Astrophysical Big Bang, Interdisciplinary theoretical science, and Advanced Intelligence

Shigehiro Nagataki

10-17 September 2016, Moorea, French Polynessia: Presentation Date: 14 Sep.

PACIFIC 2016

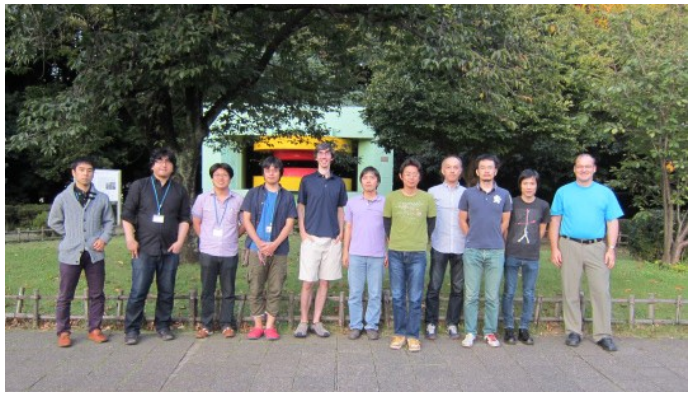
Astrophysical Big Bang Lab.

From 1st Apr. 2013

- PI: Nagataki
- Current PDs: H. Ito, J. Matsumoto, A. Wongwathanarat, D. Warren, S. Inoue, G. Ferrand, M. Ono, H. He (UCLA→ABBL: Tomorrow!)
- Alumni: Lee(JAXA→Kyoto), Tolstov(Kavli IPMU), Mao(Yunnan Obs.), Dainotti (Stanford), Teraki (Kyoto), Takiwaki (NAOJ), Wada (Company), Barkov (Potsdam/DESY)
- Long-Term Visitor: Zhaoming Gan (Shanghai Obs.)

2013, Aug.1

2014, Dec.17



2015, Sep.30

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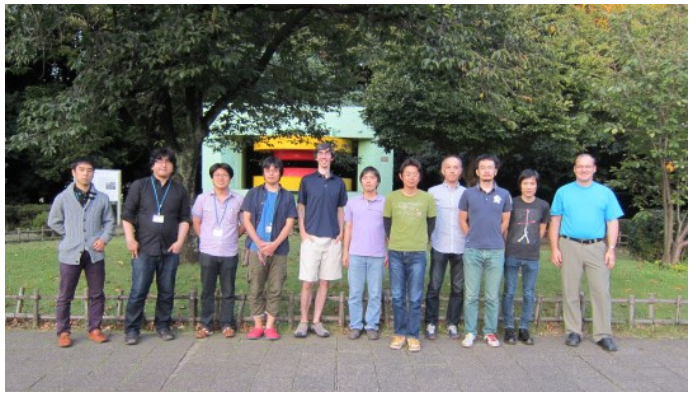
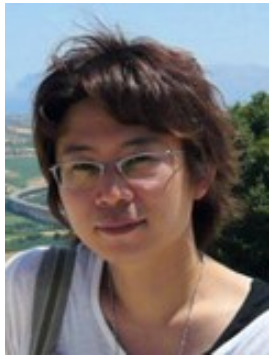


2015, Sep.30

Interdisciplinary Theoretical Science (iTHES)

Program of FY2013-FY2018.

Tetsuo Hatsuda
Group Director



S. Nagataki
A Team Leader

A. Tanaka
(Particle Phys.)

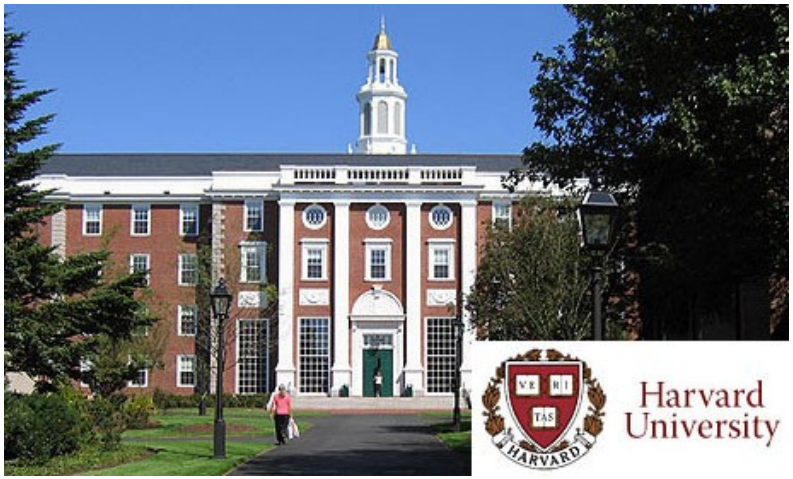
Y. Yokokura
(Particle Phys.)

M. Hongo
(Nucl. Phys.)

K. Kyutoku

T. Terasawa

MOU : iTHES-Kavli IPMU 04/Dec/2013



MOU: iTHES-CfA 01/June/2016

S. Wanajo
→Sopia U.

Our Group Members and Collaborators

From 1st April 2013

～Toward Full-Understanding of Supernovae and GRBs～

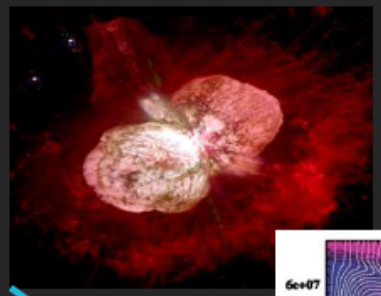
Small Radi

Large Radi

- Central Engine: Nagataki (PI), Takiwaki, Barkov, Baiotti (Osaka)
- Explosive Nucleosynthesis:Wongwathanarat, Ono, Mao
- Shock Breakout/Light Curve/Spectrum: Tolstov, Blinnikov (ITEP/Kavli-IPMU), 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, Ferrand, Ono, Slane (CfA), Patnaude (CfA)
- UHECRs, VHE-neutrinos/gamma-rays: He, Inoue, Kusenko (UCLA), Allard (APC)
- GRB Cosmology: Dainotti
- The Universe itself: Tanaka, Yokokura

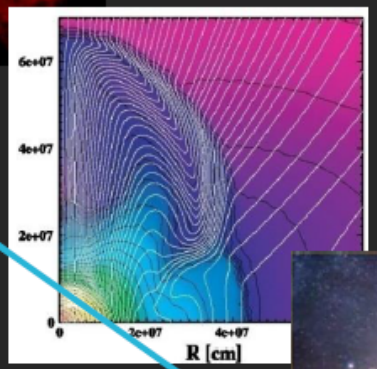
… and More!

Evolution of SNe and observational signatures



Opt-IR

ν



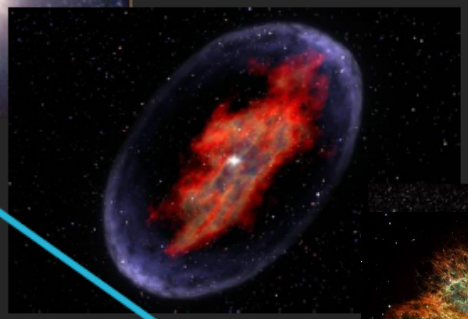
GW

ν

ms - sec

UV-X

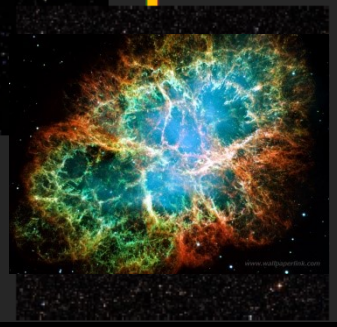
sec - day



Opt-IR
Radio, X

γ

day - year



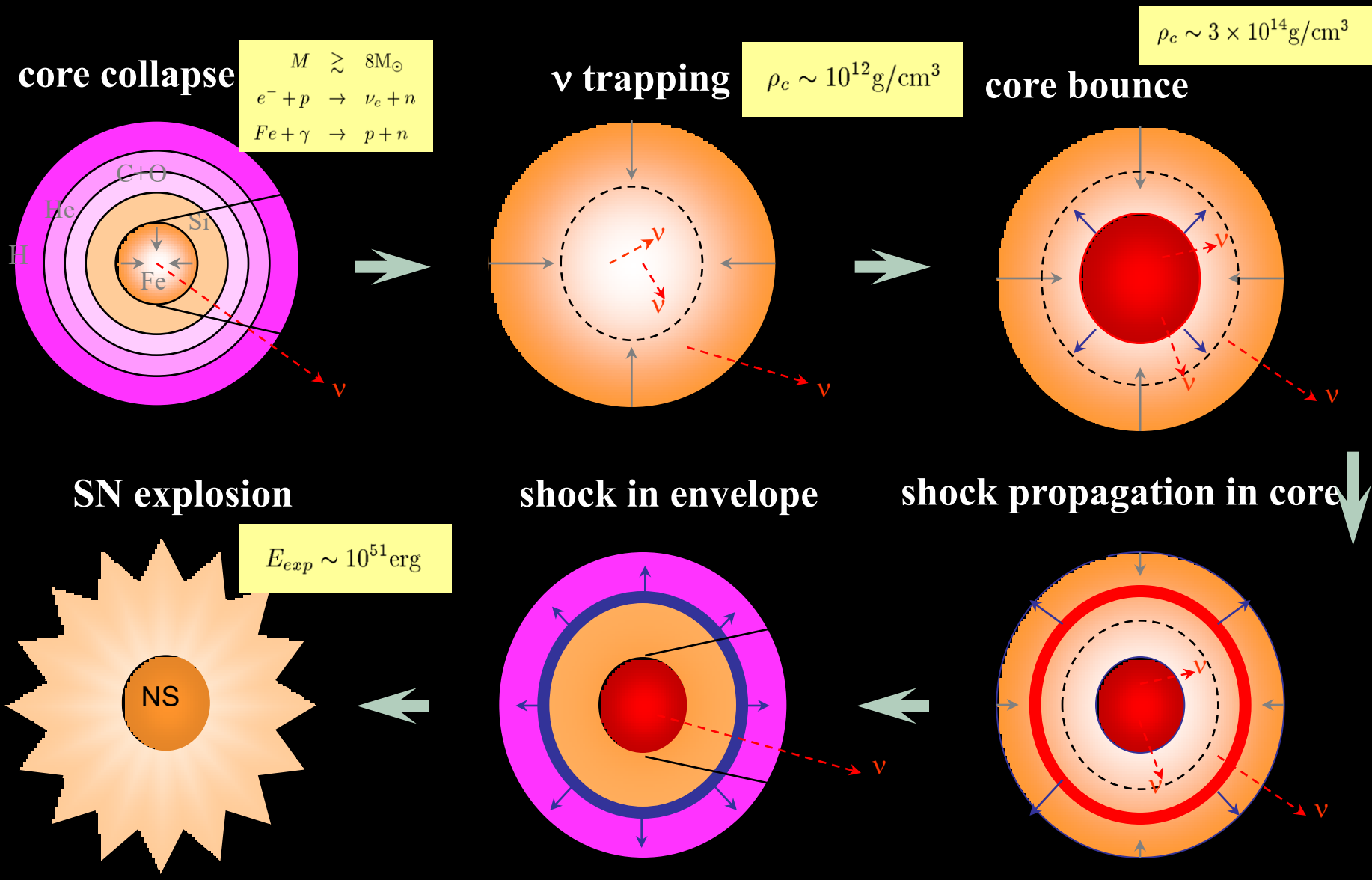
Opt-IR
Radio
X
VHE γ

decade - centuries

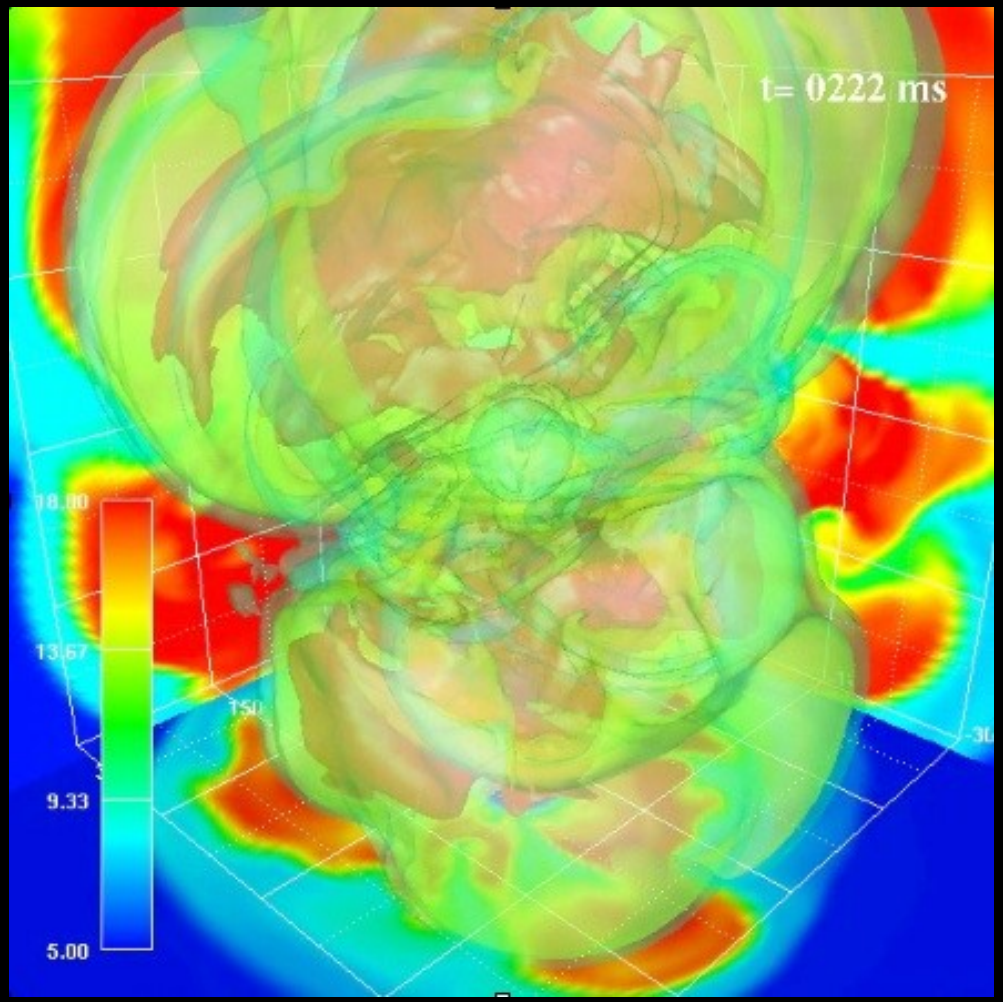
Slide from K. Maeda

§ Central Engine of CC-Supernovae

The Explosion Mechanism is Being Unveiled



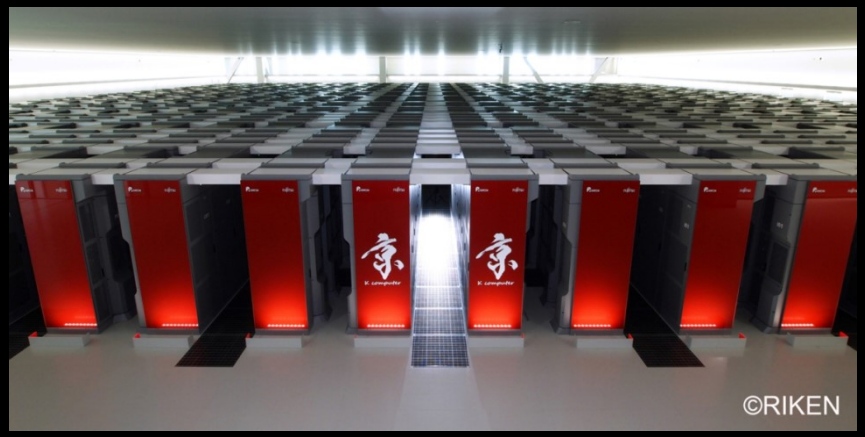
Simulations of CC-SNe Using K-Computer of RIKEN



