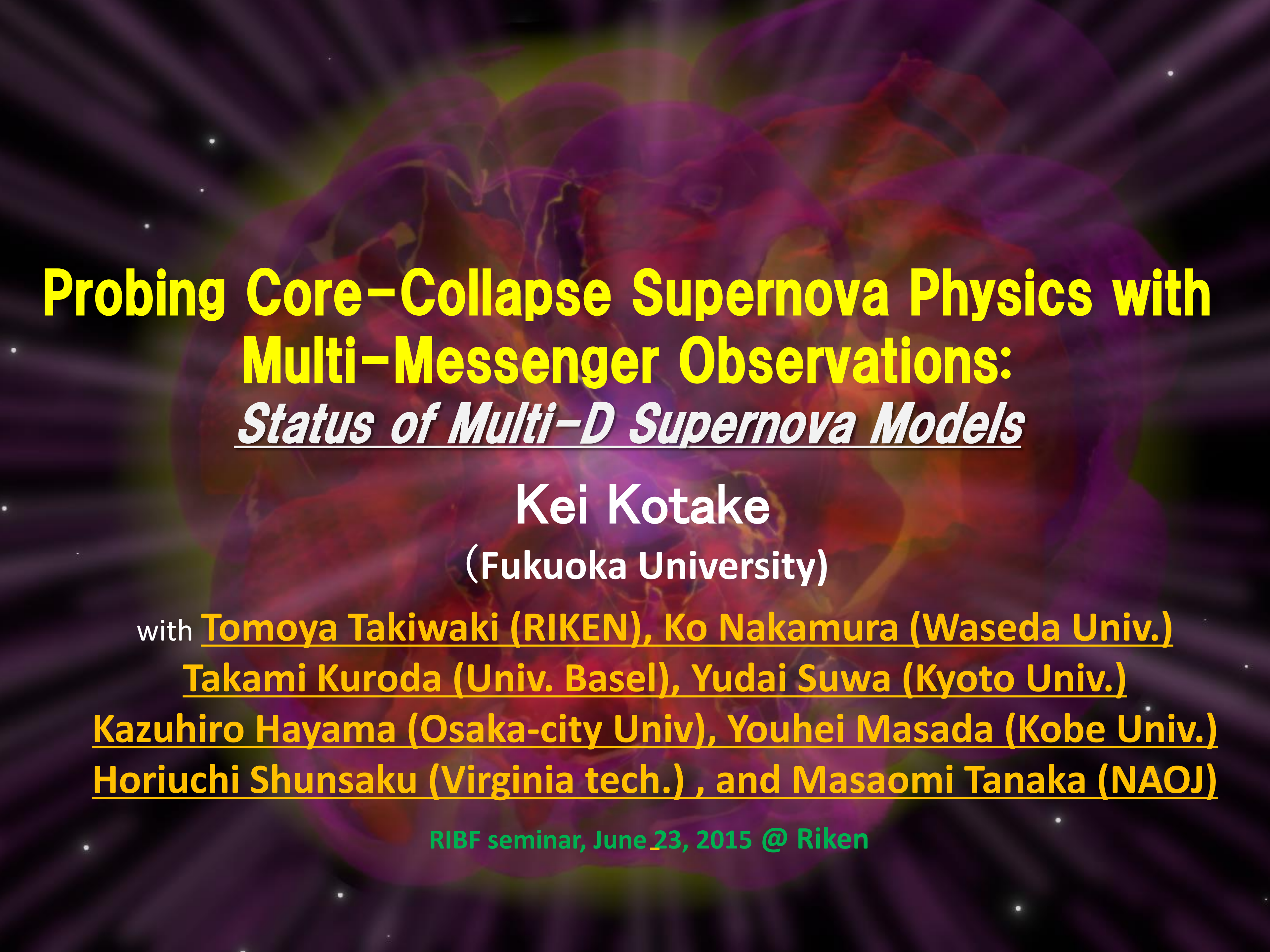


Probing Core-Collapse Supernova Physics with Multi-Messenger Observations:

Status of Multi-D Supernova Models

Kei Kotake
（Fukuoka University)

with Tomoya Takiwaki (RIKEN), Ko Nakamura (Waseda Univ.)
Takami Kuroda (Univ. Basel), Yudai Suwa (Kyoto Univ.)
Kazuhiro Hayama (Osaka-city Univ), Youhei Masada (Kobe Univ.)
Horiuchi Shunsaku (Virginia tech.) , and Masaomi Tanaka (NAOJ)

RIBF seminar, June 23, 2015 @ Riken

Outline

✓ Short Introduction

- Standard Core-Collapse Supernova (CCSN) theory

✓ Recent Status of CCSN Modeling

- Neutrino-Radiation Hydrodynamics Simulations
- Fostering weak explosions (strangeness, rotation, GR)

✓ Multi-Messenger Signatures

- How can we learn the central engine from neutrinos and gravitational-waves ?
- Strategies toward the final goal ?

Bottom-line

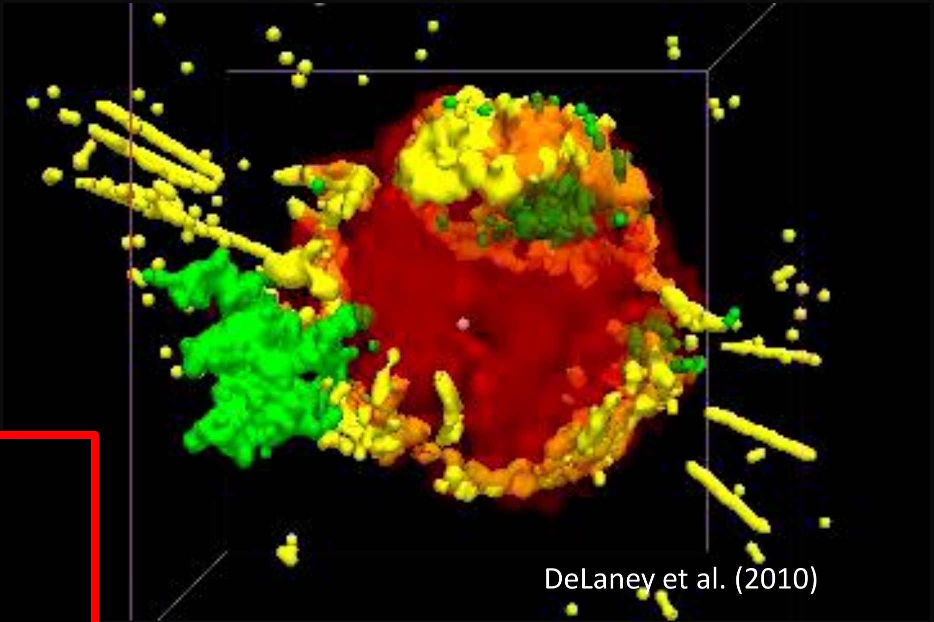
LETTER

February 19, 2014

doi:10.1038/nature12997

Asymmetries in core-collapse supernovae from maps of radioactive ^{44}Ti in Cassiopeia A

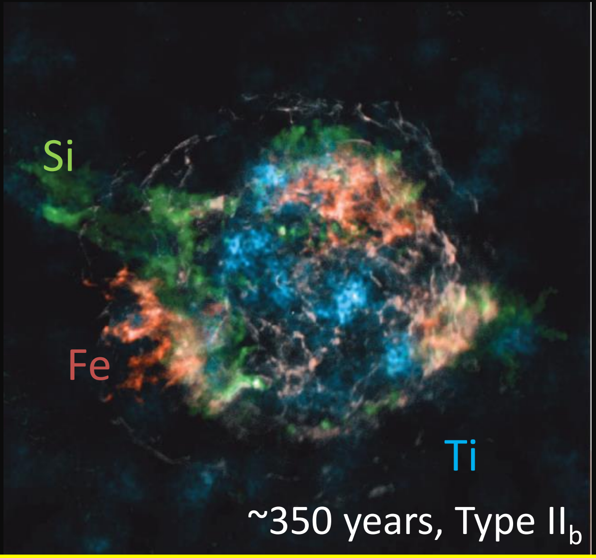
B. W. Grefenstette[1], F. A. Harrison[1], S. E. Boggs[2], S. P. Reynolds[3], C. L. Fryer[4], K. K. Madsen[1], D. R. Wik[5], A. Zoglauer[2], C. I. Ellinger[6], D. M. Alexander[7], H. An[8], D. Barret[9,10], F. E. Christensen[11], W. W. Craig[2,12], K. Forster[1], P. Giommi[13], C. J. Hailey[14], A. Hornstrup[11], V. M. Kaspi[8], T. Kitaguchi[15], J. E. Koglin[16], P. H. Mao[1], H. Miyasaka[1], K. Mori[14], M. Perri[13,17], M. J. Pivovaroff[12], S. Puccetti[13,17], V. Rana[1], D. Stern[18], N. J. Westergaard[11] & W. W. Zhang[5]



DeLaney et al. (2010)

Progression of a Supernova Explosion

http://www.nasa.gov/jpl/nustar/supernova-explosion-



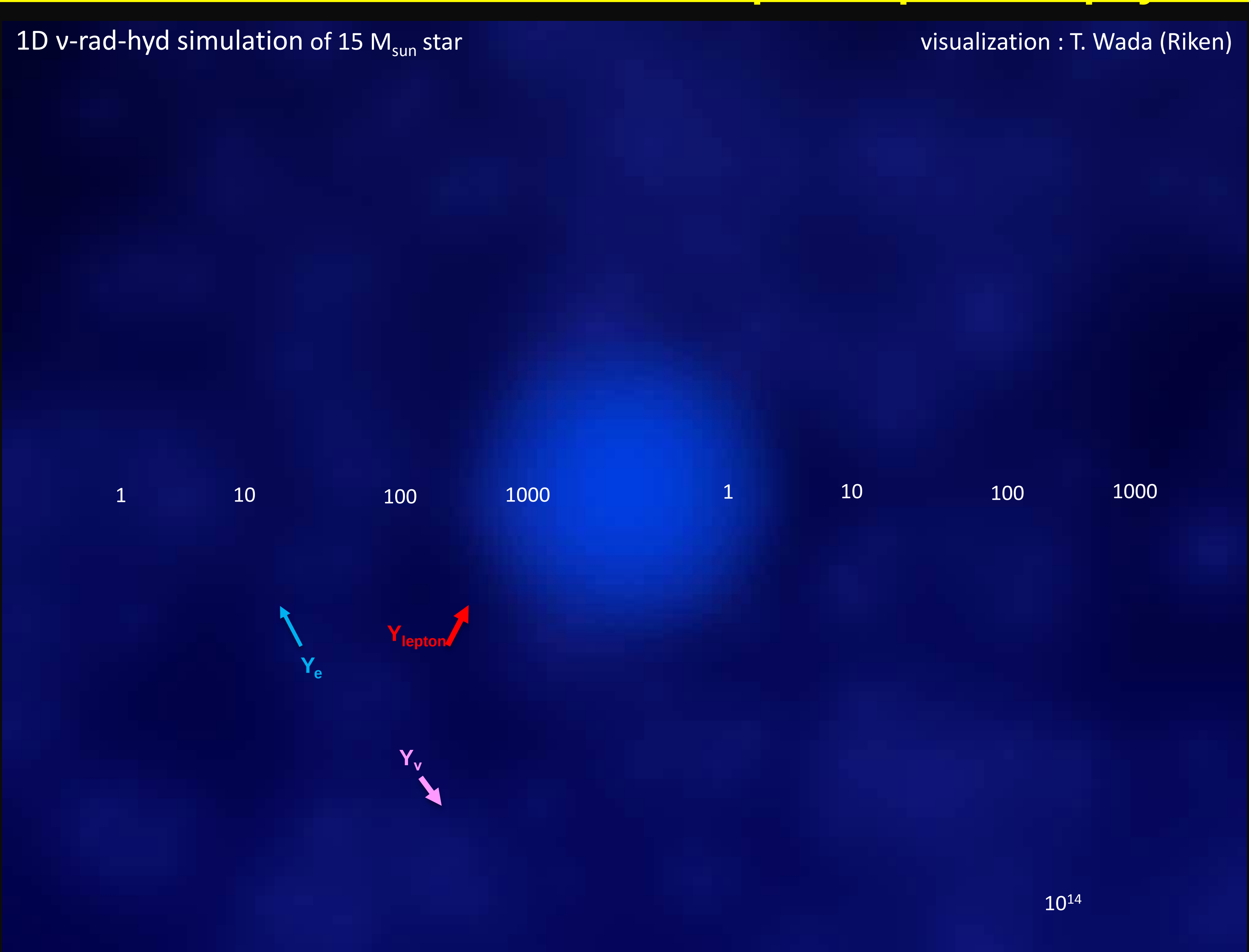
~350 years, Type II_b

H. Bethe

- ✓ Origin of explosion asymmetry
- ✓ Origin of heavy elements
- ✓ Origin of explosion energy (～ 10^{51} erg = 1 Bethe)

Explosion Mechanism

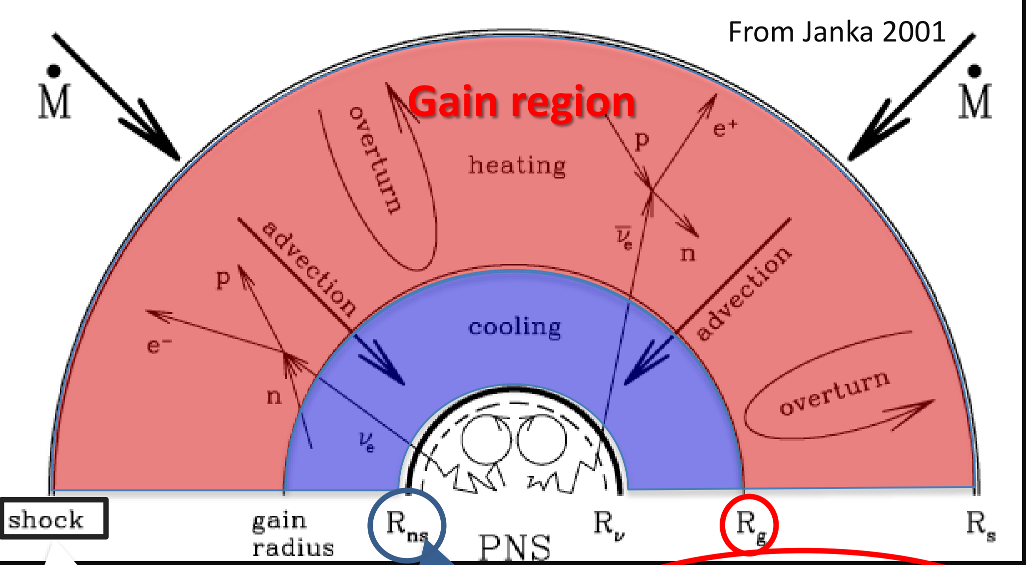
“3 minutes” to overview Core-Collapse Supernova physics



1D ν-rad-hyd simulation of $15\ M_{sun}$ star

visualization : T. Wada (Riken)

Typical scales after bounce and Density-Temperature relation

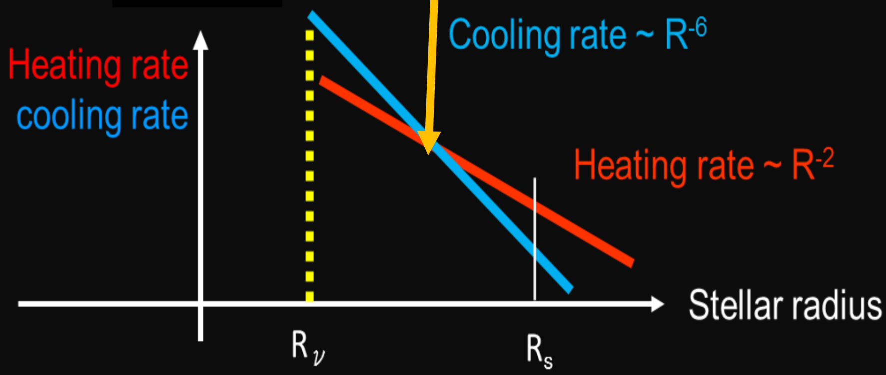


heating

$$p + e^- \rightleftarrows n + \nu_e$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

cooling

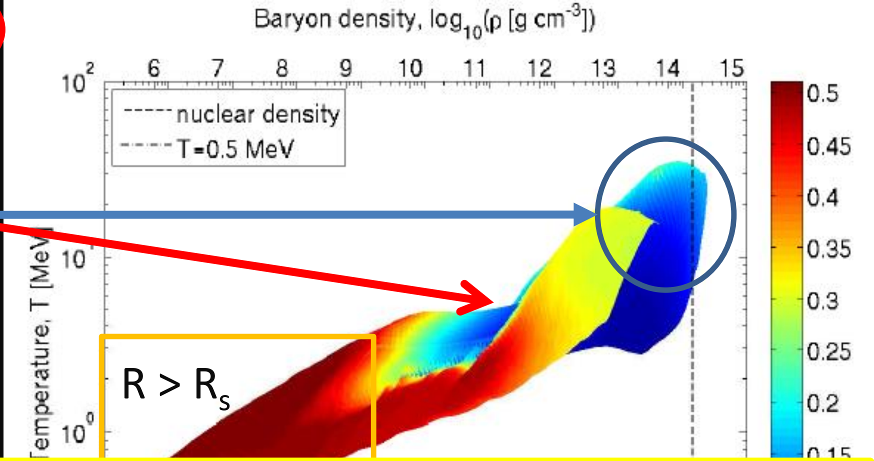
Gain radius



Gain Radius
R_g ~ 80km

R_{PNS}, R_ν ~ 50km
ρ_c ~ 10^{14} g/cc, T_c ~ 10 MeV

$R_{stalled\_shock}$ ~ 200km
(R_{core} ~ 1500 km)
$\rho < 10^9$ g/cc, T < 1 MeV



✓ Travel time (τ_{gain}) in the “gain region” ***longer***
Gain mass (M_{gain} :mass in the “gain region”) ***bigger***,
more favorable for explosions !

