Gravitational-wave predictions from multi-D modeling of core-collapse supernovae

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with

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"From Quarks to Neutron Stars: Insights from kHz Gravitational Waves" @ Univ. Tokyo, April 23-24, 2025

Gravitational Waves (GWs) from Stellar Collapse

(see reviews Vickey et al. (2022), Abdikamalov et al. (2021), Kotake and Kuroda (2016)), Kotake (2013), Ott (2011))

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)

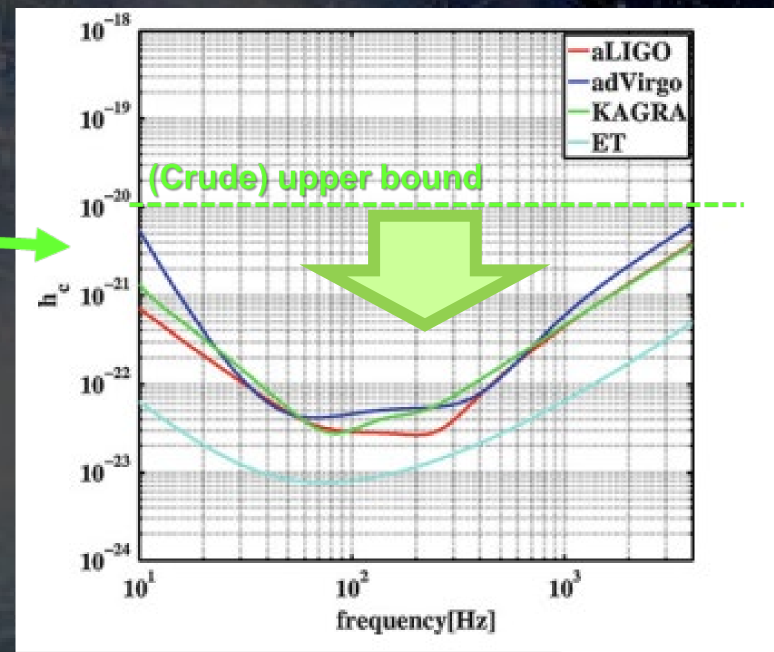
$$R_s = 3\ \mathrm{km}\left(\frac{M}{M_\odot}\right) \quad v/c = 0.1 \quad \underline{R = 10\ \mathrm{kpc}}$$

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

$$f_{\mathrm{GW,hydro}} \sim \frac{1}{\sqrt{G\rho}} \sim O(100\ \mathrm{Hz}) \sim k\mathrm{Hz}$$

for $\rho \sim 10^{11} \sim 10^{14\sim 15}\ \mathrm{g/cm^3}$

(Proto-Neutron Star (PNS), PNS interior)



✓ 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 !

Gravitational Waves (GWs) from Stellar Collapse

GW amplitude from the quadrupole formul

“kHz” detectors !! (see talks by Somiya, Aso, Lasky!)

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Quadrupole moment

Typic

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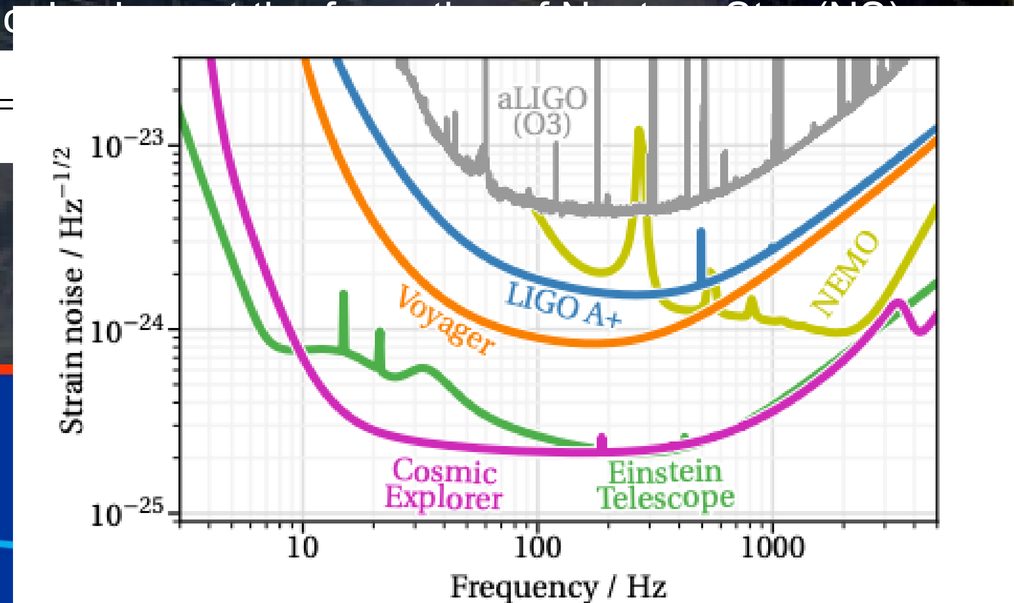
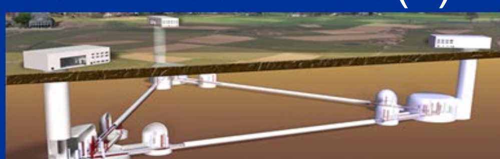
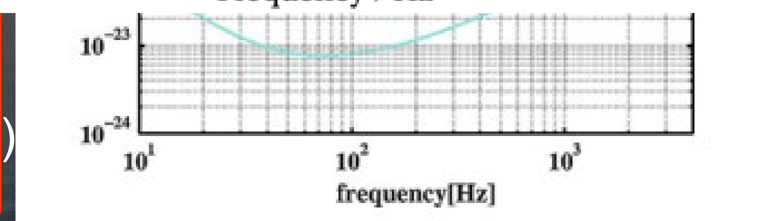


Good news ! (Future)

10 km long:
Einstein Telescope (ET)
could start ~2028(?)



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



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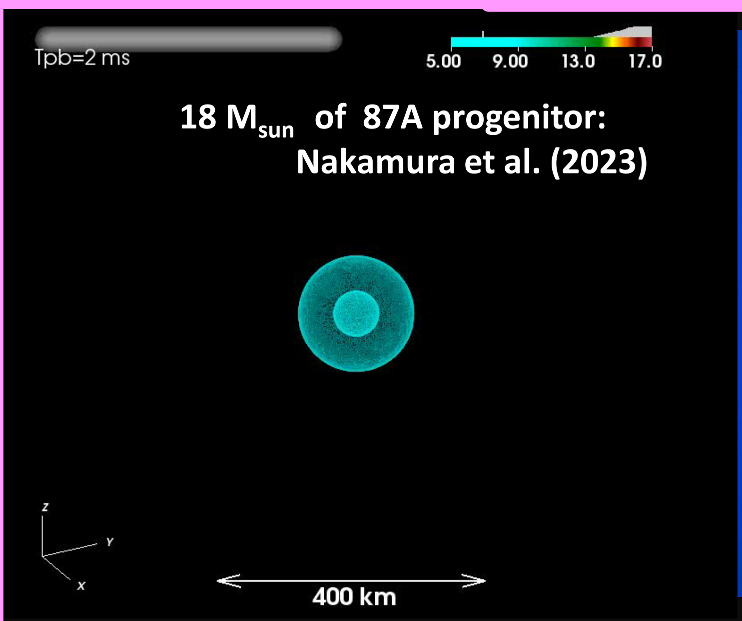
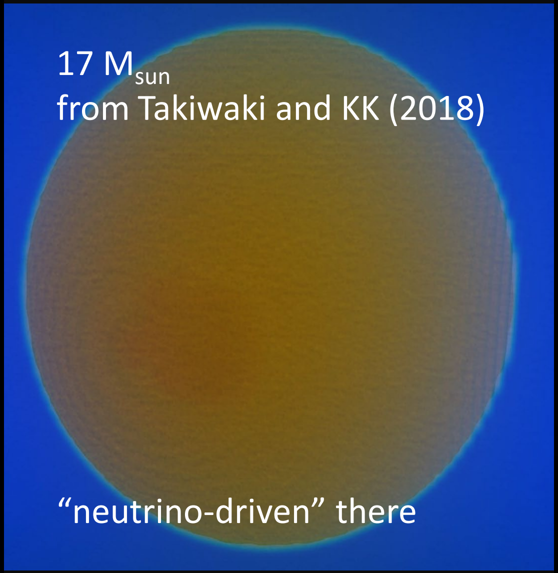
What makes the SN-dynamics deviate from spherical symmetry is essential for the GW emission mechanism !

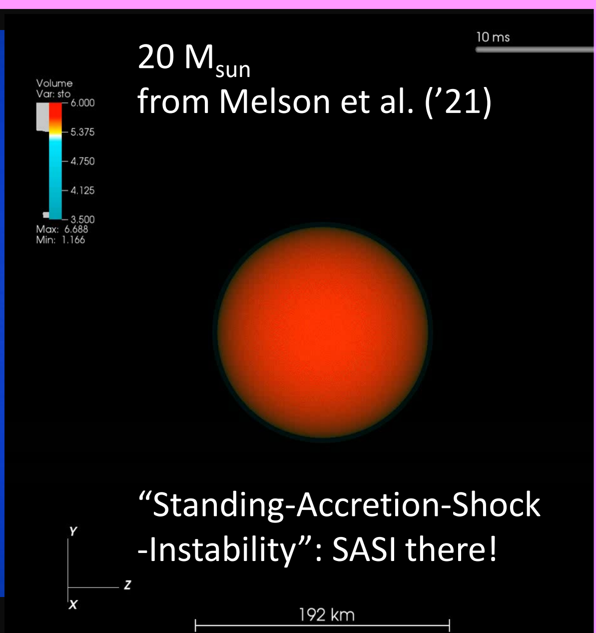
Two candidate mechanisms of core-collapse supernovae

(See reviews in Janka ('25), Yamada et al. ('25), Vartanyan and Burrows ('23), Mueller ('20), Kotake+ ('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., Vartanyan+ (22), Melson+('21)) ✓ **Precollapse Inhomogenities/structures** (e.g., Mueller et al. ('22), Yoshida et al. ('21)) ✓ **Novel microphysics:** Bollig+(17), Fischer+('21)	✓ **Field winding and the MRI** (e.g., Obergaulinger & Aloy (2017), Rembiasz et al. (2016), Moesta et al. (2016), Masada + (2018)) ✓ **Non-Axisymmetric instabilities** (e.g., Takiwaki, et al. (2018), Summa et al. (2017))
Progenitor fraction	Main players!	~<1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)



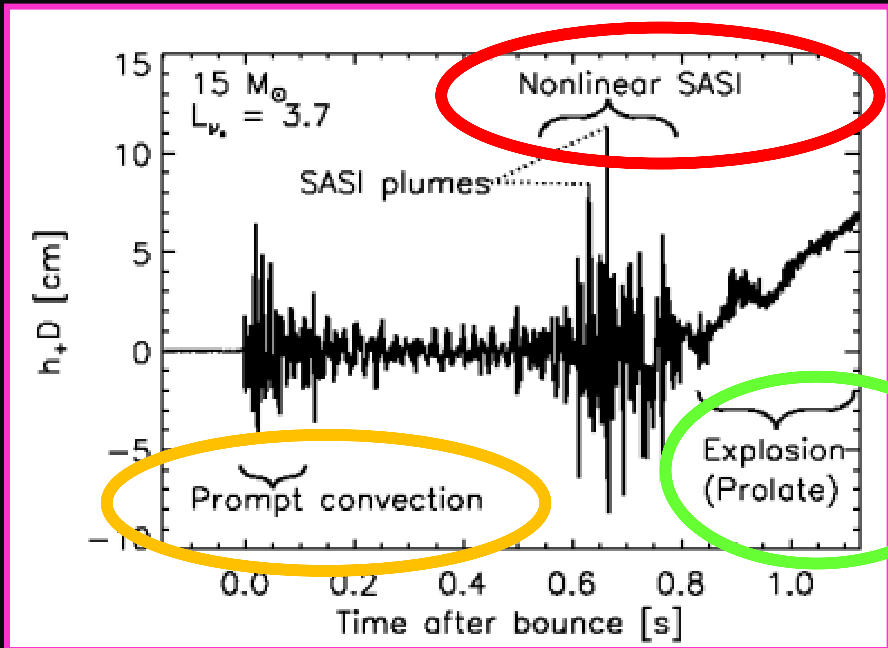




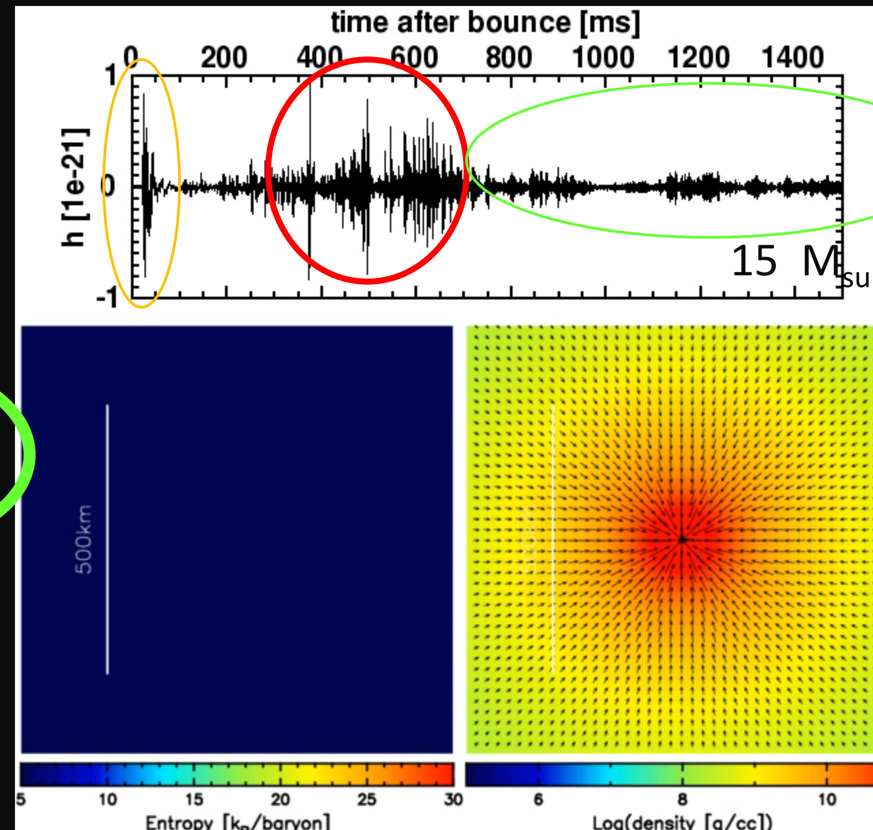
(e.g., Burrows et al. ('24), Bollig et al. ('21), Mezzacappa+ ('21), Vartanyan et al. (2022),O'Conner et al. ('22), Mueller ('22)

Generic GW signatures of neutrino-driven explosions

Waveform from Murphy et al. (2009) ApJ



Waveform from Nakamura et al. ('16) MNRAS



(Later confirmed by B. Mueller et al. ('18), ApJ,
Mezzacappa et al. (2023), PRD)

✓ **Three generic phases** in neutrino-driven models: "burst-type" GW

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

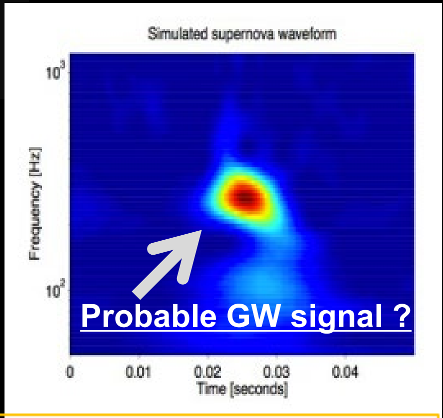
(Müller et al. (2020, ApJ), Cerda-Duran et al. (2013, ApJ), Kuroda et al. (2018))

✓ Waveforms **have no template character**: "stochastic" explosion processes!