Takiwaki et al. 2012

京
K computer

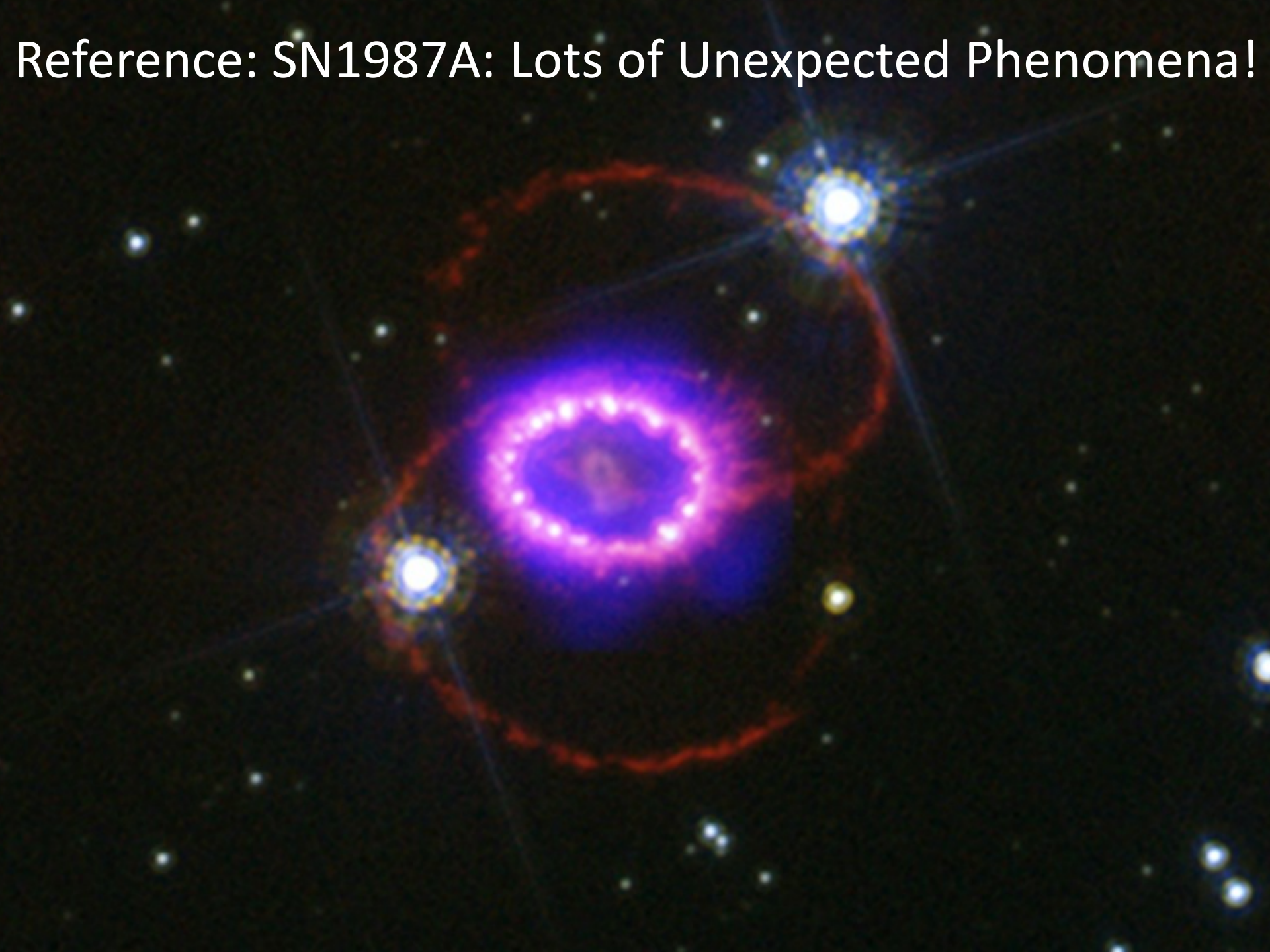
Simulation by
T. Takiwaki
(RIKEN→NAOJ)



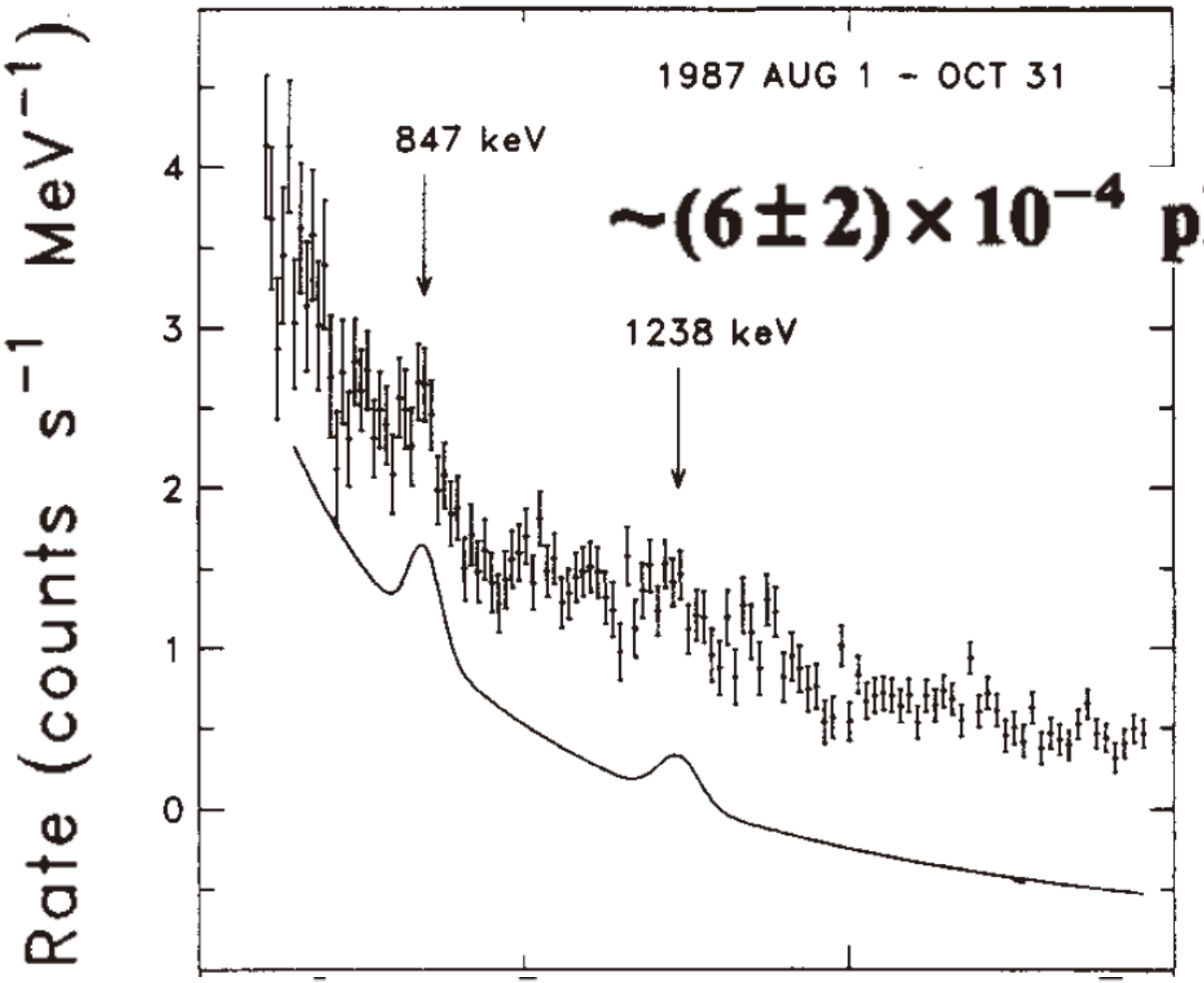
京(KEI) = 10 Peta=10^16.

§ Supernova Ejecta Dynamics
&
Explosive Nucleosynthesis

Reference: SN1987A: Lots of Unexpected Phenomena!



Early Detection of Gamma-Ray Lines !



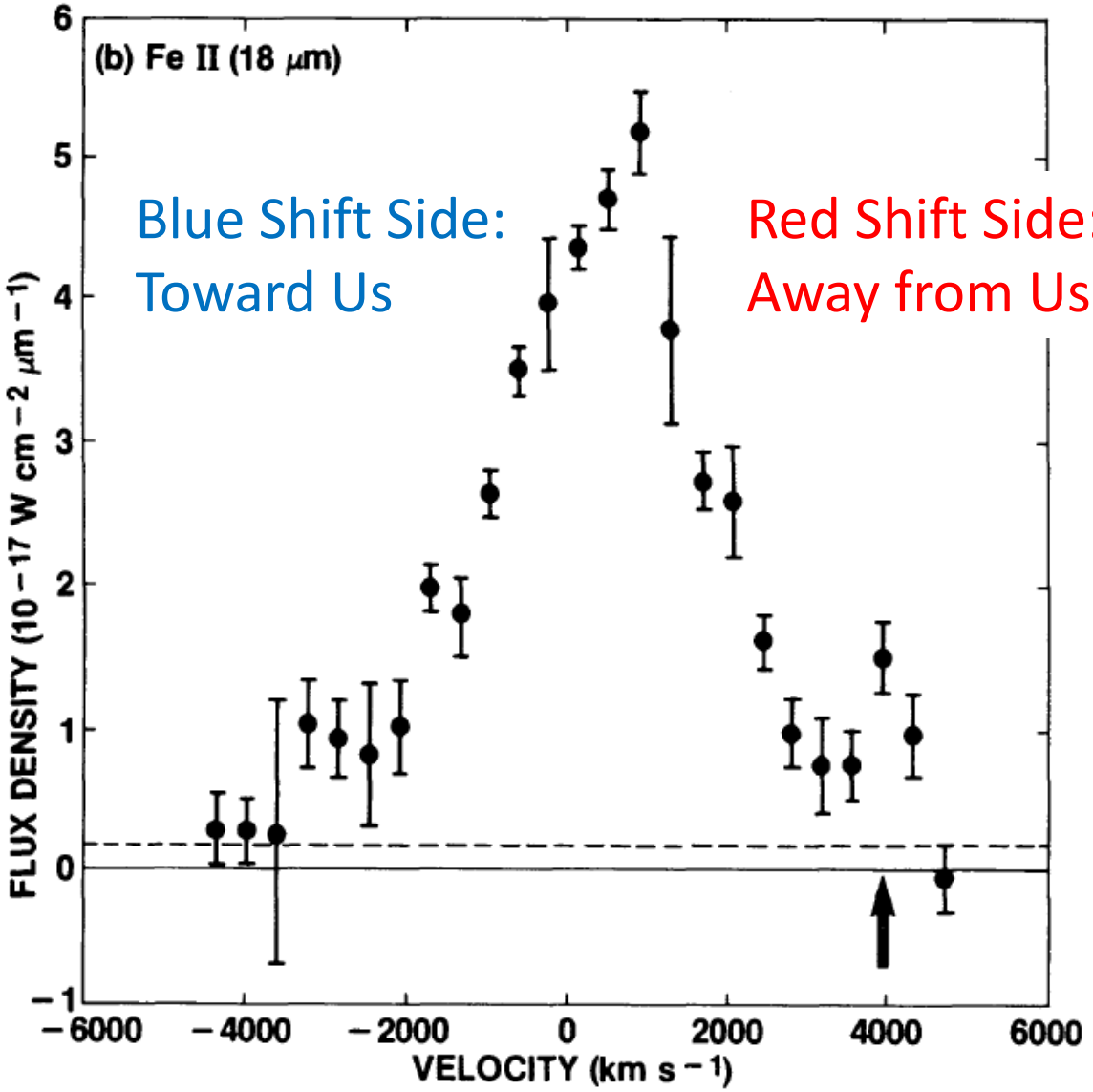
Matz et al. Nature 1988

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

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

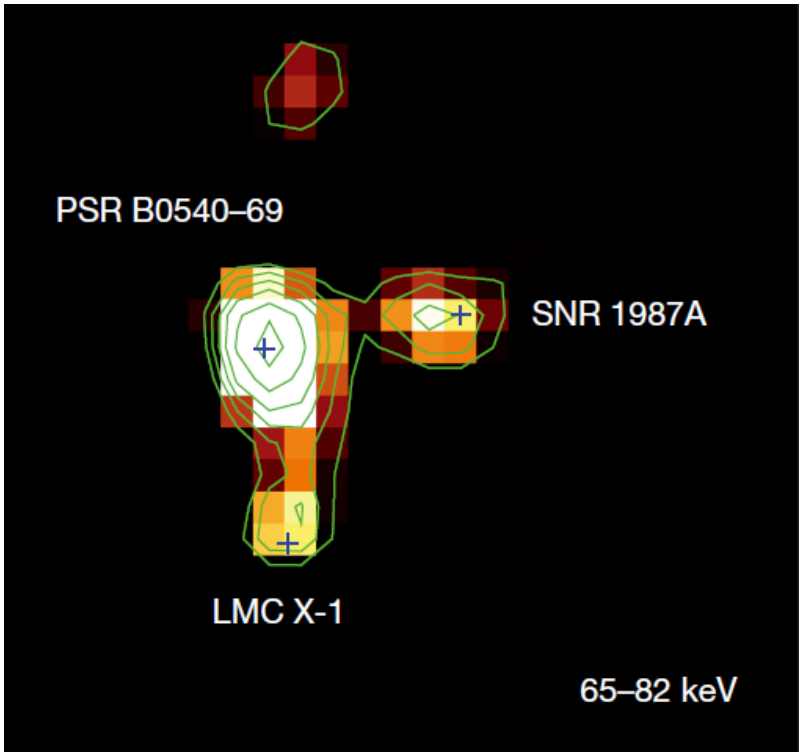
~1.3% of the total mass of ^{56}Co

Velocity Profile of Iron（409days）！



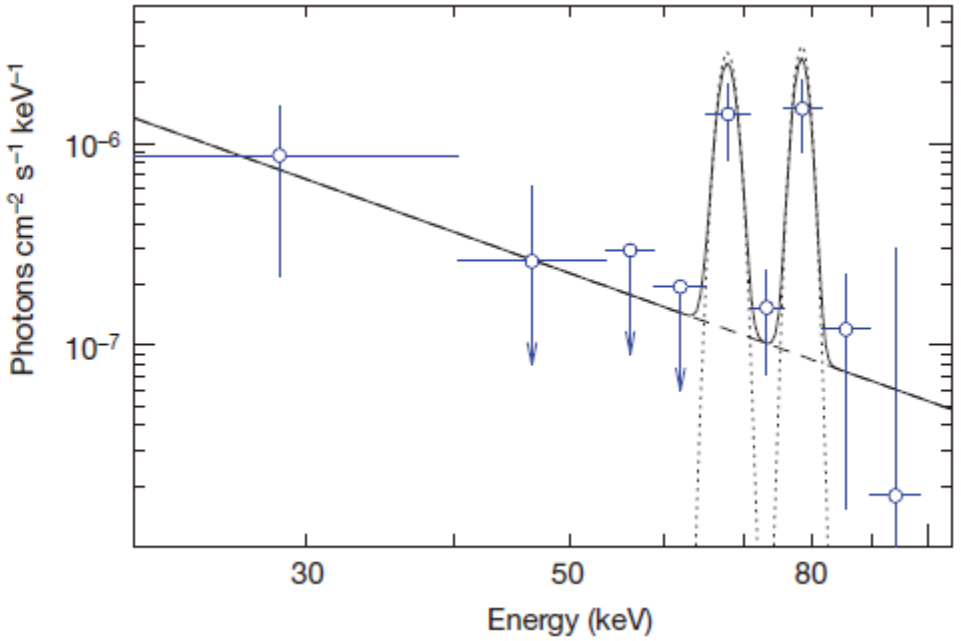
Haas et al. 1990

Lots of ^{44}Ti was Found in SN1987A!



