From SNe to SNRs

～Hunting Legacies of Supernova Explosions in Supernova Remnants～

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RIKEN

Astrophysical Big Bang Laboratory (ABBL)
Interdisciplinary Theoretical & Mathematical Sciences Program (iTHEMS)

N3AS Seminar (remote), Presentation Date: 26 Apr. 2022.

Astrophysical Big Bang Lab. (ABBL)

From 01.Apr.2013. 10th Year !

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- PI: Shigehiro Nagataki
- Research Staff: Akira Mizuta
- Current PDs: H.Ito, G. Ferrand, M. Ono, H. Sotani, E. Kido, N. Nishimura, Y. Sekino, R. Higuchi, D. Warren (concurrent)
- Visiting Scientists: Barkov (RAS), He (PMO), Just (GSI), Inoue (Bunkyo), Kawazura (Tohoku), Globus (NYU), Tamii (Osaka), Mao (Yunnan), Takei (Tokyo)
- Almuni: Lee(Kyoto), Tolstov(Company), Dainotti (NAOJ), Teraki (City Hall), Takiwaki (NAOJ), Wada (Tohoku), Wongwathanarat(Company), Matsumoto (Keio U.), Arakawa (Company)

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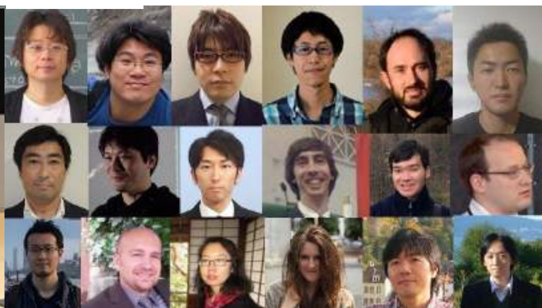
2016

2019

2021



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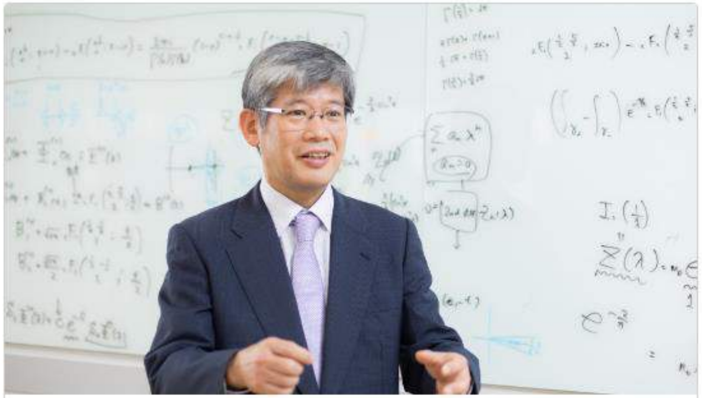

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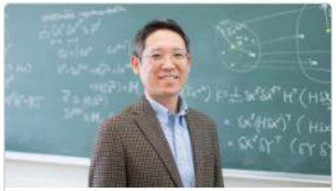

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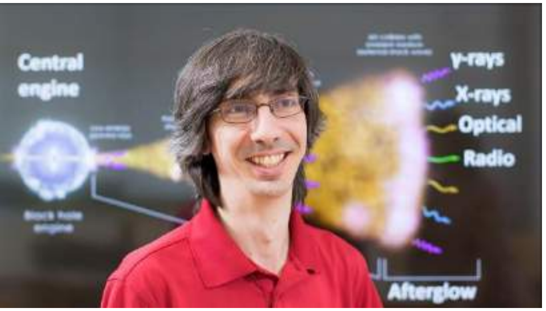

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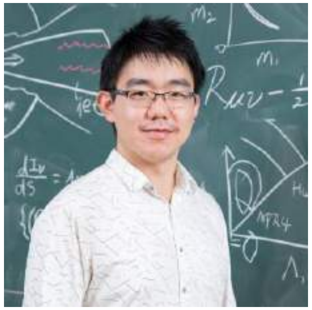
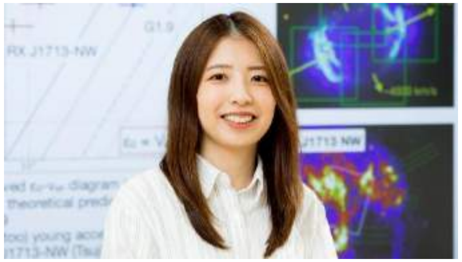


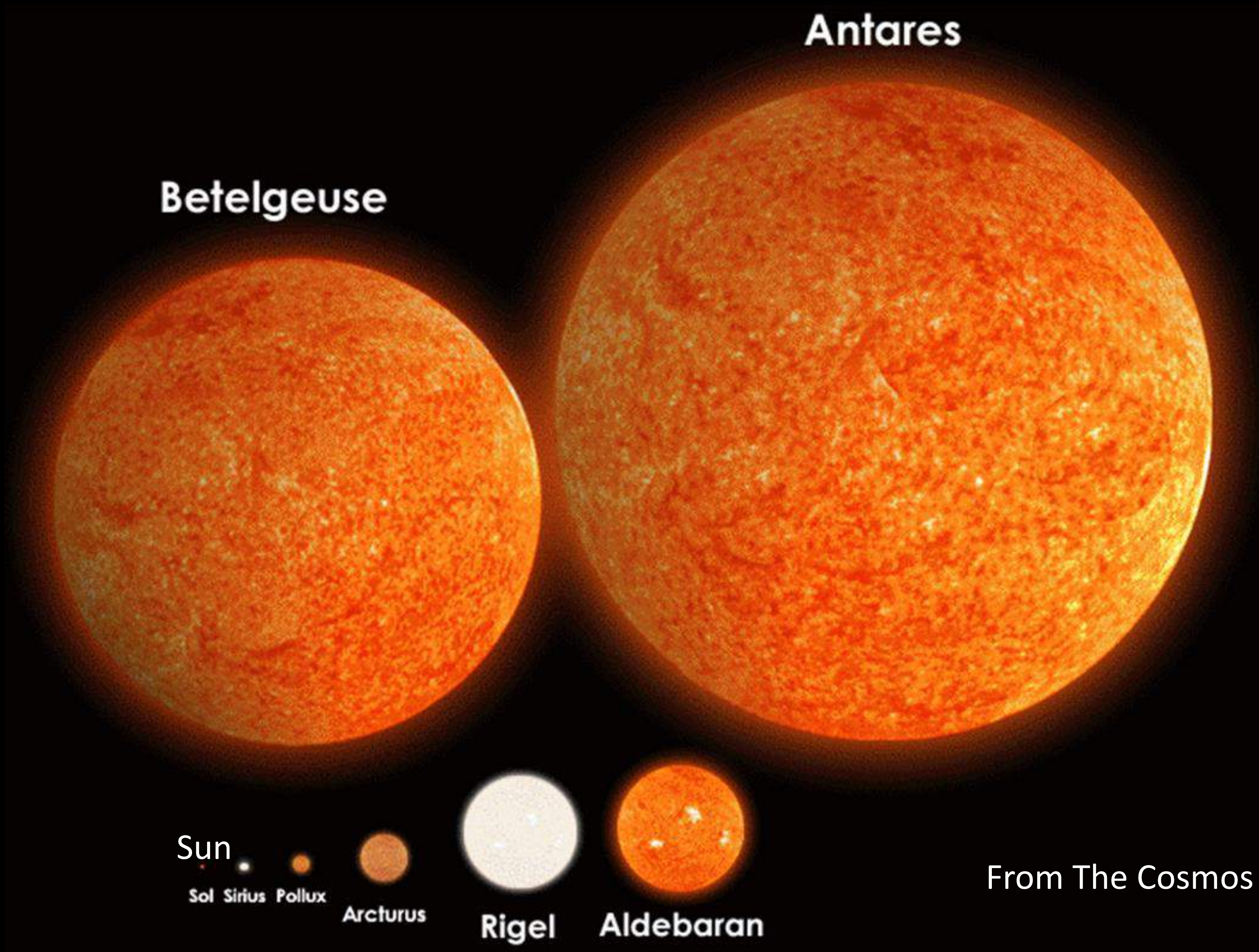
Y. Huang



N. Tsuji

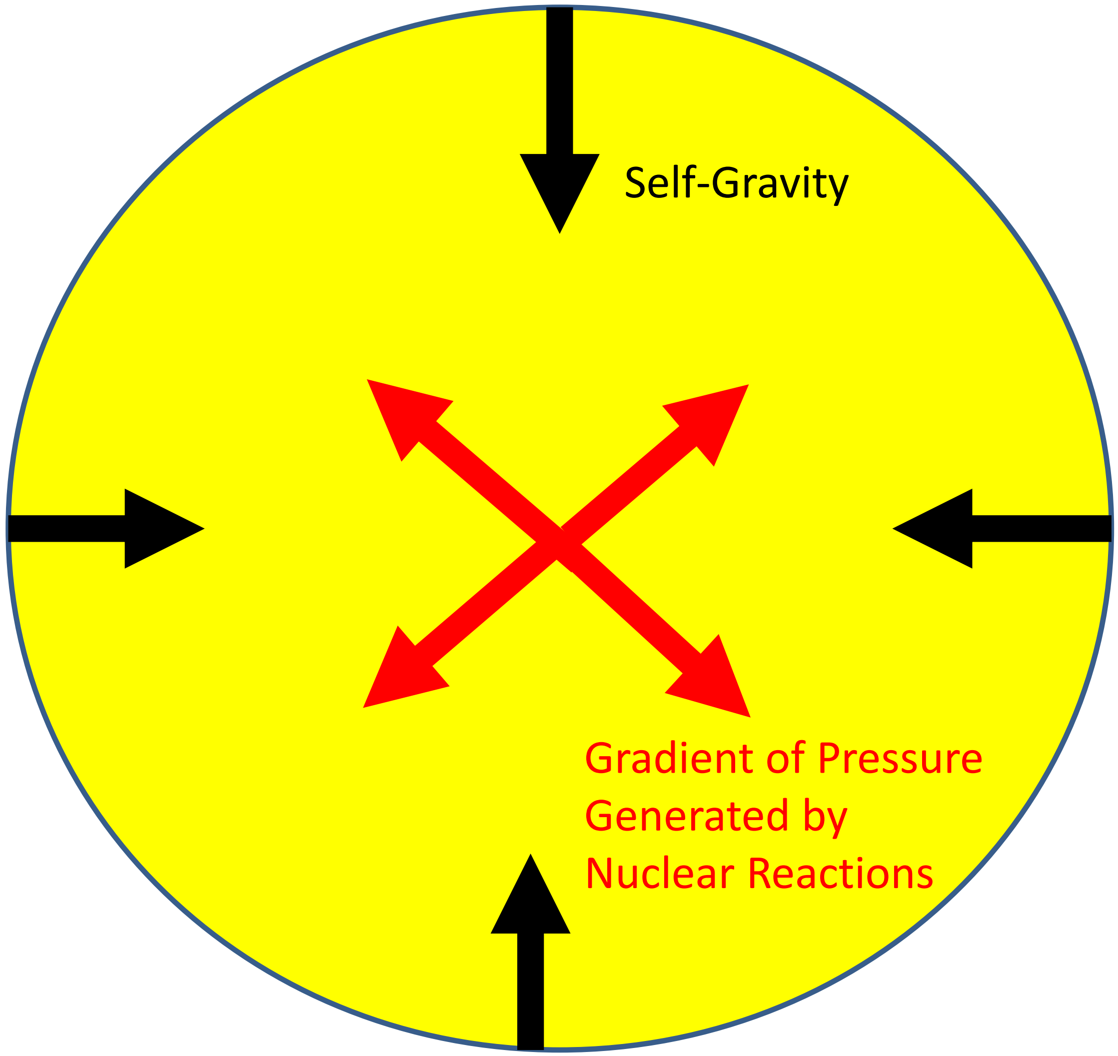
§ Explosion Mechanism of Massive Stars (Supernovae)

Massive Stars Explode

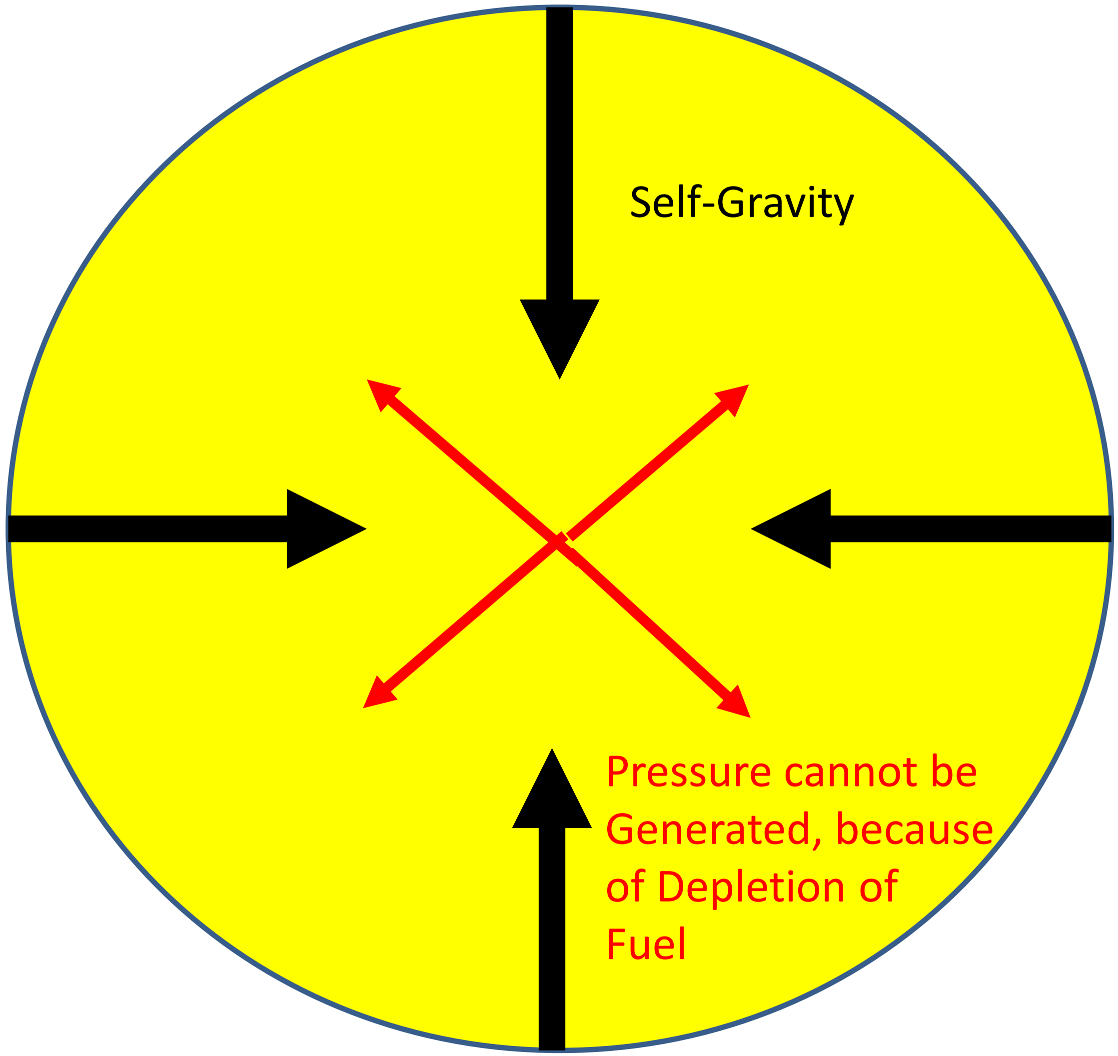


From The Cosmos News

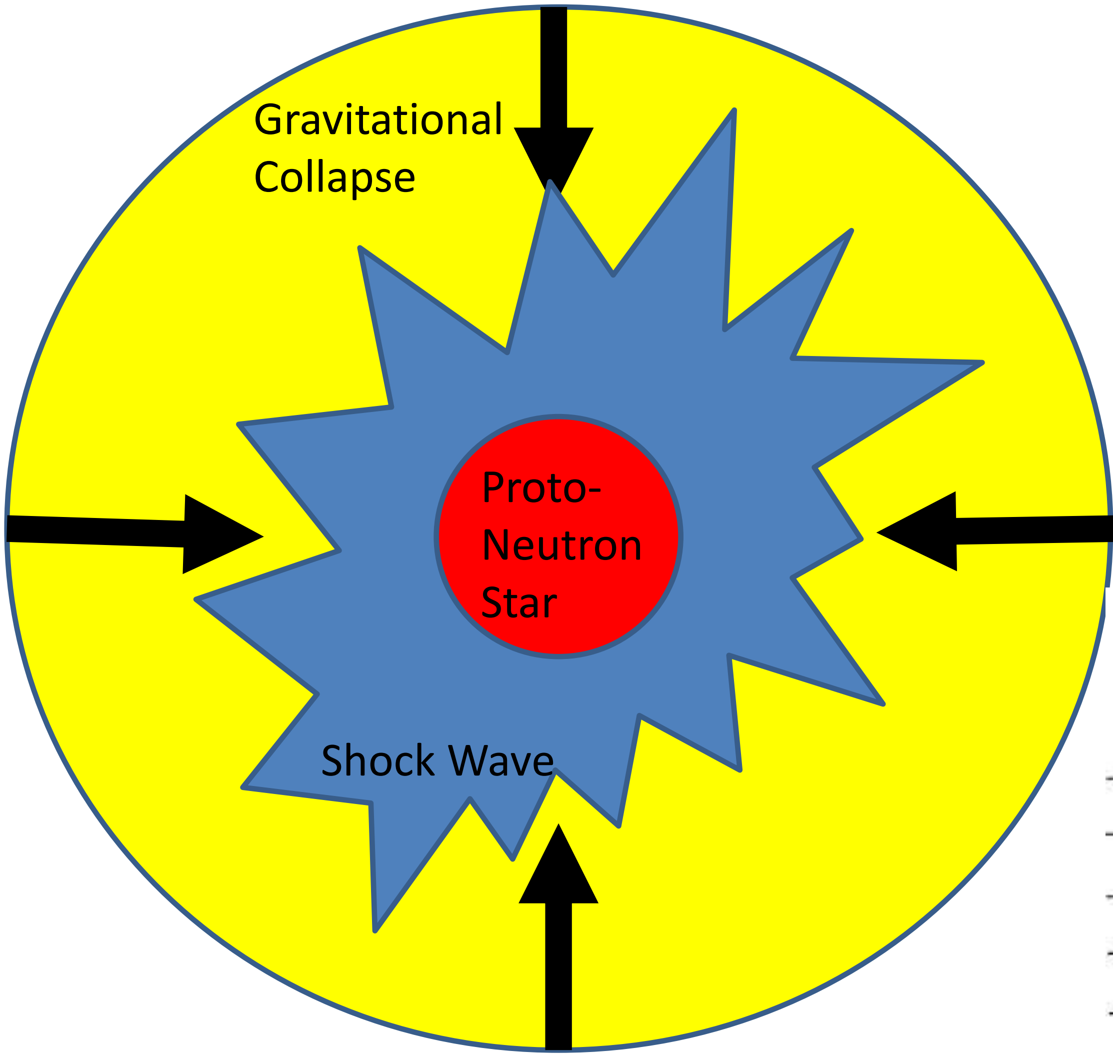
Stable, Hydrostatic Equilibrium in Stars



