

***Brainstorming for “Next Steps” of
Core-Collapse Supernova Modelling
and MM predictions***

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with

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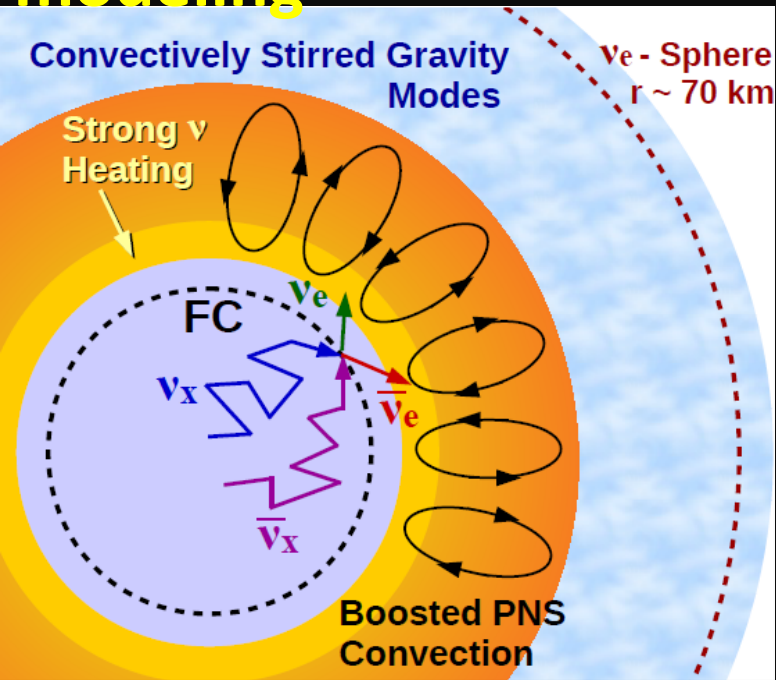
Tomoya Takiwaki (NAOJ), Shota Shibagaki (Wroclaw Tech),

Kanji Mori (Keio), Takami Kuroda (AEI)

Jin Matsumoto(Fukuoka Univ.), Tobias Fischer (Wroclaw Tech)

BRAINSTORMING WORKSHOP ON MULTIMESSENGER ASTROPHYSICS
WITH CORE-COLLAPSE SUPERNOVAE AND BINARY NEUTRON STAR MERGERS
@Wroclaw University of Science and Technology, September 9 -11, 2026

Challenging themes → My modeling



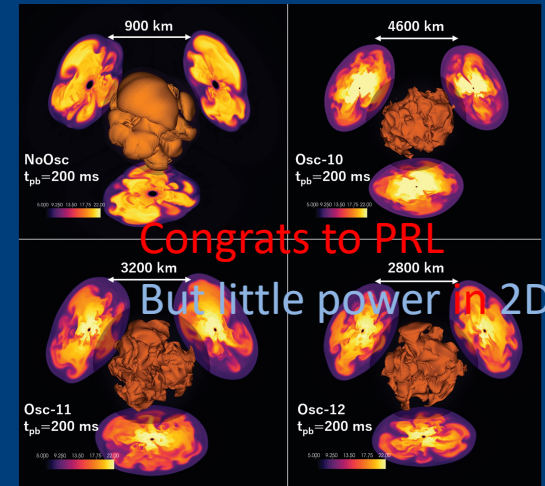
Ehring et al. (2025), PRL

✓ Phenomenological treatment of Fast-Flavor Conversion (FC)

→ Following the prescription, Mori et al. (2025) reported 3D-IDSA models with stronger explosion with FC parametrization ($10^{10\sim 13}$ g/cm³) → **Should be fixed!**

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Publications of the astronomical society of Japan



Congrats to PRL
But little power in 2D..

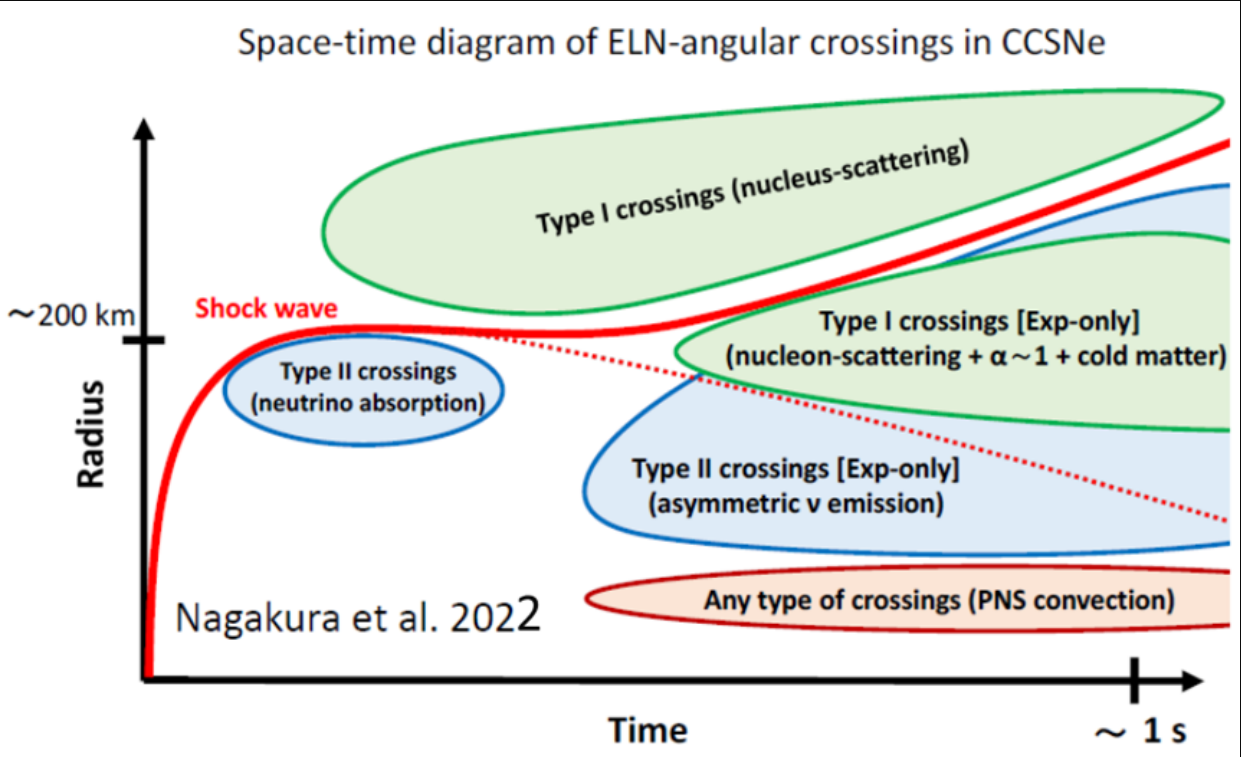
(See page L11)

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Nature is not that simple!



