SN Gravitational-waves at the "crossroads": Synergetic analysis with SN neutrinos

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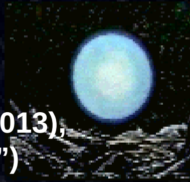
SN neutrinos at the crossroads @ ECT* May, 2019

Gravitational Waves (GWs) from Stellar Collapse



(see reviews in Ott (2009), Fryer & New (2011), Kotake (2013), Kotake and Kuroda (2016) in “Handbook of Supernovae”)

GW amplitude from the quadrupole formula

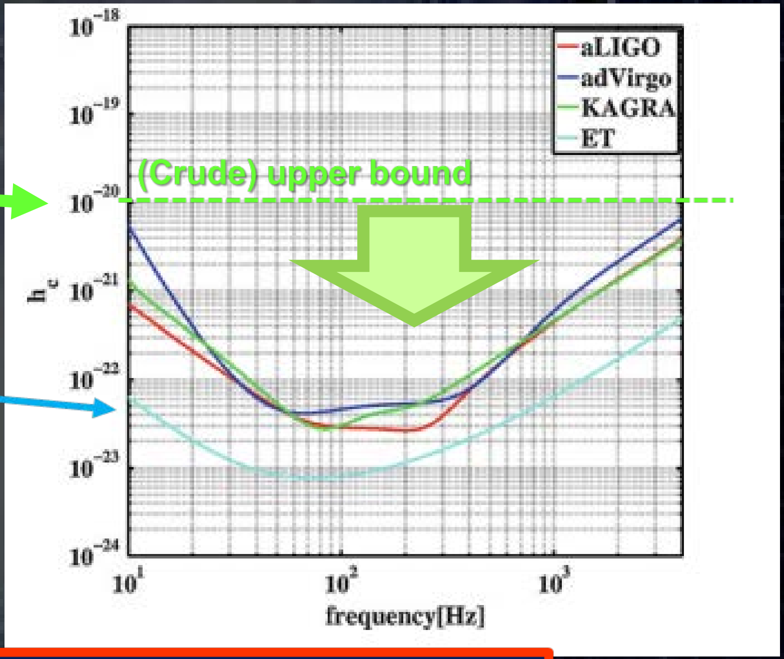
$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2} Q_{ij} \sim \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

Quadrupole moment

Typical values at the formation of Neutron Star (NS)

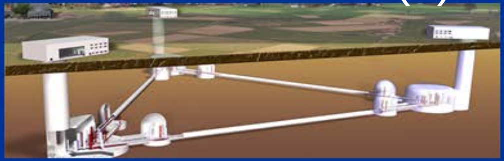
$$R_s = 3\ \mathrm{km}\left(\frac{M}{M_\odot}\right) \quad v/c = 0.1 \quad R = 10\ \mathrm{kpc}$$

$$h \sim 10^{-20}$$



Good news ! (Future)

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



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

✓CCSN event in our galaxy (several/century) is primary target !

More correctly..

$$h_{ij} = \epsilon \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

ϵ : the degree of anisotropy.

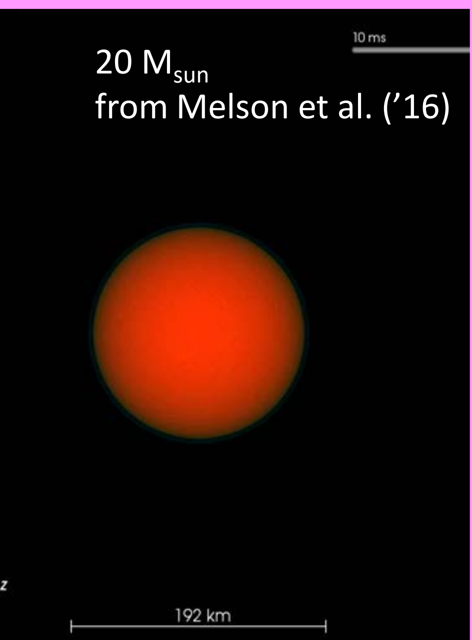
If collapse proceeds spherically, $\epsilon = 0$ no GWs !

What makes the SN-dynamics deviate from spherical symmetry is essential for the GW emission mechanism !

Two candidate mechanisms of core-collapse supernovae

(Reviews in Janka ('17), Müller ('16), Foglizzo+('15), Burrows('13), Kotake+ ('12), Mezzacappa('05))

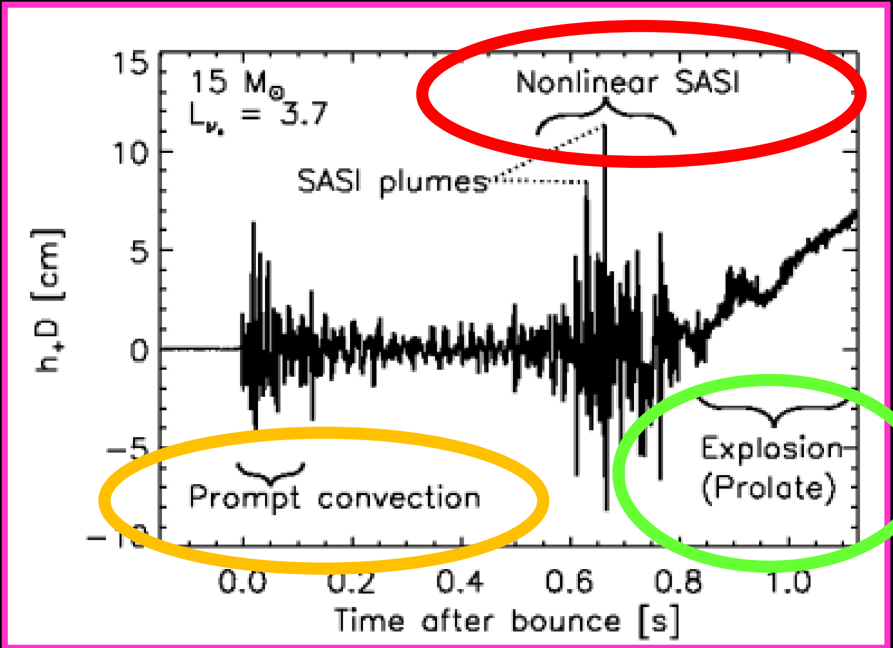
	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s)	Rapidly rotation with strong B ($\Omega_0 > \sim\pi$ rad/s, $B_0 > \sim 10^{11}$ G)
Key ingredients	✓**Turbulent Convection and SASI** (e.g., Kazeroni, Guilet, Foglizzo, (2017)) ✓**Precollapse Inhomogenities/structures** (e.g., B.Mueller et al. (17), Suwa & Mueller (16)) ✓**Novel microphysics:** Bollig+(17), Fischer+(18)	✓**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	Main players	~<1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)



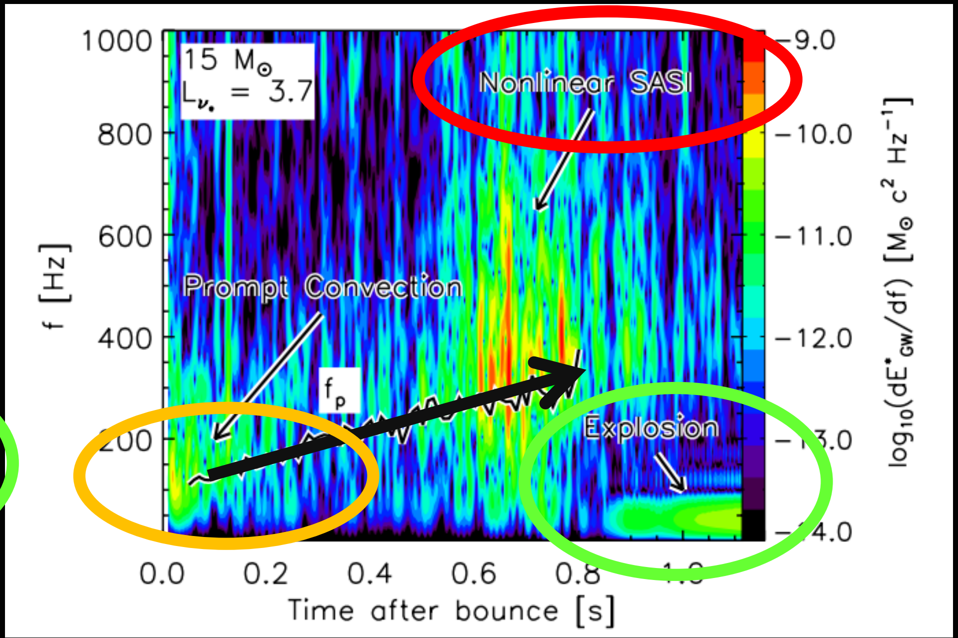
(see also, Burrows et al. ('17), Melson et al. ('15), Lentz et al. ('15), Roberts et al. ('16), B. Mueller ('15), Takiwaki et al. ('16))

GW signatures from neutrino-driven explosion: how to detect ?

