超新星爆発による
重力波、電磁波、ニュートリノ放出

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Shio Kawagoe（U. Tokyo) ,Tomohide Wada (NAOJ),
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Yu Yamamoto（Waseda U.）and M. Tanaka（NAOJ)

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重力波源とその電磁波、ニュートリノ対応天体

LETTER

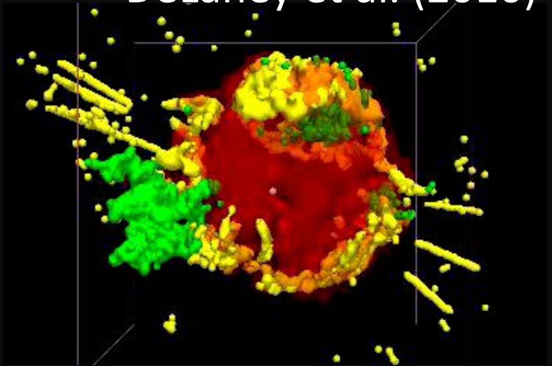
February 19, 2014

doi:10.1038/nature12997

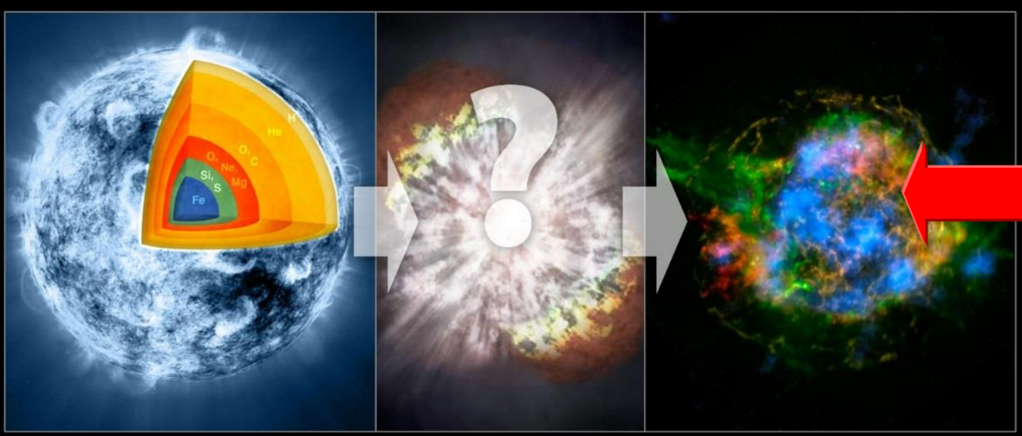
Asymmetries in core-collapse supernovae from maps of radioactive ^{44}Ti in Cassiopeia A

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]

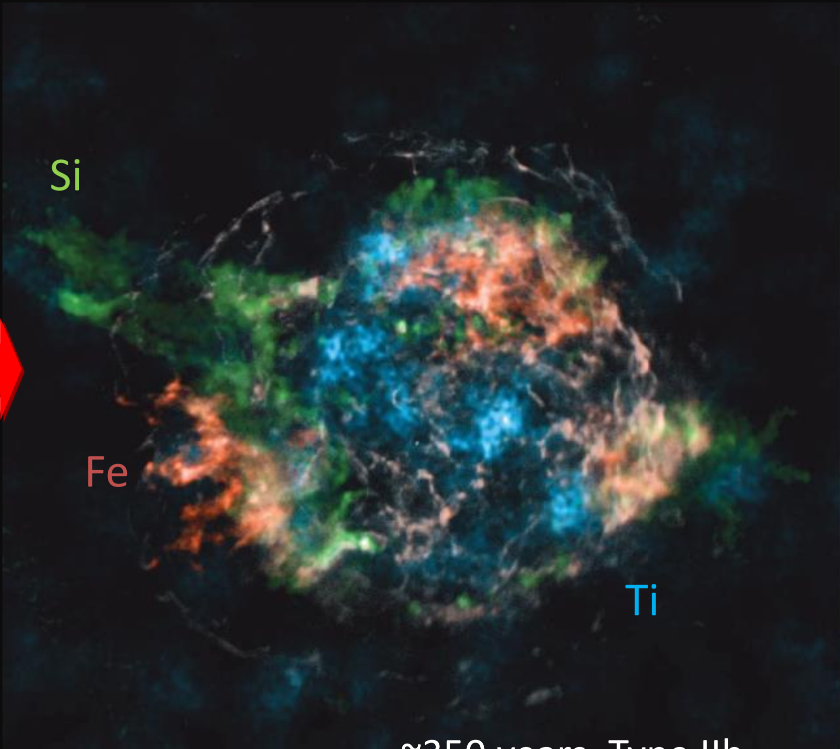
DeLaney et al. (2010)



Progression of a Supernova Explosion



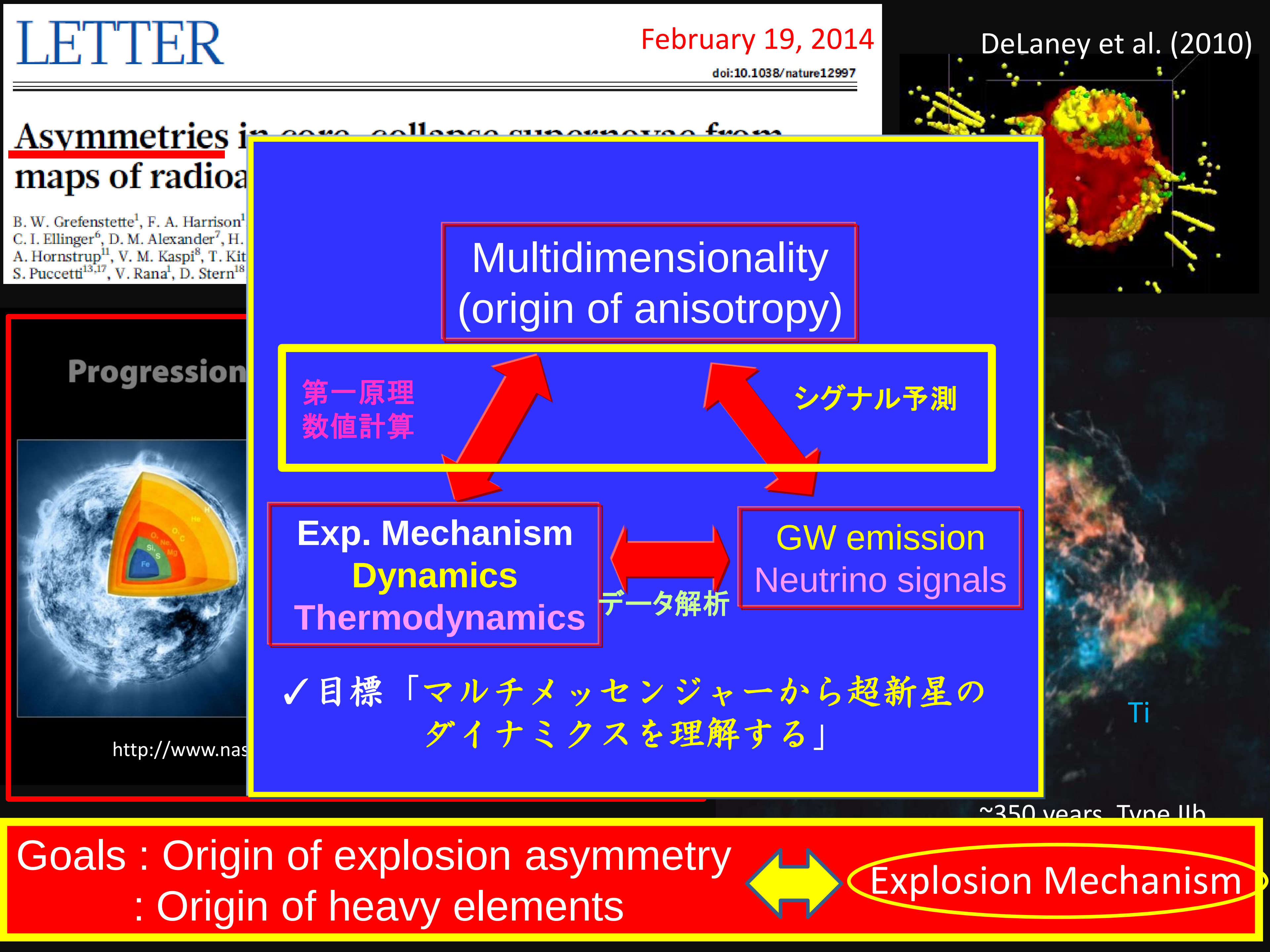
http://www.nasa.gov/jpl/nustar/supernova-explosion-20140219/



~350 years, Type IIb

Goals : Origin of explosion asymmetry ⟺ Explosion Mechanism

: Origin of heavy elements



LETTER
February 19, 2014
doi:10.1038/nature12997
DeLaney et al. (2010)
Progression
http://www.nas
Multidimensionality
(origin of anisotropy)
第一原理
数値計算
シグナル予測
Exp. Mechanism
Dynamics
Thermodynamics
データ解析
GW emission
Neutrino signals
✓目標「マルチメッセンジャーから超新星の
ダイナミクスを理解する」
Ti
Goals : Origin of explosion asymmetry
: Origin of heavy elements
Explosion Mechanism

✓ Status of Neutrino-Radiation Hydrodynamics Supernova Simulations

(e.g., Kotake et al. (2012) PTEP)

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	E_{exp}(B) @t_{pb} (ms)	ν transport (Dim, $\mathcal{O}(v/c)$)
8.8 $M_\odot$ (NH88)	MPA (2006,201[illegible])	ν-driven	1D(2D) (PN)	~200	0.1 (~800)	Boltzmann 2, $\mathcal{O}(v/c)$
	Princeton+ (2006)	ν-driven	2D (N)	≲125	0.1 -	MGFLD 1, (N)
10 $M_\odot$ (WHW02)	Basel (2009)	ν+(QCD transition)	1D (GR)	255	0.44 (350)	Boltzmann 2, (GR)
11 $M_\odot$ (WW95)	Princeton+ (2006)	Acoustic	2D (N)	≳550	~0.1* (1000)	MGFLD 1, (N)
11.2 $M_\odot$ (WHW02)	MPA (2006,201[illegible])	ν-driven	2D (PN, C-GR)	~100 *~200*	~ 0.005, *0.025* ~200, *900*	"RBR" Boltz-mann, 2, $\mathcal{O}(v/c)$
	Princeton+ (2007)	Acoustic	2D (N)	≳1100	~0.1* (1000)	MGFLD 1, (N)
	Tokyo+ (2011)	ν-driven	3D (N)	~100	0.01 (300)	IDSA 1, (N)
12 $M_\odot$ (WH07)	Oak Ridge+ (2009)	ν-driven	2D (PN)	~300	0.3 (1000)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
13 $M_\odot$ (WHW02)	Princeton+ (WH07)	Acoustic	2D (N)	≳1100	~0.3* (1400)	MGFLD 1, (N)
(NH88)	Tokyo+ (2010)	ν-driven	2D (N)	~200	0.1 (500)	IDSA 1, (N)
15 $M_\odot$ (WW95)	MPA (2009,201[illegible])	ν-driven	2D (PN, C-GR)	~600 *~400*	0.025, *0.125* (~700, *800*)	Boltzmann 2, $\mathcal{O}(v/c)$
(WHW02)	Princeton+ (2007)	Acoustic	2D (N)	-	- (-)	MGFLD 1, (N)
(WH07)	OakRidge+ (2009)	ν-driven	2D (PN)	~300	~ 0.3 (600)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
20 $M_\odot$ (WHW02)	Princeton+ (WH07)	Acoustic	2D (N)	≳1200	~0.7* (1400)	MGFLD 1, (N)
25 $M_\odot$ (WH07)	Princeton+ (2007)	Acoustic	2D (N)	≳1200	- (-)	MGFLD 1, (N)
	Oak Ridge+ (WH07)	ν-driven	2D (PN)	~300	~ 0.7 (1200)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$

Big breakthrough :

✓Wilson (1985)以来20年ぶりの爆発 (publishされた結果で)

✓ Success for 8.8 to 27 M_{sun} stars in 2D self- consistent simulations !

