Massive Star Explosions

Astrophysical Big Bang Laboratory

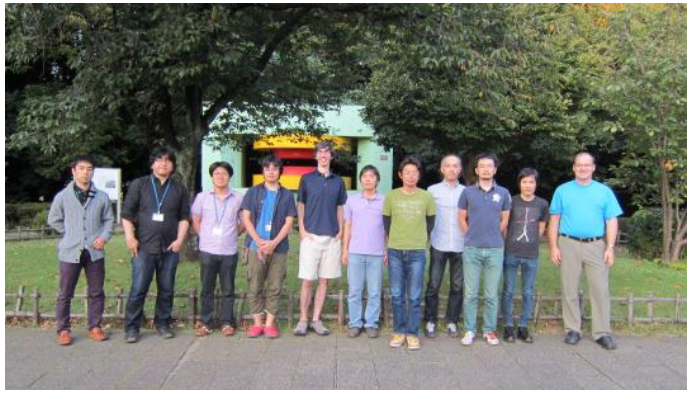
Shigehiro Nagataki

8-11 March 2017, Program of the International Workshop on Quantum Many-Body Problems in Particle, Nuclear, and Atomic Physics: Presendation Day: 10 March

Astrophysical Big Bang Lab (ABBL).

- PI: Nagataki From 1st Apr. 2013
- Current PDs: H. Ito, J. Matsumoto, A. Wongwathanarat, D. Warren, S. Inoue, G. Ferrand, H. He, M. Ono
- Alumni: Lee(Kyoto), Tolstov(Kavli IPMU), Mao(Yunnan Obs.), Dainotti (Stanford), Teraki (Kyoto), Takiwaki (NAOJ), Wada (Tohoku), Barkov (Potsdam/DESY)
- Future（Apr. 2017-）: Oliver Just (MPA→ABBL), Sarira Sahu (UNAM), Masanori Arakawa (Rikkyo/JRA), Tyler Parsotan (Oregon)

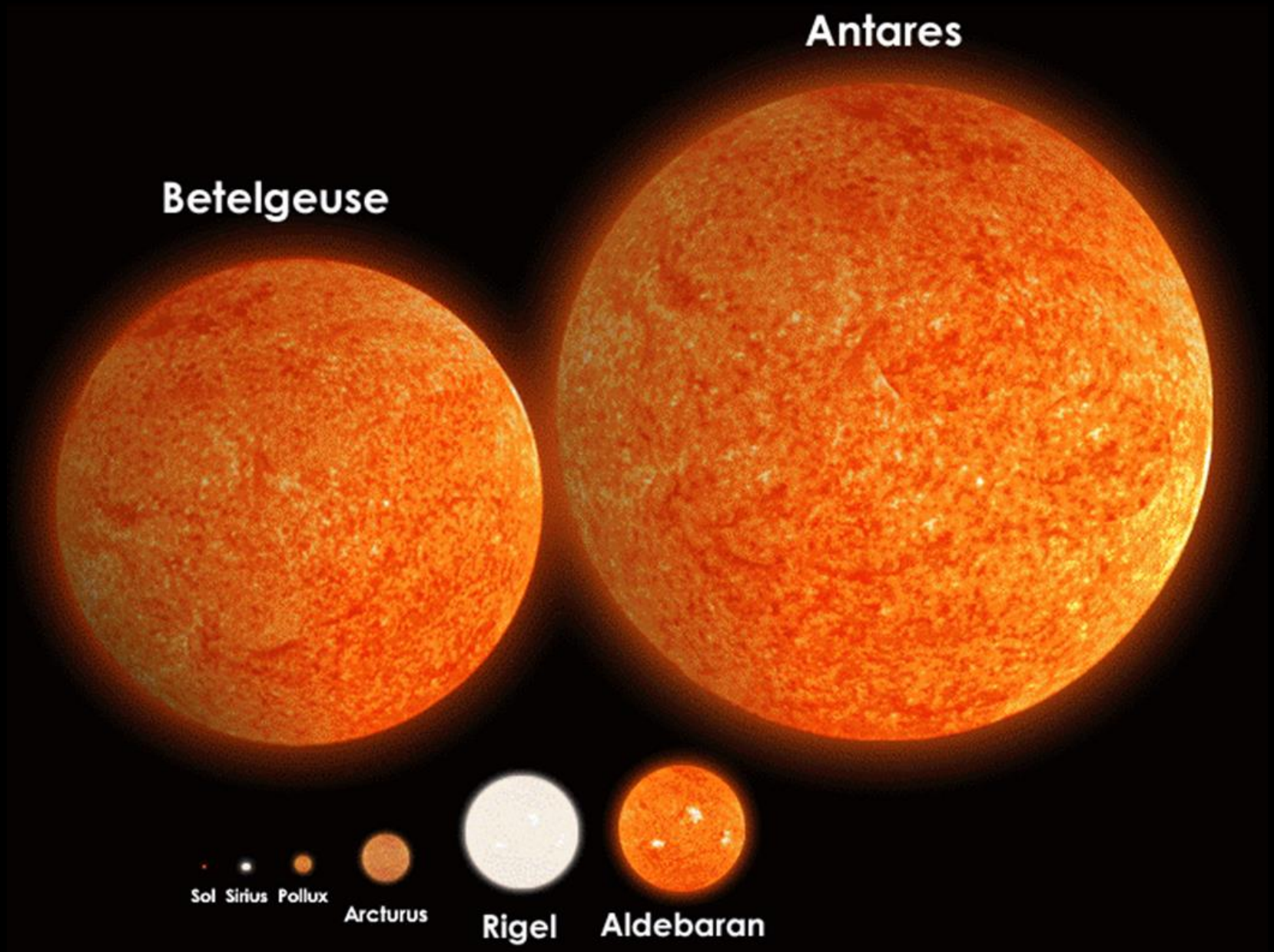
2014, Dec.17



2015, Sep.30

2016. Oct. 6

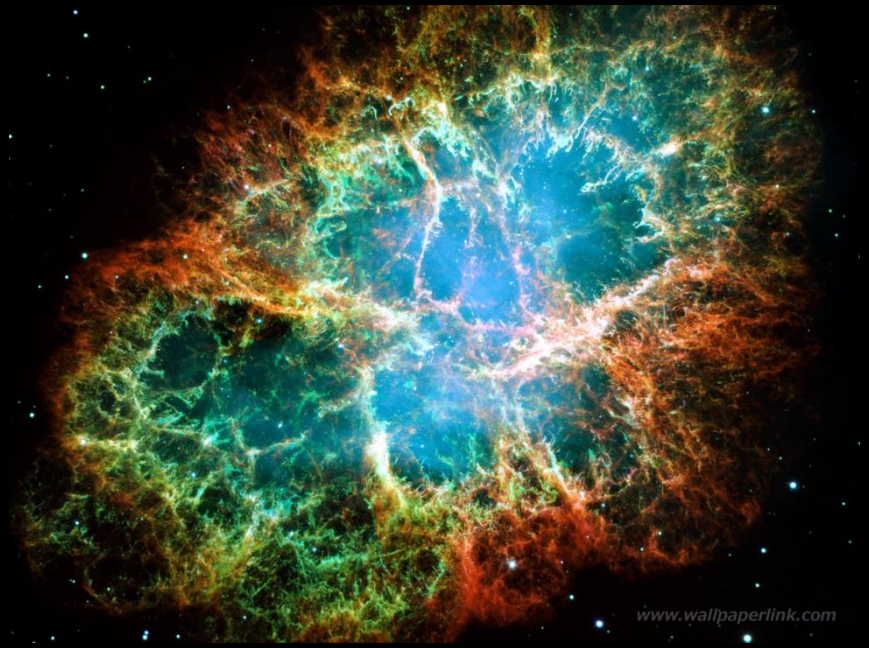
Massive Stars Explode.



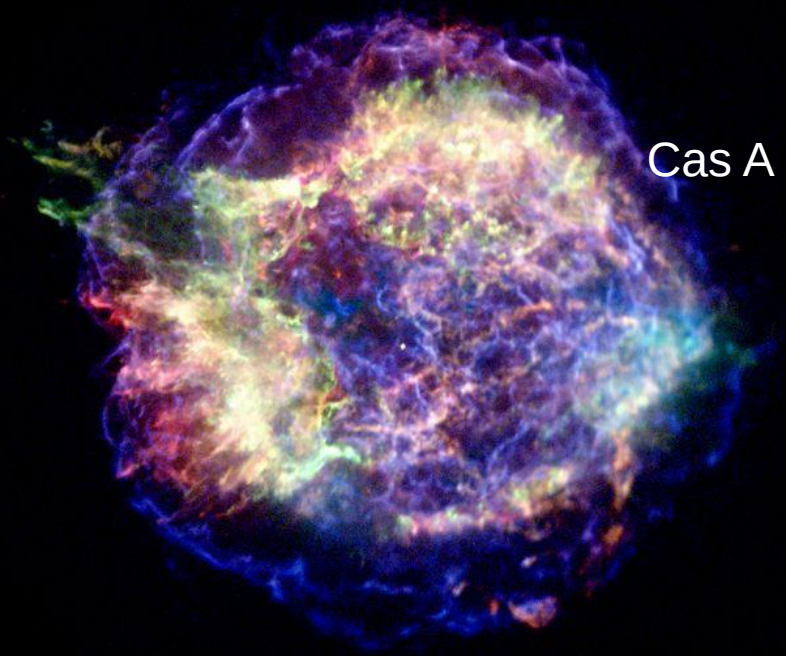
A Supernova can Happen Even Tonight.
～Betelgeuse～

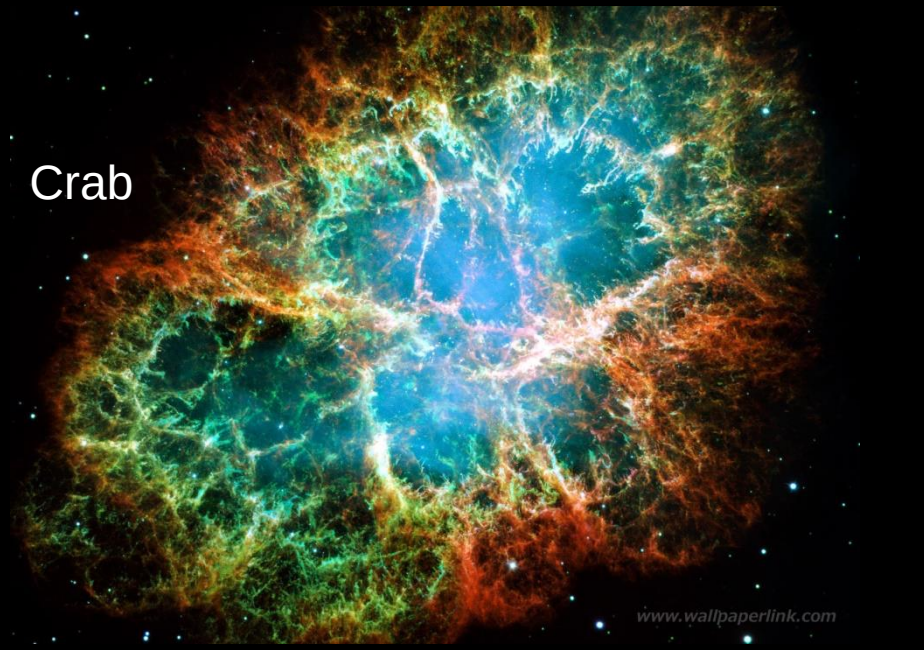
Human beings Saw Supernova Explosions in Naked Eyes!

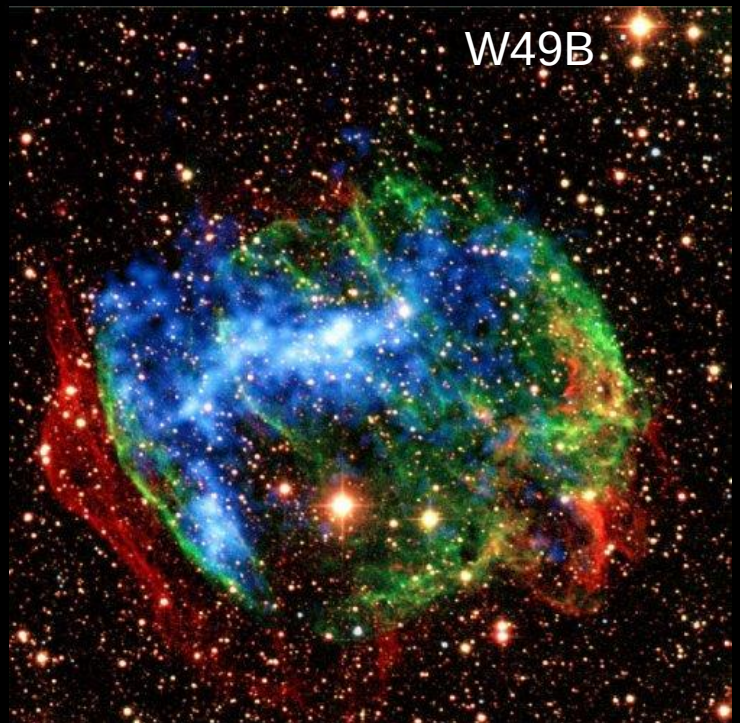
Supernova Remnant (Crab Nebula)
(A.D.1064)

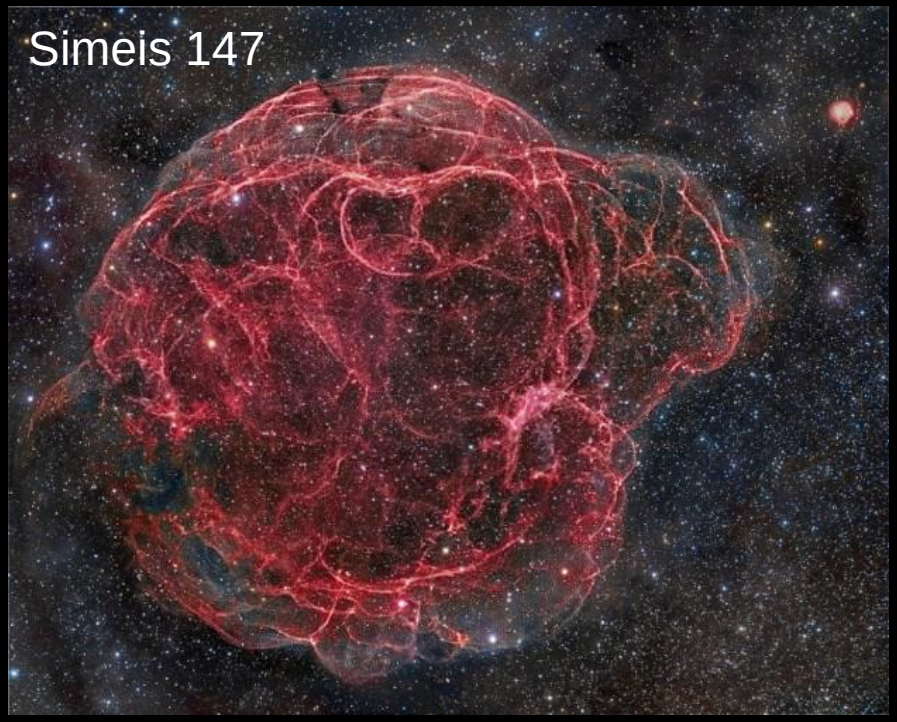


A record on SN1064
in Meigetsu-Ki by
T. Fujiwara.

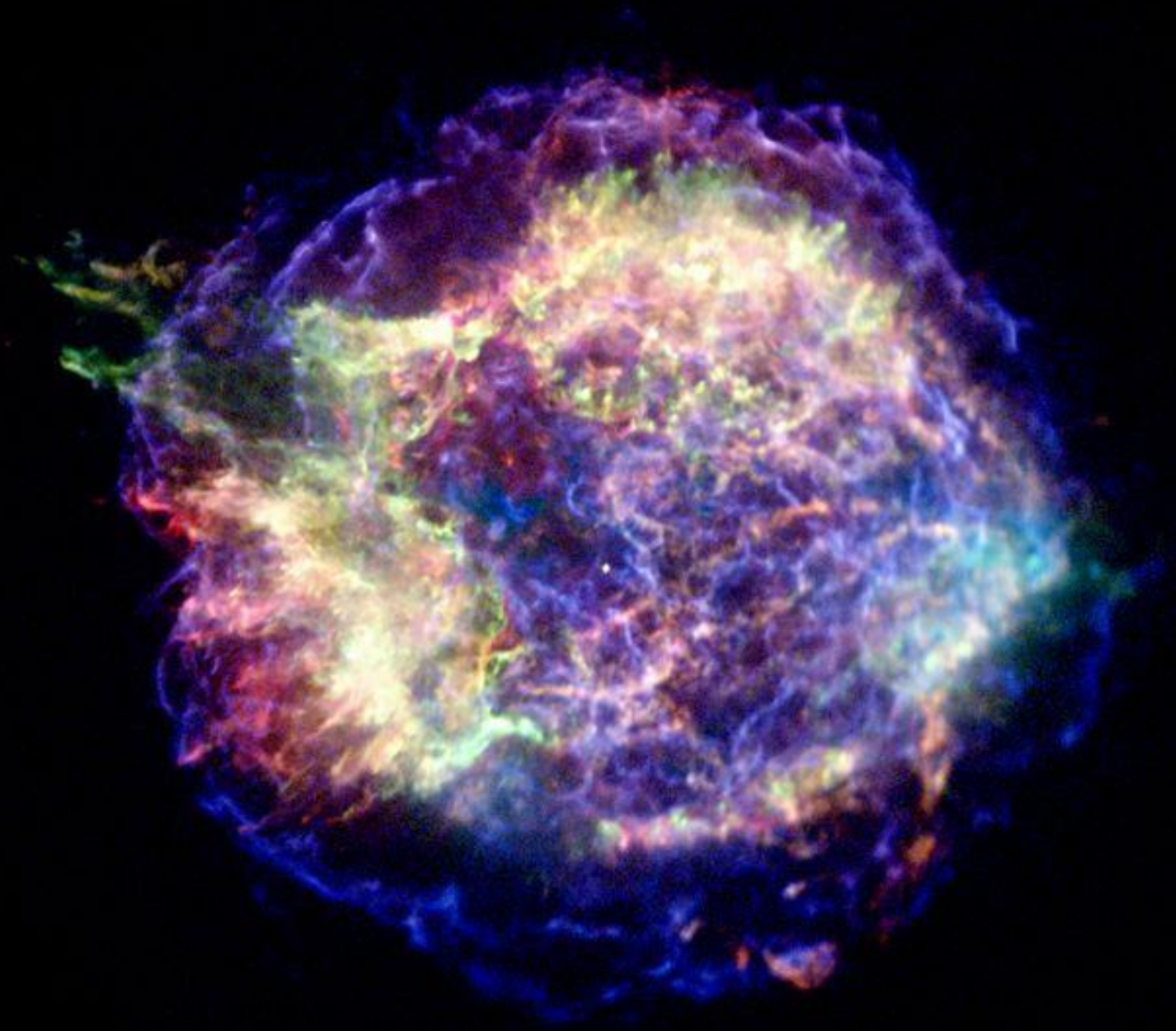

Cas A


Crab
www.wallpaperlink.com

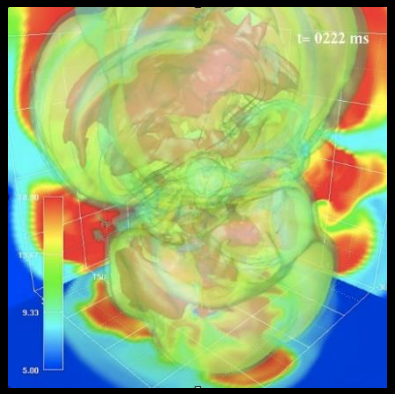

W49B

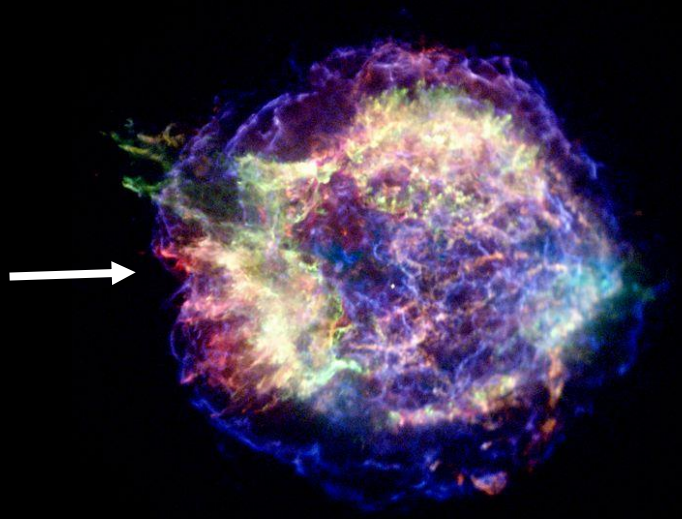

Simeis 147

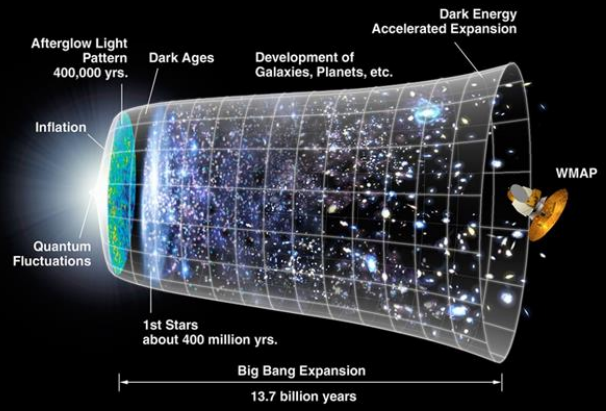
Massive Stars Explode. Why?