See review by Yamada et al. (2025)

- Nagakura (2023) PRL
- Nagakura, Sumiyoshi et al. PRD, (2025)
- Highlights include:
Zaizen and Nagakura (2024)
Akaho et al. (2026)

→ Postprocessing treatment, approximate GR models.
No quantitative predictions on CCSN treasures made in 3D-GR models..

From Nagakura’s presentation

Quantum Kinetics neutrino transport

Vlasenko et al. 2014, Volpe 2015,
Blaschke et al. 2016, Richers et al. 2019

$$p^\mu \frac{\partial f^{(-)}}{\partial x^\mu} + \frac{dp^i}{d\tau} \frac{\partial f^{(-)}}{\partial p^i} = -p^\mu u_\mu \overset{(-)}{S}_{\text{col}} + \underbrace{ip^\mu n_\mu [H, f]^{(-)}}_{\text{Oscillation term}},$$

Density matrix

$$\overset{(-)}{f} = \begin{bmatrix} \overset{(-)}{f}_{ee} & \overset{(-)}{f}_{e\mu} & \overset{(-)}{f}_{e\tau} \\ \overset{(-)}{f}_{\mu e} & \overset{(-)}{f}_{\mu\mu} & \overset{(-)}{f}_{\mu\tau} \\ \overset{(-)}{f}_{\tau e} & \overset{(-)}{f}_{\tau\mu} & \overset{(-)}{f}_{\tau\tau} \end{bmatrix}$$

Hamiltonian

$$\overset{(-)}{H} = \overset{(-)}{H}_{\text{vac}} + \overset{(-)}{H}_{\text{mat}} + \underbrace{\overset{(-)}{H}_{\nu\nu}}_{\text{Self-interaction}},$$

$$H_{\nu\nu} = \sqrt{2}G_F \int \frac{d^3q'}{(2\pi)^3} (1 - \sum_{i=1}^3 \ell'_{(i)} \ell_{(i)}) (f(q') - \bar{f}^*(q')),$$

See Wu and Xiong’s talk!

Behind the scenes ; -)

Multi-D full GR rad-hydro code by T. Kuroda

Kuroda, Takiwaki, KK(2016), ApJS (see talk on this Friday)

“mariage” with

Agile-Boltztran:

Matysiak-Fischer+ in prep.

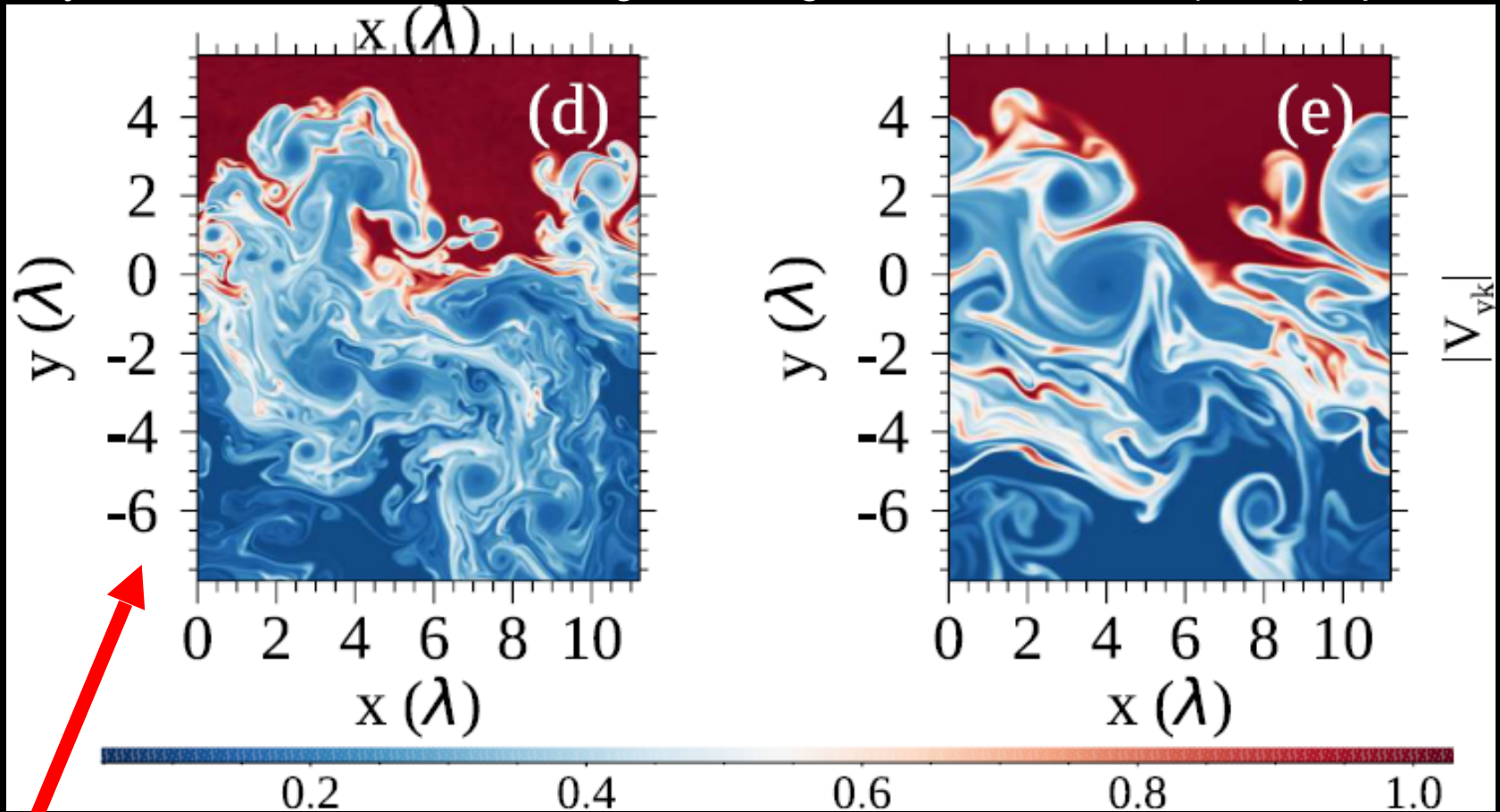
→ Should be real!

