Unresolved riddles about the CCSN mechanisms: "difficulty of reverse engineering from multimessenger signals to the precollapse stellar parameters"

Kei Kotake

(Fukuoka University)

Brainstorming workshop 2022 to Revolutionize the Core-Collapse Supernova Theory
August 1–5, 2022 **@ Univ. Wroclaw**

Wow...

Europe/Warsaw English

Brainstorming workshop 2022 to Revolutionize the Core-Collapse Supernova Theory

31 July 2022 to 5 August 2022
Institute of Theoretical Physics, University of Wroclaw
Europe/Warsaw timezone

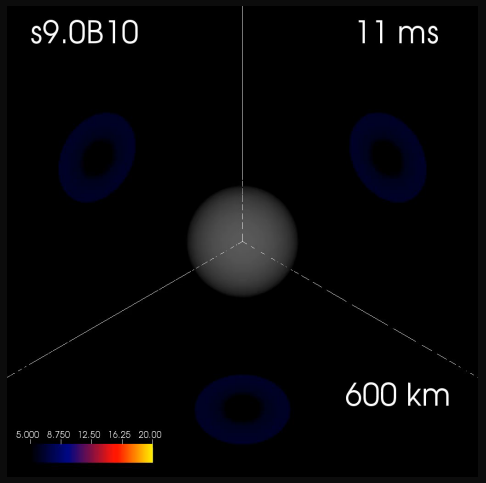
Dziękuję, Tobias, Shota et al. !

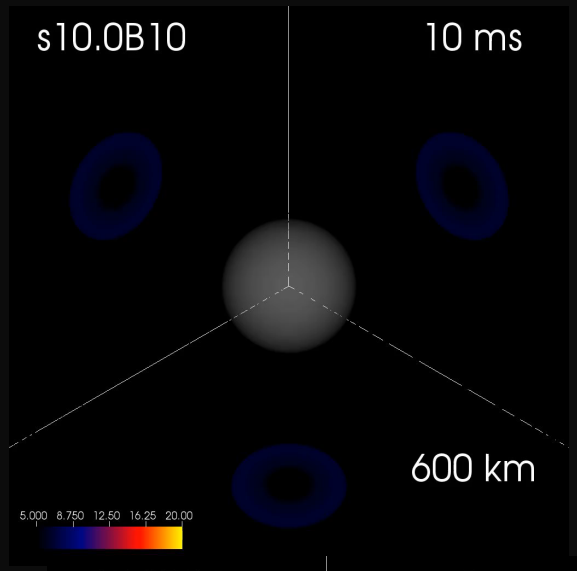
Unresolved riddles #1. Still under-energetic …

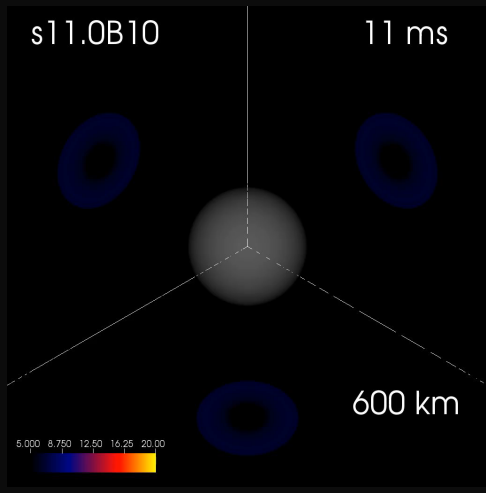
✓3D MHD modeling possible (Swiss-made IDSA+detailed opacities!)

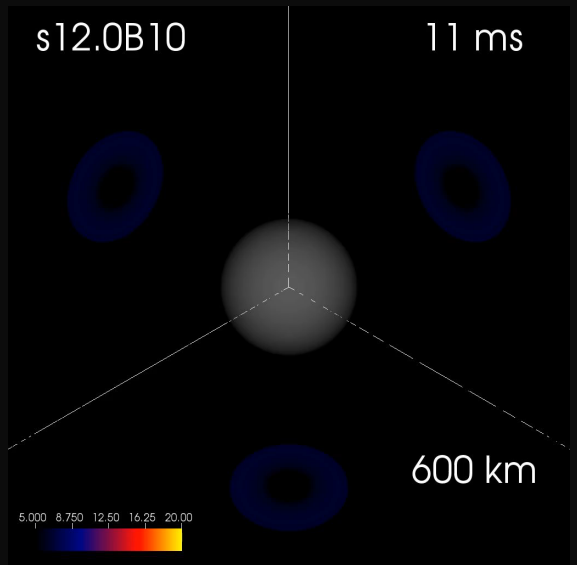
✓ 9-20 solar mass progenitors (Sukhbold et al. (2016), Initial B-field: 10^{10} G (uniform), Non-rotation)

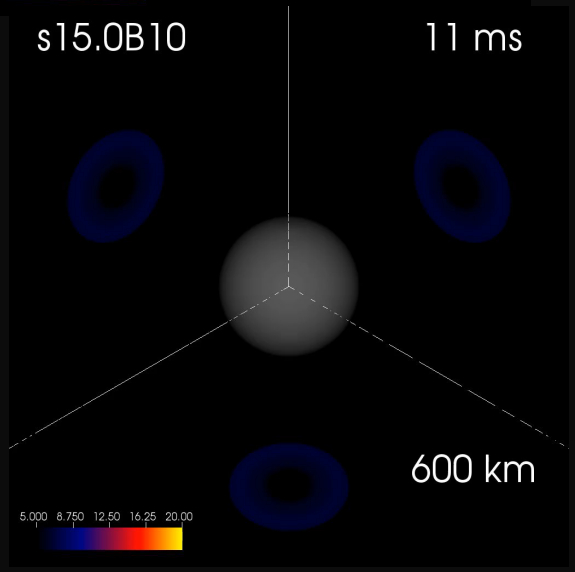
Nakamura, Takiwaki, KK (2022), Matsumoto et al. submitted

