Evolution of SN1987A

～From Progenitor Star to 30 Years after the Explosion～

Shigehiro Nagataki

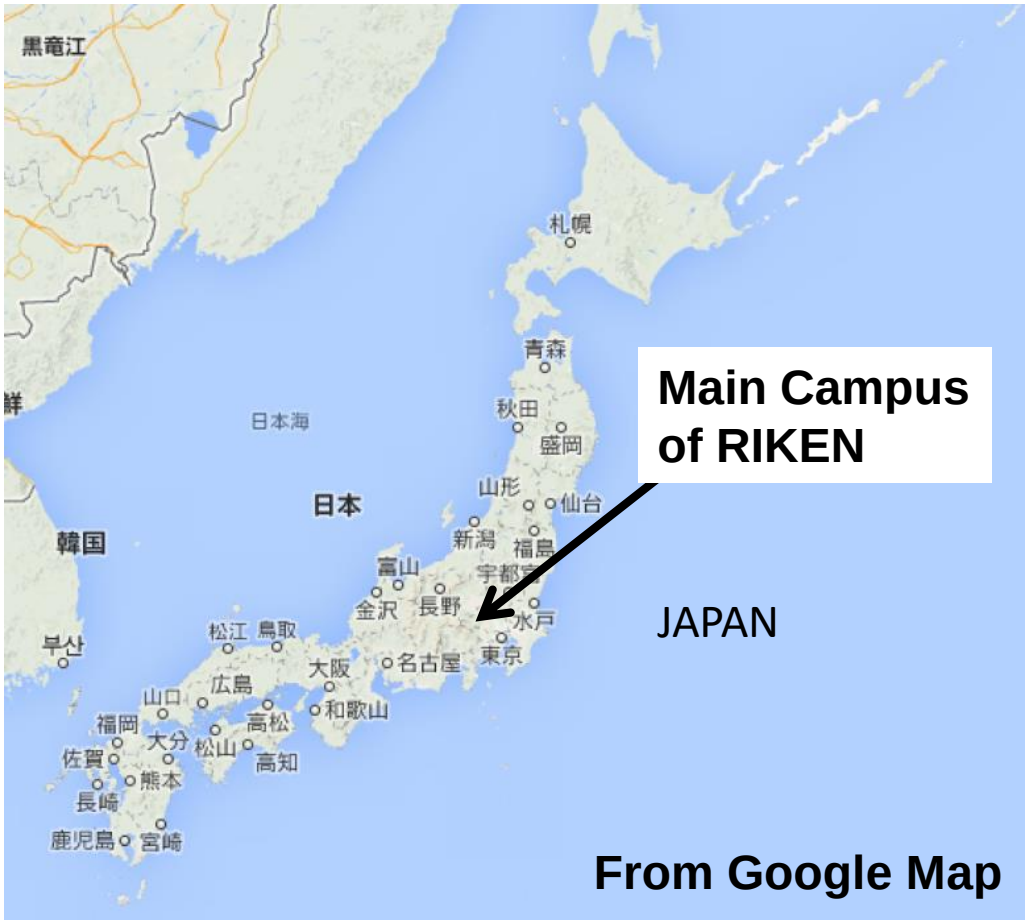
RIKEN

Astrophysical Big Bang Laboratory (ABBL)

PACIFIC2019, Moorea, French Polynesia Presentation Date: 1st September 2019.

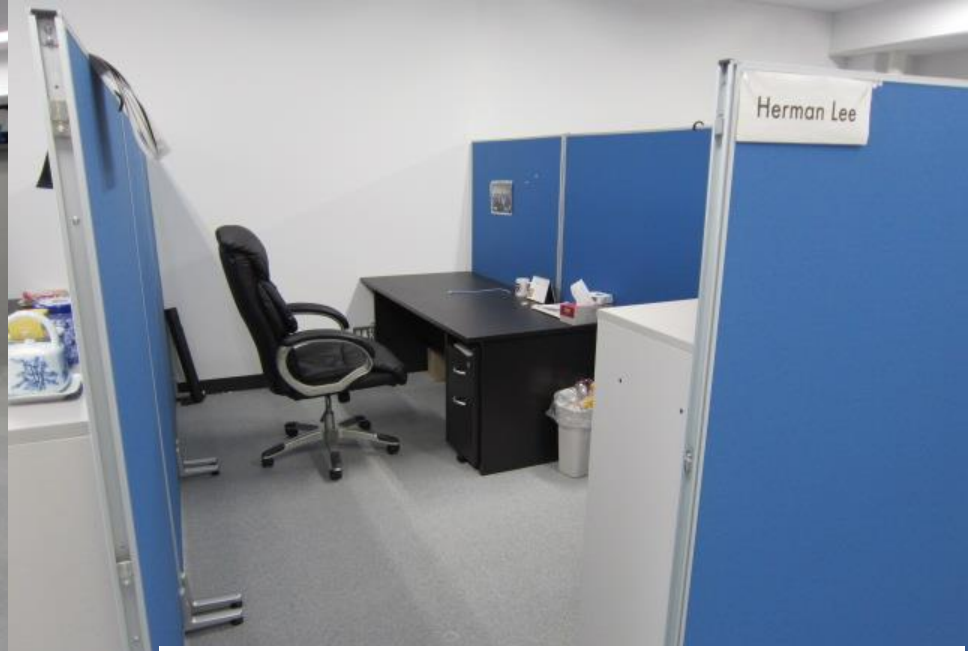
RIKEN (理化学研究所)

The largest comprehensive research institution in Japan



Main Research Build. in Main Campus

My Office in the Main Research Build.



One of Our Offices for PDs & Students.

Astrophysical Big Bang Lab. (ABBL)

From 01.Apr.2013.
7th Year !

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- PI: Shigehiro Nagataki
- Research Staff: Akira Mizuta
- Current PDs: H.Ito, G. Ferrand, H. He, M. Ono, O.Just, +3 Postdocs
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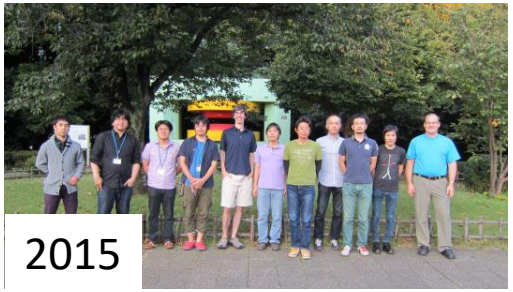
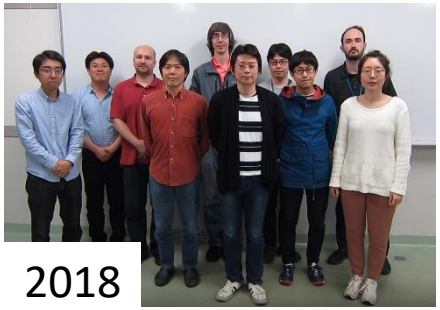
2013


2015


2017


2018

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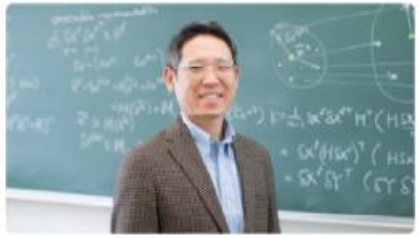

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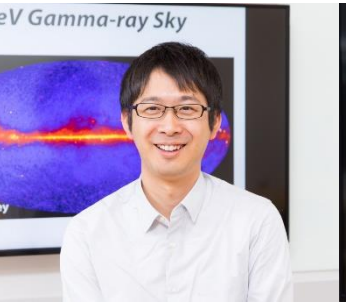
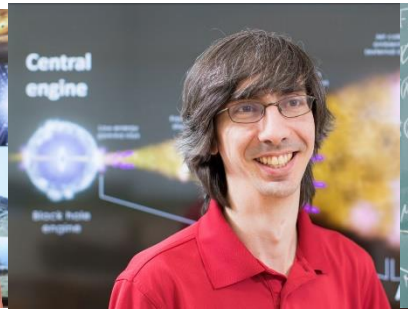
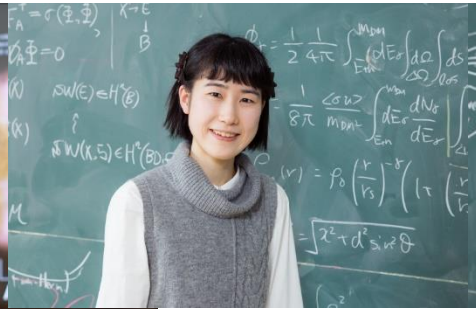


Y. Inoue

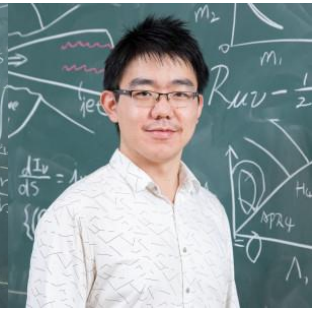
S. Inoue



D. Warren



N. Hiroshima



Y. Huang

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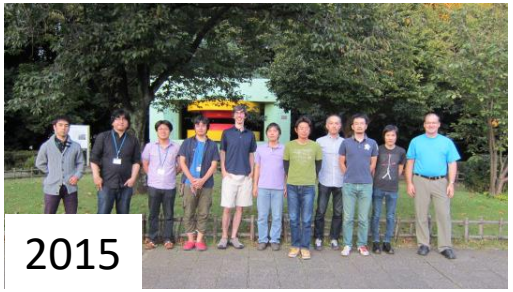
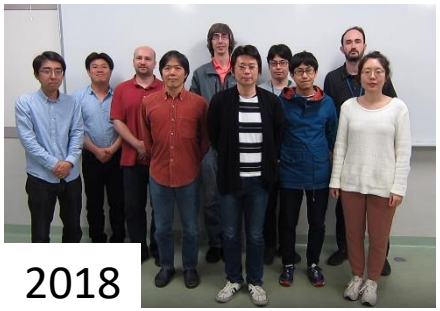

2015


2017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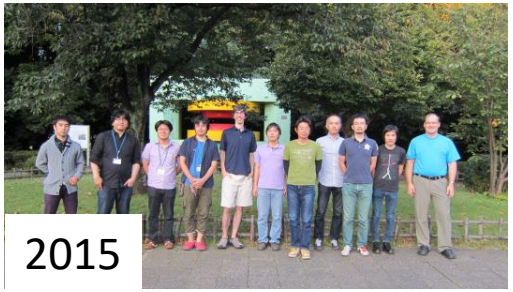
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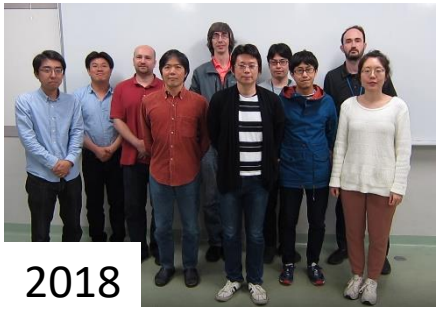
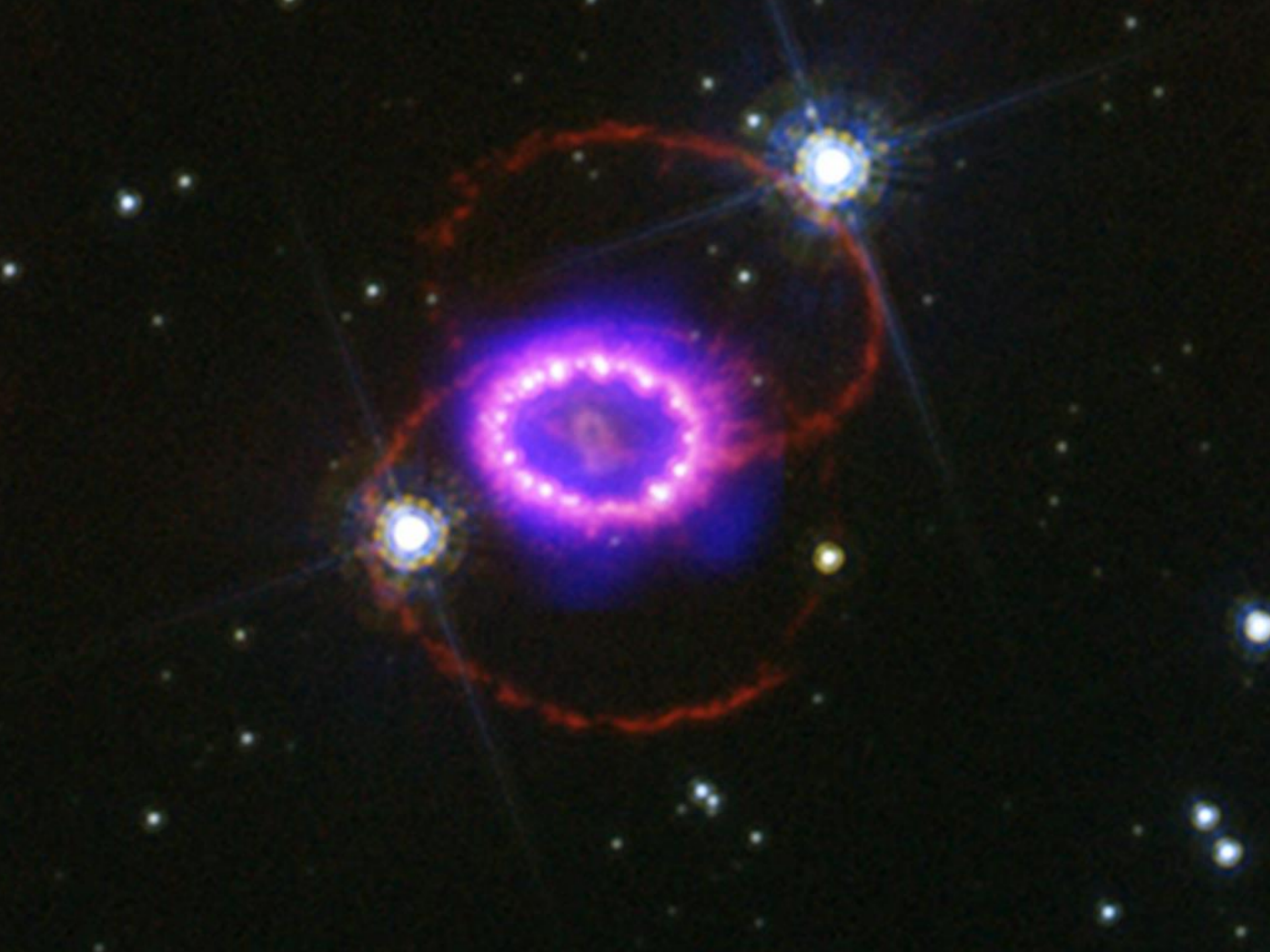
2017


2018

§ Observations of SN1987A

Hubble Heritage

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



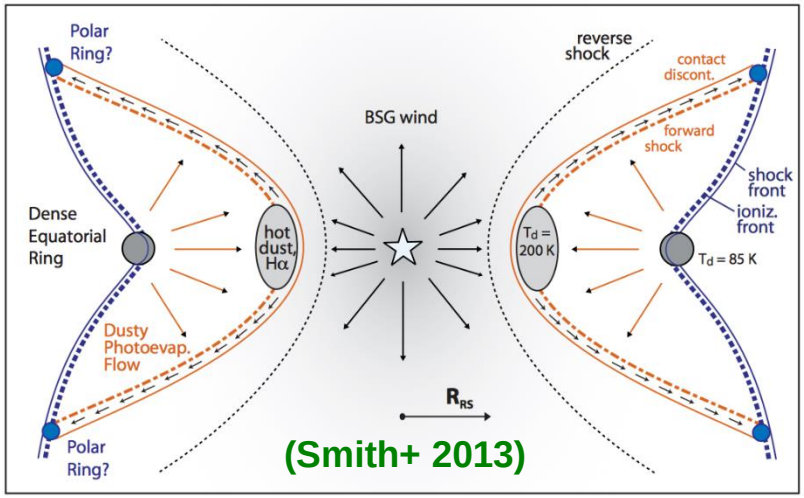
SN 1987A & its Ring.