Loss of the Force Balance (Gravitational Collapse)

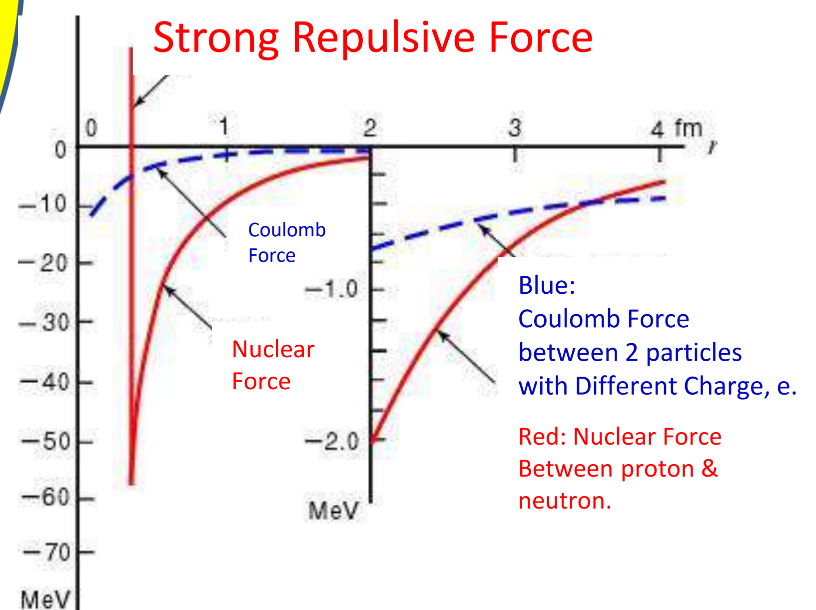


Formation of Proto-Neutron Star

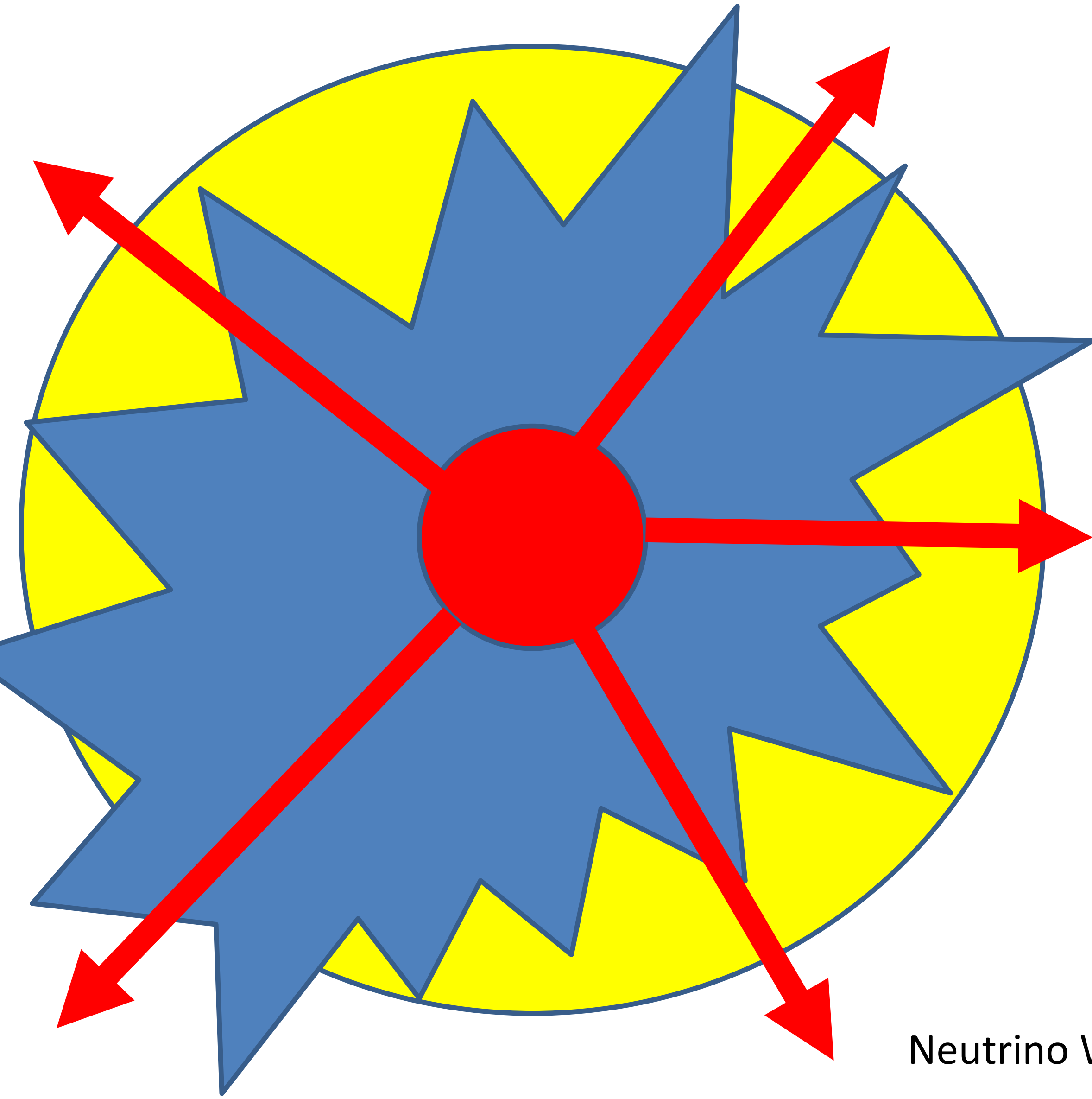


When the central density of the Collapsing star reaches to the saturation Density, the central region becomes like a huge, single nuclei (Formation of a Proto-Neutron Star).

The "Nuclei" is stiff (repulsion core) enough to hold back the gravitational Collapse. Rather, the out-going shock Wave is formed by the repulsion.



Neutrino Wind from the Proto-Neutron Star

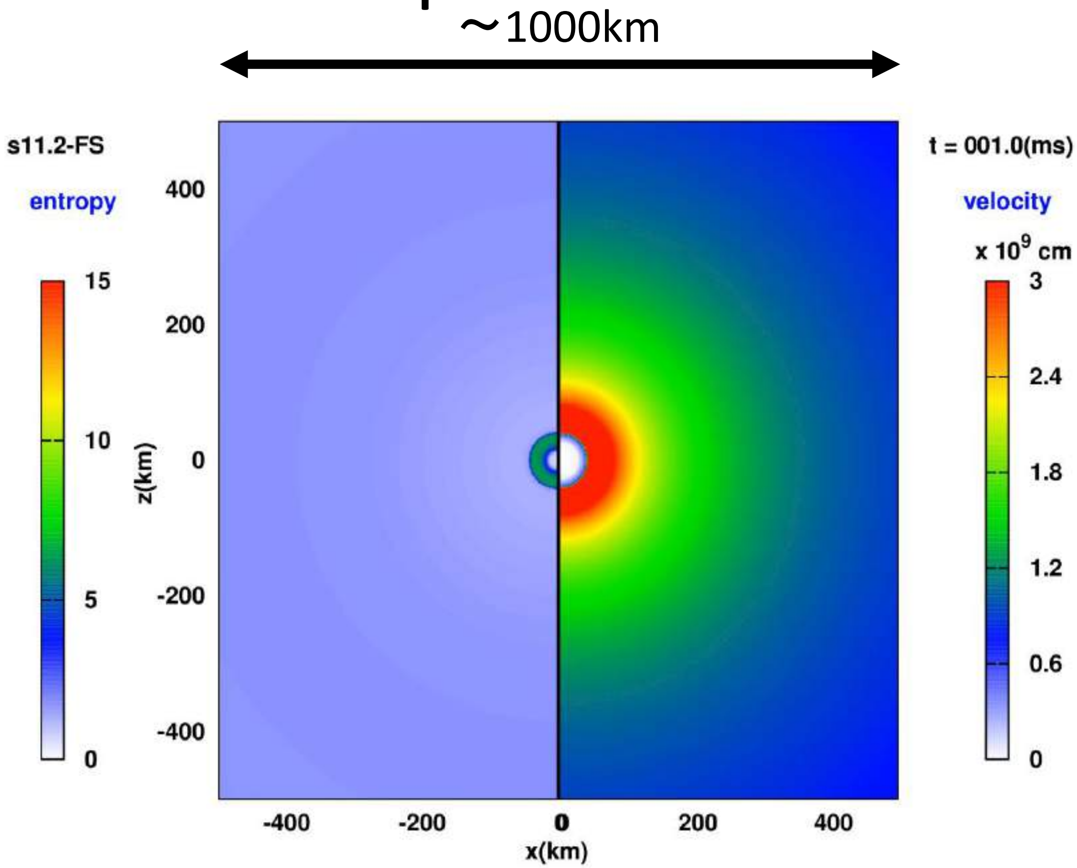


The Proto-Neutron Star is Hot
（about 10MeV～10^10K）, and
Huge flux of neutrinos is coming out
From the proto-neutron star
(neutrino wind).

The neutrino wind interacts with the
surrounding matter. The matter is
heated up, and the shock wave is
pushed outward.
Finally, the star itself explodes as
a supernova explosion.

Neutrino Wind

Examples of Multi-D, Self-Consistent Supernova Simulations at RIKEN



A Supernova Simulation from Nagakura+ 2018.

Ref. Furusawa-san's talk at N3AS Seminar, 2022

Tomoya Takiwaki
(A-ABBL)

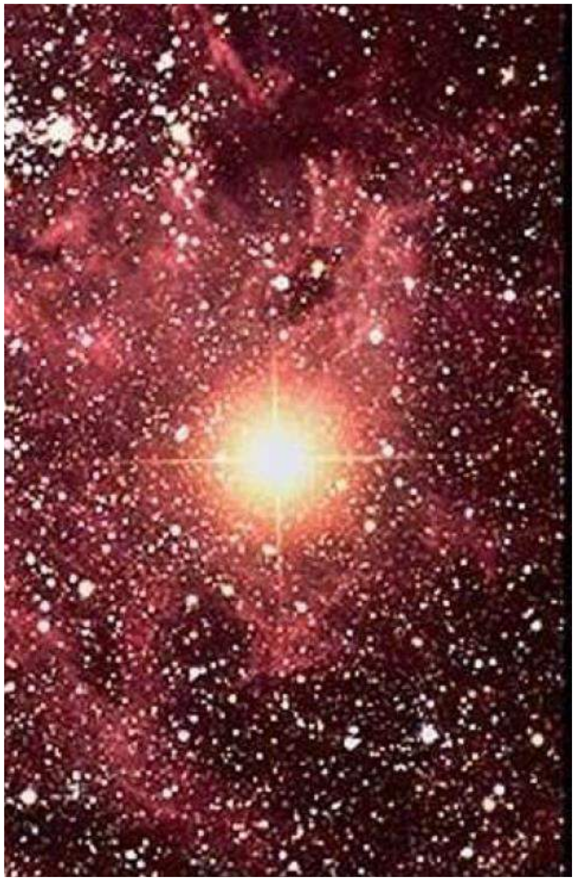
Takiwaki+ '12.

Oliver Just
(A-ABBL)

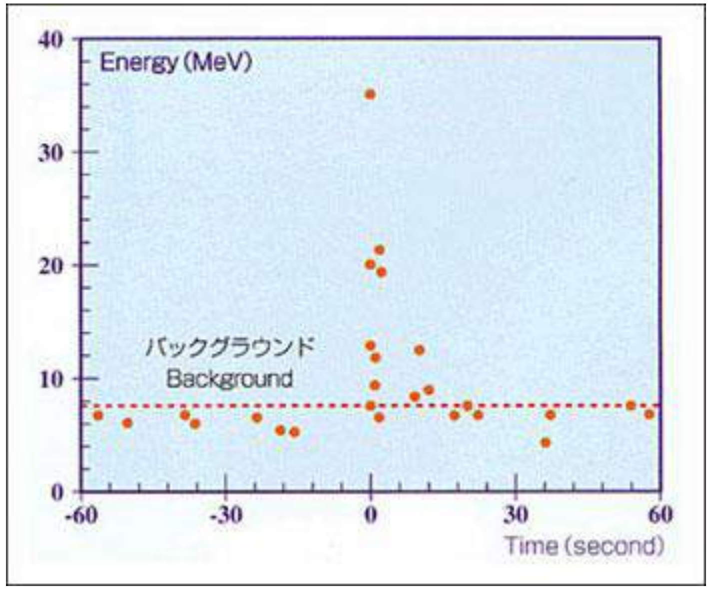
O.Just+ '18.

Akira Harada
(iTHEMS)
Harada+'20

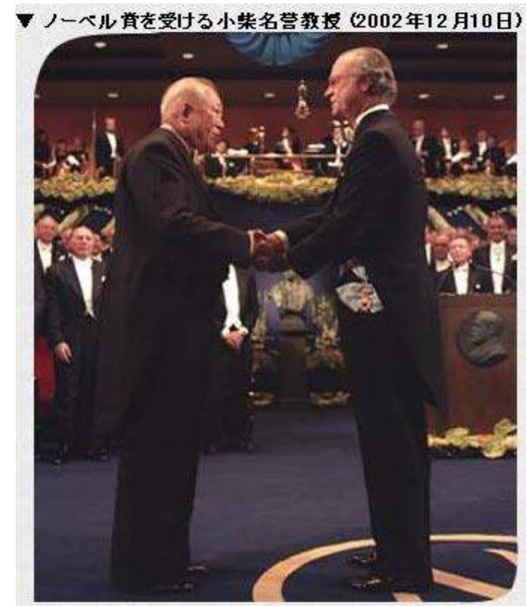
A Proof of Supernova Explosion Mechanism :
Detections of Supernova Neutrinos



SN1987A happened in Large Magellanic Clouds in 23 Feb. 1987.
The visible SN by naked eyes, about 350yrs after the last one (Cassiopeia A).



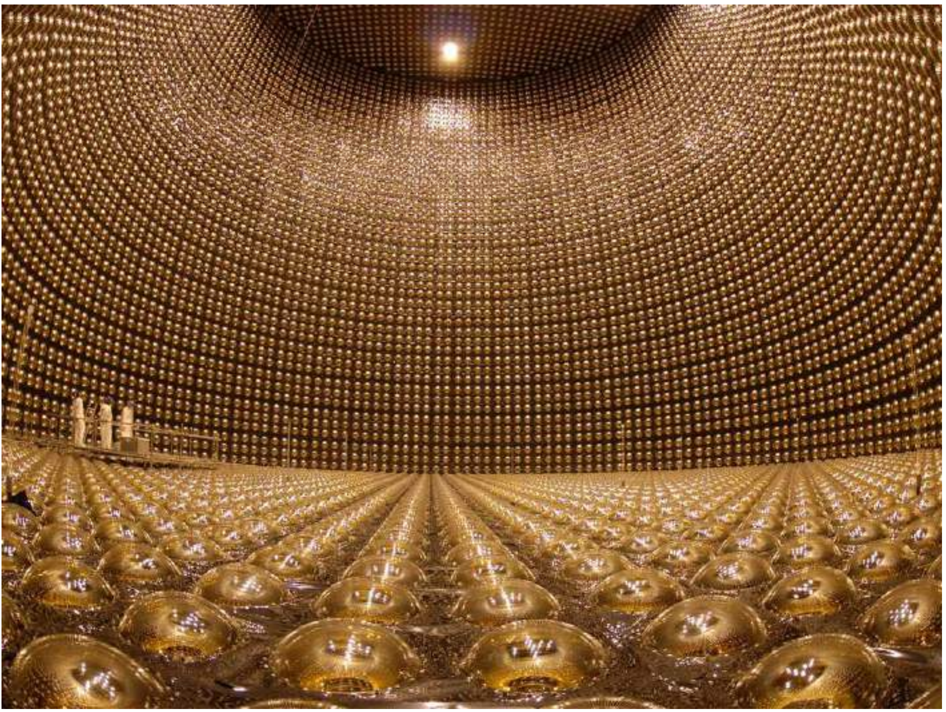
The 11 events of neutrinos from SN1987A, detected by Kamiokande.