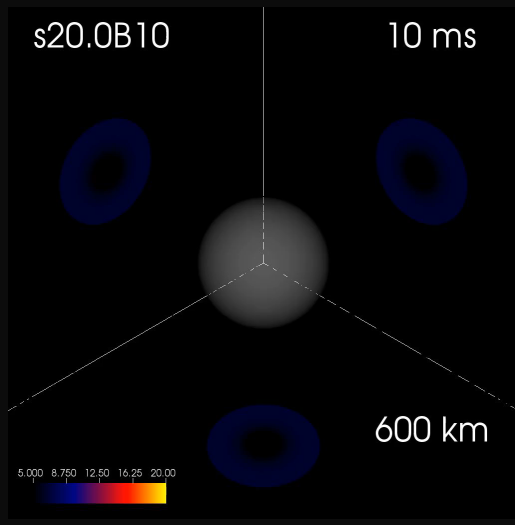


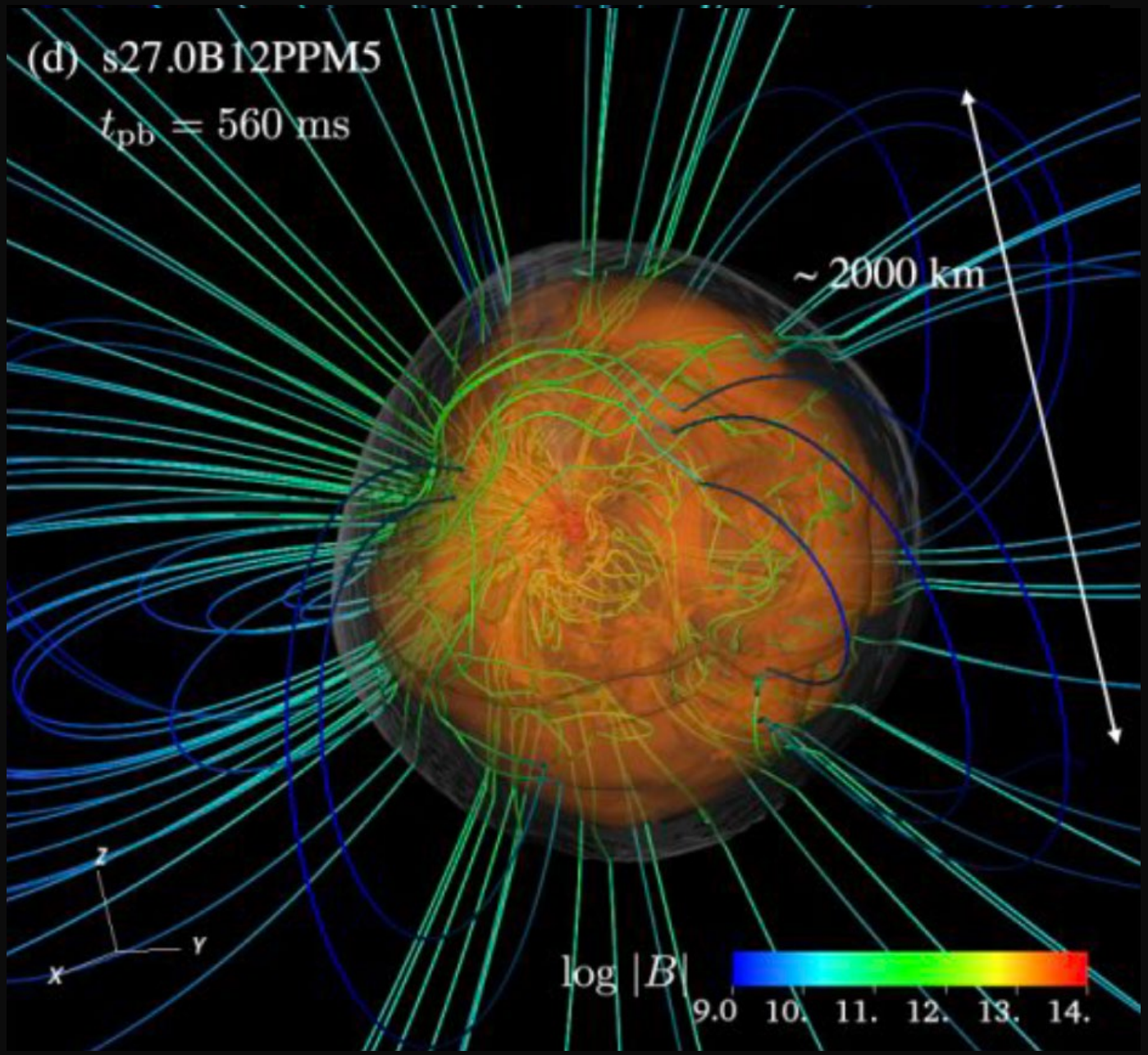












Matsumoto, Asahina, Takiwaki, KK, Takahashi (2022)

Three-dimensional simulation of a core-collapse supernova for a binary star progenitor of SN 1987A

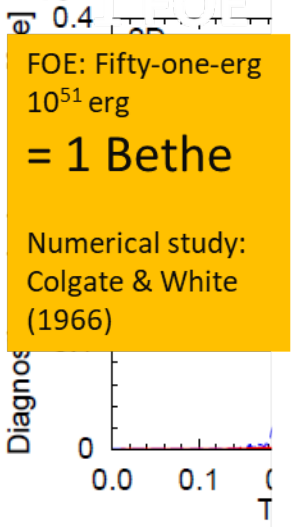
Ko Nakamura,[1,2⋆] Tomoya Takiwaki[3] and Kei Kotake[1,2]
[1] *Department of applied physics, Fukuoka University, Nanakuma Jonan 8-19-1, Fukuoka 814-0180, Japan*
[2] *Research Institute of Stellar Explosive Phenomena, Fukuoka University, Nanakuma Jonan 8-19-1, Fukuoka 814-0180, Japan*
[3] *National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan*

~ 10FOE

ls)

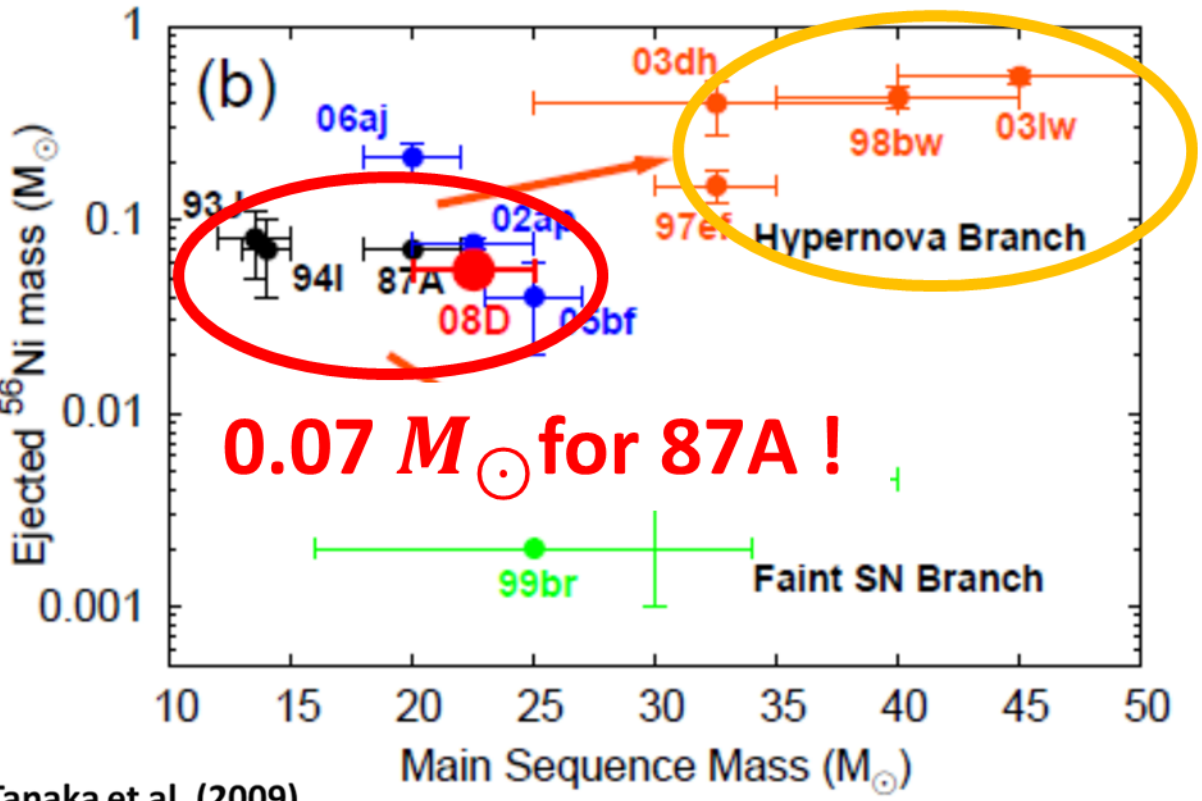
8 *K. Nakamura et*

≃ 1 FOE



FOE: Fifty-one-erg
10^{51} erg
= 1 Bethe

Numerical study:
Colgate & White
(1966)



Tanaka et al. (2009)

Figure 8. Time evolution of diagnostic explosion energy (left panel) and unbound Ni mass (right panel) of 2D and 3D models.

✓Shall boost the 3D models: Revolution needed !

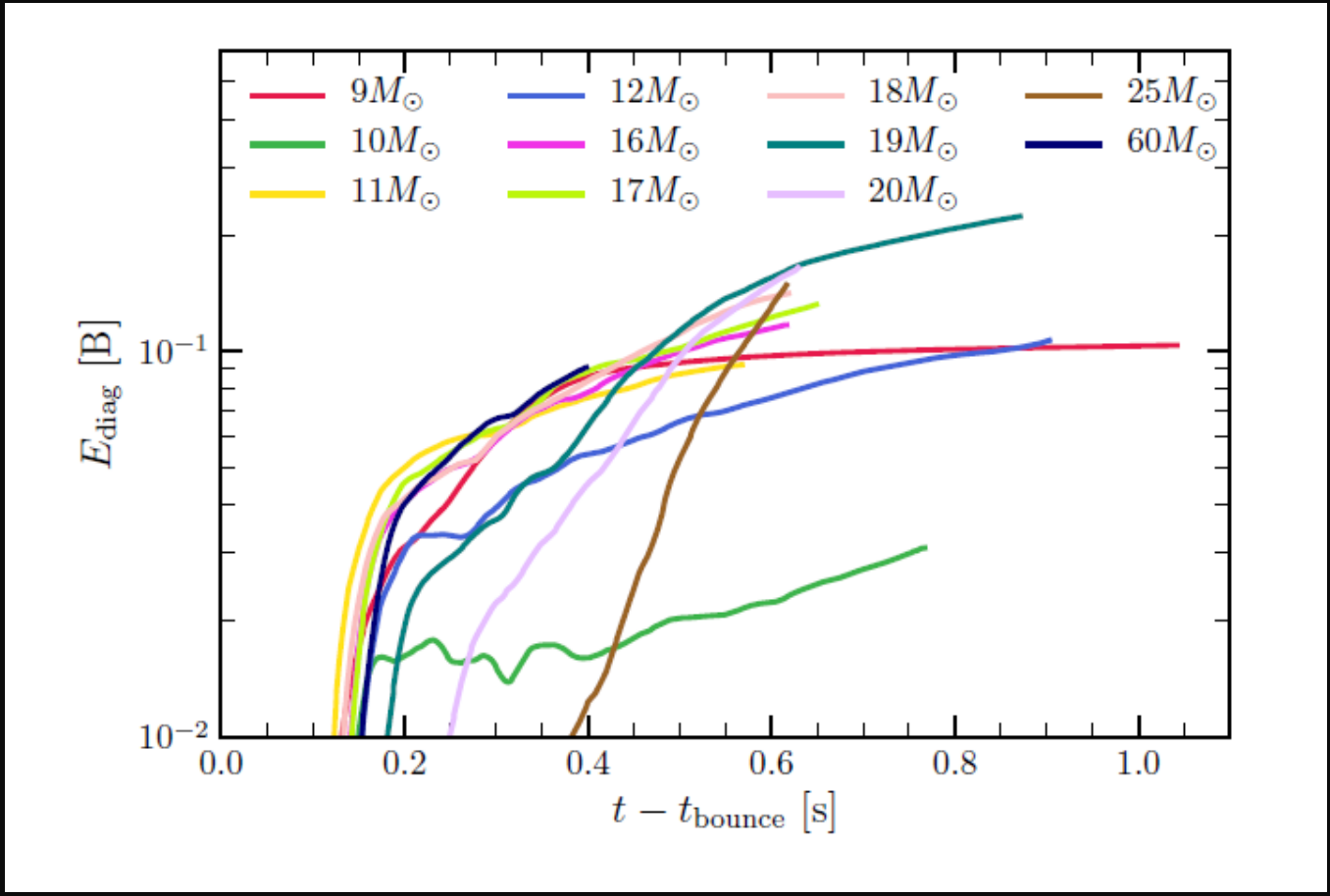
3D models (non-rot/rot) around the globe in vogue