✓ Similar trends between Garching and our team.

(Hanke et al., Suwa et al. (2013) Nakamura et al. (2014))

成功例：15モデル

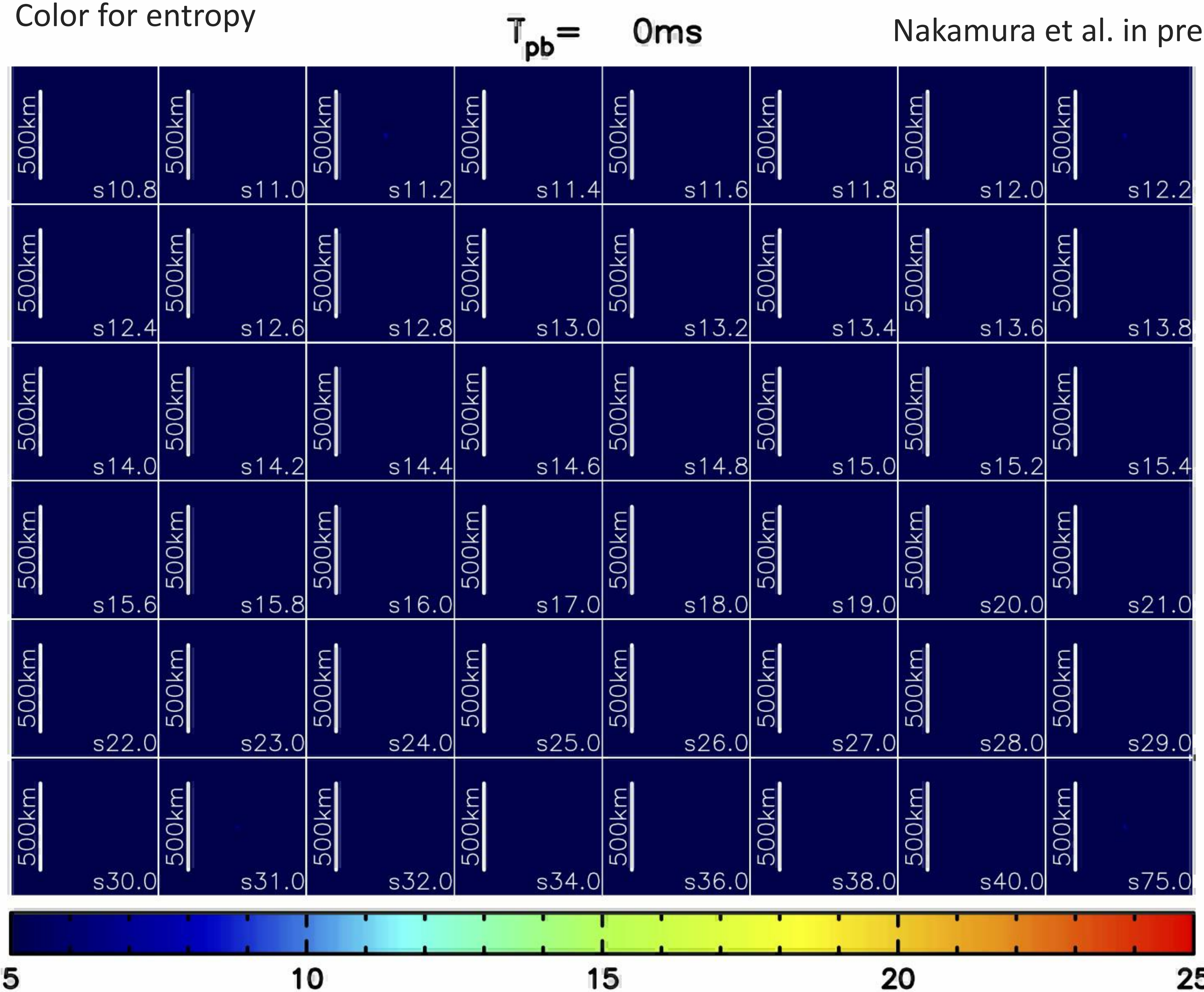
✓残りの親星は？

✓研究潮流

"2DでProgenitor hunting！"

Color for entropy

Nakamura et al. in prep



爆発しやすさの指標は何か！？

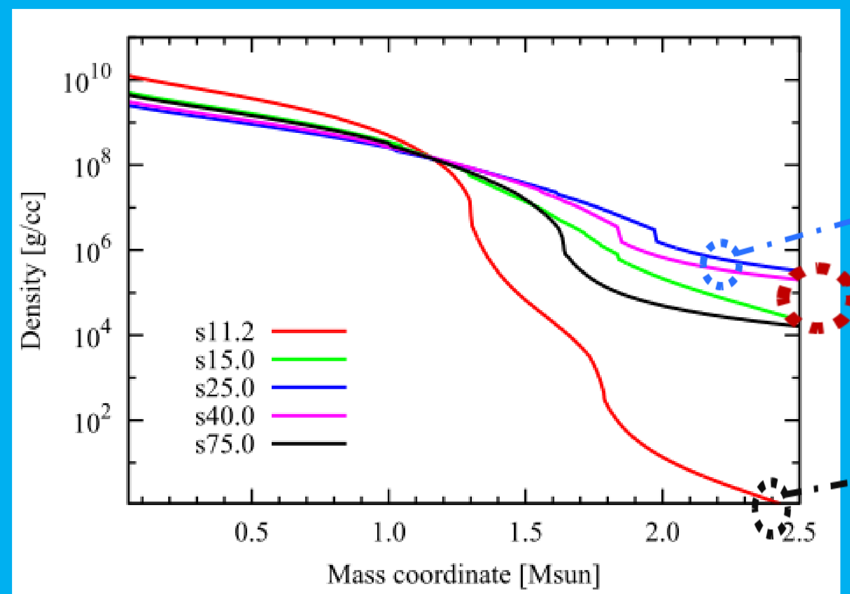
"Systematics" from 101 solar-metalicity models from Woosley et al. (2002)

Nakamura et al. in prep,
Hanke et al. in prep

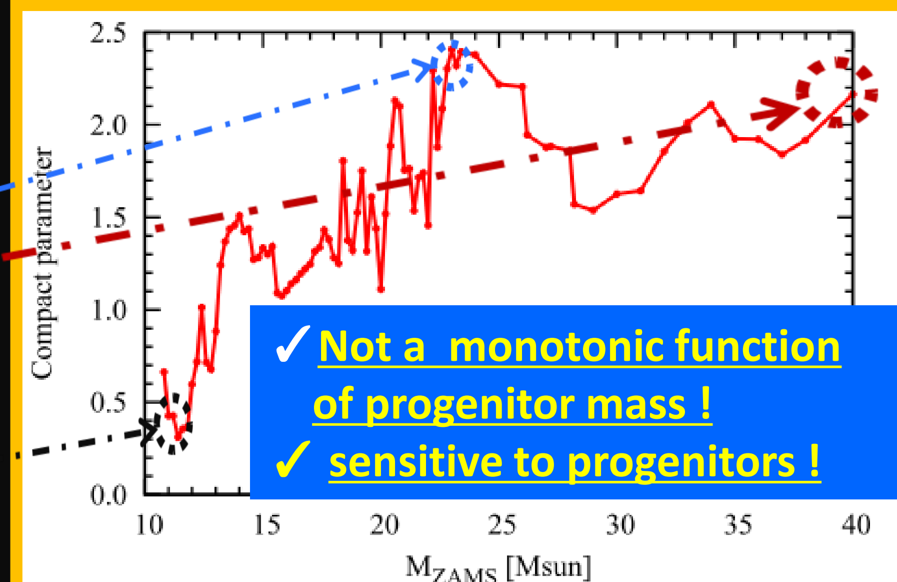
Key : "Compactness: M_{core} /R_{core} "

(see O'Connor & Ott '11, Ugliano et al. (2012) for 1D idealized models)

重力崩壊前の密度プロファイル



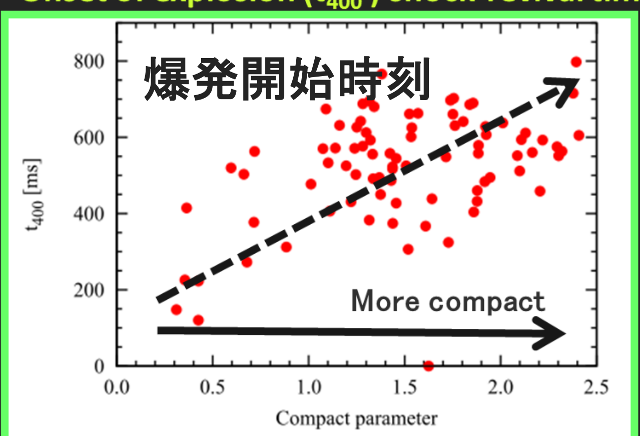
Compactness parameter



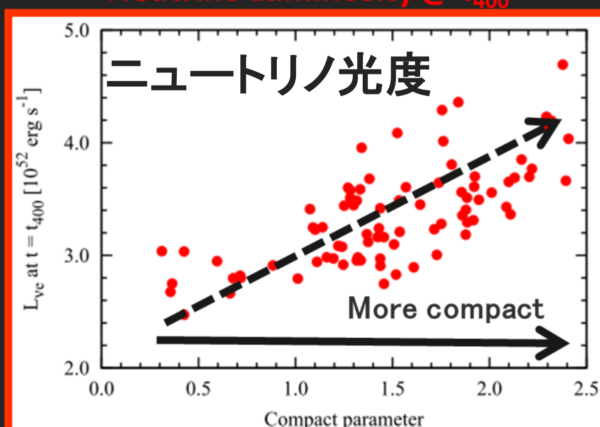
✓ Not a monotonic function of progenitor mass !

✓ sensitive to progenitors !

