Multi-dimensional simulations of Core-Collapse Supernovae: neutrinos and gravitational waves

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The "multi-D" neutrino mechanism of core-collapse supernovae:

Blowing up massive stars ! (since Colgate & White (1966) and Bethe and Wilson (1985))

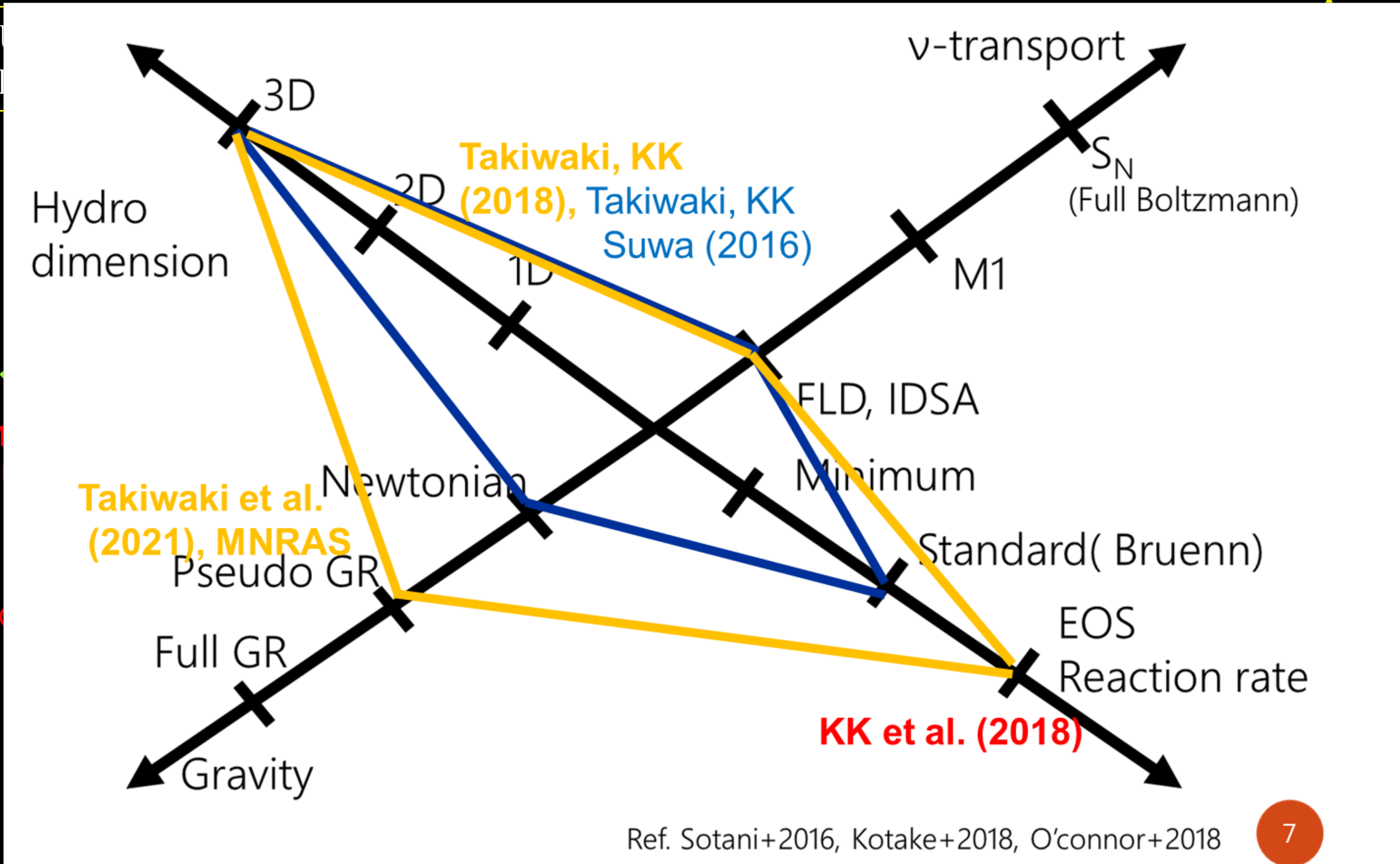
(See reviews in Mezzacappa+(2020), Radice+(2018), Janka ('17), Müller ('16), Kotake et al. ('12))

For the next Galactic event (several/century..),
how do we observe neutrino and gravitational waves
and what we can learn about the
supernova physics ?
(For this …. Sweat, Sweat, Sweat !)

Numerical modeling supernova explosion

Big simulation codes – Experimental facilities

✓ Progress report of our supernova code: *Updated ν reactions in 3D code*



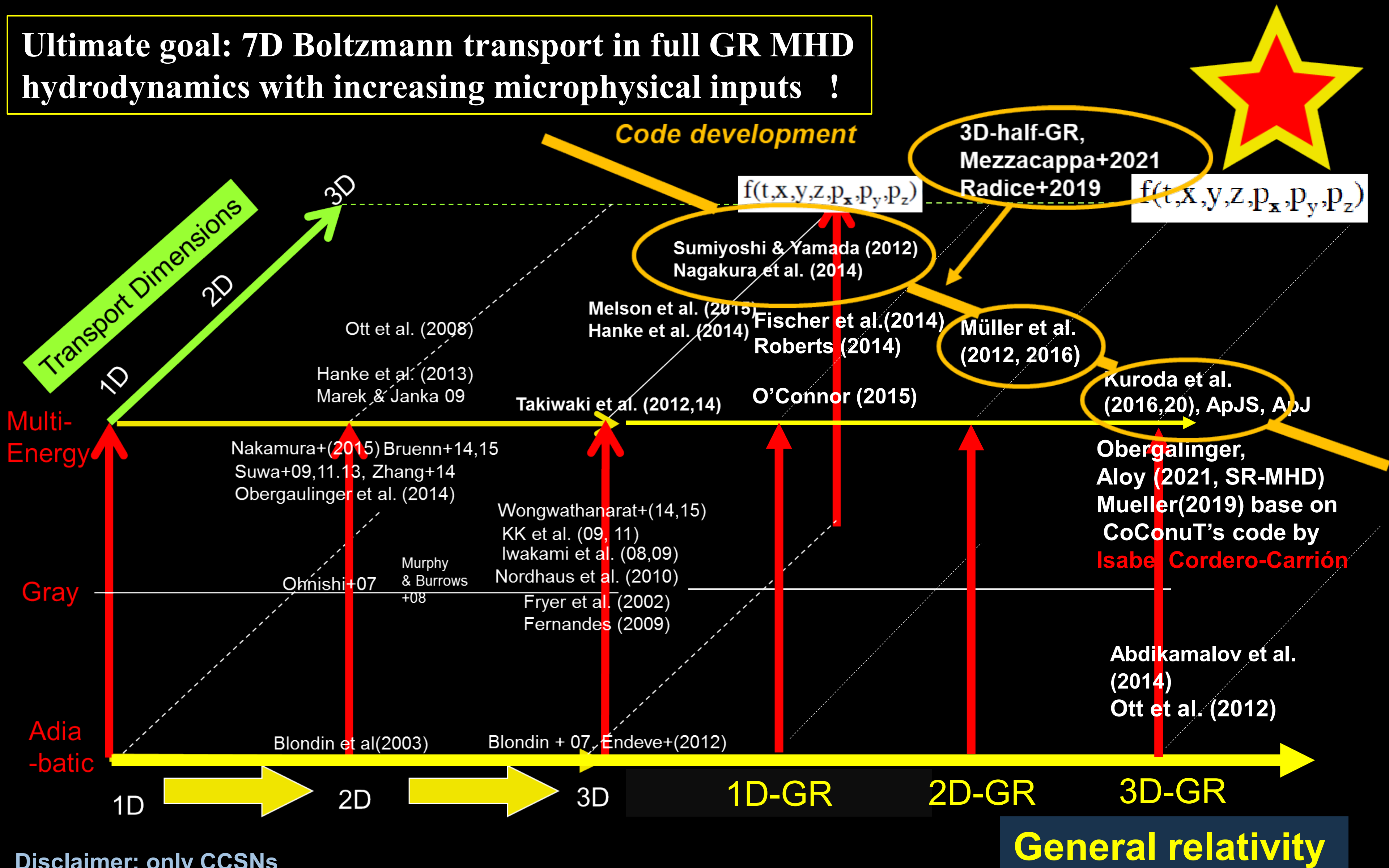
Disclaimer: only CCSNs

General relativity

Numerical modeling supernova explosion

Big simulation codes = Experimental facilities

Ultimate goal: 7D Boltzmann transport in full GR MHD hydrodynamics with increasing microphysical inputs !



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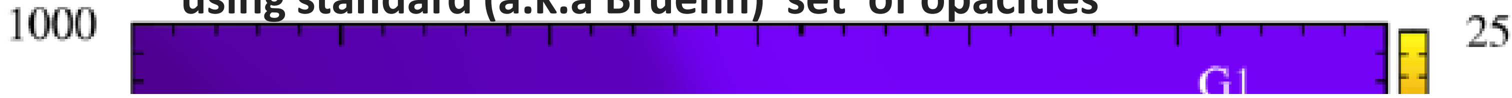
2D IDSA simulation of 20 M_{sun} (Woosley and Heger (2007)) using standard (a.k.a Bruenn) set of opacities



KK, Takiwaki, Fischer, Nakamura, et al. ApJ

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)
	$N N \rightleftharpoons \nu\bar{\nu} N N$	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	$N N \rightleftharpoons \nu\bar{\nu} N N^*$	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)

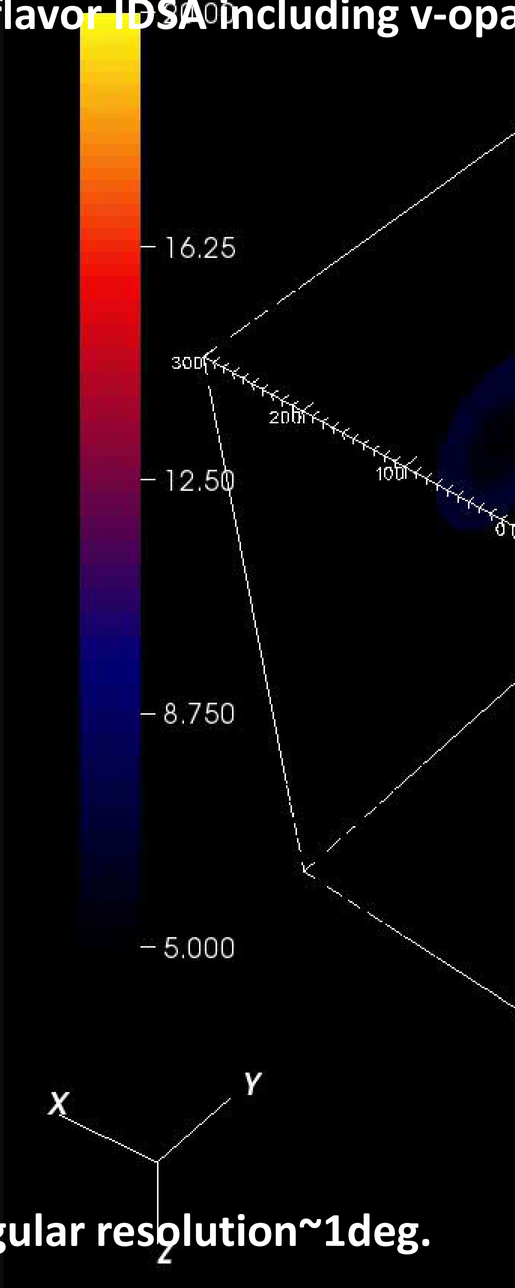
Table 1 in Kotake+ '18

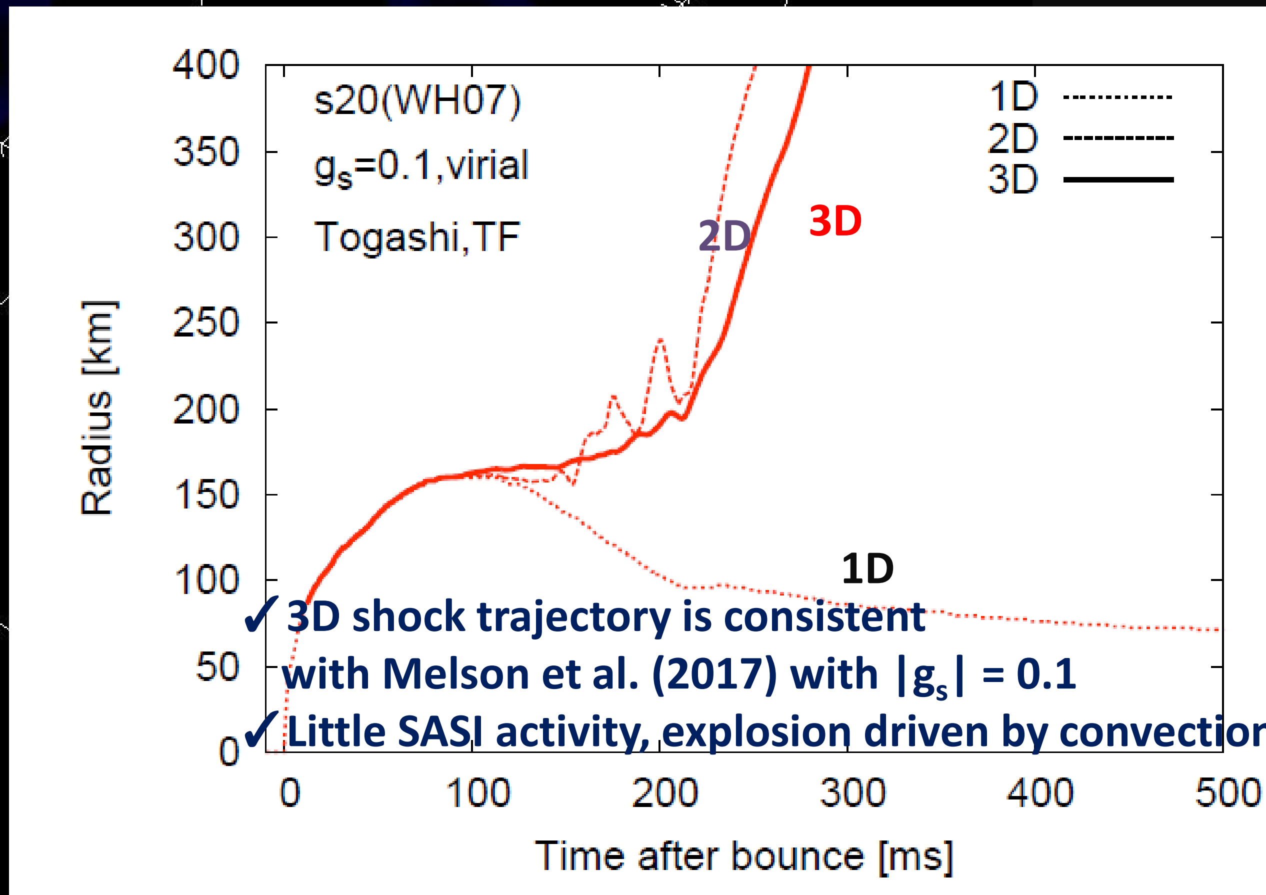
✓Quantitative GW・neutrino signal prediction, the updates in opacities mandatory!