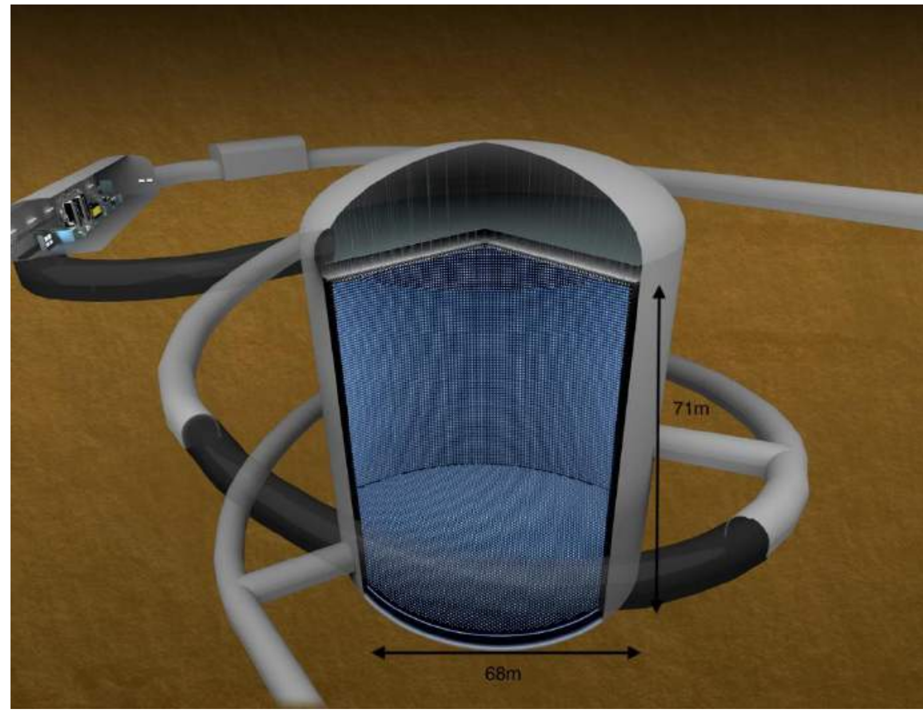
Masatoshi Koshiba (1926-2020).
Nobel Prize in Physics in 2002 for the detection of cosmic neutrinos.

A miniature of Kamiokande (1983-1996).
At Institute for Cosmic Ray Research, UT.

For Future Observations of Supernova Neutrinos.



Super-Kamiokande（1996-）
50 K ton of Water with Water Cherenkov Detectors
c.f. 3K ton for Kamiokande.
About 10,000 neutrino events are expected when
a next core-collapse supernova explosion will happen
in Milky Way.



Hyper-Kamiokande（under-construction,
2027-）
260 K ton.
Figure from ICRR HP.

The Next Supernova in Milky Way as a Source of Gravitational Waves

ALIGO (2015-)
The US.

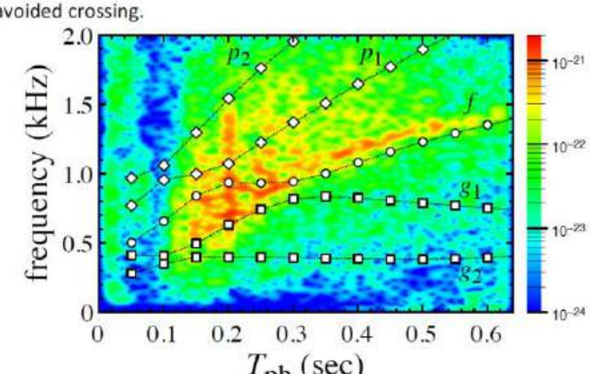
AVIRGO (2017-) Italy-France

KAGRA (2020-)
Japan.

Hajime Sotani (ABBL)

comparison with GW signals in numerical simulation

- GW signals correspond to g_1-mode in early phase and f-mode after avoided crossing.



Sotani & Takiwaki 2020

Future Prospect for Supernova Study

- More Advanced, Multi-D Supernova Simulations.
- Supernova Event Rate is about 1/100yr/Galaxy.
- Last Core-Collapse Supernova Event in Large Magellanic Cloud: SN1987A (35 yrs ago).
- Last Core-Collapse Supernova Event in Milky Way: Cassiopeia A (about 350 yrs ago).
- Once it will happen, detailed comparison of observations and simulations will tell us about supernova explosion mechanism, neutrino physics, GWs, nucleosynthesis, EOS,… A Very Exciting Event!!
- However, we don’t know when it will happen.

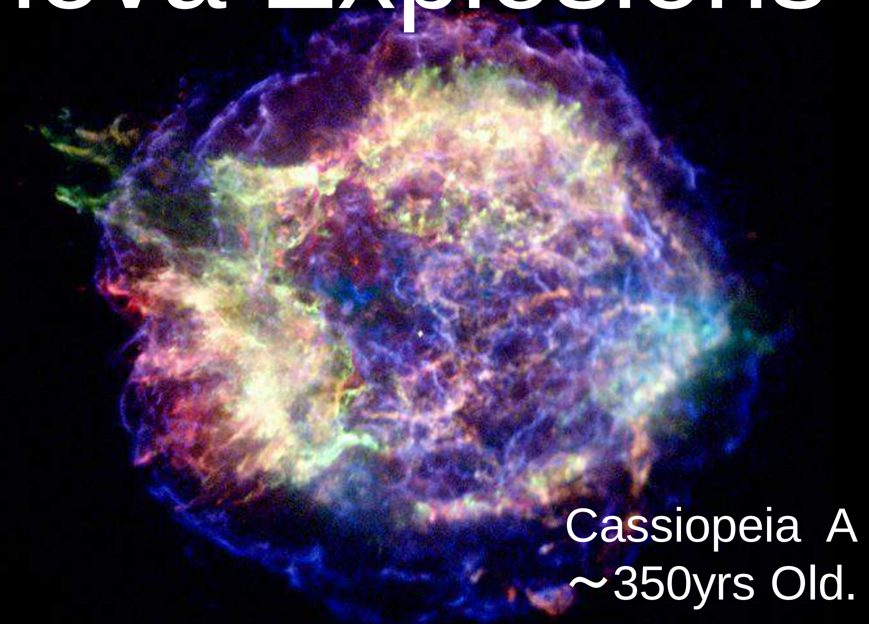
§ From Supernovae to Supernova Remnants

Why Supernova Remnants?

- Currently, many supernovae are observed by Optical/Infra-red telescopes.
- However, they are so far. They are observed as point sources.
- They are too far to be observed by neutrinos or gravitational waves.
- On the other hand, in Milky Way & local galaxies, there are some “young” supernova remnants (SNRs). Observations tell us Detailed, Multi-D morphologies of SNRs.
- Legacies of Supernova Explosions may be still imprinted in “young” supernova remnants.

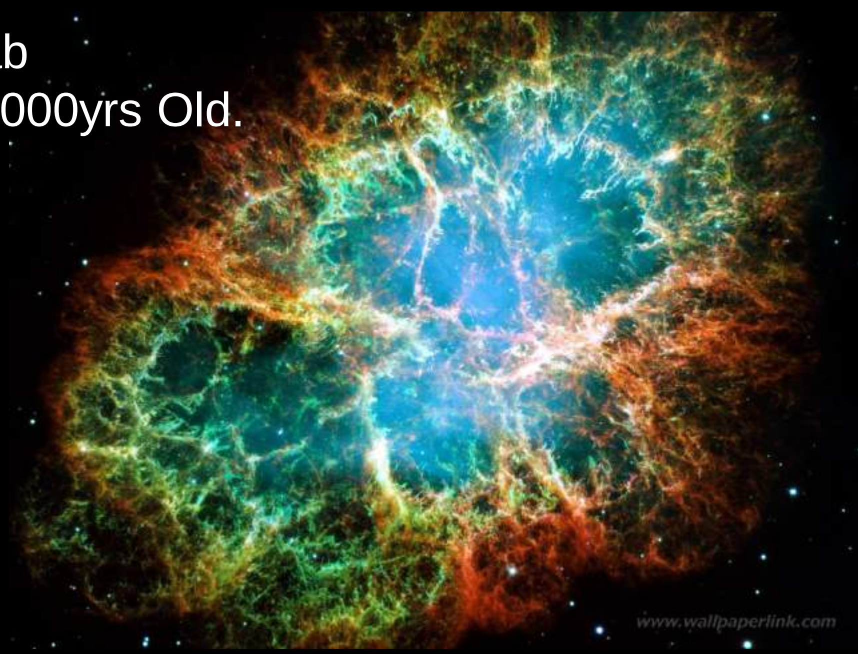
Legacies of Supernova Explosions

SN1987A
～35yrs Old.

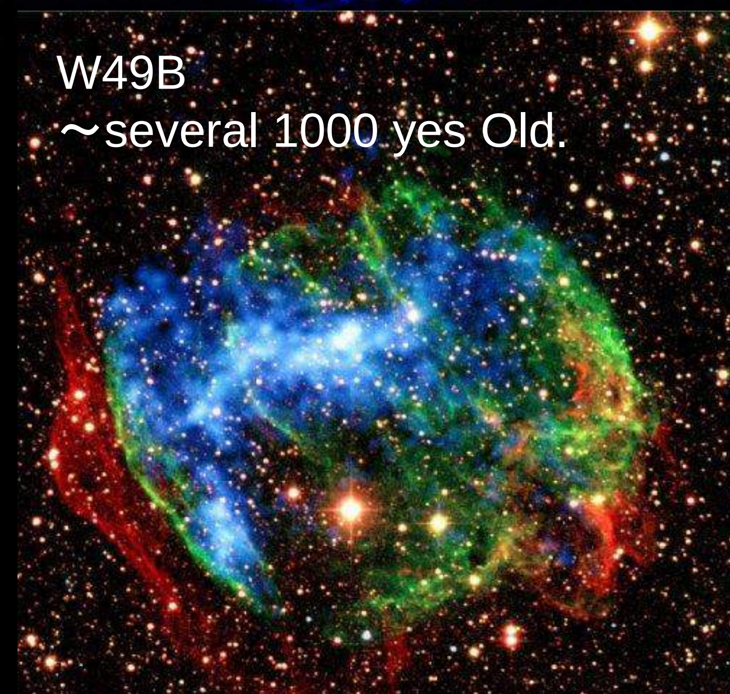


Cassiopeia A
～350yrs Old.

Crab
～1000yrs Old.



W49B
～several 1000 yes Old.



An Analogy: From T-REX Fossil to T-REX

The Tyrannosaurus rex fossil known as Stan is displayed in a gallery at Christie's auction house in New York City on September 17, 2020.
PHOTOGRAPH BY SPENCER PLATT, GETTY IMAGES

?

From Amazon Free-download.

?

By **Chris Packham (2017)**

Without any doubt, Fossils of Dinosaurs contain lots of information on Dinosaurs.
The problem is how accurately we understand Dinosaurs from their fossils.

Current Status

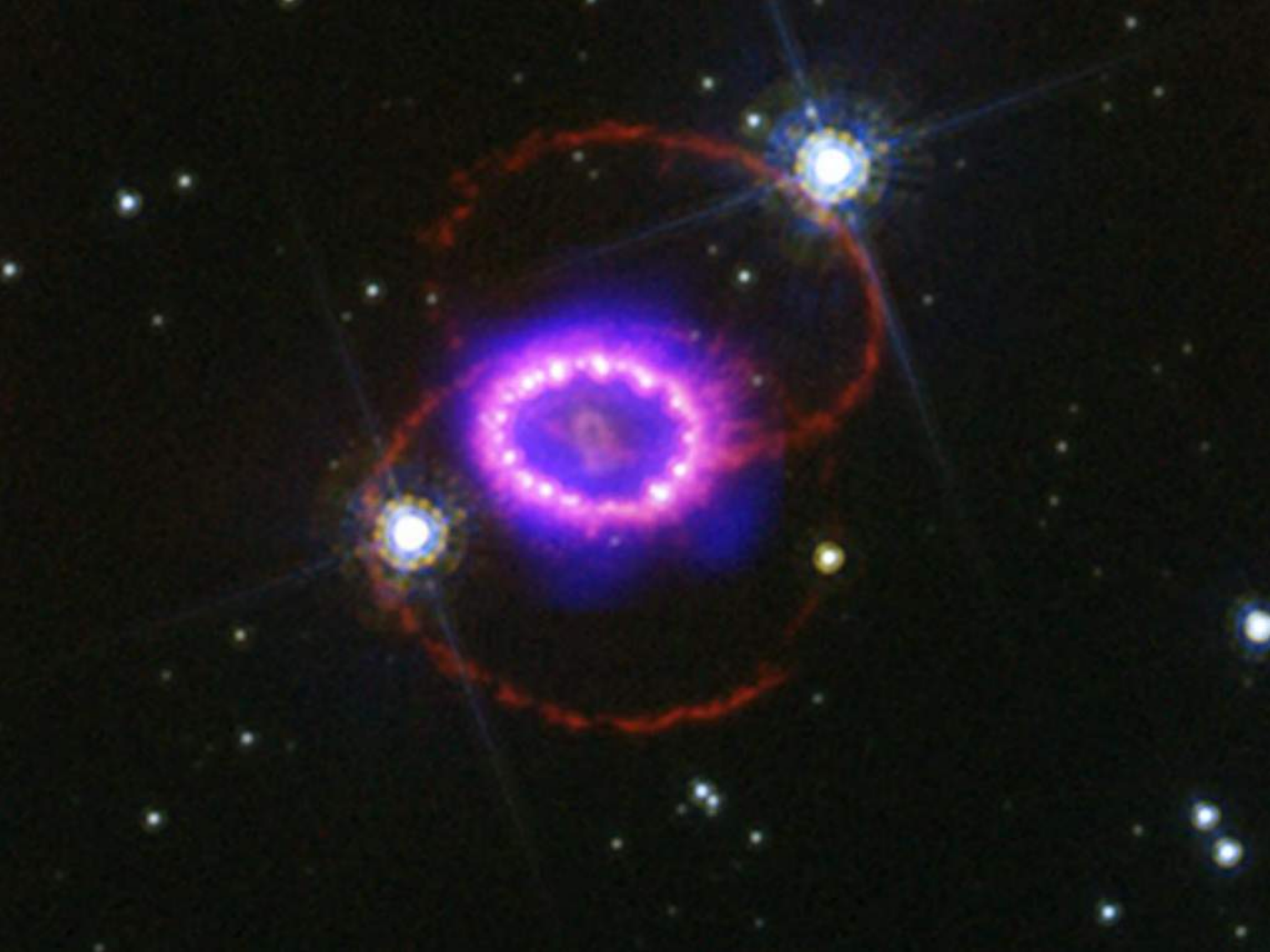
- Lack of Successful Supernova Explosion Models (none?).
- Supernova Simulations follow the dynamics less than ～1 sec.
- In future, we would like to use successful, self-consistent multi-D supernova models as our initial conditions.

- Currently, we mimic successful supernova explosions in some ways (mentioned later), which are used as initial conditions of supernova remnant simulations.
- We did 3-dimensional hydro simulations that covered from supernova explosion phase to the supernova remnant phase.
- Such multi-D simulations with a wide range of scales (in time and length) have never been done before.
- We could demonstrate that such simulations are possible thanks to excellent international collaborations.

§ SN1987A

Hubble Heritage

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



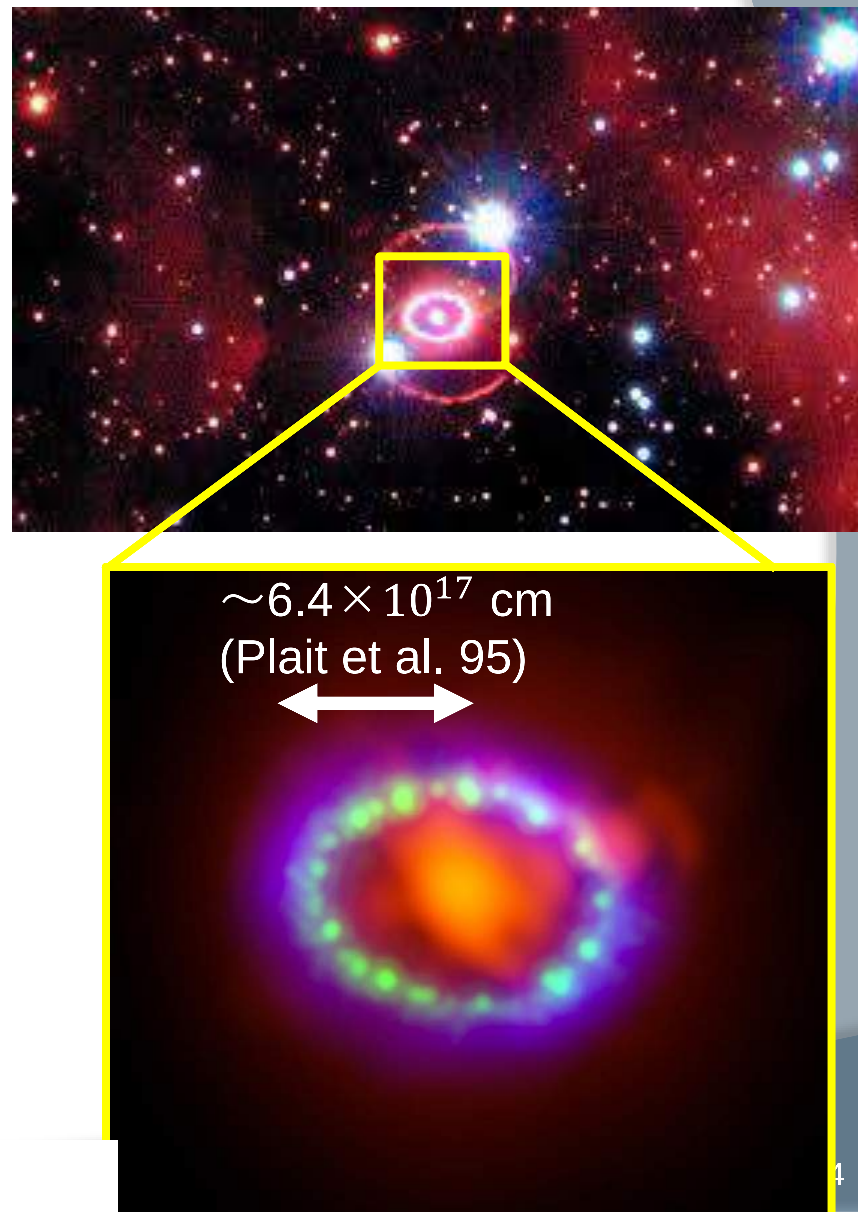
SN 1987A & its Ring.