“T” is the key of the neutrino-mechanism!

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

✓ “High” numerical resolution required to capture the nature of “T” !

“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 “

2D-ID

10

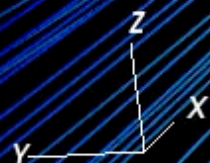
1000

DB: Sc00212.xmf

Time: 11 ms

✓ 27 M_{sun} star

(Woosley + 2002)



✓Quant

$\log(|B|/[G])$

11. 12. 13. 14. 15.

✓The PNS formation of

$B_{\text{PNS, surface}} \sim 10^{12} \text{ G}$

$M_{\text{PNS}} \sim 1.6 M_{\text{sun}}$

$P_{\text{PNS}} \sim 200 \text{ ms}$

(in good agreement with
obs. e.g., Utrobin+19,
Ertl +20, ApJ)

talk !

atory!

More 3D CCSN MHD modeling, but limited to ~500 ms p.b.

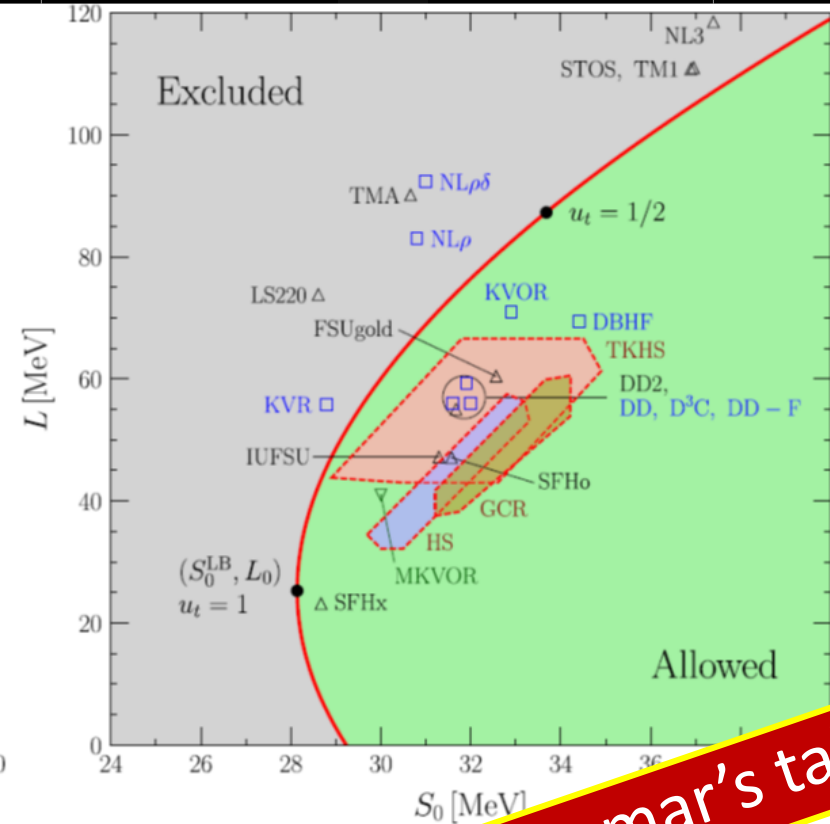
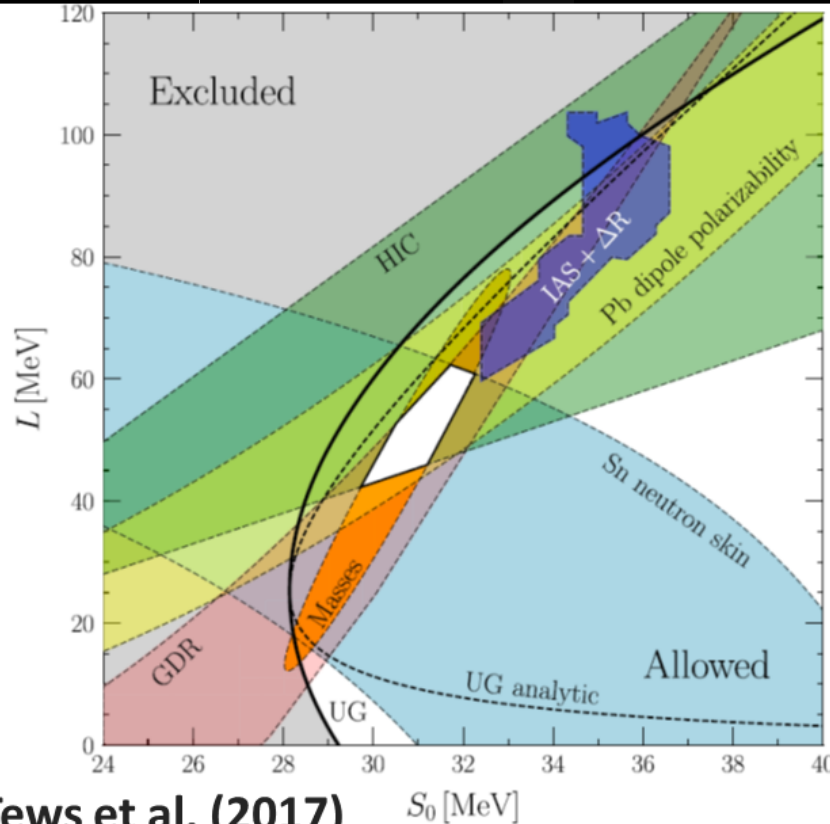
Nakamura, Takiwaki, KK (2025), MNRAS Matsumoto et al. (2024)

✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B field: 1010 G (uniform), Non-rotation)

s9.0B10

But all these: Wrong by design !

