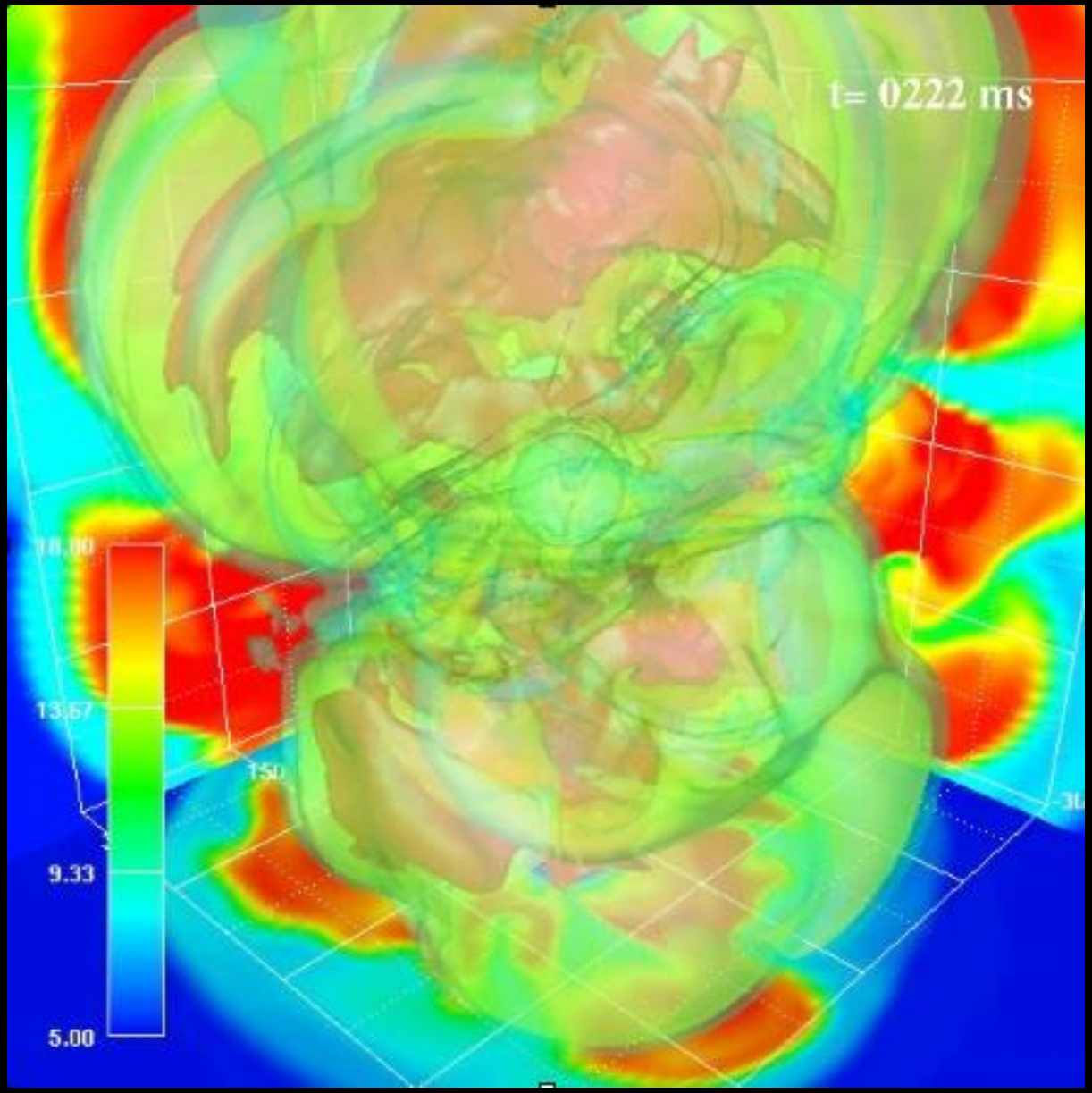
Astrophysical Big Bang: From Engine to Remnant

RIKEN Shigehiro Nagataki

15-19 September 2014, Moorea, French Polynessia

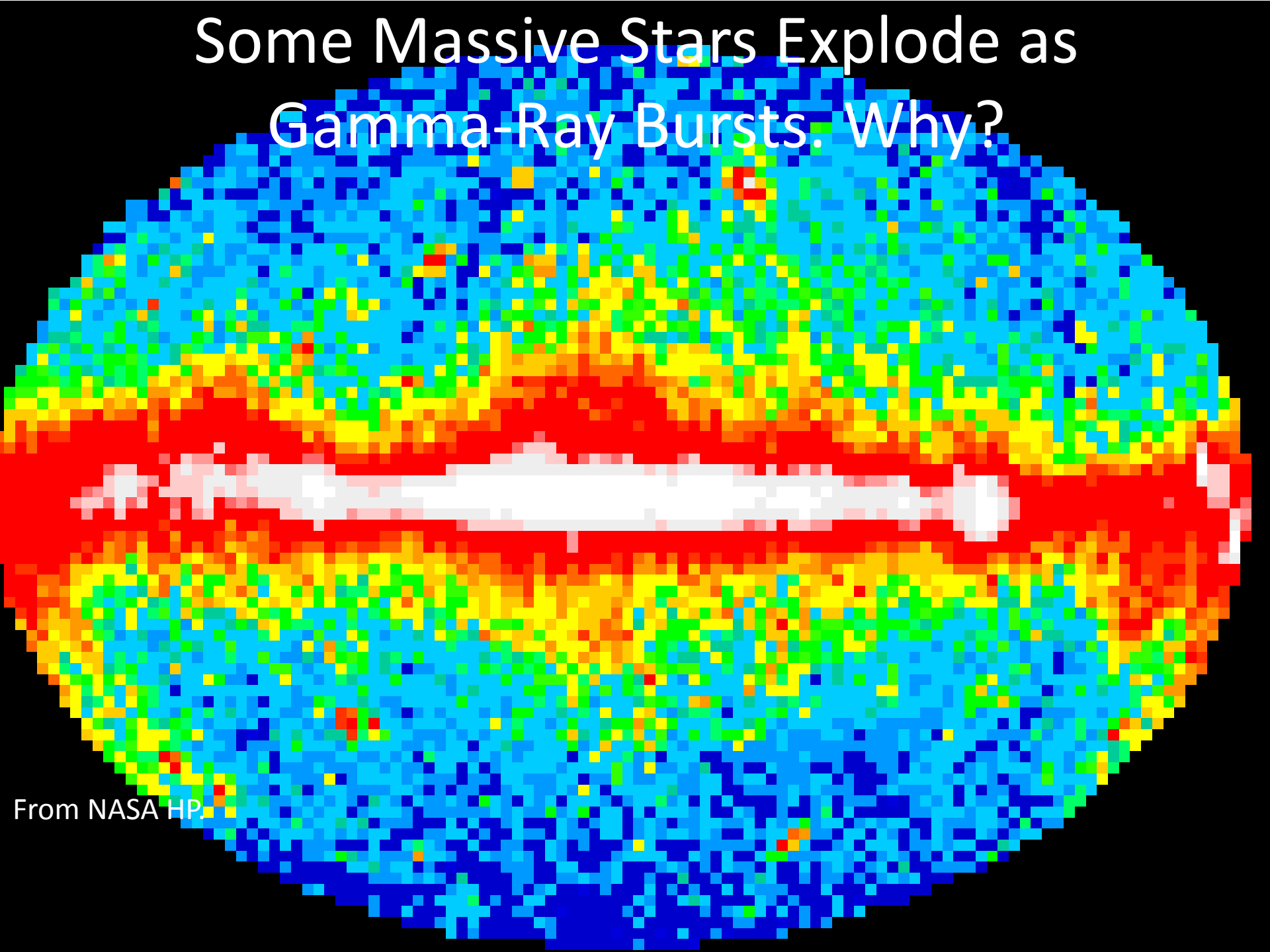
PACIFIC 2014

Massive Stars Explode. Why?



Simulation by
T. Takiwaki
(RIKEN)

Some Massive Stars Explode as Gamma-Ray Bursts. Why?

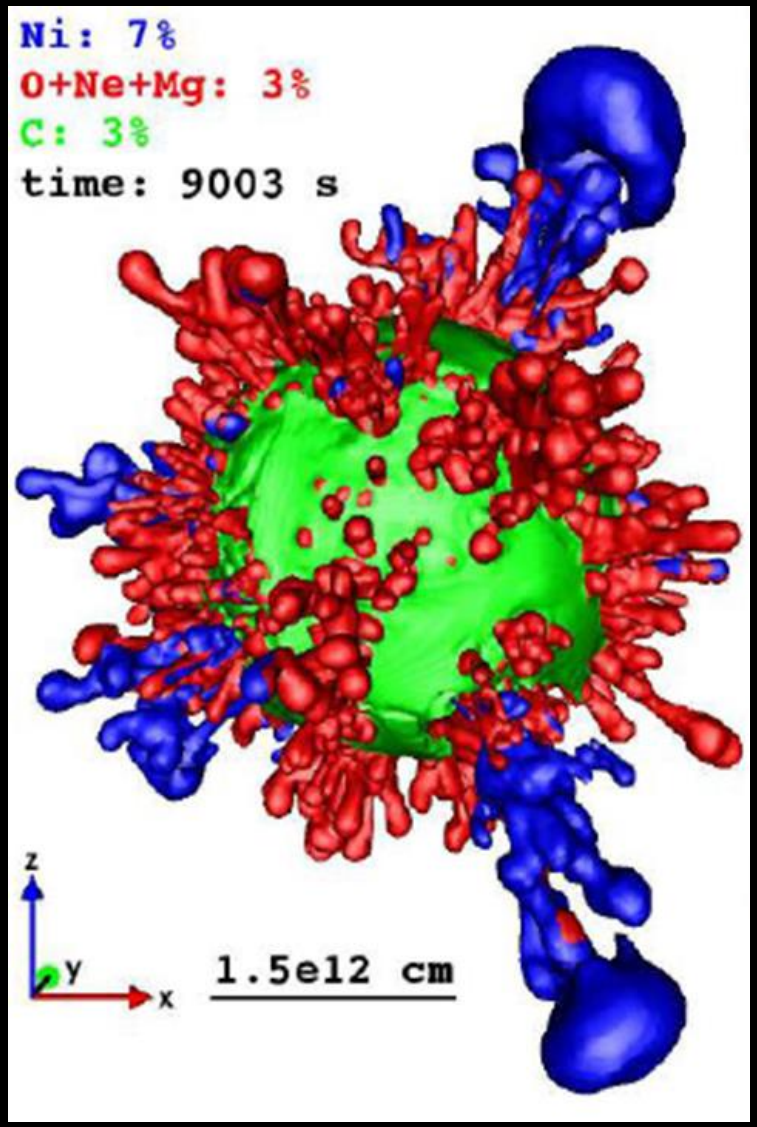


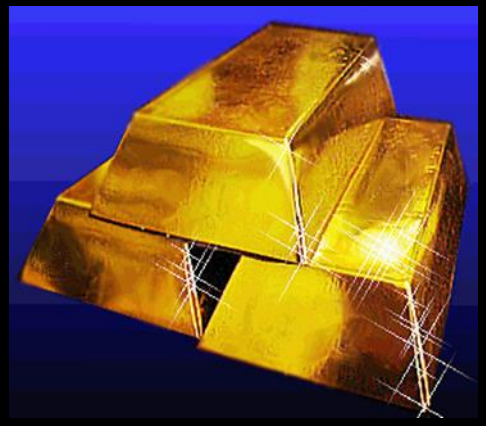
From NASA HP.