The Overarching Framework of Core-Collapse Supernova Explosions as Revealed by 3D FORNAX Simulations

Adam Burrows[1], David Radice[1,2,3,4], David Vartanyan[1], Hiroki Nagakura[1], M. Aaron Skinner[5], and Joshua C. Dolence[6]

ApJ 2020

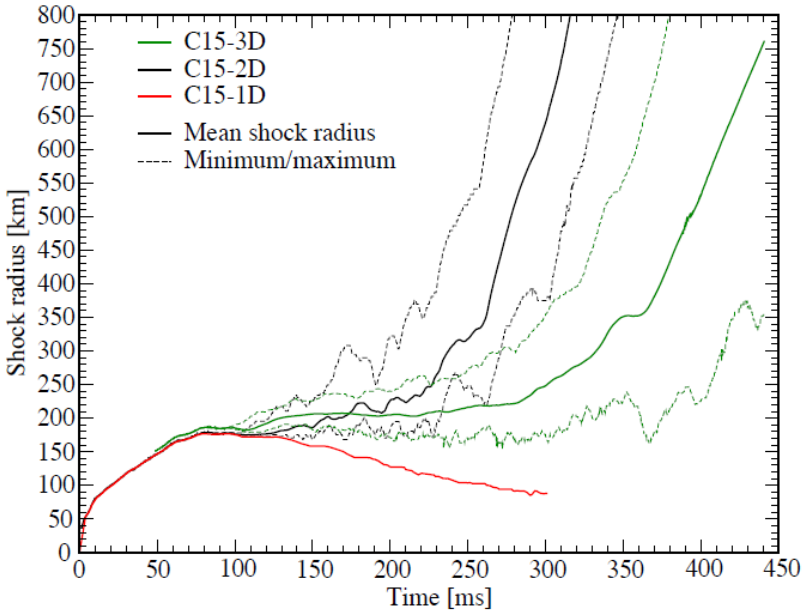
The group very active! Though, the models under-energetic..

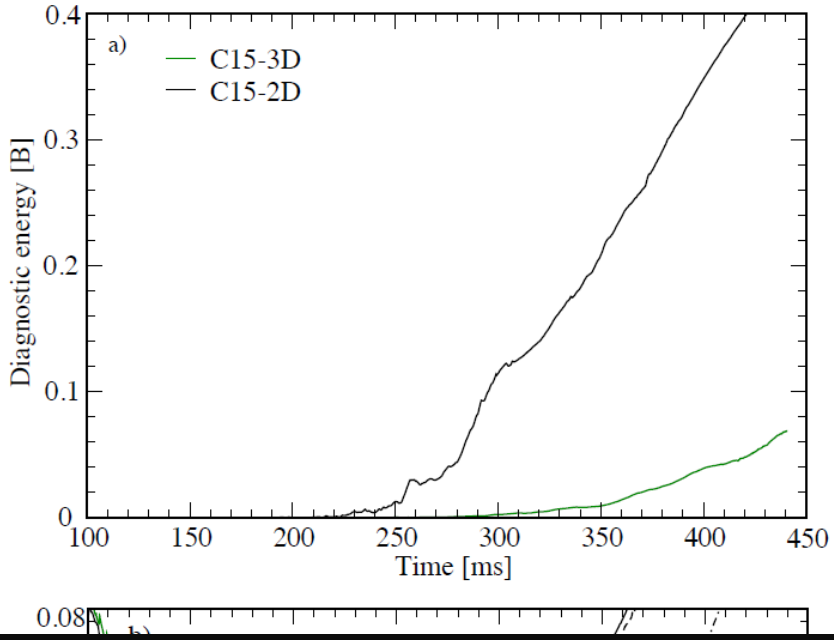


THREE-DIMENSIONAL CORE-COLLAPSE SUPERNOVA SIMULATED USING A 15 $M_\odot$ PROGENITOR

ERIC J. LENTZ[1,2], STEPHEN W. BRUENN[3], W. RAPHAEL HIX[2,1], ANTHONY MEZZACAPPA[1,4], O. E. BRONSON MESSER[5,2,1], EIRIK ENDEVE[6,1,4], JOHN M. BLONDIN[7], J. AUSTIN HARRIS[2], PEDRO MARRONETTI[8], AND KONSTANTIN N. YAKUNIN[1,2,4]

Accepted for publication in ApJ Letters: June 9, 2015





ApJ 2015.

✓Though again under-energetic..

Self-consistent 3D Supernova Models From −7 Minutes to +7 Seconds: A 1-bethe Explosion of a ∼19 $M_\odot$ Progenitor

Robert Bollig,[1] Naveen Yadav,[1,2] Daniel Kresse,[1,3] Hans-Thomas Janka,[1] Bernhard Müller,[4,5,6] and Alexander Heger[4,5,7,8]

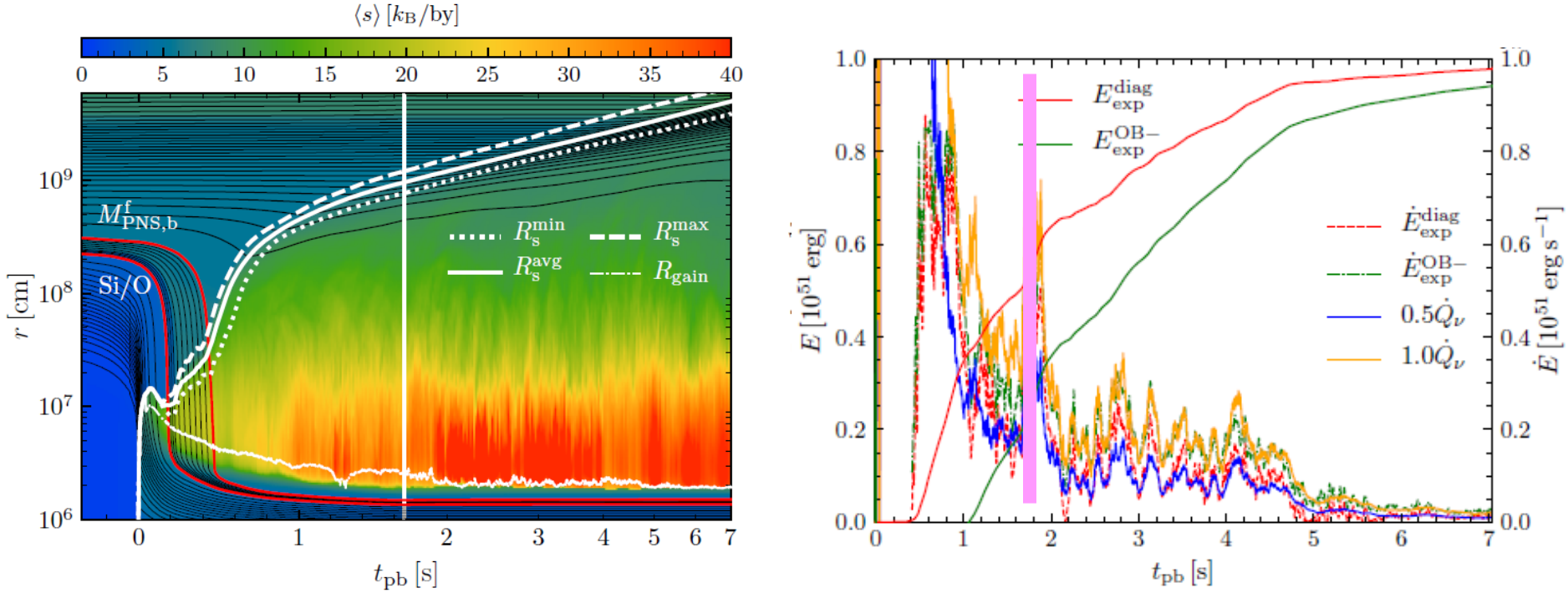


Figure 1. Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of Si/O shell interface and final NS mass are marked. The vertical white line separates Vertex transport (left, time linear) and HC neutrino approximation (right, time logarithmic). *Right:* Emitted luminosities and mean energies of ν_e, $\bar{\nu}_e$, and a single species of heavy-lepton neutrinos. The time axis is split as in the left panel. Right of the vertical solid line we show neutrino data from the artificially exploded 1D simulation.

