

Astrophysical Big Bang Simulations



Shigehiro Nagataki

12-19 September 2015, Moorea, French Polynesia: Presentation Date: 14 Sep.

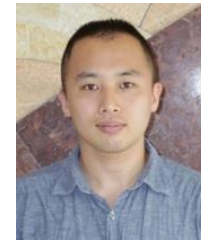
PACIFIC 2014



Astrophysical Big Bang Lab.

From 1st Apr. 2013

- PI: Nagataki
- Current PDs: Ito, Matsumoto, Barkov, Takiwaki, Wongwathanarat, Warren, Wada, Inoue, Tanaka: iTHES
- Future PD: Yokokura from Nov. 2015: iTHES
- Alumni: Ono (Kyushu Univ.), Lee (JAXA), Tolstov (Kavli IPMU), Mao (Yunnan Obs.), Dainotti (Stanford), Teraki (RIKEN)
- Long Term Visitor in FY2015: Fujimoto (Kumamoto Nat. Inst. Tech.)



iTHES : Interdisciplinary Theoretical Science

(FY2013-FY2017) \$6M. Will be Extended?



Tetsuo Hatsuda
Group Director



S. Nagataki
A Team Leader



A. Tanaka



Y. Yokokura
(From Nov.2015) → Sophia U.



S. Wanajo

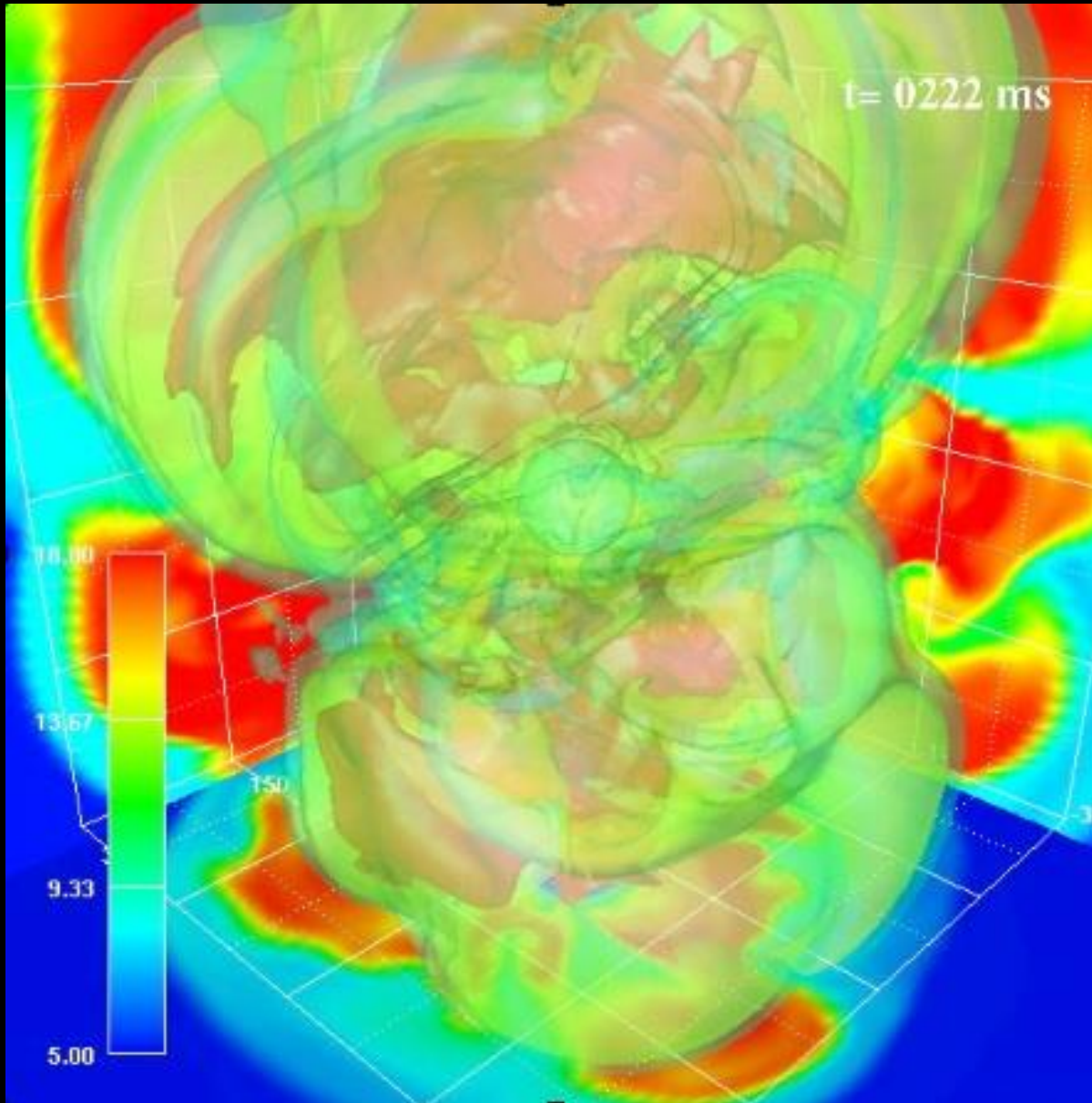


K. Kyutoku



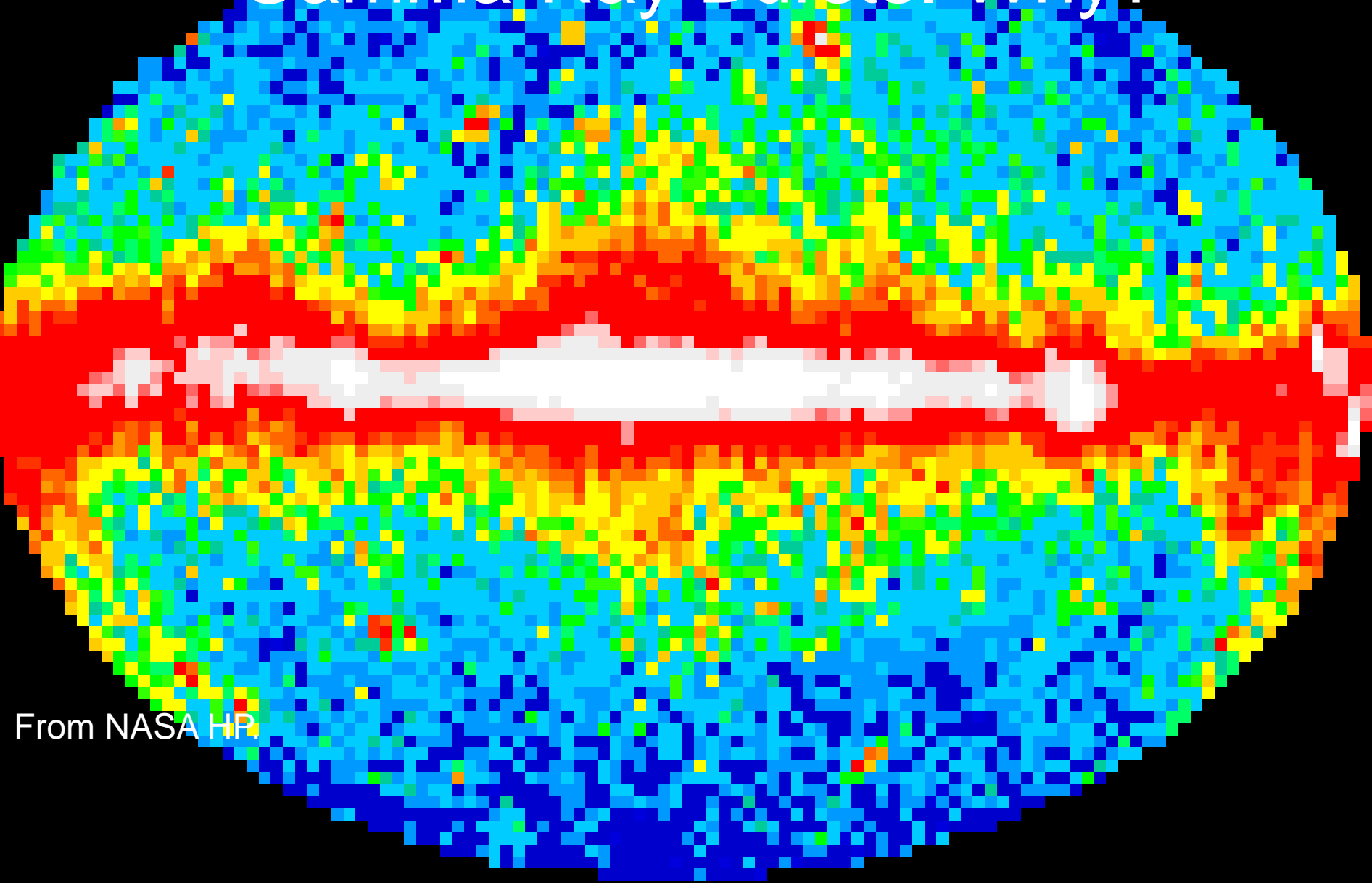
T. Terasawa

Massive Stars Explode. Why?



Simulation by
T. Takiwaki
(RIKEN)

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



From NASA HP

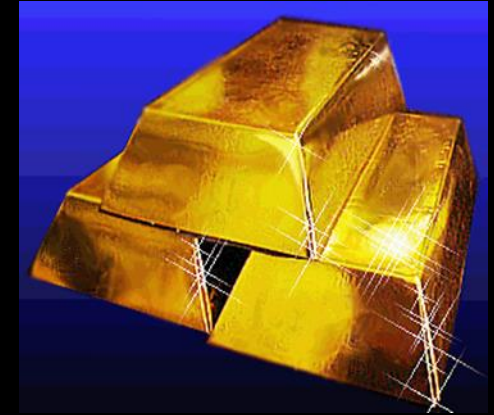
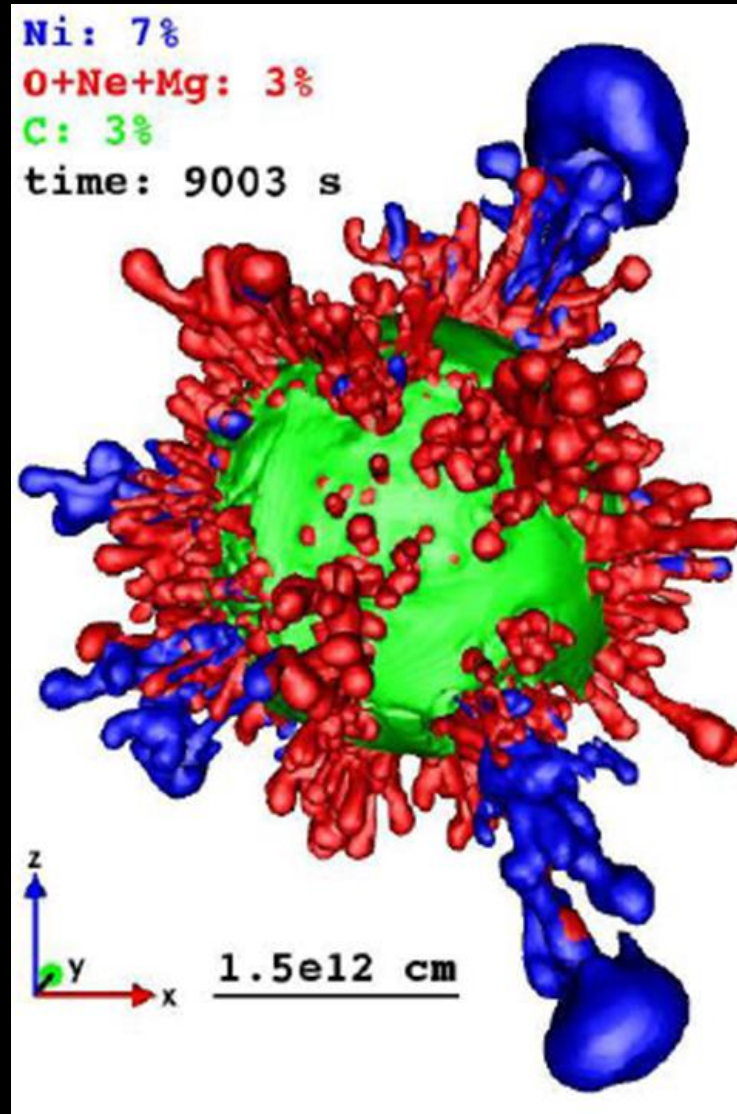
Supernovae are Origin of Heavy Metals. But what kind of metals are really produced?



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)



H. Ito (RIKEN)



J. Matsumoto (RIKEN)

Are Gamma-Ray Bursts the Greatest Particle Accelerators ?

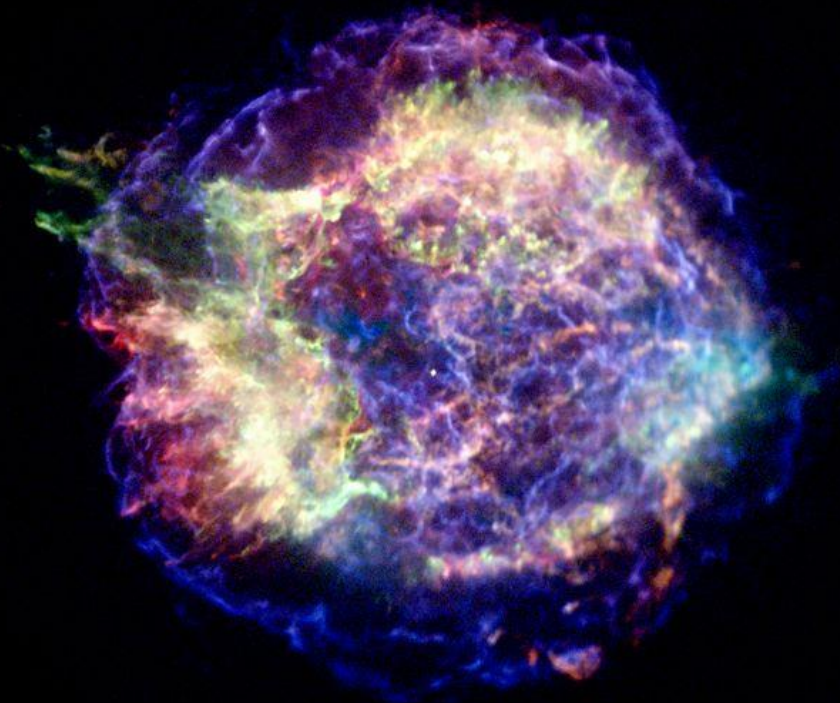


Susumu Inoue
(MPP→RIKEN)

Figure (Imagination):
© A. Roquette (ESO)

Extra-Galactic
UHECRs?
Neutrinos?
TeV Gamma-rays?

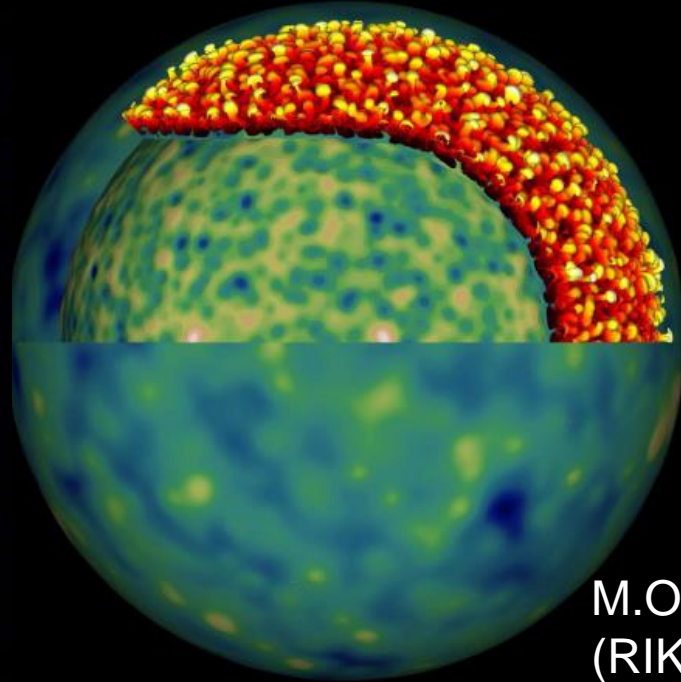
Lots of Mysteries & Physics in Supernova Remnants



Observation

Cassiopeia A (350 years old)
By Chandra Satellite

Cosmic-Ray Production? Morphology?
Composition?



