超新星の多次元爆発メカニズムとニュートリノ・重力波シグナル

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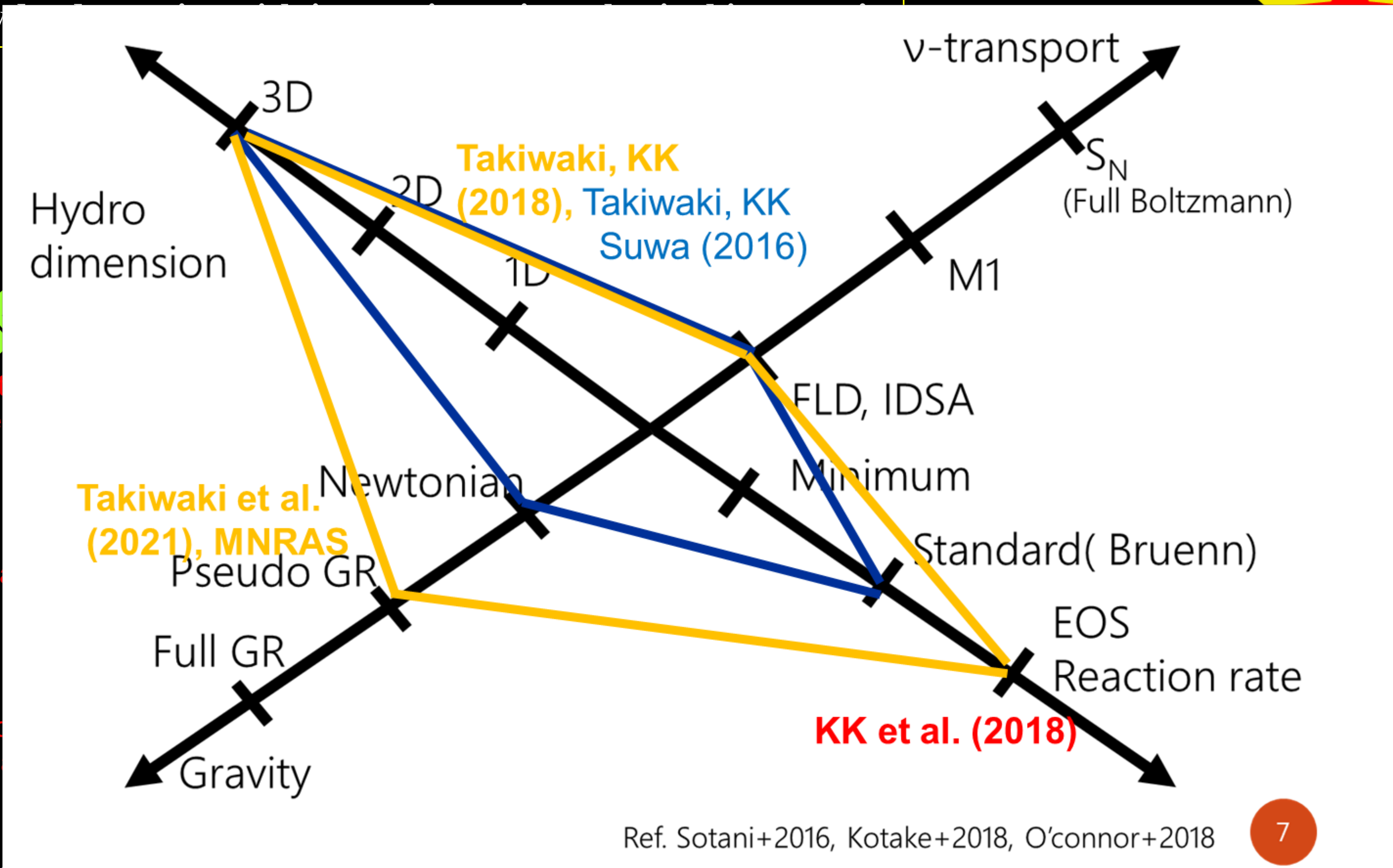
日本物理学会秋季年会シンポジウム
「地下から解き明かす宇宙の歴史と物質の進化」9/10/2022

★"ニュートリノ": 日本の至芸：SK, T2K, KamLand: Sweat ……

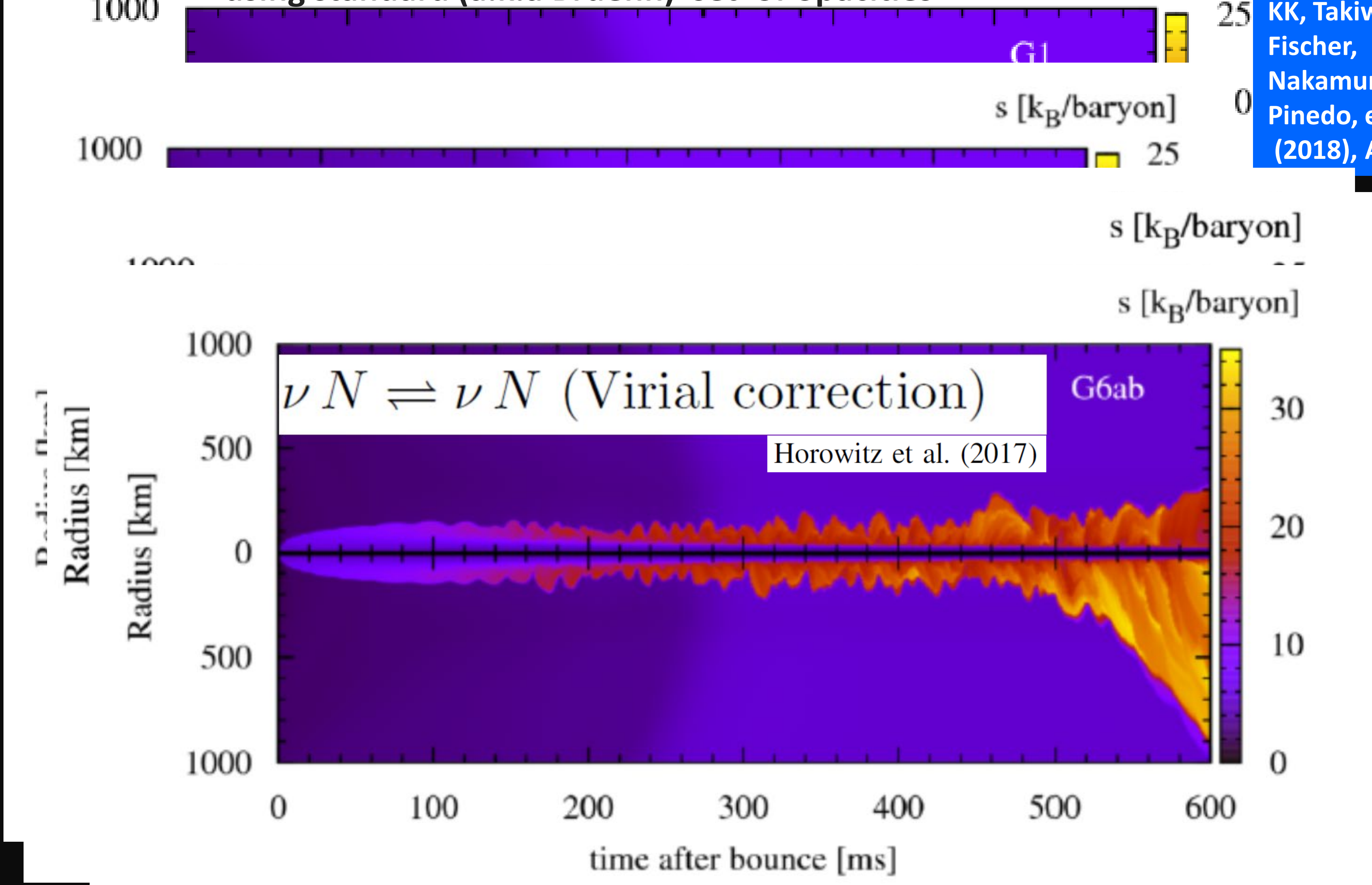
(Hillebrant-Mueller-Janka-B.Mueller.., Matzner-Mezzacappa-Liebendoerfer-…., Lattimer-Burrows-, Sato-Suzuki-Yamada…me ;-), the God father is H. Bethe !)