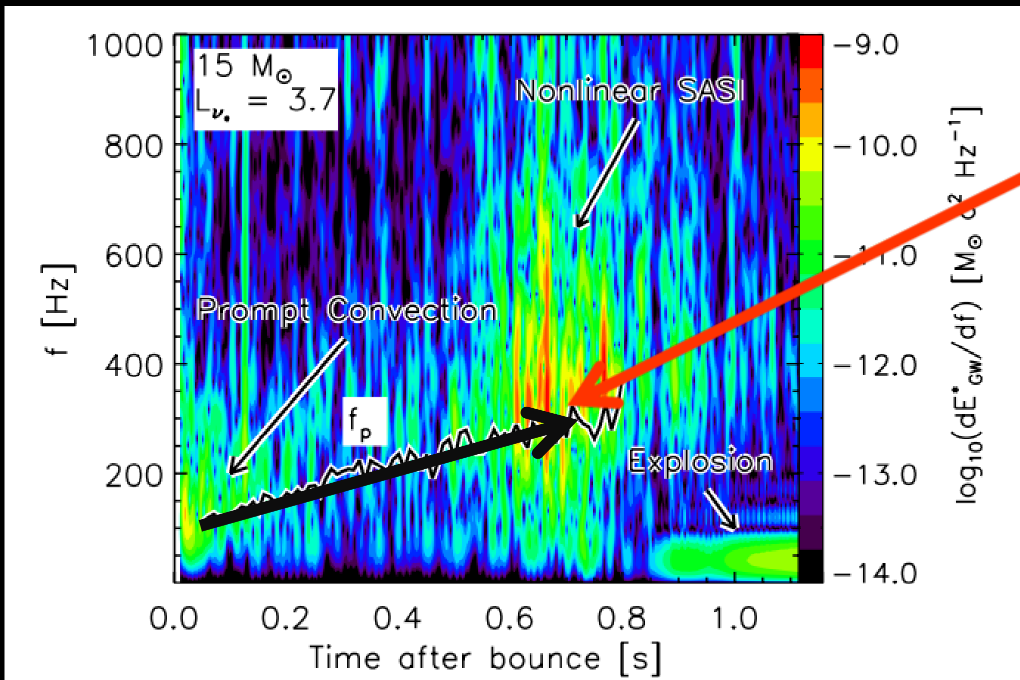
How to detect GWs with no-template features…

✓ **Excess power method**: Flanagan & Hugh (1998)

⇒ **Decompose data-stream into time-frequency domains**
⇒ **Search for "hot" regions with excess power in the spectrogram !**



✓ GW spectrogram from Murphy et al. ('09) ApJ.



☆ **Increase of typical frequency**
⇒ the "ramp up" mode (buoyancy-driven)

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

M, R, T : mass, radius & temperature of PNS, Γ : stiffness of EOS
Due to mass accretion, M↗, R↘

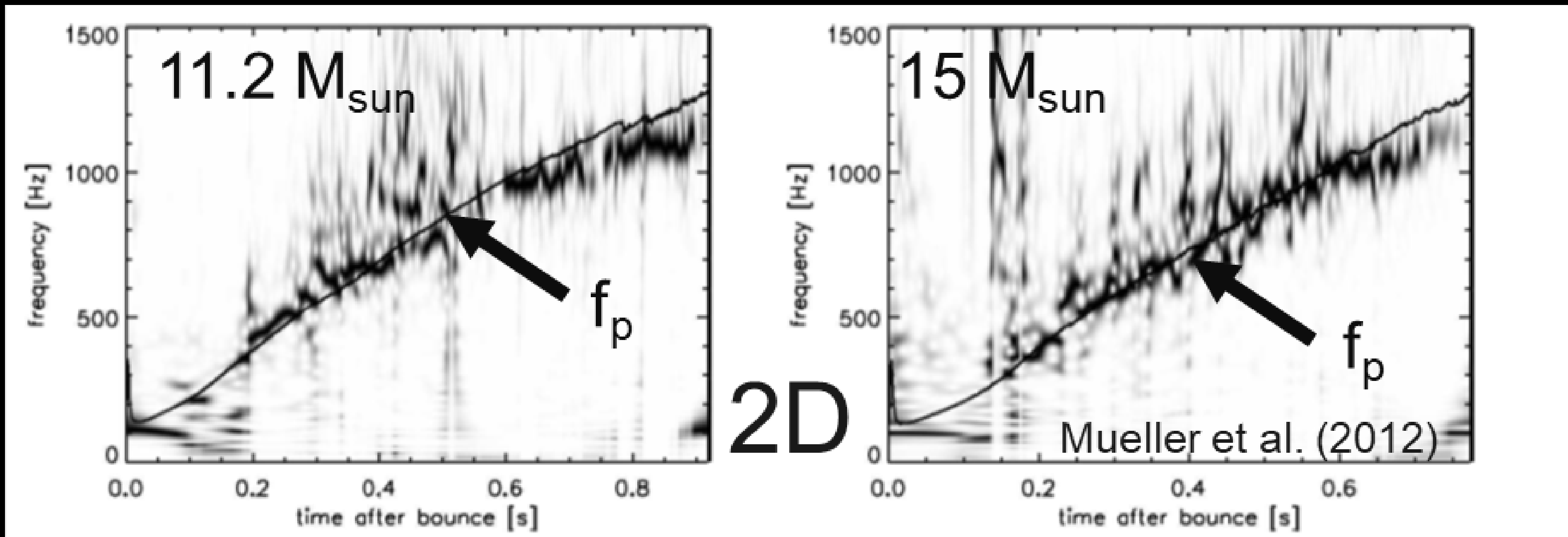
⇒ f_p ↗

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

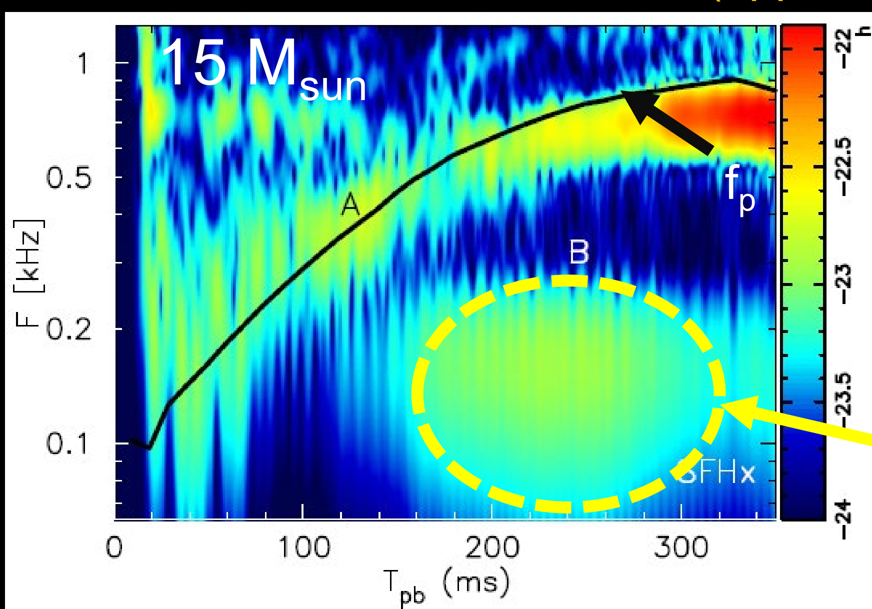
✓ (With no template character…) **Generic GW phases are in the spectrogram !**
✓ Secular increase of the typical GW frequency (f_p) **reflects the PNS evolution.**
✓ On top of f_p, the high frequency component comes from strong downflows to PNS.
✓ **These qualitative features : Common to more recent 2D and 3D models.**

GW Spectrograms from State-of-the-Art: "Ramp-up" is there!

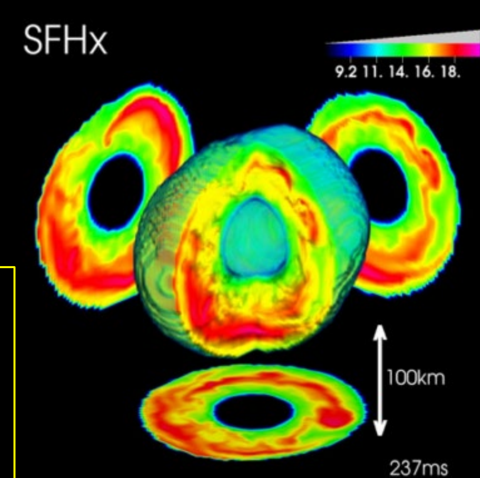
✓ 2D GR simulations with VEF (detailed) transport (Vertex-Coconuts code by MPA)



✓ 3D full GR simulations with M1 (approx.) transport: Kuroda et al. (2016,18,20)



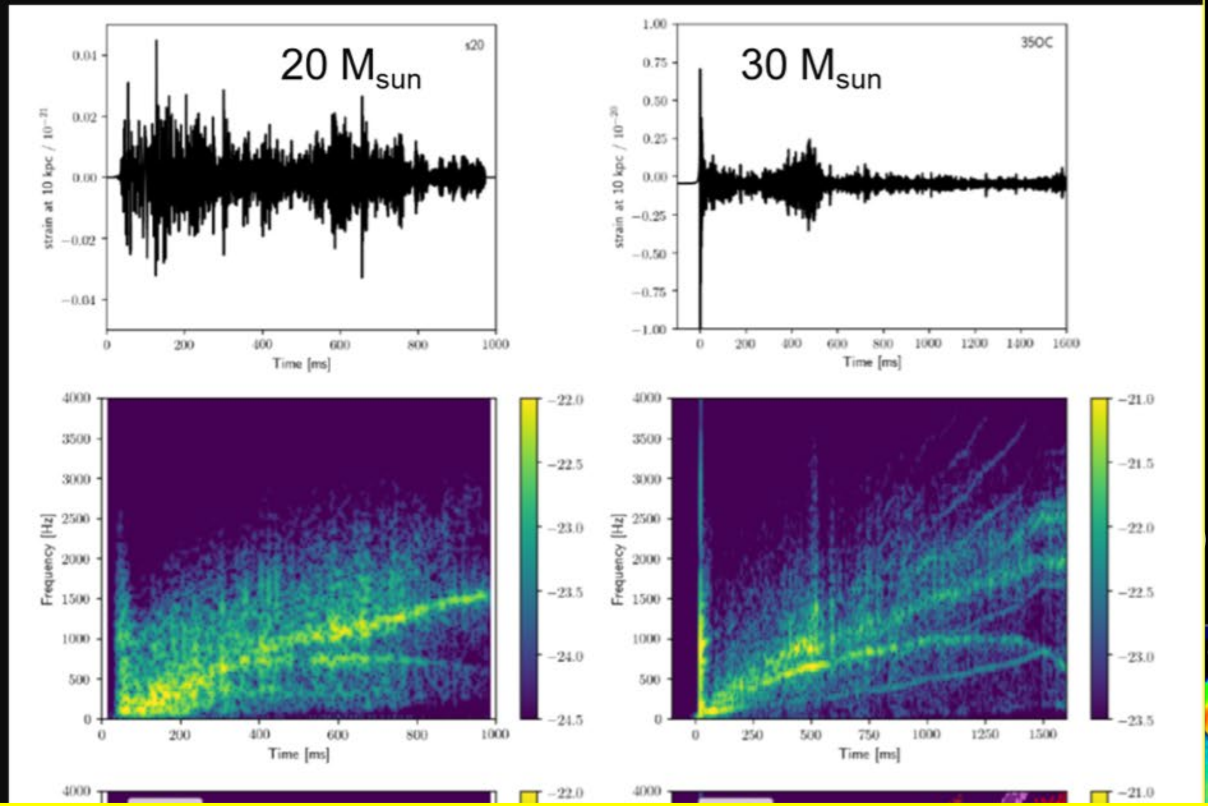
from
"SASI" activity
("3D" dynamical
phenomena!)

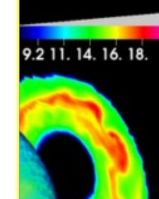


GW Spectrograms from State-of-the-Art: "Ramp-up" is there!

"PNS" asteroseismology : Linear analysis of the PNS oscillations

Torres-Forné et al. (2017, 2018), MNRAS





✓ The waveforms "look" **different !**

✓ Excess in

☆ Important lessons:

✓ A universal "relation" proposed; (see talk by Zhao!)
low modes of "*f*", "g_1" insensitive to progenitor, EOS, and numerical details.
→ Direct information to the PNS "M-R" relation! (Torres-Forne+2017, Sotani+2021).

✓ For the detection, "kHz" detectors crucially needed !

GW Spectrograms from State-of-the-Art: "Ramp-up" is there!

"PNS" asteroseismology : Linear analysis of the PNS oscillations

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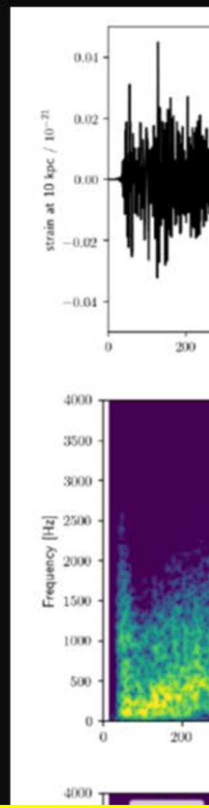
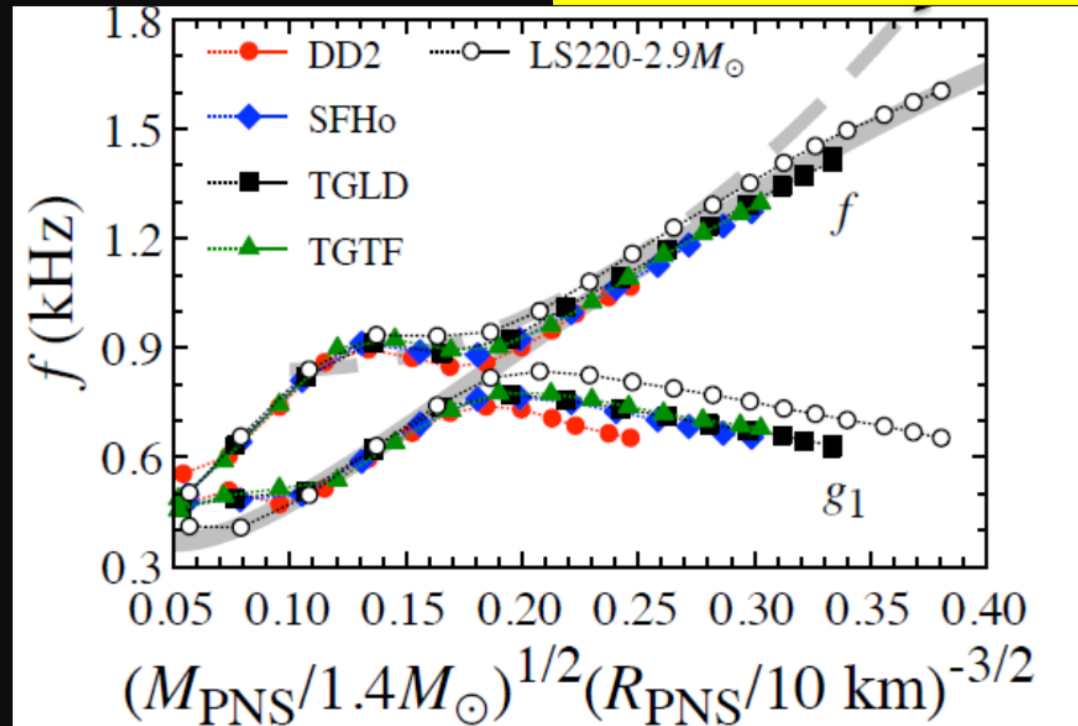


Sotani et al. (2021) PRD



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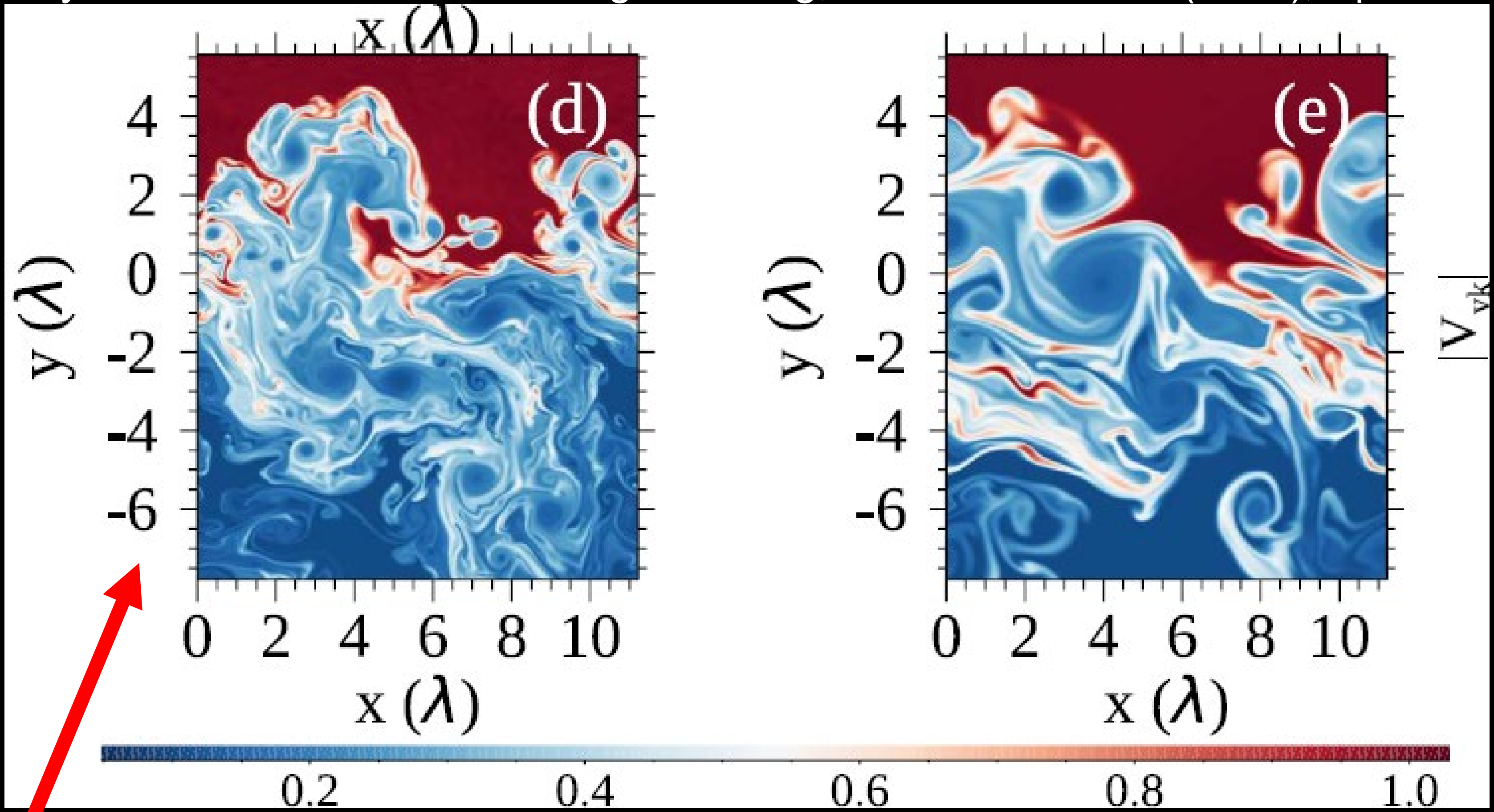
✓ For the detection, "kHz" detectors crucially needed !