11 ms



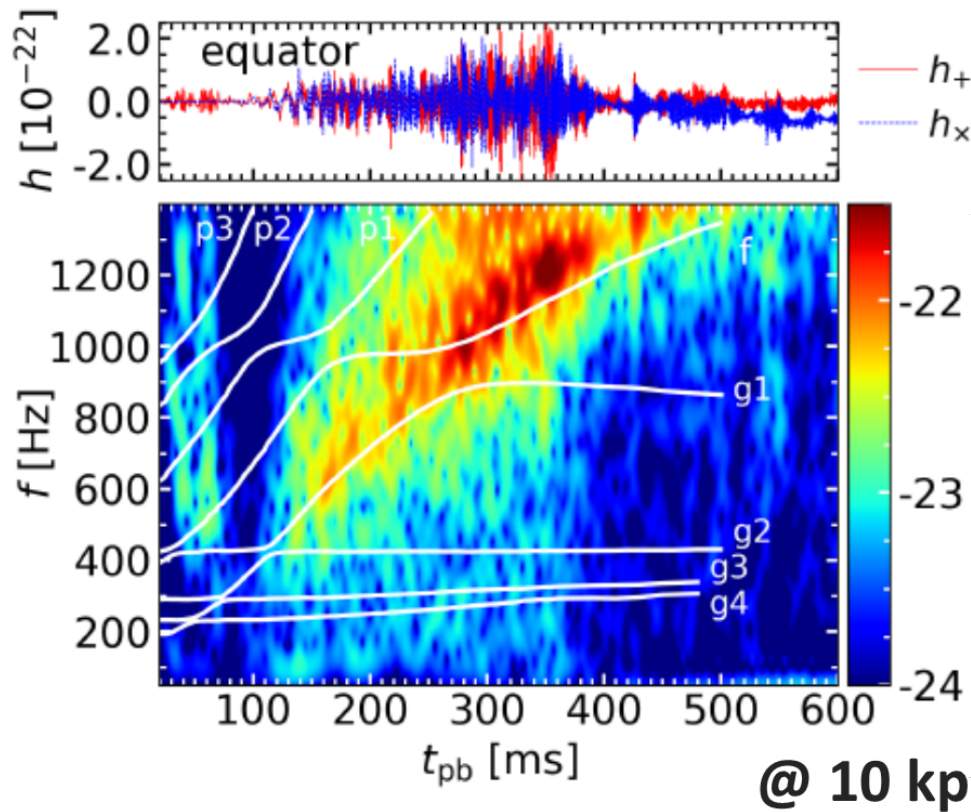
Tews et al. (2017)

Figure 9. UG bounds on symmetry energy parameters. The thick lines show the bound Equation (24) using the conservation of energy and momentum (Equation (25)). Excluded regions are shown by shading. Left panel: Experimental constraints are from Lattimer & Lim (2013) and Lattimer & Steiner (2016). The thick solid curve shows the bound from Equation (24) using the conservation of energy and momentum (Equation (25)). The thick dashed curve shows the analytic bound from Equation (32). Right panel: Filled circles show the point (S_0^{LB}, L_0) at the tangent density $u_t = 1$ and the point where $u_t = 1/2$. Triangles show values for interactions commonly used in tabulated equations of state for astrophysical simulations (notation and data from Fischer et al. 2014), and open squares (from Klähn et al. 2006) and the inverted triangle (from Maslov et al. 2016) show those of other frequently used interactions. The shaded regions TKHS, GCR, and HS show the parameter ranges inferred from the PNM calculations of Tews et al. (2013), Gandolfi et al. (2012), and Hebeler et al. (2010), respectively.

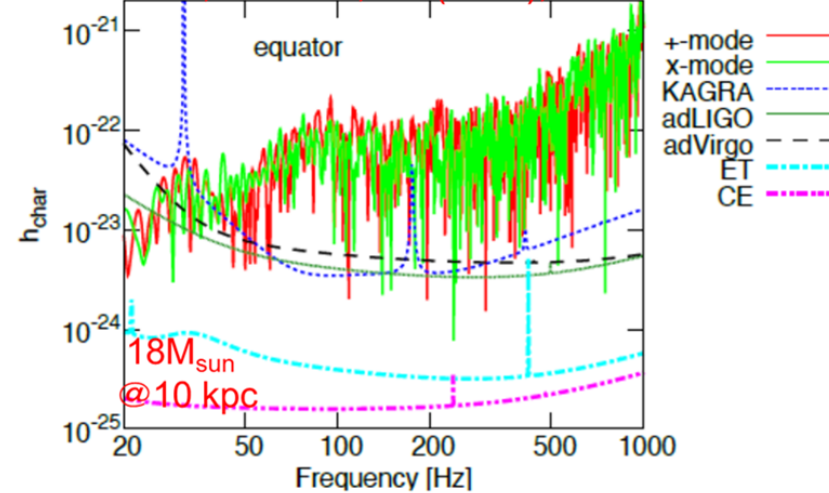
See Kumar's talk !

✓ GW landscape from systematic 3D MHD modeling

Nakamura, Takiwaki, KK (2025) MNRAS



Nakamura, Takiwaki, KK (2022), MNRAS



✓ The ramp-up mode(s) (“f” and “g₁”)

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

☆ Important lessons:

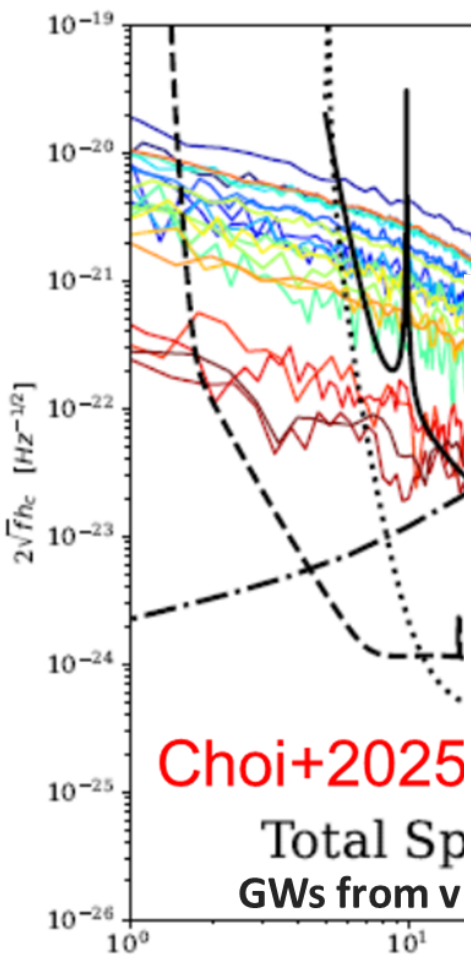
- ✓ A universal “relation” proposed (Torres-Forne et al. 2017, Sotani et al. 2017) for low modes of “f”, “g₁” insensitive to progenitor, EOS, and numerical details.
- Direct information to the PNS evolution (the “M-R” relation)!

