MM (Neutrino & GW) signal predictions from 3D "MHD" modeling of Core-Collapse Supernovae on the Verge of Success

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with
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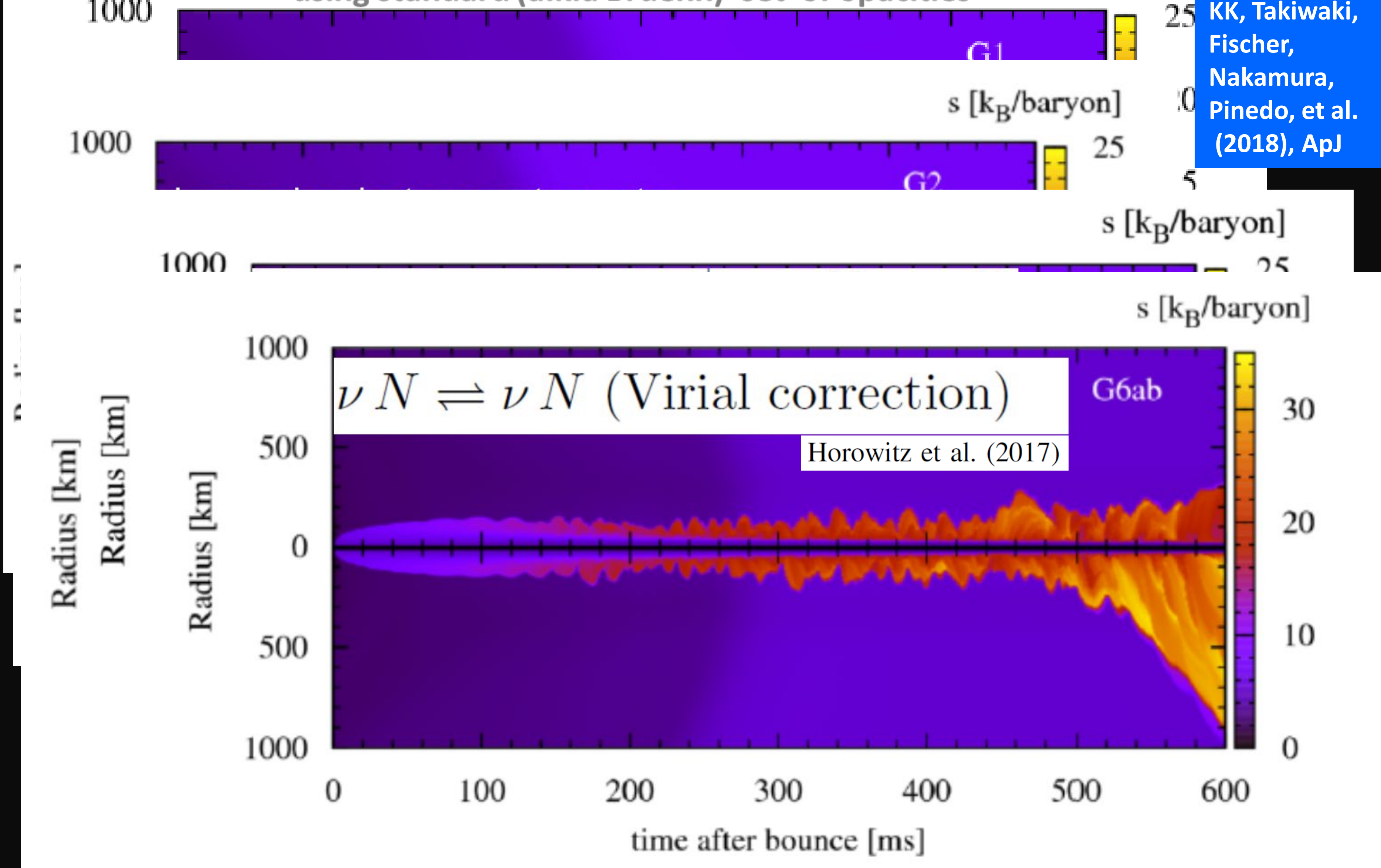
Jin Matsumoto (Keio Univ.), Tobias Fischer (Univ. Wroclaw)

August 10th @INT workshop, 2023

"Devil" is always in the details: 2D-IDSA, 20 M_{sun} (Woosley & Heger (2007))

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

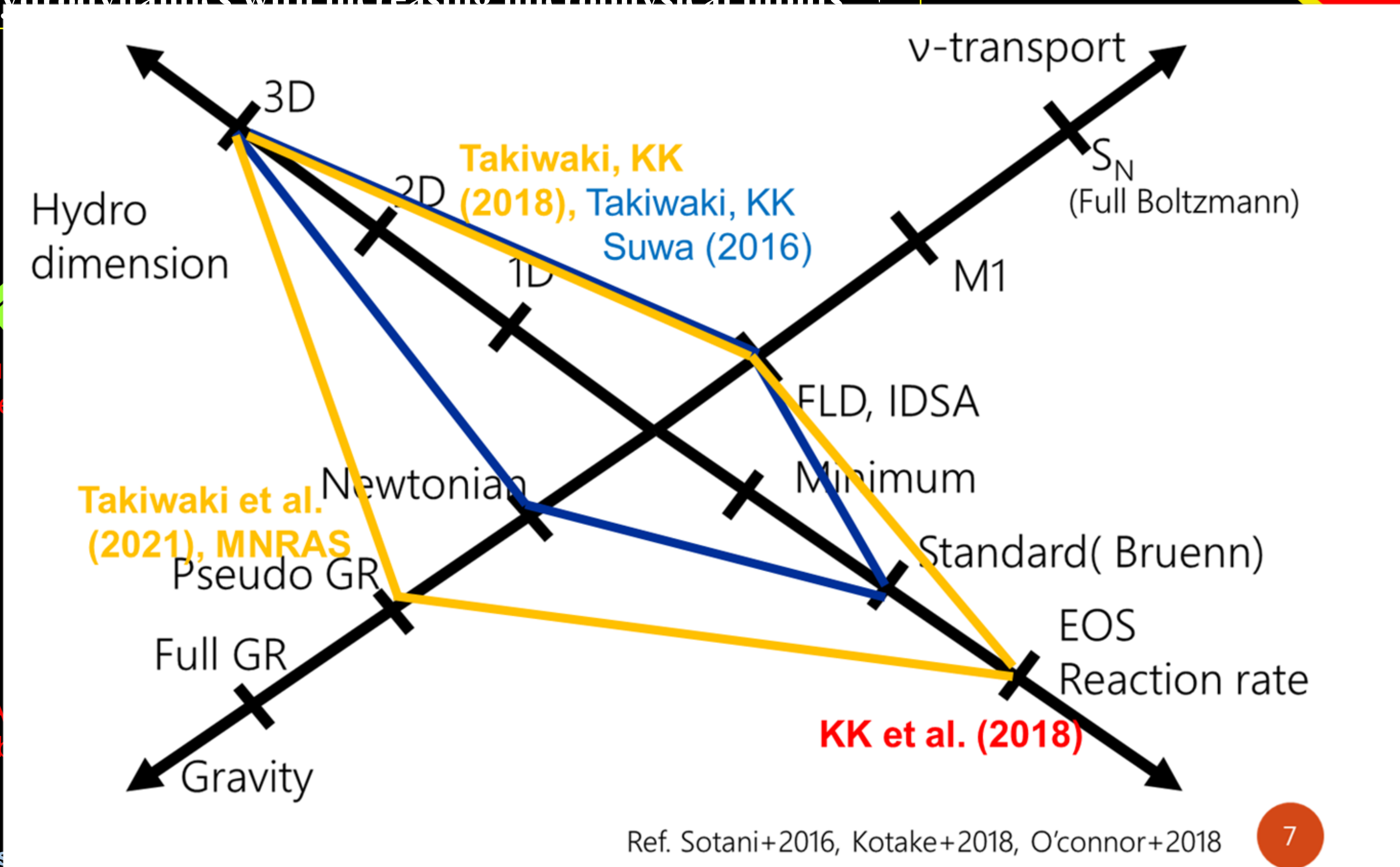
KK, Takiwaki, Fischer, Nakamura, Pinedo, et al. (2018), ApJ



✓ Quantitative ν/GW signal prediction, "updates" (non-limited ν opac.) mandatory!

Sweat, Sweat, Sweat ! (Hillebrant-Müller-Janka-B.Müller-Obergaulinger Cerdá−Durán…, Matzner-Mezzacappa-Fischer, Lattimer-Burrows-Ott-O’Connor, Sato-Yamada… KK, Takiwaki, Suwa, Matsumoto…), the God father… H. Bethe !)

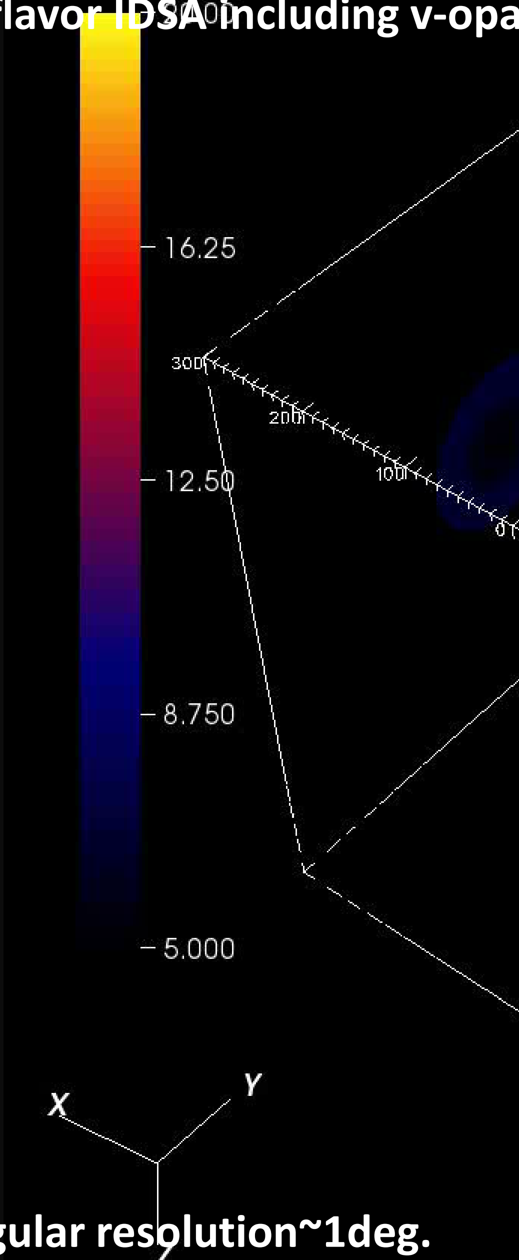
✓ Progress report of **our supernova code**: *Updated ν reactions in 3D code*

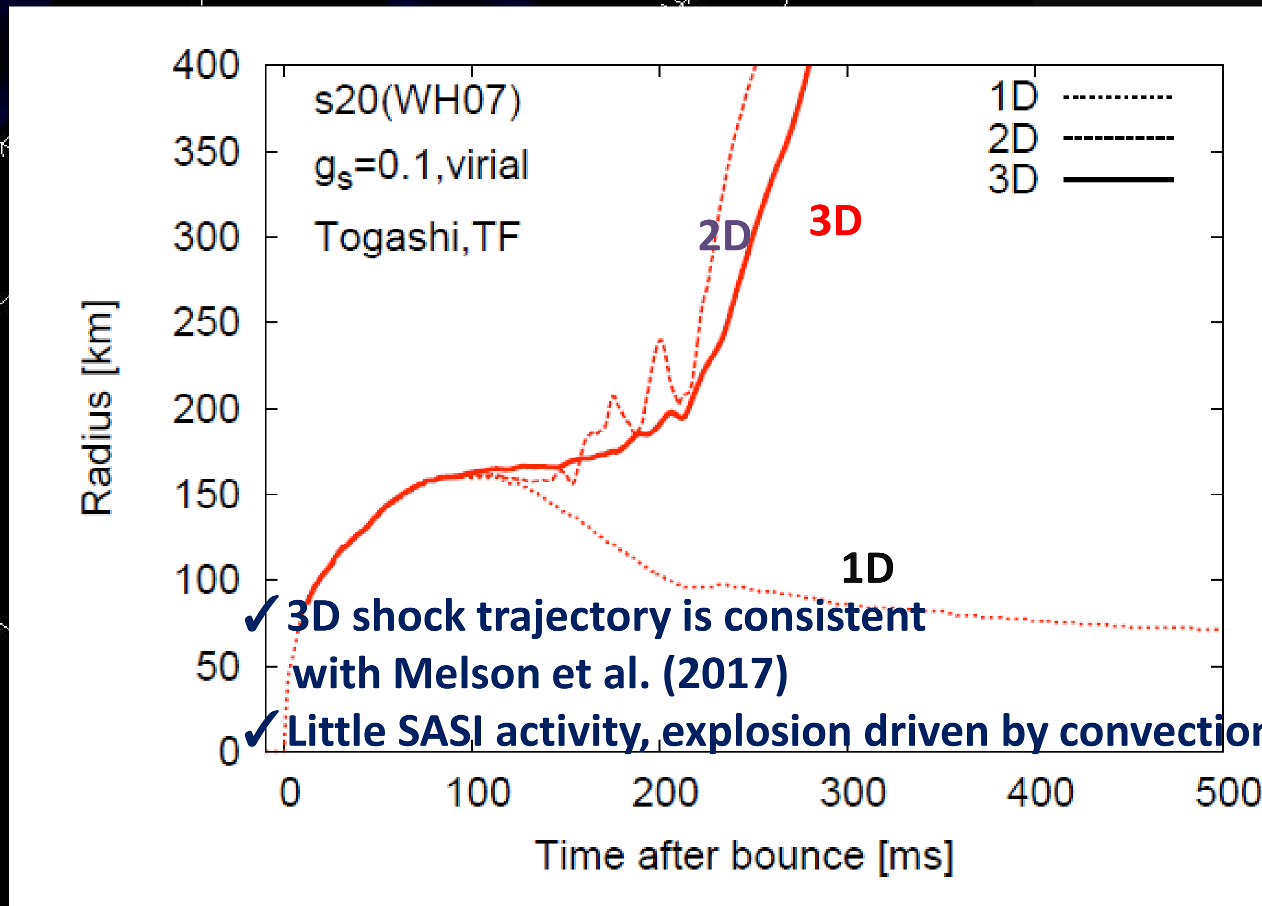


20 M_{sun} progenitor (WH07) using Togashi EOS, 3flavor IDSA including ν-opacity updates (w.o. muons)

11 ms

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





✓ 3D shock trajectory is consistent with Melson et al. (2017)

