Supernovae and Neutron Stars

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Rough Outline

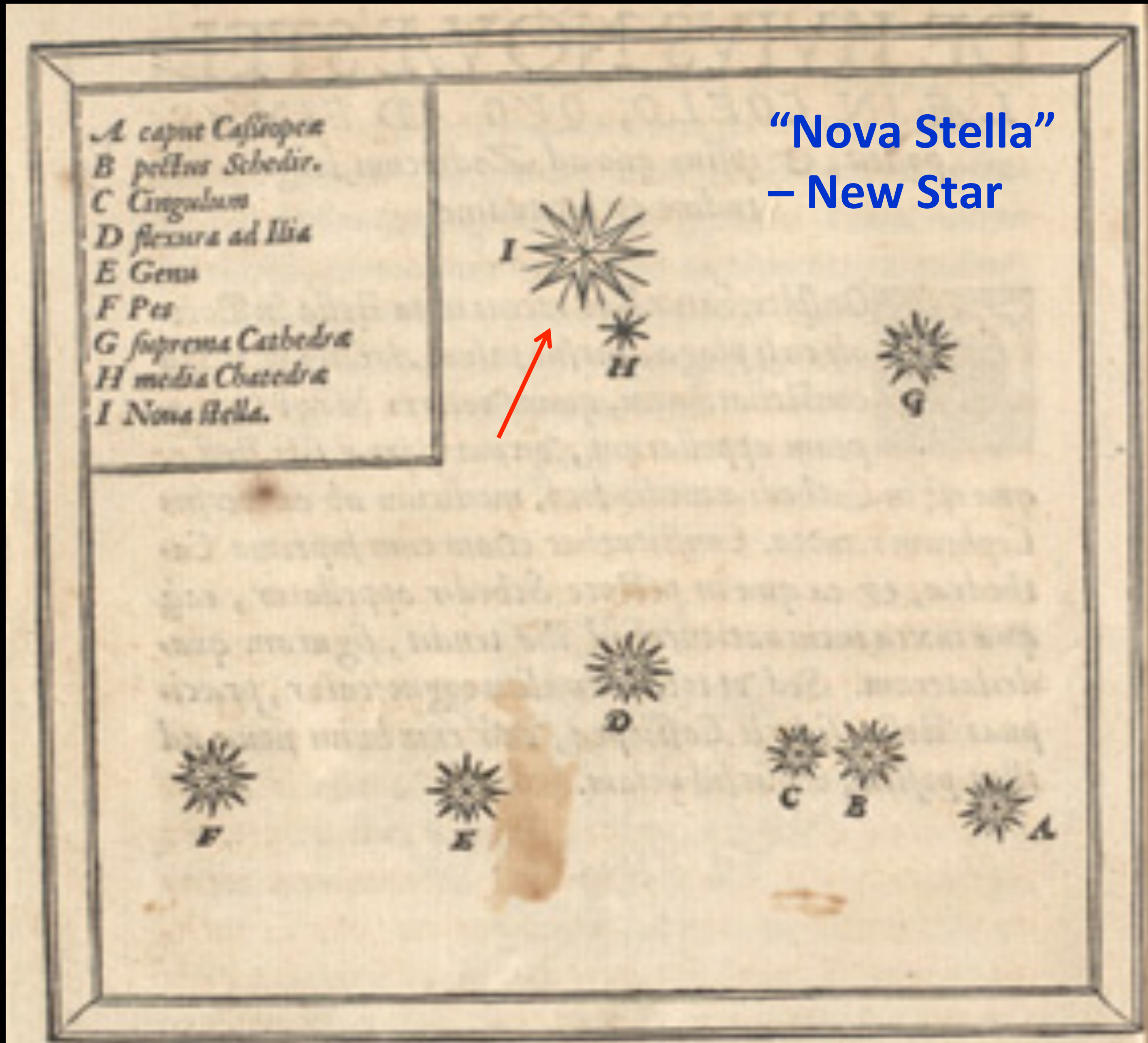
-- Lecture I --

- Supernova Basics
- Thermonuclear Supernovae
- Core Collapse of Massive Stars

-- Lecture II --

- Core-Collapse Supernova Models and Mechanisms.
- Multi-Messenger Probes of Core-Collapse Supernova Physics.
- Neutron Stars and Astrophysical Constraints on the Nuclear Equation of State.

~1 SN / sec in the Universe.
~1 SN / day discovered
(many discovered by amateur astronomers!).
~1 SN / 30-50 years in the Milky Way.



Tycho Brahe (1572): „De Nova Stella“

Fritz Zwicky
1898-1974

Walter Baade
1893-1960

Palomar 18” Schmidt telescope

Fritz Zwicky
1898-1974

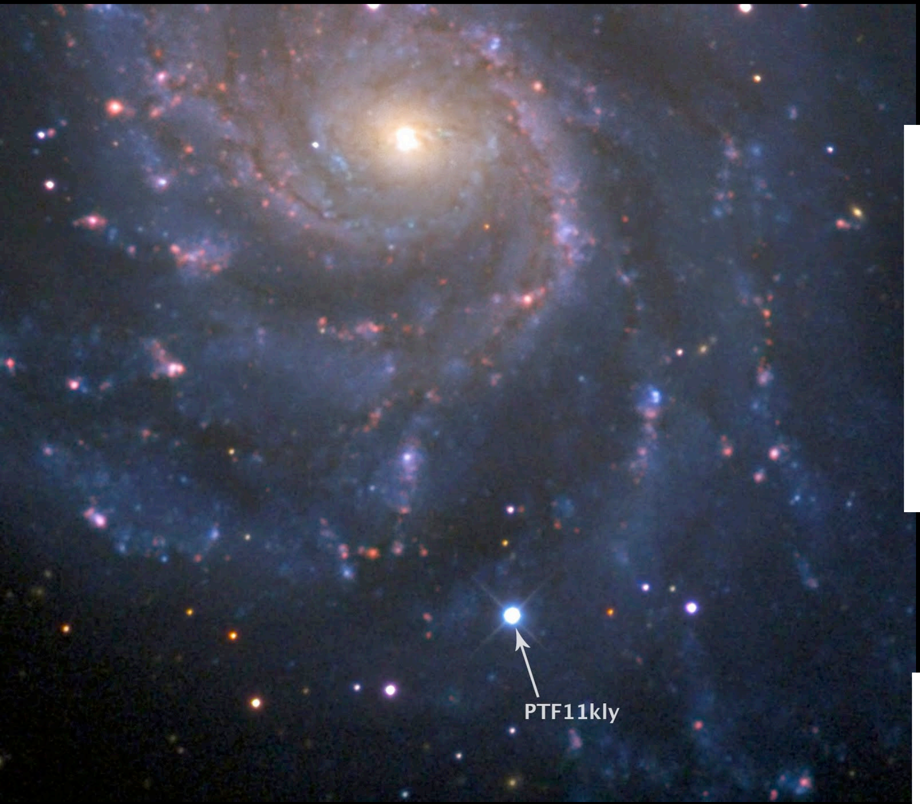
Walter Baade

"Supernova" (1934)

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place,

[PNAS, 20:259, 1934, APS 12/33]

A Supernova Primer



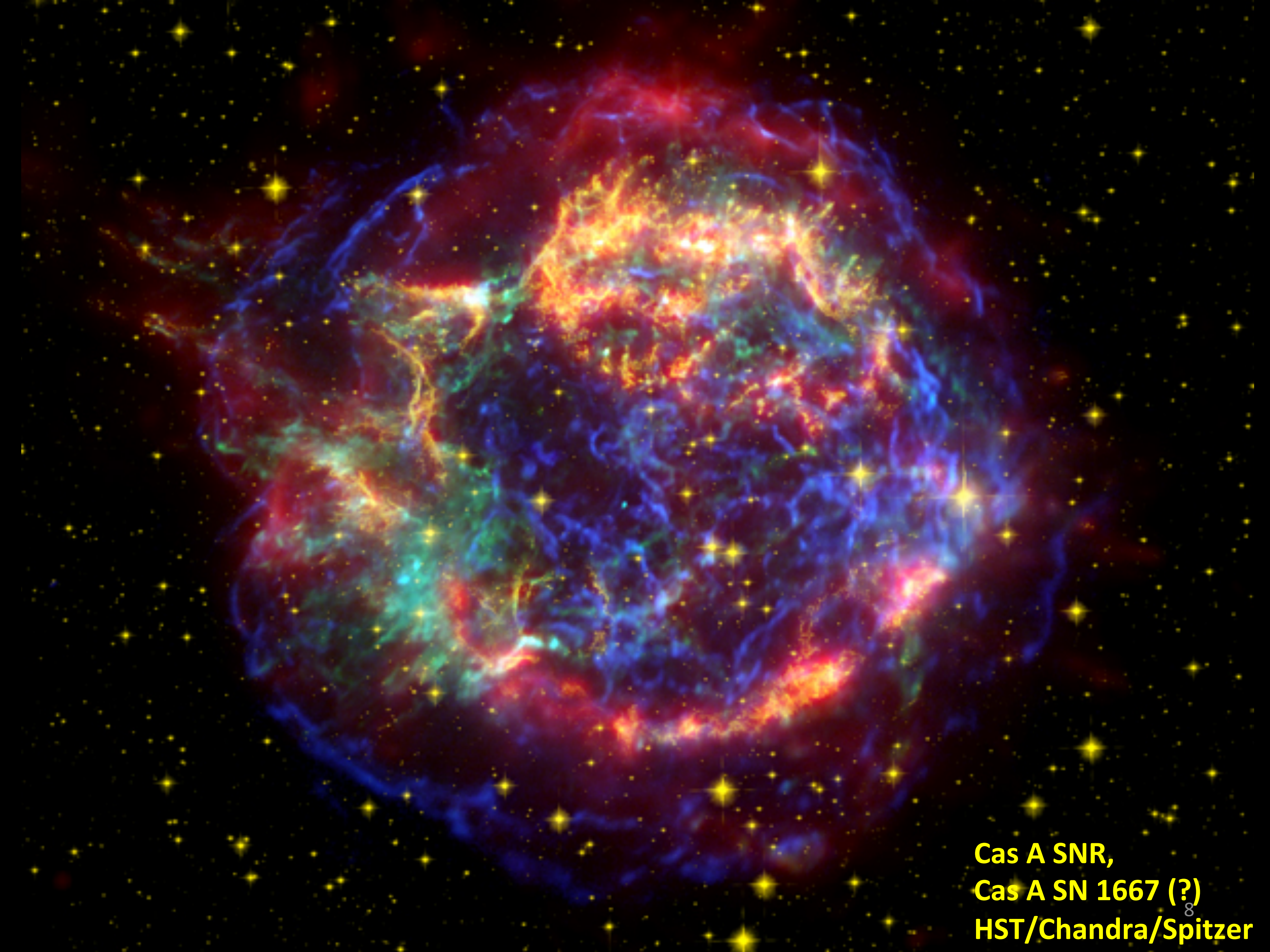
M101 -- Pinwheel Galaxy
PTF11kly – SN 2011fe, 2011/08/24
(Palomar Transient Factory)

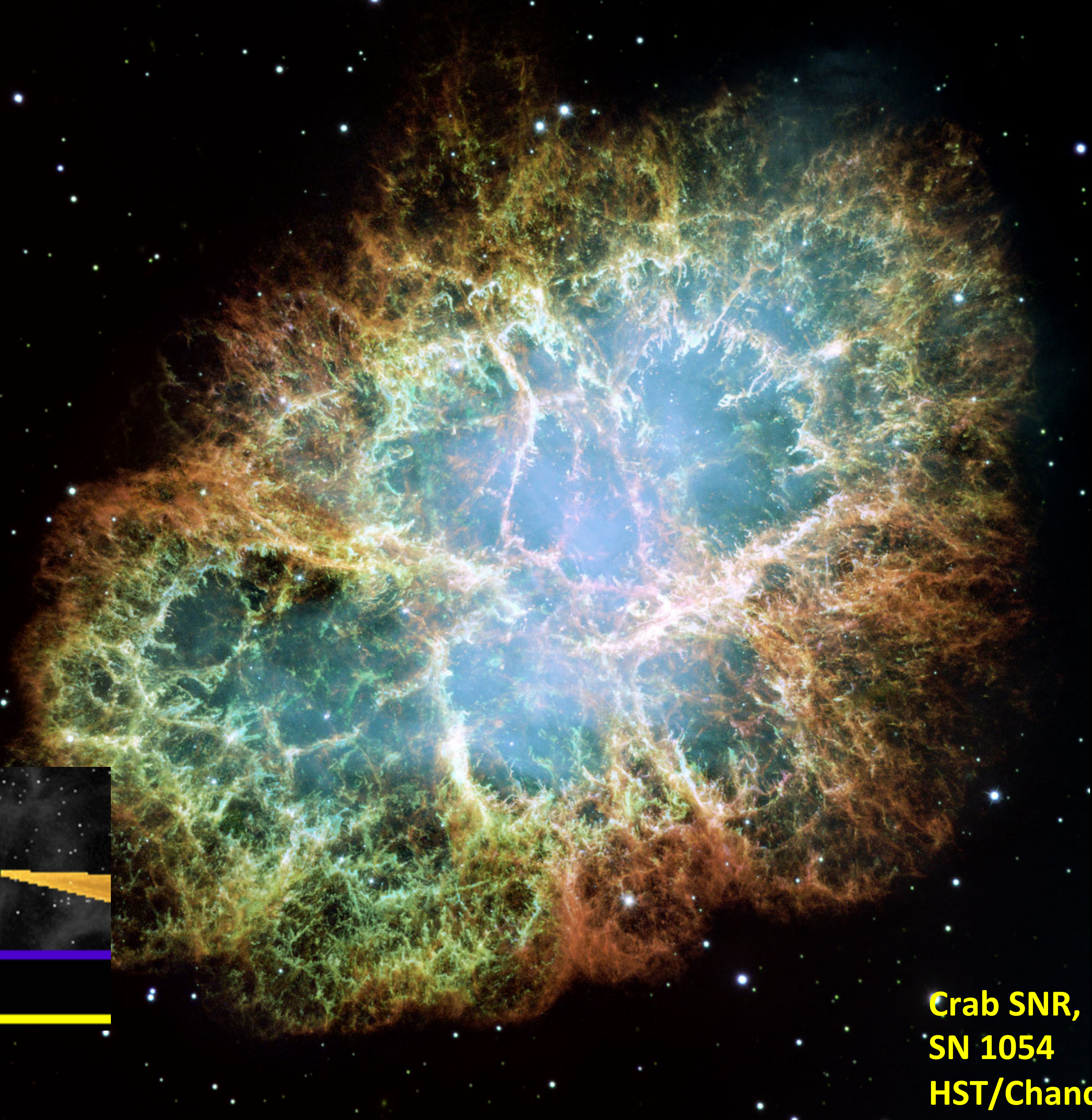
Thermonuclear Supernovae

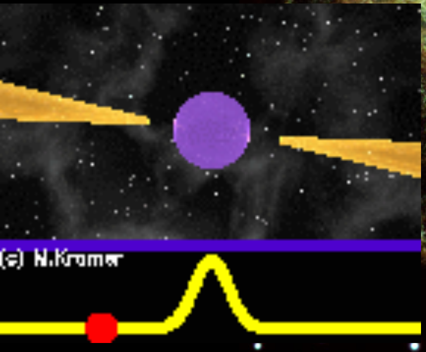
- Thermonuclear explosion of a White Dwarf star (end stage of low-mass stellar evolution).
- "Type Ia" supernova.
- No compact remnant.

Core-Collapse Supernovae

- **Gravitational collapse** of a massive star's core ($M > 8\text{-}10\ M_{Sun}$).
- Supernova Type II, Ib, Ic.
- **Neutron Star** or **Black Hole** remnant.
- Related to Gamma-Ray Bursts (GRBs).

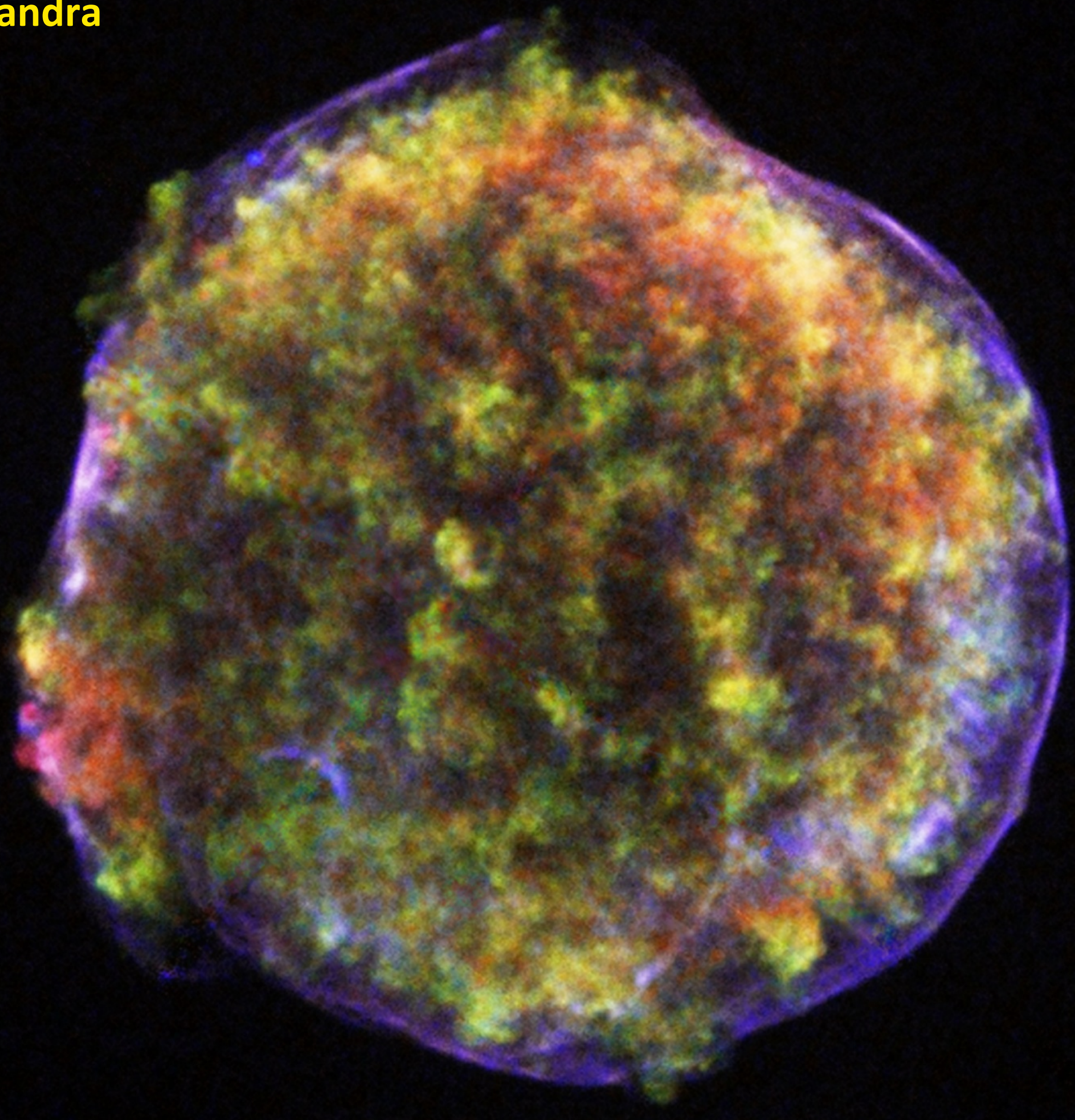

Cas A SNR,
Cas A SN 1667 (?)
HST/Chandra/Spitzer



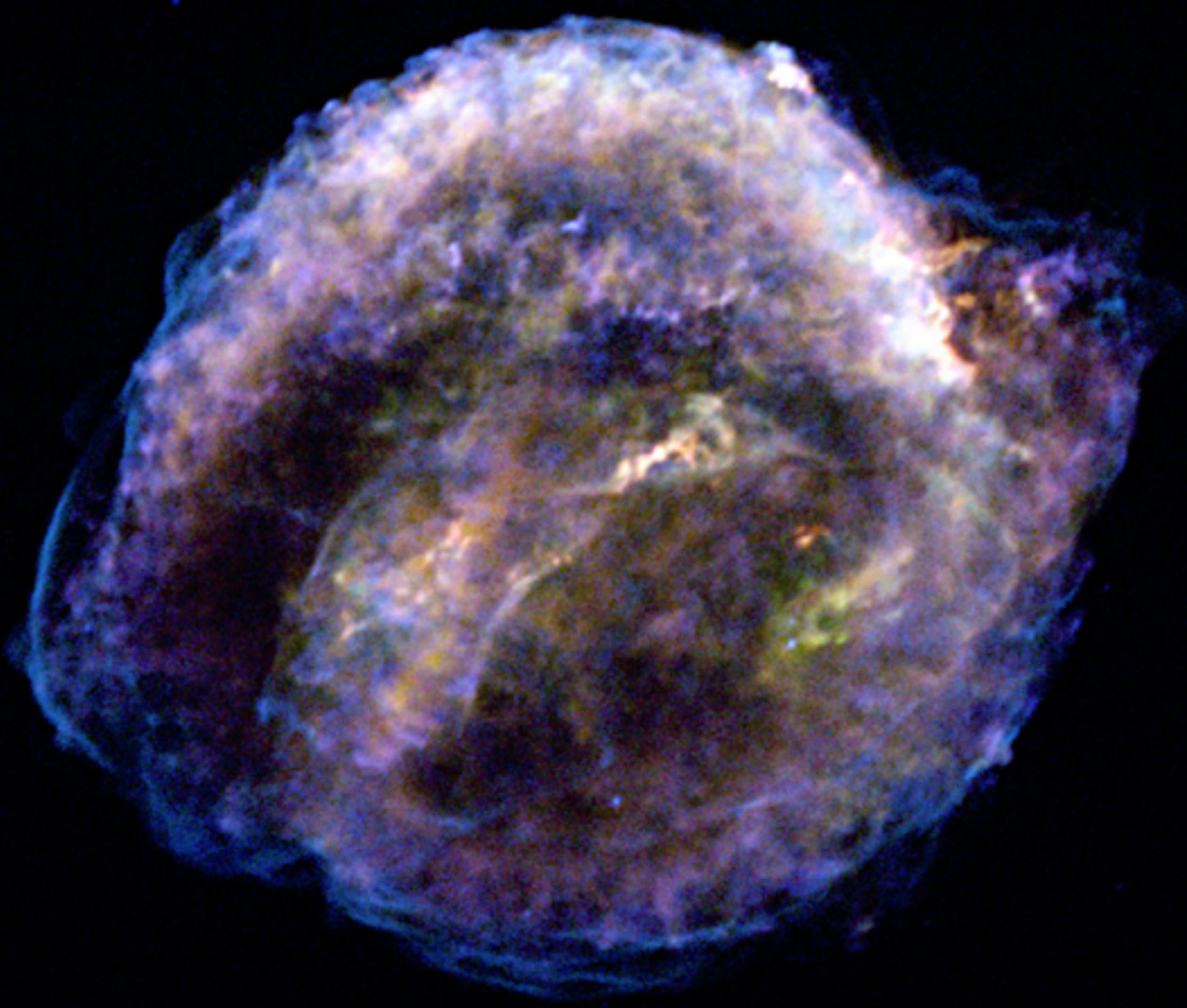


Crab SNR,
SN 1054
HST/Chandra/Spitzer

Tycho‘s SN 1572
NASA: Spitzer/Chandra



Kepler‘s SN 1604
NASA: Chandra Teleskop



Betelgeuse as seen by the HST, D ≈ 200 pc

Rigel, D ≈240 pc

Supernova Explosion

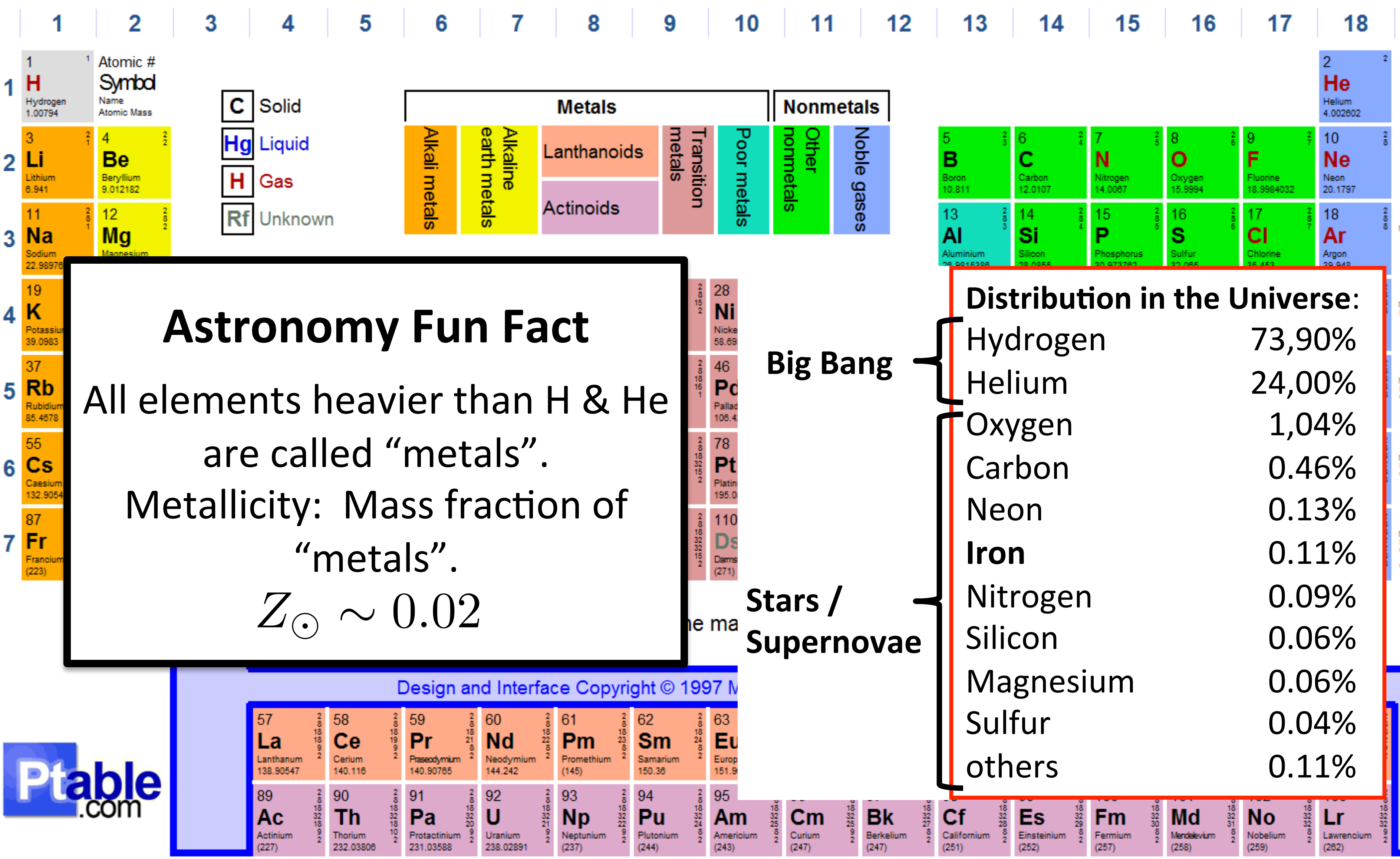
Betelgeuse as seen by the HST, D $\approx$ 200 pc

Rigel, D $\approx$240 pc

SN1987A, LMC, D $\approx$ 51.4 kpc
Progenitor: BSG Sanduleak -69° 220a, 18 M_{SUN}

Why do we care about Supernovae?

