Death of Massive Stars: Supernovae and Gamma-Ray Bursts with Explosive Nucleosynthesis

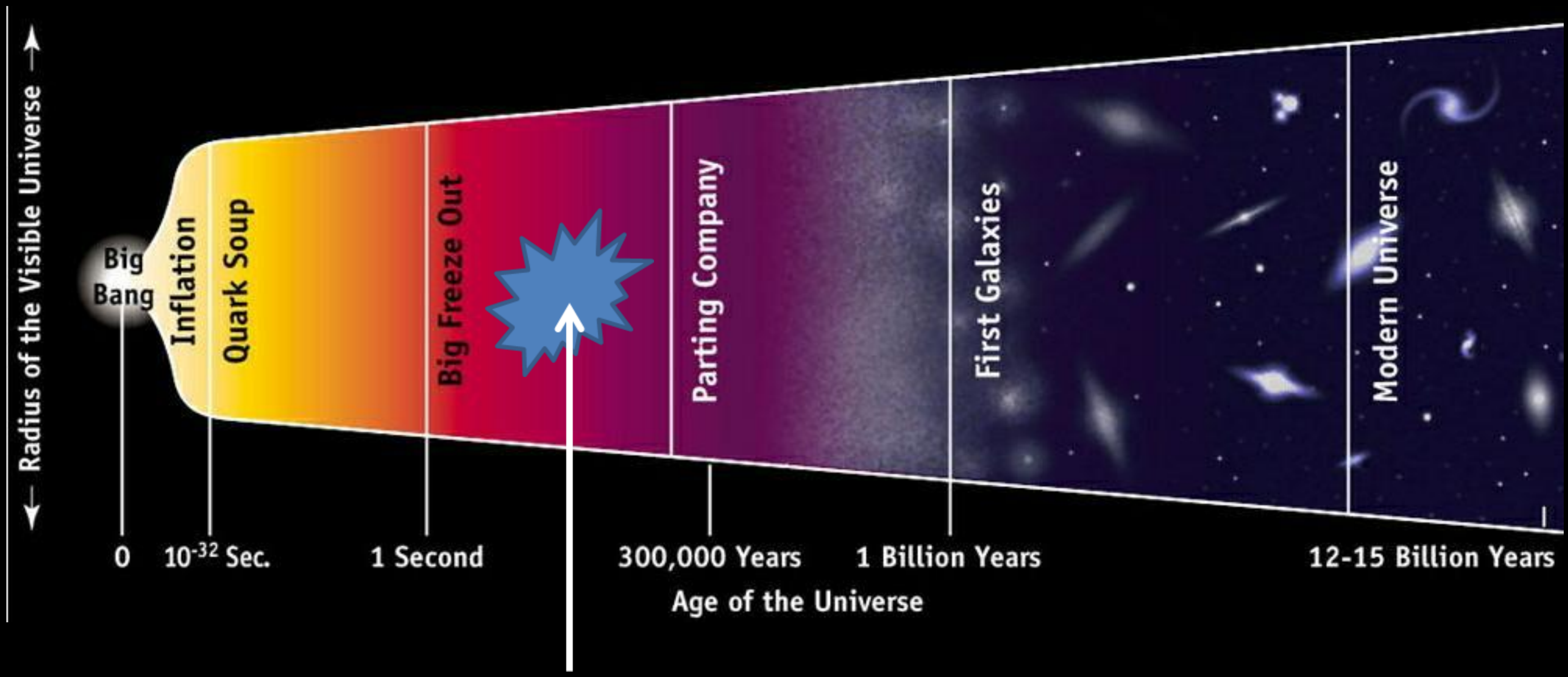
Astrophysical Big Bang Laboratory

Shigehiro Nagataki

13-17 June 2016, NIC School. Presentation Dates: 13 & 14 June 2016.

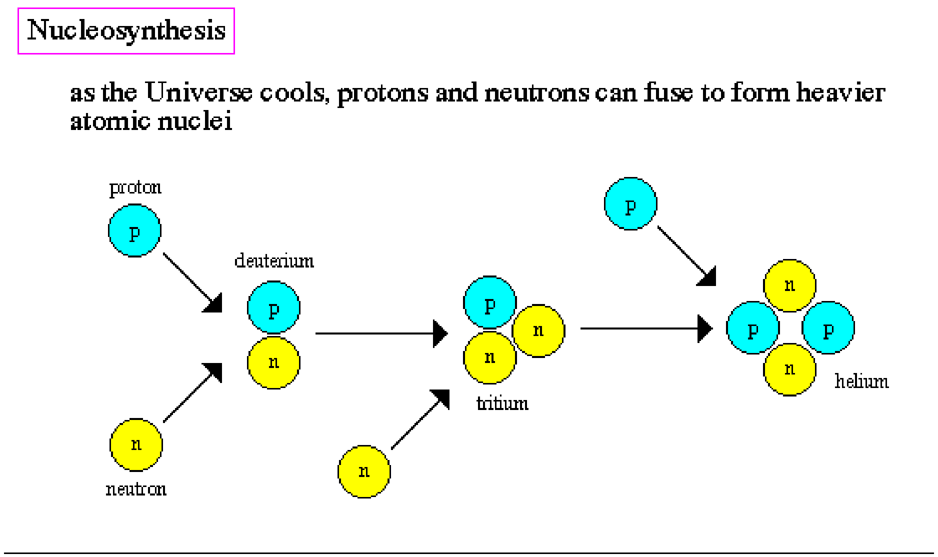
From NASA HP

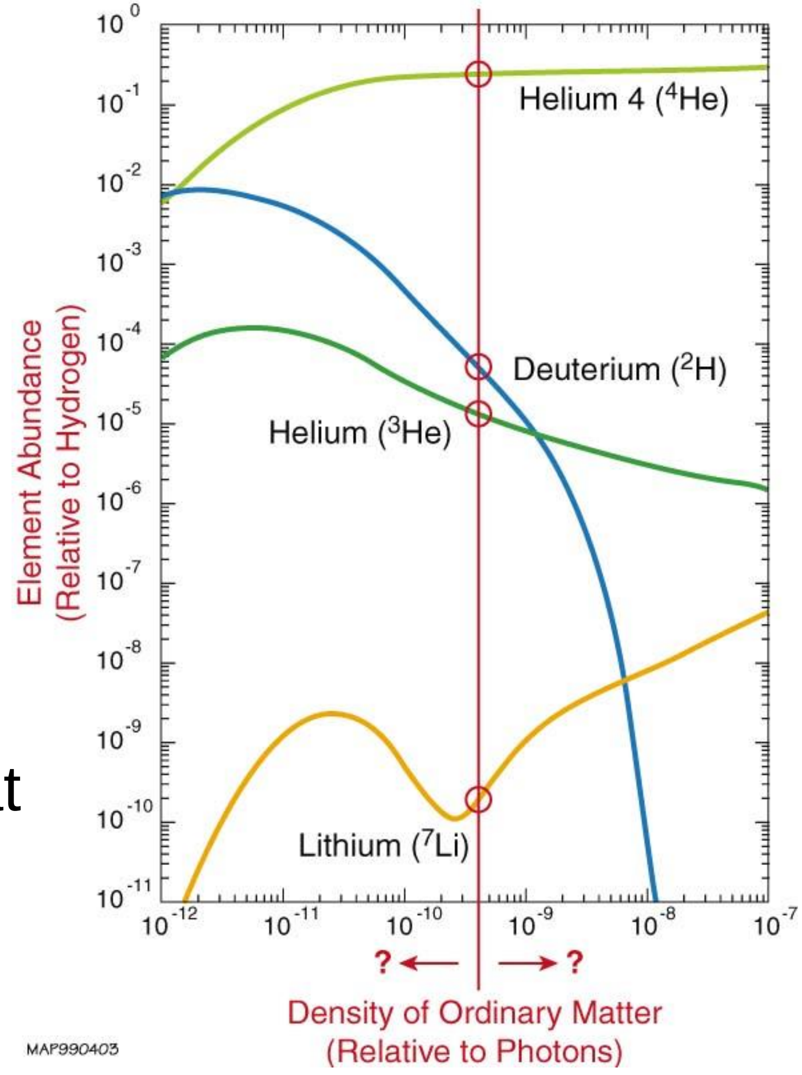
Big-Bang Nucleosynthesis



Big-Bang Nucleosynthesis
Age of the Universe is 3-20 minutes.

Big Bang Nucleosynthesis (2)



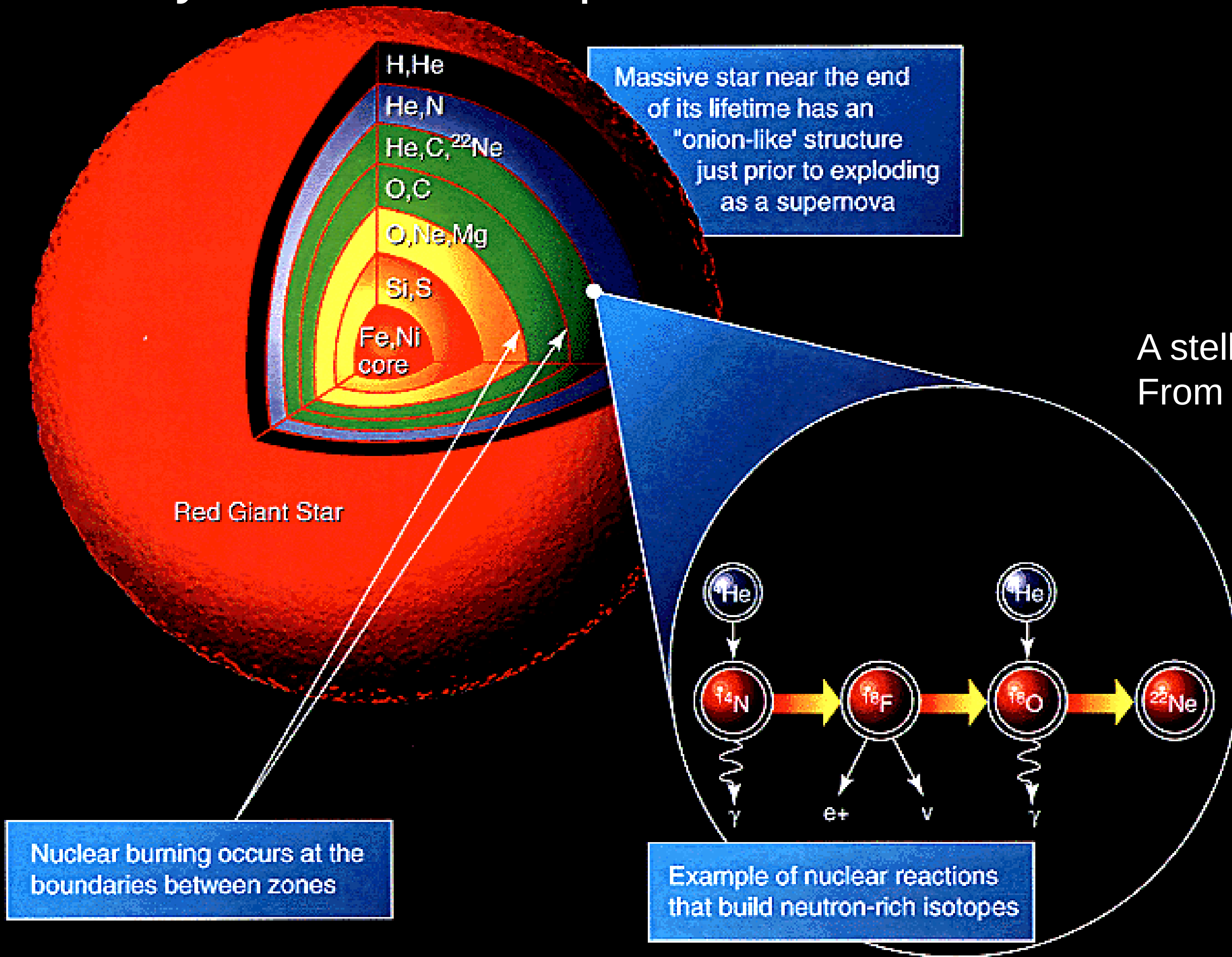


Only light elements are produced at Big Bang Nucleosynthesis.

Where are Heavy Elements?

Heavy Elements are in Massive Stars.

Self-Gravity is Supported by Nuclear Burning → Heavy Elements are produced In Massive Stars.



A stellar Structure.
From NASA HP

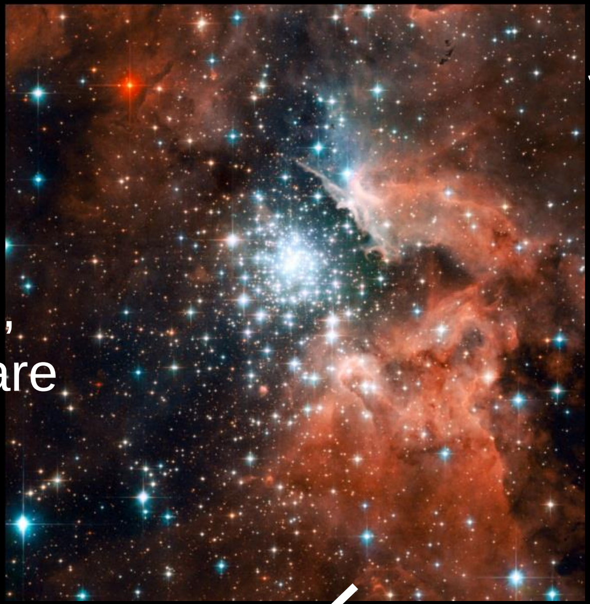
How are the Heavy Elements Ejected?

Supernova Explosions

From NASA HP

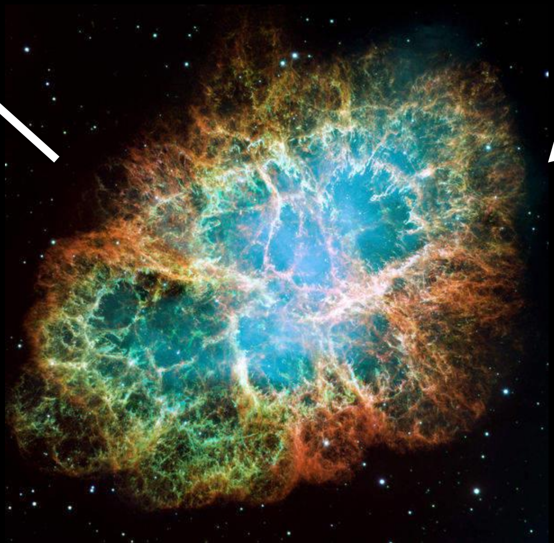
Cycles of Gas-Stars in the Universe

Gas

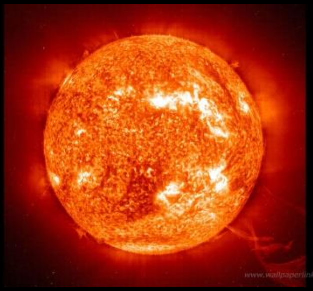


Stars

Through the cycle, Heavy Elements are Increasing in the Universe



Supernova Explosions



No Supernova, No Life.

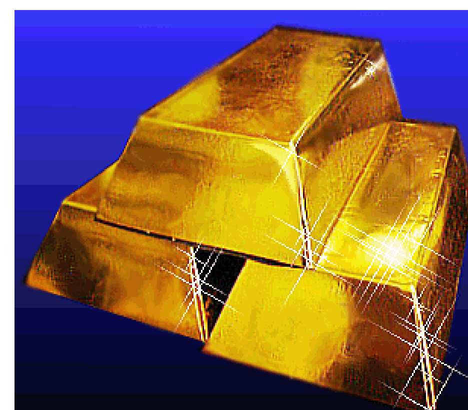
Carbon

Magnesium

Iron

Cupper

Silver

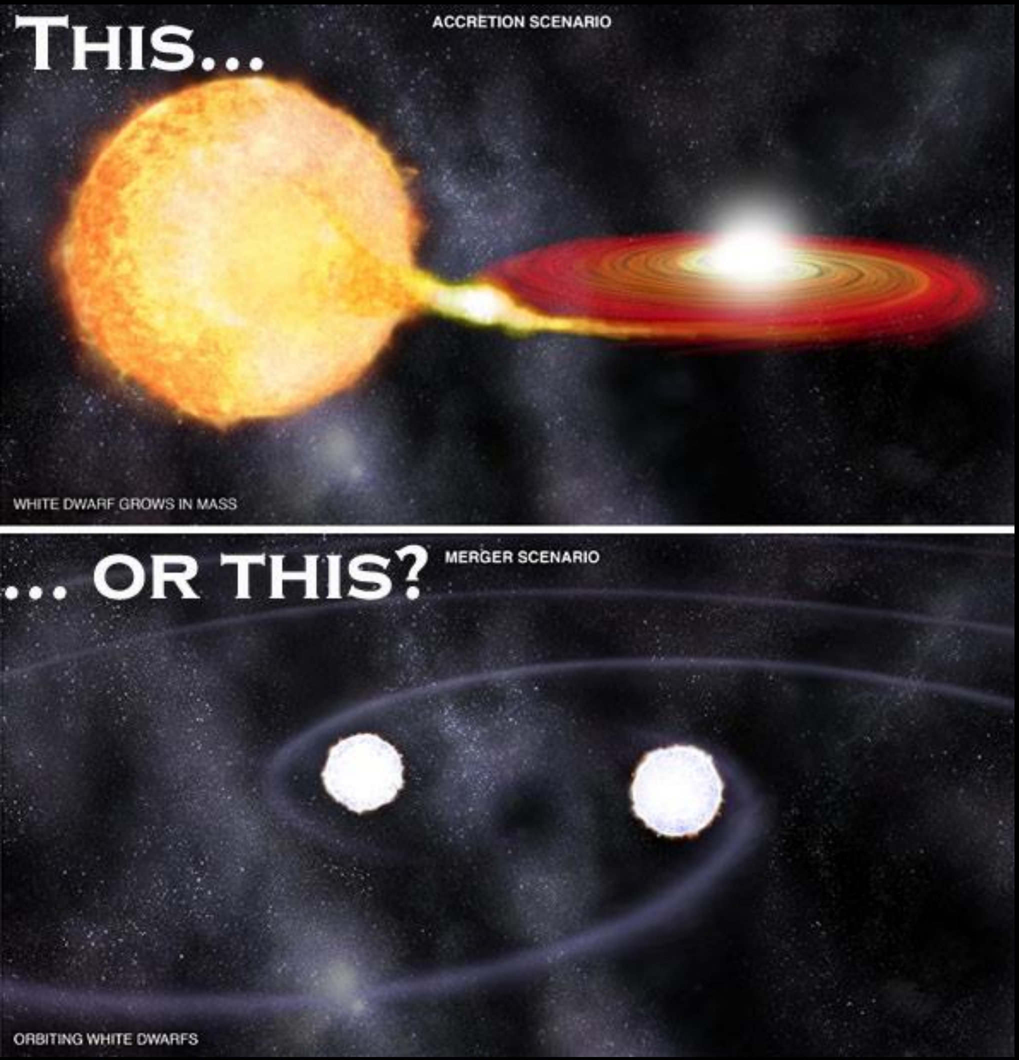


Gold

Composition of the Earth

Fe	：３４．６３％	Na	：０．５７％
O	：２９．５３％	Cr	：０．２６％
Si	：１５．２６％	Mn	：０．２２％
Mg	：１２．７０％	Co	：０．１３％
Ni	：２．３９％	P	：０．１０％
S	：１．９３％	K	：０．０７％
Ca	：１．１３％	Ti	：０．０５％
Al	：１．０９％		

Type Ia Supernovae

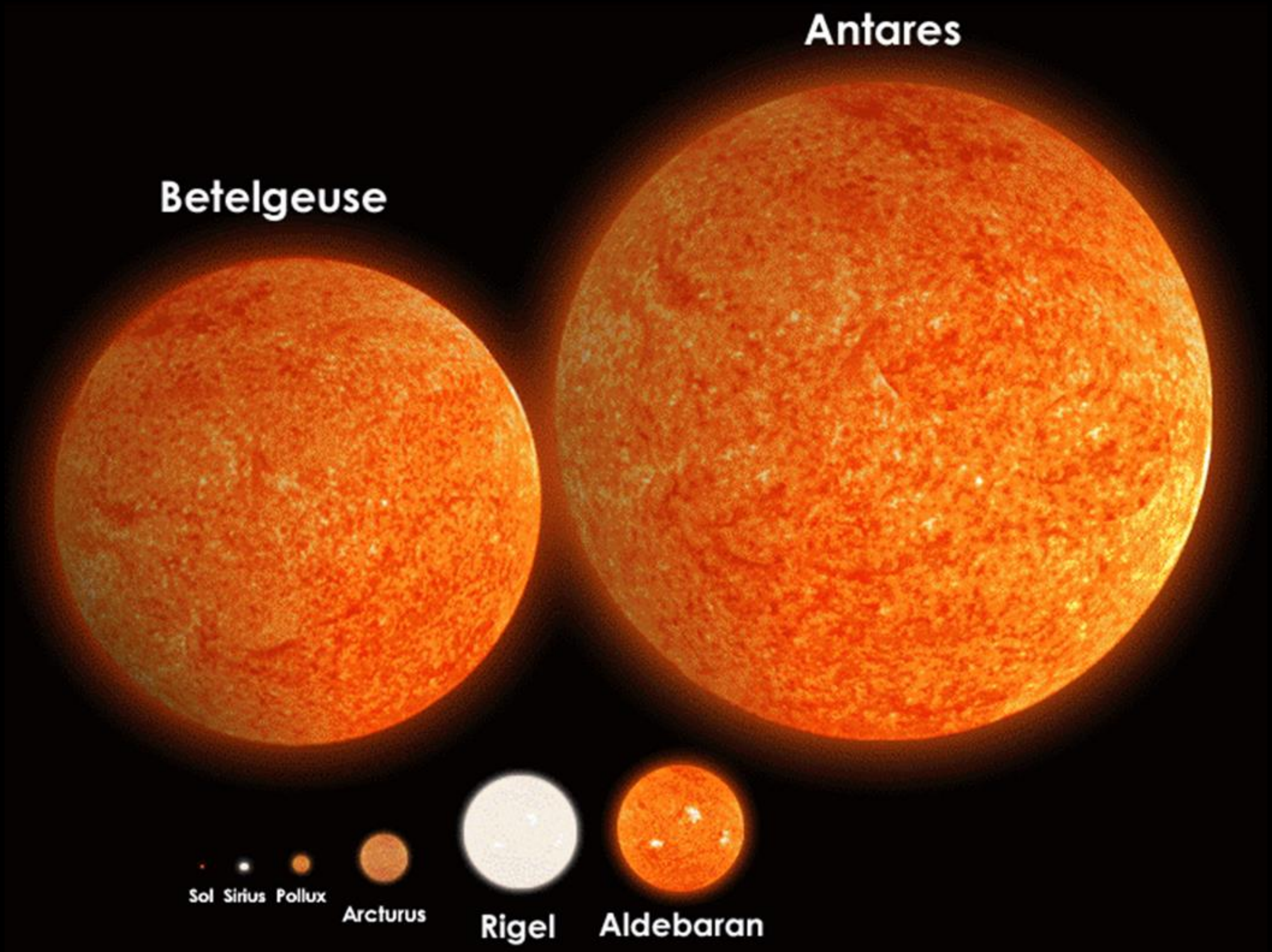


Explosion of White Dwarf(s).

Contribution of Type Ia SNe Especially to Fe is not Negligible.

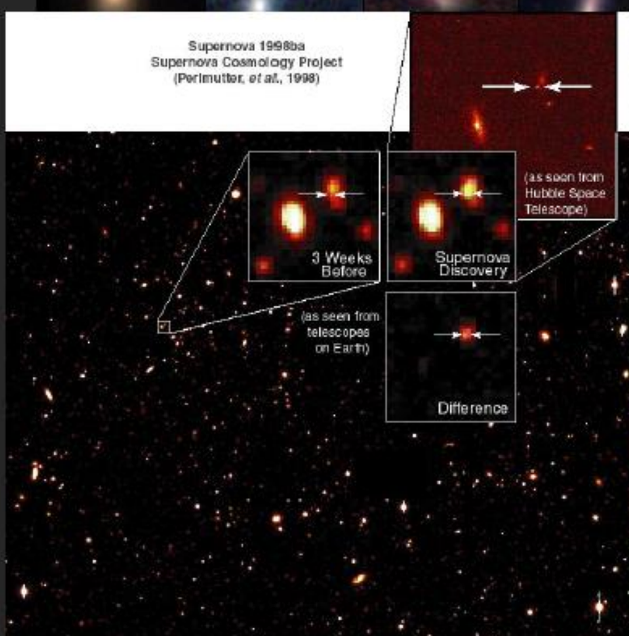
By Phil Plait
Science for the Curious Discovery

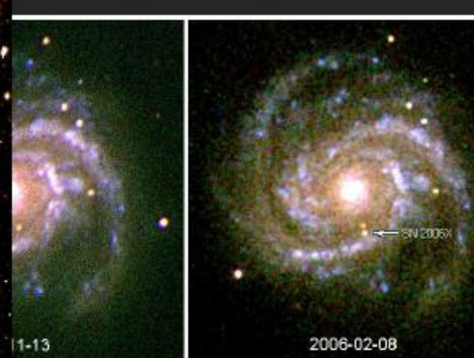
Massive Stars Explode.



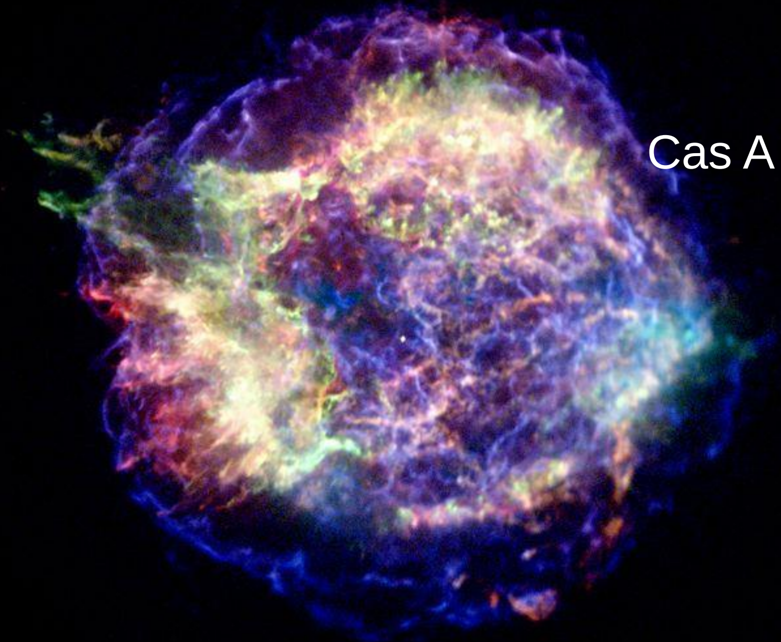
A Supernova that can Happen Even Tomorrow ～Betelgeuse～

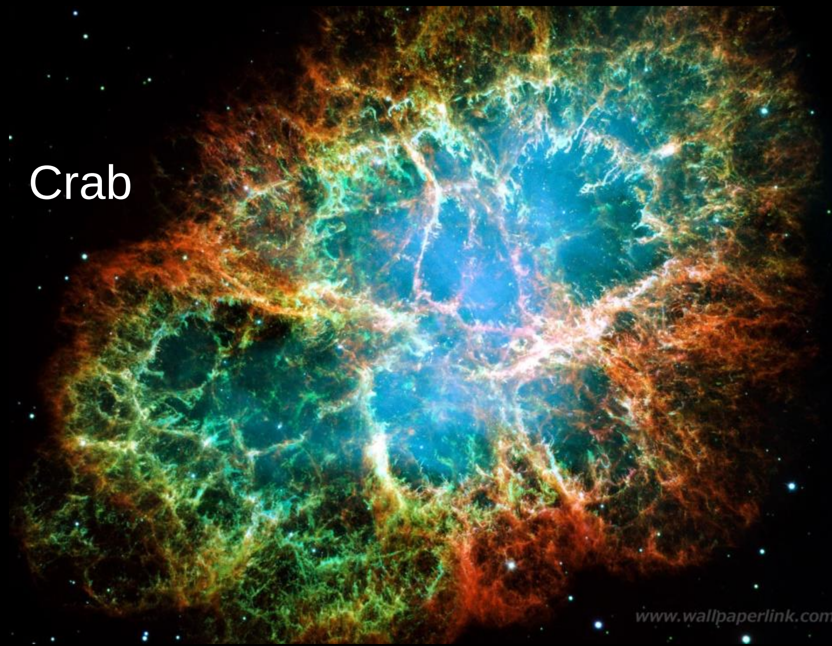
Extragalactic Supernovae (> Mpc, days to yrs)

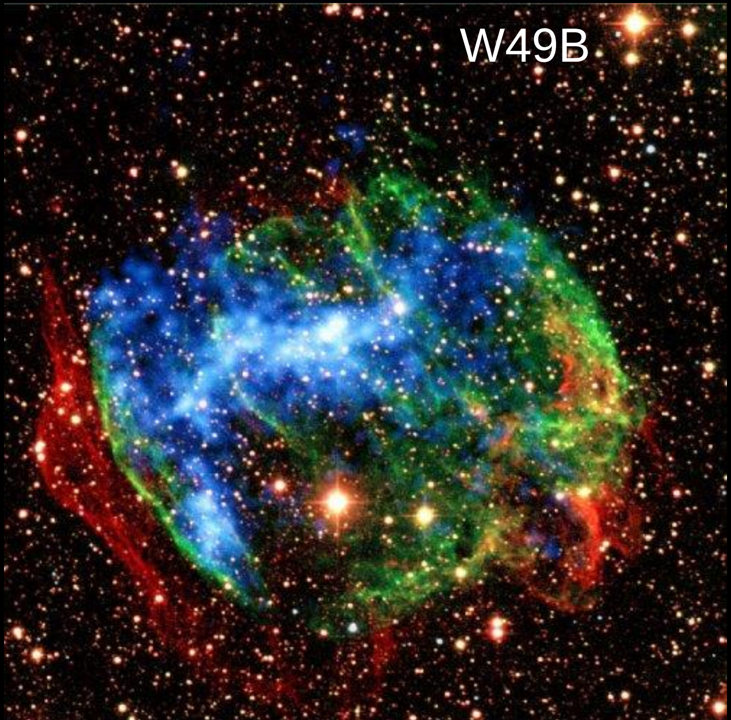


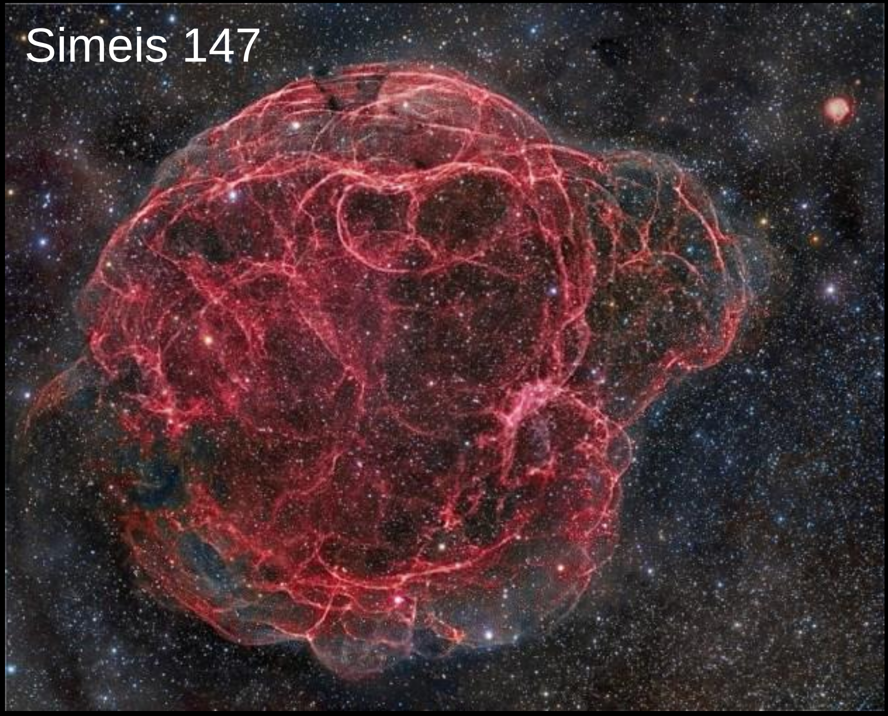


Slide from Keiichi Maeda

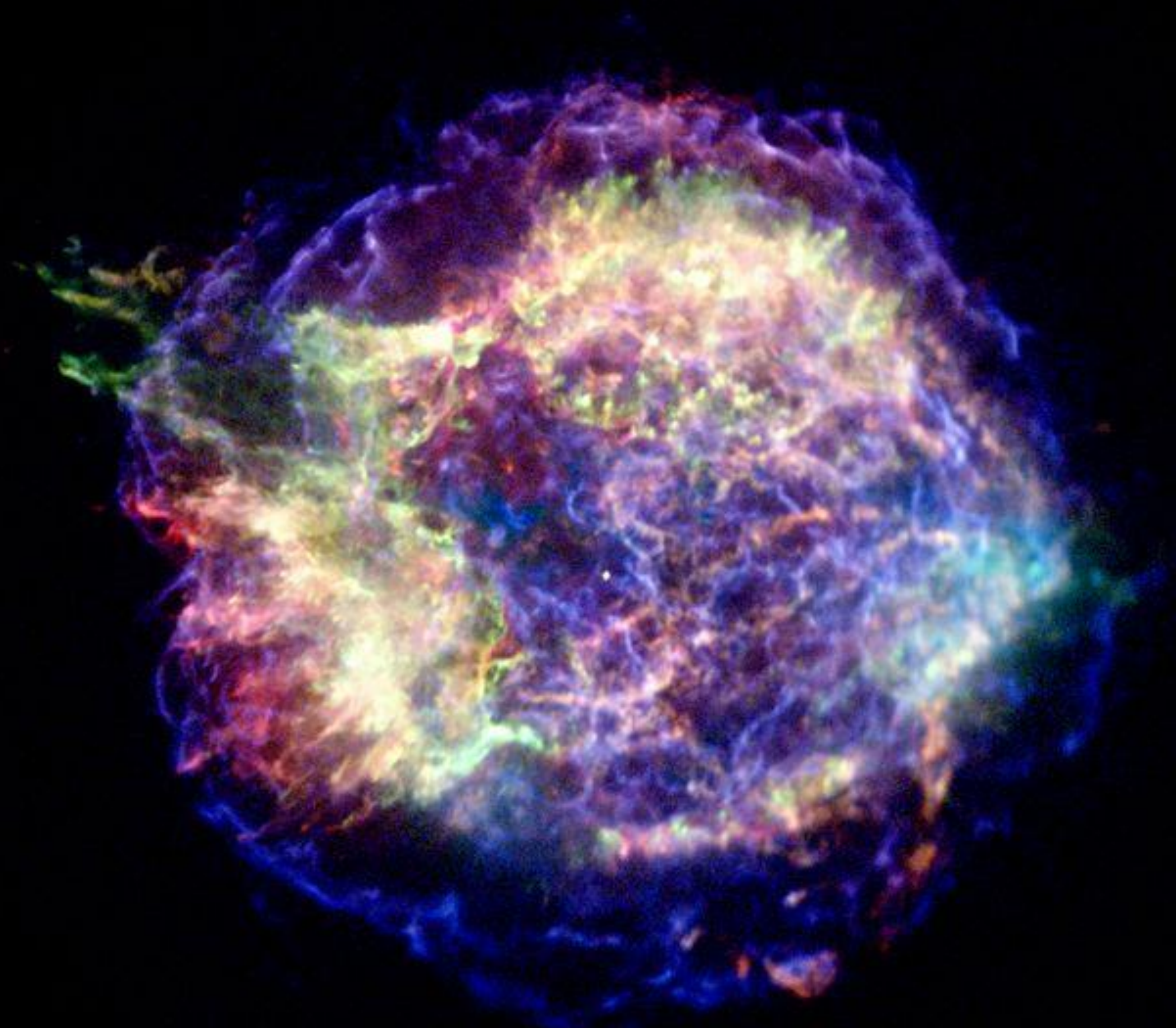

Cas A


Crab
www.wallpaperlink.com


W49B


Simeis 147

Massive Stars Explode. Why?



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.

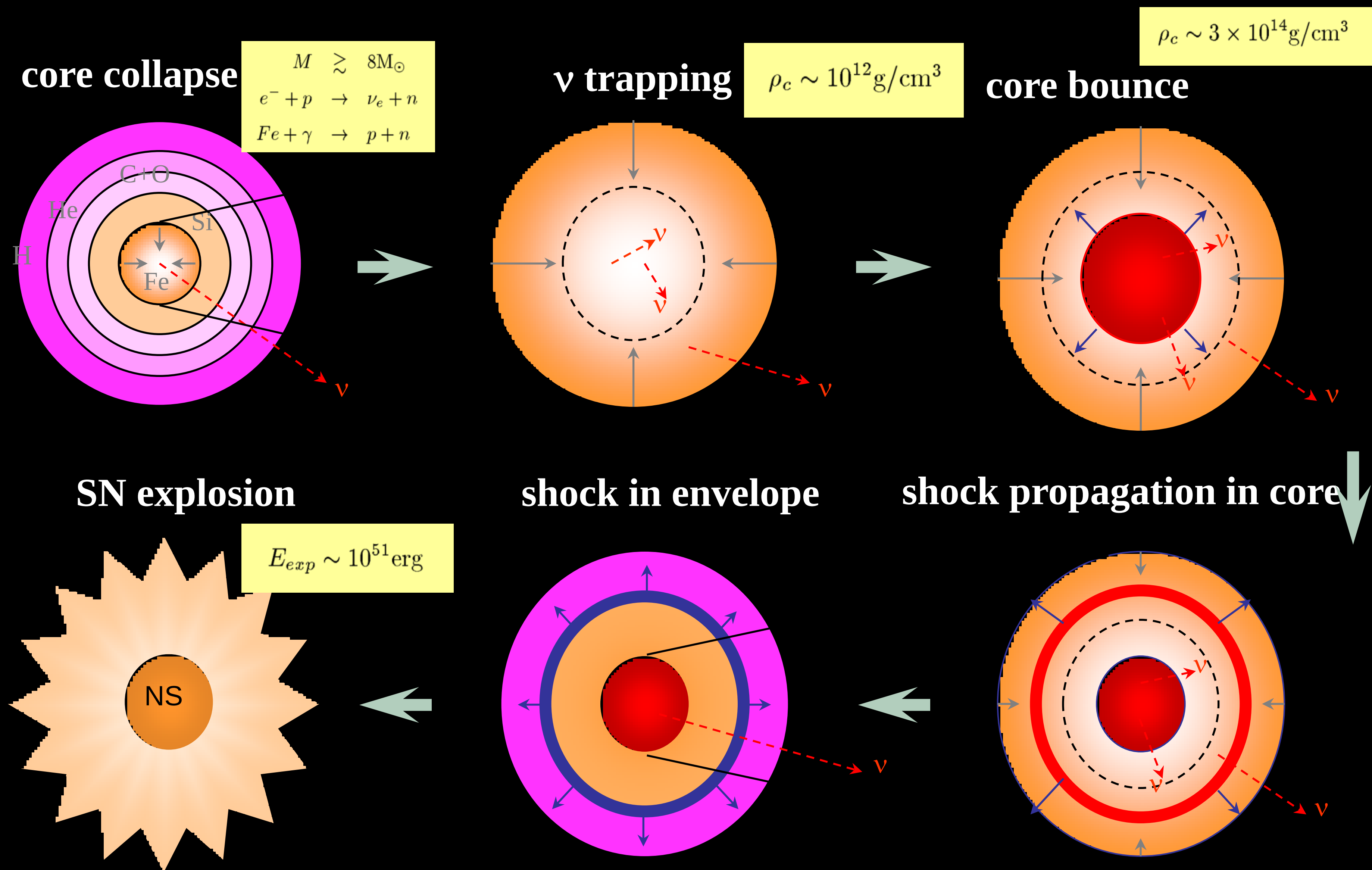
W. BAADE
F. ZWICKY

1934

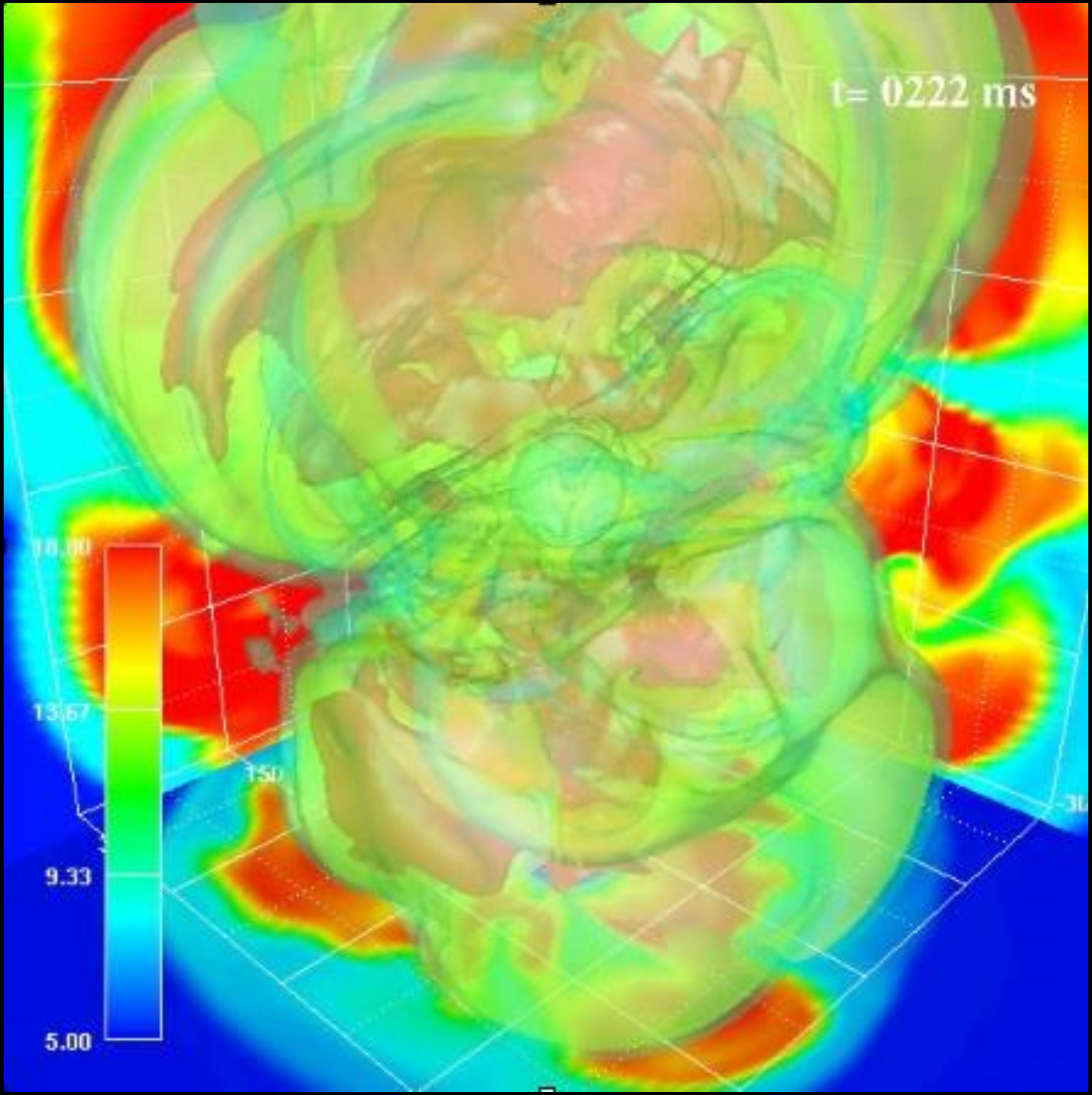
→ For details: Lectures by Kotake (Wed.-)

Outline of Explosion Mechanism

From S. Yamada



Almost Exploded.

