The Physics of Stellar Collapse (and GR Hydrodynamics)

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Outline

Part 1 (a not so big picture overview)

- Core-Collapse Supernova Basics
- The Supernova Problem & Supernova Mechanisms

Part 2

- When things don’t work out: BH formation and what not...
- GR hydrodynamics
- **`GRHydro`**, the Einstein Toolkit 3D hydro code.
- **`GR1D`**

For more details...

- H. Bethe, *Supernova mechanisms*, Rev. Mod. Phys. 62:4, 1990
- H.-T. Janka, *Conditions for shock revival by neutrino heating in core-collapse supernovae*, A & A, 368:527, 2001
- H.-T. Janka et al., *Theory of core-collapse supernovae*, Physics Reports 442, 38

Betelgeuse as seen by the HST, D ≈ 200 pc

Rigel, D ≈240 pc

Supernova Explosion

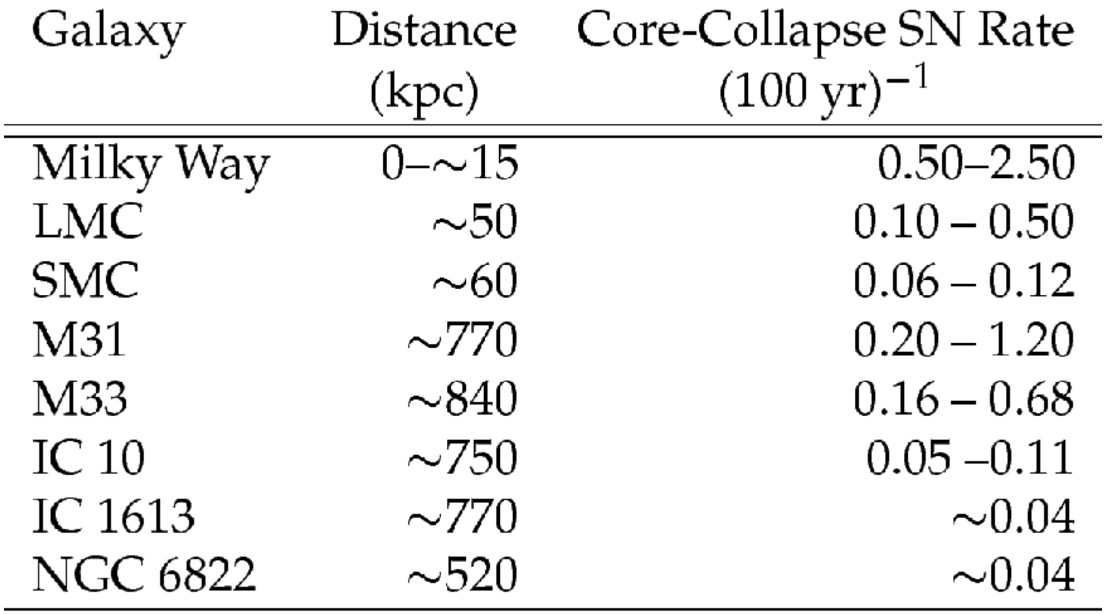
SN1987A, LMC, D ≈ 51.4 kpc
Progenitor: BSG Sanduleak -69° 220a, 18 M_{SUN}

Betelgeuse as seen by the HST, D ≈ 200 pc

Rigel, D ≈240 pc

Core-Collapse Supernova Rates

- Local group of galaxies: V ~ 30 Mpc^3
- Milky Way, Andromeda (M31), Triangulum (M33)
  + ~30 small galaxies/satellite galaxies (incl. SMC & LMC).



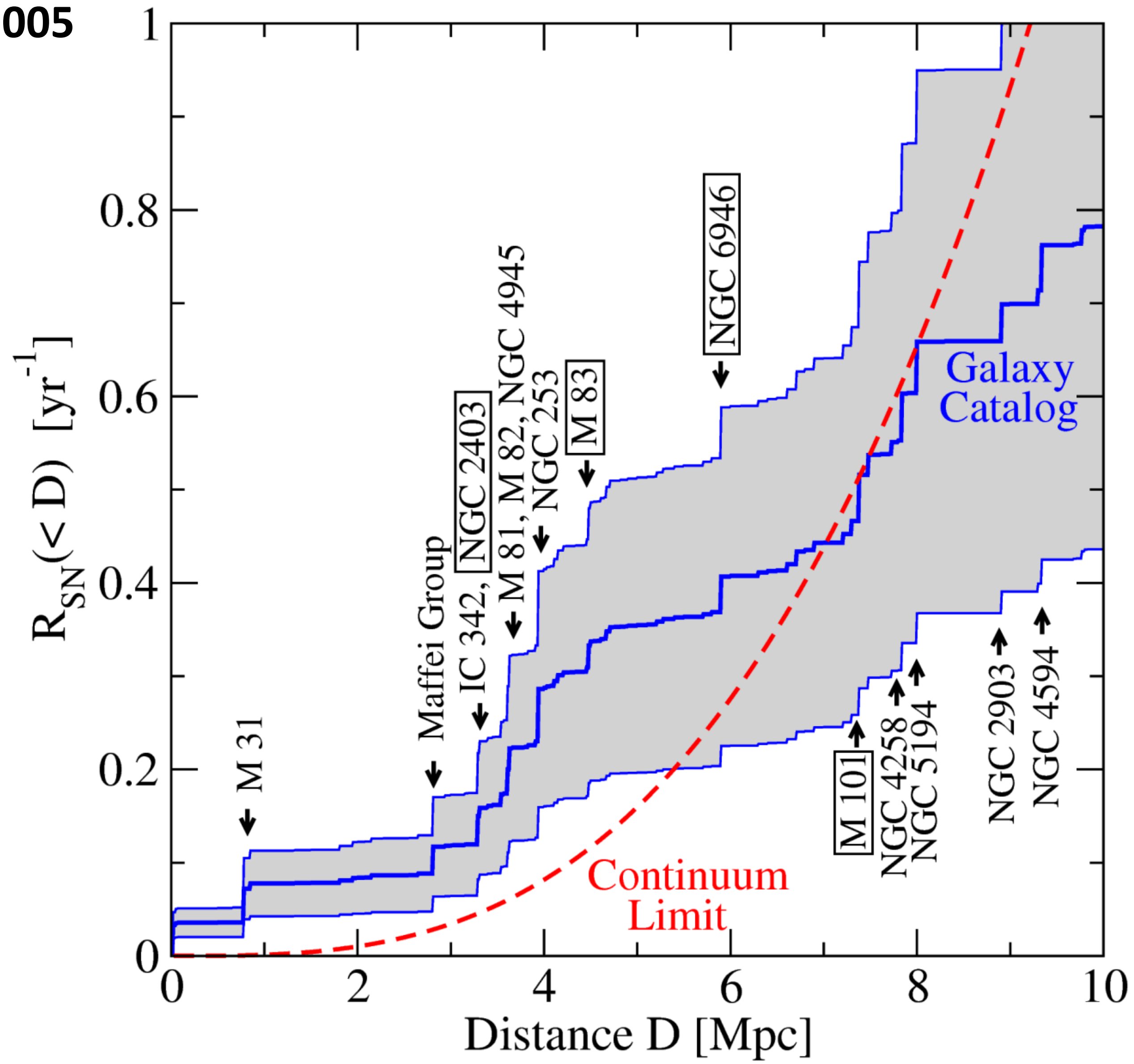
Galaxy	Distance (kpc)	Core-Collapse SN Rate $(100\ \mathrm{yr})^{-1}$
Milky Way	0–~15	0.50–2.50
LMC	~50	0.10 – 0.50
SMC	~60	0.06 – 0.12
M31	~770	0.20 – 1.20
M33	~840	0.16 – 0.68
IC 10	~750	0.05 –0.11
IC 1613	~770	~0.04
NGC 6822	~520	~0.04

Compiled from
long list of references,
e.g. Cappellaro et al.,
den Bergh & Tammann.

