Supernovae as Origins of Life

Shigehiro Nagataki

Astrophysical Big Bang Laboratory (ABBL), RIKEN
Interdisciplinary Theoretical & Mathematical Sciences Program (iTHEMS), RIKEN
Astrophysical Big Bang Group (ABBG), Okinawa Institute of Science and Technology (OIST)

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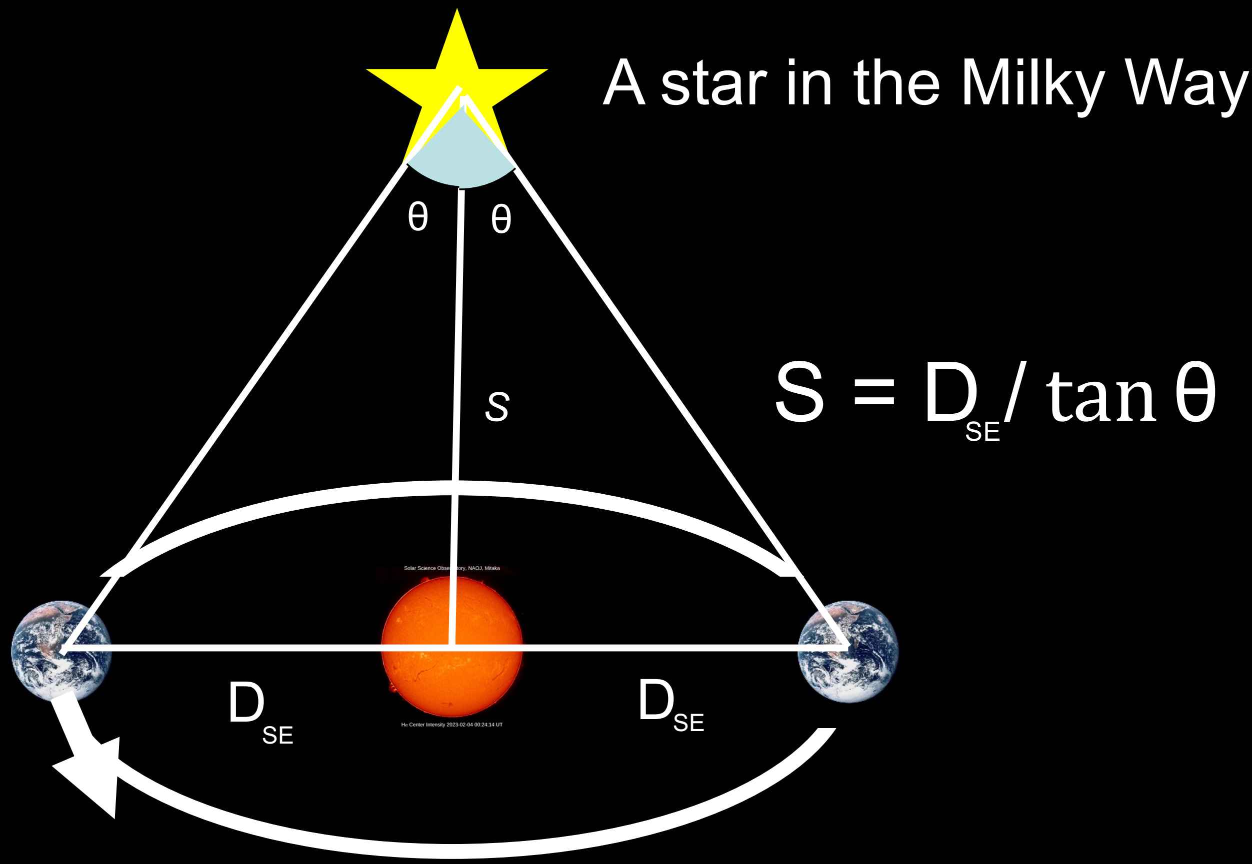
RIKEN OIST

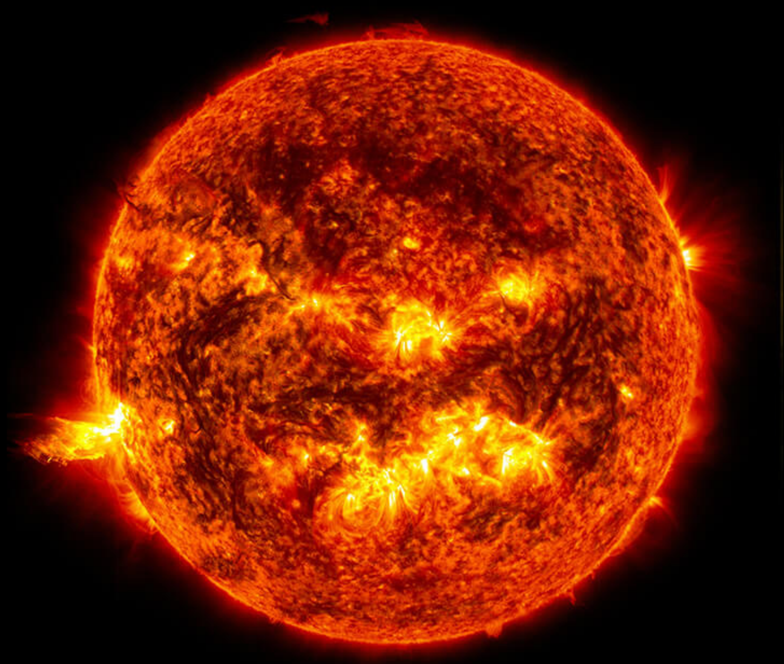
Image: M44, Credit: NAOJ

How can we measure Distances to Stars?

Image: Pleiades,
～444 light years.
Credit: NAOJ

First Step: Measure the Distance to the Sun.



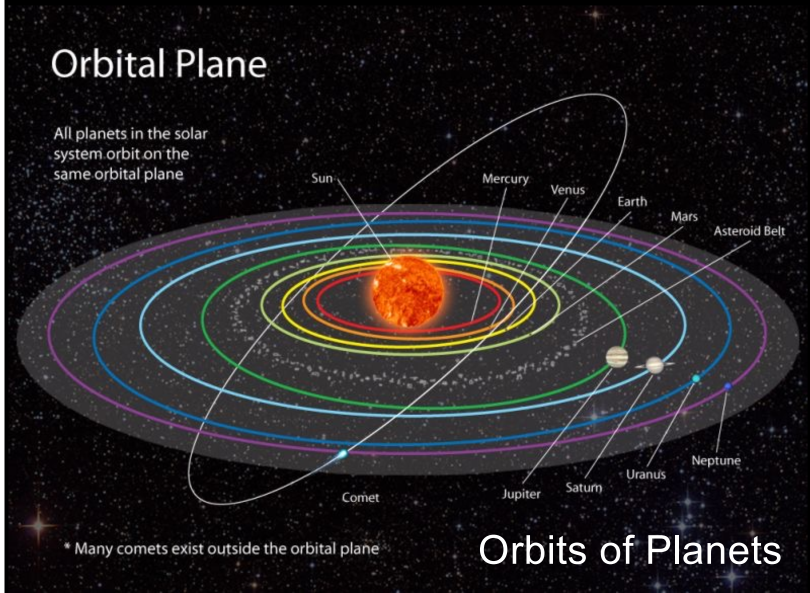


The Sun. Image Credit: NASA

$D_{SE} \sim 1.5\times10^{8}$ km.

How could we measure it?

Newton's Law and Radar tell us the Distance



A transit of Venus across the Sun

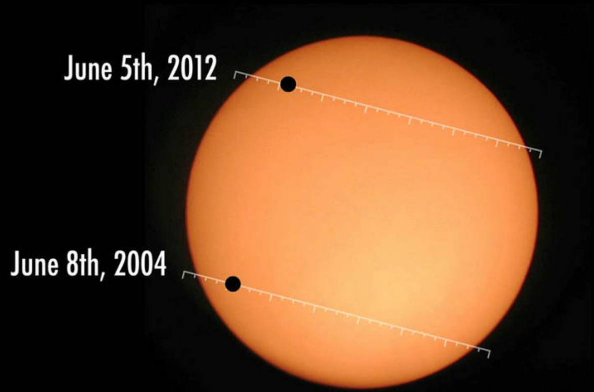
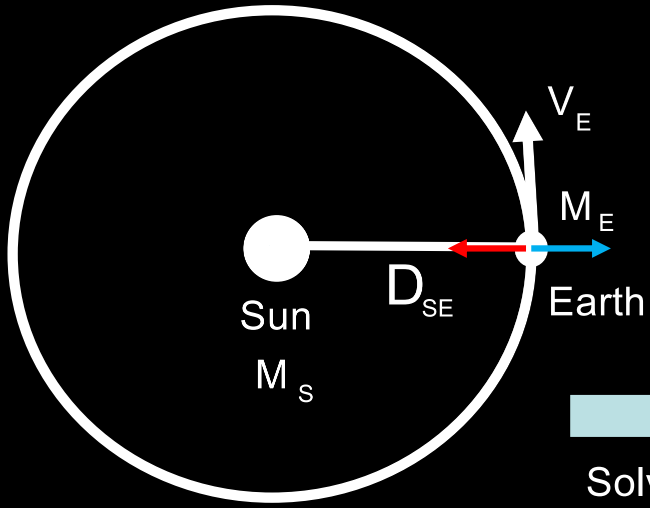
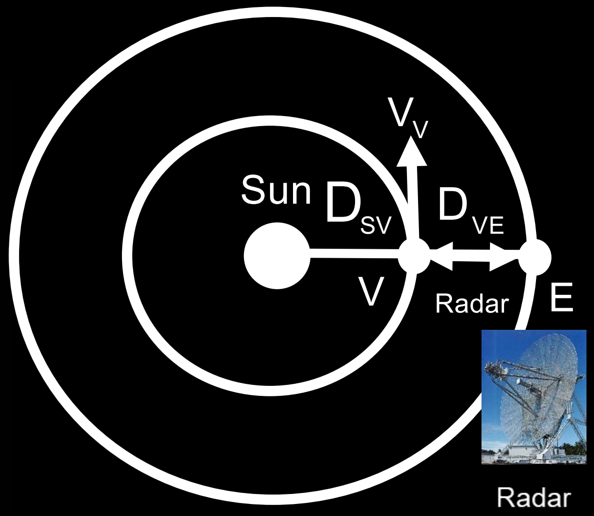


Image Credit: NASA





Gravity Force — Centrifugal Force

$$\frac{G\,M_S M_E}{D_{SE}^2} = \frac{M_E V_E^2}{D_{SE}}$$

$$2\pi D_{SE} = V_E\,T_E$$

$(T_E \sim 365$ days)

Solve

$$M_S = \frac{(2\pi)^2}{G}\frac{D_{SE}^3}{T_E^2}$$

$$= \frac{(2\pi)^2}{G}\frac{D_{SV}^3}{T_V^2}$$

$(T_V \sim 225$ days)

$$D_{VE} = \Delta t \times C/2 \sim 4 \times 10^{12}\,\mathrm{cm}$$

Δt : Round-trip Time of Radio Waves between Earth & Venus.

C : Speed of Light.

$$D_{SE} = D_{SV} + D_{VE}$$

Human Beings Could Estimate the Distances w/o Yardstick.

$$\mathrm{D_{SE}} = \mathrm{D}_{SV} + \mathrm{D}_{V\mathrm{E}}$$

Sun-Earth Sun-Venus Venus-Earth

$\mathrm{D}_{VE} \sim 4 \times 10^{12}$ cm : Radar

$$\frac{D_{SE}^3}{T_E^2} = \frac{D_{SV}^3}{T_V^2}$$ (Kepler's Third Law) $$\rightarrow \mathrm{D_{SE}} = \left(\frac{T_E}{T_V}\right)^{2/3} \mathrm{D}_{SV}$$

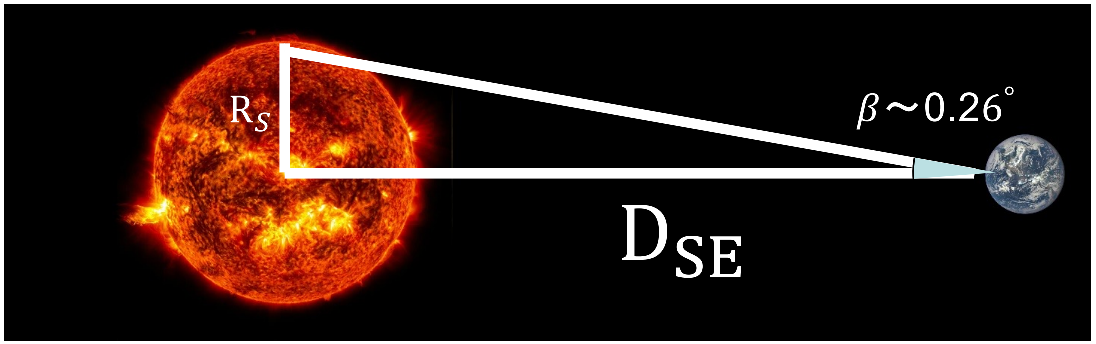
$$\sim 1.38\ \mathrm{D}_{SV}$$

$$\therefore\ \mathrm{D_{SE}} \sim 1.5\times10^{13}\ \mathrm{cm},\ \mathrm{D}_{SV} \sim 1.1\times10^{13}\ \mathrm{cm}$$

Now we can know more about the Sun.

$$M_S = \frac{(2\pi)^2}{G}\frac{D_{SE}^3}{T_E^2} \sim 2 \times 10^{33}\ \text{g.}$$

We could estimate mass of the Sun w/o weight scale!



$$R_S = D_{SE} \tan\beta \sim 6.9 \times 10^{10}\ \text{cm.}$$

We can estimate Luminosity of the Sun, L_S , as $L_S = 4\pi {D_{SE}}^2 \times F \sim 3.8 \times 10^{33}$ erg s^{-1}.

F is radiation flux from the Sun [erg/cm^2] at the Earth.

