Neutrinos and Gravitational waves prediction: multi-dimensional "MHD" modeling of core-collapse supernovae:

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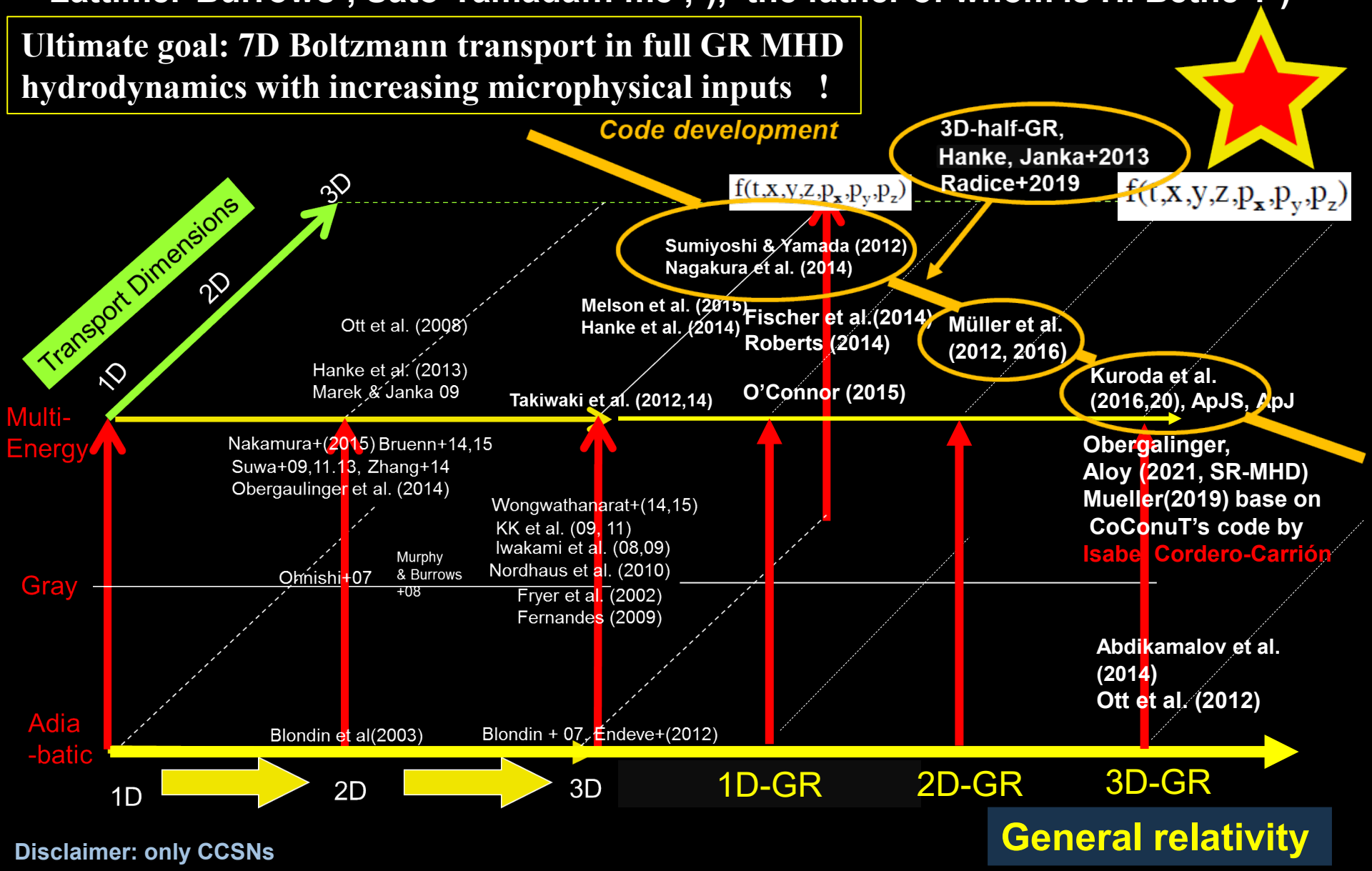
Neutrino Oscillation Workshop, Otsuni, Sep. 1-6. 2022

Sweat, Sweat, Sweat……

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

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



General relativity

Disclaimer: only CCSNs

Sweat, Sweat, Sweat……

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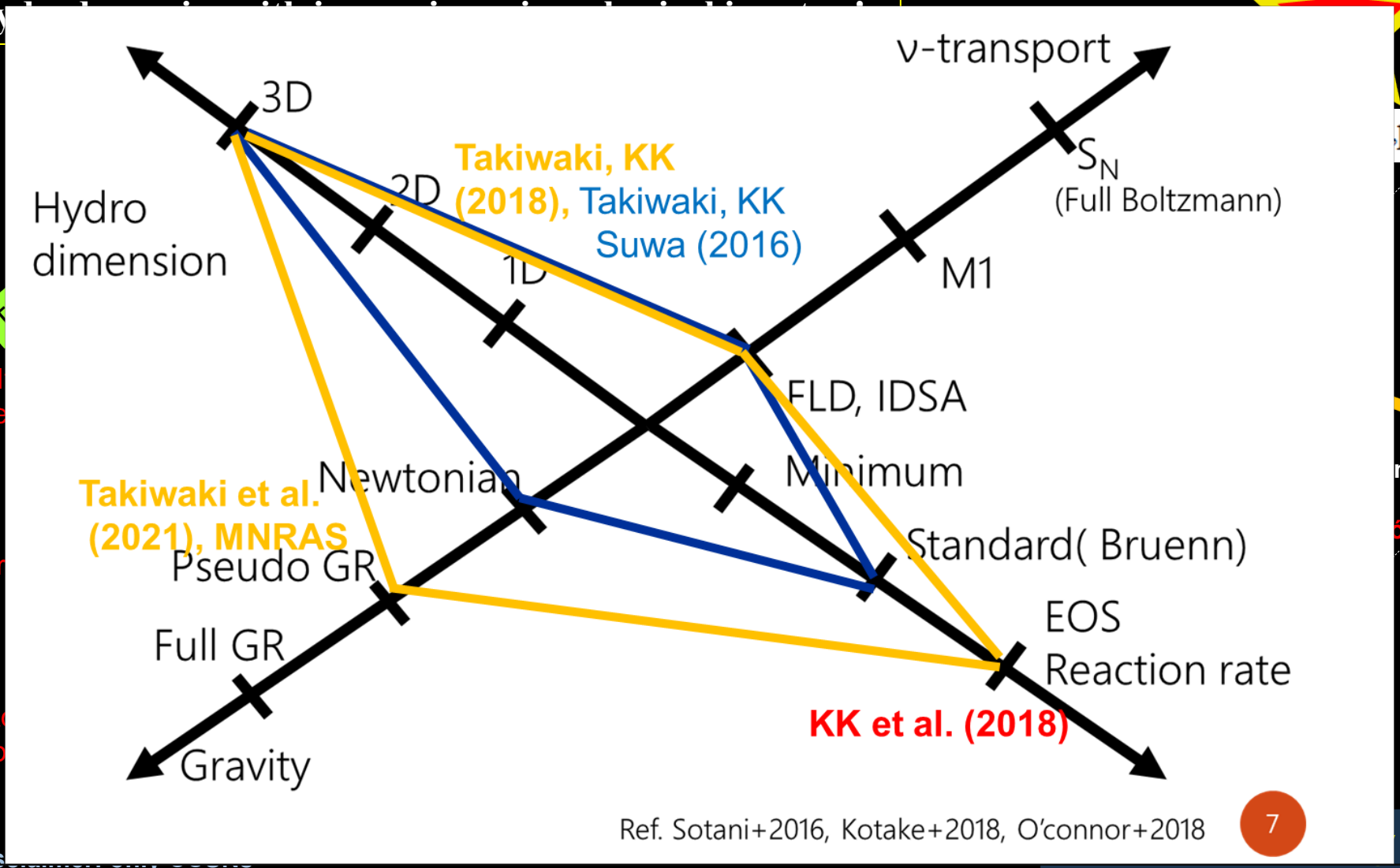
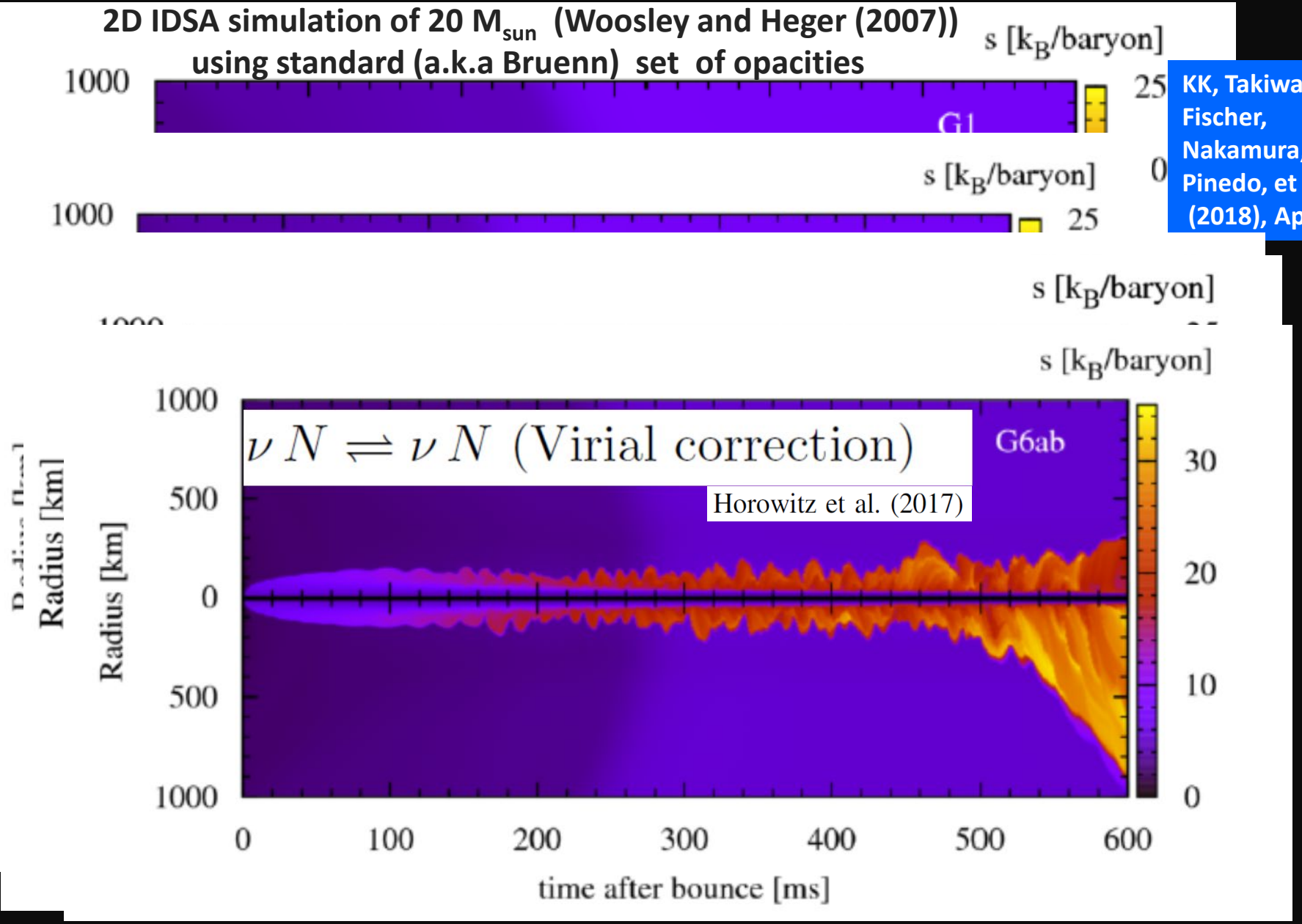
✓ Progress report of our supernova code: *Updated ν reactions in 3D code*