Grebenev et al. Nature 12

By INTEGRAL



$$^{44}\mathrm{Ti} \sim (3.1 \pm 0.8) \times 10^{-4} M_{\odot}$$

Doppler Shift was also detected (Red-Shifted). Consistent with [Fe II] (Boggs et al. 15) by NuSTAR

c.f. Theories: $\sim 10^{-5}\ M_{solar}$

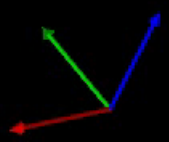
(Hashimoto 95, Thielemann+96, Nagataki 97, Rausher+02, Fujimoto+11,…)

Where is the Neutron Star in SN1987A?

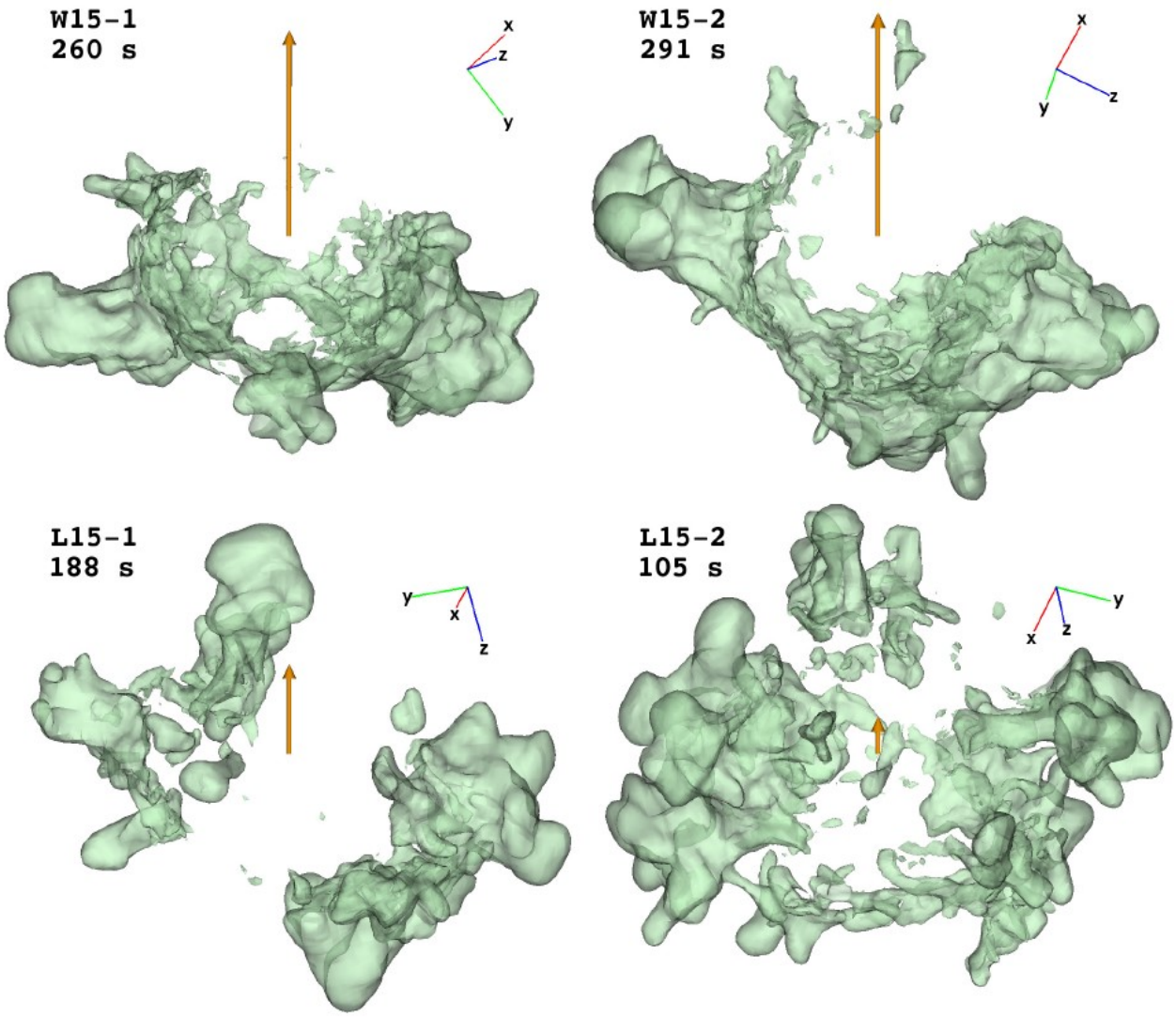
Asymmetric Explosion & Neutron Star Kick

A. Wongwathanarat
(MPA → RIKEN)

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

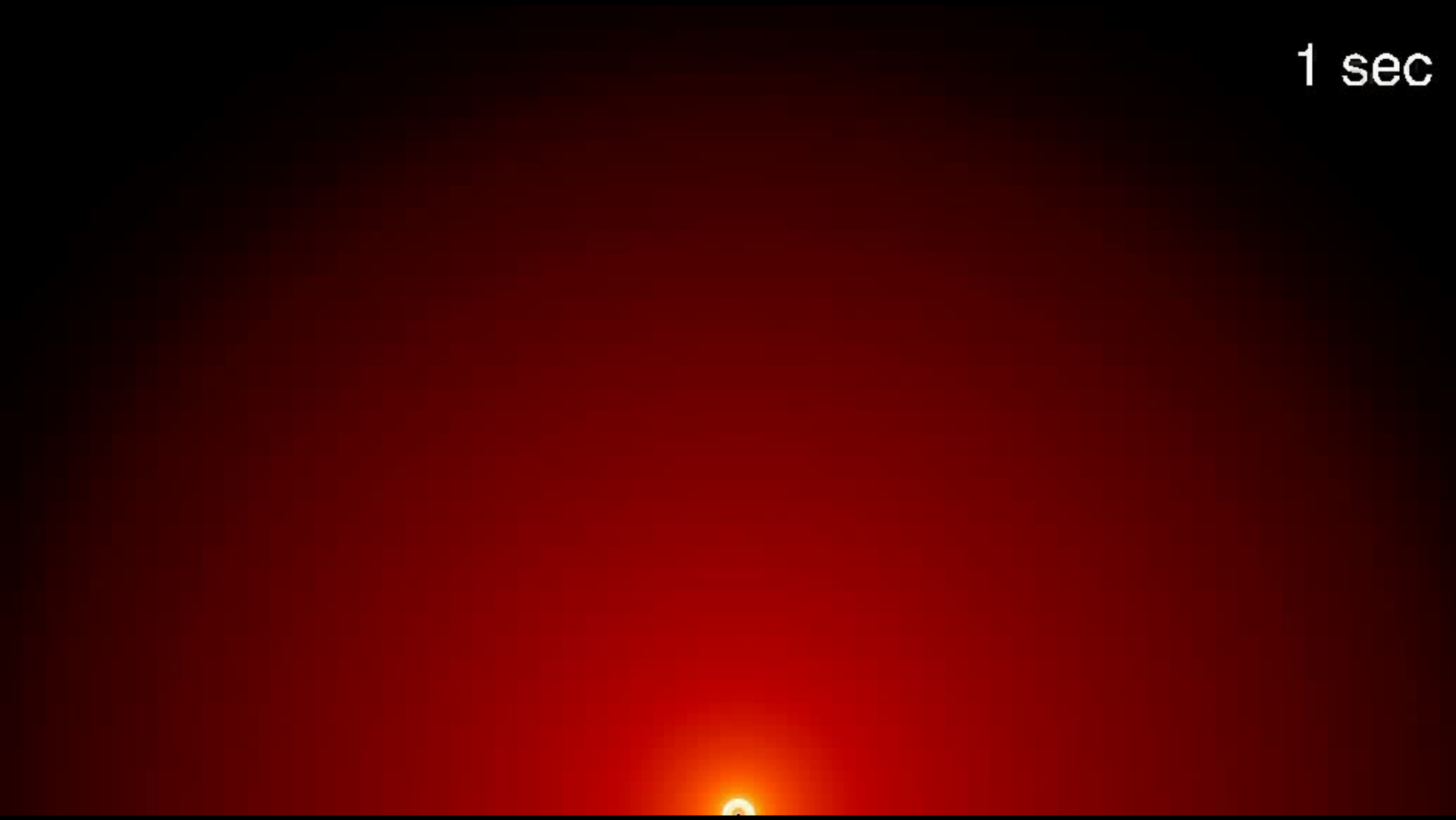


Asymmetric Ejection of 56Ni & Neutron Star Kick



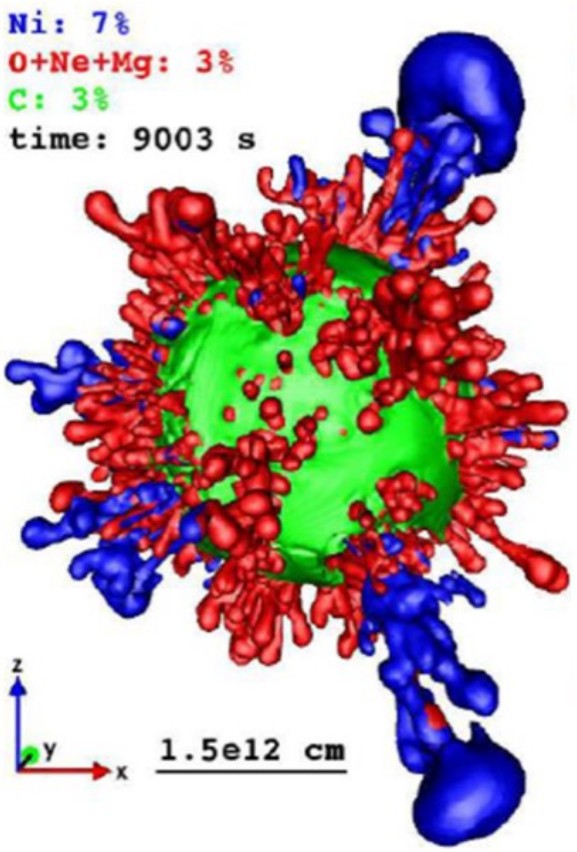
A. Wongwathanarat (RIKEN) + 2013

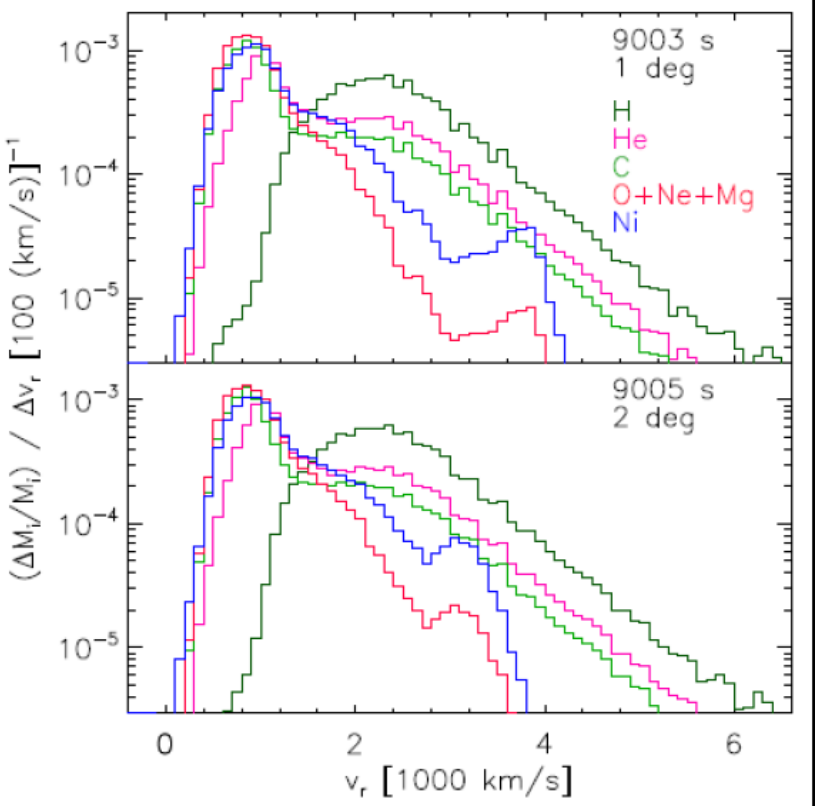
Rayleigh-Taylor Instabilities



Simulation by Kifonidis, MPA.

Successful Reproduction of 56Ni with High-Velocities !

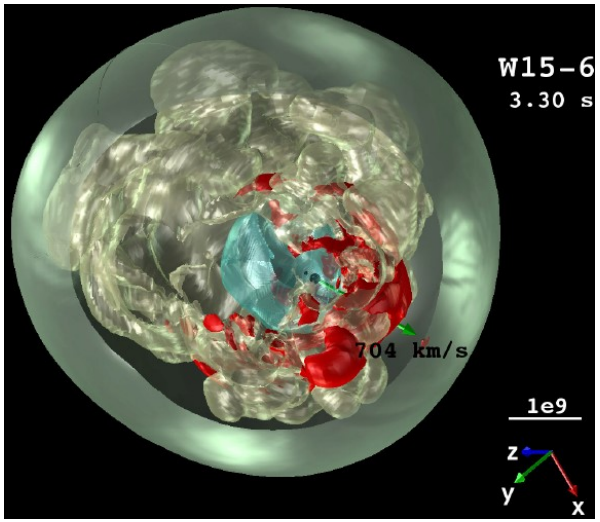


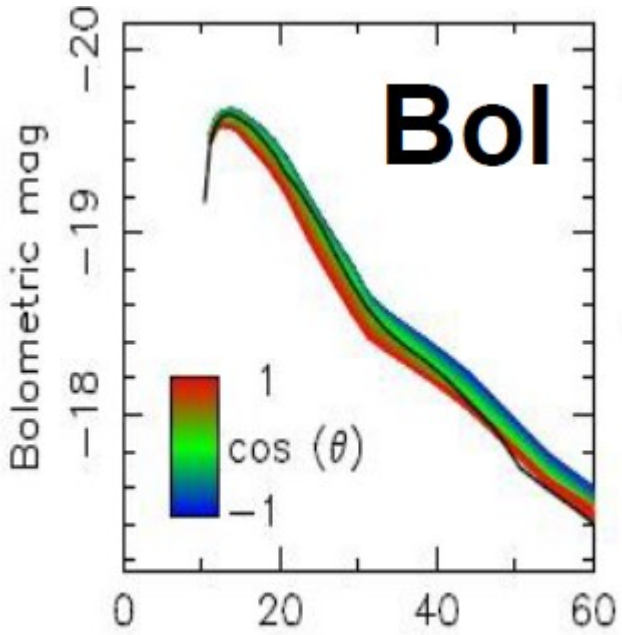


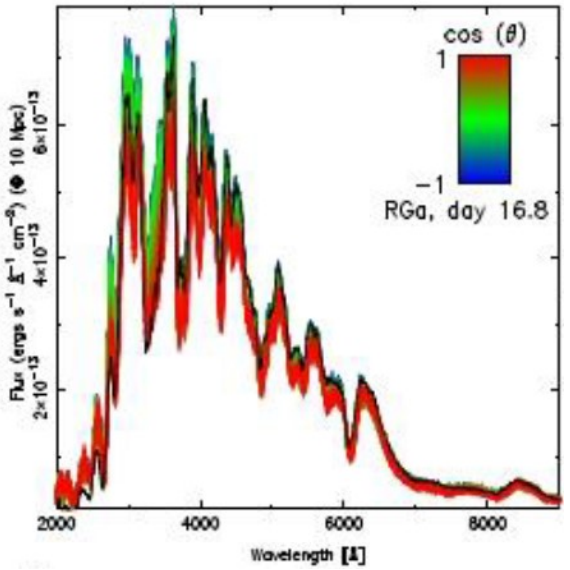
A. Wongwathanarat (RIKEN)

Great Collaborations Started

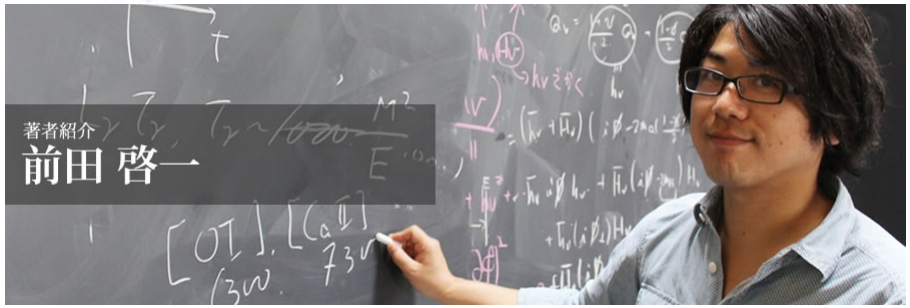
- Radiation Transfer, including Gamma-Ray Line Transfer.