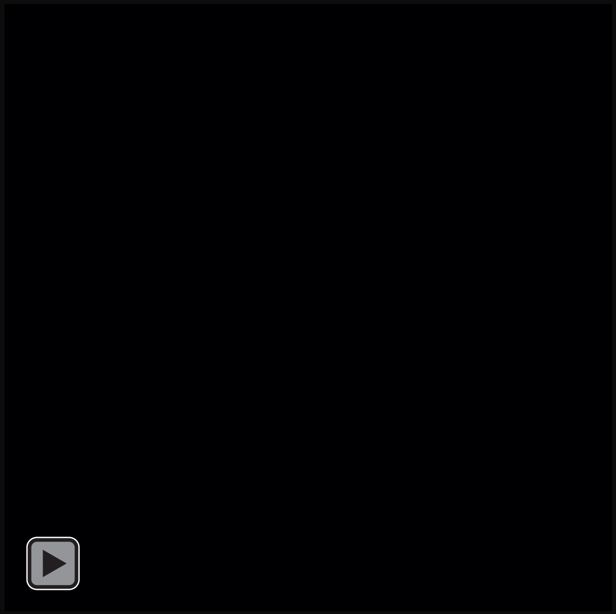
✓ Little SASI activity, explosion driven by convection

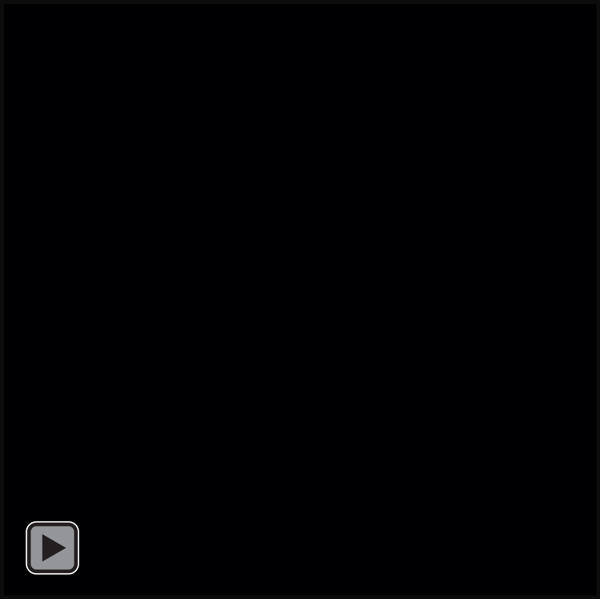
Angular resolution~1deg.

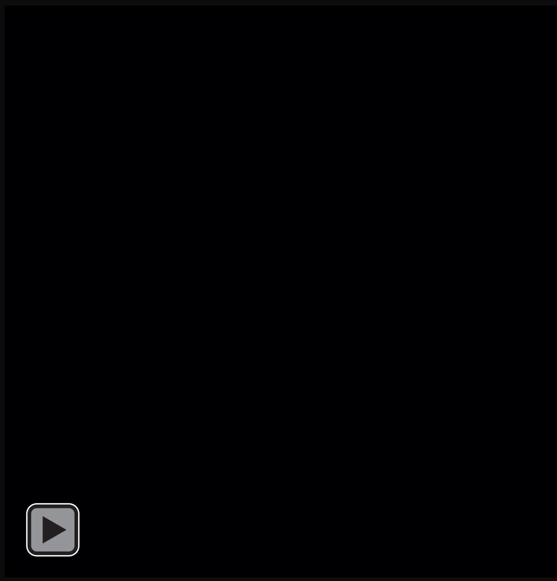
Many more 3D modeling with MHD possible (on ArXiv this Month)

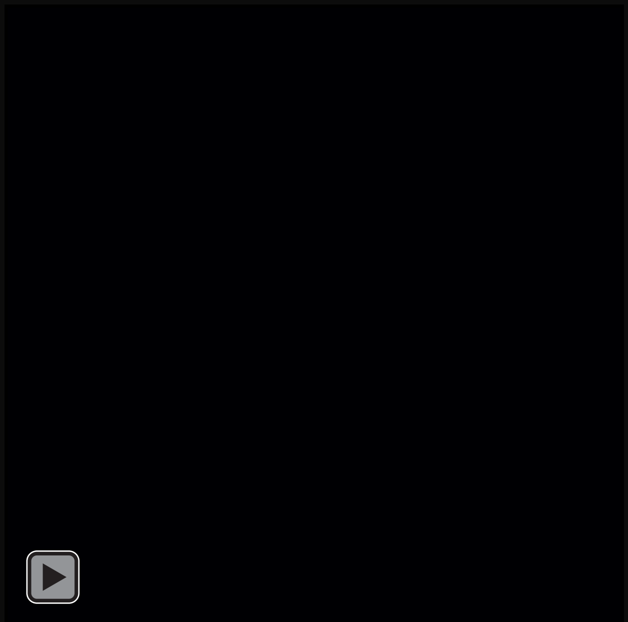
Matsumono, Takiwaki, KK in prep (see also Nakamura, Takiwaki, KK, (2022), MNRAS)

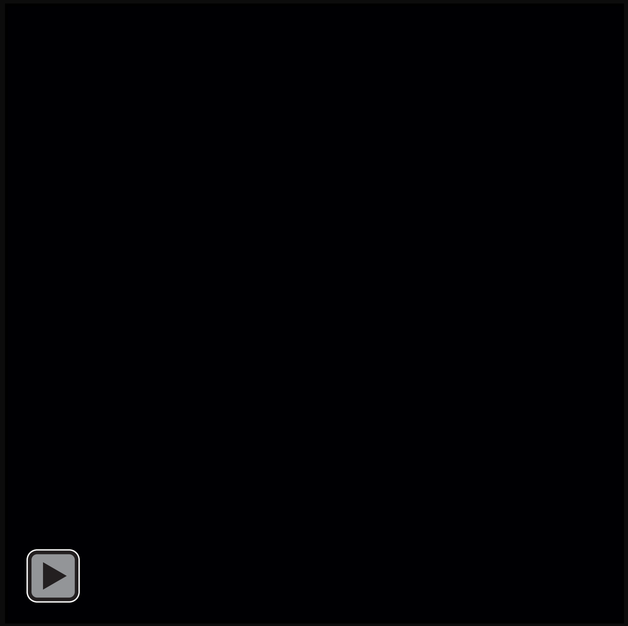
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform)), Non-rotation)