Periodic Table of Elements



Astronomy Fun Fact

All elements heavier than H & He are called "metals".

Metallicity: Mass fraction of "metals".

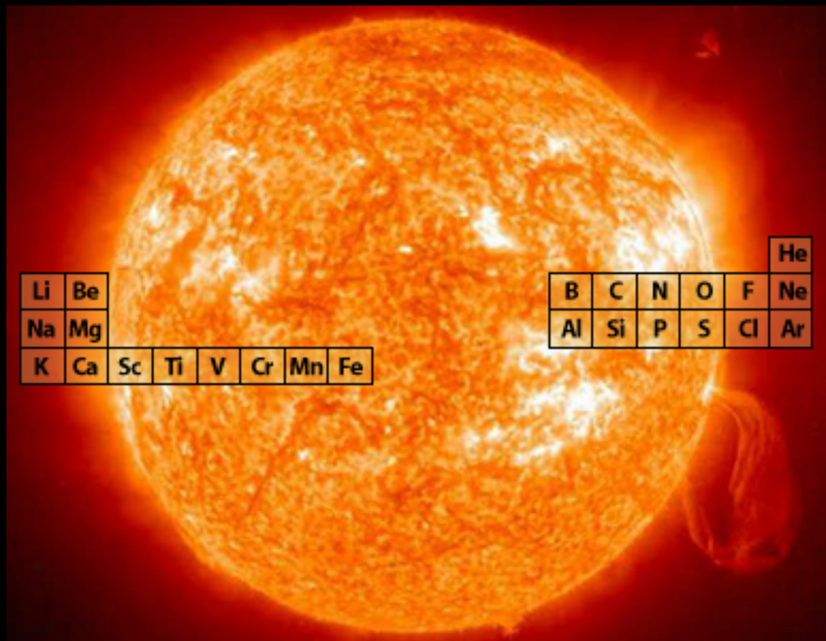
$$Z_{\odot} \sim 0.02$$

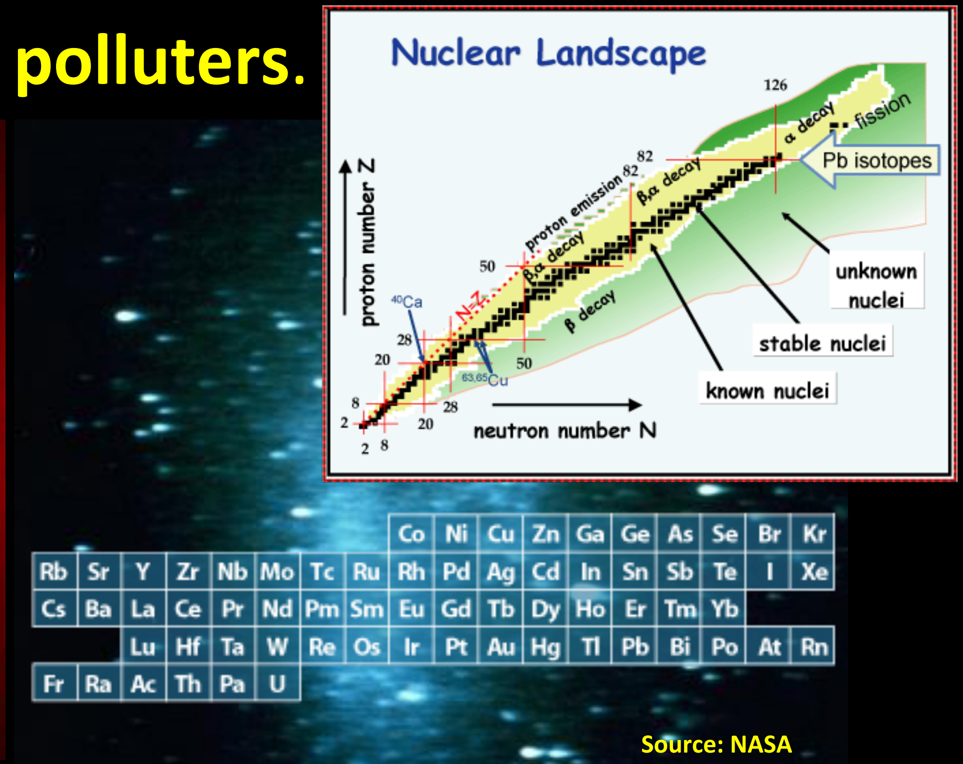
Distribution in the Universe:

Big Bang	Hydrogen	73,90%
	Helium	24,00%
Stars / Supernovae	Oxygen	1,04%
	Carbon	0.46%
	Neon	0.13%
	Iron	0.11%
	Nitrogen	0.09%
	Silicon	0.06%
	Magnesium	0.06%
	Sulfur	0.04%
	others	0.11%

Why do we care about Supernovae?

- SNe are the main cosmic polluters.





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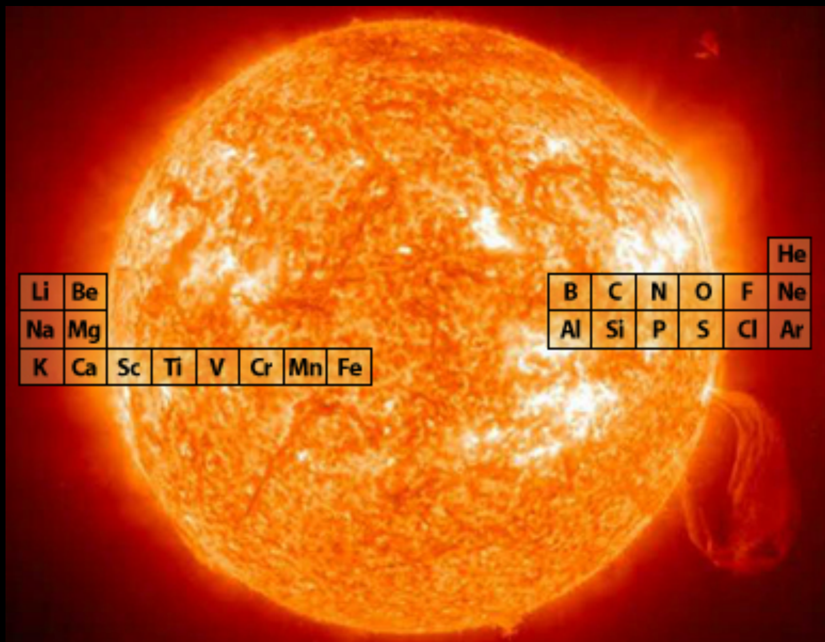
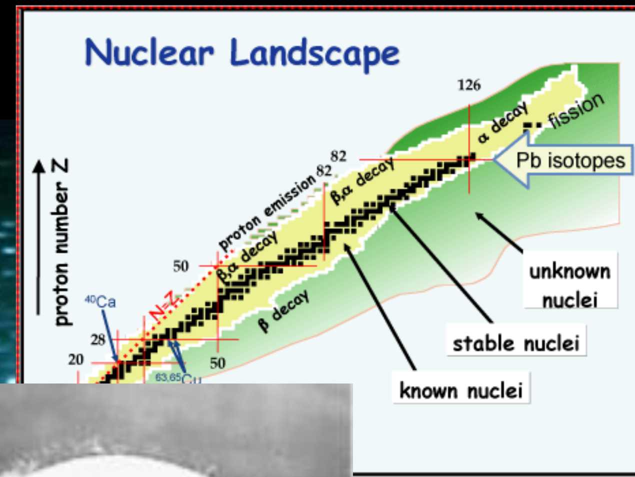
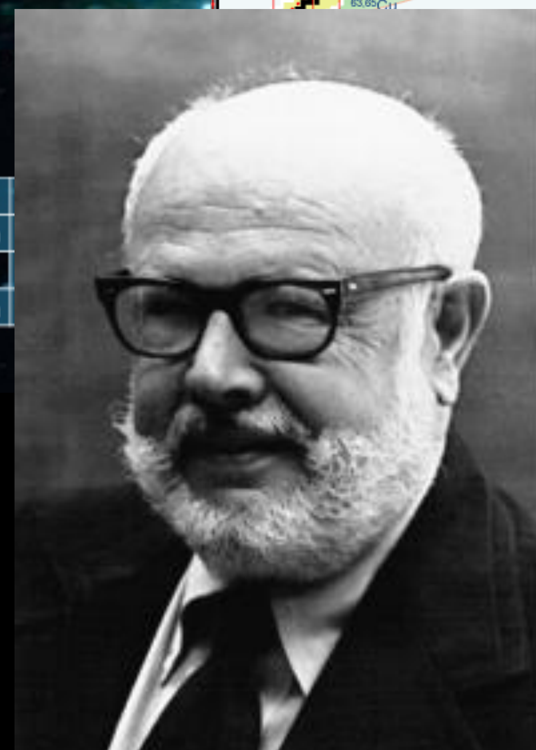






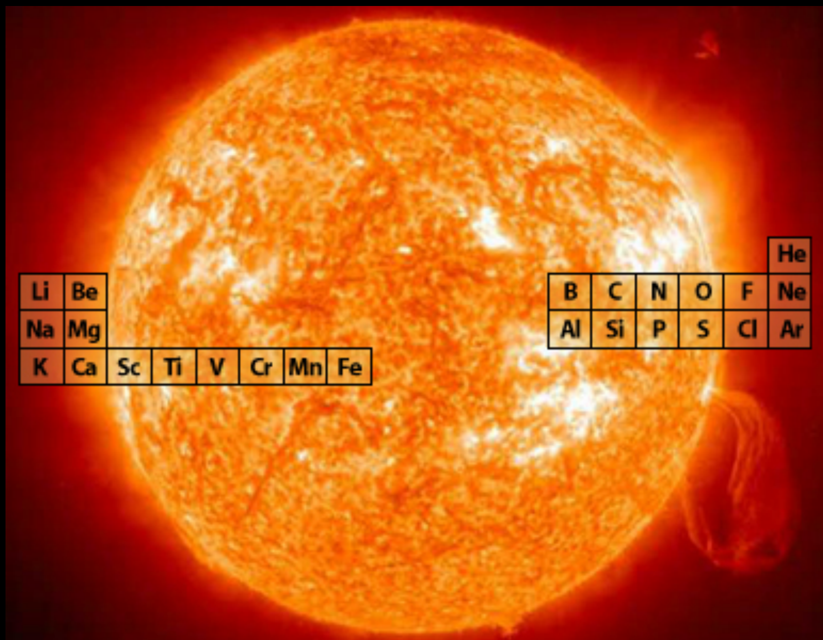
Willy Fowler
1911-1995

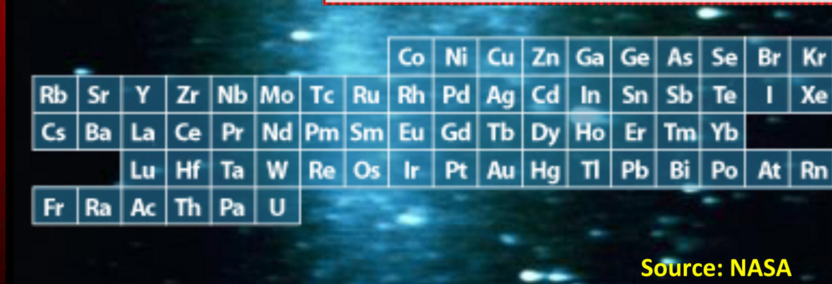
Burbidge, Burbidge, Fowler, Hoyle
"Synthesis of the Elements in Stars"
1957

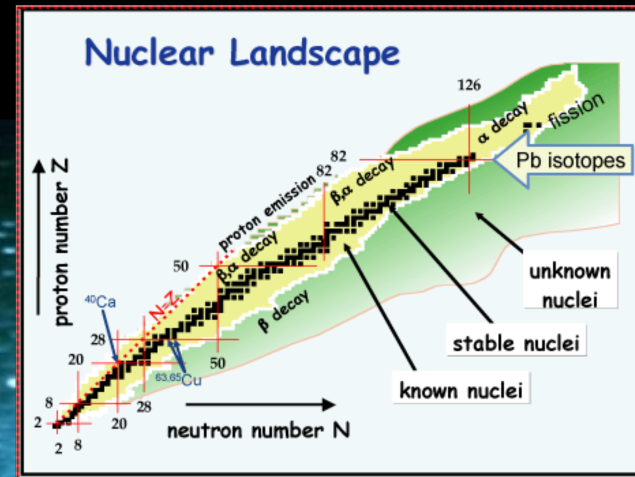
Nobel Prize in Physics 1983

Why do we care about Supernovae?

- **SNe are the main cosmic polluters.**







- Dynamical impact on galaxy evolution.

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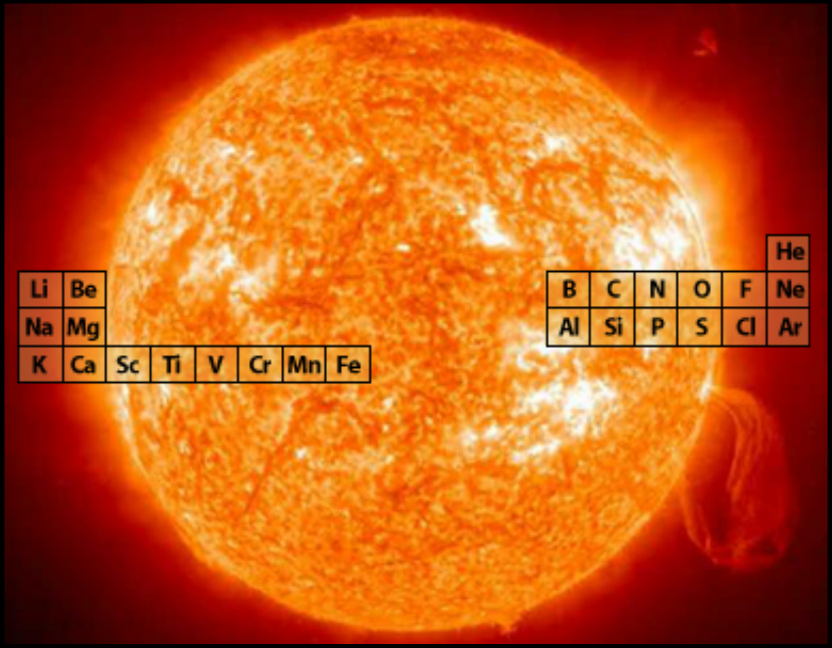
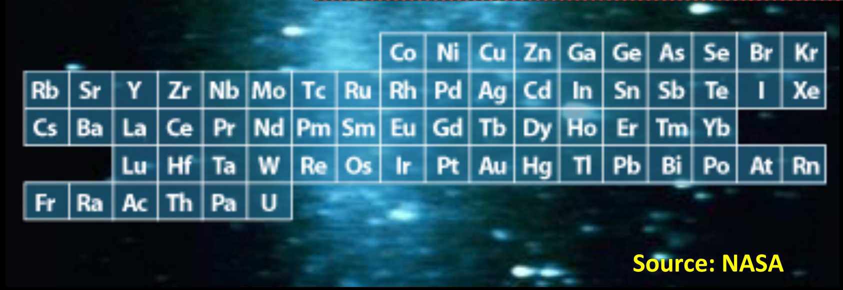
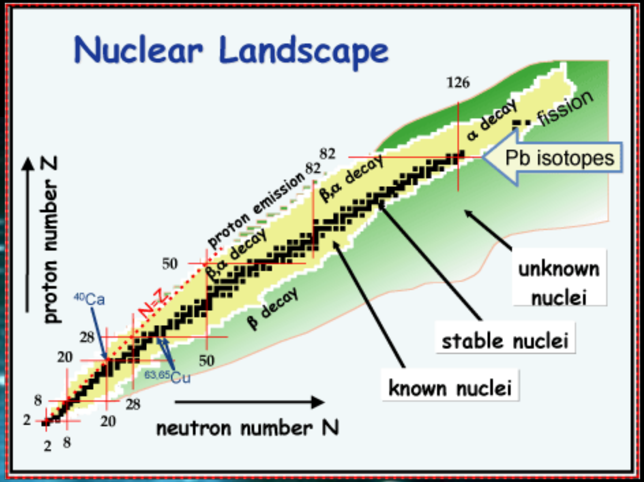


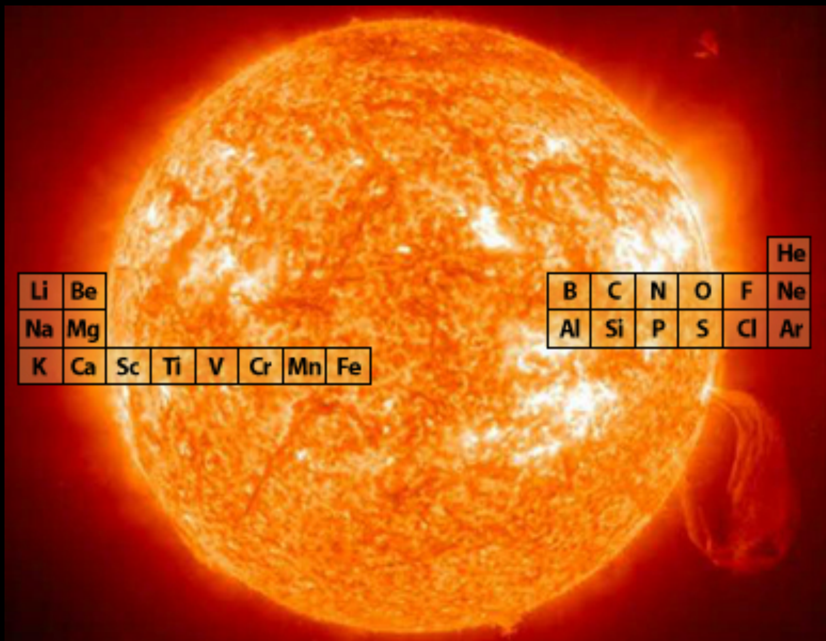


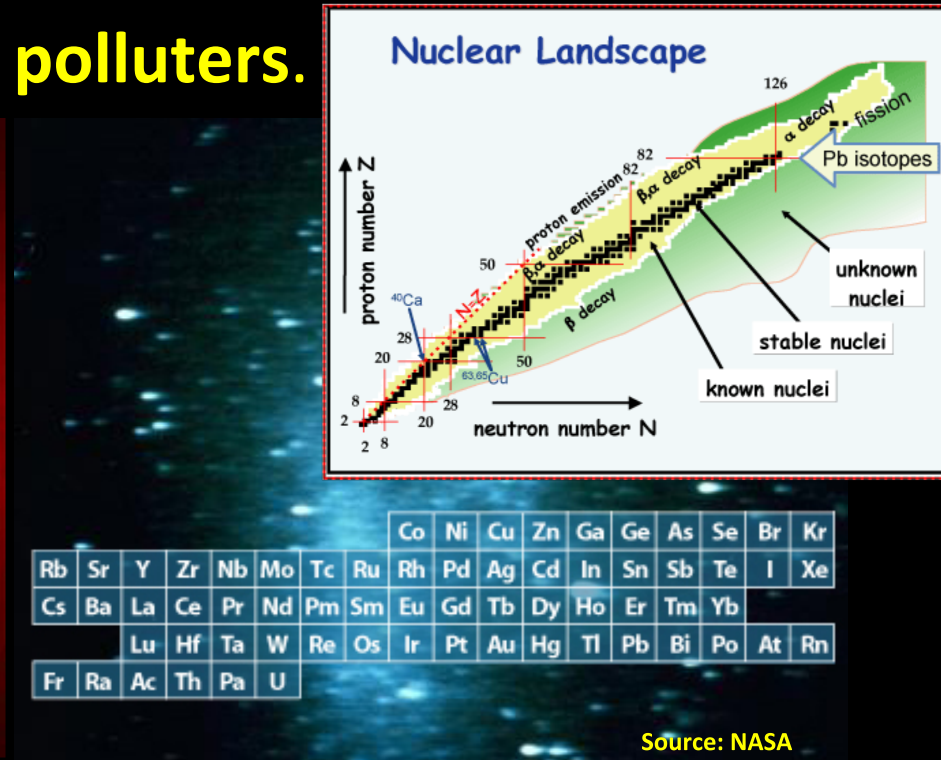


- Dynamical impact on galaxy evolution.
- Core-Collapse Supernovae:
  Birth sites of neutron stars and black holes.

Why do we care about Supernovae?

- **SNe are the main cosmic polluters.**



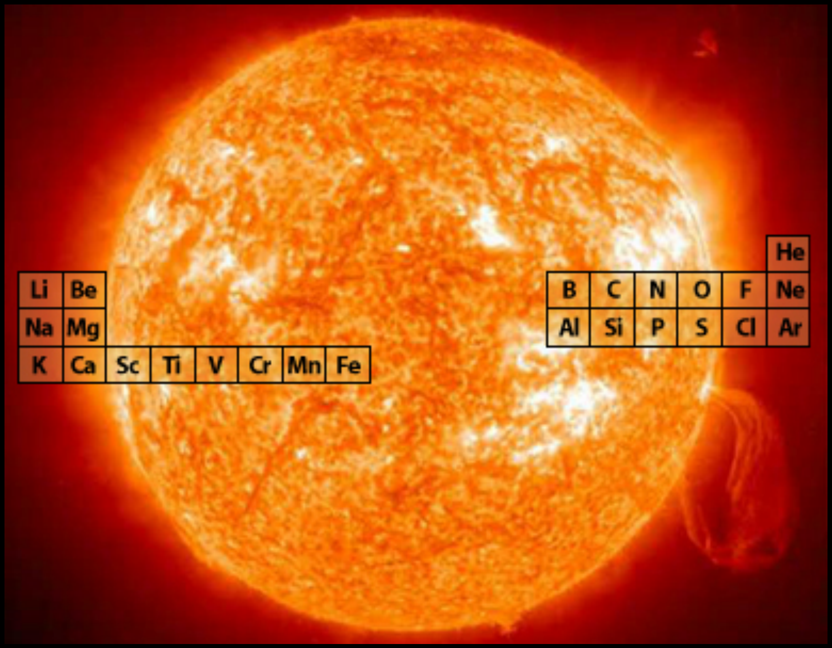


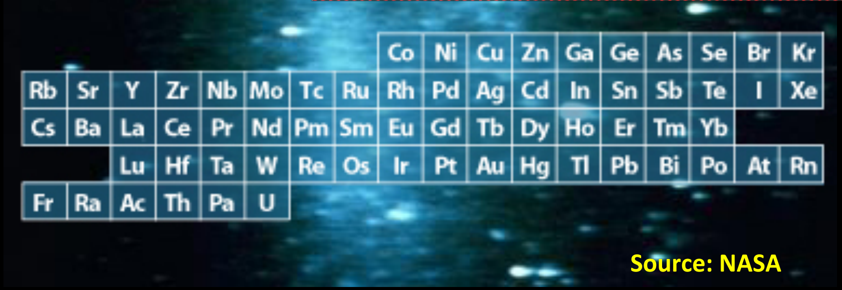
- Dynamical impact on galaxy evolution.
- Core-Collapse Supernovae:
  Birth sites of neutron stars and black holes.
- Gigantic cosmic laboratories for fundamental physics.

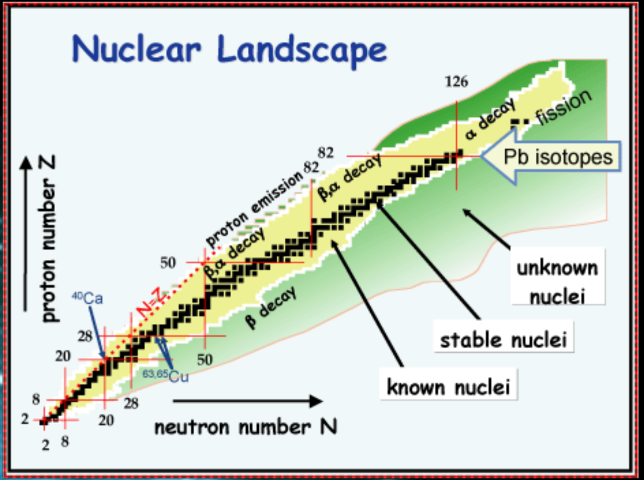
Neutrinos!!!
Nuclear EOS

Why do we care about Supernovae?

- SNe are the main cosmic polluters.





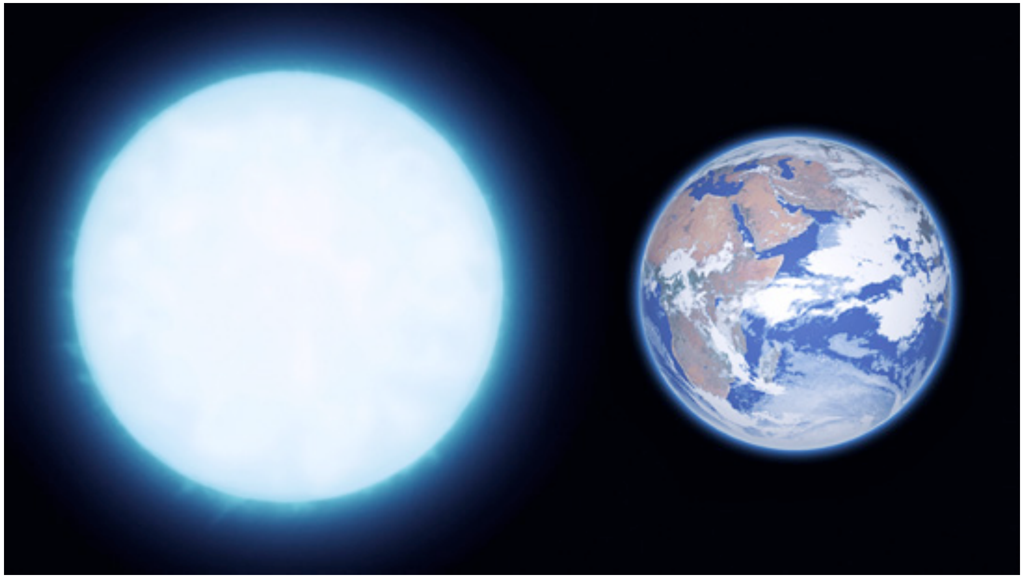


- Dynamical impact on galaxy evolution.
- Core-Collapse Supernovae:
  Birth sites of neutron stars and black holes.
- Gigantic cosmic laboratories for fundamental physics.
- Cosmic standard candles (-> Nobel Prize in Physics 2011).