Waveform from Murphy et al. (2009) ApJ



✓ GW spectrogram



(Later confirmed by B. Mueller et al. (‘13), ApJ,
Yakunin et al. (2015), PRD) ,Andresen+(17,19) MNRAS

✓ **Three generic phases** **in neutrino-driven models:**

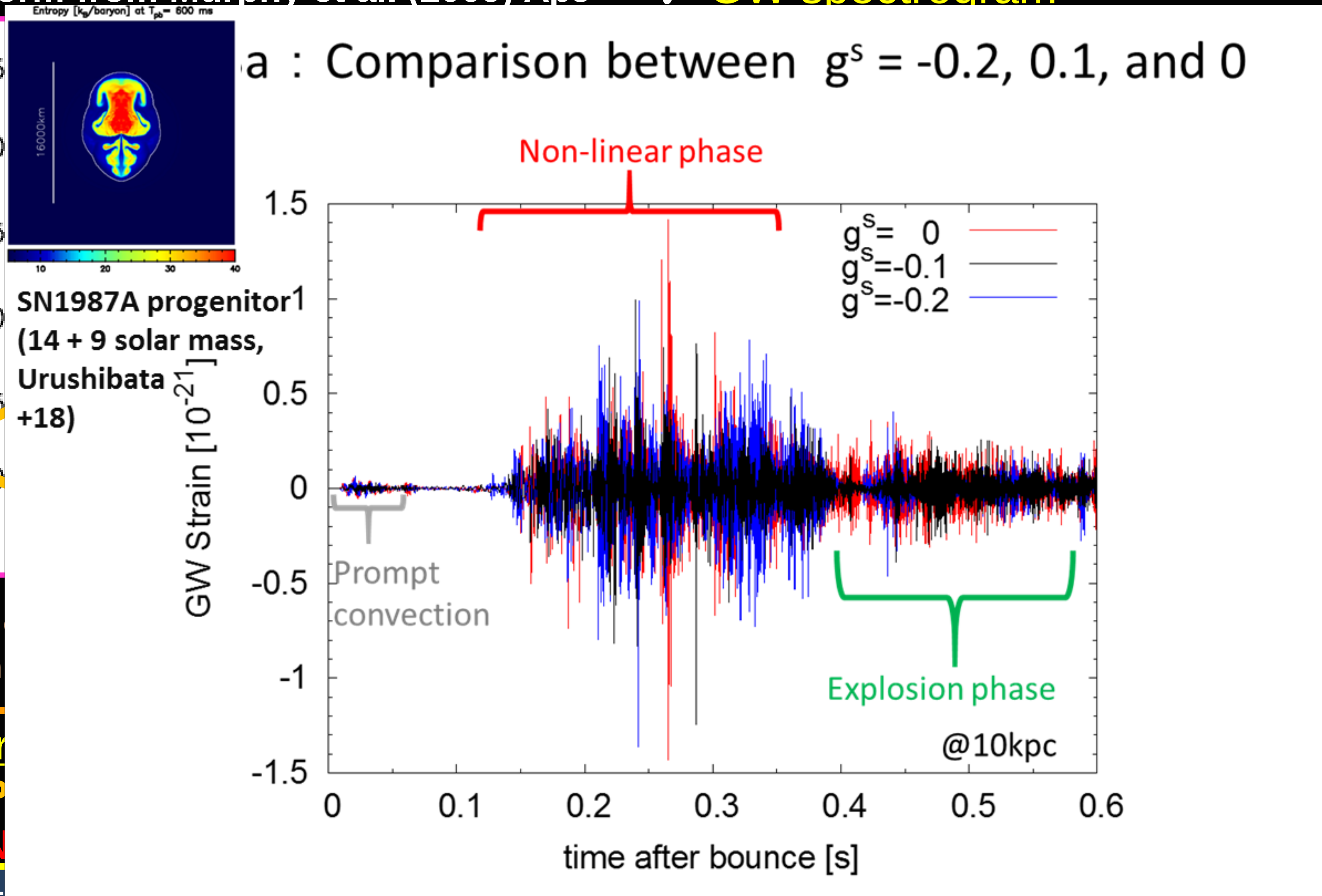
1. **Prompt-convection phase : within ~50 ms post-bounce**
2. **Non-linear phase (Convection/SASI) : Downflows hit he PNS surface**
3. **Explosion phase : Long-lasting signal but terminates if BH forms**

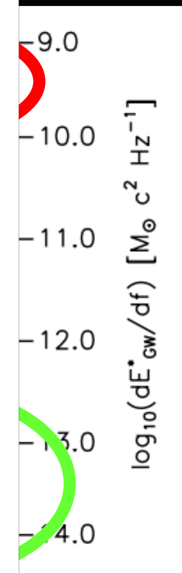
(Müller et al. (2004, ApJ), Cerda-Duran et al. (2013, ApJ))

✓ **Waveforms have no template character: stochastic explosion processes.**

GW signatures from neutrino-driven explosion: how to detect ?

Waveform from Murphy et al. (2009) ApJ ✓ GW spectrogram





(Later ...
Yakun...

...ency
... of PNS

$\left(\frac{GM}{Rc^2}\right)^{3/2}$

...emperature
...ss of EOS
, R↘
f_p ↗

✓ **Thr...**
1. P...
2. N...

✓The three generic GW phases commonly observed for models with different g^s.

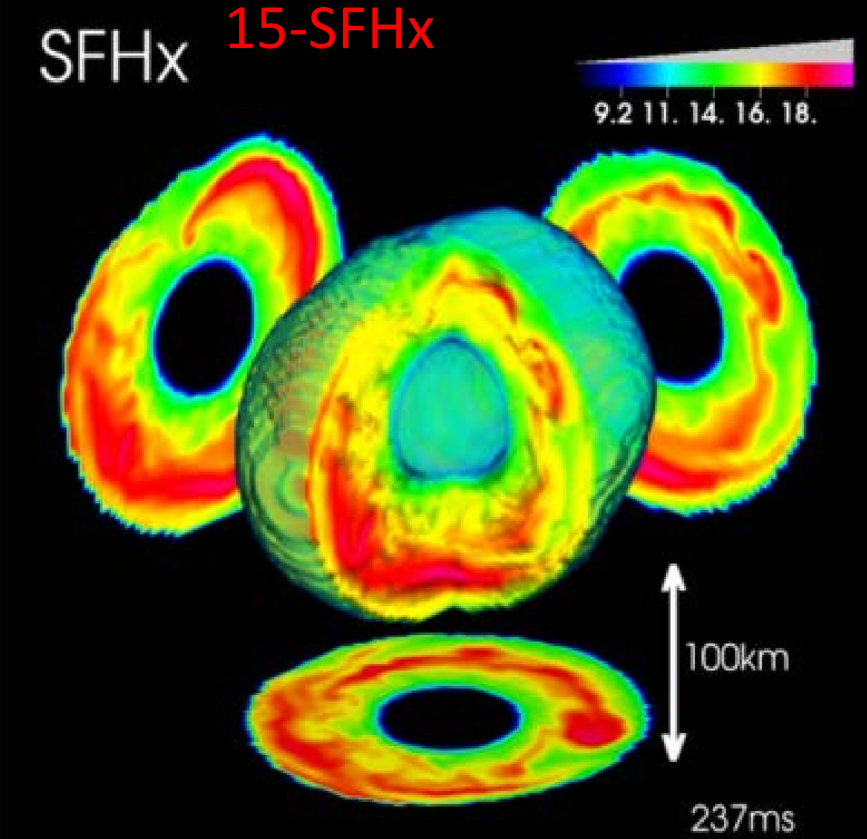
✓ (Wi... !
✓ Se... .
✓ On top of f_p , the high frequency component comes from strong downflows to PNS.
✓ **These qualitative features : Common to more recent 2D and 3D models** !

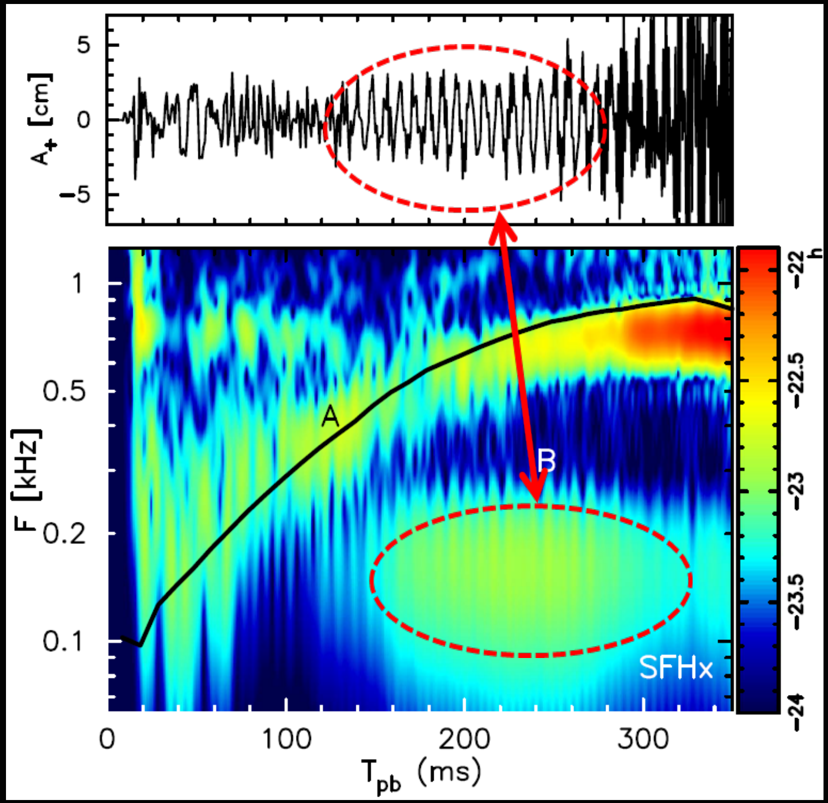
GW and neutrino signatures from 3D-GR models showing strong SASI activity