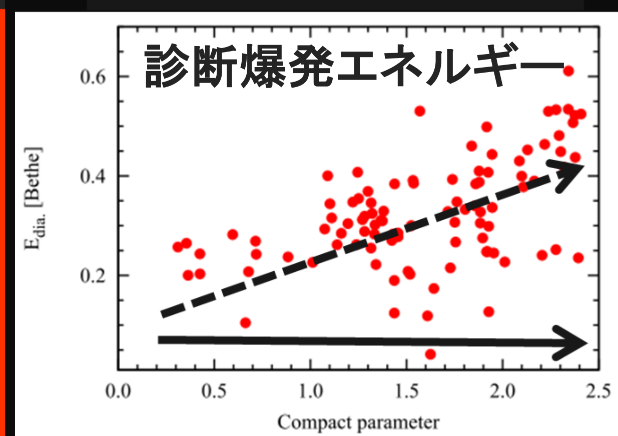
Onset of explosion (t_{400}) shock-revival time



Neutrino Luminosity @ t_{400}



"Diagnostic" explosion energy



爆発しやすさの指標は何か！？

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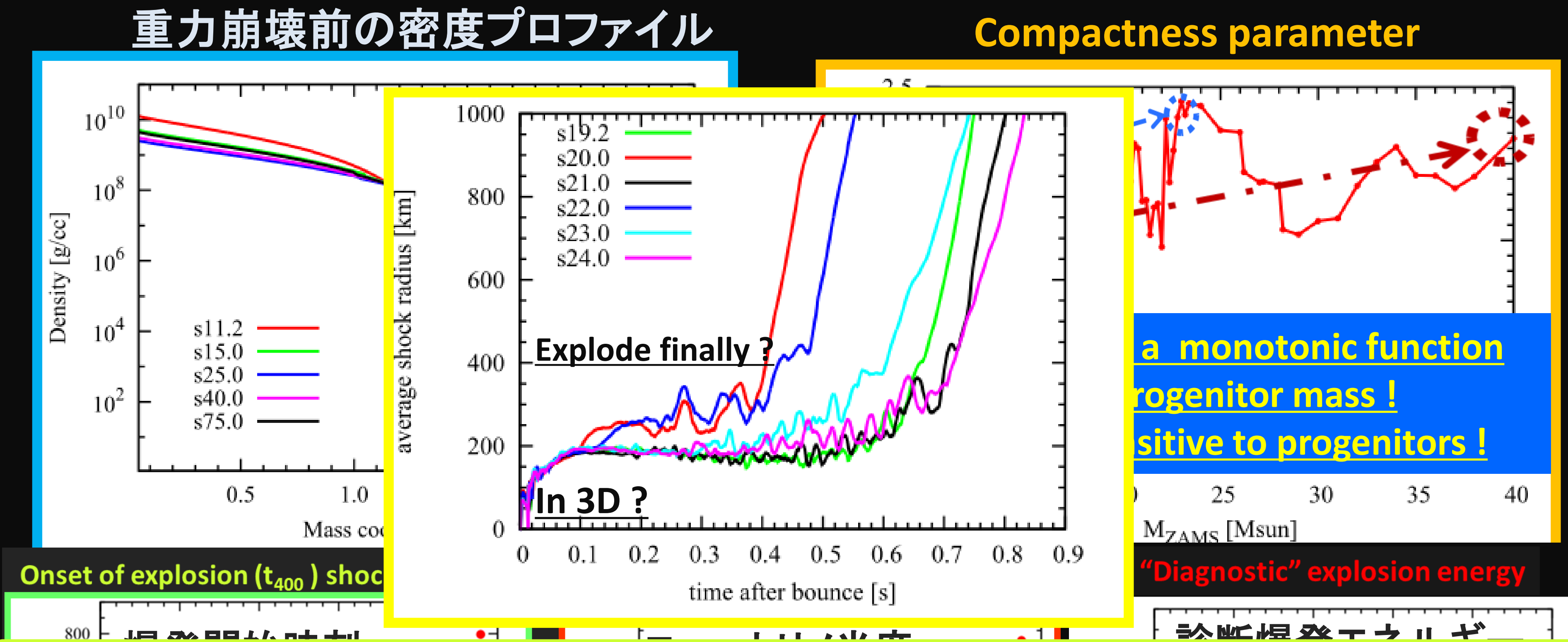


超新星メカニズム研究(ここまで) : Short summary

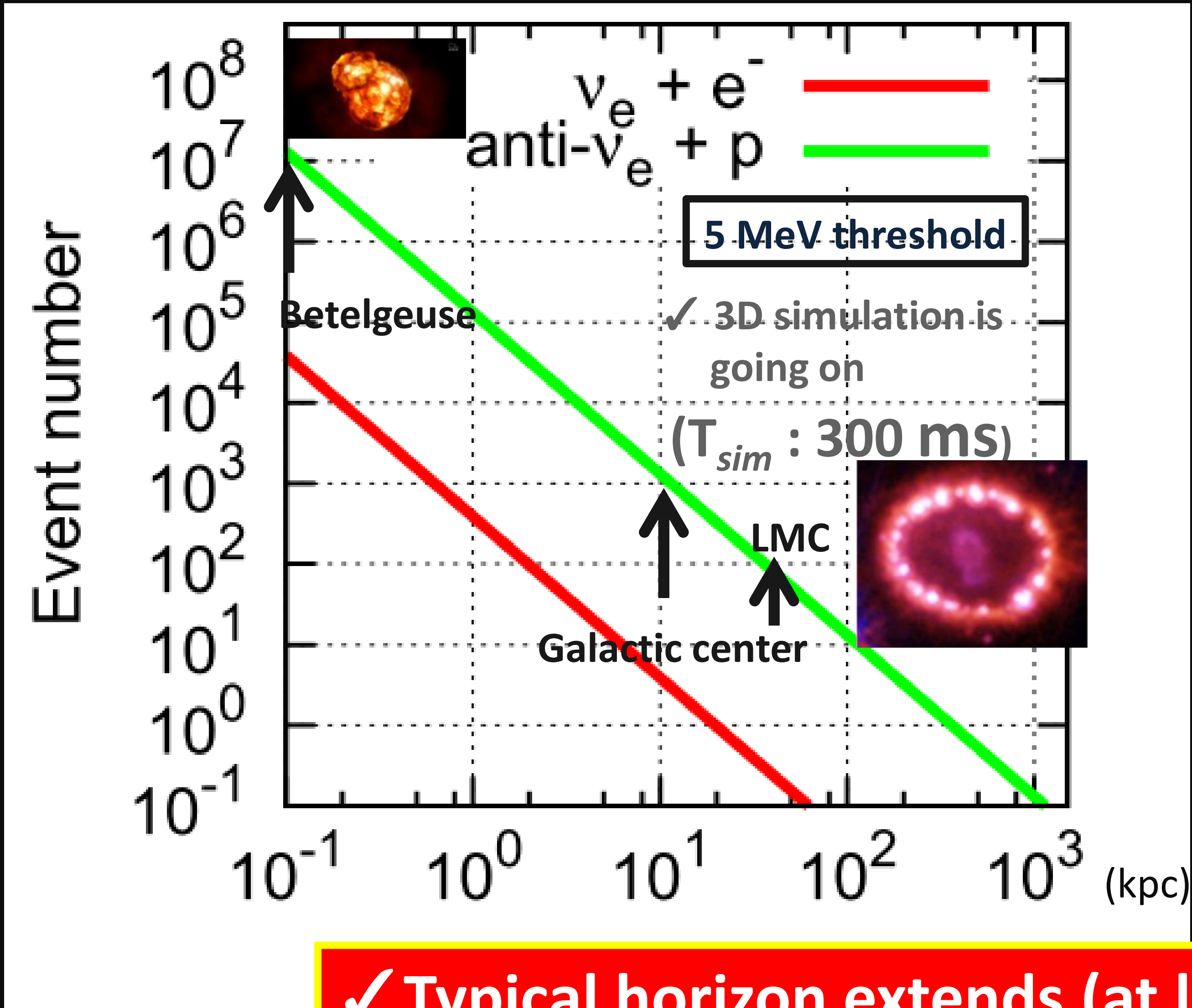
- ✓ No surprise from 2D exploding models ! (Detailed comparison will come soon.)
- ✓ Core-Compactness is a key to multi-D explosion systematics

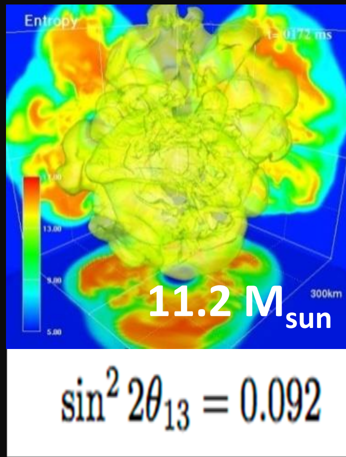
"Long-term" evolution : Needed to determine "final" E_{exp} (increasing), final M_{rem} (NS or BH), v_{kick}, M_{Ni}, L_{ν}, h_{GW} .... etc.

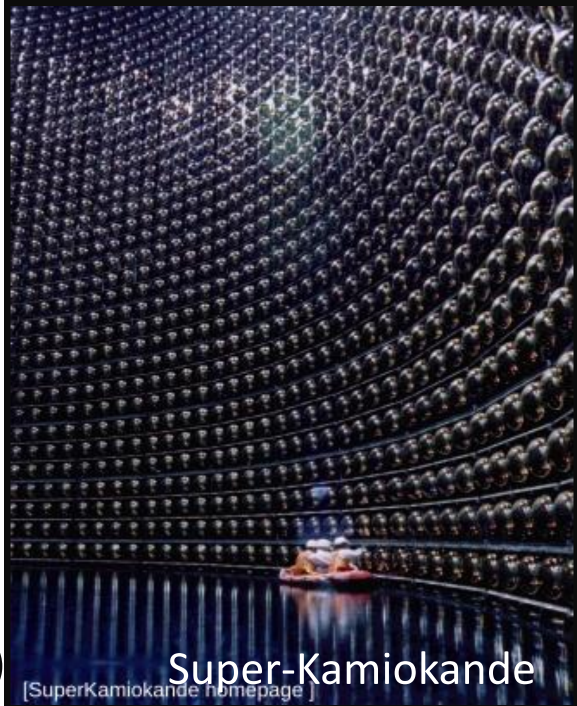
Neutrino signals from ab-initio 3D models : 11.2 M_{sun} (1/2)

(Kawagoe, Takiwaki , KK in prep based on Takiwaki et al. (2012 ApJ))

✓ **Inverted mass-hierarchy** (self-interaction: single-angle approx.)