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



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

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

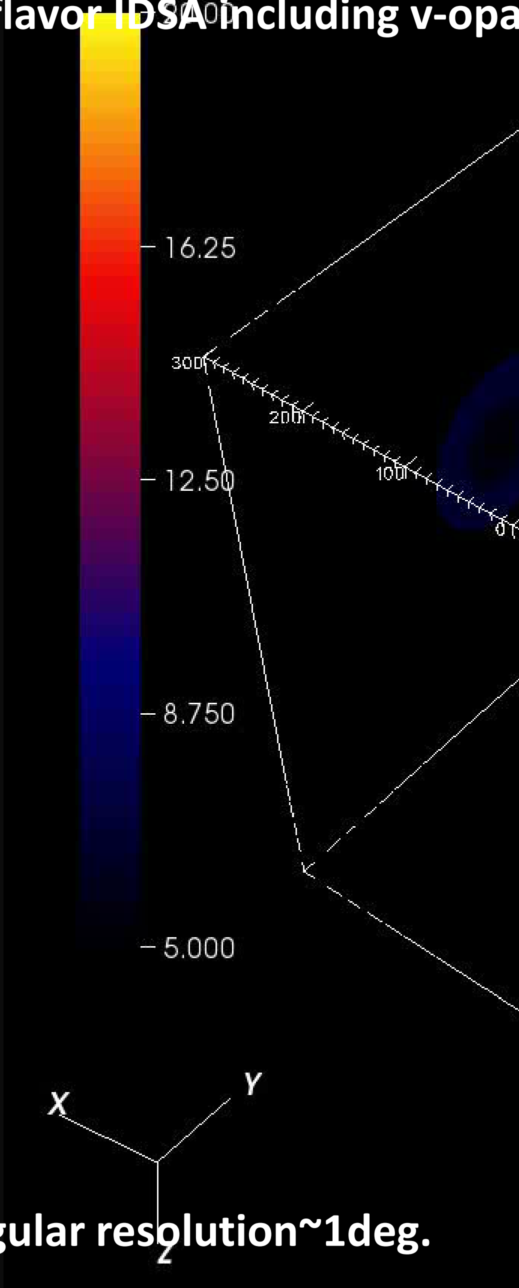


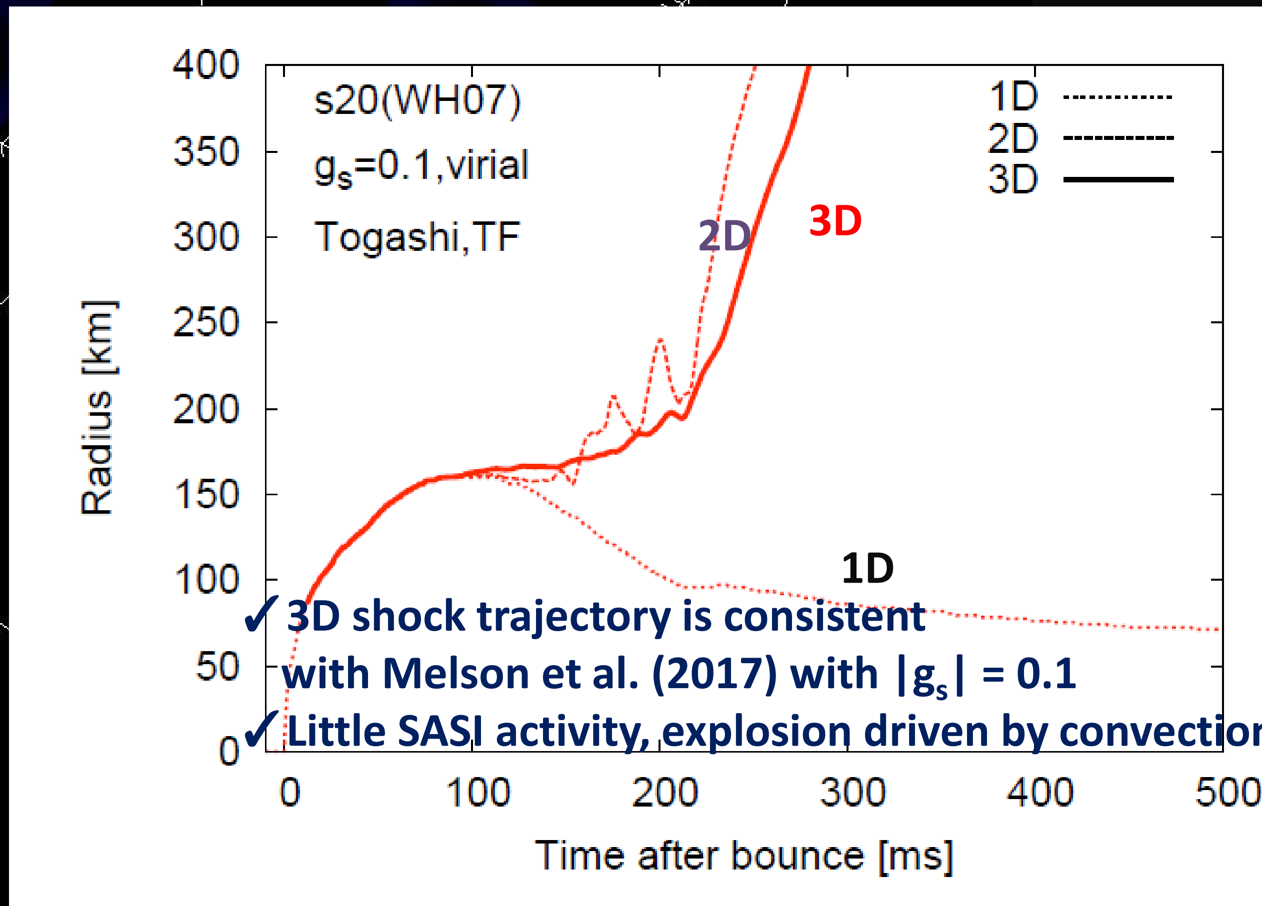
✓Quantitative GW・neutrino signal prediction, the updates in opacities mandatory!

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 $|g_s| = 0.1$

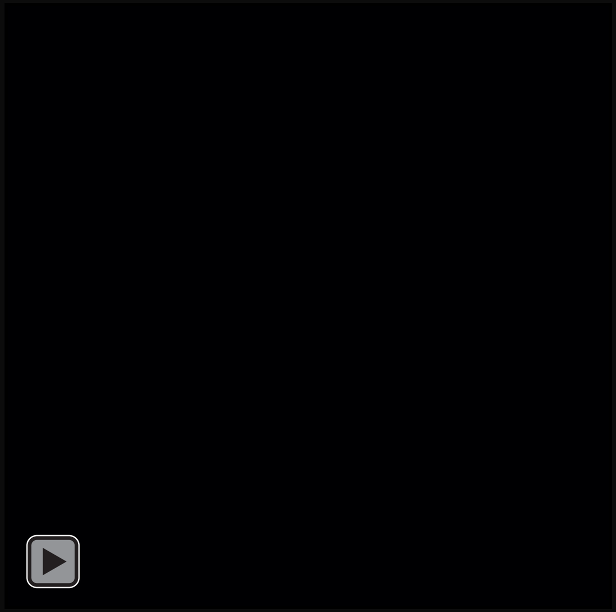
✓ Little SASI activity, explosion driven by convection

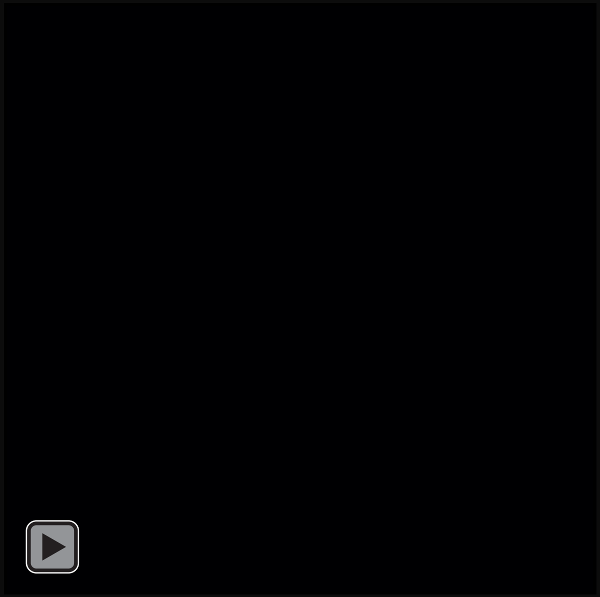
Angular resolution~1deg.

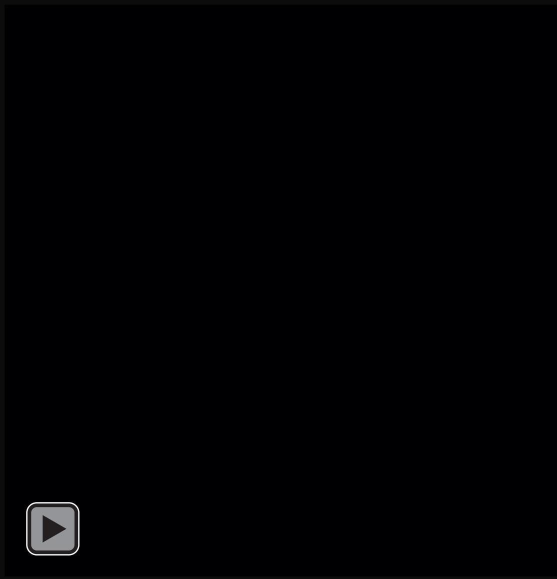
Many more 3D modeling with MHD possible !!!

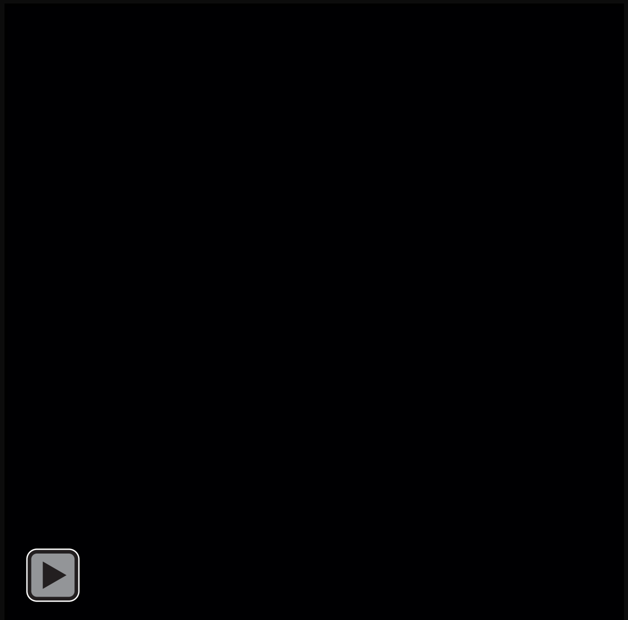
Nakamura, Takiwaki, KK (2022), Matsumoto et al. MNRAS(2022)

