Neutrino and gravitational-wave predictions in the "pre-" to "post"-collapse phases of massive stars from 3D "MHD" CCSN modeling

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with
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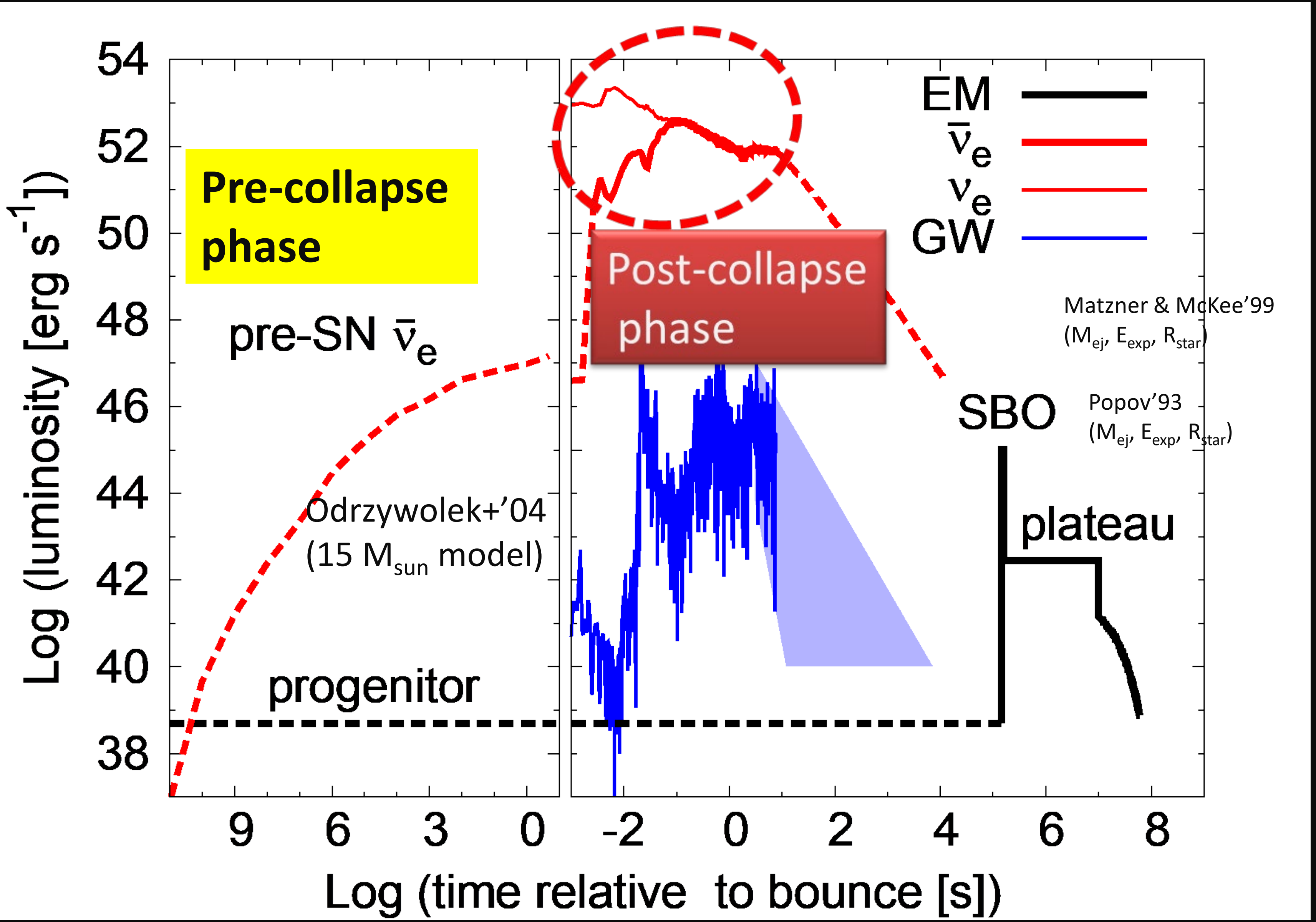
May 30th @SNvD2023, Gran Sasso, LNGS, 2023

Recap of "CCSN Multi-messengers" (exploding 17 M_{sun} star (2D))

Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, KK (MNRAS) 2016

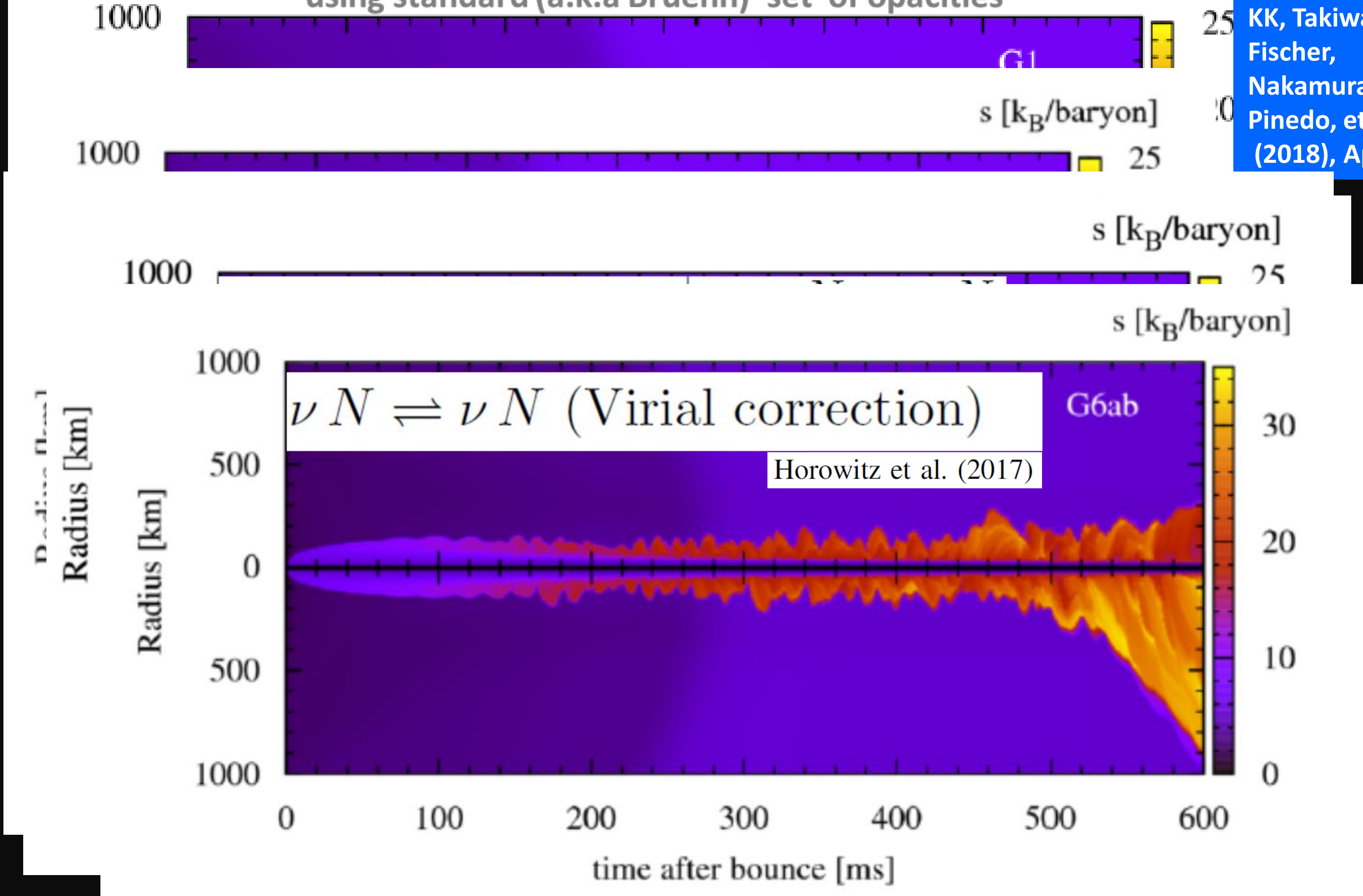
Energetics: $E_{neutrino} \sim 10^{53}$ erg, $E_{kinetic} \sim 10^{51}$ erg, $E_{photon} \sim 10^{49}$ erg, $E_{GW} \sim 10^{46}$ erg



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

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

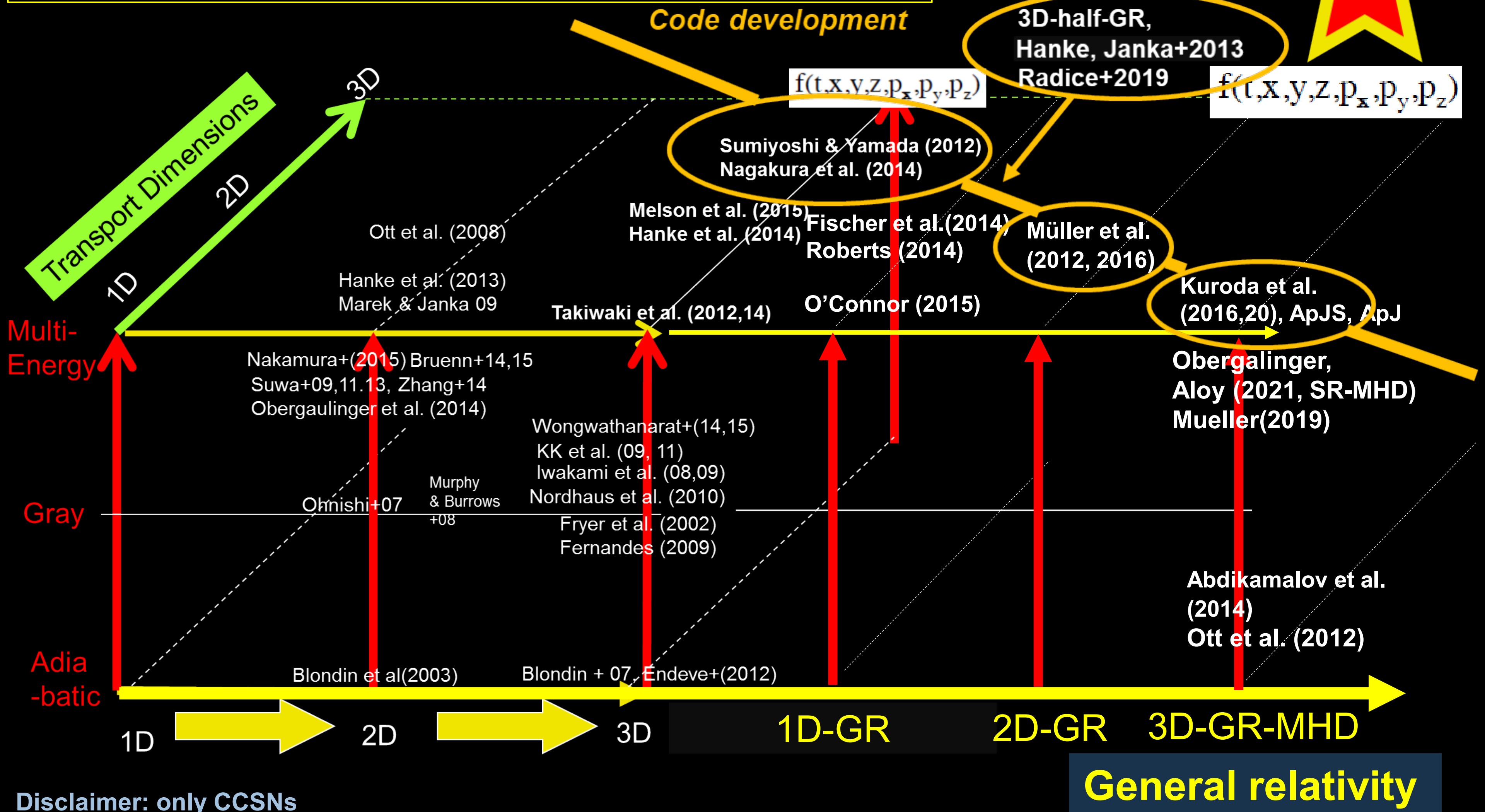
KK, Takiwaki, Fischer, Nakamura, Pinedo, et al. (2018), ApJ



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

WE: All “GRIT”y ! (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 !)

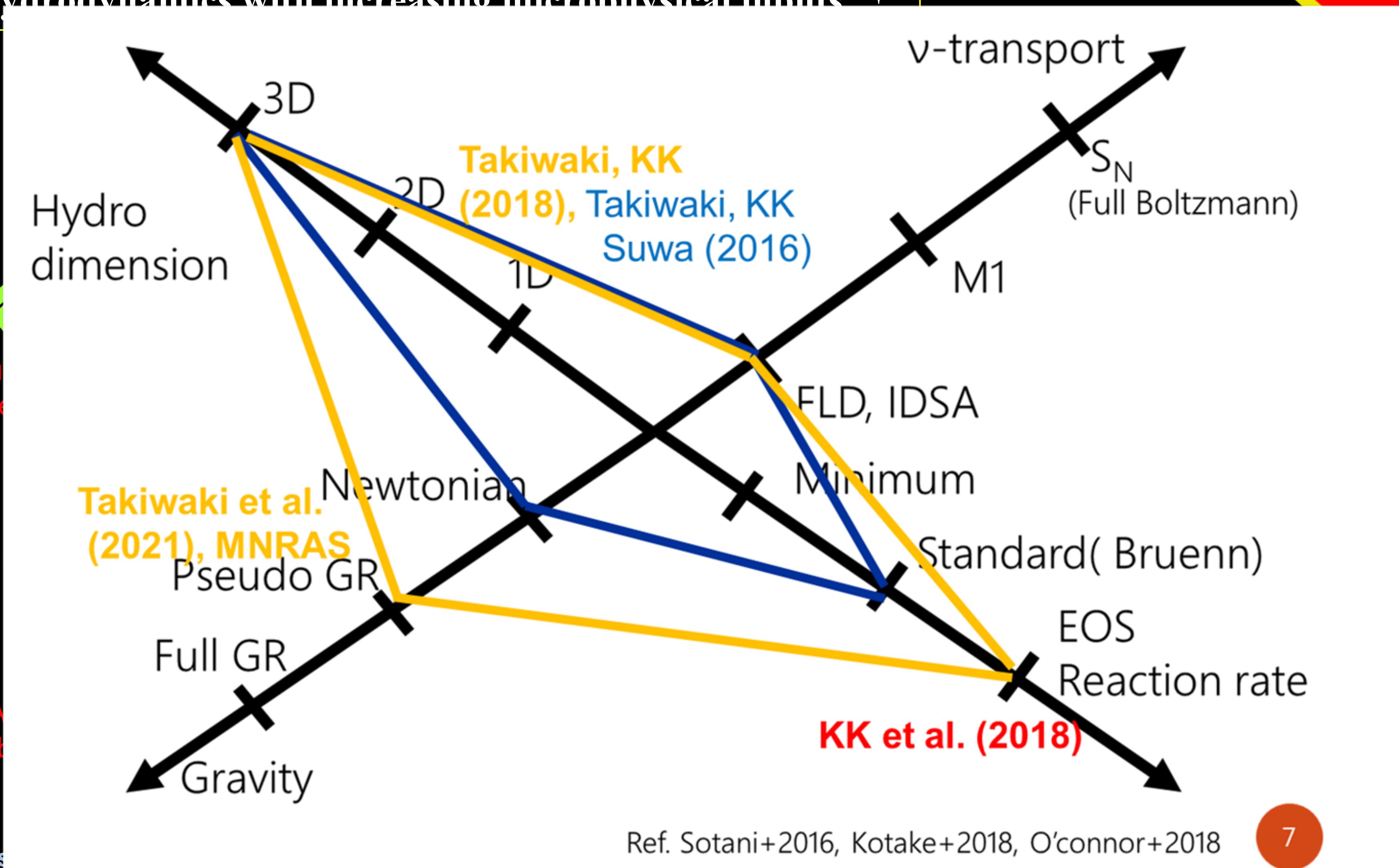
Ultimate goal: 7D Boltzmann transport in full GR MHD hydrodynamics with increasing microphysical inputs !