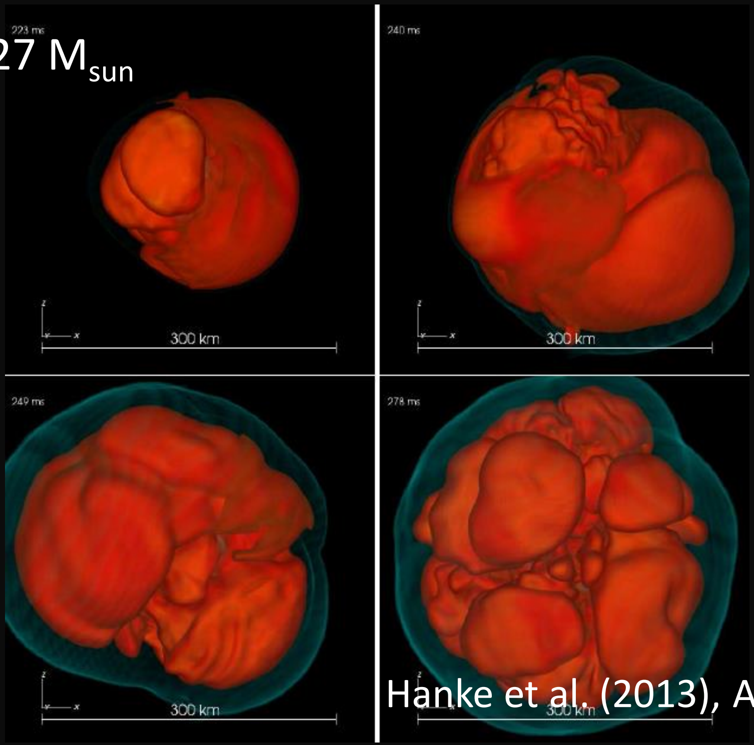




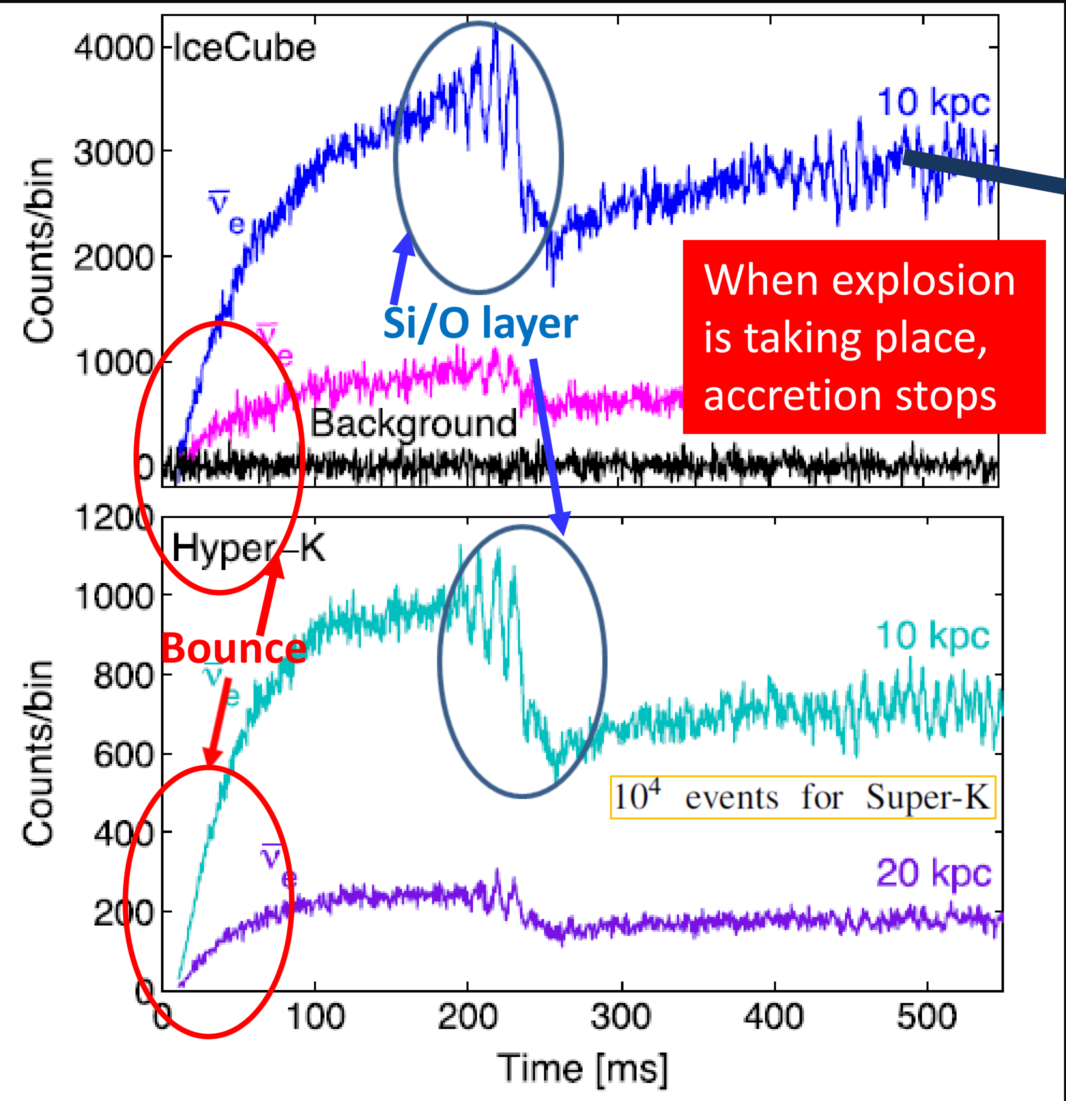
✓Typical horizon extends (at least) out to LMC.

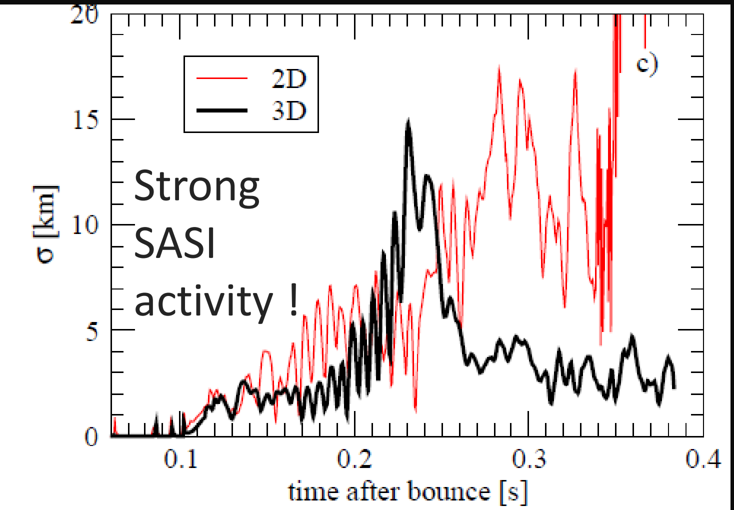
Neutrino signals from ab-initio 3D models : 27 M_{sun} (2/2)

Tamborra et al. (2013), PRL



Hanke et al. (2013), ApJ

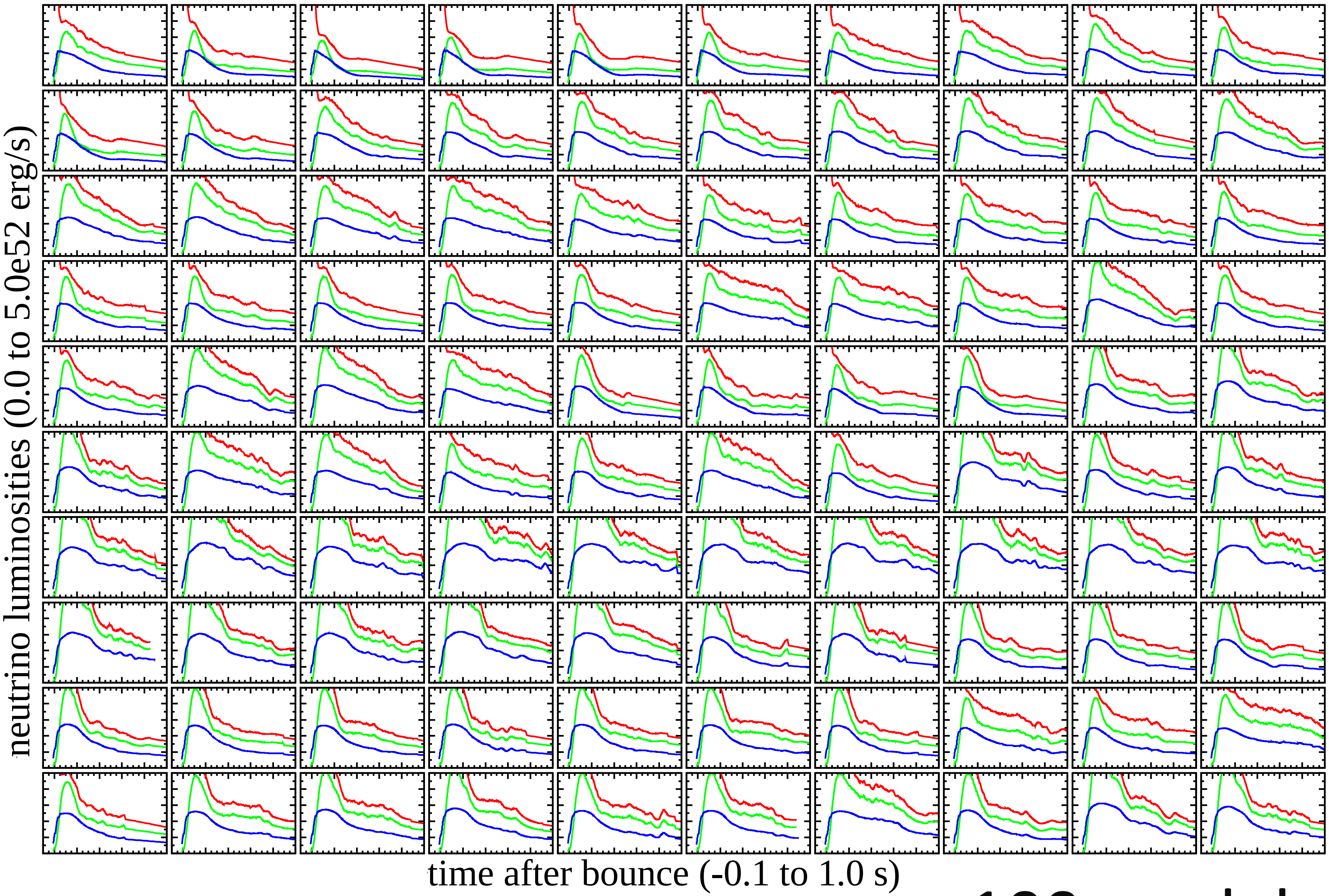




✓ **For a galactic source, we can learn much about SN physics ! (Bounce time, explosion onset/offset time, progenitor structure, SASI modulation timescales).**