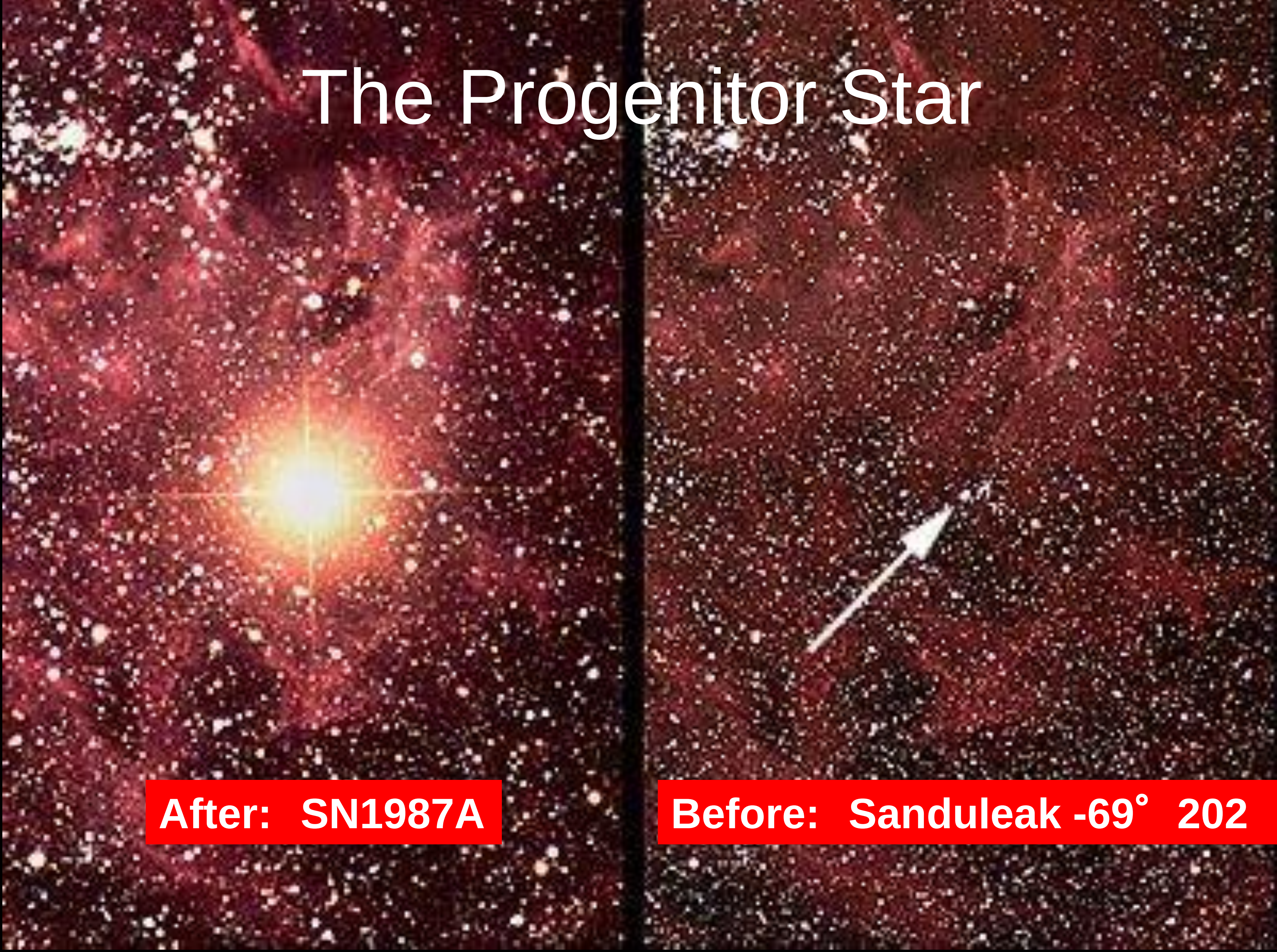


Simulation by
T. Takiwaki
(RIKEN→NAOJ)

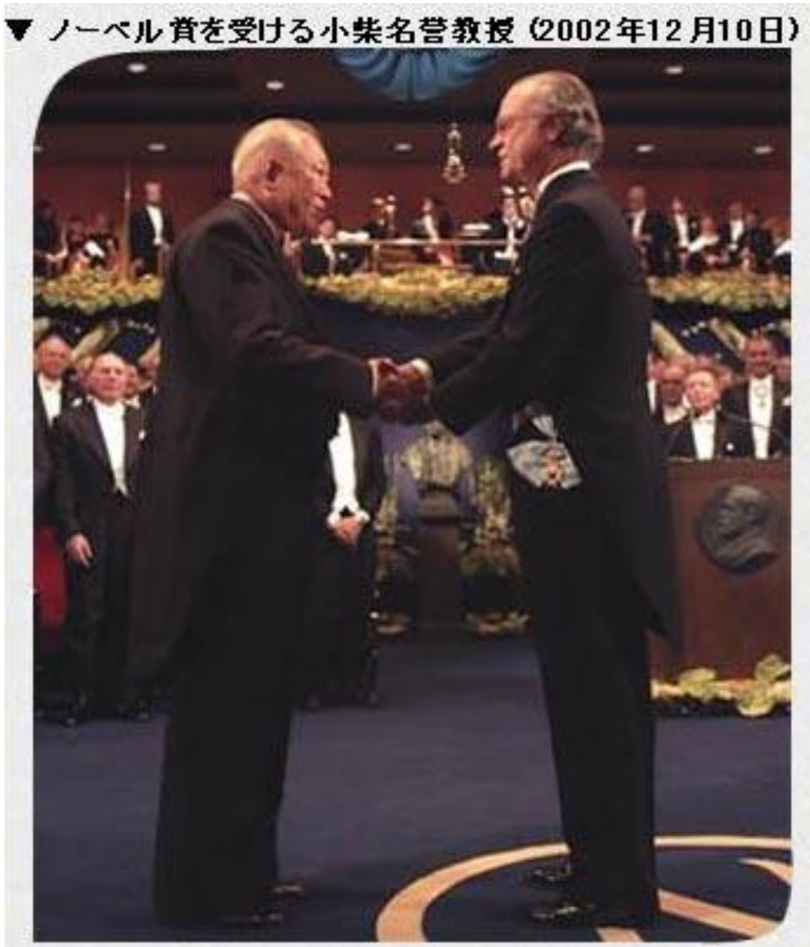
§ Explosive Nucleosynthesis
&
SN1987A

PRC99-04 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

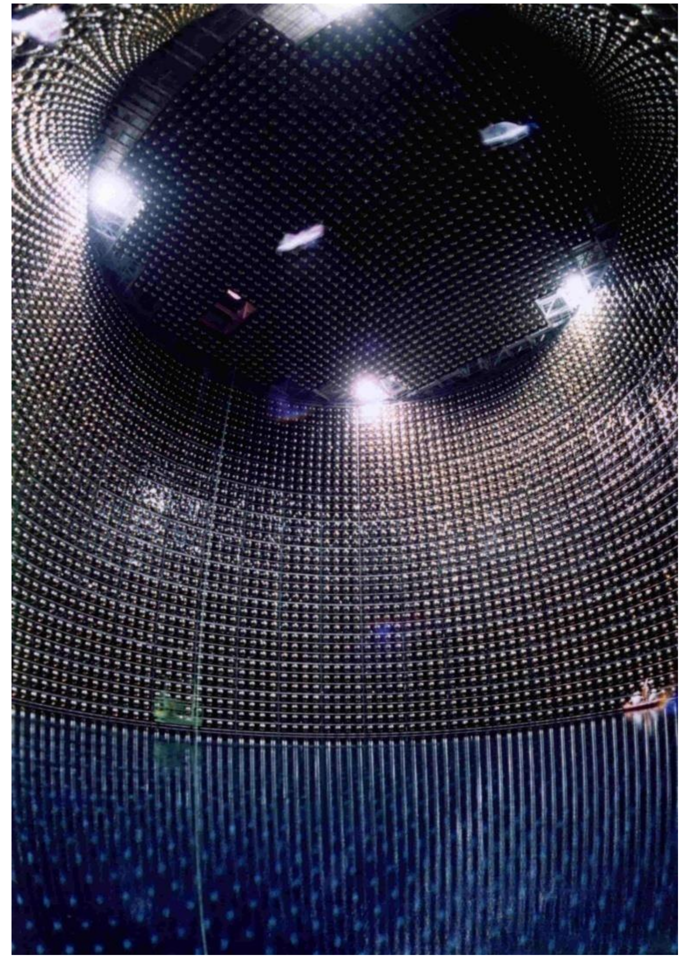
The Progenitor Star



Detection of Neutrinos from SN1987A

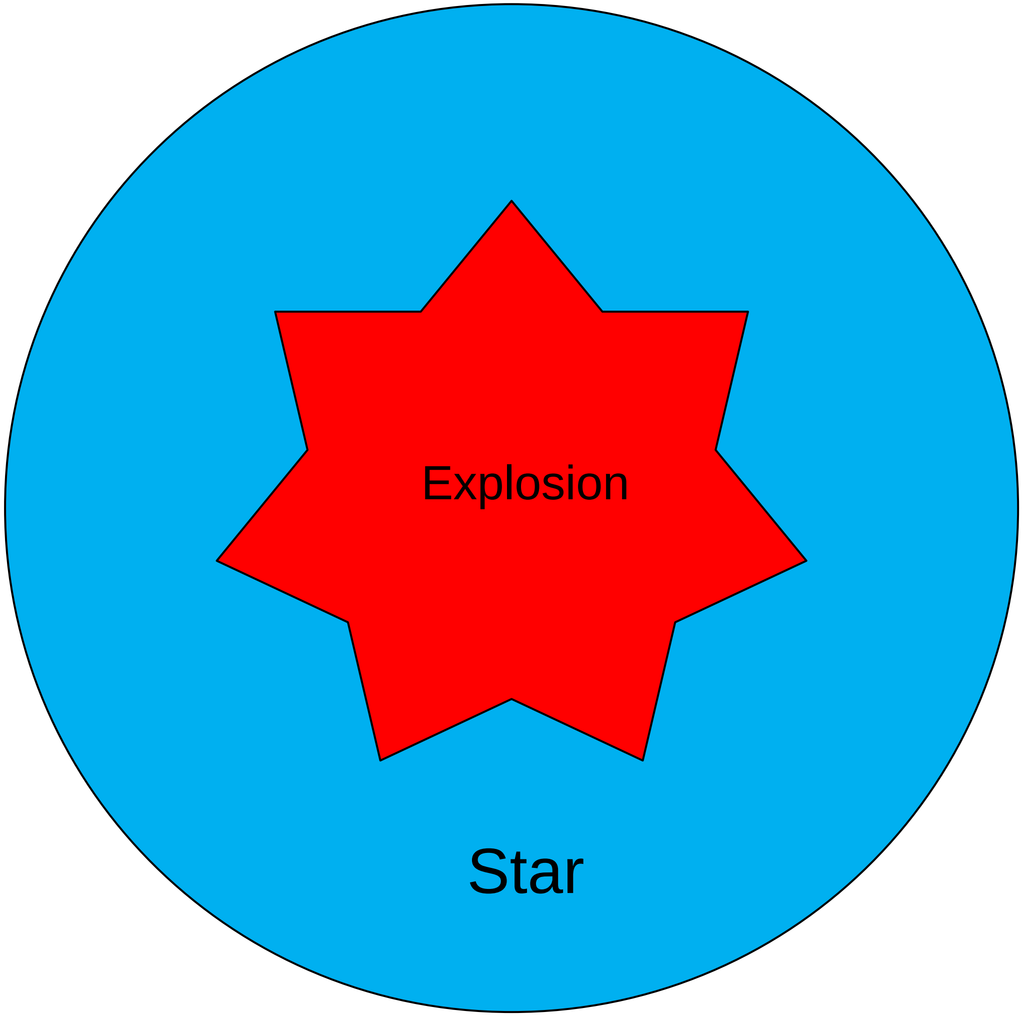


Prof. Koshiba



Super-Kamiokande

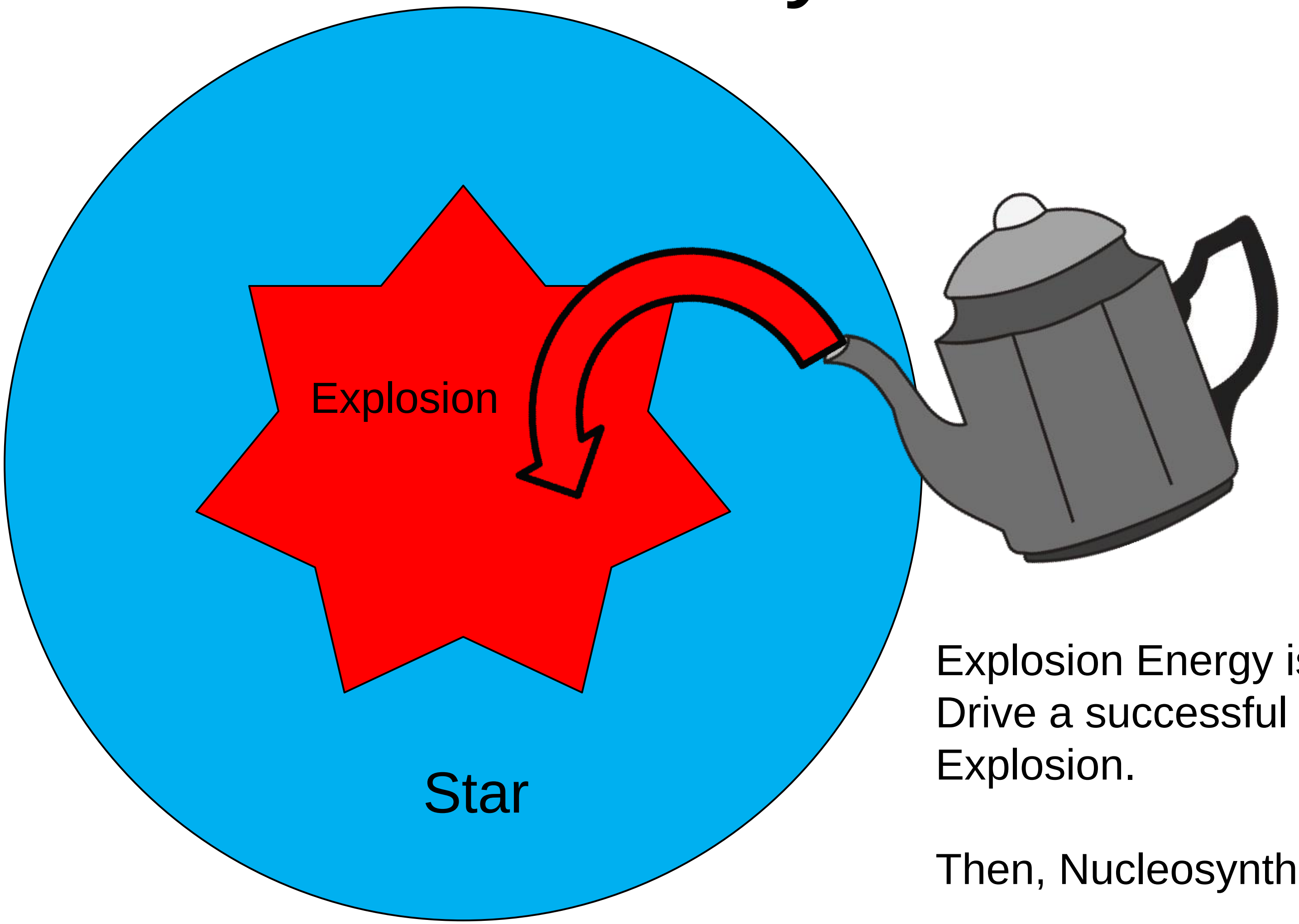
Explosive Nucleosynthesis



NSE (T > $5 \times 10^9\ K$)
Nuclear Statistical Equilibrium

O, Si $\longrightarrow$ Fe, Ni

Calculation of Explosive Nucleosynthesis



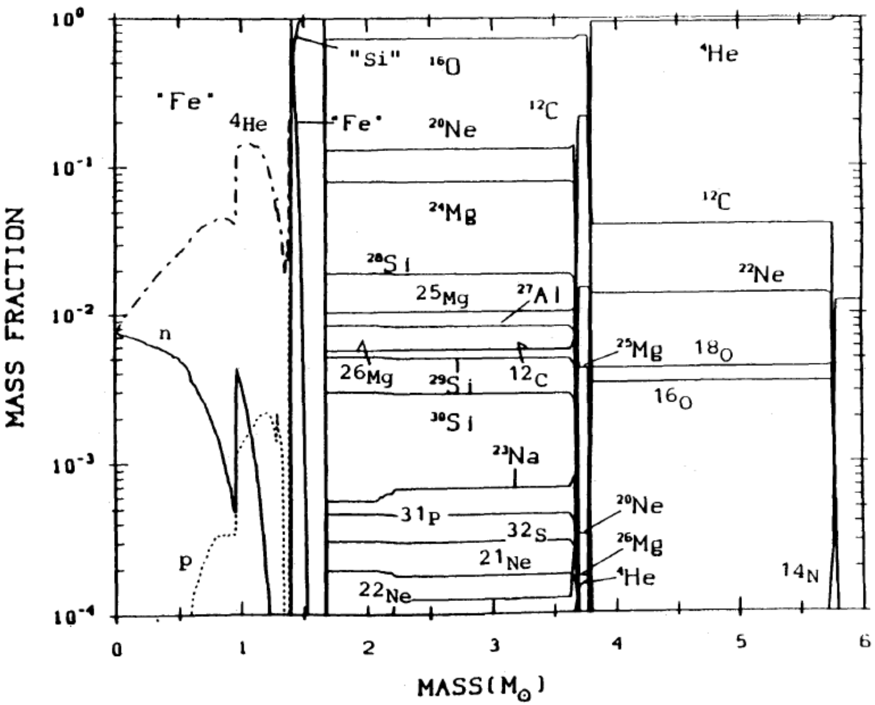
Explosion Energy is Injected to Drive a successful supernova Explosion.

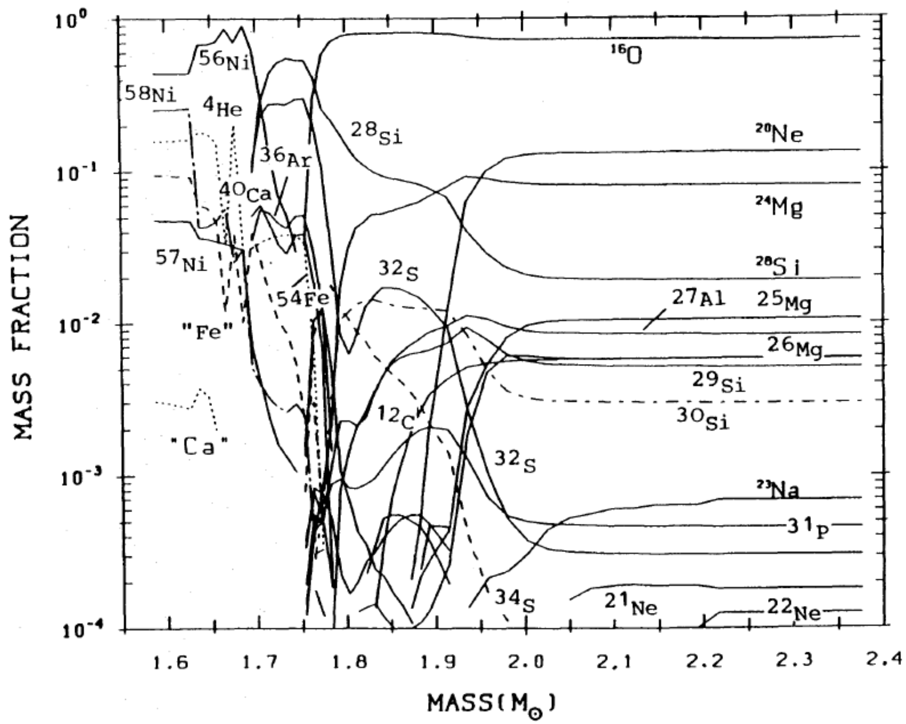
Then, Nucleosynthesis is calculated.

Explosive Nucleosynthesis

Spherical Explosion Model

Hashimoto, Nomoto, Shigeyama 1989





0 3 6 1.6 2.4

Before Explosion（Progenitor）

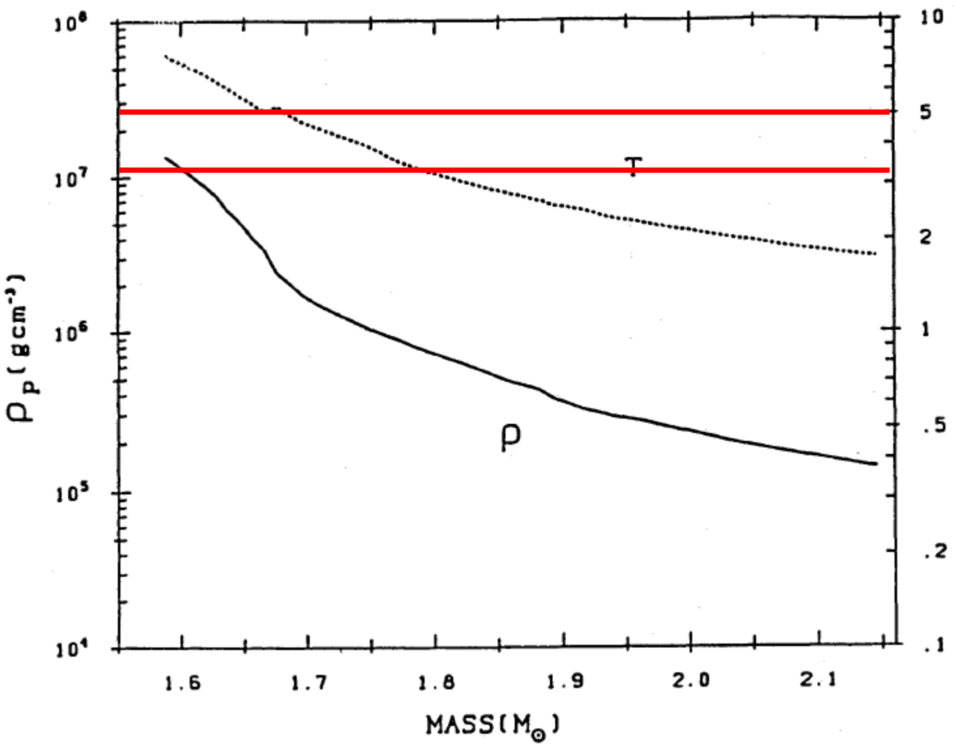
Enclosed Mass (M) = $\int_0^R 4\pi\rho r^2 dr$

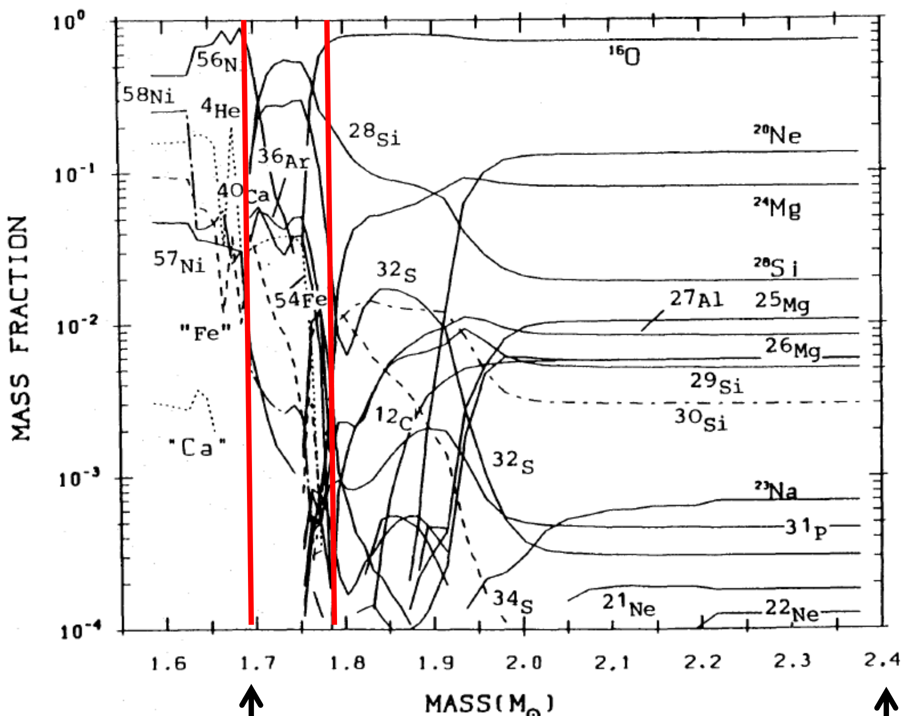
After Explosion
(< ～10 sec.)

Explosive Nucleosynthesis is Sensitive to Temperature.

Hashimoto, Nomoto, Shigeyama 1989

44Ti is here.





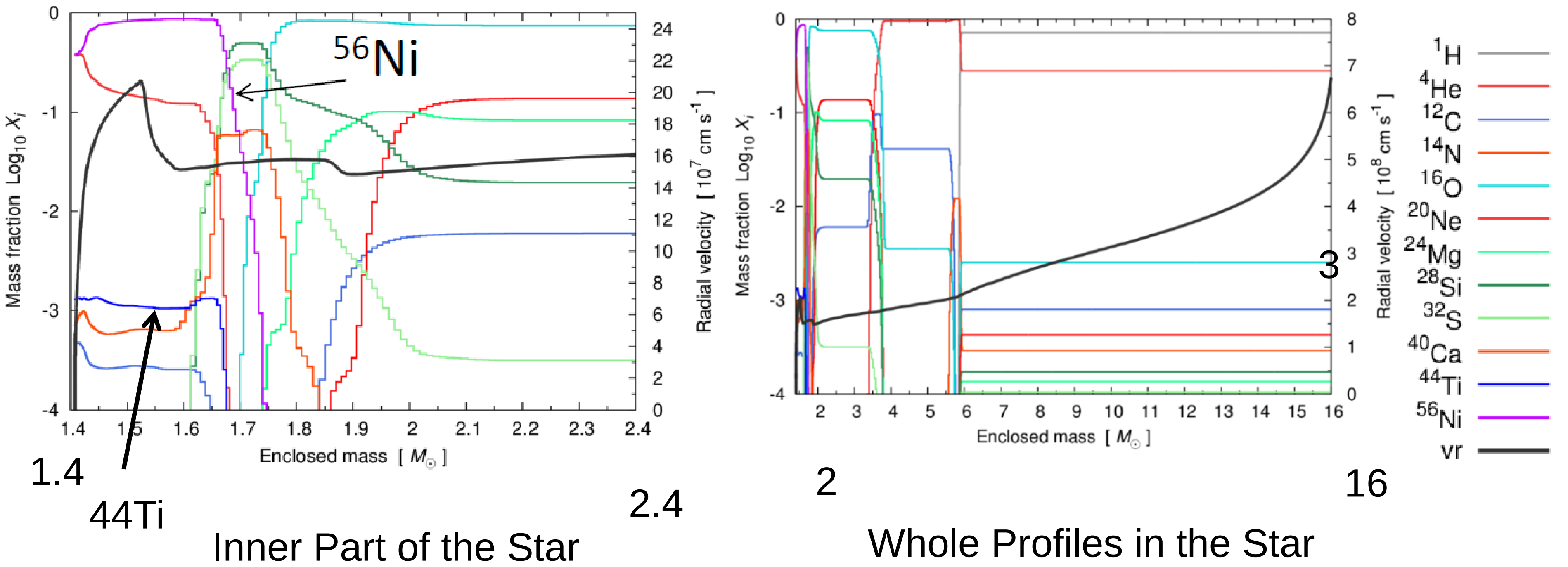
↑ ~1500km/s

↑ ~1600km/s

After the Explosion

Composition & Velocity Profiles

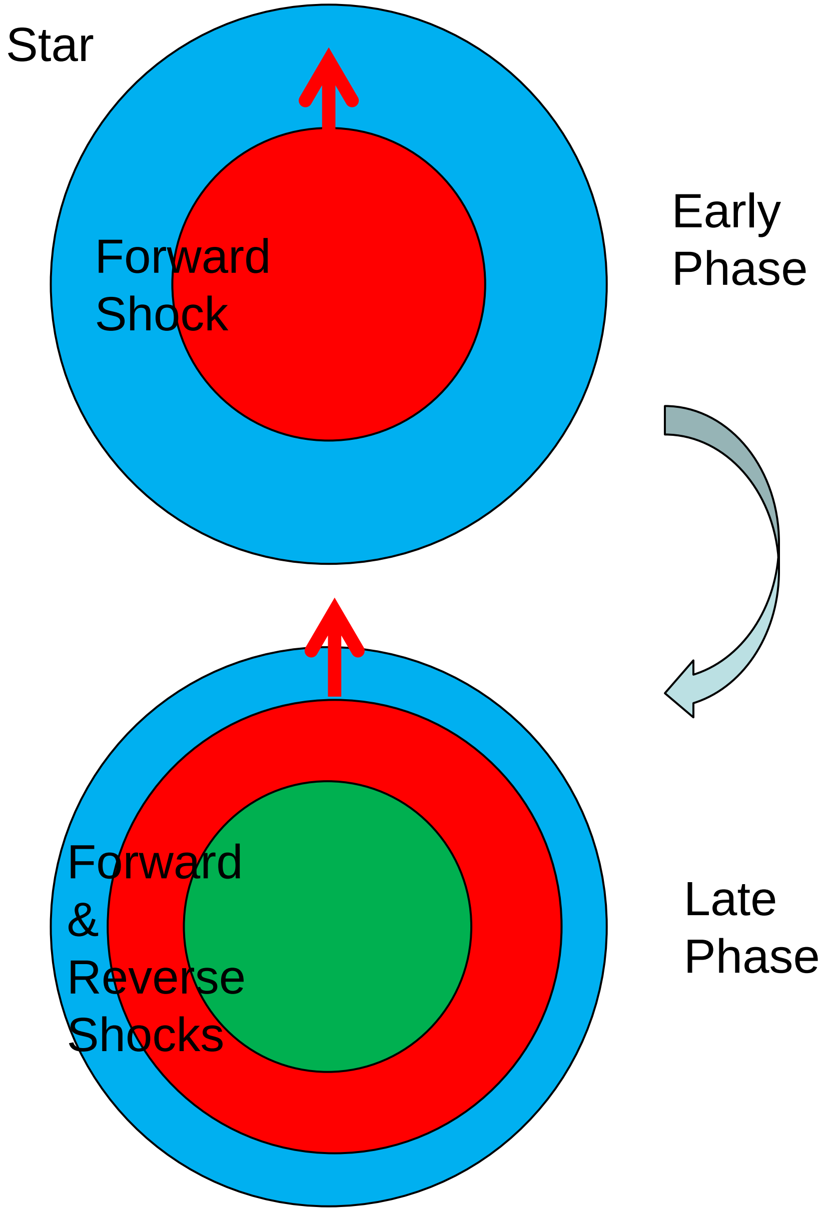
Enclosed Mass (M) = $\int_0^R 4\pi\rho r^2 dr$

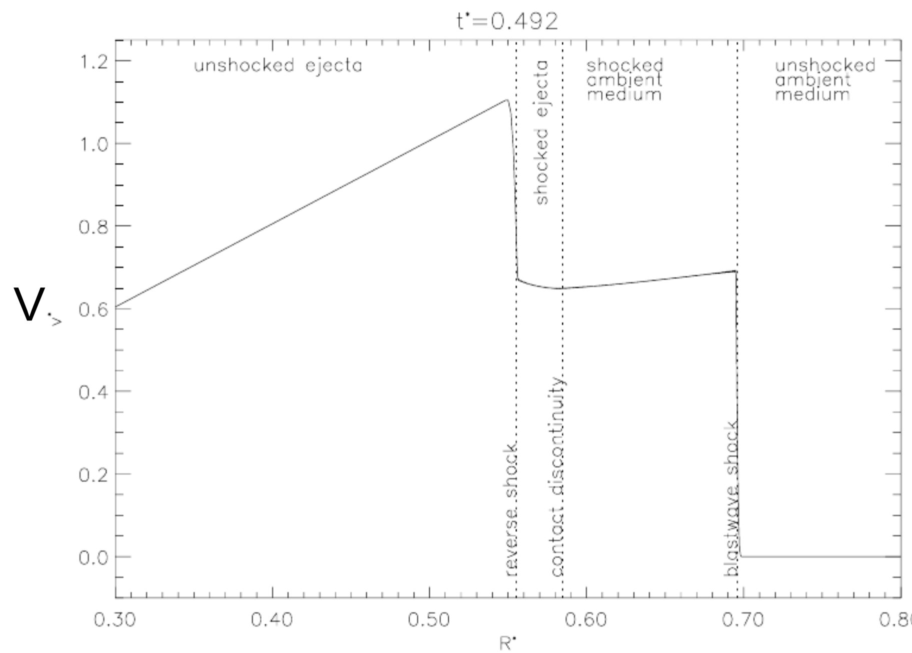


～ a few hours after the explosion.

56Ni & 44Ti are trapped inside, with low velocity.

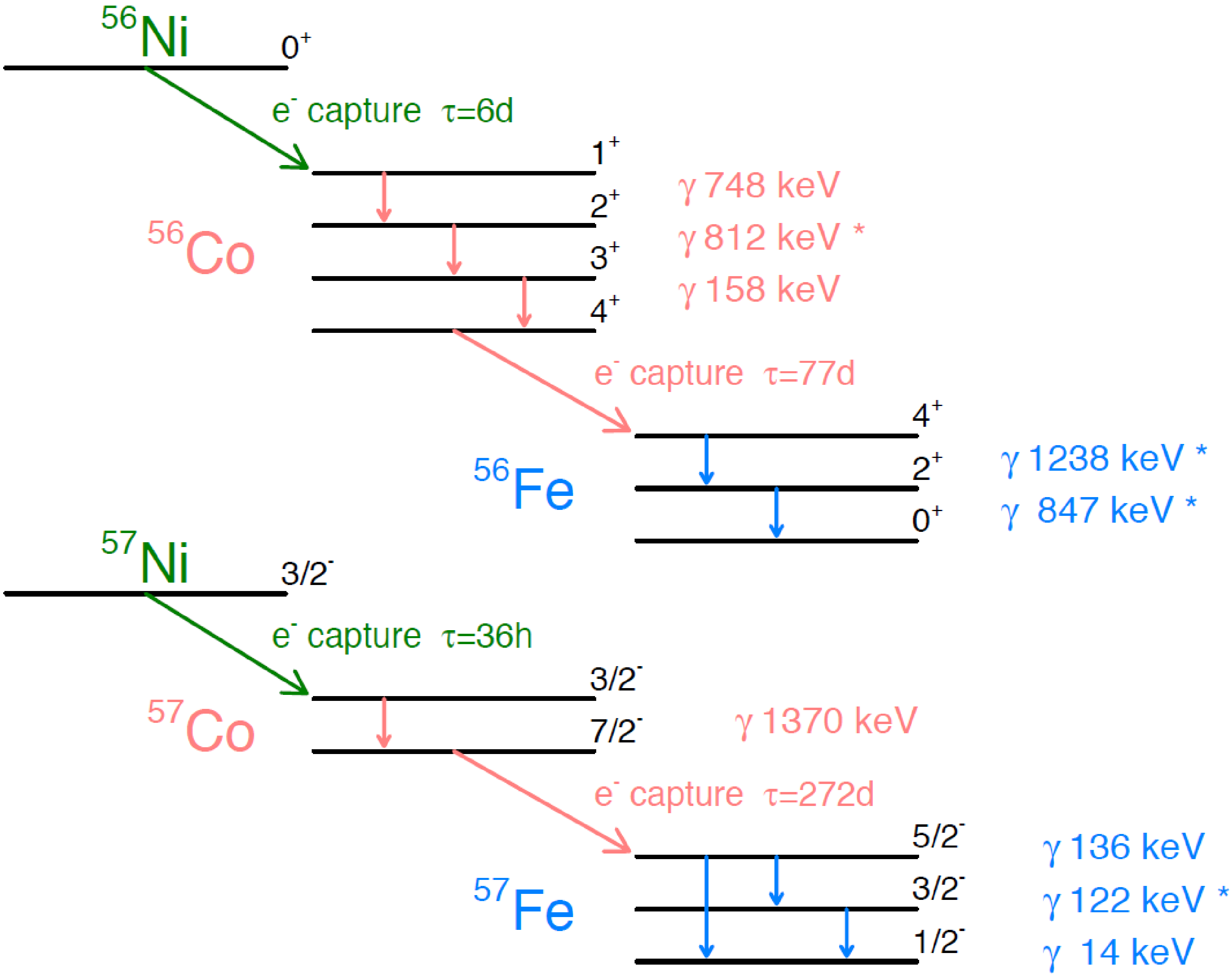
Shock Structure





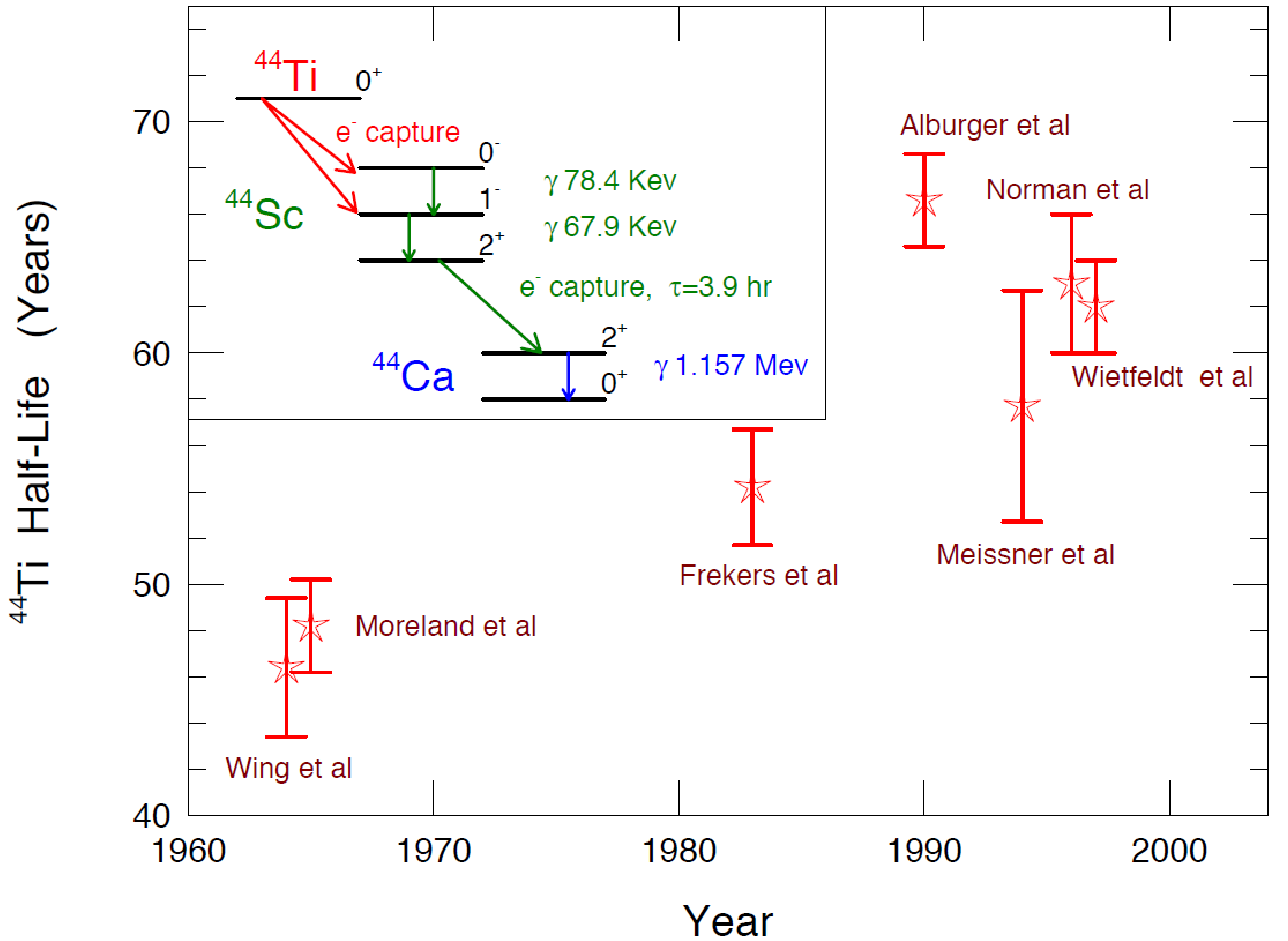
Radius

T.DeLaney et al. (2010).



