Gravitational-wave (GW) and neutrino signatures from multi-D core-collapse supernova models

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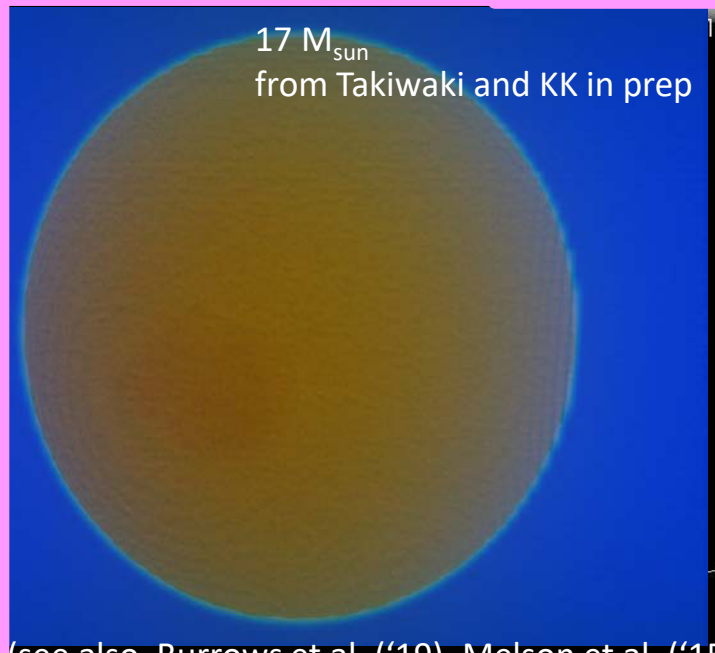
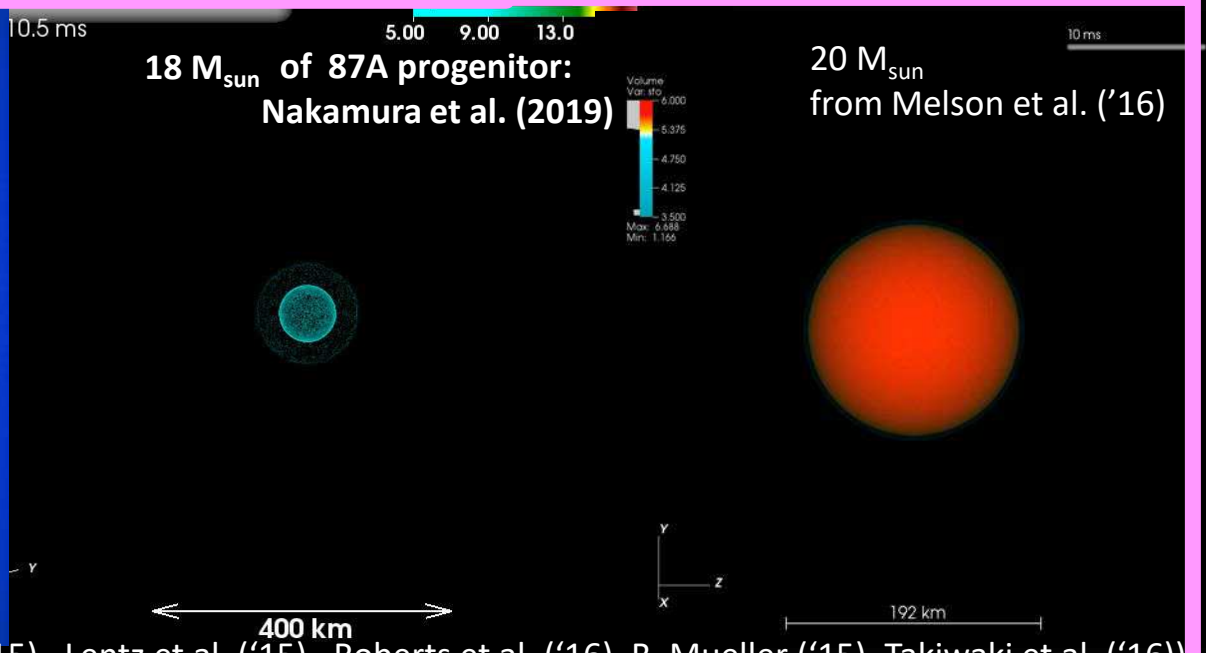
Evolution of Massive Stars and Formation of Compact Stars:
from the Cradle to the Grave, Waseda University, February 28, 2020

Two candidate mechanisms of core-collapse supernovae

(Talk by Vartanyan ! reviews in Janka ('17), Müller ('16), Foglizzo+('15), Burrows('13), Kotake+ ('12))

	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s)	Rapidly rotation with strong B ($\Omega_0 > \sim \pi$ rad/s, $B_0 > \sim 10^{11}$ G)
Key ingredients	✓**Turbulent Convection and SASI** (e.g., Radice+ (2018), Kazeroni+ (2017)) ✓**Precollapse Inhomogenities/structures** (e.g., B.Mueller et al. (17), Suwa & Mueller (16)) ✓**Novel microphysics:** Bollig+(17), Fischer+(18)	✓**Field winding and the MRI** (e.g., Obergaulinger & Aloy (2017), Rembiasz et al. (2016), Moesta et al. (2016), Masada + (2015)) ✓ **Non-Axisymmetric instabilities** (e.g., Takiwaki, et al. (2016), Summa et al. (2017))
Progenitor fraction	Main players	~<1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)

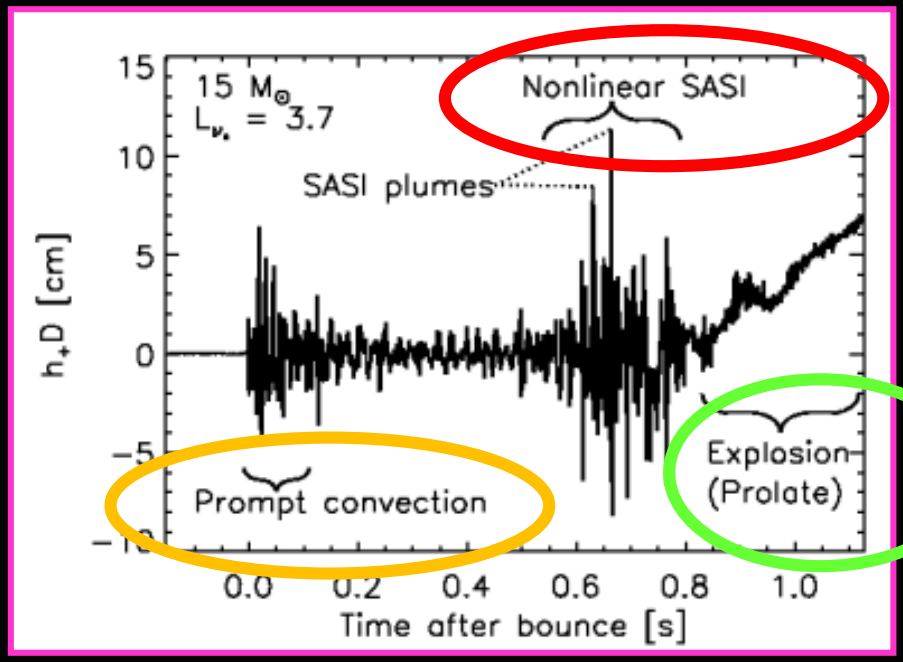




(see also, Burrows et al. ('19), Melson et al. ('15), Lentz et al. ('15), Roberts et al. ('16), B. Mueller ('15), Takiwaki et al. ('16))

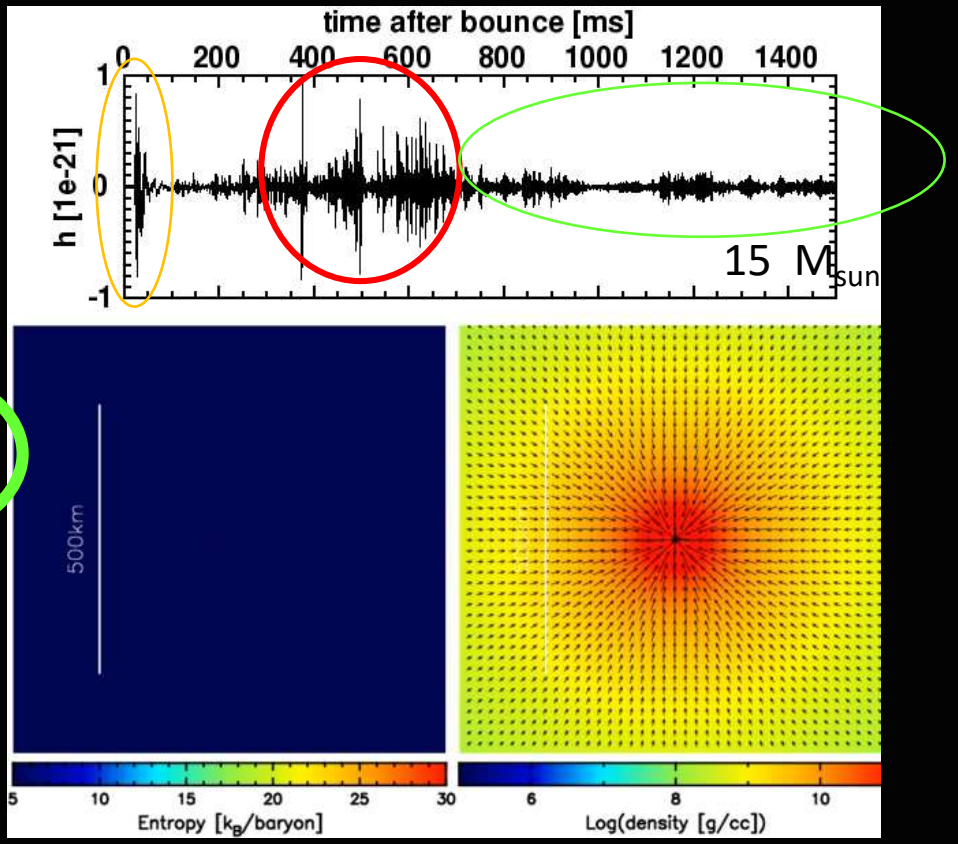
GW signatures from 2D neutrino-driven explosion (1/2)

Waveform from Murphy et al. (2009) ApJ



(Later confirmed by B. Mueller et al. ('13), ApJ, Yakunin et al. (2015), PRD)

Waveform from Nakamura et al. ('16) MNRAS



✓ Three generic phases in neutrino-driven models:

1. Prompt-convection phase : within ~50 ms post-bounce
2. Non-linear phase (Convection/SASI) : Downflows hit the PNS surface
3. Explosion phase : Long-lasting signal but terminates if BH forms

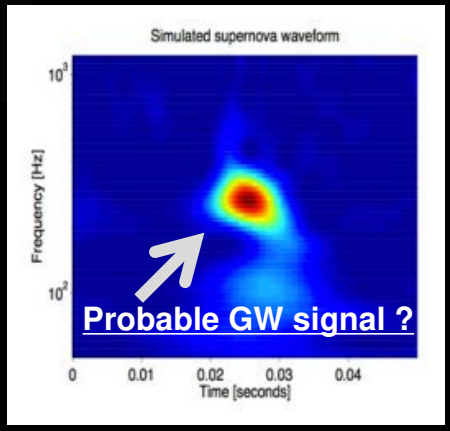
(Müller et al. (2004, ApJ), Cerda-Duran et al. (2013, ApJ))

✓ Waveforms have no template character: stochastic explosion processes.