Legacy of Supernovae in Supernova Remnants?







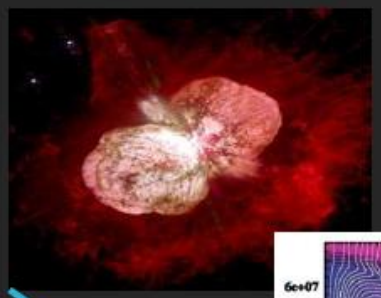
10^6-10^8cm
0.1-1 sec.

10^18-10^19cm
100-1000yrs,

c.f. Information on Early Universe Imprinted on CMB

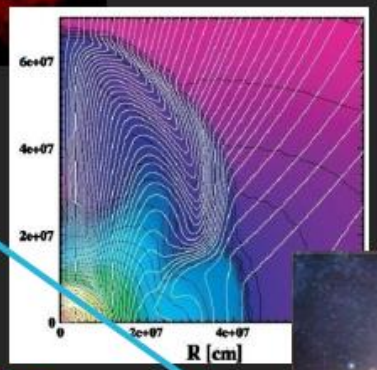
Evolution of SNe and observational signatures

Slide from K. Maeda



Opt-IR

ν



GW

ν

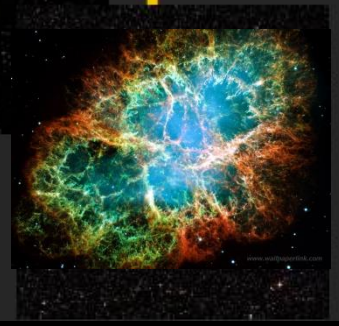
ms - sec

UV-X

sec - day

Opt-IR
Radio, X
γ

day - year



Opt-IR
Radio
X
VHE γ

decade - centuries

§ Explosion Mechanism of Massive Stars (Supernovae)

The Mystery Lasting Over 80 Years

5. *The super-nova process*

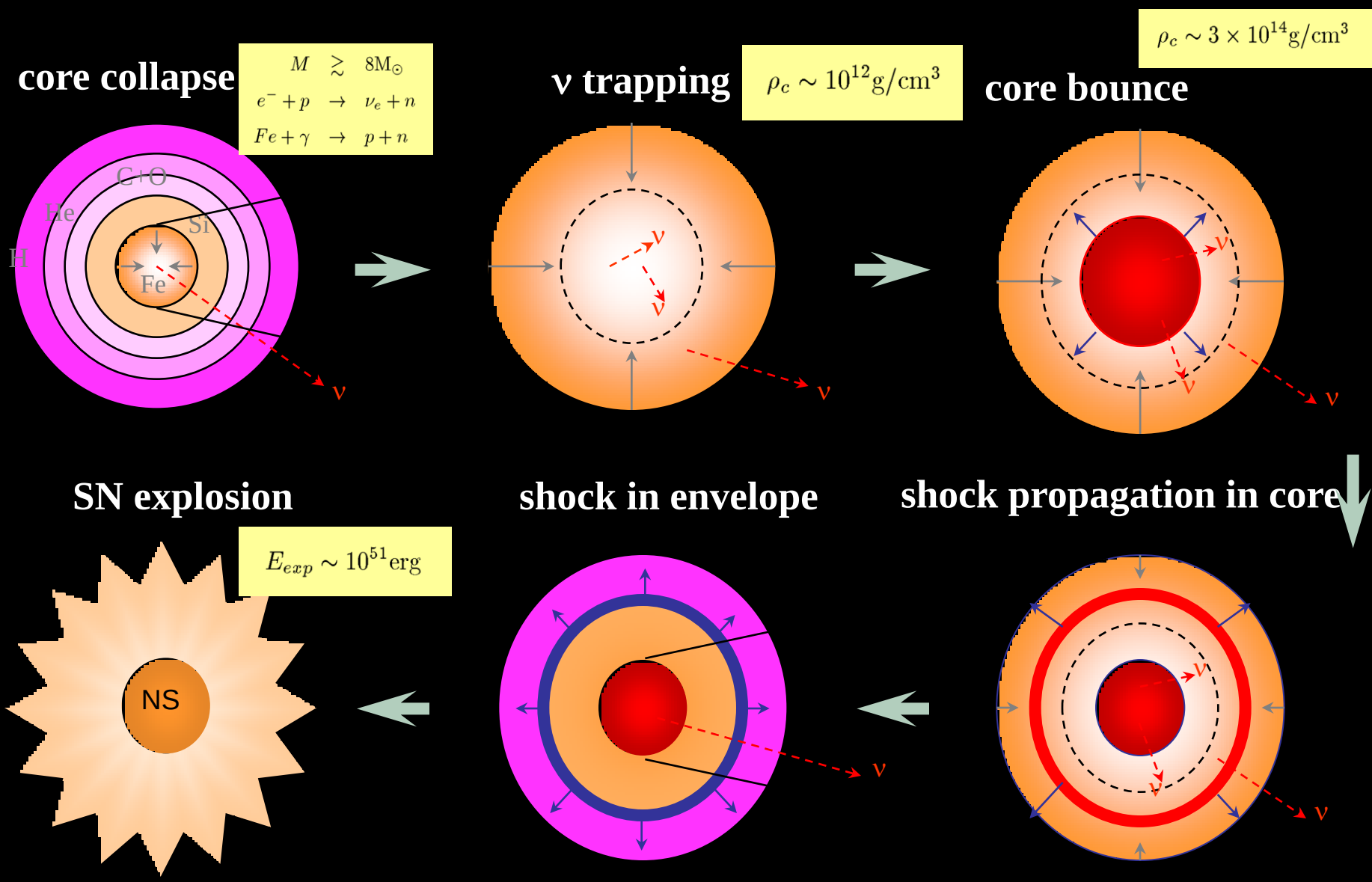
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This 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

Outline of Explosion Mechanism

From S. Yamada



T. Takiwaki
(NAOJ/RIKEN)

Supernova Simulations by K-Computer

京(KEI) = 10 Peta=10^16.

K-Computer's Speed is 10 Peta Flops (Fastest in the World in Jun. –Nov. 2011).

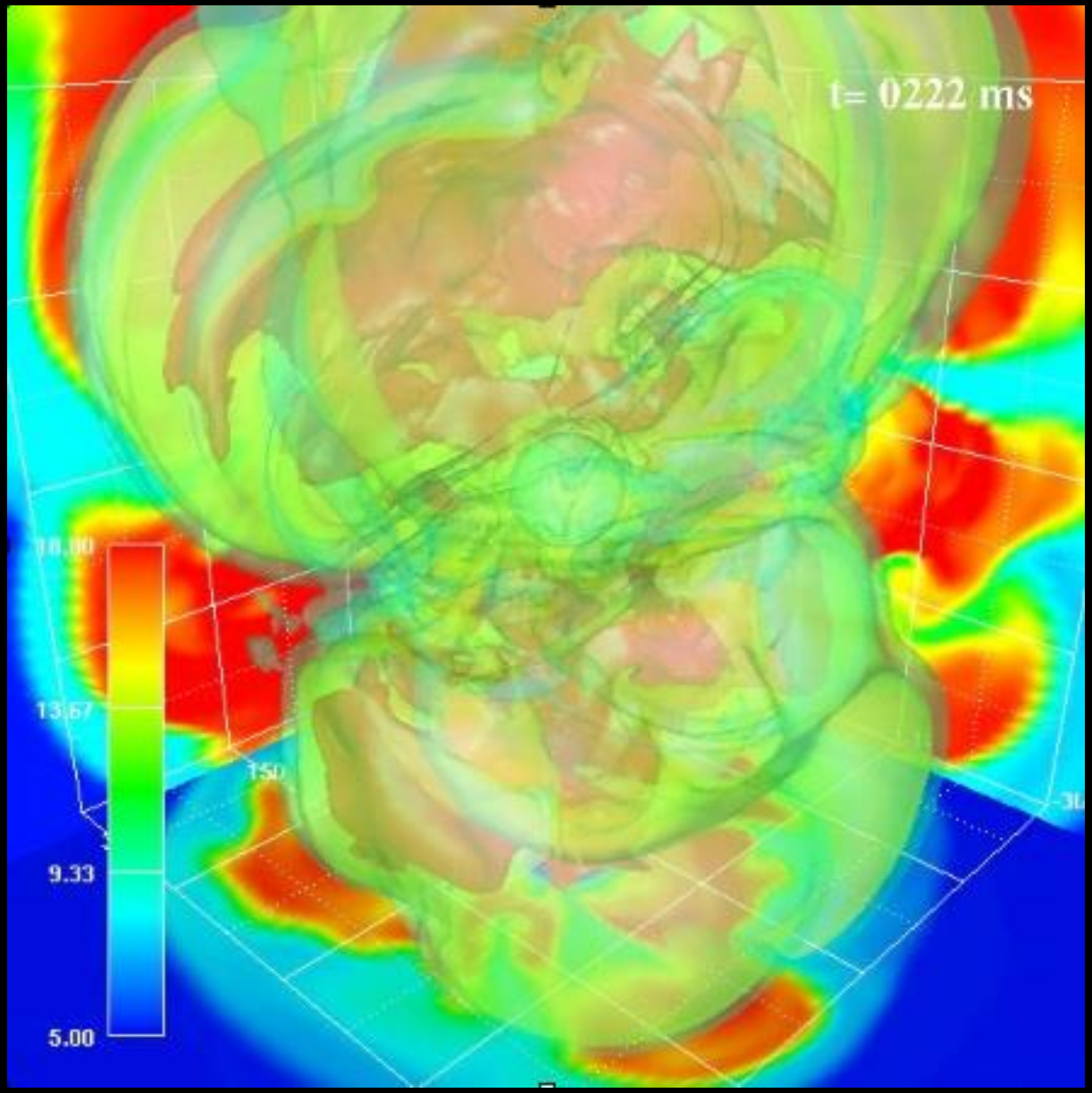
The Post-K-Project (Exa-Flops, 2020-) has already started in RIKEN.

Copyright of the Music

JASAC (Japanese Society for Rights of Authors, Composers and Publishers)

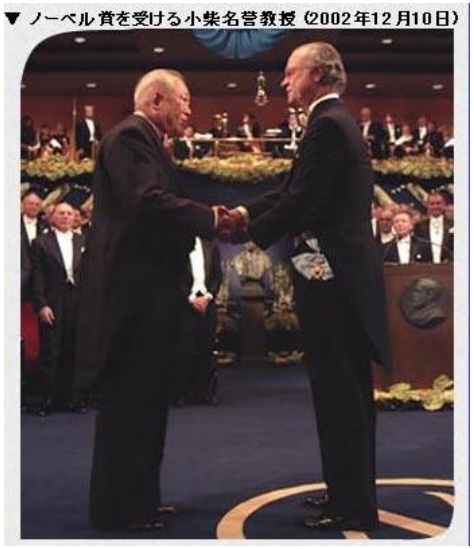
- 010-5082 交響組曲宇宙戦艦ヤマト「序曲」

Almost Exploded.

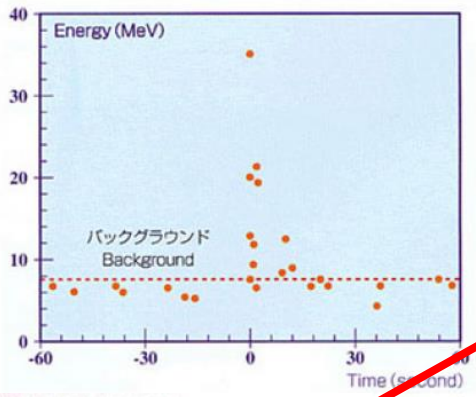


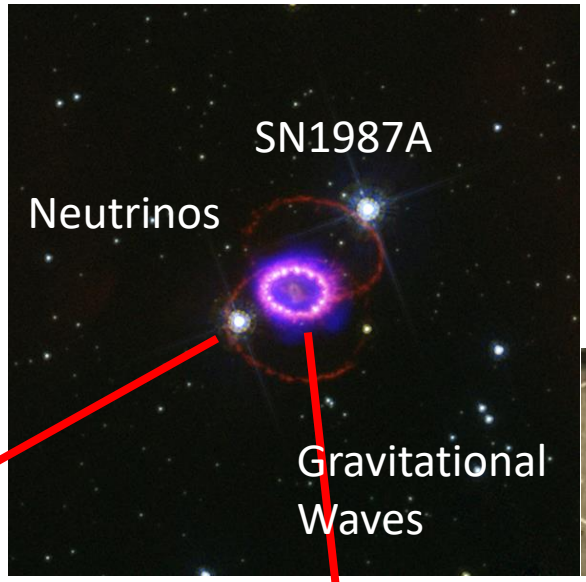
Simulation by
T. Takiwaki
(RIKEN→NAOJ)

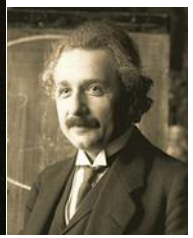
Supernova as a Source of Neutrinos and GWs

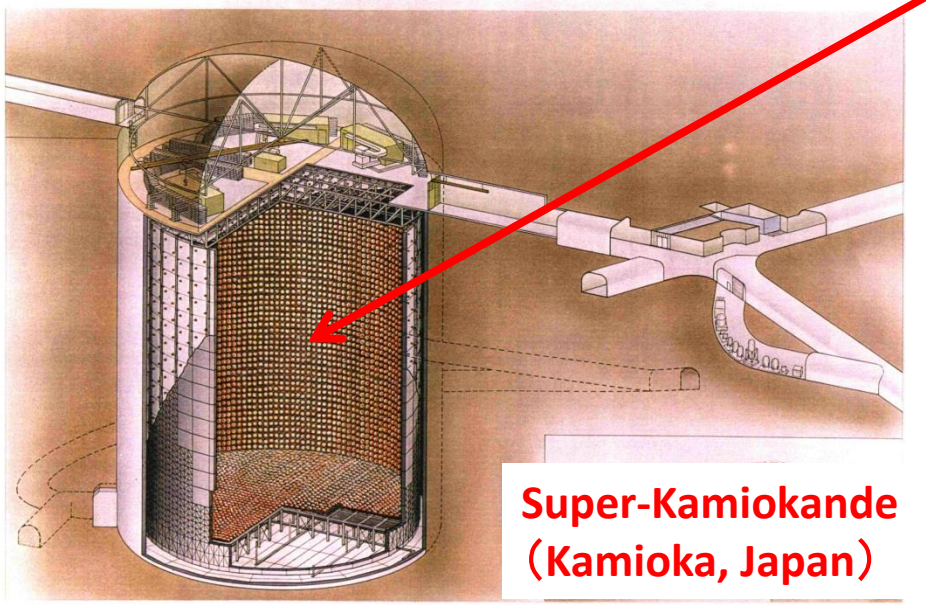


Prof. M. Koshiba,
Awarded the Nobel Prize
in Physics (2002).

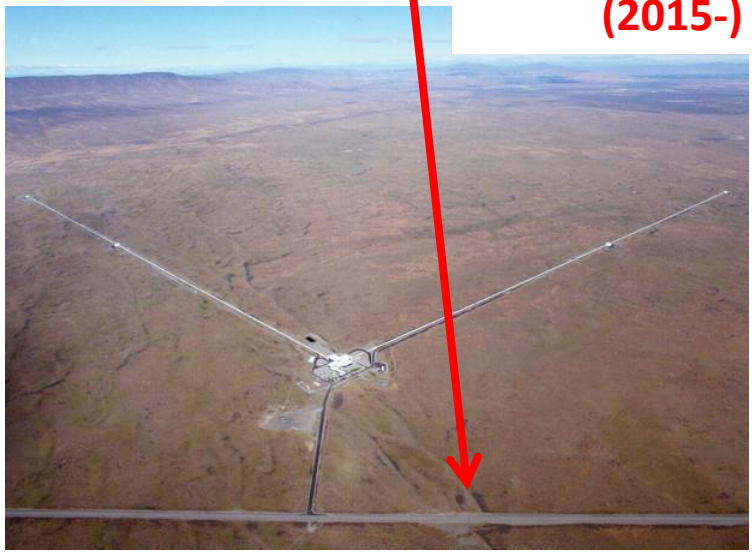




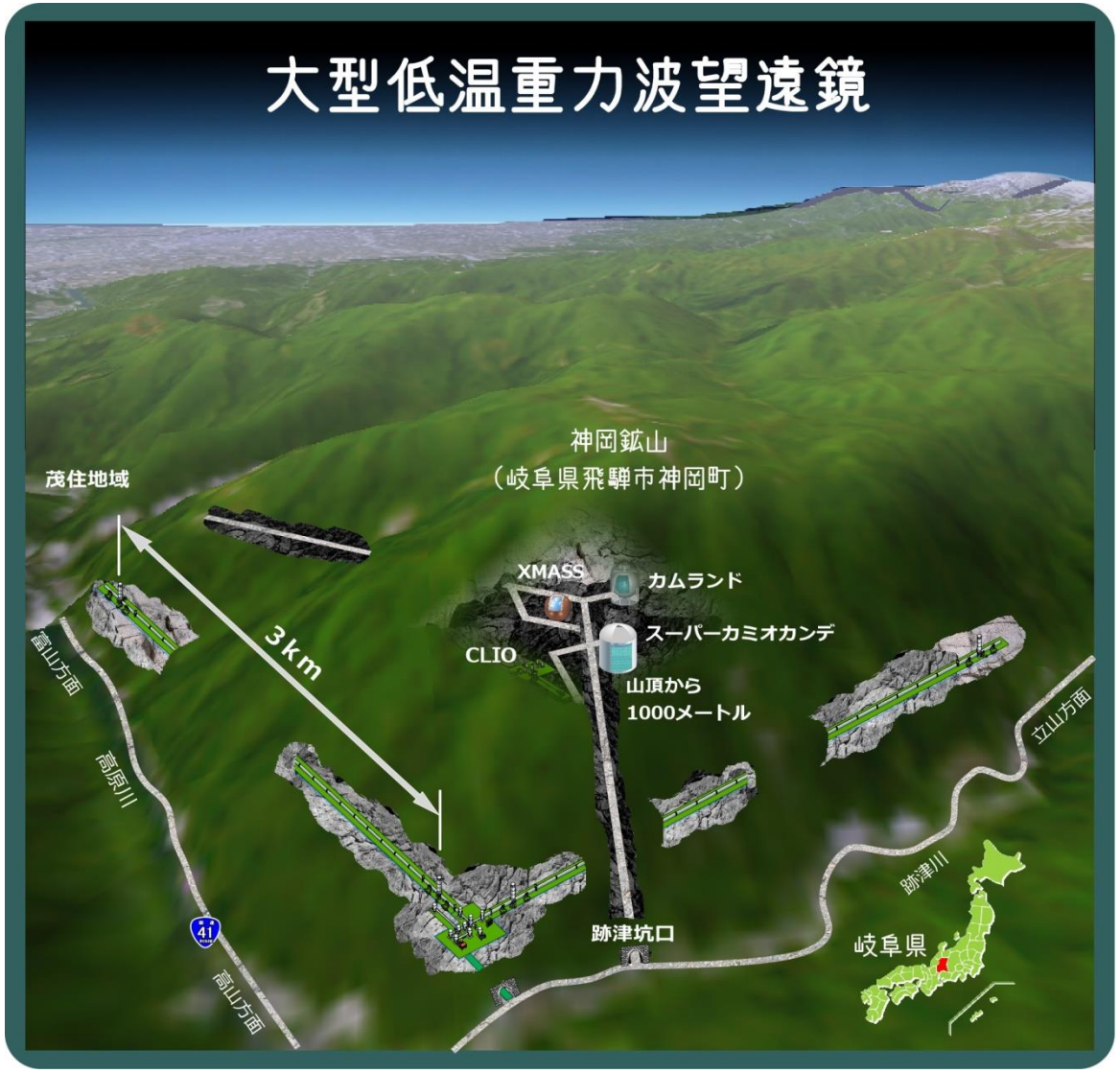




ALIGO (USA)
(2015-)



KAGRA in Japan (under-construction)



Prof. T. Kajita
PI of KAGRA Mission
Nobel Prize in Physics in 2015 for Finding Neutrino Oscillation.