What about rapid rotation/MHD including QCD, BSM physics?

- ✓ For the detection, LVK collaborations and dedicated analysis crucially needed !

See Yip’s talk !

✓ GW landscape from systematic 3D HD modeling olution (~4 s)



ET Detection Ranges							
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
11	9.37	11.03	10.08	4.94	111.34	65.44	75.52

- ✓ Detection horizon (setting a SNR ratio as 8) for LVK, throughout our Galaxy!
- ✓ for ET/CE, “beyond” neighboring galaxies (e.g. Andromeda (765kpc)!)

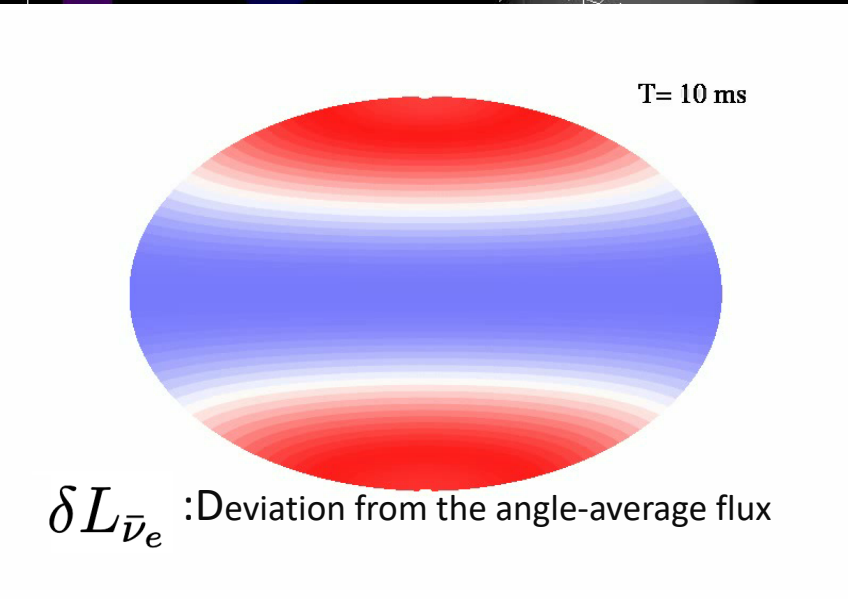
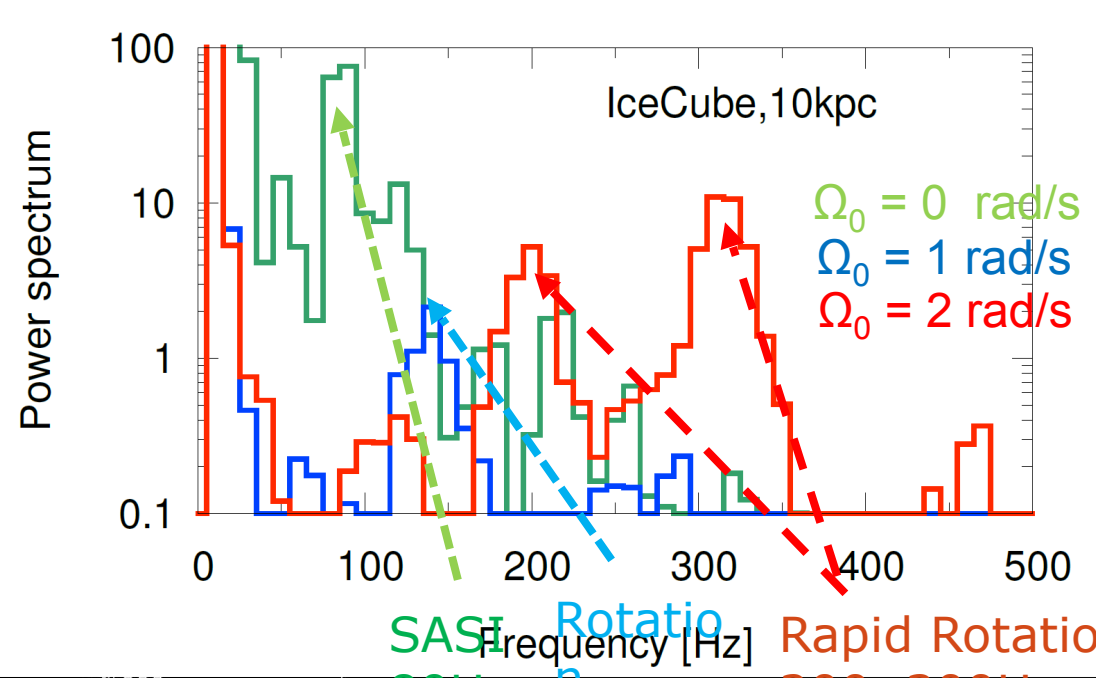
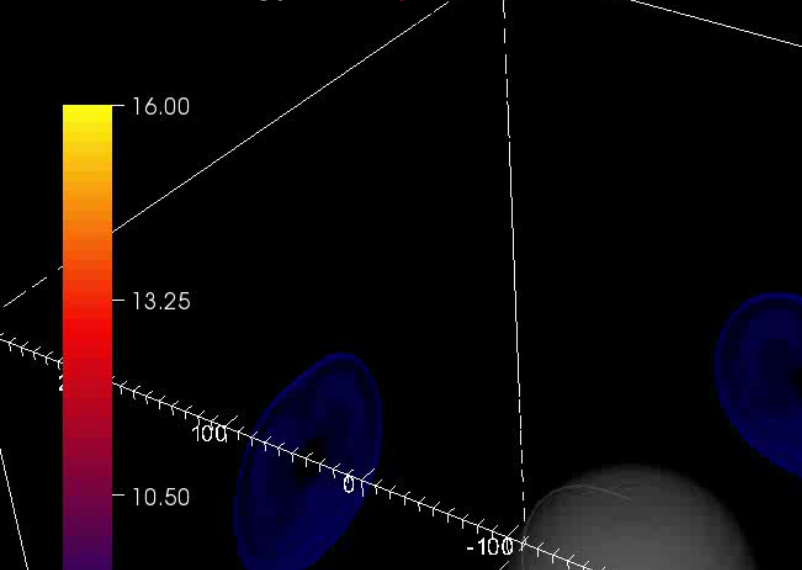
$$\rho^2 = 4 \int_0^\infty df \frac{|\tilde{h}(f)|^2}{S_n(f)}$$
- Final words “Need” long-term simulations with MHD!

