# Plasma Physics

TU Dresden
Lecture: Prof. Dr. Hideaki Takabe
Date: July 6, 2020

**Lecture S: Astrophysical Plasmas and Laboratory Astrophysics**

Introduction
1. **Turbulent Mixing and Supernova Explosion**
2. **Collisionless Shocks and Cosmic-rays**
Conclusion

# The Physics to know the Universe

- Cosmology
  - Big bang, Inflation universe,
  - Black hole, time and space (General relativity)
- Astrophysics
  - Particle physics
  - Nuclear physics
  - Plasma physics (relativistic plasma physics)
  - Atomic physics
  - Chemical physics
- Planetary physics
  - Condense matter physics
  - Chemistry, Biology

# Plasma Astrophysics

- Physics of high-temperature hydrodynamics
  - Shock waves
  - Hydrodynamic instabilities
  - Nuclear burning
  - Equation of state
  - Radiation transport
- Physics of charged particle acceleration
  - Electric field generation
  - Collisionless shock wave
  - Statistical acceleration
  - Wave-rarticle coupling and accelaration

# The Physics of Laser Plasma and its Applications

**Hideaki Takabe**
Helmholtz-Zentrum-Dresden-Rossendorf (HZDR)

## Volume -1 Physics of Laser Matter Interaction

(400 pages, publ. Sept. 2020)

1. Introduction
2. Laser absorption by Coulomb collision
3. Absorption of ultra-short pulse and collisionless processes
4. Nonlinear laser-plasma interactions
5. Relativistic laser electron interactions
6. Relativistic laser propagation in plasmas
7. Relativistic laser and solid target interactions
8. Stochastic electron heating by relativistic lasers
9. Theory of stochasticity and chaos of electrons in relativistic lasers

# Volume -2 Hydrodynamics of Laser Produced Plasmas

(400 pages, publ. Dec. 2020)

10. Introduction
11. Fluid model of laser-produced plasmas
12. Atomic process in laser plasmas
13. Electron and radiation energy transports
14. Plasmas in non-ideal high-density states
15. Hydrodynamics of compressible plasma and shocks
16. Physics integrated codes and laser fusion
17. Multi-dimensional hydrodynamics and magnetic fields
18. Hydrodynamic instabilities in laboratory and Universe
19. Turbulence and turbulent mixing in dynamical fluids

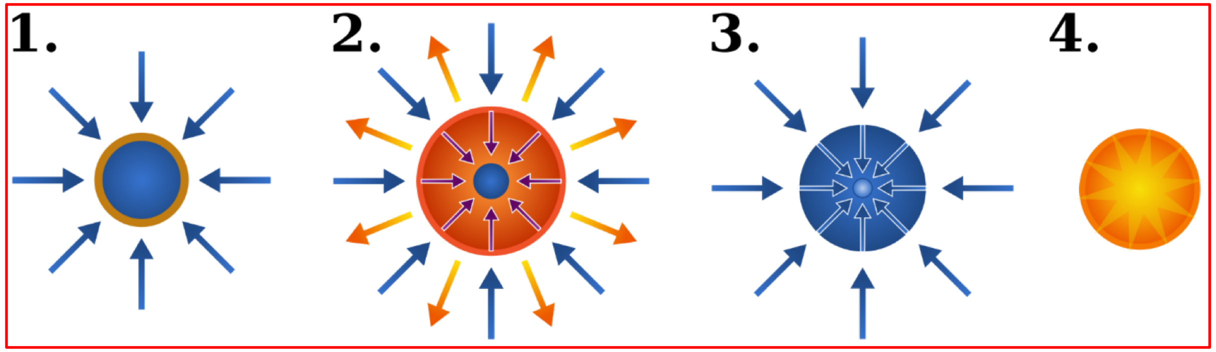
## Volume -3 Particle and Kinetic Physics in Laser Plasmas

(400 pages, publ. April, 2021)

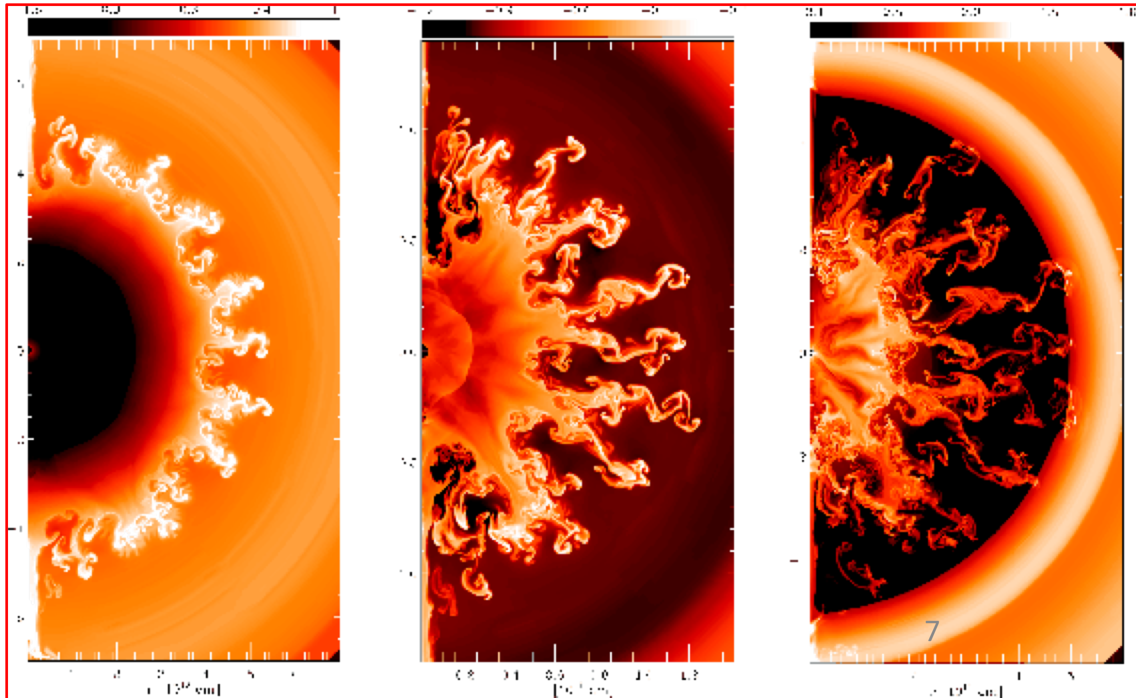
20. Introduction
21. Plasma instability and magnetic field generation
22. Kinetic theory and plasma turbulence
23. Collisionless shocks and magnetic turbulence
24. Cosmic-ray generation and stochastic acceleration
25. Wake field acceleration of electrons by ultra-intense and ultra-short lasers
26. Ion acceleration by relativistic lasers
27. Vacuum breakdown and anti-matter production by relativistic lasers

# Rayleigh-Taylor Instabilities in mm, and bigger than the Sun.

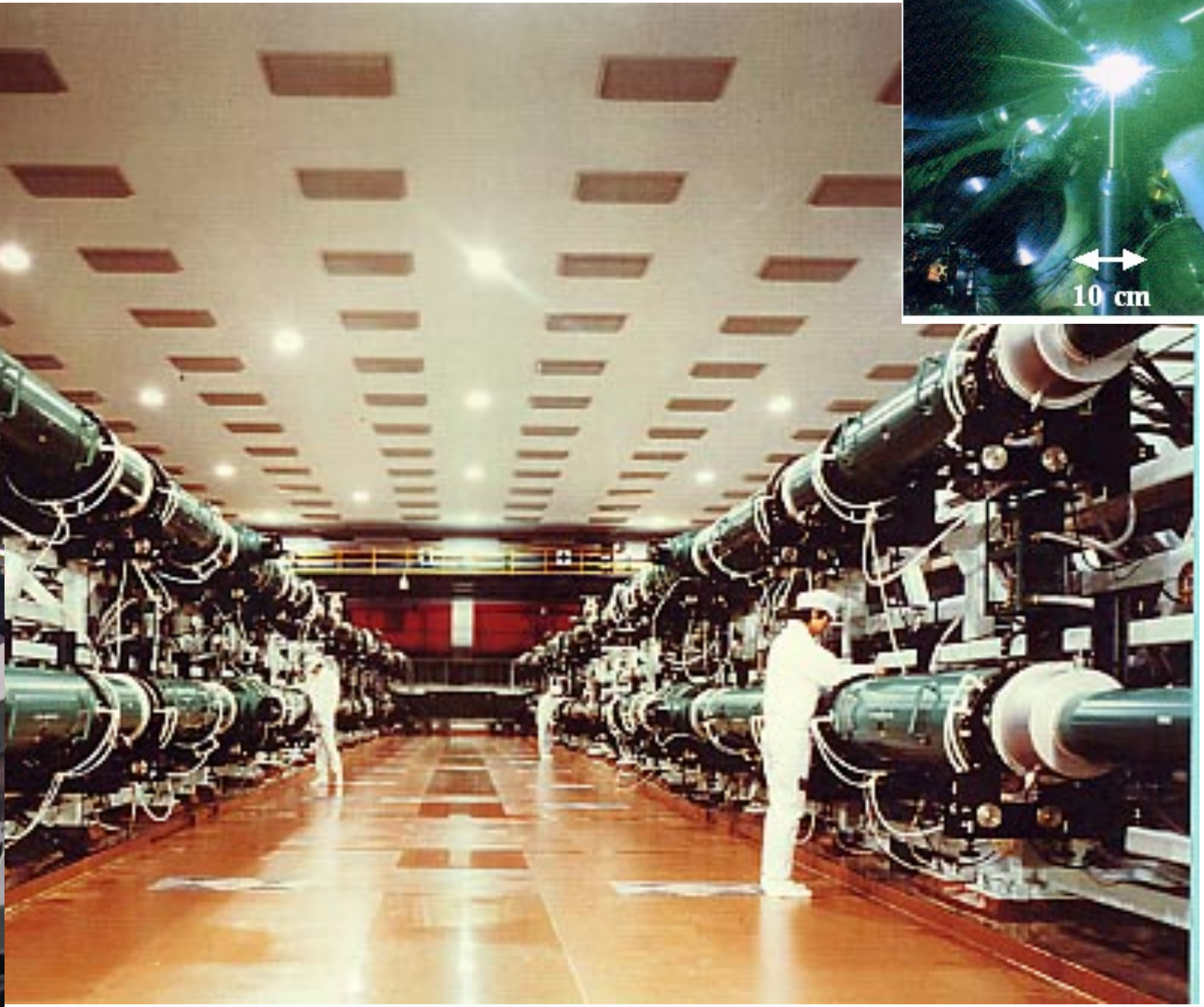
(a) Laser fusion (implosion)

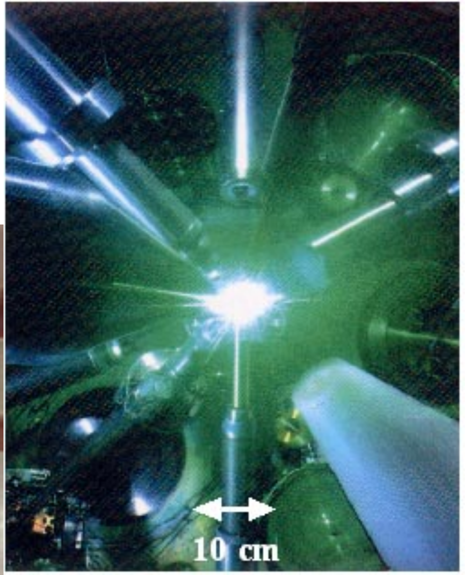



(b) Supernova explosion

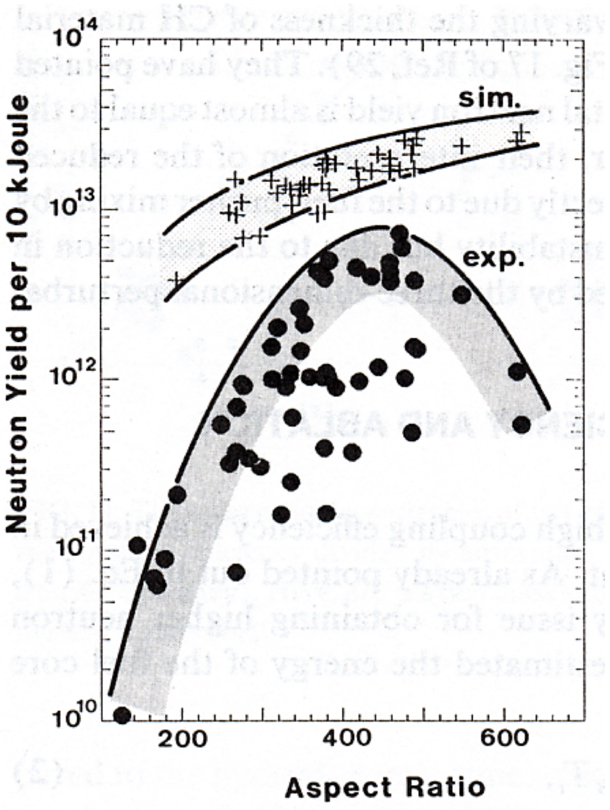


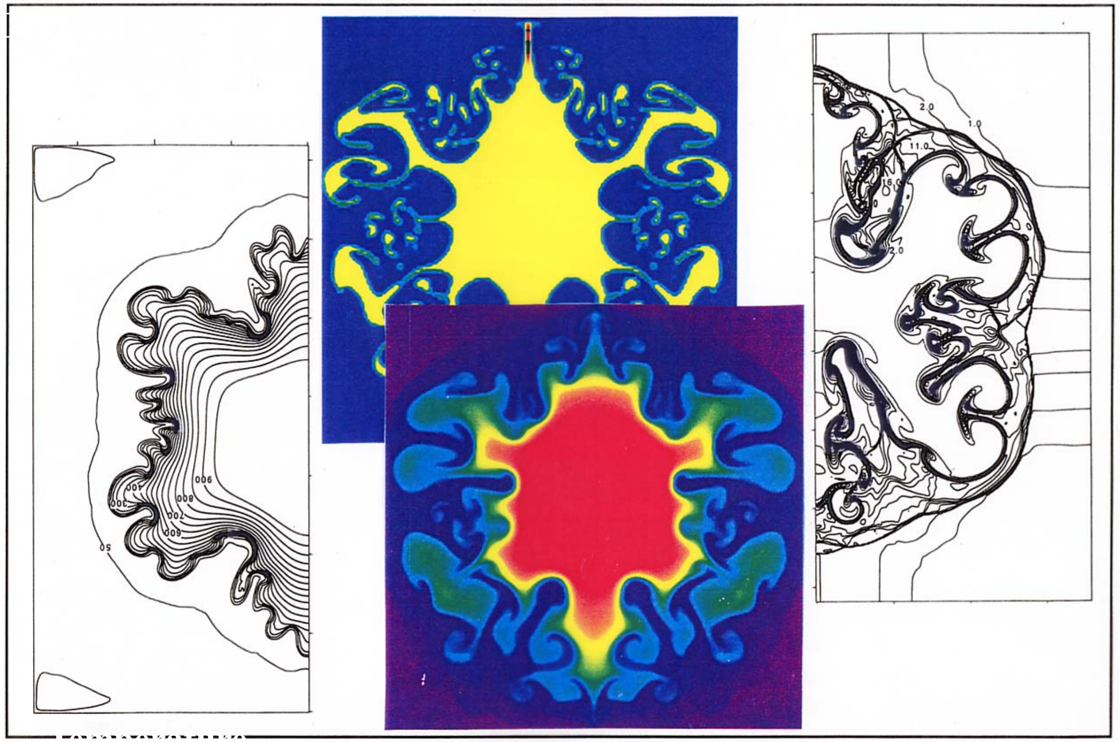
# Gekko XII Laser Facility at ILE, Osaka University