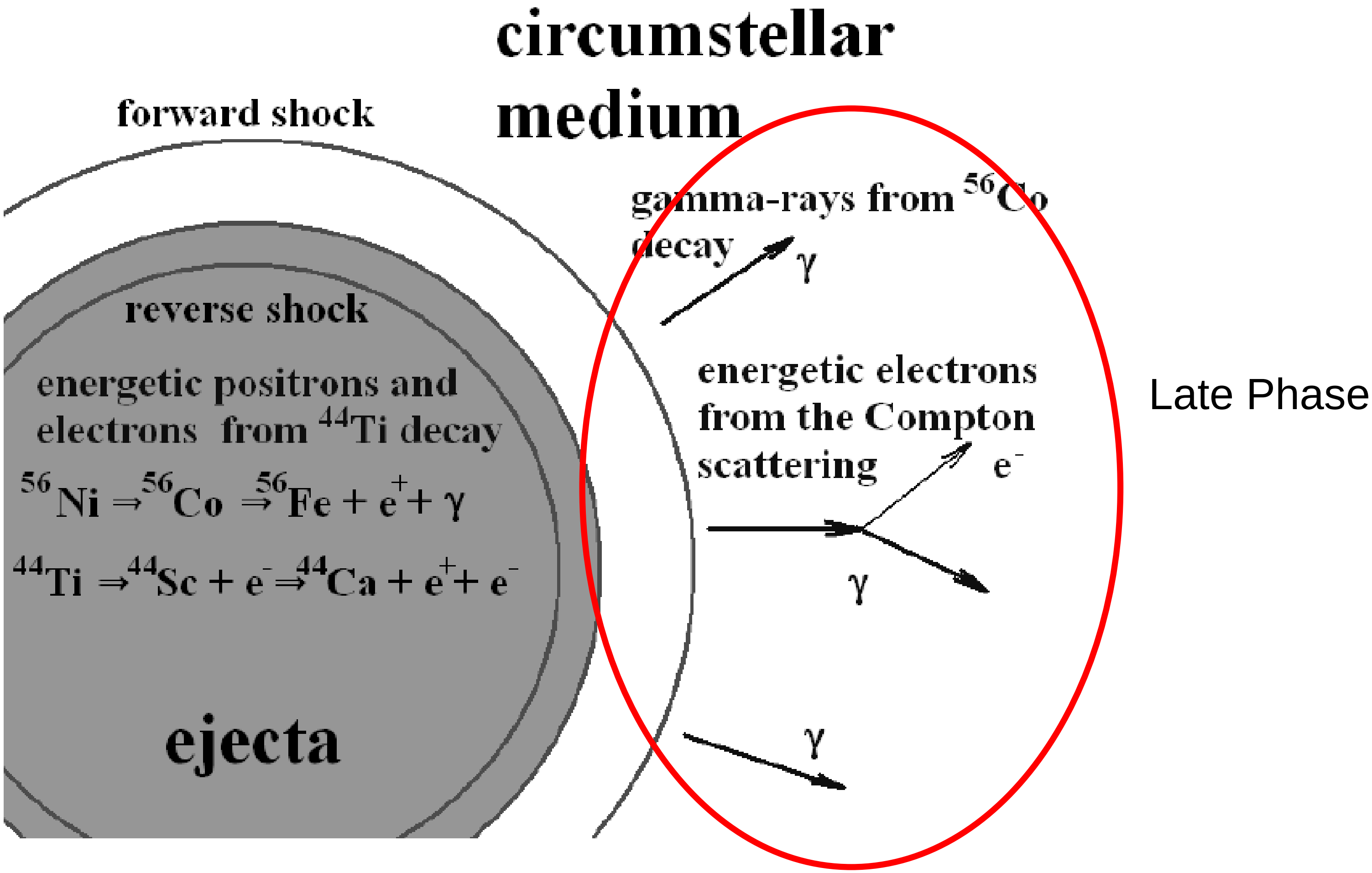
From Cococubed.com

http://cococubed.asu.edu/research_pages/ti44_co60_ni56.shtml



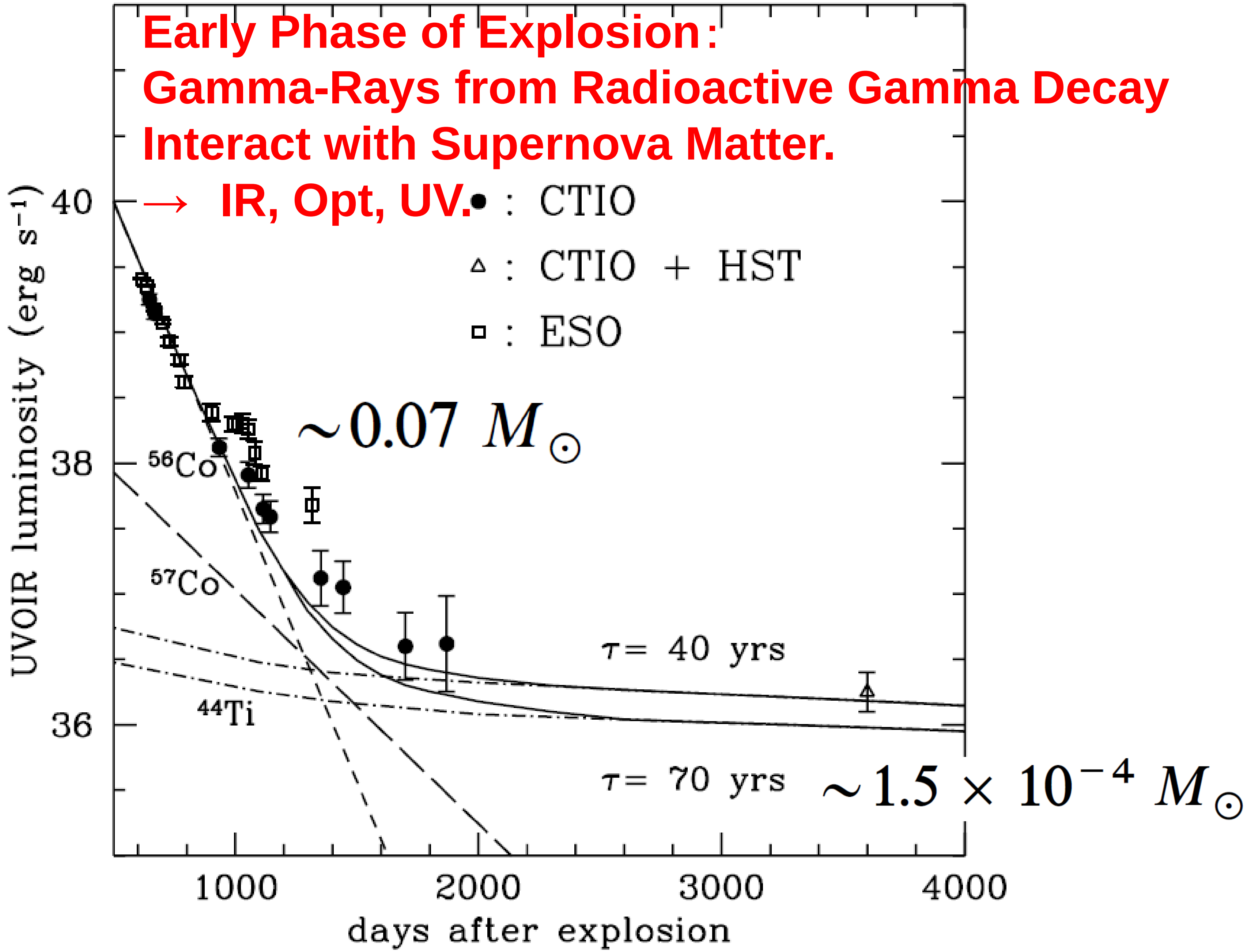
44Ti 0+
e- capture
0-
1-
2+
44Sc
γ 78.4 Kev
γ 67.9 Kev
e- capture, τ=3.9 hr
2+
0+
44Ca
γ 1.157 Mev
Alburger et al
Norman et al
Wietfeldt et al
Meissner et al
Frekers et al
Moreland et al
Wing et al
44Ti Half-Life (Years)
Year
40
50
60
70
1960
1970
1980
1990
2000

Supernovae are Heated by Radioactive Nuclei

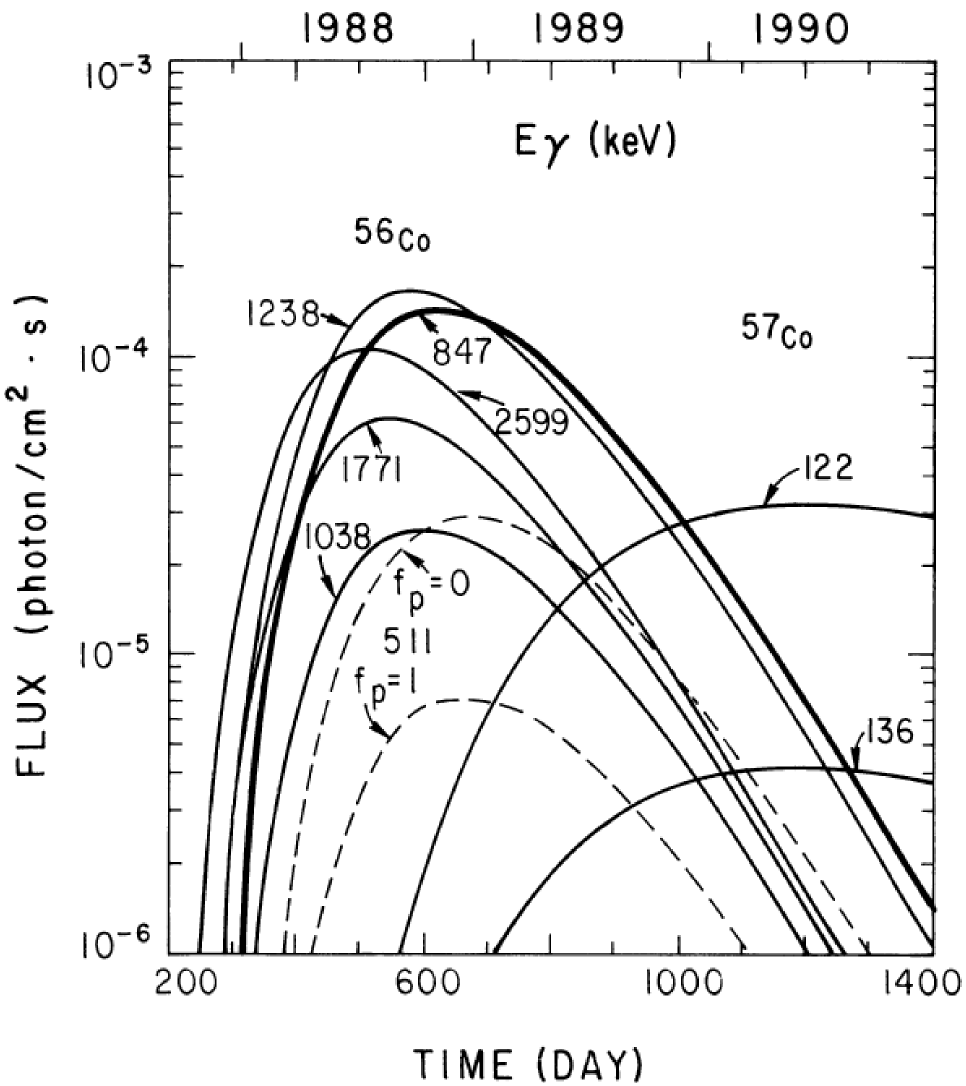


V.N.Zirakashvili[1,2] and F.A.Aharonian[3,2]

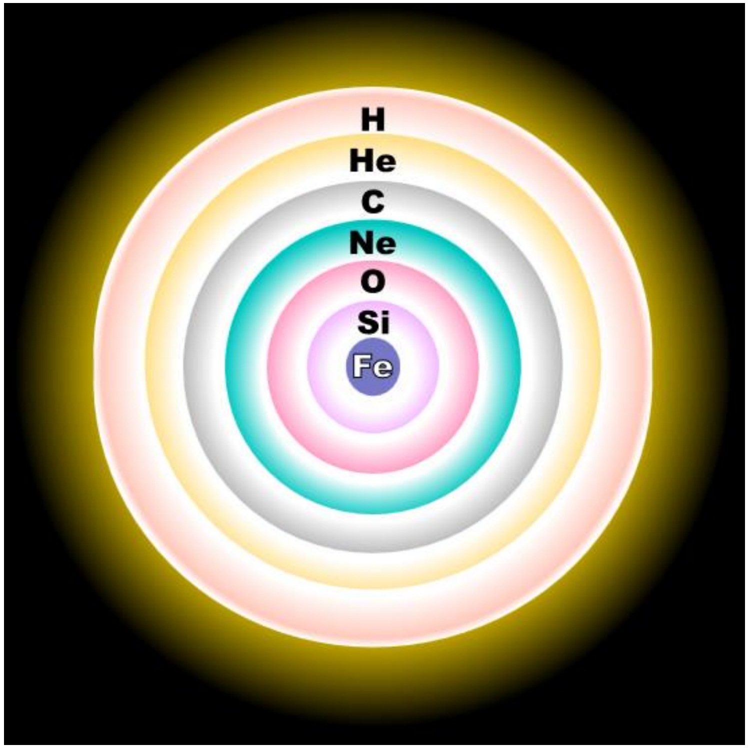
Early Phase of Explosion:
Gamma-Rays from Radioactive Gamma Decay Interact with Supernova Matter.
→ IR, Opt, UV.



A Simple & Important Prediction on Gamma-Ray Lines from Radioactive Gamma Decays

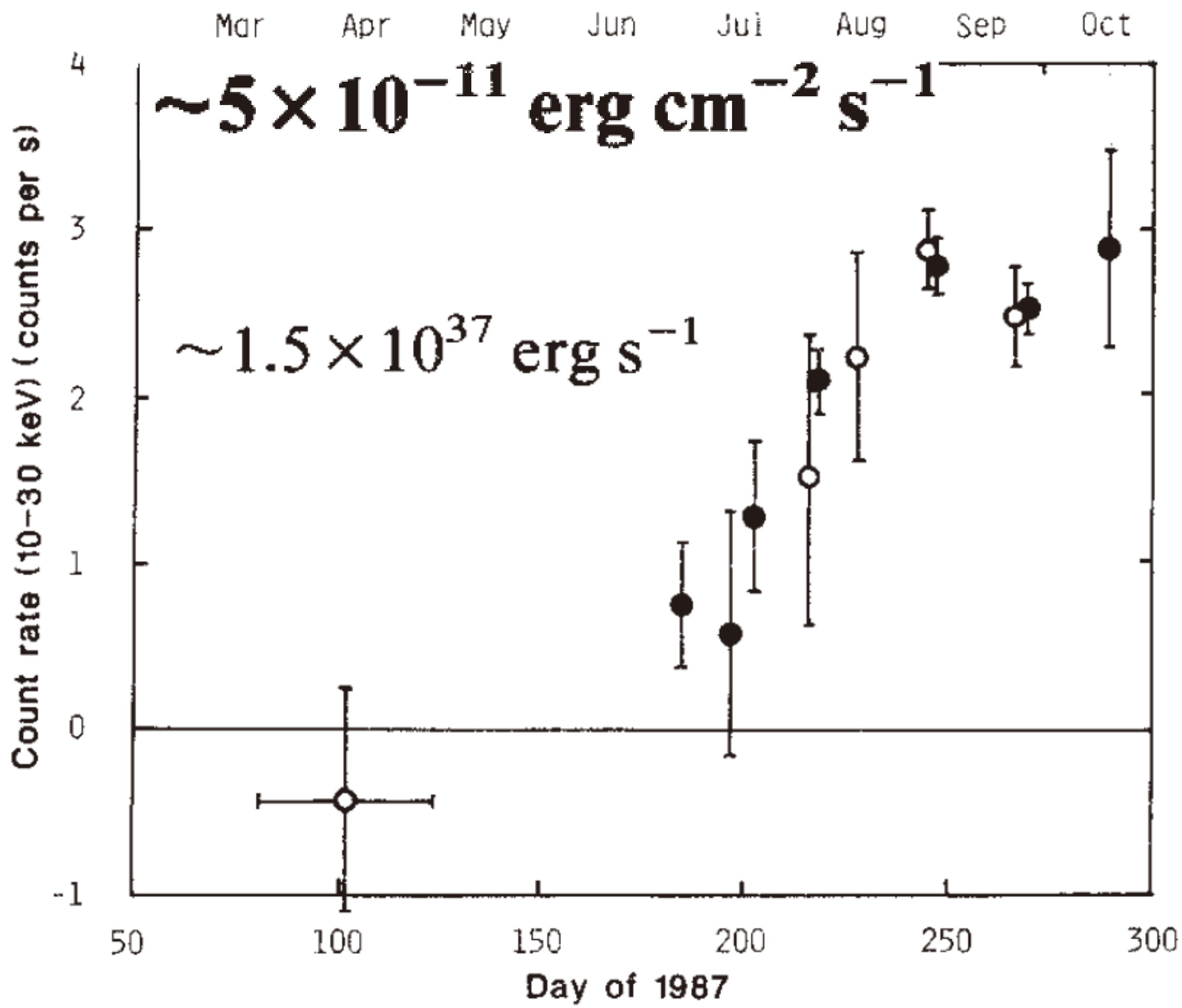


Chan & Lingenfelter 1987 ApJL



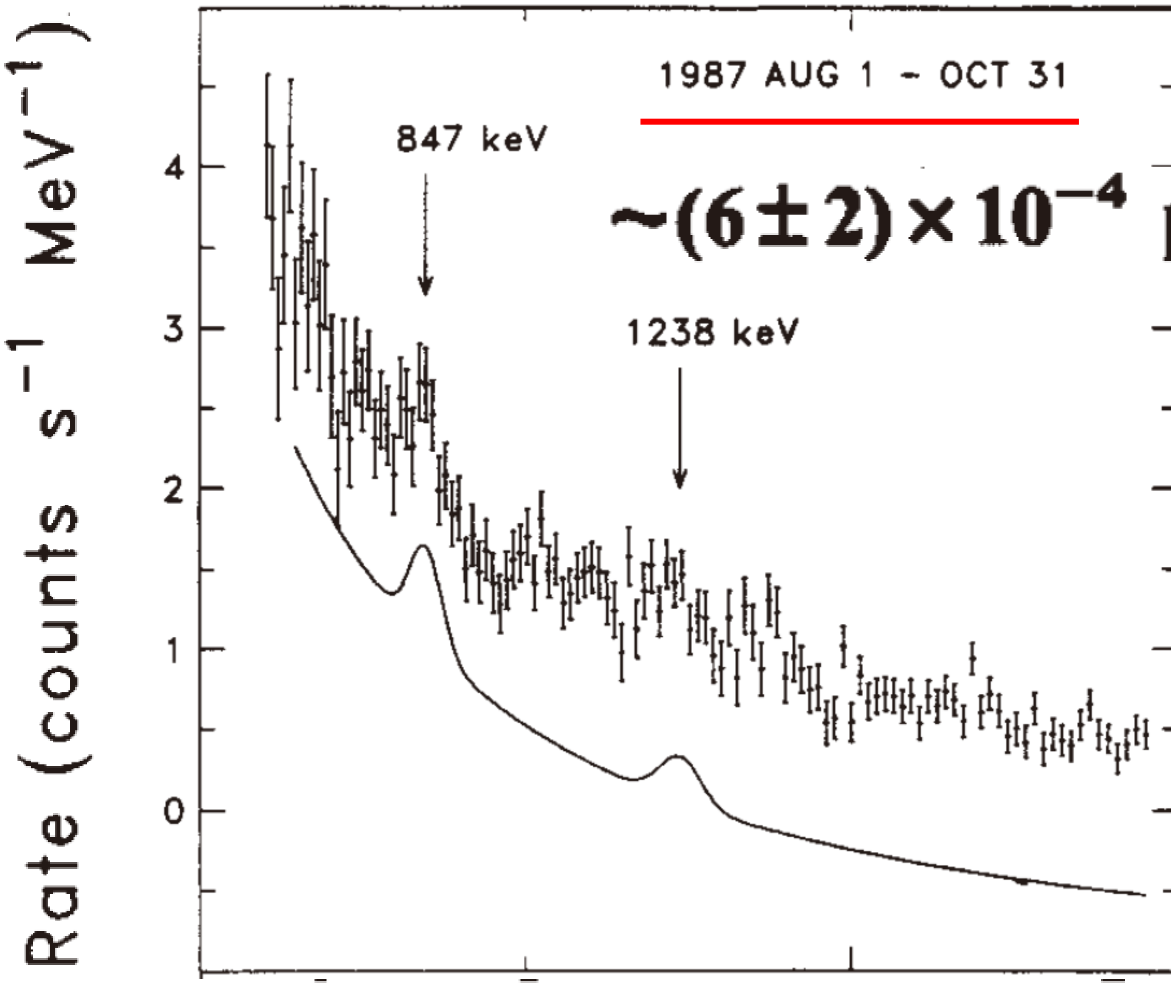
Early Detection of X-rays Originated from Radioactive Gamma Decays!

Dotani et al. Nature 1987 by GINGA



Early Detection of Gamma-Ray Lines !

Matz et al. Nature 1988

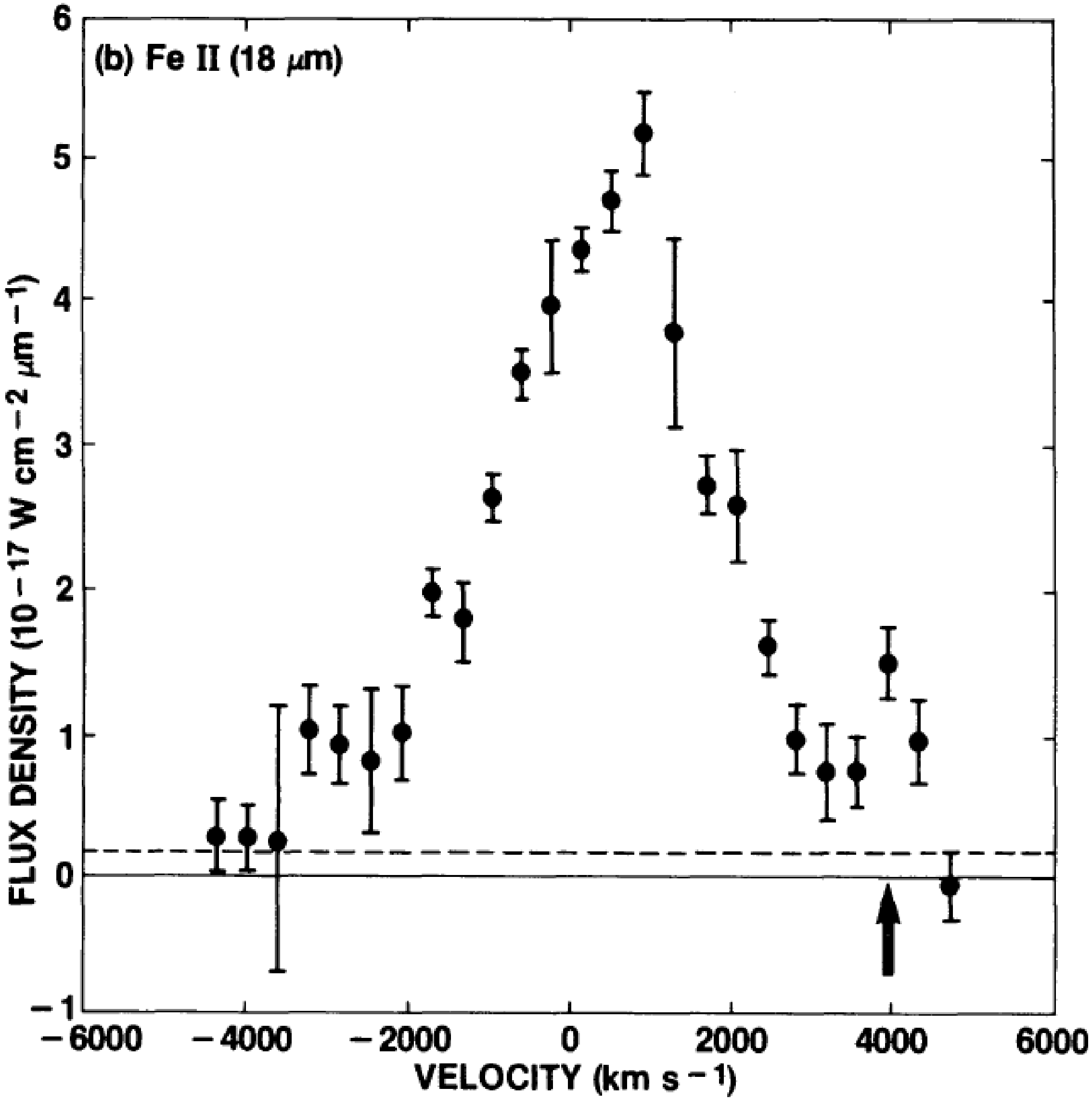


$\sim(6 \pm 2) \times 10^{-4}$ photons cm^{-2} s^{-1}

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

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

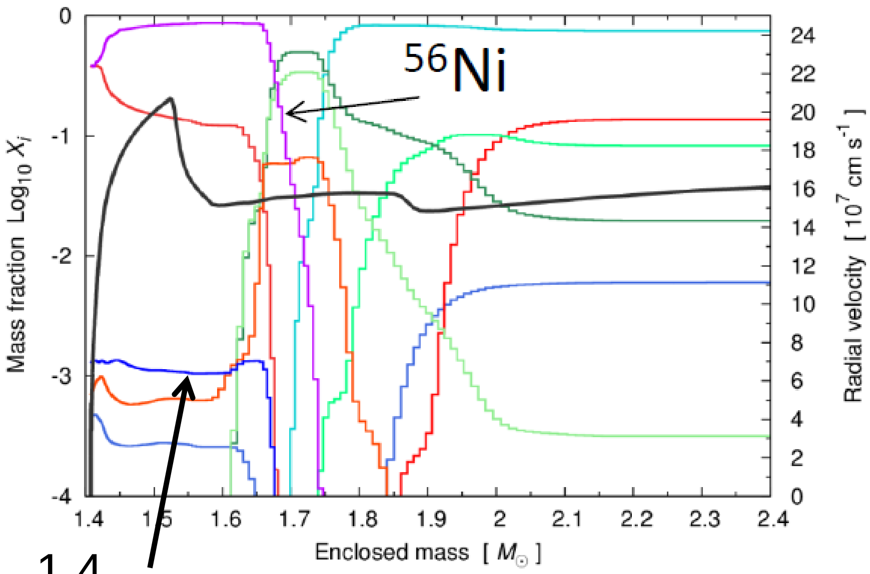
Velocity Profile of Iron（409days）！



Haas et al. 1990

Composition & Velocity Profiles

Enclosed Mass (M) = $\int_0^R 4\pi\rho r^2 dr$

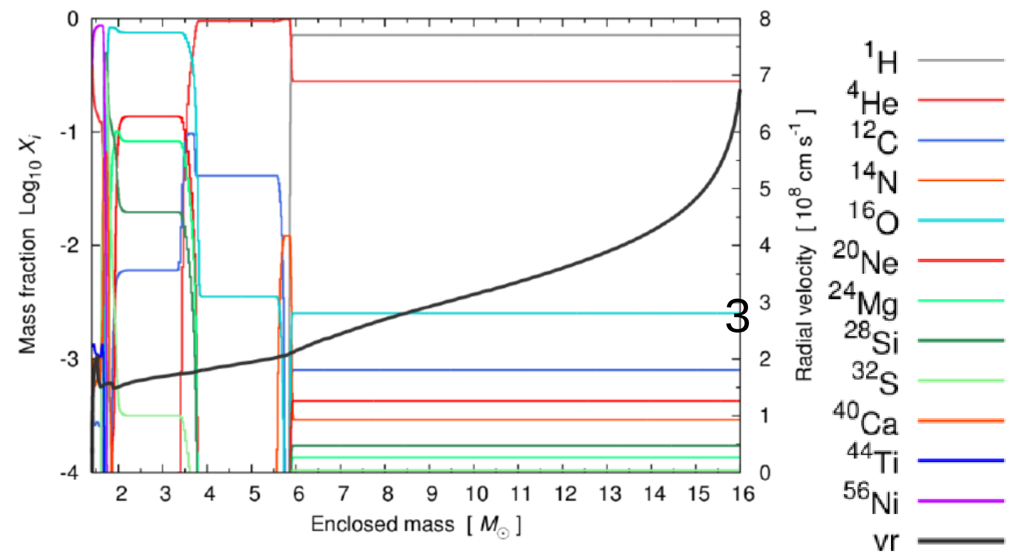


1.4

44Ti

2.4

Inner Part of the Star



3

2

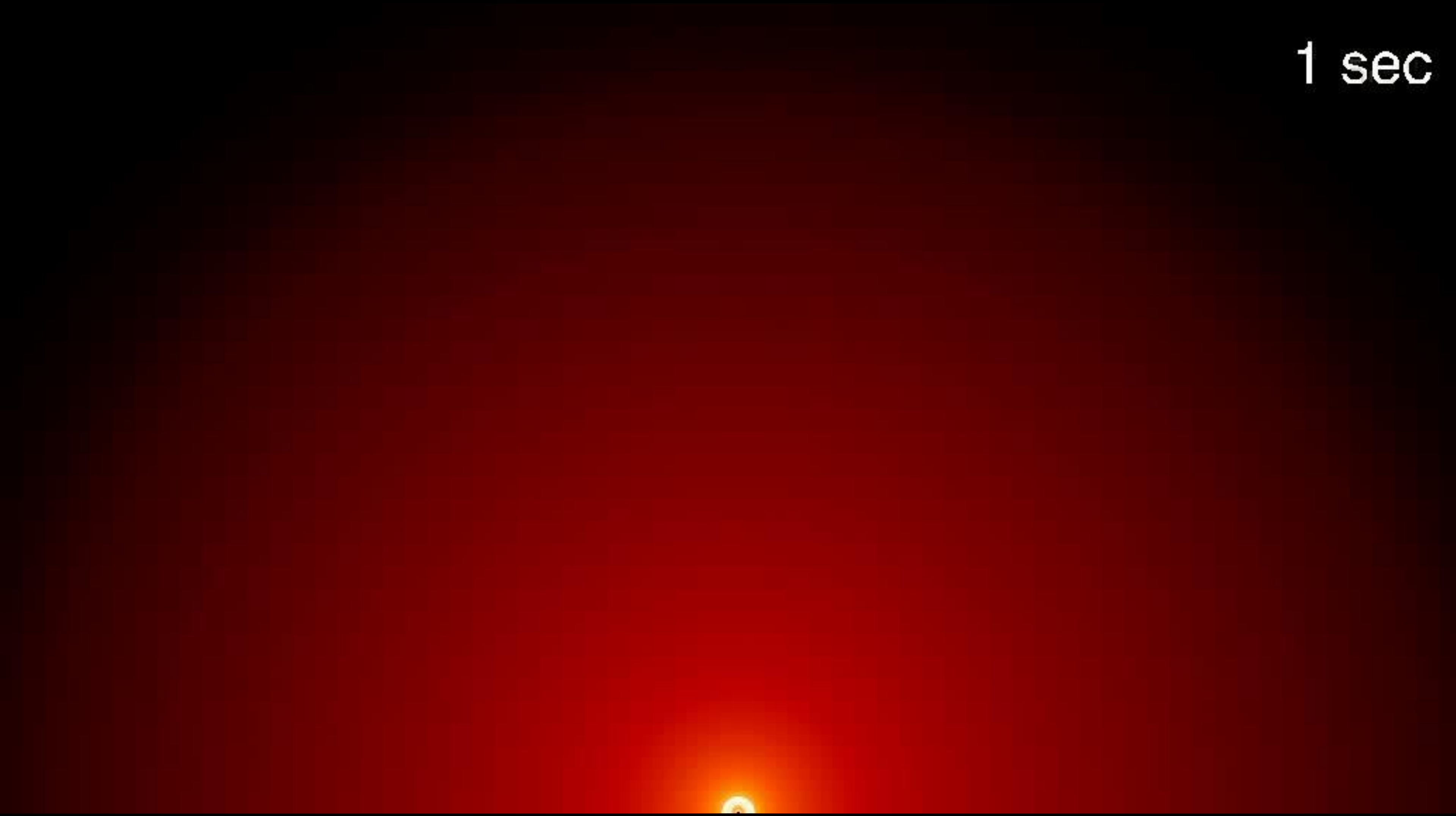
16

Whole Profiles in the Star

～ a few hours after the explosion.

56Ni & 44Ti are trapped inside, with low velocity.

Rayleigh-Taylor Instabilities



Simulation by Kifonidis, MPA.

Rayleigh-Taylor Instabilities in Supernovae

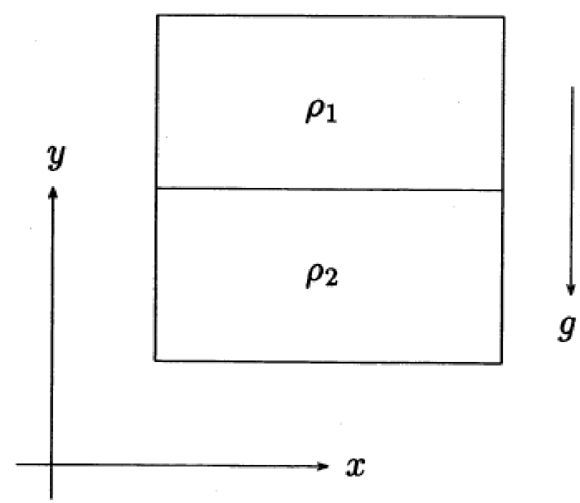
Falk & Arnett 1973 ApJ

Numerical calculations of shock waves in extended circumstellar envelopes, with radiation transport via photon diffusion, have been performed; they suggest a satisfactory explanation for the light curves of (at least) Type II supernovae. This model predicts the development of a severe Rayleigh-Taylor instability after peak light, and also predicts the presence of high- and low-density phases in the expanding matter.

Heavy Matter

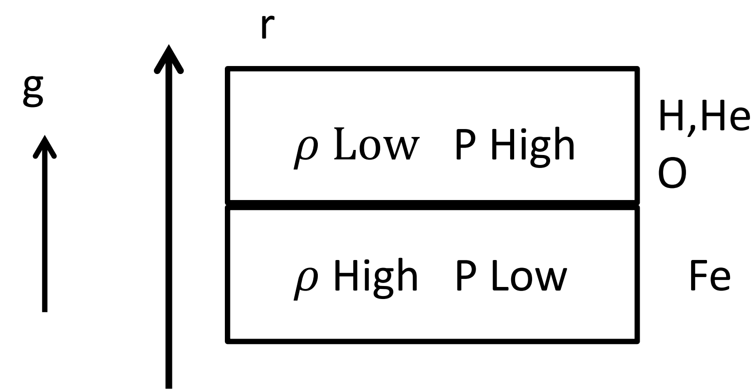
Gravity

Light Matter



Growth of R-T Instabilities in SNe

Surface of the Star.



Center of the Star.

Unstable Situation.

Acceleration $a = -\frac{1}{\varrho}\frac{dp}{dr}$

Effective Gravity $g = -a$

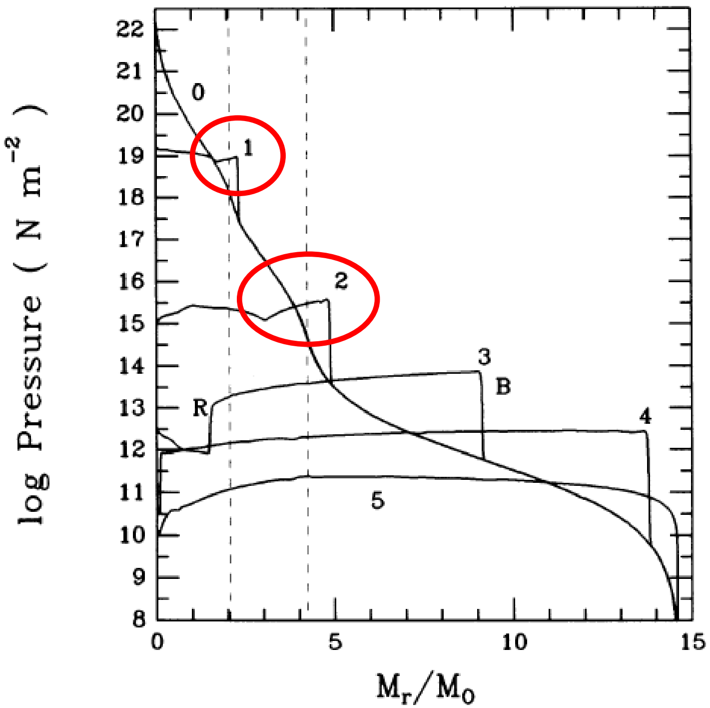
Criteria for R-T Instabilities.

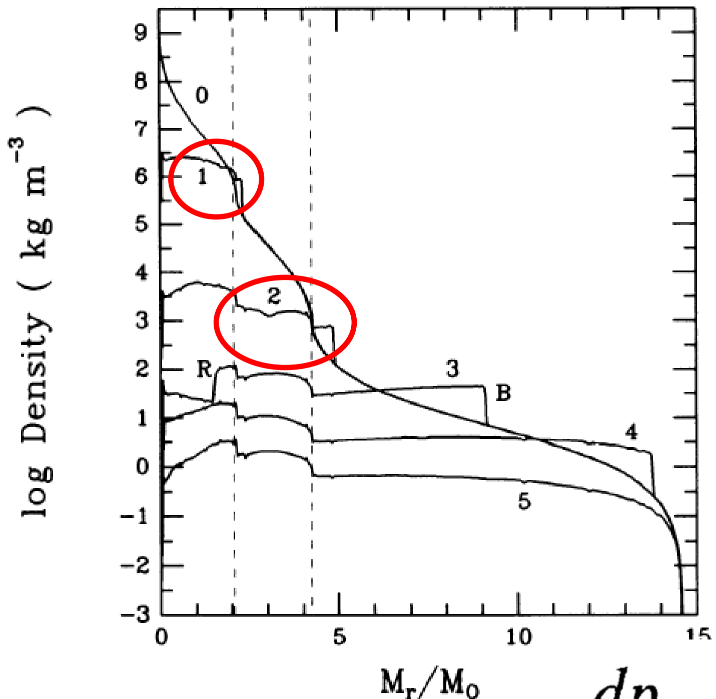
$$g \times \frac{d\rho}{dr} = \frac{1}{\varrho}\frac{dp}{dr} \times \frac{d\rho}{dr} < 0$$

Location is at boundaries of layers.

Ebisuzaki, Shigeyama, Nomoto 89

He/O H/He





$$\frac{dp}{dr} \times \frac{d\rho}{dr} < 0$$

Unstable！！

$$a = - \frac{1}{\varrho}\frac{dp}{dr}$$

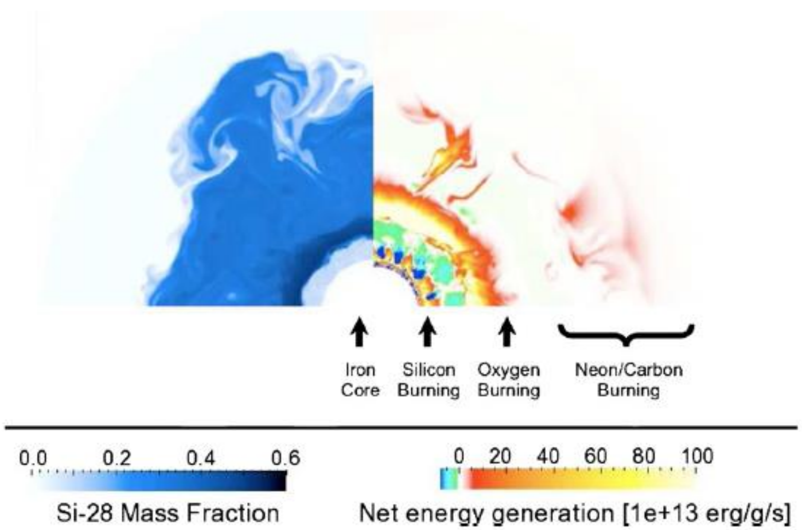
At the boundaries, the first term is positive and Second term is negative.
From the first term, effective gravity is outward.
From the second term, heavy matter is inside and light matter is outside.

Open Question:Where are Seeds?

$$\frac{dp}{dr} \times \frac{d\rho}{dr} < 0$$: Where the seeds of instabilities？

Candidate 1. Density perturbations in Progenitor Star

Bazan & Arnett 94, 98. Arnett & Meakin 11
Amplitude of Density fluctuation is less than 10%.



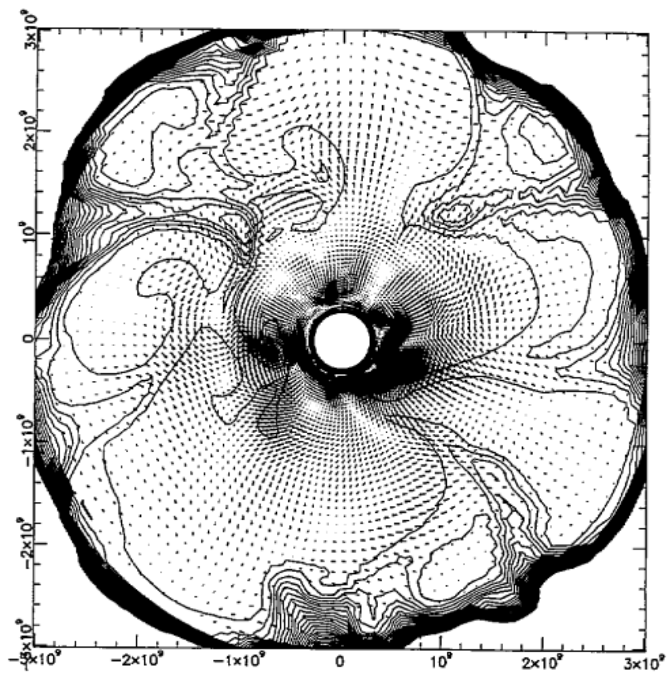
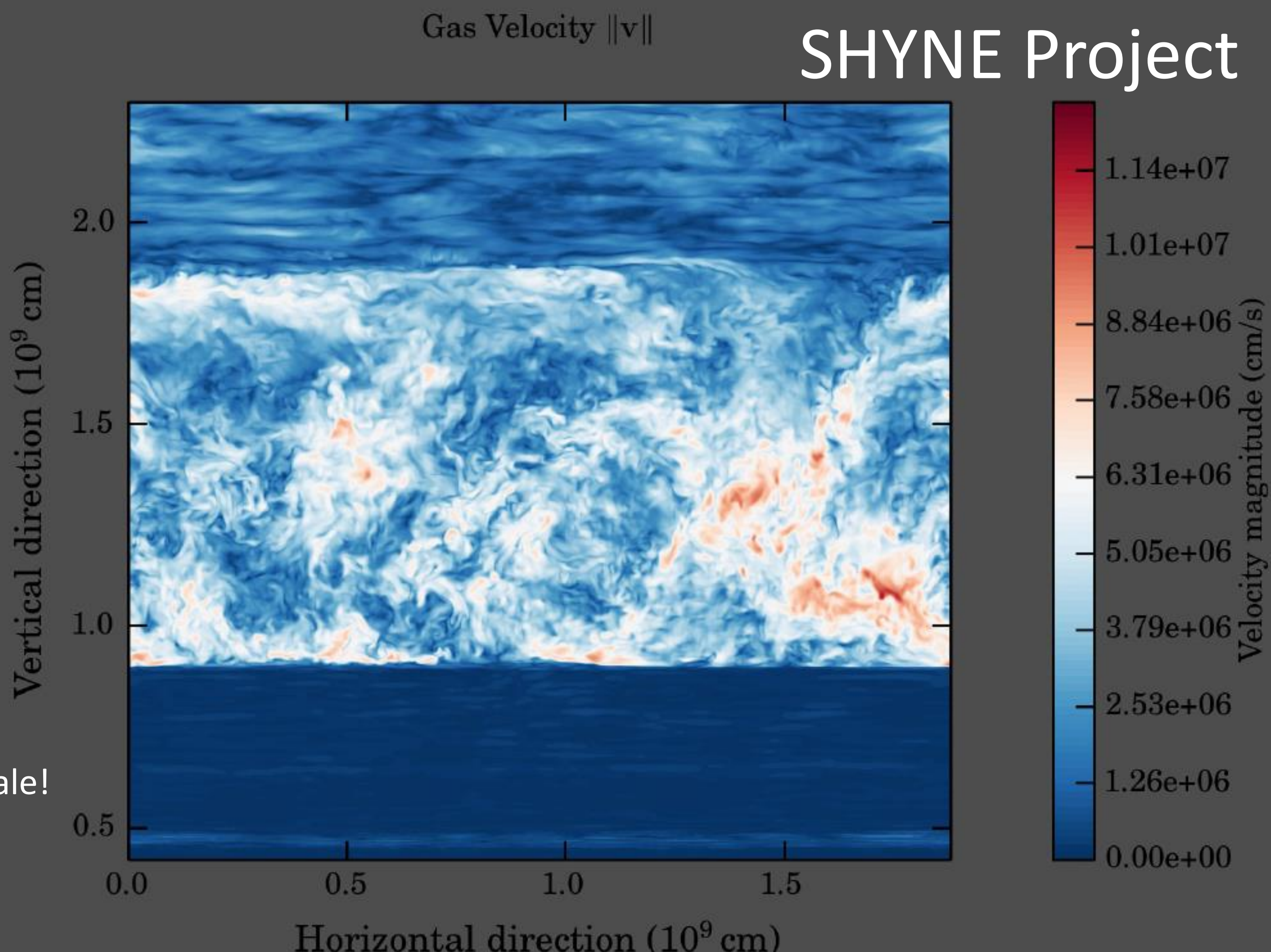


FIG. 2.—Silicon-calcium abundance

C-shell Simulations

Snapshot from 1024^3 resolution run:

SHYNE Project



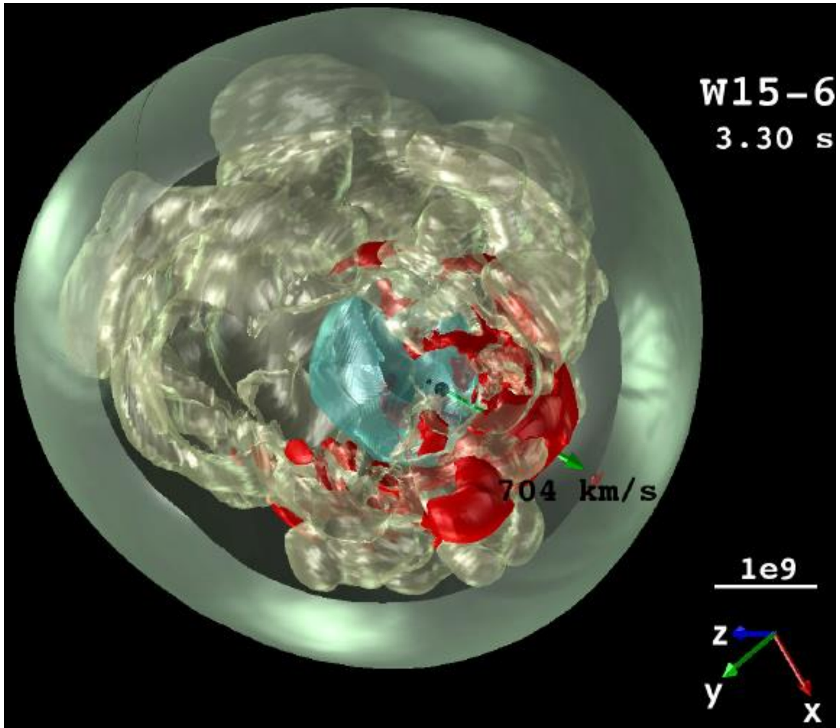
Good Try, but
Short Timescale!

Open Question: Where are Seeds?

$$\frac{dp}{dr} \times \frac{d\rho}{dr} < 0$$: Where the seeds of instabilities？

Candidate 2. Supernova Explosion.

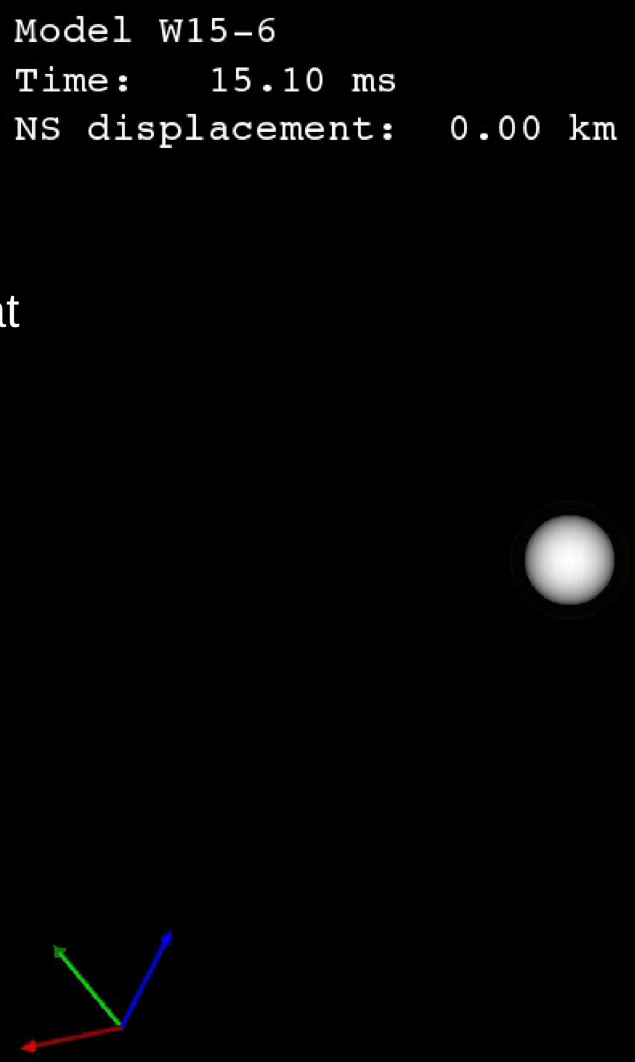
Amplitude of density
Fluctuation can be
Greater than 10%.