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

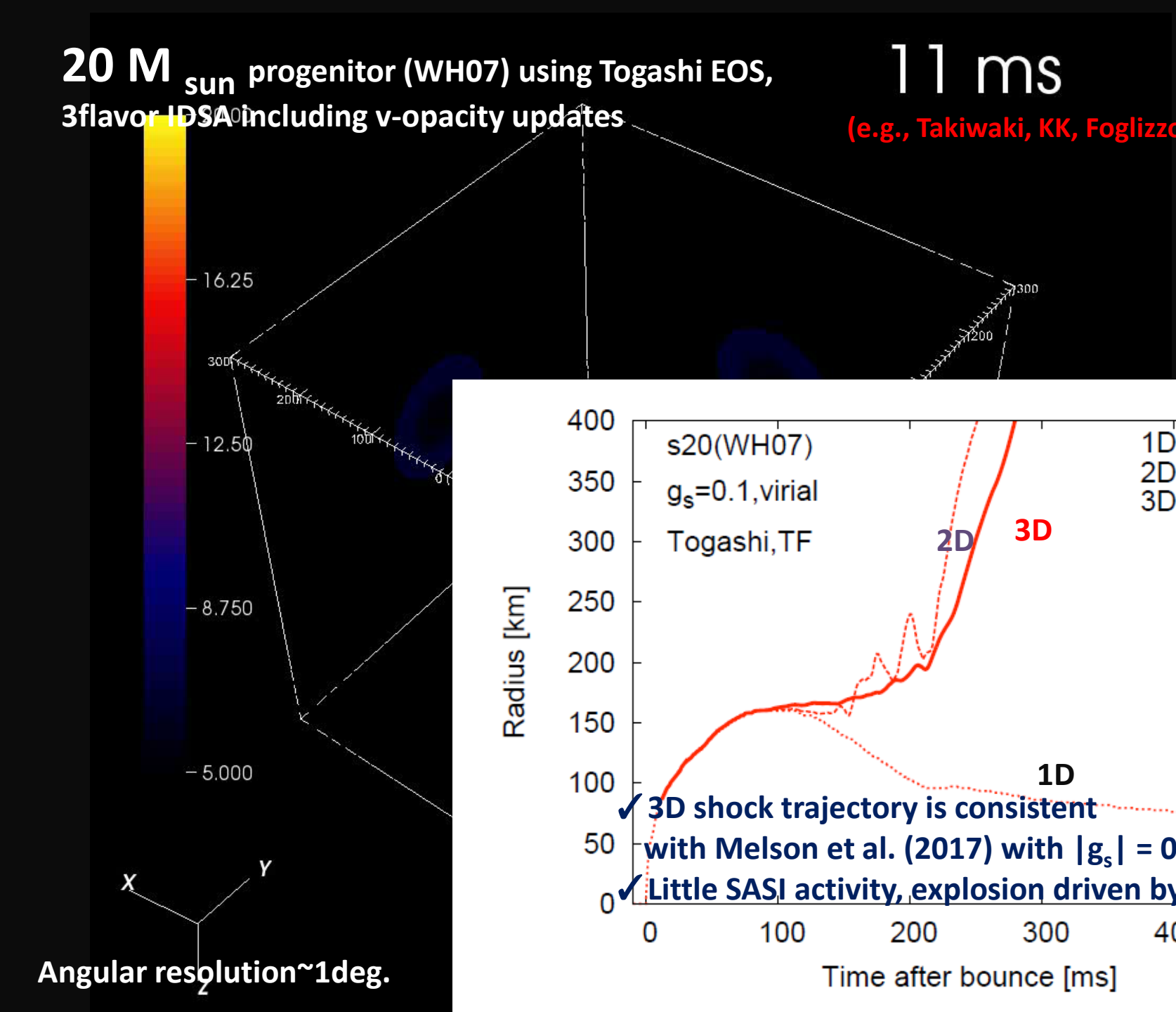


✓Quantitative GW･neutrino signal prediction, the updates in opacities mandatory!