Supernovae are Origin of Heavy Metals. But what kind of metals are really produced?

Simulation by
A. Wongwathanarat
(MPA → RIKEN)

S. Wanajo
（RIKEN）



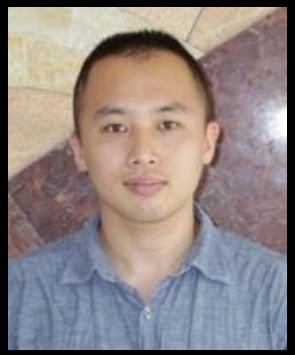


Origin of Gold?

Origin of Uran?

Why are SNe/GRBs so Bright?

A. Tolstov (RIKEN→IPMU)

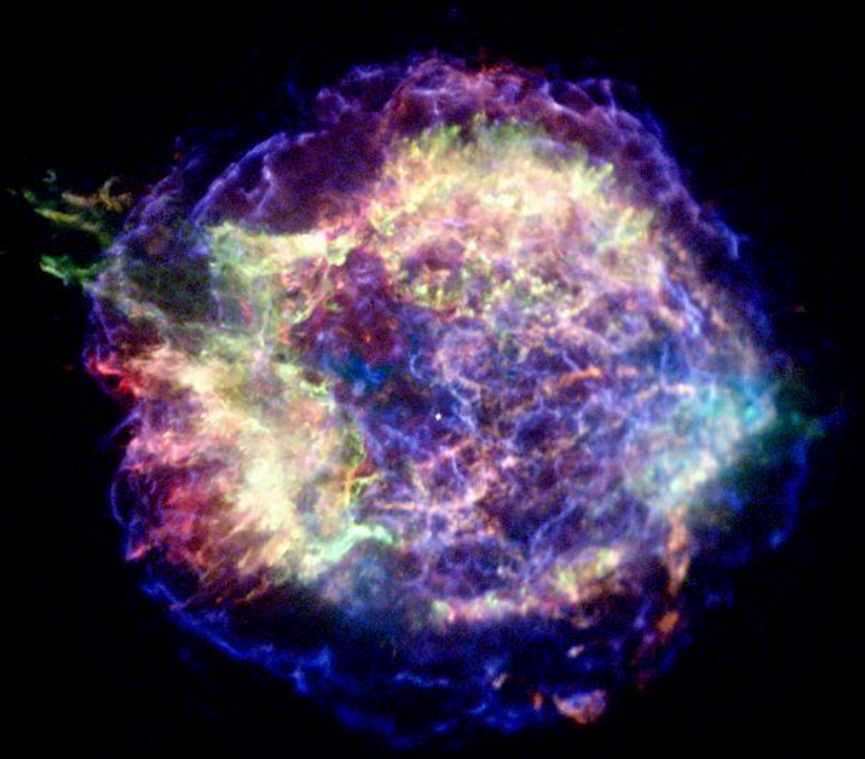


Y. Teraki(RIKEN)

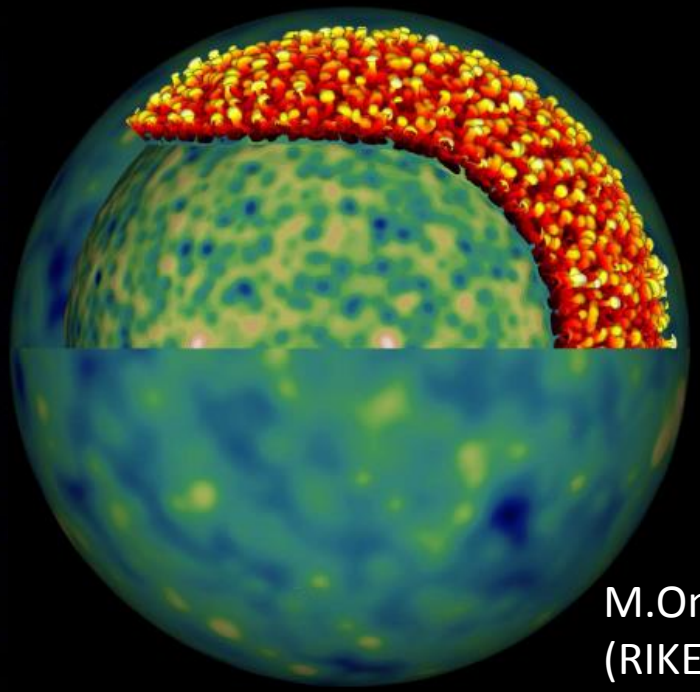
H. Ito (RIKEN)

J. Matsumoto (RIKEN)

Lots of Physics in Supernova Remnants



X-ray Image of Cassiopeia A by Chandra



Simulation by D. Warren

S.H. Lee (RIKEN→ JAXA)

M.Ono (RIKEN→Kyushu U.)

D. Warren (NCSU→RIKEN?)

Morphology? Composition? Cosmic-Ray Production?

Our Group Members and Collaborators

From 1st April 2013

～Toward Full-Understanding of Supernovae and GRBs～

Small Radi

Large Radi

- Central Engine: Nagataki (PI), Takiwaki , Barkov
- Explosive Nucleosynthesis:Wongwathanarat, Wanajo, Mao
- Shock Breakout/Light Curve/Spectrum: Tolstov, Blinnikov (ITEP), Tominaga (Konan), Tanaka (NAOJ), Maeda(Kyoto)
- Propagation of Relativistic Jet: Matsumoto, Mizuta
- Prompt Emission: Ito, Teraki, Pe'er (UCC)
- Afterglow: Warren, Ellison (NCSU), MacFadyen(NYU).
- Remnants: Lee, Ono, Warren, Slane (CfA), Patnaude (CfA)
- UHECRs, VHE-neutrinos/gamma-rays: Allard (APC), Kusenko (UCLA), He (PAO)
- GRB Cosmology: Dainotti

… and More!

§ Supernova Explosion

The Mystery Lasting Over 80 Years

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. BAADE
F. ZWICKY

1934

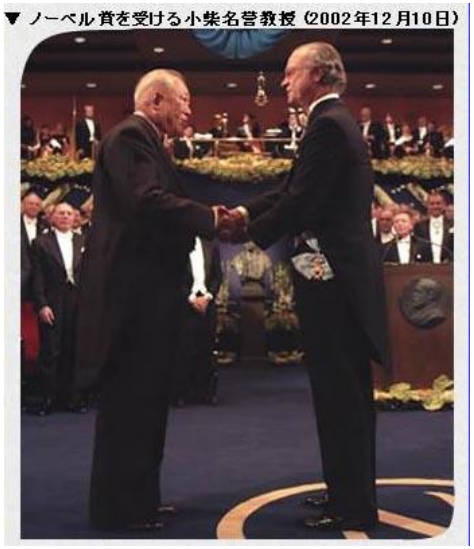
The Simulation of Core-Collapse Supernova Using K-Computer

京(KEI) = 10 Peta=10^16.

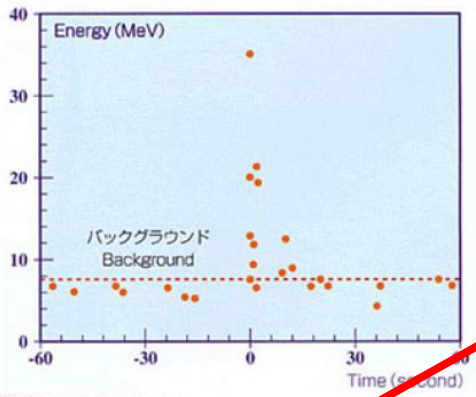
T. Takiwaki (RIKEN)

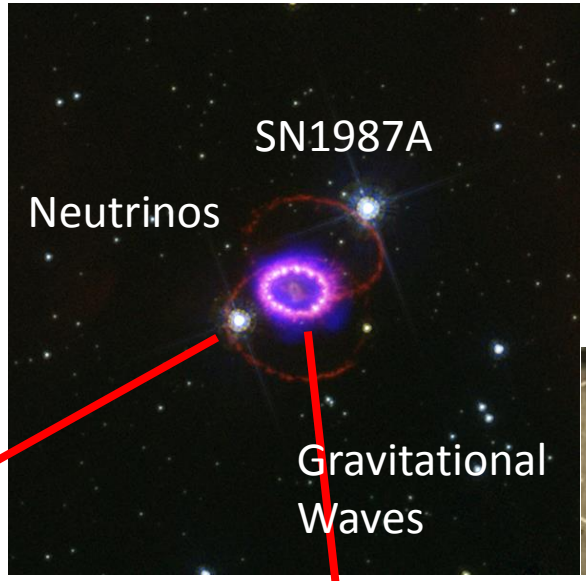
- Selected as an Important Program of HPCI (High Performance Computing Infrastructure), Strategic Program Field 5, “The origin of matter and the universe”.
- Selected as One of Seven Strategic Program of K-Computer in FY2013.
- Toward Full Understanding of Explosion Mechanism of CC-SNe by the Post-K-Computer (Exa-Flops) Program (2020-), RIKEN.

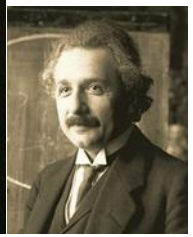
Supernova as a Source of Neutrinos and GWs

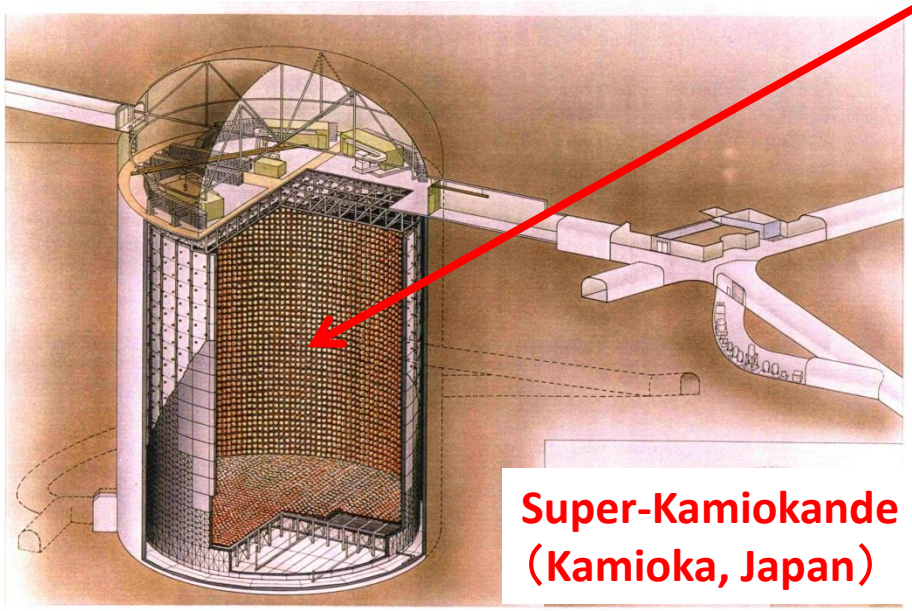


Prof. M. Koshiba,
Awarded the Nobel Prize
in Physics (2002).