19.56	20.66	26.90	23.97	15.80	106.85	56.12	80.09
20	11.43	16.08	13.79	14.18	59.49	35.14	48.93
21.68	17.03	21.06	19.23	12.48	82.33	44.64	63.87
23	9.29	12.53	10.94	11.18	90.17	48.44	59.38
24	14.35	18.09	16.09	11.99	71.37	38.83	54.92
25	11.70	17.28	14.69	14.50	54.33	33.58	48.27
40	23.19	27.00	25.26	15.51	159.53	90.05	115.31
60	14.04	17.26	15.60	9.47	92.17	55.16	70.76

✓ ET/CE (< 100
 both needed

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

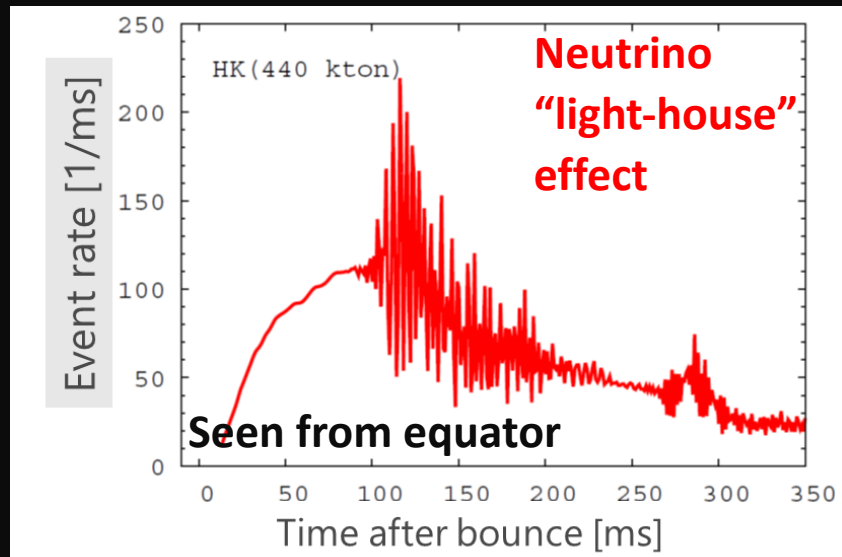
Rapidly rotating collapse
of a $27 M_{\text{sun}}$ ($\Omega_0 = 2 \text{ rad/s}$)



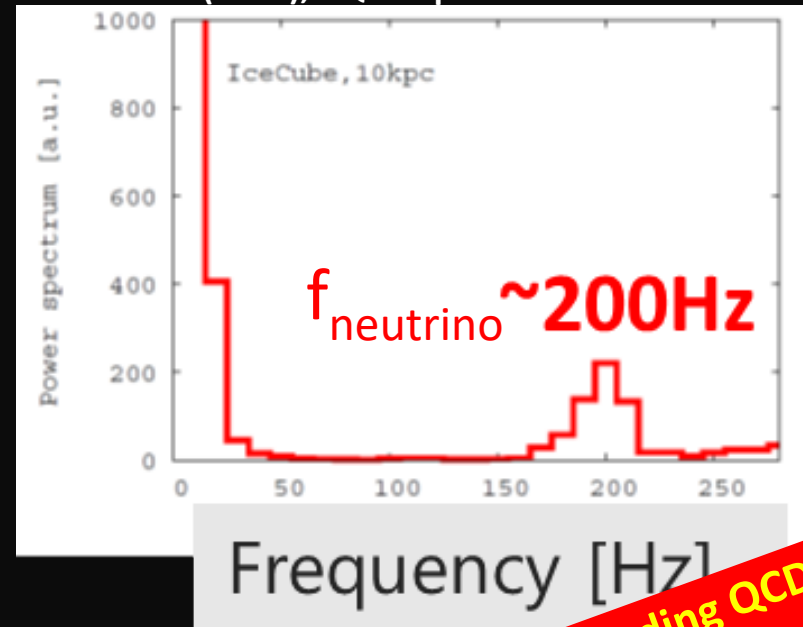
✓ **Peak frequencies become higher with progenitor rotation !**
because rapid rotation leads to rapidly rotating PNS and neutrino sphere.
→ The light-house effect
600 km

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

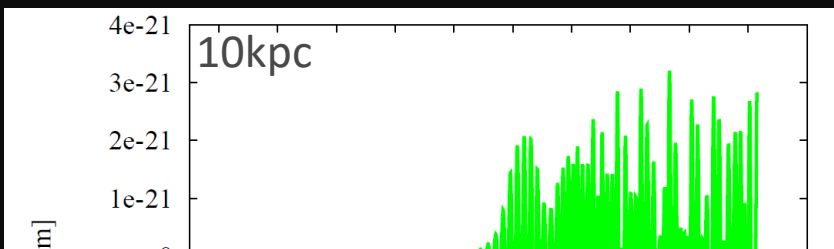
Neutrino event rate ($27 M_{\text{sun}}, \Omega_0 = 2 \text{ rad/s}$)



Takiwaki, KK, Foglizzo, (2021), MNRAS, Shibagaki+2021. MNRAS
Cusinato et al. (2026), CQG in press