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



Progenitor dependence is Huge

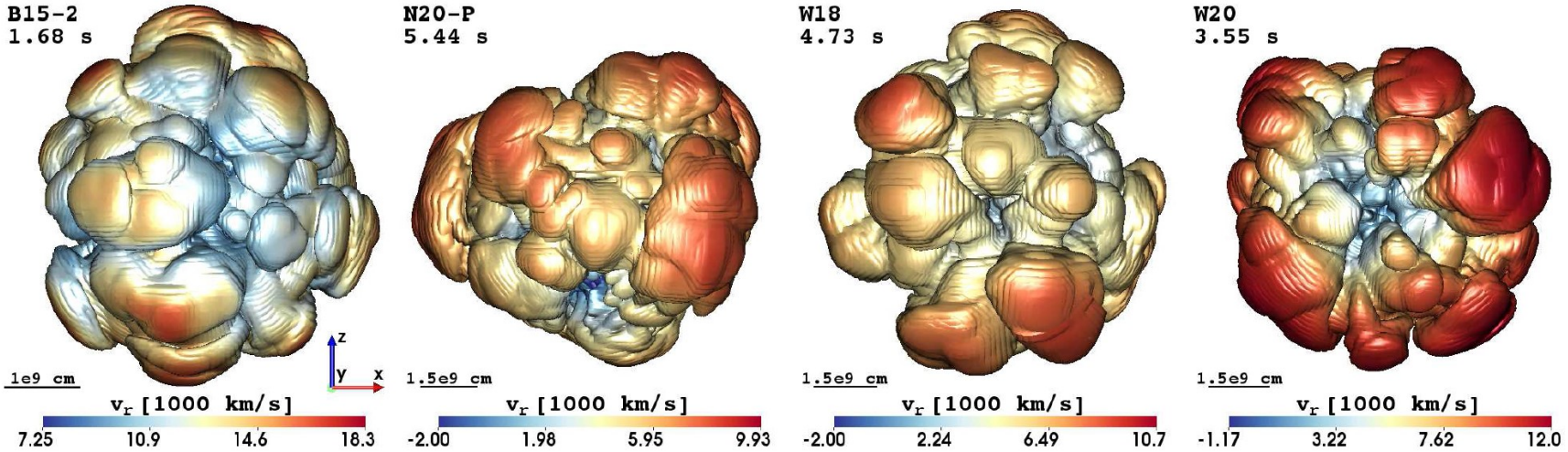
Wongwathanarat et al. (2015)

Woosley et al. (1988)

Shigeyama & Nomoto (1990)

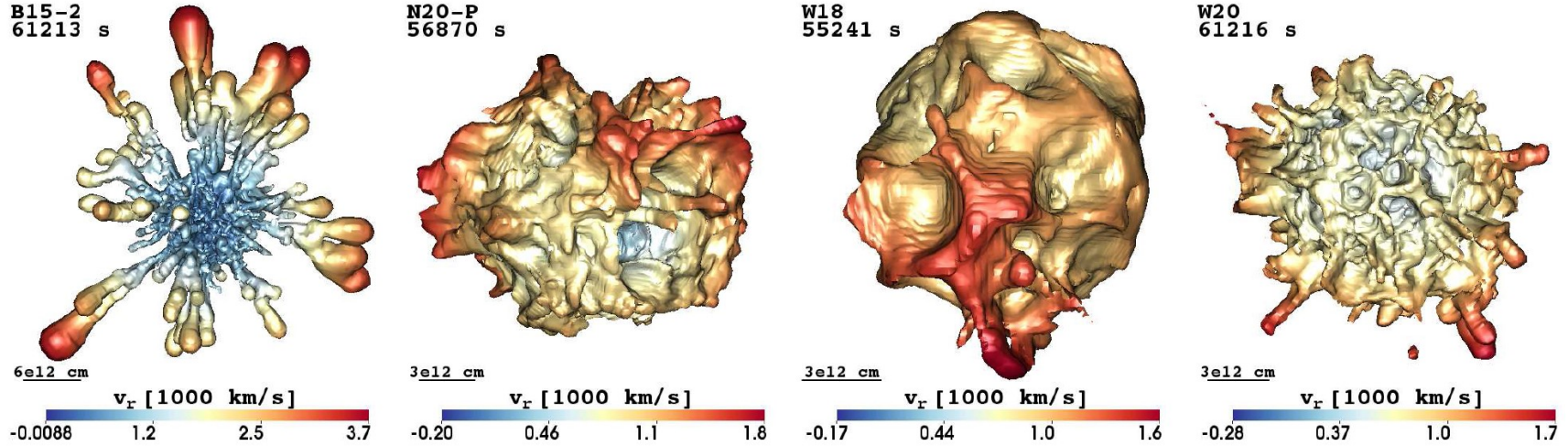
Woosley (2007)

Woosley et al. (1997)

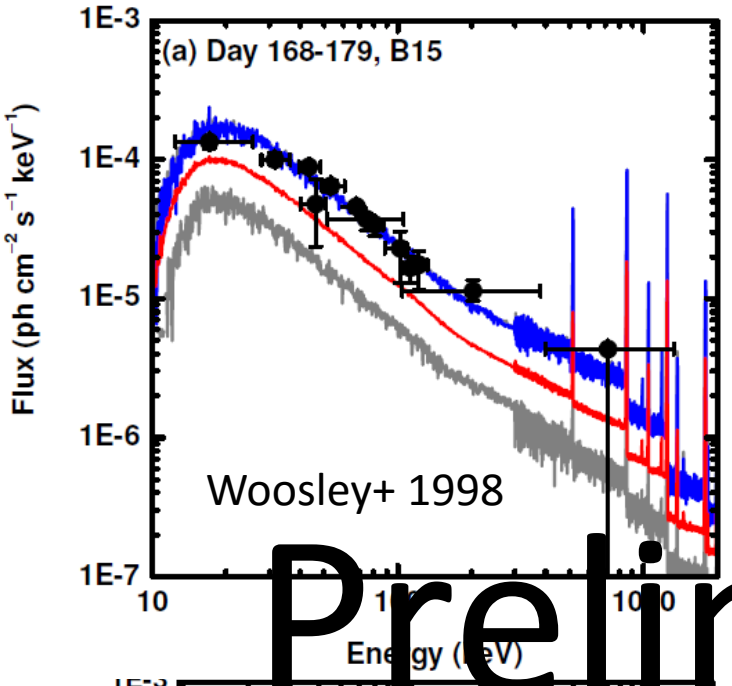


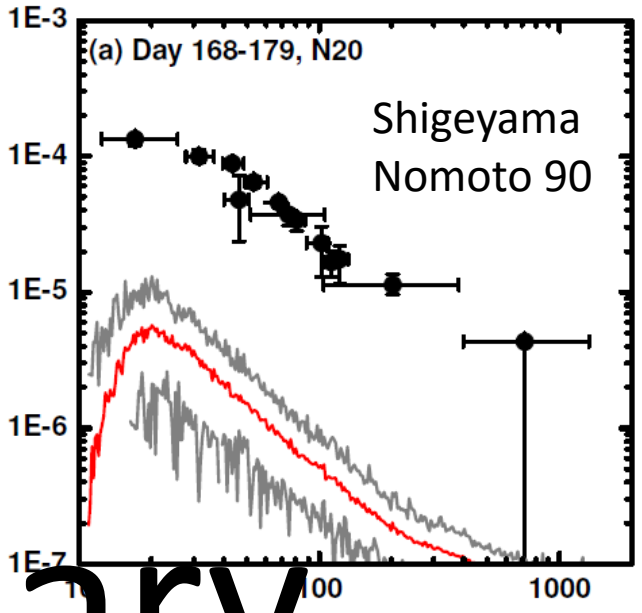
~ 3700 km/s

< 2000 km/s

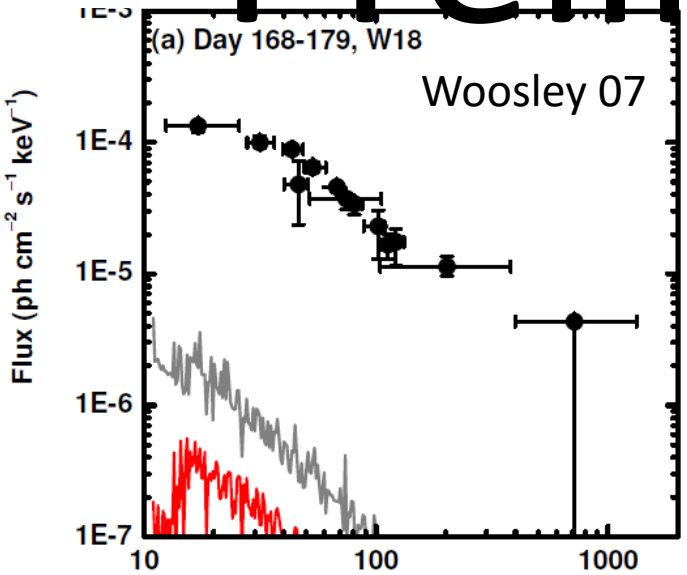


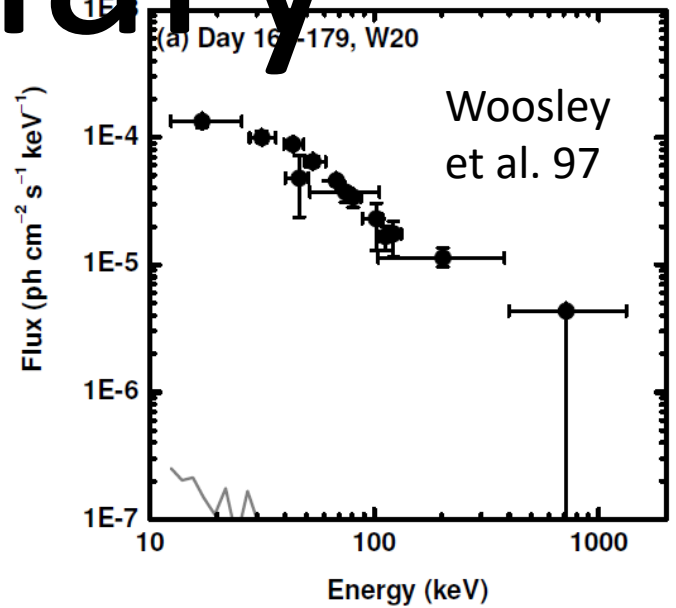
Comparison with SN1987A



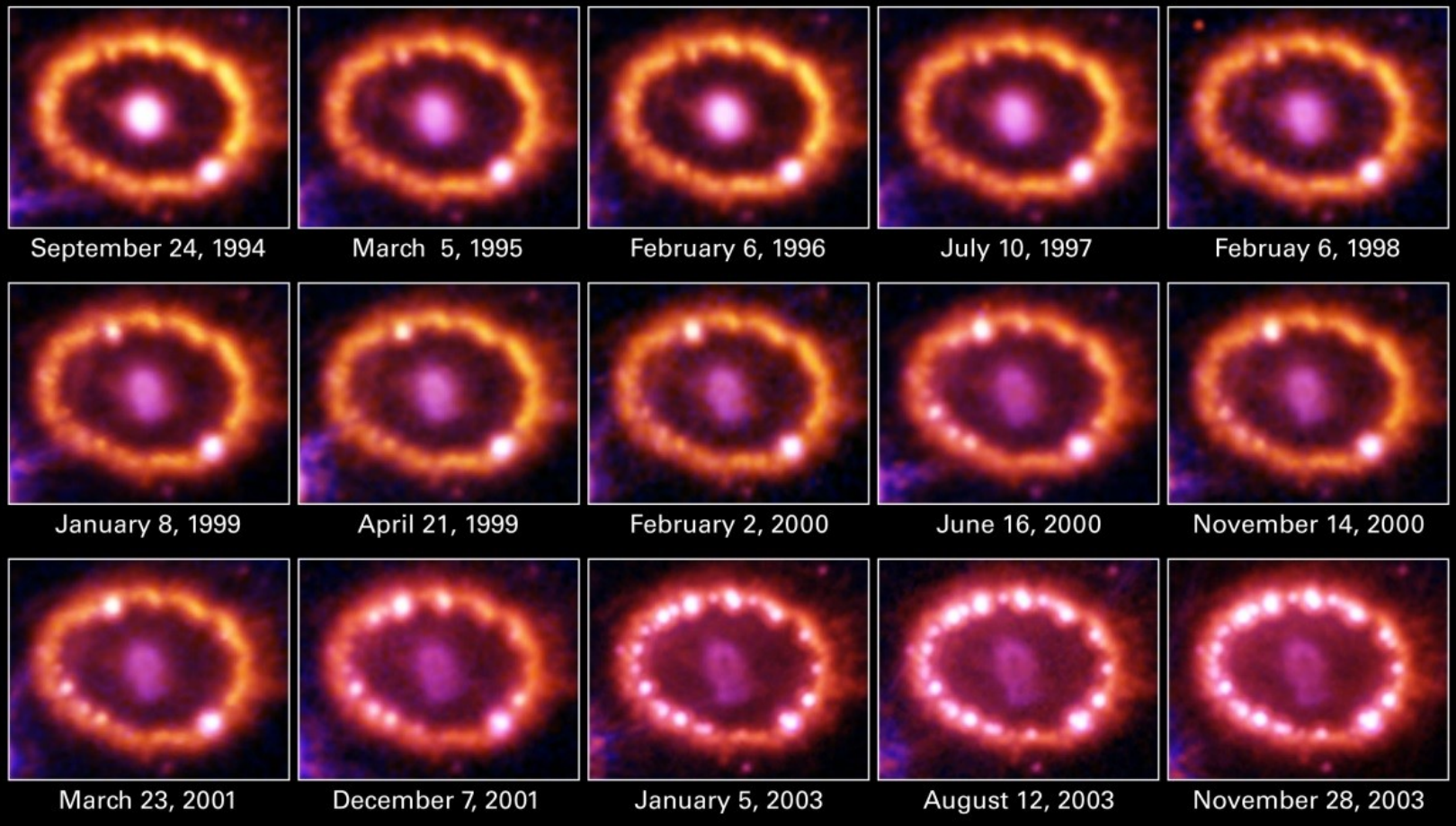


Preliminary

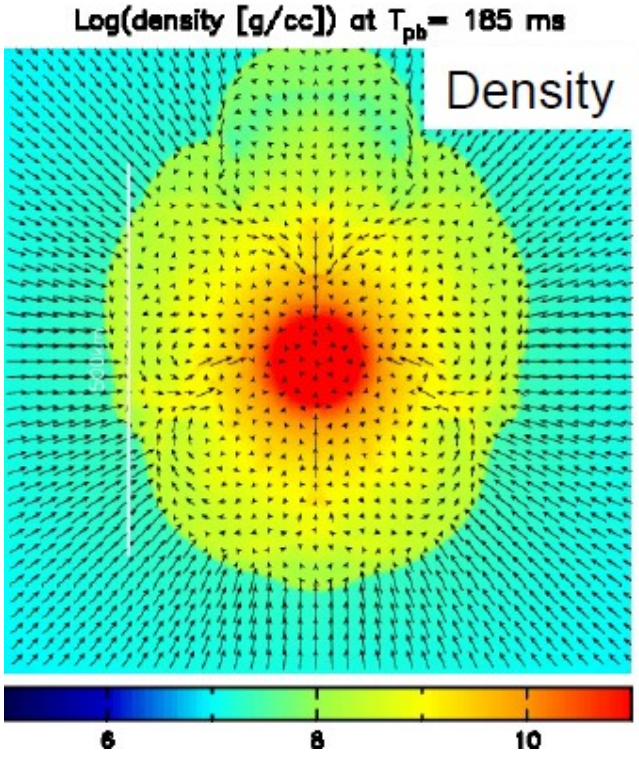




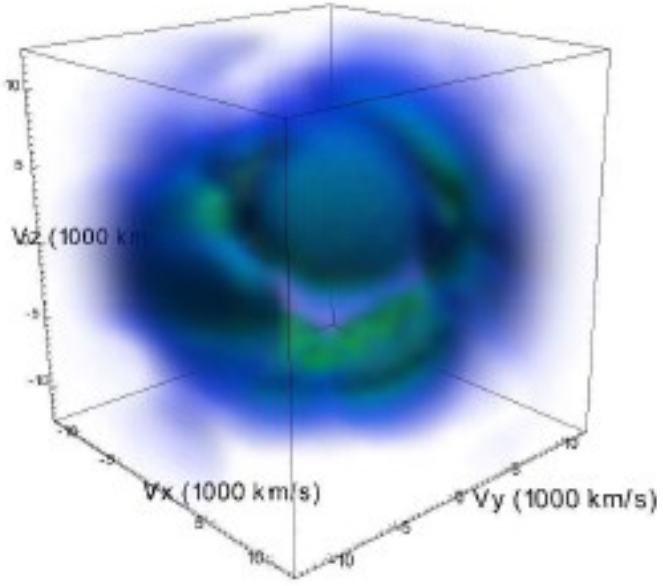
Bipolar Explosion is Seen in SN1987A

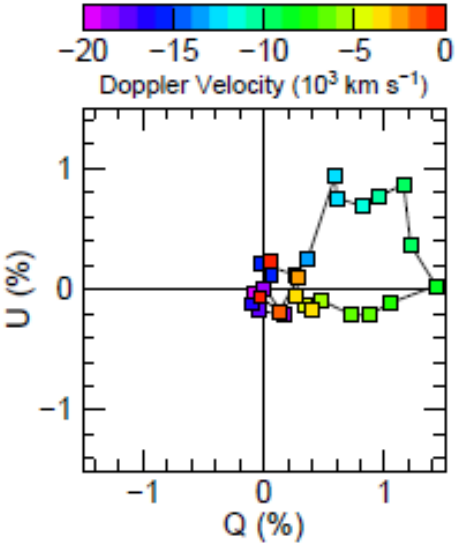


A Great Collaboration Started (2016-)