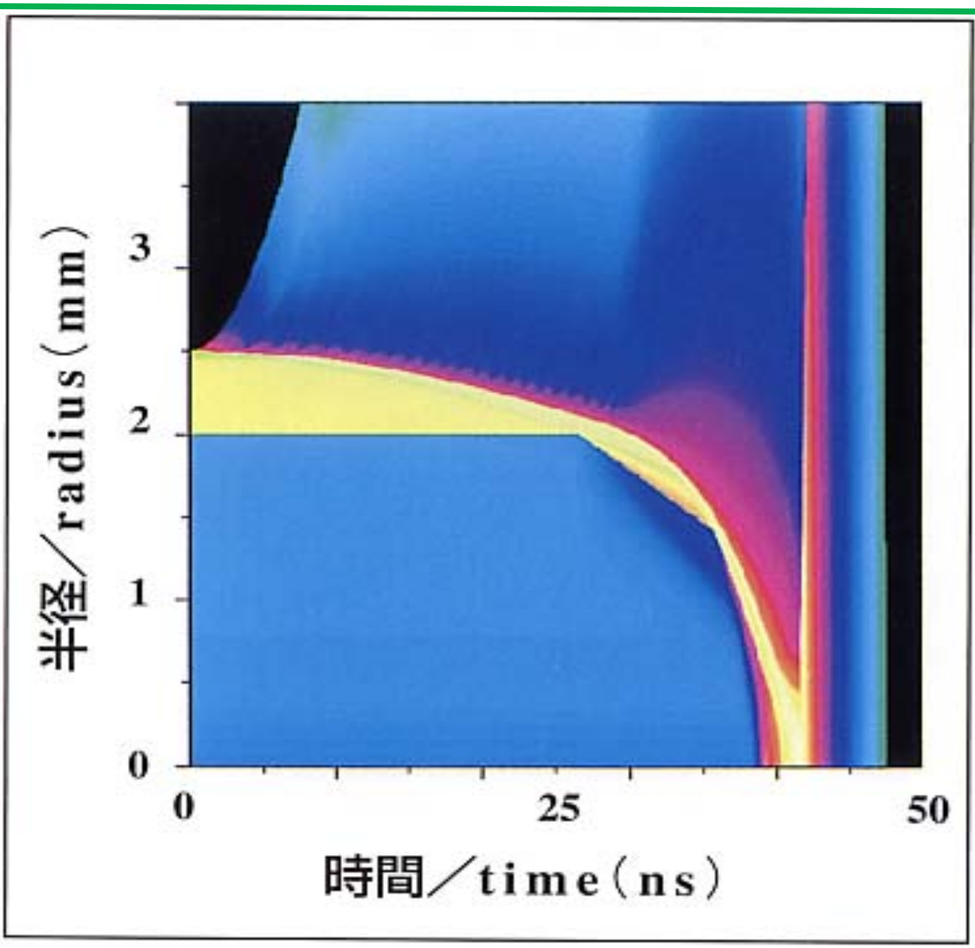

# “The nature is not kind”:  RT instability in laser fusion



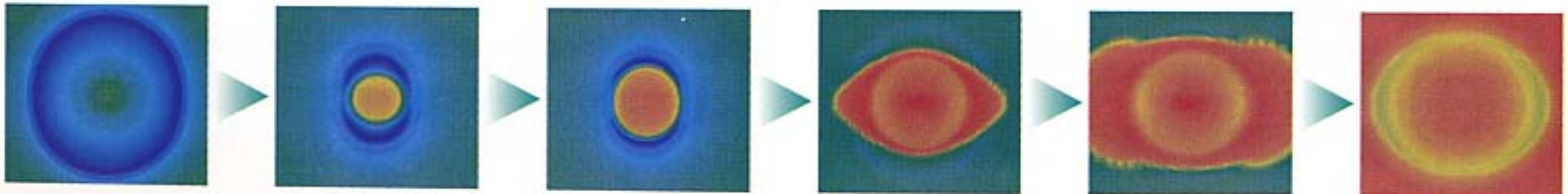
H Takabe et al., *Scalings of implosion experiments for high neutron yield* Physics of fluids 31, 2884-2893 **(1988)**

# 2-D integrated code simulation of High-Gain at 3MJ/3ω laser with tailored pulse

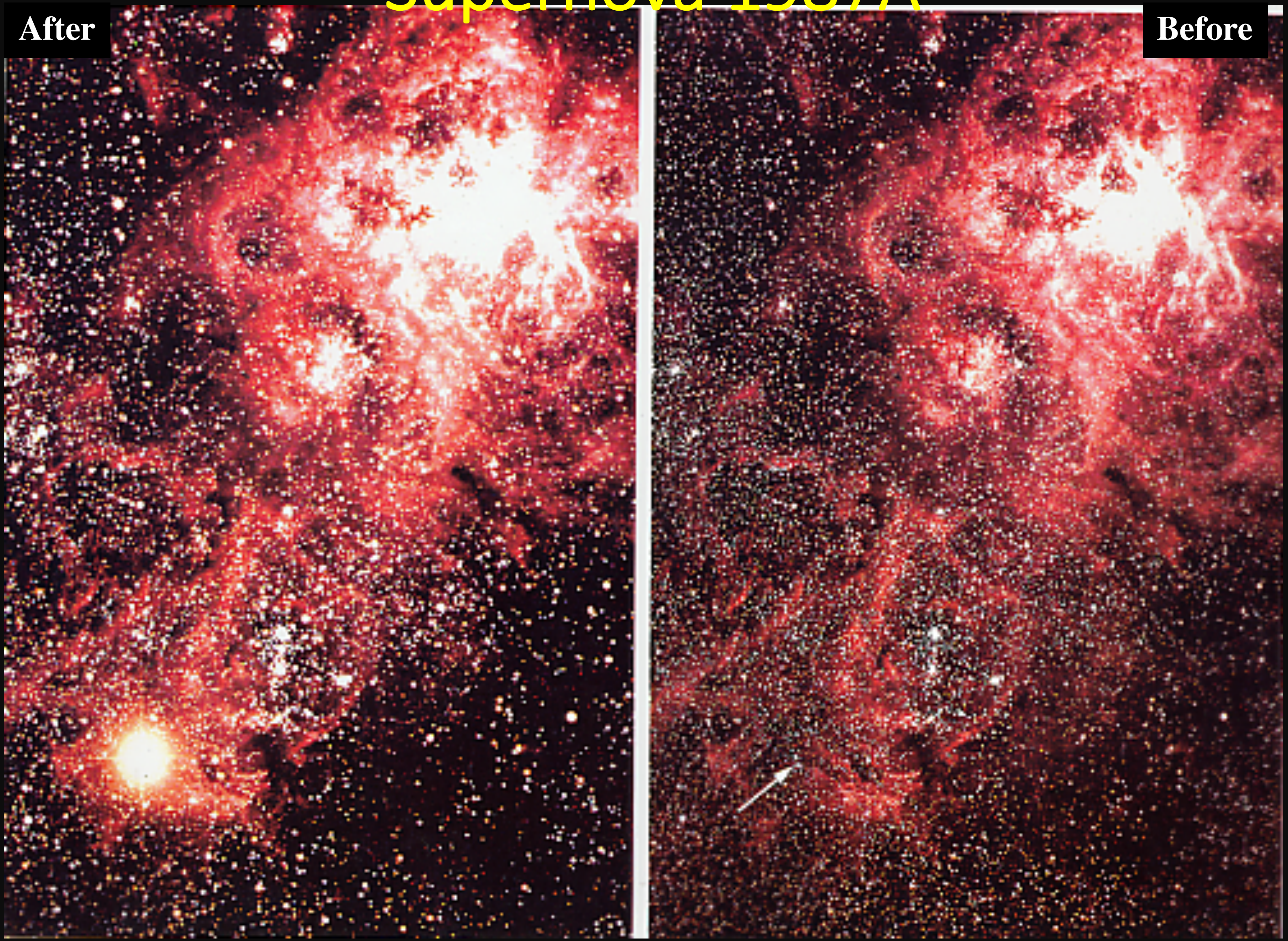



## High Gain Target Design

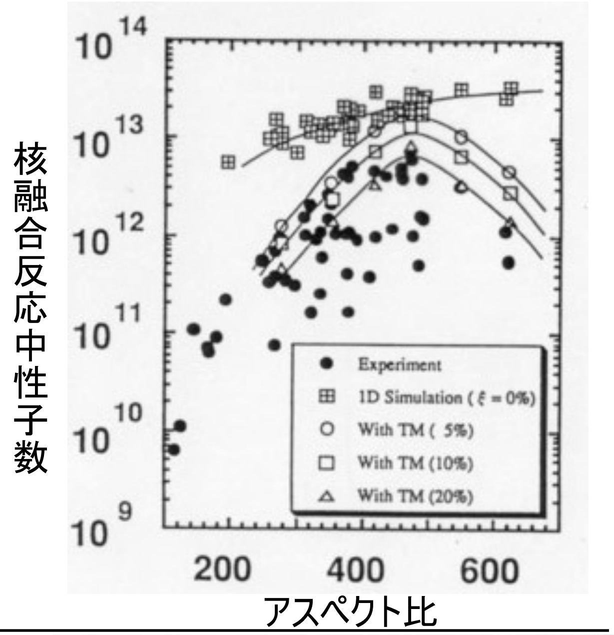
A radius-time diagram of the high gain target obtained with one-dimensional implosion code. The target fuel is accelerated up to 300 km/s toward the target center to produce a hot spark. Once the fusion ignition takes place, the burning wave seen in below six snapshots of 2-D simulation propagates to burn the whole of surrounding fuel, consequently producing fusion energy of 100 times more than the input laser energy.