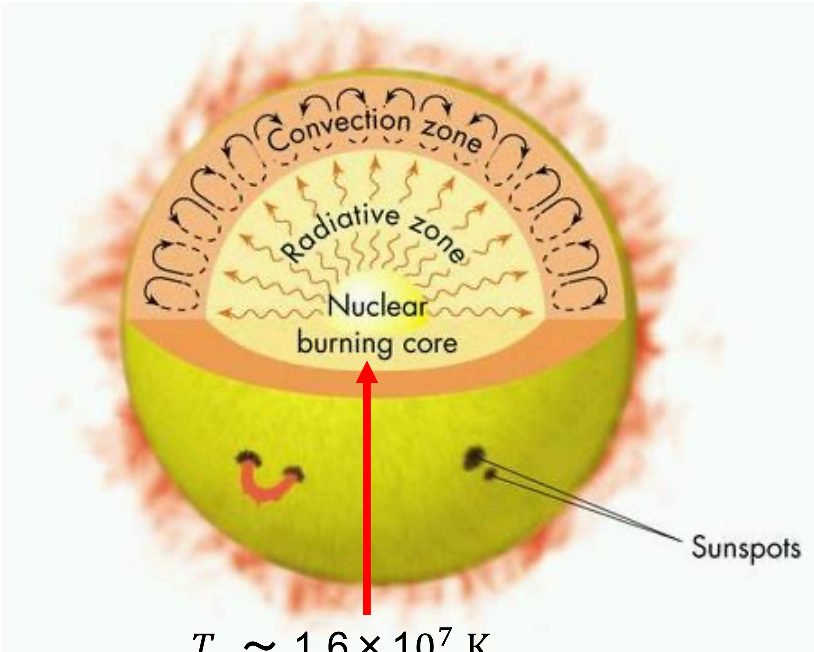
We also know surface temperature of the Sun = 5,800 K, and surface composition ($X_H \sim 73\%$, $X_{He} \sim 25\%$ in mass).

Close to Big Bang Nucleosynthesis.

Furthermore, we also know that the age of the Sun ~ 4.6 billion yrs old from analysis of meteorites.

Standard Solar Model (SSM)

We can construct hydro-static model to satisfy the properties of the Sun (Mass, Radius, Luminosity, Surface temperature & composition, age), using hydrostatic equations with micro-physics (nuclear reactions, Radiation transfer (scatterings, absorption, emission), equation of state). Physics!

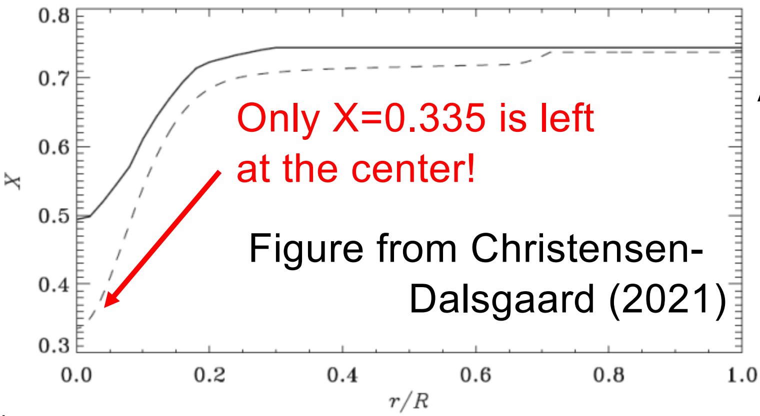


$T_c \sim 1.6 \times 10^7$ K
$\rho_c \sim 1.6 \times 10^2$ g cm^{-3}

From HP of Prof. Min S. Yun.
https://people.astro.umass.edu/~myun/teaching/a100_old/longlecture10.html

$4\text{H} \rightarrow {}^4_2\text{He} + 2e^+ + 2\overline{\nu}_e + 3.7 \times 10^{-5}$ erg.
$\sim$ 6 tons of hydrogen is burning to Helium per 1 second.

To support self-gravity of the Sun, Nuclear Reactions by Strong Force are happening penetrating Coulomb Potential Barrier between 2 protons, followed by Weak Interactions to change protons to neutrons.
All Four Forces in Nature are working efficiently to realize the Sun.



Mass Fraction of Hydrogen
As a Function of Normalized Radius.

Solid: Weymann (1957)
Dashed: Christensen-Dalsgaard+ (1996)

Remaining Life-time of the Sun is ～5 billion yrs.

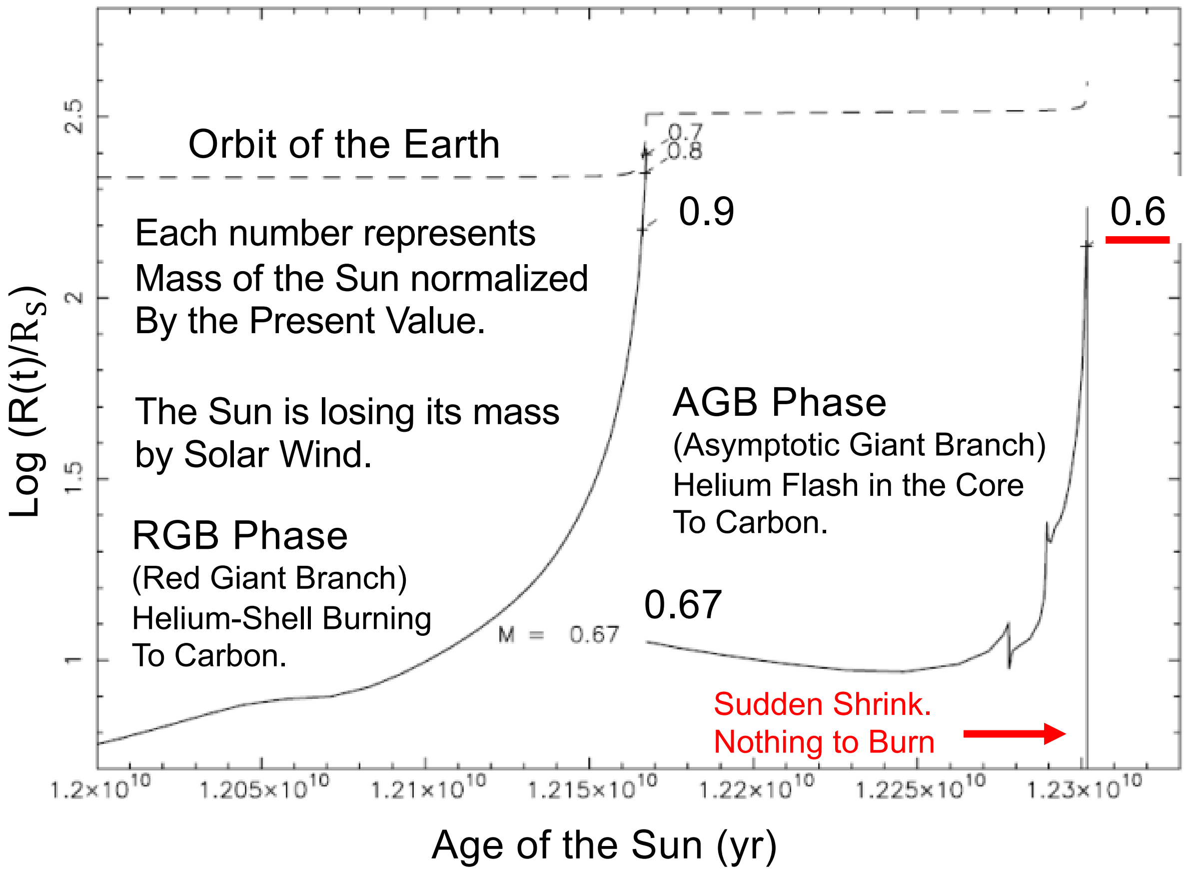


Figure from SchrÖder and Smith (2008)

Self-gravity is not supported by nuclear reactions Anymore.

Does it collapse and form a black hole?
No, degenerate pressure of electrons support the Self-gravity and form a white dwarf (WD).

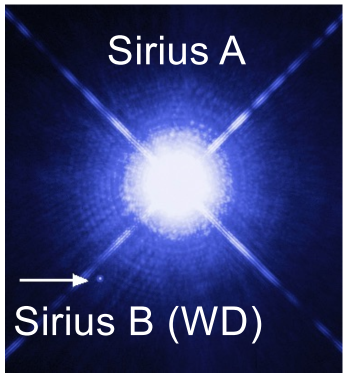
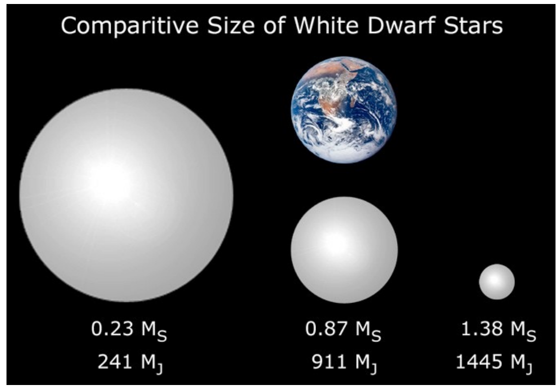


Image Credit: NASA



From HP of Prof. David Taylor

It is considered that stars with (0.07–10) M_S end their lives as White Dwarfs.

Supernova Explosions in the Milky Way

The Painting was done by Camille Flammarion (1880)

Tycho Brahe Observed a Supernova in 1572 near Cassiopeia.
Peak apparent magnitude was ～-4 deg, comparable to Venus.
It became invisible to the naked eye in 1574.

Supernova event rate in the Milky Way is ～ 1 event per Century.
Rare events.

Type Ia Supernova in an Extra-Galaxy

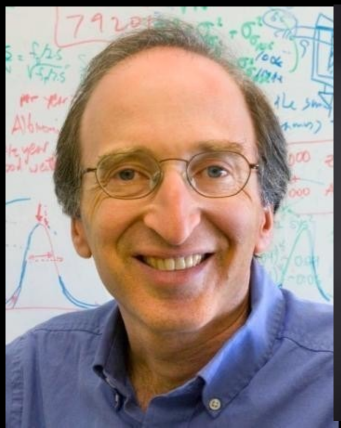
Properties of Type Ia Supernovae:

- **(Almost) Common Light Curve.**
- **Bright Peak Luminosity.**
- Lack of Hydrogen (no hydrogen lines).
- Strong Si[II] Absorption line.
- Strong Blends of Fe emission lines.

SN1994D in NGC4251.
～55 Million Light Year from the Earth.

NASA/ESA/Hubble Key Project Team/
High-Z Supernova Search Team

Type Ia Supernovae as the Brightest Standard Candles in the Universe


S. Perlmutter


B. Schmidt


A. Riess

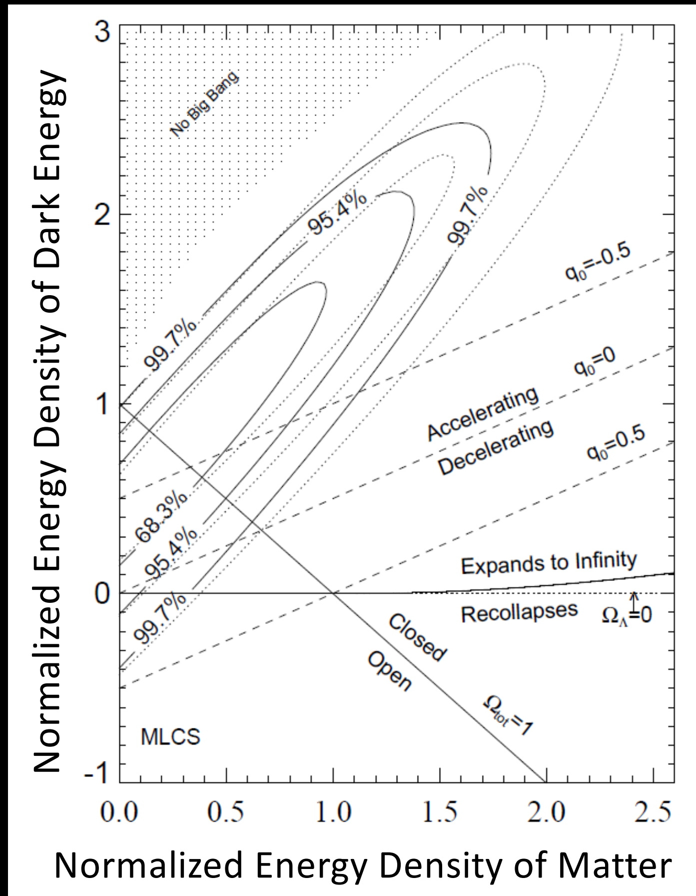
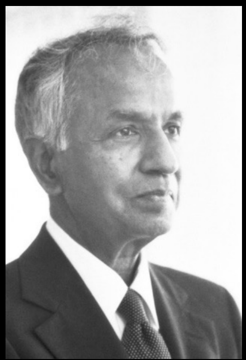


Figure from Riess et al. 1998.

Noble Prize in Physics 2011 for the Discovery of the Accelerating Expansion of the Universe through Observations of Distant Supernovae

Type Ia Supernovae are Explosions of White Dwarfs

- Most of Astrophysicists believe that Type Ia Supernovae are Explosions of White Dwarfs (WDs).
- The (almost) common light curves are understood by the scale of Chandrasekhar Mass Limit (1938) and explosive nucleosynthesis of the WD itself (e.g. Hoyle and Fowler 1960).
- Theoretical Simulations of Type Ia SN reproduce Observed Light Curves and Spectrum very well.



S. Chandrasekhar

W. Fowler

The Chandrasekhar Mass Limit

$$M_{CR} = 1.45 \left(\frac{2}{\mu_e}\right)^2 M_S$$

$$\mu_e \equiv \frac{Number\ of\ nucleons\ per\ unit\ volume}{Number\ of\ electrons\ per\ unit\ volume}$$

WD mass cannot exceed the mass limit.

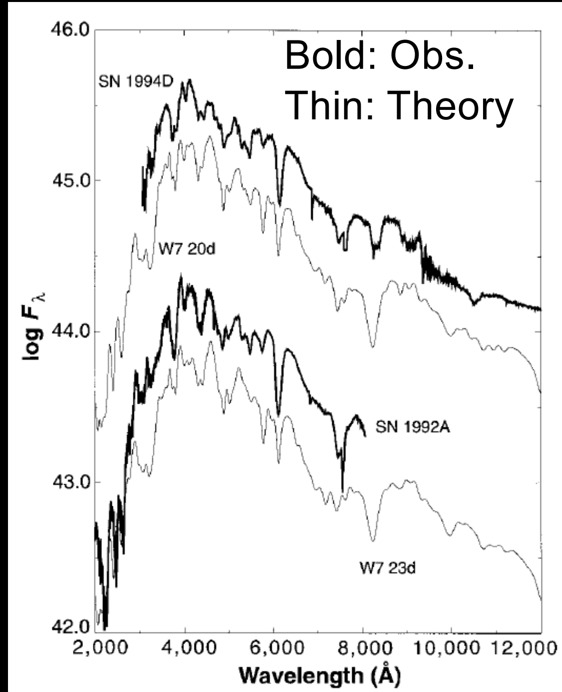


Figure from Nomoto et al. 1997

Nobel Prize in Physics 1983

Subramanyan Chandrasekhar "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars"

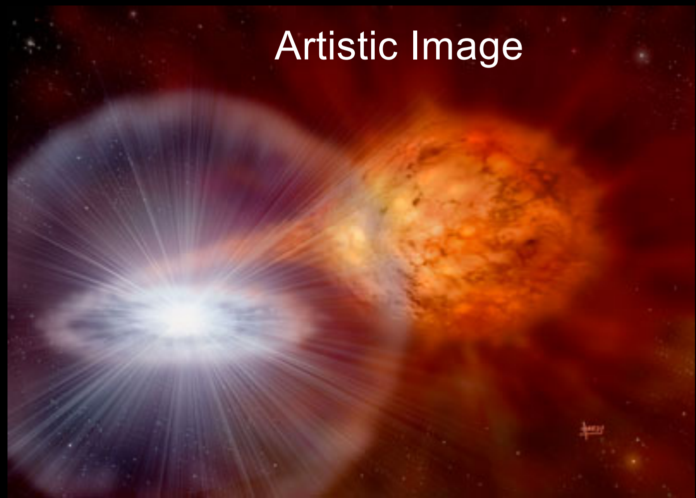
William Alfred Fowler "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"

Long Lasting Mystery: How do WDs exceed the Chandrasekhar Mass Limit?

