中国科学院云南天文台
YUNNAN OBSERVATORIES, CHINESE ACADEMY OF SCIENCES

Introduction to supernova physics

Shuai Zha (查帅)
zhashuai@ynao.ac.cn
Yunnan Observatories, CAS
OECE 2026 @ BUAA

OECE 2026 — Shuai

BPS GROUP

ICESUN
International CEntre of SUperNOvae

Lecture outline

I. Introduction, Type Ia Supernovae, Pre-core-collapse

II. Explosion mechanism of core-collapse supernovae and modeling

III. Recent progress and frontier

OECE_2026_by_Shuai

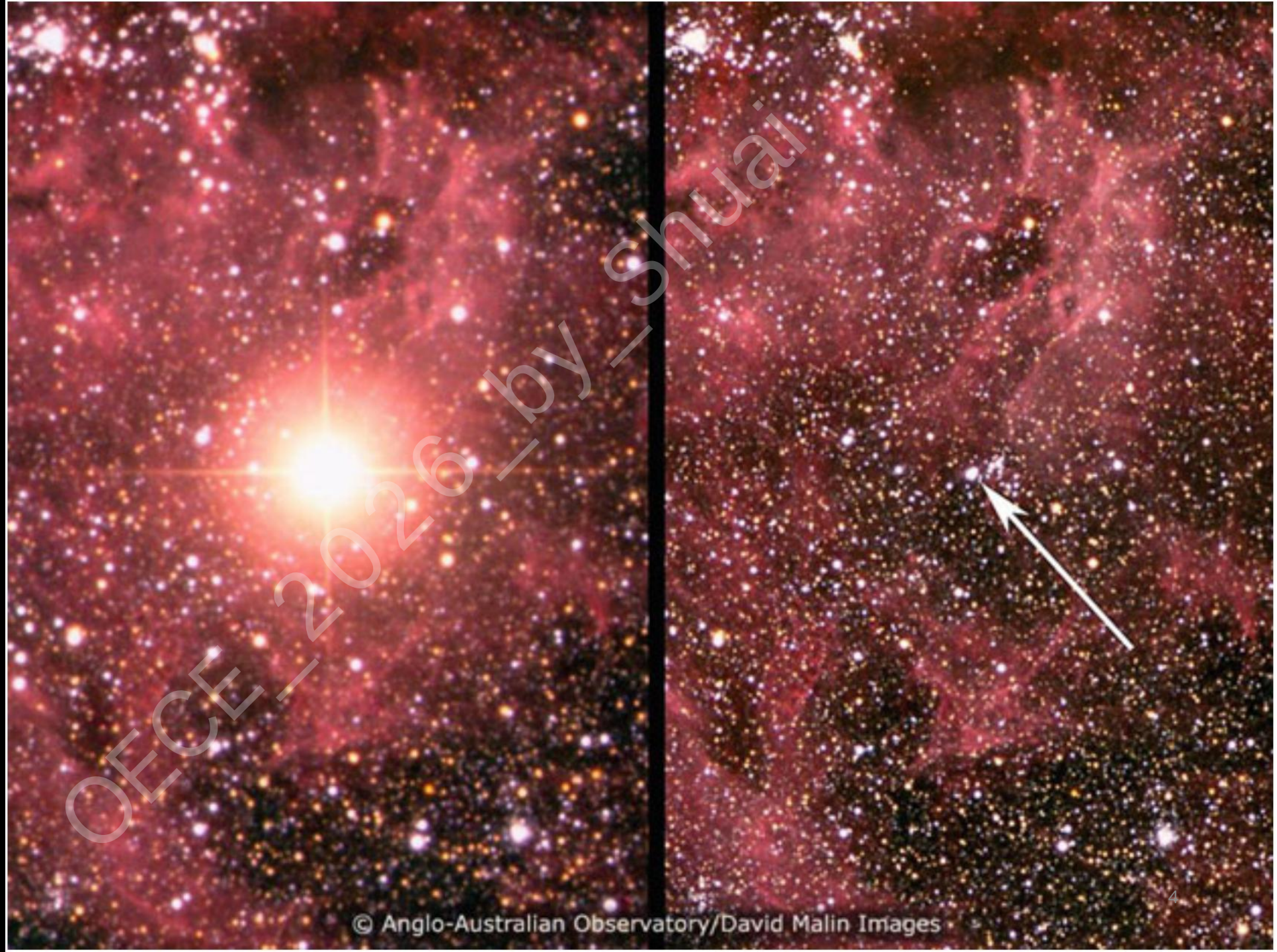


OECE_2025_by_Shuai

SN 1987A

~50 kpc away

neutrino detected!!!



OFCE_2026_by_Shuai

Supernova discoveries across the sky

Each flash marks a catalogued discovery • Equatorial coordinates (J2000)

1885

0 discoveries shown

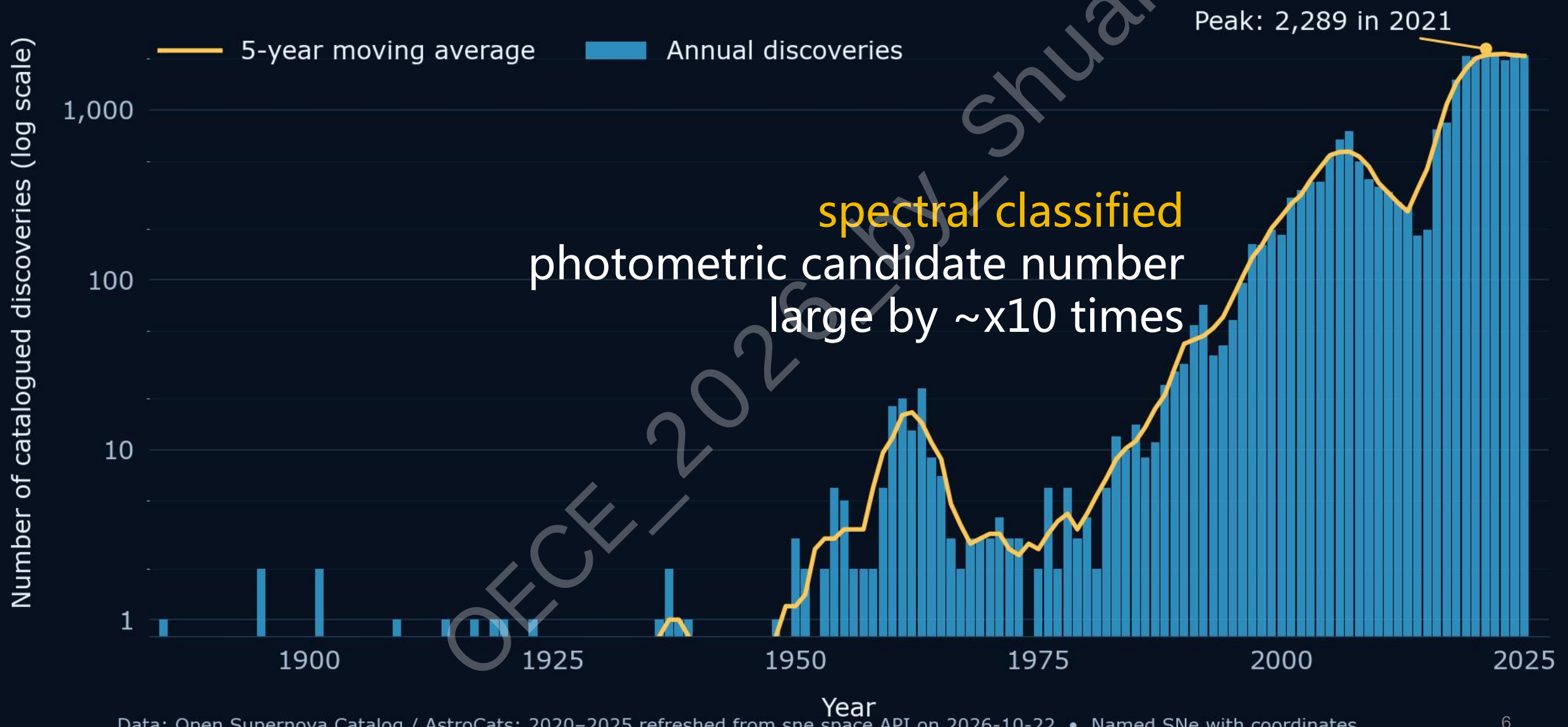


OECE_2026_by_Shuai

Data: Open Supernova Catalog / AstroCats • CC BY 4.0 • Visualization generated 2026

Supernova discoveries rose sharply with modern surveys

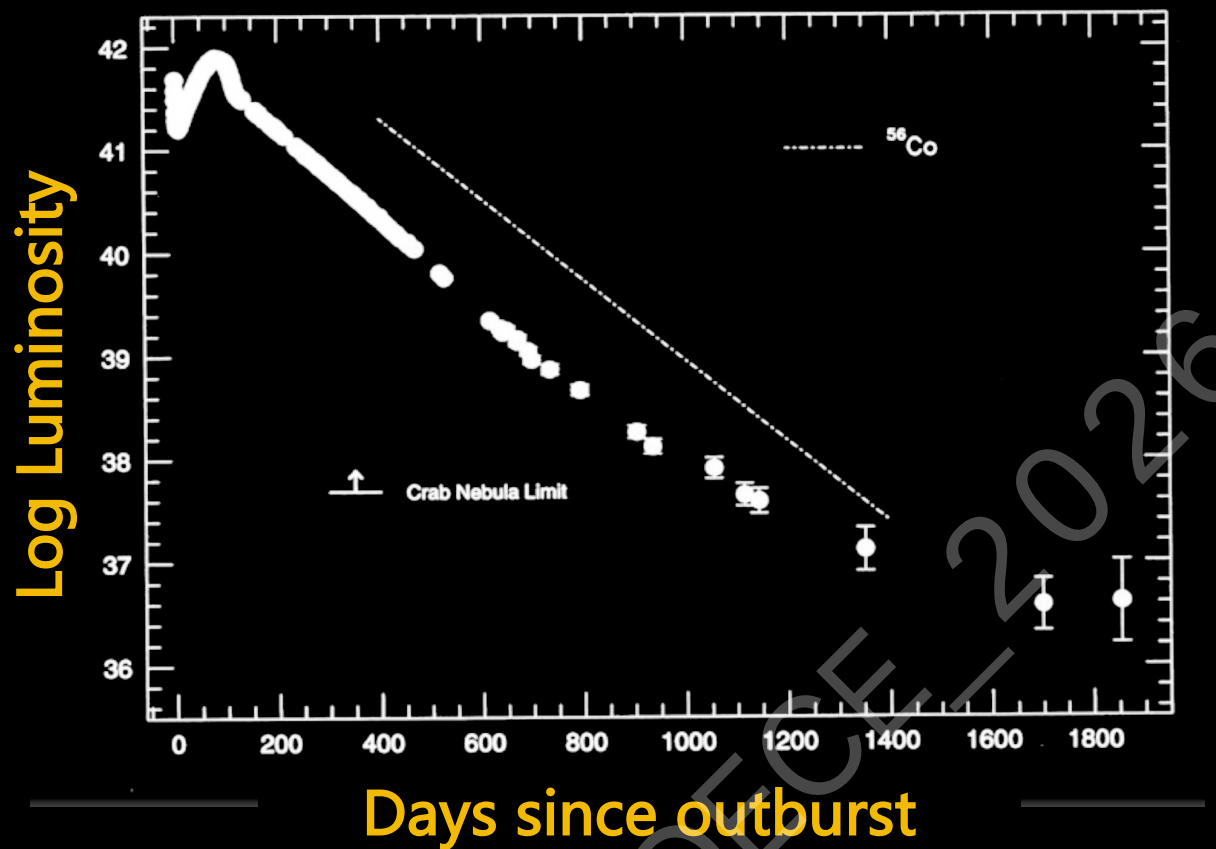
Annual discoveries with reported sky coordinates, 1885–2025

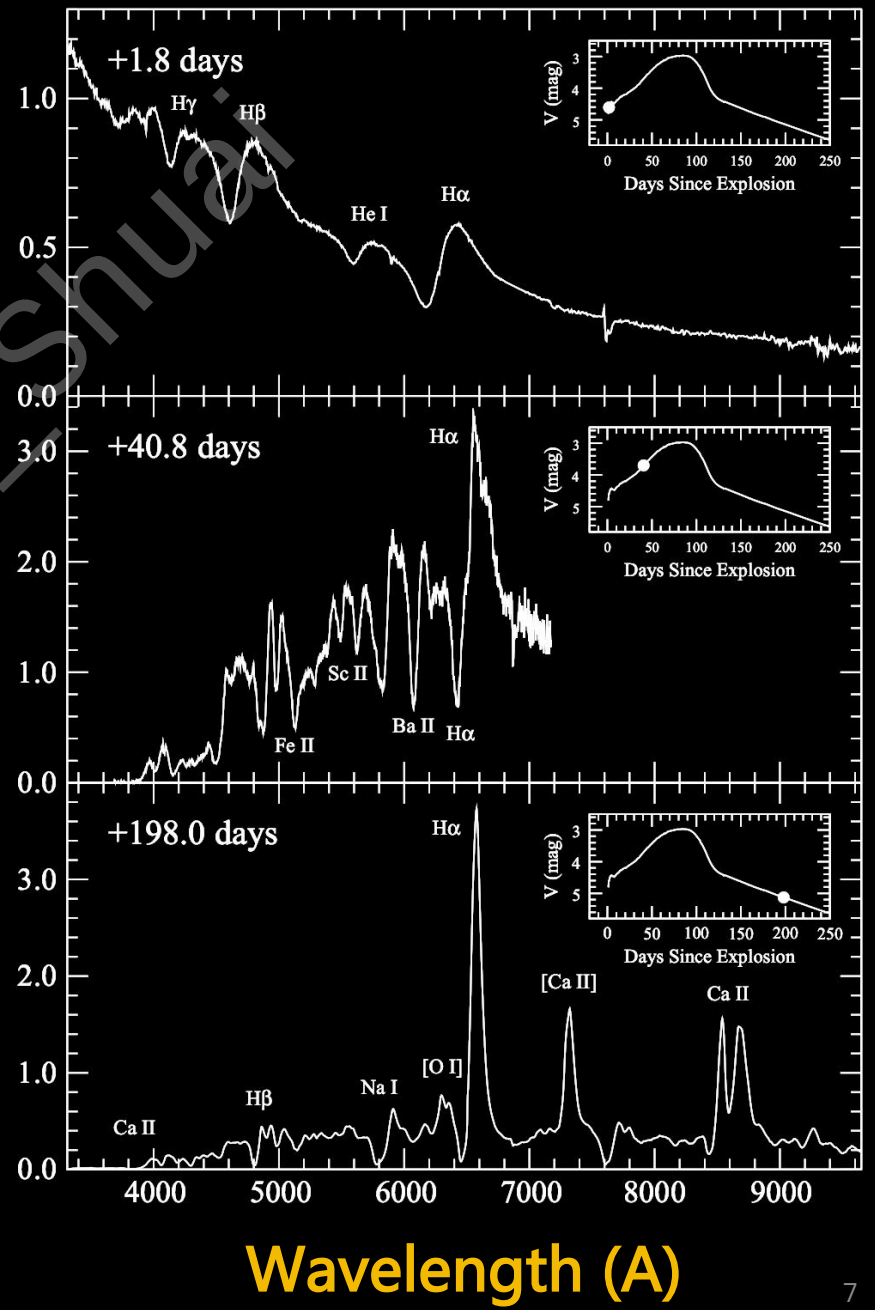


OECE_2026_by_Shuai

Data: Open Supernova Catalog / AstroCats; 2020–2025 refreshed from sne.space API on 2026-10-22 • Named SNe with coordinates

Astronomer's supernovae: light curves and spectra

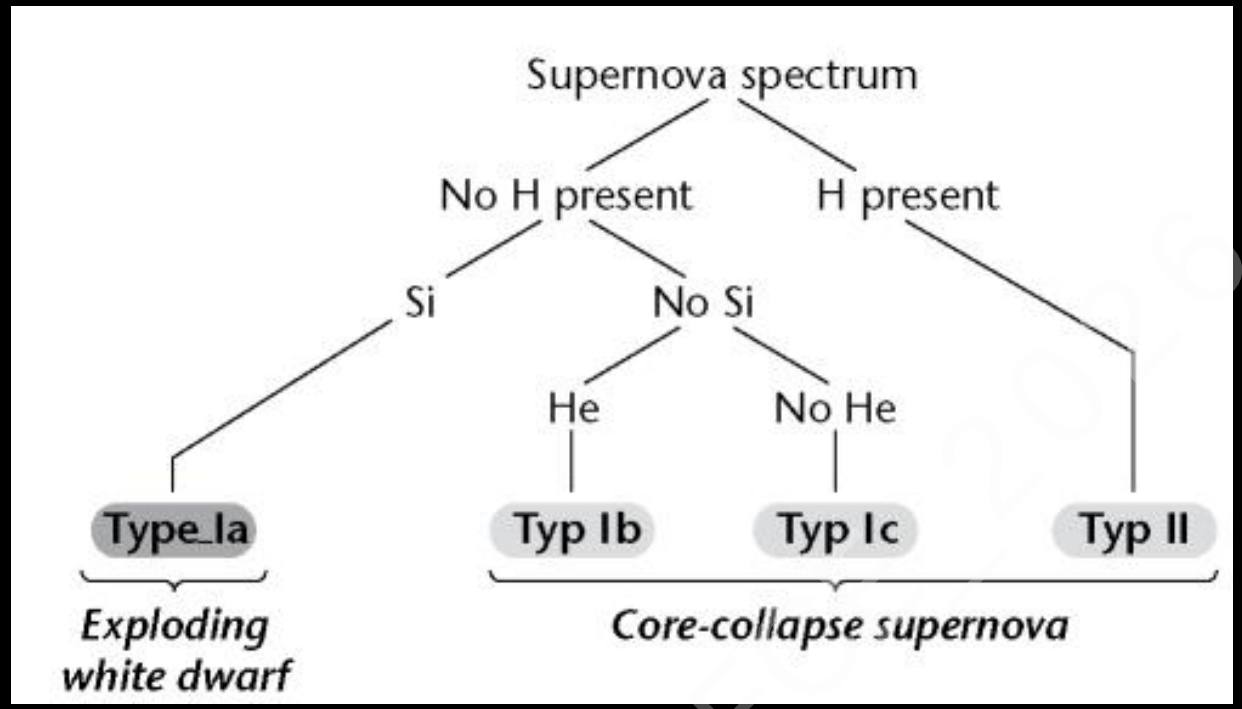


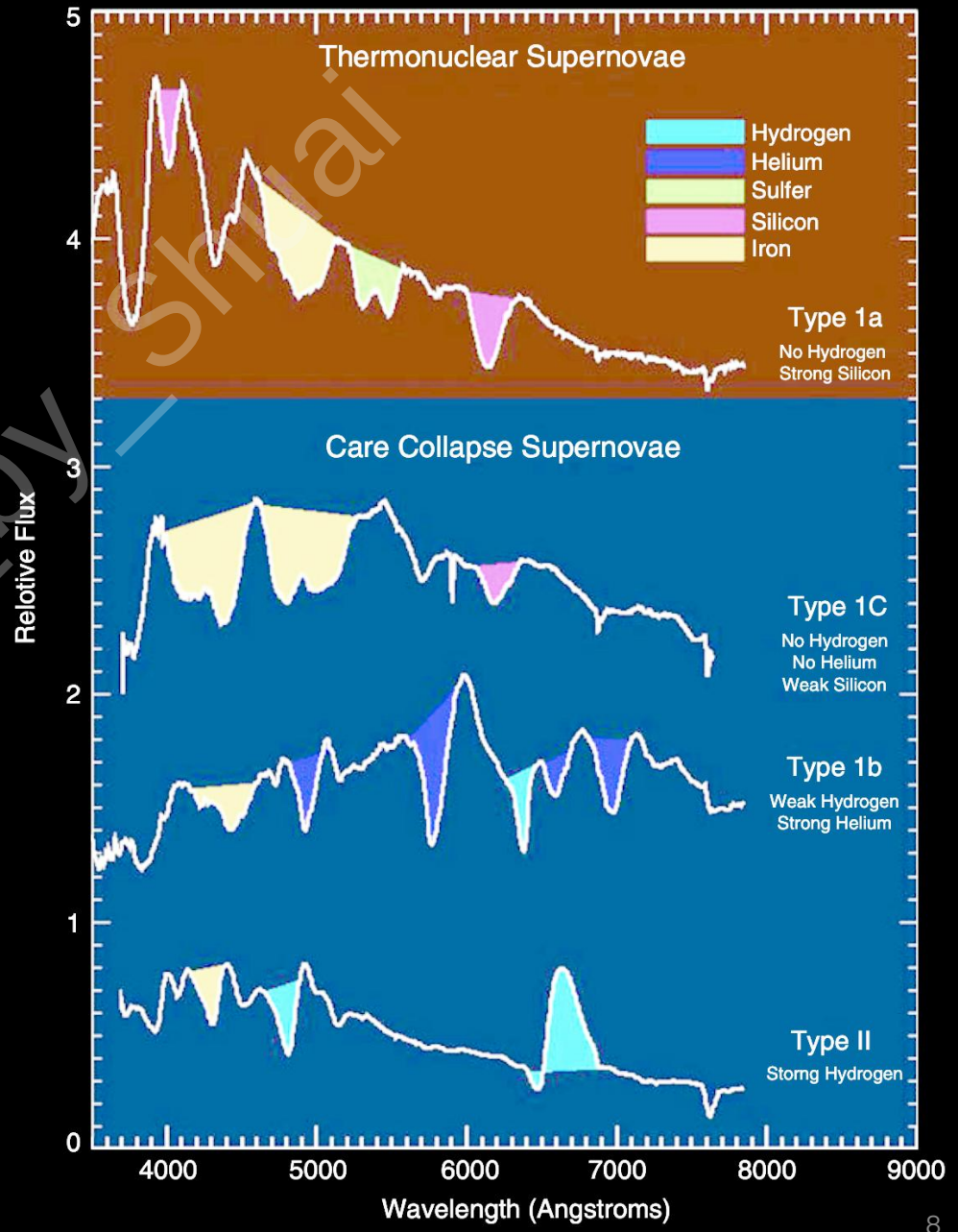


Wheeler & Branch 2017

OECF_2026_by_Shuai

Astronomer's supernovae: Classification

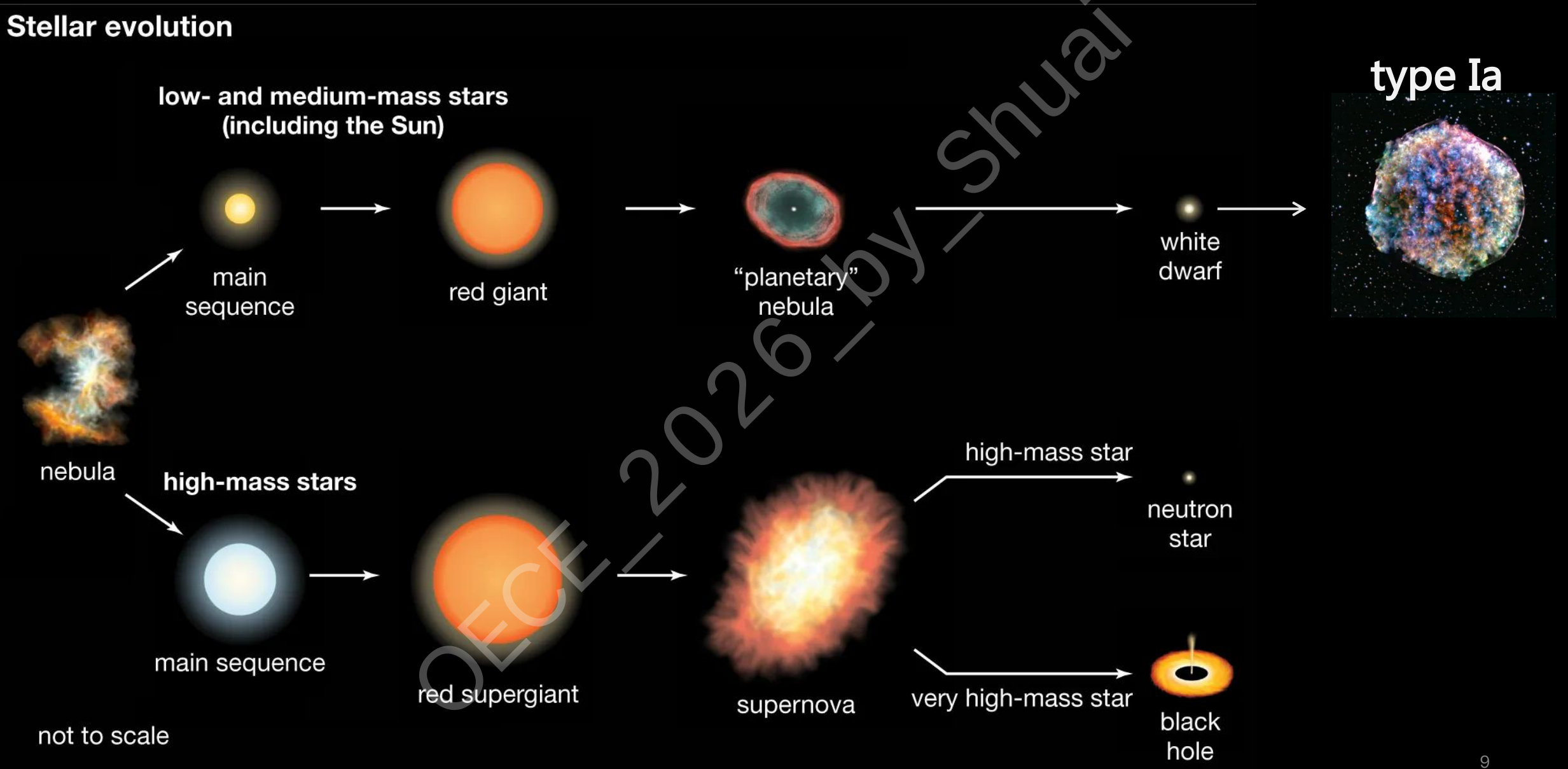




Wheeler & Branch 2017

OE 2018 by Shilai

Supernovae as end products of stellar evolution



type Ia

OECF_2026_by_Shuai

Why do we care about SNe ?

Supernovae (SNe): Death of Stars
- White dwarf → SN Ia
- Massive stars –> core–collapse



SN 1987A (HST+JWST)

Feedbacks by
- explosion shocks
- nucleosynthesis

to galactic evolution

Compact remnant
- Neutron stars
- Black holes

Multi-messengers
- IR, optical, UV
- X-rays, γ-rays
- kHz GWs
- MeV neutrinos

© H. Nomoto

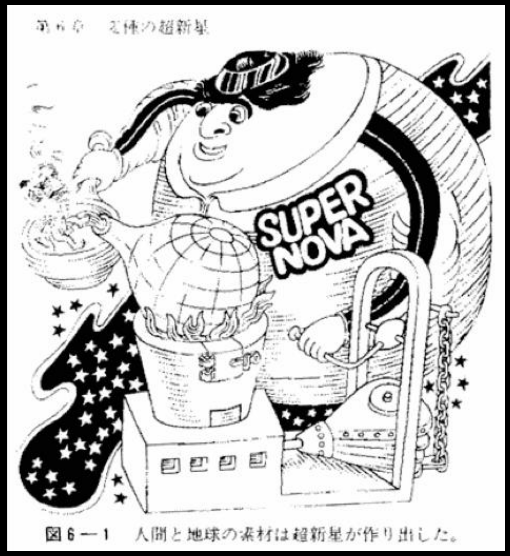


図6－1　人間と地球の素材は超新星が作り出した。

OECF_2026_by_Shudai

The key topic of this lecture



Artist's conception of a star exploding as a supernova ©NASA

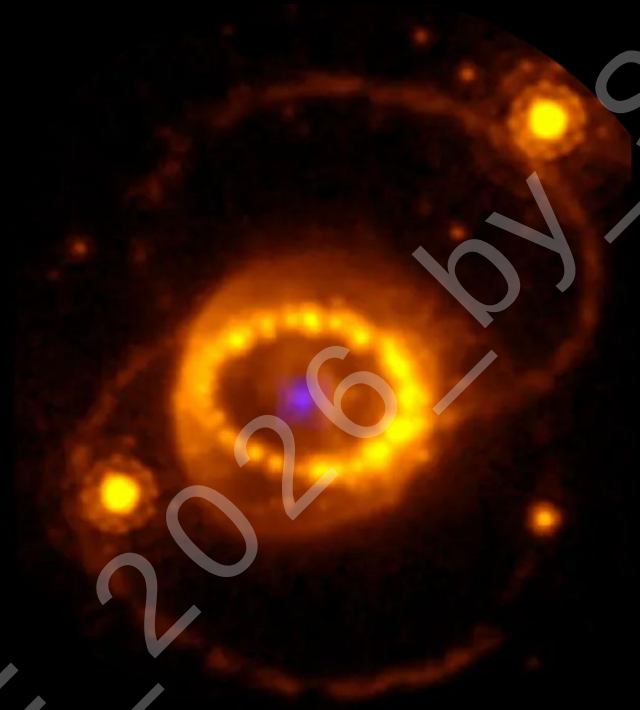
- We know that stars are exploding and we observe numerous supernovae in electromagnetic waves
- But what is the physics driving the explosion?
- Can we reproduce the explosions on computers?
- If yes, how can we verify that we are correct?

OECE_2026_by_Shuai

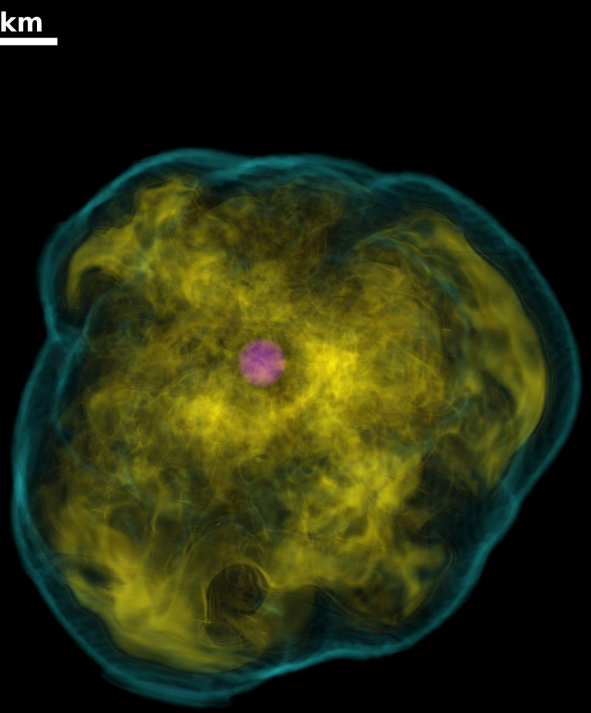
Different views of supernovae



“Usual” supernova discoveries ~10^4/year



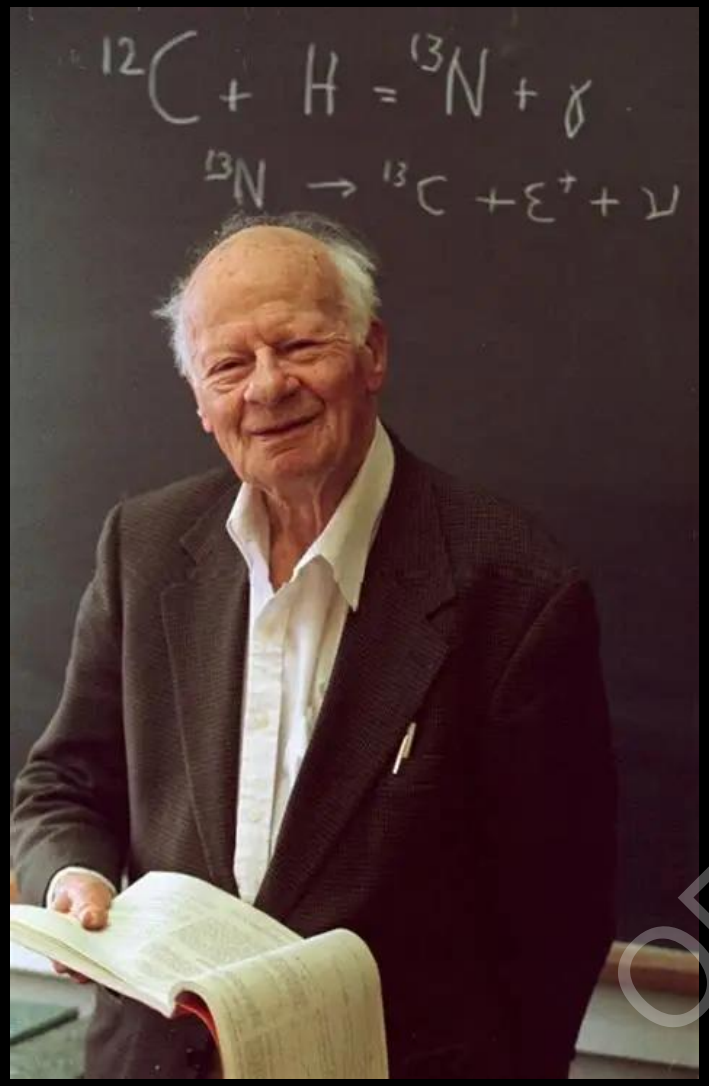
Nearby supernova



‘Our’ supernova core

OECE_2026_by_Shuai

Hans A. Bethe and supernova theory



- Nobel prize in Physics (1967) for the theory of nuclear reactions in stars, pp-chain, CNO cycle
- From age of 70 to 95, enjoyed supernova theory
- Typical explosion energy: 1 B(ethe) = 10^{51} erg

Bethe 1990 RvMP

Supernova mechanisms

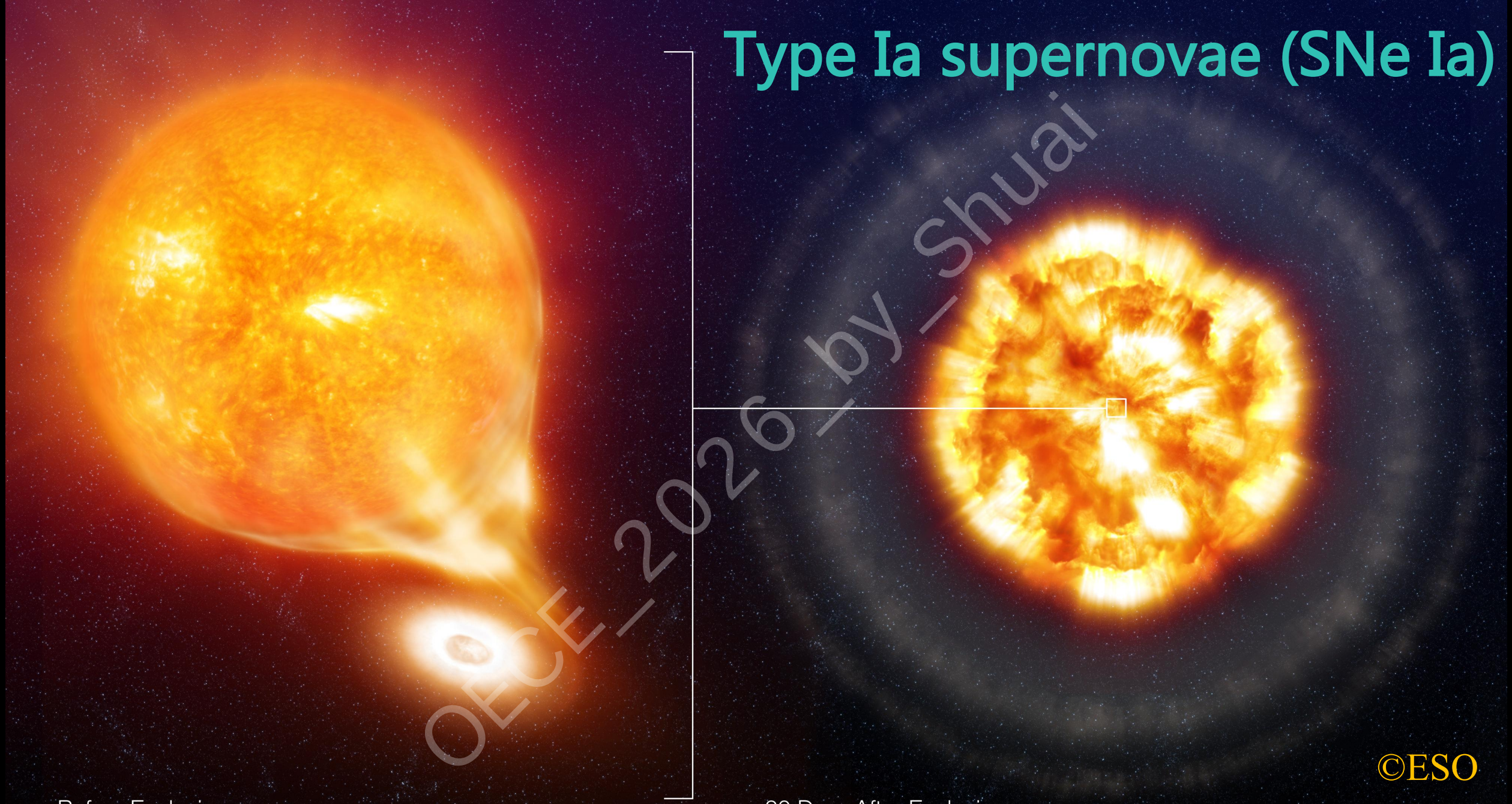
H. A. Bethe

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

Supernovae of Type II occur at the end of the evolution of massive stars. The phenomenon begins when the iron core of the star exceeds a Chandrasekhar mass. The collapse of that core under gravity is well understood and takes a fraction of a second. To understand the phenomenon, a detailed knowledge of the equation of state at the relevant densities and temperatures is required. After collapse, the shock wave moves outward, but probably does not succeed in expelling the mass of the star. The most likely mechanism to do so is the absorption of neutrinos from the core by the material at medium distances. Observations and theory connected with SN 1987A are discussed, as are the conditions just before collapse and the emission of neutrinos by the collapsed core.