Neutrinos!!!
Nuclear EOS

Thermonuclear Supernovae:

Explosions of White Dwarfs



BBC

Stellar Evolution

Nuclear Burning:

H -> He -> C/O -> O/Ne/Mg -> Si -> Fe

$\sim 0.5\,M_\odot < M < \sim 7\,M_\odot$

Envelope ejection

C-O White Dwarf

$\sim 7\,M_\odot < M < \sim 10\,M_\odot$

Envelope ejection

O-Ne White Dwarf

$M > \sim 10\,M_\odot$

(will talk about that later)

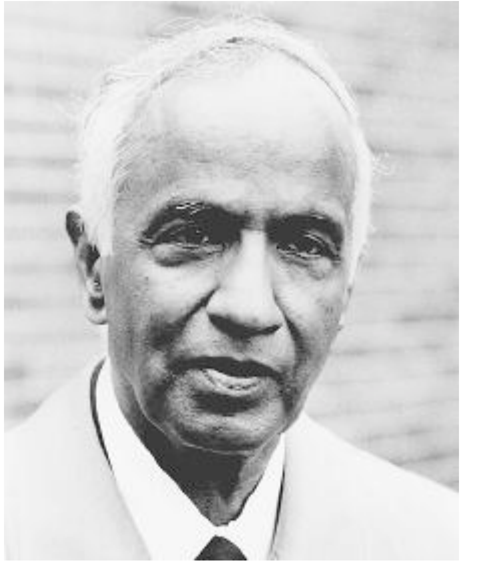
White Dwarf ejecting its Envelope

Cat's Eye Nebula

How can we explode a White Dwarf?

Carbon/Oxygen White Dwarf

Chandrasekhar Limit



- White dwarfs -> supported by the degeneracy pressure of electrons.

$$P = K\rho^{\Gamma} \quad \Gamma = 4/3$$ (relativistic electrons)

$$M_{\max} \approx (\hbar c/G)^{3/2}/m_p^2 \quad \frac{dP}{dr} = -\frac{GM\rho}{r^2}$$

- Chandrasekhar mass:

$$M_{\mathrm{Ch}} \approx 1.44(2Y_e)^2 M_{\odot}$$

$$Y_e = 0.5$$ (in C/O white dwarfs)

- Radial instability if $M > M_{\mathrm{Ch}}$

Carbon Ignition

(see, e.g., Woosley+ 04)

- $M > M_{Ch}$ WD contracts, heats up.

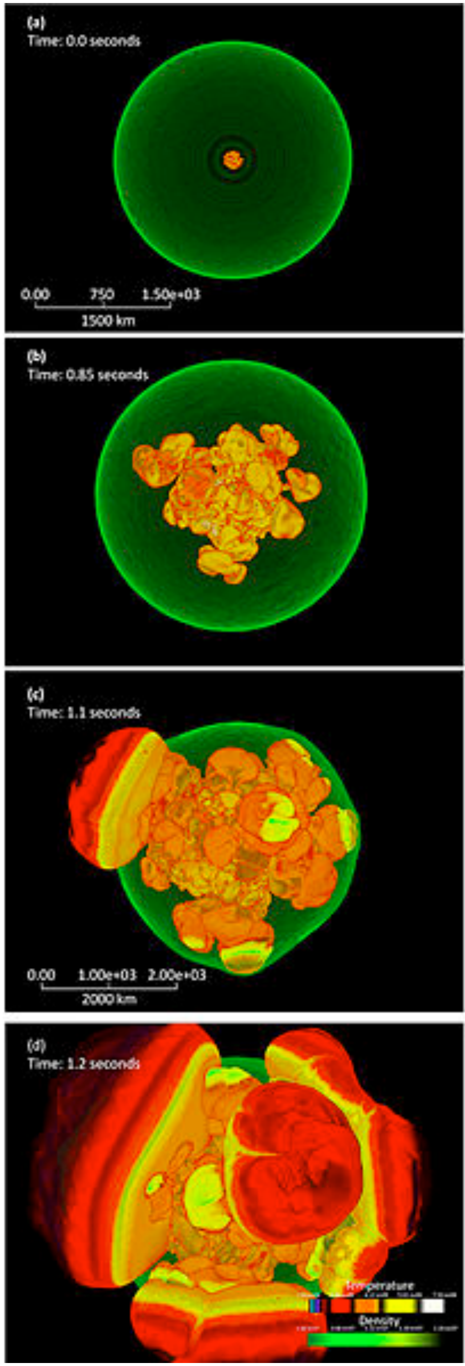
$$\lambda_{12,12} \approx 7.6 \times 10^{-16} \left(\frac{T_8}{7}\right)^{30}$$

Carbon fusion rate (Caughlan & Fowler 88)

- WD degenerate
  -> increased T does not lead to expansion.
  -> thermonuclear runaway!

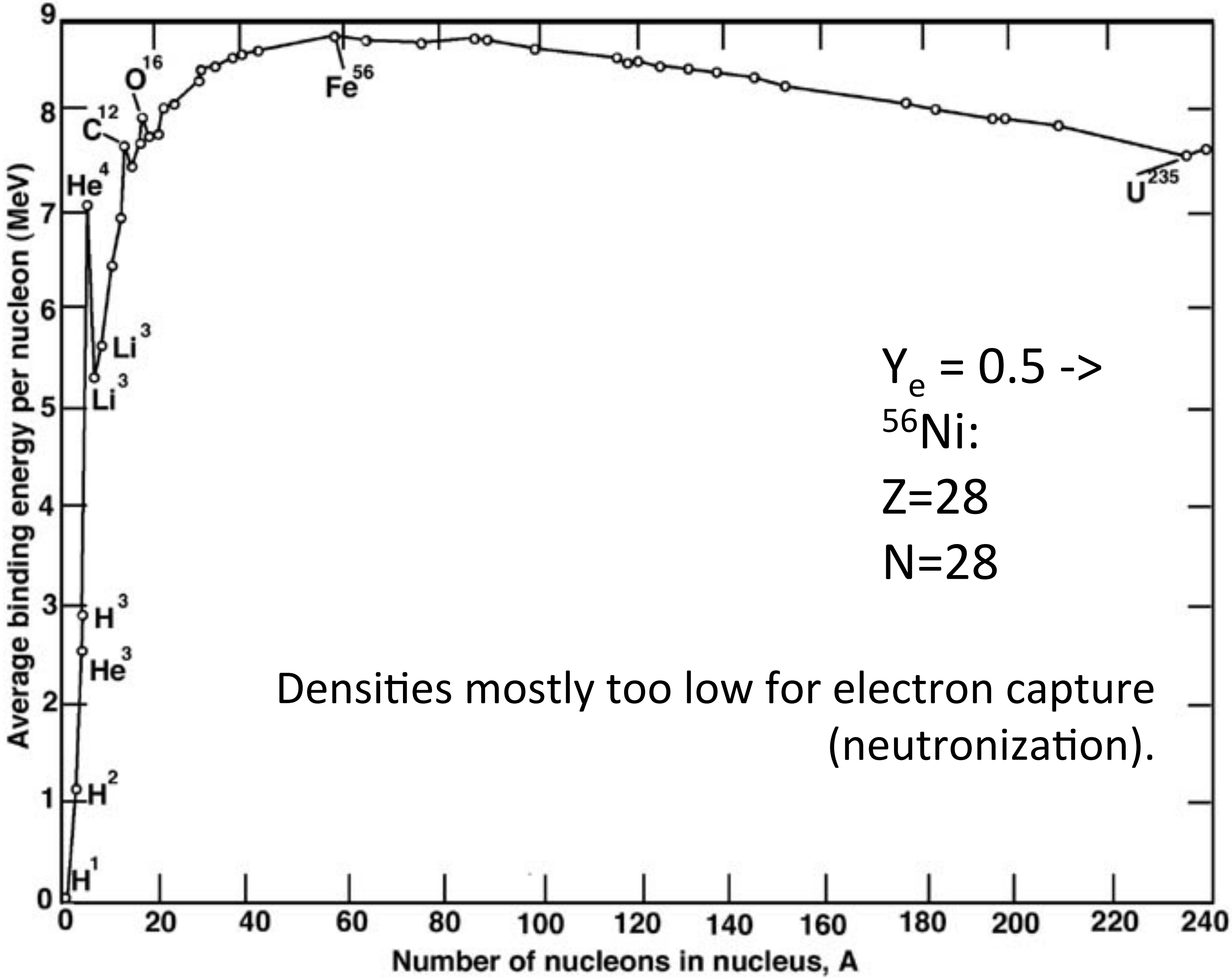
- Ignition details still uncertain. Most likely: First subsonic burning (*deflagration*) than supersonic flame propagation (*detonation*).

- Burning proceeds into nuclear statistical equilibrium (NSE, T ~5×10^9 K).
  Main product: ^{56}Ni, typically 0.6 $M_\odot$



Flash Center, U Chicago/Argonne

Why stop at Nickel 56?



Y_e = 0.5 ->

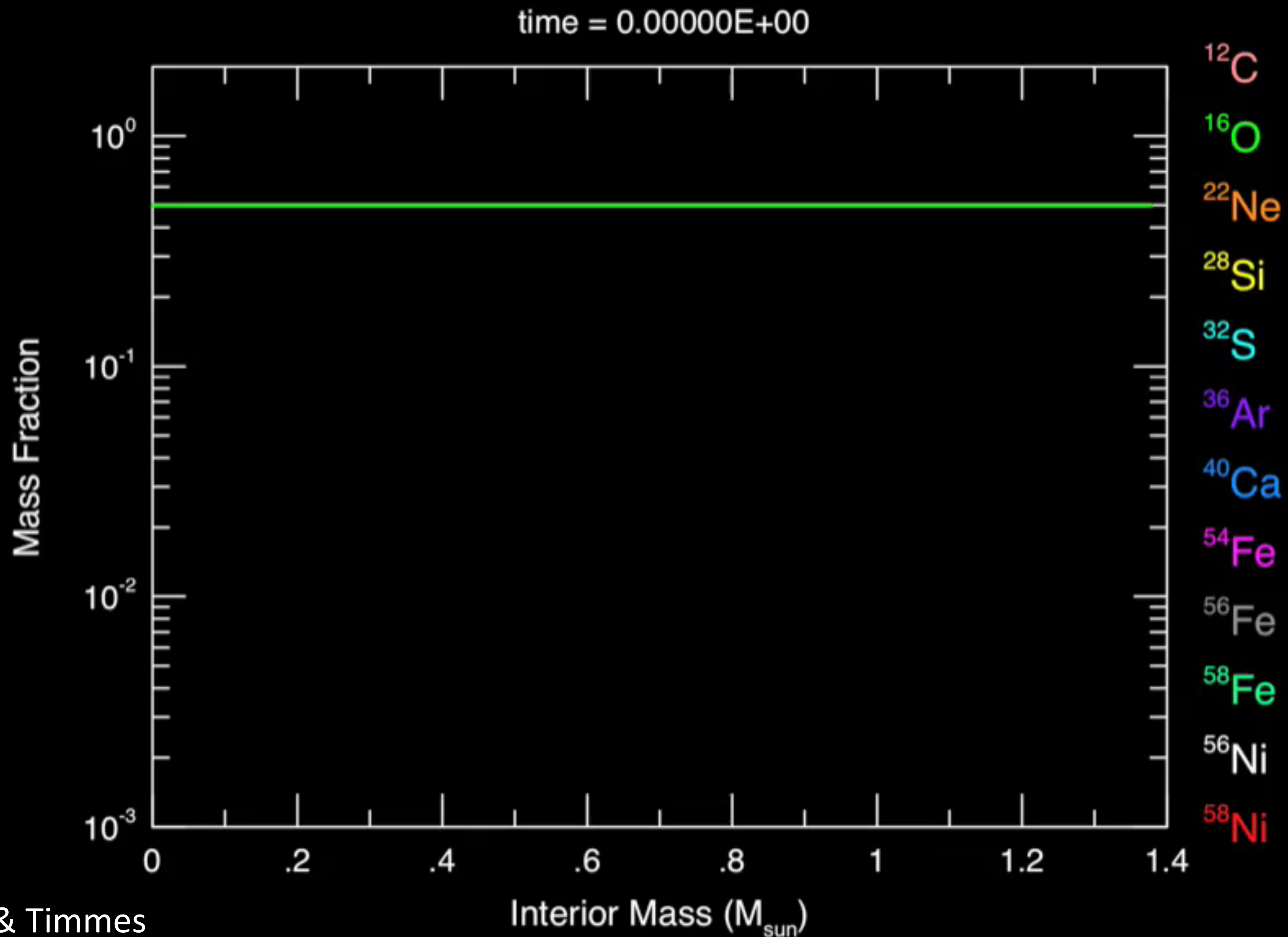
^{56}Ni:

Z=28

N=28

Densities mostly too low for electron capture (neutronization).

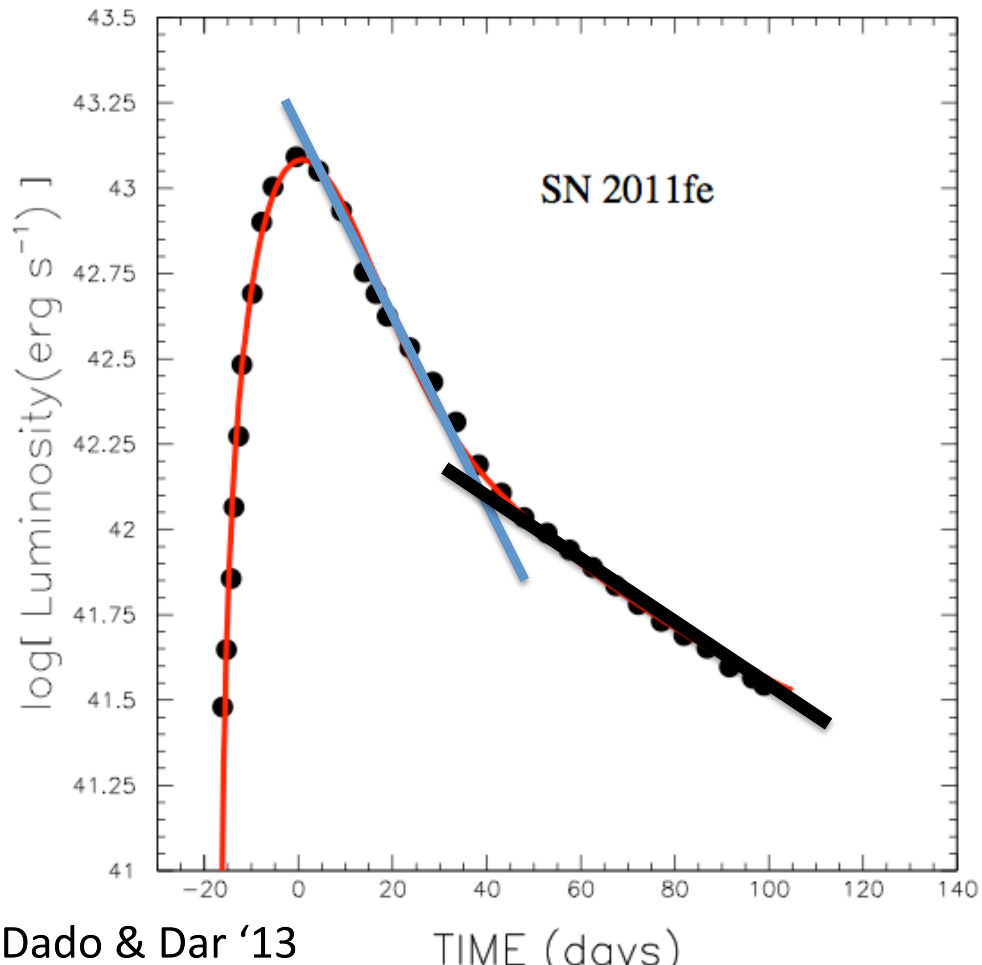
Explosive Nucleosynthesis



Piro & Timmes

Energetics and Lightcurve

- Burning of C+O to Ni gives ~10^{18} erg/g (~1 MeV/nucleon).
  -> get ~10^{51} erg for burning 0.6-0.8 $M_\odot$.

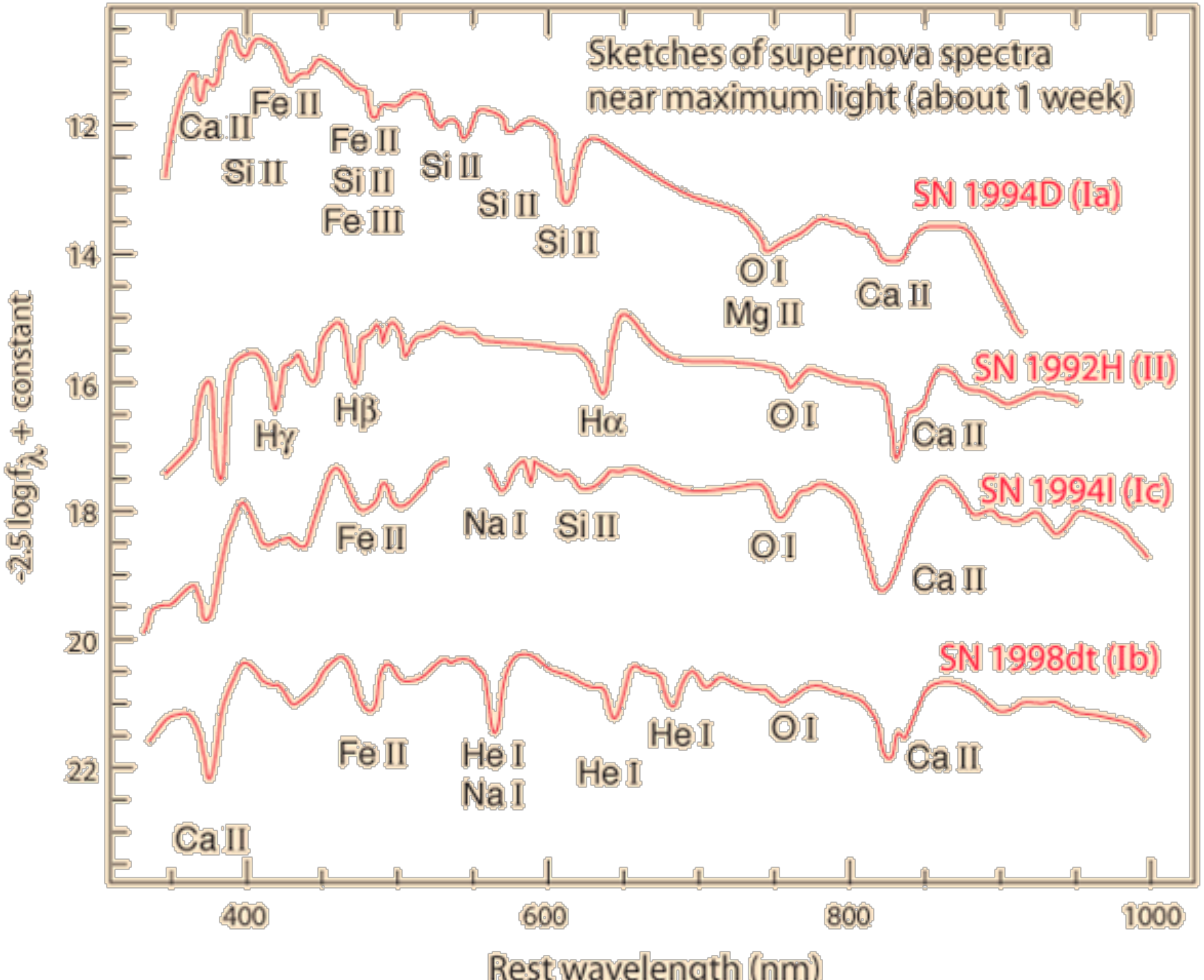


Dado & Dar '13

- Powered by radioactive decay!

$$^{56}\mathrm{Ni} \xrightarrow{6\,\mathrm{d}} {}^{56}\mathrm{Co} \xrightarrow{77\mathrm{d}} {}^{56}\mathrm{Fe}$$

Supernova Spectra & Types



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

http://hyperphysics.phy-astr.gsu.edu/hbase/astro/imgast/snovspects.gif

Thermonuclear:
Type Ia:
no H, He,
strong Si

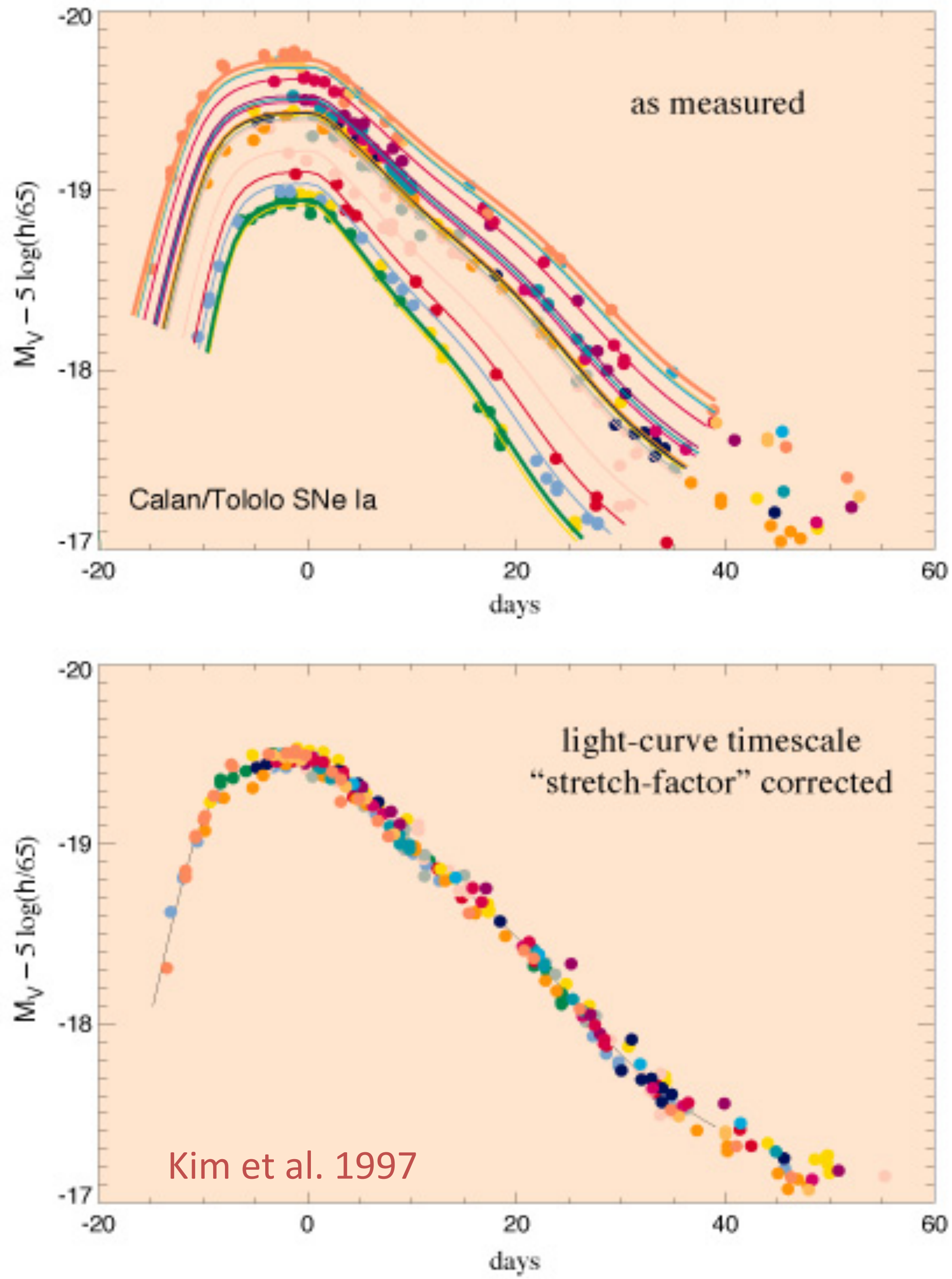
Core Collapse:
Type II: H
Type Ib: no H
Type Ic: no H, He,
weak Si

Type Ia SNe: Standard Candels

- “Width-Luminosity” Relation -> intrinsic luminosity of distant SNe

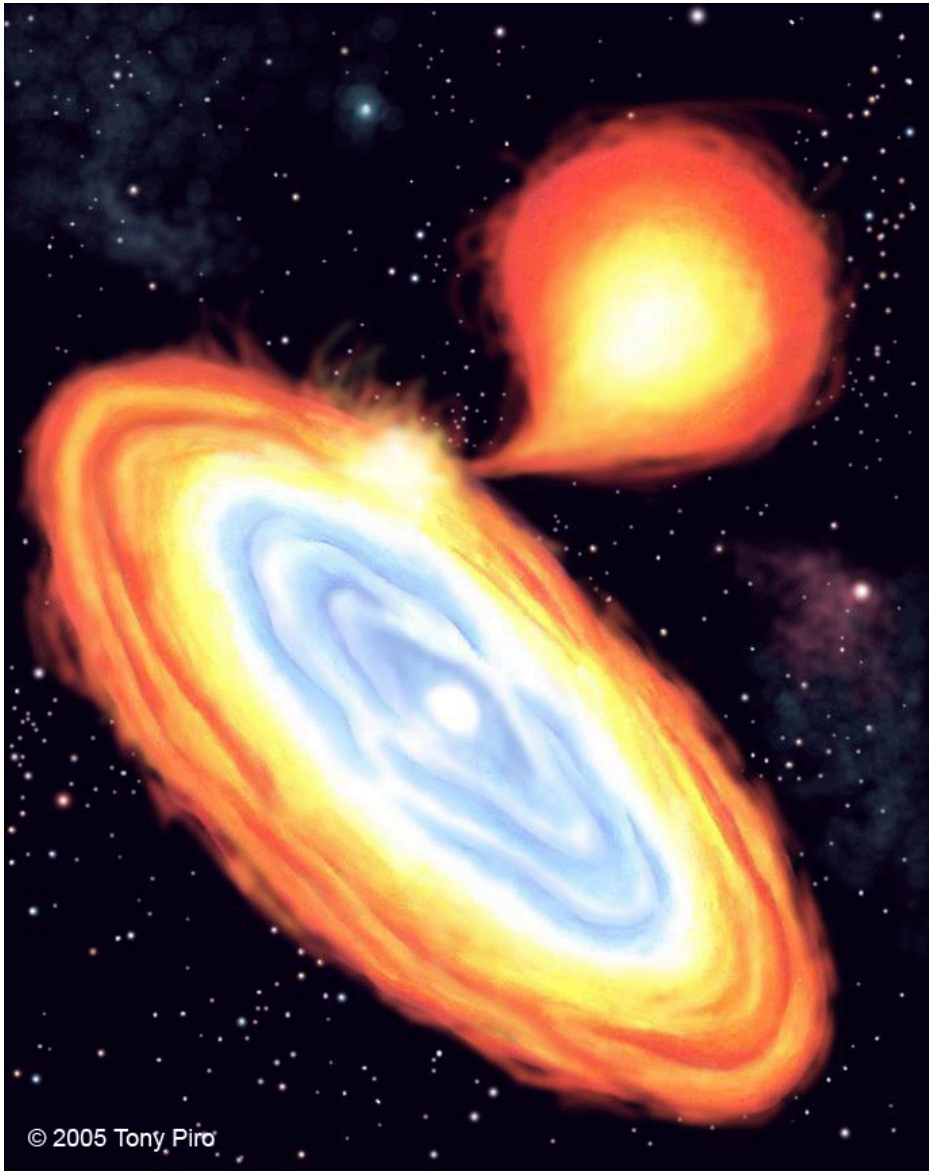
$$F = \frac{L}{4\pi r^2}$$

- 2011 Nobel Prize in Physics to Perlmutter, Riess, & Schmidt: The expansion of the universe is accelerating.