✓ "Turbulence" the key for the neutrino-mechanism!

✓"Pulsars": rotate and magnetized: Magnetohydrodynamics (MHD) is mandatory !

✓ "High" numerical resolution required to capture "High" frequency GW !

"Eddy" simulations with the same grid setting; Matsumoto et al. (2020), ApJ



Accuracy: Our SN code (3DSn-MHD)

3rd order in time & 5th order (PPM5) in space : x3 expensive than HD!

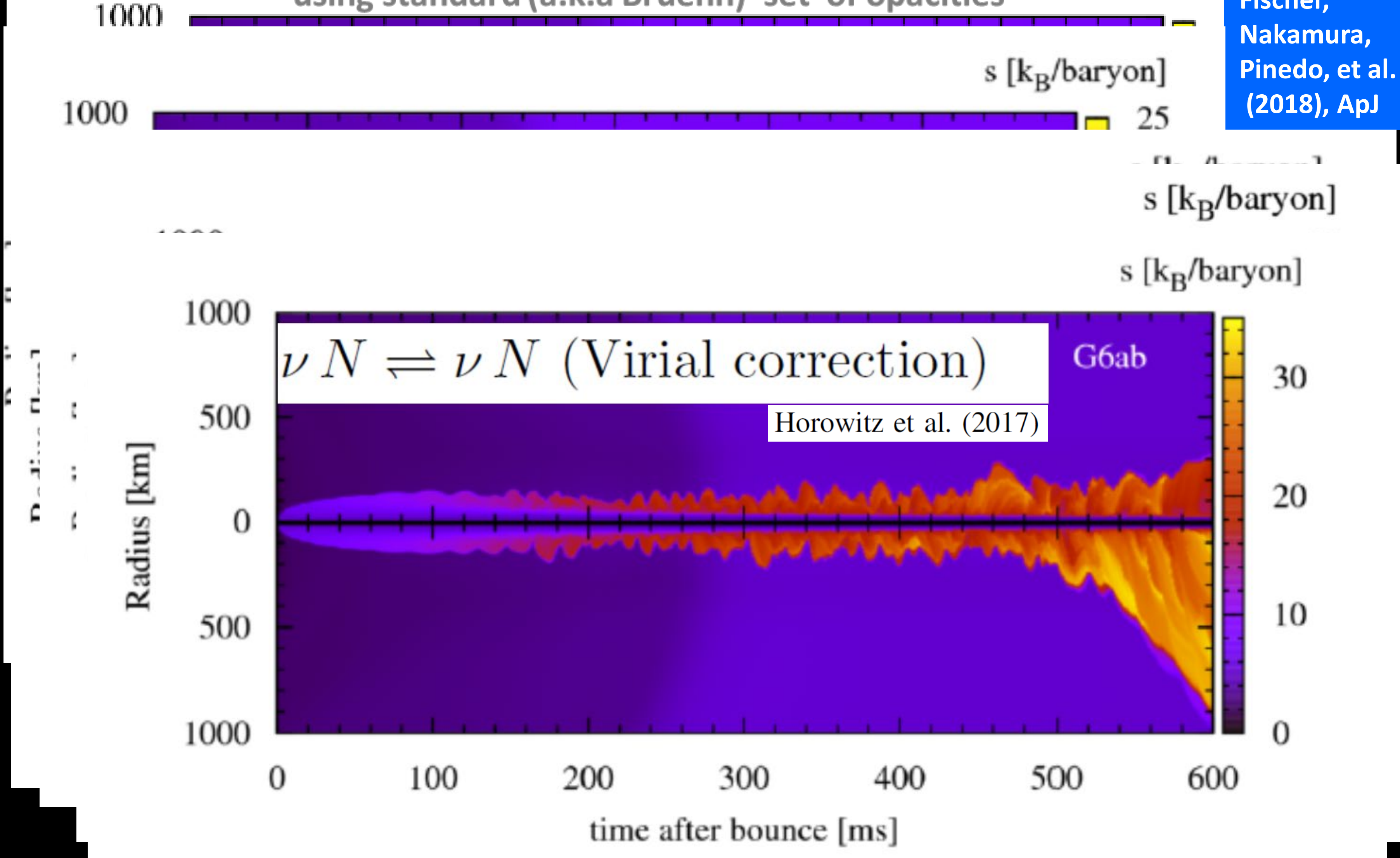
Previous SN codes (Fornax):
2nd order in time & 3rd in space

The "devil" is in the details ...(of neutrino physics)

2D-IDSA, 20 M_{sun} (Woosley & Heger (2007))

using standard (a.k.a Bruenn) set of opacities

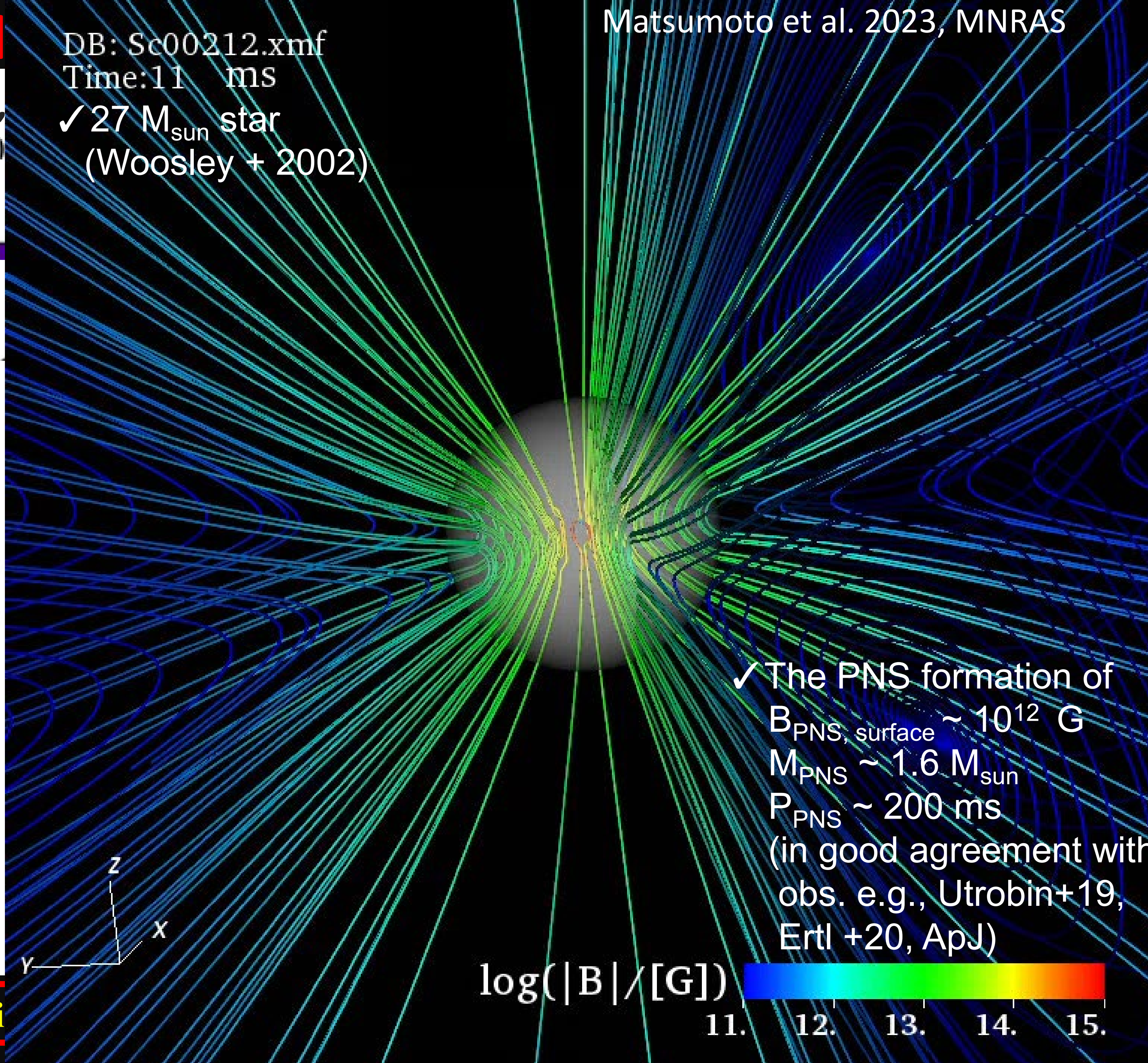
KK, Takiwaki, Fischer, Nakamura, Pinedo, et al. (2018), ApJ



✓ Quantitative GW/ν signal prediction, "updates" (MHD, ν physics, GR...) mandatory!

The “d

2D-IDSA,



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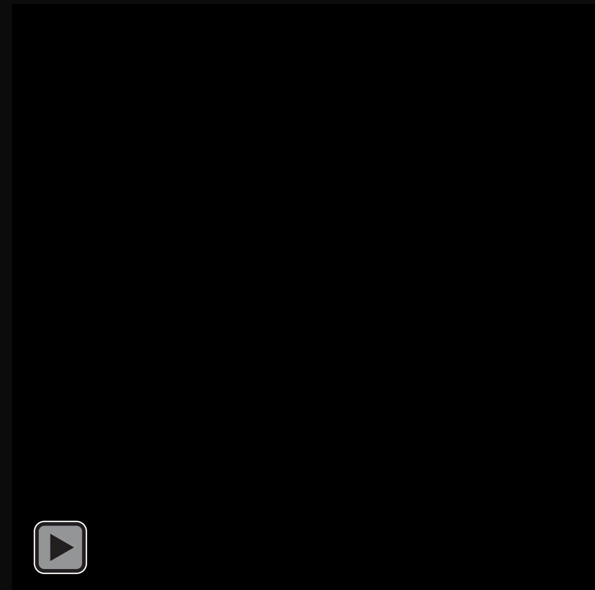
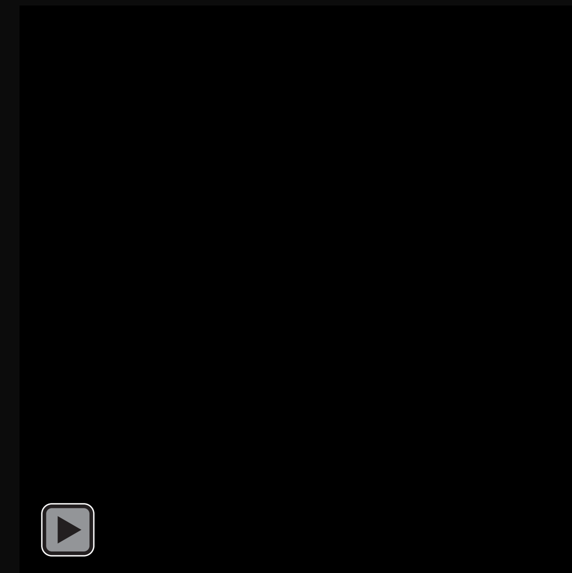
✓Quanti ory!

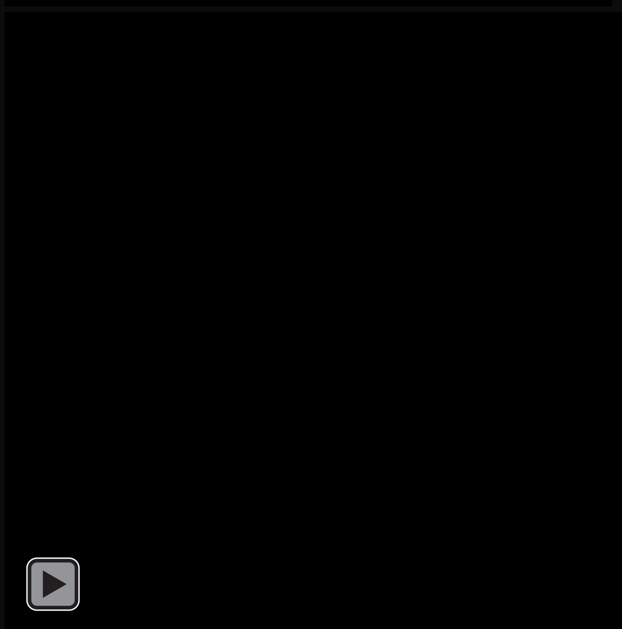
More 3D CCSN modeling with MHD are now possible !!!