OECP_Slides_by_Shuai

Type Ia supernovae (SNe Ia)



OECE_2026_by_Shuai

©ESO

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **454,** 1238–1259 (2015) doi:10.1093/mnras/stv1923

A new hydrodynamics code for Type Ia supernovae

S.-C. Leung,★ M.-C. Chu and L.-M. Lin

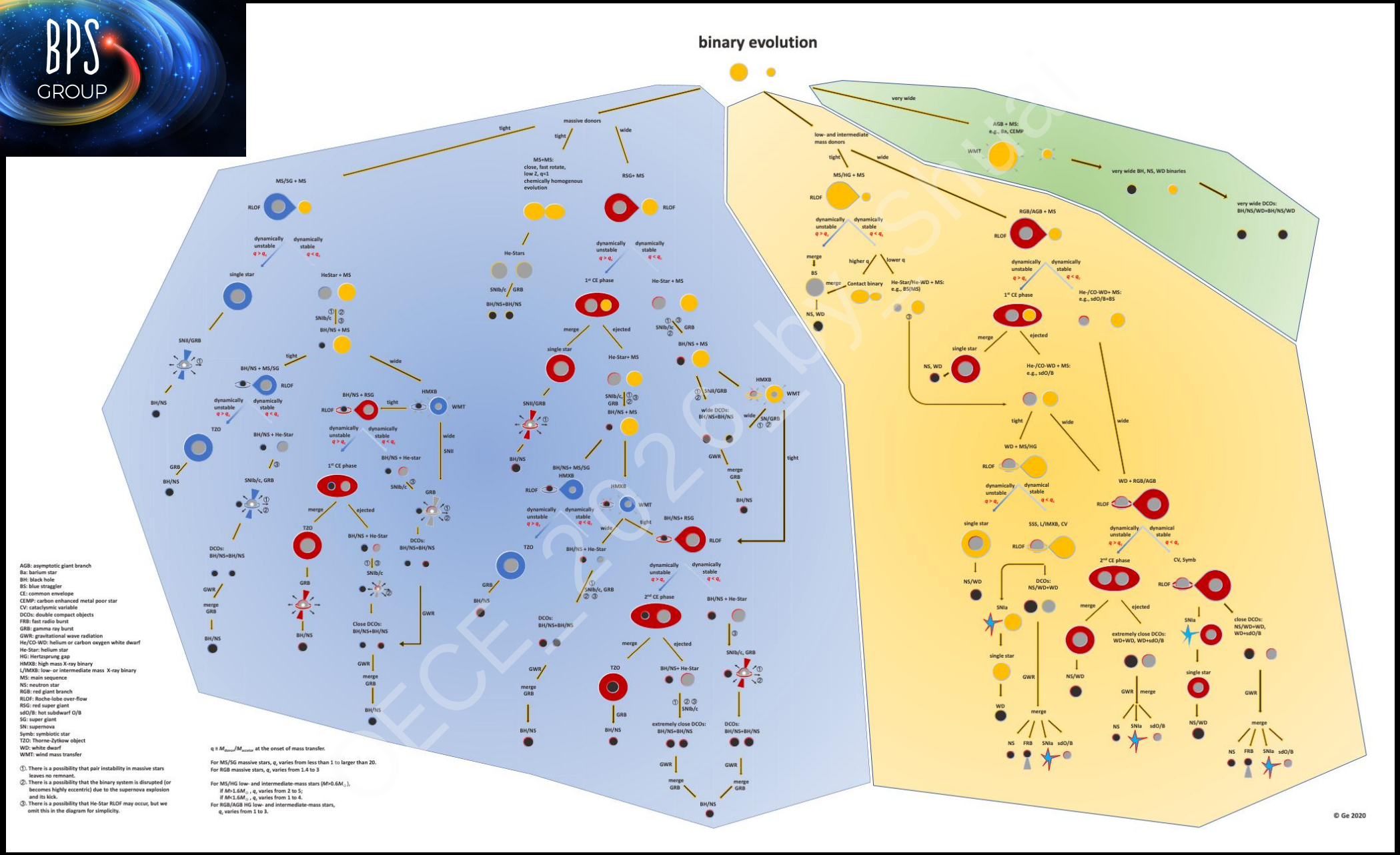
Department of Physics and Institute of Theoretical Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong S.A.R., China

Accepted 2015 August 18. Received 2015 August 18; in original form 2015 May 26

ABSTRACT

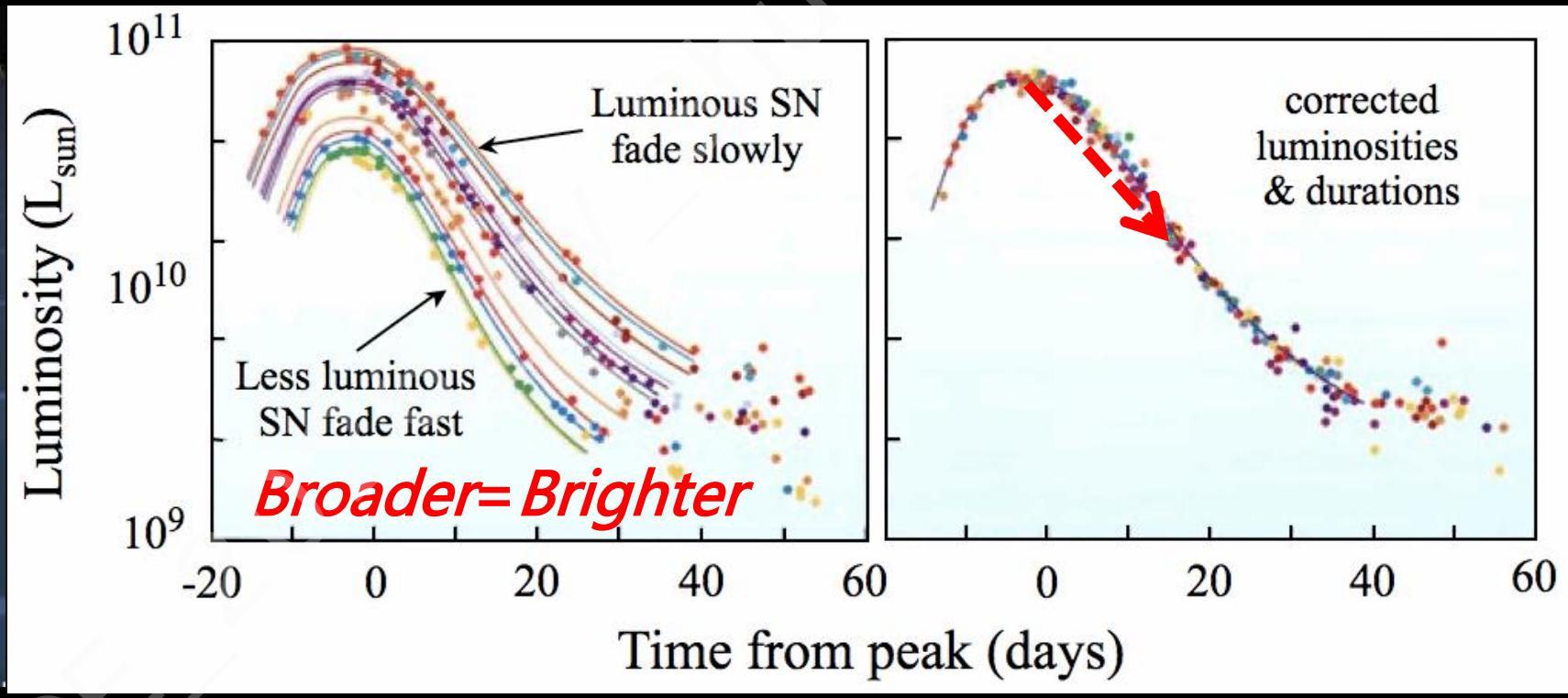
A two-dimensional hydrodynamics code for Type Ia supernova (SNIa) simulations is presented. The code includes a fifth-order shock-capturing scheme WENO, detailed nuclear reaction network, flame-capturing scheme and sub-grid turbulence. For post-processing, we have developed a tracer particle scheme to record the thermodynamical history of the fluid elements. We also present a one-dimensional radiative transfer code for computing observational signals. The code solves the Lagrangian hydrodynamics and moment-integrated radiative transfer equations. A local ionization scheme and composition dependent opacity are included. Various verification tests are presented, including standard benchmark tests in one and two dimensions. SNIa models using the pure turbulent deflagration model and the delayed-detonation transition model are studied. The results are consistent with those in the literature. We compute the detailed chemical evolution using the tracer particles' histories, and we construct corresponding bolometric light curves from the hydrodynamics results. We also use a GPU to speed up the computation of some highly repetitive subroutines. We achieve an acceleration of 50 times for some subroutines and a factor of 6 in the global run time.

Downloaded from academic.oup.com/mnras/arti


binary evolution
massive donors
tight
wide
MS/SG + MS
RLOF
dynamically unstable
dynamically stable
single star
HeStar + MS
SNIb/c
BH/NS + MS
SNII/GRB
BH/NS
BH/NS + MS/SG
BH/NS + RSG
HMXB
WMT
TZO
GRB
BH/NS + He-Star
SNIb/c, GRB
1st CE phase
merge
ejected
DCOs: BH/NS+BH/NS
GWR
Close DCOs: BH/NS+BH/NS
MS+MS: close, fast rotate, low Z, q=1 chemically homogenous evolution
RSG+ MS
He-Stars
BH/NS+BH/NS
He-Star+ MS
SNII
BH/NS+ MS/SG
BH/NS+ RSG
2nd CE phase
extremely close DCOs: BH/NS+BH/NS
very wide
AGB + MS: e.g., Ba, CEMP
very wide BH, NS, WD binaries
very wide DCOs: BH/NS/WD+BH/NS/WD
low- and intermediate mass donors
MS/HG + MS
RGB/AGB + MS
merge
BS
higher q
lower q
Contact binary
He-Star/He-WD + MS: e.g., BS(MS)
NS, WD
He-/CO-WD+ MS: e.g., sdO/B+BS
He-/CO-WD + MS: e.g., sdO/B
WD + MS/HG
WD + RGB/AGB
SSS, L/IMXB, CV
CV, Symb
NS/WD
DCOs: NS/WD+WD
SNIa
extremely close DCOs: WD+WD, WD+sdO/B
close DCOs: NS/WD+WD, WD+sdO/B
WD
NS
FRB
sdO/B
AGB: asymptotic giant branch
Ba: barium star
BH: black hole
BS: blue straggler
CE: common envelope
CEMP: carbon enhanced metal poor star
CV: cataclysmic variable
DCOs: double compact objects
FRB: fast radio burst
GRB: gamma ray burst
GWR: gravitational wave radiation
He/CO-WD: helium or carbon oxygen white dwarf
He-Star: helium star
HG: Hertzsprung gap
HMXB: high mass X-ray binary
L/IMXB: low- or intermediate mass X-ray binary
MS: main sequence
NS: neutron star
RGB: red giant branch
RLOF: Roche-lobe over-flow
RSG: red super giant
sdO/B: hot subdwarf O/B
SG: super giant
SN: supernova
Symb: symbiotic star
TZO: Thorne-Żytkow object
WD: white dwarf
WMT: wind mass transfer
①. There is a possibility that pair instability in massive stars leaves no remnant.
②. There is a possibility that the binary system is disrupted (or becomes highly eccentric) due to the supernova explosion and its kick.
③. There is a possibility that He-Star RLOF may occur, but we omit this in the diagram for simplicity.
q = Mdonor/Maccretor at the onset of mass transfer.
For MS/SG massive stars, q, varies from less than 1 to larger than 20.
For RGB massive stars, q, varies from 1.4 to 3
For MS/HG low- and intermediate-mass stars (M>0.6M⊙),
if M>1.6M⊙ , q, varies from 2 to 5;
if M<1.6M⊙ , q, varies from 1 to 4.
For RGB/AGB HG low- and intermediate-mass stars, q, varies from 1 to 3.
© Ge 2020

SNe Ia as cosmic standardizable candles



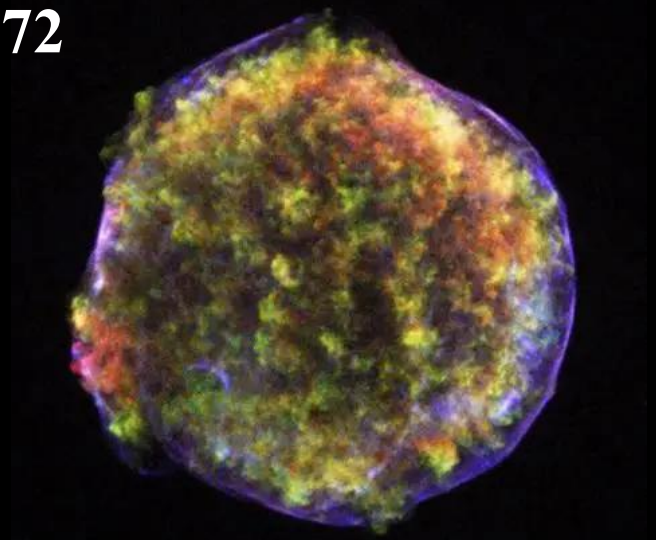


The Phillips relation: $M_{max}(B) = -21.726 + 2.698\Delta m_{15}(B)$

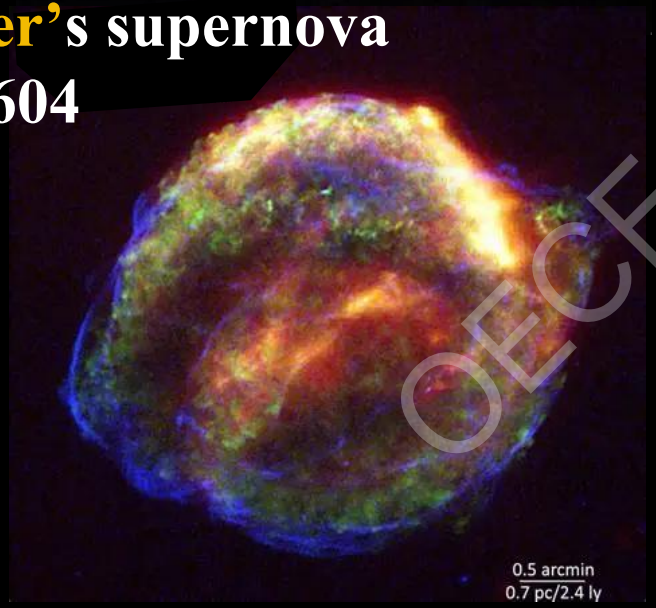
☐ the relation between absolute peak brightness and fading rate in 15 days

Facts about SNe Ia

Tycho's supernova
SN 1572



Kepler's supernova
SN 1604

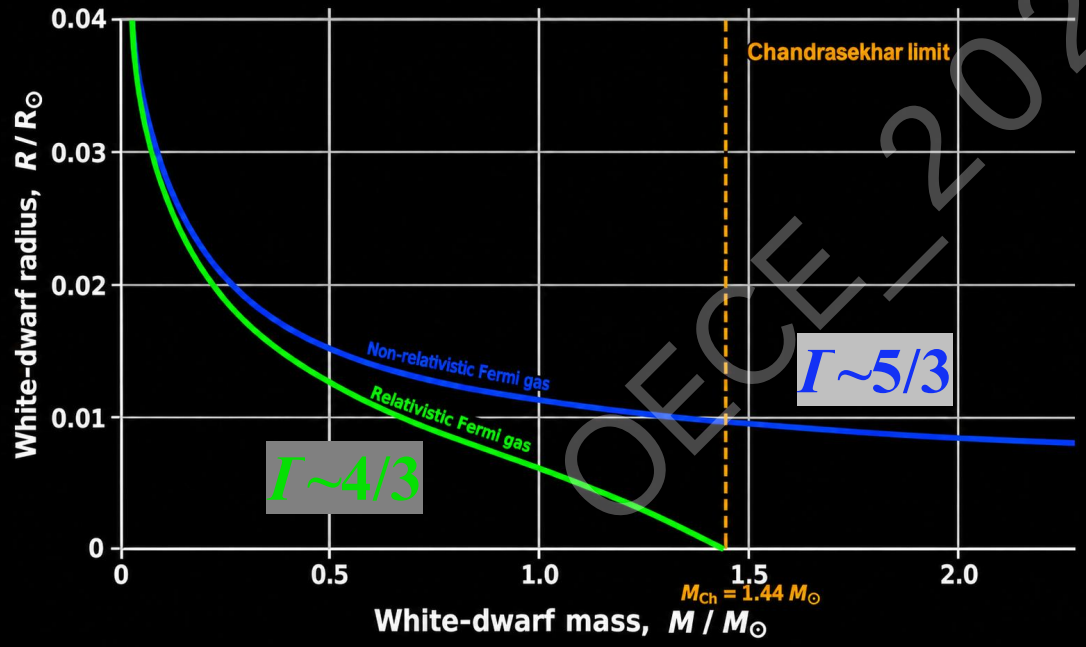


- Very bright, regular peak luminosity ~$10^{10}\ L_{\odot}$
- Associated with old stellar population
- No hydrogen in spectra; strong lines of Si, Ca, Fe
- Total kinetic energy ~1 B and no compact remnant
- ~3/4 in all observed supernovae, but intrinsically 1/4 (they are brighter; survey dependent)
- Thermonuclear explosions of white dwarfs

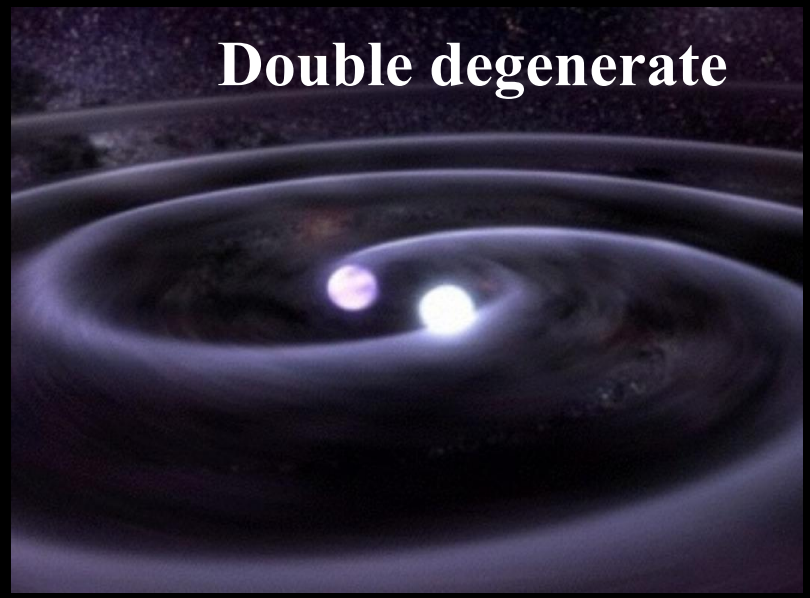
OECE_2026_by_Shuai

Progenitors of SNe Ia

- White dwarfs (He, CO, ONe): Electron degeneracy pressure against gravity
- Maximum mass of a cold, non-rotating WD (Chandrasekhar limit) @ ~1.44 $M_\odot$, and becomes unstable when reaching it
- Can be sub-Chandra. in WD mergers







OECE_2026_by_Shuai

Physics driving SN Ia explosions

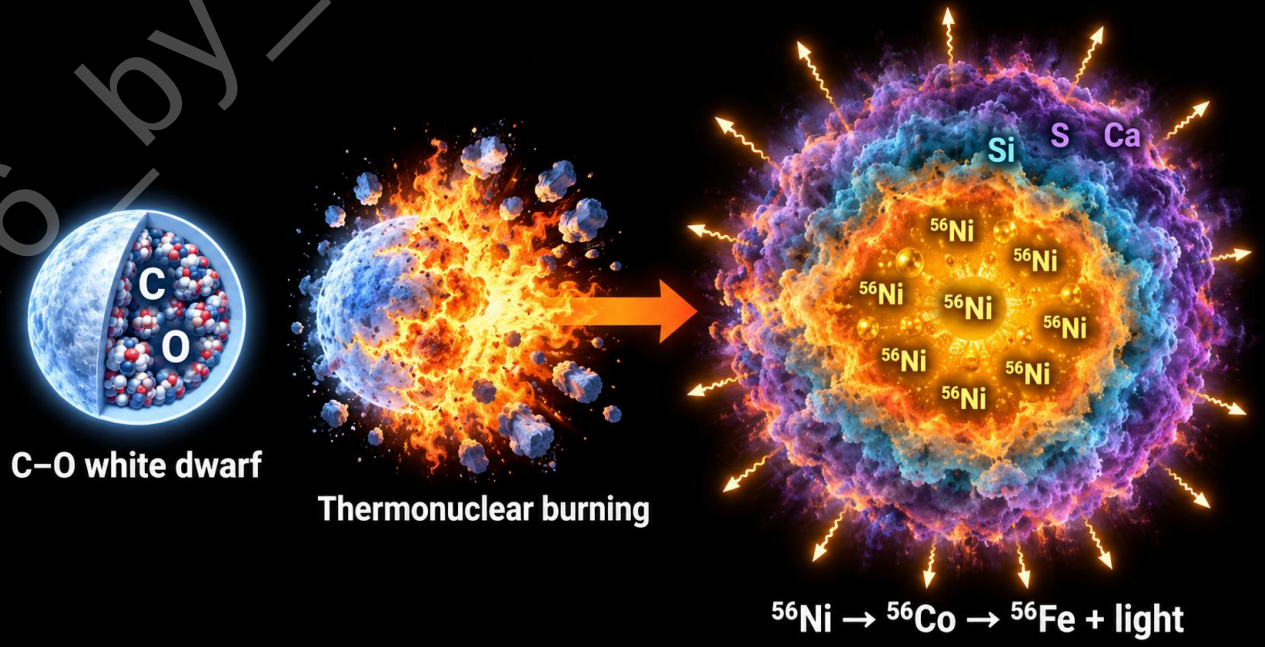
Rule of thumb: **thermonuclear burning of ^{12}C and ^{16}O in the progenitor WD producing iron-group elements, especially: ^{56}Ni**

$$\frac{M_{^{56}\mathrm{Ni}}}{m_u}\times\left[\frac{B(^{56}\mathrm{Ni})}{56}-0.5\times\left(\frac{B(^{12}\mathrm{C})}{12}+\frac{B(^{16}\mathrm{O})}{16}\right)\right]$$

$$\simeq\frac{M_{^{56}\mathrm{Ni}}}{M_\odot}\times\frac{1.99\times10^{33}\,\mathrm{g}}{1.66\times10^{-24}\,\mathrm{g}}$$

$$\times\,[8.64\,\mathrm{MeV}-0.5\times(7.68\,\mathrm{MeV}+7.98\,\mathrm{MeV})]$$

$$\simeq\frac{M_{^{56}\mathrm{Ni}}}{M_\odot}\times1.56\times10^{51}\,\mathrm{erg},$$

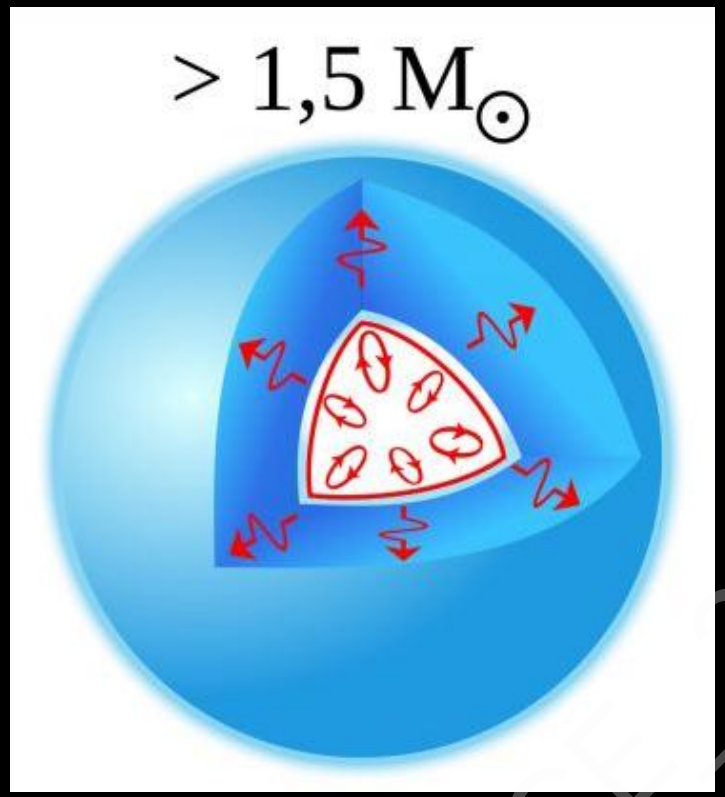


- $B=[(A-Z)m_n+Zm_p-M_{nuc}]c^2$; nuclear binding energy,
- M_{56Ni} is the mass of synthesized ^{56}Ni

Credit: ChatGPT

©ECE_2026_by_Shuai

More details on the thermonuclear burning



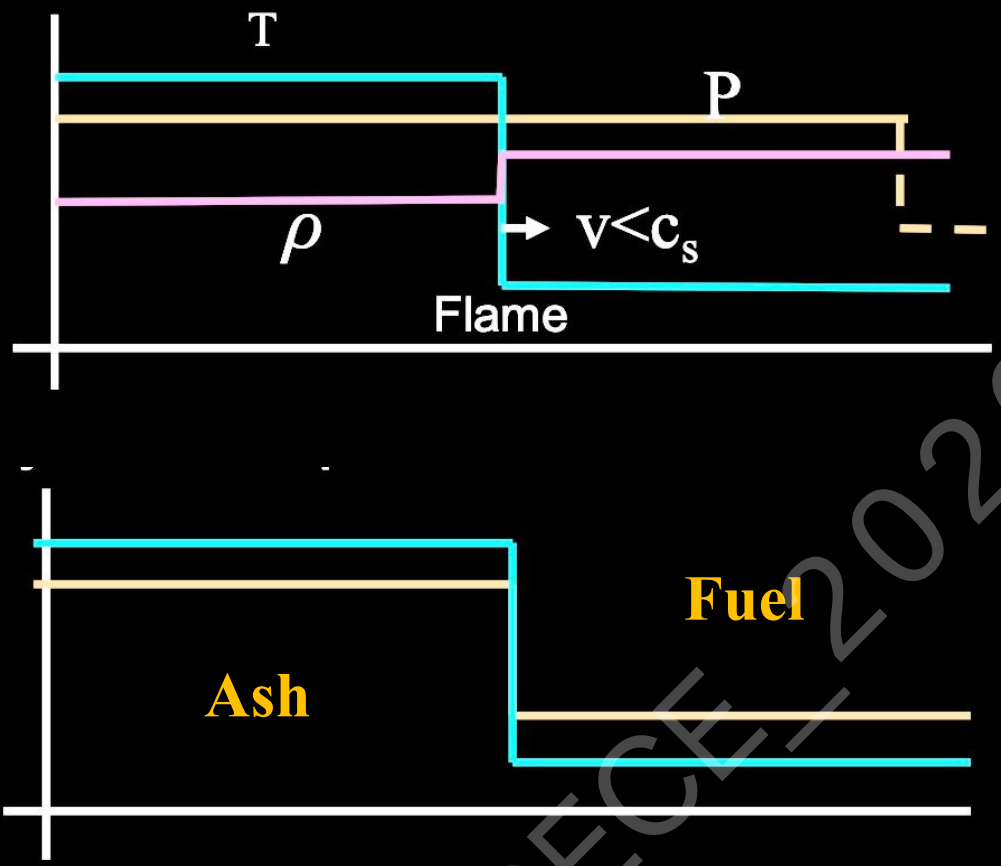
Quiescent burning in stars
CO -> ONe -> SiS -> Fe
lasts for years



Explosive burning in a second

OEC_2026_by_Shual

More details on the thermonuclear burning



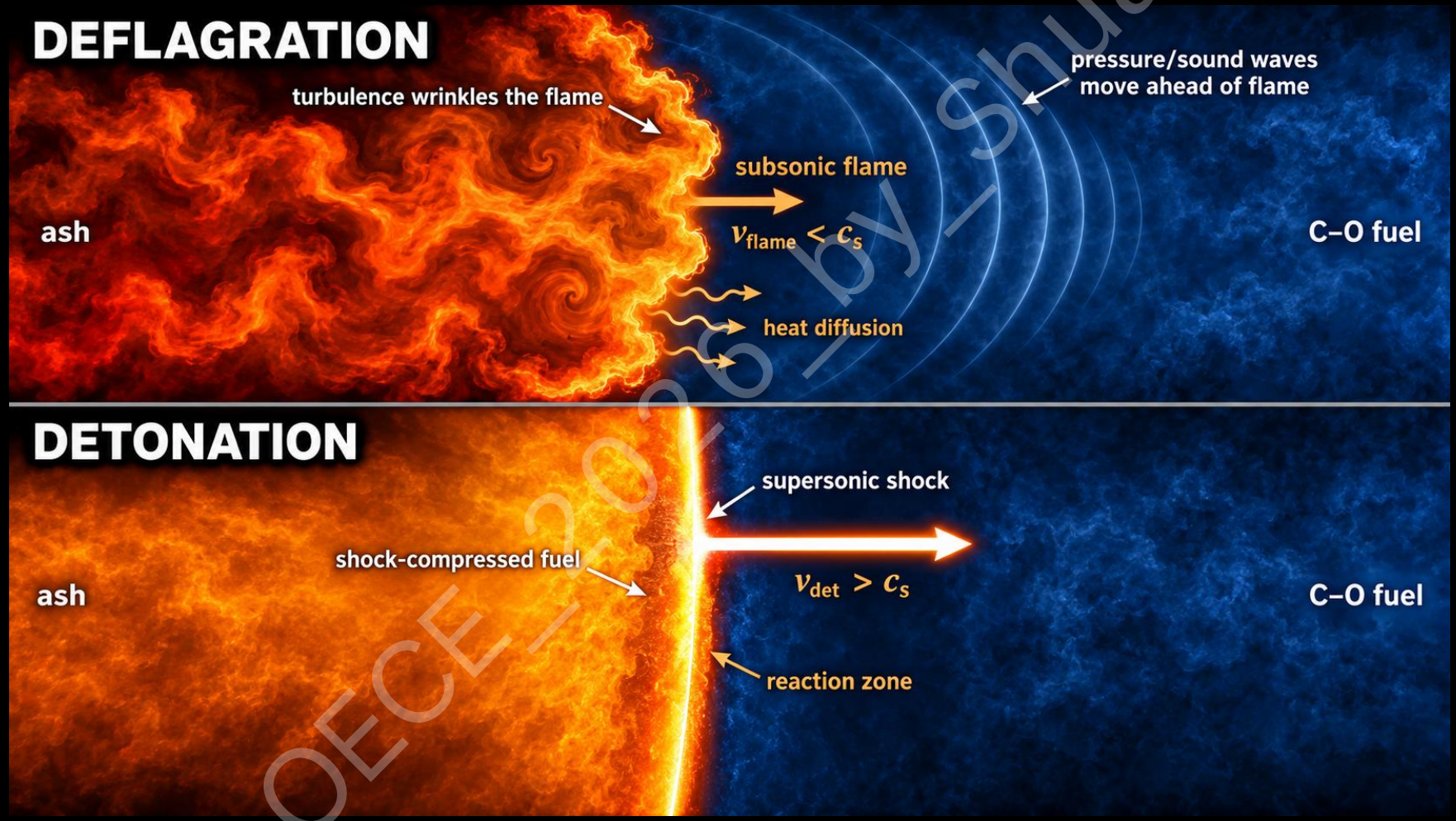
Credit: Woosley

Deflagration wave (subsonic): propagate by heat diffusion (electron conduction) & turbulent mixing

Detonation wave (supersonic): propagate by shock heating and compression

OEC_2026_by_Shuai

More details on the thermonuclear burning



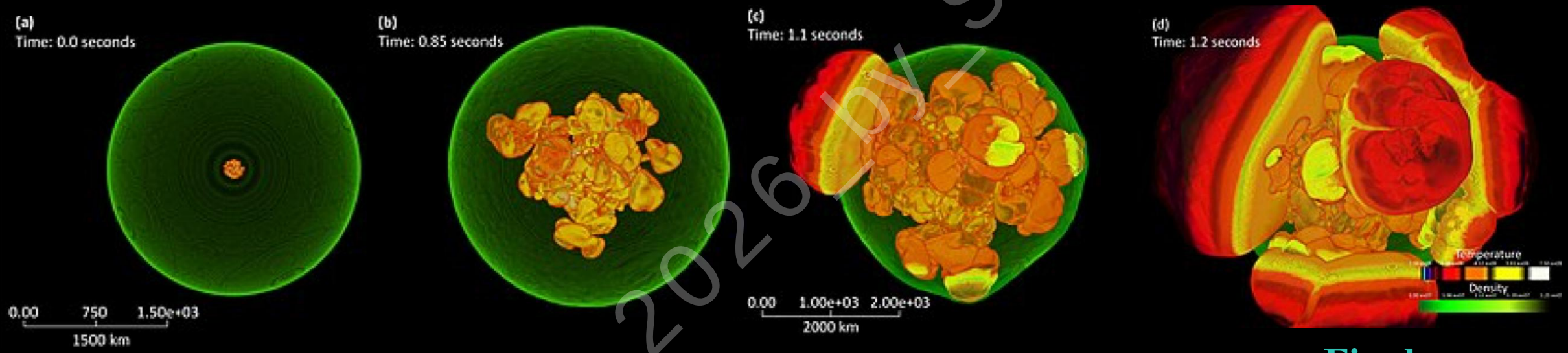
OECE_2026_by_Shuai

Credit: ChatGPT

Potential explosion mechanism: single degenerate

Deflagration to detonation transition (DDT)

Credit: HITS



Ignition kernel → **Deflagration** → **Transition to detonation** → **Final explosion**

Pros: decent balance of IMEs (Si, Ar, Ca, etc.) to ^{56}Ni
Cons: unknown condition of the DD transition

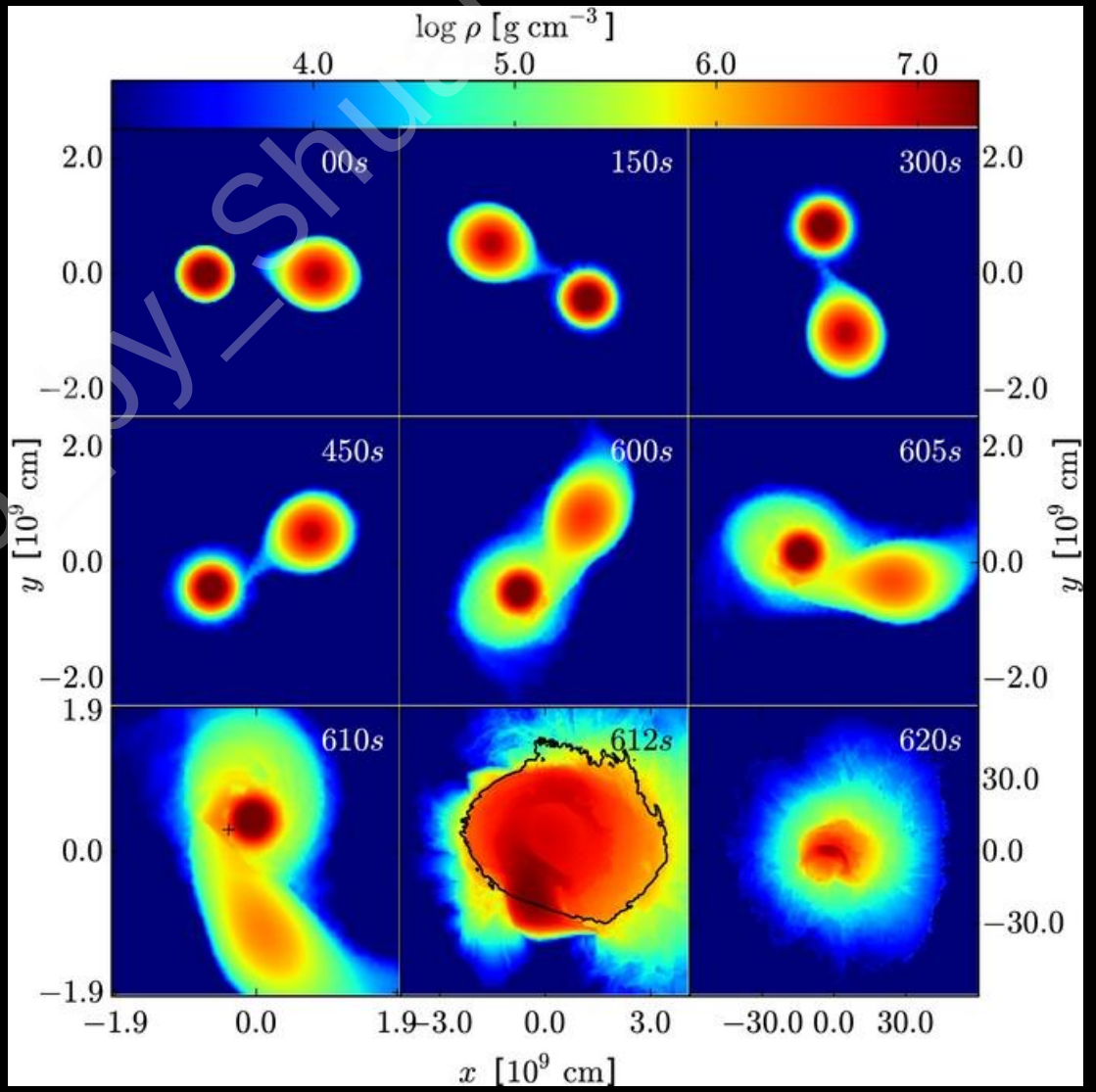
OFCE - 2026 - by Shuai

Potential explosion mechanism: double degenerate

Violent merger

1. 2 WDs merge violently
2. The secondary WD is tidally disrupted
3. Accreted matter on the primary WD is compressed，creating a hot spot
4. Carbon detonates and consume both WDs

Pros: can naturally explain various ^{56}Ni mass
Cons: uncertain ignition condition; rate?

