超新星の爆発メカニズムとマルチメッセンジャー

Explosion Mechanisms of Core-Collapse Supernovae and the Multi-messenger Observables

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コンパクト天体における高エネルギー現象
「宇宙線研究所共同利用小研究会」

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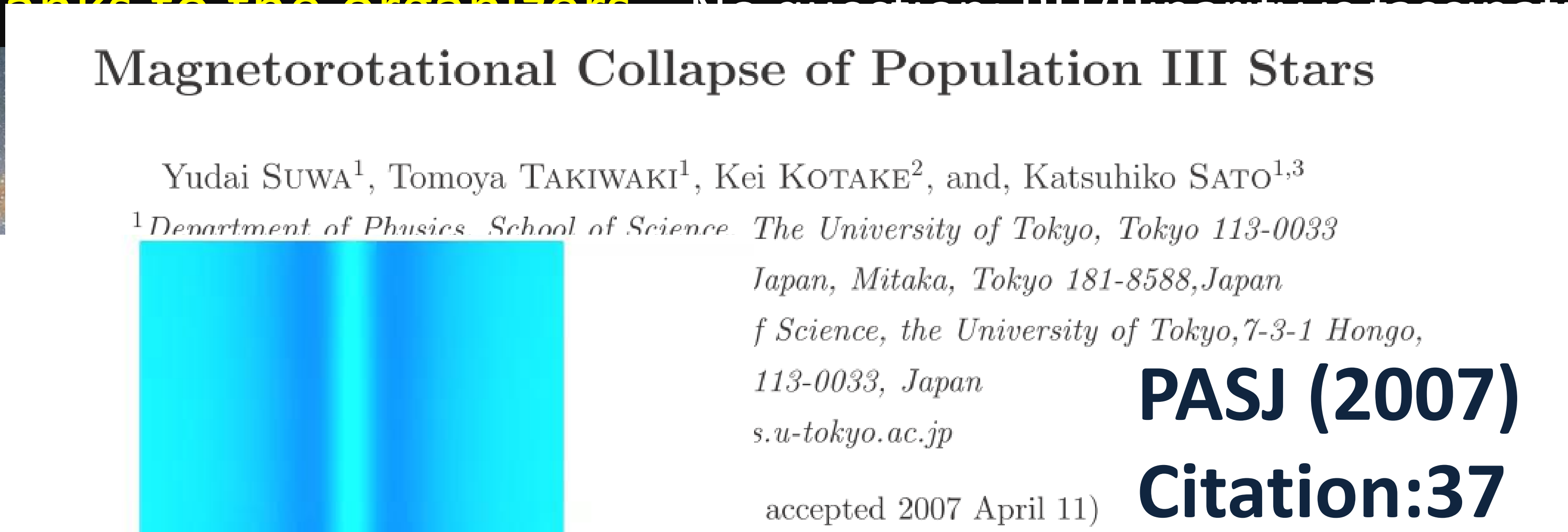

Magnetorotational Collapse of Population III Stars

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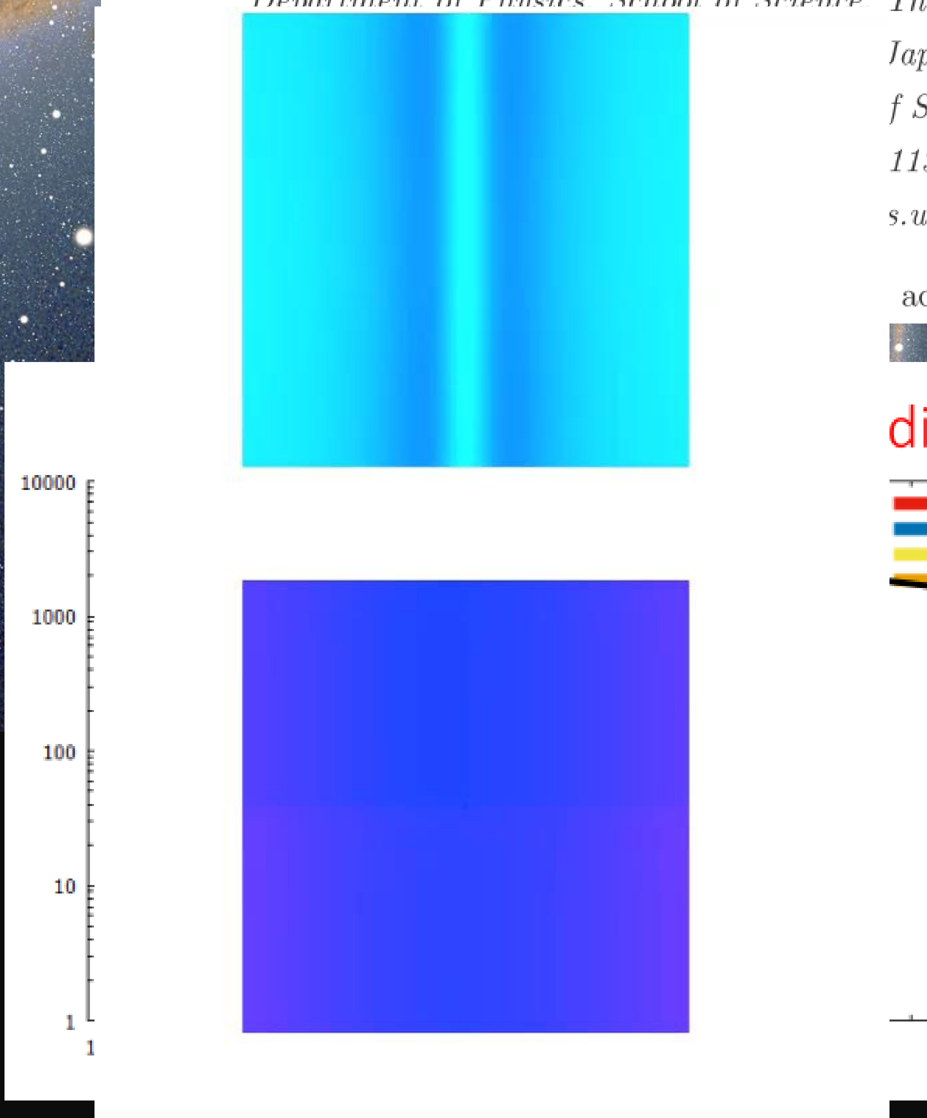
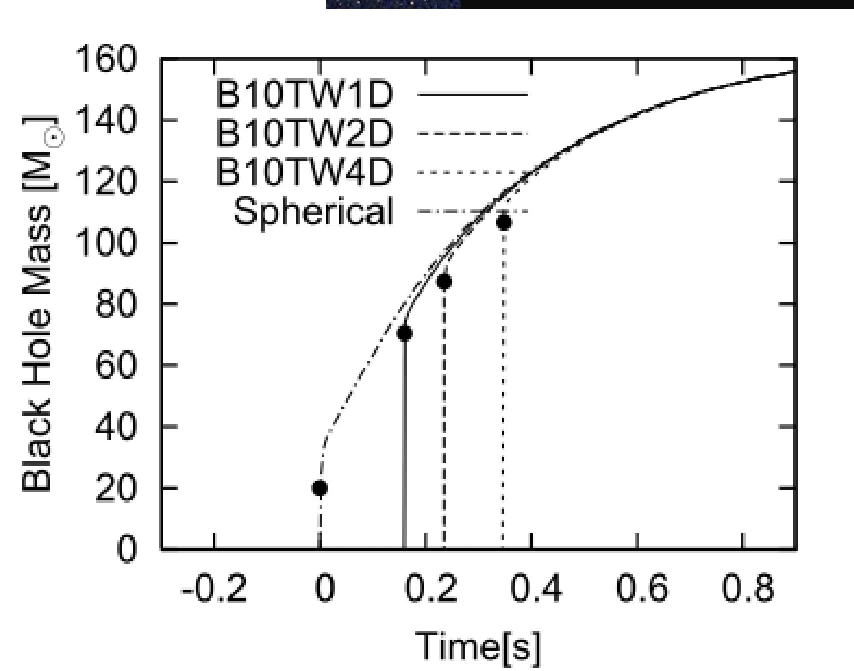
PASJ (2007)

Citation:37





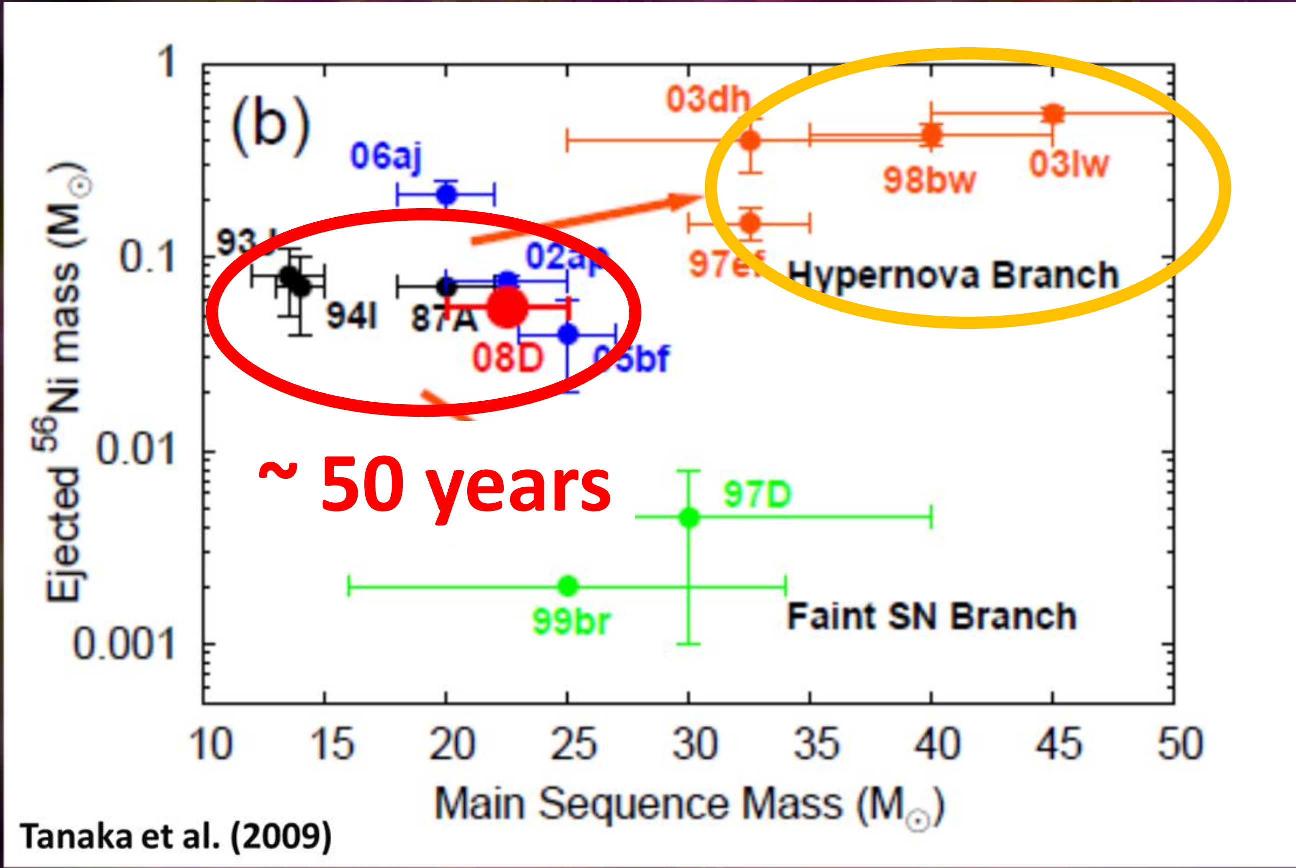
FOE2015, NCSUでの
パネルDiscussion資料より

The base-line and final goal (s)

: How rotation/B-fields affects core collapse and SN/GRB explosion ?

~ 10FOE

~ 1 FOE

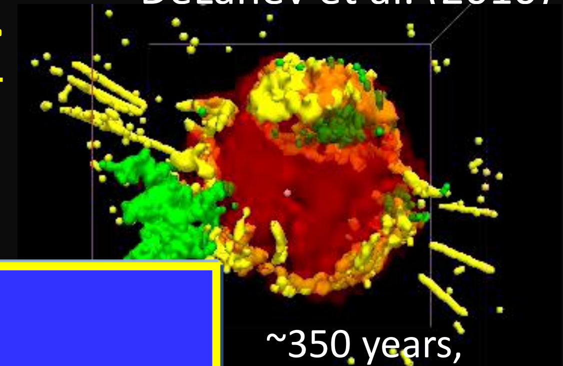


FOE: Fifty-one-erg
= 1 Bethe
をスパコンで
再現しよう。
Colgate & White
(1966)~

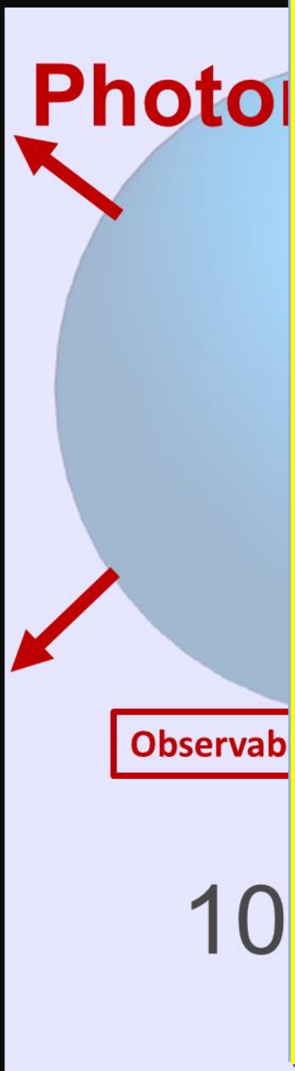
1). For which types of the progenitors (IIp, Ib/Ic, IIn) is rotation most important ?
2). and 3). If important, why and how ?
4). Collapsar, Magnetar scenarios: Which one successful (or other) ? why ?
5). How long will it take before first-principles doable ? Strategies ?