When: 23 February 1987
Where: Large Magellanic Cloud

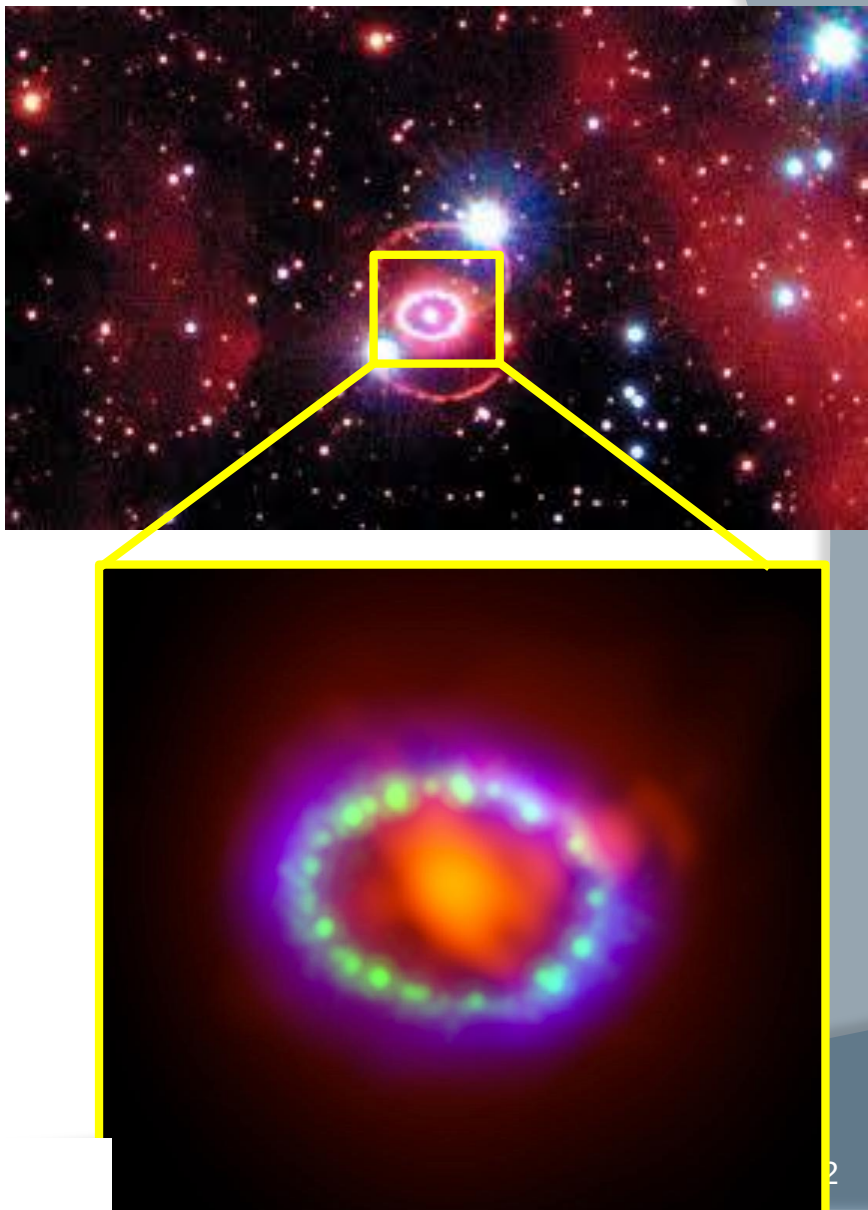
Stellar progenitor: Sk -69º202

Nearest supernova explosion observed by human eyes in hundreds of years

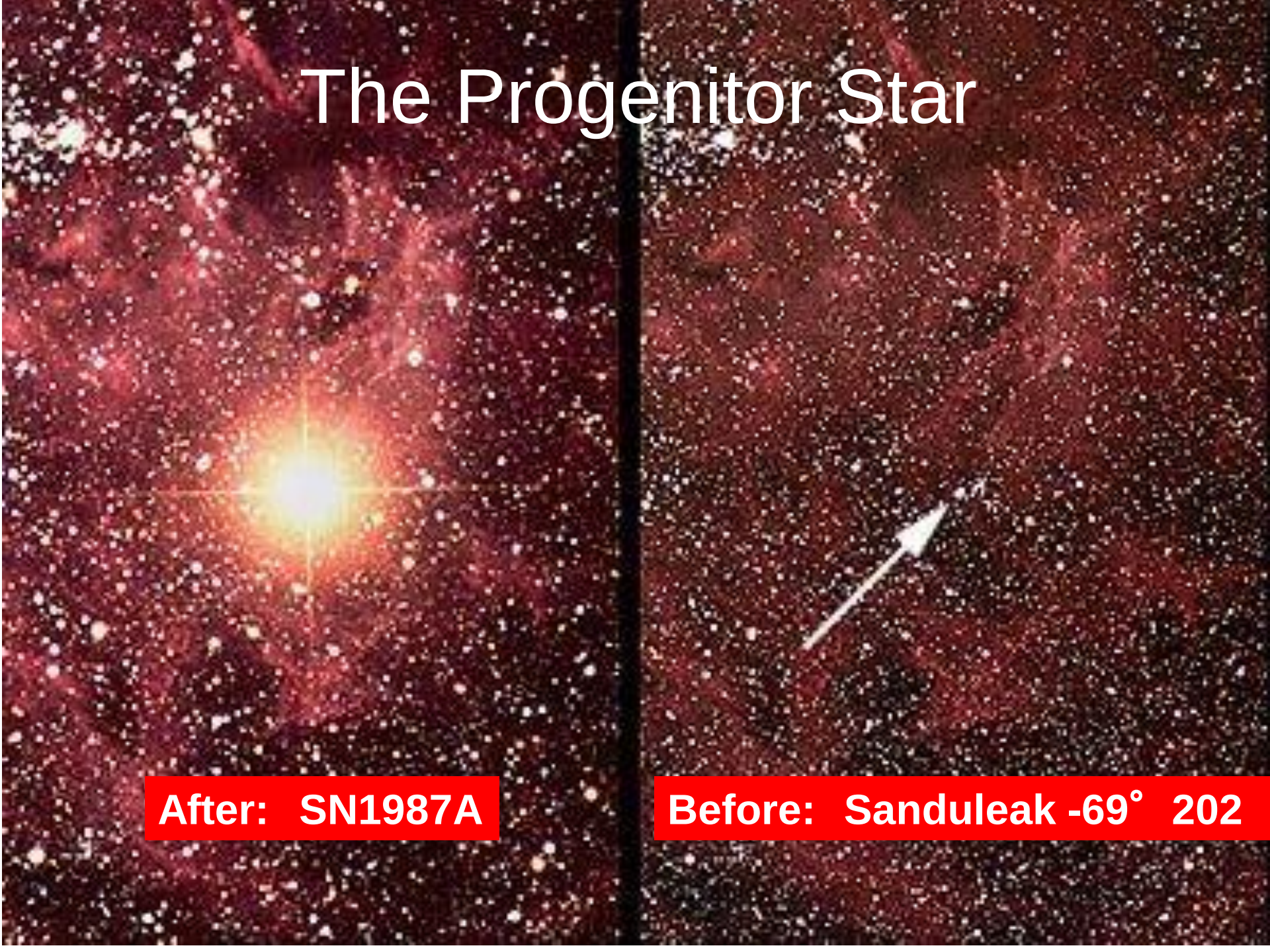
Unique opportunity to watch a SN change into a SNR



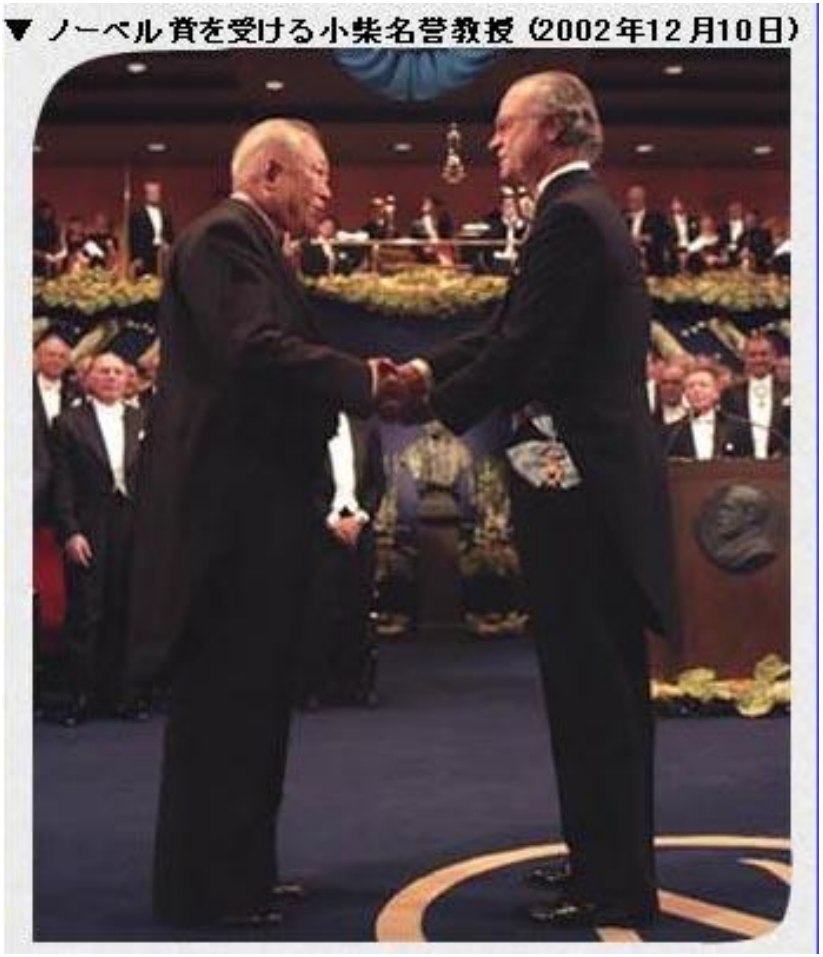
(Smith+ 2013)



