Current Status & Future Prospects of ABBL & iTHES

RIKEN

Astrophysical Big Bang Laboratory

Shigehiro Nagataki

25-27 July 2016, RESCEU-RIKEN Workshop, U. Tokyo: Presentation Date: 25 July.

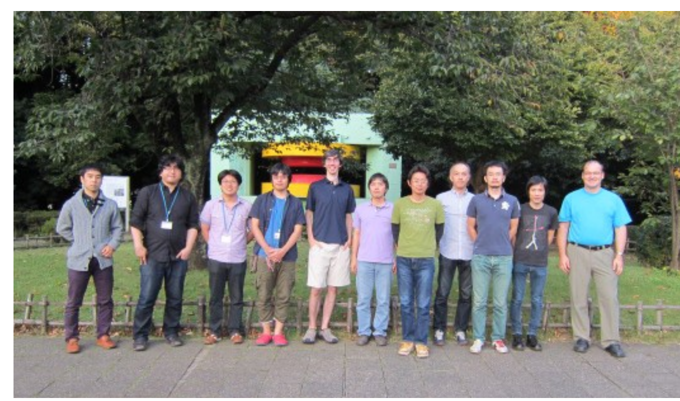
Astrophysical Big Bang Lab.

From 1st Apr. 2013

- PI: Nagataki
- Current PDs: H. Ito, J. Matsumoto, A. Wongwathanarat,
  D. Warren, S. Inoue
- From Fall 2016: G. Ferrand, H. He, M. Ono
- Alumni: Ono (Kyushu Univ.), Lee(JAXA), Tolstov(Kavli IPMU), Mao(Yunnan Obs.), Dainotti (Stanford), Teraki (RIKEN), Takiwaki (NAOJ), Wada (Company), Barkov (Potsdam/DESY)

2013, Aug.1

2014, Dec.17



2015, Sep.30

Our Group Members and Collaborators

Small Radi

From 1st April 2013

Large Radi

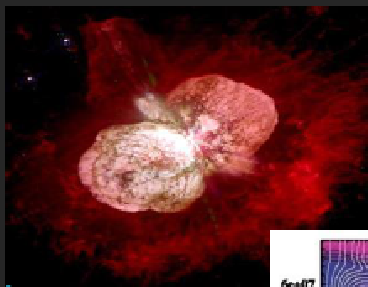
～Toward Full-Understanding of Supernovae and GRBs～

- 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!

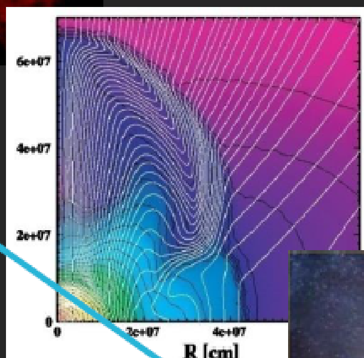
Evolution of SNe and observational signatures

Slide from K. Maeda



Opt-IR

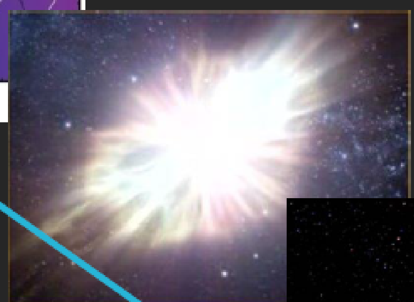
ν



GW

ν

ms - sec



UV-X

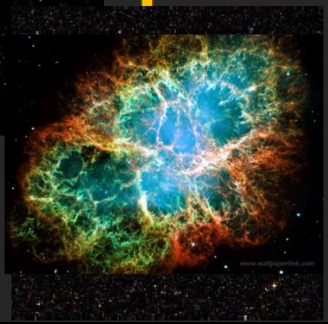
sec - day

Opt-IR

Radio, X

γ

day - year



Opt-IR

Radio

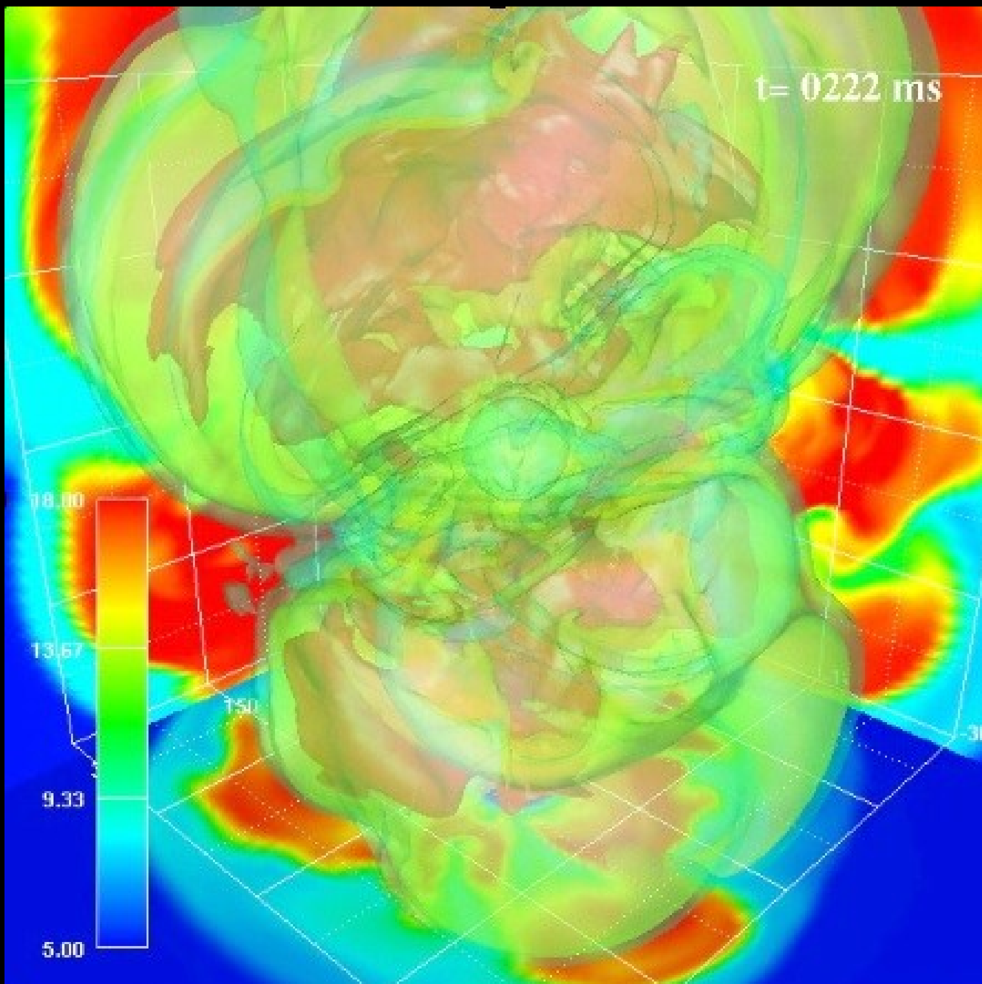
X

VHE γ

decade - centuries

§ Central Engine of CC-Supernovae

Simulations of CC-SNe Using K-Computer of RIKEN



Takiwaki et al. 2012

京

K computer

Simulation by
T. Takiwaki
(RIKEN→NAOJ)

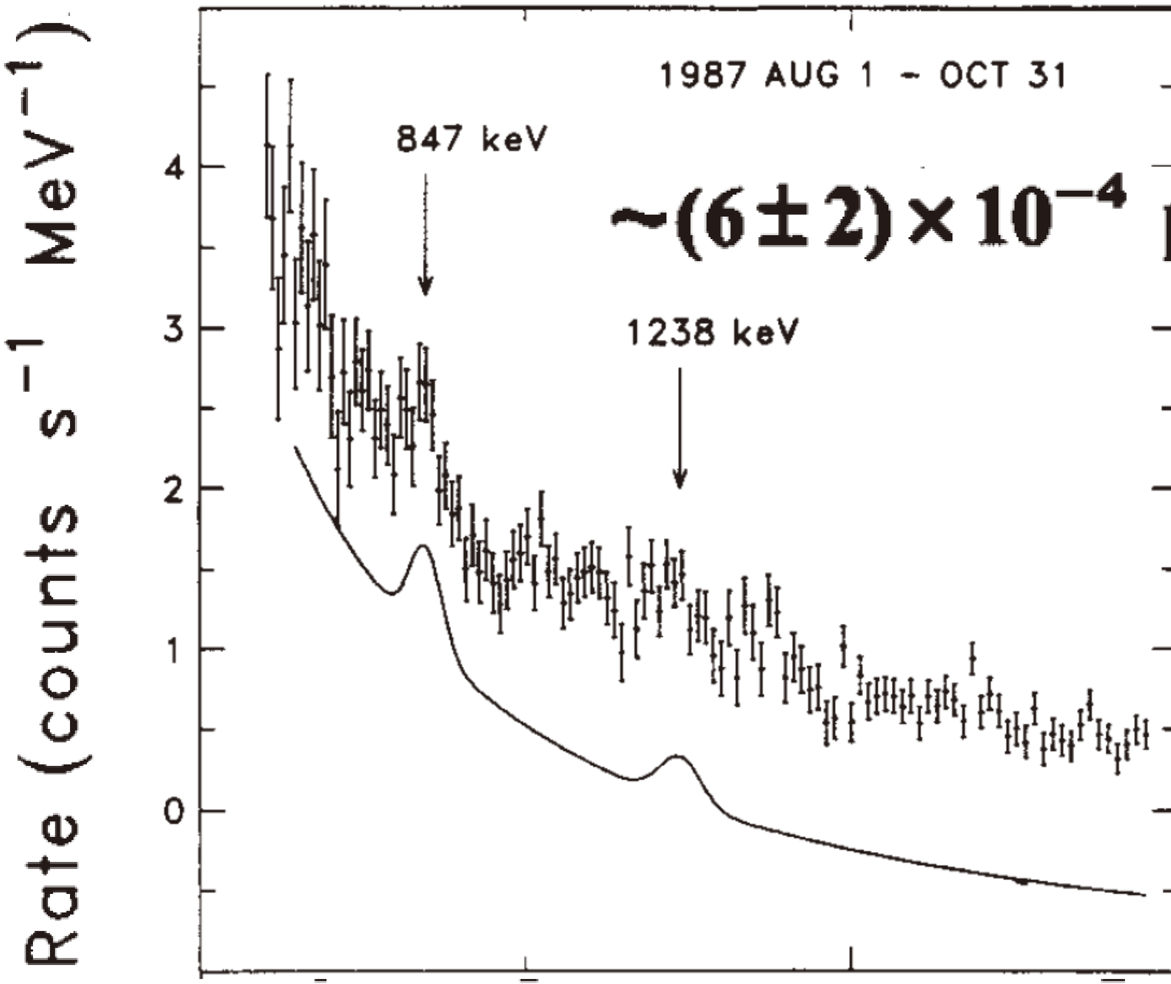
京(KEI) = 10 Peta=10^16.

§ Supernova Ejecta Dynamics & Explosive Nucleosynthesis

Reference: SN1987A: Lots of Unexpected Phenomena!

