Neutrino and Gravitational-wave signatures from 3D core-collapse supernova models

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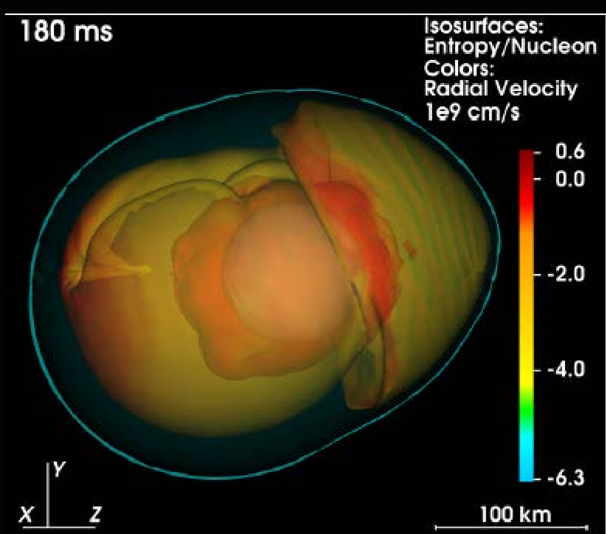
Two candidate mechanisms **of core-collapse supernovae**

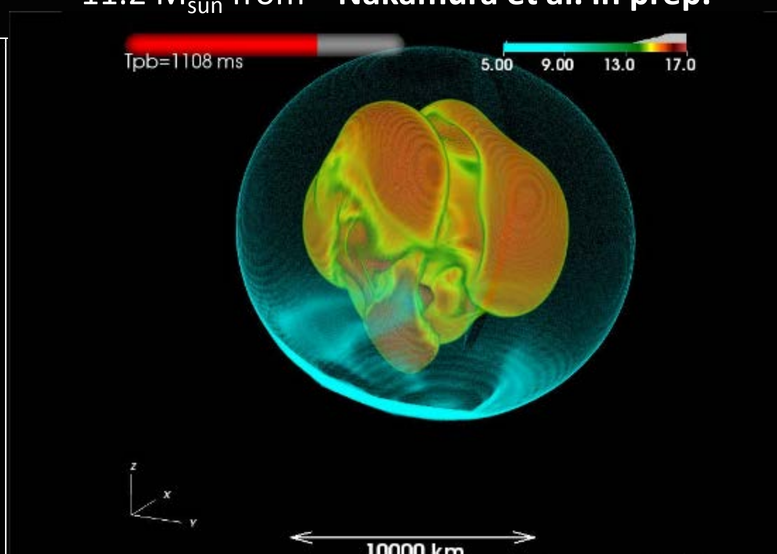
(See reviews in Janka ('17), Müller ('16), Foglizzo et al. ('15), Burrows ('13), Kotake et al. ('12))

	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)

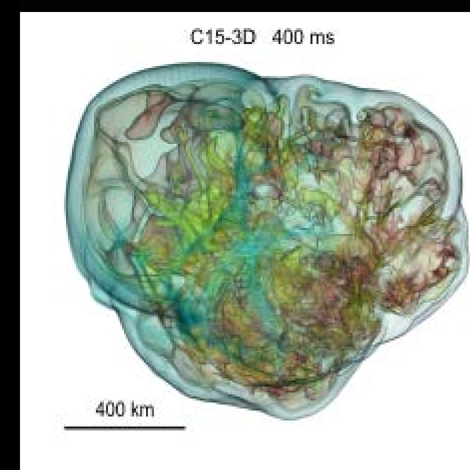


11.2 M_{sun} from **Nakamura et al. in prep.**



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))

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

Kuroda, KK, Takiwaki, Thielemann **MNRAS Letters (2018)**

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

✓ "FUGRA" : Fully General Relativistic code with multi-energy neutrino transport or **FUSRA(grey)**

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. (2018)**, 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

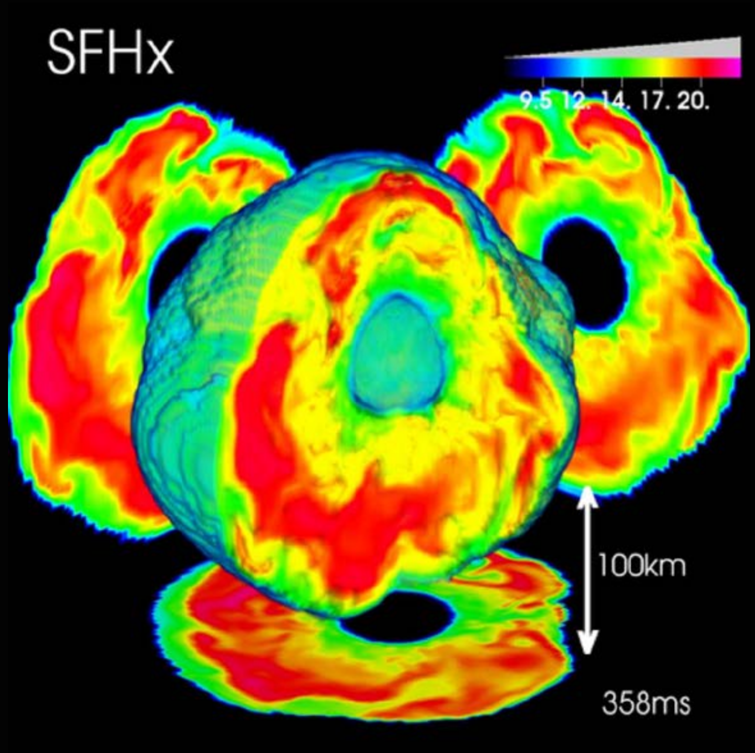
✓Base-line opacity

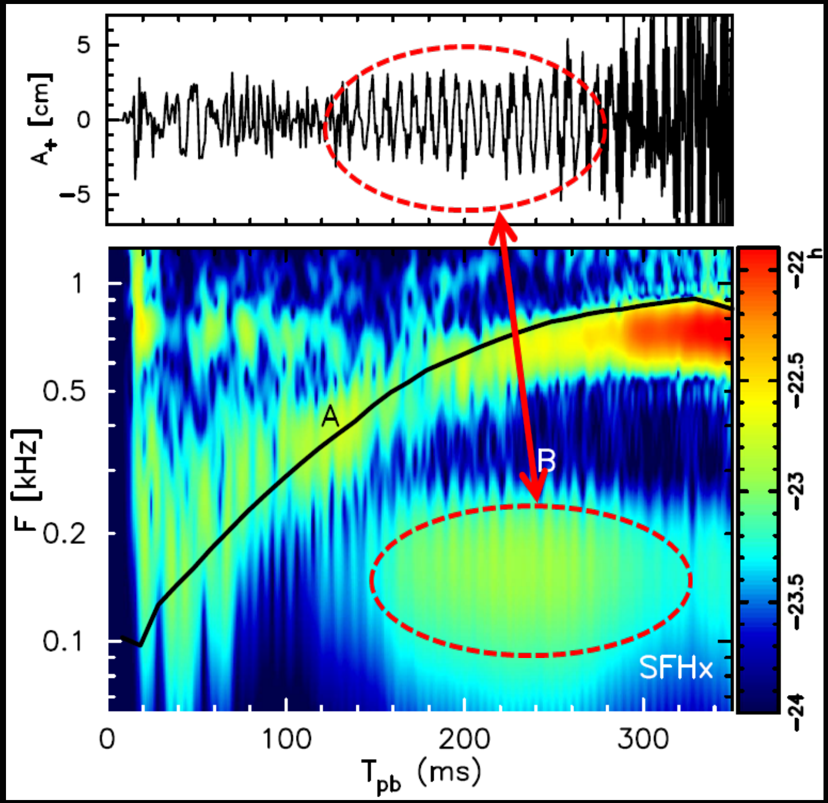
(t.b.updated)

FUSRA 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 every Galactic event will be detectable for **ET and CE (>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, ApJ)).