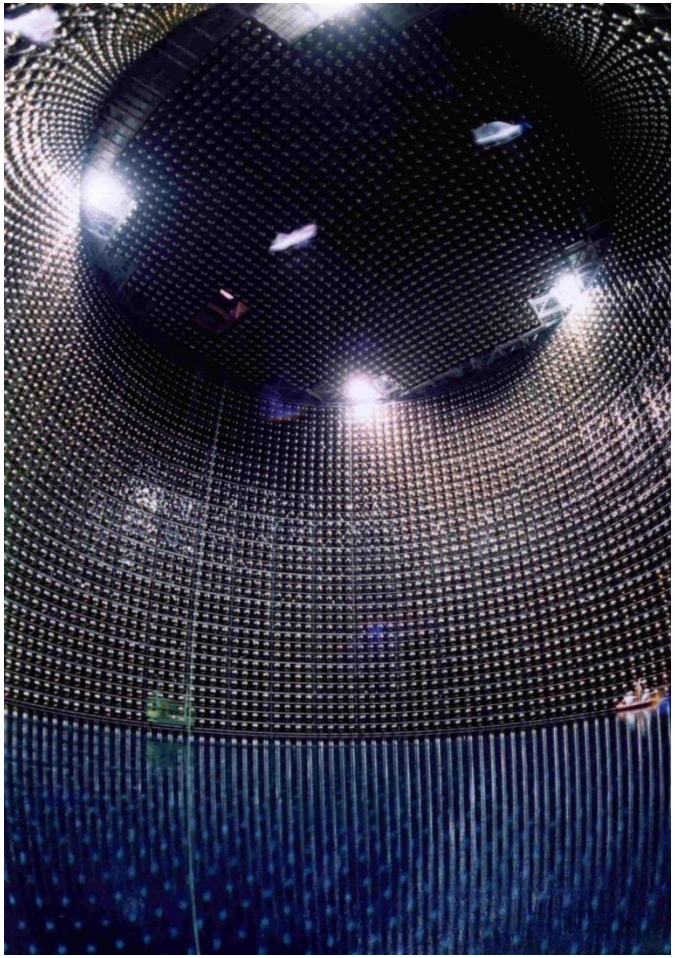
The Progenitor Star



Detection of Neutrinos from SN1987A

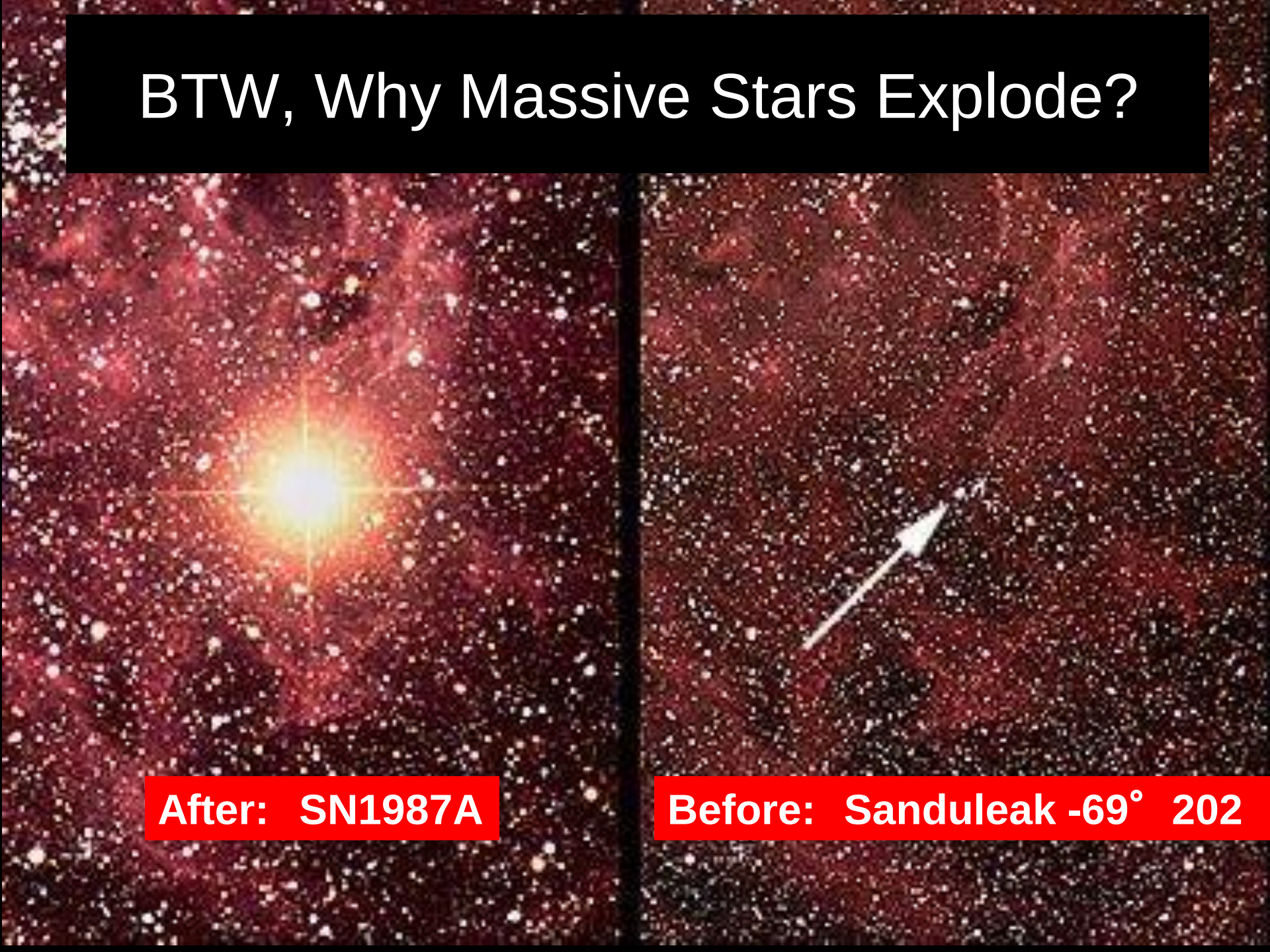


Prof. Koshiba

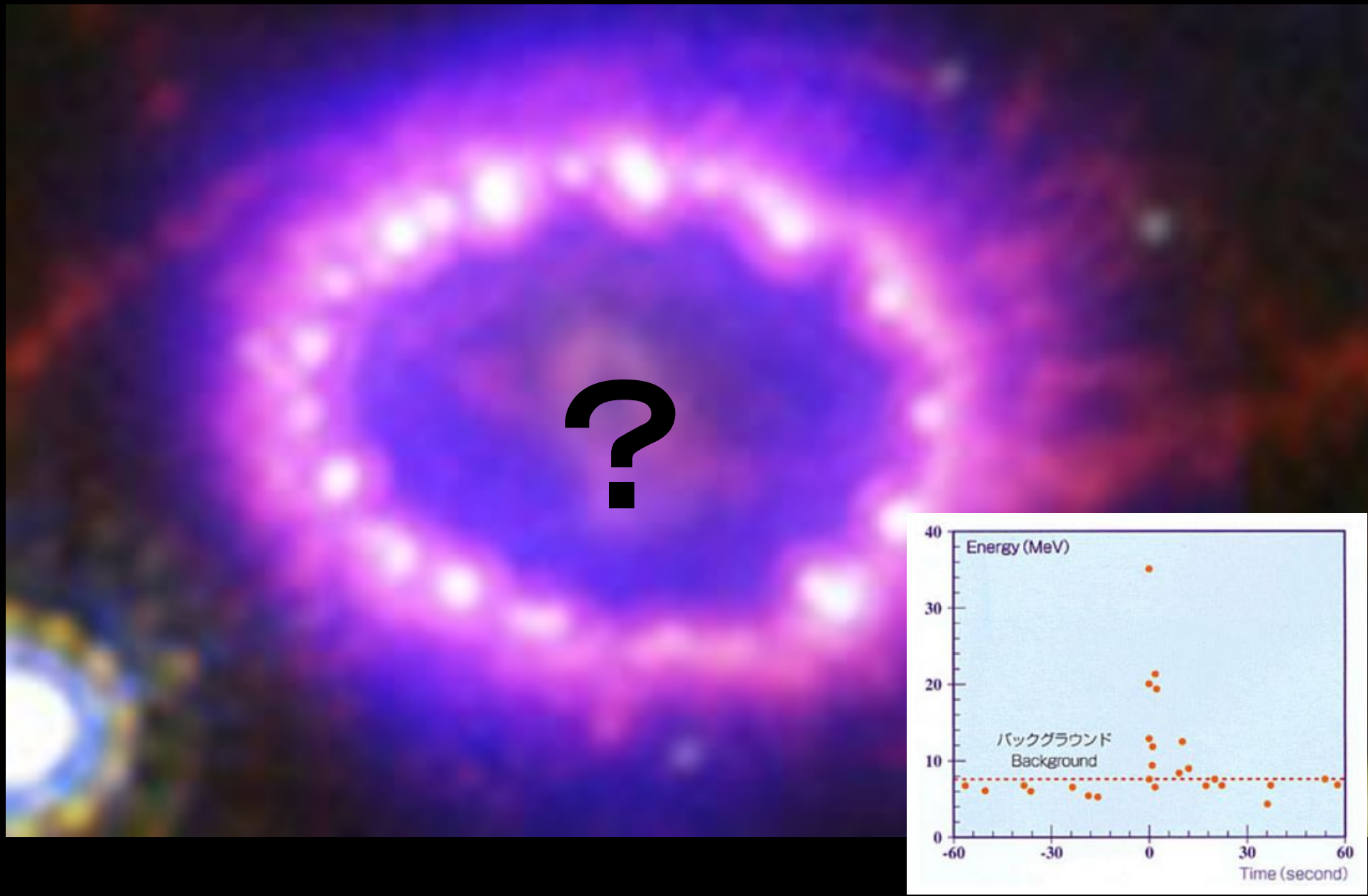


Super-Kamiokande

BTW, Why Massive Stars Explode?

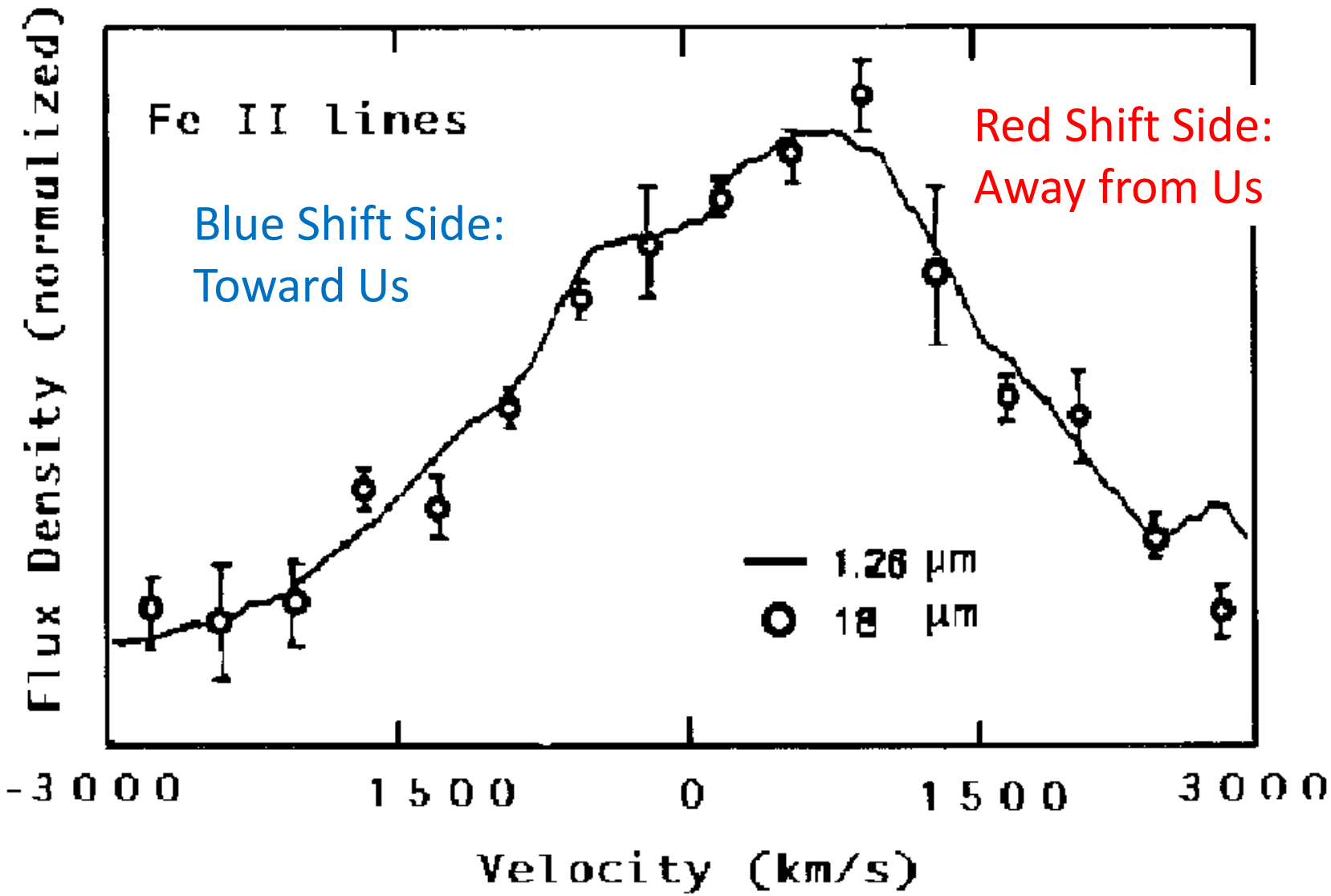


Where is the Neutron Star in SN1987A?

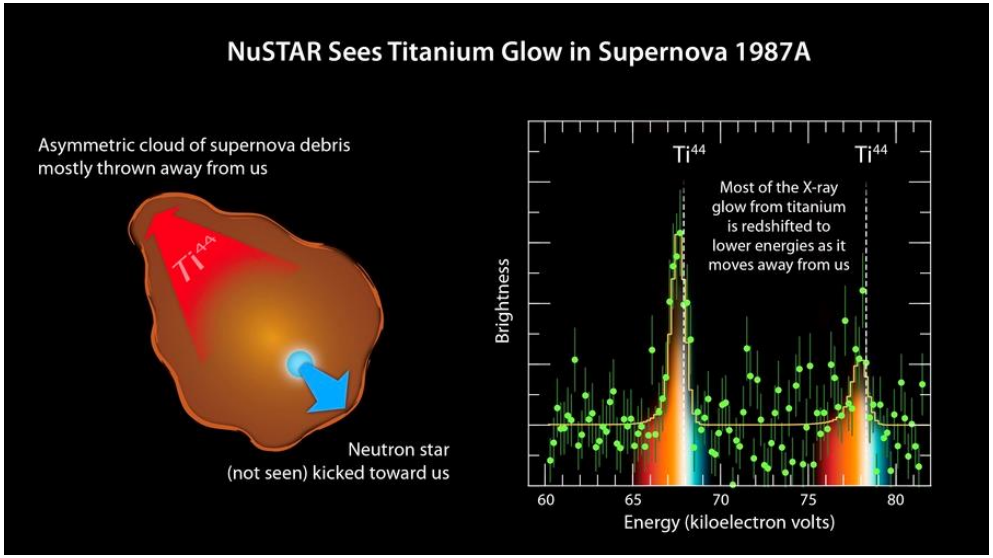


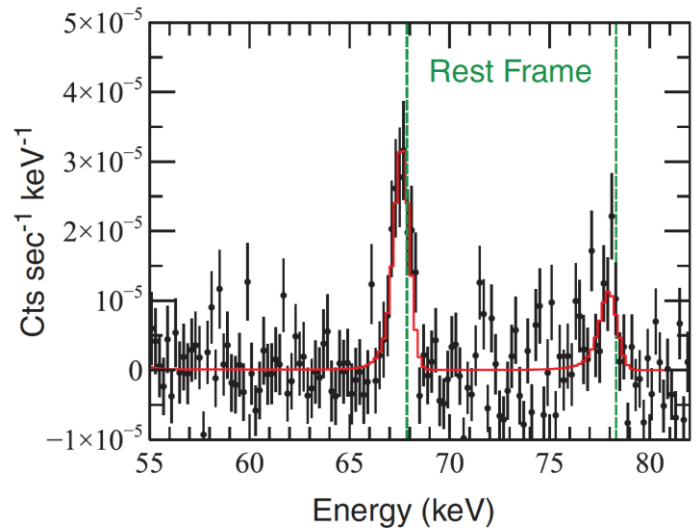
Asymmetric Velocity Profile of Iron

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

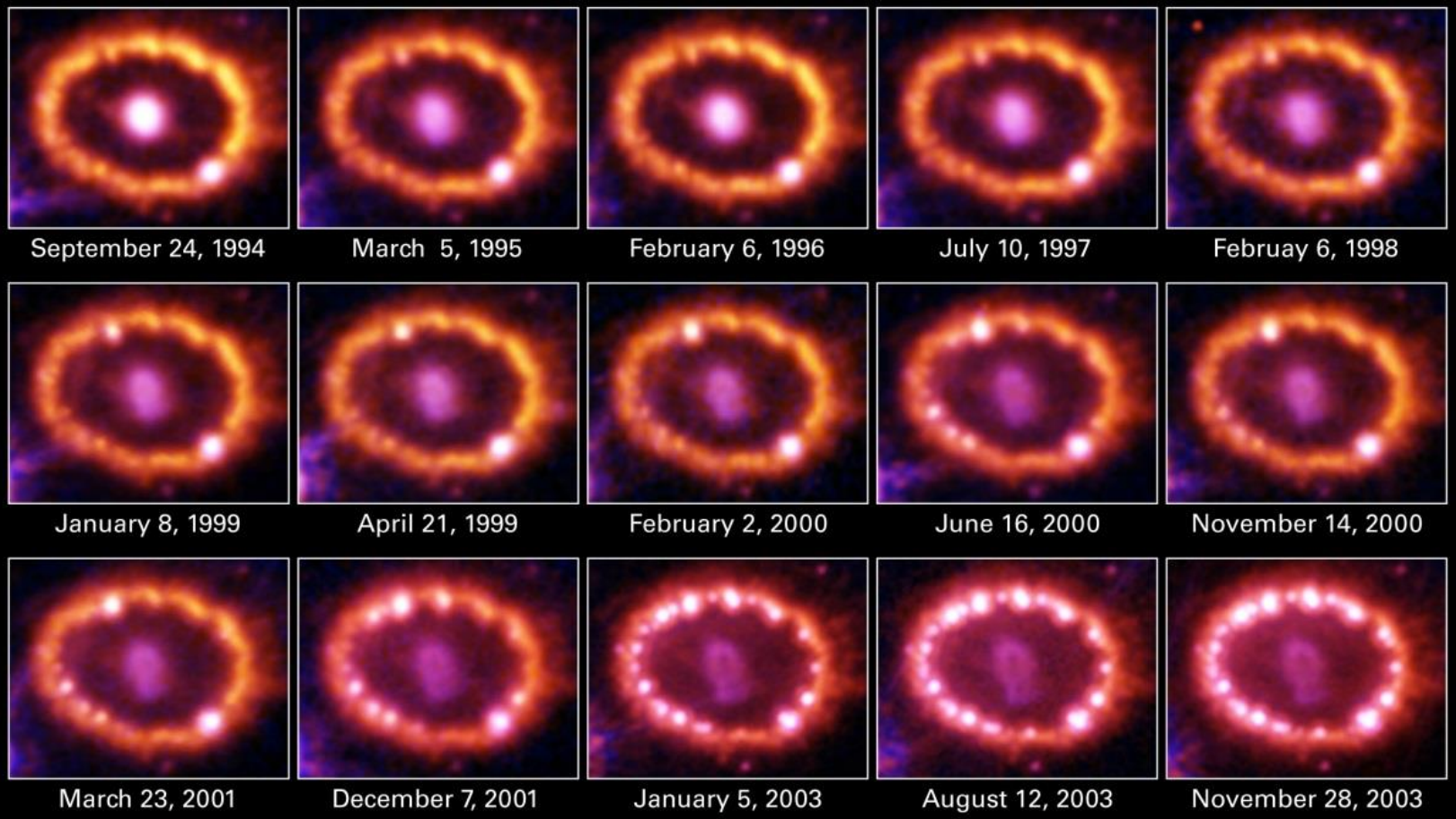
Boggs et al. 2015, Science, 348, 670

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



Supernova 1987A • 1994-2003
Hubble Space Telescope • WFPC2 • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

STScI-PRC04-09b

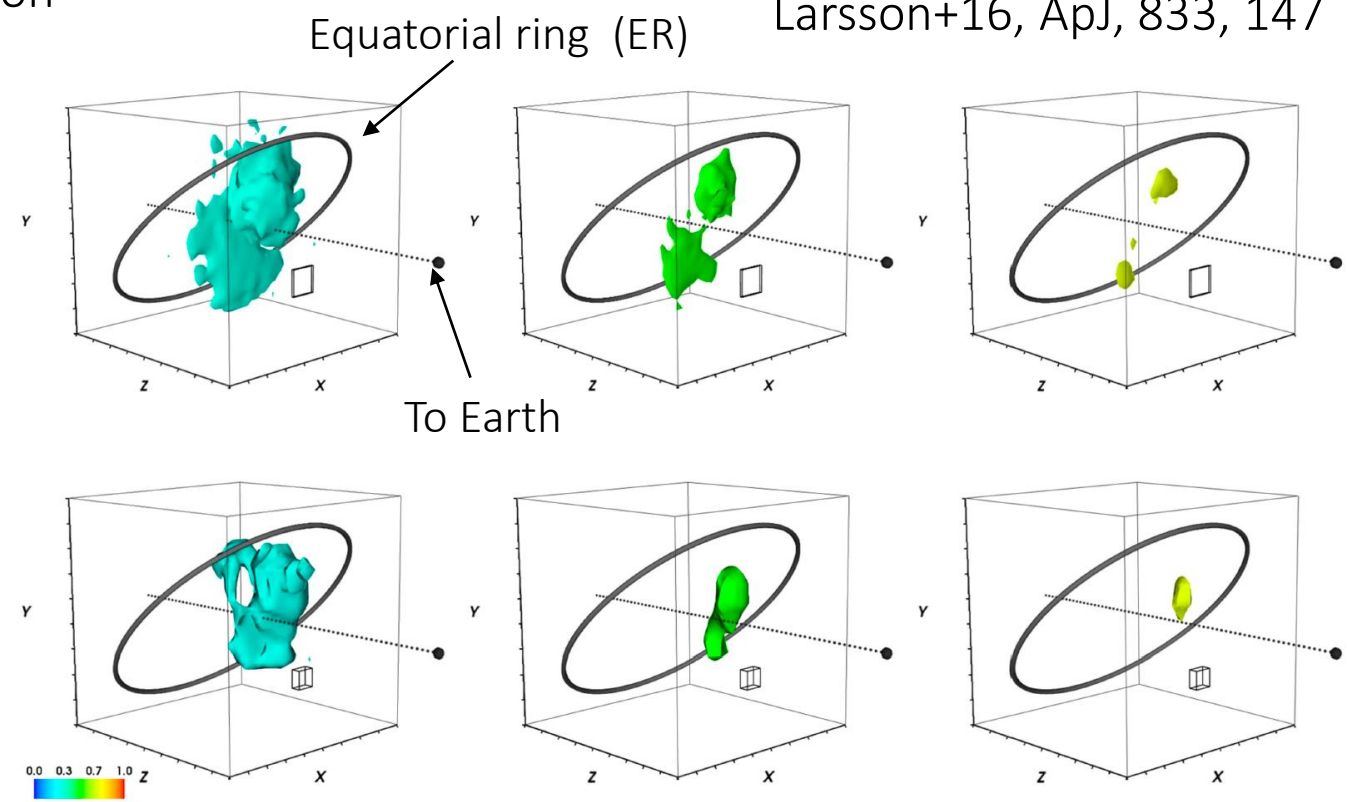
3D distribution of inner ejecta of SN 1987A