Simulation

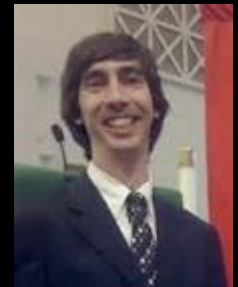
by D. Warren



S.H. Lee
(Stanford→
RIKEN→JAXA)

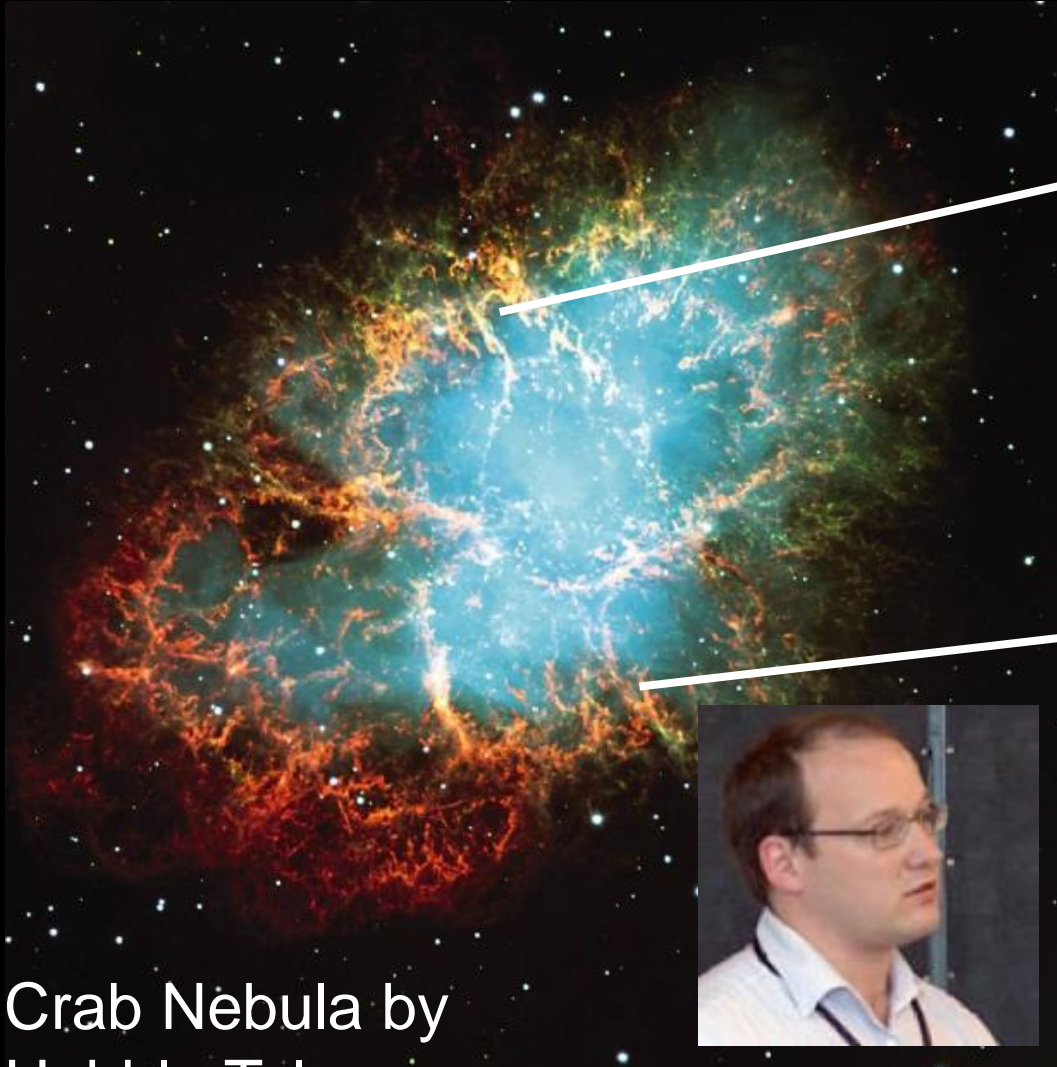


M. Ono
(RIKEN→Kyushu U)

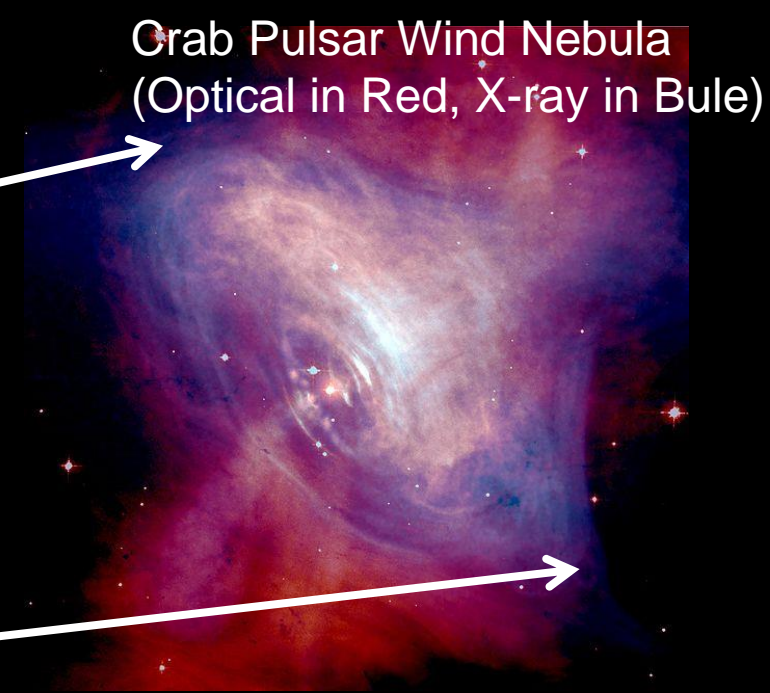


D. Warren
(NCSU→RIKEN)

Can We Understand Neutron Stars & Pulsar Wind Nebulae?



Crab Nebula by Hubble Telescope



Crab Pulsar Wind Nebula (Optical in Red, X-ray in Blue)



M. Barkov (RIKEN)



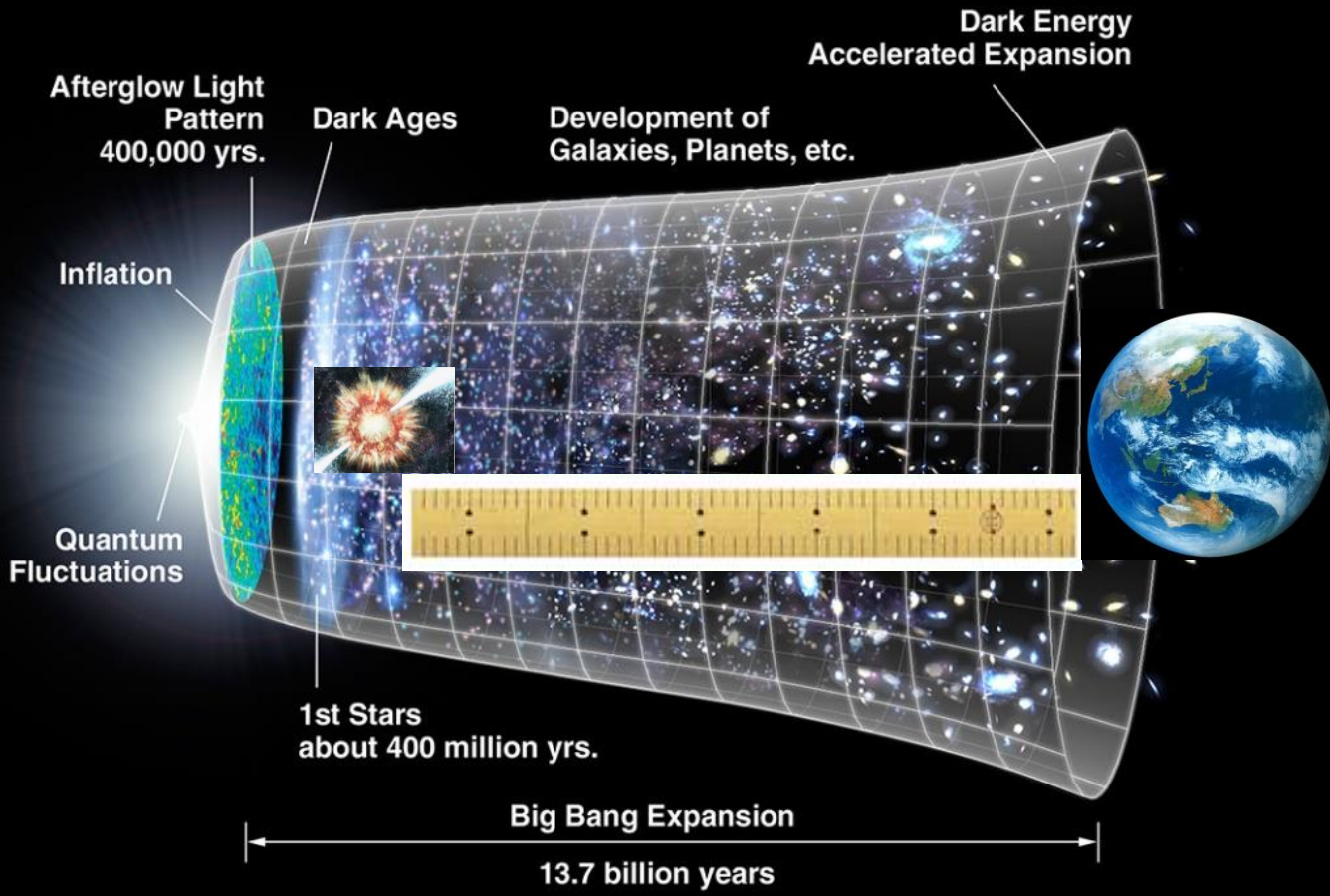
T. Wada (RIKEN)



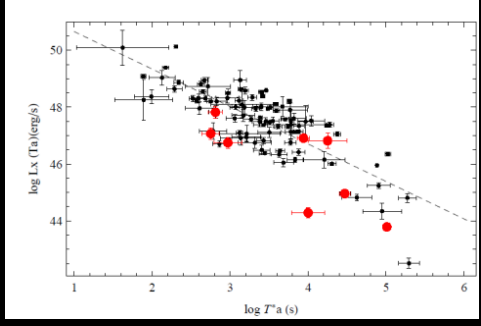
Y. Teraki (RIKEN)

Can Gamma-Ray Bursts be the Longest Cosmic Rulers?

From WMAP HP. Modified.



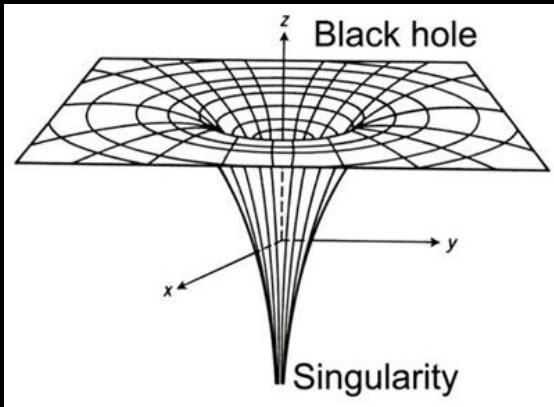
M. Dainotti
(RIKEN → Stanford)



The Dainotti's Relation

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

Formation of a Black Hole: Related with Creation/End of the Universe?



Analogy?

Common Physics?

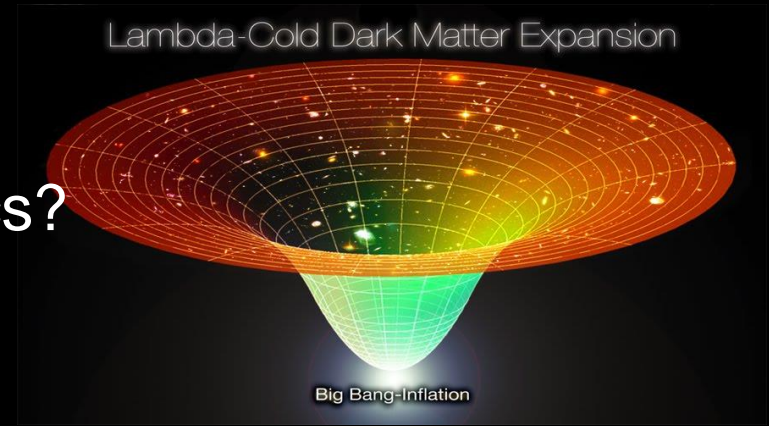
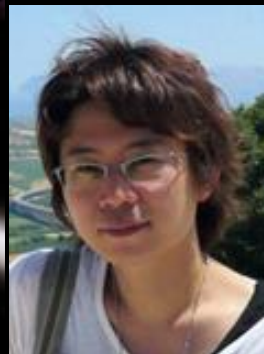


Figure from Universetoday



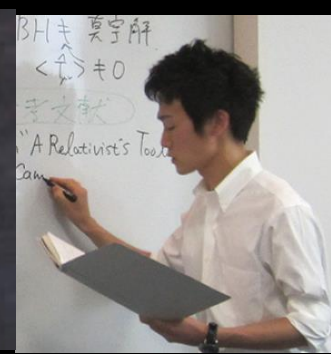
Engine of GRBs.
BH is formed?



S. Nagataki
(RIKEN)



M. Barkov
(RIKEN)



Y. Yokokura
(iTHES)



A. Tanaka
(iTHES)

Our Group Members and Collaborators

From 1st April 2013

~Toward Full-Understanding of Supernovae and GRBs~

- Central Engine: Nagataki (PI), Takiwaki, Barkov, Baiotti (Osaka)
- Neutron Star/Pulsar: Teraki, Wada
- Explosive Nucleosynthesis: Wongwathanarat, Fujimoto, Wanajo, Mao
- Shock Breakout/Light Curve/Spectrum: Tolstov, Blinnikov (ITEP), Maeda (Kyoto), Tanaka (NAOJ)
- Propagation of Relativistic Jet (GRBs): Matsumoto, Mizuta
- Gamma-Ray Emission (GRBs): Ito, Pe'er (UCC)
- Afterglow(X-ray,Opt,Radio): Warren, Ellison (NCSU), MacFadyen(NYU).
- Remnants: Lee, Ono, Warren, Slane (CfA), Patnaude (CfA)
- UHECRs, VHE-neutrinos/gamma-rays: Inoue, Kusenko (UCLA), He (UCLA/PAO), Allard (APC)
- GRB Cosmology: Dainotti
- The Universe itself: Tanaka, Yokokura

... and More!

Small
Radi



Large
Radi

§ 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 of RIKEN

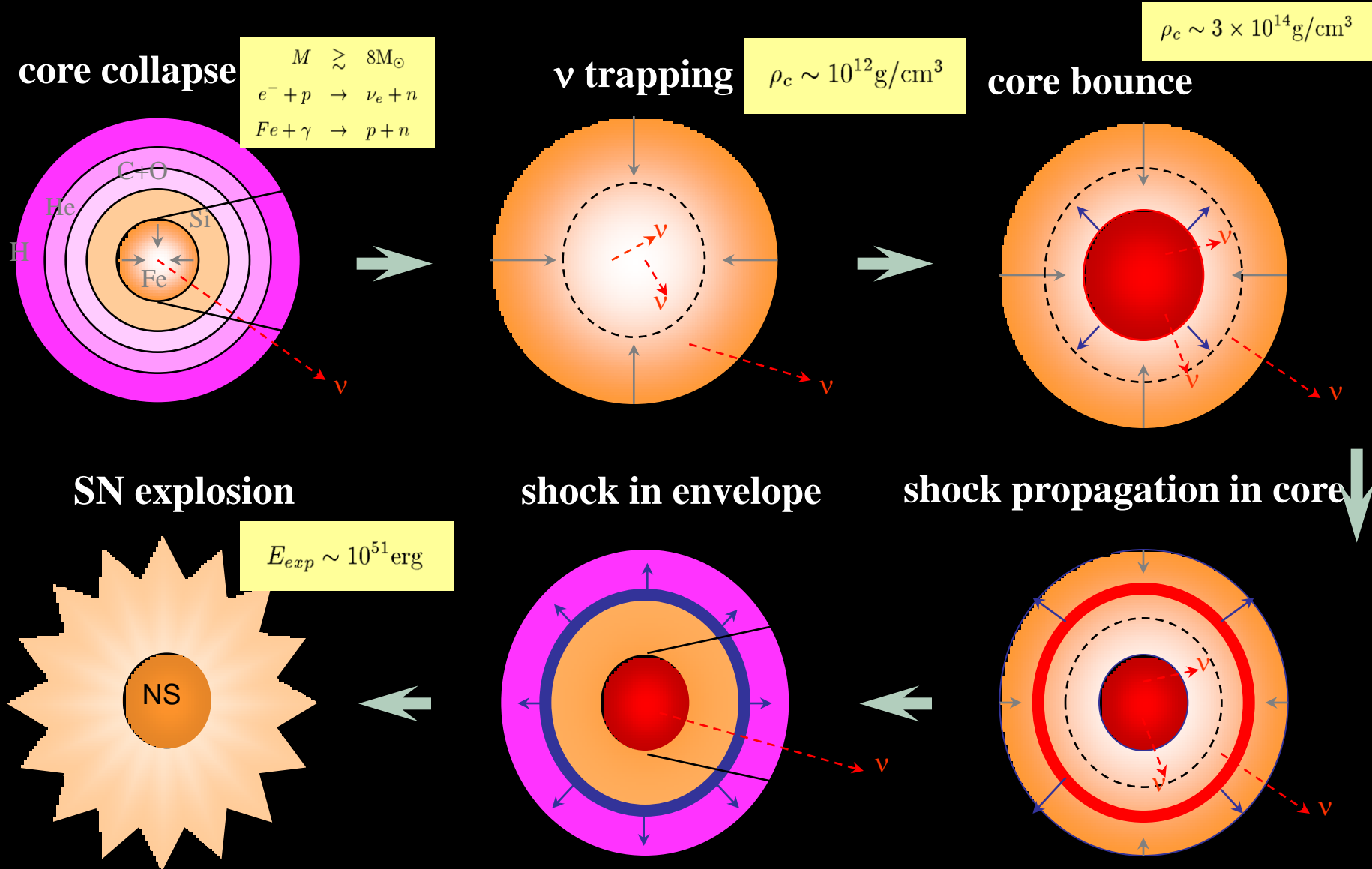
京(KEI) = 10 Peta=10¹⁶.