Early Detection of Gamma-Ray Lines！

Matz et al. Nature 1988

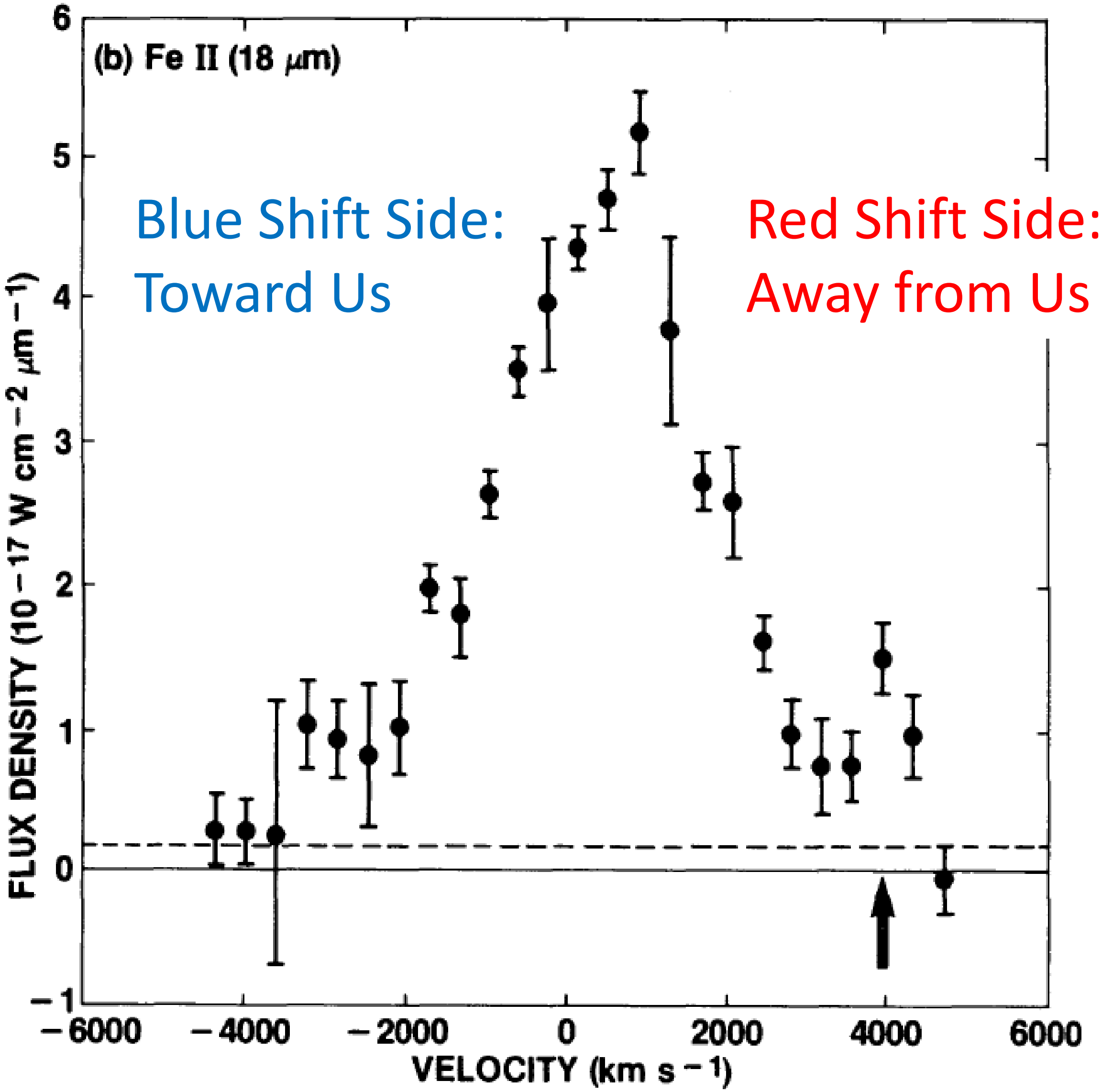


$\sim(6 \pm 2) \times 10^{-4}$ photons cm^{-2} s^{-1}

$\sim 2.3 \times 10^{-4}$ M

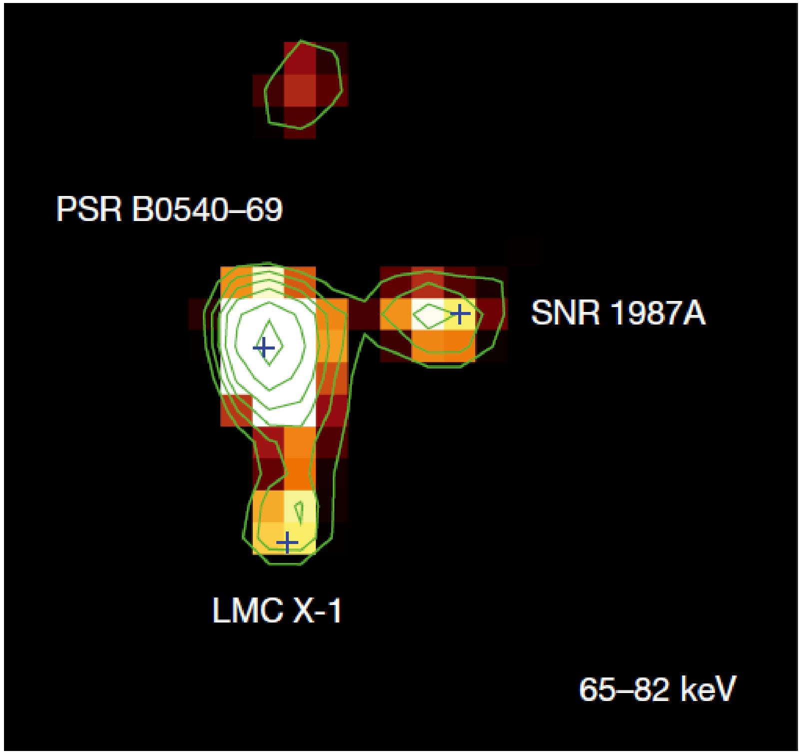
$\sim$1.3% of the total mass of ^{56}Co

Velocity Profile of Iron（409days）！

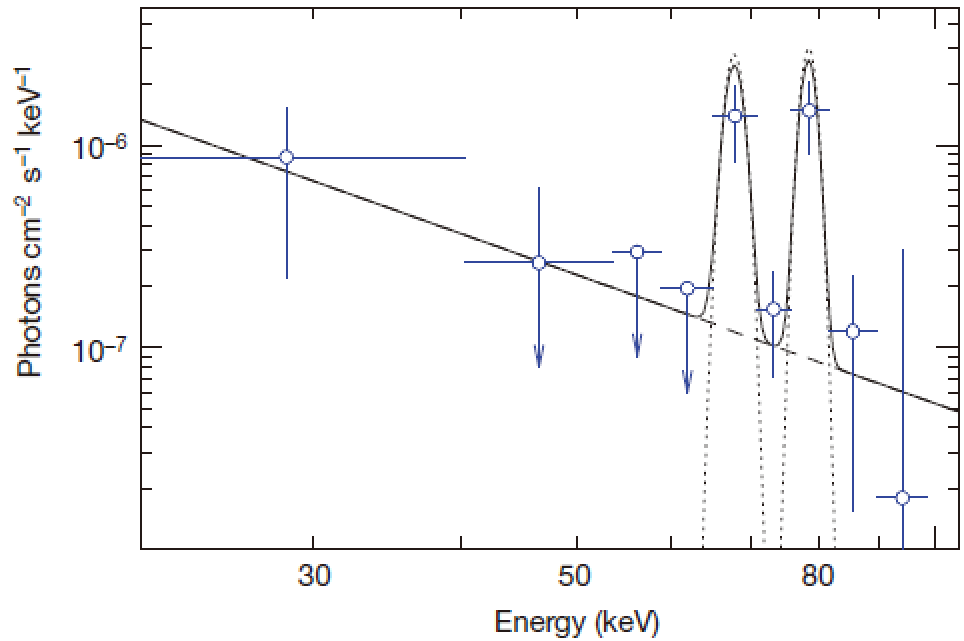


Haas et al. 1990

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

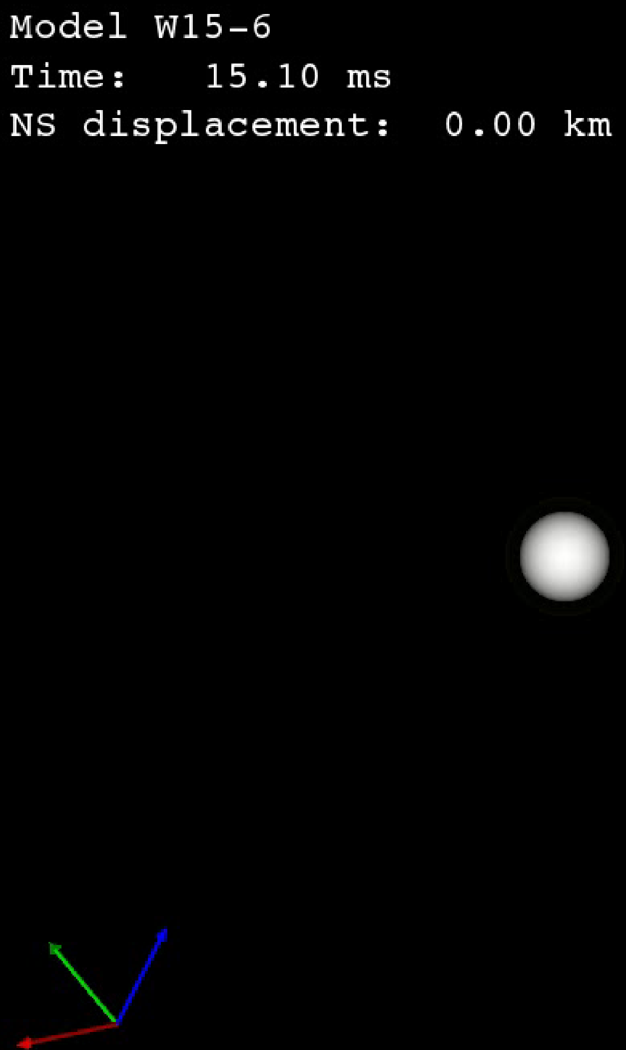
c.f. Theories: $\sim 10^{-5}\ M_{solar}$

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

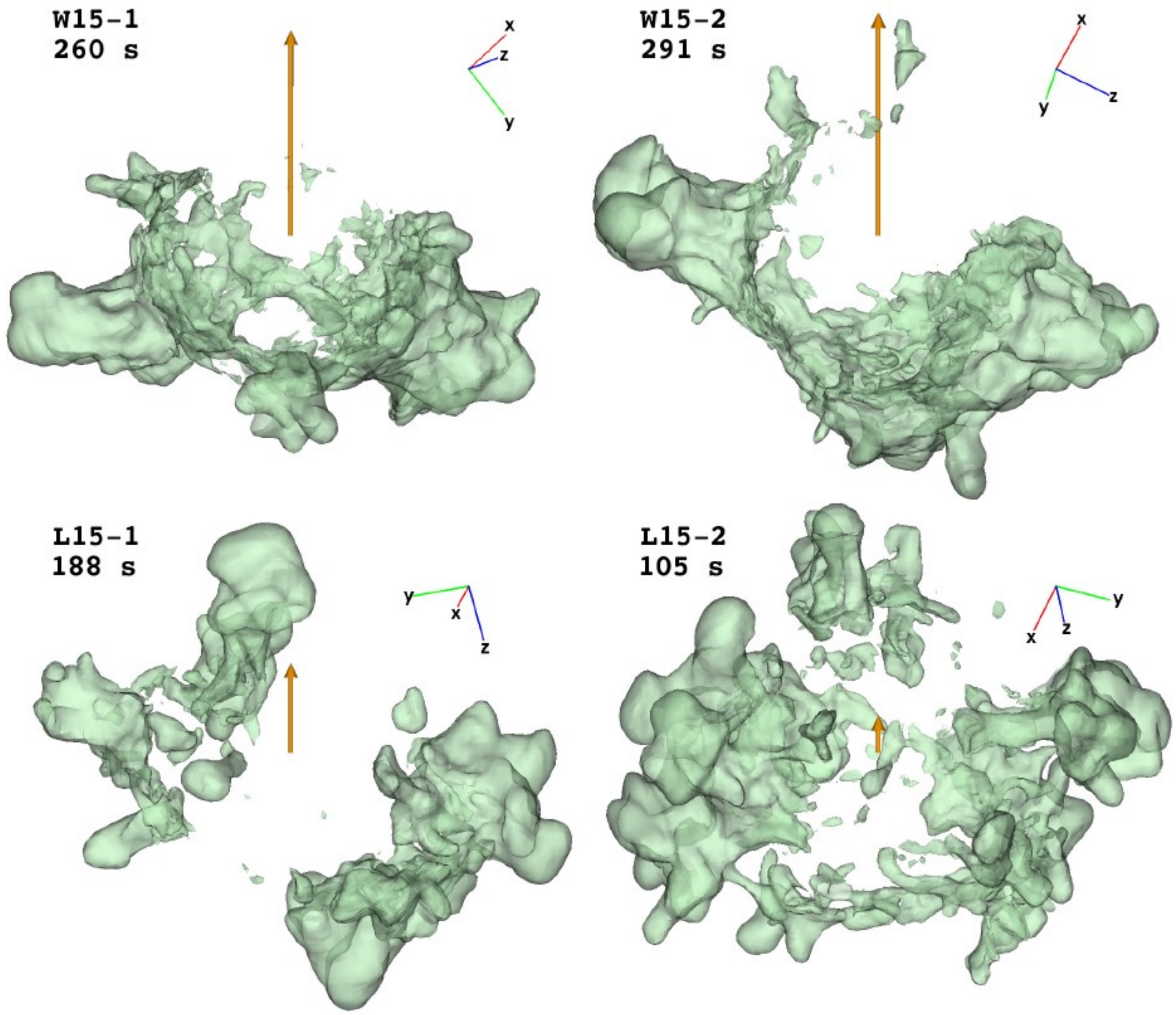
Where is the Neutron Star in SN1987A?

Asymmetric Explosion & Neutron Star Kick

A. Wongwathanarat
(MPA → RIKEN)

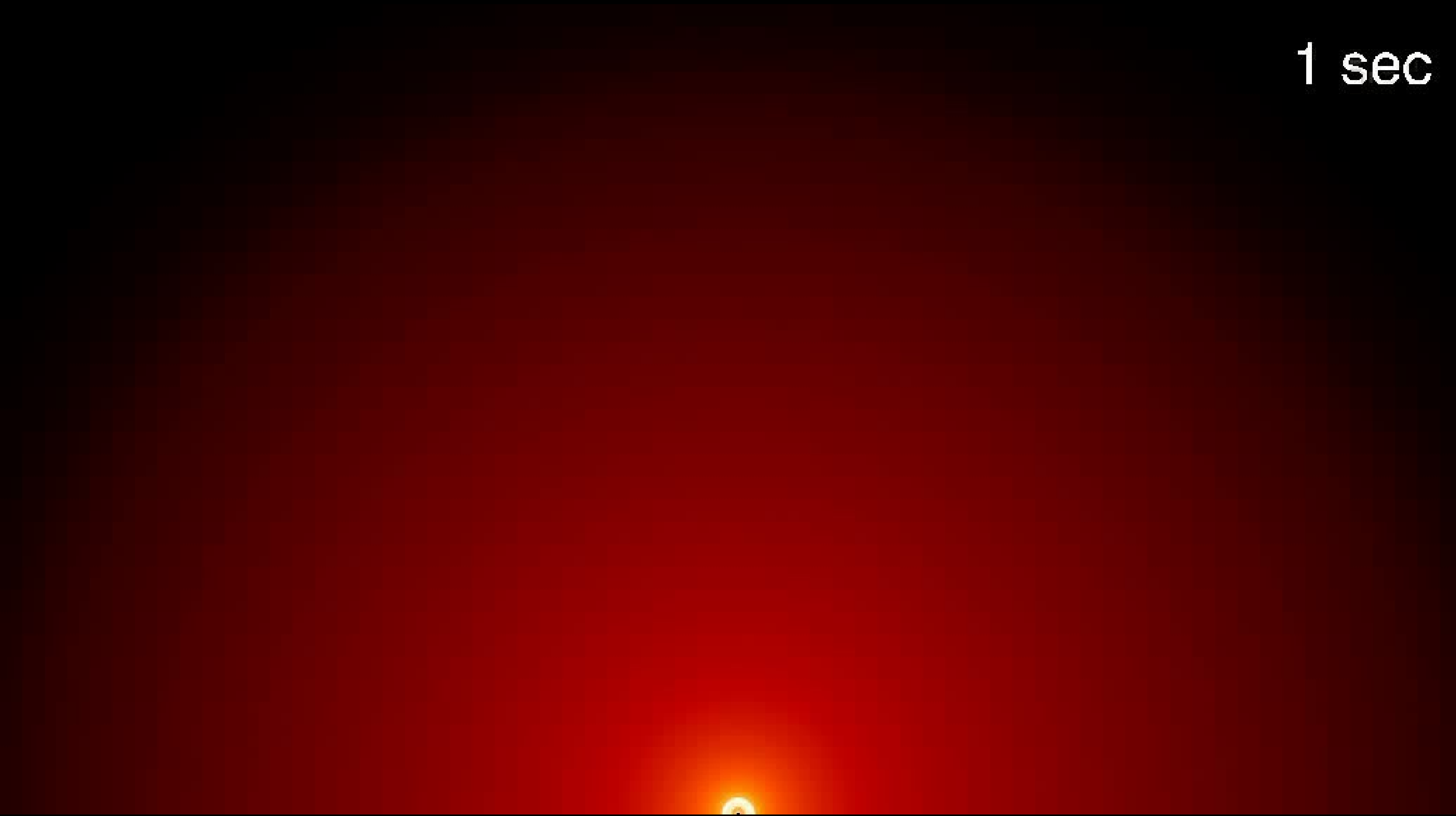


Asymmetric Ejection of 56Ni & Neutron Star Kick



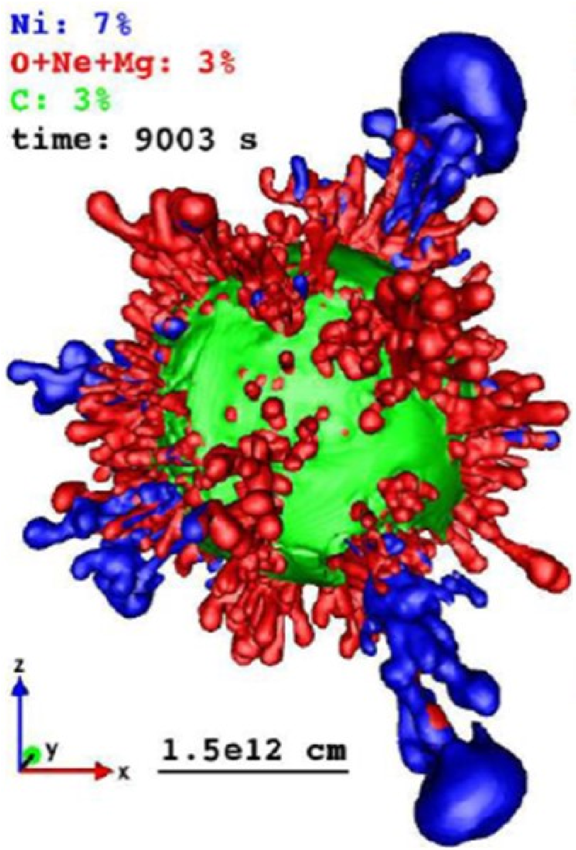
A. Wongwathanarat
(RIKEN) + 2013

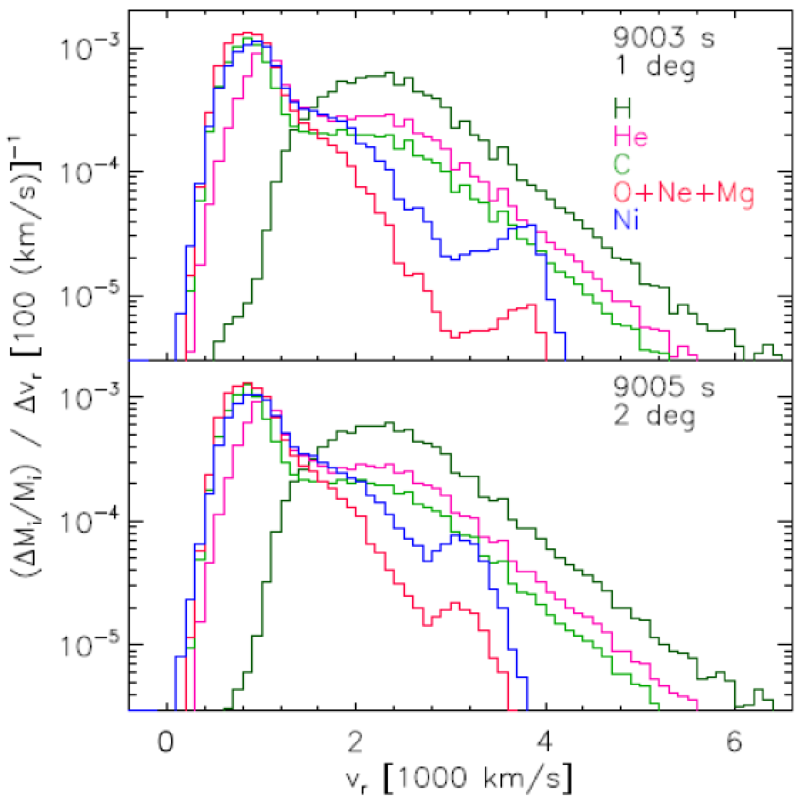
Rayleigh-Taylor Instabilities



Simulation by Kifonidis, MPA.