Disclaimer: only CCSNs

WE: All "GRIT"y ! (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 !)

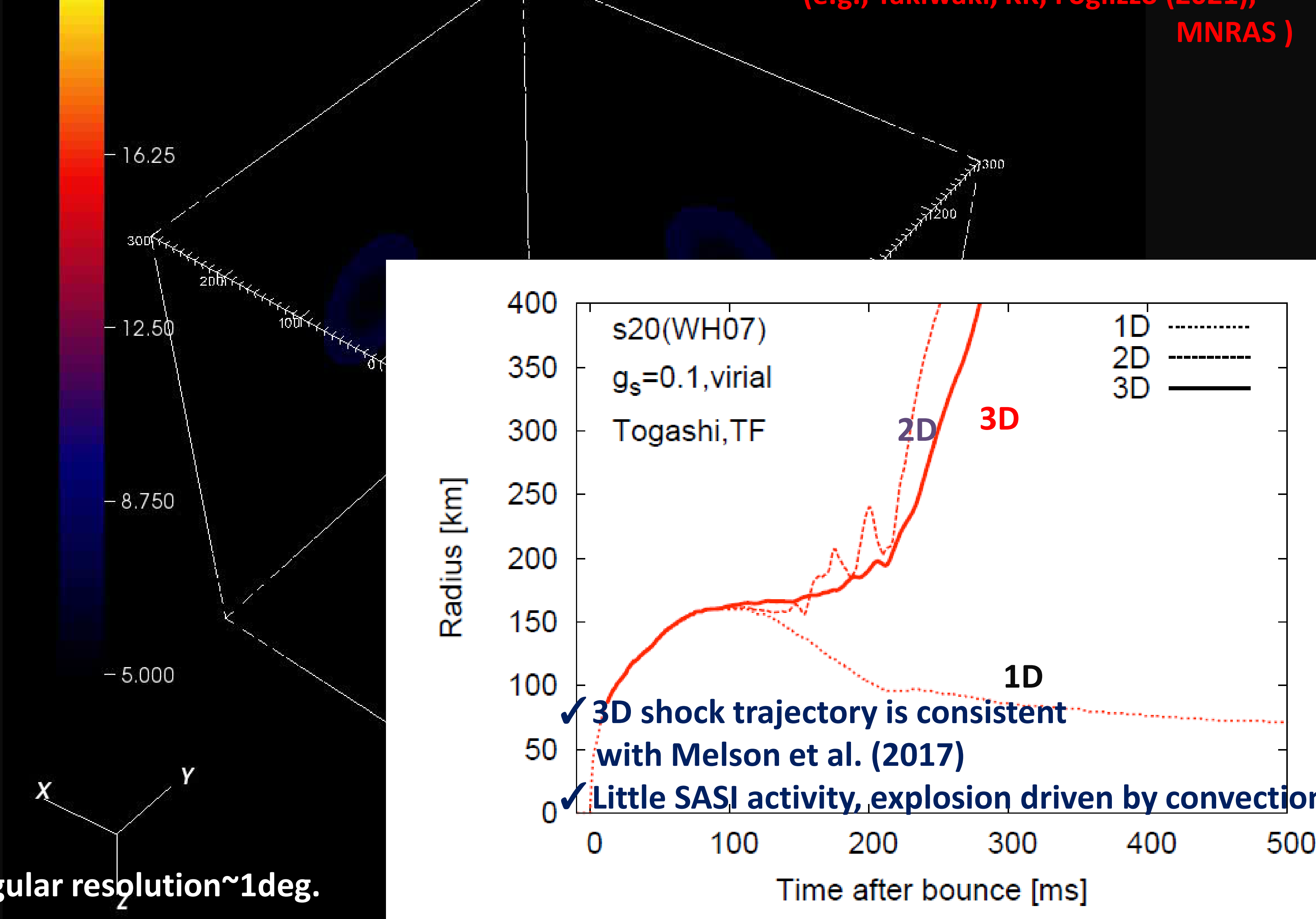
✓ Progress report of **our supernova code**: ***Updated ν reactions in 3D code***



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)

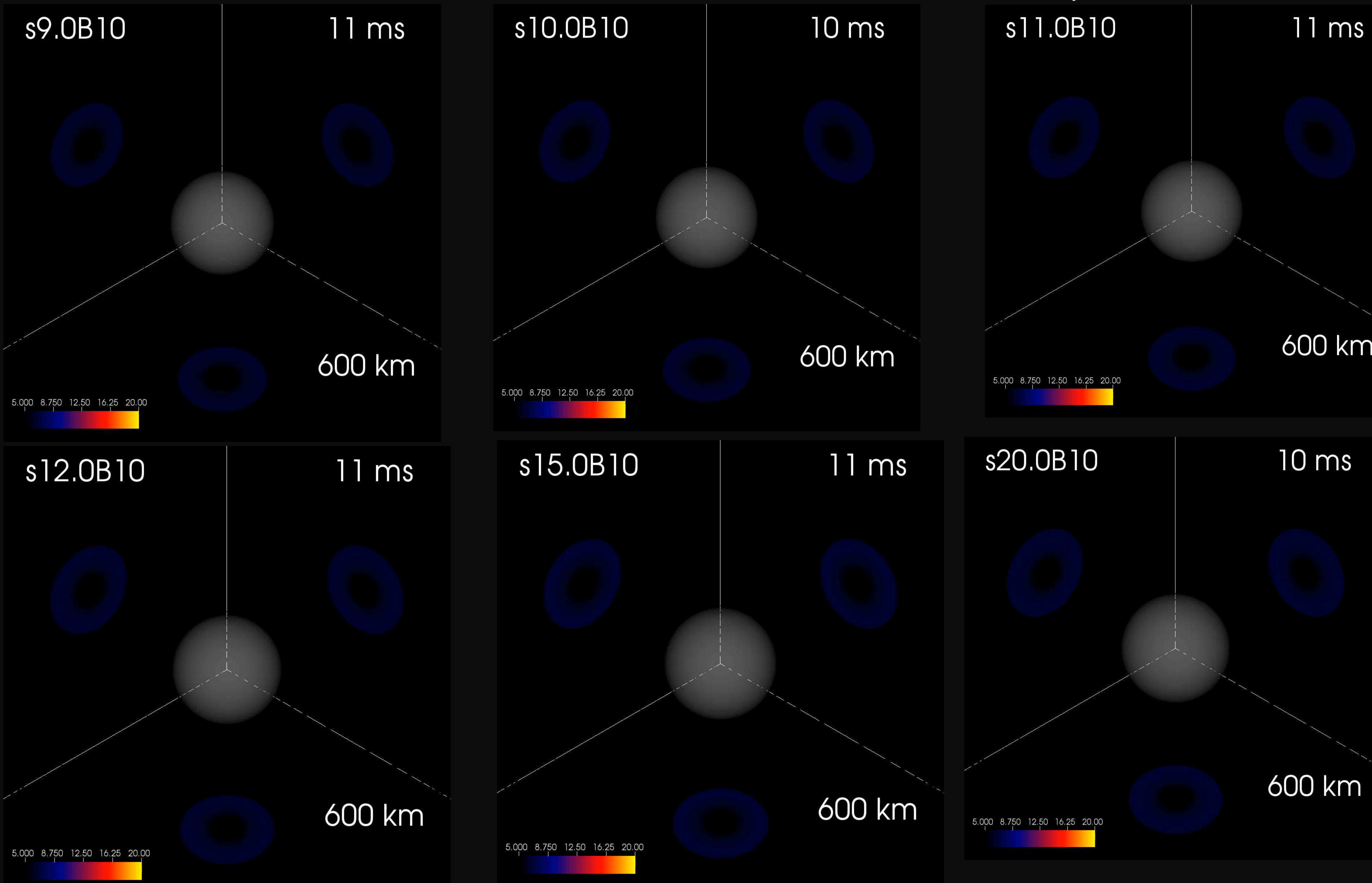
✓ Little SASI activity, explosion driven by convection

Angular resolution~1deg.

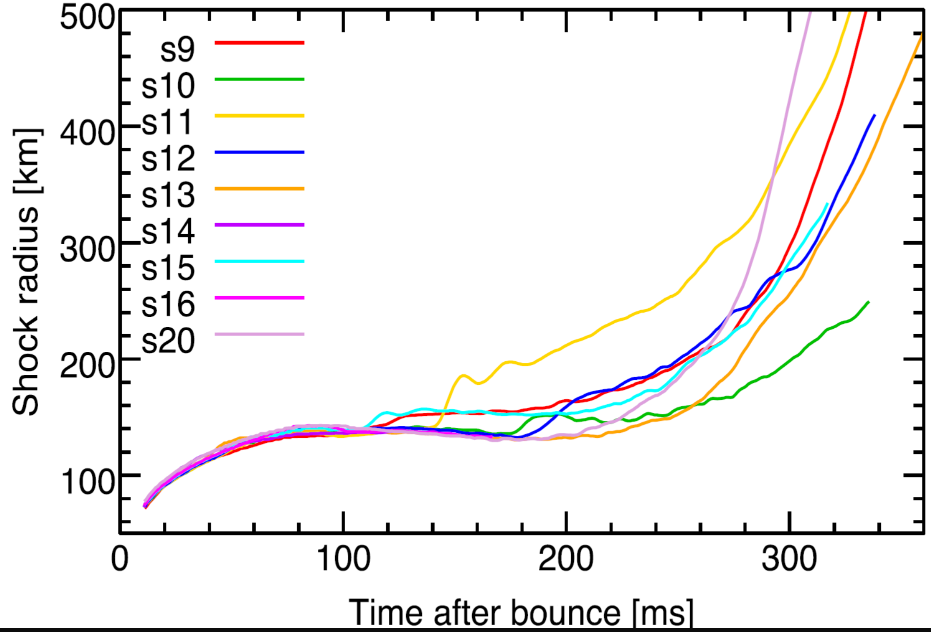
Many more 3D modeling with MHD possible (on ArXiv this Month)

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

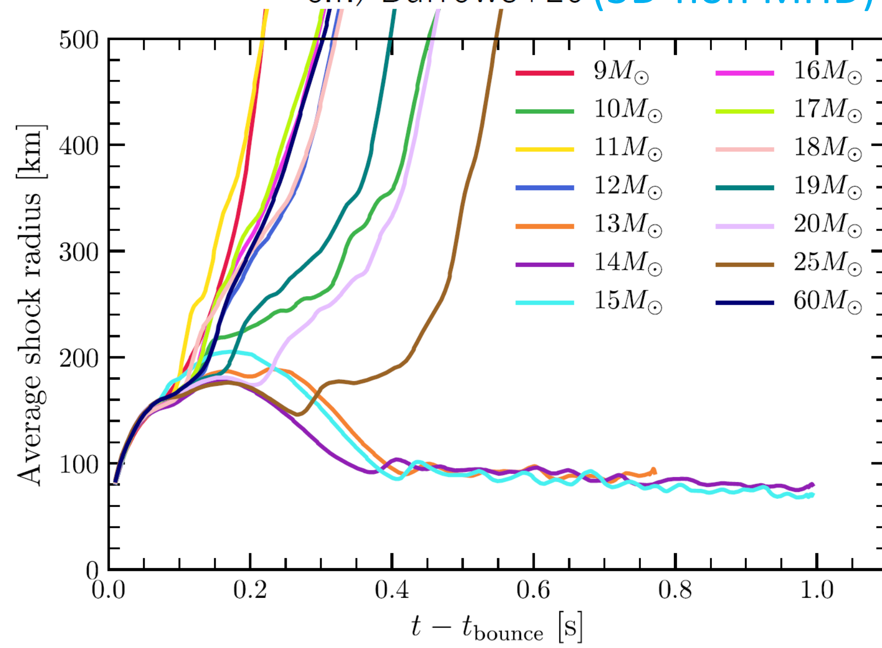
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform)), Non-rotation)



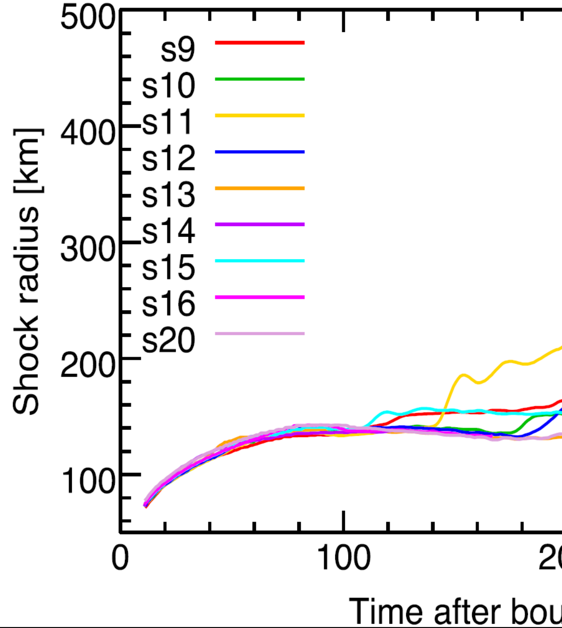
Nakamura, Matsumoto, KK+ in prep (3D-MHD)

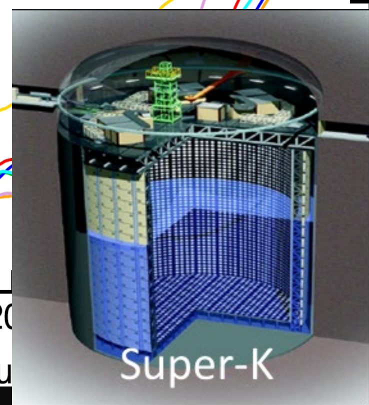


c.f.) Burrows+20 (3D-non MHD)

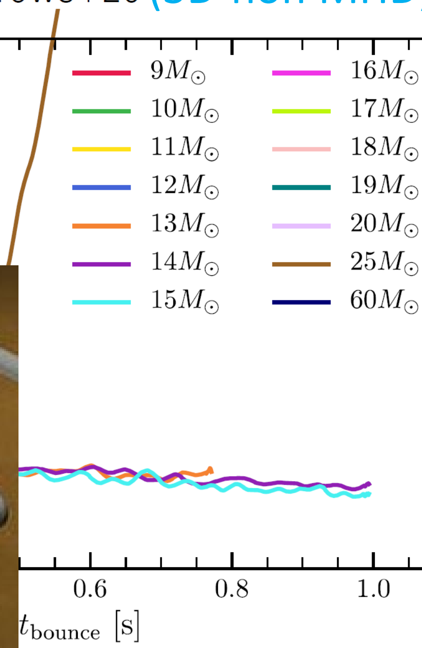


Nakamura, Matsumoto, KK+ in prep (3D-MHD)