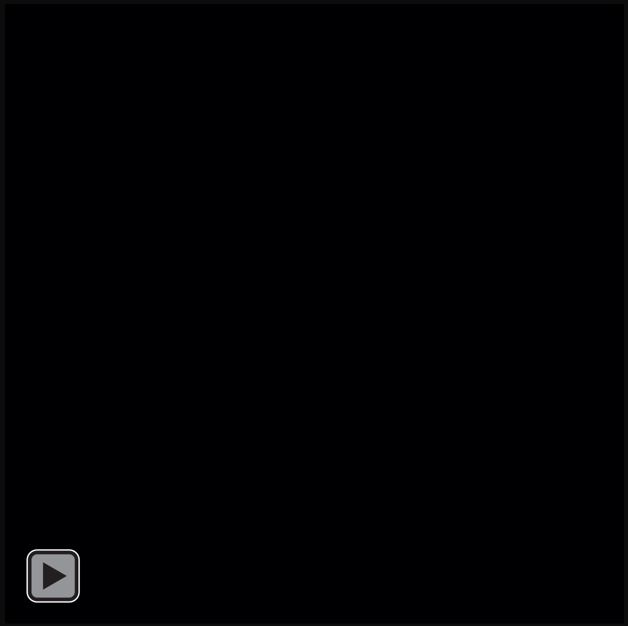
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform), Non-rotation)

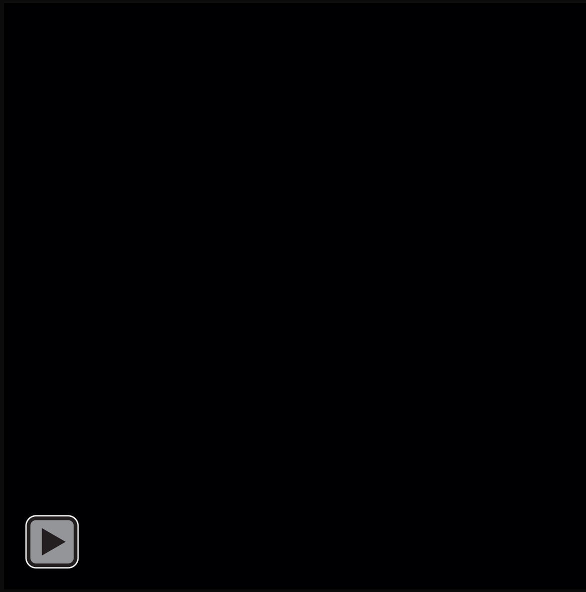






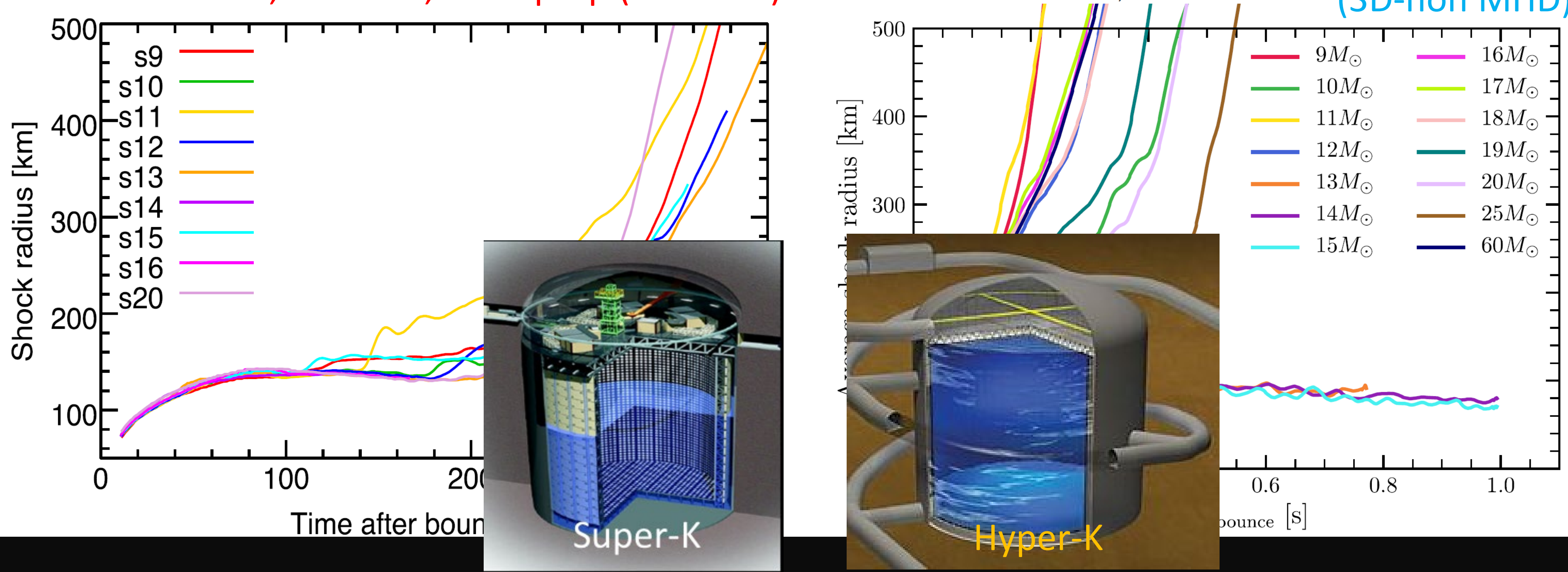




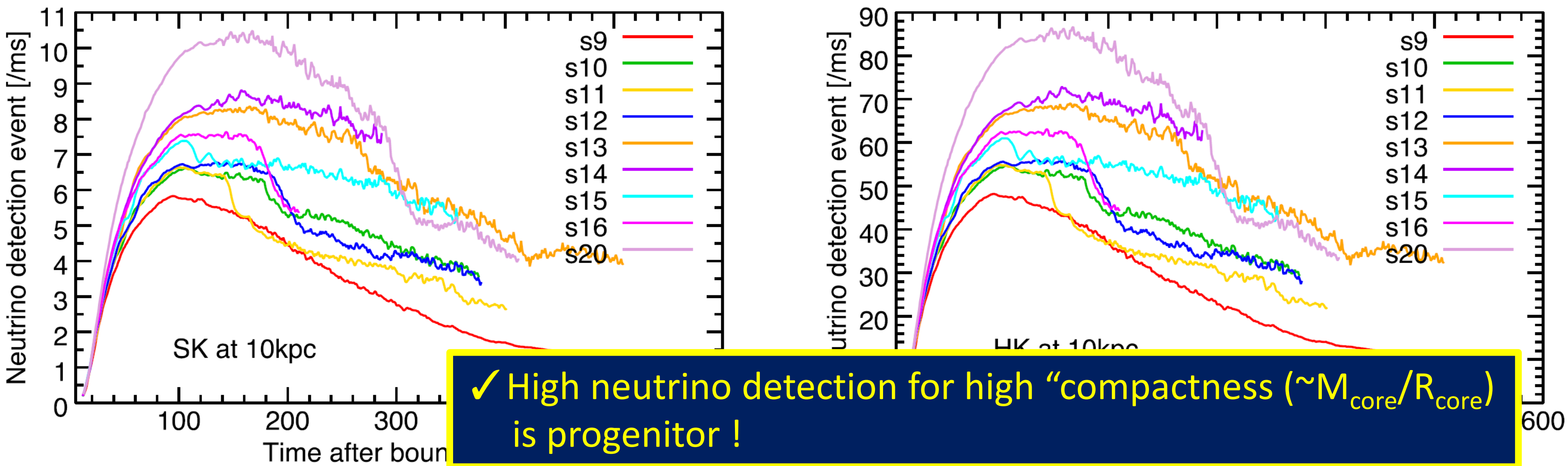


Nakamura, Takiwaki, KK in prep (3D-MHD)

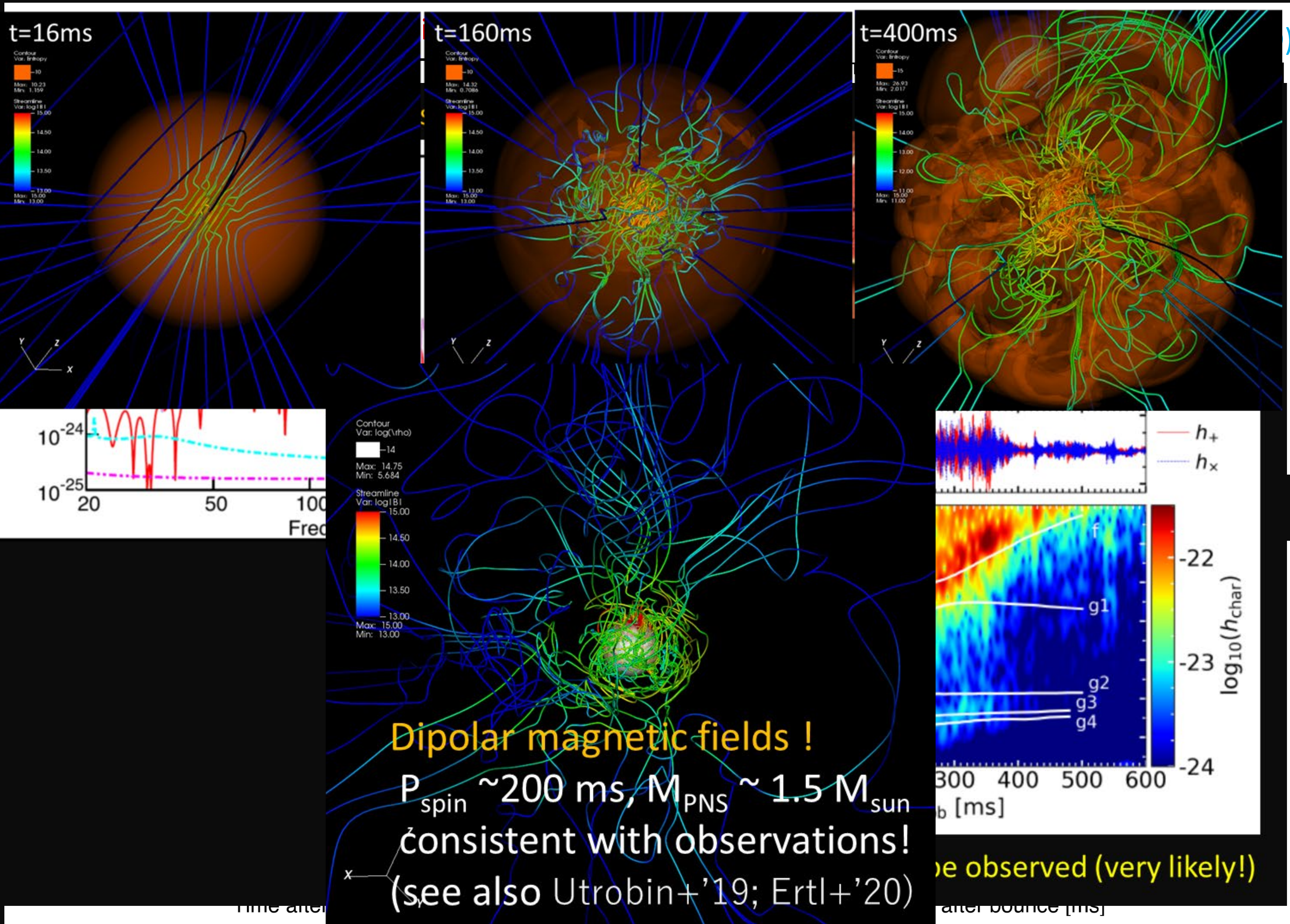
c.f.) Burrows+20 (3D-non MHD)