20 M $_{sun}$ progenitor (WH07) using Togashi EOS,
3flavor IDSA including ν-opacity updates

11 ms

(e.g., Takiwaki, KK, Foglizzo (2021))





✓ 3D shock trajectory is consistent with Melson et al. (2017) with $|g_s| = 0.1$

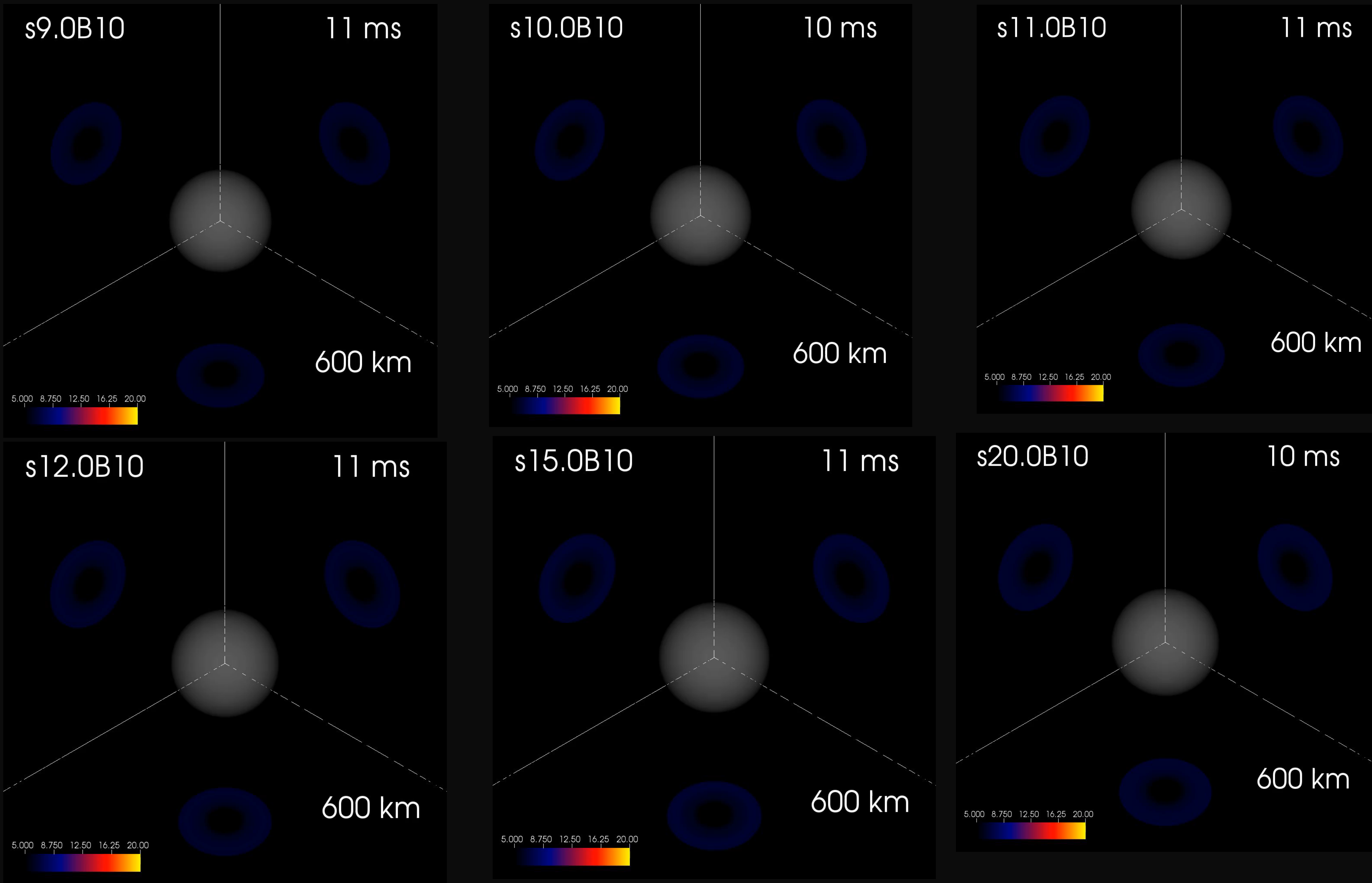
✓ Little SASI activity, explosion driven by convection

Angular resolution~1deg.

Many more 3D modeling with MHD possible !!!

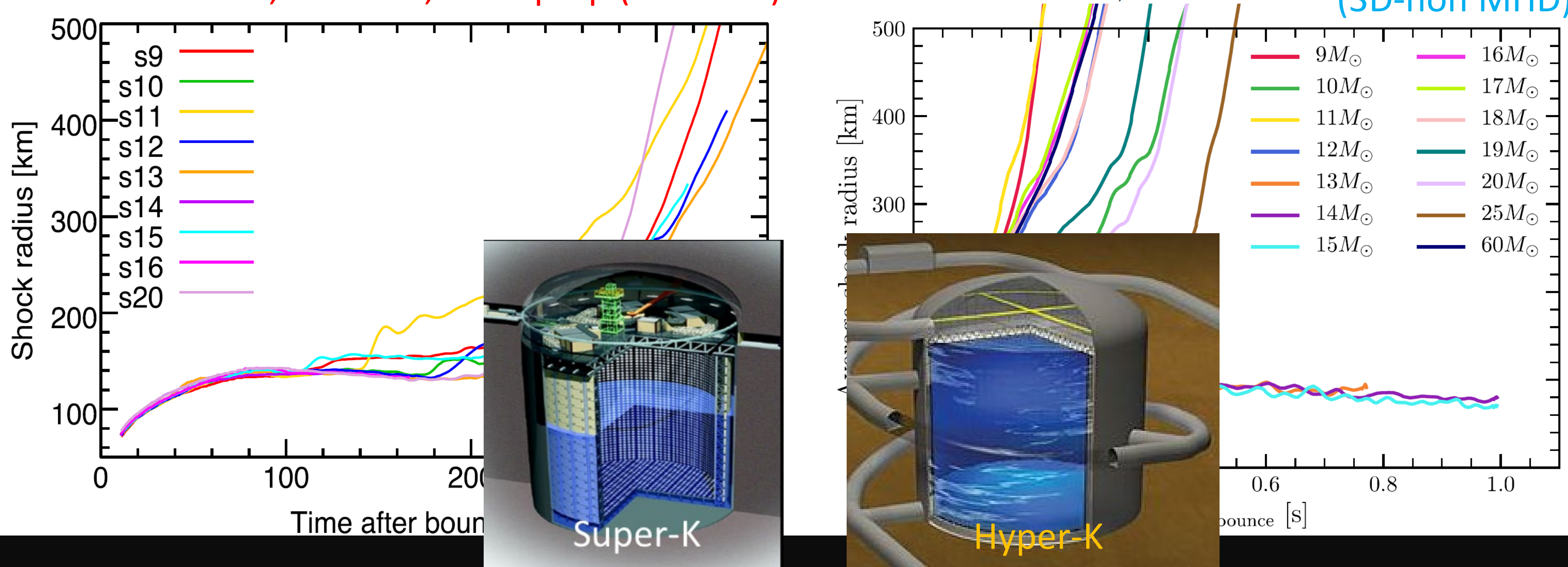
Nakamura, Takiwaki, KK in prep, Matsumoto et al. in prep

✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform), Non-rotation)

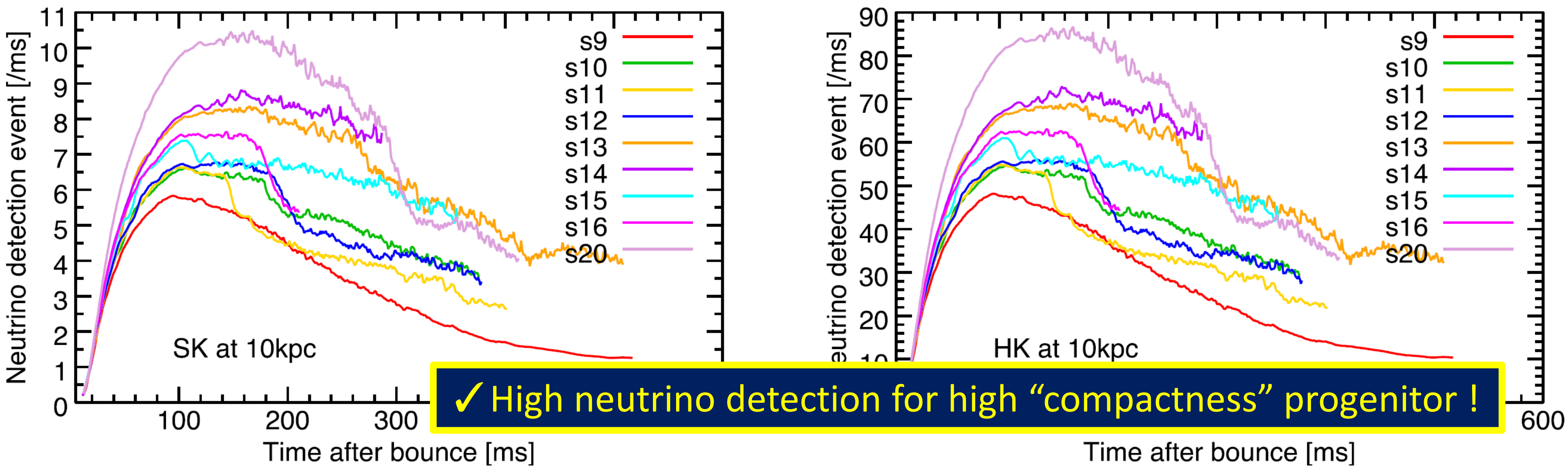


Nakamura, Takiwaki, KK in prep (3D-MHD)

c.f.) Burrows+20 (3D-non MHD)



✓Neutrino detection rate at SuperKamokande and HyperKamiokande

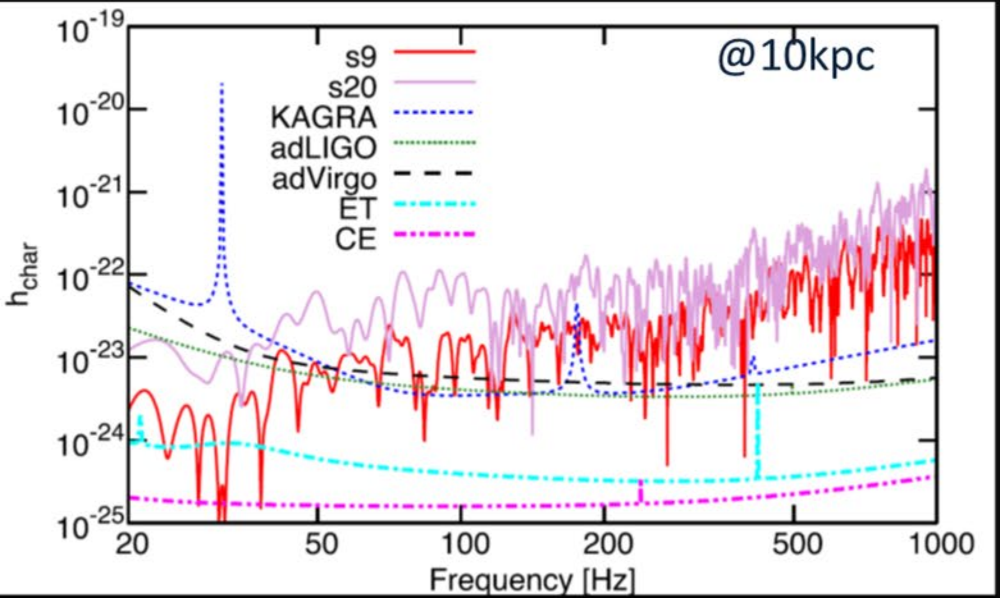


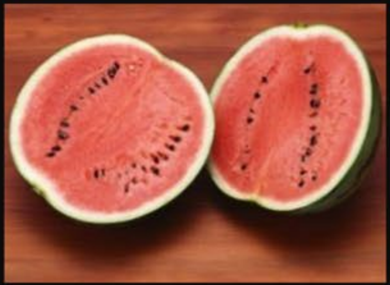
✓High neutrino detection for high "compactness" progenitor !

Nakamura, Takiwaki, KK in prep (3D-MHD)

c.f.) Burrows+20 (3D-non MHD)

Comparison with GW sensitivity curves

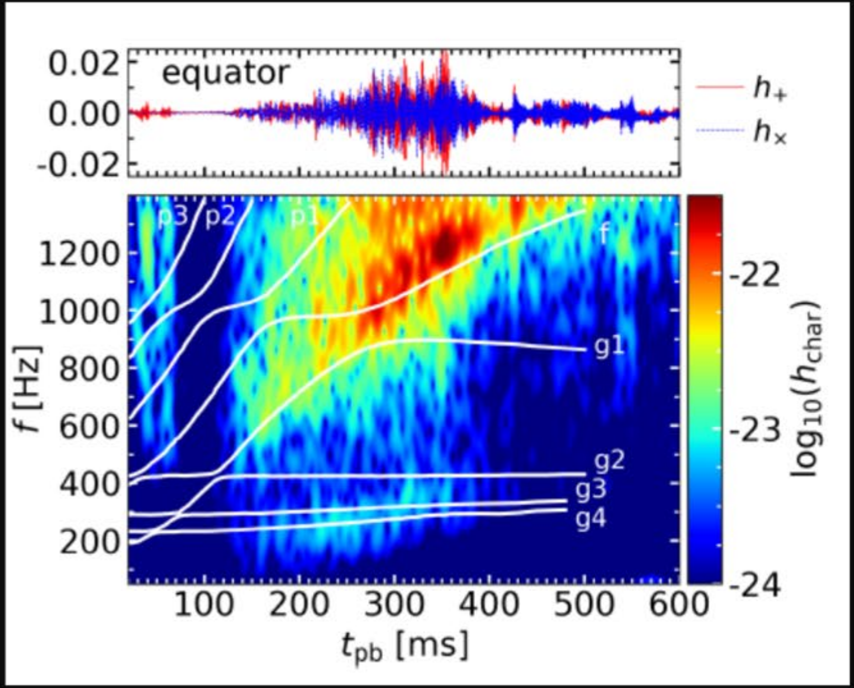




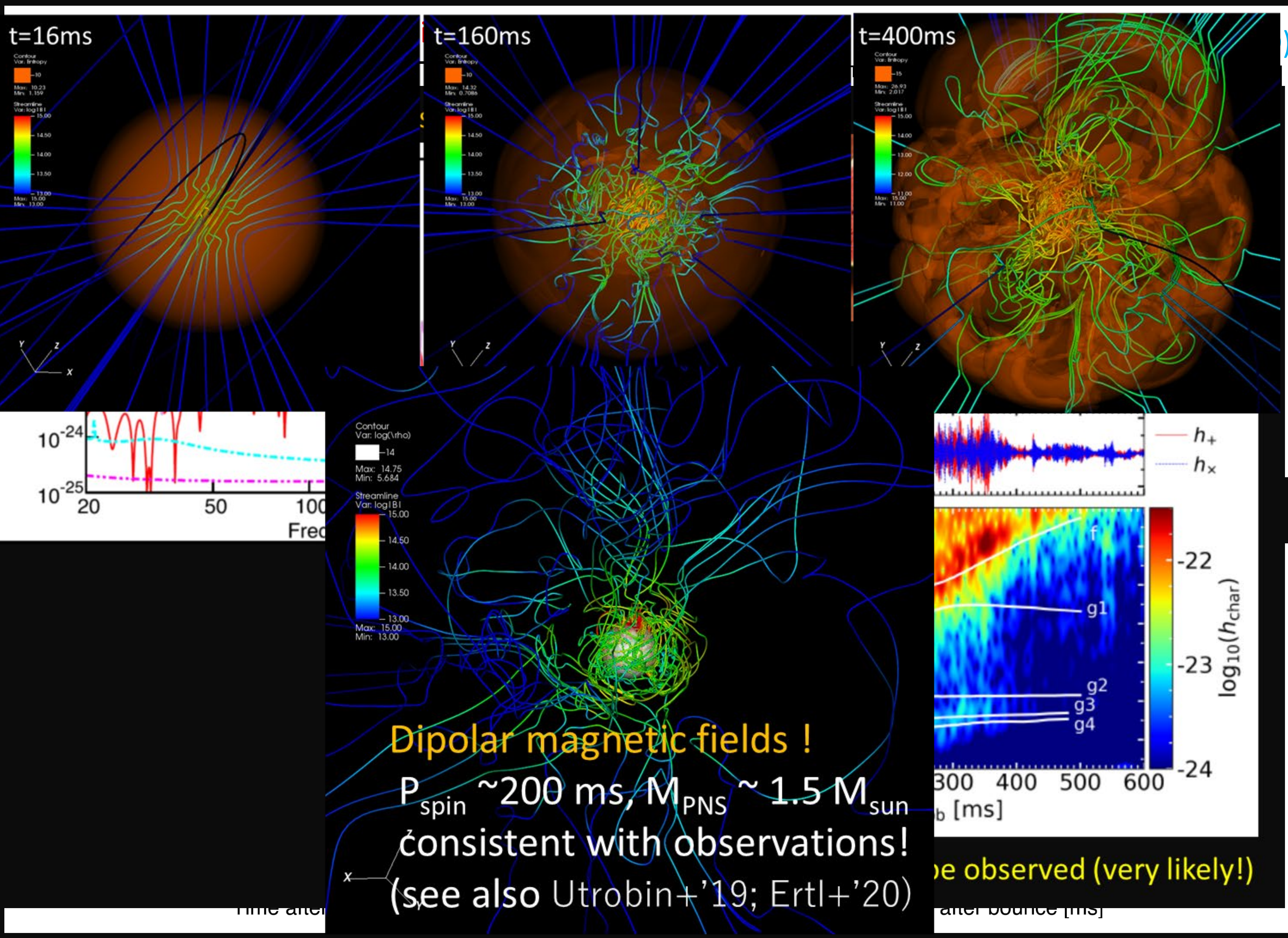
Knock the watermelon!