Nakamura et al. in prep

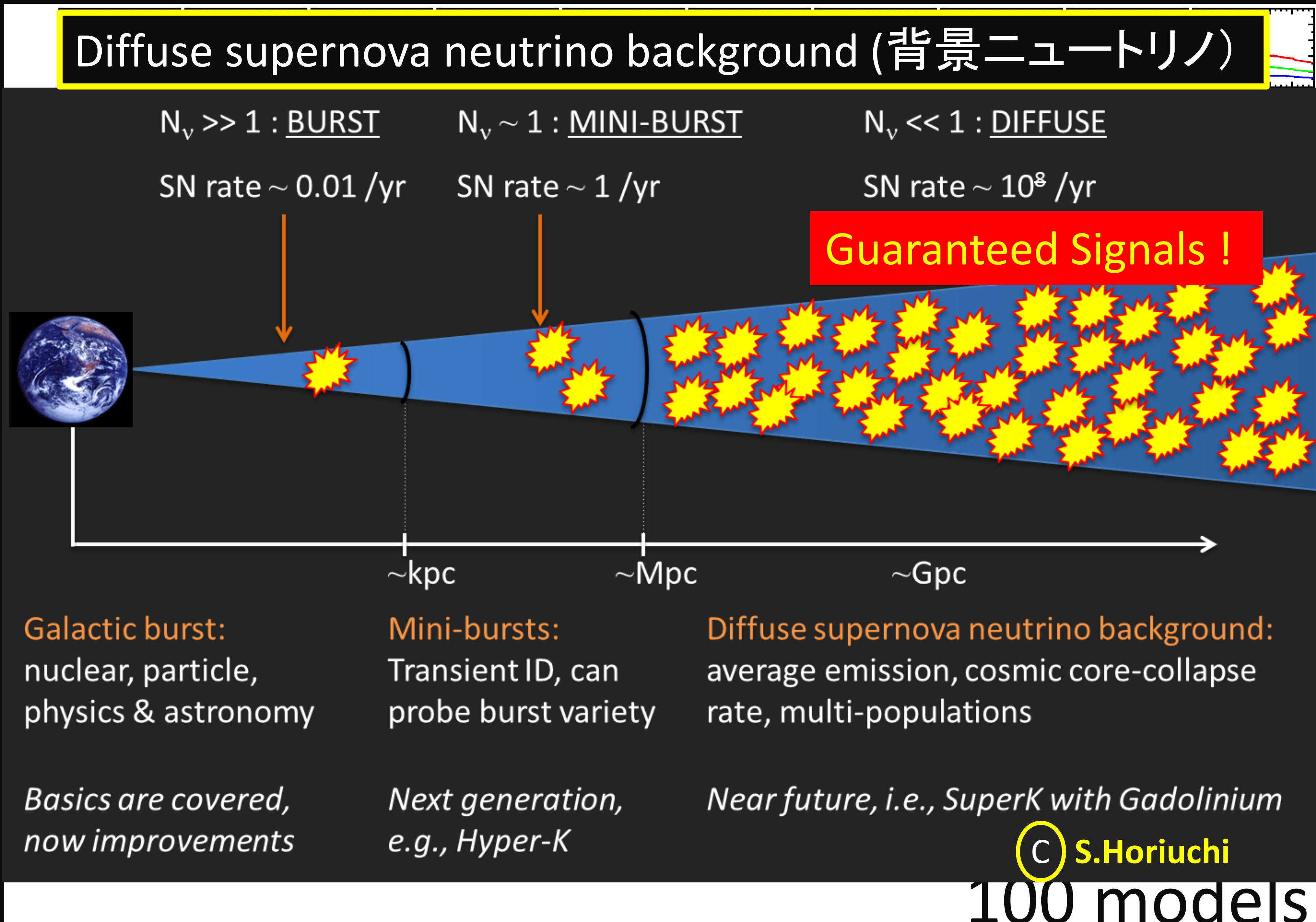
Neutrino Signals from Multiple 2D models



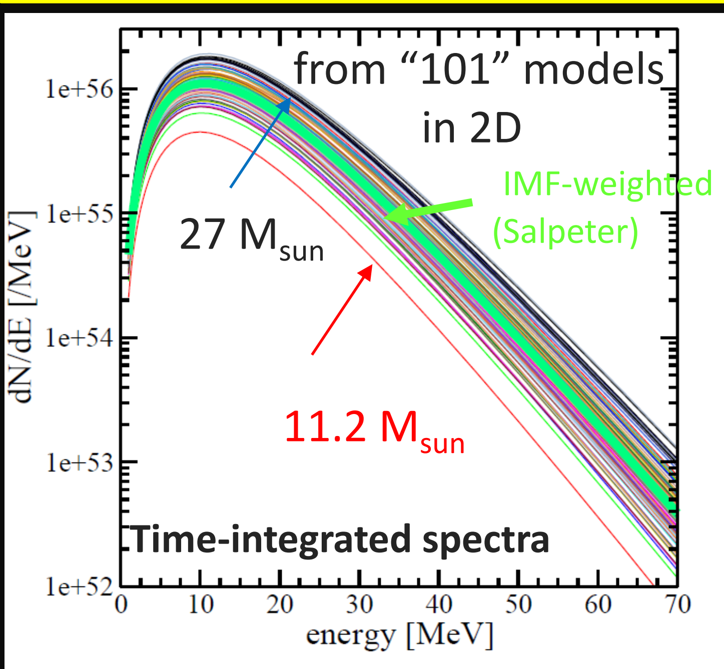
100 models

Nakamura et al. in prep

Neutrino Signals from Multiple 2D models

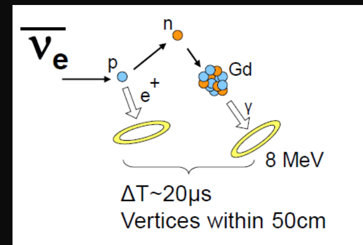


Diffuse supernova neutrino background (背景ニュートリノ)



$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu) \int R_{\rm CCSN}(z) \left|\frac{cdt}{dz}\right| (1+z) \frac{dN_\nu}{dE_\nu}[E_\nu(1+z)]\,dz$$

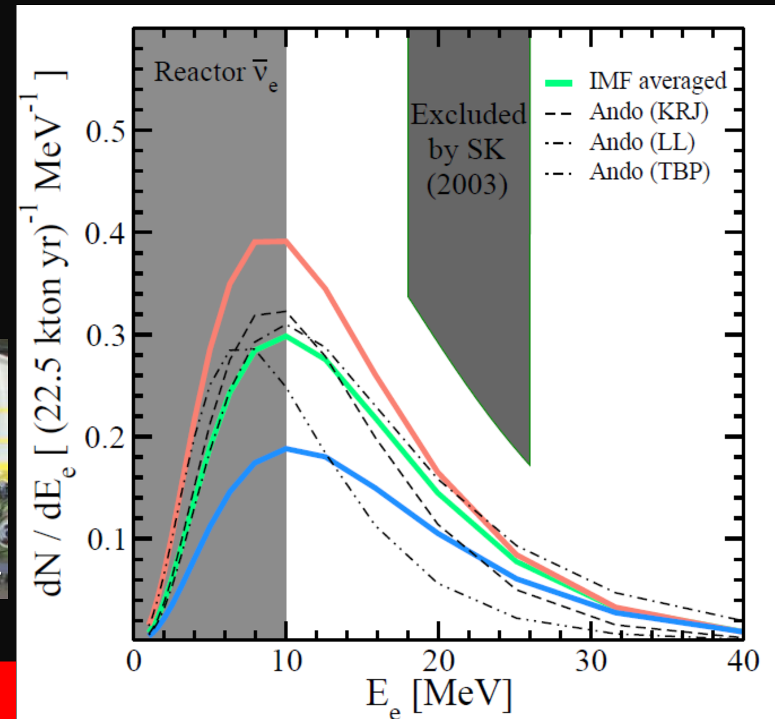
GAZOOKS !



Beacom & Vagins (2004)

EGADS

Flux spectrum @ SK + Gd



Horiuchi et al. (2014), in prep

Spectrum	Current Super-K [/10yr] E_+ = 18 – 26 MeV	With Gd upgrade [/10yr] E_+ = 10 – 26 MeV
2D multiple models	9.40	29.2
5 MeV	9.90	30.5

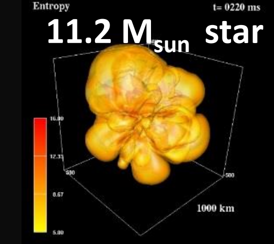
Diffuse supernova neutrino background (DSNB) : "guaranteed" signals !

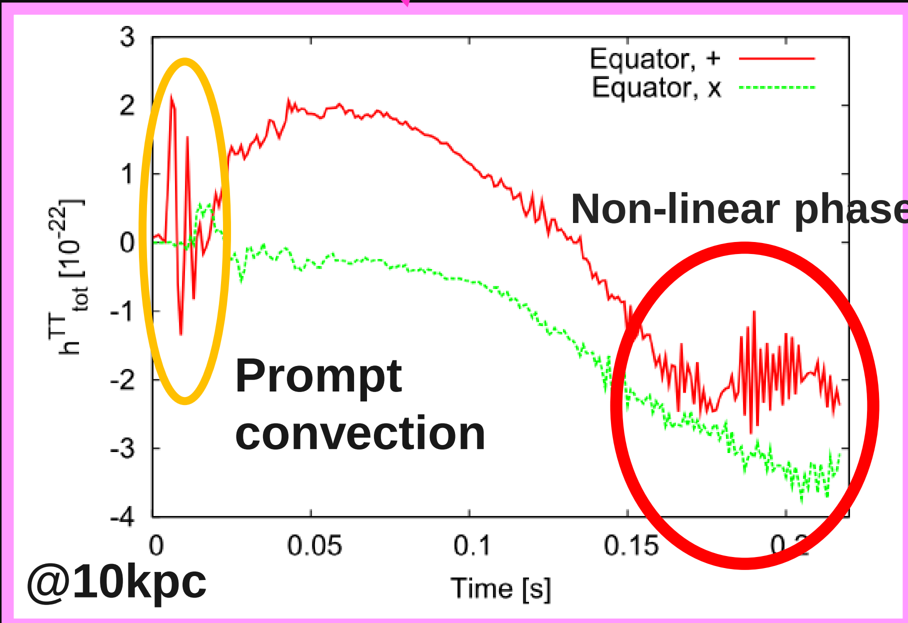
✓ its flux is close to Super-Kamiokande's ability !

✓ GAZOOKS & EGADS (See Koshio-san's talk !) are indispensable for the detection !