Successful Reproduction of 56Ni with High-Velocities！

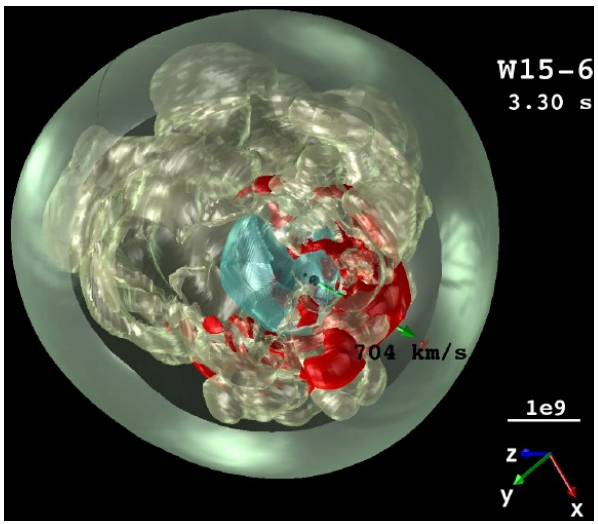


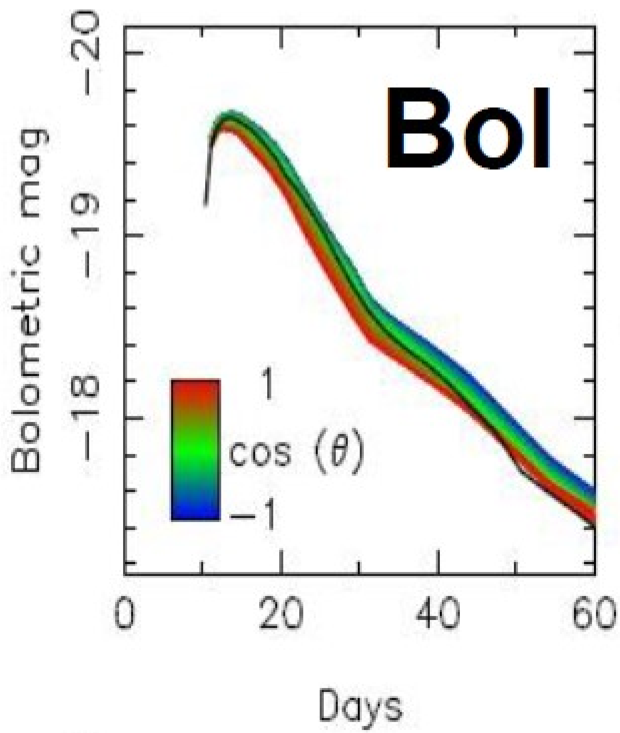


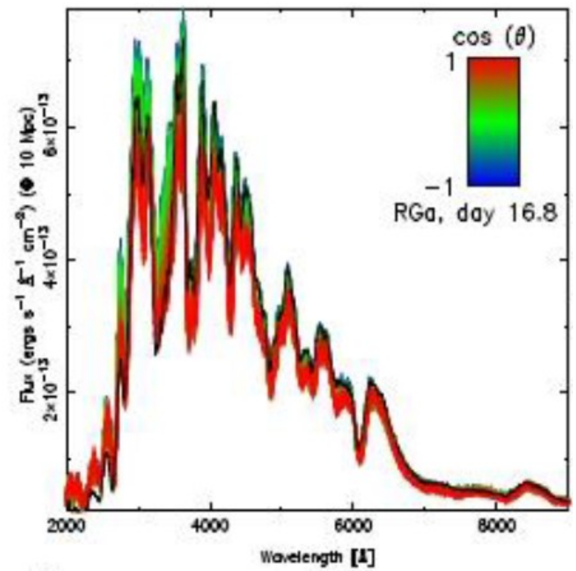
A. Wongwathanarat
(RIKEN)

Great Collaborations Started

- Radiation Transfer, including Gamma-Ray Line Transfer.





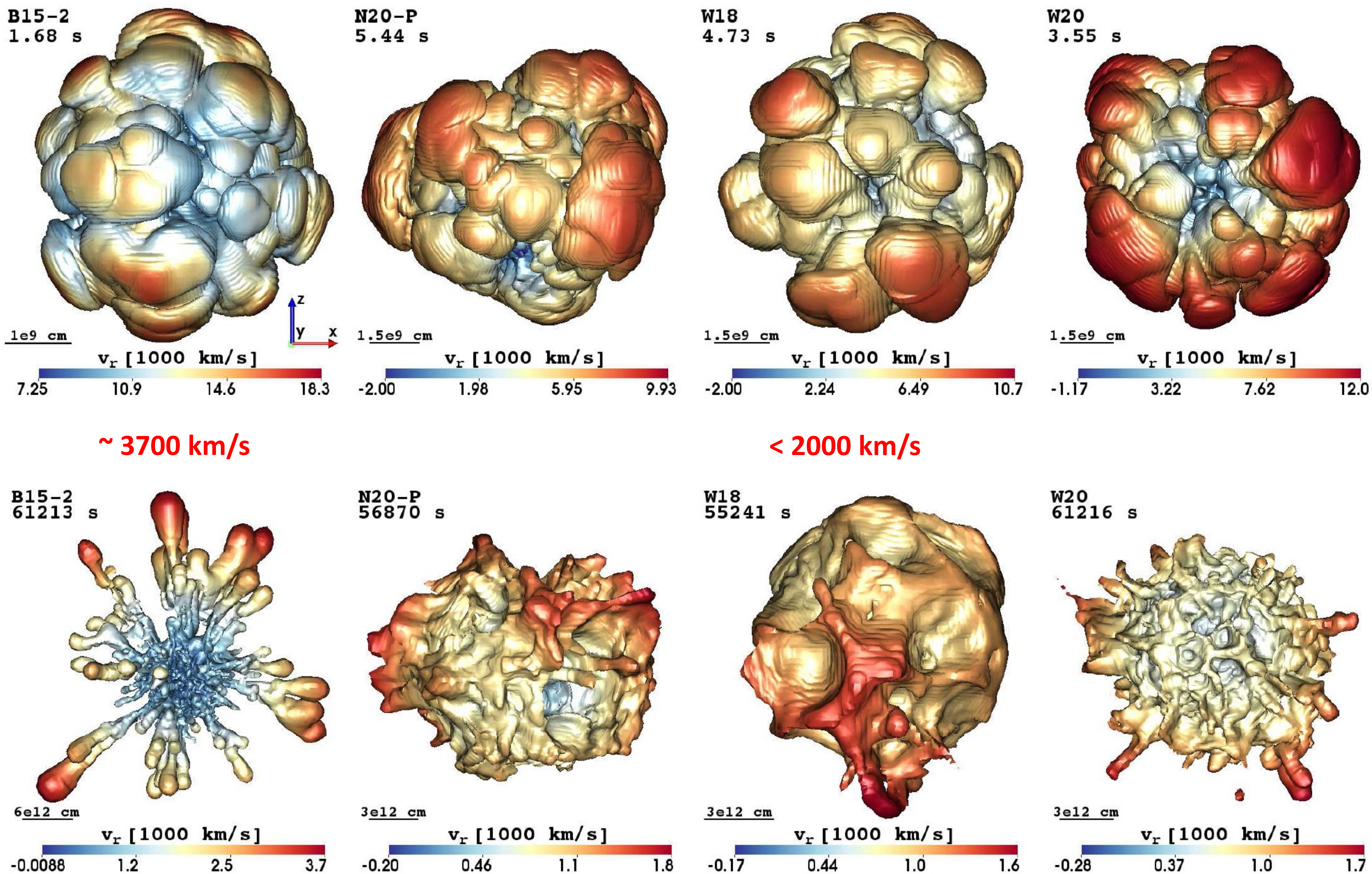


Left:
A. Wongwathanarat (RIKEN)
Right:
K. Maeda (Kyoto)

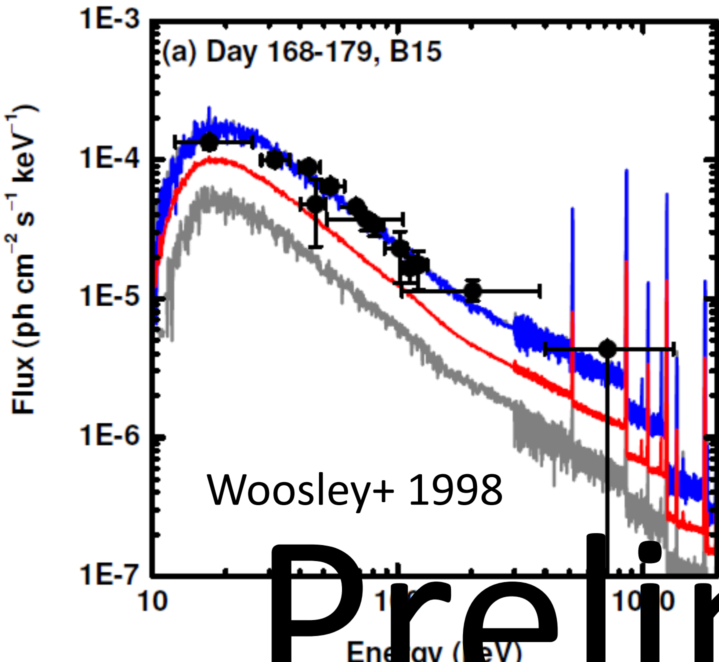
Progenitor dependence is Huge

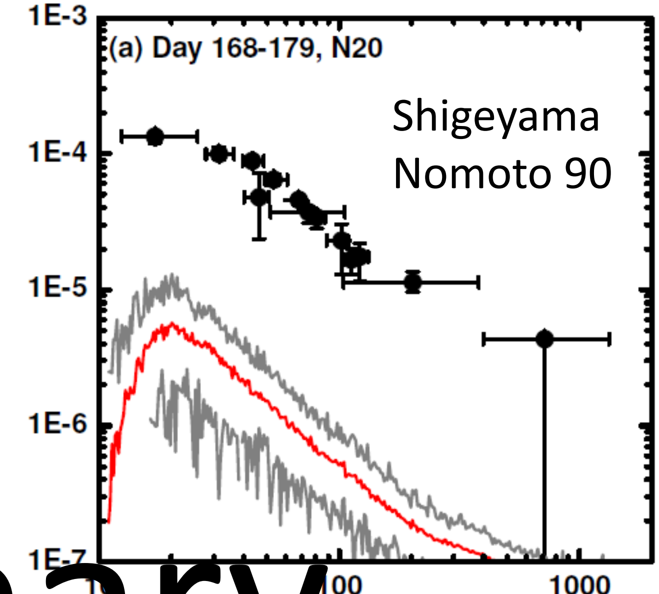
Wongwathanarat et al. (2015)

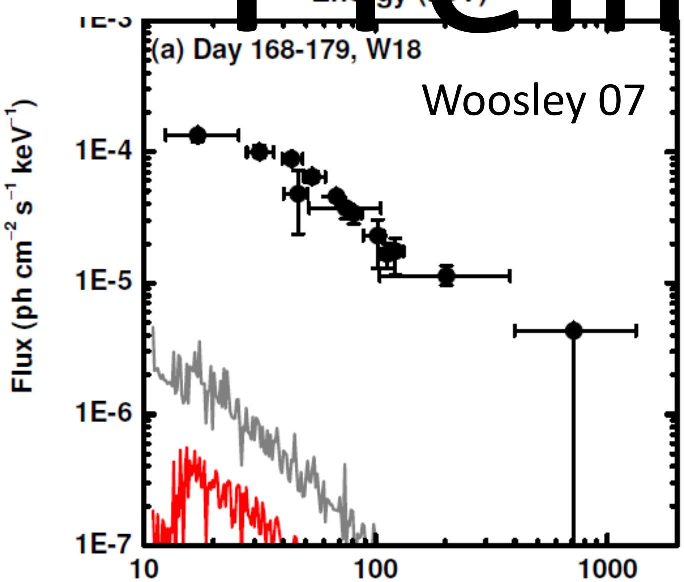
Woosley et al. (1988) | Shigeyama & Nomoto (1990) | Woosley (2007) | Woosley et al. (1997)