→ PNS seismology

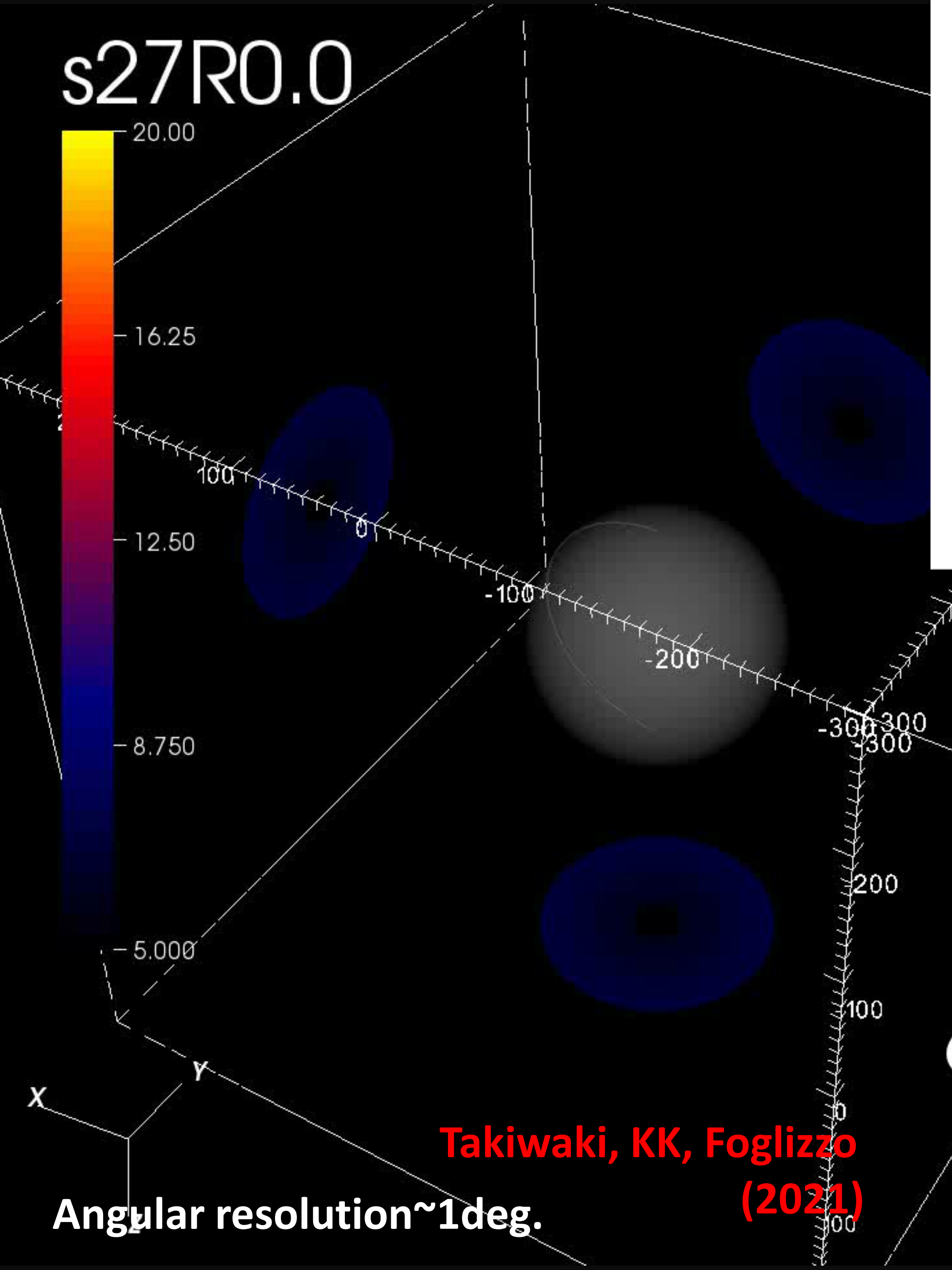
(Torres-Forné, Cerdá-Durán, Font et al. PRL, 2019: GREAT code)

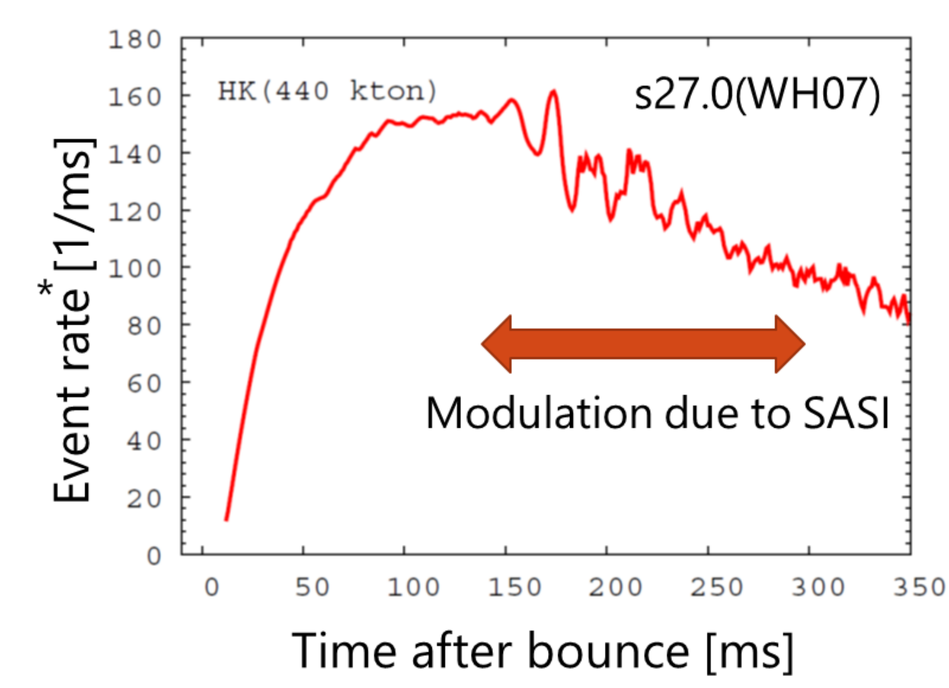


✓ "f" mode can be observed (very likely!)

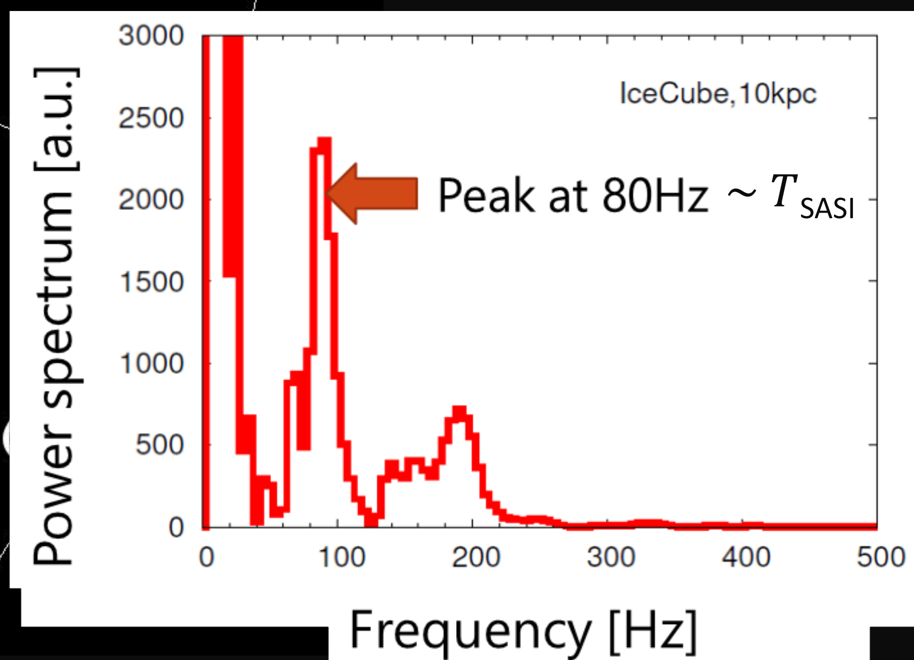

t=16ms
t=160ms
t=400ms
Contour
Var: log(\rho)
Max: 14.75
Min: 5.684
Streamline
Var: log|B|
15.00
14.50
14.00
13.50
13.00
Max: 15.00
Min: 13.00
10^{-24}
10^{-25}
20
50
h_+
$h_\times$
f
g1
g2
g3
g4
-22
-23
-24
$\log_{10}(h_{char})$
300
400
500
600
Dipolar magnetic fields !
P_{spin} ~200 ms, M_{PNS} ~1.5 M_{sun}
consistent with observations!
(see also Utrobin+'19; Ertl+'20)

27 M $_{sun}$ progenitor (WH07)





(consistent with Tamborra et al. (2013,2014))

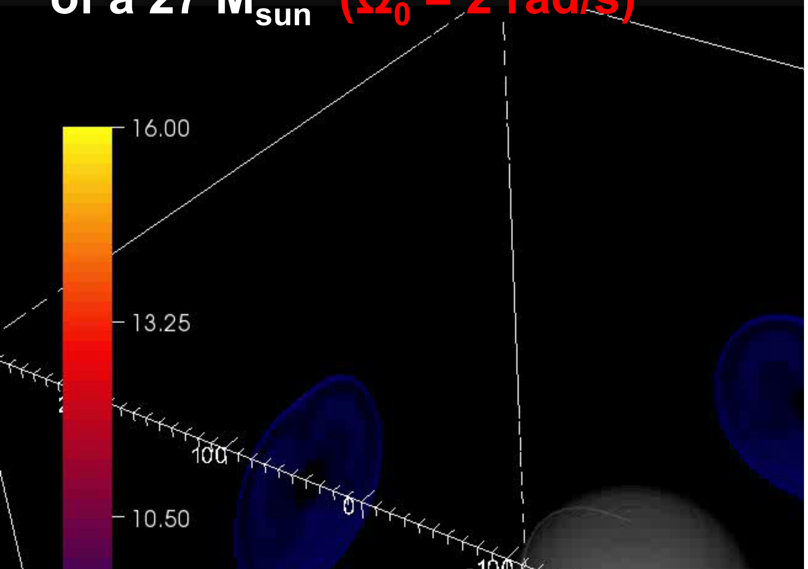


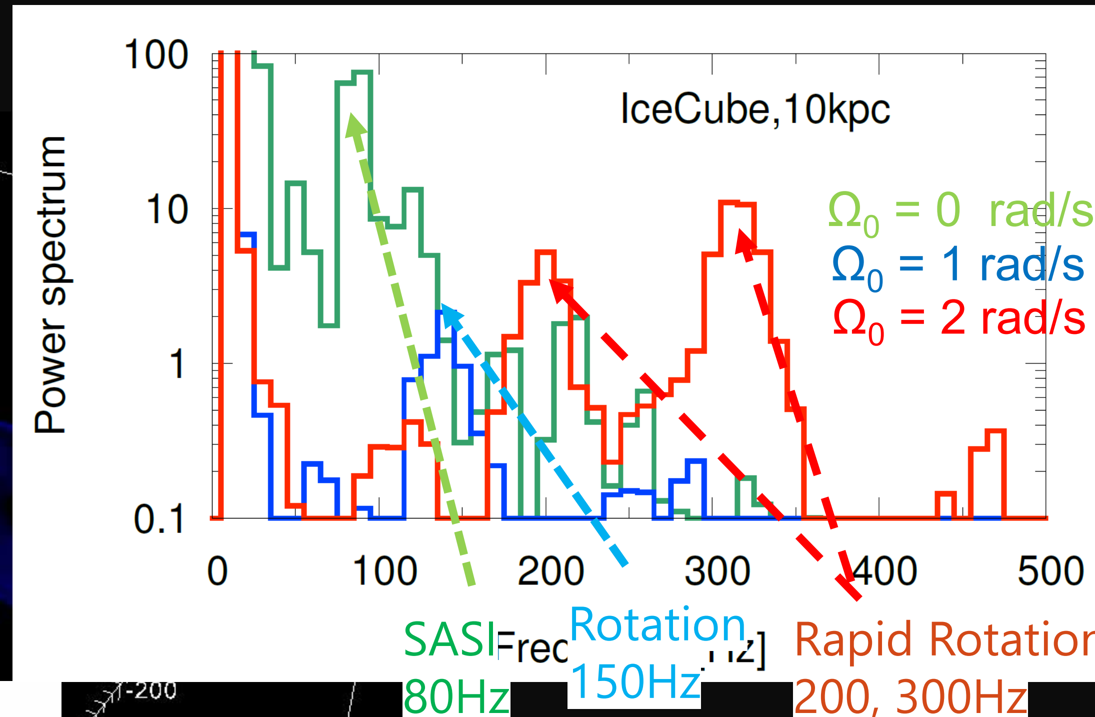
Takiwaki, KK, Foglizzo (2021)

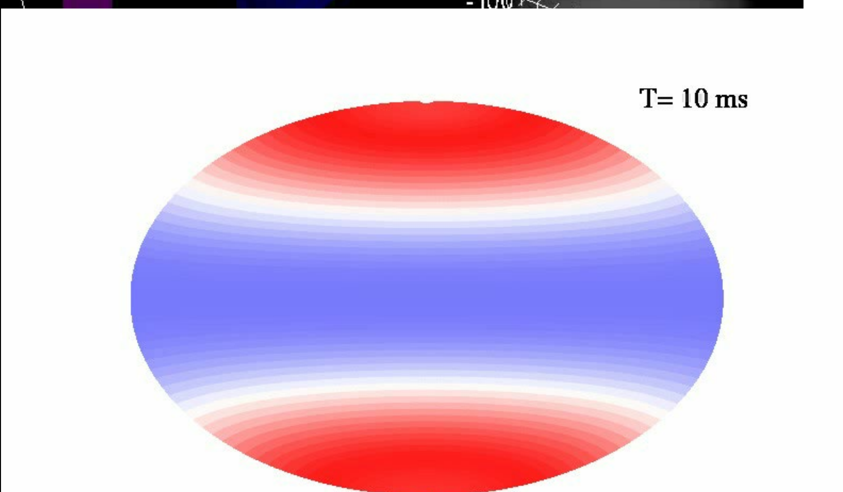
Angular resolution~1deg.