Type Ia SN Progenitors?

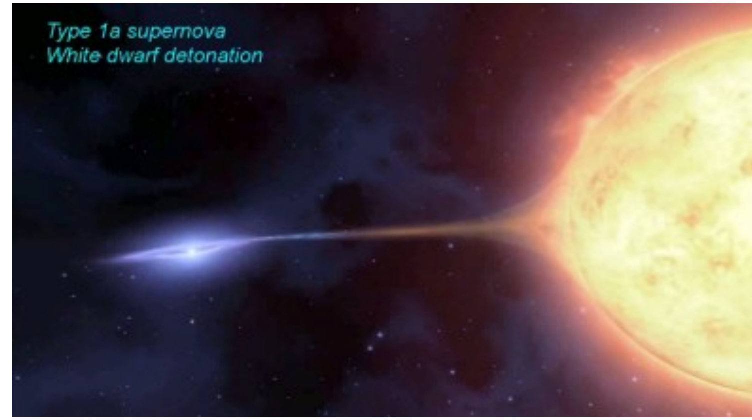
- ~97% of all stars end their lives as C/O WDs.
- Typical WD mass: 0.6 $M_\odot$
- How is M_{Ch} reached?
- Explosions produce range of Nickel yields: Are sub-Chandra and super-Chandra explosions possible?
- Basic idea: a WD somehow gains mass from a companion.

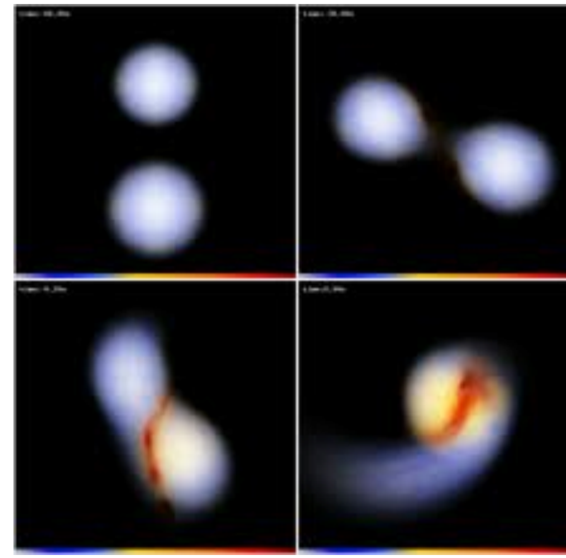


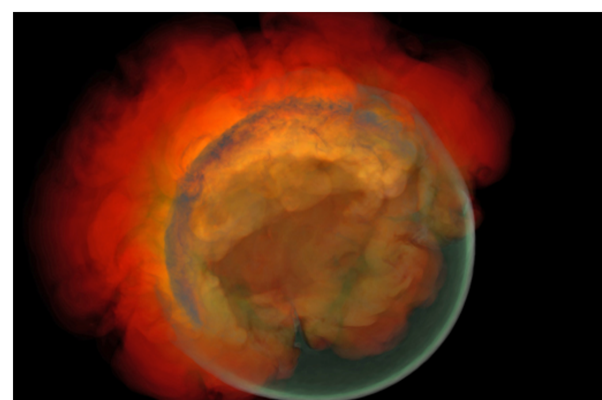
(slide by Tony Piro)

Ia Progenitor Scenarios

- **Single Degenerate** (SD):
  WD accretes from normal star companion until M_{Ch}.
- **Double Degenerate** (DD):
  Merger of two white dwarfs.
  Problem: $0.6 + 0.6 = 1.2 < M_{Ch}$
  Would need rare high-mass WDs.
- White dwarf (head-on) collisions & "violent" mergers -> ignition upon merger.
- Double detonation model:
  Detonation of surface He layer ignites C/O.







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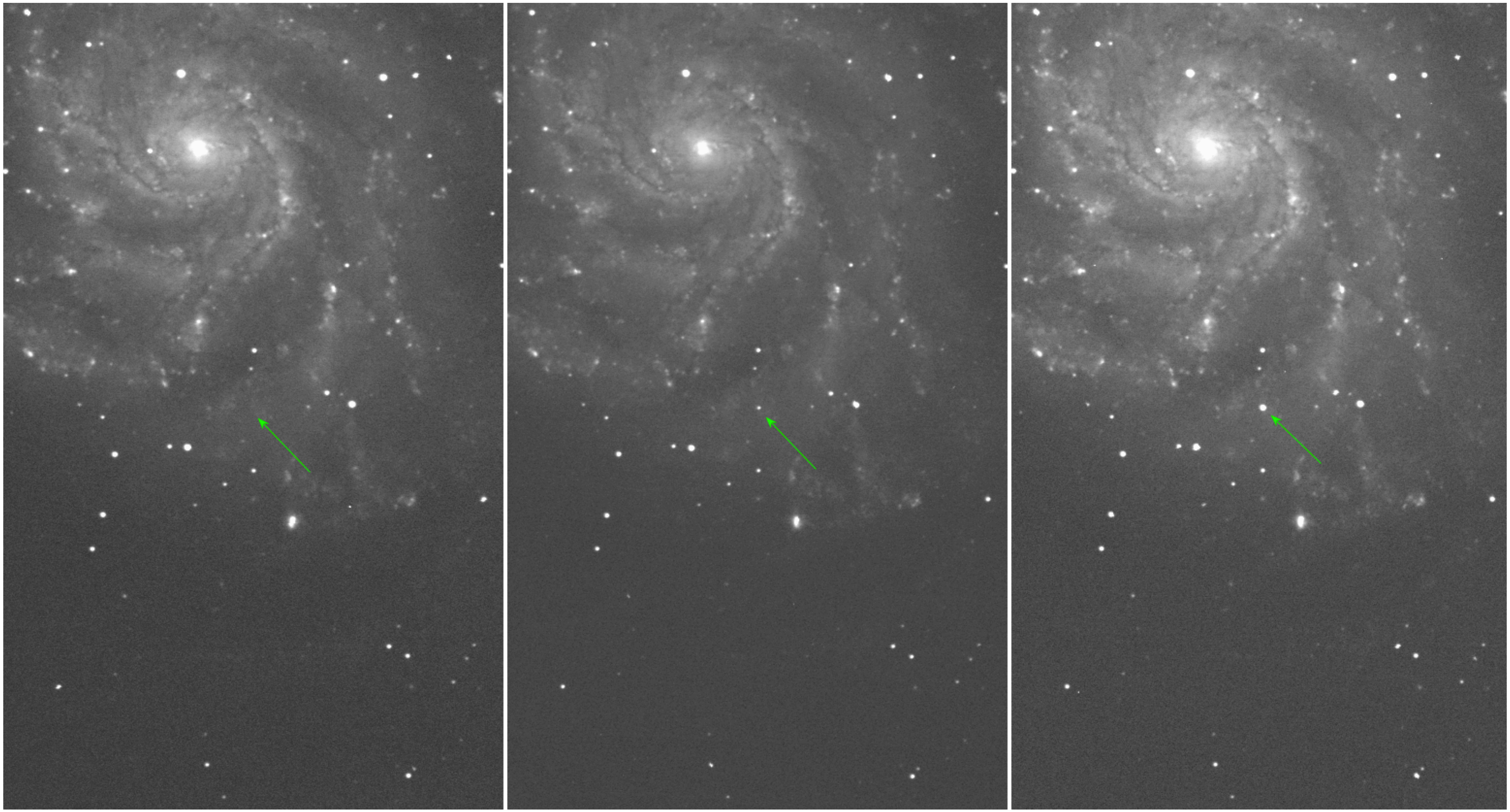
SN 2011fe: A Nearby Type Ia SN

Review: Chomiuk '13, arXiv:1307.2721

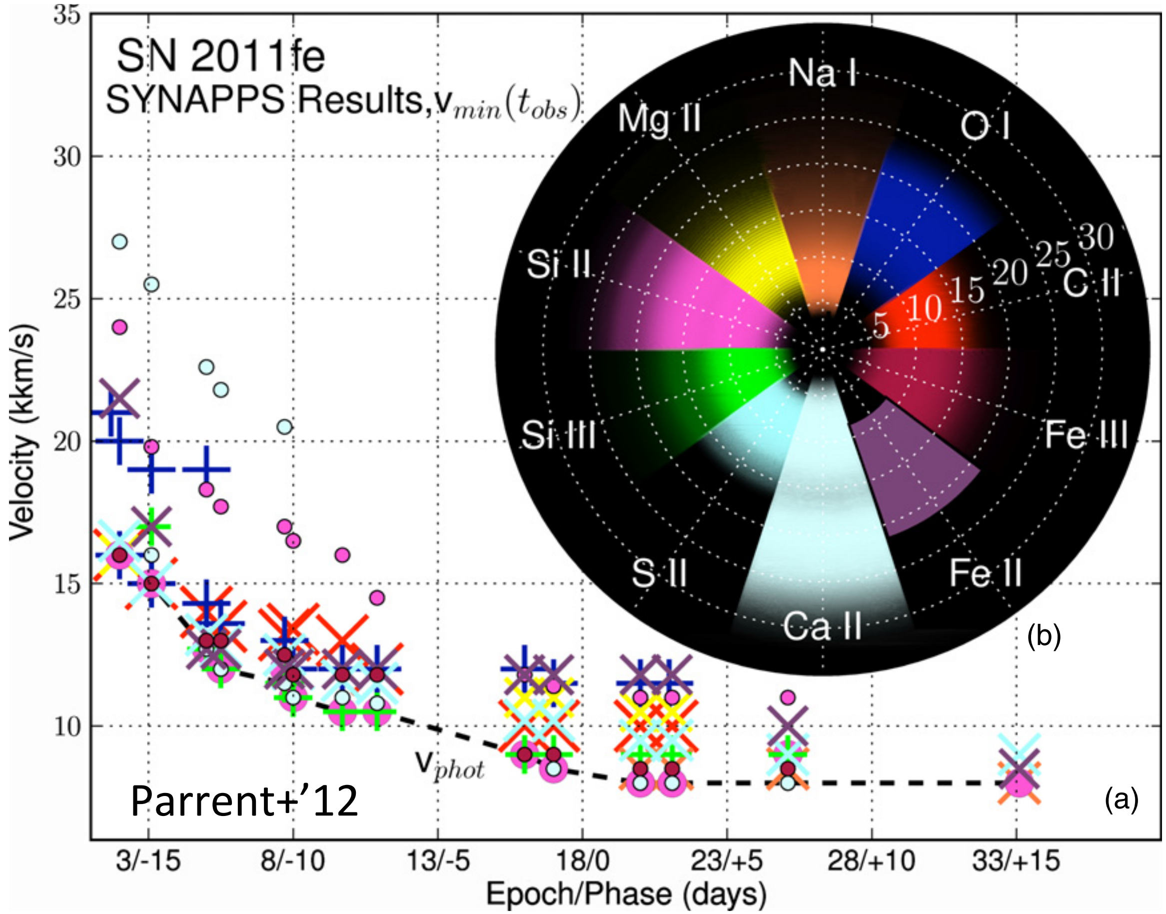


M101 Pinwheel Galaxy, August 24, 2011. Discovery by the Palomar Transient Factory (PTF)
D ~ 7 Mpc.

SN 2011fe: A Nearby Type Ia SN

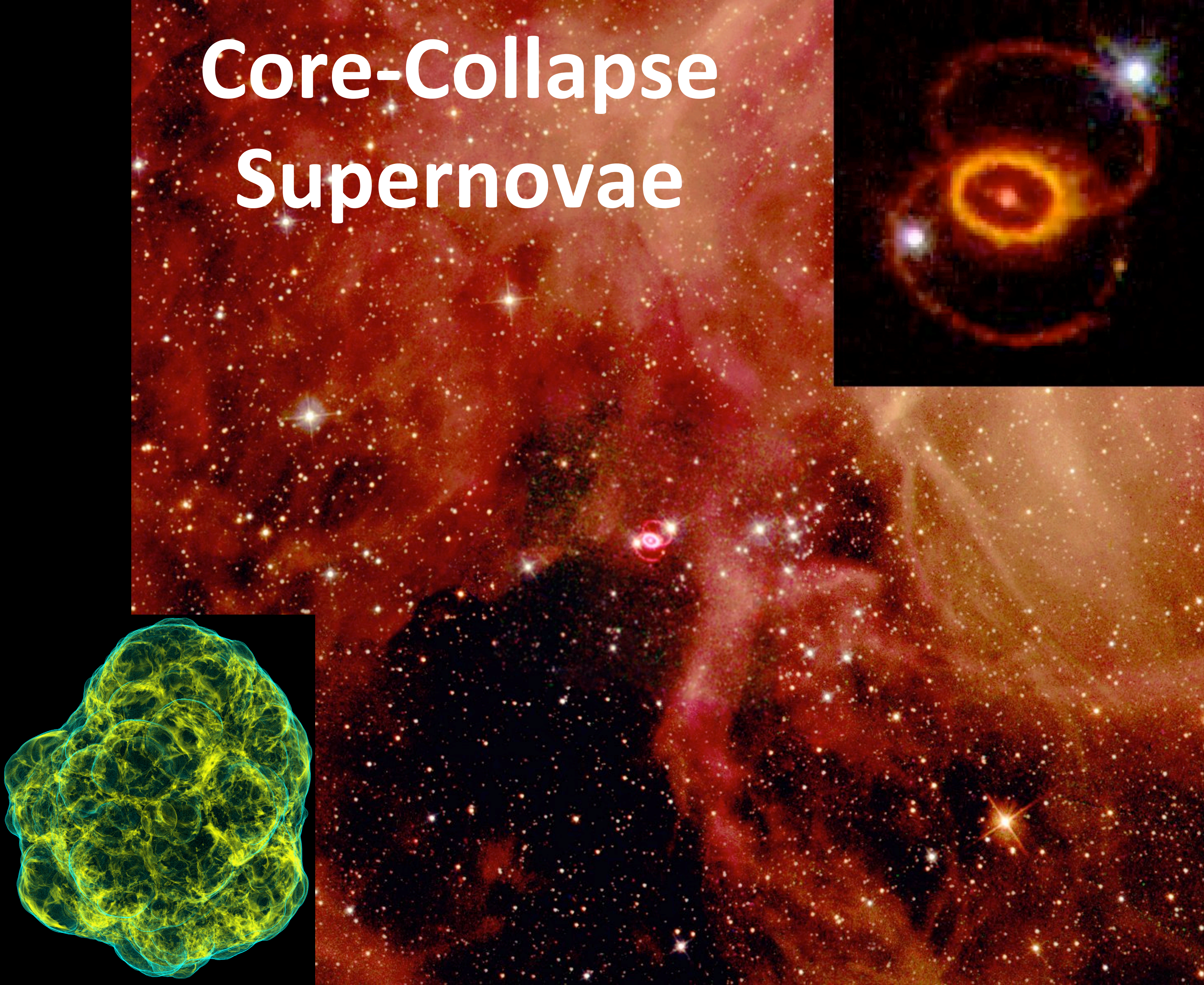
Review: Chomiuk '13, arXiv:1307.2721

- Typical type Ia SN.
- NO companion star found.
- 1.1 $M_\odot$ visible ejecta,
- 0.5 $M_\odot$ Ni.
- Consistent with explosion of C/O WD of sub-solar metalllicity.



- **Observations disfavor single degenerate scenario, favor double degenerate scenario.**

Core-Collapse Supernovae



- Mass: $\sim 7\,M_\odot \leq M \leq \sim 130\,M_\odot$.

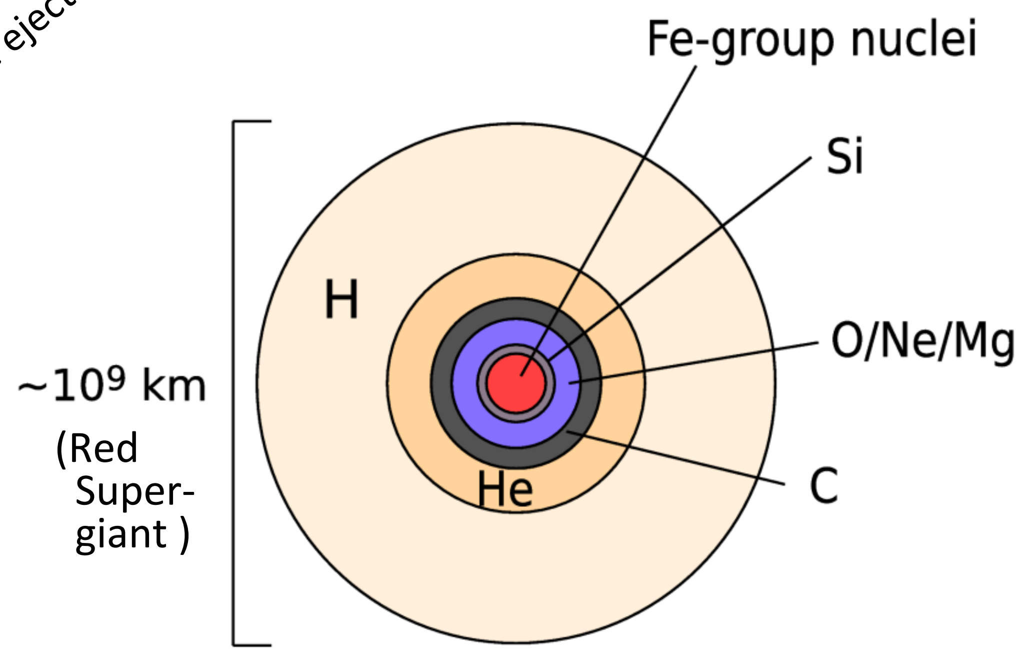
Nuclear Burning:

H -> He -> C/O -> O/Ne/Mg -> Si -> Fe

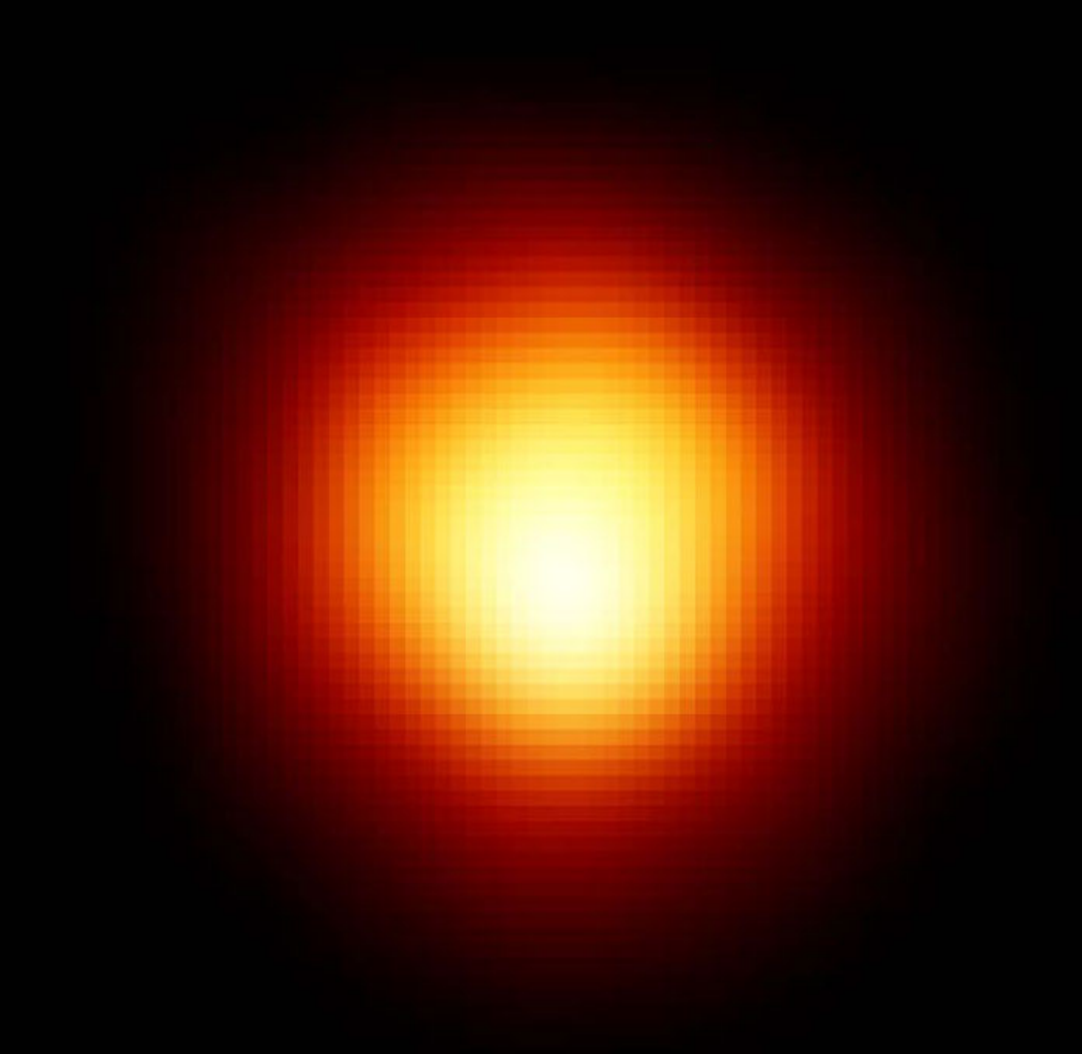
$M < \sim 7\,M_\odot$ — Envelope ejection → C-O White Dwarf

$\sim 7\,M_\odot < M < \sim 10\,M_\odot$ — Envelope ejection → O-Ne White Dwarf

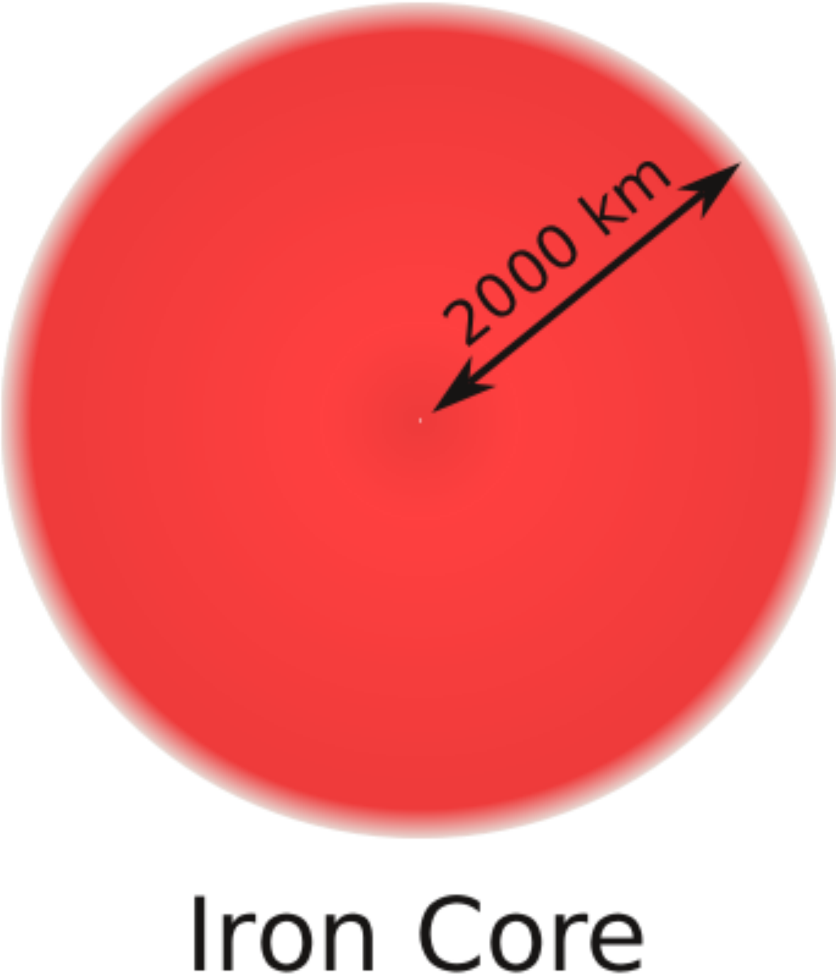
$M > \sim 10\,M_\odot$



- Key parameters controlling stellar evolution:
  - Mass
  - Metallicity
  - Binary Interactions
  - **Rotation**



Betelgeuse, $M \sim 20\ M_{\odot}$, $R \sim 8 \times 10^{13}$ cm $\sim 1000\ R_{\odot}$
(HST)

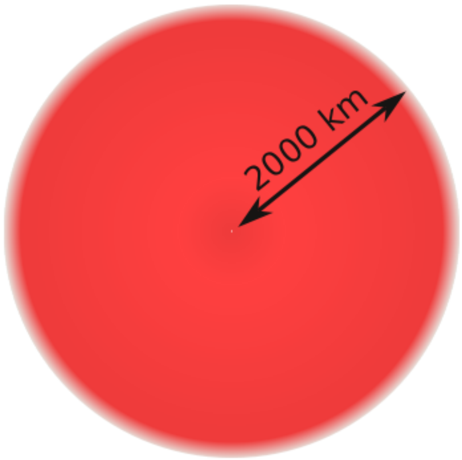


$\rho_c \approx 10^{10}$ g/cm^3
T ≈ 1 MeV = 1.16 x 10^{10} K
$Y_e \approx 0.45$

Hydrostatic Equilibrium:

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

Hydrostatics of the Iron Core and the Onset of Collapse



Iron Core

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

T ≈ 1 MeV

$Y_e \approx 0.5$

(in reality: T lower and Ye slightly lower)

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \qquad P = P_{\rm ion} + P_{\rm rad} + P_e$$

Ions: Assume pure Fe 56 (not quite right, of course)

$$P_{\rm ion} = Y_{\rm Fe} N_{\rm A} \rho k_{\rm B} T \qquad \boxed{P_{\rm ion} \approx 2 \times 10^{26}\,{\rm dyn/cm^2}}$$

Radiation pressure:

$$P_{\rm rad} = \frac{1}{3} a T^4 \qquad \boxed{P_{\rm rad} \approx 3 \times 10^{25}\,{\rm dyn/cm^2}}$$

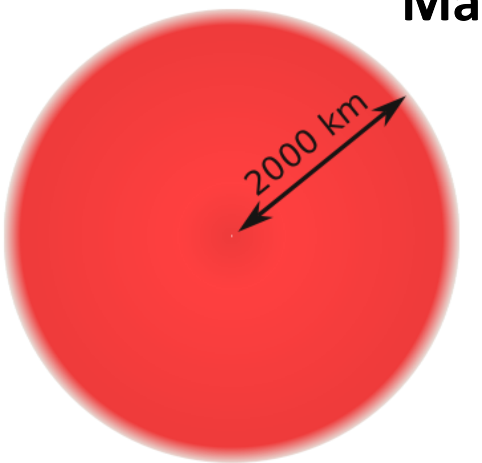
Electrons: degenerate and relativistic

$$P_e \approx \frac{2\pi}{3} \frac{1}{c^3 h^3} \mu_e^4 \qquad \mu_e \approx 1.11 (\rho_7 Y_e)^{1/3}\,{\rm MeV}$$

$$\boxed{P_e \approx 10^{28}\,{\rm dyn/cm^2}}$$

$$P_e \gg P_{\rm ion} \gg P_{\rm rad}$$

Chandrasekhar Mass



Iron Core

$\rho_c \approx 10^{10}$ g/cm^3
T ≈ 1 MeV
$Y_e \approx 0.5$

(in reality: T lower and Ye slightly lower)

Maximum mass for a relativistically degenerate object:

$$M_{\text{Ch}} \approx 1.44(2Y_e)^2 M_\odot$$

+ GR, thermal, and other corrections.