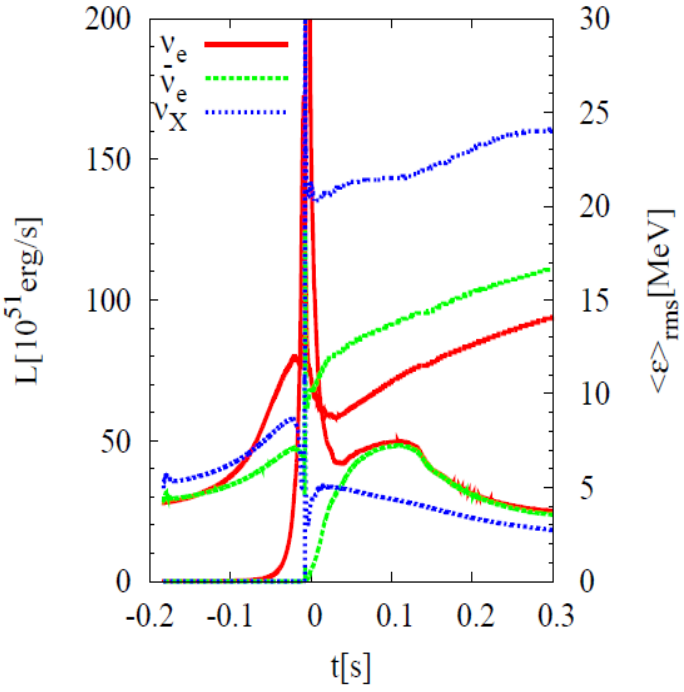




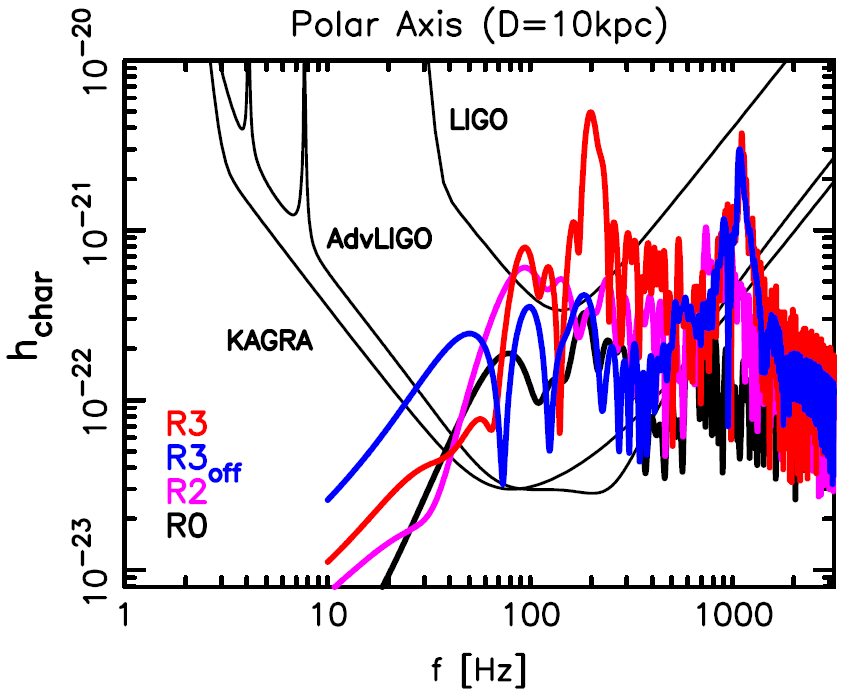


KAGRA (2017-)
（Kamioka, Japan）

Neutrino/GW Signals from a SN



Time Evolution of Neutrino Luminosity

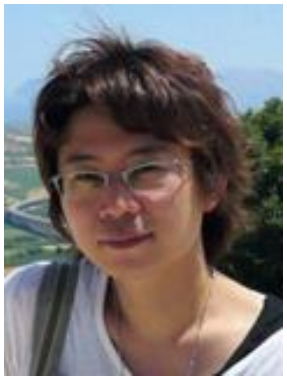


Signal of Gravitational Wave in Freq. Space

T. Takiwaki
(RIKEN)

§ Engine of Gamma-Ray Bursts

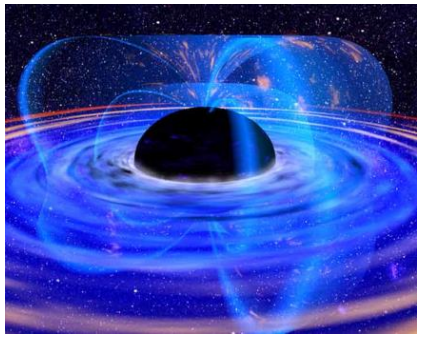
Engine of GRBs is Hardly Known

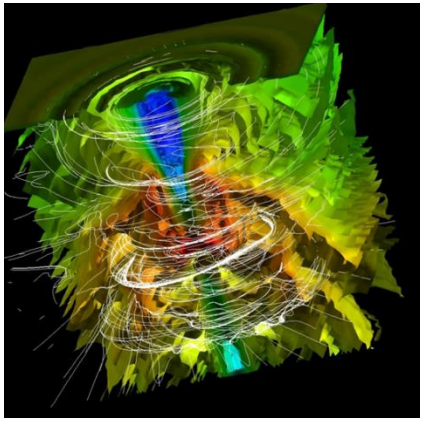


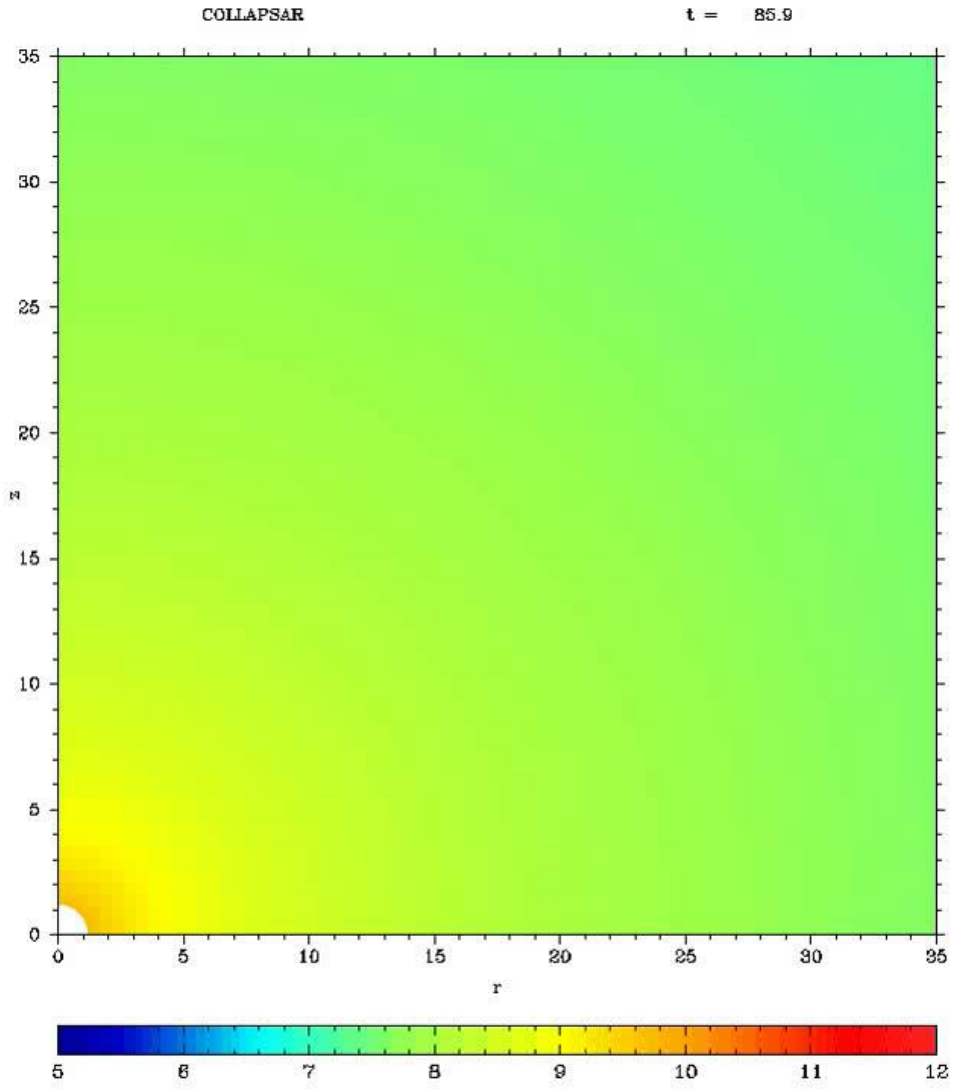
S. Nagataki
(RIKEN)

M. Barkov
(RIKEN)

One Possibility:
A Rapidly-Rotating
Black Hole might be
Formed at the Center!



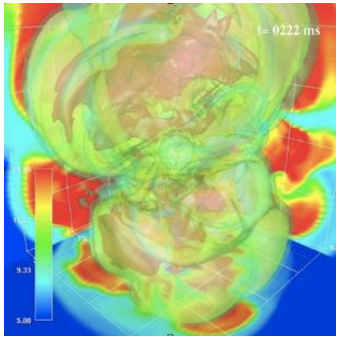


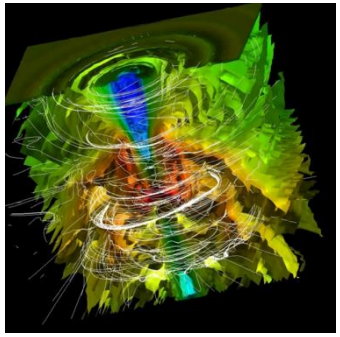


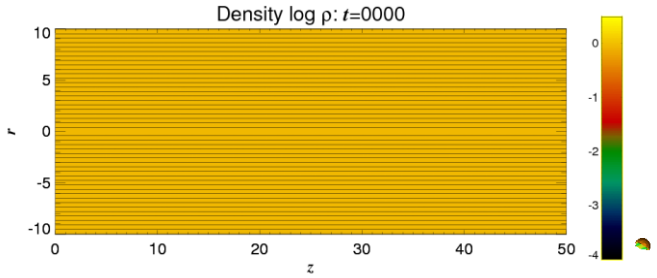
Rotation Energy of a BH can be Extracted efficiently with a help of EM Field (Blandford-Znajek Effect).

Toward GRMHD-ESM

- Our Plan to Develop a New Code “General Relativistic MHD with Einstein-eqs Solver and Microphysics(GRMHD-ESM)”








Hiro


Maxim


Jin


Tomoya


Annop

And More!

