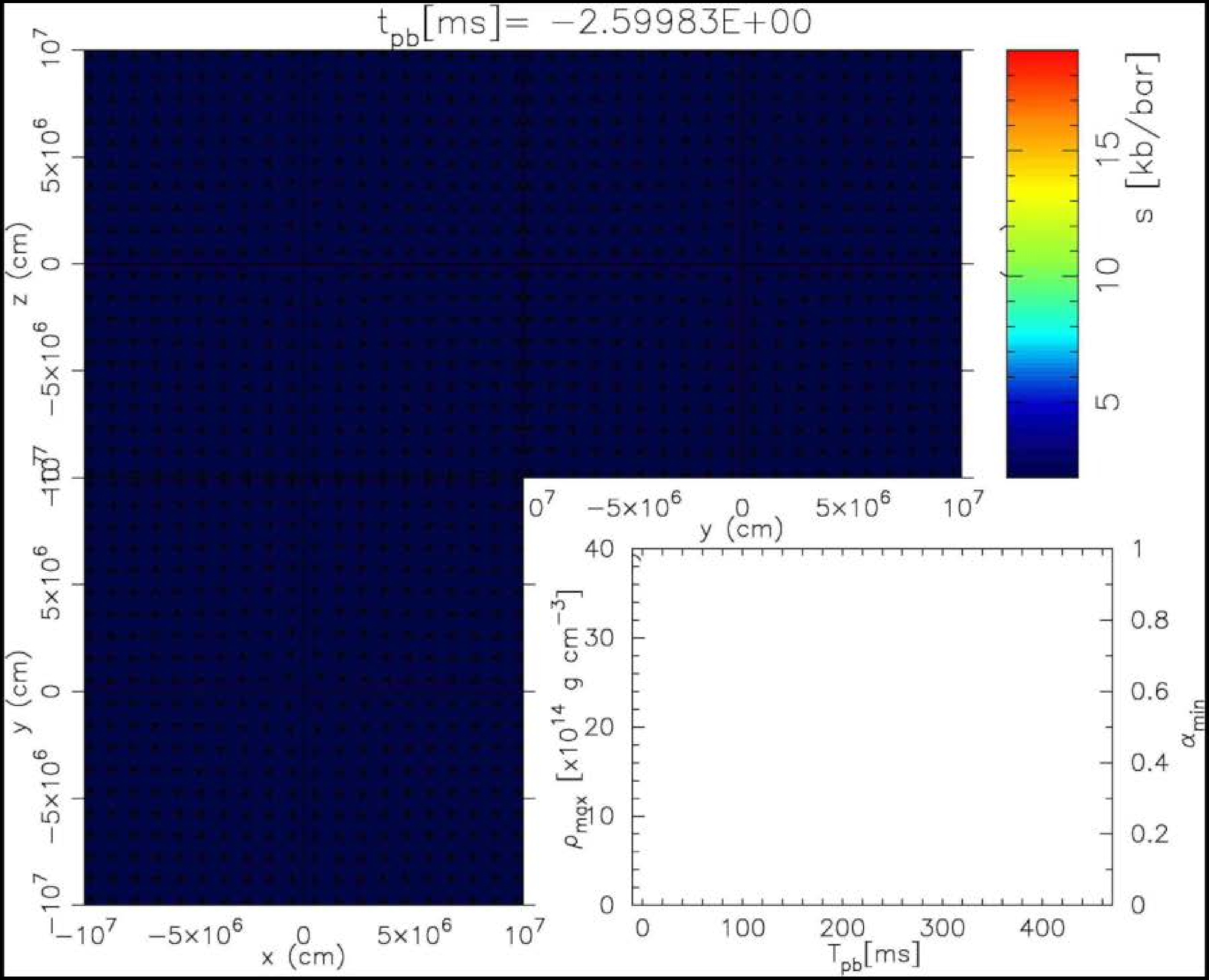
✓ <u>**Low metallicity**</u> environment needed for large stellar mass BH formation.
(e.g., Kinugawa et al .(2014,2016))

✓ One of them.. "Isolated binaries"




Marchant, Langer, Podsiadlowski et al. (2006)

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



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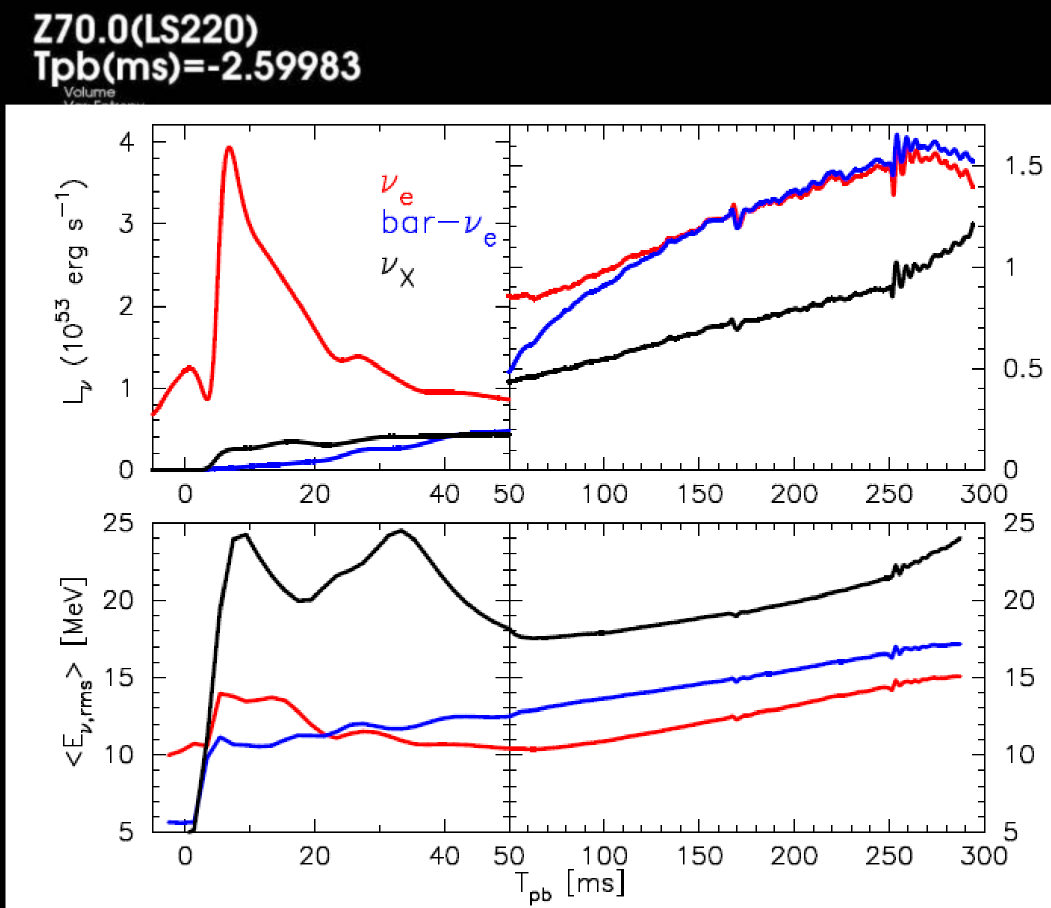
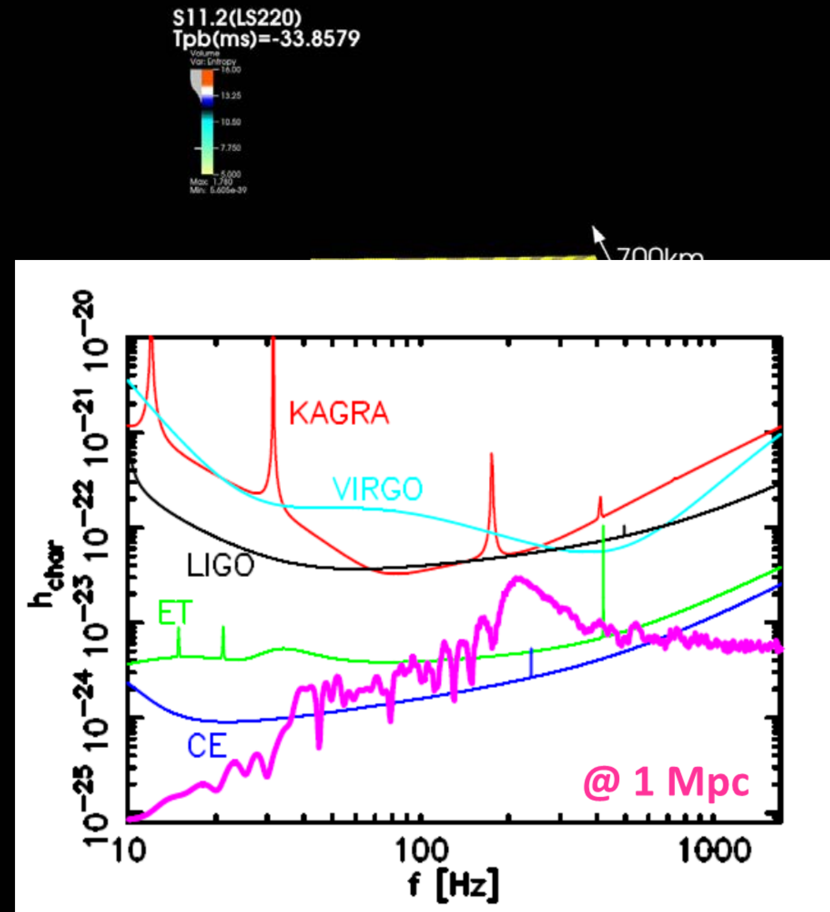