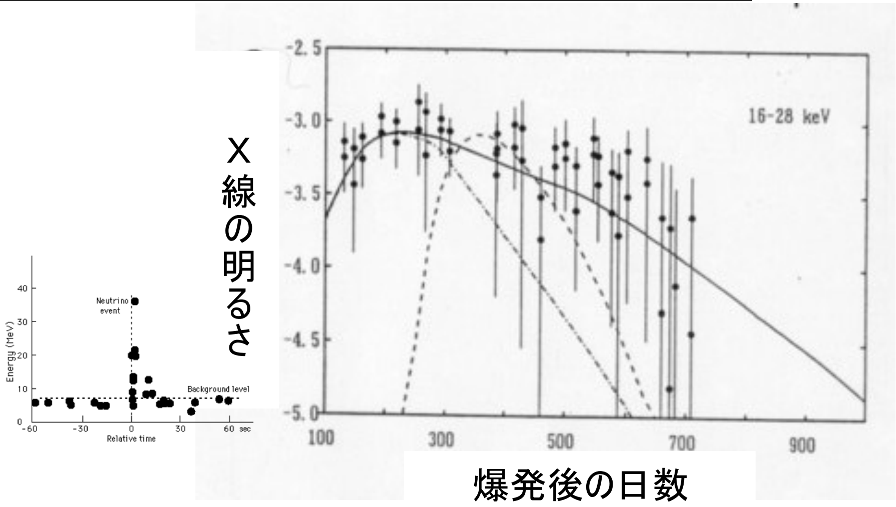


# Supernova 1987A

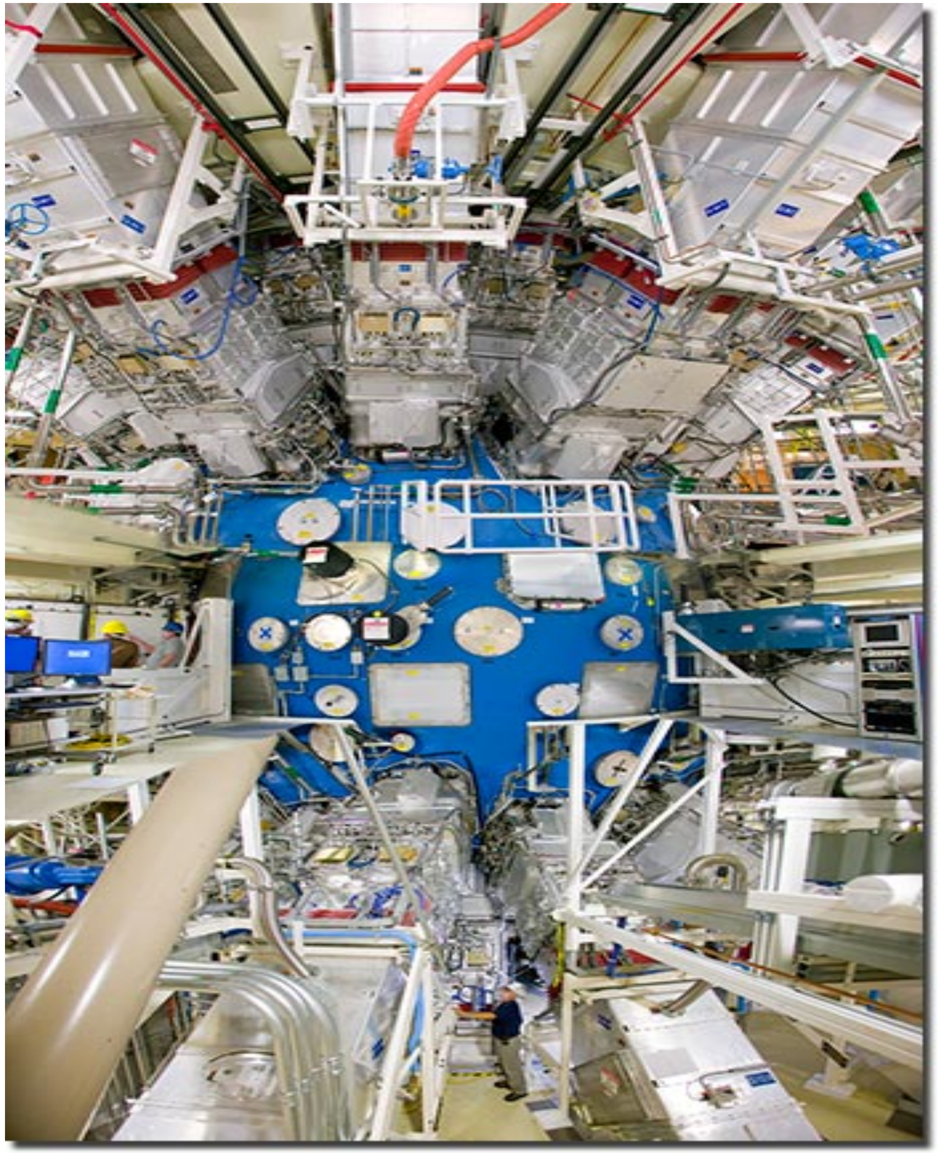


# Implosion and explosion are not symmetric

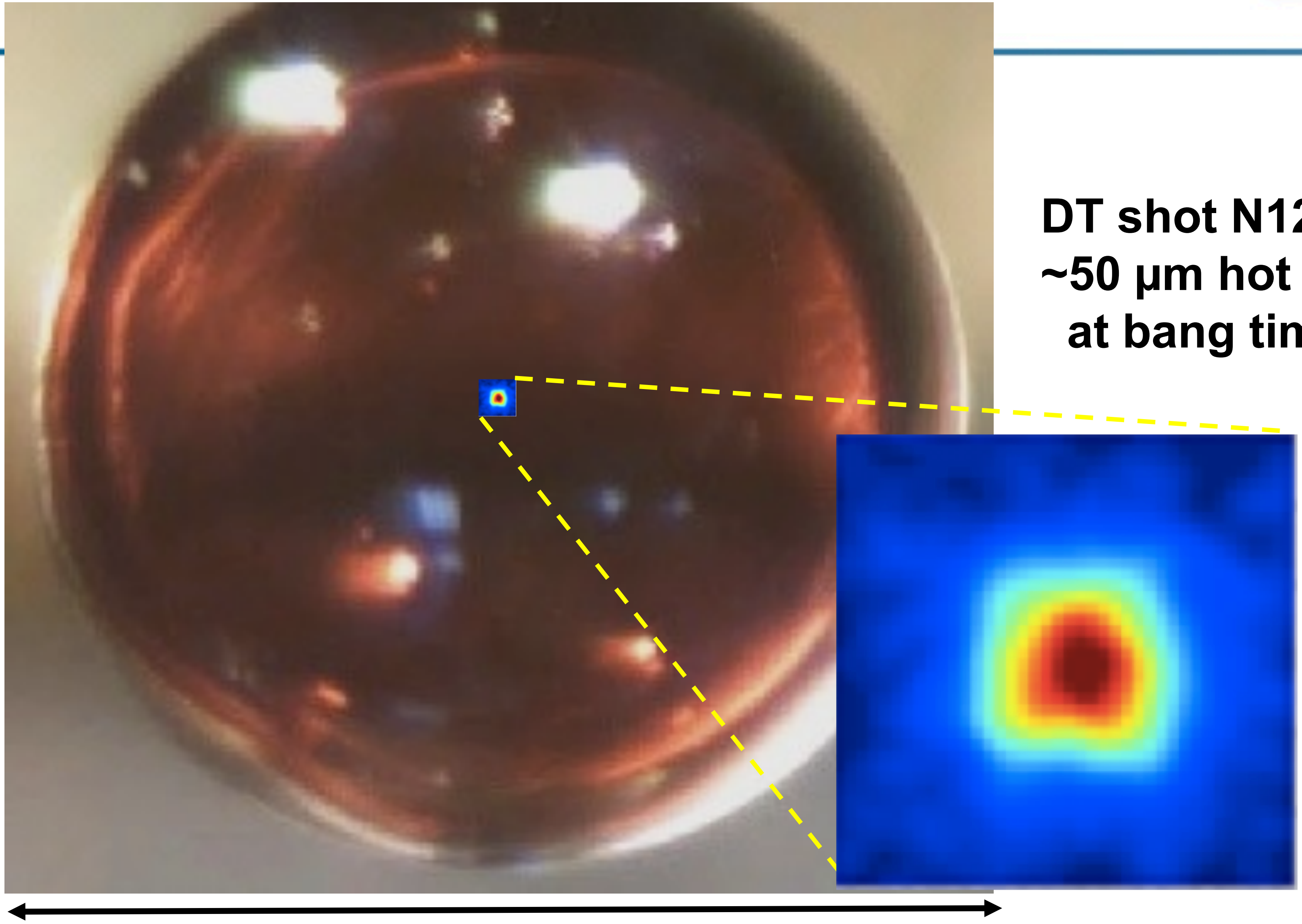



# National Ignition Facility

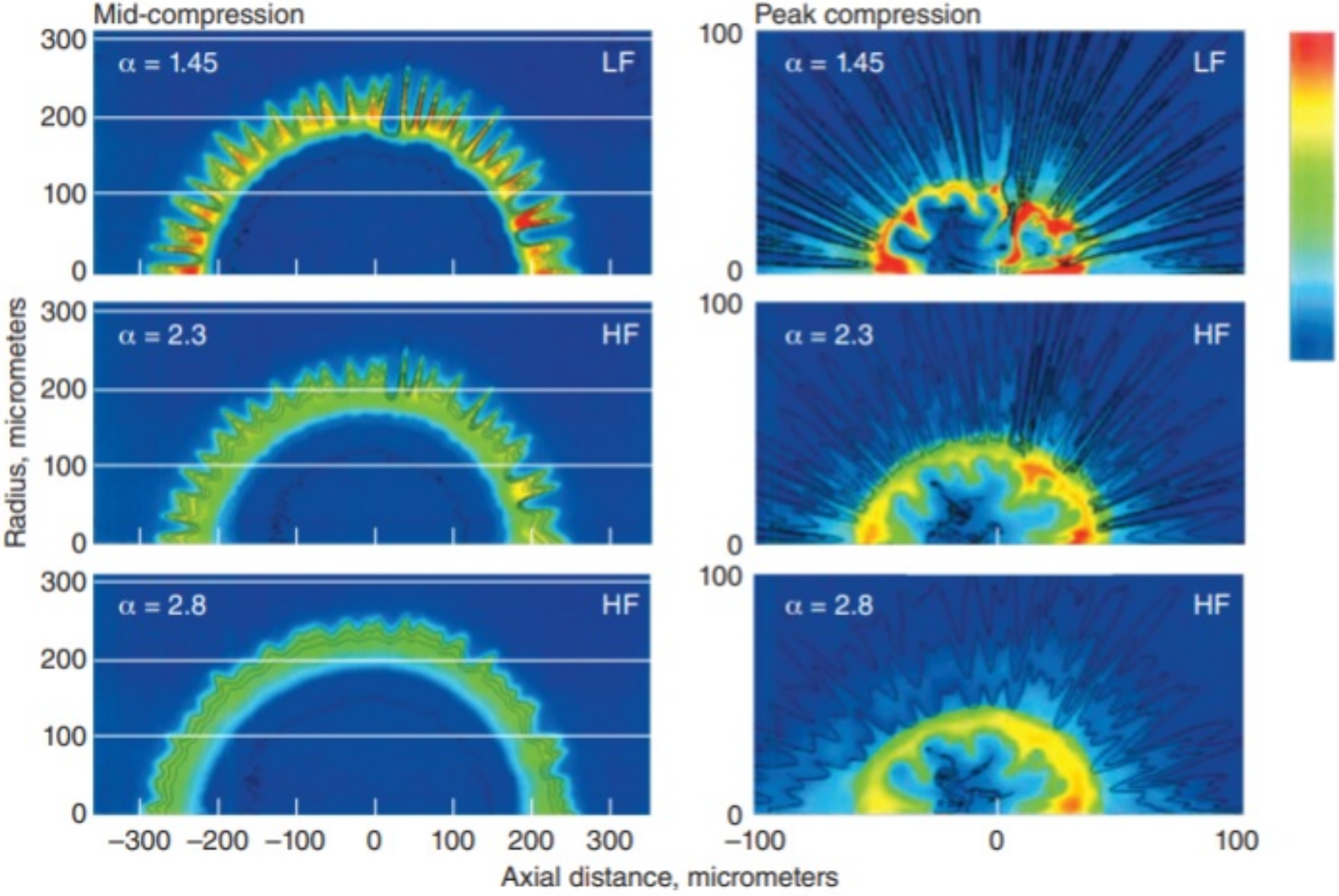
NIF

## The challenge: the capsule has to compress by a factor of 30-40 and remain round to reach the required densities and temperatures for ignition




**DT shot N120716**
**~50 μm hot spot at bang time**

[Dave Bradley, IFSA (2013)]




Computer simulations show how a plastic fuel capsule filled with deuterium–tritium fuel responds to compression in low-foot (LF) and high-foot (HF) experiments. The capsule's plastic shell has been "roughened" to better illustrate the effect of instabilities. At mid-compression (left column), the LF pulse (top row) produces an adiabat (α, a measure of entropy) of 1.45, whereas the HF pulse results in adiabats of (middle row) 2.3 and (bottom row) 2.8. At peak compression (right column), the low-foot capsule suffers extensive mixing.

# Rayleigh-Taylor Instability

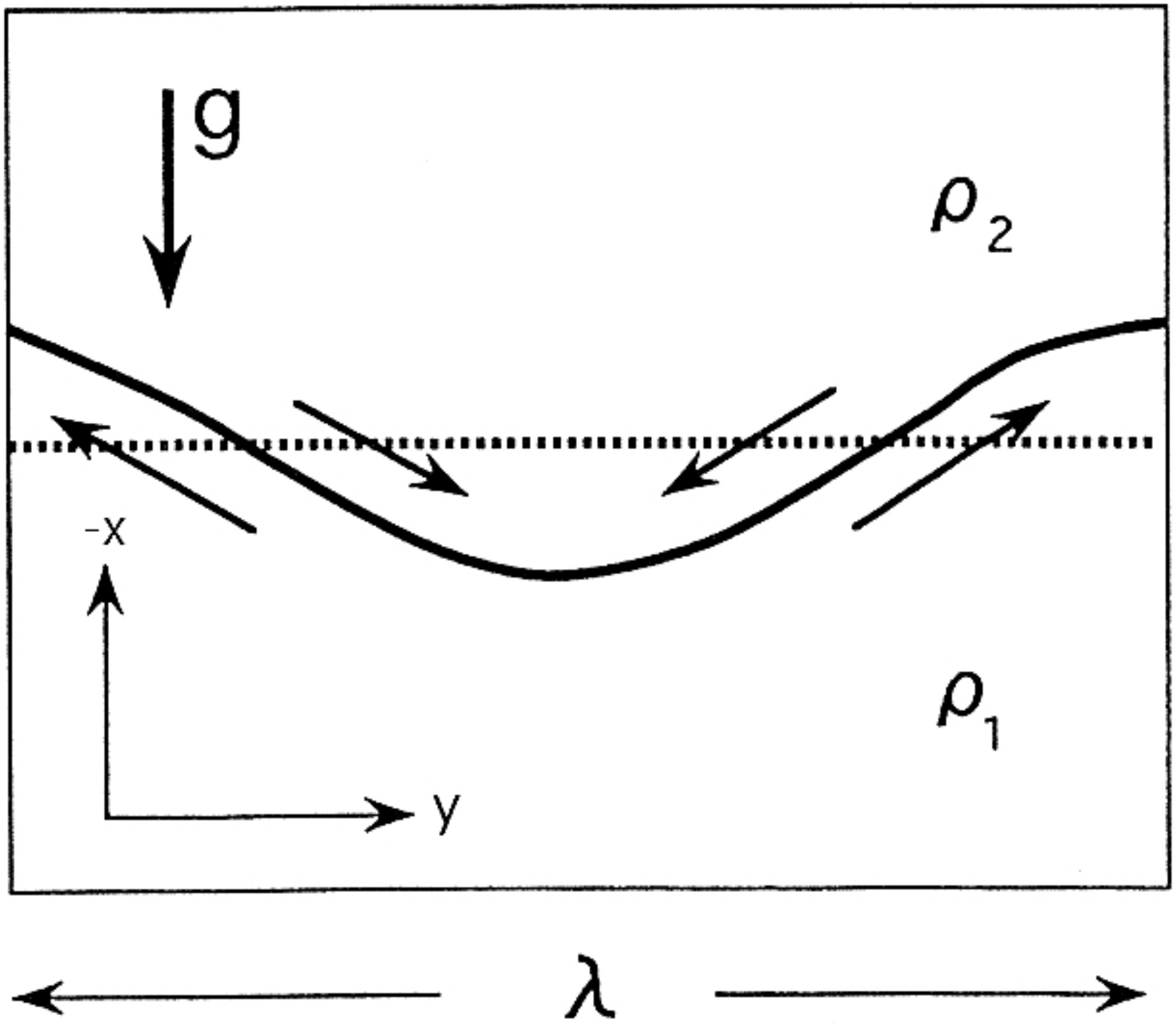
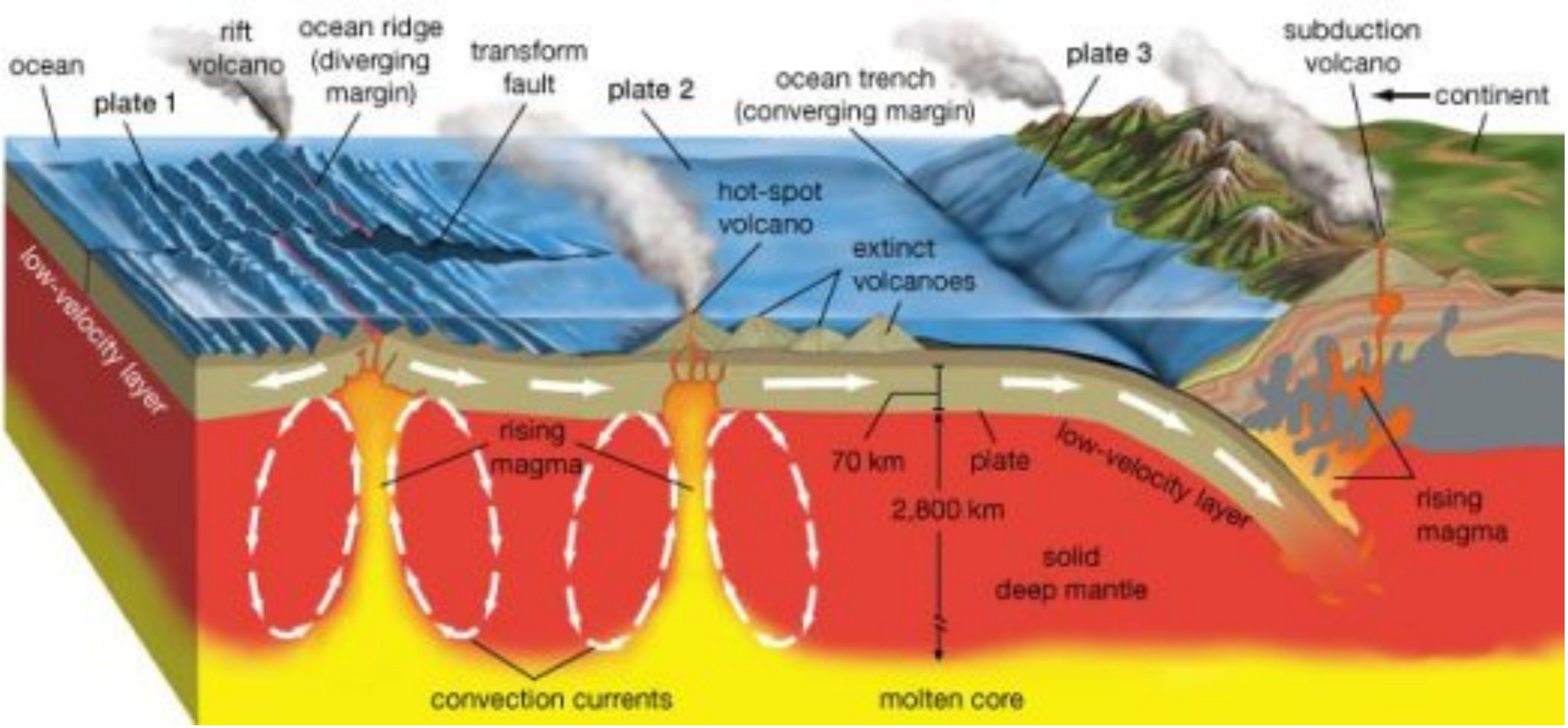