- Most of Astrophysicists believe that Type Ia Supernovae are Explosions of White Dwarfs (WDs).
- However, no one has identified the progenitor WD(s) that exploded as a Type Ia supernova.

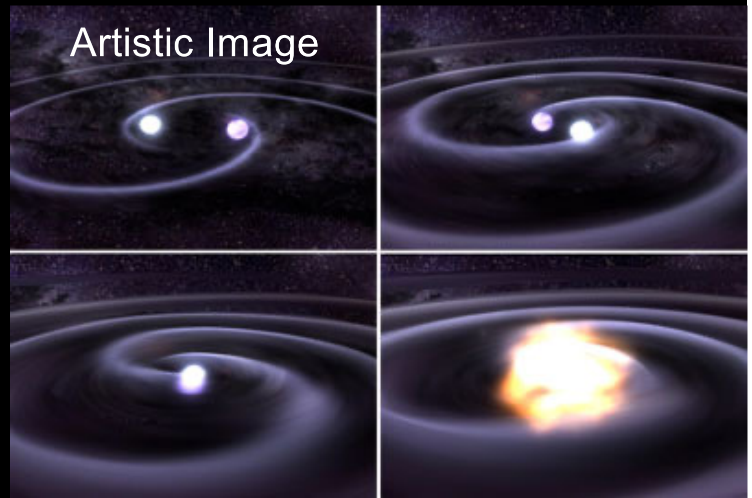
Type Ia supernovae are observed as point sources in extra-galaxies. Progenitor stars are not identified.

NASA/ESA/Hubble Key Project Team/High-Z Supernova Search Team



Mass Transfer from a Companion Star? Single Degenerate Scenario (SD).

Image Credit: STFC/David Hardy



Merger of double white dwarfs? Double Degenerate Scenario (DD).

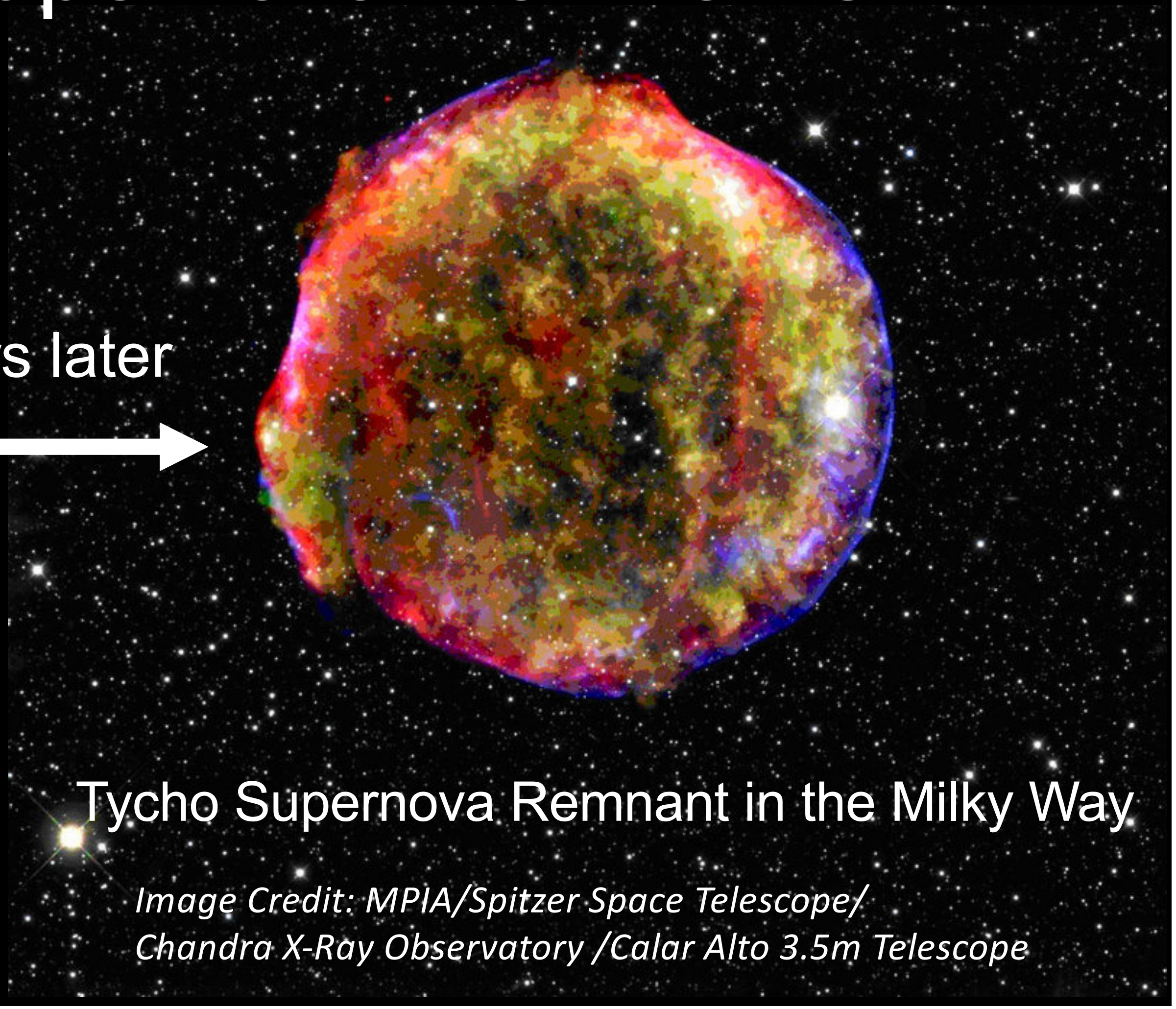
Image Credit: *NASA/Tod Strohmayer (GSFC)/ Dana Berry (Chandra X-Ray Observatory)*

Our Strategy: Finding Legacies of Supernova Explosions in Supernova Remnants

The Painting was done by Camille Flammarion (1880)

Tycho Supernova in 1572

～450yrs later →



Tycho Supernova Remnant in the Milky Way

Image Credit: MPIA/Spitzer Space Telescope/ Chandra X-Ray Observatory /Calar Alto 3.5m Telescope

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

?

?

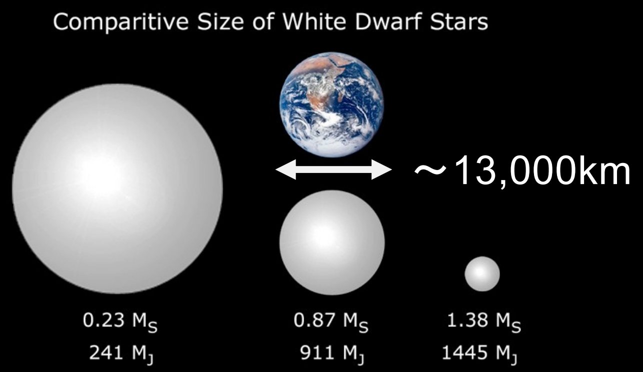
From Amazon Free-download.

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.

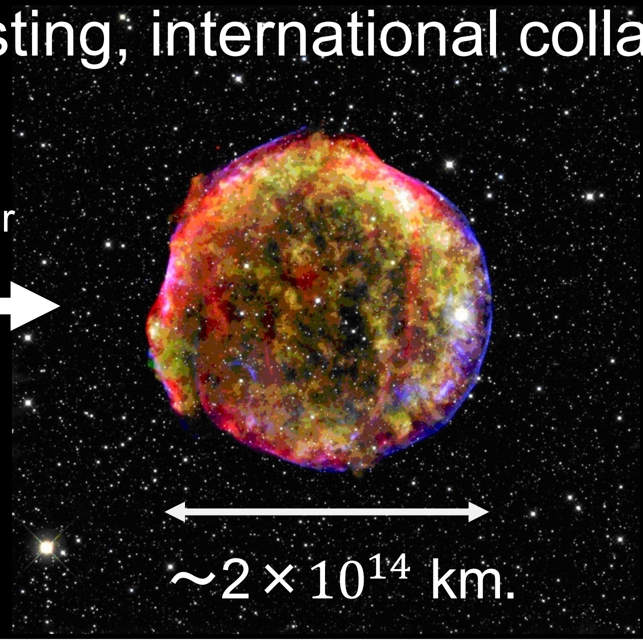
Our Strong Points

- Only our group succeeded to perform 3-dimensional simulations of supernova remnants from supernova phase.
- Only our group succeeded to solve rate equations of atomic processes for non-thermal ionizations for 3-dimensional simulations of supernova remnants from supernova phase.
- Our group is sustained by long-lasting, international collaborations.



From HP of Prof. David Taylor

～450yrs later

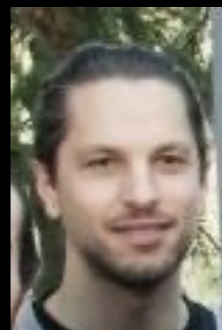


We adopt a co-moving grid system for Hydro simulations.

A Type Ia Supernova Simulation (SD Model)

Friedrich Röpke

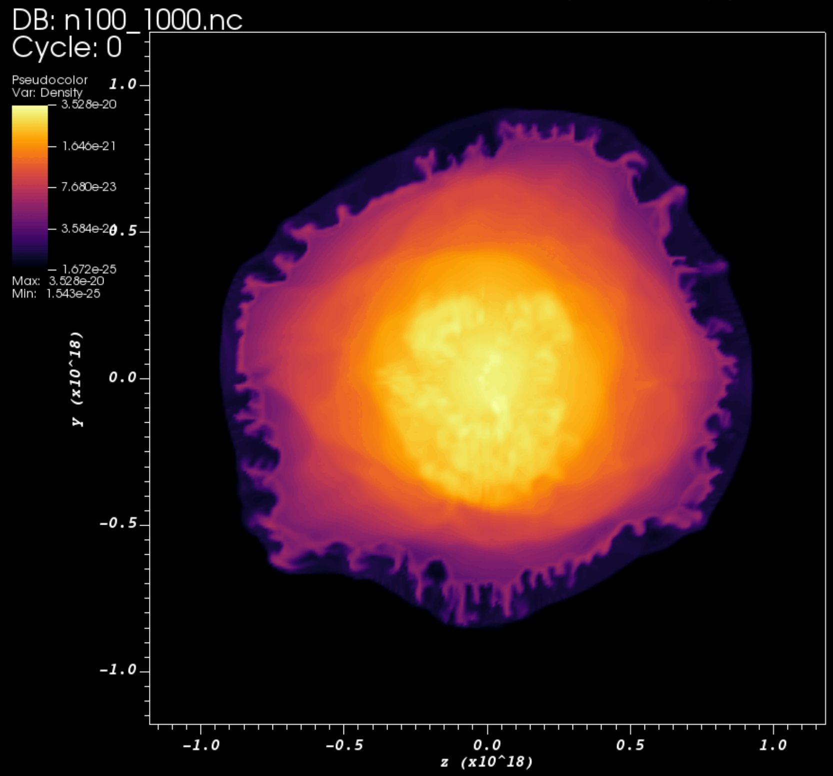
Ivo Seitenzhal



Florian Lach

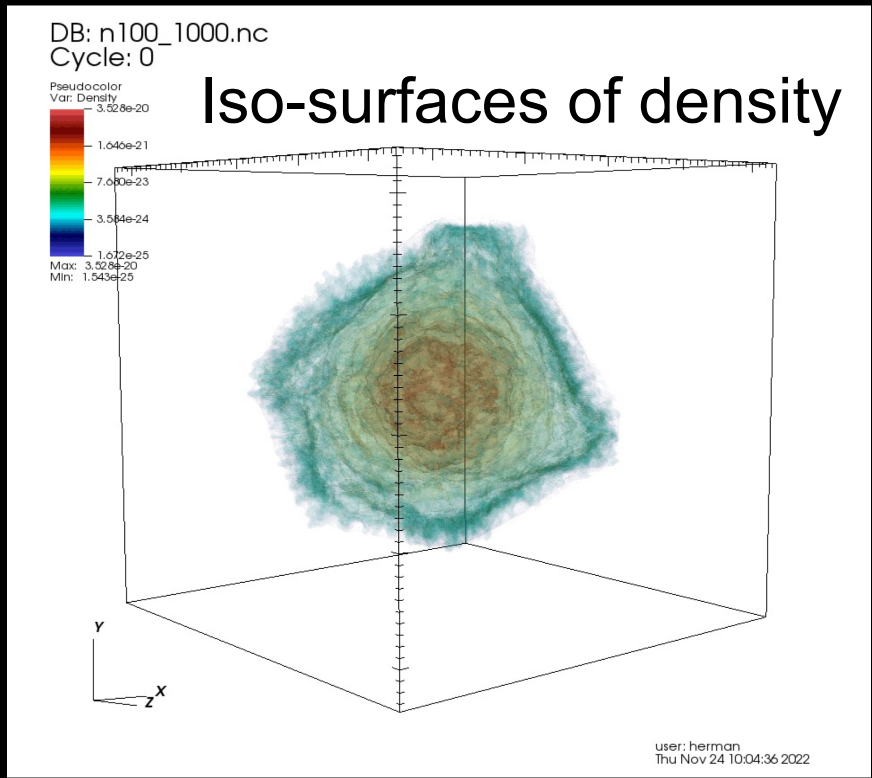
From a Supernova to a Supernova Remnant

x=0 slice (Density)