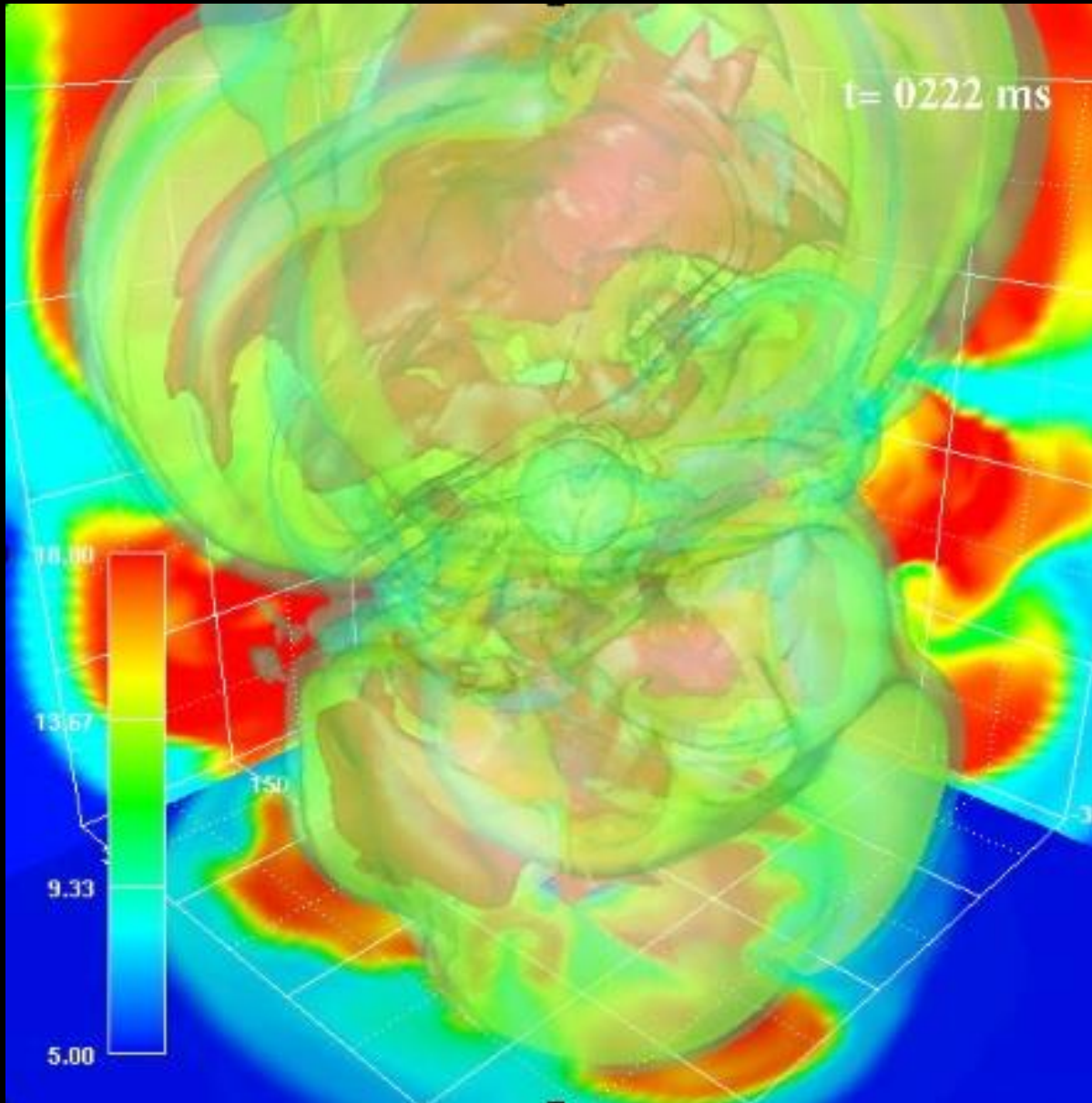
T. Takiwaki (RIKEN)

- 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.

The Explosion Mechanism is Being Unveiled

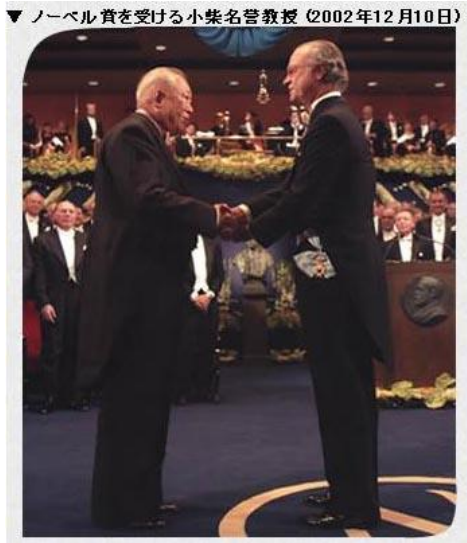


Almost Exploded.

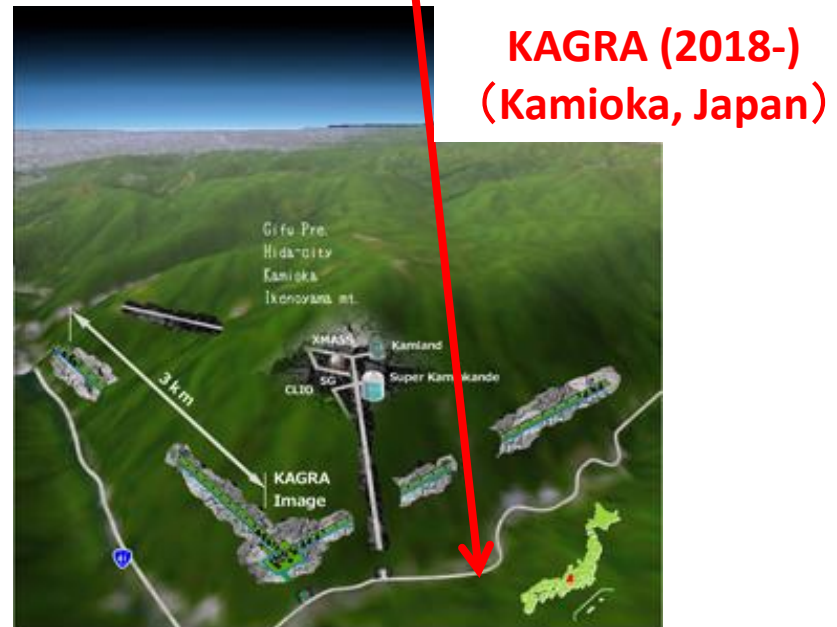
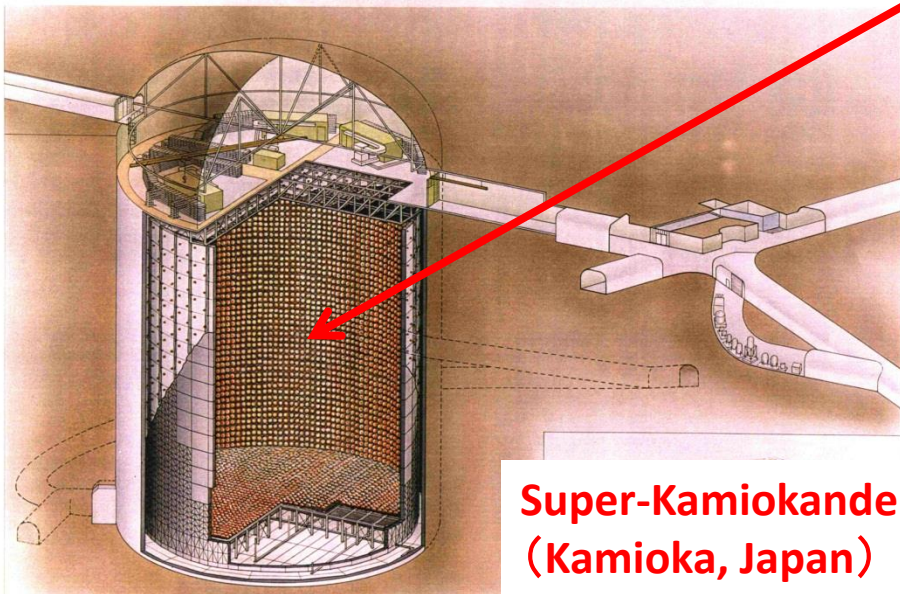
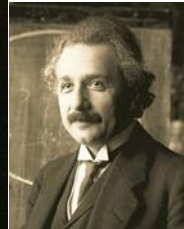
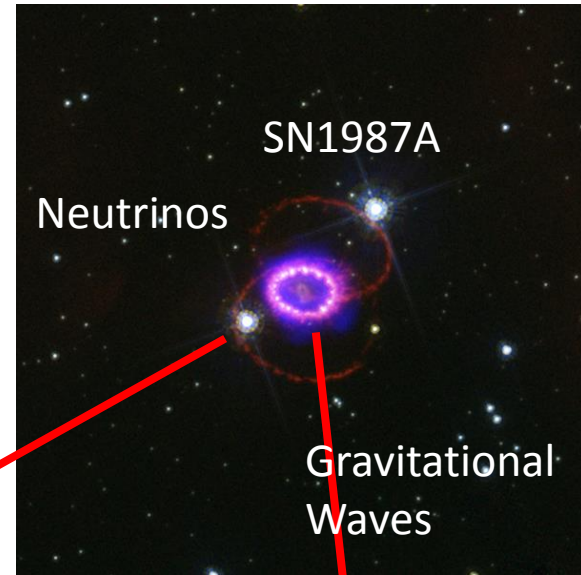
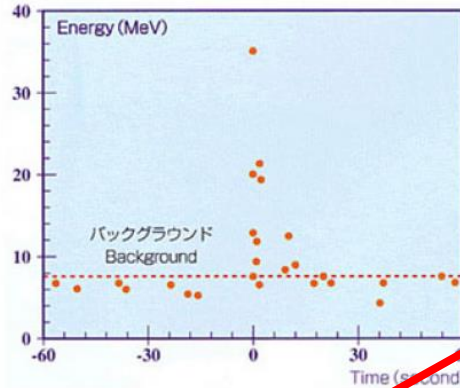


Simulation by
T. Takiwaki
(RIKEN)

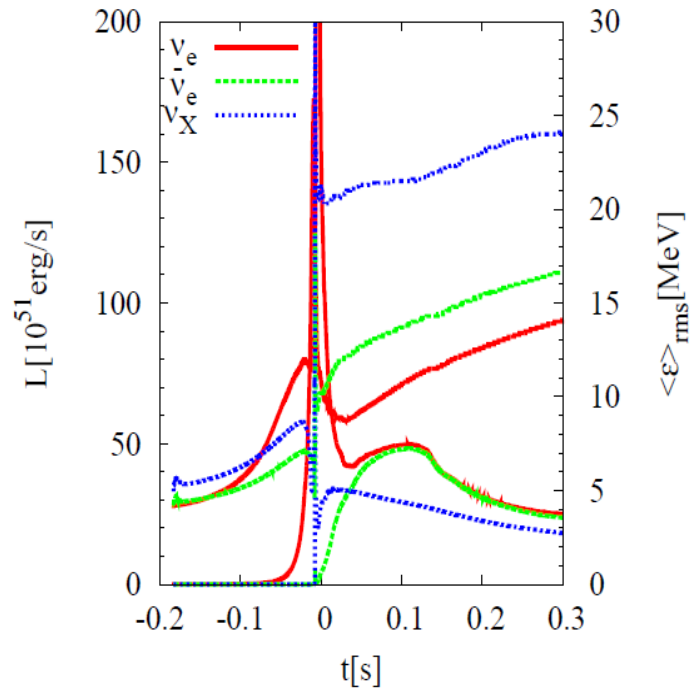
Supernova as a Source of Neutrinos and GWs



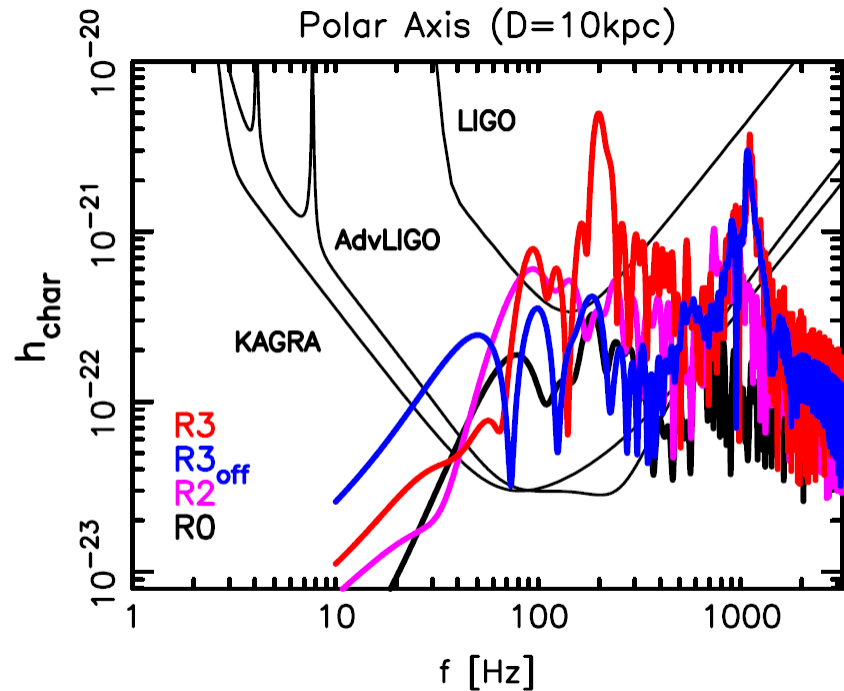
Prof. M. Koshiba,
Awarded the Nobel Prize
in Physics (2002).



Neutrino/GW Signals from a SN



Time Evolution of Neutrino Luminosity



Signal of Gravitational Wave in Freq. Space

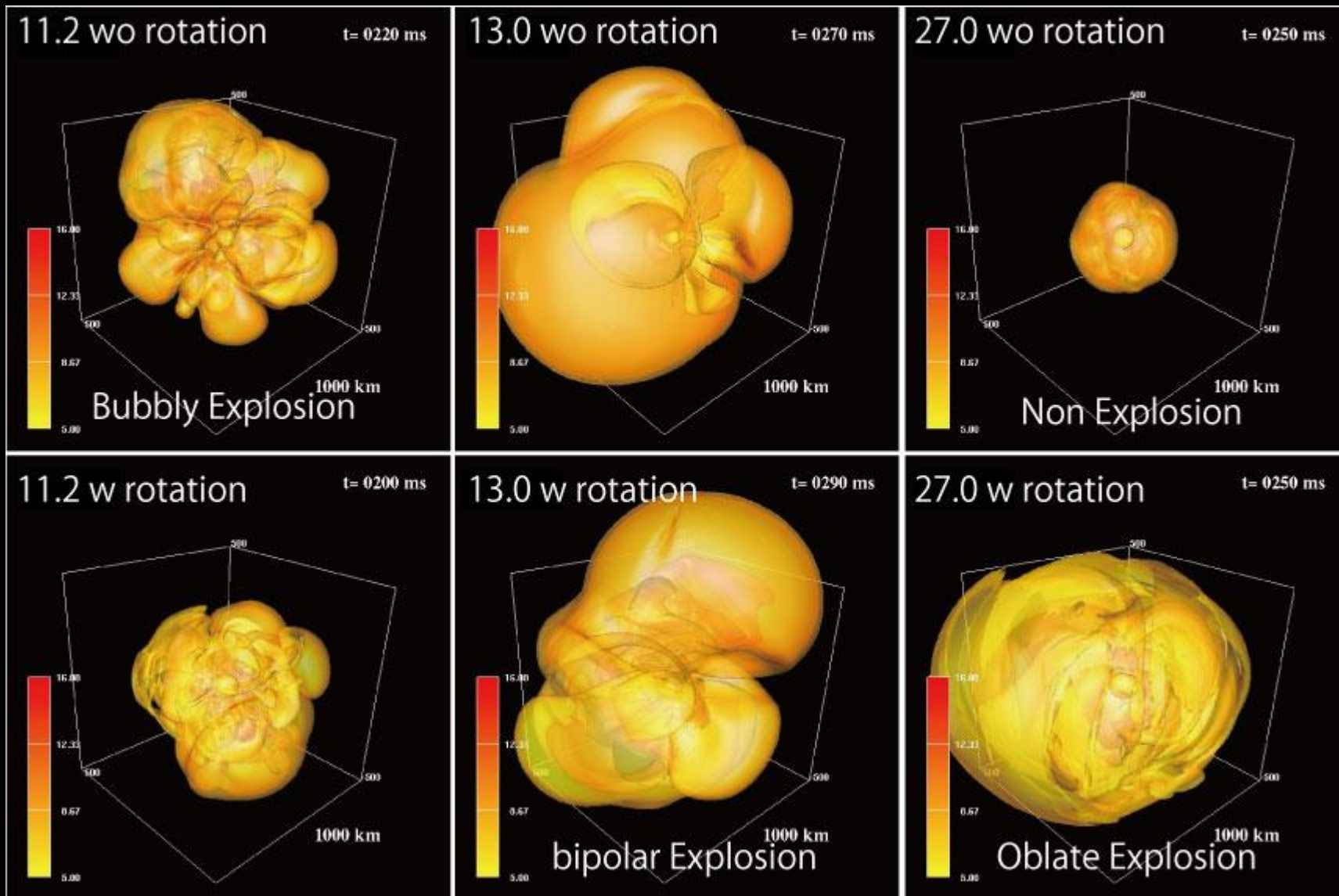


T. Takiwaki
(RIKEN)

Rotation Can Change the Dynamics

Spiral Waves Convey Rotation Energy Outside.

The Dynamics Depends on Progenitor Structures & Their Rotation.



Pan Kuo-Chuan May Join Us from FY2016!