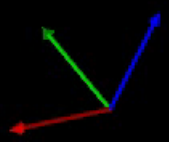
§ Nucleosynthesis
&
Hydrodynamic Instabilities

in Supernovae

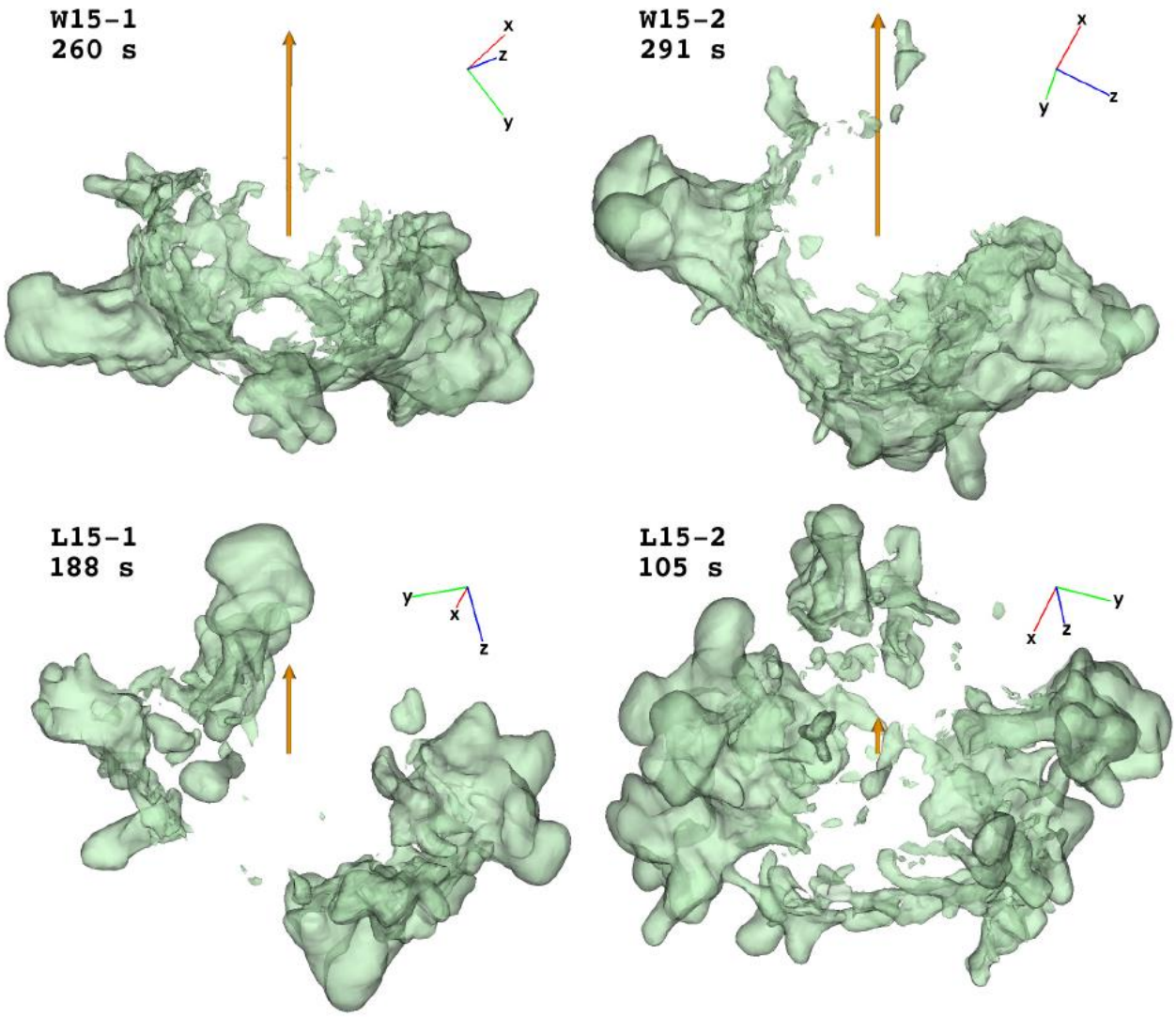
Spontaneous Asymmetric Explosion

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

A. Wongwathanarat
(RIKEN)



Asymmetric Ejection of 56Ni & Neutron Star Kick

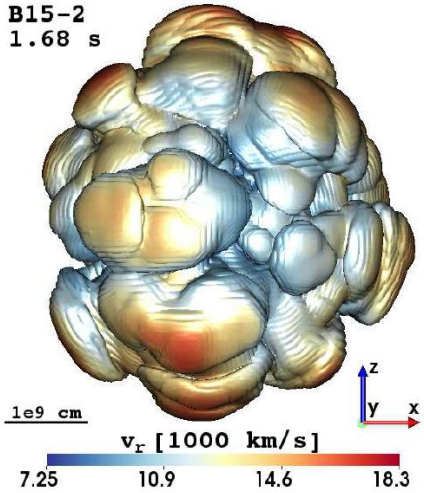


A. Wongwathanarat
(RIKEN)

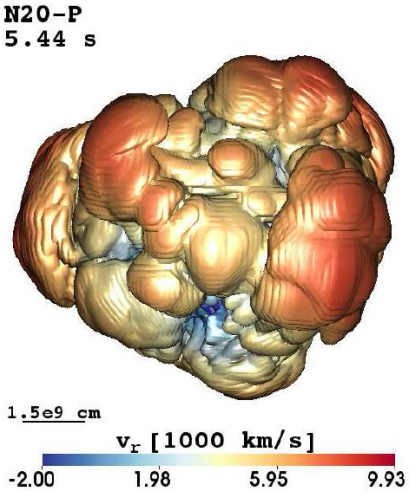
Progenitor dependence is Huge

Wongwathanarat et al. (2015)

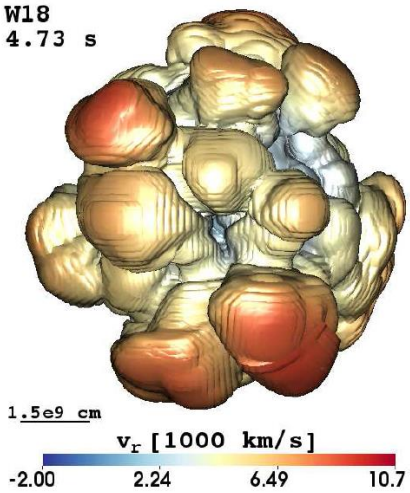
Woosley et al. (1988)



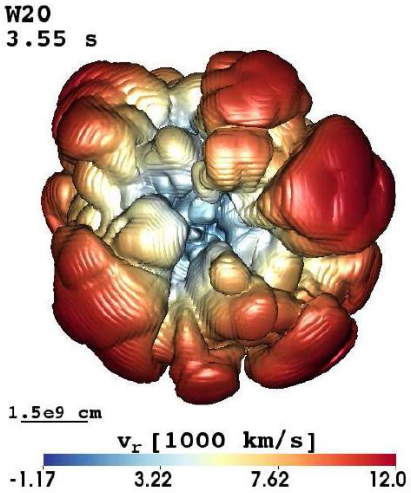
Shigeyama & Nomoto (1990)



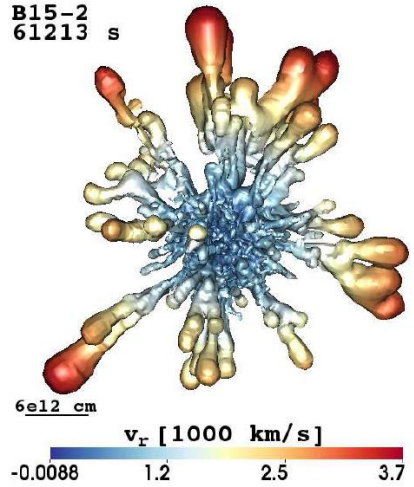
Woosley (2007)

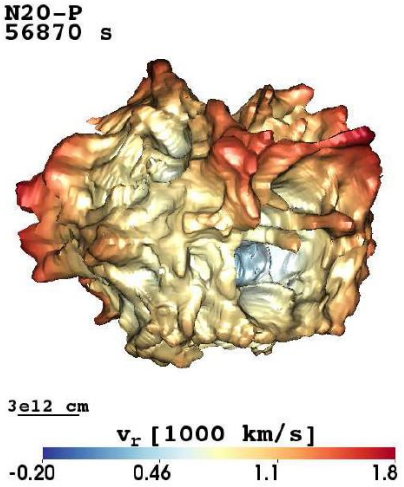


Woosley et al. (1997)

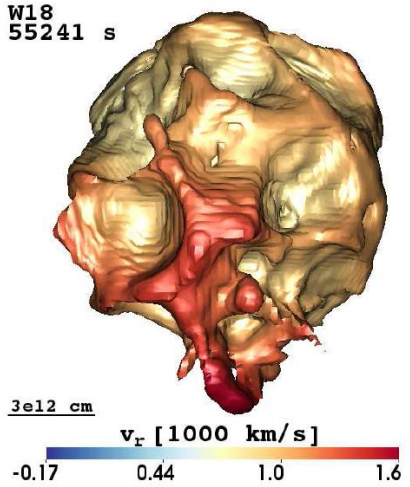


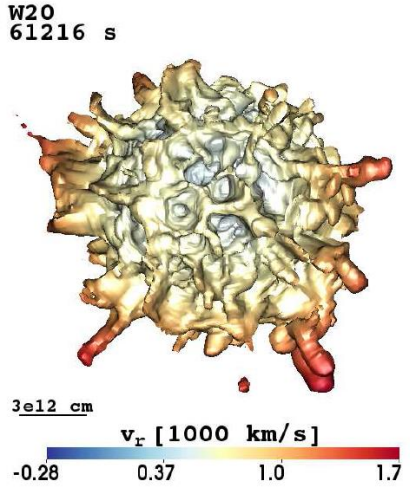
~ 3700 km/s





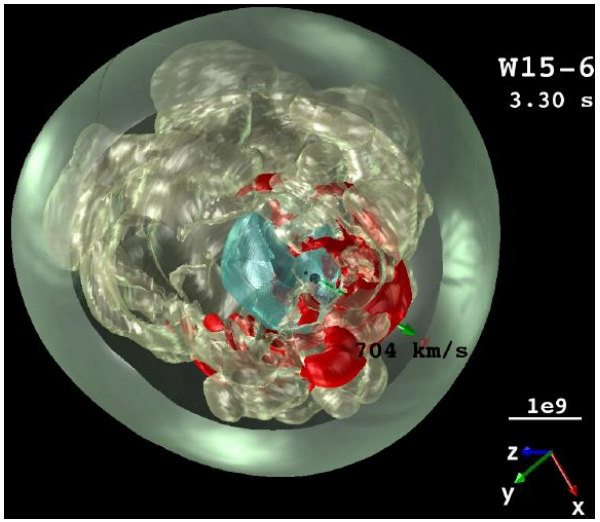
< 2000 km/s

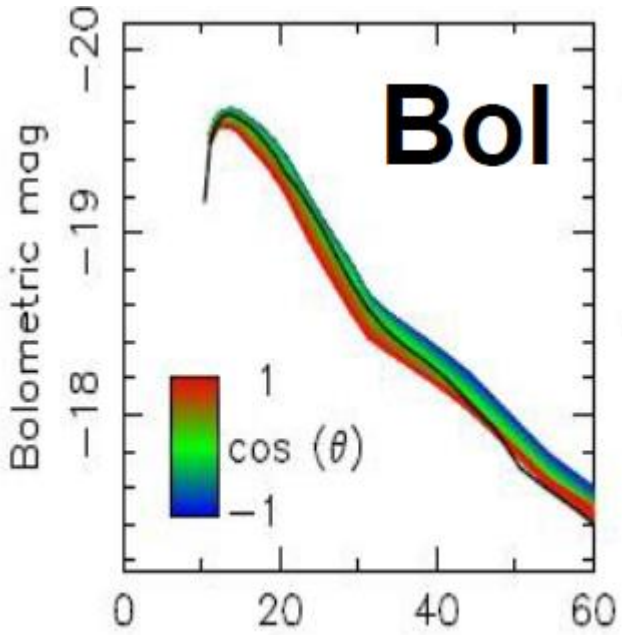


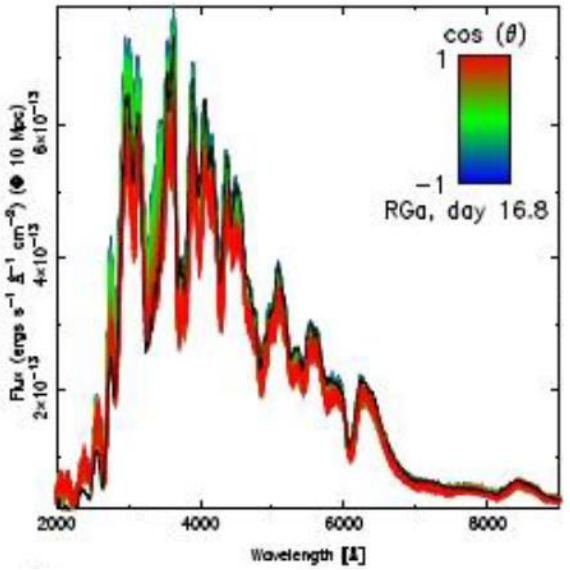


Great Collaborations Started

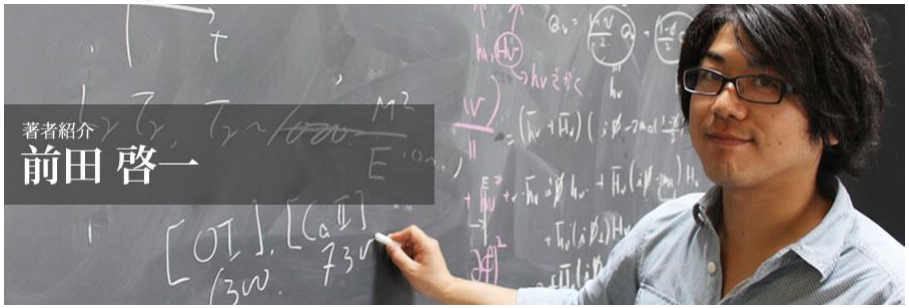
- Radiation Transfer, including Gamma-Ray Line Transfer



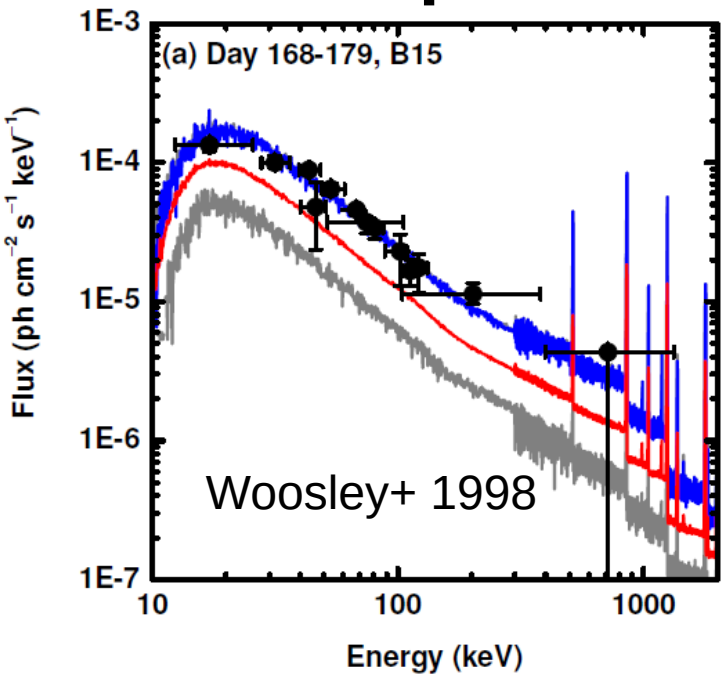


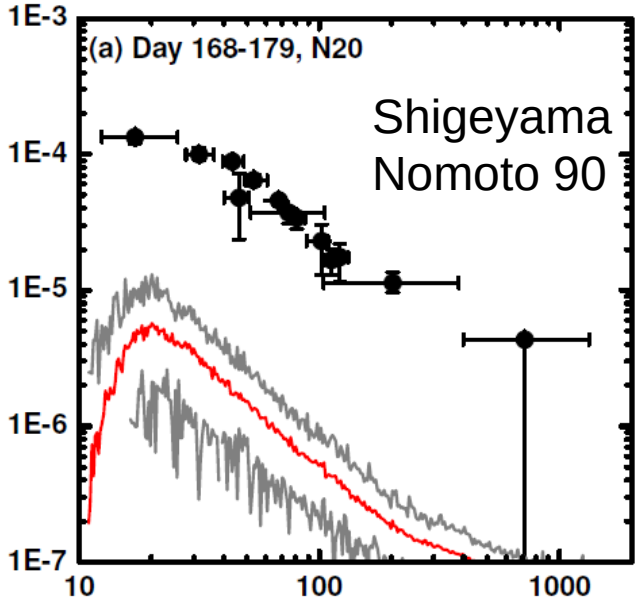


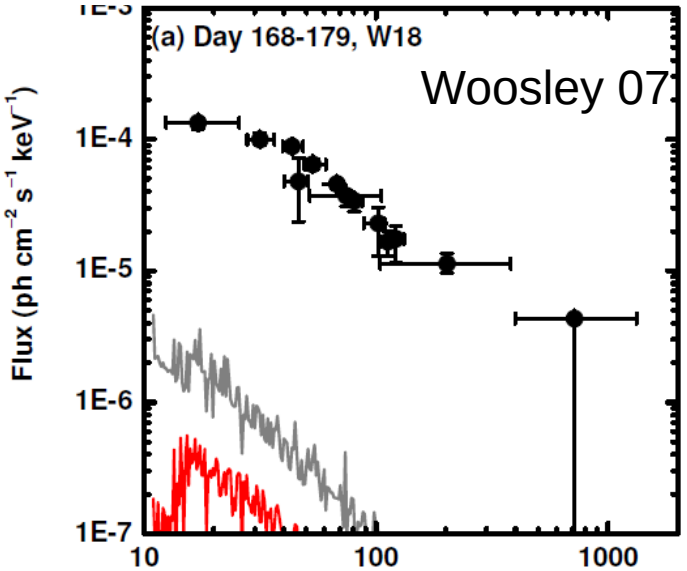
Left:
A. Wongwathanarat (RIKEN)
Right:
K. Maeda (Kyoto)