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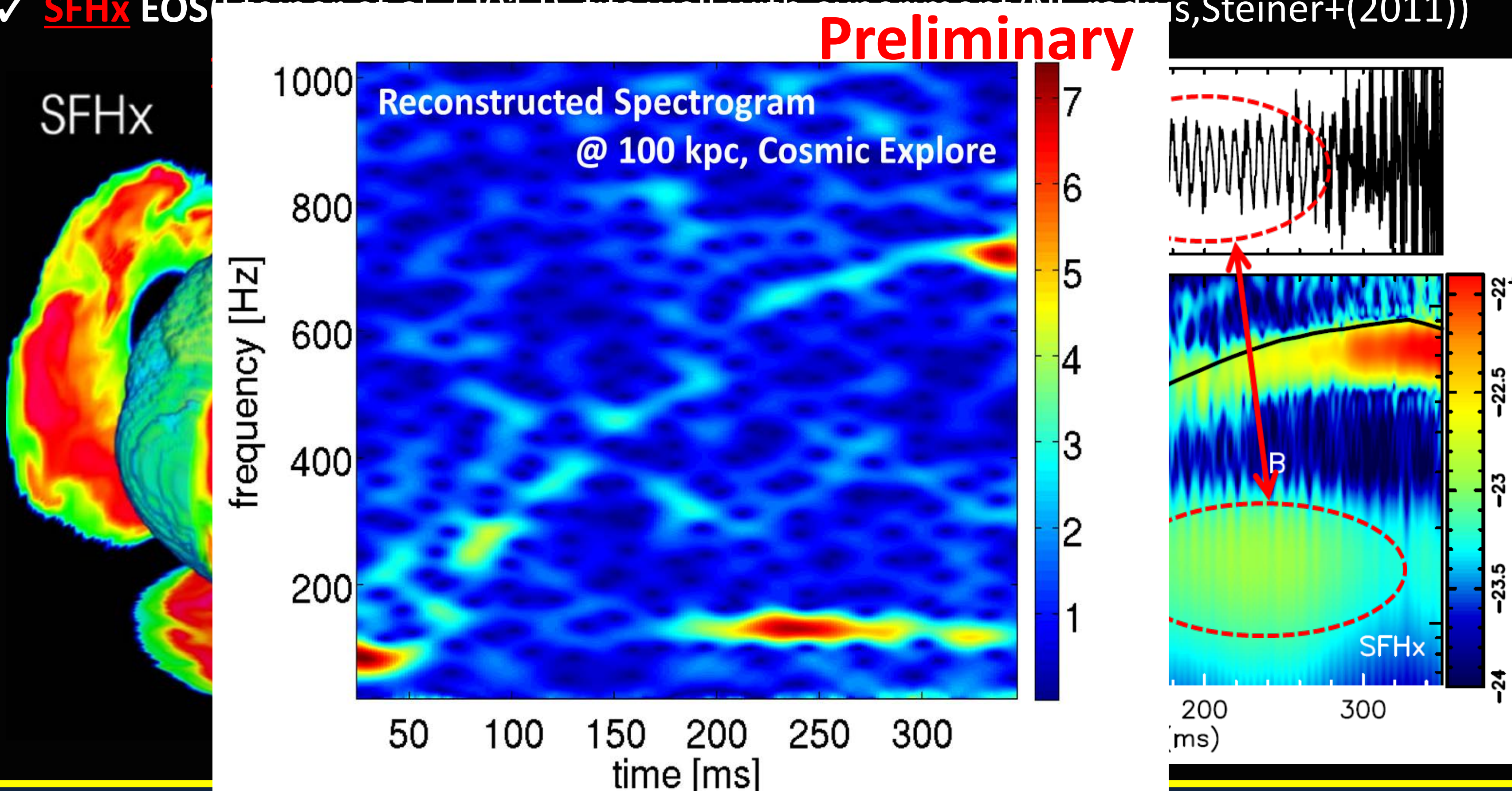

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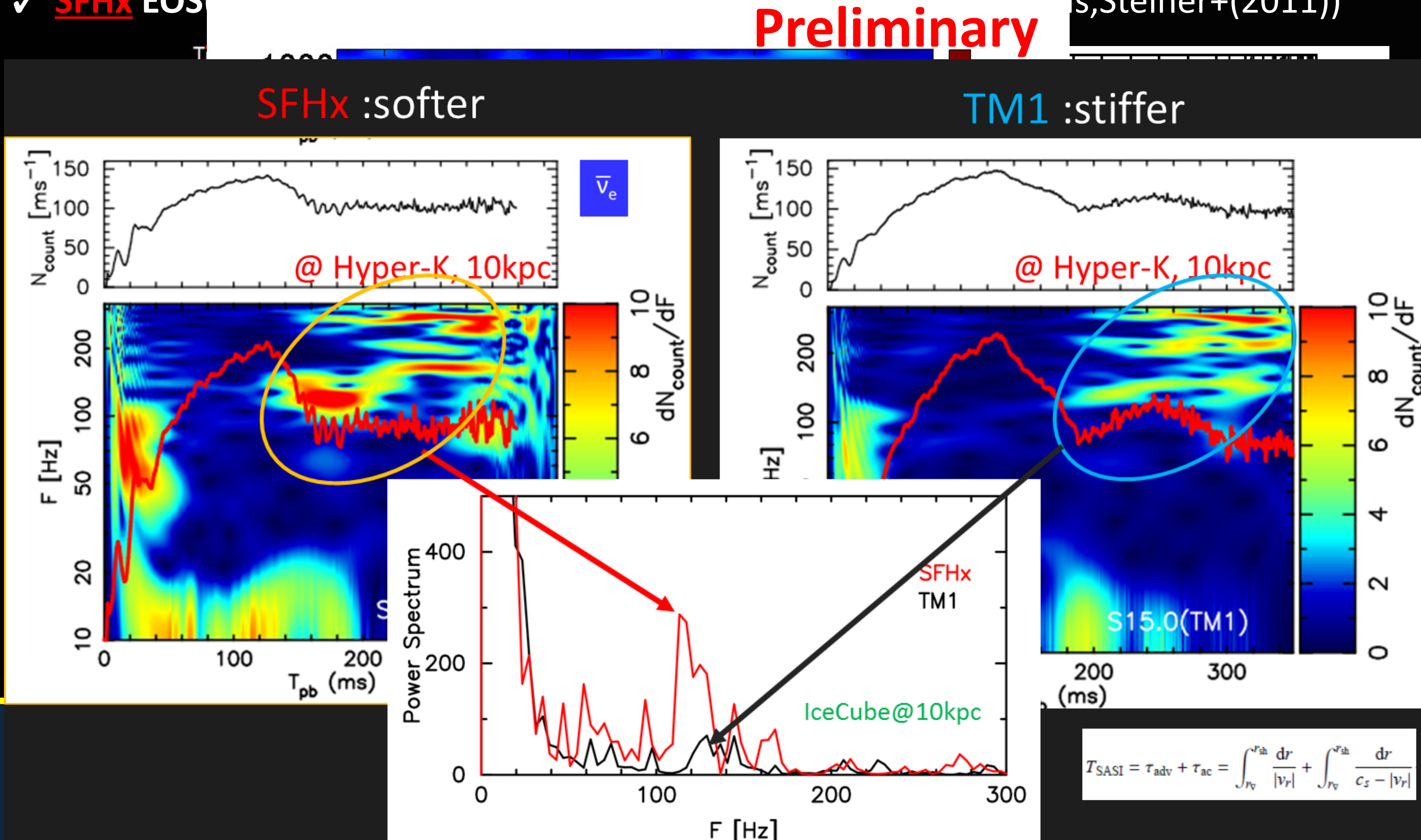

$$T_{SASI} = \tau_{adv} + \tau_{ac} = \int_{r_\nu}^{r_{sh}} \frac{dr}{|v_r|} + \int_{r_\nu}^{r_{sh}} \frac{dr}{c_s - |v_r|}$$