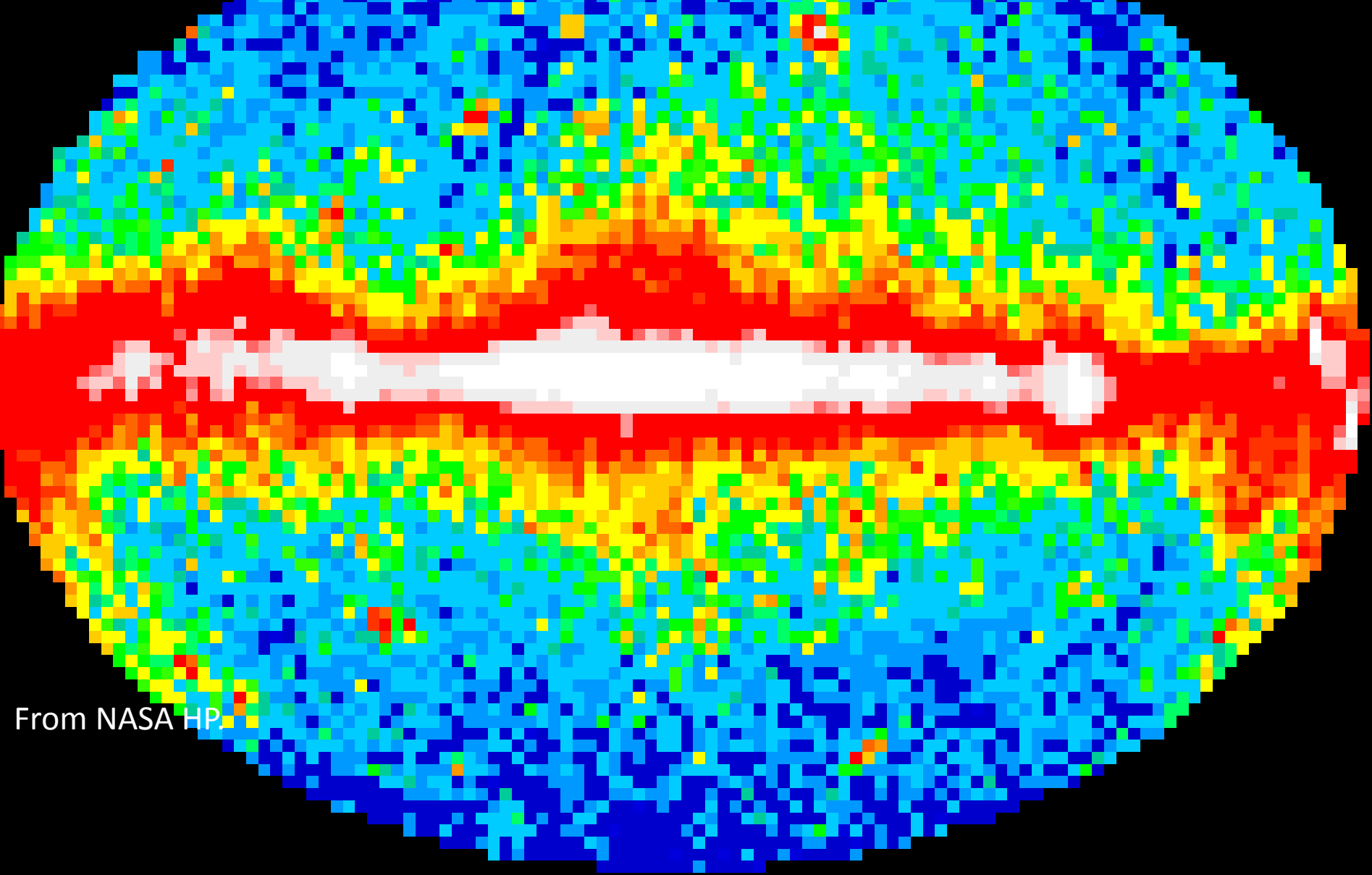


3D simulations of CC-Sne using FLASH AMR & IDSA
(Published as Pan et al., 2015, in prep.)



§ Engine of Gamma-Ray Bursts

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



From NASA HP.



Imagination of a Gamma-Ray Burst

From NASA HP

Central Engine of Gamma-Ray Bursts is Hardly Known.



?

A Black Hole is Formed in a Gamma-Ray Burst?

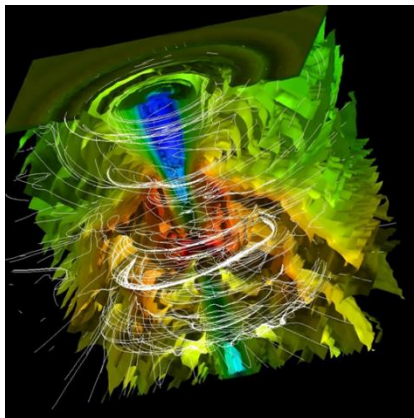


S. Nagataki
(RIKEN)

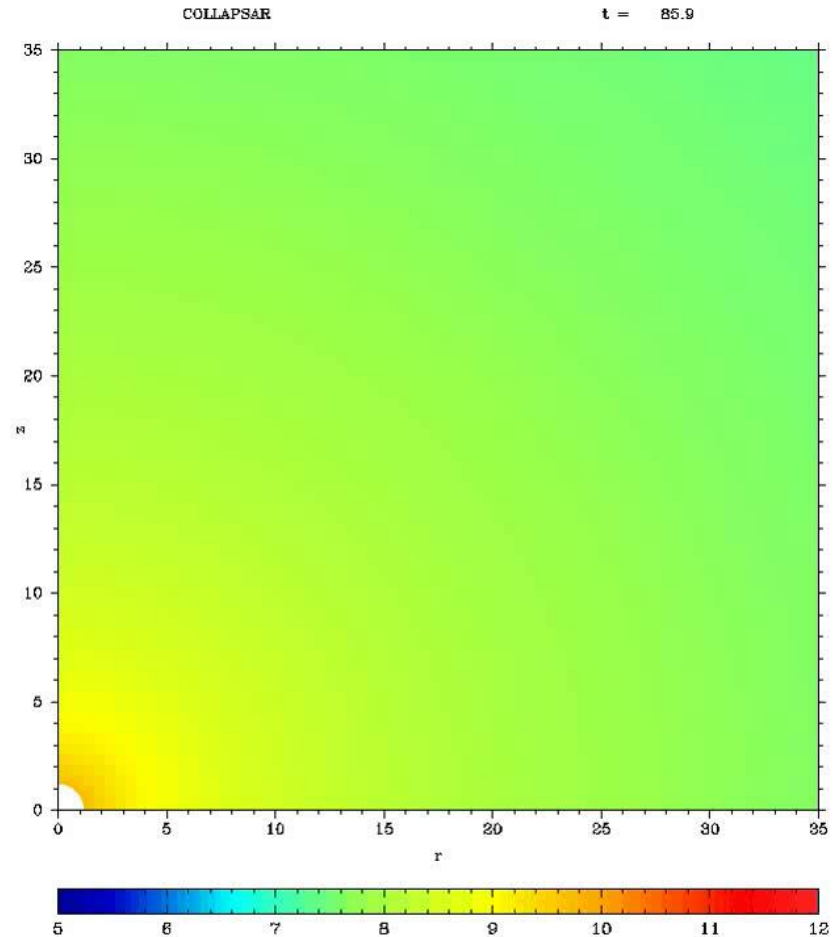


M. Barkov
(RIKEN)

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



Rotation Axis



Equatorial Plane

Rotation Energy of a BH can be Extracted
efficiently with a help of EM Field (BZ-Process).

Our Roadmap to Develop the “Complete” Code

2 Big Issues

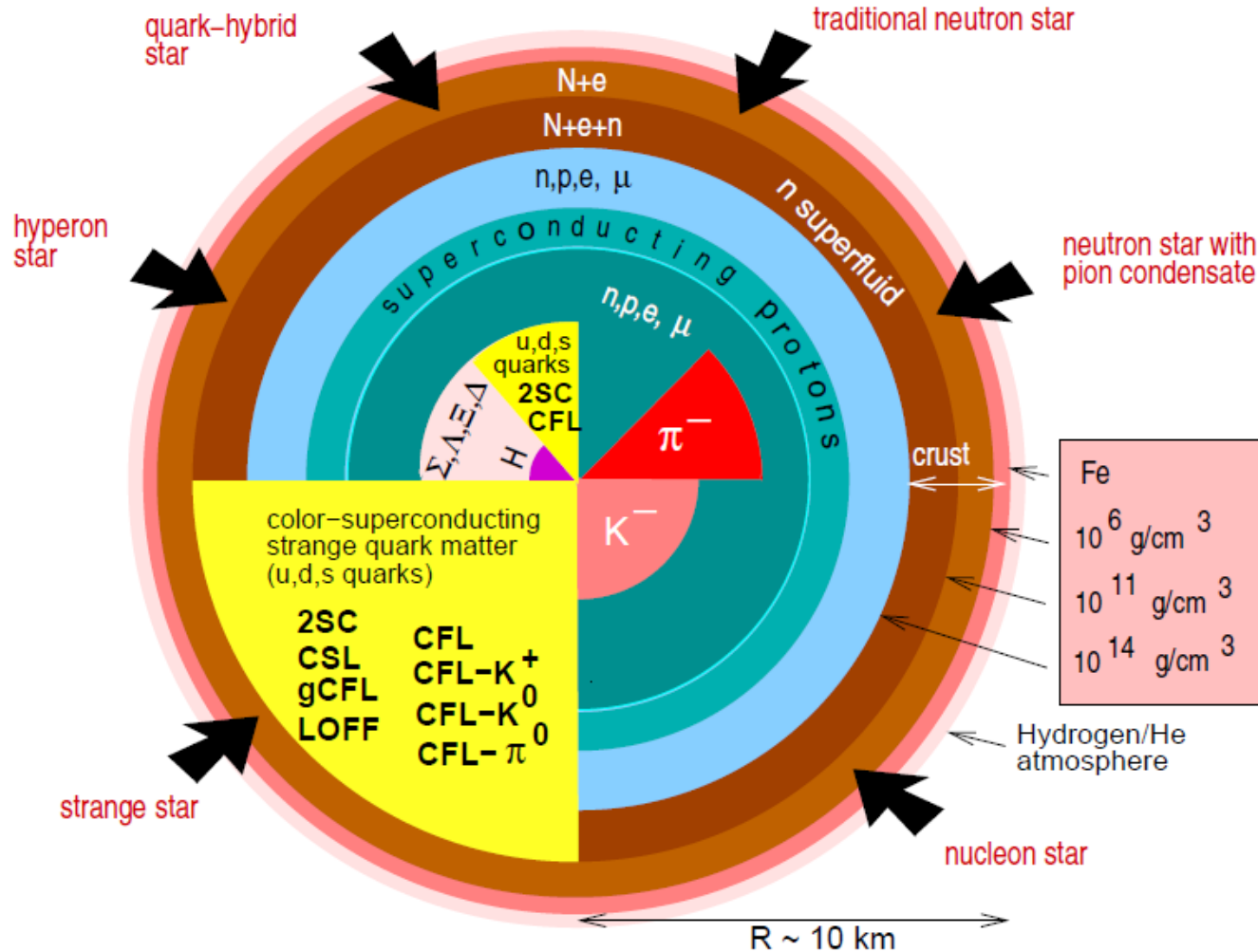
- We need to implement a realistic **EOS** as well as microphysics of **neutrinos**.
- We need an **Einstein-Eqs Solver** to follow time evolution of Space-Time according to General Relativity.

Expected Results

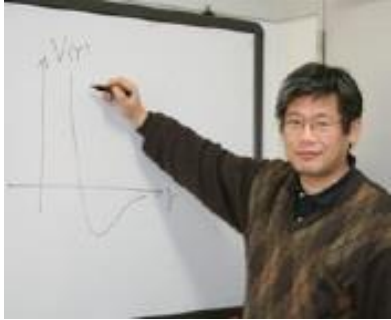
- We can follow the formation of a black hole in stars.
- Complete understanding of Central Engine of GRBs.
- Our studies can be applied to other fields ?

Nuclear Physics for the Dynamics

~ Equation of State in Dense Matter ~



Theoretical Nuclear Physics Groups in RIKEN



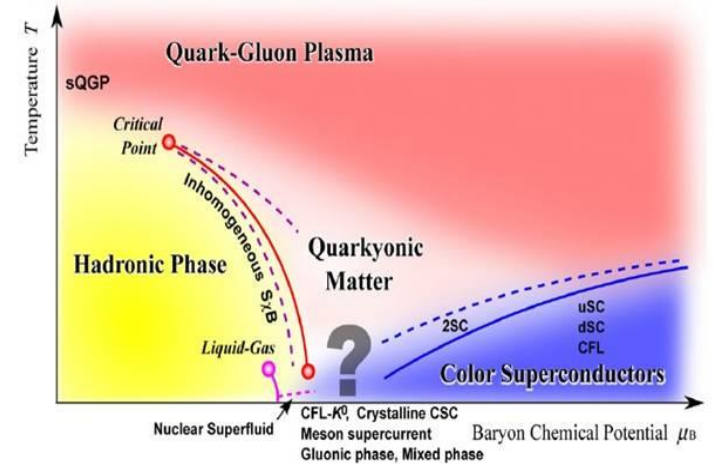
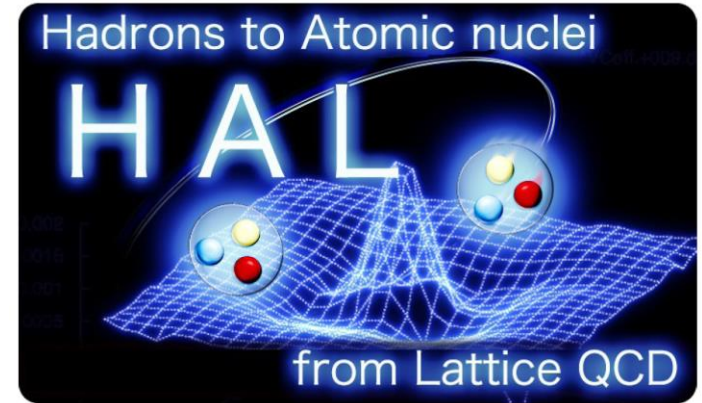
Dr. T. Hatsuda



Dr. E. Hiyama



Dr. T. Nakatsukasa

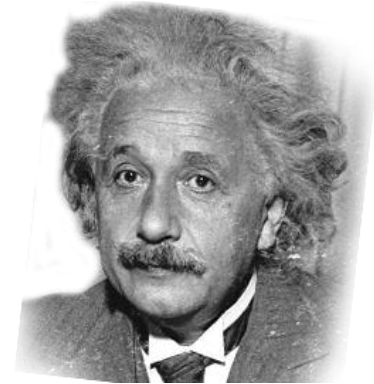
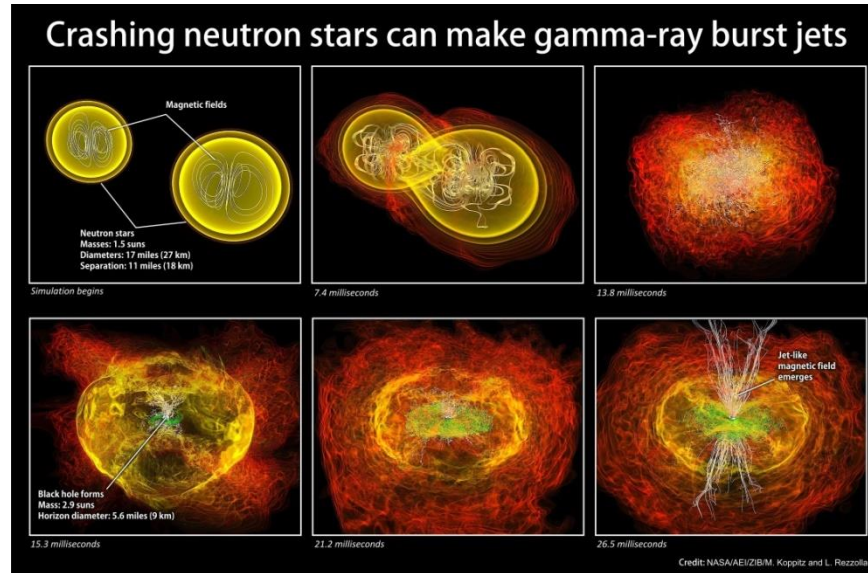


A New Table for EOS for Dense Matter can be Provided.

A Great Collaboration Started (2014-).

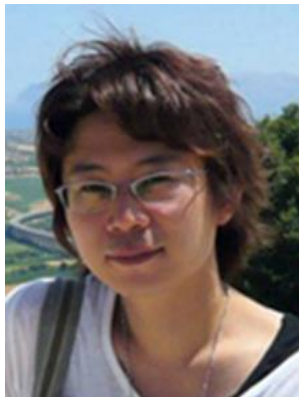


Luca Baiotti (Osaka Univ.)
A developer of Whisky Code



Einstein's Eqs.
(1915)

$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$



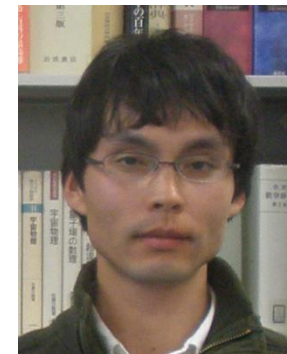
Nagasaki (RIKEN)



Barkov (RIKEN)

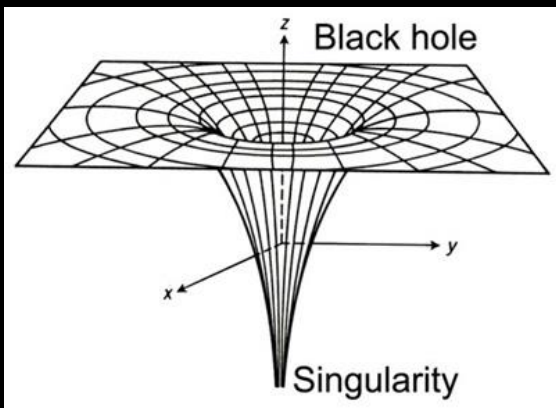


Takiwaki (RIKEN)



Kuroda (Basel Univ.)