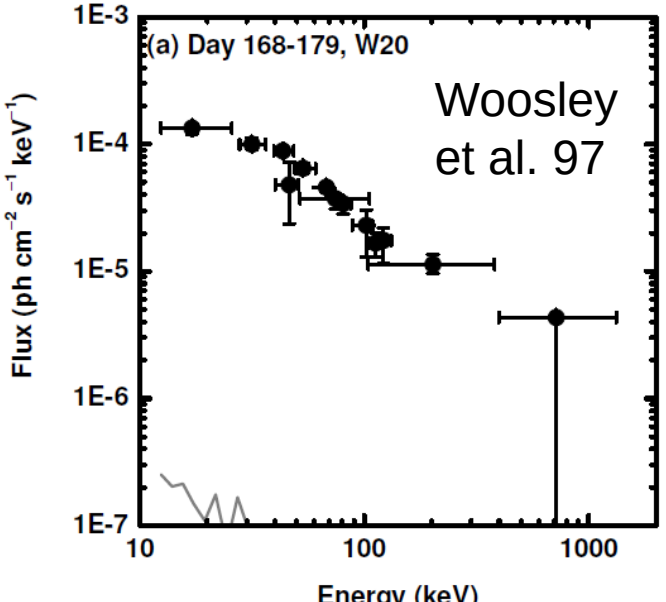


Comparison with SN1987A

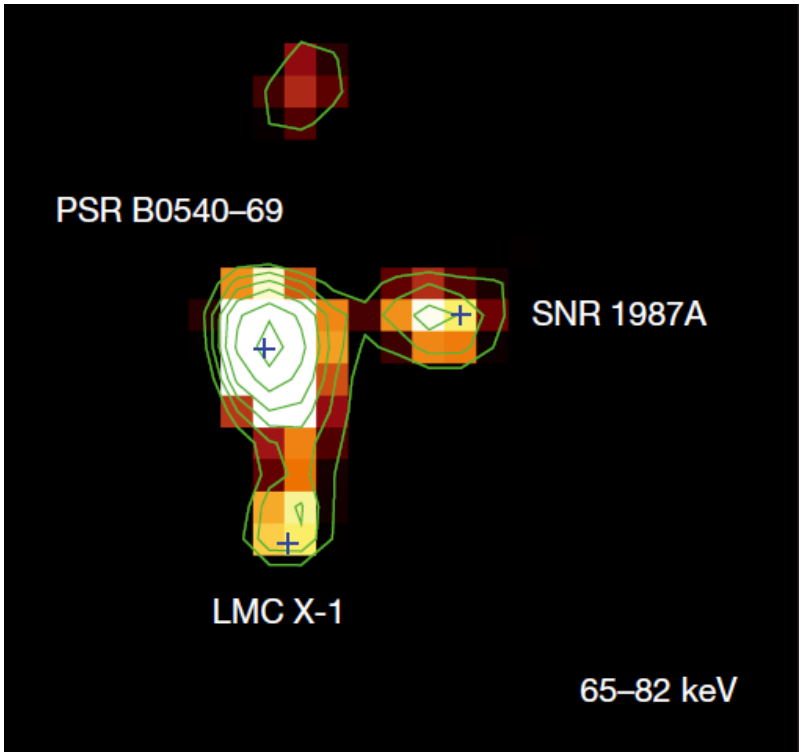






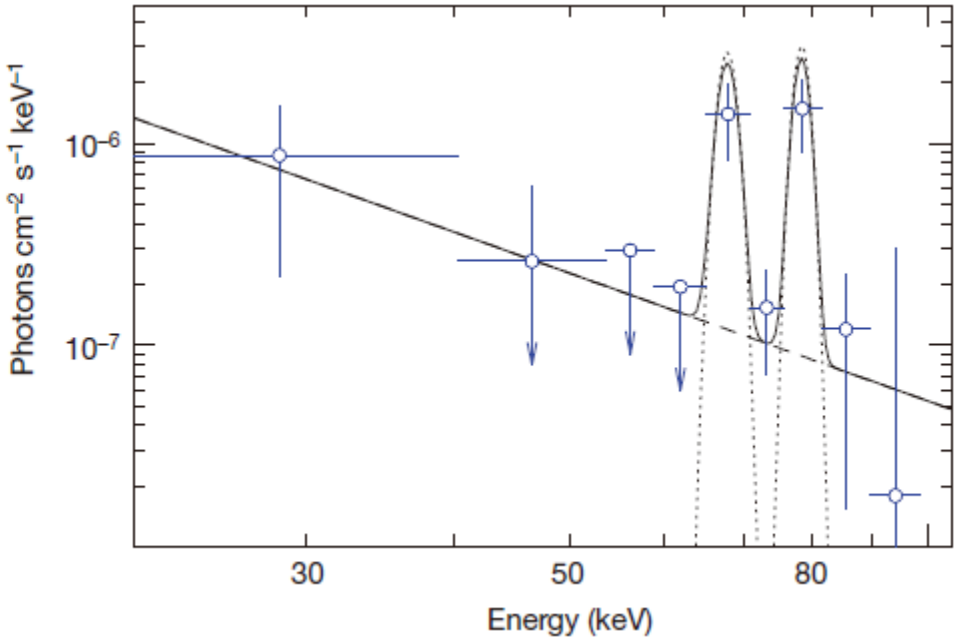


Lots of ^{44}Ti was Found in SN1987A!



Grebenev et al. Nature 12

By INTEGRAL



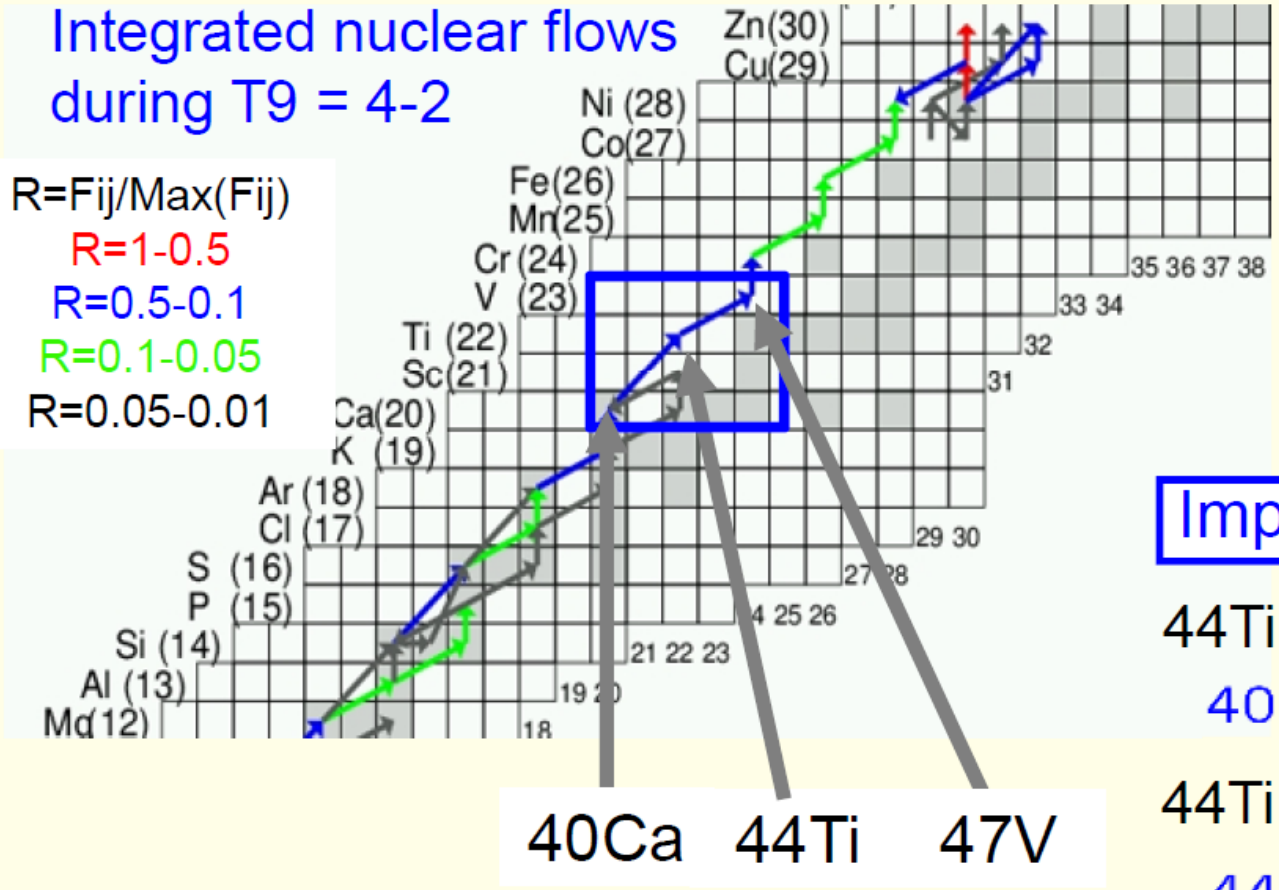
$$^{44}\mathrm{Ti} \sim (3.1 \pm 0.8) \times 10^{-4} M_{\odot}$$

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,…)

44Ti is produced through α-rich Freezeout.



Important reactions

44Ti Production

$^{40}Ca(\alpha,\gamma)^{44}Ti$

44Ti destruction

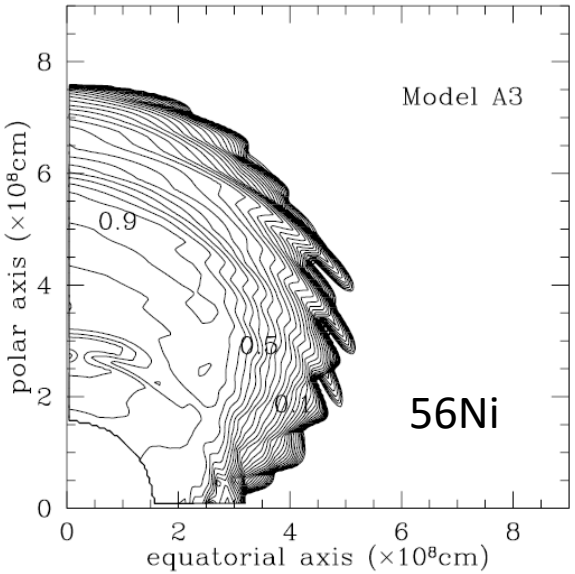
$^{44}Ti(\alpha,p)^{47}V$

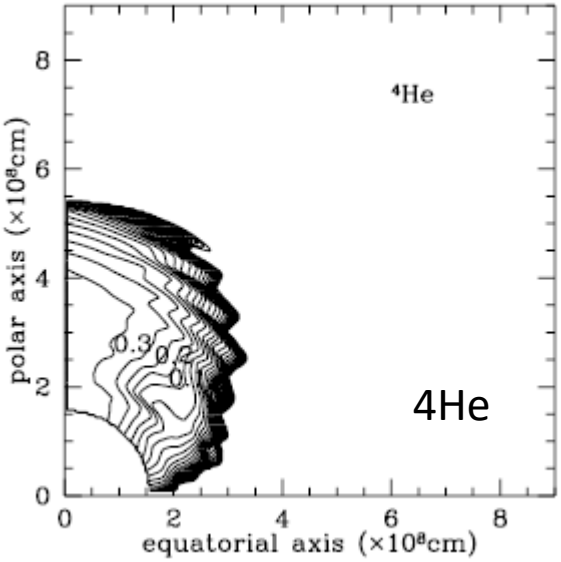
Slide from S. Fujimoto

For α-rich, High Entropy per Baryon.

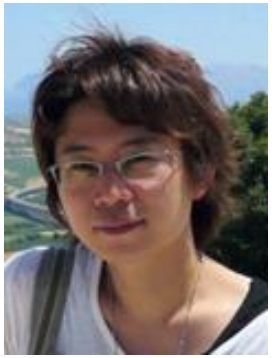
- $S \sim T^3/\rho$.
- For High Entropy per baryon (*S*), high temperature & (relatively) low density are preferred.
- The balance between Fe ⇔ He, p, n depends on entropy.
- *T* is related with photo-dissociations, while ρ is related with nuclear reactions.

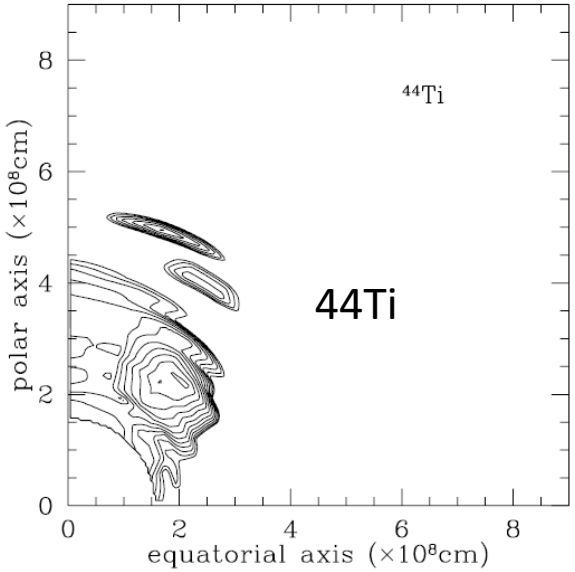
Lots of 44Ti in Bipolar Explosion?





Nagataki et al. 97,
Nagataki 00





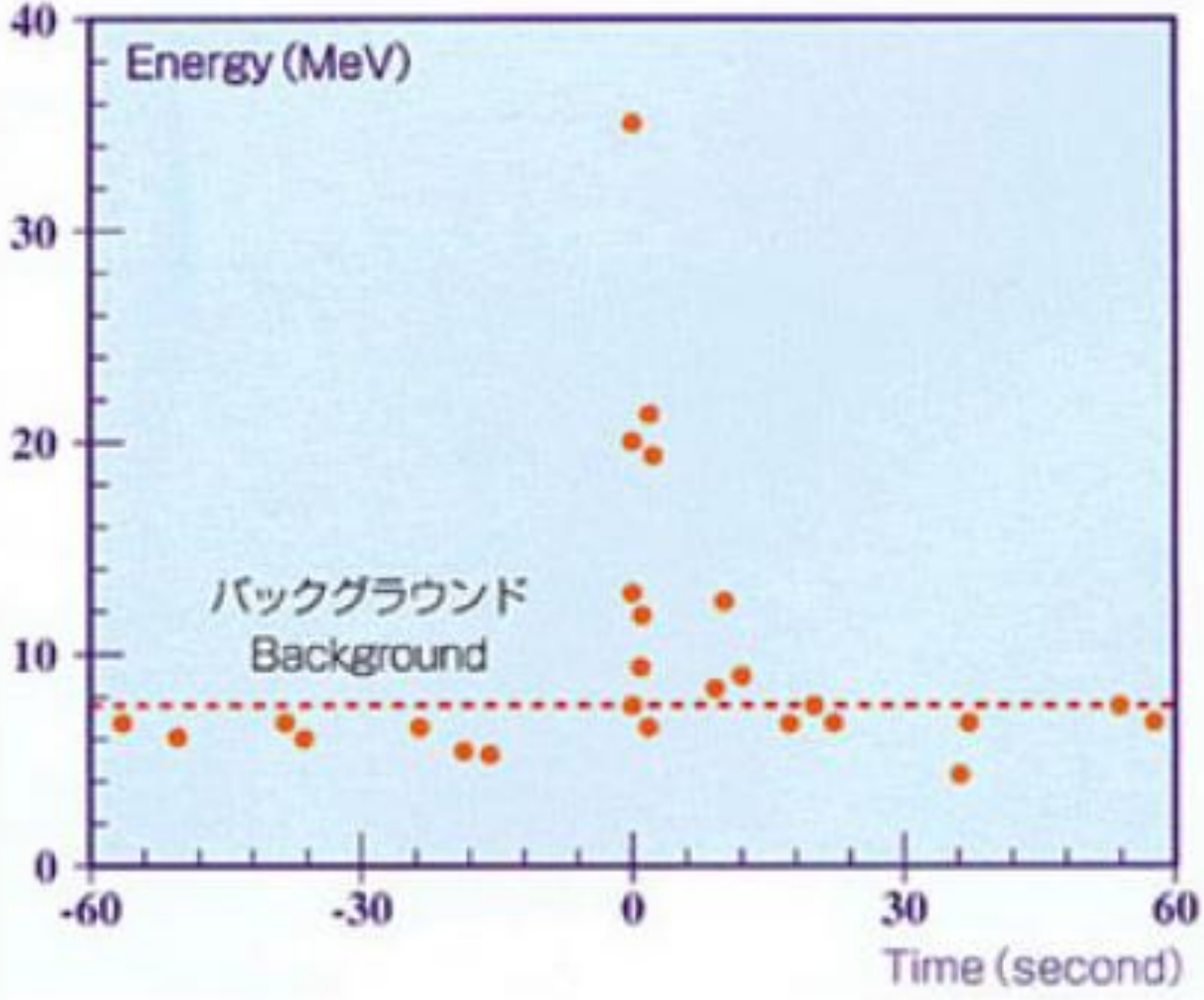
Produced amount of 44Ti:

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

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

c.f. Wongwathanarat et al. (2017).