Impact of Stellar Rotation of SASI-modulated ν and GW signals

Rapidly rotating collapse of a 27 M_{sun} (Ω_0 = 2 rad/s)







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

- ✓ **Peak frequencies become higher with progenitor rotation !**
  because rapid rotation leads to rapidly rotating PNS and neutrino sphere.

=> ***The light-house effect***

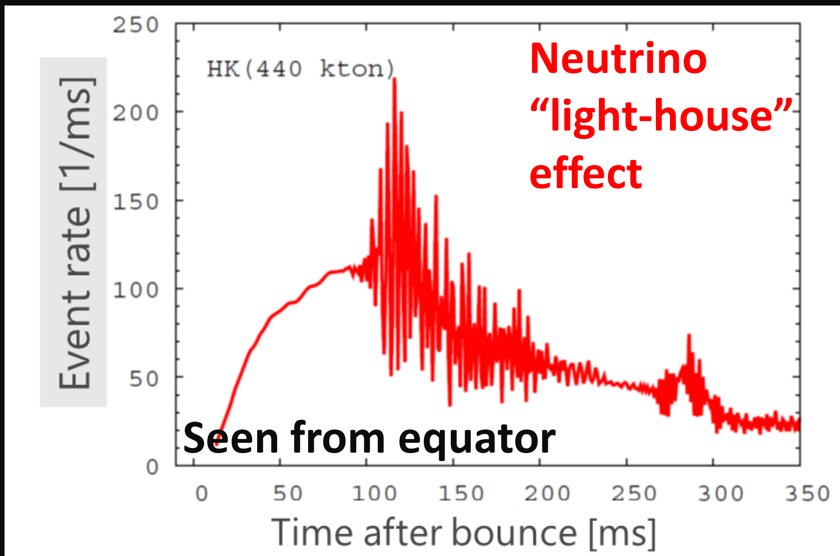
600 km

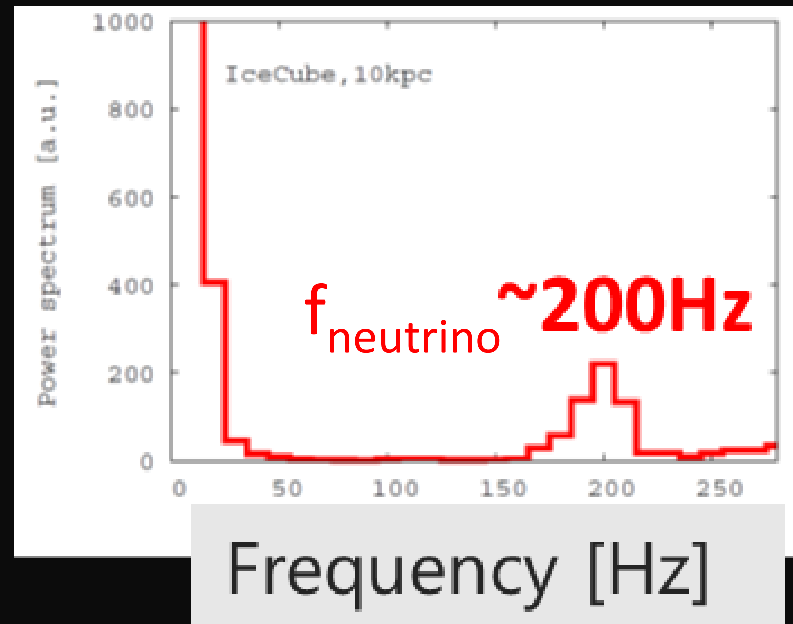
(found in simplified 3D model by Takiwaki and KK (2018)).

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

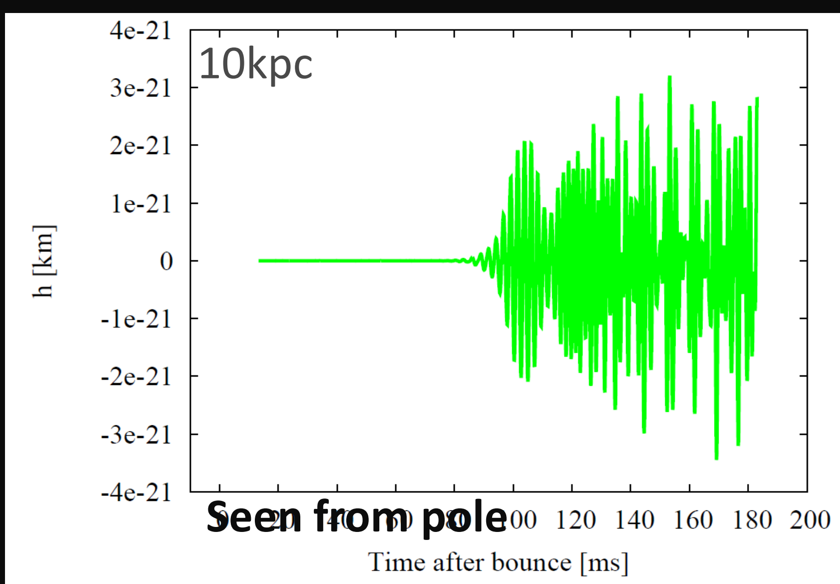
Takiwaki, KK, Foglizzo, (2021)

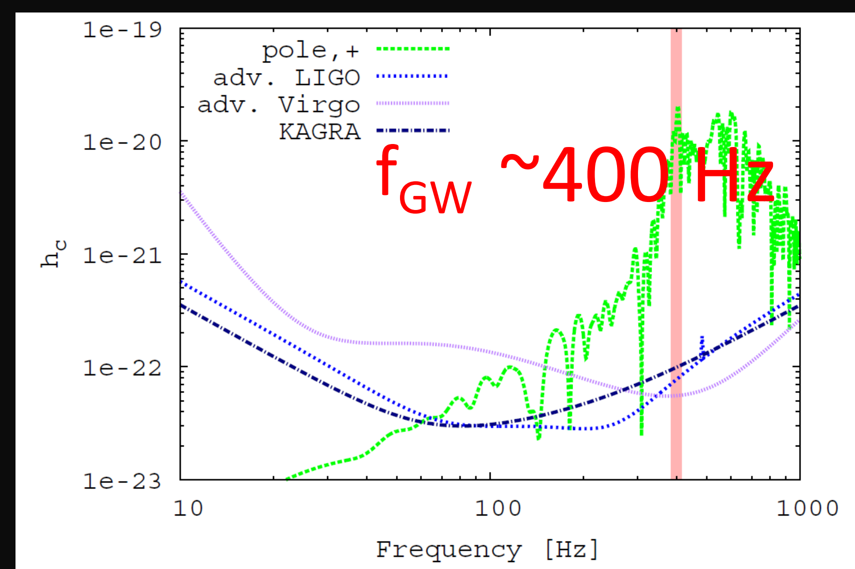
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





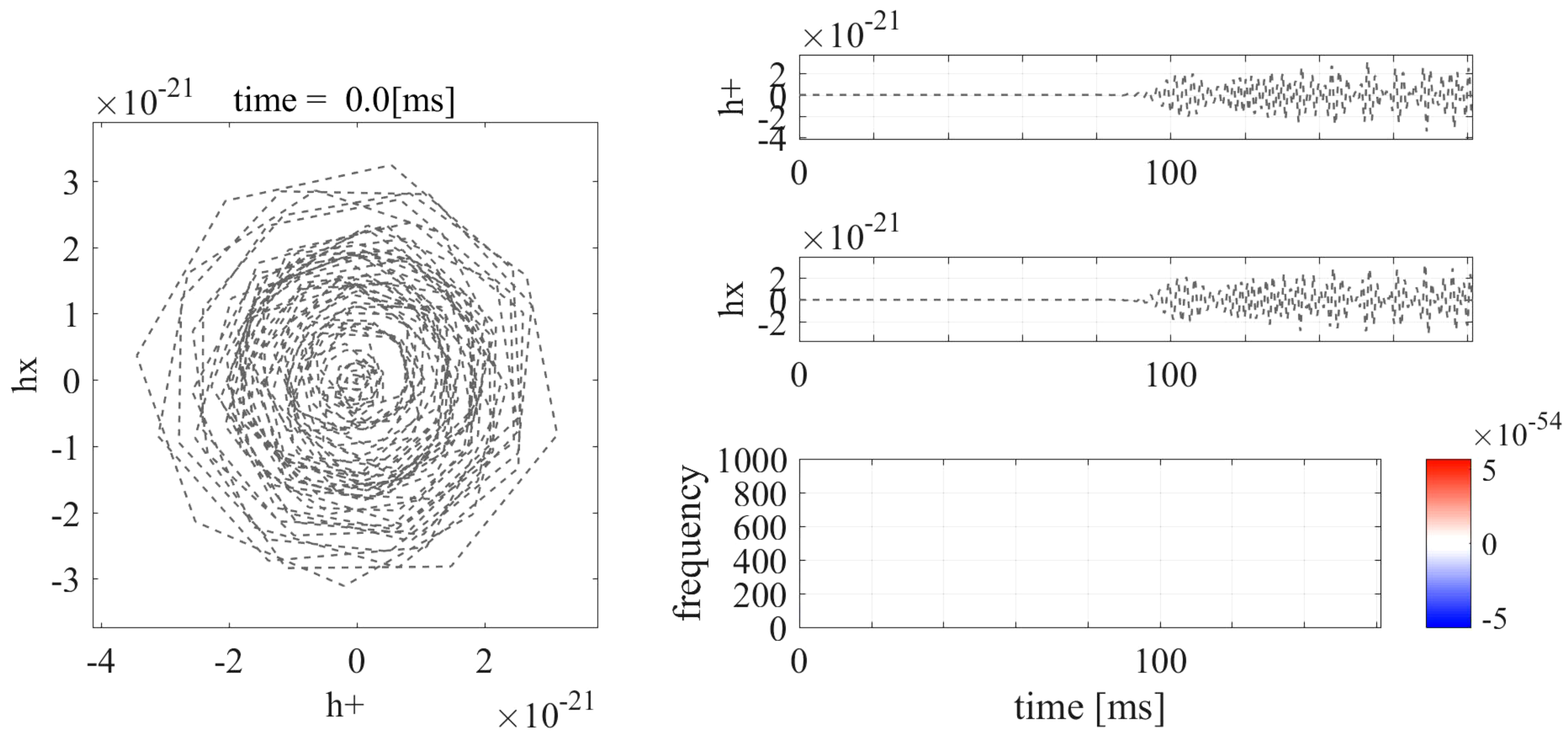
Gravitational waveform





Circular polarization of GW from rapidly rotating Supernovae

(preliminary, Hayama, KK et al.)



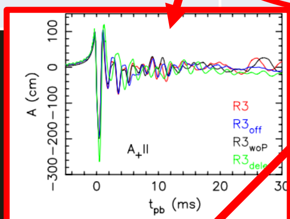
- ✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)
- ✓ Also the case for non-rotating progenitor, $f_{neutrino, SASI}$~80 Hz, QUIZ f_{gw} ~80 or 160 Hz
- ✓ Coincident detection between GW and *ν* : smoking gun signature of rapid core rotation !

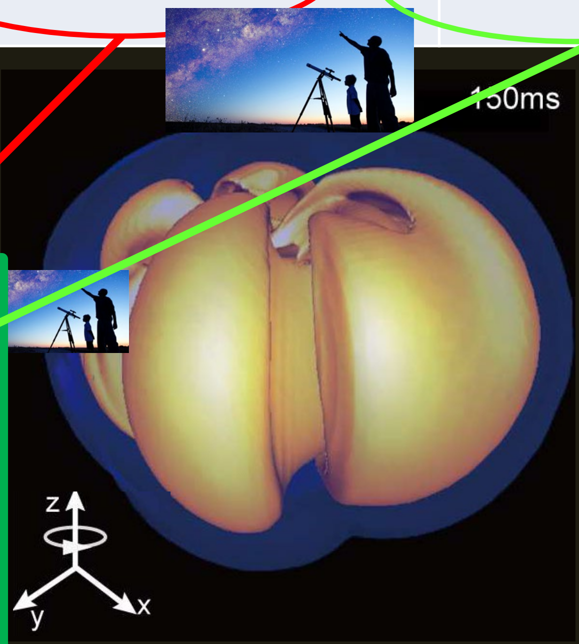
Correlation of ν and GW signals from a rapidly rotating 3D model

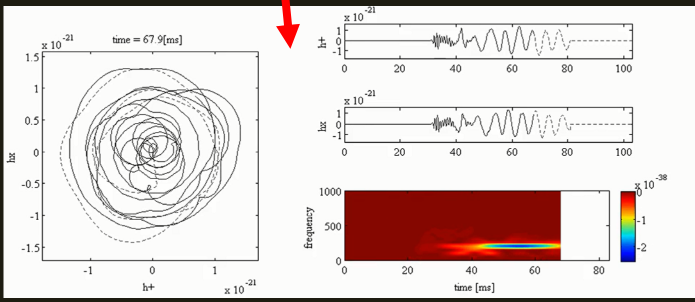
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

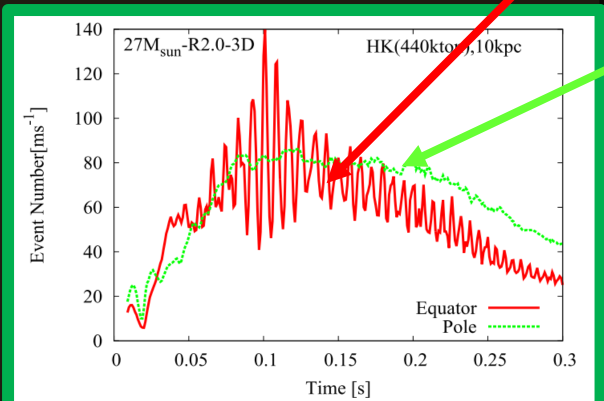
Takiwaki, KK, Foglizzo（2021, MNRAS)

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









✓ **Multi-messengers from rotating CCSNe : rich information ！**

Circular Polarization (CP) of GW from non-rotating supernovae ? Yes because of "SASI"

Stokes Parameters:

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

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

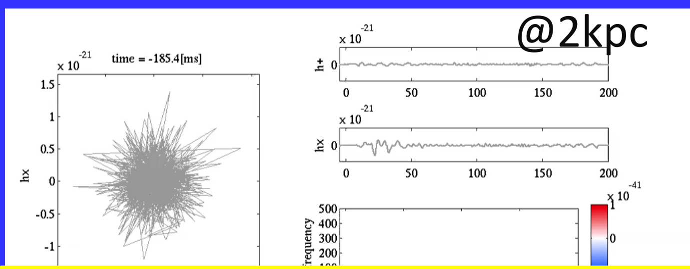
V parameter = Asymmetry of right and left modes

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

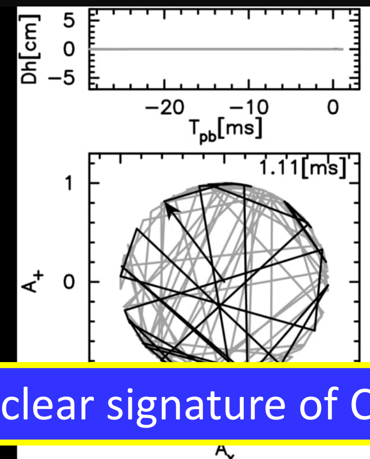
$$h_L := (h_+ + ih_\times)/\sqrt{2}$$

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

Non-rotating 11.2 M_{sun} ; Convection dominant

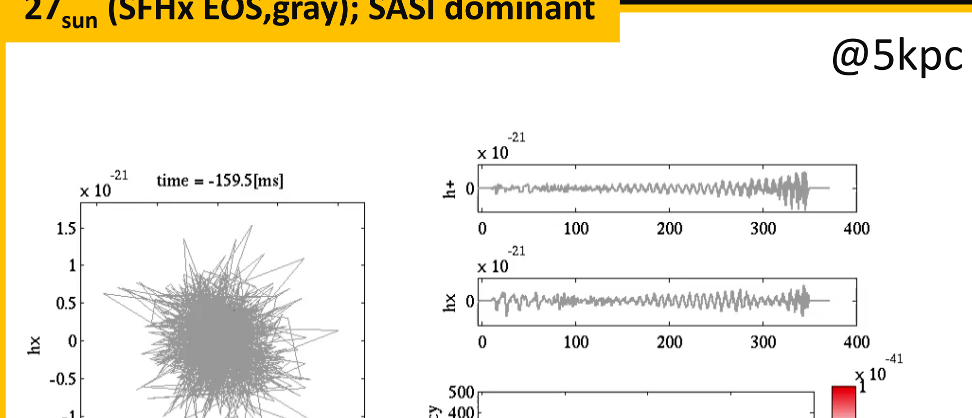


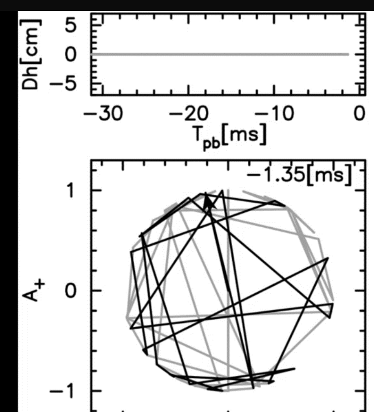
Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_x$)



If convection-dominant (likely for low compactness stars), no clear signature of CP !