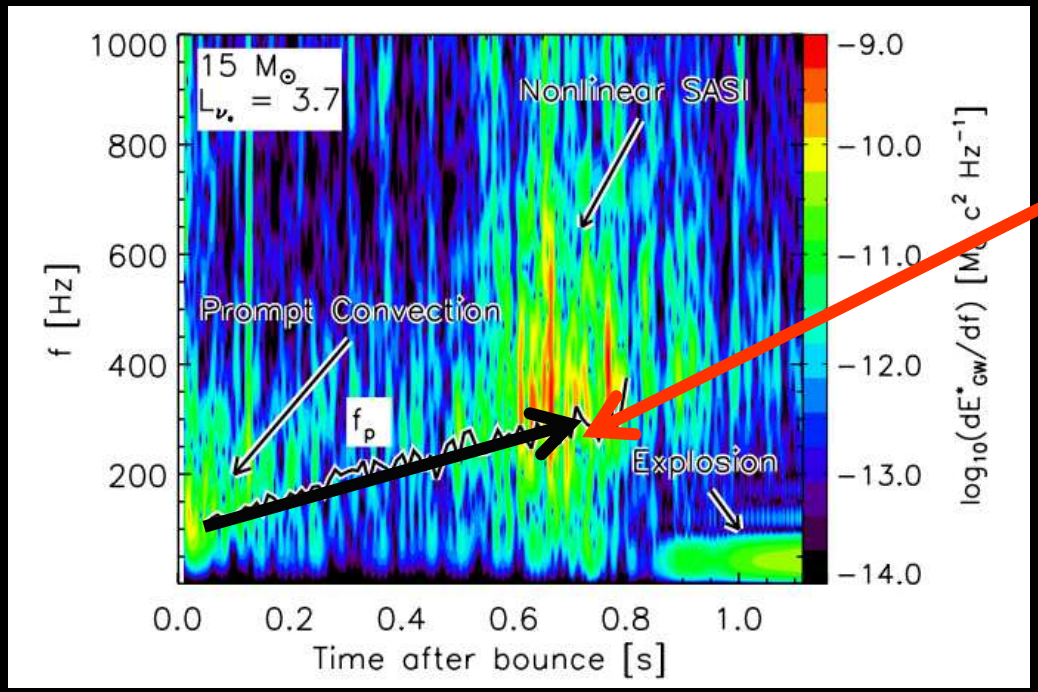
How to detect GWs with no-template features…

✓ **Excess power method**: Flanagan & Hugh (1998)

⇒ Decompose data-stream into time-frequency domains
⇒ Search for "hot" regions with excess power in the spectrogram !



✓ GW spectrogram from Murphy et al. ('09) ApJ.



☆ Increase of typical frequency
⇒ the g-mode frequency of PNS

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

M, R, T : mass, radius & temperature of PNS, Γ : stiffness of EOS
Due to mass accretion, M↗, R↘

⇒ f_p ↗

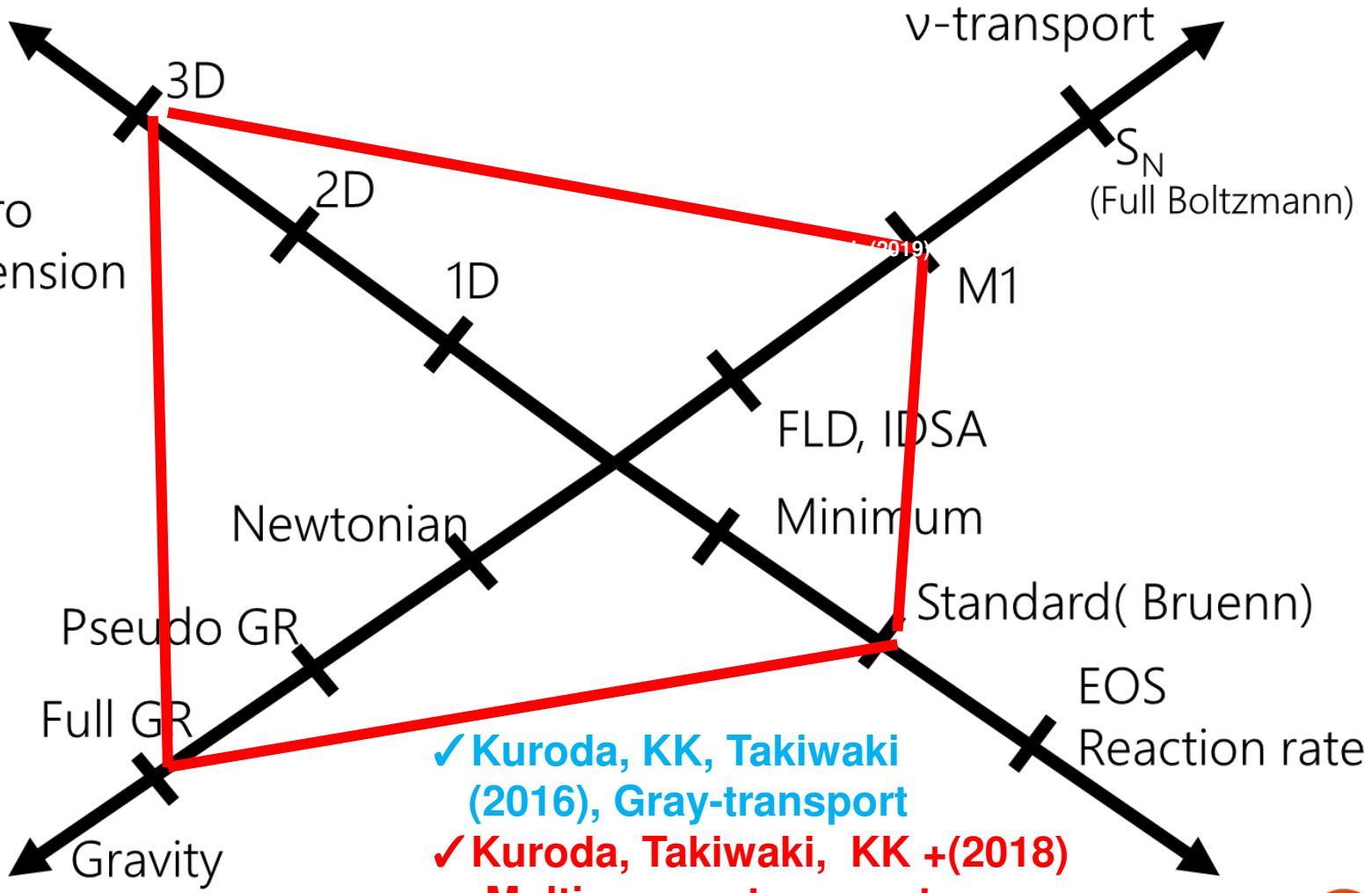
(see complete derivation in B. Mueller et al. ('13), ApJ)

✓ (With no template character…) **Three generic phases are in the spectrogram !**
✓ Secular increase of typical GW frequency (f_p) **reflects the PNS evolution.**
✓ **These qualitative features : Common to more recent 2D and 3D models**
✓ **2D overestimates GW amplitudes relative to 3D. Need 3D !**

Sweat, Sweat, Sweat….

Big simulation codes = Experimental facilities

Ultimate goal: 7D Boltzmann transport in full GR MHD



✓ Kuroda, KK, Takiwaki (2016), Gray-transport

✓ Kuroda, Takiwaki, KK +(2018) Multi-energy transport

Ref. Sotani+2016, Kotake+2018, O'connor+2018

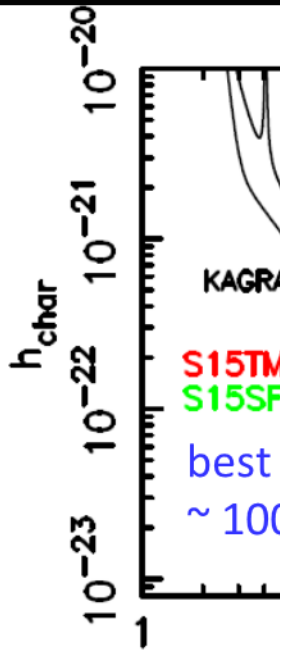
GW Spectrograms from 3D-GR models (gray) with strong SASI vs. weak SASI activity

SFHx :softer

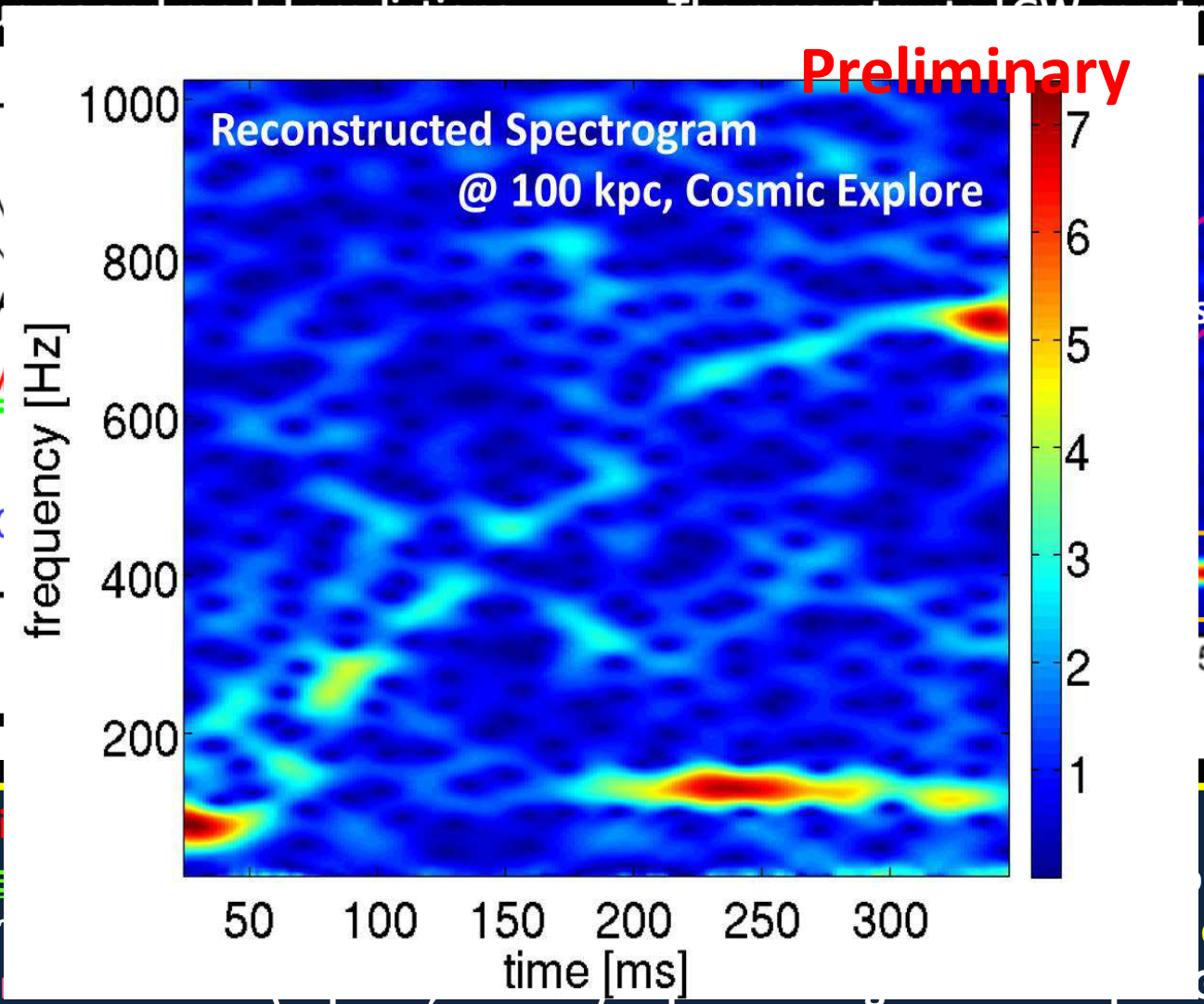
TM1 :stiffer

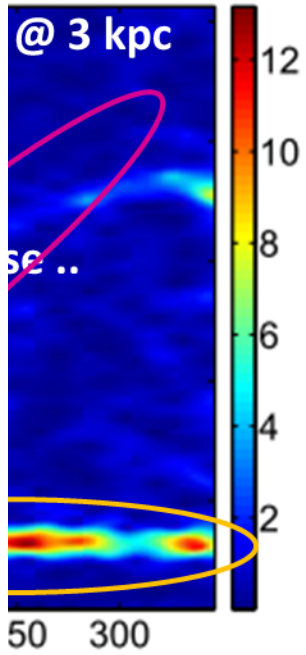
Sensitivity cu

ogram



Preliminary





✓ The quasi … softer EOS.