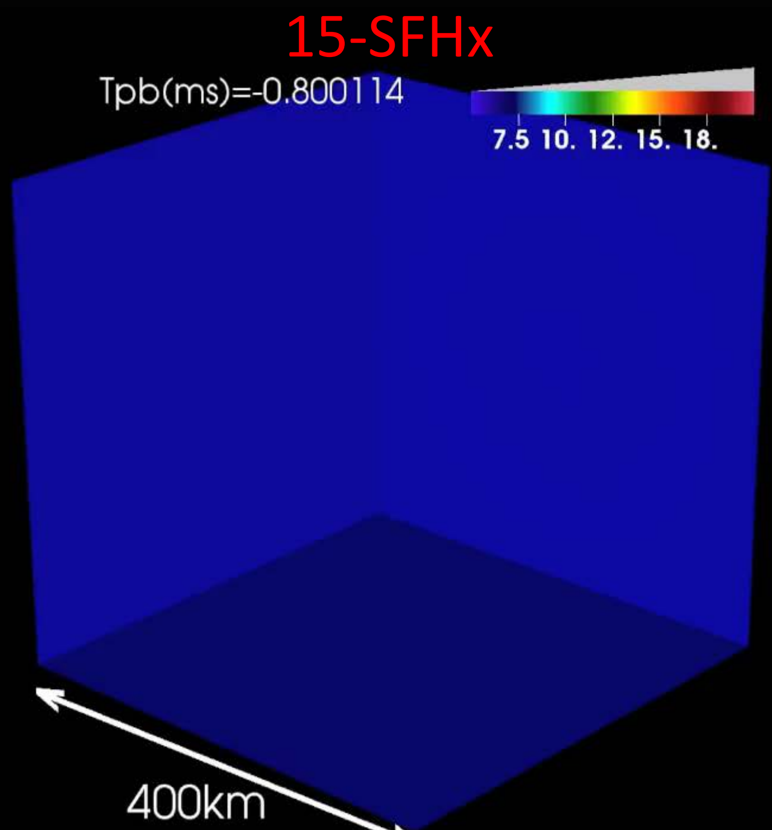



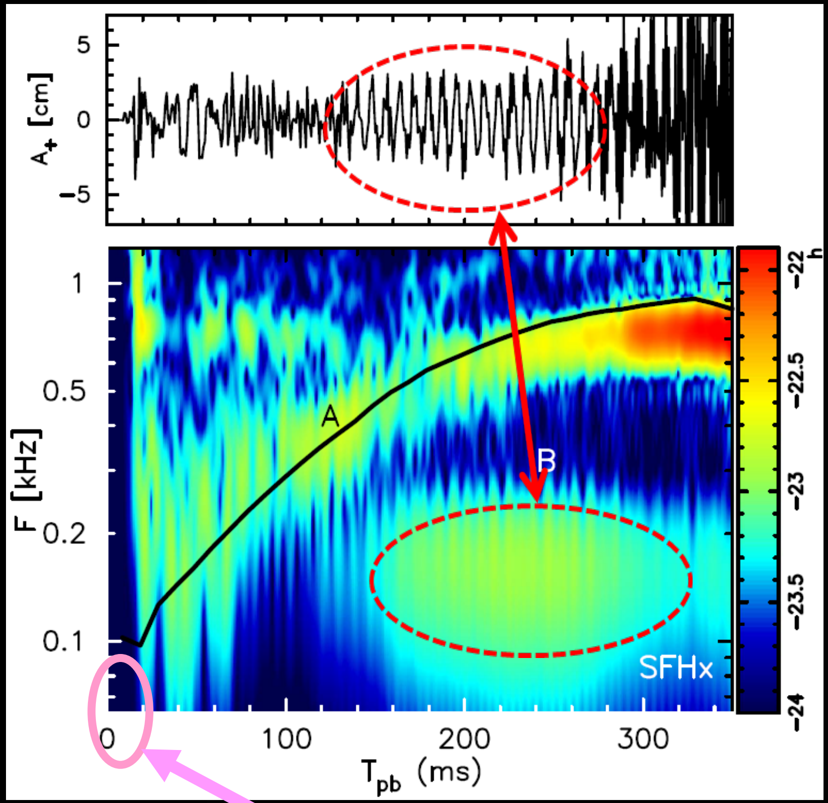

- ✓ **Earliest BH formation** after bounce (〜300 ms postbouce) !
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.
  (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Fischer+ (2009), Huedepohl+(2016))
- ✓ Strong GW emission is visible to 1 Mpc, **but not** O(100)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