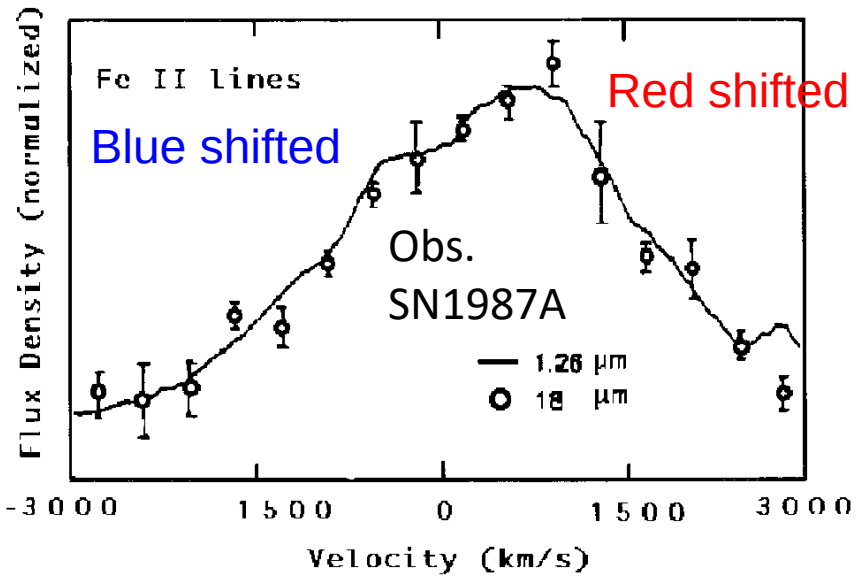
The Missing Neutron Star in 87A

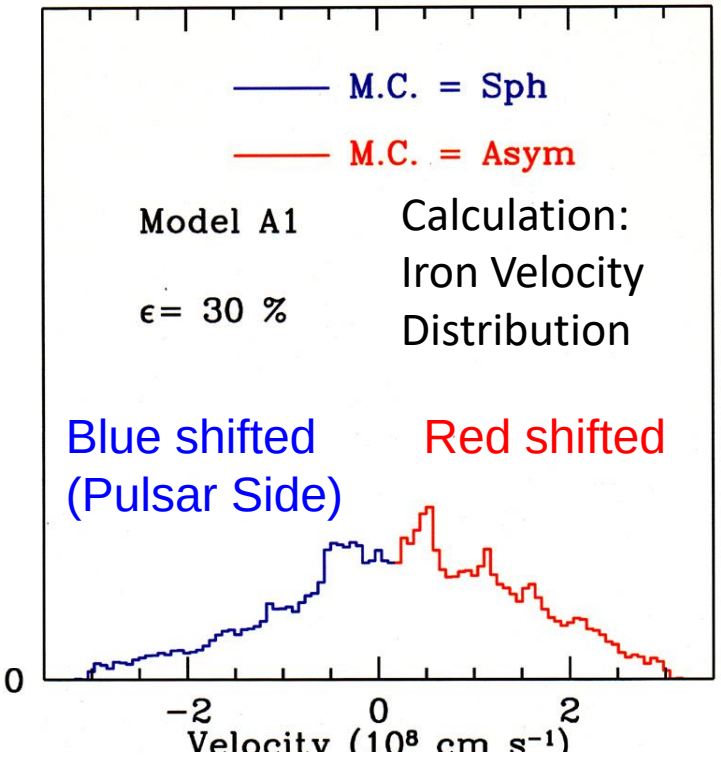


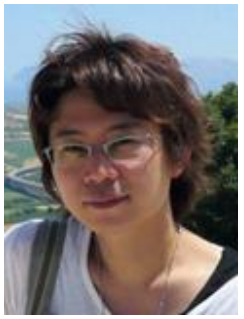
The Neutrino Events For SN1987A at Kamiokande (1987).

However, currently, No counter part was Identified by photons In any wavelength (from radio to gamma-rays).

Very Dim?
Did it Collapse to a Black Hole?





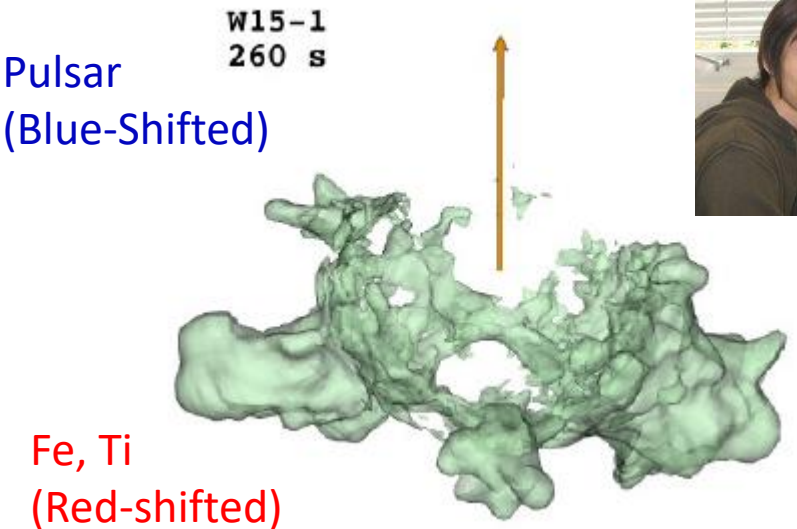


SN 2000

Asymmetry with Respect of Equatorial Plane
Is Suggested for SN1987A.

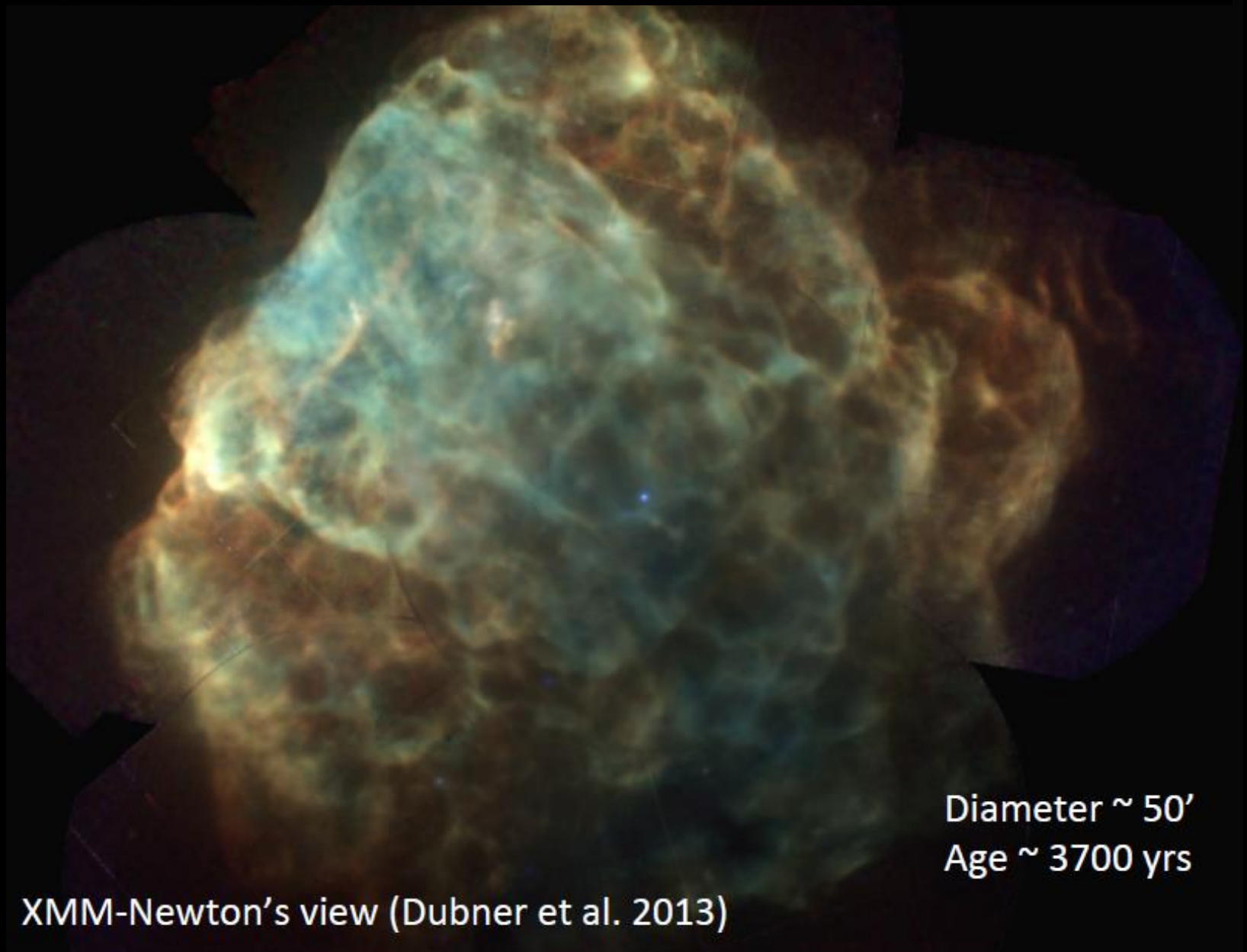
↓

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

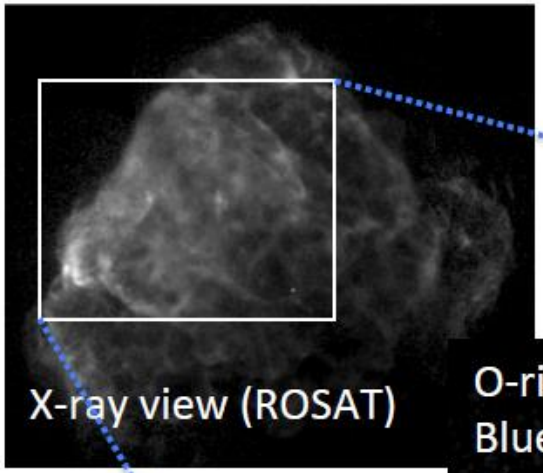


Wongwathanarat+ 2013

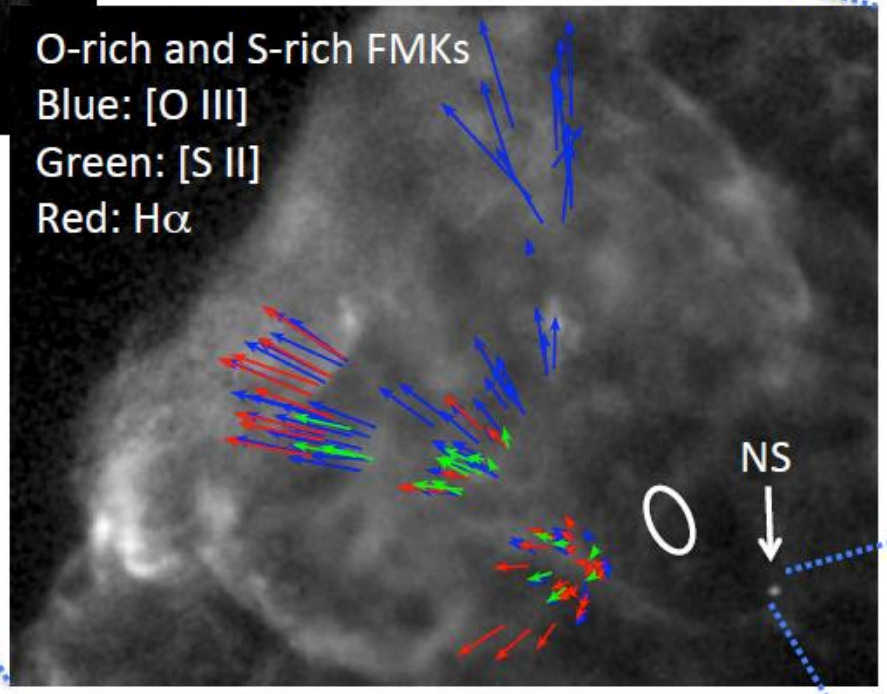
SNR Puppis A: A Globally Asymmetric Explosion



Recoil between Ejecta and NS



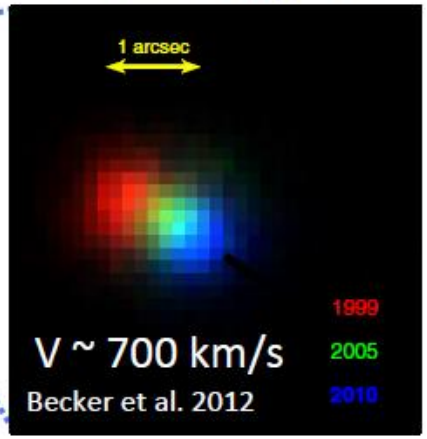
Proper motions of fast-moving ejecta knots



Winkler & Kirshner 1985; Garber et al. 2010

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

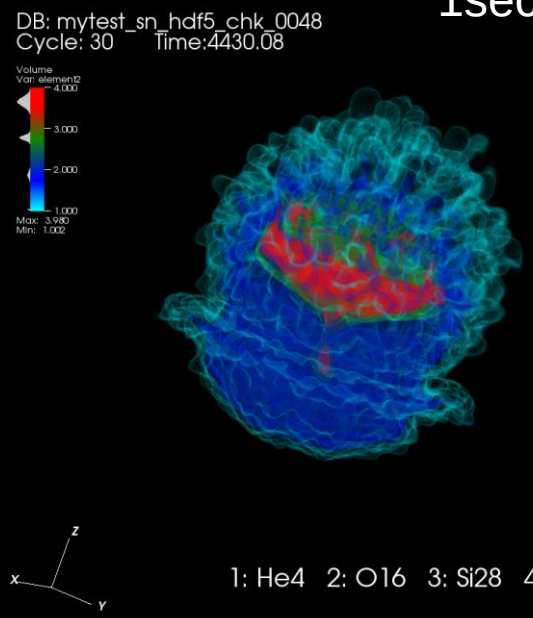
Fast-moving NS



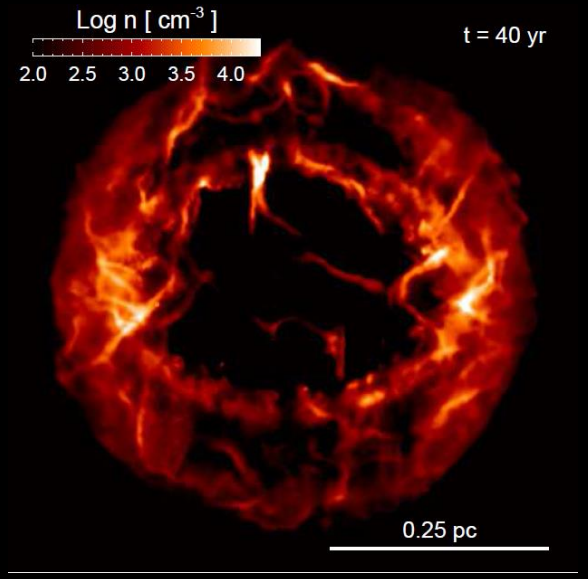
- One-sided O-rich fast-moving knots
- A recoiling (fast-moving) neutron star

SN-SNR Project for SN1987A (2017-)

1sec-1Day



1Day-100yrs

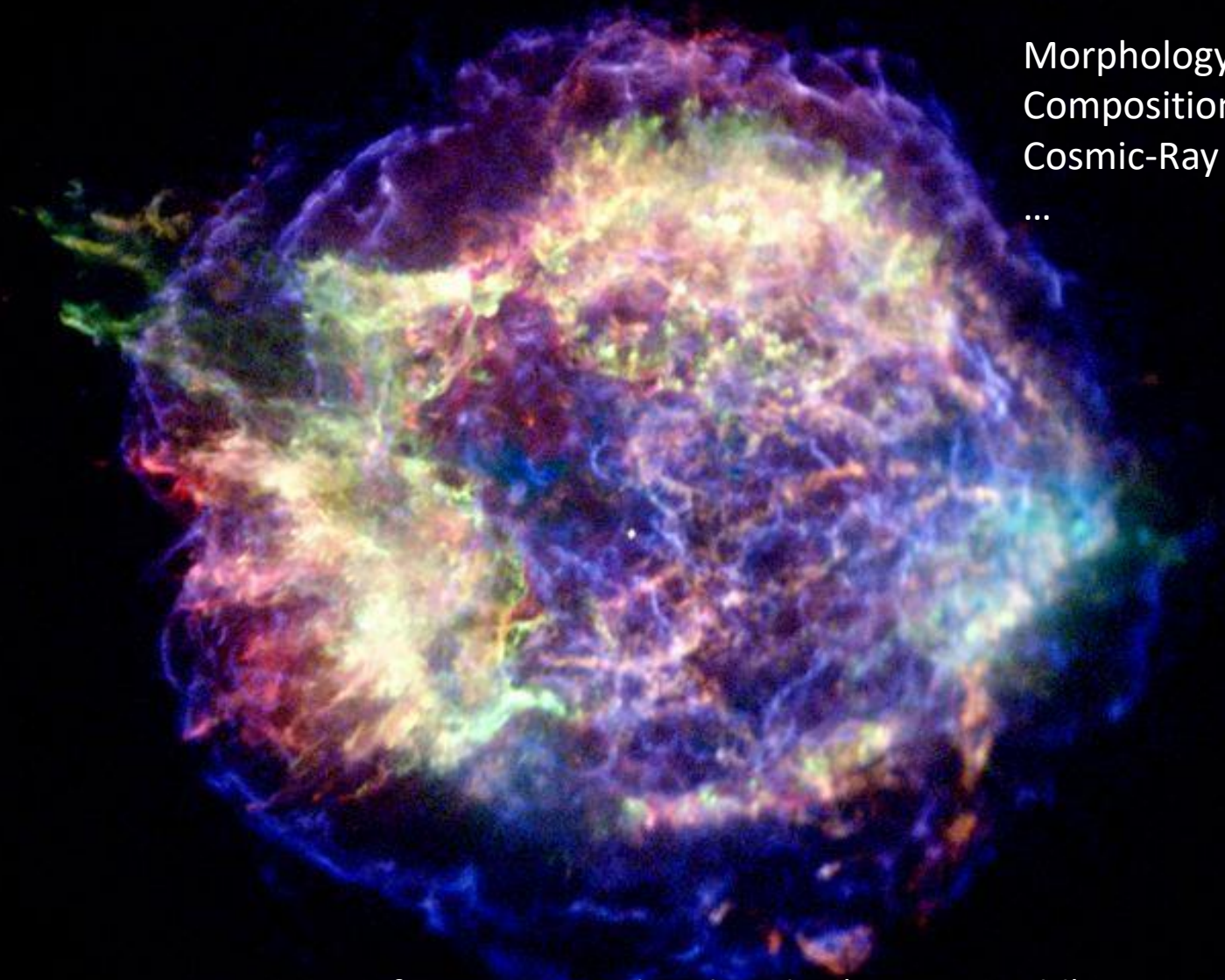


M. Ono (RIKEN)

S. Orlando (Palermo)

§ Supernova Remnants

Lots of Physics in Supernova Remnants



Morphology?
Composition?
Cosmic-Ray Production?
…

X-ray Image of Cassiopeia A by Chandra (～350yrs old).