Congratulations ! But…

Looking into more detail of Bollig et al !

Model Name[a]	$t_{\rm bounce}$[b] [ms]	$t_{\rm pb}^{\rm exp}$ [ms]	$t_{\rm pb}^{\rm f}$ [ms]	$M_{\rm PNS,b}^{\rm f}$ [$M_\odot$]	$M_{\rm PNS,g}^{\rm f}$ [$M_\odot$]	$R_{\rm PNS}^{\rm f}$ [km]	$E_{\rm exp}^{\rm diag}$ [B]	$E_{\rm exp}^{\rm OB-}$ [B]	$R_{\rm s}^{\rm 270ms}$ [km]	$R_{\rm s}^{\rm f}$ [km]
H_P1D_LS220_m-	357		288						107^{120}_{96}	98^{107}_{89}
H_P3D_LS220_m-	357		285						158^{213}_{114}	168^{245}_{120}
M_P1D_LS220_m-	357	∅	579	1.8788	1.8115	26.00	∅	∅	142^{170}_{122}	82^{95}_{64}
M_P3D_LS220_m-	357	418	1675	1.8655	1.7548	17.89	0.5071	0.2024	165^{213}_{126}	9704^{12203}_{7852}
M_P3D_LS220_m-HC	∅	∅	7035	1.8654	1.6749	13.57	0.9779	0.9411	∅	49470^{66024}_{38333}
M_P3D_SFHo_m-	362	426	545	1.8635	1.8025	28.97	0.0184	−0.3978	156^{206}_{122}	549^{948}_{251}
L_P1D_LS220_m-	357	∅	489	1.8503	1.7910	27.96	∅	∅	173^{213}_{141}	81^{96}_{70}
L_P3D_LS220_m-	357	400	1884	1.8530	1.7359	17.41	0.6314	0.3728	159^{190}_{136}	11996^{15332}_{9425}
L_P1D_SFHo_m-	362	∅	486	1.8302	1.7798	30.12	∅	∅	148^{169}_{128}	87^{108}_{67}
L_P3D_SFHo_m-	362	602	742	1.9154	1.8399	25.27	0.1001	−0.2994	162^{184}_{141}	1254^{1933}_{545}

✓ **Their successful model with SFHo no energetic !**

✓ **Precollapse density perturbations (Yadev+20) allegedly assist the explosion. But. it doesn't happen for Yoshida 3D progenitor (Nakamura +in prep).**

→ **Need a miracle (Quicker turbulent O/Si layer drops postbounce, works better)**

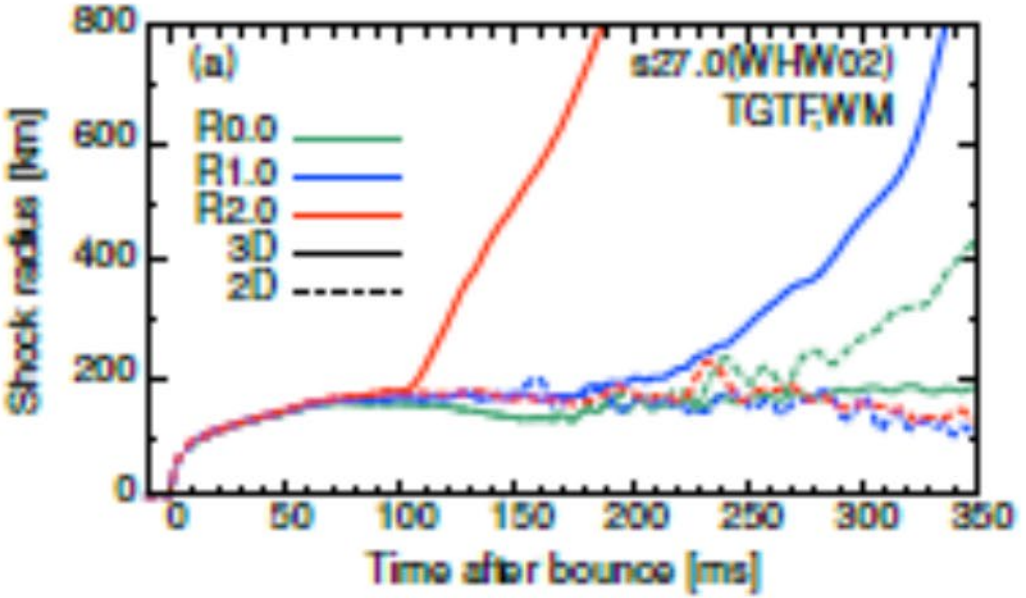
Switching gears to rotating 3D models!

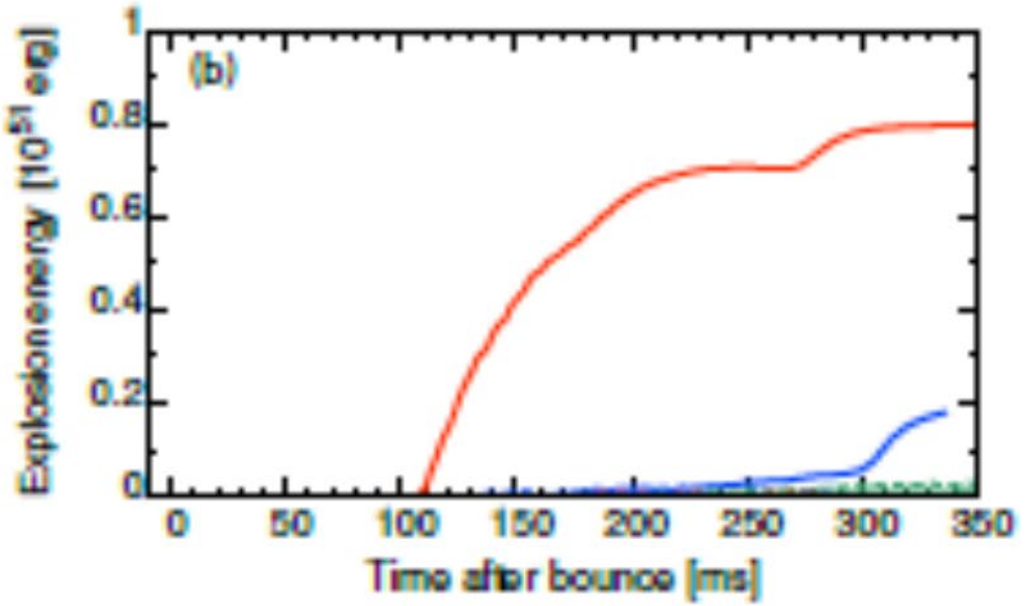
Insights into non-axisymmet
rotating supernova models w
signatures

Tomoya Takiwaki[1], Kei Kotake[2,3], a
[1]Division of Science, National Astronomical Observatory of Jap
[2]Department of Applied Physics, Fukuoka University, 8-19-1, Na
[3]Research Institute of Stellar Explosive Phenomena, Fukuoka Un
[4]Laboratoire AIM (CEA/Irfu, CNRS/INSU, Univ. Paris Diderot),

Ω_0 = 0, 1, 2 rad/s

Rapid rotation
(Ω_0 > 0.1 rad/s) aids
the explosion onset !