Evolution: 10 to 450 yrs

user: herman
Thu Nov 24 09:46:43 2022



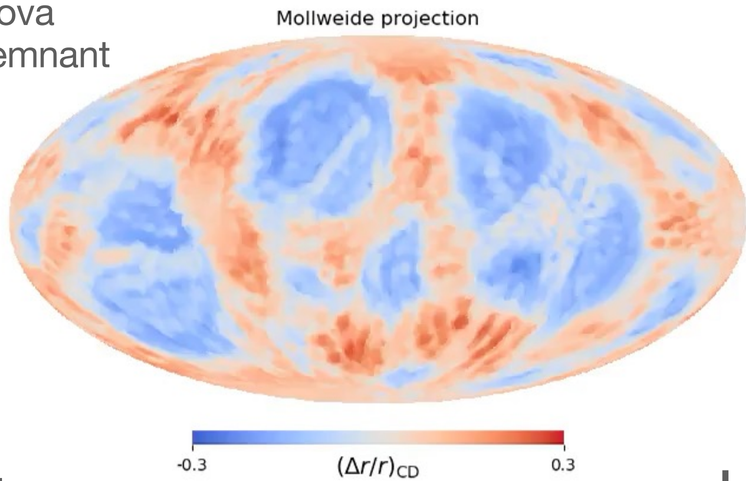
Gilles Ferrand

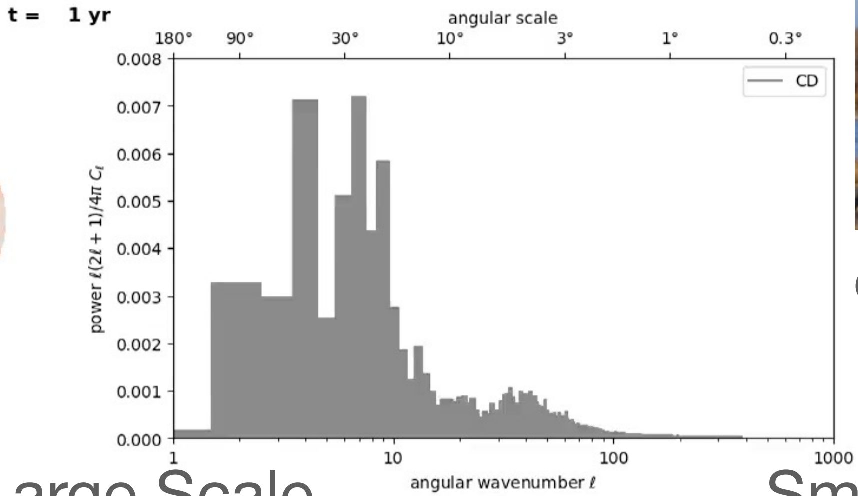
Shiu-Hang Lee
(Herman)

Spherical harmonics expansion of the wavefronts

contact discontinuity (CD) from 1 yr to 500 yr

From Supernova
To Supernova Remnant



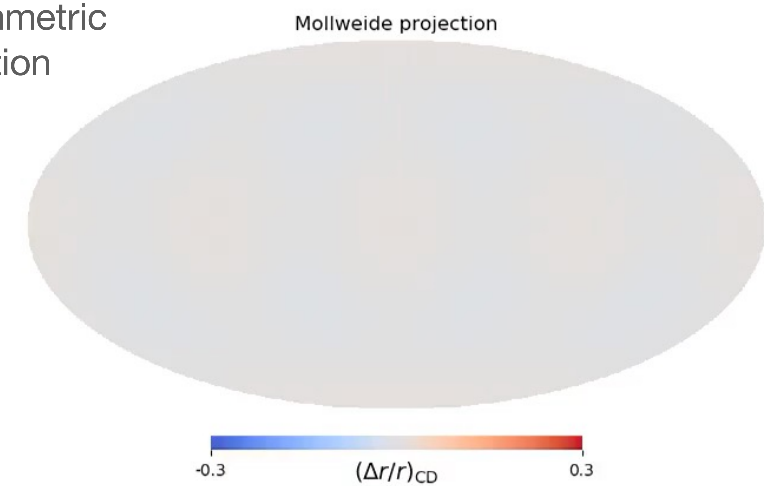


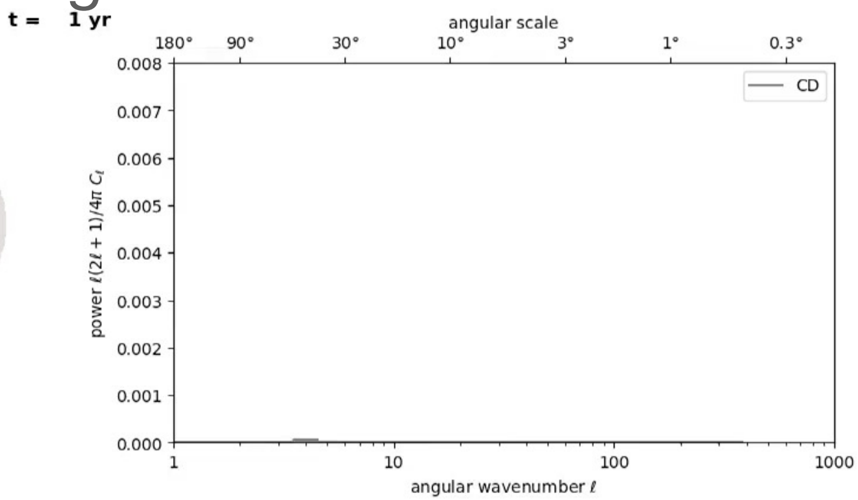
Gilles Ferrand

Large Scale

Small Scale

From a Simple
Spherically Symmetric
Initial Condition

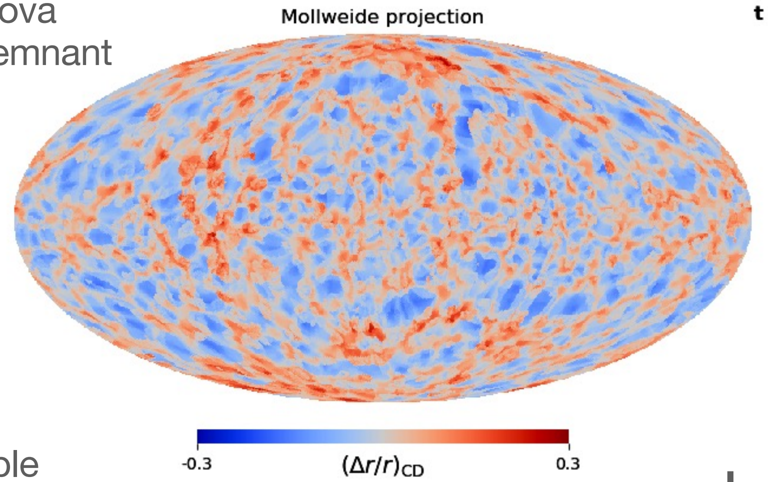


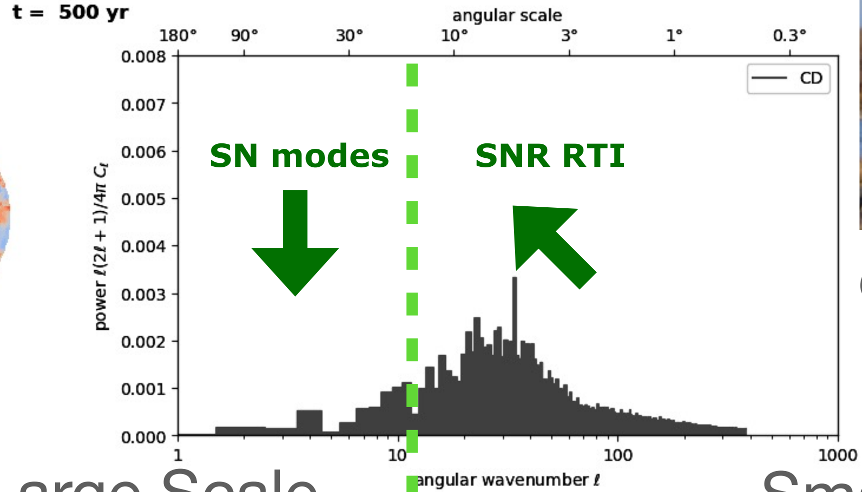


Rayleigh-Taylor from the SN and SNR phases

contact discontinuity (CD) at 500 yr

From Supernova
To Supernova Remnant



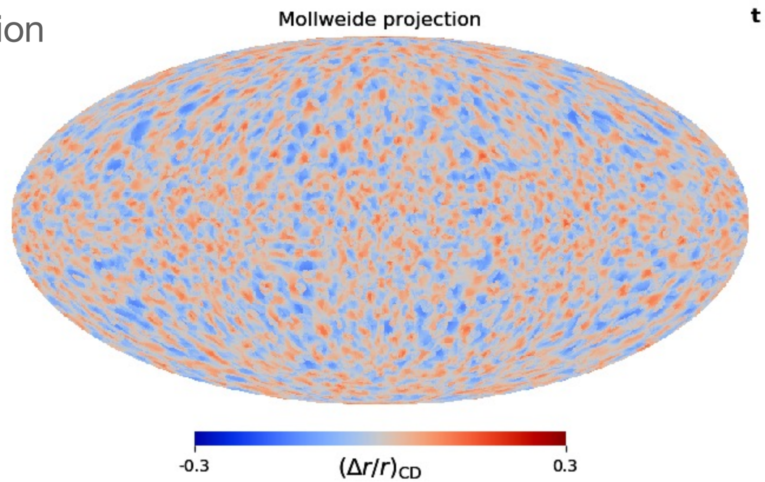


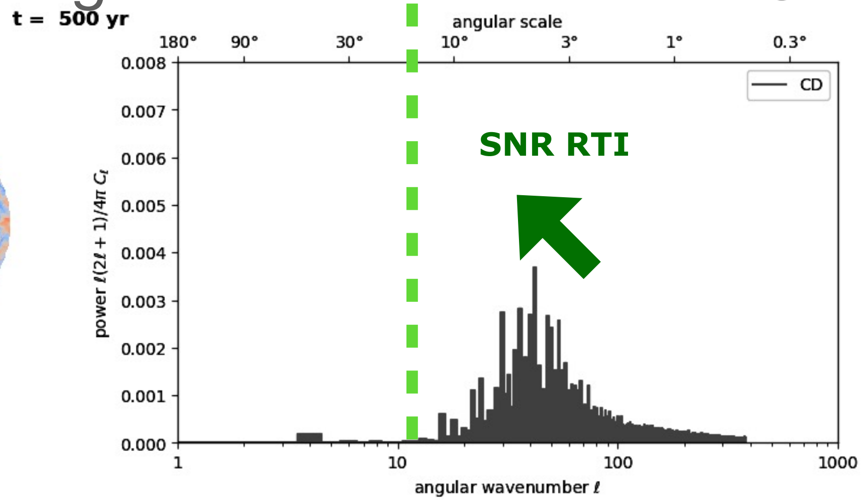
Gilles Ferrand

Large Scale

Small Scale

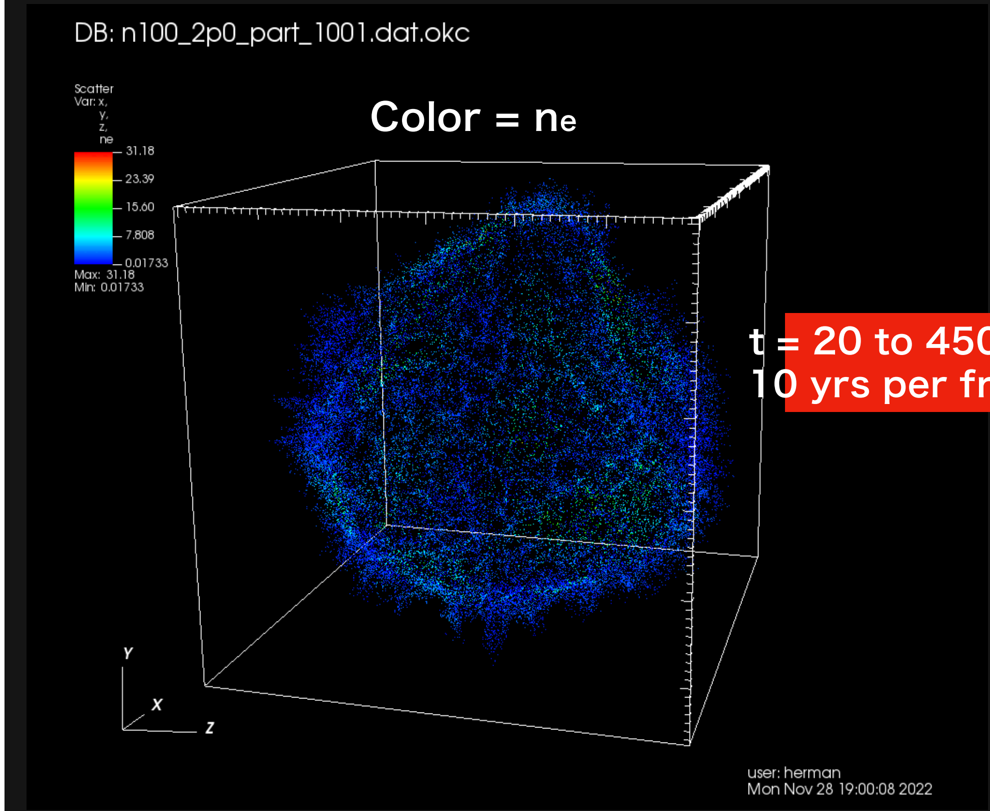
From a Simple
Spherically Symmetric
Initial Condition