Typical Scales of CCSN multimessenger

DeLanev et al. (2010)



~350 years,
Type IIb



Multidimensionality
(origin of anisotropy)

Self Consistent models

Signal Prediction

Exp. Mechanism
Thermodynamics
Dynamics

Data analysis

Neutrino signals
GW emission

✓A Final goal of SN modelers.
:To decipher explosion dynamics via
Muti-messenger observables
(neutrinos, GW, electromagnetic waves

Outline

✓ Brief introduction (5 min)

what we can learn from SN multi-messengers ?

✓ Recent progresses in "Supernova Theory" (20 min)

☆ The Core-Collapse Supernova Theory

:what is the essence to blow up massive stars?

☆ Candidate mechanisms: based on first-principle multi-D radiation-hydrodynamic simulations

✓ Observational Signatures (20 min)

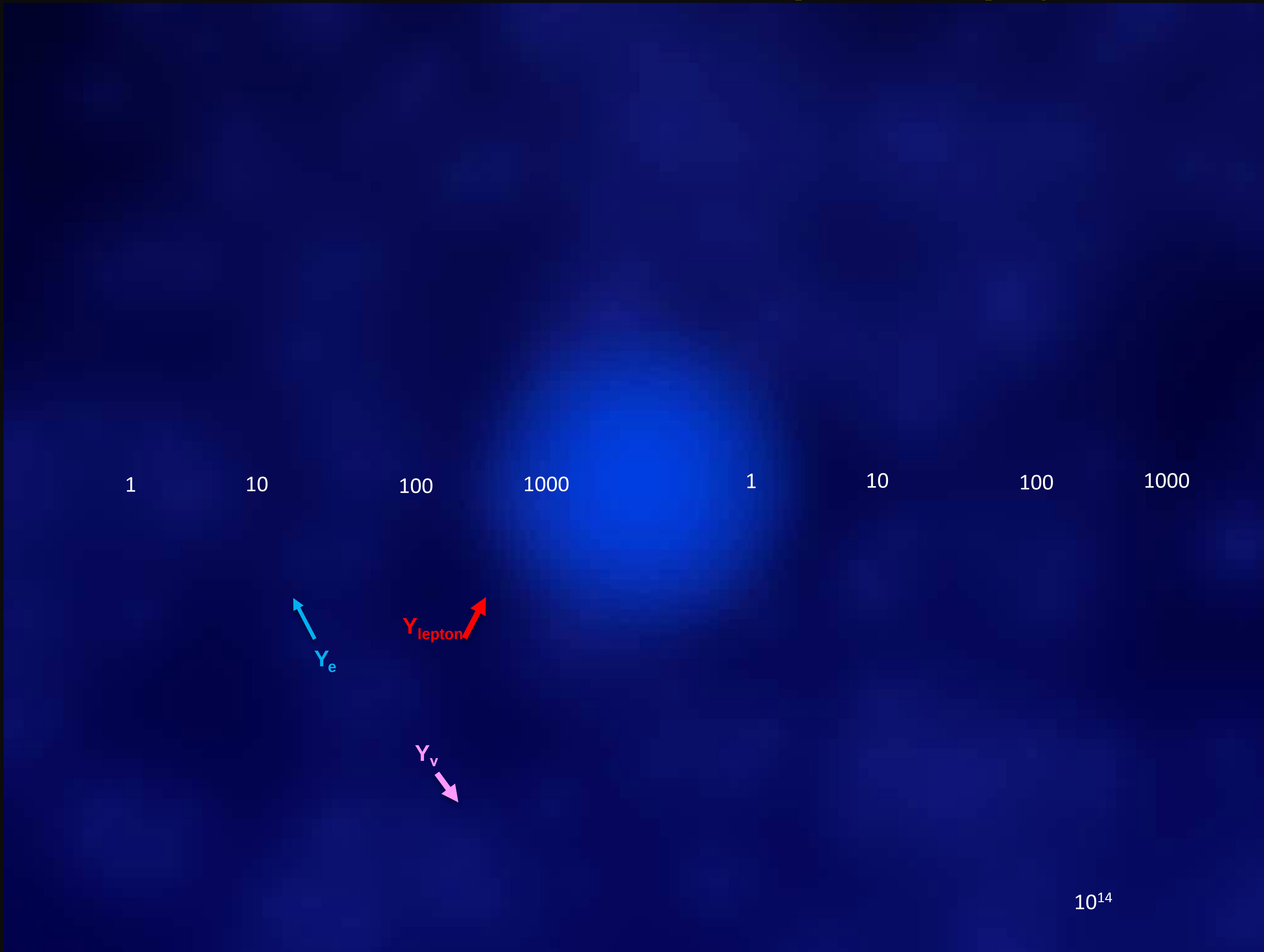
☆ Detectability of neutrino and gravitational-wave signals

☆ Perspectives toward "MM" astronomy

(correlation analysis between GWs/neutrinos, electromagnetic messengers)

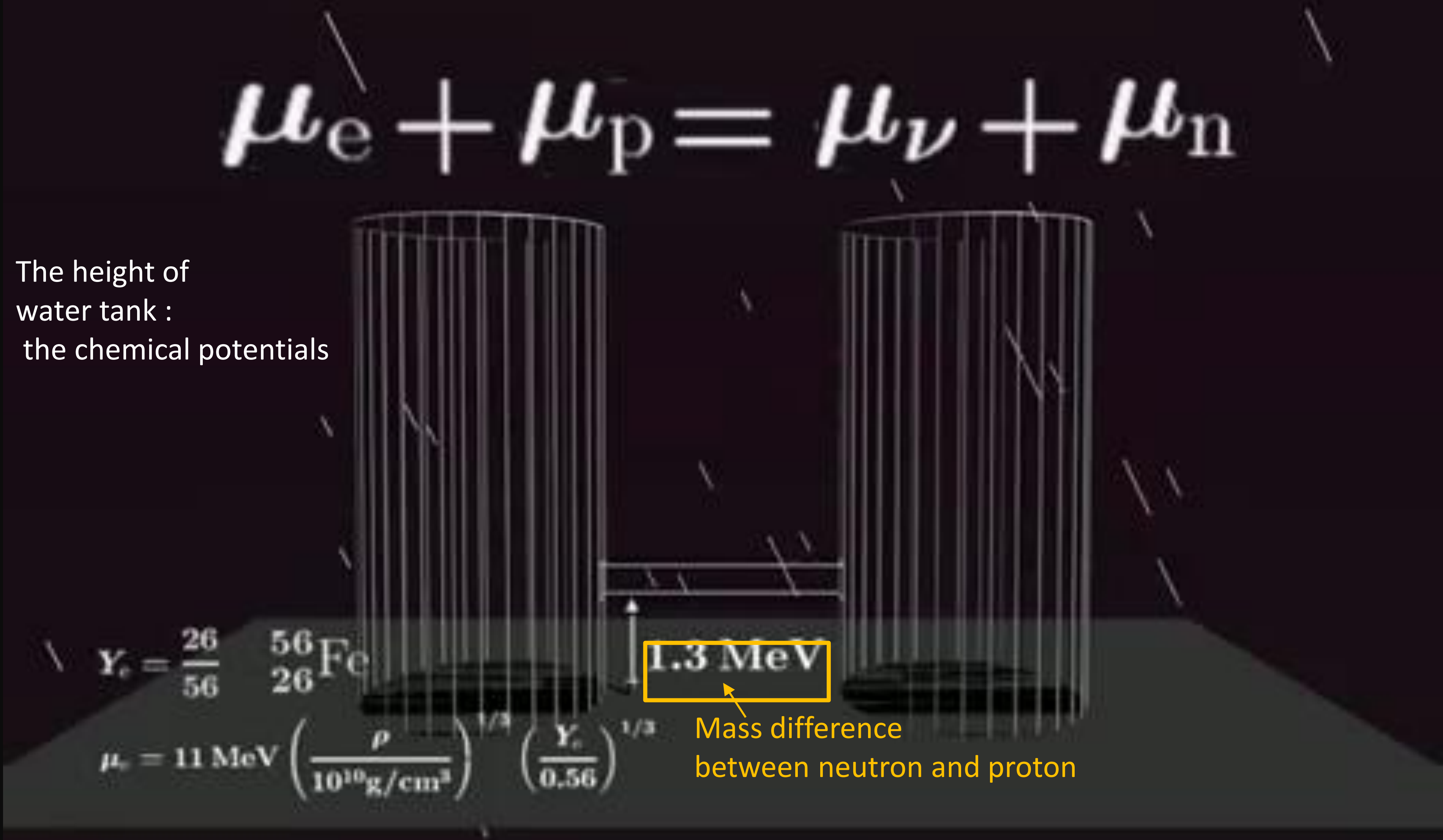
What can we learn from the central engine ?

"*90 seconds*" to overview CC-supernova physics



Trying to visualize “neutrino trapping”...

The height of
water tank :
the chemical potentials



Mass difference
between neutron and proton

After +50 years of CCSN modeling : "Multi-D" neutrino mechanism

(pioneered by Colgate & White (1966), review by Kotake & Kuroda (2016), Janka (2012), Burrrows (2013))

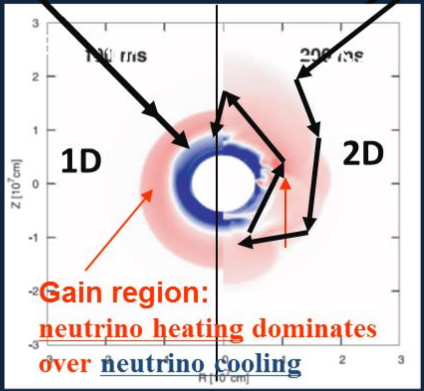
"Four steps" in neutrino-driven explosions

(see, e.g., Suwa et al. 2010,2011,2013, ApJ)

1st : After bounce, the bounce shock stalls.

2nd: Neutrino-driven convection and the SASI.
(Standing-Accretion-Shock-Instability)

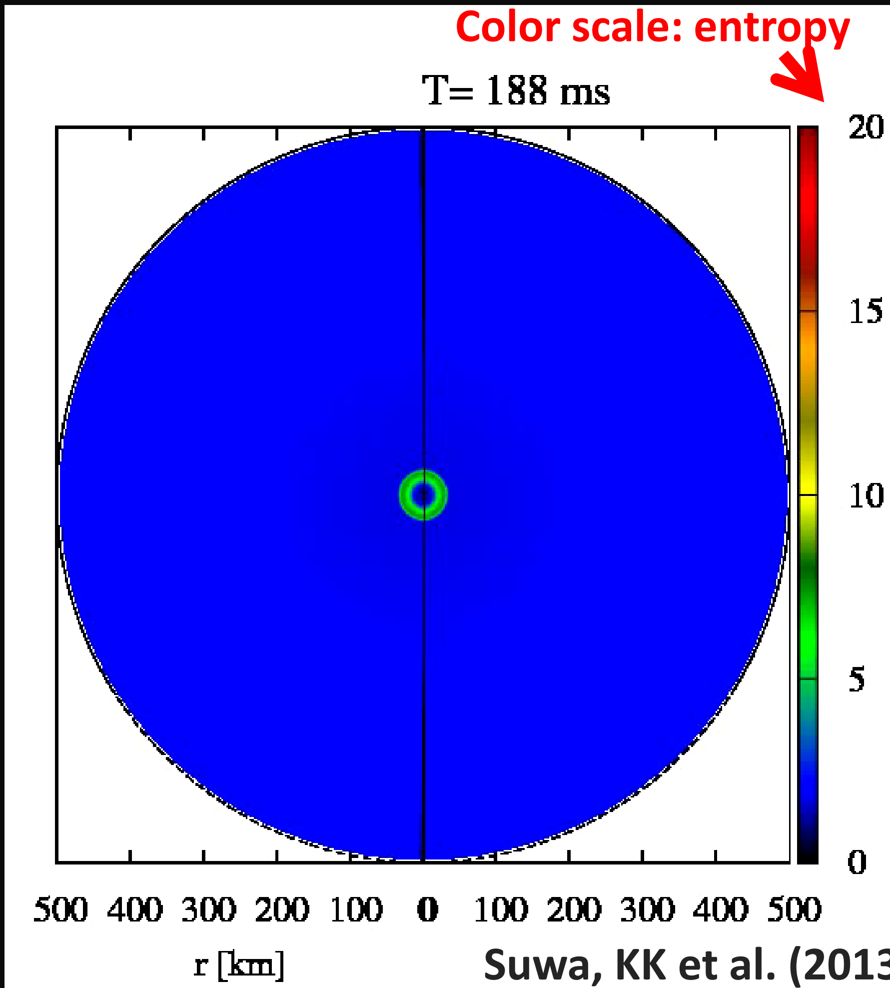
3rd: In the heating region, dwell-time of material gets longer due to non-radial motions in multi-D environments. (Turbulence helps explosion).



4th: At around O(100)s ms after bounce, neutrino-driven explosions set in.