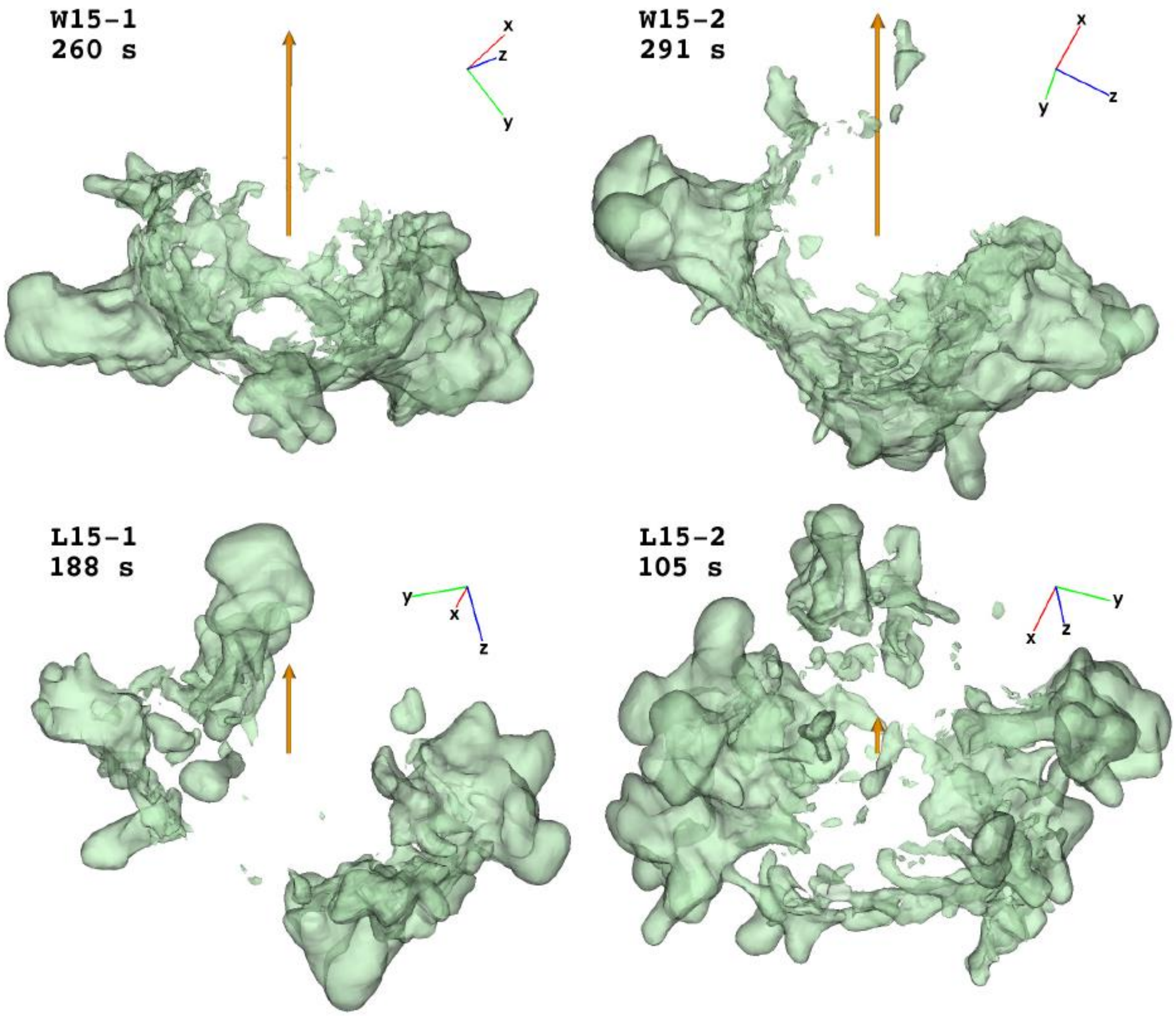
A. Wongwathanarat
(RIKEN)

Spontaneous Asymmetric Explosion

A. Wongwathanarat
(RIKEN)

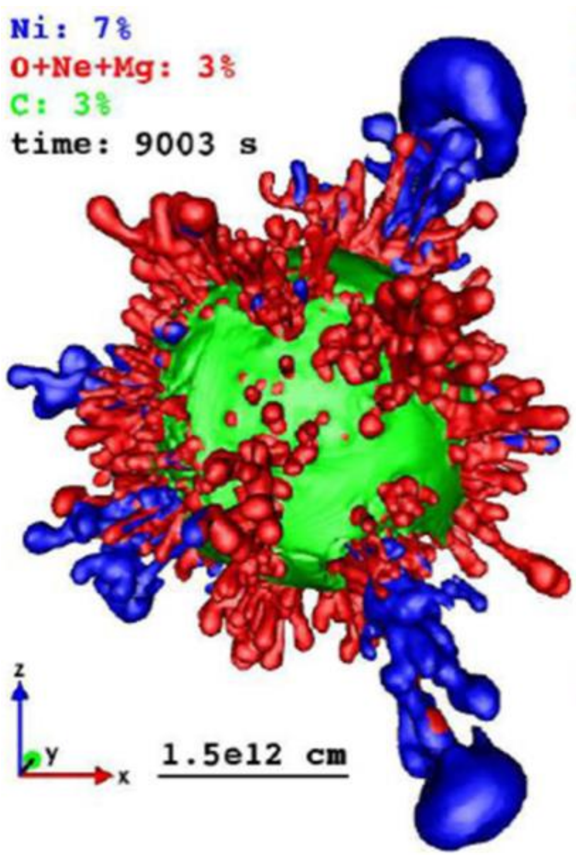


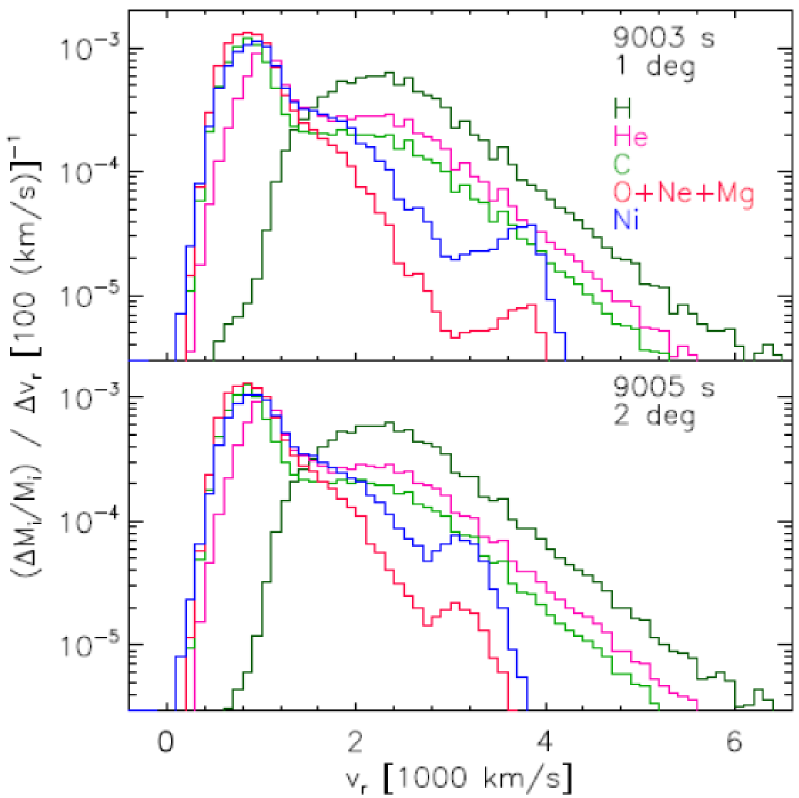
Asymmetric Ejection of 56Ni & Neutron Star Kick



A. Wongwathanarat
(RIKEN)

Successful Reproduction of High Velocity Component of 56Ni



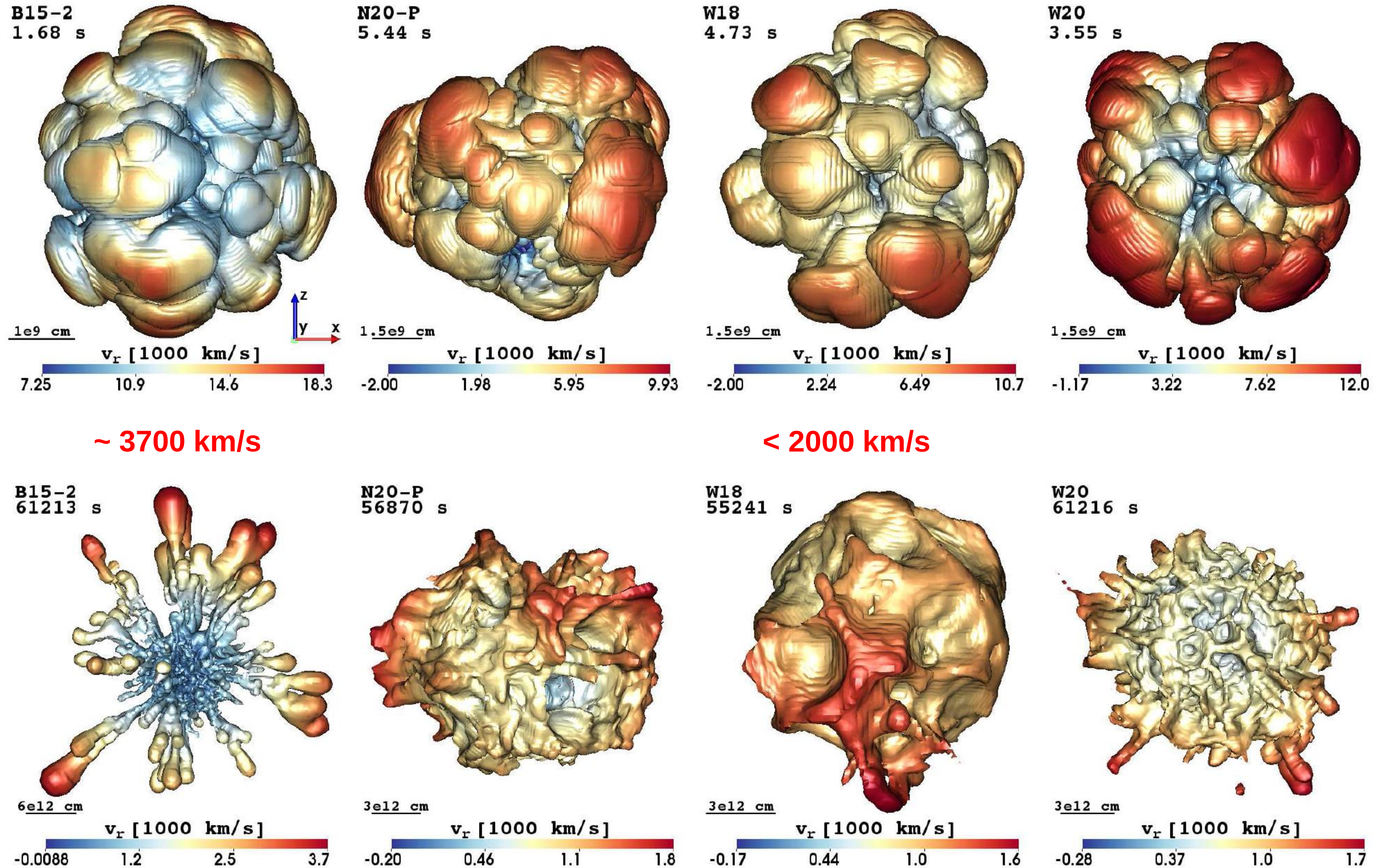


A. Wongwathanarat (RIKEN)

Progenitor dependence is Huge

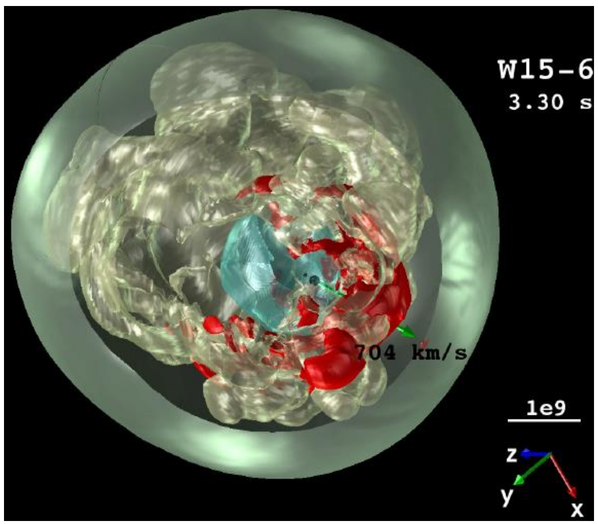
Wongwathanarat et al. (2015)

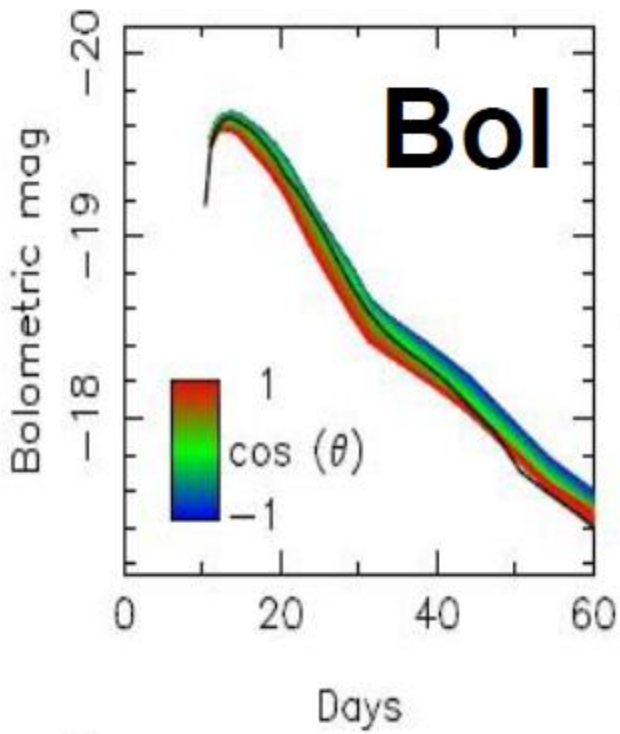
Woosley et al. (1988)	Shigeyama & Nomoto (1990)	Woosley (2007)	Woosley et al. (1997)

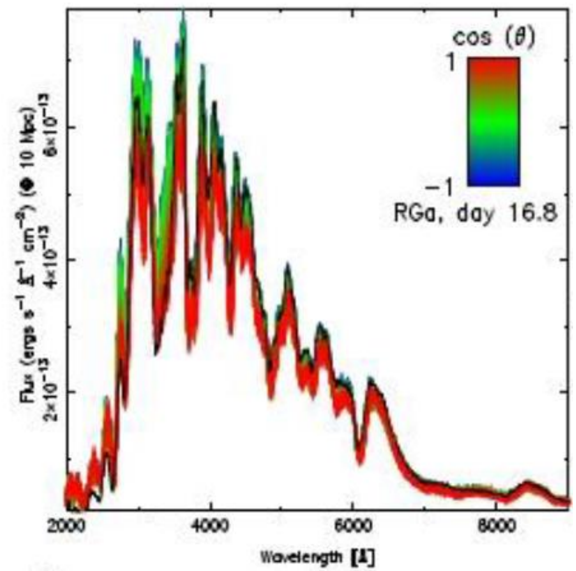


Great Collaborations Started

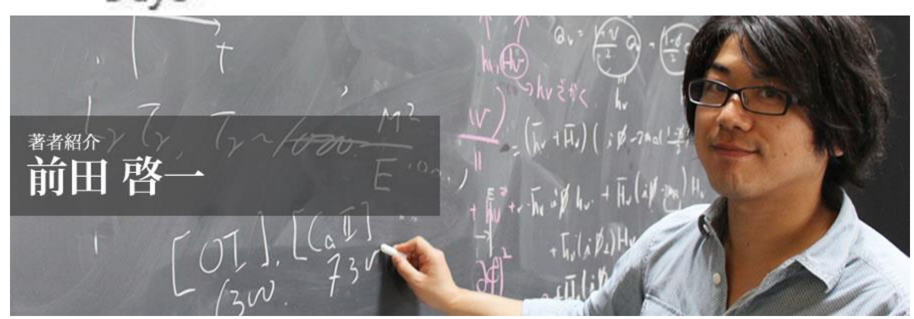
- Radiation Transfer, including Gamma-Ray Line Transfer



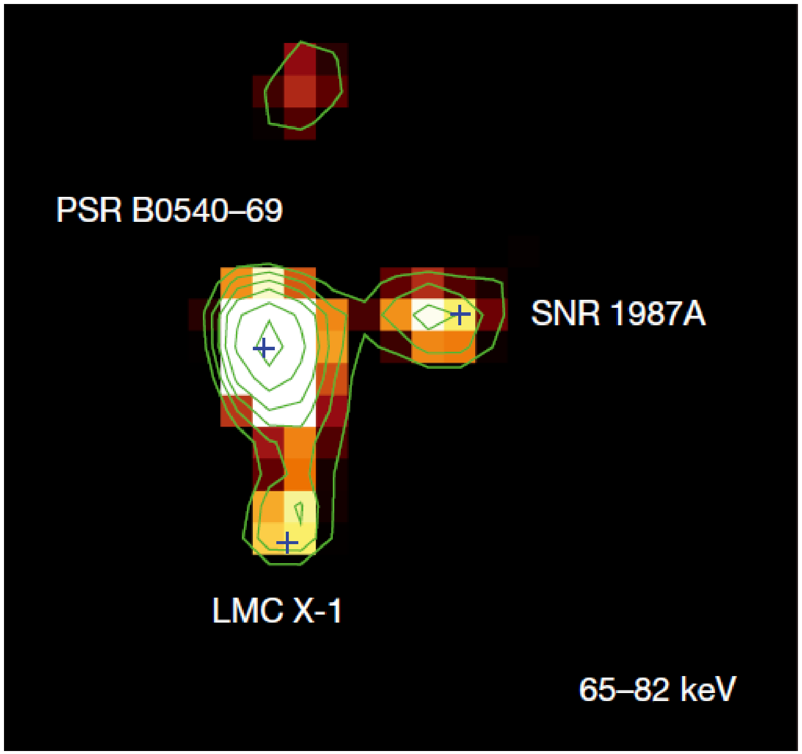


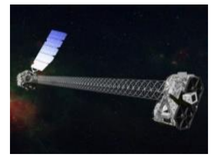


Left:
A. Wongwathanarat (RIKEN)
Right:
K. Maeda (Kyoto)

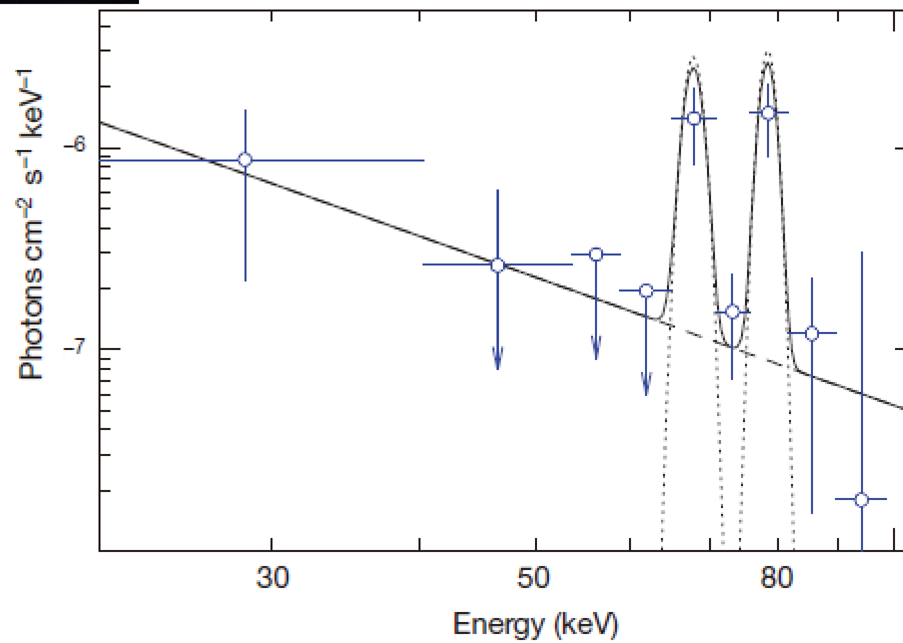


Recent & Exciting Observations (1)
Lots of 44Ti in SN1987A!





Grebenev et al. Nature 12
NuSTAR(2012-)

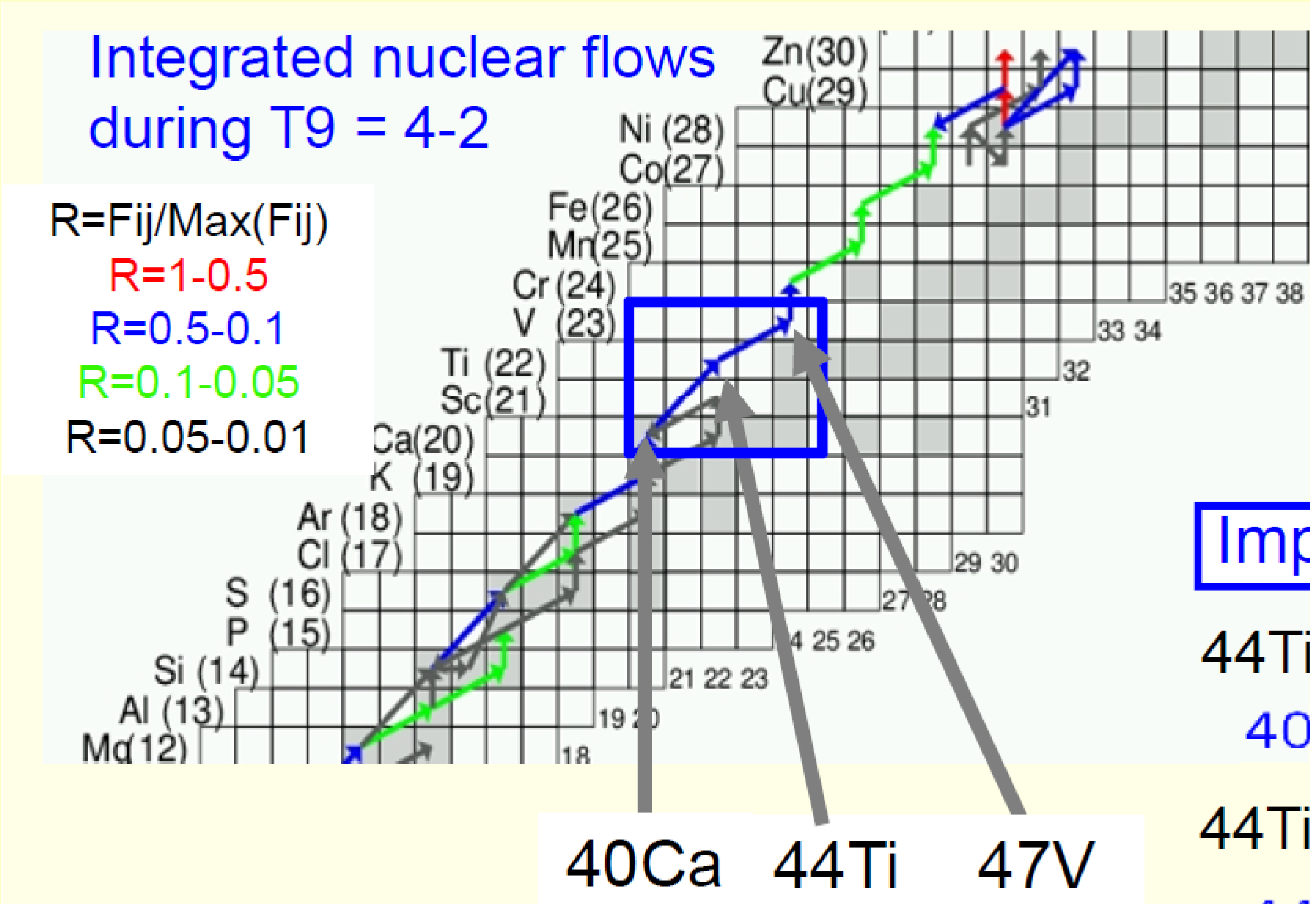


$$^{44}\mathrm{Ti} \sim (3.1 \pm 0.8) \times 10^{-4} M_{\odot}$$

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

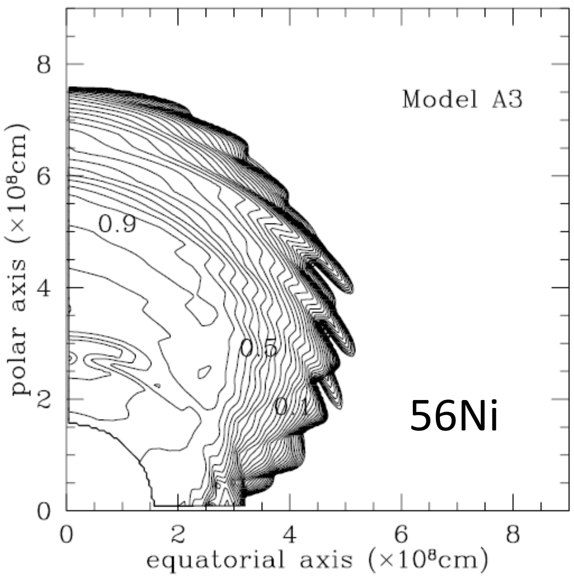
$^{44}Ti(\alpha,p)^{47}V$

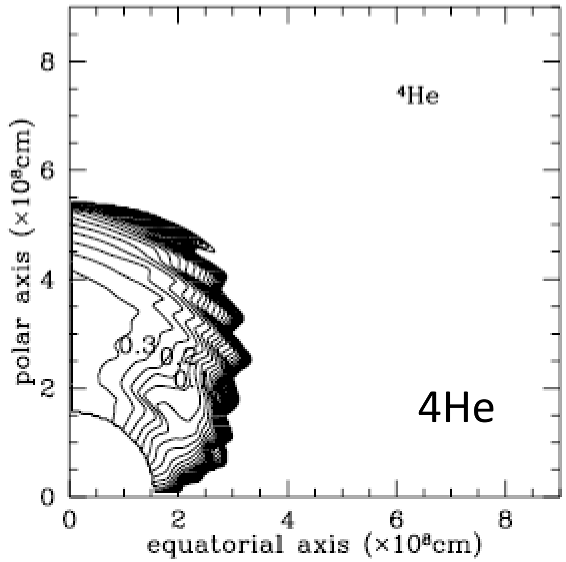
Slide from S. Fujimoto

For α-rich, High Entropy per Baryon.

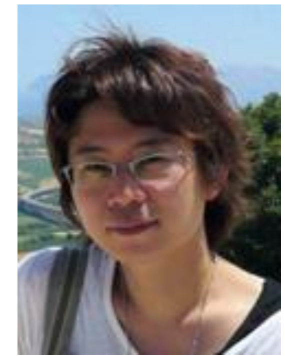
- $S \sim T^3/\rho$.
- For High Entropy per baryon (S),
  high temperature & (relatively) low density are preferred.
- The balance between Fe ⇔ He, p, n depends on entropy.
- T is related with photo-dissociations, while ρ is related with nuclear reactions.

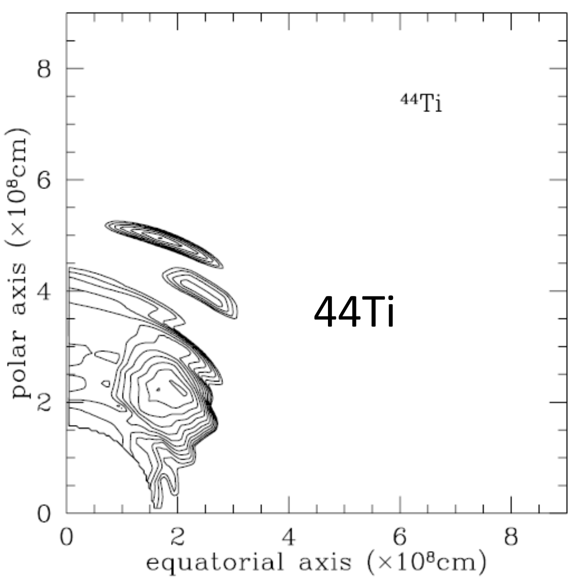
Lots of 44Ti in Bipolar Explosion?





Nagataki et al. 97,
Nagataki 00



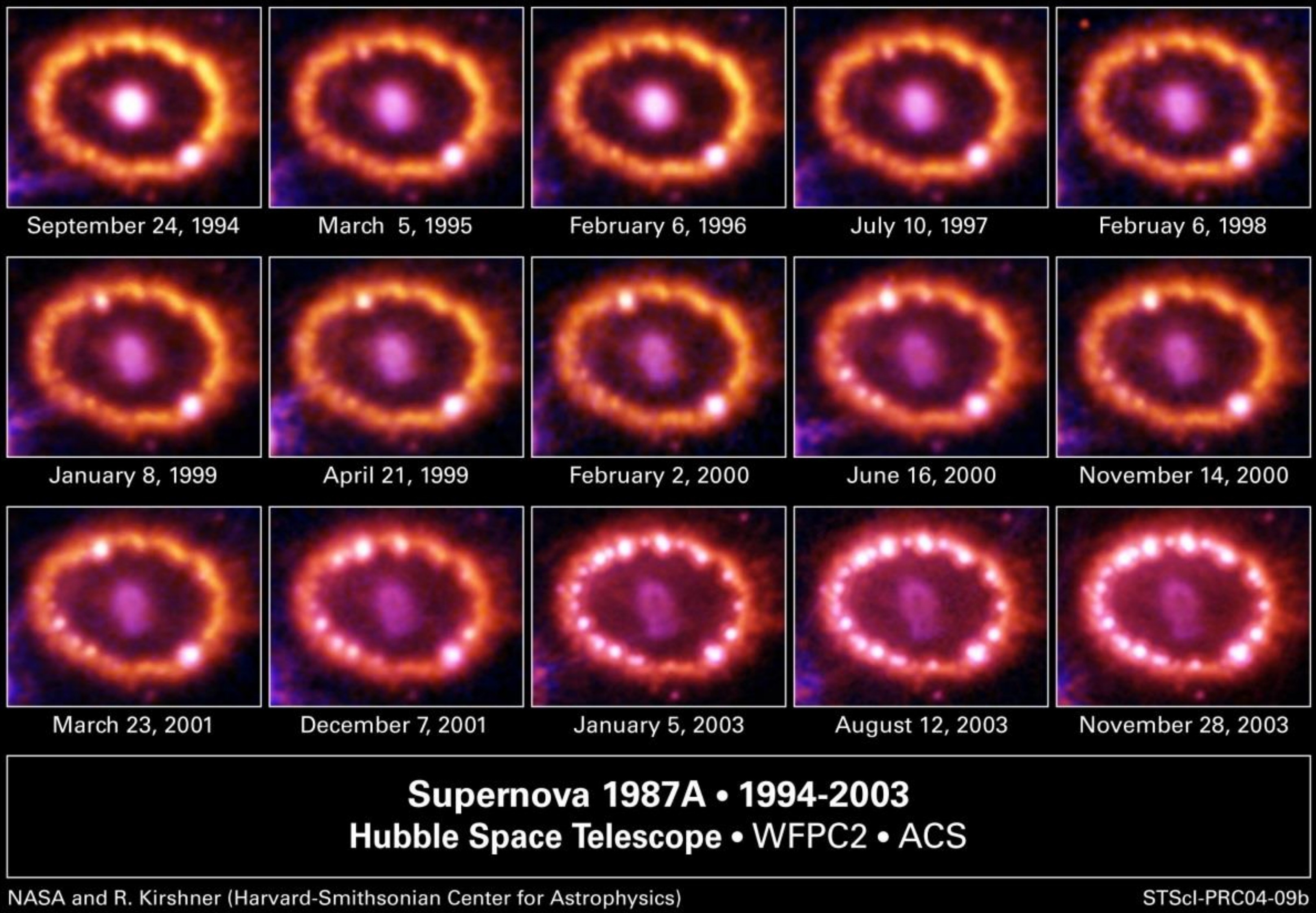


Produced amount of 44Ti:

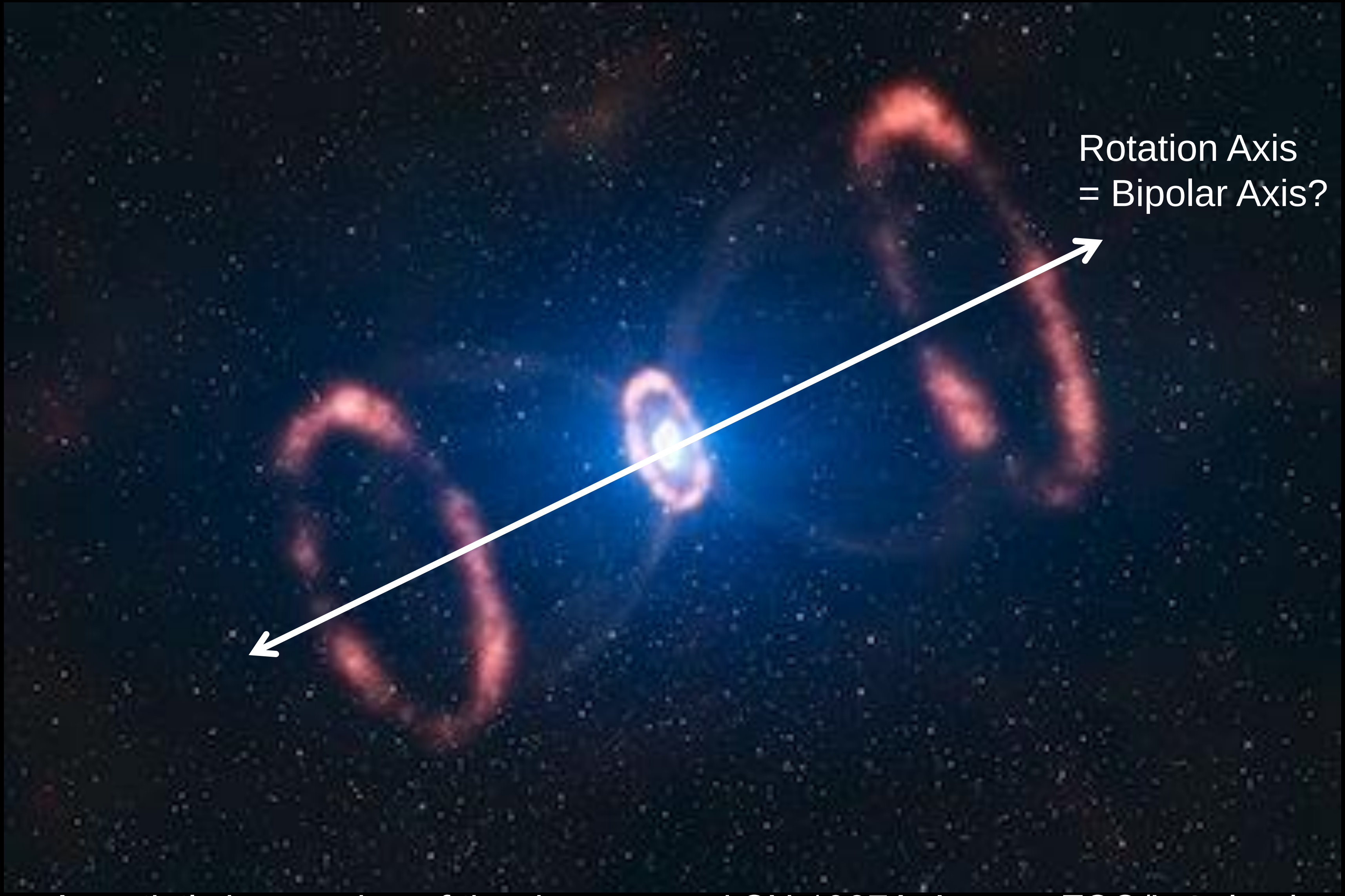
$$(1\text{-}5) \times 10^{-4} M_{\odot}$$

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

Bipolar Explosion in SN1987A ?



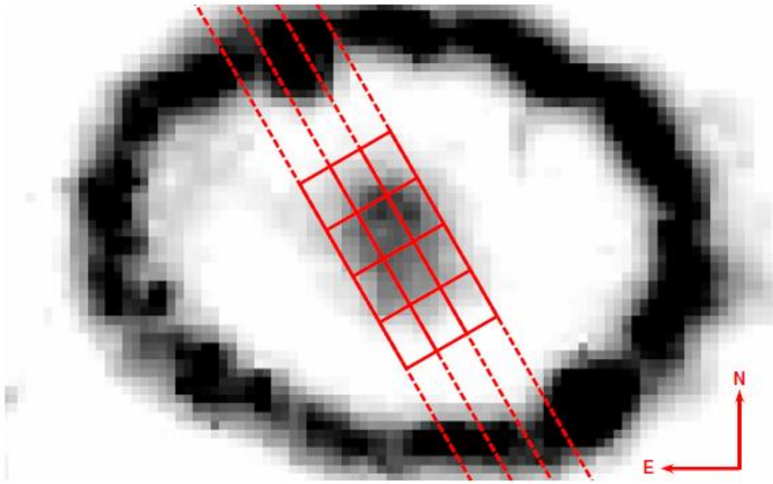
Rotation Axis at the Progenitor Phase

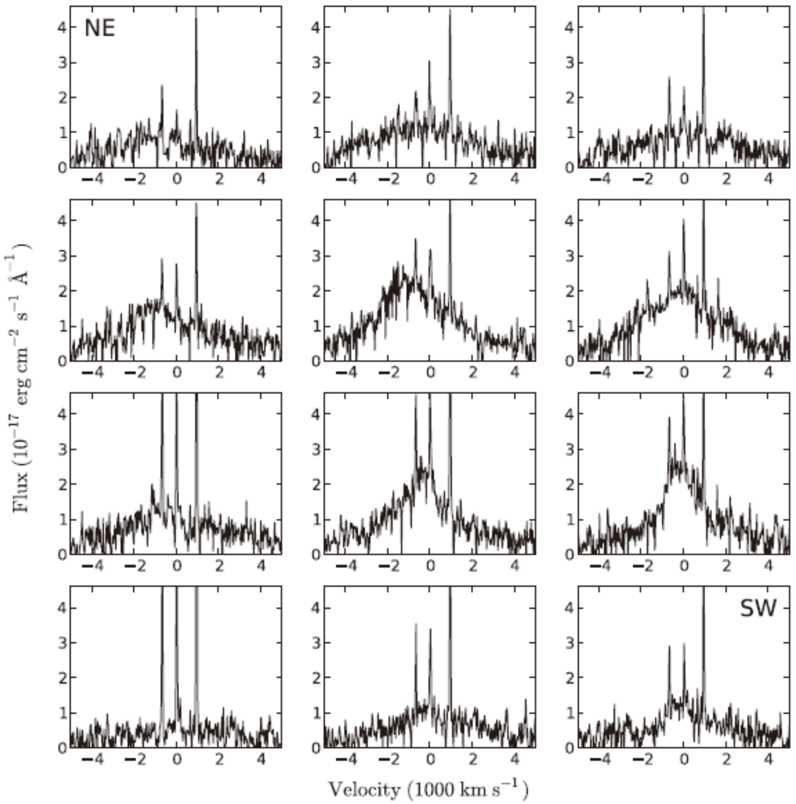


An artist’s impression of the rings around SN 1987A. Image: ESO/L Calçada

Velocity Distribution is Resolved Now.

Larsson et al. 2013



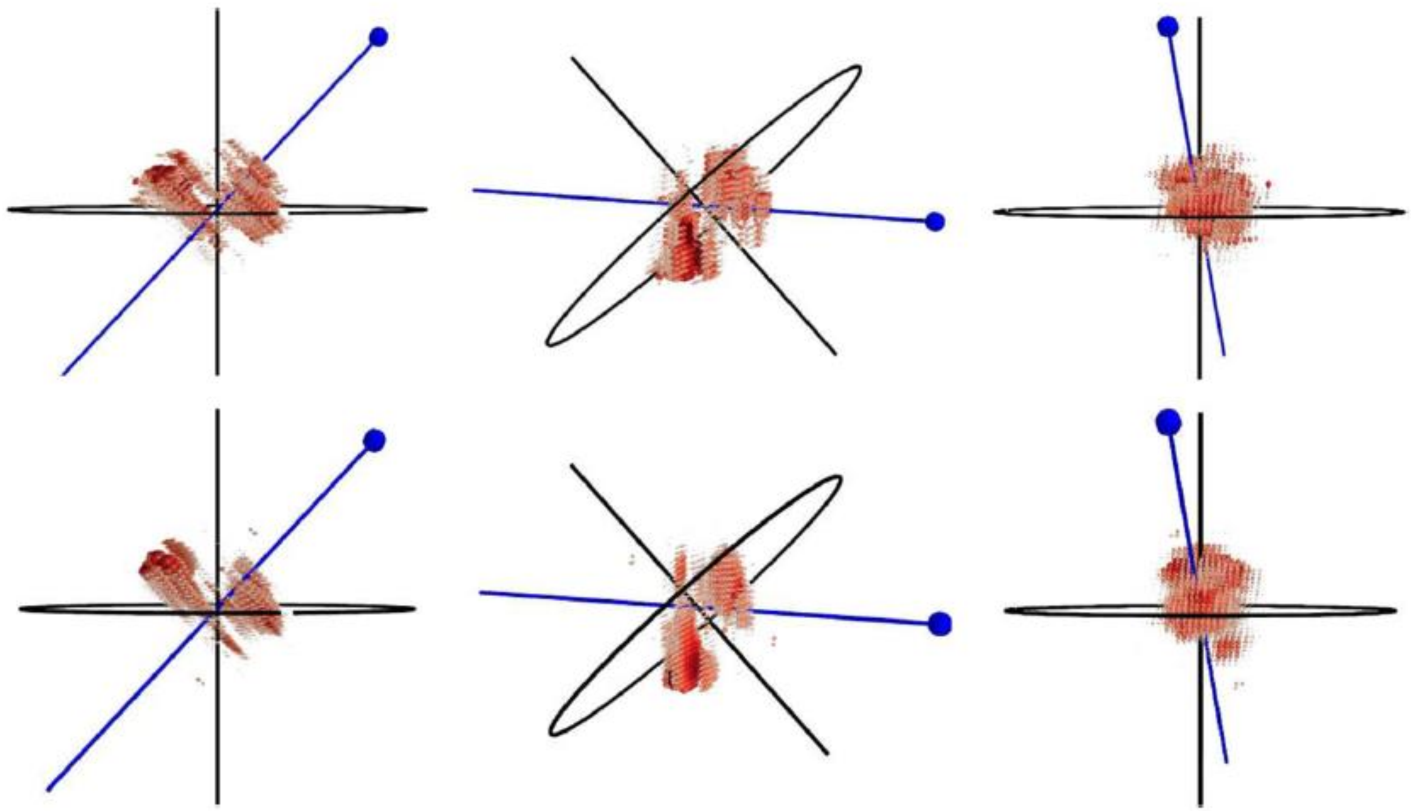


Thanks to the Expansion of the Ejecta, Velocity of each segment can be obtained.

Nature is More Complicated.

Larsson et al. 2013

Blue : Earth Black : Ring & Rotation Axis (at the progenitor phase)
Red : Matter Distribution of Si & Fe.