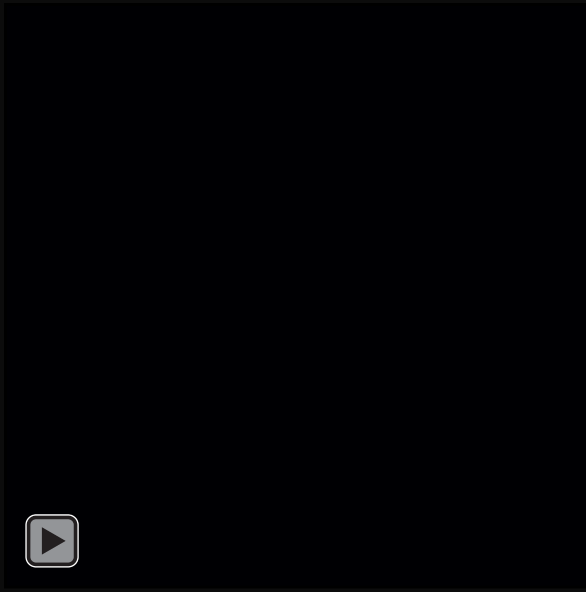


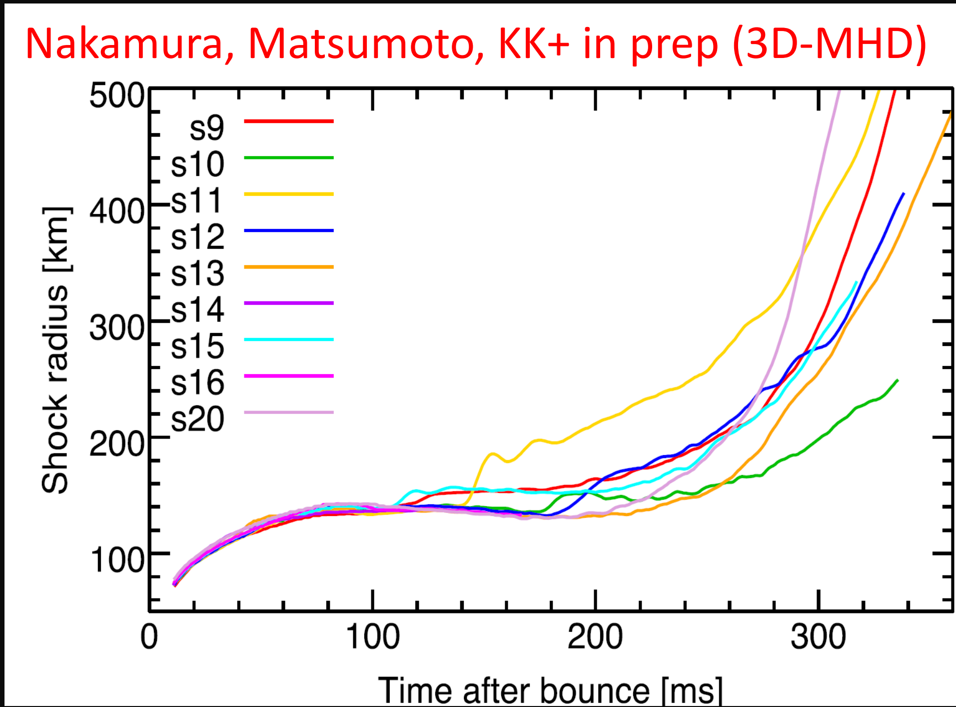


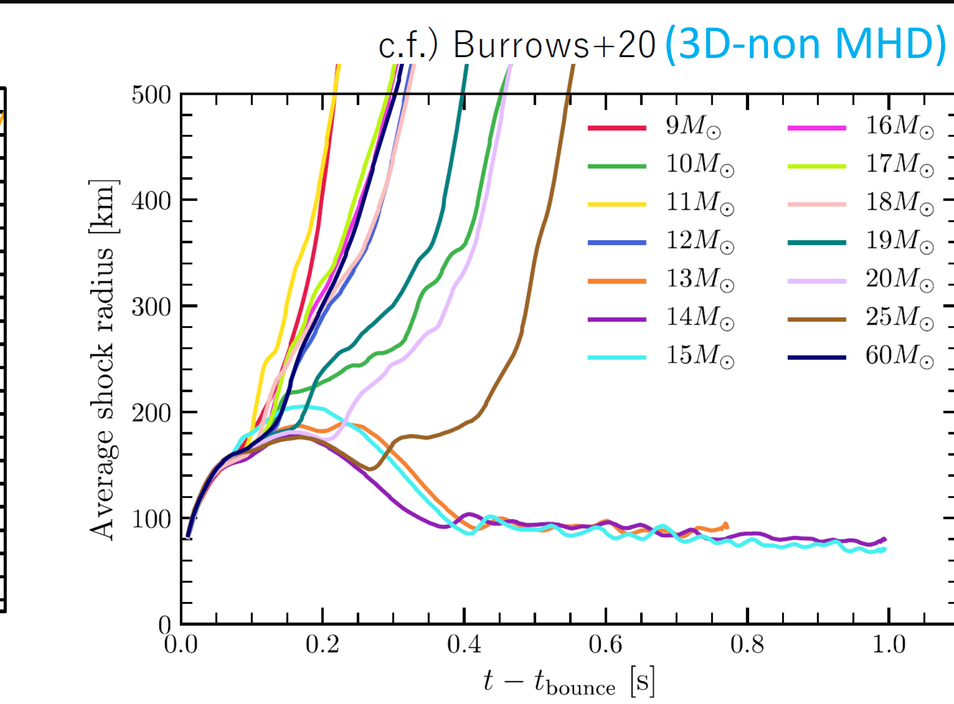






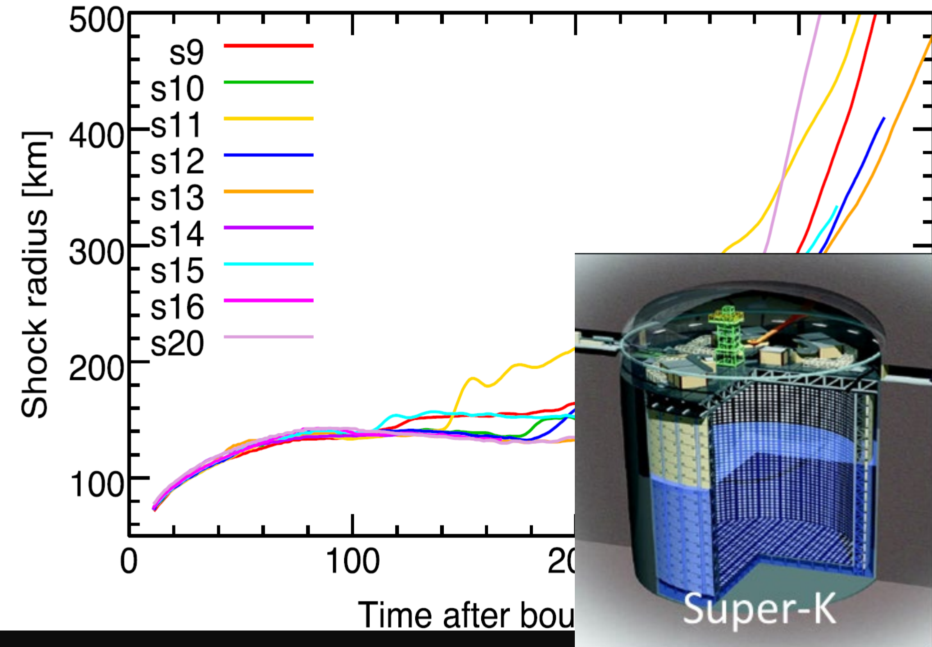




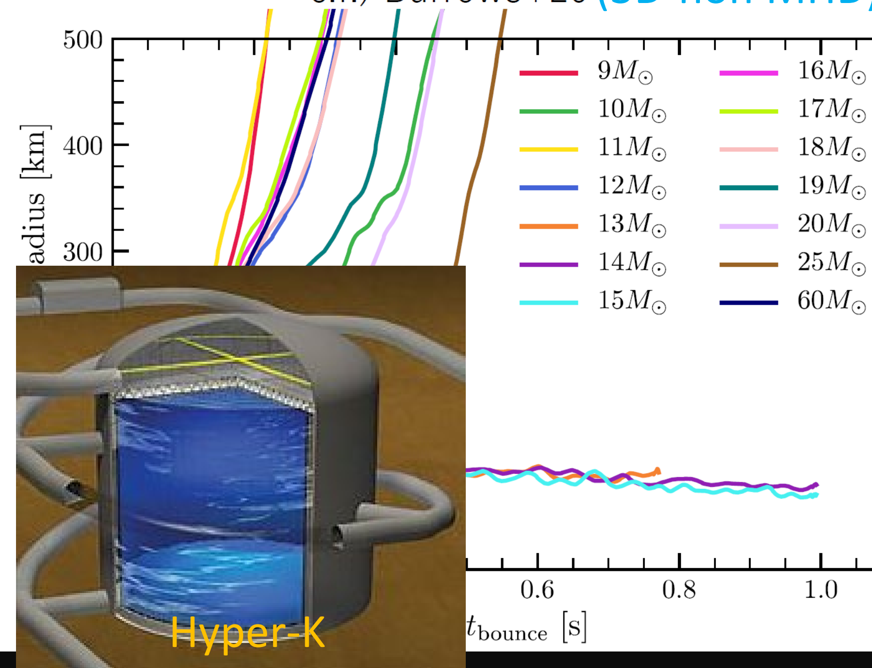


✓ High neutrino detection for high "compactness ($\sim M_{core}/R_{core}$) is progenitor !

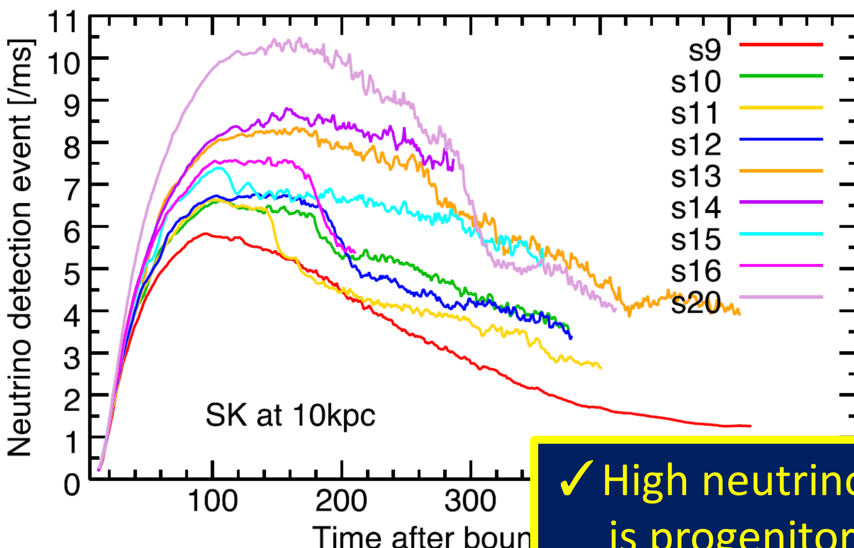
Nakamura, Matsumoto, KK+ in prep (3D-MHD)

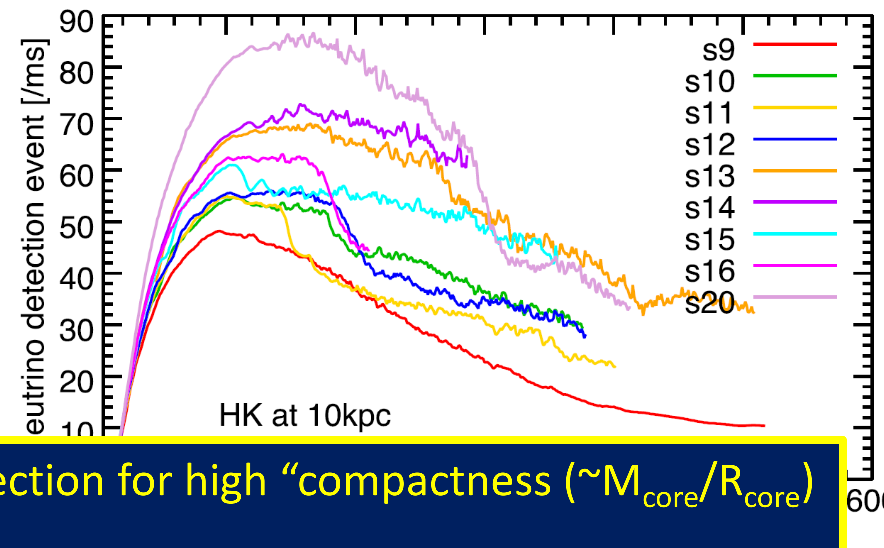


c.f.) Burrows+20 (3D-non MHD)



✓Neutrino detection rate at SuperKamokande and HyperKamiokande





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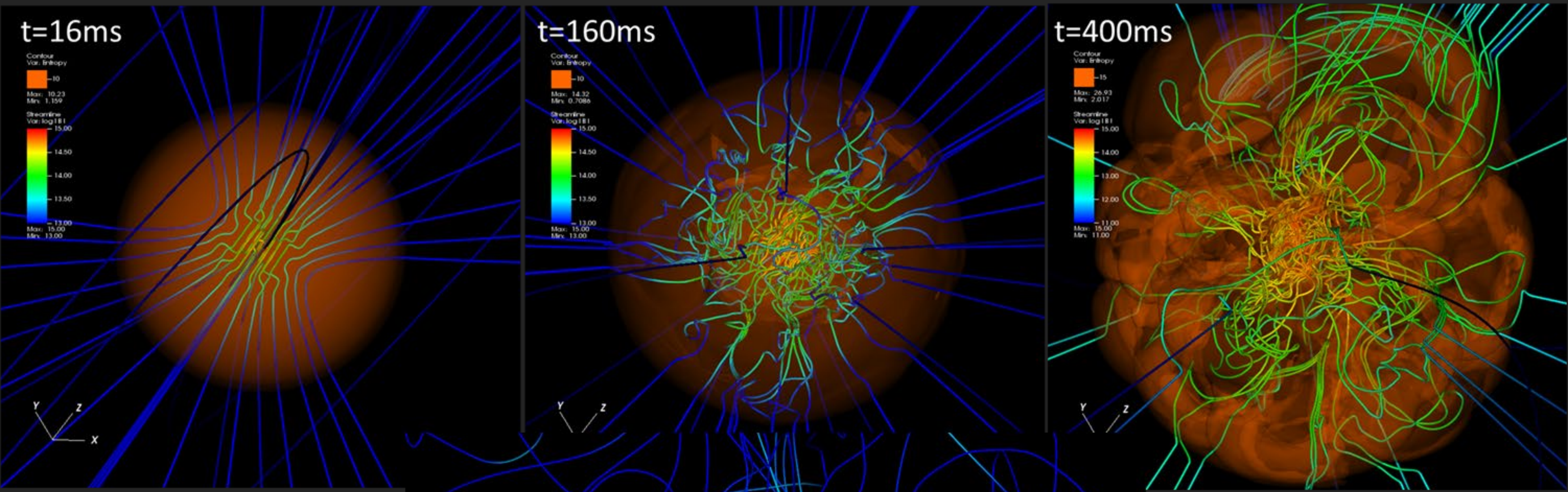
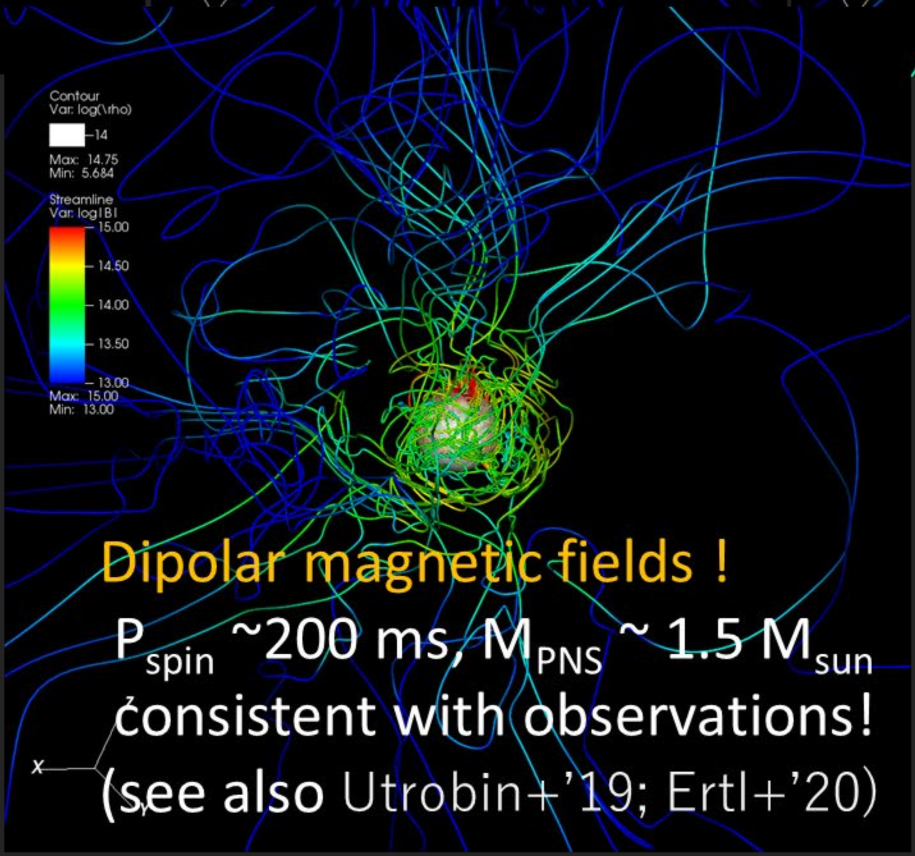




Dipolar magnetic fields !

P_{spin} ~200 ms, M_{PNS} ~ 1.5 M_{sun} consistent with observations!