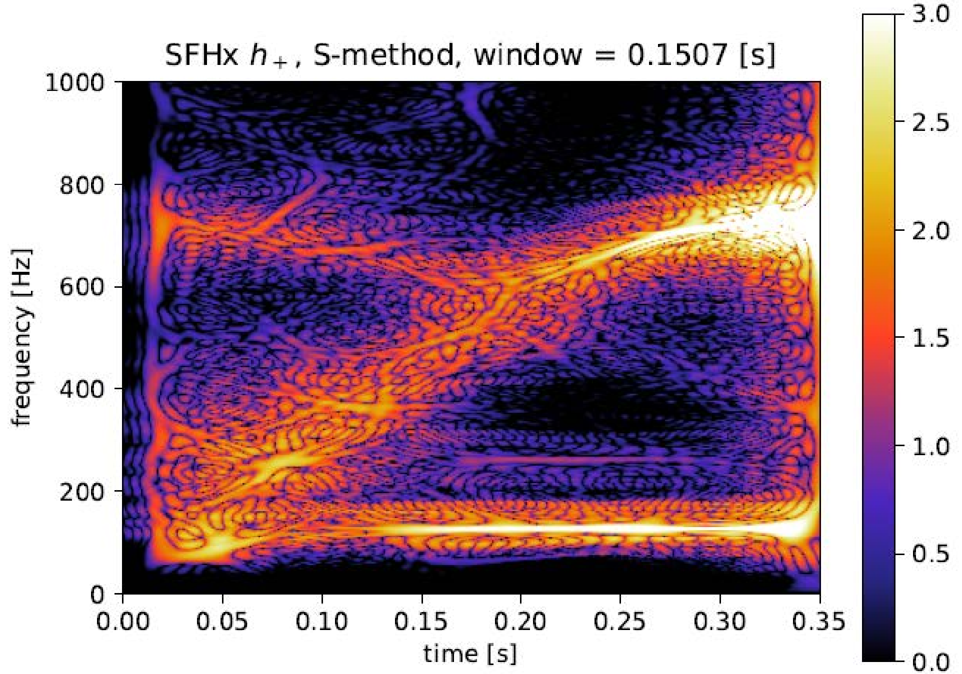




- ✓ **The quasi-periodic modulation is associated with SASI, clearly visible with softer EOS.**
- ✓ By coherent network analysis of LIGO, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc, but could miss every Galactic events when **ET and CE are on-line (>2035).**
- ✓ **Detection of neutrinos (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)).

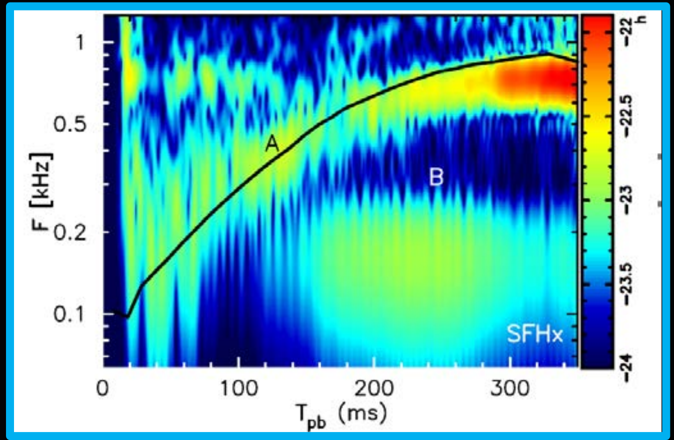
# Detailed spectrogram analysis reveals several interesting features !

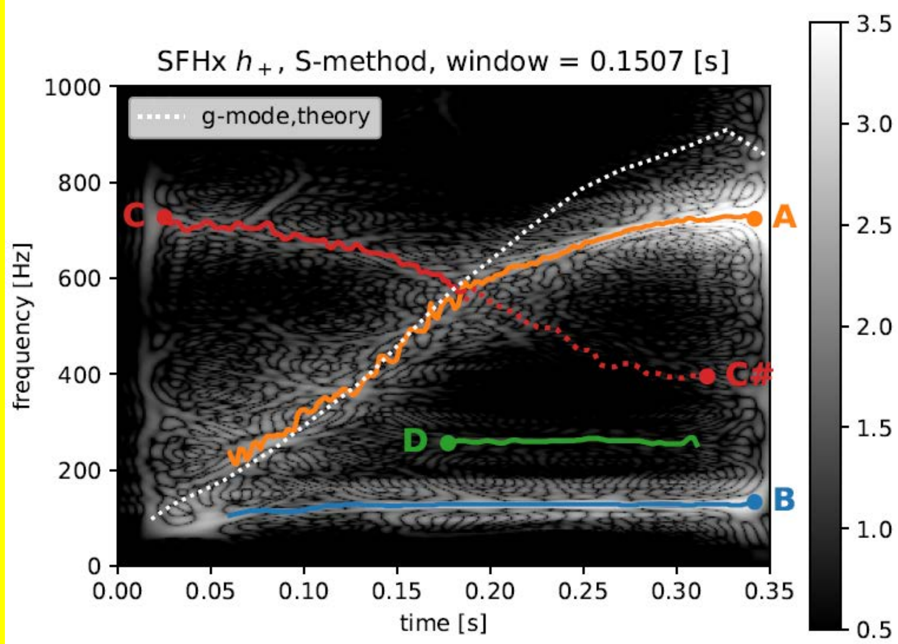
✓ **Wigner-Ville transformation: precise method to extract "instantaneous" frequency**

(Kawahara, Hayama, Kuroda, KK+ in prep)