(at $Y_e = 0.5$ -> $M_{Ch} \approx 1.45\ M_{Sun}$)

$M \geq M_{Ch}$ -> radial instability -> collapse

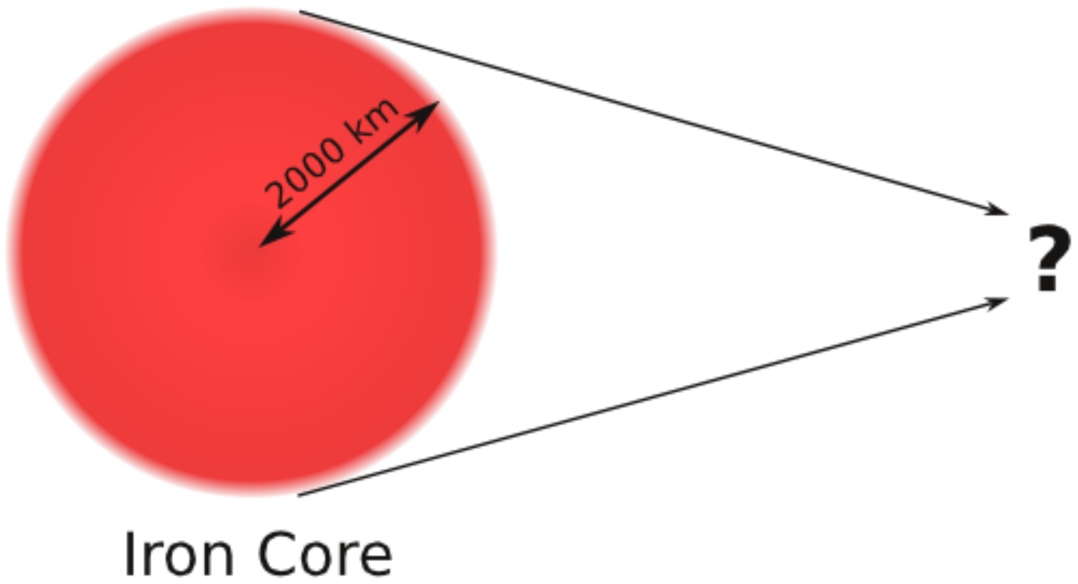
Two ways to get there:

(1) Silicon shell burning adding mass to the core.

(2) Reduction of Y_e.

-> electron capture

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


2000 km
?
Iron Core

In collapse, pressure support is reduced by

- **Photodissociation** of heavy nuclei: ~125 MeV/reaction

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

- **Electron Capture**

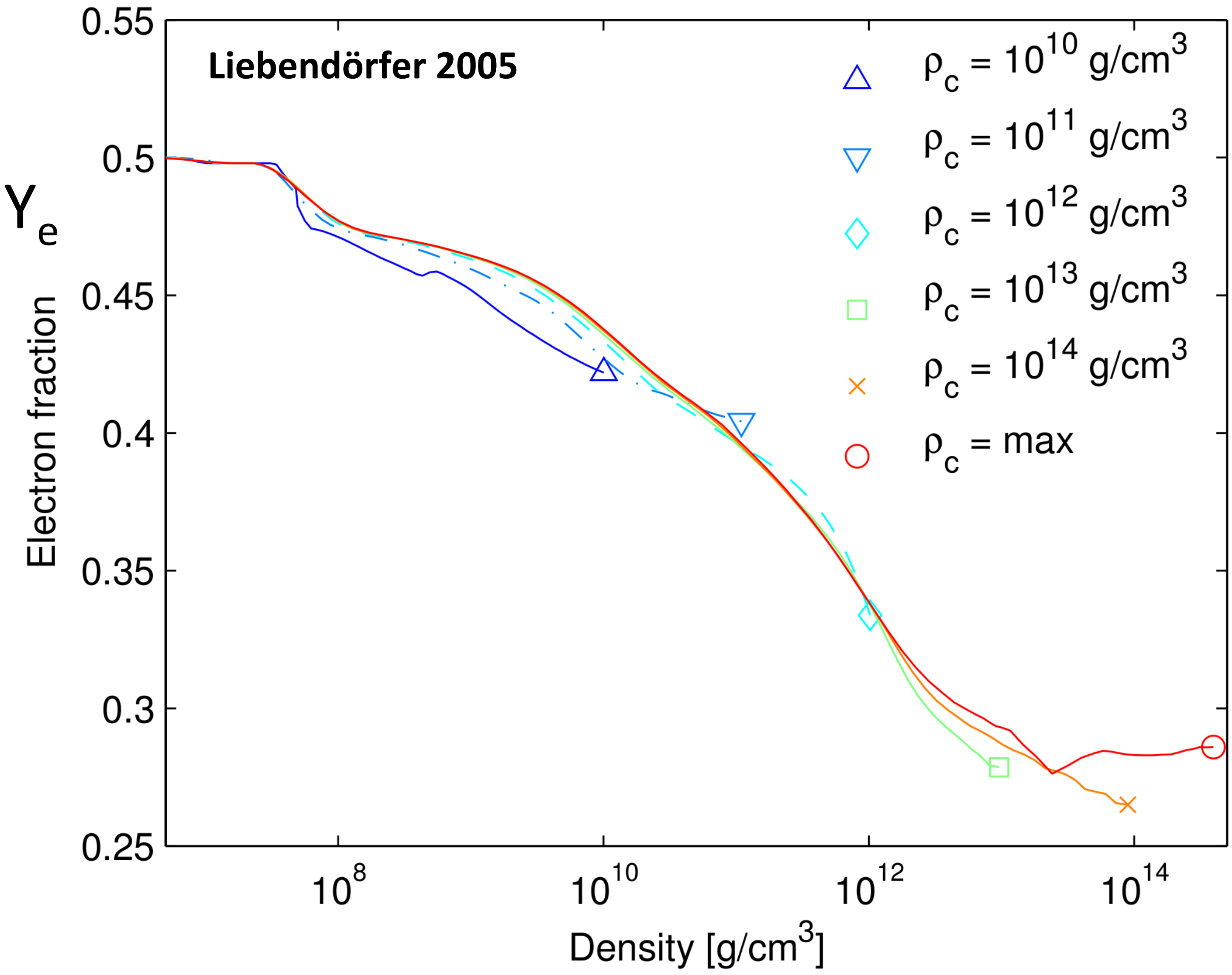
$$e^- + (Z, A) \overset{(W)}{\longrightarrow} \nu_e + (Z-1, A)$$

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

$$\frac{\partial}{\partial t} Y_e \propto \mu_e^5 \propto \rho^{5/3}$$

- Neutrinos stream off almost freely at densities below ~10^{12} g/cm^3.
  -> core "deleptonizes" during collapse.
- Net entropy change is small,
  -> **collapse proceeds practically adiabatically.**

More Collapse Physics: Deleptonization



Neutrino Trapping

- Collapse phase: Neutrino opacity dominated by coherent neutrino-nucleus scattering: $\nu + (A,Z) \longleftrightarrow \nu + (A,Z)$

  Neutrino mean-free path: $\lambda_\nu \approx 10^7\,\mathrm{cm}\left(\frac{10^{12}\,\mathrm{g\,cm^{-3}}}{\rho}\right)\frac{A}{N^2}\left(\frac{10\,\mathrm{MeV}}{\epsilon_\nu^2}\right)$

- For $\rho \geq 3 \times 10^{12}$ g/cm^3, diffusion time τ_{diff} >> collapse time -> **neutrinos become dynamically trapped in the collapsing core.**

- **Consequences**:

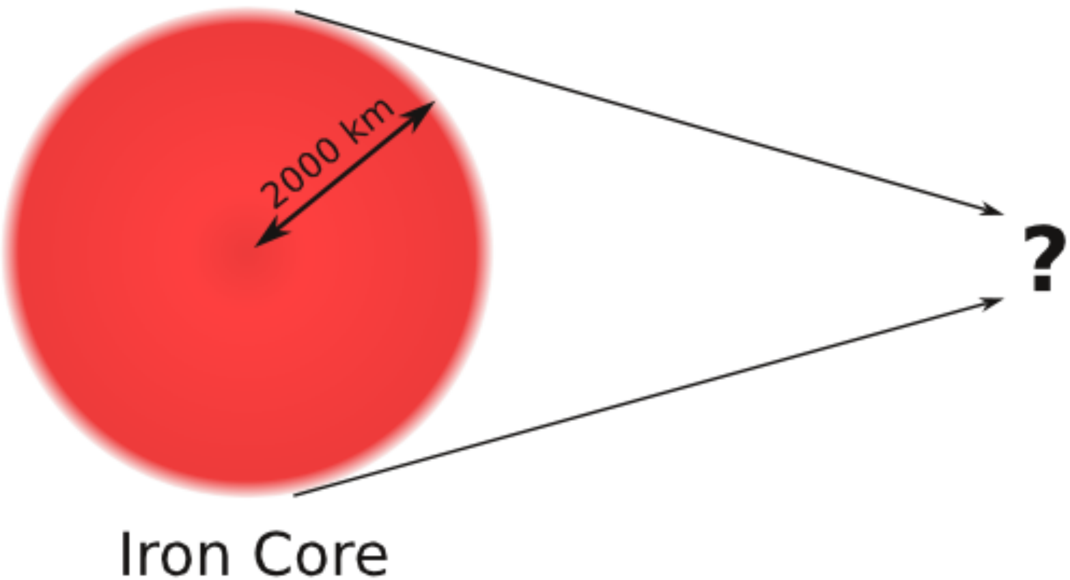
  Deleptonization stopped $Y_{\mathrm{lep}} = Y_e + Y_\nu = \mathrm{const.}$

  Detailed simulations: $Y_{\mathrm{lep}} \approx 0.32$

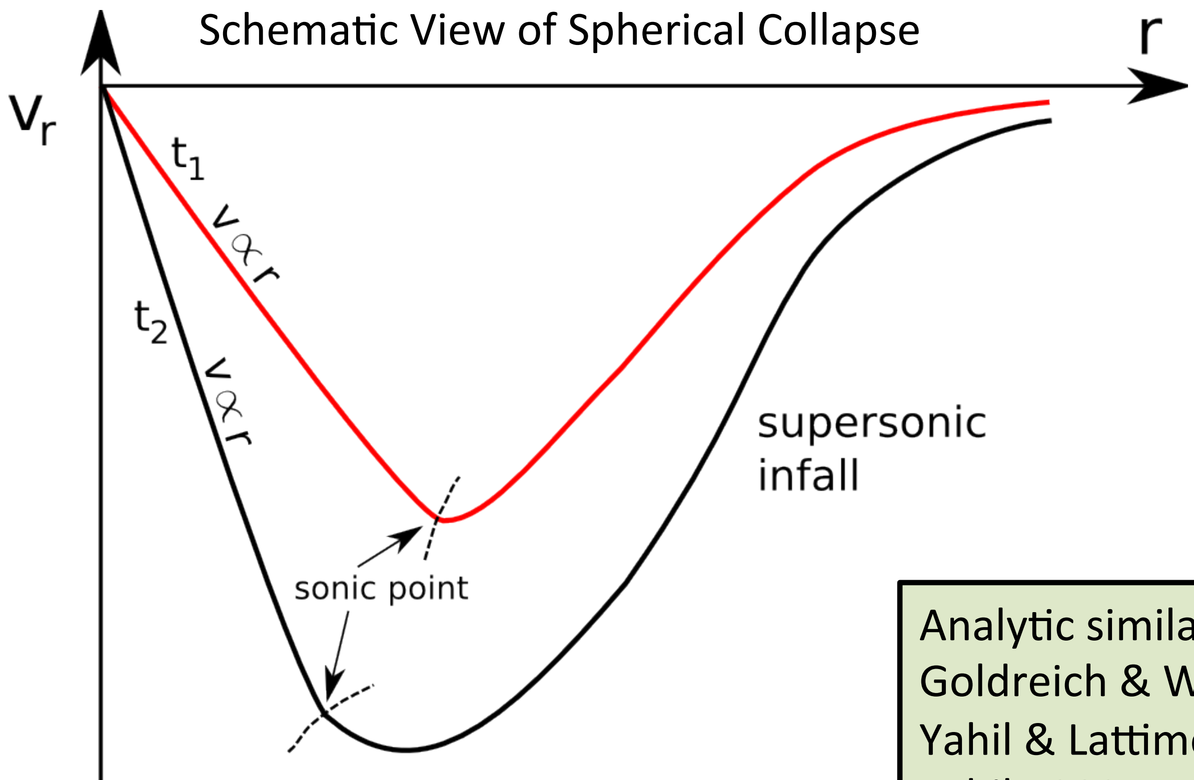
  Beta Equilibrium $e^- + p \longleftrightarrow \nu_e + n$

  $$\mu_e + \mu_p = \mu_\nu + \mu_n$$

still collapsing...



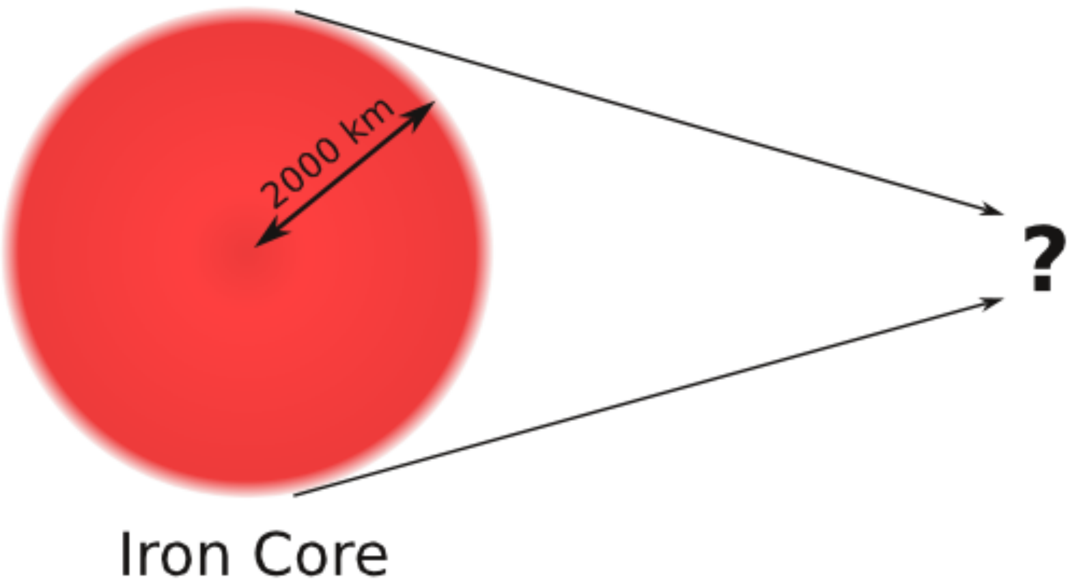
Self-Similarity in Stellar Collapse



Analytic similarity solutions:
Goldreich & Weber 1980
Yahil & Lattimer 1982
Yahil 1983

- Separation into **homologously ($v \propto r$) collapsing inner core** and **supersonically collapsing outer core**.

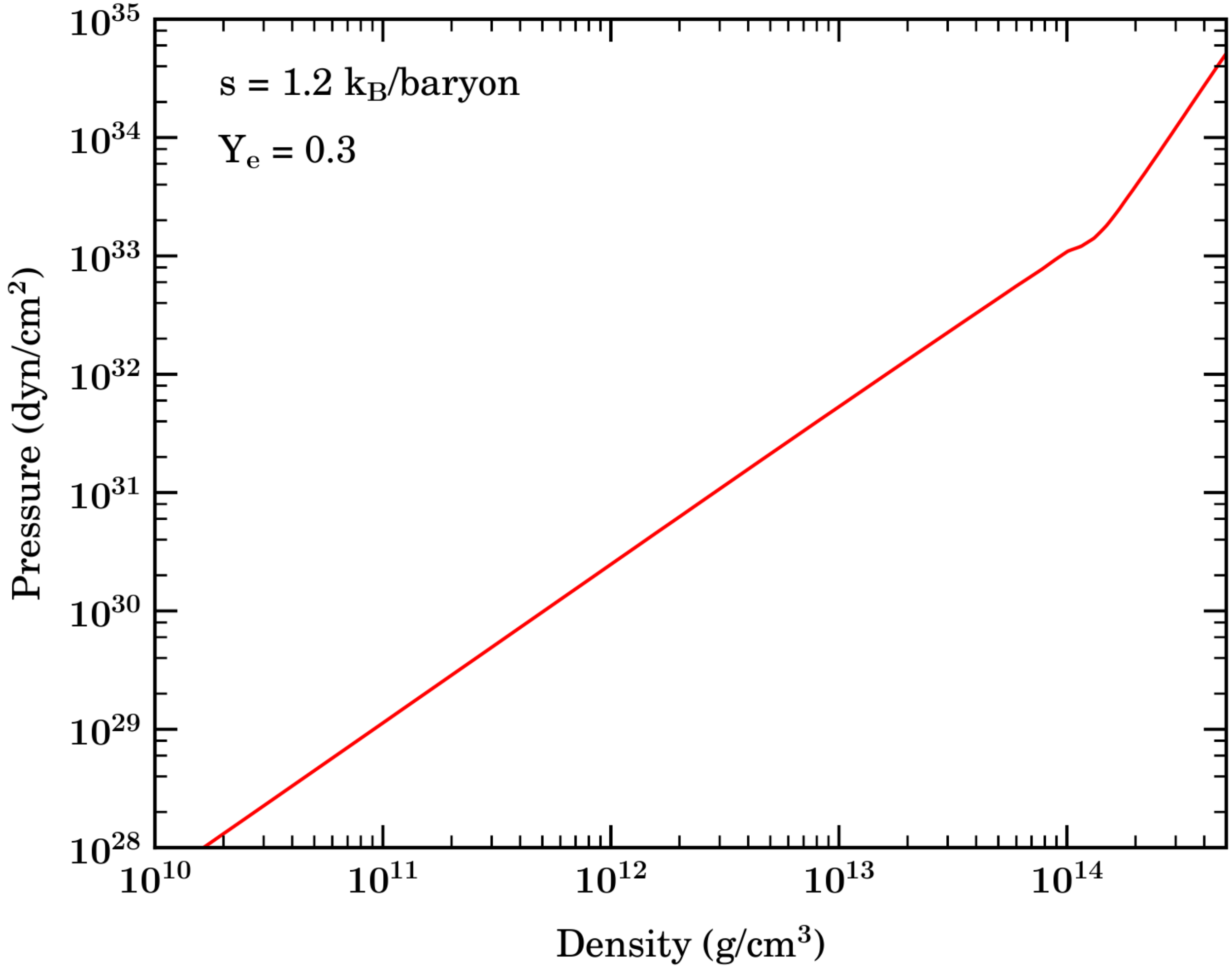
Still collapsing... is there an end?



The Nuclear Equation of State (EOS)

Nuclear Statistical Equilibrium ($\rho > 10^7$ g/cm^3, $T > 0.5$ MeV)

-> $P = P(\rho, T, Y_e)$



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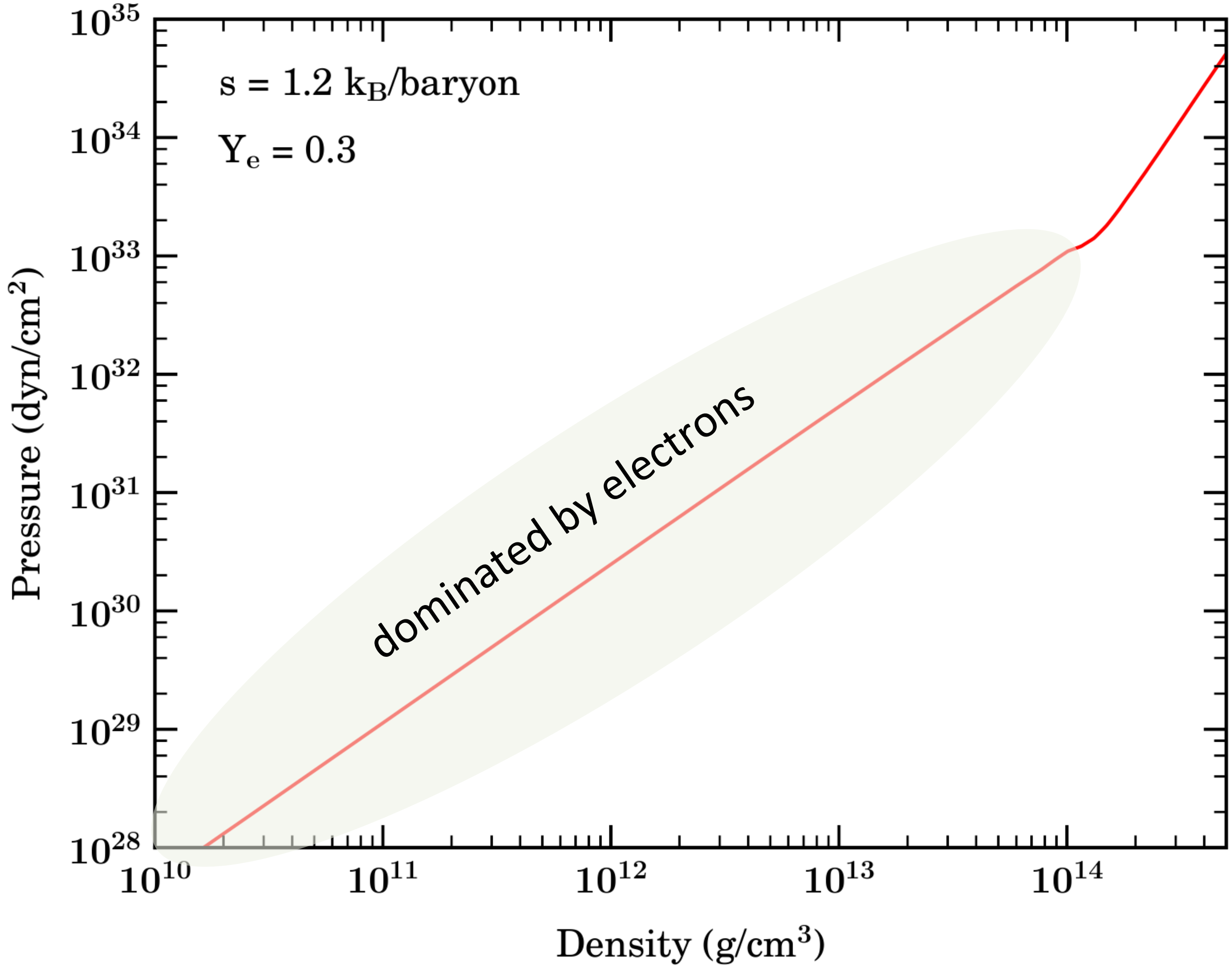