Gravitational waveform



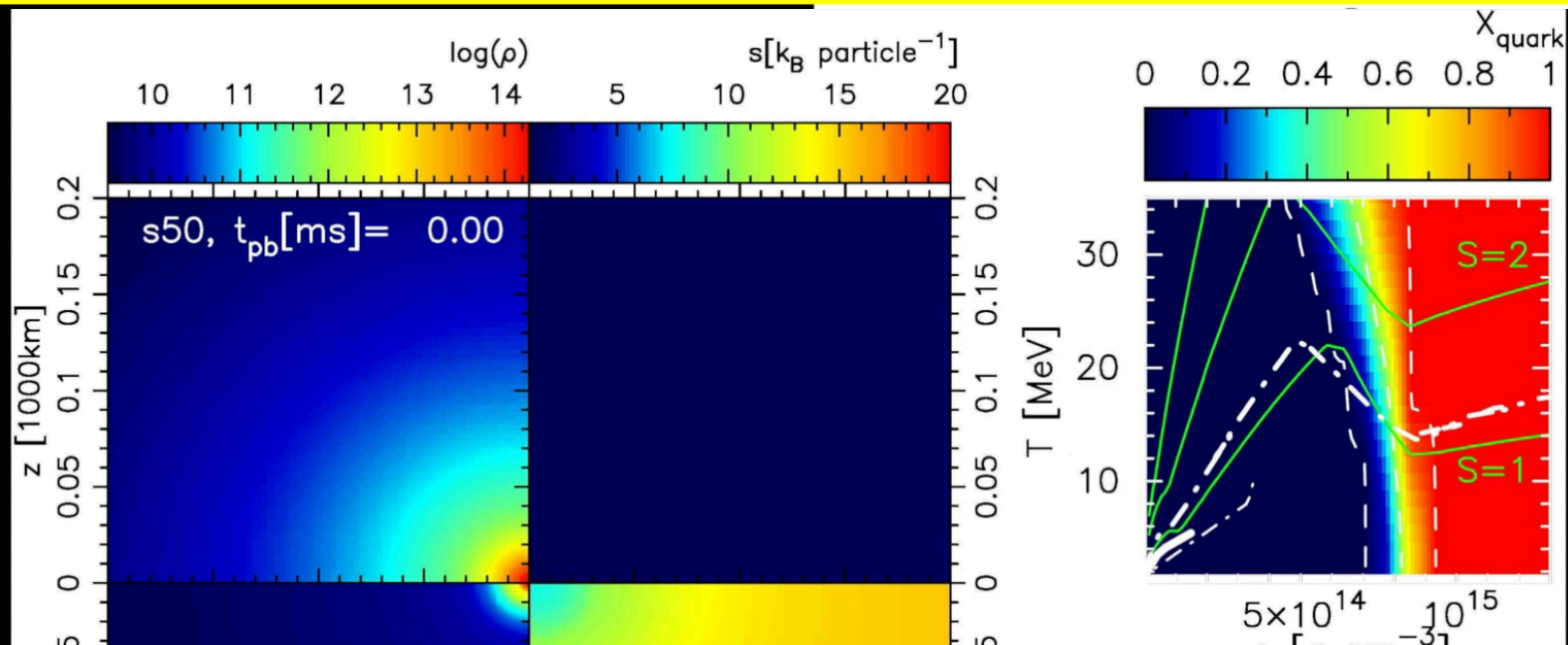
(EOS dependence including QCD PT, not explored !)

- ✓ 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, $f_{\text{neutrino, SASI}} \sim 80 \text{ Hz}$, QUIZ $f_{\text{gw}} \sim 80$ or 160 Hz
- ✓ Coincident detection between GW and ν : smoking gun signature of rapid core rotation !

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

If the PT be the “first-order” (should be proven!!!!, ask Niels and Tobias!)

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



✓ 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!)

See Largani's talk !

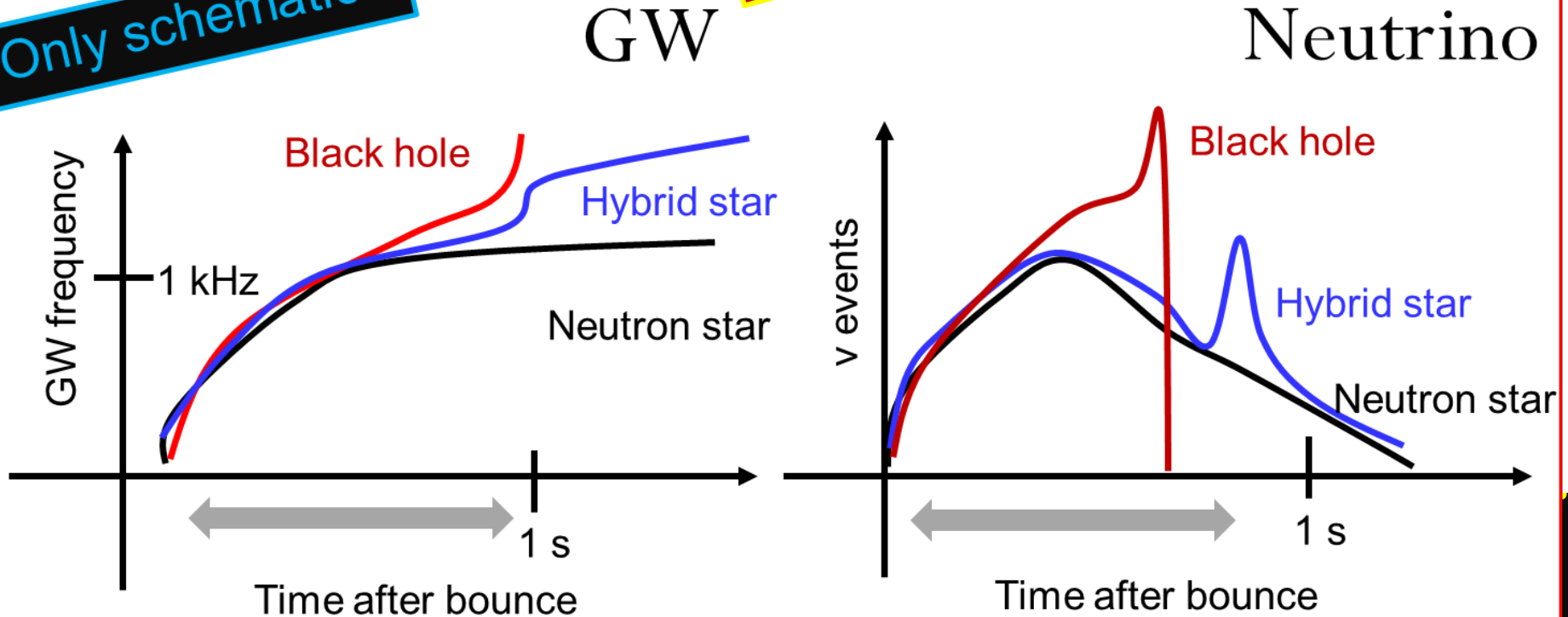
✓ Probe into **PT physics** : **Multi-messenger signals** !