2D radiation-hydro simulation of a 15 M_{sun} star

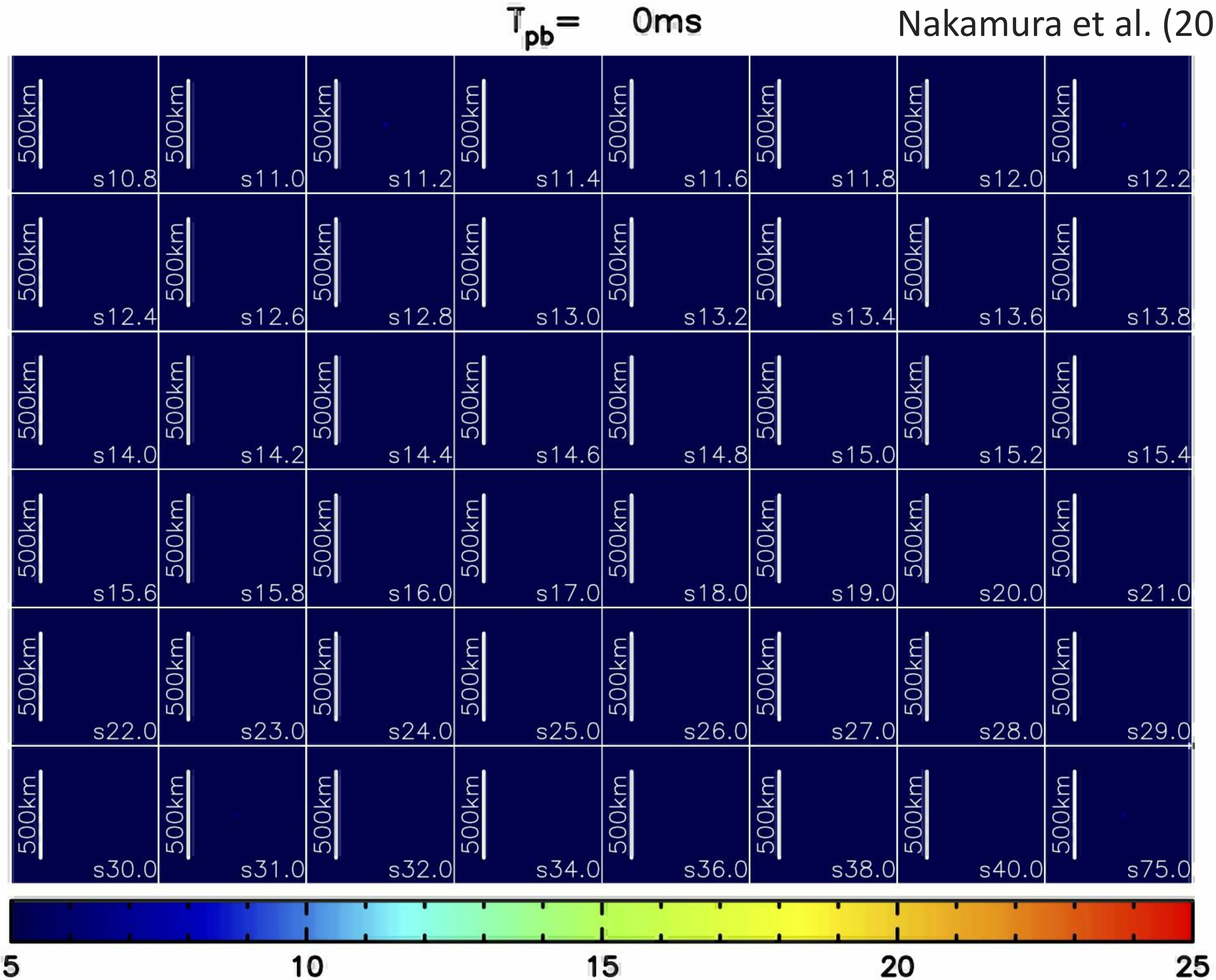
✓IDSA scheme for spectral neutrino transport
✓Lattimer-Swesty EOS (K=220 MeV)
:compatible with 2 M_{sun} NS observation



Suwa, KK et al. (2013

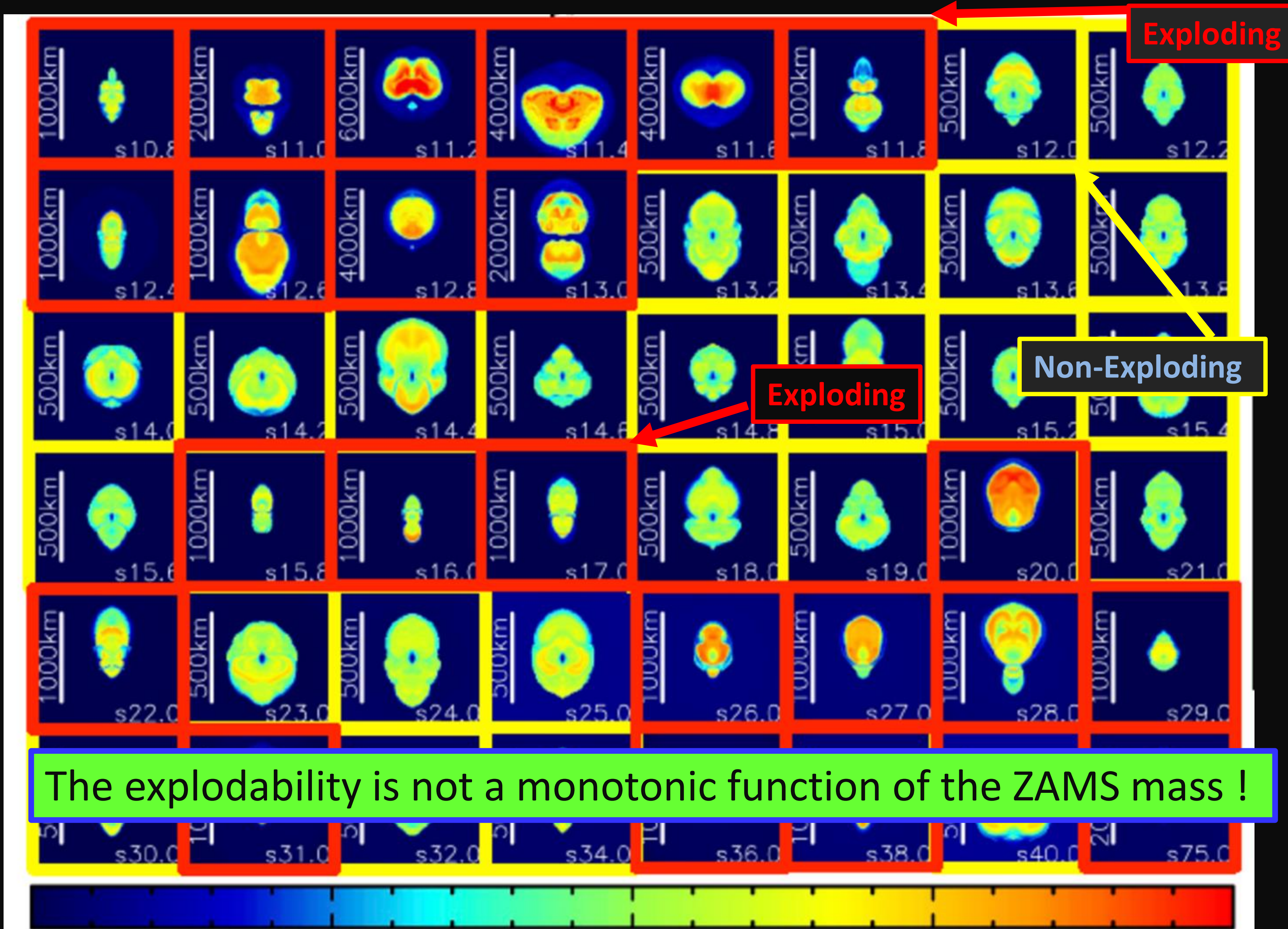
2D-IDSA simulations for 101 progenitors with solar metallicity

Nakamura et al. (2015)



“Systematics” between progenitor and explodability connections ?

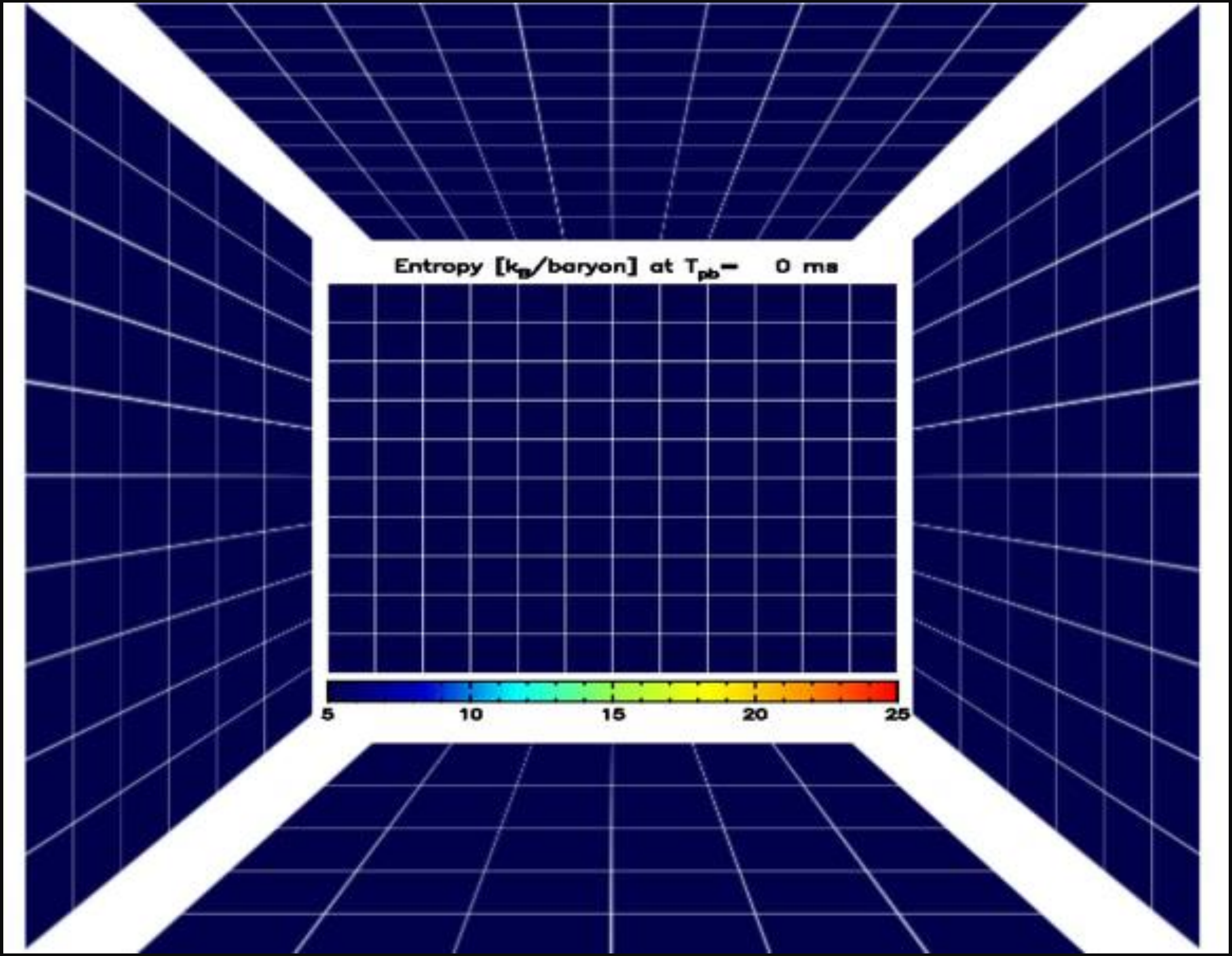
Nakamura et al. (2015)



The explodability is not a monotonic function of the ZAMS mass !

2D landscape simulations for 378 progenitors (WHW02)

Nakamura et al. (2015)



✓"Progenitor Compactness" Parameter

as an explosion diagnostics

(O'Connor and Ott (2011))

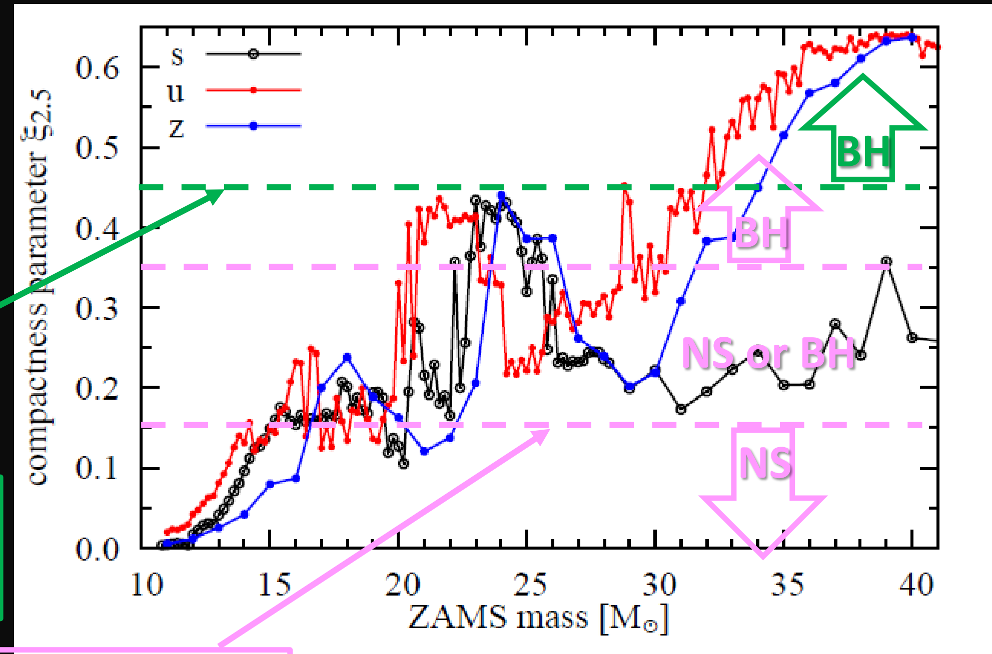
$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}} \quad @\, M = 2.5\, M_\odot$$