- Local group: worst case 1 SN in 90 years, best case 1 SN in 20 years.
- Most local group events with ~100 kpc from Earth.
- Next jump in rate around M82 at 3.5 Mpc.

Core-Collapse Supernova Ratees

Ando et al. 2005



Massive Stars and Their Evolution

- Mass: $\sim 7\ M_{SUN} \leq M \leq \sim 130\ M_{SUN}$.

Nuclear Burning:

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

$M < \sim 7\ M_{SUN}$

Envelope ejection

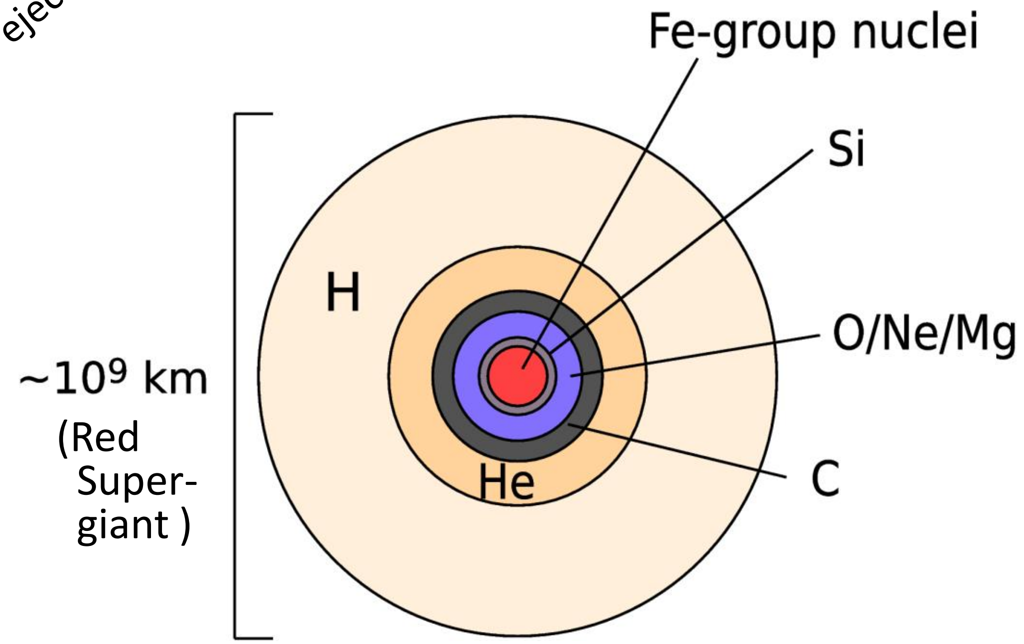
C-O White Dwarf

$\sim 7\ M_{SUN} < M < \sim 10\ M_{SUN}$

Envelope ejection

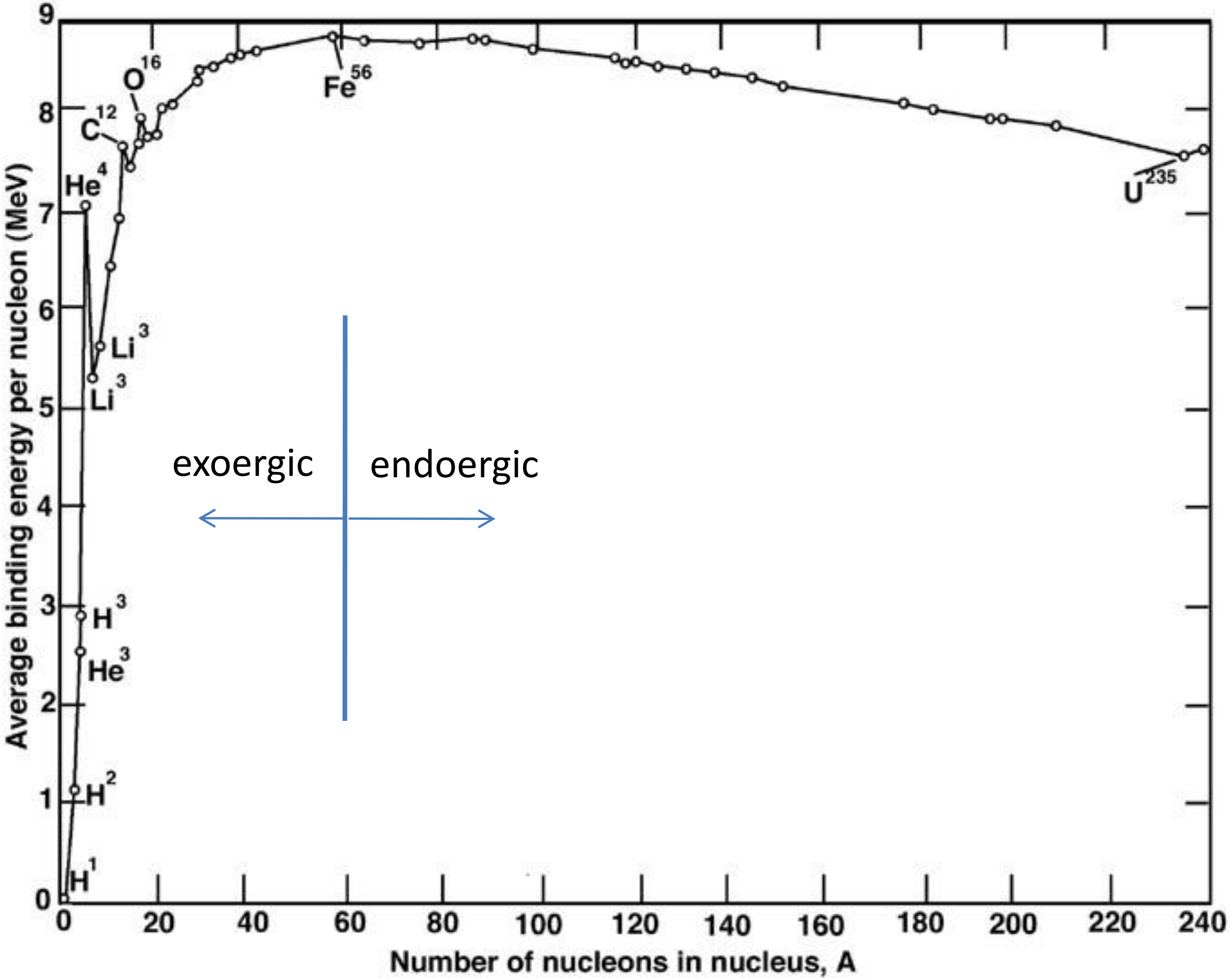
O-Ne White Dwarf

$M > \sim 10\ M_{SUN}$



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

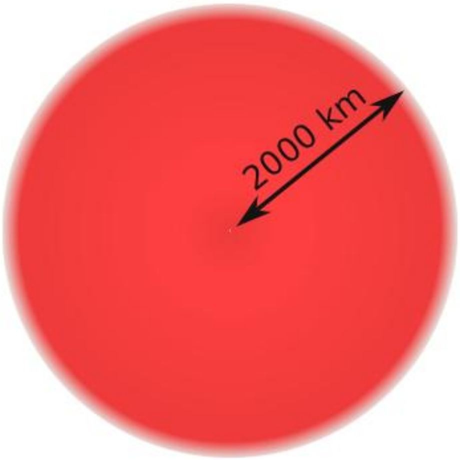
The End of Nuclear Fusion



exoergic

endoergic

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)

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

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

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

Radiation pressure:

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

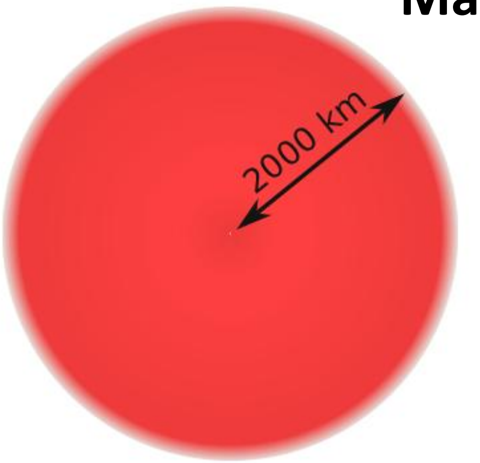
Electrons: degenerate and relativistic

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