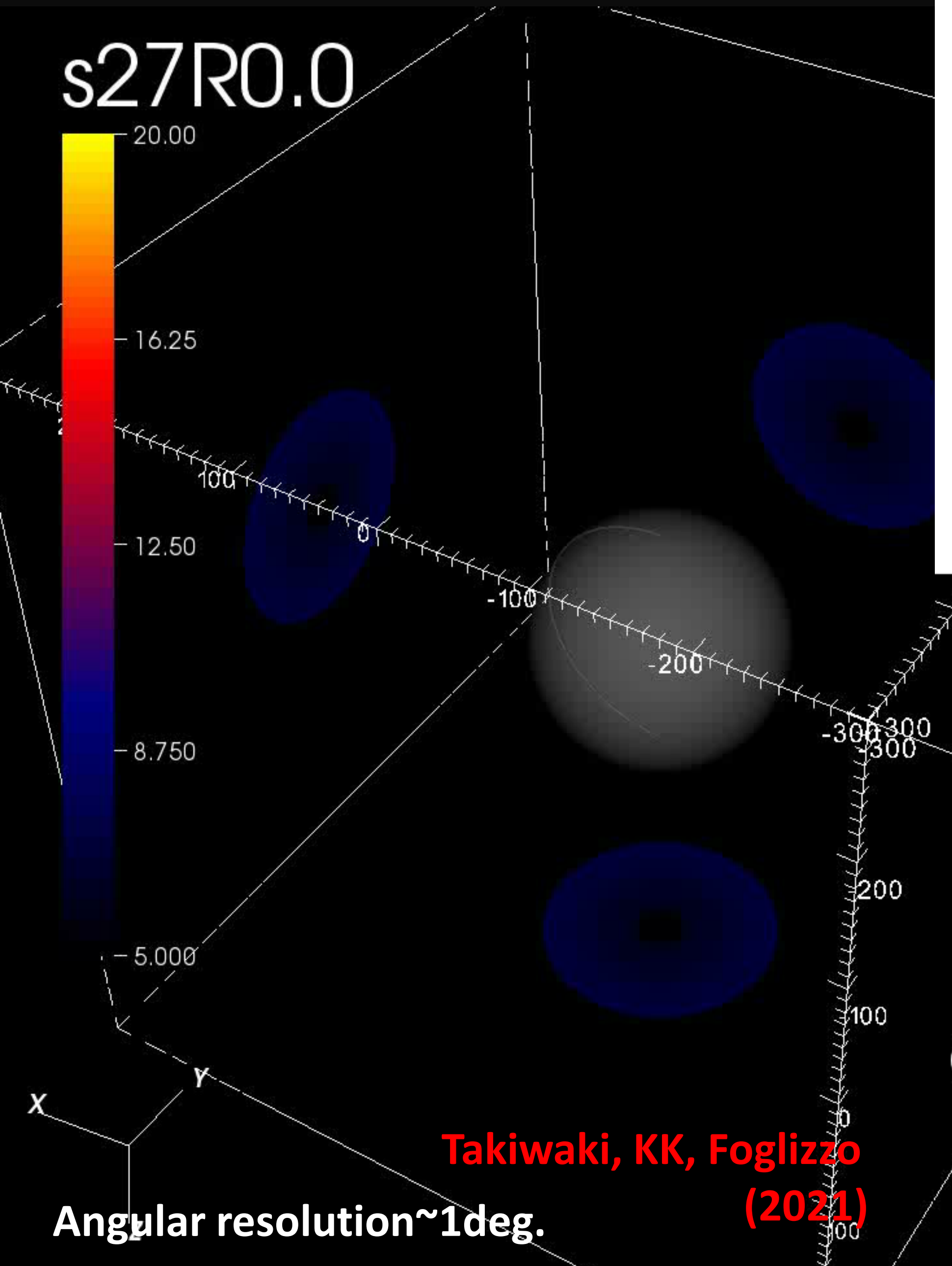
✓Neutrino detection rate at SuperKamokande and HyperKamiokande

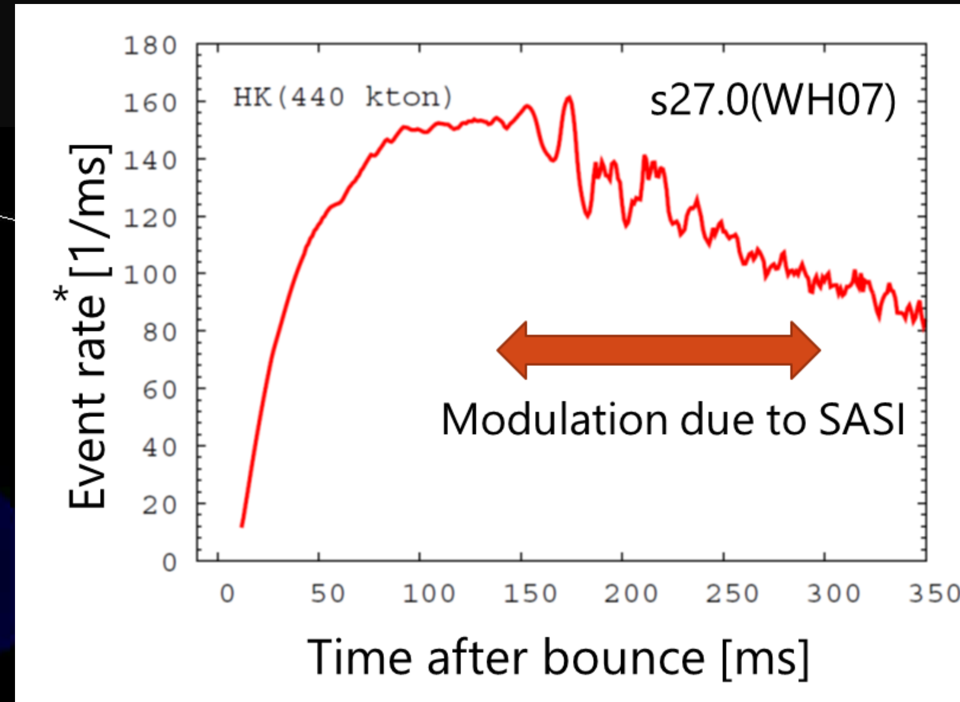


✓High neutrino detection for high "compactness ($\sim M_{core}/R_{core}$) is progenitor !

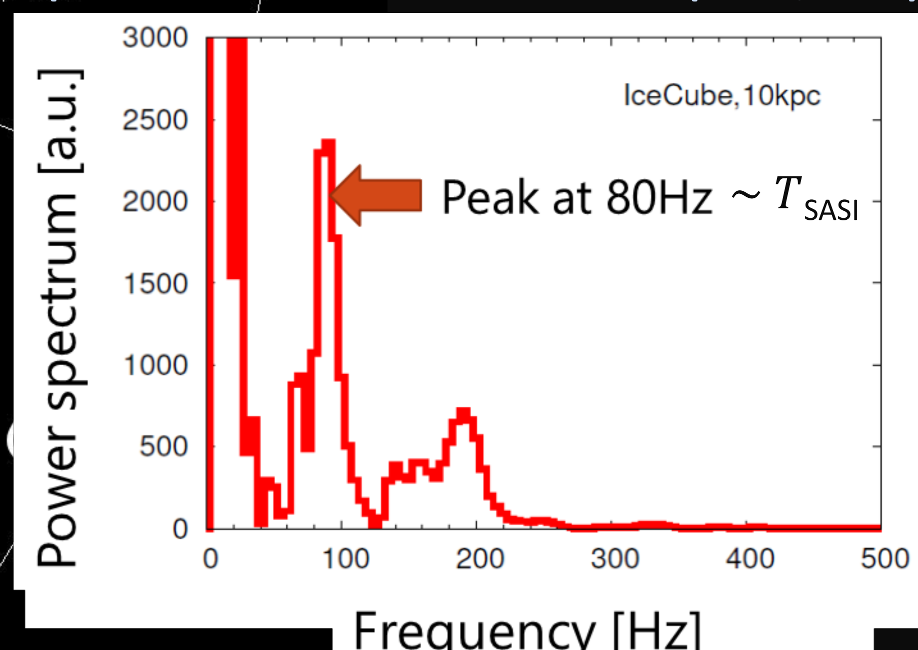

t=16ms
t=160ms
t=400ms
Contour
Var: log(\rho)
14
Max: 14.75
Min: 5.684
Streamline
Var: log|B|
15.00
14.50
14.00
13.50
13.00
Max: 15.00
Min: 13.00
10^{-24}
10^{-25}
20
50
100
Freq
h_+
$h_\times$
f
g1
g2
g3
g4
300 400 500 600
-22
-23
-24
$\log_{10}(h_{char})$
Dipolar magnetic fields !
P_{spin} ~200 ms, M_{PNS} ~1.5 M_{sun}
consistent with observations!
(see also Utrobin+'19; Ertl+'20)
be observed (very likely!)