Numerical Modeling of Broadband Emission of SNRs

S.H.Lee
(JAXA/RIKEN)

S.Nagataki
(RIKEN)

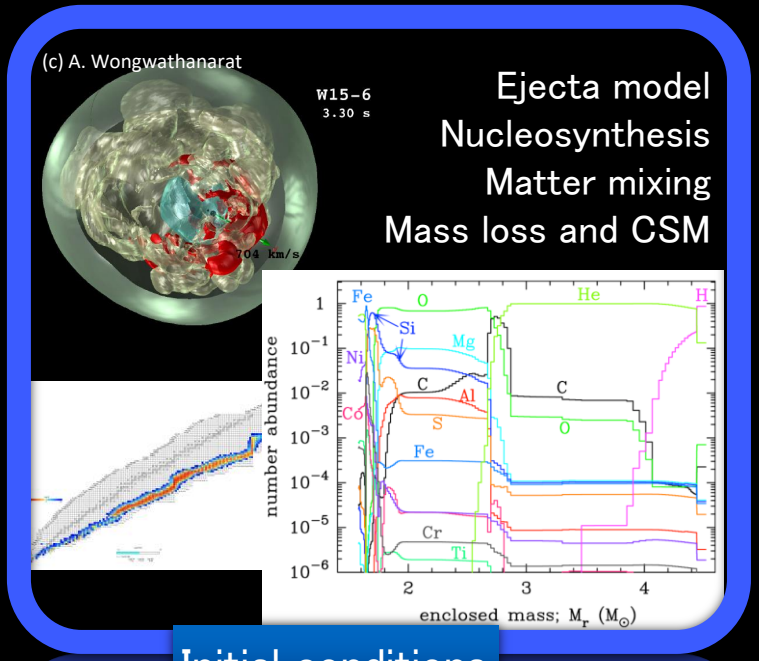
D.Ellison
(NCSU)

D.Patnaude
(CfA/Harvard)

P.Slane
(CfA/Harvard)

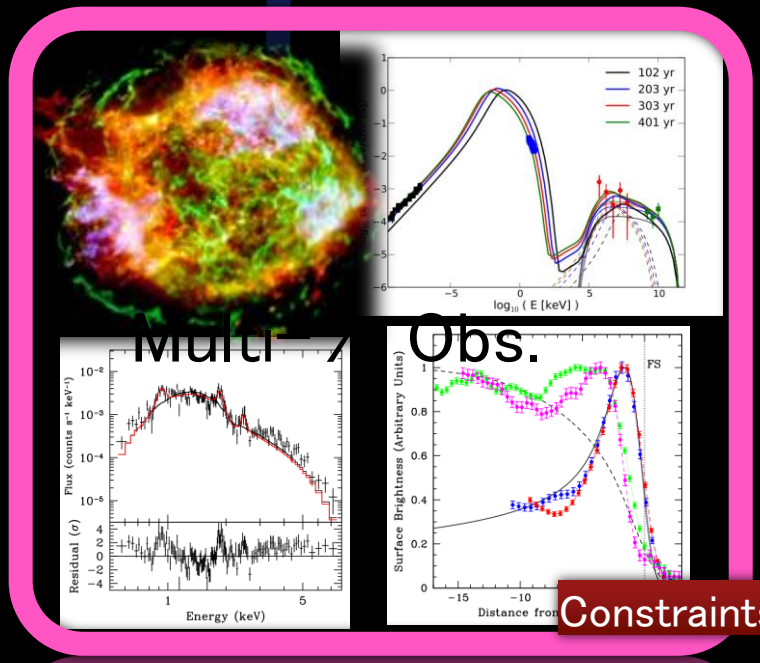
Also, John Raymond, Alex Heger, Carles Badenes, Masaomi Ono,..

Currently, 1-D Iterative Work Flow

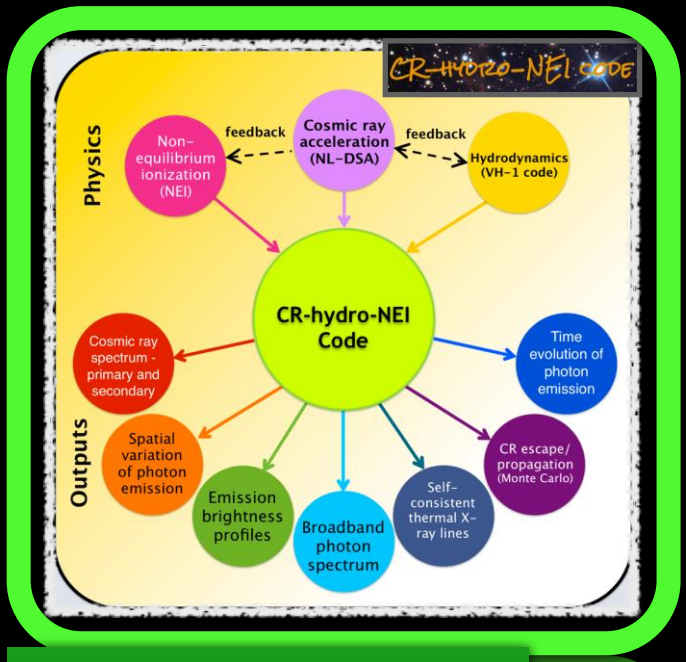


Initial conditions

CR-hydro SNR Model



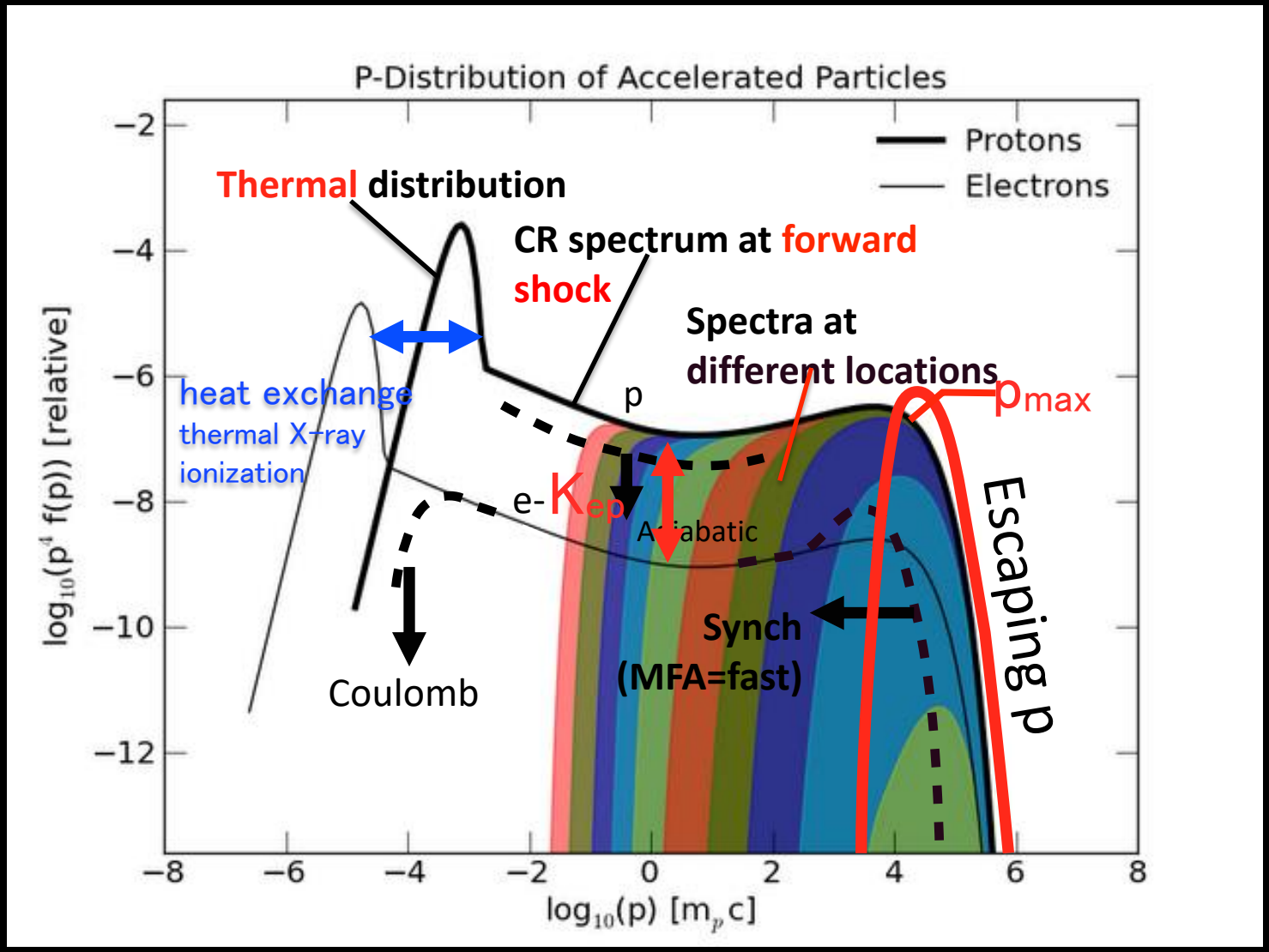
Constraints!



Dynamics, NLDSA,
B-field, ionization, radiation

Non-linear DSA model

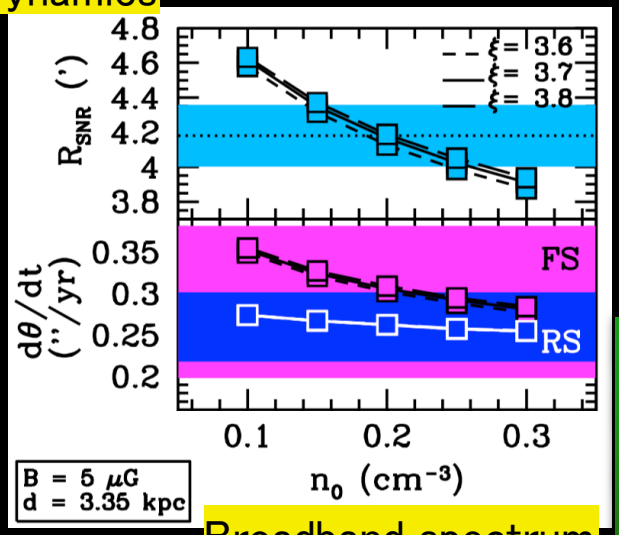
Lee, Ellison & Nagataki (2012)

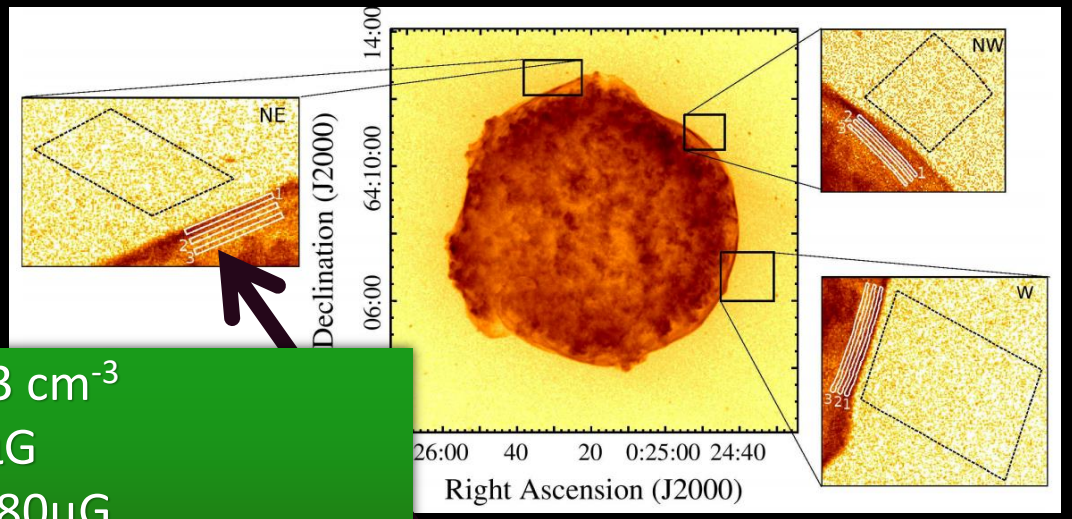


Broadband Model of Young SNRs

e.g. Slane, Lee+ (2014) Tycho's SNR (440 yr old)

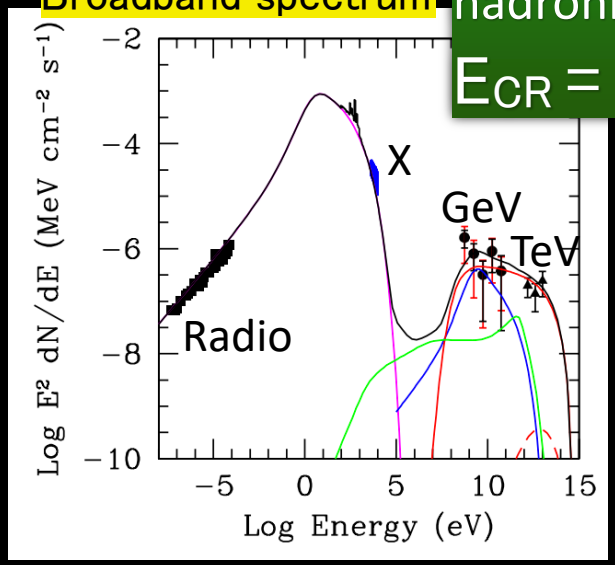
Dynamics



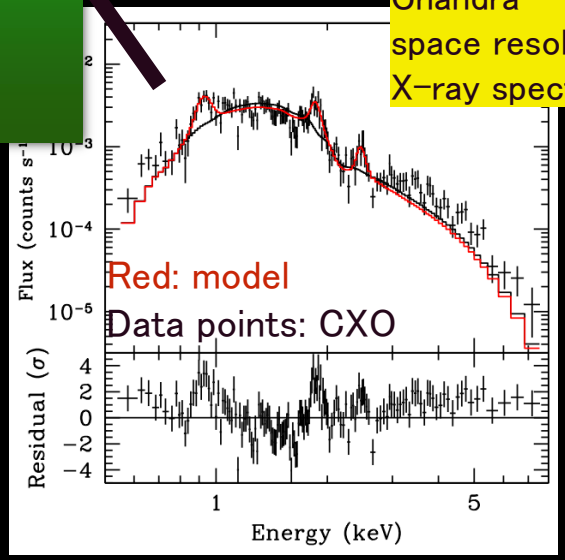


$n_0 = 0.3$ cm^{-3}
$B_0 = 5\mu G$
$B_{DS} = 180\mu G$
hadronic + leptonic!
$E_{CR} = 0.16\ E_{SN}$

Broadband spectrum



Chandra space resolved X-ray spectrum



Thermal X-ray can constrain Gamma-ray origin.

$P+P \rightarrow P+P+\pi^0$ or

$e^- + \gamma \rightarrow e^- + \gamma$

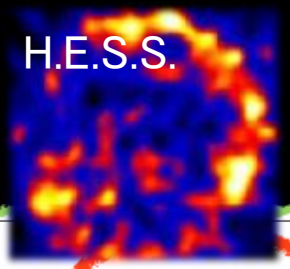
In young SNRs, thermal X-ray emission *coupled* to broadband emission!

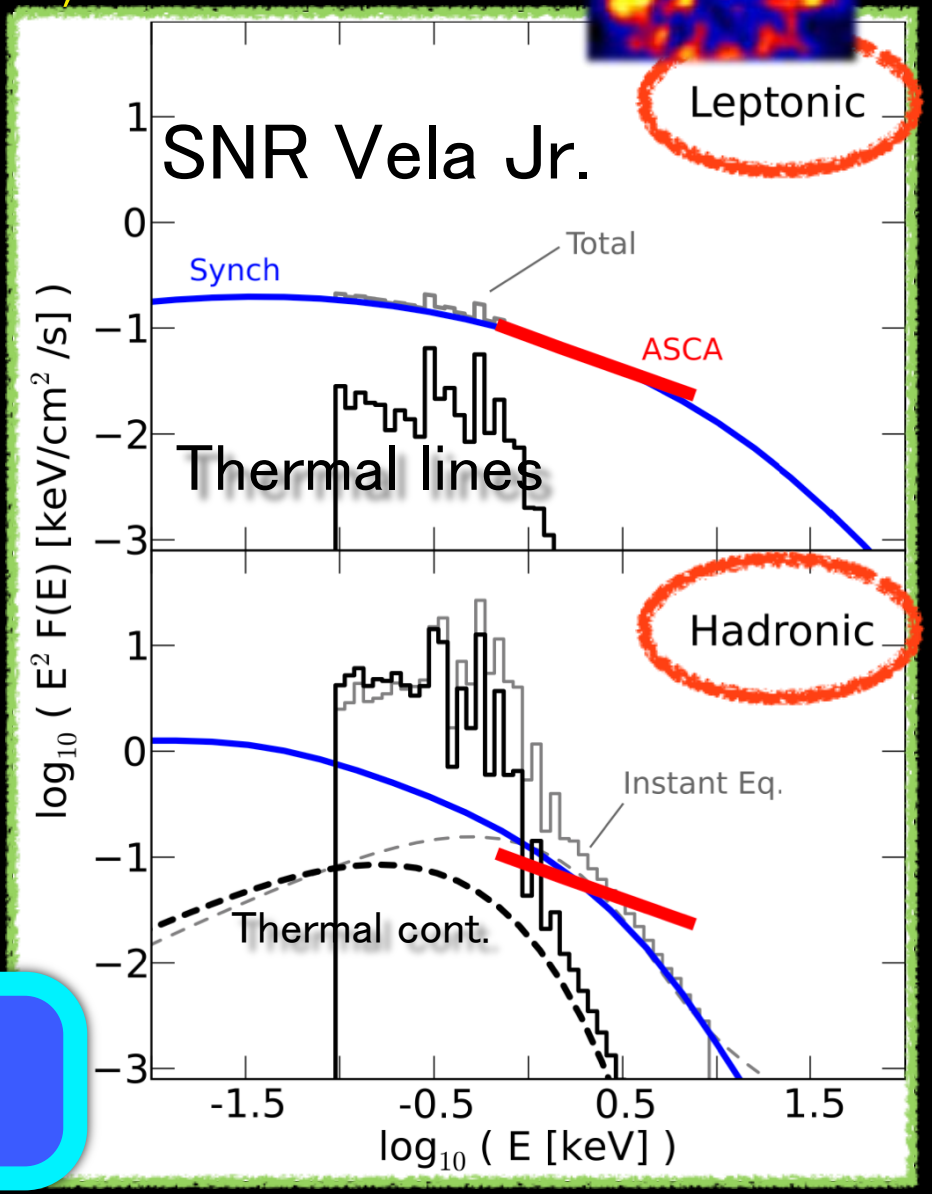
Predicted thermal flux must not exceed observed X-ray flux