✓ By cohere … rizon is only 2… e (>2035).

✓ Detectio… GW detection.

✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (e.g., Tamborra et al. (2012) for SASI-induced neutrino signals).

Validation needed: 3D-MHD full GR code with multi-energy transport !

✓ "FuGRMA-1" : Fully General Relativistic Magnetohydrodynamics
with multi-energy neutrino transport via M1 **scheme**

Kuroda, Arcones, Takiwaki, KK, in prep

The marriage of **BSSN formalism** (3D GR code, Kuroda & Umeda (2010, ApJS))
+ **M1 scheme**; Shibata+2011, Thorne 1981, (see also, **Just et al. (2018)**, O'Connor (2015) for recent work)

✓ **Non-rotating s20 solar-mass star (Woosley and Heger (2007): "R0B00"**

Validation needed: 3D-MHD full GR code with multi-energy transport !

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Kuroda, Takiwaki, and KK, ApJS. (2016)

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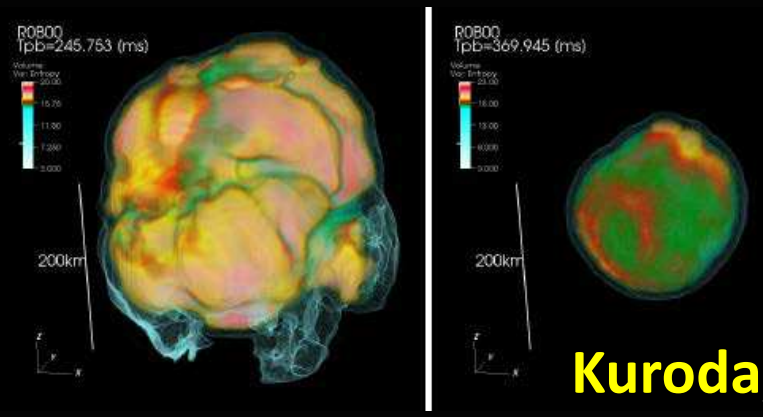
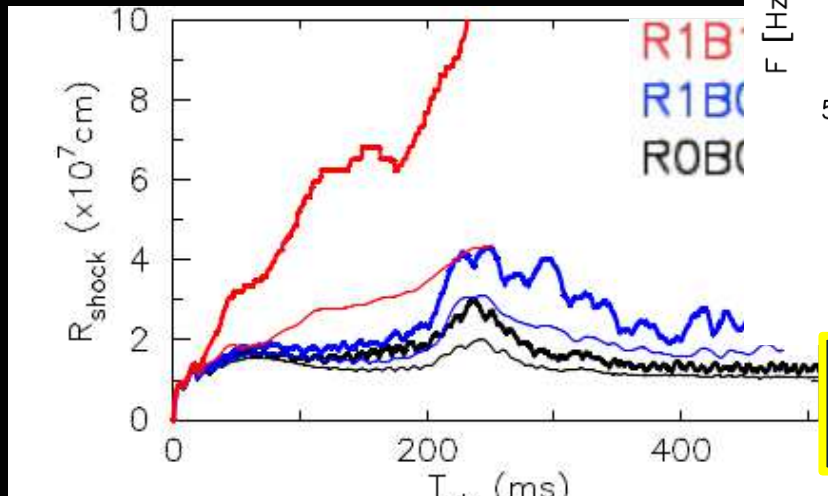
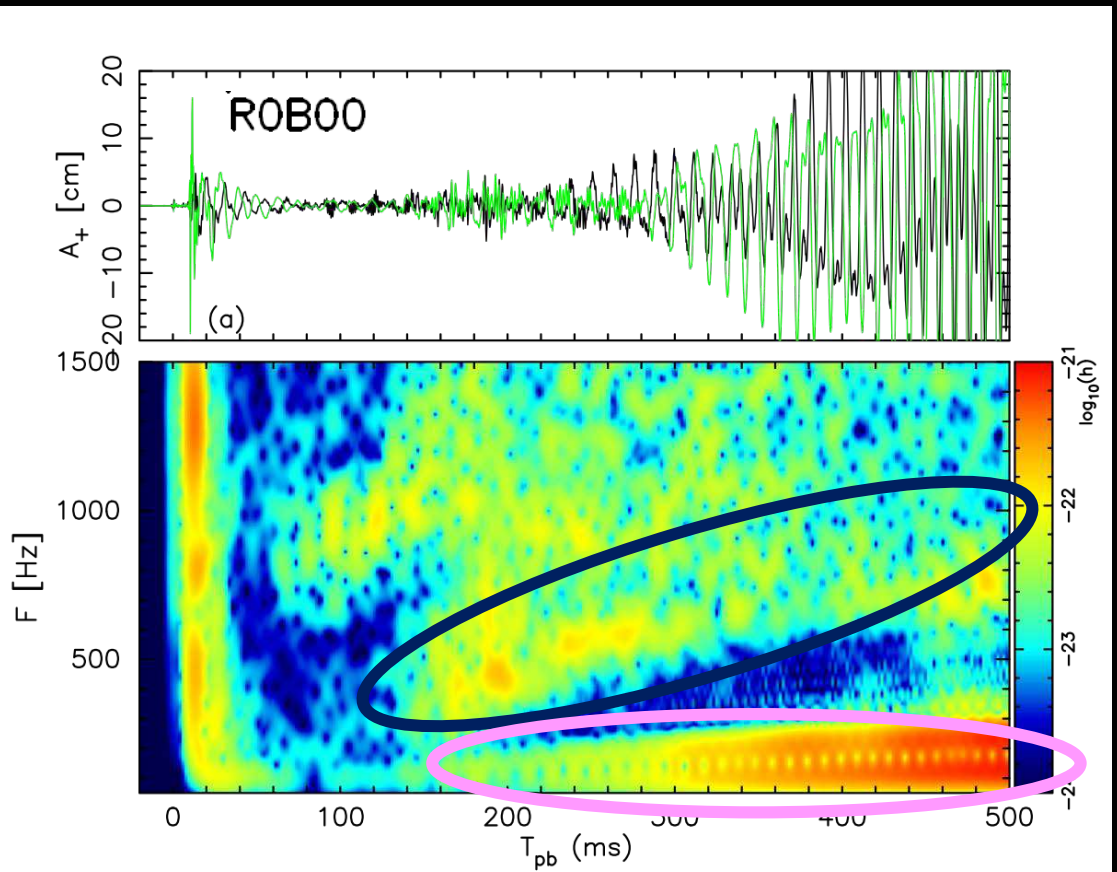
✓ **Non-rotating s20 solar-mass star (V**



Kuroda



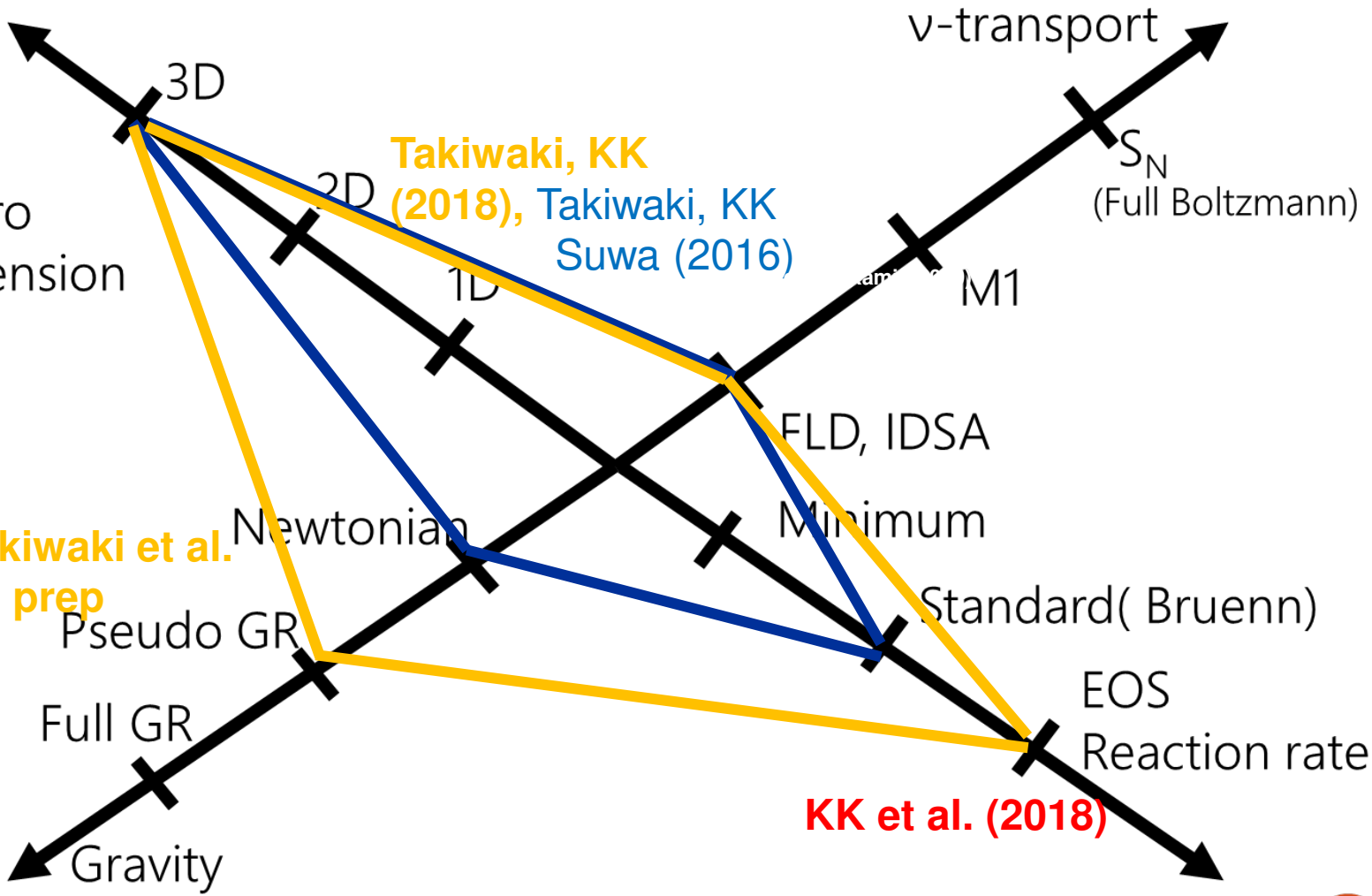


✓ **Ramp-up and low-frequency signature also observed in the upgraded 3D-GR model !**