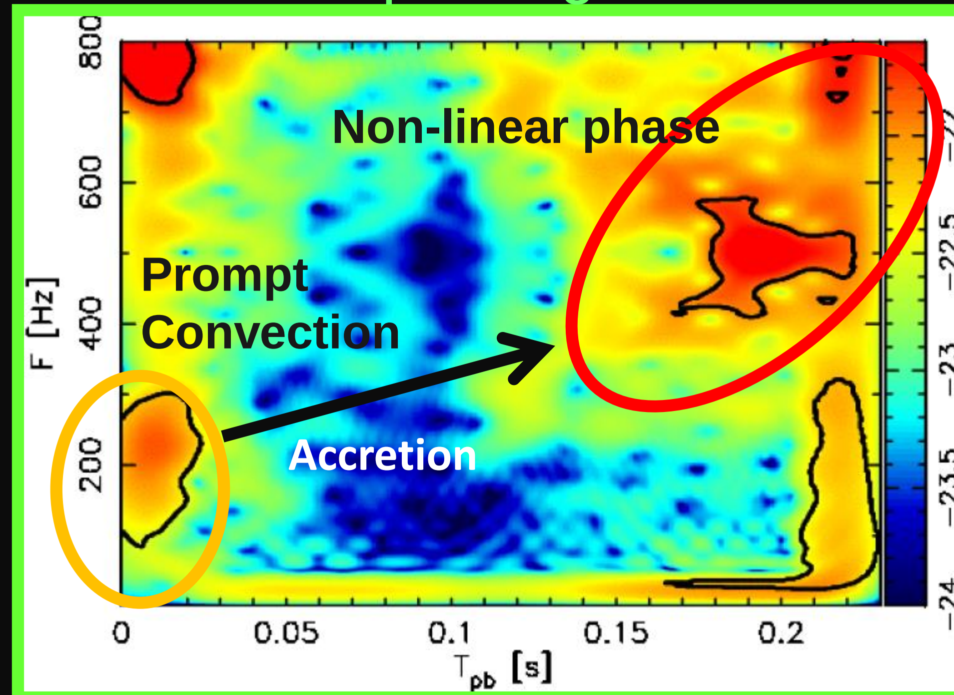
Gravitational waveform from a self-consistent 3D model

Takiwaki & KK in prep.





GW spectrogram



Summary on GWs from CCSN:

✓ Waveforms have no template features :stochastic explosion process

✓ Three generic GW features in neutrino-driven explosion models:

1. Prompt-convection phase : within ~20 ms post-bounce
2. Non-linear phase (SASI, Convection) : Plumes hit the PNS surface (< ~1 s)
3. Explosion phase : shock launched (> ~0.6 s(?))

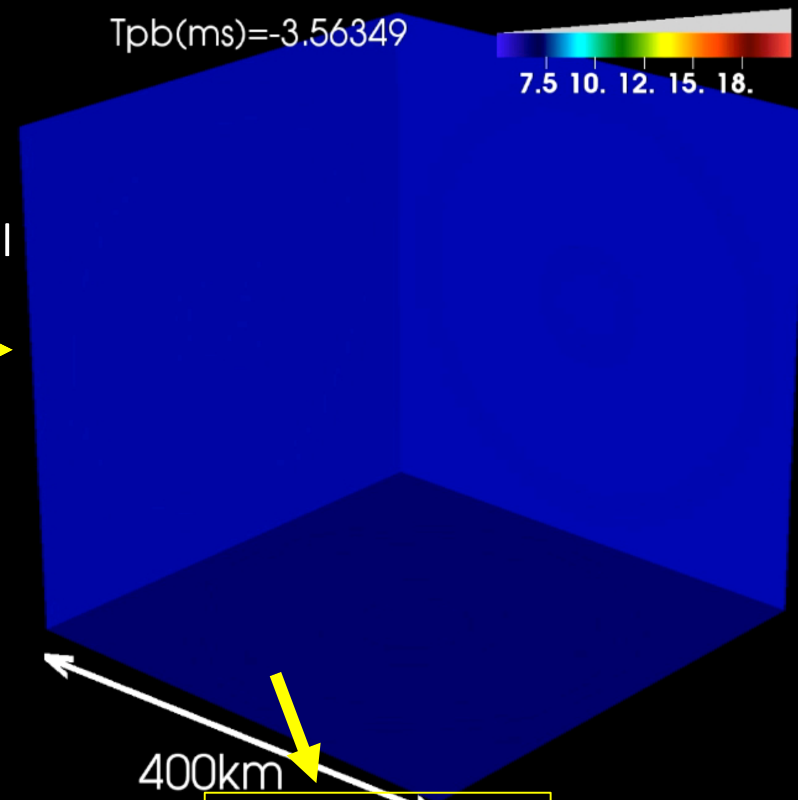
(e.g., Ott (2009), Kotake (2013) for reviews)

"General Relativity (GR) important !

3D full GR simluations with 3 flavor gray neutrino transport

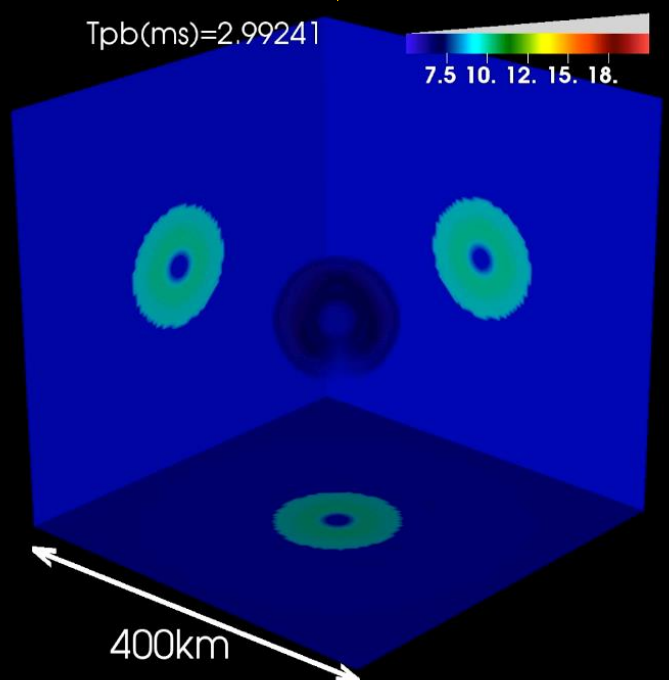
(Kuroda, Takiwaki and KK, 2012, ApJ, 2014, PRD)

27 M_{sun} model
from WHW02



SASI-driven

11.2 M_{sun} model
from WHW02



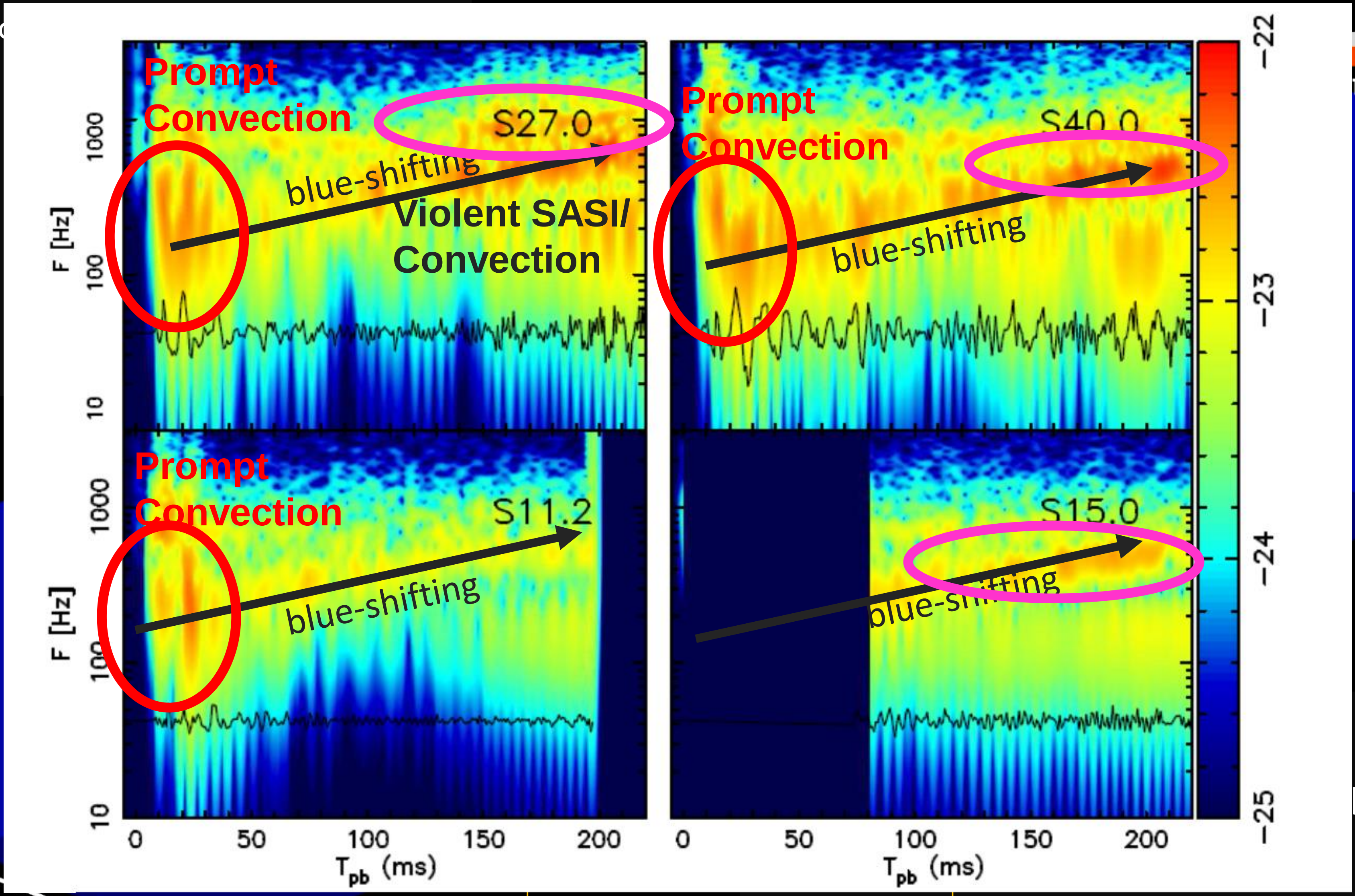
Convection-driven

Kuroda et al. (in prep)

"General Relativity (GR) important !