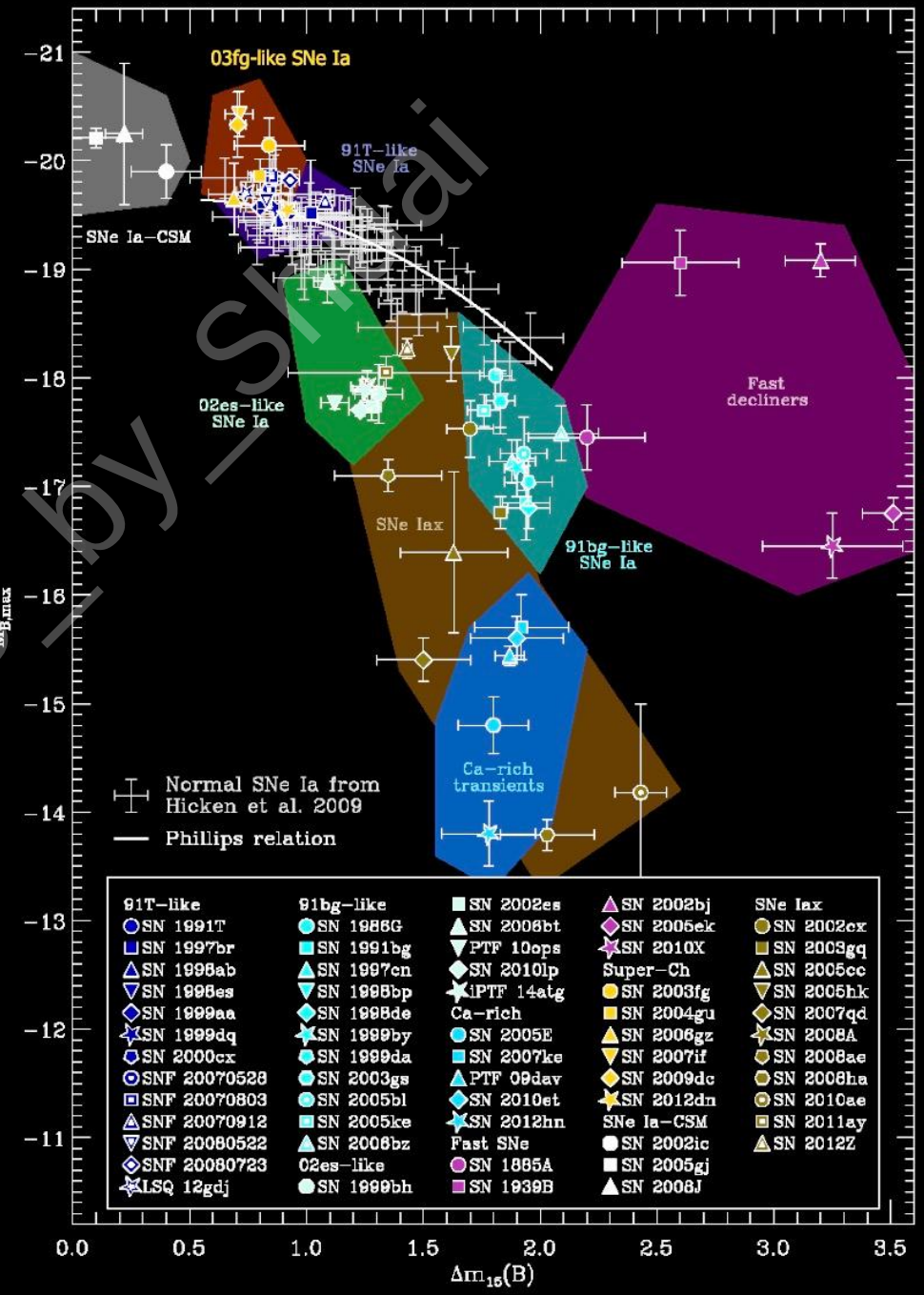


Pakmor+12

OECE_2026_by_Shuai

The real world

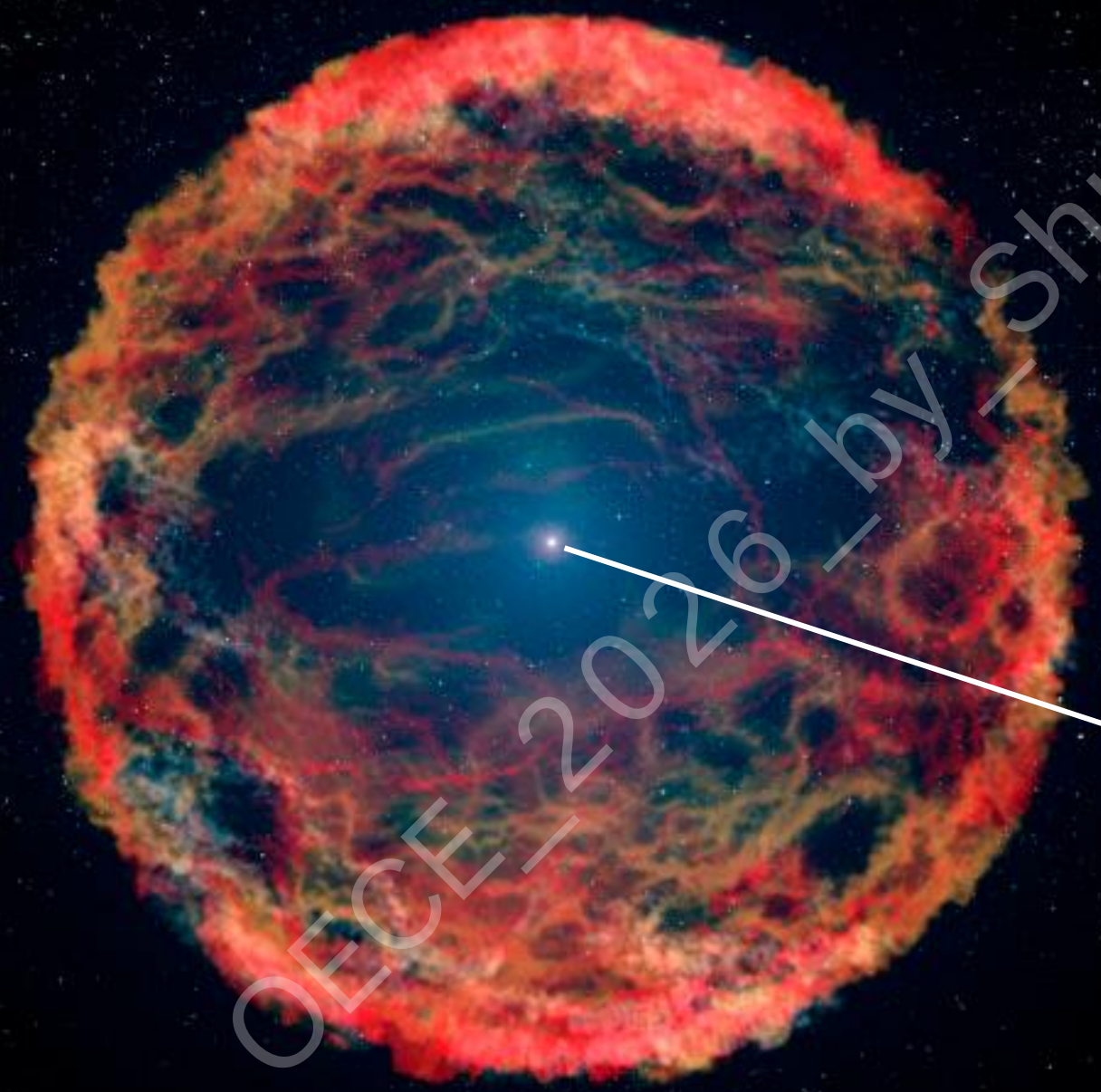
- SNe Ia are very diverse.
- May imply multiple progenitor systems and/or explosion scenarios.



Taubenberger (2017)

OECE_2026_by_Shi_Cai

Core-collapse supernovae (CCSNe)



central compact object (NS/BH)

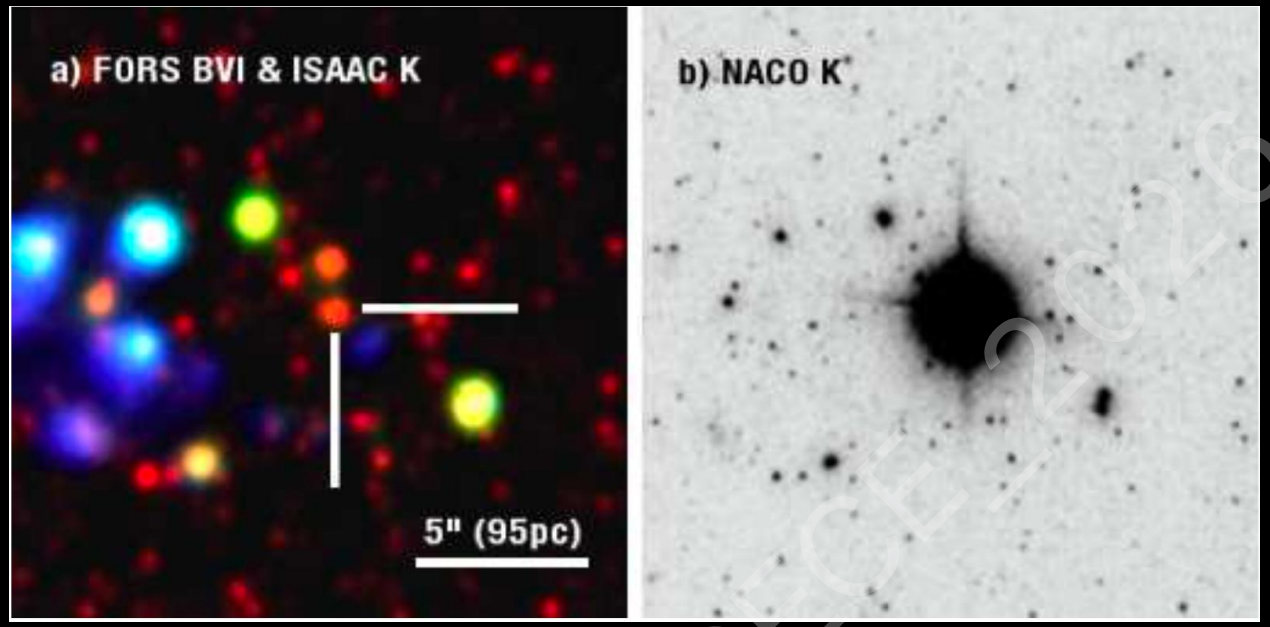
Artiest conception

OECE_2026_by_Shuai

Massive star-CCSNe connection

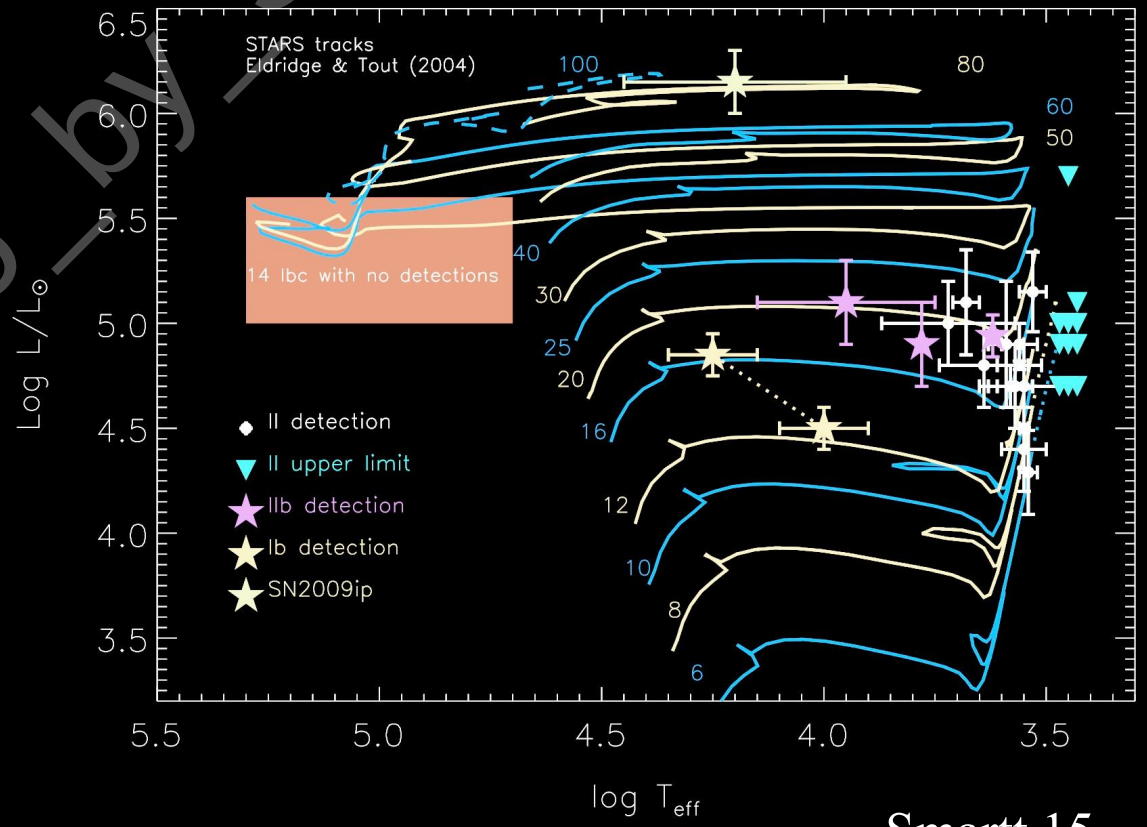
Some CCSN progenitors (mostly Type II) were directly detected as massive stars.

SN 2008bk pre- and post-explosion images



Smartt 09/Mattila+08

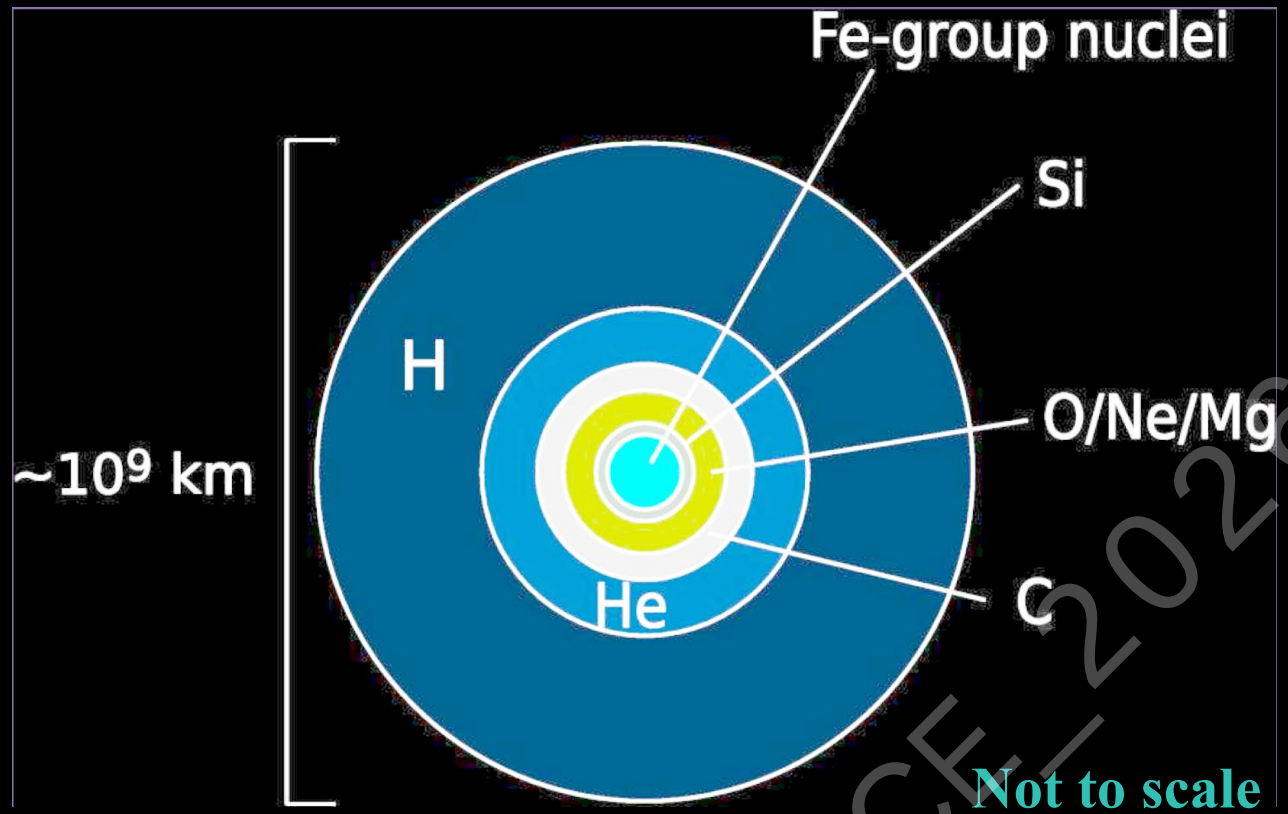
CCSN progenitors at H-R diagram



Smartt 15

OLC_2016_by_shuai

Pre-core-collapse



- Nuclear fusion (quiescent) from H all the way to the Fe-group, **onion-like structure**.
- Fe core is like a 'hot white dwarf', with **effective Chandrasekhar mass**:

$$M_{\mathrm{Ch,eff}} \simeq M_{\mathrm{Ch}}\left[1+\left(\frac{s_e}{\pi Y_e}\right)^2\right] \quad \sim 1.35\text{-}2.0 M_\odot$$

$$s_e = \frac{S_e}{N_A k} = \frac{\pi^2 T Y_e}{\epsilon_{\mathrm{F}}} \qquad Y_{\mathrm{e}} = n_{\mathrm{e}}/n_{\mathrm{B}}$$

- Gravitational collapse starts as:

$$e^- + p \overset{(W)}{\rightarrow} \nu_e + n$$

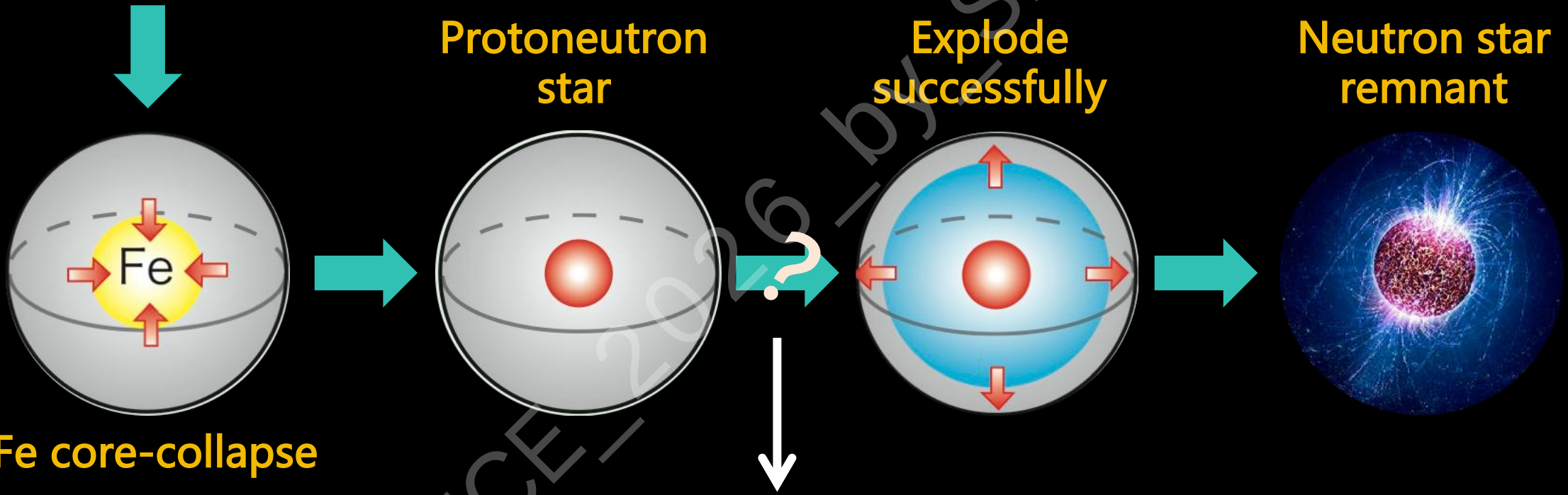
$$\gamma + {}^{56}_{26}\mathrm{Fe} \rightleftharpoons 13\alpha + 4n$$

Prof. Marco Limongi will give a detailed introduction on Thursday.

OECF_2026_by_Shuai

Core-collapse supernovae

Massive stars
~9-100 $M_\odot$



Protoneutron star

Explode successfully

Neutron star remnant

Fe core-collapse

$\rho_c \approx 10^{10}$ g/cm^3

$T \approx 0.6 - 0.5$ MeV

$Y_e \approx 0.43 - 0.48$

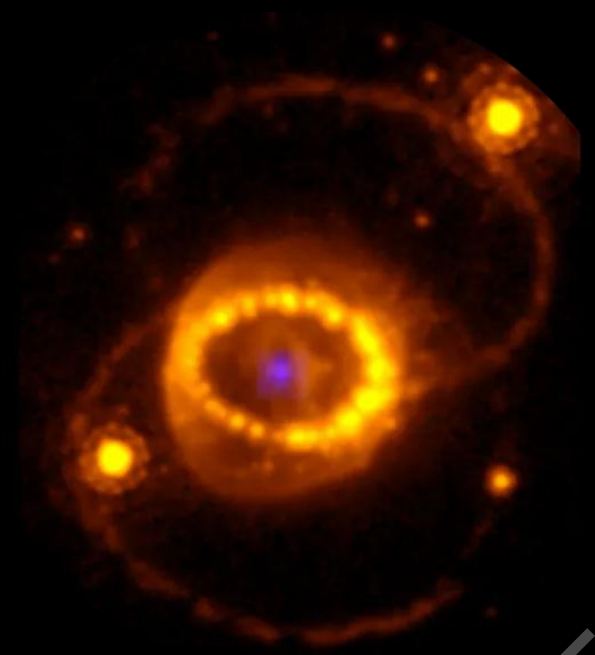
Explosion mechanism and modeling

OECE_2026_by_Shuai

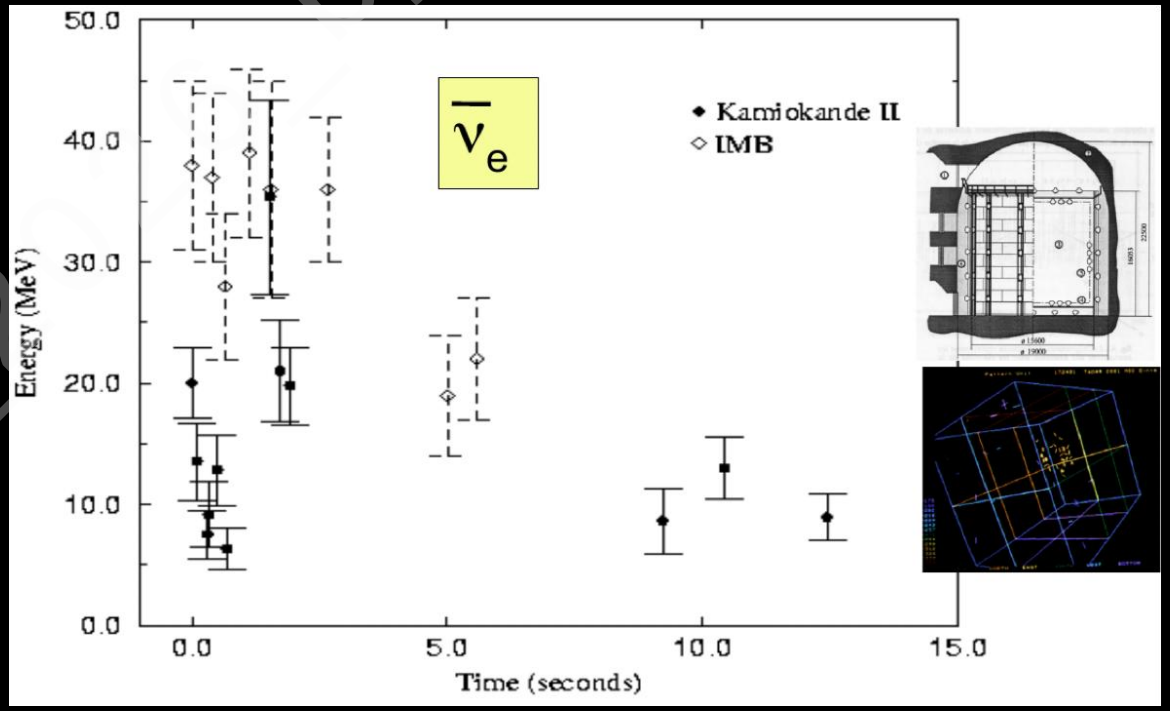
Key evidence of the core collapse to neutron star

- Gravitational collapse releases ~10^{53} erg of gravitational potential energy, ~99% carried away by neutrinos.

$$\frac{GM_{\rm NS}^2}{R_{\rm NS}} \simeq 3.45\times10^{53}\,{\rm erg}\times\left(\frac{M_{\rm NS}}{1.4\,M_\odot}\right)^2\left(\frac{R_{\rm NS}}{15\,{\rm km}}\right)^{-1}$$



SN 1987A in the Large Magellanic Cloud (50 kpc)



Scholberg 2017

©ECE_2021 by Shuai

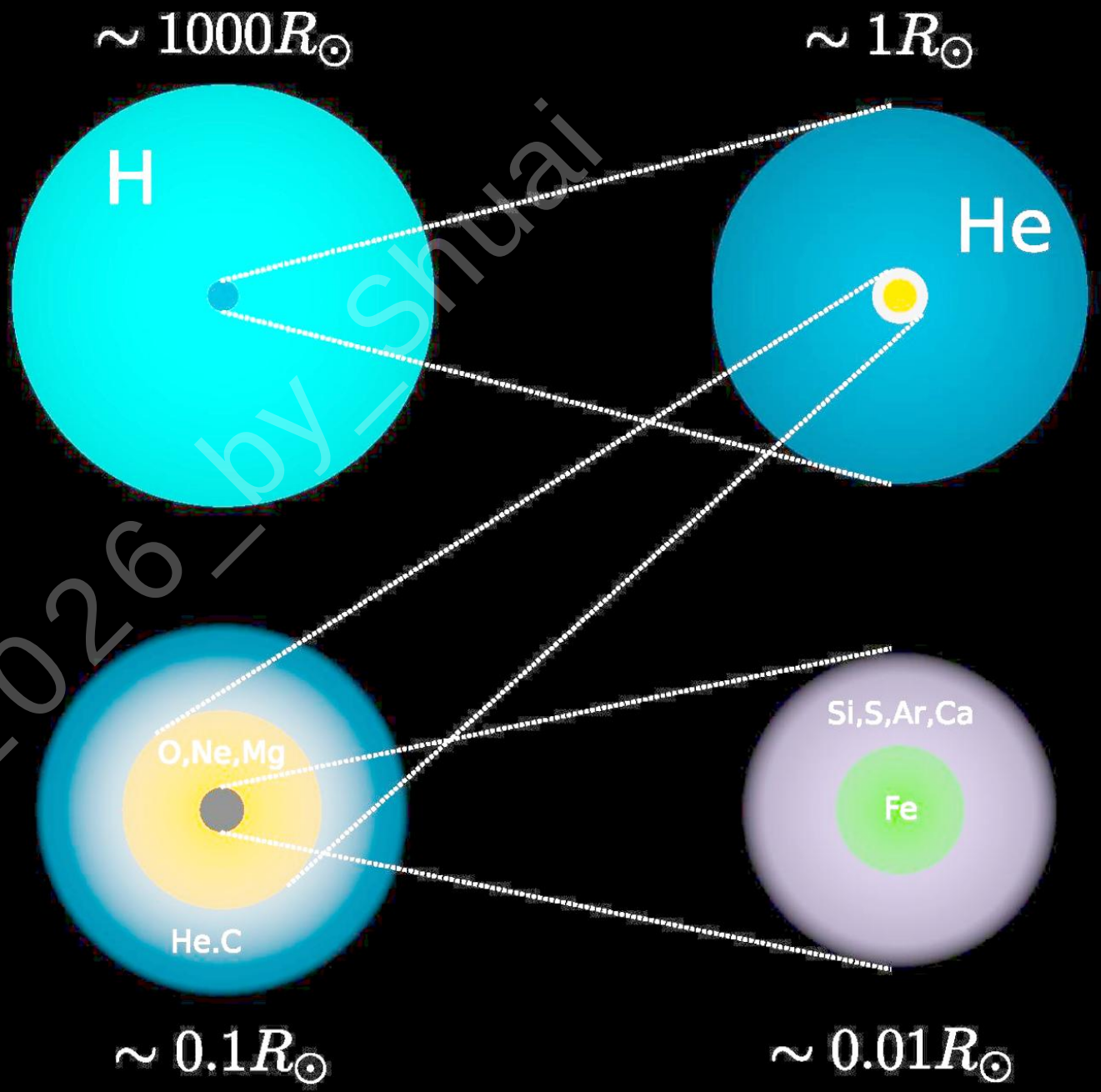
Initial condition:

Presupernova structure

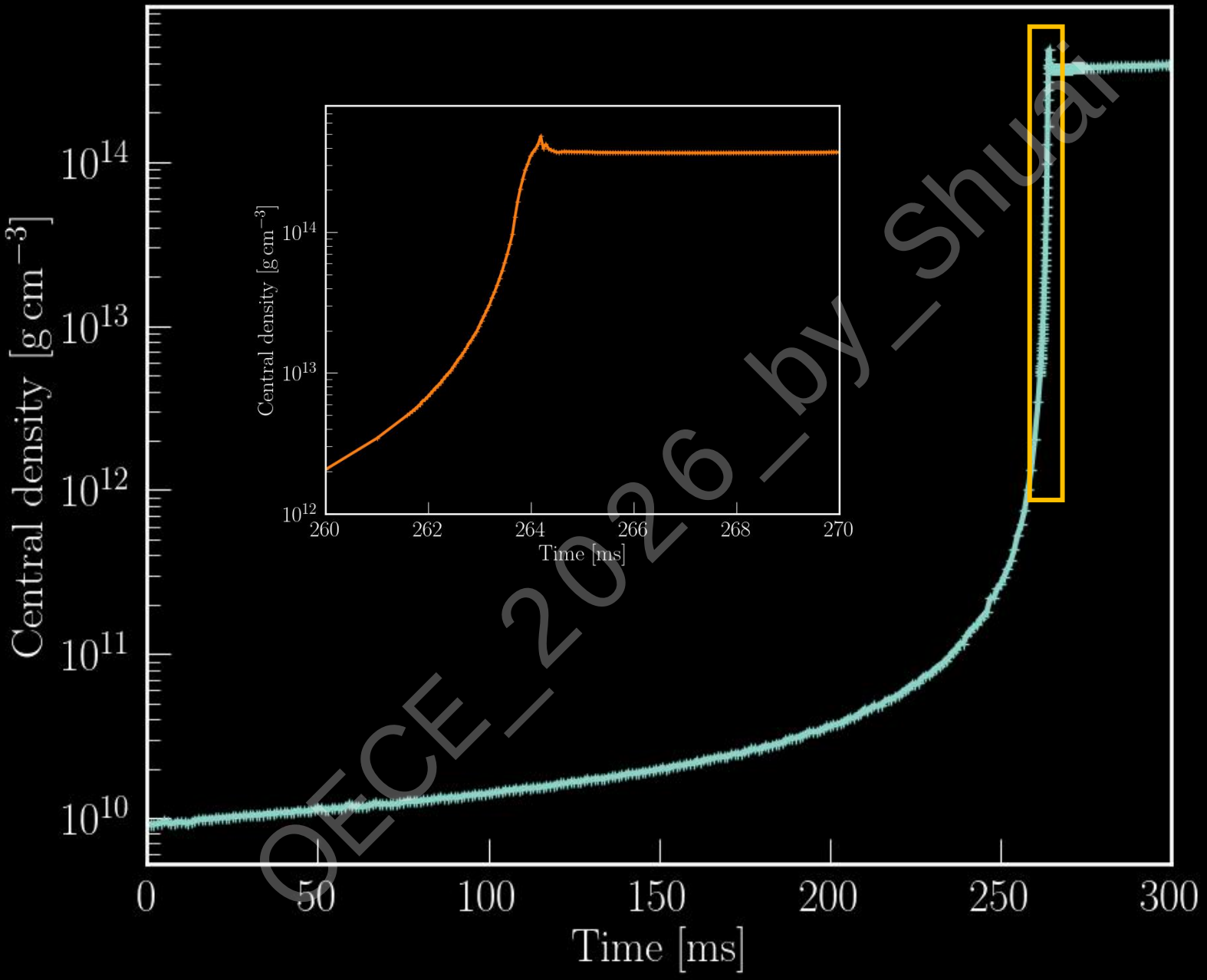
In hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2}$$

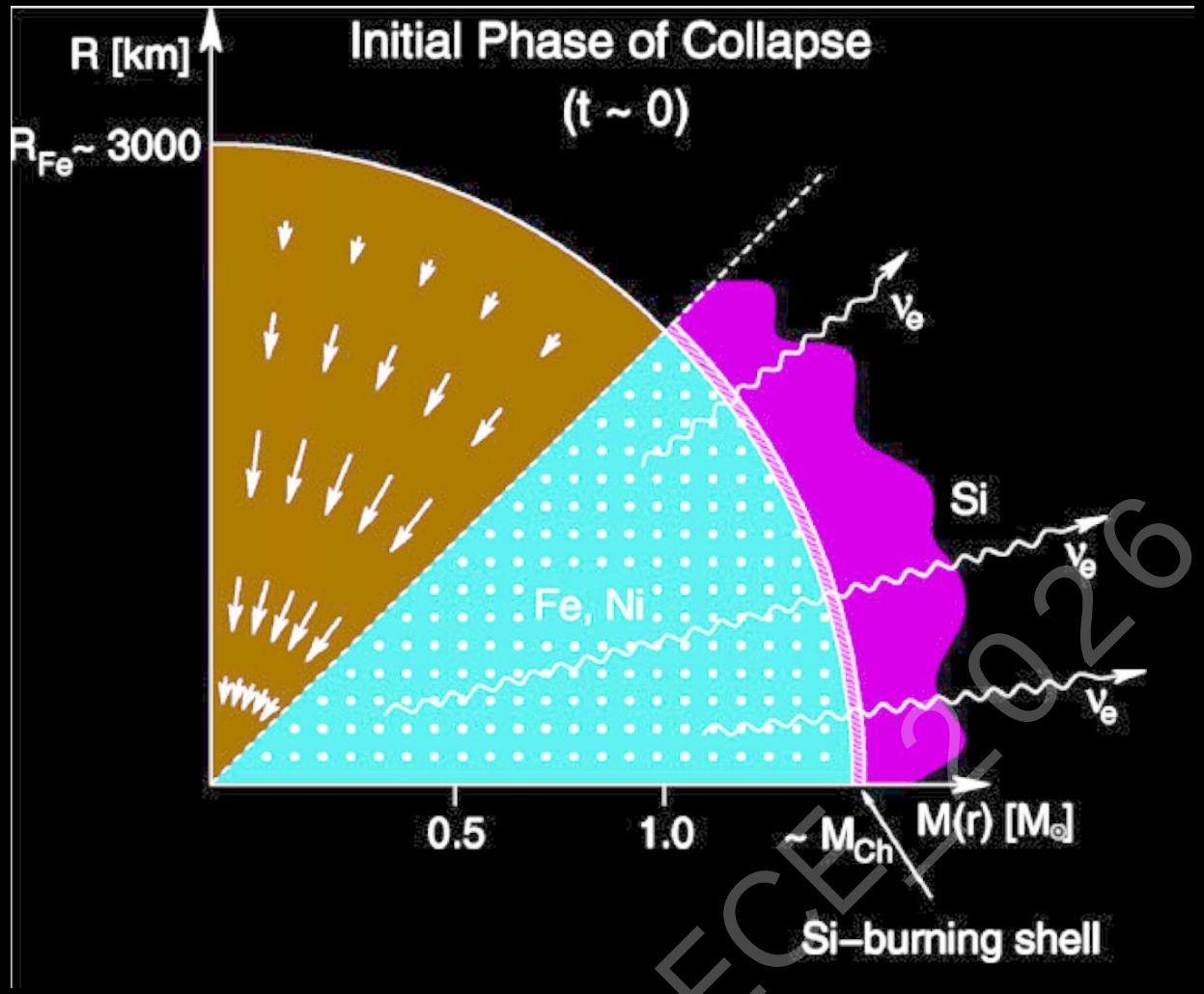
- **Equation of state:** $P = P(\rho, T, Y_e)$
  $Y_e = n_e/n_B$
- **In the iron core, pressure is dominated by degenerate electrons.**
- **Electron-capture -> $P\downarrow$ -> collapse**