27 M_{sun} progenitor (WH07)





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

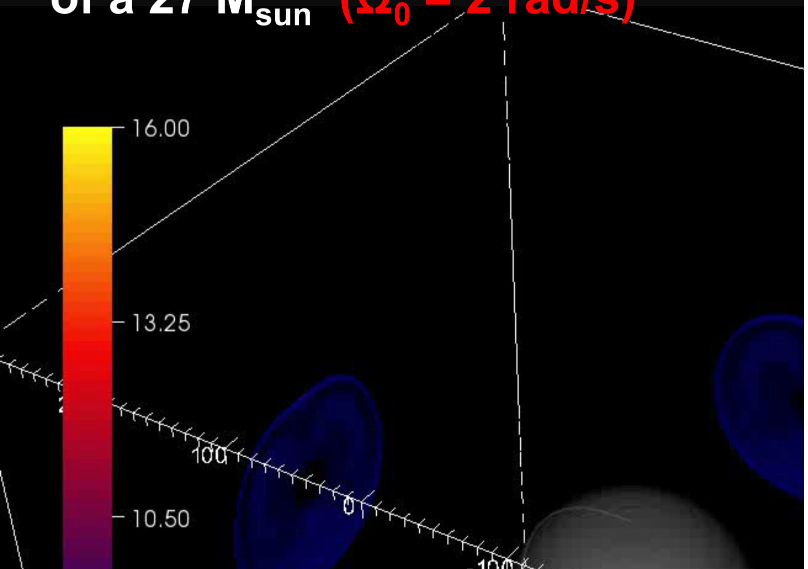


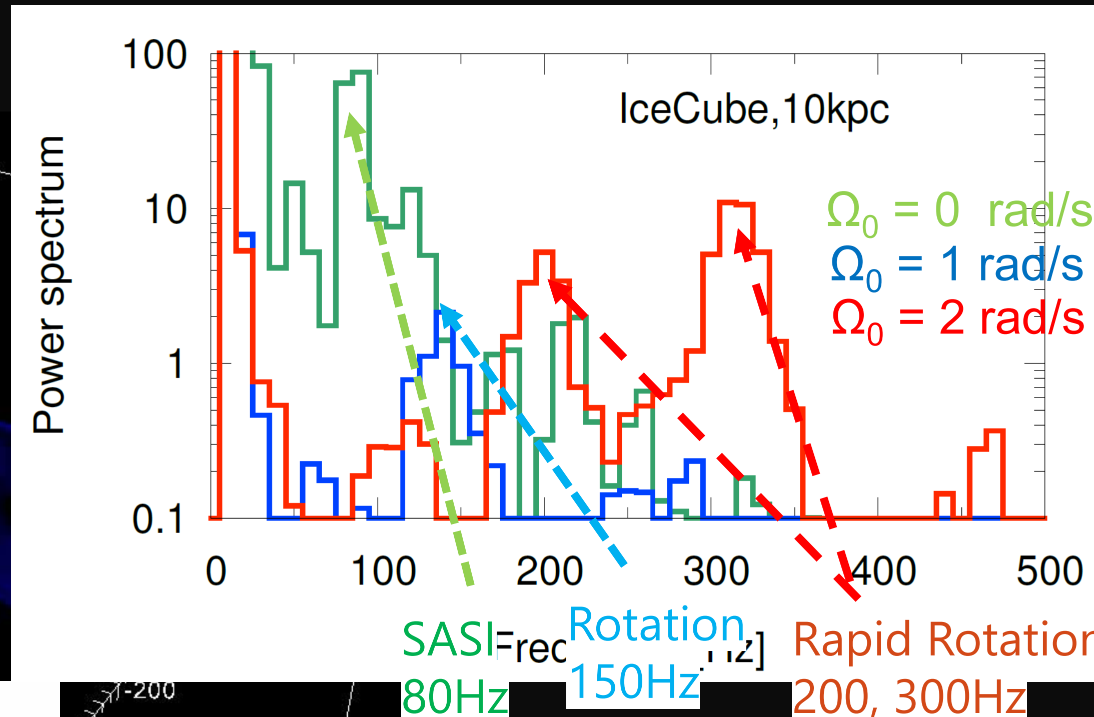
Takiwaki, KK, Foglizzo (2021)

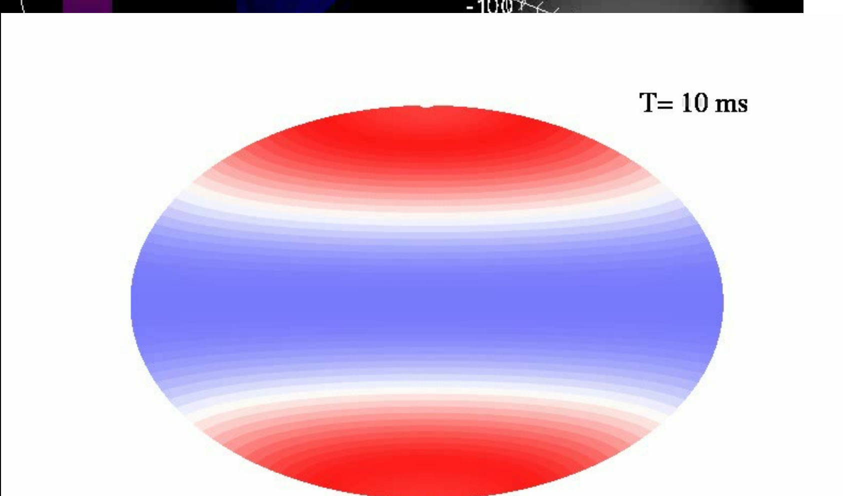
Angular resolution~1deg.

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.

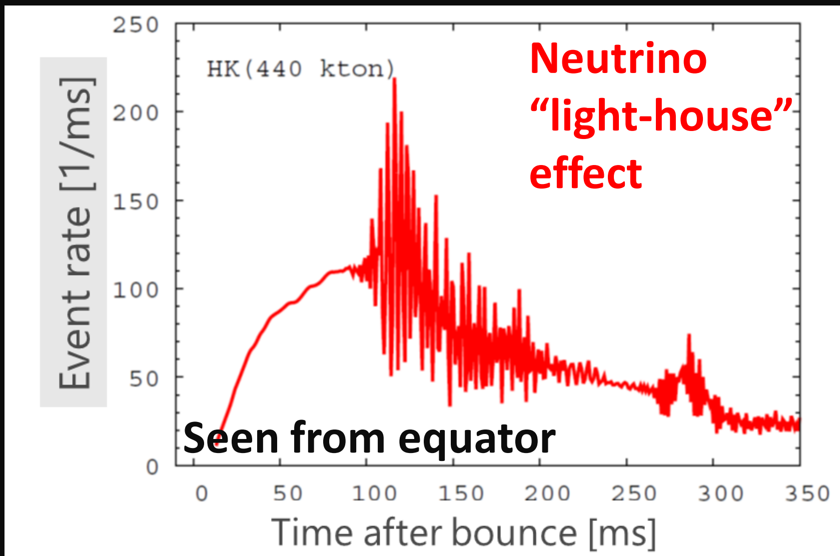
=> *The light-house effect*

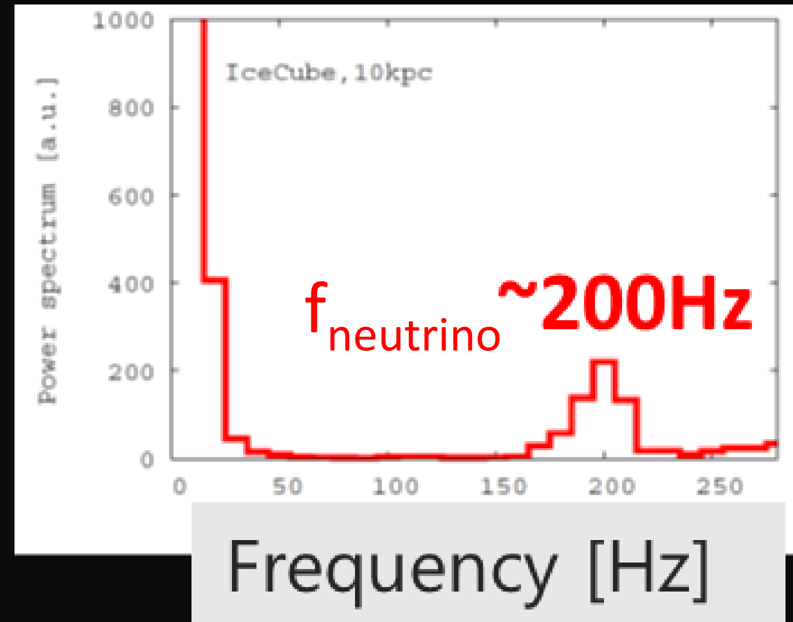
600 km **(found in simplified 3D model by Takiwaki and KK (2018)).**

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

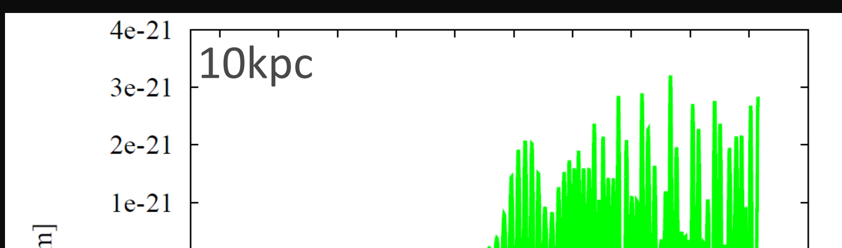
Takiwaki, KK, Foglizzo, (2021)