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

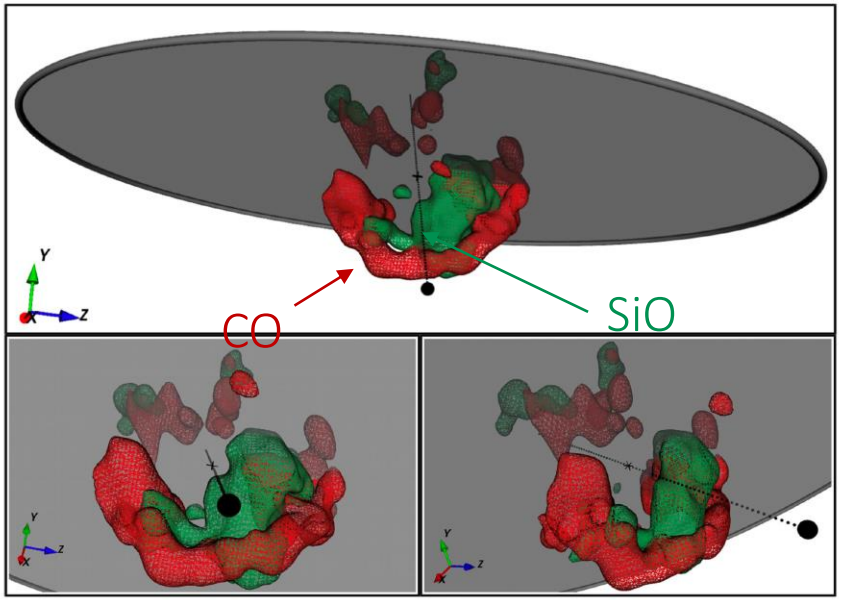


Figure 2. 3D view of cold molecular emission in SN 1987A. The CO 2−1 (red) and SiO 5−4 (green) emission is shown from selected view angles. The central region is devoid of significant line emission. The emission contours are at the 60% level of the peak of emission for both molecules. The black dotted 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.)

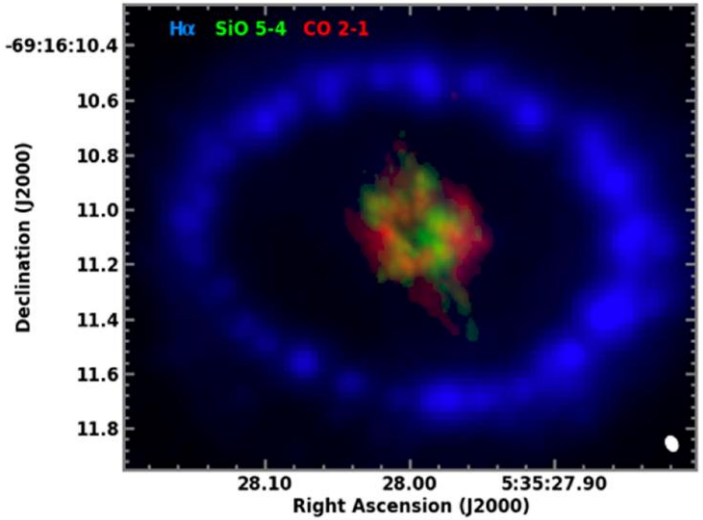
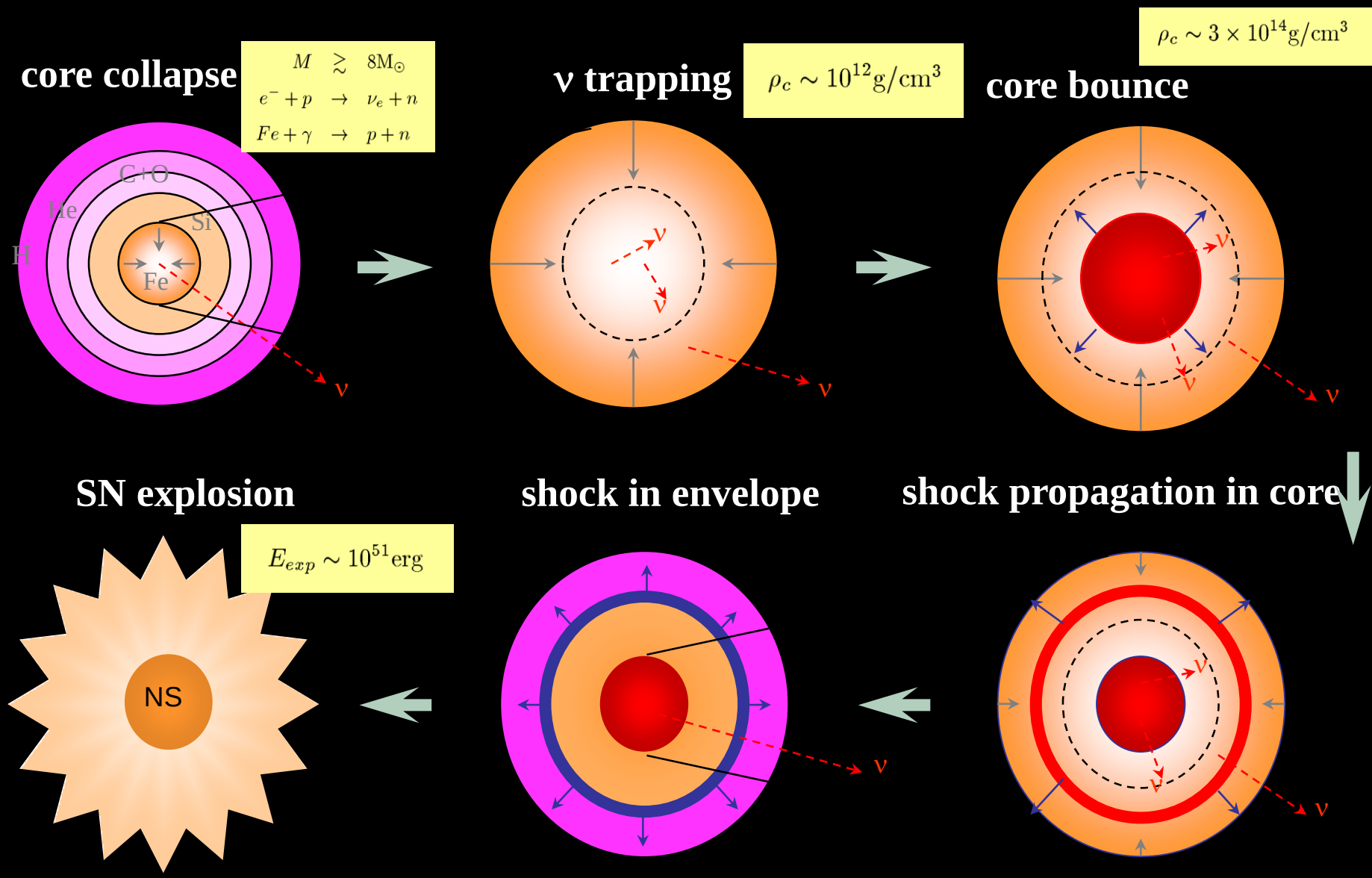


Figure 1. Molecular emission and Hα emission from SN 1987A. The more compact emission in the center of the image corresponds to the peak intensity maps of CO 2−1 (red) and SiO 5−4 (green) observed with ALMA. The surrounding Hα emission (blue) observed with *HST* shows the location of the circumstellar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

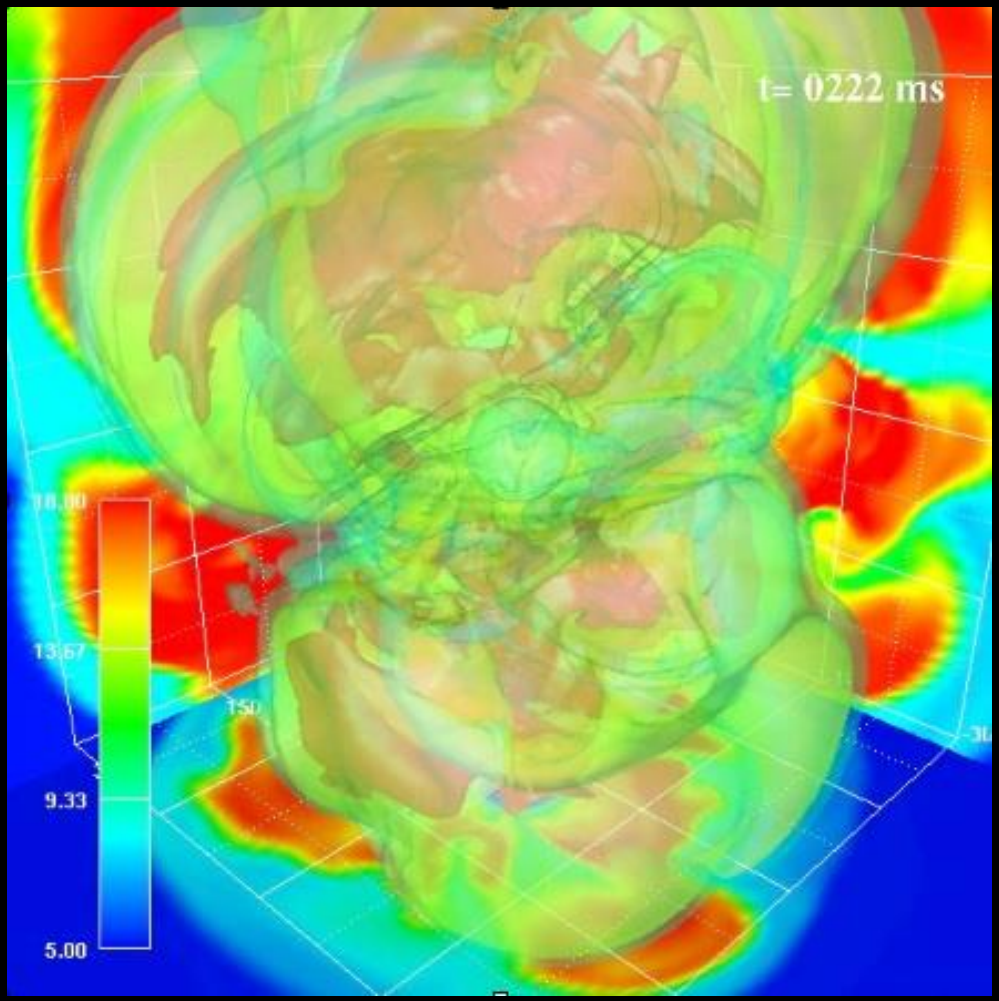
§ Our Theories for SN1987A

Outline of Explosion Mechanism

From S. Yamada

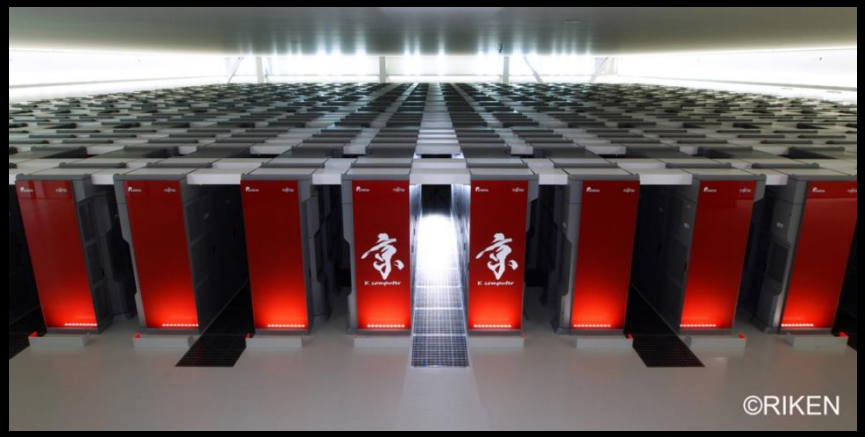


Simulations of CC-SNe Using K-Computer of RIKEN



Takiwaki et al. 2012

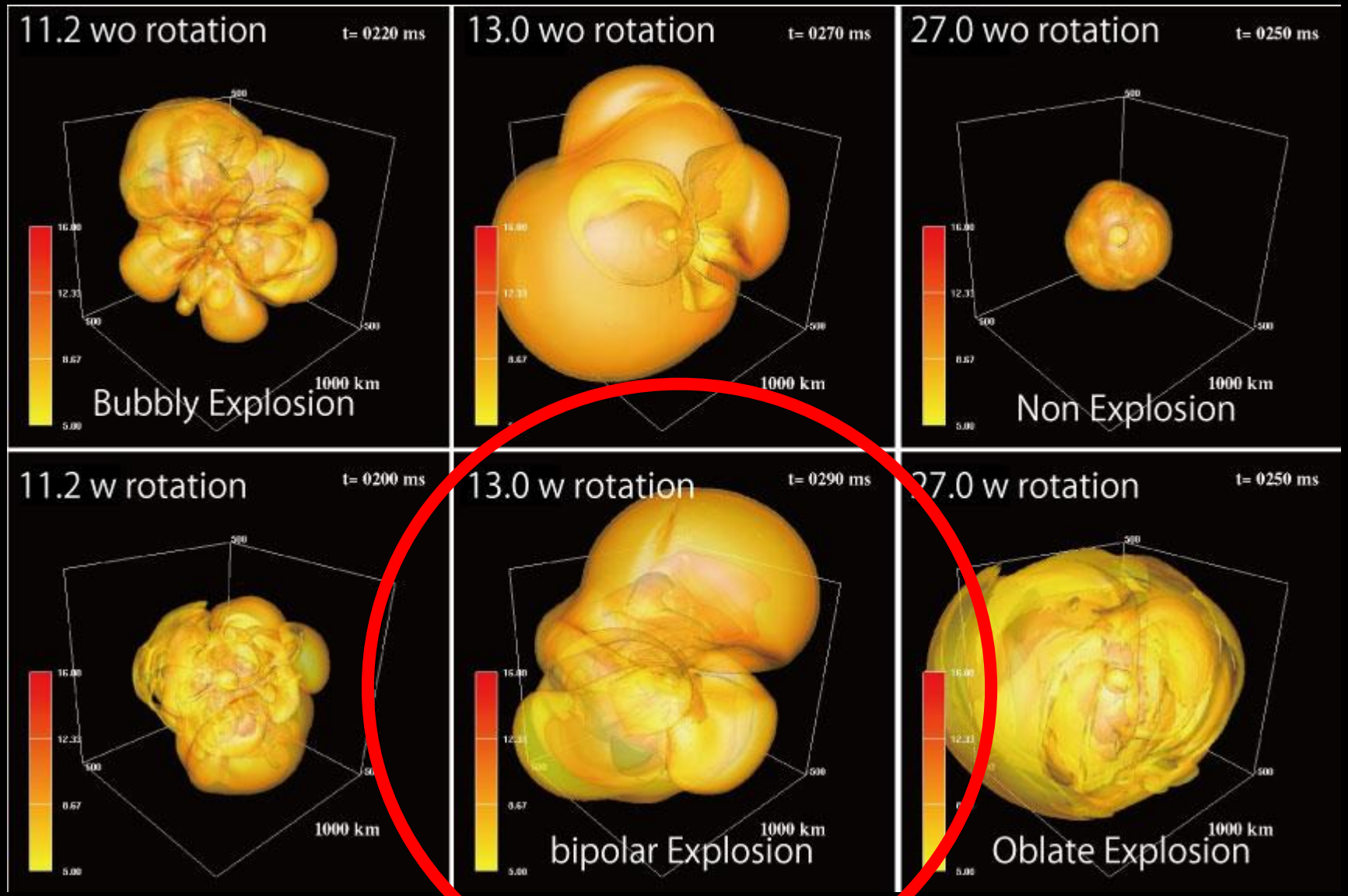
Simulation by
T. Takiwaki
(A-ABBL)



京(KEI) = 10 Peta=10^16.