(from **Kuroda, KK, & Takiwaki ApJL (2016), see also Andresen, B, E Müller and Janka (2017,19))**

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

15-SFHx



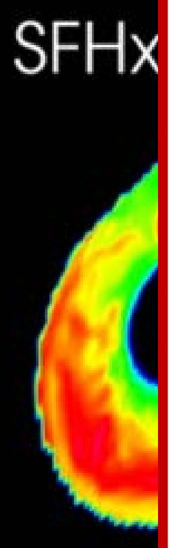


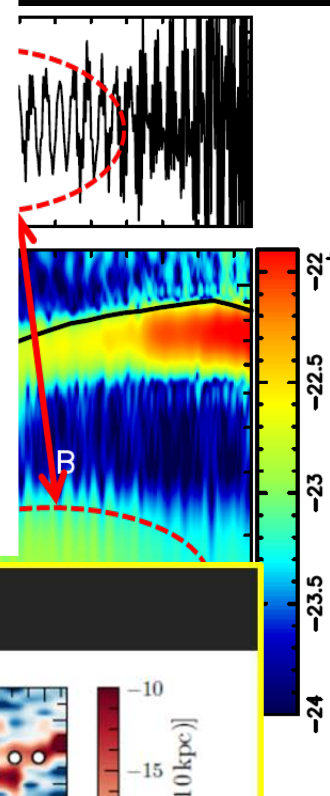
- ✓**The quasi-periodic modulation commonly observed in 3D models with SASI activity**
- ✓By coherent network analysis of LIGO, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc. Won't miss every Galactic events when **ET and CE are on-line (>2035).**
- ✓ **PNS Asteroseismology study has started ! (Morozova et al. (2018), Torres-Forne et al. (2017,2019), Sotani et al. (2017))**

GW and neu ... ASI activity

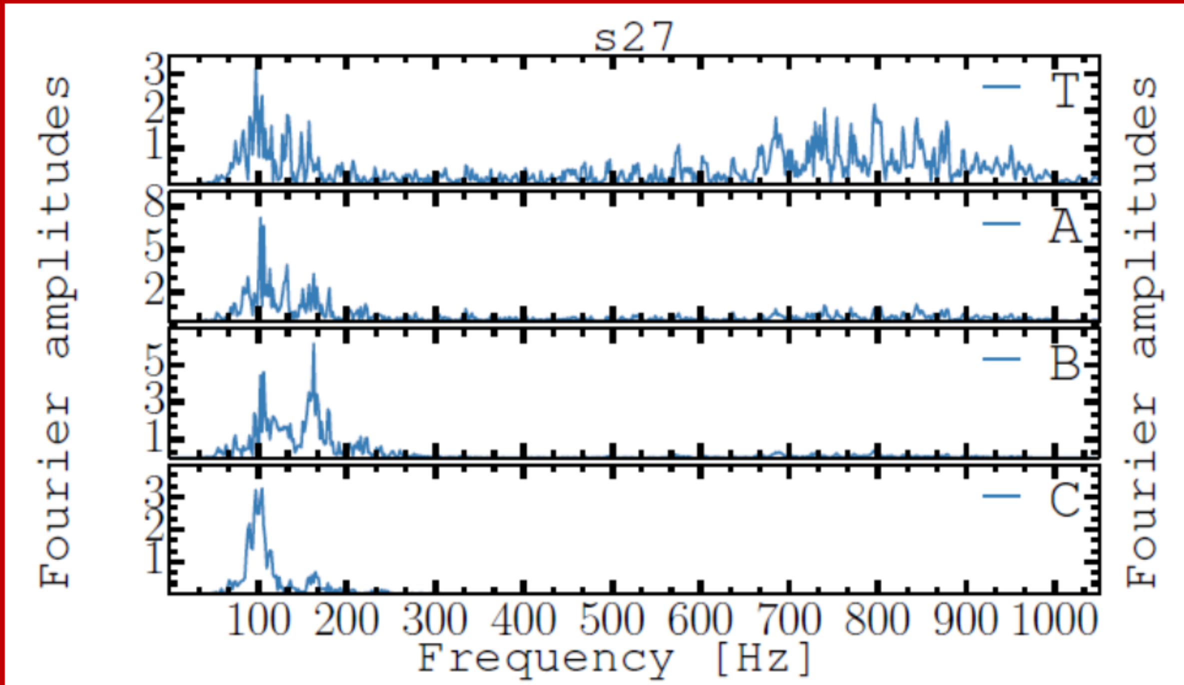
(from ... and Janka (2017,19))

✓ SFHx EC ... einer+(2011))

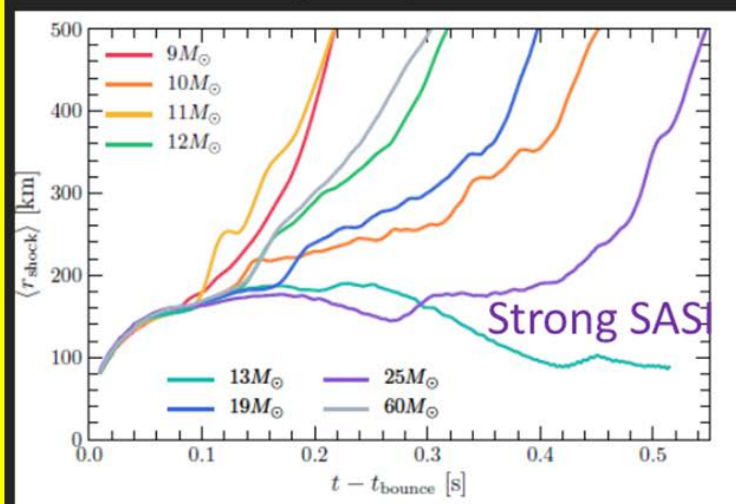


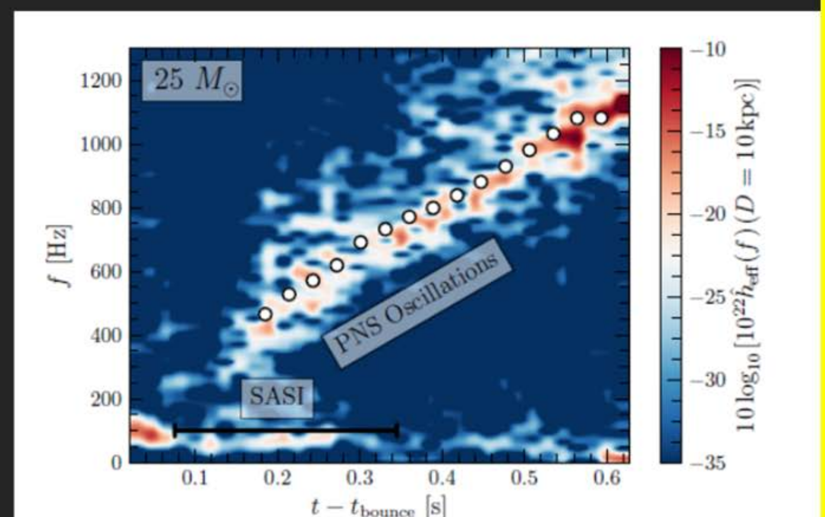


Andresen et al. (2017), MNRAS, GW spectra from 27 Msun



Radice et al. (2018) arXiv:1812.07703





✓ T ... ty

✓ I ...

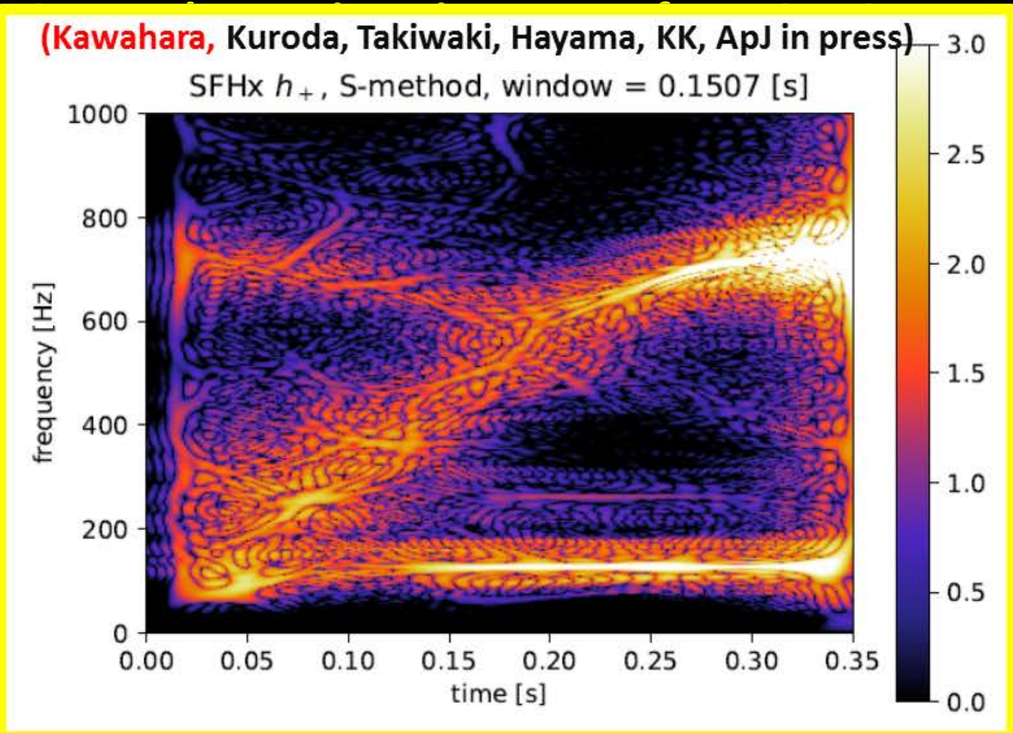
... 035).