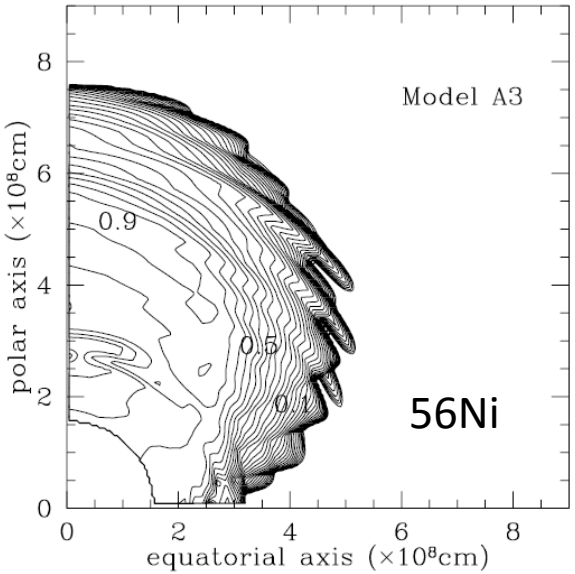
Polarization in Supernova Phase?
Constraints on Asymmetry？

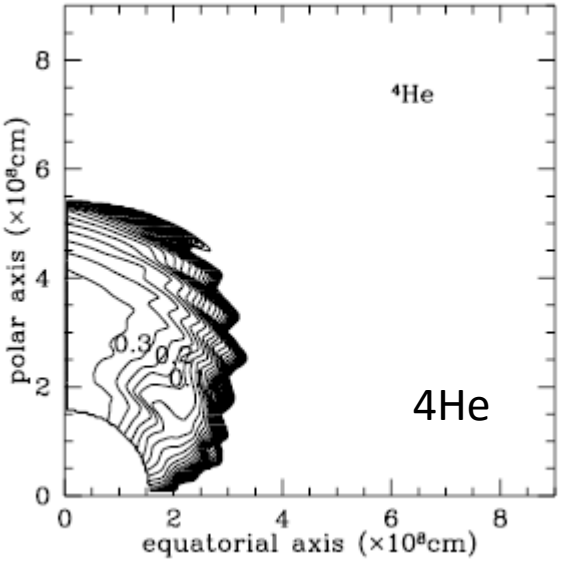




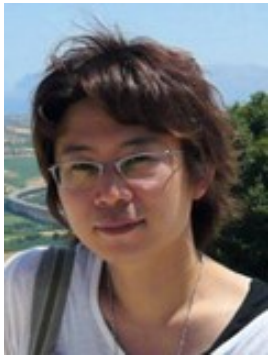
From Left to Right:
K. Nakamura (YITP)
A. Wongwathanarat (RIKEN)
M. Ono (Kyushu U.)
M. Tanaka (NAOJ)
+ Y. Ohtani (NAOJ)

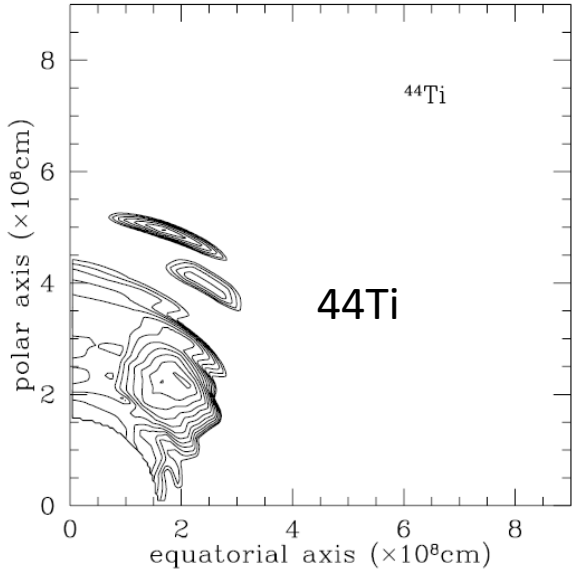
Lots of ^{44}Ti Produced in Bipolar Explosions





Nagataki et al. 97,
Nagataki 00





Produced amount of 44Ti:

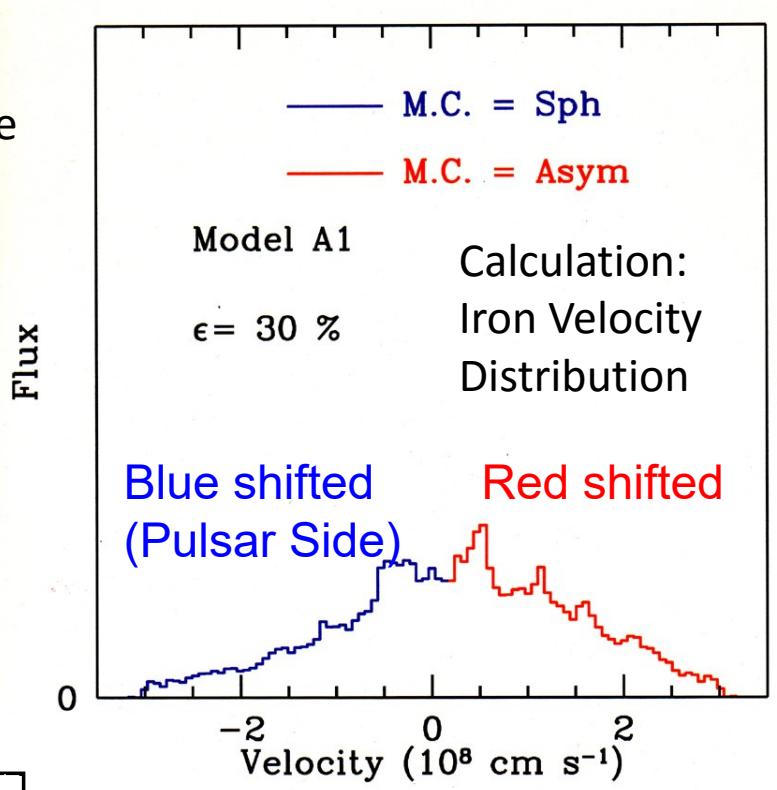
$$(1\text{-}5) \times 10^{-4}\, M_{\odot}$$

Consistent with Obs. of 44Ti by NuStar

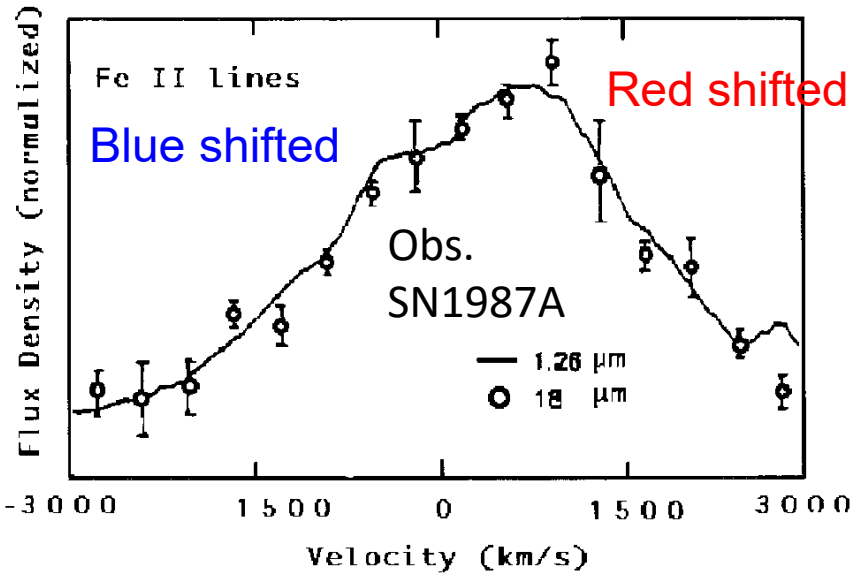
In Jet (bipolar) region, entropy per baryon becomes high!

Asymmetry with Respect of Equatorial Plane
Is Suggested for SN1987A.

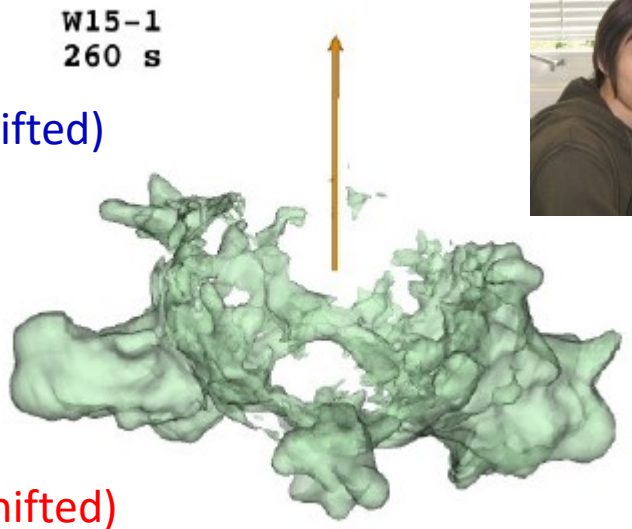
The Missing Neutron Star should be
Moving toward Us (Blue-Shifted Side)!
S.N ApJS 2000.



SN 2000



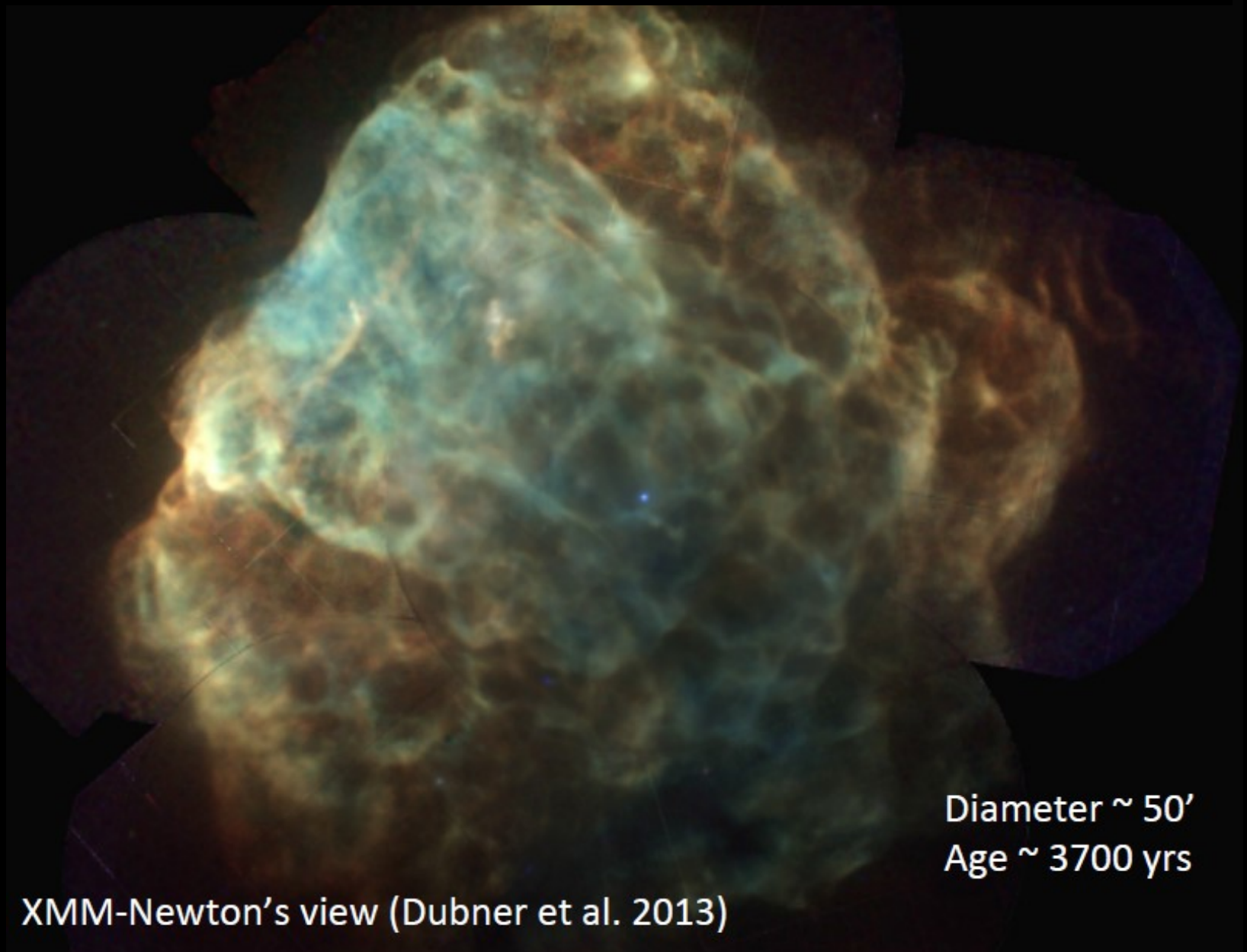
Pulsar
(Blue-Shifted)



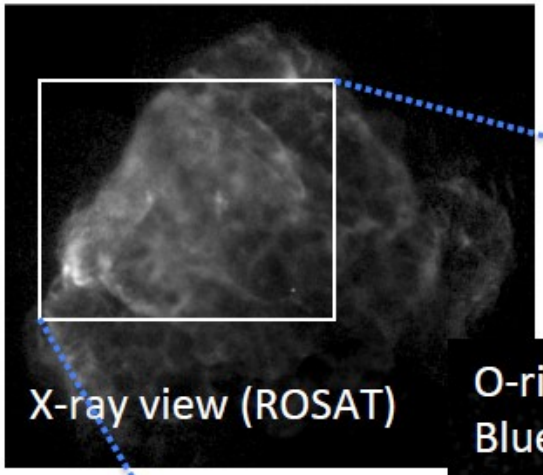
Fe, Ti
(Red-shifted)