27_{sun} (SFHx EOS,gray); SASI dominant



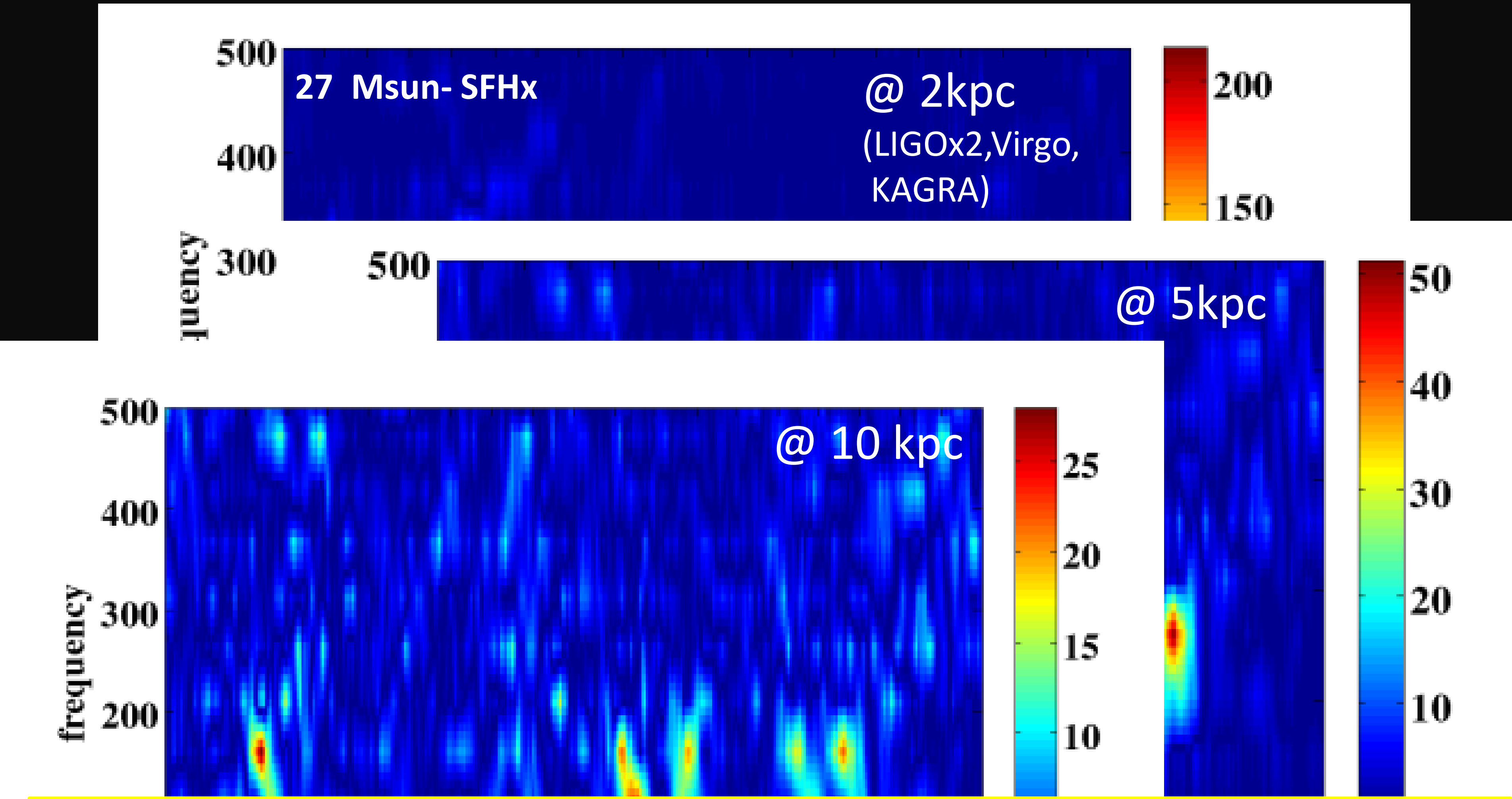


If the SASI dominant (likely for high ξ stars), clear signature of CP !

⇒ indication of high SASI activity, highly asymmetric accretion to the PNS

(Hayama et al, MNRAS (2018))

SNR of Circular Polarization of GW relative to background

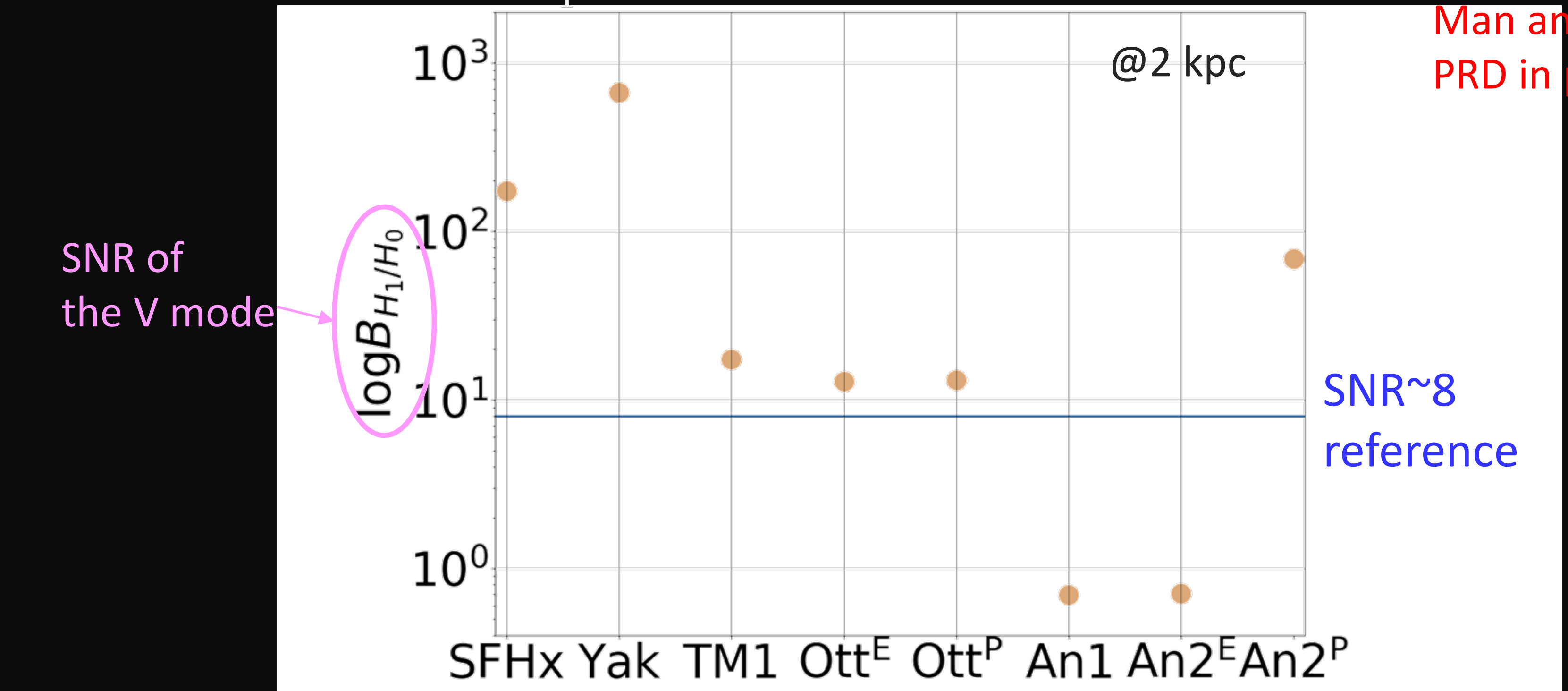


- ✓ The detection of GW amplitude is within several kpc using LIGO (e.g.,Andresen et al. (2017))
- ✓ The detection of CP could extend (far) beyond the detection horizon of GW waveform
- ✓ The CP would provide new window to detect GW signals (Hayama et al. MNRAS (2018))
- ✓ Need four-detectors to detect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

What about detectability of GW CP from 3D models (globe)?

Comparison of the circular polarization signatures (V mode) of simulated supernova waveforms

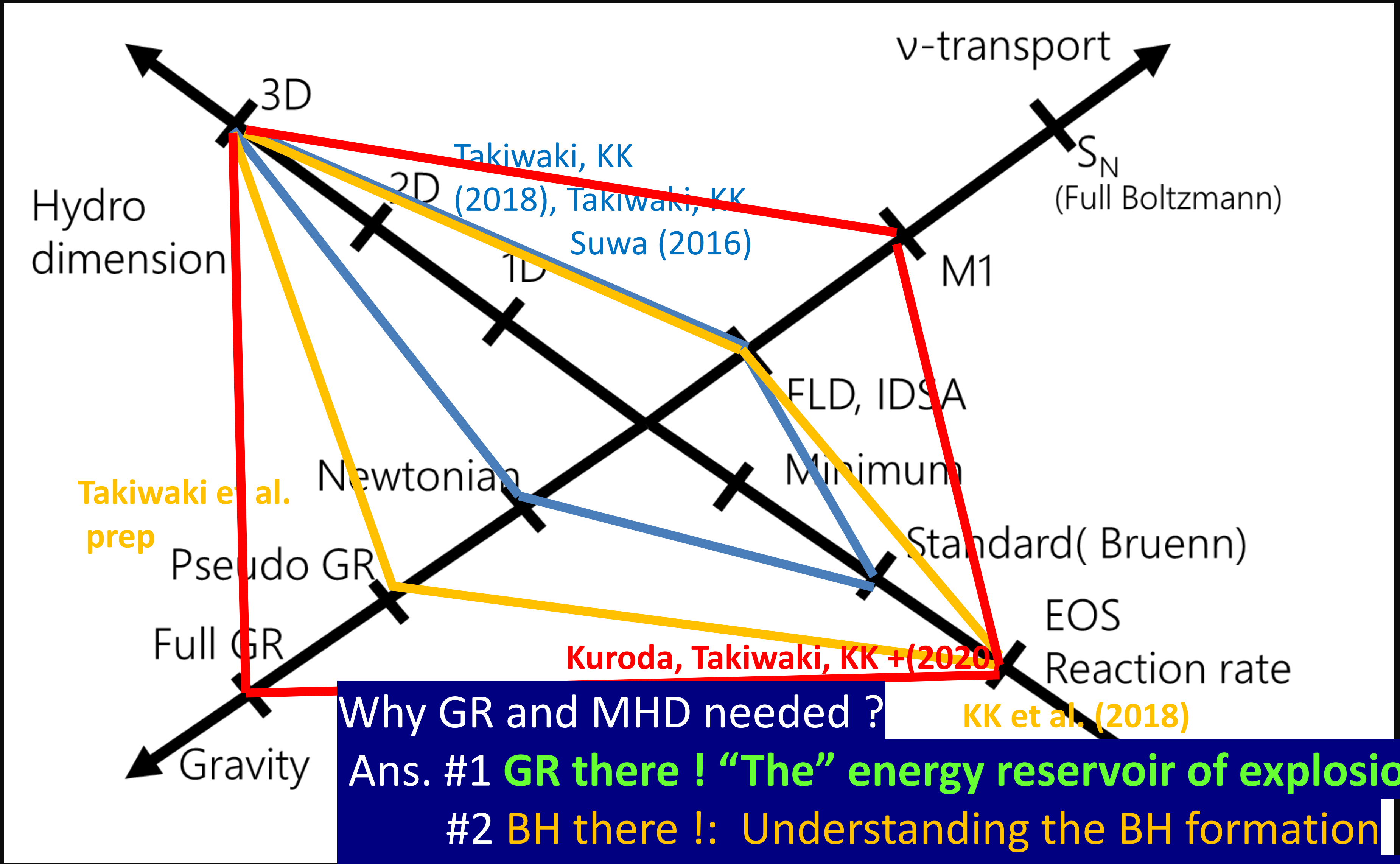
From Fig.12 Man and Hayama, PRD in press



- [1]Yakunin, K. N., Mezzacappa, A., Pedro Marronetti, P., et al.The gravitational wave signal of a core collapse superno… explosion of a 15 M star. ArXiv preprint arXiv:1701.07325, 2017
- [2]Kuroda, T., Kotake, K., and Takiwaki, T. A new gravitational-wave signature from standing accretion … supernovae. The Astrophysical Journal Letters, 829(1):L14, 2016.
- [3]Ott, D. C., Abdikamalov, E., Mösta, P., et al. General-relativistic simulations of three-dim… …ovae. The Astrophysical Journal, 768(2):115, 2013.
- [4]Andresen, H., Müller, B., Ewald Müller, and Janka, H. Gravitational wave signals from 3d … …rodynamics simulations of core-collapse supernovae. Monthly Notices of the Royal Astronomical Society, 468 (2):2032-…31, 2017.
- [5]Andresen, H. Mller, B., Janka, H., et al. Gravitational waves from 3D core-collapse supernova models: The impact of moderate progenitor rotation. Monthly Notices of the Royal Astronomical Society, 486(2):2238–2253, 04 2019. ISSN 0035-8711. doi: 10.1093/mnras/stz990. URL https://doi.org/10.1093/mnras/stz990.

✓ Nearby SN event (2~3 kpc) would be the real target !

✓ Progress report of *our supernova code* : *two-decade of long and winding road from 2000* (KK, Yamada, Sato, ApJ, 2003)



Why GR and MHD needed ?