20 M_{sun} progenitor (WH07) using Togashi EOS, 3flavor IDSA including v-opacity updates

11 ms

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



✓3D shock trajectory is consistent with Melson et al. (2017) with $|g_s| = 0.1$

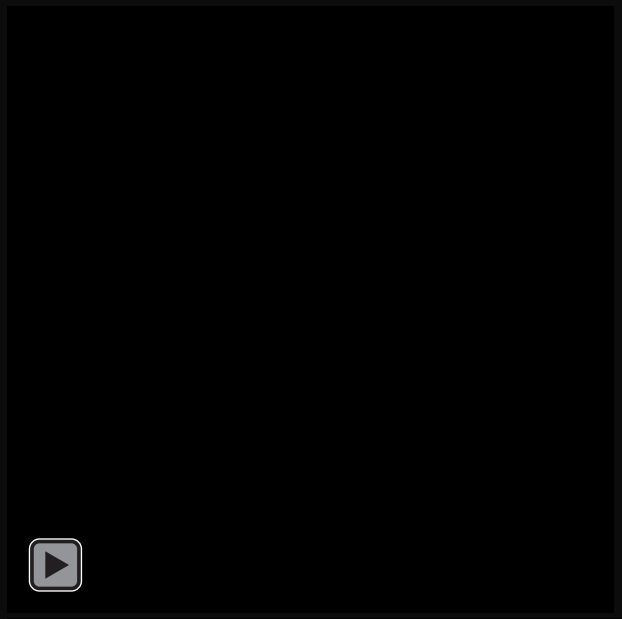
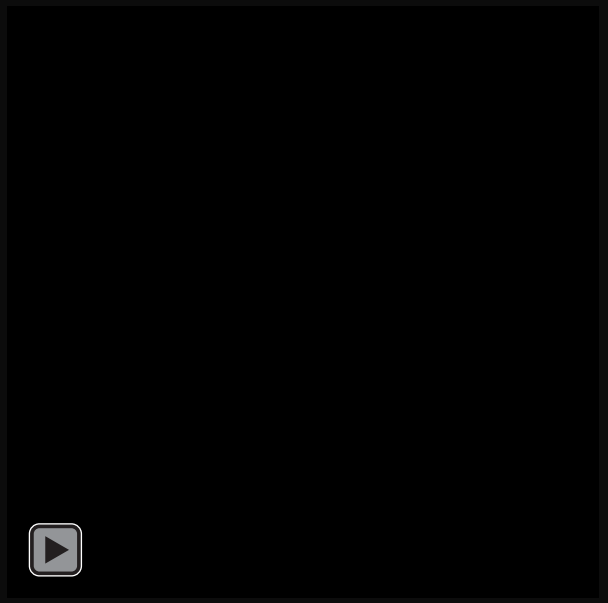
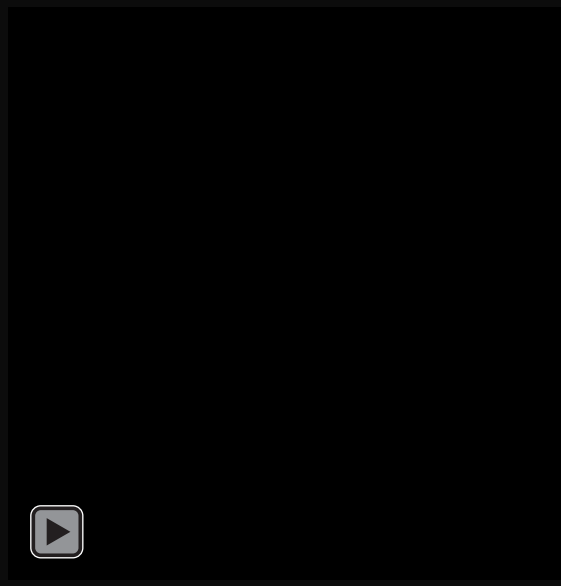
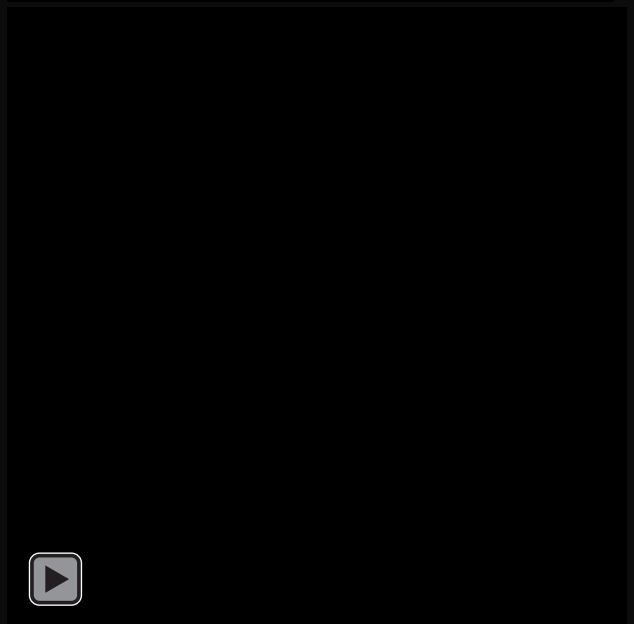
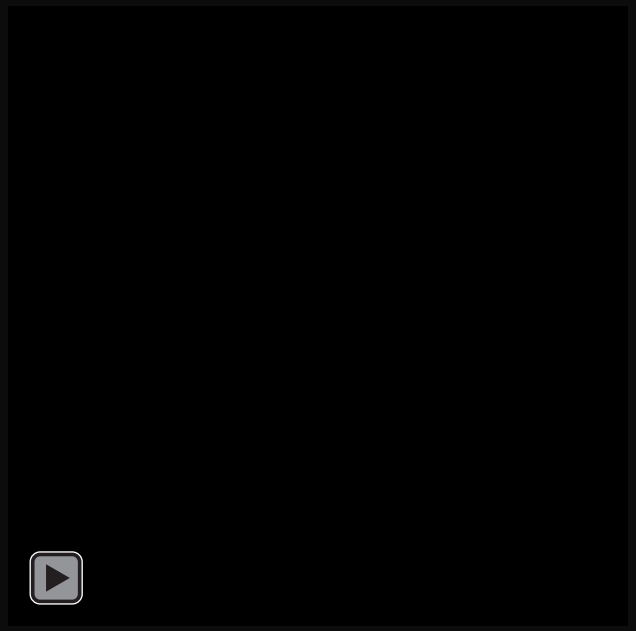
✓Little SASI activity, explosion driven by convection

Angular resolution~1deg.

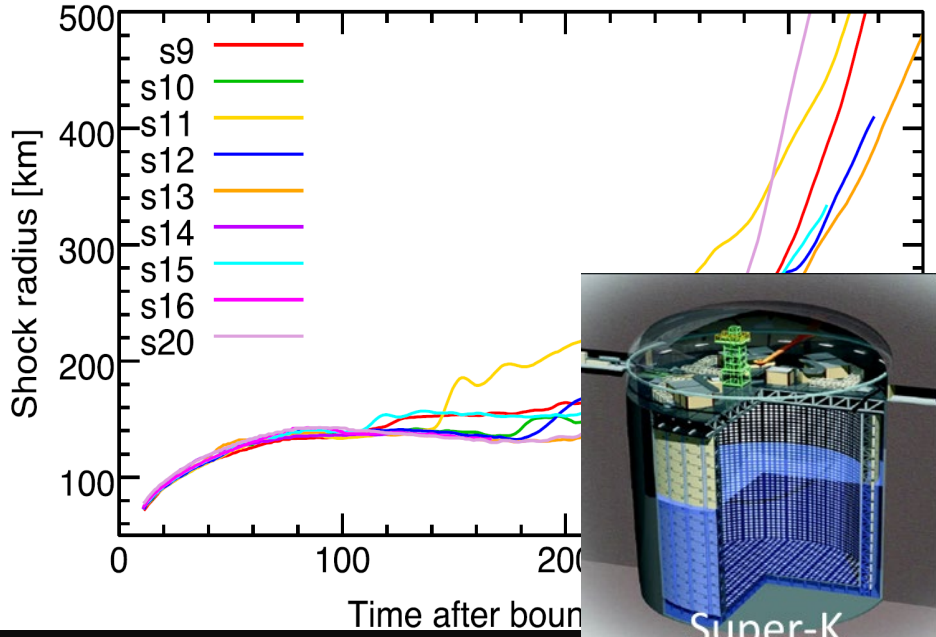
Many more 3D modeling with MHD possible !!!

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

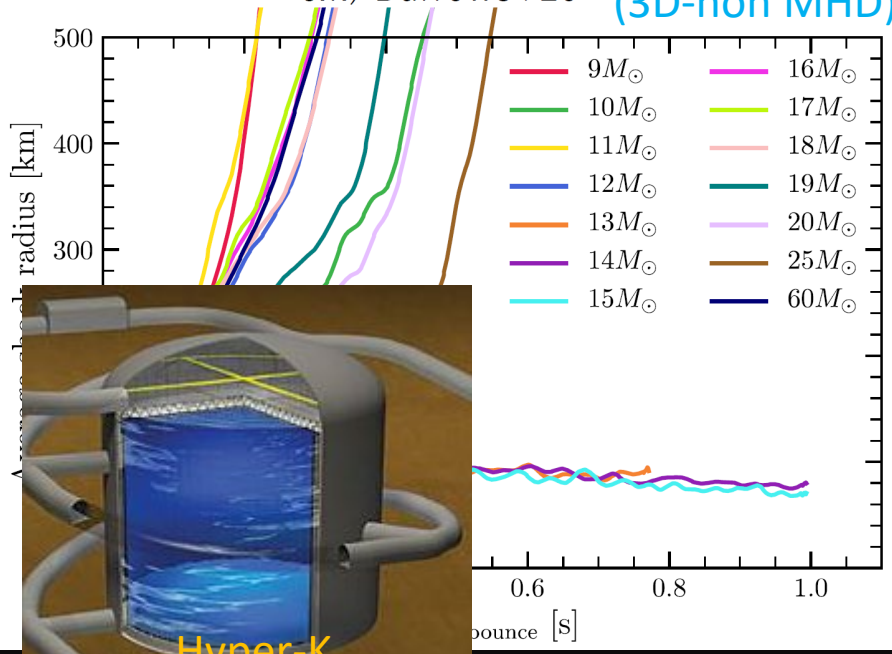
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform), Non-rotation)

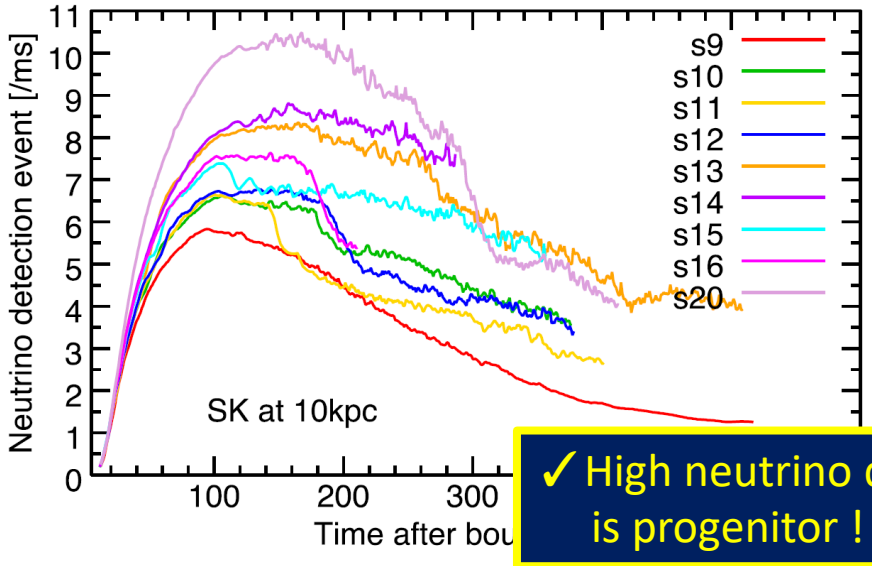

Nakamura, Takiwaki, KK in prep (3D-MHD)