Our Road Map

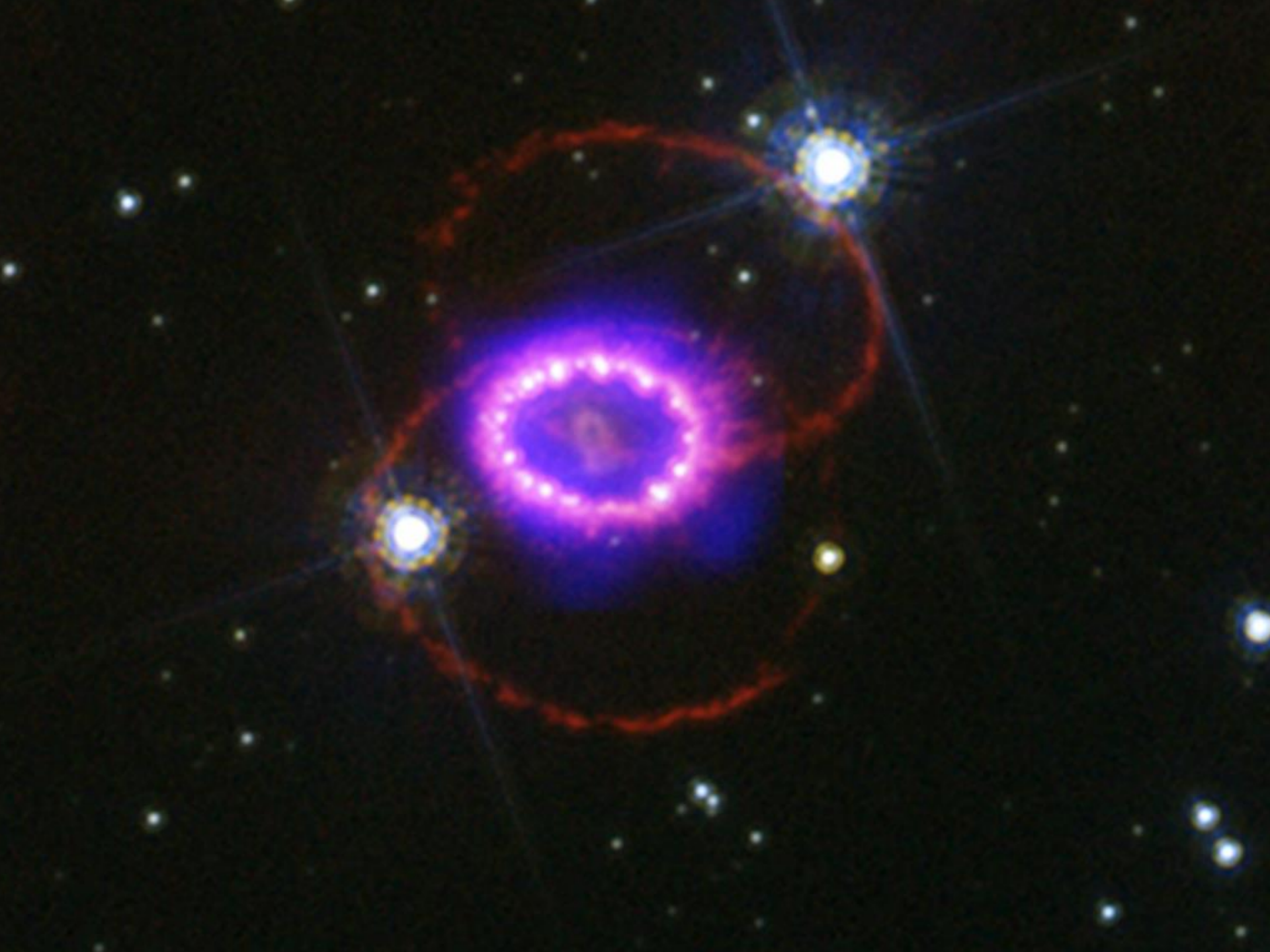
- 2017: K-Computer Up-Graded (～100PFlops).
- 2018: KAGRA Full Operation (GW).
- 2020: Post K-Computer Full Operation (Exa-Flops).
- 2020: 6D Supernova Simulation Done.
- 2025: 6D Gamma-Ray Burst Simulation Done.
- 203X: A SN Explodes in Milky Way (Betelgeuse?).

  Neutrinos & GWs Detected.

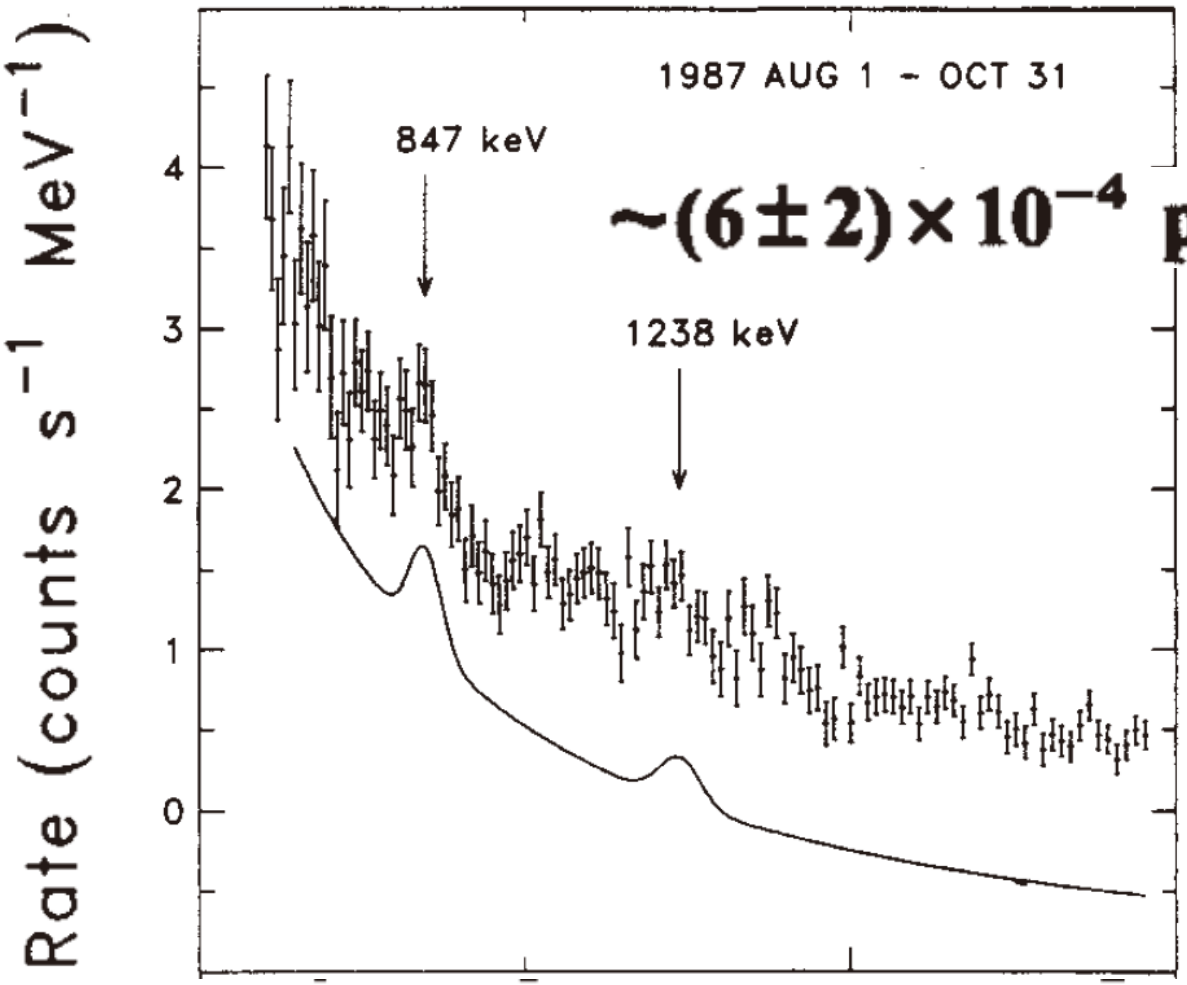
  EOS for Dense Matter Determined.

  Our Theory Confirmed.
- 204X: Lots of Nobel Prize Winners from Japan.
- … Our Dreams Will Continue…

§ Supernova Nucleosynthesis, Neutron Star Kicks, Light Curve & Spectrum



Early Detection of Gamma-Ray Lines !