(the choice is arbitrary)

✓ Previous 1D models

O'Connor & Ott (2011); the BH formation requires $\xi_{2.5} > 0.45$

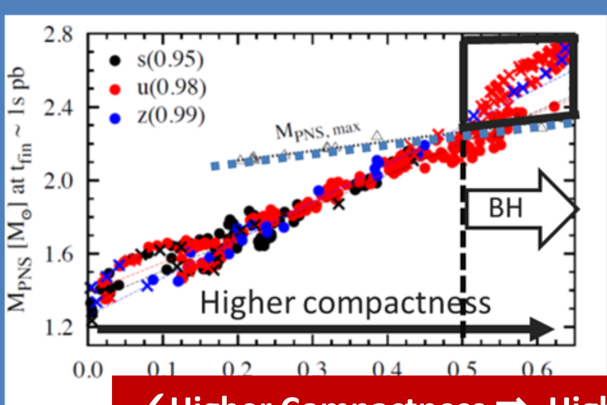
Ugliano et al. (2012); explosion $\xi_{2.5} < 0.15$, BH $\xi_{2.5} > 0.35$

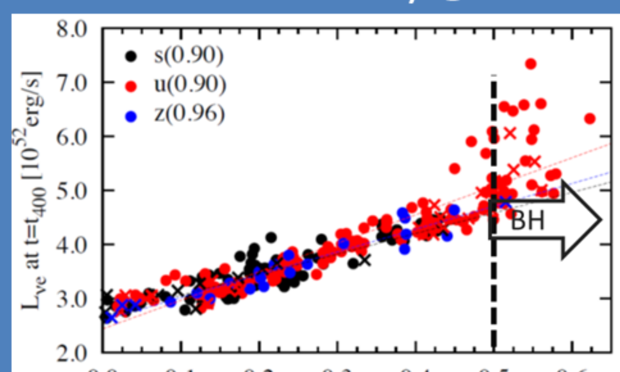


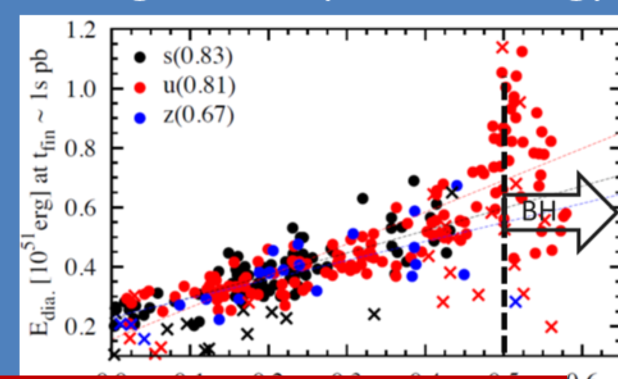
378 models (101 solar(s), 247 ultra-metal poor (Z = 10^{-4}), 30 zero metal, Woosley et al. (2002), hereafter WHW02).

How about in multi-D self-consistent models ?

Mass accretion rate to PNS	Neutrino luminosity @ revival	Diagnostic explosion energy



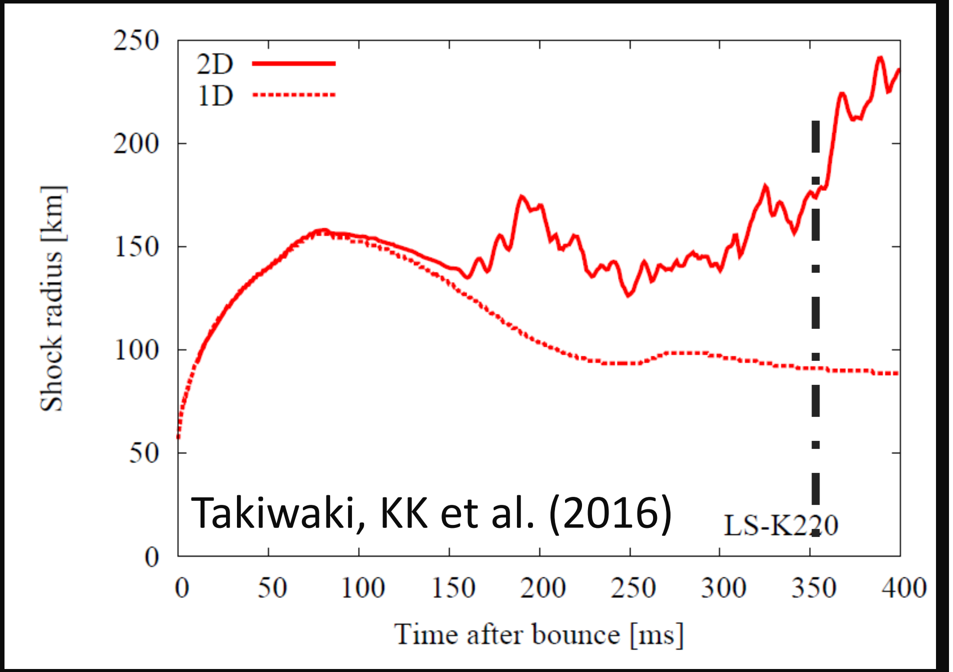


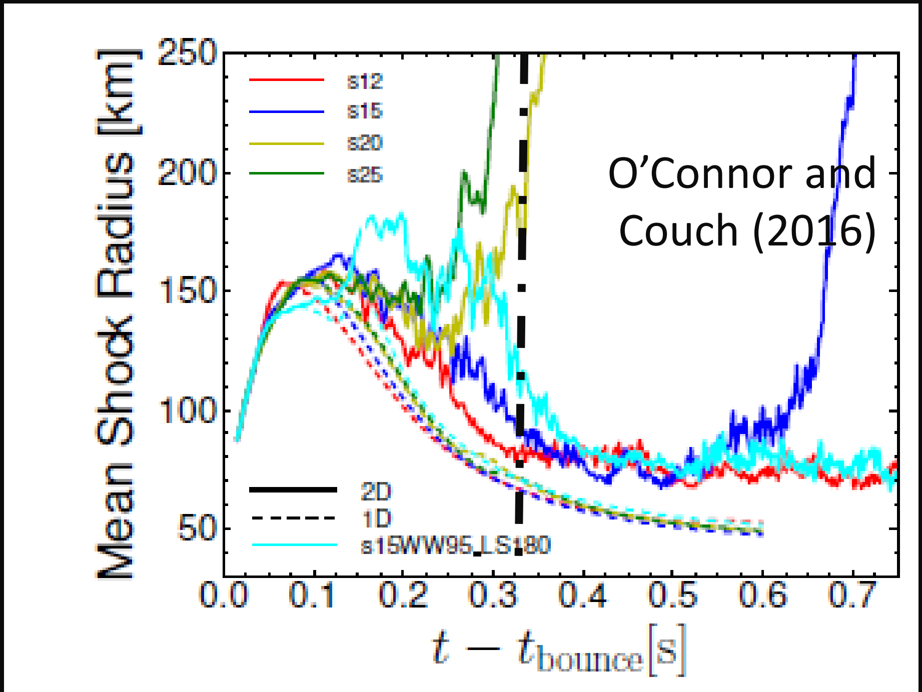


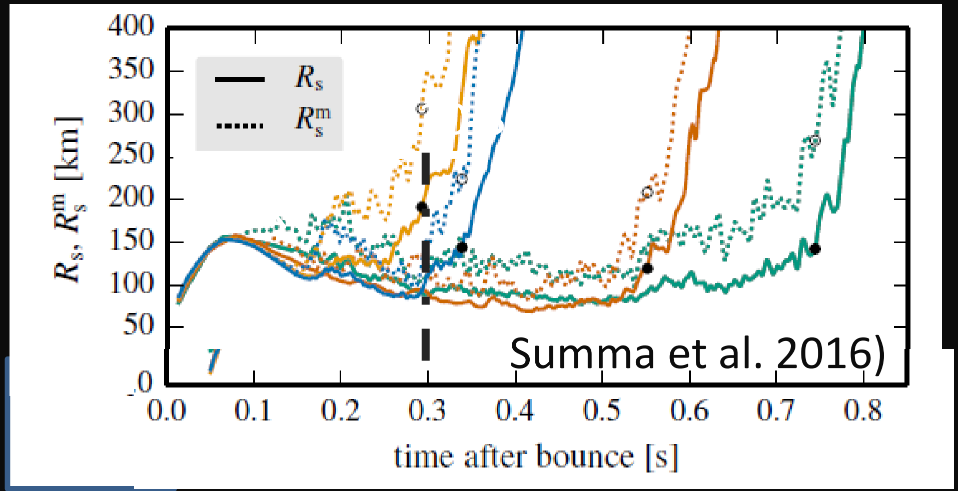
✓Higher Compactness ⇒ Higher mass accretion to PNS ⇒ Heavier PNS ⇒ Higher neutrino luminosity ⇒ "Diagnostic" Exp. energy and Nickel mass higher (for the NS forming case) : Core-Collapse Supernova is initial value problem !

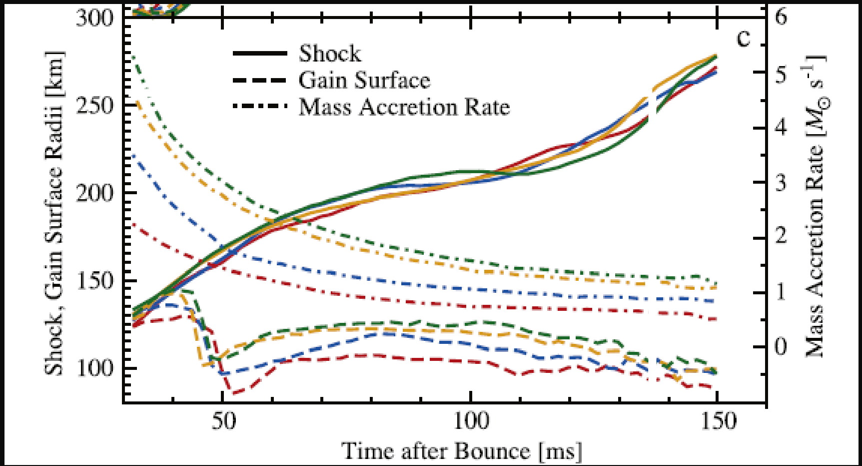
Nakamura et al. (2015)

Detailed comparison between different SN codes (Garching, Caltech, Oakridge, Japan) using same progenitor ($20M_{sun}$ Woosley and Heger (2007)), same grids…









Oakridge (Bruenn et al. 16)

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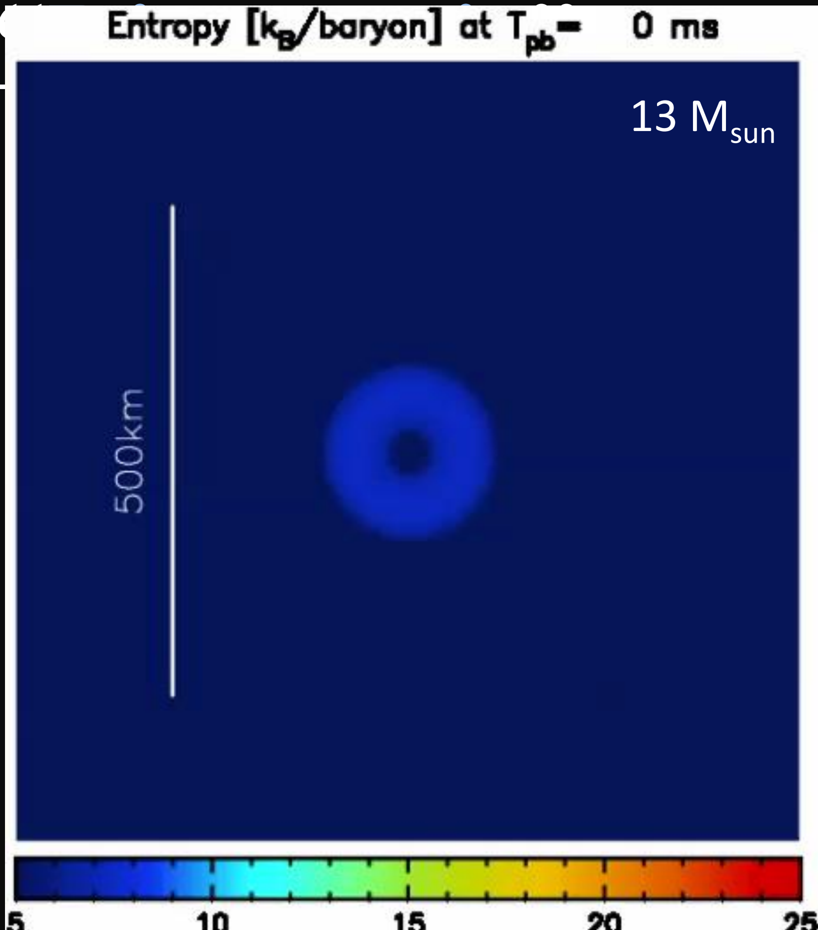
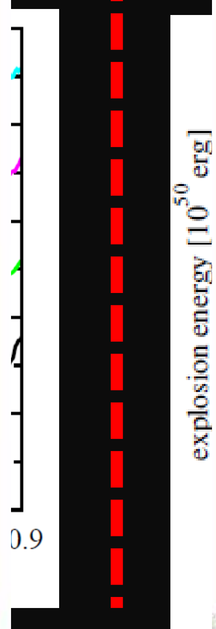
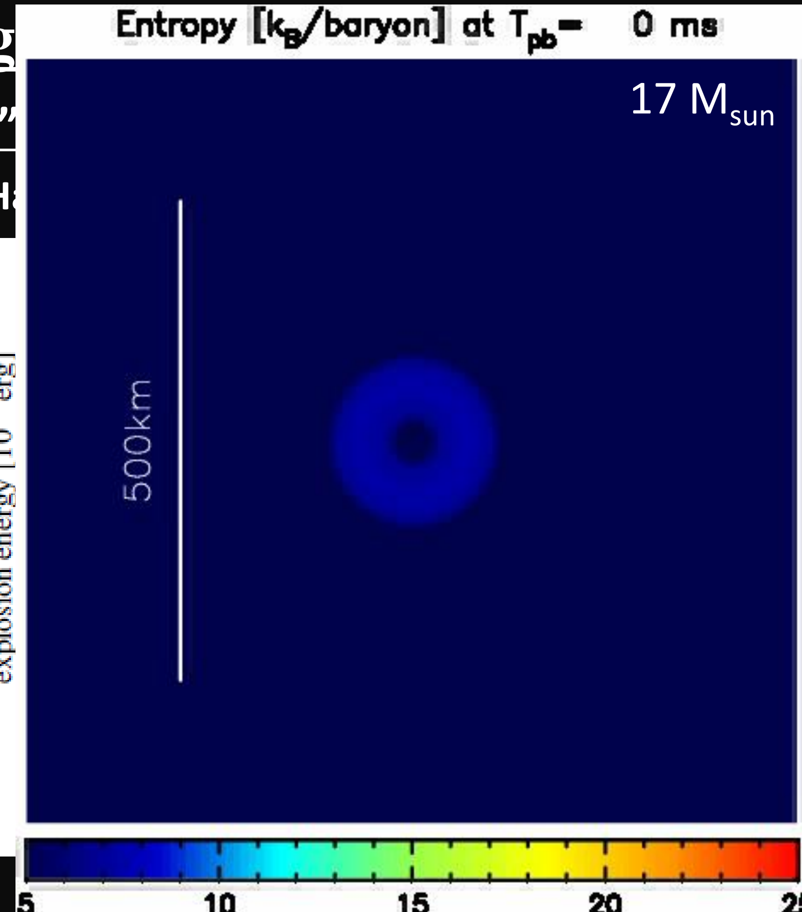
Ha