Ans. #1 **GR there ! "The" energy reservoir of explosion**

#2 BH there !: Understanding the BH formation

#3 L-GRBs there! Understanding the hypothetical link to Collapsars or Superluminous SNe.

3D-MHD full GR runs for a 20 solar-mass star

Kuroda, Takiwaki, KK, Alcones, MNRAS (2020)

✓ Strongly magnetized and rapidly rotating model of s20 solar-mass star (Woosley and Heger (2007))

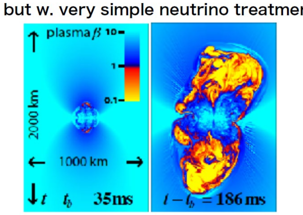
- Cylindrical rotational law

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

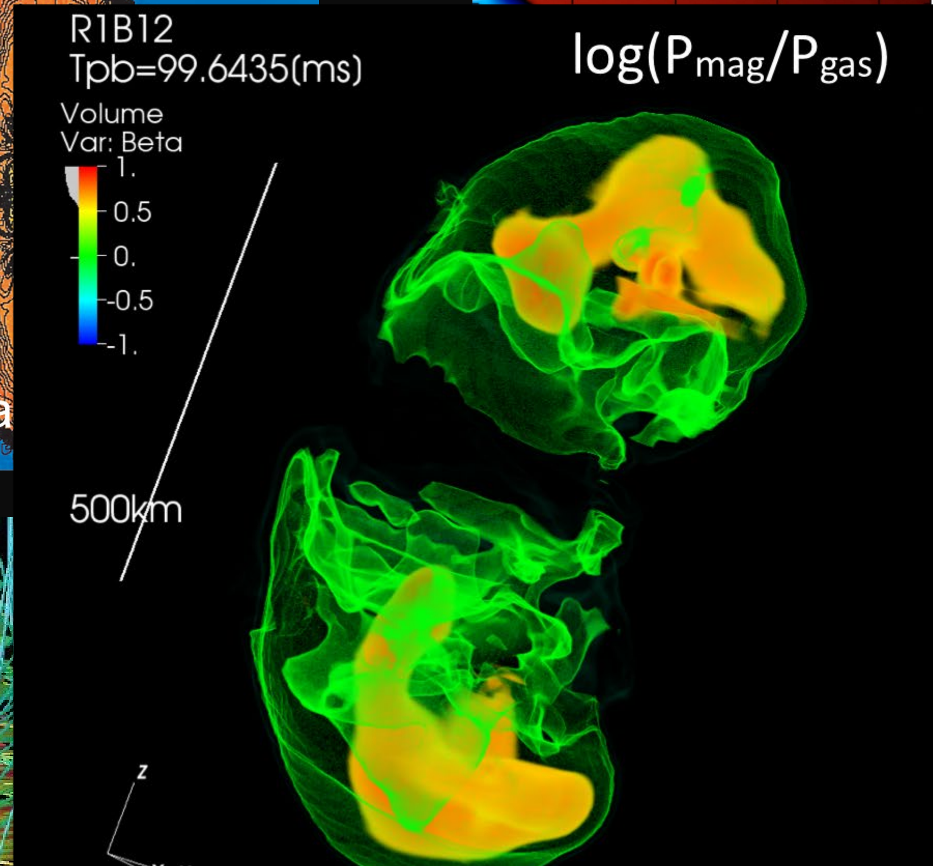
- Dipole-like B

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

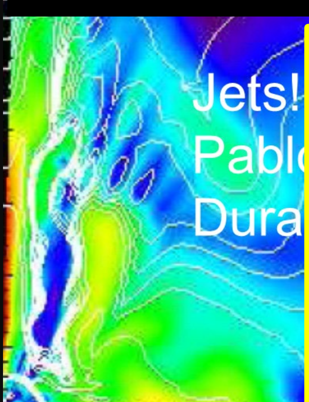
In 3DGR context,
Mösta+,'14 is the latest work
but w. very simple neutrino treatment



Renaissance of



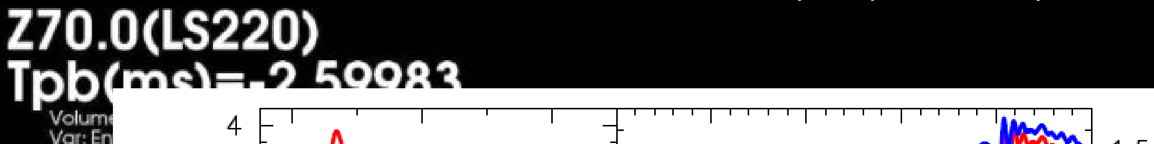
Kuroda, Takiwaki, KK, Alcones in prep

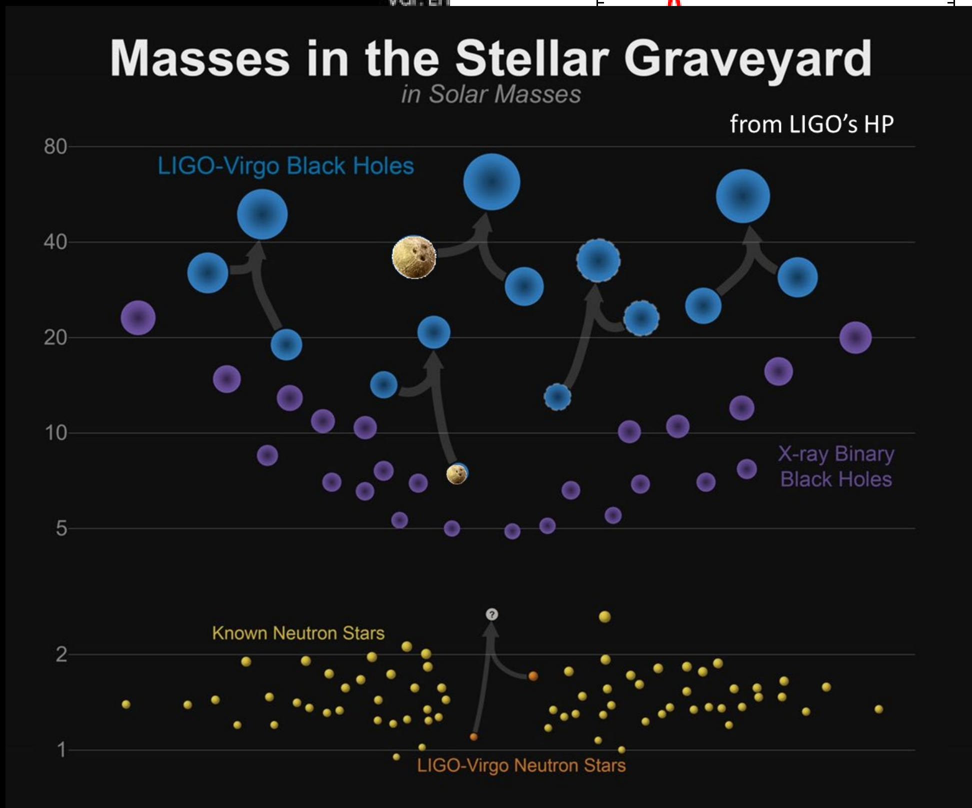


- ✓ **First MHD-driven jets in full 3D-GR MHD with multi-energy neutrino transport !**
  (The Valencia CCSN group is also world-leading!
  Obergaulinger & Aloy (2019, 2020, 2021), SR-MHD
  Moesta et al. (2014), GR-MHD with leakage scheme)
- ✓ Analysis of GW and *ν* predictions underway !

✓ BH forming simulations of a 70 M_{sun} (M_{CO} ~ 28.5 M_{sun})

Kuroda, KK, Taiwaki, Thieleman, MNRAS, 2018





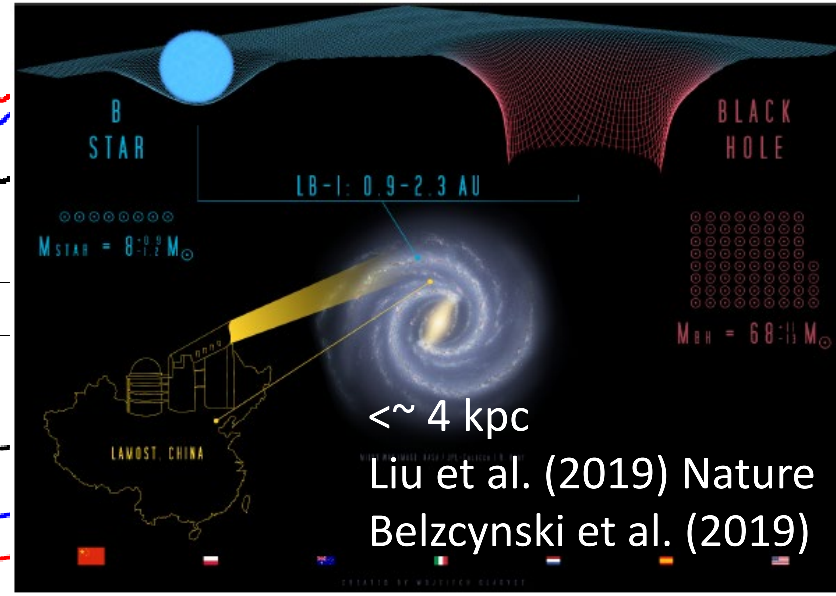
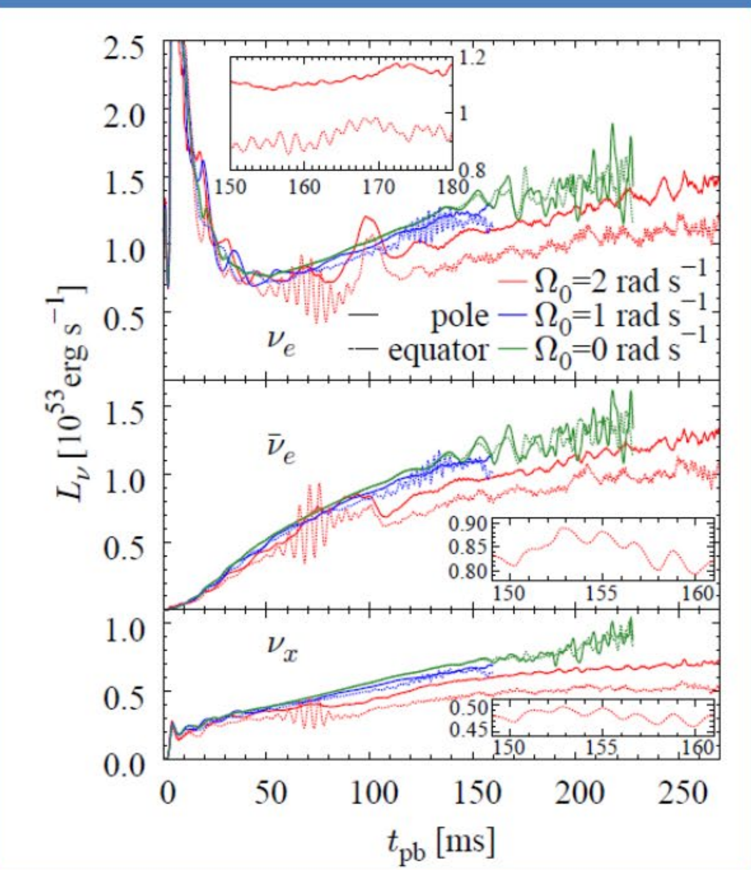


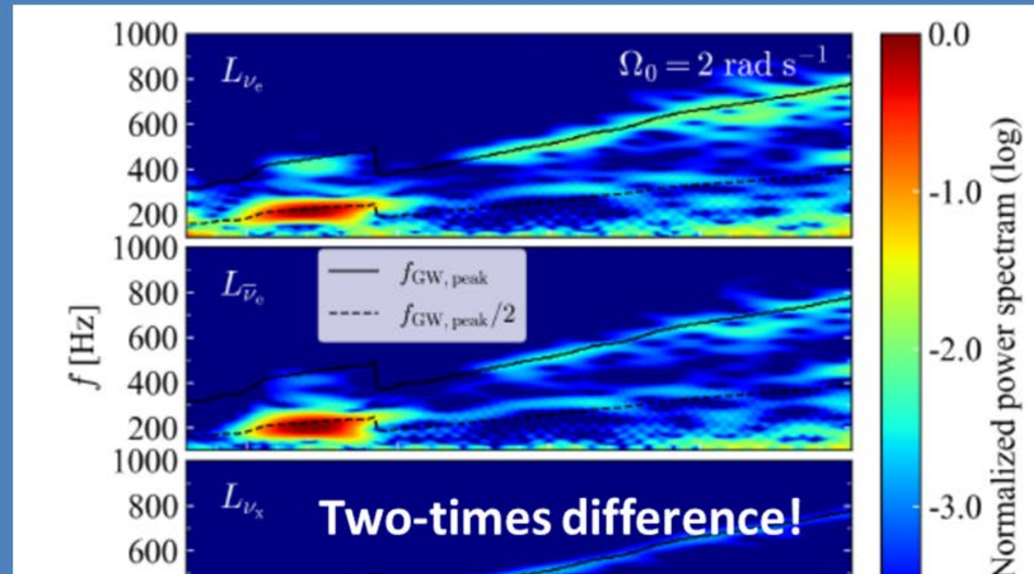
FIG. 1.— An artist visualization of the Milky Way LB-1 binary star system hosting a ~ 70 $M_\odot$ black hole.

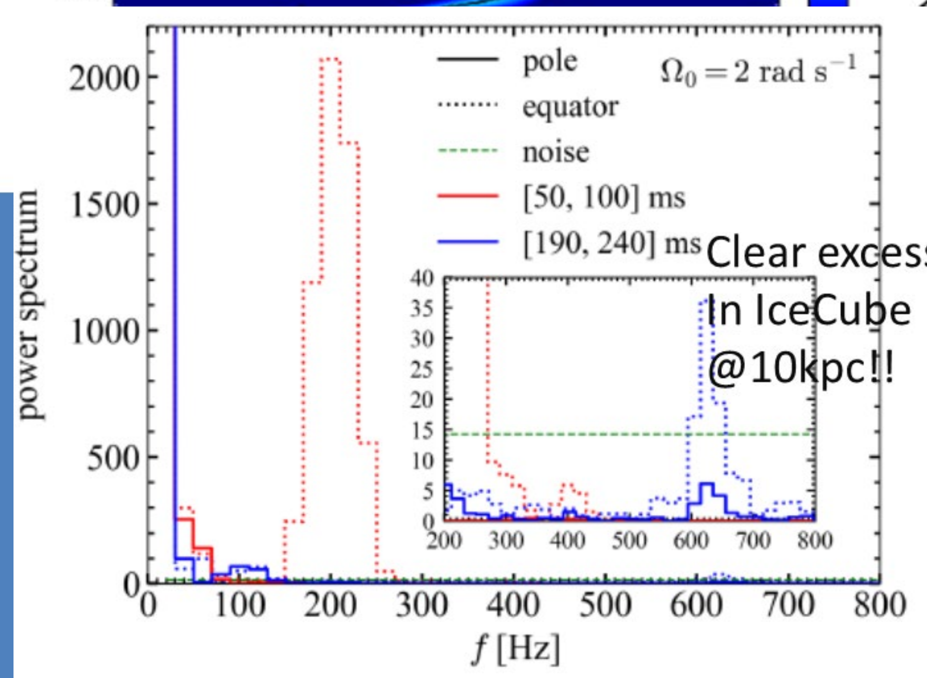
- ✓ <u>Earliest BH formation</u> after bounce (〜300 ms postbouce) ！
- ✓ Before the BH formation, <u>monotonic increase</u> of neutrino luminosity and rms energy. (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Nakazato(+2008,2013), Fischer+ (2009), Huedepohl+(2016))
- ✓ **Sudden disappearance of the neutrino signals -> BH formation !**
- ✓ **These BHs may explain LIGO-Virgo BHs, be detectable for a galactic event ！**

✓ *If rapidly rotating* ? BH forming simulations of a 70 M_{sun}

Summary of neutrino properties:







Caveat1.Started from wrong? Multi-D stellar evol. possible !