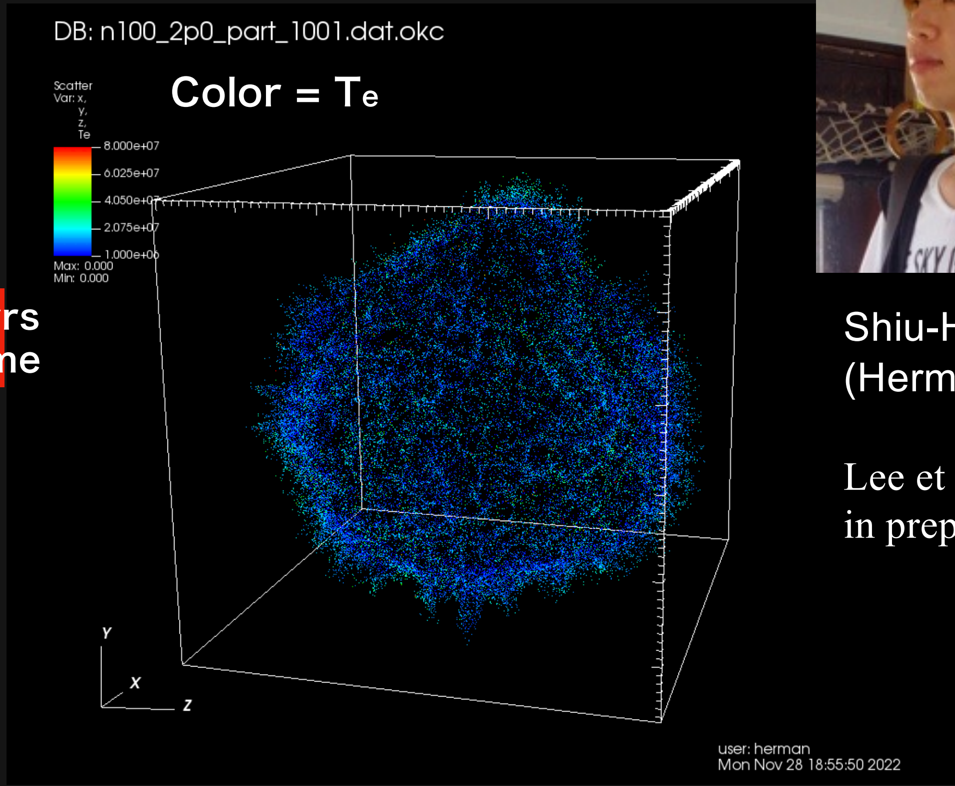


Solving Rate Equations for Non-Equilibrium Ionization States

<u>Shocked</u> particles in ejecta
($N_{particle}$ = 100,000 in shown example)

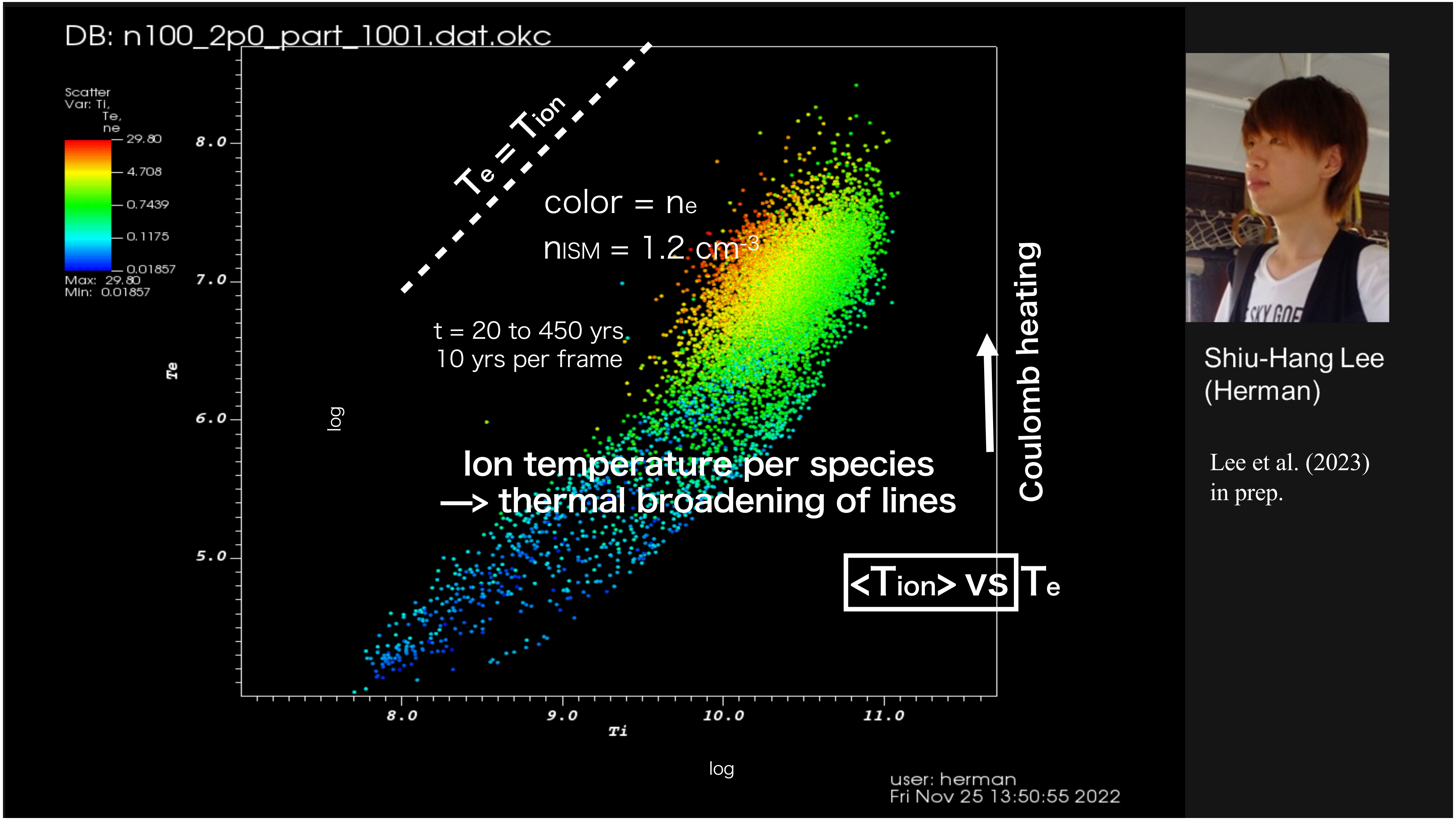


t = 20 to 450 yrs
10 yrs per frame



Shiu-Hang Lee
(Herman)

Lee et al. (2023)
in prep.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Scatter
Var: Ti,
Te,
ne
29.80
4.708
0.7439
0.1175
0.01857
Max: 29.80
Min: 0.01857
8.0
7.0
6.0
5.0
Te
log
Te = Tion
color = ne
nISM = 1.2 cm-3
t = 20 to 450 yrs
10 yrs per frame
Ion temperature per species
—> thermal broadening of lines
Coulomb heating
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8.0
9.0
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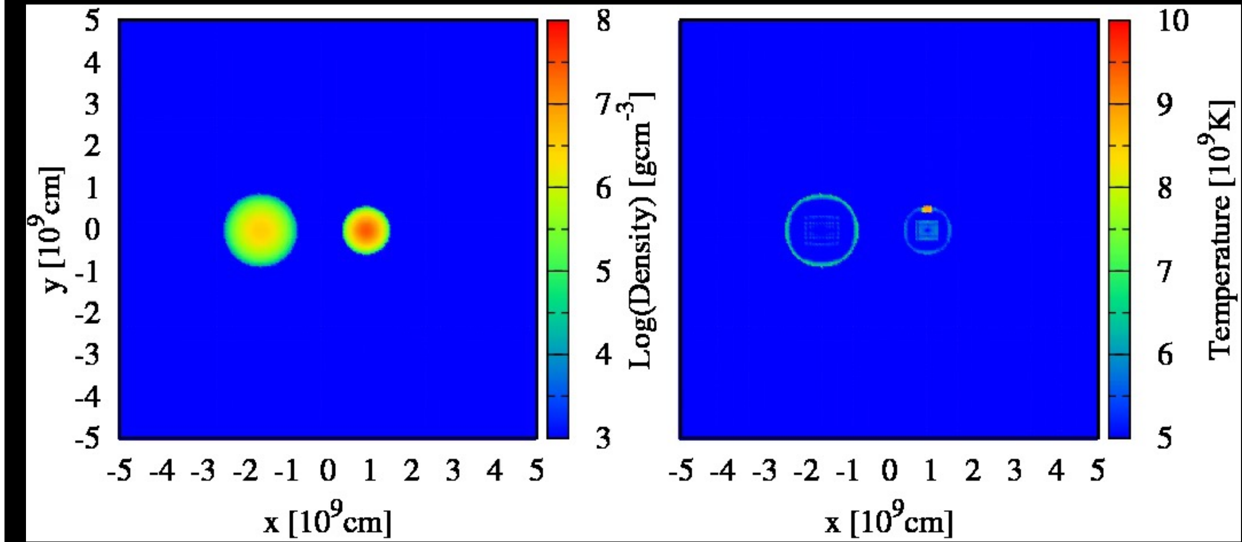
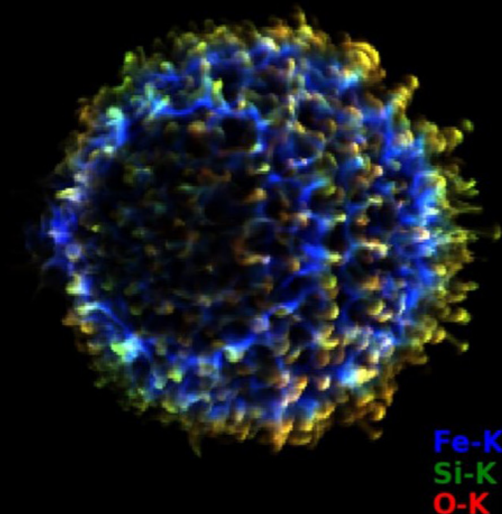
11.0
Ti
log
user: herman
Fri Nov 25 13:50:55 2022
Shiu-Hang Lee
(Herman)
Lee et al. (2023)
in prep.

From DD-Type Ia Supernova to Supernova Remnant



500 yrs →

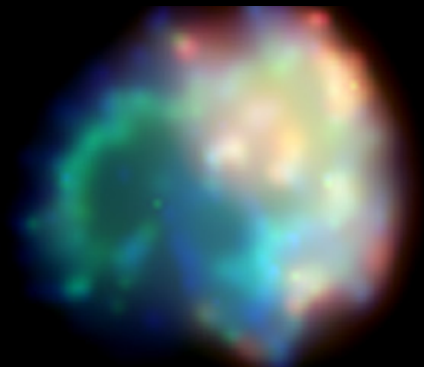
x



Ataru Tanikawa

Gilles Ferrand

c.f. Type Ia SNR 0509-68.7
in Large Magellanic Cloud.
X-ray Image.

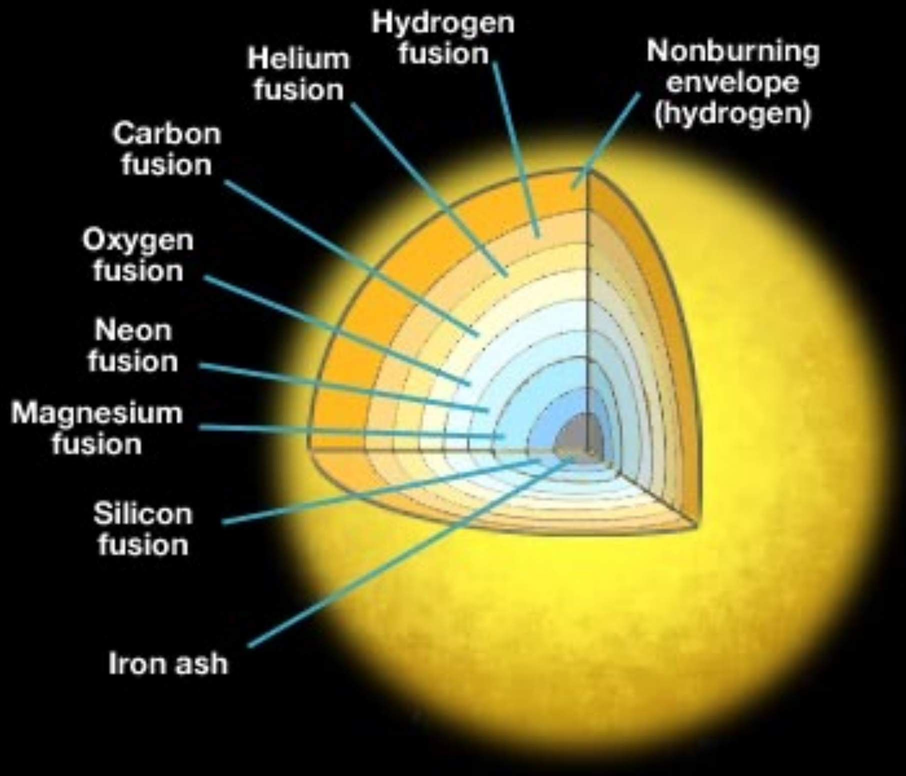


Asymmetries of Supernova Explosion
are imprinted in Supernova Remnants
in Large Angular Scale.

Credit: NASA/CXC/SAO

Massive Stars also Explode as Supernovae

Massive Stars ≡ Stars with mass of (10–25) M_s.



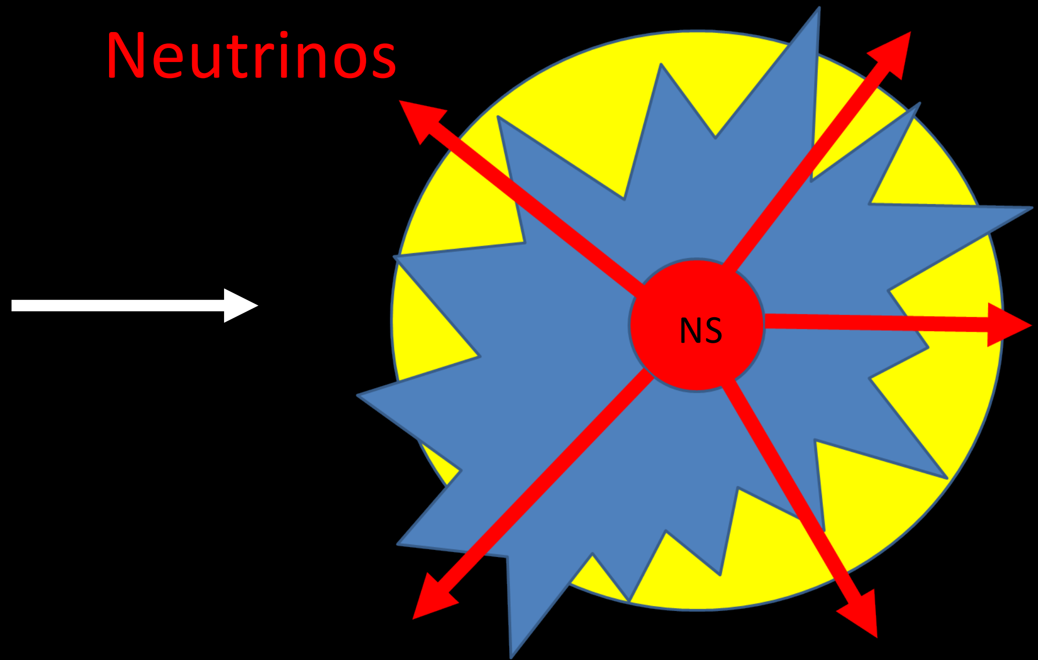


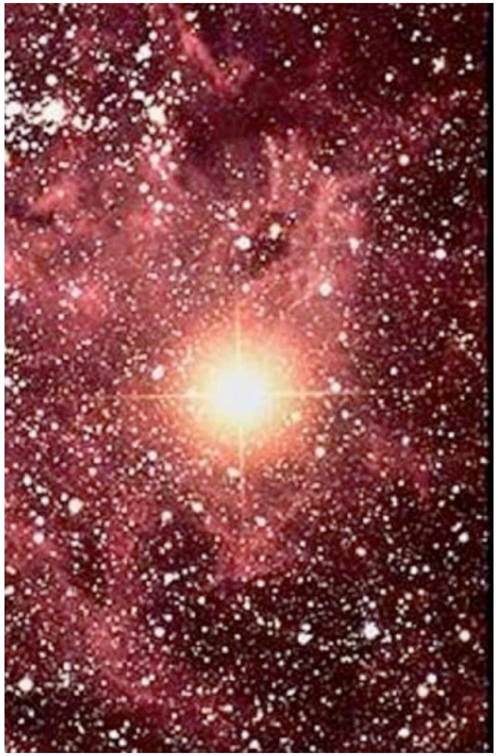
Image Credit: Penn State Astronomy & Astrophysics

Iron Core Collapses and Neutron Star (NS) is formed at the Center.
The stiff NS makes an out-going shock wave and neutrinos from the NS heat the shock wave, which results in a supernova (e.g. Bethe & Wilson 1985).