When: **23 February 1987**
Where: **Large Magellanic Cloud**

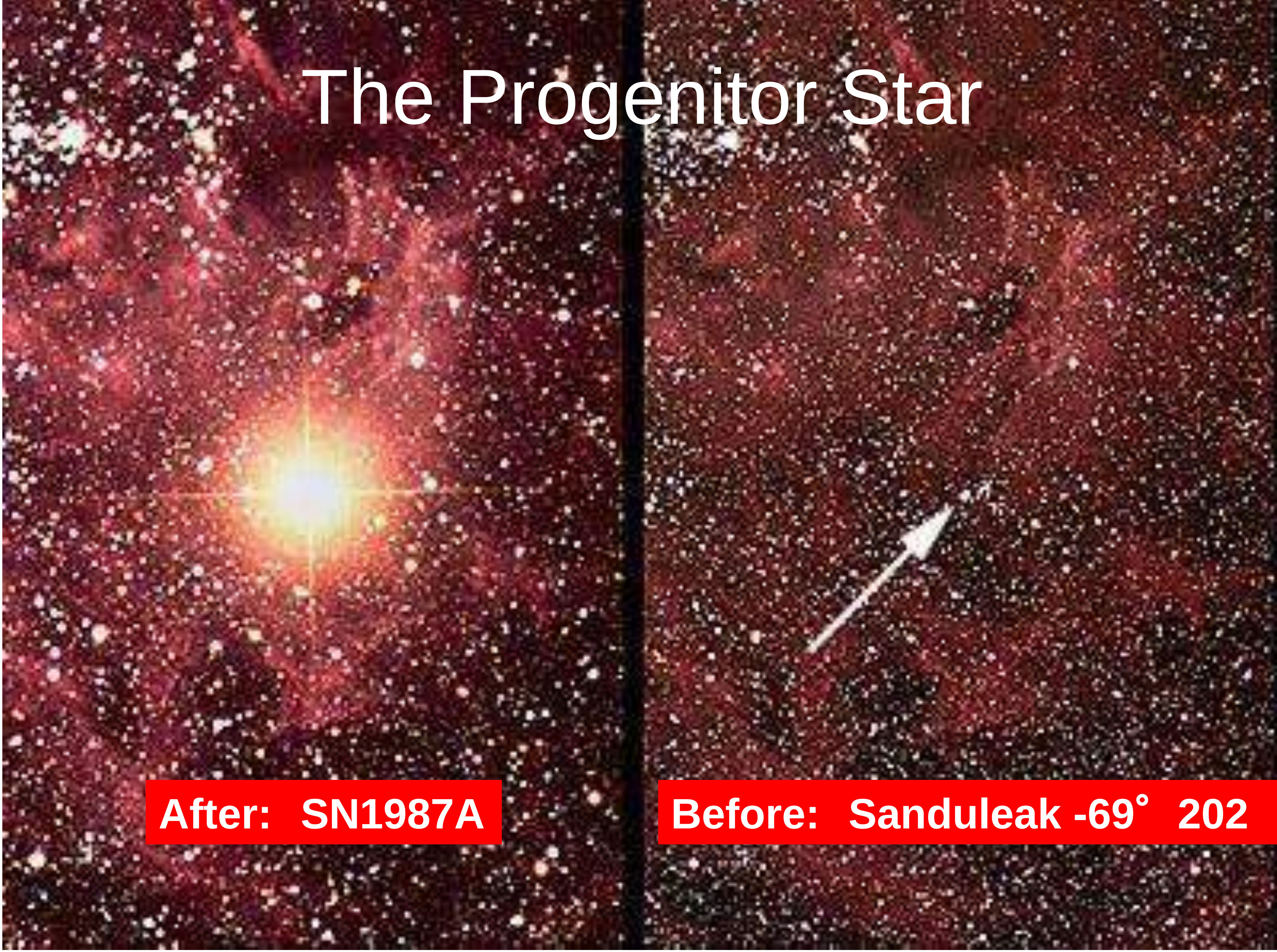
Stellar progenitor: Sk -69^{o}202

Nearest supernova explosion observed by human eyes in hundreds of years

Unique opportunity to watch a SN change into a SNR

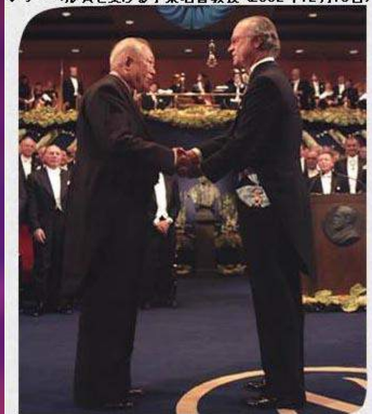


The Progenitor Star

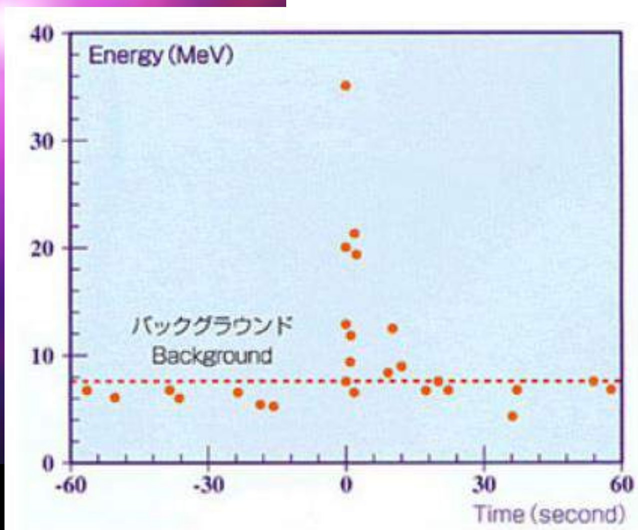


Where is the Neutron Star in SN1987A?

▼ ノーベル賞を受ける小柴名誉教授（2002年12月10日）

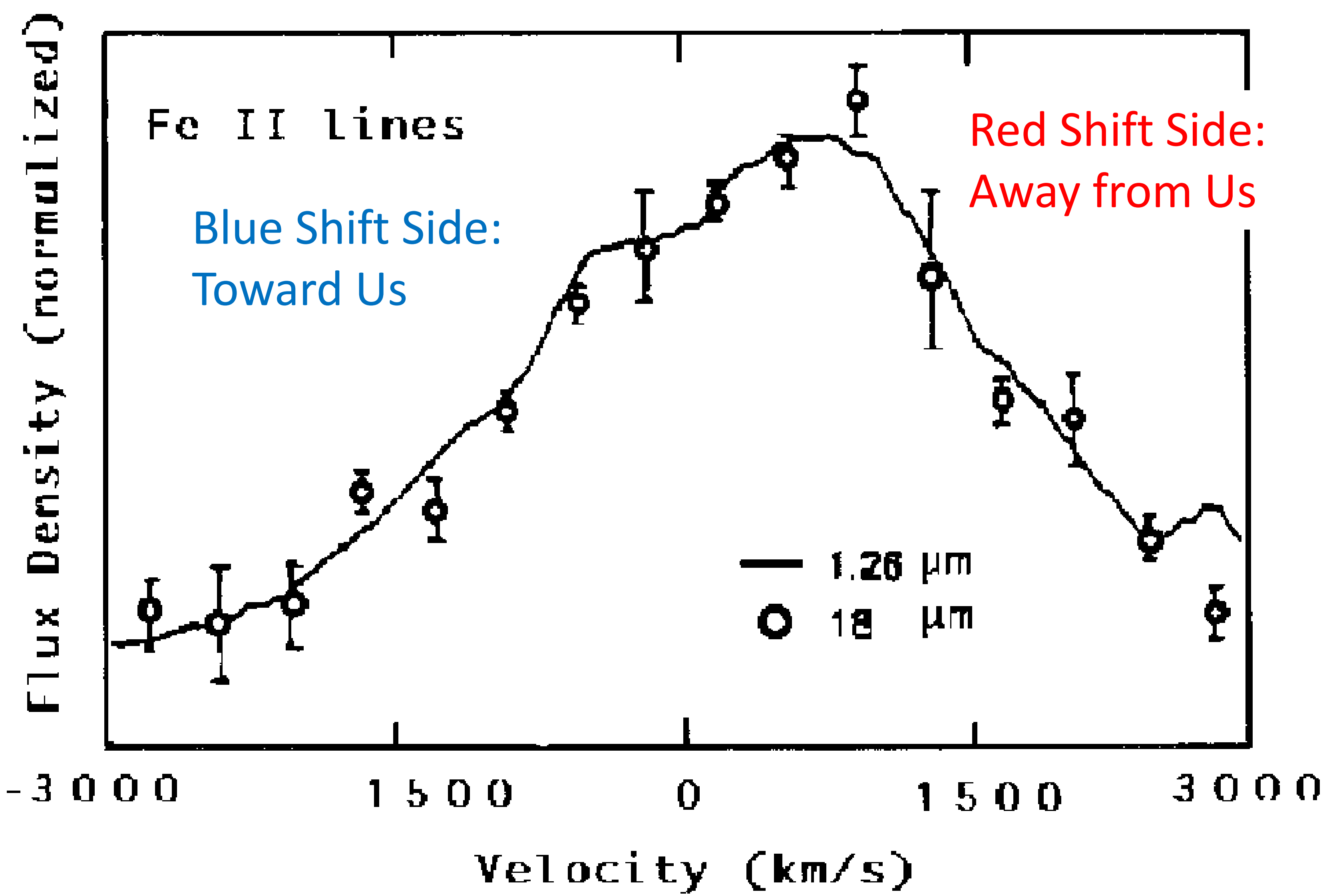


Prof. Koshiba

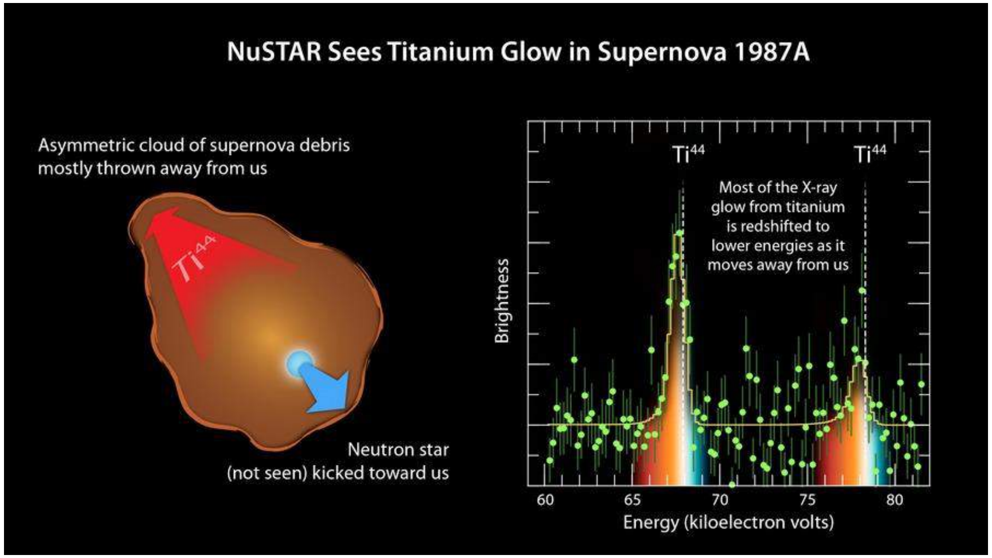


Asymmetric Velocity Profile of Iron

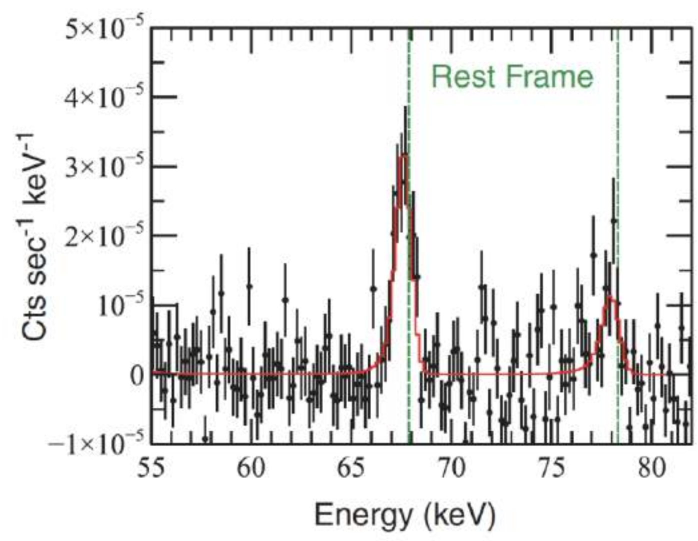
Haas et al. 1990



Asymmetric ^{44}Ti Profile: Redshift Component is More.



59-80 keV NuSTAR spectrum of SN1987A with detected ^{44}Ti emission lines.
[Credit: NASA/JPL-Caltech/UC Berkeley]
Figure from
https://nustar.ssdc.asi.it/news.php



- Observations of ^{44}Ti lines by NuSTAR
- Lines are redshifted with a Doppler velocity of about 700 km/s