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

DB: visSi00001.bov
Time:1

T. Yoshida, Takiwaki, KK, et al. (ApJ, 2019,2020)

Msun star
burning

Presupernova neutrinos from multi-D O shell burning shell

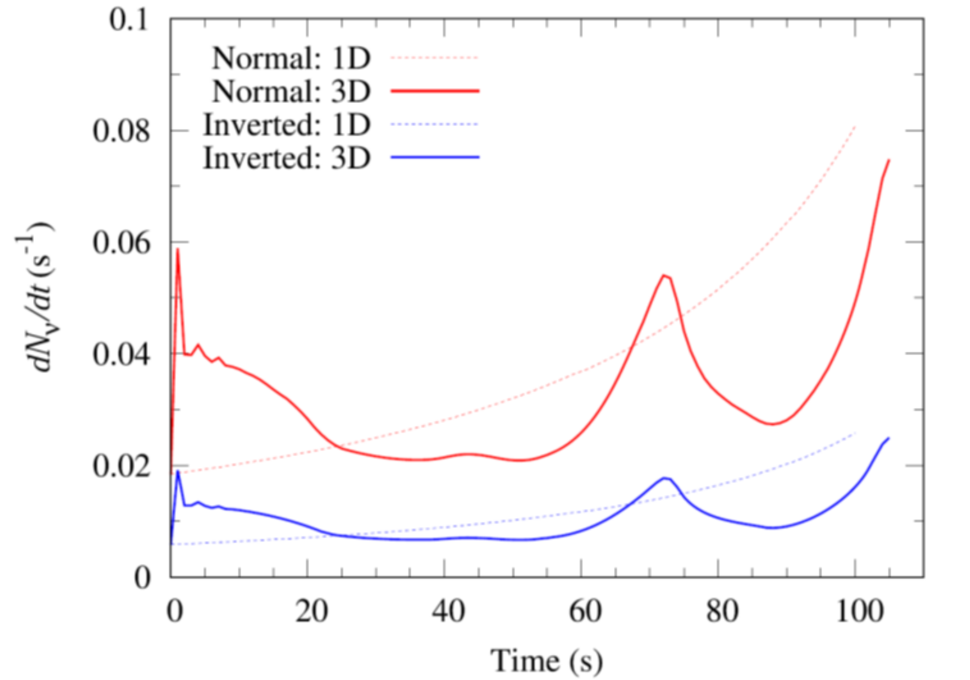


Figure 11. The evolution of the neutrino event rate of model 25M with KamLAND. The thick solid and thin dashed curves correspond to the results of the 3D and 1D simulations, respectively. The red and blue curves correspond to the normal and inverted orderings.

- ✓ **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 !**

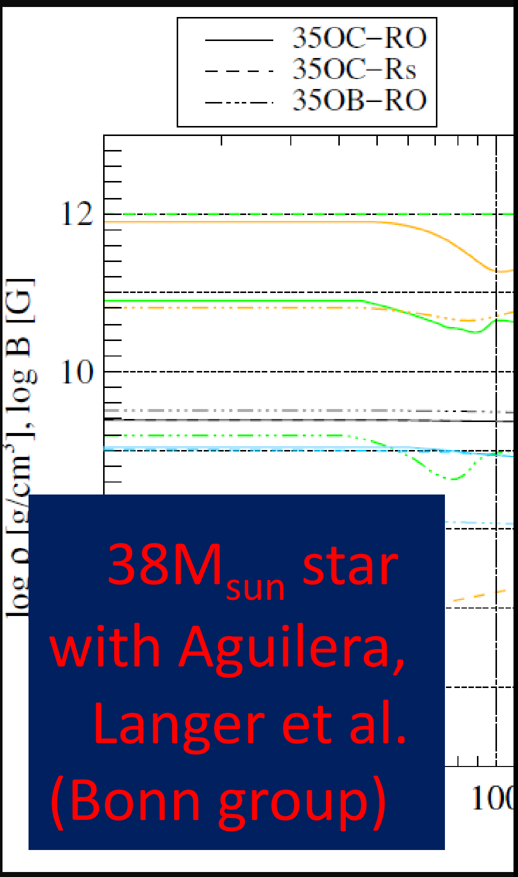
✓ One-Bethe 3D model was reported by Garching SN team using **3D progenitor**! (Bollig et al. (2021)

First 3D stellar evolution: what about the precollapse spiral flows ?

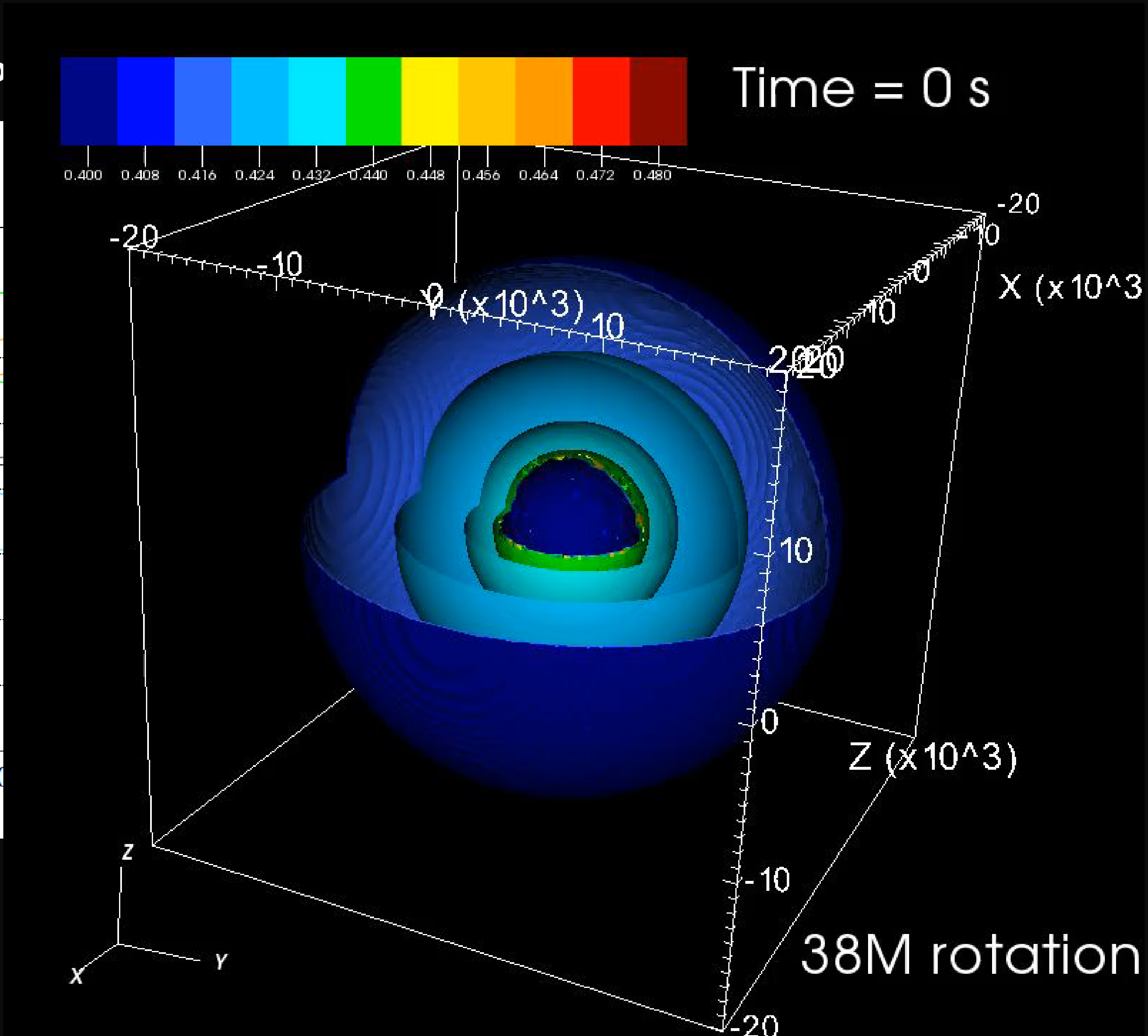
(3D stellar evolution calculations: Couch et al. (2015), Mueller et al. (2016))

Yoshida, Agulera, Takiwaki, KK, et al. (MNRAS Letters, 2021)

35C model : collapsar pro



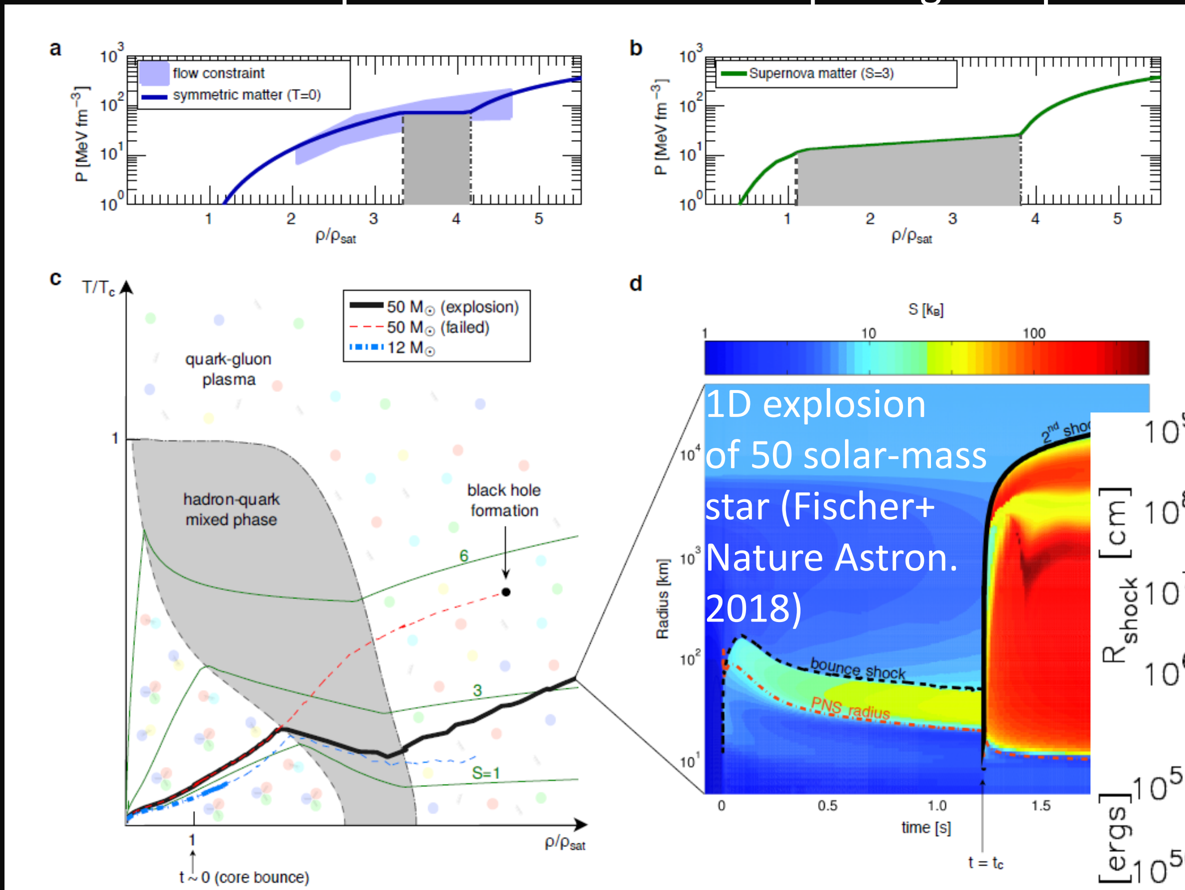
38M$_{sun}$ star with Aguilera, Langer et al. (Bonn group)



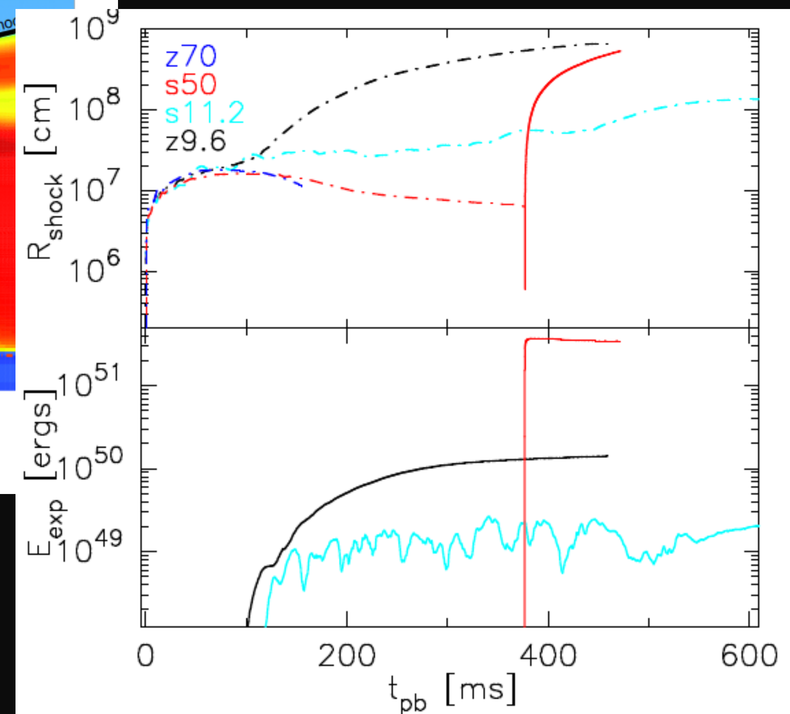
Caveat2. QCD phase transition could power explosion !!

If "first-order" phase transition to the quark-gluon phase takes place… then

✓Original idea:
Takahara & Sato (1988)
Gentile et al. (1993)



1D explosion of 50 solar-mass star (Fischer+ Nature Astron. 2018)



Caveat2. QCD phase transition could power explosion !!