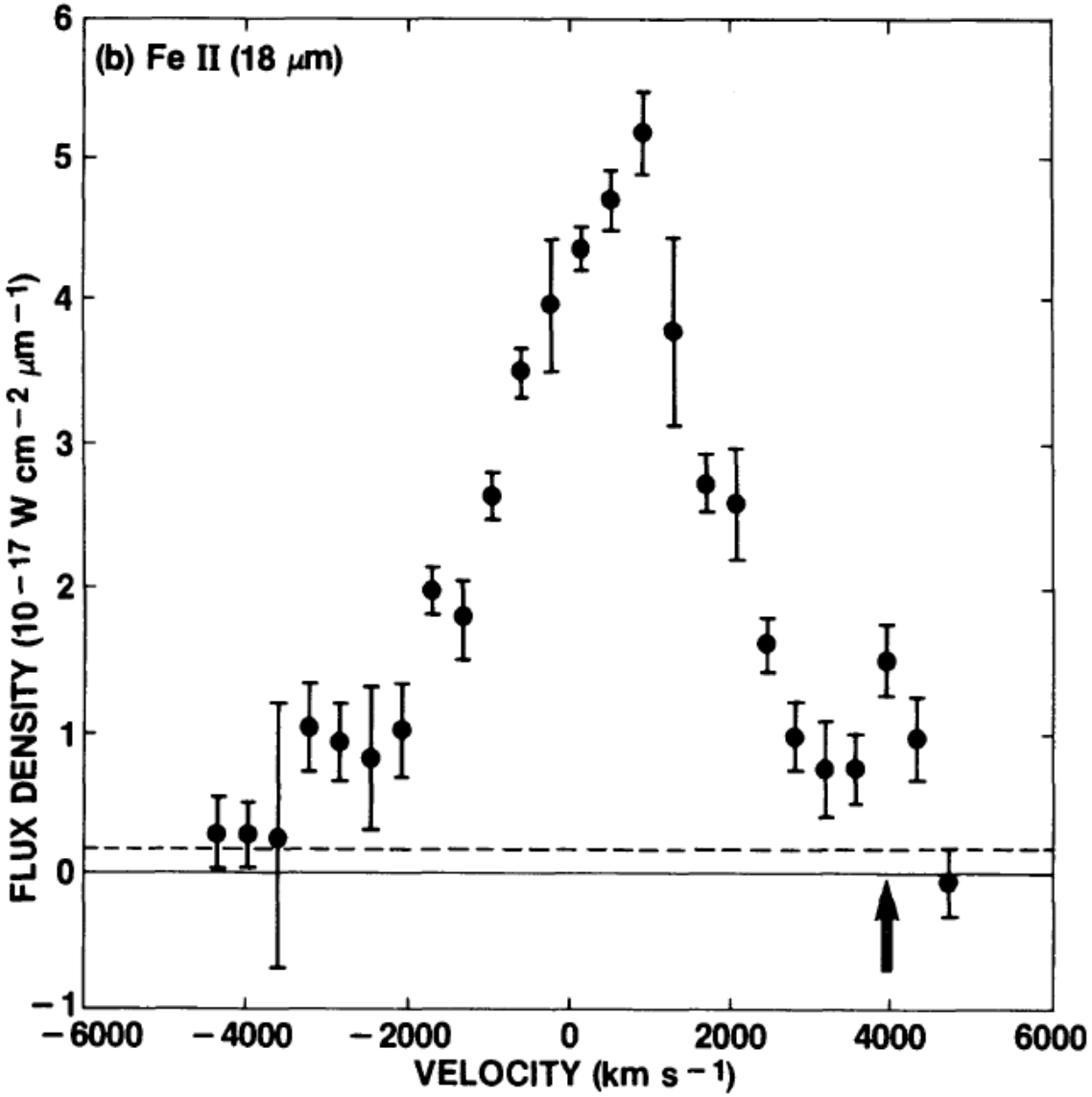
Matz et al. Nature 1988

$\sim(6\pm2)\times10^{-4}$ photons cm^{-2} s^{-1}

$\sim2.3\times10^{-4}$ M

~1.3% of the total mass of ^{56}Co

Velocity Profile of Iron（409days）

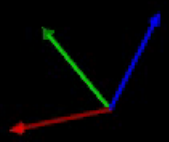


Haas et al. 1990

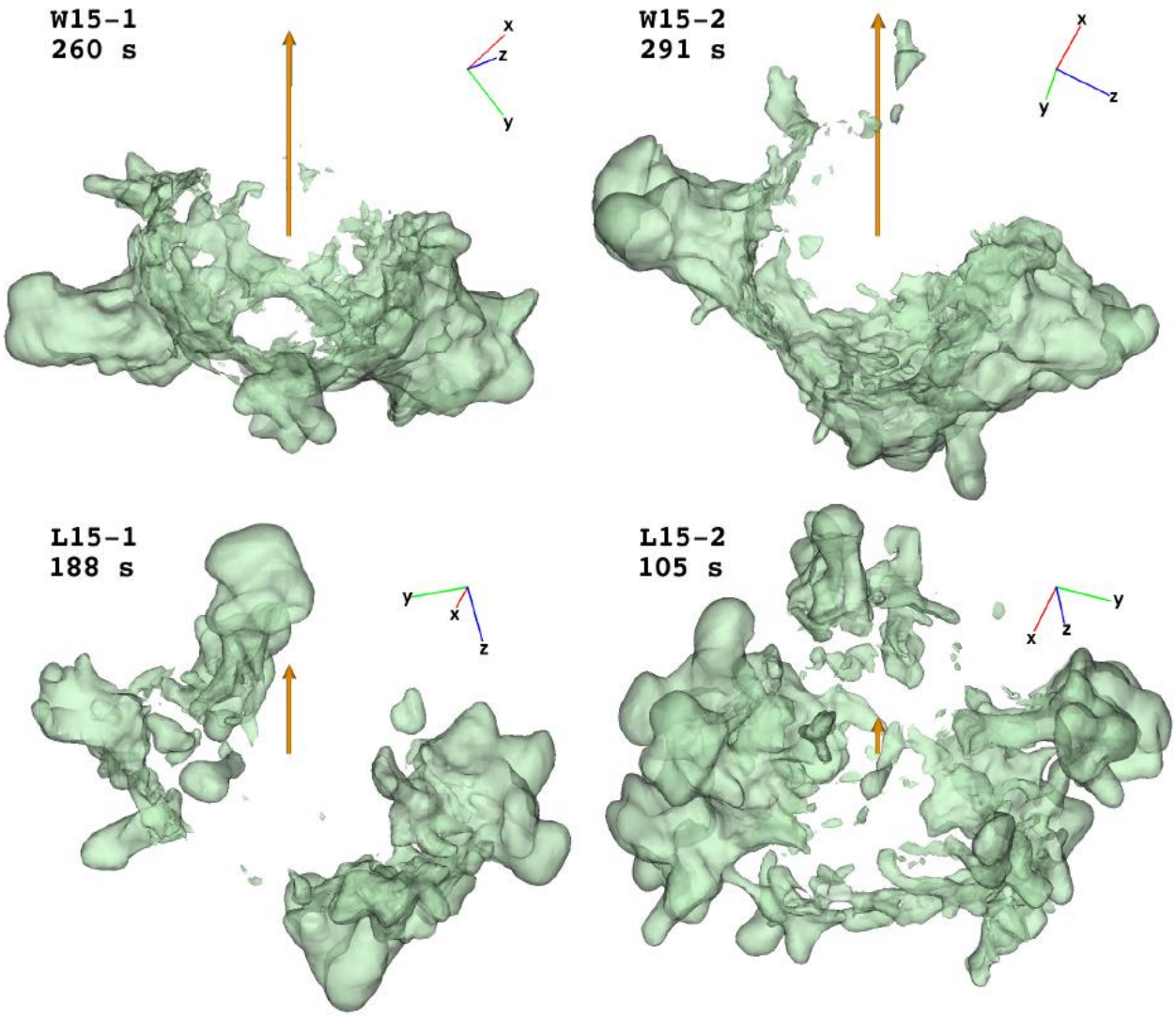
Asymmetric Explosion Can Happen Natulally

Model W15-6
Time: 15.10 ms
NS displacement: 0.00 km

A. Wongwathanarat
(MPA → RIKEN)

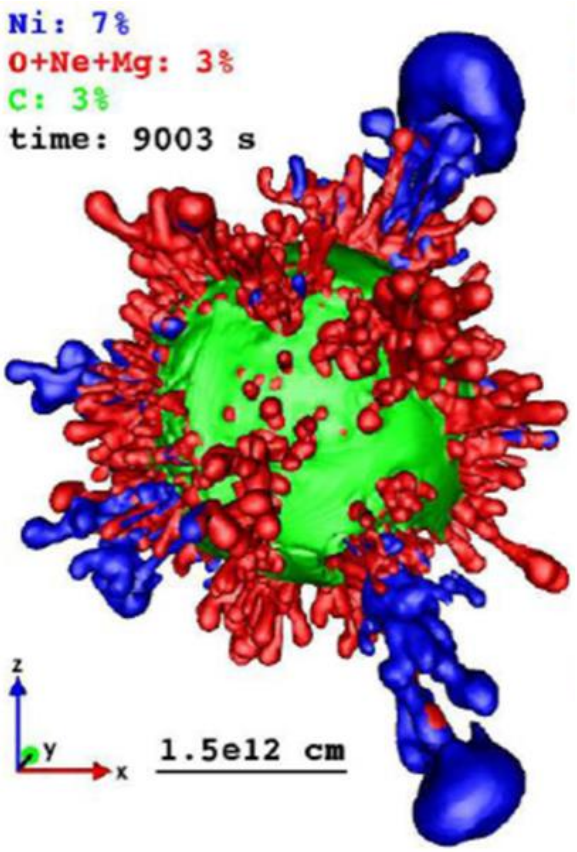


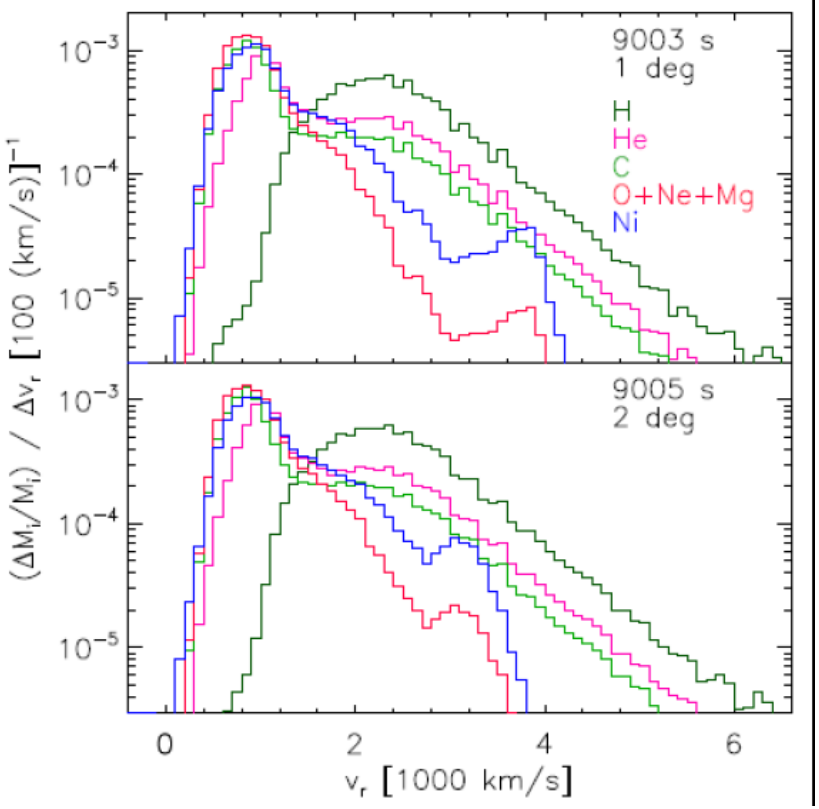
Asymmetric Ejection of 56Ni & Neutron Star Kick



A. Wongwathanarat
(RIKEN)

Successful Reproduction of High Velocity Component of 56Ni

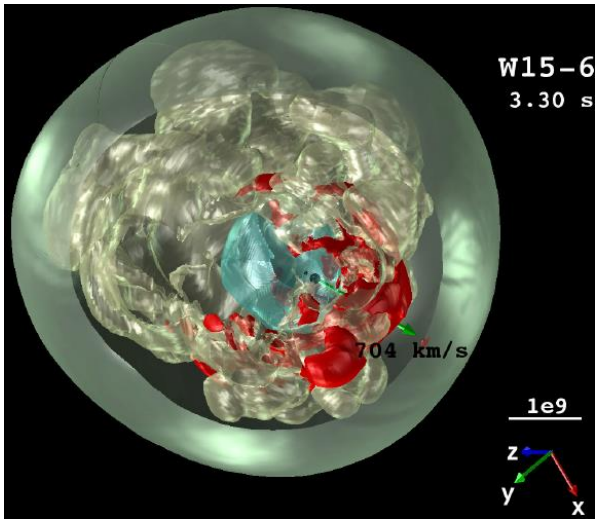


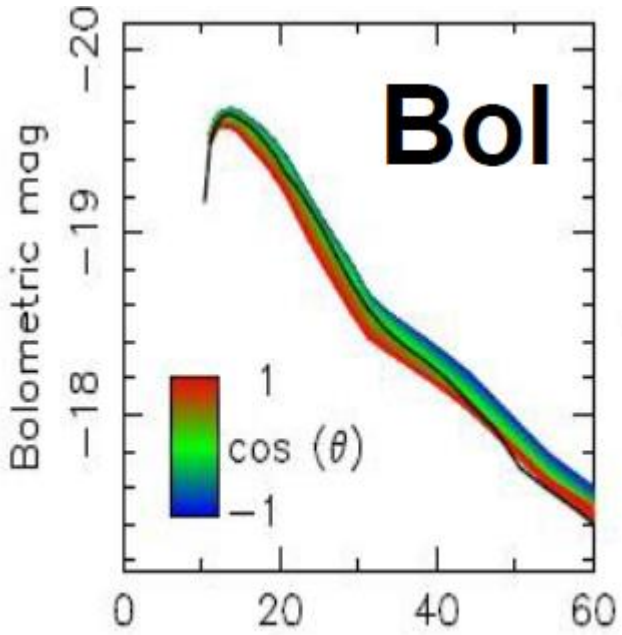


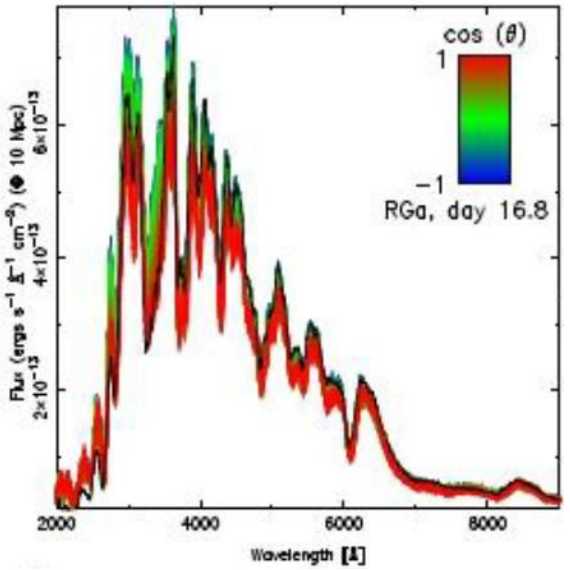
A. Wongwathanarat (RIKEN)

Great Collaborations Started

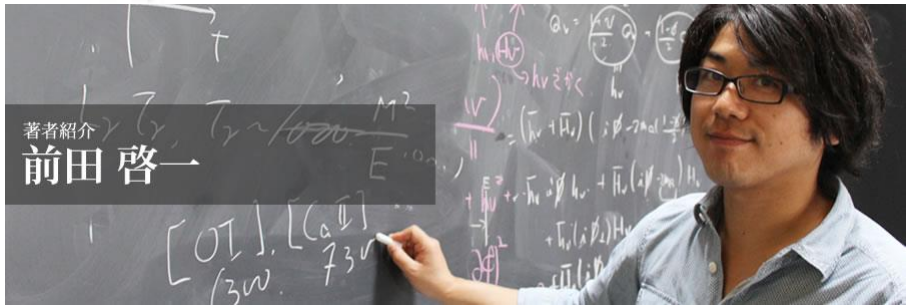
- Radiation Transfer, including Gamma-Ray Line Transfer.







