Multi-messengers from Core-Collapse Supernovae

"Multi-Dimensionality as a key to bridge theory and observation"

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with Tomoya Takiwaki(NAOJ), Yudai Suwa(Kyoto)
Matthias Liebendoerfer(Basel Univ.), Katsuhiko Sato(IPMU)

Astrophysical transients: Multi-messenger-pr
of Nuclear Physics @ INT July, 2011

ADS survey on “**Multi-messenger**” as of yesterday

(1)Horowitz, C. J. (2011) "Multi-messenger observations of neutron rich matter“, arXiv, arXiv:1106.1661-.
(2)Manuela Vecchi for the ANTARES Collaboration (2011) "ANTARES: Status, first results and multi-messenger astronomy", arXiv, arXiv:1105.6242-.
(3)Ribordy, M. and IceCube coll, f. t. (2011) "Multi-Messenger Astrophysics with IceCube", arXiv, arXiv:1101.1187-.
(4)Pradier, T. and Antares Collaboration (2010) "The Antares neutrino telescope and multi-messenger astronomy", CQGra, 27, 194004-.
(5)Smith, M., Gehrels, N., Cowen, D., Nousek, J., Franckowiak, A., and Taboada, I. (2010) "Multi-messenger Astrophysics with Swift and IceCube", APS..APR., 1033-.
(6)Shawhan, P. (2010) "Multi-Messenger Astronomy and Astrophysics with

- ✓Please keep in mind what I’m going to talk today may contain a number of premature (speculative) proposals!
- ✓In my talk, I put together our best knowledge of current theoretical predictions of SN multi-messengers.
- ✓ Comments are welcome, and let’s discuss future directions!

(10)Halzen, F. (2003) "Multi-Messenger Astronomy:. Cosmic Rays, Gamma-Rays and Neutrinos", tsra.symp, 117-131.

Outline

✓ **General introduction**

- what is the "headache" to SN modelers over 40 years?

✓ **Current Supernova Paradigm**

- based on multi-D supernova simulations

✓ **Multi-messengers from Supernova Explosions**

- Gravitational Waves, Neutrino Signals, and photons

✓ **Summary and Perspectives**

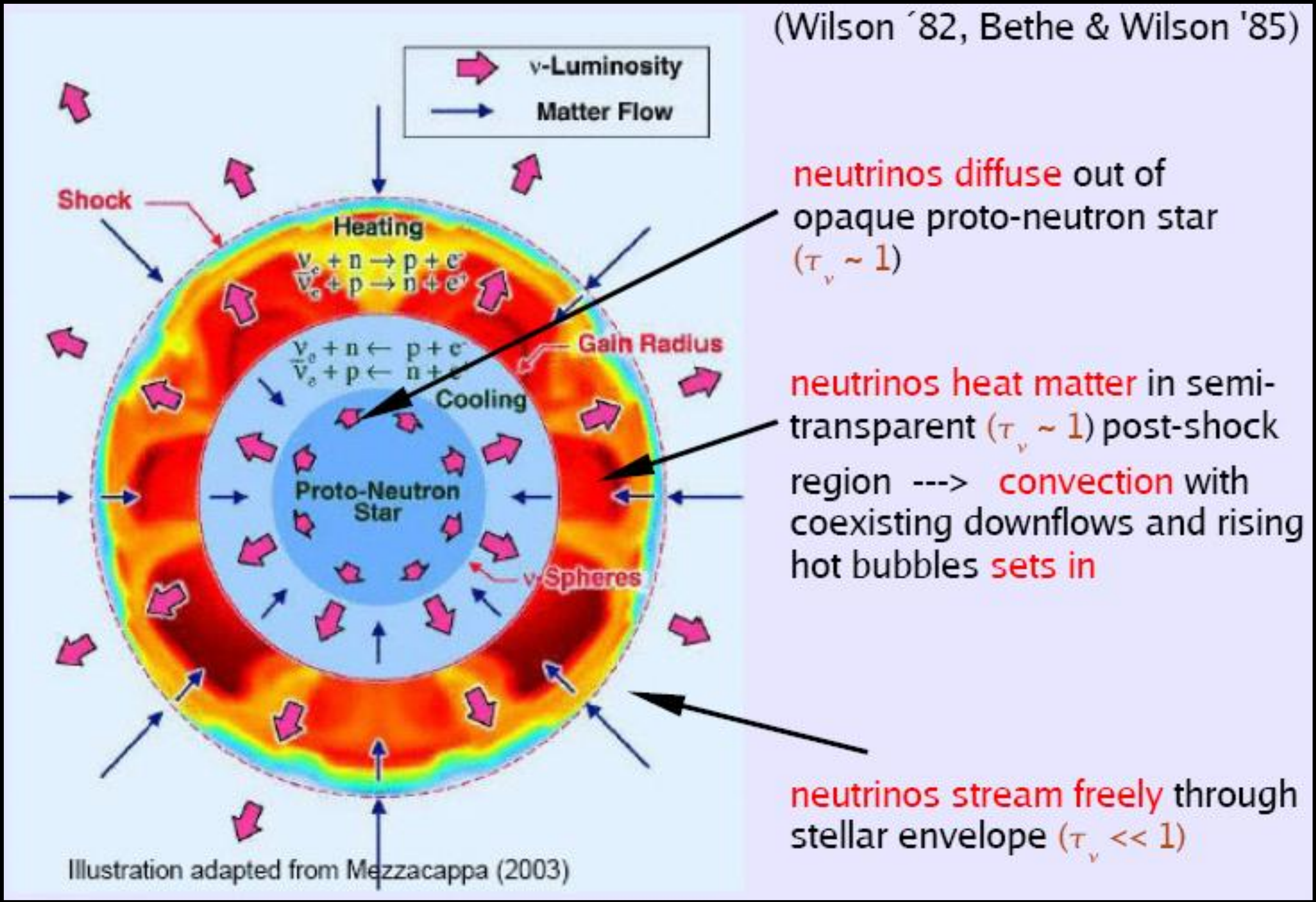
- how we can learn the mechanism of the engine from multi-messenger observations ?

The supernova shock reaches to the stellar surface somehow… with its kin. E of 10^{51} erg !

But… we don't understand the mechanism of explosion over these 40 years ! (the supernova problem)

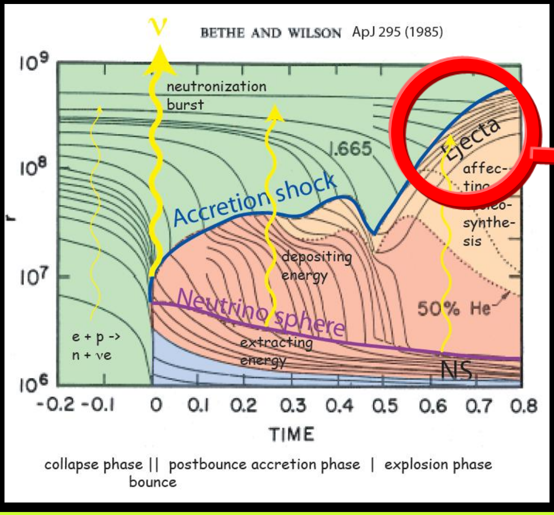
Neutrino heating mechanism

- Best-studied and most promising way to explode stars(> $10M_{sun}$).

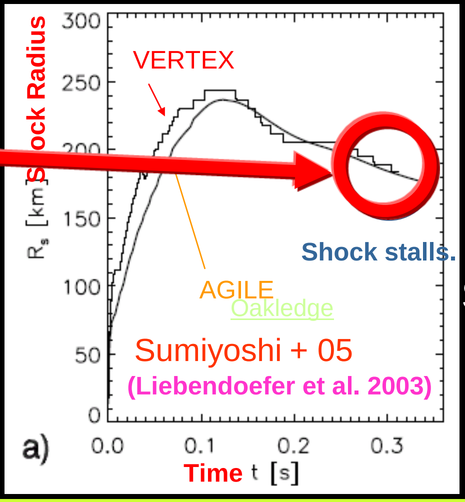


Looking back 20+ Years of Modeling & Theory

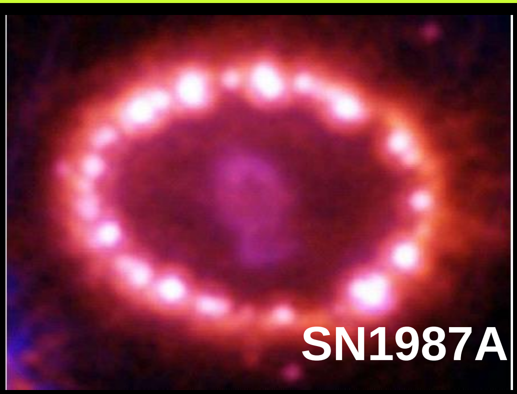
- Neutrino-heating mechanism (Wilson '82,Bethe'85) in spherical symmetry fails to explode massive stars with iron cores.



~20 years



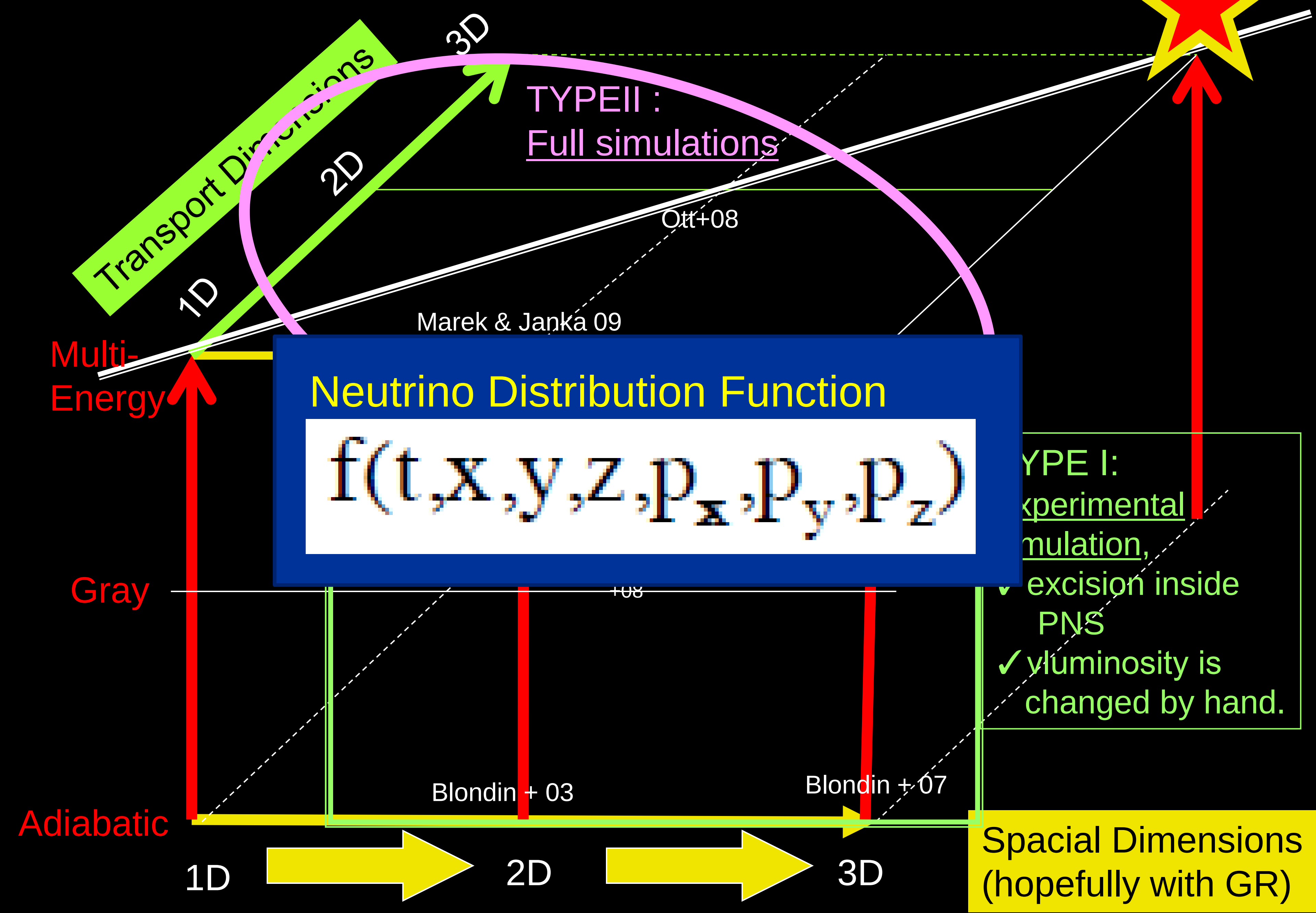
Doing-best simulations, but..