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

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

Chandrasekhar Mass



Iron Core

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

$T \approx 1$ MeV

$Y_e \approx 0.5$

(in reality: T lower and Ye slightly lower)

Maximum mass for a relativistically degenerate object:

$$M_{\mathrm{Ch}} \approx 5.8 (Y_e)^2 M_\odot$$

+ 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

Electron Capture

Simplest case: Capture on free protons, neutrinos escape

$$e^- + p \overset{(W)}{\longrightarrow} \nu_e + n \qquad \mu_{\nu_e} = 0$$

capture if $\mu_e > \mu_n - \mu_p$

At zero T, non-degenerate nucleons:

$$\mu_e > 939.565\,\mathrm{MeV} - 938.272\,\mathrm{MeV} = 1.293\,\mathrm{MeV}$$

In core collapse: Capture typically at μ_e ~ >10 MeV -> excess energy given to ν.

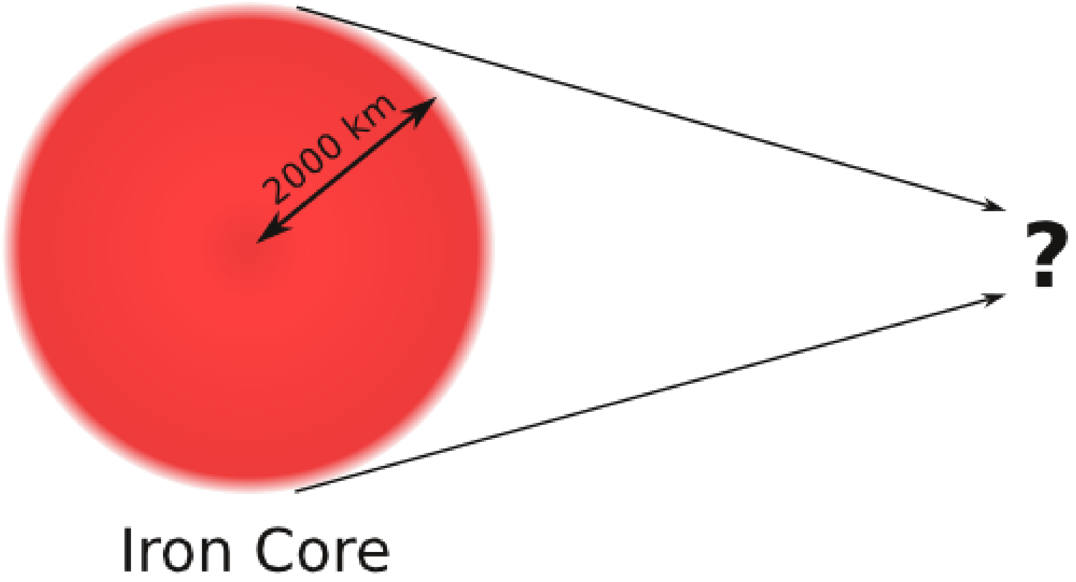
Capture rates: (see, e.g., Bethe et al. 1979, Bethe 1990, Burrows, Reddy & Thompson 2006)

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

Complications:

- Capture on nuclei more complicated; can be blocked due to neutron shells filling up.
- Pauli blocking of low-energy states, since neutrinos don’t exactly leave immediately.