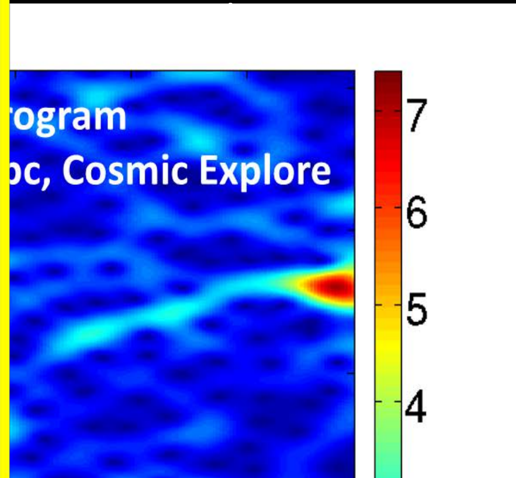
✓ ... et al.

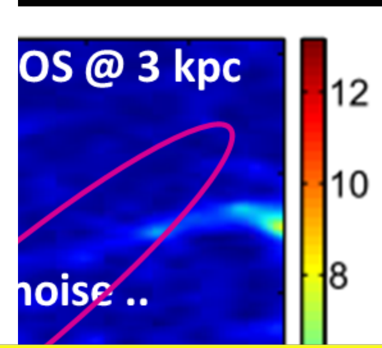
...els showing strong SASI activity

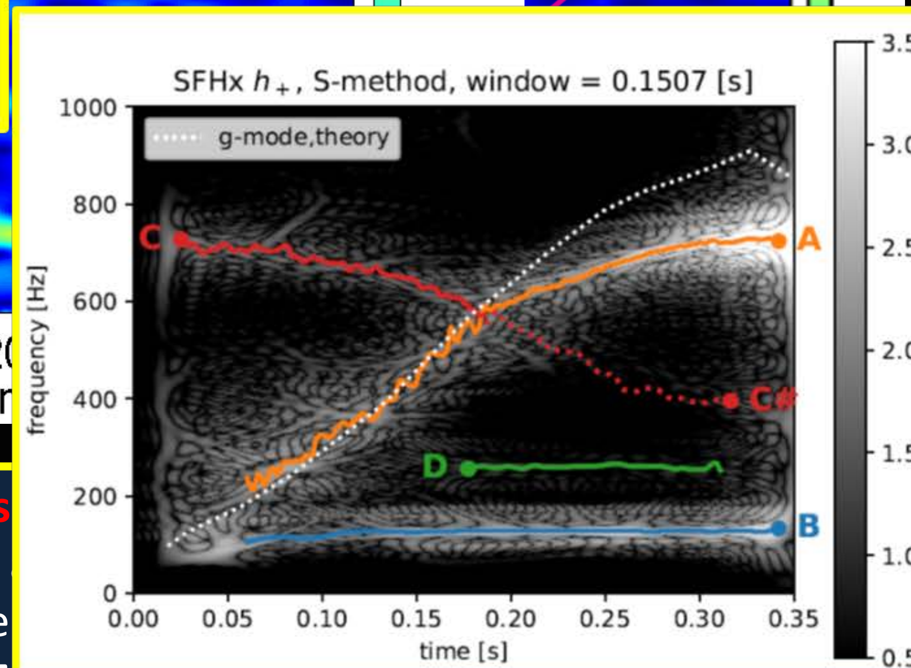
...also Andresen, B, E Müller and Janka (2017,19))

...er+(2011))









Four features in the GW spectrogram:

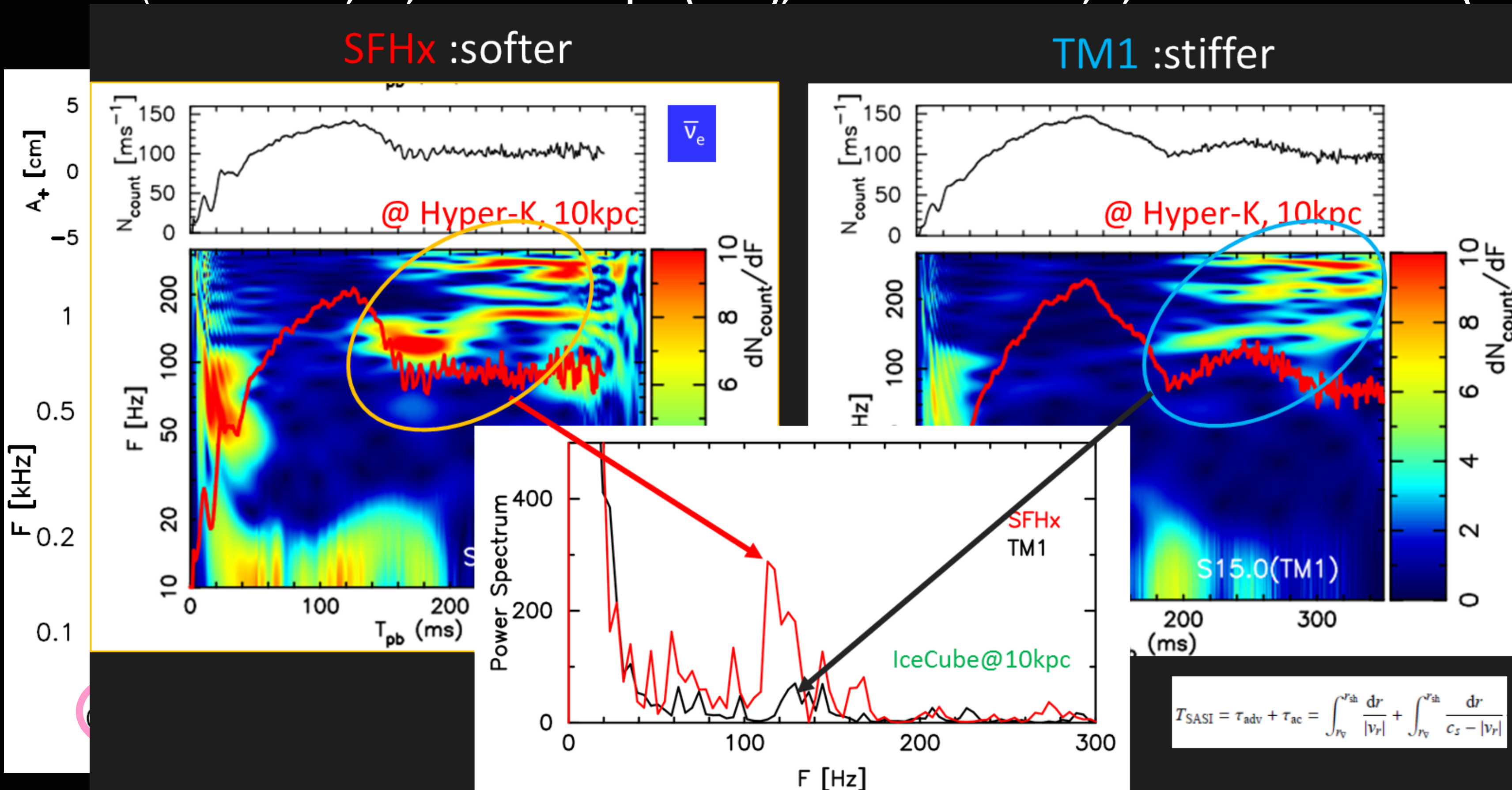
- ✓ A: Ramp-up buoyant mode (e.g., Andresen+(2017))
- ✓ C: (likely) g_2 mode of the PNS osciilation (Torres-Forne et al. (2018), MNRAS)
- ✓ B: Fundamental mode of SASI-induced GW $f_{GW\text{-}SASI}$ ~126-128 Hz
- ✓ D: Overtone of "B"

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

✓ **PNS Asteroseismology study has started ! (Morozova et al. (2018), Torres-Forne et al. (2017,2019), Sotani et al. (2017))**