Left:
A. Wongwathanarat (RIKEN)
Right:
K. Maeda (Kyoto)

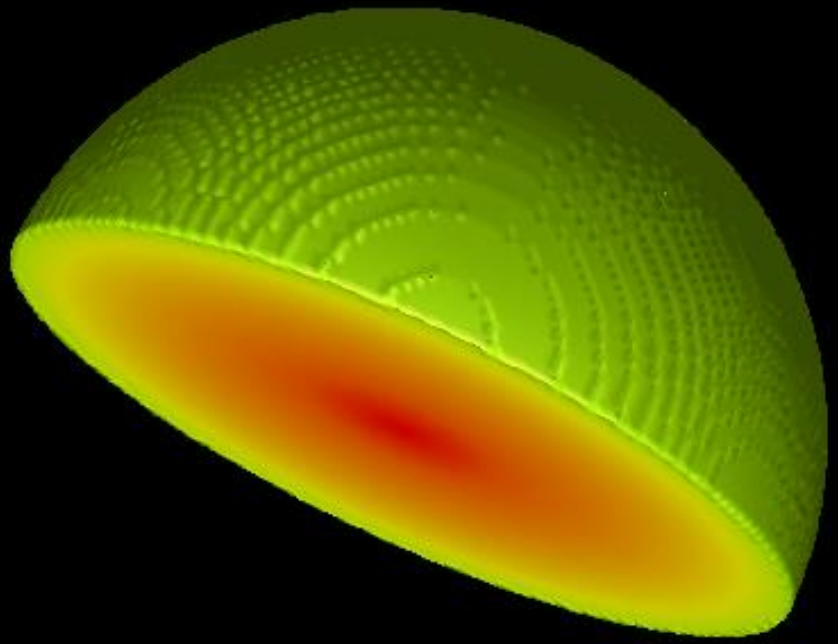


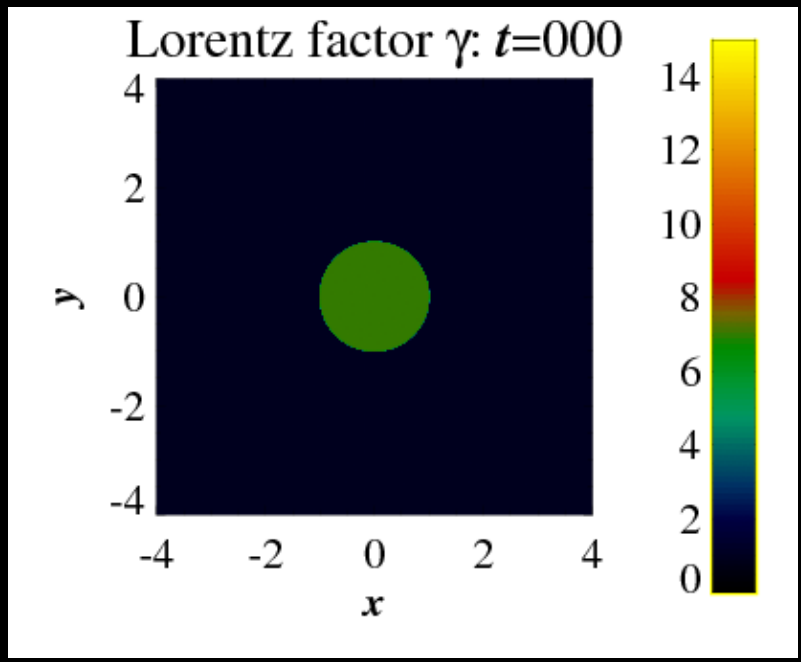
§ GRB Jets, Emissions, & Cosmology

How GRB Jet Propagates?

$$L_{\rm jet} = 10^{51}{\rm erg/s}$$
$$\gamma_{\rm jet} = 5$$
$$h_{\rm jet} = 41$$
$$\theta_{\rm jet} = 0$$
$$r_{\rm jet} = 10^{8}{\rm cm}$$

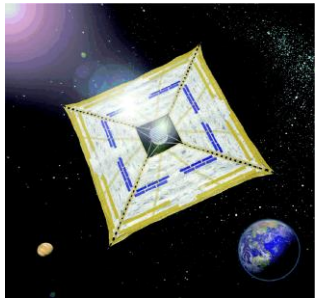
J. Matsumoto (RIKEN)



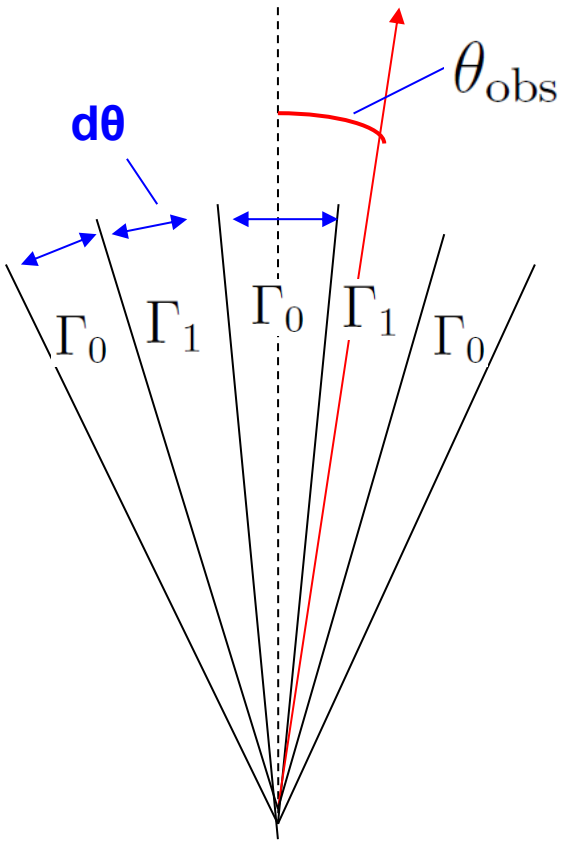


Structured Photospheric Emission Explains GRB Spectrum & Polarization Well

H. Ito
(RIKEN)

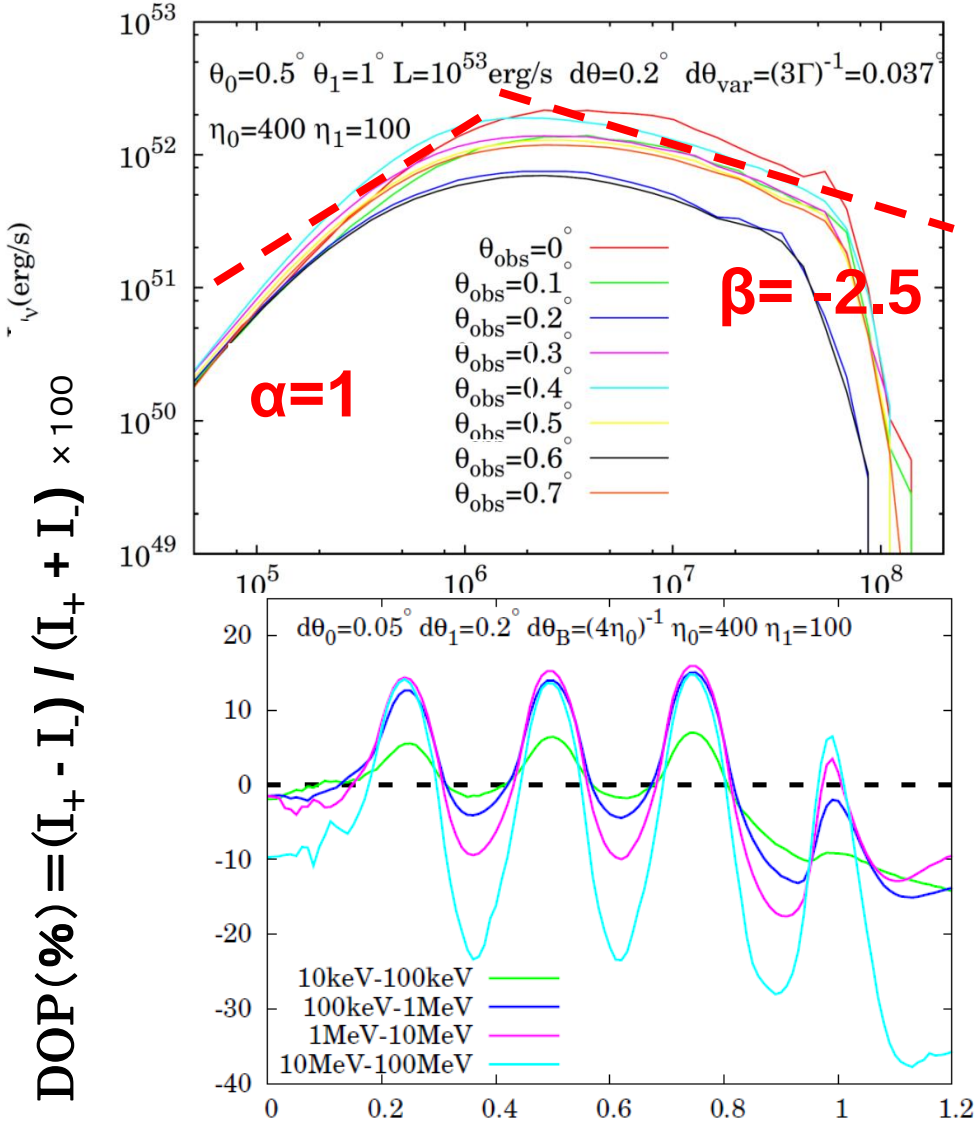


IKAROS, Japan
(2010-)