1D fails⇒ Current paradigm "Multi-D" neutrino mechanism

(pioneered by Colgate & White (1966), see Janka (2012), Burrrows (2013) ,Kotake et al. (2012) for review)

"Four steps" from collapse to explosion

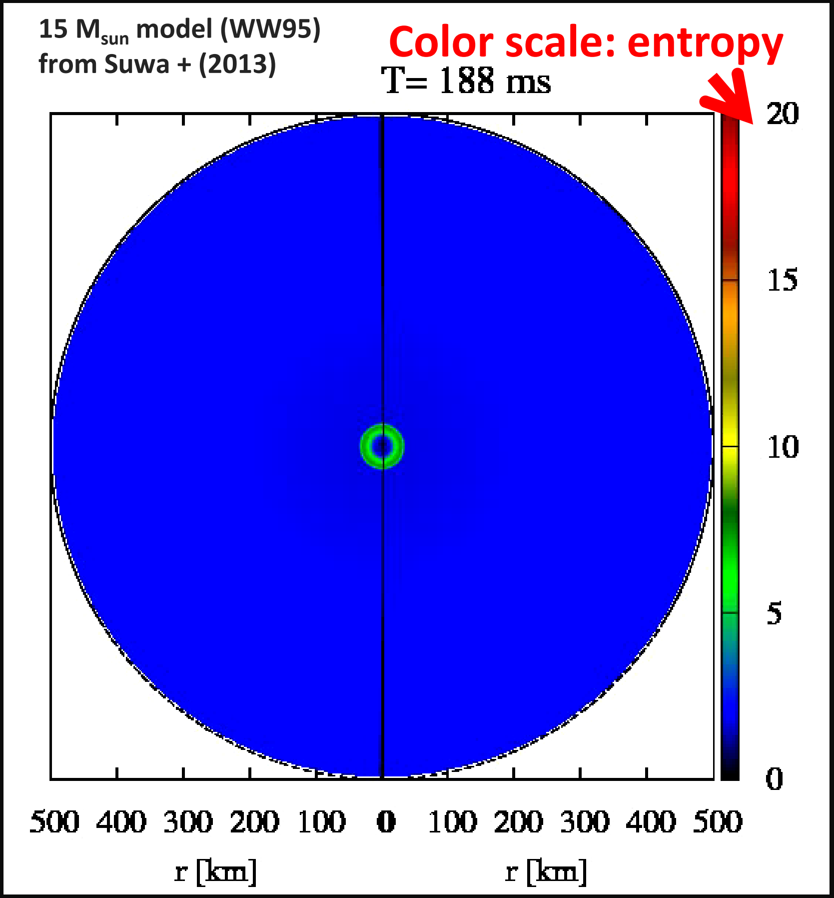
(see, e.g., Suwa et al. 2010,2011,2013, ApJ)

1st : After bounce, bounce shock stalls.

2nd: Neutrino-driven convection and the SASI.

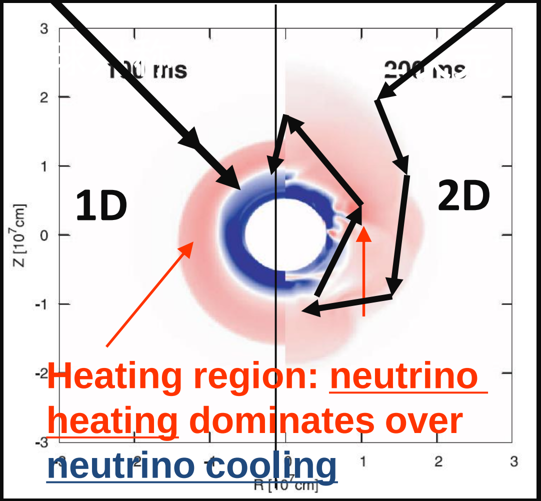
3rd: In the heating region, dwell-time of material gets longer due to non-radial motions. (turbulent pressure helps explosion).

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



15 M_{sun} model (WW95) from Suwa + (2013)

Color scale: entropy



Heating region: neutrino heating dominates over neutrino cooling

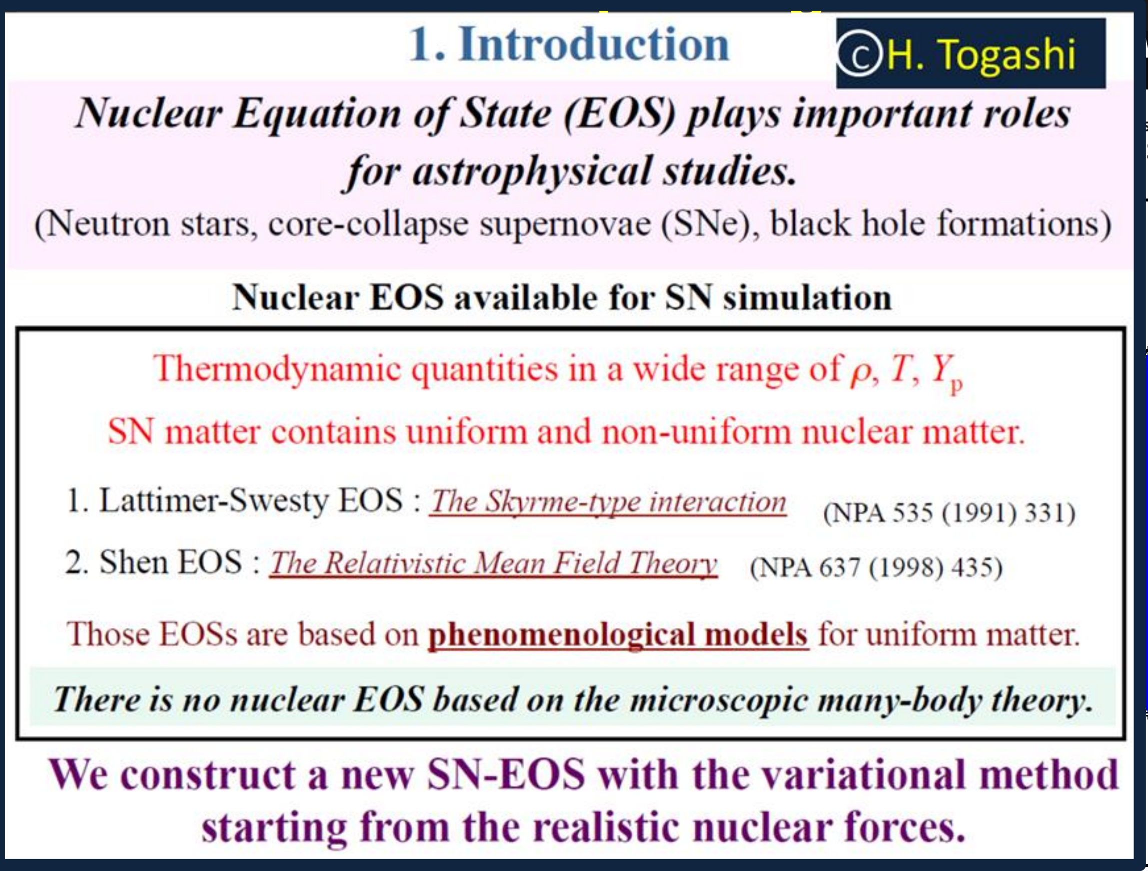
Numerics both in our 2D and 3D models

- ✓ **IDSA spectral transport (Liebendoerfer+09) + Newtonian hydro**
- ✓ **Lattimer-Swesty (1991) EOS (K=220 MeV): consis. with 2 M_{sun} NS.**
- ✓ **2D results** between our code, Valencia, Garching code **similar** !

(e.g., Obergaulinger et al. (2014), Hanke et al. (PhD)) Detailed comparison in progress.

1D fails⇒ Current paradigm “Multi-D” neutrino mechanism

ws (2013) ,Kotake et al. (2012) for review)



1. Introduction

©H. Togashi

Nuclear Equation of State (EOS) plays important roles for astrophysical studies.

(Neutron stars, core-collapse supernovae (SNe), black hole formations)

Nuclear EOS available for SN simulation

Thermodynamic quantities in a wide range of ρ, T, Y_p

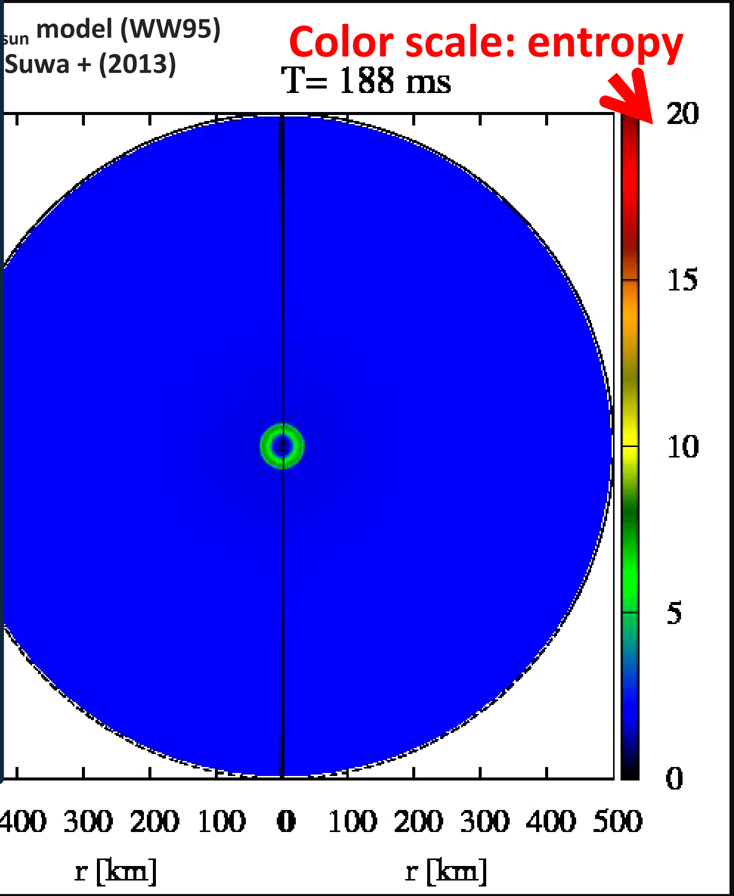
SN matter contains uniform and non-uniform nuclear matter.

1. Lattimer-Swesty EOS : *The Skyrme-type interaction* (NPA 535 (1991) 331)
2. Shen EOS : *The Relativistic Mean Field Theory* (NPA 637 (1998) 435)

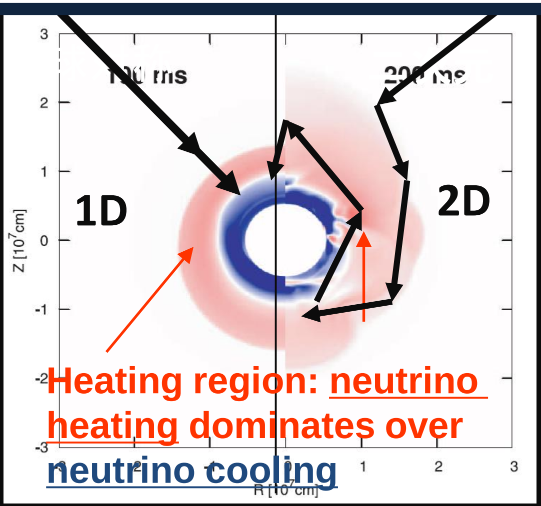
Those EOSs are based on **phenomenological models** for uniform matter.

There is no nuclear EOS based on the microscopic many-body theory.

We construct a new SN-EOS with the variational method starting from the realistic nuclear forces.



Color scale: entropy



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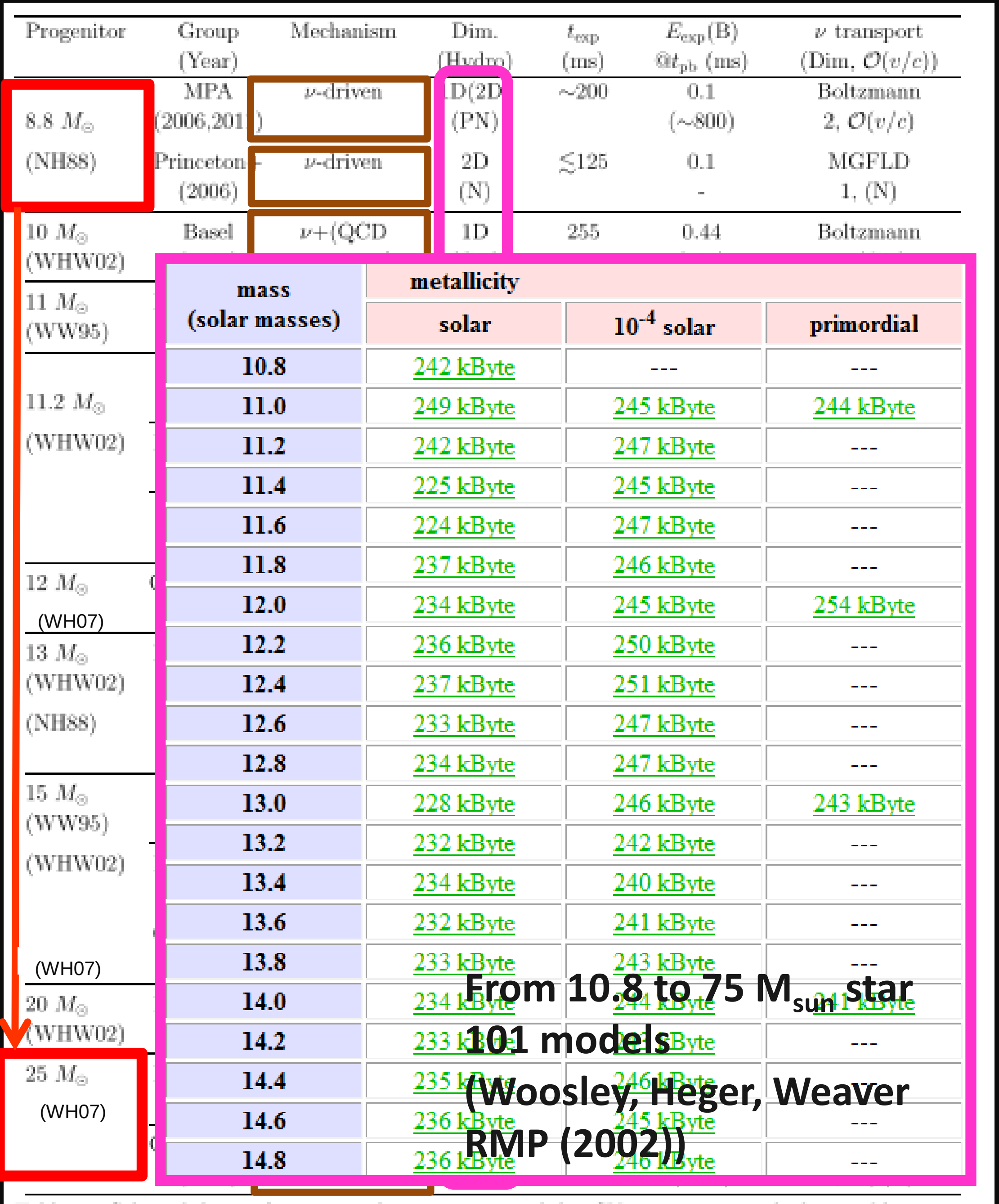
- ✓ **IDSA spectral transport (Liebendoerfer+09) + Newtonian hydro**
- ✓ **Lattimer-Swesty (1991) EOS (K=220 MeV): consis. with 2 M_{sun} NS.**
- ✓ **2D results** between our code, Valencia, Garching code **similar** !

(e.g., Obergaulinger et al. (2014), Hanke et al. (PhD)) Detailed comparison in progress.