Formation of a Black Hole: Related with Creation/End of the Universe?



Analogy?

Common Physics?

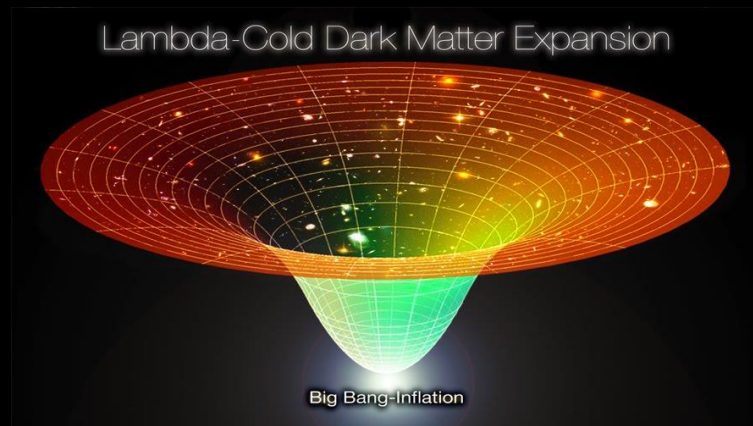
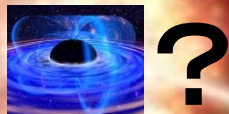
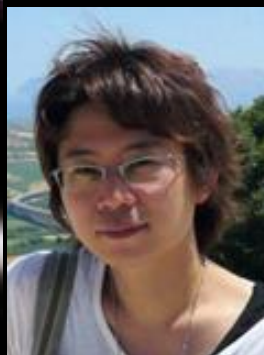


Figure from Universetoday



Engine of GRBs.
BH is formed?



S. Nagataki
(RIKEN)



M. Barkov
(RIKEN)



Y. Yokokura
(RIKEN)



A. Tanaka
(RIKEN)

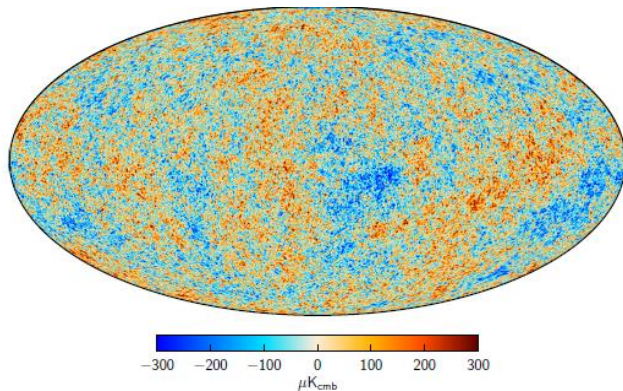
The Idea of Inflating Universe Came from Studies on Neutron Stars.

Mon. Not. R. astr. Soc. (1981) 195, 467–479

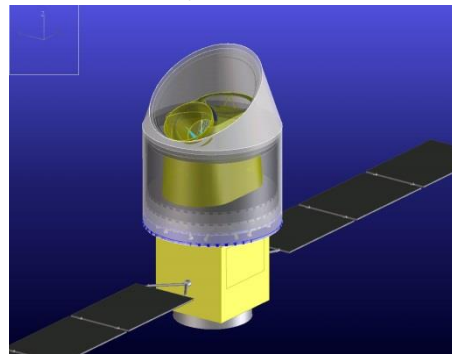
First-order phase transition of a vacuum and the expansion of the Universe

Katsuhiko Sato *Nordita, Blegdamsvej 17, DK-2100 Copenhagen ϕ , Denmark**
and Department of Physics, Kyoto University, Kyoto, Japan†

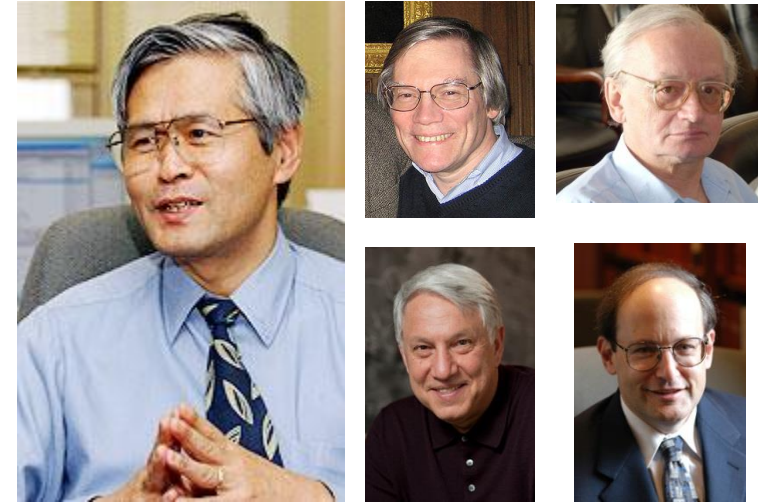
Received 1980 September 9; in original form 1980 February 21



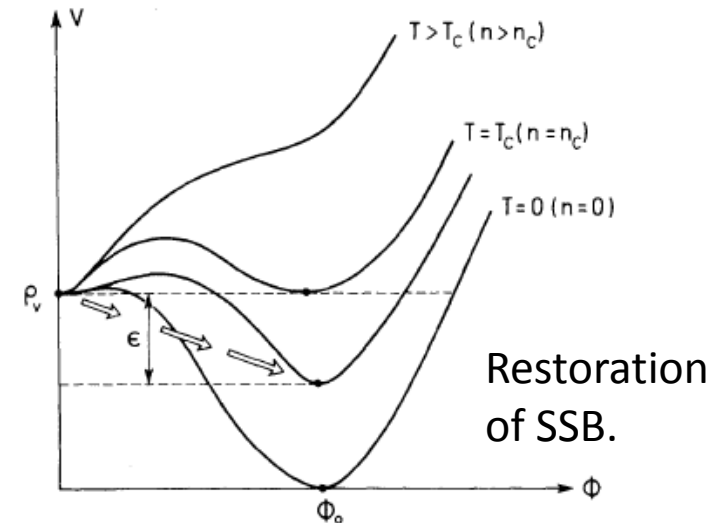
Planck Collaboration, 2015



From LiteBIRD HP



Sato, Guth, Linde, Starobinsky, Steinhardt

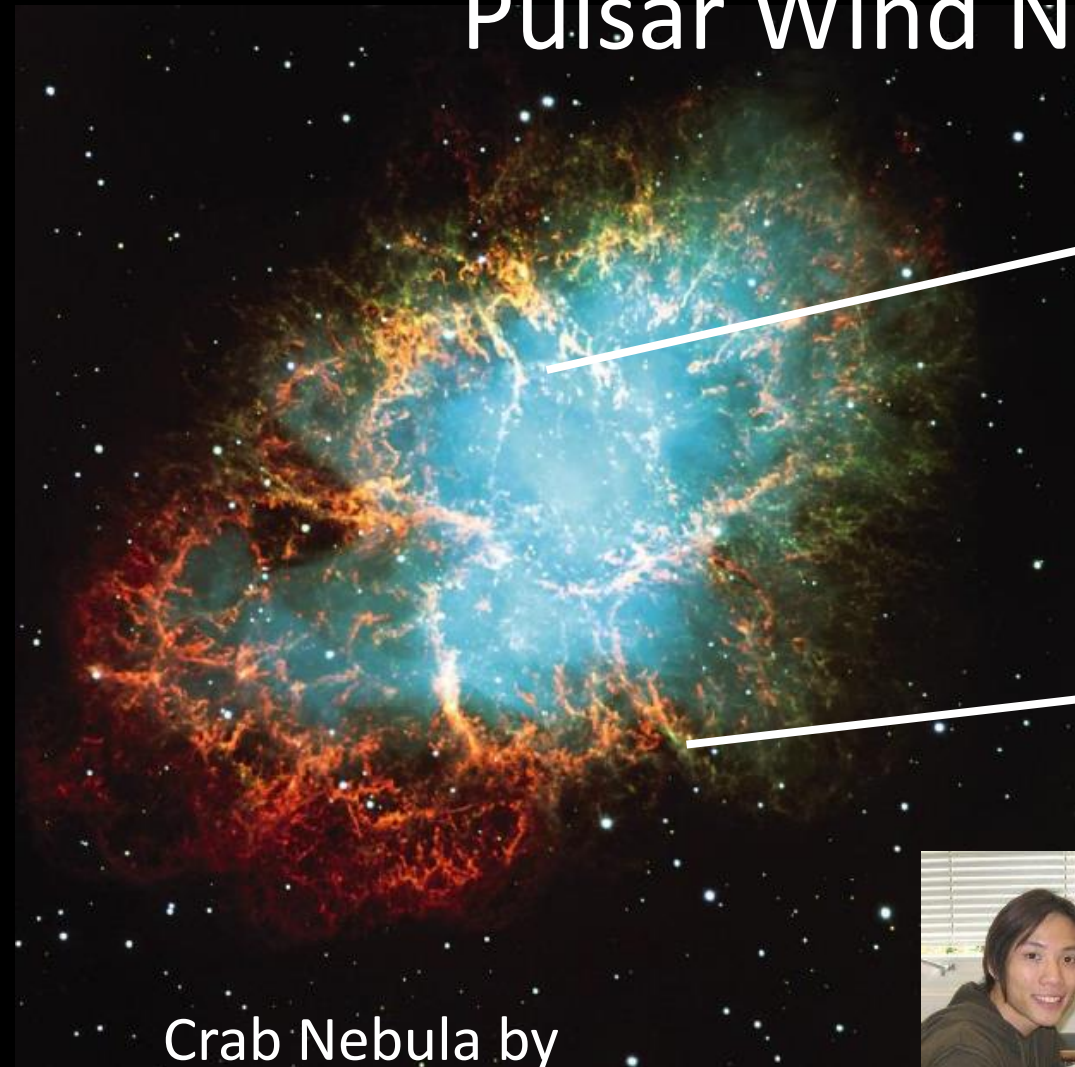


Our Road Map

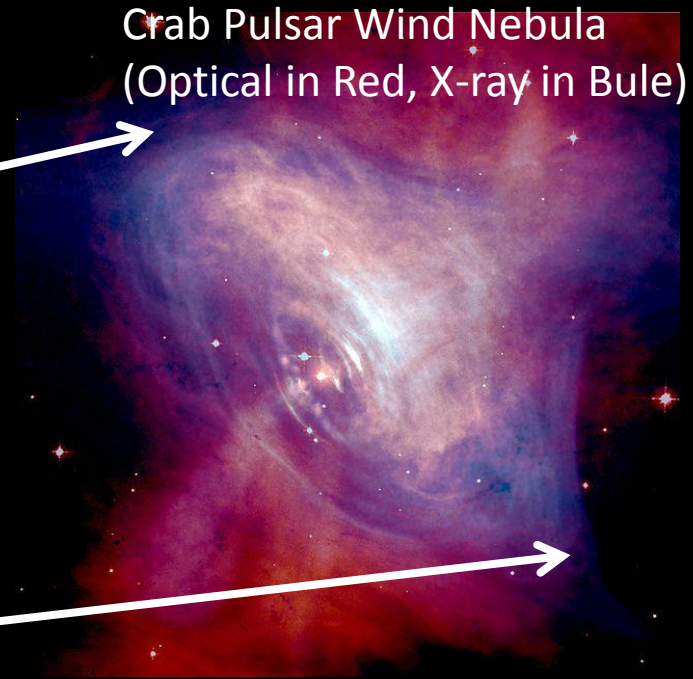
- 2018: KAGRA Full Operation (Gravitational Waves).
- 2020: Post K-Computer Full Operation (Exa-Flops).
- 2020: Complete Supernova Simulation Done.
- 2025: Complete Gamma-Ray Burst Simulation Done.
- 203X: A SN Explodes in Milky Way (Betelgeuse?).
Neutrinos & GWs Detected.
Our Theory Confirmed.
- 204X: Lots of Nobel Prize Winners from Japan.
- ... Our Dreams Will Continue...

§ Neutron Stars, Pulsar Wind Nebulae, & Nucleosynthesis

Can We Understand Neutron Stars & Pulsar Wind Nebulae?



Crab Nebula by
Hubble Telescope



Crab Pulsar Wind Nebula
(Optical in Red, X-ray in Blue)



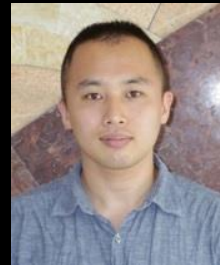
A. Wongwathanarat



M. Barkov



T. Wada



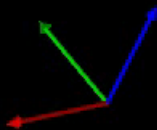
Y. Teraki

Asymmetric Explosion & Neutron Star Kick

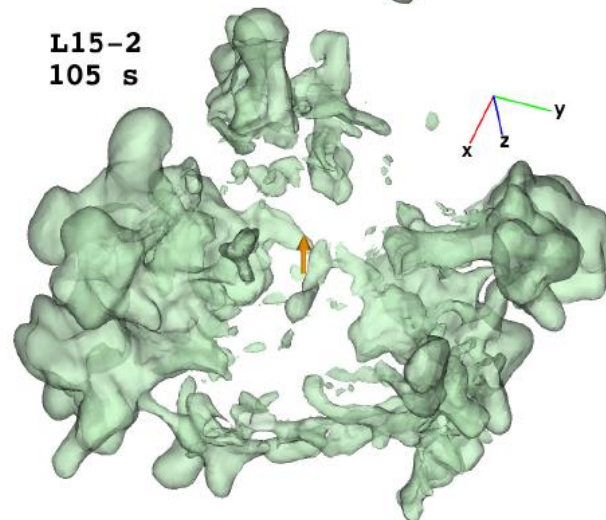
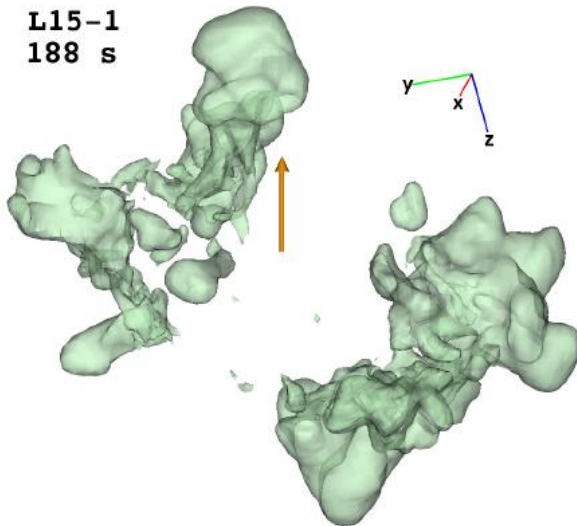
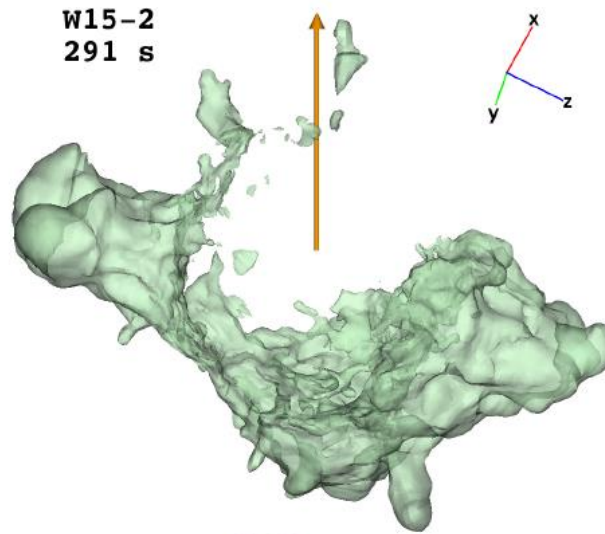
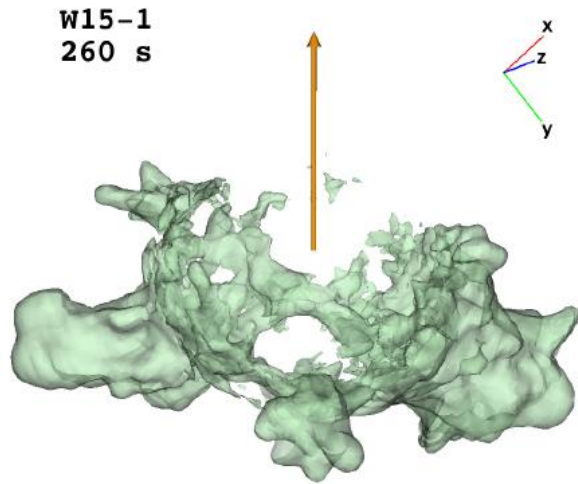