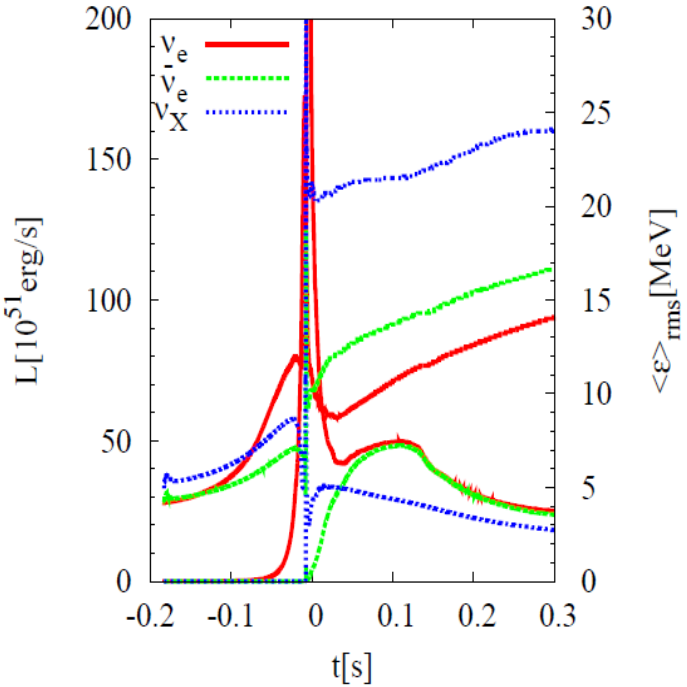
Rotation Can Change the Dynamics

Spiral Waves Convey Rotation Energy Outside.

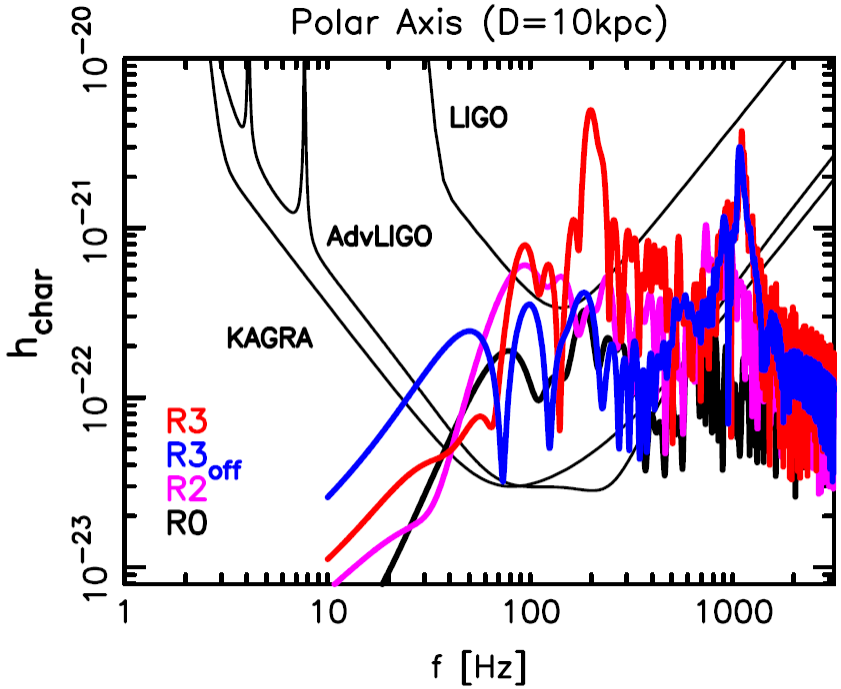


The mass of the progenitor and rotation make various type of Explosion(or Non Explosion).

Neutrino/GW Signals from a Supernova



Time Evolution of Neutrino Luminosity

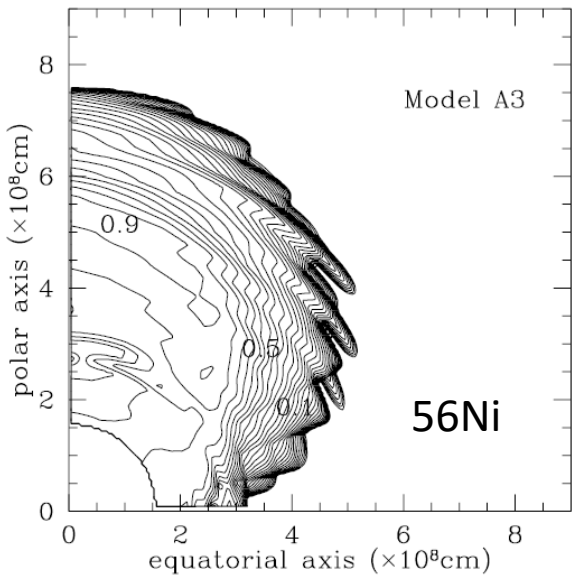


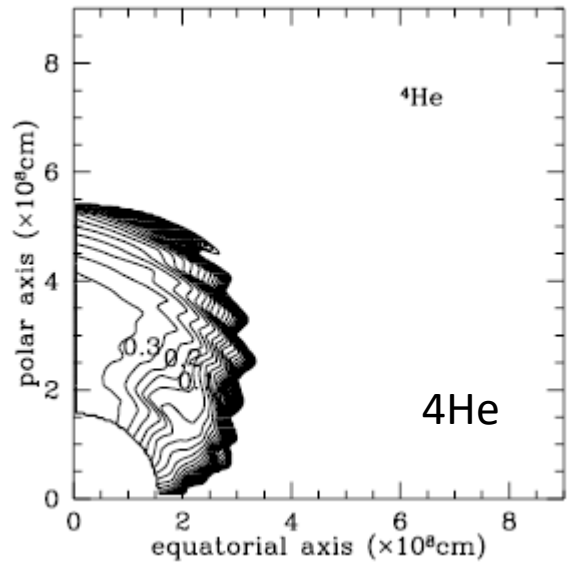
Signal of Gravitational Wave in Freq. Space

T. Takiwaki
(A-ABBL).

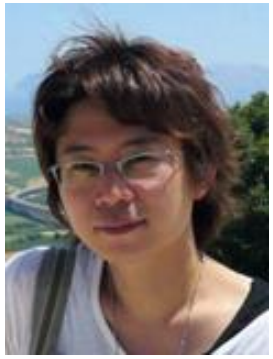
H. Sotani
(NAOJ→ABBL)

Lots of ^{44}Ti Produced in Bipolar Explosions

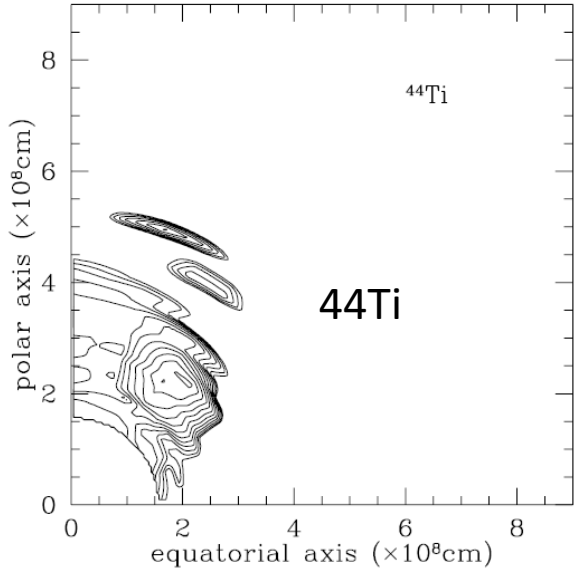




Nagataki et al. 97,
Nagataki 00



S. Nagataki (ABBL)



Produced amount of 44Ti:

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

Consistent with Obs. of 44Ti by NuStar

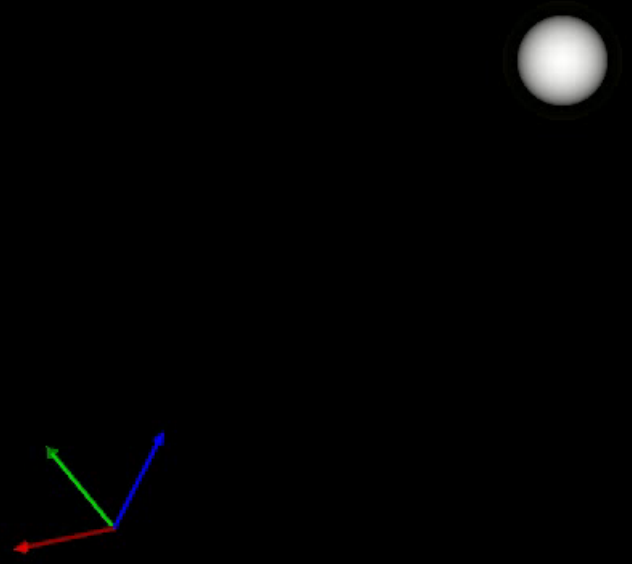
In Jet (bipolar) region, entropy per baryon becomes high!

For α-rich, High Entropy per Baryon.

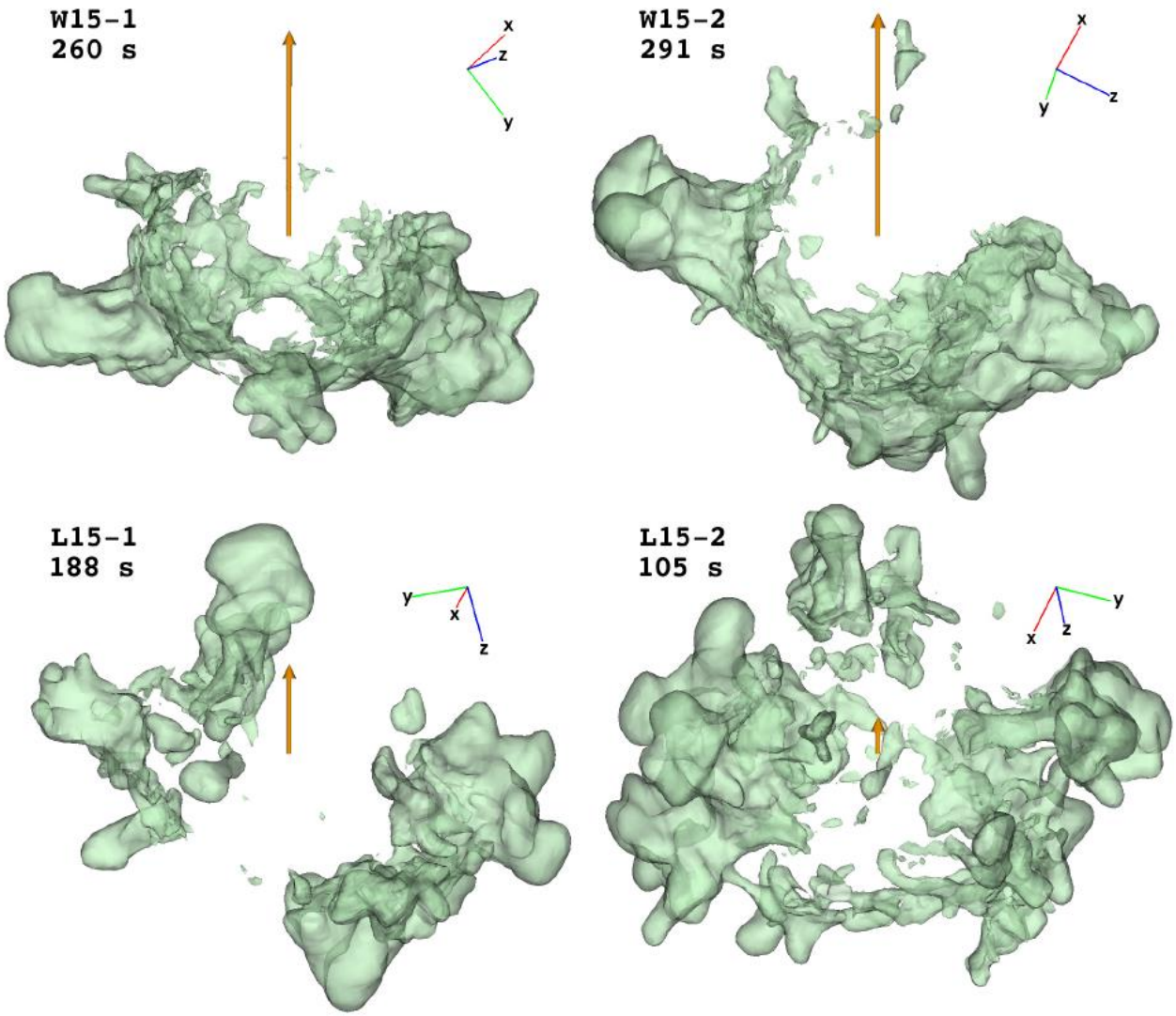
- $S \sim T^3/\rho$.
- For High Entropy per baryon (*S*), high temperature & (relatively) low density are preferred.
- The balance between Fe ⇔ He, p, n depends on entropy.
- *T* is related with photo-dissociations, while ρ is related with nuclear reactions.

Asymmetric Explosion & Neutron Star Kick

A. Wongwathanarat
(A-ABBL)



Asymmetric Ejection of 56Ni & Neutron Star Kick

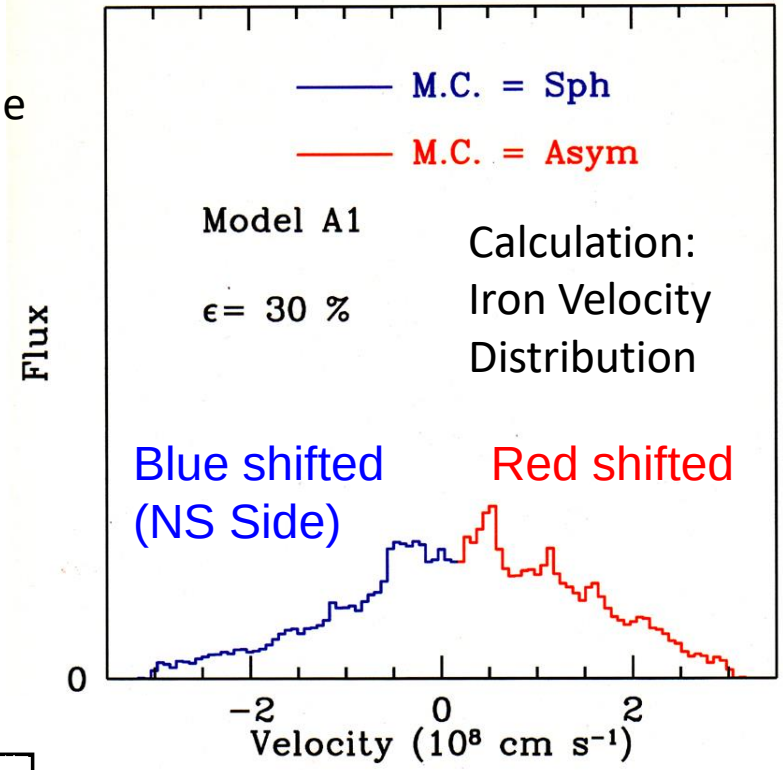


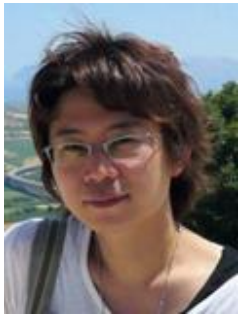
A. Wongwathanarat
(A-ABBL)

Asymmetry with Respect of Equatorial Plane
Is Suggested for SN1987A.