✓ Status of Neutrino-Radiation Hydrodynamics Supernova Simulations

(KK+ (2012) *PTEP*, Mezzacappa+(2015))



Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	$t_{\rm exp}$ (ms)	$E_{\rm exp}$(B) @$t_{\rm pb}$ (ms)	ν transport (Dim, $\mathcal{O}(v/c)$)
8.8 $M_\odot$ (NH88)	MPA (2006,201	ν-driven	1D(2D (PN)	~200	0.1 (~800)	Boltzmann 2, $\mathcal{O}(v/c)$
	Princeton+ (2006)	ν-driven	2D (N)	$\lesssim$125	0.1 -	MGFLD 1, (N)
10 $M_\odot$ (WHW02)	Basel	ν+(QCD	1D	255	0.44	Boltzmann

mass (solar masses)	metallicity		
	solar	10^{-4} solar	primordial
10.8	242 kByte	---	---
11.0	249 kByte	245 kByte	244 kByte
11.2	242 kByte	247 kByte	---
11.4	225 kByte	245 kByte	---
11.6	224 kByte	247 kByte	---
11.8	237 kByte	246 kByte	---
12.0	234 kByte	245 kByte	254 kByte
12.2	236 kByte	250 kByte	---
12.4	237 kByte	251 kByte	---
12.6	233 kByte	247 kByte	---
12.8	234 kByte	247 kByte	---
13.0	228 kByte	246 kByte	243 kByte
13.2	232 kByte	242 kByte	---
13.4	234 kByte	240 kByte	---
13.6	232 kByte	241 kByte	---
13.8	233 kByte	243 kByte	---
14.0	234 kByte	244 kByte	241 kByte
14.2	233 kByte	[illegible]	---
14.4	235 kByte	246 kByte	---
14.6	236 kByte	245 kByte	---
14.8	236 kByte	246 kByte	---

From 10.8 to 75 M_{sun} star
101 models
(Woosley, Heger, Weaver
RMP (2002))

Big breakthrough :

✓ **Success of the neutrino mechanism: (shock-revival) for 8.8 to 27 M_{sun} stars in 2D self- consistent simulations !**

~40 successful models

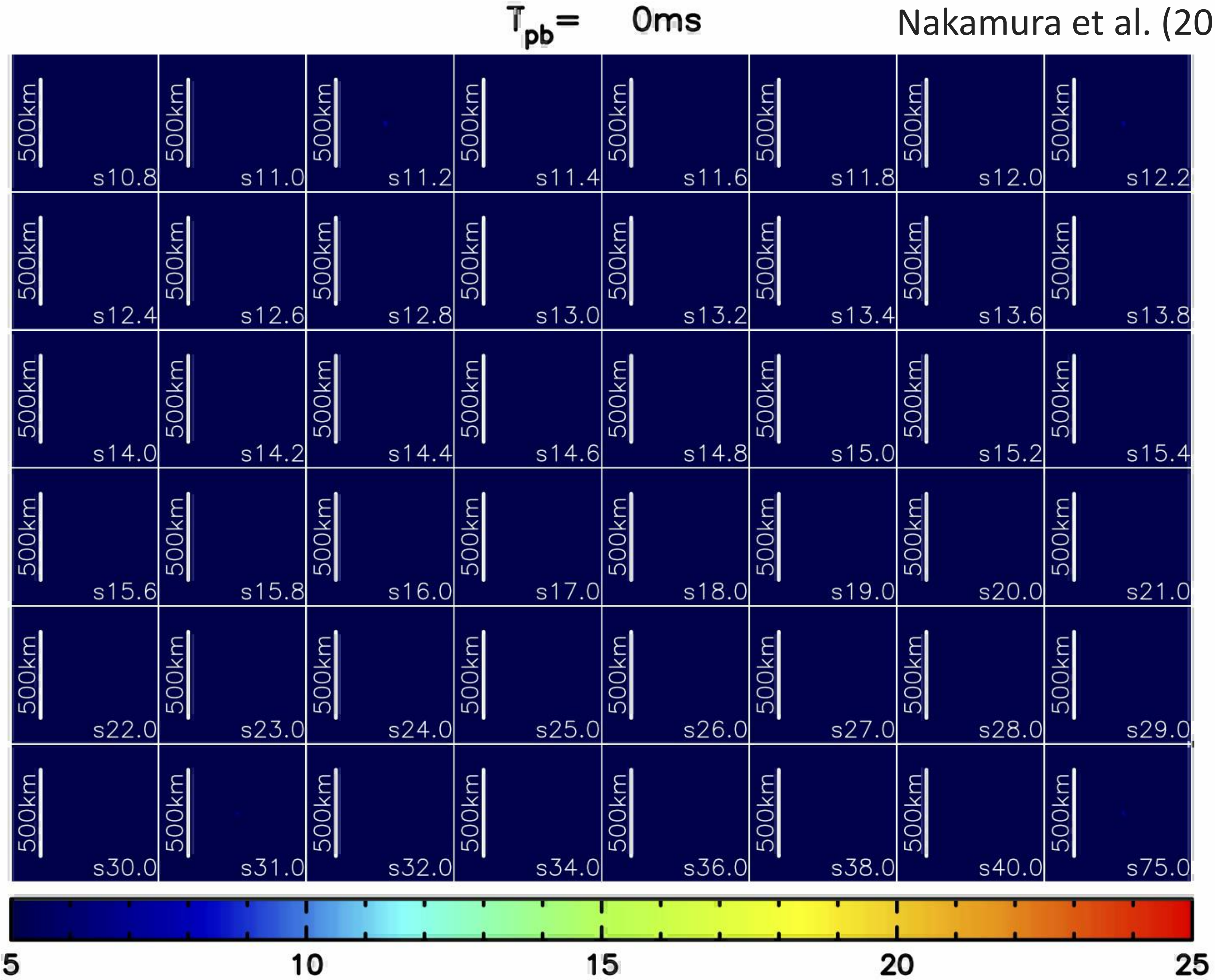
But still,
The neutrino mechanism:
Unexplored >90 %

Systematic study needed:

Self-consistent (in 2D, firstly) sim. to gain a "Landscape view" of explosion dynamics !

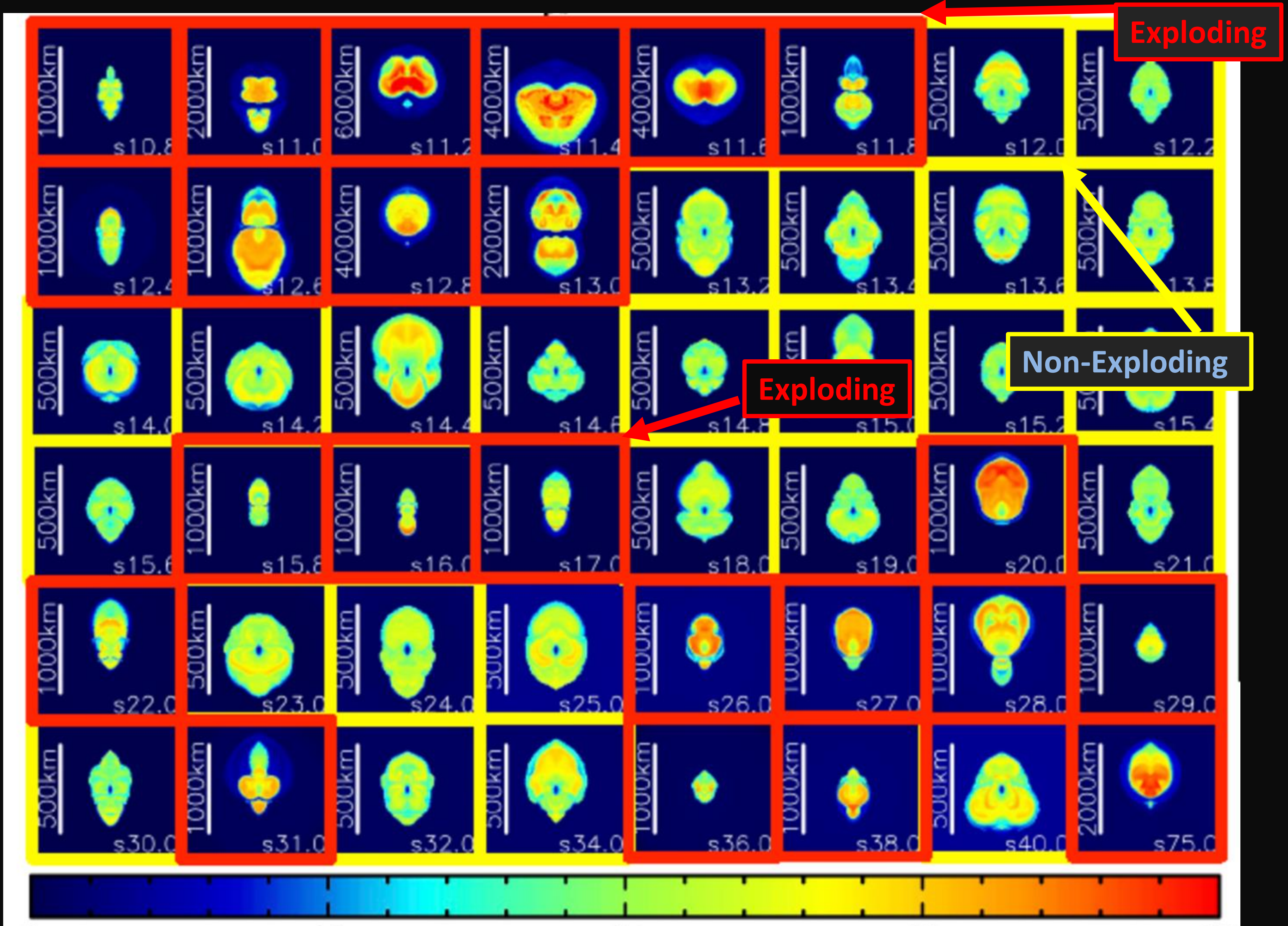
2D-IDSA simulations for 101 progenitors with solar metallicity

Nakamura et al. (2014)



"Systematics" between progenitor and explodability connections ?

Nakamura et al. (2015)



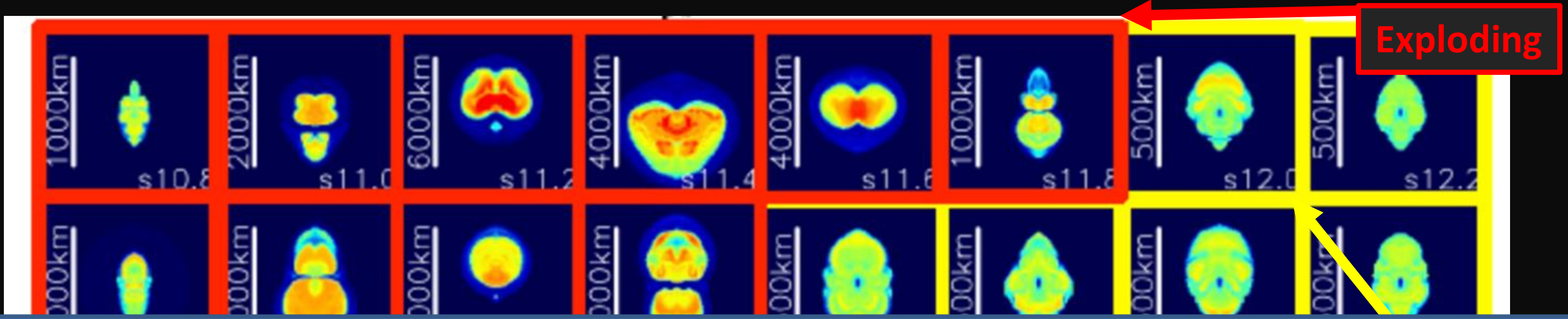
Exploding

Exploding

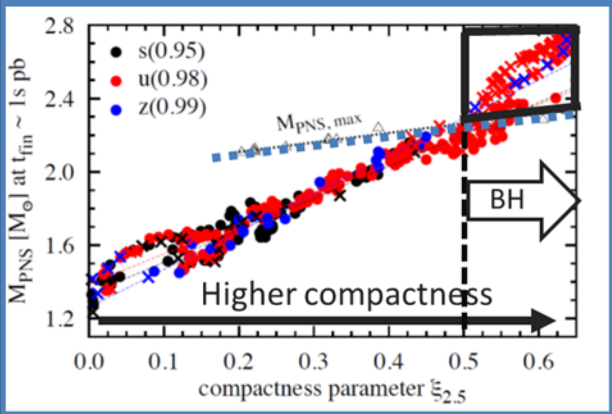
Non-Exploding

“Systematics” between progenitor and explodability connections ?

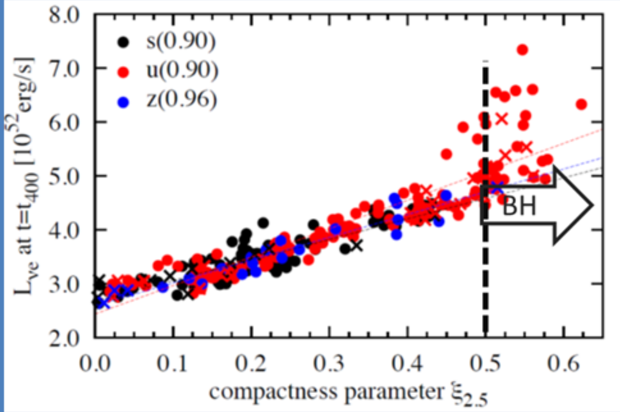
Nakamura et al. (2015)



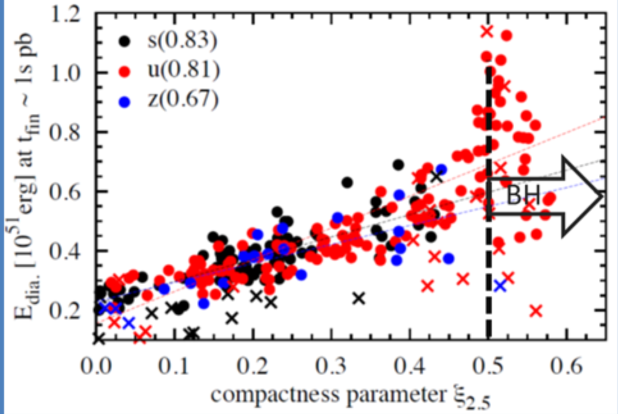
Mass accretion rate to PNS



Neutrino luminosity @ revival



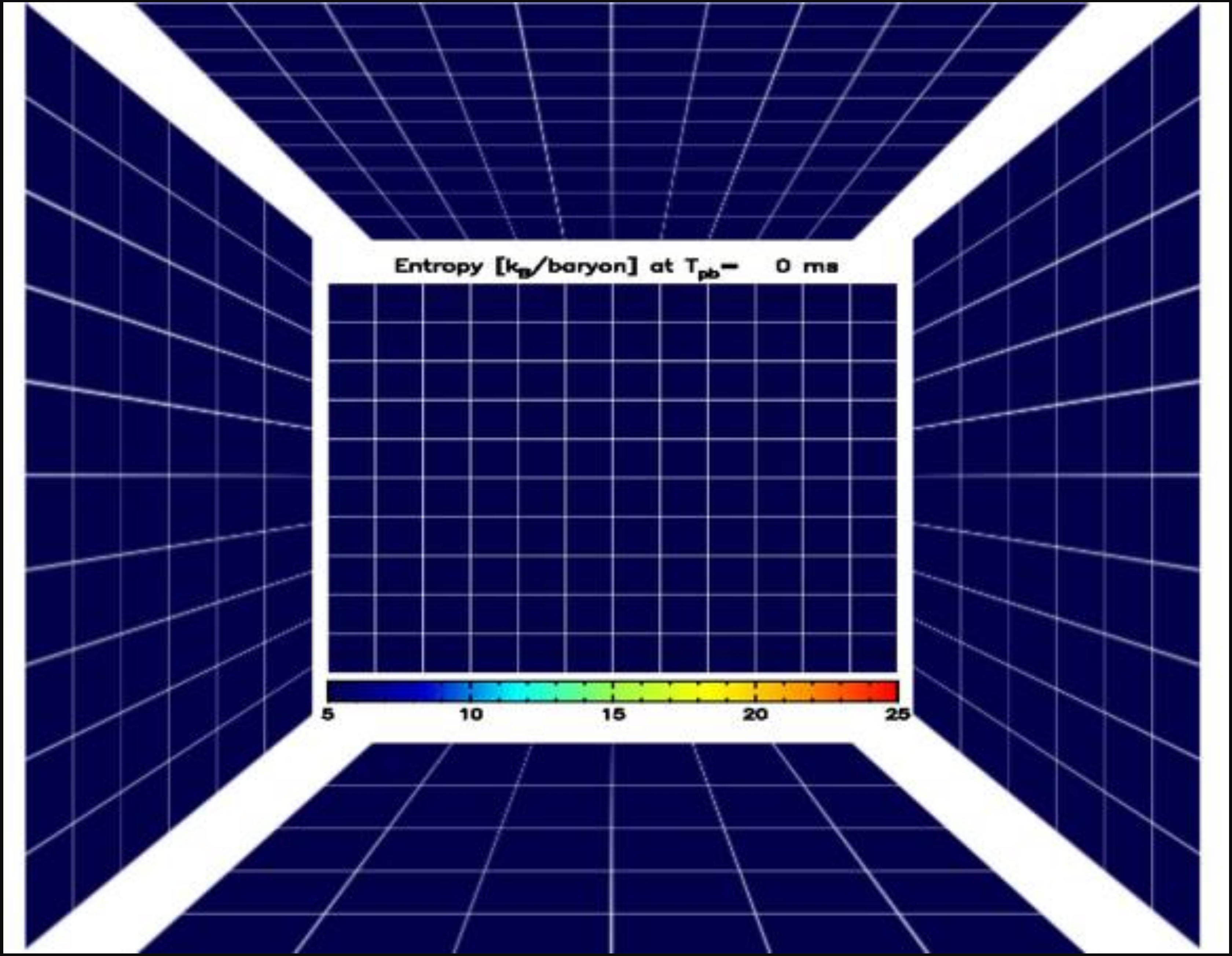
Diagnostic explosion energy



- ✓ “Progenitor mass” is a “not” good diagnostics for explosion.
- ✓ **Key : “Compactness: M_{core} /R_{core}”** (O’Connor and Ott (2011))
- ✓ 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 !