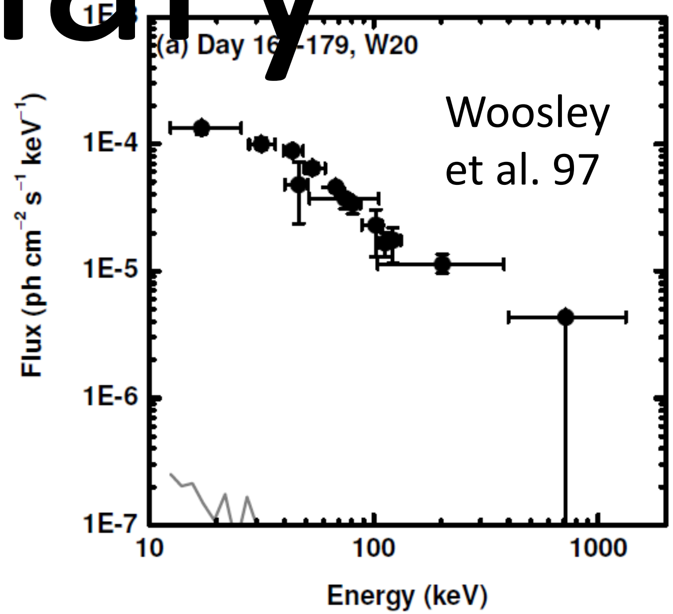


Comparison with SN1987A



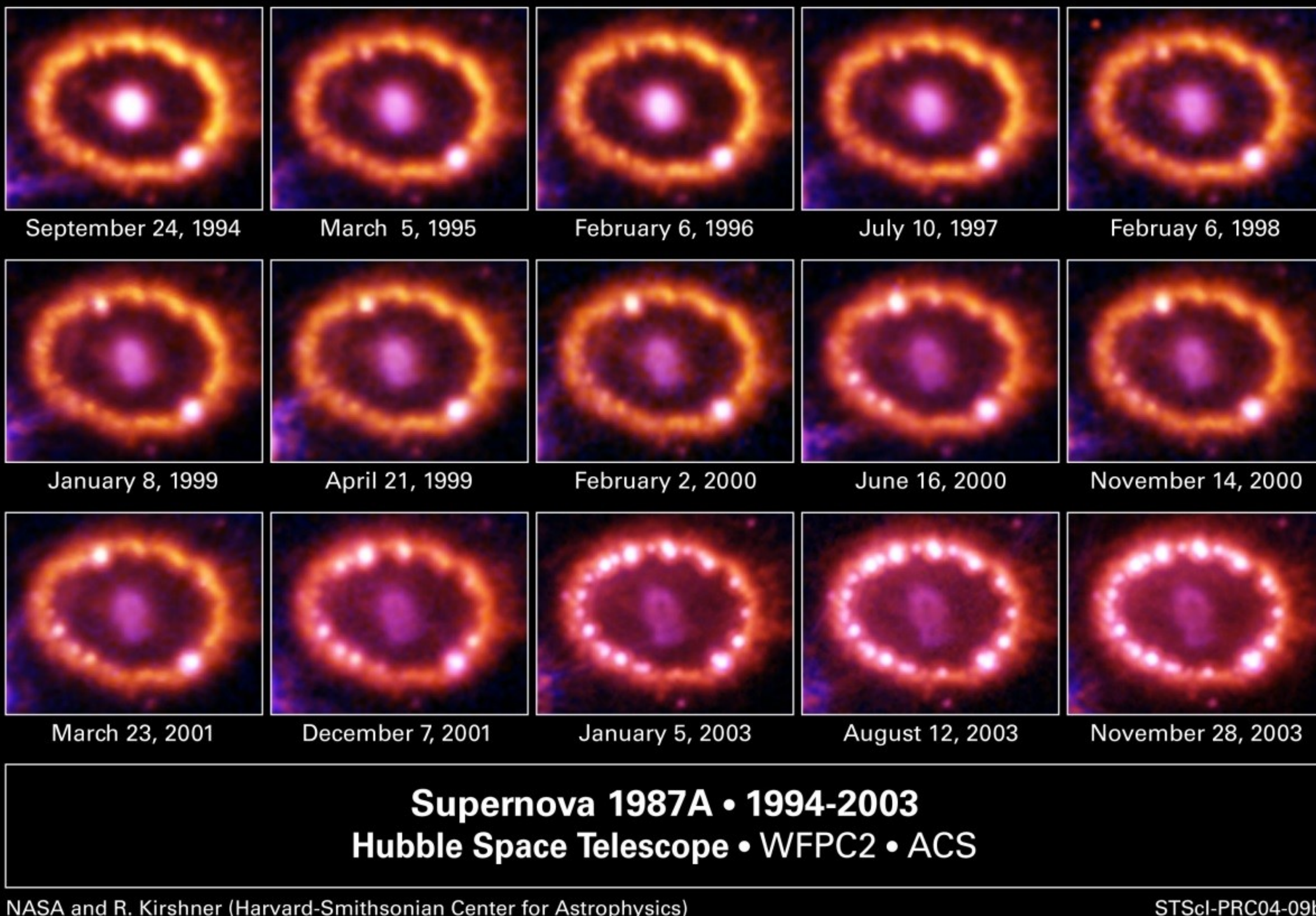




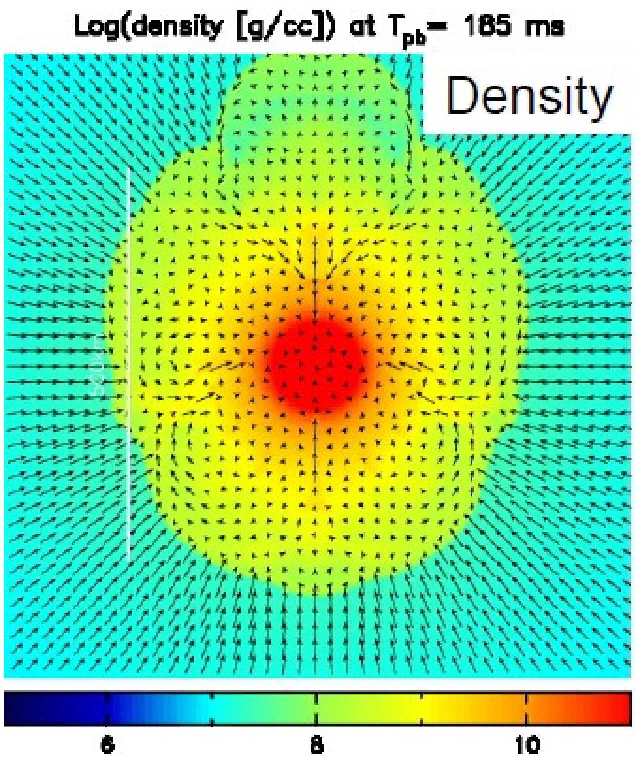


Preliminary

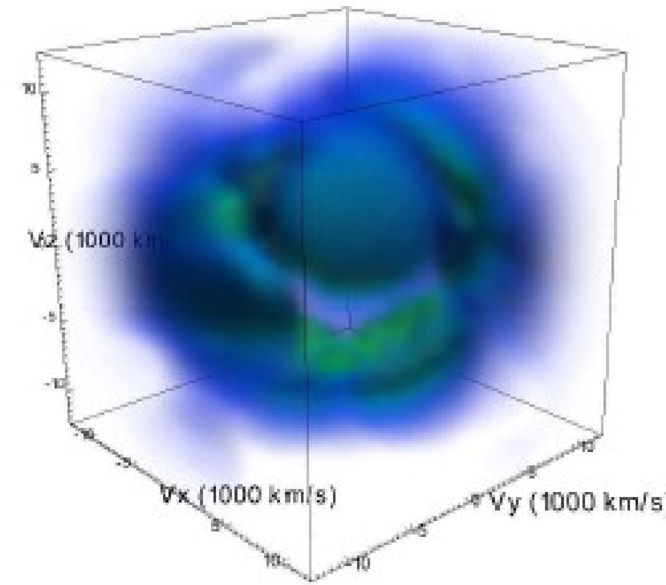
Bipolar Explosion is Seen in SN1987A

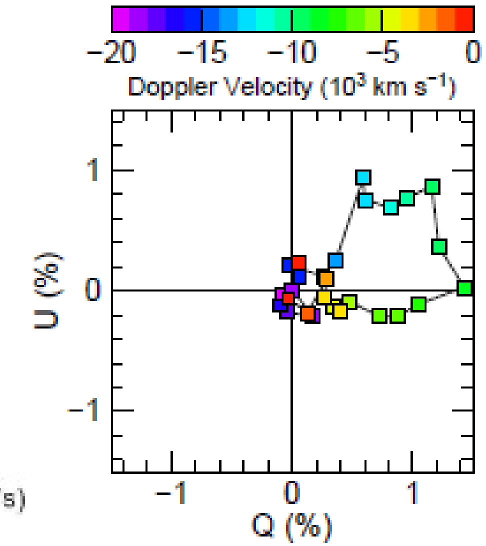


A Great Collaboration Started (2016-)



Polarization in Supernova Phase?
Constraints on Asymmetry？

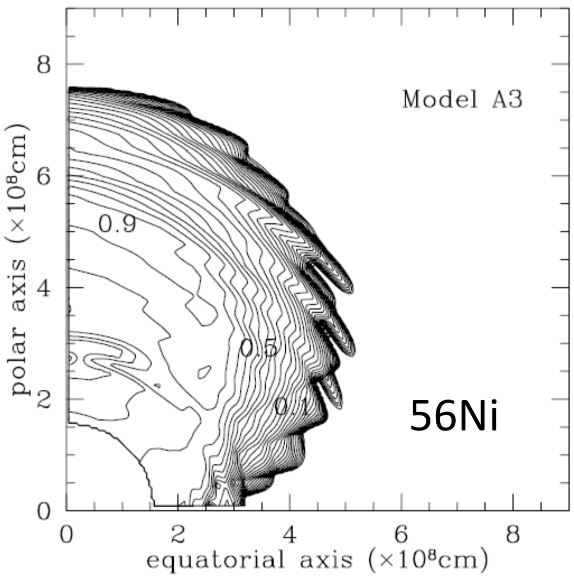


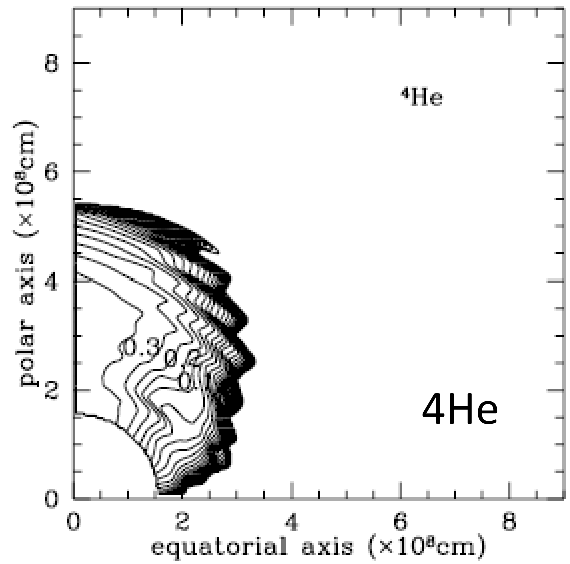




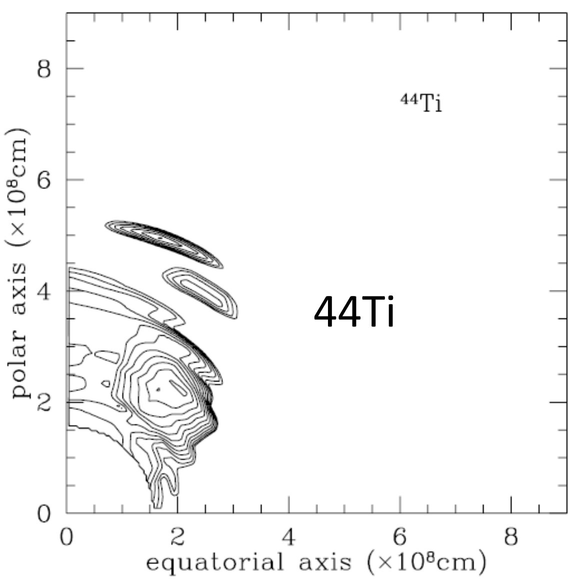

From Left to Right:
K. Nakamura (YITP)
A. Wongwathanarat (RIKEN)
M. Ono (Kyushu U.)
M. Tanaka (NAOJ)
+ Y. Ohtani (NAOJ)

Lots of ^{44}Ti Produced in Bipolar Explosions





Nagataki et al. 97,
Nagataki 00



Produced amount of 44Ti:

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

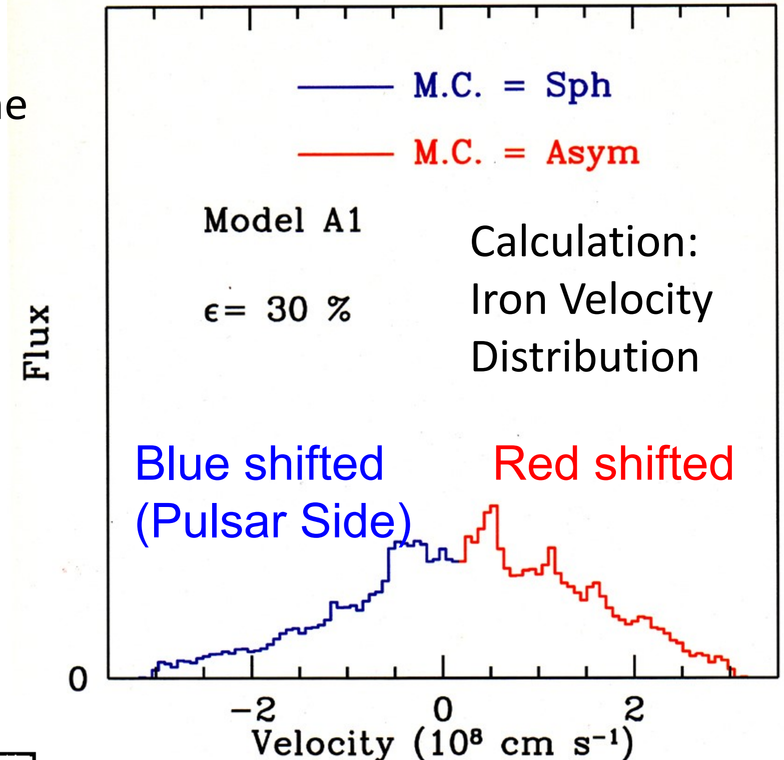
Consistent with Obs. of 44Ti by NuStar

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

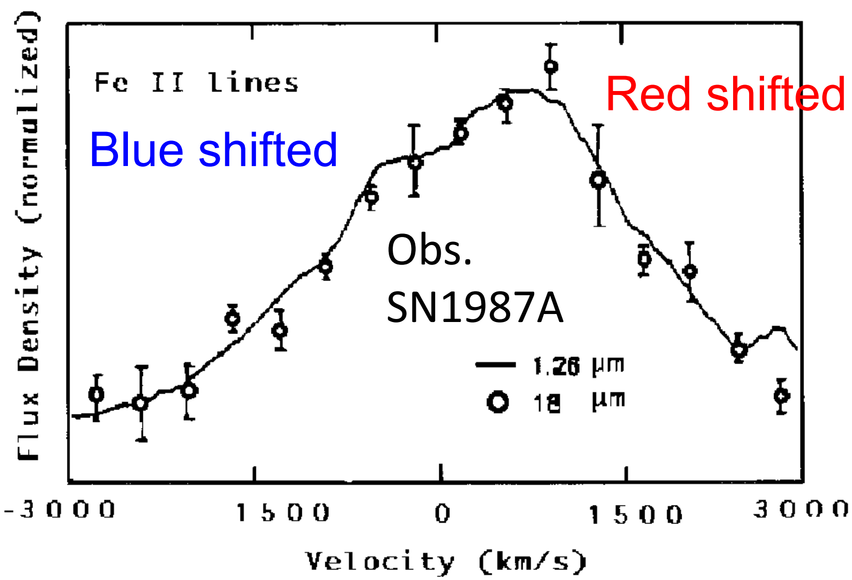
Asymmetry with Respect of Equatorial Plane
Is Suggested for SN1987A.

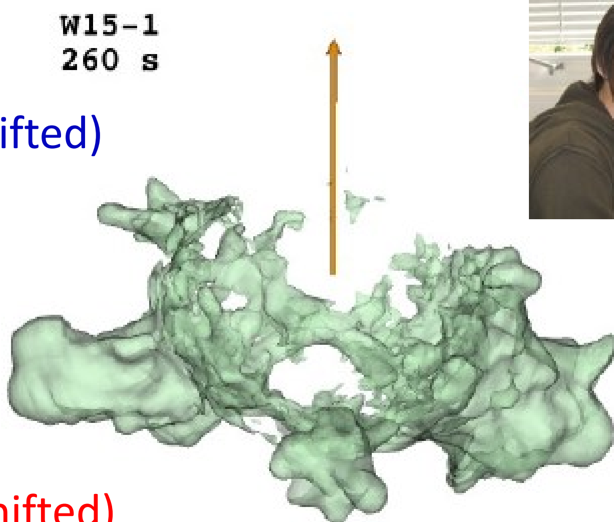
↓

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



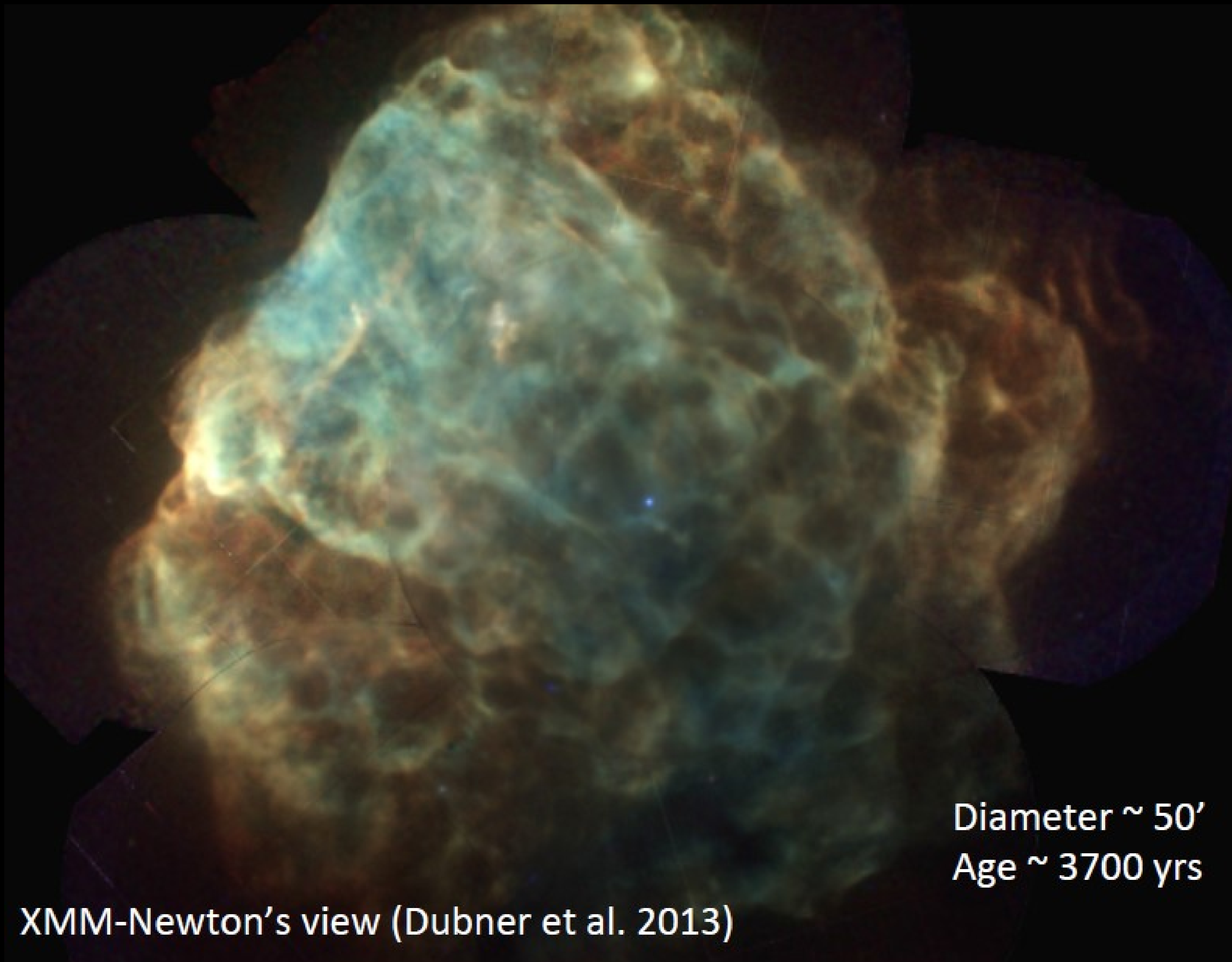
SN 2000



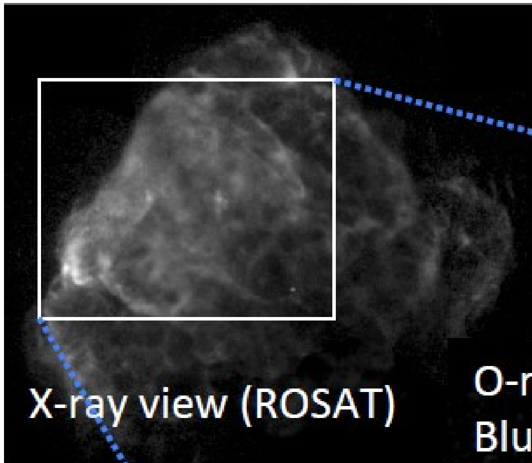


Wongwathanarat+ 2013

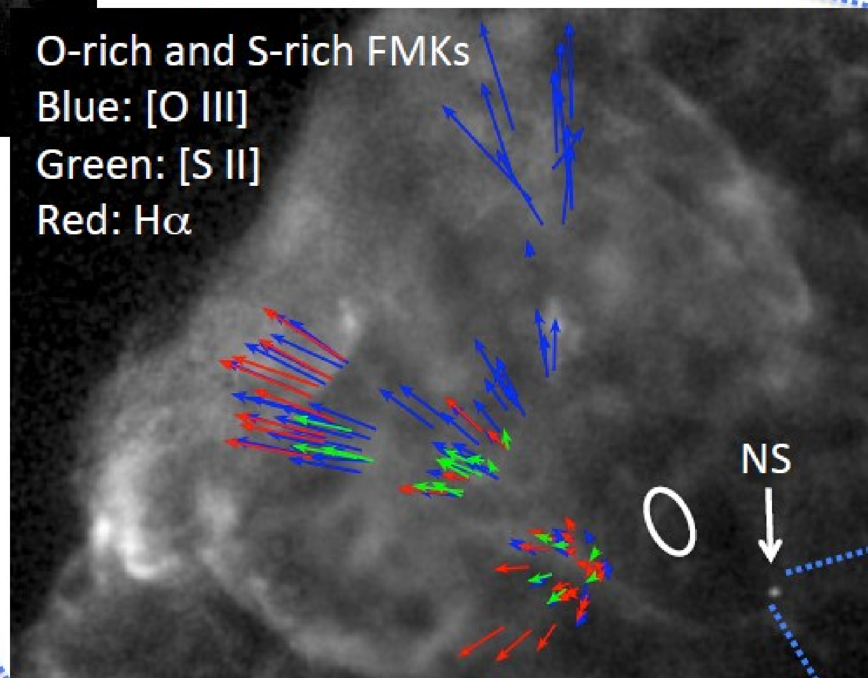
SNR Puppis A: A Globally Asymmetric Explosion