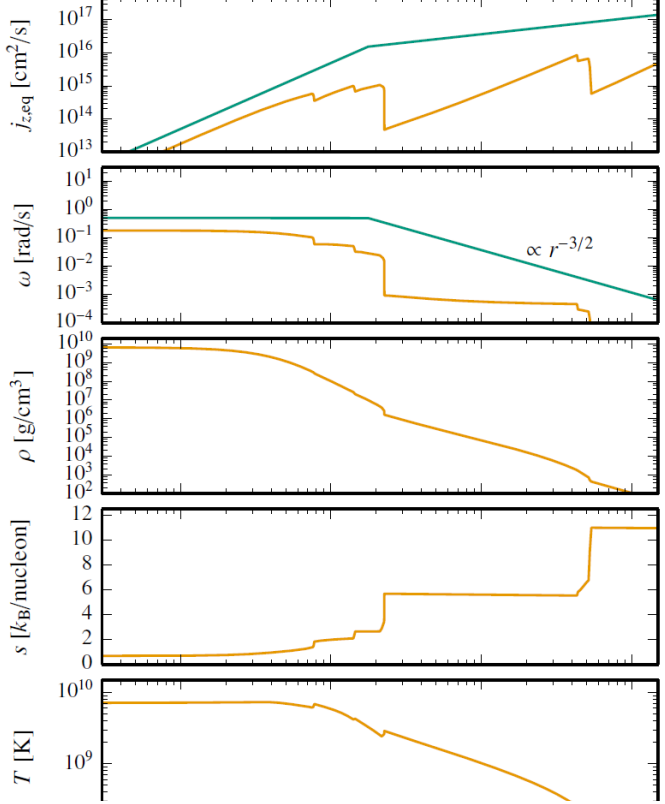


Even for "moder… …models, it works !

ROTATION-SUPPORTED NEU… …SIONS IN THREE DIMENSIONS AND …ITION

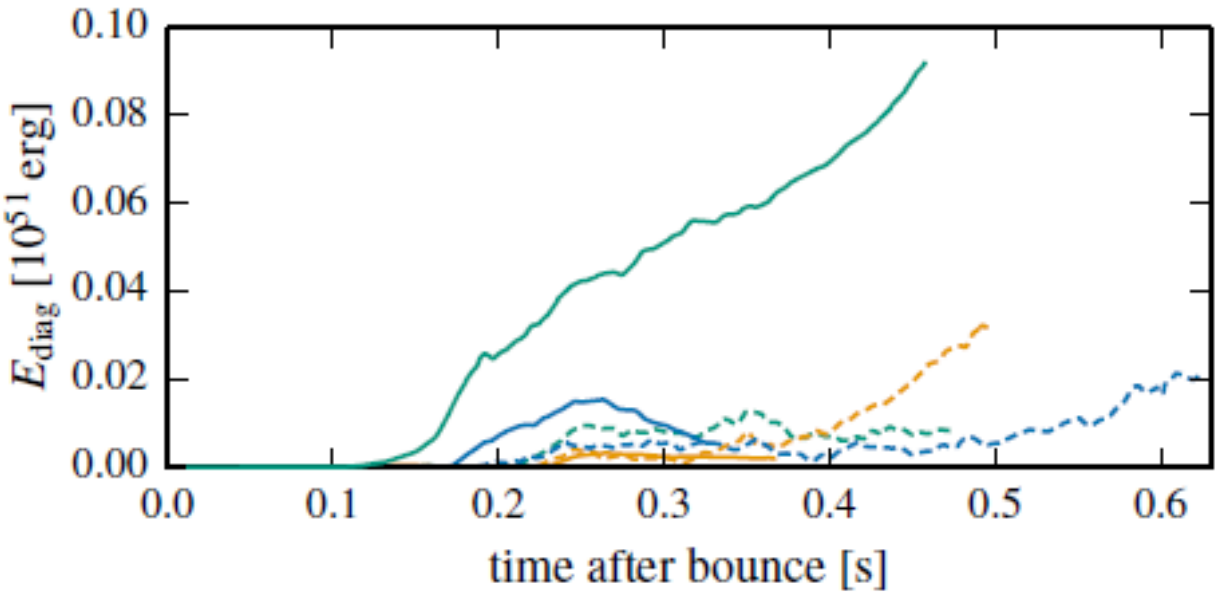
ALEXANDER SUMMA[1], … AND ANDREAS MAREK[2]

ApJ 2018



Tab…

model	dimension	…losion time[a]	end of simulation
m15_3D_artrot_2deg	3D	0.217 s	0.460 s
m15_3D_rot_2deg	3D	-	0.368 s
m15_3D_rot_6deg	3D	-	0.453 s
m15_3D_norot_4deg	3D		
m15_3D_norot_6deg	3D		



At most
0.1 Bethe…

Short summary: Recent status of 3D non-rotating/rapidly rotating models

✓ No "1-Bethe" models
except the miracle (Bolling+20)

Any ideas ?!!!

→ Some booster apparently needed to confront observations !

→ To obtain "1-Bethe model" needed for quantitative GW/neutrino predictions

Candidates and Candidates to chin up 3D models?

personal perspective in pink

Spice1. Rotation + B fields (even weak) : rather solid

(see talks by Foglizzo, Takiwaki)

Spice2. QCD phase transition : possibly

(see talk by Kuroda)

Spice3. Axion : exploratory

(see talk by Mori)

✓Other Solid possibilities include inclusion detailed physics

"light clusters in the postshock region" (Talk by Shibagaki)

"muonization" (Bollig, Fischer 2020, 2021)

"Collective neutrino oscillation" (talks by Takawaki, Horiuchi)

"Precollapse inhomogenities in the burning shells" (Nakamura)

and so on.

Not going into detail.....

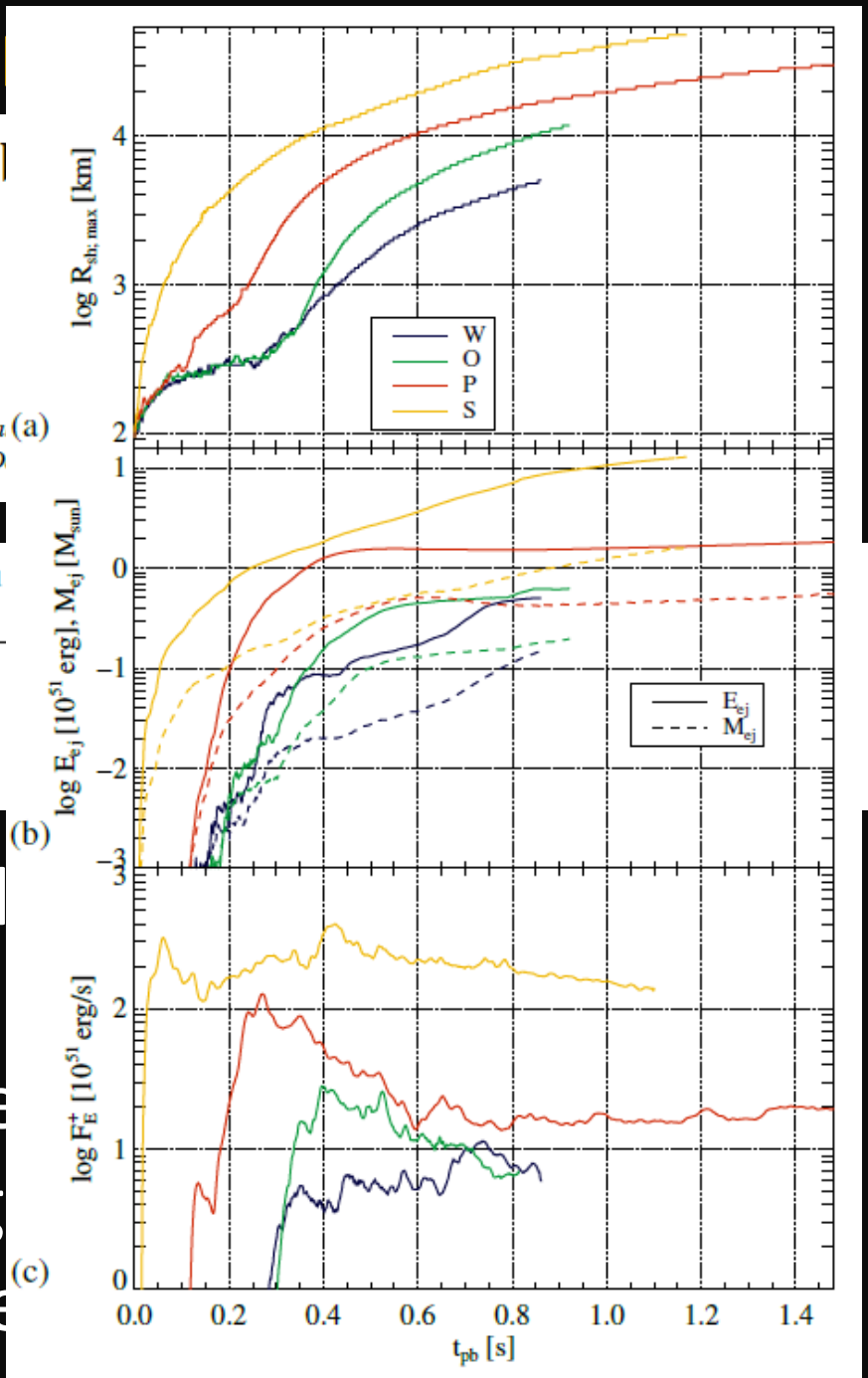
✓list up unresolved riddles that we shall and can solve together towards collaboration !