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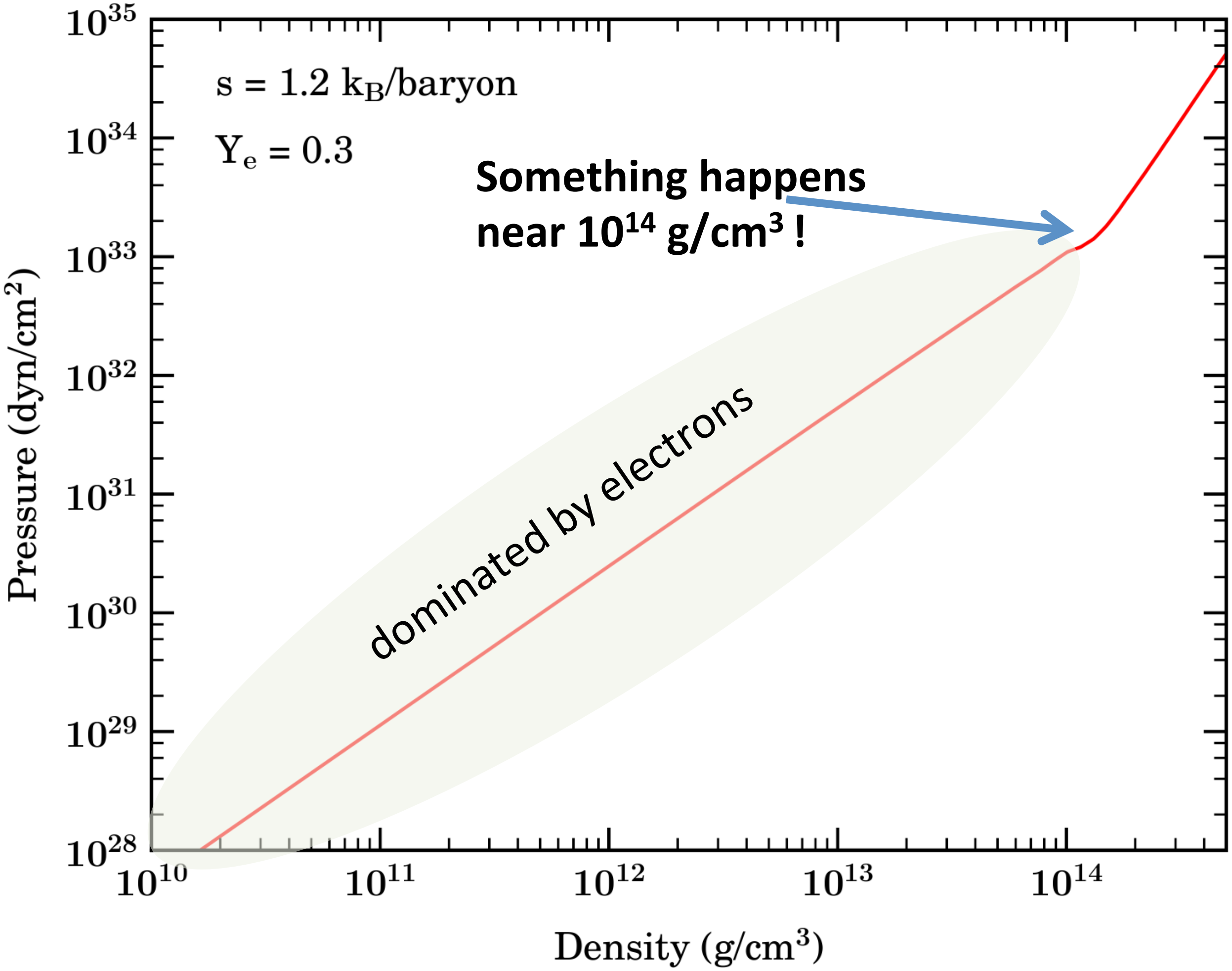


The Nuclear Equation of State (EOS)

Nuclear Physics:

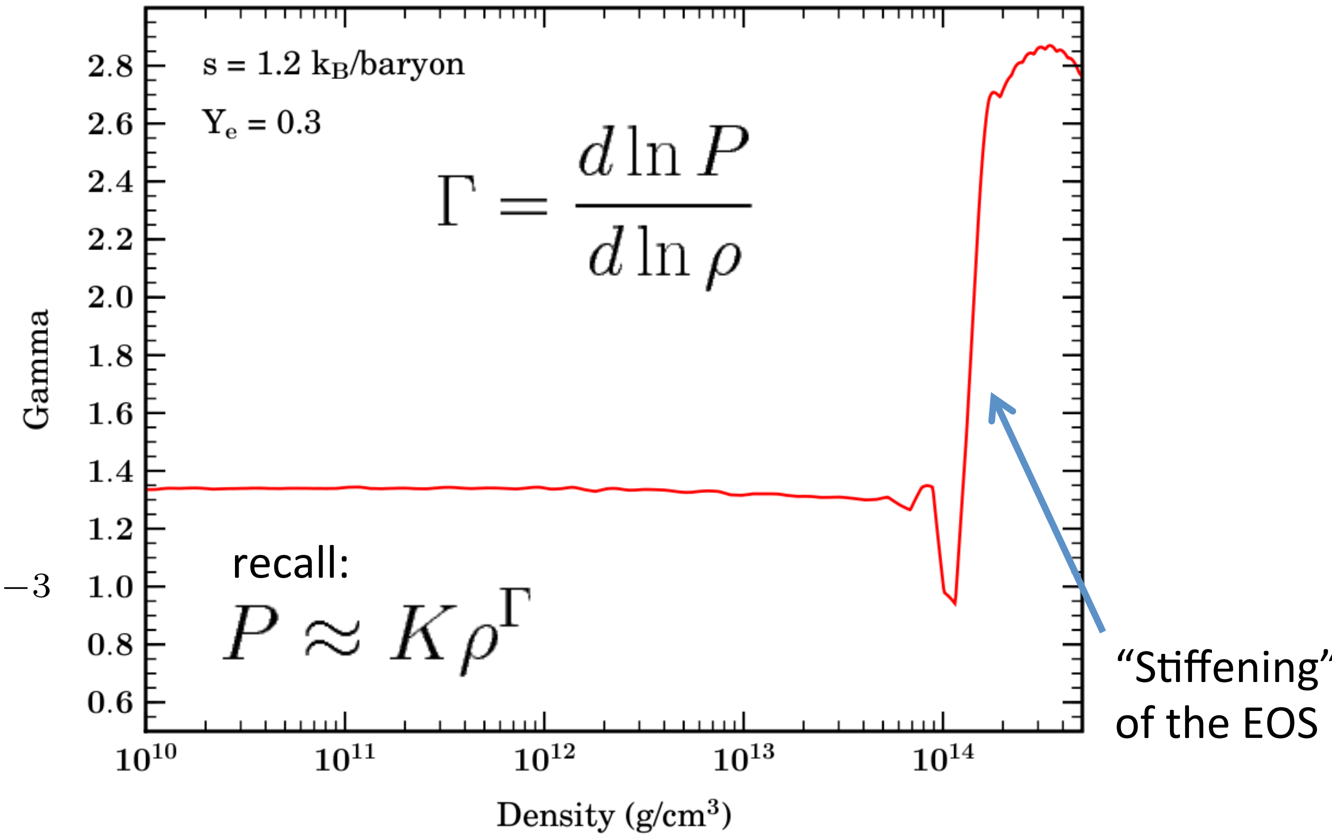
$$R_{\rm nuc} = A^{1/3} r_0$$

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

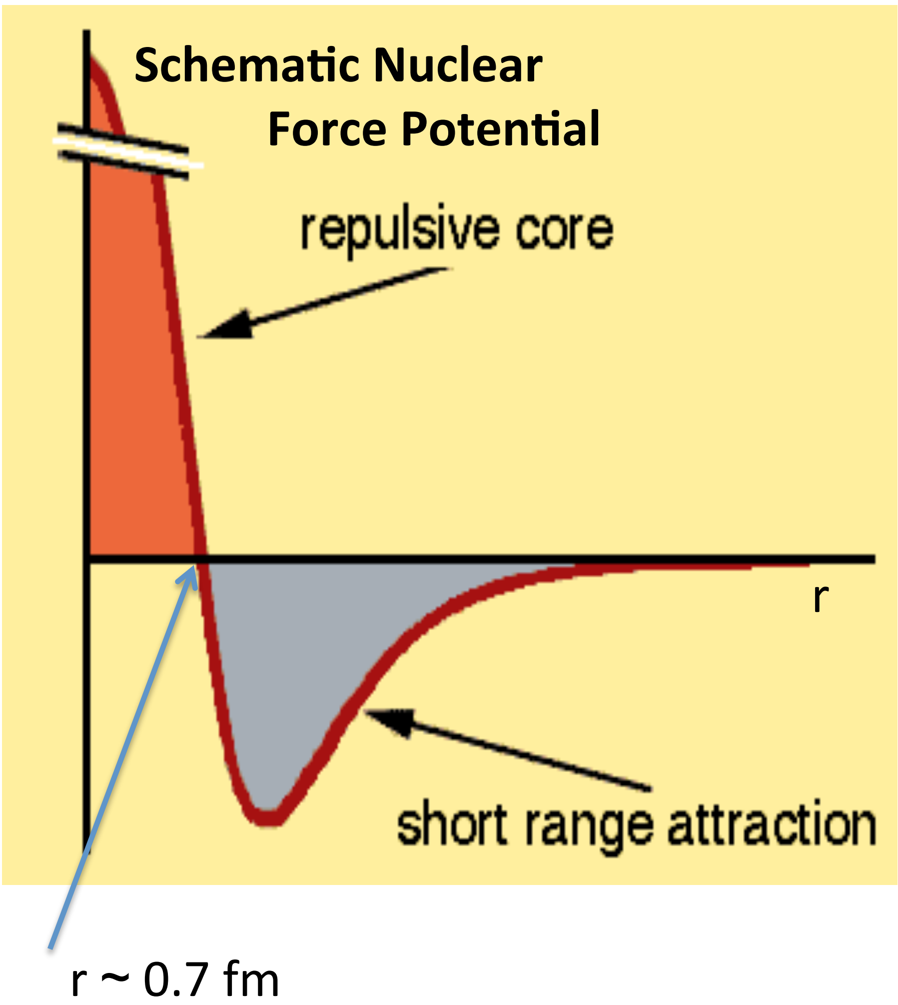
Nuclear Density:

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

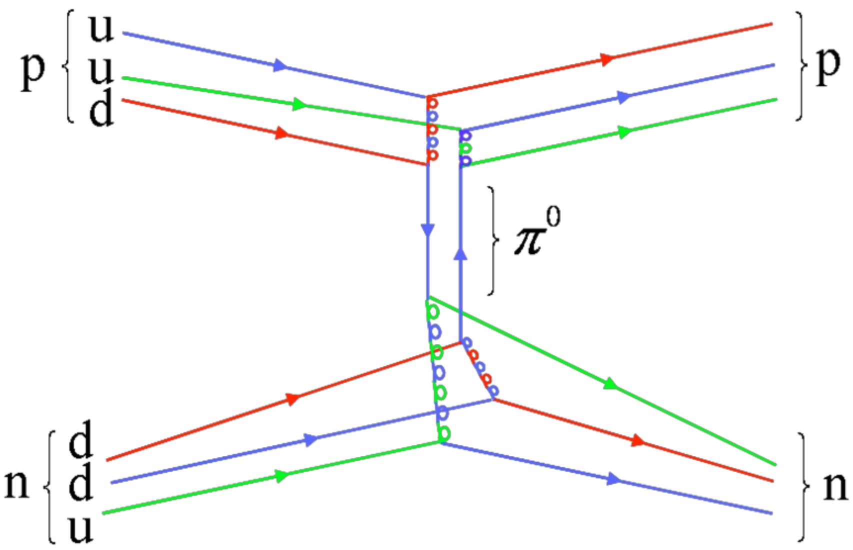
$$\rho_{\rm nuc} \sim 2.7\times 10^{14}\,\mathrm{g\,cm^{-3}}$$



Nuclear Force -> Nuclear Equation of State



- Nucleon-nucleon many-body interaction.
- Consequence of strong force.
- Details unknown.



Nuclear EOS: What happens near ρ_{nuc}?

Nuclear Physics:

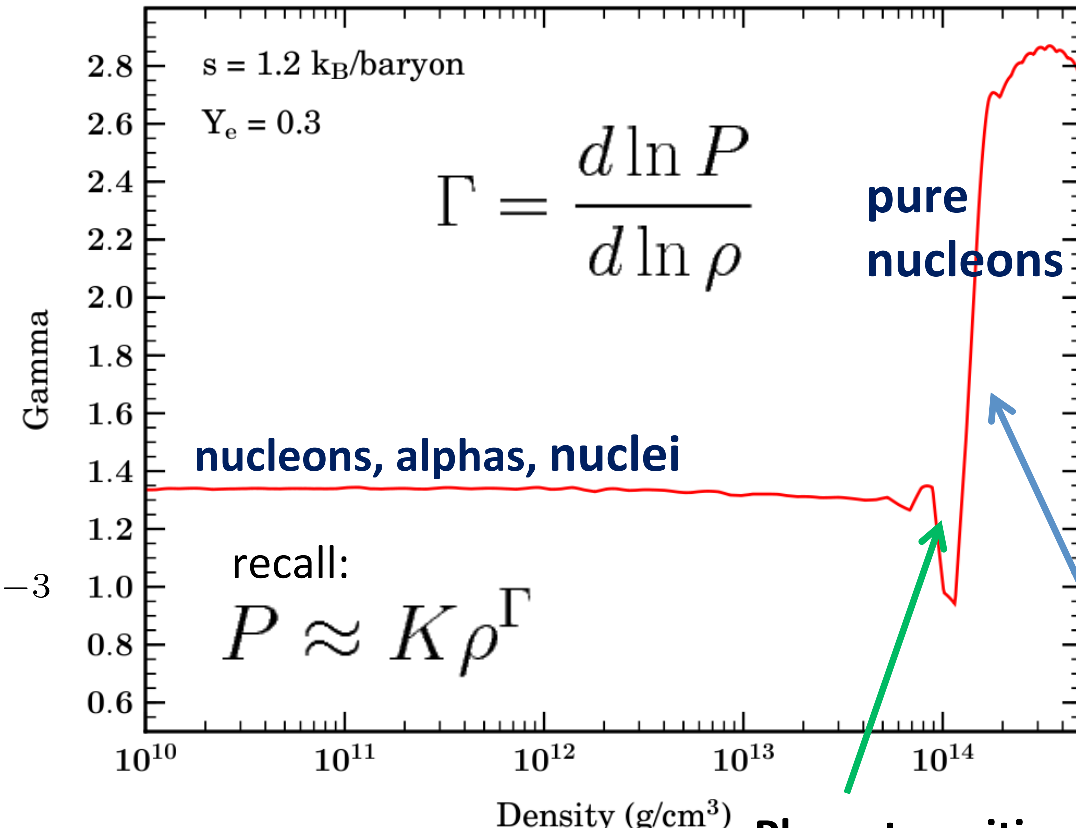
$$R_{\rm nuc} = A^{1/3} r_0$$

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

Nuclear Density:

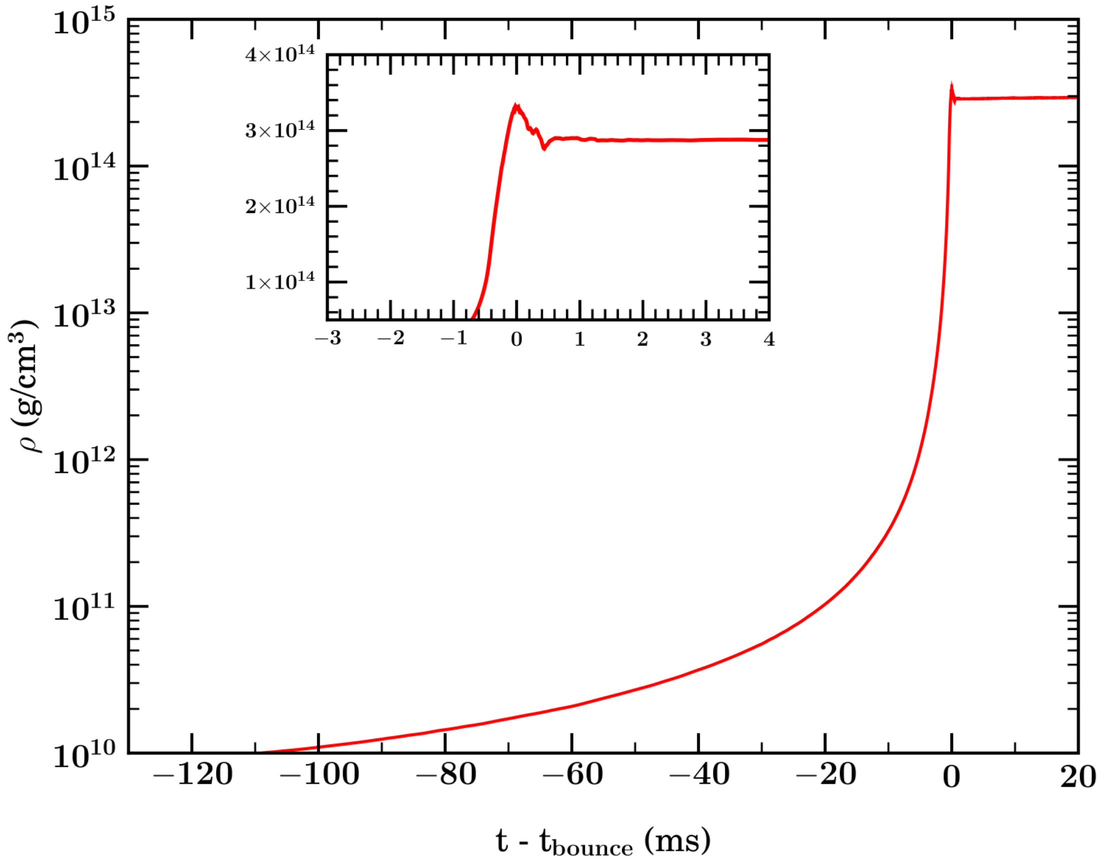
$$\bar{\rho}_{\rm nuc} = \frac{A m_b}{\frac{4}{3}\pi R^3_{\rm nuc}}$$

$$\rho_{\rm nuc} \sim 2.7 \times 10^{14}\,{\rm g\,cm^{-3}}$$



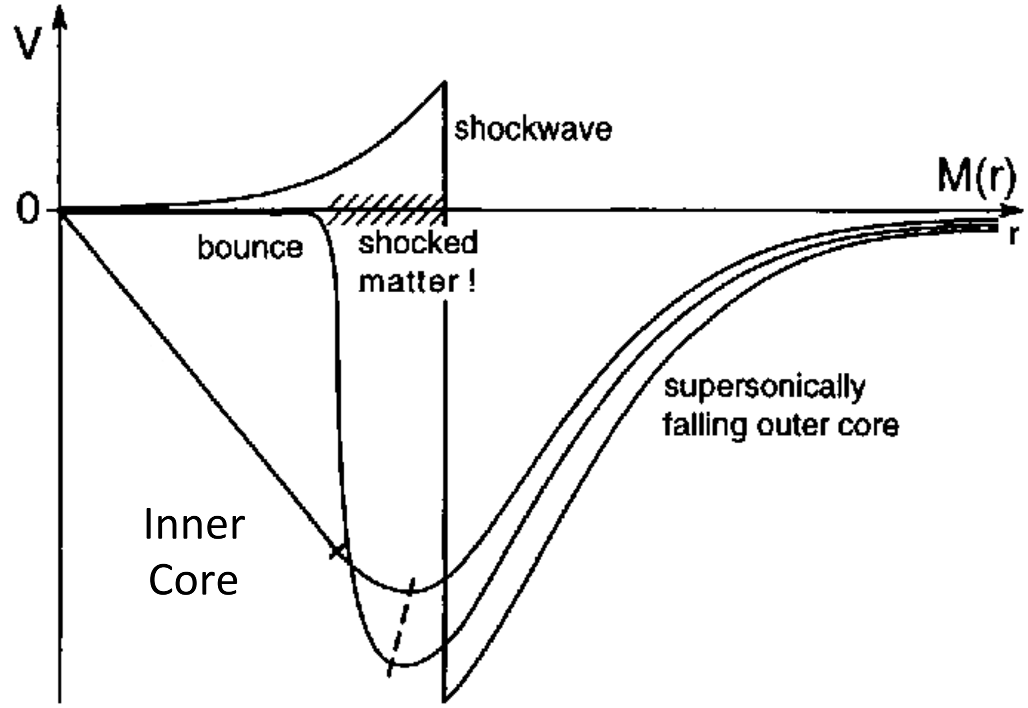
- Above $\approx\rho_{nuc}$: repulsive core

Collapse and Bounce



- **Inner Core** reaches ρ_{nuc}, rebounds ("bounces") **into still infalling outer core**.

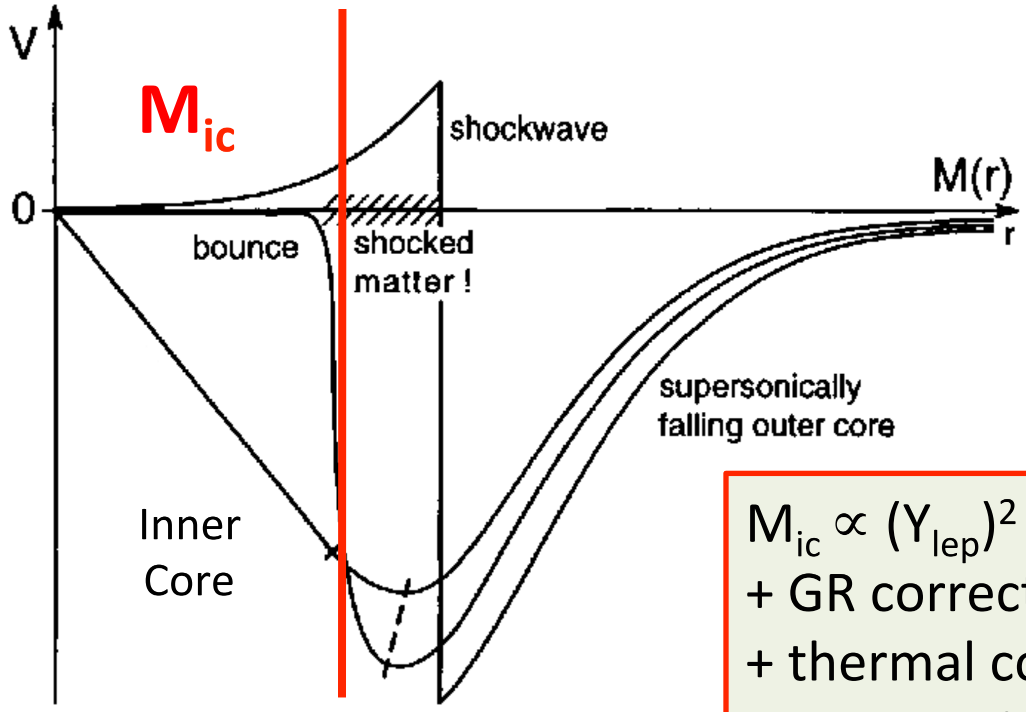
Shock Formation



Credit:
E. Müller
Saas-Fee Lectures 1998

- Stiffening of EOS leads to sound wave that propagates through the inner core and steepens to a shock at the sonic point.