FFT

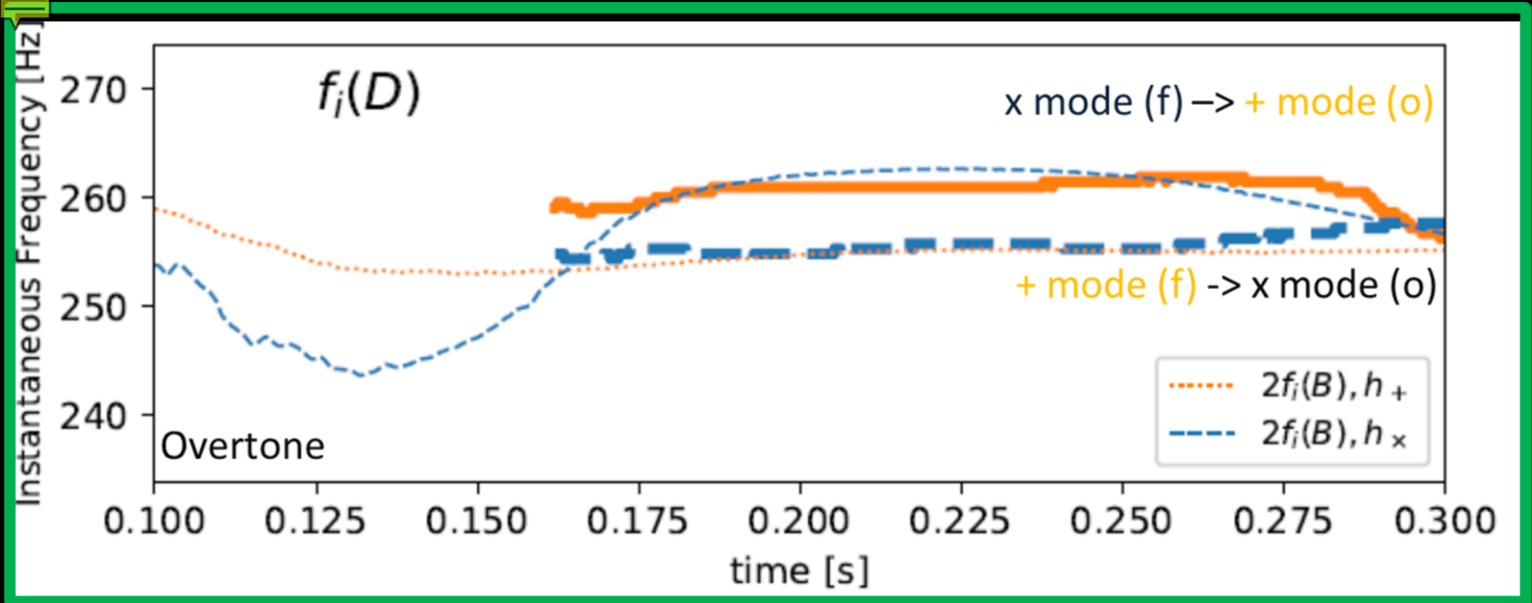


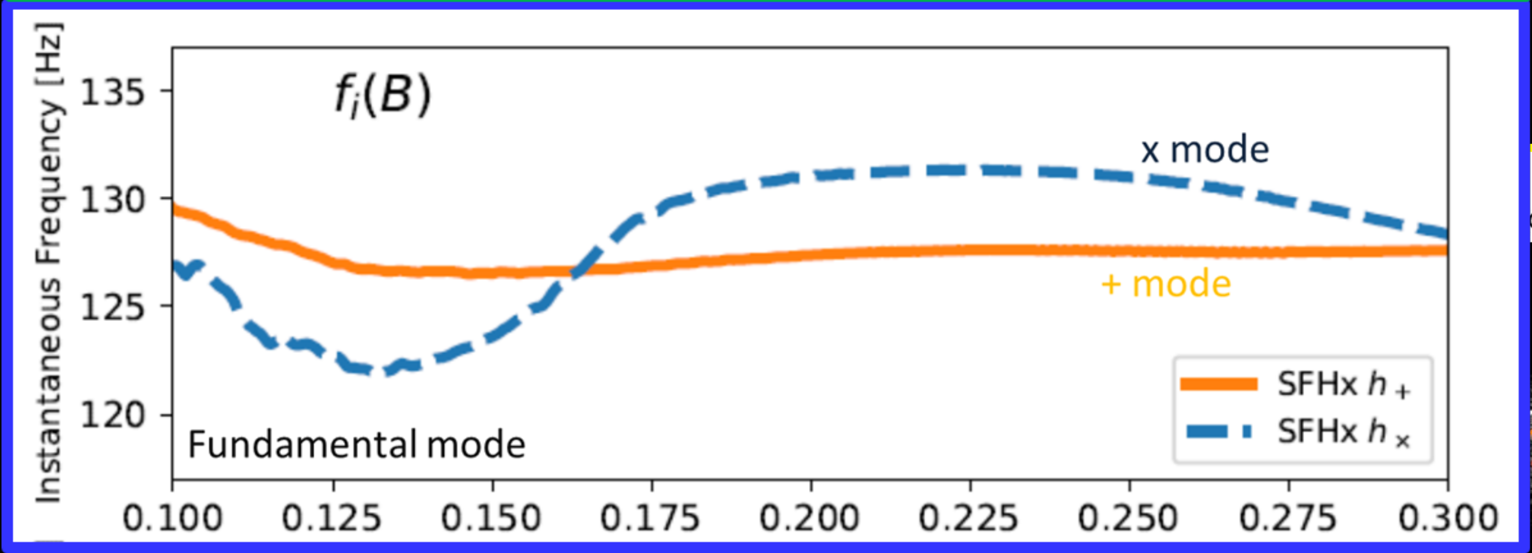



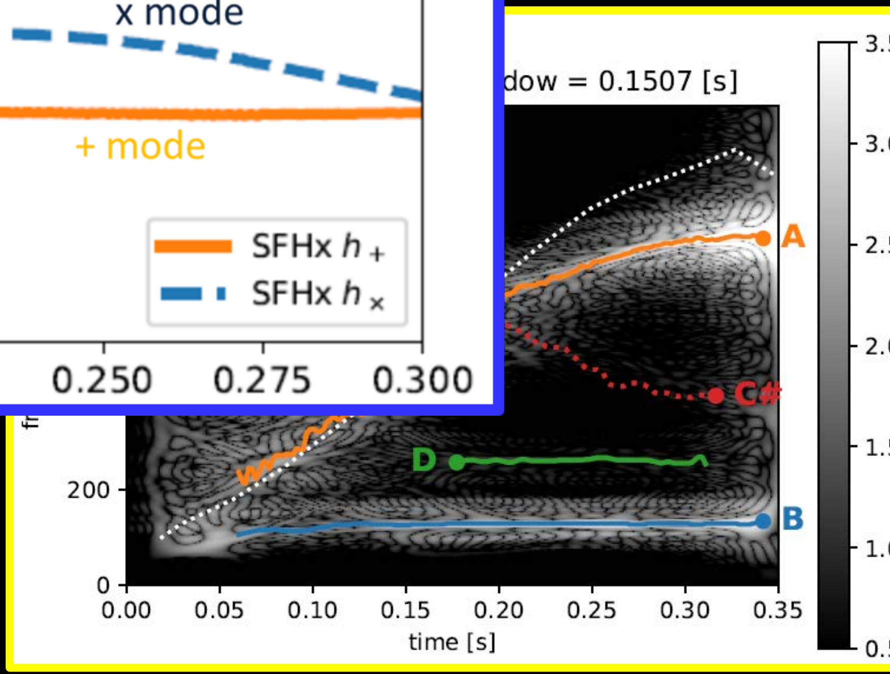

**Four features** in the GW spectrogram:

- ✓ A: Ramp-up g-mode (e.g., Andresen+(2017))
- ✓ C: Prompt Convection + PNS convection (decrease/increase dependent on EOS)
- ✓ B: Fundamental mode of SASI-induced GW $f_{GW\text{-}SASI}$ ~126-128 Hz
- ✓ D: Overtone of "B"