The **shocking** ! result from Va

Magnetorotational core collapse of possi
Three-dimensional models

M. Obergaulinger[1,2], M.Á. Aloy[1]
[1] *Departament d´Astronomia i Astrofísica, Universitat de València,*
Edifici d´Investigació Jeroni Munyoz, C/ Dr. Moliner, 50, E-46100 Burjassot (València), Spa
[2] *Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 D*

name	2D name	field	t_f [s]	fate	M_{exp} [$M_\odot$]	$E_{exp,51}$
W	35OC-Rw	$a(10, 10)$	0.85	ν-Ω	0.58	0.50
O	35OC-RO	Or ($1.1 \times^{11}$ G)	0.81	MR	0.21	0.62
P	35OC-Rp3	3p, 1t ($1.5 \times^{11}$ G)	1.5	MR	0.16	1.7
S	35OC-Rs	$a(12, 12)$	1.15	MR	1.7	13



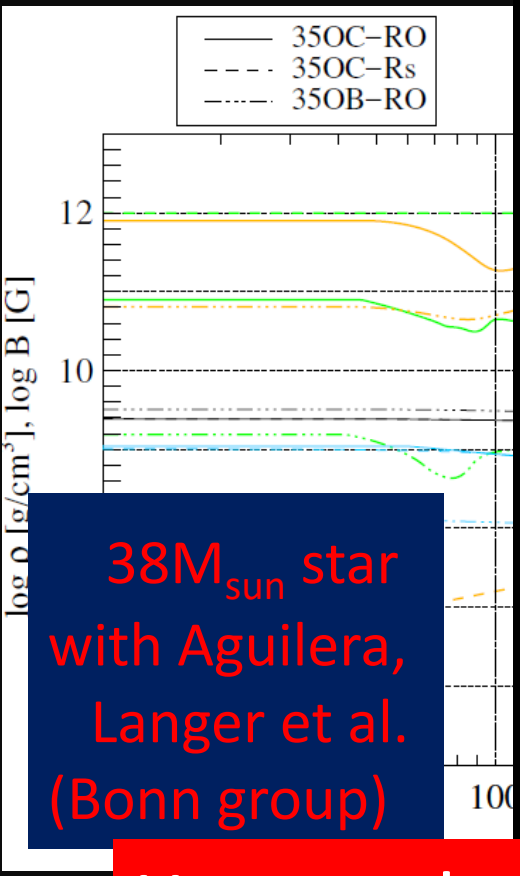
✓ The first 10-Bethe model
35OC progenitor (Ω_0 ~2
✓ Model "P" leads to 1-Be
" Ω_0 =3π rad/s" (Scheideg
→ The urgent task to validate

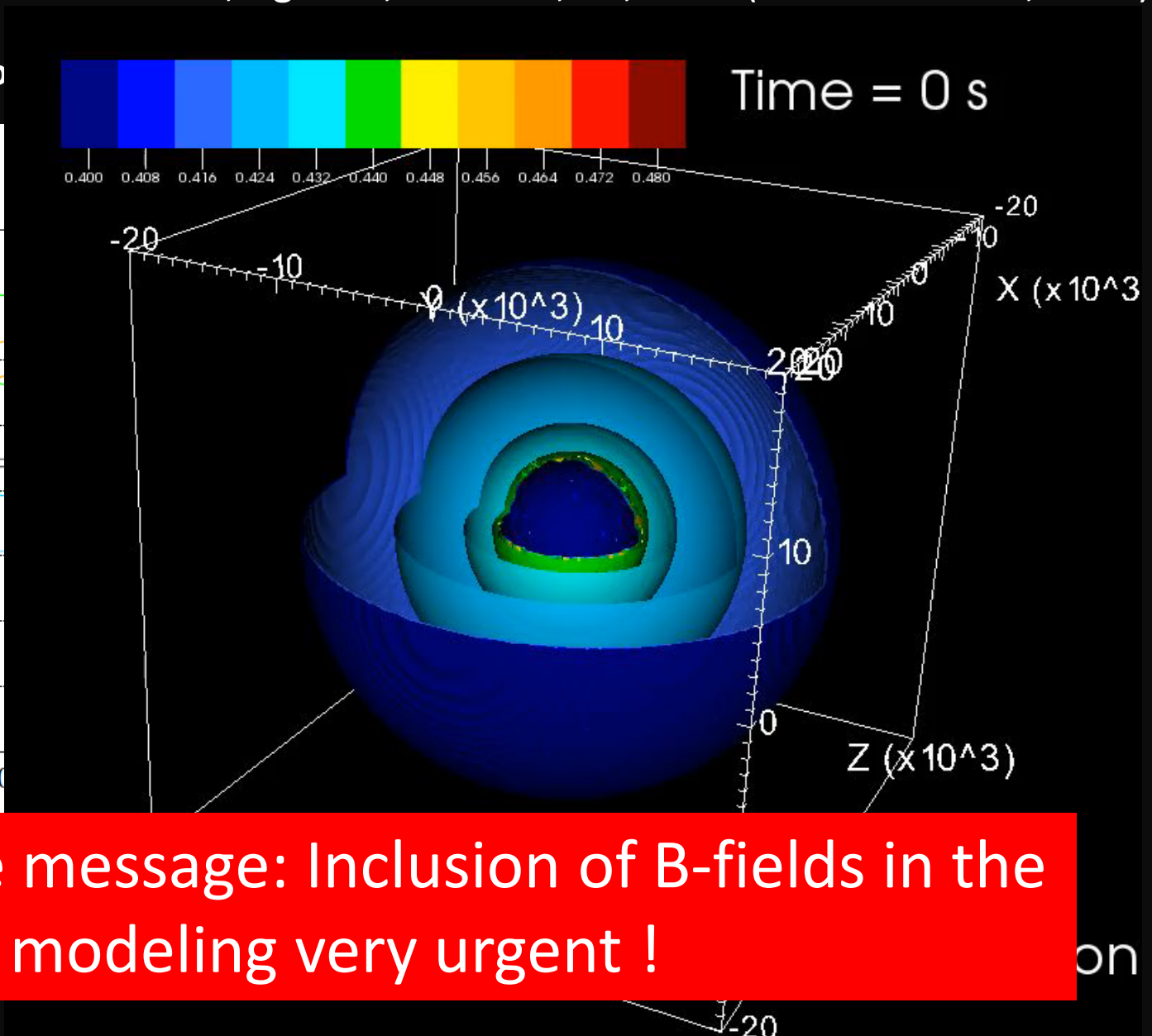
First 3D stellar evolution: what about the precollapse spiral flows ?

(3D stellar evolution calculations: Couch et al. (2015), Mueller et al. (2016))

Yoshida, Agulera, Takiwaki, KK, et al. (MNRAS Letters, 2021)