Model W15-6
Time: 15.10 ms
NS displacement: 0.00 km

A. Wongwathanarat
(MPA → RIKEN)



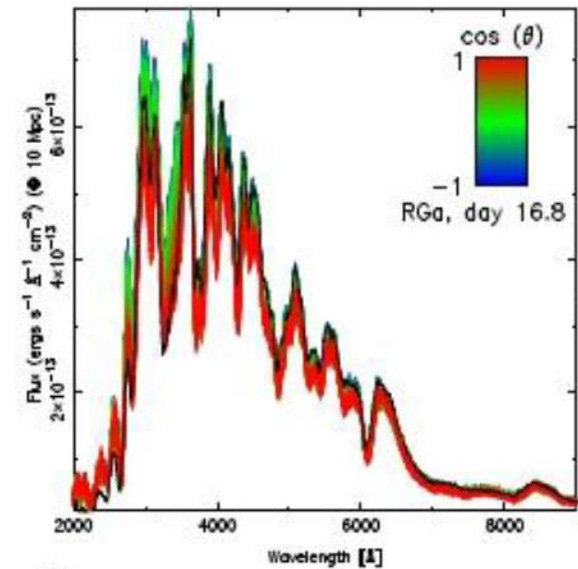
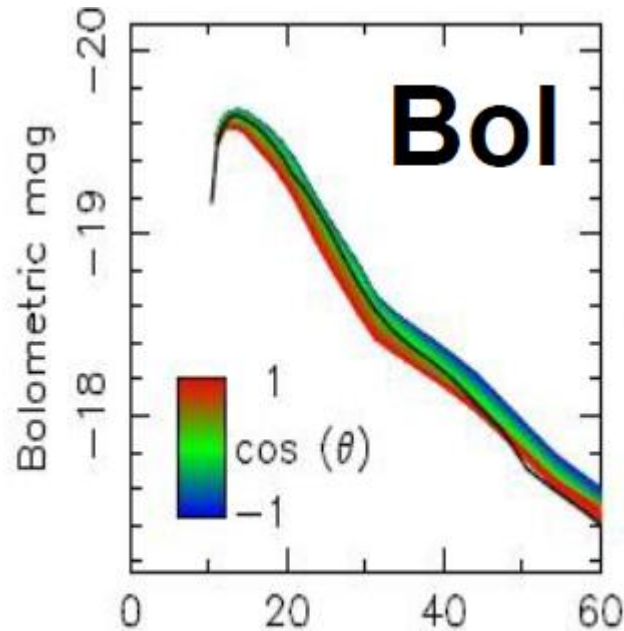
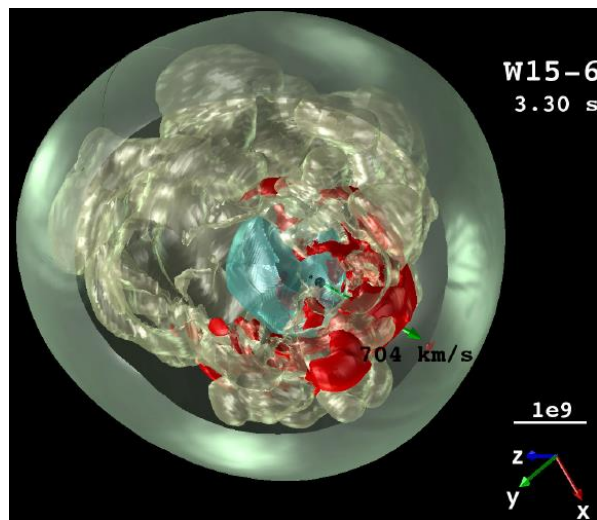
Asymmetric Ejection of ^{56}Ni & Neutron Star Kick



A. Wongwathanarat
(RIKEN)

Great Collaborations Started

- Radiation Transfer, including Gamma-Ray Line Transfer.



Left:
A. Wongwathanarat
(RIKEN)

Right:
K. Maeda (Kyoto)



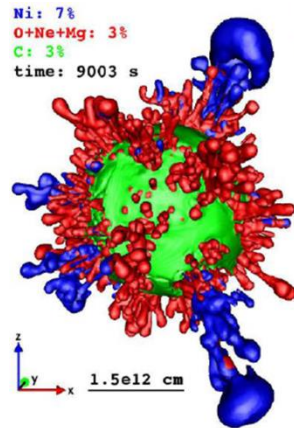
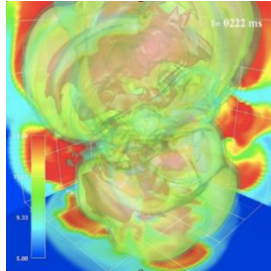
§ Supernova Remnants

Our Big Challenge:

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



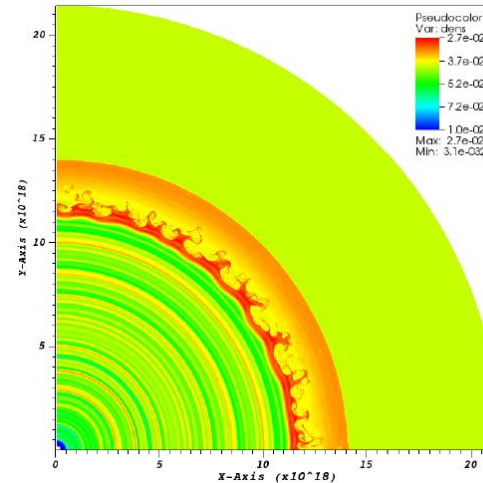
T. Takiwaki
(RIKEN)



A. Wongwathanarat
(RIKEN)



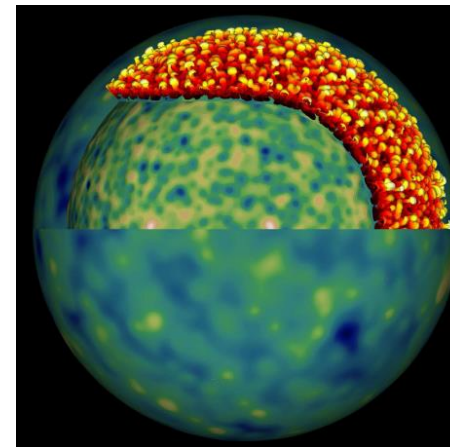
Ono+14, in prep.



How do they
Evolve?

Origin of
Asymmetries?

Legacy of
Supernovae?



Warren & Blondin 13



S.H. Lee
(RIKEN → JAXA)

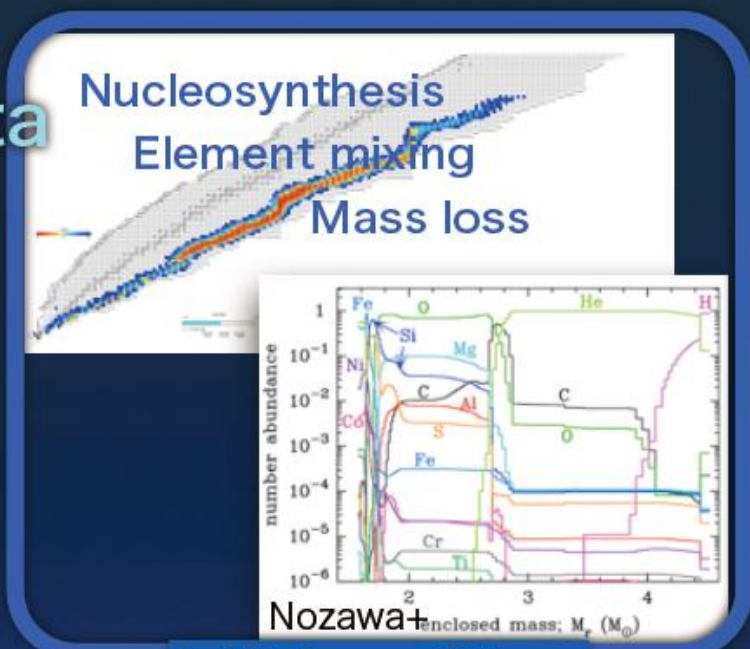


M. Ono
(RIKEN → Kyushu U.)



D. Warren
(NCSU → RIKEN?)

SN ejecta Model

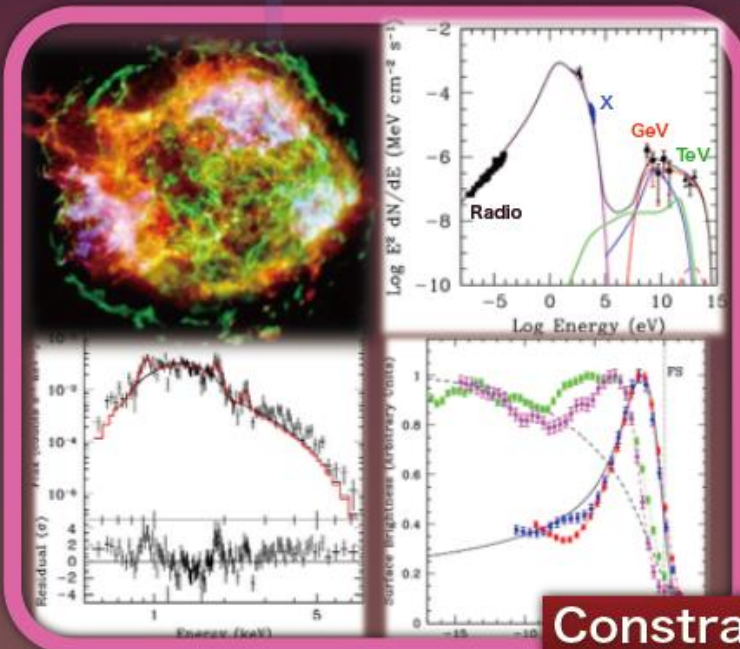


Initial conditions

Iterative Work Flow

(1-D)

CR-hydro Model



Multi- λ Data

Constraints!



Dynamics, DSA, B-field, ionization, radiation

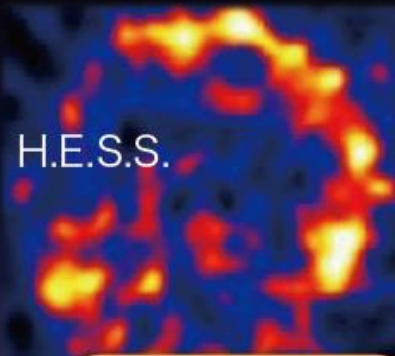
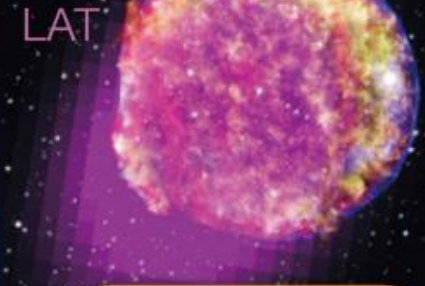


Hydro + Spectral Model of Young SNRs

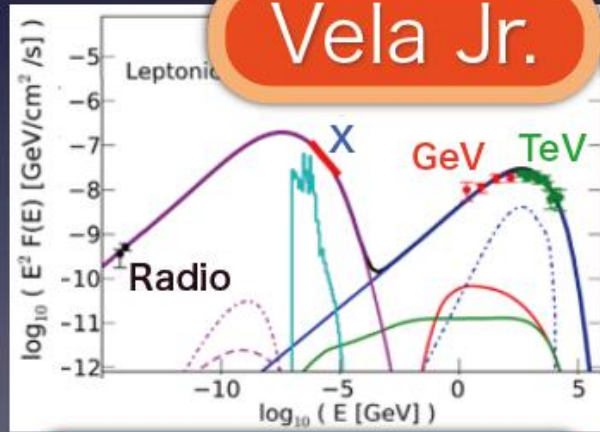
S.H. Lee (RIKEN→JAXA)

e.g. HL+ (2013) **Vela Jr.**

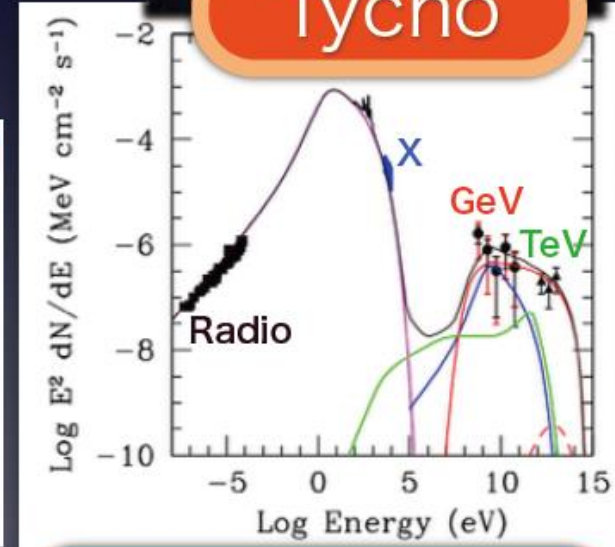
Slane, HL+ (2014) **Tycho's SNR**



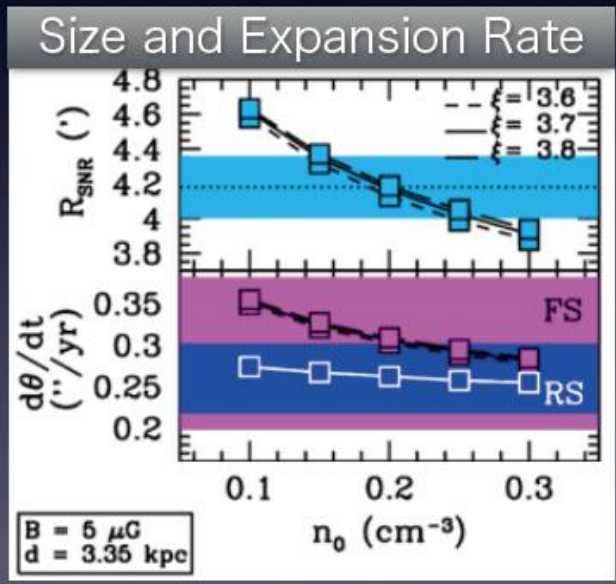
Vela Jr.



Leptonic
 $E_{CR} = 0.15 E_{SN}$



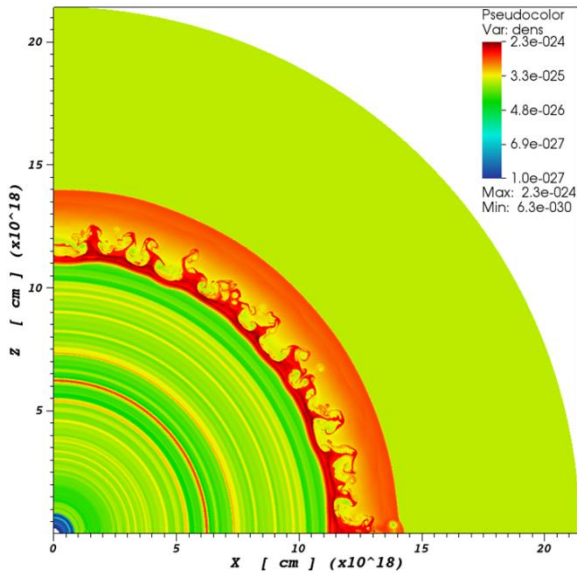
Hadronic
 $E_{CR} = 0.16 E_{SN}$



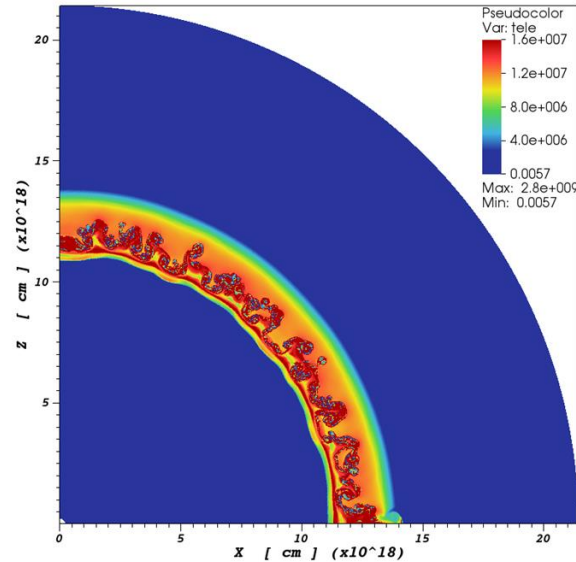
Multi-D Hydro-NEI for SNRs

FLASH with Electron Temperature & Ionization/Recombination

Density



Electron Temp.



Averaged Valence of Ion

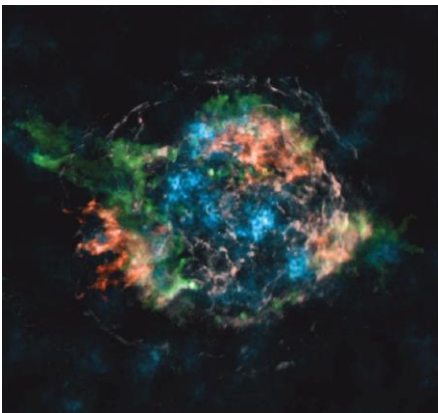
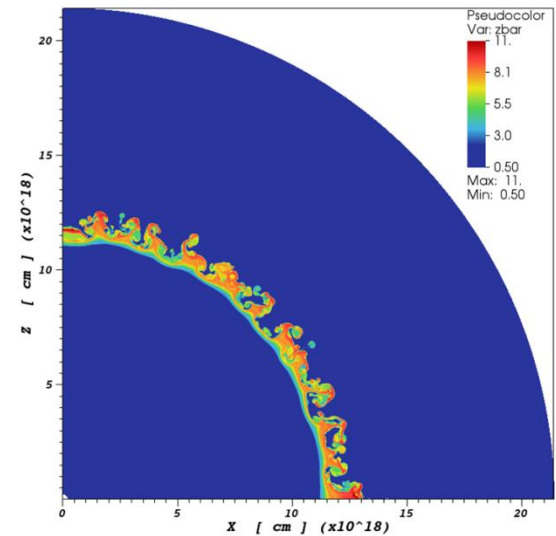
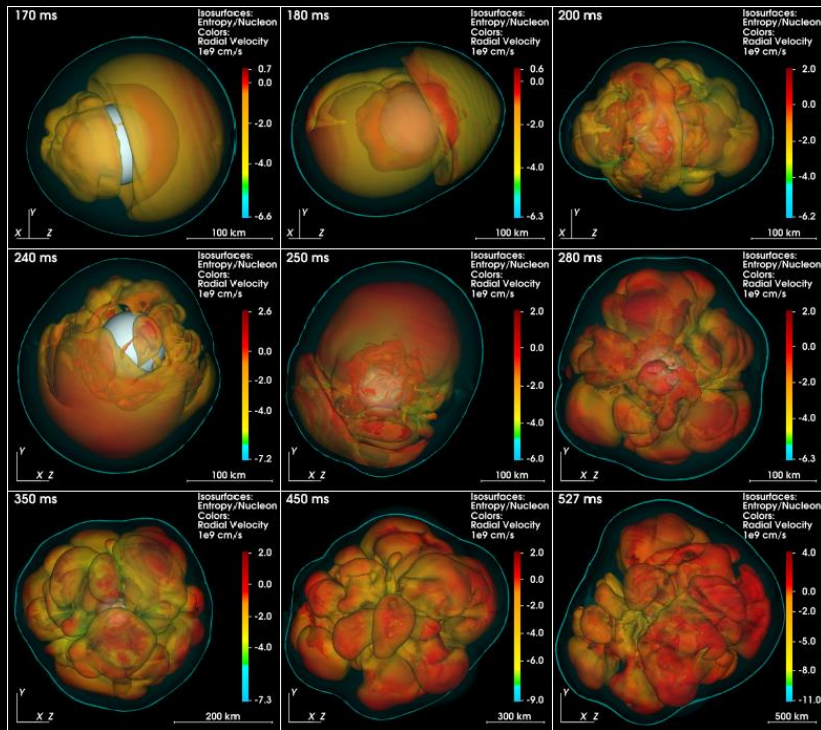


Image of
Cas A.