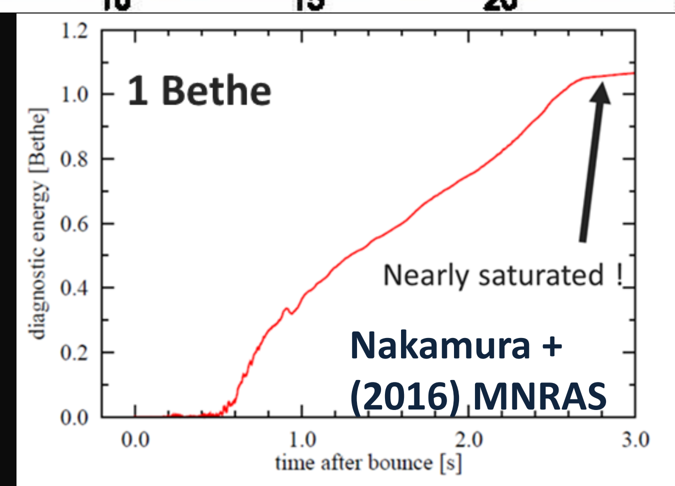






✓ The saturation timescales of explosion energy:
sensitive to the progenitor structures
→ Need to perform long-term evolutions for > 378 models !
(Nakamura et al. in prep)

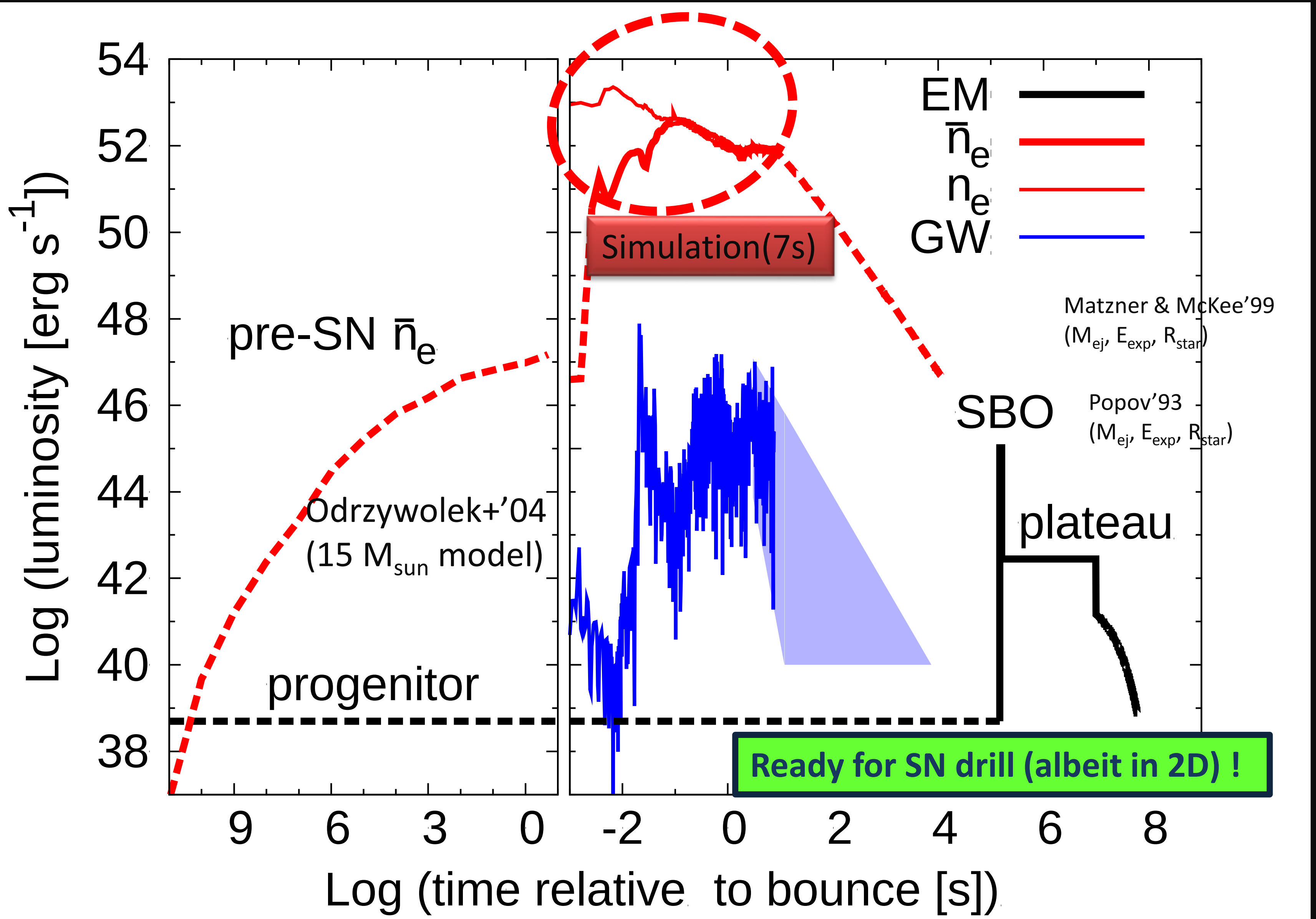
✓ 2D で観測との比較に資する爆発モデルが発表されてきた。
Bruenn et al. (2014)など



Overview of "Multi-messenger signals" from exploding 17 M_{sun} star

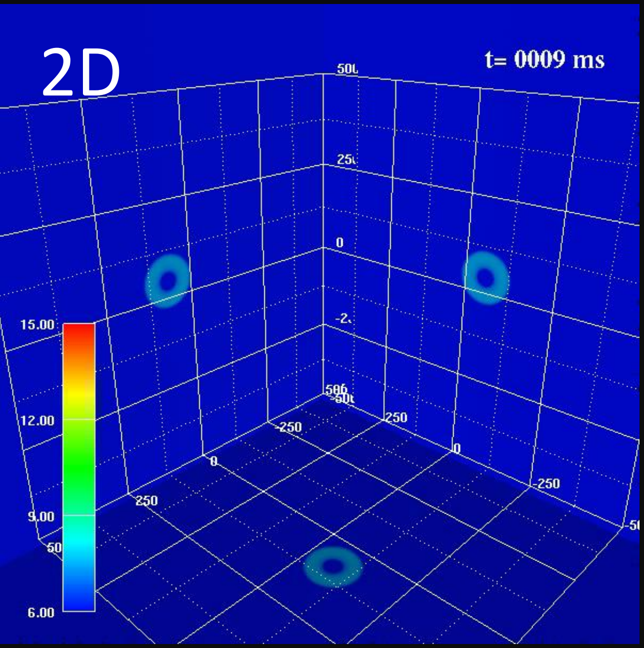
Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, KK (MNRAS) 2016

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

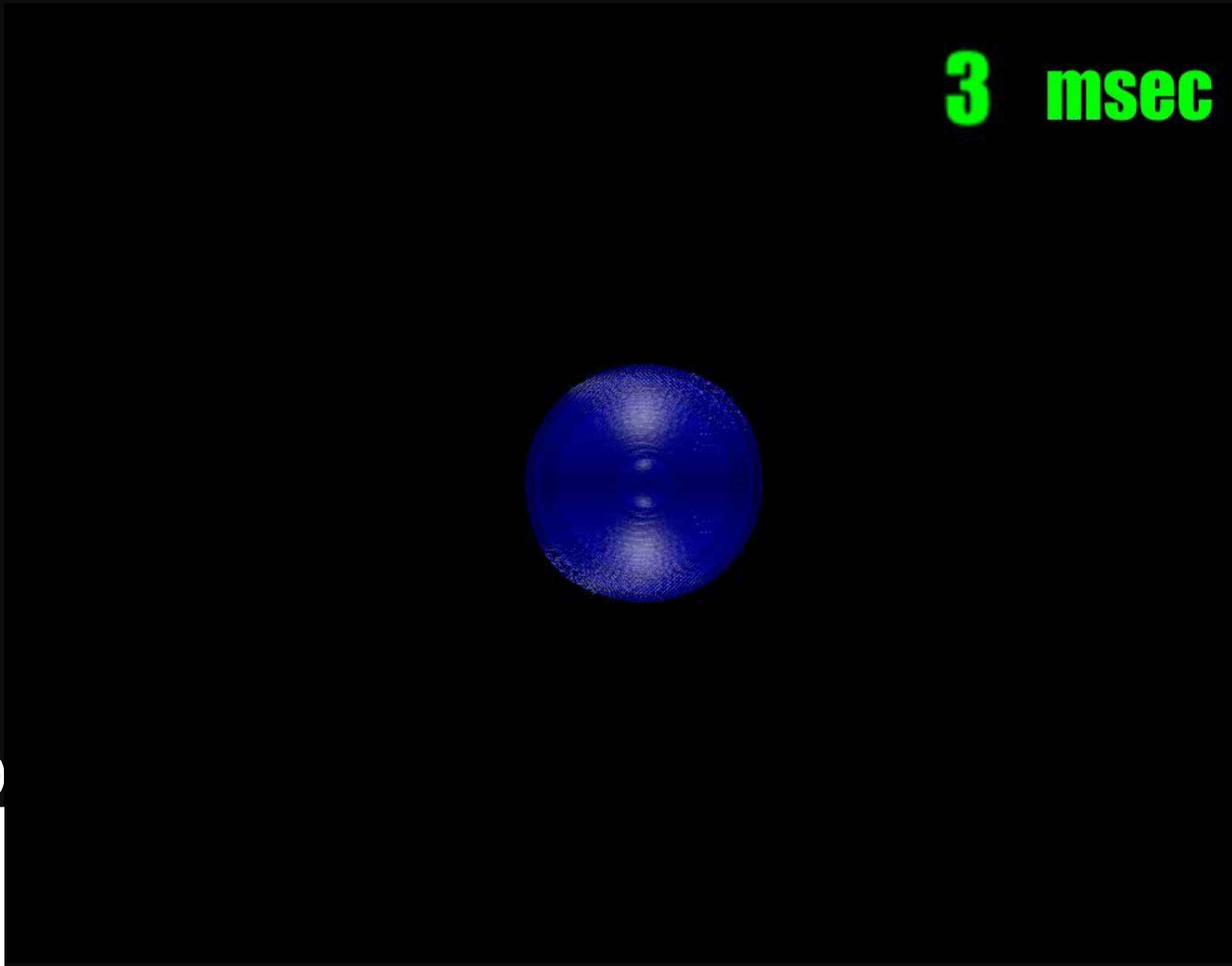


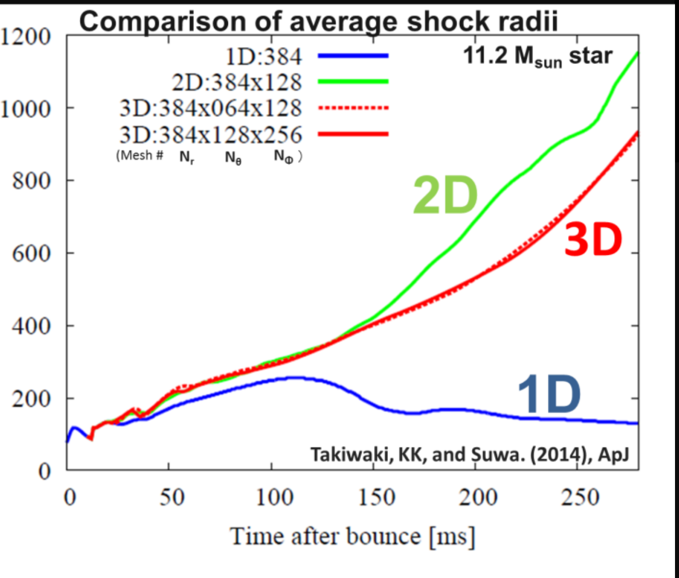
Ready for SN drill (albeit in 2D) !