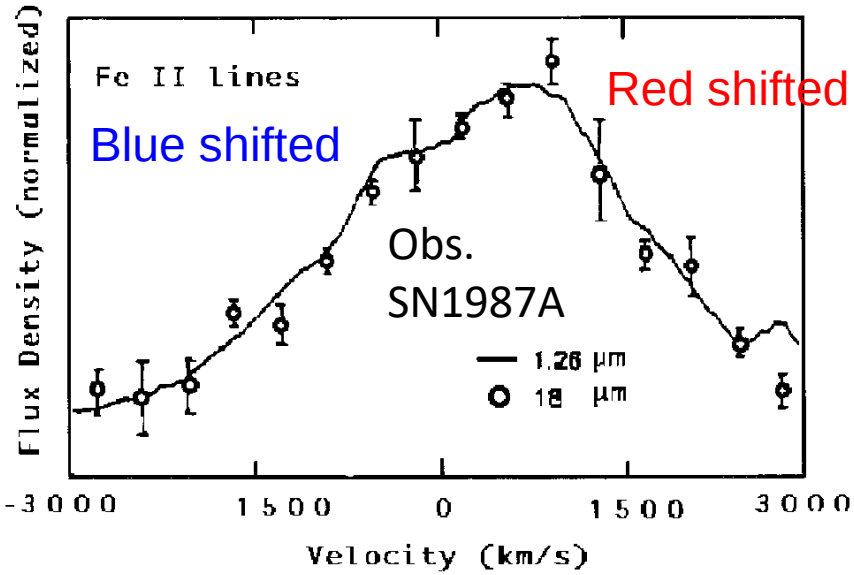
↓

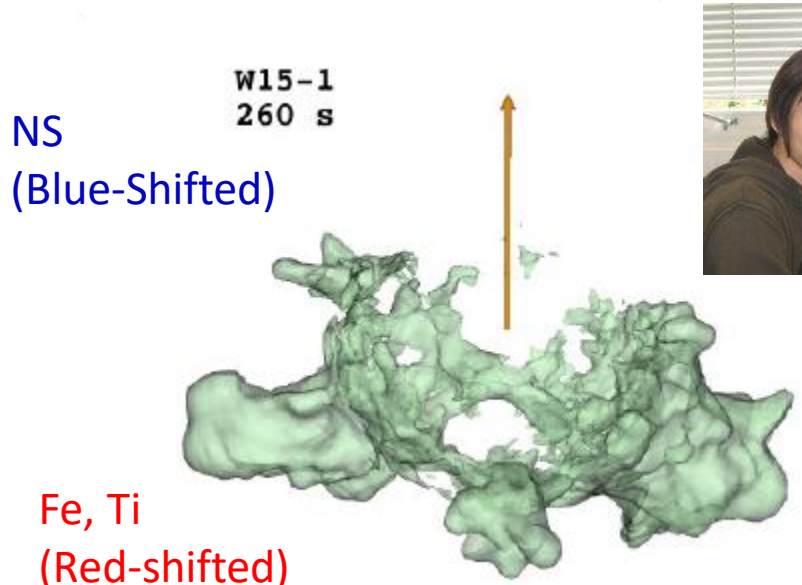
The Missing Neutron Star should be
Moving toward Us (Blue-Shifted Side)!
S.N ApJS 2000.





SN 2000





Wongwathanarat+ 2013

§ Advanced Studies for SN1987A:
From Progenitor Star to 30 Years after the Explosion

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

Ono et al. in Prep. (2019), will be submitted to ApJ soon.

Orlando et al in Prep (2019), submitted to Science Advances.

Masaomi Ono (ABBL)

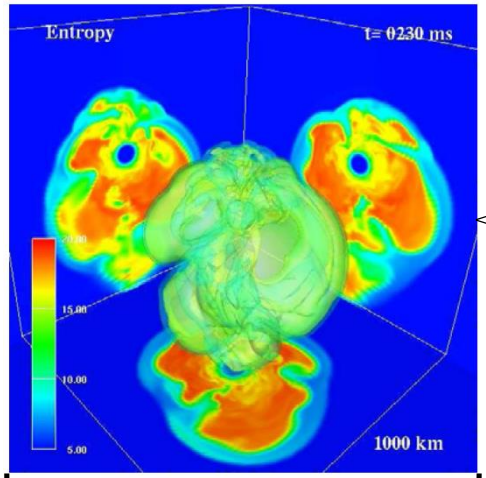
Supernova explosions to their supernova remnants (SNRs)

Supernova explosion
$t < 1$ sec

Shock breakout
$t < 1000$ sec

supernova
$t < 1$ yr

Supernova remnant
$t \sim 500$ yr



Takiwaki (A-ABBL)

Mixing?

Electromagentic signals

Radius of the progenitor star

$10^7 - 10^9$ cm

$10^{12} - 10^{14}$ cm

$\sim 10^{18}$ cm (1 pc)

Stellar evolution of the progenitor star

Asymmetric explosion
Explosive nucleosynthesis

Matter mixing

Formation of molecules and dust?

Asymmetric distribution of elements

Chemical evolution (Nucleosynthesis/Molecule formation/dust formation) during the progenitor–SNe–SNRs sequence

Linking SNR 1987A to the SN and progenitor star

1D stellar progenitor model

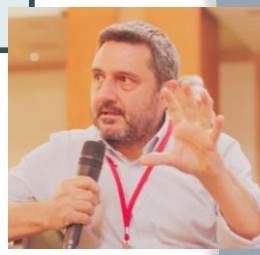
3D cc SN model

(Ono+2019 in preparation for ApJ)

M. Ono (ABBL)

3D SNR model

(Orlando+2019 submitted to Science Advances)



Progenitor star

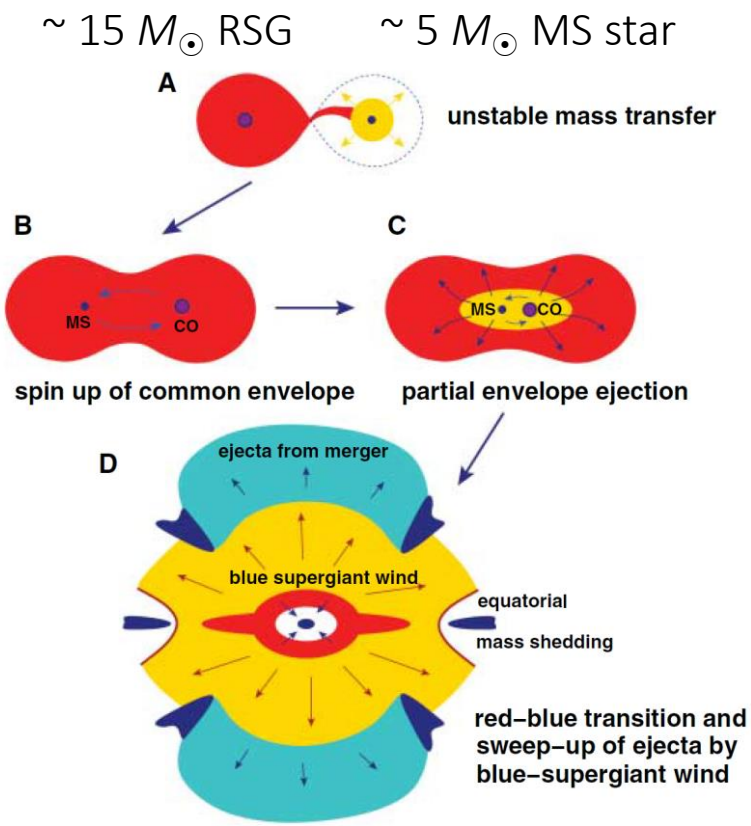
- 16.3$M_\odot$ BSG (Nomoto & Hashimoto 1988)
- 19.8$M_\odot$ RSG (Woosley+2002)
- 18.29 $M_\odot$ BSG resulting from the merging of 14 and 9 $M_\odot$ stars (Urushibata+2018)

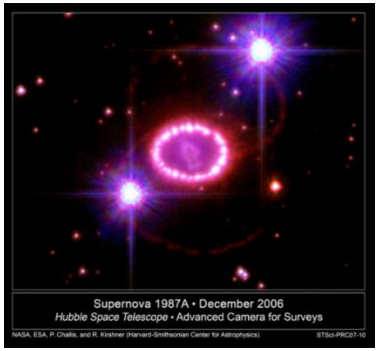
The 18.29 $M_\odot$ BSG model reproduces the main observables of Sk −69° 202

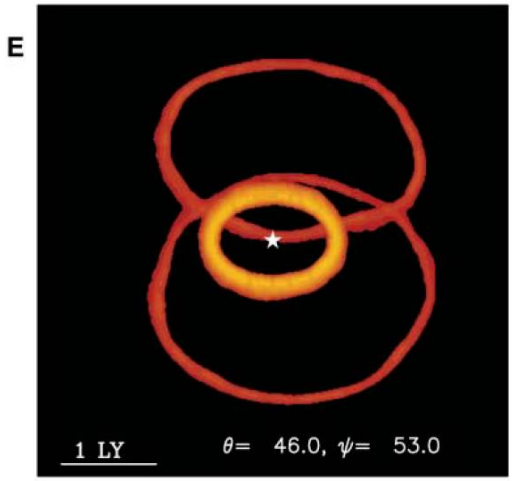
- red-to-blue evolution
- total mass and position in the HR diagram at collapse (Blue Super Giant)

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

- 3D smoothed particle hydrodynamic (SPH) simulation



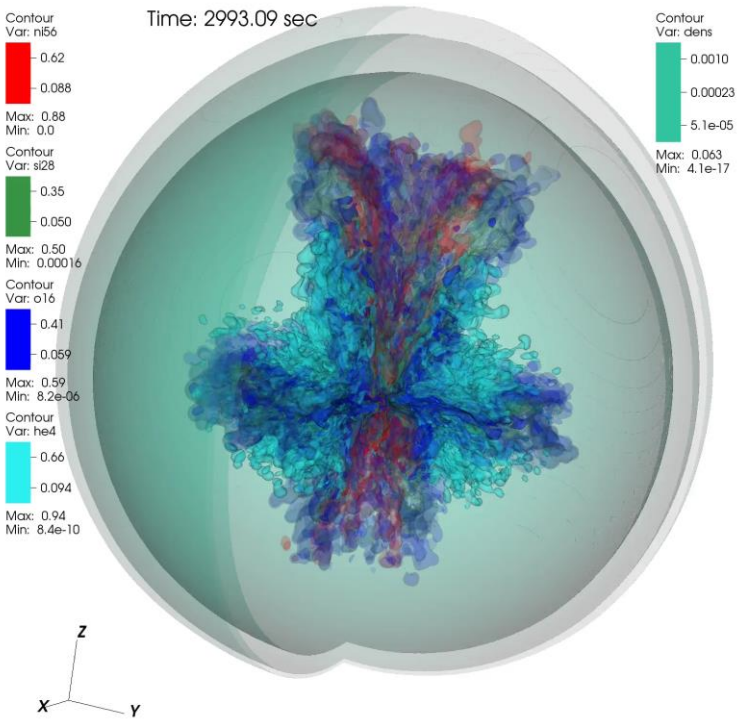




Morris & Podsiadlowsky 2007, Science, 315, 1103

Rapid Rotation is Introduced by the merger?

The SN explosion



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

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

Numerical code:
FLASH
(Fryxell+ 2000)

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:

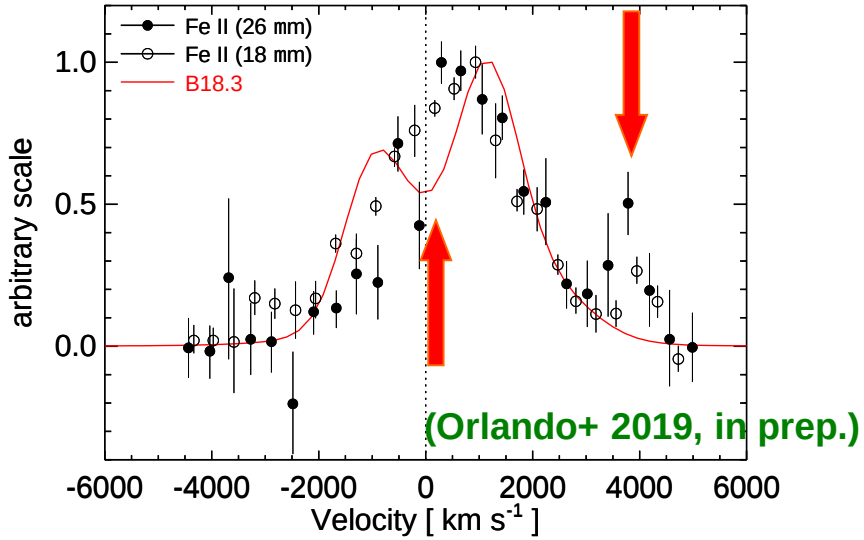
$v_{pol}/v_{eq} = \beta =$ **[2.0 – 16]**

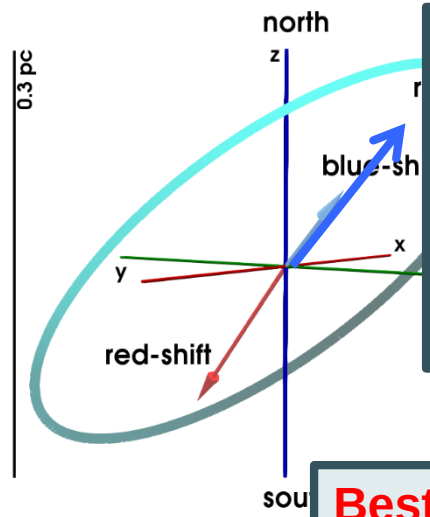
$v_{up}/v_{dw} = \alpha =$ **[1.1 – 1.5]**

(Ono+2019, in prep.)