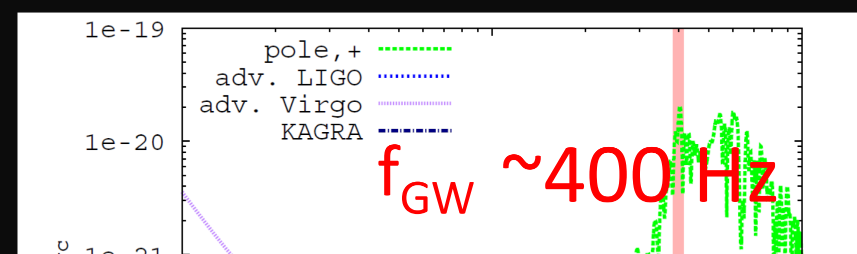
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform





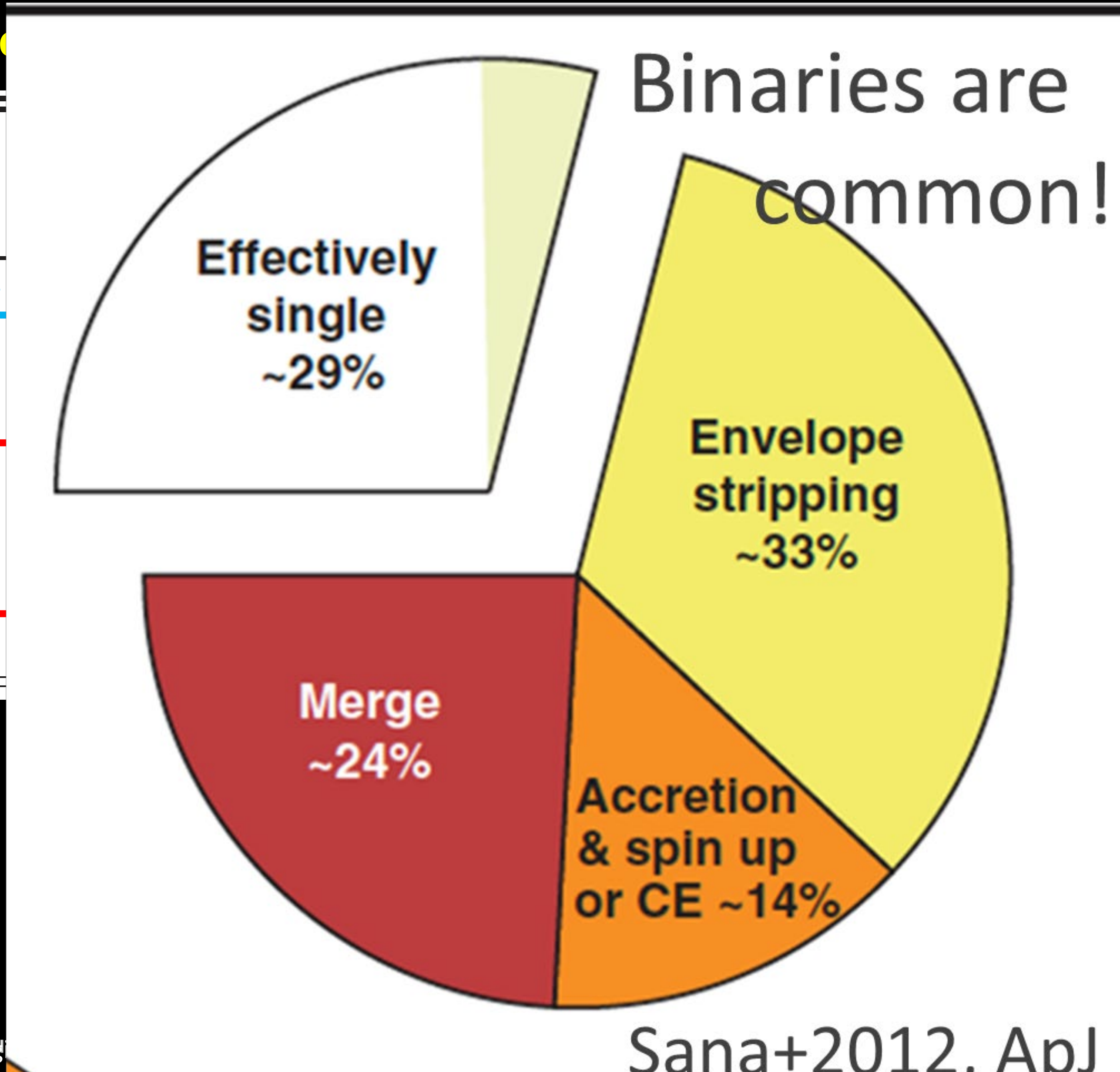
- ✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)
- ✓ Also the case for non-rotating progenitor, $f_{neutrino, SASI}$~80 Hz, QUIZ f_{gw} ~80 or 160 Hz
- ✓ Coincident detection between GW and ν : smoking gun signature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

Diffuse SN ν background (DSNB) predictions

Horiuchi, Kinugawa, Takiwaki, KK (2021) MNRAS

✓ **Inclusion … n prospects**

No binary
Binary $\alpha\lambda$
Binary $\alpha\lambda$
Binary $\alpha\lambda$
Binary $\alpha\lambda$
Binary $\alpha\lambda$
Binary $\alpha\lambda$



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Diffuse SN ν background (DSNB) predictions

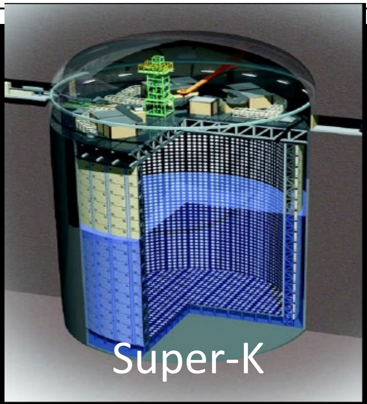
Horiuchi, Kinugawa, Takiwaki, KK (2021) MNRAS

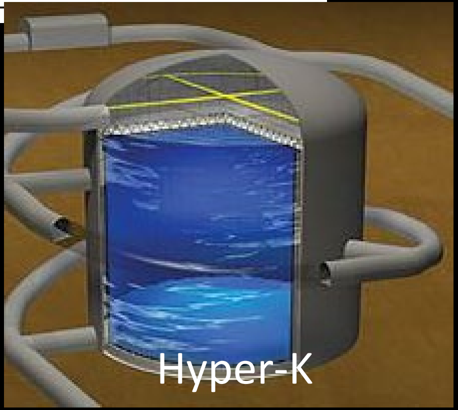
✓ **Inclusion of binary treatment leads to improved (20%) detection prospects**

Binaries are common

	SK-Gd [/yr]		HK [/yr]	
	Normal	Inverted	Normal	Inverted
No binary evolution	2.3	2.4	5.5	6.2
Binary $\alpha\lambda = 0.1$ Extrapolated	4.7	4.6	11.4	12.0
Binary $\alpha\lambda = 0.1$ Fiducial	2.7	2.7	6.4	7.1
Binary $\alpha\lambda = 0.1$ No rotation	2.3	2.4	5.5	6.2
Binary $\alpha\lambda = 1$ Extrapolated	3.8	3.8	9.1	9.9
Binary $\alpha\lambda = 1$ Fiducial	2.7	2.7	6.3	7.0
Binary $\alpha\lambda = 1$ No rotation	2.3	2.5	5.5	6.4

**Important: black hole contributions are not included here, real rates can be even higher





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

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

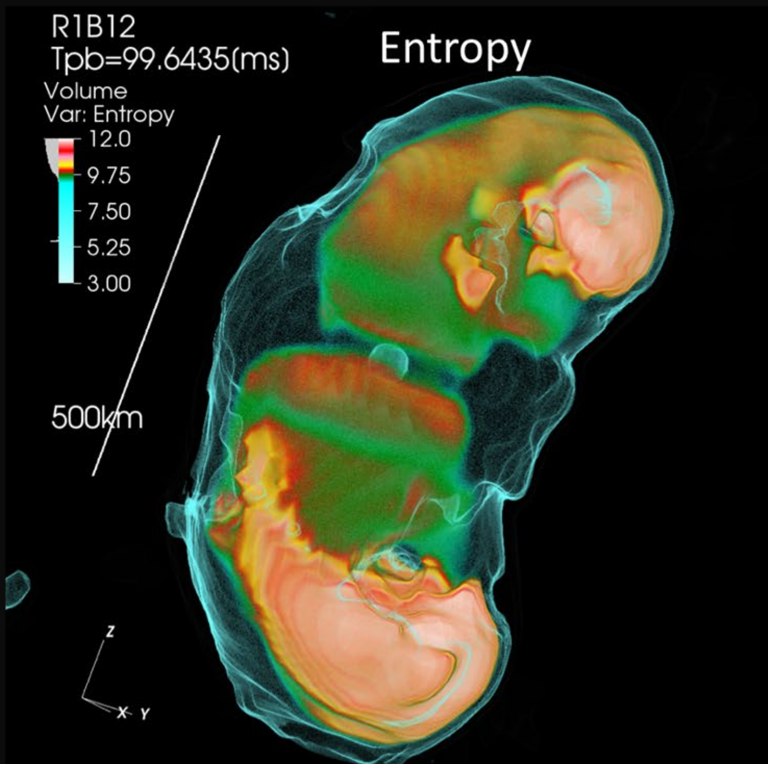
✓ Strongly magnetized and rapidly rotating model of s20 solar-mass star (Woosley and Heger (2007))