Wongwathanarat+ 2013

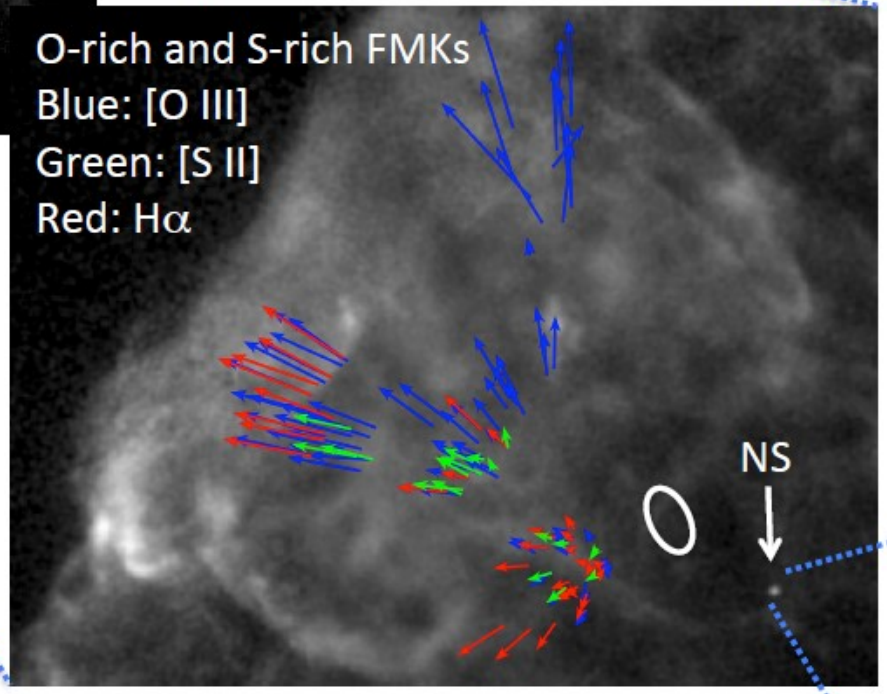
SNR Puppis A: A Globally Asymmetric Explosion



Recoil between Ejecta and NS



Proper motions of fast-moving ejecta knots



Winkler & Kirshner 1985; Garber et al. 2010

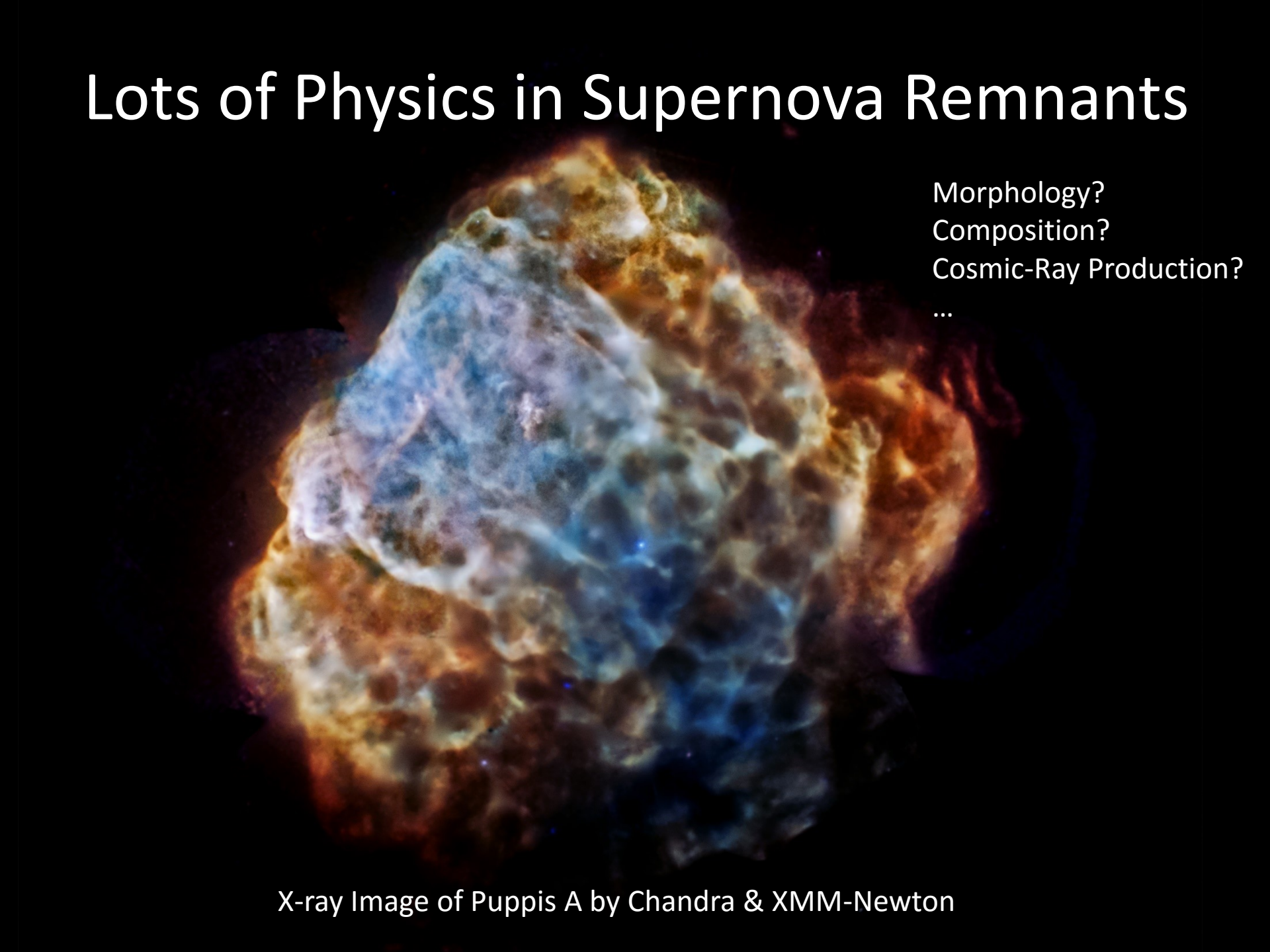
Composition shows That these are not ISM but SN Ejecta (Katsuda+ 2008).

Fast-moving NS

- One-sided O-rich fast-moving knots
- A recoiling (fast-moving) neutron star

§ Supernova Remnants

Lots of Physics in Supernova Remnants



Morphology?
Composition?
Cosmic-Ray Production?
…

X-ray Image of Puppis A by Chandra & XMM-Newton

Numerical simulations with Ramses

Gilles Ferrand
(U.Manitoba→RIKEN)

parameters: Tycho (SN Ia)

$t_{\rm SN} = 440$ years
$E_{\rm SN} = 10^{51}$ erg
$n = 7$, $M_{\rm ej} = 1.4\,{\rm M}_\odot$
$s = 0$, $n_{\rm H,ISM} = 0.1\,{\rm cm}^{-3}$

Chevalier 1982, 1983

Teyssier 2002, Fraschetti et al 2010

SNR initialization: self-similar profiles from **Chevalier**

SNR evolution: 3D hydro code **ramses**

A Simplified Initial Condition.
→ This can be improved.

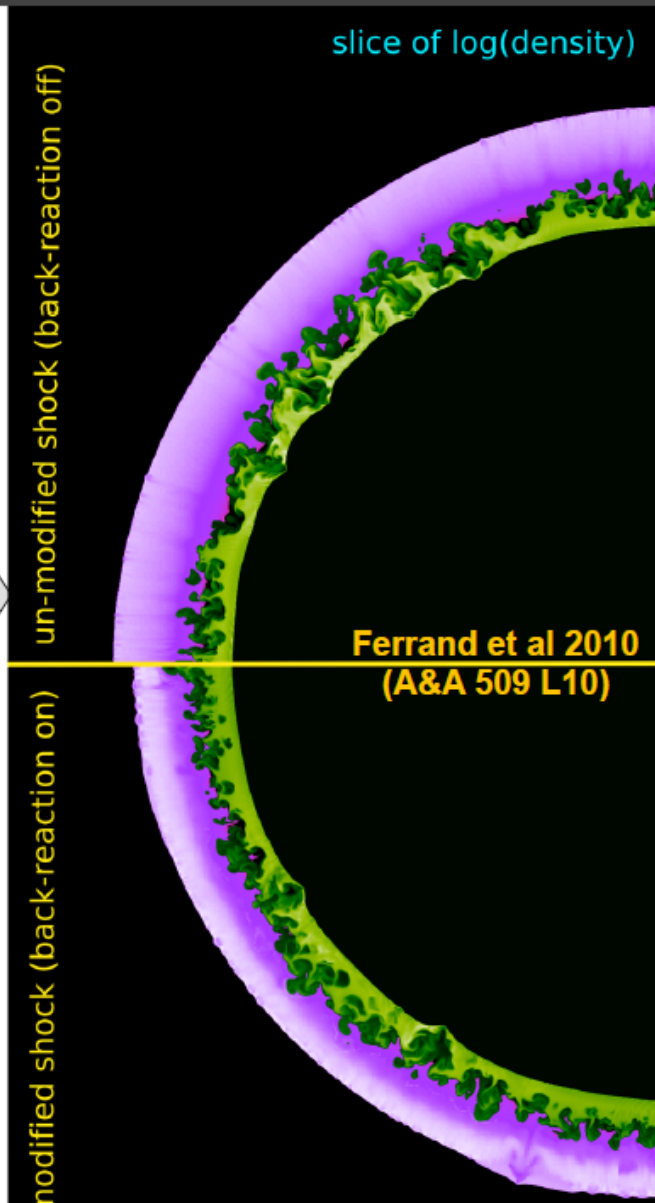
shock diagnostics

back-reaction: varying gamma

Ellison et al 2007

Blasi et al 2002, 2004, 2005 + Caprioli 2008, 2009

particle acceleration: non-linear model of **Blasi**



Thermal + non-thermal emission from a SNR

simulations

observations

test-particle case

modified shock
with magnetic field amplification

Gilles Ferrand
(U.Manitoba→RIKEN)

Energetic protons, accelerated at the shock front, don't radiate as efficiently as electrons, however:

1/ they impact the dynamics of the shock wave, and therefore the **thermal emission** from the shell (optical, X-rays)

Ferrand, Decourchelle, Safi-Harb 2012

2/ they impact the evolution of the magnetic field, and therefore the **non-thermal** emission from the electrons (radio – X-rays – γ-rays)

Ferrand, Decourchelle, Safi-Harb 2014

3D hydro+kinetic simulations of SNRs

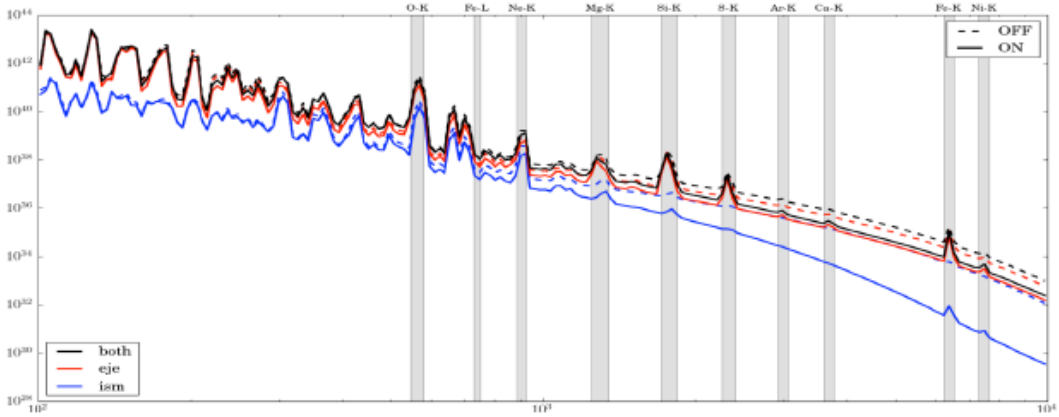
hydro profiles

un-modified shock (back-reaction off)

Ferrand et al 2010
(A&A 509 L10)

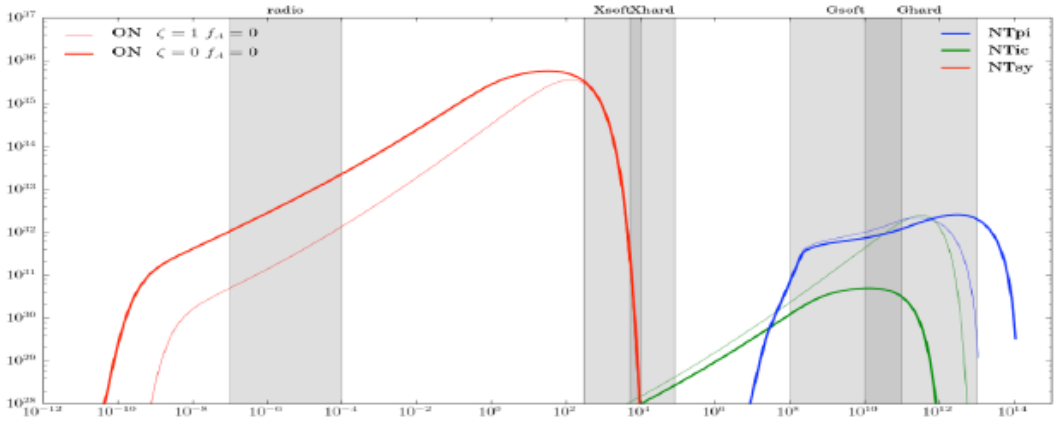
modified shock (back-reaction on)

→ density, temperature
→ ionization state (out of equilibrium)
→ thermal emission from 15 elements



Ferrand, Decourchelle, Safi-Harb 2012

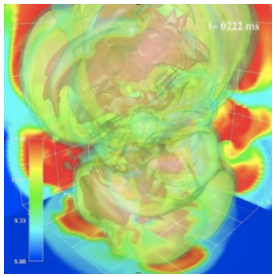
+ recipes for the magnetic field amplification
+ transport downstream of the shock
→ non-thermal emission of electrons and protons



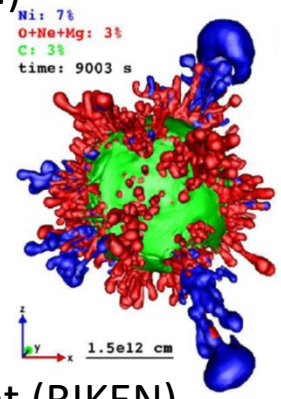
Ferrand, Decourchelle, Safi-Harb 2014

Our Big Mission

From (Takiwaki, Wongwathanarat, Reopke) To (Lee, Ono, Ferrand)



Takiwaki (RIKEN)



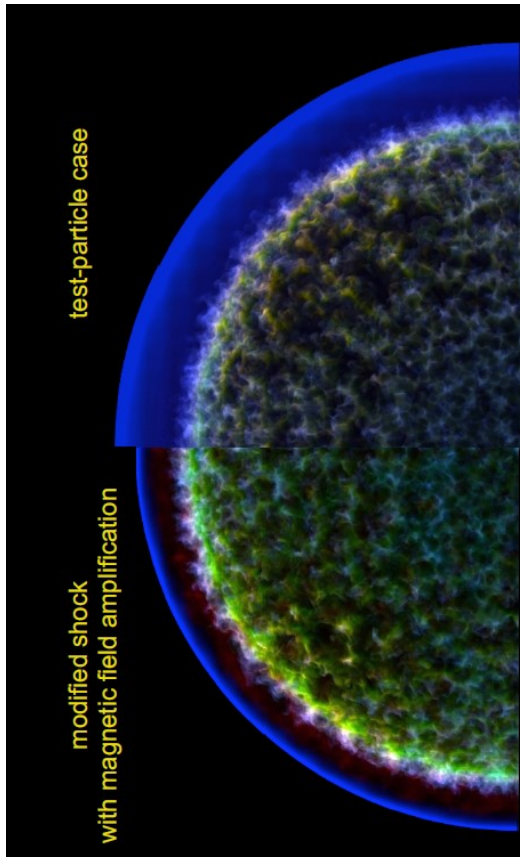
Wongwathanarat (RIKEN)

Reopke (Wurzburg U.)