- CC SNe are generally aspherical. (Wang+.01,02)
- Multidimensional explosions are favorable for reproducing the synthesized elements. (Kifonidis+03,Hungerford+05,Maeda-Mazzali+08…)

Multidimensional modeling is crucial !

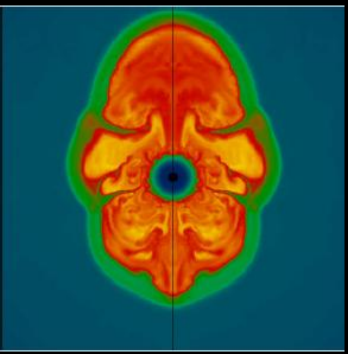
Requirement of core-collapse supernova simulation ?



A la carte of recent 2D exploding models

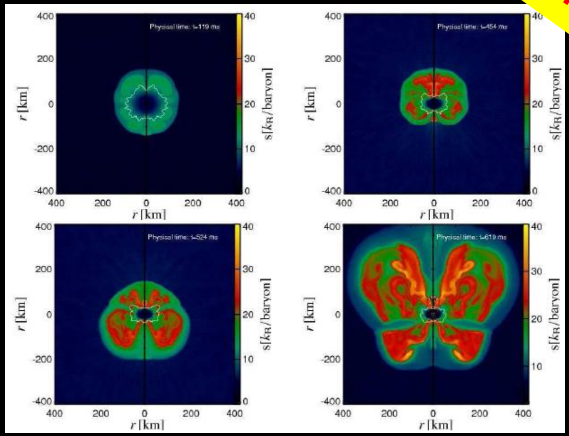
Type II

From Garching simulations (MPA),



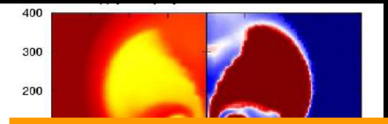
✓ non-rotating 11.2 Msun star (Buras et al. (2006))

✓ mildly-rotating 15 Msun star (Marek & Janka 2009)



✓ Rapidly-rotating 13 Msun star (Tokyo)

Suwa, Kotake, Takiwaki, Whitehouse, Liebendoefer, Sato (2010)



Time evolution of explosion energy

From Oak Ridge simulations

☆ **Fundamental problems** remained !

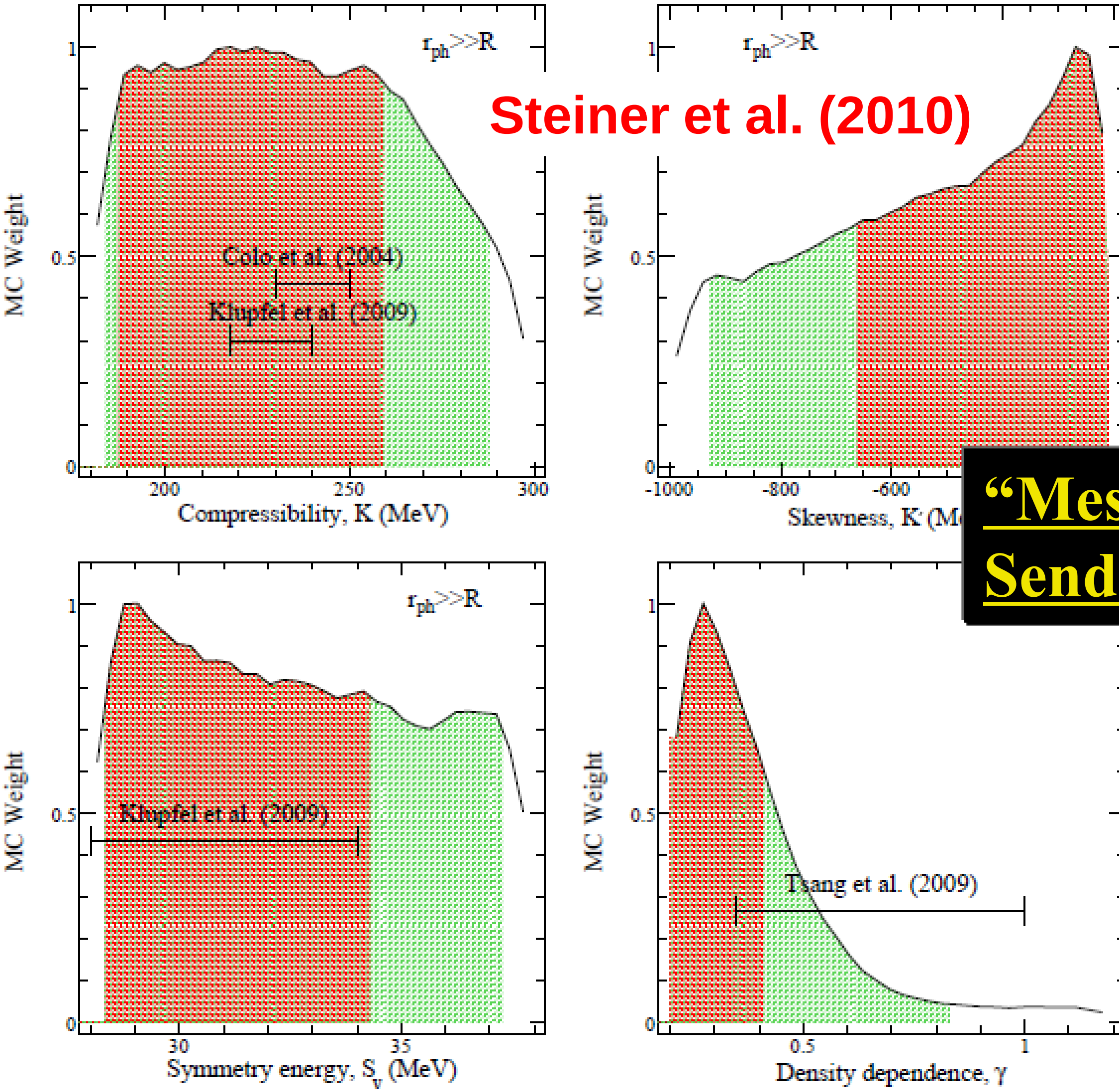
✓ **The obtained explosion energies are typically underpowered by 1 or 2-orders-magnitudes** compared to observation (SN kinetic energy of 10^{51} erg).

✓ All of the exploding models assume a very soft nuclear EOS (K=180 MeV).

onal SN simulations

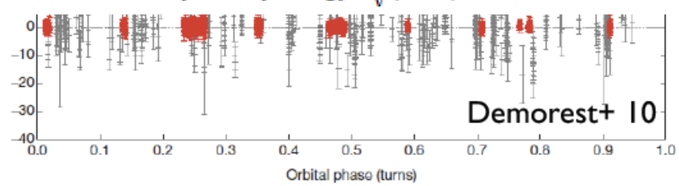
(2009), Furusawa+(2011))

Steiner et al. (2010)

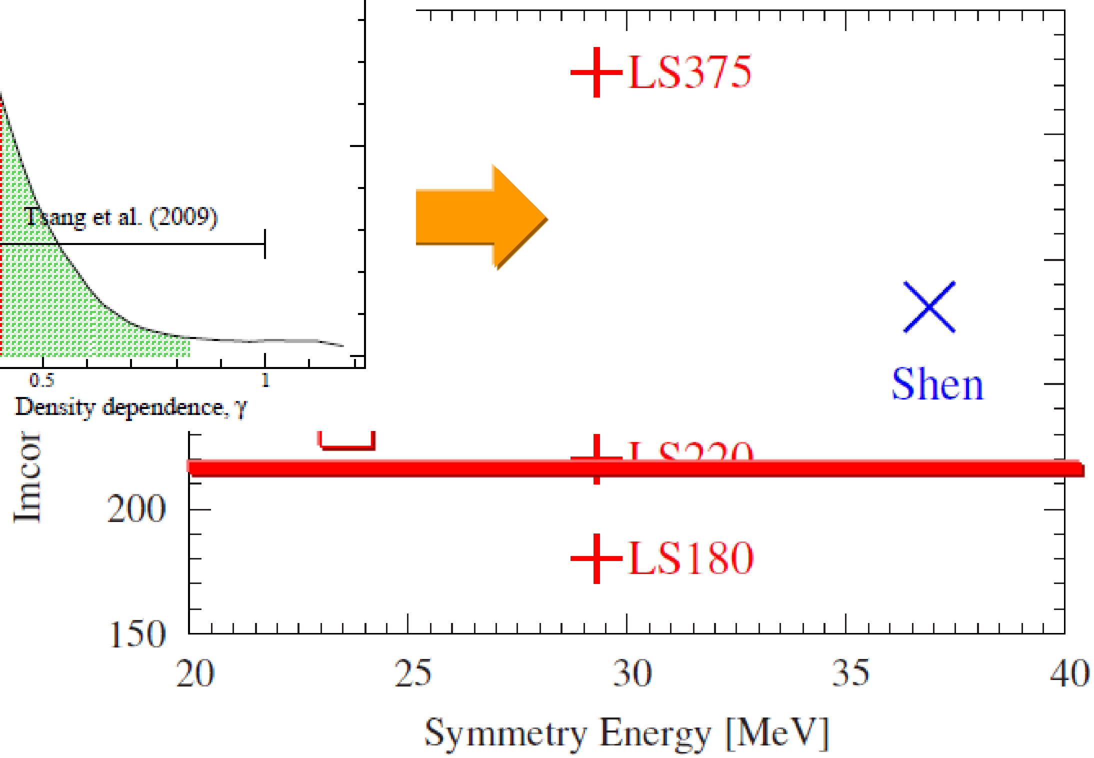


“Message to nuclear theorists”

Send email when you ….!