3D vs. 2D



(e.g., Takiwaki,KK, Suwa (2012,2014), ApJ)





✓ For 11.2 M_{sun}, 3D explosions are weaker than 2D.
(27 M_{sun} : Hanke et al. (2014), however, not for 9.6 M_{sun} Melson et al. (2015))

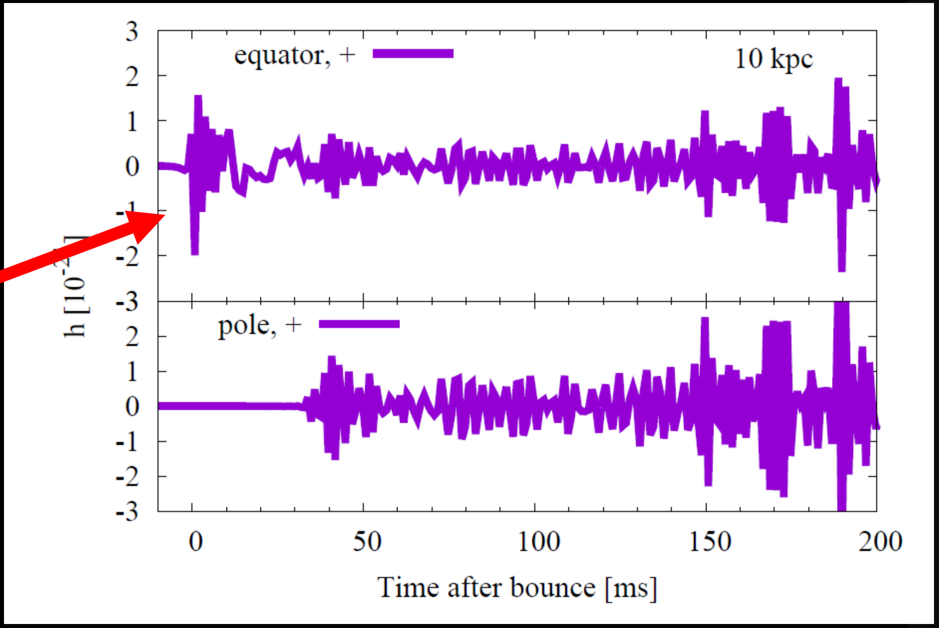
⇒ The "3D vs. 2D problem" is progenitor dependent.

✓ No "Bethe" models obtained in 3D….

⇒ Need to find ingredients to foster 3D explosions !
Candidates: Rotation, General Relativity, Microphysics

Rapid Rotation ⇒ A possible key to hypernovae ?

✓3D rotating core-collapse of 27 M_{sun} star (Ω_0 = 2 rad/s) with IDSA.
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016))

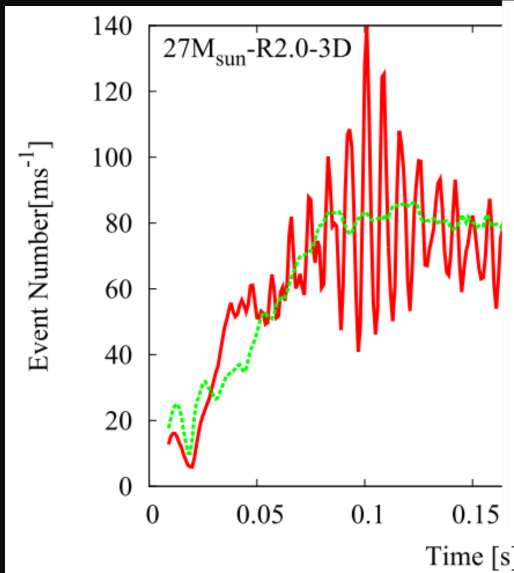


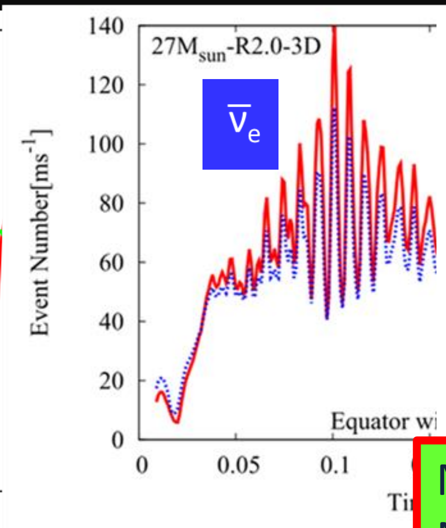
Seen from equatorial direction,
the GW burst (type I) with rotating bounce
⇒ Smoking-gun signature of rapid rotation

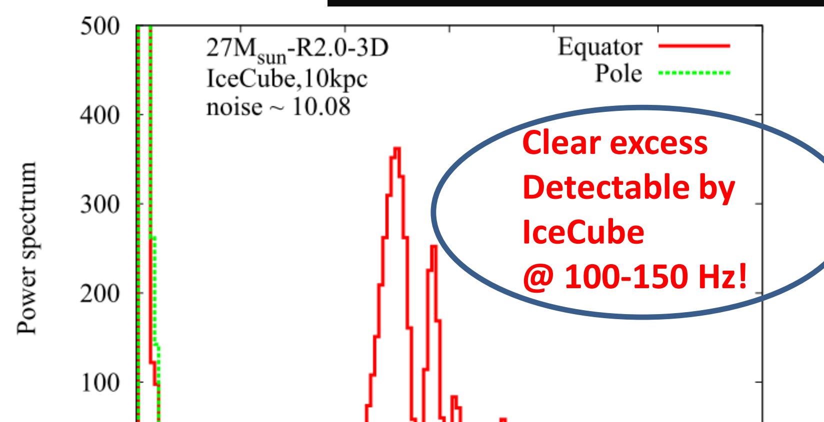
Neutrino signatures from rapidly rotating explosion of 27 M_{sun} star

Takiwaki and KK in prep

Quasi-periodic variation ! May survive with coll. oscillation



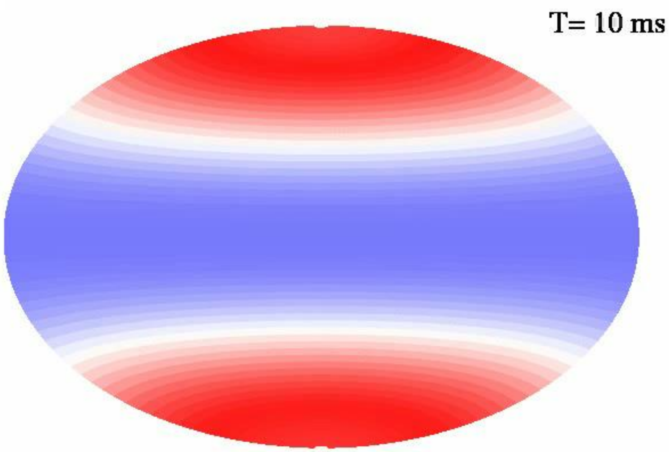




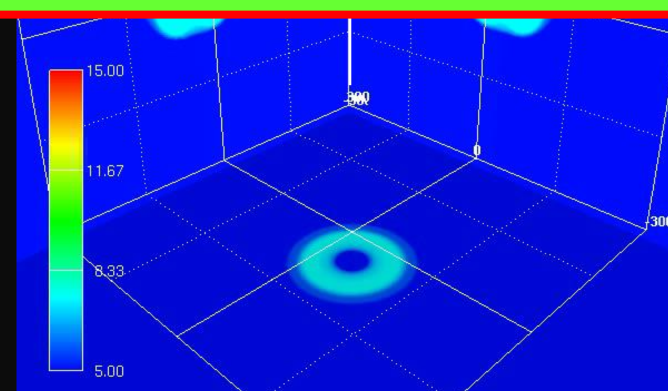
Clear excess Detectable by IceCube @ 100-150 Hz!

> **Multimessenger features:**
> Neutrino:
> The rotational frequency of the spiral arm is marked in the neutrino signals.
> ← The "***lighthouse*** effect".
> GW: The type I signal emitted near bounce

$\delta L_{\bar{\nu}_e}$: RMS deviation from the angle-average luminosity



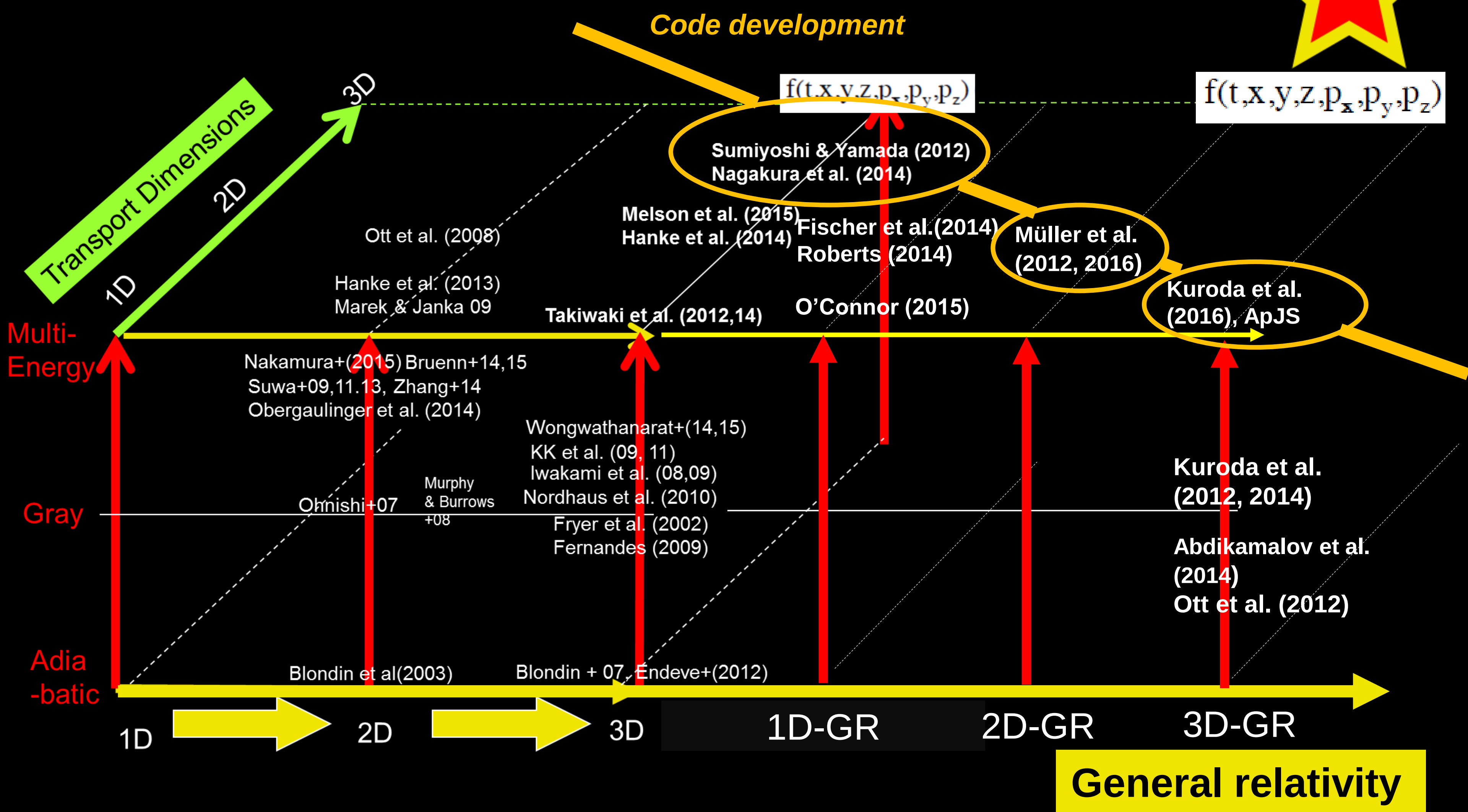
"Lighthouse effect" **Seen from equator**