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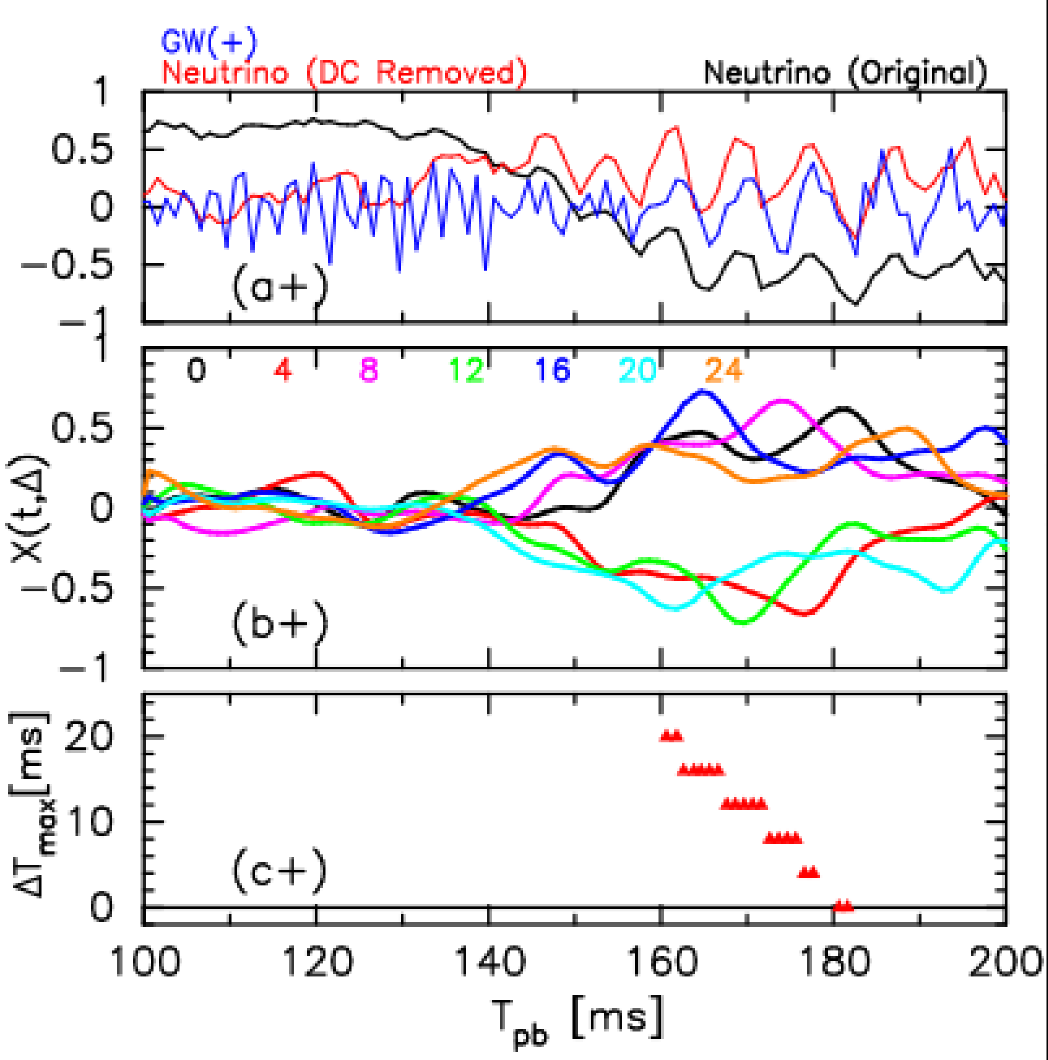
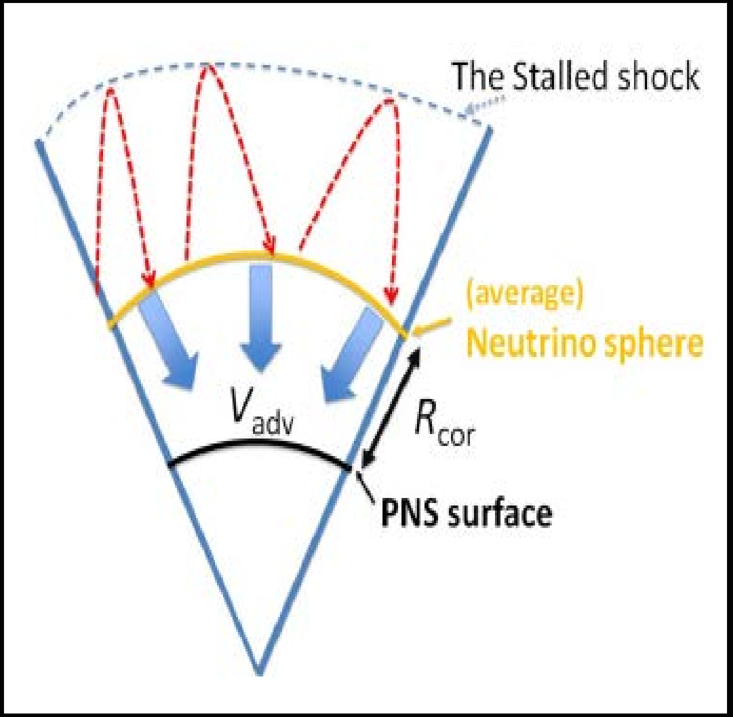
Correlation between GWs and neutrinos with strong SASI activity (15 M_{sun} + SFHx)

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

Kuroda, KK, Hayama, Takiwaki (2017, ApJ)





$\Delta T_{max} \sim R_{cor} / V_{adv}$

$\sim O(10)$ km/($10^{7\sim8}$ 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

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

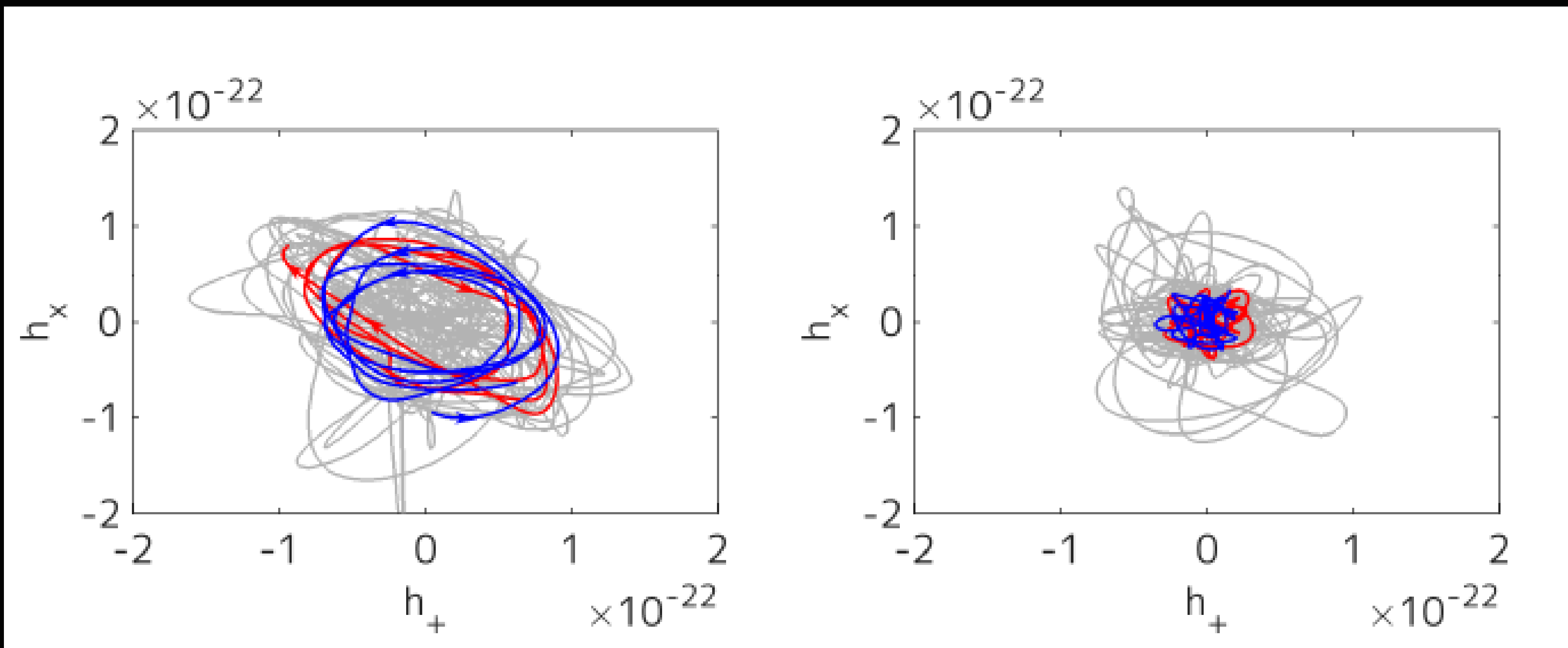
$$h_R := (h_+ - \mathrm{i}h_\times)/\sqrt{2}$$