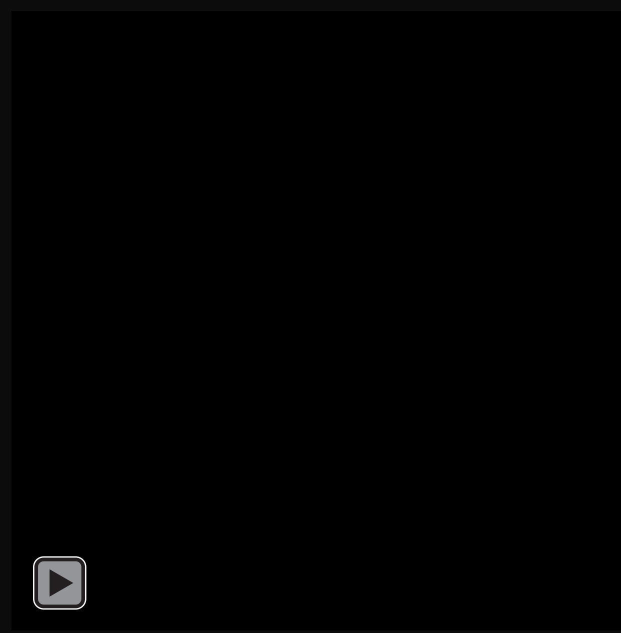
Nakamura, Takiwaki, KK (2024), MNRAS Matsumoto et al. (2023)

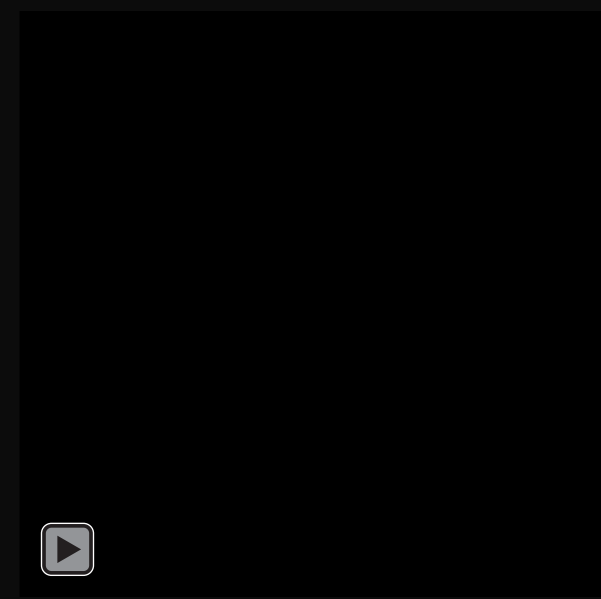
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform), Non-rotation)





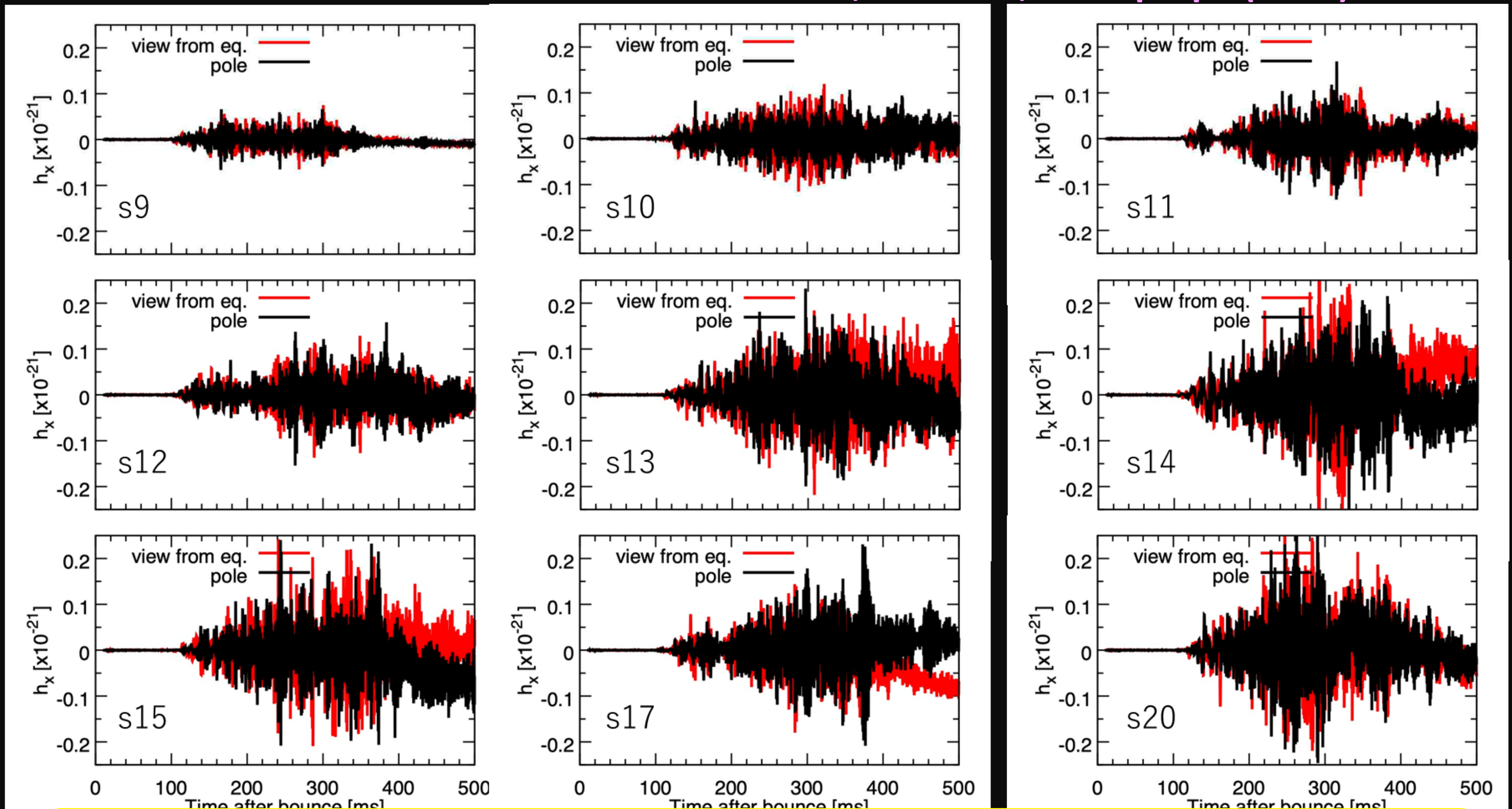






✓GW landscape from systematic 3D MHD modeling

Nakamura, Takiwaki, KK in prep. (2022) MNRAS



✓ The amplitudes become higher for models (with high progenitor mass) with **progenitor's compactness (~M_{core}/R_{core})"**
(= abundant gravitational energy releasable)
predominantly because of strong gravity.

✓GW landscape from systematic 3D MHD modeling

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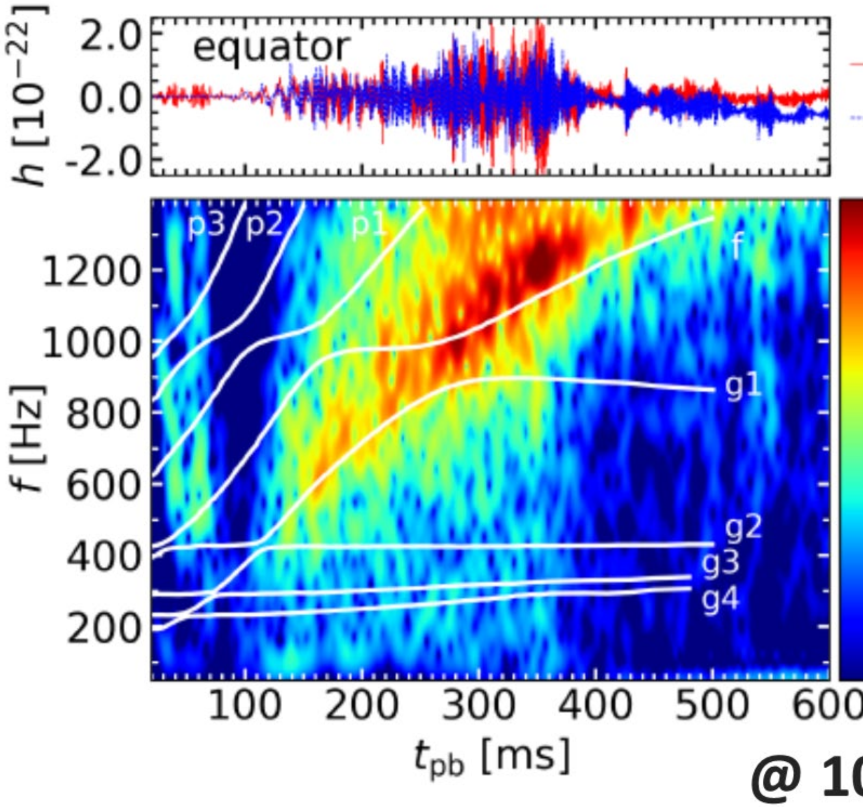

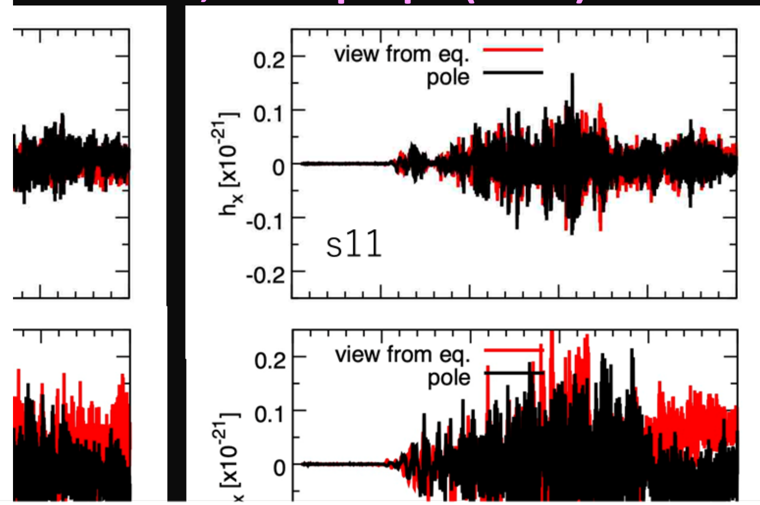

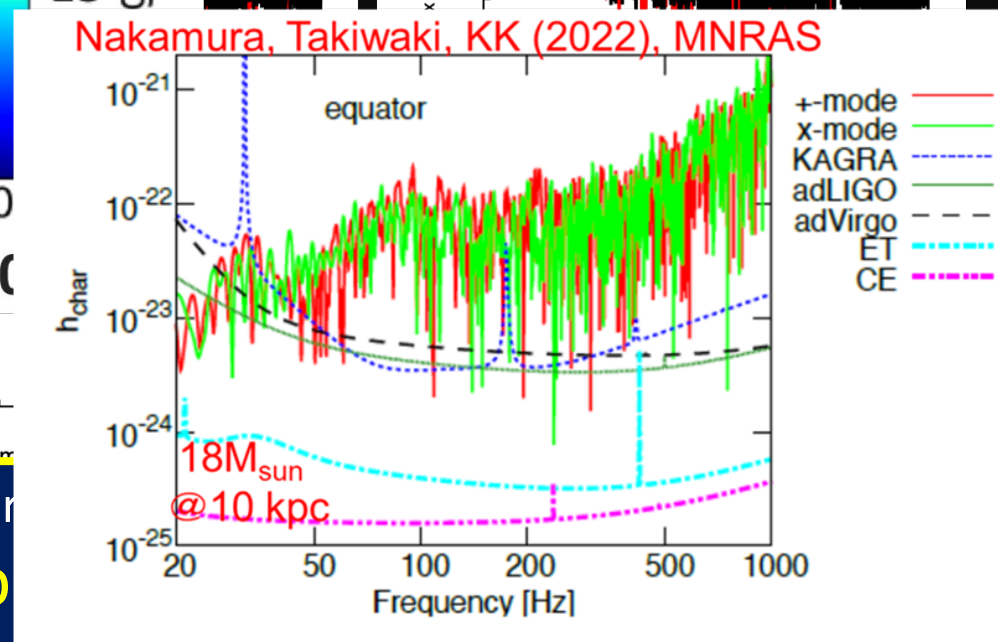

✓The ramp-up mode(s) ("f" and "g_1") universally there!

✓ The amplitudes become higher

with progenitor's comp

(= abundant gravitatio

predominantly because of stron

✓ Setting S/N as 10, "ET" and "CE" needed for a Galactic SN event (below 1kHz).

✓GW landscape from systematic 3D MHD modeling

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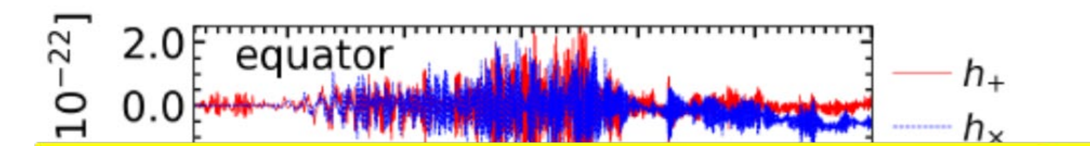
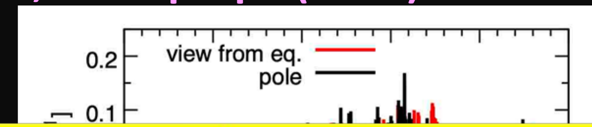
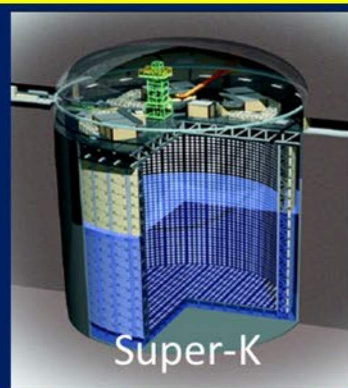
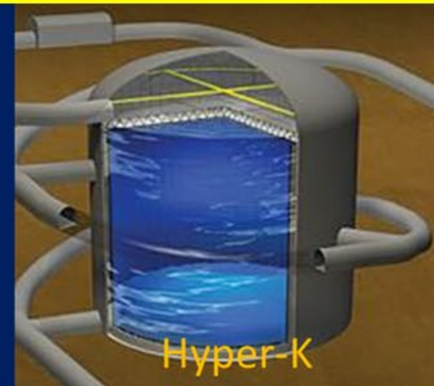
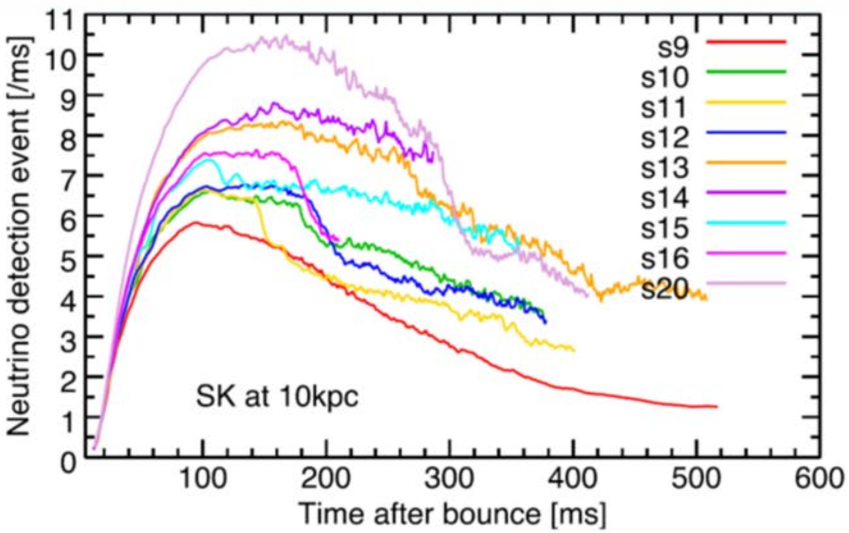