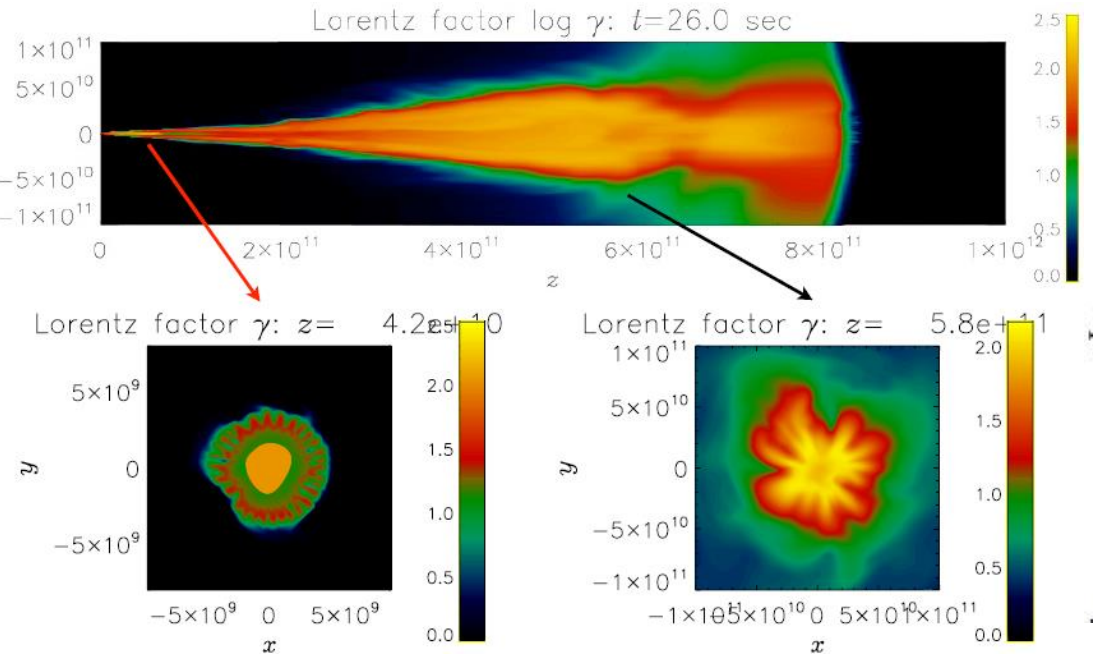


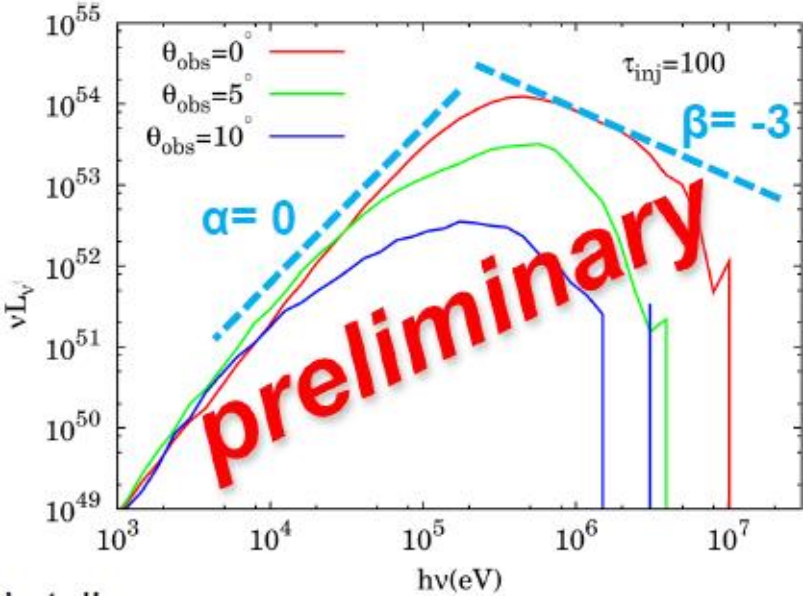
Γ_0=400 Γ_1=100

dθ～0.2°



Great Collaborations Started

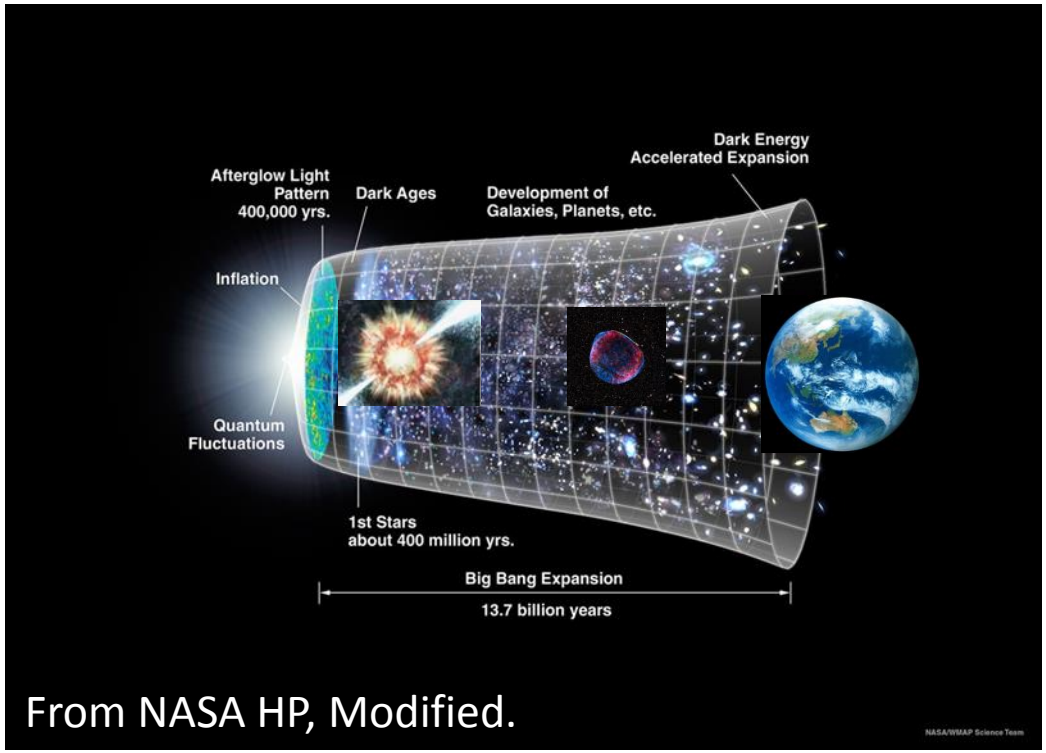




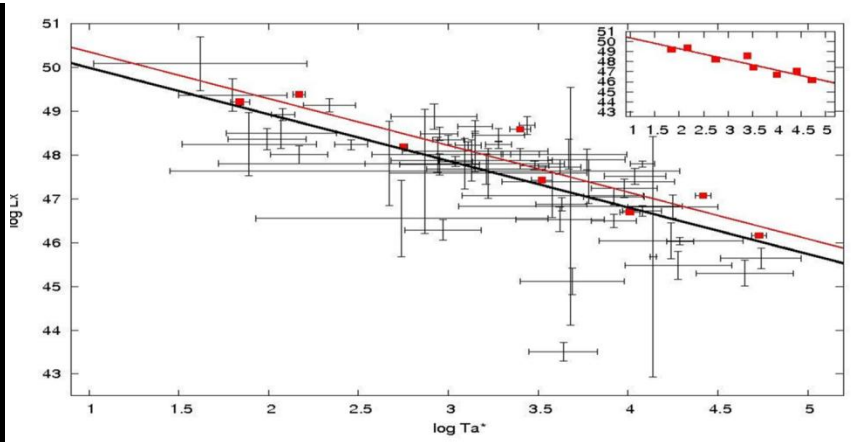
Left:
Jin Matumoto (RIKEN)

Right:
Hirotaka Ito (RIKEN)

Toward GRB Cosmology



From NASA HP, Modified.



Dainotti's Relation

Dainotti et al. (2010) , ApJ 722, 215

GRBs are the brightest objects, but their absolute luminosities are not constant. They are variable.

→ An Empirical Relation is necessary to deduce the Absolute luminosity of each GRB (The Longest Ladder in the Universe).

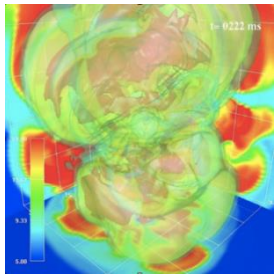
Maria Dainotti (RIKEN)
Awarded an Order of Merit of the Italian Republic for the Discovery (2013).

§ Supernova Remnants

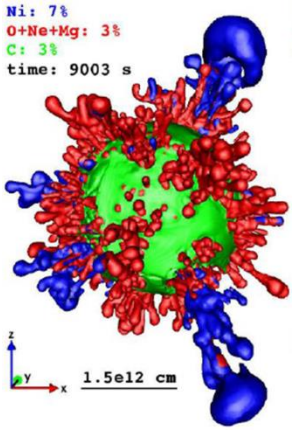
Our Big Challenge:

From (Takiwaki & Wongwathanarat) To (Lee, Ono, Warren)

T. Takiwaki
(RIKEN)



A. Wongwathanarat
(RIKEN)

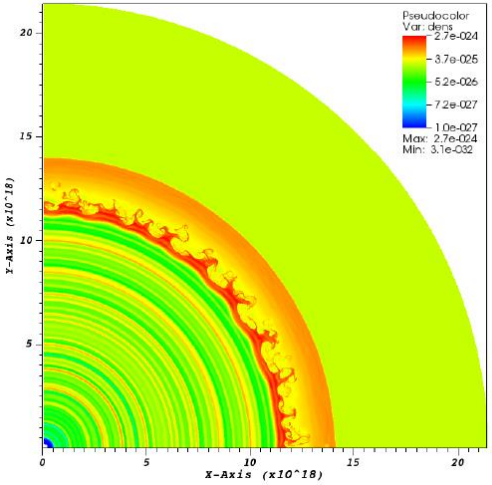


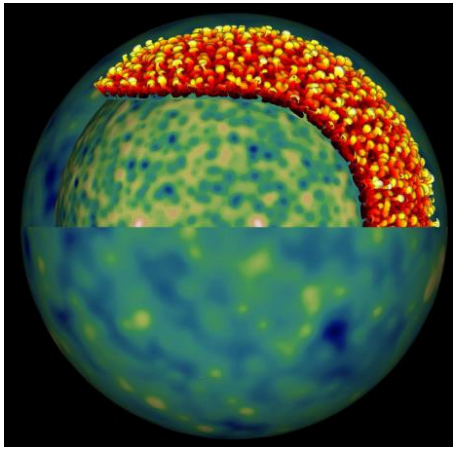
How do they Evolve?

Origin of Asymmetries?

Legacy of Supernovae?

Ono+14, in prep.





Warren & Blondin 13

S.H. Lee
(RIKEN→ JAXA)

M.Ono
(RIKEN→Kyushu U.)

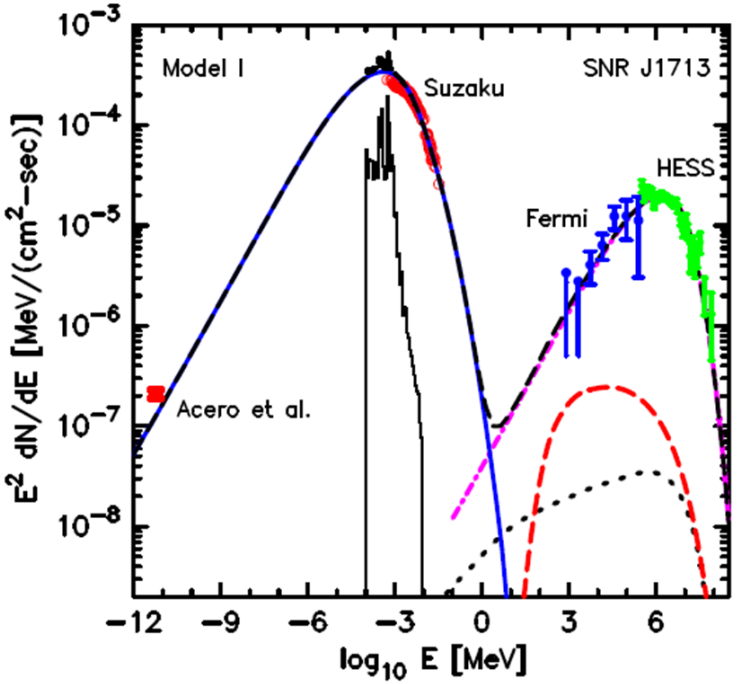
D. Warren
(NCSU→RIKEN?)