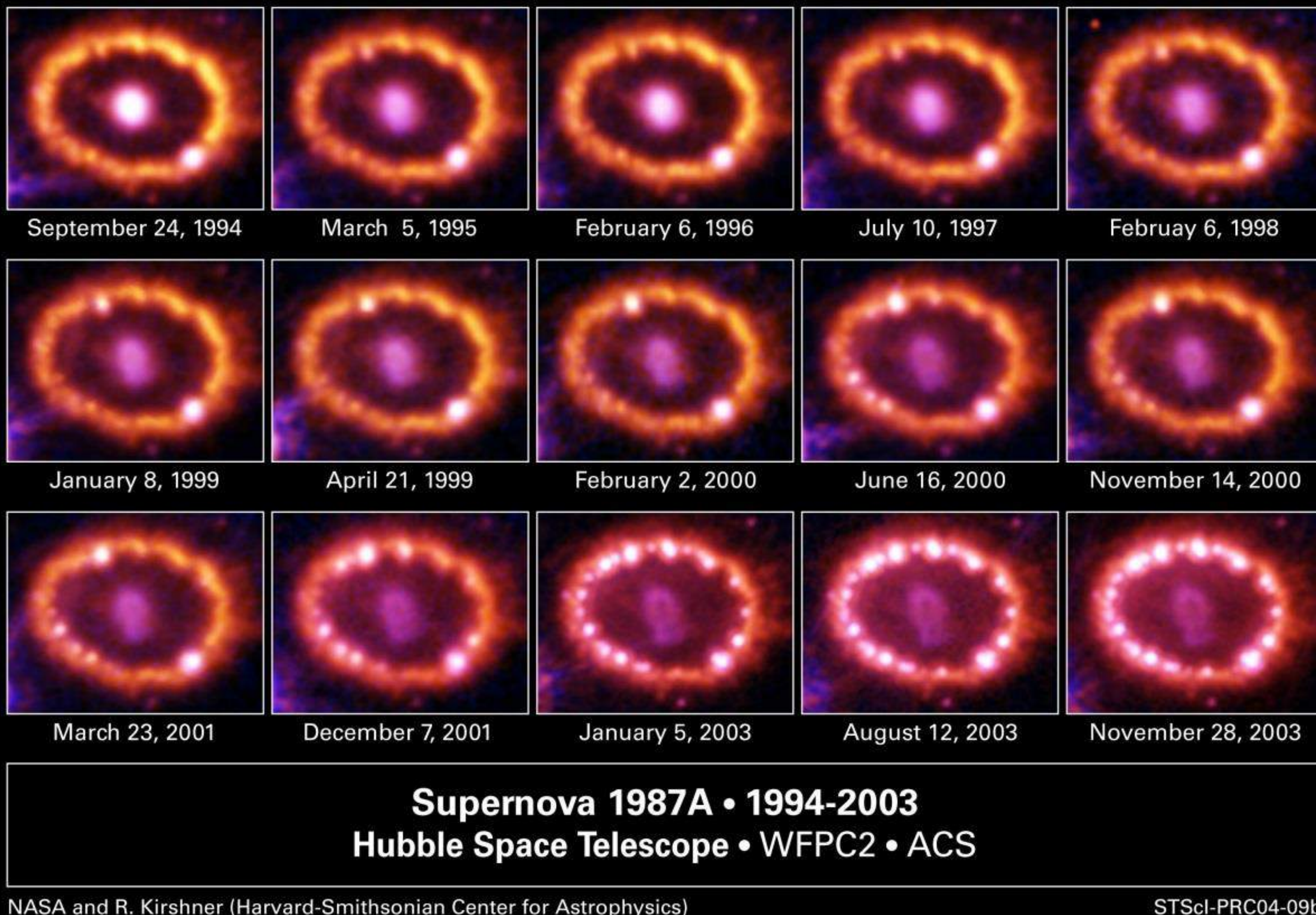
Boggs et al. 2015, Science, 348, 670

Obs. $^{44}\mathrm{Ti} \sim 10^{-4}\ M_{solar}$

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

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

Bipolar Explosion is Seen in SN1987A



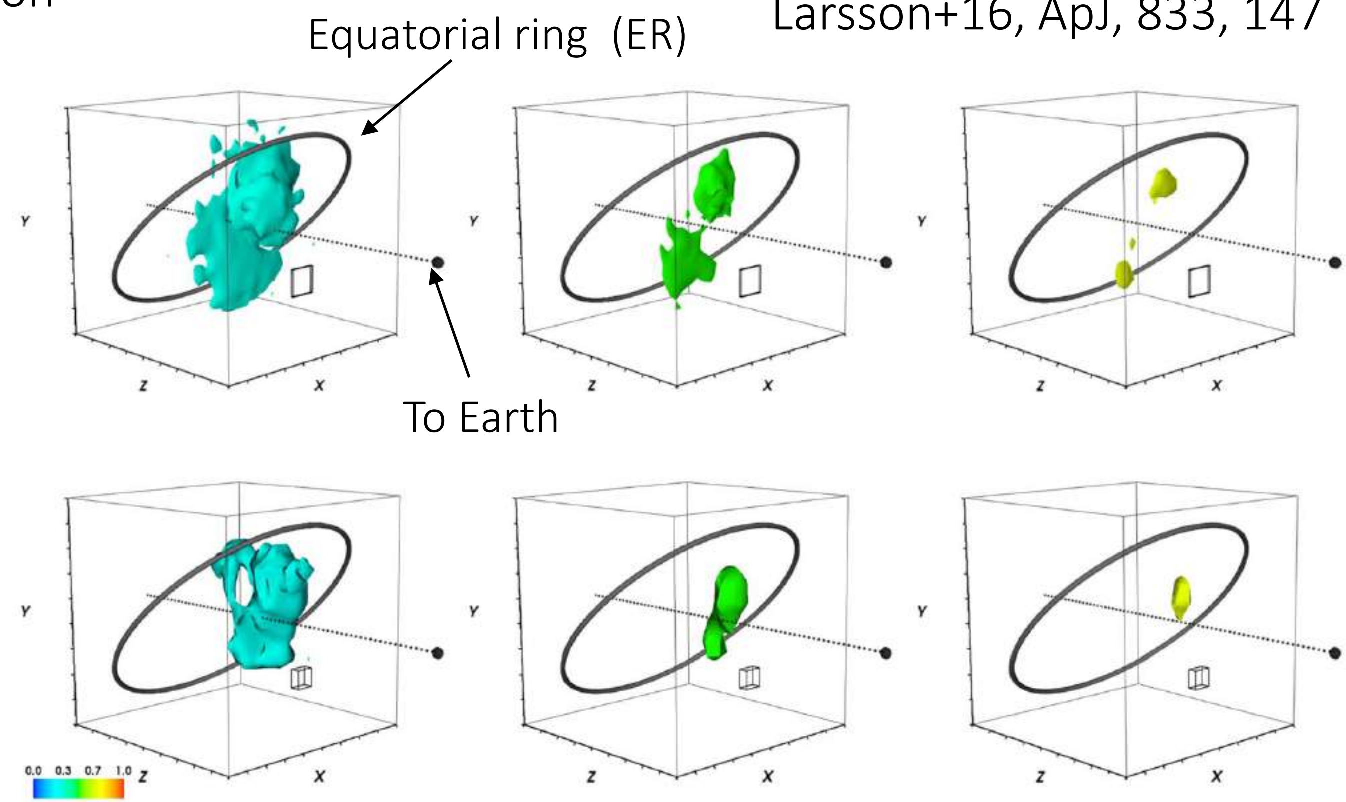
3D distribution of inner ejecta of SN 1987A

Observation from HST/STIS and VLT/SINFONI at 10,000 days after the explosion

Larsson+16, ApJ, 833, 147

Top: [Si I] + [Fe II] 1.644 μm

Bottom: H_α



Molecule distribution in 3D

Abellán et al. 2017, ApJ, 842, L24

ALMA observations of CO J = 2 -1, SiO J = 5 – 4, 6 -5 rotational transitions

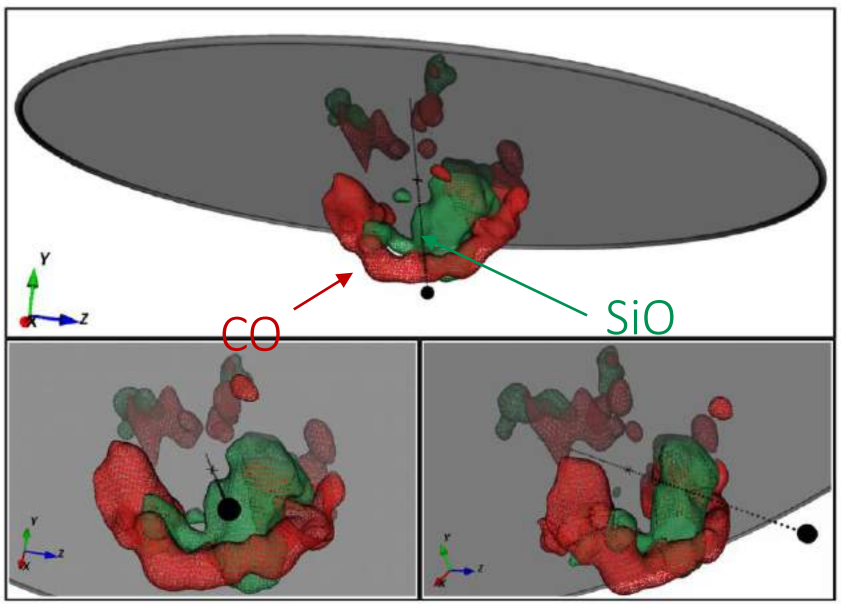


Figure 2. 3D view of cold molecular emission in SN 1987A. The CO 2−1 (red) and SiO 5−4 (green) emission is shown from selected view angles. The central region is devoid of significant line emission. The emission contours are at the 60% level of the peak of emission for both molecules. The black dotted line and black filled sphere indicate the line of sight and the position of the observer, respectively. The gray ring shows the location of the reverse shock at the inner edge of the equatorial ring (*XZ* plane). The black cross marks the geometric center.

(An animation of this figure is available.)

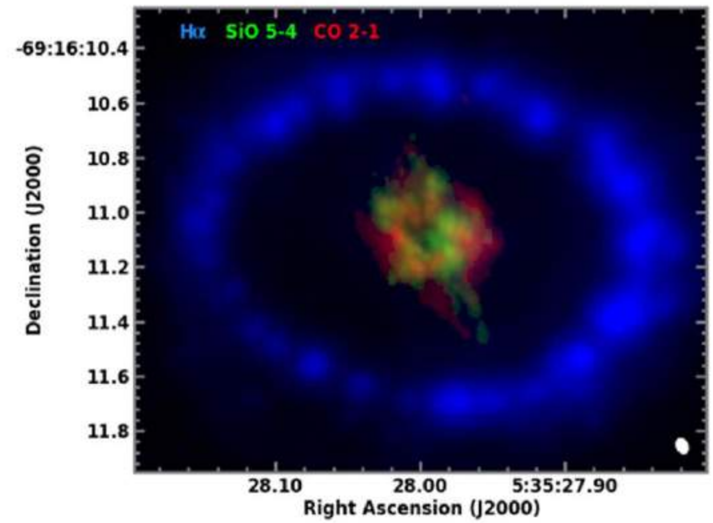
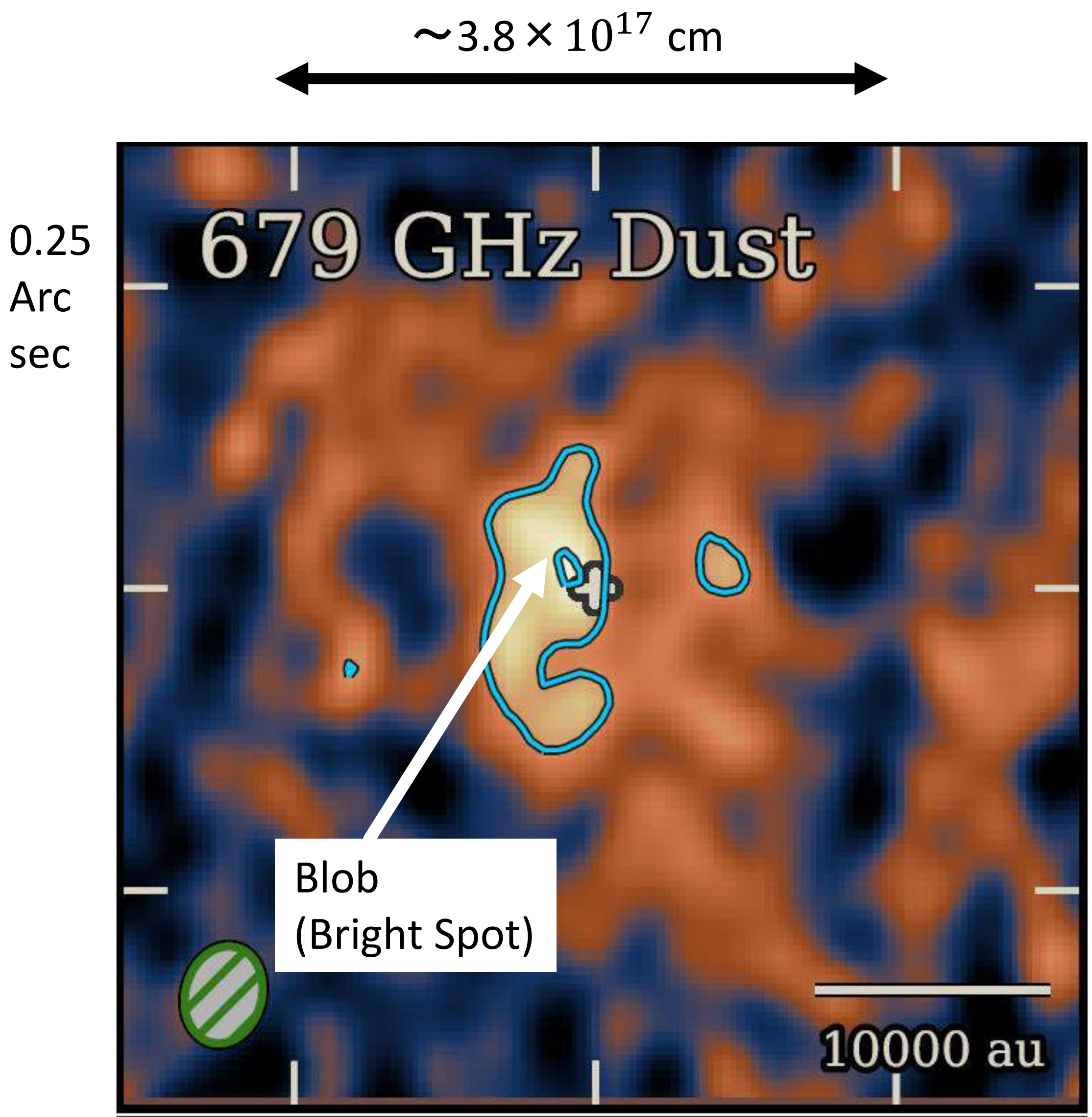


Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2−1 (red) and SiO 5−4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar equatorial ring (Larsson et al. 2016).

A Sign of the CCO in 87A?



Cigan et al. (2019)

✙ : Center of 87A
(Progenitor Location)

Contours of Cyan:
679 GHz emission at 3σ
& 5σ(”BLOB”).

Offset of the blob from
The center is 72mas to
the east and 44mas to the north.
(corresponds to ∼700 km/s).

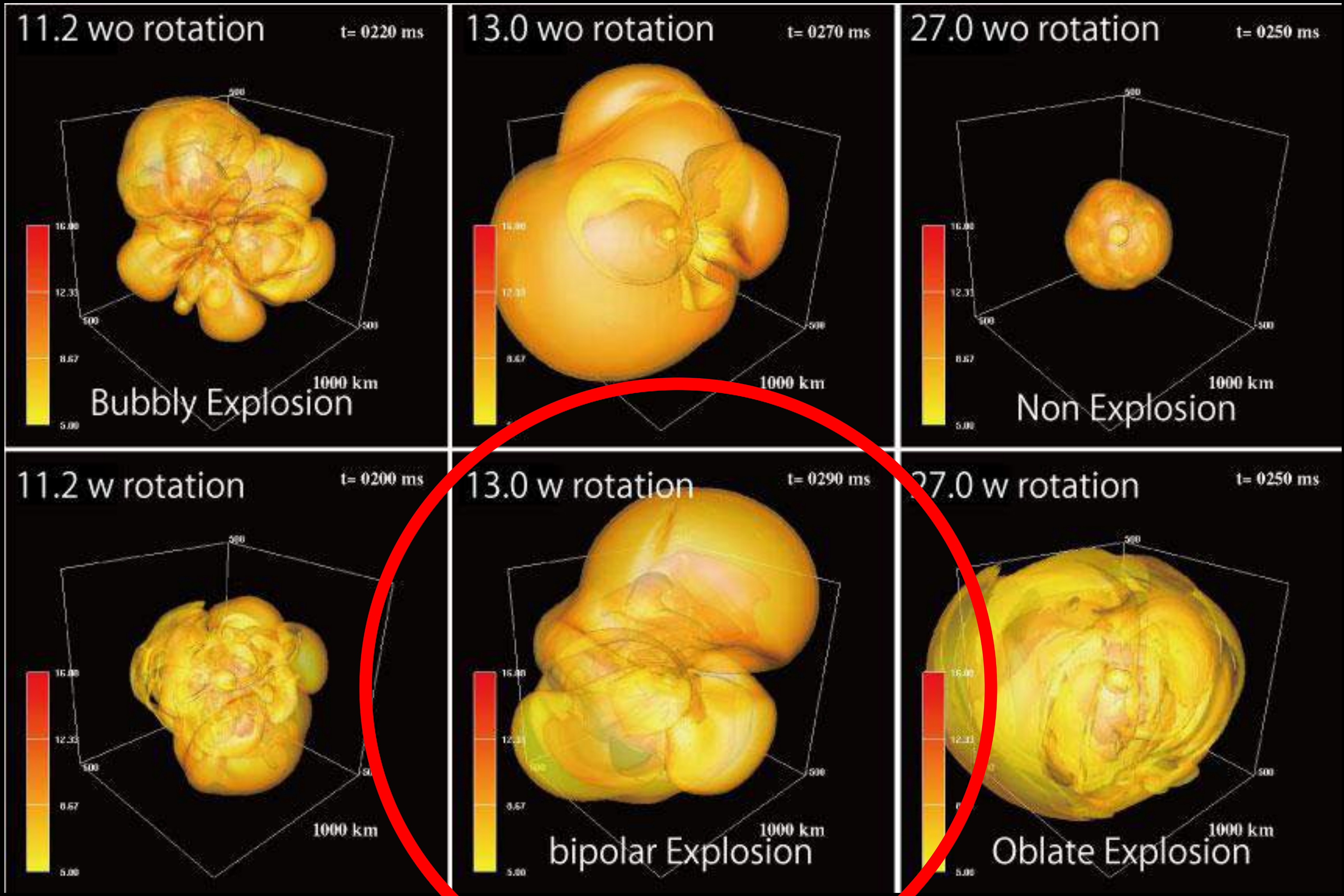
§ Our Theories for SN1987A

Rotation Can Change the Dynamics

Takiwaki+16

T. Takiwaki
(A-ABBL)

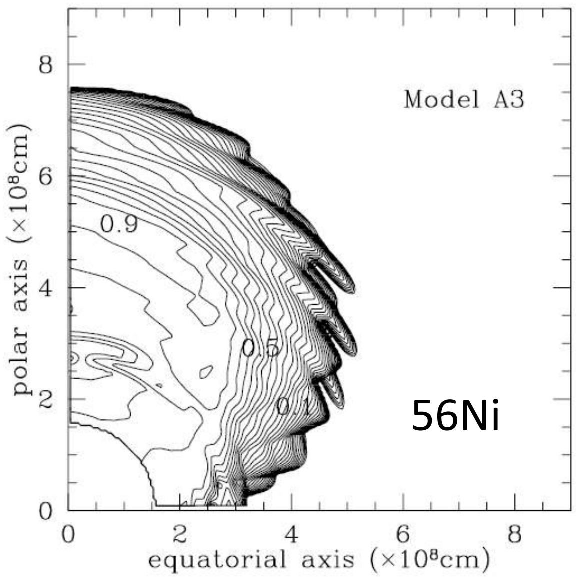
Spiral Waves Convey Rotation Energy Outside.

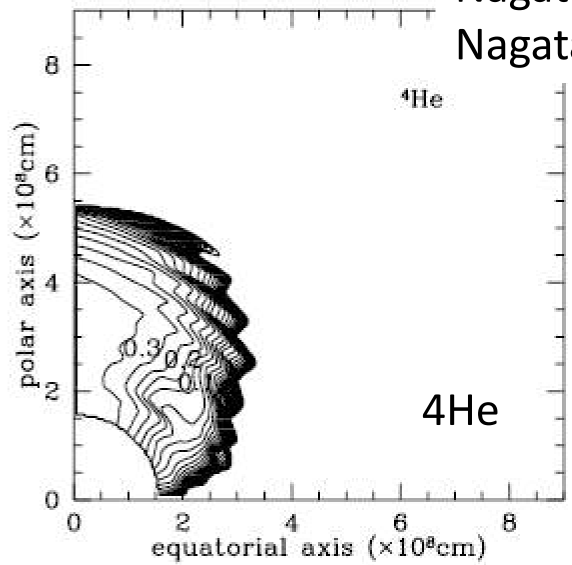


The mass of the progenitor and rotation make various type of Explosion(or Non Explosion).