2D landscape simulations for 378 progenitors (WHW02)

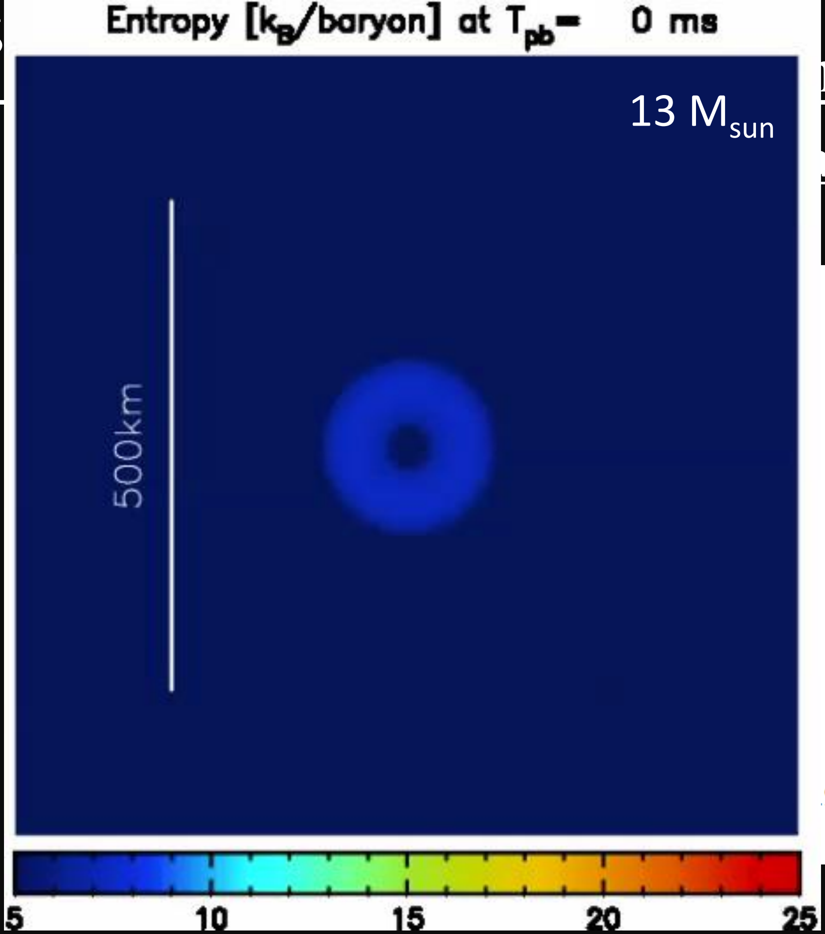
Nakamura et al. (2015)



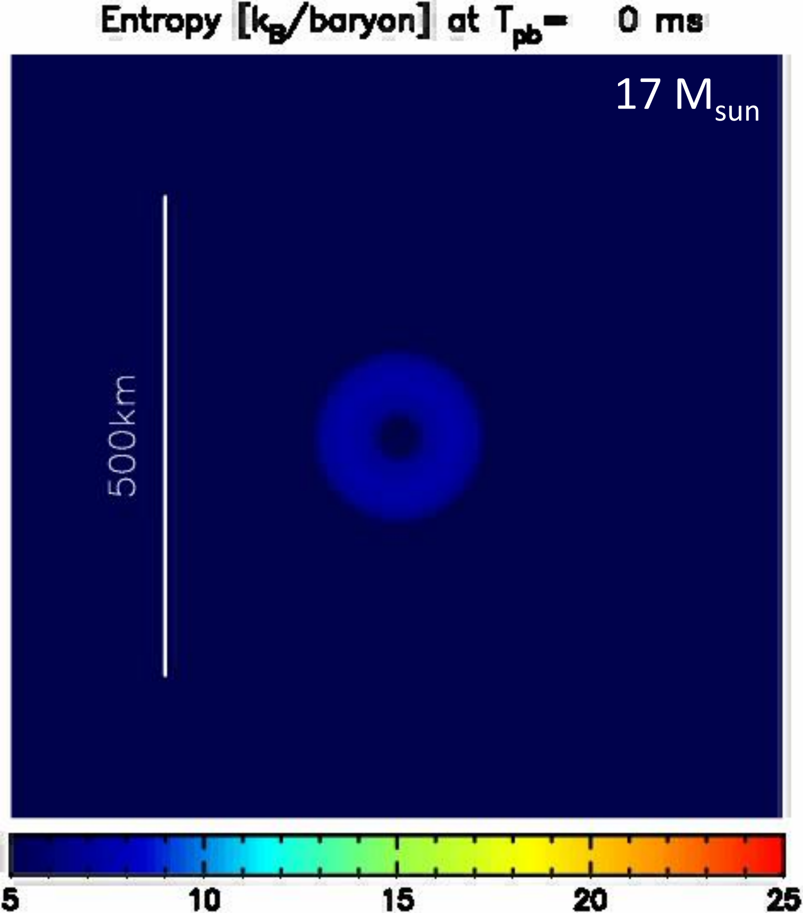
“ n energy

gnostic”

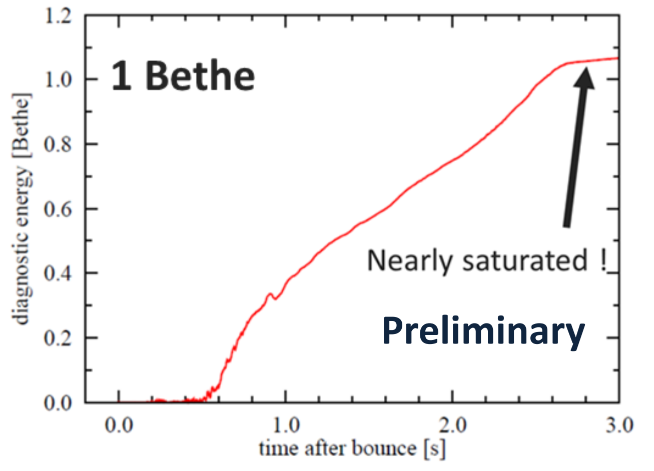
Ha



.9

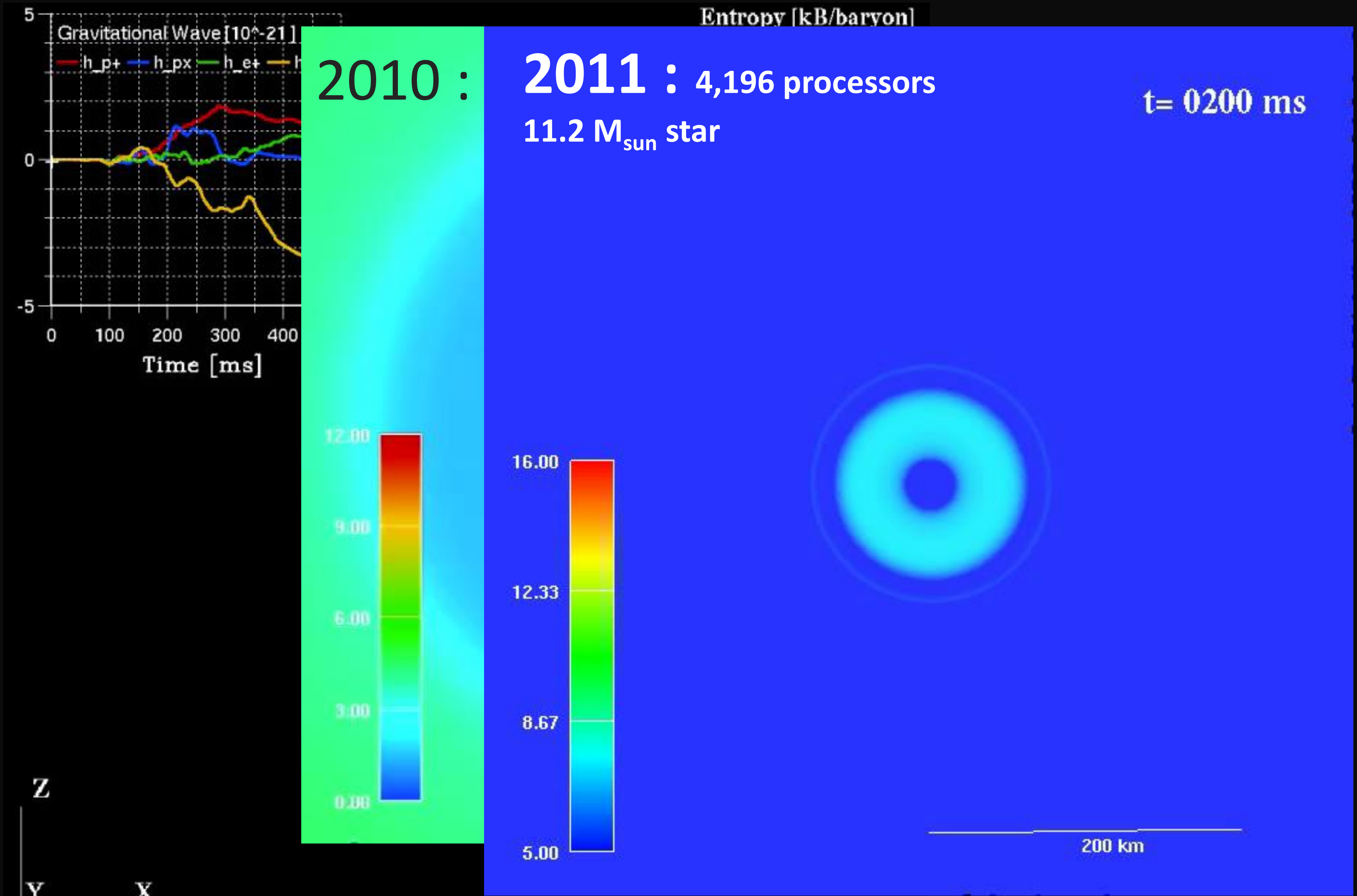


- ✓ The saturation timescales of explosion energy:
  sensitive to the progenitor structures
  → Need to perform long-term evolutions for > 378 models !
  (Nakamura et al. in prep)
- ✓ ***Must go to 3D*** **!**



Our code development toward 3D Neutrino-driven Models

2009 : Light-bulb 3D model

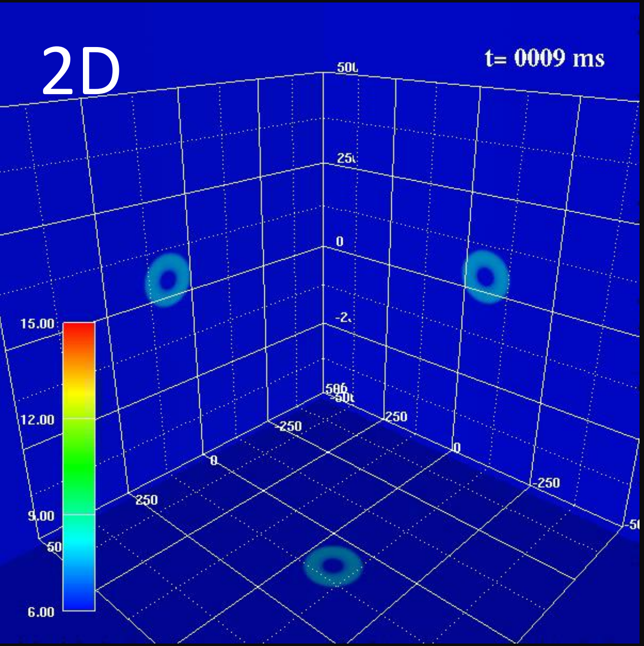


2010 :

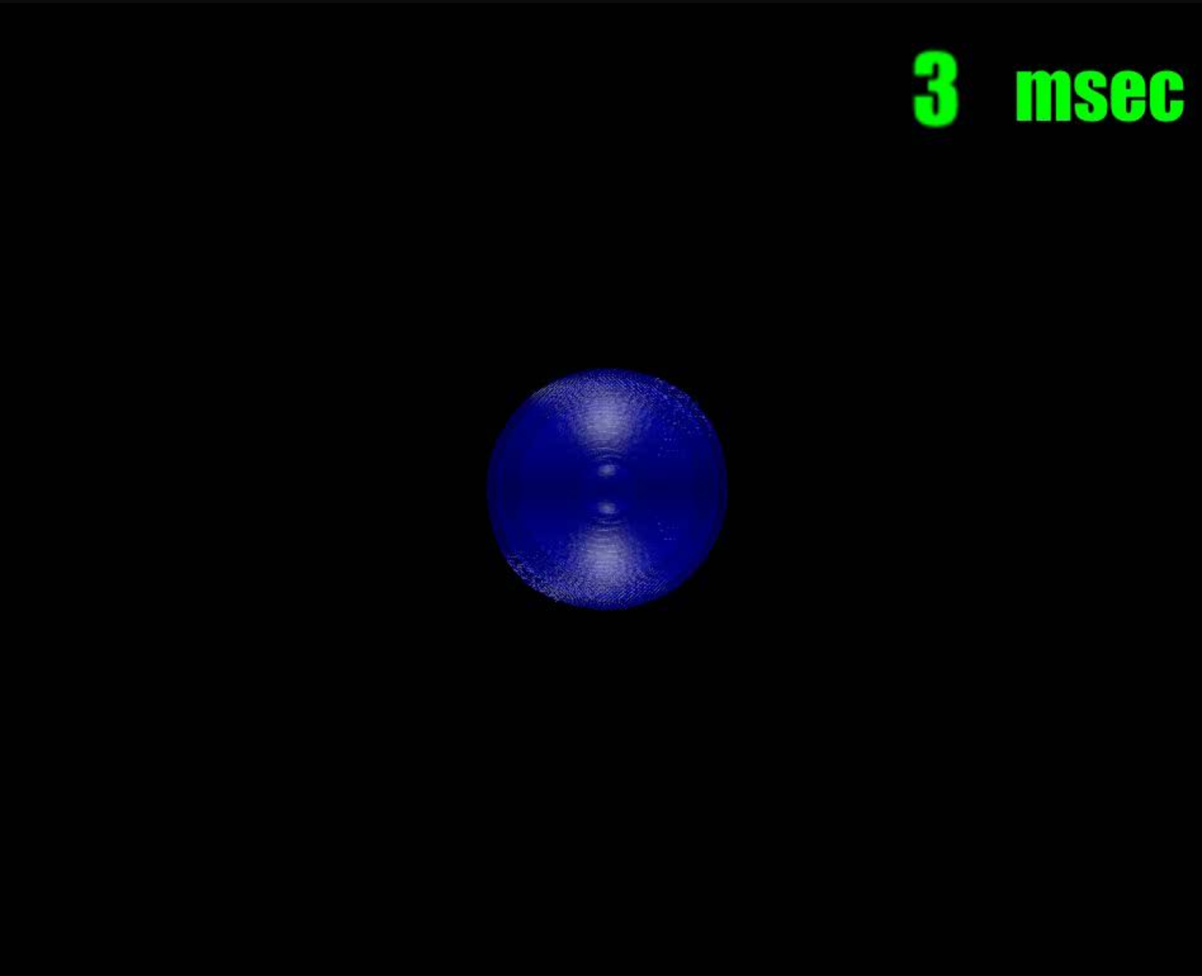
2011 : **4,196 processors**

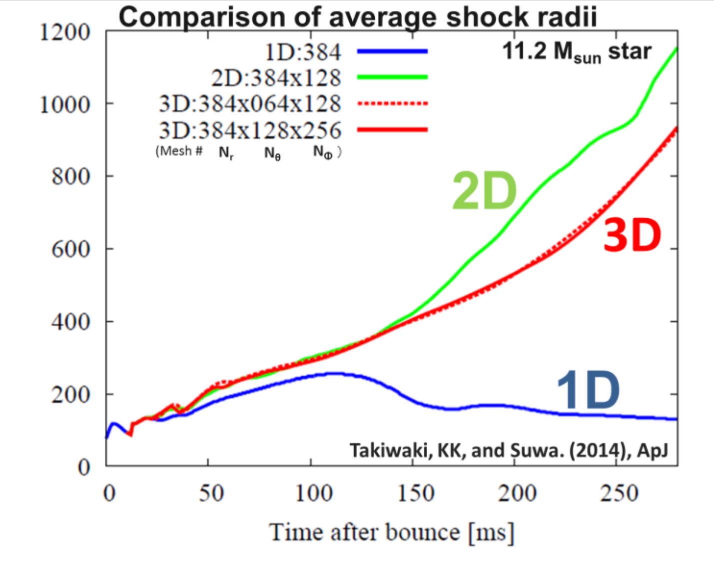
11.2 M_{sun} star

3D vs. 2D



(e.g., Takiwaki + (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))