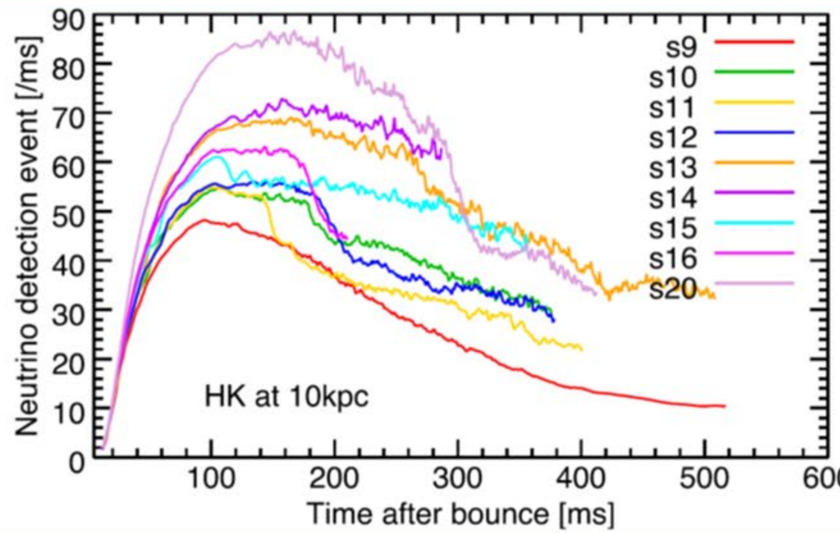






✓Neutrino detection rate at SuperKamokande and HyperKamiokande





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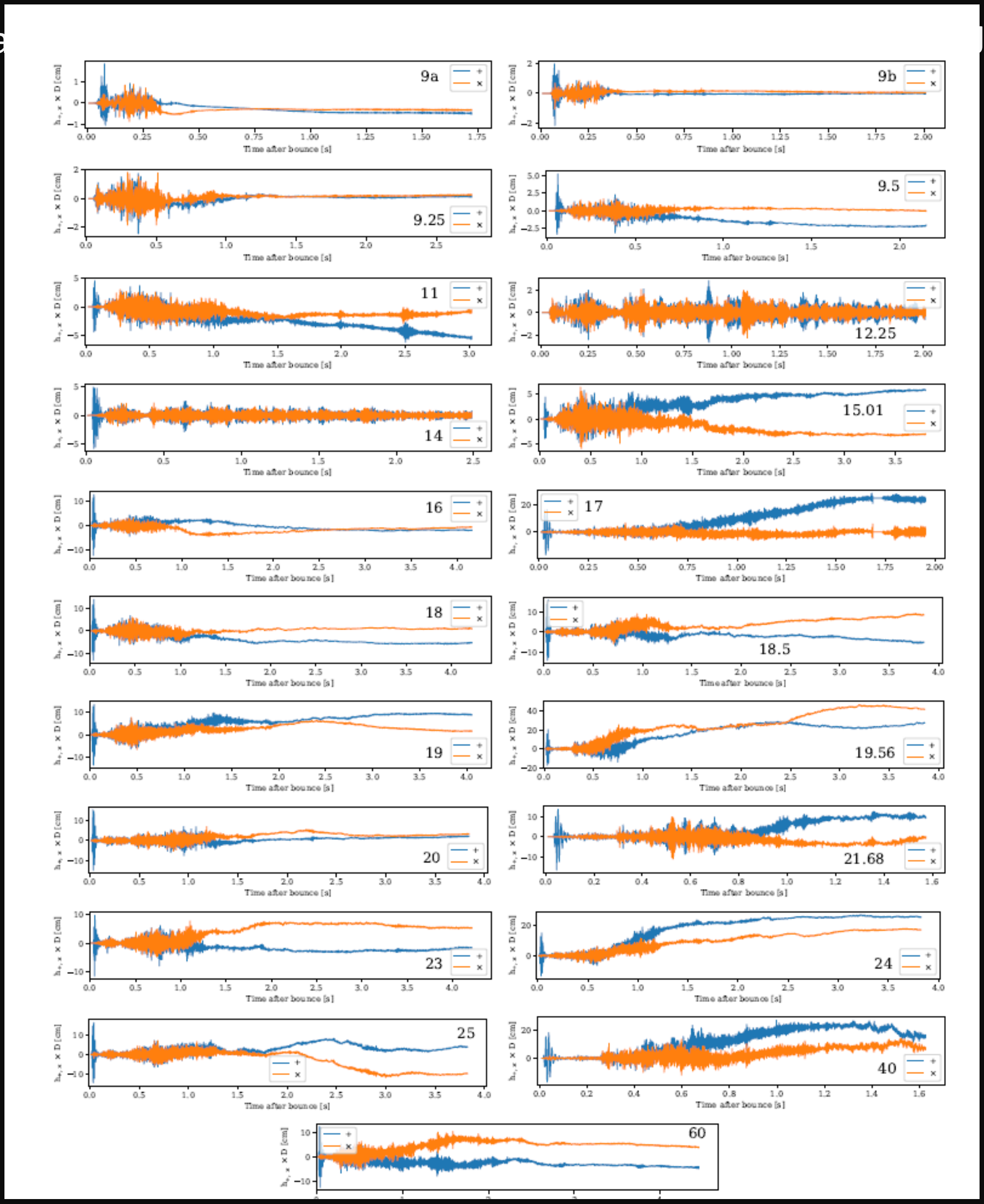
predominantly

✓High neutrino detection for high "compactness ($\sim M_{core}/R_{core}$) is progenitor !

✓GW landscape from systematic 3D HD modeling covering a "long-term" evolution (~4 s)

Choi et a

- ✓ 21 models computed in 3D from 9 to 60 M_{sun} stars.
- ✓ High GW emitted energies for high progenitor compactness (consistent with ours!)
- ✓The longer, The bigger due to
  1. long-lasting mass accretion to the PNS
  2. GW from anisotropic neutrino emission



✓GW landscape from systematic 3D HD modeling covering a "long-term" evolution (~4 s)

Typical amplitude :

$$|h_\nu| \sim 10^{-21}\left(\frac{\alpha}{0.01}\right)\left(\frac{L_\nu}{10^{52}\mathrm{erg/s}}\right)\left(\frac{\delta t}{1\ \mathrm{sec}}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)^{-1}$$

$$|h_\nu| \sim h_{\mathrm{bounce}} \sim 10^{-21} \quad (10\mathrm{kpc})$$

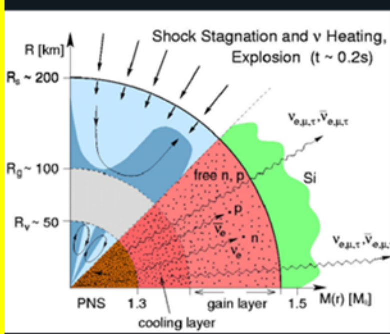
~ as large as the matter GW

Typical frequency :

$$t_\nu \sim \frac{1}{\sqrt{G\rho}} \geq 10\ \mathrm{msec}\left(\frac{\rho_{\mathrm{trap}}}{10^{11}\ \mathrm{gcm^{-3}}}\right)^{-1/2}$$

$$\nu_\nu \sim \frac{1}{t_\nu} \leq 100\ \mathrm{Hz}$$

, longer than the matter GW signal because the dynamical time scale is determined at the position of neutrino sphere, where forms further out from the center.



Frequencies of GWs from neutrinos are typically lower than ~ 100 Hz.

$$h^{\mu\nu}(t,\boldsymbol{x}) = 4\int \frac{T^{\mu\nu}(t-|\boldsymbol{x}-\boldsymbol{x}'|,\boldsymbol{x}')}{|\boldsymbol{x}-\boldsymbol{x}'|}d^3x'$$

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{matter}} + \underline{T^{\mu\nu}_{\mathrm{neutrino}}}$$

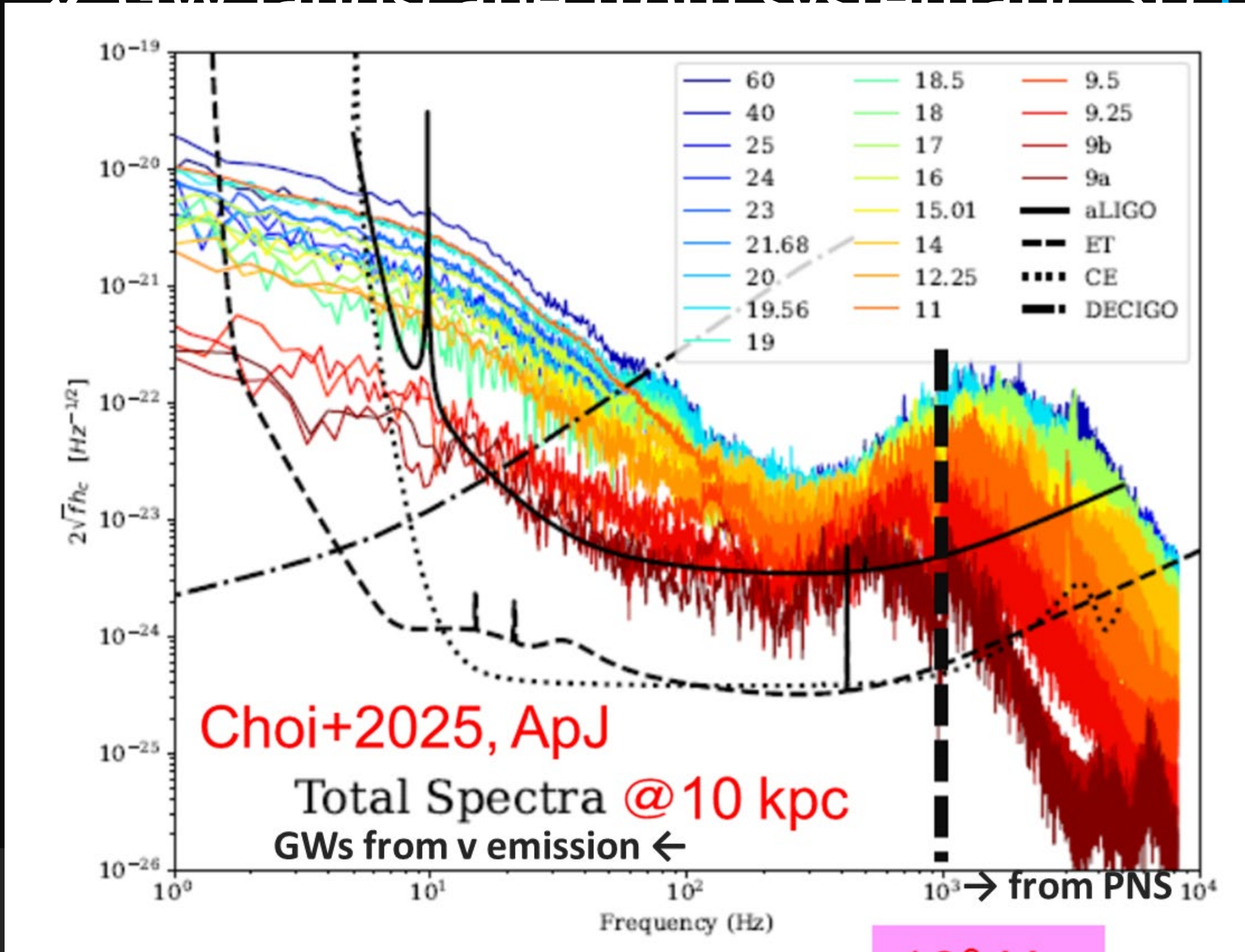
Epstein(78), Mueller & Janka (97), KK+2007

$$h_\nu(t) = \frac{2G}{c^4R}\int_0^t dt L_\nu(t')\alpha(t')$$

Neutrino anisotropy: degree of anisotropic neutrino emission (zero if spherical)

✓ GW landscape from systematic 3D HD modeling

evolution (~4 s)



10^3 Hz

$\left(\frac{\delta t}{1\ \mathrm{sec}}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)^{-1}$

ne matter GW

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ned at the position of
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out from the center.

os are typically

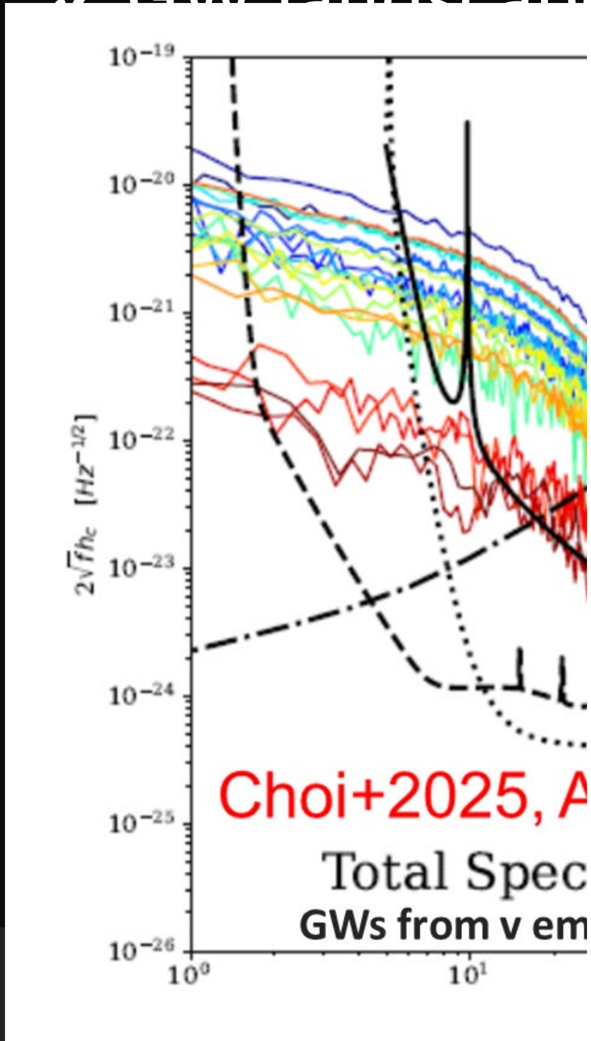
$T^{\mu\nu}_{\mathrm{matter}} + T^{\mu\nu}_{\mathrm{neutrino}}$

$|x - x'|$

anisotropic neutrino
(zero if spherical)

✓ ET/CE (< 100Hz) and kHz detectors both needed for SN GWs !

✓ GW landscap



aLIGO Detection Ranges (kpc)

ET Detection Ranges

Progenitor	Matter	Matter	Matter	Neutrino	Neutrino	Neutrino	Combined
18.5	108.96	153.99	133.38	232.81	1308.77	686.45	819.83
19	132.07	166.42	149.27	137.92	2070.83	1248.35	1397.62
19.56	195.89	265.83	231.85	241.62	2502.41	1278.68	1510.53
20	105.51	150.35	128.39	211.01	1371.91	767.43	895.82
21.68	149.93	190.84	171.76	176.60	1905.45	1011.43	1183.19
23	85.30	116.51	101.27	178.57	2107.92	1114.24	1215.51
24	132.86	172.41	152.48	196.13	1668.61	874.15	1026.63
25	109.74	161.45	137.83	225.88	1260.74	742.87	880.70
40	215.27	258.24	237.30	247.51	3731.75	2092.88	2330.18
60	133.47	161.82	147.17	143.61	2160.75	1280.57	1427.74

✓ Detection horizon (setting a SNR ratio as 8) for LVK, throughout our Galaxy!

$$\rho^2 = 4\int_0^\infty df \frac{|\tilde{h}(f)|^2}{S_n(f)}$$

✓ for ET/CE, "beyond" neighboring galaxies (e.g. Andromeda (765kpc)!)

→ Final words "Need" long-term simulations with MHD!

$|x - x'|$

10^3 Hz

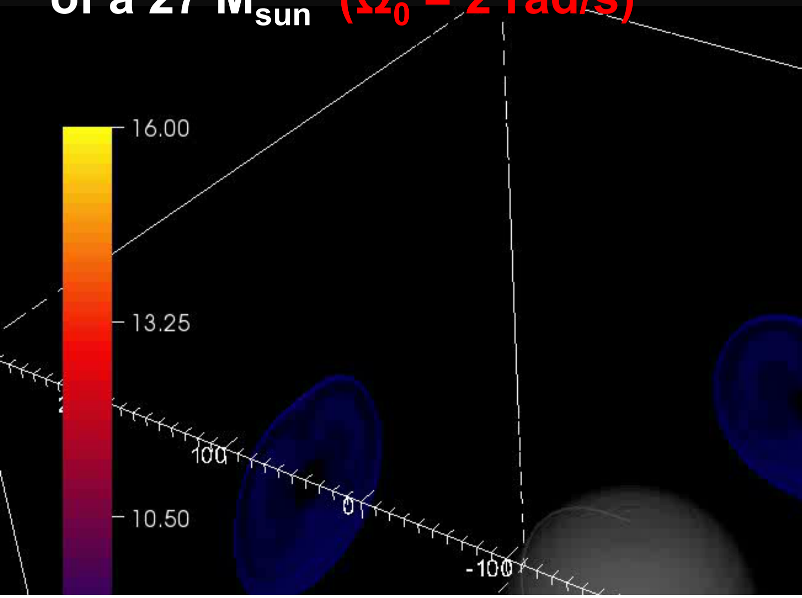
matter neutrino

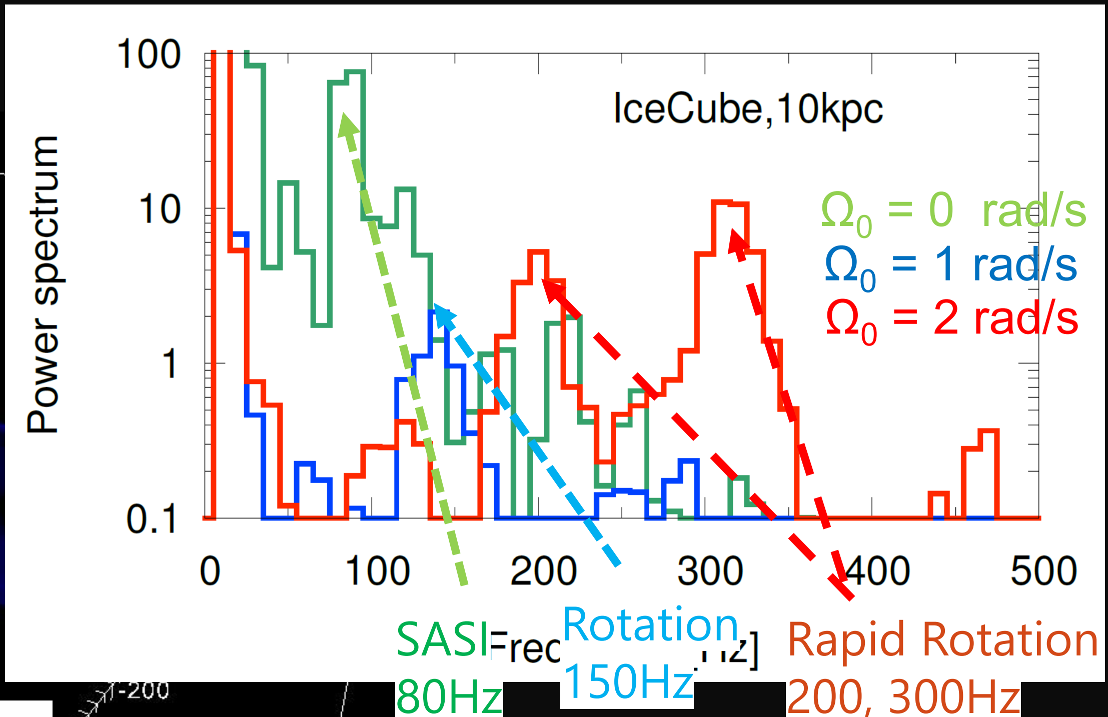
✓ ET/CE (< 100Hz) and kHz detectors both needed for SN GWs !