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

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

SFHx (Strong SASI)

TM1 (stiff, Weak SASI)



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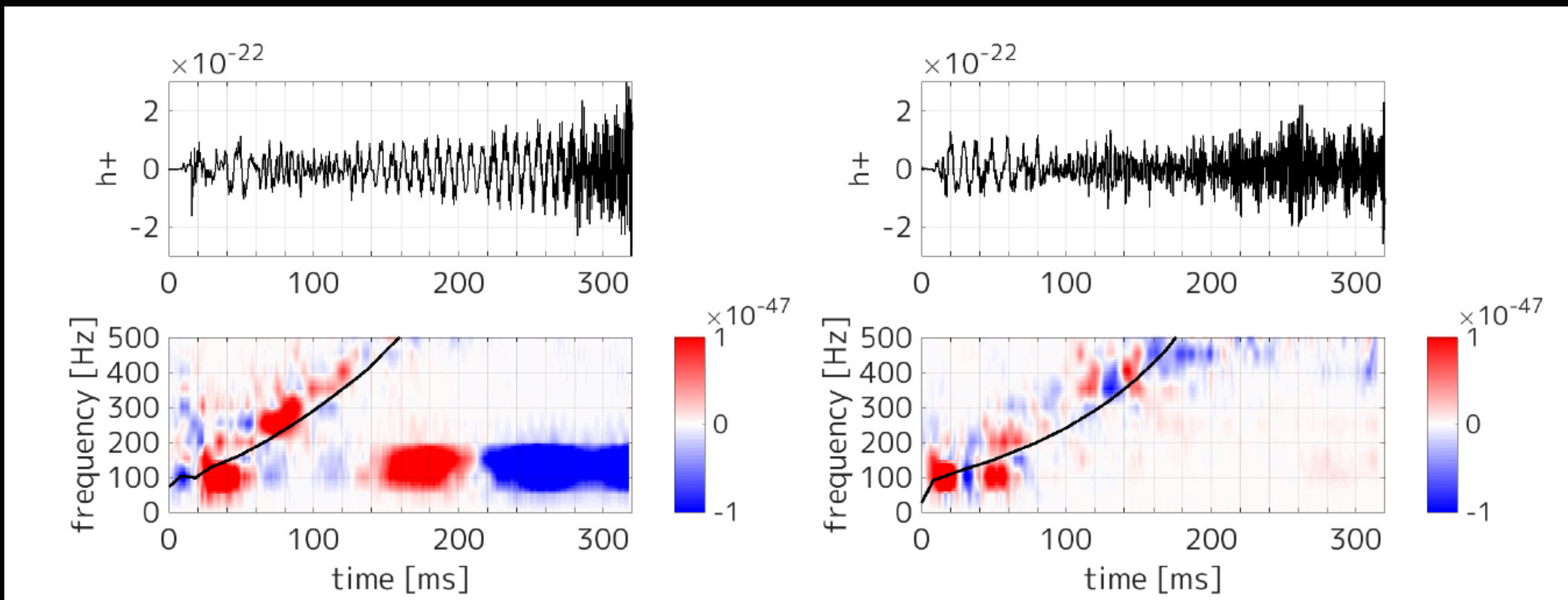
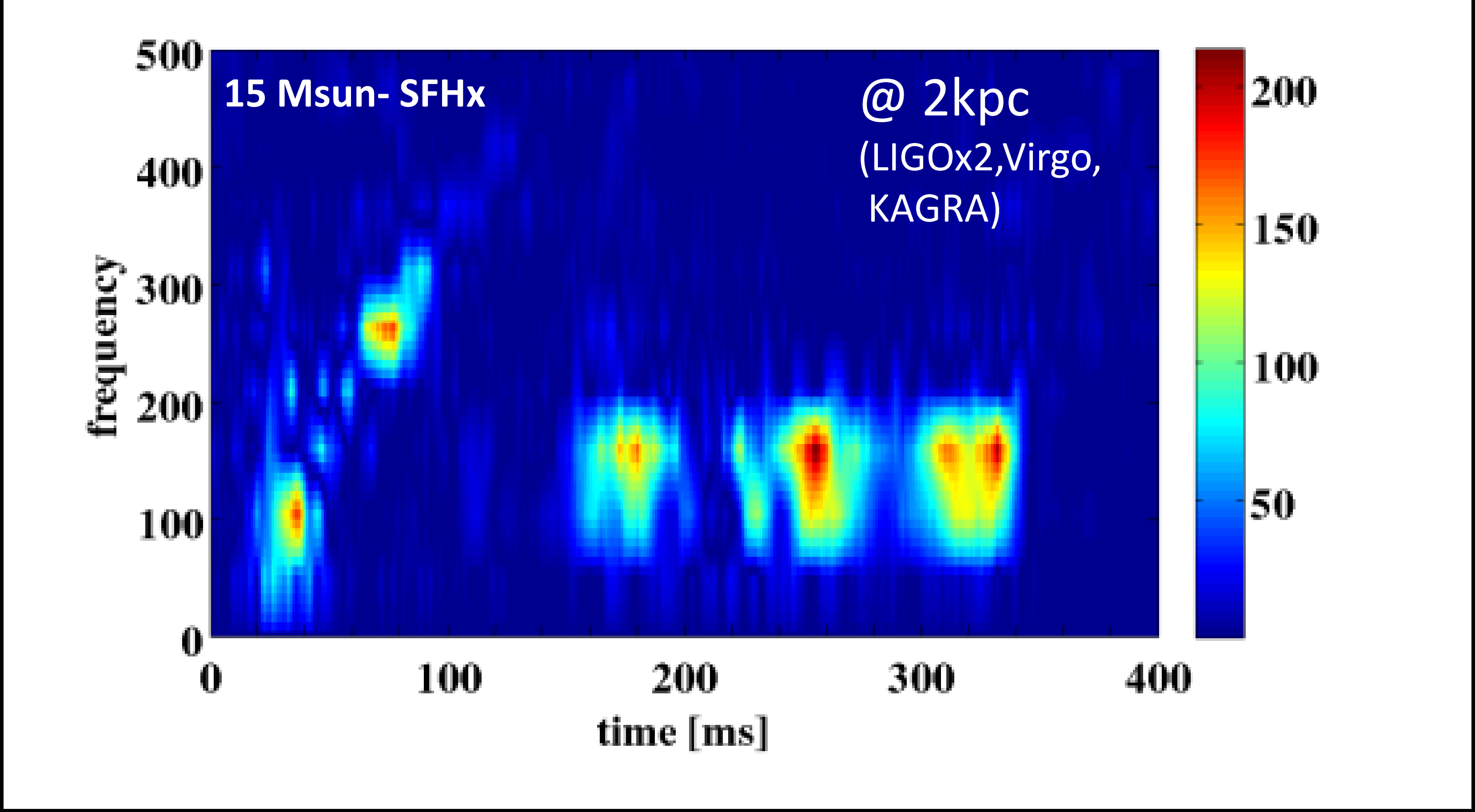


If the SASI is active in the supernova core, clear signature of Circular Polarization of GW !
⇒ indication of SASI motions non-spherical mass accretion (Hayama et al, MNRAS (2018))