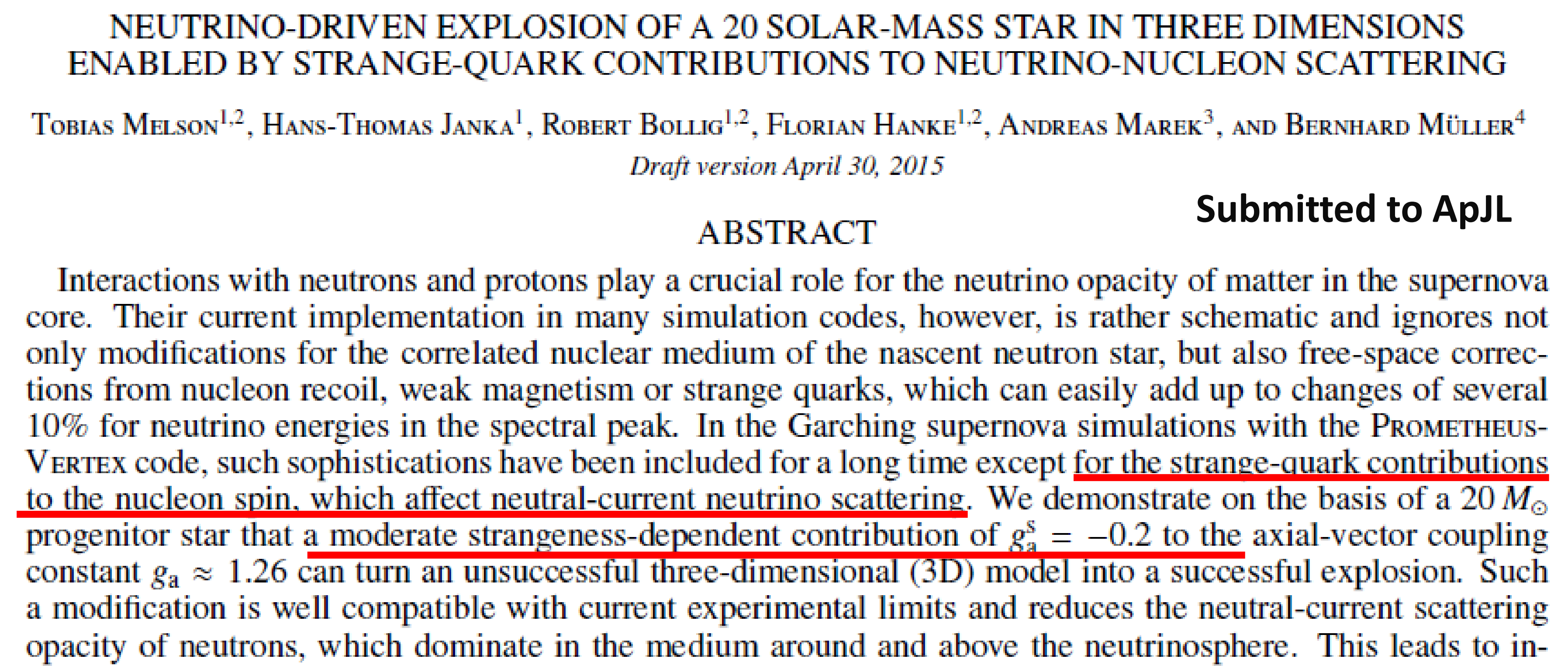
⇒ **The "3D vs. 2D problem" is progenitor dependent.**

✓ **No "Bethe" models obtained in 3D….**

⇒ **Need to find ingredients to foster 3D explosions !**

Candidates: Rotation, General Relativity, Microphysics

Detailed microphysics important : Strangeness effects power explosions



NEUTRINO-DRIVEN EXPLOSION OF A 20 SOLAR-MASS STAR IN THREE DIMENSIONS ENABLED BY STRANGE-QUARK CONTRIBUTIONS TO NEUTRINO-NUCLEON SCATTERING

TOBIAS MELSON[1,2], HANS-THOMAS JANKA[1], ROBERT BOLLIG[1,2], FLORIAN HANKE[1,2], ANDREAS MAREK[3], AND BERNHARD MÜLLER[4]

Draft version April 30, 2015

Submitted to ApJL

ABSTRACT

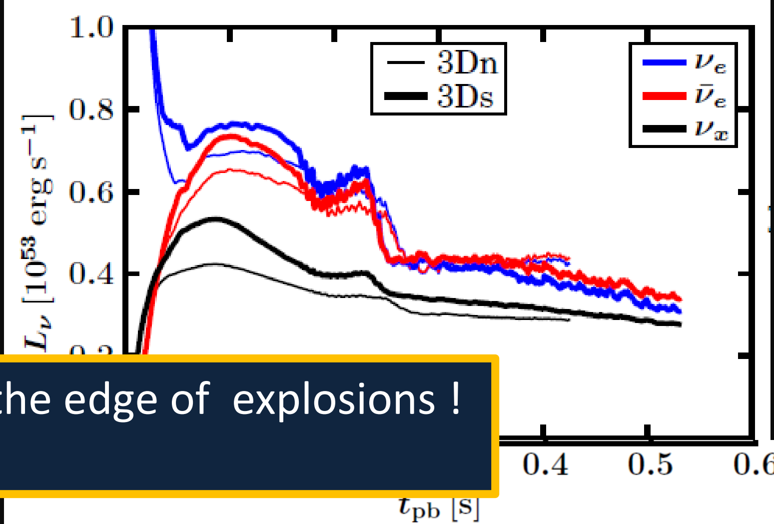
Interactions with neutrons and protons play a crucial role for the neutrino opacity of matter in the supernova core. Their current implementation in many simulation codes, however, is rather schematic and ignores not only modifications for the correlated nuclear medium of the nascent neutron star, but also free-space corrections from nucleon recoil, weak magnetism or strange quarks, which can easily add up to changes of several 10% for neutrino energies in the spectral peak. In the Garching supernova simulations with the PROMETHEUS-VERTEX code, such sophistications have been included for a long time except for the strange-quark contributions to the nucleon spin, which affect neutral-current neutrino scattering. We demonstrate on the basis of a 20 $M_\odot$ progenitor star that a moderate strangeness-dependent contribution of $g_a^s = -0.2$ to the axial-vector coupling constant $g_a \approx 1.26$ can turn an unsuccessful three-dimensional (3D) model into a successful explosion. Such a modification is well compatible with current experimental limits and reduces the neutral-current scattering opacity of neutrons, which dominate in the medium around and above the neutrinosphere. This leads to in-

$\nu n \longrightarrow \nu n$: Leading order cross section

$$\frac{d\sigma_0}{d\Omega} = \frac{G_F^2 \epsilon^2}{4\pi^2}\left[c_v^2(1+\cos\theta) + c_a^2(3-\cos\theta)\right]$$

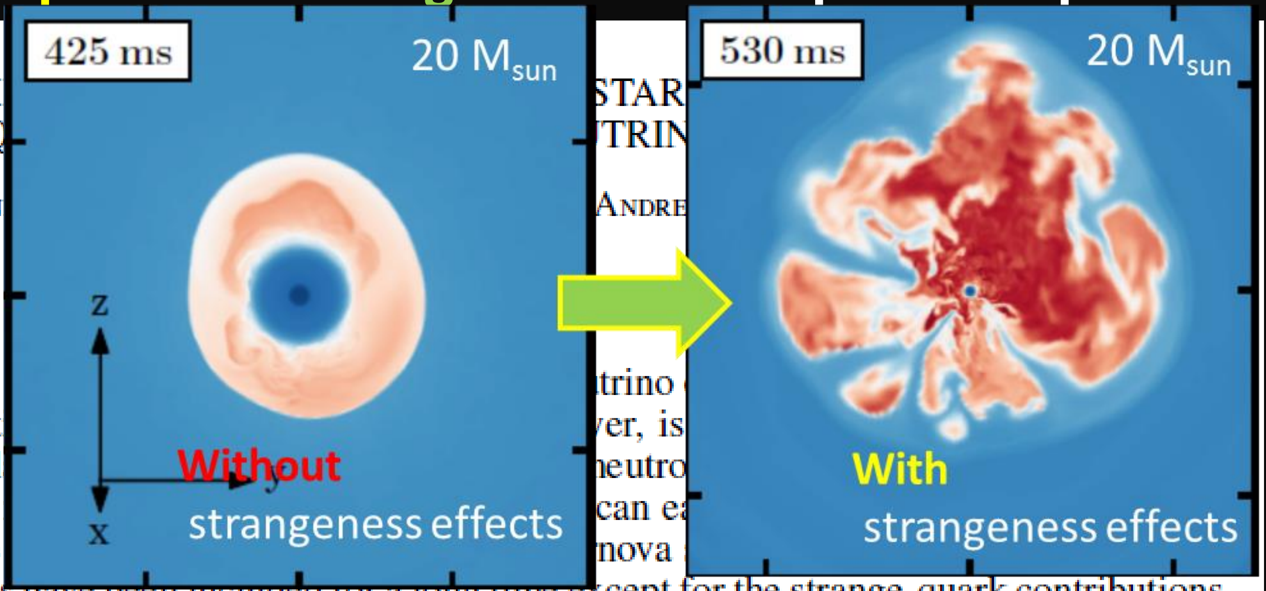
Strangeness contribution: Horowitz (2002, PRD)

$c_a = \frac{1}{2}(\pm$



- ✓Current 3D Supernova models are on the edge of explosions !
- ✓10 % effects important !

Detailed microphysics important : Strangeness effects power explosions



NEUTRINO-DRIVEN EX STAR
ENABLED BY STRANGE-Q TRIN

Tobias Melson[1,2], Hans-Thomas Jan Andre

Interactions with neutrons and trino
core. Their current implementat ver, is
only modifications for the correl neutro
tions from nucleon recoil, weak can e
10% for neutrino energies in the nova
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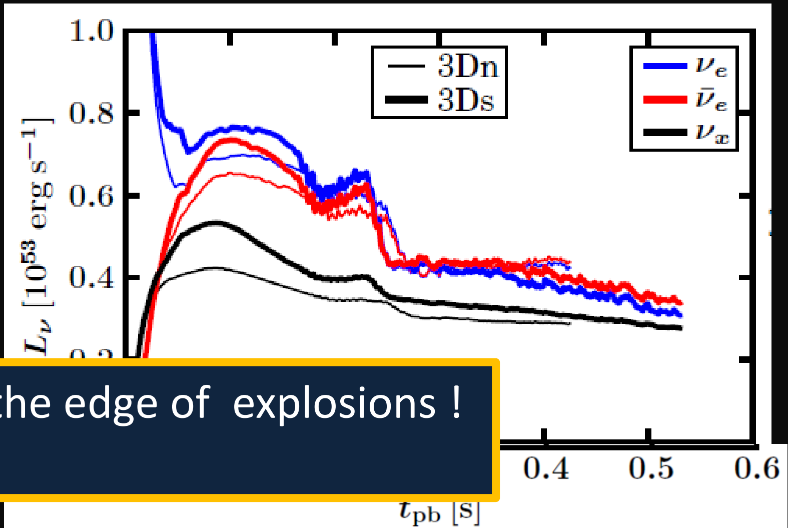


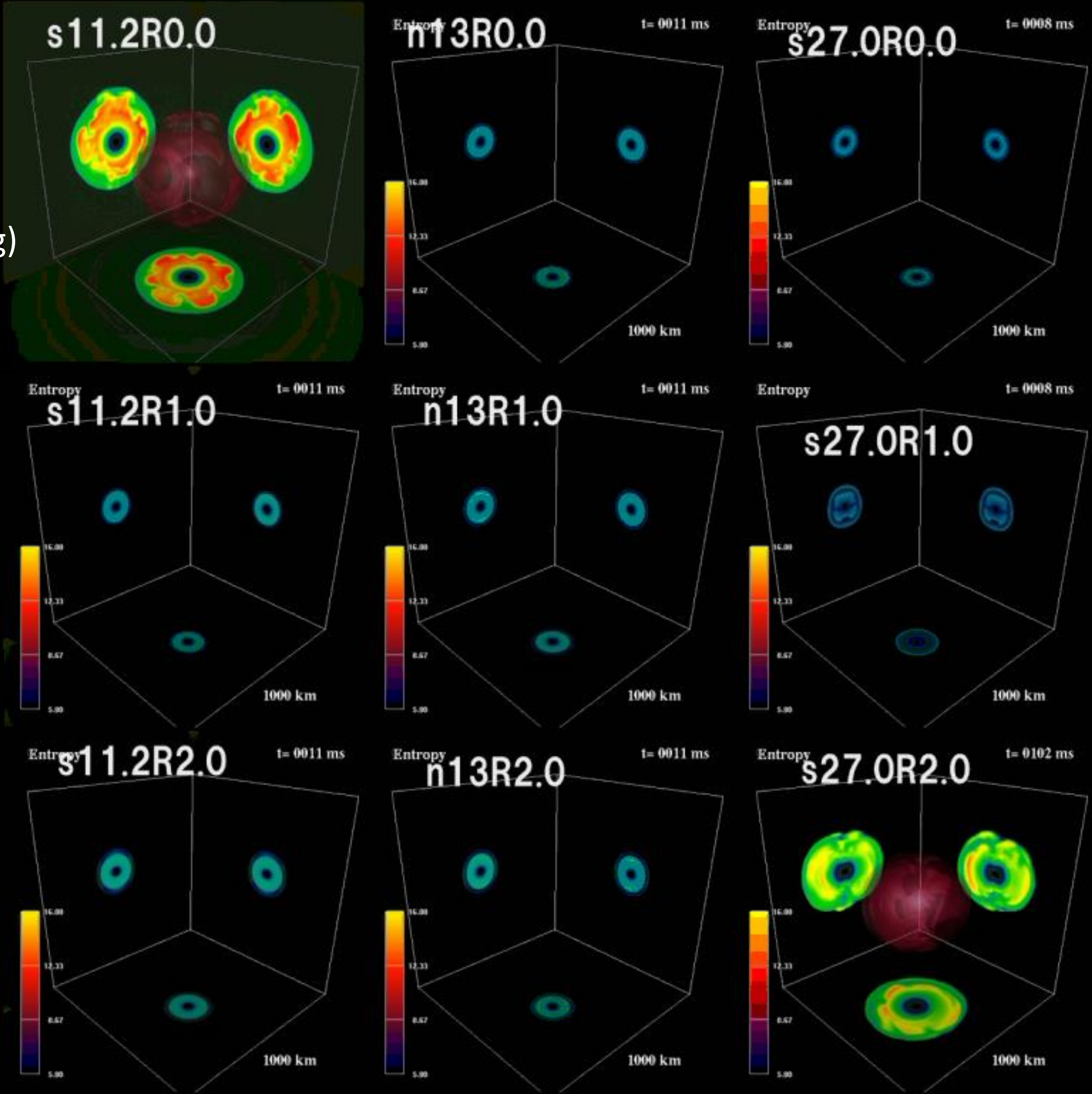
✓Current 3D Supernova models are on the edge of explosions !
✓10 % effects important !