Fig. 8.1

[Science of Cycles](https://scienceofcycles.com)




https://scienceofcycles.com/tag/plate-tectonics/

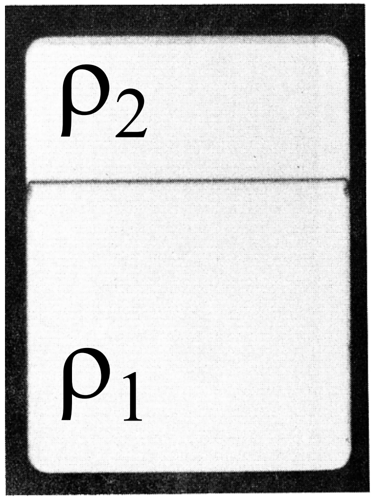
RT

# Rayleight-Tayor Instability and Turbulent Mixing

$$\gamma = \sqrt{\alpha_A k g}$$

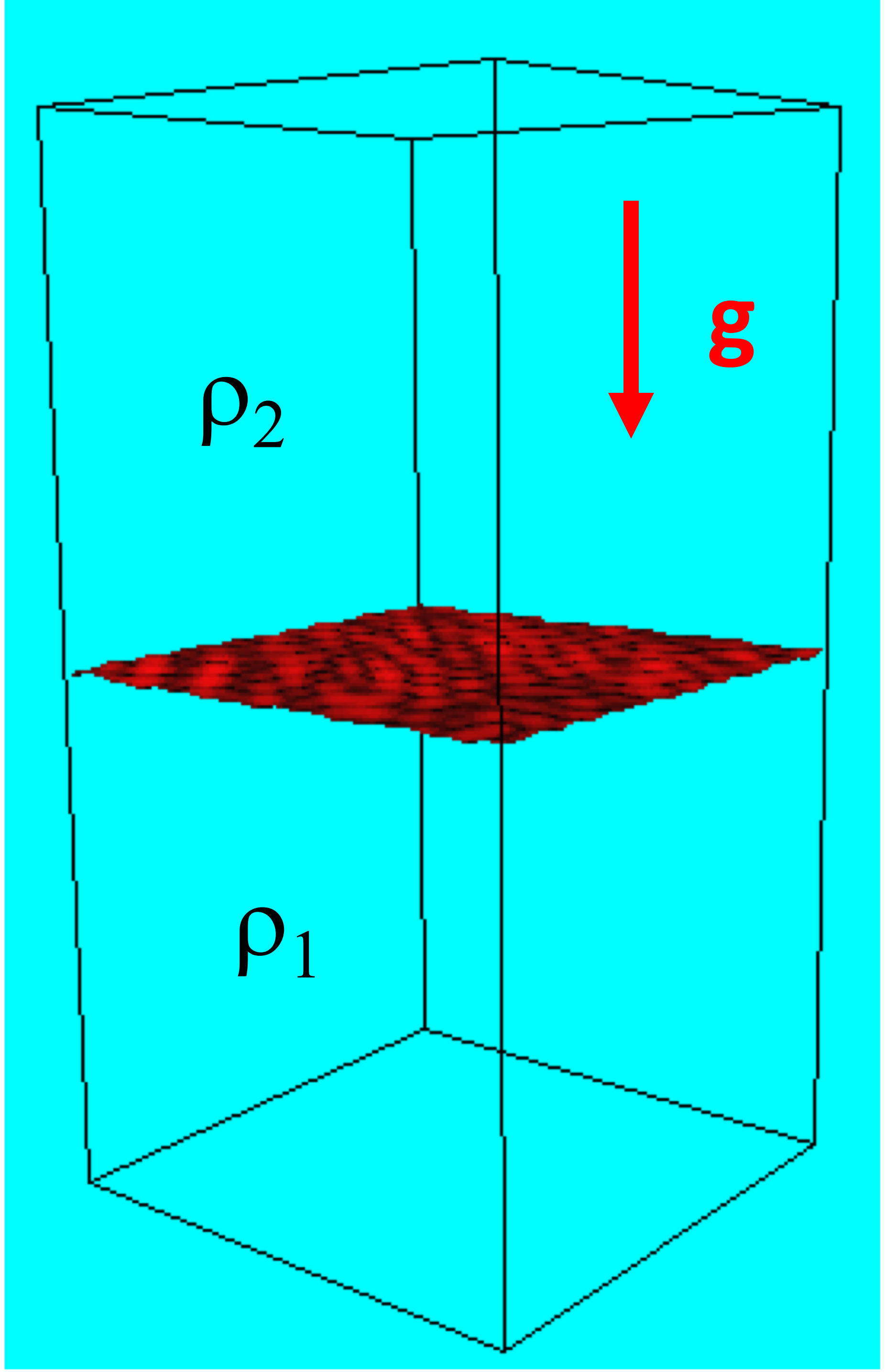
$\rho_2 > \rho_1$

$$h(t) = 0.07 g t^2$$




time

K. L. Read and D. L. Youngs
Physica 12D, 45, 1984



# Hydrodynamic equation with turbulence model

$$\frac{d\rho}{dt} = -\rho\nabla\mathbf{u}$$

$$\rho\frac{dc}{dt} = \nabla(\rho D_c \nabla c)$$

$$\rho\frac{d\mathbf{u}}{dt} = -\nabla P - \nabla R$$

$$\rho\frac{de}{dt} = -P\nabla\mathbf{u} - S_{RT} + \nabla\left[\rho D_e \nabla\left(e + \frac{P}{\rho}\right)\right] + \rho\varepsilon$$

$$\rho\frac{dk}{dt} = -R\nabla\mathbf{u} + S_{RT} + \nabla(\rho D_k \nabla k) - \rho\varepsilon$$

$$\rho\frac{d\varepsilon}{dt} = -C_{\varepsilon 1}\frac{\varepsilon}{k}R\nabla\mathbf{u} + C_{\varepsilon 0}\frac{\varepsilon}{k}S_{RT} + \nabla(\rho D_\varepsilon \nabla\varepsilon) - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

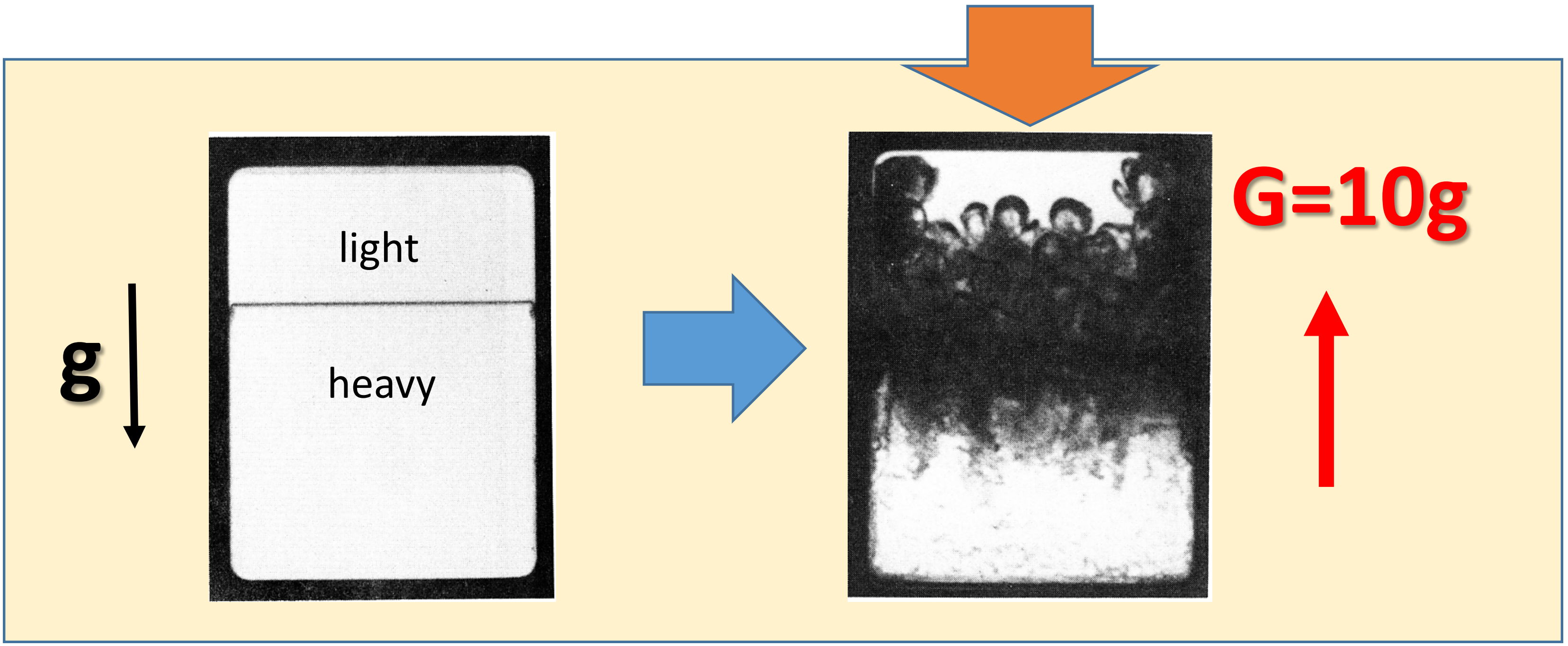
where

$$R = -\frac{4}{3}C_D\rho\frac{k^2}{\varepsilon}\nabla\mathbf{u} + \frac{2}{3}\rho k$$

$$S_{RT} = -\frac{1}{\rho}D_\rho \nabla\rho\nabla P \quad , \quad D_\phi = \frac{C_D}{\sigma_\phi}\frac{k^2}{\varepsilon}$$

$k$: Turbulence energy density

$\varepsilon$: Dissipation rate of $k$




K. L. Read, Physica 12D, 45 (1984)

**Hydrodynamic Turbulent (by RT)**

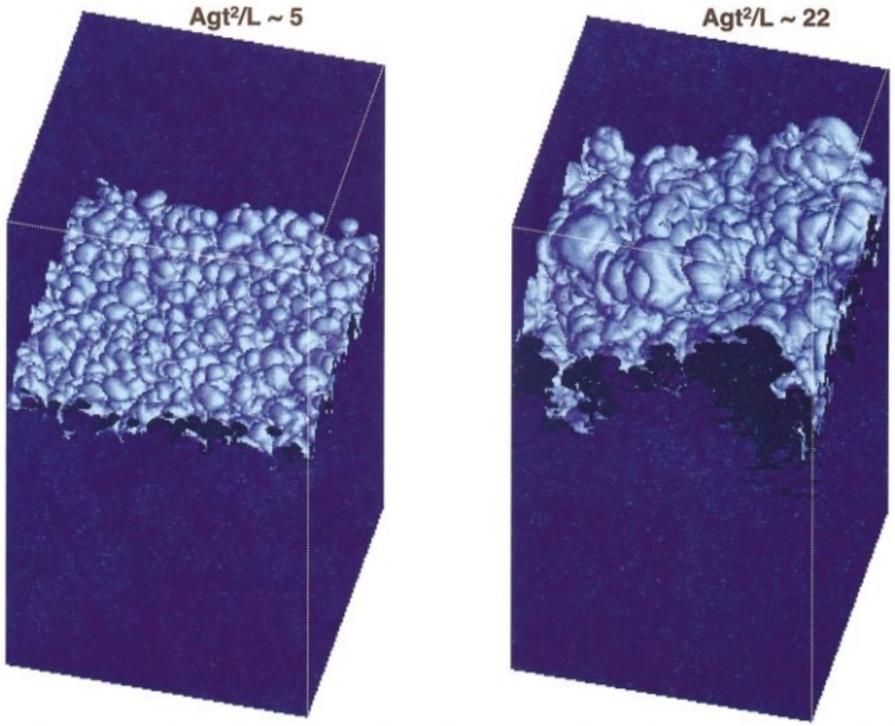
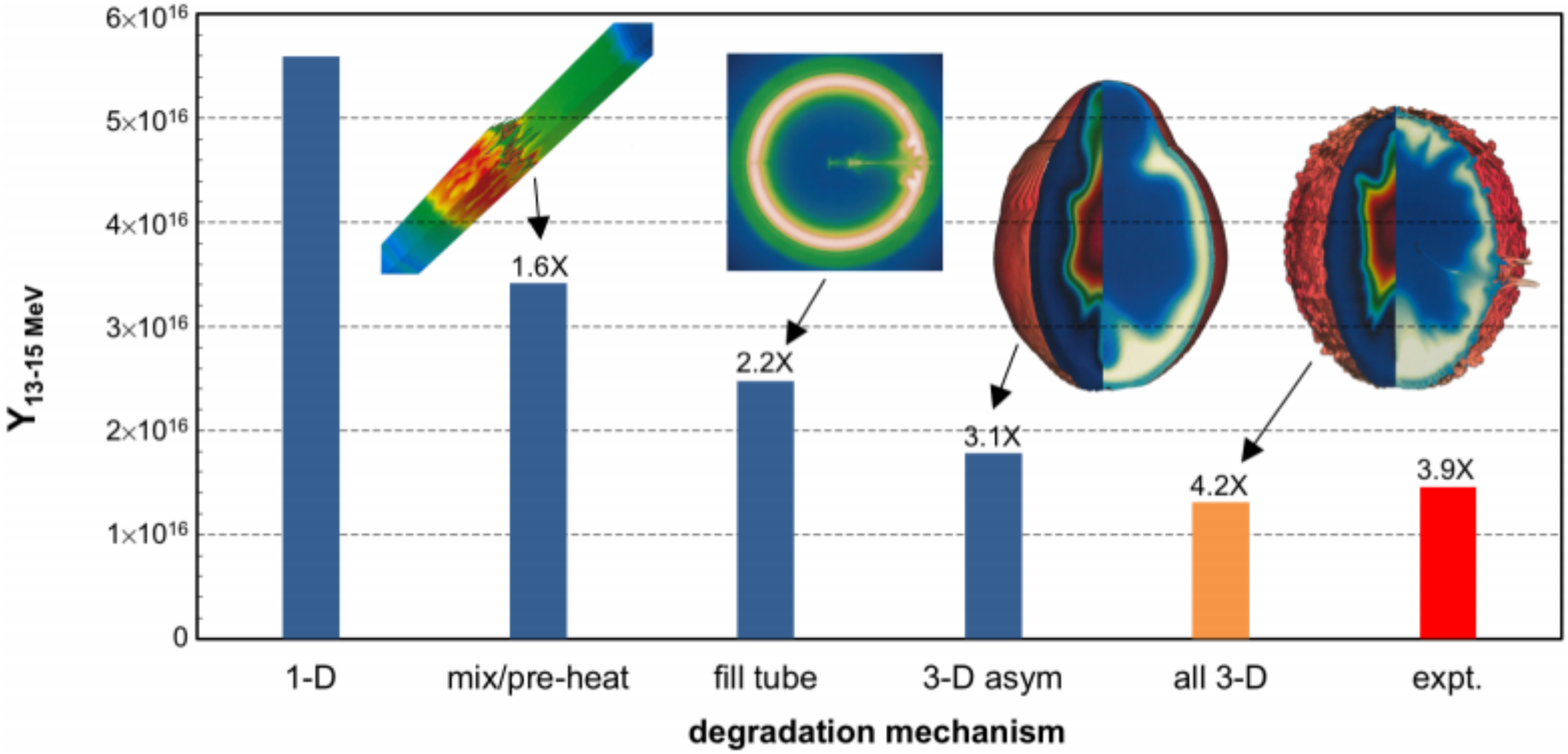



FIG. 6. (Color) Isosurfaces from TURMOIL3D where "heavy" fluid concentration=0.99.