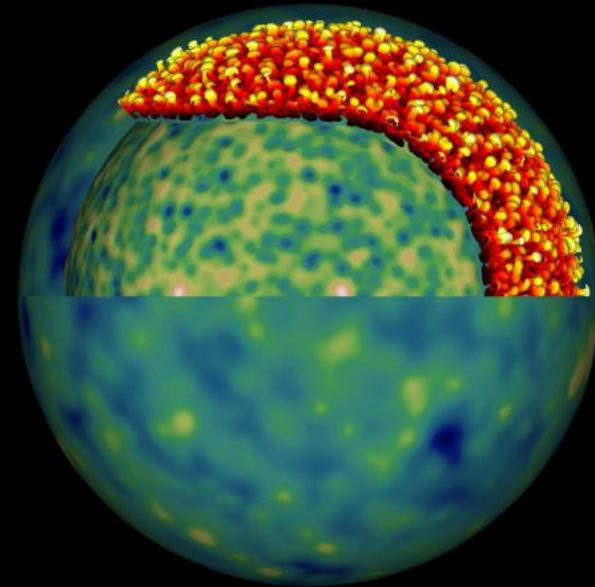


M. Ono (RIKEN→Kyushu U.) S.H. Lee (RIKEN→JAXA)

A Collaboration with the MPA Group?



From SN
To SNR



Annop Wongwathanarat
(MPA → RIKEN)

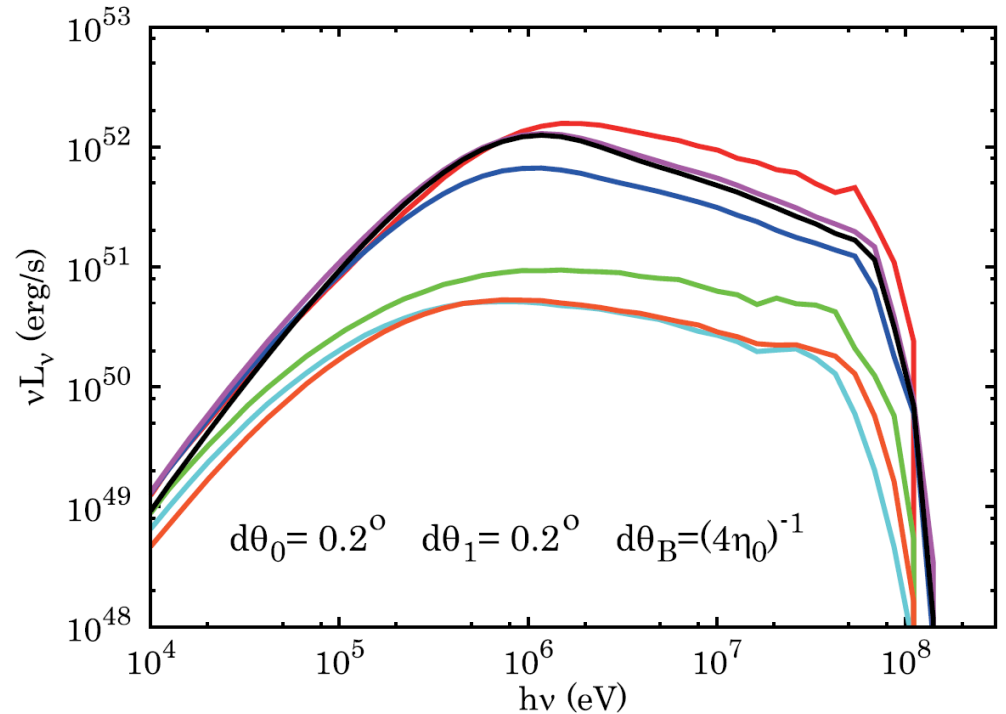
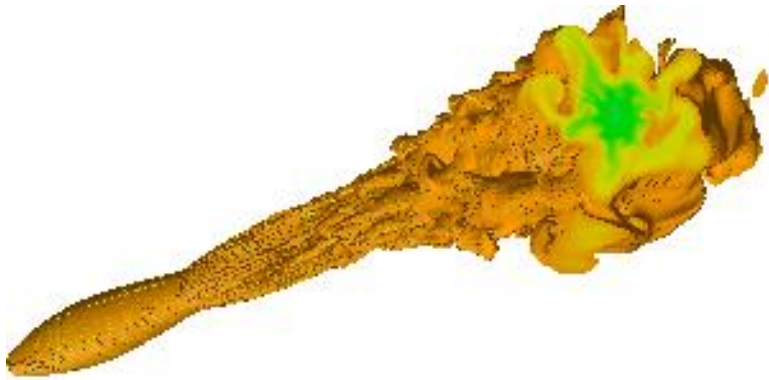


T. Janka (MPA) E. Mueller(MPA)

Our SNR Members: Lee , Ono, Warren

§ High-Energy Astrophysics
in
Astrophysical Big Bang Laboratory

Emission Mechanism of GRBs



Matsumoto (RIKEN)

KeV-MeV Spectrum of GRBs (Band-Function)

Light Curve (Rapid Variable) of GRBs

Polarization in Prompt Emissions.



Ito (RIKEN)

Nonlinear DSA in relativistic shocks

Ellison et al. (2013) (2013ApJ...776...46E)

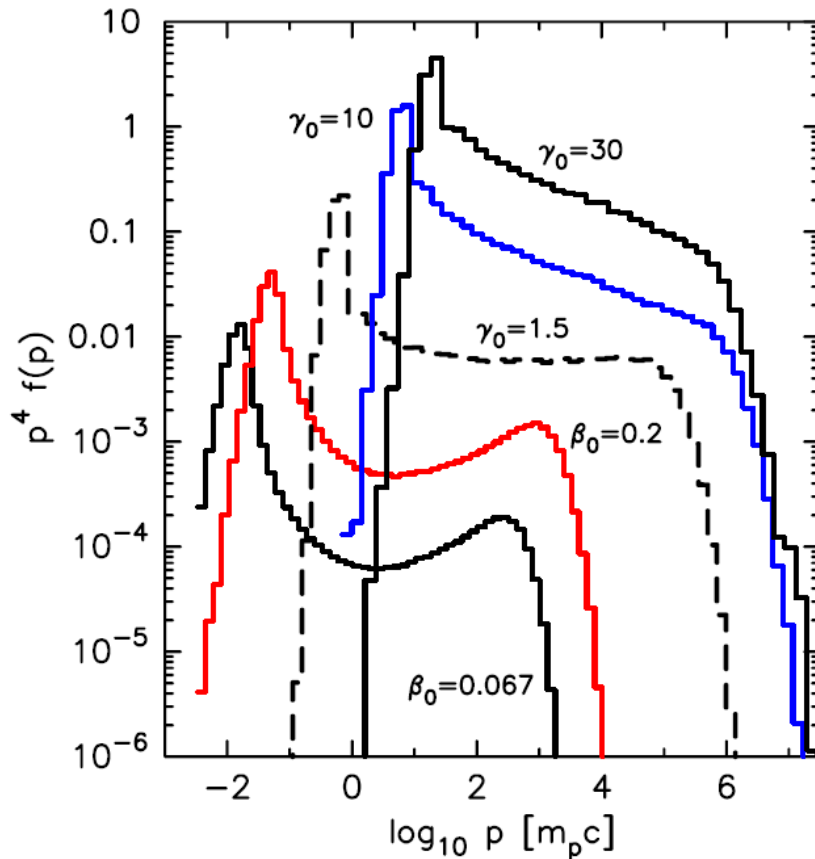
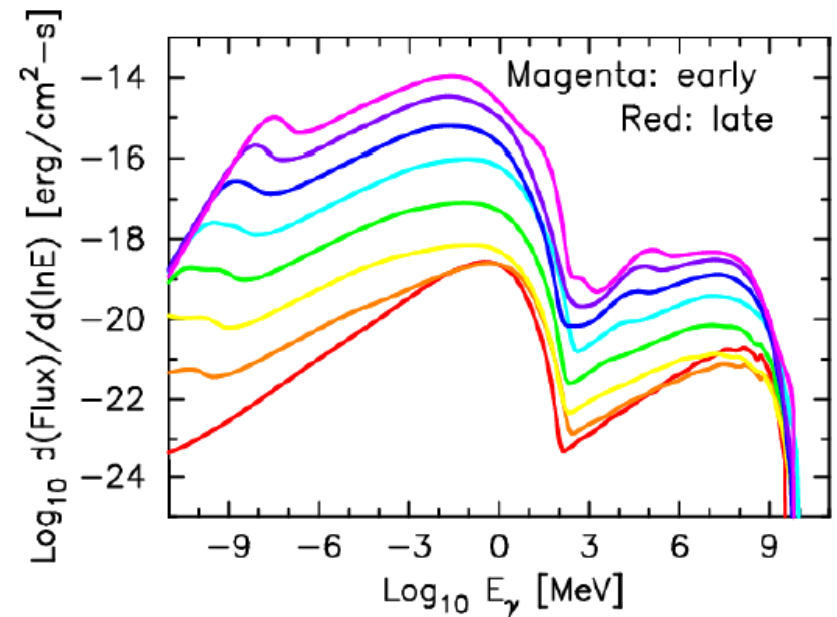


Figure 10. Nonlinear particle distributions calculated downstream from the shock in the shock rest frame for various shock speeds as indicated (Models A–E in Table 1). The spectrum for the $\gamma_0 = 1.5$ shock (dashed black curve) shows the transitional nature of nonlinear DSA.

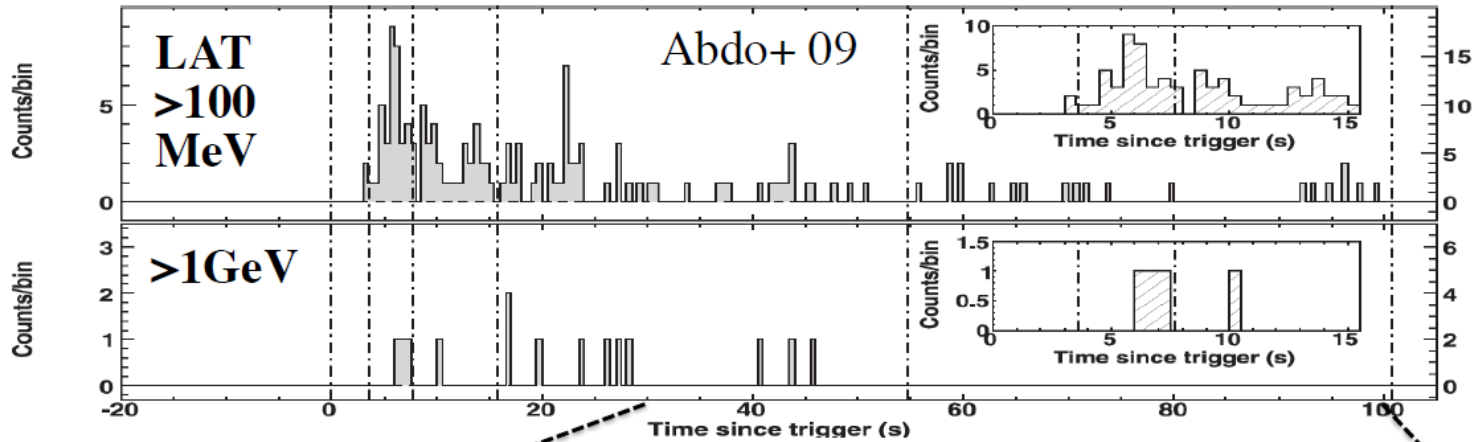


Warren (RIKEN)

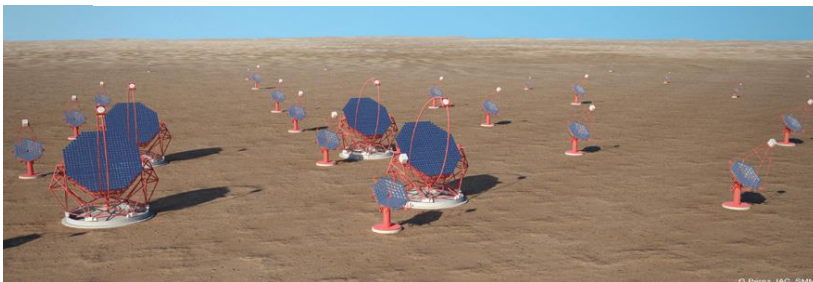
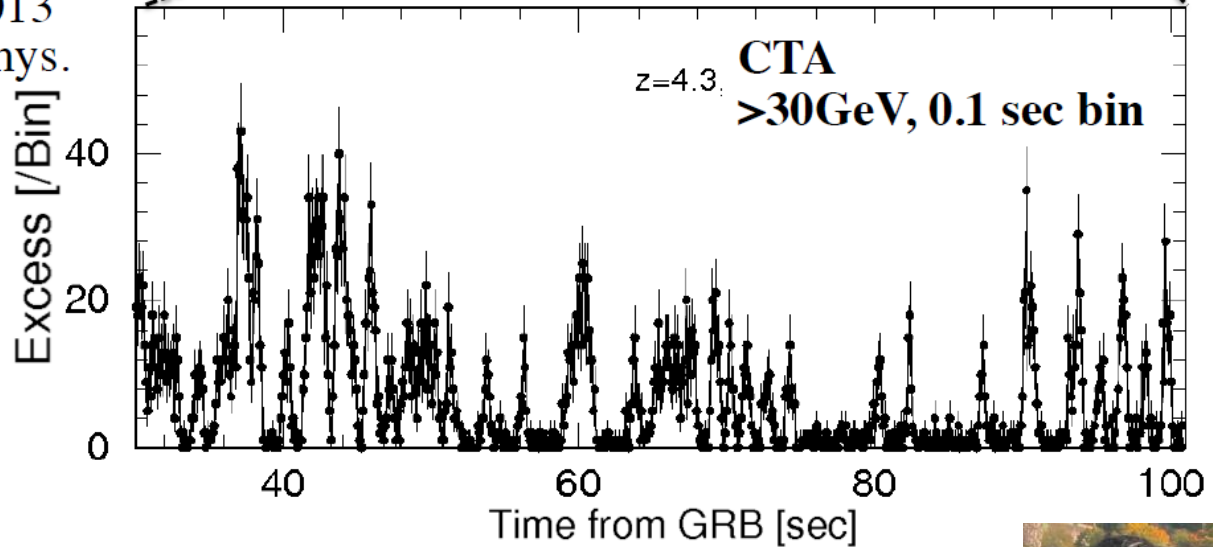
GRB
Afterglow Phase