M_{ns} ~(1.97±0.04)$M_\odot$



2D model with K=220MeV LS EOS

Suwa, Kotake, Takiwaki, Liebendoefer, Sato in preparation

Type II

✓ $15M_{sun}$ progenitor by Woosley et al. (2002)

(the IDSA for the spectral neutrino transport: a la Liebendoerfer + 09)

✓ After bounce, the bounce shock stalls.

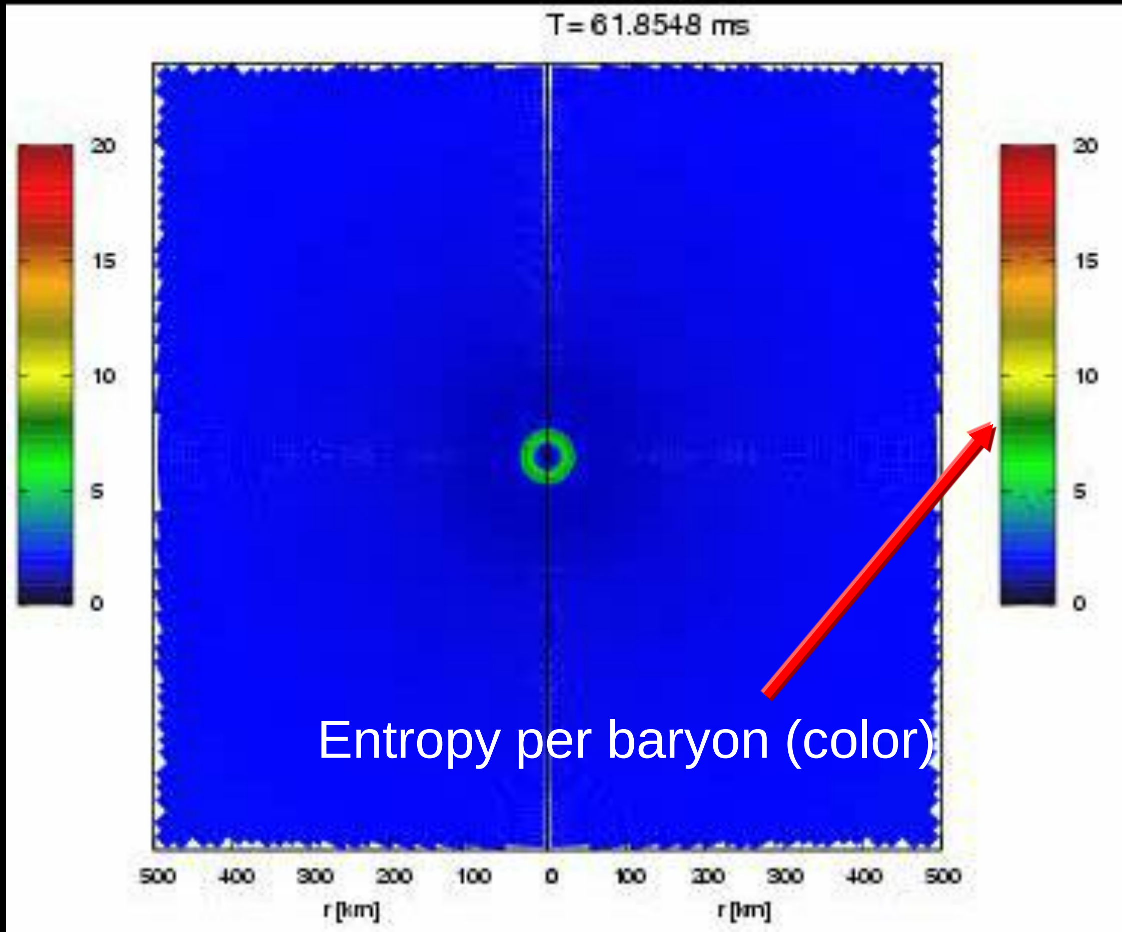
✓ "Standing Accretion Shock Instability (SASI)" is observed

: "low-modes" oscillations of the stalled shock

✓ The traveling timescales of matter in the neutrino-heated regions become longer due to non-radial oscillations.

✓ At around 300 ms after bounce, the neutrino-driven explosion sets in.

Right panel is zoom up in the central region

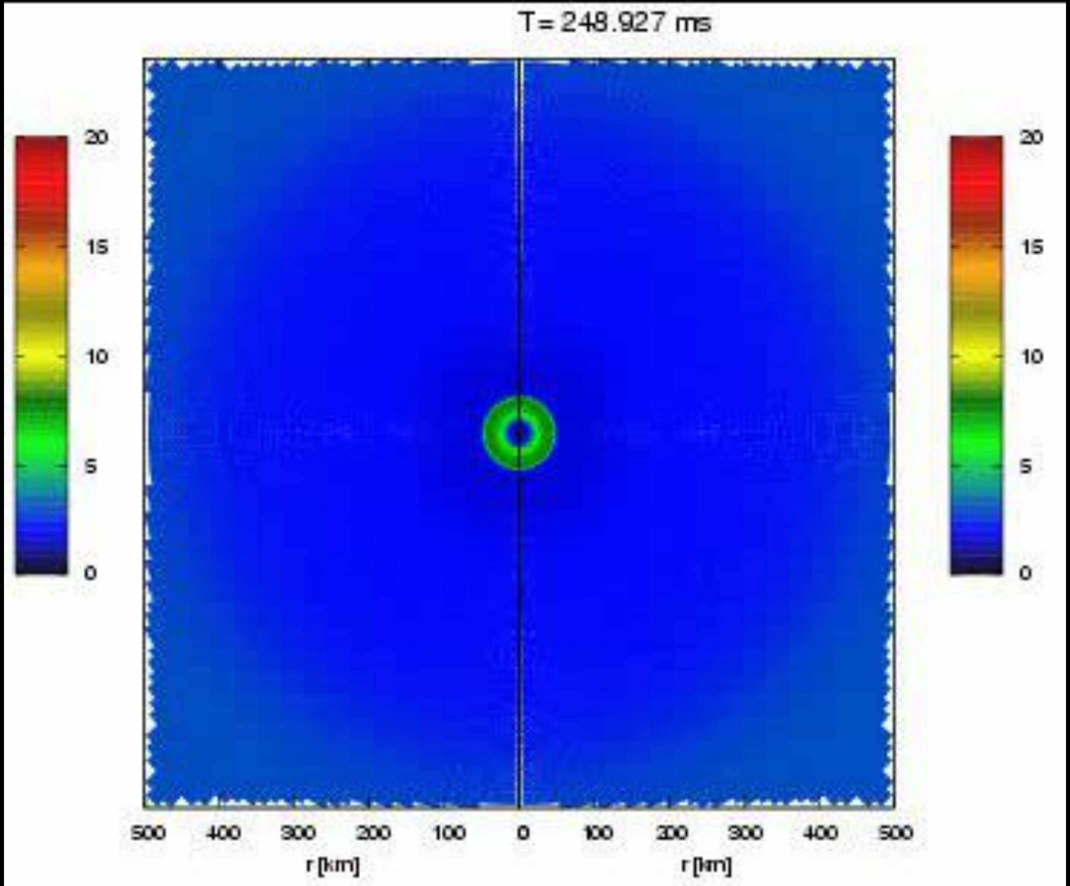


2D model with H.SHEN EOS

Suwa, Kotake, Takiwaki, Liebendoefer, Sato in preparation

✓ The SASI continues. but .we have not observed the shock-revival yet.

✓ This model seems not to be exploding …



☆In 2D, it's more easier to obtain explosions than 1D.

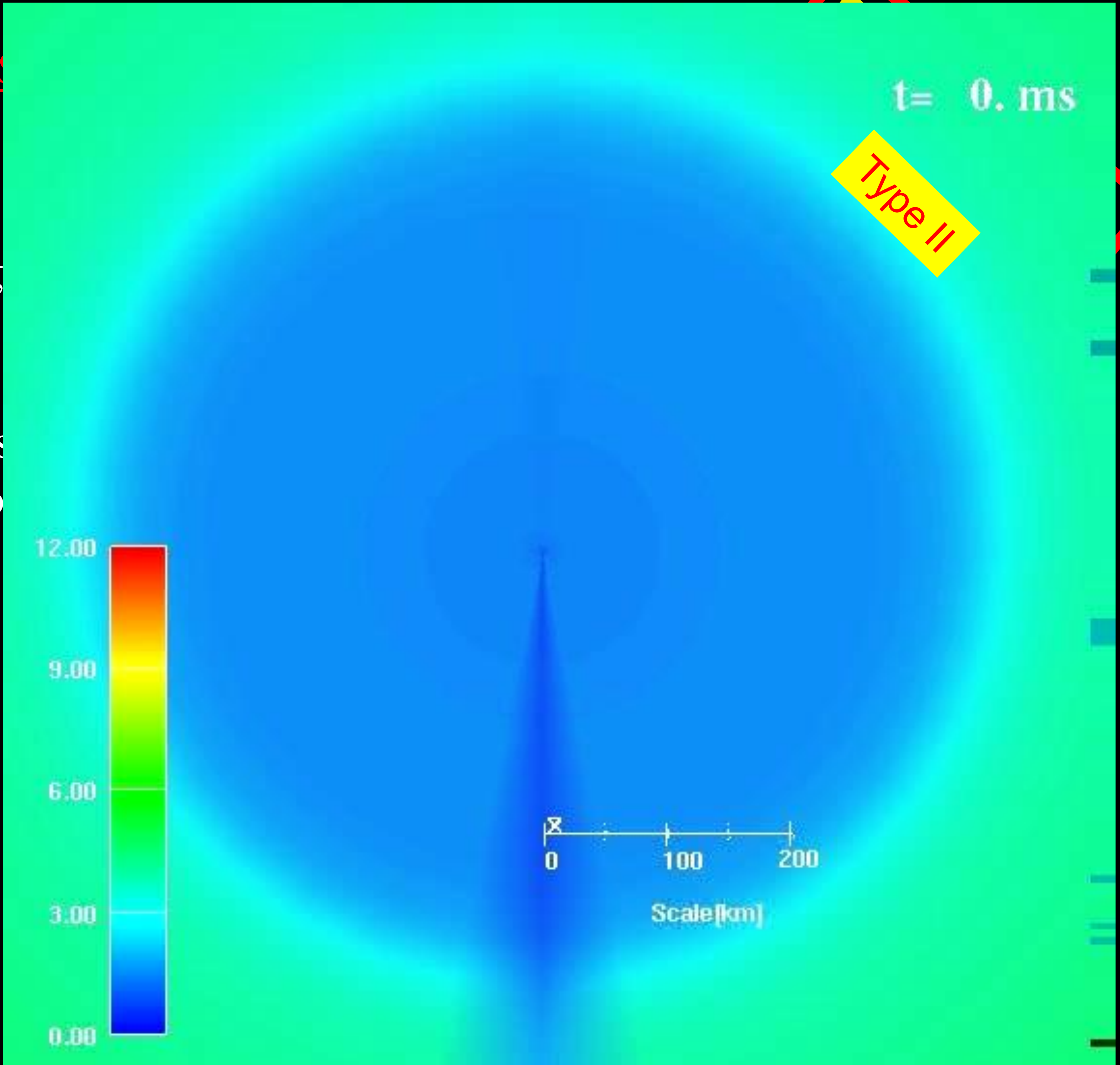
(because the non-radial motions can elongate the neutrino-heating timescales)

☆ In 3D, one might expect a more favorable situation!