SNR of Circular Polarization of GW relative to background



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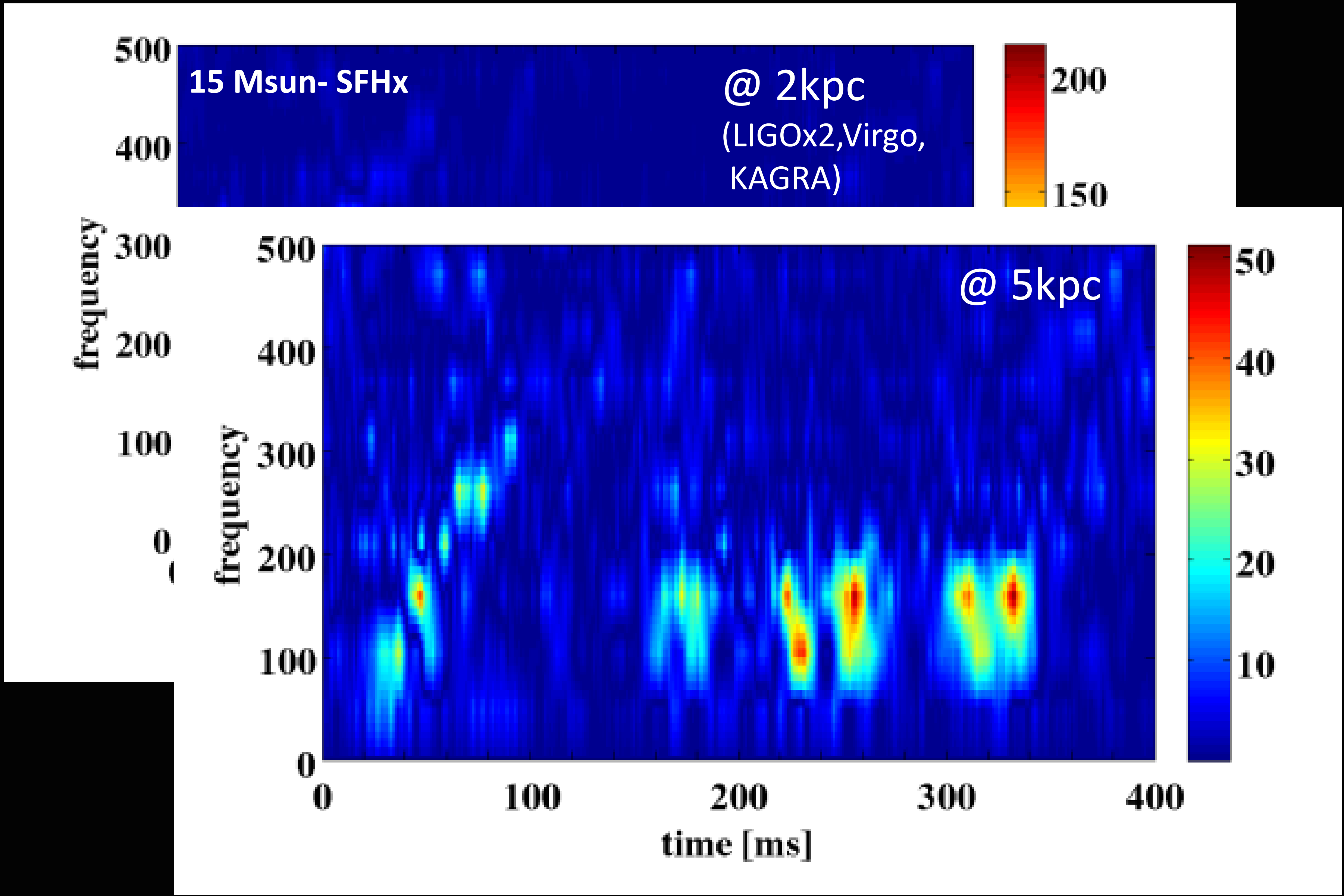

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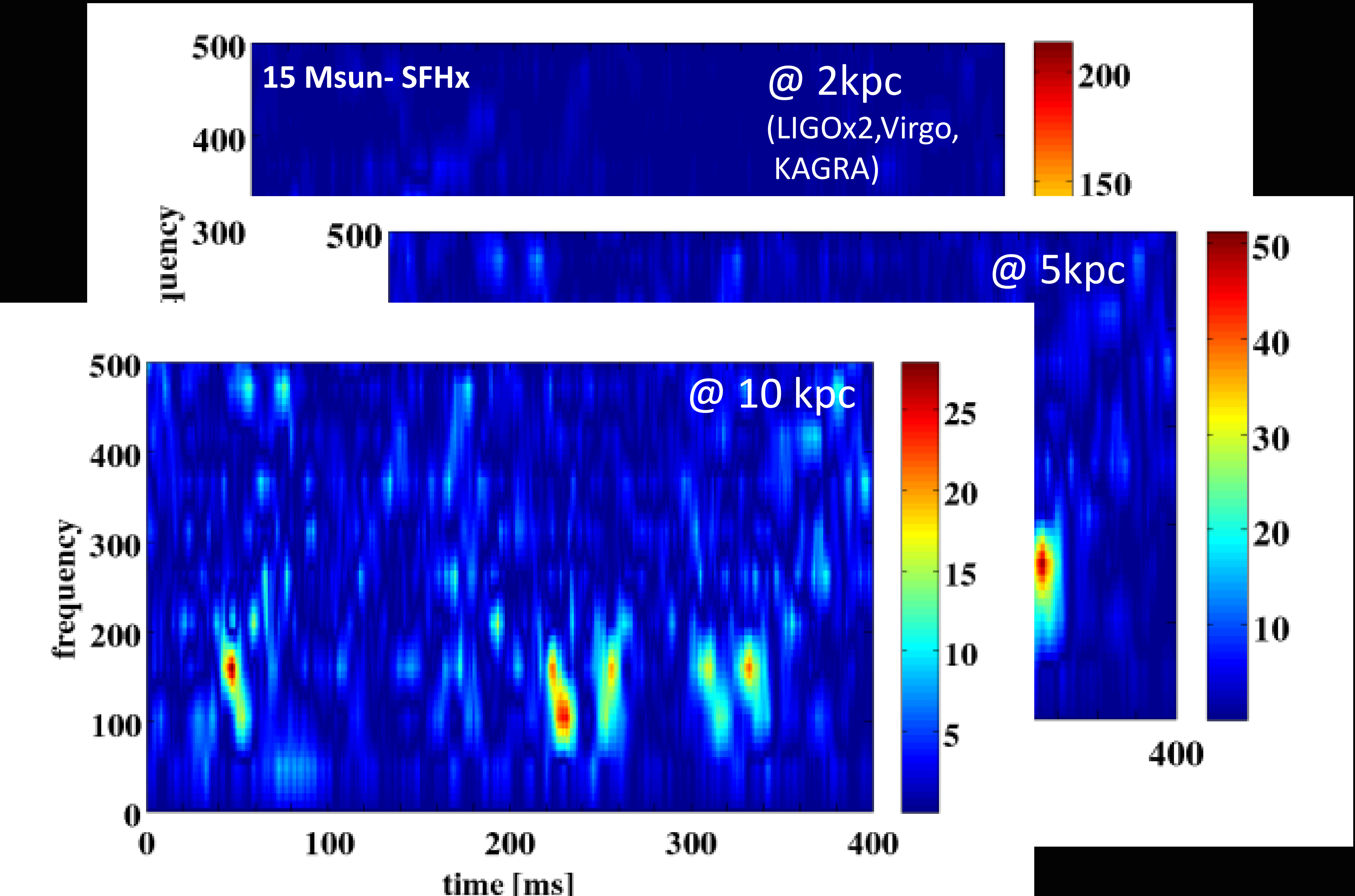