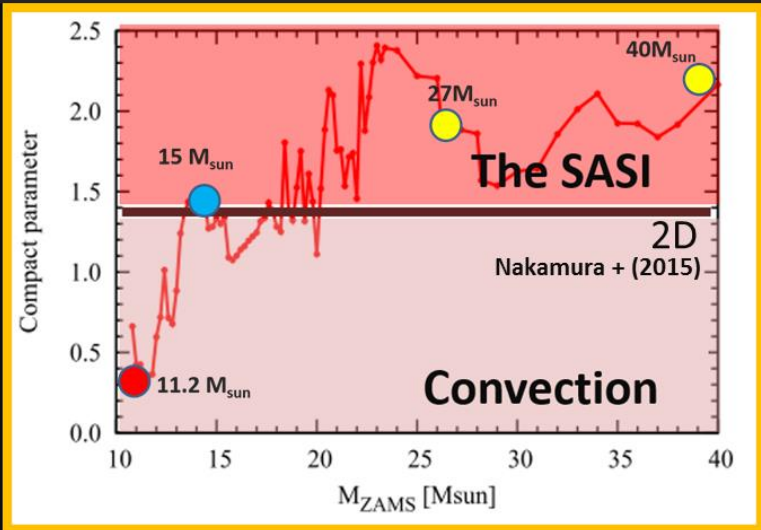
Recent Status of CCSN simulations

Disclaimer: only CCSNs

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

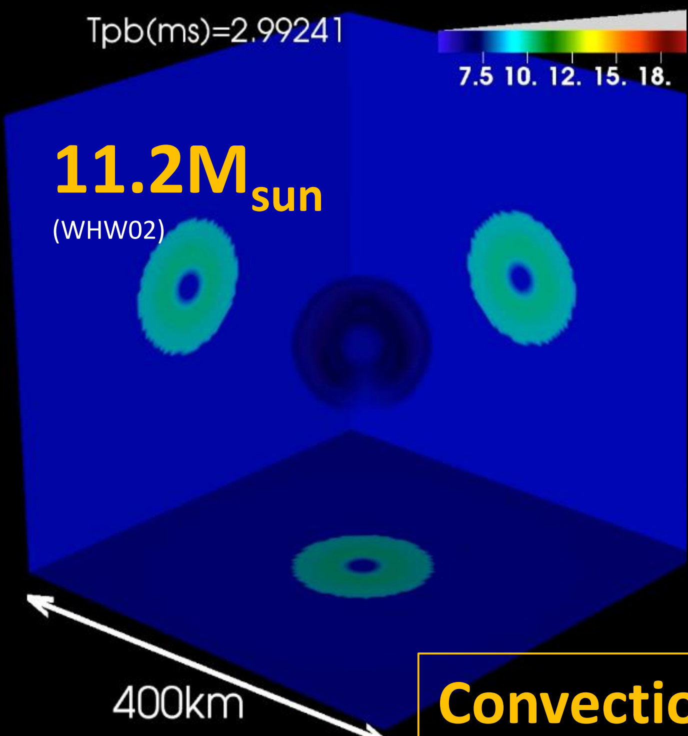


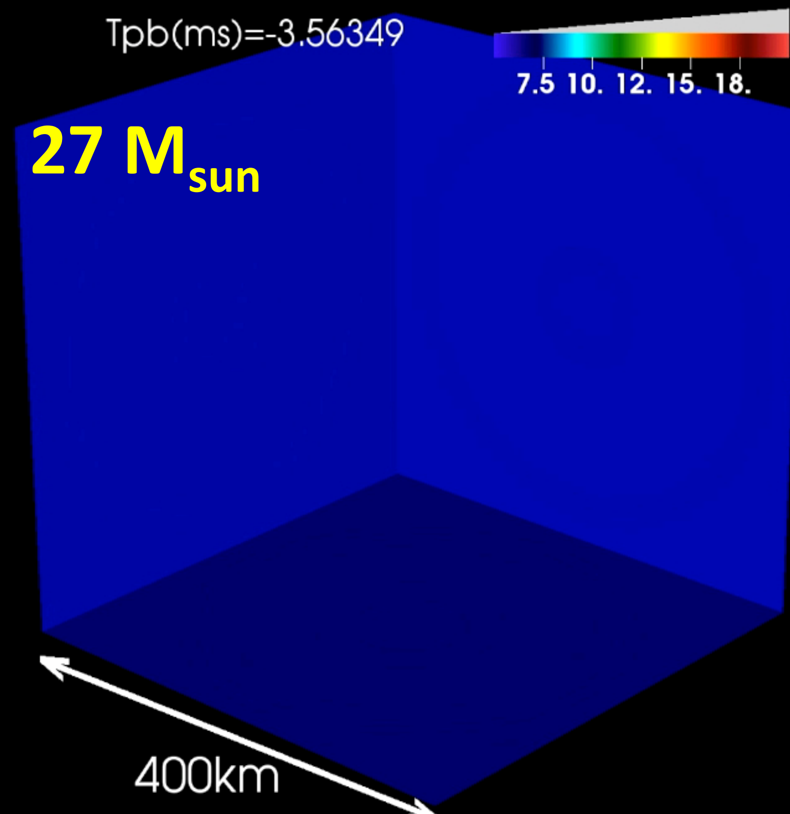
SASI vs. Convection plot in 3D-GR



<u>3D full General Relativistic (GR) simulations (BSSN) with 3 flavor neutrino transport (gray, M1 scheme)</u>

(Kuroda, KK, and Takiwaki 2012, ApJ, 2014, PRD)
see **multi-energy version available !**
in Kuroda,Takiwaki, & KK. ApJS (2016))





Convection-dominant

SASI-dominant

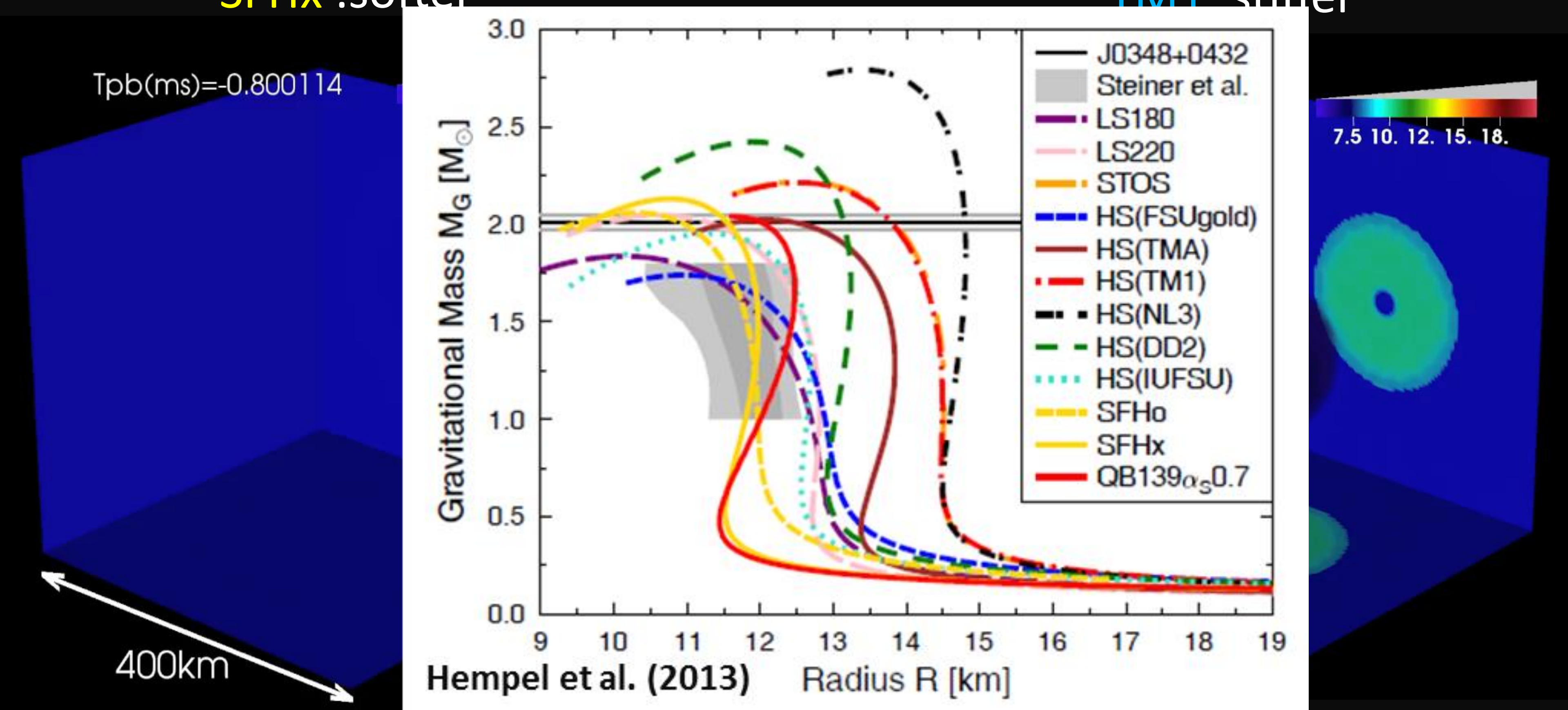
Neutrino signals from 3D-GR models with different EOSs (1/2)

✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)), **HS(TM1)** (Shen et al. (1998), Hempel & Schaffner-Bielich (2010)).

✓15 M_{sun} star (Woosley & Weaver (1995))

SFHx :softer

TM1 :stiffer



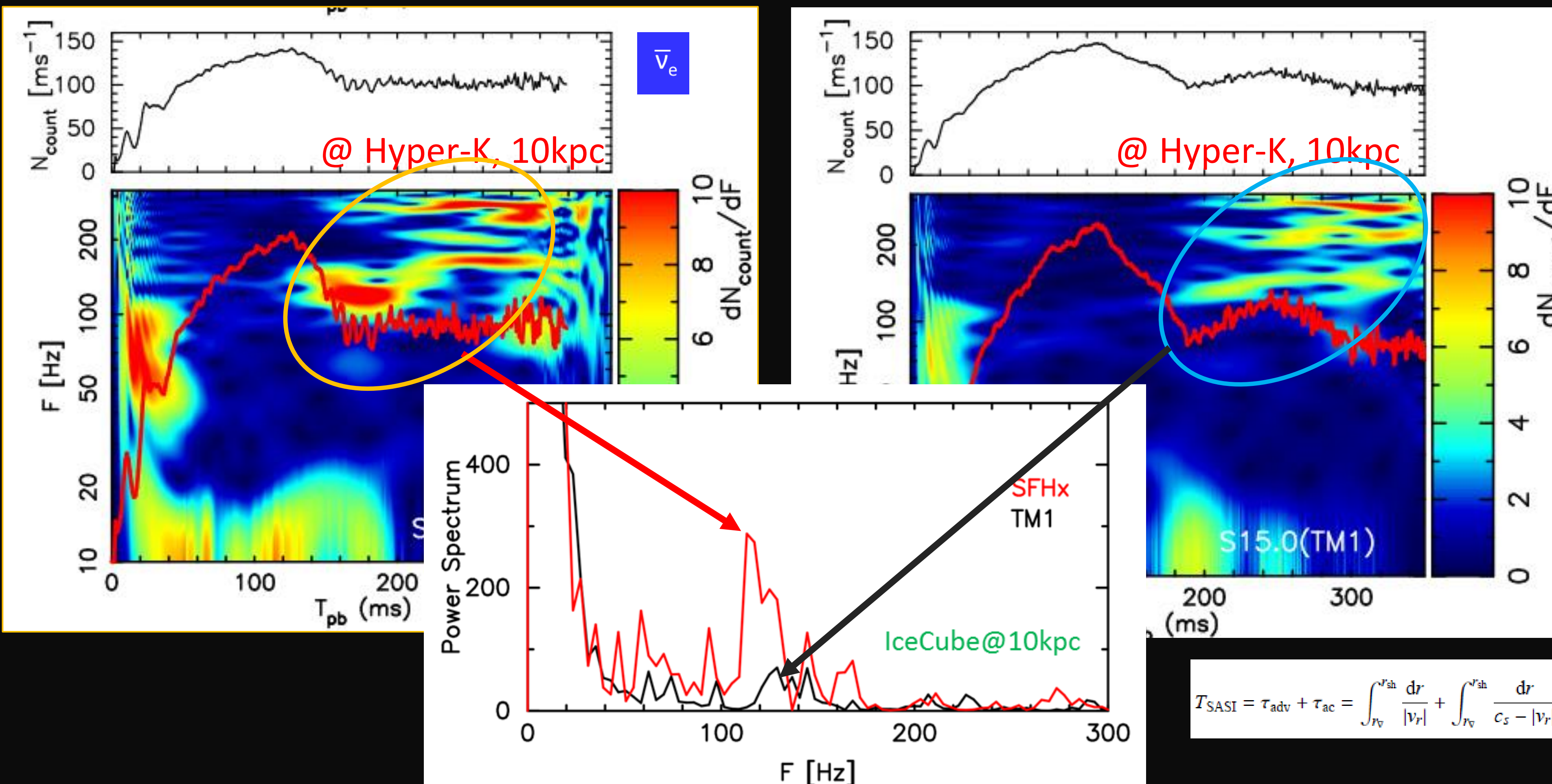
✓**SASI activity higher for softer EOS** (due to shorter growth rate, e.g., Foglizzo et al. ('06)).