How do they Evolve?

Origin of Asymmetry?

Can We find Legacies of SNe in SNRs?



G. Ferrand et al. (2014)

S.H. Lee
(JAXA→Kyoto)

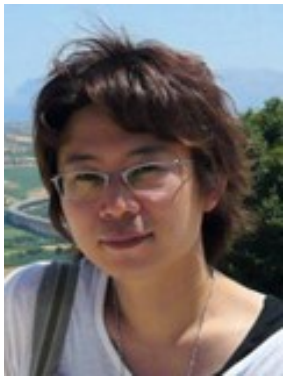
M.Ono
(Kyushu→RIKEN)

G. Ferrand
(U. Manitoba→RIKEN)

§ Engine of Gamma-Ray Bursts

Central Engine of Gamma-Ray Bursts is Hardly Known.

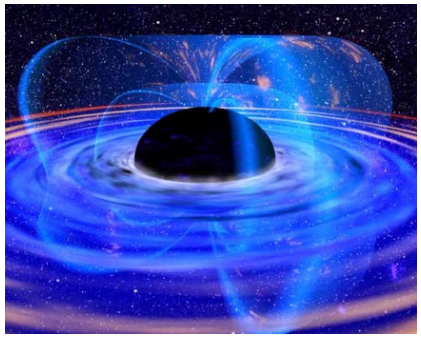
A Black Hole is Formed?

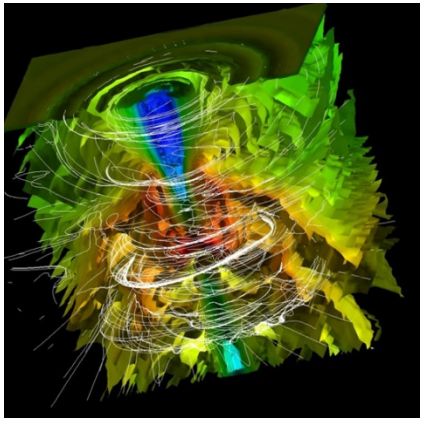


S. Nagataki
(RIKEN)

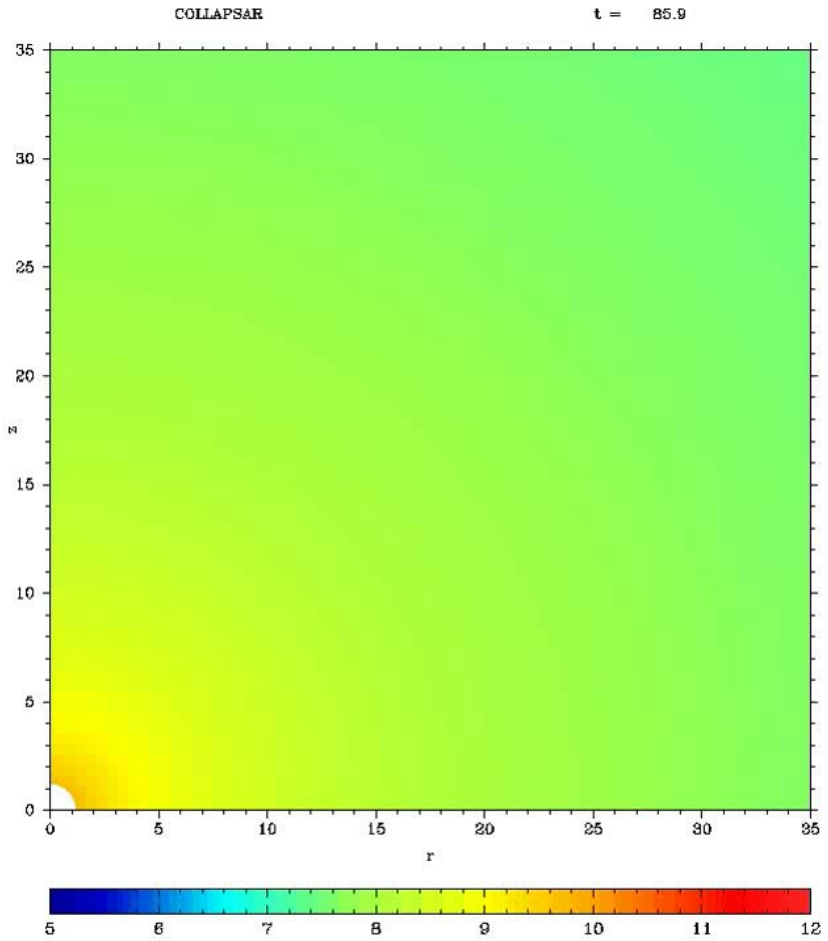
M. Barkov
(RIKEN)

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





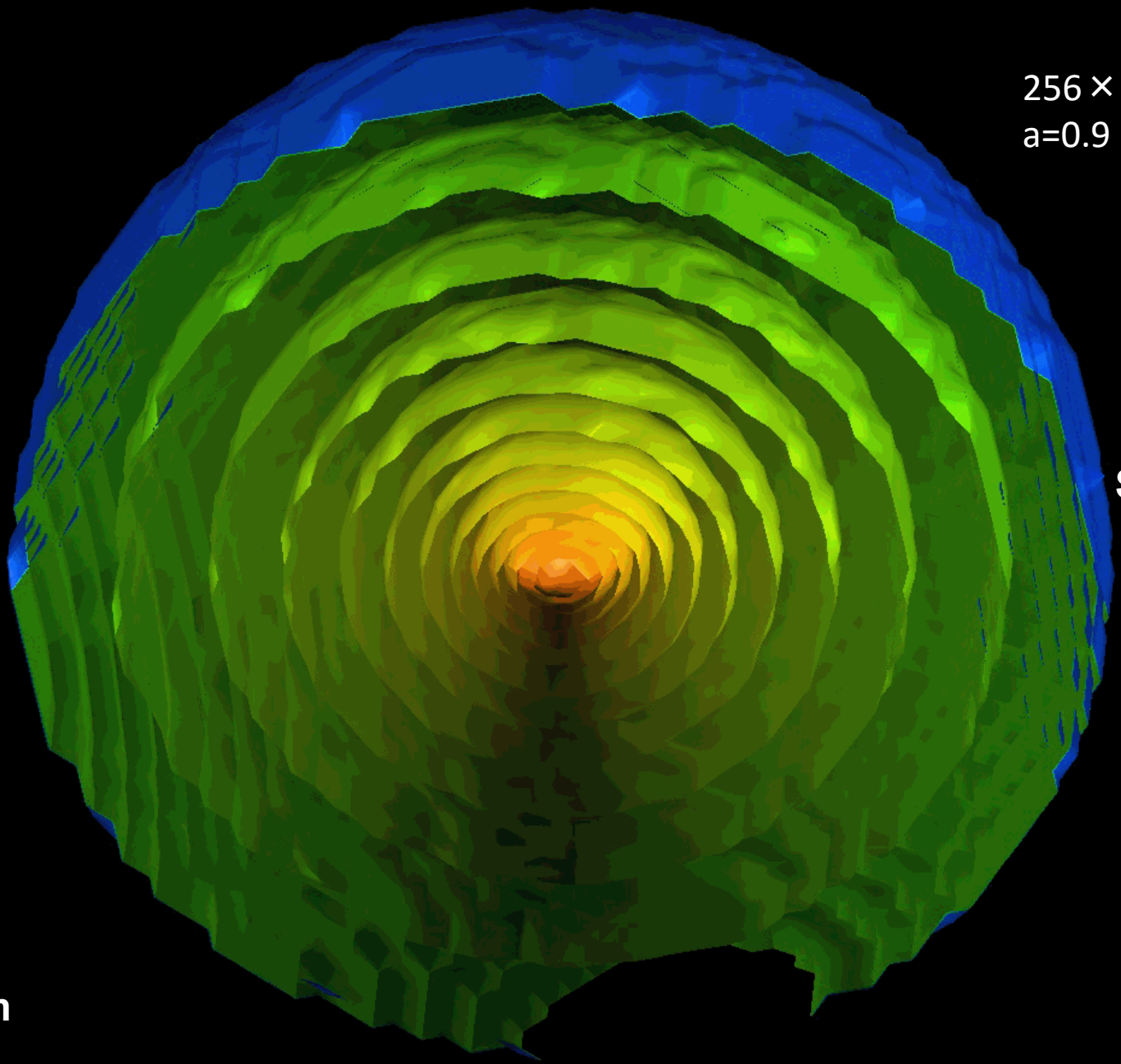
Rotation Axis



Equatorial Plane

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

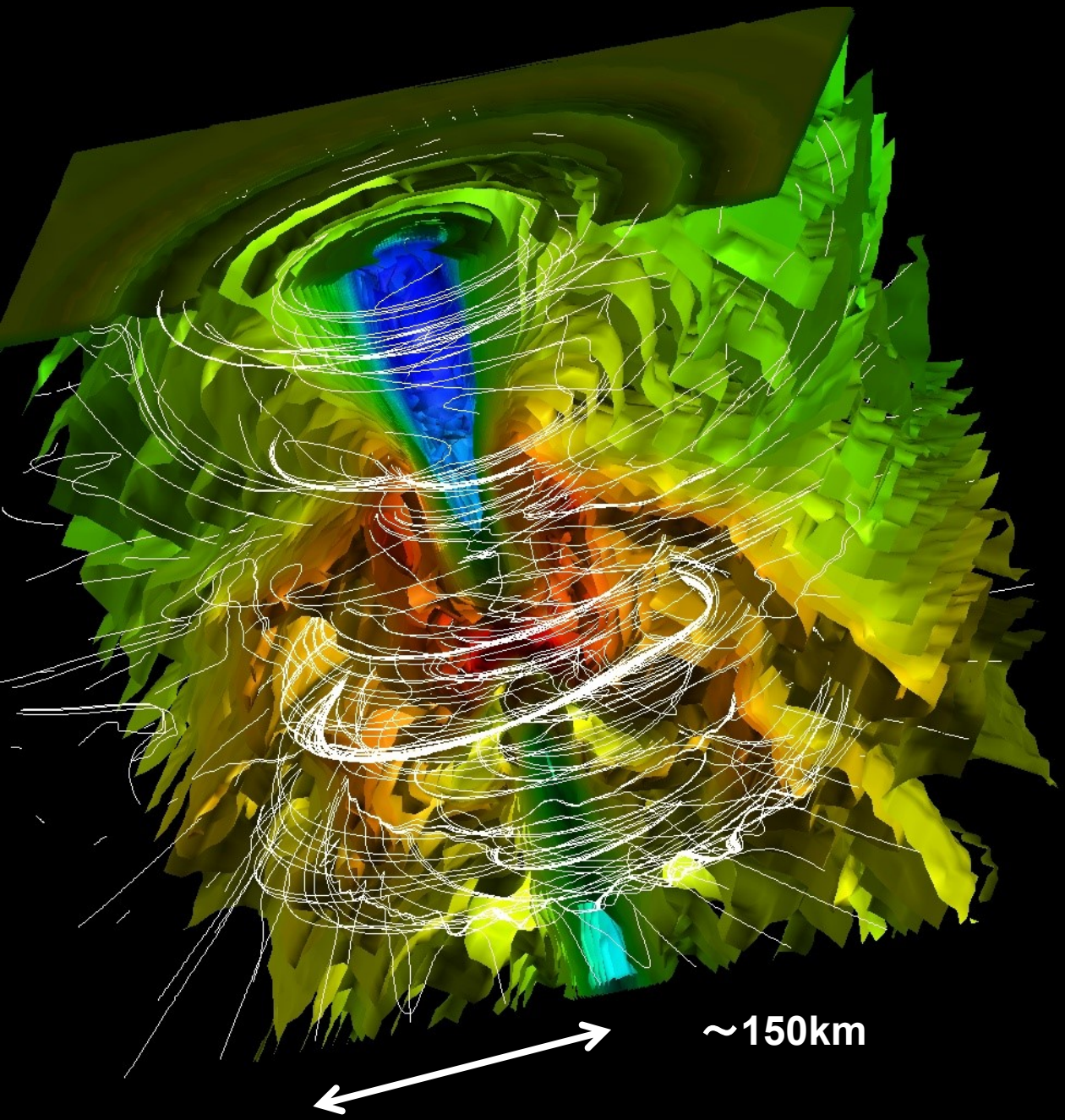
3D-GRMHD Simulation of GRBs



256 × 256 × 128
a=0.9

S.N. 2013

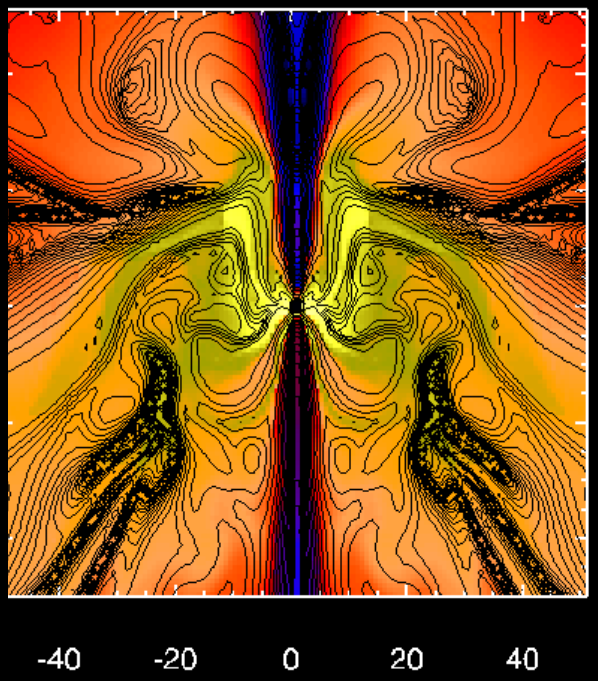
~3000km



a=0.9
T～0.9sec.

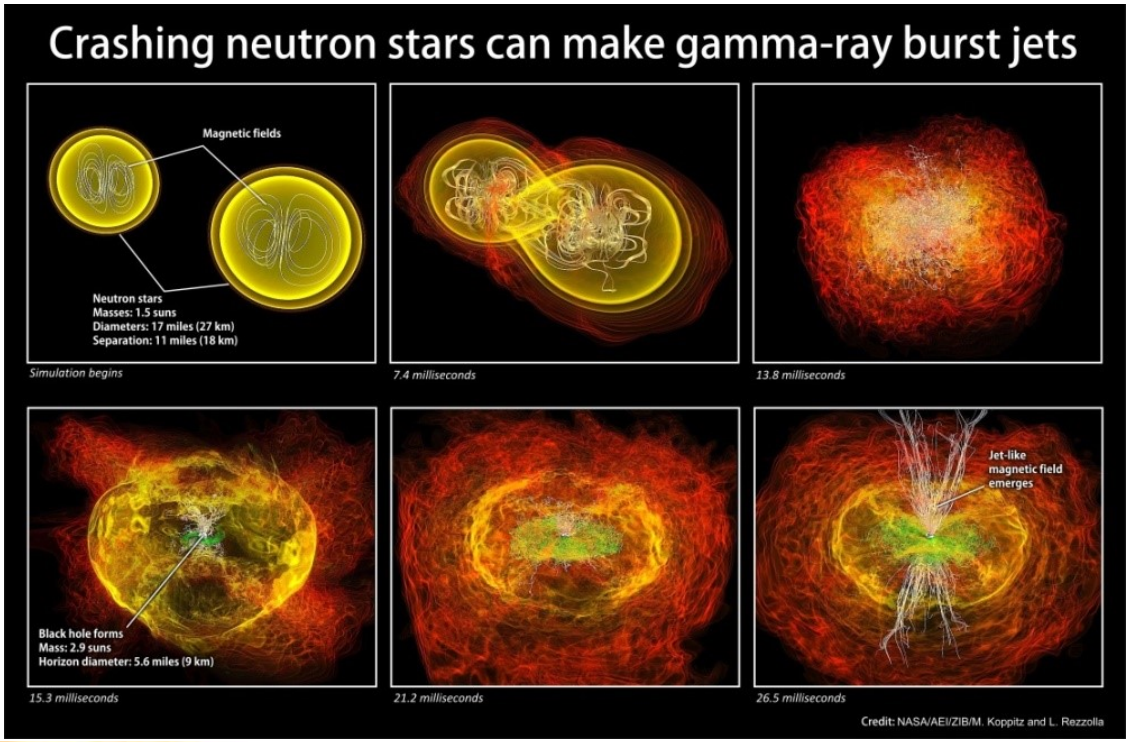
Same Simulations.
Left: 3D Image.
Density+B-fields.