Universality of Core Collapse

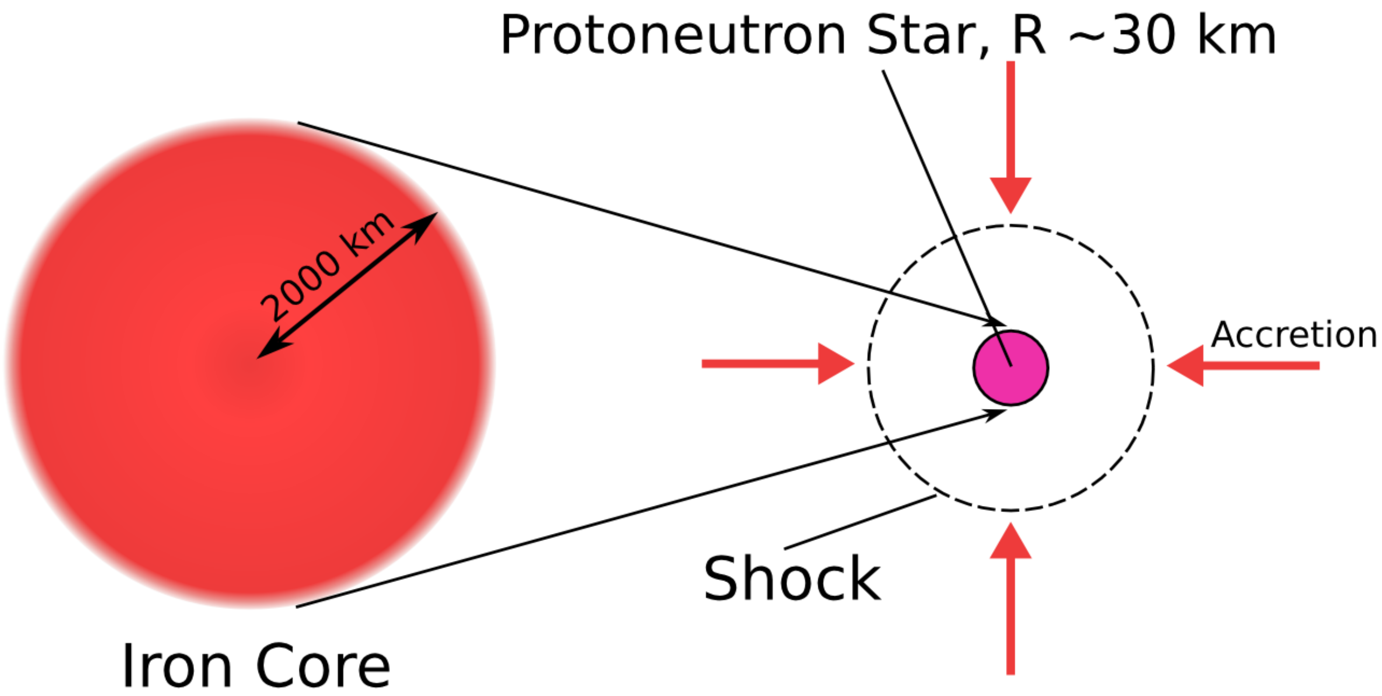


Credit:
E. Müller
Saas-Fee Lectures 1998

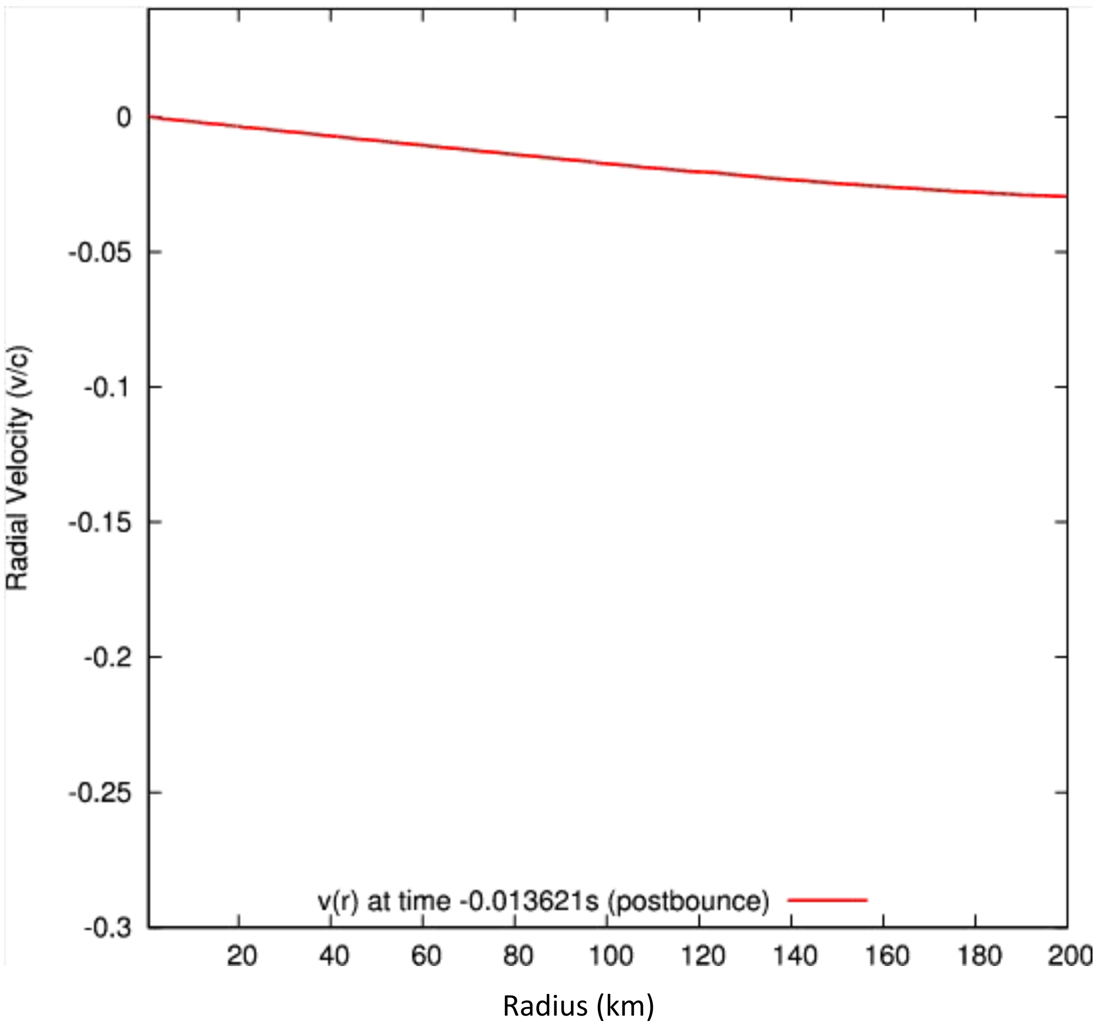
$M_{ic} \propto (Y_{lep})^2$
+ GR correction (-)
+ thermal correction (+)
+ rotation (+)

The Mass M_{ic} of the inner core at bounce is determined by nuclear physics and weak interactions, is ~0.5 M_{SUN}, and is practically independent of progenitor star mass and structure.

Core Bounce and Shock Formation



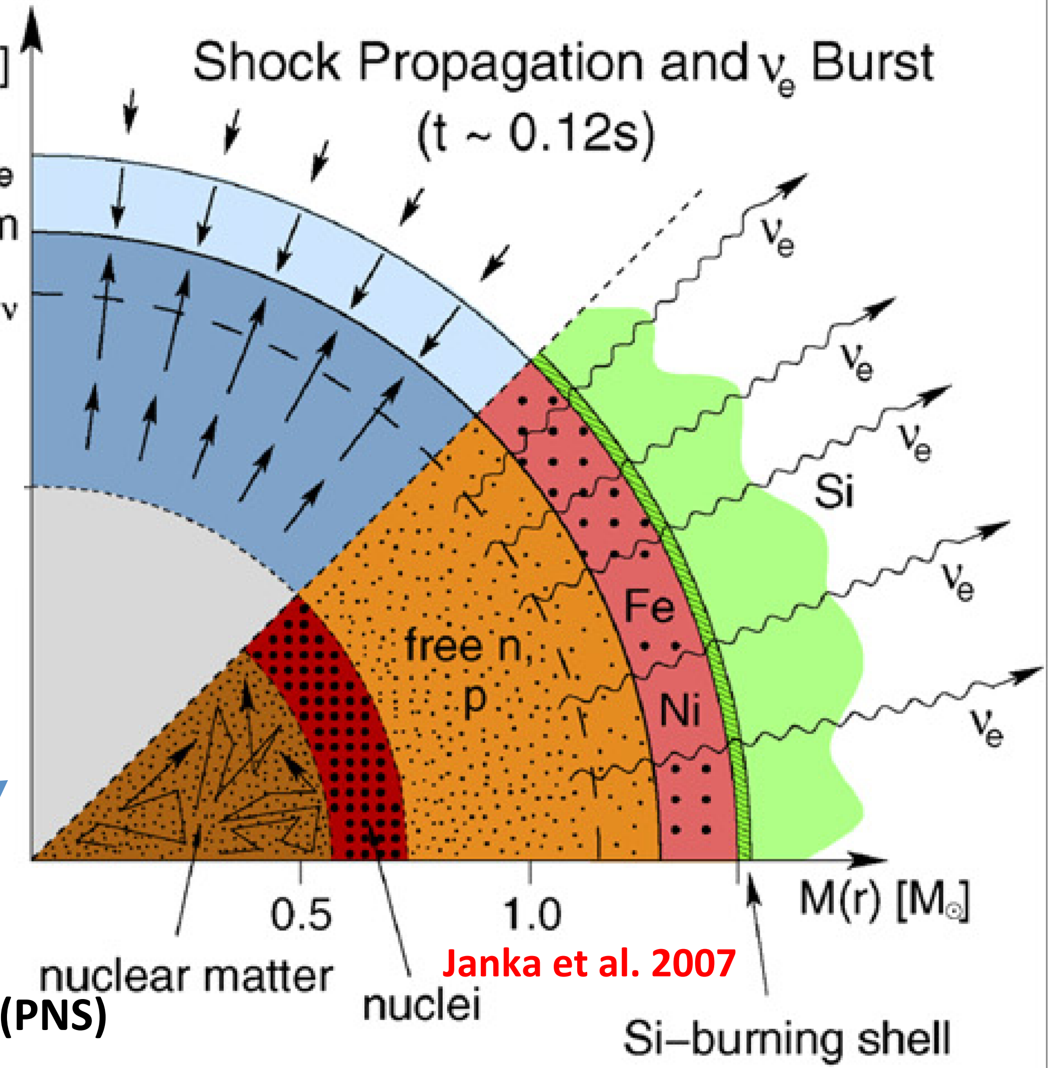
The Supernova Problem



Movie by Evan O'Connor

Why Does the Shock stall?

- Shock loses energy to:
  - Dissociation of infalling heavy nuclei: ~8.8 MeV/baryon -> 17 x 10^{51} erg / $M_\odot$
  - Neutrinos that stream away from behind the shock.



Janka et al. 2007

Inner core -> Core of the proto-neutron star (PNS)

Neutrino Burst

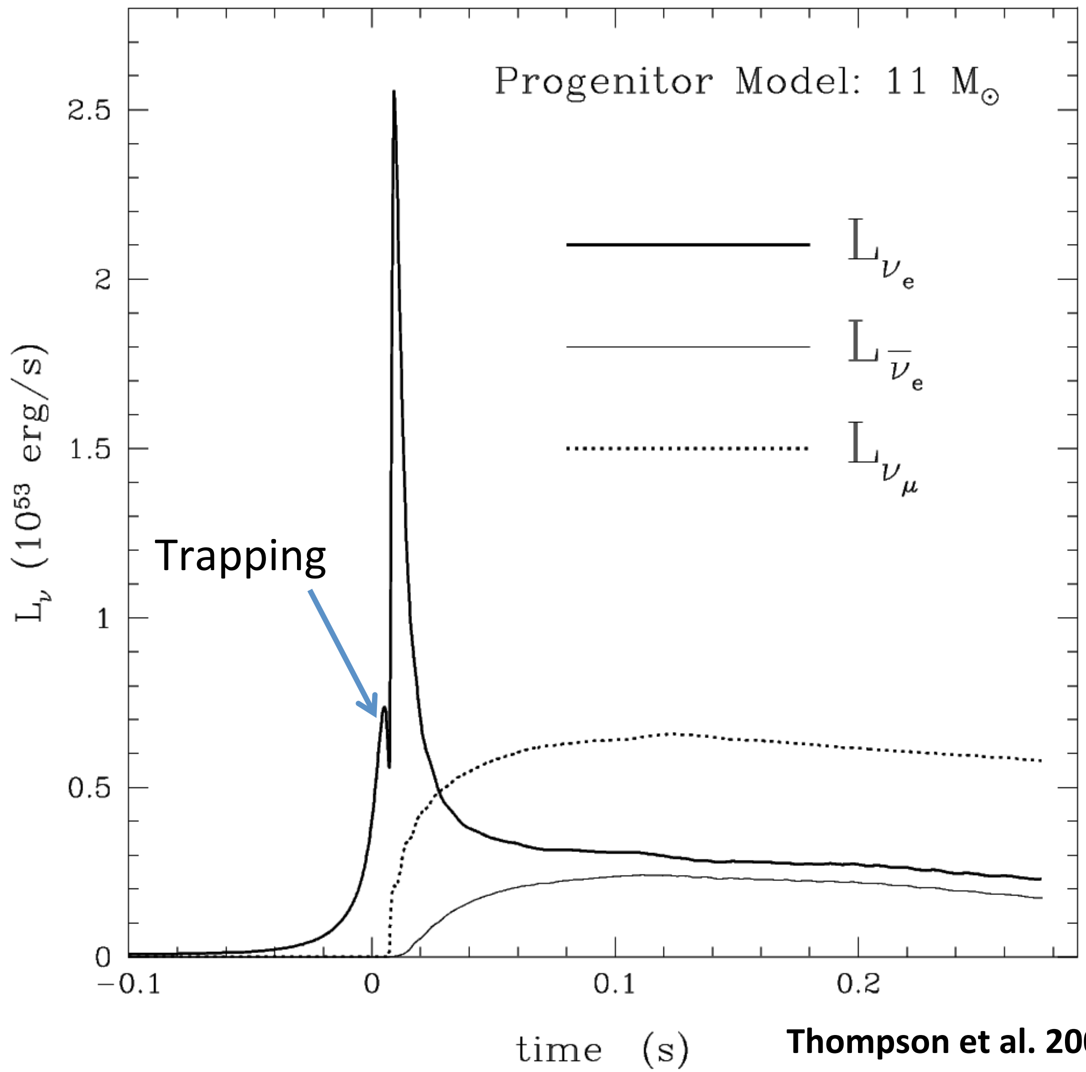
- Optical depth

$$\tau_\nu(r) = \int_\infty^r \frac{1}{\lambda_\nu} dr'$$

- Neutrinosphere:

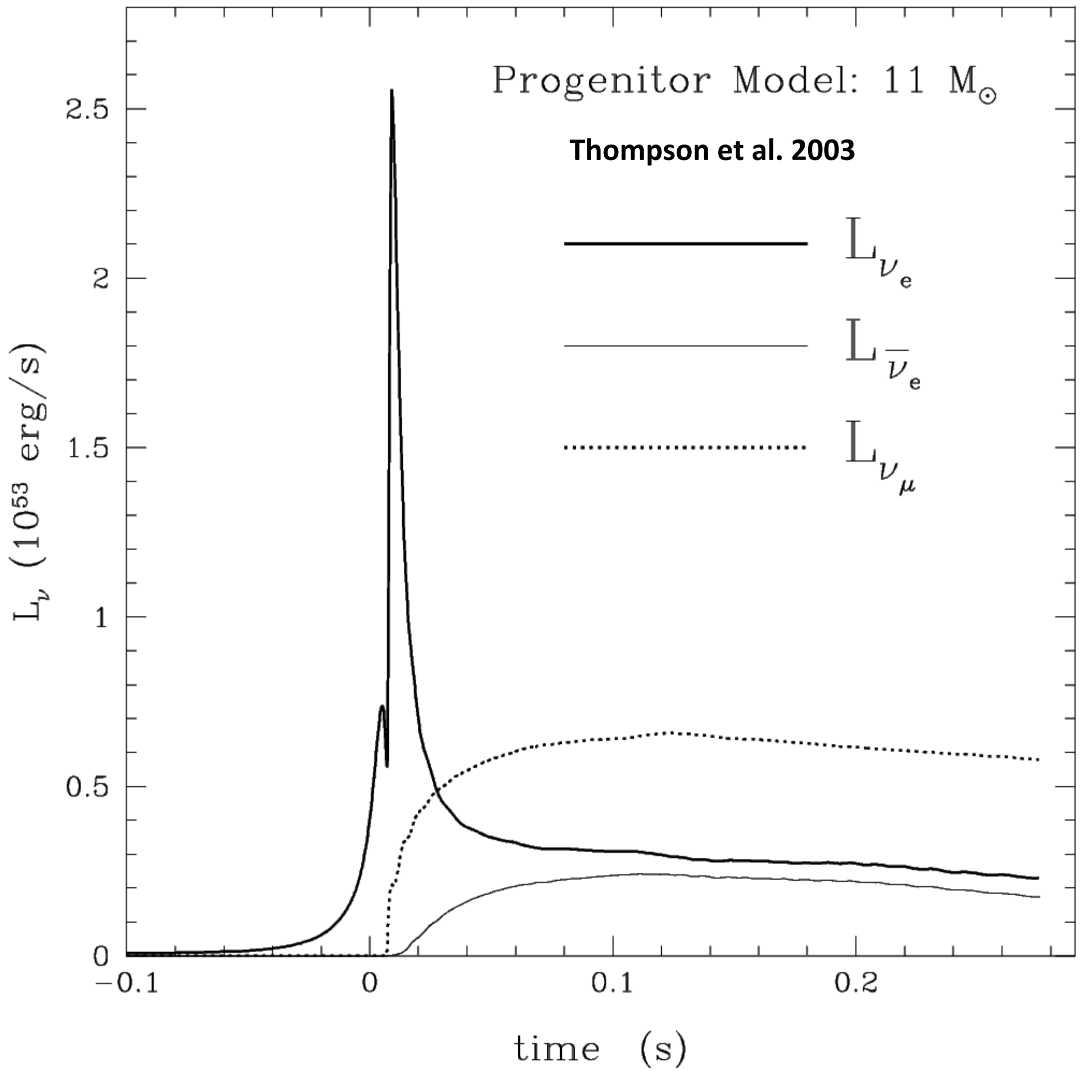
$$R_\nu = R\left(\tau_\nu = \frac{2}{3}\right)$$

Depends on $(\epsilon_\nu)^2$



Thompson et al. 2003

Postbounce Neutrino Emission



- Neutrinos and Anti-neutrinos of ALL species:

$$\nu_e,\ \bar{\nu}_e,\ \text{``}\nu_\mu\text{``} = \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$$

Don't participate in charged-current reactions. Can be treated as 'one'.

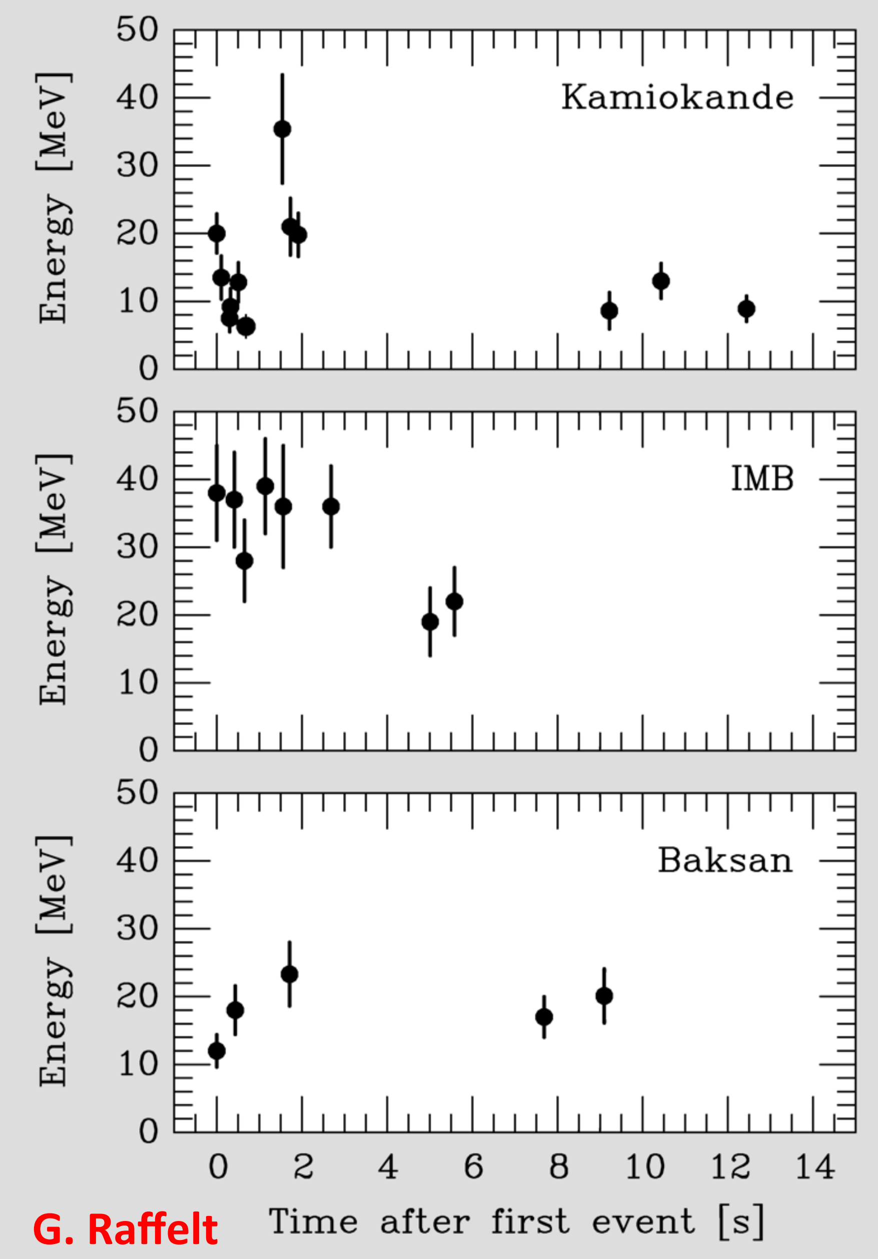
- Emission:

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

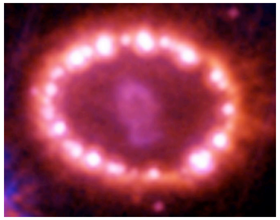
$$e^- e^+ \rightleftharpoons \nu_i \bar{\nu}_i$$
$$NN \rightleftharpoons \nu_i \bar{\nu}_i$$
$$\tilde{\gamma} \rightleftharpoons \nu_i \bar{\nu}_i$$

Pair processes: hot & dense environment needed

- Accretion luminosity and diffusive luminosity.

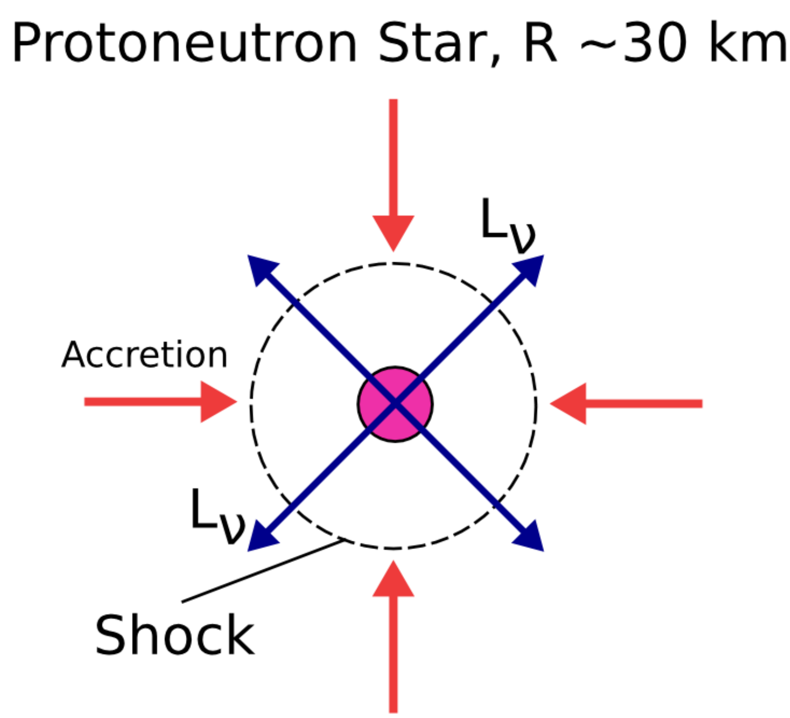


Neutrinos from SN 1987A

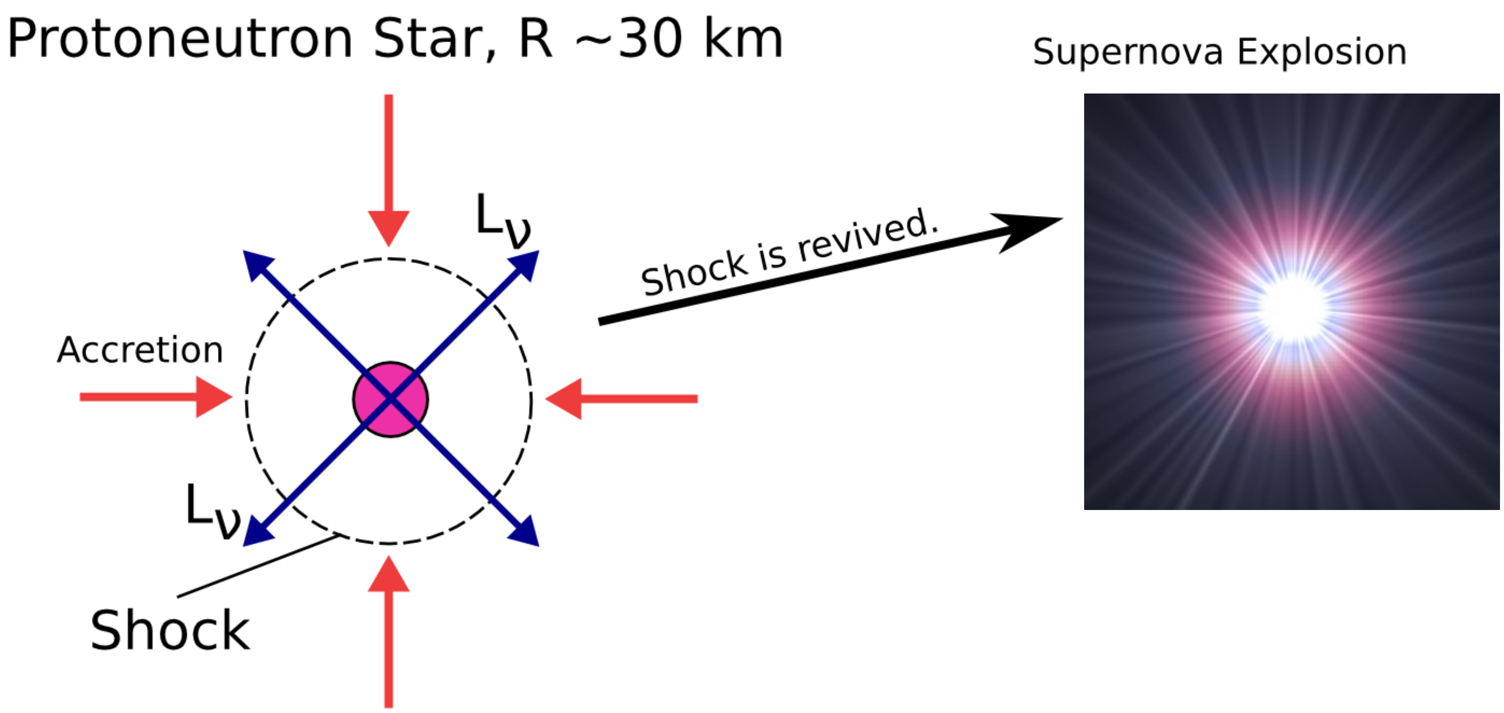


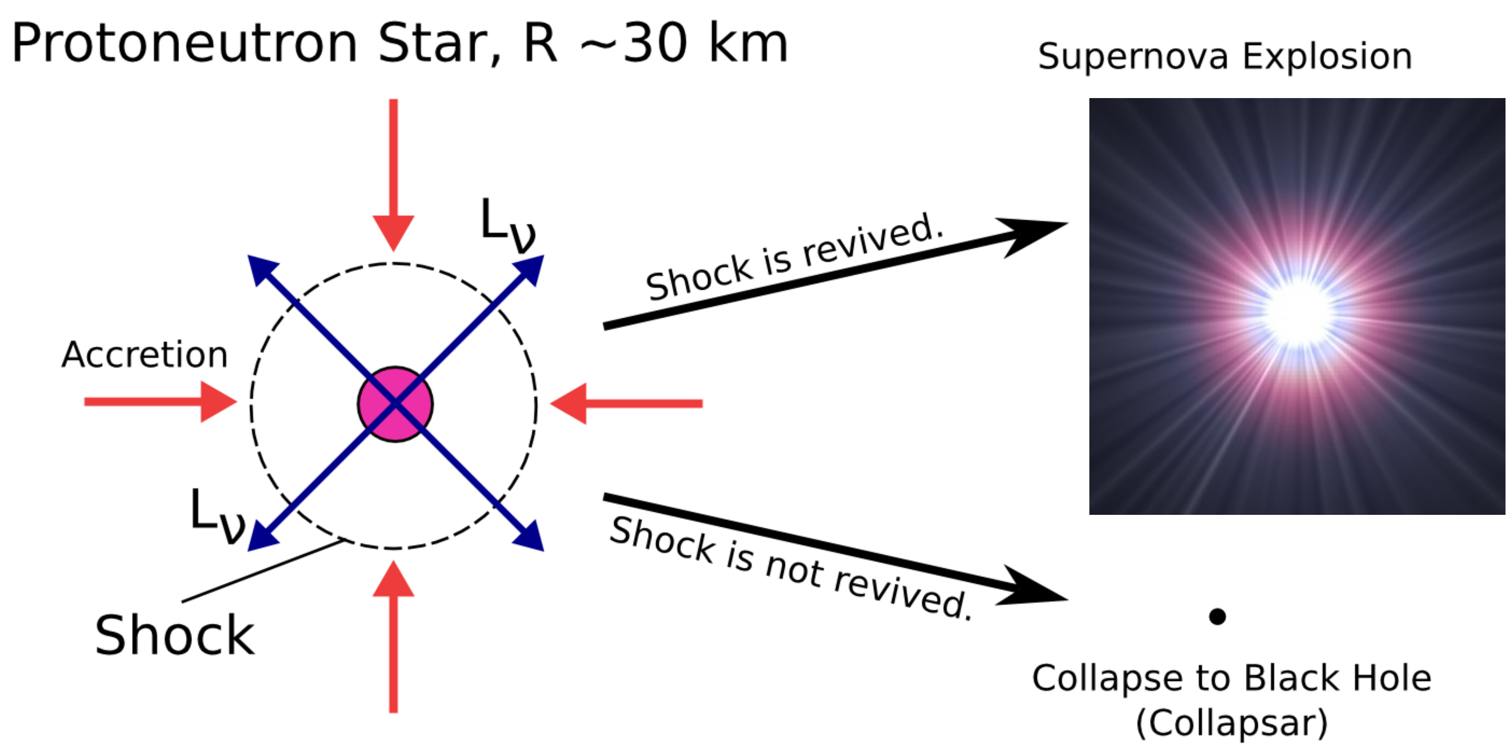
Observed about 20 neutrinos from SN 1987A in the LMC in Kamiokande II (Japan) and IMB (US) experiments.