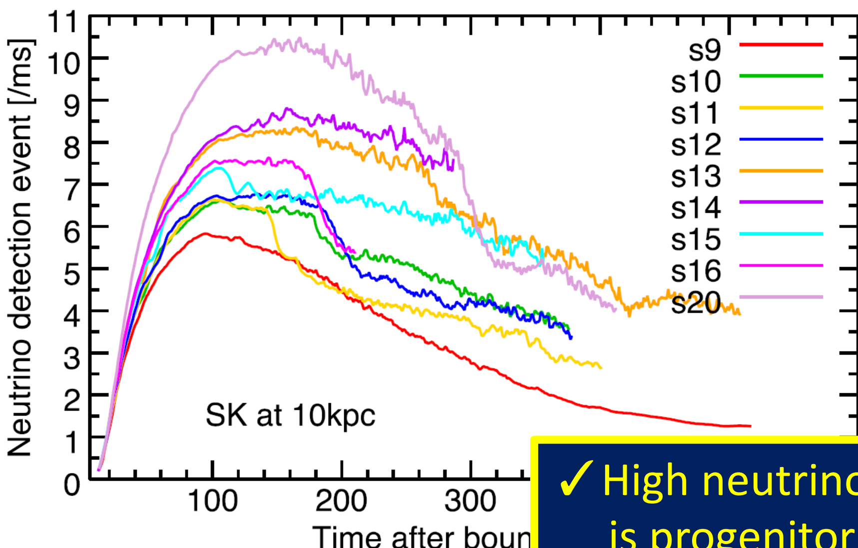


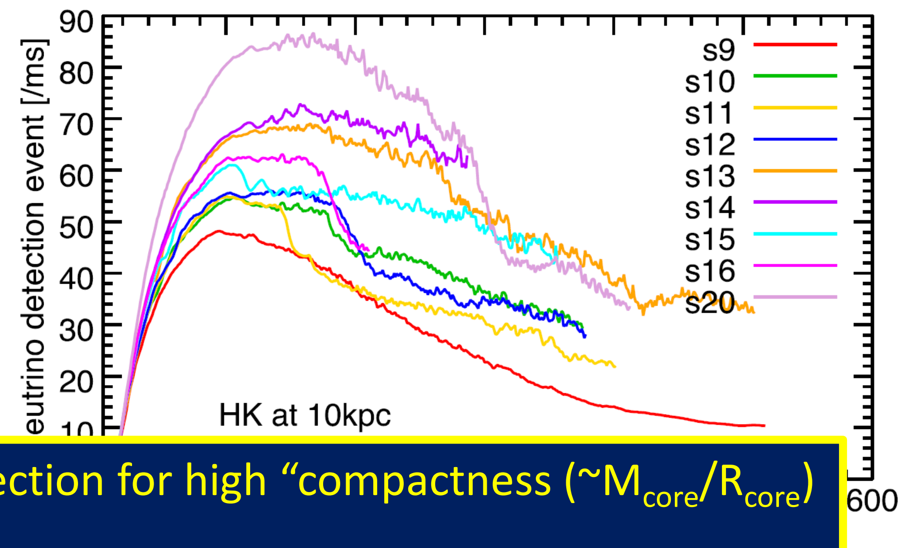


c.f.) Burrows+20 (3D-non MHD)

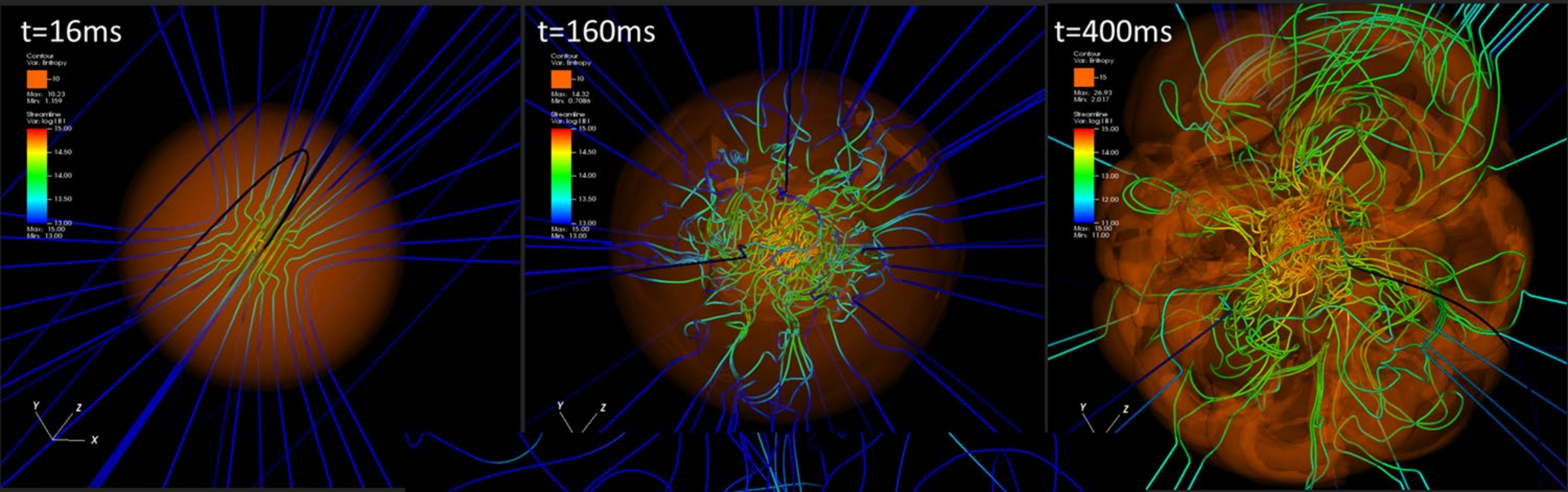


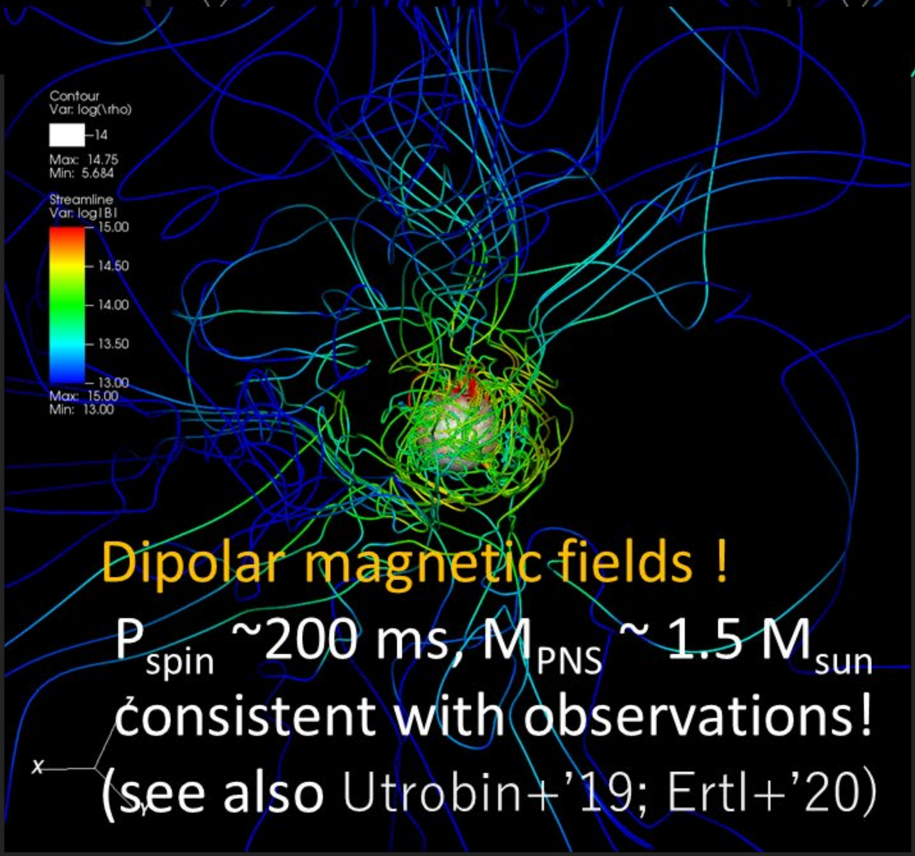
✓Neutrino detection rate at SuperKamokande and HyperKamiokande





✓High neutrino detection for high “compactness (~M_{core}/R_{core}) is progenitor !





✓ 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)