anisotropic neutrino (zero if spherical)

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

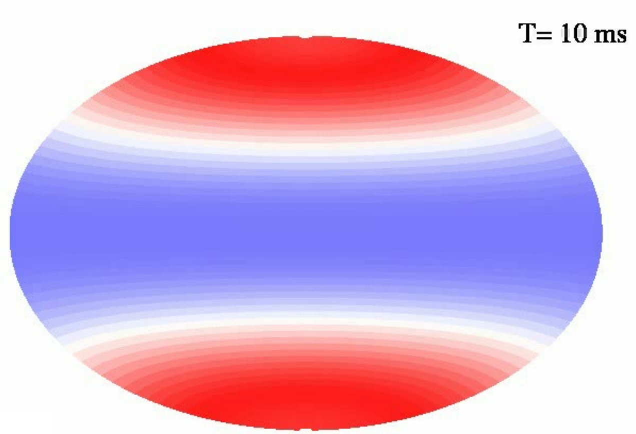
Rapidly rotating collapse of a 27 M_{sun} (Ω_0 = 2 rad/s)





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

→ ***The light-house effect***

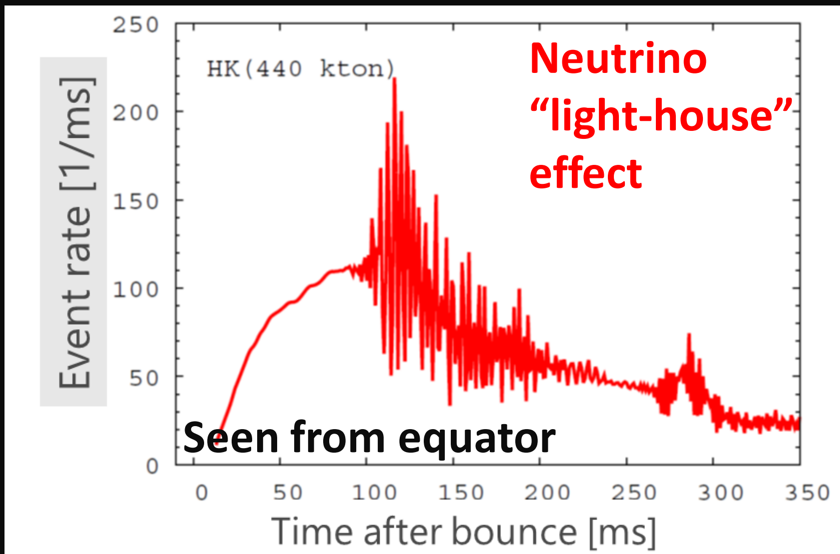


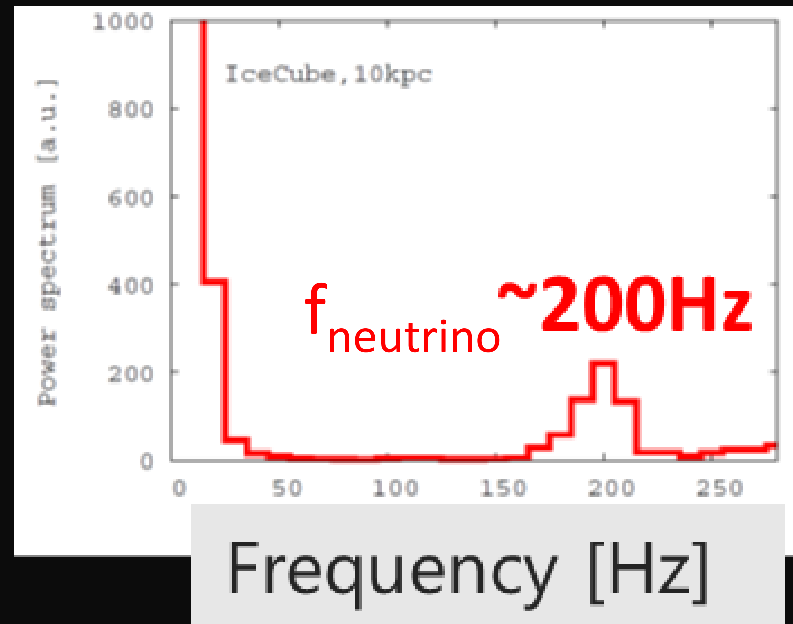
$\delta L_{\bar{\nu}_e}$:Deviation from the angle-average flux

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

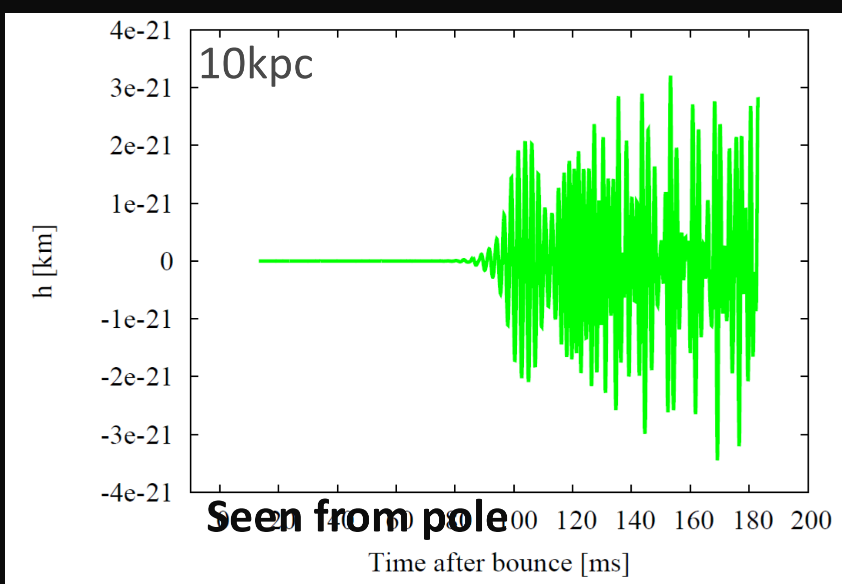
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

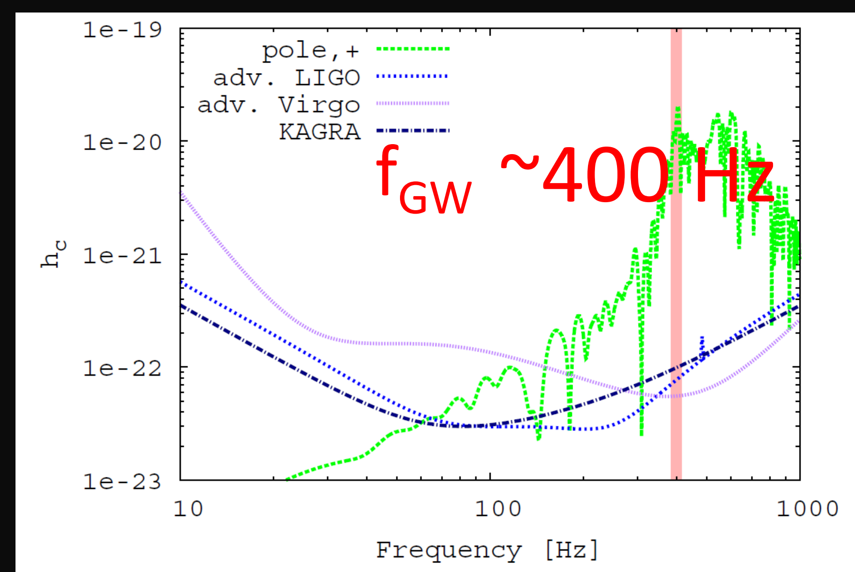
Takiwaki, KK, Foglizzo, (2021), Shibagaki et al. (2023)





Gravitational waveform





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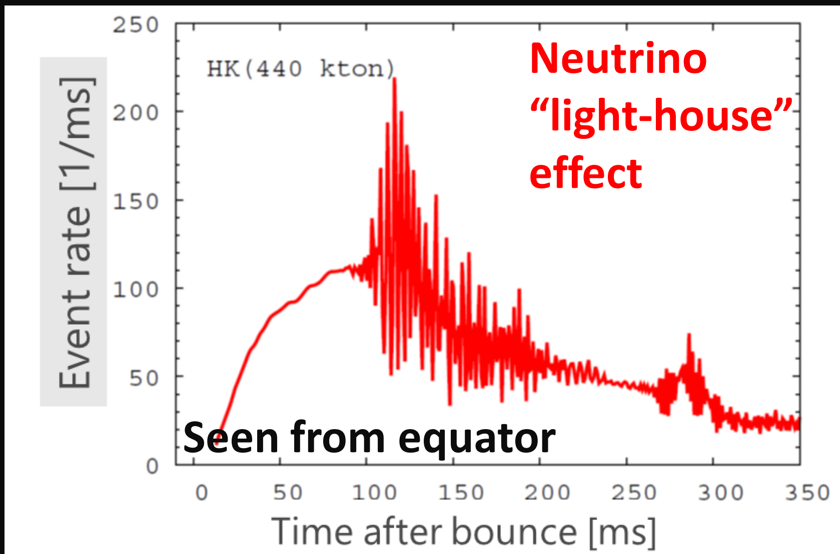

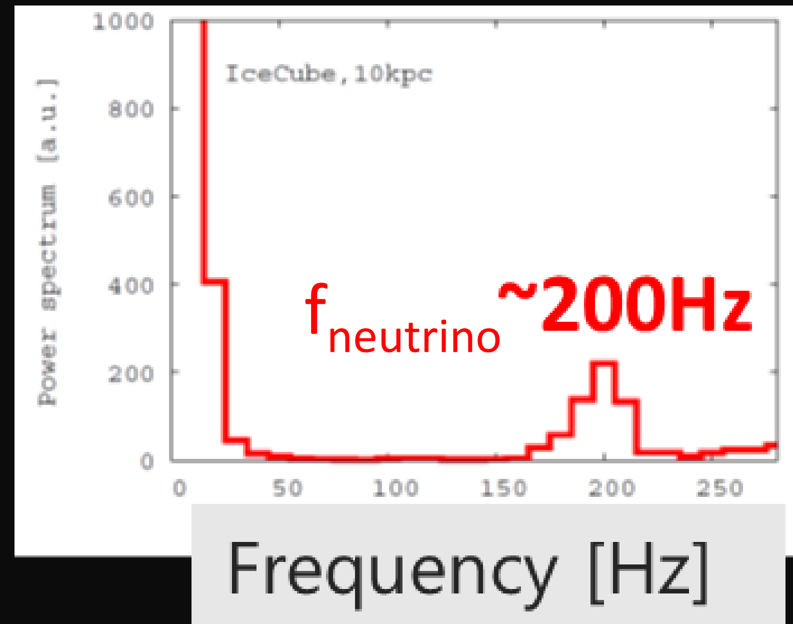

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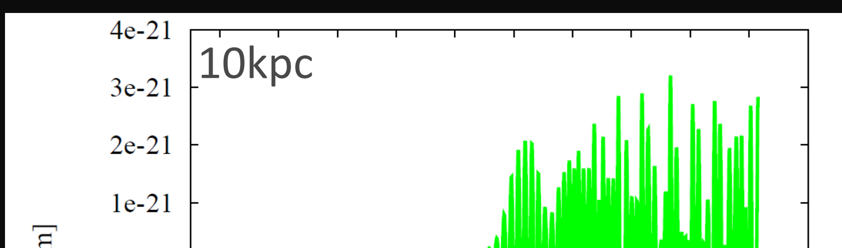

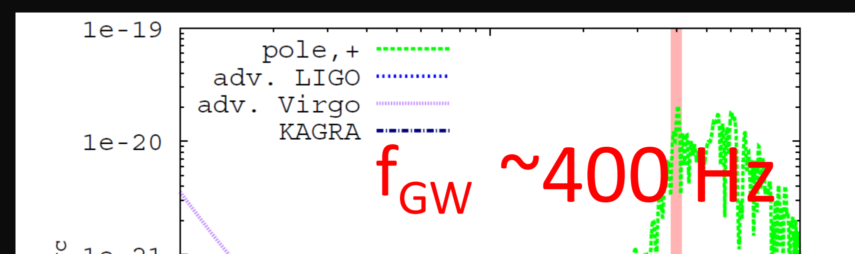

✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)

✓ 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 !

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

Kuroda et al. MNRAS, 2018, 2022, and in prep

- ✓ **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), Nakazato(+2008,2013), Fischer+ (2009), Huedepohl+(2016))
- ✓ **Sudden disappearance of the GW and neutrino signals -> BH formation !**

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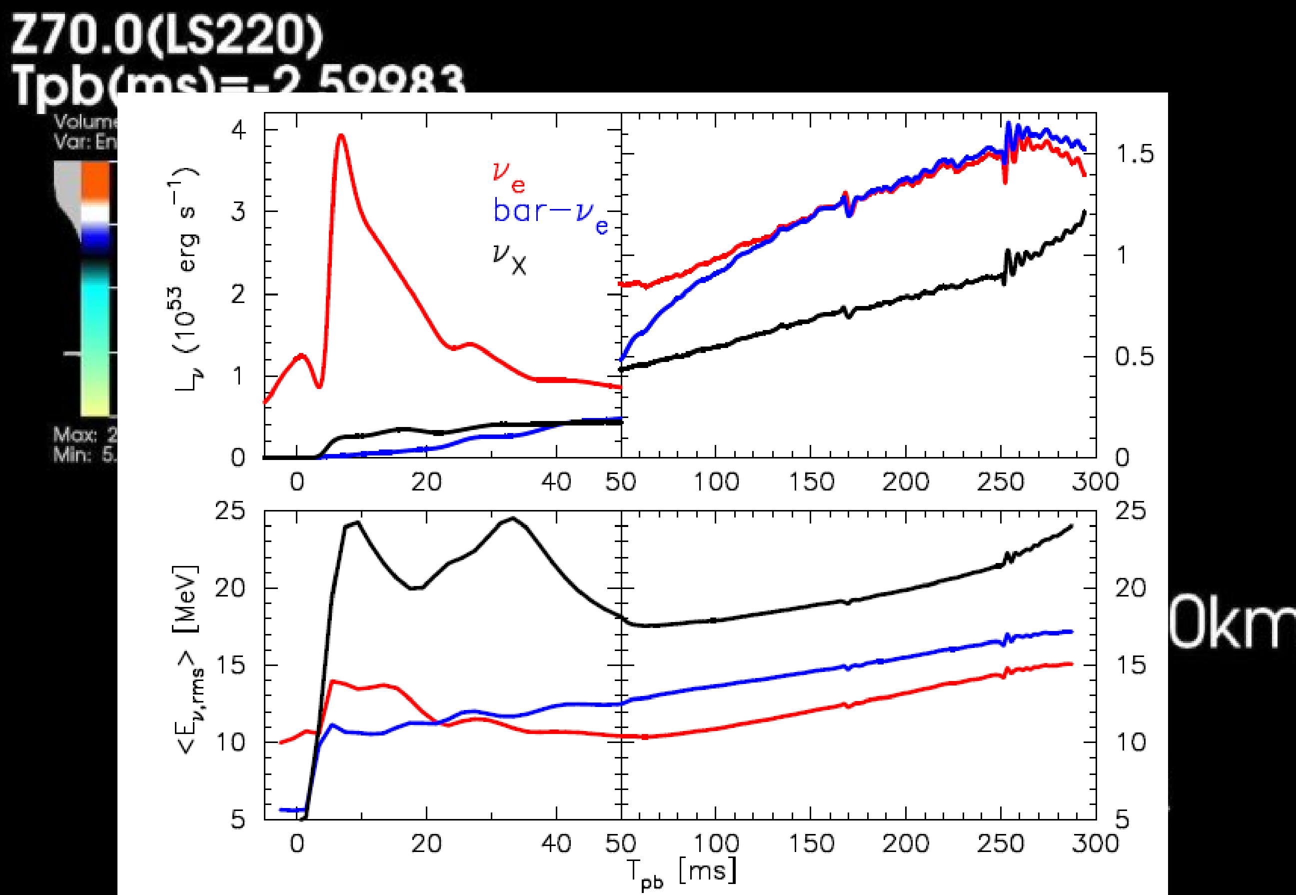