(see also Utrobin+'19; Ertl+'20)

✓ Dynamo in the PNS needs to be studied In detail as in Raynaud, Guilet et al. (2020), Masada, Takiwaki, KK ApJ in press

3D MHD CCSN modeling with slow rotation (be ArXiv this Month)

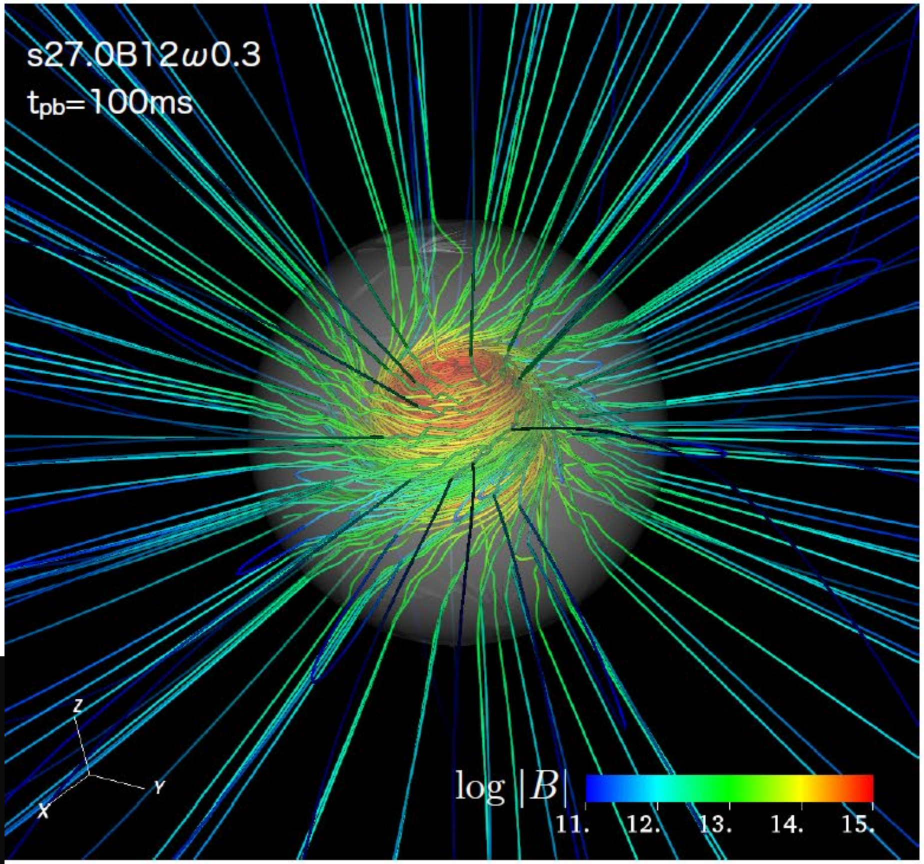
Settings

- 3DnSNe code (Takiwaki+16) updated to MHD (See JM+20)
- approximate Riemann solver: HLLD (Miyoshi & Kusano 05)
- three-flavour neutrino transport based on

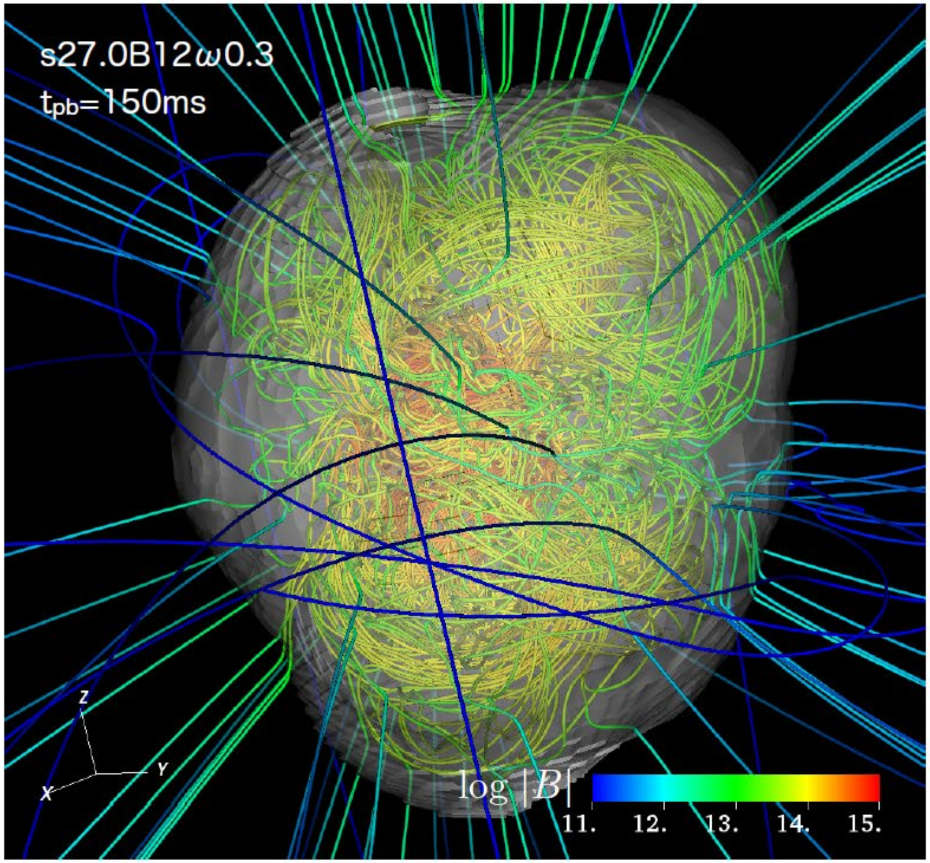
- rigid rotation

$\omega_0 = 0.3, 0.1, 0$ rad/s

onset of neutrino-driven convection

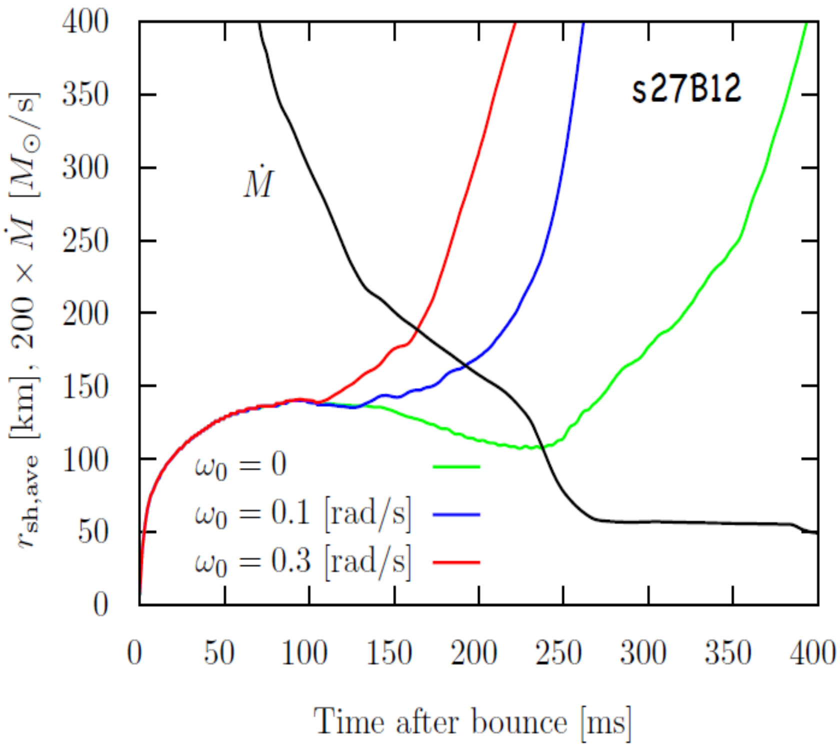


after shock revival



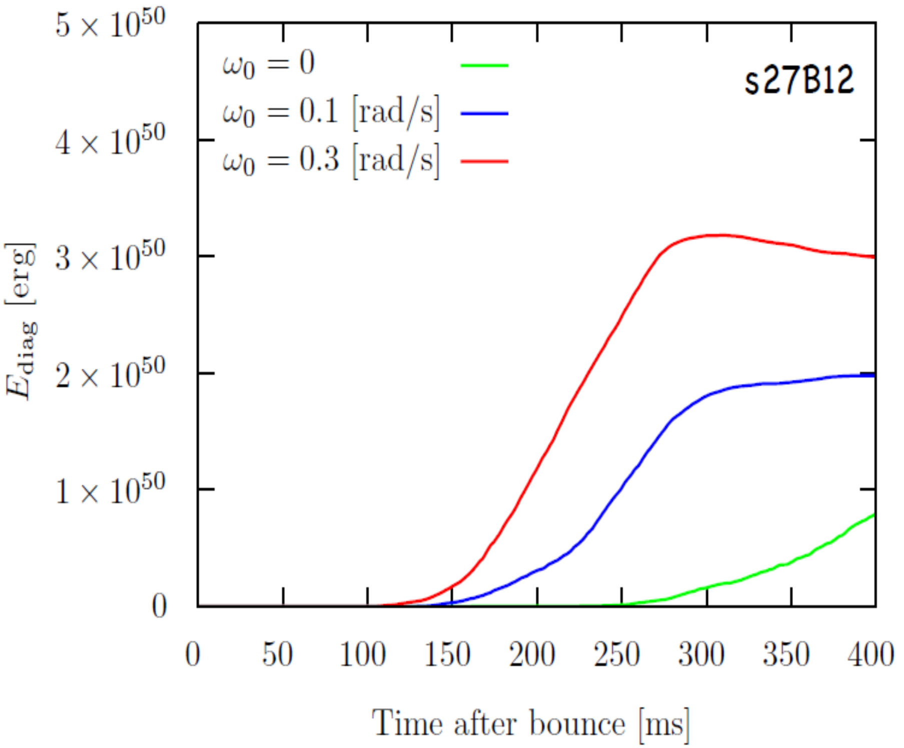
Dependence of the rotation

shock evolution



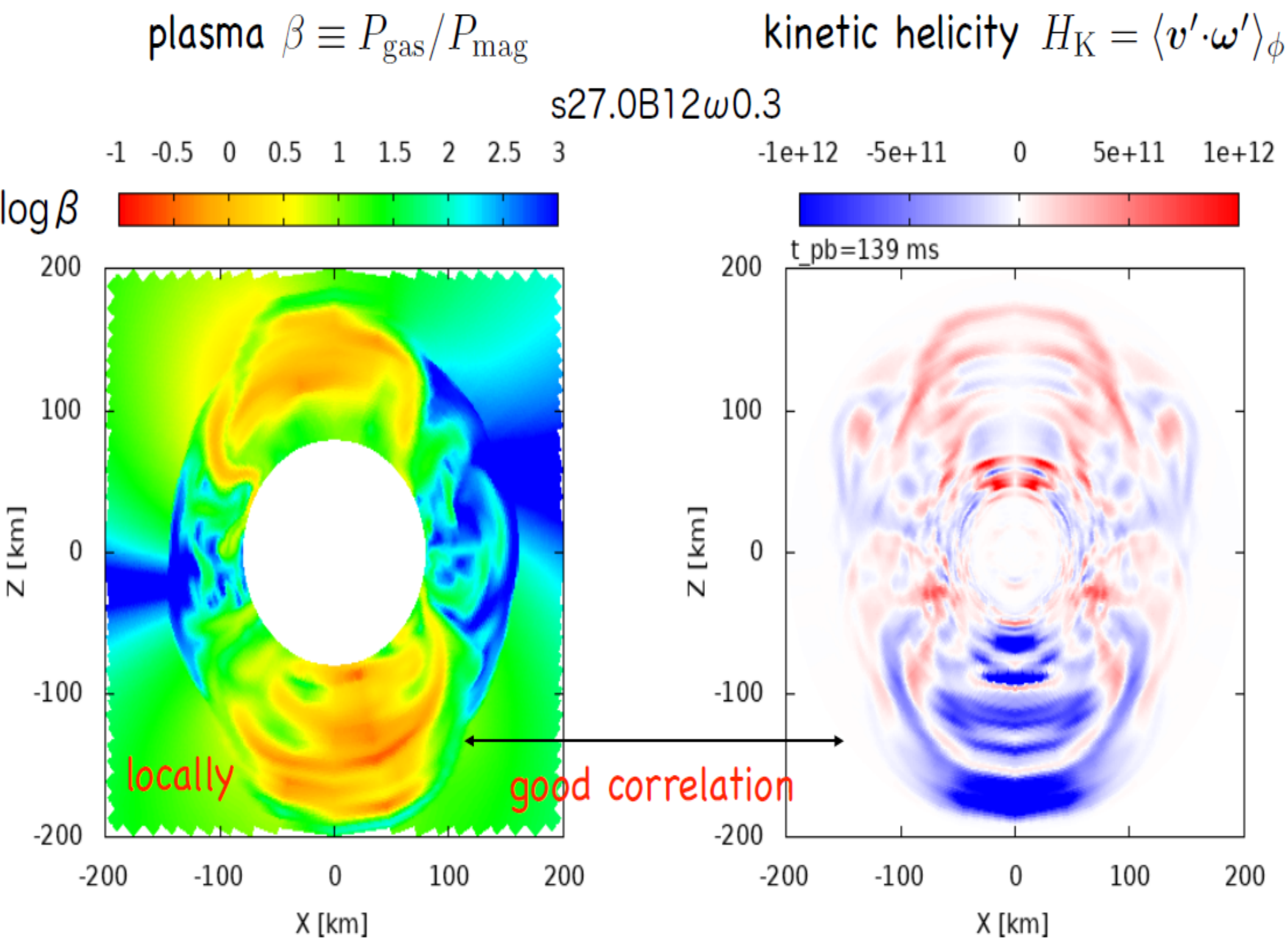
Magnetic pressure driven explosion occurs in rotating models. The magnetic field is fully amplified due to the effect of turbulence.

evolution of explosion energy



Explosion energy in faster explosion model is larger.