OFCE_2026_by_Shuai

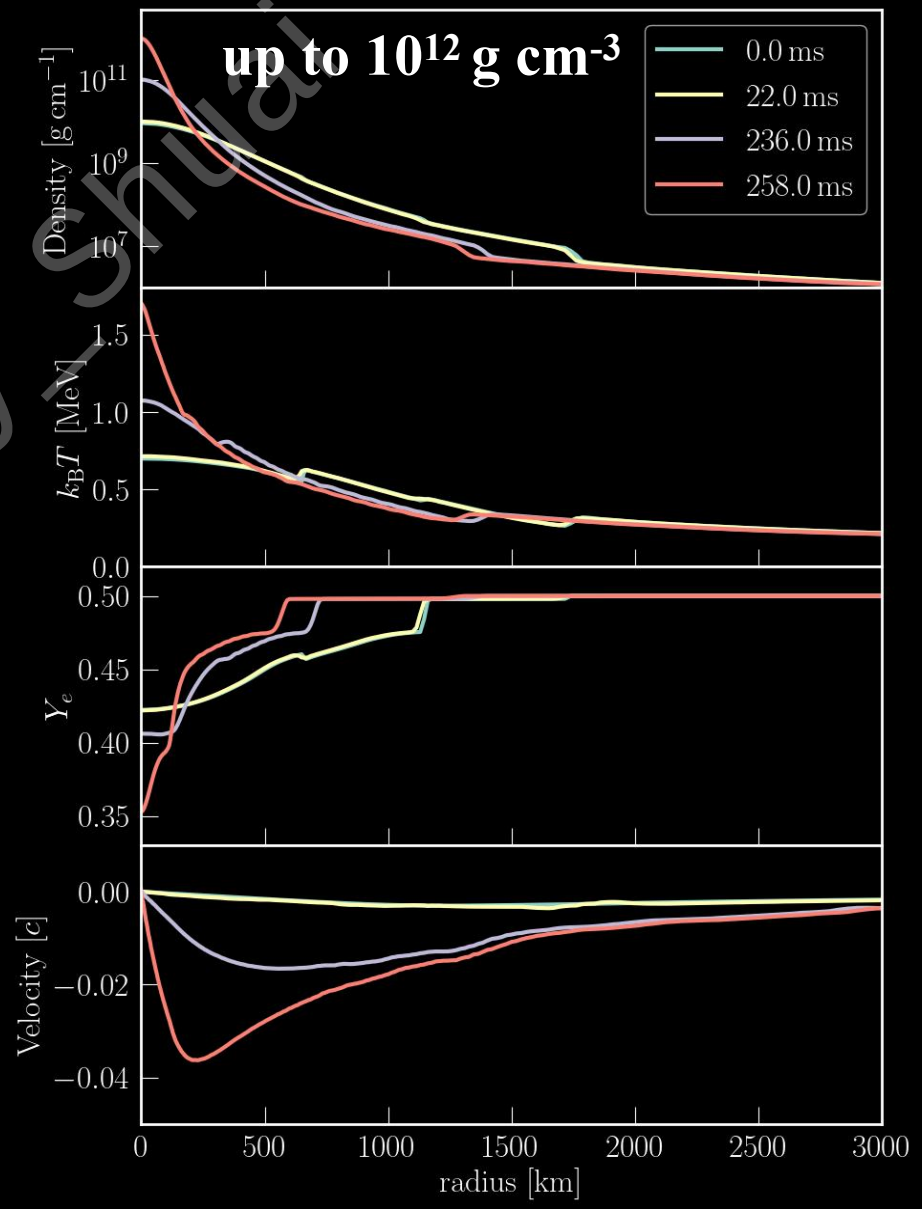


OECE_2026_by_Shuai



Janka 2007

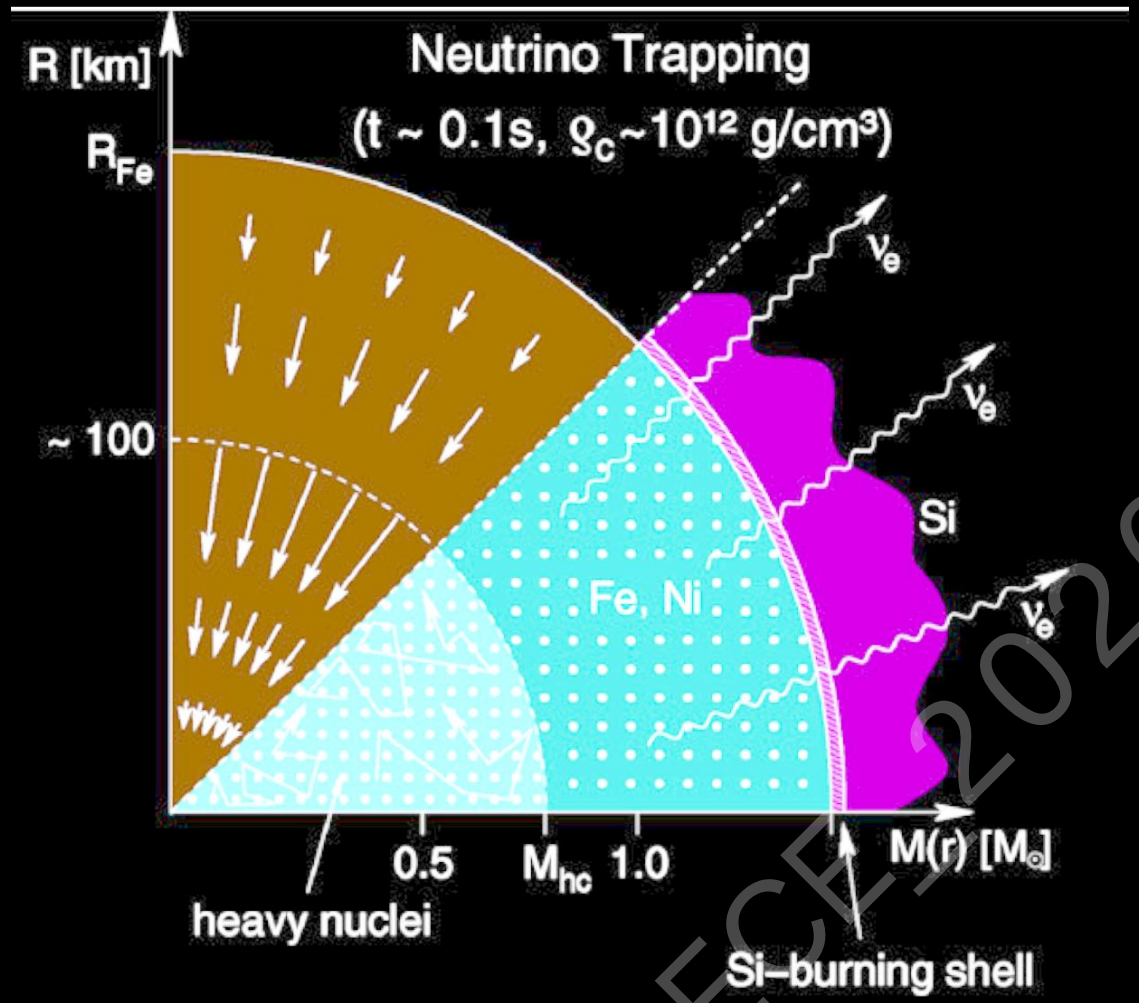
Simulation data of GR1D



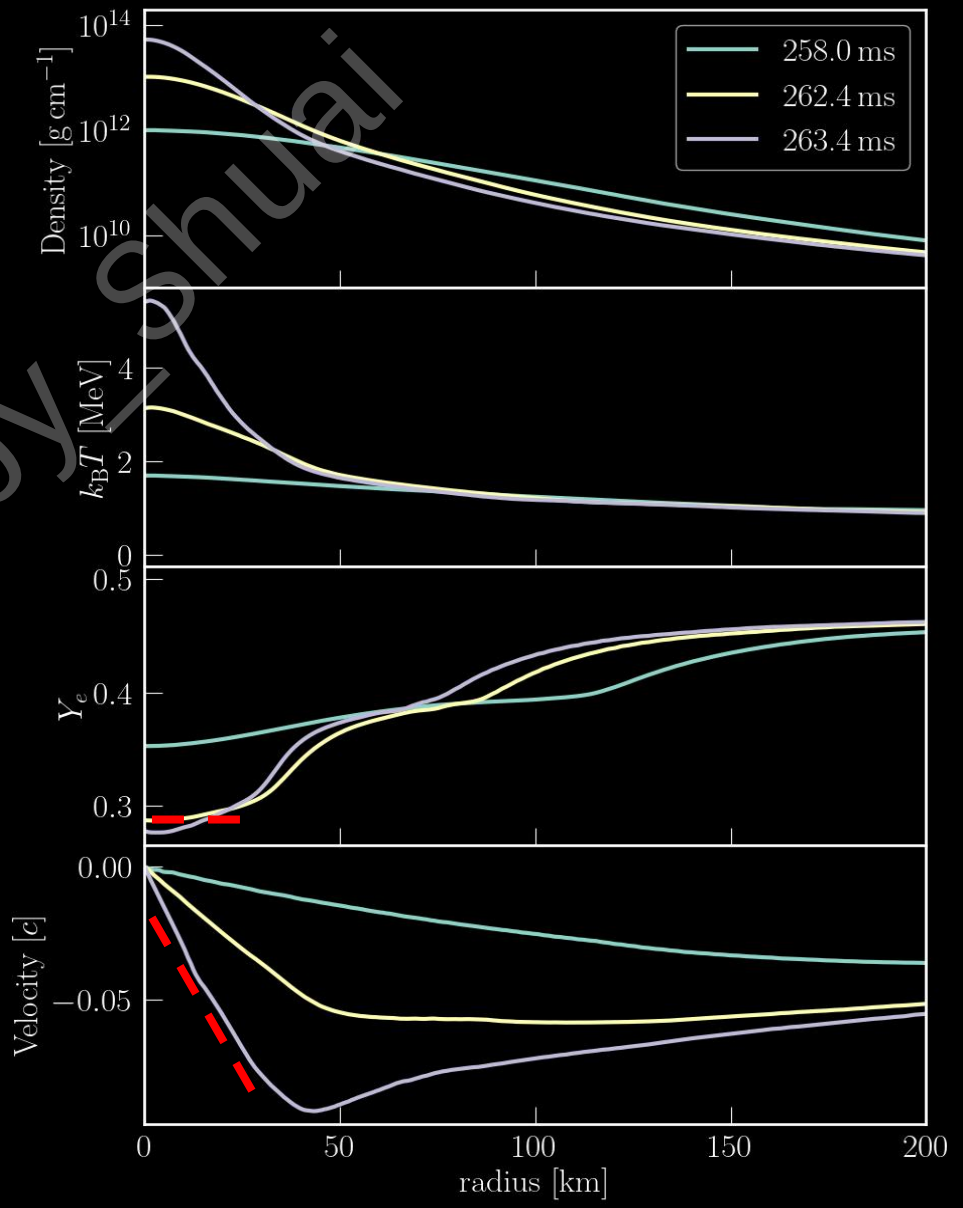
$e^- + (A,Z) \rightarrow \nu_e + (A,Z-1)$

(A,Z): nuclei with Z protons and (A-Z) neutrons

OECE_2026_by Shuai

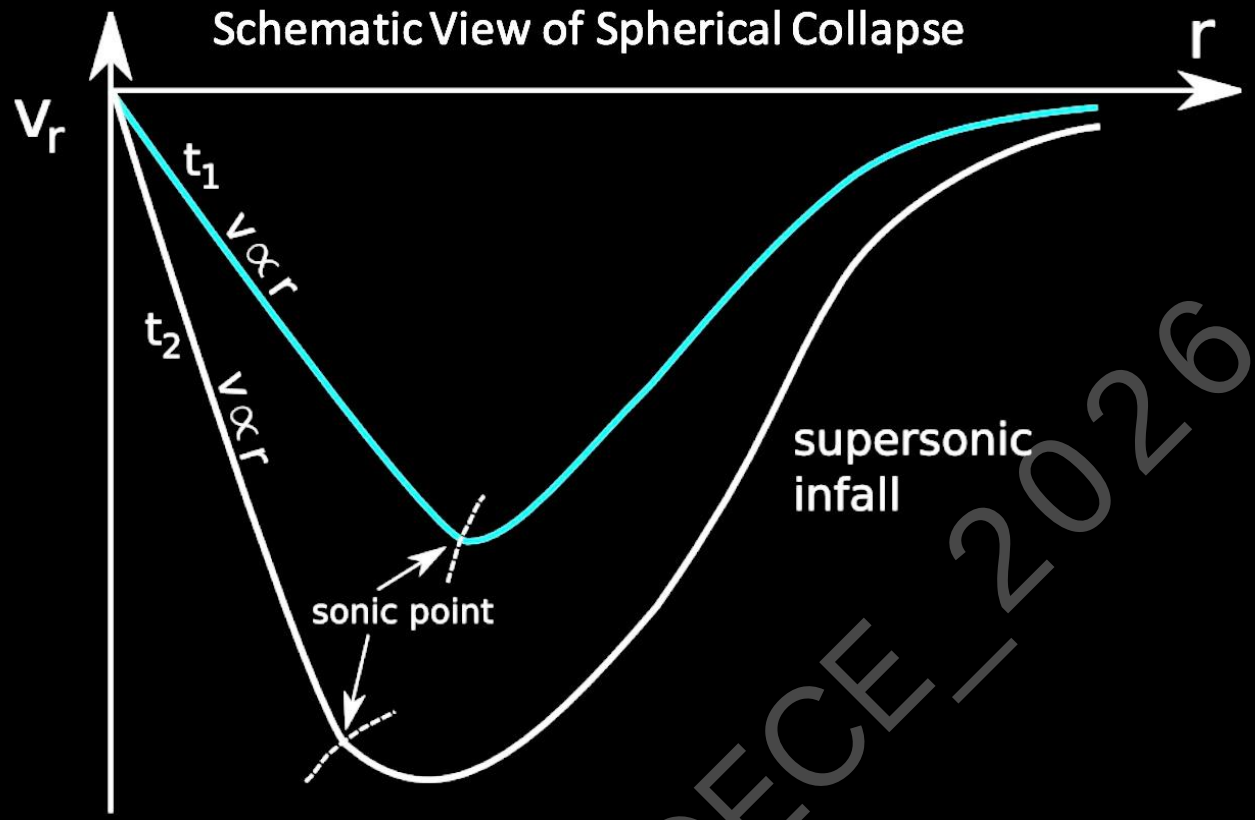


up to 5×10^{13} g cm^{-3}



OECF_2026_by_shuai

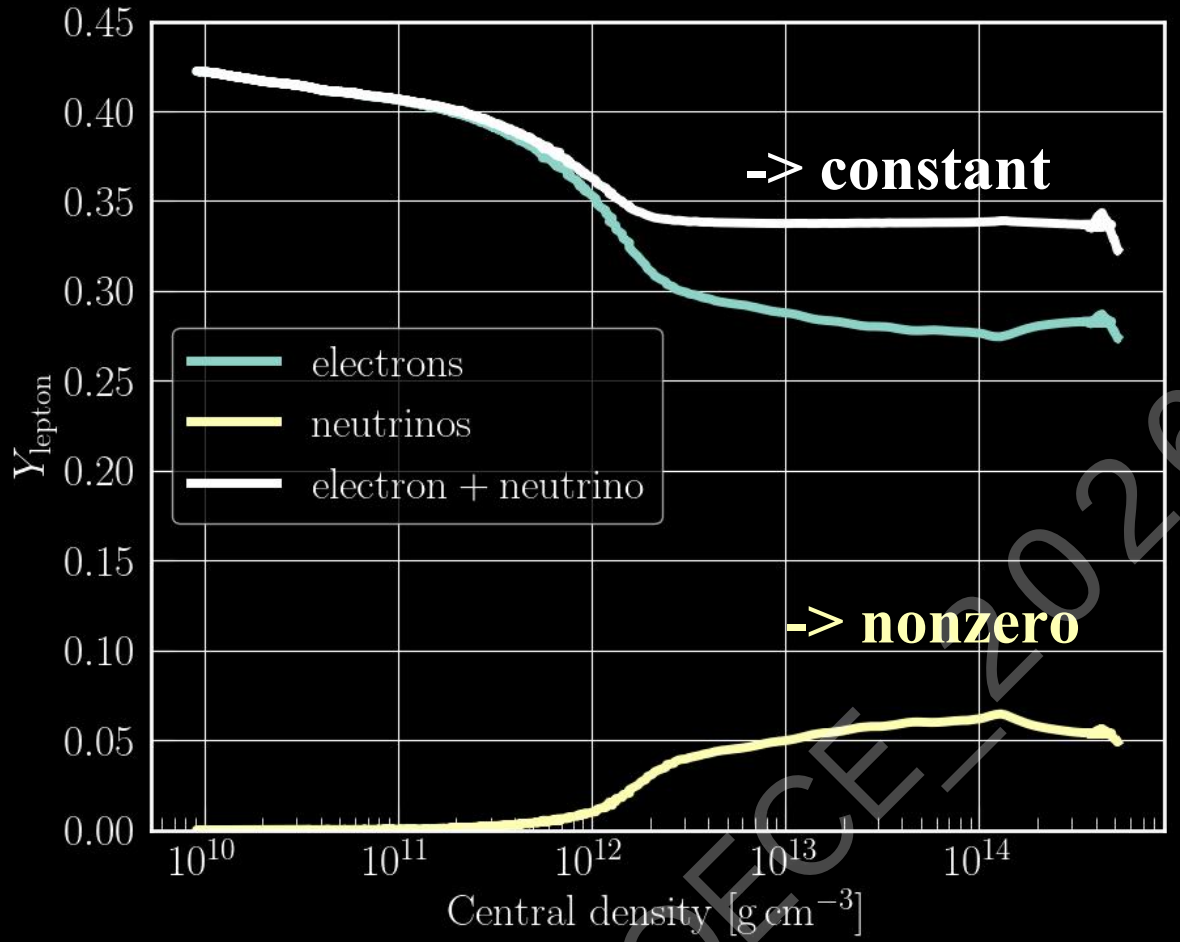
Dynamic behavior in the collapse phase



- Self-similar collapse
- Homologous collapsing inner core with $v_r \propto r$
- Supersonically collapsing outer core with $|v| > c_{sound}$
- Later, as inner core reaches nuclear density, it rebounds and forms a bounce shock wave near the sonic point

OECE_2026_by_Shuai

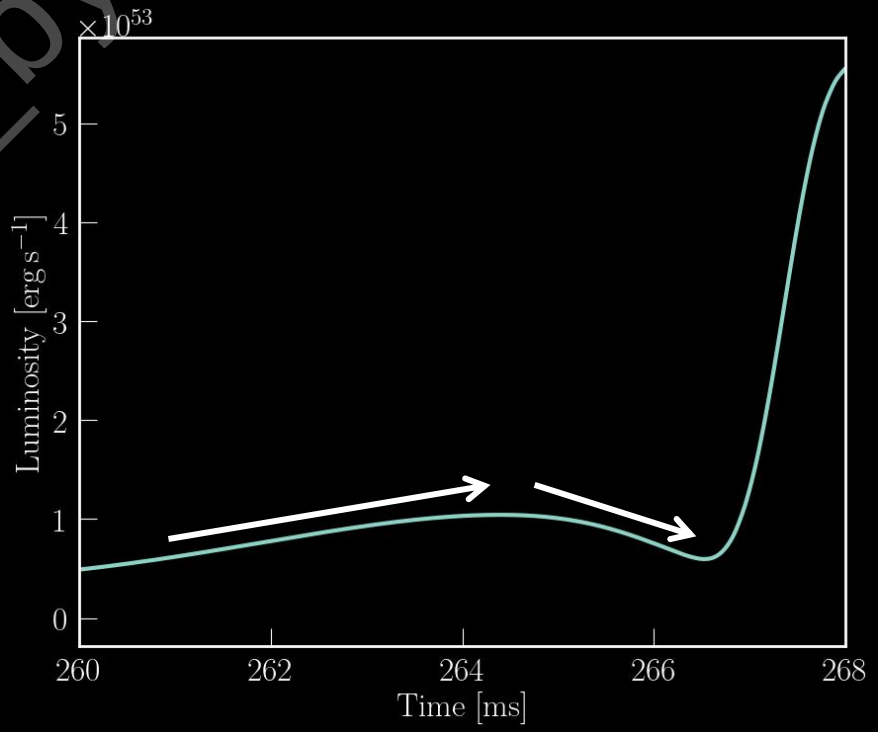
Key concepts in thecollapse phase: neutrino trapping



$Y=n/n_{\rm B}$

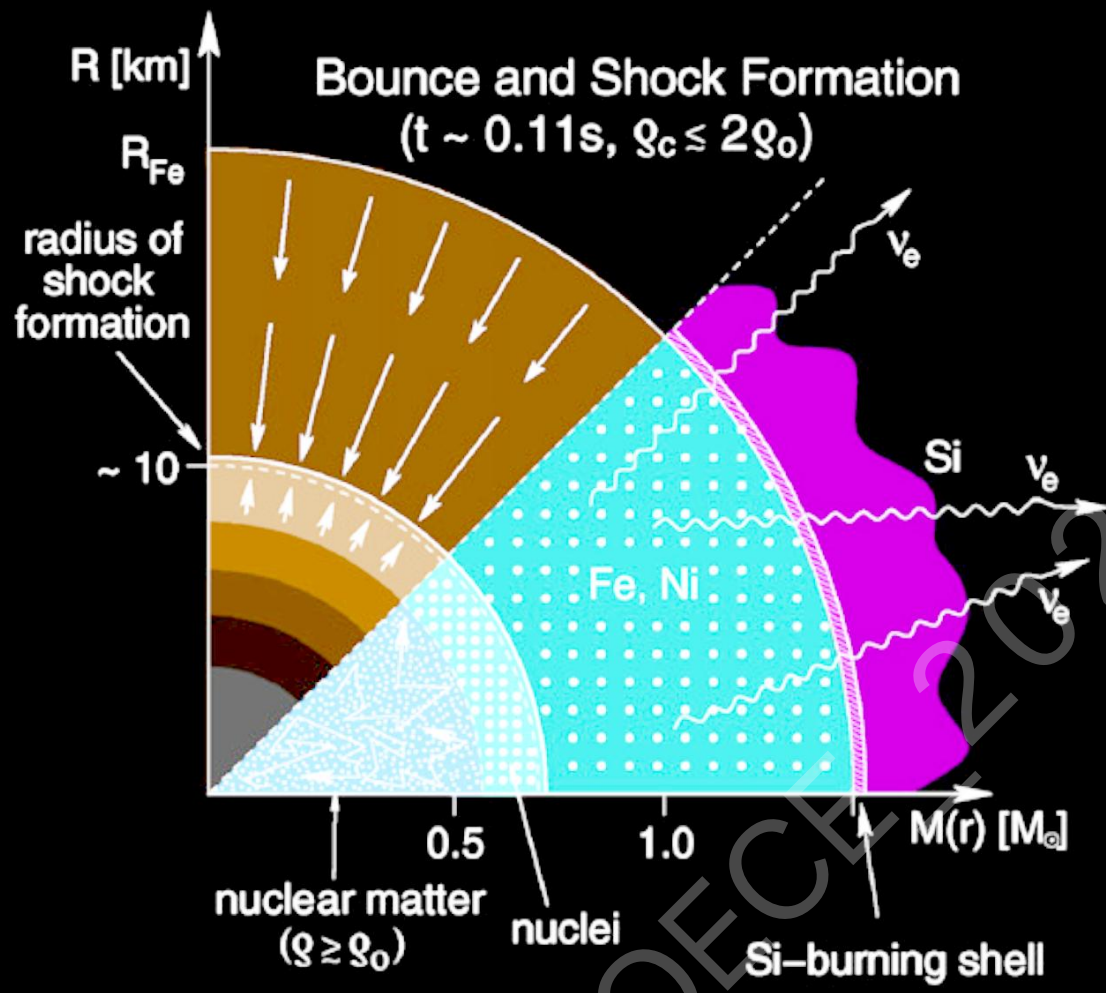
- Above 10^{12} g cm^{-3}, even neutrinos can't freely escape

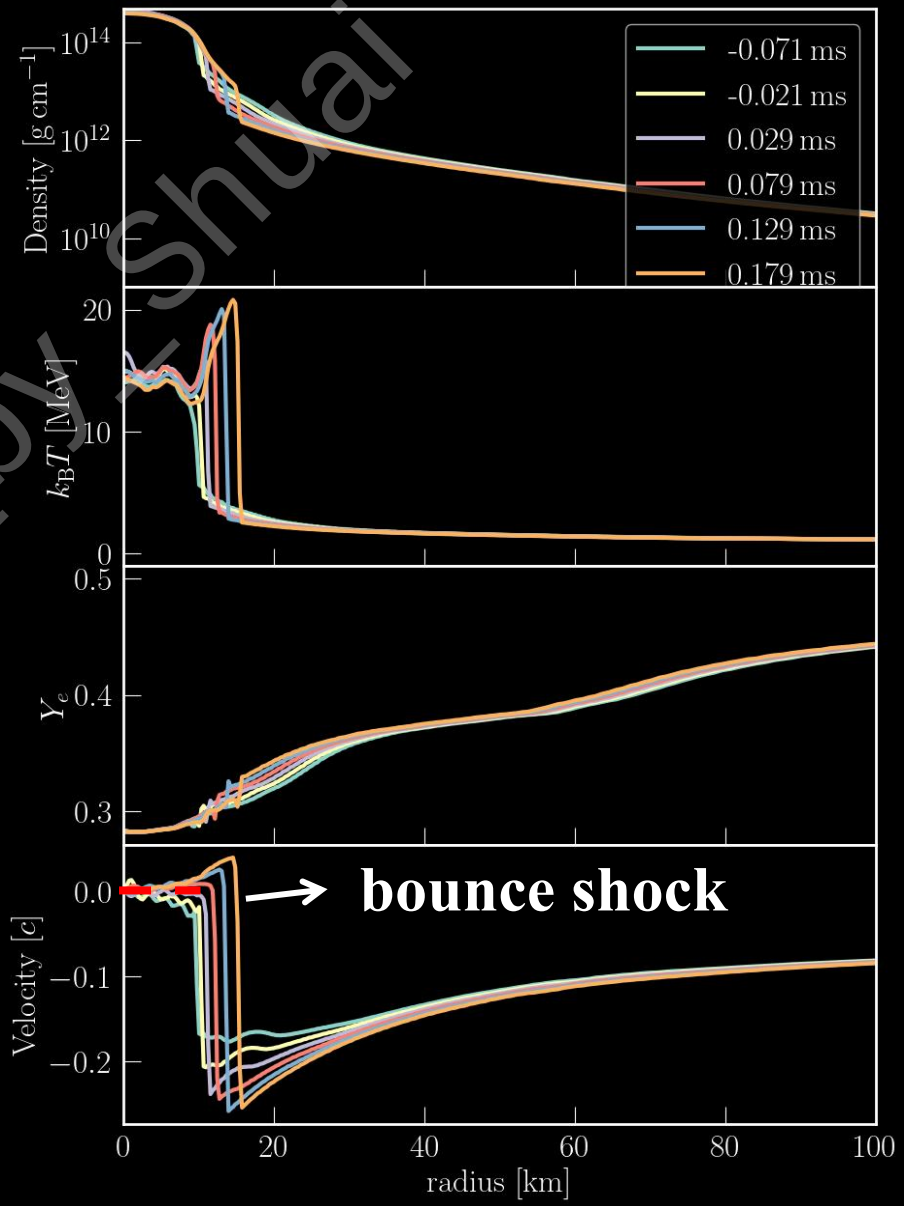
Neutrino luminosity curve



CECE_2026_by_Shuai

From now on, time 0 sets at the bounce (t_bounce)





OECE_2026_by_Shuai

☐ shock wave: discontinuity in all variables (ρ, T, Ye, v)

Stiffening of equation of state

- Recall that $P = P(\rho, T, Y_e)$
- Something happens at density ~ 10^{14} g cm^{-3}

Nuclear Physics:

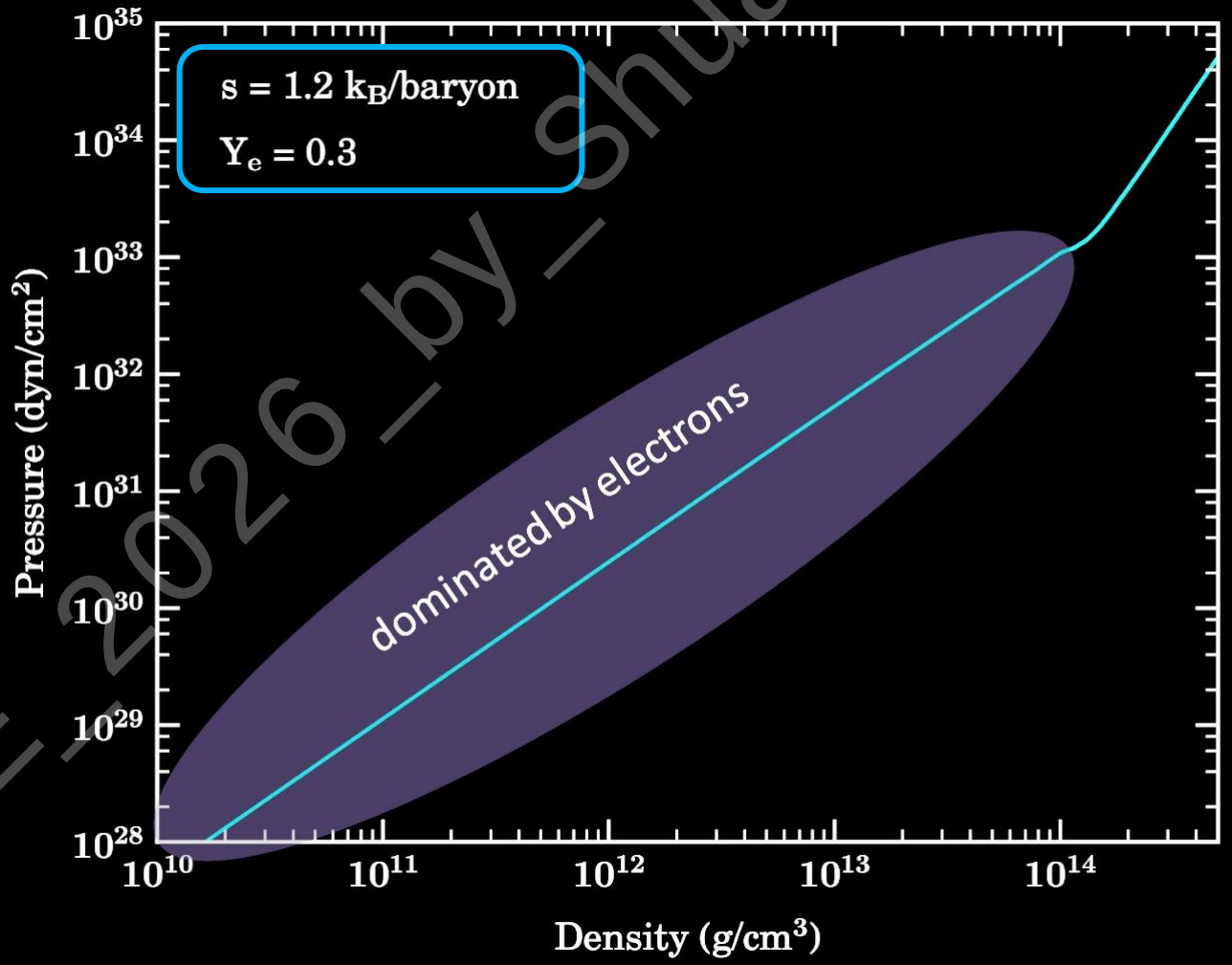
$$R_{\rm nuc} = A^{1/3} r_0$$

$$r_0 = 1.25\,{\rm fm}$$

Nuclear Density:

$$\bar{\rho}_{\rm nuc} = \frac{A\, m_b}{\frac{4}{3}\pi R_{\rm nuc}^3}$$

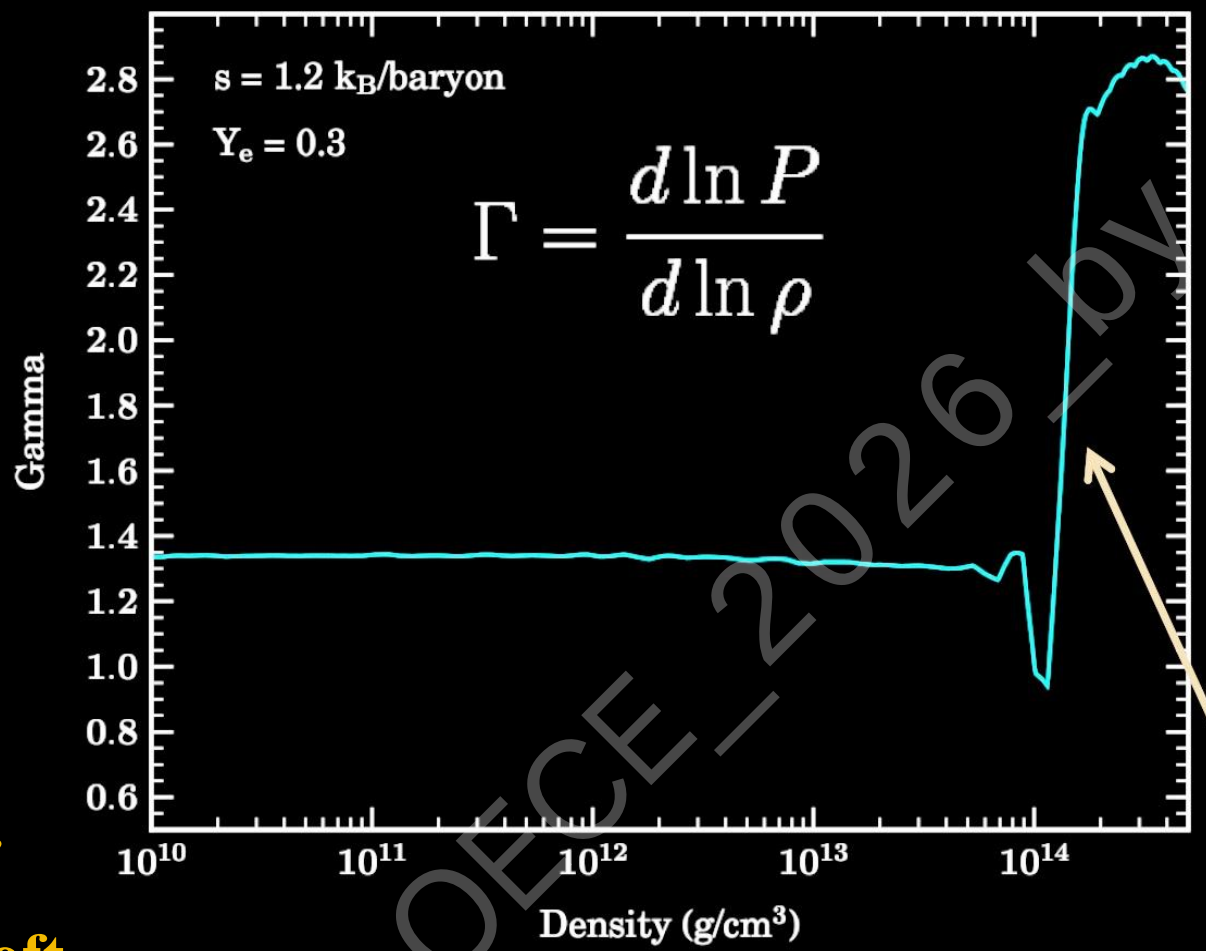
$$\bar{\rho}_{\rm nuc} \approx 2 \times 10^{14}\,{\rm g/cm^{-3}}$$