Collapse



More Collapse Physics

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**

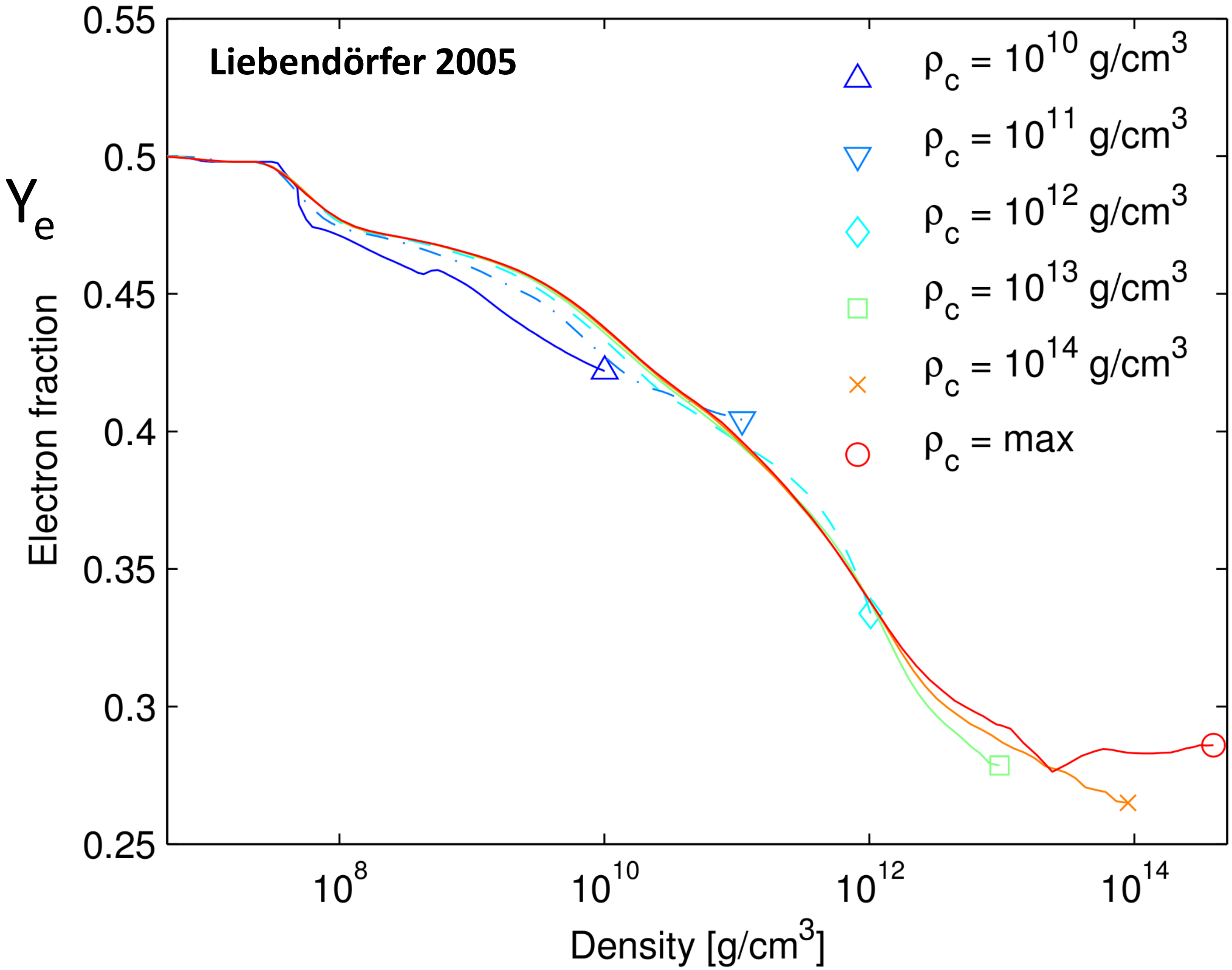
$$e^- + (Z, A) \overset{(W)}{\longrightarrow} \nu_e + (Z-1, A)$$

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

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

- 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} >> time between collisions τ_{coll} -> **neutrinos become trapped in the collapsing core.**

- **Consequences**:

Deleptonization stopped

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

Detailed simulations:

$$Y_{\mathrm{lep}} \approx 0.32$$

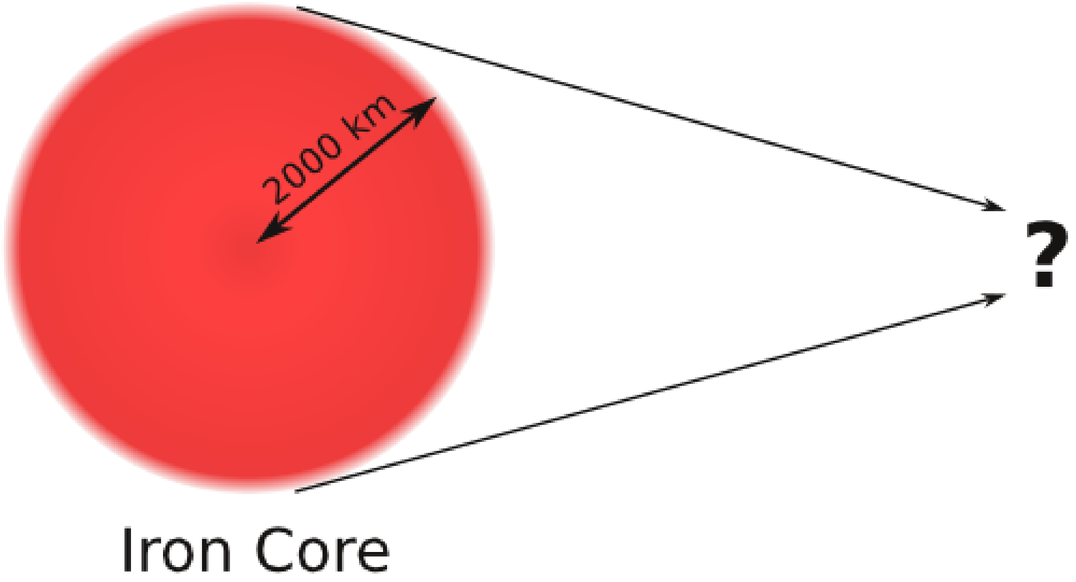
Beta Equilibrium

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

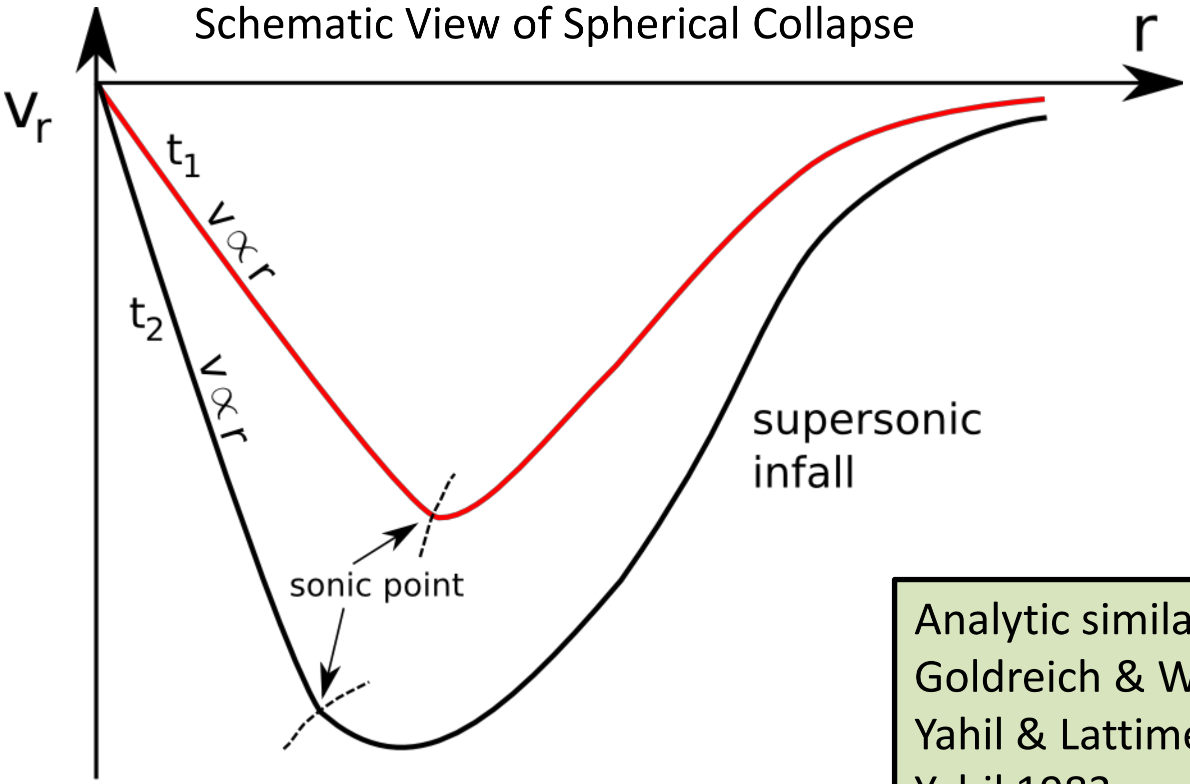
$$\mu_e + \mu_p = \mu_\nu + \mu_n$$

Collapse

still collapsing...