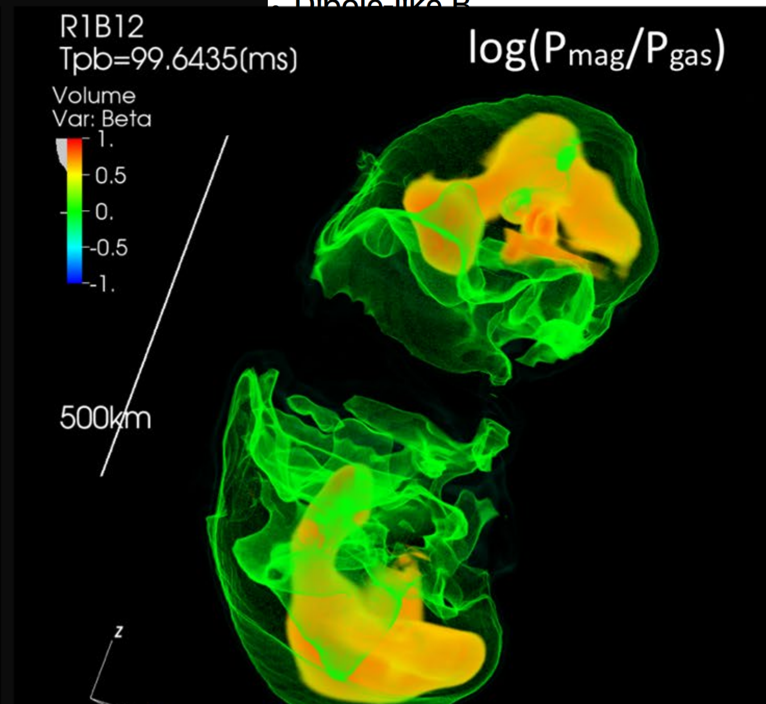
- Cylindrical rotational law

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

- Dipole-like B

$(\beta_{mag,b} \sim 1\%)$





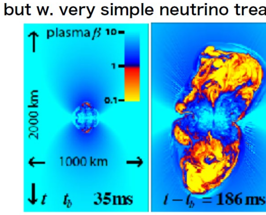
Kuroda, Takiwaki, KK, Alcones in prep

✓ **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 !

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



Started from wrong? Multi-D stellar evolution possible !

Mueller et al. (2016))

020,2021)

un star

urning

One-Bethe
D model
s reported
Garching
team using
progenitor!
llig et al.
21)

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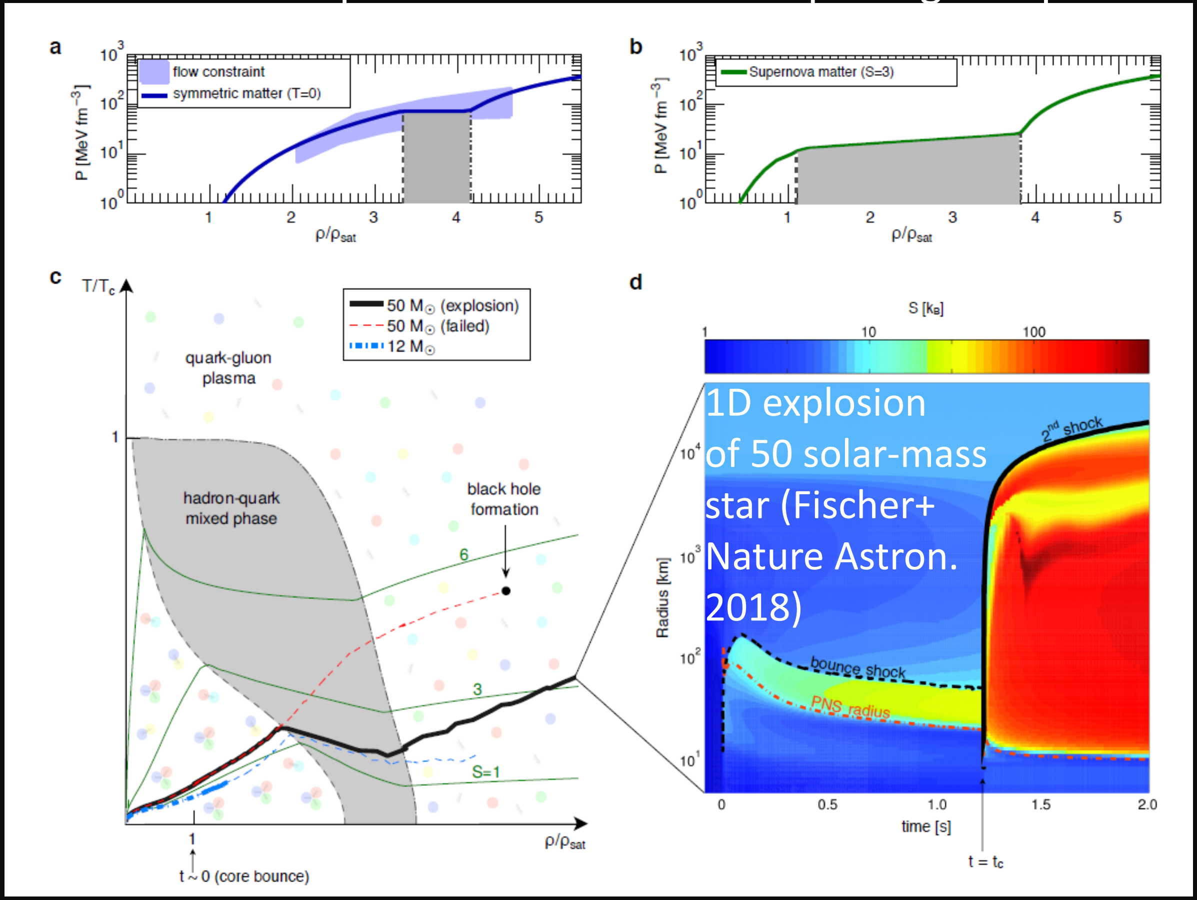
Caveat2. QCD phase transition could power explosion !!

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



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

Caveat2. QCD phase transition could power explosion !!

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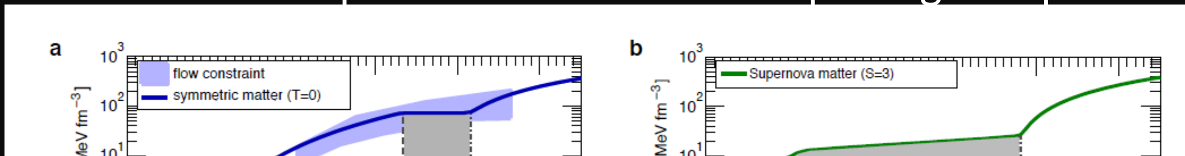

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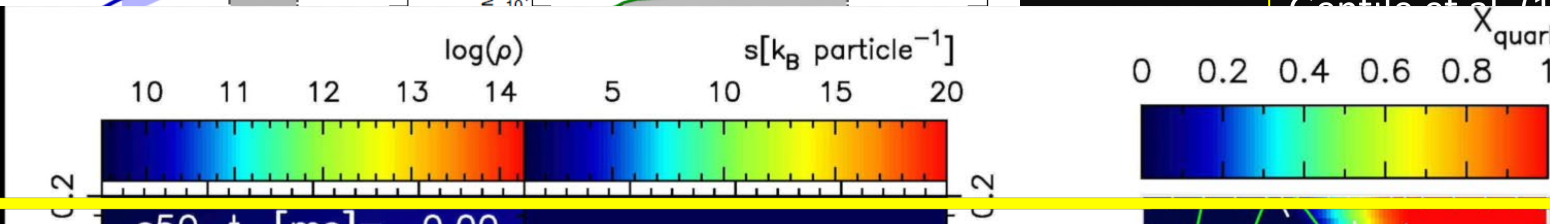
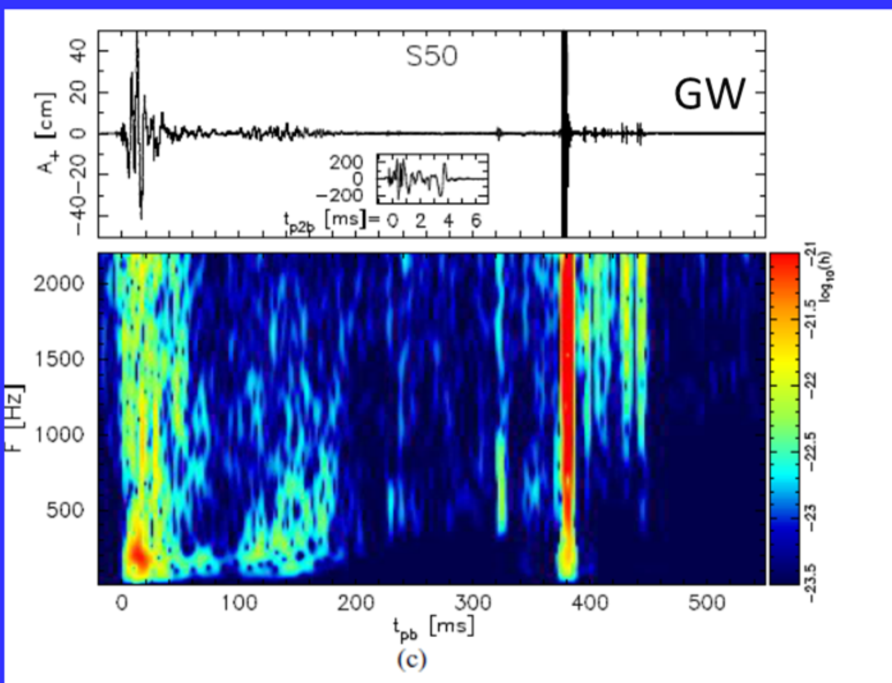
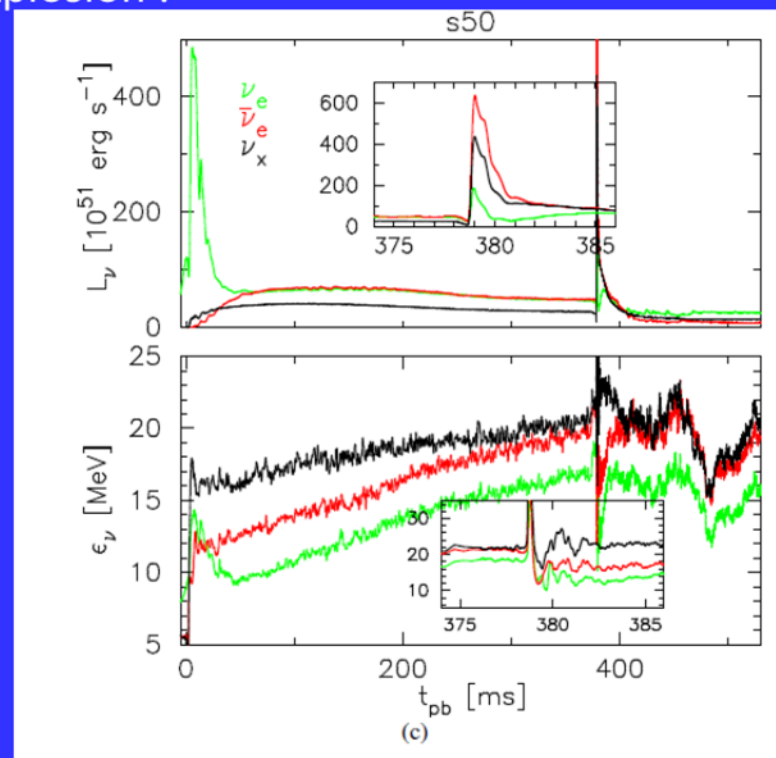
Takahara & Sato (1988)