Numerical modeling supernova explosion

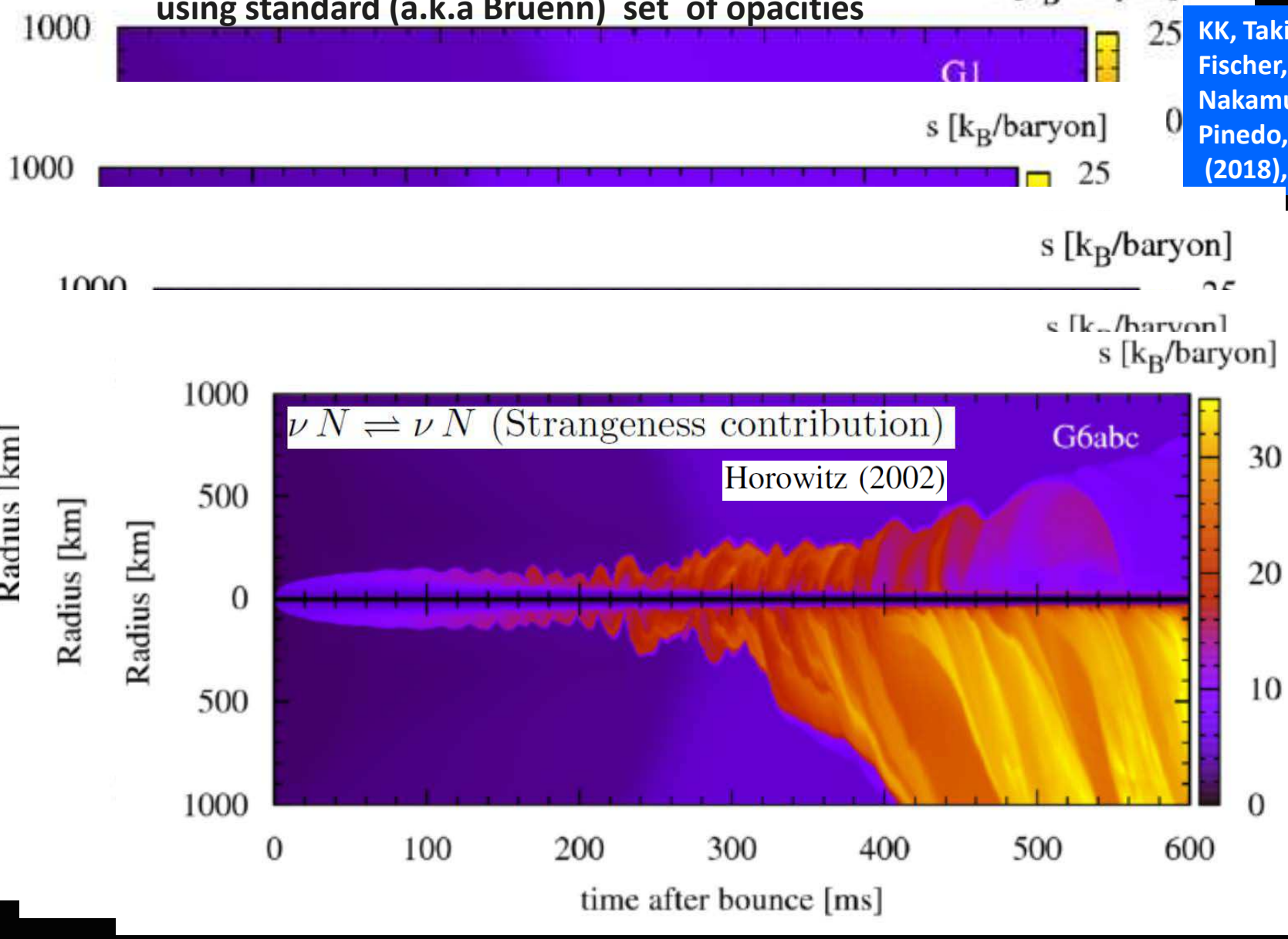
Big simulation codes = Experimental facilities

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



Ref. Sotani+2016, Kotake+2018, O'connor+2018

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



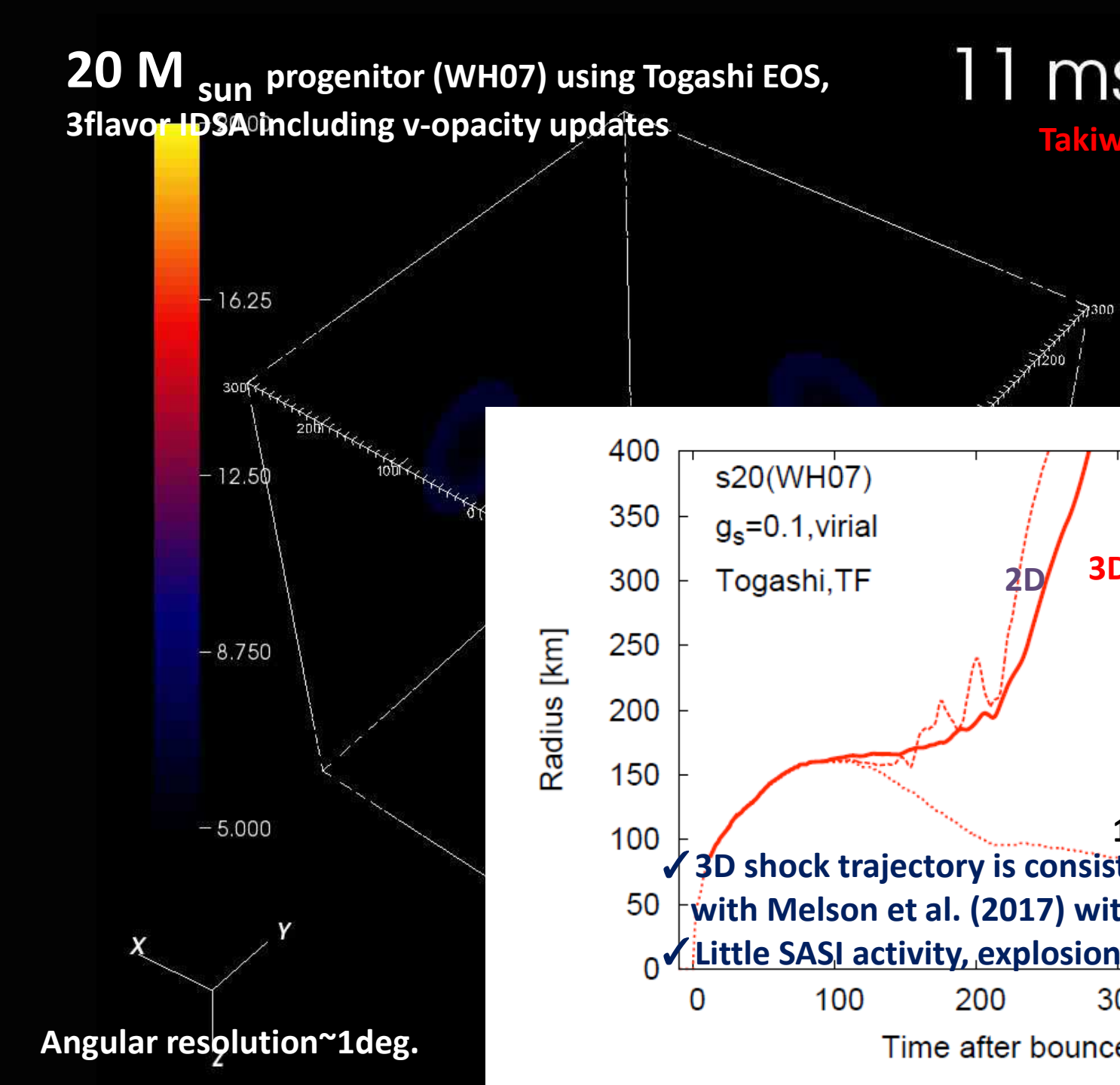
KK, Takiwaki, Fischer, Nakamura, Pinedo, et al. (2018), ApJ

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

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

11 ms

Takiwaki, KK et al. prep



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

✓Little SASI activity, explosion driven by convection

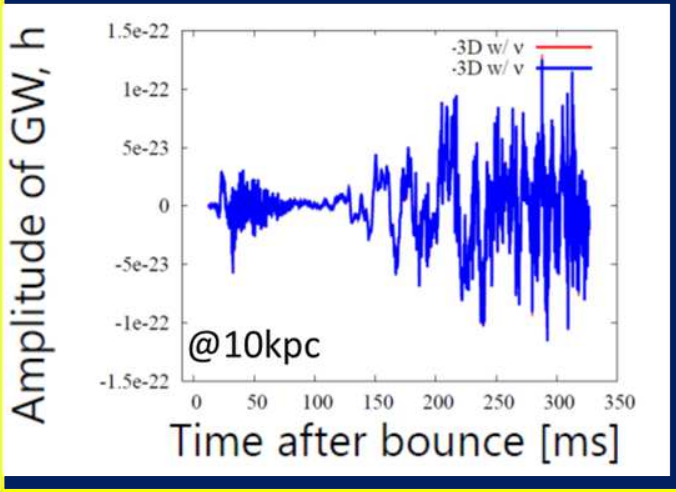
Angular resolution~1deg.

Neutrino prediction from best available EOS : Togashi EOS

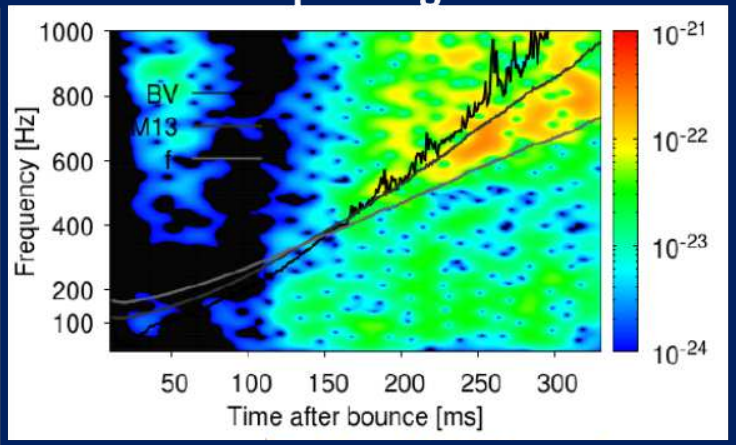
From nuclear potentials (Argonne v18 and Urbana IX)), new EOS by cluster variational principle reported !

Togashi, et al. (2017), NPA (see talk by Takano-san!)