Amplification of the magnetic field



Magnetic pressure driven explosion

mean field theory

$$\boldsymbol{v}(r,\theta,\phi) = \langle \boldsymbol{v} \rangle(r,\theta) + \boldsymbol{v}'(r,\theta,\phi)\ ,$$

$$\boldsymbol{B}(r,\theta,\phi) = \langle \boldsymbol{B} \rangle(r,\theta) + \boldsymbol{B}'(r,\theta,\phi)\ .$$

induction equation:

$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \nabla \times (\langle \boldsymbol{v} \rangle \times \langle \boldsymbol{B} \rangle - \eta \nabla \times \langle \boldsymbol{B} \rangle + \boldsymbol{\epsilon})$$

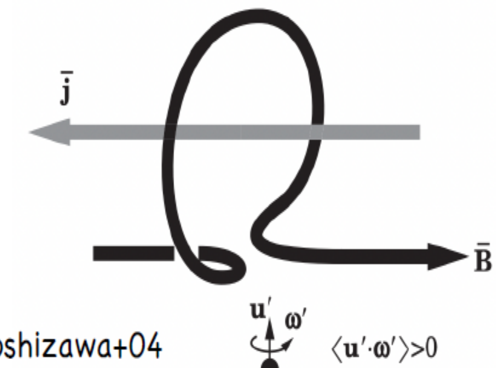
$$\boldsymbol{\epsilon} \equiv \alpha \langle \boldsymbol{B} \rangle - \eta_t \nabla \times \langle \boldsymbol{B} \rangle$$

$$\alpha \equiv -\frac{1}{3}\tau_{\rm cor} h_{\rm K}$$

$$\eta_t \equiv \frac{1}{3}\tau_{\rm cor}\langle v'^2 \rangle$$

Brandenburg+05

α -effect

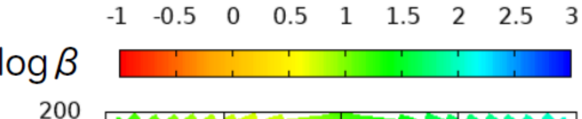


Yoshizawa+04

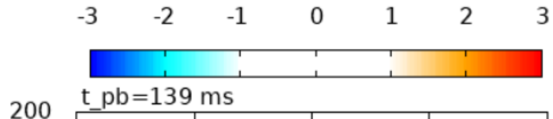
Amplification of the magnetic field

plasma $\beta \equiv P_{gas}/P_{mag}$

s27.0B12ω0.3



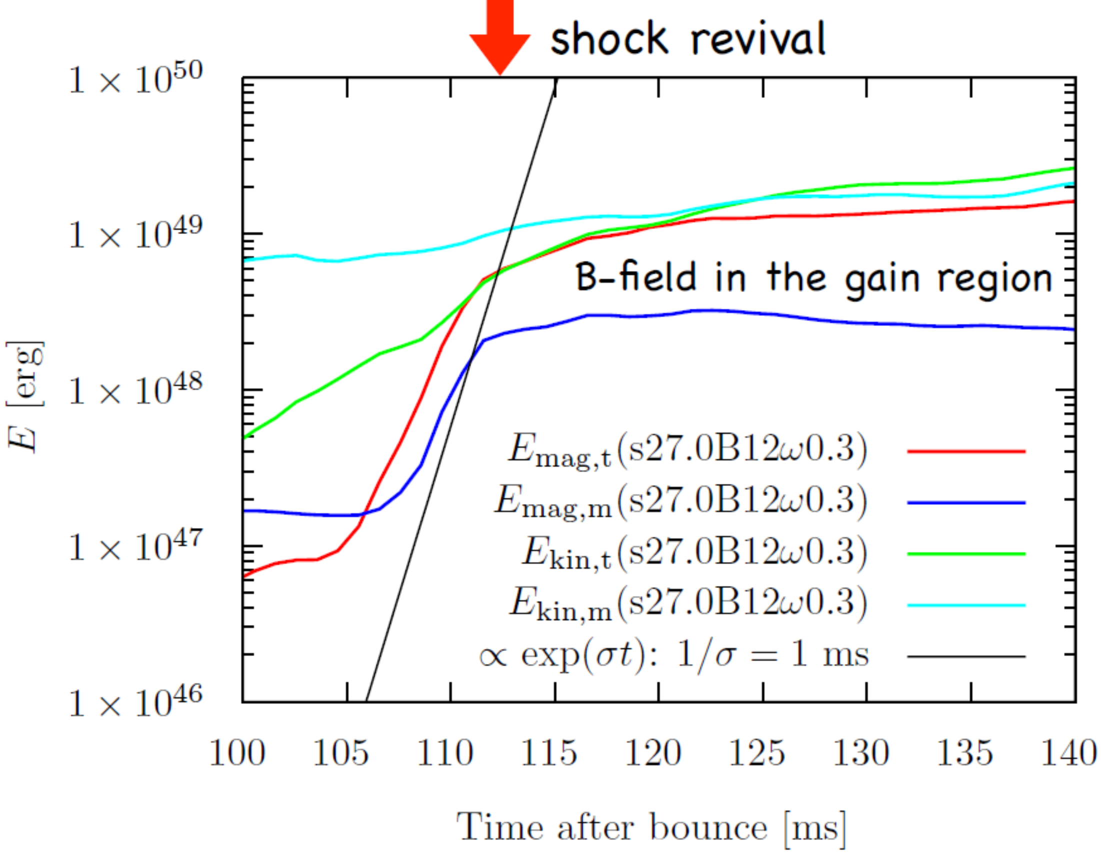
dynamo number
in gain region



$$\frac{\partial \langle \boldsymbol{B} \rangle}{\partial t} = \nabla \times (\alpha \langle \boldsymbol{B} \rangle) + \eta_t \Delta \langle \boldsymbol{B} \rangle$$

dispersion relation:

σ



Mean magnetic field is amplified by α-effect.

In addition, turbulent magnetic field is also amplified via α-dynamo action of mean magnetic field.

Induction equation for turbulent magnetic field:

$$\frac{\partial \boldsymbol{B}'}{\partial t} = \nabla \times (\boldsymbol{v}' \times \underline{\langle \boldsymbol{B} \rangle})$$

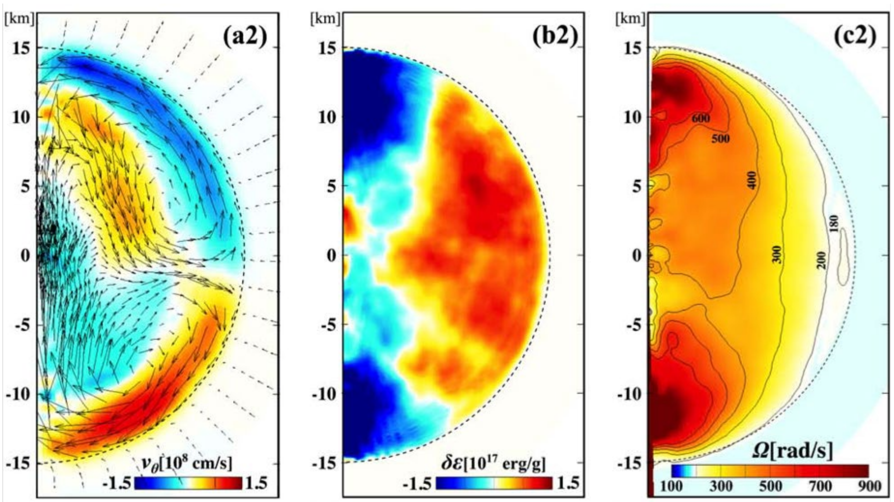
mean magnetic field

Magnetic pressure amplified due to α-effect is responsible for fast explosion in our rotating model.

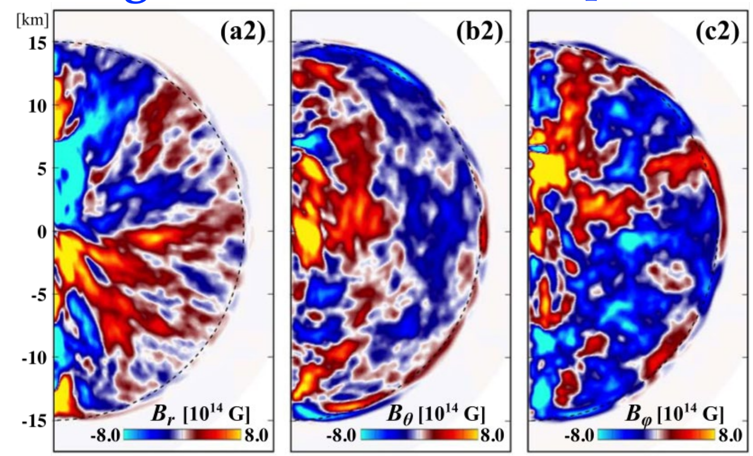
GW Signals from A fully-convective PNS (Masada et al. 2022, ApJ)

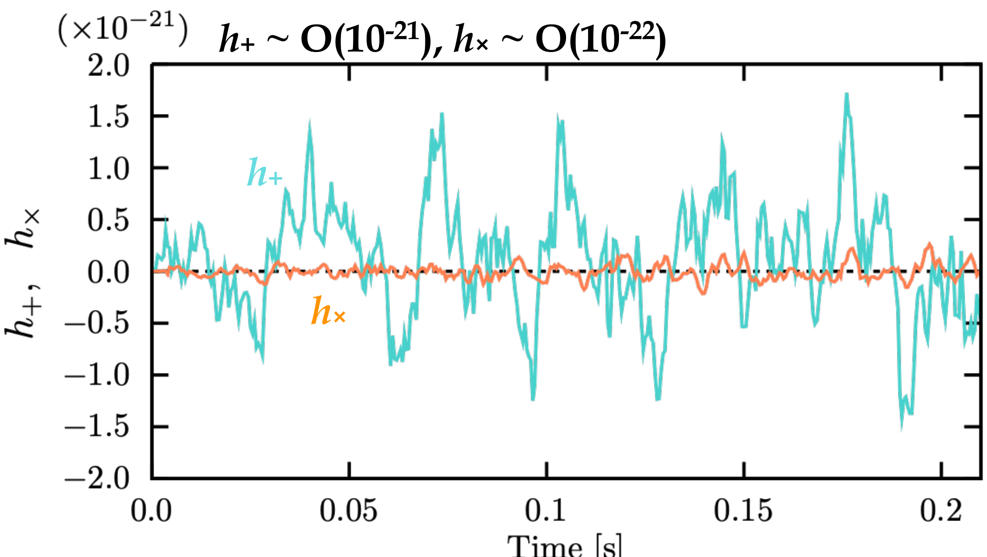
From a fiducial model with Ω_0= 60π (rad/s) imposed at the PNS surface:

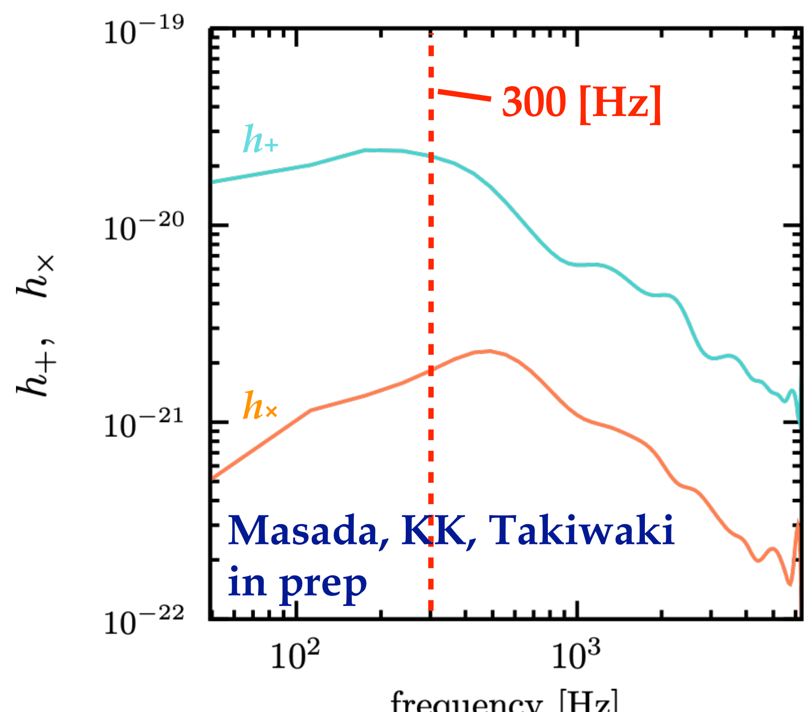
flow field



magnetic field (mean component)