GW and neutrino signatures from 3D-GR models showing strong SASI activity

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



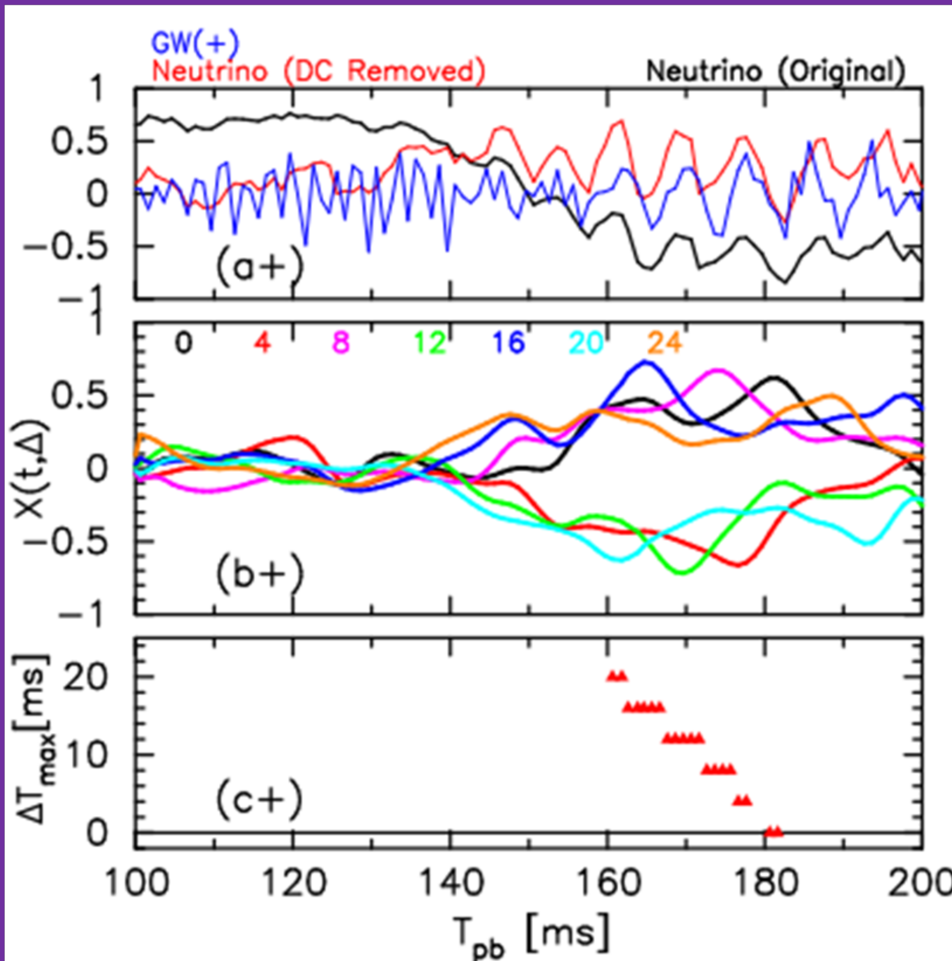
- ✓ **Detection of neutrinos (Super-K, IceCube) important to get timestamp of GW detection.**
- ✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (e.g., Tamborra et al. (2013,2014), Kuroda, KK et al. (2017, ApJ).
- ✓ **The simultaneous detection potentially tells the distance between the neutrino sphere and PNS radius！** (Need to follow long-term 3D evolution how long this continues)

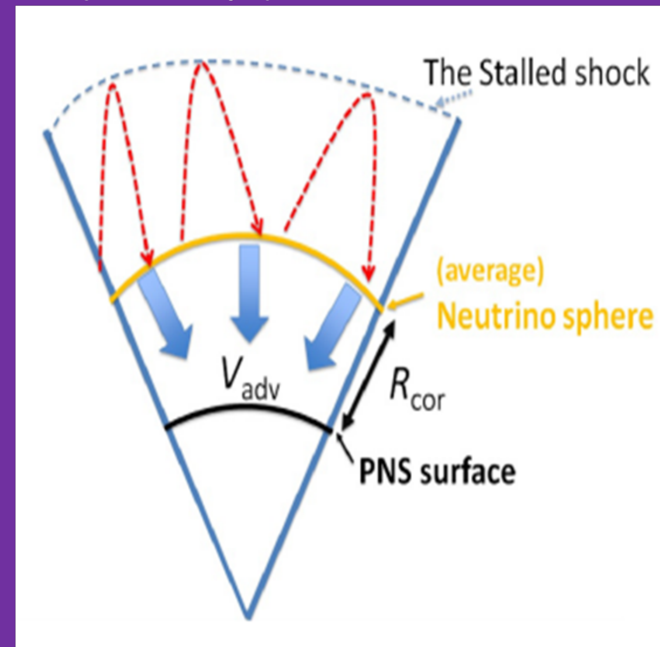
GW and neutrino signatures from 3D-GR models showing strong SASI activity

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 (incl. low T/|W|, spiral SASI)

Stokes Parameters:

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

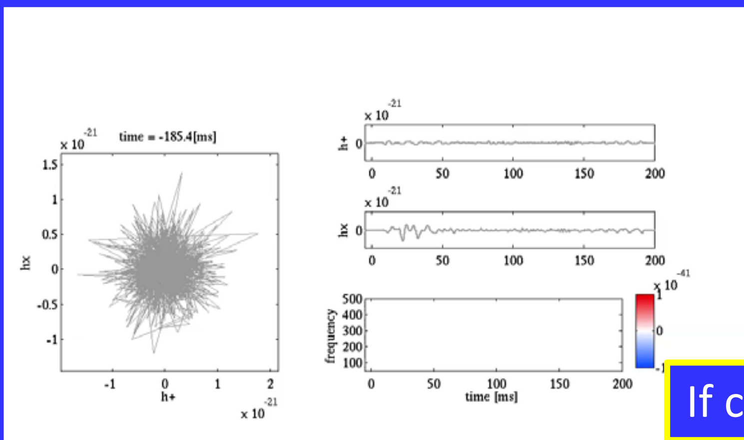
Hayama et al. (2016), PRL (see also Klimenko et al. (2015) PRD)

V parameter = Asymmetry of right and left modes

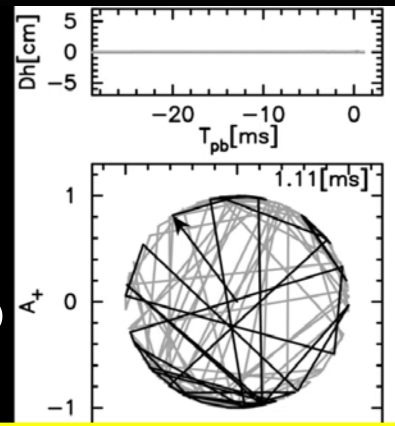
$$h_R := (h_+ - ih_\times)/\sqrt{2}$$

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

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

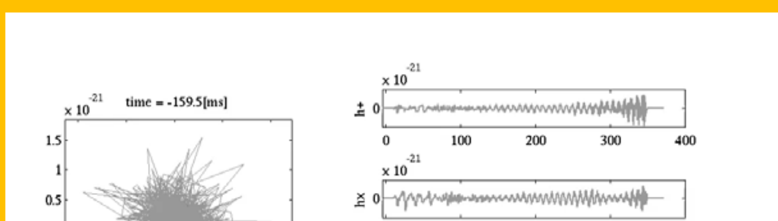


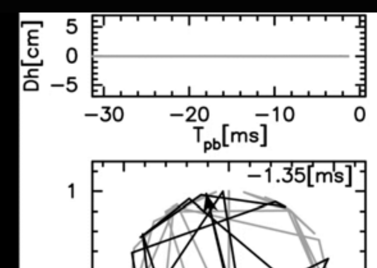
Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_\times$)



If convection-dominant, no clear signature of CP !

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





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. 2018)

⇒ **The detection horizon extends a few times than the GW waveform (due to low noise).**

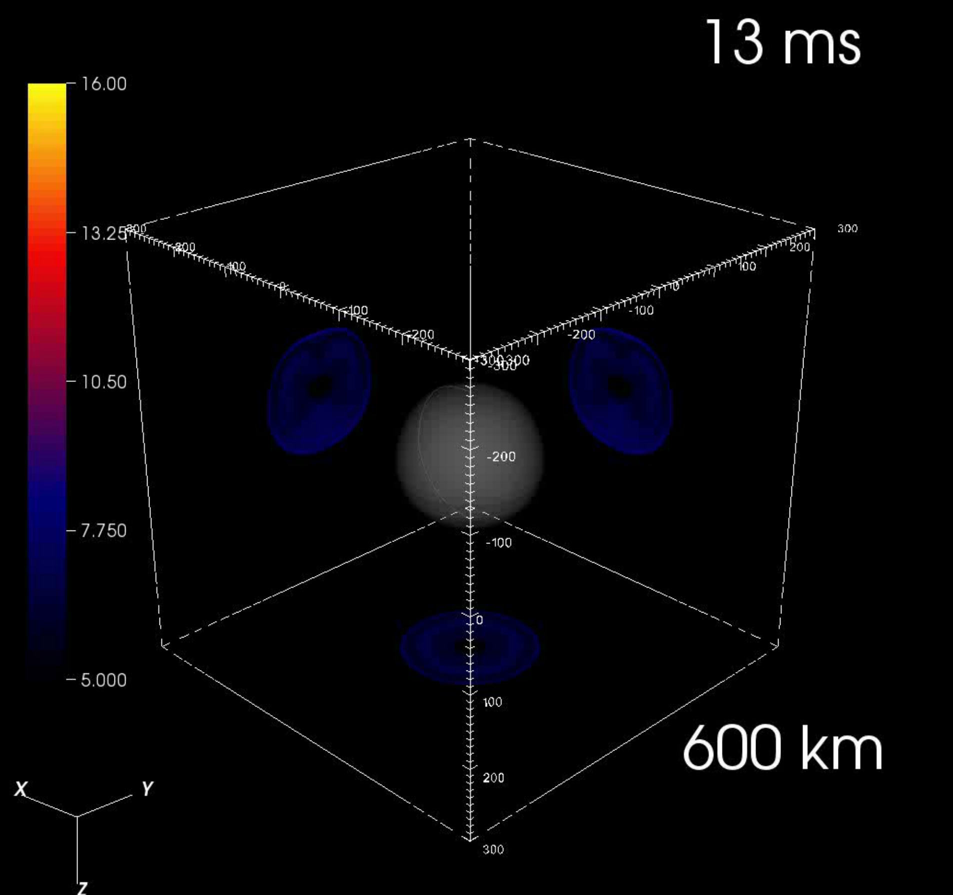
Switching gears to MHD mechanism (rapid rotation required !!)

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)).