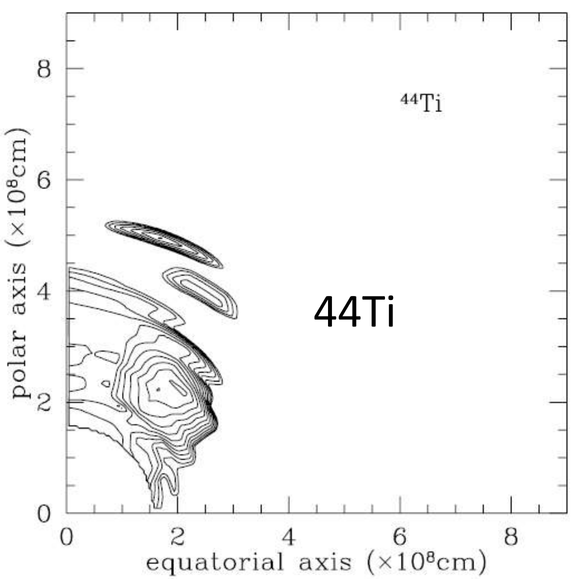
Lots of $^{44}\mathrm{Ti}$ Produced in Bipolar Explosions

Nagataki, Hashimoto, Sato, Yamada 97
Nagataki 00





S. Nagataki
(ABBL)



Produced amount of 44Ti:

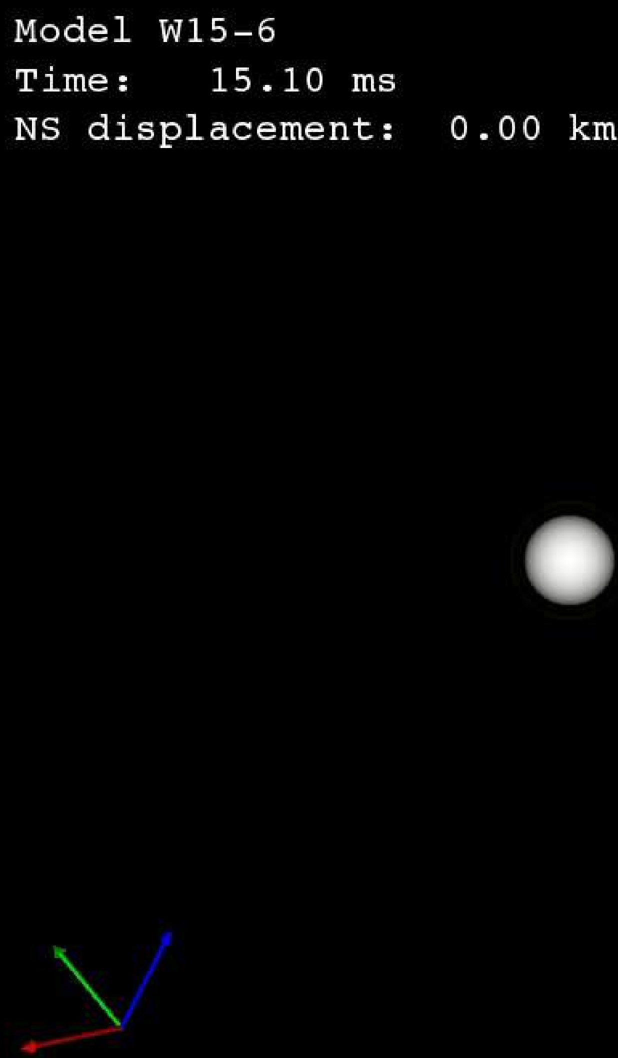
$$(1\text{-}5) \times \underline{10^{-4}\, M_\odot}$$

Consistent with Obs. of 44Ti by NuStar

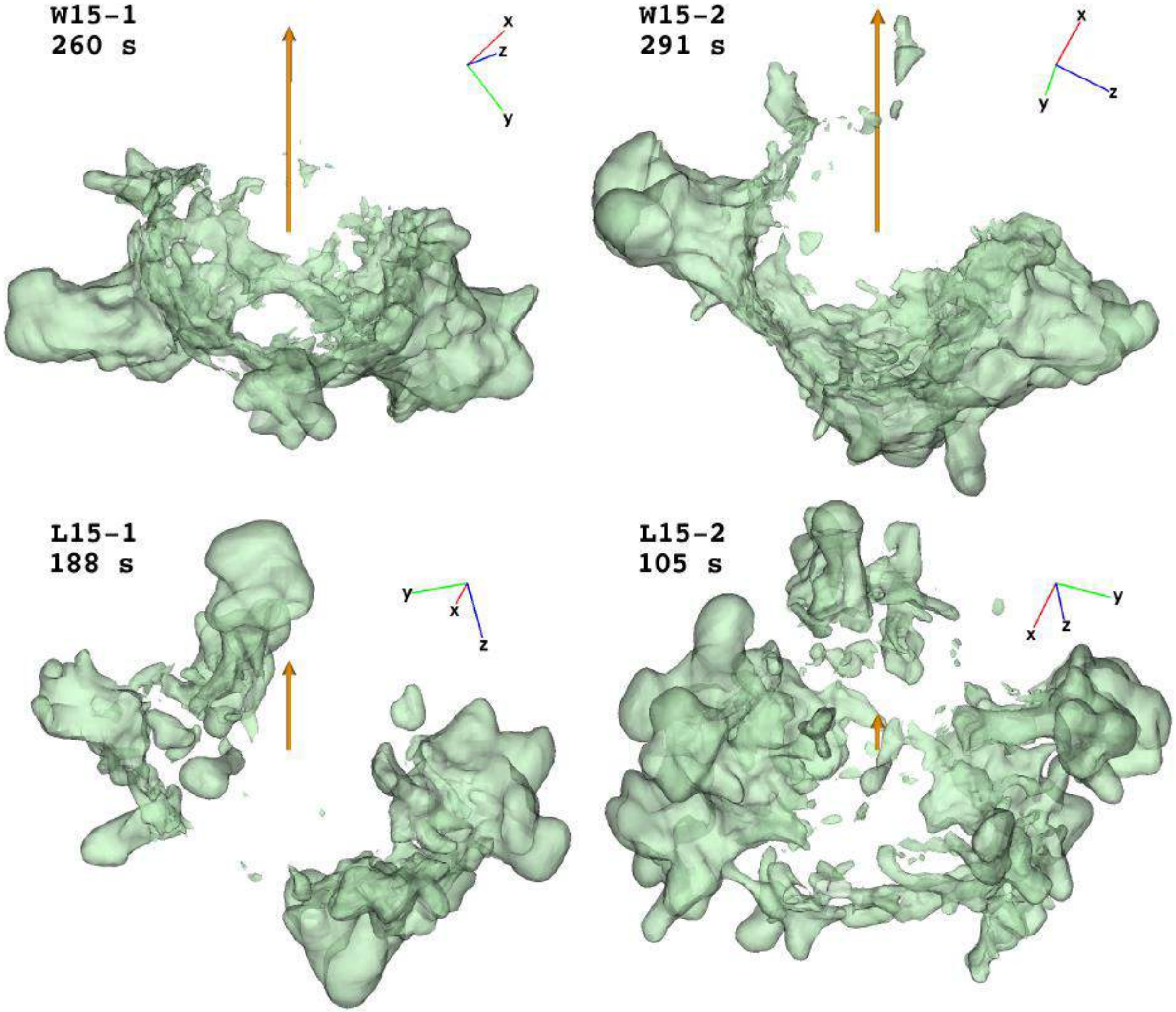
In Jet (bipolar) region, entropy per baryon becomes high!

Asymmetric Explosion & Neutron Star Kick

A. Wongwathanarat
(A-ABBL)



Asymmetric Ejection of 56Ni & Neutron Star Kick

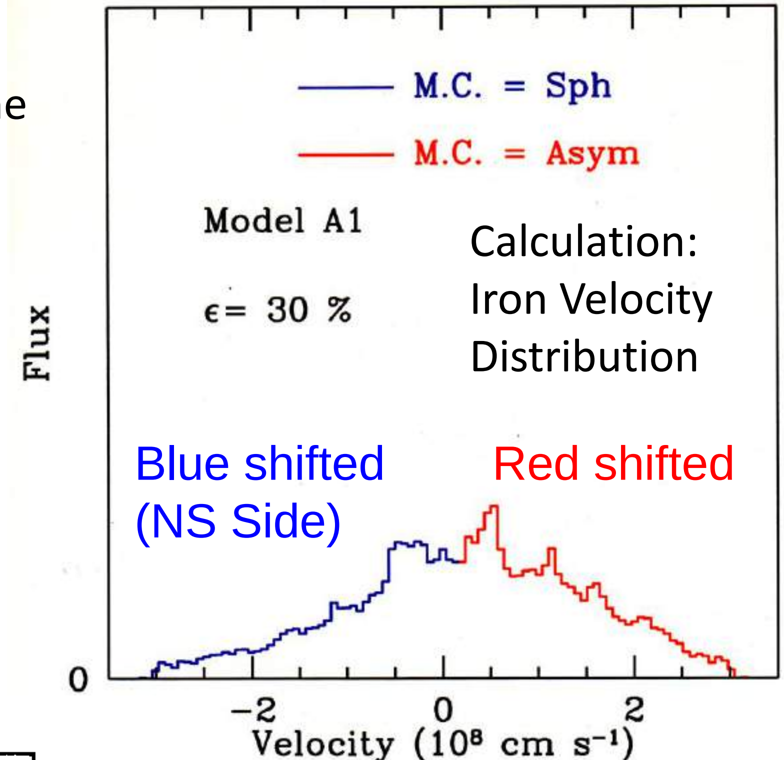


A. Wongwathanarat
(A-ABBL)

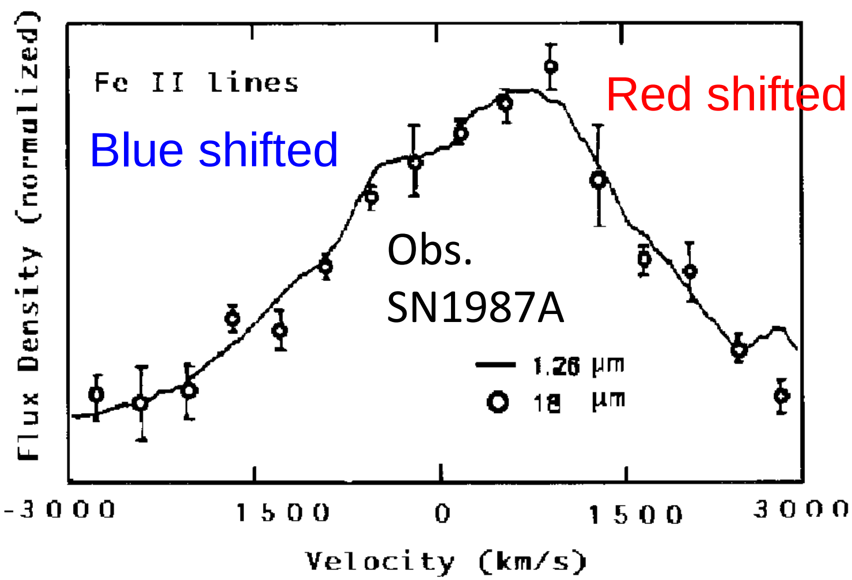
Asymmetry with Respect of Equatorial Plane Is Suggested for SN1987A.

↓

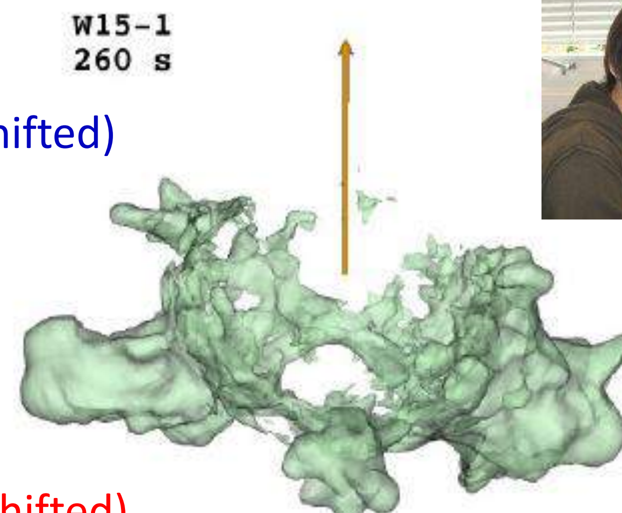
The Missing Neutron Star should be Moving toward Us (Blue-Shifted Side)!
S.N ApJS 2000.



SN 00



NS
(Blue-Shifted)



Fe, Ti
(Red-shifted)

Wongwathanarat+ 2013

§ Advanced Studies for SN1987A:
From Progenitor Star to 35 Years after the Explosion

Masaomi Ono (ABBL)

Orlando, Miceli, Petruk, Ono, Nagataki,
Aloy, Mimica, Lee, Bocchino, Peres, Guarrasi A&A (2019).

Ono, Nagataki, Ferrand, Takahashi, Umeda, Yoshida,
Orlando, Miceli ApJ (2020).

Orlando, Ono, Nagataki, Miceli, Umeda, Ferrand, Bocchino,
Petruk, Peres, Takahashi, Yoshida A&A (2020).

Linking SNR 1987A to the SN and progenitor star

M. Ono (ABBL)

1D stellar progenitor model

3D cc SN model

(Ono+2020)

3D SNR model

(Orlando+2019, 2020)

S. Orlando
(Palermo Obs.)

Progenitor stars (3 Models are used)

- **16.3$M_\odot$ BSG (Nomoto & Hashimoto 1988)**
- **19.8$M_\odot$ RSG (Woosley+2002)**
- **18.29 $M_\odot$ BSG resulting from the merging of 14 and 9 $M_\odot$ stars (Urushibata+2018)**

The 18.29 $M_\odot$ merging BSG model reproduces the main observables of Sk −69° 202

- **red-to-blue evolution**
- **total mass and position in the HR diagram at collapse (Blue Super Giant)**

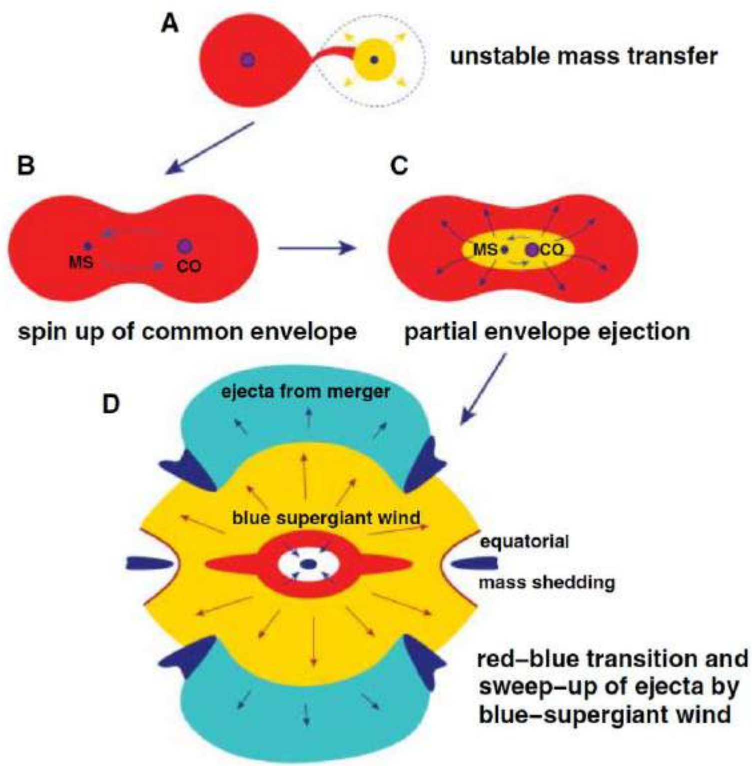
Hideyuki
Umeda
(U Tokyo)

Takashi
Yoshida
(Kyoto U)

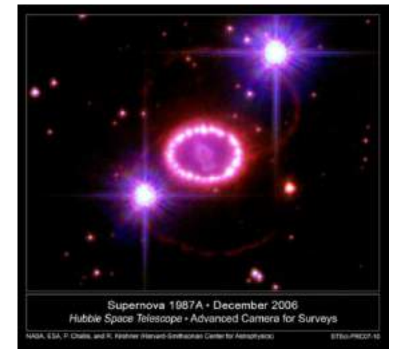
The progenitor of SN1987A was the outcome of a binary merger?