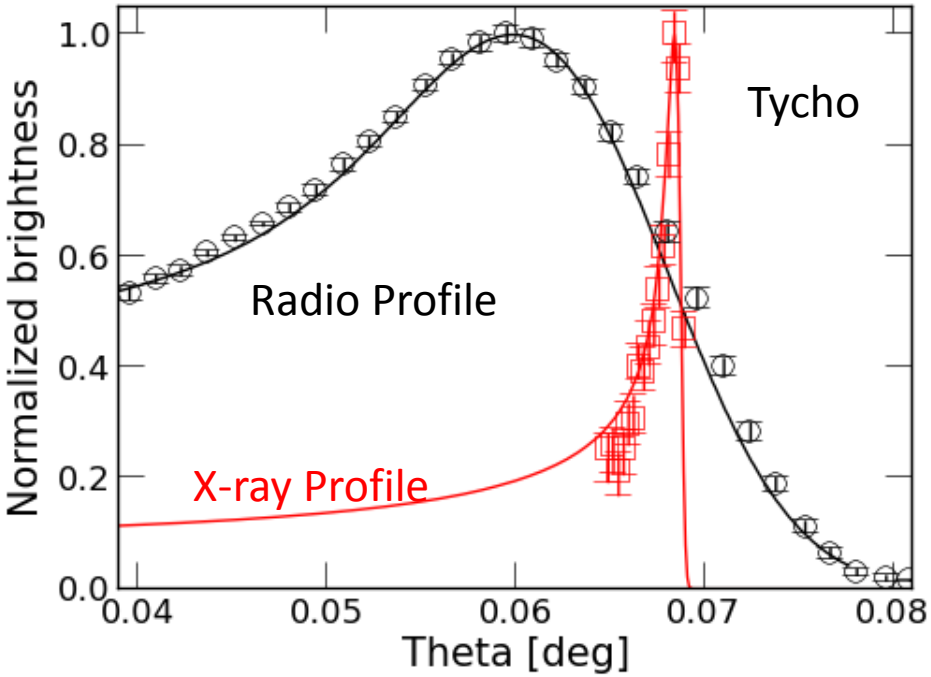
SNRs as Sites of Cosmic-Ray Accelerators

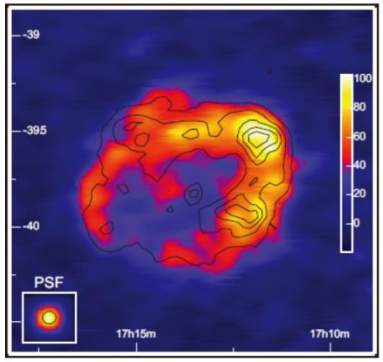
CR-HYDRO-NEI CODE

S.H. Lee (RIKEN→JAXA)

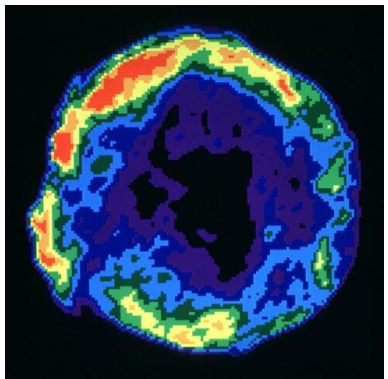
CR Production (Fermi 1st Order).
Hydro-Code (VH1) with Back-Reaction from CRs.
Ionization of Heavy Nuclei.

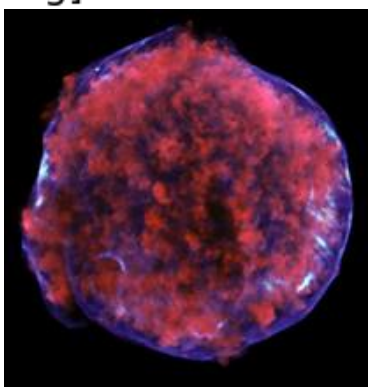






Left : RXJ1713
Rights :
Tycho（Left : Radio
Right : X-ray）.

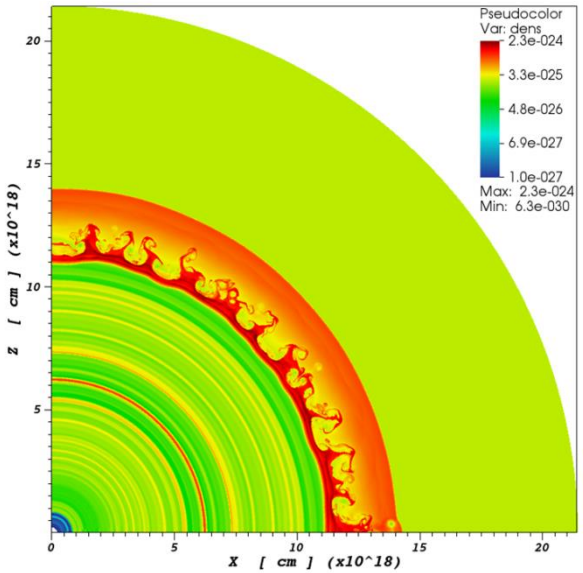




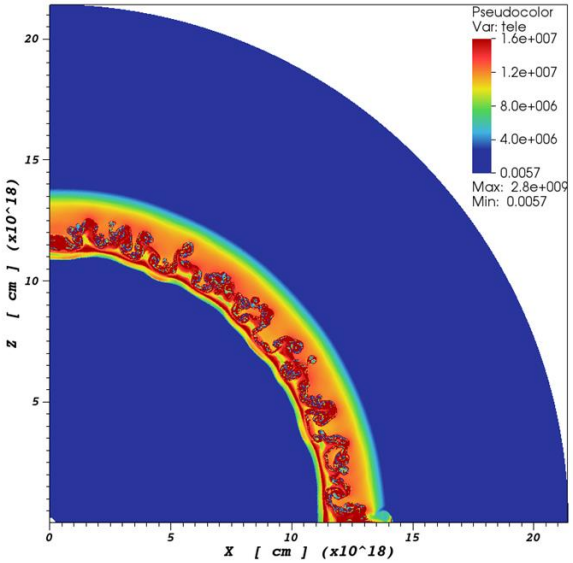
Multi-D Hydro-NEI for SNRs

FLASH with Electron Temperature & Ionization/Recombination

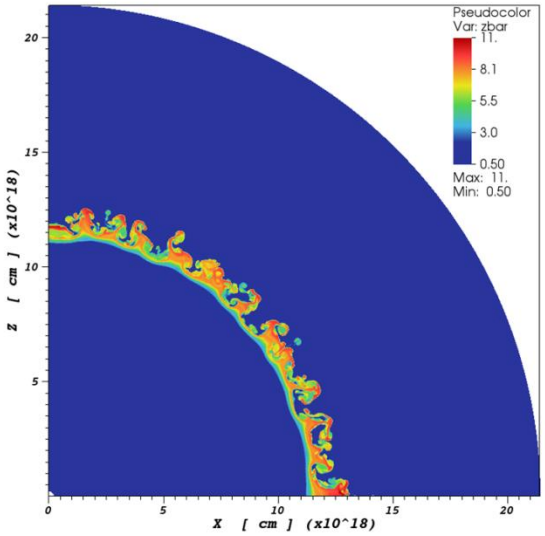
Density



Electron Temp.



Averaged Valence of Ion



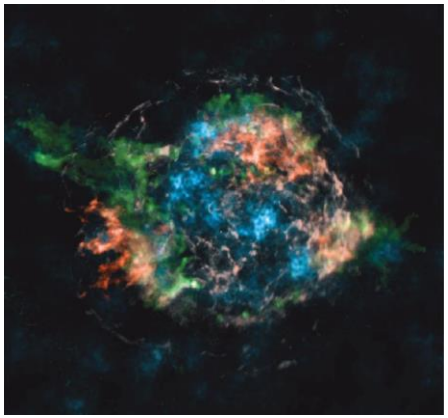


Image of Cas A.

M. Ono (RIKEN→Kyushu U.)

S.H. Lee (RIKEN→JAXA)

References of Our Group (Published Only)

- Supernova Simulations:

  Takiwaki, Kotake, Suwa ApJ 755 84 (2012); Kuroda, **Takiwaki**, Kotake PRD 89 id044011 (2014)
  Takiwaki, Kotake, Suwa ApJ 786 id.83 (2014)

- Gamma-Ray Burst Simulations:

  Nagataki ApJ 704 937 (2009); **Nagataki** PASJ 63 1243 (2011);
  Barkov & Komissarov MNRAS 385 28 (2008); Komissarov & **Barkov** MNRAS 394 1182 (2009)

- Nucleosynthesis & NS Kicks:

  Wongwathanarat et al. (2010), ApJL 725, L106; **Wongwathanarat** et al. (2013), A&A 552, A126

- GRB Jet, Spectrum, and Polarization

  Ito, **Nagataki**, **Ono**, **Lee**, **Mao**, Yamada, Pe'er, **Mizuta**, Harikae ApJ 777 id.62 (2013)
  Matsumoto & Masada ApJ 772 L1 (2013); **Teraki** & Takahara ApJ 735 id.44 (2011);
  Teraki & Takahara ApJ 763 id.131 (2013); **Teraki** & Takahara ApJ 787 id.28 (2014)

- GRB Relations for Cosmology:

  Dainotti, et al. MNRAS 391 79 (2008) ; Cardone, Capozziello & **Dainotti** MNRAS 400, 775 (2009);
  Dainotti, et al. ApJ 722, 215 (2010); Cardone, **Dainotti** et al. MNRAS, 408,1181 (2010);
  Dainotti, et al. MNRAS 418 2202 (2011); **Dainotti**, et al. APJ, 730,135, (2011); **Dainotti**, et al. MNRAS,436,82 (13)
  Dainotti, et al. ApJ, 774, 157 (2013); Postnikov, **Dainotti**, hernandez, Capozziello ApJ 783 id.126 (2014)

- Supernova Remnants:

  Lee, Ellison, **Nagataki** ApJ 759 id.70 (2012)
  Lee, Slane, Ellison, **Nagataki**, Patnaude ApJ 767 id.20 (2013)
  Slane, **Lee**, Ellison, Patnaude, Hughes, Eriksen, Castro, **Nagataki** ApJ 783 id.33 (2014)
  Lee, Patnaude, Ellison, **Nagataki**, Slane ApJ 791 id.97 (2014)
  Warren, Blondin MNRAS 429 3099 (2013)

References in Slides

- Neutrino Signals from SN1987A detected by KAMIOKANDE: Hirata, Kajita, Koshiba, Nakahata, Oyama PRL 58 1490 (1987)
- Velocity Profile of Fe in SN1987A: Spyromilio, Meikle, Allen MNRAS 242 669 (1990)
- Image of RXJ1713: Aharonian+06 A&A 449 223; Koyama+97 PASJ 49 L7
- X-ray/Radio Images of Tycho: Warren+05 ApJ 634 376; Reynoso+97 ApJ 491 816
- Image of Cas A: Grefenstette+14, Nature, 506, 339

Summary

- Super-Computing of CC-SNe & GRBs with K(10Peta)- and Post-K (Exa) Computers in RIKEN for Full-Understanding their Explosion Mechanisms is Our Grand Challenge.
- Resulting Neutrino Signals and GWs can be Detected by SK/HK and KAGRA (and ALIGO/AVIRGO) in the (Near) Future.
- Asymmetric Explosions & Neutron Star Kicks Happen Naturally, which Affects on Nucleosynthesis. Great Collaborations to Calculate SN Light Curve & Spectrum.
- 3D GRB Jet Propagation with Magnetic Fields are being Simulated. Structured Photospheric Emission Model can Explain GRB Spectrum & Polarization.
- Dynamics and Physics in SNRs are Very Exciting, which can be Confirmed by Current and Future Observations (e.g. Chandra, Astro-H, HESS, CTA, …).
- Our Group is Ready to Challenge Ourselves to Understand the Whole Sequence of Astrophysical Big Bangs (Supernovae and Gamma-Ray Bursts): From Engine to Remnants.