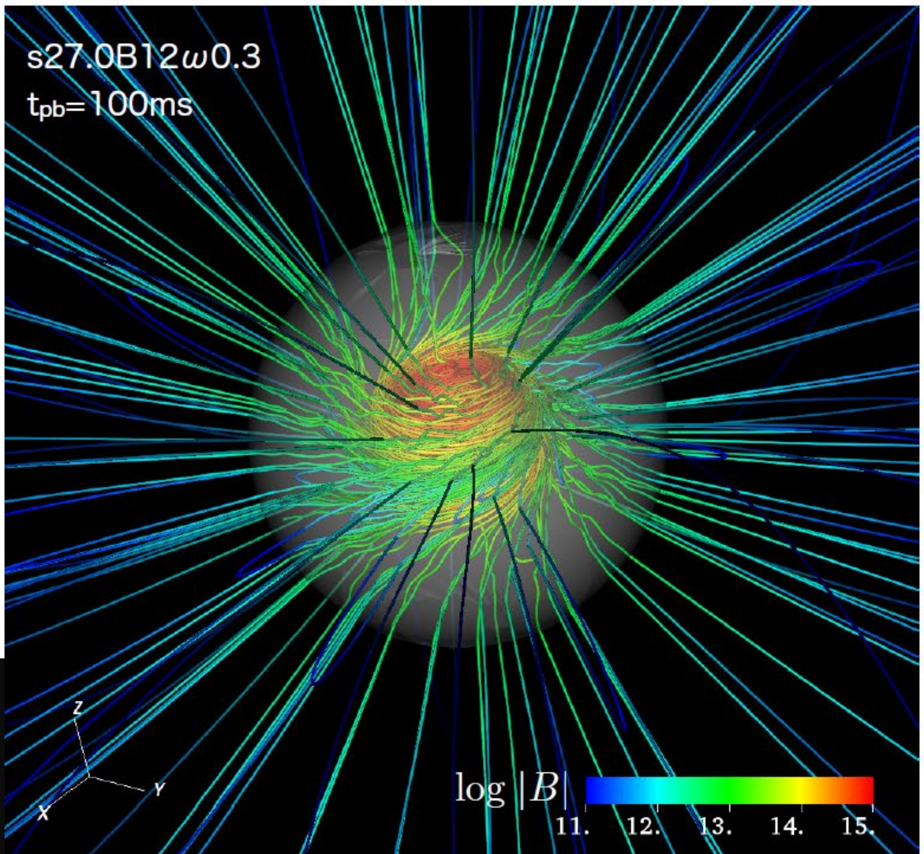
Settings

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

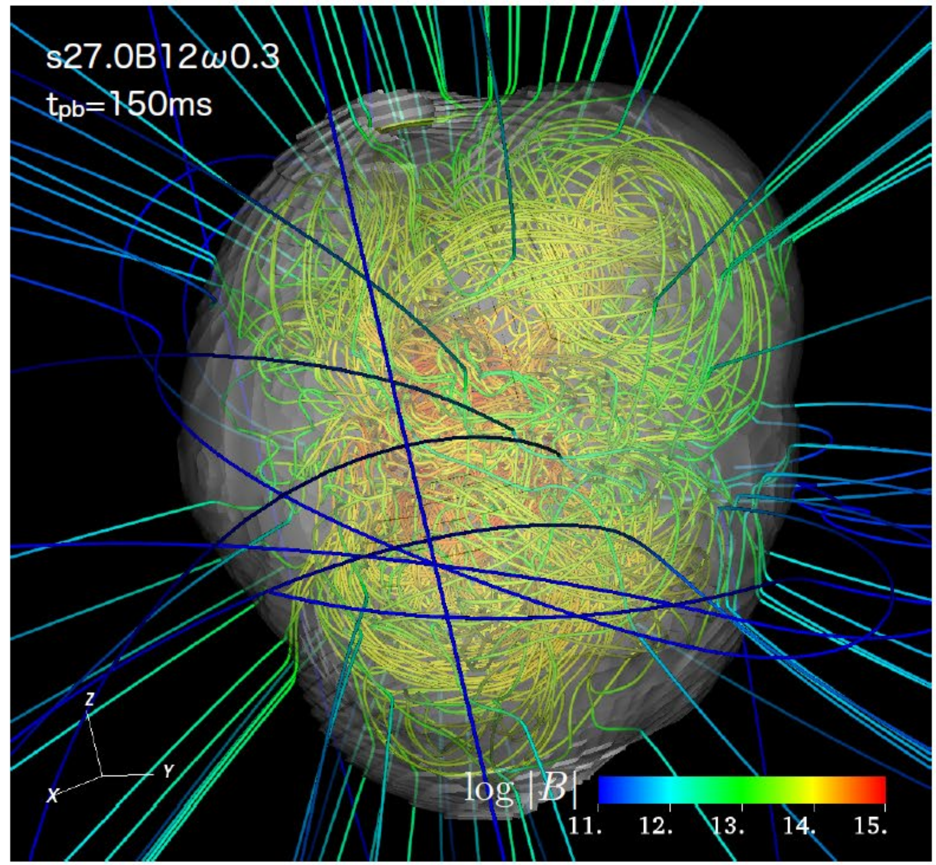
- rigid rotation

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

onset of neutrino-driven convection

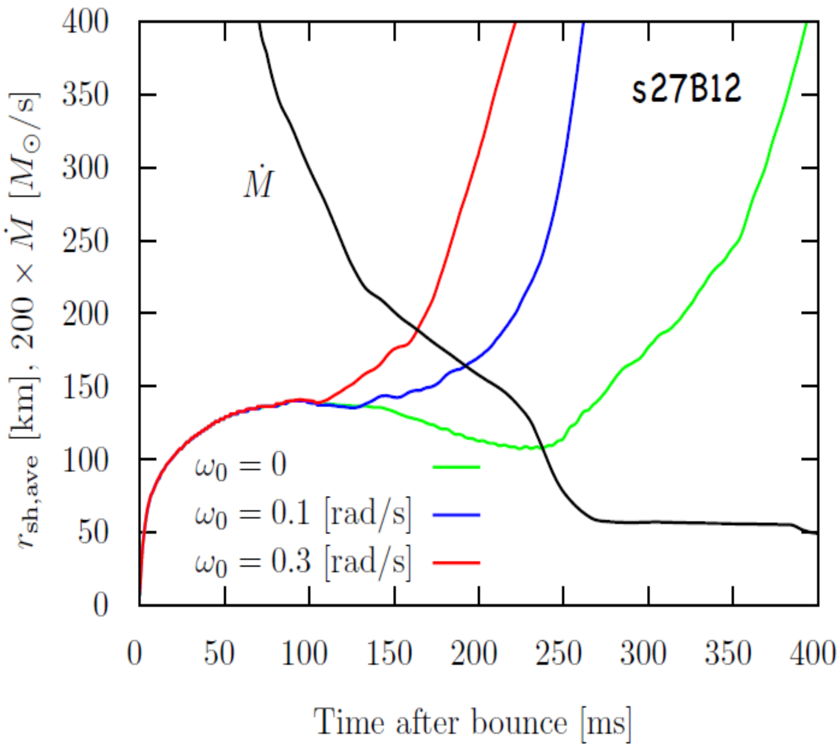


after shock revival



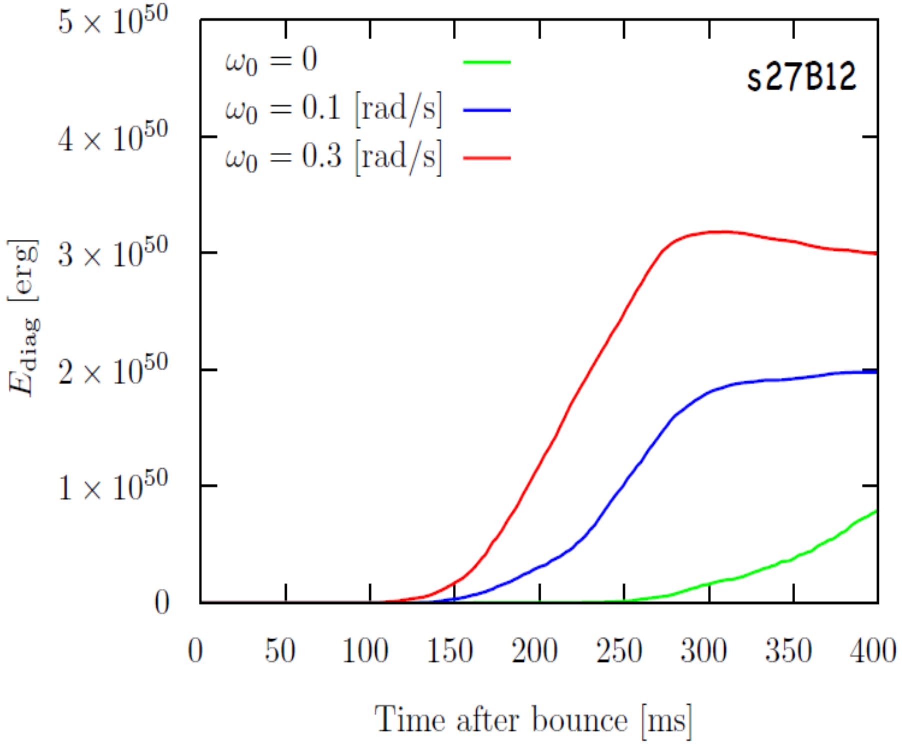
Dependence of the rotation

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



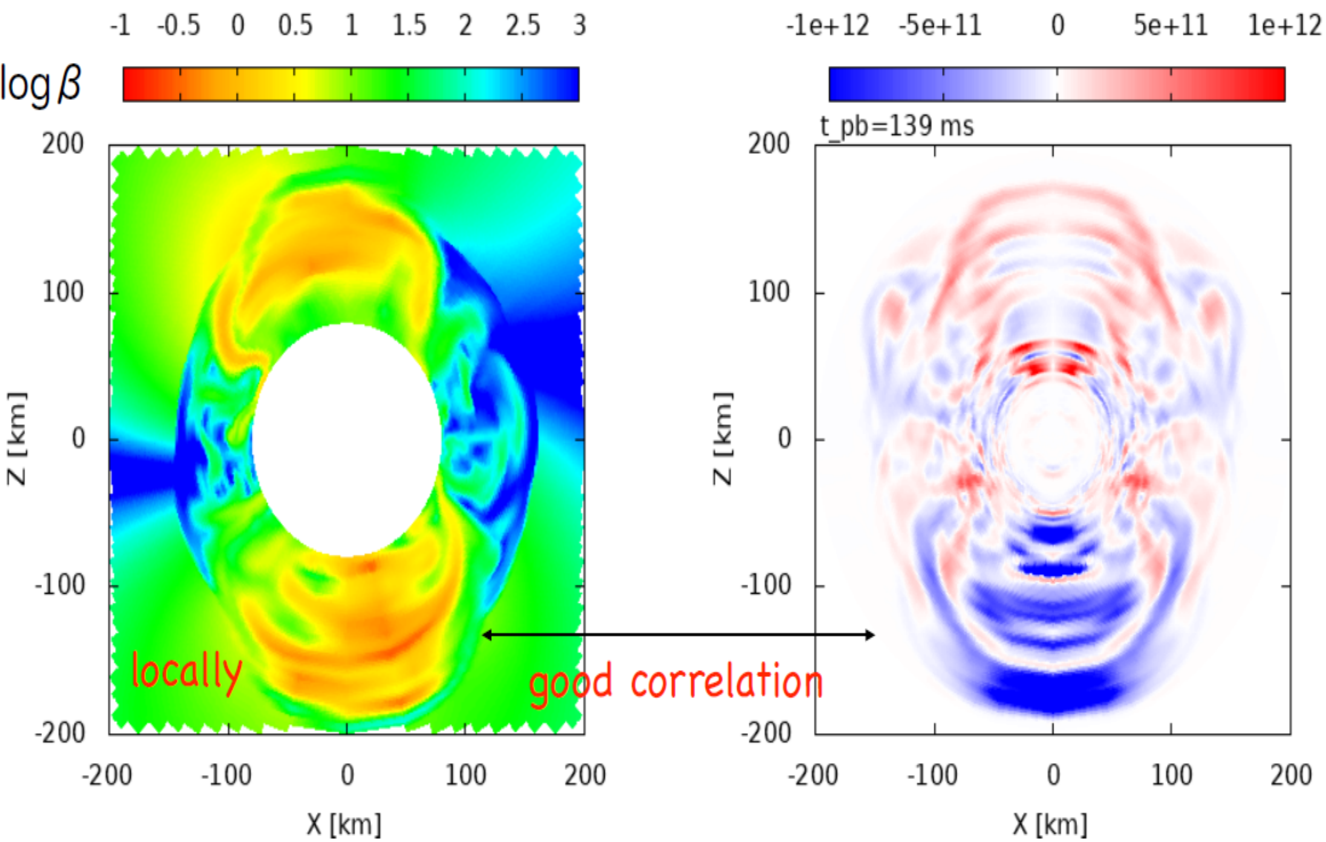
Explosion energy in faster explosion model is larger.

Amplification of the magnetic field

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

kinetic helicity $H_{\rm K} = \langle v' \cdot \omega' \rangle_\phi$

s27.0B12ω0.3



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:

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

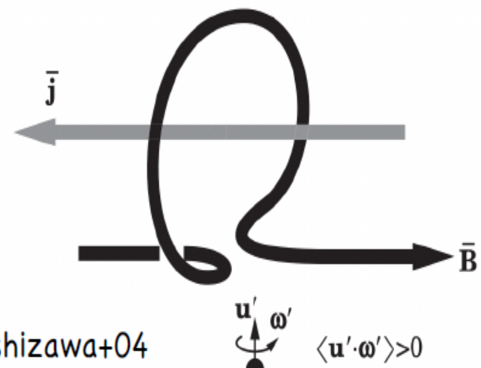
$$\boldsymbol{\epsilon} \equiv \alpha \langle \boldsymbol{B} \rangle - \eta_t \nabla \times \langle \boldsymbol{B} \rangle$$

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

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

Brandenburg+05

α -effect

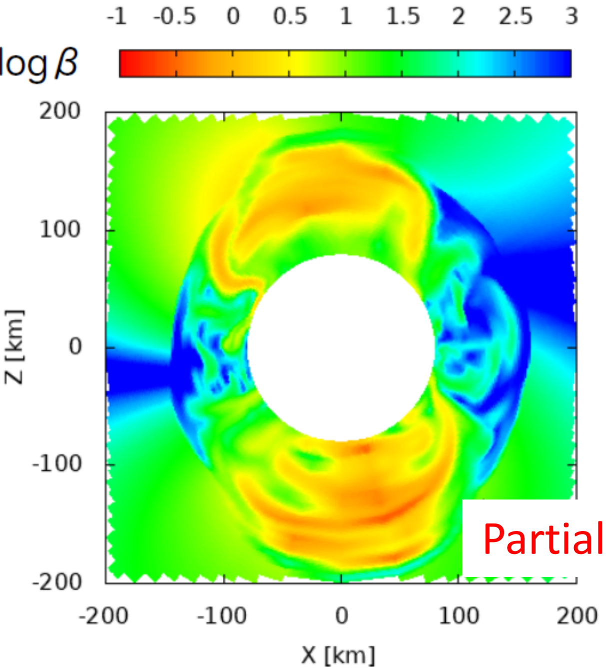


Yoshizawa+04

Amplification of the magnetic field

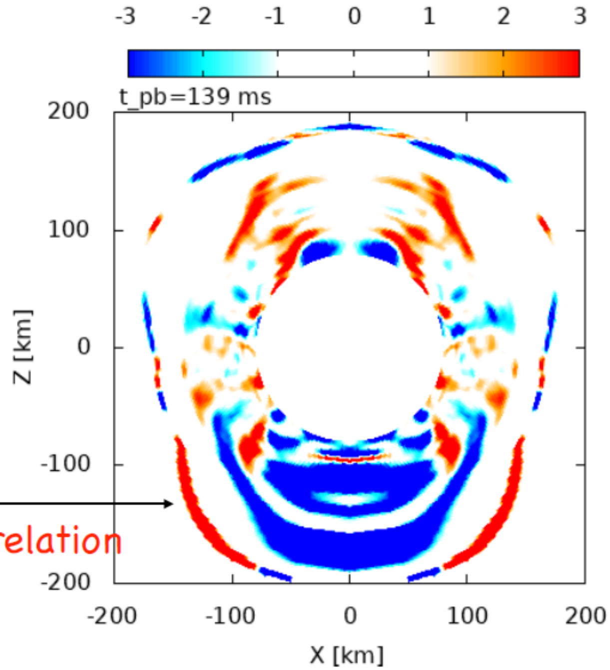
plasma $\beta \equiv P_{\rm gas}/P_{\rm mag}$

s27.0B12ω0.3



Partial correlation

dynamo number in gain region

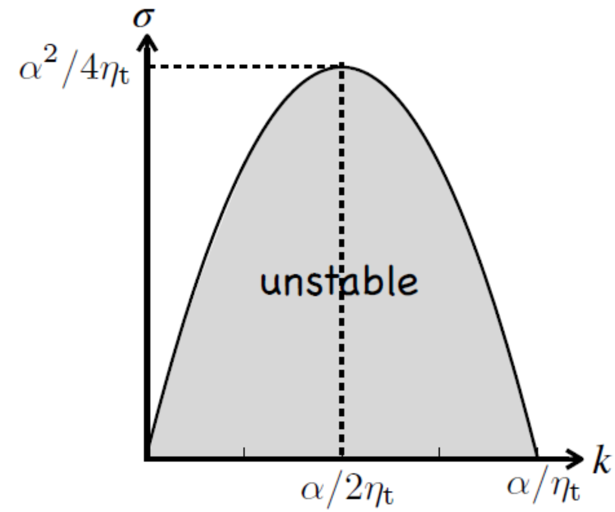


$|D| > 1$

α-dynamo occurs.

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

dispersion relation:



condition for exponential growth: $\alpha/\eta_{\rm t} > k$

$\Rightarrow$ $D \equiv \alpha/k\eta_{\rm t} > 1$

Magnetic pressure driven explosion

Amplification of the magnetic field

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

s27.0B12ω0.3

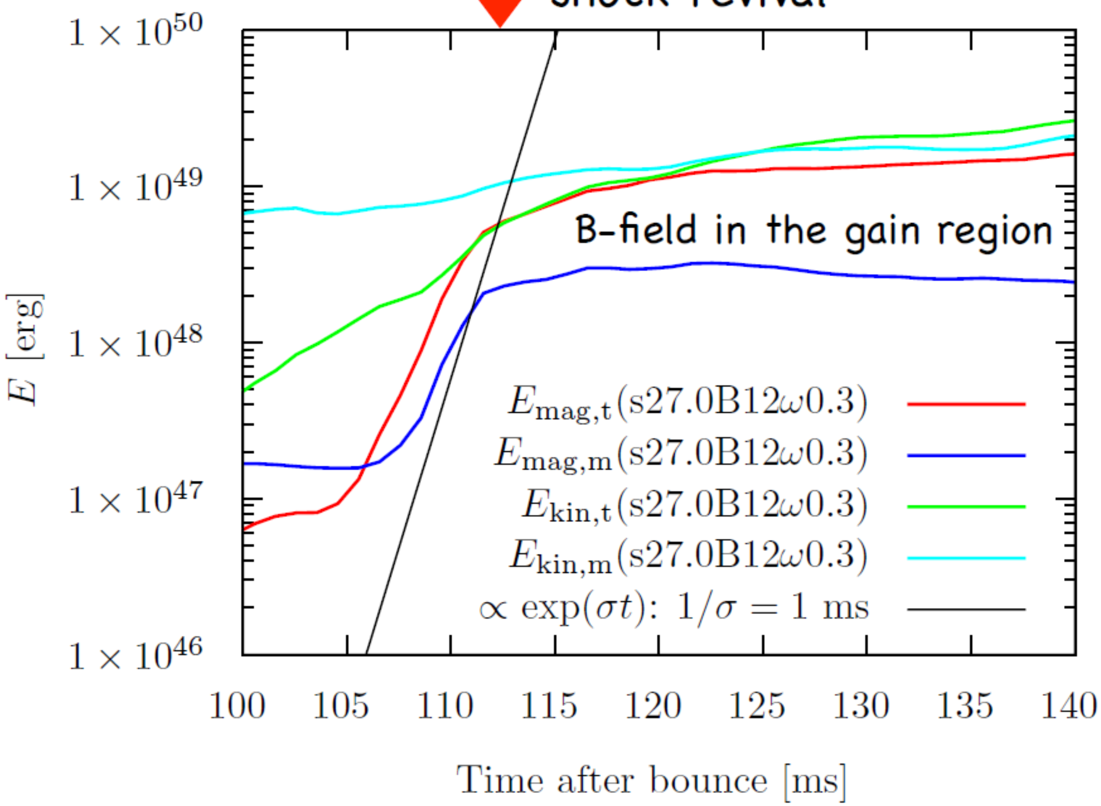
dynamo number in gain region

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

dispersion relation:

σ

shock revival



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:

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

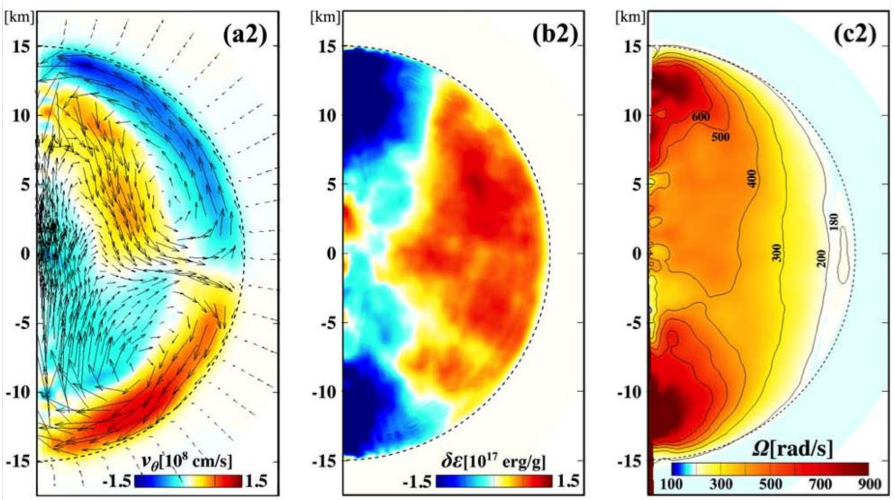
mean magnetic field

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

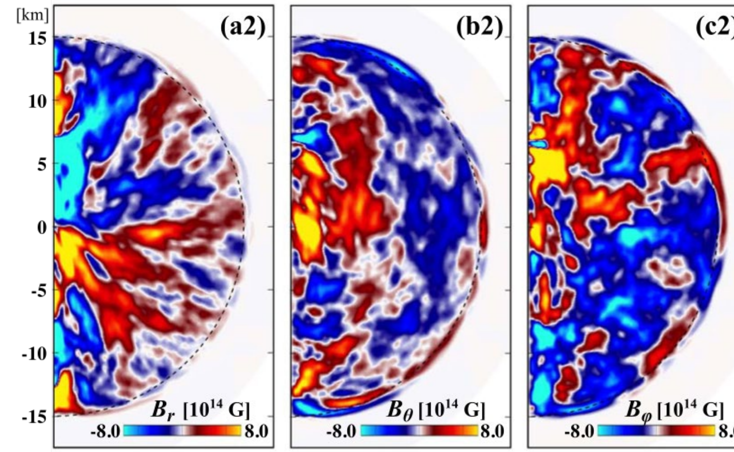
GW Signals from A fully-convective PNS (Masada et al. 2022, ApJ)

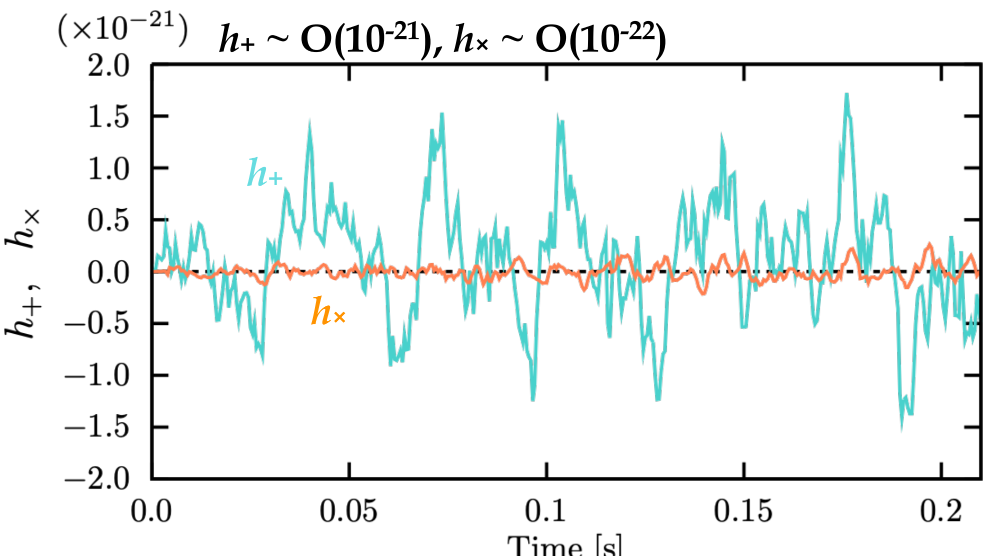
From a fiducial model with Ω_0= 60π (rad/s) imposed at the PNS surface:

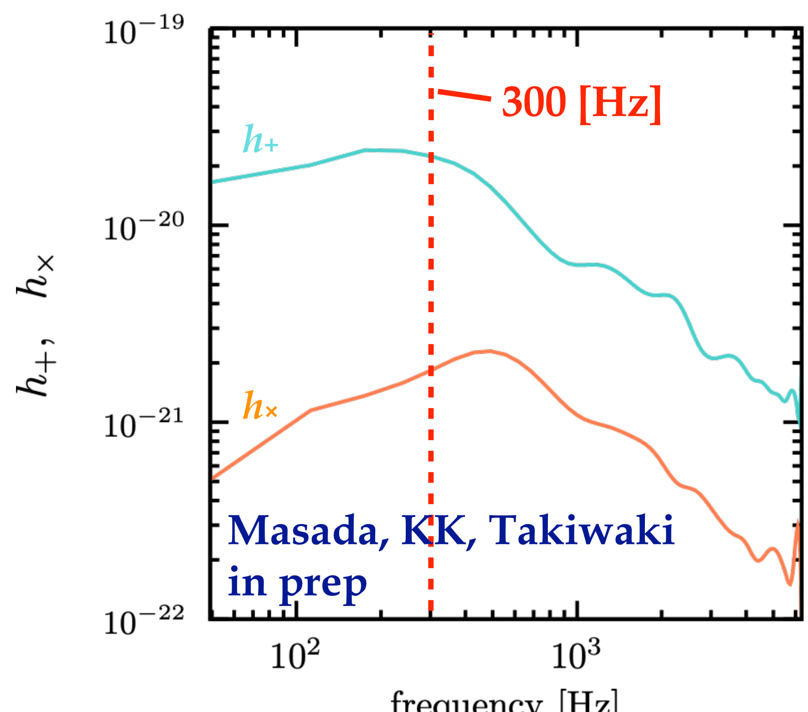
flow field



magnetic field (mean component)



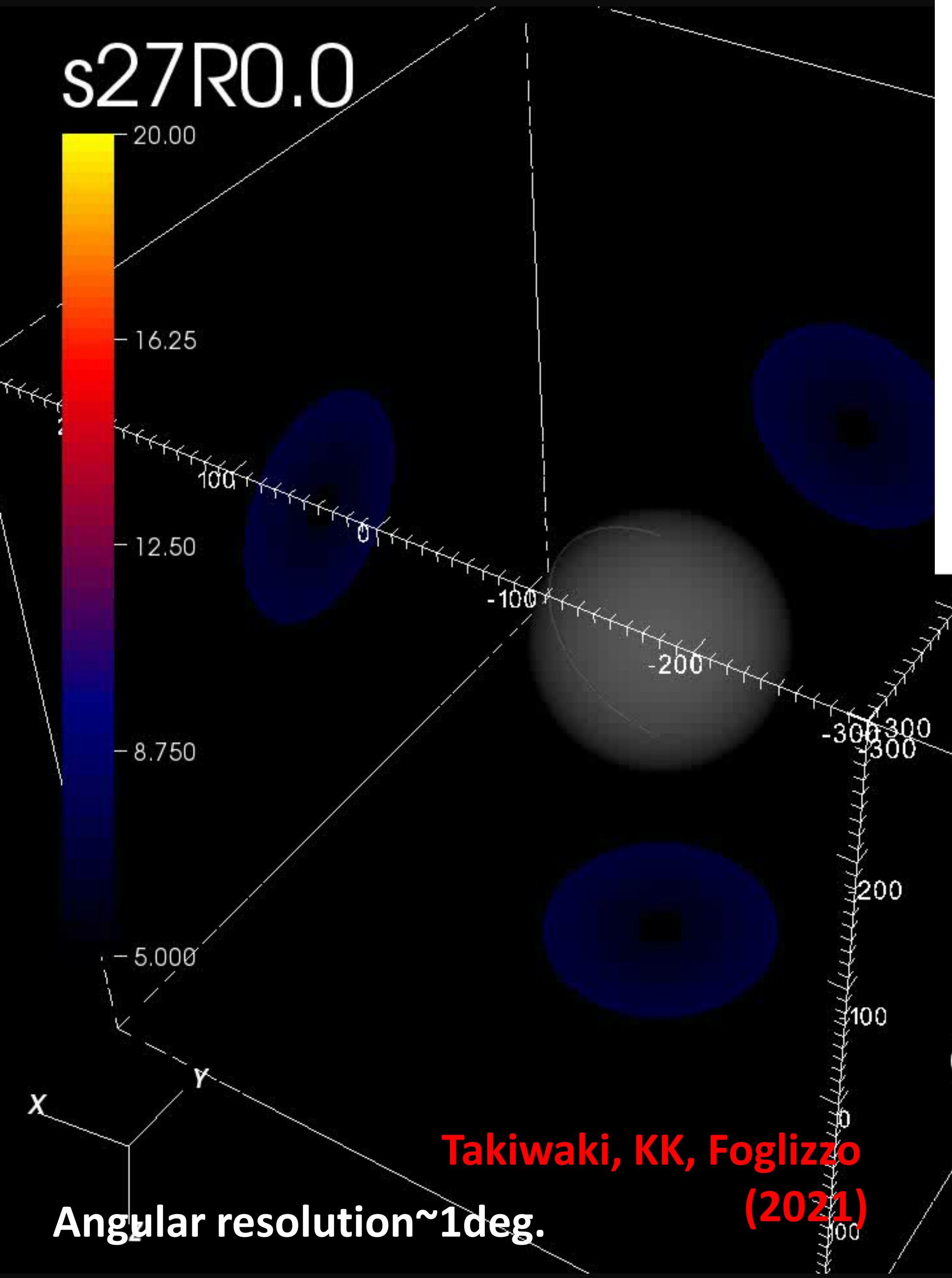


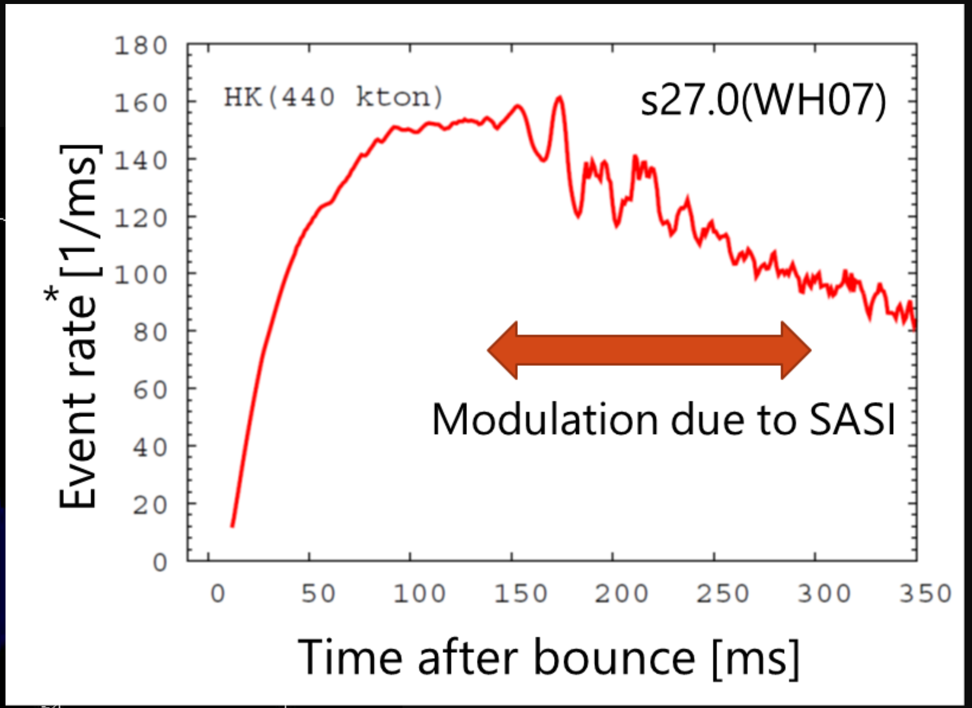


- **convective turn-over time : $\tau \sim 2\times10^{-2}$ [s]**
- **convective frequency : $f = 2\pi/\tau \sim 300$ [Hz] :**

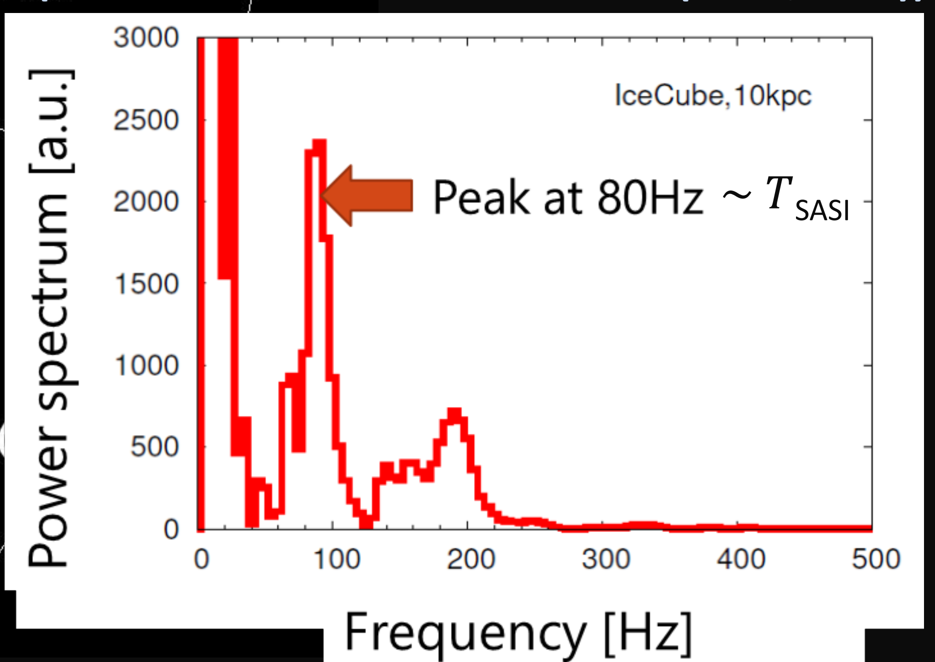
→ The dynamo activity footprints in the future GW observation !

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





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



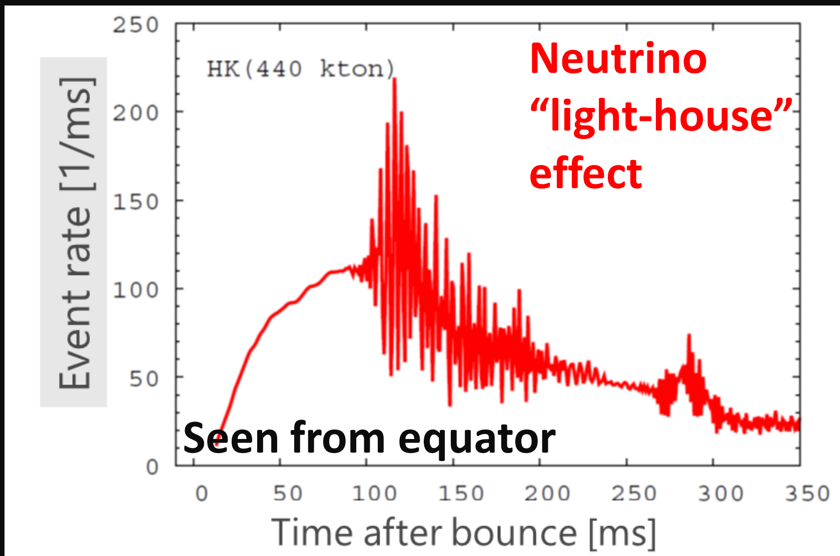
Takiwaki, KK, Foglizzo (2021)

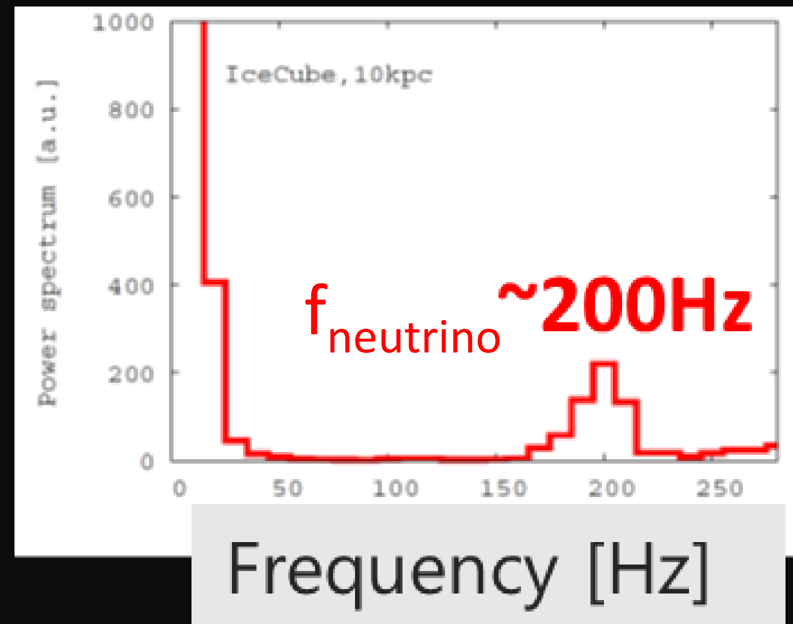
Angular resolution~1deg.

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

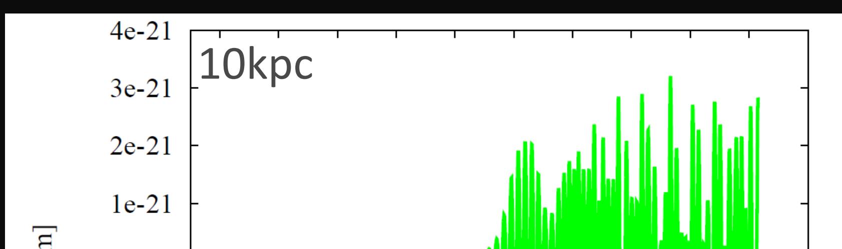
Takiwaki, KK, Foglizzo, (2021)

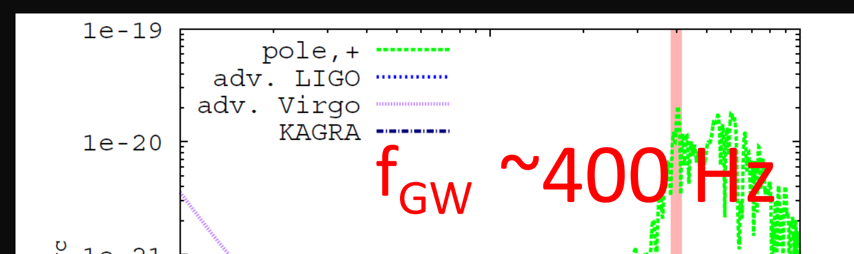
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform

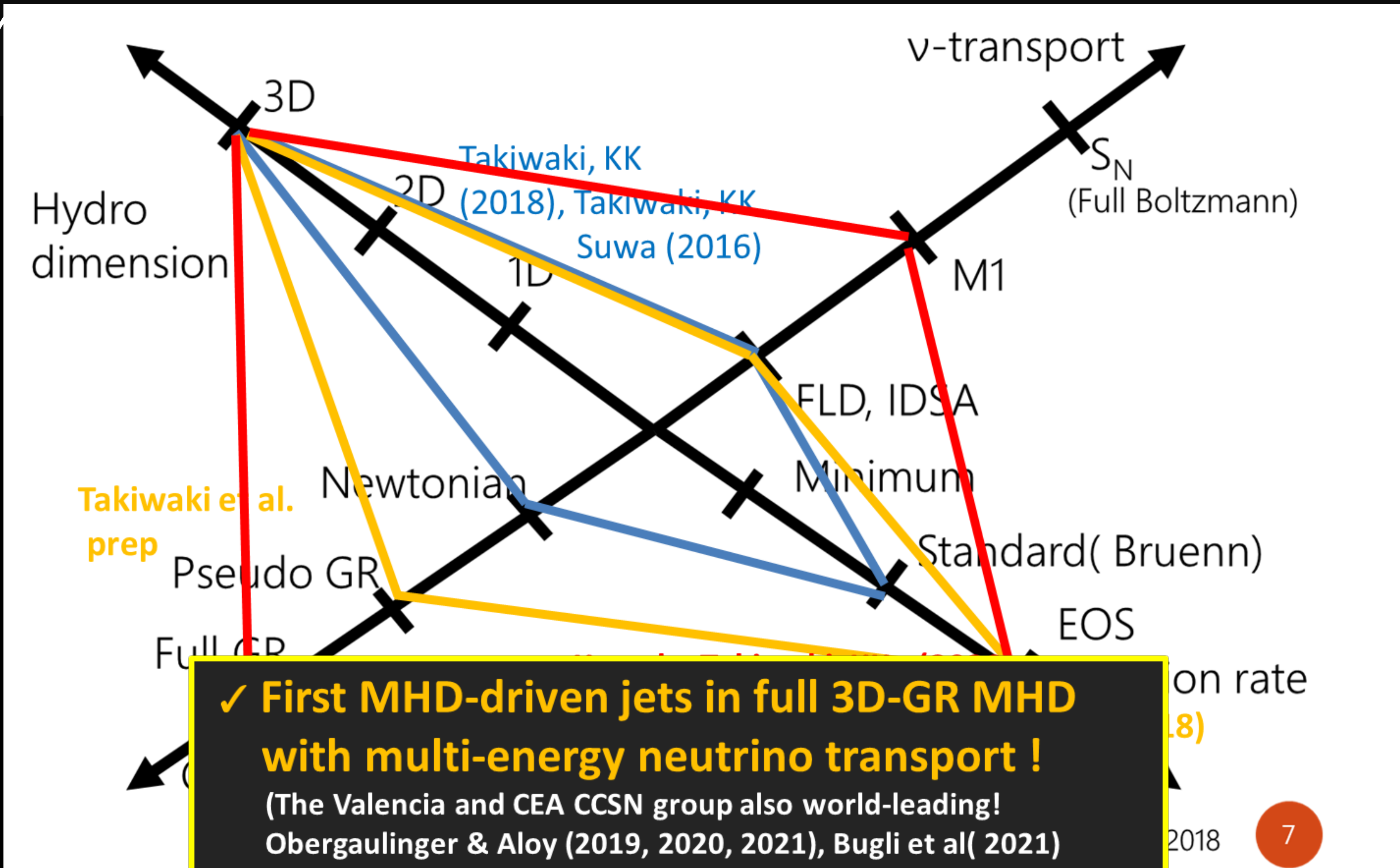


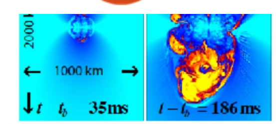


- ✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)
- ✓ Also the case for non-rotating progenitor, $f_{neutrino, SASI}$~80 Hz, QUIZ f_{gw} ~80 or 160 Hz
- ✓ Coincident detection between GW and ν : smoking gun signature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

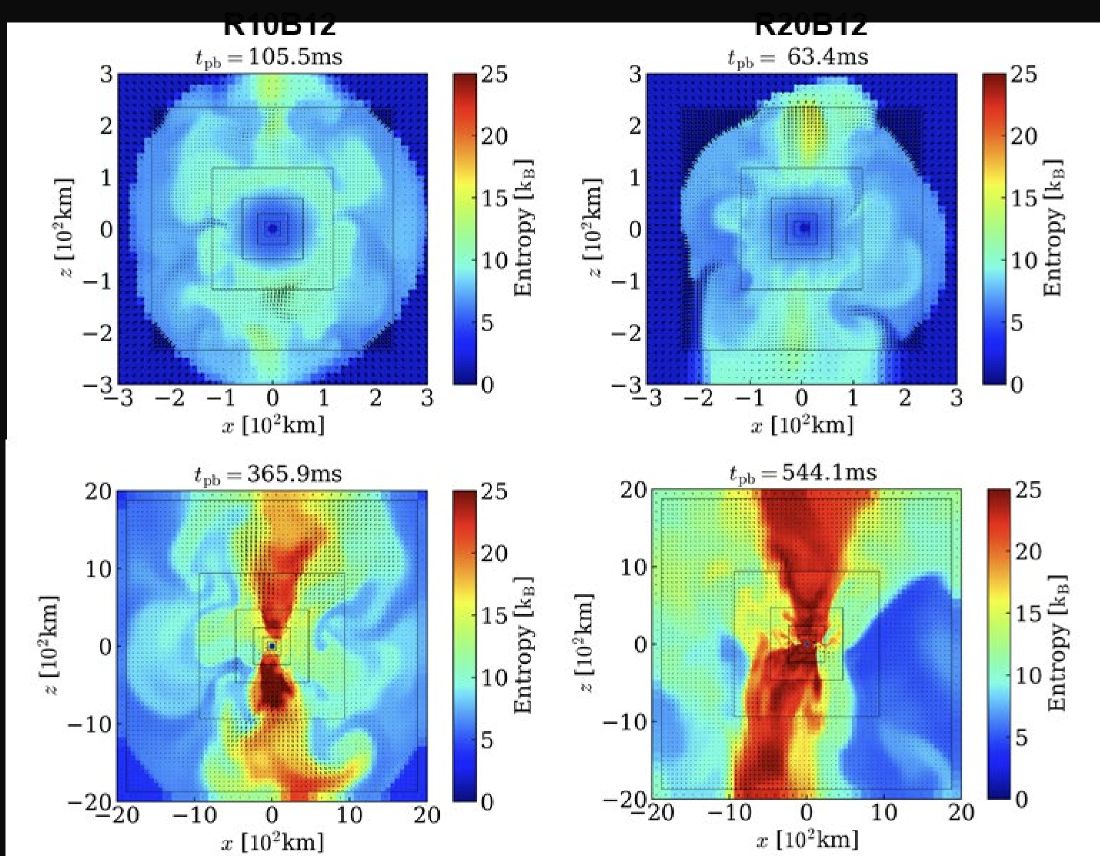
✓ Analysis of GW and ν predictions underway !

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

Shibagaki, Kuroda, KK, Takiwaki, in prep

Model	Ω_0 [rad s^{-1}]	$\frac{B_0}{\sqrt{4\pi}}$ [10^{12}G]
R05B12	0.5	1
R10B12	1.0	1
R10B13	1.0	10
R20B12	2.0	1

R10B12 R20B12

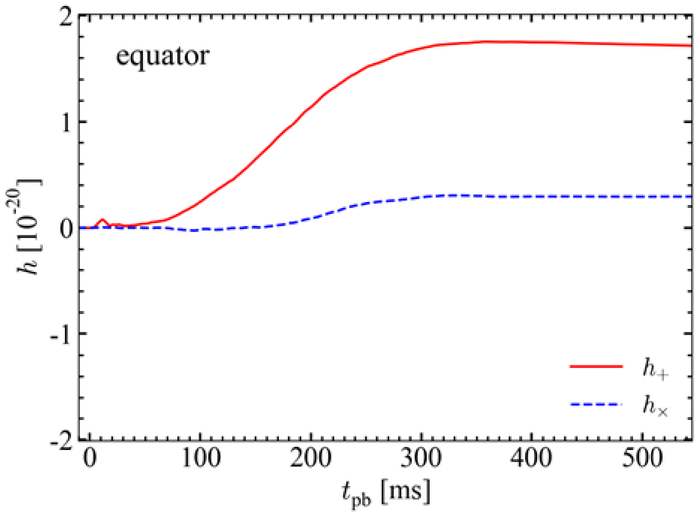


Preliminary results on 3D-GR MHD for a 20 M_{sun} star: 10B explosion

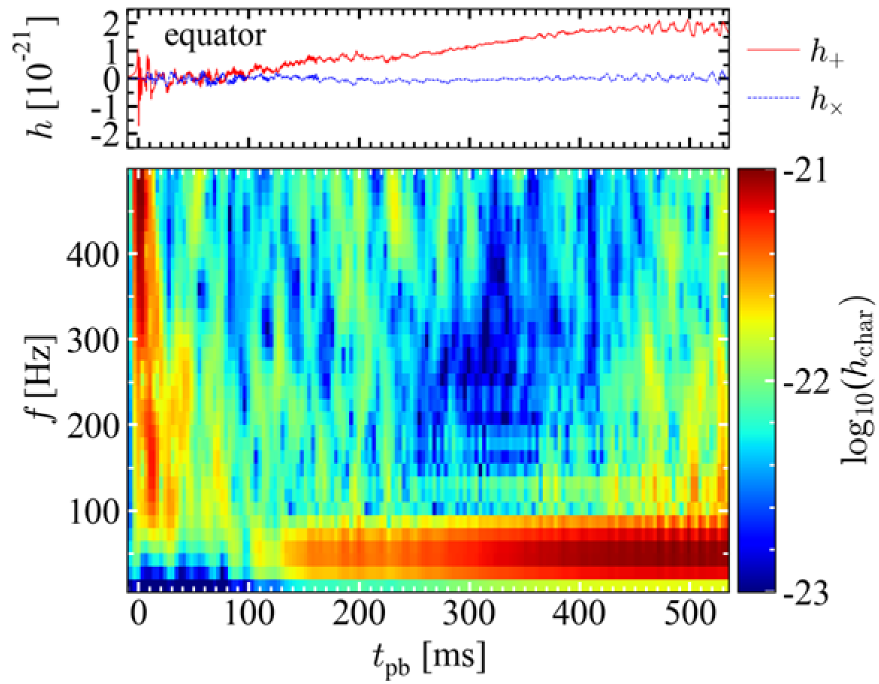
Shibagaki, Kuroda, KK, Takiwaki, in prep

GW Spectrogram of model R20B12

neutrino



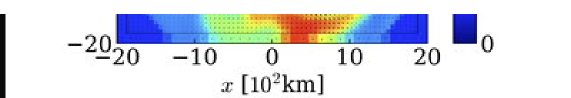
matter

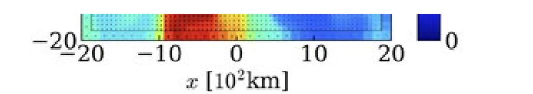


on the equatoria

$\frac{B_0}{\sqrt{4\pi}}$ [10^{12}G]
1
1
10
1

✓ Both of the MHD jet and asymmetric neutrino emission contribute to the generation of low-frequency GW (due to the Christodoulou-Epstein memory effect !)

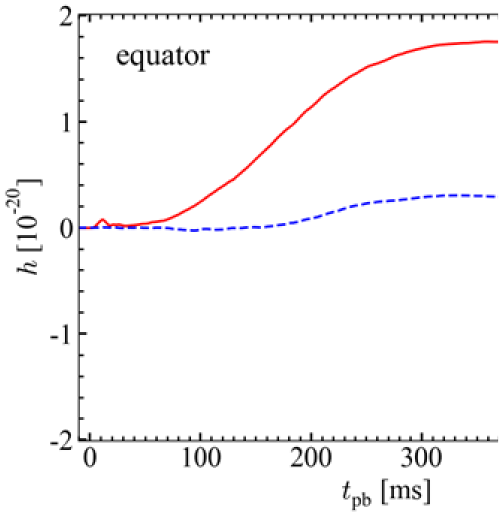


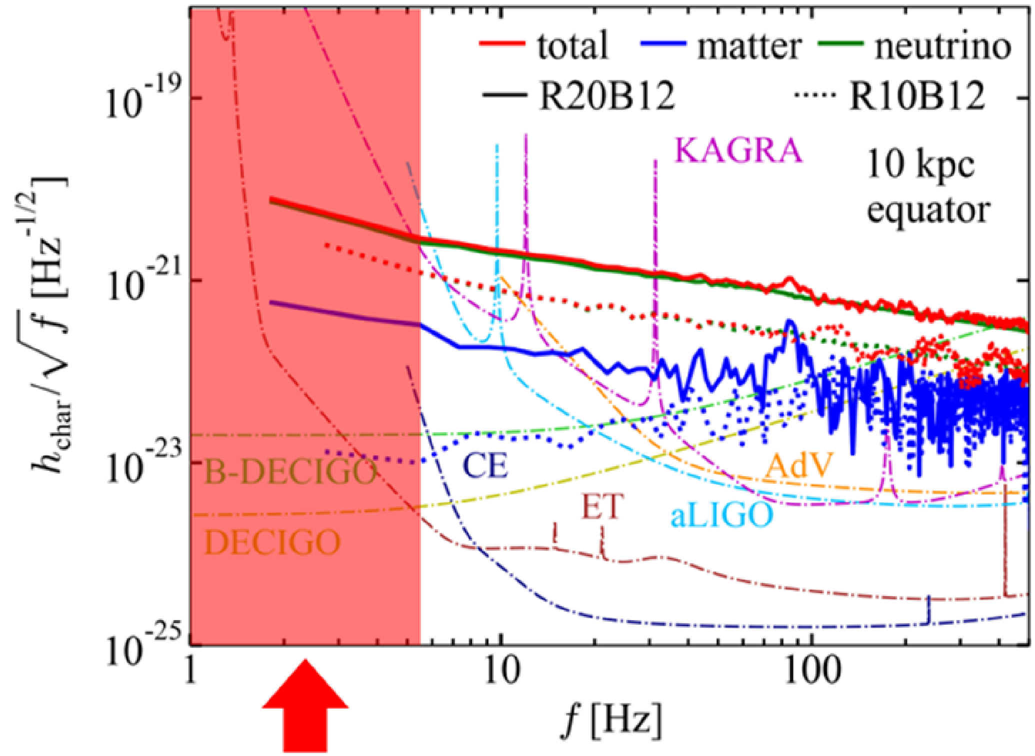


Preliminary results on 3D-GR MHD for a 20 M_{sun} star: 10B explosion

Shibagaki , Kuroda, KK, Takiwaki, in prep

GW Spectr



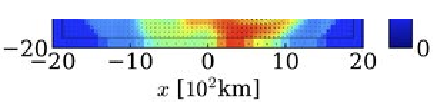


on the

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

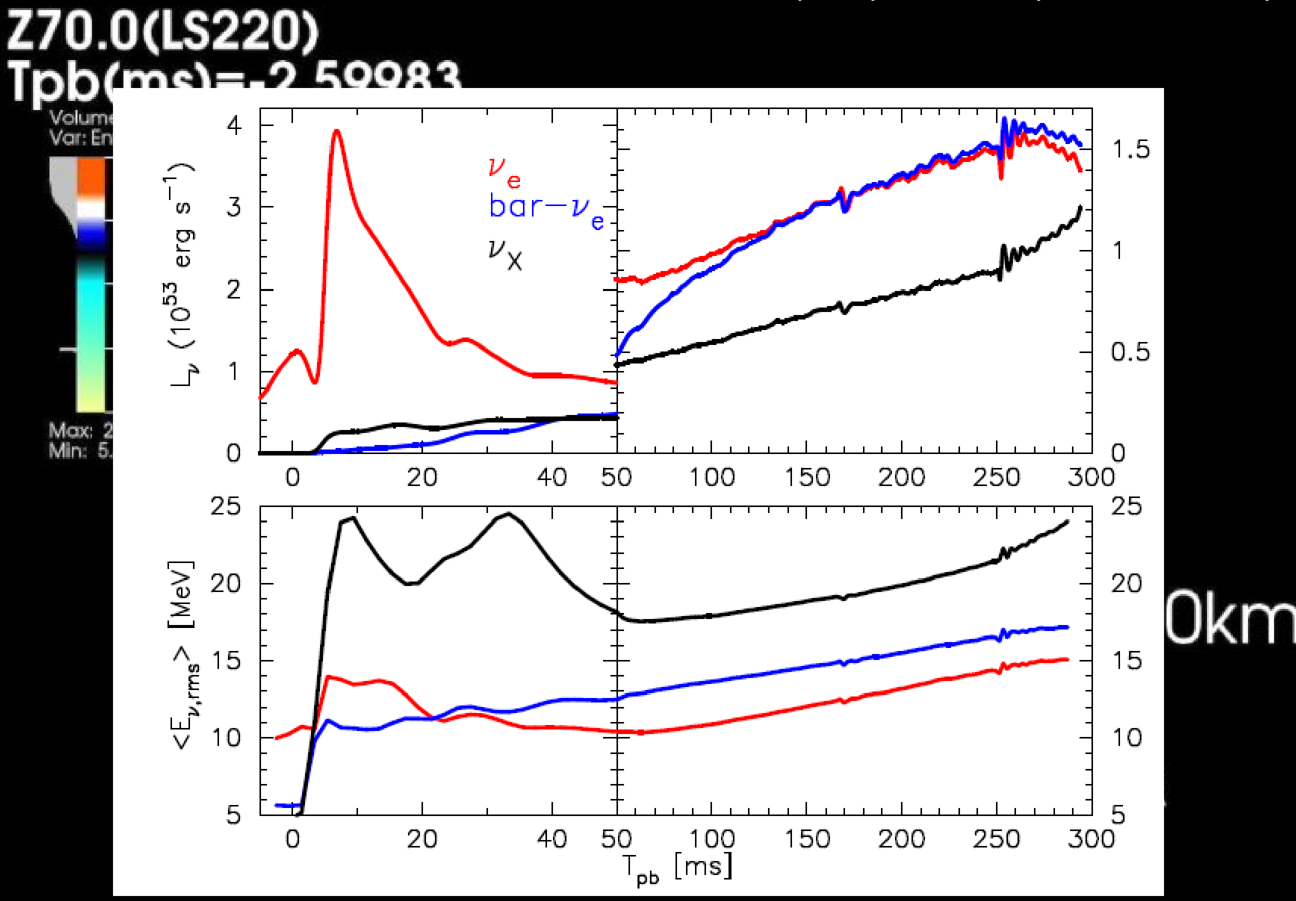
✓ For the detection, DECIGO; important role ! ("DEC"iherz "I"nterferometic "G"rav. "O"bs. Seto et al. PRL (2001)), which I first pointed out in Kotake et al. (2007) ApJ !