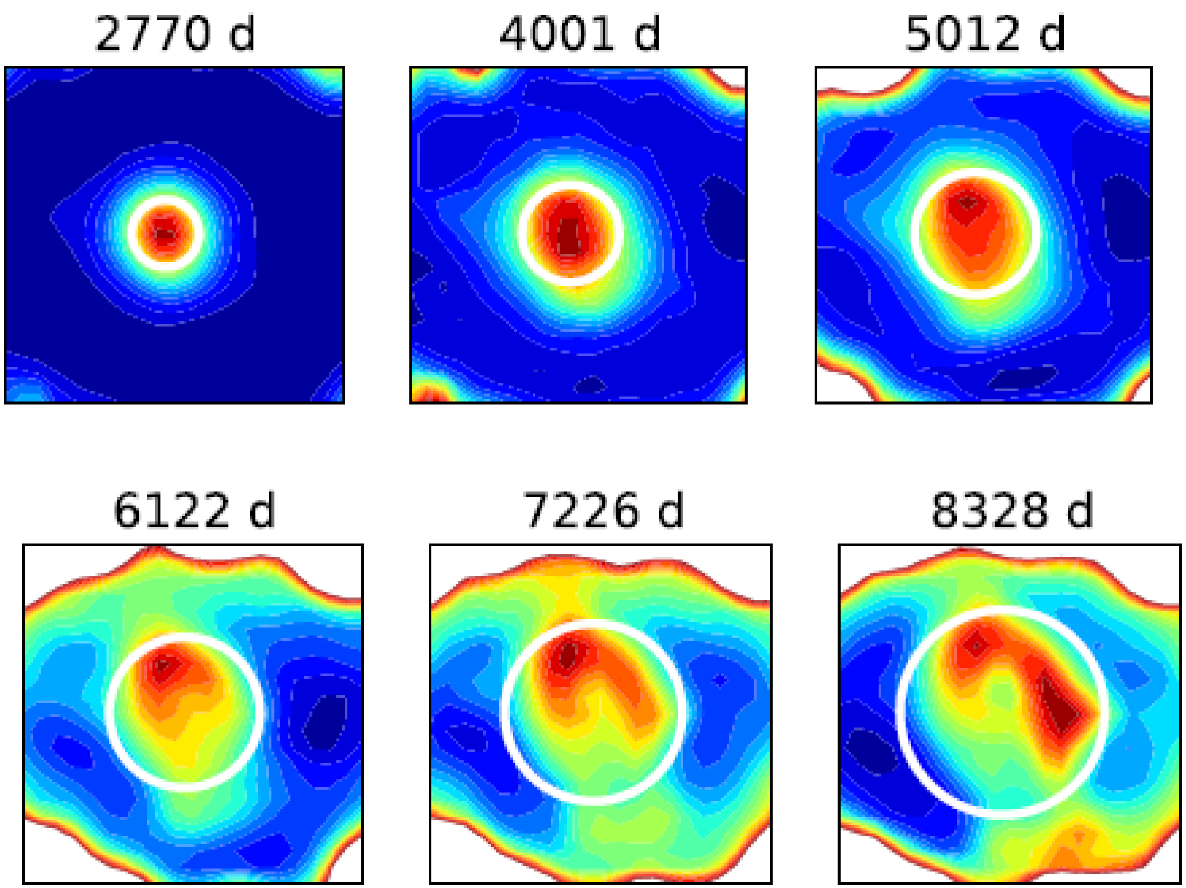
Bipolar Like. But Bipolar Axis ≠ Rotation Axis. Why?

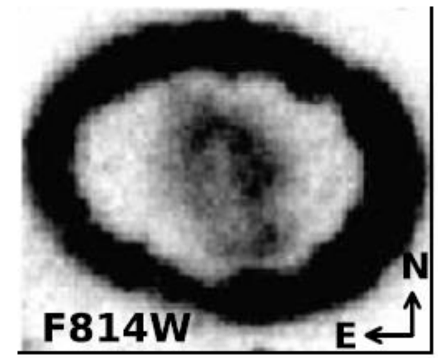
Recent & Exciting Observations (2)
Ejecta Start to Interact with the Ring!

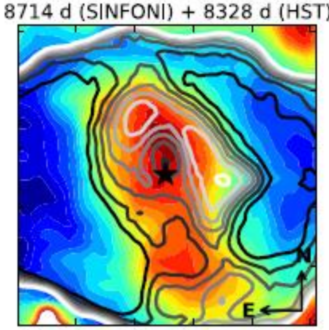
～ From Supernova to Remnant ～

Larsson et al. 2013

Hubble Telescope



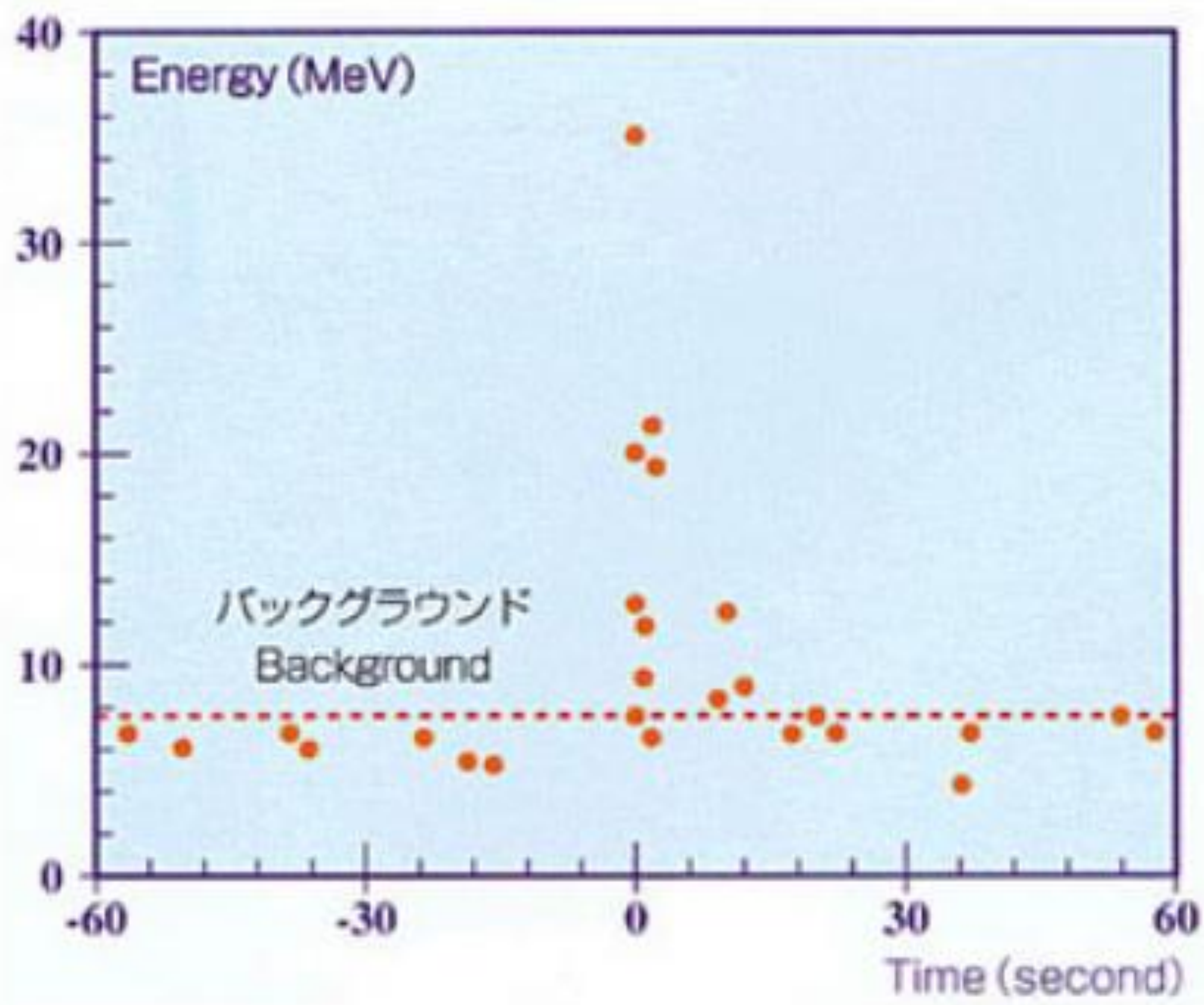




Line: Hα
Color: Si+Fe lines

Image of SN1987A by Hα line. Ring is Outside.

The Missing Neutron Star.



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?

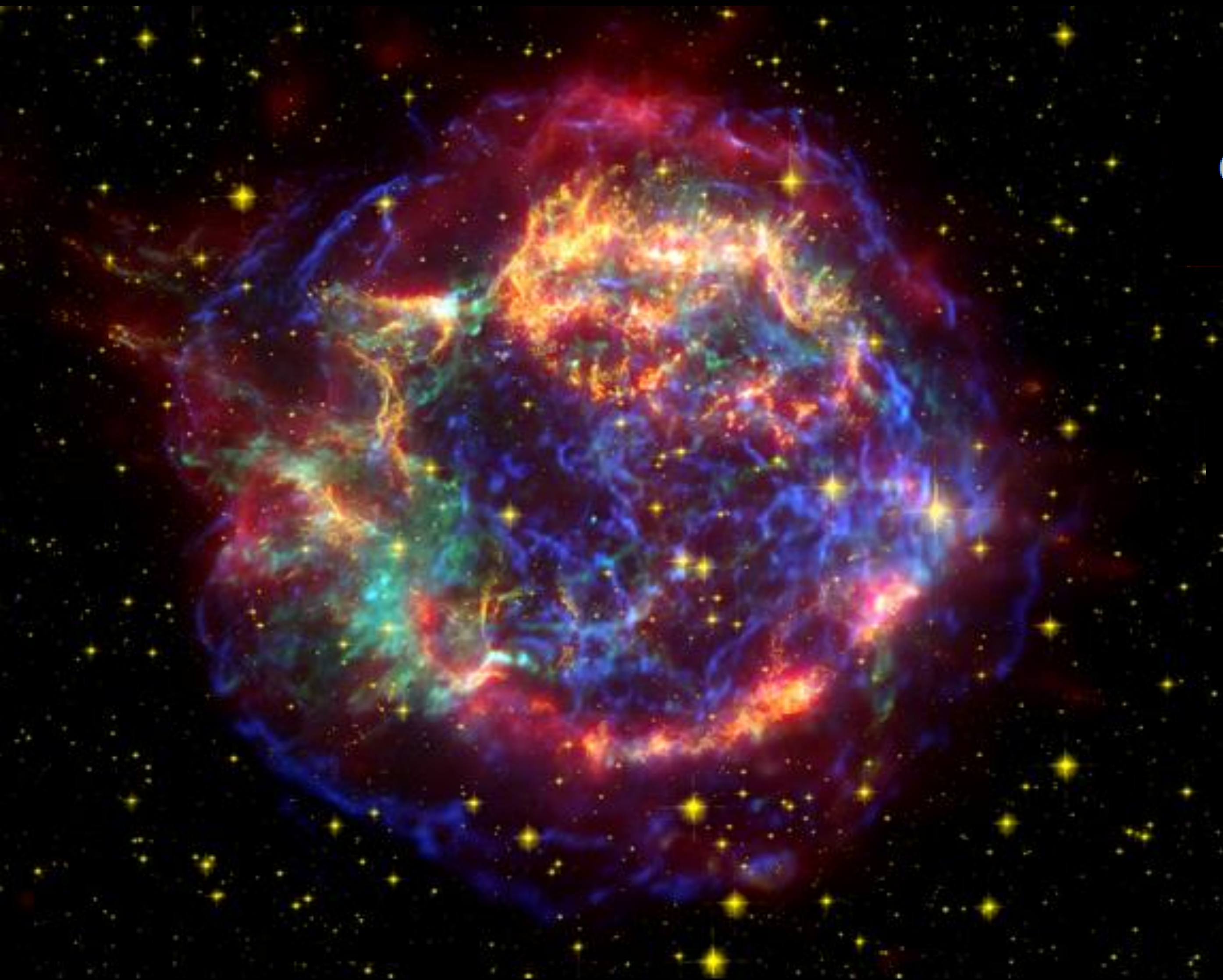
Questions for SN1987A

- Did Bipolar/Jet-like Explosion Happen for SN1987A?
- Why the Bipolar-Like Axis is Different from the Axis of Rotation in the Progenitor Star Phase?
- How will the SN Ejecta Evolve?
  How the Ejecta will Collide with the Ring?
- Where is the Central Compact Object (Probably Neutron Star, but maybe Black Hole Now)?

Very Exciting!

§ Explosive Nucleosynthesis
&
Cassiopeia A

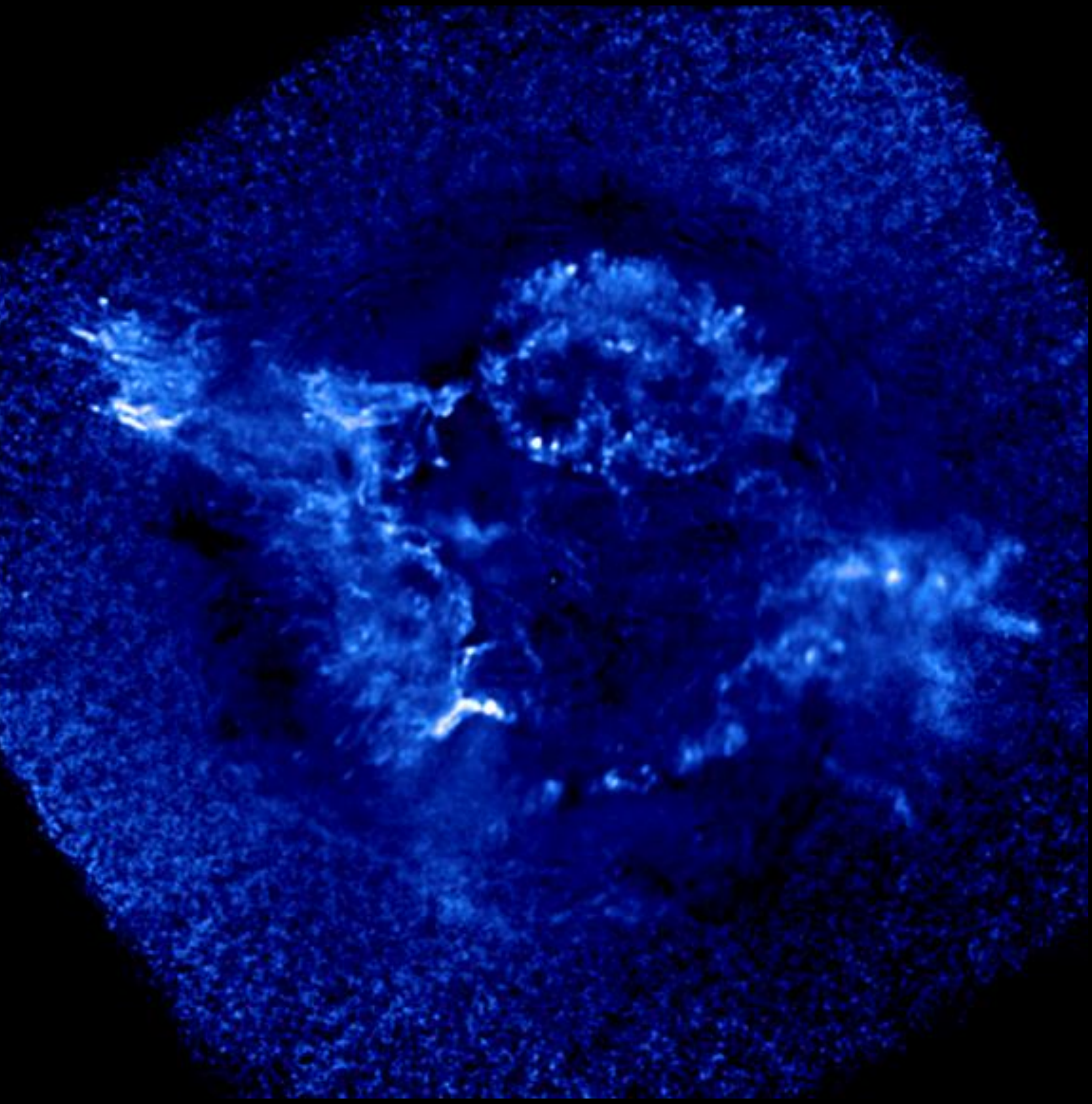
Cassiopeia A: Young Supernova Remnant



age: ~350 yr
distance: 3-4 kpc
size: 5' ~5-7 pc

multi-wavelength composite:
- X-rays (Chandra)
- near IR (Hubble)
- infrared (Spitzer)

Jets in Cas A Seen by Chandra?

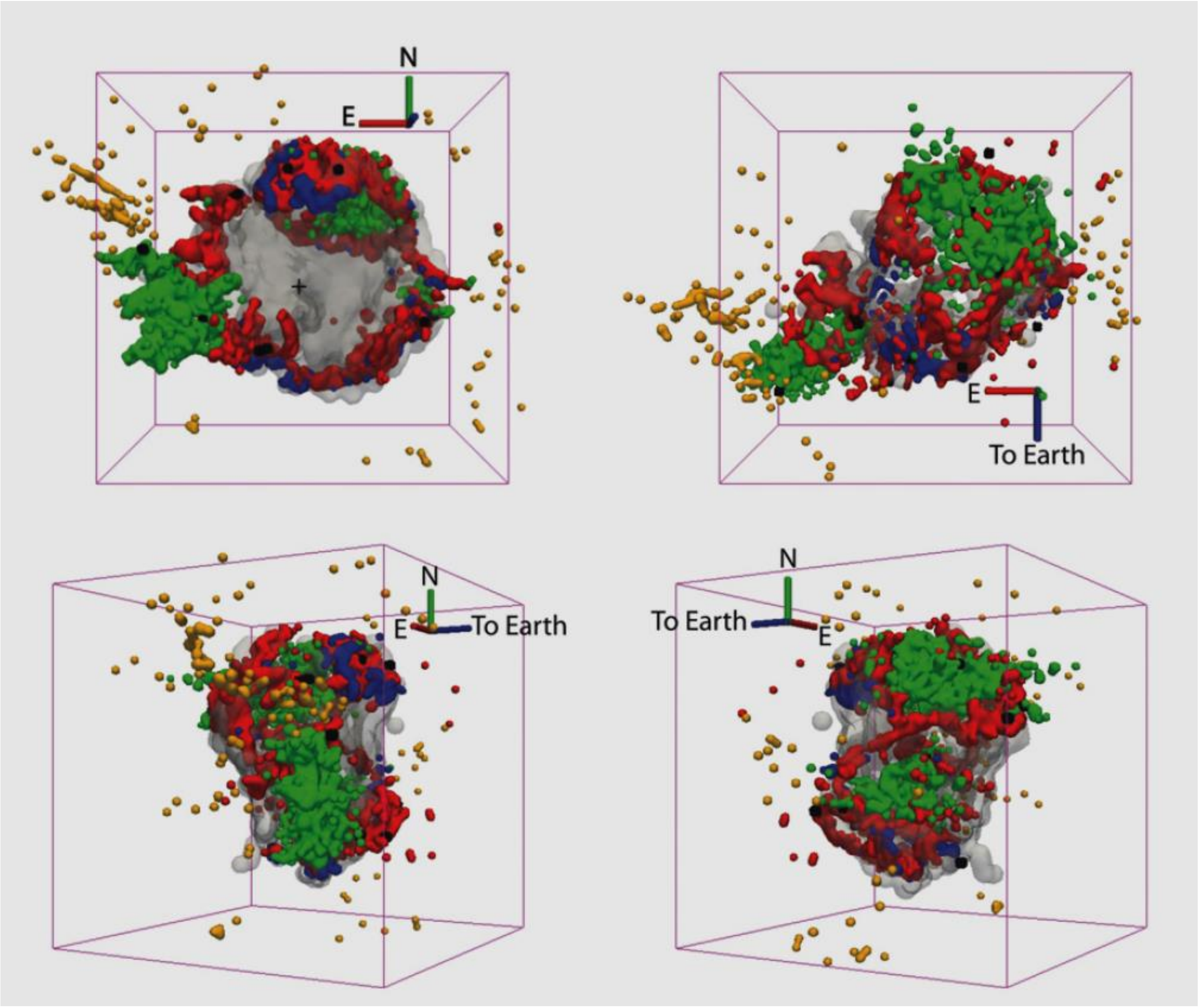


age: ~350 yr
distance: 3-4 kpc
size: 5’ ~5-7 pc

From Chandra HP

This image shows the ratio of the intensity of the X-radiation from silicon ions with two orbital electrons to the intensity of X-radiation at slightly lower energies, which is due primarily to magnesium and iron ions.

3D structure of Cas A: Fe is Outside!



Delaney et al. 2010

Green: X-ray Fe-K

Black: X-ray Si XIII

Red: IR [Ar II]

Blue: [Ne II]/[Ar II]

Grey: IR [Si II]

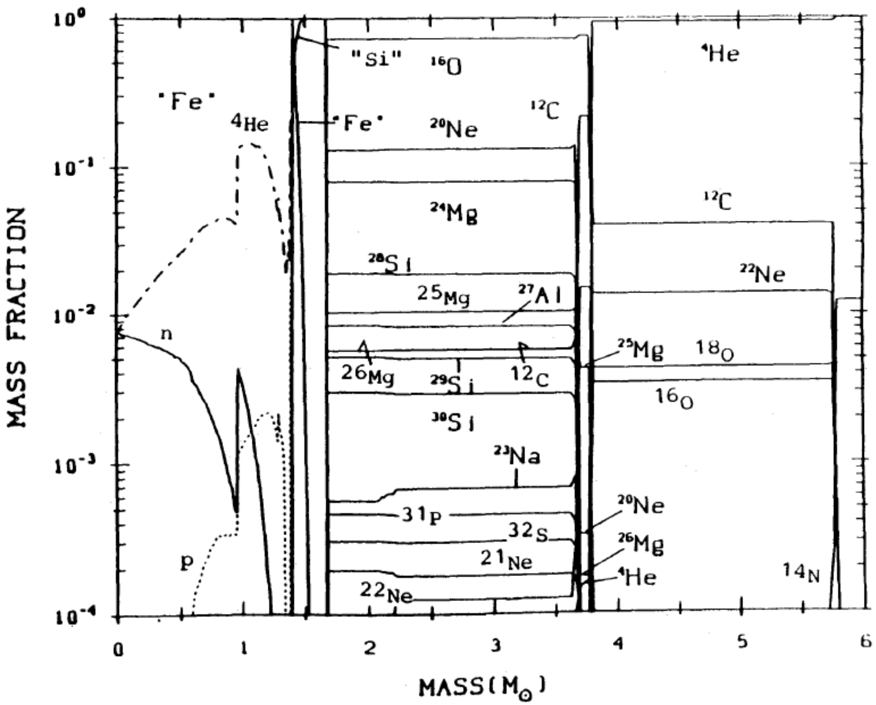
Yellow: optical outer ejecta

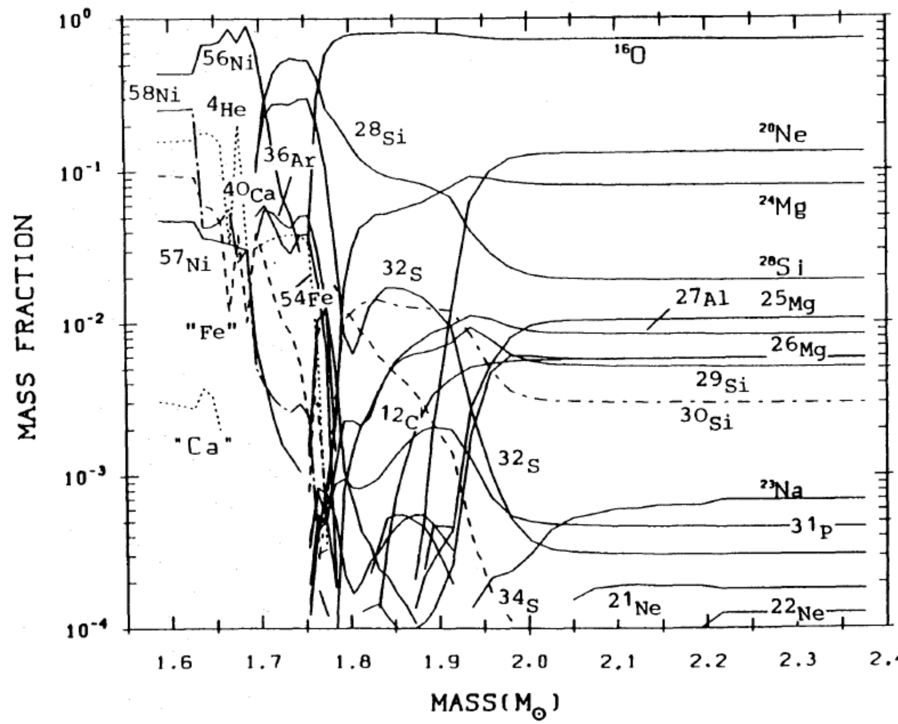
Chandra 's X-rays & Spitzer 's Infrared

Explosive Nucleosynthesis

Spherical Explosion Model

Hashimoto, Nomoto, Shigeyama 1989





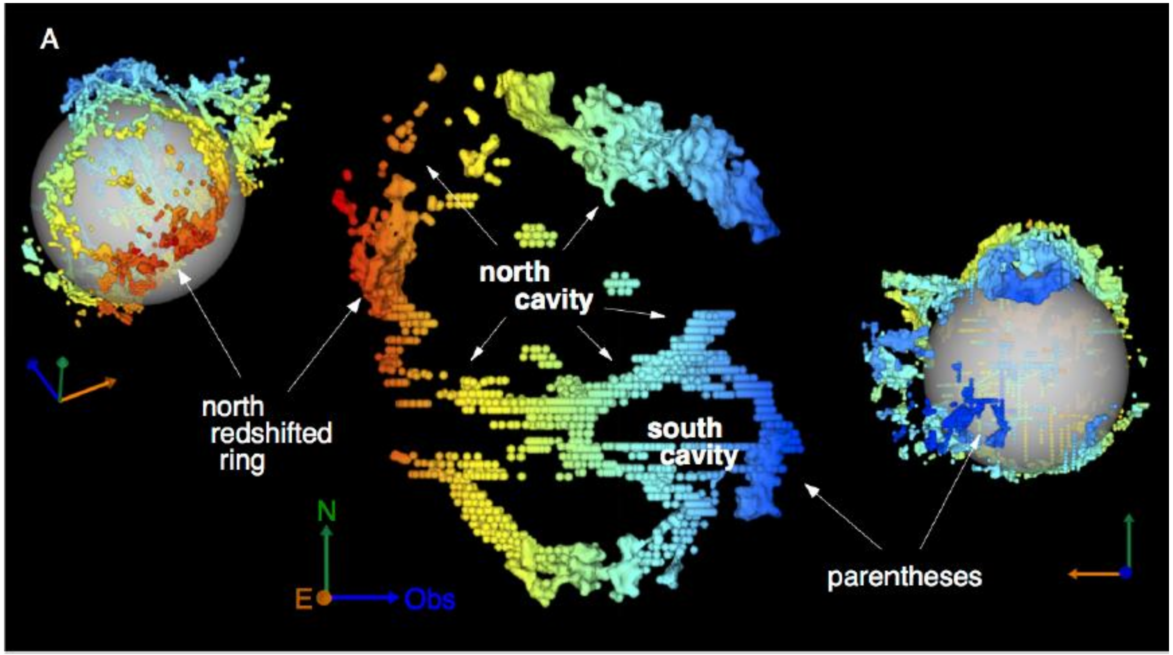
0 3 6 1.6 2.4

Before Explosion（Progenitor）

After Explosion (< ～10 sec.)

Enclosed Mass (M) = $\int_0^R 4\pi\rho r^2 dr$

3D Structure of Cassiopeia A



Milsarvljevic & Fesen Science (2015).

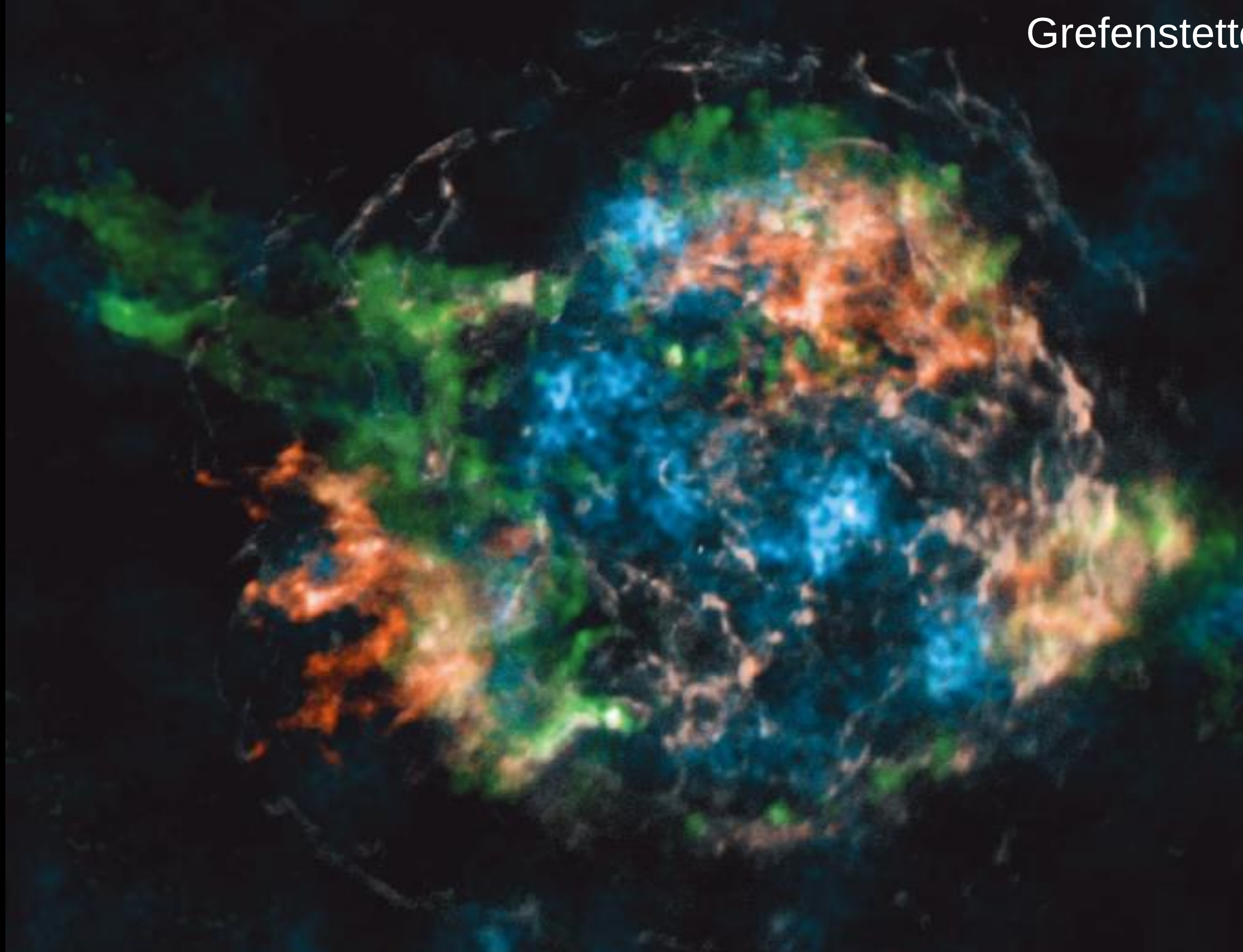
Dan Milsarvljevic
CfA Postdoctoral Fellow

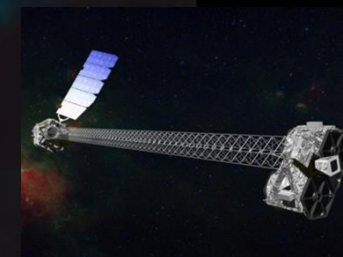
Bubble-Like Structure, deduced from [Si III] line.
Colors represent Doppler velocities from -4000km/s to 6000 km/s.

https://www.cfa.harvard.edu/~dmilisav/Homepage_of_Dan_Milisavljevic_(SAO)/Welcome.html

44Ti is inside of Cas A!

Grefenstette et al. 2014

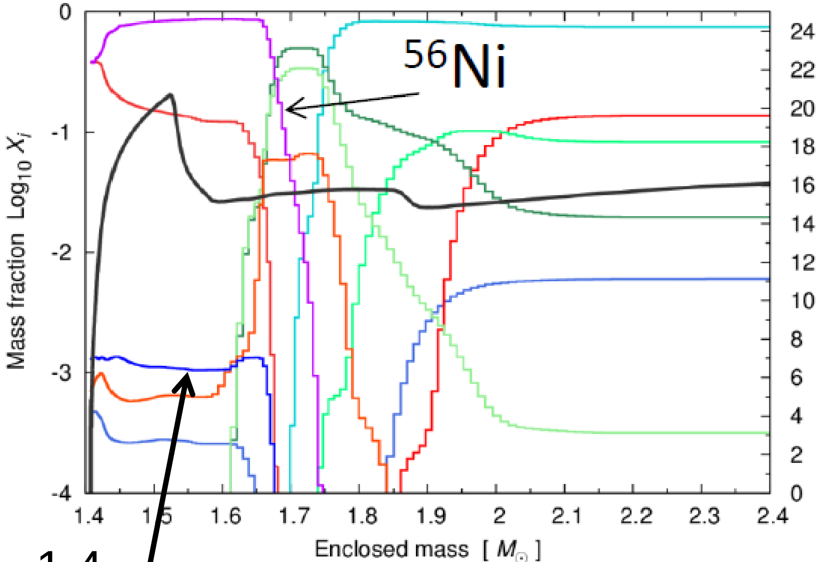




Blue: 44Ti, Green: Si/Mg, Red: Fe.

Composition & Velocity Profiles

Enclosed Mass (M) = $\int_0^R 4\pi\rho r^2 dr$

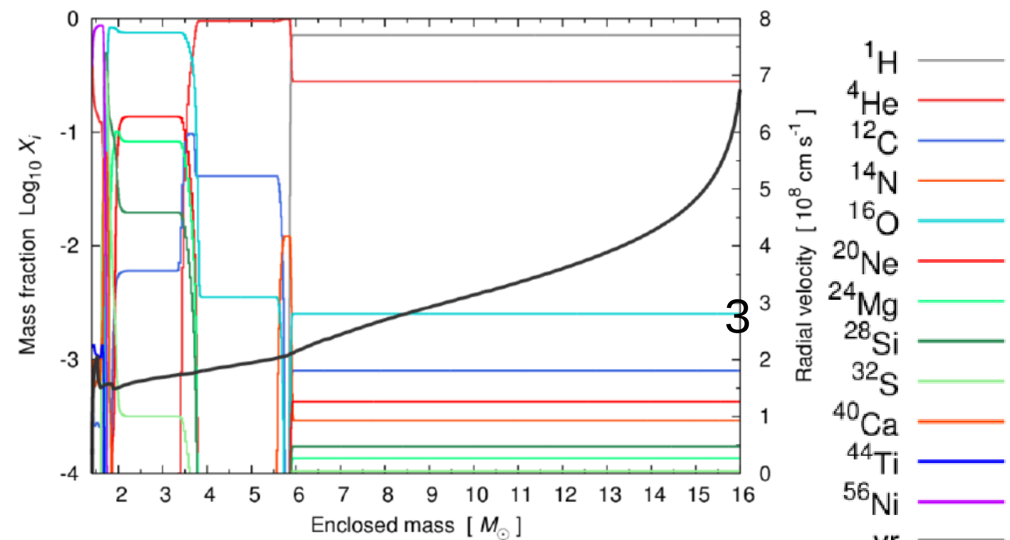


1.4

44Ti

2.4

Inner Part of the Star



2

16

Whole Profiles in the Star

～ a few hours after the explosion.

56Ni & 44Ti are trapped inside, with low velocity.

Lots of Mysteries

- Overturn of the Composition.
- Distribution of 44Ti & Fe.
- Bubbles?
- Jets?
- Si/S in the Jets?

Atomic Transition

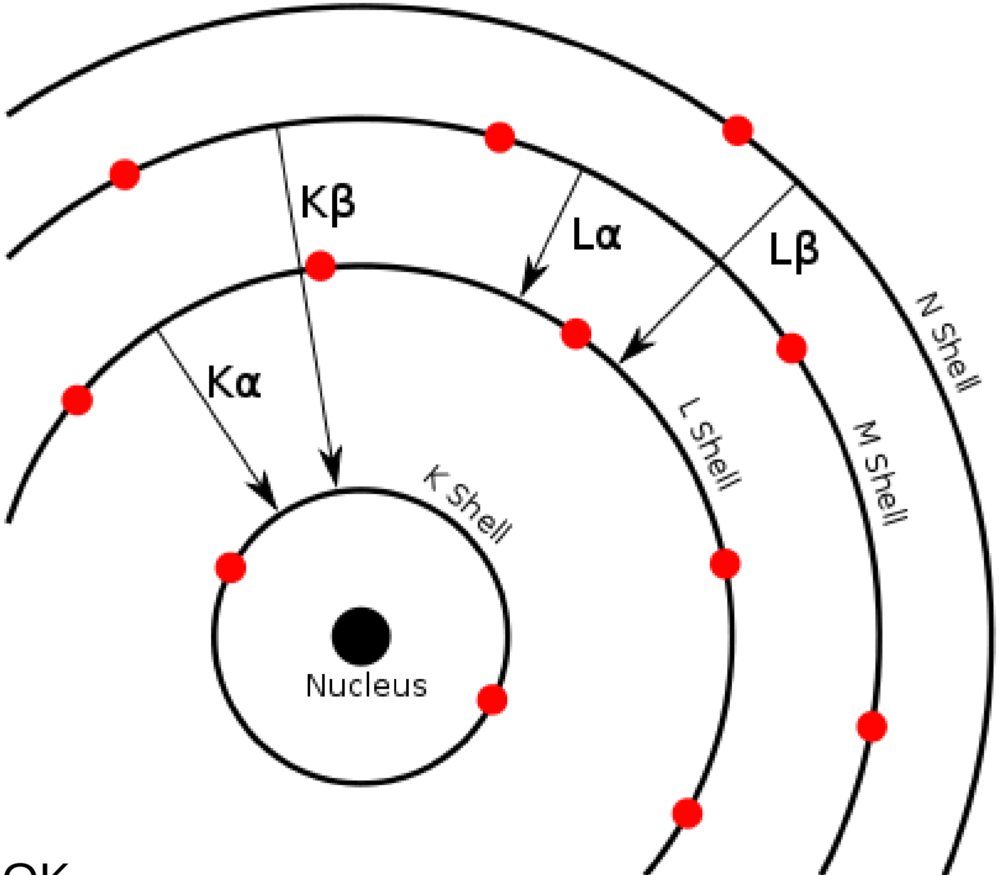


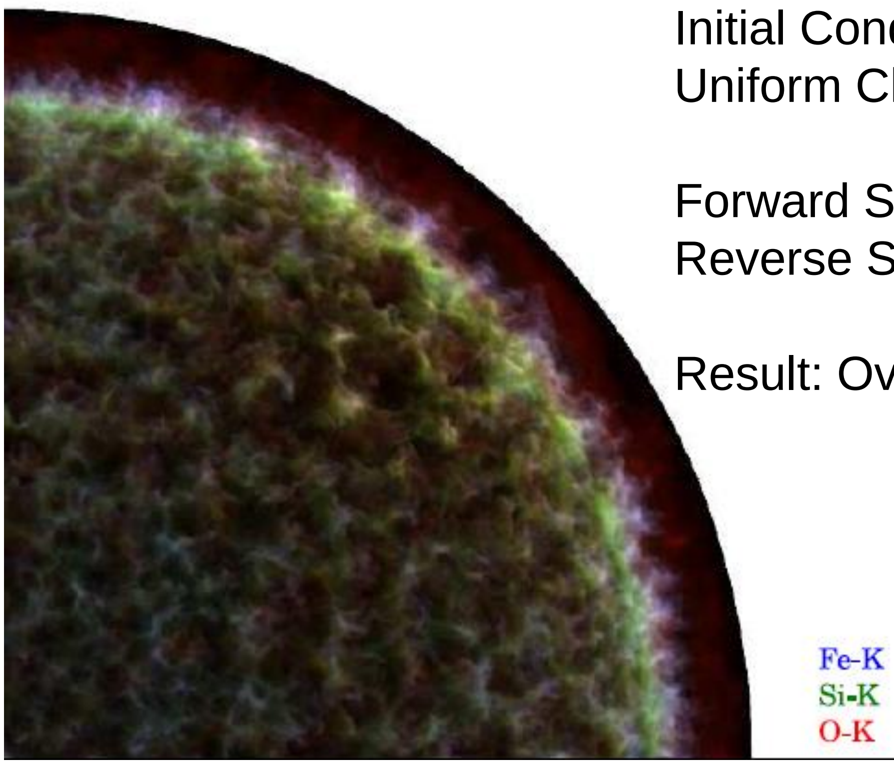
Figure from WIKIBOOK

https://en.wikibooks.org/wiki/Chemical_Sciences:_A_Manual_for_CSIR-UGC_National_Eligibility_Test_for_Lectureship_and_JRF/X-ray_fluorescence

Are We Seeing the Real Mass Distribution?

- Observed Intensity = Mass × Emissivity.
- Emissivity depends on Ionization State.

ON



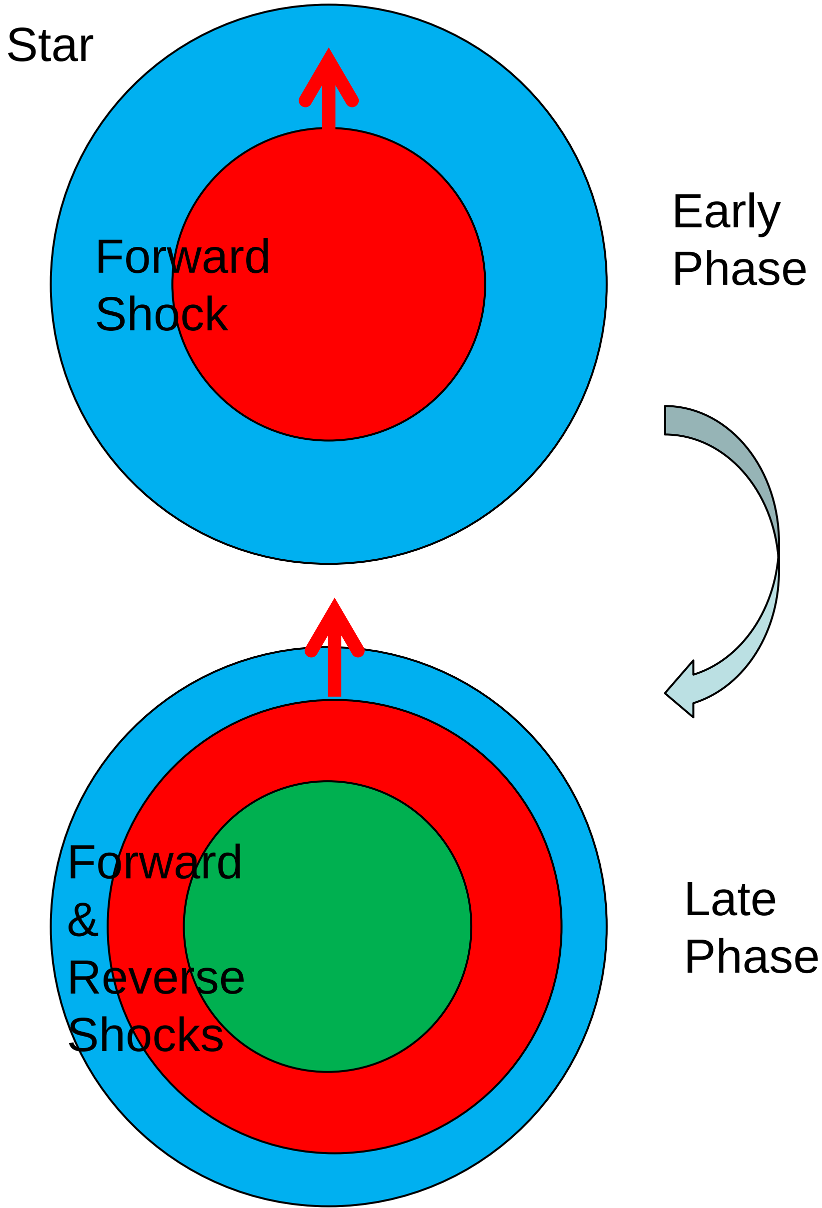
Initial Condition:
Uniform Chemical Composition.

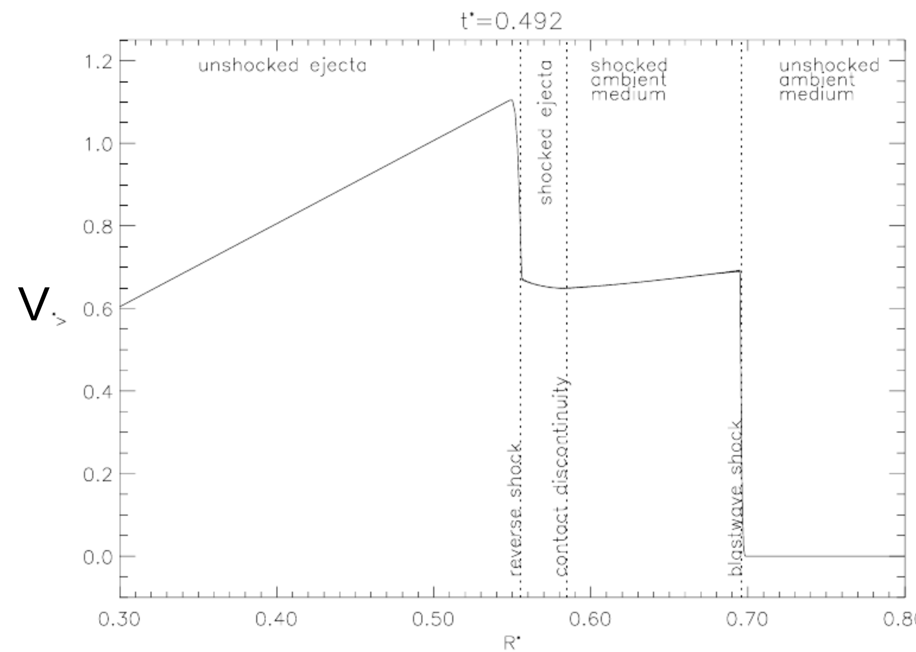
Forward Shocked Region: Hot (Strong Fe-K)
Reverse Shocked Region: Relatively Cold (Strong O/Si-K)
Result: Overturn is Seen!