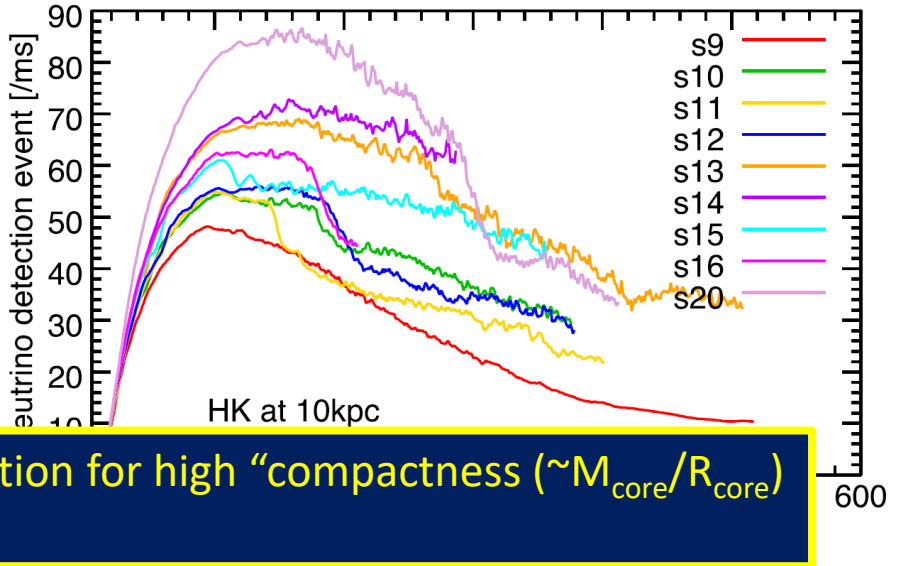


c.f.) Burrows+20 (3D-non MHD)

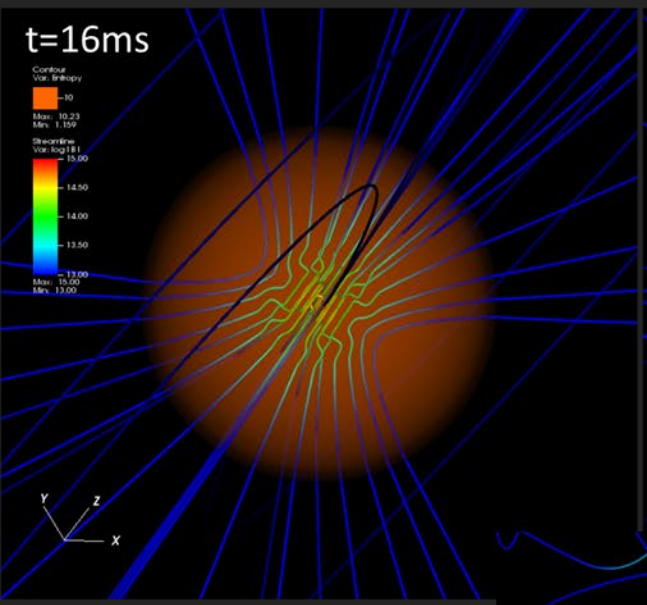


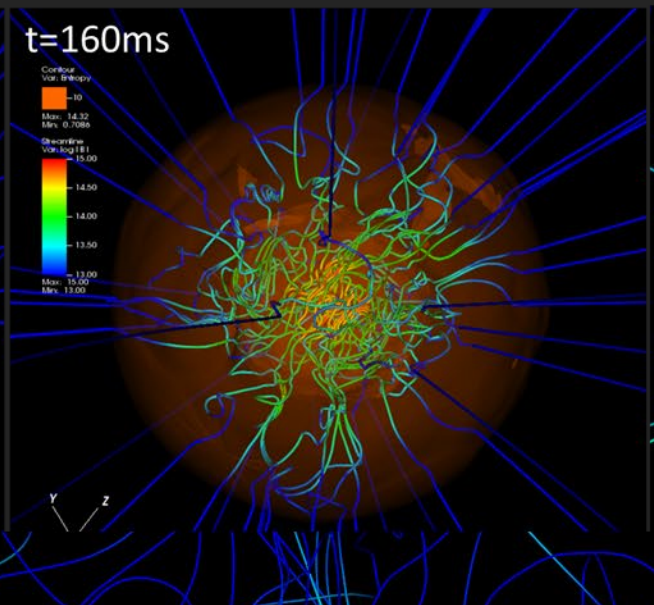
✓Neutrino detection rate at SuperKamokande and HyperKamiokande

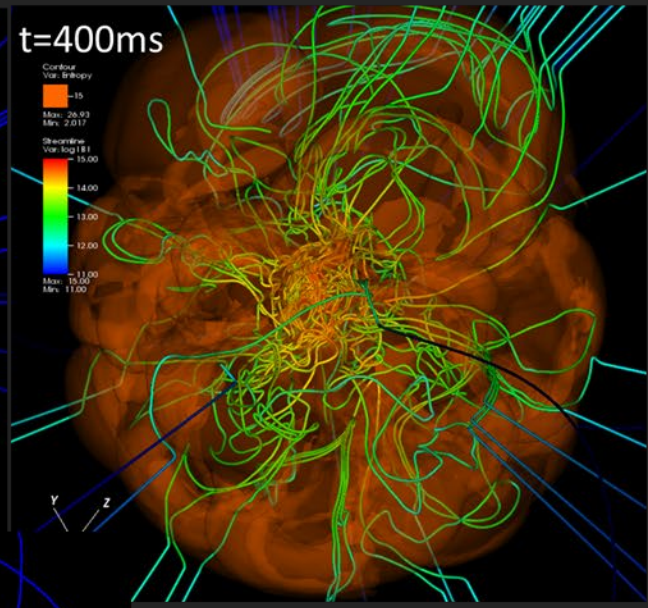


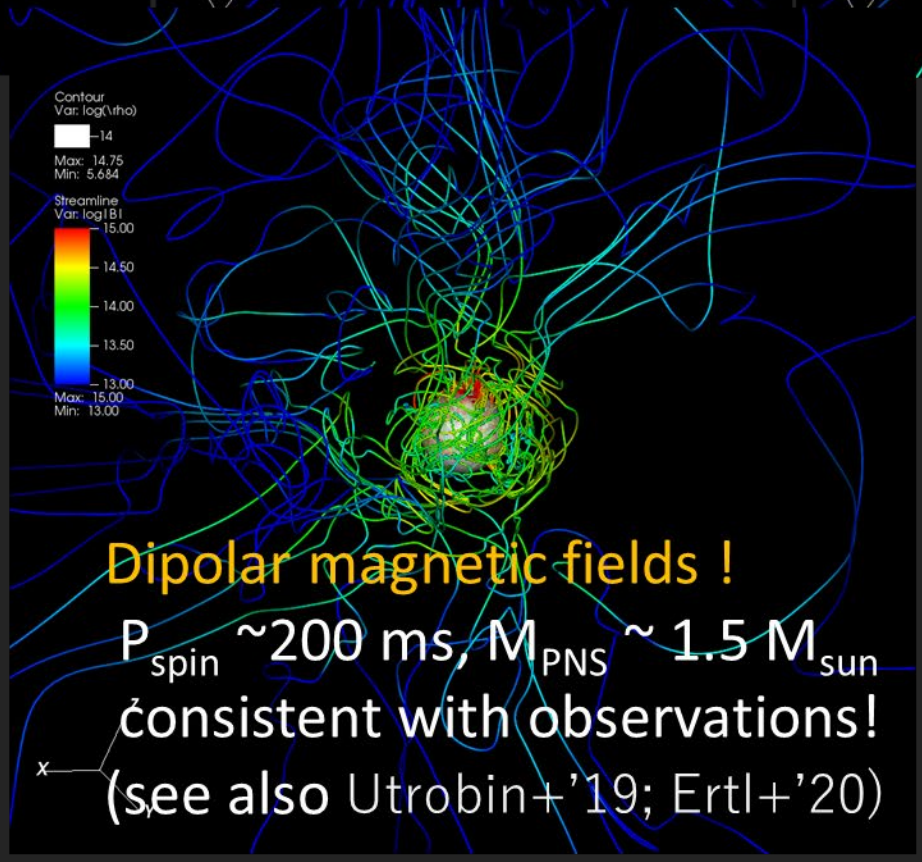


✓High neutrino detection for high "compactness (~M_{core}/R_{core}) is progenitor !