G. Dimonte et al., Phys. Fluids, 16, 1668 (2004)

# Present understanding of yield reduction

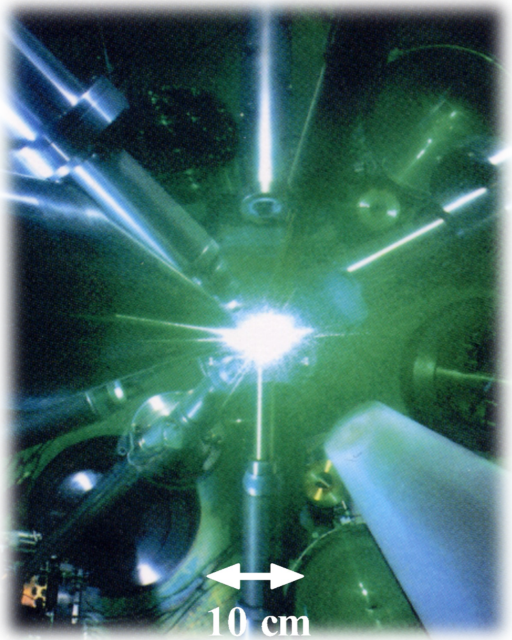



N170601

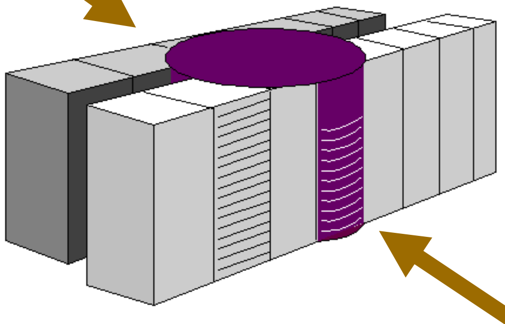
D. S. Clark et al., Physics of Plasmas, to be published (2019)

# Challenging Basic Science in Laboratory Astrophysics

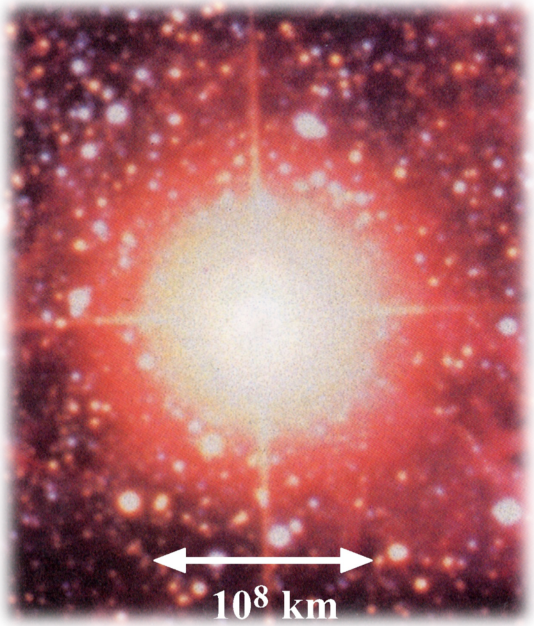
1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Provide Challenging Plasma Physics
4. Prediction of Astrophysical Phenomena