Recoil between Ejecta and NS



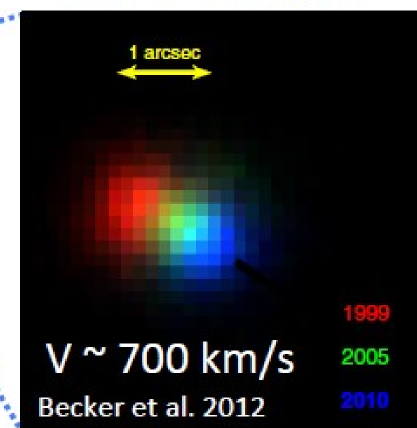
Proper motions of fast-moving ejecta knots



Winkler & Kirshner 1985; Garber et al. 2010

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

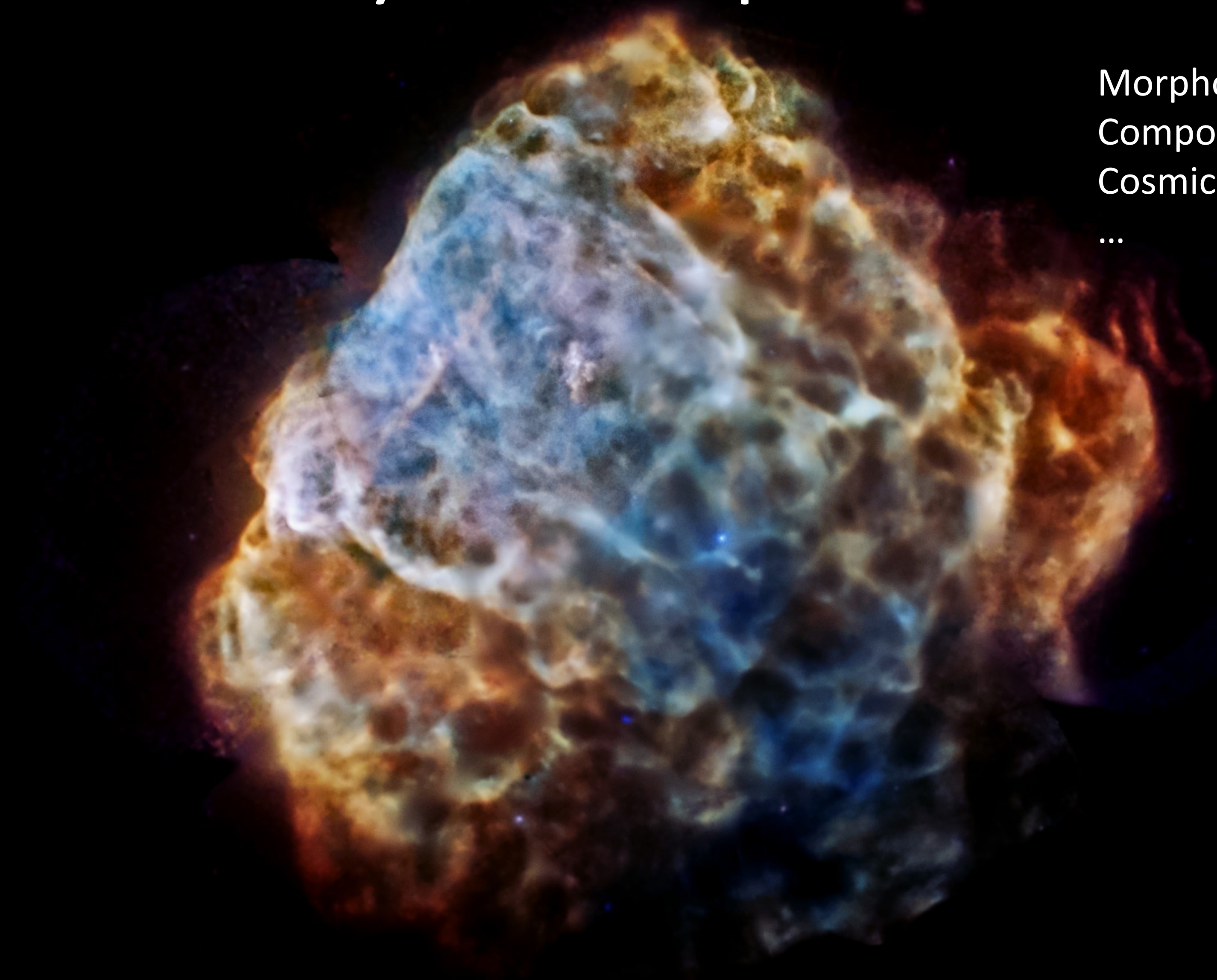
Fast-moving NS



- □ 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

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

→

Teyssier 2002, Fraschetti et al 2010

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

shock diagnostics ↓

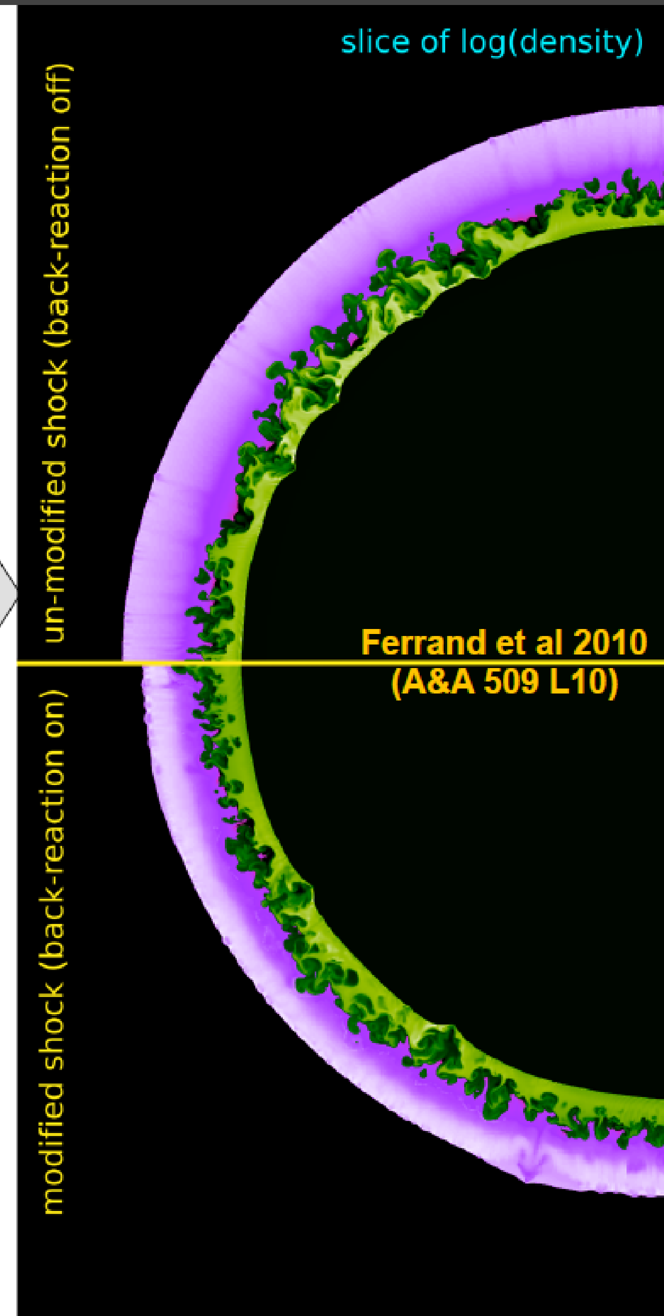
↑ back-reaction: varying gamma

Ellison et al 2007

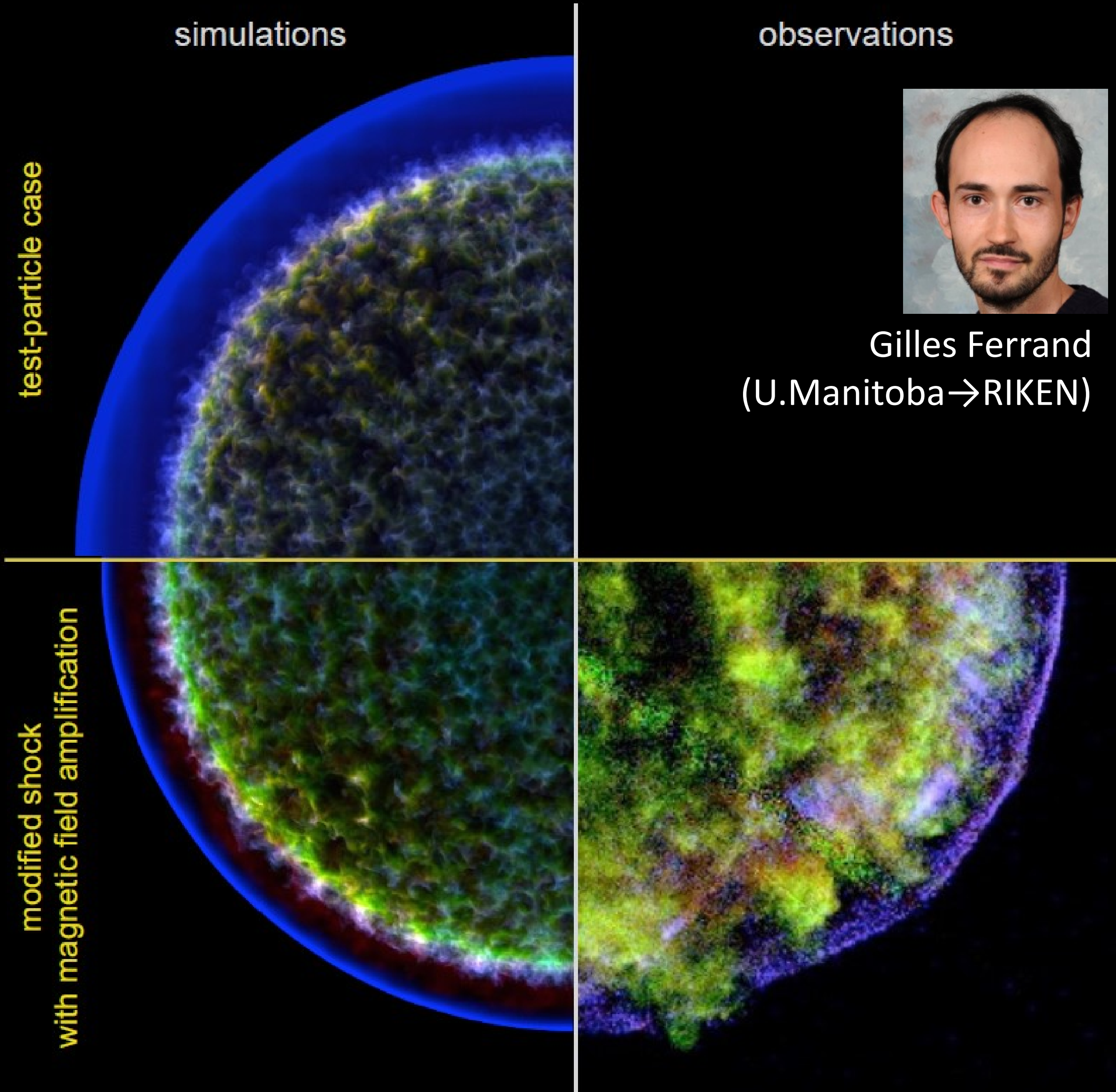
particle acceleration: non-linear model of **Blasi**

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

A Simplified Initial Condition.
→ This can be improved.



Thermal + non-thermal emission from a SNR



Gilles Ferrand
(U.Manitoba→RIKEN)

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

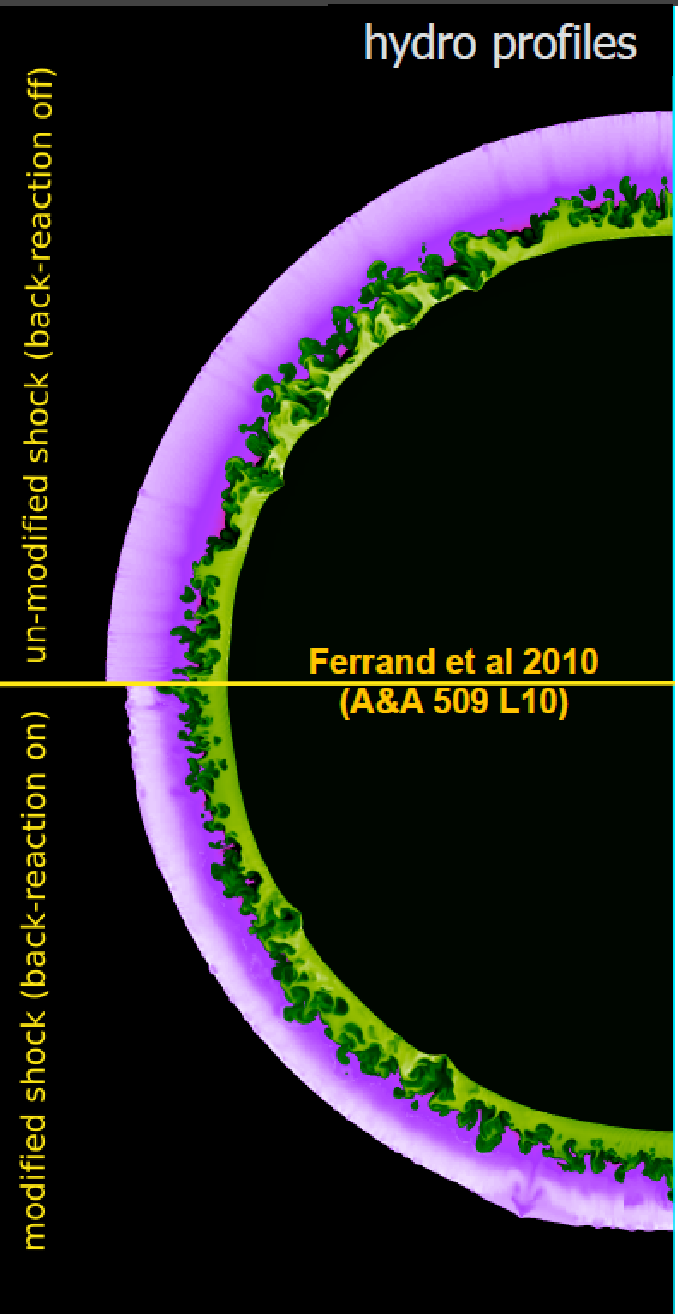
1/ they impact the dynamics of the shock wave, and therefore the **thermal emission** from the shell (optical, X-rays)