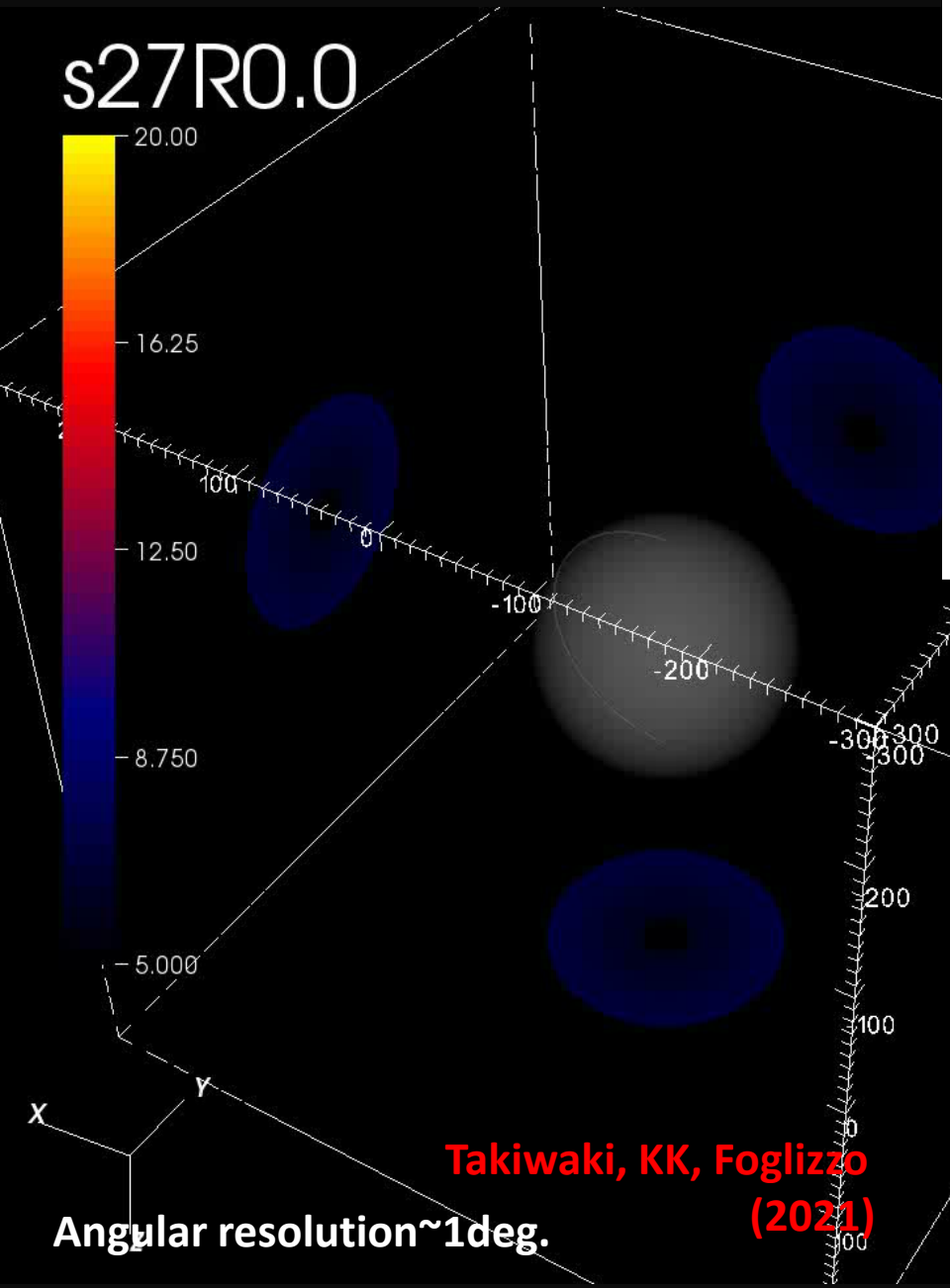


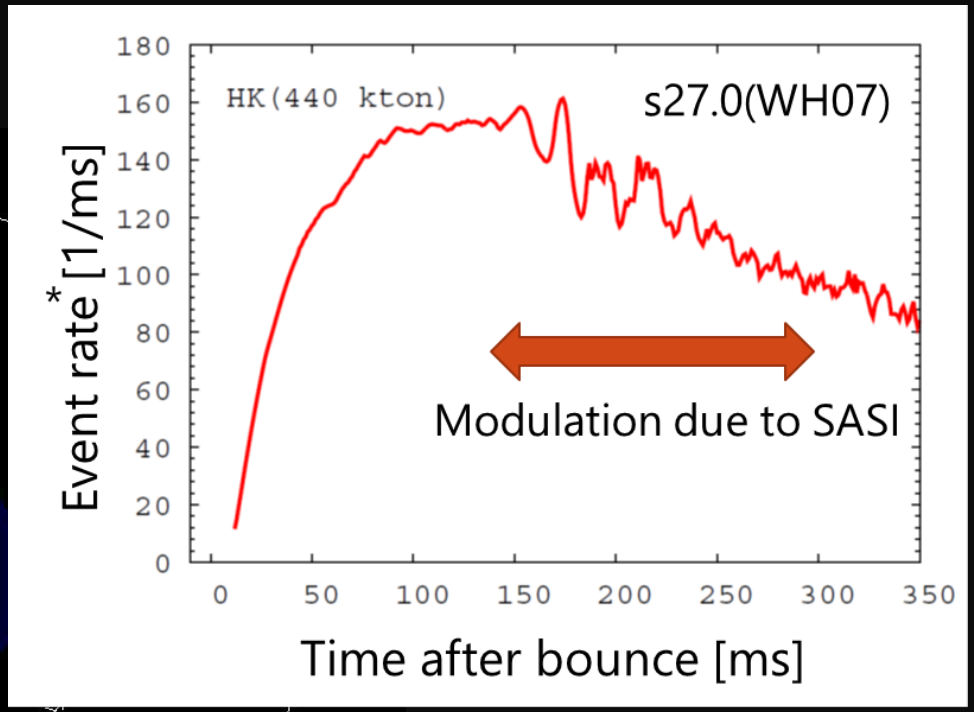




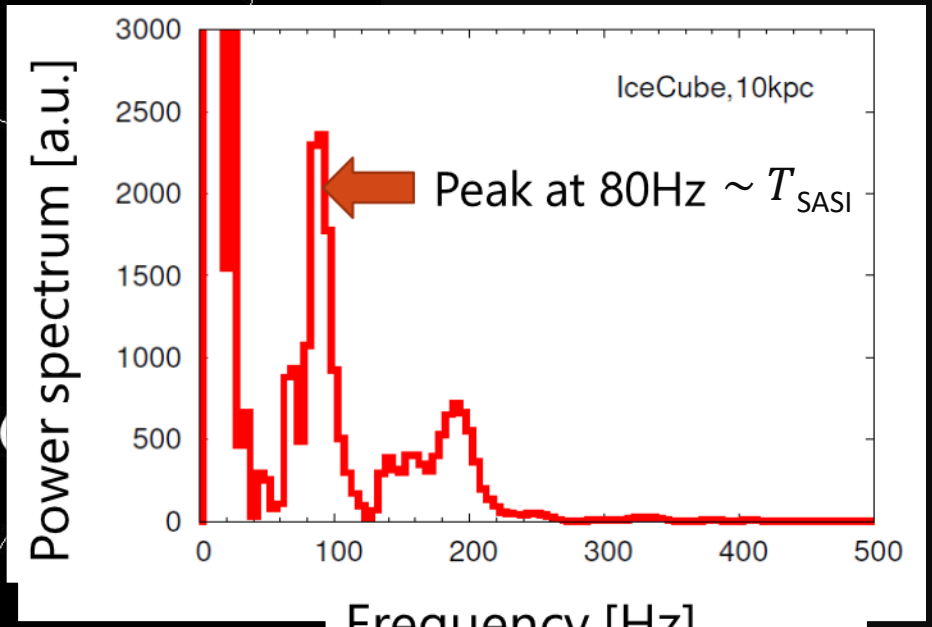
✓ **Dynamo in the PNS needs to be studied In detail** as in Raynaud, Guilet et al. (2020), Masada, Takiwaki, KK ApJ in press