Neutrino signals from 3D-GR models with different EOSs (2/2)

Kuroda, KK, Takiwaki in prep

SFHx :softer

TM1 :stiffer



$$T_{SASI} = \tau_{adv} + \tau_{ac} = \int_{r_\nu}^{r_{sh}} \frac{dr}{|v_r|} + \int_{r_\nu}^{r_{sh}} \frac{dr}{c_s - |v_r|}$$

☺ The **SASI modulation appears more clearly in 3D-GR model with best EOS available !**

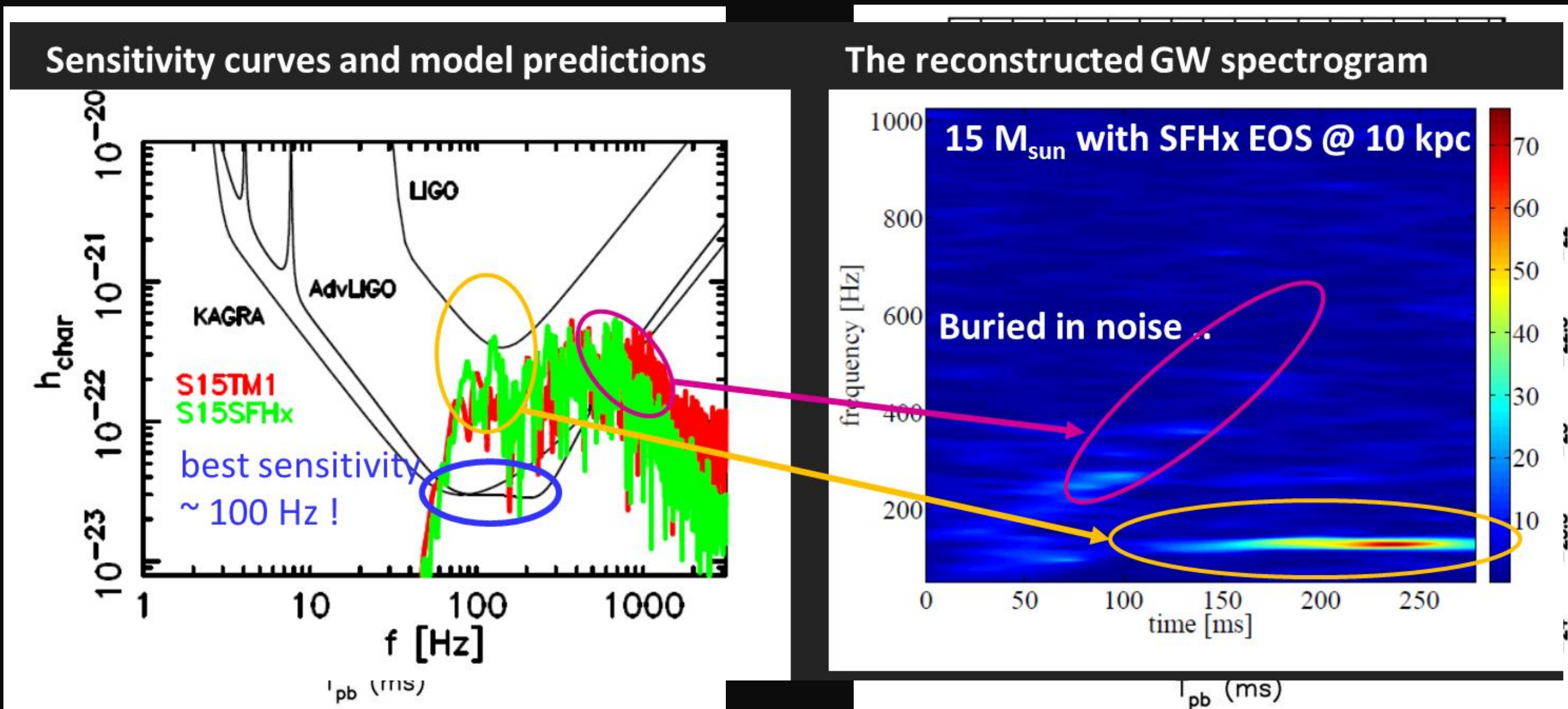
☹ **The modulation freq. from the SASI and rapid rotation: in the range (100 – 200 Hz).**

So… how to tell the difference ?

Gravitational Wave (GW) : the key !

(Kuroda, KK, & Takiwaki ApJL 2016, see also Andresen et al.)

SFHx :softer **TM1** :stiffer



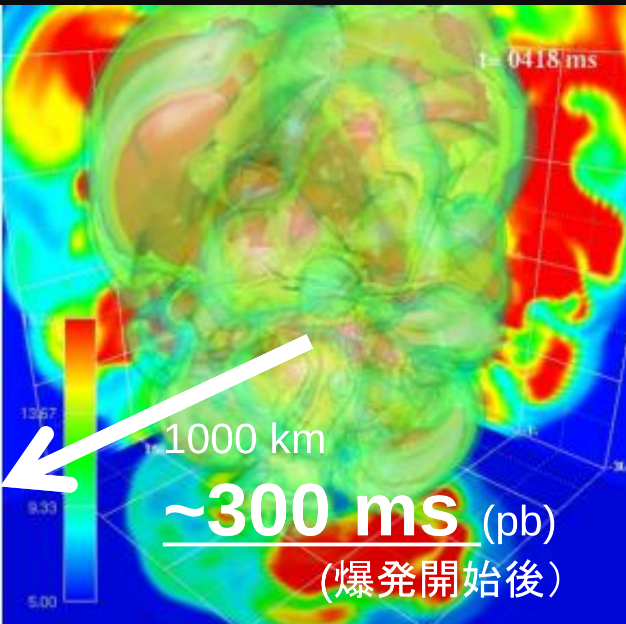
✓**The quasi-periodic modulation is associated with SASI, clearly visible with soft EOS.**

✓By coherent network analysis of LIGOx2, VIRGO, and KAGRA, the signal detectable out to the LMC (50 kpc, Hayama, Kuroda, KK et al. (2015, PRD)).

✓The SASI activity, if very high, results in characteristic signatures in both GWs and neutrino signals (even for non-rotating progenitors !).

Perspectives: Where are we and where are we going ?

"A" self-consistent 3D model

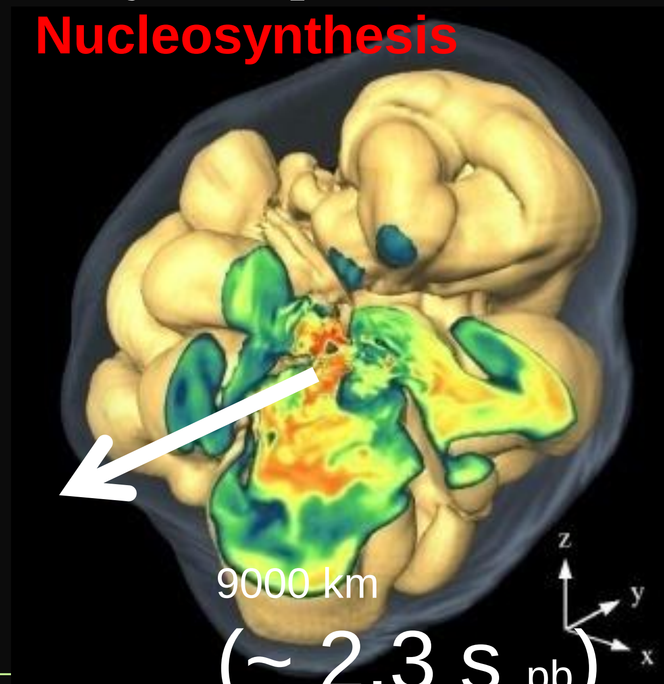


Takiwaki, KK, Suwa (2014,2012 ApJ)

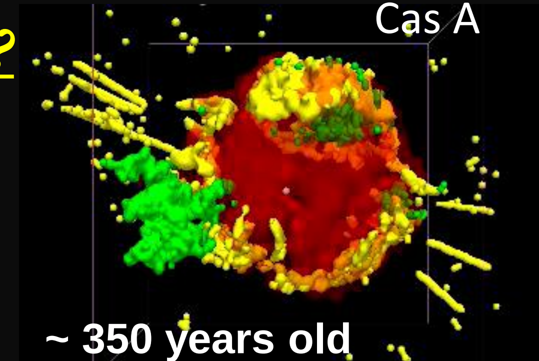
For an 11.2 M_{sun} star,
the stalled shock revived !
(4D with approximate transport)

Gray-transport simulation

Nucleosynthesis

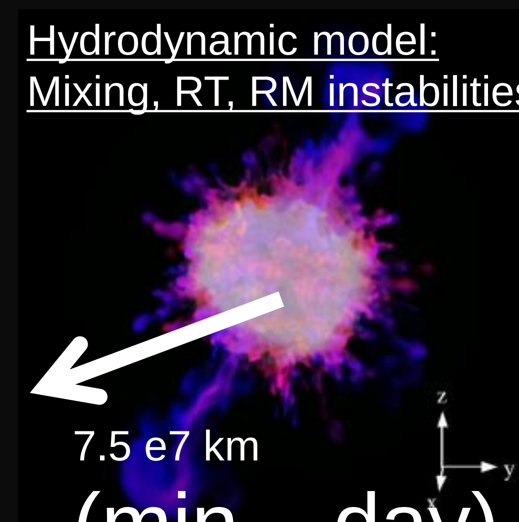


Wongwathanarat et al. (2012)



DeLaney et al. (2010)

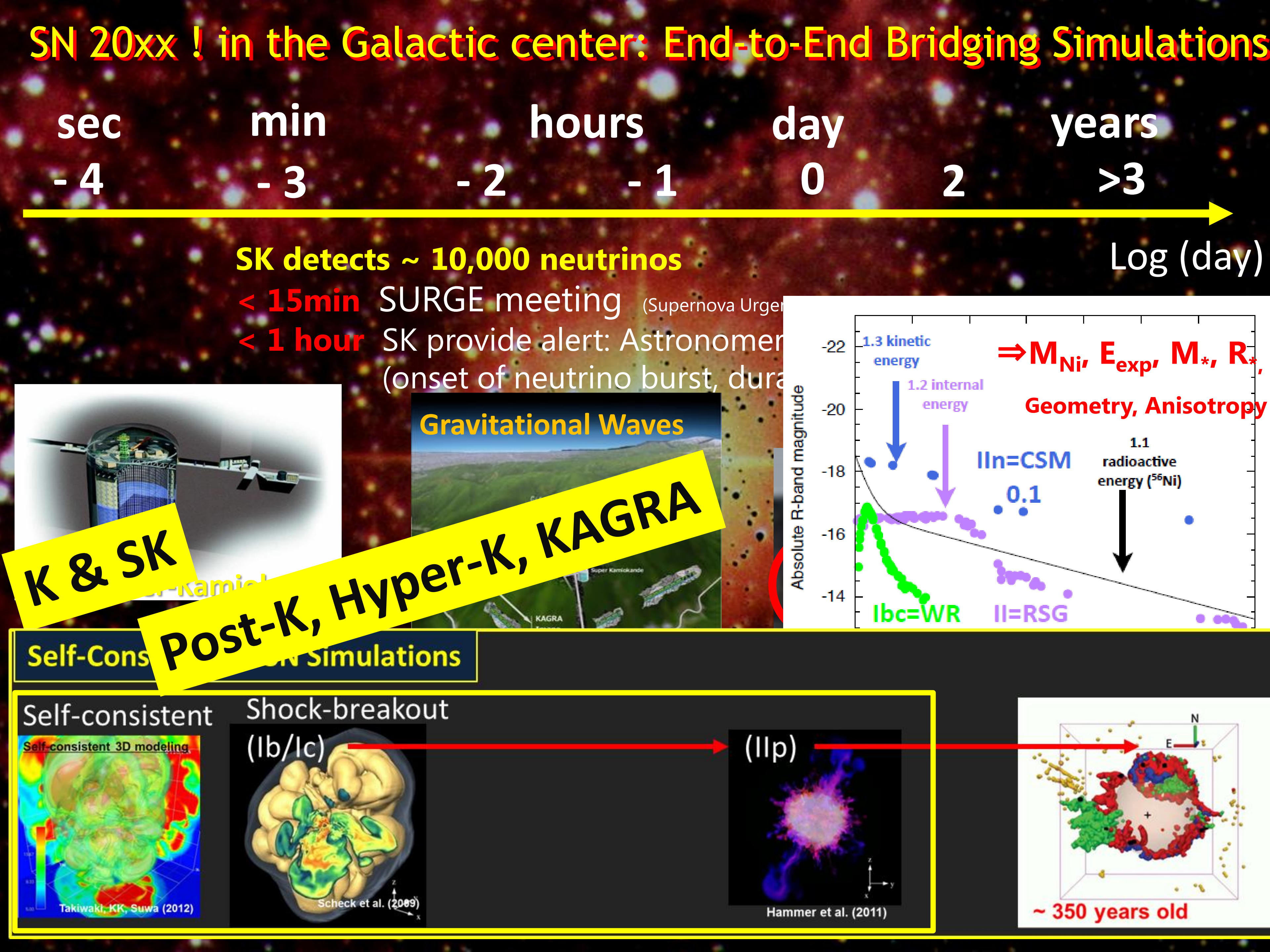
Hydrodynamic model:
Mixing, RT, RM instabilities



Wongwathanarat et al. (2014)

To-do-1: Long-term evolution in self-consistent 3D (GR) models
⇒ confront CCSN theory with observation ⇒ Post K project 1

To-do-2 : Full Boltzmann project :
⇒ ultimately test whether the stalled shock would revive. ⇒ Post K project 2


SN 20xx ! in the Galactic center: End-to-End Bridging Simulations
sec
min
hours
day
years
- 4
- 3
- 2
- 1
0
2
>3
Log (day)
SK detects ~ 10,000 neutrinos
< 15min SURGE meeting (Supernova Urge
< 1 hour SK provide alert: Astronomer
(onset of neutrino burst, dura
Gravitational Waves
Super Kamiokande
KAGRA
K & SK
Post-K, Hyper-K, KAGRA
Self-Cons
SN Simulations
1.3 kinetic energy
1.2 internal energy
⇒M_Ni, E_exp, M_*, R_*,
Geometry, Anisotropy
IIn=CSM
0.1
1.1 radioactive energy (56Ni)
Absolute R-band magnitude
-22
-20
-18
-16
-14
Ibc=WR
II=RSG
Self-consistent
Self-consistent 3D modeling
Takiwaki, KK, Suwa (2012)
Shock-breakout
(Ib/Ic)
Scheck et al. (2009)
(IIp)
Hammer et al. (2011)
N
E
~ 350 years old

Summary

1. In 2D, a number of explosion models (> 400) obtained by independent groups.
   Some are enough energetic to account for observations (E_{exp}, Ni).

2. 3D explosions generally under-energetic than 2D.
   - progenitor dependence yet unclear.

   ✓ Need to find some ingredients to foster 3D explosions.
   - some missing neutrino physics ? (e.g., Melson et al. (2015))
   - Impacts of rotation (and magnetic fields) yet to be clarified in 3D self-consistent models.
     (e.g., MRI, Obergaulinger+2009, Masada, Takiwaki, KK, 2015, ApJL)

3. 3D GR modelling has just started with increasing microphysical inputs.
   (e.g., FUGRA, it takes time … next generation machines needed !)

4. Multi-messenger analysis of neutrino and GWs are in steady progress.
   : ⇒ important probe to the explosion physics for the SN20xx !

Many thanks!