The gravitational-waveform of s20



Spectrogram

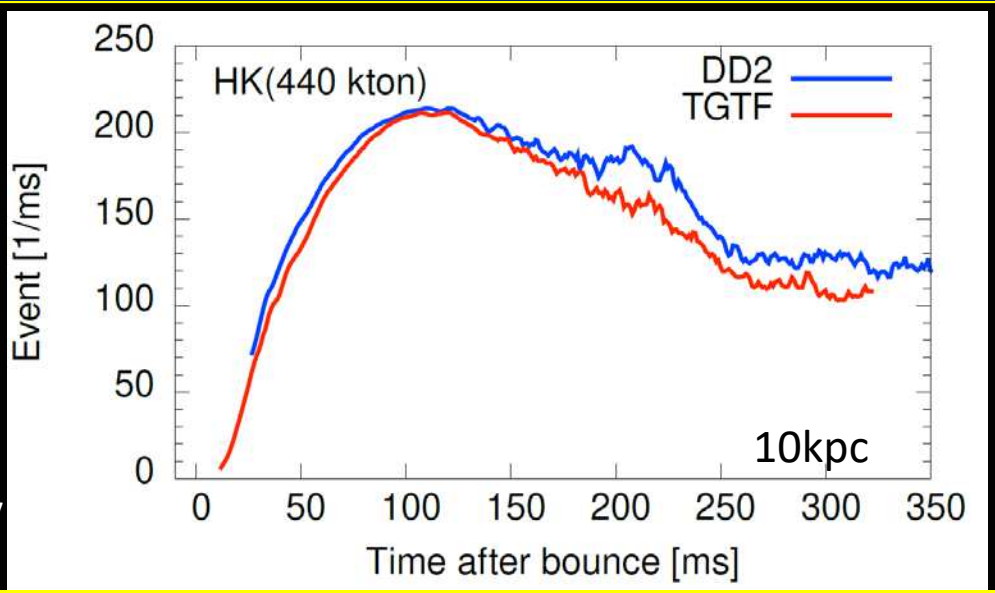


Takiwaki, KK et al. prep

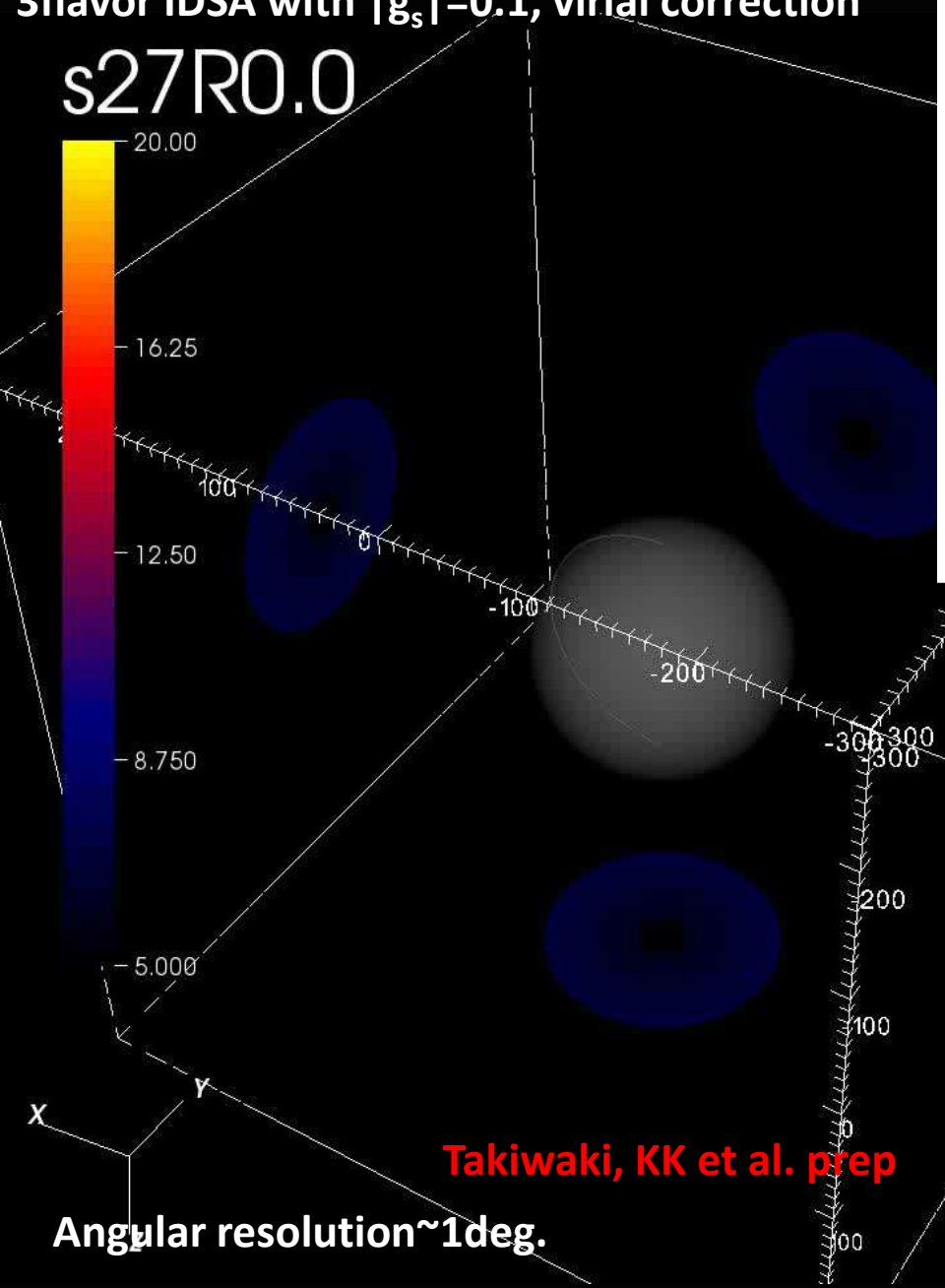
- ✓ Only ramp-up mode appears (no SASI activity)
- ✓ Controversy: "g" vs. "f" mode
  - Morosova + (18) :"f"
  - Sotani+(19) :"f"
  - Torres-Forne (16,19) "g"

Detection rates (nue bar) at HK

- ✓ Softer EOS (**Togashi**) leads to easier explosion !
- ⇒ This makes accretion luminosity to the PNS smaller, thus event rates < 20 % smaller than **stiff EOS(DD2)** in the accretion phase.
- ✓ 3D self-consistent models show that ν detectability is **rather unaffected** by the difference of nuclear EOS !

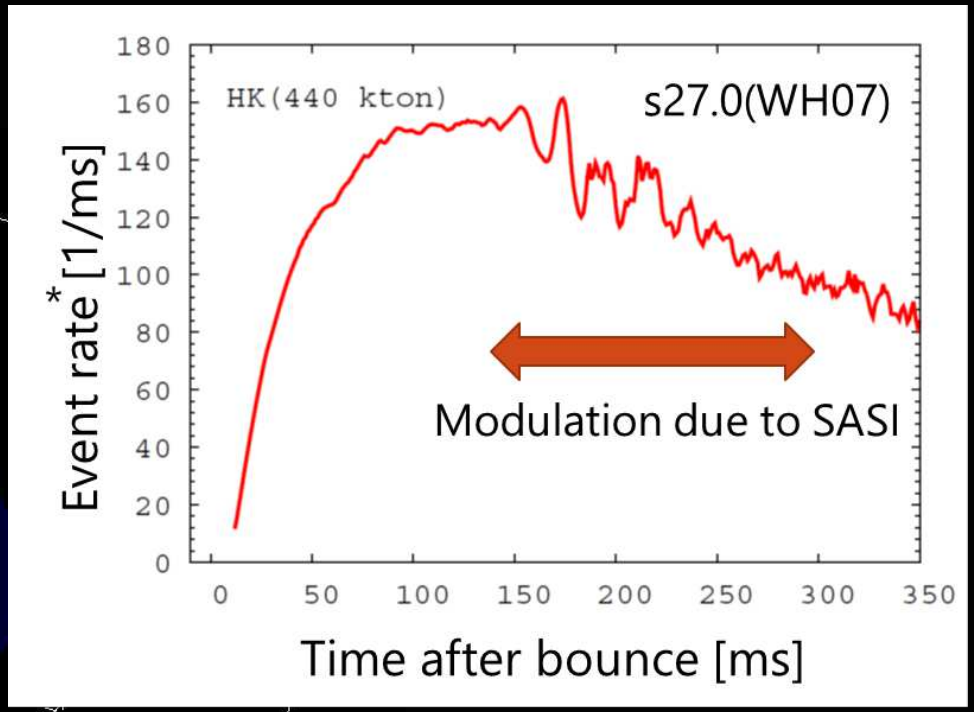


27 M_{sun} progenitor (WH07), Togashi EOS, 3flavor IDSA with $|g_s|$=0.1, virial correction

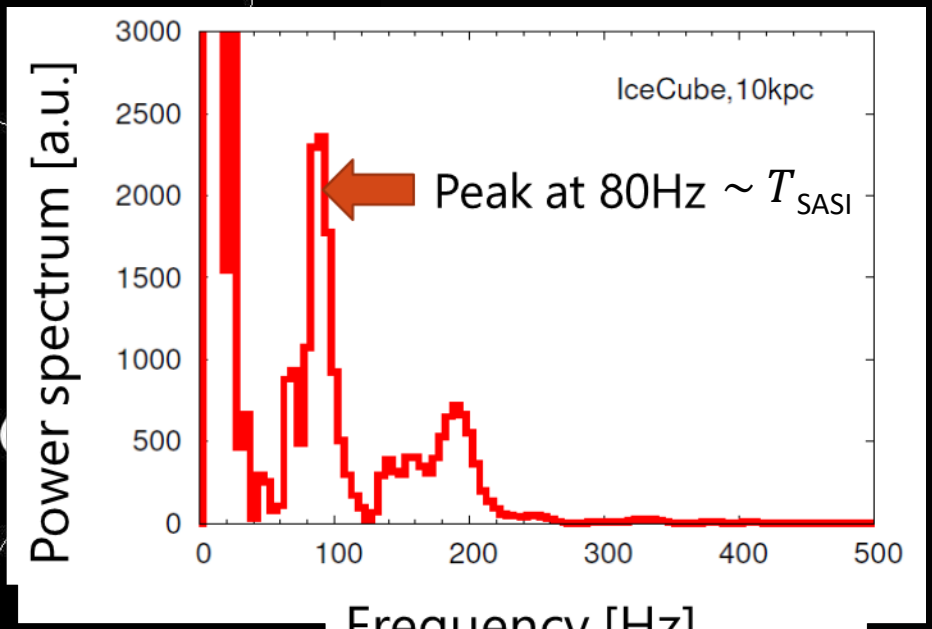


Takiwaki, KK et al. prep

Angular resolution~1deg.

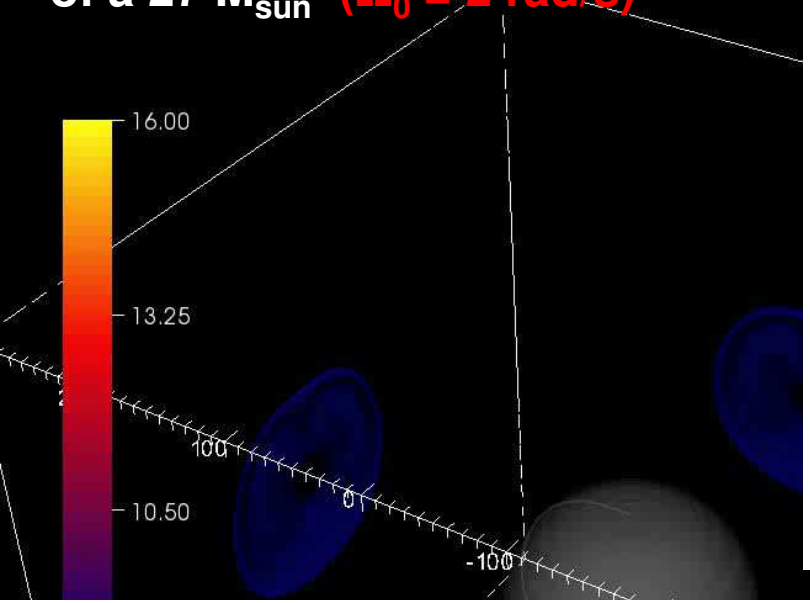


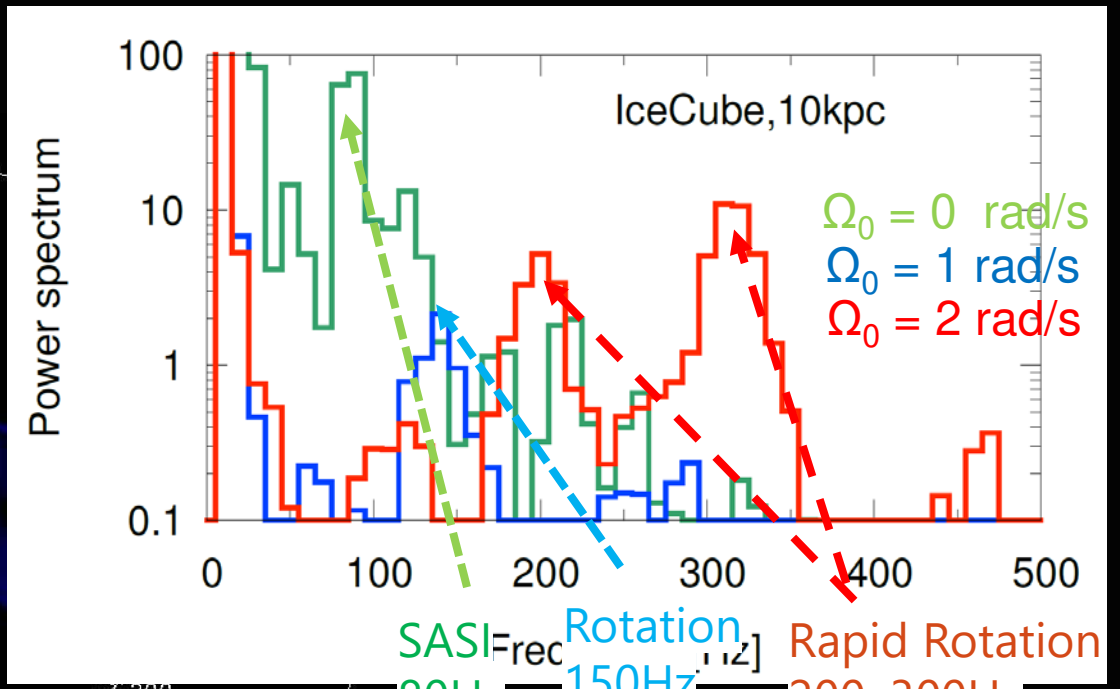
(consistent with Tamborra et al. (2013,2014))