GRB light curve: Fermi vs CTA

GRB 080916C



S. Inoue+ 2013
Astropart. Phys.
43, 252
inc.
Yamamoto
Y. Inoue
Yamazaki
(for CTA)

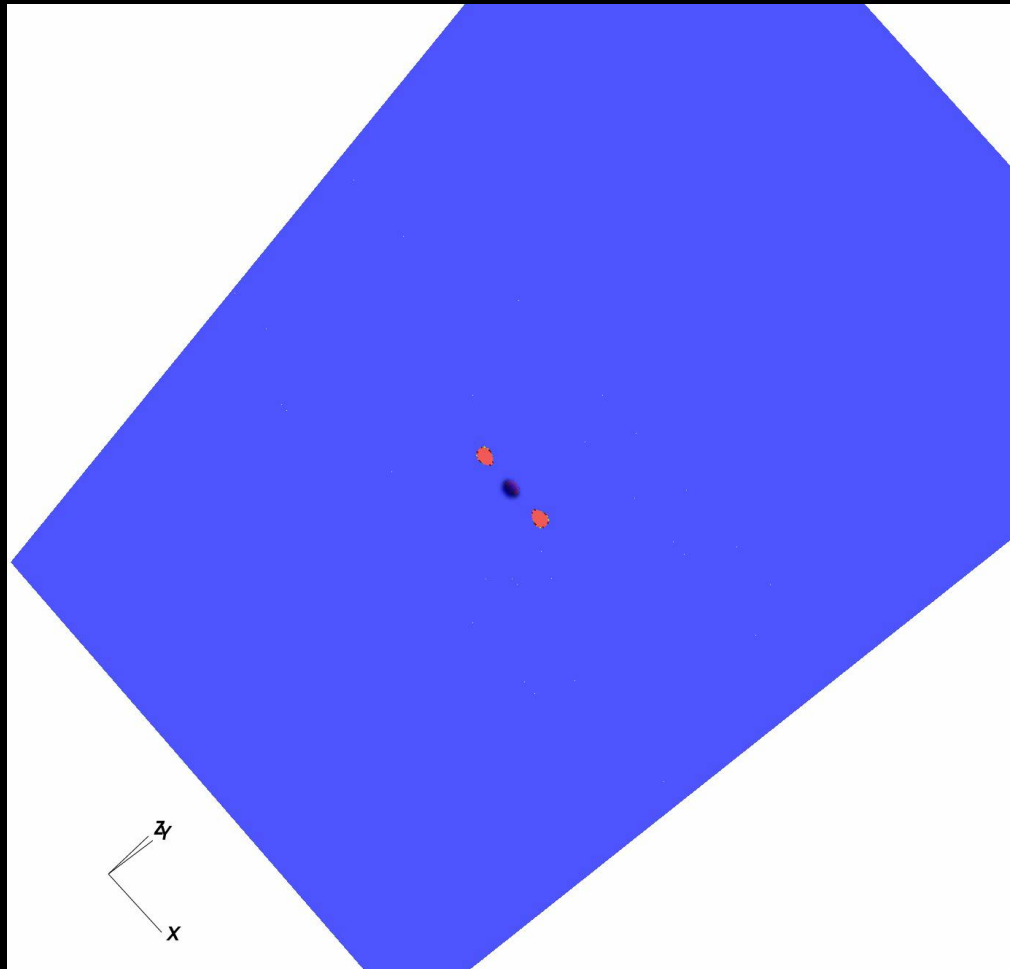


CTA Project: ~2020
GeV-TeV Gamma-Rays

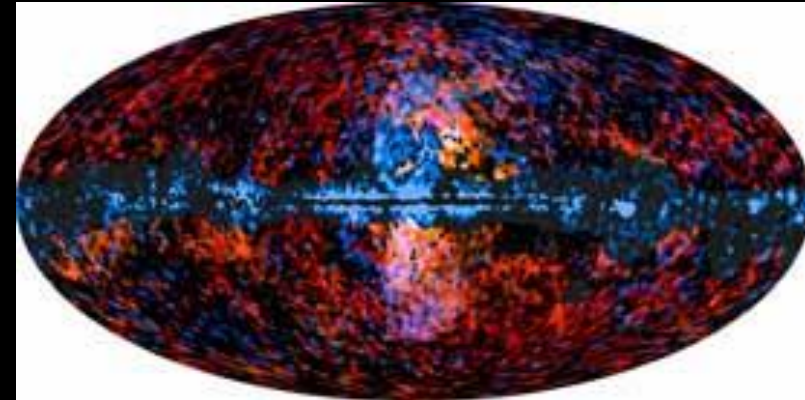
Inoue RIKEN

Can Fermi Bubble/Massive BH at GC be a source of VHE- γ / ν ?

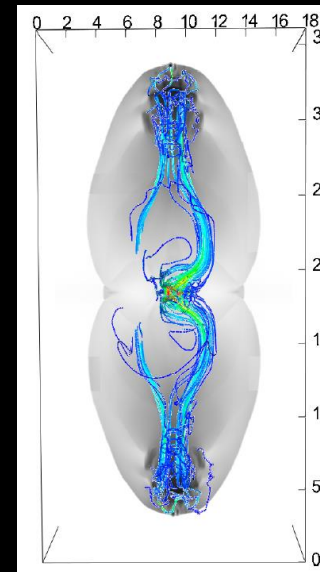
arXiv:1311.6722



MHD Hydro by PLUTO.
→ Particle Acc.

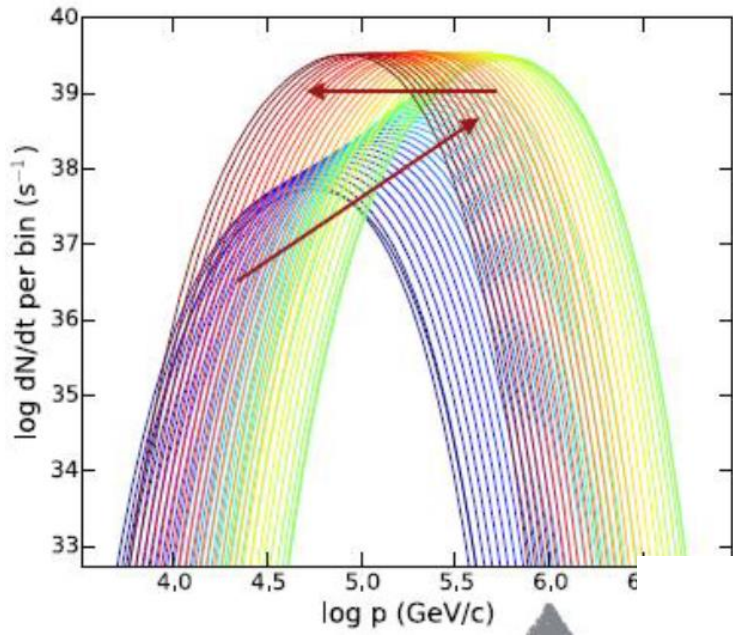


Blue: Gamma-ray (Fermi)
Red: Radio (Planck)

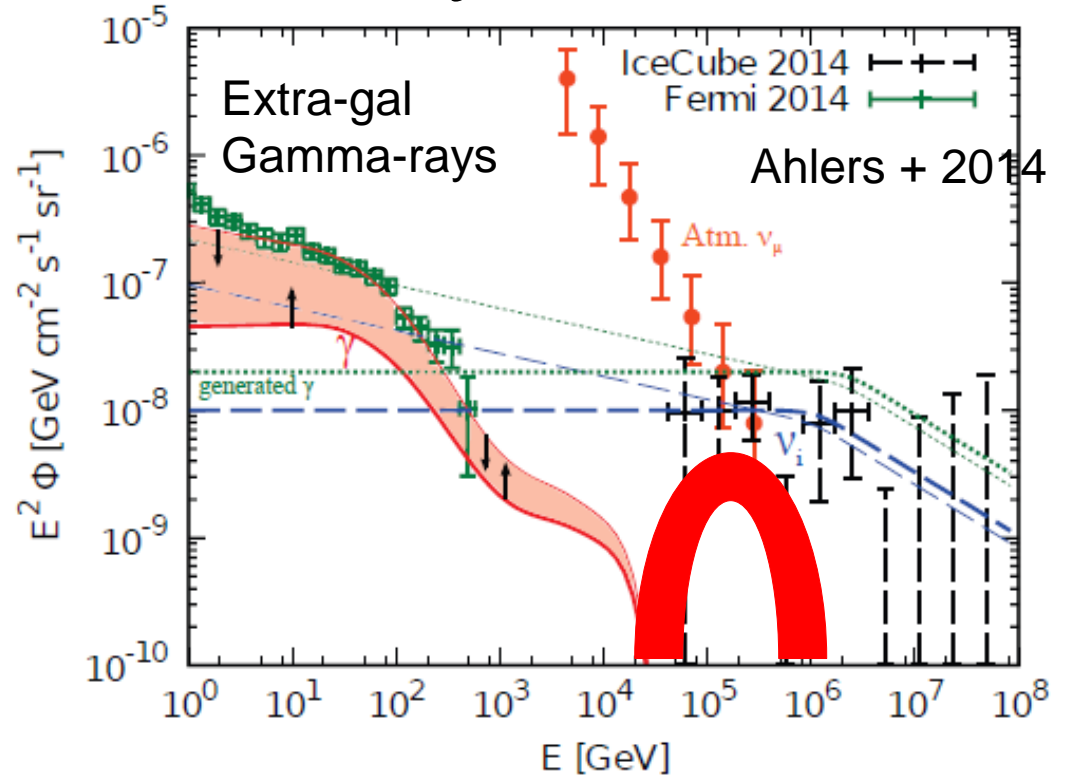


M. Barkov
(RIKEN)

Can a Hyper-Nova be a Source of VHE-Neutrinos & Gamma-rays at GC?



CRs Escaping from a HNR
May Have a Hard Spectrum.



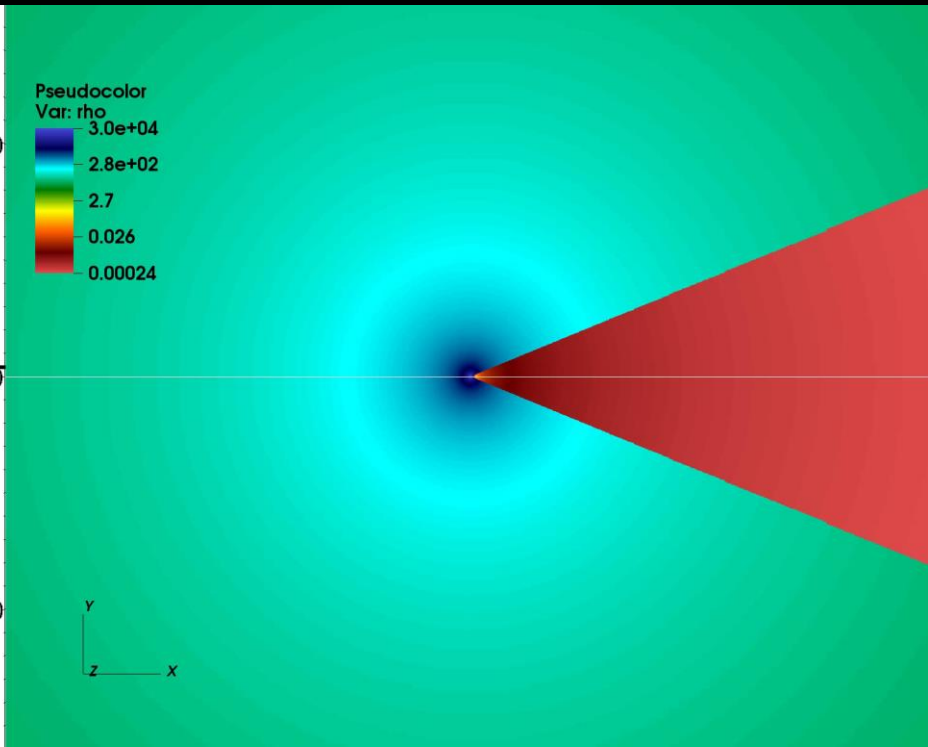
Hard Spectrum & Steep Cutoff is Welcomed.



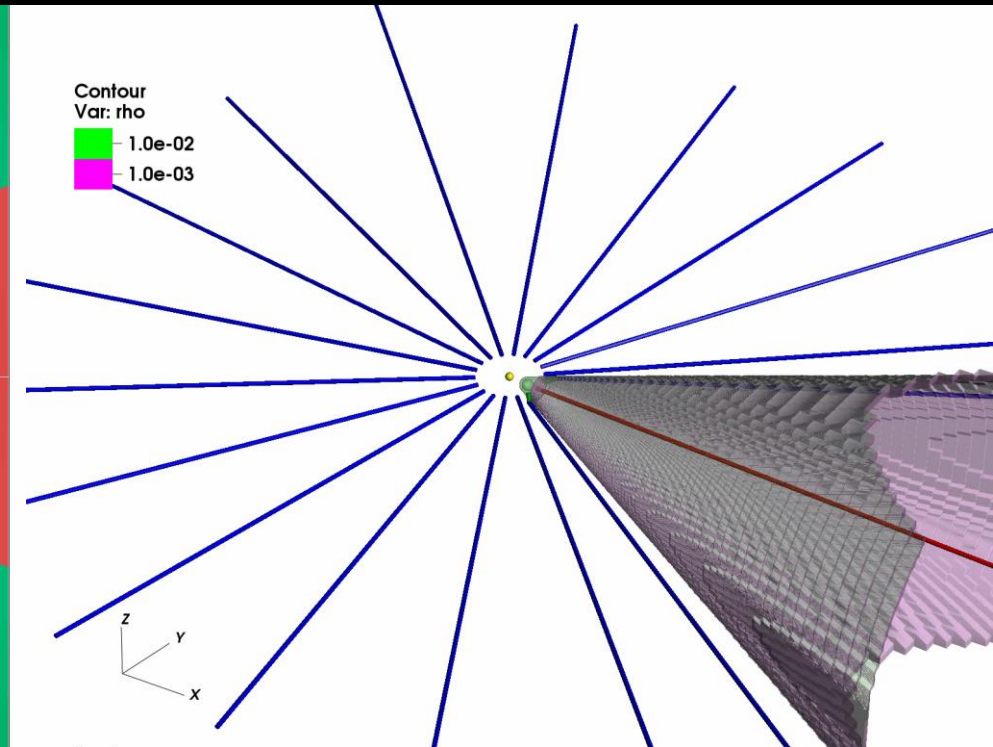
From Left to Right:
Dr. Lee (JAXA)
Dr. He (UCLA/PMO)
Prof. Kusenko
(UCLA/Kavli IPMU)

NS-Normal Star Binary: Wind-Wind Interactions

Top View

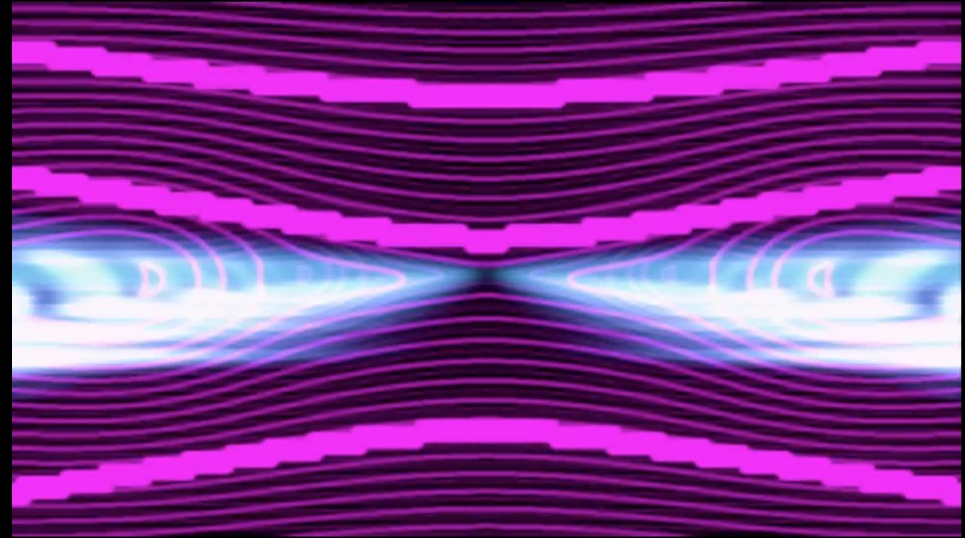
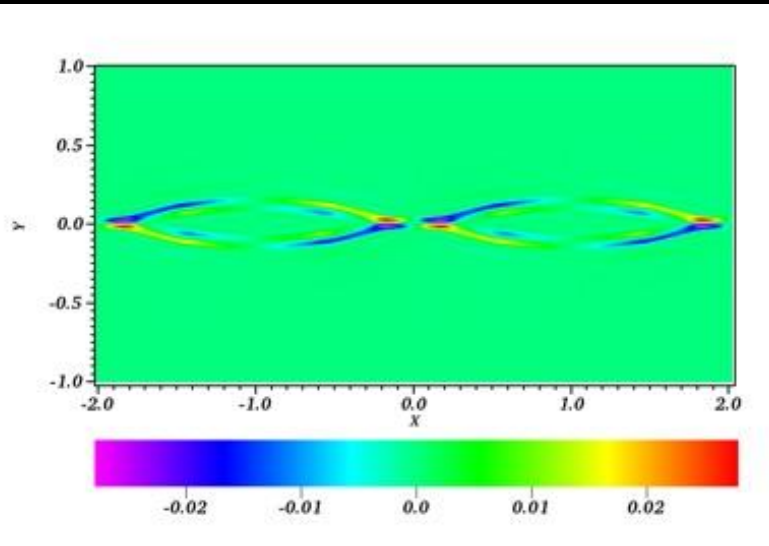


Side View



Dynamics of Wind-Wind Interactions are Performed.
Future Work: CR-Productions & Radiation Transfer in
the System.

Some Local Simulations of Fluid/Plasmas



2-Fluid Relativistic MHD Simulations MHD Simulations for Reconnection



Maxim Barkov
(RIKEN)

Tomohide Wada
(RIKEN)



Summary

- Super-Computing of Central Engine of CC-SNe & GRBs with K(10Peta)- and Post-K (Exa-) Computers in RIKEN is a Grand Challenge of Our Group.
- Resulting Neutrino Signals and GWs can be Detected by SK and KAGRA (and ALIGO/AVIRGO) in the (Near) Future.
- Asymmetric Explosion of CC-SNe can be Related with Neutron Star Kicks, Peculiar Explosive Nucleosynthesis, Matter Mixing, as well as Asymmetric Morphology of SNRs.
- ABBL is Becoming Stronger in High-Energy Astro Fields.
- Our Group is Ready to Challenge Ourselves to Understand the Whole Sequence of Astrophysical Big Bangs from Engine to Remnants.

Thank You Very Much.

- PI: Nagataki From 1st Apr. 2013
- Current PDs: Ito, Matsumoto, Barkov, Takiwaki, Wongwathanarat, Warren, Wada, Inoue
- iTHES: Tanaka, Yokokura (from Nov. 2015)
- Alumni: Ono (Kyushu Univ.), Lee (JAXA), Tolstov (Kavli IPMU), Mao (Yunnan Obs.), Dainotti (Stanford), Teraki (RIKEN)
- Long Term Visitor in FY2015: Fujimoto (Kumamoto Nat. Inst. Tech.)