Model Experiment



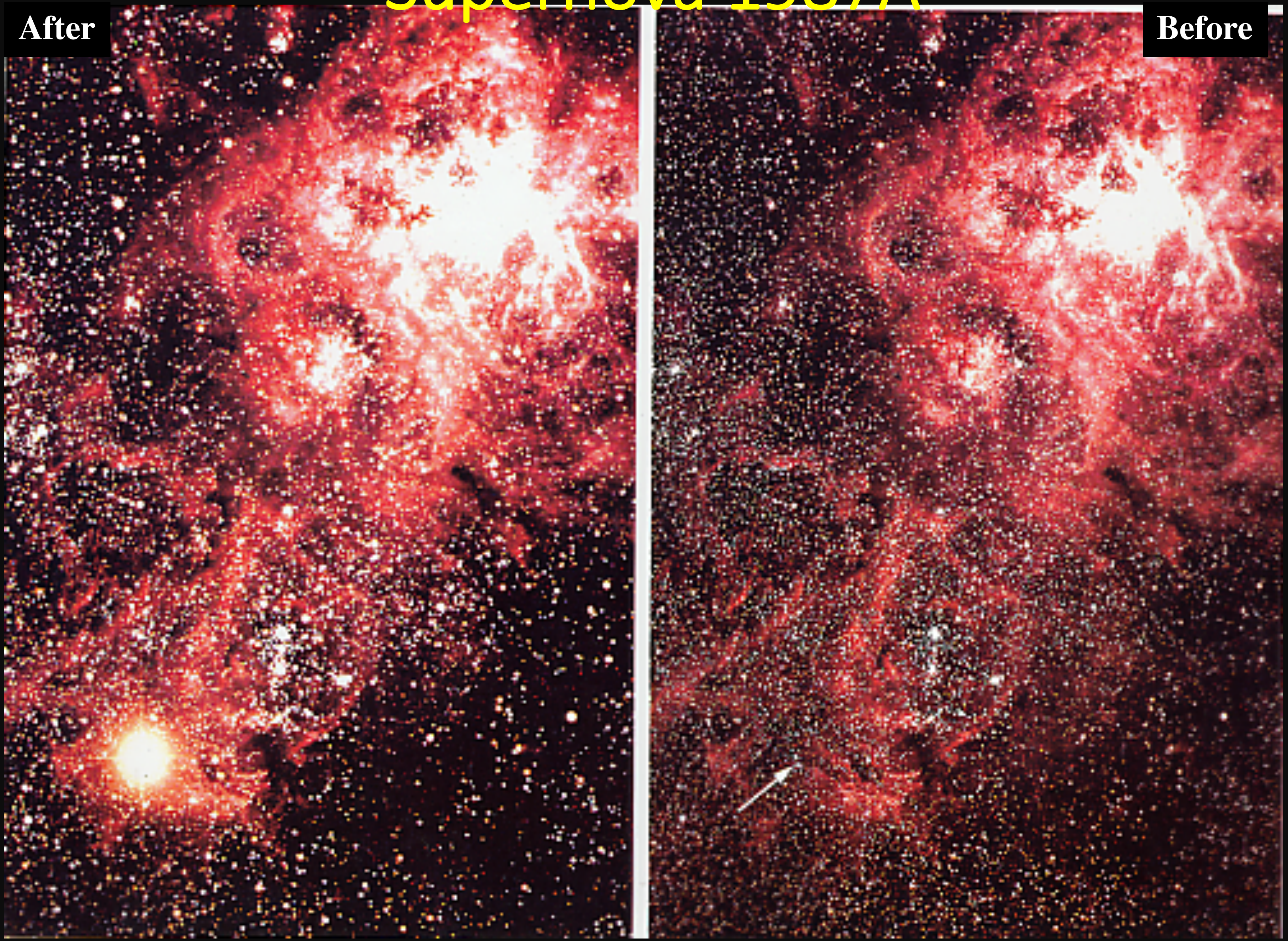
Supercomputer

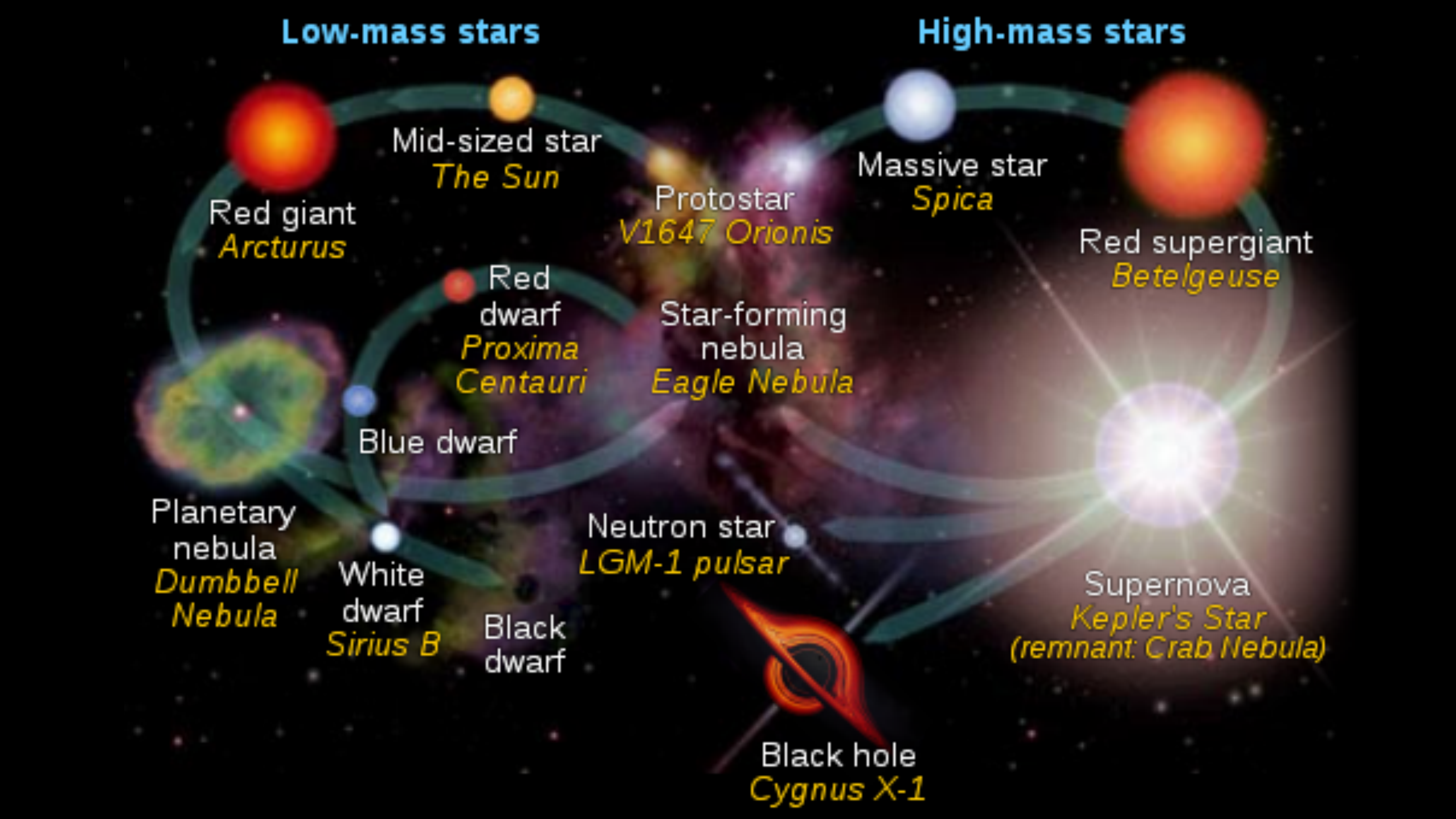


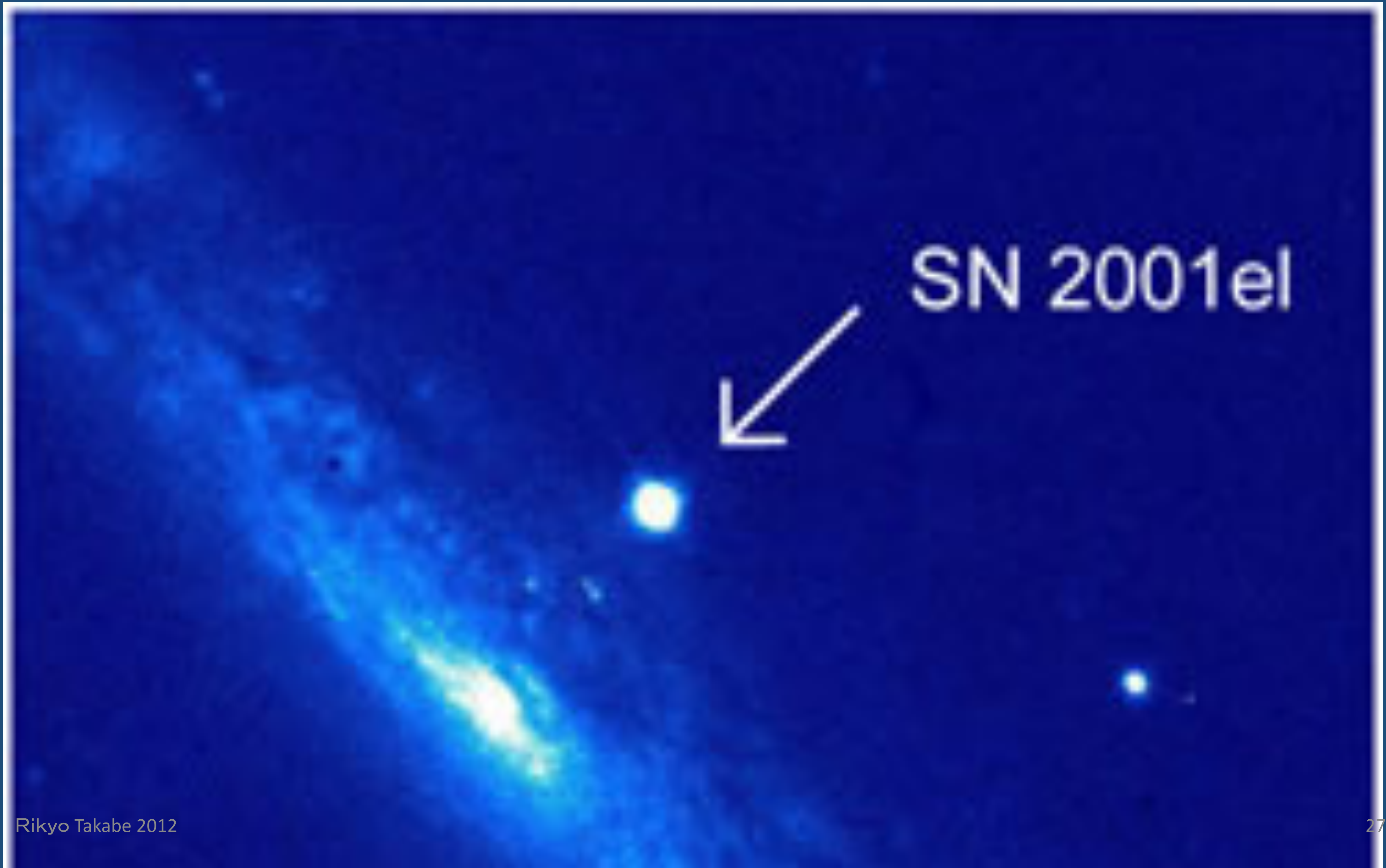

Supernova

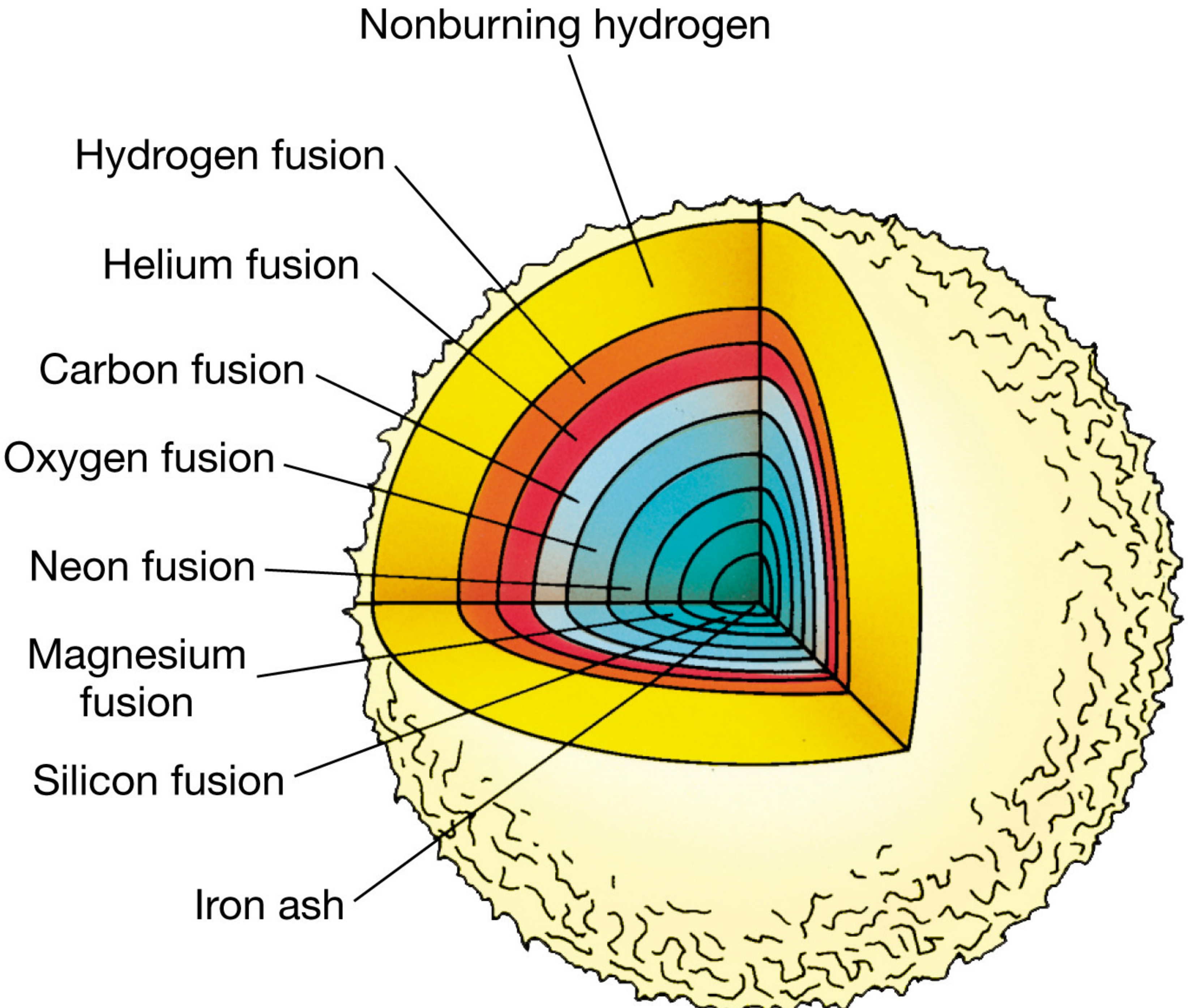
$(\times 10^{14})$ Space & Time

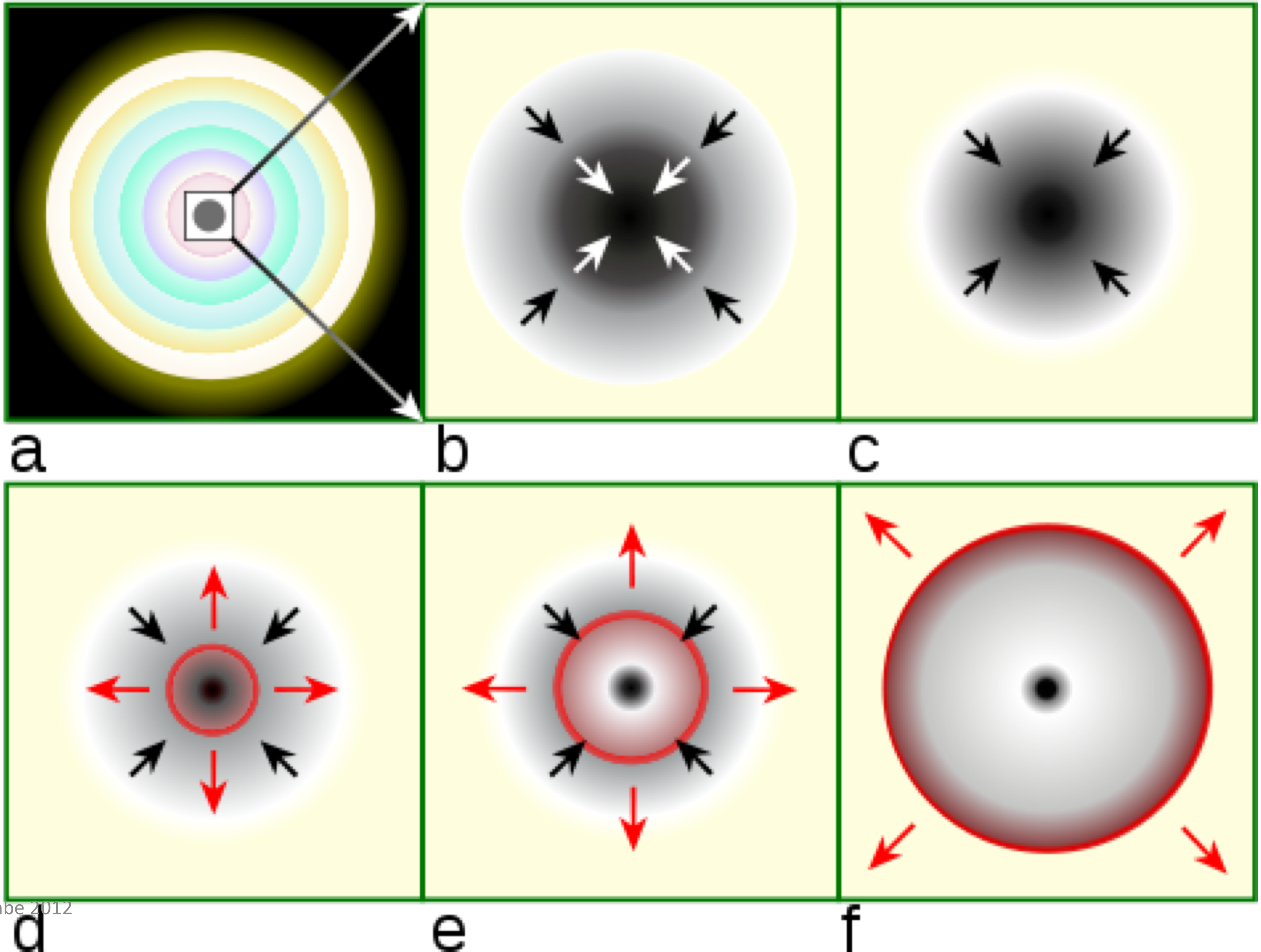
# Supernova 1987A



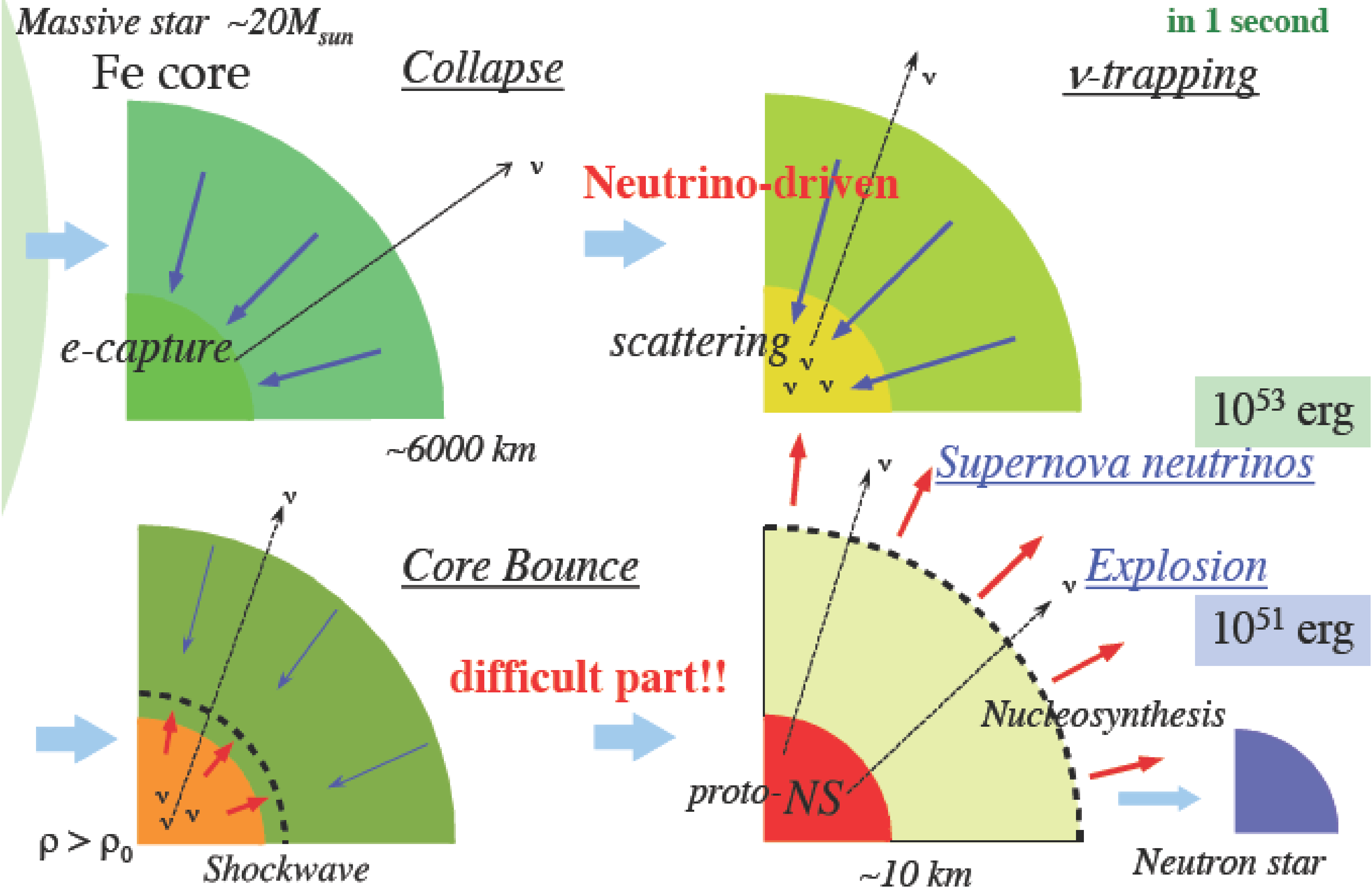

Low-mass stars
High-mass stars
Mid-sized star
The Sun
Red giant
Arcturus
Protostar
V1647 Orionis
Massive star
Spica
Red supergiant
Betelgeuse
Red
dwarf
Proxima
Centauri
Star-forming
nebula
Eagle Nebula
Blue dwarf
Planetary
nebula
Dumbbell
Nebula
White
dwarf
Sirius B
Black
dwarf
Neutron star
LGM-1 pulsar
Supernova
Kepler's Star
(remnant: Crab Nebula)
Black hole
Cygnus X-1


SN 2001el


Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash


a
b
c
d
e
f

# Core-collapse SNe: collapse, bounce and explosion



# Boltzmann Equation for Particles

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \left( \frac{df}{dt} \right)_{coll}$$

$$\left( \frac{df}{dt} \right)_{coll} = -\int f_s(\mathbf{v}_s) d\mathbf{v}_s \int d\mathbf{\Omega} \sigma(g, \theta) g f(\mathbf{v}) + G(\mathbf{v})$$

$$g = |\mathbf{v} - \mathbf{v}_s|$$

# Transport Equation for Photons

$$\frac{1}{c} \frac{\partial}{\partial t} \boldsymbol{I}^\nu(t, r, \Omega) + \Omega \cdot \nabla \boldsymbol{I}^\nu(t, r, \Omega) = \eta^\nu(t, r) - \chi^\nu(t, r) \boldsymbol{I}^\nu(t, r, \Omega)$$

# Boltzmann Equation for Neutrino

$$\frac{\partial f_\nu}{c\partial t} + \mathbf{\Omega} \cdot \frac{\partial f_\nu}{\partial \mathbf{r}} = \frac{1}{c}\left(\frac{d f_\nu}{dt}\right)_{coll}$$