KK, Takiwaki, Fischer, G.M. Pinedo+ (2018)

Model	Weak Process or Modification	References
set1	$\nu_e\, n \rightleftharpoons e^-\, p$	Bruenn (1985)
	$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Bruenn (1985)
	$\nu_e\, A' \rightleftharpoons e^-\, A$	Bruenn (1985)
	$\nu\, N \rightleftharpoons \nu\, N$	Bruenn (1985)
	$\nu\, A \rightleftharpoons \nu\, A$	Bruenn (1985), Horowitz (1997)
	$\nu\, e^\pm \rightleftharpoons \nu\, e^\pm$	Bruenn (1985)
	$e^-\, e^+ \rightleftharpoons \nu\, \bar{\nu}$	Bruenn (1985)
	$NN \rightleftharpoons \nu\bar{\nu}NN$	Hannestad & Raffelt (1998)
set2	$\nu_e\, A \rightleftharpoons e^-\, A'$	Juodagalvis et al. (2010)
set3a	$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_x + \bar{\nu}_x$	Buras et al. (2003), Fischer et al. (2009)
set3b	$\nu_x + \nu_e(\bar{\nu}_e) \rightleftharpoons \nu'_x + \nu'_e(\bar{\nu}'_e)$	Buras et al. (2003), Fischer et al. (2009)
set4a	$\nu_e\, n \rightleftharpoons e^-\, p,\ \ \bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Martínez-Pinedo et al. (2012)
set4b	$NN \rightleftharpoons \nu\bar{\nu}NN^*$	Fischer (2016)
set5a	$\nu_e\, n \rightleftharpoons e^-\, p,\ \ \bar{\nu}_e\, p \rightleftharpoons e^+\, n, \nu\, N \rightleftharpoons \nu\, N$	Horowitz (2002)
set5b	$m_N \rightarrow m_N^*$	Reddy et al. (1999)
set6a	$g_A \rightarrow g_A^*$	Fischer (2016)
set6b	$\nu\, N \rightleftharpoons \nu\, N$ (many-body and virial corrections)	Horowitz et al. (2017)
set6c	$\nu\, N \rightleftharpoons \nu\, N$ (strangeness contribution)	Horowitz (2002)

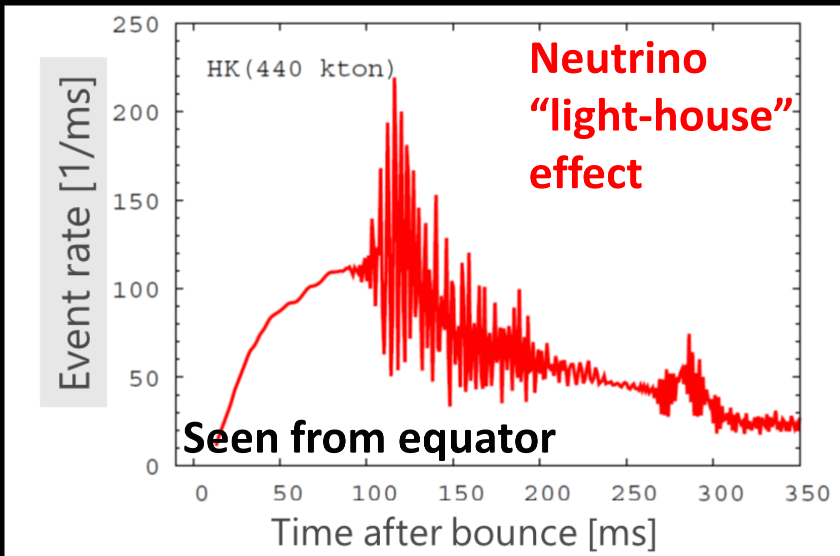
3flavor IDSA with updated microphysics
(KK et al. (2018)) with GR correction, SFHo EOS

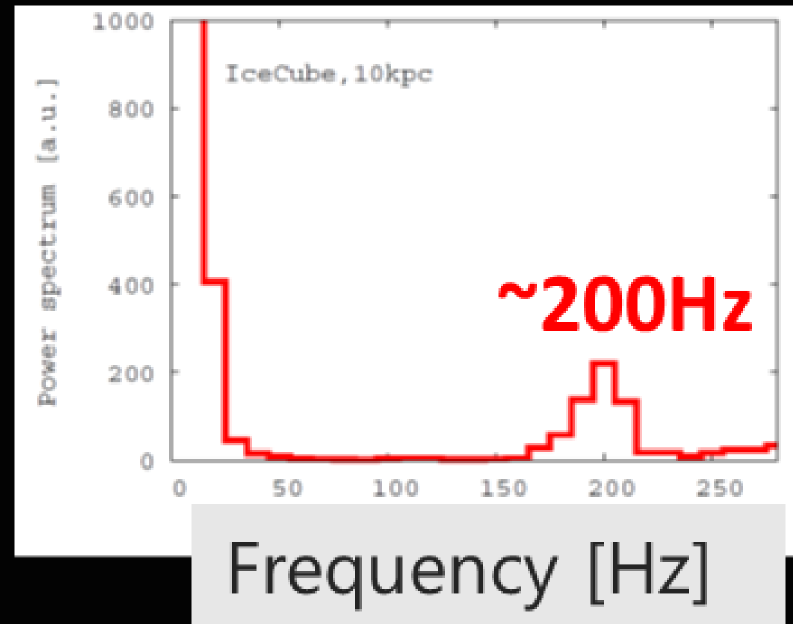


Correlation of GW and ν signals from a rapidly rotating 3D model

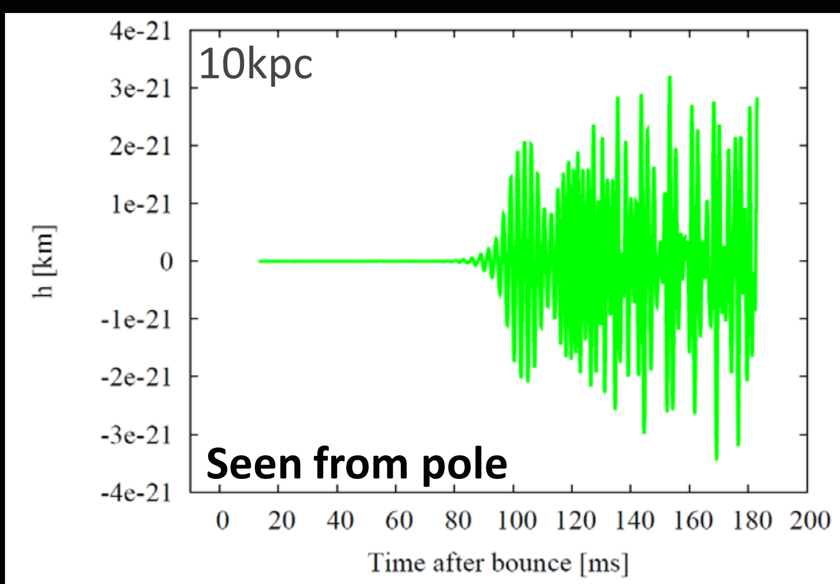
Takiwaki & KK in prep

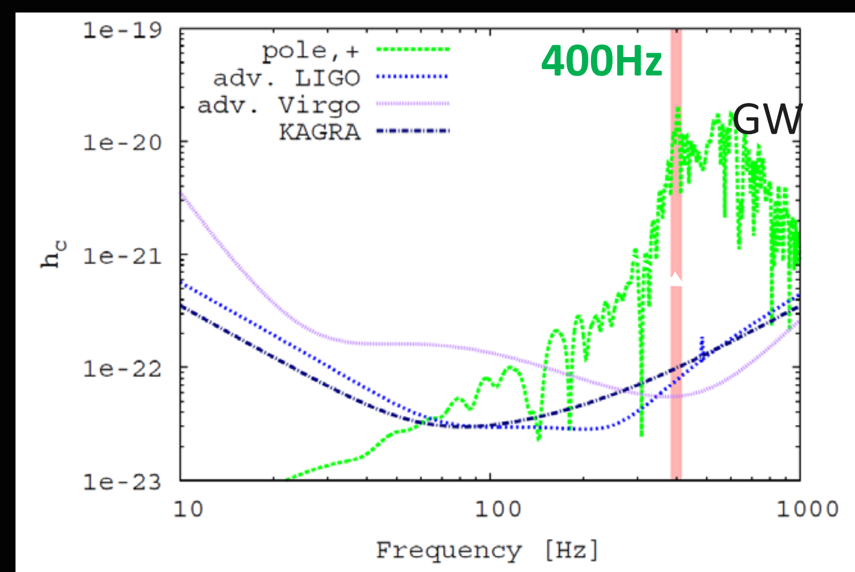
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform