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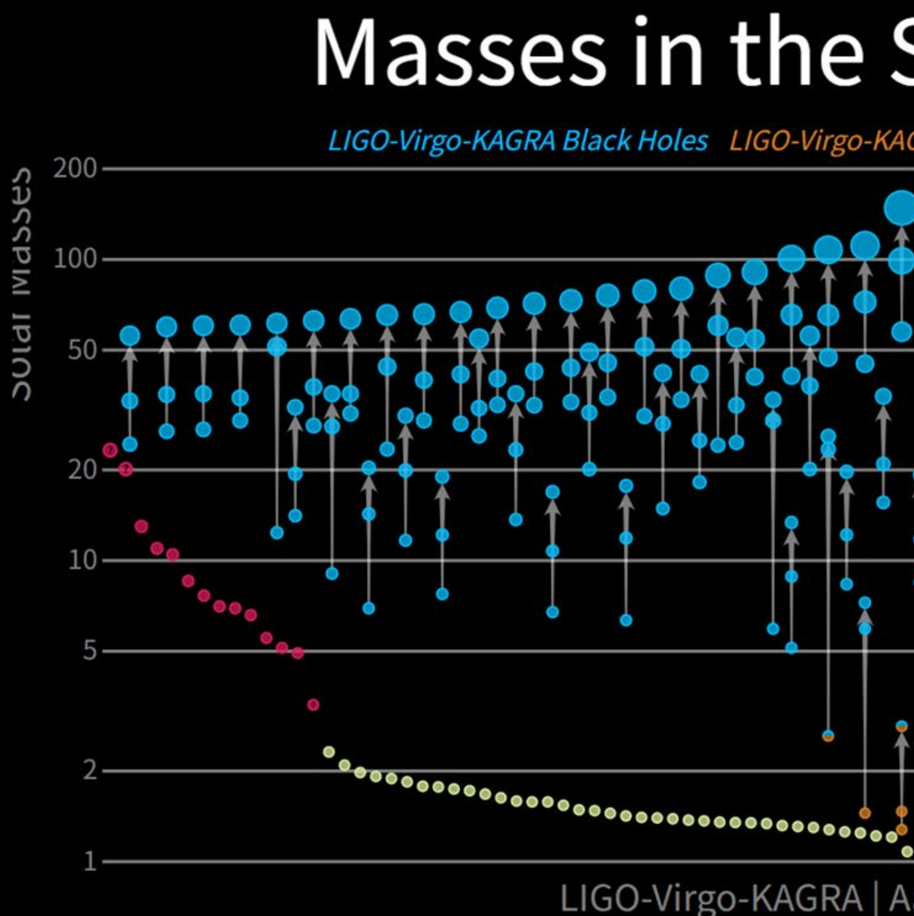

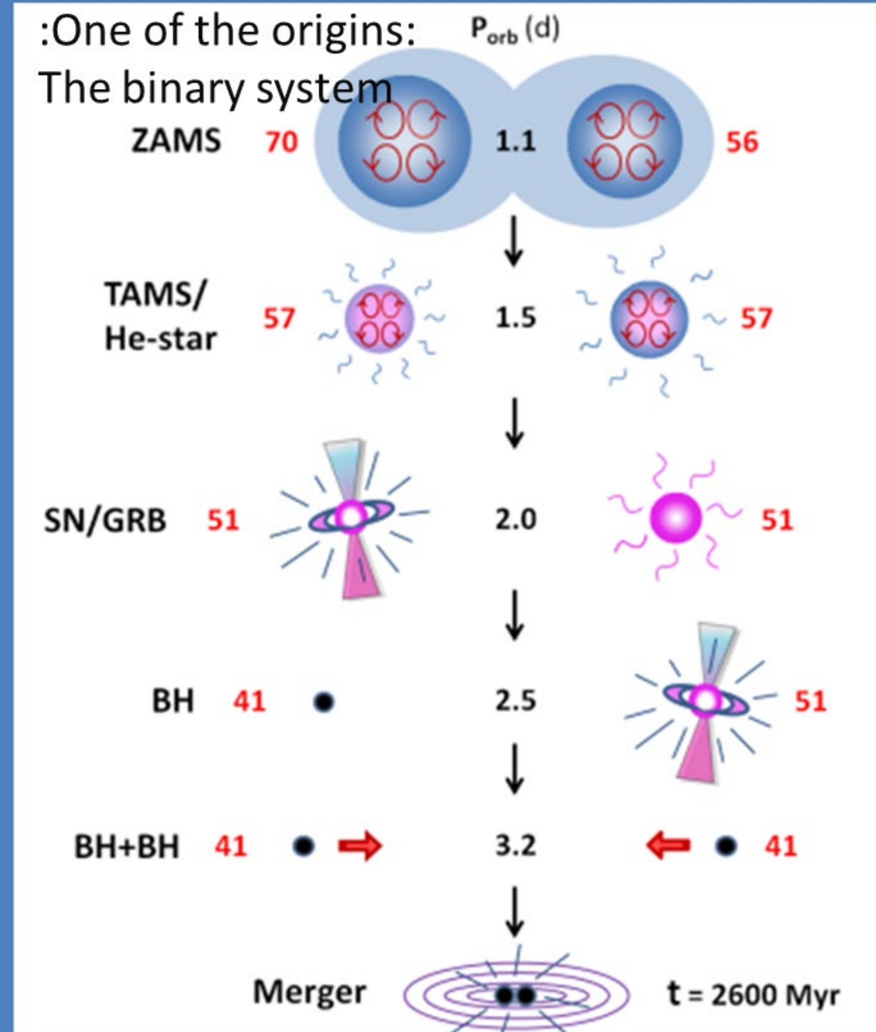

Marchant, Langer, Podsiadlowski et al. (2006)

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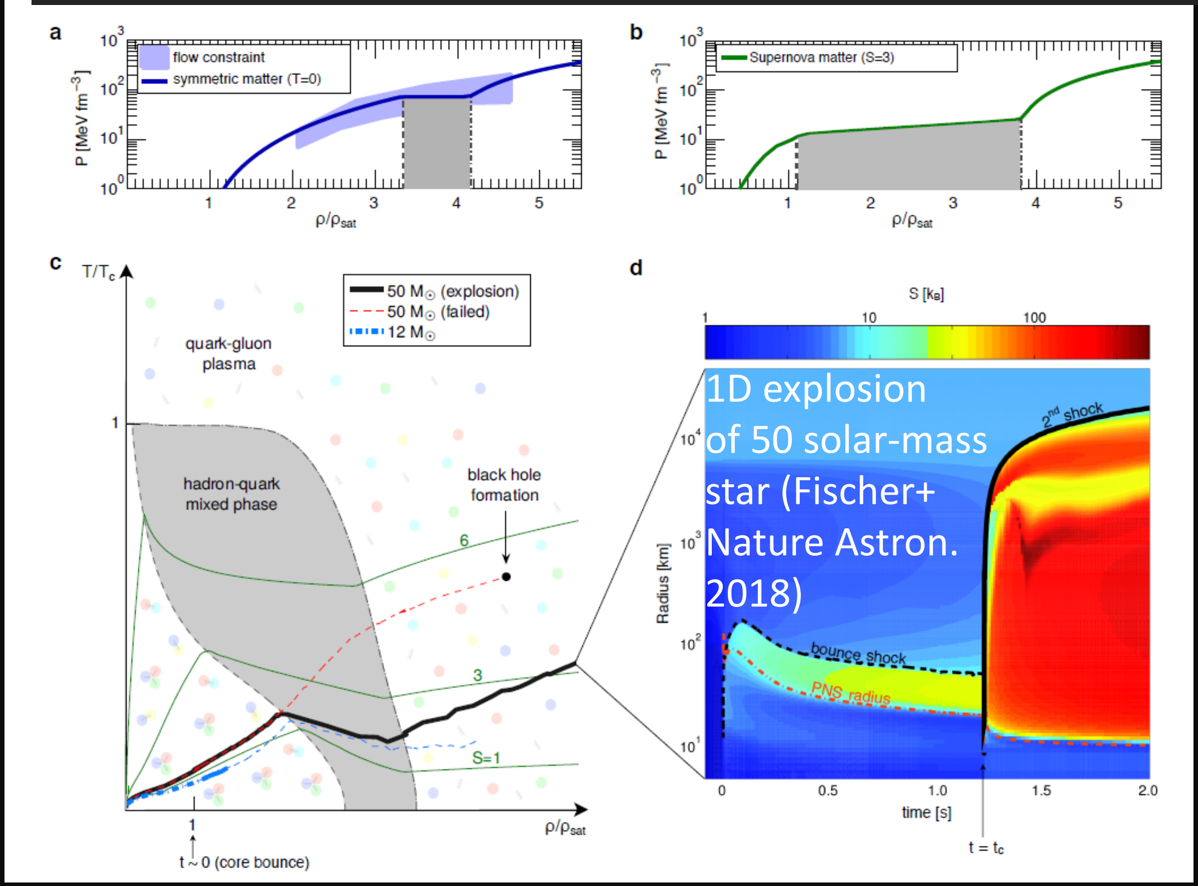
✓ **Low metallicity** environment needed for large stellar mass BH formation.
(e.g., Kinugawa et al .(2014,2016))

✓ Probe into high-density EOS with "QCD" phase transition

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



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

✓ Probe into high-density EOS with “QCD” phase transition

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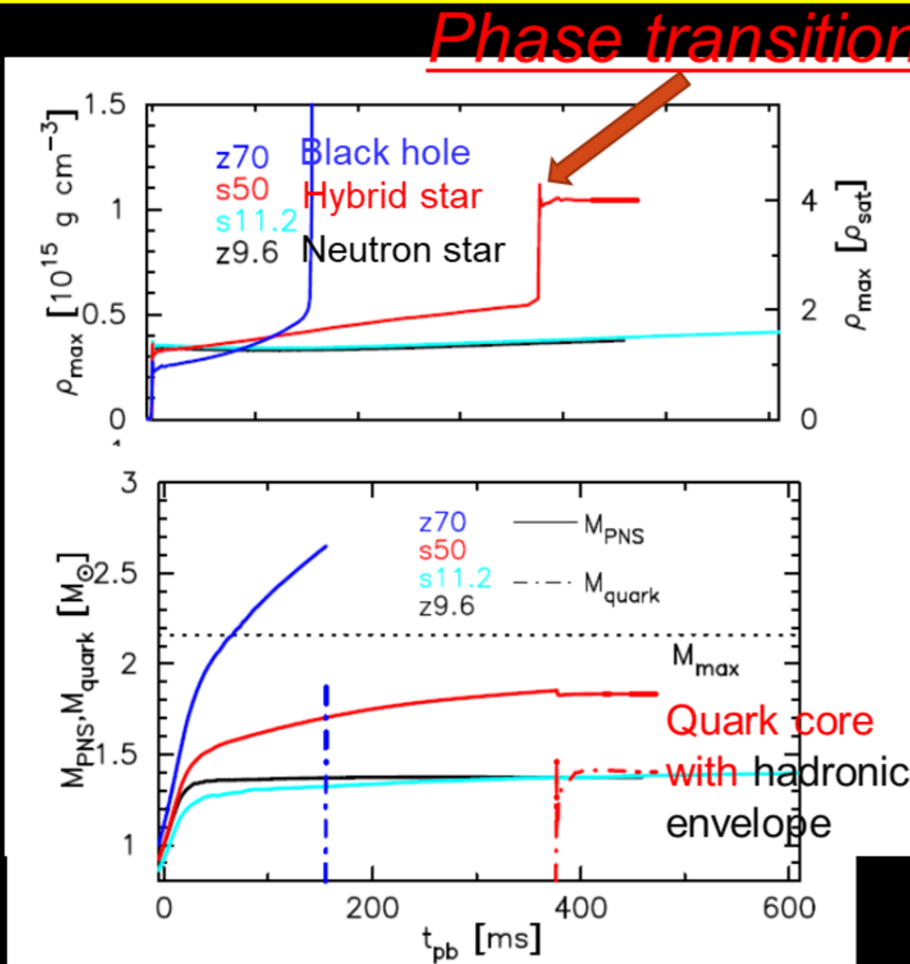
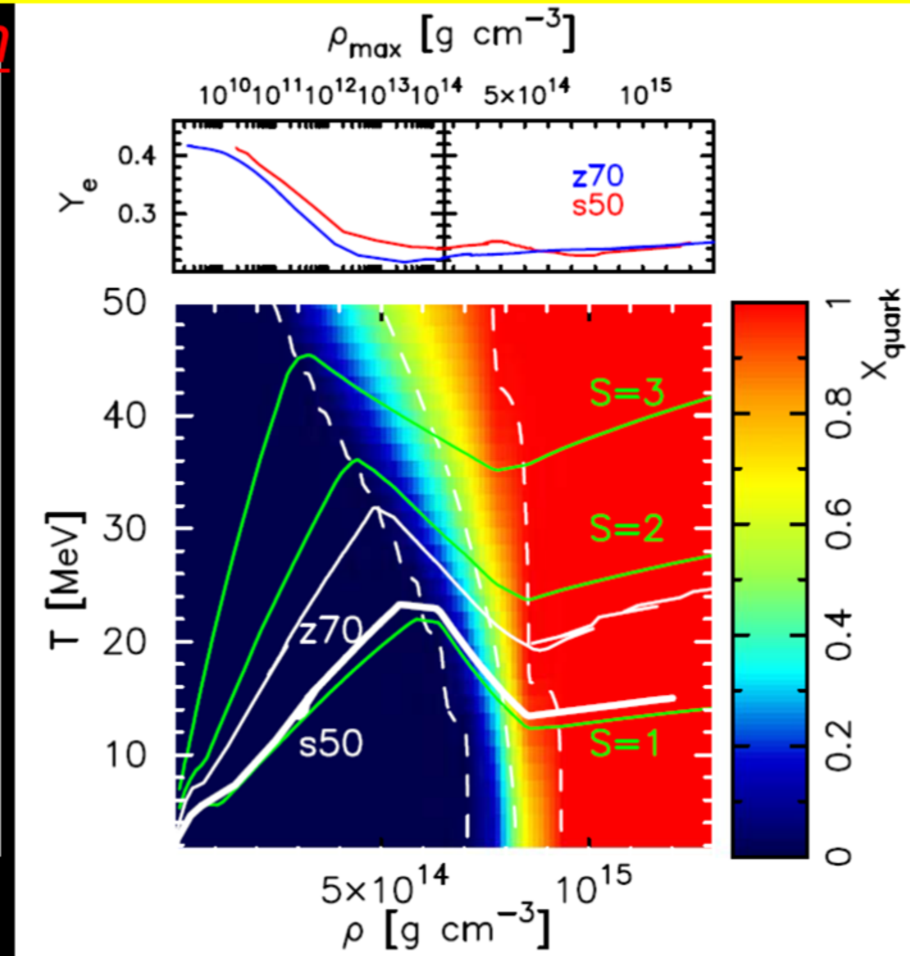
Full GR 2D simulation (Kuroda et al. 2022) including updated ν opacities (Kotake + 2018, ApJ)





✓ Probe into *high-density EOS* with *“QCD” phase transition*

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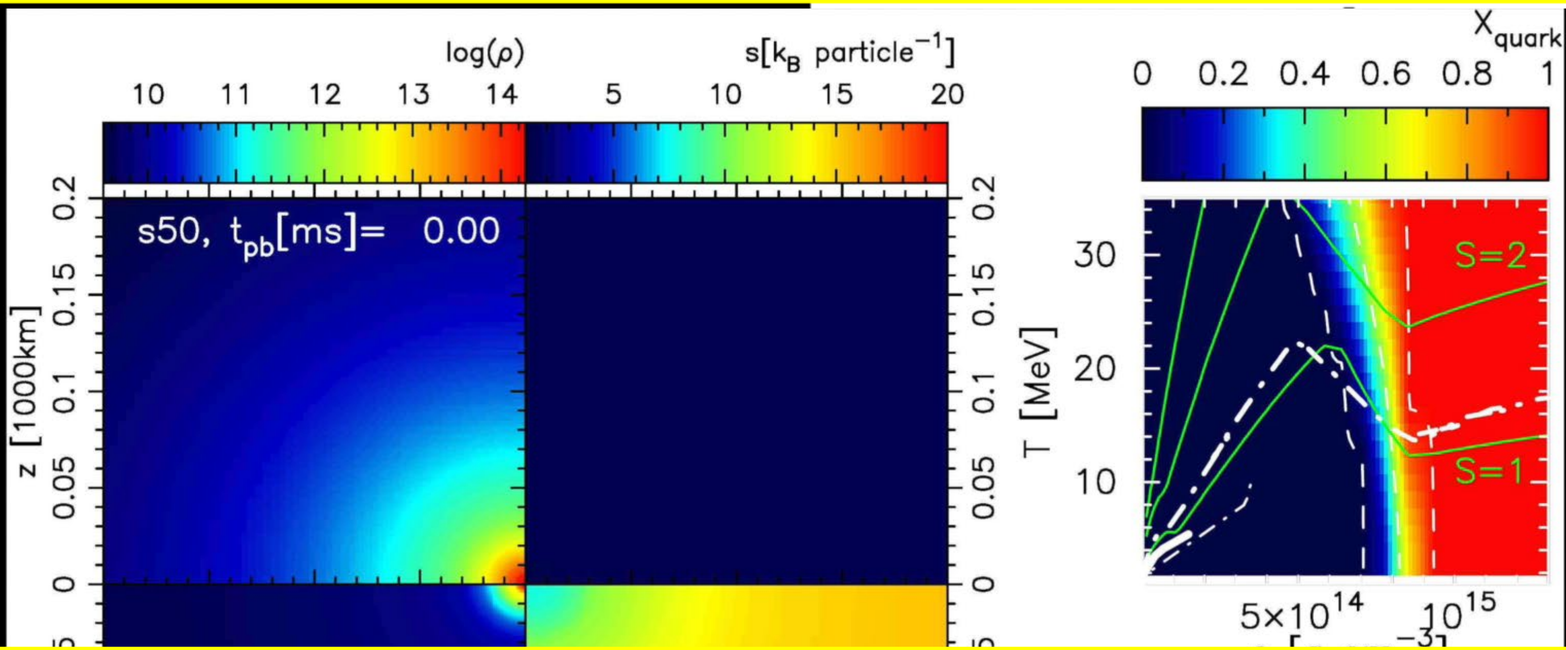


✓ Depending on the progenitor mass and PT physics, the fate to neutron star, hybrid star (HS), black hole!