(because matter can travel freely in the azimuthal(φ) direction!)

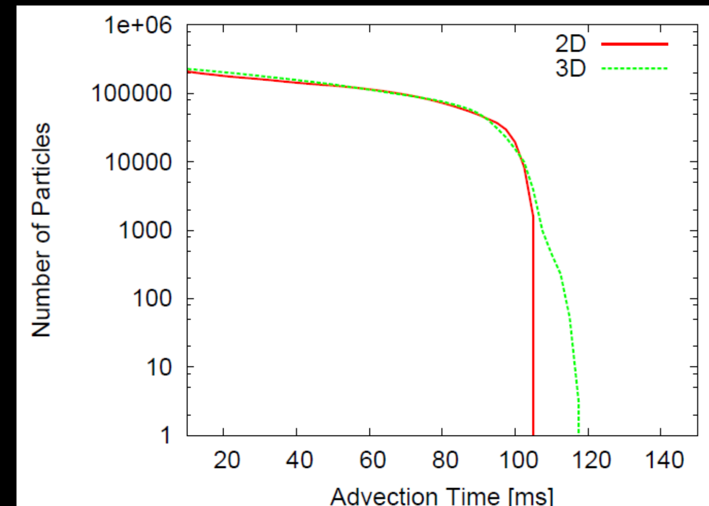
3D Results

- ✓ 13 Ms prog
- ✓ Numerical
  - Grid: 3
  - Process
  - Non-ro



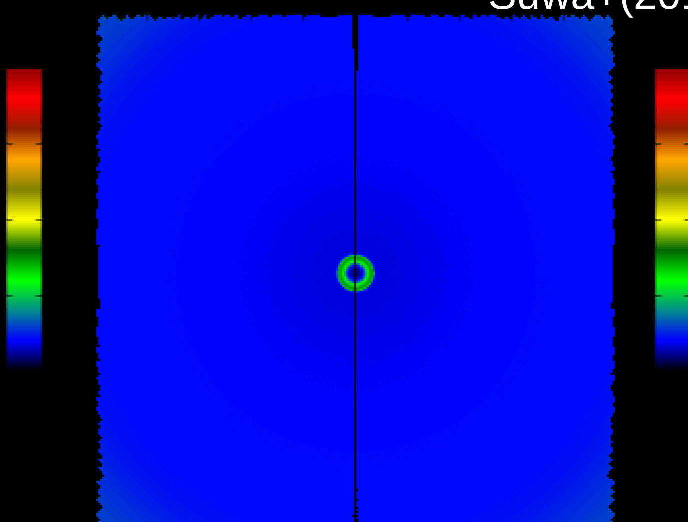
Easy to obtain explosions in 3D ?(Yes or No!)

✓**<u>For working the neutrino-heating mechanism</u>**



The residency timescales become longer in 3D than in 2D.

Suwa+(2010)



✓**<u>From the hydrodynamic point of view, it may be more easier for 2D.</u>**

(because matter motions can be concentrated along the special direction)

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TOP500 S... ページ(P)

TOP500 SUPERCOMPUTER SITES

PROJECT | LISTS | STATISTICS | RESOURCES | NEWS | CONTACT | SUBMISSIONS | LINK

TOP 10 Systems - 06/2011

1	K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect
2	Tianhe-1A - NUDT TH MPP, X5670 2.93Ghz 6C, NVIDIA GPU, FT-1000 8C
3	Jaguar - Cray XT5-HE Opteron 6-core 2.6 GHz
4	Nebulae - Dawning TC3600 Blade, Intel X5650, NVidia Tesla C2050 GPU
5	TSUBAME 2.0 - HP ProLiant SL390s G7 Xeon 6C X5670, Nvidia GPU, Linux/Windows

Japan Reclaims Top Ranking on Latest TOP500 List of World's Supercomputers

Thu, 2011-06-16 19:24

HAMBURG, Germany—A Japanese supercomputer capable of performing more than 8 quadrillion calculations per second (petaflop/s) is the new number one system in the world, putting Japan back in the top spot for the first time since the Earth Simulator was dethroned in November 2004, according the latest edition of the TOP500 List of the world's top supercomputers. The system, called the K Computer, is at the RIKEN Advanced Institute for Computational Science (AICS) in Kobe.

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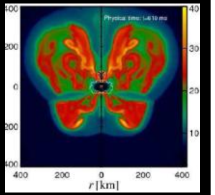
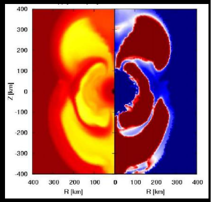
Summary of current status of SN mechanism

Energy-drivers for explosions:	Explosion
☆Neutrino heating mechanism aided by convection/SASI **(Marek & Janka 09, Suwa et al. 10)** also aided by rotation **(KK+03,06, Walder+05,Ott+08, Suwa et al. 10)**	Likely ! (but the explosion energy is still less than 10^{51} erg..)





☆ Which one is the final answer ?

☆ To pin down the proposed explosion scenarios,
⇒important to discuss a connection to observables!

Primary observables: "direct" information of engine

✓ supernova nucleosynthesis

✓ gravitational-wave and neutrino astronomy

One Slide for Gravitational Waves (GWs)

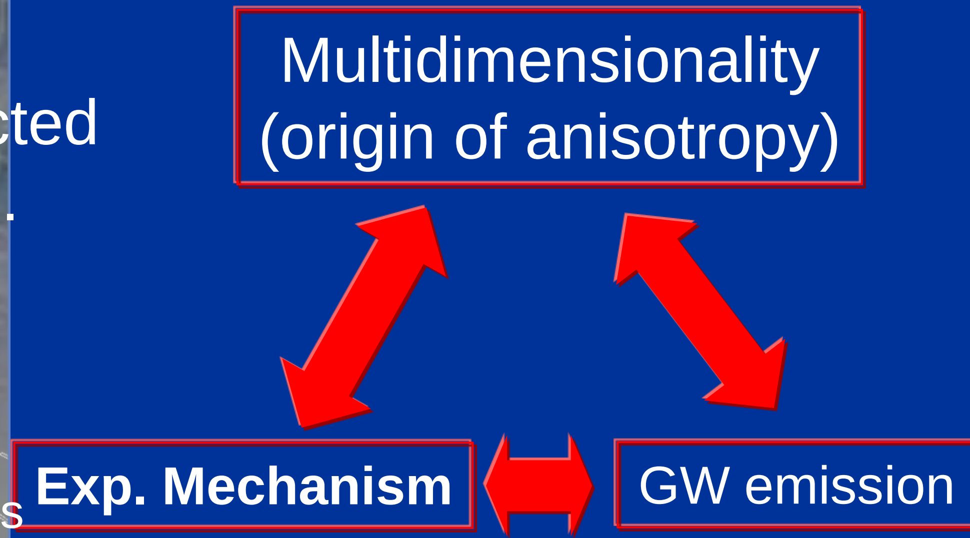
(see recent reviews in Kotake et al. (2006), Ott (2009), Fryer & New (2011))

☆ Gravitational Wave (GW) is "a ripple" of space-time, predicted Einstein's theory of GR (1916).

☆ Emitted when matter moves with acceleration.

- stellar collapse or neutron star mergers

☆ Nobody ever detected the strain.



(20XX)

GW

h_{ij}

W ... f anisotropy ... mics deviate

If ... fr ... ?, y, $\epsilon = 0$

nc

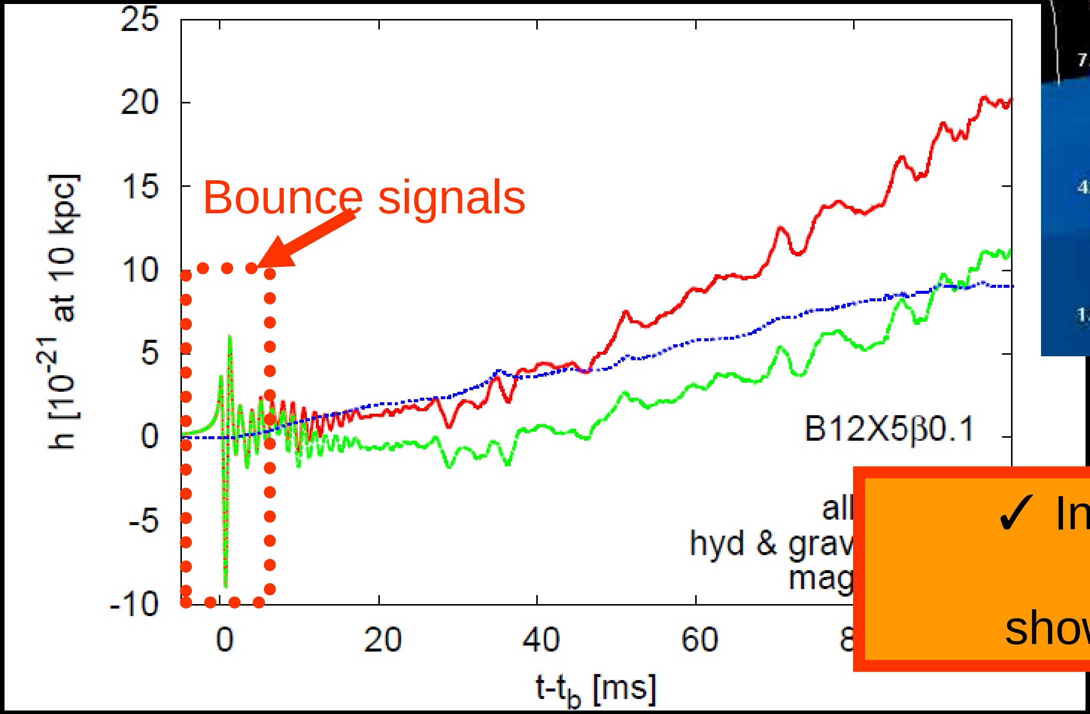
Gravitational-wave features in MHD explosions