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



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

Kuroda, KK, Taiwaki, Thieleman, MNRAS, 2018



✓ **Earliest BH formation** after bounce (～300 ms postbouce) ！

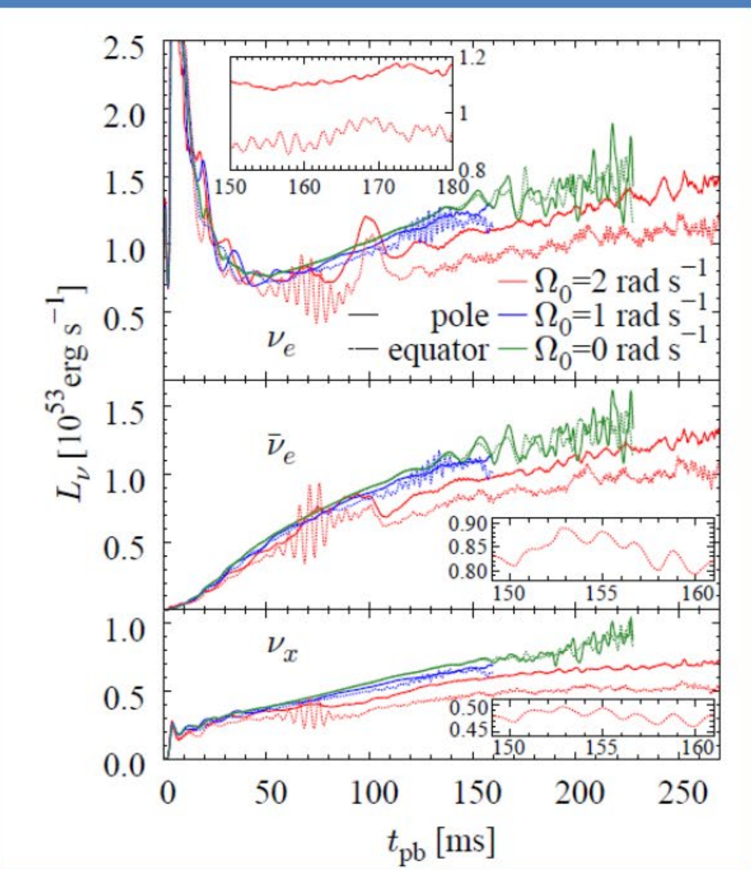
✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.

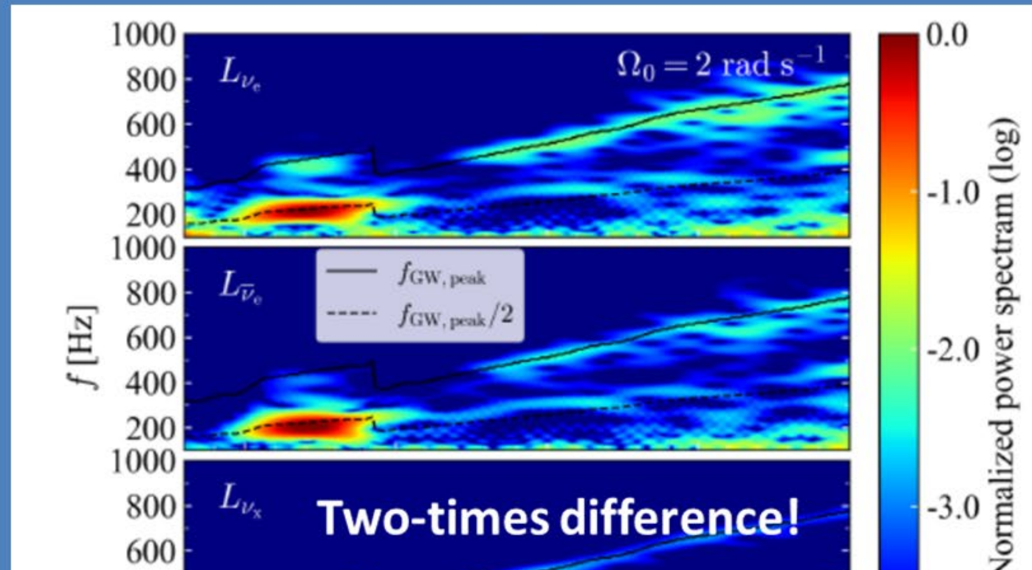
(**consistent with** 1D, e.g., Sumiyoshi+ (2006), Nakazato(+2008,2013), Fischer+ (2009), Huedepohl+(2016))

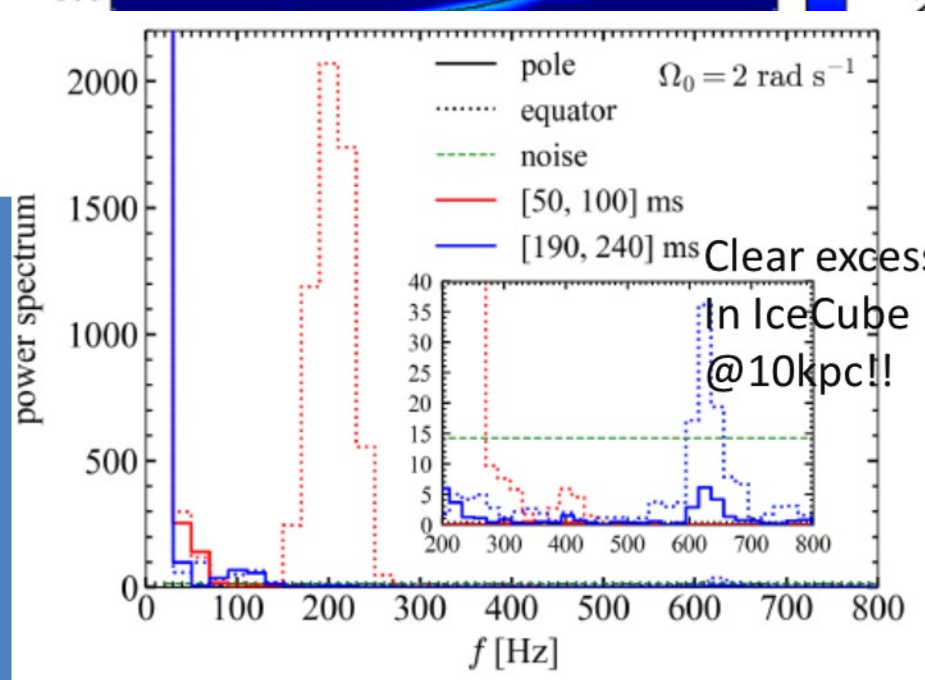
✓ **Sudden disappearance of the neutrino signals -> BH formation !**

✓ *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))

DB: visSi00001.bov
Time:1

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

Presupernova neutrinos from multi-D O shell burning shell

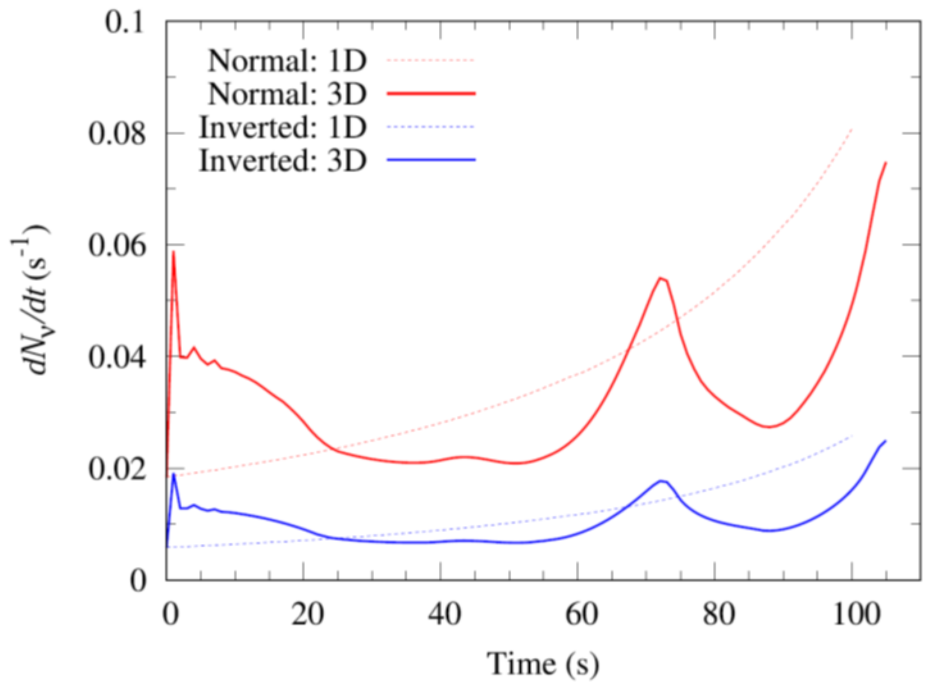


Figure 11. The evolution of the neutrino event rate of model 25M with KamLAND. The thick solid and thin dashed curves correspond to the results of the 3D and 1D simulations, respectively. The red and blue curves correspond to the normal and inverted orderings.

- ✓ **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 !**

5M_{sun} star
O burning

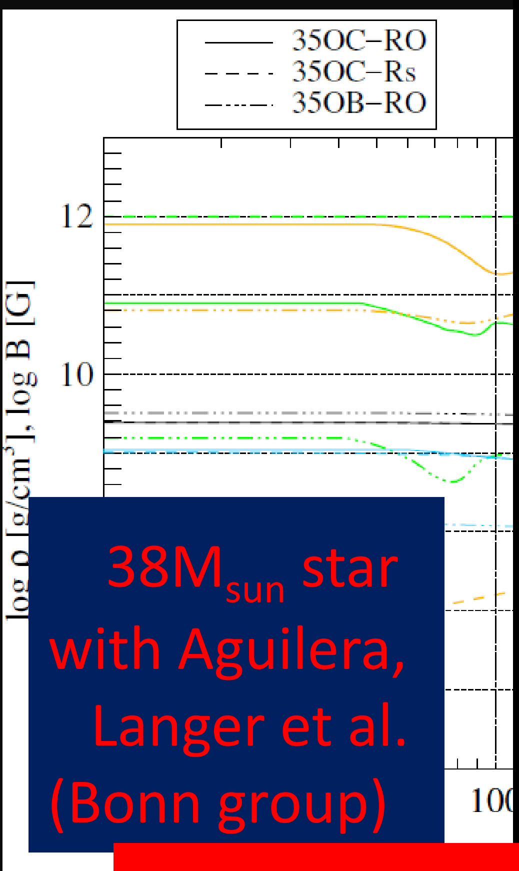
✓ One-Bethe 3D model was reported by Garching SN team using **3D progenitor**! (Bollig et al. (2021)

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

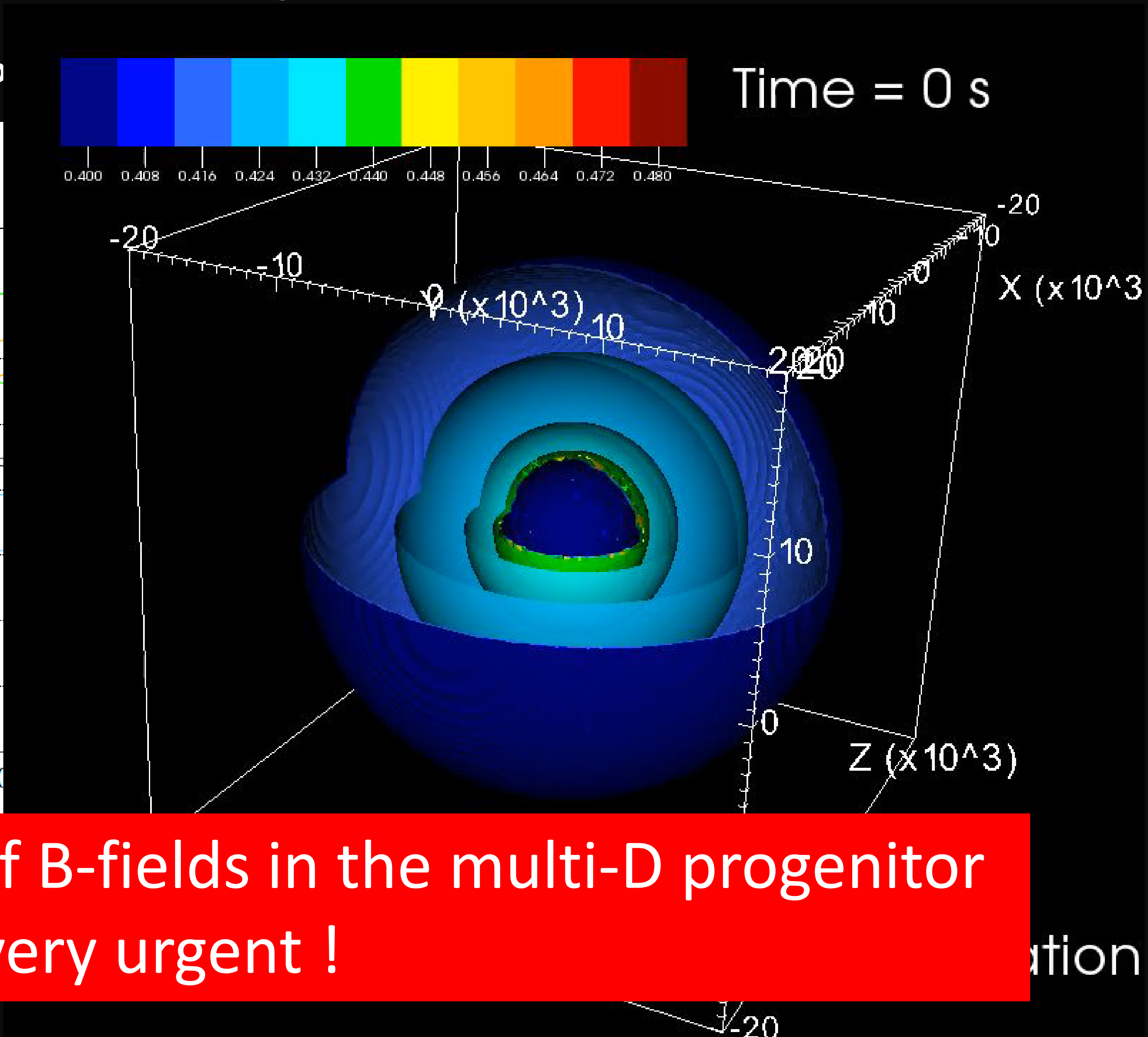
(3D stellar evolution calculations: Couch et al. (2015), Mueller et al. (2016))