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-transition induced

See Shibagaki's talk !

Only schematic !



→ Simply “**schematic**”, is being “**quantified**”! (Shibagaki et al. in prep)

Started from wrong? 3D-MHD precollapse models needed!

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

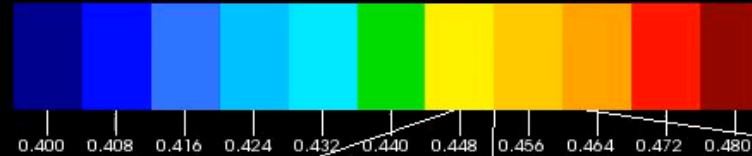
DB: visSi00001.bov
Time: 1

T. Yoshida, Takiwaki, KK, et al. (ApJ, 2019,2020,2021)

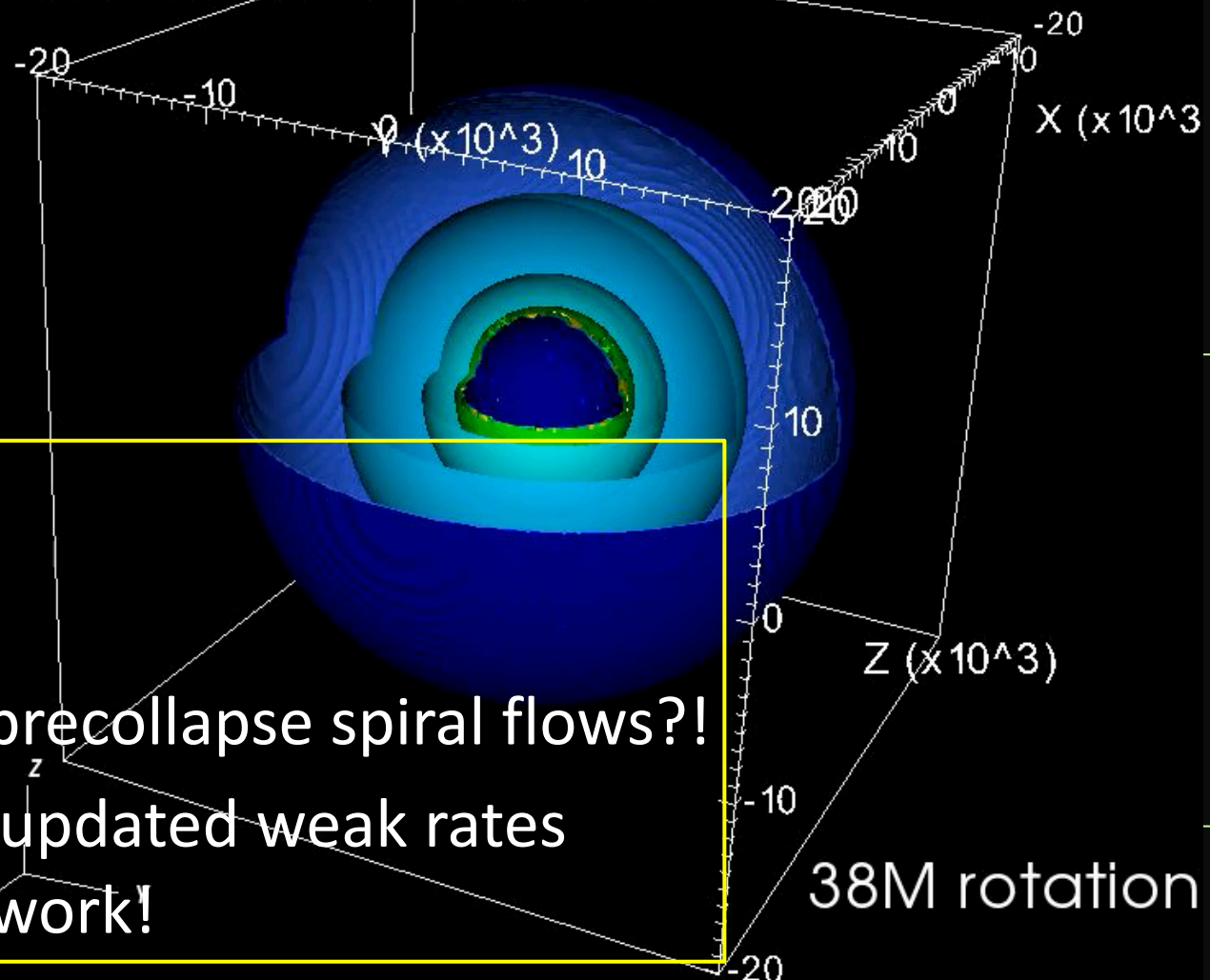
Contour
Var: $X_{\text{Jp_Si_rp_}}$



Max: 0.7098
Min: $5.605e-39$



Time = 0 s



MHD modeling
in progress

(Takata et al. in prep):

Consequence of precollapse spiral flows?!

✓ Should include updated weak rates
and larger network!

3D modeling and the MM prediction in the next decade

- ✓ Systematic 3D MHD modeling with GW/v signal predictions are **in steady progress** (P and F) → **Need long-term simulation** ($>\sim 10$ s, GPU: see talk by Takami)
- ✓ Inclusion of **neutrino flavour conversion** (Ehring+2023, Nagakura+2023, Akaho 2026)
- ✓ **Detailed weak Interactions**/BSM physics/EOS incl. hyperons/axion. sterile ν , dark photon.. (Zatini+(2026), Fischer+(2025), Mori+(2025))
- ✓ GW signals from 3D SN models targets of LVK throughout our Galaxy, of CE/ET nearby Gal. (Detection of “kHz” GW new probe to **QCD physics**)
- ✓ Multi-D **MHD** progenitor modeling and observation (binary evolution) (Griffiths+(2026), Mueller & Varma (2023))
- ✓ **Upgrade** of GW and ν detectors (LVK extension, CE, ET, hyper-K, Dune)
- ✓ **Coincident analysis of GW and ν** , pivotal, providing the smoking gun of the engine!
- ☆ Signal prediction from Hypernovae!
- 3D-MHD modeling of “Jets”, BH/accretion-disk** (:3D-GR MHD code with neutrino transport)

Who can revolutionize the CCSN theory in the next decades?

But what about BS models?!

about the **central engines**? Unexplored.)