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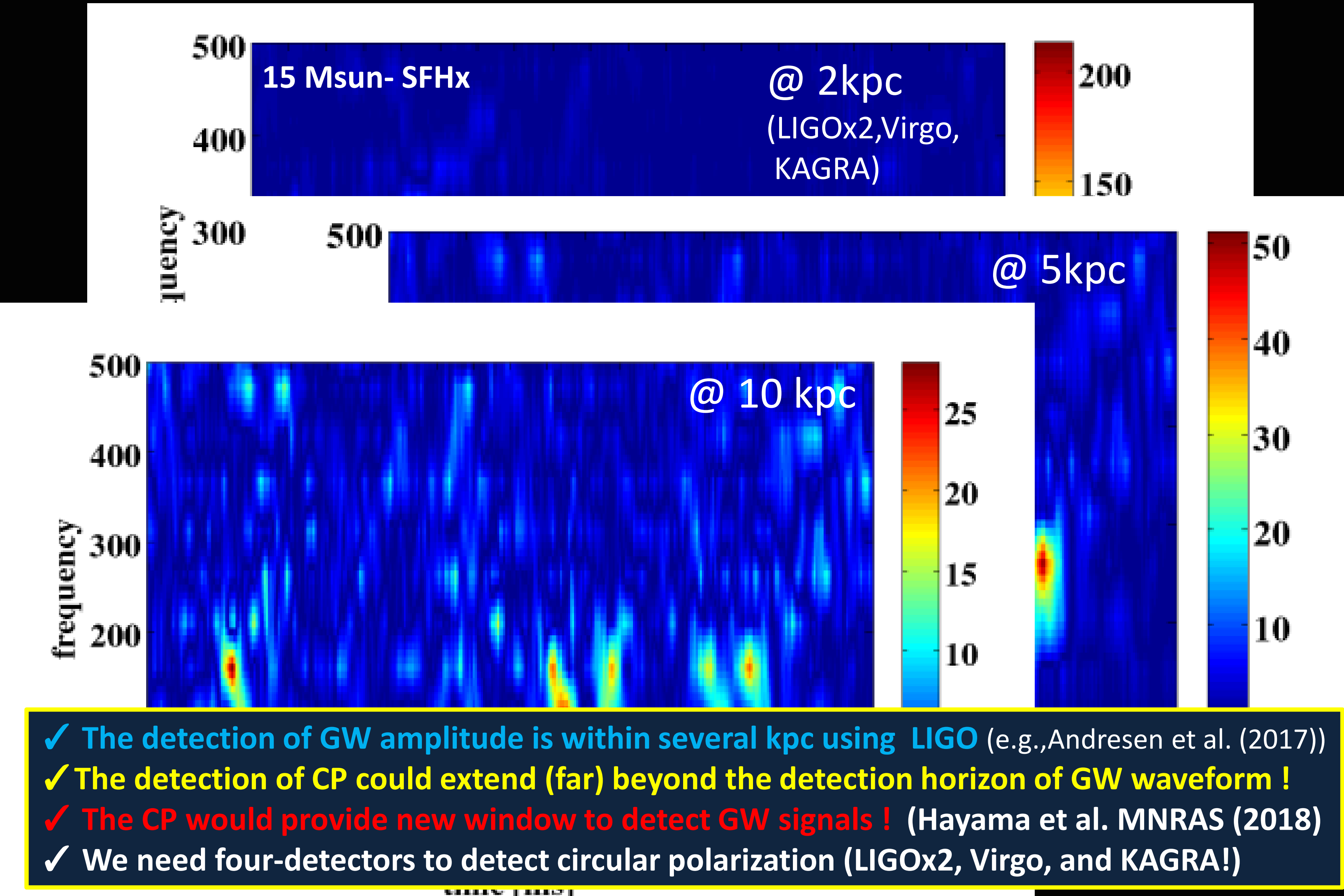
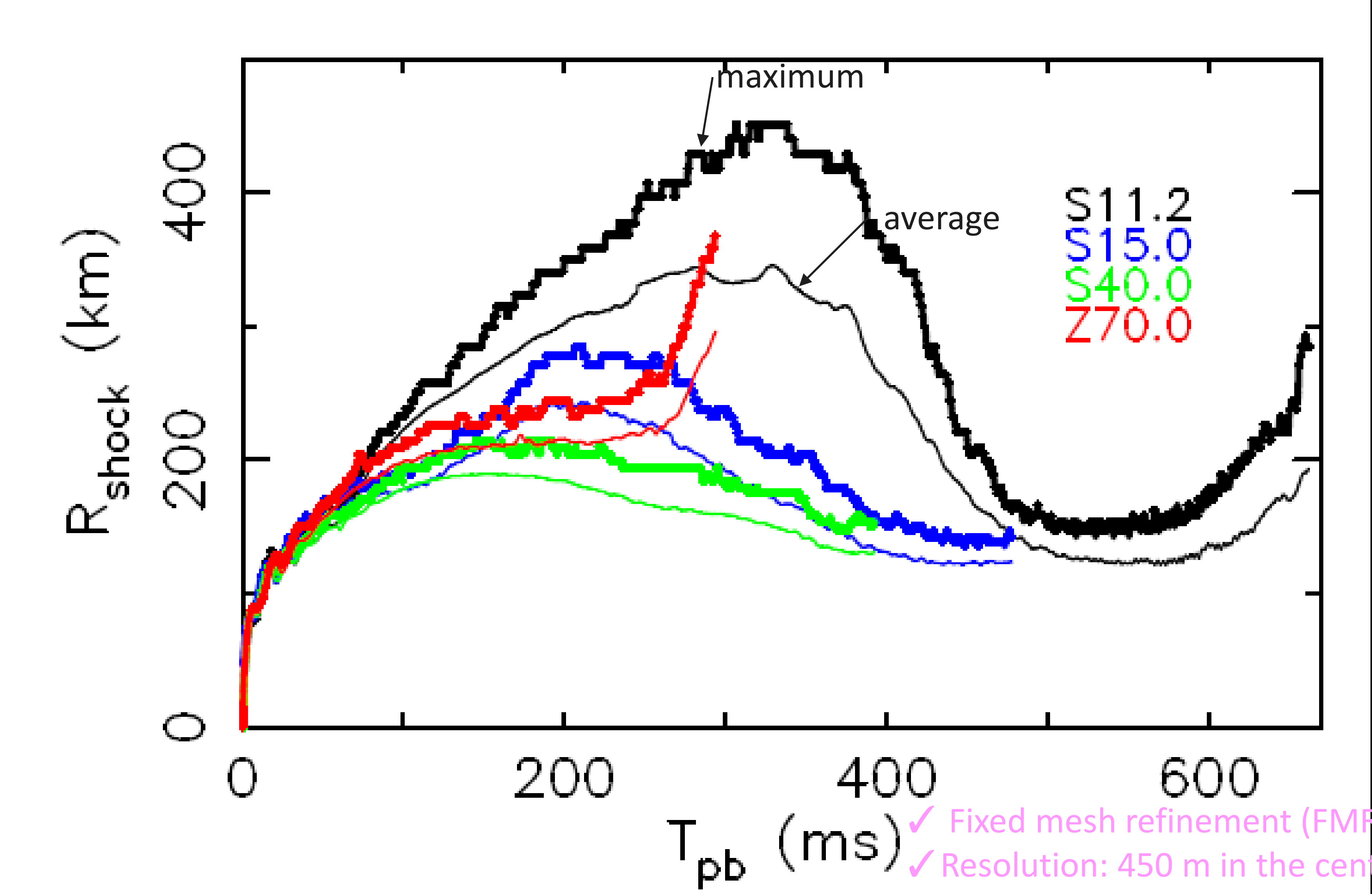


- ✓ The detection of GW amplitude is within several kpc using LIGO (e.g.,Andresen et al. (2017))
- ✓ The detection of CP could extend (far) beyond the detection horizon of GW waveform !
- ✓ The CP would provide new window to detect GW signals ! (Hayama et al. MNRAS (2018)
- ✓ We need four-detectors to detect circular polarization (LIGOx2, Virgo, and KAGRA!)