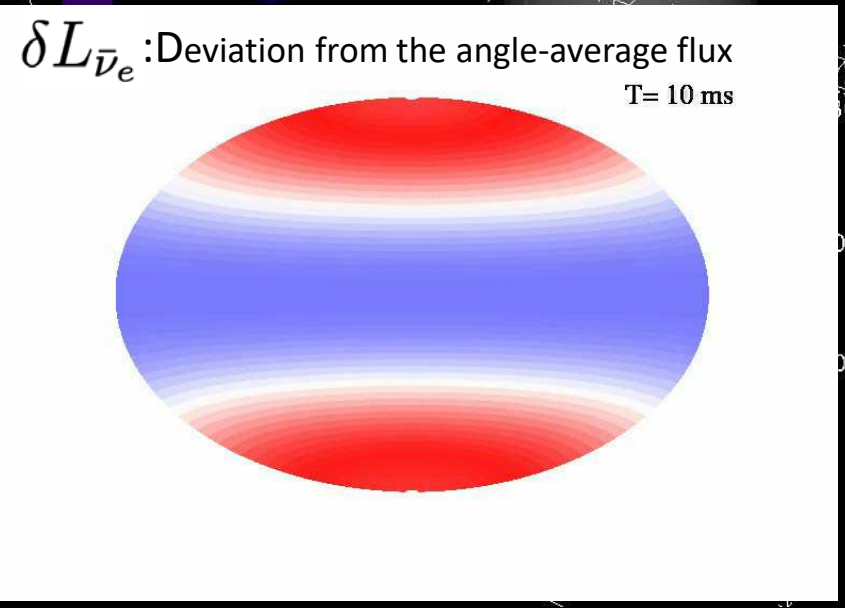
Impact of Stellar Rotation of SASI-modulated ν and GW signals

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.

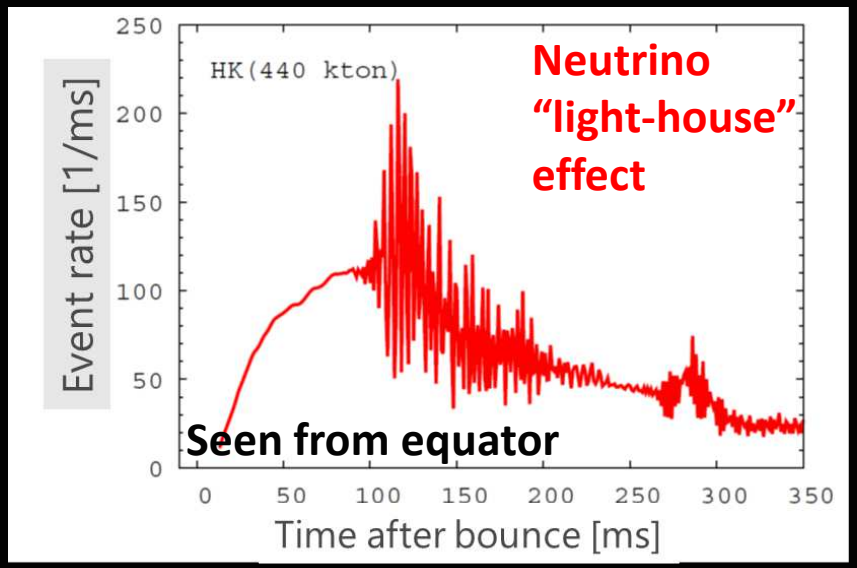
=> ***The light-house effect***

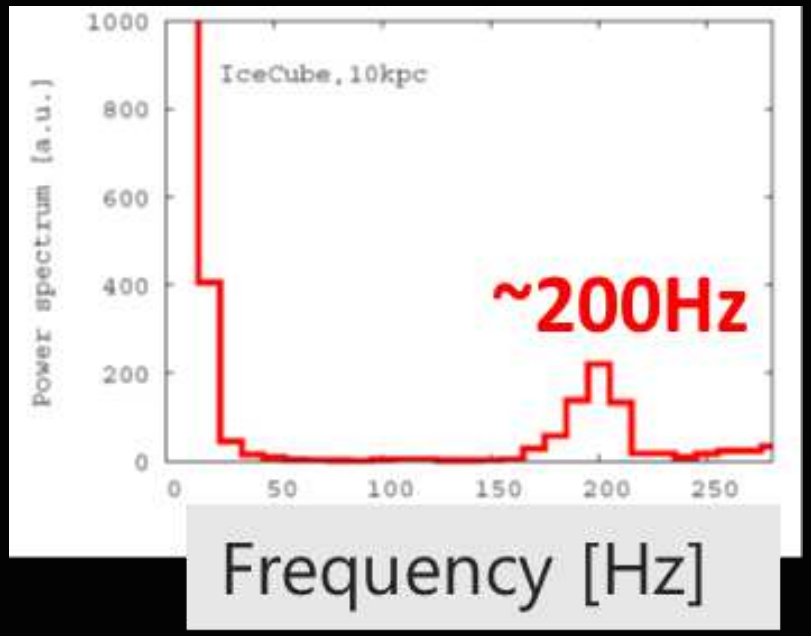
600 km (found in simplified 3D model by Takiwaki and KK (2018)).

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

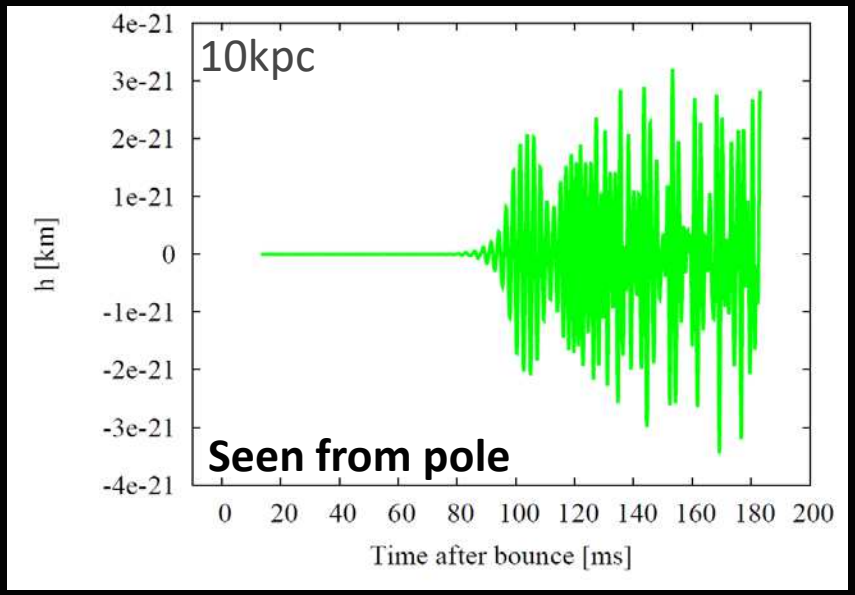
Takiwaki, KK, Foglizzo in prep

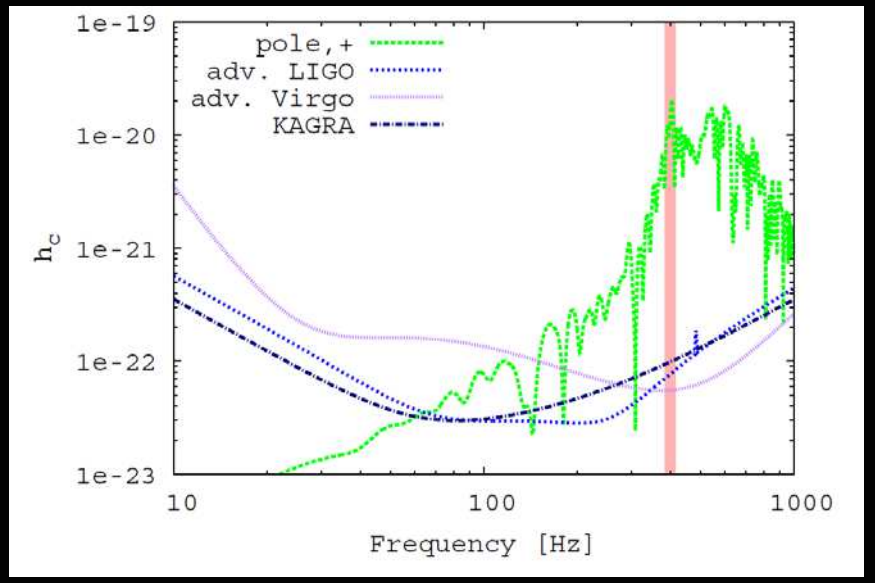
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)





Gravitational waveform



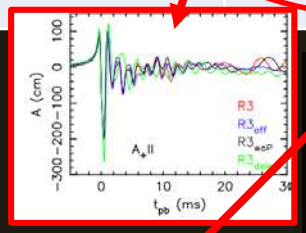


Correlation of ν and GW signals from a rapidly rotating 3D model

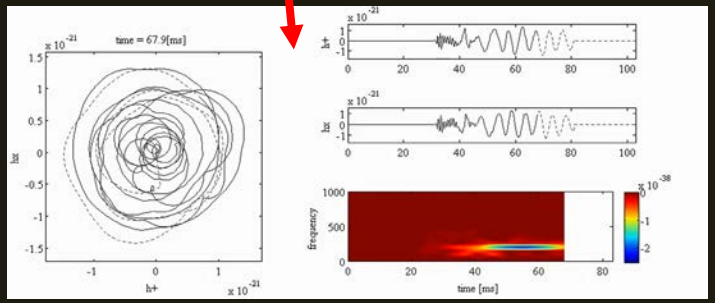
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

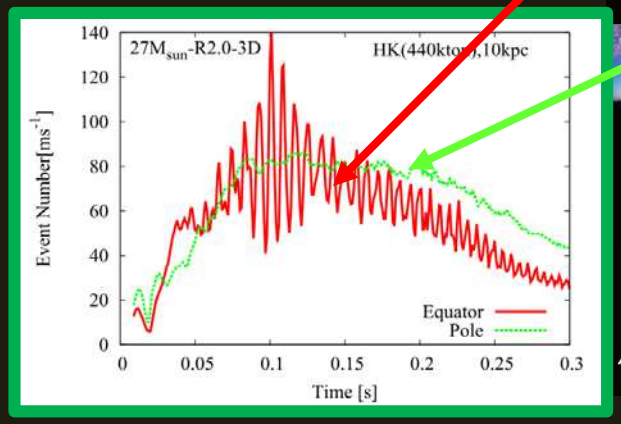
Takiwaki, KK, Foglizzo in prep

Directionality	Equator	Pole
Gravitational Wave	Type I signal	✓Quasi-periodic signals from non-axis. instability ✓Circular polarization
Neutrinos	Light-house effect	No surprise …