Ferrand, Decourchelle, Safi-Harb 2012

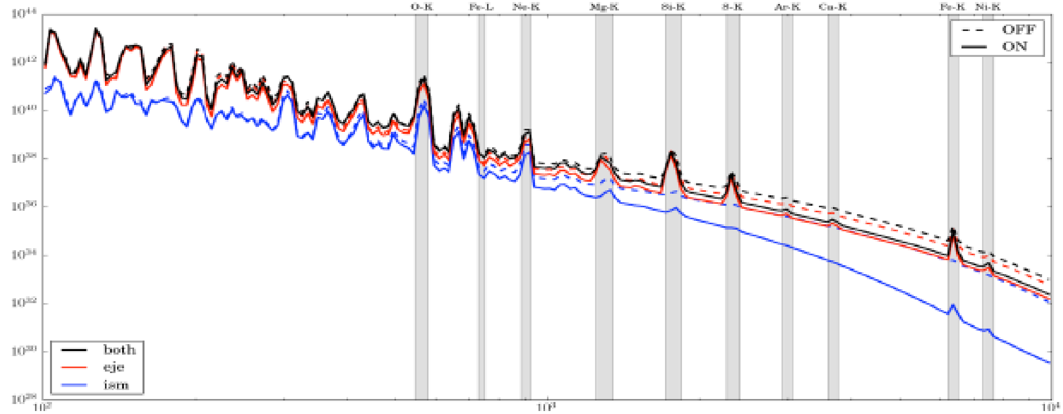
2/ they impact the evolution of the magnetic field, and therefore the **non-thermal** emission from the electrons (radio – X-rays – γ-rays)

Ferrand, Decourchelle, Safi-Harb 2014

3D hydro+kinetic simulations of SNRs

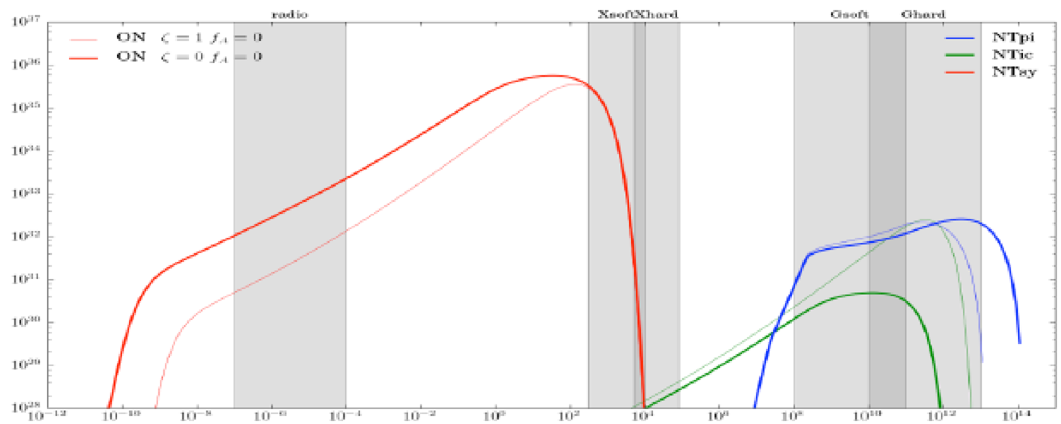


→ density, temperature
→ ionization state (out of equilibrium)
→ thermal emission from 15 elements



Ferrand, Decourchelle, Safi-Harb 2012

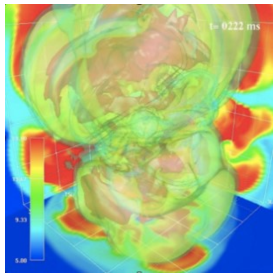
+ recipes for the magnetic field amplification
+ transport downstream of the shock
→ non-thermal emission of electrons and protons



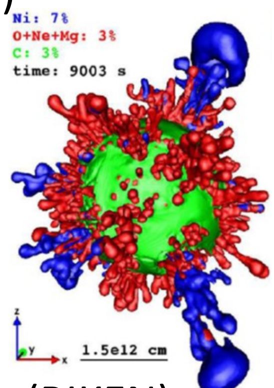
Ferrand, Decourchelle, Safi-Harb 2014

Our Big Mission

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



Takiwaki (RIKEN)



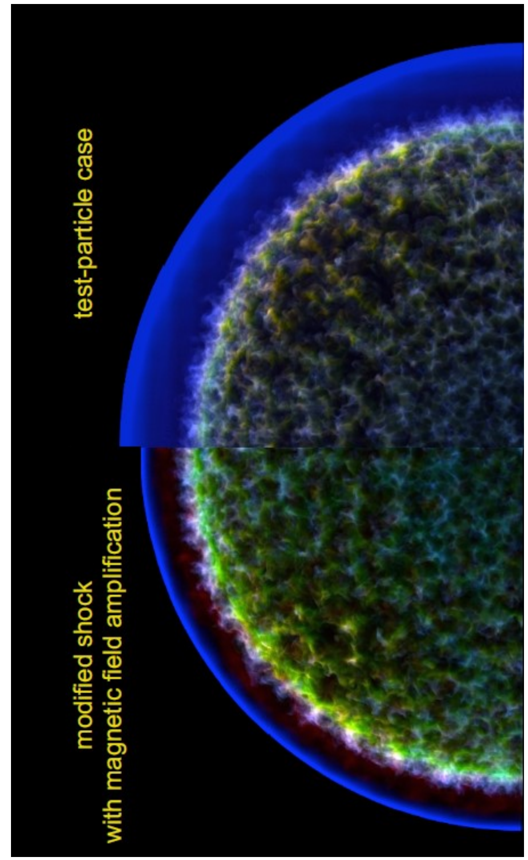
Wongwathanarat (RIKEN)

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
(RIKEN→ JAXA)

M.Ono
(RIKEN from Oct.16)

G. Ferrand
(U. Manitoba→RIKEN)

§ Engine of Gamma-Ray Bursts

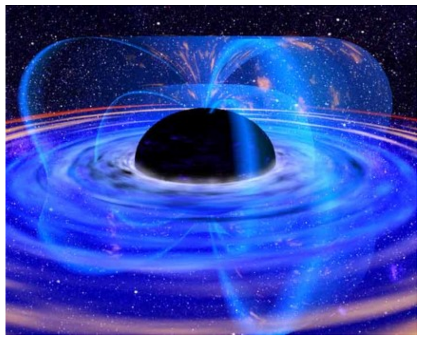
Central Engine of Gamma-Ray Bursts is Hardly Known.

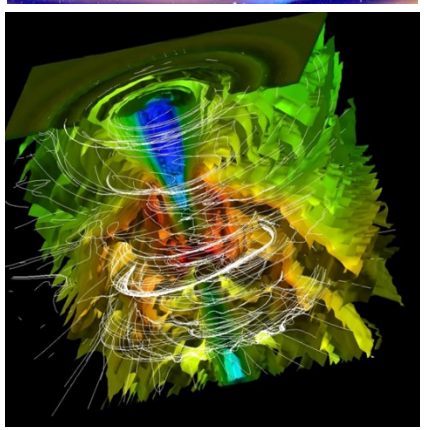
A Black Hole is Formed?

S. Nagataki
(RIKEN)

M. Barkov
(RIKEN)

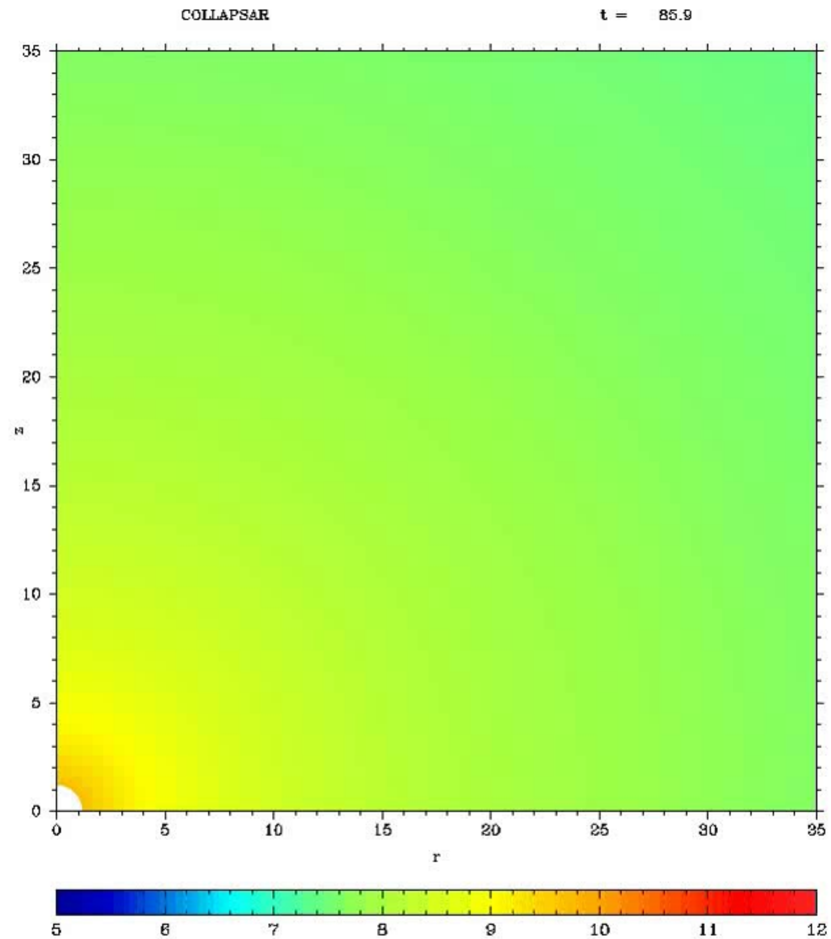
One Possibility:
A Rapidly-Rotating Black Hole might be Formed at the Center!





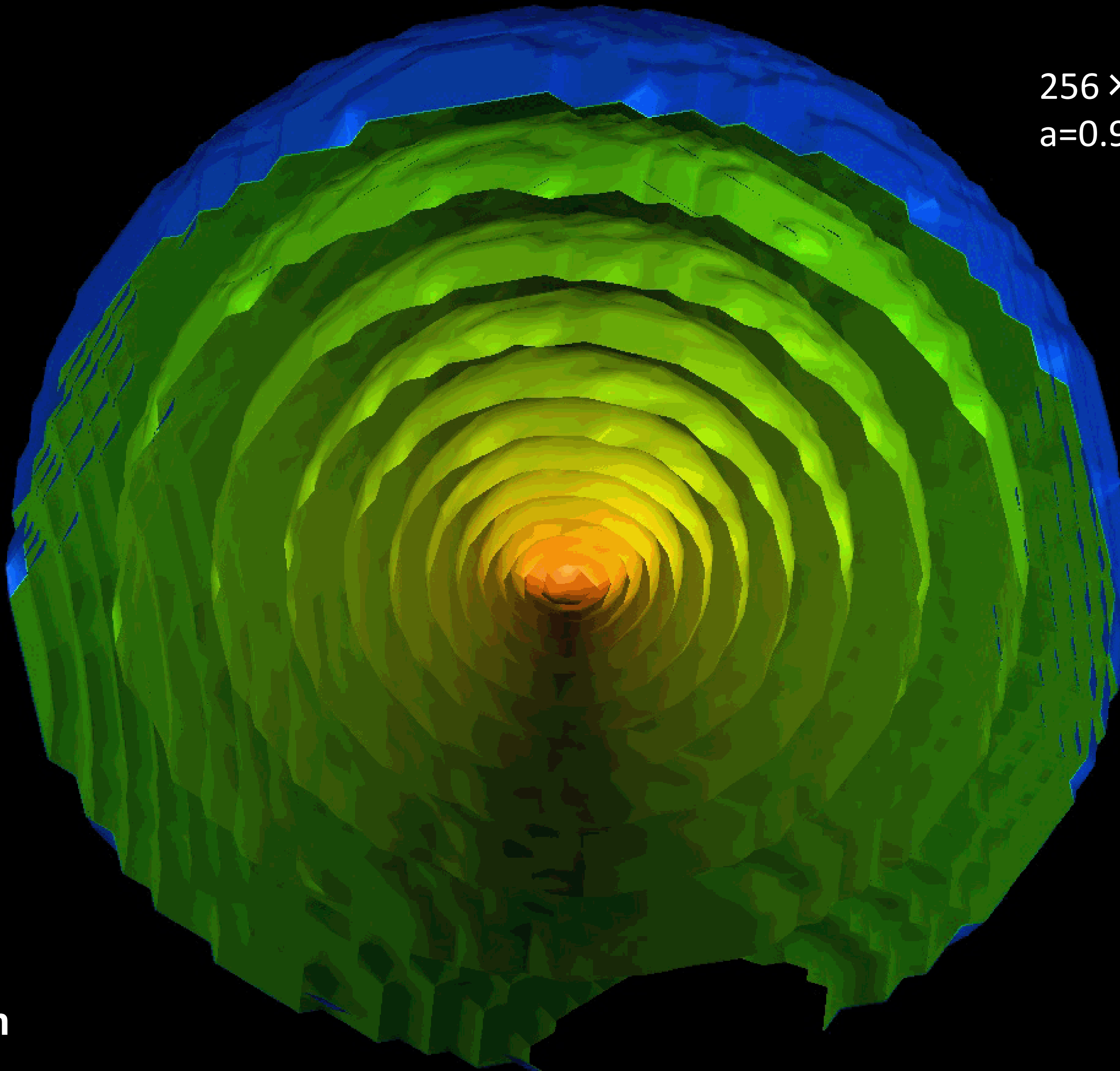
Rotation Energy of a BH can be Extracted efficiently with a help of EM Field (BZ-Process).