500yr

G. Ferrand
(U. Manitoba→
RIKEN from 1st Sep.)

Shock Structure





Radius

T.DeLaney et al. (2010).

Most of 44Ti is unshocked?

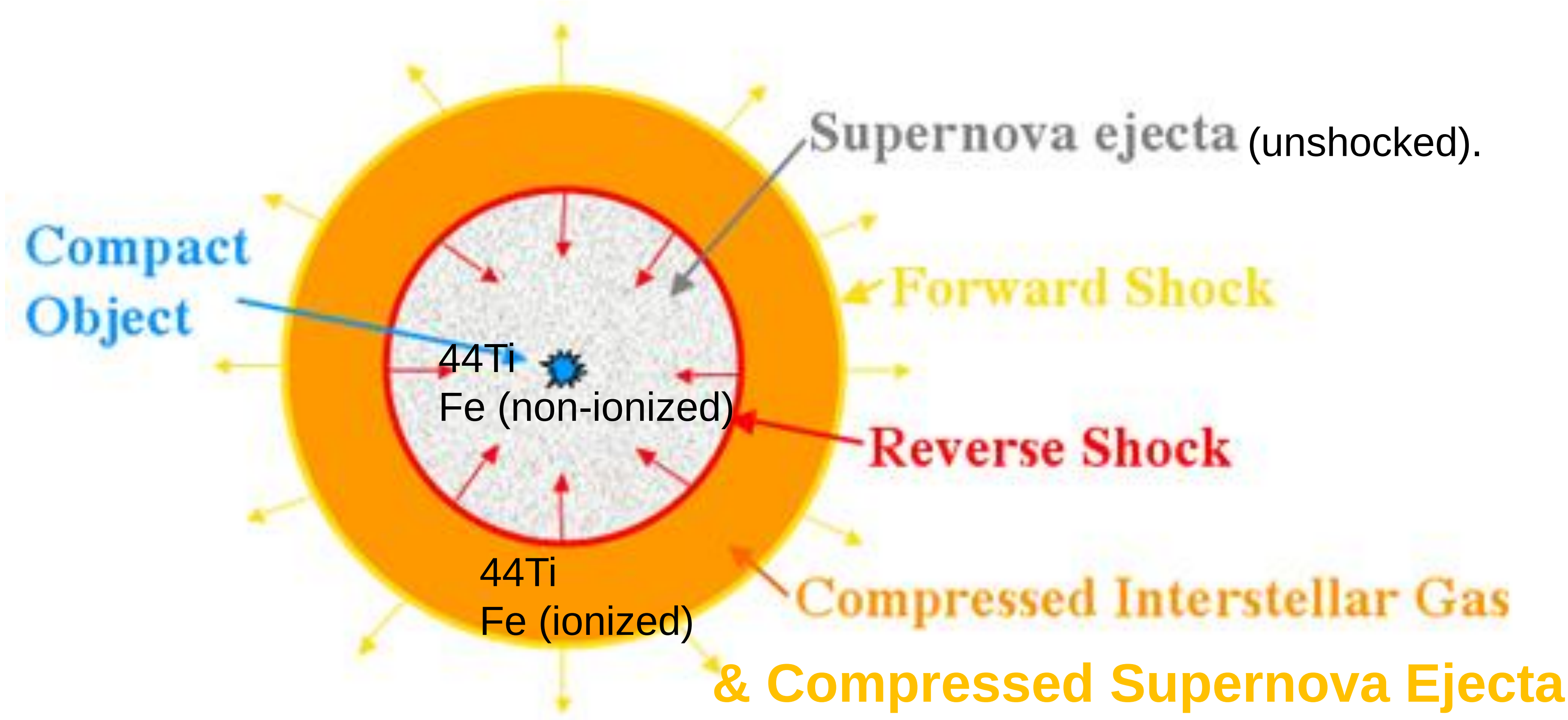
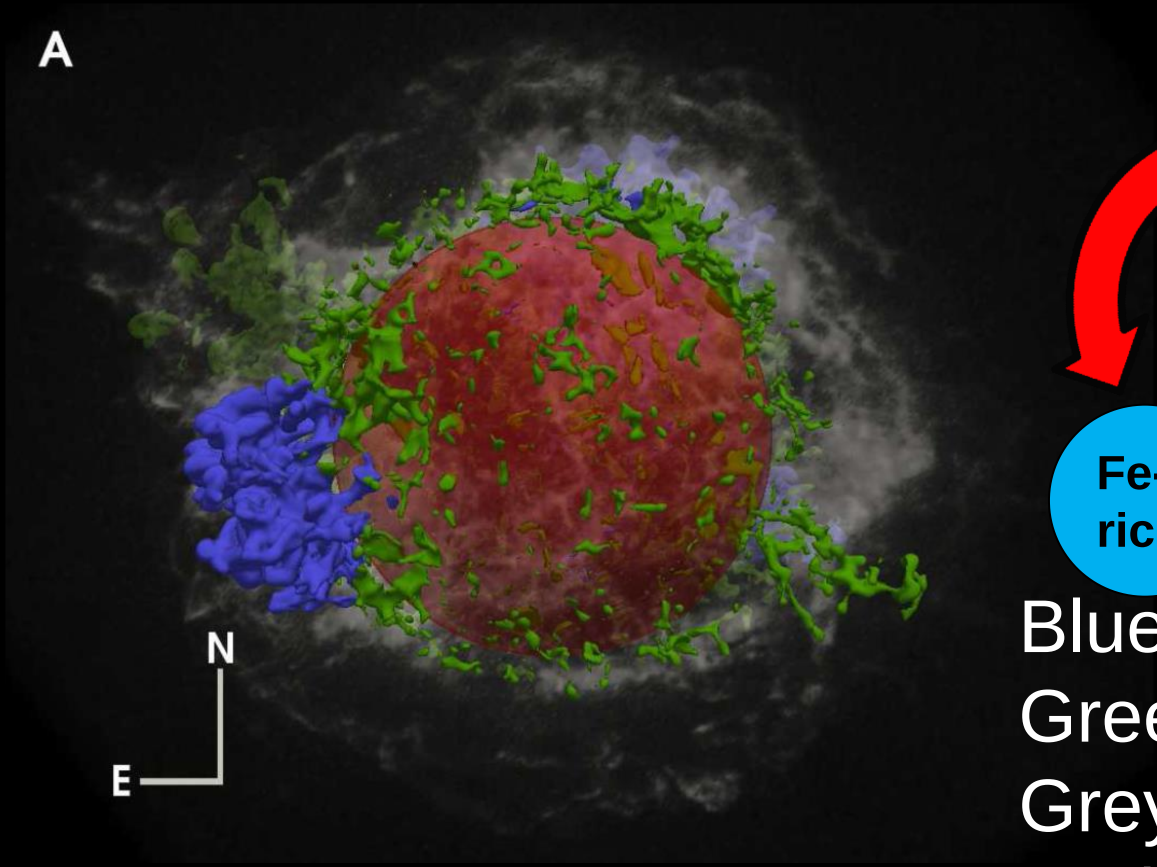


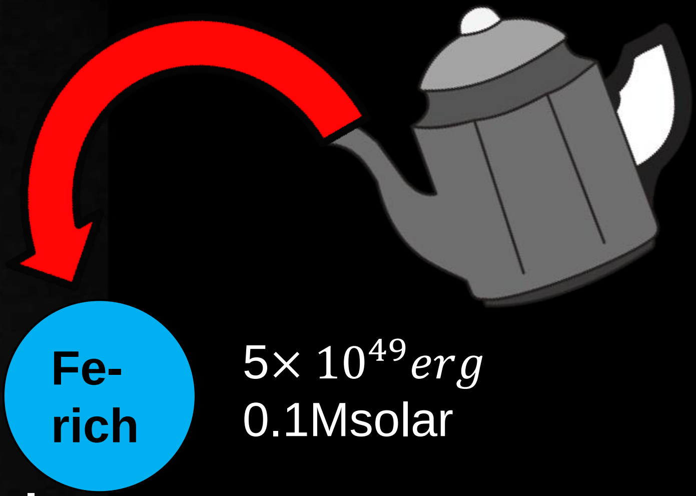
Figure from Cosmos (Modified)

http://astronomy.swin.edu.au/cosmos/S/Supernova+Remnant

The Overturn & Bubble are Real?

Orlando et al. 2016



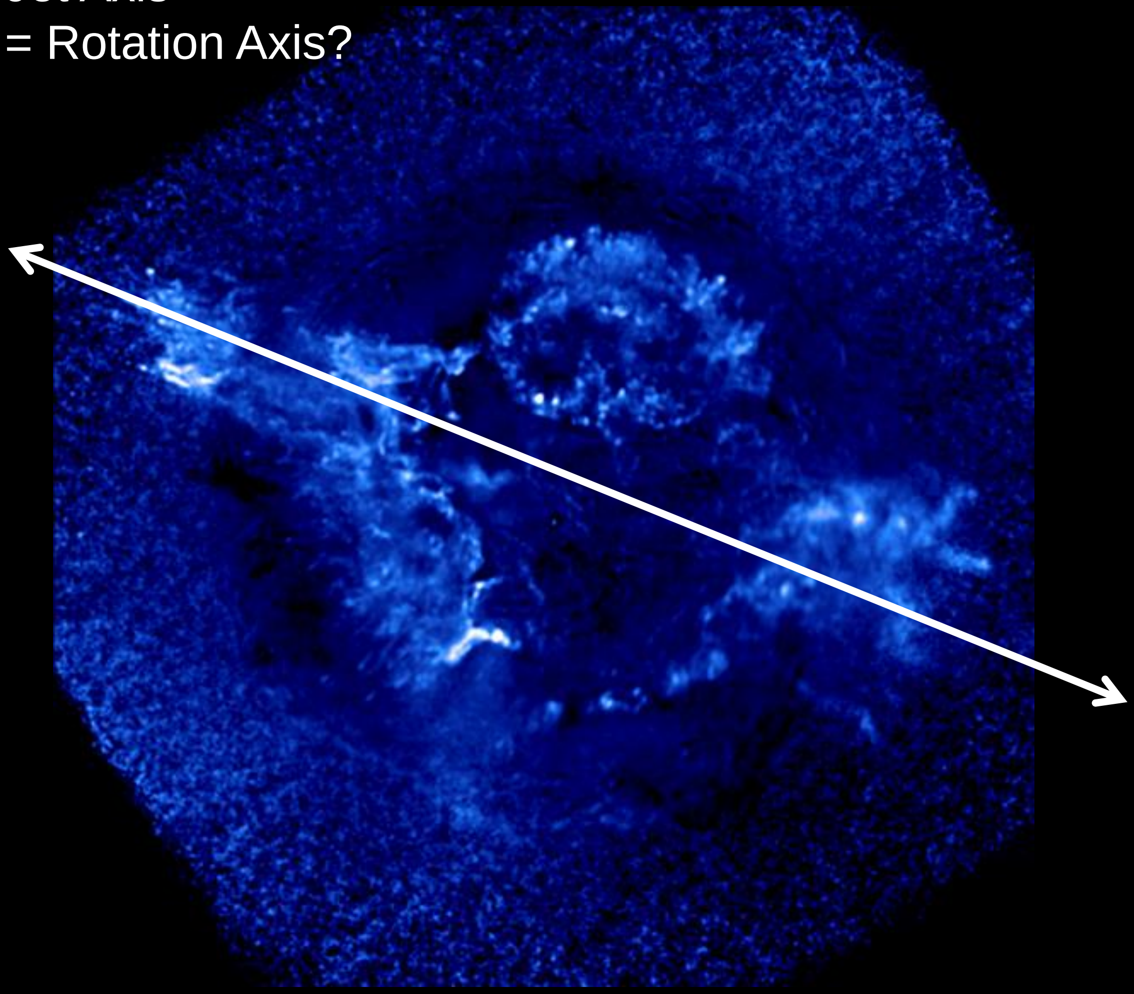


$5\times 10^{49} erg$
0.1Msolar

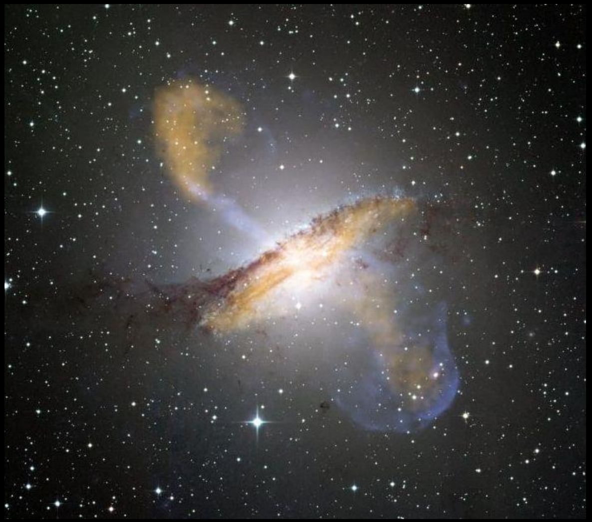
Blue: Fe
Green: Si/S
Grey: X-ray Obs.
Red: Artistic Image of
the Reverse Shock

Related with R-T Instabilities?

Mysteries on the Jet



A Jet of a Pulsar



A Jet of An Active Galactic Nuclei

Theories of Jet Formation

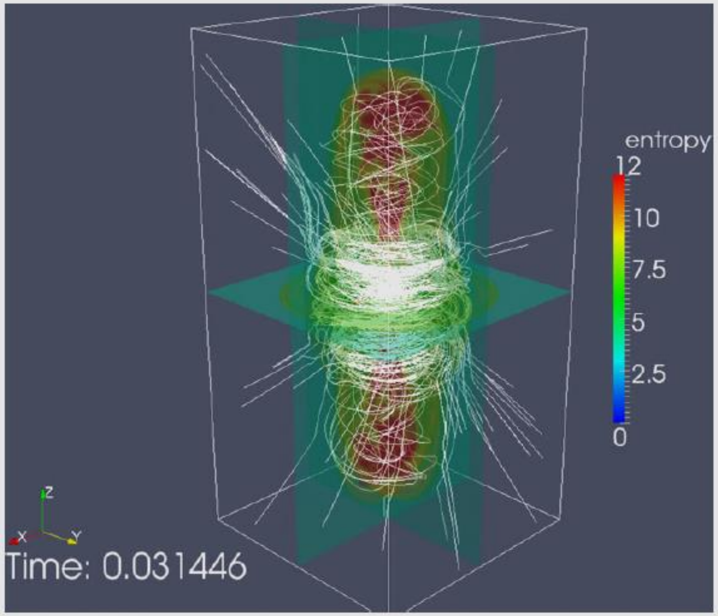
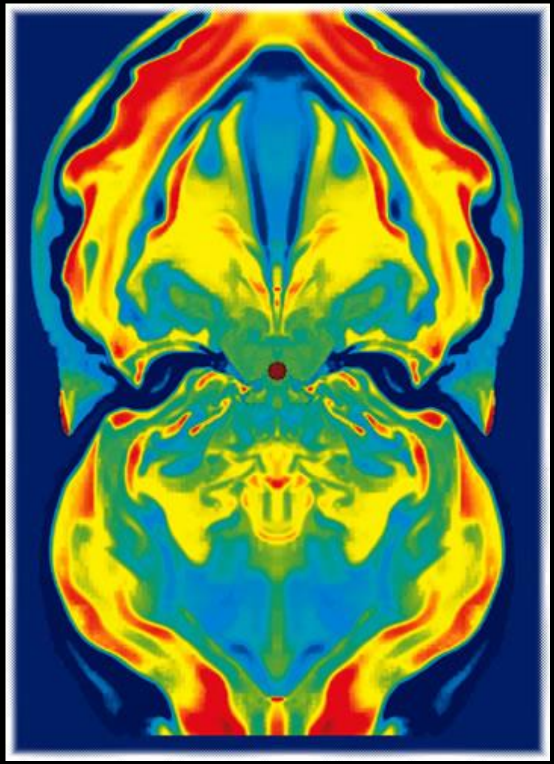


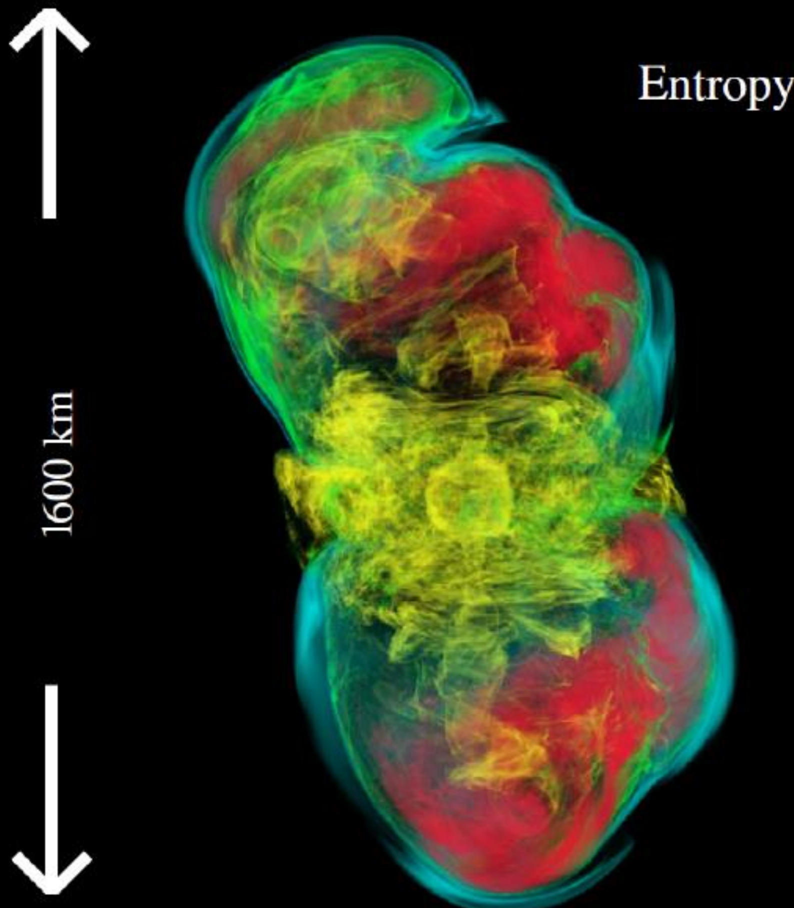
Figure 1. 3D entropy contours spanning the coordinates planes with magnetic field lines (white lines) of the MHD-CCSN simulation ∼31 ms after bounce. The 3D domain size is 700 × 700 × 1400 km.

Magnetar Model
(2-Dimensional)
(Rotation + B-Fields)
Winteler+12

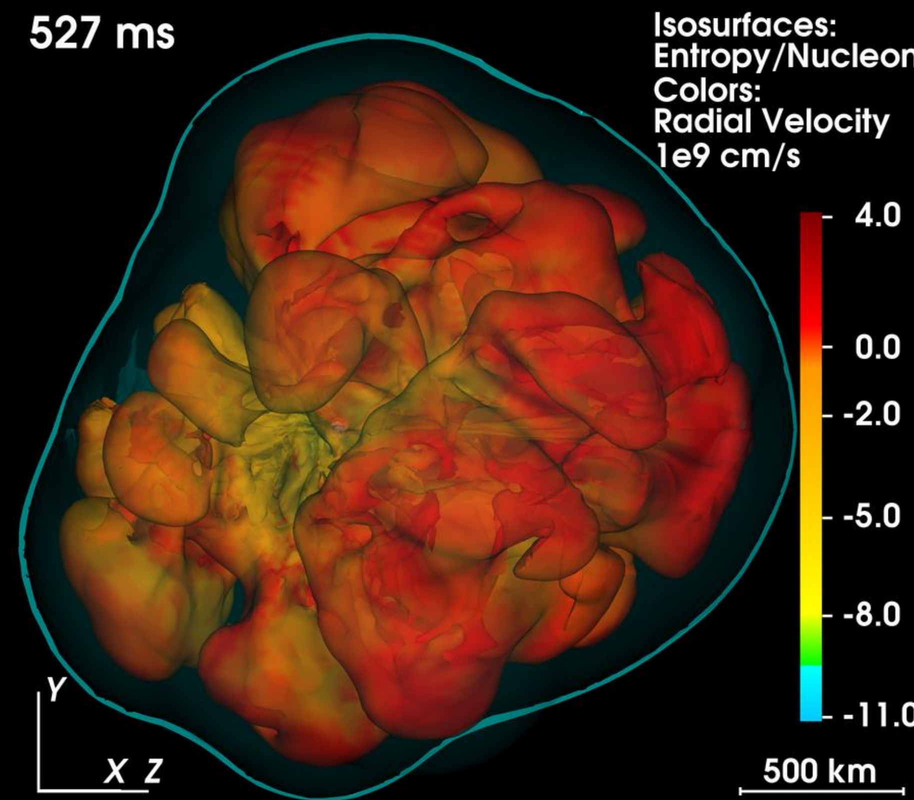


Standing Accretion Shock Instabilities.
(2-Dimensional) T. Mezzacappa,
Oak Ridge National Lab. Review

3-Dimnsional Calculations does NOT show Strong Jets…

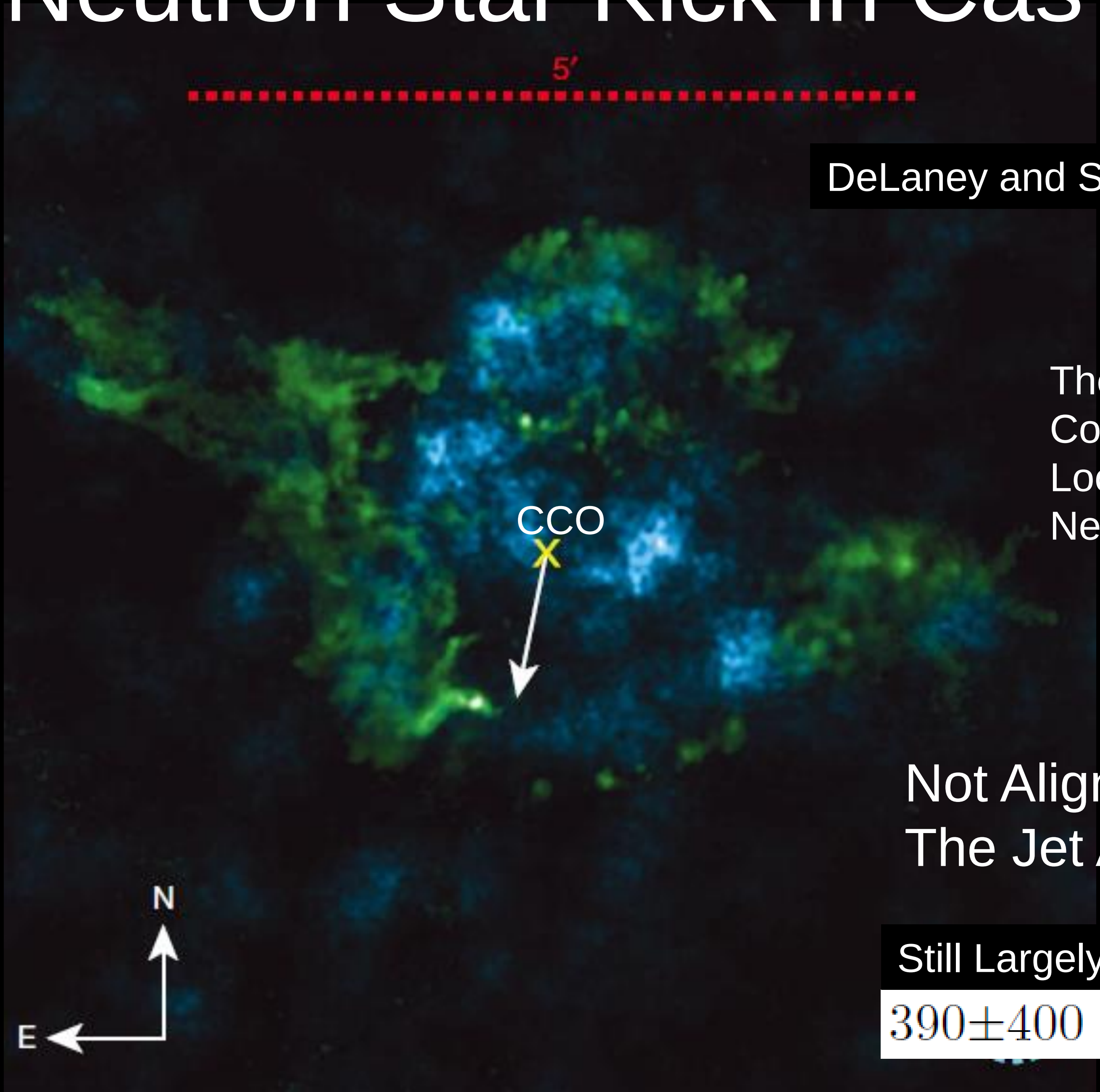


Moesta et al. 2014
Rotation+B-fields.



Melson + 2015
Non-Rotating. No B-fields.

Neutron Star Kick in Cas A



DeLaney and Satterfield 2013

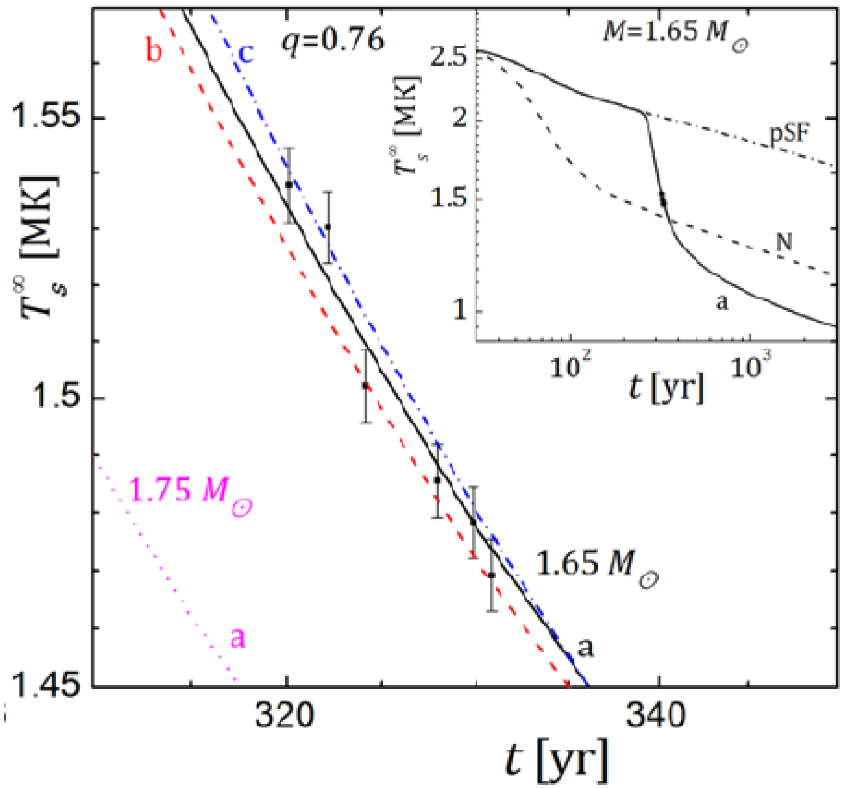
The CCO (Central Compact Object) Looks to be a Neutron Star.

Not Aligned with The Jet Axis!

Still Largely Uncertain

$390 \pm 400\ \mathrm{km\ s^{-1}}$

The CCO should be a Neutron Star.



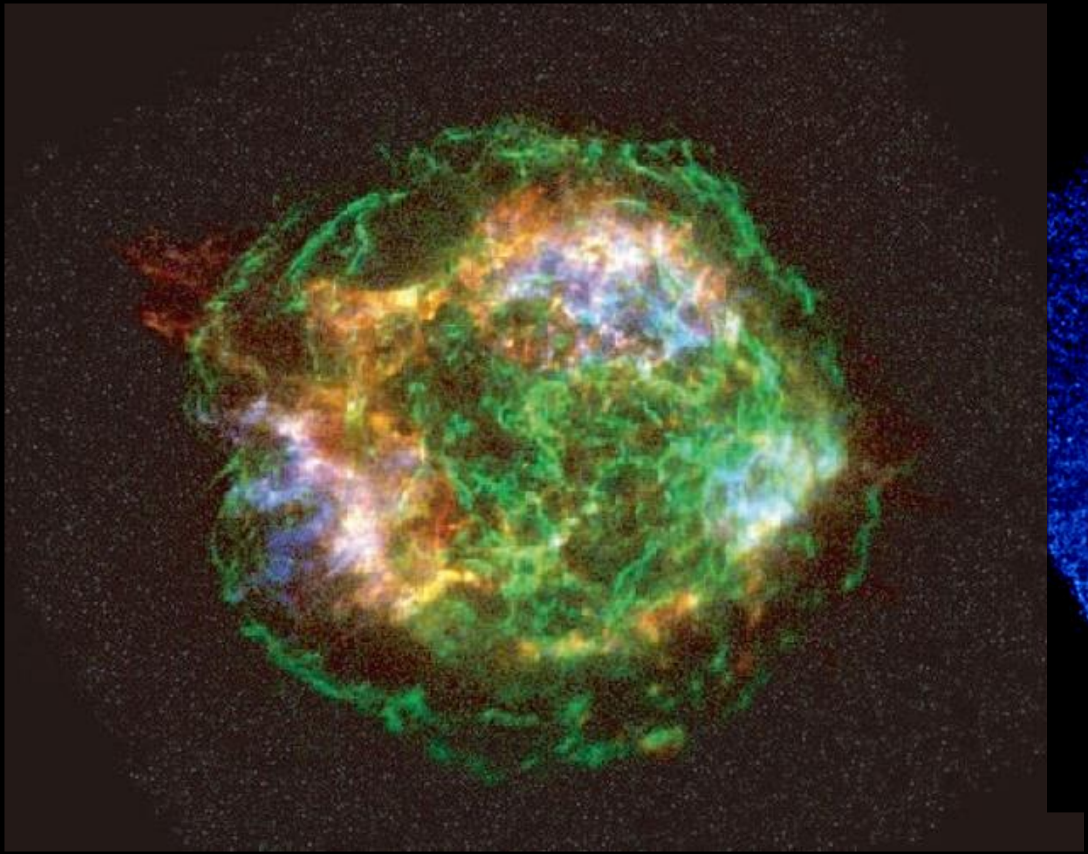
Best fit parameter:
M=1.65Msolar
(APR Equation of State).
Shternin et al. 2011.

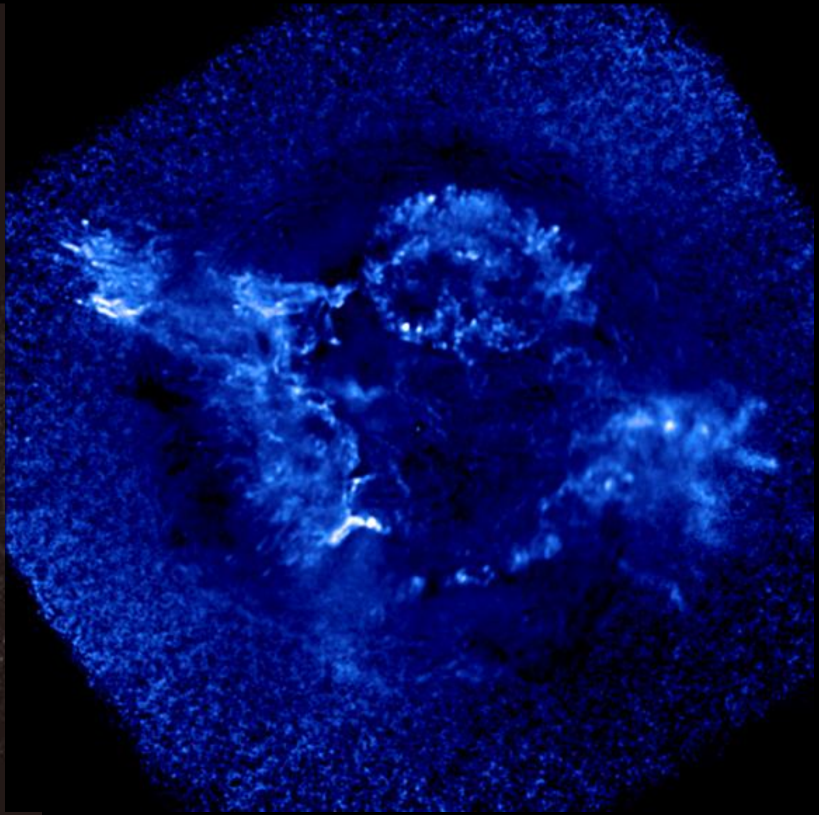
NS parameters (from spectral analysis)

$$M \approx 1.5 - 2.4 M_\odot$$
$$R \approx 8 - 18 \text{ km}$$
$$T_s \sim 2 \times 10^6 \text{ K}$$
$$B \lesssim 10^{11} \text{ G}$$

Conclusion:
Central compact object in supernovae remnant Cas A – neutron star with a carbon atmosphere

The Jet is Really Si-rich?

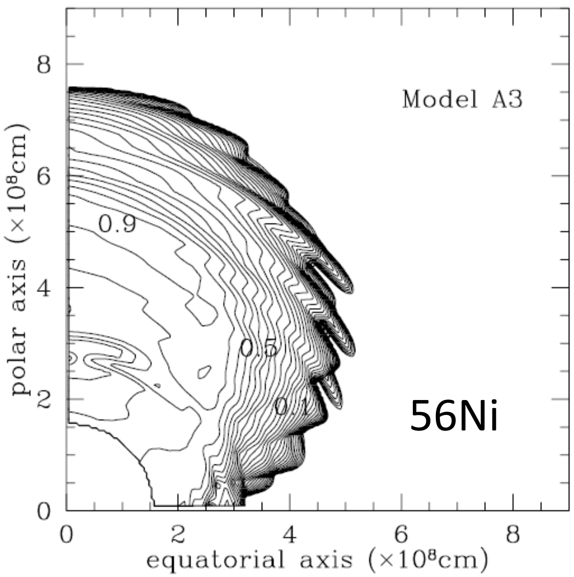


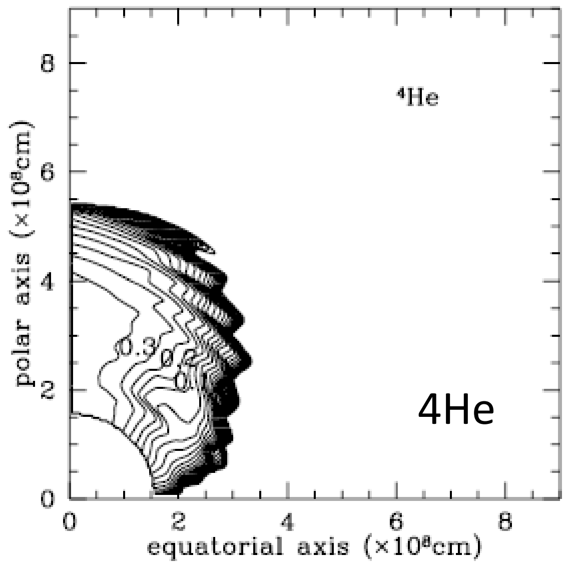


X-rays (Chandra)
Blue：Fe
Red: Si
Green：Continuum.

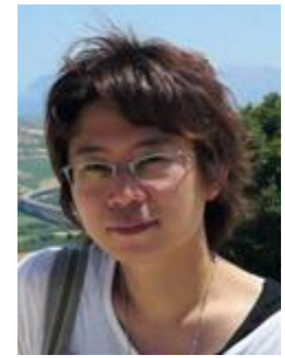
X-rays (Chandra)
Intensity ratio of ～Si Lines/(Mg+Fe) Lines.

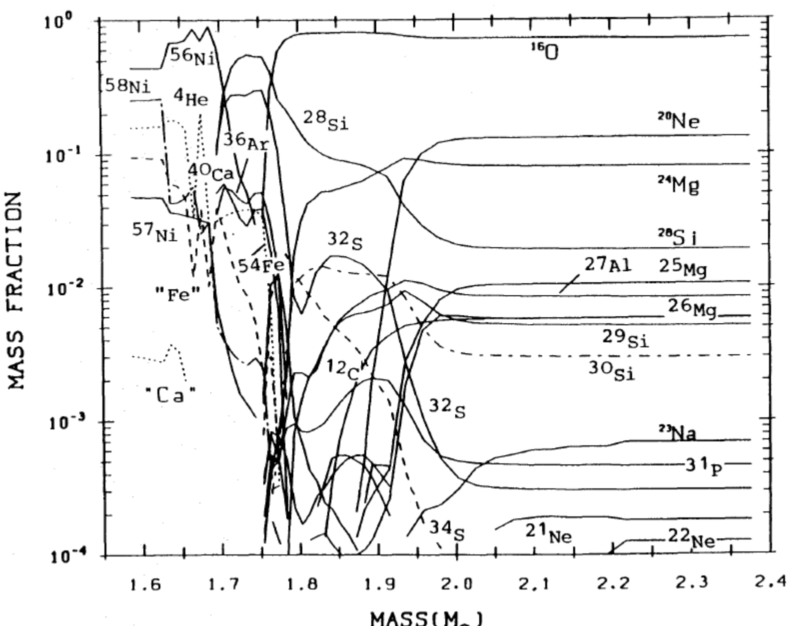
Lots of Fe is expected in Bipolar Explosion…





Nagataki et al. 97,
Nagataki 00



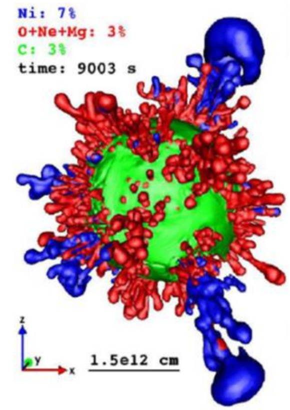


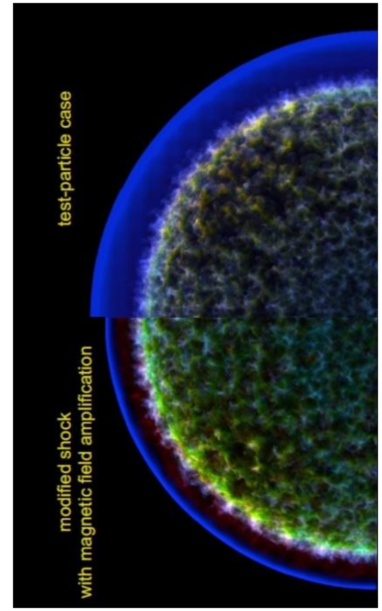
Si/S should be produced outside of Fe
In the Jet Region too. But…

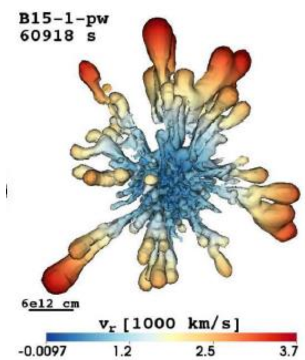
Ionization effect?

Something else?

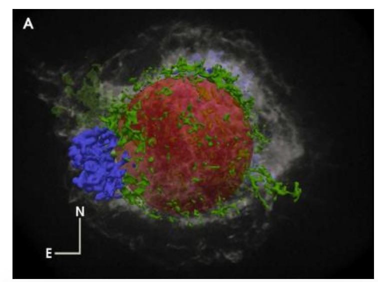
Our Project: From SN to SNR

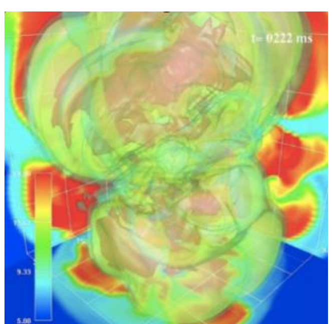


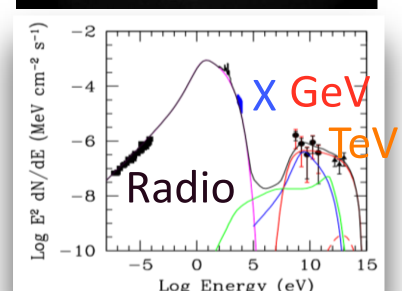




From 1 Sec to 1000 yrs!

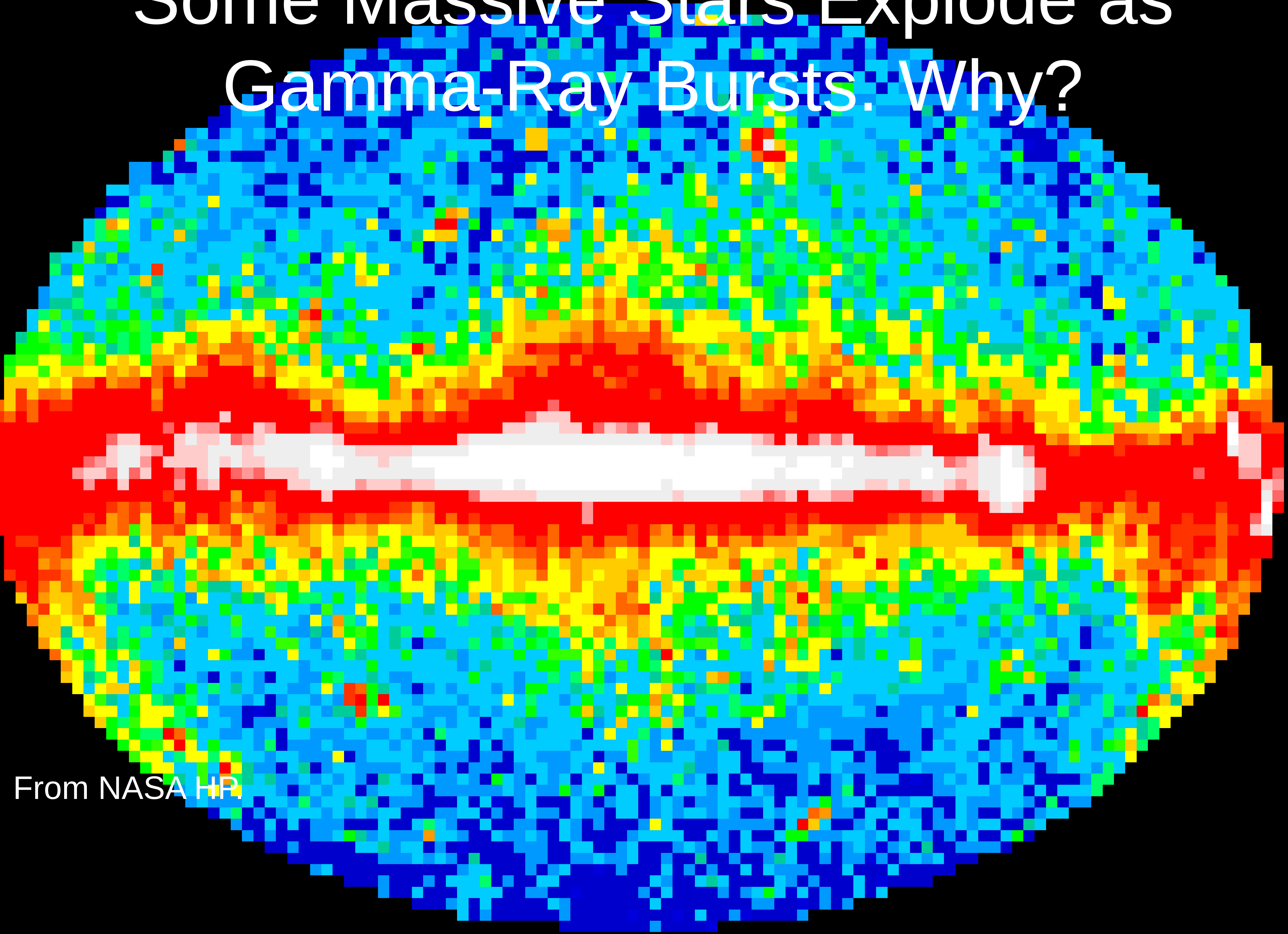






§ Gamma-Ray Bursts
(Probably Super-Jet Supernovae)

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



From NASA HP.

History of GRBs: The first report in 1973.