35C model : collapsar pro



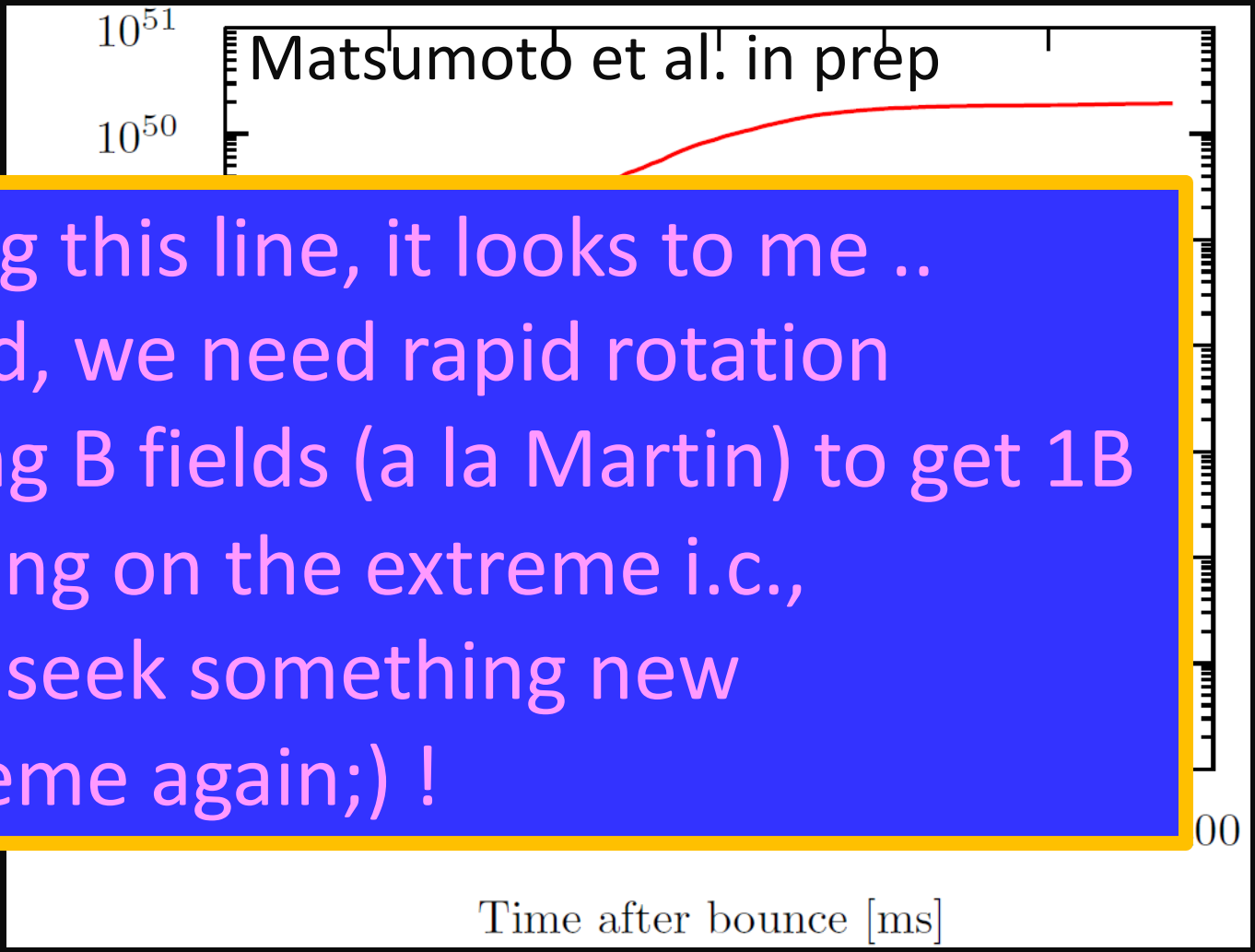


38M_{sun} star with Aguilera, Langer et al. (Bonn group)

Home-take message: Inclusion of B-fields in the progenitor modeling very urgent !

Calm down, Don't be puzzled by such extreme …

- ✓ Given B fields initially, rotation favors explosion (green vs red)
- ✓ Given rotation initially



- ✓ But, along this line, it looks to me .. in the end, we need rapid rotation and strong B fields (a la Martin) to get 1B
- ✓ Not relying on the extreme i.c., we may seek something new (or extreme again;) !

Candidates and Candidates to chin up 3D models?

personal perspective in pink

Spice1. Rotation + B fields (even weak) : rather solid

(see talks by Foglizzo Takiwaki)

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(see talk by Kuroda)

Spice3. Axion : exploratory

(see talk by Mori)

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"Precollapse inhomogenities in the burning shells" (Nakamura)

and so on.

Not going into detail.....

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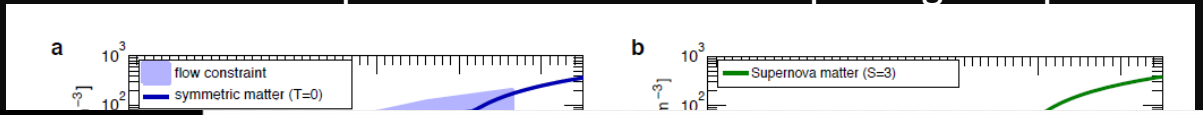
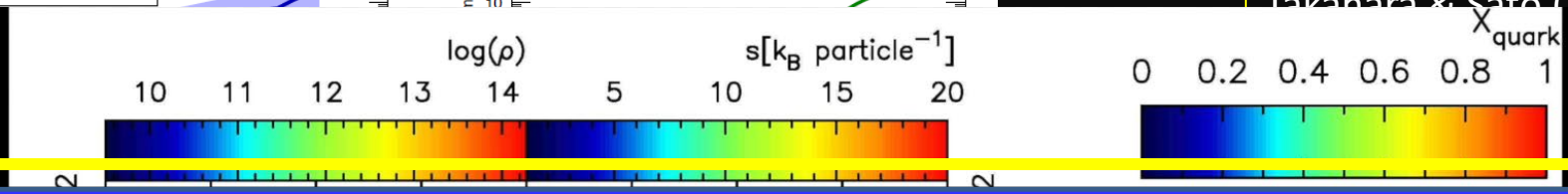
Spice2 QCD phase transition could power explosion !!

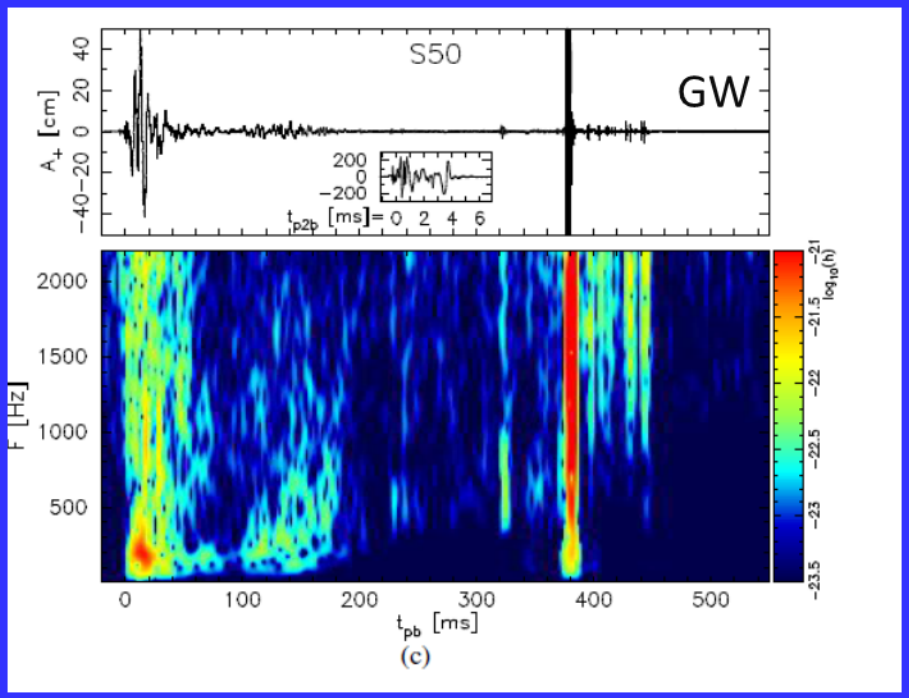
If “first-order” phase transition to the quark-gluon phase takes place… then

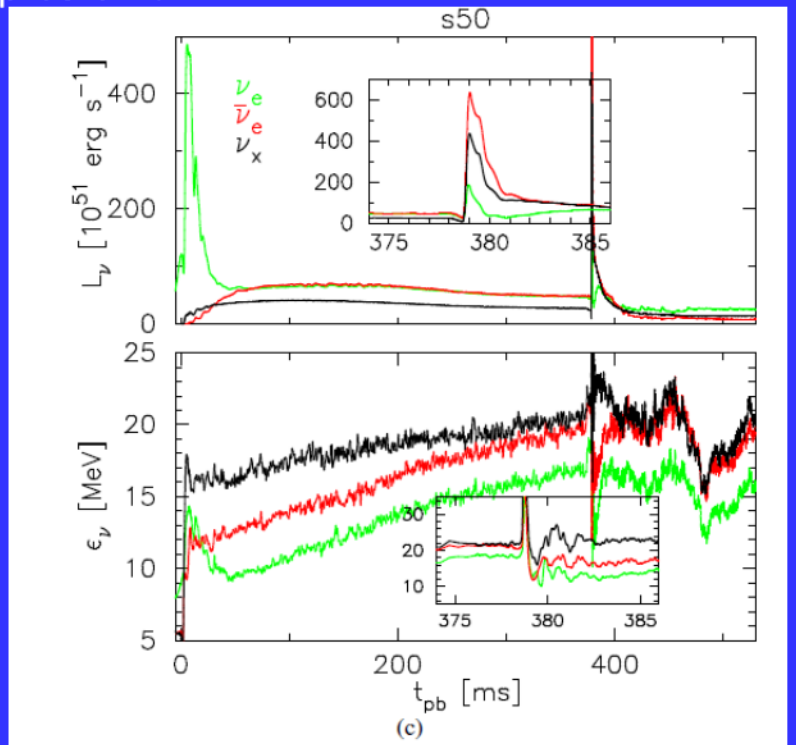


✓Original idea:
Takahara & Sato (1988)



Distinct second burst signals in GW and neutrinos:
a smoking gun of the phase-transion induced explosion !