Self-Similarity in Stellar Collapse

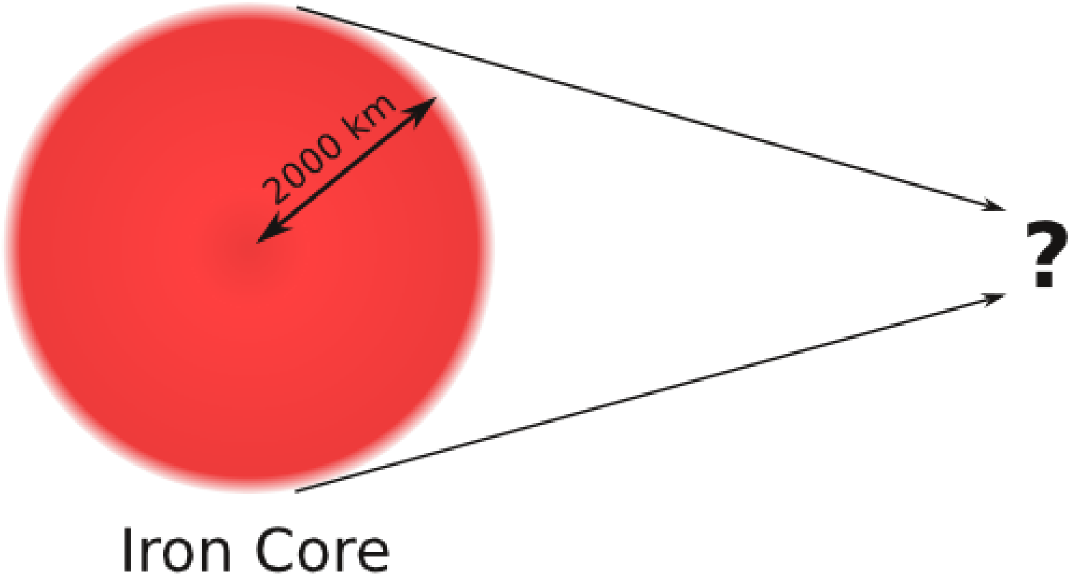


Analytic similarity solutions:
Goldreich & Weber 1980
Yahil & Lattimer 1982
Yahil 1983

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

Collapse

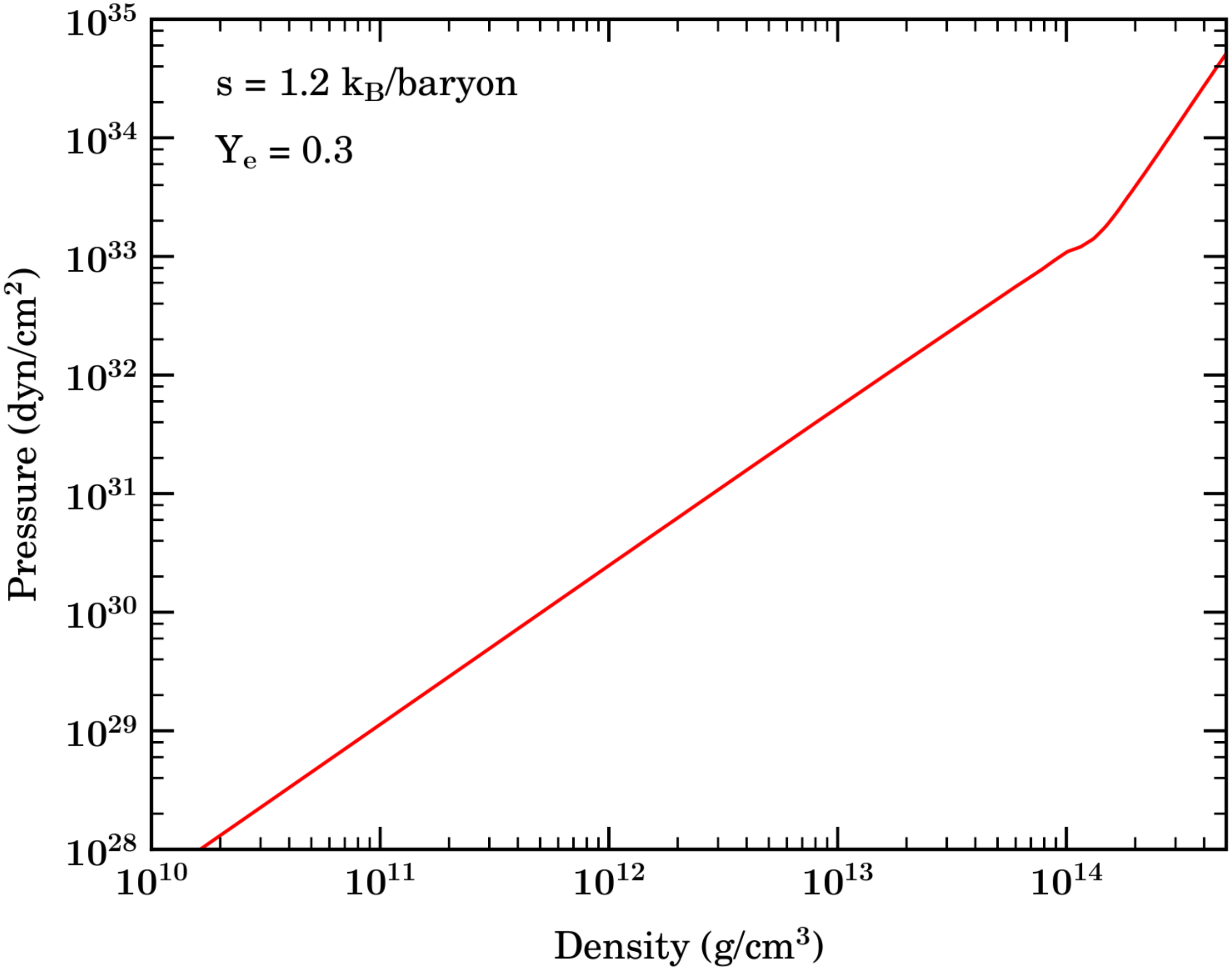
Still collapsing... is there an end?