27 M_{sun} progenitor (WH07)





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

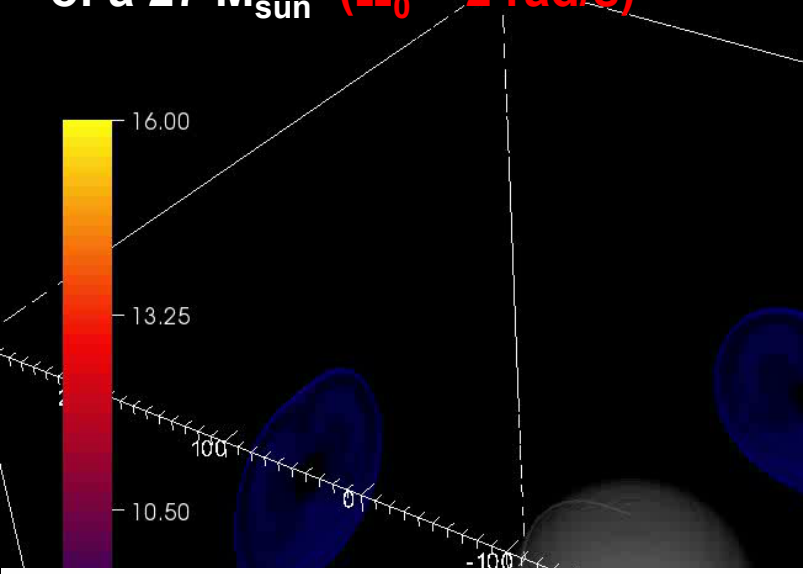


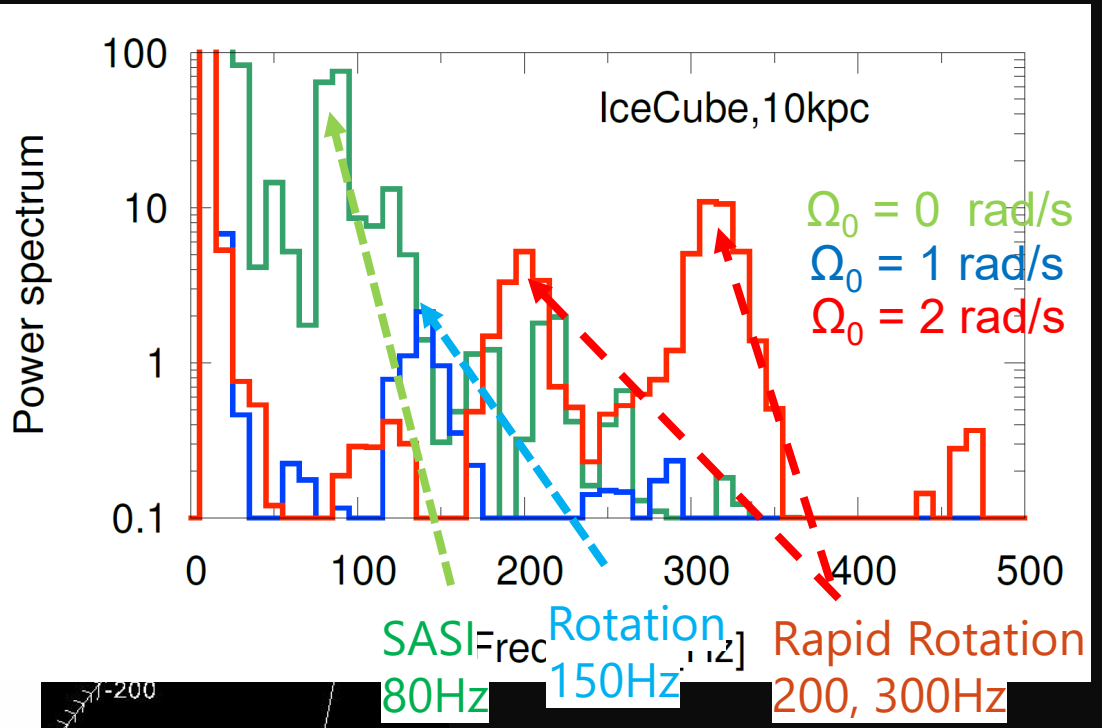
Takiwaki, KK, Foglizzo (2021)

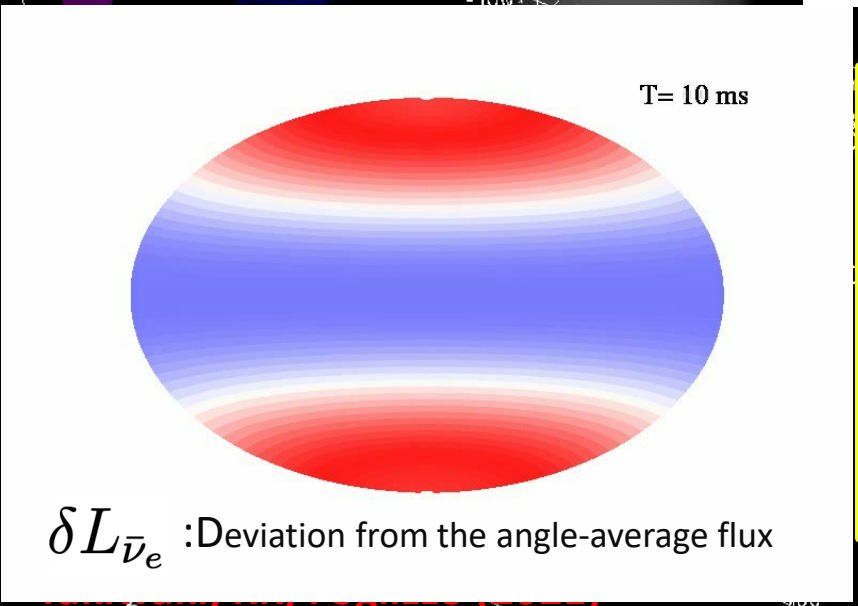
Angular resolution~1deg.

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

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







✓ **Peak frequencies become higher with progenitor rotation !**

because rapid rotation leads to rapidly rotating PNS and neutrino sphere.

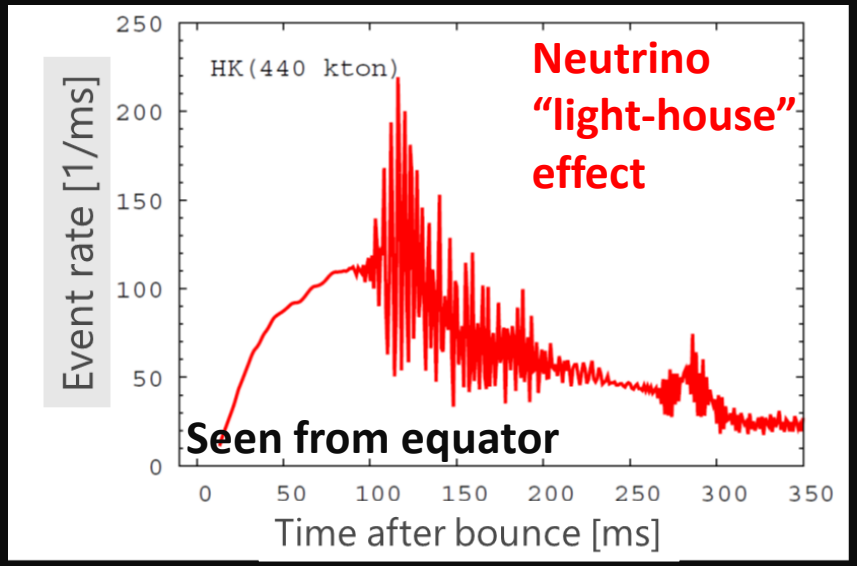
=> *The light-house effect*

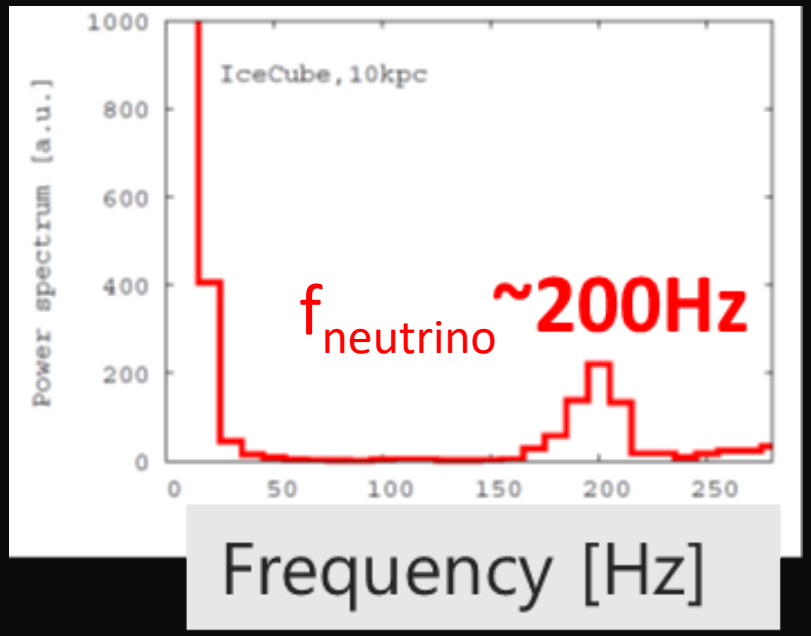
600 km **(found in simplified 3D model by Takiwaki and KK (2018)).**

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

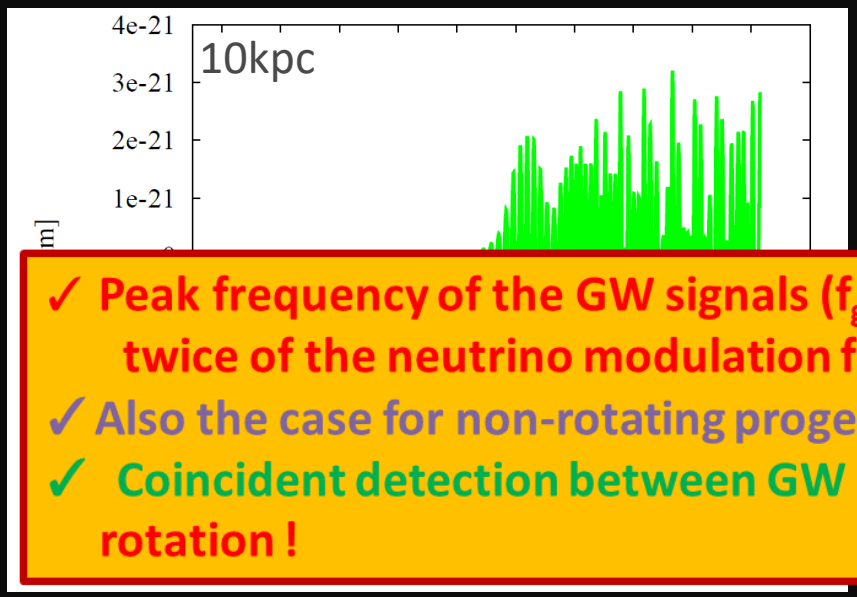
Takiwaki, KK, Foglizzo, (2021)

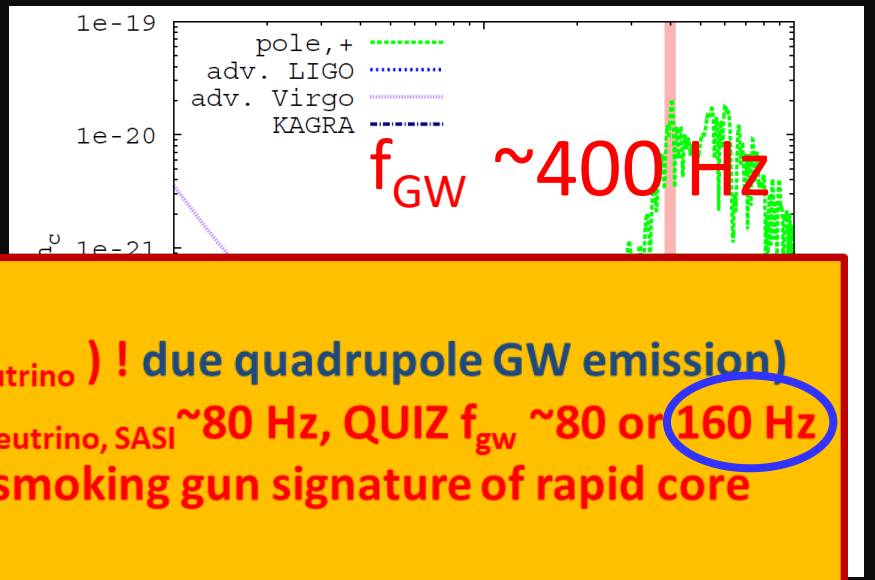
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform





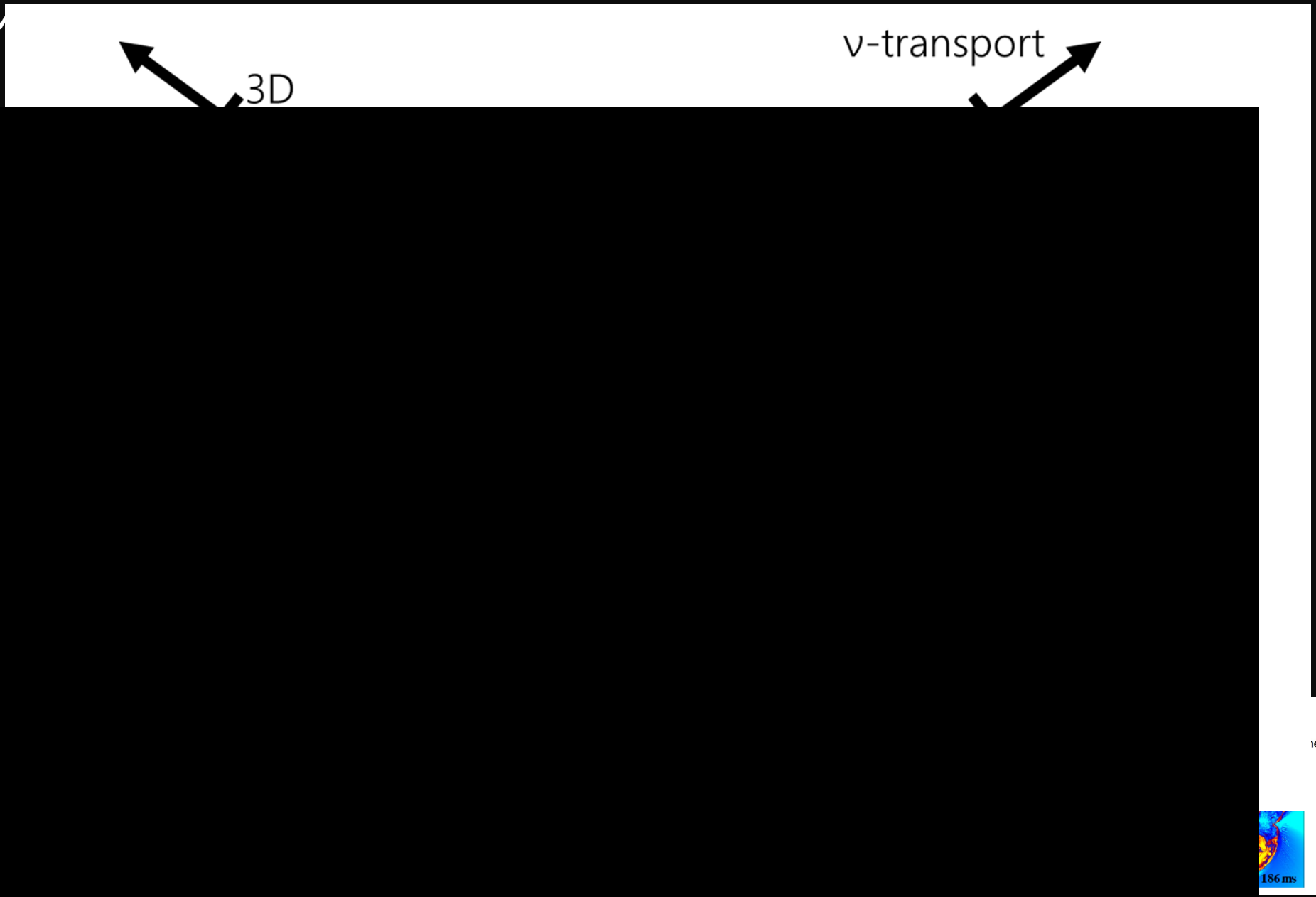
✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)

✓ 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 !

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

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



Started from wrong? Multi-D stellar evolution possible !

Mueller et al. (2016))

020,2021)

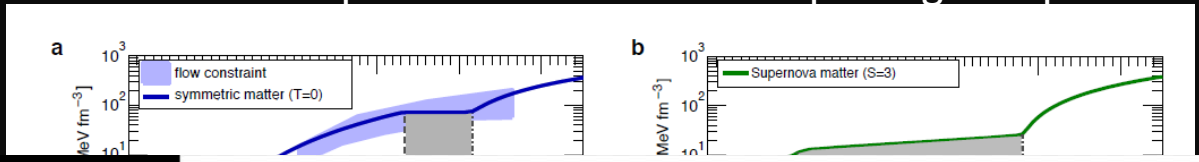
un star

urning

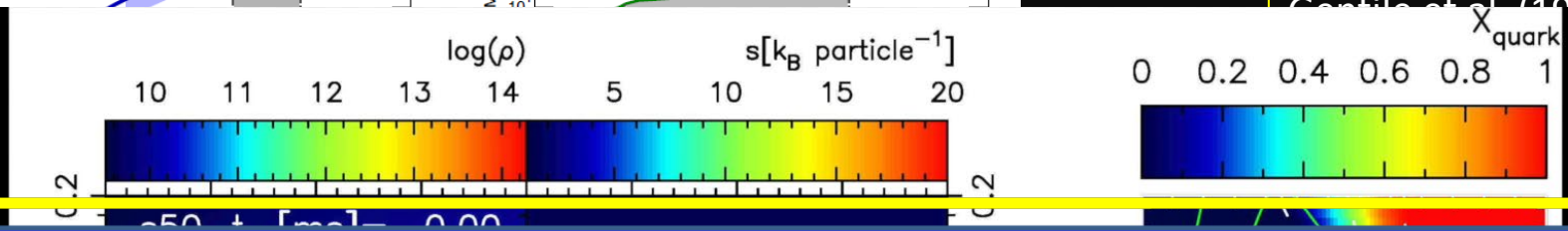
One-Bethe
D model
s reported
Garching
team using
progenitor!
llig et al.
21)

Caveat2. QCD phase transition could power explosion !!

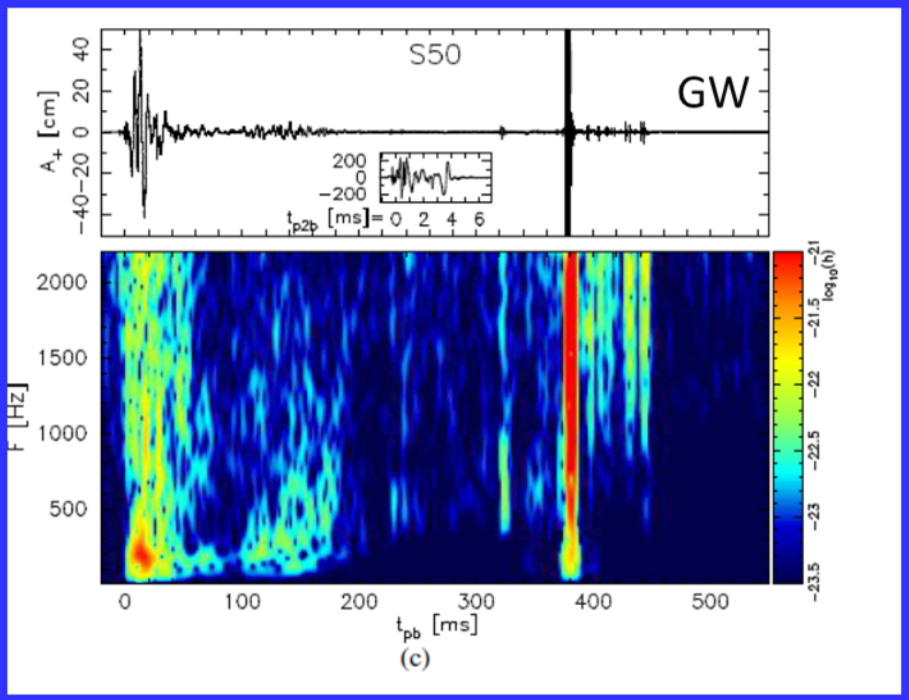
If “first-order” phase transition to the quark-gluon phase takes place… then