(see also, Torres-Forné et al. (2017))




✓ Between fundamental (B) and overtone (D), interchange of the GW polarization ( + and x) is observed. (Physical interpretation missing …)

# "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)**

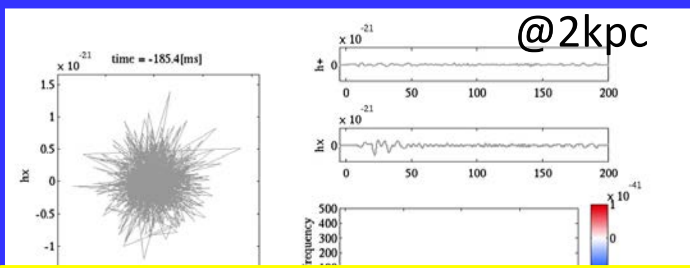
***V parameter*** =
Asymmetry of right and left modes

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

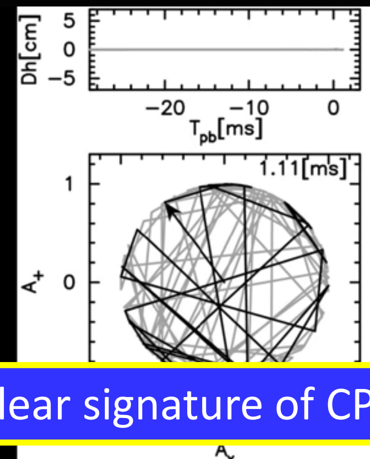
**(See definitions in Seto and Taruya (2007), PRL)**

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

@2kpc



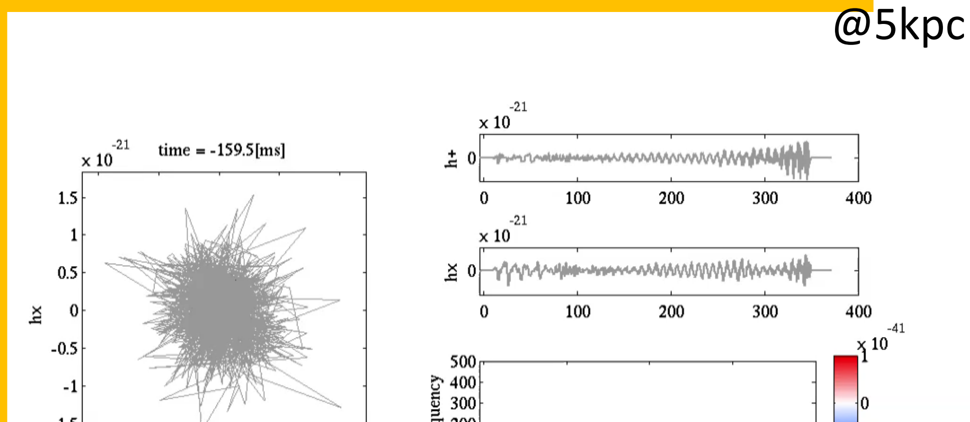

Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_\times$)

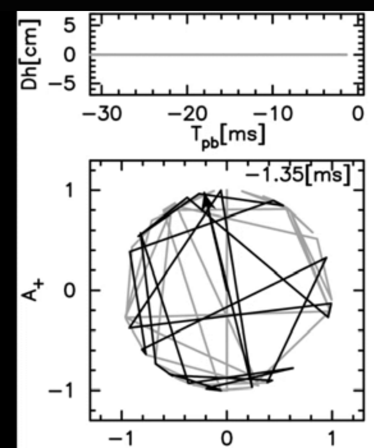



If the core is convection-dominant (likely for low ξ stars), no clear signature of CP !

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

@5kpc



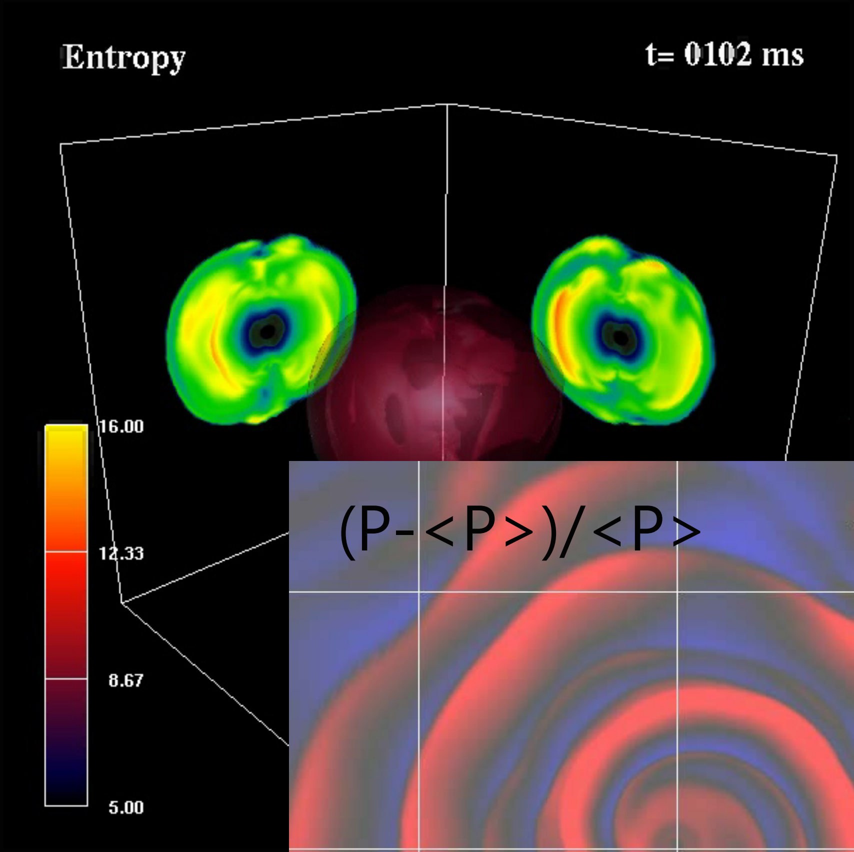




If the SASI dominant (likely for high ξ stars), clear signature of CP !
⇒ indication of SASI motions non-spherical mass accretion (Hayama,KK et al. in prep)

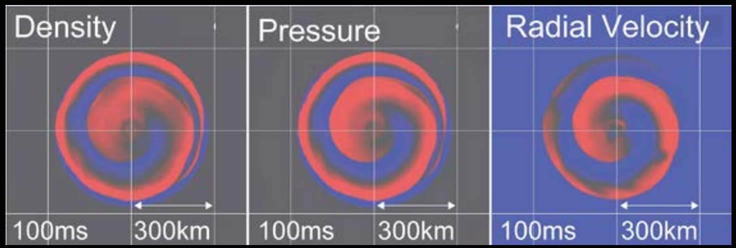
# Switching gears to MHD mechanism (rapid rotation required !!)