THE ASTROPHYSICAL JOURNAL, **182:**L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

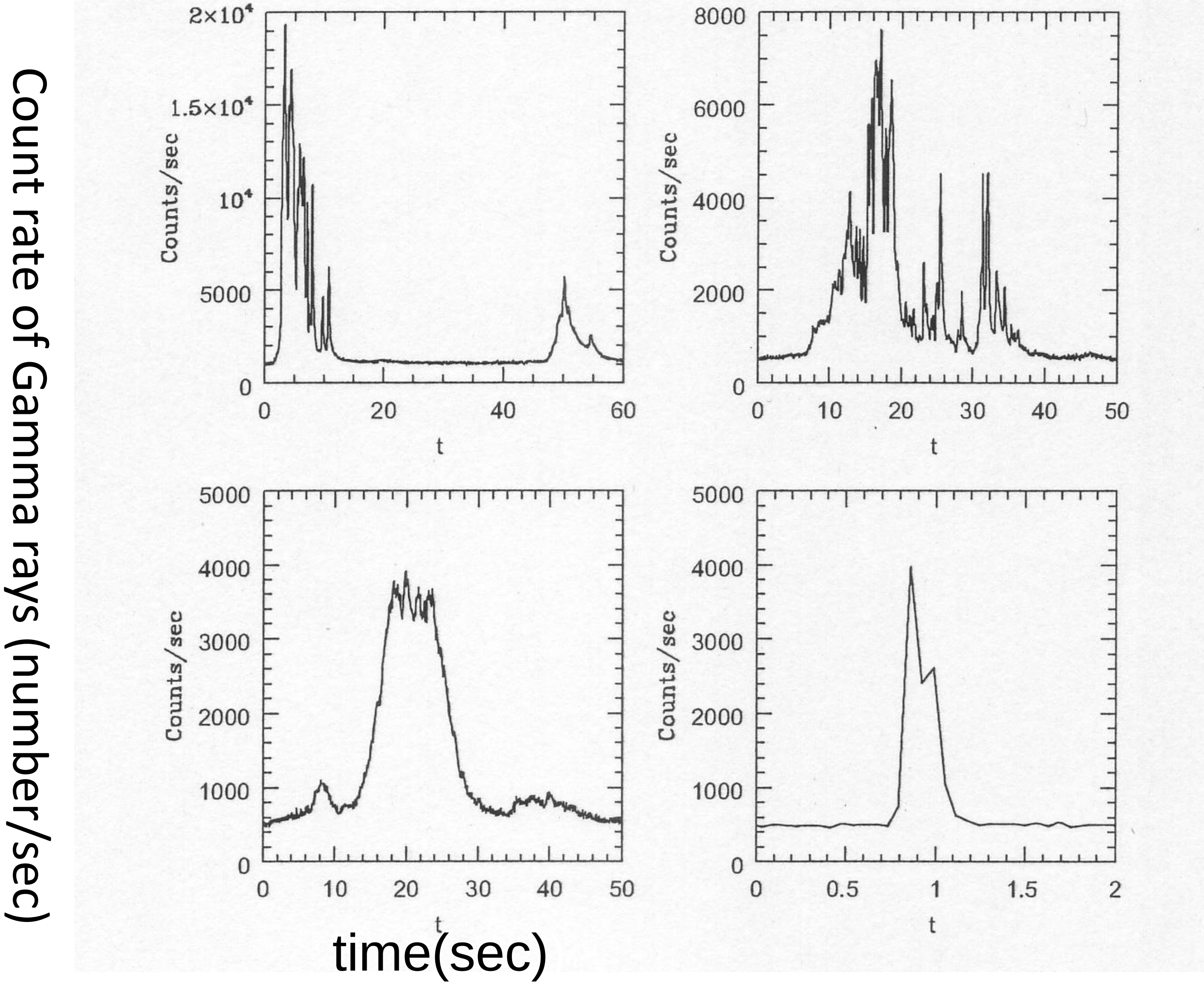
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

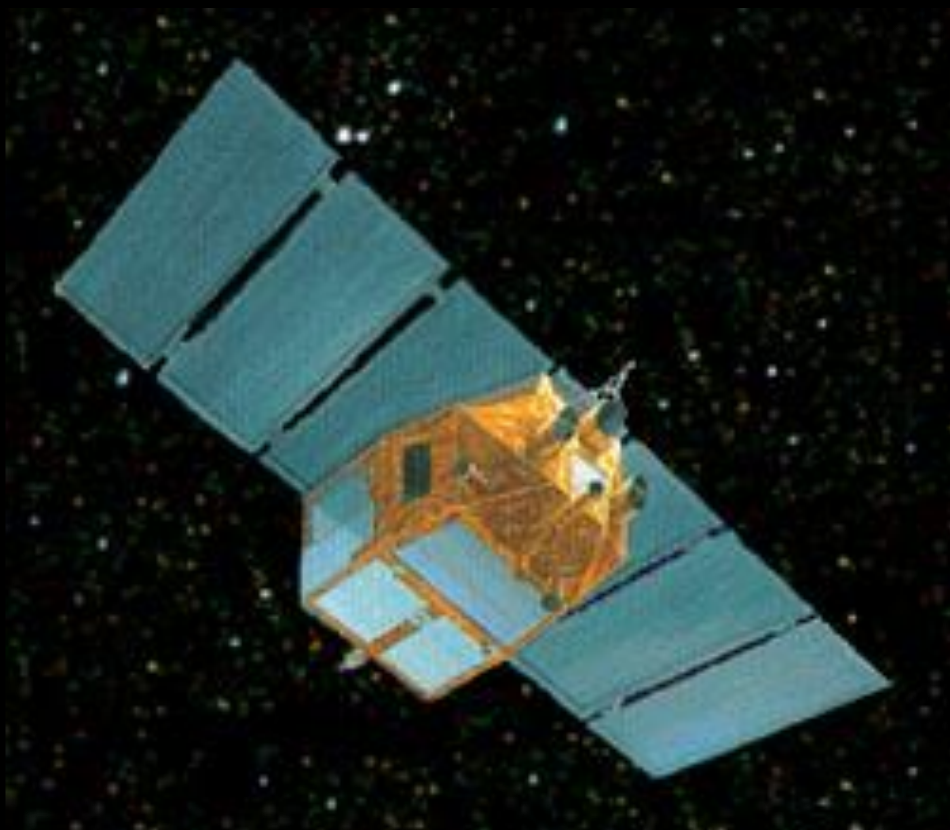
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

By Vela5A,5B,6A,6B: Satellites for Checking Nuclear Weapon Experiments in the World.

From Where GRBs are Coming?



BeppoSAX (Italy-Netherlands) (Apr.1996-Apr.2003)

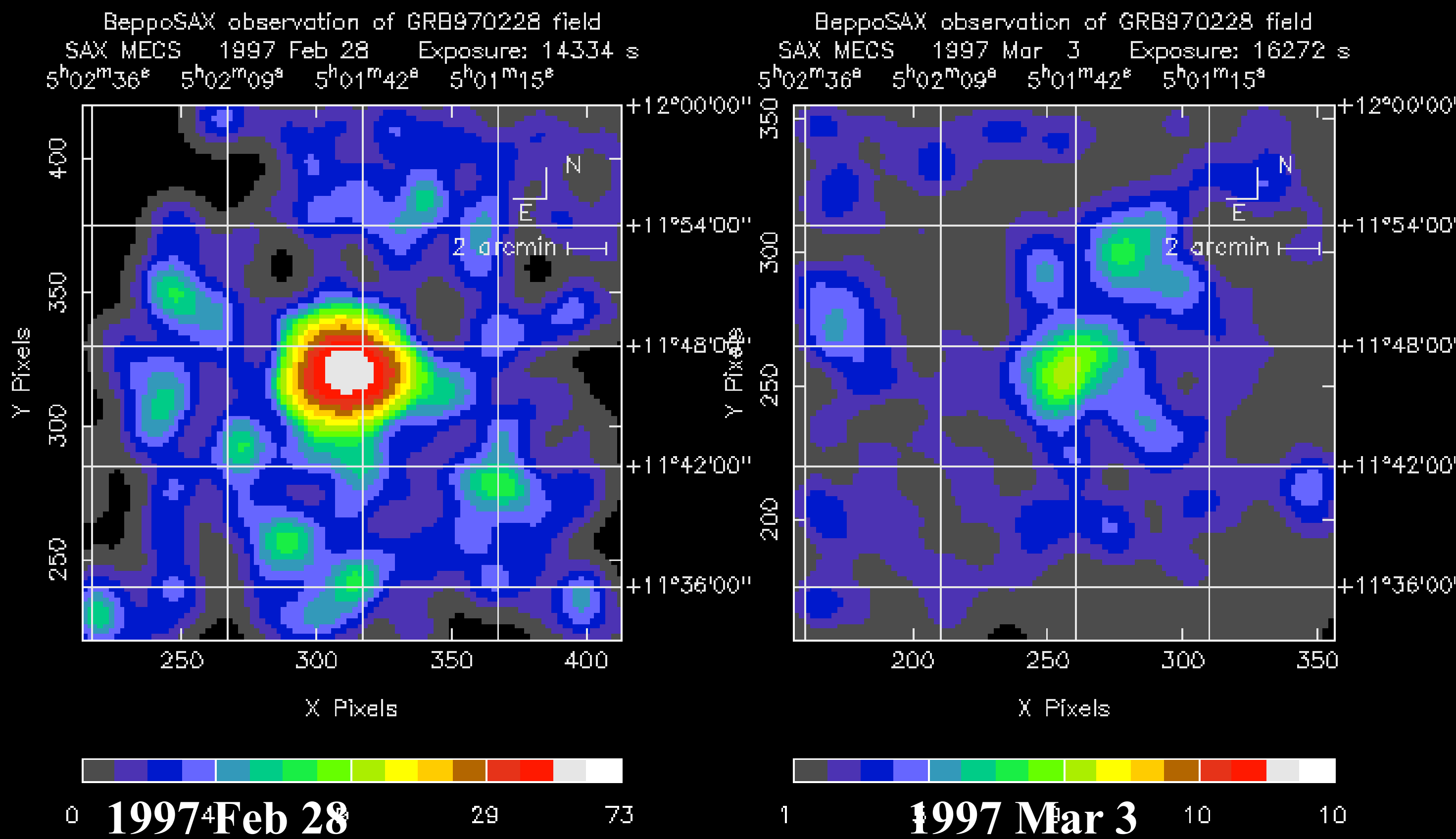


0.1 -   300 keV.
Not only Gamma-rays, but also X-rays!

Good angular resolution for X-rays ～1‘ (1arcmin).
c.f. gamma-rays ～ 1deg.
1deg = 60arcmin.
1arcmin = 60arcsec.

More accurately the position of a GRB can be determined!

First Discovery of X-ray Afterglow



8 hours later

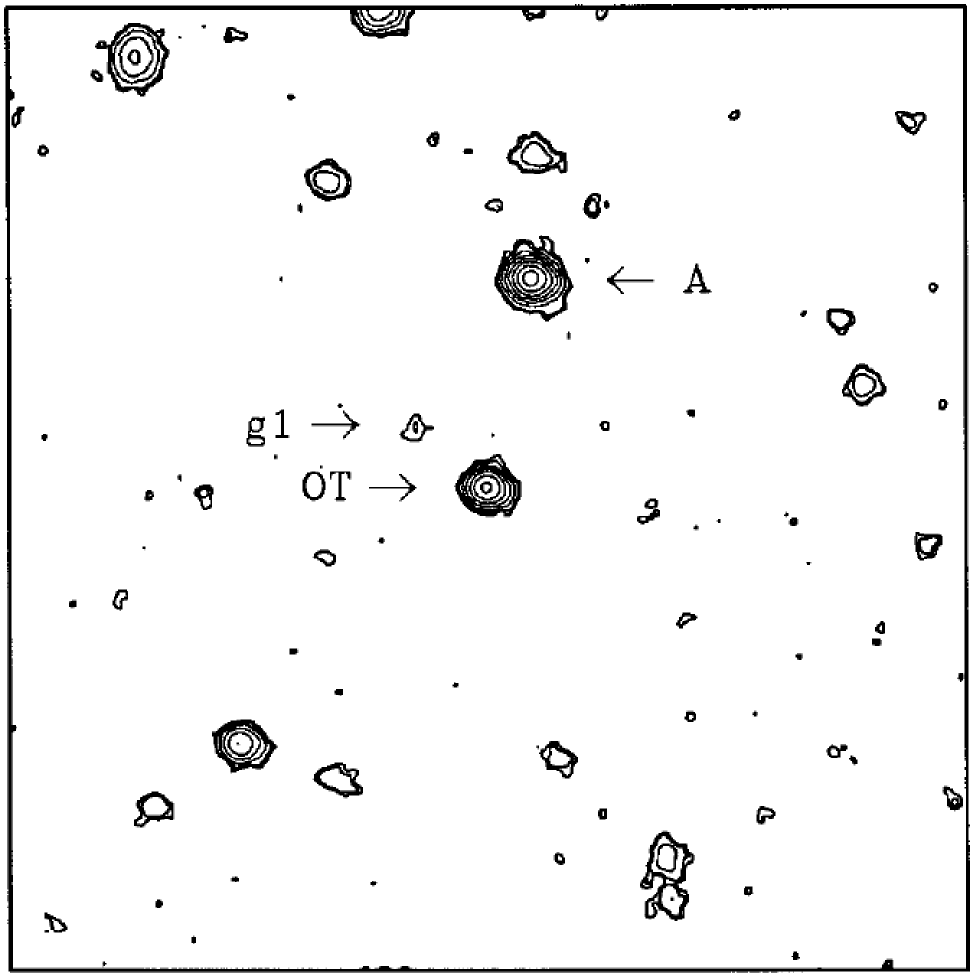
3days later

Following GRB970228, an X-ray afterglow was detected!

Afterglow was detected in Optical too！

GRB970508

Djorgovski et al. Nature 1997



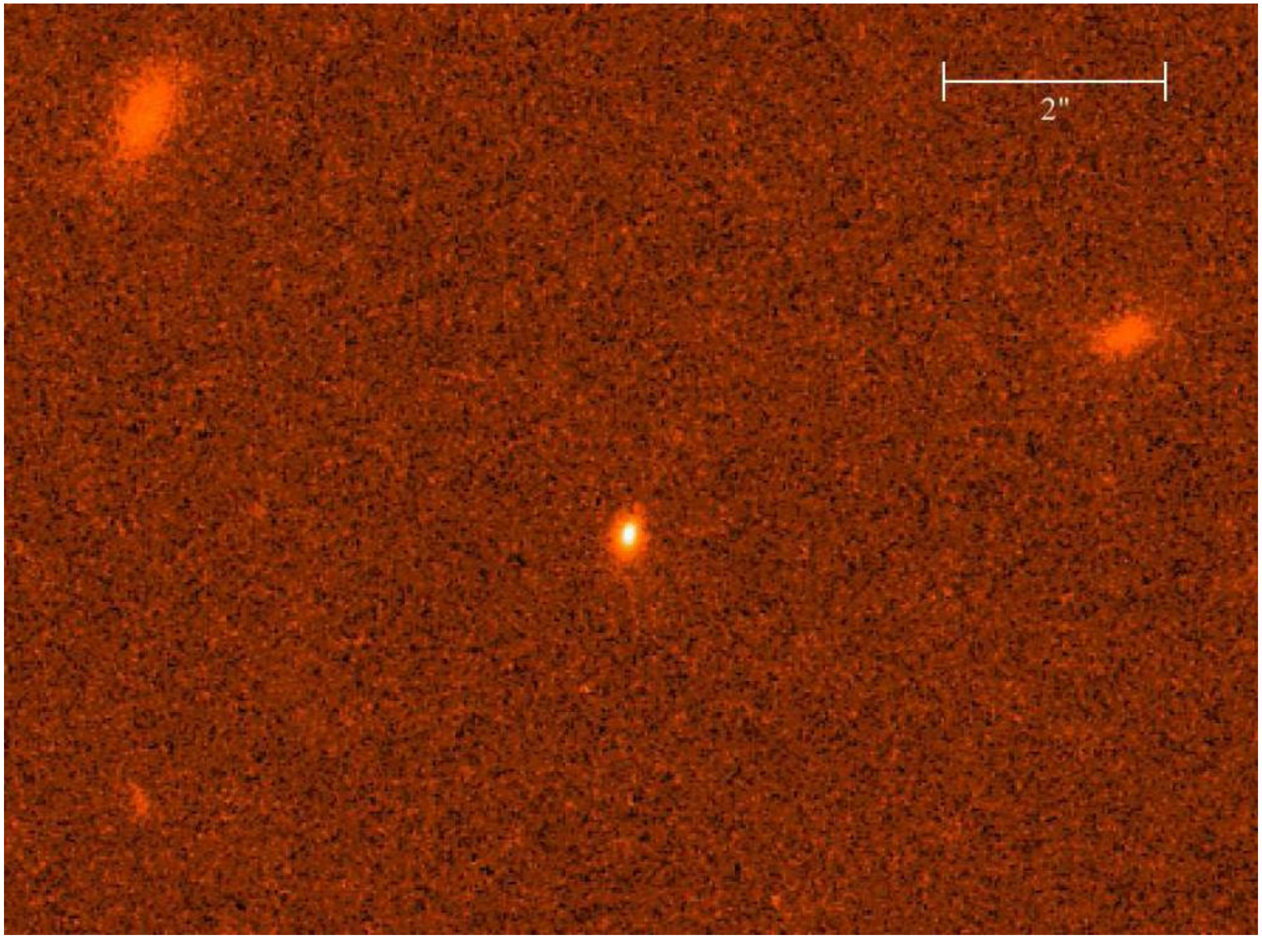
Follow-up by a ground-based telescope.

Palomar Observatory, California, US

Image of 1arc min × 1arc mim in Optical.

454 Days later, the host galaxy for GRB970508 was identified by HST.

Fruchter et al. 2000.

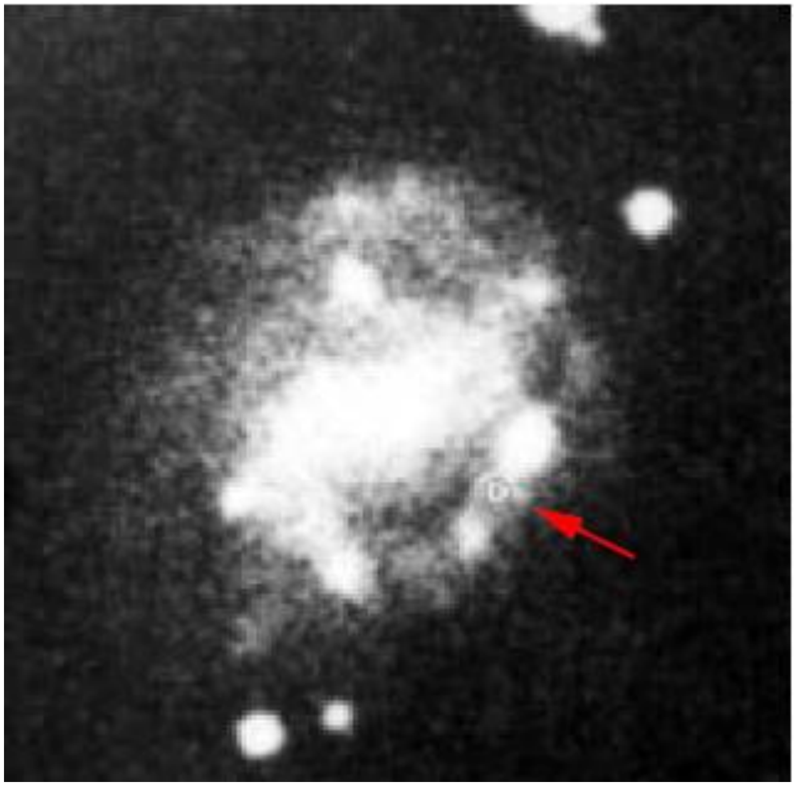


Hubble Space Telescope

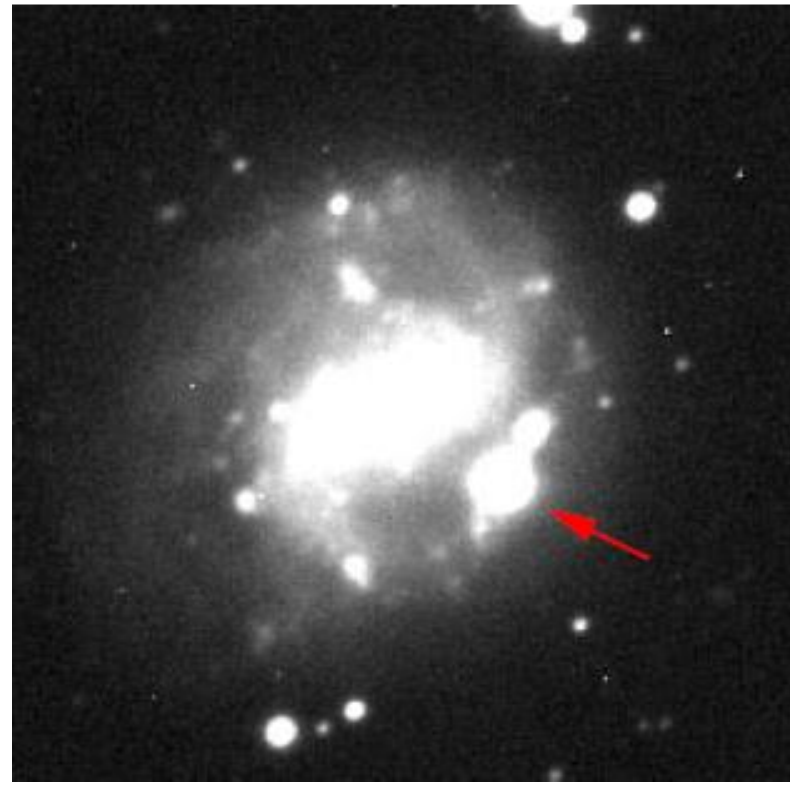
The host galaxy. Optical Afterglow is now too dim to be detected.

GRB980425/SN1998bw：
GRB-SN are happening Simultaneously！

Galama et al. Nature 1998, Iwamoto et al. Nature 1998



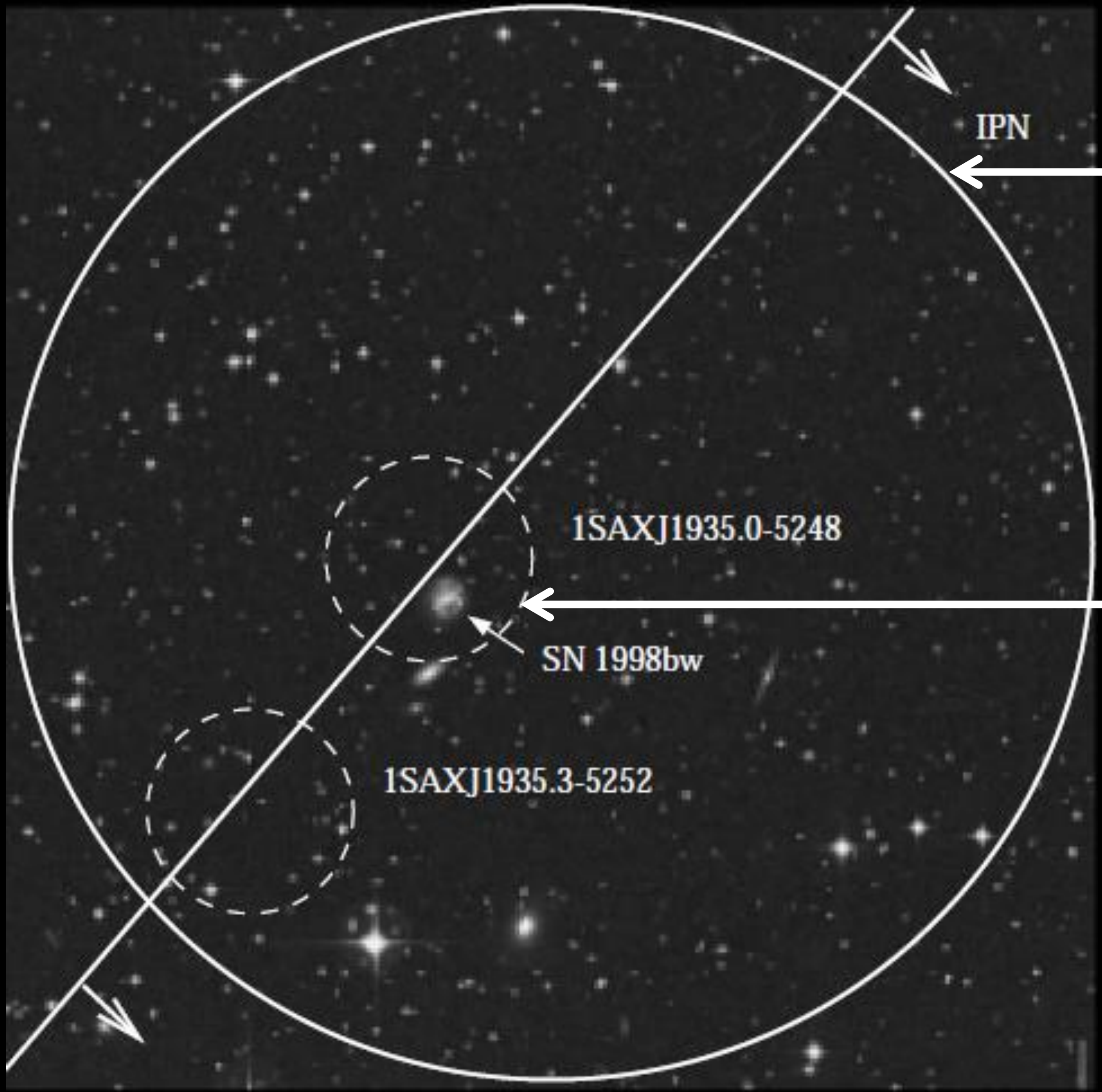
Spiral Gal. ESO 184-G82（1976）
Z=0.0084 (= 37.5Mpc).



SN1998bw in the galaxy（May 1st, 1998）.
(Galama et al. 1998)。

Location of GRB980425 & SN1998bw

Galama et al. (1998)



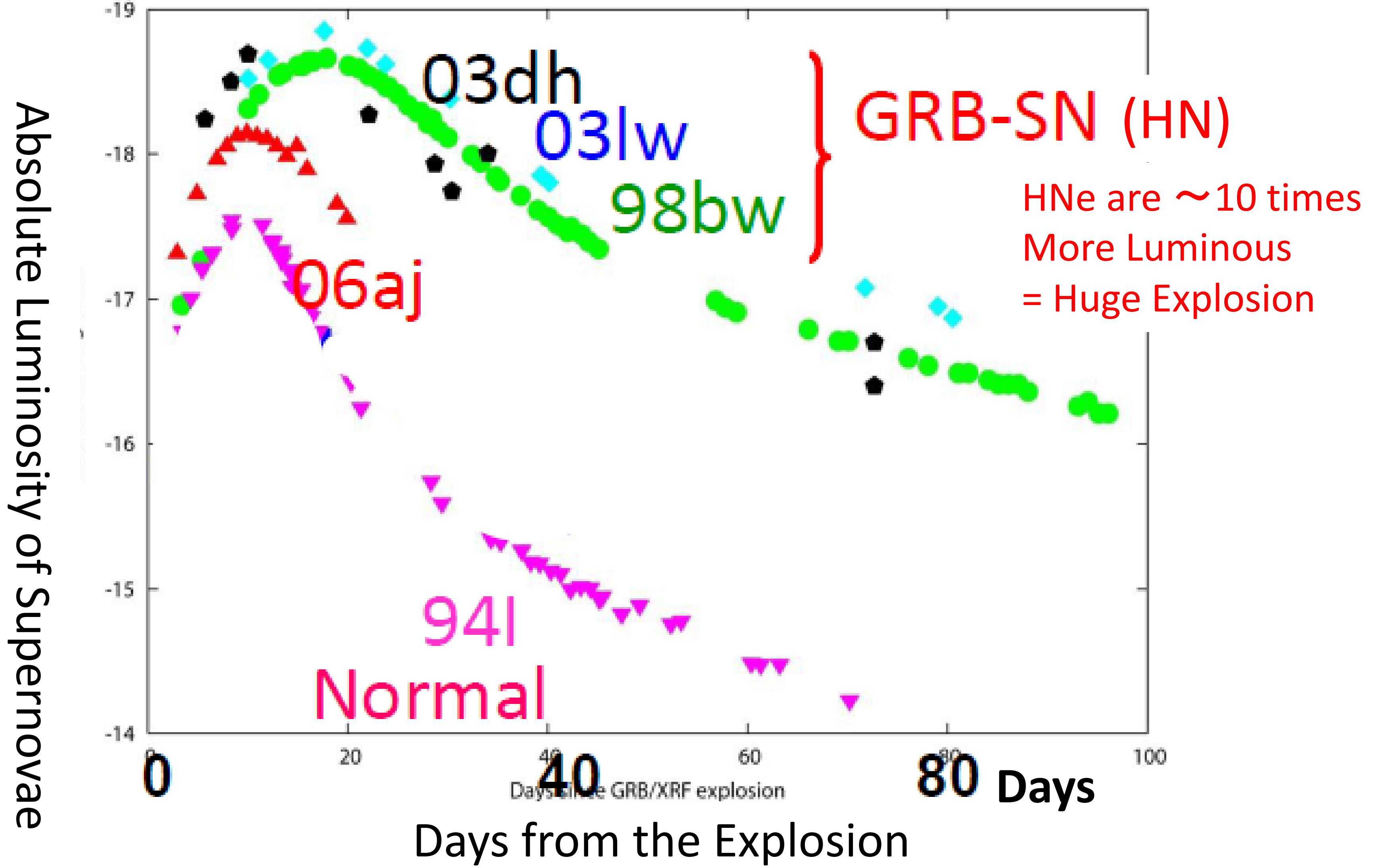
Angular Resolution of WFC(2-28keV). ～8 arc min.

Angular Resolution of NFI (0.1-10keV:Narrow Field Instruments) ～1 arc min.

Background is An Optical Image.

A hypernova is frequently associated with a GRB

Slide from
K. Maeda(Kyoto)

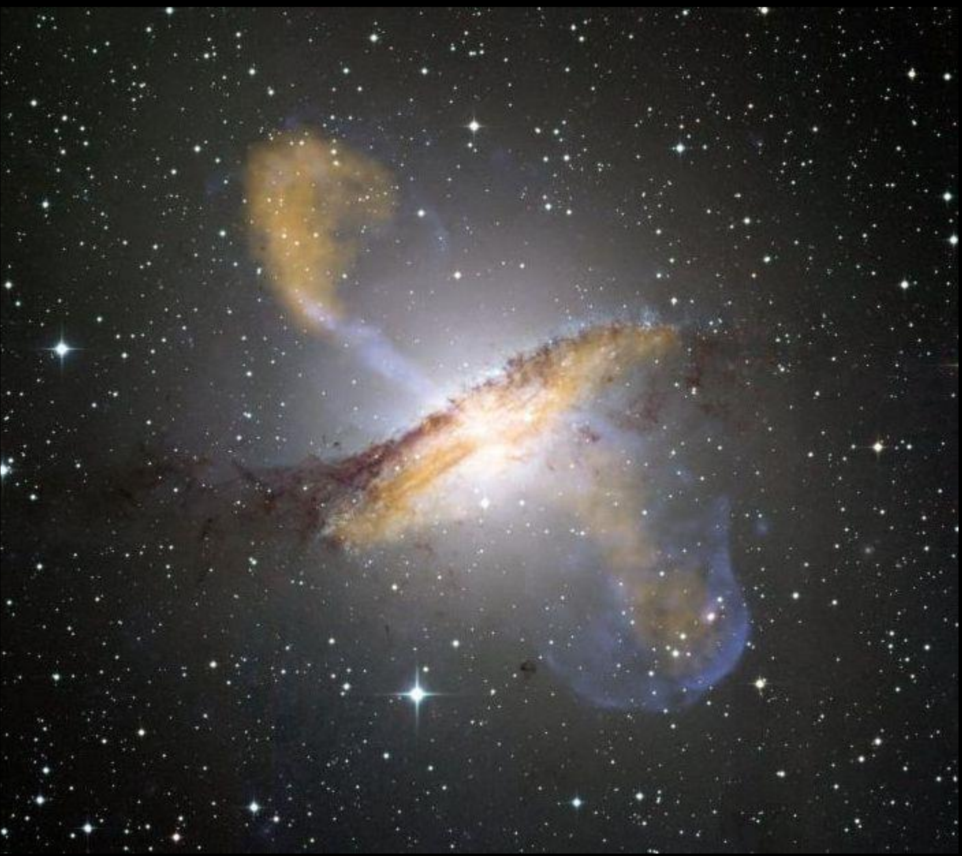


Central Engine of Gamma-Ray Bursts is Hardly Known.

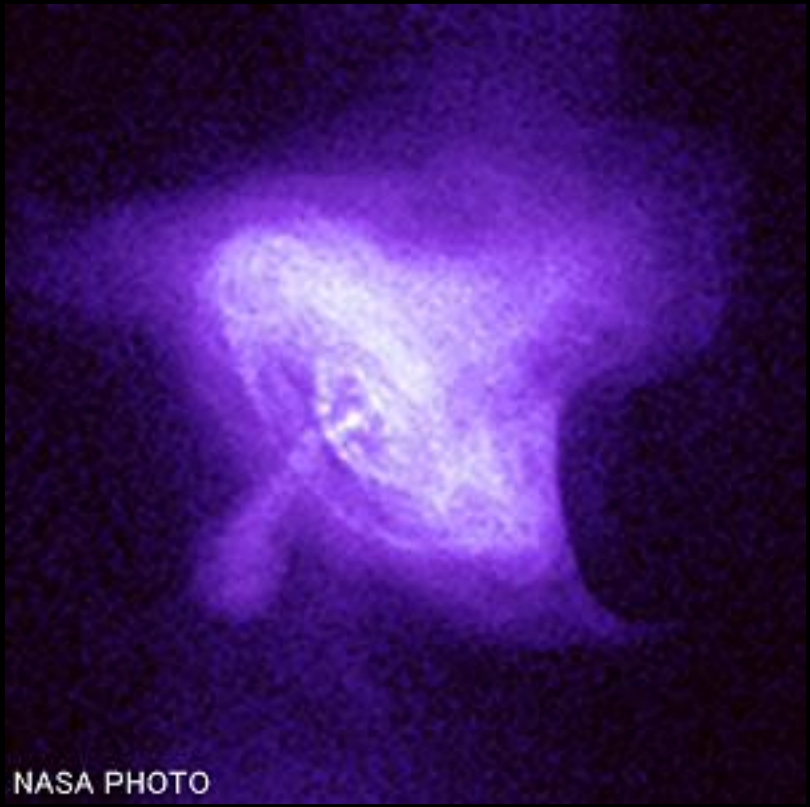
At least,
it should be very different from the one of Supernovae.

An Artist’s Movie of a GRB

Rotation is Essential if GRBs are Jets.



Active Galactic Nuclei
Centaurus A (Black Hole + Accretion Disk)



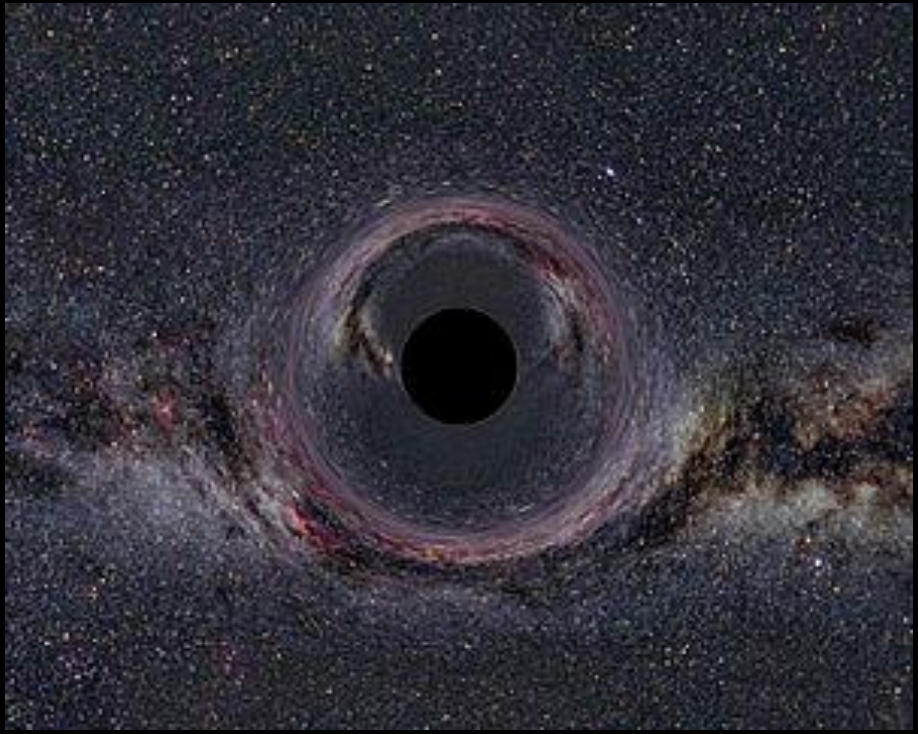
Crab Pulsar
（Rotating Neutron Star）

Promising Models for the Most Powerful Explosion in the Universe

- BH+Accretion Disk Models (Collapsar Model)
  Neutrino-Driven Model (Original Collapsar Model)
  Blandford-Znajeck Model (B-Fields)
- Magnetar Models
  Rapidly Rotating Neutron Star (Quark Star) with Strong B-Fields.

The Black Hole

- It has an Event Horizon.
- Nobody (even a photon) cannot come back to our world once it enters into the horizon.



A Mock Observation of BH Effects.
A Black Hole with 10 Msolar is put at 10km from the Earth.
（Ute Kraus, 2004）

Can Energy of a BH be Extracted?

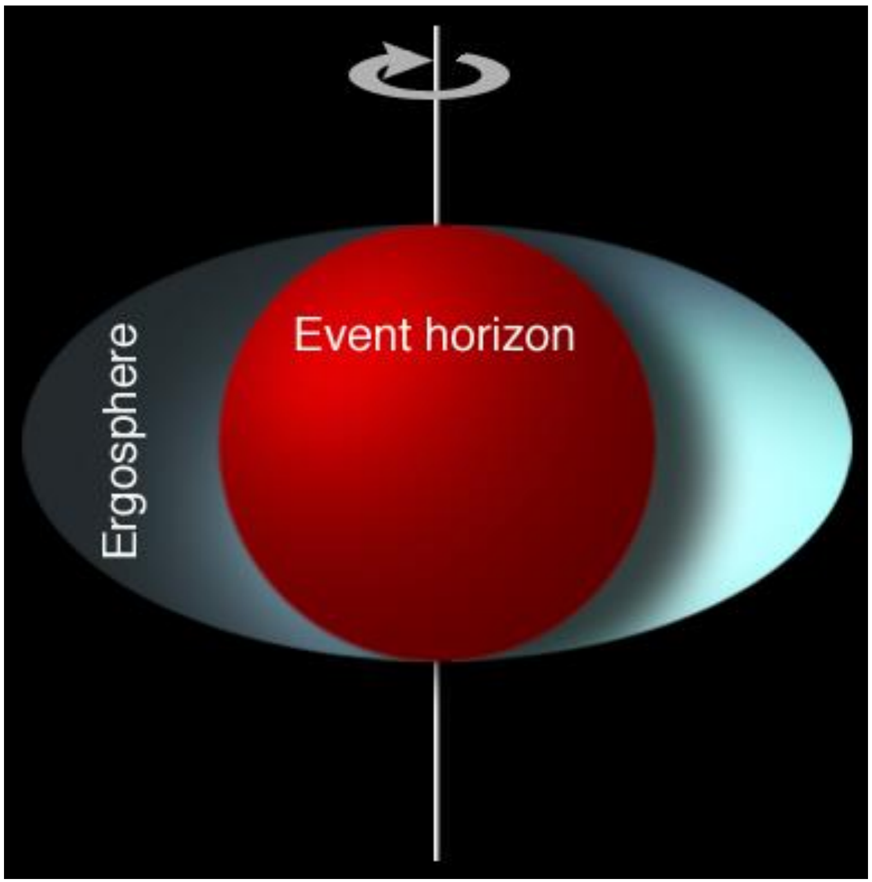
- Mass Energy of a BH is Extracted due to Evaporation of the Black Hole (S. Hawking 1974).

  Hawking Radiation. Quantum Effect.

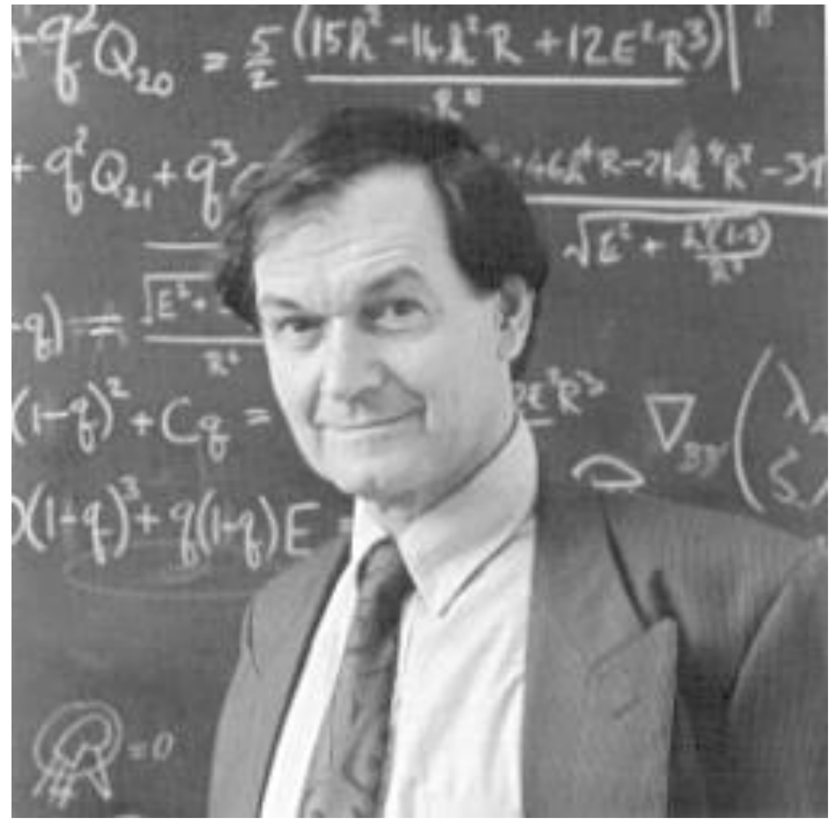
  Efficiency is Low (It takes $\sim 10^{70} yrs$ for a BH with 10M_solar to Evaporate).

- Rotation Energy of a BH can be Extracted Efficiently (R.Penrose 1971, R.Blandford & Znajek 1977). Classical Effect.