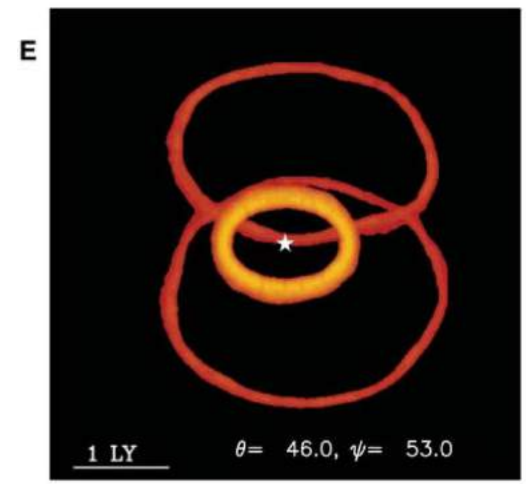
- 3D smoothed particle hydrodynamic (SPH) simulation

~ 15 $M_\odot$ RSG ~ 5 $M_\odot$ MS star



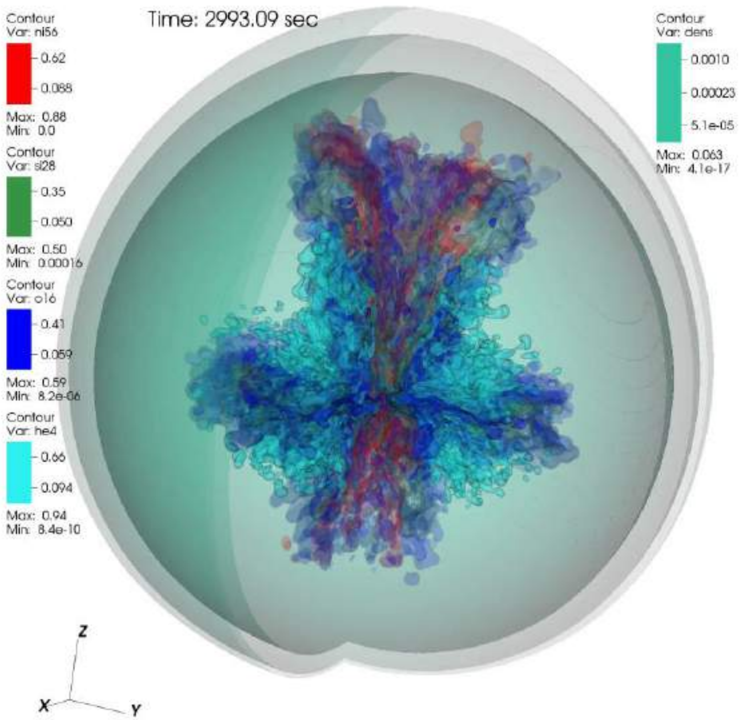
Morris & Podsiadlowsky 2007, Science, 315, 1103





Rapid Rotation is Introduced by the merger?

The SN explosion



Simulations start:

- **soon after the core-collapse**
- **SN explosion initiated by injecting kinetic and thermal energies artificially around the central compact object**

Explored range of injected energy

(1.8 – 3.0) FOE, 1 FOE = 10^51 erg

Explored range of initial anisotropy:

$v_{pol}/v_{eq} = \beta =$ **[2.0 – 16]**

$v_{up}/v_{dw} = \alpha =$ **[1.1 – 1.5]**

Adapted from the model of Ono+ (2013) to 3D

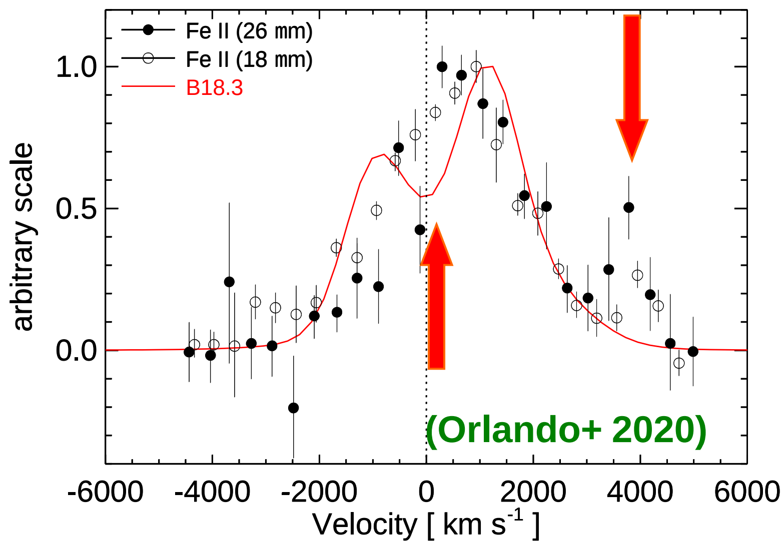
- **explosive nucleosynthesis through a nuclear reaction network (19 isotopes);**

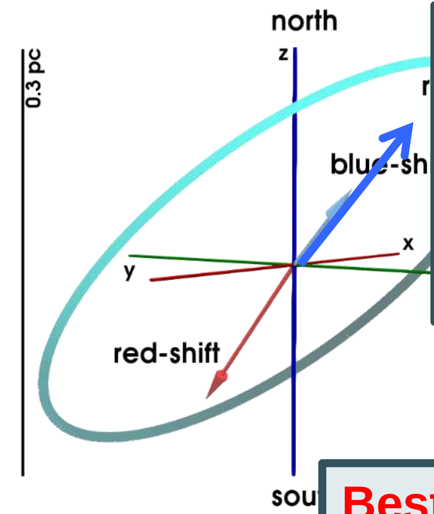
Numerical code: FLASH
(Fryxell+ 2000)

(Ono+2020)

Masaomi Ono
(ABBL)

Post-explosion anisotropies: [Fe II] line profiles

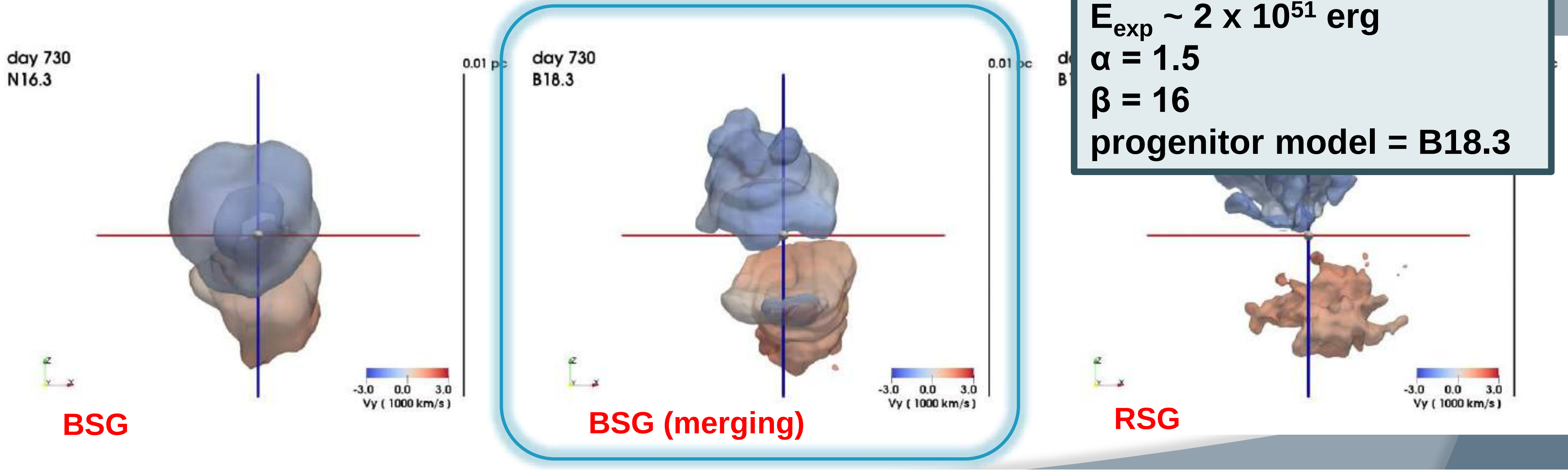




NS kick
~ 300 km/s
toward us to the north
(Nagataki 2000; Wongwathanarat 2013)

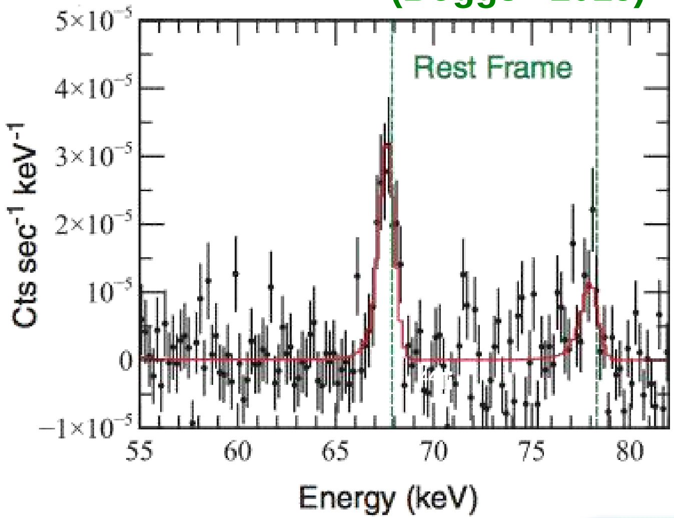
Best-fit parameters

E_{exp} ~ 2 x 10^{51} erg
α = 1.5
β = 16
progenitor model = B18.3

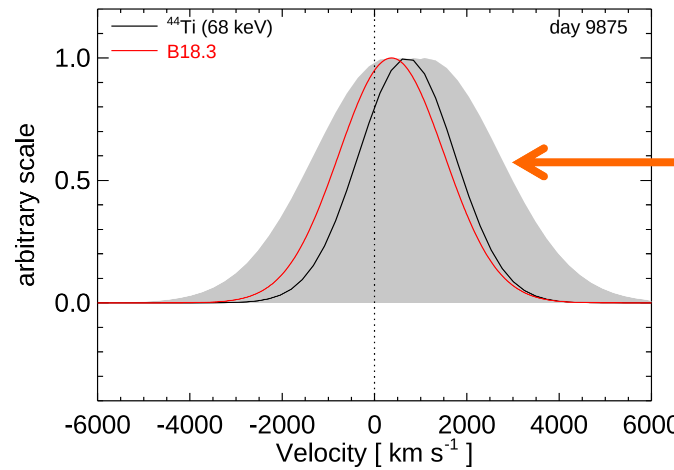


Distribution of ^{44}Ti in the evolved SNR

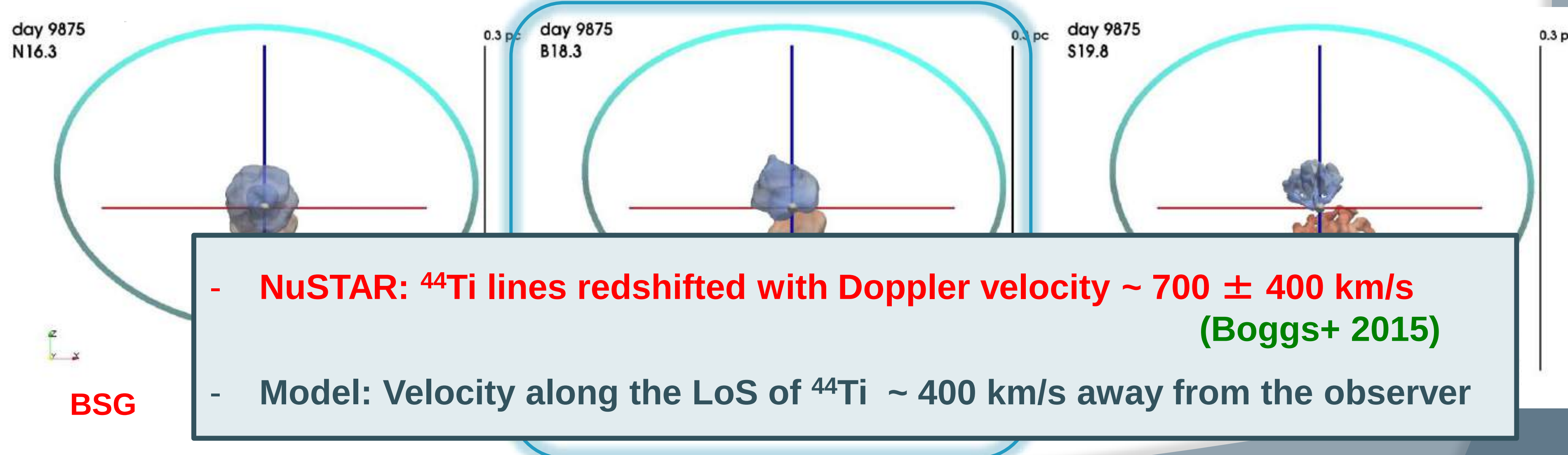
(Boggs+ 2015)



(Orlando+ 2020)



90% confidence area of observed 44Ti for the position of the peak and for the width of the Gaussian.

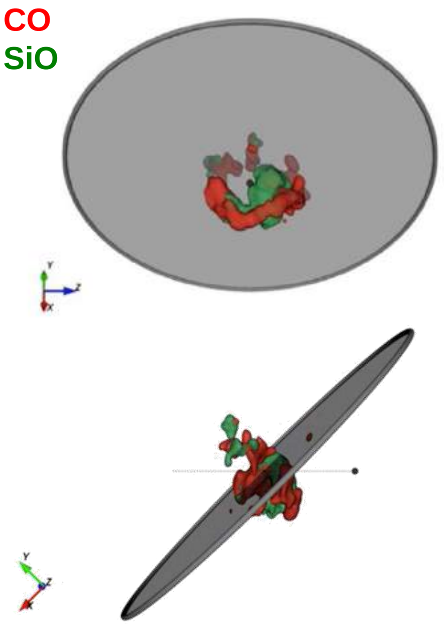


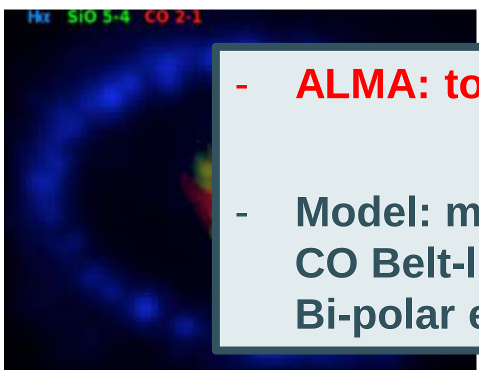
BSG

- **NuSTAR: ^{44}Ti lines redshifted with Doppler velocity ~ 700 ± 400 km/s (Boggs+ 2015)**
- **Model: Velocity along the LoS of ^{44}Ti ~ 400 km/s away from the observer**

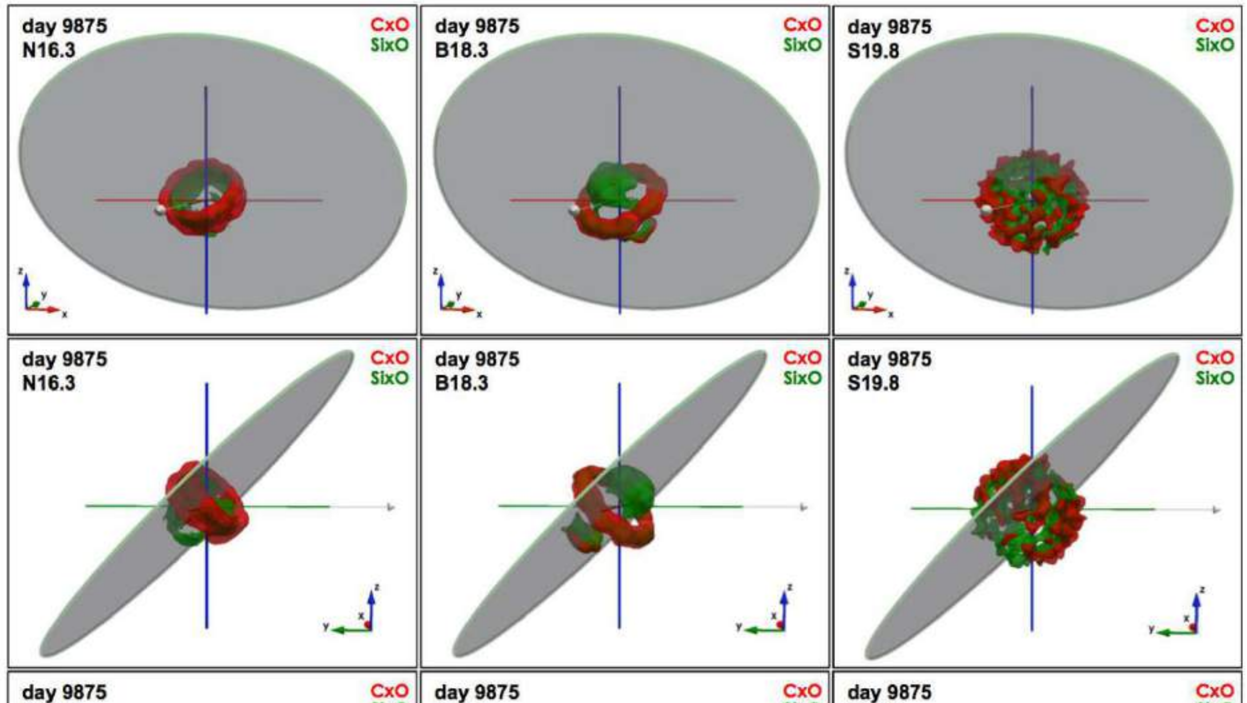
Molecular structure in the evolved SNR

(Abellan+ 2017)