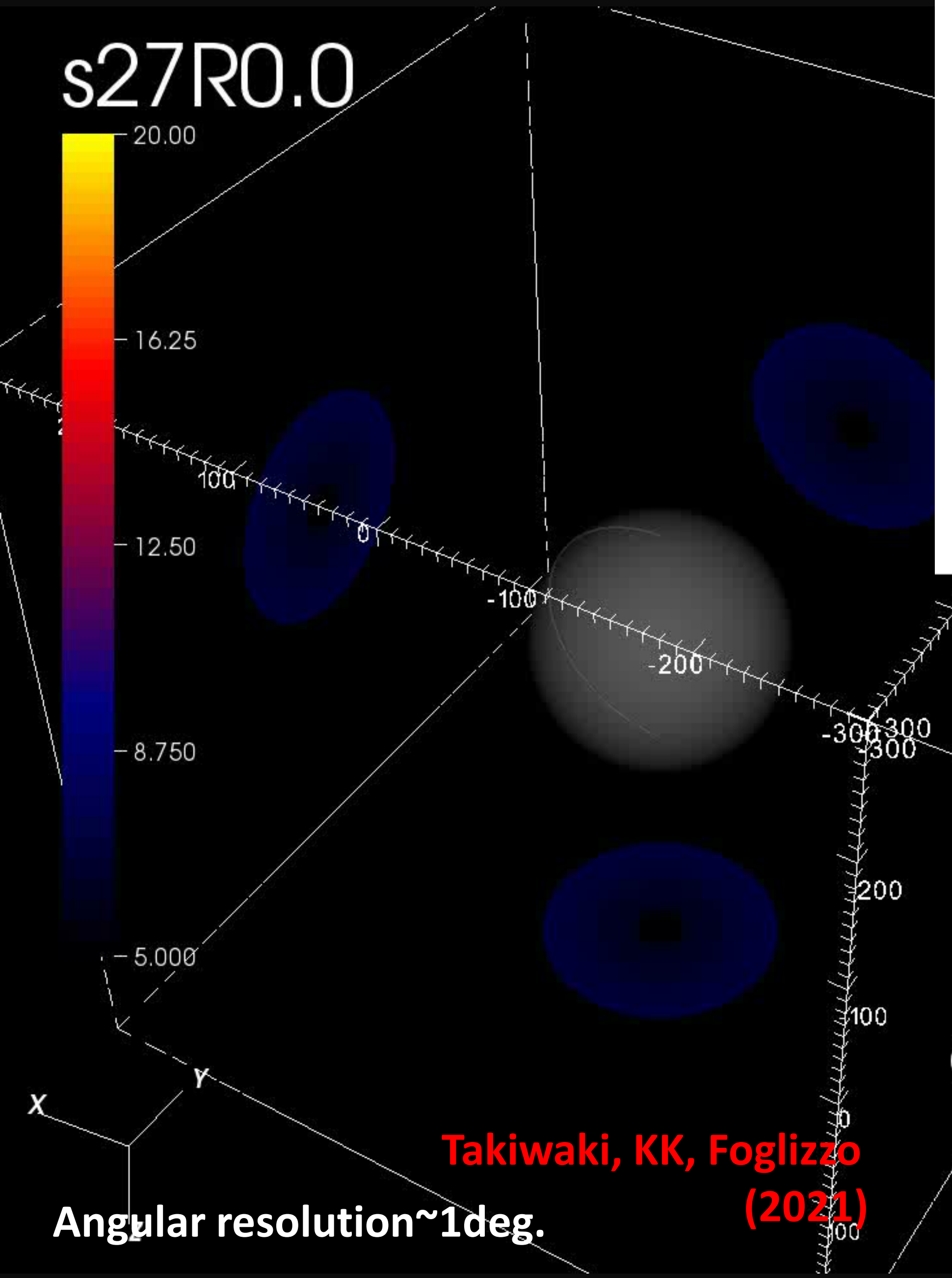




- **convective turn-over time : $\tau \sim 2\times10^{-2}$ [s]**
- **convective frequency : $f = 2\pi/\tau \sim 300$ [Hz] :**

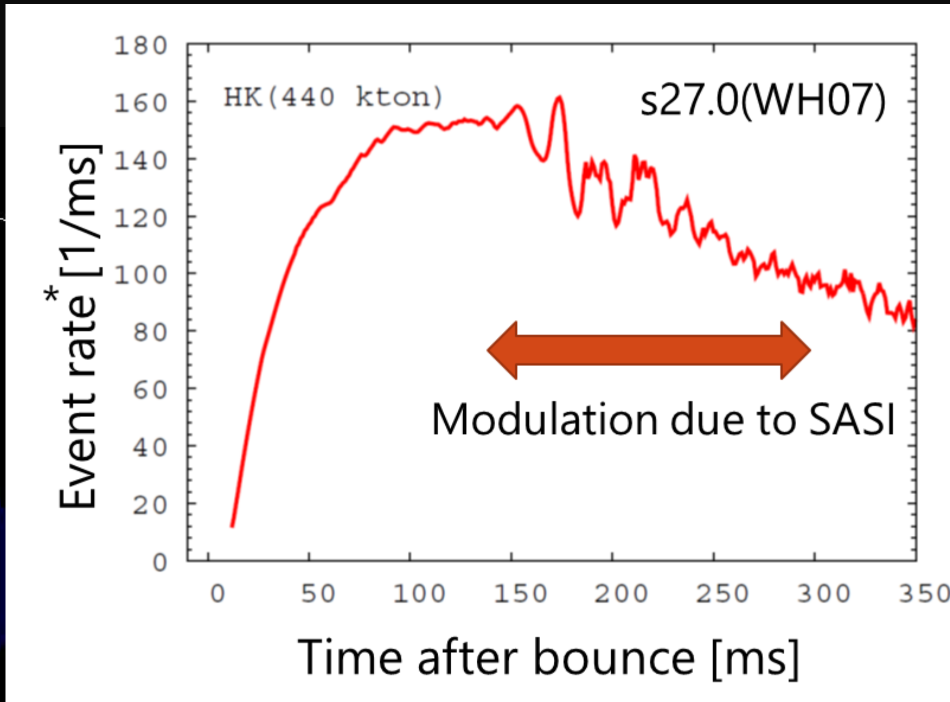
→ The dynamo activity footprints in the future GW observation !

27 M_{sun} progenitor (WH07)

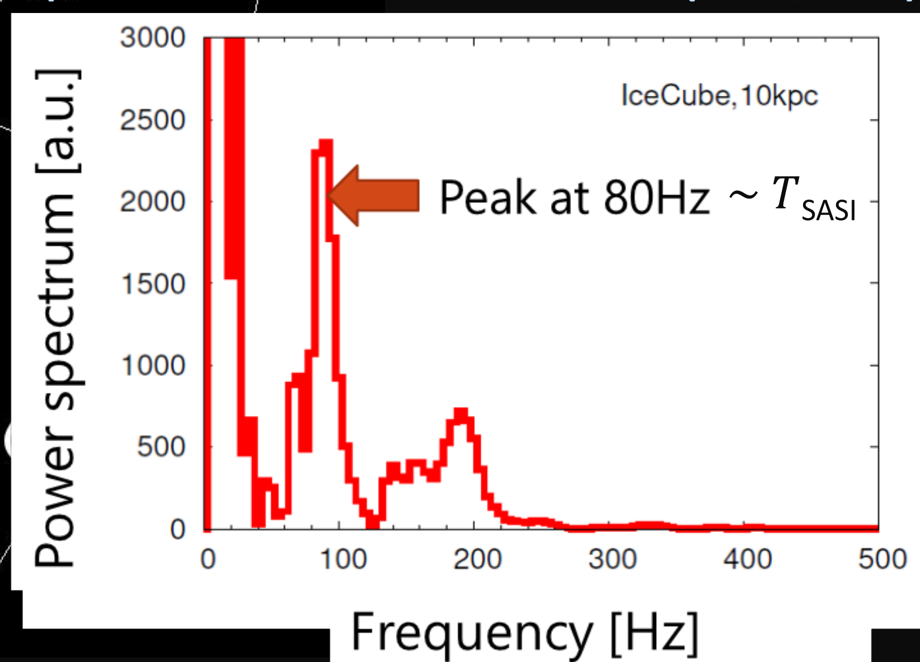


Takiwaki, KK, Foglizzo (2021)

Angular resolution~1deg.



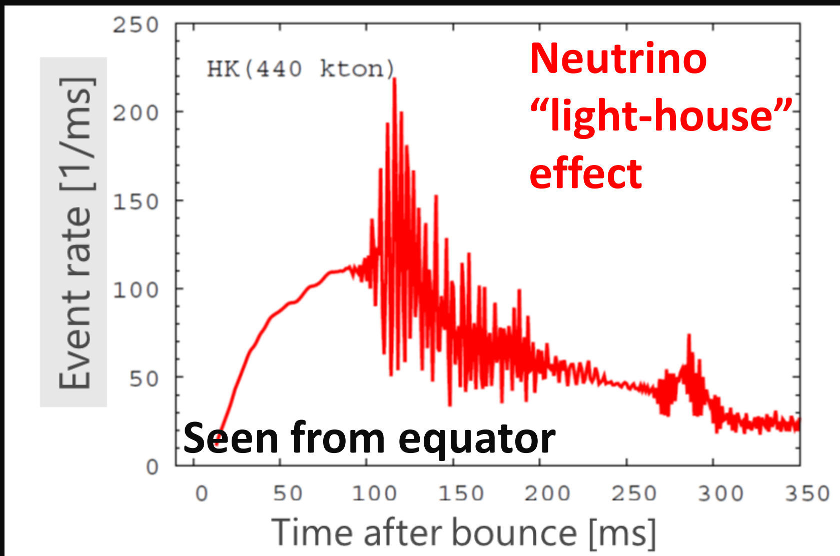
(consistent with Tamborra et al. (2013,2014))

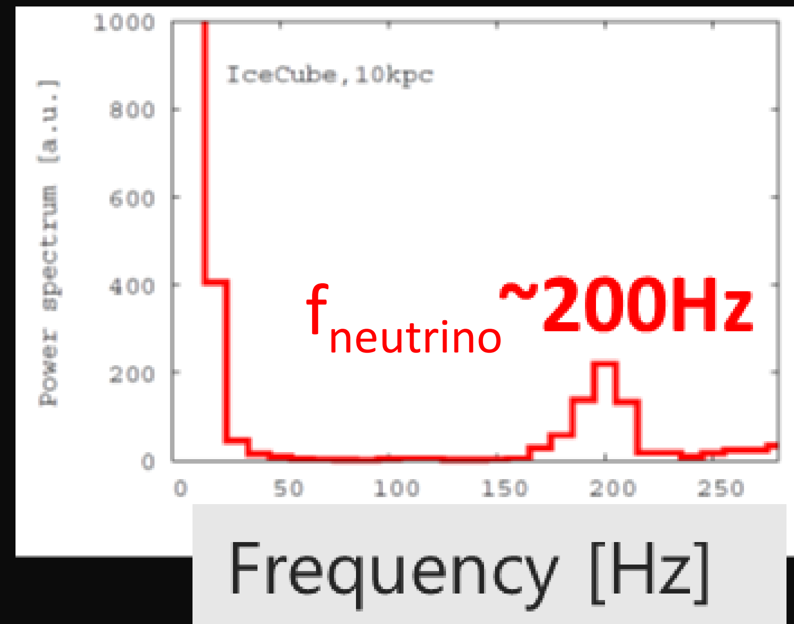


Correlation of ν and GW signals from a rapidly rotating 3D model

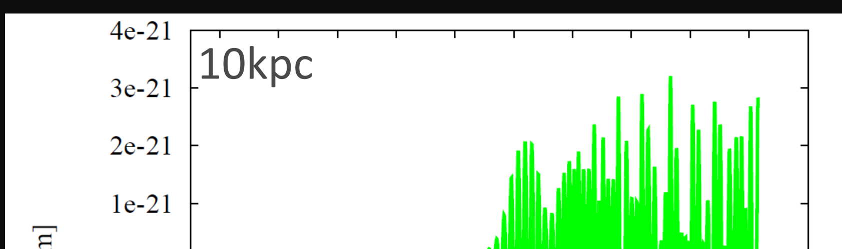
Takiwaki, KK, Foglizzo, (2021)

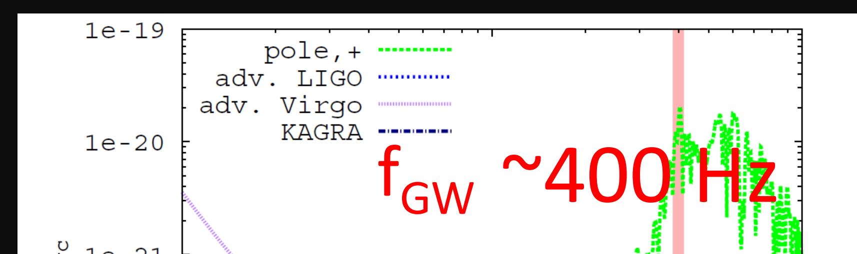
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform