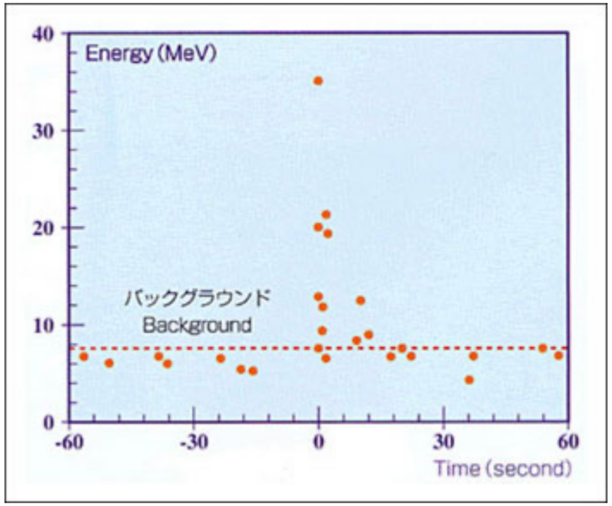
Theory of Astrophysics!

The Observational Proof : Detections of Supernova Neutrinos

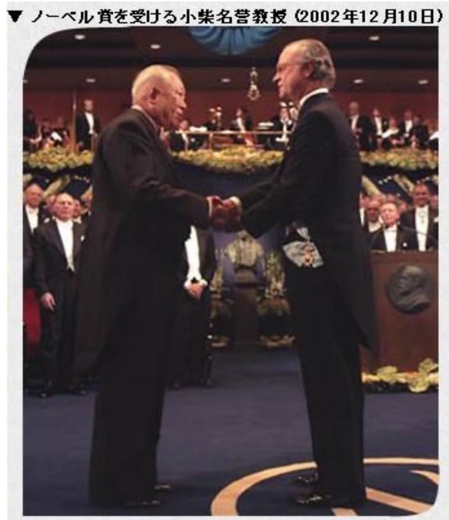
Sanduleak -69° 202, the Progenitor Star of SN1987A. Blue-Super Giant. ～20 M_S.



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

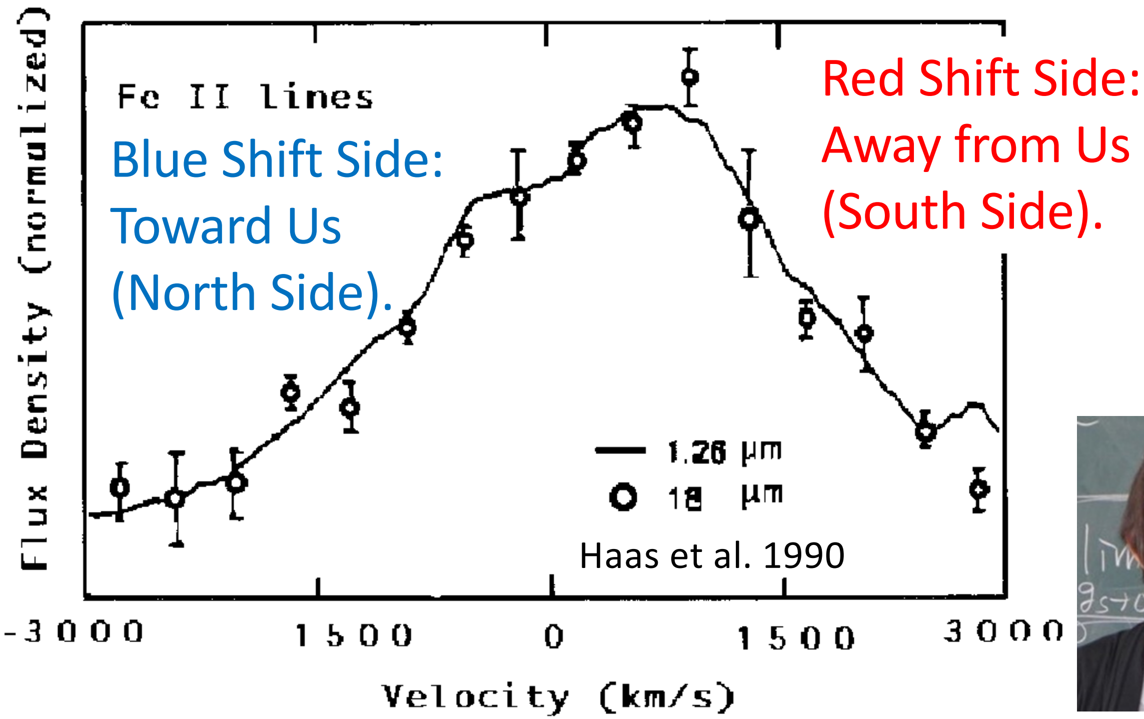


The 11 events of neutrinos from SN1987A, detected by Kamiokande.



Masatoshi Koshiba Nobel Prize in Physics 2002 for the detection of cosmic neutrinos.

The Iron Emission Lines from SN1987A Changed My Life.



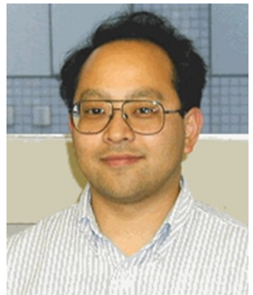
From this line profile, we concluded in 1997-2000 that

- SN1987A was a Bi-Polar like explosion.
- Explosion was stronger in Red Shift Side and weaker in Blue Shift Side.
- The Neutron Star of SN1987A should be moving toward Blue Shift Side.

S. Nagataki

K. Sato

M. Hashimoto



S. Yamada

I got my Ph.D. degree in 1998, and I became an assistant professor in 2001.
Thesis Title: "Effects of Jet-Like Explosions in Collapse-Driven Supernovae"

Bi-Polar Explosion was Confirmed.

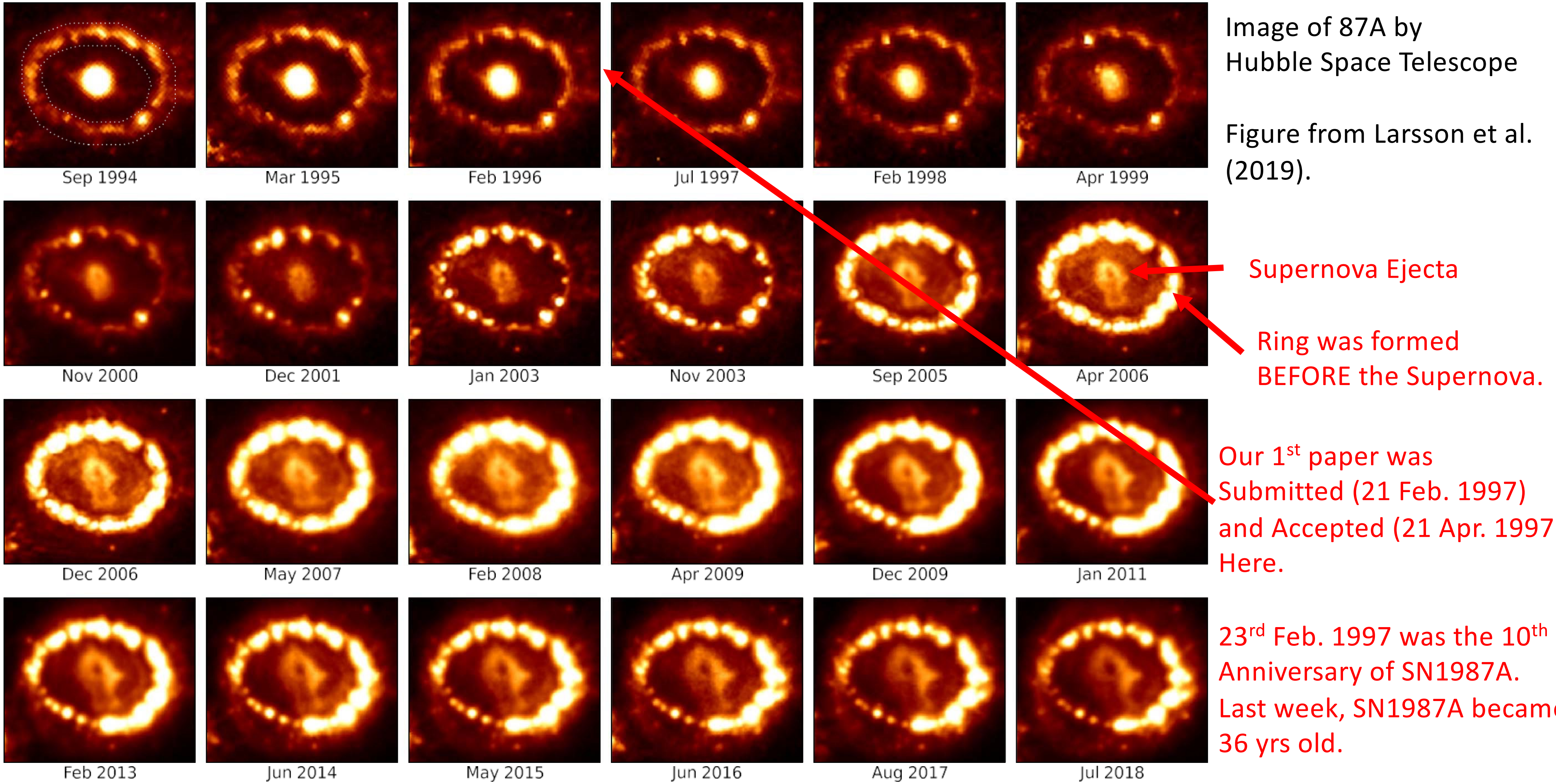


Image of 87A by Hubble Space Telescope

Figure from Larsson et al. (2019).

Our 1st paper was Submitted (21 Feb. 1997) and Accepted (21 Apr. 1997) Here.

23rd Feb. 1997 was the 10th Anniversary of SN1987A. Last week, SN1987A became 36 yrs old.

Evidence of Stronger Explosion in Red-Shift Side (South Side)