3D full GR simluations with 3 flavor gray neutrino transport

(Kur



prep)

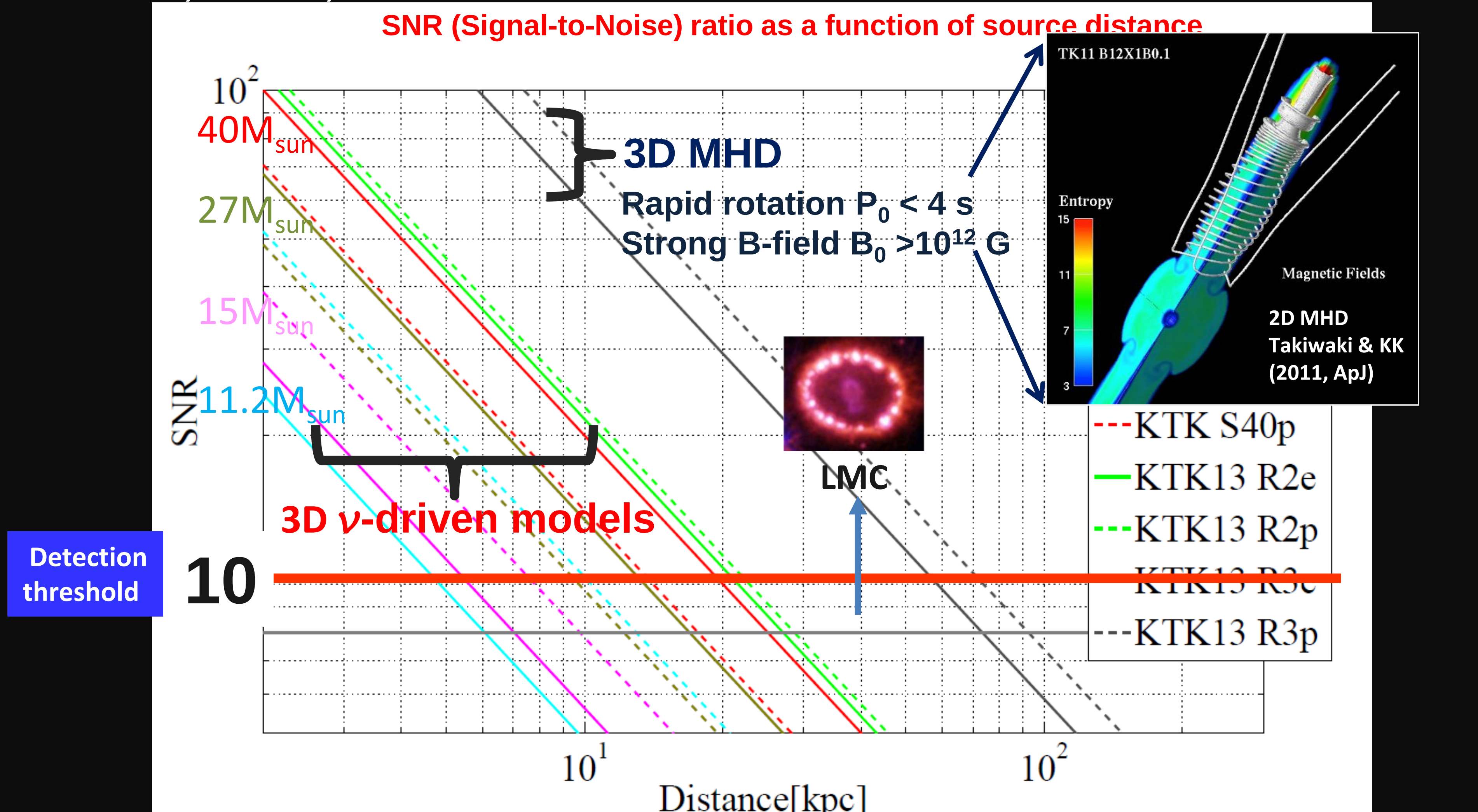
✓ "Excess power" blue-shifts with time ⇒ Traces the activity of SN engine !

(see, e.g., 2D: Murphy+(09), B.Mueller+(13), Yakunin+(09), e.g., Kotake (2013) for review)

Identifying SN mechanisms from Coherent Network Analysis

Hayama, Kuroda,Takiwaki & KK (2014a,b) in prep

✓LIGOx2, VIGRO, KAGRA

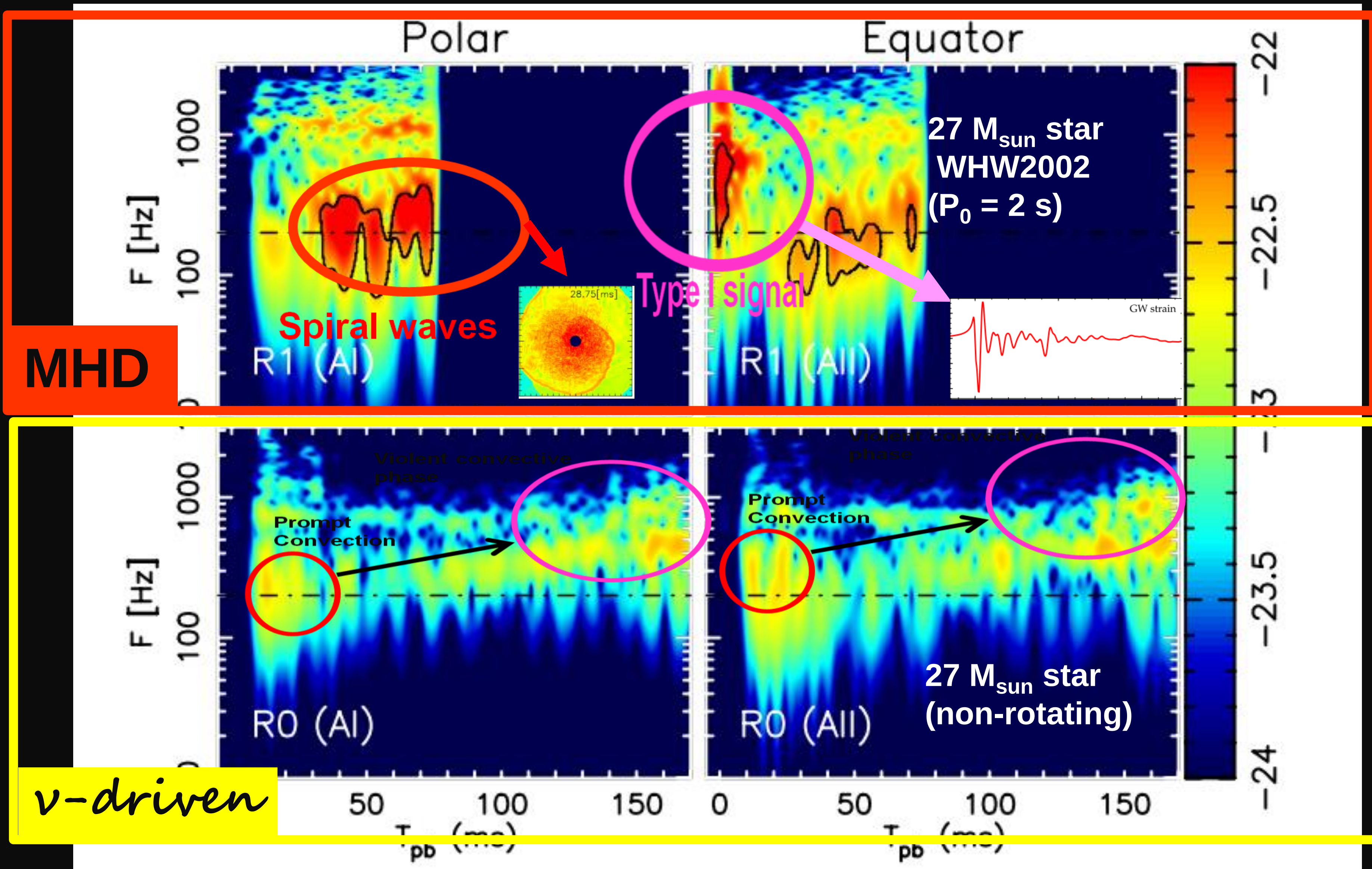


✓Method robust for ν-driven mechanism out to a few kpc (better for high compact).

✓Can identify for MHD mechanism out to LMC (50kpc).

Comparison between MHD vs. ν-driven mechanism

- Spectrogram between neutrino-driven vs. MHD-driven mechanism : <u>different !</u>



Kuroda et al. in prep

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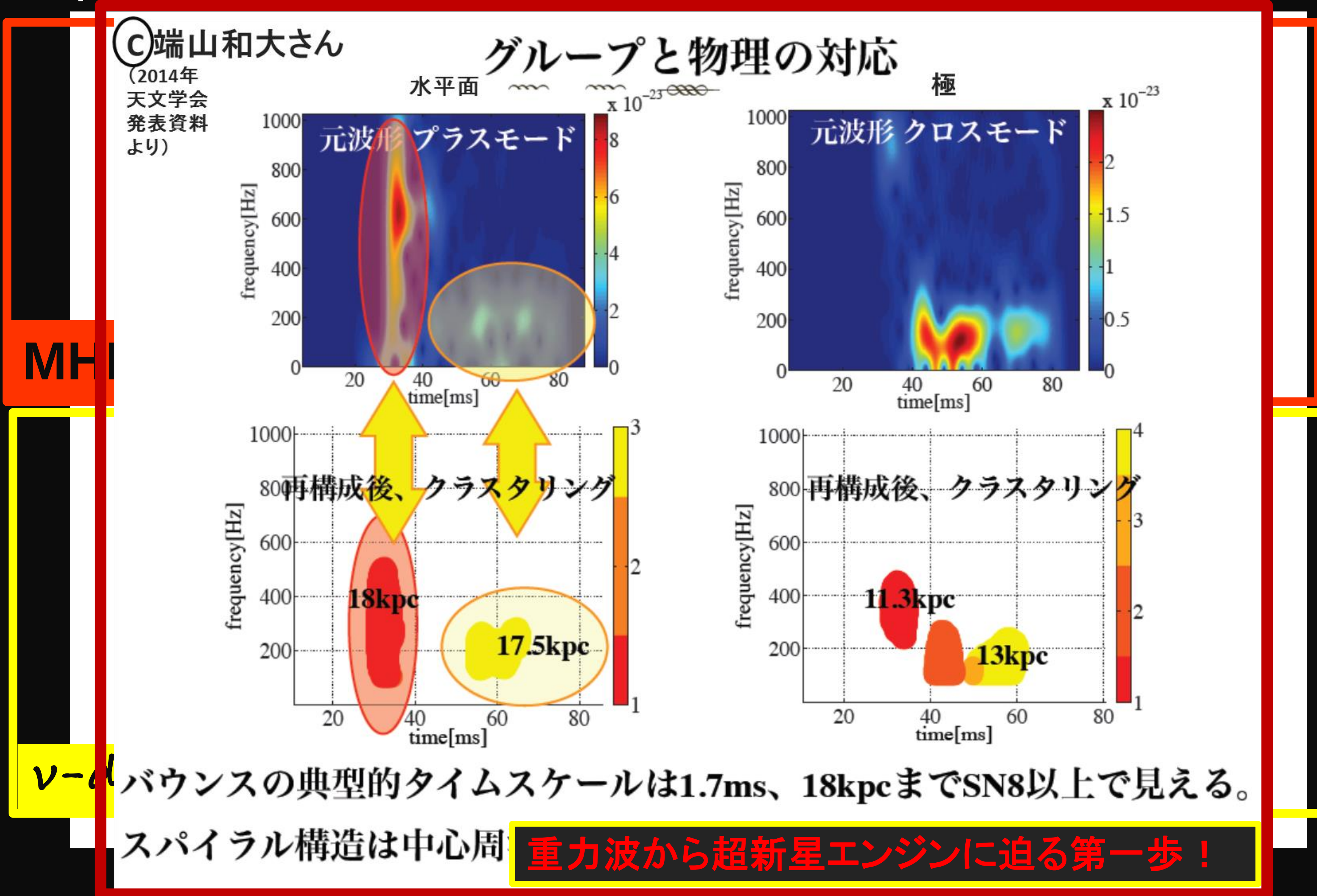
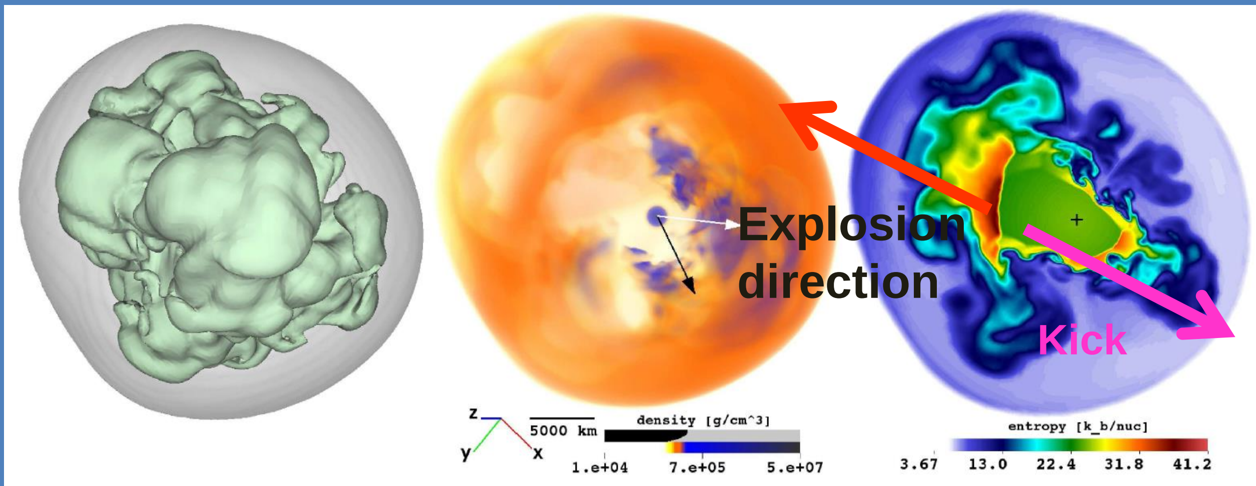
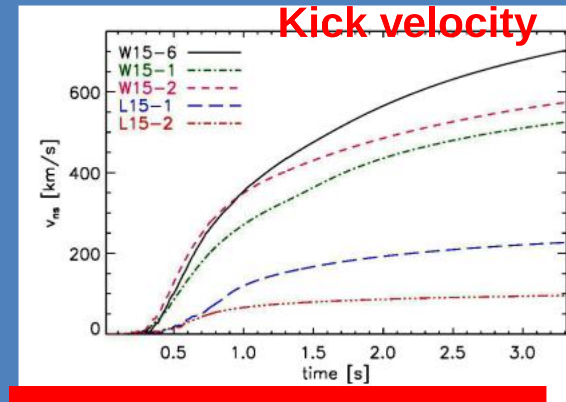