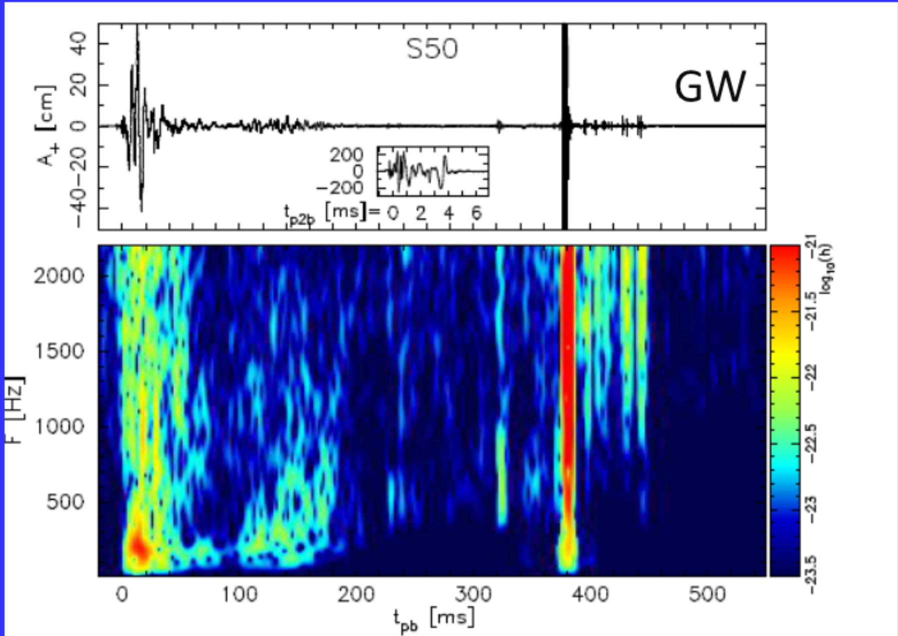
☆ If the PT transition is **“cross-over”,** no “PT-induced” explosions obtained (e.g., Jakobus et al. (2022) using “CMF” EOS).

→ Probe into “Dense QCD” regime (almost unexplored!)

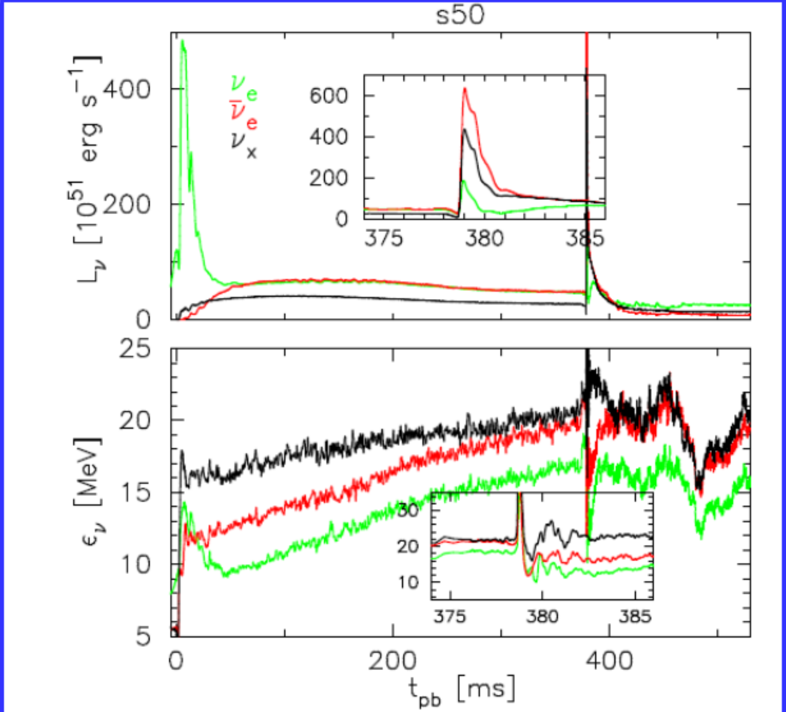
✓ Probe into PT physics : Multi-messenger signals !

Kuroda et al. (2022), MNRAS, Jakobus et al. (2022), (2024) PRL

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



(c)



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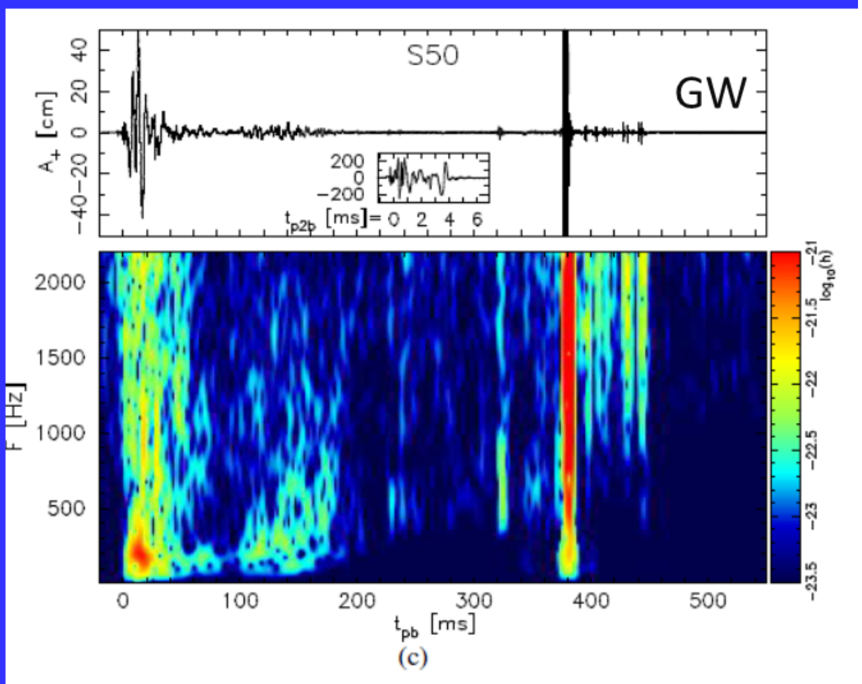

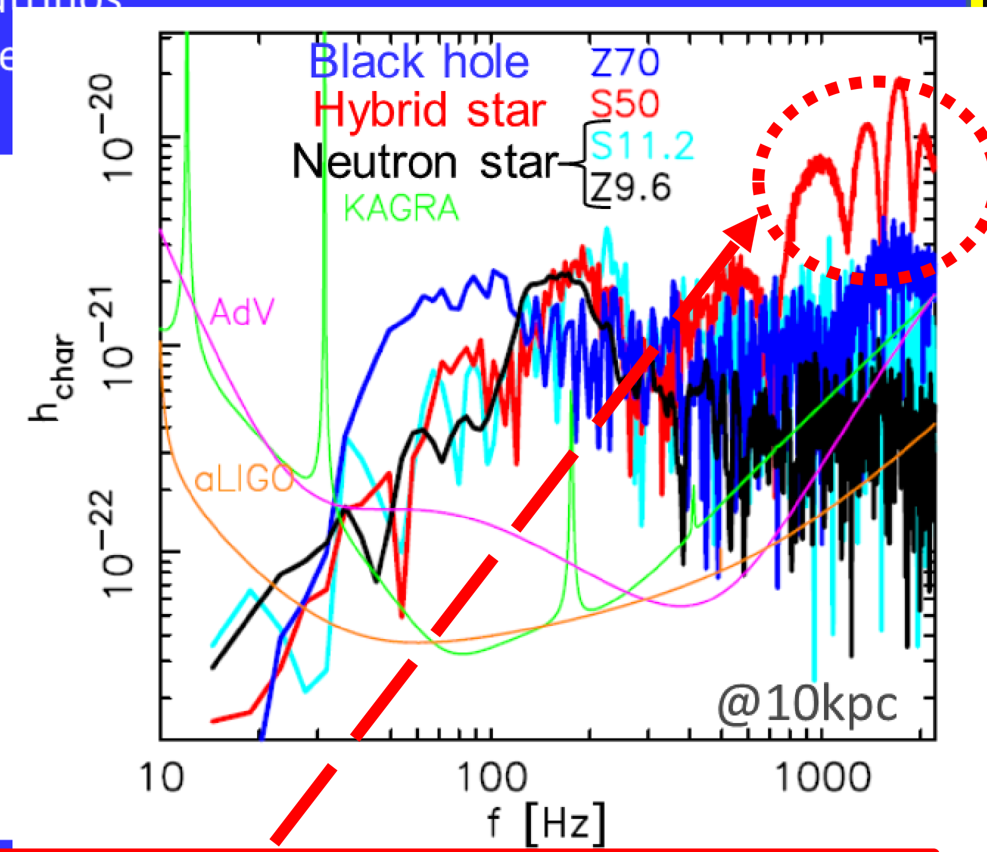

✓ Very strong and *high-freq.* (≳1kHz) GW emission obtained only from a *"baby"* hybrid star.

✓ The GW and ν signals provide the secret to the birth history!

✓ Probe into *PT* physics : *Multi-messenger signals !*

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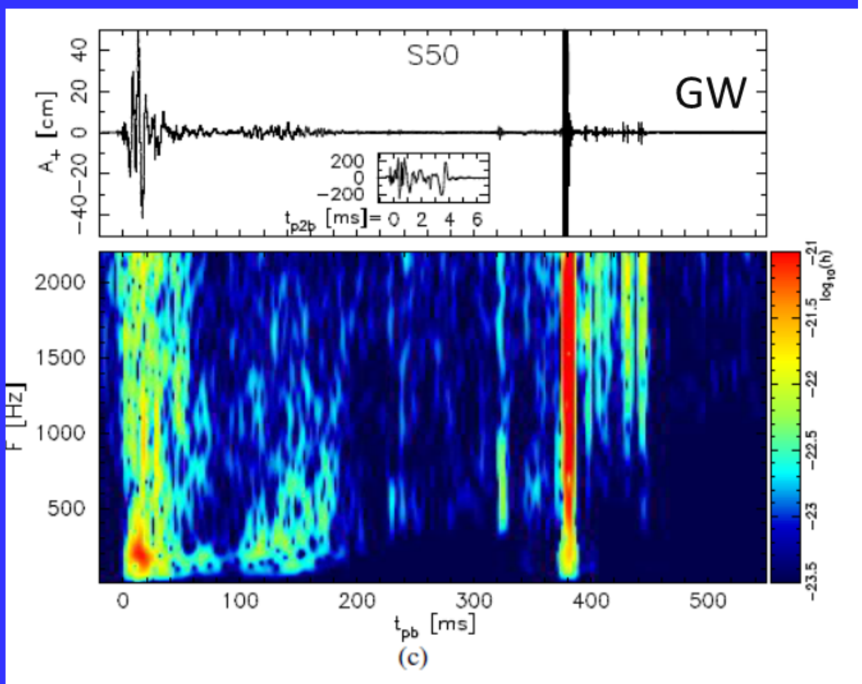

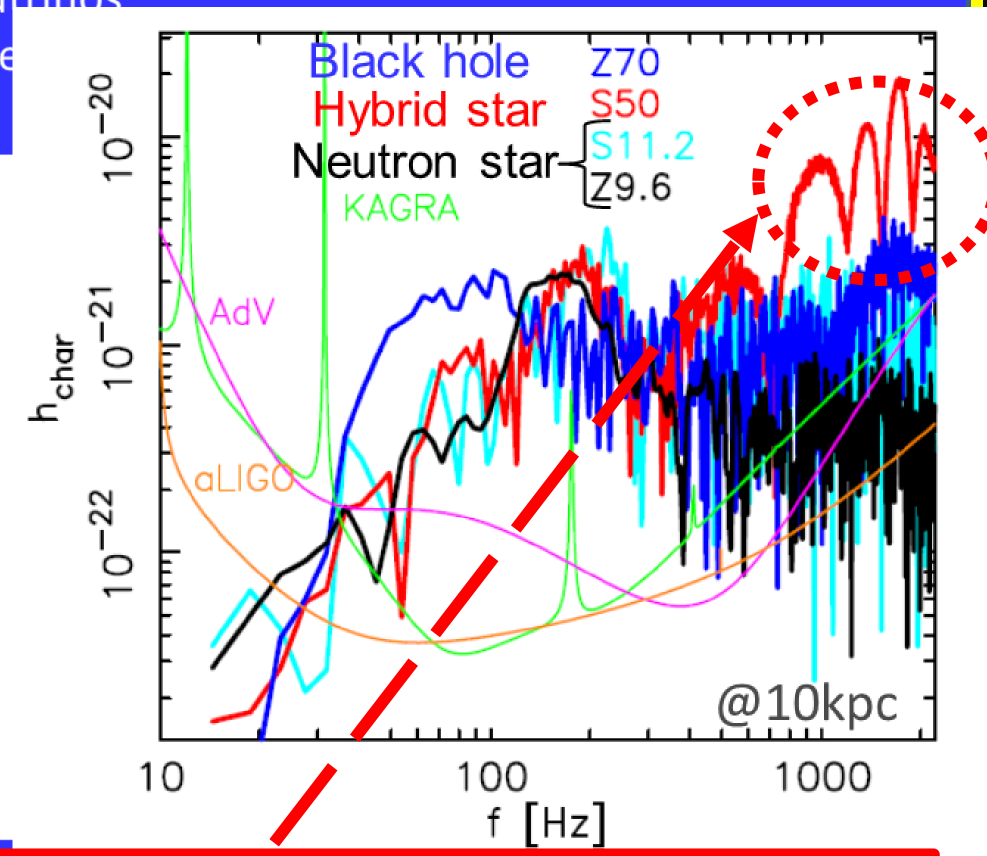

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3D modeling on the verge of success and the MM prediction

- ✓ Systematic 3D MHD modeling with GW/v signal predictions are in steady progress.
- ✓ GW signals from 3D SN models targets of LVK throughout our Galaxy, of CE/ET nearby Gal. (Detection of "kHz" GW new probe to PNS physics)
- ✓ Coincident analysis of GW and v, pivotal, providing the smoking gun of the engine!
  (✓SASI-modulation, rotation leads to the "frequency doubling" between v and GW,
  ✓Dictate BH vs. NS formation.
- ✓ No SN fight (anymore)! 3D results from different supernova teams asymptote.

- ✓ Fast-flavor conversion a new challenge ! (see paper by Ehring + 2023, Nagakura+2023)
- ✓ Upgrade of v and GW detector (Hyper-K, Dune, LVK w. kHz extension!)
- ✓ Detailed weak Interactions/ new physics incl. axions, and sterile neutrinos? (see work by Mori+(2024), Lucente+(2021))
- ✓ Multi-D MHD progenitor modeling and observation (binary evolution) (Mueller & Varma (2023), Smarrt (2022))

☆Signal prediction from Hypernovae!
3D-MHD modeling of "Jets", BH/accretion-disk
(:3D-GR MHD code with neutrino transport)
Needed to understand long-duration GRBs pair-instabiility supernova, SL-SNe, from first principles!
(MM signals predictions almost unexplored!)