**3D rotating explosion simulation of a** 27 $M_{sun}$ star ($\Omega_0$ = 2 rad/s) with IDSA.

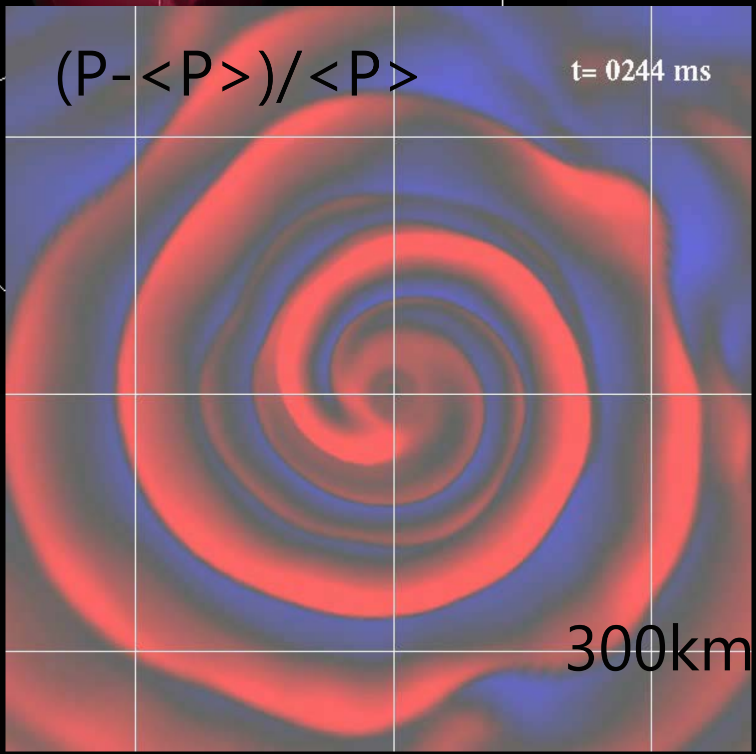
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016), see also Summa et al. (2017)).

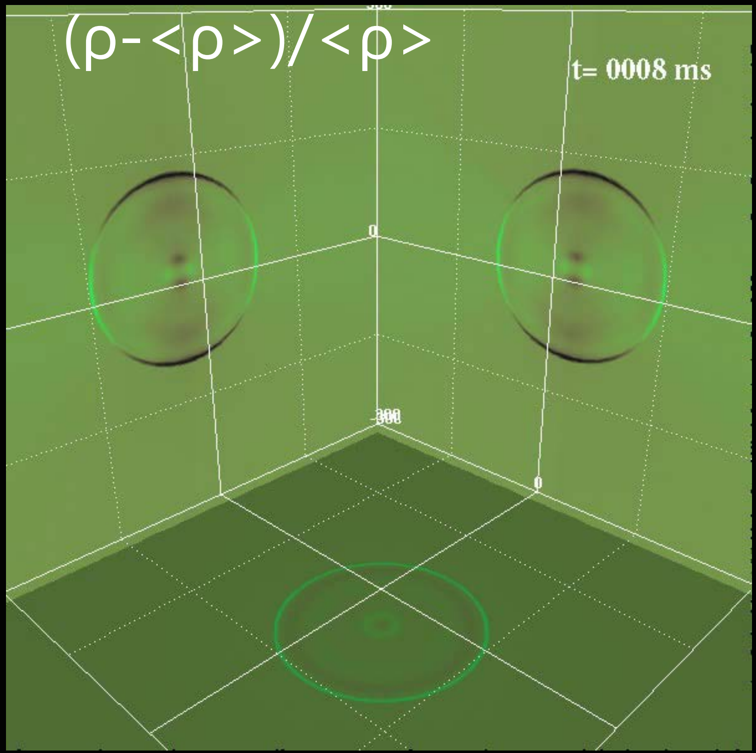



✓ One-armed (low T/|W|) instability




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



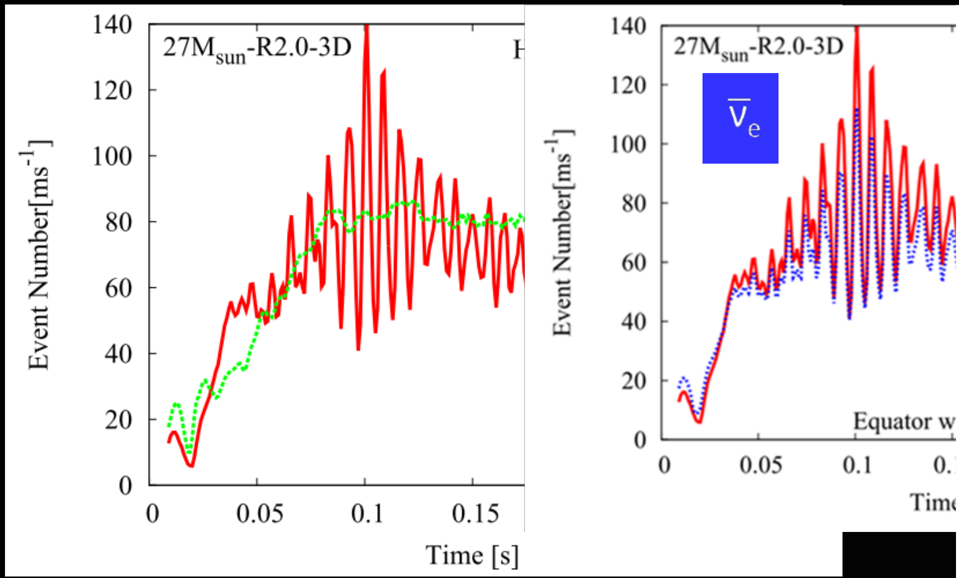



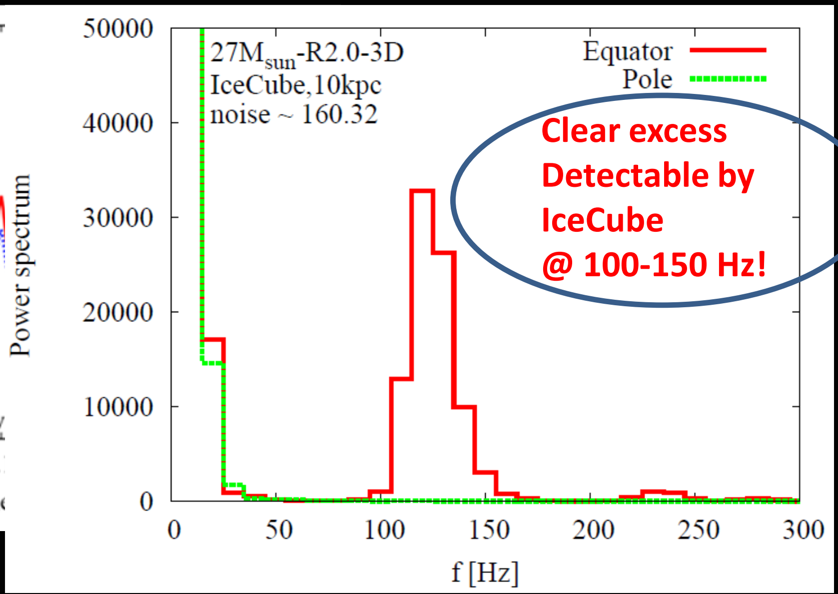
# Neutrino signatures from rapidly rotating explosion of 27 $M_{sun}$ star