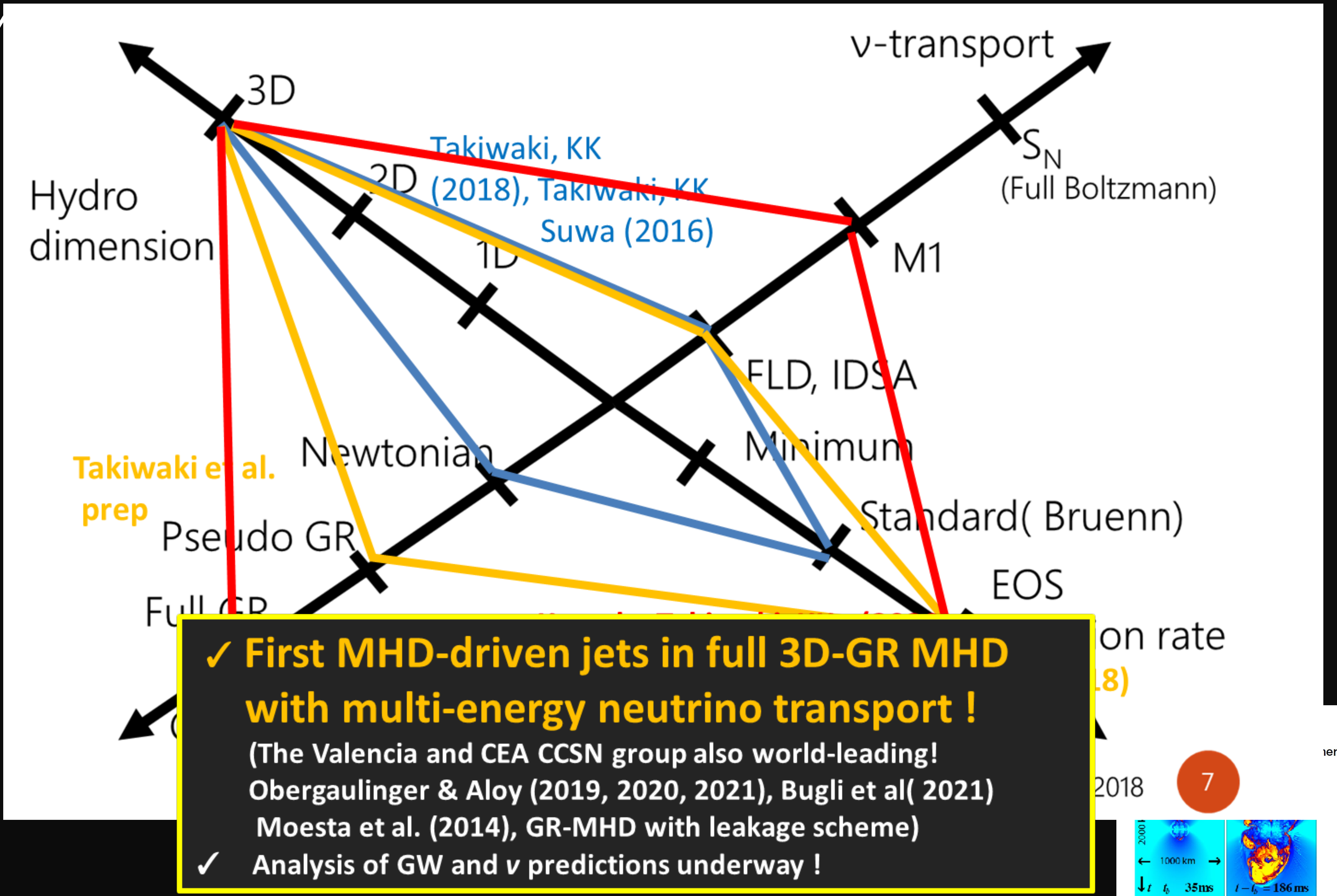
✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)

✓ 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 !

3D-MHD Numerical relativity (GR) simulatin for a 20 solar-mass star

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



✓ **First MHD-driven jets in full 3D-GR MHD with multi-energy neutrino transport !**

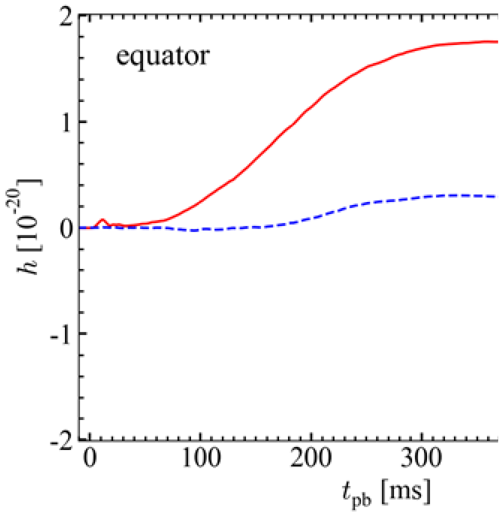
(The Valencia and CEA CCSN group also world-leading!
Obergaulinger & Aloy (2019, 2020, 2021), Bugli et al(2021)
Moesta et al. (2014), GR-MHD with leakage scheme)

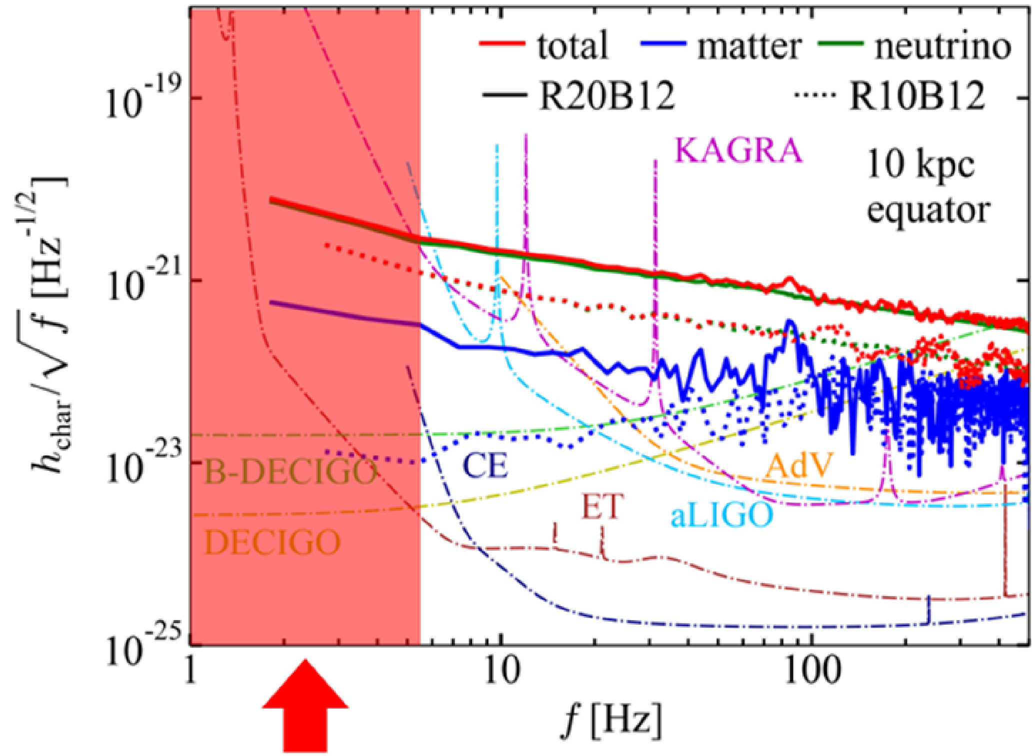
✓ Analysis of GW and ν predictions underway !

Preliminary results on 3D-GR MHD for a 20 M_{sun} star: 10B explosion

Shibagaki, Kuroda, KK, Takiwaki, in prep

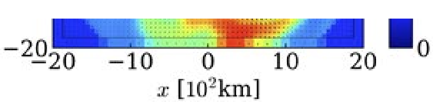
GW Spectr





on the

✓ Both of the M
contribute to
(due to the Ch

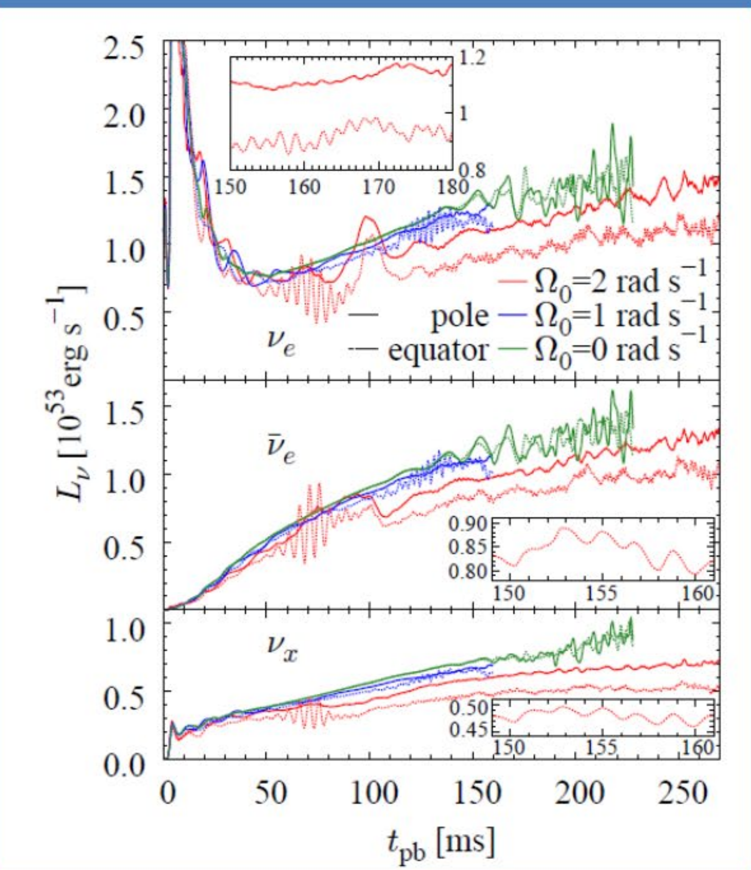


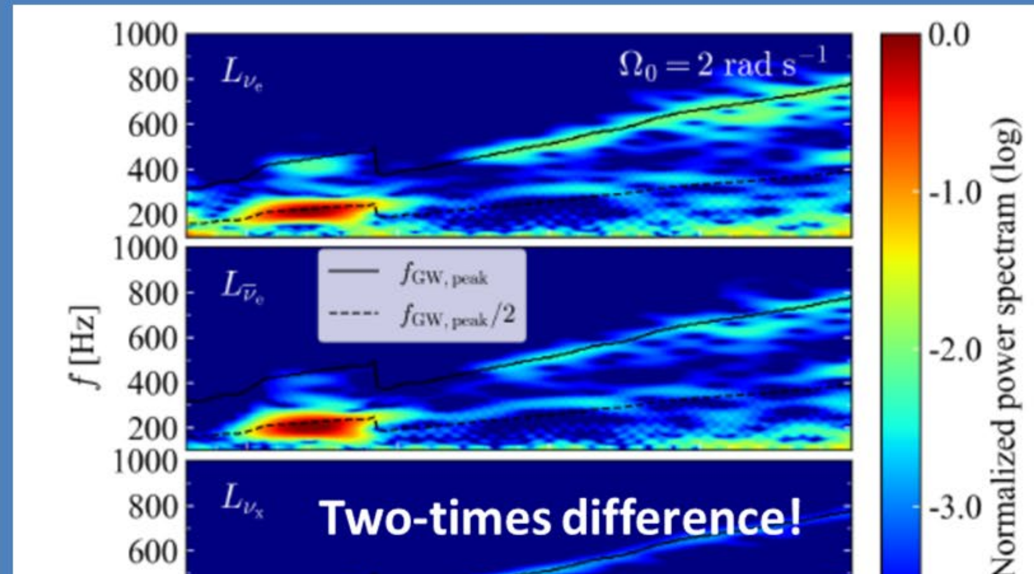
✓ At low frequencies, the neutrino GW dominates over the jet-driven matter GW.