Takiwaki, KK, Suwa in prep

Ω_0 = 0 rad/s (Non-rotating)

Ω_0 = 1 rad/s

Ω_0 = 2 rad/s



s11.2, s27.0 from WHW02,

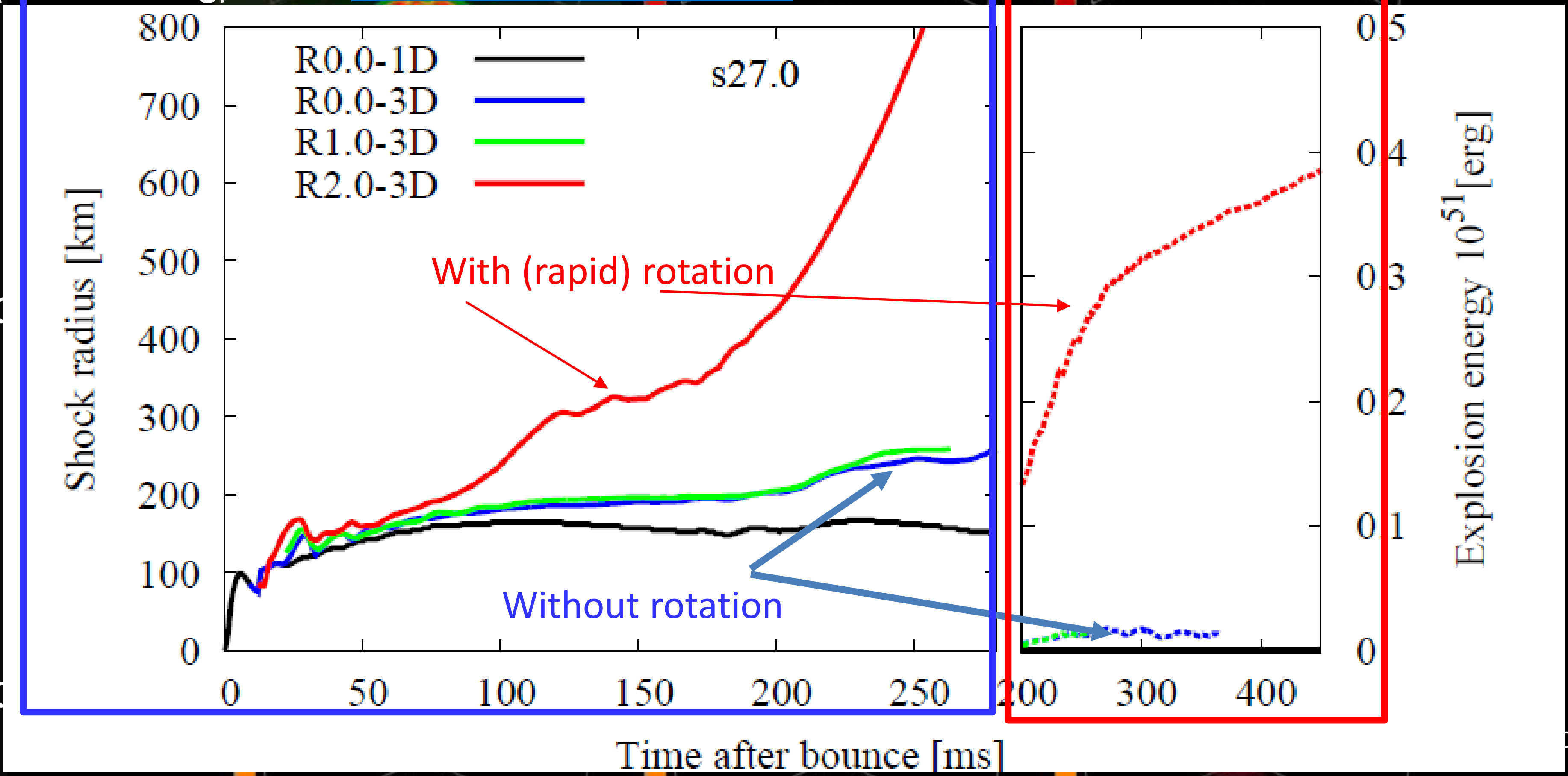
N13 from Nomoto & Hashimoto (1988)

Takiwaki, KK, Suwa in prep

Ω_0 = 0 rad/s (Non-rotating)

Evolution of shock radii

Dia. Exp. Energy

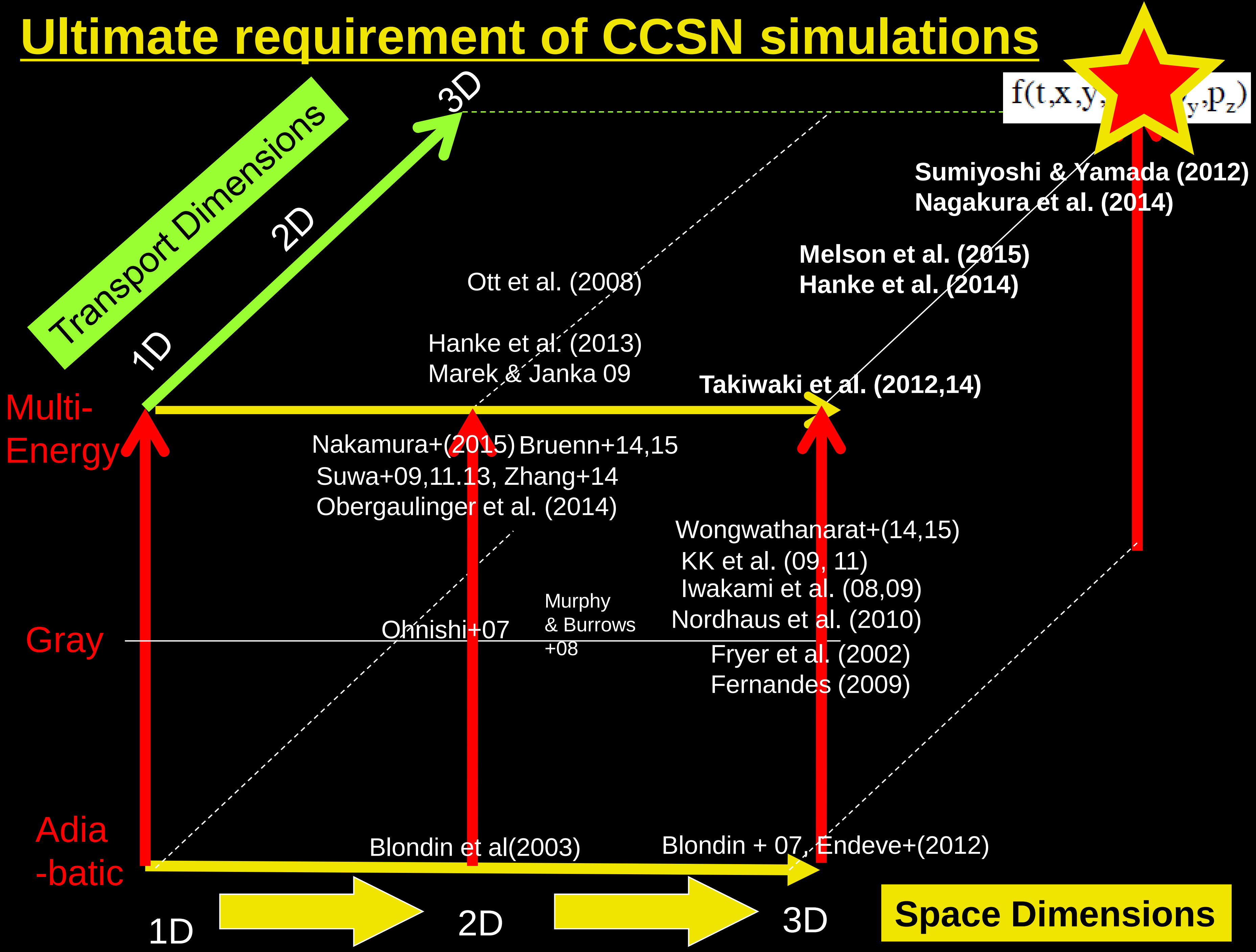


With (rapid) rotation

Without rotation

Rotation, depending on the initial rotation rates, can foster neutrino-driven explosions (see also, Nakamura et al. (2014), ApJ)

Ultimate requirement of CCSN simulations



Space Dimensions

Sumiyoshi & Yamada (2012)
Nagakura et al. (2014)

Melson et al. (2015)
Hanke et al. (2014)

Ott et al. (2008)

Hanke et al. (2013)
Marek & Janka 09

Takiwaki et al. (2012,14)

Nakamura+(2015) Bruenn+14,15
Suwa+09,11.13, Zhang+14
Obergaulinger et al. (2014)

Wongwathanarat+(14,15)
KK et al. (09, 11)
Iwakami et al. (08,09)
Nordhaus et al. (2010)

Ohnishi+07

Murphy
& Burrows
+08

Fryer et al. (2002)
Fernandes (2009)

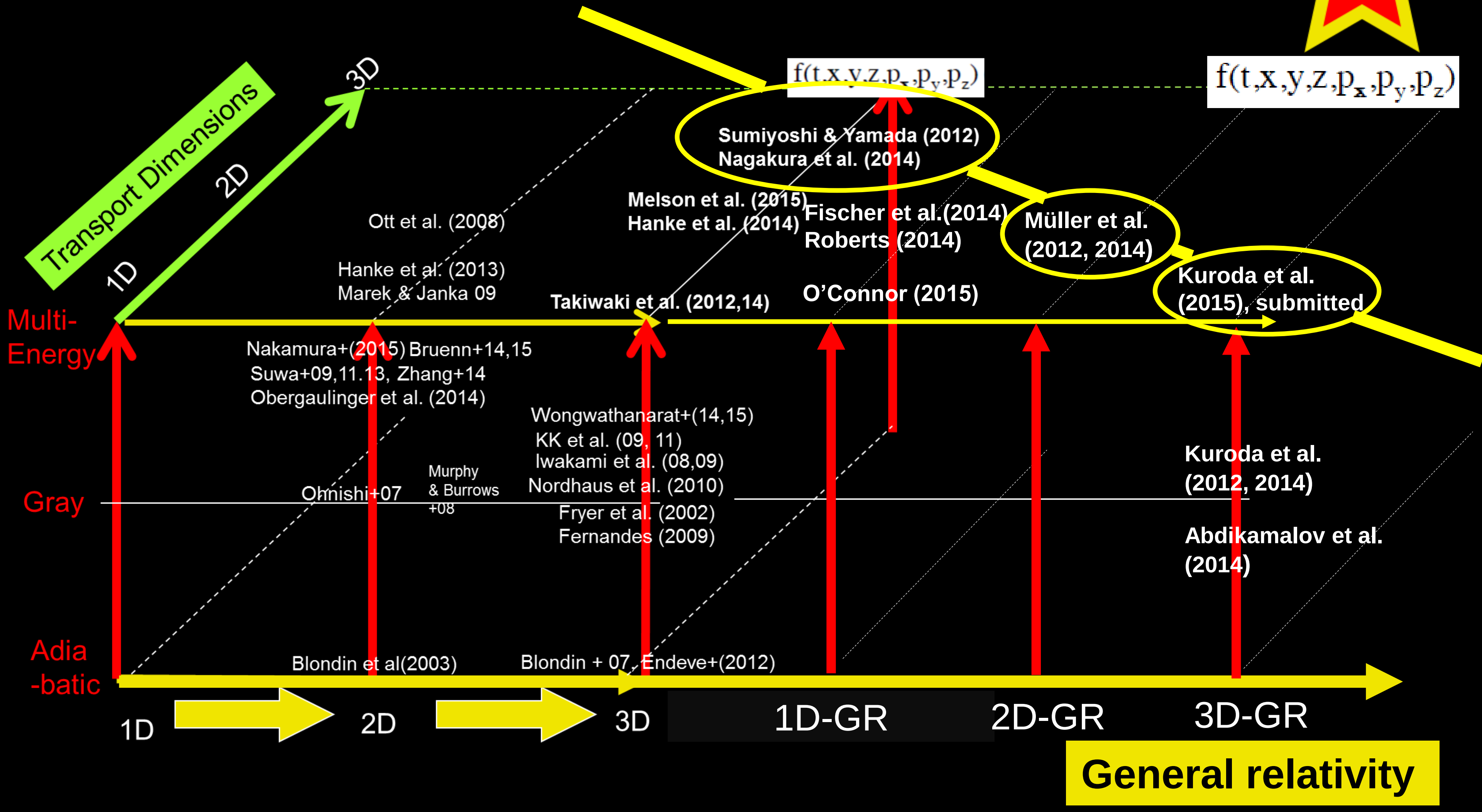
Blondin et al(2003)

Blondin + 07, Endeve+(2012)

Ultimate requirement of CCSN simulations

Disclaimer: only CCSNs

: 6D Boltzmann transport in full GR MHD hydrodynamics
with increasing microphysical inputs (quark-hadron physics) !



Transport Dimensions

1D

2D

3D

$f(t,x,y,z,p_x,p_y,p_z)$

$f(t,x,y,z,p_x,p_y,p_z)$

Sumiyoshi & Yamada (2012)
Nagakura et al. (2014)

Melson et al. (2015)
Hanke et al. (2014)

Fischer et al.(2014)
Roberts (2014)

Müller et al.
(2012, 2014)

Kuroda et al.
(2015), submitted

Ott et al. (2008)

Hanke et al. (2013)
Marek & Janka 09

Takiwaki et al. (2012,14)

O'Connor (2015)

Multi-
Energy

Nakamura+(2015) Bruenn+14,15
Suwa+09,11.13, Zhang+14
Obergaulinger et al. (2014)

Wongwathanarat+(14,15)
KK et al. (09, 11)
Iwakami et al. (08,09)
Nordhaus et al. (2010)
Fryer et al. (2002)
Fernandes (2009)

Gray

Ohnishi+07

Murphy
& Burrows
+08

Kuroda et al.
(2012, 2014)

Abdikamalov et al.
(2014)

Adia
-batic

Blondin et al(2003)

Blondin + 07, Endeve+(2012)

1D

2D

3D

1D-GR

2D-GR

3D-GR

General relativity

General Relativity (GR) important: Aid the onset of an explosion

(Deeper potential well : core structures smaller ⇒making both $\langle E_\nu \rangle$ and L_ν higher)

(e.g., B. Mueller et al. (2013), Kuroda et al. (2012))

✓ **3D full GR code with multi-energy neutrino transport via the M1 scheme:**

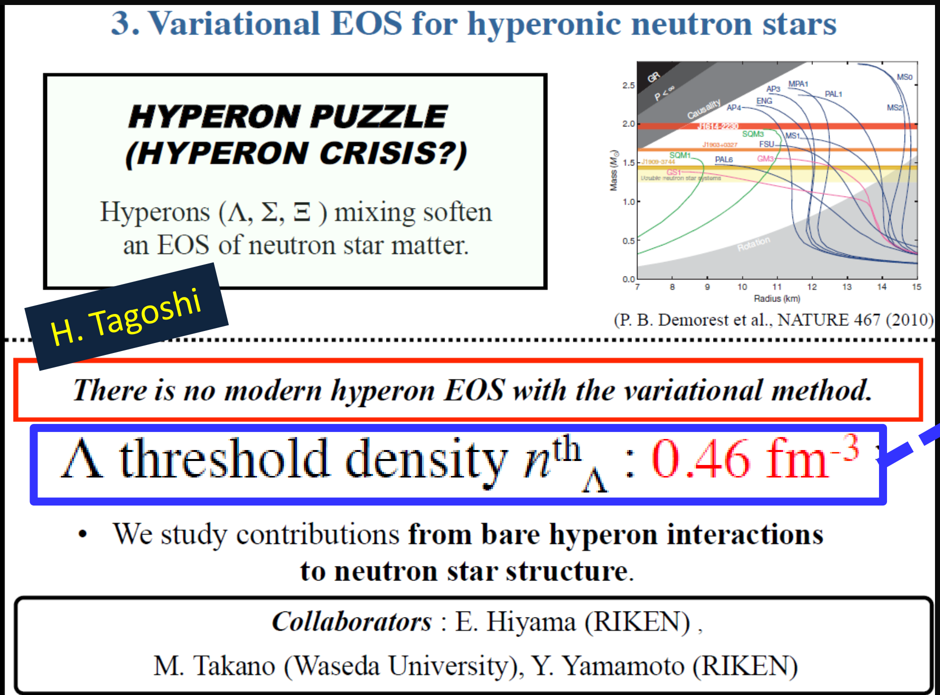
"FUGRA" : Fully General Relativistic code with neutrino transport

Kuroda, Takiwaki, and KK, submitted to ApJS. (arXiv:1501.06330)

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

✓ **Best nuclear physics should be included in "general-relativistic hydrodynamics" code.**

✓Hyperons ubiquitous in BH-forming CCSNe
✓Hyperons interesting in SN dynamics !



3. Variational EOS for hyperonic neutron stars

HYPERON PUZZLE
(HYPERON CRISIS?)

Hyperons (Λ, Σ, Ξ) mixing soften an EOS of neutron star matter.

(P. B. Demorest et al., NATURE 467 (2010))

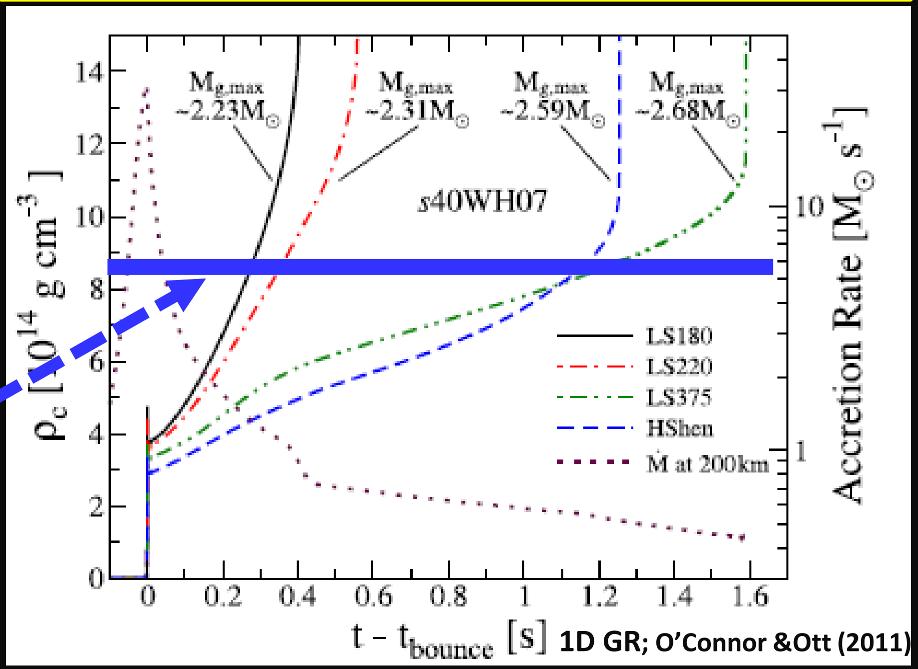
H. Tagoshi

There is no modern hyperon EOS with the variational method.