OECE_2026_by_Shuai

Stiffening of equation of state

Stiff



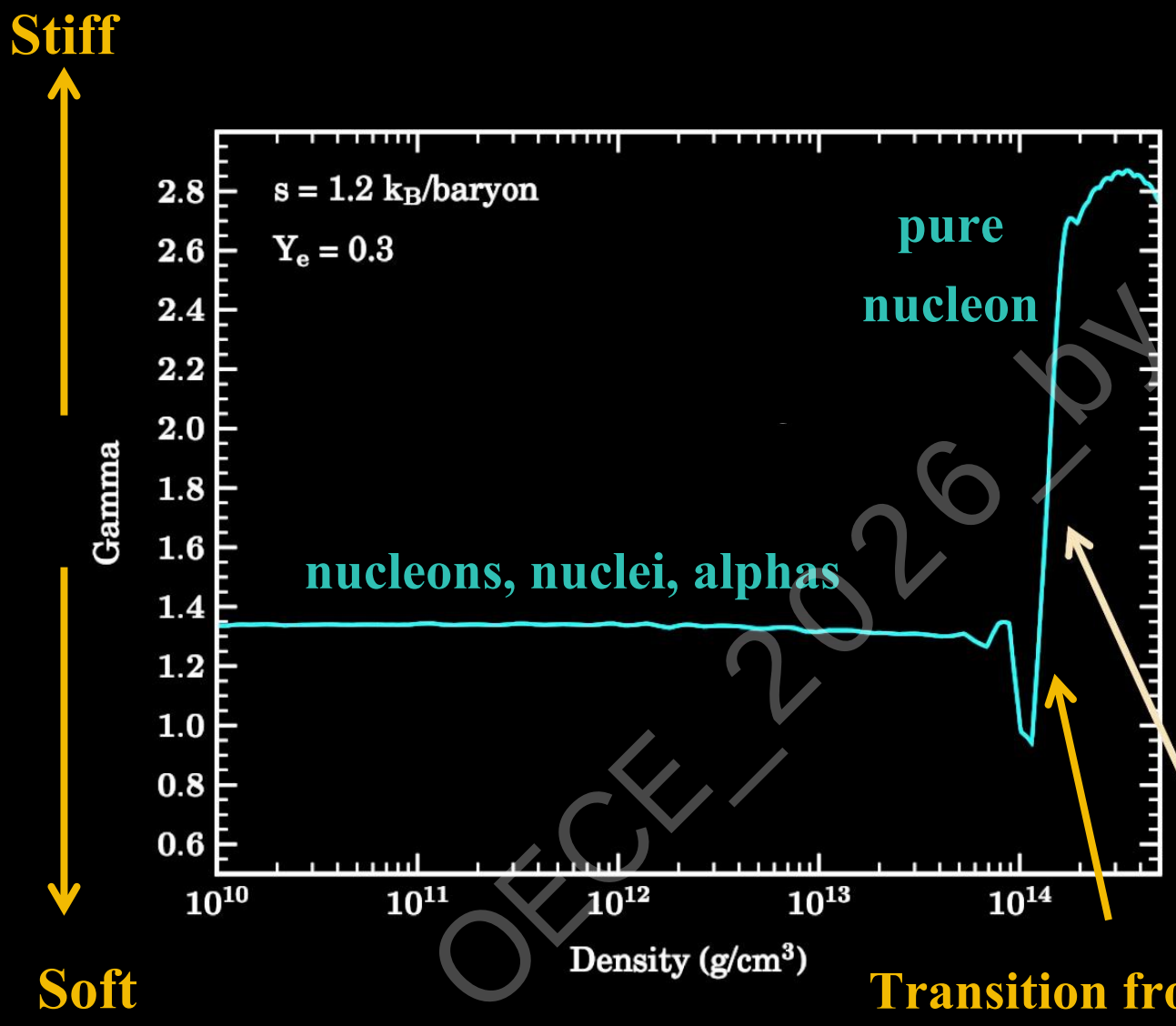
Soft

- $P \approx K\rho^{\Gamma}$; for relativistic & degenerate electrons, Γ~4/3

"Stiffening" of the EOS

OECE_2026_by_Shuai

Stiffening of equation of state

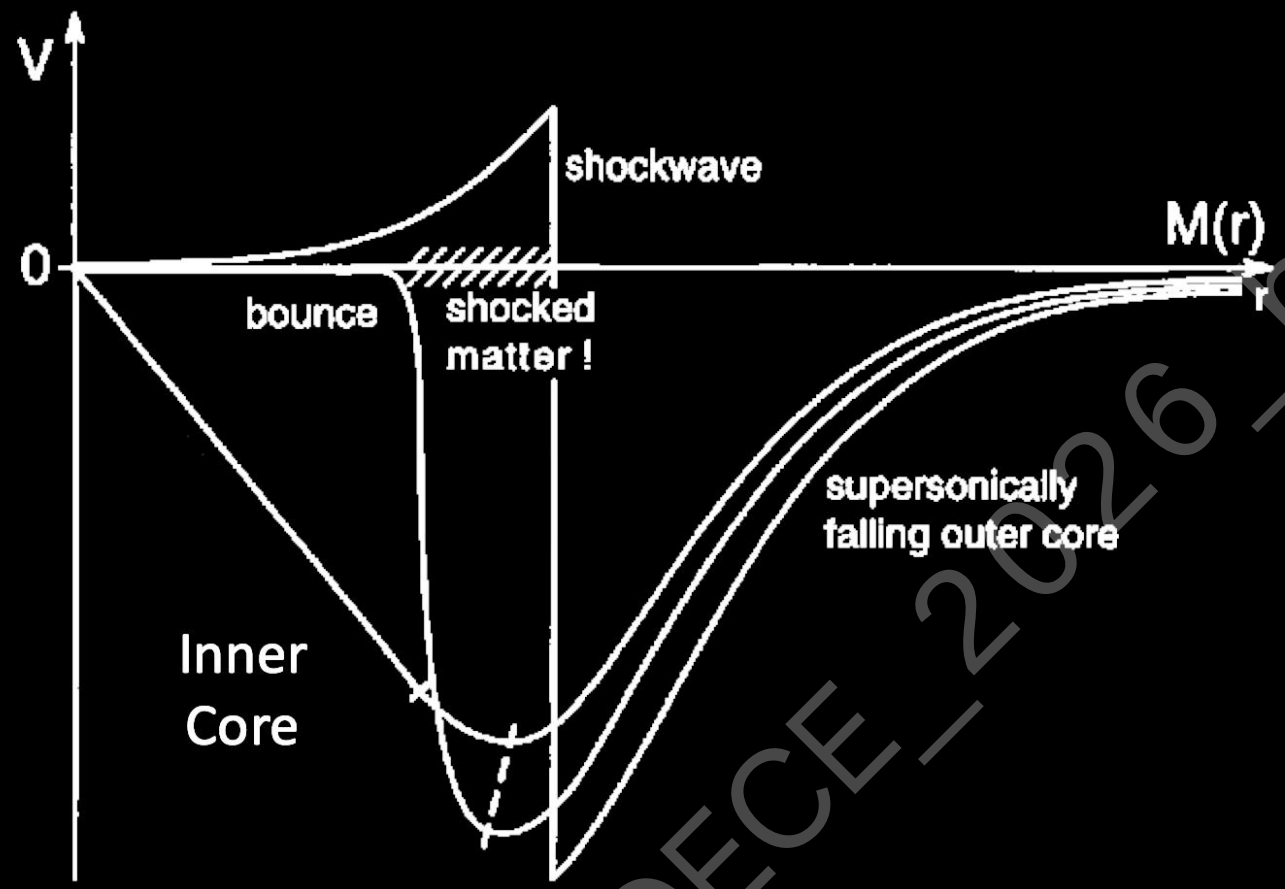


- $P \approx K\rho^{\Gamma}$; for relativistic & degenerate electrons, Γ~4/3
- Above ~ρ_{nuc} n,p are so close that "repulsive core" of the strong force kicks in and leads to the stiffening of the EOS, Γ~2.8

Transition from inhomogeneous to homogeneous nuclear matter

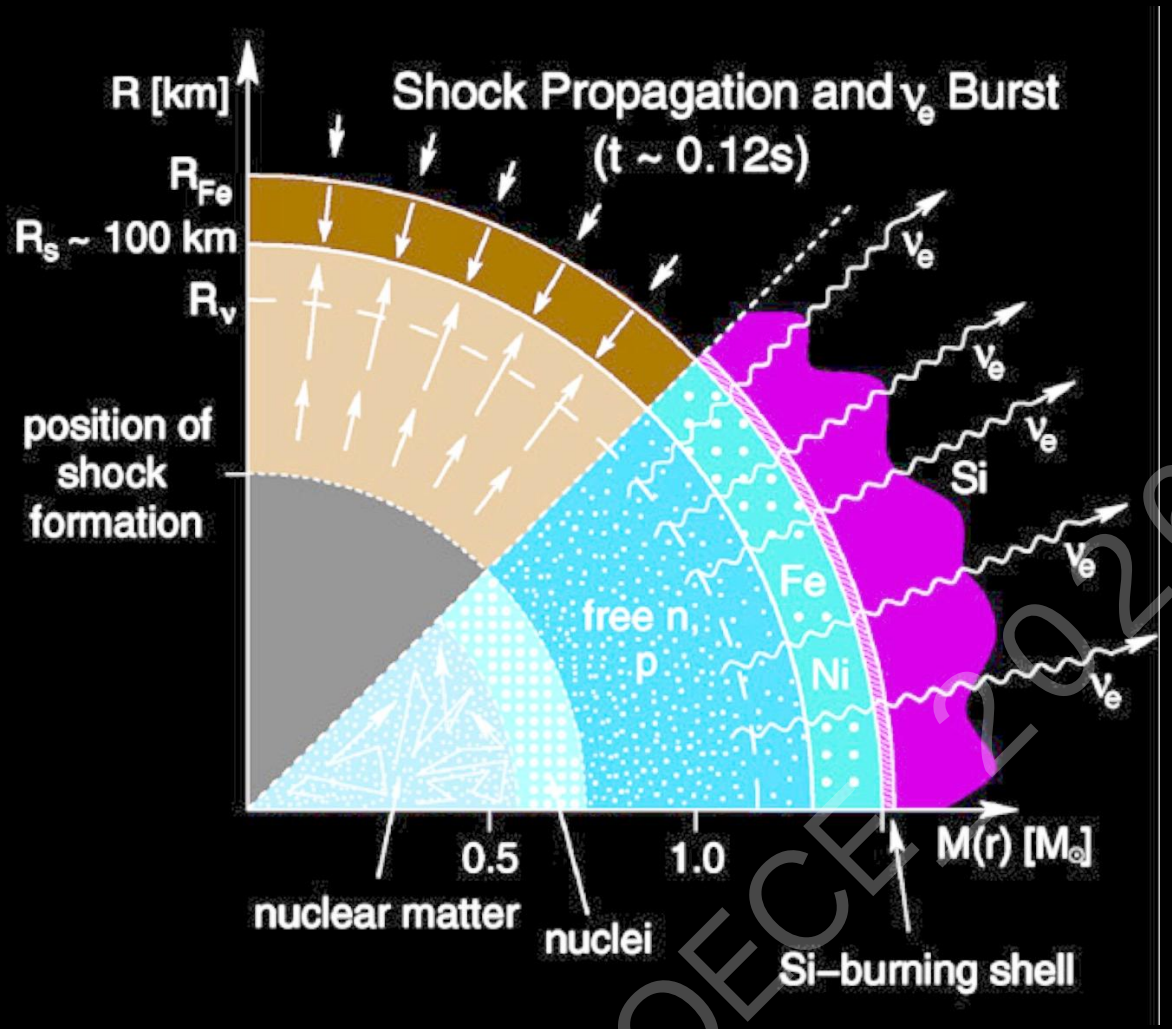
OECE_2026_by_Shuai

Formation of the bounce shock

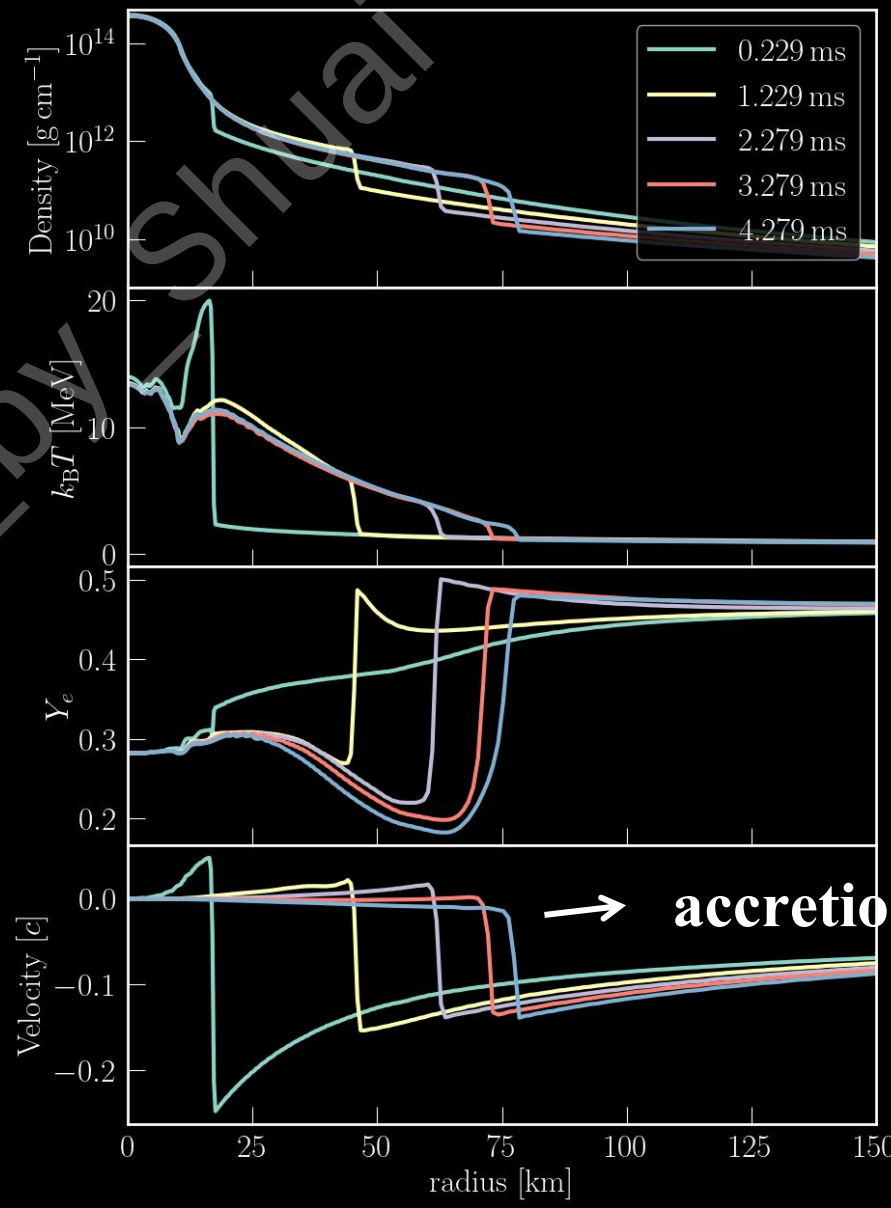


- EOS stiffens -> inner core bounces -> forms a shock wave at the sonic point.
- Inner core mass ~0.5 $M_\odot$, easily supported by the nuclear EOS.
- No 'direct' black hole formation, always a protoneutron star.

OECE_2026_by_Shuai



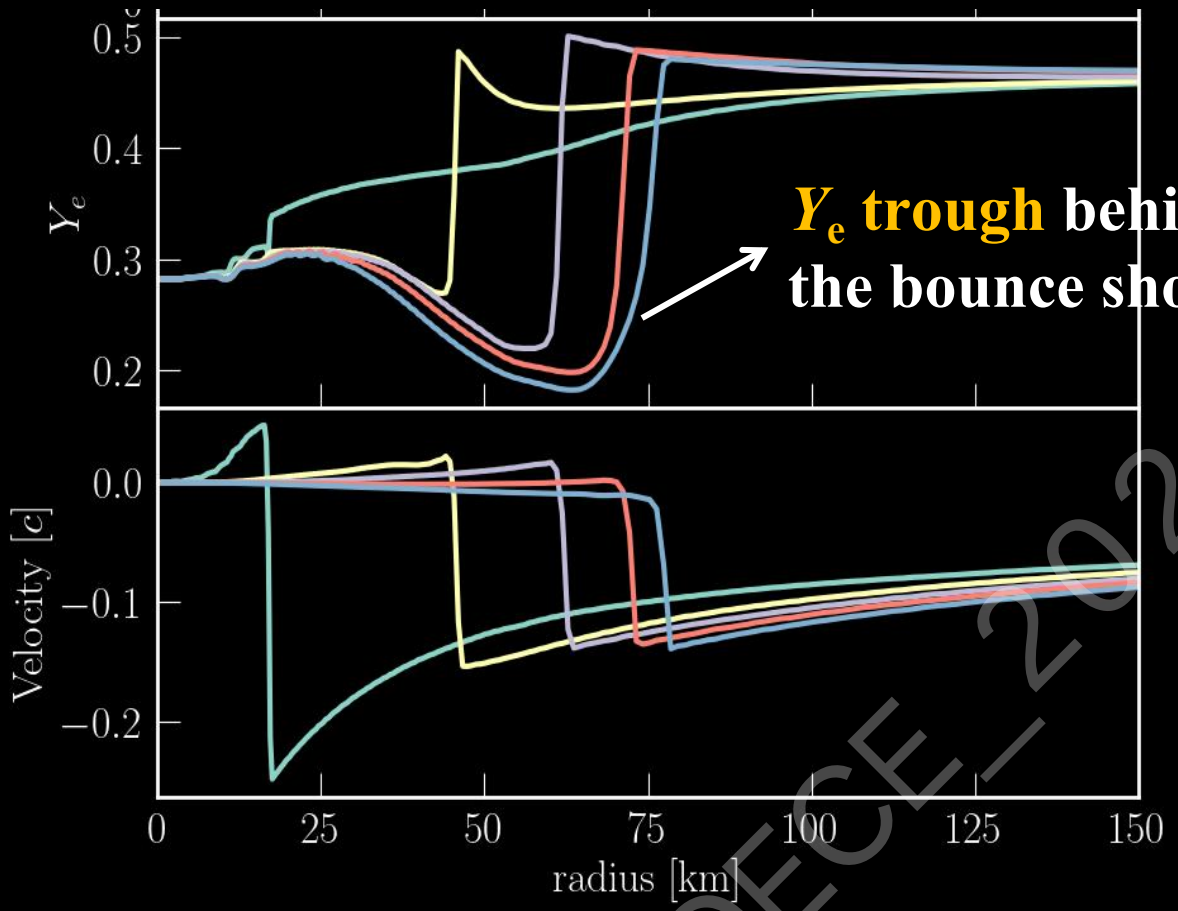
bounce shock stalls



→ accretion shock

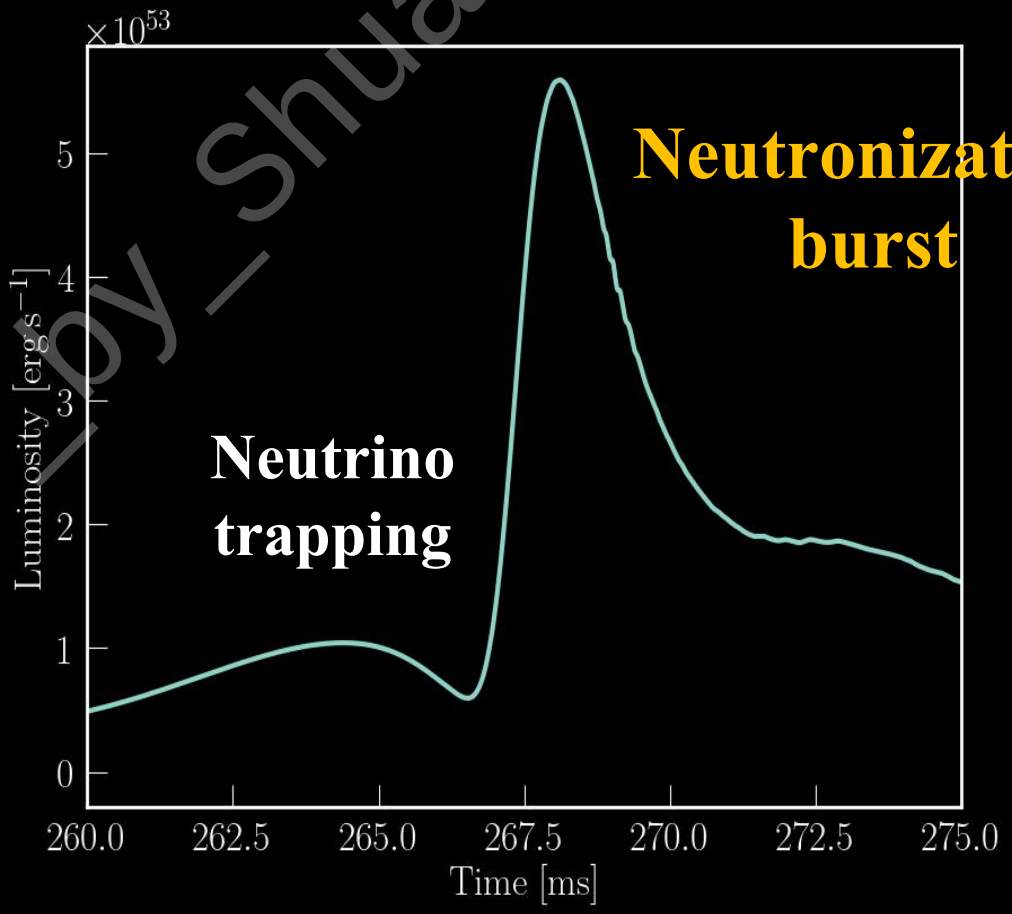
OECE 2026 _by_ Shyai

Neutronization burst



Y_e trough behind the bounce shock

$e^- + p \rightarrow \nu_e + n$

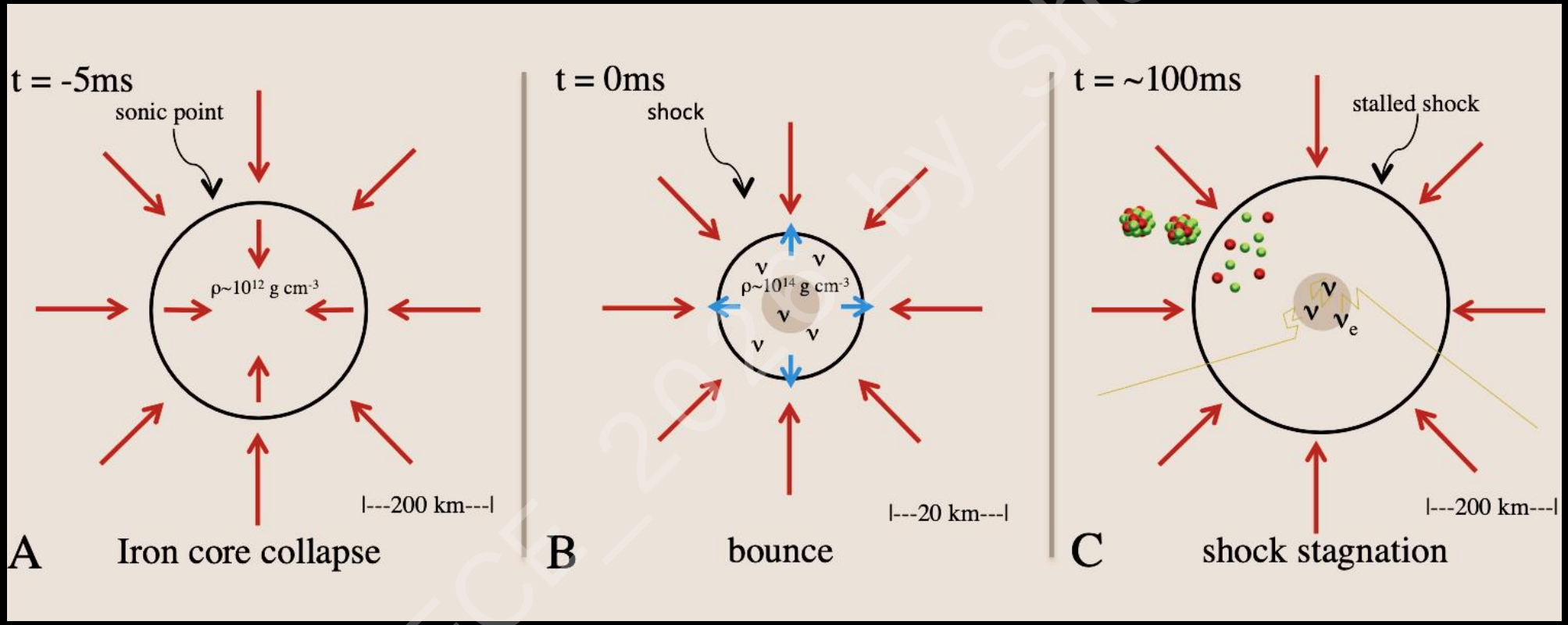


Neutrino trapping

Neutronization burst

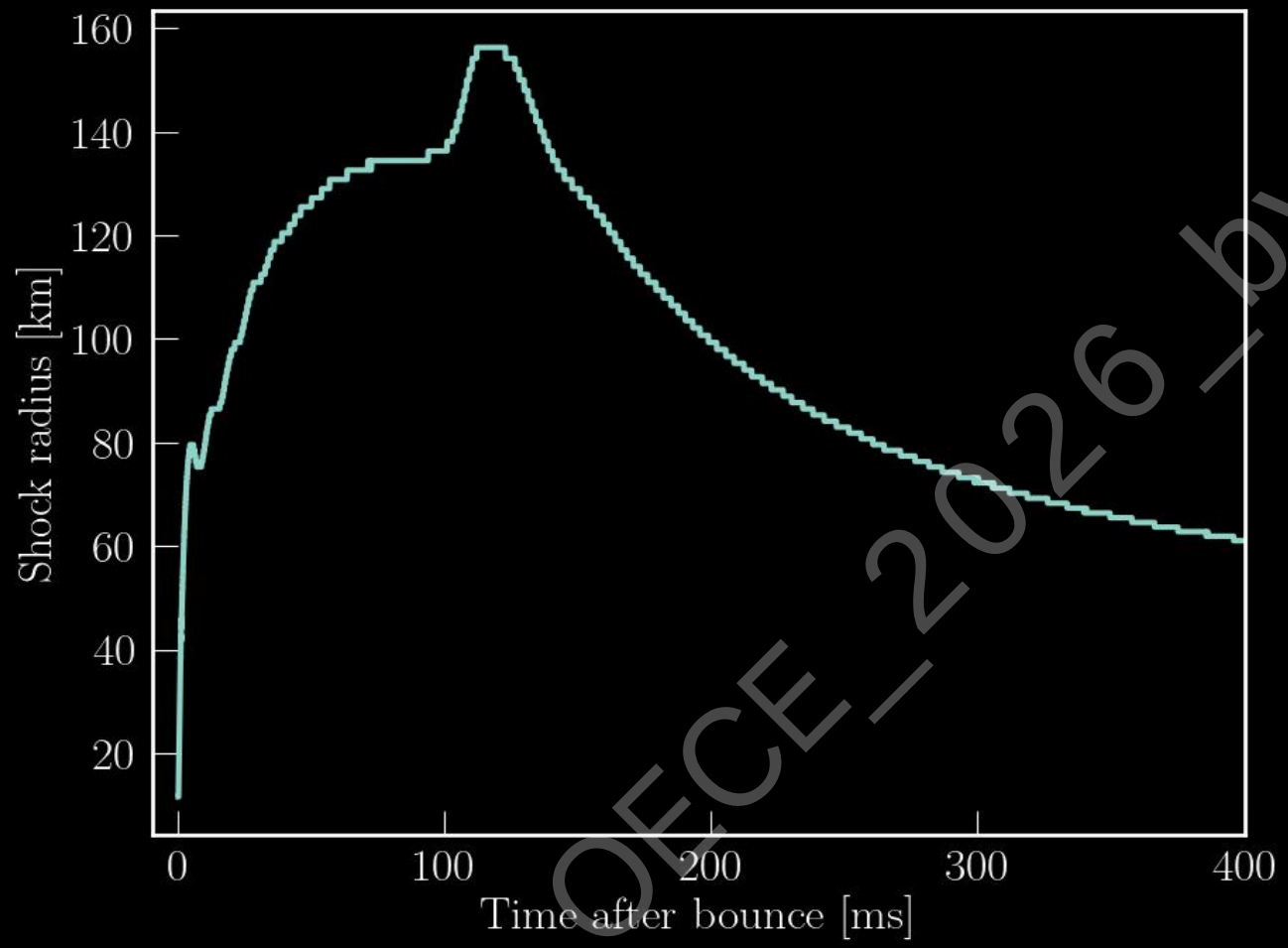
OECE_2026_by_Shuai

Summary of the collapse and bounce



OEC – 2021 by Shuai

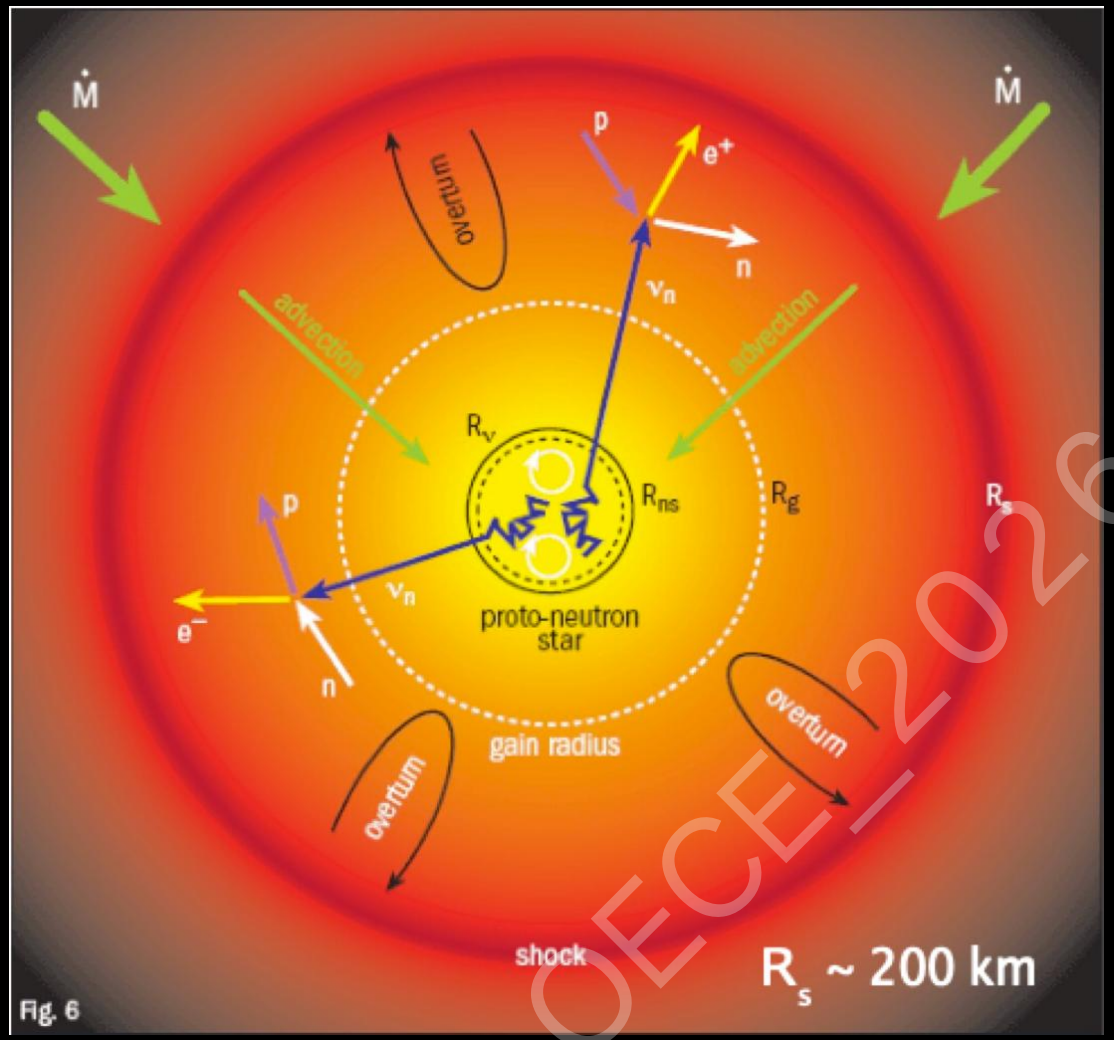
Now we have the supernova problem



- Shock radius reaches a maximum of ~200 km and then recedes
- No successful explosion in spherical symmetry except some rare low-mass progenitor models
- How to revive the shock?

OECE_2026_by_Shuai

The leading explosion mechanism: delayed neutrino-driven



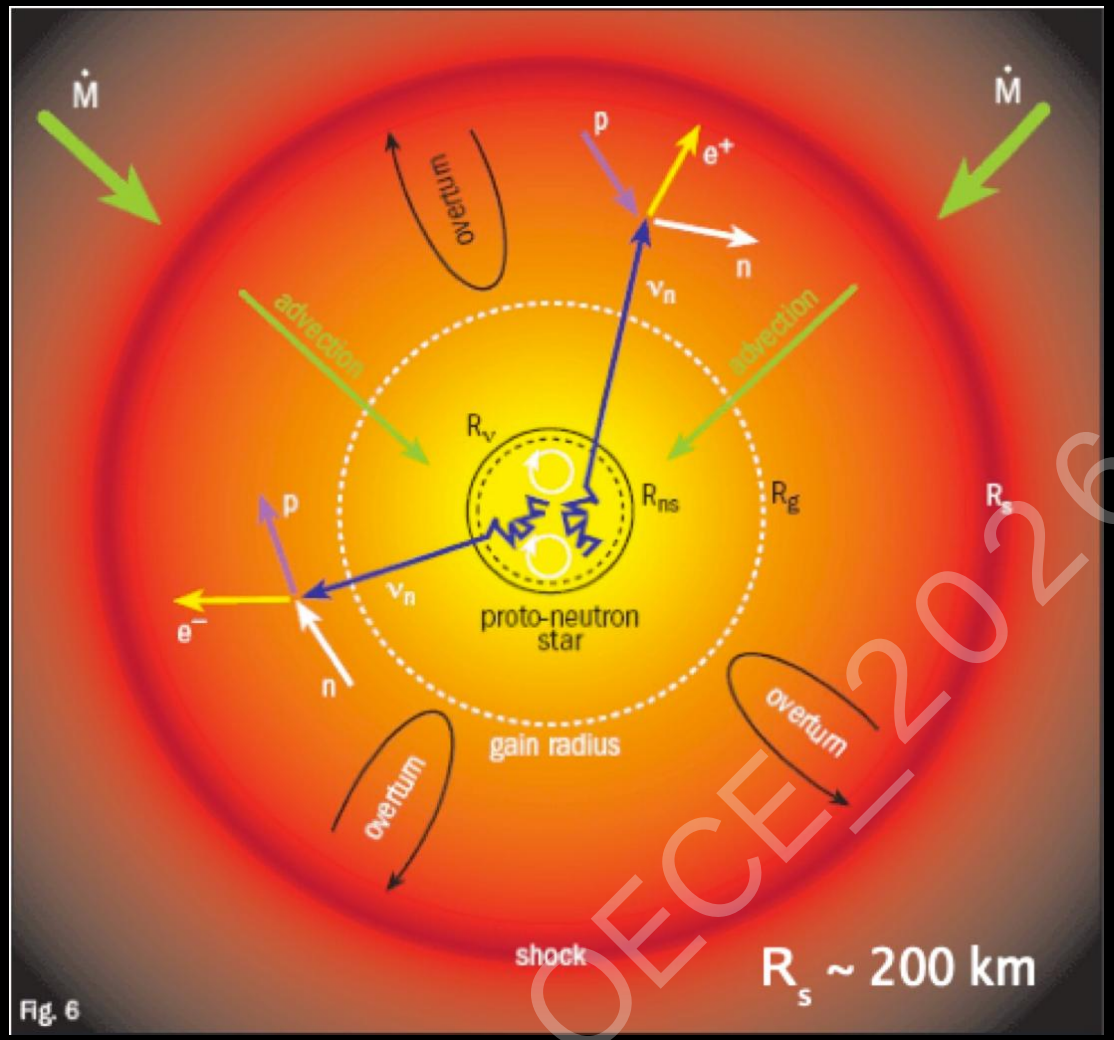
Credit: Thomas Janka

From large to small r:

- $\dot{M}$: mass accretion rate of the still infalling matter
- R_s: (mean) shock radius
- R_g: gain radius separating net heating and cooling region
- R_ν: neutrino sphere at 'optical' depth $\tau=2/3$
- R_{ns}: neutron star surface, usually defined at density of 10^{11} g cm^{-3}

OECE_2026_by_shuai

The leading explosion mechanism: delayed neutrino-driven



Credit: Thomas Janka

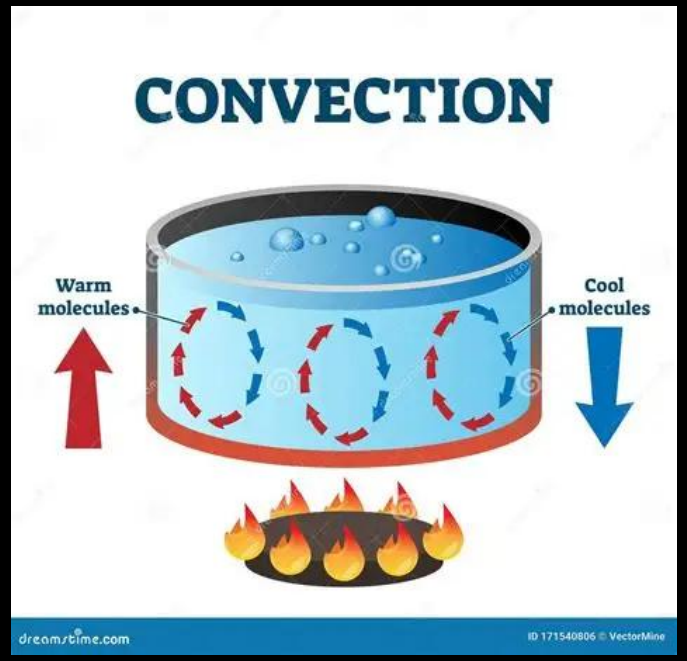
Crucial for successful explosions:

- ☐ **Neutrino heating**
- ☐ **Hydrodynamic instabilities (eg.: overturn) enhance neutrino heating and provide turbulence stress (i.e. extra pressure)**

So: we need multi-dimensional, neutrino-transport, hydrodynamic simulations.