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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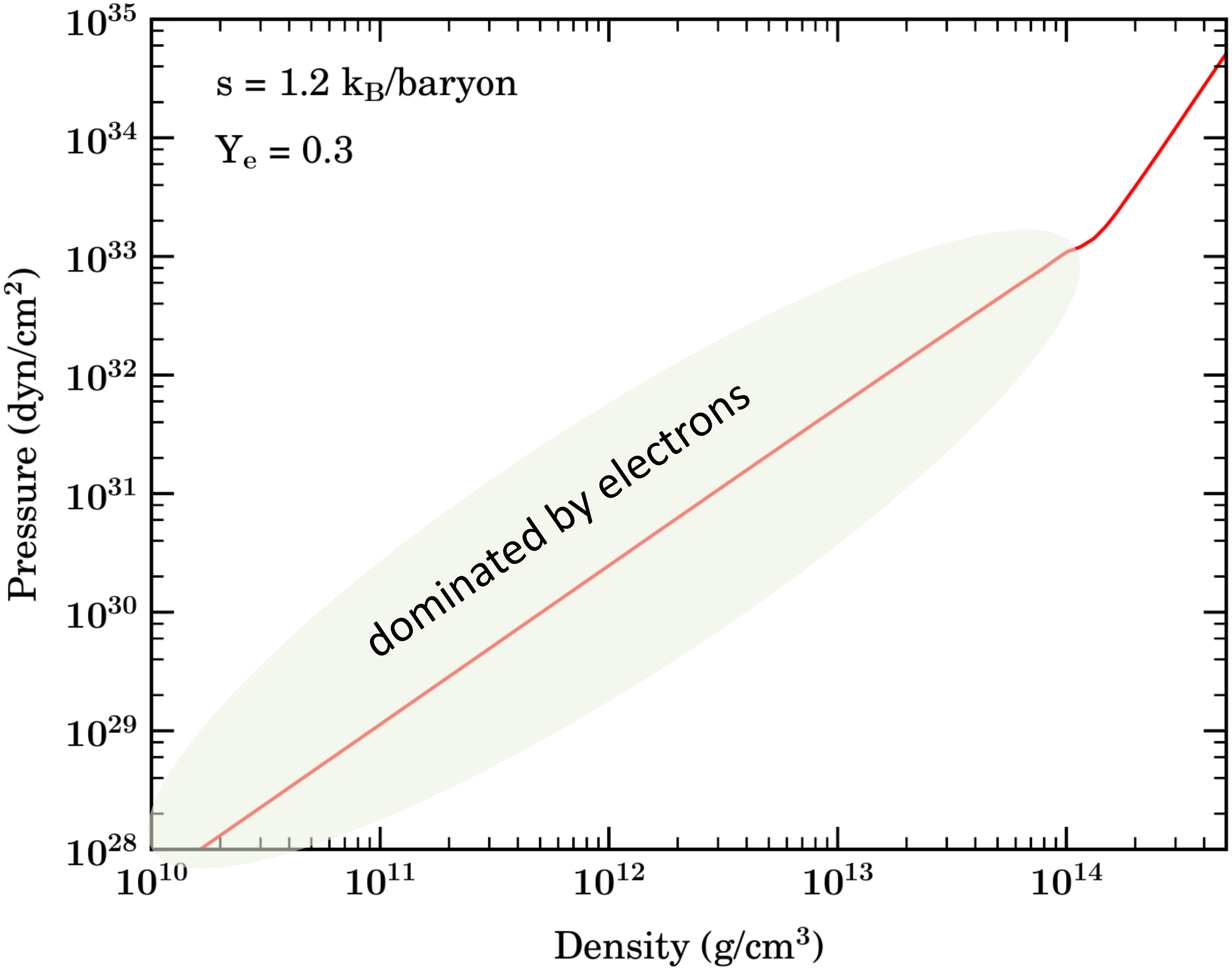

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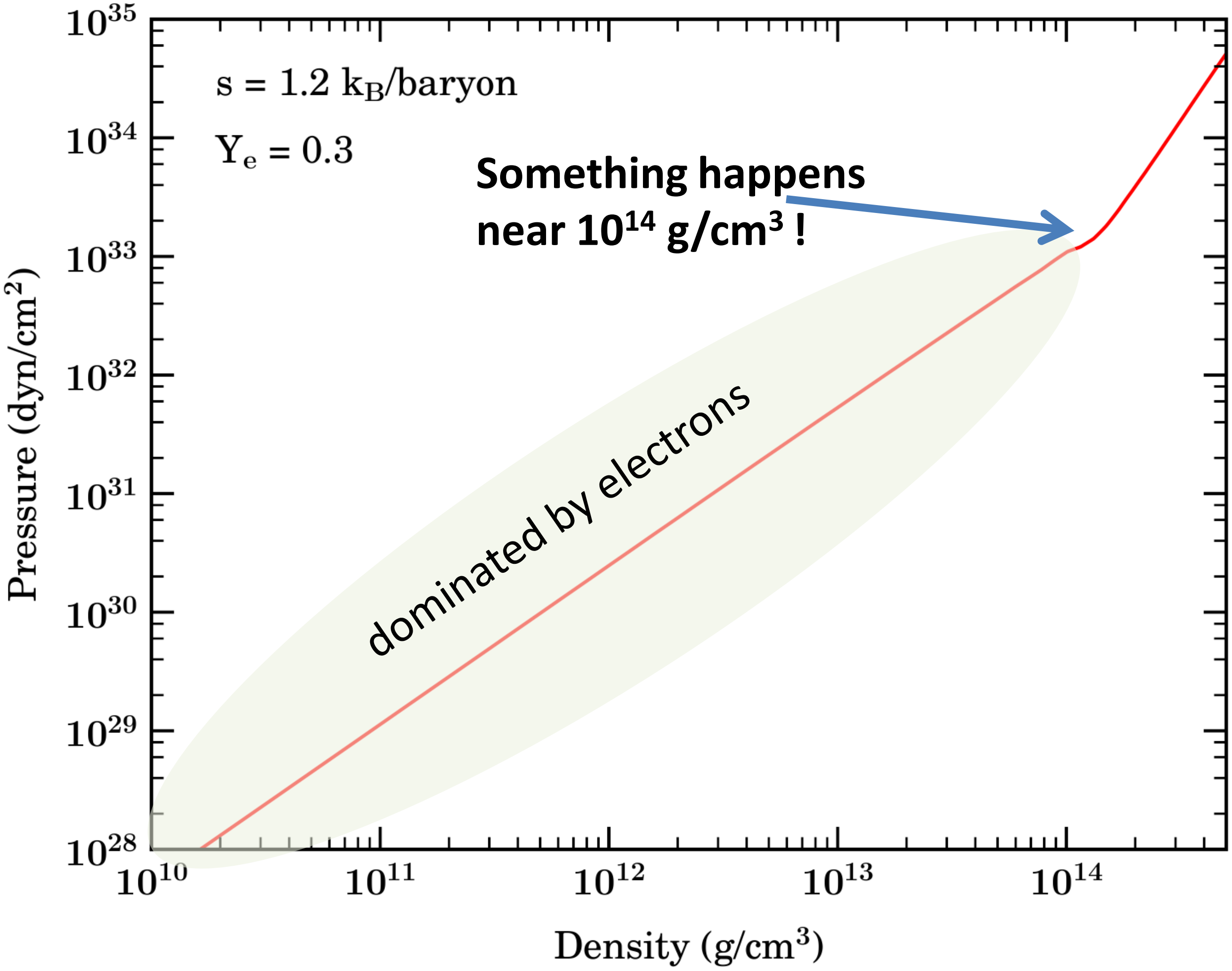