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





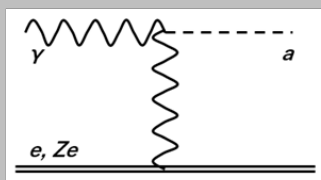
“Axions” assists the explosion onset !

(Mori, KK, Takiwaki (2022) PRD, Fischer et al. (2017), PRD, Lucente et al. (2020), JCAP)

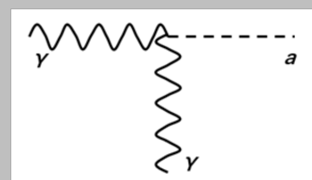
Axion-photon interaction: $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$

Axion production processes:

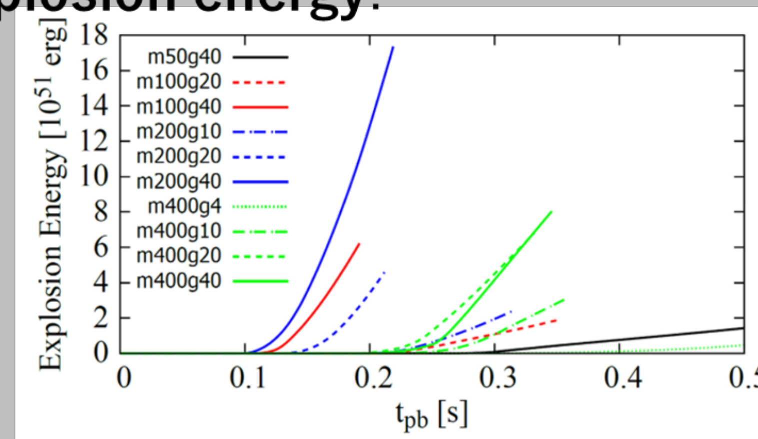
Primakoff process



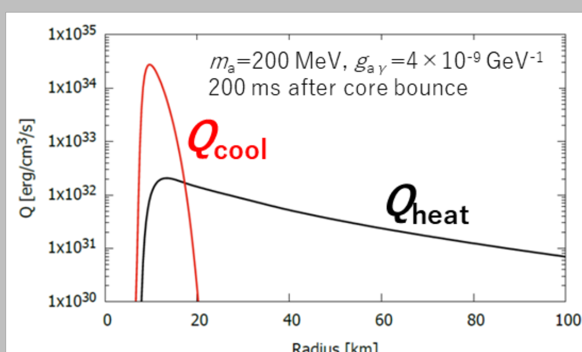
Photon coalescence



Explosion energy:

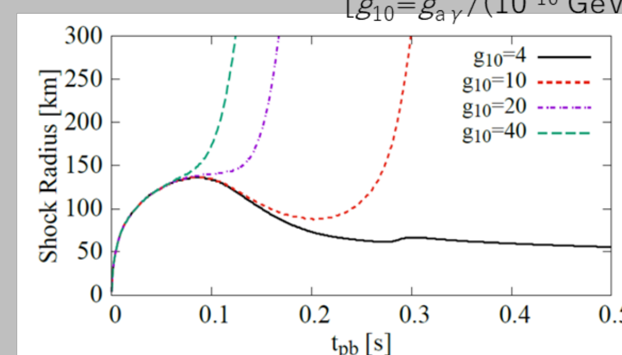


Axion cooling and heating:



Shock radius w/ m_a=200 MeV:

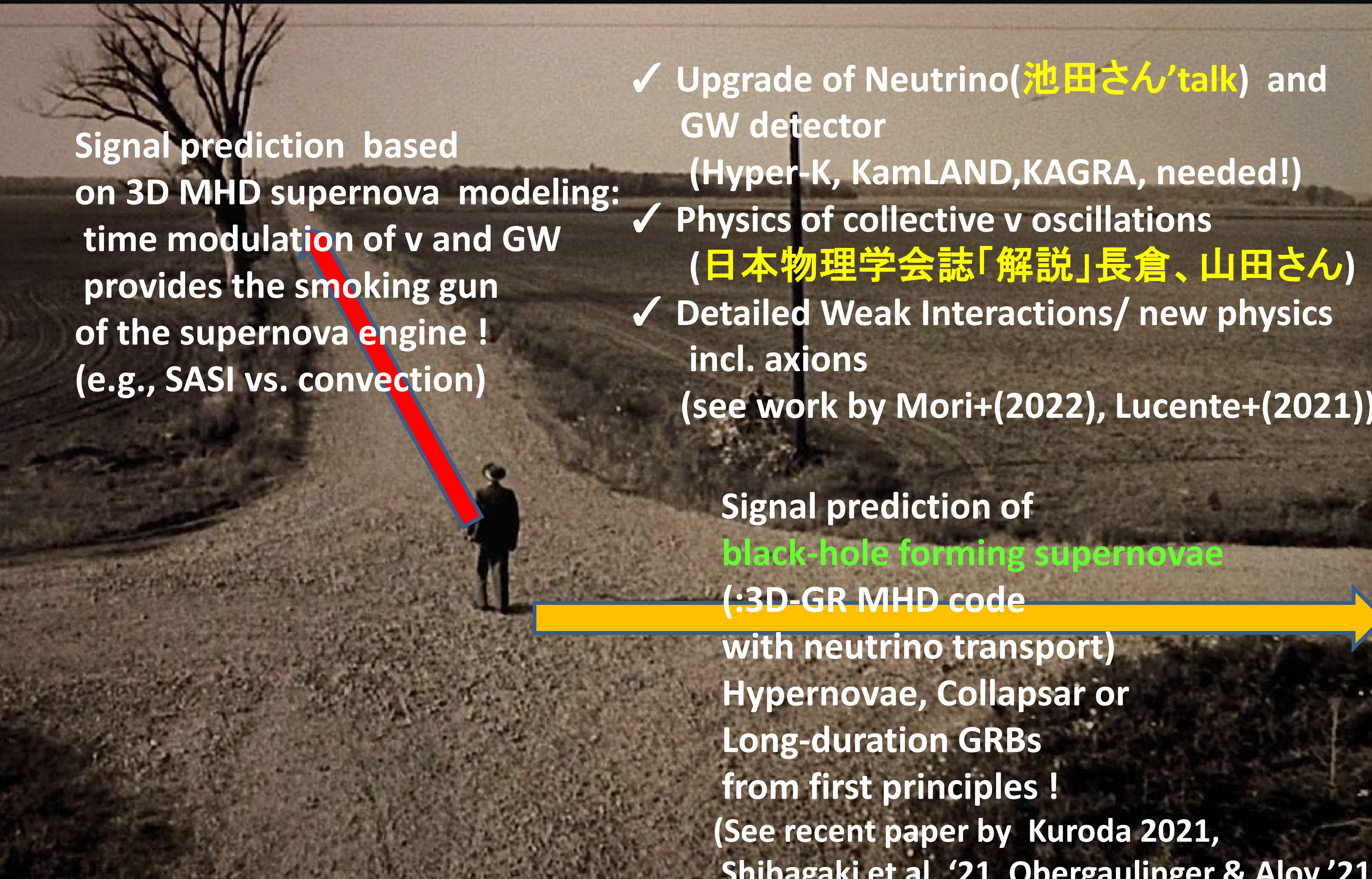
$[g_{10} = g_{a\gamma}/(10^{-10}\ \mathrm{GeV}^{-1})]$



✓ Axion cooling/heating is implemented in 1D model !

✓ Could boost under-energetic 3D models to “1-Bethe”ish !

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



Signal prediction based on 3D MHD supernova modeling:
time modulation of ν and GW provides the smoking gun of the supernova engine !
(e.g., SASI vs. convection)

- ✓ Upgrade of Neutrino(池田さん'talk) and GW detector (Hyper-K, KamLAND,KAGRA, needed!)
- ✓ Physics of collective ν oscillations (日本物理学会誌「解説」長倉、山田さん)
- ✓ Detailed Weak Interactions/ new physics incl. axions (see work by Mori+(2022), Lucente+(2021))

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