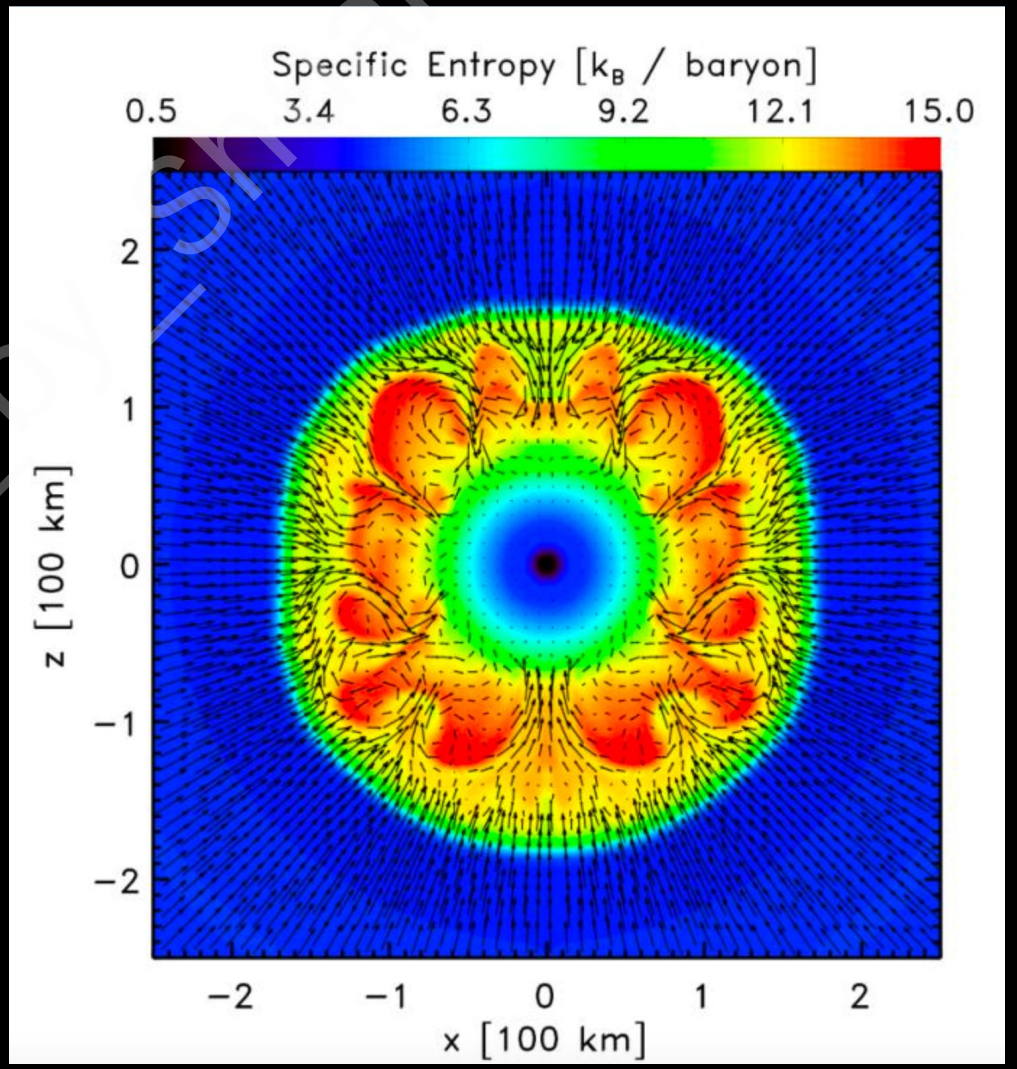
OECE_2026_by_Shuai

Neutrino-driven convection



- Prolong **dwell time:** time spent in the heating region
- Additional pressure support (Couch 2015)

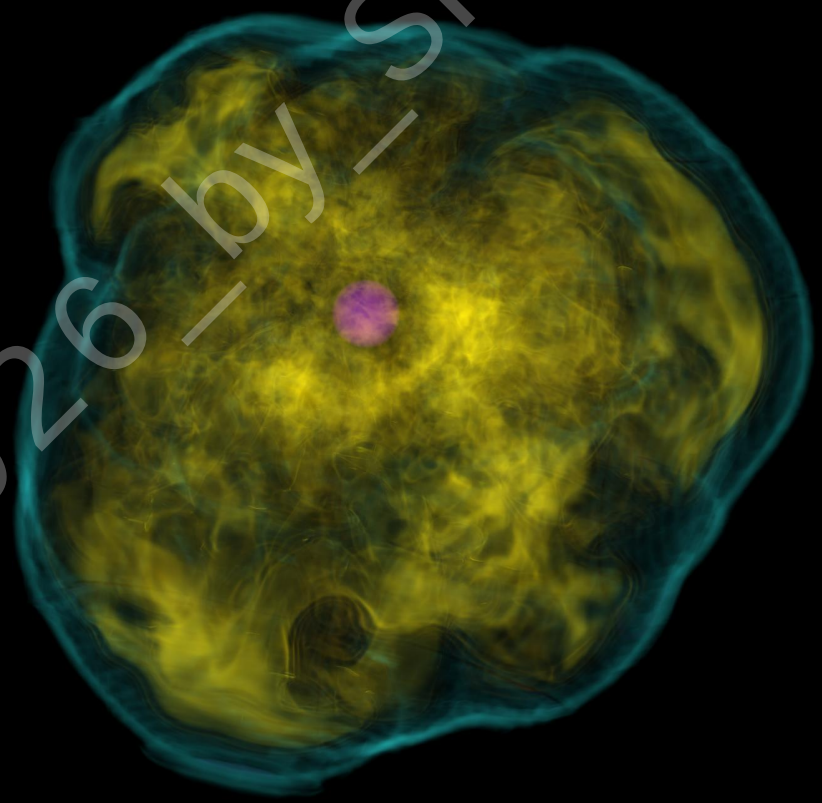
$$P_{\rm turb} \simeq \rho \langle \delta v_r^2 \rangle$$



OECE_2026_bi_SH

3D neutrino-hydrodynamic simulation to see how the explosion starts

neutron star
neutrino-heated bubbles
accretion/expanding shock



Enabled by FLASH-BANG

AMR
Driver
MPI

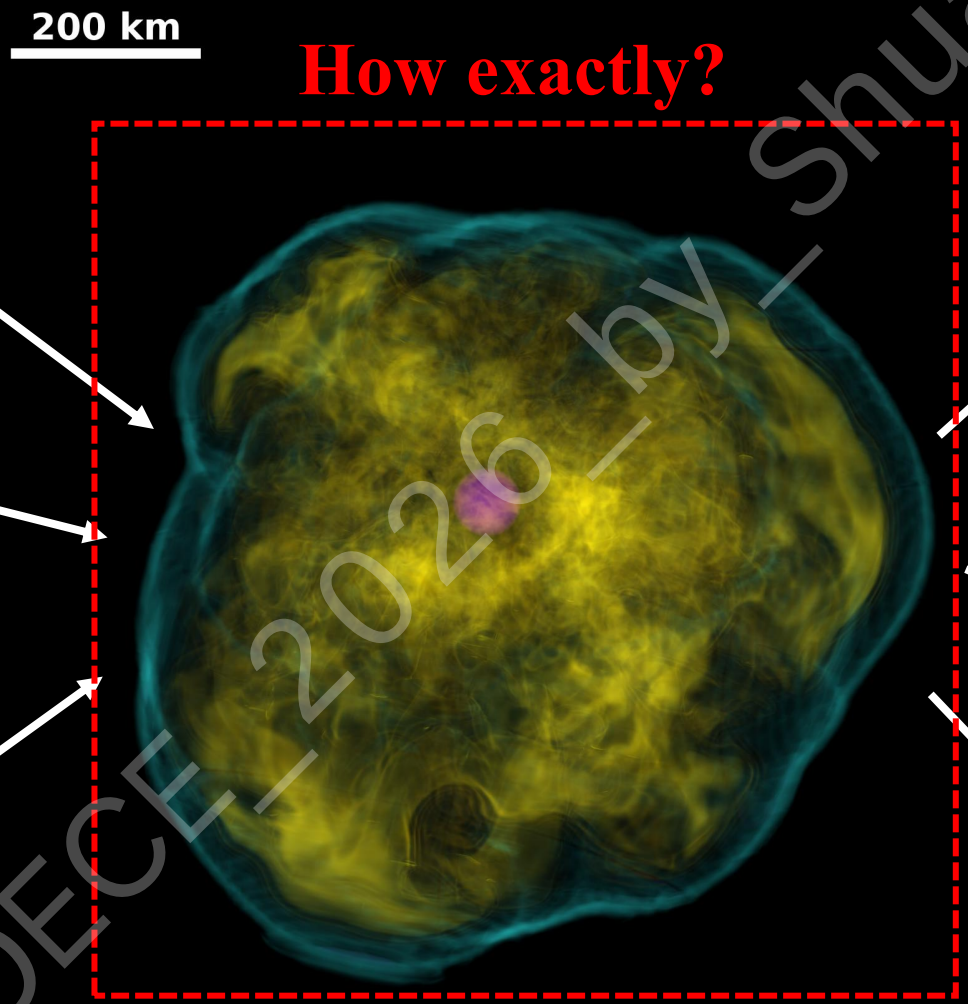
Hydrodynamics
Neutrino
Equation of state
self-gravity

w/ Evan O'Connor & Sean Couch

Zha+ in prep.

OECE_2026_by_Shuai

3D neutrino-hydrodynamic simulation to see how the explosion starts



OECE_2026_by_Shuai

Summary of Simulation Ingredients

- ✓ Hydrodynamics
- ✓ Self-gravity
- ✓ Microphysics: nuclear & neutrino
- ✓ Neutrino transport

} Fully coupled

OECE_2026_by_Shuai

Hydrodynamics+self-gravity

Newtonian version

$$\text{Mass:} \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\text{Momentum:} \quad \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u} + p\mathbf{I}) = \rho \mathbf{g}$$

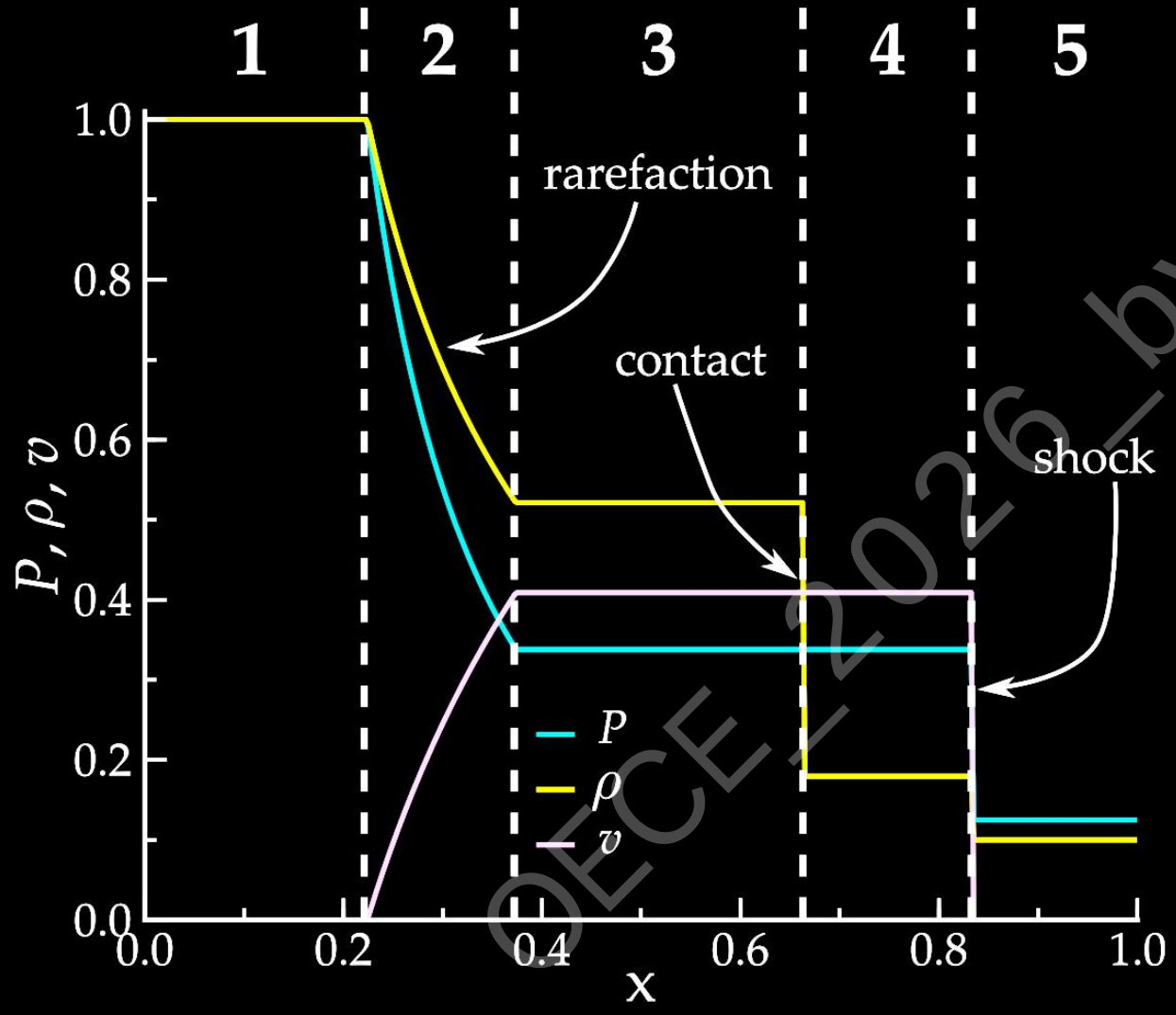
$$\text{Energy:} \quad \frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathbf{u}] = \rho \mathbf{g} \cdot \mathbf{u}$$

$$\text{Gravity:} \quad \mathbf{g} = -\nabla \phi, \ \nabla^2 \phi = 4\pi G \rho$$

Usually a **TOV potential** added for GR effect

Essential: continuity equations plus work done by pressure gradient and gravitational force

Key of hydro: shock capturing



- **PPM:** piecewise parabolic method
- **WENO:** weighted essentially non-oscillatory
- ....

©ECE_2026_by_Shuai

CFC general-relativistic hydrodynamics

Metric and fluid variables

$$\mathrm{d}s^2 = -\alpha^2 \mathrm{d}t^2 + \gamma_{ij}(\mathrm{d}x^i + \beta^i \mathrm{d}t)(\mathrm{d}x^j + \beta^j \mathrm{d}t), \qquad \gamma_{ij} = \psi^4 \hat{\gamma}_{ij}, \qquad K = 0$$

$$T^{\mu\nu} = \rho h u^\mu u^\nu + P g^{\mu\nu}, \quad D = \rho W, \quad S_i = \rho h W^2 v_i, \quad \tau = \rho h W^2 - P - D, \quad \widetilde{v}^i = \alpha v^i - \beta^i$$

CFC metric equations

$$\hat{\Delta}\psi = -2\pi\psi^5 \left(E + \frac{K_{ij}K^{ij}}{16\pi} \right)$$

$$\hat{\Delta}(\alpha\psi) = 2\pi\alpha\psi^5 \left(E + 2S + \frac{7K_{ij}K^{ij}}{16\pi} \right)$$

$$\hat{\Delta}\beta^i + \frac{1}{3}\hat{\nabla}^i\hat{\nabla}_j\beta^j = 16\pi\alpha\psi^4 S^i + 2\psi^{10} K^{ij}\hat{\nabla}_j\left(\frac{\alpha}{\psi^6}\right)$$

$$K^{ij} = \frac{\psi^{-4}}{2\alpha}\left(\hat{\nabla}^i\beta^j + \hat{\nabla}^j\beta^i - \frac{2}{3}\hat{\gamma}^{ij}\hat{\nabla}_k\beta^k\right)$$

$$E = \rho h W^2 - P, \qquad S^i = \rho h W^2 v^i, \qquad S = \rho h W^2 v^2 + 3P$$

Flux-conservative hydrodynamic equations

Mass

$$\partial_t(\sqrt{\gamma}D) + \partial_i(\sqrt{\gamma}D\widetilde{v}^i) = 0$$

Momentum

$$\partial_t(\sqrt{\gamma}S_j) + \partial_i\left[\sqrt{\gamma}\left(S_j\widetilde{v}^i + \alpha P\delta^i{}_j\right)\right] = \frac{\alpha\sqrt{\gamma}}{2}T^{\mu\nu}\partial_j g_{\mu\nu} + \sqrt{\gamma}Q_j$$

Energy

$$\partial_t(\sqrt{\gamma}\tau) + \partial_i\left[\sqrt{\gamma}\left(\tau\widetilde{v}^i + \alpha P v^i\right)\right] = \alpha\sqrt{-g}\left(T^{\mu 0}\partial_\mu \ln\alpha - T^{\mu\nu}\Gamma^0_{\mu\nu}\right) + \mathcal{Q}_E$$

Composition

$$\partial_t(\sqrt{\gamma}DY_e) + \partial_i(\sqrt{\gamma}DY_e\widetilde{v}^i) = \mathcal{Q}_{Y_e}$$

Neutrino transport

☐ **Solving the Boltzmann equation**

$$\underbrace{p^\alpha \frac{\partial f_\nu}{\partial x^\alpha} - \Gamma^i_{\beta\gamma} p^\beta p^\gamma \frac{\partial f_\nu}{\partial p^i}}_{\text{Liouville operator } \mathcal{L}[f_\nu]} = \underbrace{\left(\frac{\delta f_\nu}{\delta \tau}\right)_{\text{coll}}}_{\text{Collision Integral } \mathcal{C}[f_\nu]}$$

$$\mathcal{C}[f_\nu] = \eta_\nu(E)\,(1 - f_\nu) - \chi_\nu(E)\, f_\nu$$
$$+ \int dE'\, d\Omega'\; R_{\text{scat}}(E', \Omega' \to E, \Omega)\, f_\nu(E', \Omega')\,(1 - f_\nu(E, \Omega))$$
$$- f_\nu(E, \Omega) \int dE'\, d\Omega'\; R_{\text{scat}}(E, \Omega \to E', \Omega')\,(1 - f_\nu(E', \Omega'))$$
$$+ \mathcal{C}_{\text{pair}} + \mathcal{C}_{\nu\bar{\nu}} + \cdots$$

a 6D problem: *x,y,z, p_x, p_y, p_z*

Emission / absorption

$$e^- + (N, Z) \rightleftharpoons (N + 1, Z - 1) + \nu_e$$
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

Scattering

$$\nu + (N, Z) \rightleftharpoons \nu + (N, Z)$$
$$\nu + N \rightleftharpoons \nu + N$$
$$\nu + e^\pm \rightleftharpoons \nu + e^\pm$$

Pair processes

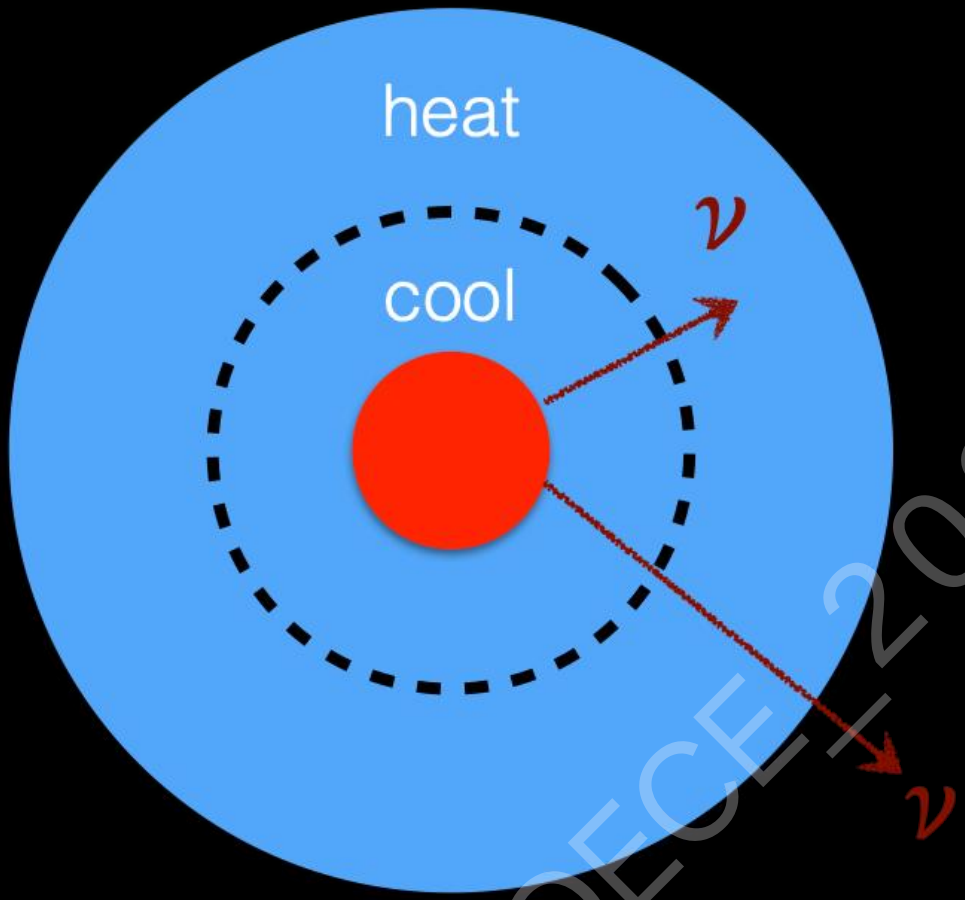
$$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$$
$$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$$

Neutrino processes

$$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_x + \bar{\nu}_x$$

Copyright © 2022 by Shuai

Limiting cases



- **Core region (PNS): opaque to neutrinos, diffusion limit**

$$\frac{\partial E_\nu}{\partial t} = \nabla \cdot (D_\nu \nabla E_\nu) \qquad D_\nu \simeq \frac{c\lambda_\nu}{3}$$

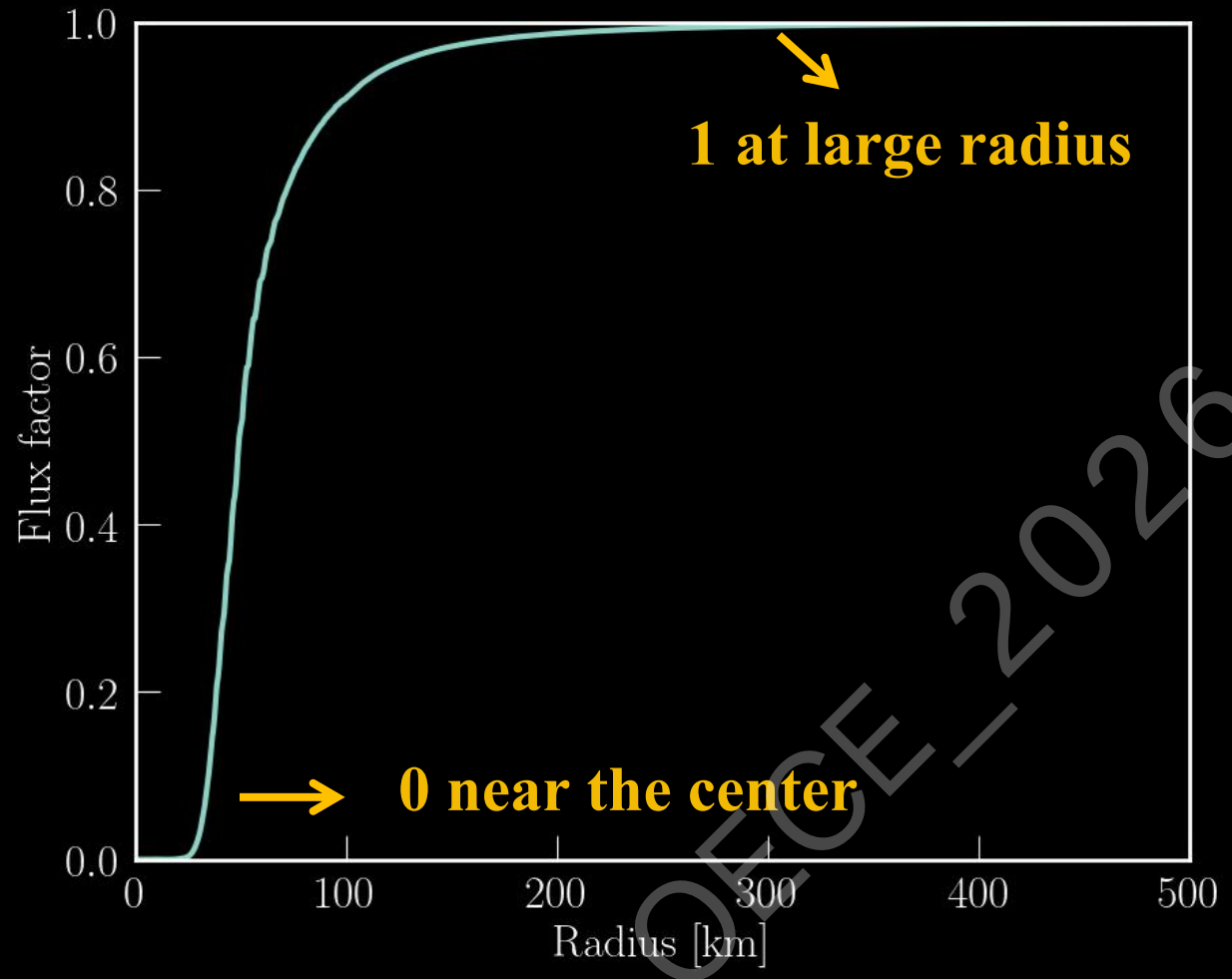
- **Far outside: transparent to neutrinos, free-streaming limit**
- **In-between: key to the neutrino transport algorithm and explosion mechanism**



Credit: Yudai Suwa

OECF_2026_by_shuai

Example in simulations: the flux factor



Zeroth moment

$$J_\nu(\epsilon) \equiv \frac{1}{4\pi}\int f_\nu(\epsilon, n)\, d\Omega$$

First moment

$$H_\nu(\epsilon) \equiv \frac{1}{4\pi}\int n\, f_\nu(\epsilon, n)\, d\Omega$$

Flux factor

$$\mathrm{ff}_\nu(\epsilon) \equiv \frac{|F_\nu(\epsilon)|}{cE_\nu(\epsilon)} = \frac{|H_\nu(\epsilon)|}{J_\nu(\epsilon)}$$

OECE_2026_by_Shuai

Coupling to hydrodynamics

Electron fraction: $\dfrac{\partial(\rho Y_e)}{\partial t} + \boldsymbol{\nabla}\cdot(\rho Y_e \boldsymbol{u}) = \rho \dot{Y}_{e,\nu}$

Composition: $\dfrac{\partial(\rho X_i)}{\partial t} + \boldsymbol{\nabla}\cdot(\rho X_i \boldsymbol{u}) = \rho \dot{X}_i$

Momentum: $\dfrac{\partial(\rho \boldsymbol{u})}{\partial t} + \boldsymbol{\nabla}\cdot(\rho \boldsymbol{u}\otimes\boldsymbol{u} + p\boldsymbol{I}) = \rho \boldsymbol{g} + \boldsymbol{S}_\nu^p$

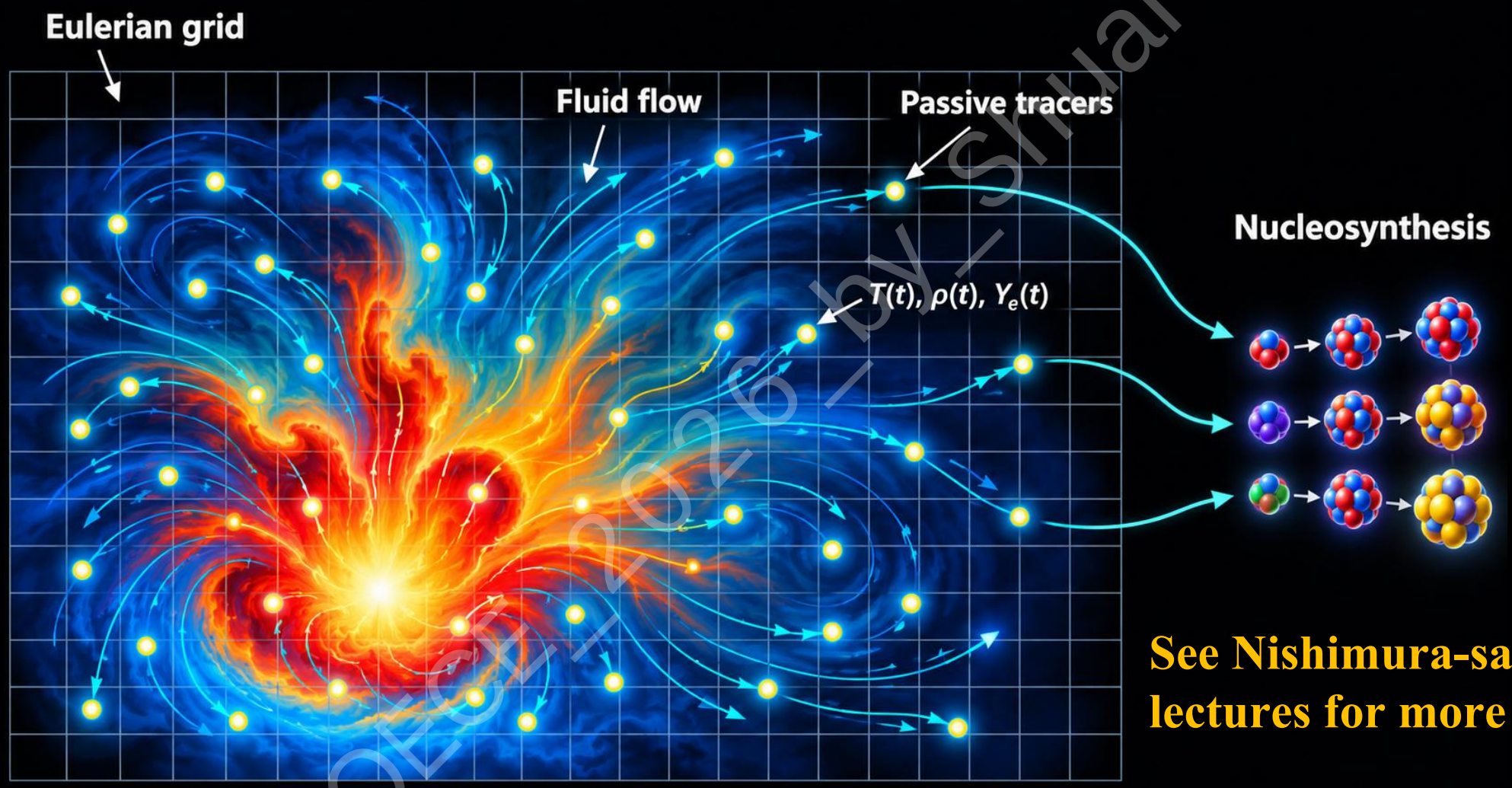
Energy: $\dfrac{\partial E}{\partial t} + \boldsymbol{\nabla}\cdot[(E+p)\boldsymbol{u}] = \rho \boldsymbol{g}\cdot\boldsymbol{u} + S_\nu^E + \rho\varepsilon_{\mathrm{nuc}}$

Feedback from neutrino transport

Feedback from nuclear reaction

OECE_2026 by_Shuai

Predicting nucleosynthesis



Credit: ChatGPT

See Nishimura-san's lectures for more details.

OEC 2026 _by_ Shuai

Zha+26 SCPMA arXiv:2609.16584

SCIENCE CHINA
Physics, Mechanics & Astronomy

• Article •
SPECIAL TOPIC: Astronomy

January 2023 Vol. 66 No. 1: 000000
https://doi.org/??

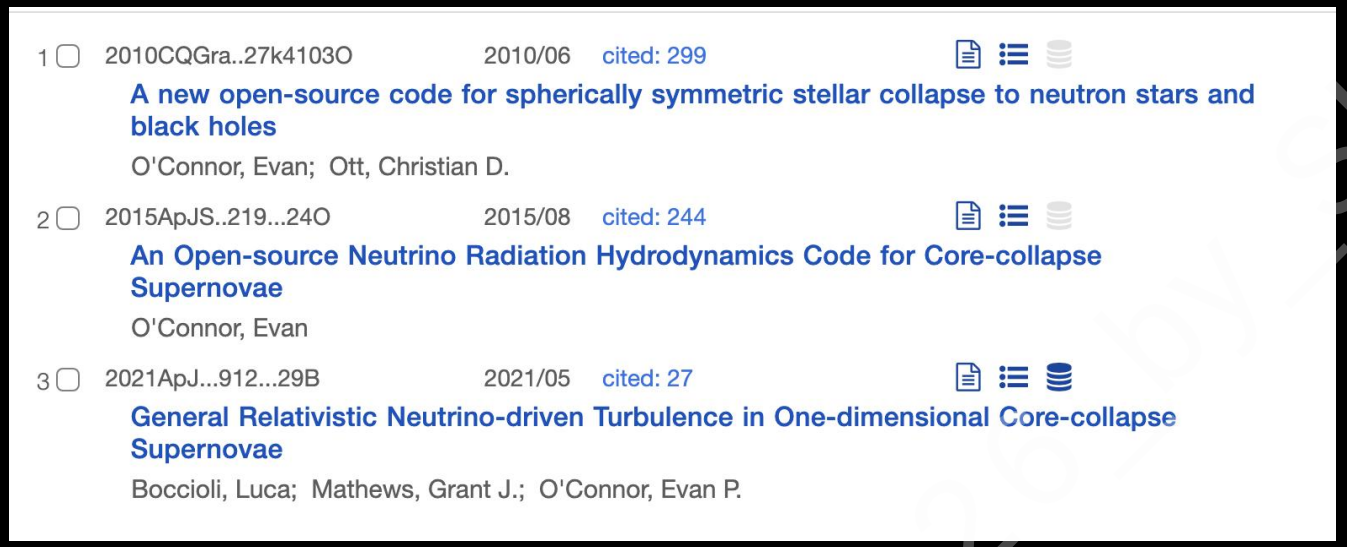
Supernova nucleosynthesis: a review

Shuai Zha[1*], Yudong Luo[2], and Zhanwen Han[1*]

[1] *International Centre of Supernovae (ICESUN), Yunnan Key Laboratory of Supernova Research, Yunnan Observatories, Chinese Academy of Sciences (CAS), 650216 Kunming, People's Republic of China;*
[2] *Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon 34126, Korea*

OB 2026 by Shuai

A first and excellent start: GR1D (+)



1 ☐ 2010CQGra..27k4103O 2010/06 cited: 299

A new open-source code for spherically symmetric stellar collapse to neutron stars and black holes

O'Connor, Evan; Ott, Christian D.

2 ☐ 2015ApJS..219...24O 2015/08 cited: 244

An Open-source Neutrino Radiation Hydrodynamics Code for Core-collapse Supernovae

O'Connor, Evan

3 ☐ 2021ApJ...912...29B 2021/05 cited: 27

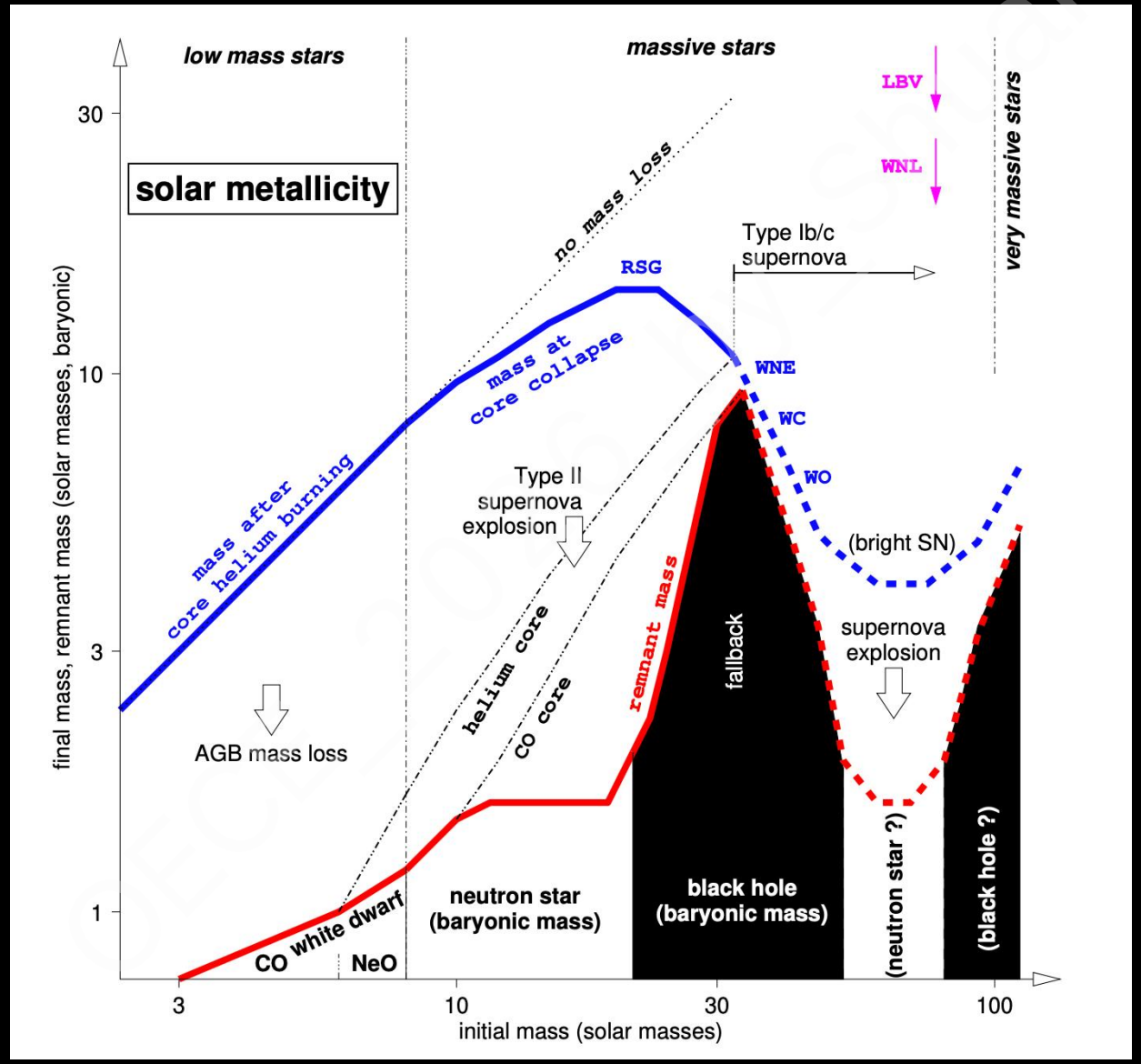
General Relativistic Neutrino-driven Turbulence in One-dimensional Core-collapse Supernovae

Boccioli, Luca; Mathews, Grant J.; O'Connor, Evan P.