Confirmation of the basics of core-collapse supernova theory.

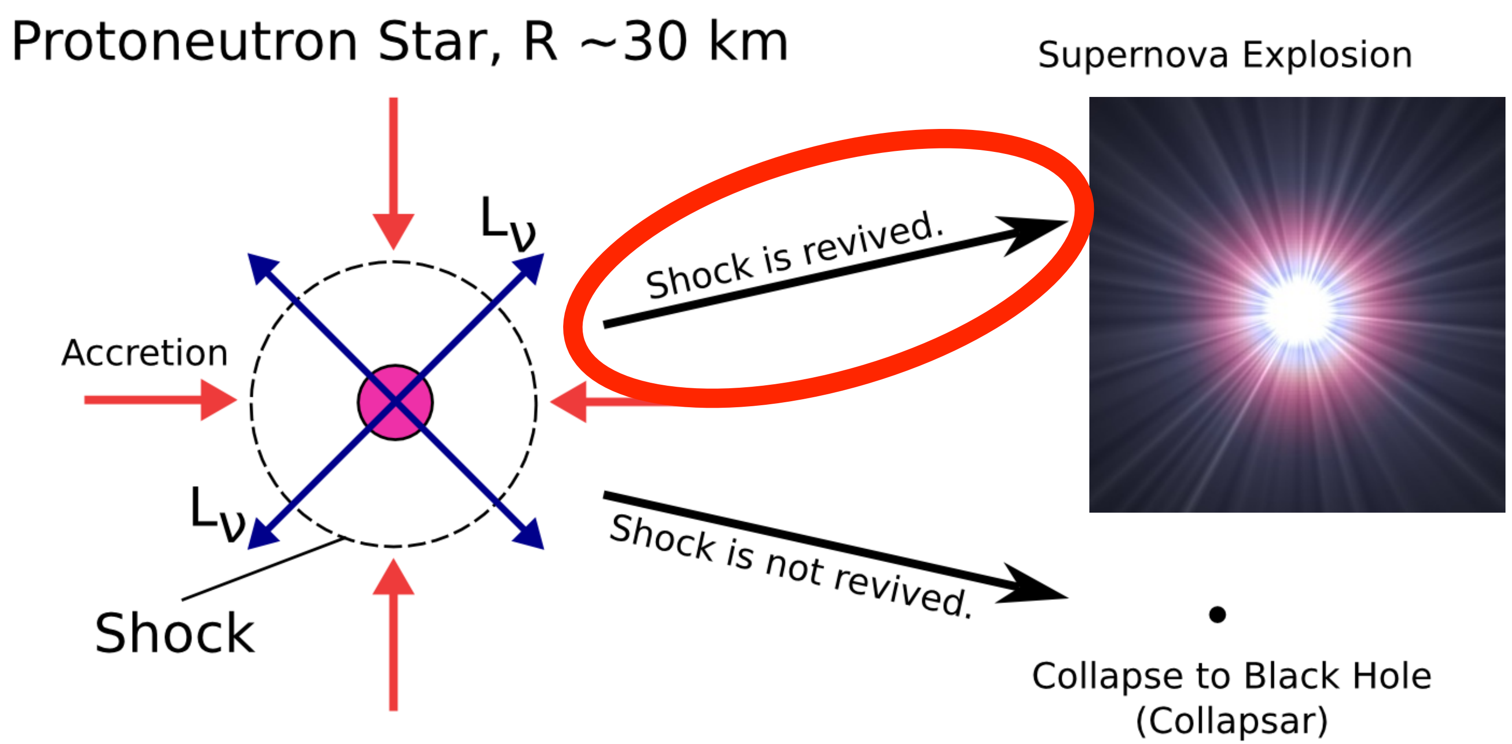

Protoneutron Star, R ~30 km
L_ν
Accretion
L_ν
Shock

The General Picture



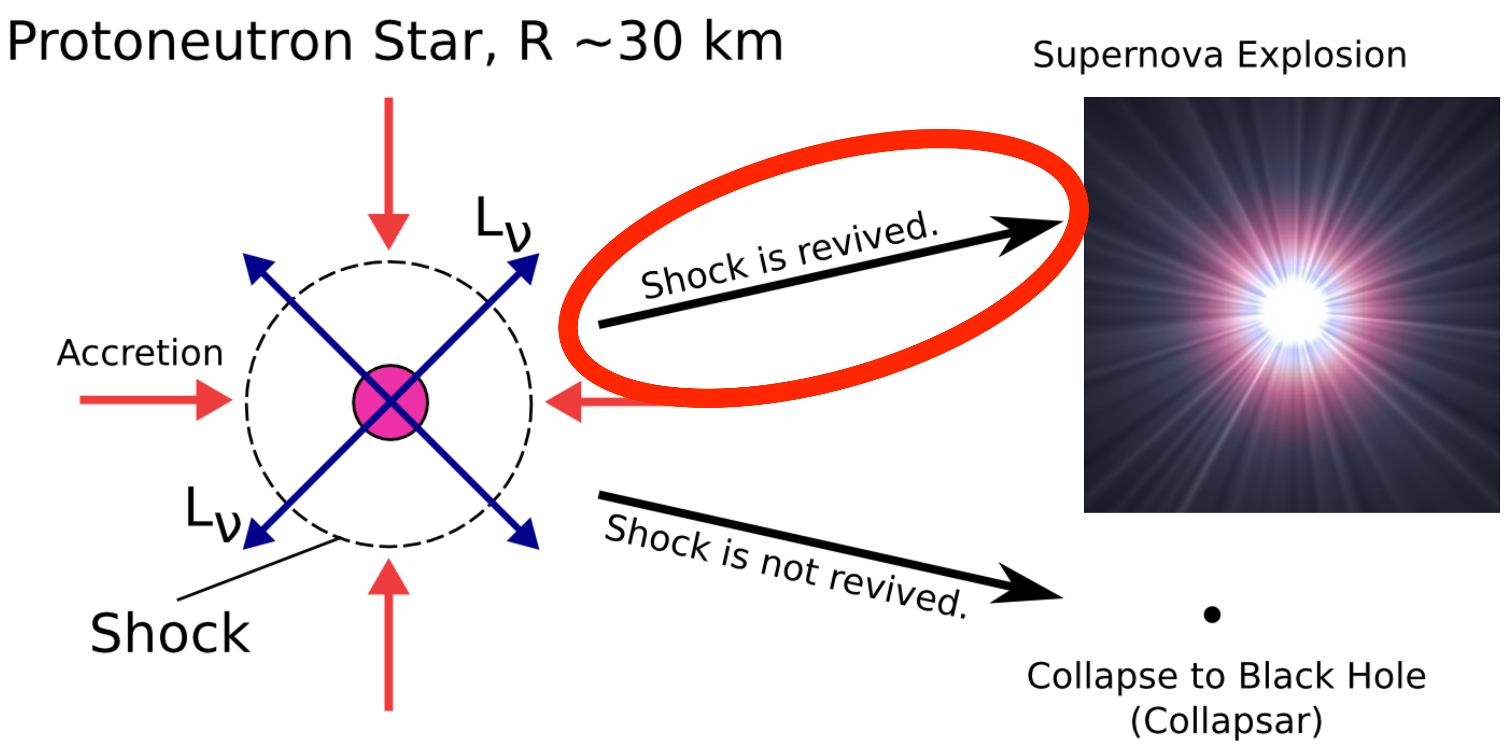

Protoneutron Star, R ~30 km
Supernova Explosion
L_ν
Shock is revived.
Accretion
L_ν
Shock is not revived.
Shock
Collapse to Black Hole
(Collapsar)

The Supernova Problem



What is the Mechanism of shock revival?

The Supernova Problem



What is the Mechanism of shock revival?

The Essence of any Supernova Mechanism

- Collapse to neutron star:
  $\sim 3 \times 10^{53}$ erg = 300 Bethe [B] gravitational energy.

- $\sim 10^{51}$ erg = 1 B kinetic and internal energy of the ejecta.
  (Extreme cases: 10^{52} erg; "hypernova")

- 99% of the energy is radiated as neutrinos over hundreds of seconds as the protoneutron star (PNS) cools.

Explosion mechanism must tap the gravitational energy reservoir and convert the necessary fraction into energy of the explosion.

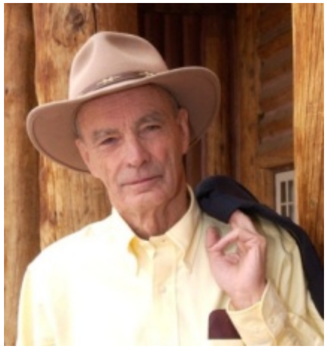
Core-Collapse Supernova Models

Fully coupled!

Magneto-Hydrodynamics / Plasma Physics	→	Dynamics of the stellar fluid.
General Relativity	→	Gravity
Nuclear and Neutrino Physics	→	Nuclear EOS, nuclear reactions & ν interactions.
Transport Theory	→	**Neutrino transport**.

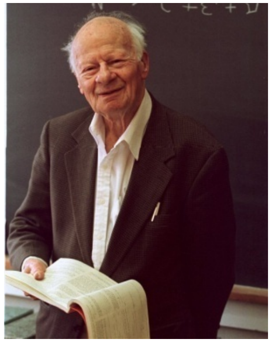
- Additional Complication: **Supernovae are 3D**
  - Rotation, **fluid instabilities** (convection, turbulence, advective-acoustic, rotational), **MHD dynamos**, precollapse multi-D perturbations.
    -> **Need multi-D (ideally 3D) treatment.**
- Route of Attack: **Computational Modeling**
  - First 1D computations in the late 1960's: **Colgate & White, Arnett, Wilson**
  - Best current simulations still 1D.
  - **Good 2D Models (with various approximations [Gravity/Transport]).**
  - **First 3D Models.**

Supernova Mechanism: First Simulations



Stirling Colgate

Dave Arnett



Hans Bethe

Jim Wilson

Colgate & White 1966

Arnett 1966

Bethe & Wilson 1985

- No supercomputers yet (Cray-I only in 1976!): Limited to spherical symmetry, low resolution, poor neutrino transport.
- Nevertheless: Very important discovery -> **Energy deposition by neutrinos may revive/drive the shock**.

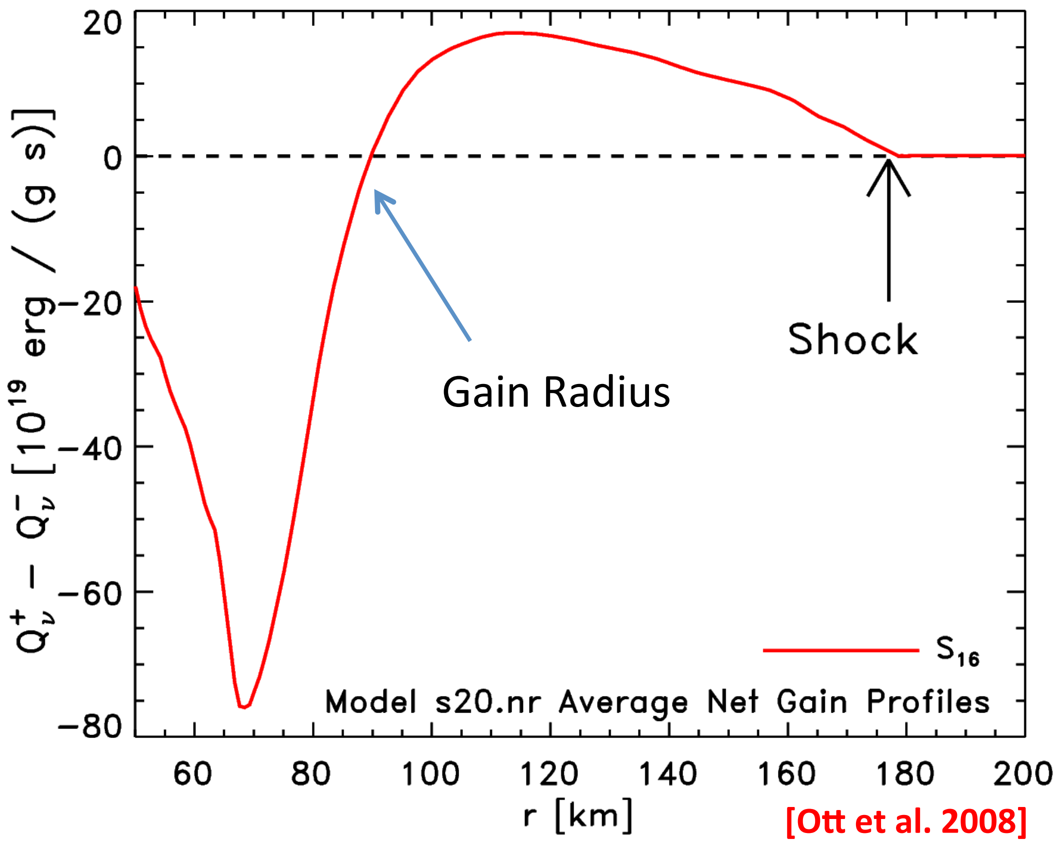
The Neutrino Mechanism

Neutrino cooling: $Q_\nu^- \propto T^6$

Neutrino heating: $Q_\nu^+ \propto L_\nu r^{-2} \langle \epsilon_\nu^2 \rangle$

Net heating where: $Q_\nu^+ > Q_\nu^-$

- Neutrino-driven mechanism: Based on subtle imbalance between neutrino heating and cooling in postshock region.



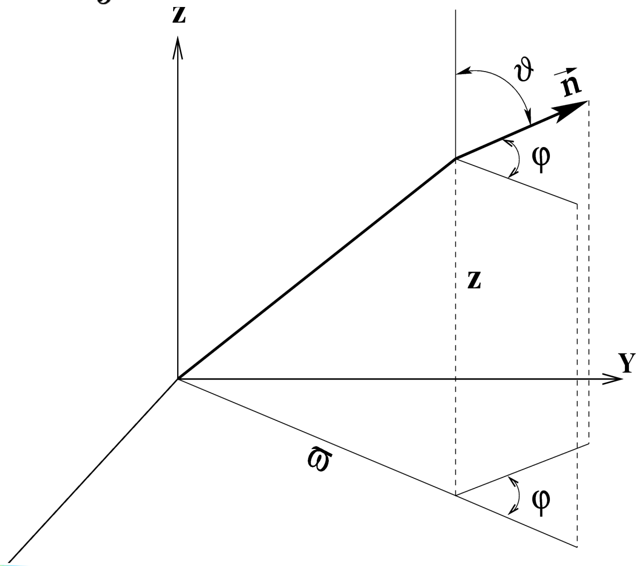
[Ott et al. 2008]

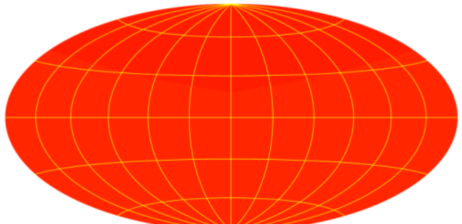
A few Words on Neutrino Transport

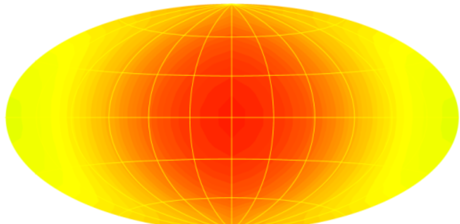
$$\frac{1}{c}\frac{\partial I(\vec{r},\vec{n},\epsilon_\nu)}{\partial t} + \vec{n}\,\vec{\nabla} I(\vec{r},\vec{n},\epsilon_\nu) = \Xi[I(\vec{r},\vec{n},\epsilon_\nu),\rho,T,Y_e]$$

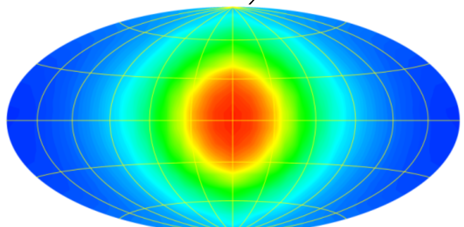
$$J = \frac{1}{4\pi}\oint I d\Omega \qquad \vec{H} = \frac{1}{4\pi}\oint \vec{n} I d\Omega \qquad \mathbf{K} = \frac{1}{4\pi}\oint \vec{n}\cdot\vec{n}\, I d\Omega$$

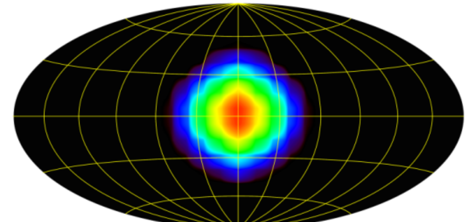
- 6D problem: 3D space, 3D (ϵ, θ, ϕ) momentum space.
- Limiting cases – easy to handle:
  (1) Diffusion (isotropic radiation field)
  (2) Free streaming ("forward-peaked" radiation field)




30 km


60 km

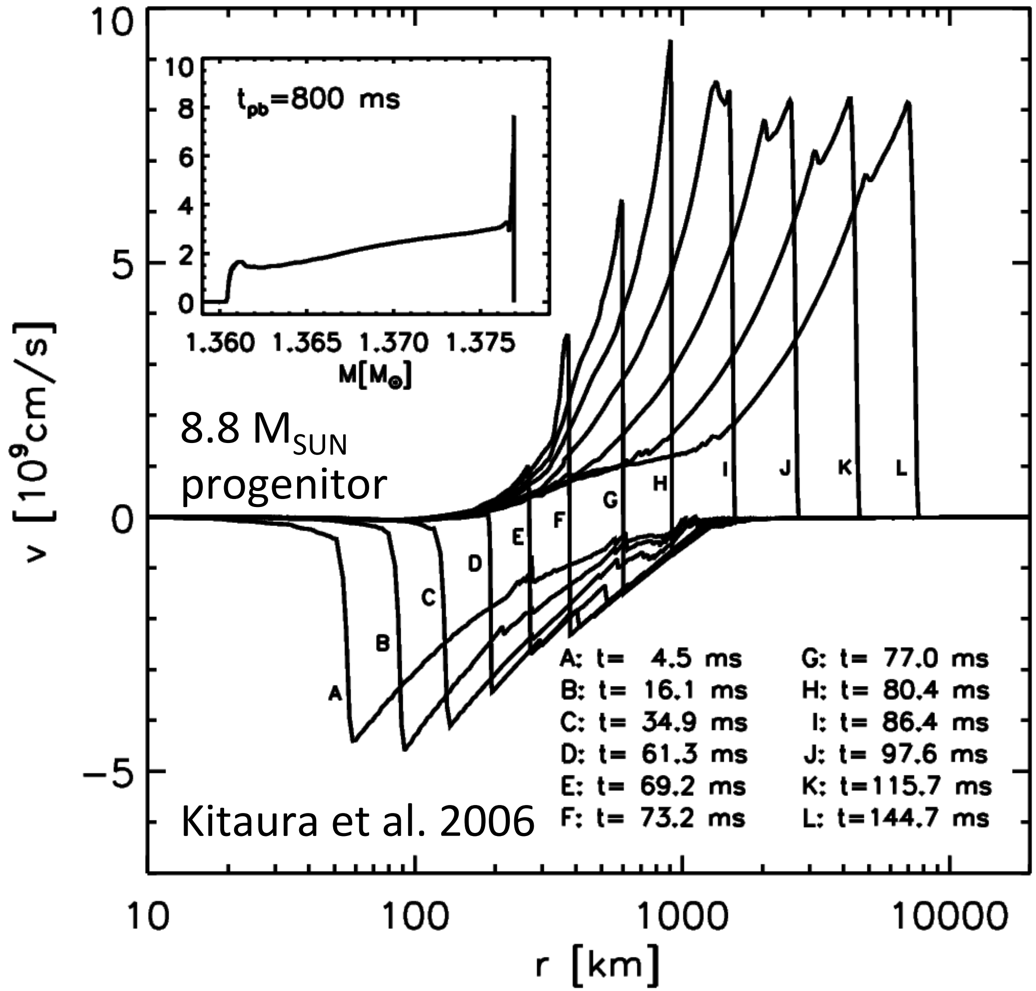

120 km


240 km

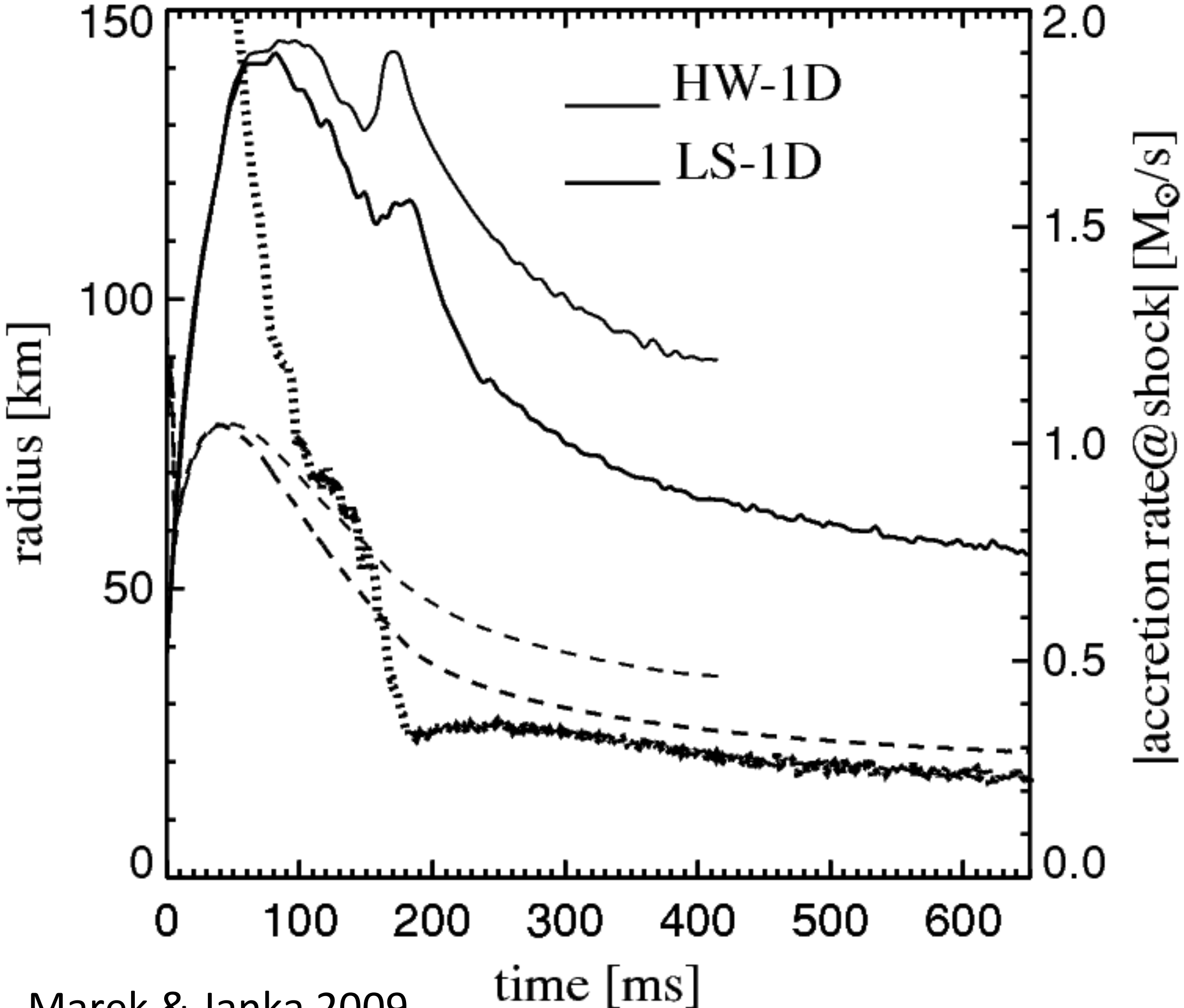
Does it work?

- **Yes!**
  BUT:
  Only for lowest-mass massive stars.
  (Kitaura et al. 2006, Burrows 1988, Burrows, Livne, Dessart 2007)

- **FAILS in spherical symmetry (1D) for more massive stars** in simulations with best neutrino physics and neutrino transport



Failure of the Neutrino Mechanism in 1D



Marek & Janka 2009

End of Lecture I

This Afternoon:

- Supernova Models & Mechanisms
- Probes of the Mechanism and Supernova Physics: Neutrinos and Gravitational Waves
- Neutron stars and Astrophysical Constraints on the Nuclear Equation of State.