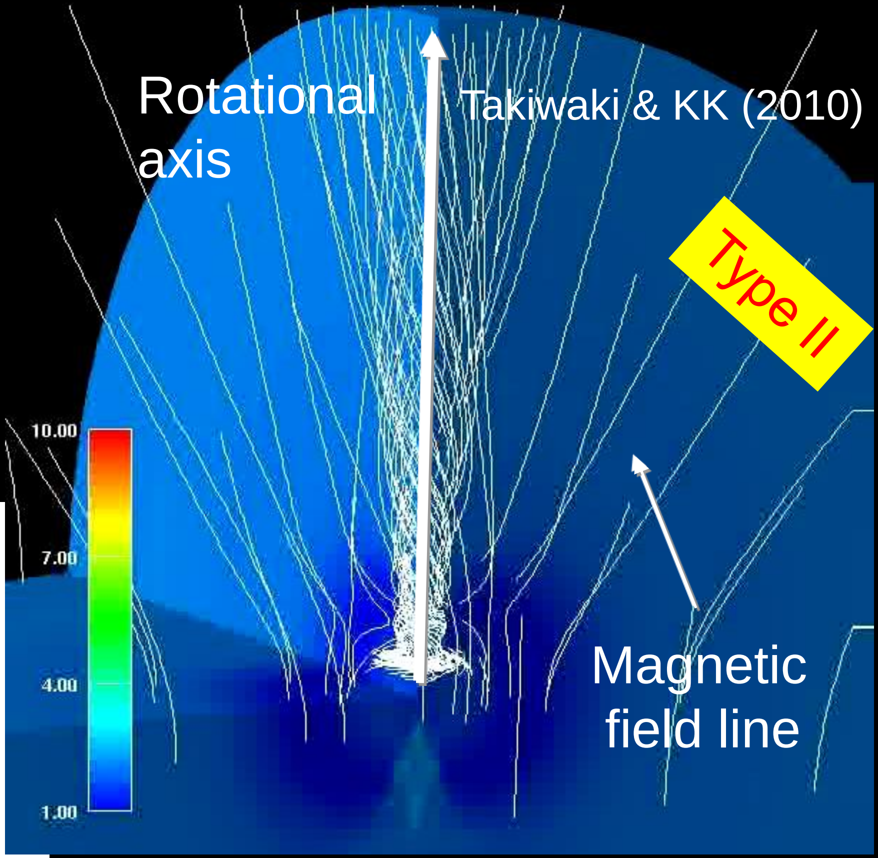
(e.g., Kotake et al. (04), Obergaulinger et al.(06), Shibata et al.(06), Takiwaki & Kotake (10))

✓The MHD mechanism works only when pre-collapse core has rapid rotation ($P_0 < 4$ s) and strong magnetic fields(B_0>10^{11}G).

✓ GW amplitudes from prolately expanding material **positively increase**

Gravitational waveform from MHD explosion

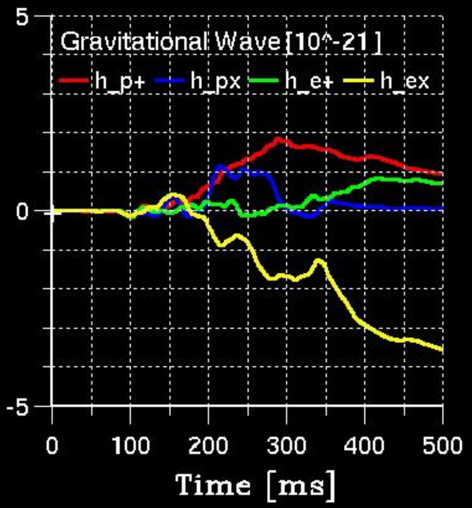




✓ In the MHD exploding models, the gravitational waveforms show an increasing trend after bounce.

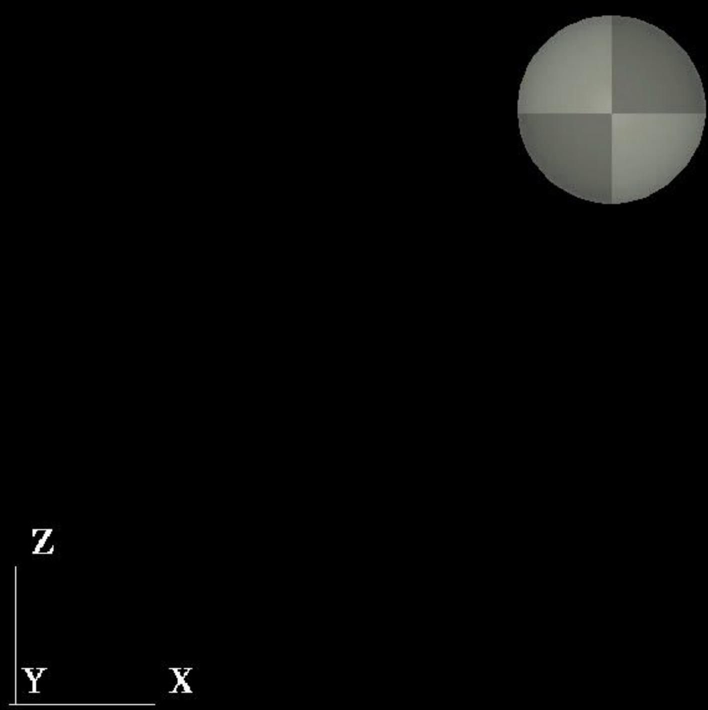
Gravitational Waves from Neutrino-driven Explosions

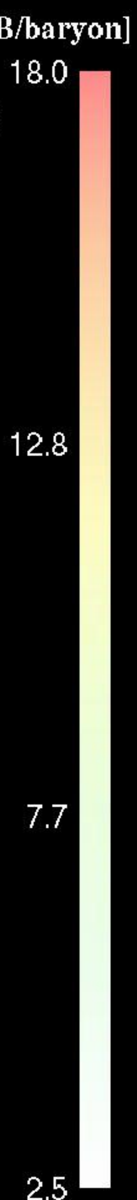
(KK et al. 09, KK et al. 11,
see also
Fryer et al. (02)
Murphy et al. (09),
Mueller et al. (11),
Mueller & Janka (97))



t = 1 ms

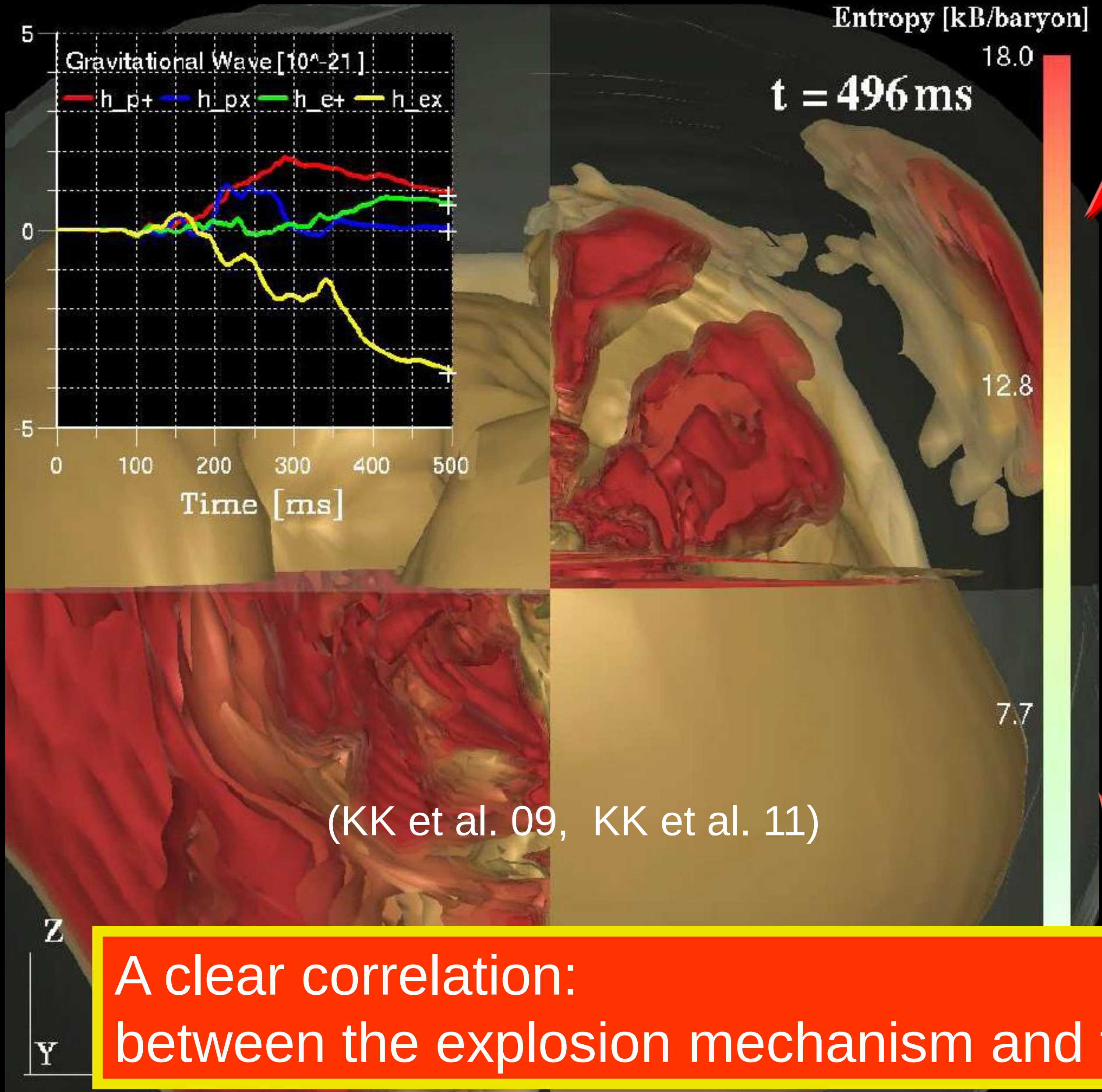
Type I





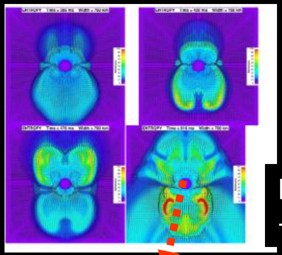
- ✓ In absence of rapid rotation,
  3D explosions :axis-free
- ✓ GWs from convection/SASI change stochastically with tine
  (governed by turbulent and chaotic fluid motion in non-linear hydrodynamics)

Comparison of Waveforms between candidate mechanisms

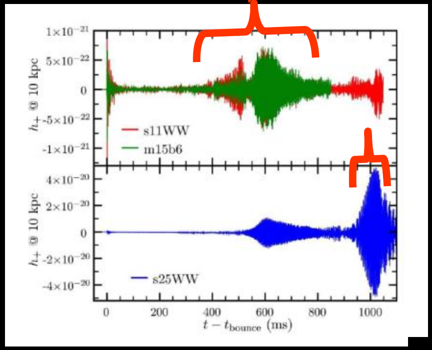


(KK et al. 09, KK et al. 11)