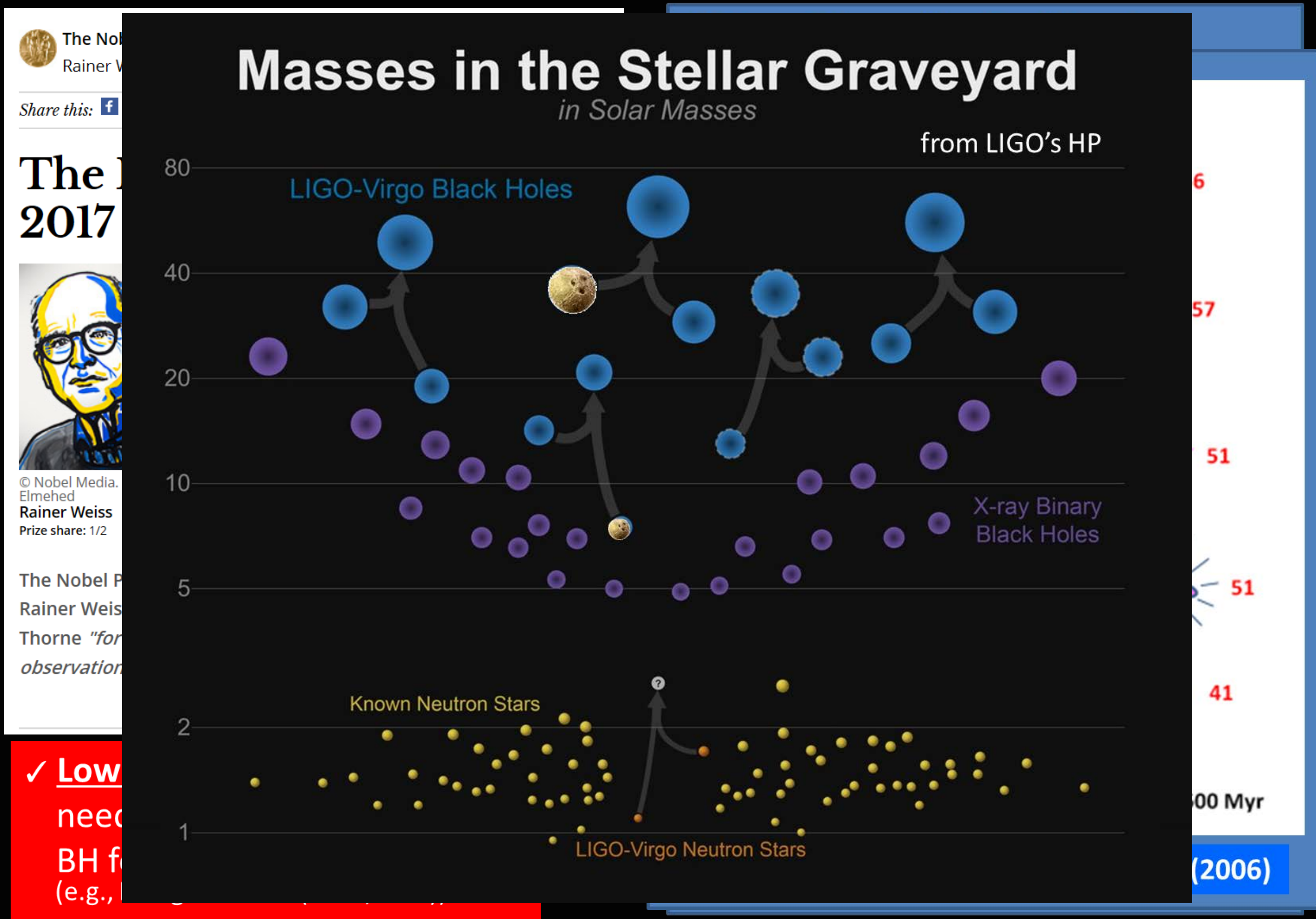
Preliminary FUGRA results for 4 progenitors: Kuroda, KK, Takiwaki to be submitted

✓ 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)



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

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



The Origin of the Nobel-Prize-awarded 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

Rainer Weiss
Prize share: 1/2

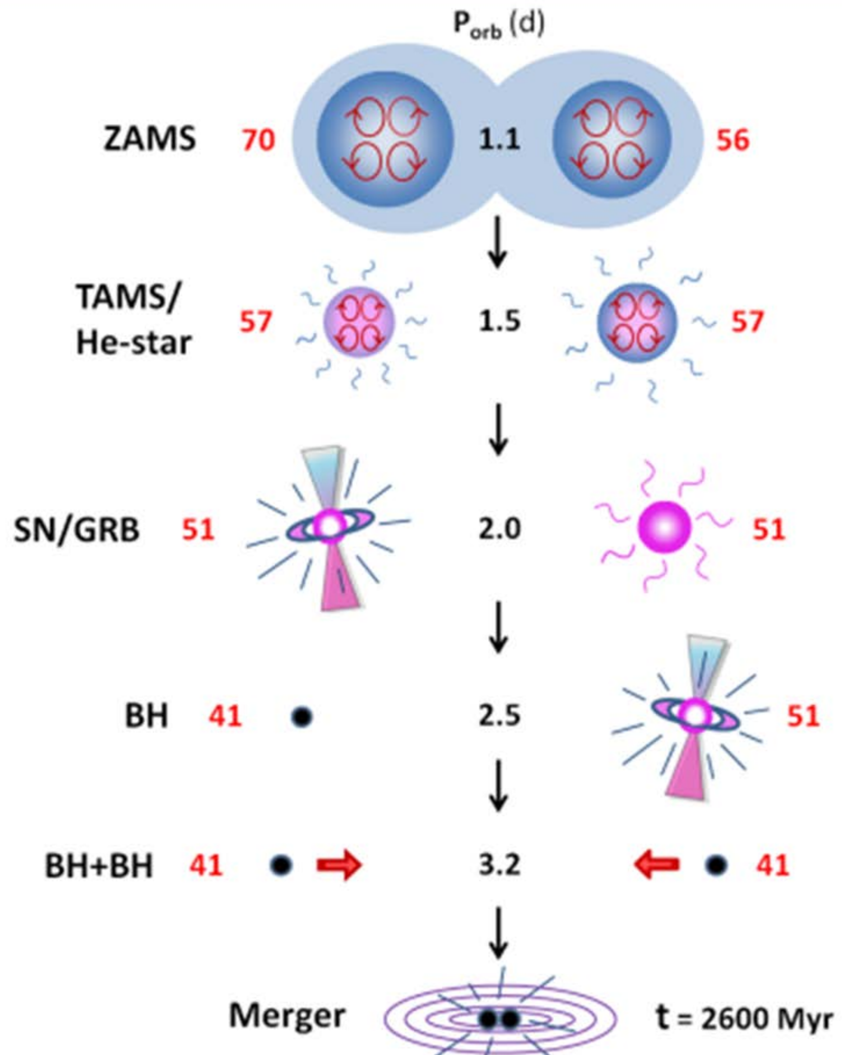
Barry C. Barish
Prize share: 1/4

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"*.