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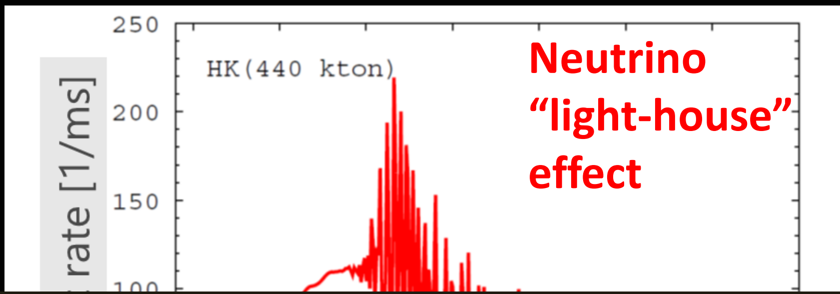
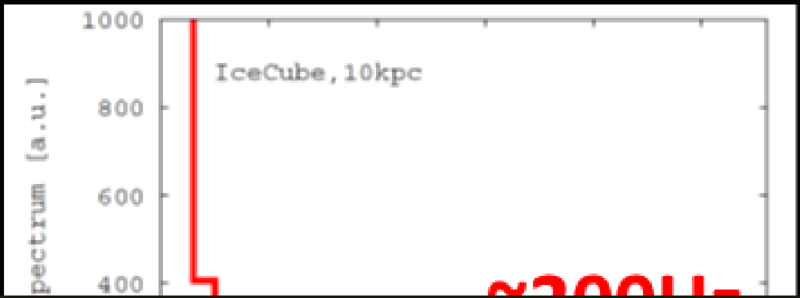
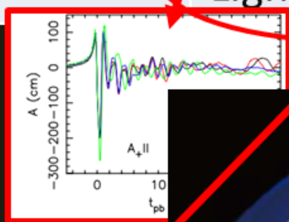
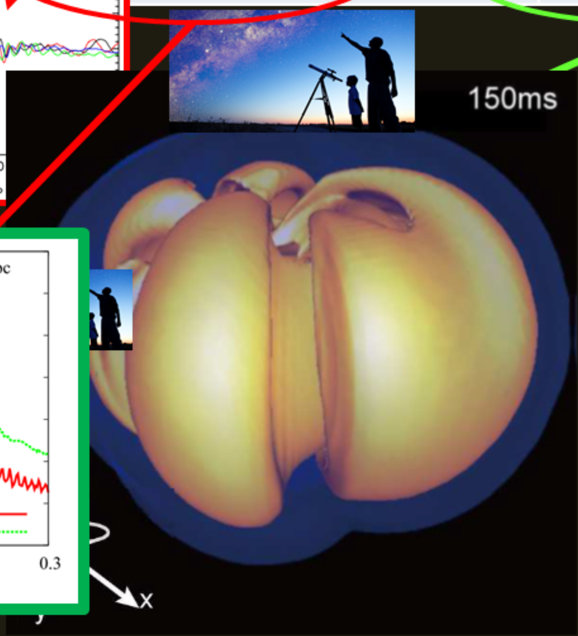
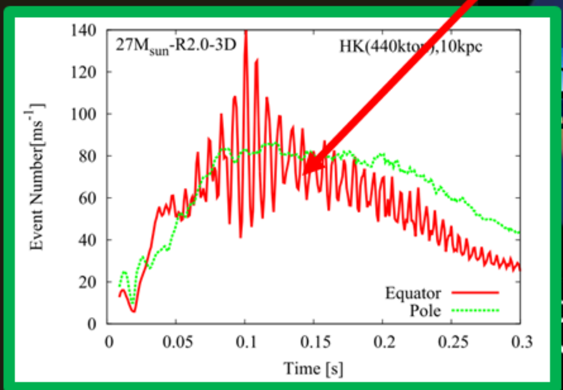


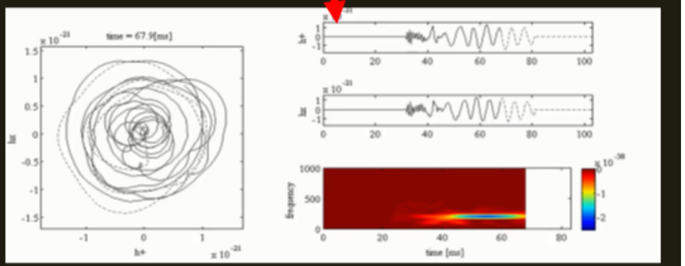


Directionality	Equator	Pole
Gravitational Wave	Type I signal	✓ Quasi-periodic signals from non-axis. instability ✓ Circular polarization
Neutrinos	Light-house effect	No surprise ...









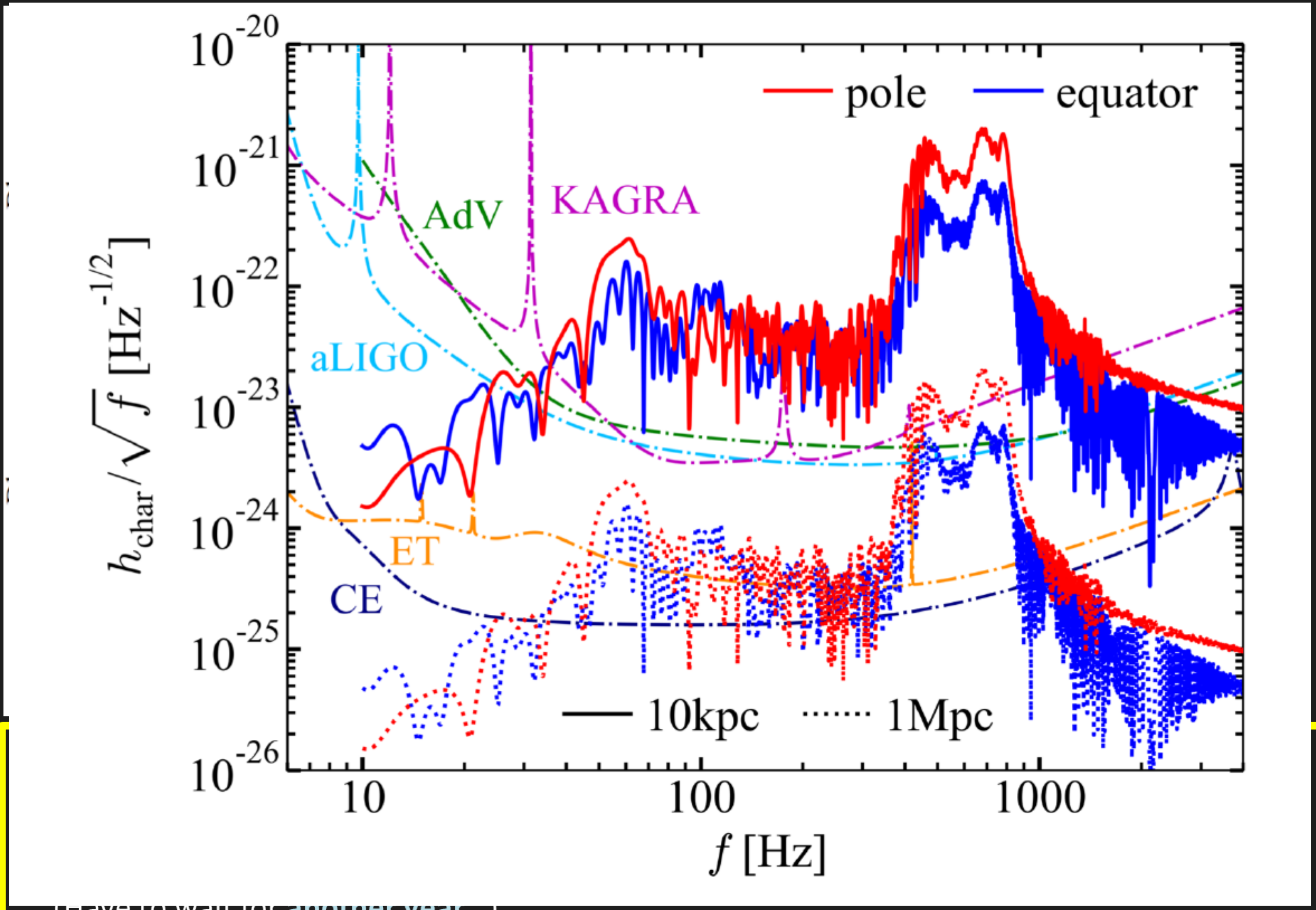
✓ "FGR1" : Fully General Relativistic code with multi-energy neutrino transport with M1

Kuroda, Takiwaki, and KK, ApJS. (2016) The marriage of BSSN formalism (3D GR code, Kuroda & Umeda (2010, ApJS))
+ M1 scheme; Shibata+2011, Thorne 1981, (see also, Rahman et al. (2019), Just et al. (2018), for recent work)

Shibagaki, Kuroda, KK in prep

Ω_0 =

Gravitational waveform



(Have to wait for another year…)

Preliminary results from “FGRM1” of a 70 solar mass star

: **Fu**lly **G**eneral **R**elativistic **M**agnetohydrodynamics code with **M1 neutrino transport**