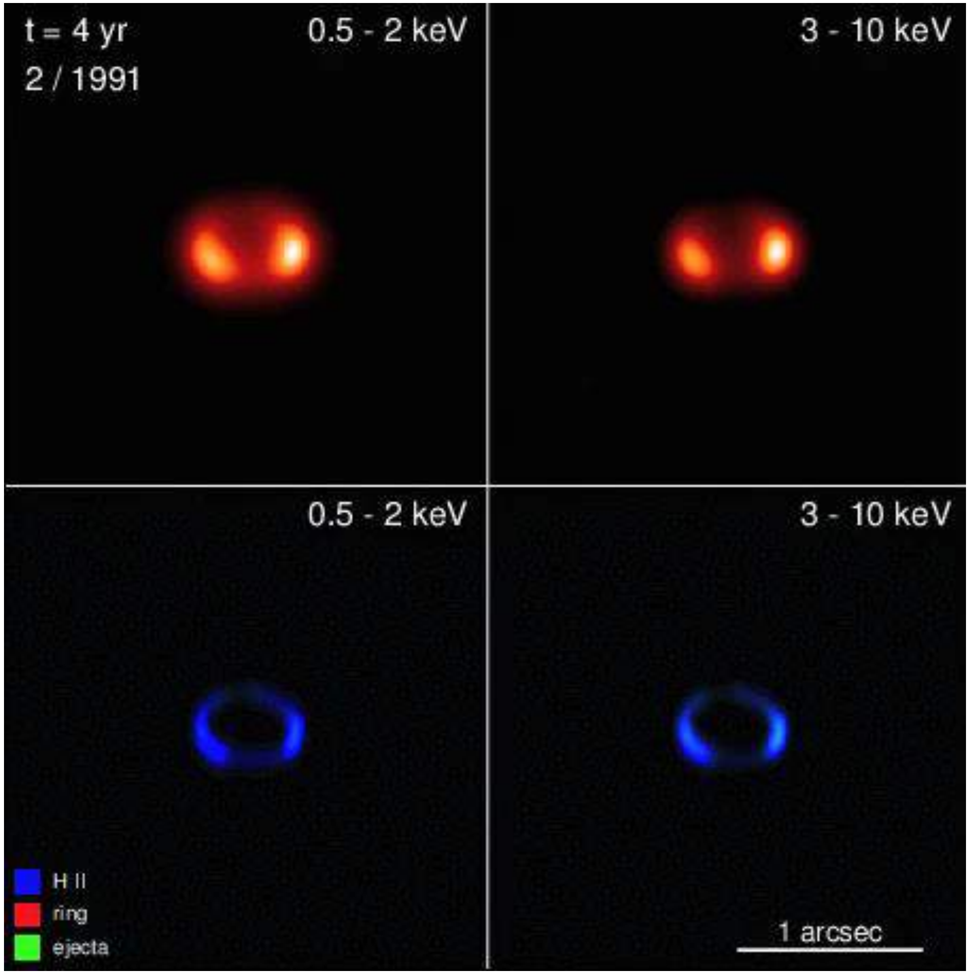
BSG | BSG (merging) | RSG



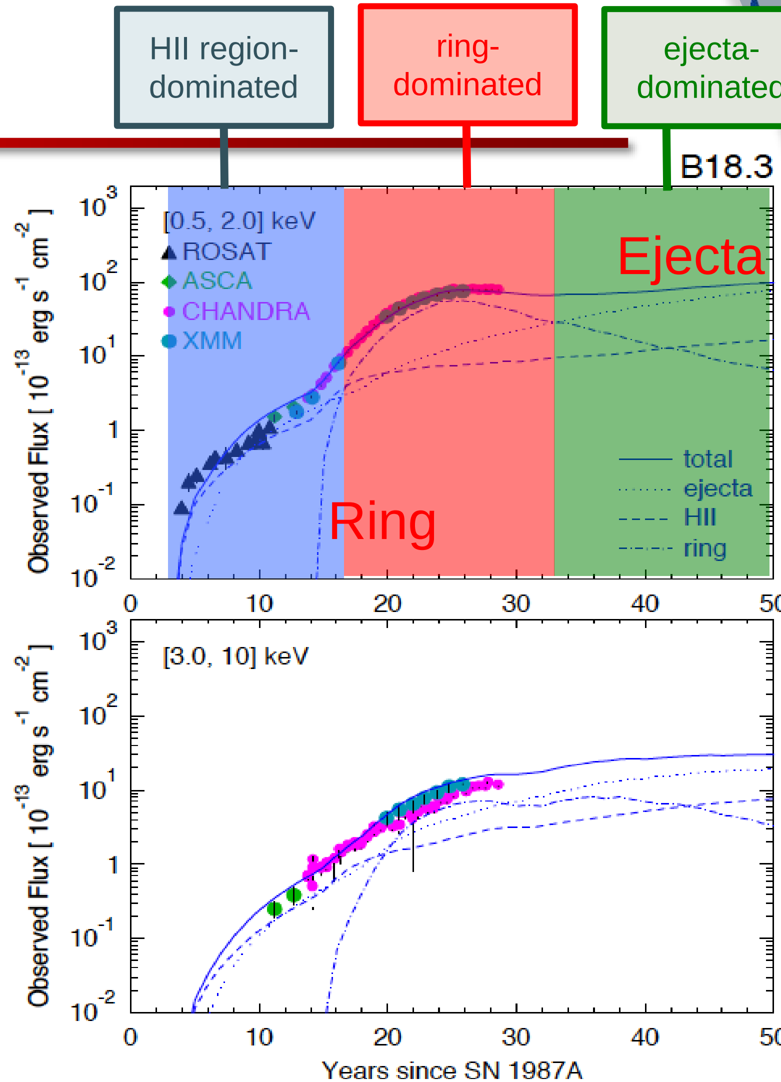
- ALMA: torus-like structure evident in CO. SiO is inside of CO. (Abellan+ 2017)
- Model: modeled torus-like feature with similar orientation and size. CO Belt-like structure corresponds to the equatorial plane of the Bi-polar eplosion

(Orlando+ 2020)

X-ray Lightcurves



Orlando+19



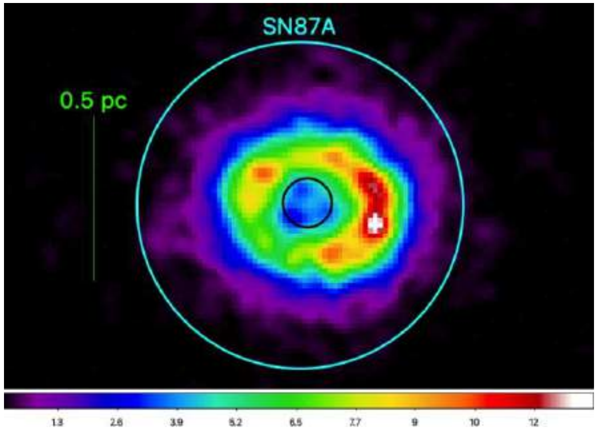
Abundances from Zhekov+ (2009)

ISM Absorption: 2.35e21 cm^{-2} (Park+ 2006)

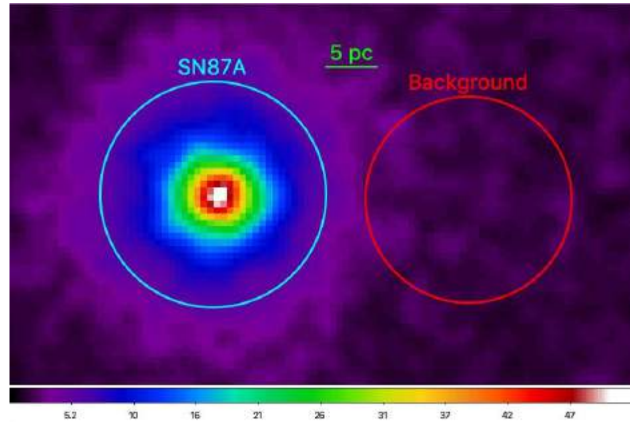
Distance: 51.4 kpc (Panagia 1999)

Finally, did we discover the NS in 87A?

Greco+ ApJ 21
Greco+ApJ 22, accepted.

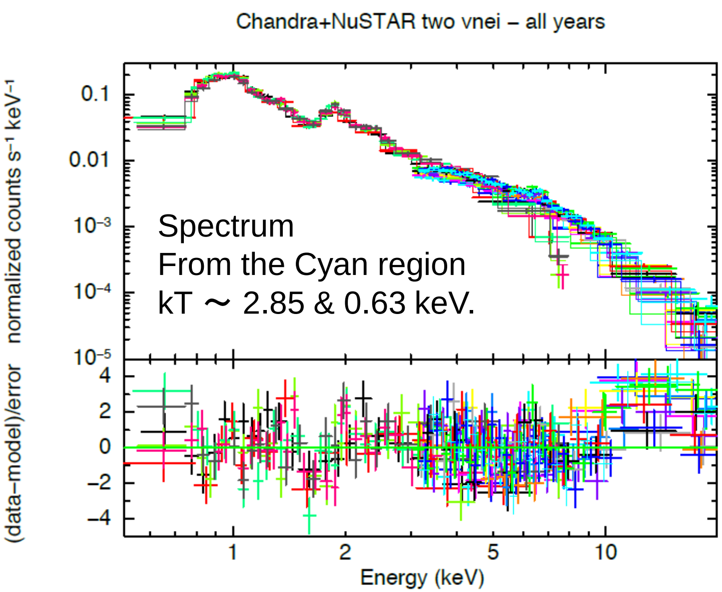


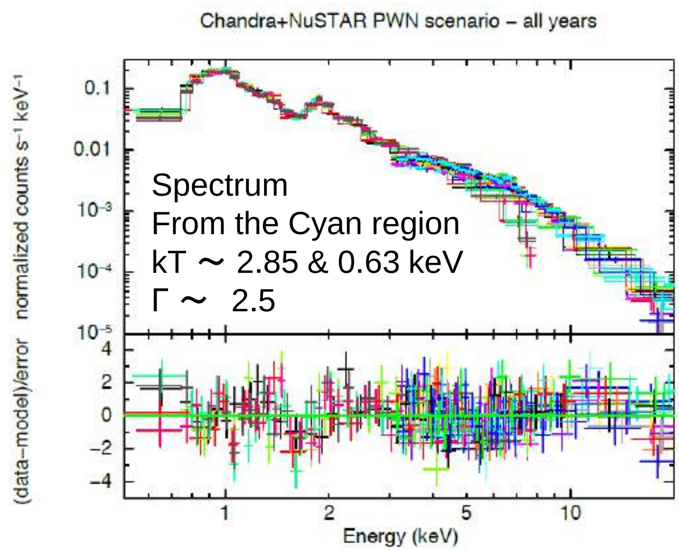
Chandra Image in 0.1-8 keV



NuSTAR Image in 3-30 keV

Emanuele Greco
(U. Amsterdam)





Marco Miceli
(Palermo Obs.)

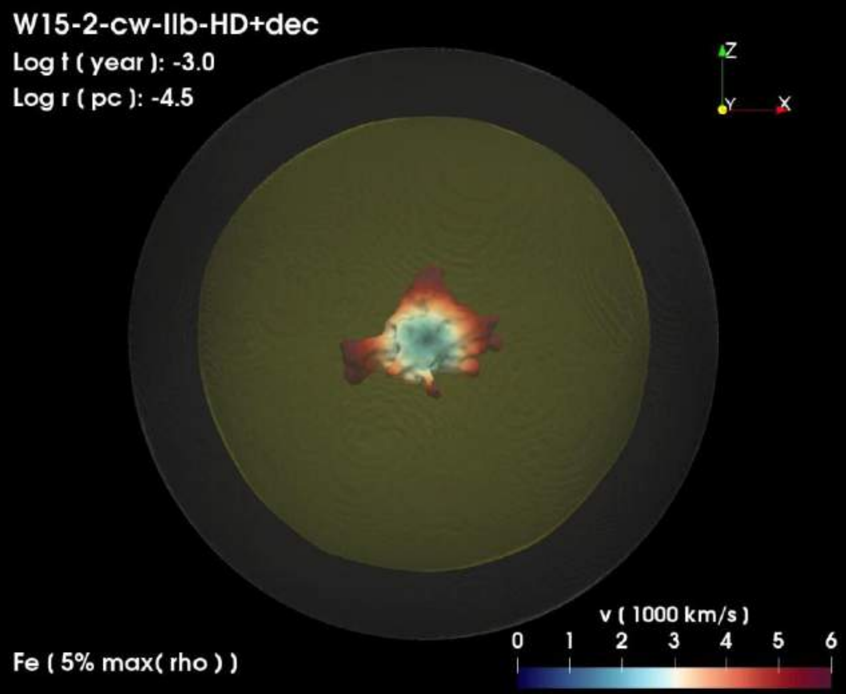
Barbara Olmi
(U. Florence)

Left: 20 Data set (in different color) and Difference between the obs & the best-fitting 2-temperature model.

$$L_{1-10} = (2.6 \pm 1.4) \times 10^{35} \quad \text{erg} \quad \text{s}^{-1}$$

Right: Same but for the best-fitting 2-temperature + Power-Law component.

Cassiopeia A (～350 yrs old)

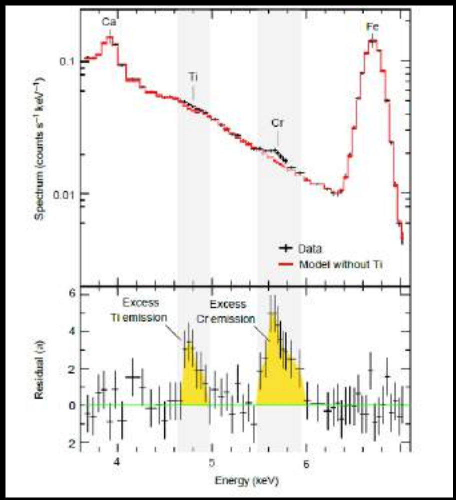


Detailed Comparison is meaningful.

T. Sato (Rikkyo U.)

Sato+'21 Nature (Cover Page of Nature Vol592, 2021).

Ref. Sato-san's talk at N3AS Seminar, 2021.



Our numerical simulation from a supernova to a supernova remnant.
Orlando+21 A&A, Orlando+22, submitted.

S. Orlando (Palermo Obs.)

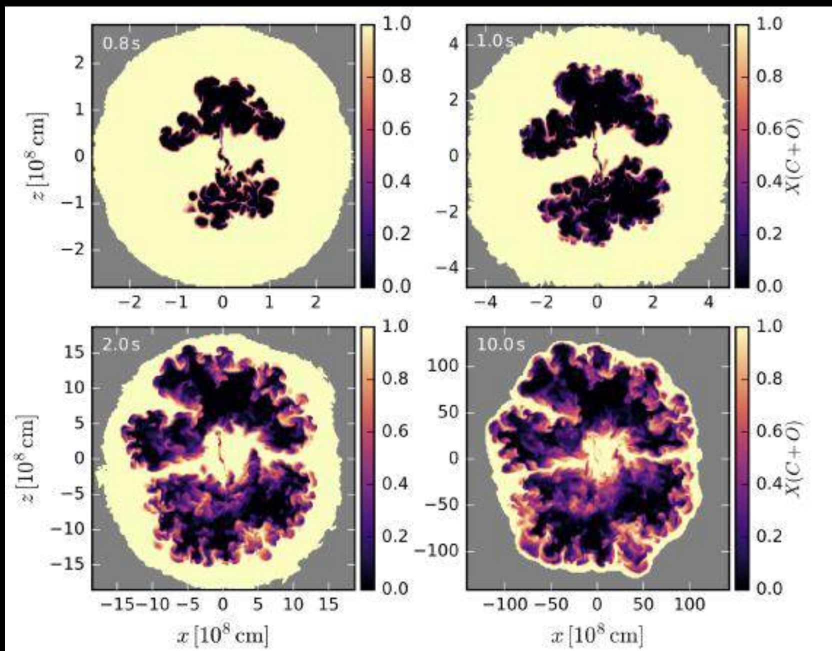
A. Wongwathanarat (A-ABBL)

T. Janka (MPA)

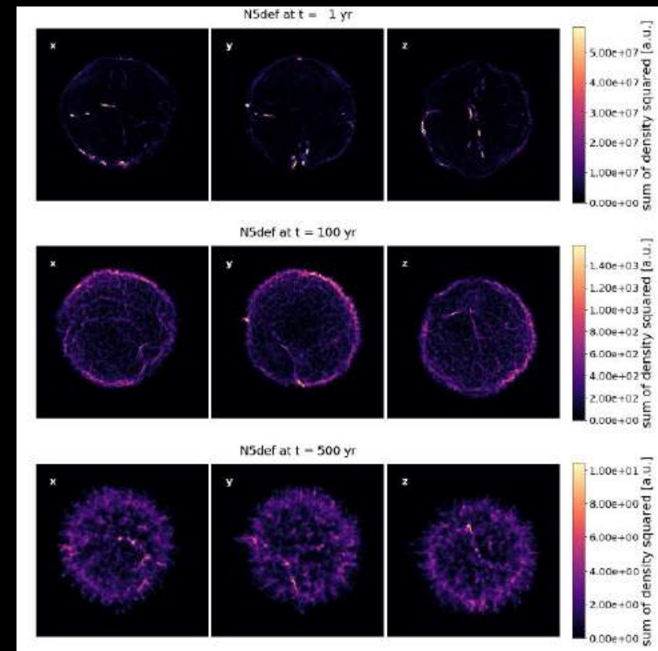
M. Ono (ABBL)

Type Ia Supernova Remnants

Ferrand＋2019, 2021, ApJ. Ferrand+2022, ApJ, accepted.



Time
Evolution



G. Ferrand
(ABBL/iTHEMS)

F. Röpke
(Heidelberg U.)

I. Seitenzhal
(ANU)

A. Tanikawa
(U. Tokyo)

S. Safi-Harb
(U. Manitoba)

A. Decourchelle
(CEA-Saclay)

Thank You Very Much!

From 01.Apr.2013. 10th Year !

ABBL members

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- Research Staff: Akira Mizuta
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- Visiting Scientists: Barkov (RAS), He (PMO), Just (GSI), Inoue (Bunkyo), Kawazura (Tohoku), Globus (NYU), Tamii (Osaka), Mao (Yunnan), Takei (Tokyo)
- Almuni: Lee(Kyoto), Tolstov(Company), Dainotti (NAOJ), Teraki (City Hall), Takiwaki (NAOJ), Wada (Tohoku), Wongwathanarat(Company), Matsumoto (Keio U.), Arakawa (Company)

A-ABBL members

2013

2016

2019

2021