Λ threshold density n^{th}_{Λ} : 0.46 fm^{-3}

- We study contributions **from bare hyperon interactions to neutron star structure.**

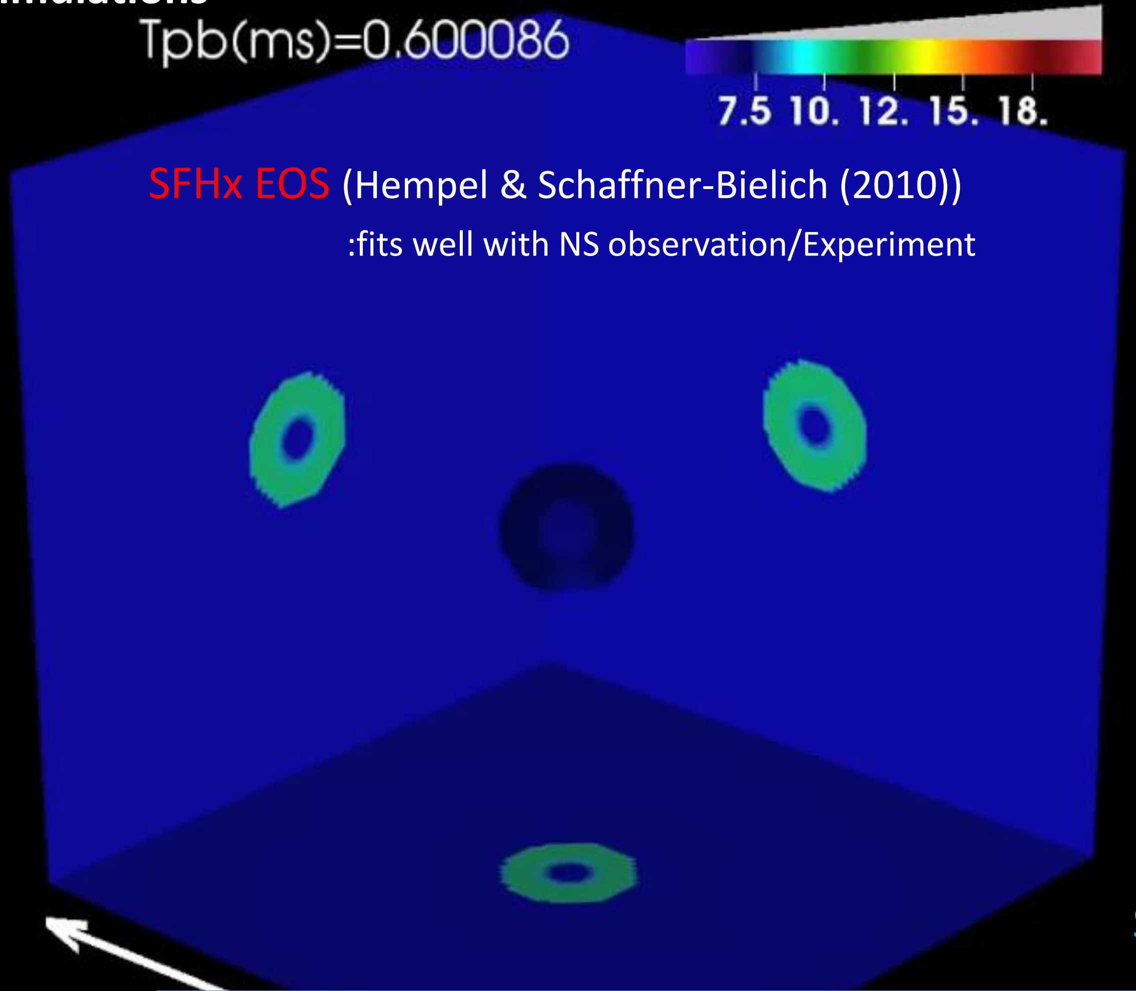
Collaborators : E. Hiyama (RIKEN) ,
M. Takano (Waseda University), Y. Yamamoto (RIKEN)



1D GR; O'Connor &Ott (2011)

3D full GR simulations

(e.g., Kuroda et al. (2012, 2014))



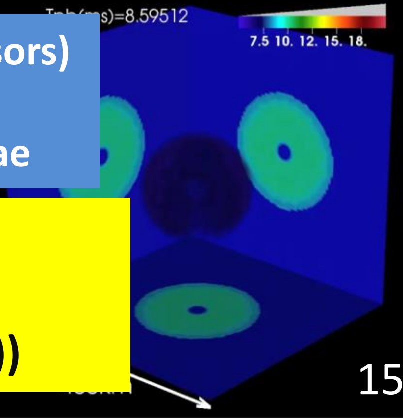
SFHx EOS (Hempel & Schaffner-Bielich (2010))

:fits well with NS observation/Experiment

15 M_{sun}

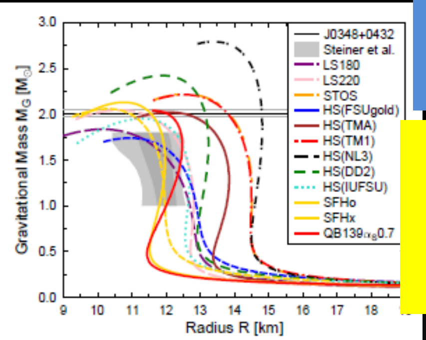
✓ SASI activity higher for softer EOS

Shen EOS : Stiff (Shen+98)



- ✓ 1000ms/(4 ms (gray FUGRA) per day @4096 processors)
  ~ 250 days …. ($R_{shock} > R_{iron}$)
  > 2500 days … ($R_{shock} > R_{star}$); fall-back/BH supernovae

- ✓ **Need next-generation (exa-scale) platforms !**
  (such as the upgrade of Tianhe (China),
  Titan (Oak-Ridge) /Coral (Livermore), K (Riken))

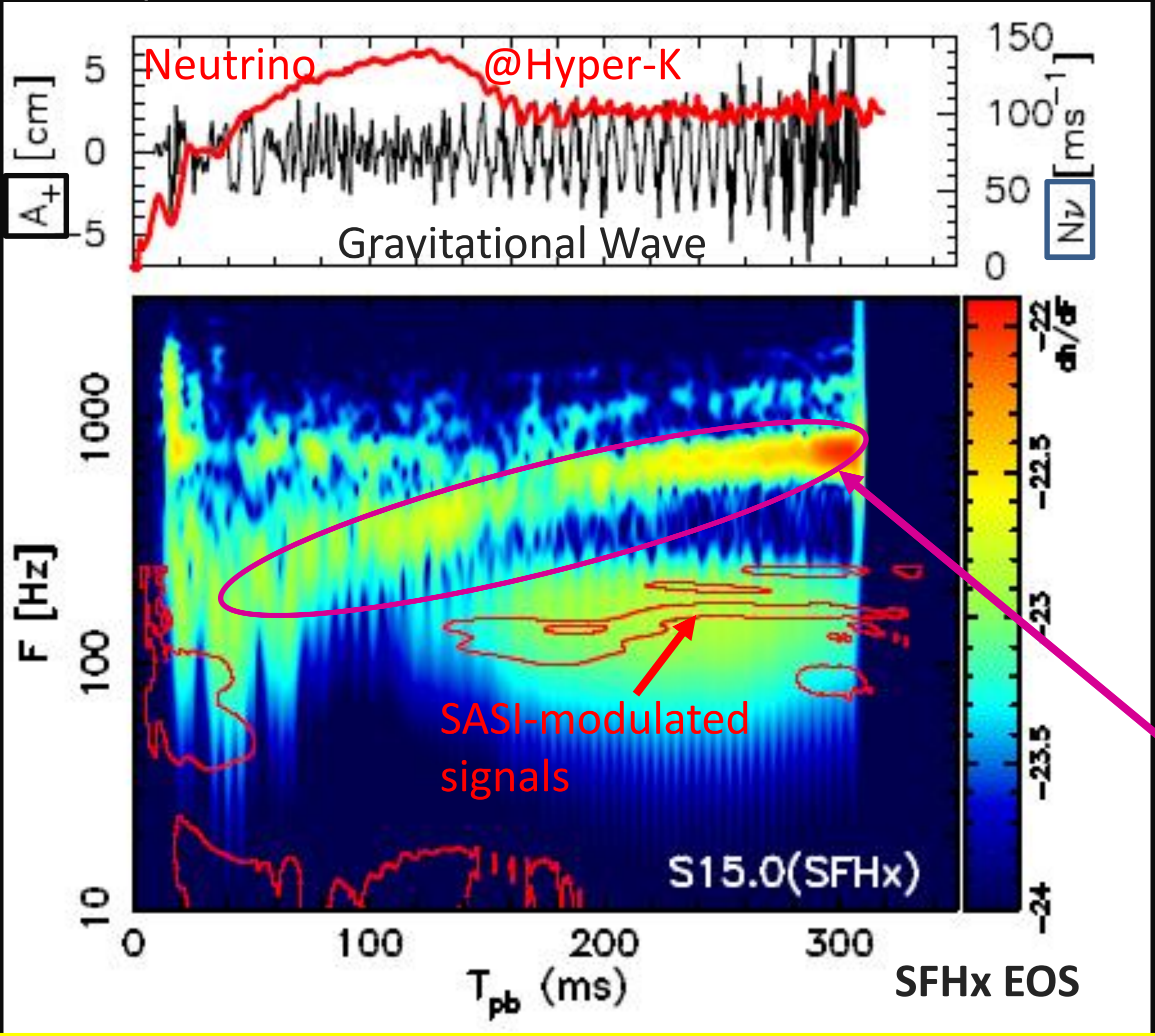


15 M_{sun}

Neutrino and Gravitational-Wave signatures from 15 M_{sun} with SFHx (or SHEN EOS)

Kuroda, KK, & Takiwaki (in prep)

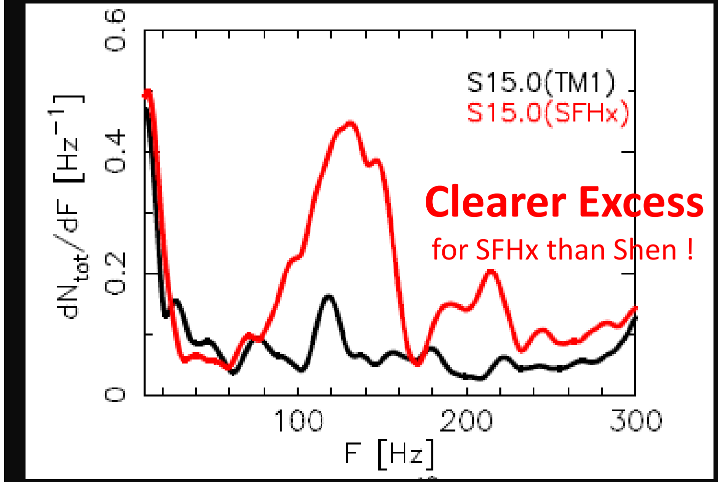
@ 10 kpc



SASI-modulated signals

SFHx EOS

✓ Typical neutrino mod. frequency



Clearer Excess

for SFHx than Shen !

✓ Blue-shift of peak GW frequency: violent downdraft to PNS

Murphy et al. (2009), Mueller et al. (2013)

☆ Increase of typical frequency
⇒ the buoyancy frequency

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

M, R, T : mass, radius, & temperature of PNS, Γ : stiffness of EOS

(see also Lentz et al. (2015) !)

- ✓ **The modulation of neutrino signals ⇒ the SASI timescales !** **(e.g., Tamborra et al. (2014))**
- ✓ **More clearer excess for softer EOS ⇒ Possible probe to EOSs.**
- ✓ **Super-Kamiokande** : back-ground free (nicer than ICECUBE), can detect SASI-mod. signals for a Galactic event, Hyper-Kamiokande (2020) for an extragalactic event !

Neutrino and Gravitational-Wave signatures from 15 M_{sun} with SFHx (or SHEN EOS)

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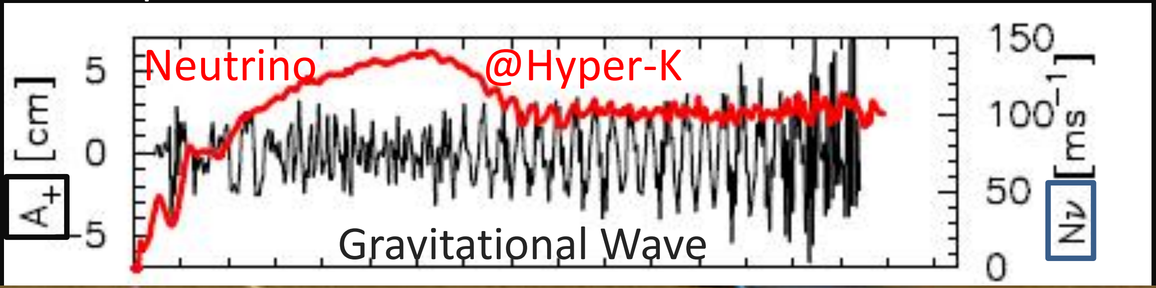

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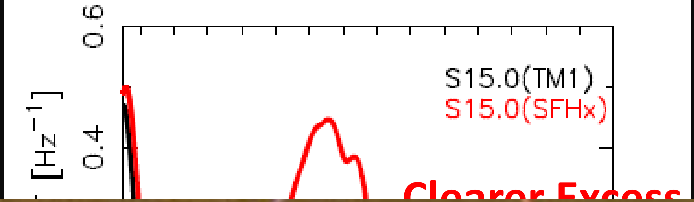

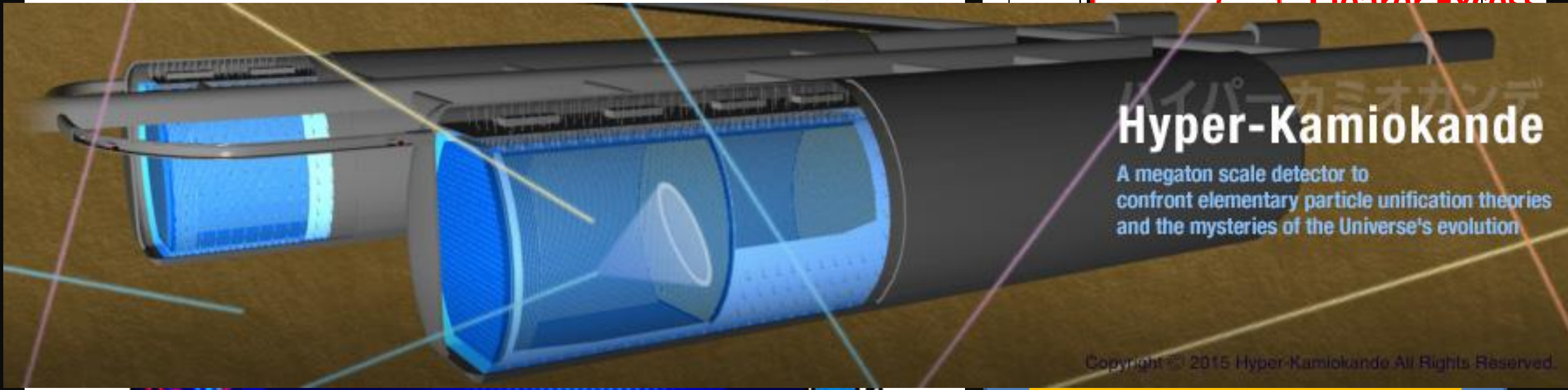

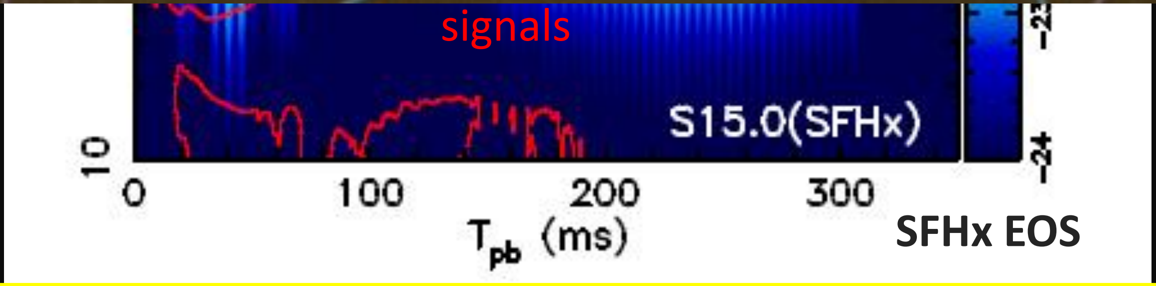

SFHx EOS

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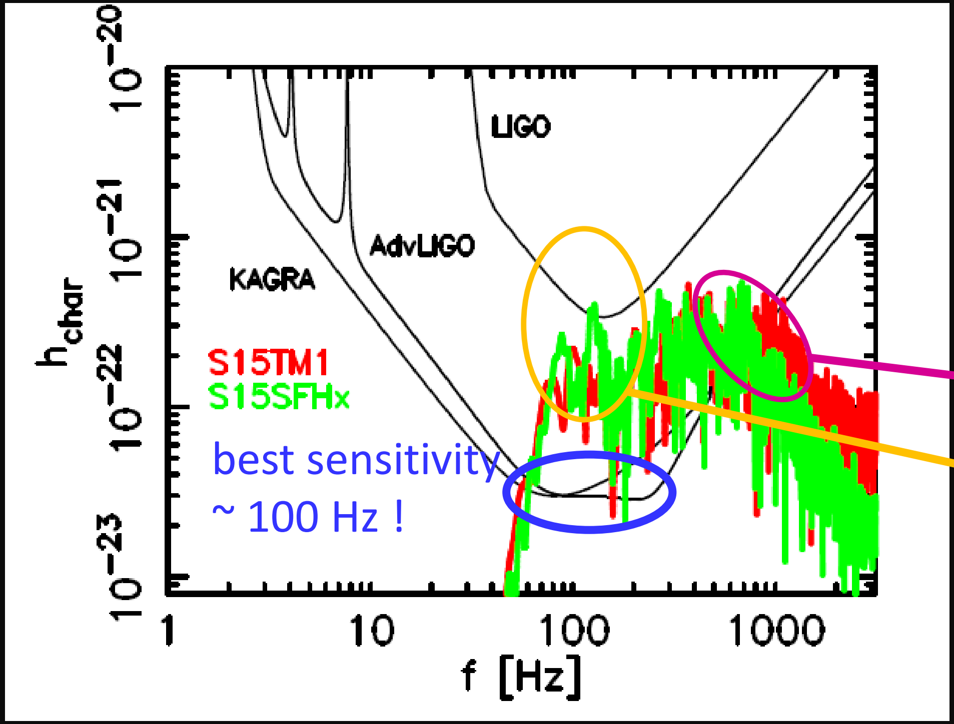
GW signal reconstruction by Coherent Network Analysis