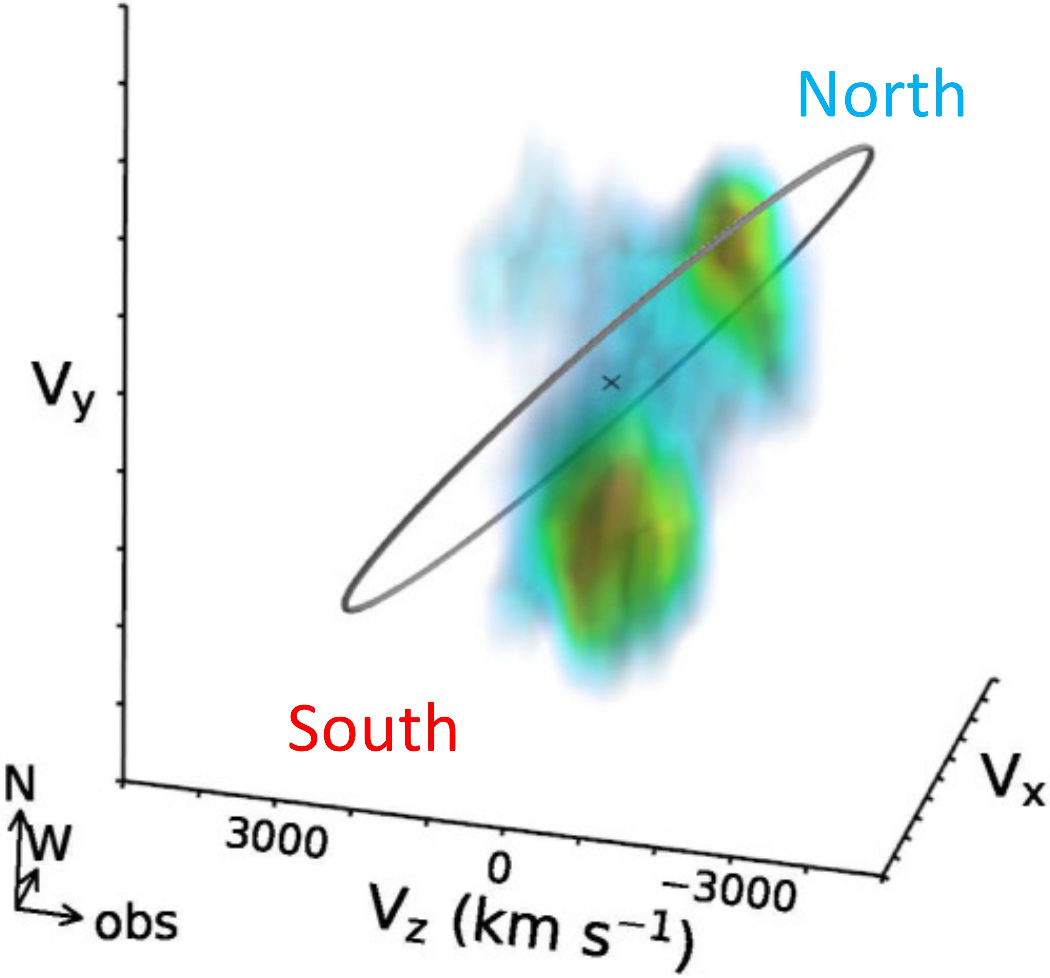
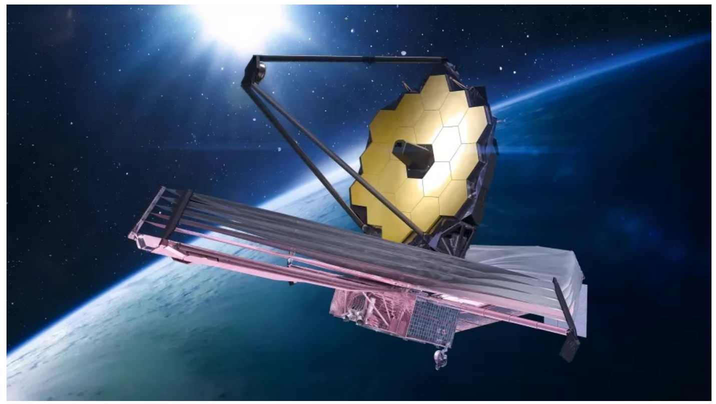
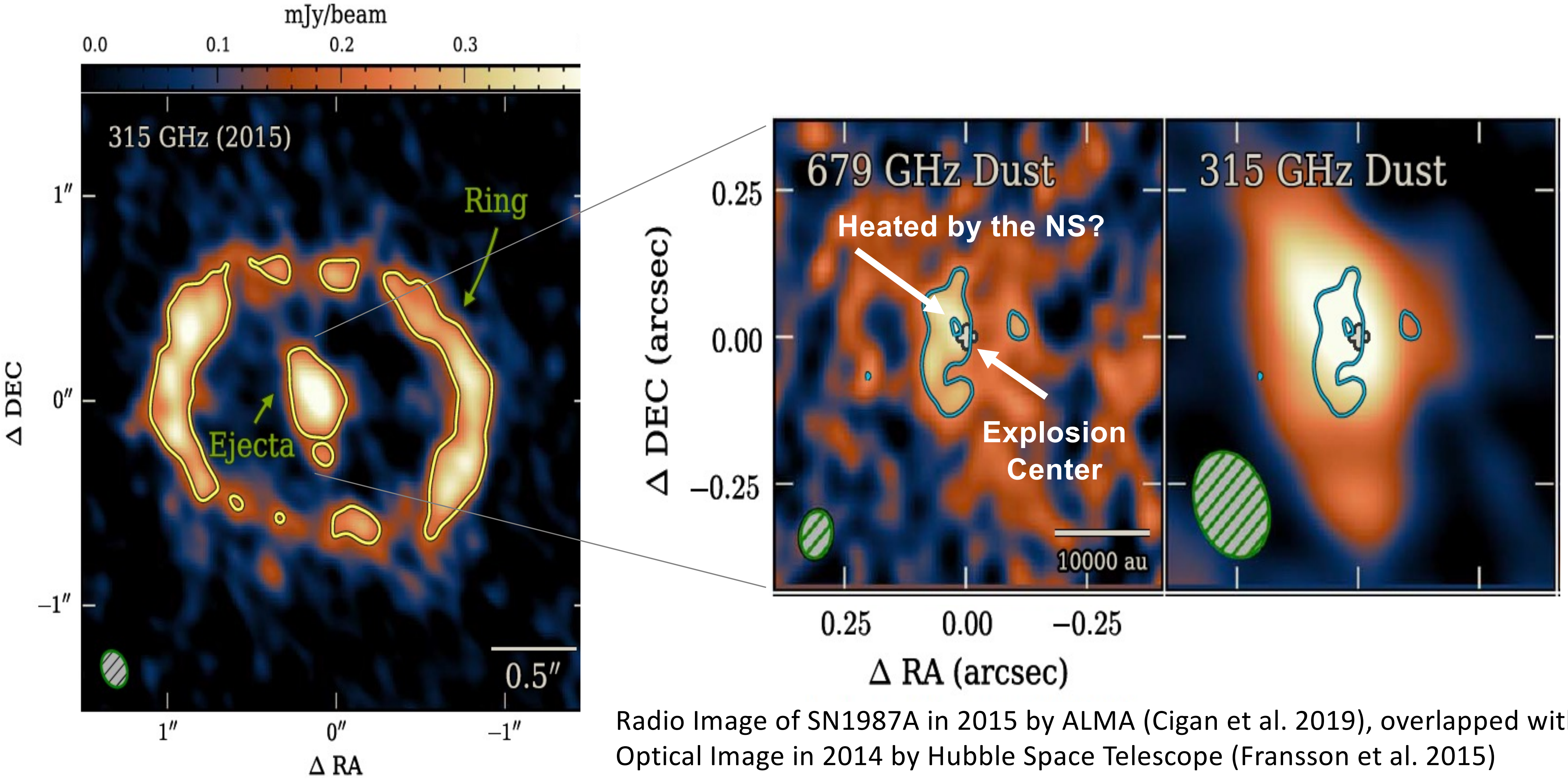


Image of [Fe I] 1.443μm line by JWST.
Larsson et al. (2023)



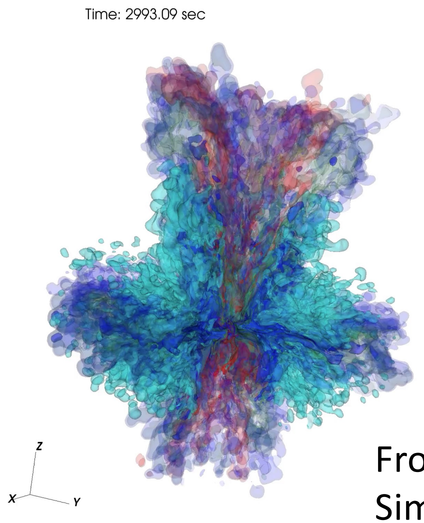
The James Webb Space Telescope
(JWST, 2021-)

Evidence of the NS running toward the North?

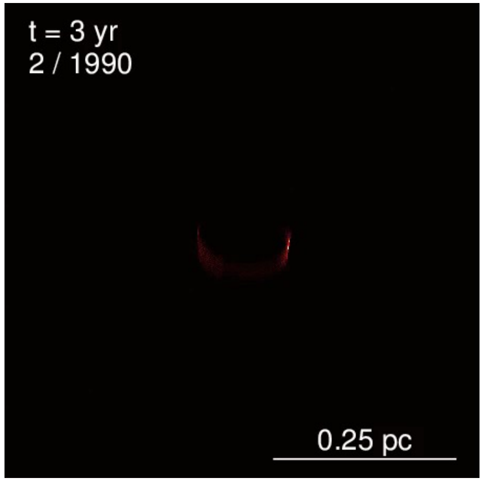


Radio Image of SN1987A in 2015 by ALMA (Cigan et al. 2019), overlapped with Optical Image in 2014 by Hubble Space Telescope (Fransson et al. 2015)

Our Recent SN1987A Simulation from Progenitor Star



From SN to SNR Simulation.



H. Umeda

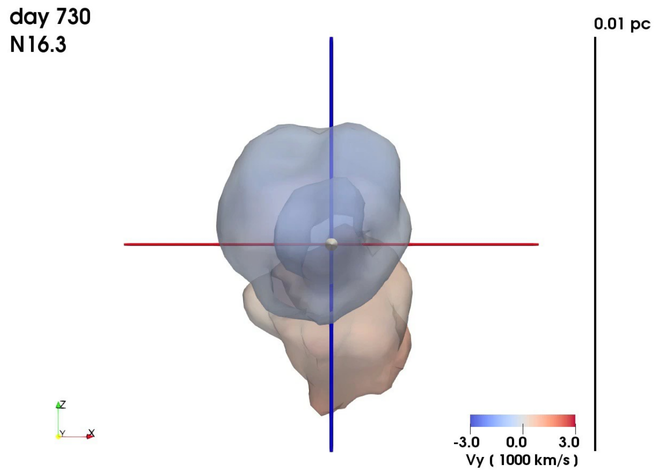
T. Yoshida

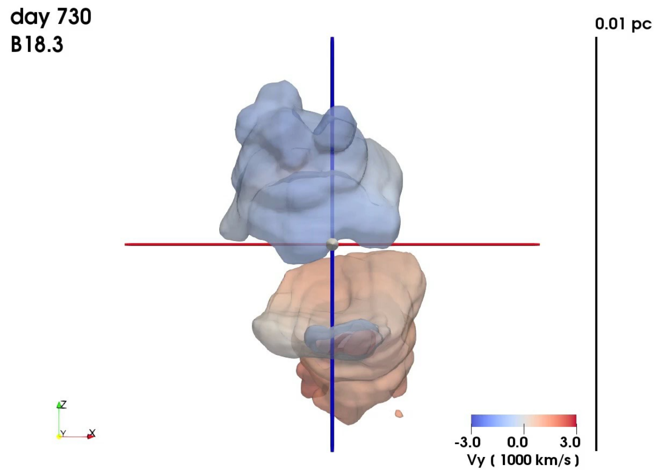
M. Ono

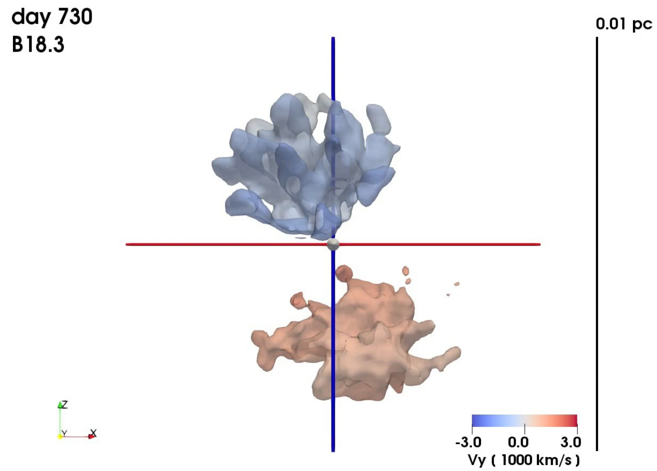
S. Orlando

We found that Bi-polar like explosions of a binary Progenitor star model explain many observations of 87A.

Distribution of Iron for different progenitor models.

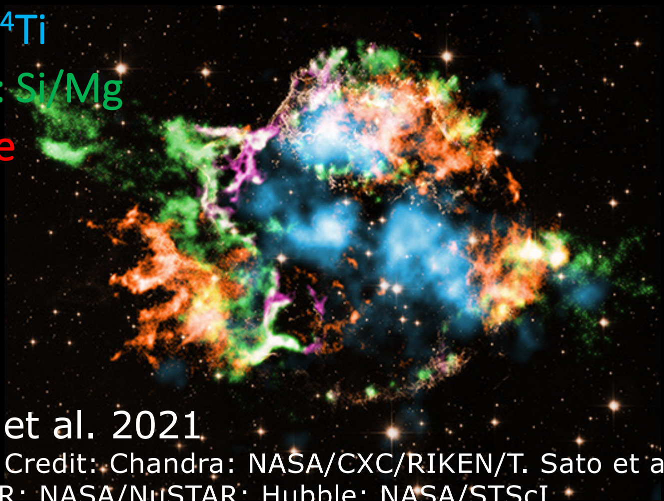




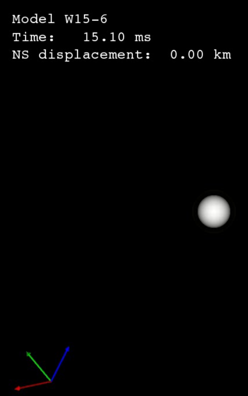


Our SN-SNR Project solved the Long-Lasting Mystery of Cas A.

Blue: ^{44}Ti
Green: Si/Mg
Red: Fe



Sato et al. 2021
Image Credit: Chandra: NASA/CXC/RIKEN/T. Sato et al.; NuSTAR: NASA/NuSTAR; Hubble: NASA/STScI



SN Phase

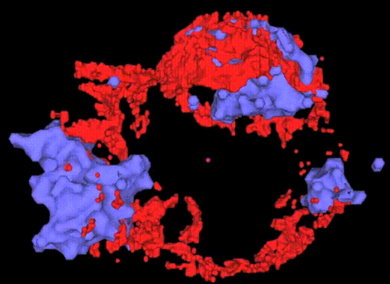
SNR Phase

A. Wongwathanarat

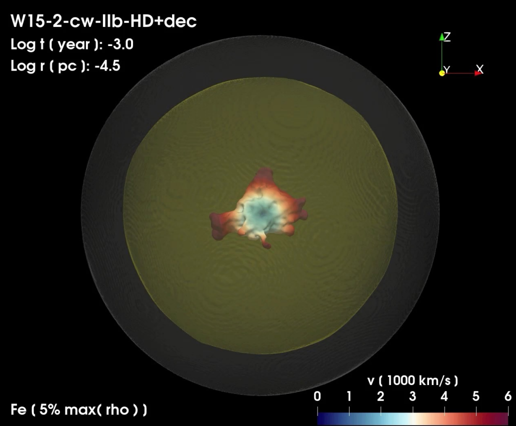
S. Orlando

T. Janka

Fe-rich
S/O-rich

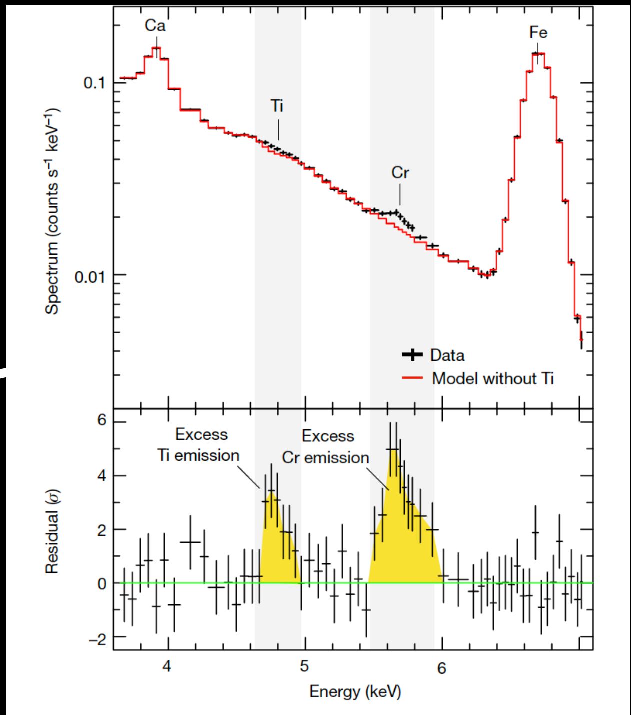


Milisavljevic & Fesen 2013



Cassiopeia A, the Youngest CC-SNR in the Milky Way (～350 yrs old).