- ☐ **Publicly available @ https://github.com/evanoconnor/GR1D**
- ☐ **General-relativistic hydro, accurate energy-dependent neutrino transport.**
- ☐ **All presented 1D illustration plots are from a standard simulation with GR1D.**
- ☐ **It is spherically symmetric, but now can explode with effective turbulence (+).**

OFCF_2025 by Shuai

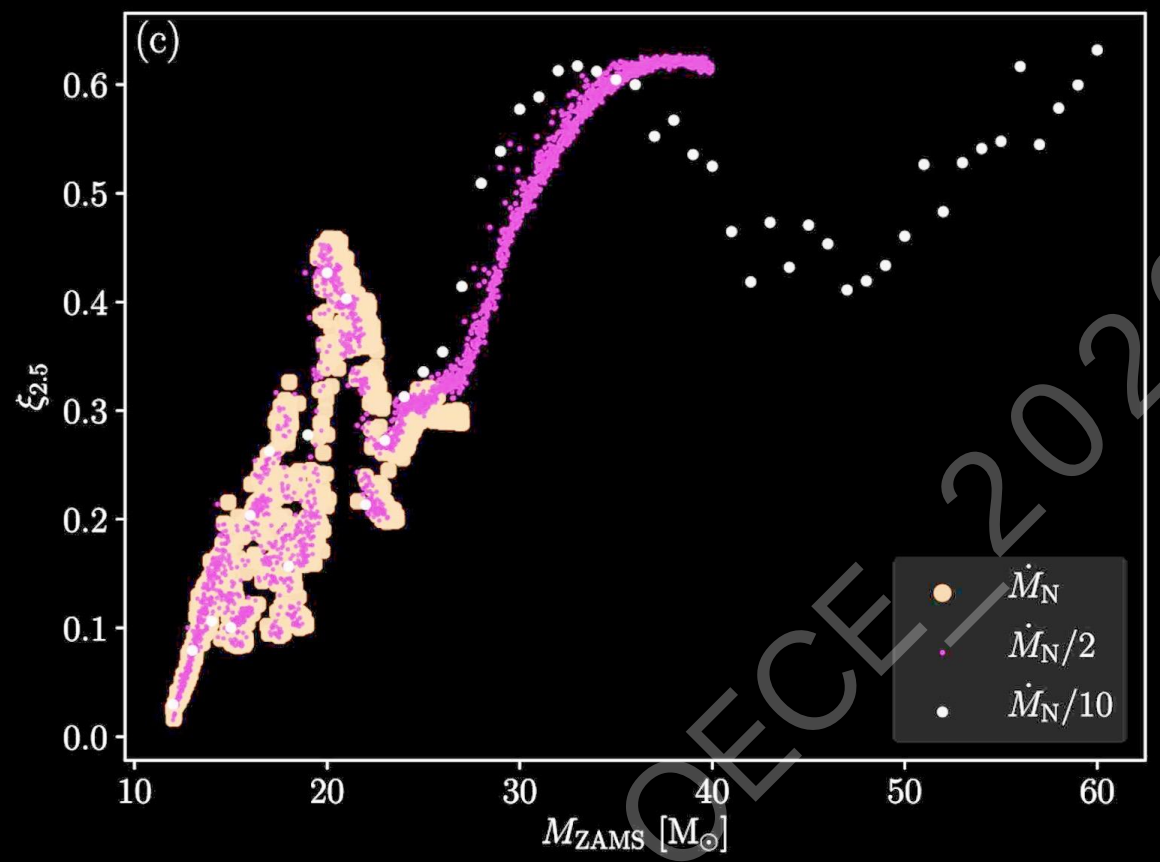
The zeroth-order problem: explodability



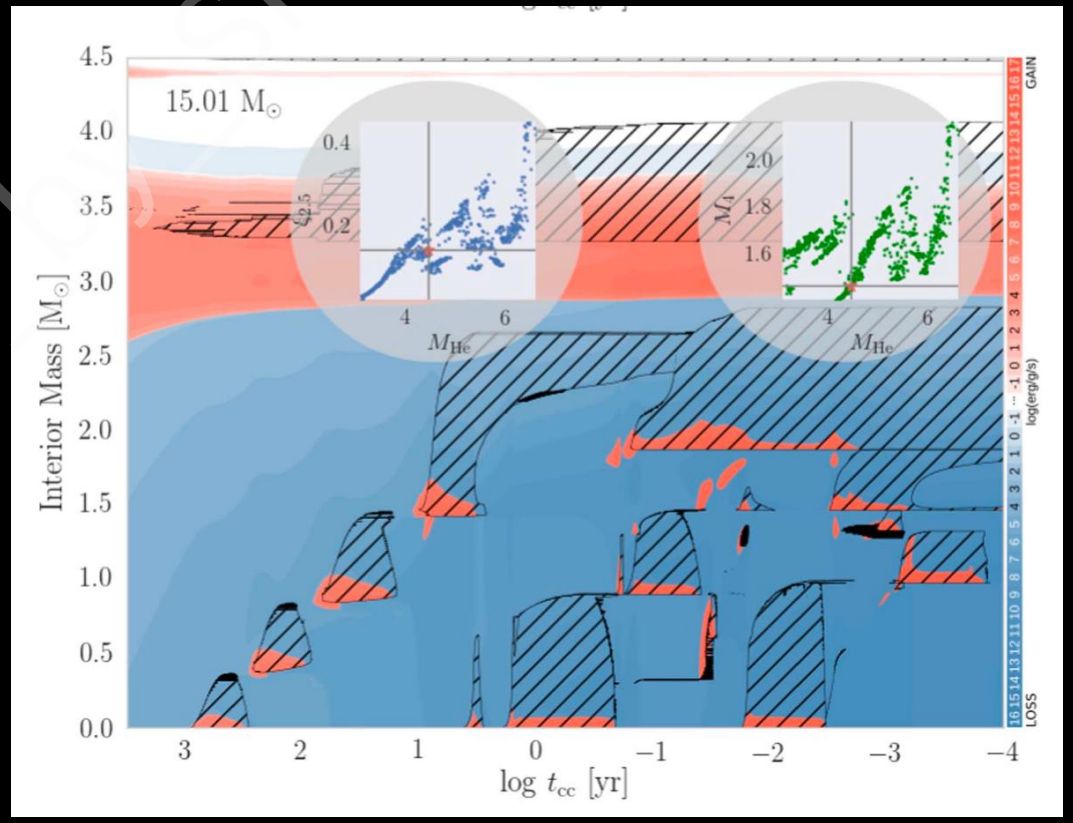
Herger, Woosley+

But: progenitor models show stochasticity

$$\xi_{\rm M} = \left. \frac{M/{\rm M}_\odot}{R(M_{\rm bary} = M)/1000\ {\rm km}} \right|_{t_{\rm bounce}}$$



Kippenhahn diagram

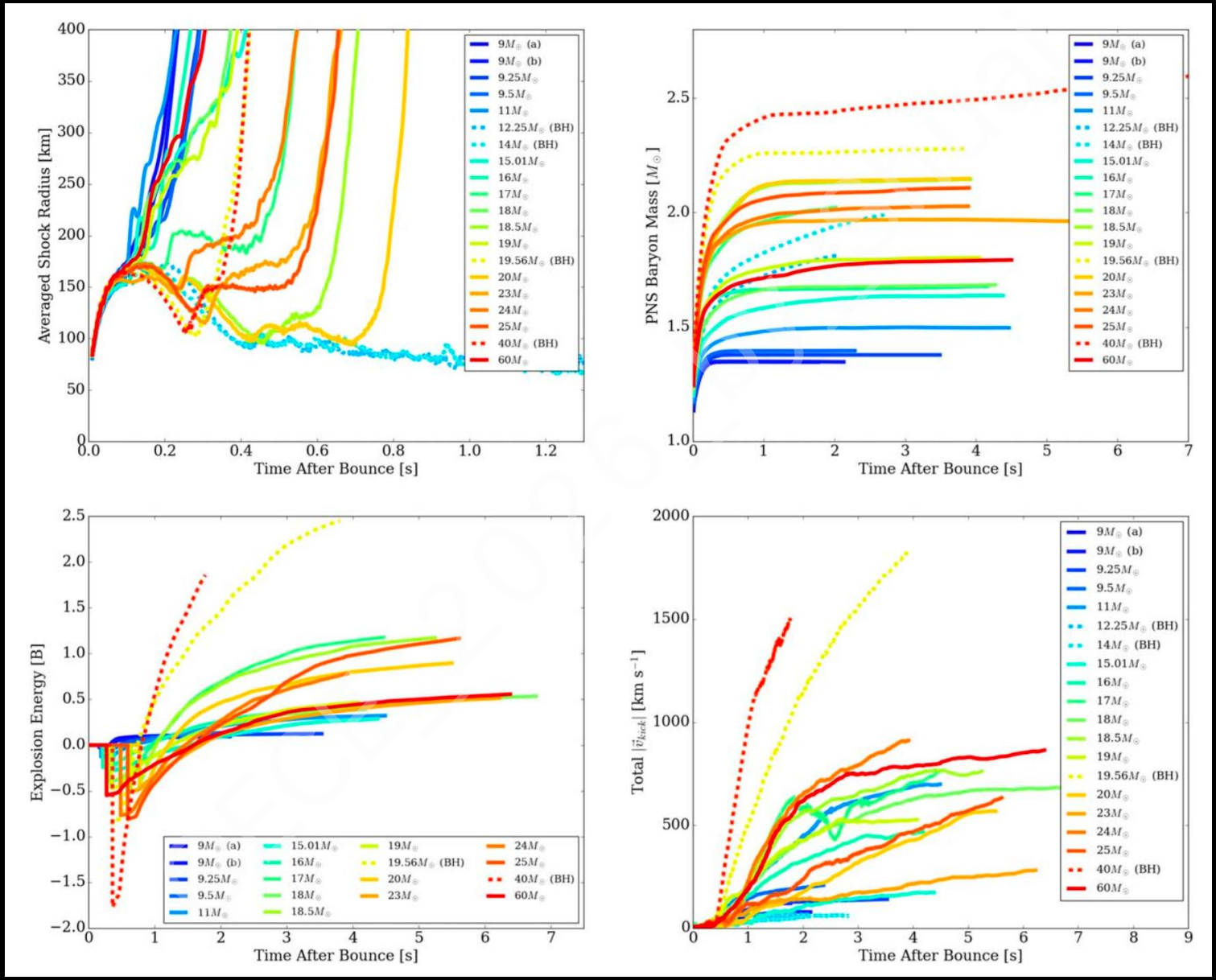


Sukhbold+

Marco has a different opinion on this, ask him!

OECE 2026 Shuai

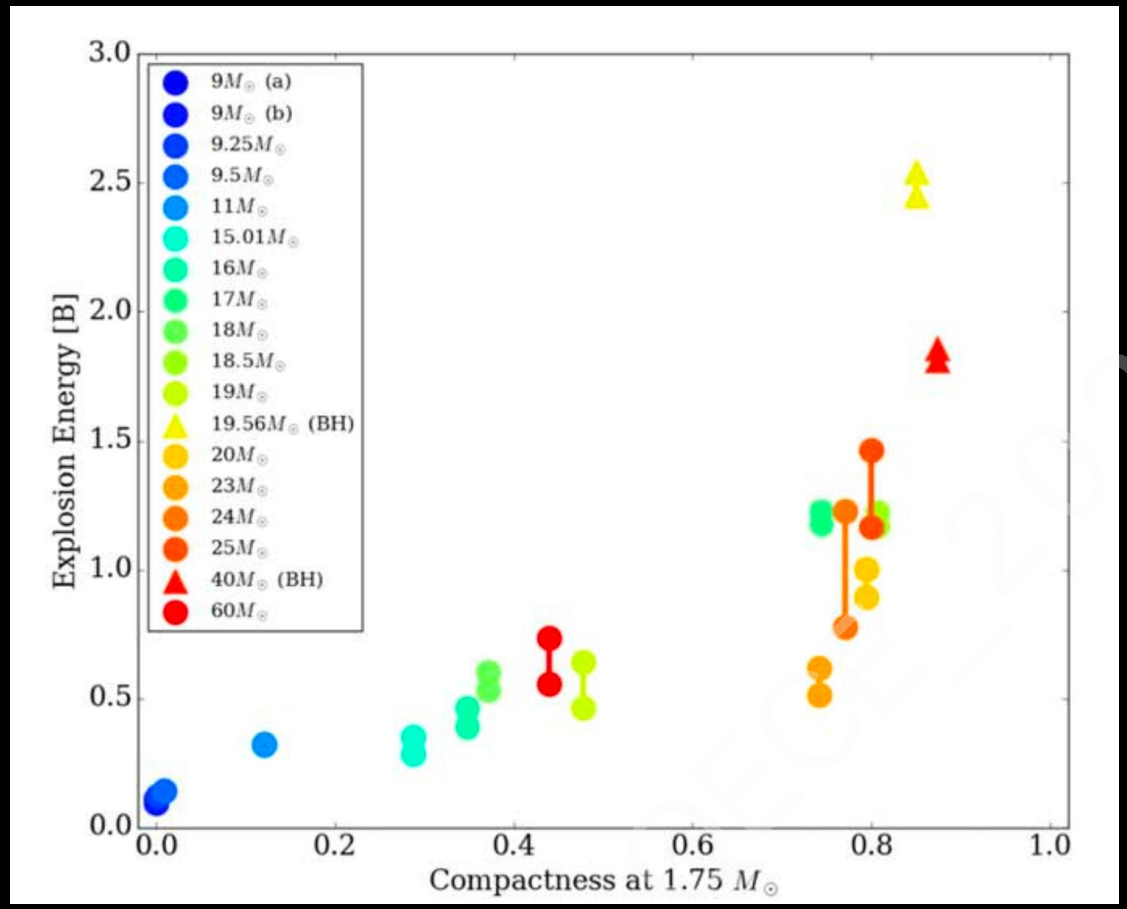
Princeton's 3D Fornax models



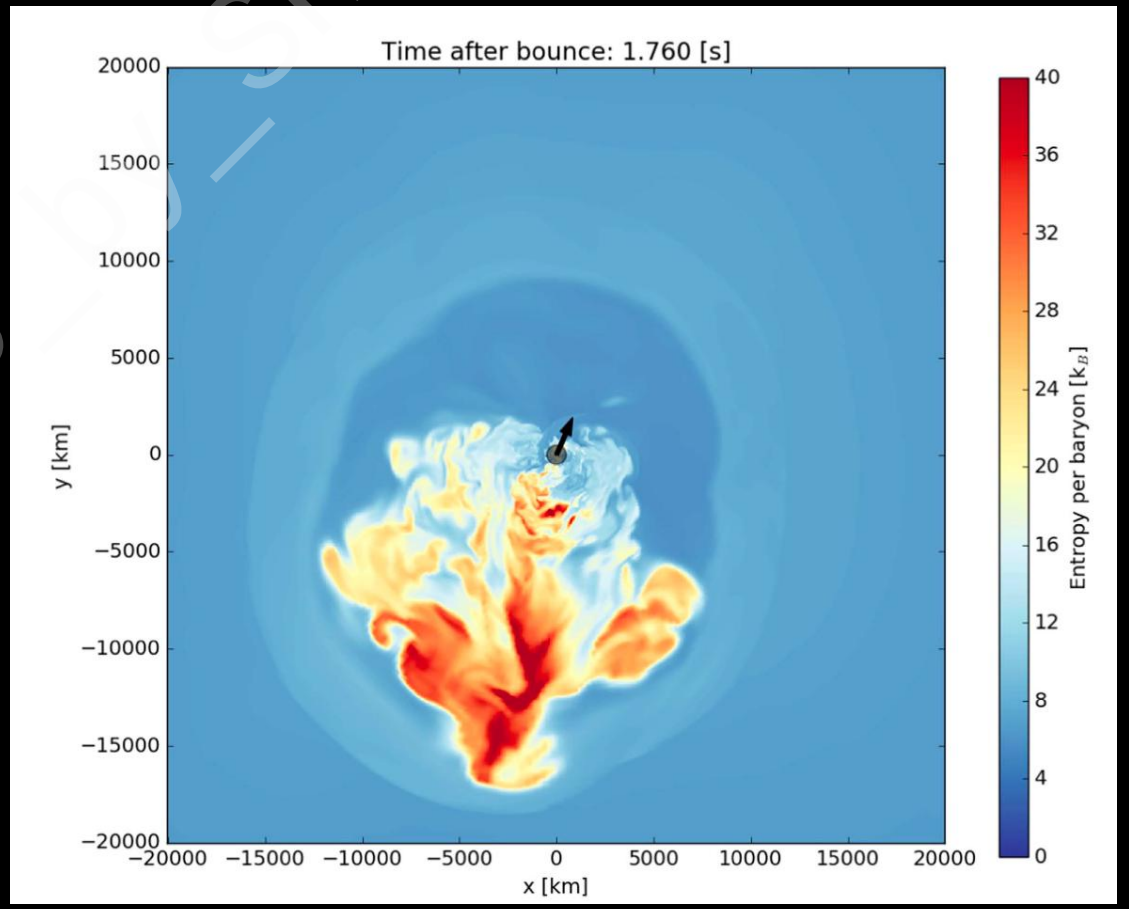
Burrows+24

Two trends

Some correlations between outcomes and compactness ξ



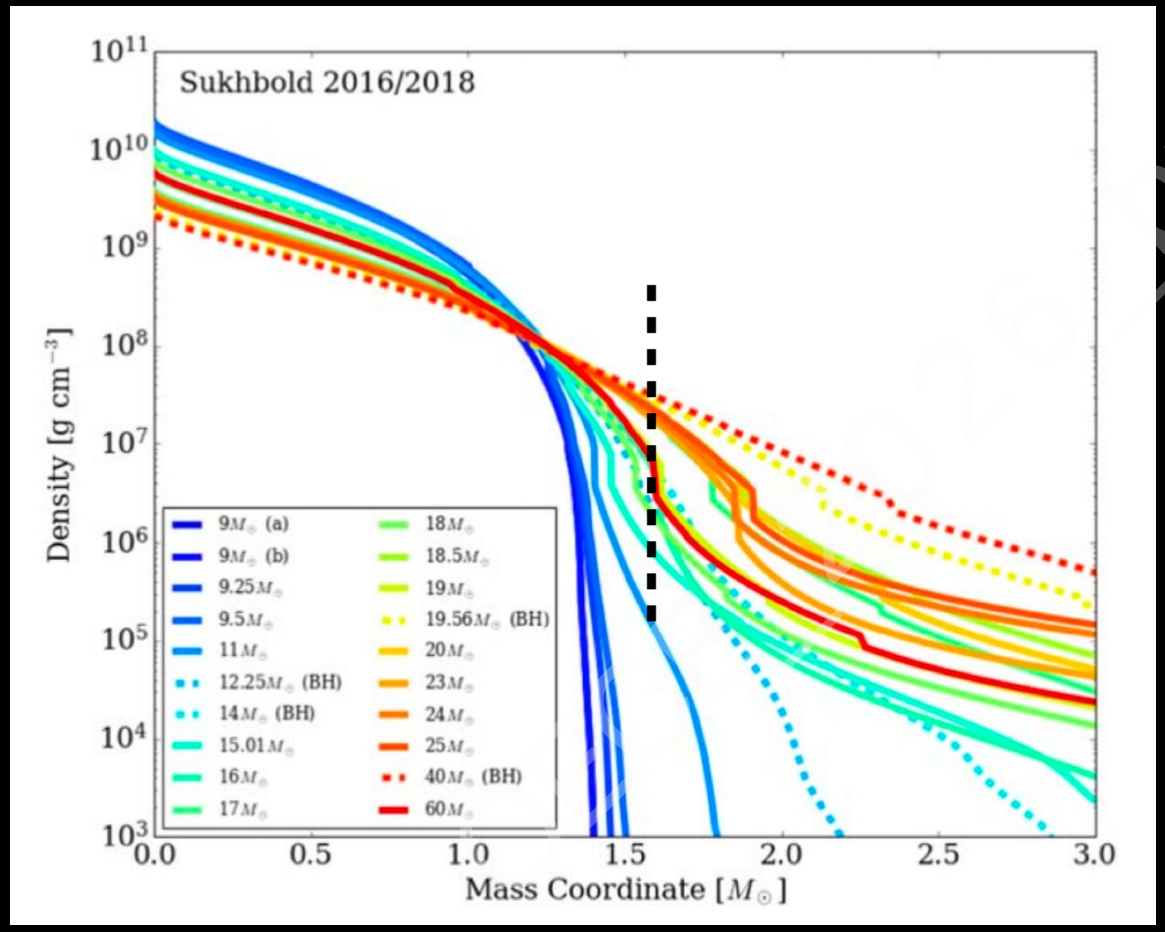
Some very asymmetric explosion with persistent accretion onto PNS



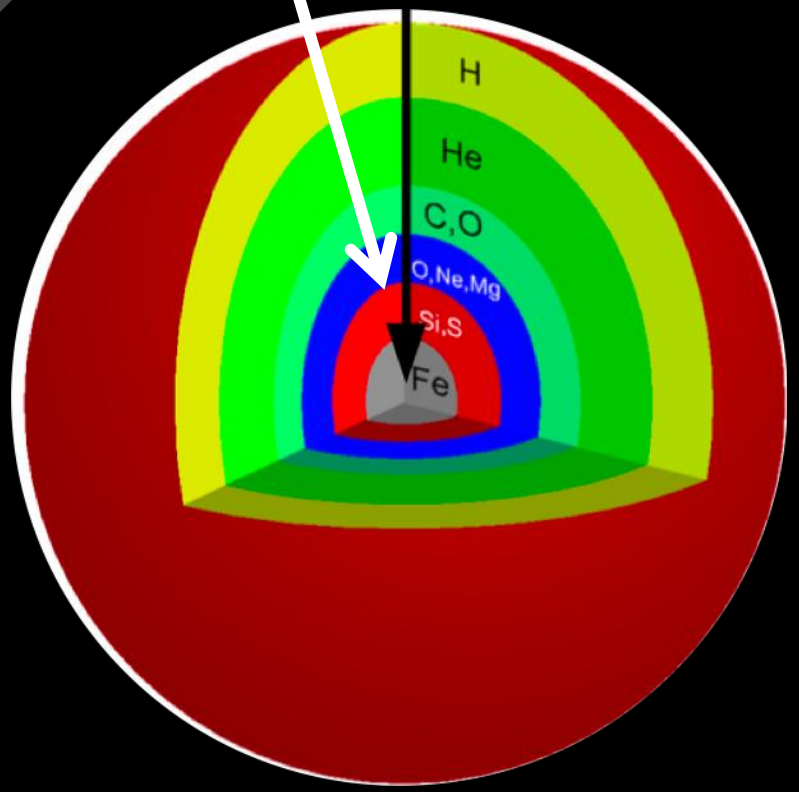
Burrows+23, 24

Back to the explodability

ξ, (M_4, μ_4) were suggested for the gauge, but now it seems more subtle.



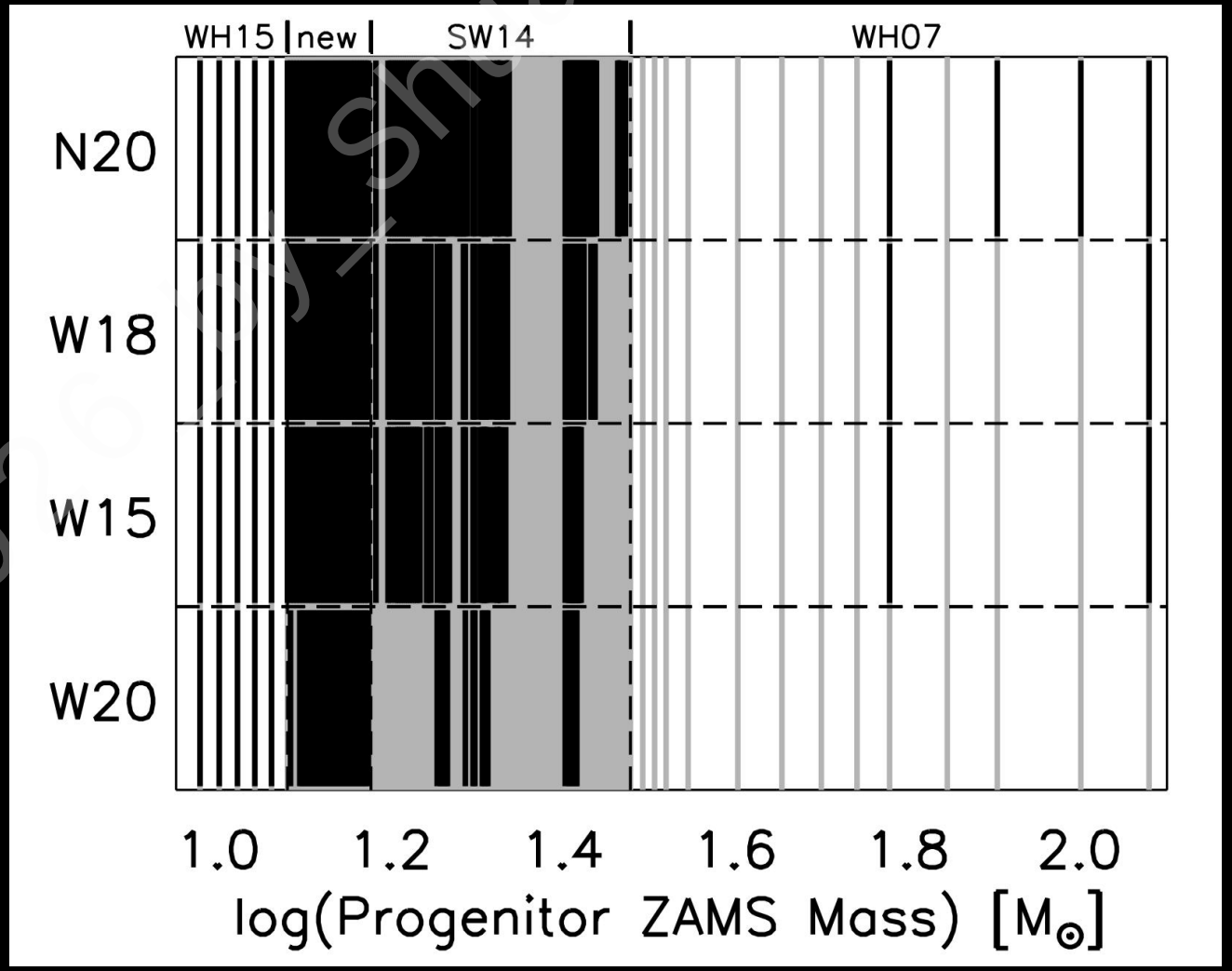
A sharp density drop at O/Si shell interface



Sukhbold_Shuai

1D surrogates

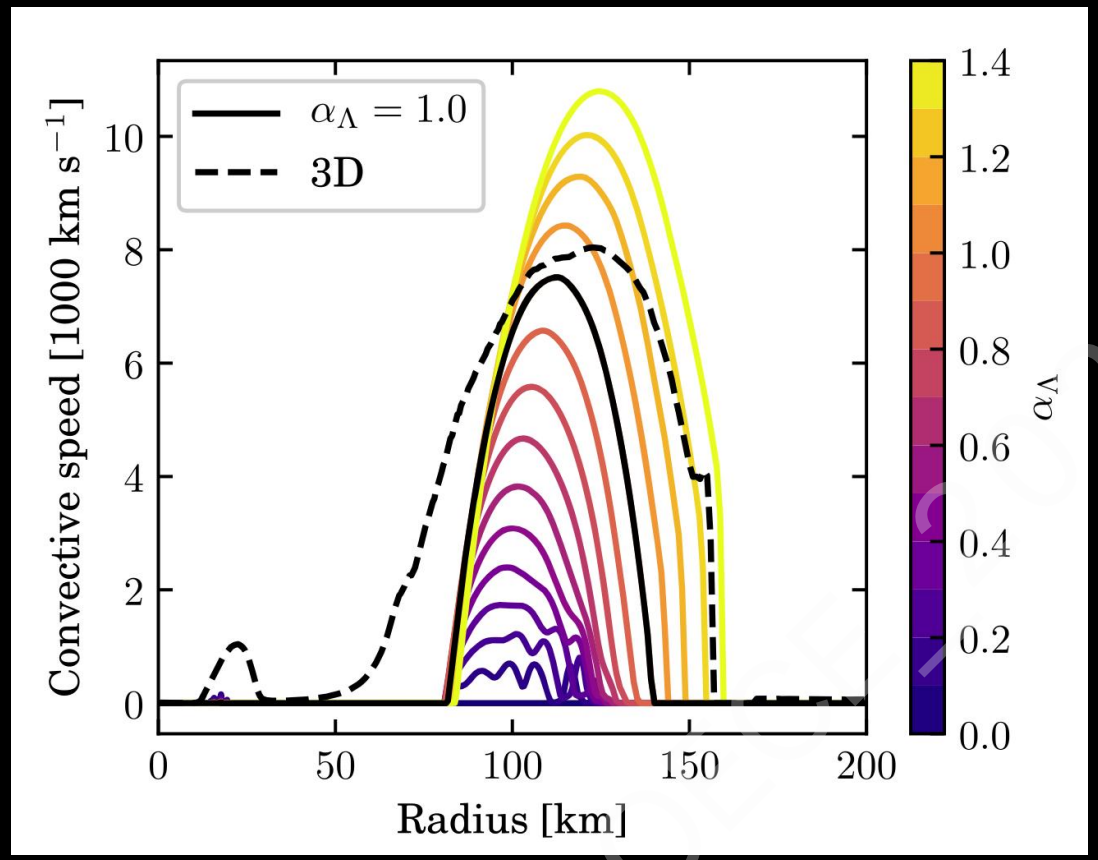
- 3D is good, but too expensive
- Need 1D explosions ...
- Early prescription: enhance the heating, eg. by a $f_{heat}>1$
  - ✓ in GR1D
  - ✓ P-HOTB
  - ✓ PUSH



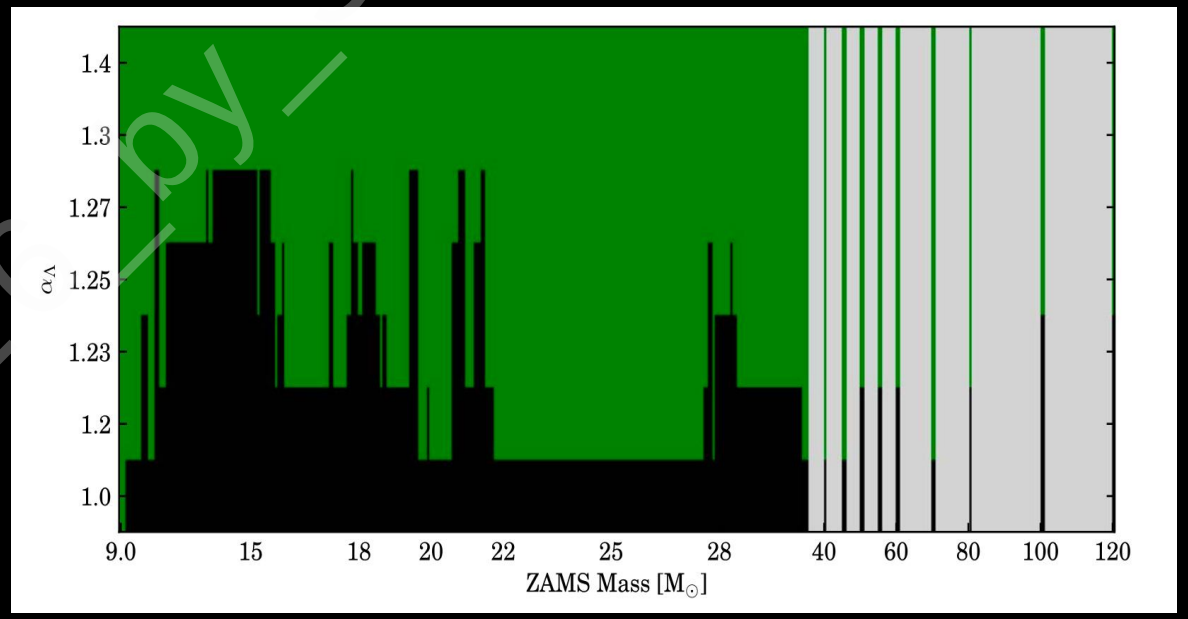
OECE_2020 by Shuai

A more elaborate approach: effective turbulence model

Recall: $P_{\rm turb} \simeq \rho \left\langle \delta v_r^2 \right\rangle$



Couch+20, Boccioli+21



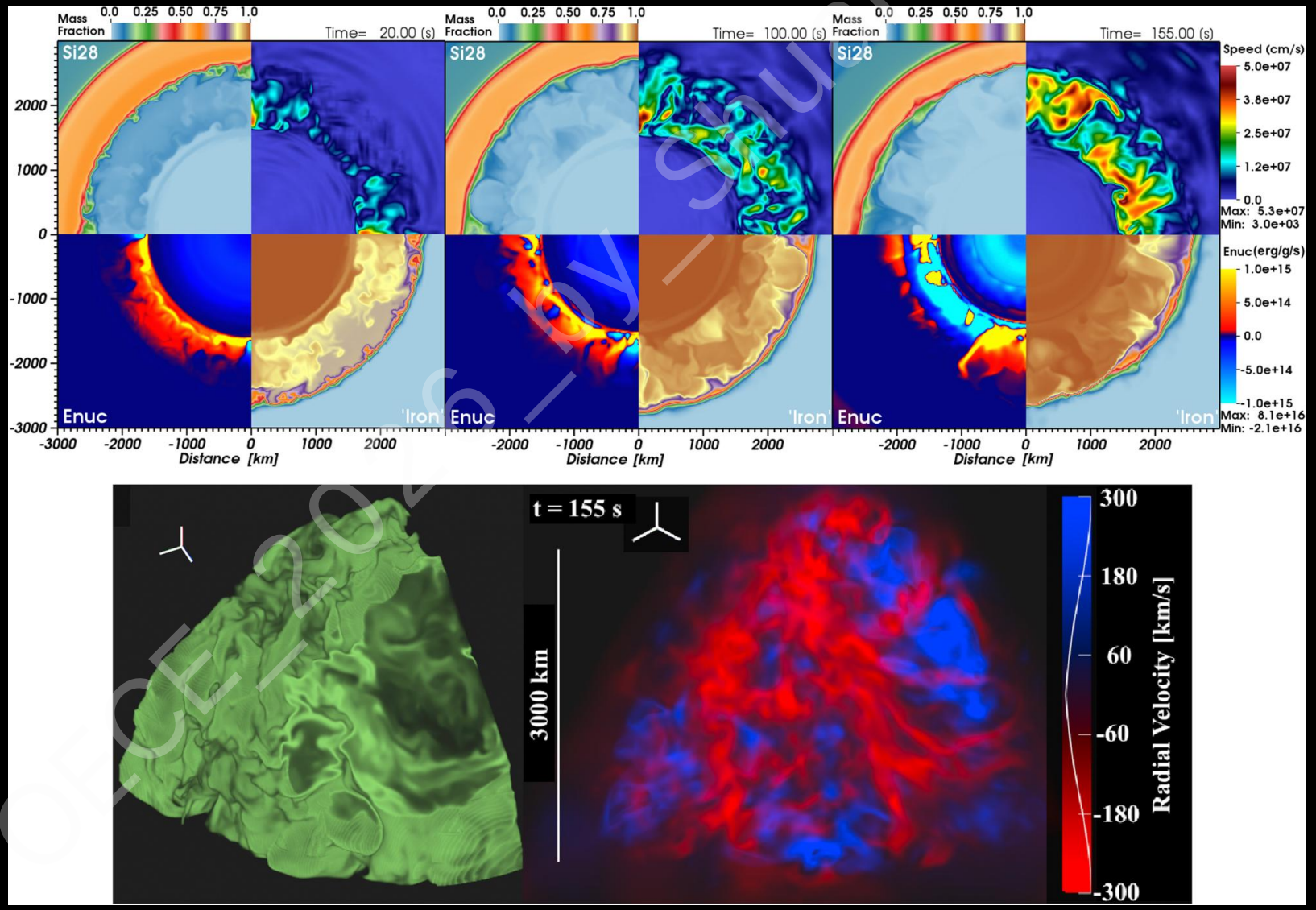
❑ **This is the GR1D+.**

Oct-2020 by Shuai

Breaking the Onion: progenitor in 3D

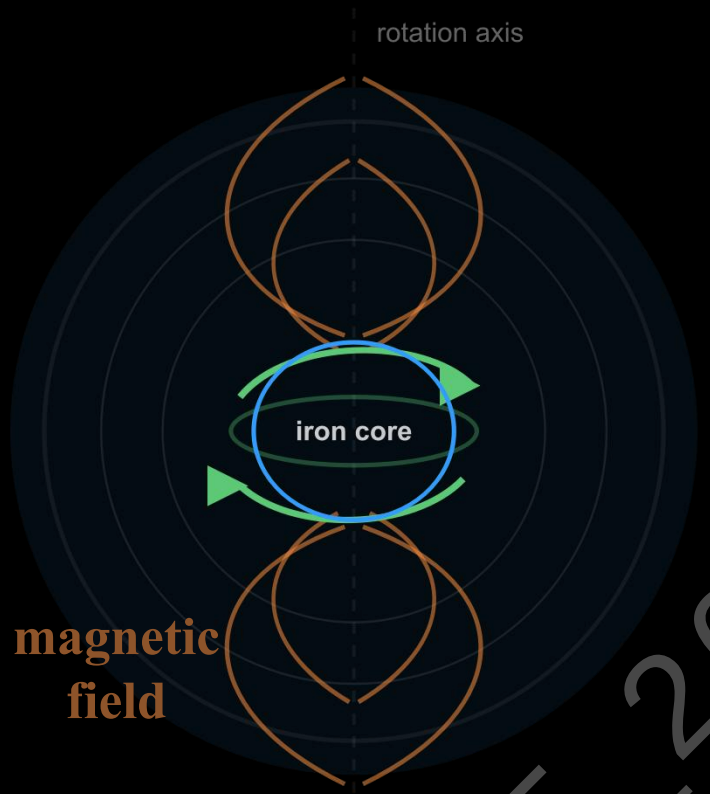
Final minutes of silicon shell burning

Arnett+, Couch+, Fields+, Muller+, Nadav+, Chen+, Andresen+, ...