Acoustic-wave mechanism



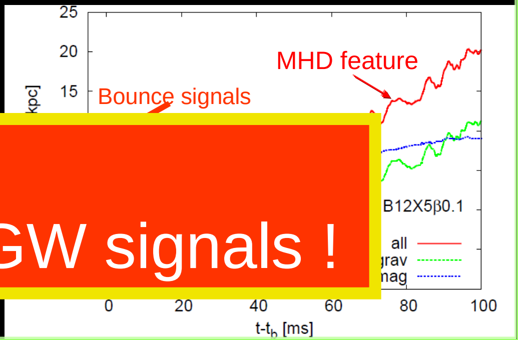
Burrows +06



Ott+06

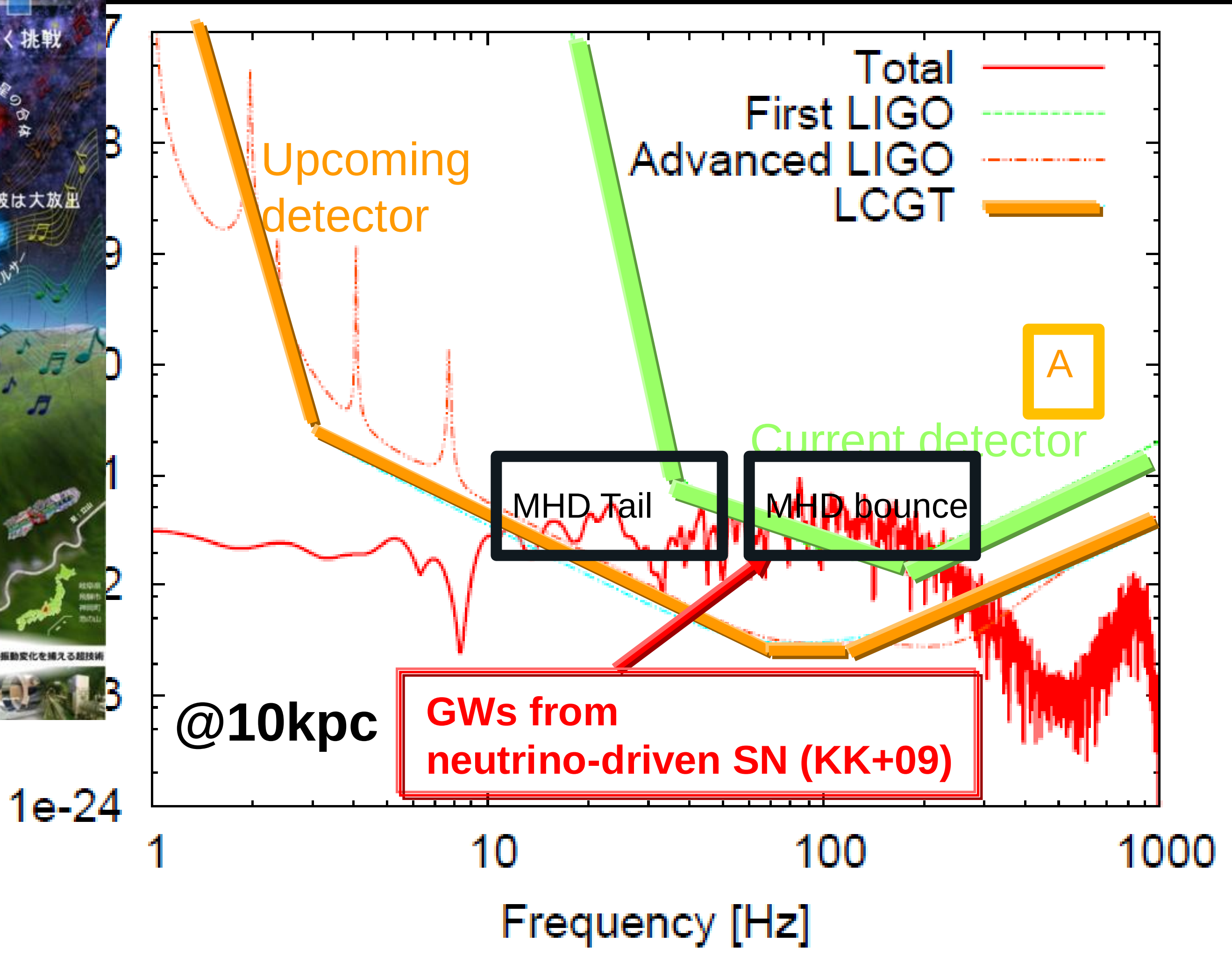
MHD mechanisms

(Takiwaki and KK 10)



A clear correlation:
between the explosion mechanism and the GW signals !

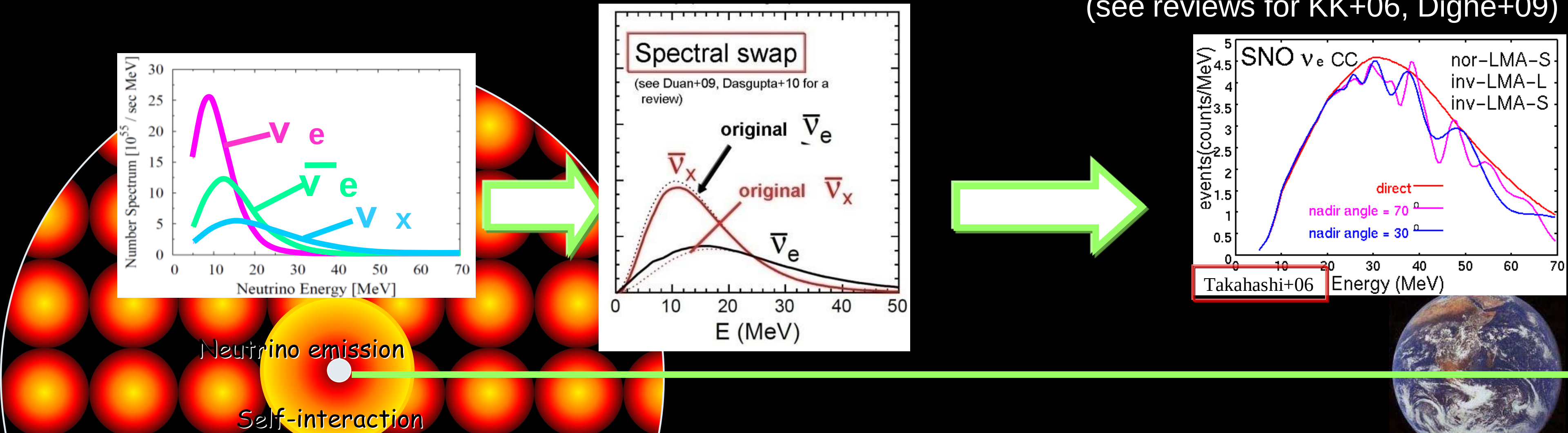
Detectability of GW signals

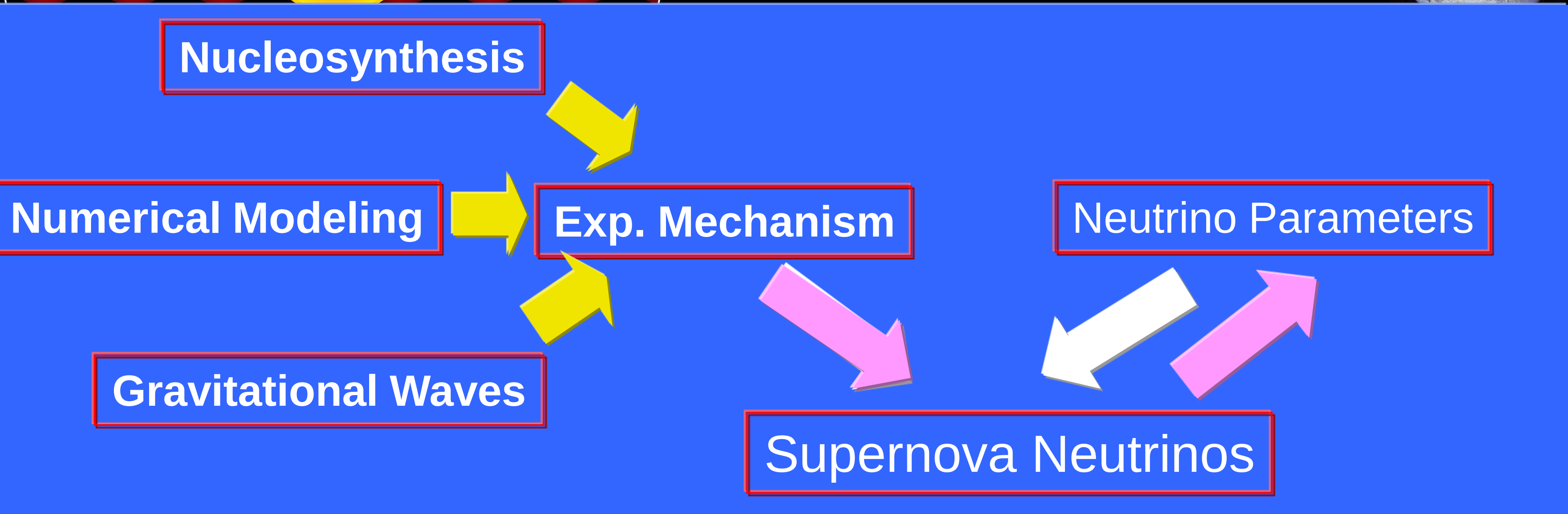


☆To detect the GW signals, the next generation detectors are needed.
☆By only by GWs, it is difficult to tell the difference between them.

Supernova neutrinos

(see reviews for KK+06, Dighe+09)