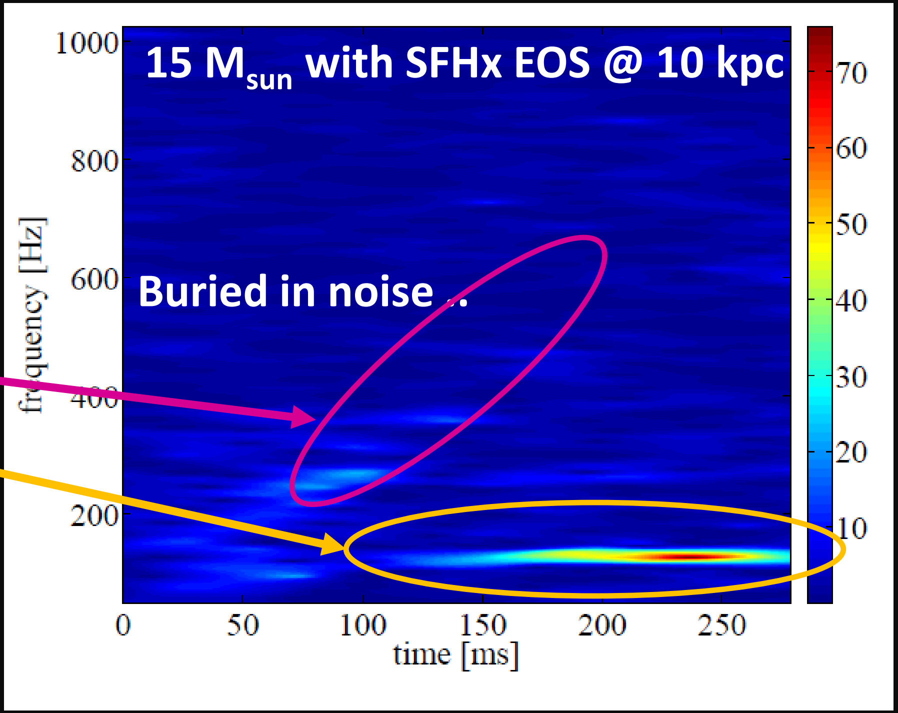
✓LIGOx2, VIGRO, KAGRA

Hayama, Kuroda, KK, & Takiwaki
(2015) & in prep

Sensitivity curves and model predictions



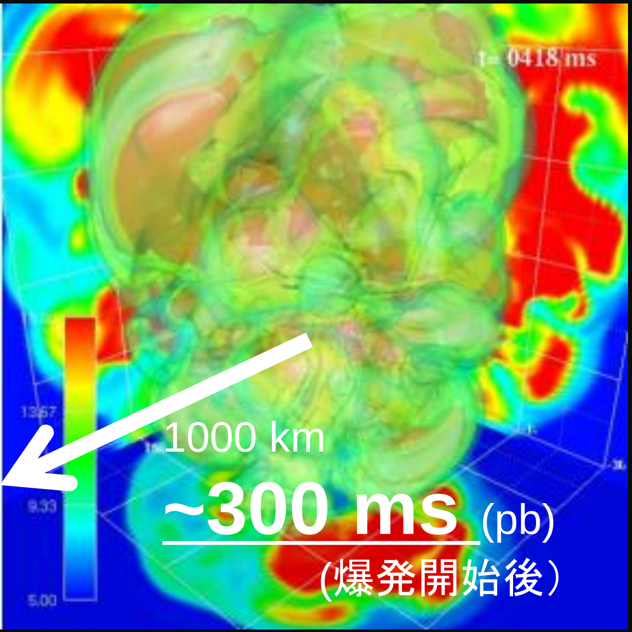
The reconstructed GW spectrogram



✓ The, quasi-periodic, SASI-modulated GW in the best sensitivity range of interferometers.
✓ Coherent network analysis: these signals detectable out to the LMC (50 kpc).

Perspectives: Where are we and where are we going ?

"A" self-consistent 3D model



1000 km

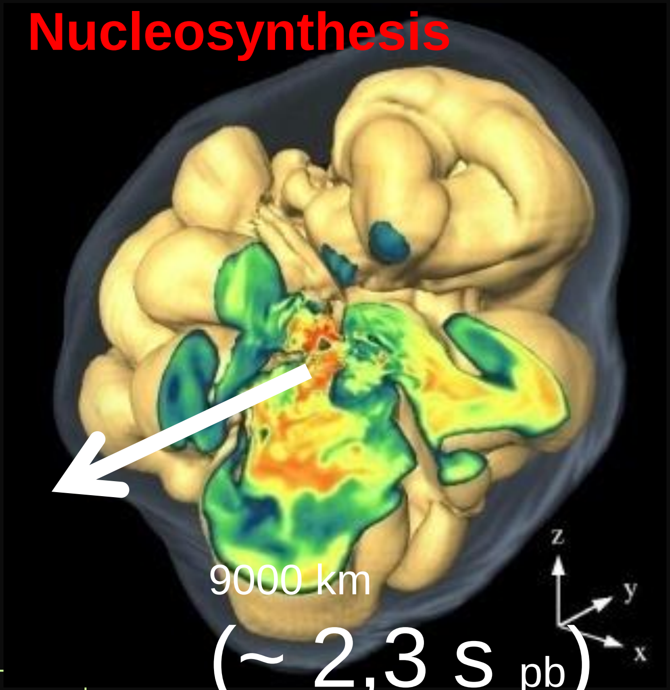
~300 ms (pb)

（爆発開始後）

Takiwaki, KK, Suwa (2014,2012 ApJ)

Gray-transport simulation

Nucleosynthesis

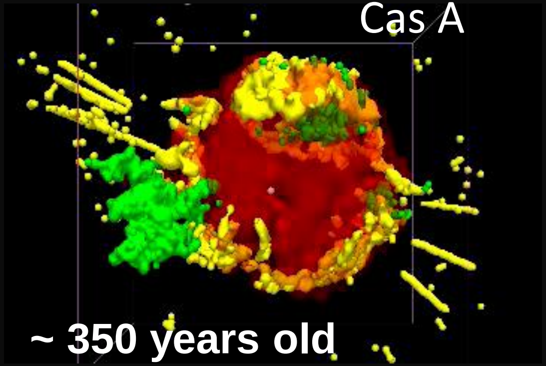


9000 km

(~ 2,3 s pb)

Wongwathanarat et al. (2012)

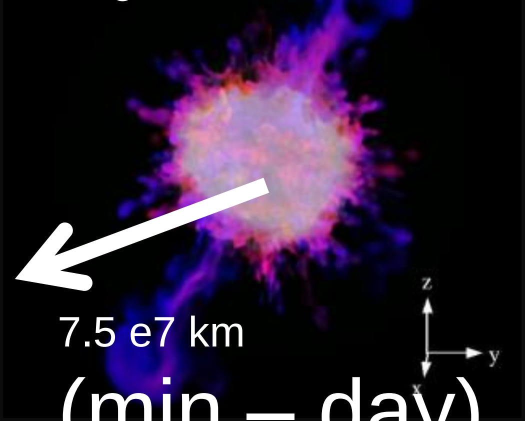
Cas A



~ 350 years old

DeLaney et al. (2010)

Hydrodynamic model:
Mixing, RT, RM instabilities



7.5 e7 km

(min – day)

Wongwathanarat et al. (2014)

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

Project L: Long-term evolution in self-consistent 3D (GR) models
⇒ confront CCSN theory with observation (Takiwaki-Kuroda-Nakamura-Kotake)

Project F : Full Boltzmann project : Sumiyoshi-Nagakura-Iwakami-Yamada
⇒ ultimately test whether the stalled shock would revive.

SN 20xx ! in the Galactic center: End-to-End Bridging Simulations

sec min hours day years

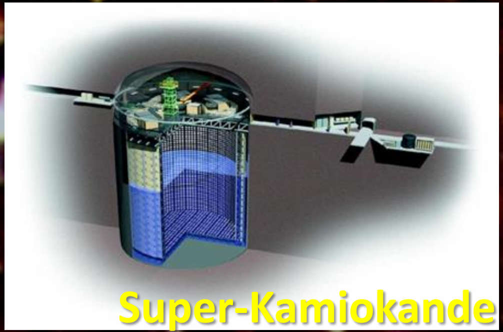
- 4 - 3 - 2 - 1 0 2 >3

Log (day)

SK detects ~ 10,000 neutrinos

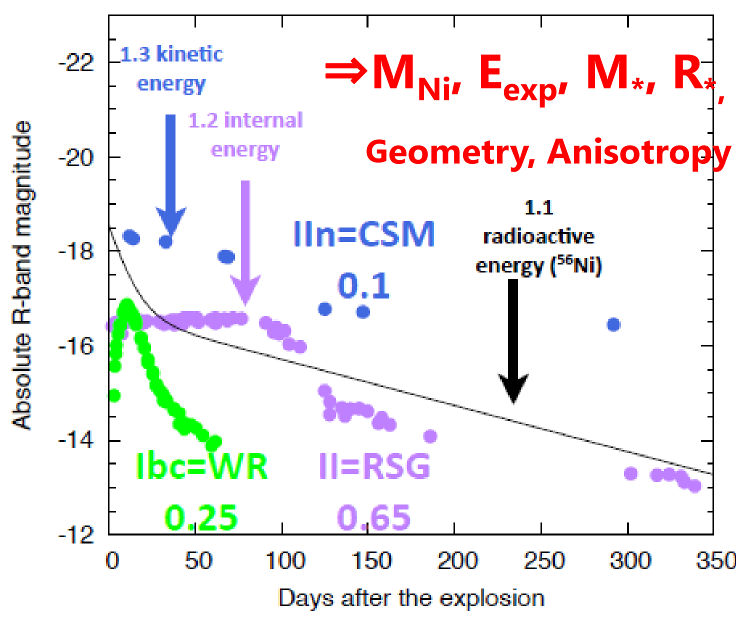
< 15min SURGE meeting (Supernova Urger

< 1 hour SK provide alert: Astronomer
(onset of neutrino burst, dura


Super-Kamiokande


Gravitational Waves

KAGRA

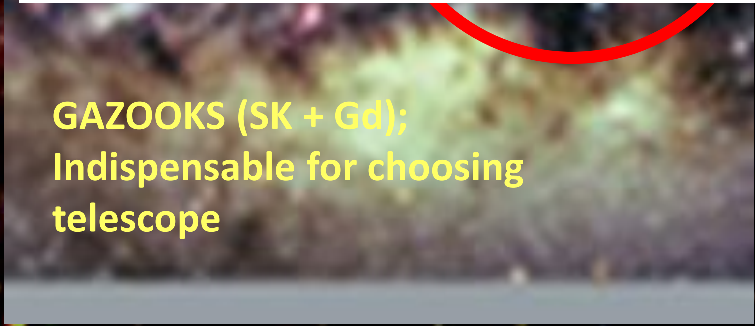


$\Rightarrow M_{Ni}, E_{exp}, M_{*}, R_{*},$

Geometry, Anisotropy

~ **1 min**
- Small telescope
(**ASAS-SN, MASTER**, etc)

~ **1 hour** - Large telescopes (**Subaru** etc)
~ **1 day**, Shock Break-out
> **Years**, Direct image



**GAZOOKS (SK + Gd);
Indispensable for choosing
telescope**

SN 20xx ! in the Galactic center: End-to-End Bridging Simulations

sec min hours day years

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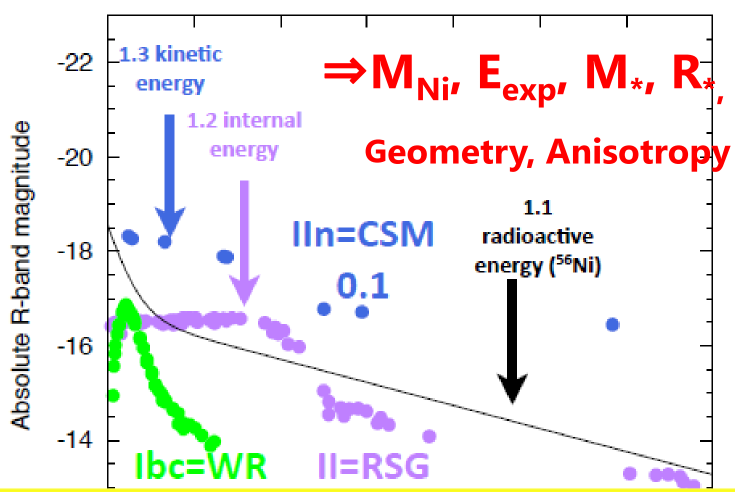
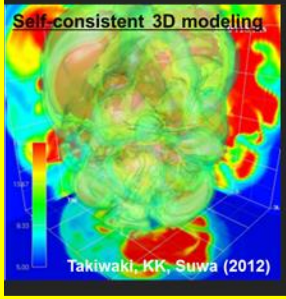


K

Post-K, Hyper-K, KAGRA

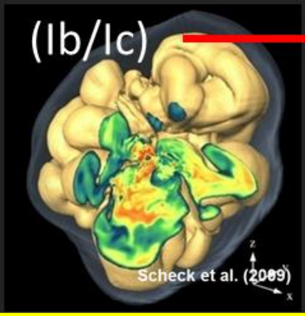
Self-Cons SN Simulations

Self-consistent

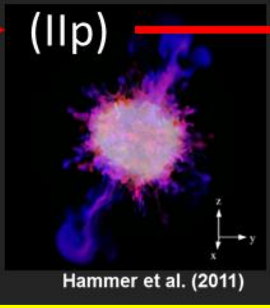


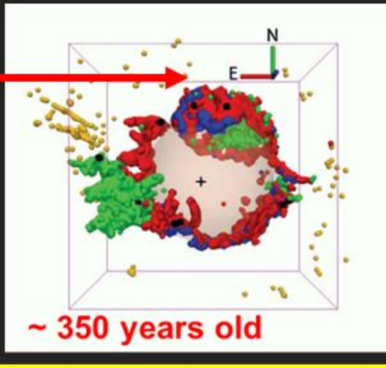
Shock-breakout

(Ib/Ic)



(IIp)





Summary

1. **“Progenitor Compactness” is (one of) the key(s)** to characterize diversity of 2D neutrino-driven explosions.

2. For high compact progenitors,
   - ✓ **3D explosions generally under-energetic than 2D.**
     - progenitor dependence yet unclear.
   - ✓ **Need to find some ingredients to foster 3D explosions.**
     - Strangeness effects attracting attention (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, KK, Takiwaki 2012, Sawai+2014))

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

4. **Detailed correlation analysis of neutrino and GWs signatures mandatory.** : provide information to break the degeneracy (M_{PNS}, R_{PNS}, T_{PNS}, R_{shock}, EOS etc.) ⇒ important probe to the explosion physics!

5. **Post-K, Hyper-K, and KAGRA** : the village !

Many thanks!