Masaomi Ono
(ABBL)

Post-explosion anisotropies: [Fe II] line profiles

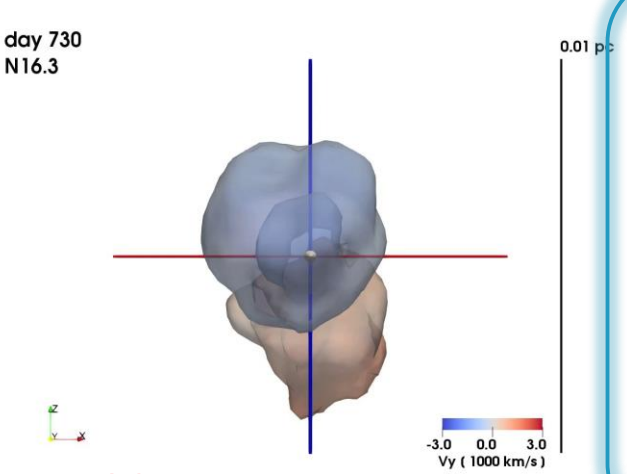




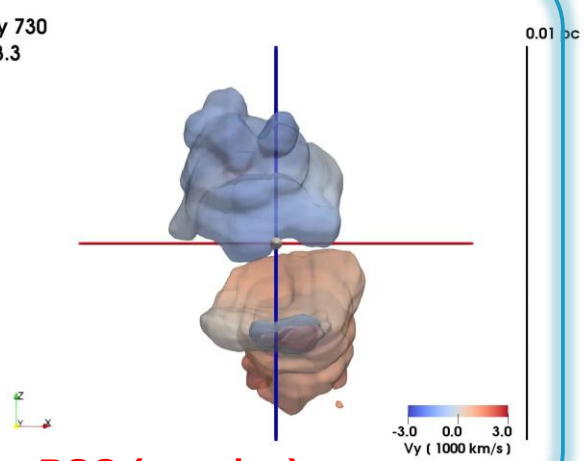
NS kick
~ 300 km/s
toward us to the north
(Nagataki 2000; Wongwathanarat 2013; Janka 2017)

Best-fit parameters

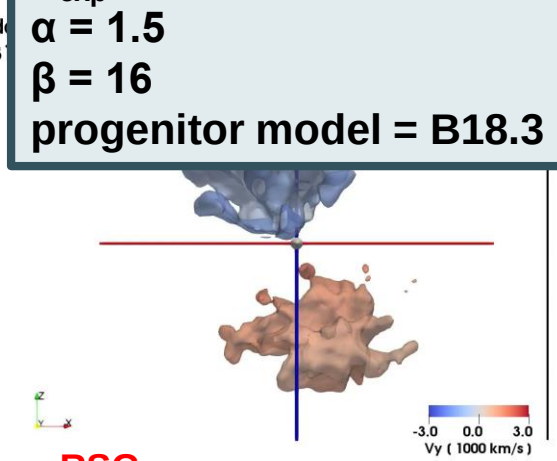
E_{exp} ~ 2 x 10^{51} erg
α = 1.5
β = 16
progenitor model = B18.3



BSG



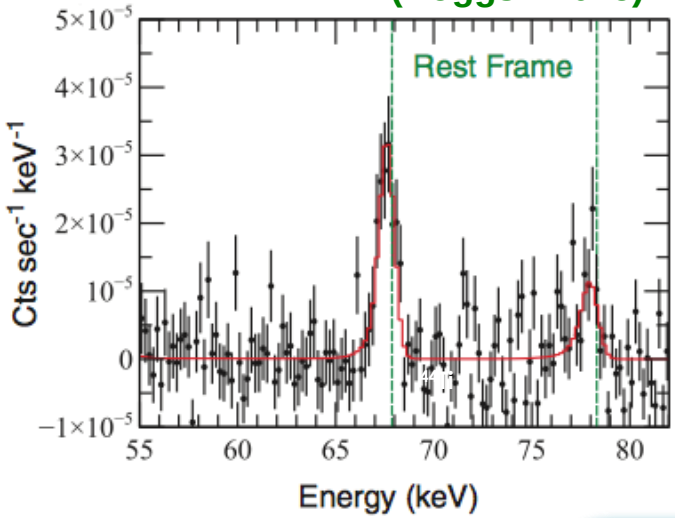
BSG (merging)



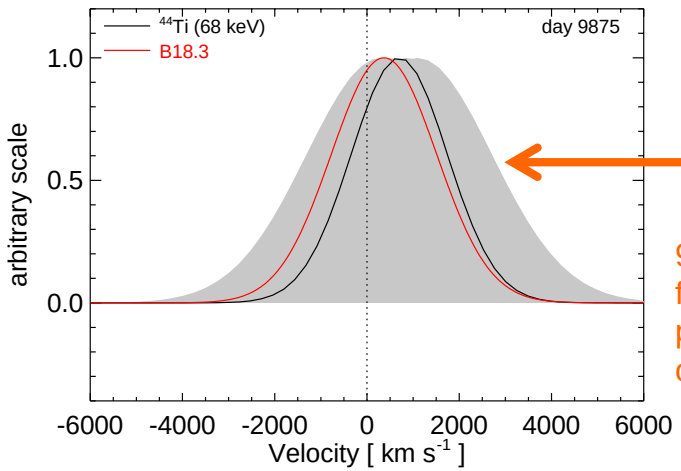
RSG

Distribution of ^{44}Ti in the evolved SNR

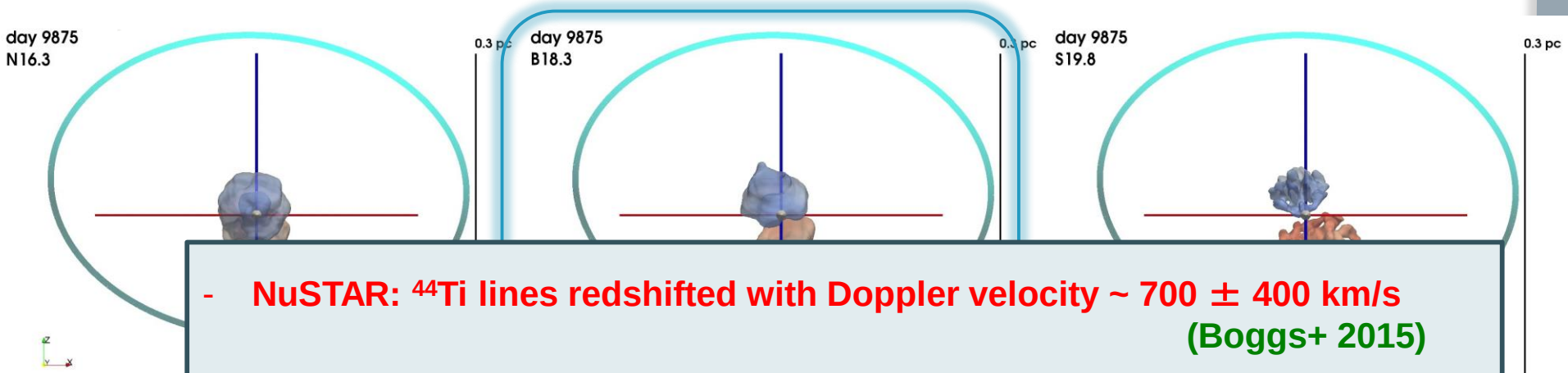
(Boggs+ 2015)



(Orlando+ 2019, submitted)



90% confidence area for the position of the peak and for the width of the Gaussian



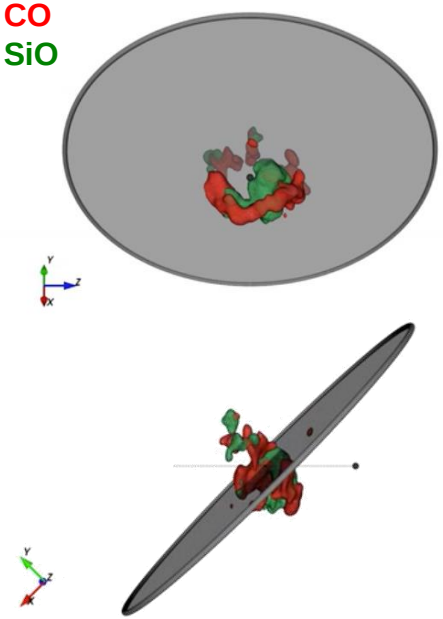
BSG

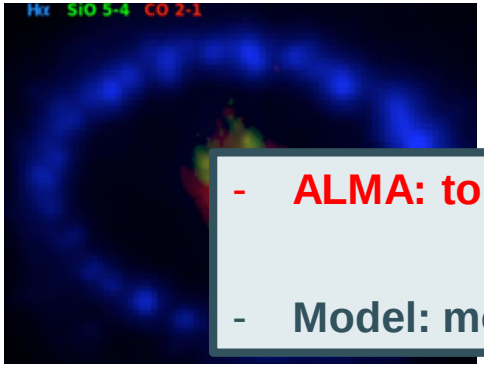
- **NuSTAR: ^{44}Ti lines redshifted with Doppler velocity ~ 700 ± 400 km/s (Boggs+ 2015)**
- **Model: Velocity along the LoS of ^{44}Ti ~ 400 km/s away from the observer**

Molecular structure in the evolved SNR

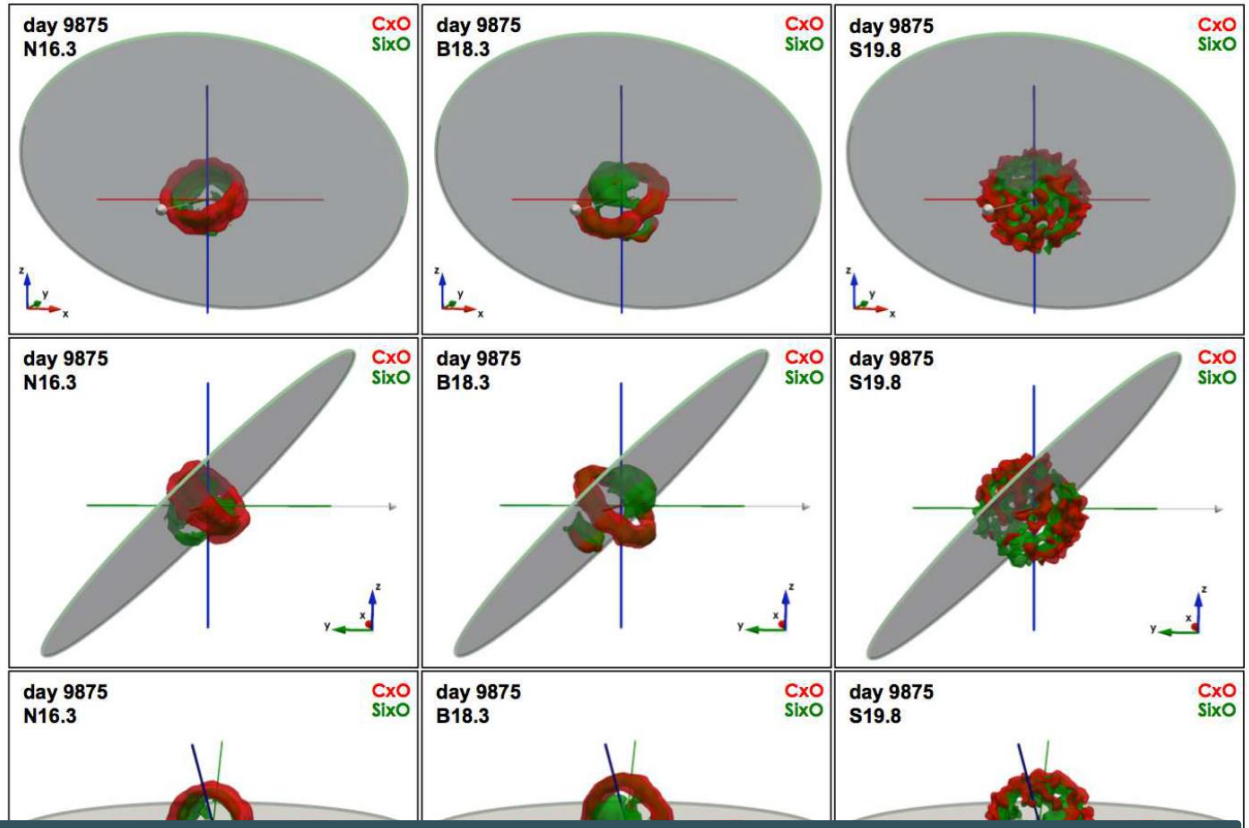
(Abellan+ 2017)

CO
SiO





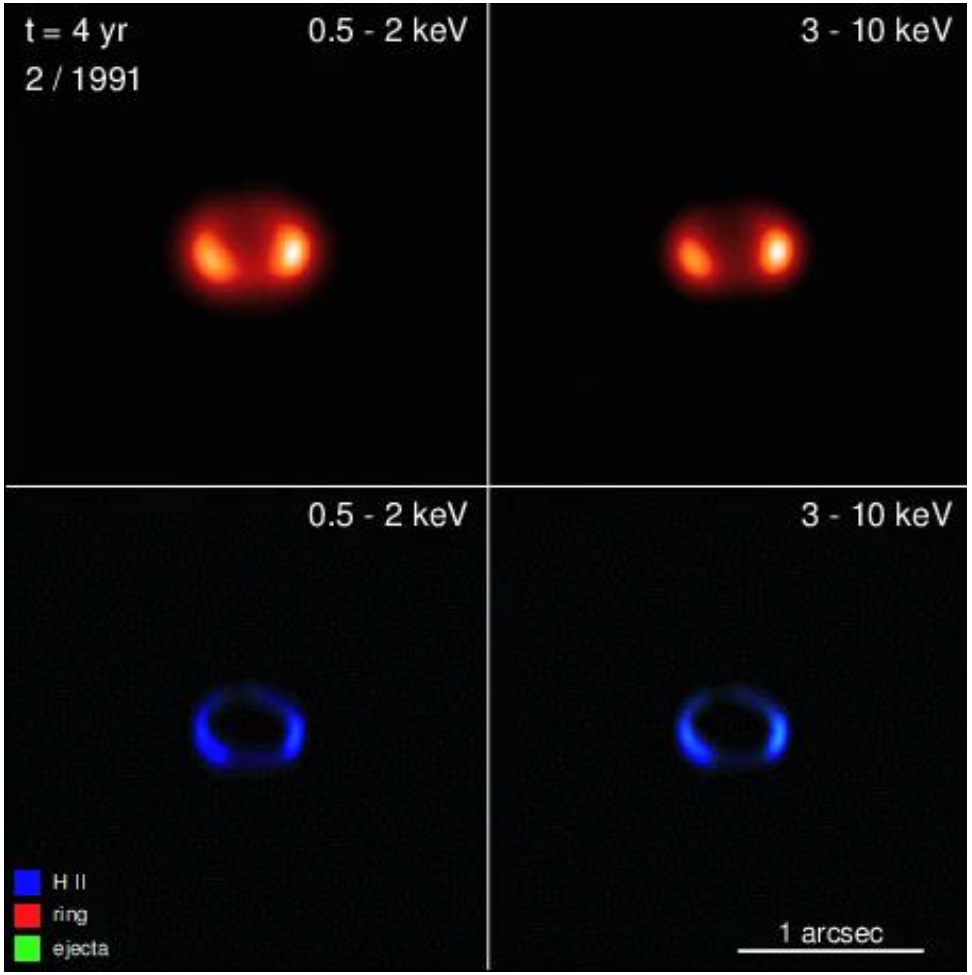
BSG | BSG (merging) | RSG

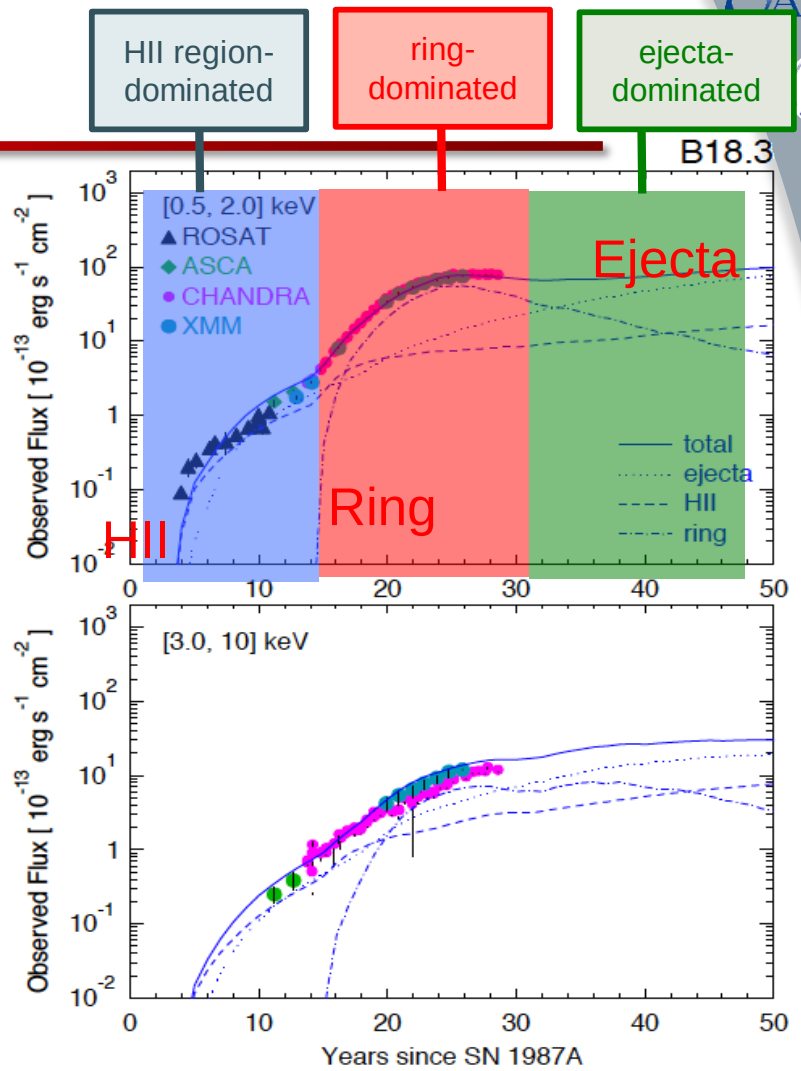


- ALMA: torus-like structure evident in CO. SiO is inside of CO. (Abellan+ 2017)
- Model: modeled torus-like feature with similar orientation and size