Rotation Axis



Equatorial Plane

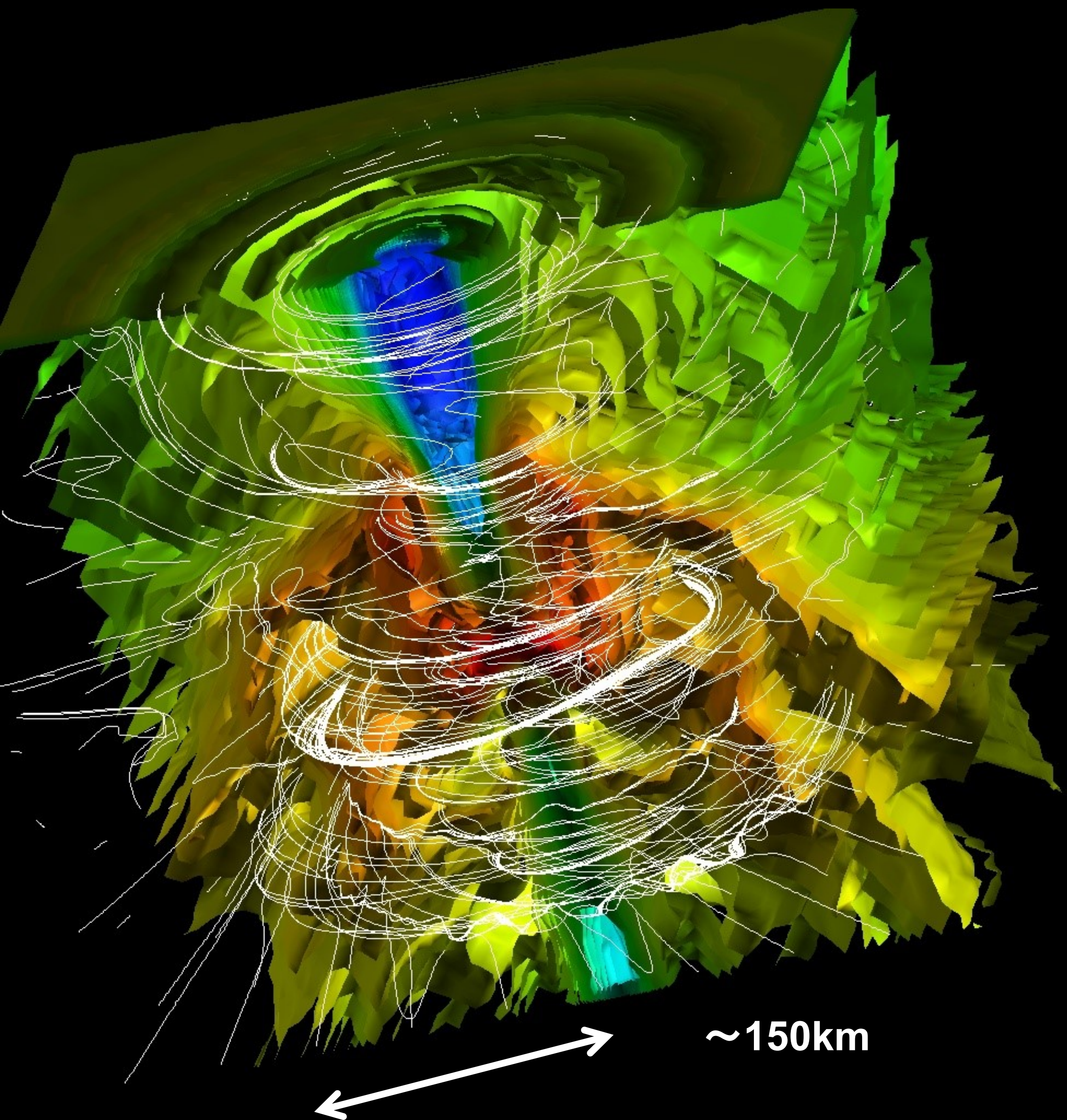
3D-GRMHD Simulation of GRBs



～3000km

256 × 256 × 128
a=0.9

S.N. 2013

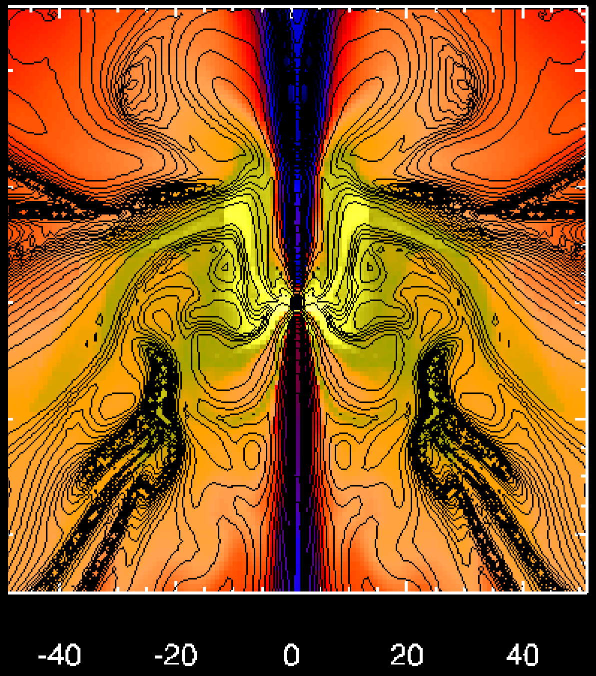


a=0.9
T～0.9sec.

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

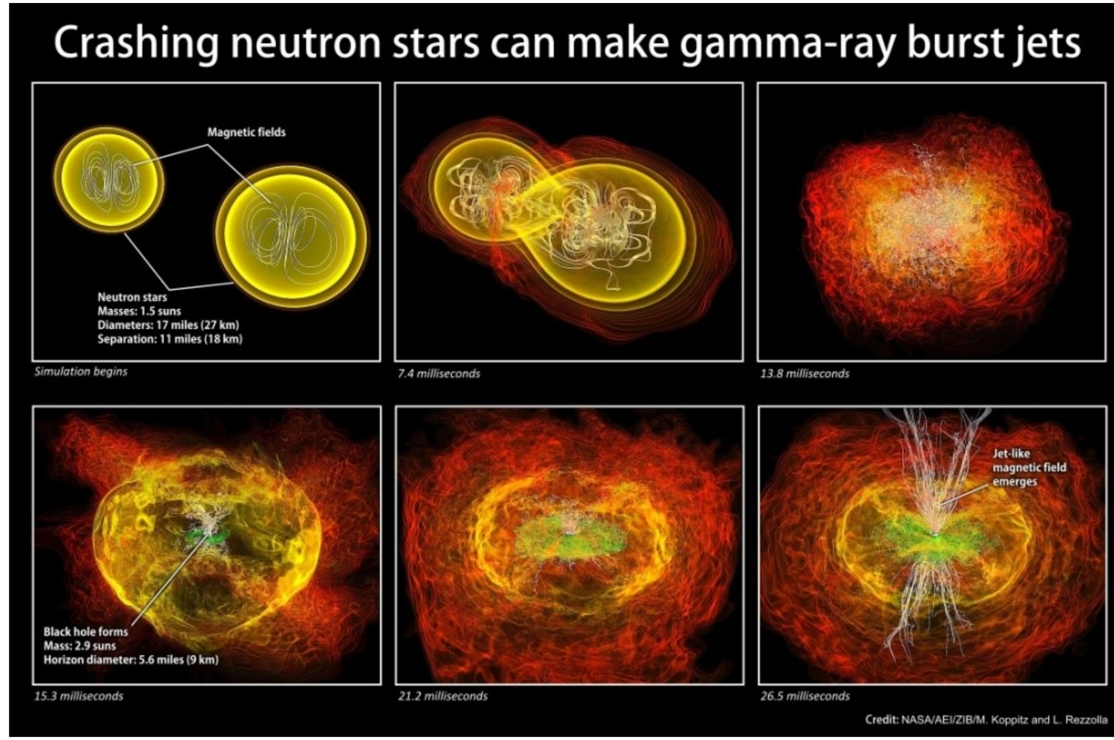
Bottom: 2D Slice
Density+Poloidal
B-Fields

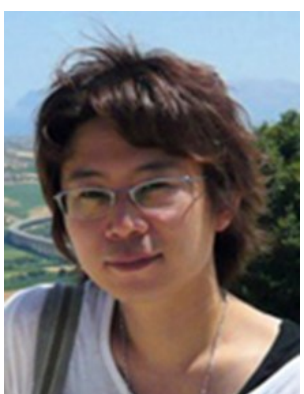
～150km



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!

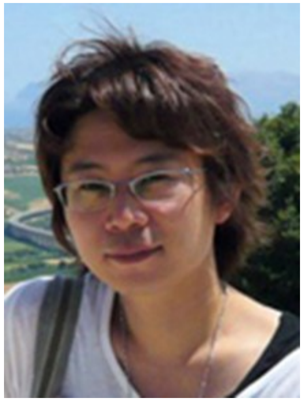
§ Monte-Carlo Simulations of Photon-Propagation For Photospheric Emission Model

Ito, S.N., et al. ApJ 777, 62 (2013)
Ito, S.N., Matsumoto, et al. ApJ 789, 159 (2014)
Ito, Matsumoto, S.N. et al. ApJL 814, 29 (2015)

RIKEN


Hirotaka Ito


Jin Matsumoto


Shigehiro Nagataki

How to Make Non-Thermal Spectrum?

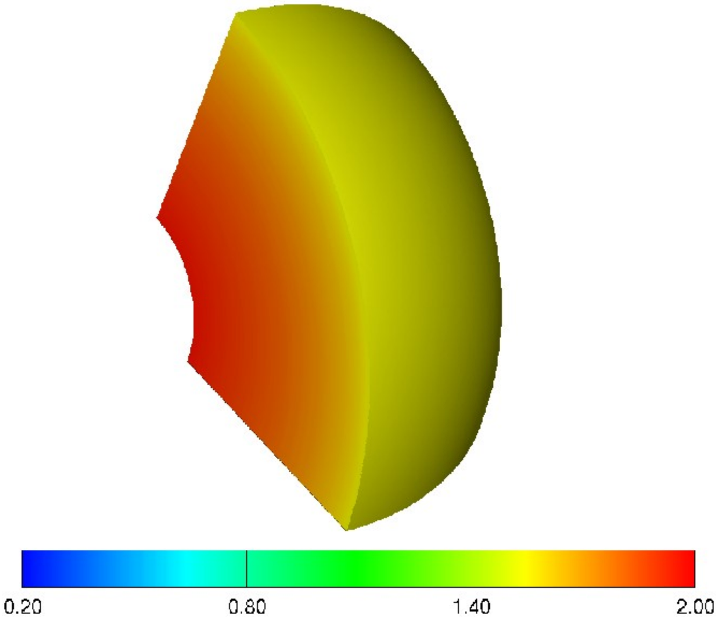
- **Dissipative Processes**
  (Shocks, Magnetic Reconnections, Proton-Neutron Flow):

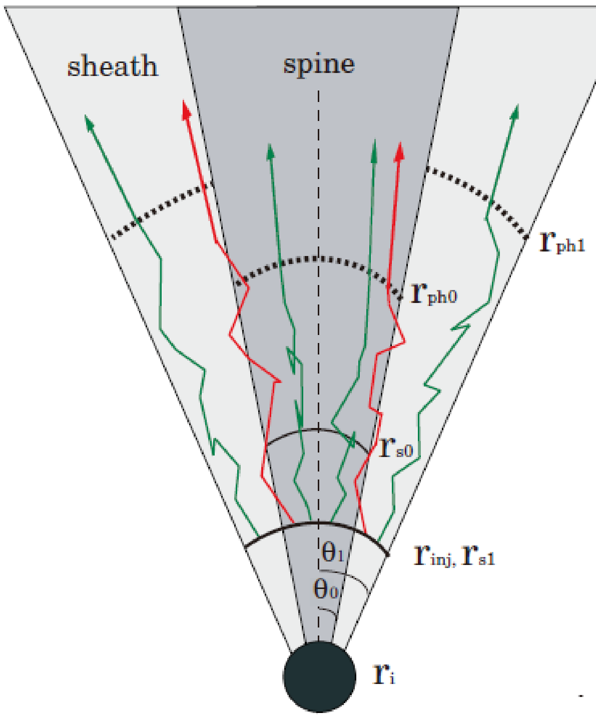
Pe'er et al. 05,06, Ioka et al. 07, Levinson & Bromberg 08, Lazzati & Begelman 10,
Budnik et al. 10, Bromberg et al. 11
Giannios 06,08, Giannios & Sprite 07, Chhotray & Lazzati 15
Beloborodov 10, Vurm et al. 11, Vurm & Beloborodov 15
Ito & Levinsson 16 (in prep.)

- **Superposition of Thermal Photons (Multi-Color Effects)**
  & (Bulk) Inverse-Compton

Morsony et al. 07, Lazzati et al. 09, Mizuta et al. 11, Nagakura et al. 11, Levinson 12,
Lundman et al. 13, 14, Ito et al. 13, 14, 15, Lopez-Camara+14

Numerical Simulations of Photospheric Models





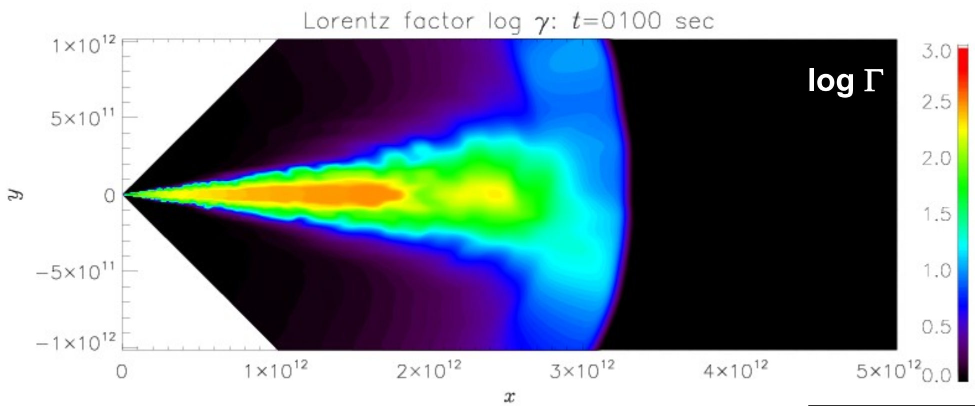
Matsumoto (RIKEN)

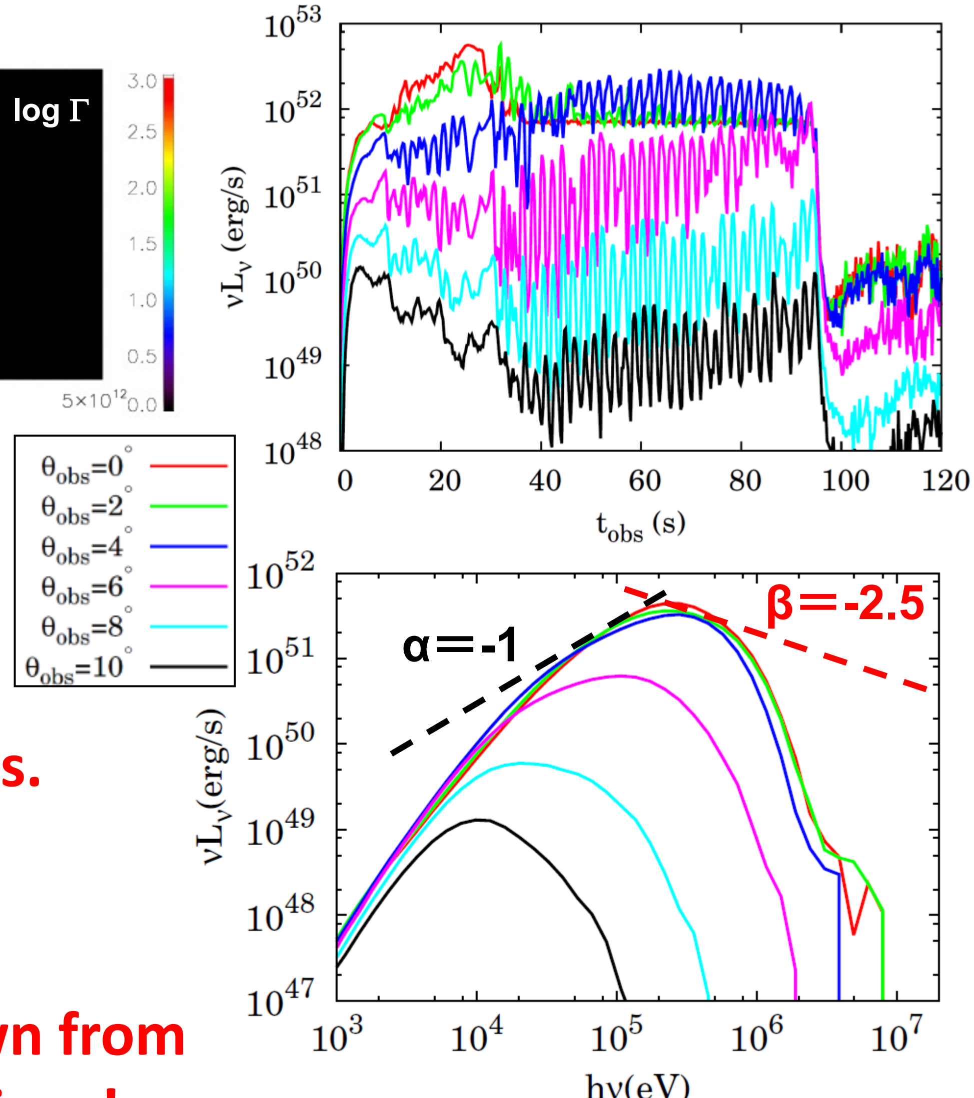
Special Relativistic
Hydro Simulations

Radiation-
Transfer
(Post-Process)

Ito (RIKEN)

A Case of Precession Model (t_{pre}=2s θ_{pre} = 3°)