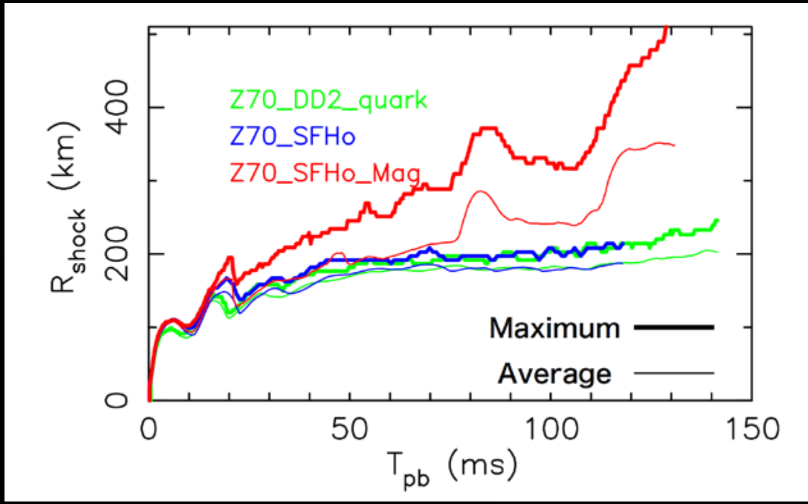
- Cylindrical rotational law

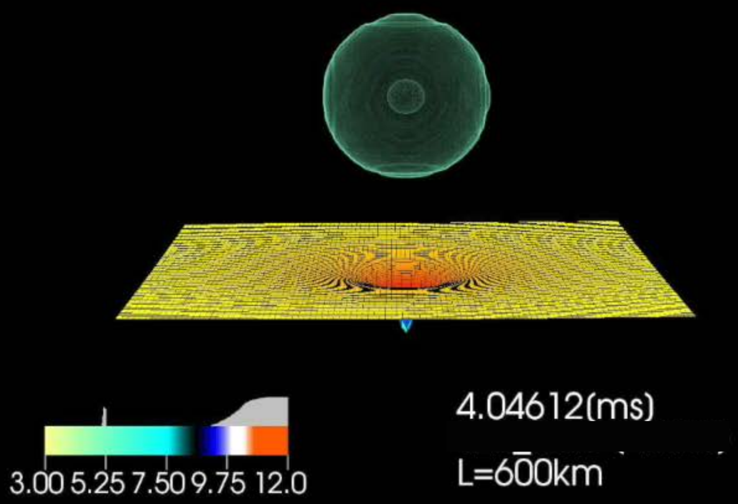
$$\Omega = \Omega_0 \frac{R_0^2}{R^2 + R_0^2} \qquad \Omega_0 = 1(\mathrm{rad/s}) \qquad (\beta_b \sim 1\%)$$

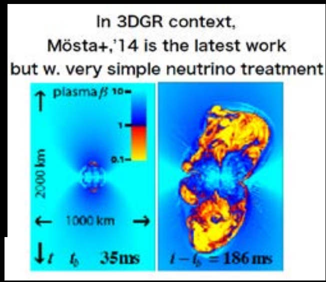
- Dipole-like B

$$A_\phi = \frac{B_0}{2}\frac{R_0^3}{R^3 + R_0^3} R\sin\theta \qquad B_0 = 10^{12}\mathrm{G} \quad (\beta_{\mathrm{mag,b}} \sim 1\%)$$

Kuroda, Takiwaki, KK et al. in prep







Presupernova neutrinos from multi-D O shell burning shell

(3D stellar evolution calculations: Couch et al. (2015), Mueller et al. (2016))

T. Yoshida, Takiwaki, KK, et al. (arXiv 190307811Y)

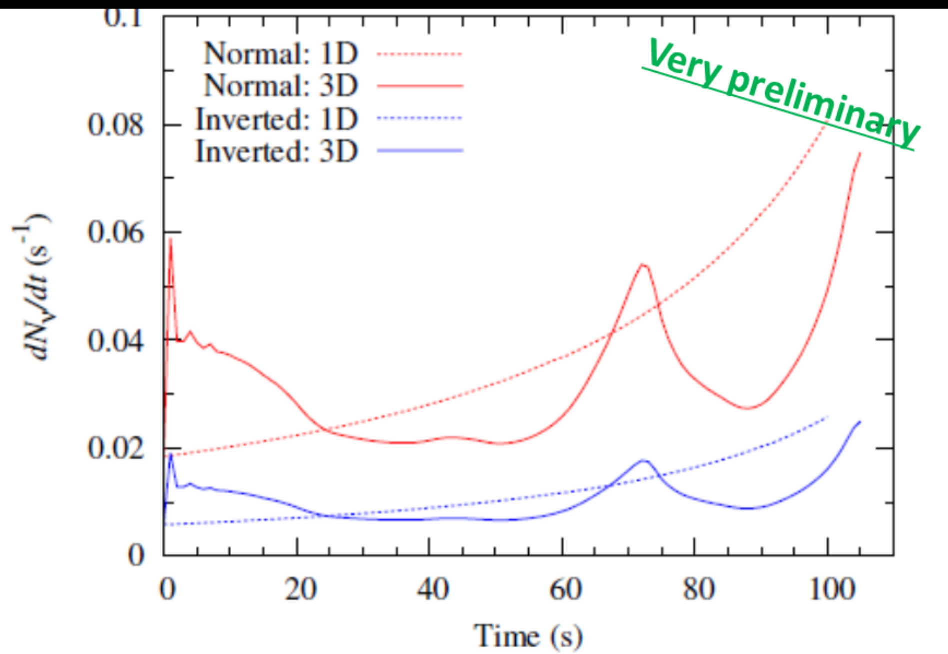


Figure 11. The evolution of neutrino event rate of model 25M by KamLAND. Thick solid and thin dashed curves correspond to the results of 3D and 1D simulations, respectively. Red and blue curves correspond to the normal and inverted orderings.

25M_{sun} star

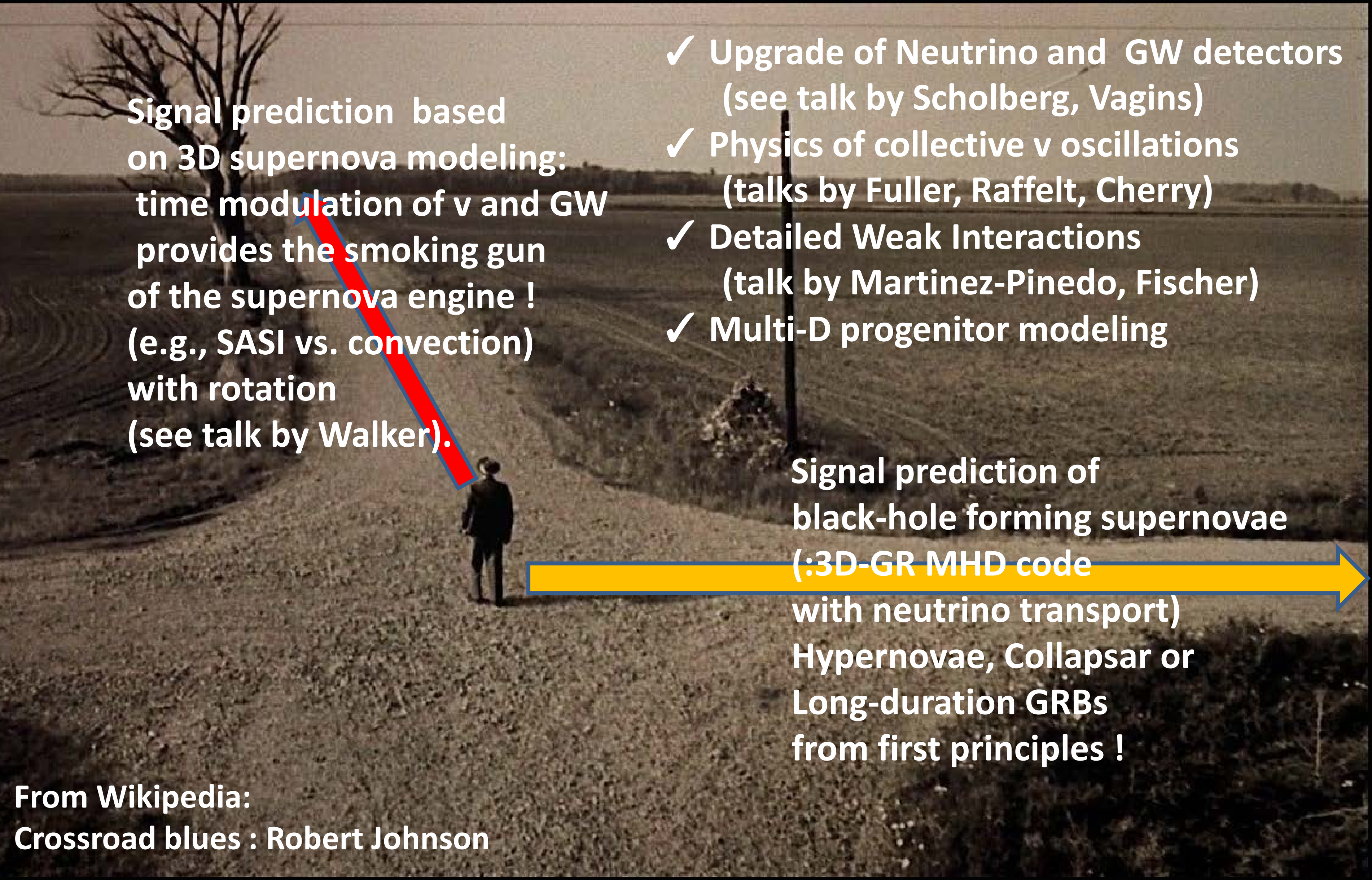
- ✓ Convection leads to modulation in presupernova neutrino signals
- ✓ Could be detectable to Hyper-K (x200, if with Gd, 2 MeV) for Betelgeuse (200pc)
- ✓ Long-term evolution needs to be followed !

SN neutrinos and GWs at the cross-roads !

Signal prediction based
on 3D supernova modeling:
time modulation of ν and GW
provides the smoking gun
of the supernova engine !
(e.g., SASI vs. convection)
with rotation
(see talk by Walker).

- ✓ Upgrade of Neutrino and GW detectors
  (see talk by Scholberg, Vagins)
- ✓ Physics of collective ν oscillations
  (talks by Fuller, Raffelt, Cherry)
- ✓ Detailed Weak Interactions
  (talk by Martinez-Pinedo, Fischer)
- ✓ Multi-D progenitor modeling

Signal prediction of
black-hole forming supernovae
(:3D-GR MHD code
with neutrino transport)
Hypernovae, Collapsar or
Long-duration GRBs
from first principles !



From Wikipedia:
Crossroad blues : Robert Johnson