✓**Multi-messengers from rotating CCSNe : rich information !**

Preliminary 3D-MHD full GR runs for a 20 solar-mass star

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

Kuroda, Takiwaki, KK, Alcones in prep

- Cylindrical rotational law

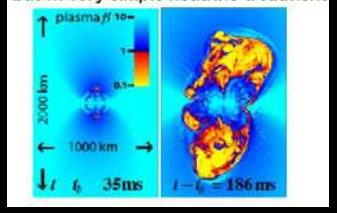
$$\Omega = \Omega_0 \frac{R_0^2}{R^2 + R_0^2} \qquad \Omega_0 = 1(\mathrm{rad/s}) \qquad (\beta_b \sim 1\%)$$

- Dipole-like B

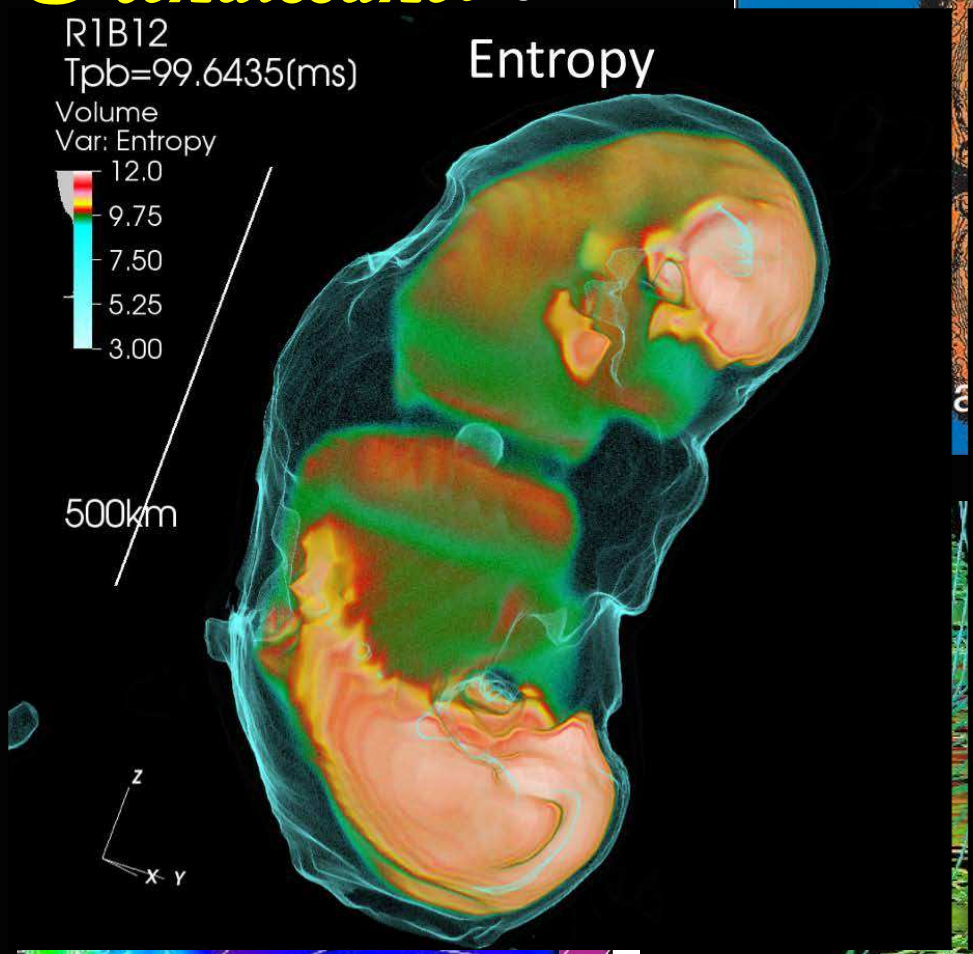
$$A_\phi = \frac{B_0}{2} \frac{R_0^3}{R^3 + R_0^3} R\sin\theta \qquad B_0 = 10^{12}\mathrm{G} \quad (\beta_{\mathrm{mag,b}} \sim 1\%)$$

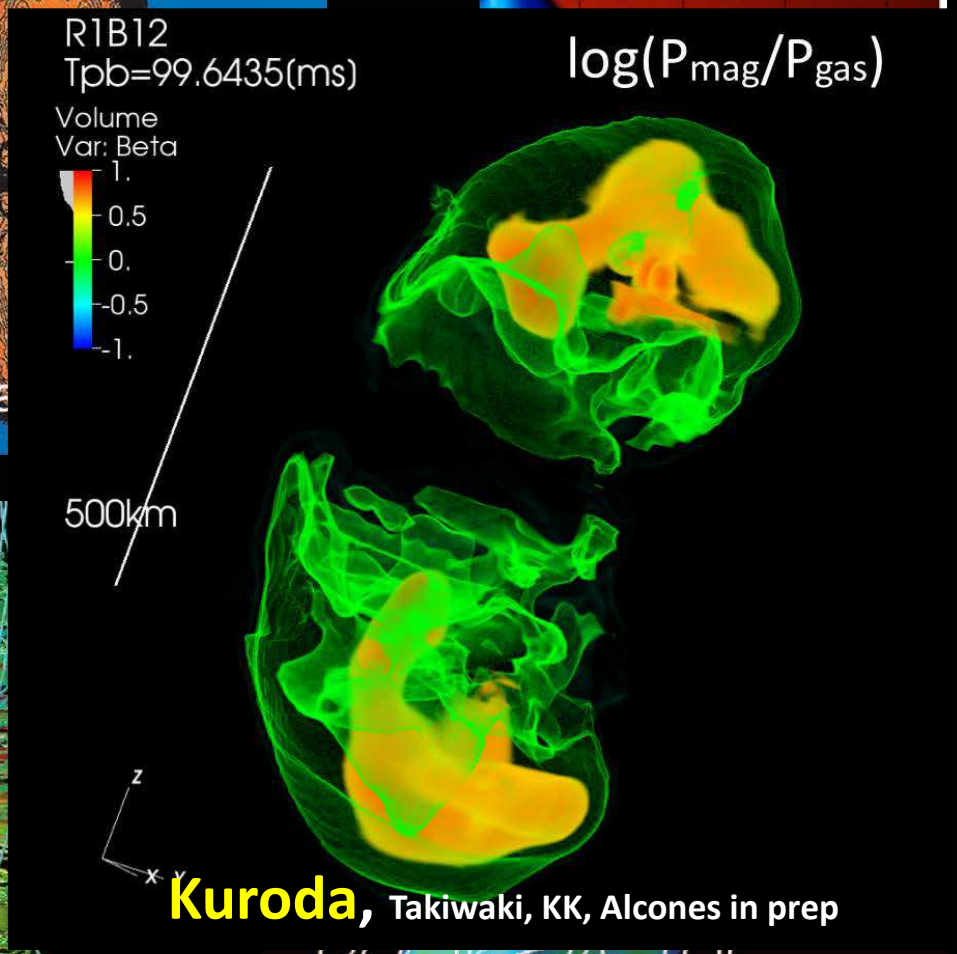
maximum

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

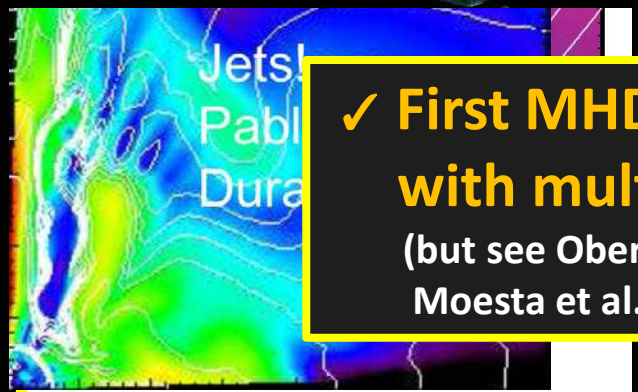


Renaissance of





Kuroda, Takiwaki, KK, Alcones in prep



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

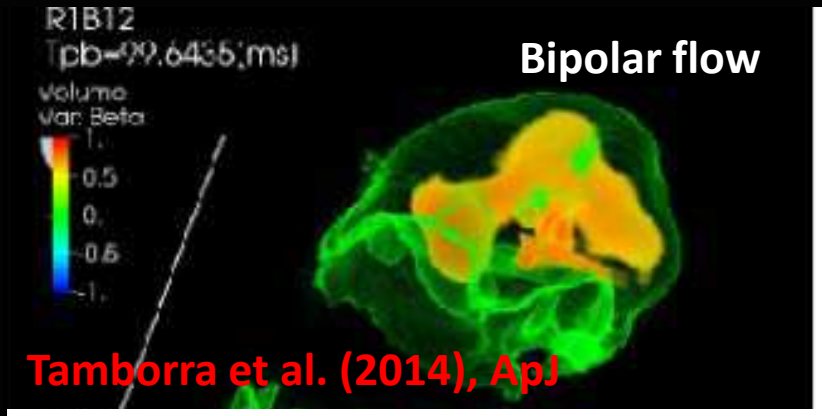
(but see Obergaulinger & Aloy (2019), SR-MHD
Moesta et al. (2014), GR-MHD with leakage scheme)

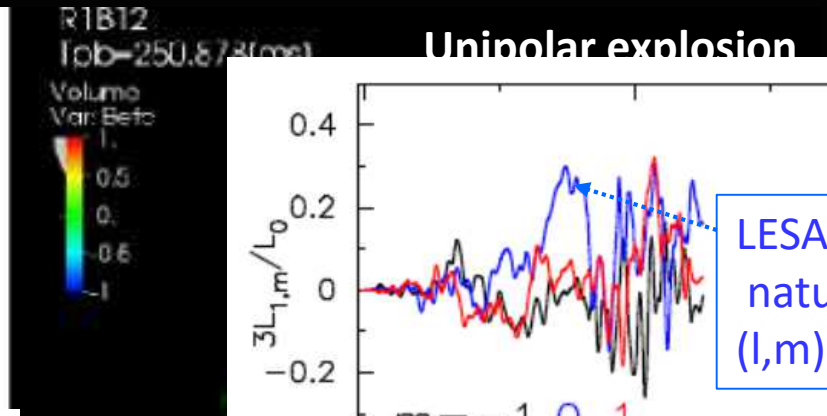
in 2D !

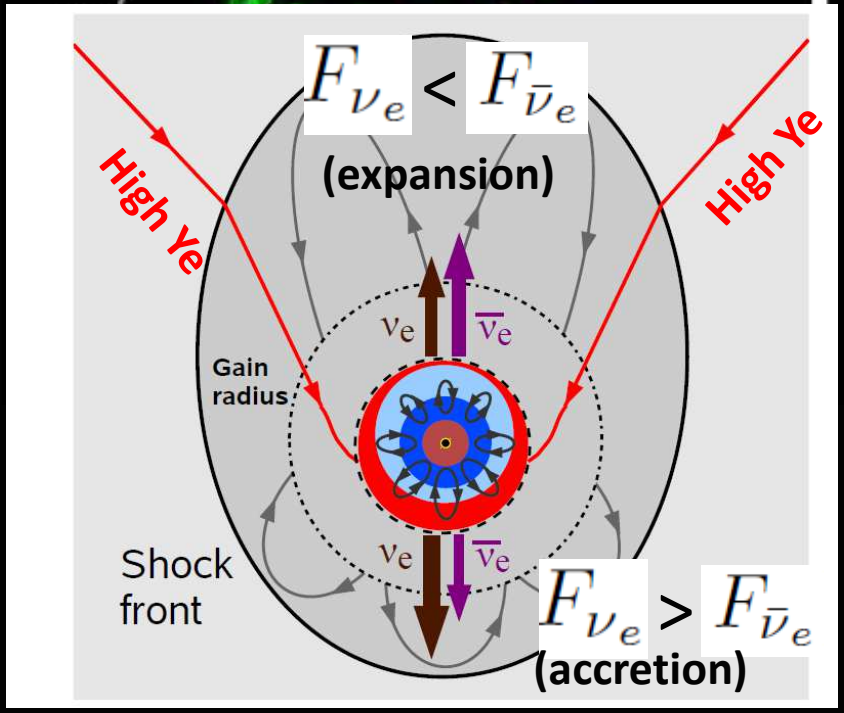
LESA (Lepton-num. Emission, Self-sustained Asymmetry) in MHD explosions !