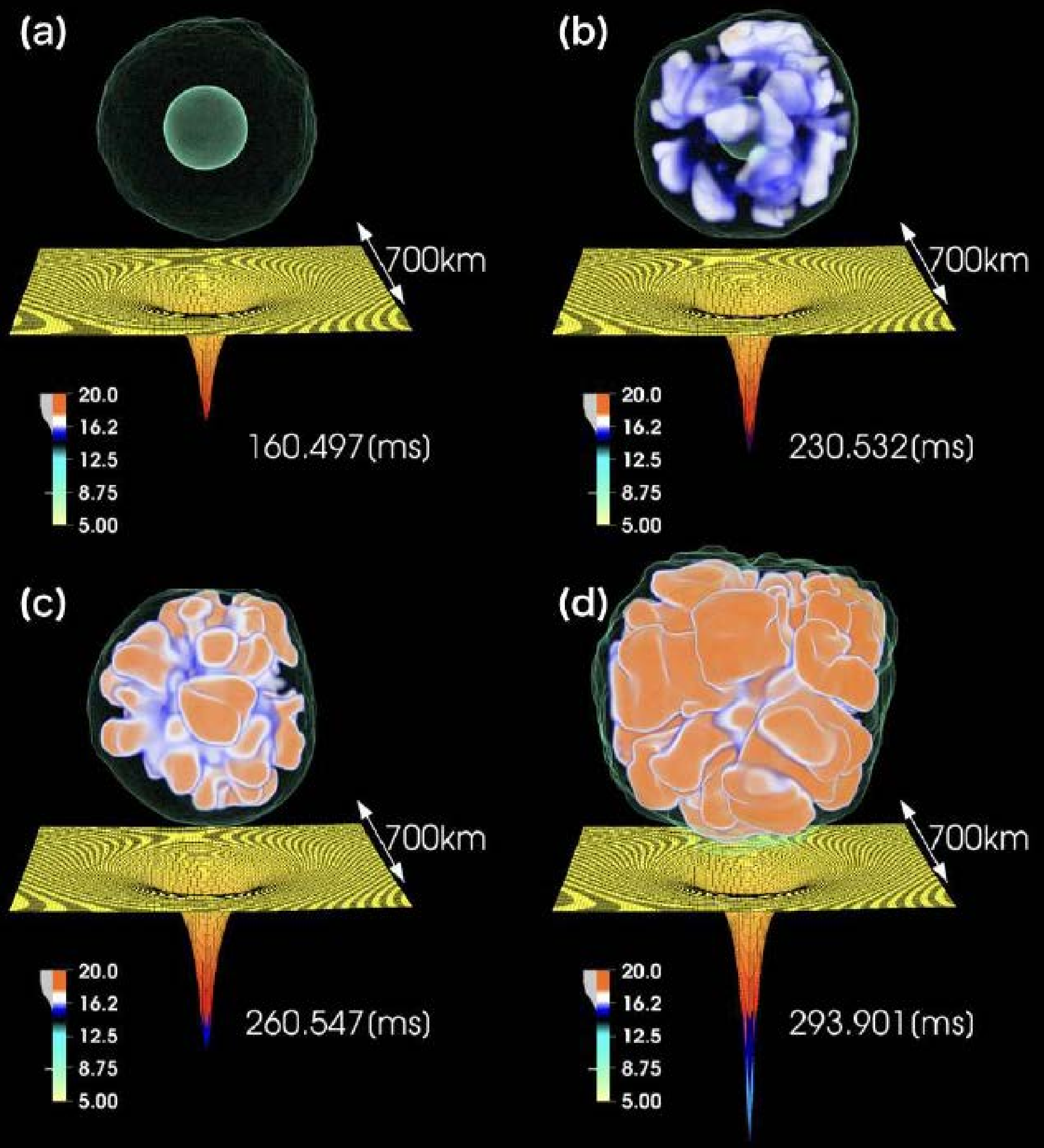
✓ **Low metallicity** environment needed for large stellar mass BH formation.
(e.g., Kinugawa et al .(2014,2016))

✓ 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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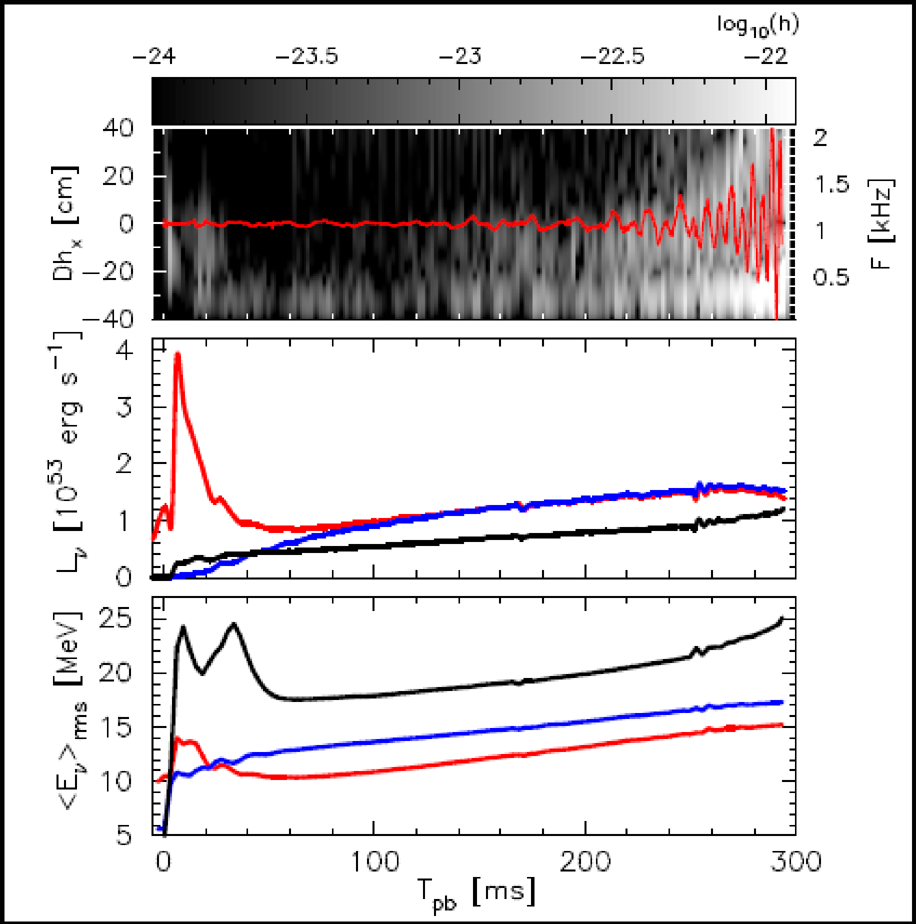

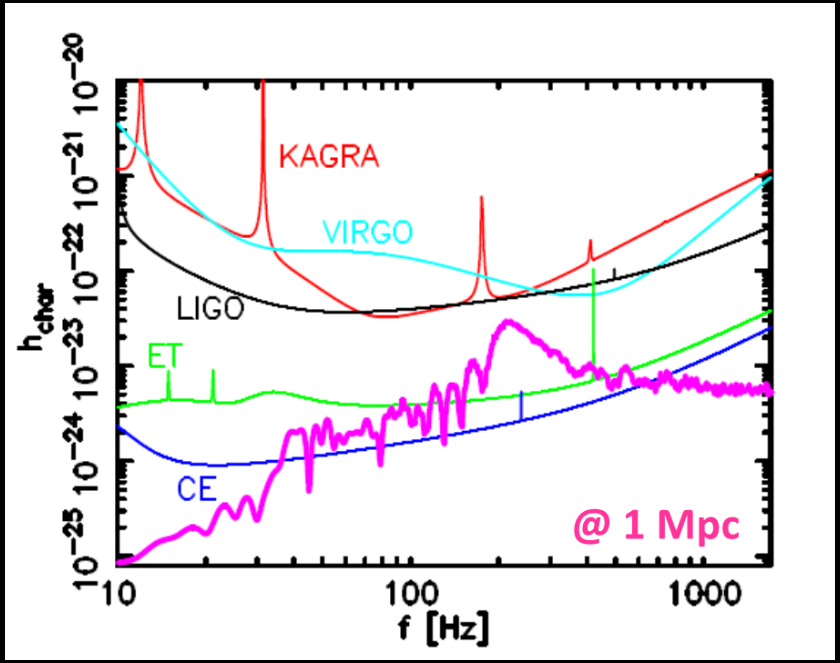

- ✓ "**Earliest BH formation**" after bounce (∼300 ms postbouce) !
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.
  (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Fischer+ (2009), Huedepohl+(2016))
- ✓ Strong GW emission is visible to 1 Mpc, **but not**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

Summary

✓ **SASI leads to characteristic time modulation in both GW and neutrino signatures**.

✓The GW signal is in the sweat spot of GW detectors (~100 Hz)!
detectable to ~10 kpc by third-generation detectors (CE, ET)
(Kuroda, KK, Takiwaki ApJ (2017), Kuroda, KK, Takiwaki, (2016), ApJL)

✓ **Circular Polarization** : could be a new tool to detect GWs.

- The Stokes "V" parameter : a measure of SASI activity.
- We need KAGRA for detecting CP !

(Hayama, Kuroda, KK, Takiwaki, MNRAS Letters (2018))

✓ **First 3D-GR simulation** with multi-energy transport where we've followed the hydrodynamics up to **BH formation.**

(Kuroda, KK, Takiwaki, Thielemann, MNRAS Letters (2018))

- 11.2 M_{sun} star is trending toward an explosion.

Thanks!