Bottom: 2D Slice
Density+Poloidal
B-Fields
～150km



A Great Collaboration Started (2015-).

Luca Baiotti（Osaka Univ.）
A developer of Whisky Code
Luciano Rezzolla,
Bruno Giacomazzo

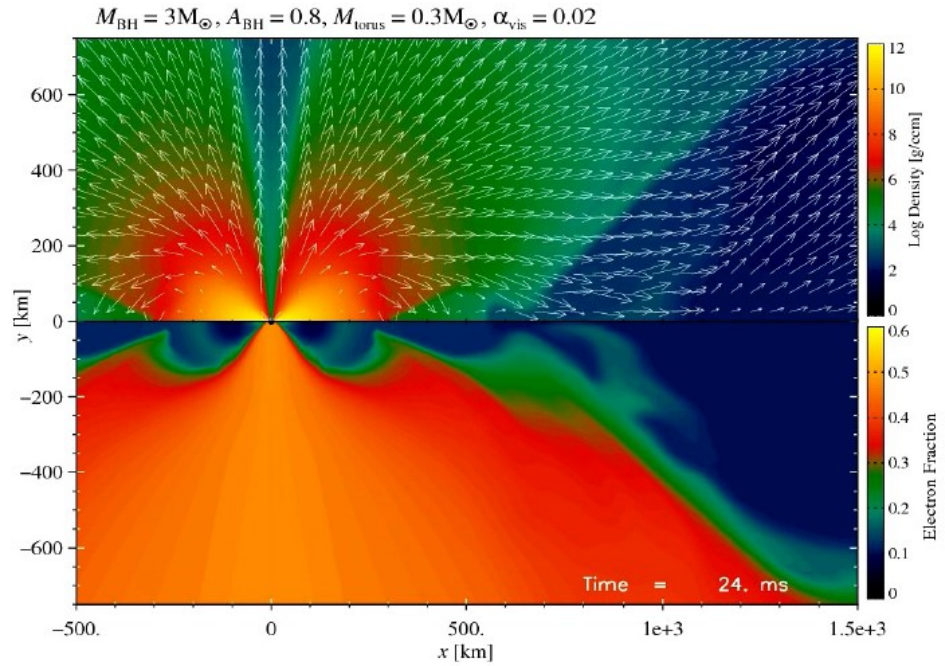


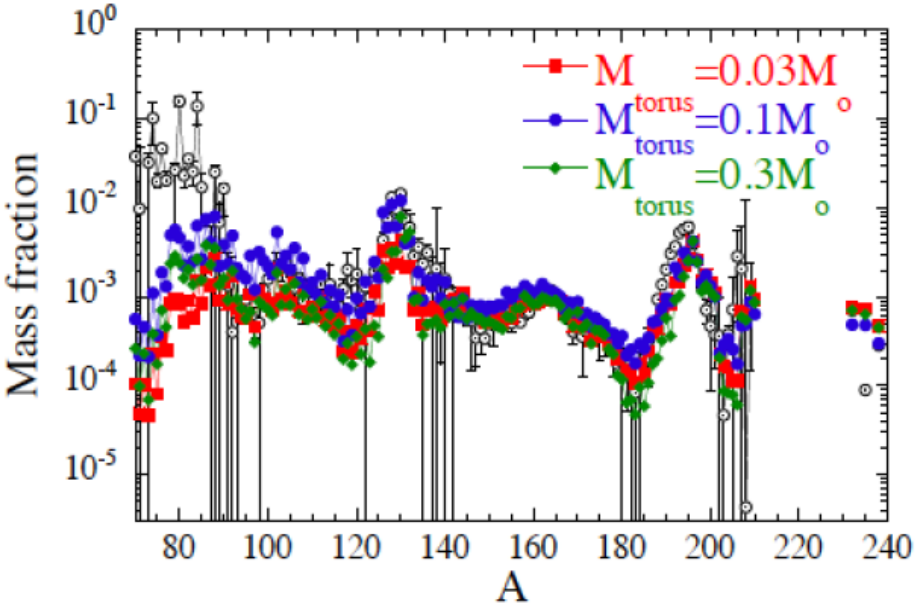
Nagataki (RIKEN)　Barkov (RIKEN)　Takiwaki(RIKEN)

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

Einstein-Eqs Solver will be attached
To our GRB Engine Simulations!

NS-NS Mergers & NS-BH Mergers





$$E = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t) \quad \leftarrow \text{energy density}$$

$$F^i = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i \quad \leftarrow \text{momentum density}$$

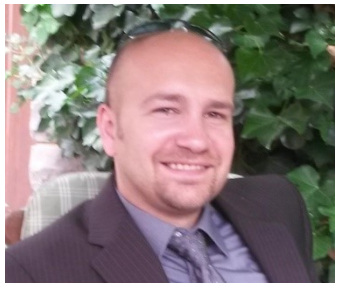
$$P^{ij} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j \quad \leftarrow \text{pressure}$$

$$Q^{ijk} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k$$

$$\left.\begin{aligned} \partial_t E + \nabla_j F^j + \nabla_j(v^j E) + (\nabla_j v_k) P^{jk} - (\nabla_j v_k)\partial_\epsilon(\epsilon P^{jk}) &= C^{(0)} \\ \partial_t F^i + c^2 \nabla_j P^{ij} + \nabla_j(v^j F^i) + F^j \nabla_j v^i - (\nabla_j v_k)\partial_\epsilon(\epsilon Q^{ijk}) &= C^{(1),i} \end{aligned}\right\} \text{evolution equations}$$

$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\} \text{approximate algebraic closure relations (e.g. "M1 closure")}$$

Left:
Post Merger BH-Torus Remnant
Right:
R-process Nucleosynthesis by Prompt+Post Merger.

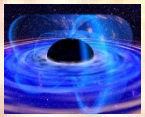


Oliver Just (MPA)

Simulations for Short GRBs are going on!

The Gamma-Ray Bursts: The Most Powerful explosion in the Universe

A Black Hole is formed at the center?

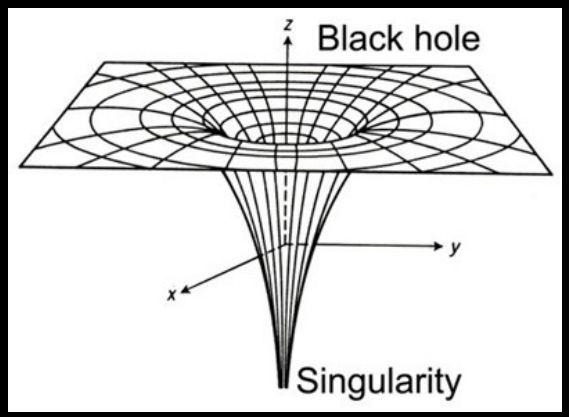


?

Image of Gamma-Ray Bursts

© A. Roquette (ESO)

Collaboration between Astrophysicists (Nagataki) & Particle physicists（iTHES: Yokokura, Tanaka, Hongo）!



Analogy between Black Hole & Creation of the Universe?

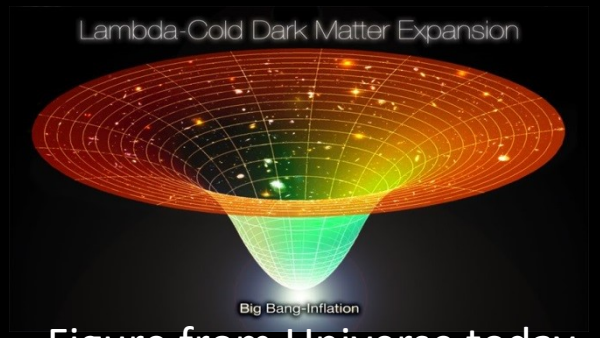
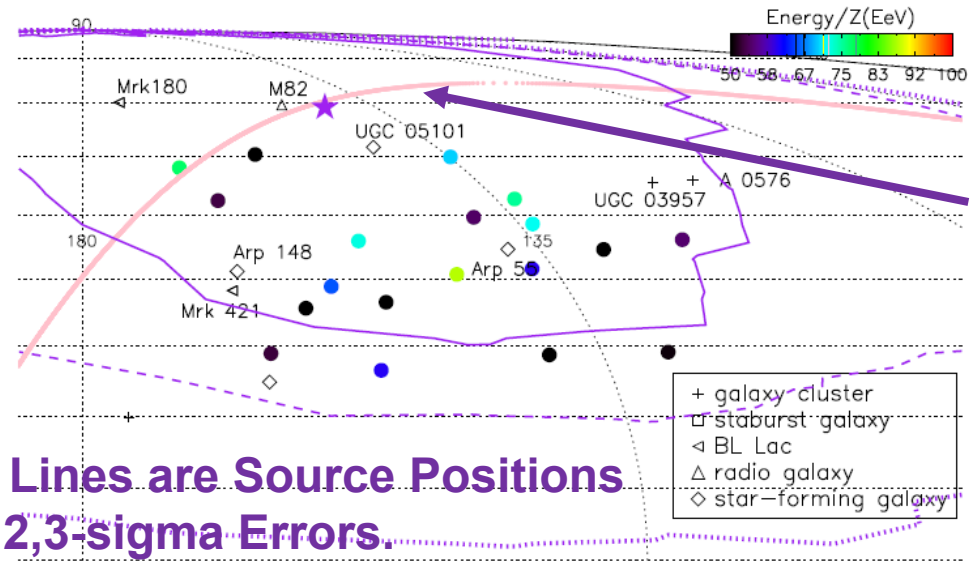


Figure from Universe today

TA Hot Spot: UHECRs from M82?

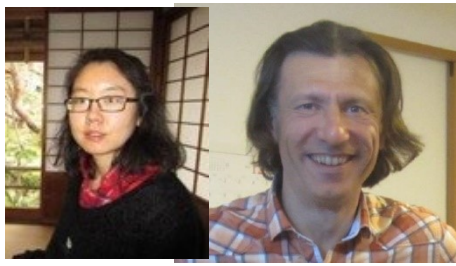


Purple Lines are Source Positions With 1,2,3-sigma Errors.

The most likely Source Position As a Result of Our Analysis.

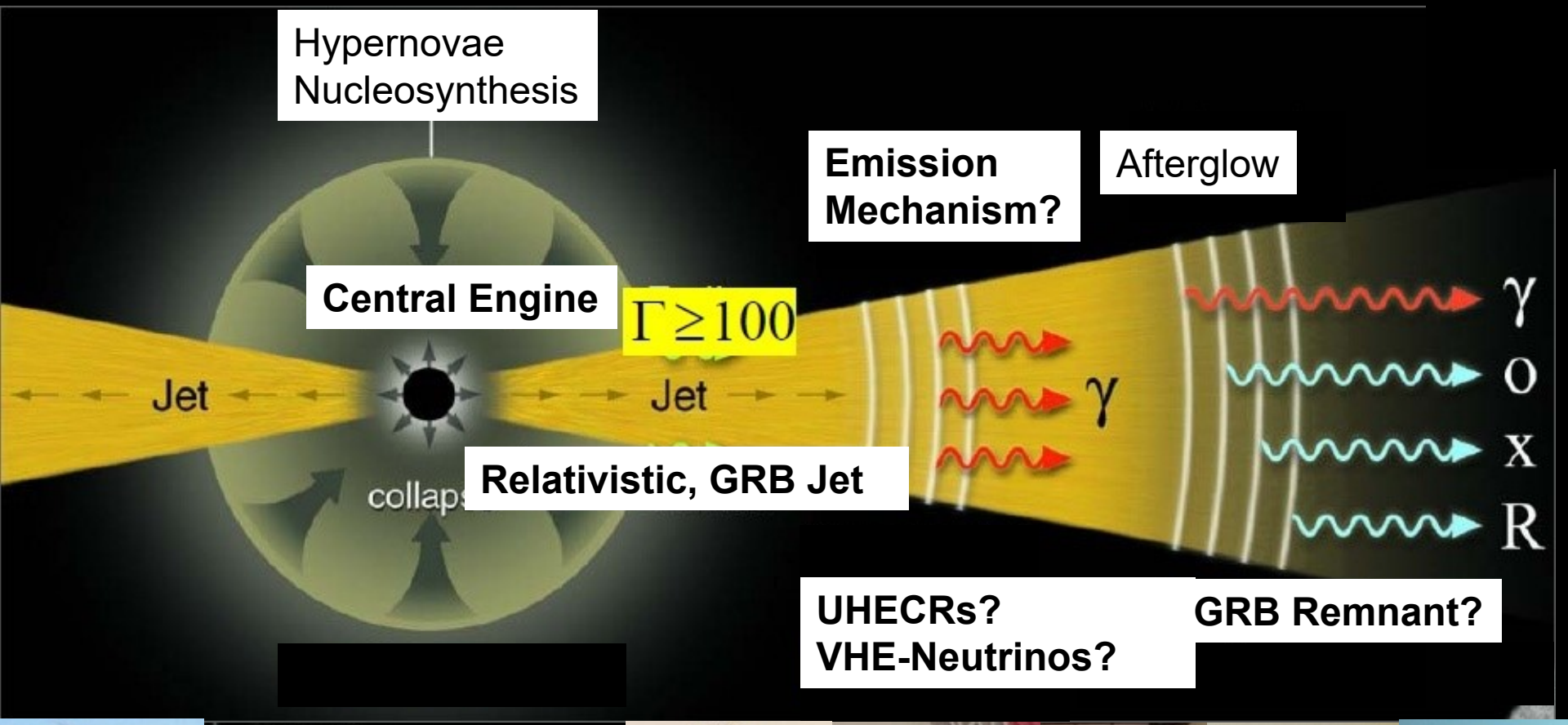
M82 is very Close from the most likely Source Position!

Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
best-fit	-	-	$17.4^{+17.0}_{11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	10.5	10.0	41.8
Mrk 421	blazar	134	11.2	9.9	35.6



H. He (ABBL from Tomorrow) & Alex

From Engine to Afterglows of GRBs



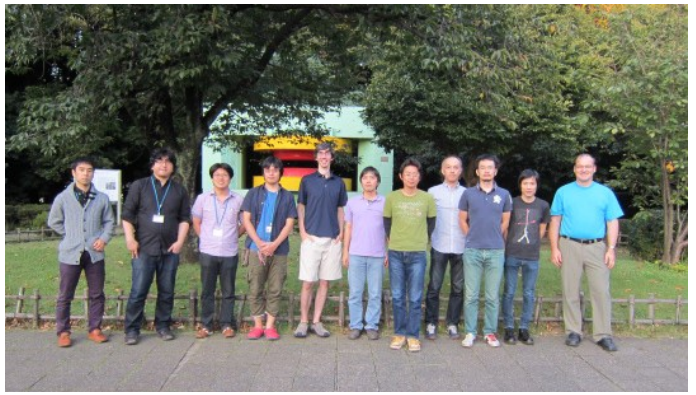
Thank You Very Much!

From 1st Apr. 2013

- PI: Nagataki
- Current PDs: H. Ito, J. Matsumoto, A. Wongwathanarat, D. Warren, S. Inoue, G. Ferrand, M. Ono, H. He (UCLA→ABBL: Tomorrow!)
- Alumni: Lee(JAXA→Kyoto), Tolstov(Kavli IPMU), Mao(Yunnan Obs.), Dainotti (Stanford), Teraki (Kyoto), Takiwaki (NAOJ), Wada (Company), Barkov (Potsdam/DESY)
- Long-Term Visitor: Zhaoming Gan (Shanghai Obs.)

2013, Aug.1

2014, Dec.17



2015, Sep.30