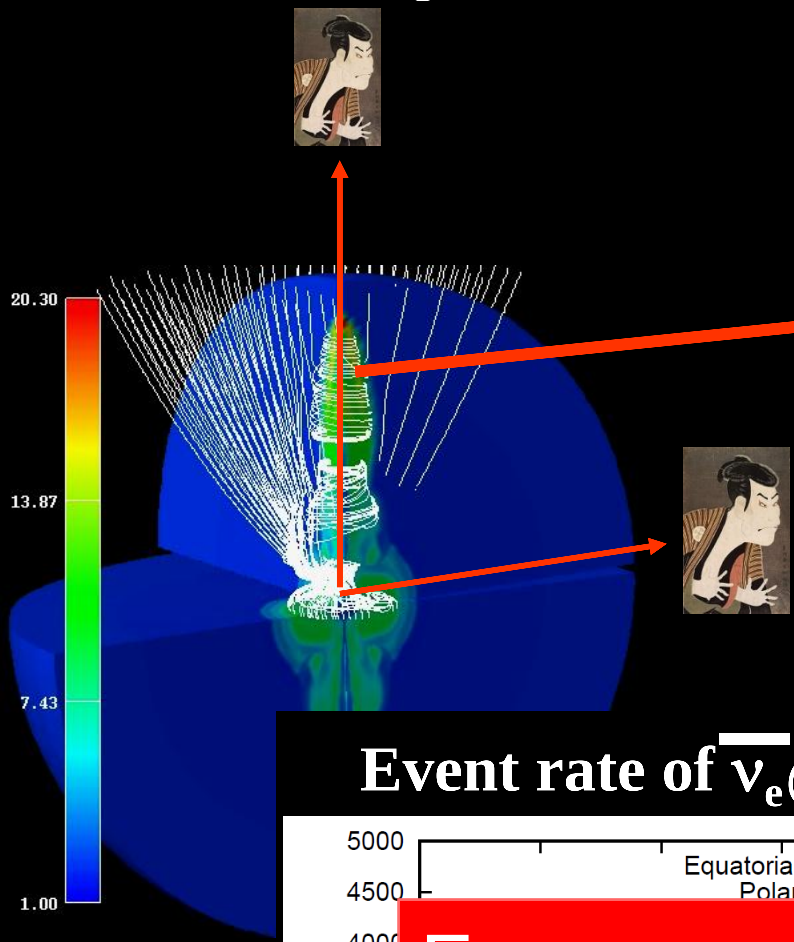


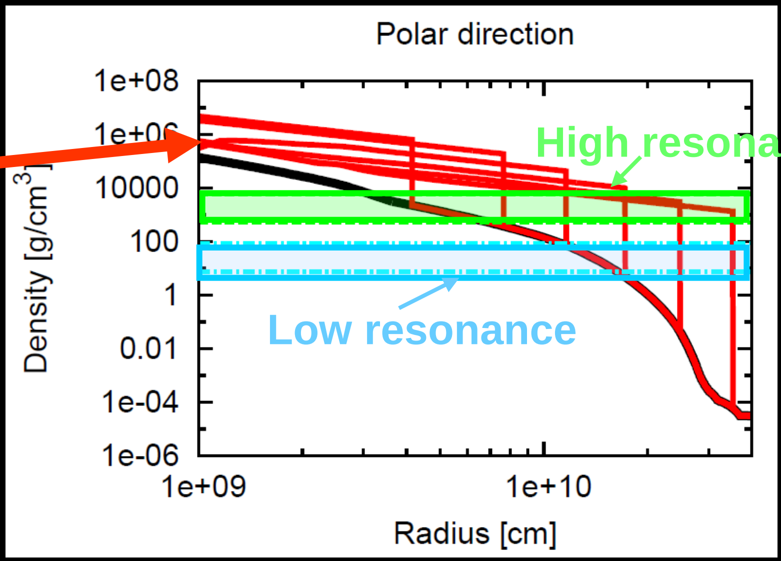


- ✓ Could have a great impact on the elementary physics
- ✓ Useful as a tomography, i.e., the time evolution of the SN dynamics!

Neutrino signatures in MHD explosion of supernovae

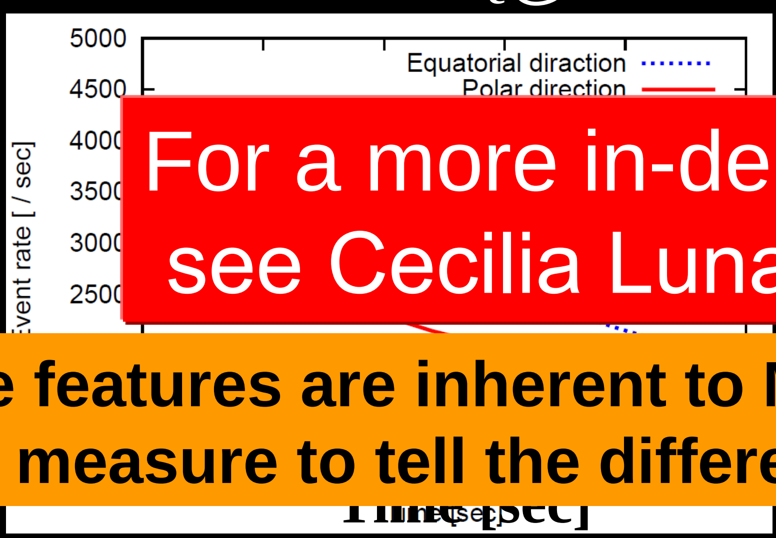
Kawagoe, Takiwaki, Kotake, JCAP(2009)



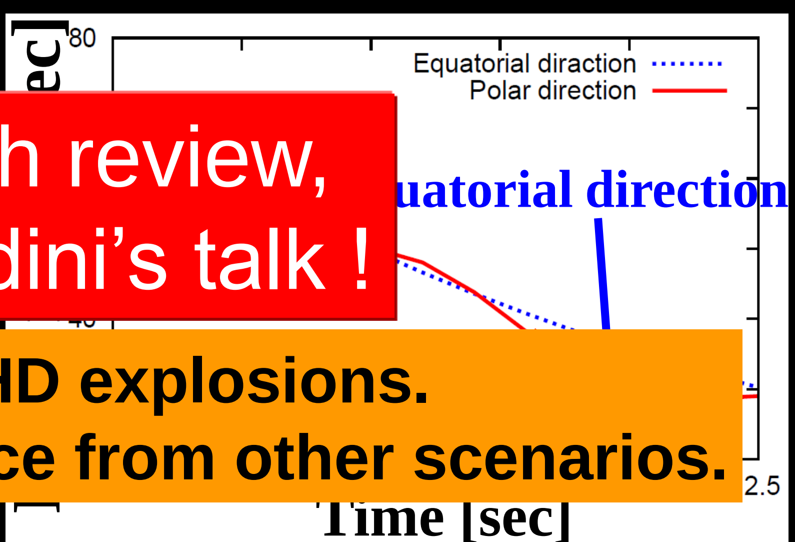


nverted mass
ierarcy

Event rate of $\bar{\nu}_e$@ SK



Event rate of ν_e @SK



For a more in-depth review, see Cecilia Lunardini's talk !

- ✓ These features are inherent to MHD explosions.
- ✓ Good measure to tell the difference from other scenarios.

Electromagnetic messengers from CC supernovae

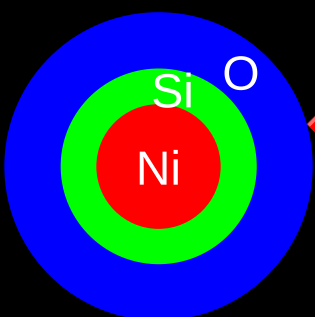
(Kifonidis et al. (2003,2006), Hungerford et al. (05), Young et al. (2006), Maeda et al. (2008))

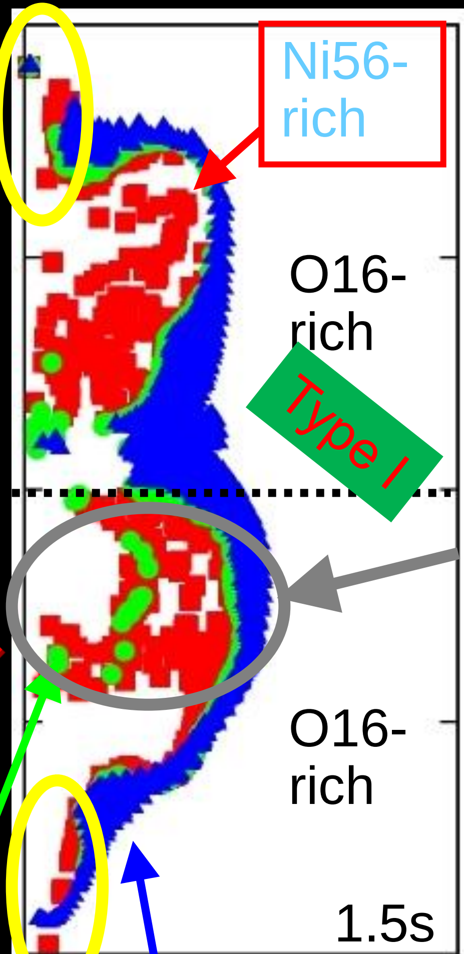
✓Explosive nucleosynthesis in SASI-aided 2D explosions

(Fujimoto, Kotake + 2011)

Si-rich jets, as in Cas A ?

Spherical model





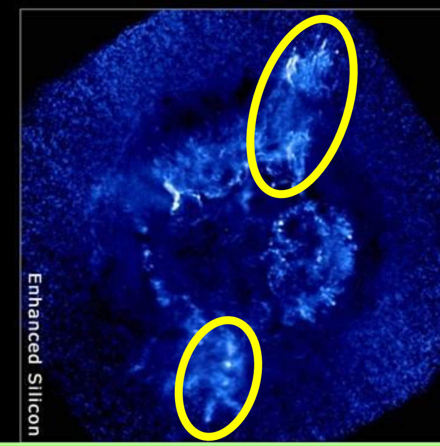
Ni56-rich

Matter Mixing

Si28-rich

O16-rich

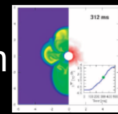
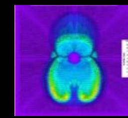
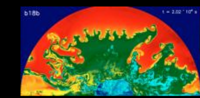
Si in Cas A (NASA)



✓Explosive nucleosynthesis occurs more drastically along the direction of explosion

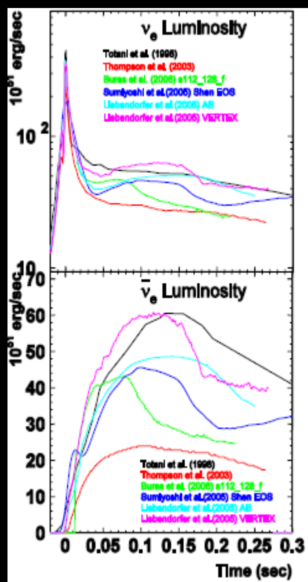
✓ This may account for some observational features such as in Cas A and SNR in the Cygnus loop.

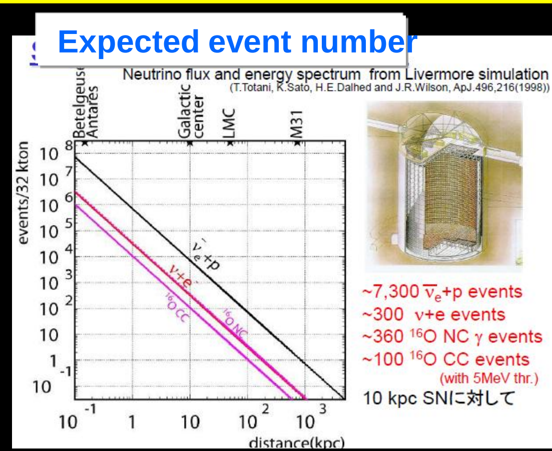
“Three eyes” to decipher the SN mechanism!


Convection

SASI

G-mode?


Time 0 milliseconds seconds（？） ＞hours

bounce

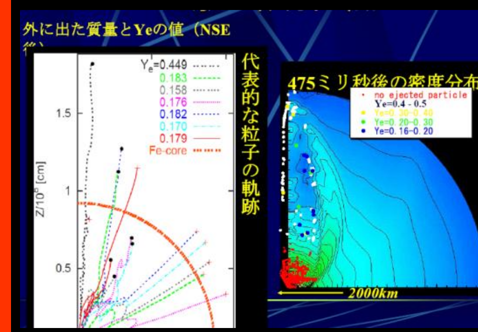




Neutrinos

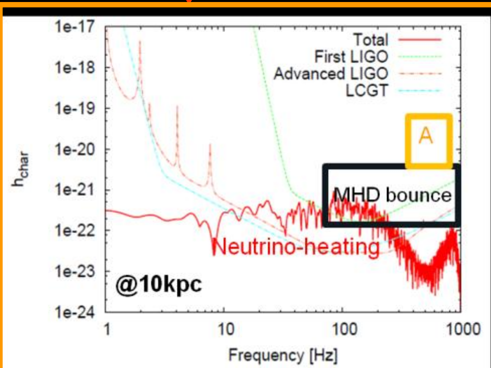
Shock-revivals (?)

Electromag. rad.



Nucleosynthesis

X-ray, optical, radio..