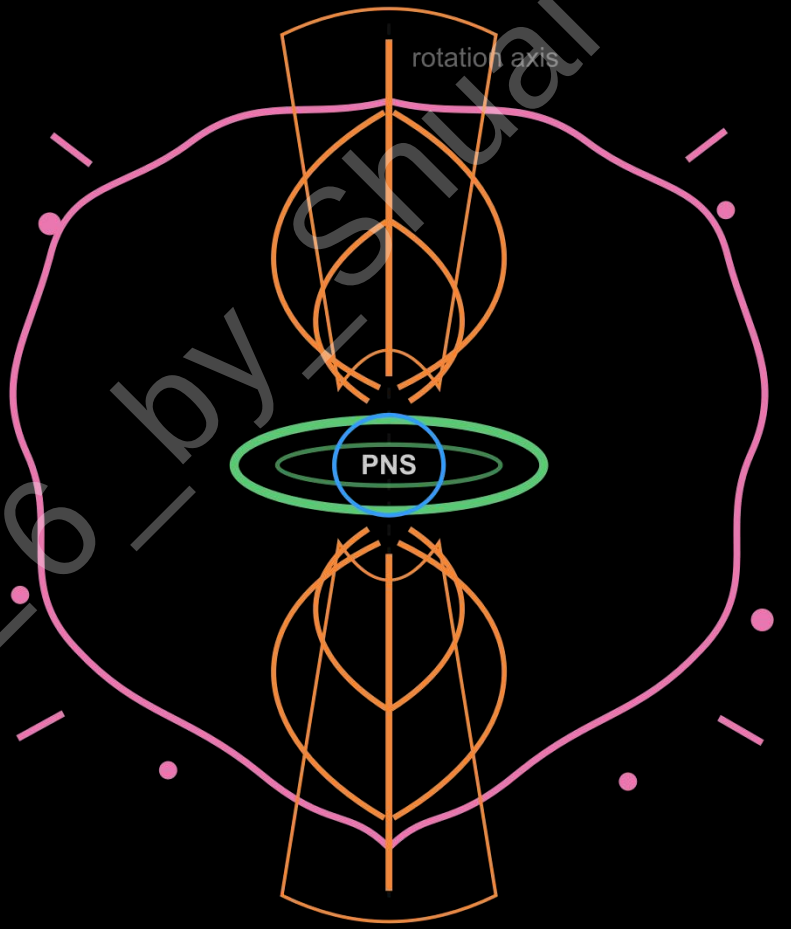


ORCE_2026_by_Shuai

Alternatives: Magneto-rotational supernova



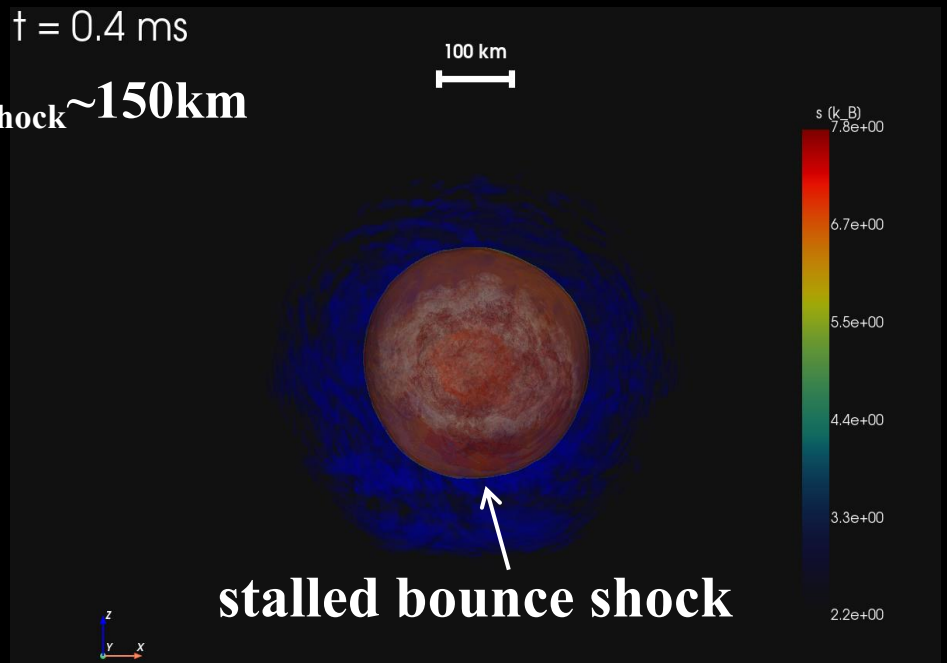
massive stars with fast rotation and magnetic field



launching jet
hypernova (~10 B)
magnetized NS

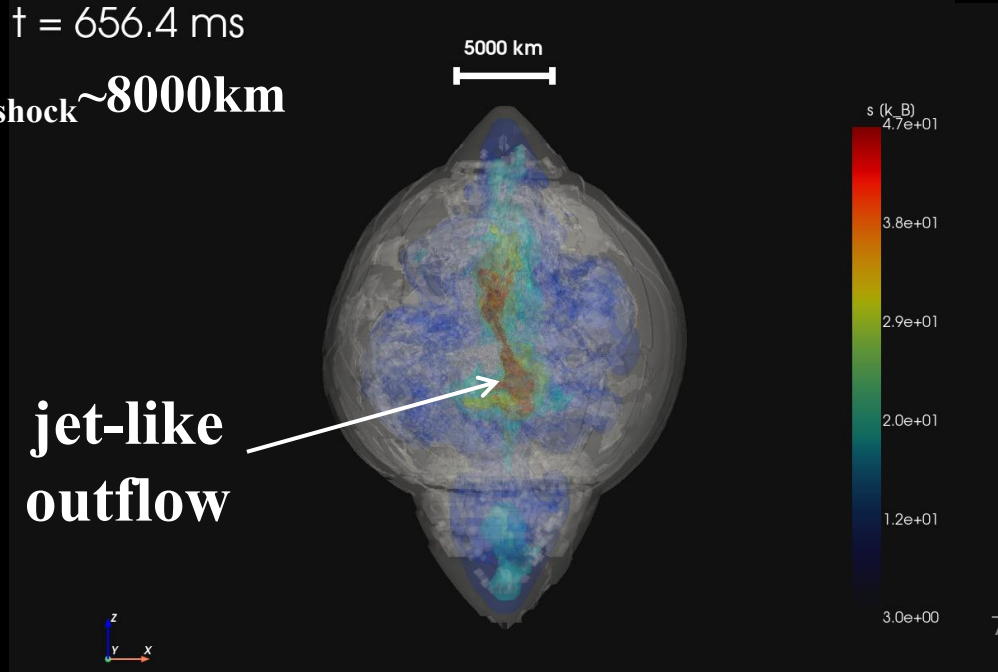
LeBlanc & Wilson
ApJ (1970)

CECE_2020_by_Shuai



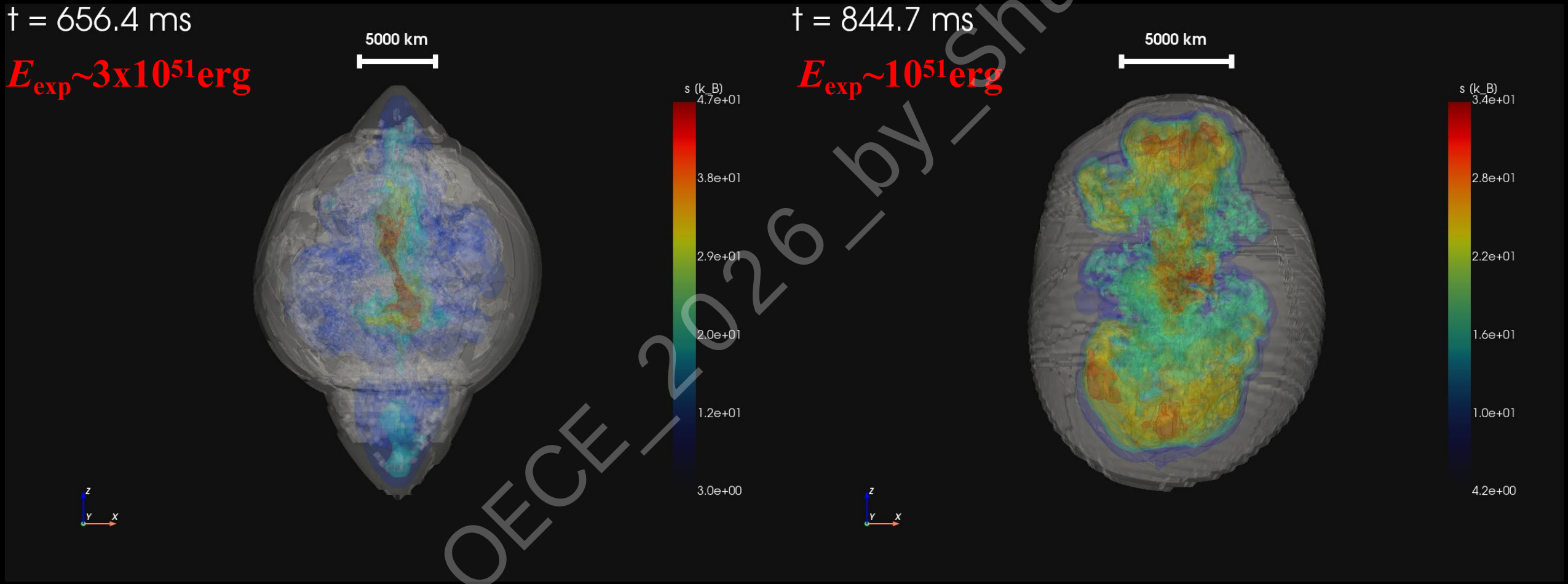






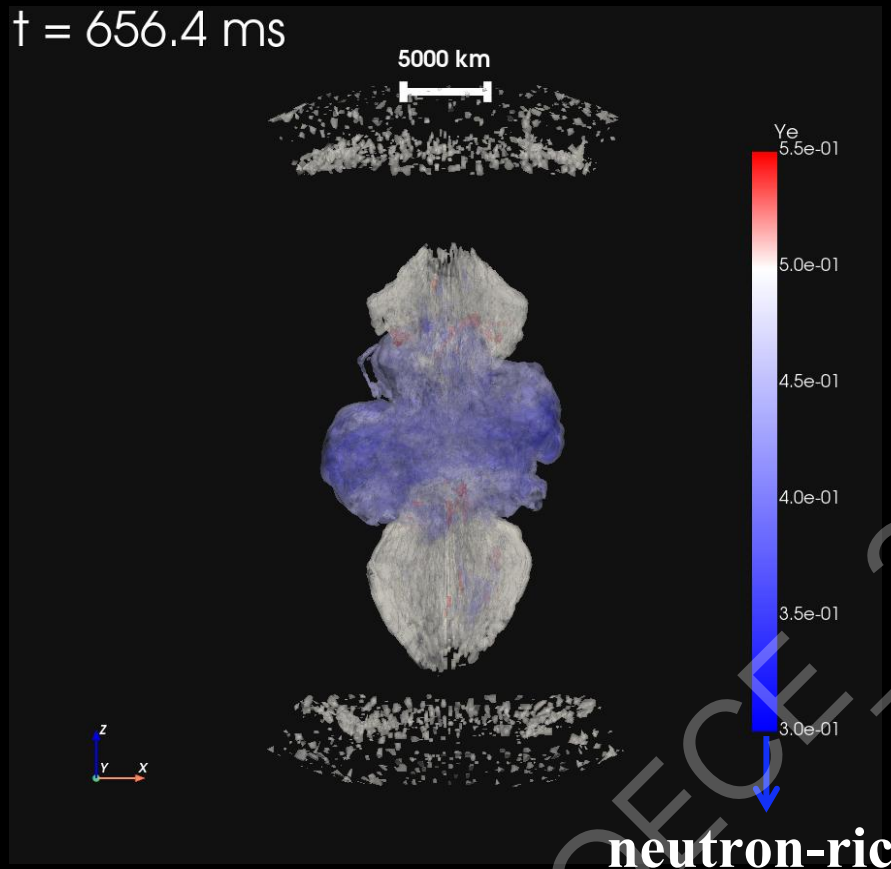
OECE_2026_by_Shuai

Magnetic vs. non-magnetic explosions



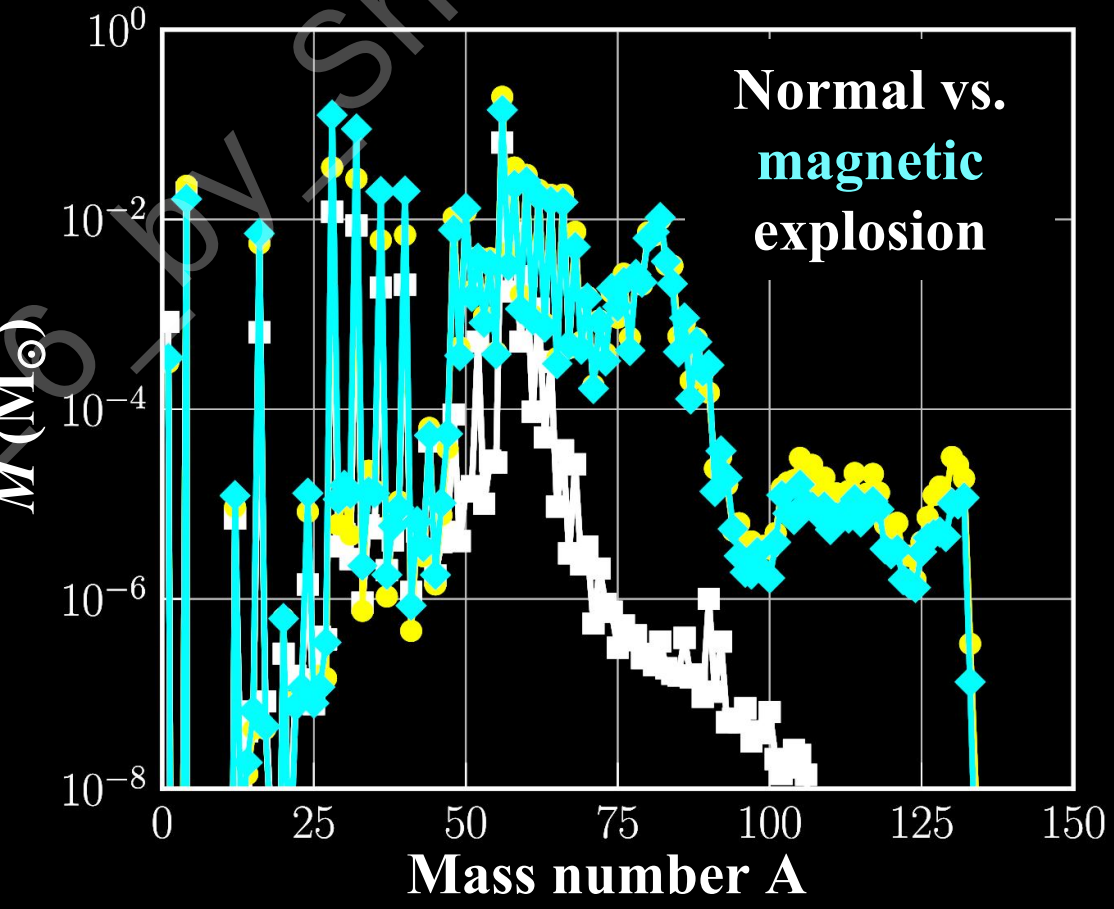
OECE_2026_by_Shuai

Nucleosynthesis yields



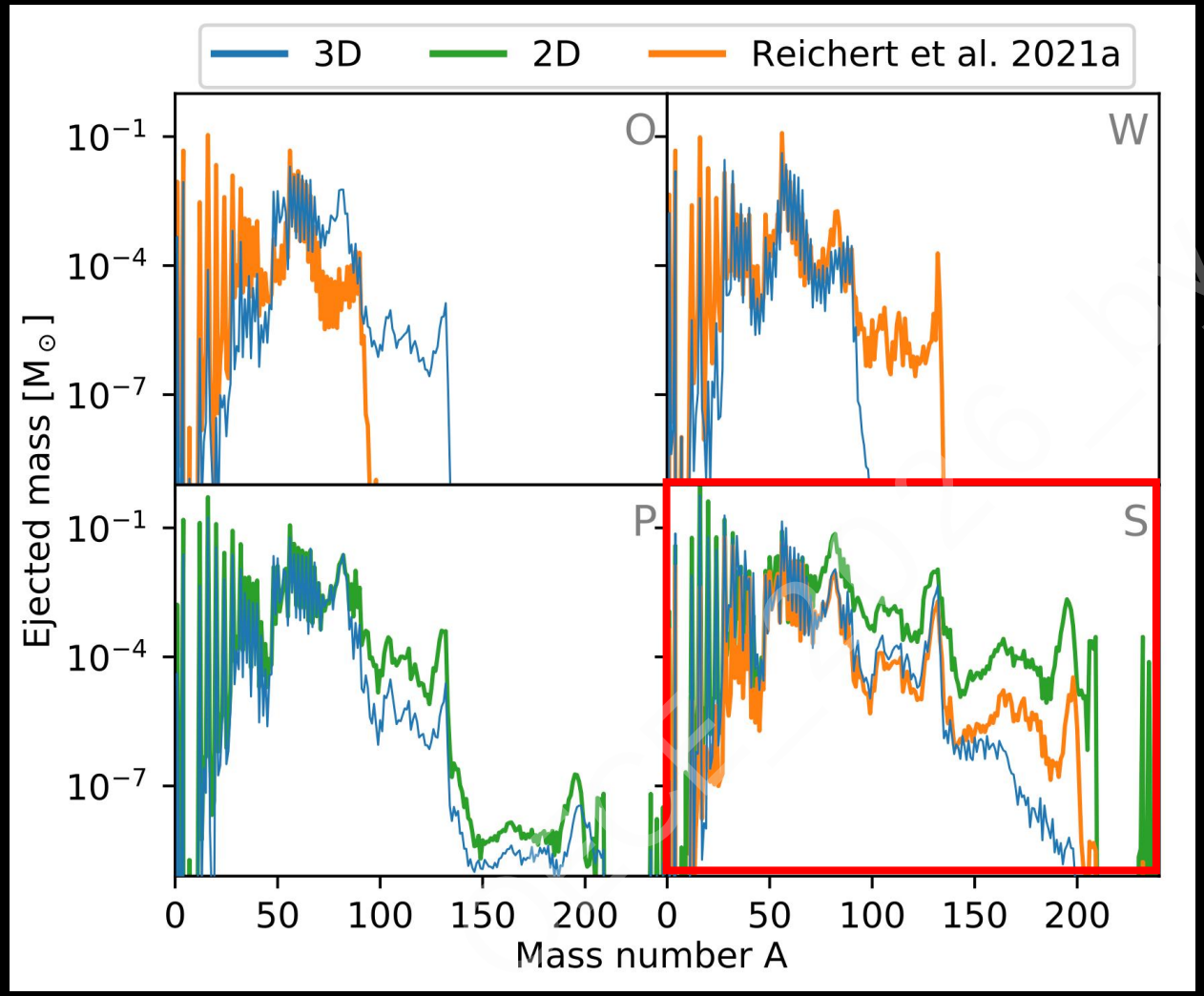
neutron-rich

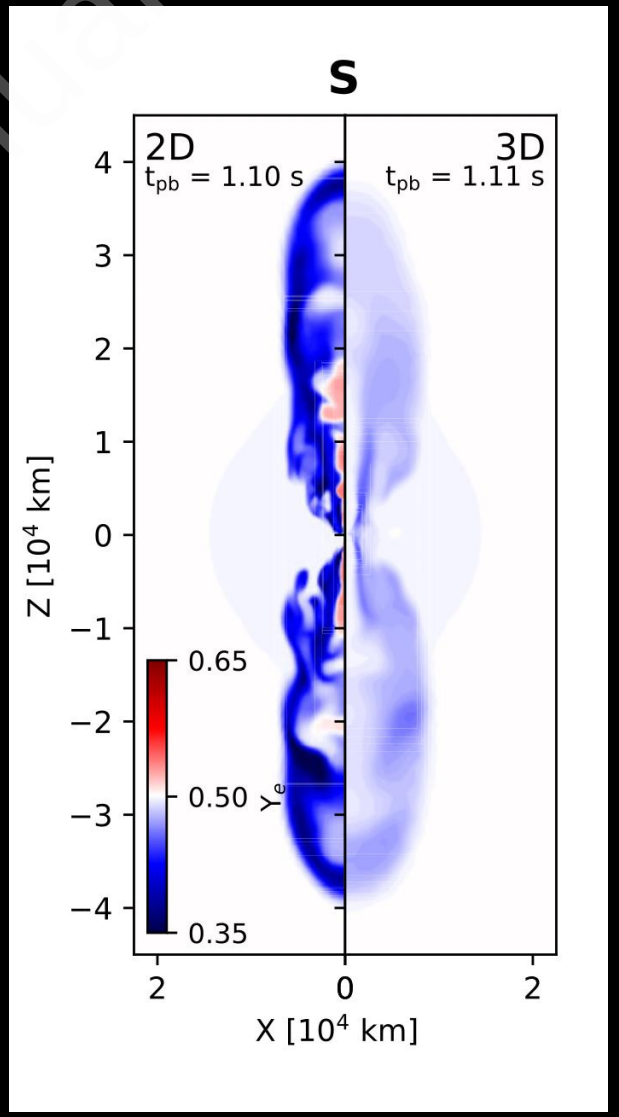
Zha+2024



OFCF_2026_by Shuai

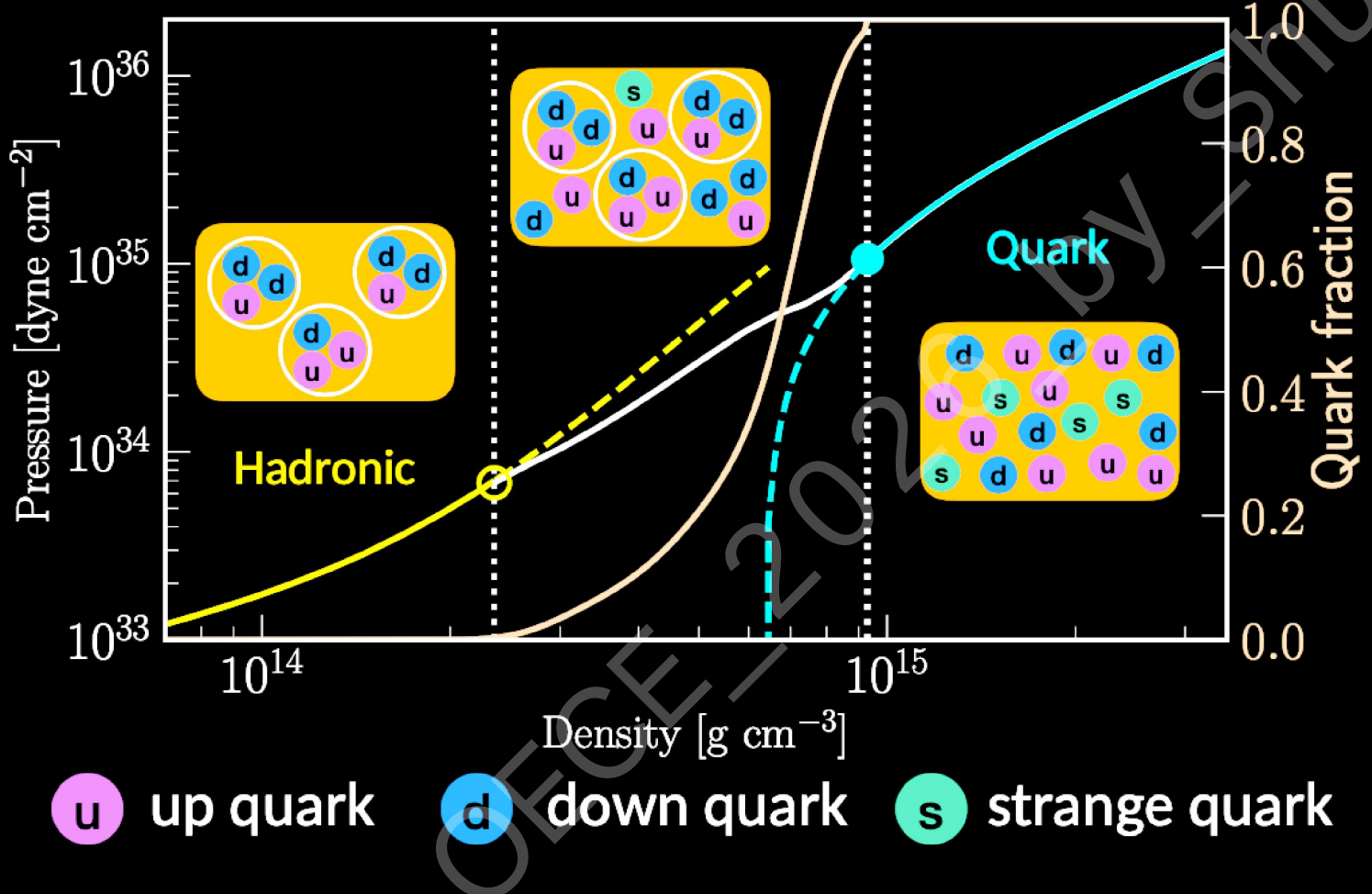
3D versus 2D. It may be a bit disappointing...



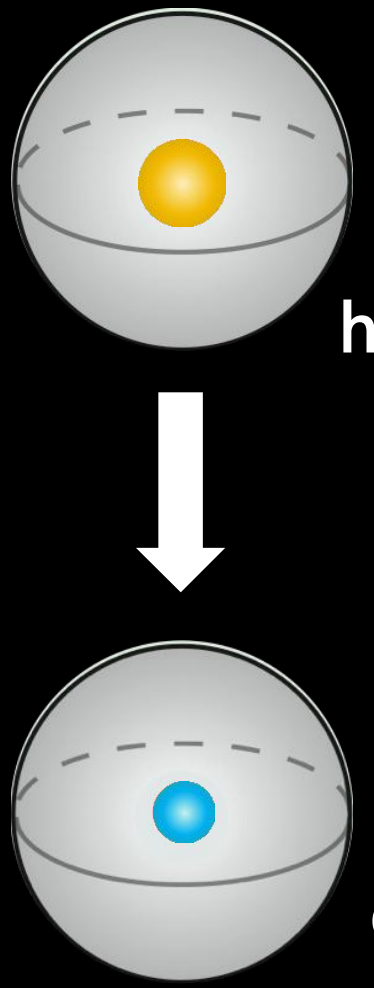


Reichert+2023

A (first-order) Hadron-Quark phase transition

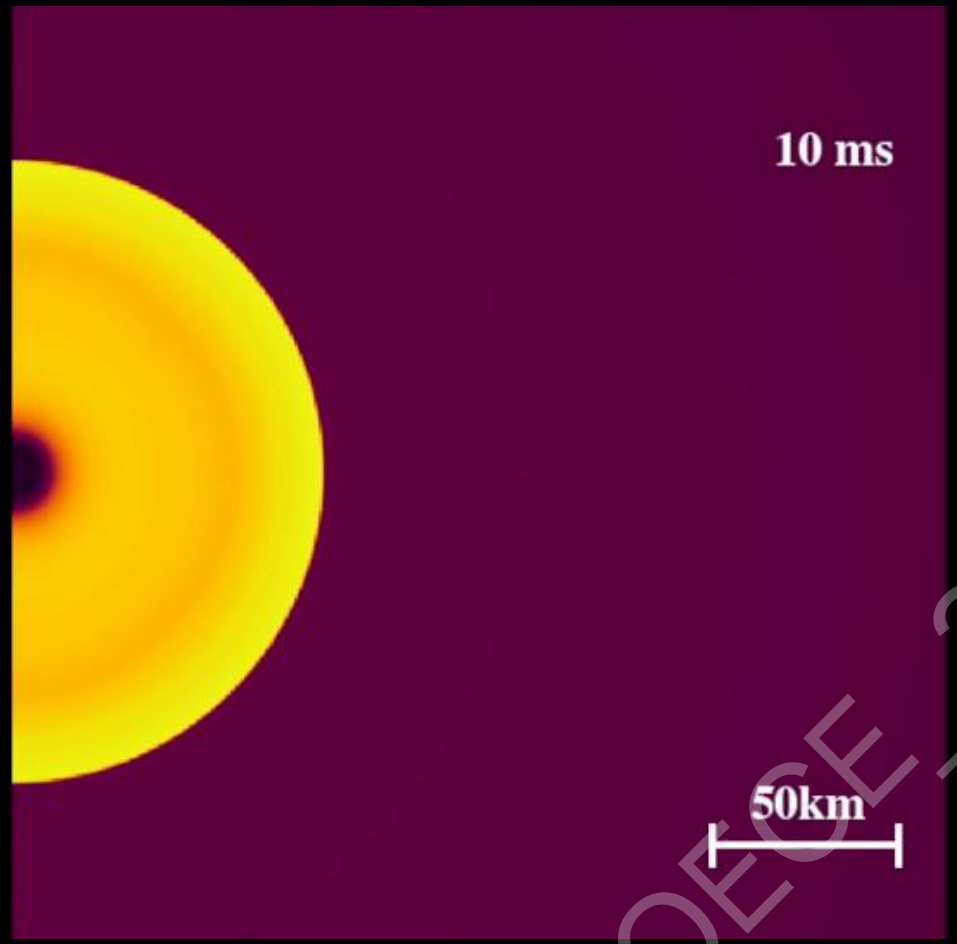


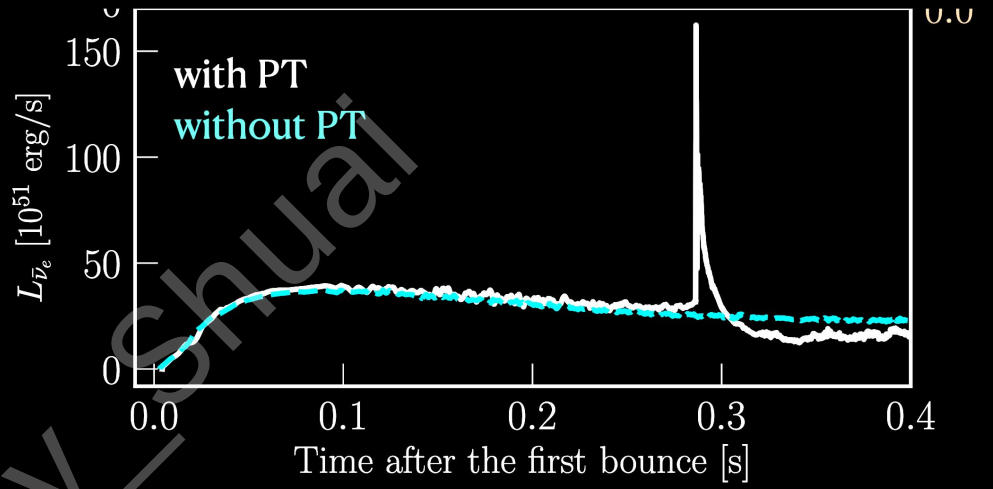
u up quark d down quark s strange quark



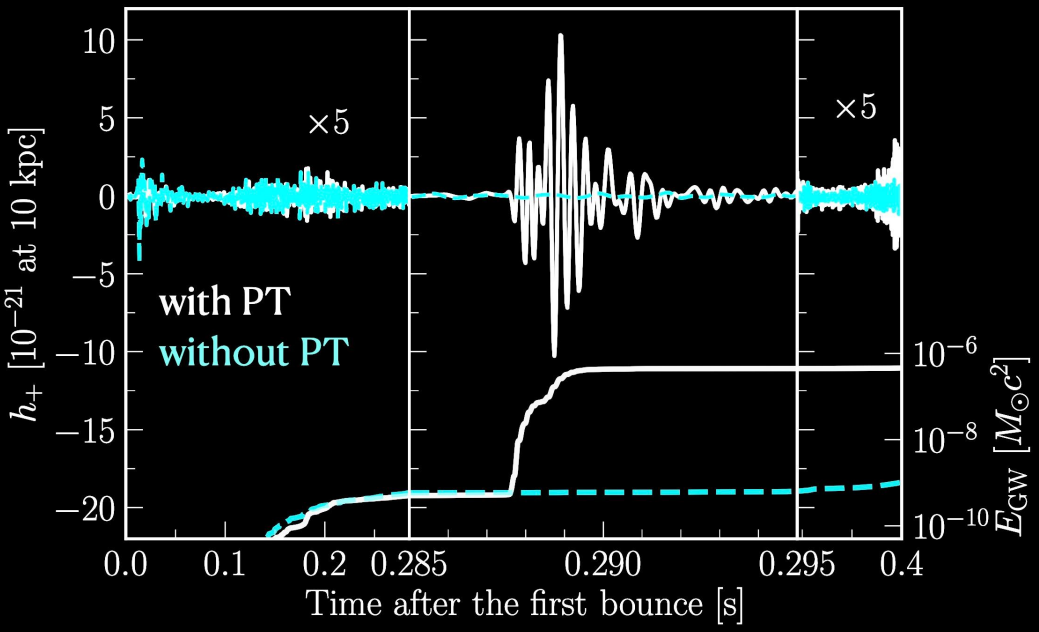
©ECE_2020 by_Shual

PT-driven explosion & possible multi-messengers





Sagert+2009 PRL

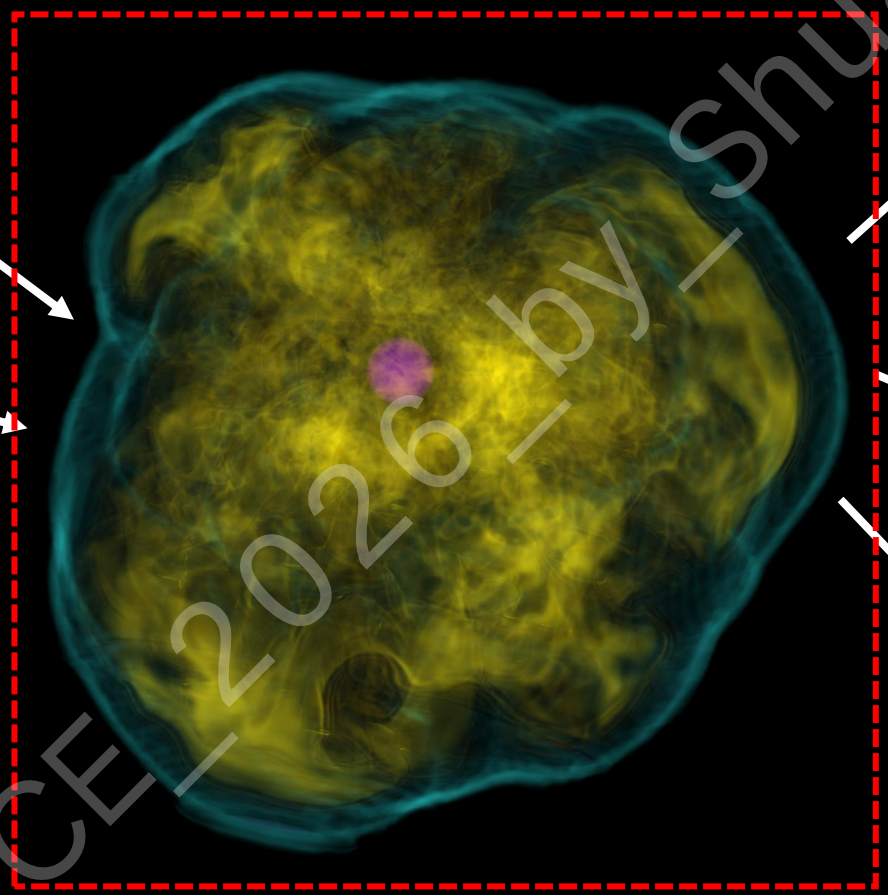


Zha+2020 PRL

See Prof. Grant Mathews' talk

OECE_2026_by_Shuai

Summary



progenitor model

(nuclear) equation of state

neutrino interactions

explosion energy (Bethe) & asymmetry

nucleosynthesis, eg. ^{56}Ni, and spatial distribution

remnant mass/spin/kick

OECE_2026_by_Shuai

Thank you!

zhashuai@ynao.ac.cn