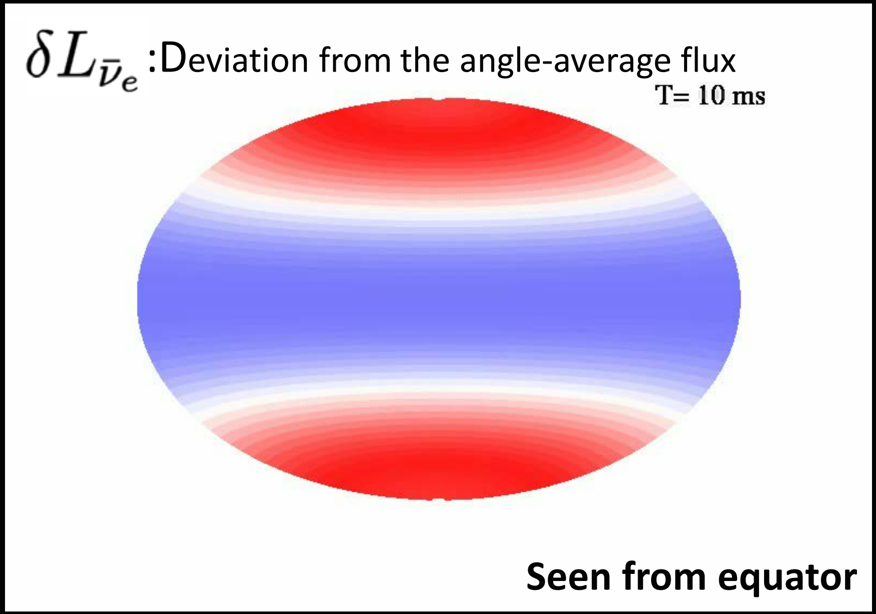
Takiwaki and KK in prep

Quasi-periodic variation !

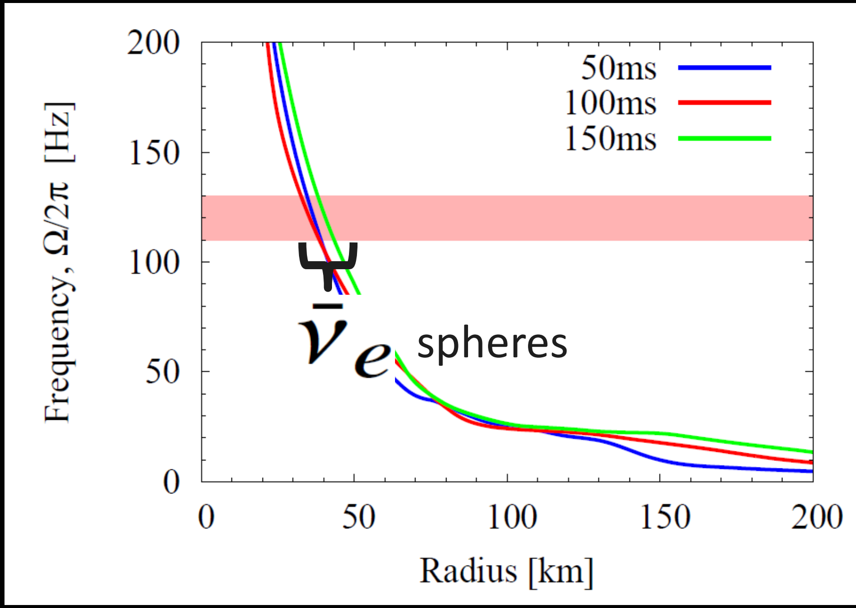
May survive with coll. oscillation



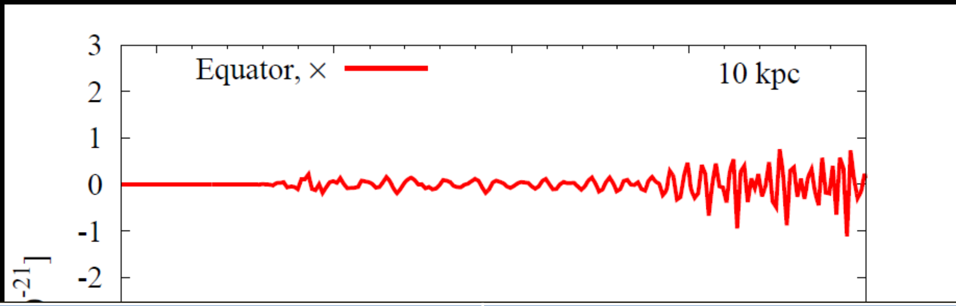

*"Lighthouse effect"*

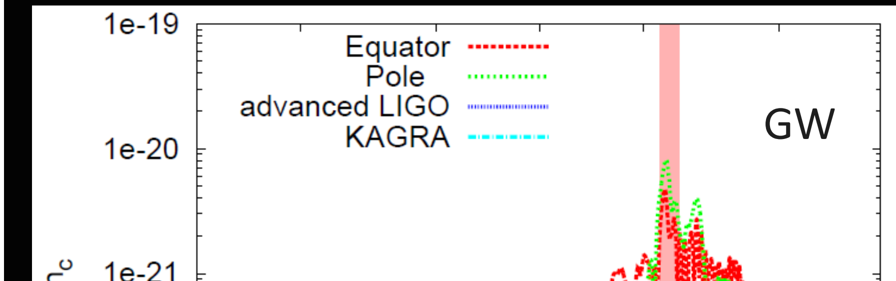


# Correlation of GW and neutrino signatures from the 3D rotating model,

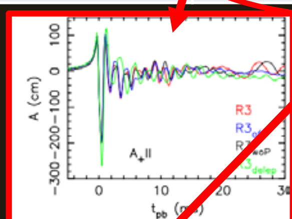
Gravitational waveform (27 $M_{sun}$, $\Omega_0$ = 2rad/s)