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

35C model : collapsar pro



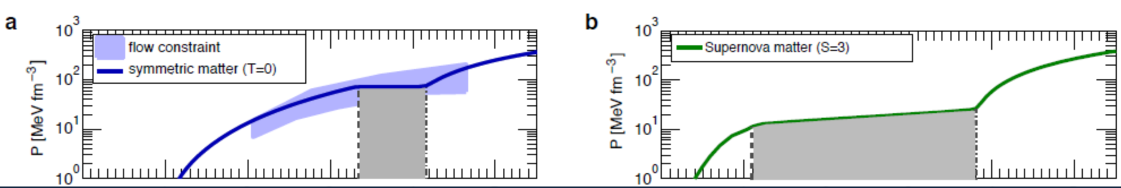
38M_{sun} star with Aguilera, Langer et al. (Bonn group)



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

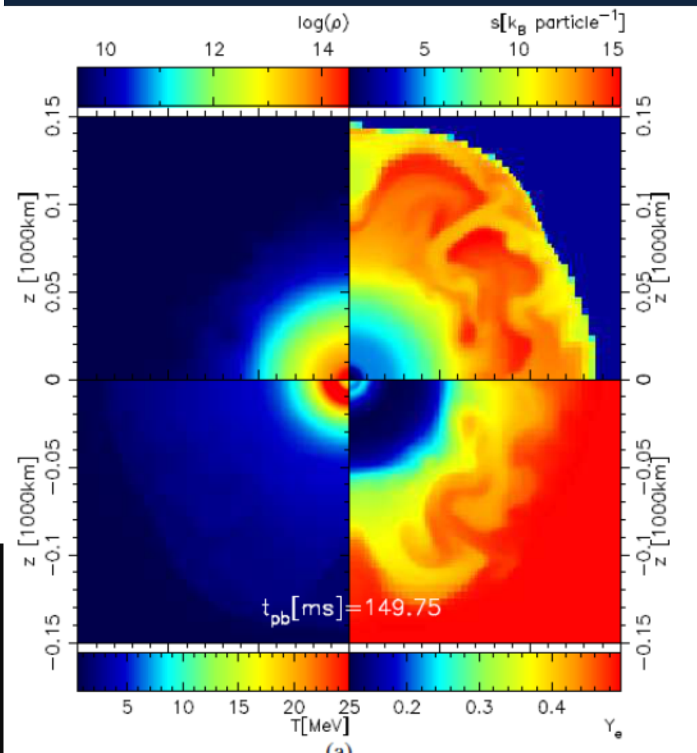
Caveat2. QCD phase transition could power explosion !!

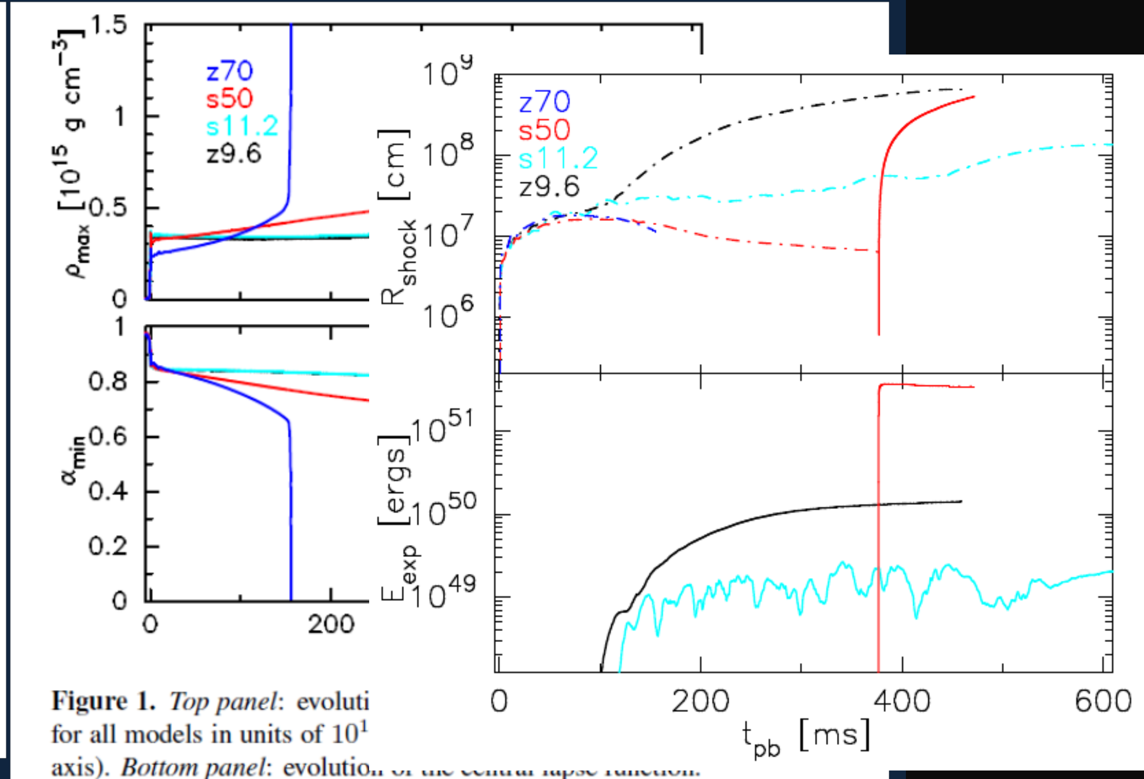
If “first-order” phase transition to the quark-gluon phase takes place… then



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

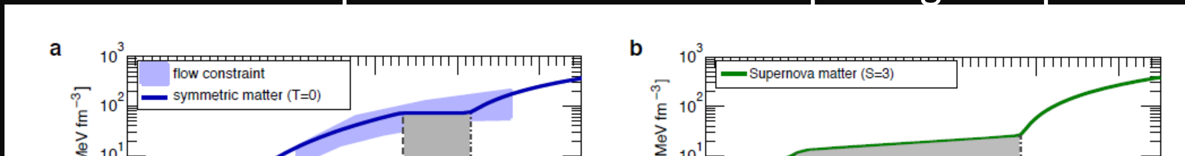
Full 2D-full-GR simulations including updated opacities（a la Kotake+(2018))
Kuroda, Fischer, Takiwaki, Kotake, submitted



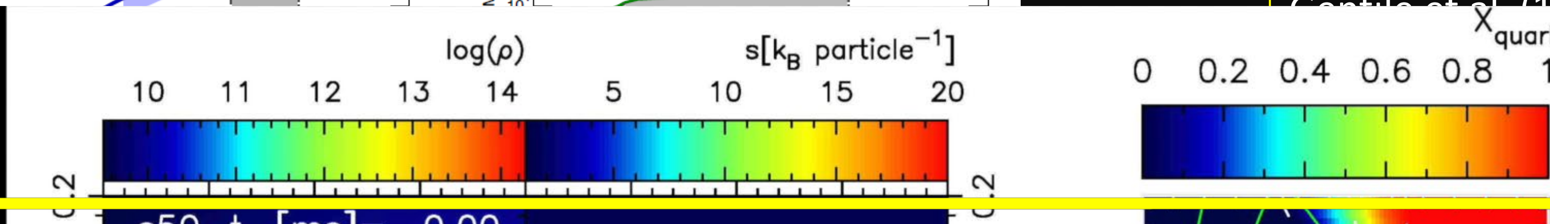


Caveat2. QCD phase transition could power explosion !!

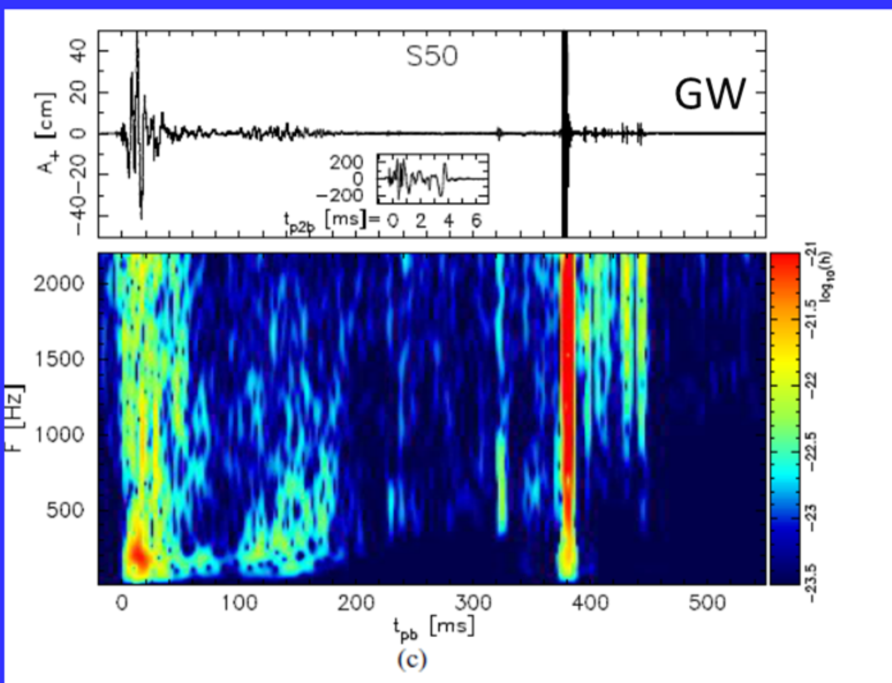
If “first-order” phase transition to the quark-gluon phase takes place… then



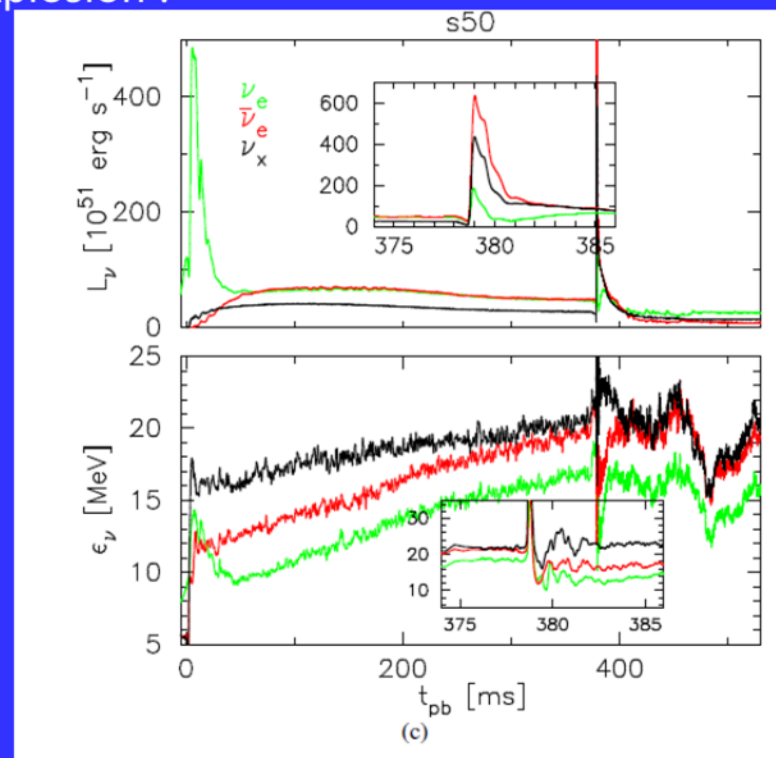
✓Original idea:
Takahara & Sato (1988)



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



(c)



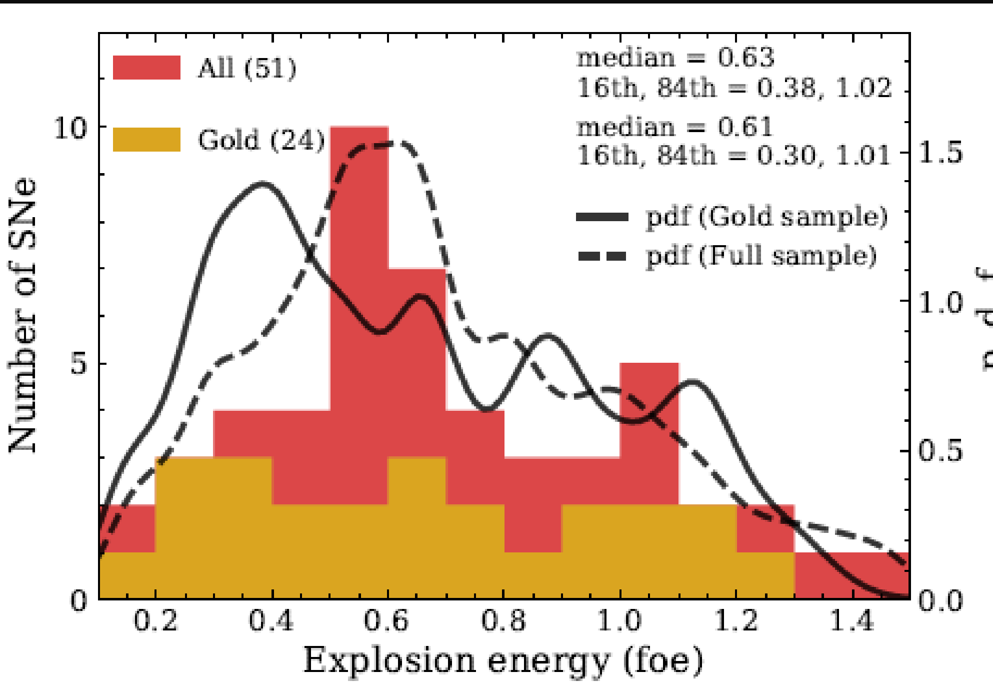
(c)

Type II supernovae from the Carnegie Supernova Project-I

II. Physical parameter distributions from hydrodynamical modelling

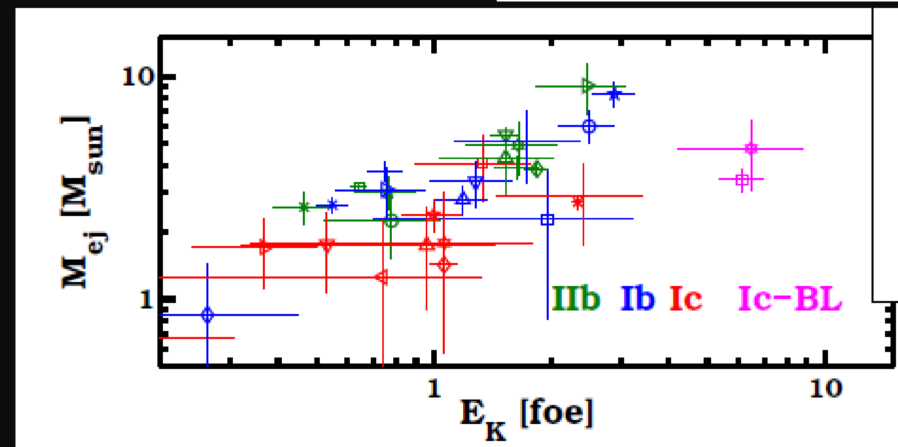
L. Martinez[1,2,3], M. C. Bersten[1,2,4], J. P. Anderson[5], M. Hamuy[6,7], S. González-Gaitán[8], F. Förster[9,10,11,12], M. Orellana[3,13], M. Stritzinger[14], M. M. Phillips[15], C. P. Gutiérrez[16,17], C. Burns[18], C. Contreras[15], T. de Jaeger[19,20], K. Ertini[1,2], G. Folatelli[1,2,4], L. Galbany[21],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



My take: Problems solved ?!!

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

✓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)

3D CCSN modeling on the verge of success!

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

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

✓ Fast-flavor conversion a new challenge !
could/could not help explosion
(See talks by Janka, Kneller!))

✓ Upgrade of v 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)