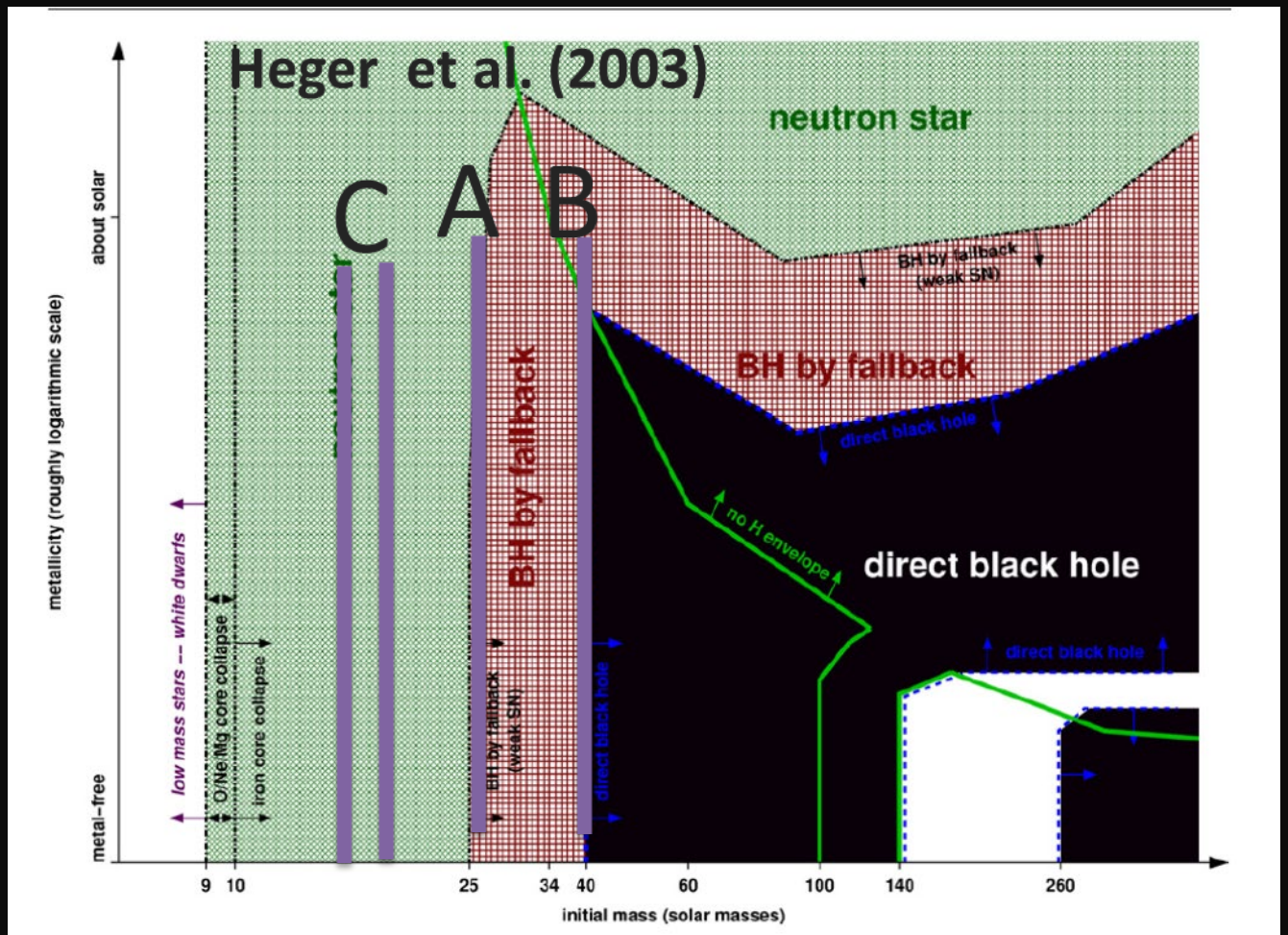


Challenges to QCD-phase-transition-induced (Q-induced) explosions !

1. Which progenitors end up with Q-induced explosions ?

Quiz: Choose of one the following : the dividing line !

#1 A
#2 B
#3 C (+A)
#4 none



Challenges to QCD-phase-transition-induced (Q-induced) explosions !

1. Which progenitors end up with Q-induced explosions ?

2. Inclusion of rotation and B fields in 3D models and GW/neutrino predictions : a vast virgin territory !
   Reverse engineering : From the signals, we can **probe into the phase transition physics.**
   ✓ Nucleosynthetic studies needed ! (r-process cites ?!)
3. In collaboration with researchers who have expertise in QCD-hardon physics (like Tobias), "first- order-phase-transition" should be validated !

✓ We can continue collaboration in the next decade to come!

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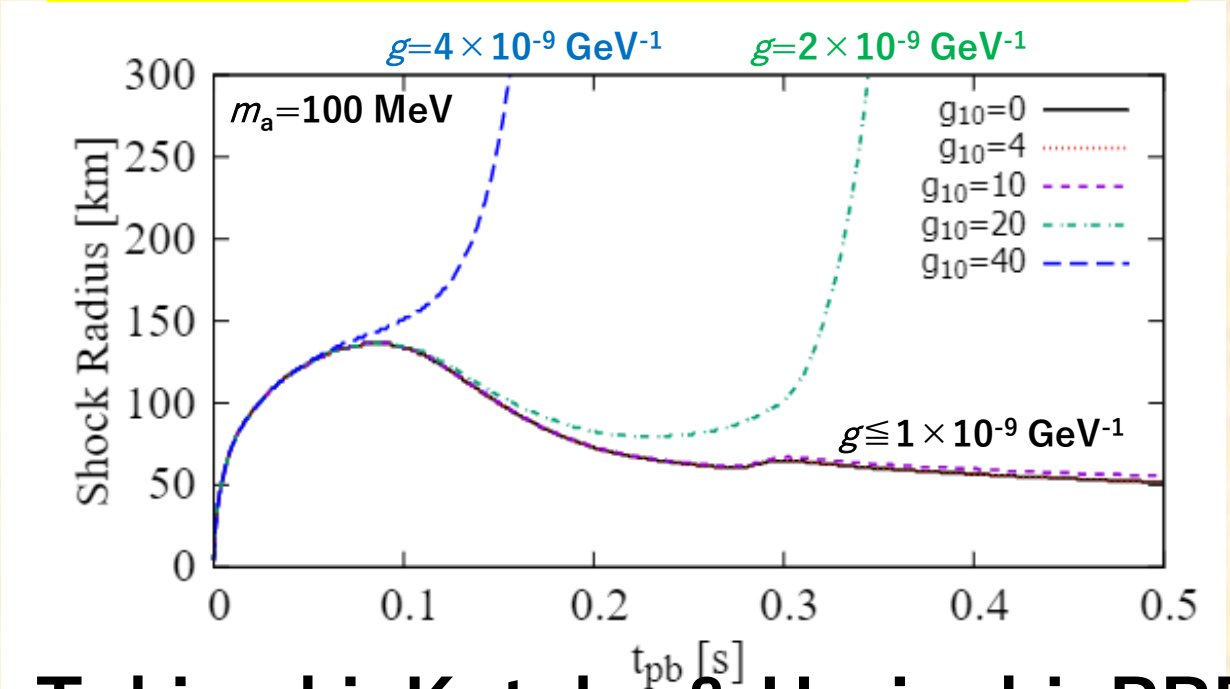
and so on.

Not going into detail.....

✓list up unresolved riddles that we shall and can solve together towards collaboration !

Shock Revival Assisted by ALPs

Kanji Mori (森寛治)
Research Institute of Stellar Explosive Phenomena,
Fukuoka University



Mori, Takiwaki, Kotake & Horiuchi, PRD,(2022)

✓ アクシオンの効果で、星が球対称であるとの仮定をおけば、
元気な爆発（10^{51} erg)を起こすことができることを示した！
✓ Nature is 3 D！ → 3 Dシミュレーションでは、どうなるか？
→「アクシオンで切り拓く革新的な超新星爆発モデルの構築」を実行！

Summary to chin up 3D models for GW/v predictions!

Spice1. Rotation + B fields: Multi-D progenitor modeling needed!

Spice2. QCD transition : Go to 3D modeling with GW/ v prediction
Reverse engineering to probe the PT physics
from MM (GW/v/nucleosynthetic signals)

Spice3. Axion : Go to 3D modeling with GW/v prediction
Reverse engineering to probe the axion
physics (mass, axion-gamma coupling)!

✓ Other Solid possibilities include inclusion detailed physics
"light clusters in the postshock region" (Talk by Shibagaki)
"muonization" (Bollig, Fischer 2020, 2021)

Happy time is (being) on surely for the decade to tackle with these issues (not limited ;-) . Have fun in Wroclaw !