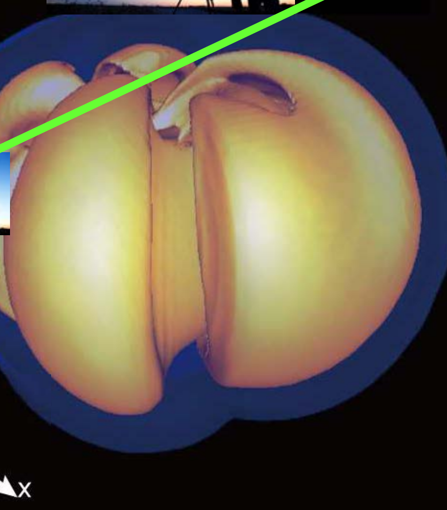
Takiwaki and KK in prep

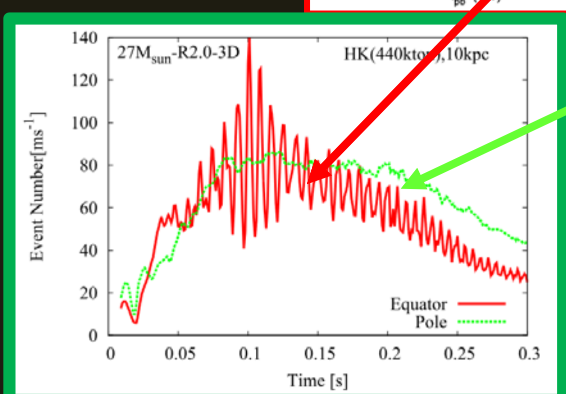


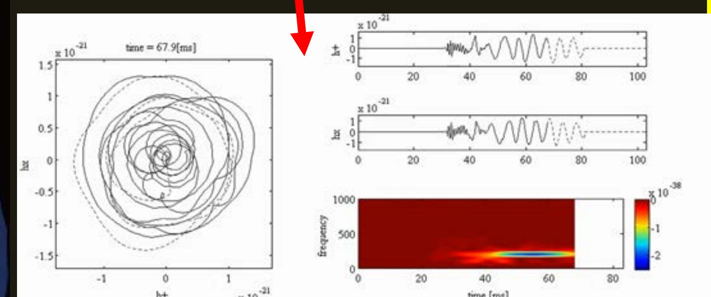




| Directionality | Equator | Pole |
|---|---|---|
| Gravitational Wave | Type I signal | ✓Quasi-periodic signals from non-axis. instability<br>✓Circular polarization |
| Neutrinos | Light-house effect | No surprise … |





# 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)

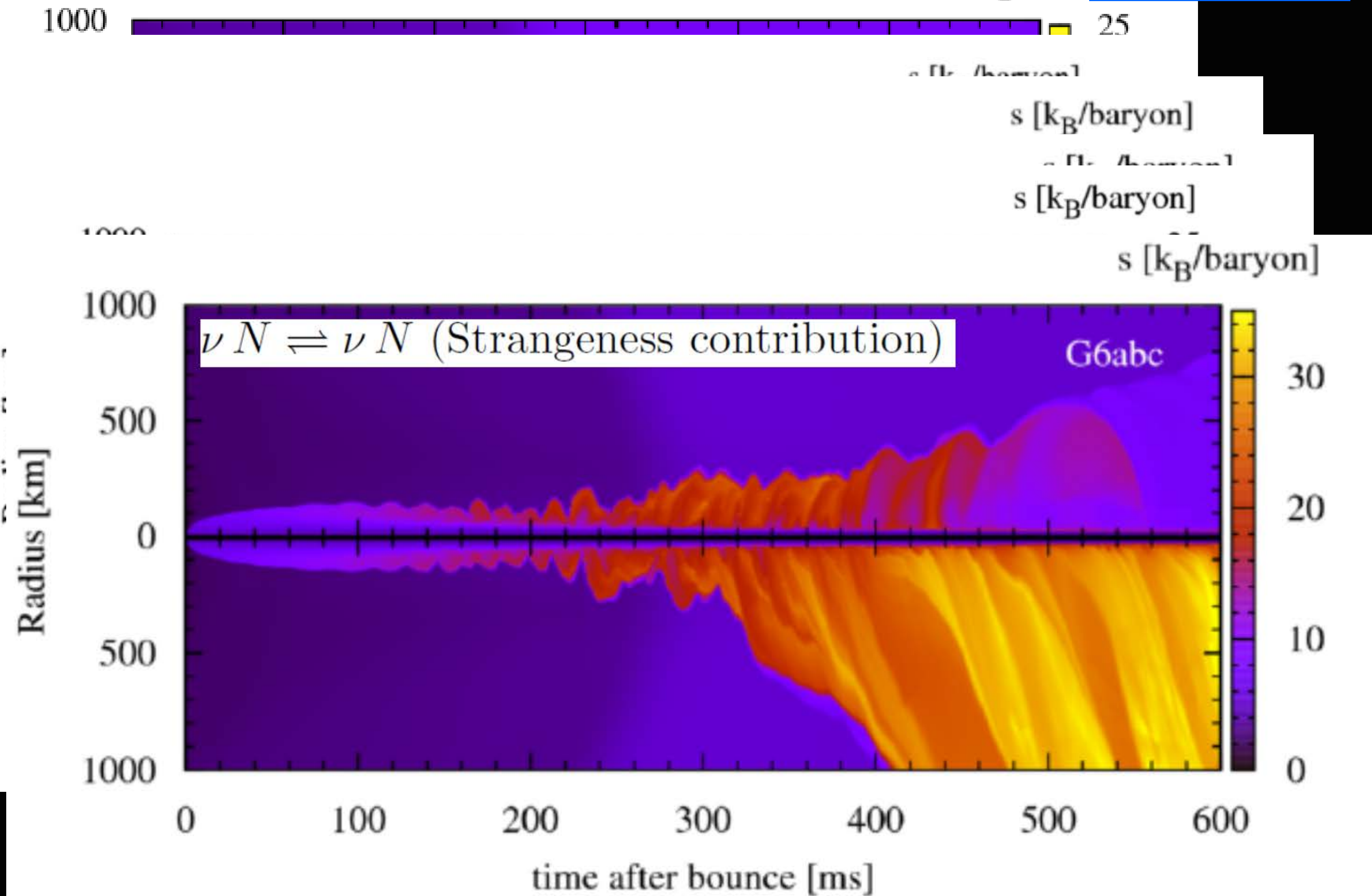
Most advanced set
(e.g., Fischer(2016),
Bollig et al. (2017))

| | 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. in prep**




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

# Summary

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

✓ <u>Circular Polarization</u> 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, in prep)**

✓ **From rapidly rotating CCSNe**, the GWs from non-axisymmetric instabilities are **detectable** for a Galactic source. If detected, the peak GW frequency <u>**should be twice**</u> of the neutrino modulation frequency, which is surely visible to IceCube.
**(Takiwaki and KK, in prep)**

✓ <u>**All above results need "upgrade"**</u> quantitatively (at least) with elaborate neutrino opacities.
**(KK, Takiwaki, Fischer, Kuroda, Nakamura, G.M. Pinedo in prep)**

Thanks!