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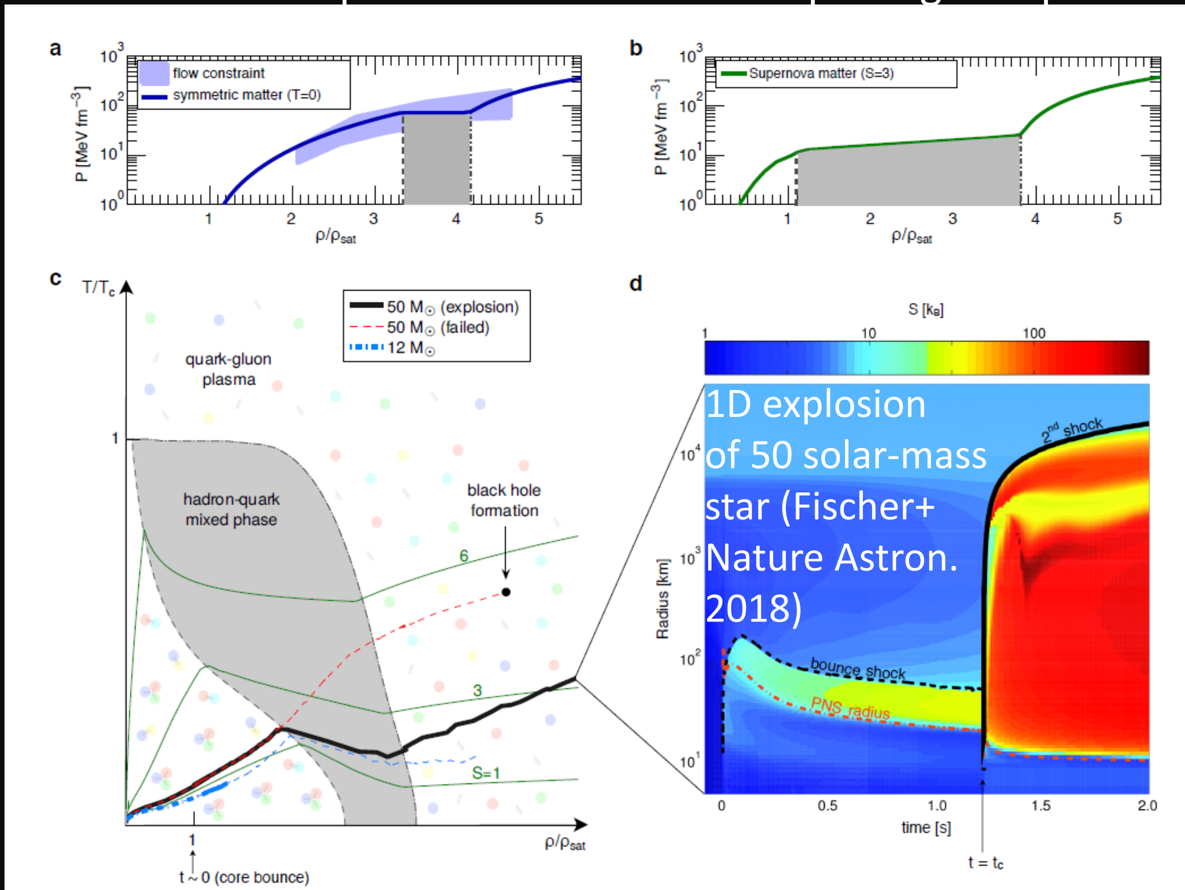

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Caveat2. QCD phase transition could power explosion !!

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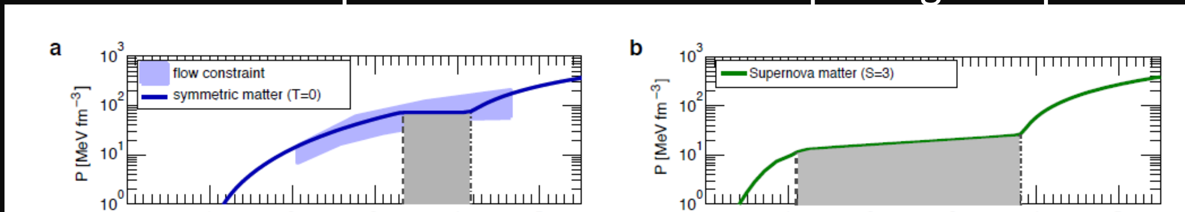


✓Original idea:
Takahara & Sato (1988)
Gentile et al. (1993)

Full 2D-full-GR simulations including updated opacities（a la Kotake+(2018))
Kuroda, Fischer, Takiwaki, Kotake, submitted

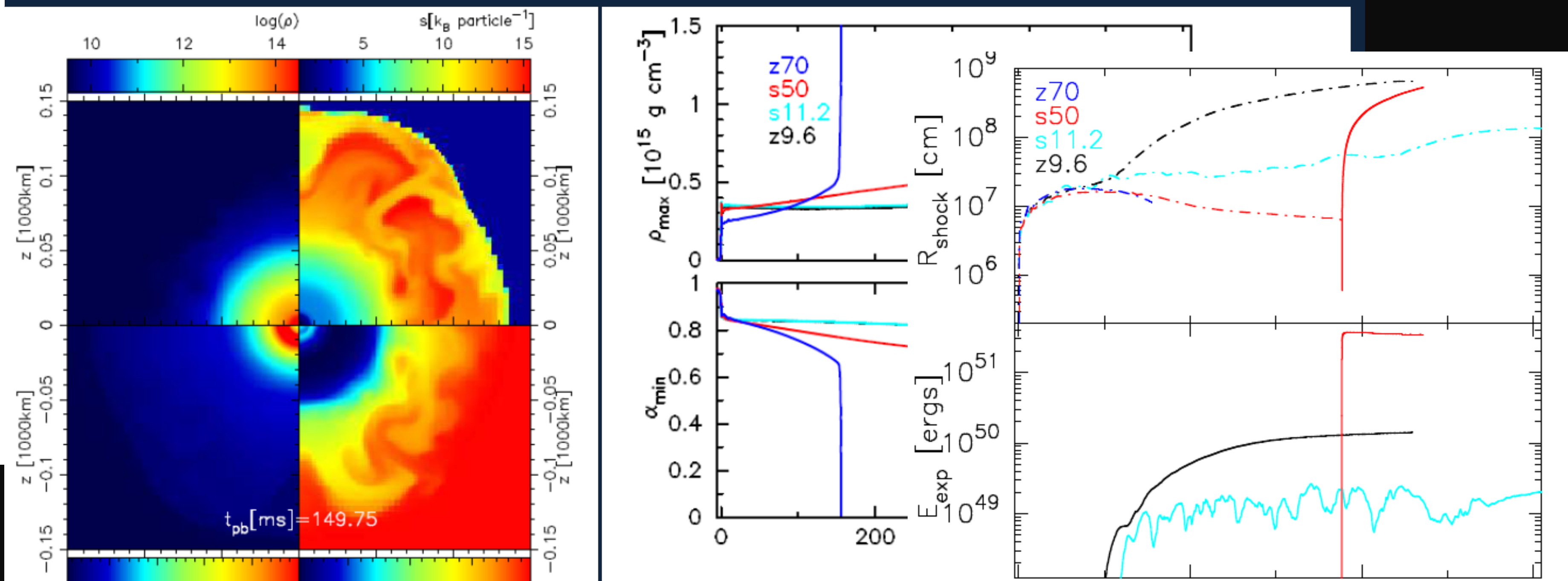
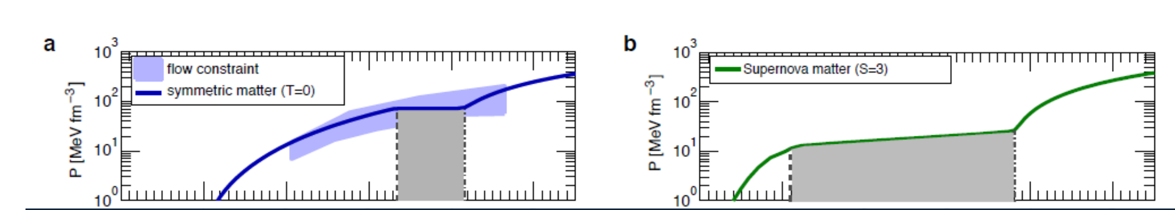


Figure 1. *Top panel*: evoluti
for all models in units of 10[1]
axis). *Bottom panel*: evolutio…

Caveat2. QCD phase transition could power explosion !!

If “first-order” phase transition to the quark-gluon phase takes place… then



✓Original idea:
Takahara & Sato (1988)
Gentile et al. (1993)

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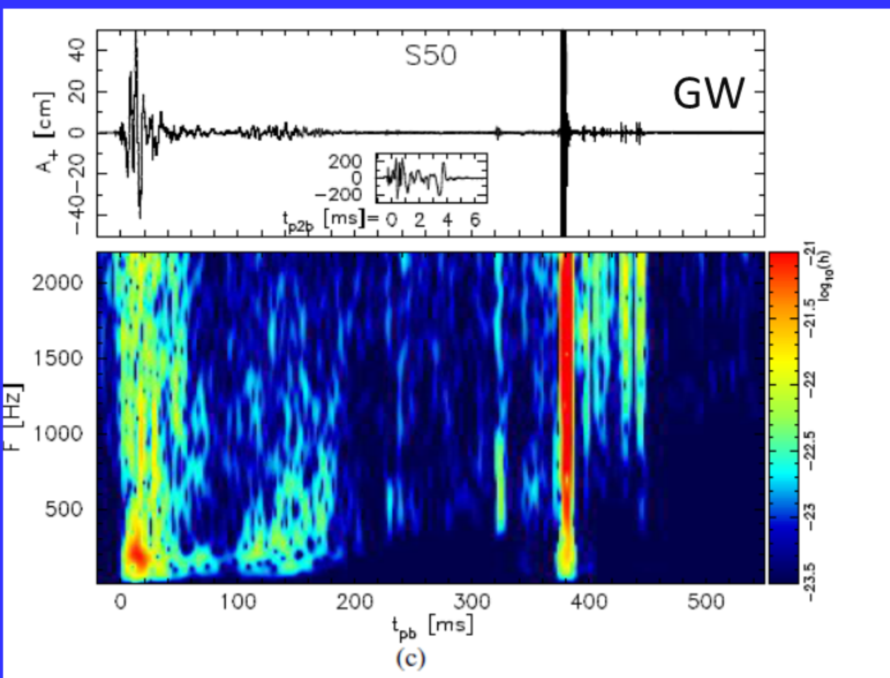
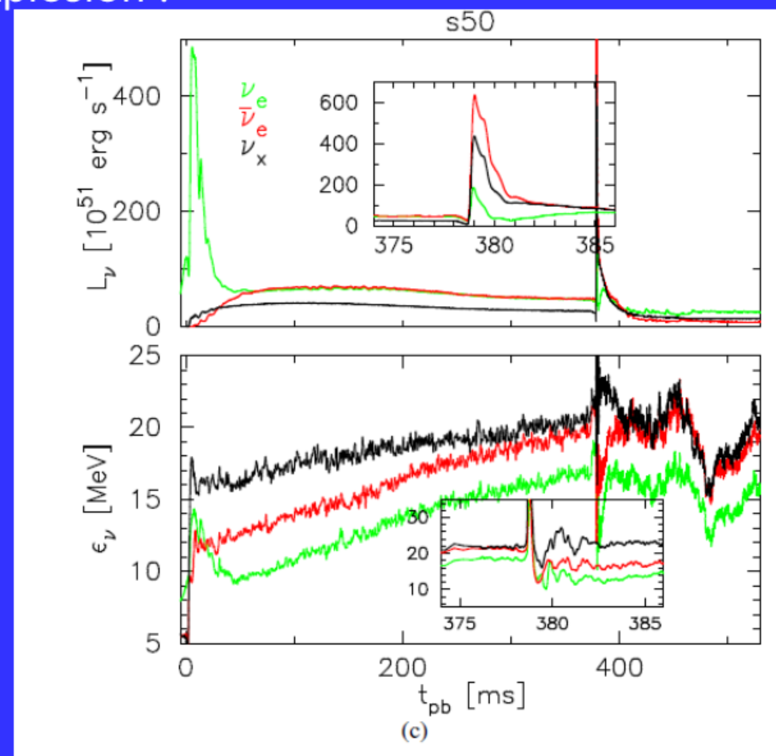
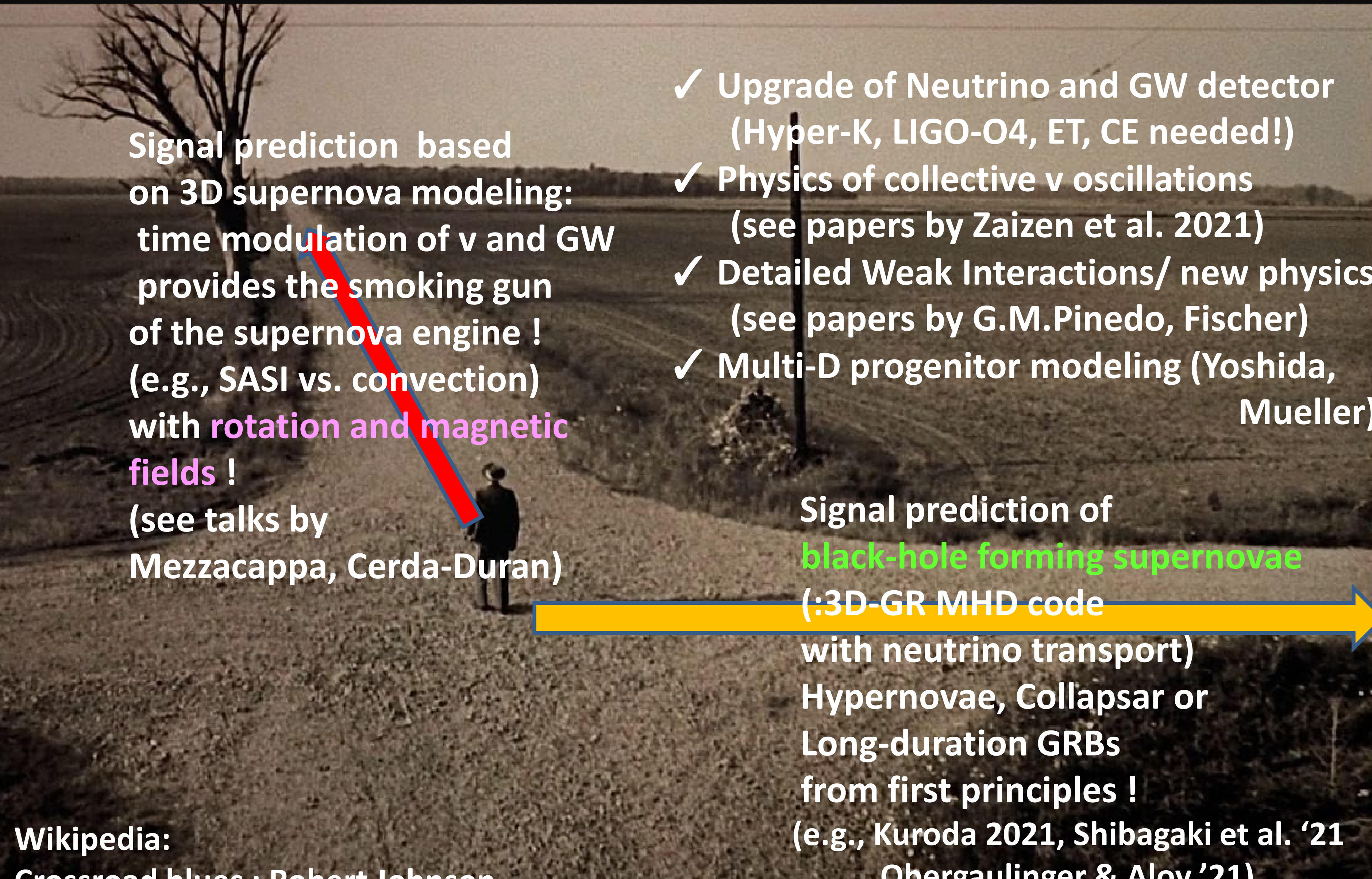
Distinct second burst signals in GW and neutrinos:
a smoking gun of the phase-transion induced explosion !





CCSN simulations, neutrinos and GWs at the cross-road !



- ✓ Upgrade of Neutrino and GW detector (Hyper-K, LIGO-O4, ET, CE needed!)
- ✓ Physics of collective ν oscillations (see papers by Zaizen et al. 2021)
- ✓ Detailed Weak Interactions/ new physics (see papers by G.M.Pinedo, Fischer)
- ✓ Multi-D progenitor modeling (Yoshida, Mueller)

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 and magnetic fields ! (see talks by Mezzacappa, Cerda-Duran)

Signal prediction of black-hole forming supernovae (:3D-GR MHD code with neutrino transport) Hypernovae, Collapsar or Long-duration GRBs from first principles ! (e.g., Kuroda 2021, Shibagaki et al. '21 Obergaulinger & Aloy '21)

Wikipedia:
Crossroad blues : Robert Johnson