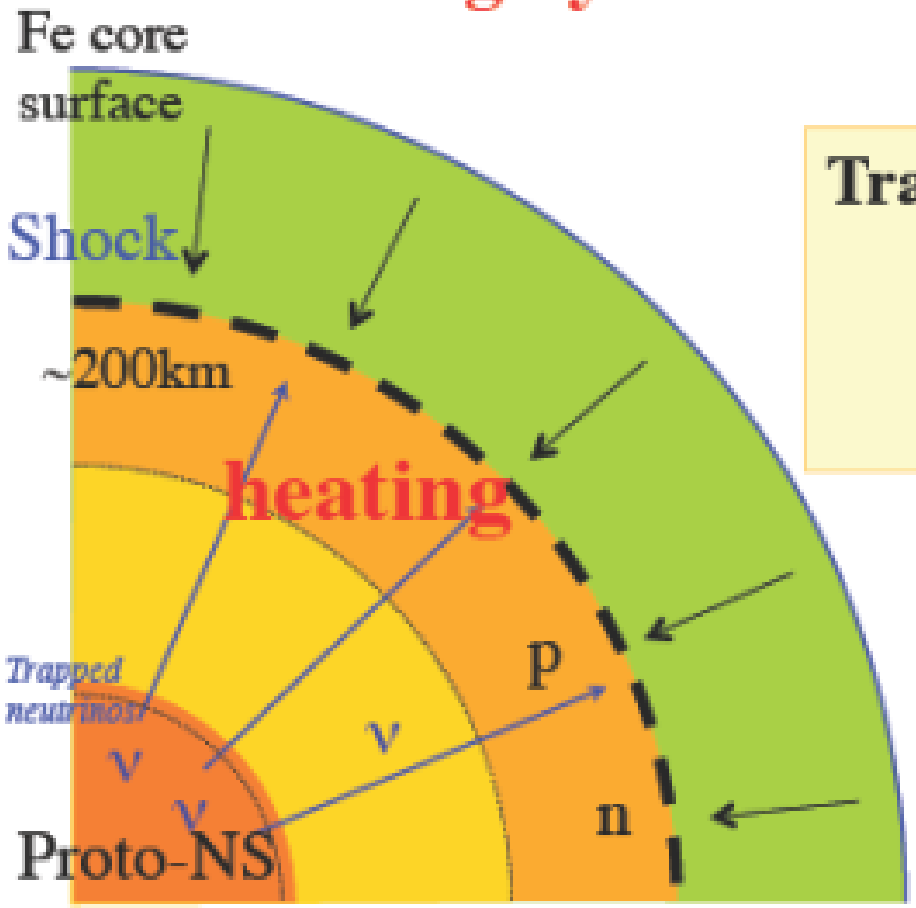
$$\begin{aligned}
e^- + p &\longleftrightarrow \nu_e + n, \\
e^+ + n &\longleftrightarrow \bar{\nu_e} + p, \\
\nu(\bar{\nu}) + N &\longleftrightarrow \nu(\bar{\nu}) + N, \\
e^- + e^+ &\longleftrightarrow \nu + \bar{\nu}, \\
N + N &\longleftrightarrow N + N + \nu + \bar{\nu},
\end{aligned}$$

$$\left(\frac{d}{dt} f\right)_{coll} = \left(\frac{d}{dt} f\right)_{em-abs} + \left(\frac{d}{dt} f\right)_{scat} + \left(\frac{d}{dt} f\right)_{pair}$$

# Neutrino heating mechanism for revival of shock

## Heating by neutrino absorption

$$\nu_e + n \rightarrow e^- + p,$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

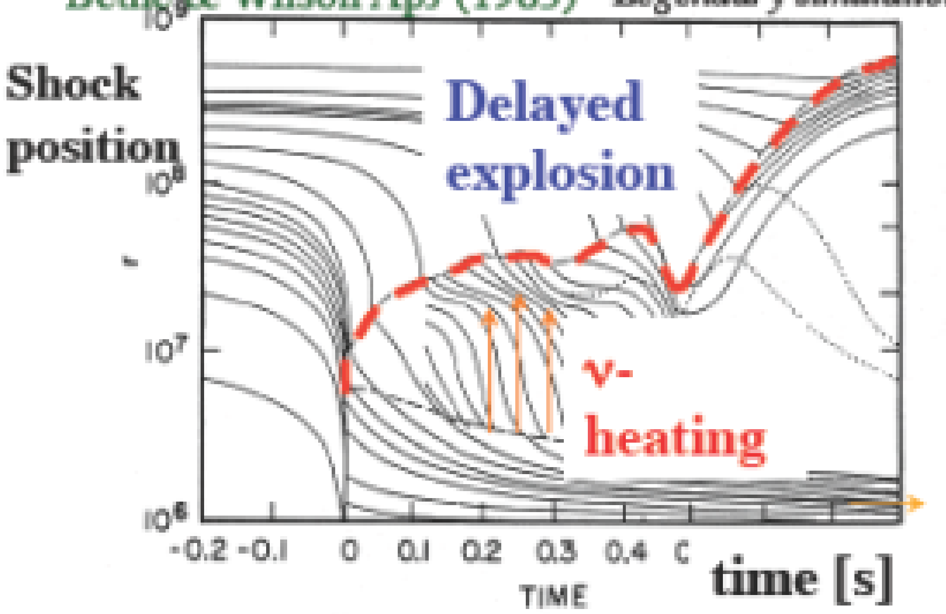



100ms after bounce

**Transfer of energy from ν** Janka A&A (1996)

$$E_{\nu-heat} \sim 2\times 10^{51}\left(\frac{\Delta M}{0.1 M_{solar}}\right)\left(\frac{\Delta t}{0.1 s}\right) erg$$

Bethe & Wilson ApJ (1985) *"Legendary simulation"*



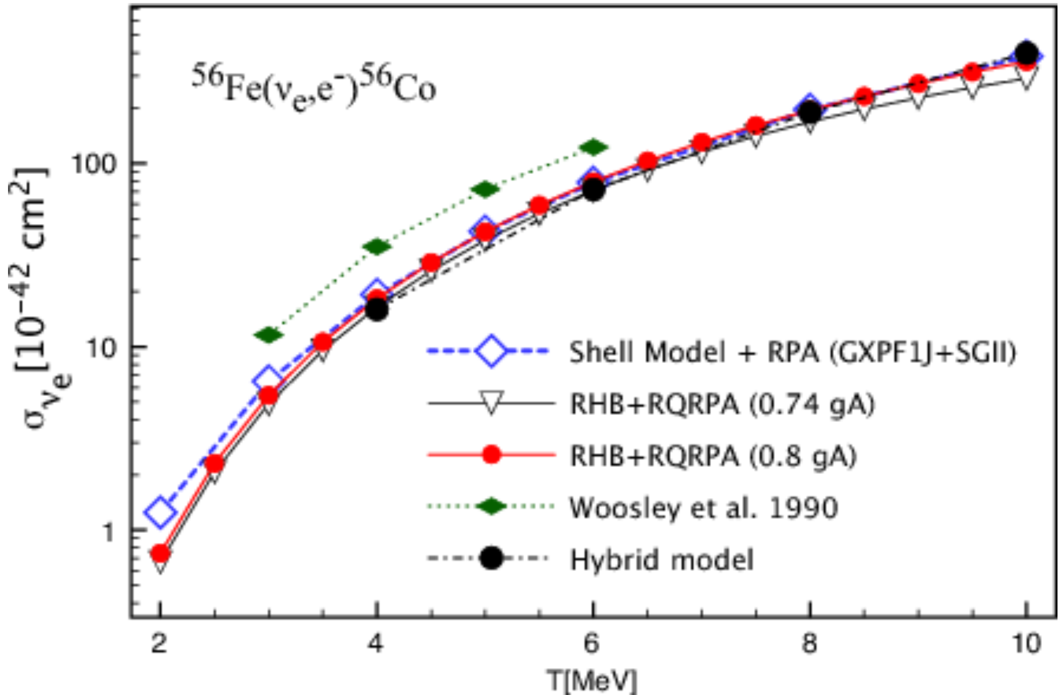

**Neutrino energy/flux from trapped neutrinos** → **neutrino transfer**

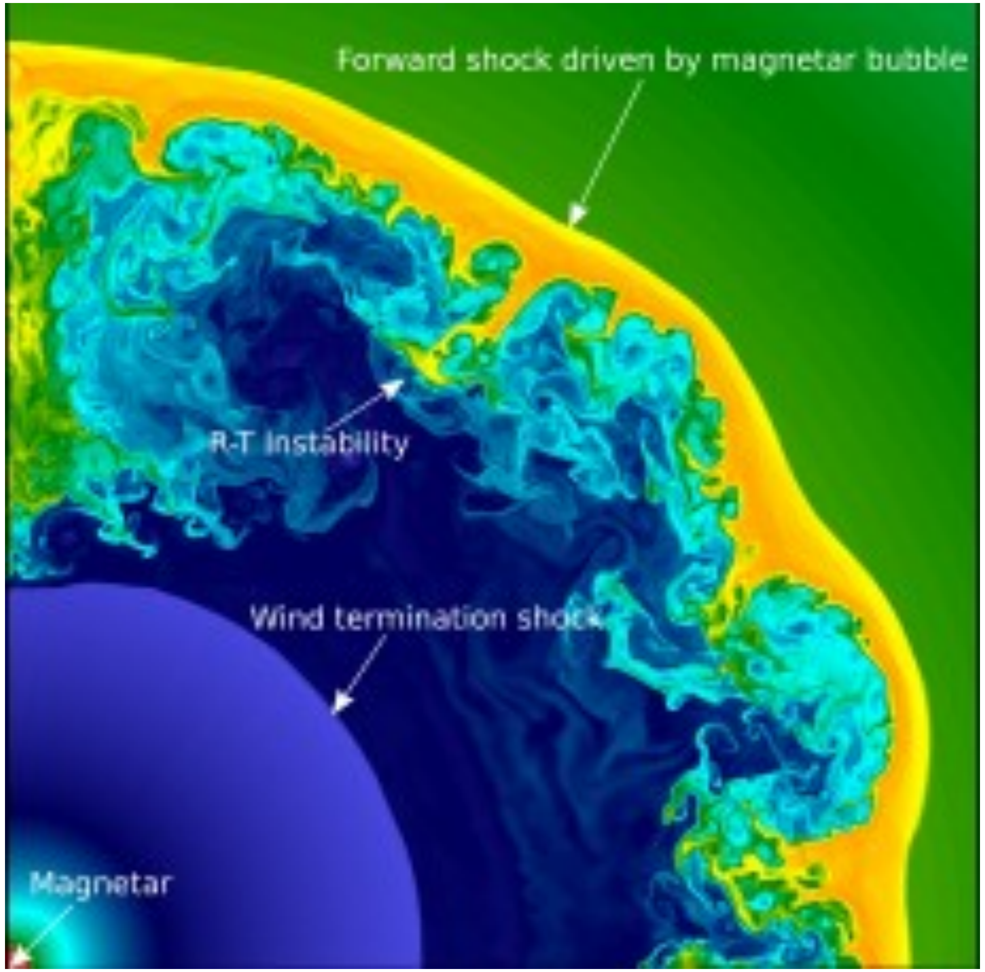
# Boltzmann eq. in spherical coordinate

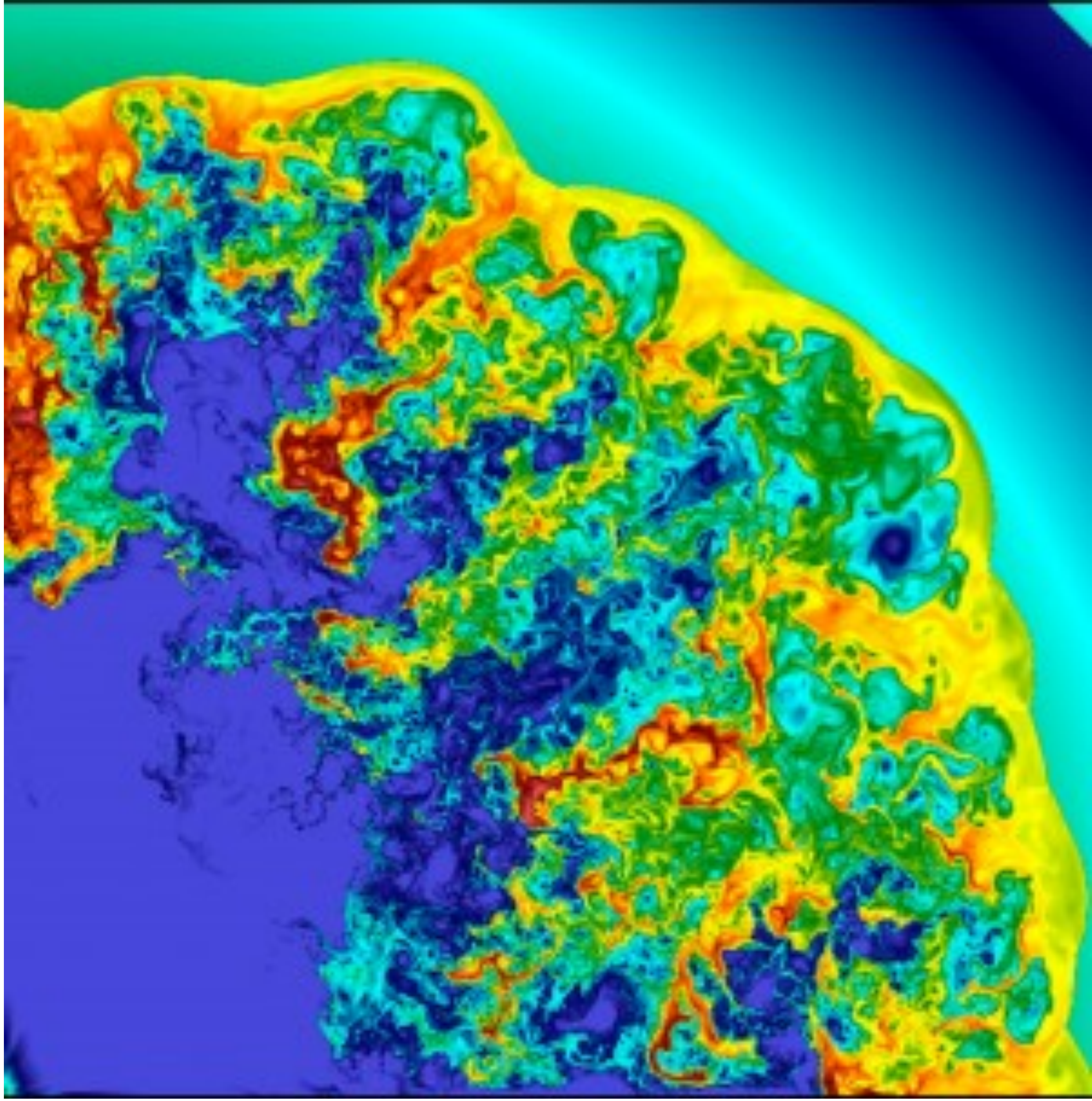
*Pomraning, Mihalas[2], Castor*

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t} + \frac{\mu_\nu}{r^2}\frac{\partial}{\partial r}(r^2 f_\nu) + \frac{\sqrt{1-\mu_\nu^2}\cos\phi_\nu}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta f_\nu) + \frac{\sqrt{1-\mu_\nu^2}\sin\phi_\nu}{r\sin\theta}\frac{\partial f_\nu}{\partial\phi}$$

$$+\frac{1}{r}\frac{\partial}{\partial\mu_\nu}[(1-\mu_\nu^2)f_\nu] + \frac{\sqrt{1-\mu_\nu^2}\cos\theta}{r\sin\theta}\frac{\partial}{\partial\phi_\nu}(\sin\phi_\nu f_\nu) = \frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$