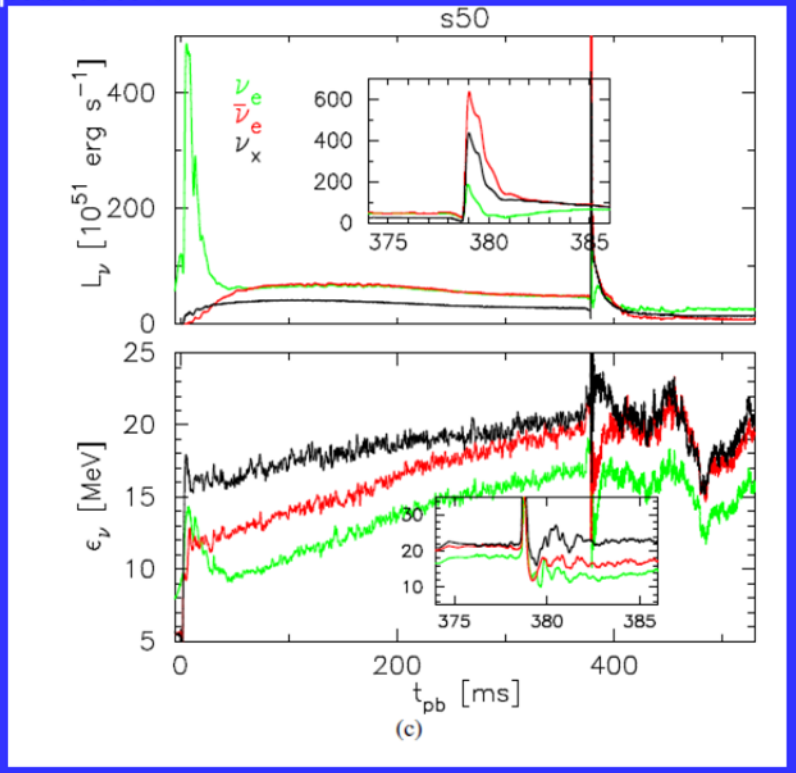


✓Original idea:
Takahara & Sato (1988)
Gentile et al. (1993)



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





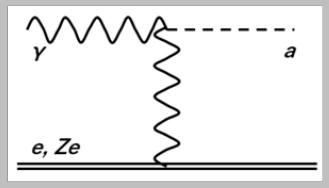
Impact of axions on CCSN mechanism

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

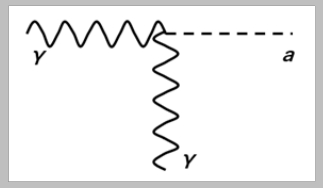
Axion-photon interaction: $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$

Axion production processes:

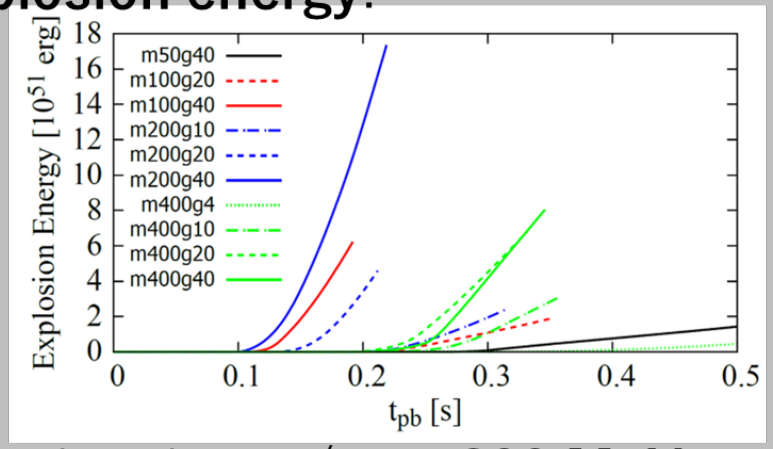
Primakoff process



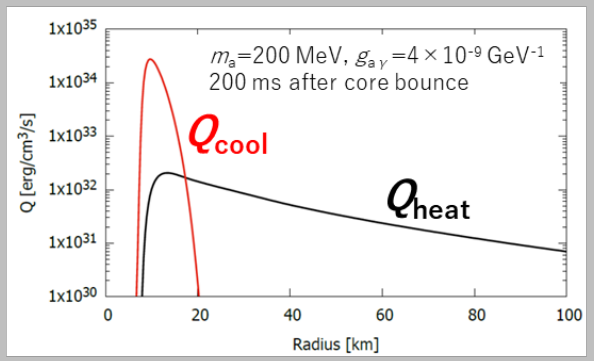
Photon coalescence



Explosion energy:

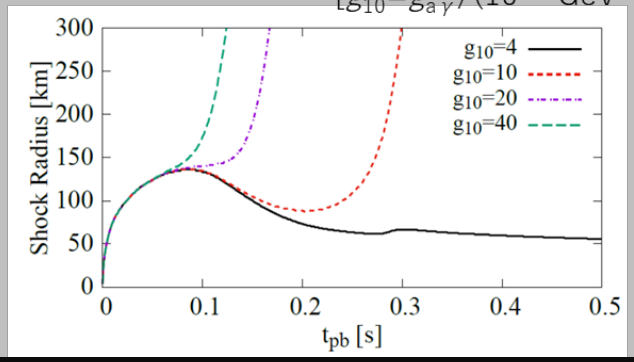


Axion cooling and heating:



Shock radius w/ m_a=200 MeV:

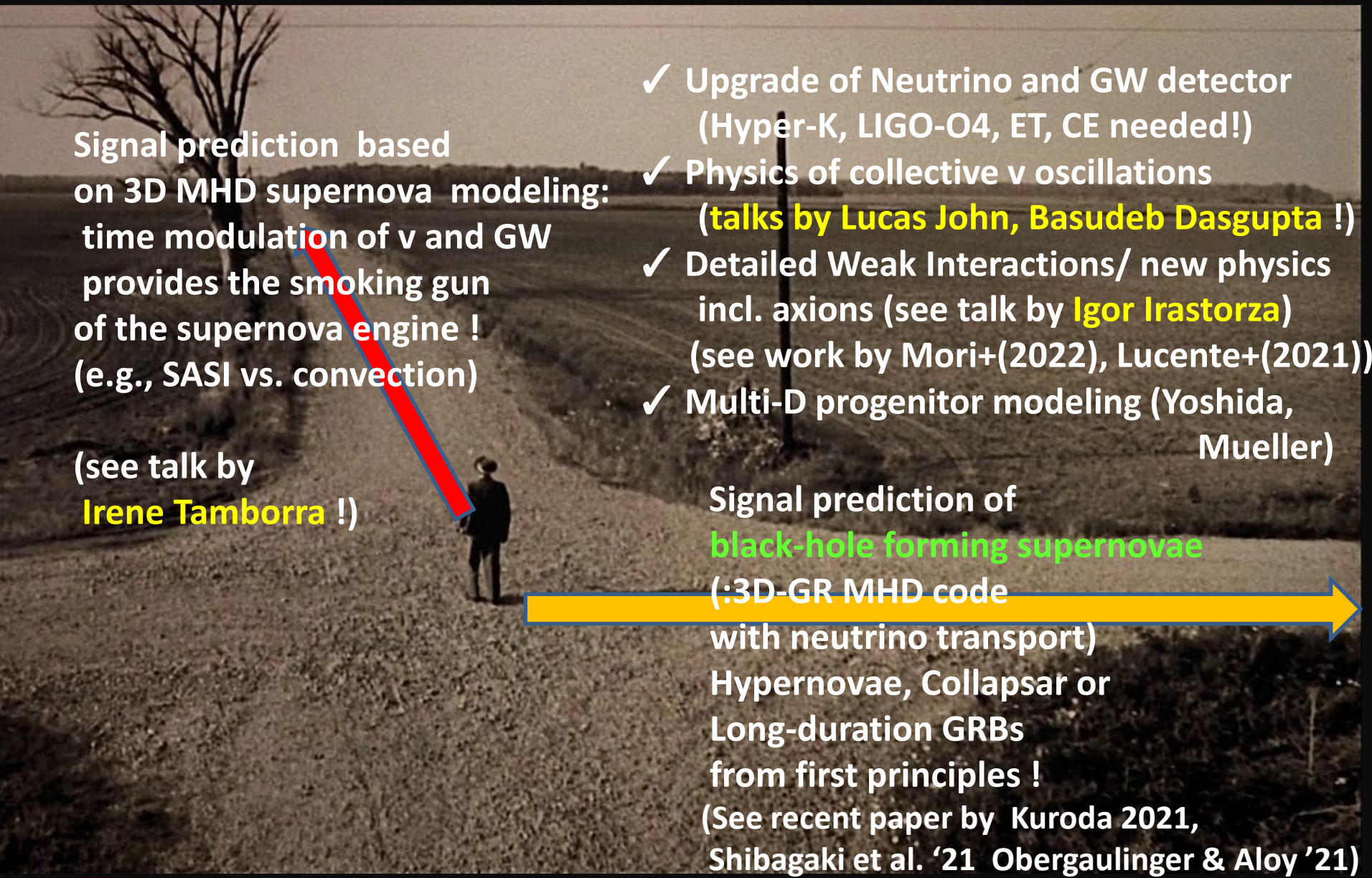
$[g_{10}=g_{a\gamma}/(10^{-10}\ \mathrm{GeV}^{-1})]$



✓ 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 v and GW provides the smoking gun of the supernova engine ! (e.g., SASI vs. convection)

(see talk by Irene Tamborra !)

✓ Upgrade of Neutrino and GW detector (Hyper-K, LIGO-O4, ET, CE needed!)

✓ Physics of collective v oscillations (talks by Lucas John, Basudeb Dasgupta !)

✓ Detailed Weak Interactions/ new physics incl. axions (see talk by Igor Irastorza) (see work by Mori+(2022), Lucente+(2021))

✓ Multi-D progenitor modeling (Yoshida, Mueller)

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)