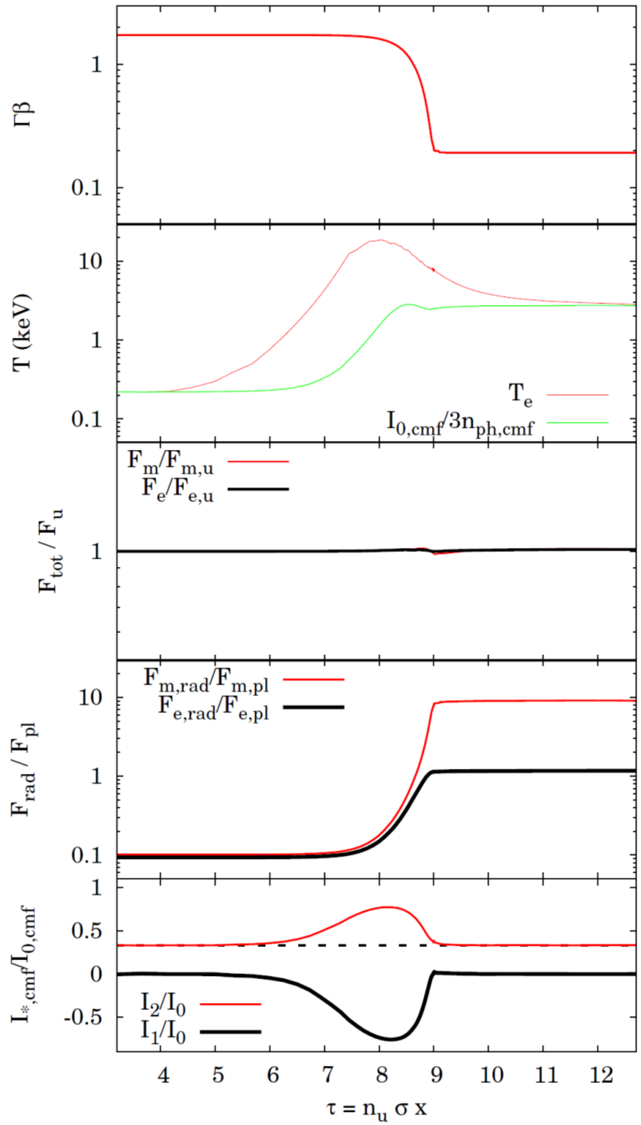




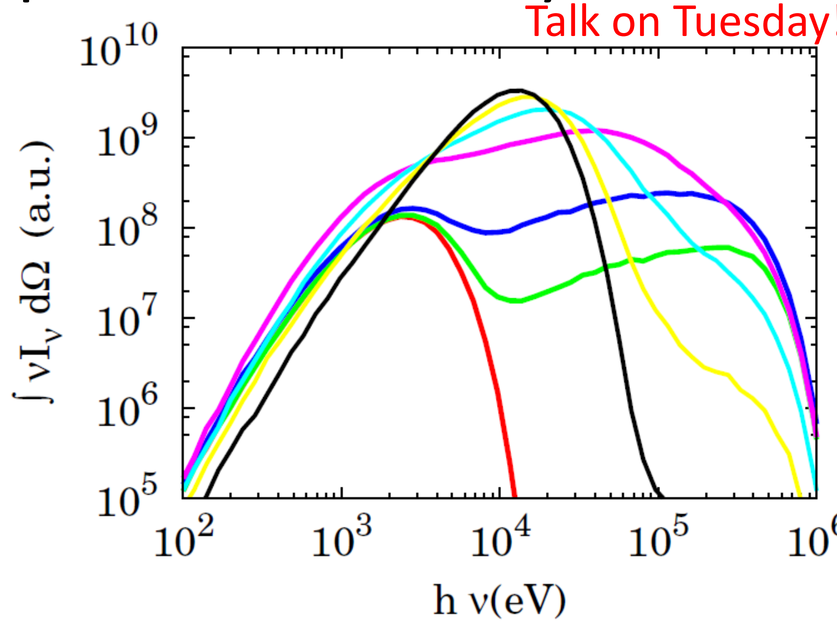
Precession Activities are Imprinted on Prompt Emissions.

Severe Constraint Can be Drawn from Observations of Prompt Emissions!

Another Possibility: Radiation Dominated Shock Reproduces the Band Spectrum Naturally.



Talk on Tuesday!



Ito (RIKEN)

Work with Levinsson (Tel Aviv U.) 2016, in prep.

τ=0.4 (red)
τ=8 (green)
τ=8.5 (blue)
τ=9 (magenta)
τ=9.5 (cyan)
τ=10.4 (yellow)
τ=11.7 (black)

Γ_u = 2

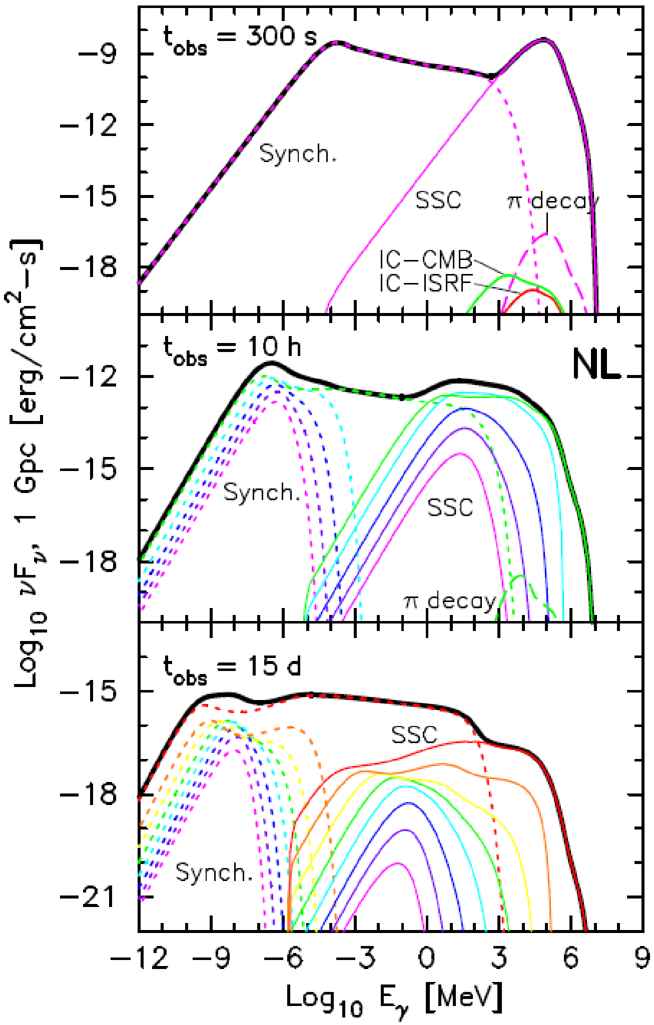
T_u = 220 eV

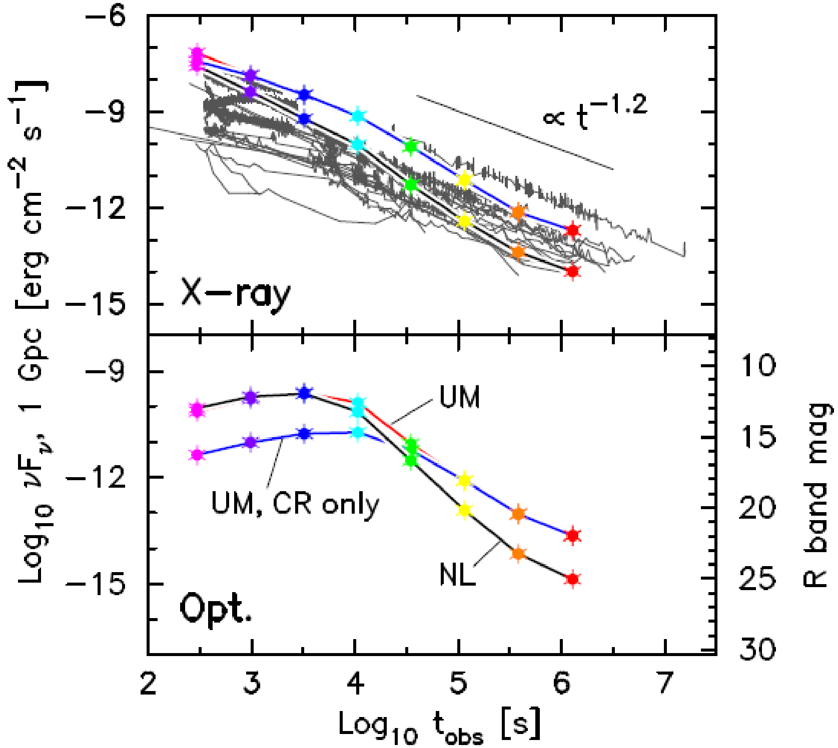
$n_{ph} / n_p = 10^5$

$\xi = e_{ru} / (n_u\ m_p\ c^2)$
$= 7.3 \times 10^{-2}$

Chromatic Break is well Explained by Nonlinear DSA

Talk on Wednesday!



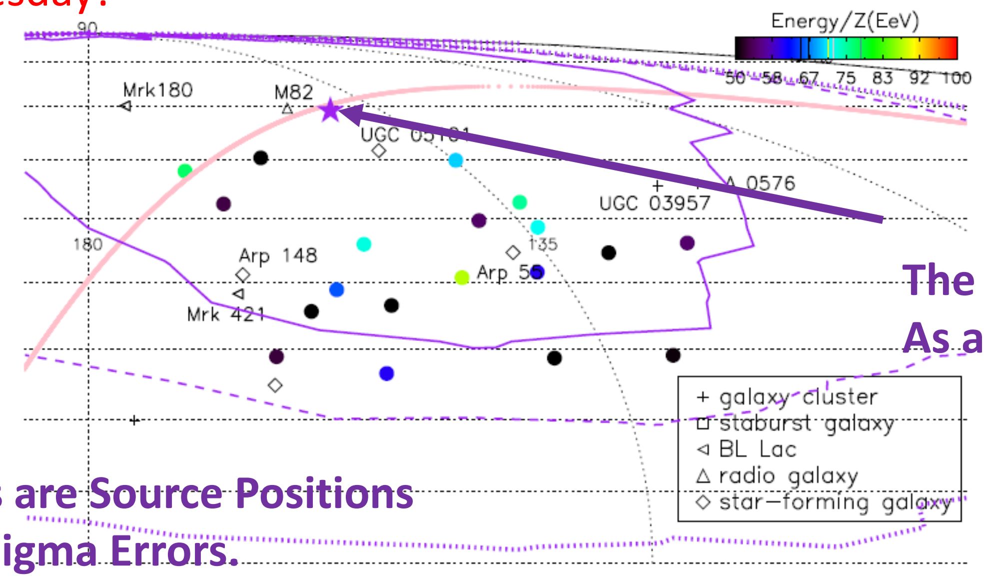


D. Warren
(RIKEN)

Blandford-McKee Solution + Non-Linear Particle Acceleration.
Left: Broadband Spectrum
Upper: X-ray & Optical Light Curve
(Chromatic break!)

TA Hot Spot: UHECRs from M82?

Talk on Tuesday!

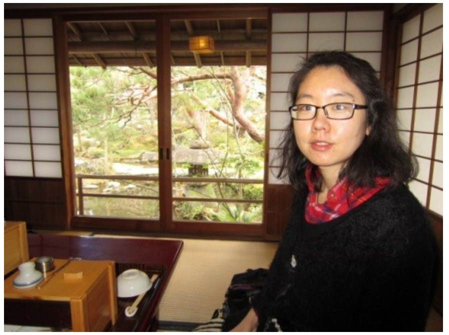


The most likely Source Position As a Result of Our Analysis.

M82 is very Close from the most likely Source Position!

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

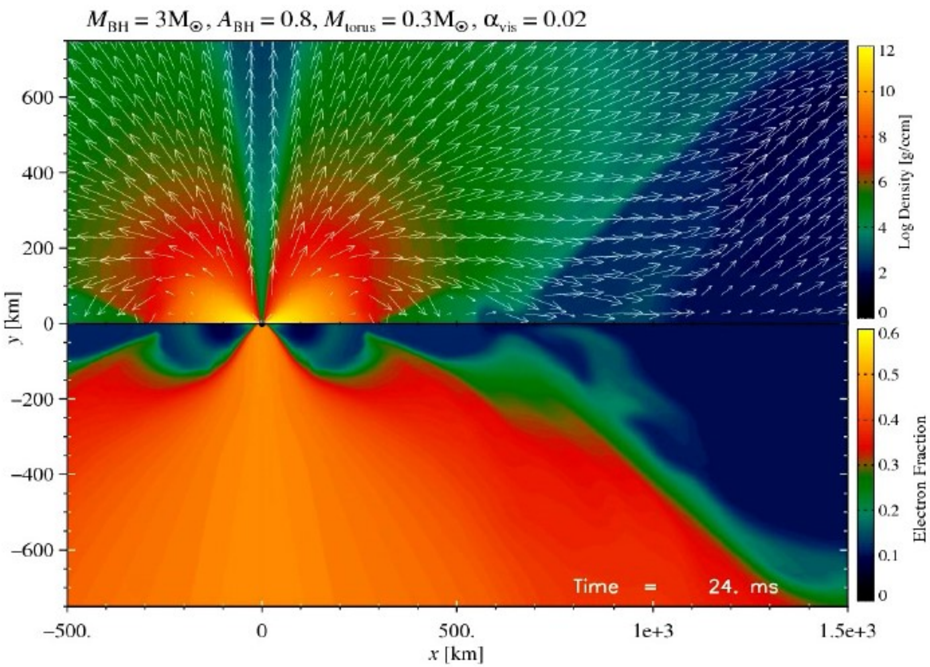
Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\text{bes-fit}}$ (%)
best-fit	-	-	$17.4^{+17.0}_{-11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	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

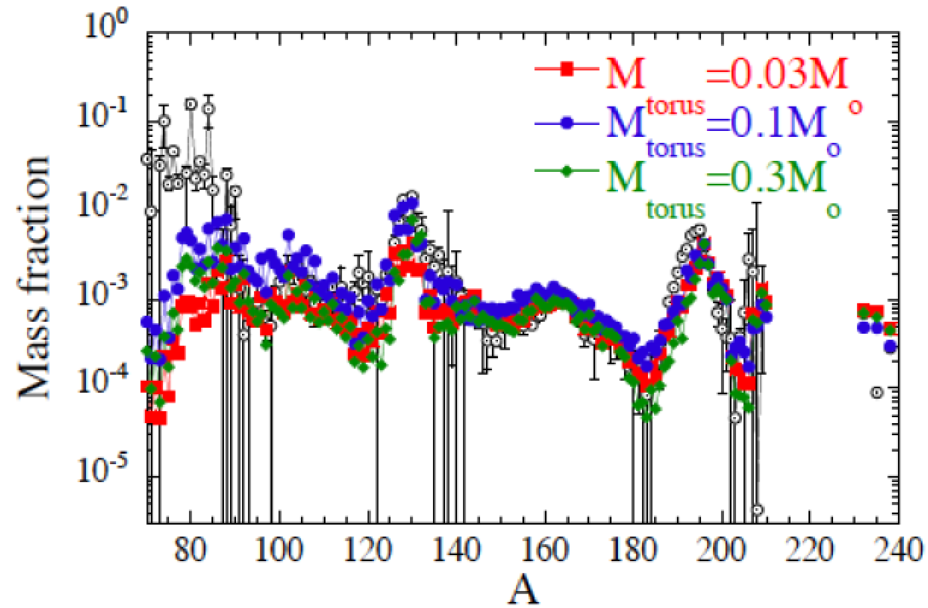


H. He (RIKEN from Sep. 2016)

NS-NS Mergers & NS-BH Mergers

Talk on Wednesday!



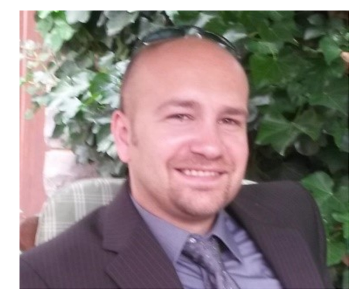


$$
\begin{aligned}
E &= \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t) && \leftarrow \text{energy density} \\
F^i &= \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i && \leftarrow \text{momentum density} \\
P^{ij} &= \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j && \leftarrow \text{pressure} \\
Q^{ijk} &= \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k
\end{aligned}
$$

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

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

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



Oliver Just (MPA)

Simulations for Short GRBs are going on!

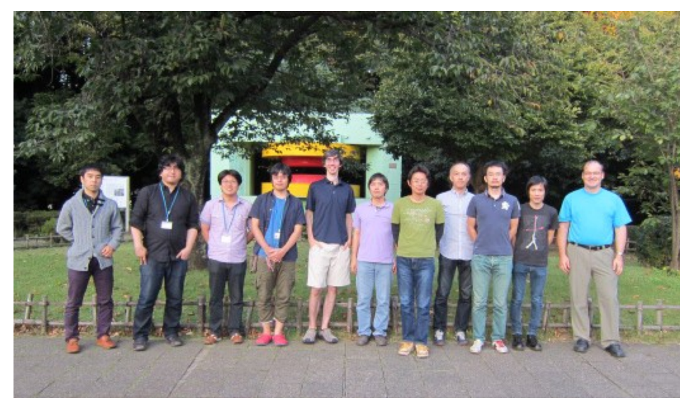
Thank You Very Much.

From 1st Apr. 2013

- PI: Nagataki
- Current PDs: H. Ito, J. Matsumoto, A. Wongwathanarat, D. Warren, S. Inoue
- From Fall 2016: G. Ferrand, H. He, M. Ono
- Alumni: Ono (Kyushu Univ.), Lee(JAXA), Tolstov(Kavli IPMU), Mao(Yunnan Obs.), Dainotti (Stanford), Teraki (RIKEN), Takiwaki (NAOJ), Wada (Company), Barkov (Potsdam/DESY)

2013, Aug.1

2014, Dec.17



2015, Sep.30