(Orlando+ 2019, Science Advances, Submitted)

X-ray Lightcurves

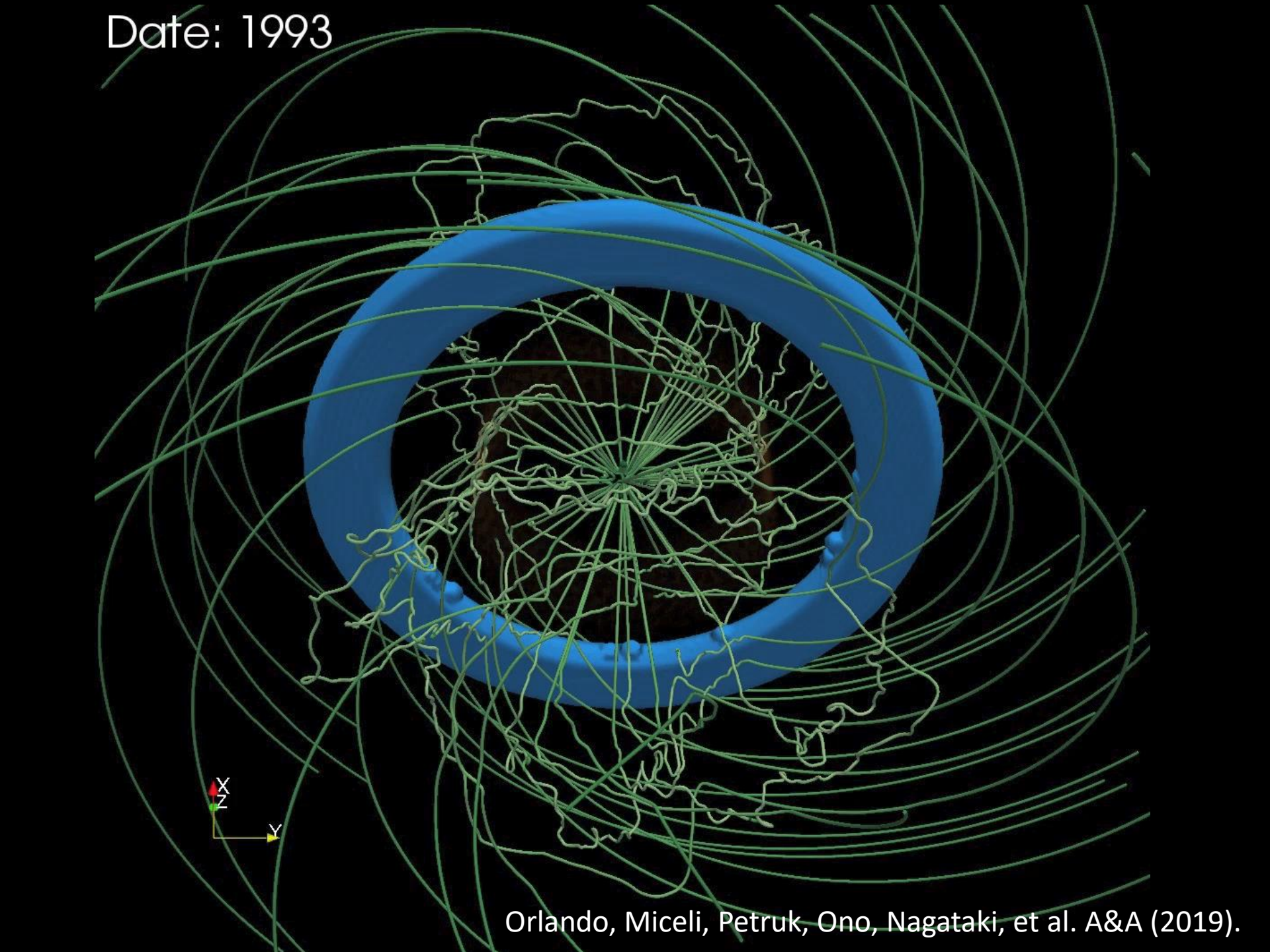




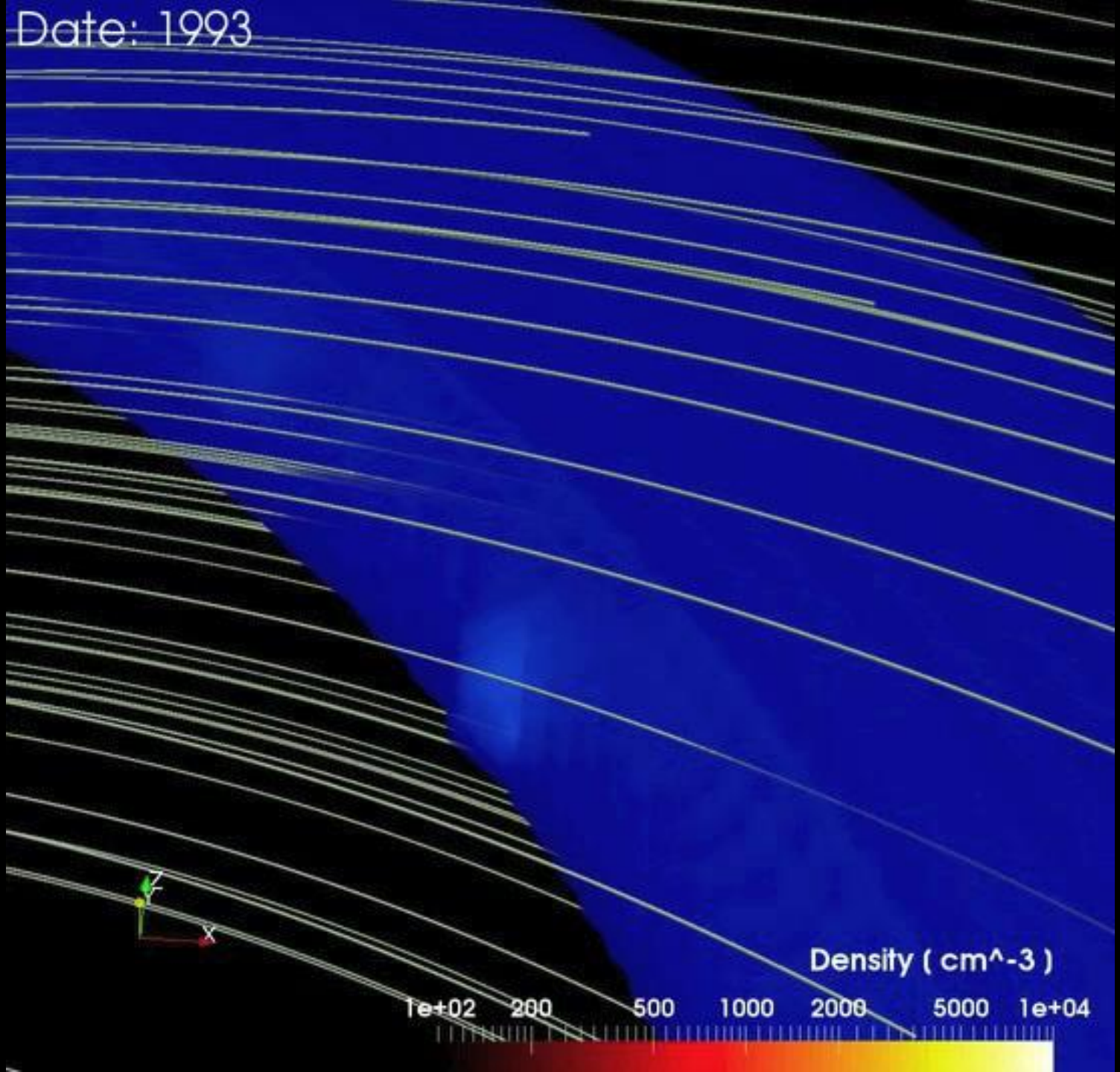
Abundances from Zhekov+ (2009)

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

Distance: 51.4 kpc (Panagia 1999)

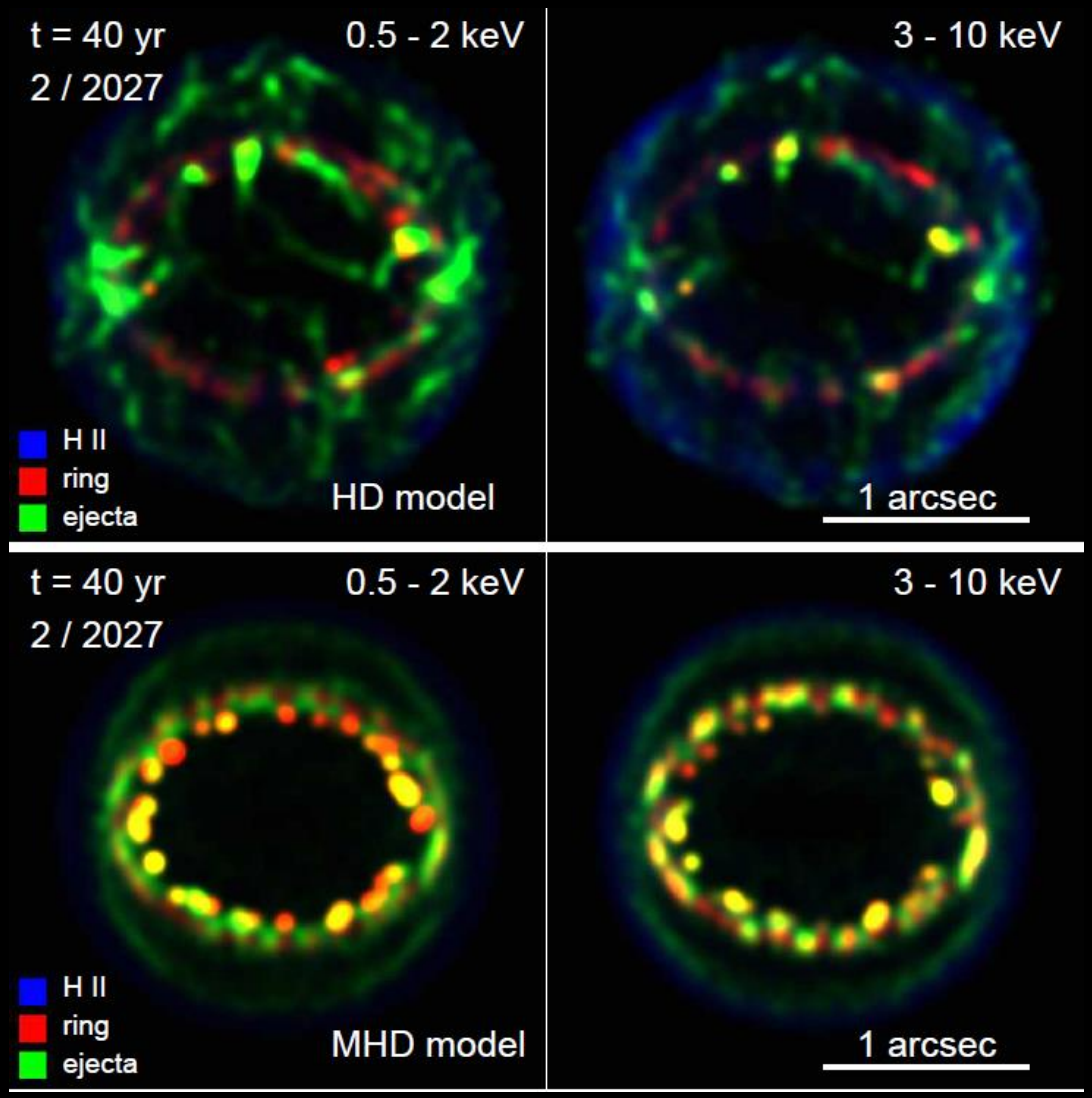


Orlando, Miceli, Petruk, Ono, Nagataki, et al. A&A (2019).


Date: 1993
Z
X
Density (cm^-3)
1e+02
200
500
1000
2000
5000
1e+04

Effects of B-Fields on X-ray Light Images

Orlando, Miceli, Petruk, Ono, Nagataki, et al. A&A (2019).



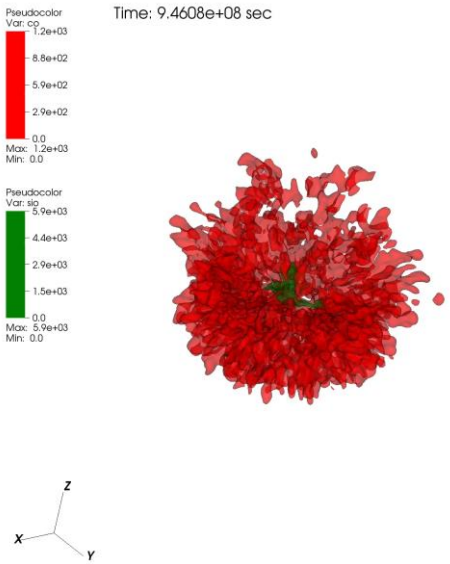
Athena (ESA, early in 2030)

～3kG at Surface of Progenitor Star (c.f. Donani & Landstreet 2009).
～μG at the Ring.

Future Directions

- Molecule Formation with a Chemical Reaction Network.

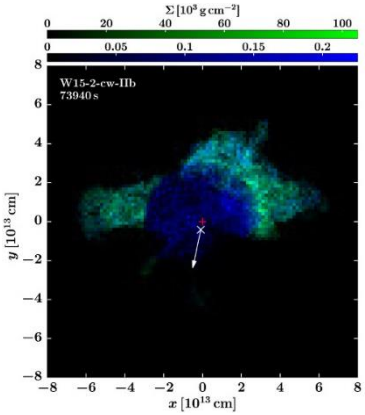
Masaomi Ono
(ABBL)

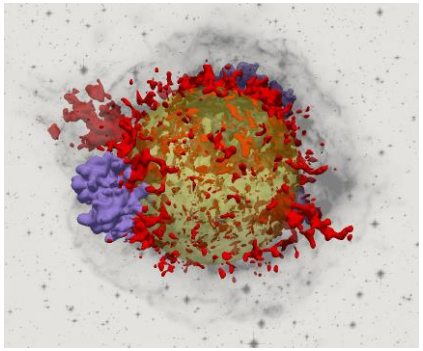


- Applying Our Method to Cas A.

A. Wongwathanarat
(A-ABBL)

S. Orlando
(Palermo Obs.)





Thank You Very Much!

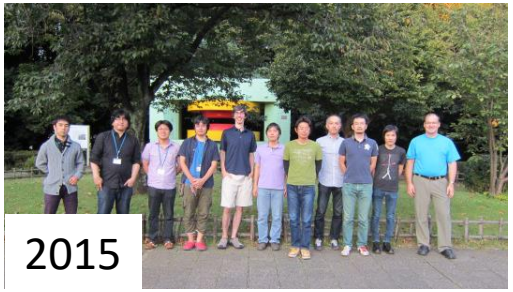
ABBL members

- PI: Shigehiro Nagataki
- Research Staff: A. Mizuta
- Current PDs: H.Ito, G. Ferrand, H. He, M. Ono, O.Just, +3 Postdocs
- Current Student: M. Arakawa (ABBL/Rikkyo), Y. Takei (ABBL/Tokyo), Y. Huang (iTHEMS/ABBL)

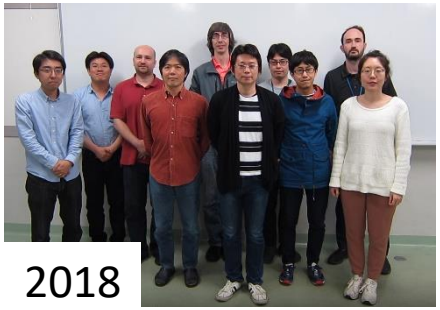
A-ABBL members

- Almuni: Lee(Kyoto), Tolstov(IT Company), Mao(Yunnan Obs.), Dainotti (Jagellonian U.), Teraki (Asahikawa CT), Takiwaki (NAOJ), Wada (Tohoku), Barkov (Purdue), Wongwathanarat(MPA), Matsumoto (Fukuoka U.), Warren (iTHEMS), Inoue (iTHEMS)


2013


2015


2017


2018