Mostly leptonic

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

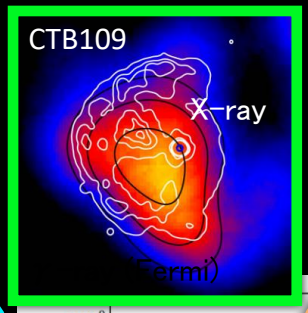
Lee, Slane+ 2013





Powerful constraint of non-thermal origin

Thermal X-rays



e.g. CR-hydro-NEI model of SNR CTB109

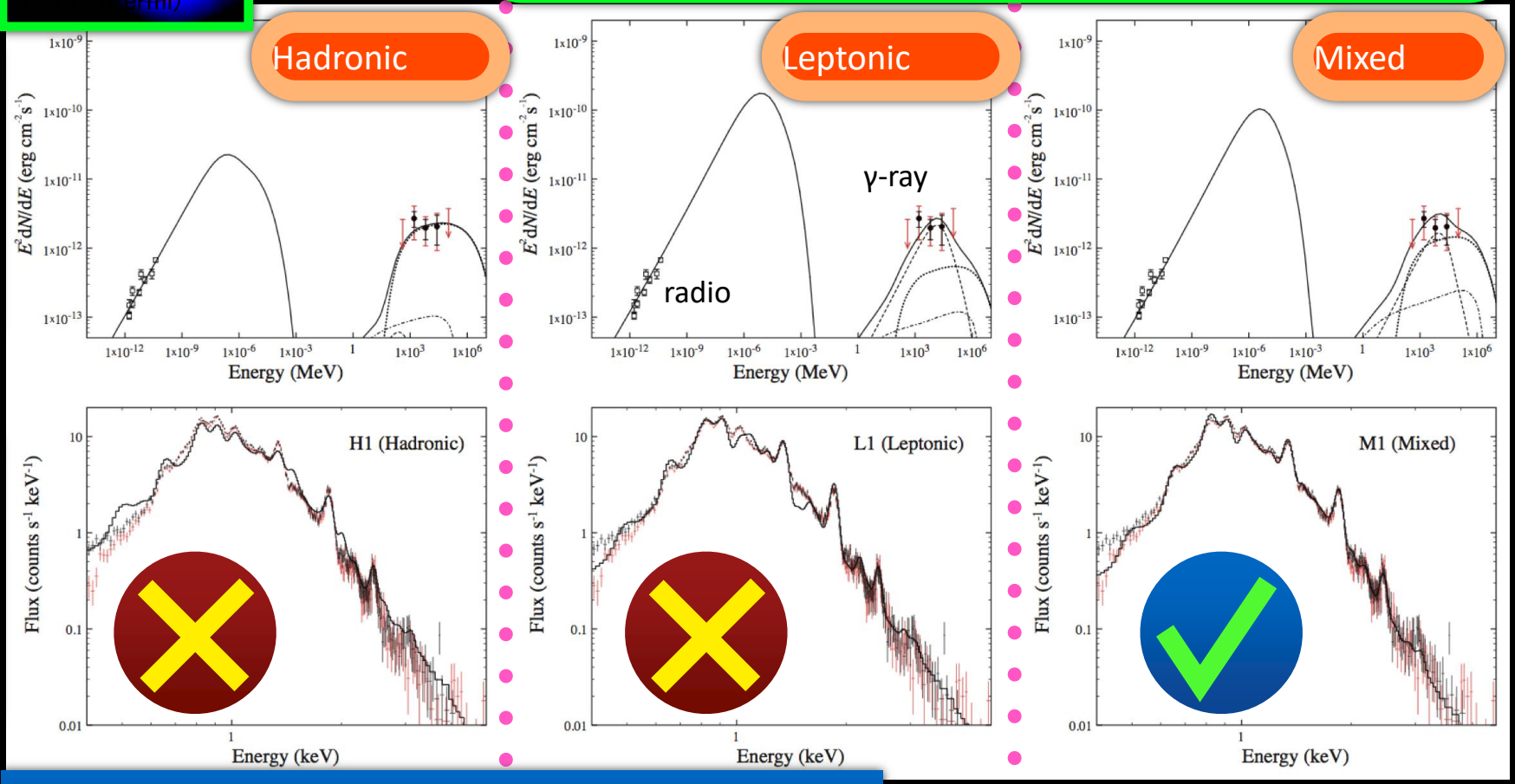
Non-thermal

Thermal X

Hadronic

Leptonic

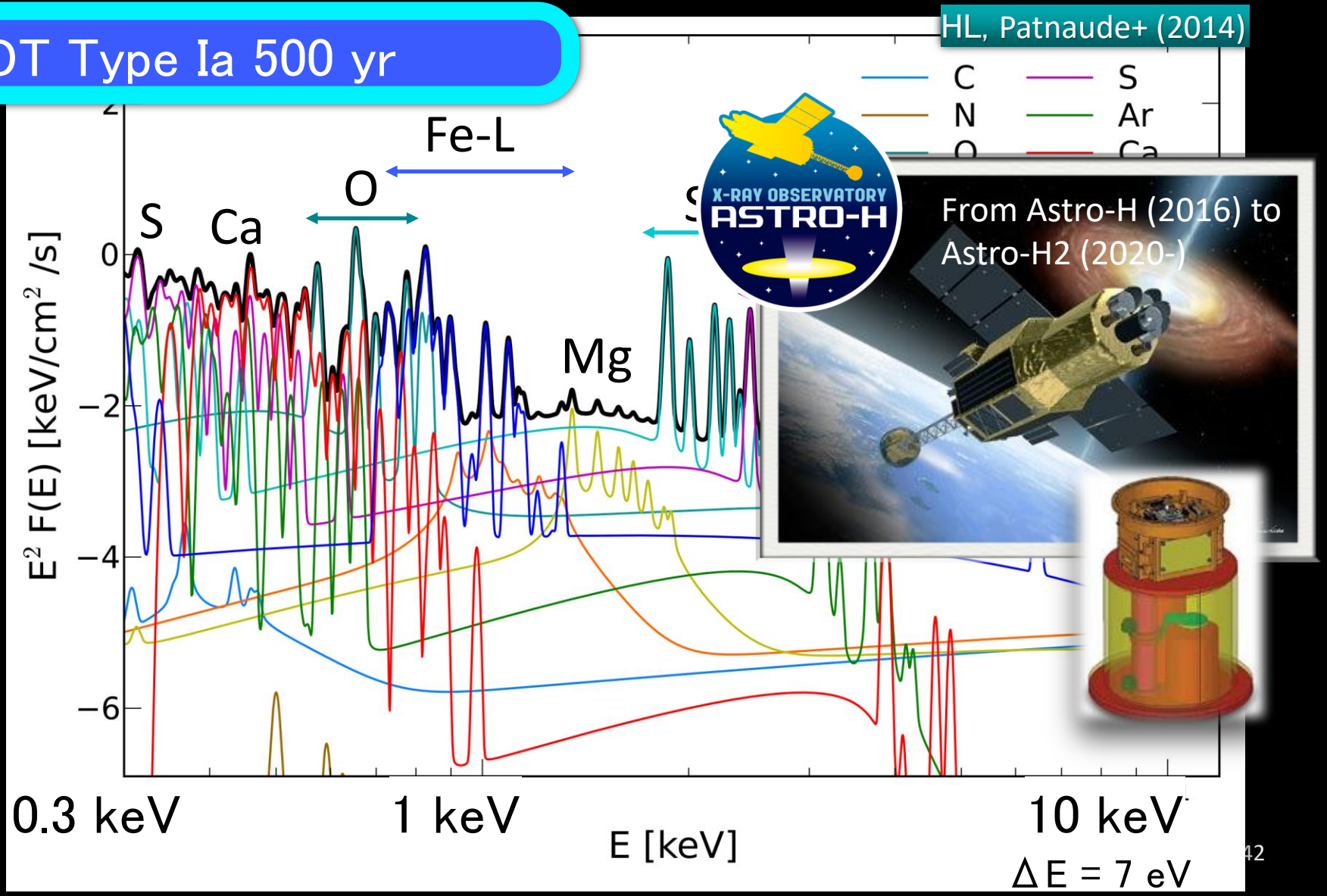
Mixed



Wrong density —> wrong ion fractions & temperature

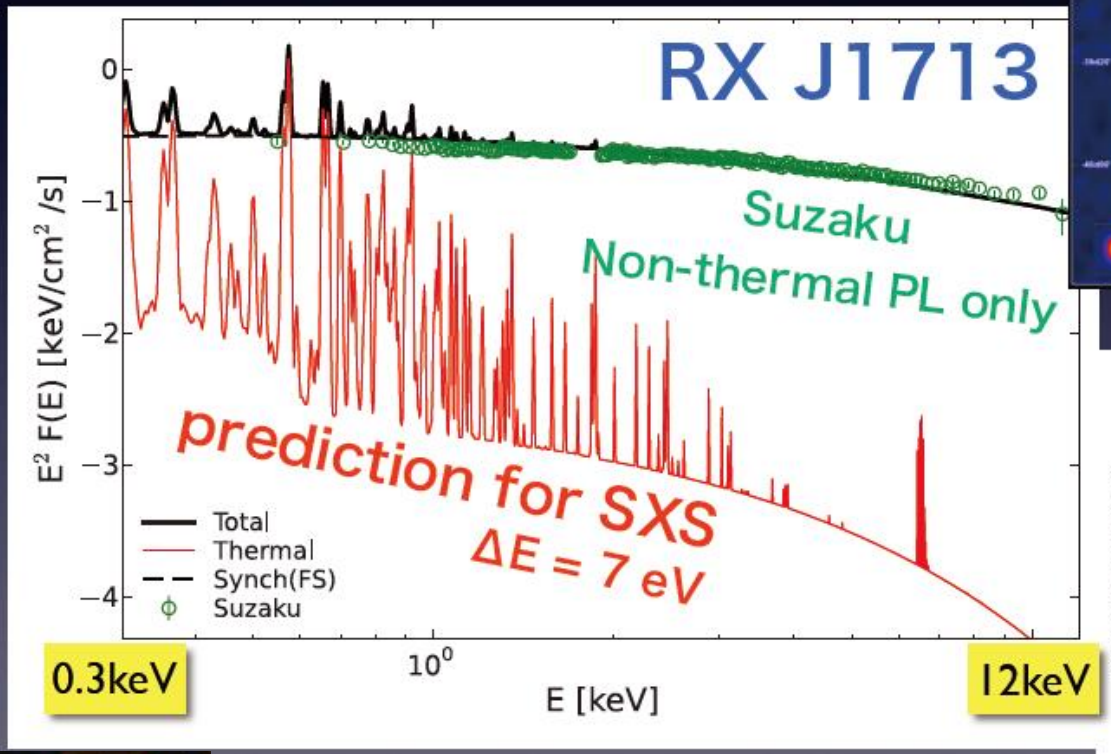
Synthesis of detailed X-ray spectra

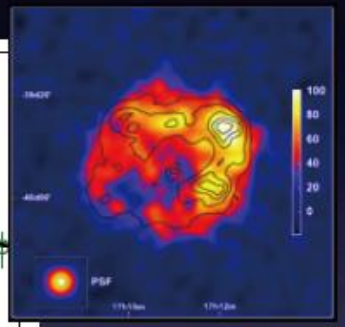
DDT Type Ia 500 yr

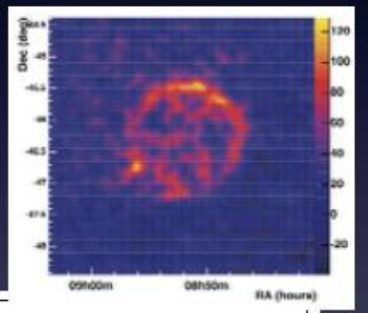


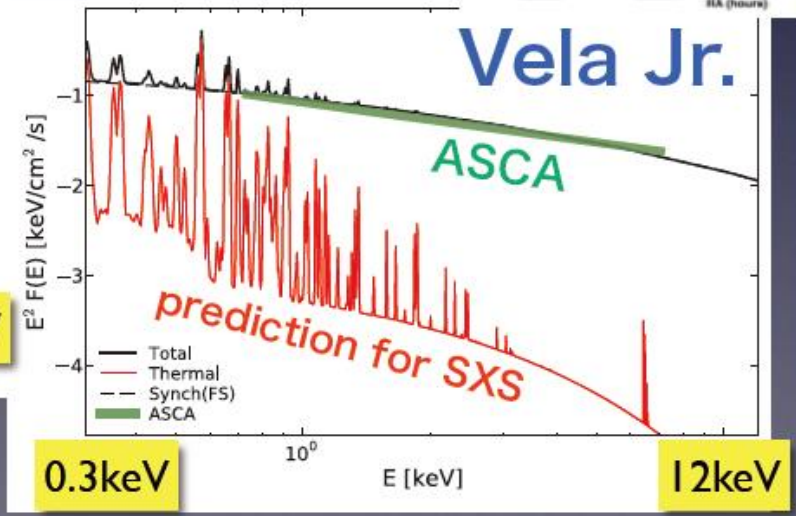
Future X-ray spectroscopy by Astro-H

Our broadband models make robust predictions for Astro-H







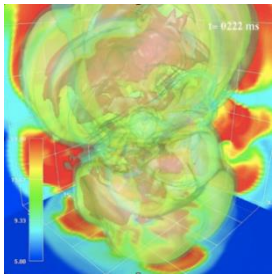


S.H. Lee (Kyoto/RIKEN)

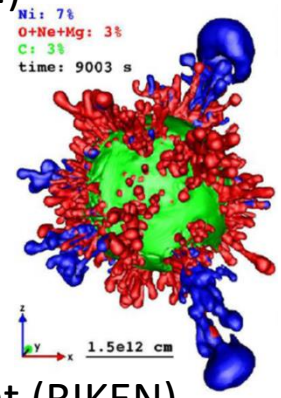
e.g. HL+ 2013

Our Big Mission

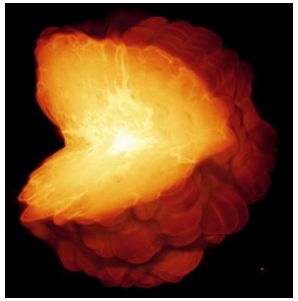
From (Takiwaki, Wongwathanarat, Roepke) To (Lee, Ono, Ferrand)



Takiwaki (RIKEN)



Wongwathanarat (RIKEN)



Reopke (Wurzburg U.)

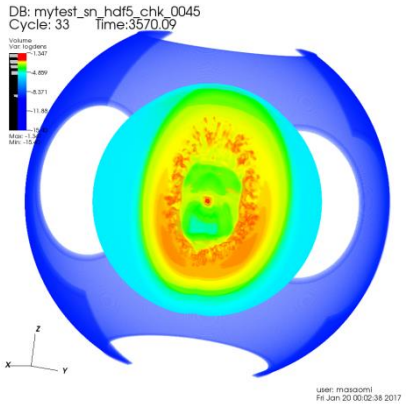
How do they Evolve?

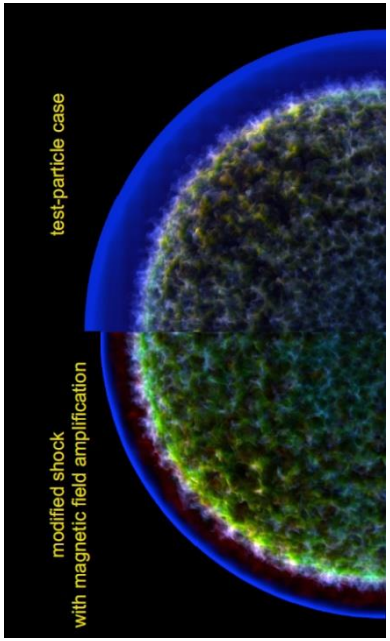
Origin of Asymmetry?

Can We find Legacies of SNe in SNRs?

Nobody Knows!

Ono+17, in prep.





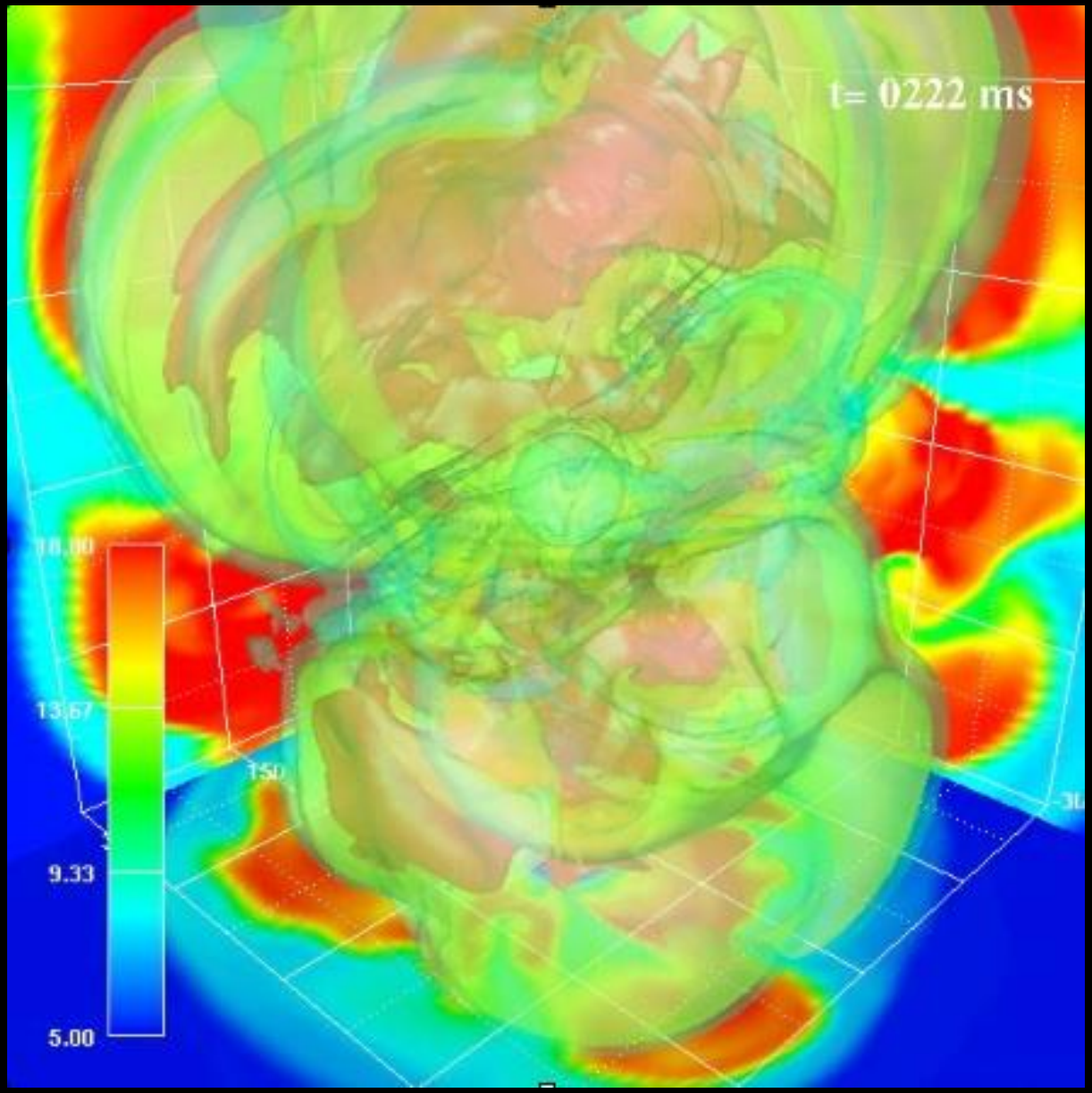
S.H. Lee (Kyto/RIKEN)

M.Ono (RIKEN)

G. Ferrand (RIKEN)

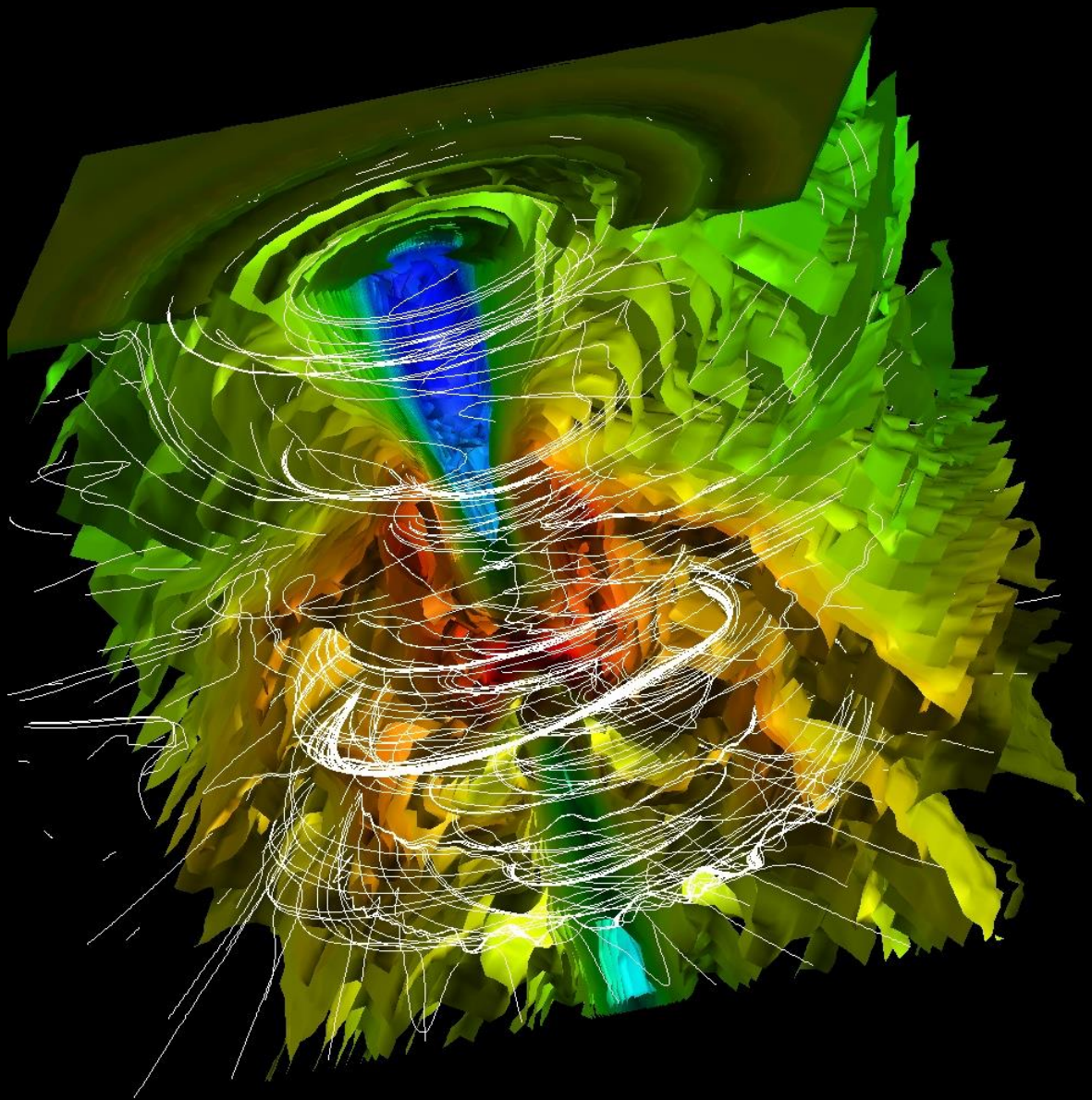
§ Summary of Our Missions

Massive Stars Explode. Why?