Rotation Energy Can be Extracted from a BH: Penrose Process (1971)

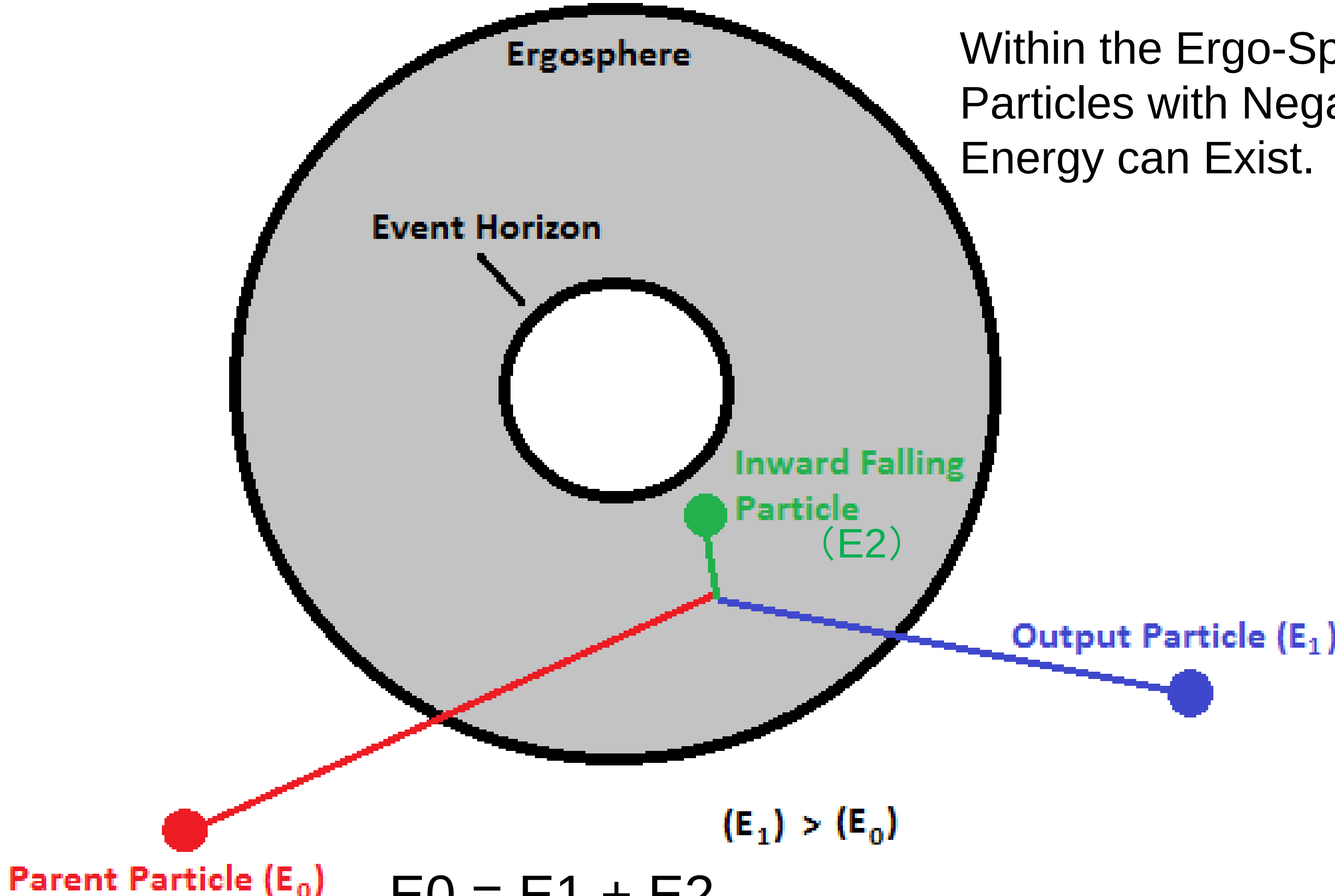


Schematic Picture of a Rotating Black Hole
(From Wikipedia)



Roger Penrose (1931-)

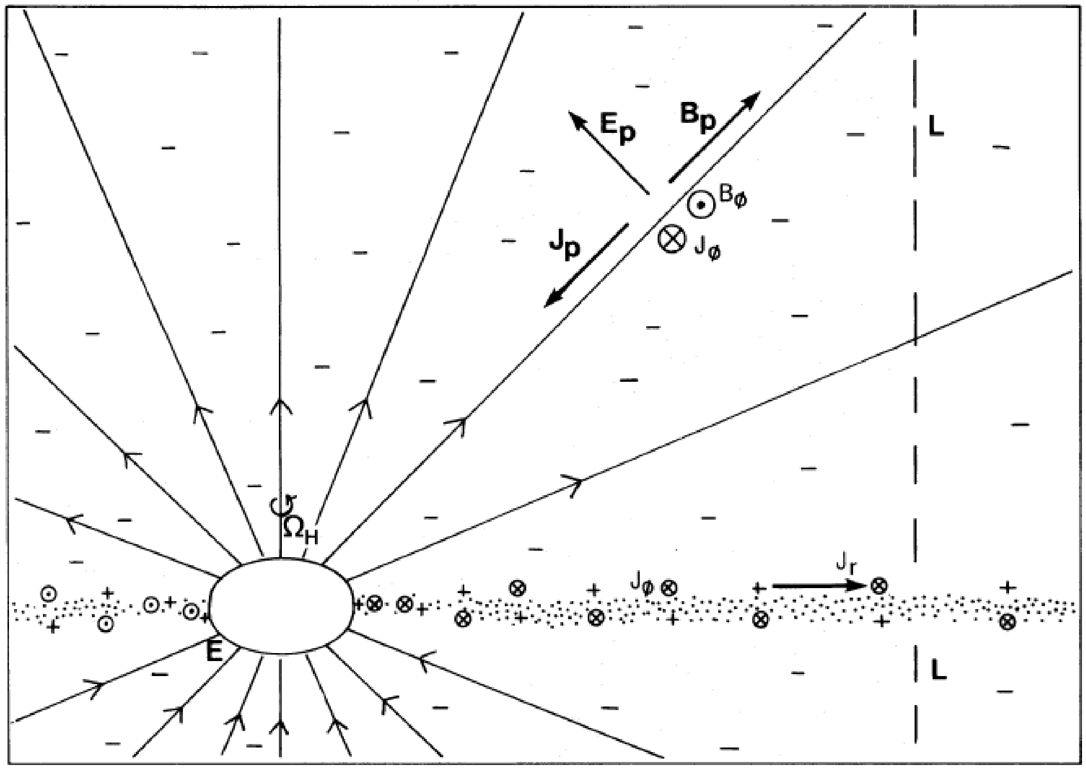
Penrose Process



Within the Ergo-Sphere, Particles with Negative Energy can Exist.

E0 = E1 + E2
E2 < 0
So, E1 > E0 （Energy Gain）.

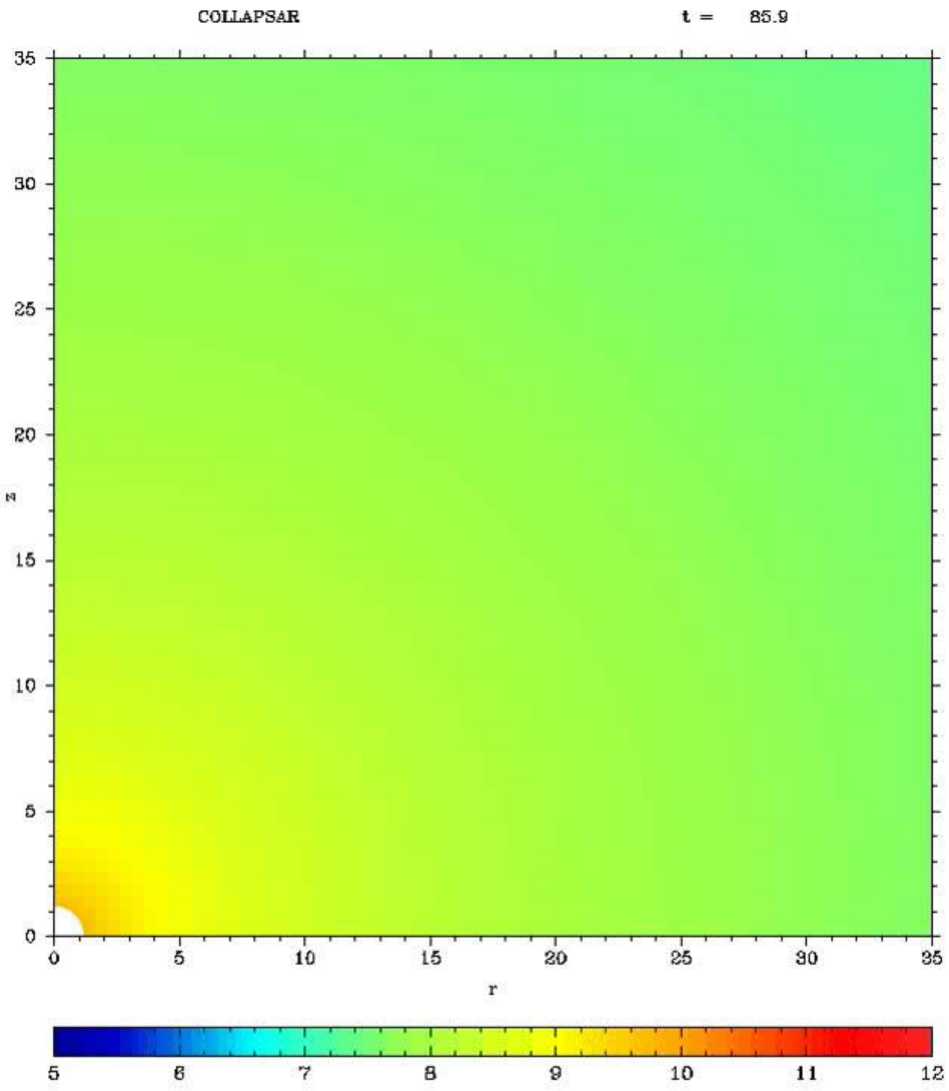
Rotation Energy Can be Extracted from a BH: Blandofrd-Znajeck Process



In 2005, Canada.
Left：Roger Blandford
Right：Me

When Slowly Rotating Electro-Magnetic Fields are Absorbed by a Rapidly Rotating BH, Outgoing Poynting Flux Emerges.
Blandford and Znajek (1977).

Example of BZ-Collapsar



Rotation
Axis

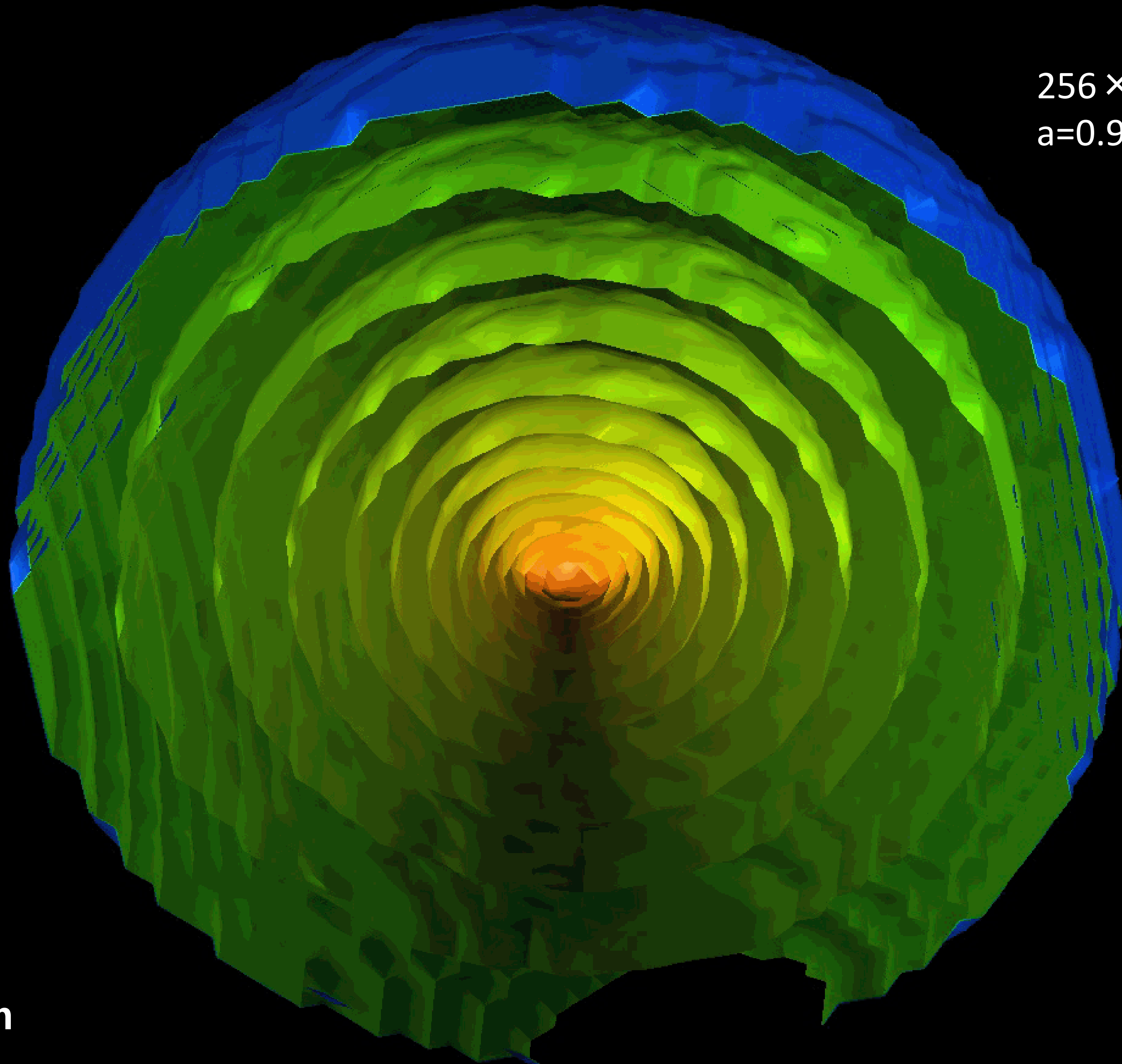
Color: Density
Lines: Poloidal
B-Fields

M. Barkov
(RIKEN →
Potsdam&DESY)

Equatorial
Plane

3D-GRMHD Simulation of GRBs

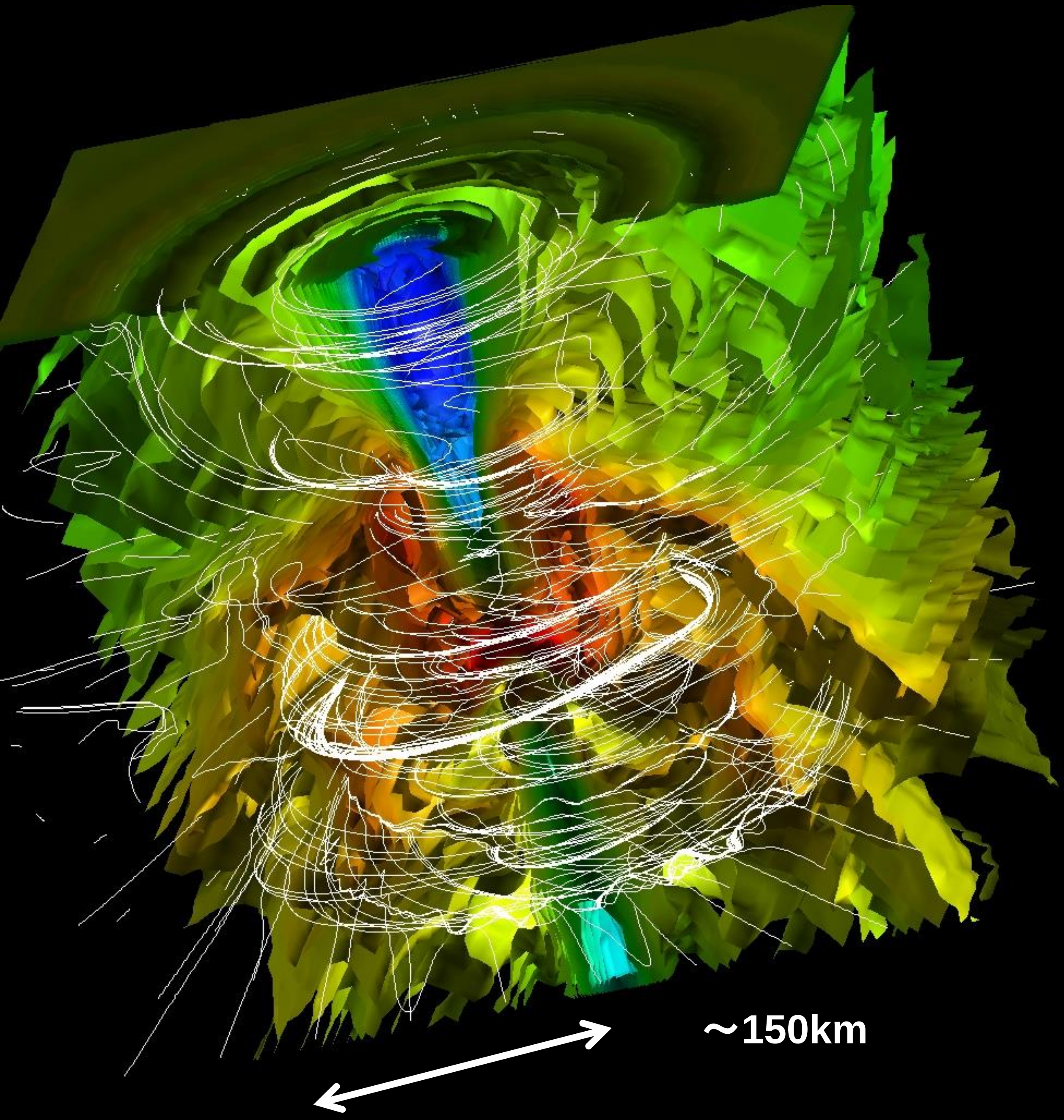
S.N. 2013.



～3000km

256×256×128
a=0.9

Nagataki
(RIKEN)

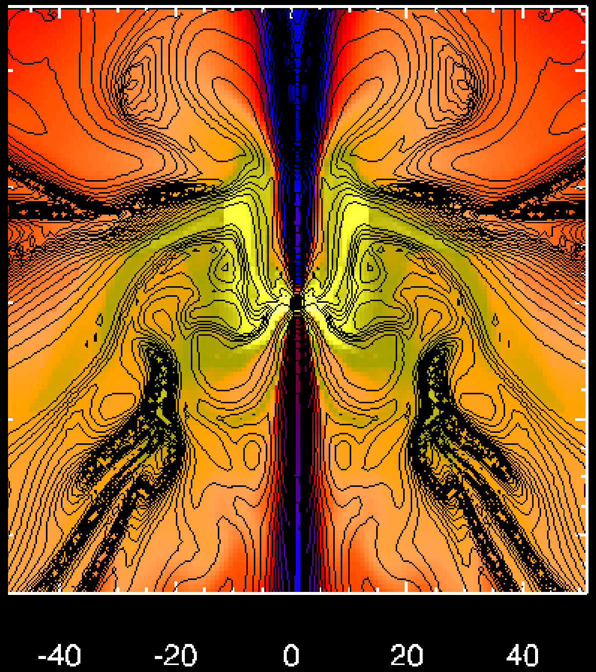


a=0.9
T~0.9sec.

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

Bottom: 2D Slice
Density+Poloidal
B-Fields

~150km



BZ-Collapsar Model

Blandford-Znajek 1977

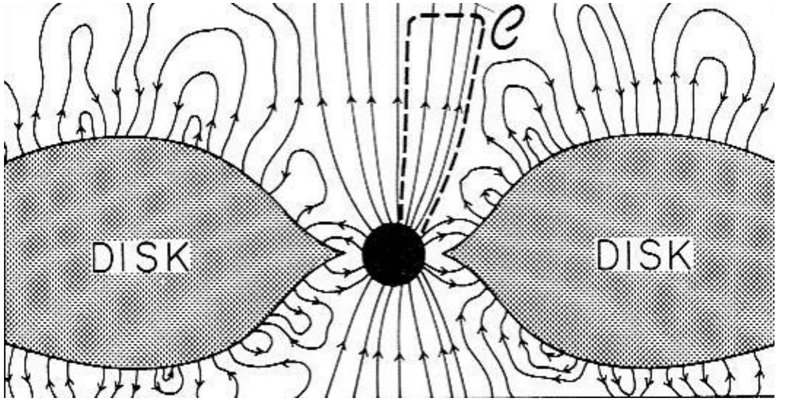
Energy source is Rotation Energy of the BH.

$$E_{\mathrm{rot,MAX}} = 1.6 \times 10^{54} \left(\frac{M_{\mathrm{BH}}}{3M_{\odot}}\right)$$

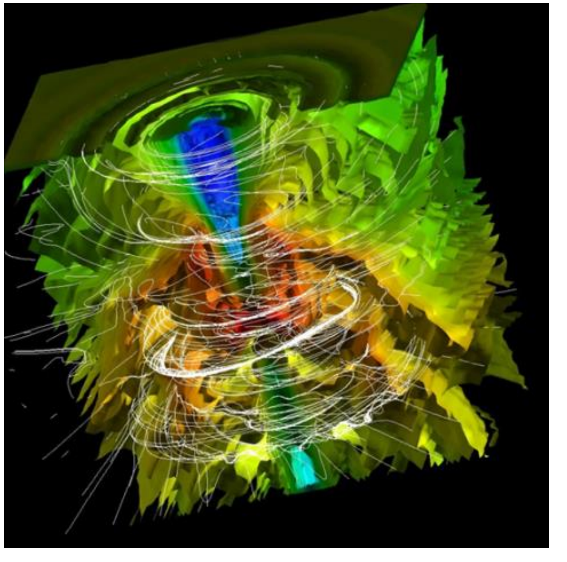
$$\dot{E} \sim 4\pi R^2 \times f \times c \left(\frac{B^2}{8\pi}\right) a^2$$

$$\sim 10^{51} a^2 \left(\frac{f}{0.1}\right) \left(\frac{R}{8\mathrm{km}}\right)^2 \left(\frac{B}{10^{15}\mathrm{G}}\right)^2 \ \mathrm{erg\ s^{-1}}$$

$$[0 \leq a \leq 1]$$



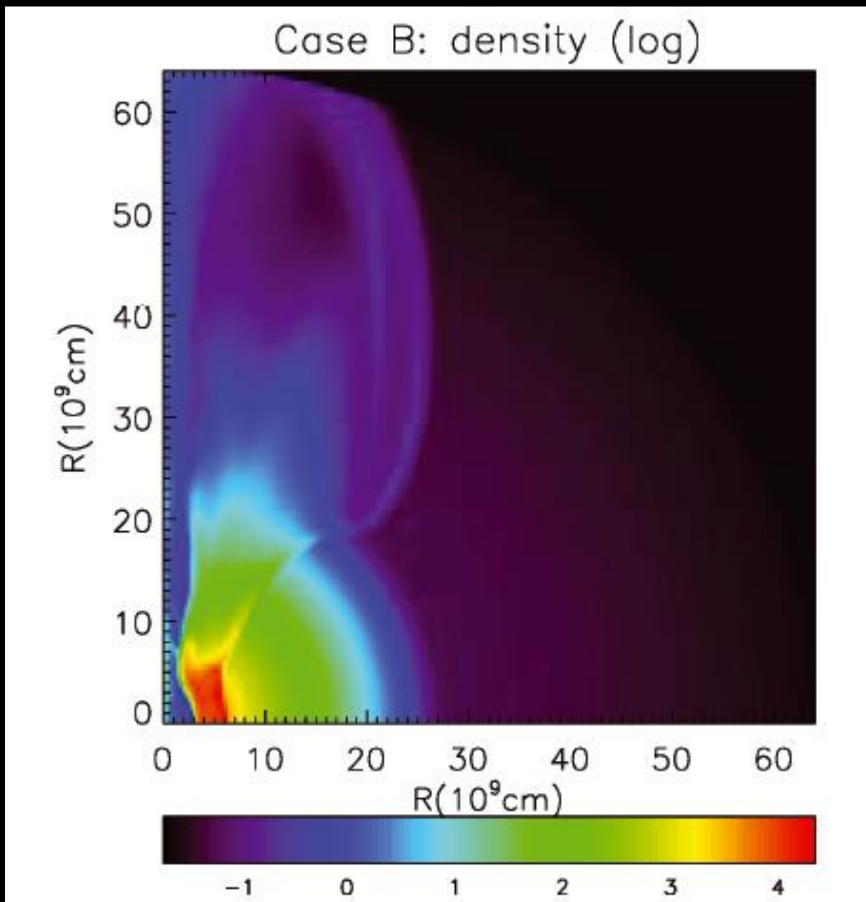
Thorne & Macdonald 1986



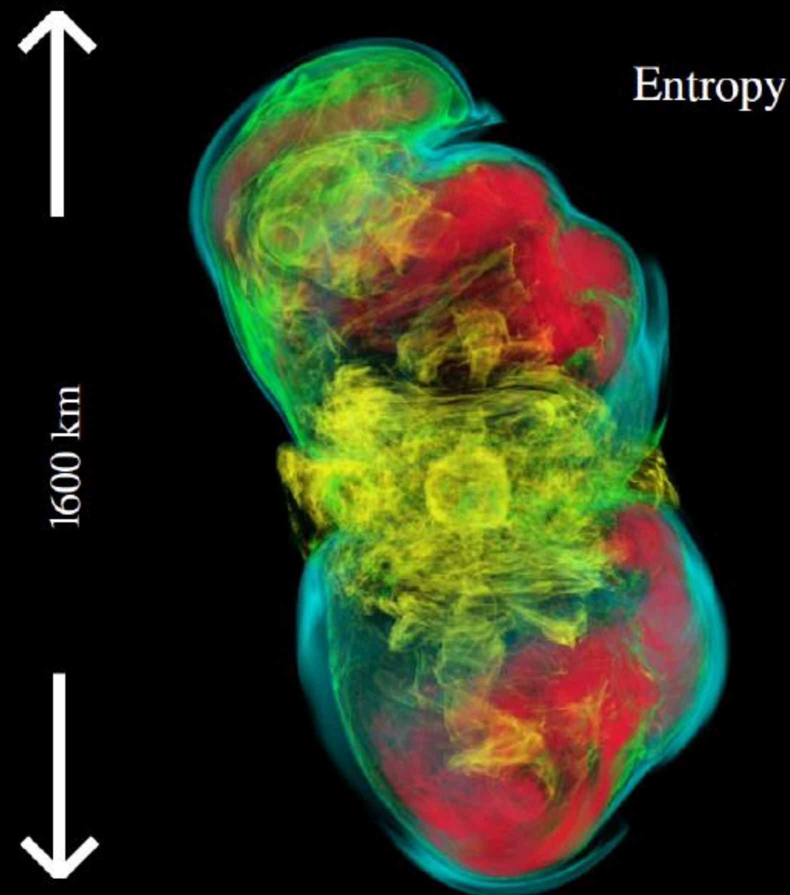
Rotation Energy of the BH can be extracted in the form of Poyinting Flux (Blandford-Znajek Effect: One of the General Relativistic Effect).

S.N. 13

Magnetar Model



Bucciantini+09 2-Dimensional



Moesta+15 3-Dimensional

Magnetar Model

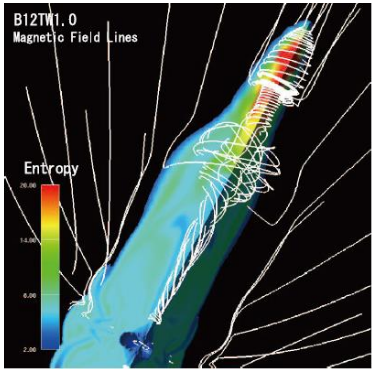
Energy Source is Rotation Energy of a Neutron Star.

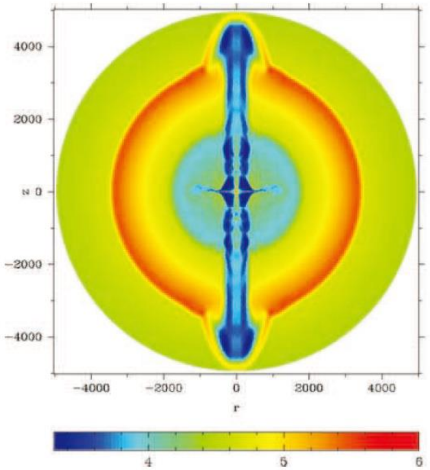
$$E_{\rm rot} = 3 \times 10^{52} \left(\frac{M}{2M_\odot}\right) \left(\frac{R}{10{\rm km}}\right)^2 \left(\frac{1{\rm ms}}{T}\right)^2 \ {\rm erg}$$

$$\dot{E} = 4\pi R^2 \times f \times c \left(\frac{B^2}{8\pi}\right)$$

$$= 1.5 \times 10^{51} \left(\frac{f}{0.1}\right) \left(\frac{R}{10{\rm km}}\right)^2 \left(\frac{B}{10^{15}{\rm G}}\right)^2 \ {\rm erg\ s^{-1}}$$

$$\longrightarrow E/\dot{E} \sim 10 \ {\rm sec}$$



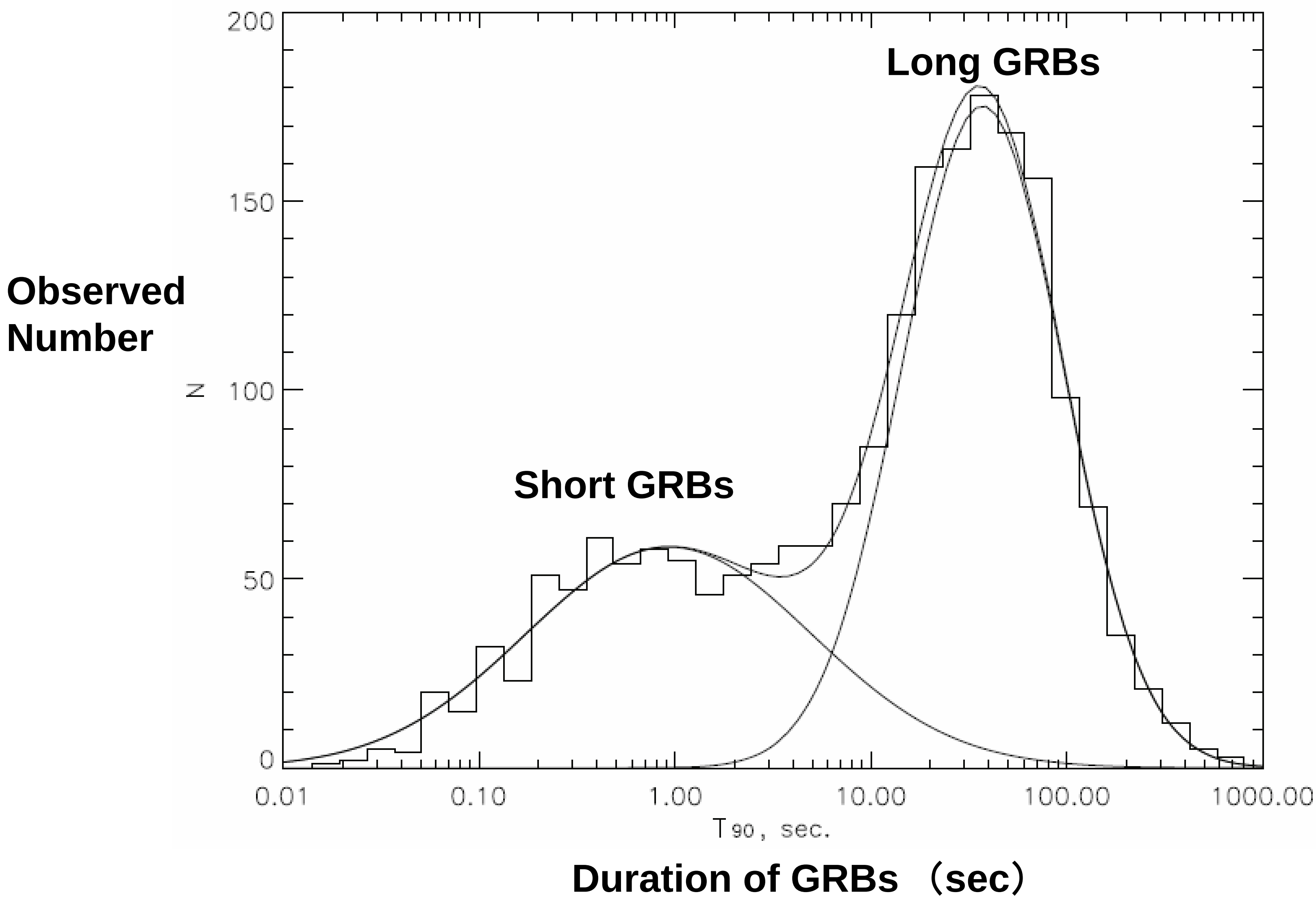


○ Good to Explain the Energy and Duration of GRBs and Hypernovae..

△ Maximum Energy is ~10^53erg?
More Energy may be OK for Quark Stars?

Figures : Top Takiwaki+09
Bottom: Komissarov & Barkov 07

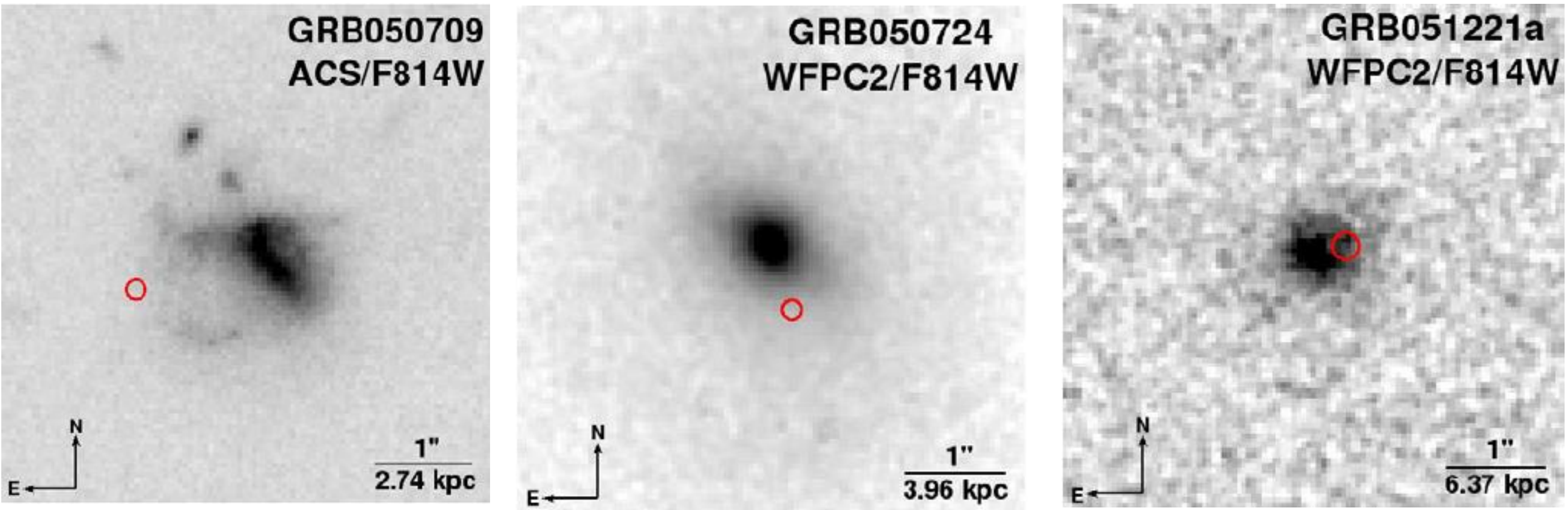
Long GRBs & Short GRBs



Origin of SGRBs is not Identified.

By Swift/HST.

Fong et al. 2010

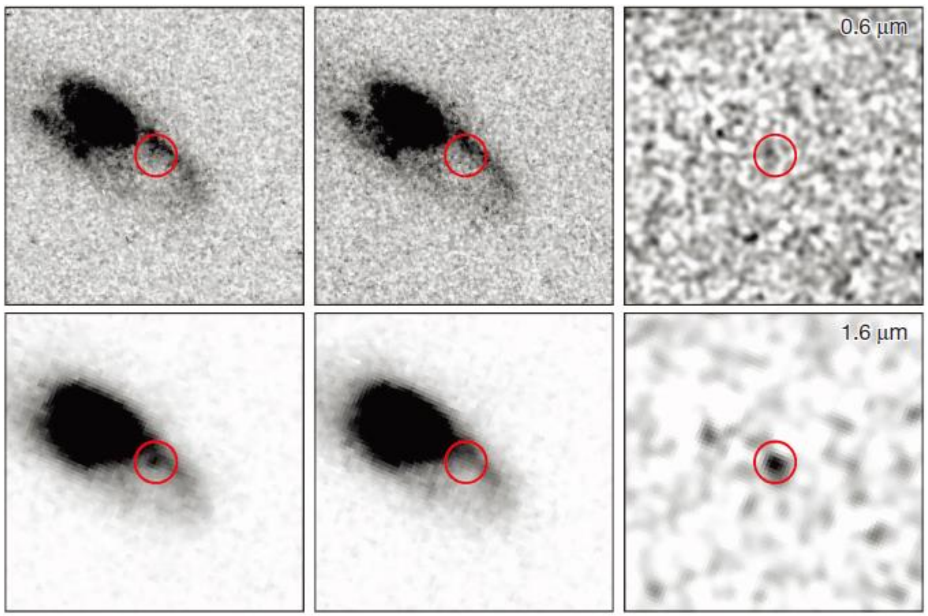


Origin of SGRBs is Unkown.
They happens far away from their host galaxies?
(～5kpc away from the center in average for 10SGRBs).

Kilonova & Short GRB130603B

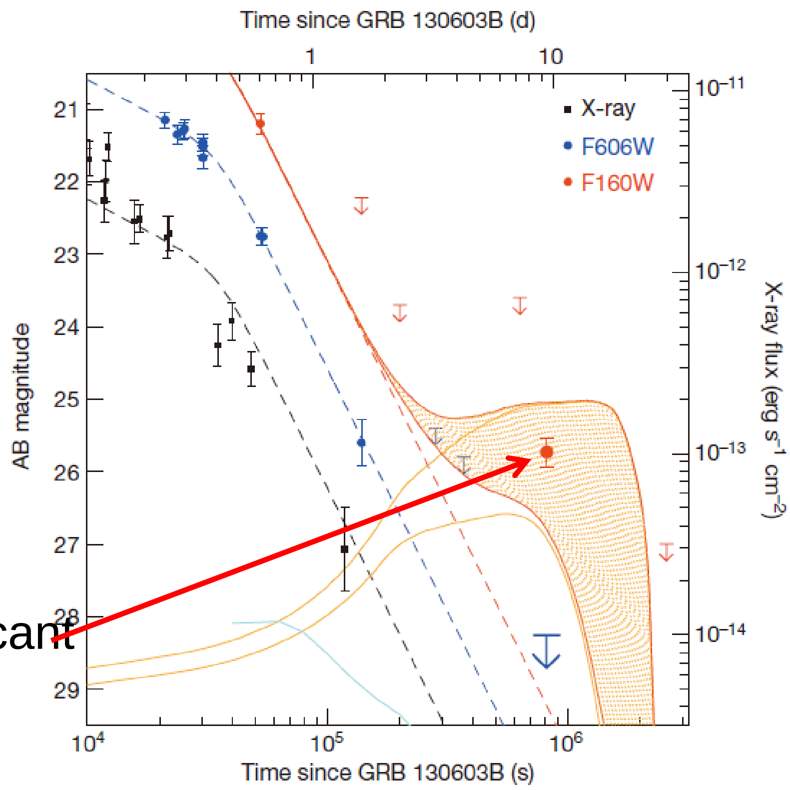
Tanvir et al. Nature 2013

9Days 30Days Residual



Optical Upper Limit Only.

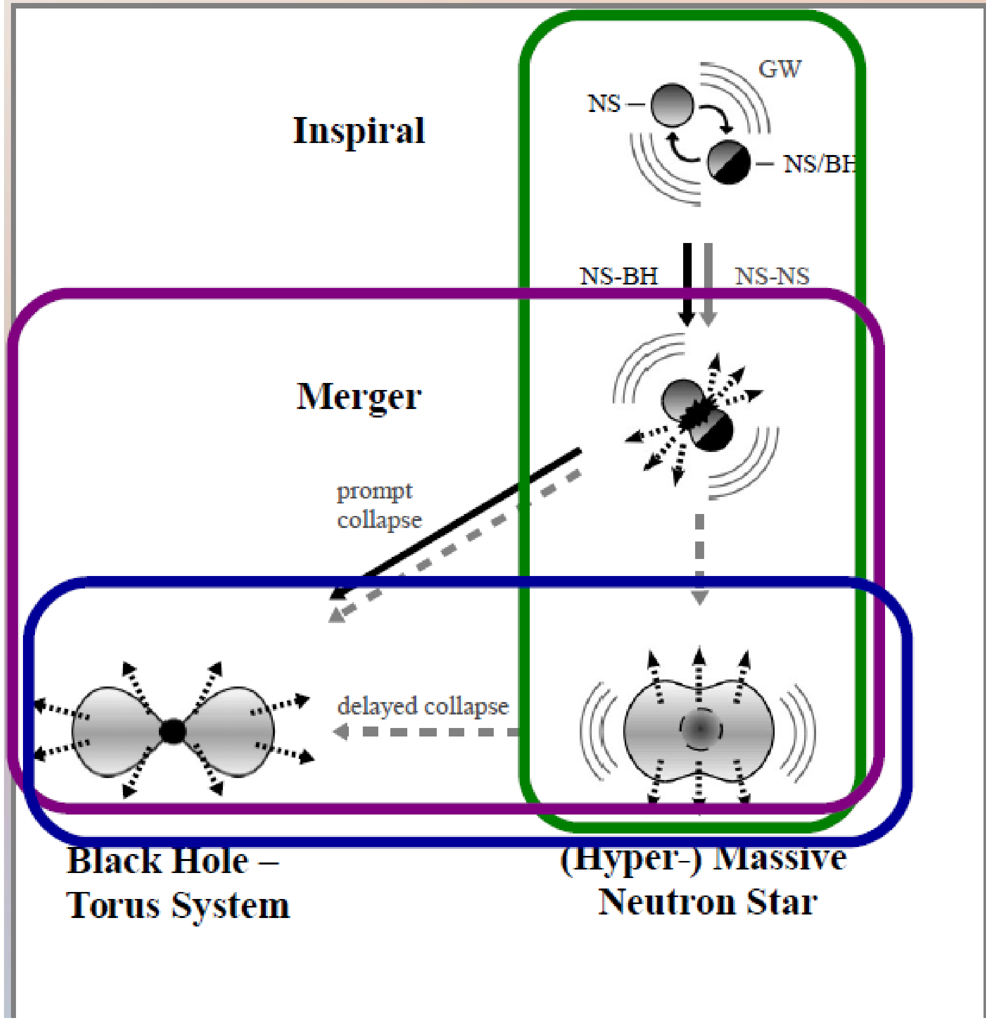
IR Significant



9Days After the SGRB.

Heating Source is newly synthesized R-process Elements?

Promising Model for Short GRBs: Mergers of Neutron Star Binaries



➔ GW signal

… binary parameters?

… nuclear EOS?

➔ short GRB

… from BH-torus system?

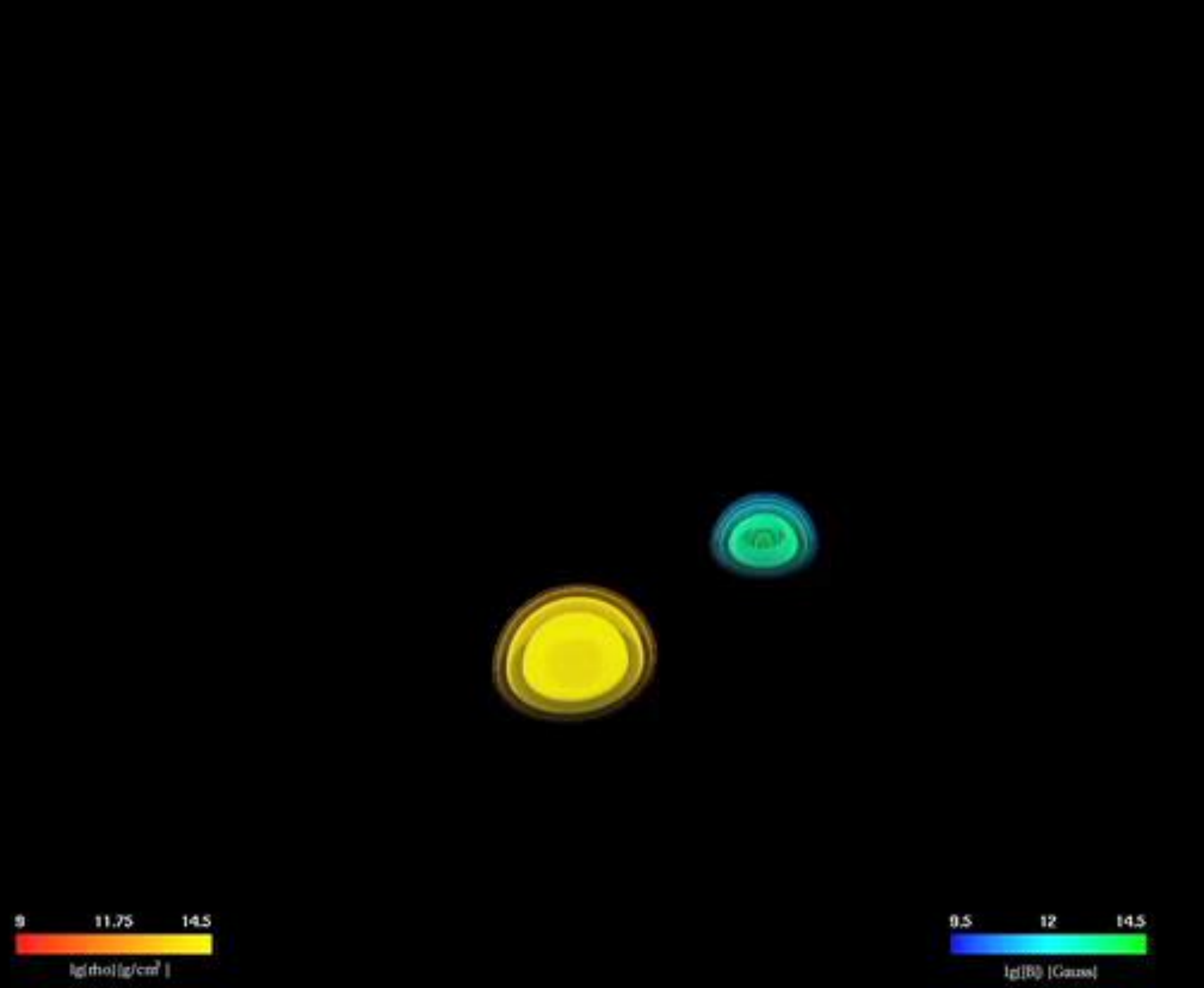
… from (H)MNS?

➔ Massive Ejecta

… sources for r-process elements?

… observable electromagnetic signals (Macro-/Kilonova)

Slide from Oliver Just (MPA)



Simulation of Binary NS Merger by Baiotti Giacomazzo Rezzolla

First Detection of Gravitational Waves in 14th Sep. 2015!

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)