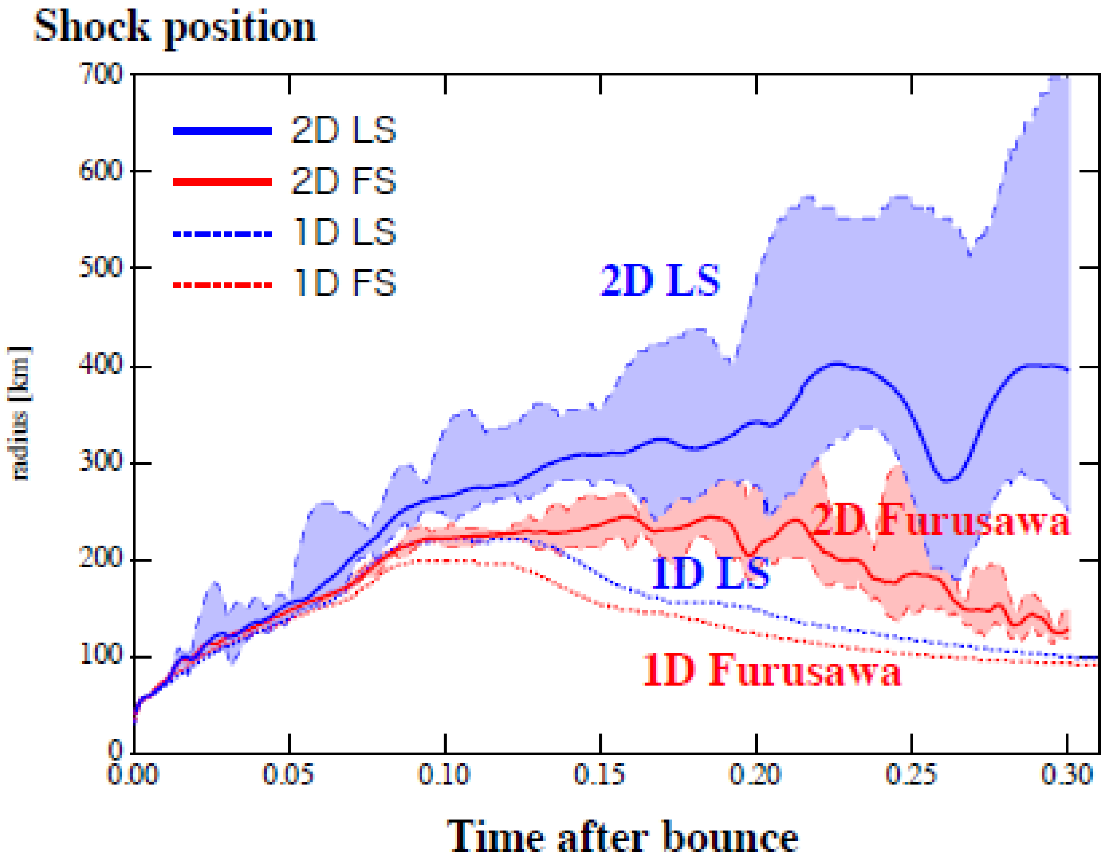


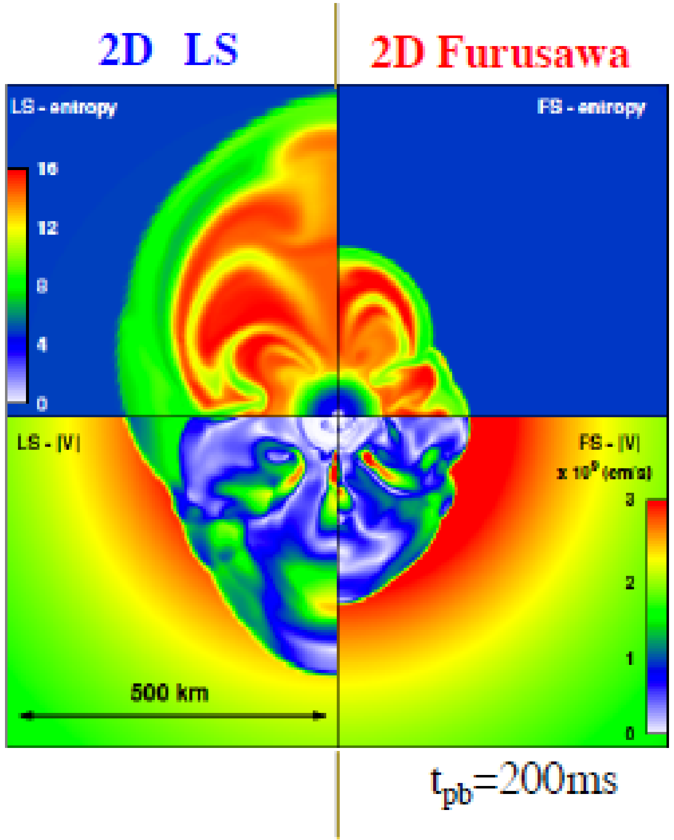



**Astrophysicist Ken Chen ran simulations on NERSC's Edison supercomputer to better understand the physical conditions that create superluminious supernova. (Credit: Ken Chen, National Astronomical Observatory of Japan)**

# Influence of EOS: simulations with Boltzmann

- 2D: Soft EOS (LS) close to explosion
  - 1D: No explosions and small difference



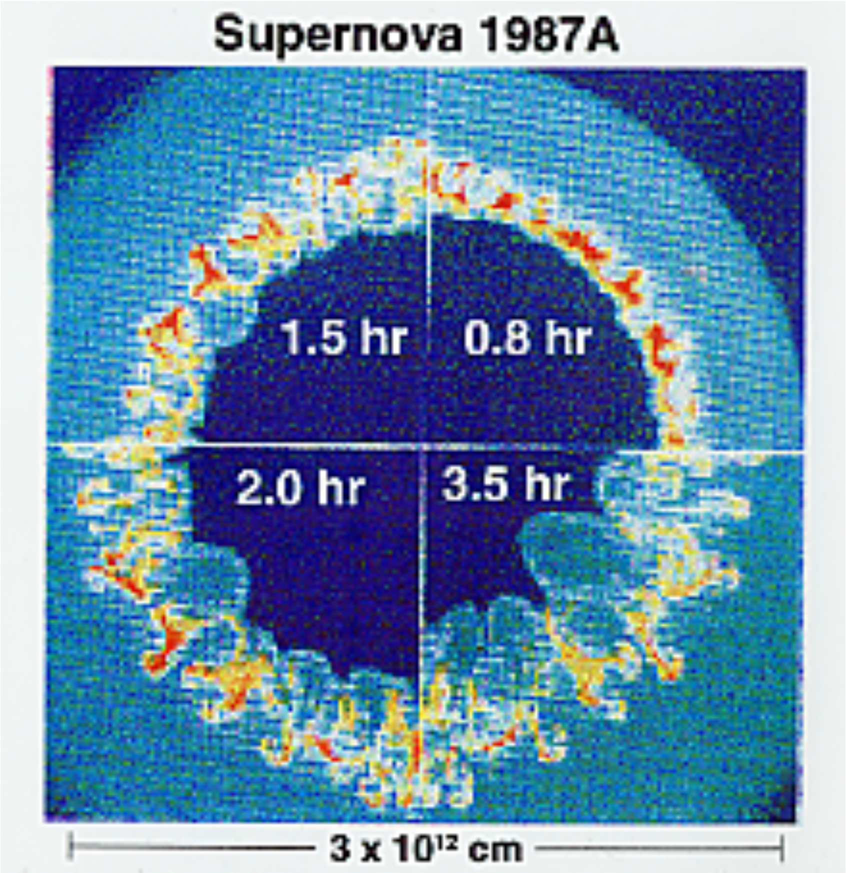



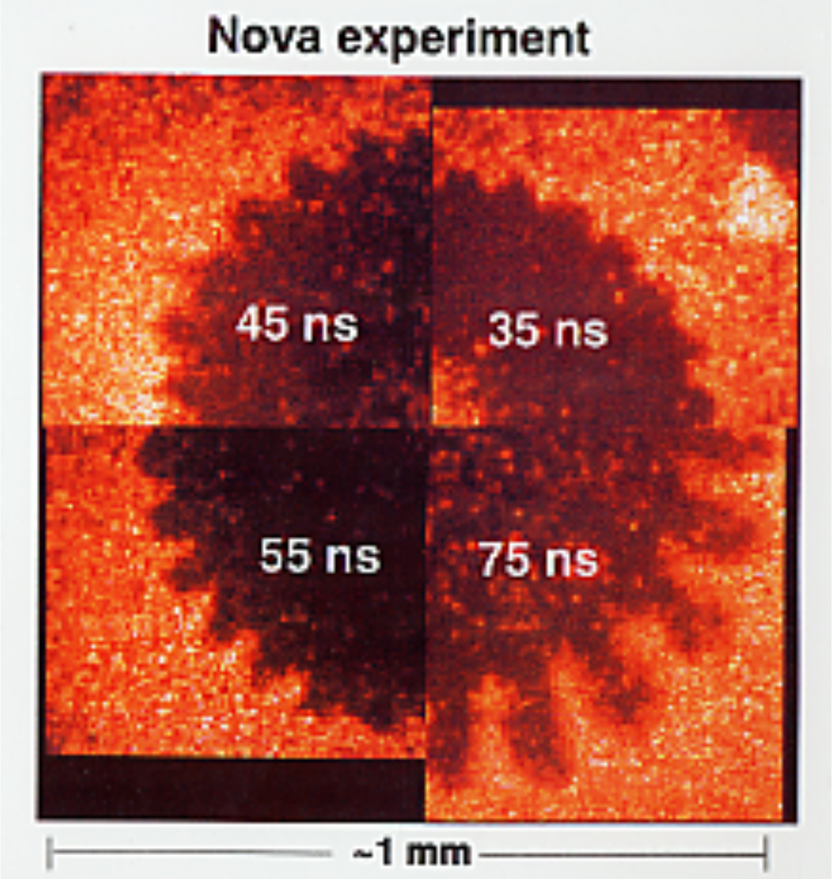

top : entropy
bottom : fluid velocity

Nagakura, Iwakami, Okawa, Harada et al. ApJ (2018)

# 1. To Validate and Verify Physics Models and Codes through Comparison with Model Experiments in Laboratory.

**Example (1): Mixing in Supernova Explosion**
**(B. Remington et al)**

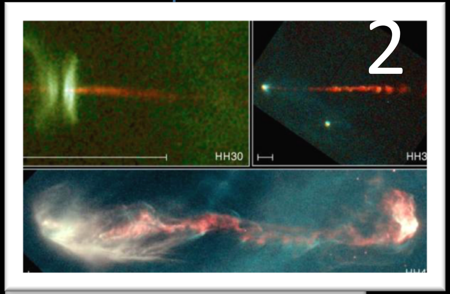


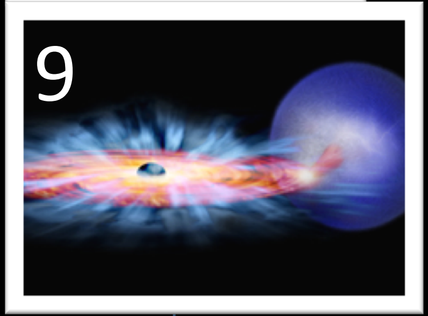

PROMETIUS Code for Astrophysics

Laser Experiment (Courtesy Kim Budil)

# Prospects


2
HH30


1
Gaseous Pillars in M16 · Eagle Nebula
Hubble Space Telescope · WFPC2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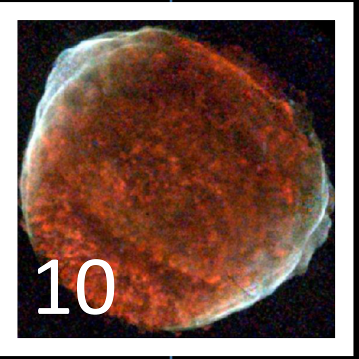
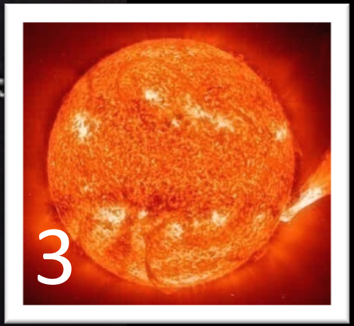

10


8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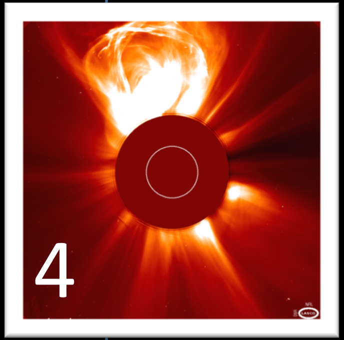
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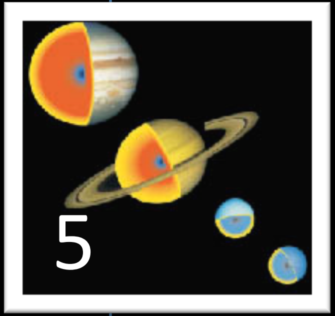
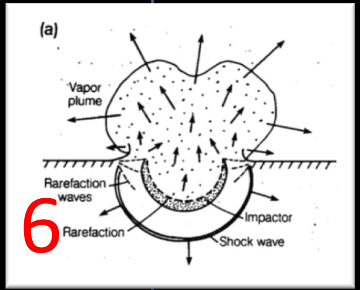
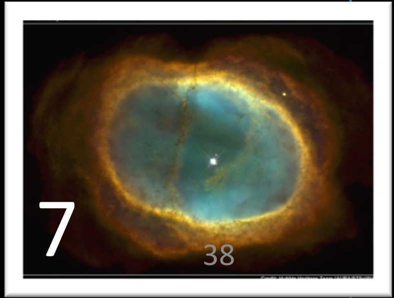

5


(a)
Vapor plume
Rarefaction waves
Impactor
Rarefaction
Shock wave
6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