Kuroda, Arcones, Takiwaki, and KK in prep

The kink instability (Begelman et al. 1998) destroys a coherent bipolar flows, resulting in a unipolar explosion !

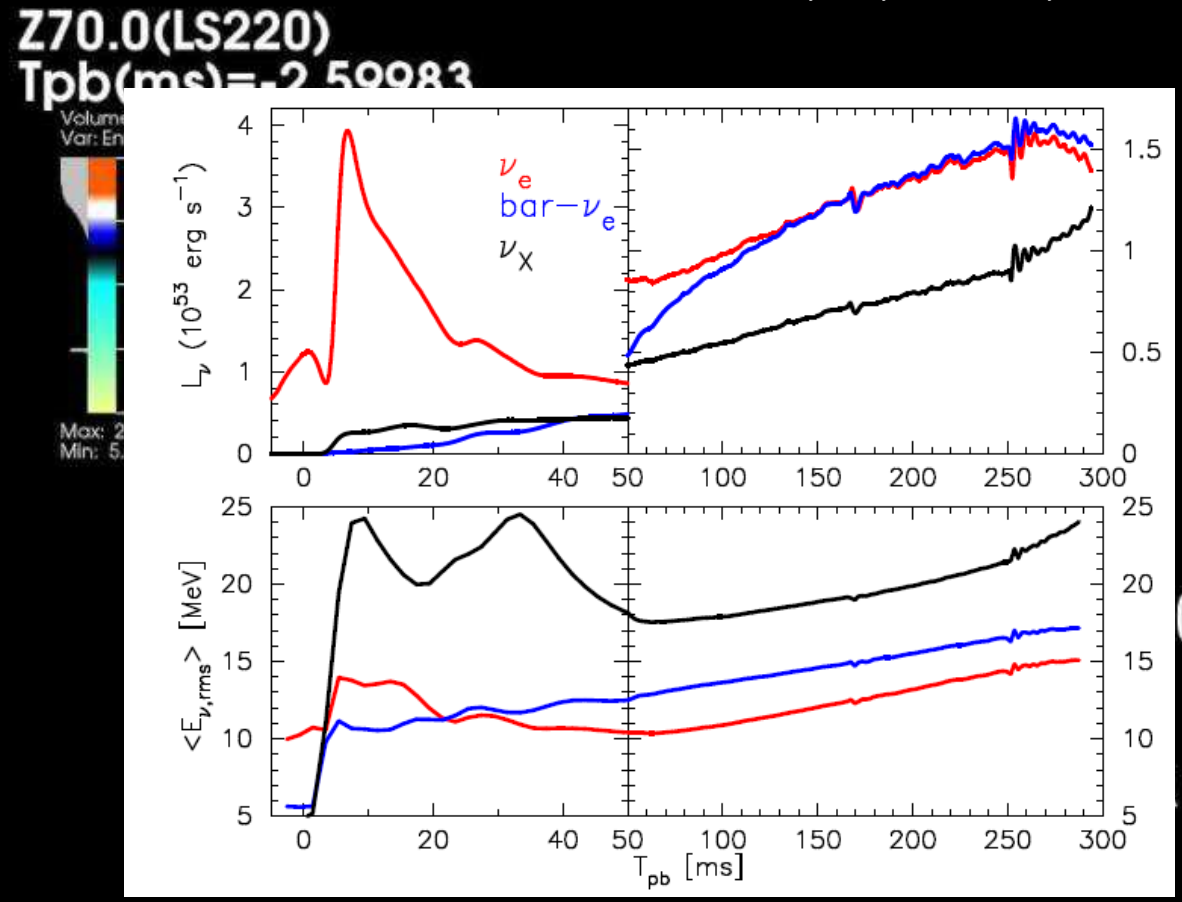






✓ **BH forming simulations** of a 70 M_{sun} (M_{CO} ~ 28.5 M_{sun})

Kuroda, KK, Taiwaki, Thieleman, MNRAS, 2018



0km

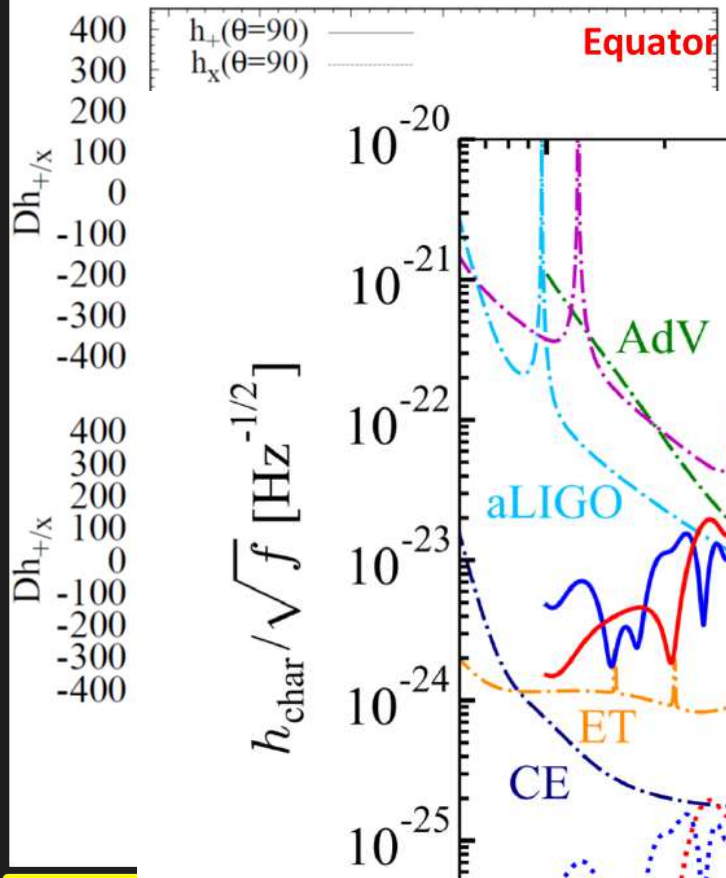
- ✓ **Earliest BH formation** after bounce (~300 ms postbouce) !
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy.
  (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Nakazato(+2008,2013), Fischer+ (2009), Huedepohl+(2016))
- ✓ **Sudden disappearance of the neutrino signals -> BH formation !**
- ✓ **These BHs may explain LIGO-Virgo BHs, detectable for nearby event(not very likely…) !**

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

Shibagaki, Kuroda, KK, Takiwaki, MNRAS Letters in press



Gravitational waveform



Rap

Ω_0 =

700km

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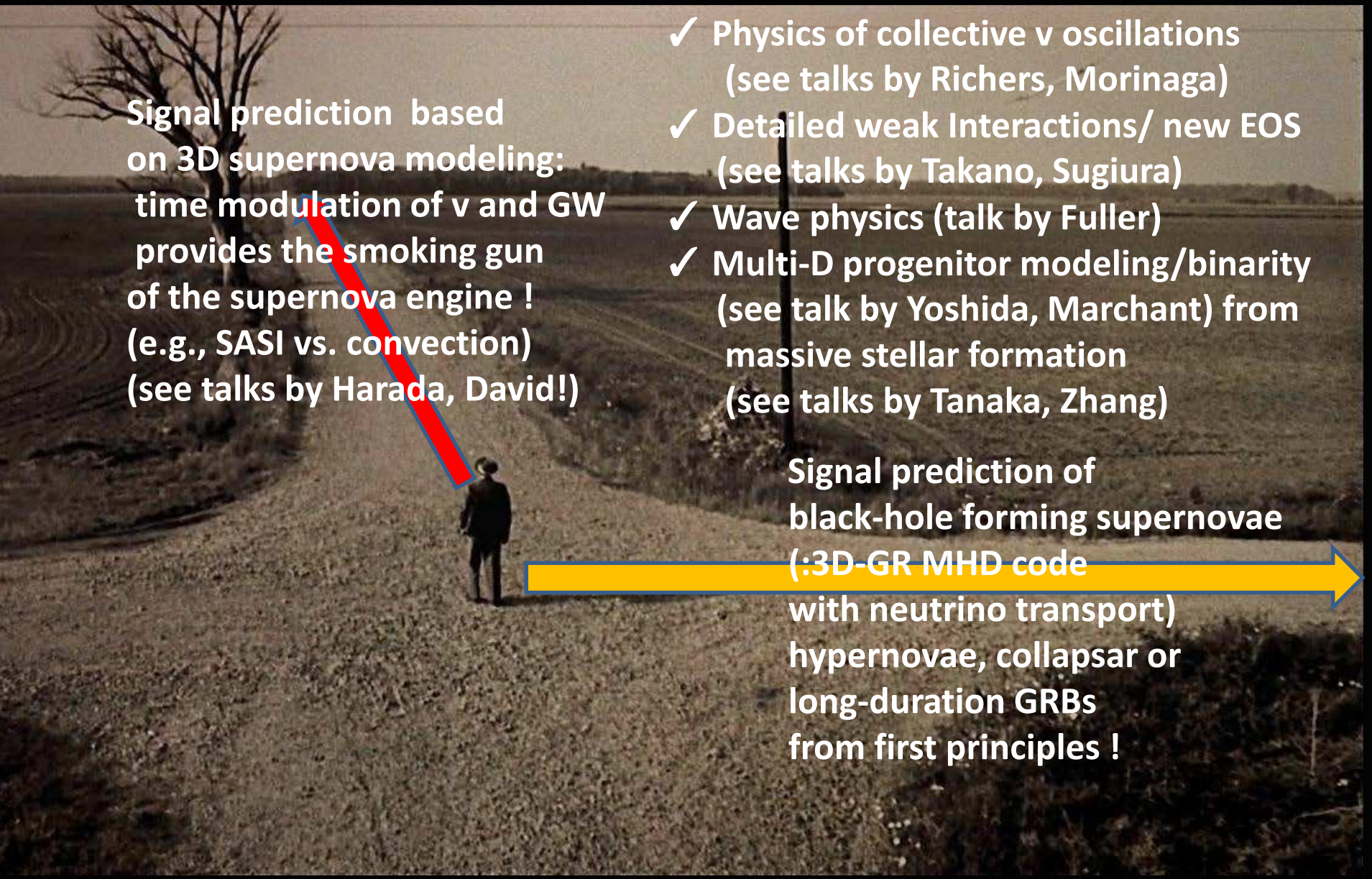
✓ **Detectable out to Mpc distance scales by 3rd gen. detectors !**

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



Signal prediction based
on 3D supernova modeling:
time modulation of v and GW
provides the smoking gun
of the supernova engine !
(e.g., SASI vs. convection)
(see talks by Harada, David!)

✓ Physics of collective v oscillations
(see talks by Richers, Morinaga)
✓ Detailed weak Interactions/ new EOS
(see talks by Takano, Sugiura)
✓ Wave physics (talk by Fuller)
✓ Multi-D progenitor modeling/binarity
(see talk by Yoshida, Marchant) from
massive stellar formation
(see talks by Tanaka, Zhang)

Signal prediction of
black-hole forming supernovae
(:3D-GR MHD code
with neutrino transport)
hypernovae, collapsar or
long-duration GRBs
from first principles !