Final Goals of Core-collapse SN Modeling

✓Origin of Kick: Wongwathanarat et al. (2010, 2013) A&A ApJL



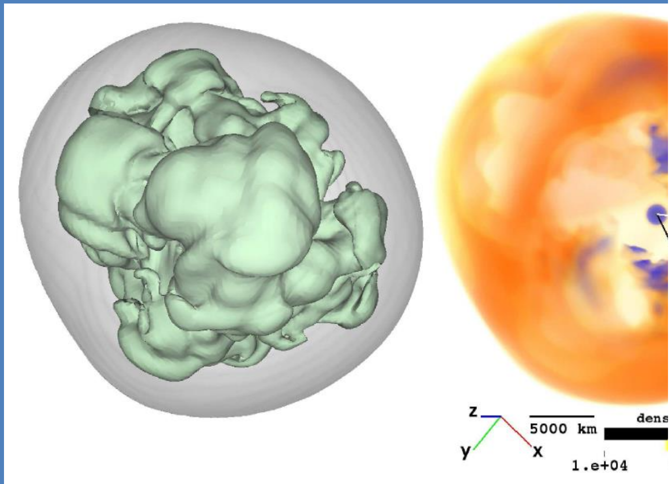


✓ Heavy element synthesis:
Opposite direction of
the kick (Cas A?)

✓Mixing instabilities in 3D for light-curve modeling: Wongwathanarat et al. in prep.

Final Goals of Core-co

✓Origin of Kick: Wongwathana



✓Mixing instabilities in 3D fo

Mixing Instabilities in 3D SN Models

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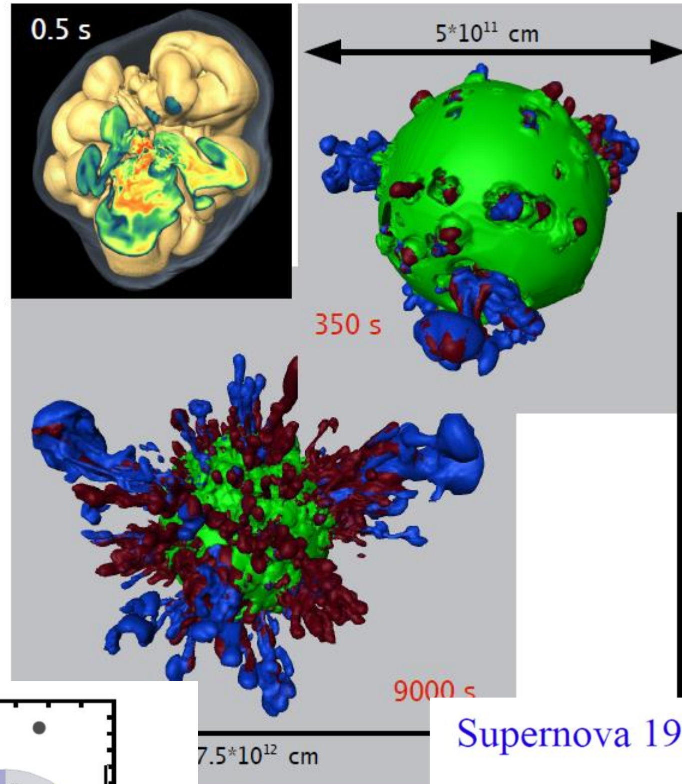
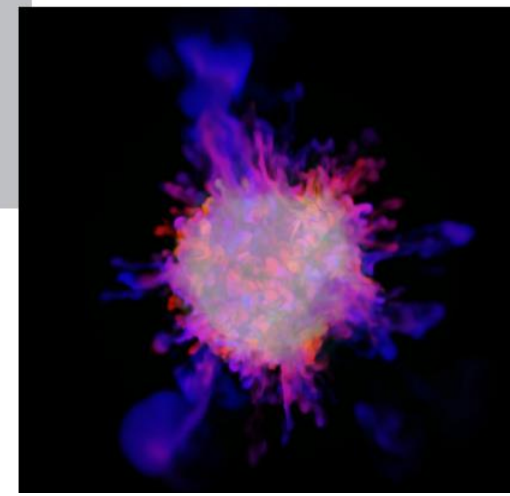
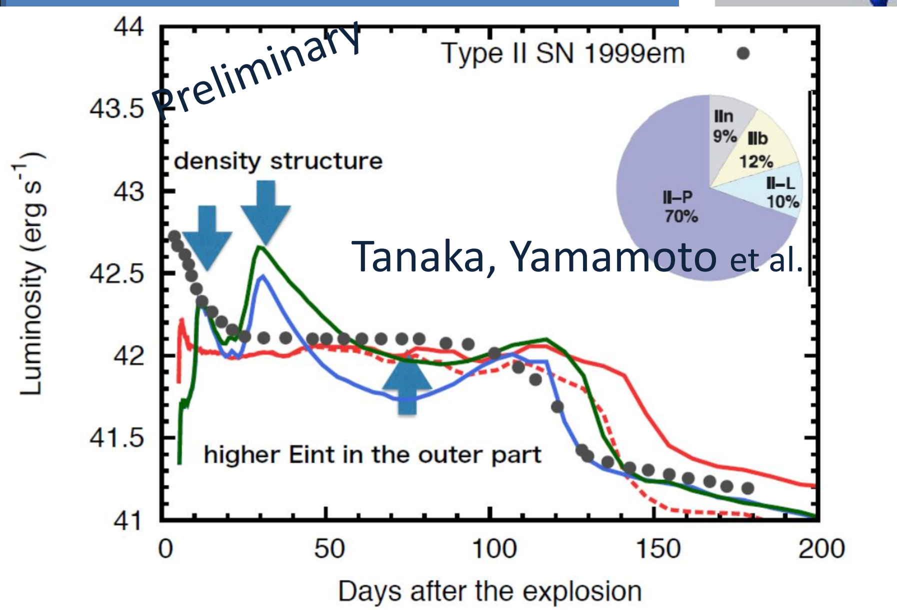


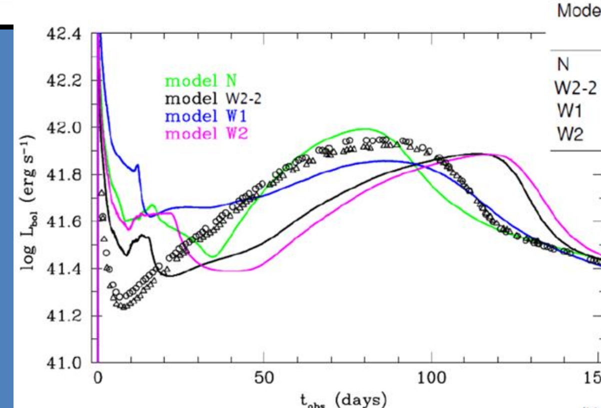
green: carbon
red: oxygen
blue: nickel





Tanaka, Yamamoto et al.

Supernova 1987A: Bolometric Lightcurves



Model	pre-SN	E (10^{51} erg)
N	Nomoto	1.68
W2-2	Woosley	1.01
W1	Woosley	2.62
W2	Woosley	1.16

$M_{Ni} = 0.0765 M_{\odot}$. Circles and triangles are the SN 1987A observations.

(Utrobin, Wongwathanarat, Janka, Müller, in preparation)

Summary

☆Explosion mechanisms:

✓ **"Compactness" is a key** to characterize diversity of neutrino-driven models.

✓ **Lots of exploding models** reported in 2D.

✓ First example of 3D models trending towards explosions "3D modeling" has just begun.

☆**GW & neutrino signals**:

✓change stochastically with time:

✓ **Spectrograms** imprint SN post-bounce activity.

✓Coherent Network analysis, Multi-variant method proposed: robust for neutrino mechanism out to 10 kpc, and for MHD mechanism out to LMC (model-dependent).

☆**Electromagnetic-wave signals**:

✓kick, explosive nucleosyntheis, light-curve modeling from **self-consistent model** just started.

Many thanks !

Multi-messengers signatures being unveiled from first-principle 3D models:

Coincident analysis should be important !