GWs

Summary of "SN Multi-messengers"

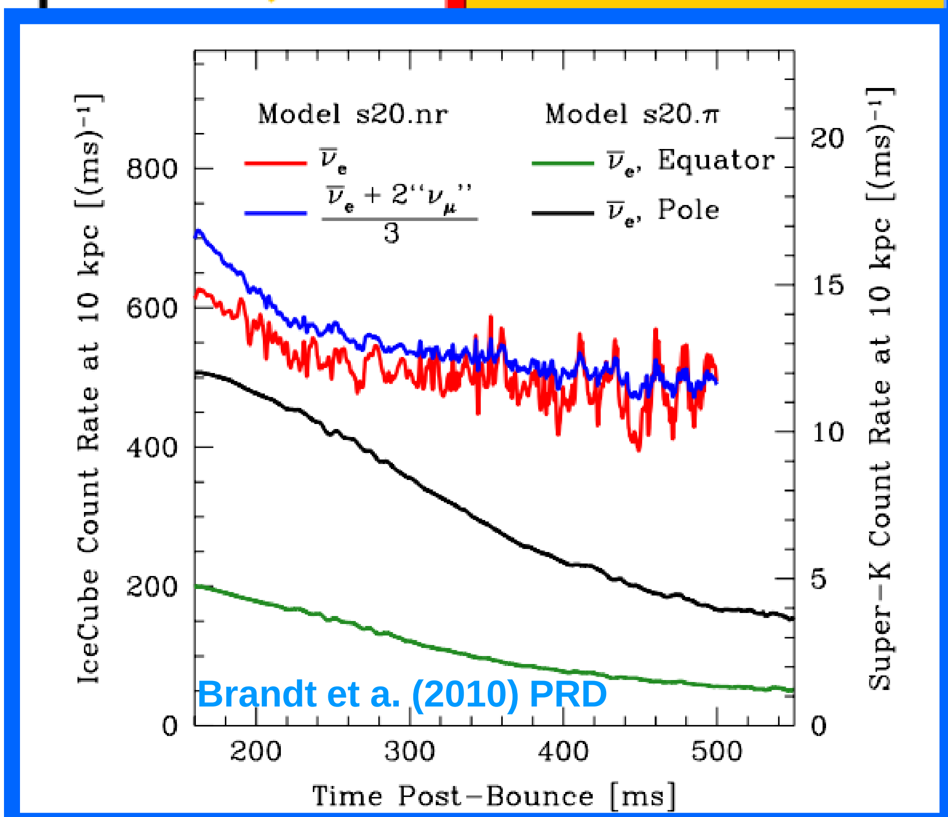
(Kotake +11)

Mechanism \ Messenger	Gravitational Waves	Neutrinos	Photons (nucleosynthesis)
Neutrino-heating mechanism: Canonical rotation	**Stochastic** (Convection & SASI)	**Stochastic** (Convection & SASI)	**ν p process** **Anisotropic explosive nucleosynthesis**
Neutrino-heating mechanism: Rapid rotation	**Excess for equator** (Spiral SASI modes)	**Polar excess**	?
Neutrino-heating mechanism: fails: black-hole forming	**Burst signals** (bounce & BH formation)	**Disappearing signals**	**No photon (?)**
MHD mechanism	**Burst & tail** (rapid rotation + magnetic fields)	· **Anisotropy in SK events** (MSW effect) · $\bar{\nu}_e$ **bursts (RSF)**	· **r-process cites** ? · **Path to hypernovae** ?

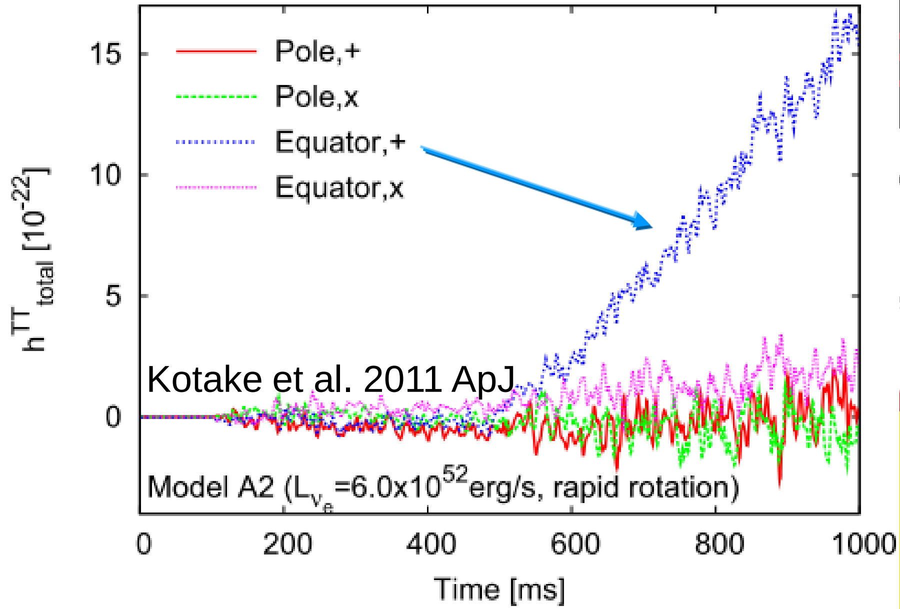
Summary of "SN Multi-messengers"

(Kotake +11)

Messenger / Mechanism	Gravitational Waves	Neutrinos	Photons (nucleosynthesis)
Canonical rotation	**Stochastic** (Convection & SASI)	**Stochastic** (Convection & SASI)	**ν p process** **Anisotropic explosive nucleosynthesis**
		Polar excess	?
		Disappearing signals	**No photon (?)**
		Anisotropy in SK events (MSW effect) · **$\overline{\nu}_e$ bursts (RSF)**	· **r-process cites** ? · **Path to hypernovae** ?

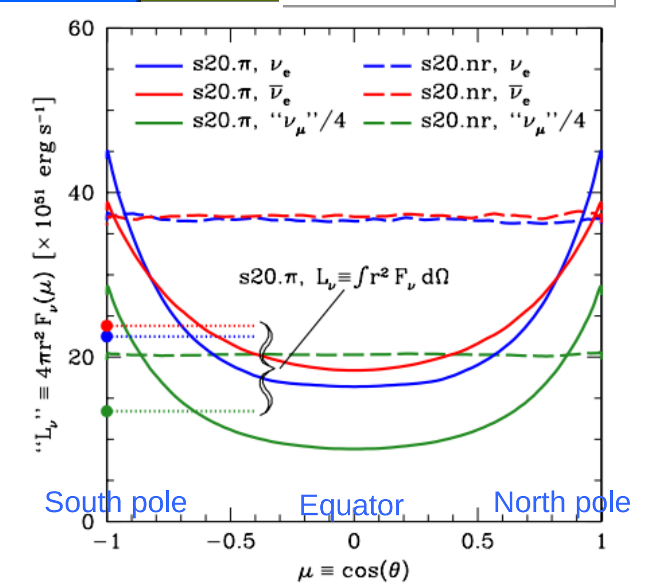


“SN Multi-messengers” (Kotake +11)

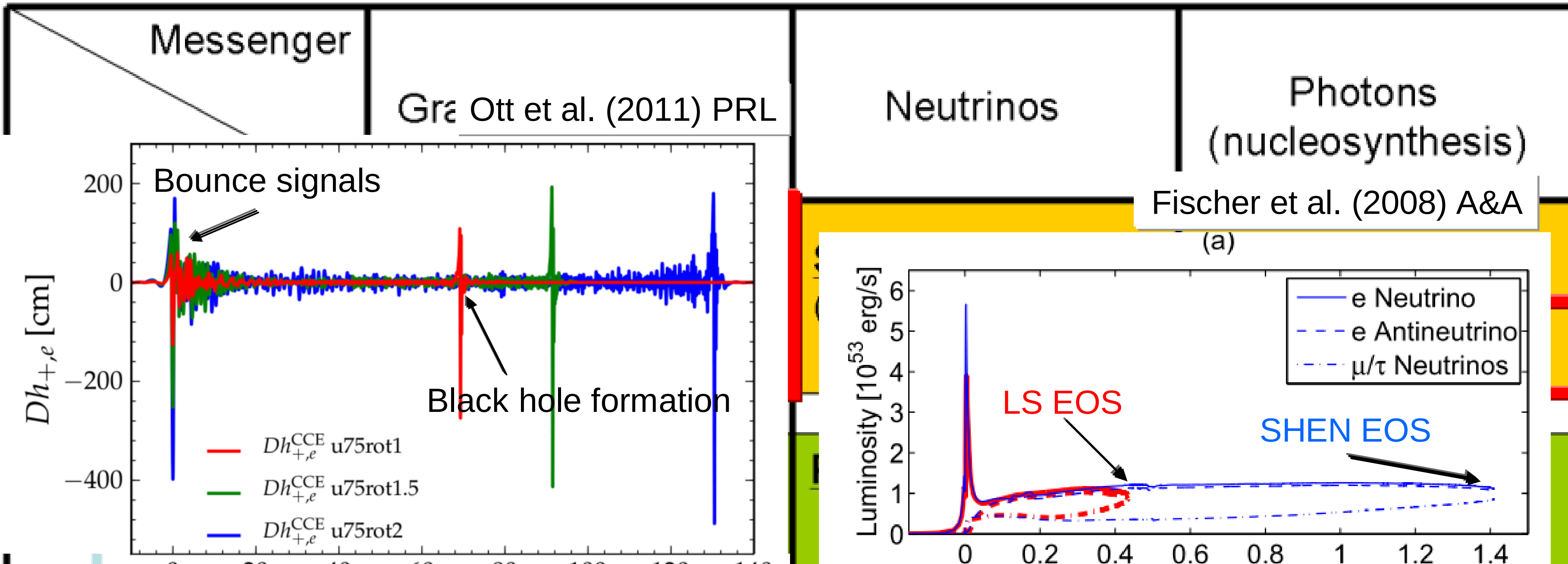


	s	Neutrinos	Photons (nucleosynthesis)
		Stochastic (Convection & SASI)	**ν p process** **Anisotropic explosive nucleosynthesis**
mechanism R… on Rapidly Rotation	**Excess for equator** (Spiral SASI modes)	**Polar excess**	?
… black-hole forming	**Burst signals** (bounce & BH formation)	**Disappearing s**	
MHD mechanism	**Burst & tail** (rapid rotation + magnetic fields)	**Anisotropy in events** (MSW · $\overline{\nu}_e$ **bursts** (RS	

Brandt et al 2010 PRD



Perspectives on “SN Multi-messengers” (Kotake +11)



✓ **<u>A correlation analysis of these messengers</u>** should be very important to get a unified picture of stellar collapse that bifurcates between NS or BH forming SNe!

✓ **<u>Multi-dimensionalities</u>**(convection, SASI, rotation, B-fields) hold a key to bridge the SN theory (incl. nuclear theory) and these multi-messenger observation.

For more details, please refer to our review article, which will be posted on astro-ph very soon !

Multimessengers from core-collapse supernovae : multidimensionality as a key to bridge theory and observation

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Thank you very much !