We proved that the Iron Blob was ejected by Neutrino-Driven Winds from the NS



By the detailed analysis, we found
Not only Fe, but also Ti and Cr.

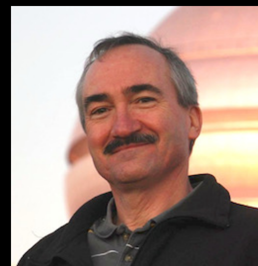
Our study was introduced at the
Cover page of Nature Vol. 592, Apr.2021

Toshiki Sato

Takashi Yoshida

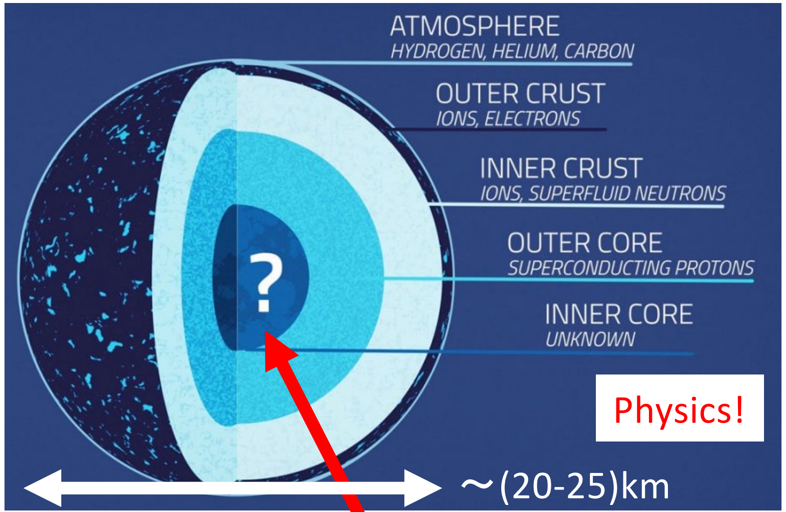
H. Umeda

K. Maeda



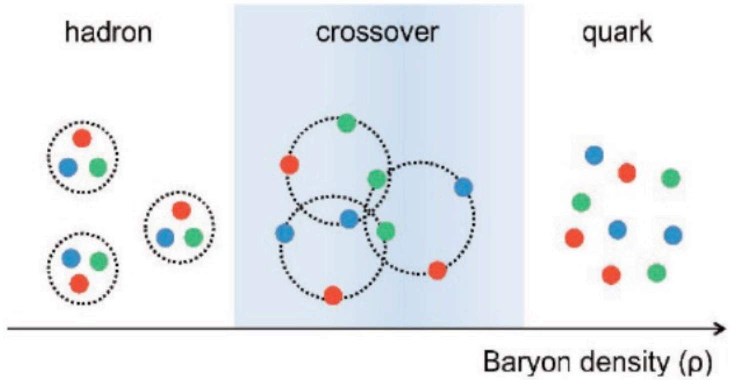
J. Hughes

Gravitational Waves may Shed Light on the Structure of Neutron Stars

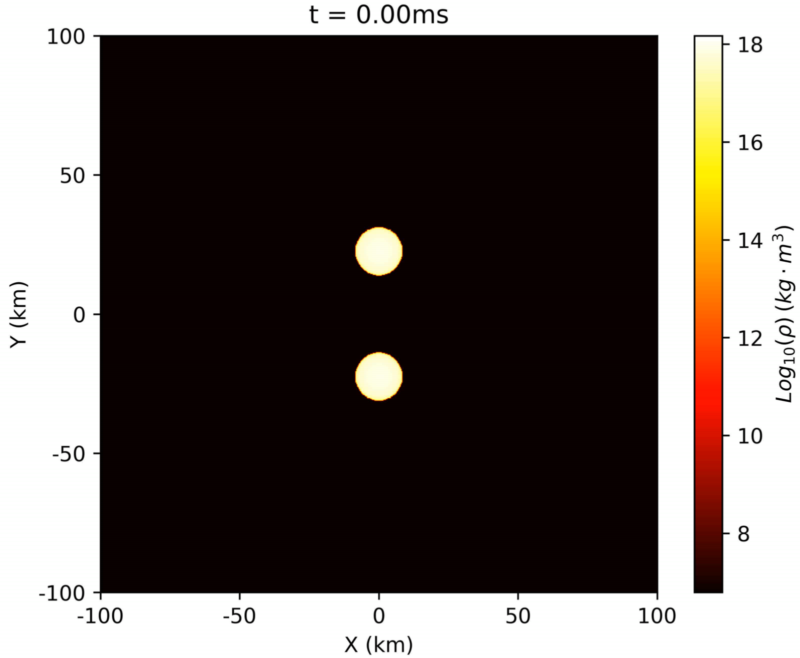


?

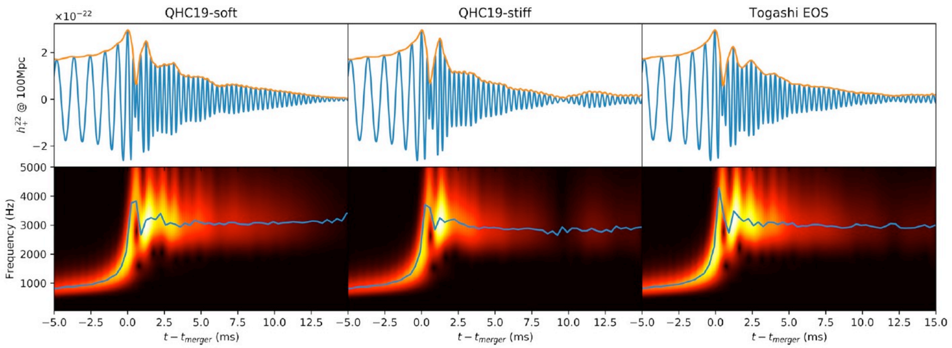
Image Credit:
NASA’s Goddard Space Flight Center
/ Conceptual Image Lab



Yamamoto, Tachibana, Baym, Hatsuda (2006)



General Relativistic Hydro Simulation and Resulting GWs



Y. Huang

L. Baiotti

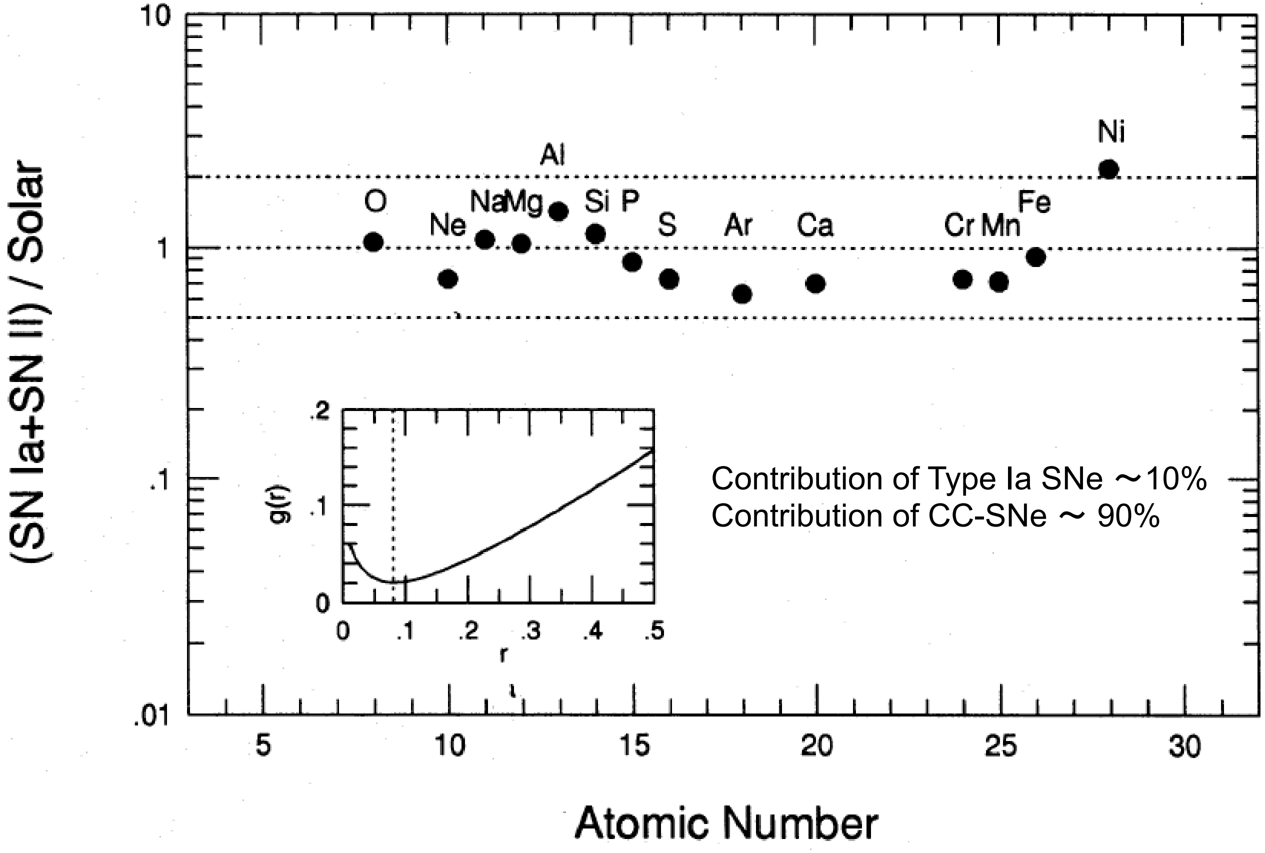
T. Kojo

T. Hatsuda

K. Takami

H. Togashi

The Origin of Life is Supernova Explosions



Contribution of Type Ia SNe ∼10%
Contribution of CC-SNe ∼ 90%

Composition of the Earth:
O ∼32.4%
Fe∼28.2%
Si ∼17.2%
Mg∼15.9%
Ni ∼ 1.6%
Ca∼ 1.6%
Al ∼ 1.5%
in mass (Wt%).
Allègre et al. 1995

Figure from Tsujimoto et al. 1995

List of Our Group's 14 Papers in This Talk

Type Ia Supernova Remnants:

- Ferrand, G., Tanikawa, A., Warren, D.C., Nagataki, S., Safi-Harb, S., Decourchelle, A. The Astrophysical Journal, 930, id.92 (2022).
- Ferrand, G., Warren, D.C., Ono, M., Nagataki, S., Röpke, F. K., Seitenzahl, I. R., Lach, F., Iwasaki, H., Sato, T., The Astrophysical Journal, 906, id.93 (2021).
- Ferrand, G., Warren, D., Ono, M., Nagataki, S., Röpke, F. K., Seitenzahl, I. R., The Astrophysical Journal, Volume 877, id. 136 (2019).
- Lee, S.H. et al. in prep. (2023).

Core Collapse Supernova Remnants:

- Orlando, S.; Wongwathanarat, A.; Janka, H. -T.; Miceli, M.; Nagataki, S.; Ono, M.; Bocchino, F.; Vink, J.; Milisavljevic, D.; Patnaude, D. J.; Peres, G., Astronomy & Astrophysics, Volume 666, id.A2, 19 pp. (2022).
- Sato, Toshiki; Maeda, Keiichi; Nagataki, Shigehiro; Yoshida, Takashi; Grefenstette, Brian; Williams, Brian J.; Umeda, Hideyuki; Ono, Masaomi; Hughes, John P., Nature, Volume 592, Issue 7855, p.537-540 (2021).
- Orlando, S.; Wongwathanarat, A.; Janka, H. -T.; Miceli, M.; Ono, M.; Nagataki, S.; Bocchino, F.; Peres, G., Astronomy & Astrophysics, Volume 645, id.A66, 32 pp. (2021).
- Orlando, S.; Ono, M.; Nagataki, S.; Miceli, M.; Umeda, H.; Ferrand, G.; Bocchino, F.; Petruk, O.; Peres, G.; Takahashi, K.; Yoshida, T., Astronomy & Astrophysics, Volume 636, id.A22, 19 pp. (2020).
- Ono, M., Nagataki, S., Ferrand, G., Takahashi, K., Umeda, H., Yoshida, T., Orlando, S., Miceli, M., The Astrophysical Journal, Volume 888, Issue 2, id.111, 40 pp. (2020).
- Orlando, S., Miceli, M., Petruk, O., Ono, M., Nagataki, S., Aloy, M. A., Mimica, P., Lee, S. H., Bocchino, F., Peres, G., Guarrasi, M., Astronomy & Astrophysics, Volume 622, id.A73, 15 pp. (2019).
- Nagataki, S., The Astrophysical Journal Supplement Series, Volume 127, Issue 1, pp. 141-157 (2000).
- Nagataki, S., Hashimoto, M., Sato, K., Yamada, S., The Astrophysical Journal, Volume 486, Issue 2, pp. 1026-1035 (1997).
- Lee, S.H. et al. in prep. (2023).

Neutron Star Mergers and Gravitational Waves:

- Huang, Yong-Jia; Baiotti, Luca; Kojo, Toru; Takami, Kentaro; Sotani, Hajime; Togashi, Hajime; Hatsuda, Tetsuo; Nagataki, Shigehiro; Fan, Yi-Zhong, Physical Review Letters, Volume 129, Issue 18, article id.181101 (2022).

Thank You Very Much.

Shigehiro Nagataki

My Lecture on
Stellar Astrophysics
at OIST will start in Sep. 2023.

Friedrich Röpke

Ivo Seitenzahl

Florian Lach

Gilles Ferrand

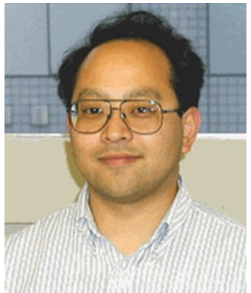
Shiu-Hang Lee (Herman)

Ataru Tanikawa

Masaomi Ono

Katsuhiko Sato

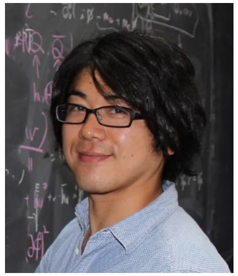
Masaaki Hashimoto



Shoichi Yamada

Hideyuki Umeda

Takashi Yoshida



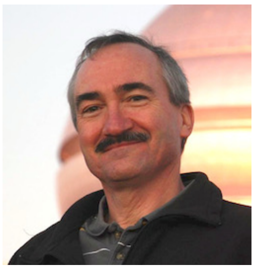
Keiichi Maeda

Toshiki Sato

Annop Wongwathanarat

Salvatore Orlando

Thomas Janka



John Hughes

Yongjia Huang

Luca Baiotti

Toru Kojo

Tetsuo Hatsuda

Kentaro Takami

Hajime Togashi