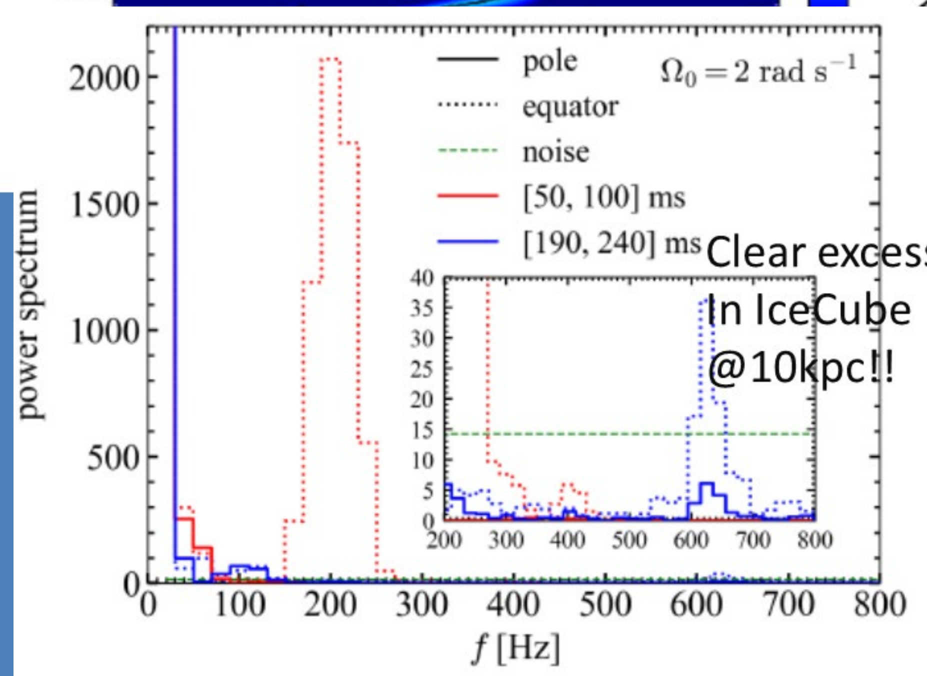
✓ For the detection, DECIGO; important role ! ("DEC"iherz "I"nterferometic "G"rav. "O"bs. Seto et al. PRL (2001)), which I first pointed out in Kotake et al. (2007) ApJ !

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

Summary of neutrino properties:







Started from wrong? Multi-D stellar evolution possible !

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

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

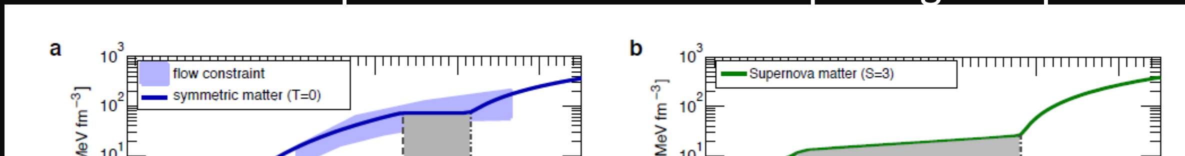
$25M_{sun}$ star
Si-O burning

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

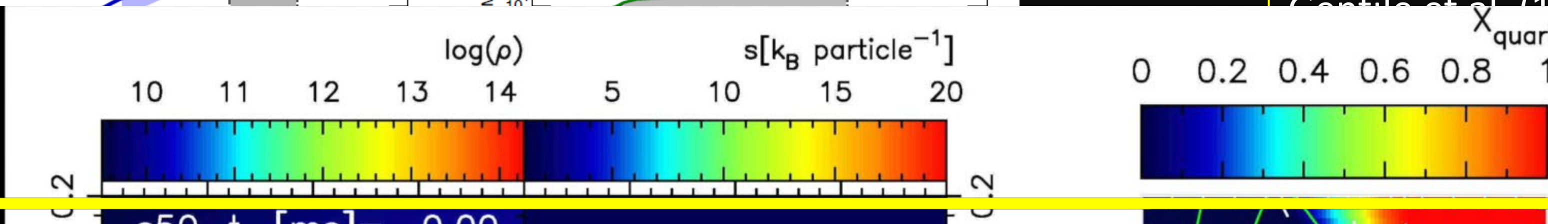
Inclusion of B-fields in the multi-D progenitor modeling very urgent !

Caveat2. QCD phase transition could power explosion !!

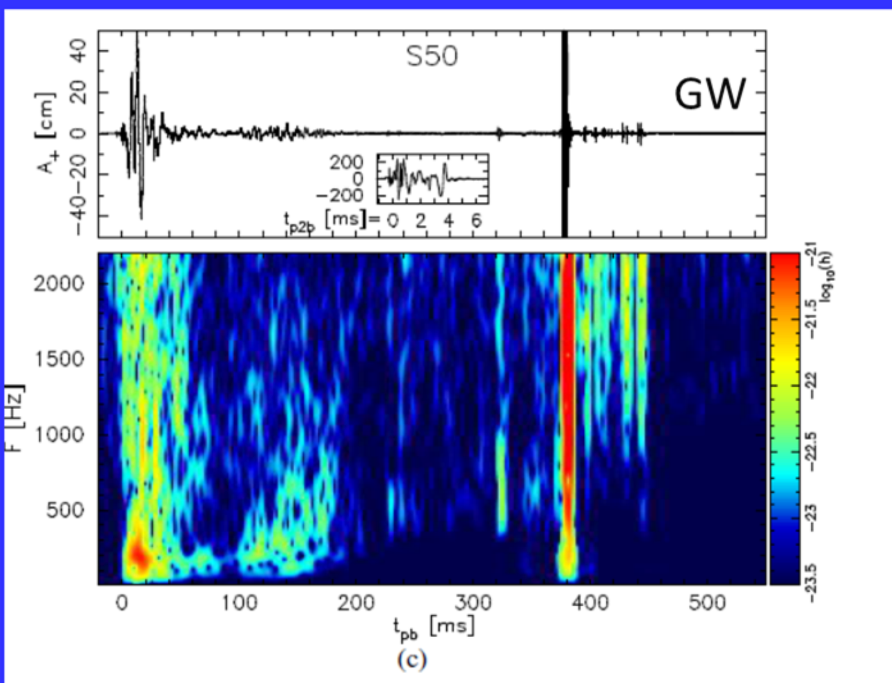
If “first-order” phase transition to the quark-gluon phase takes place… then

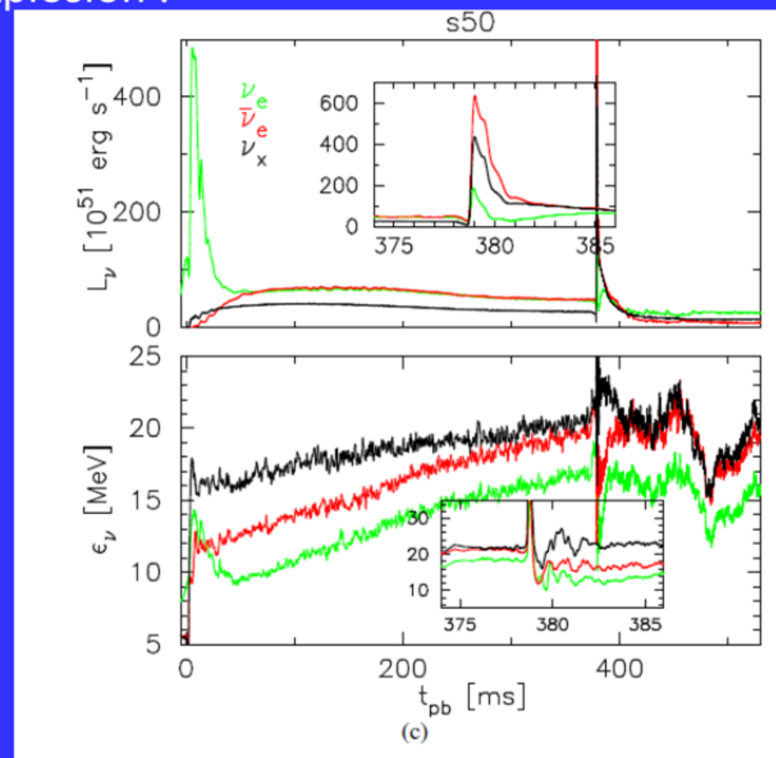


✓Original idea:
Takahara & Sato (1988)



Distinct second burst signals in GW and neutrinos:
a smoking gun of the phase-transion induced explosion !
(Kuroda, Fischer, Takiwaki, KK, ApJ, 2021)



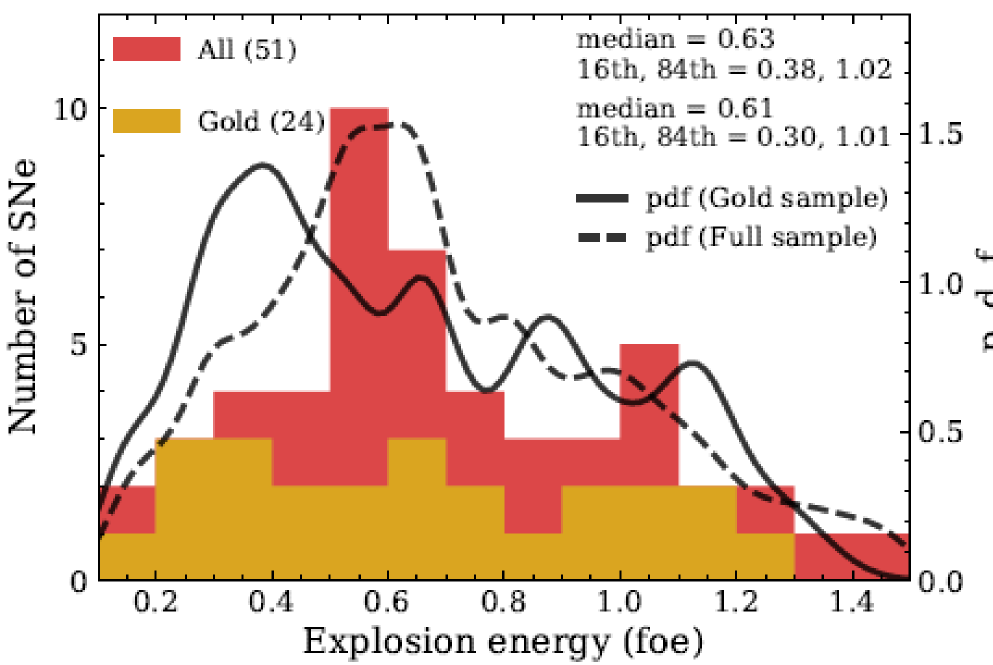


Type II supernovae from the Carnegie Supernova Project-I

II. Physical parameter distributions from hydrodynamical modelling

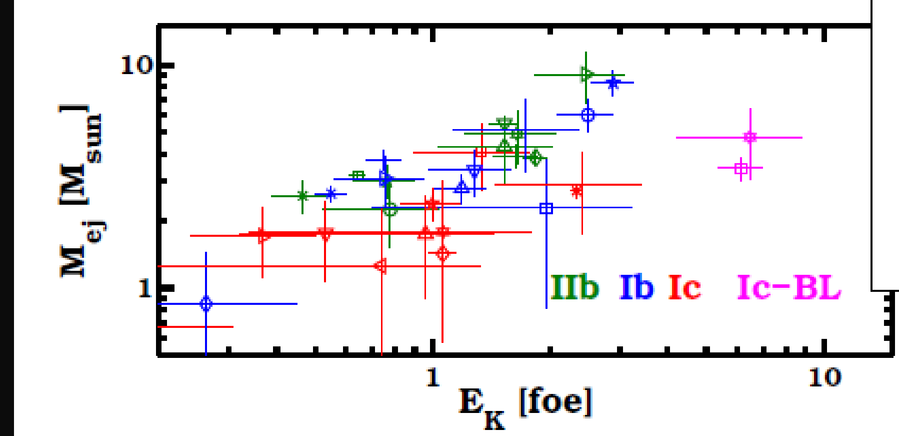
L. Martinez[1,2,3], M. C. Bersten[1,2,4], J. P. Anderson[5], M. Hamuy[6,7], S. González-Gaitán[8], F. Förster[9,10,11,12], M. Orellana[3,13], M. Stritzinger[14], M. M. Phillips[15], C. P. Gutiérrez[16,17], C. Burns[18], C. Contreras[15], T. de Jaeger[19,20], K. Ertini[1,2], G. Folatelli[1,2,4], L. Galbany[21], P. Hoeflich[22], E. Y. Hsiao[22], N. Morrell[15], P. J. Pessi[2,5], and N. B. Suntzeff[23]

A & A (2022)



F. Taddia et al.: CSP-I SE SN light-curve analysis

A&A 609, A136 (2018)



✓Ib/Ic observations, exceeding 1 foe(B) needs MHD modeling!

✓ Problems solved? MHD models close to success Hypernova (10 B)!

→Obergaulinger+(2022), Shibagaki+ (in prep)

My take: Problems solved ?!!

✓The diagnostic explosion energy from your "high-fidelity" 3D models in the range !

3D CCSN modeling on the verge of success!

☆ ν/GW signal predictions from 3D MHD supernova modeling (almost success!) are in steadily progress:

✓ Time modulation of ν and GW provides the smoking gun of the supernova engine ! (e.g., SASI-modulation, rotation leads to the "frequency doubling" between ν and GW signals)

✓ Fast-flavor conversion a new challenge ! could/could not help explosion

✓ Upgrade of ν and GW detector (Hyper-K, Dune, JUNO,KAGRA, CE, ET)

✓ Detailed Weak Interactions/ new physics incl. axions, and sterile neutrinos ? (see work by Mori+(2022), Lucente+(2021))

✓ Multi-D MHD progenitor modeling and observation (binary evolution) (Mueller & Varma (2023), Smarrt (2022))

☆Signal prediction from Hypernovae!!
3D-MHD modeling of BH/accretion-disk
(:3D-GR MHD code with neutrino transport)
Needed to understand long-duration GRBs pair-instabiility supernova, SL-Sne, from first principles !
(See, N. Rahman et al. (2022)
Oliver Just et al. though in different context)