Simulation by
T. Takiwaki
(NAOJ/RIKEN)

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

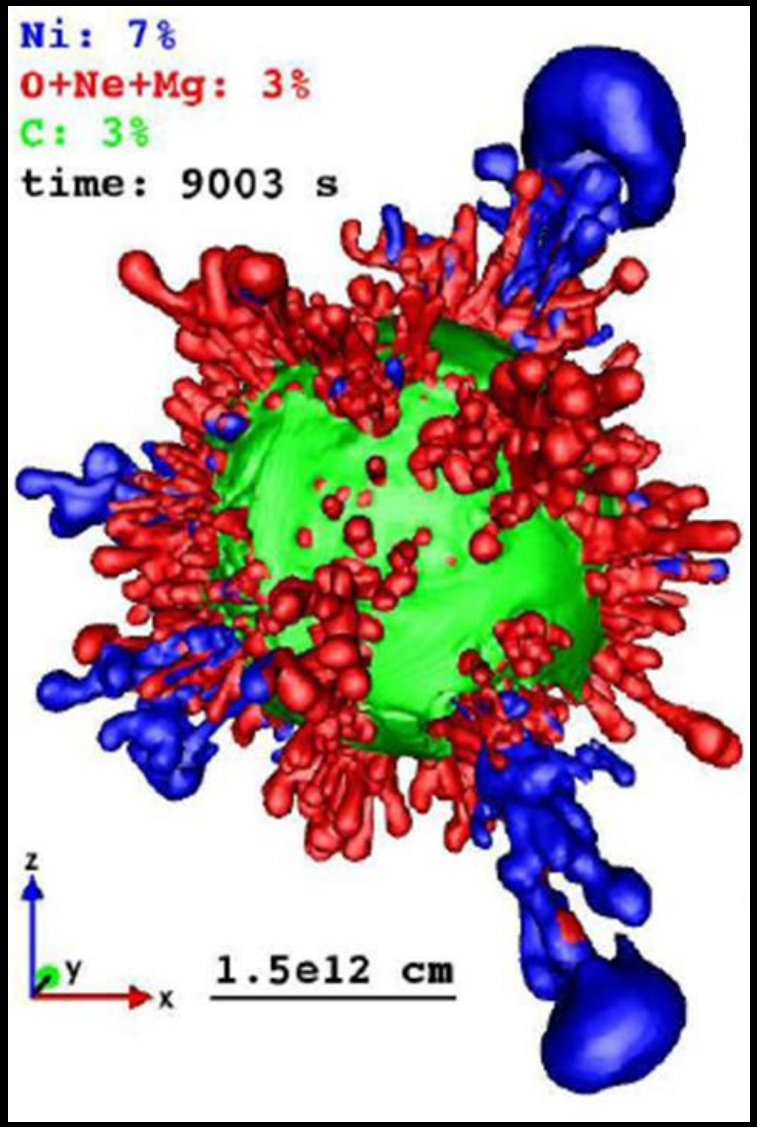


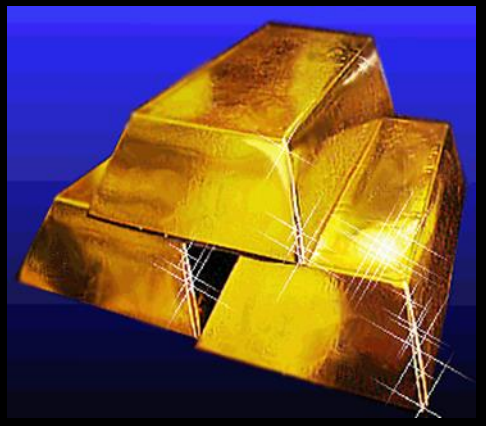
S. Nagataki
(RIKEN)

M. Barkov
(Purdue/RIKEN)

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

Simulation by
A. Wongwathanarat
(MPA → RIKEN)

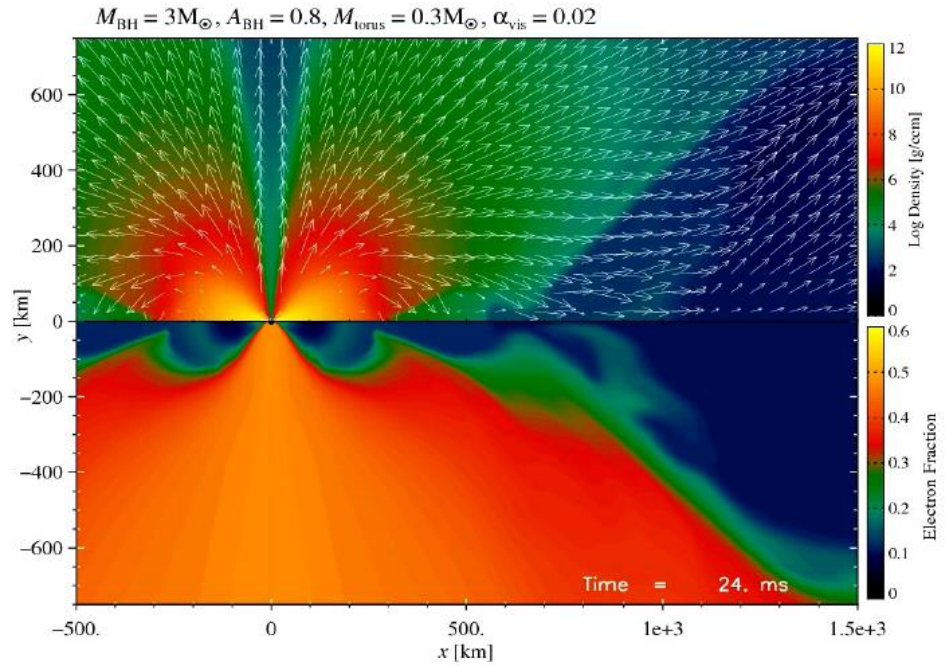


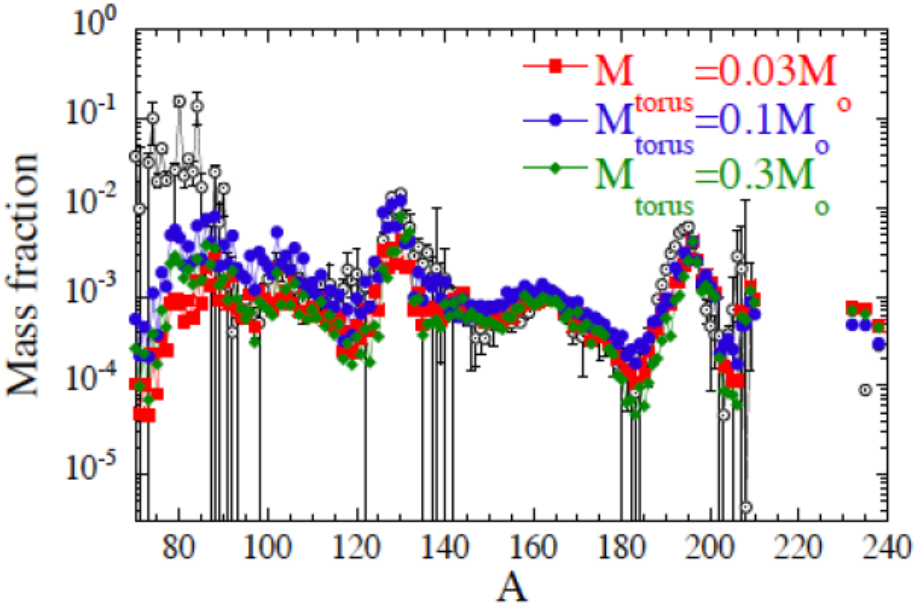


Origin of Gold?

Origin of Uran?

NS-NS Mergers & NS-BH Mergers & SGRB





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

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

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

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

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

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

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

Oliver Just
(MPA→RIKEN)

Simulations for Short GRBs are going on!

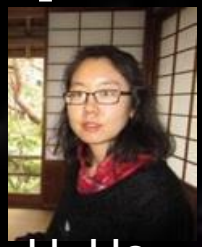
Why are SNe/GRBs so Bright?

A. Tolstov (RIKEN→IPMU)

H. Ito (RIKEN)

J. Matsumoto (RIKEN)

Are Gamma-Ray Bursts the Greatest Particle Accelerators ?



H. He
(RIKEN)

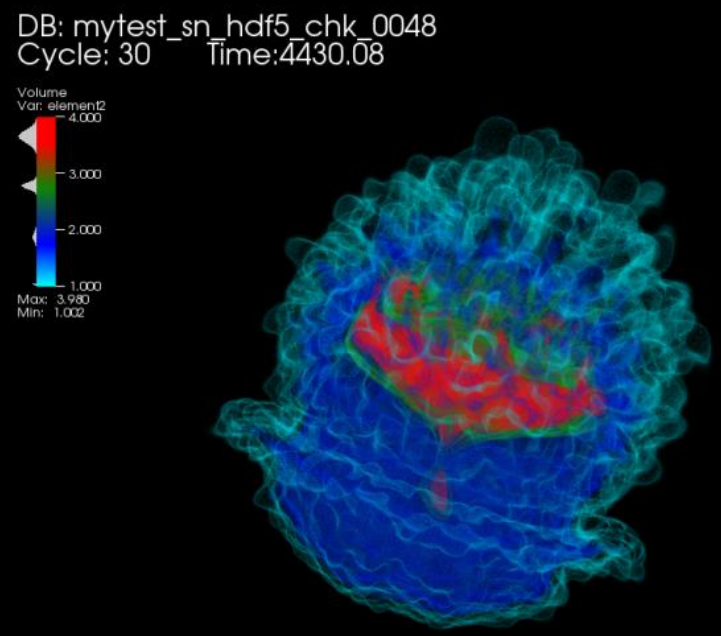
D. Warren
(RIKEN)

S. Inoue
(RIKEN)

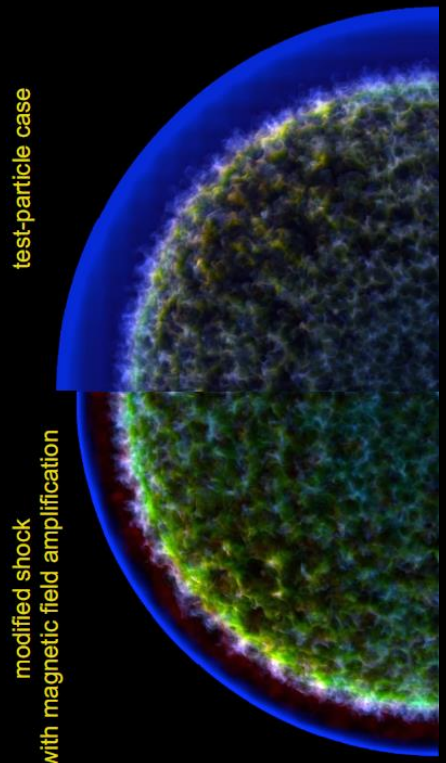
Extra-Galactic
UHECRs?
Neutrinos?
TeV Gamma-rays?

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

Lots of Mysteries & Physics in Supernova Remnants



SN Simulation
by M. Ono



SNR Simulation
by G. Ferrand

S.H. Lee
(Kyoto/RIKEN)

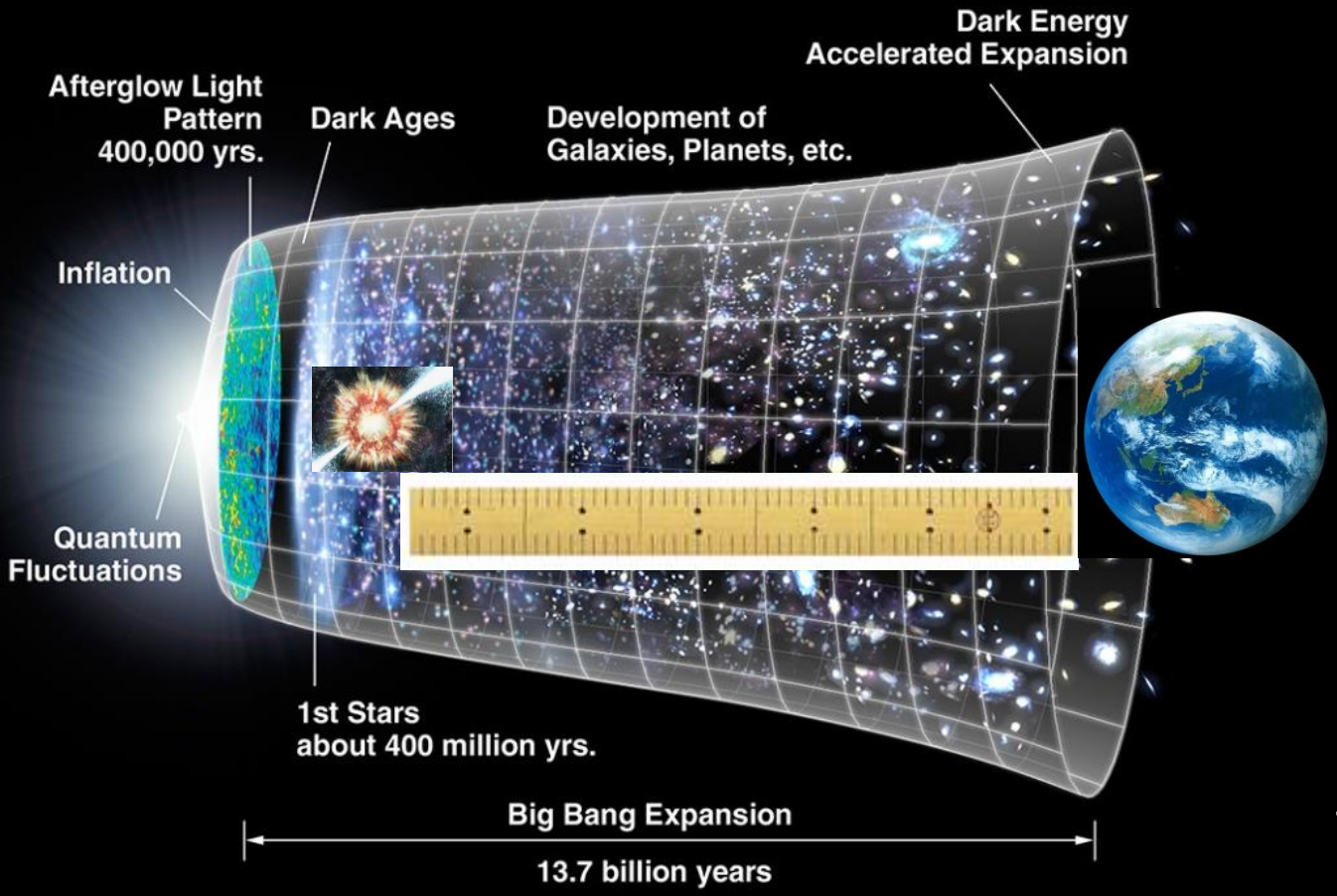
M.Ono
(Kyushu→RIKEN)

G. Ferrand
(U. Manitoba→RIKEN)

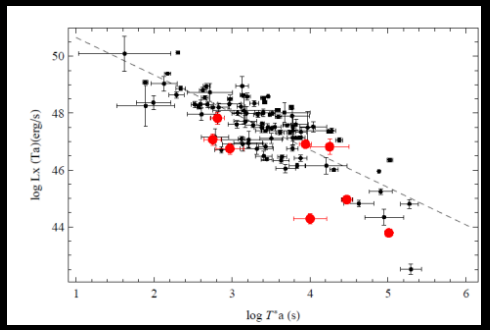
Cosmic-Ray Production? Morphology? Composition?

Can Gamma-Ray Bursts be the Longest Cosmic Rulers?

From WMAP HP. Modified.



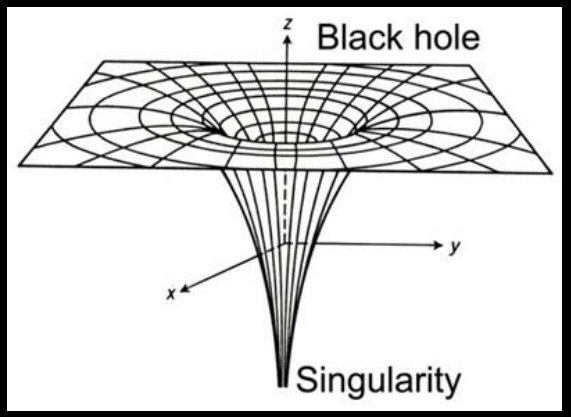
M. Dainotti
(RIKEN→Stanford)



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?

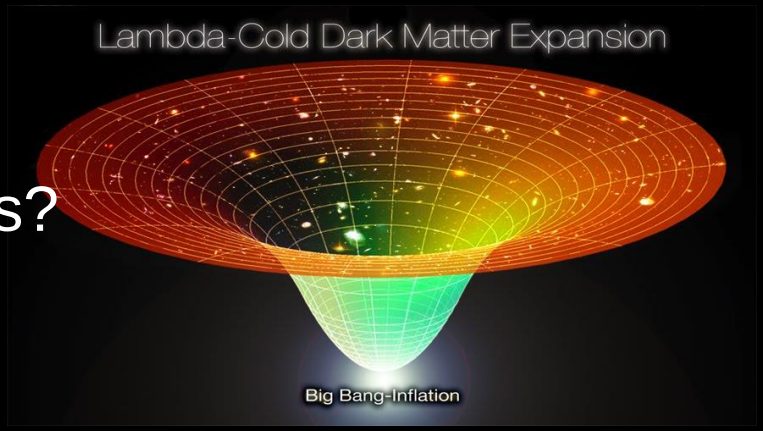


Figure from Universetoday

Engine of GRBs.
BH is formed?

S. Nagataki
(RIKEN)

M. Barkov
(Purdue/RIKEN)

Y. Yokokura
(iTHES)

A. Tanaka
(iTHES)

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, Levinson (Tel Aviv), Kumar (Texas)
- Afterglow(X-ray,Opt,Radio): Warren, Ellison (NCSU), MacFadyen(NYU).
- Remnants: Lee, Ferrand, Ono, Slane (CfA), Patnaude (CfA), Orlando (Palermo)
- UHECRs, VHE-neutrinos/gamma-rays: He, Inoue, Kusenko (UCLA)
- GRB Cosmology: Dainotti
- The Universe itself: Tanaka, Yokokura, Hongo

… and More!

Thank You Very Much.