The Nuclear Equation of State (EOS)

Nuclear Physics:

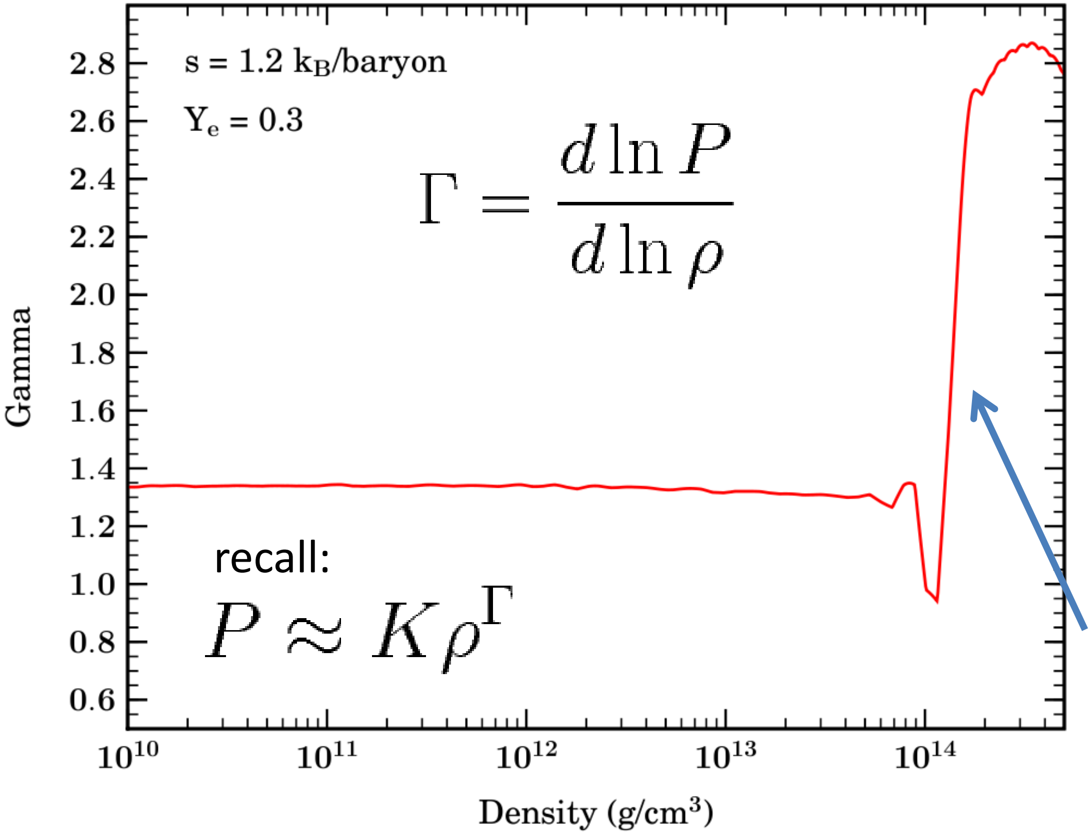
$$R_{\rm nuc} = A^{1/3} r_0$$

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

Nuclear Density:

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

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



$$\Gamma = \frac{d\ln P}{d\ln\rho}$$

recall:

$$P \approx K\rho^{\Gamma}$$

“Stiffening” of the EOS

Nuclear EOS: What happens near $\rho_{\rm nuc}$?

Nuclear Physics:

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

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

Nuclear Density:

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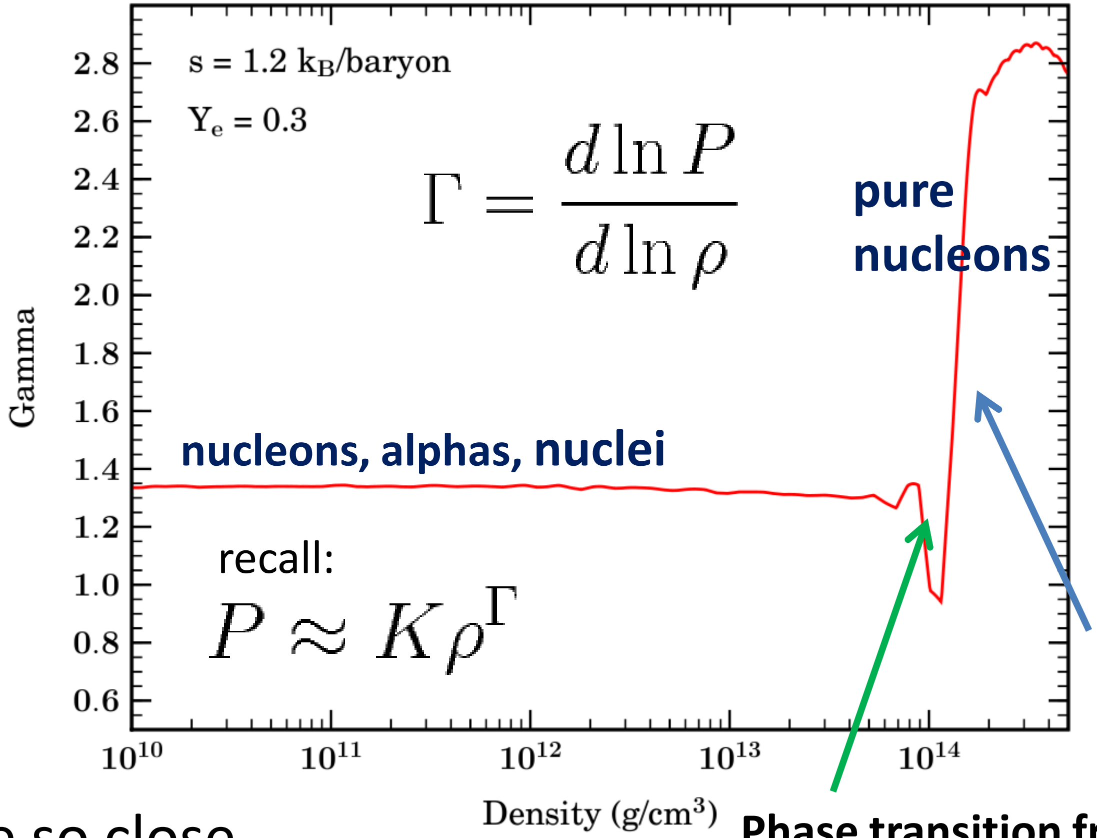


$$\Gamma = \frac{d\ln P}{d\ln\rho}$$

pure nucleons

nucleons, alphas, nuclei

recall:

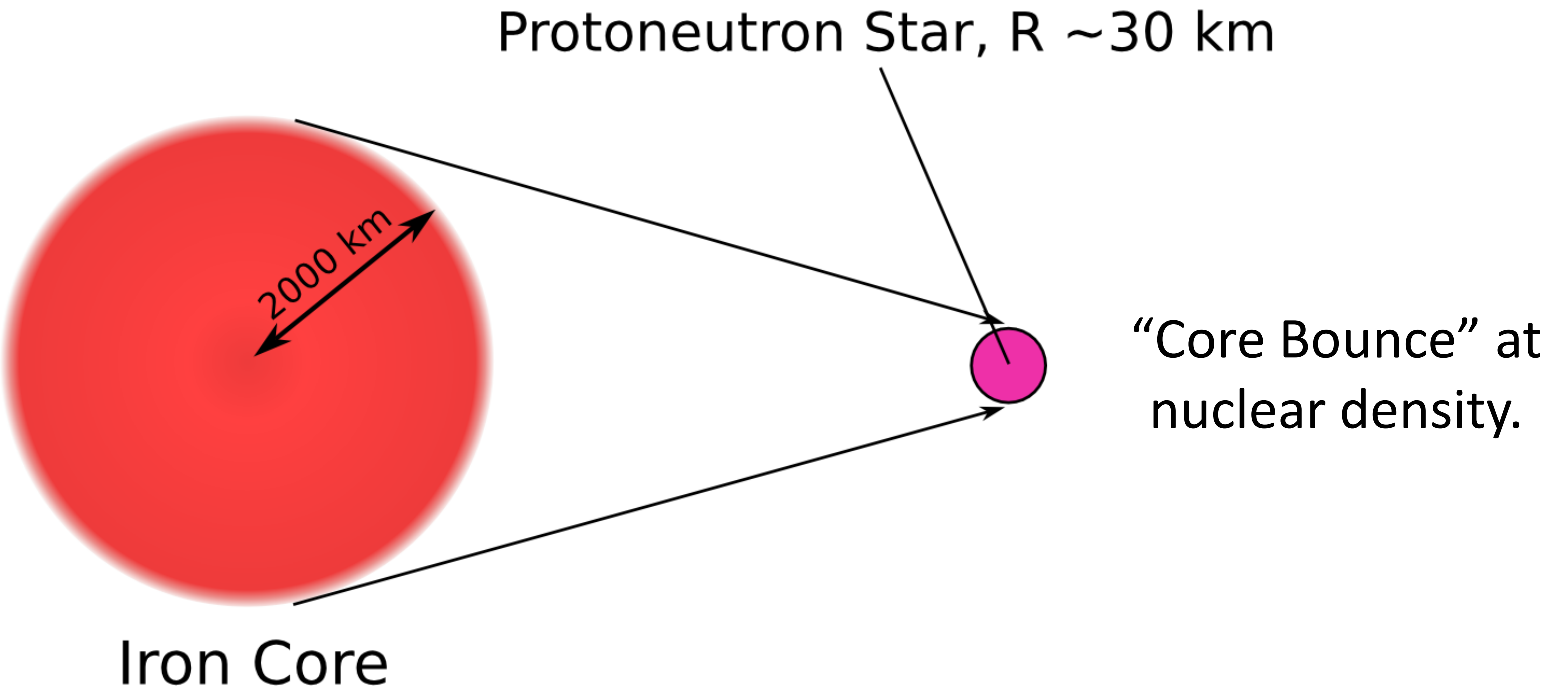
$$P \approx K\rho^\Gamma$$

“Stiffening” of the EOS

Phase transition from inhomogeneous to homogeneous nuclear matter

- Above $\approx\rho_{\rm nuc}$ n,p are so close that “repulsive core” of the strong force kicks in and leads to the stiffening of the EOS

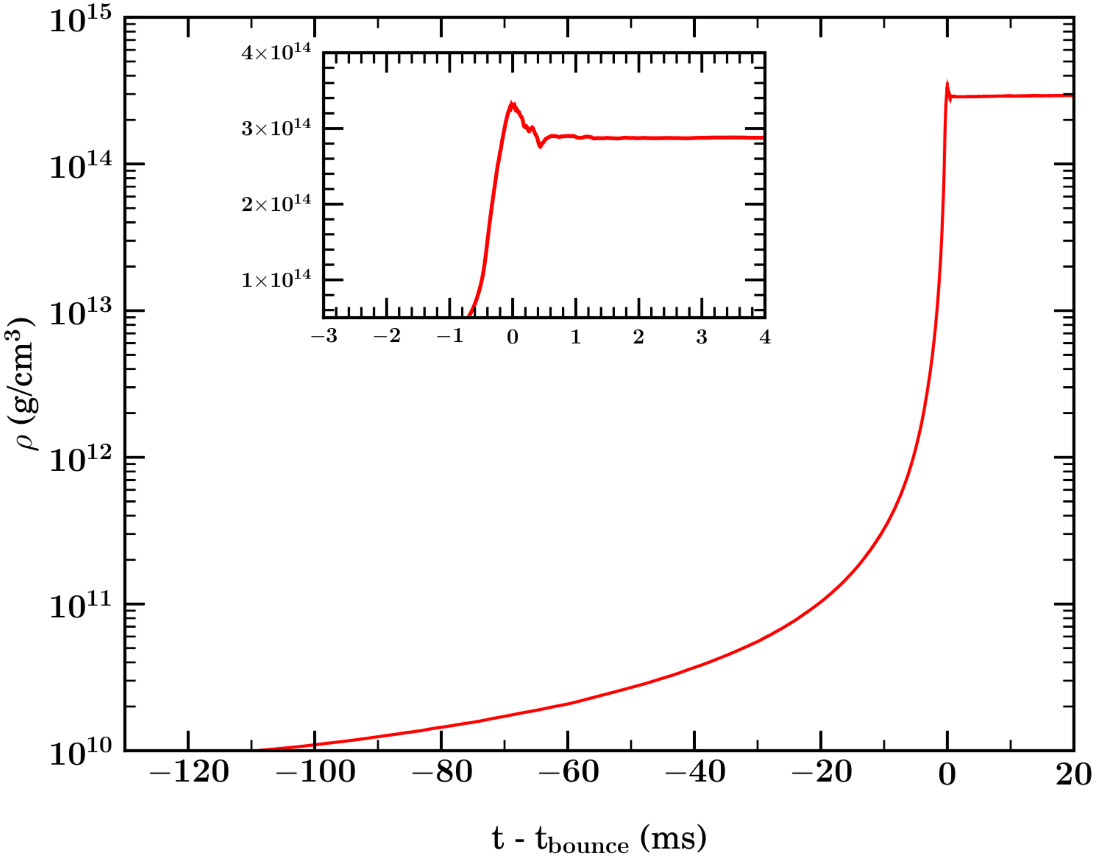
Core Bounce



$M \approx 1.3 - 2.2\ M_{SUN}$

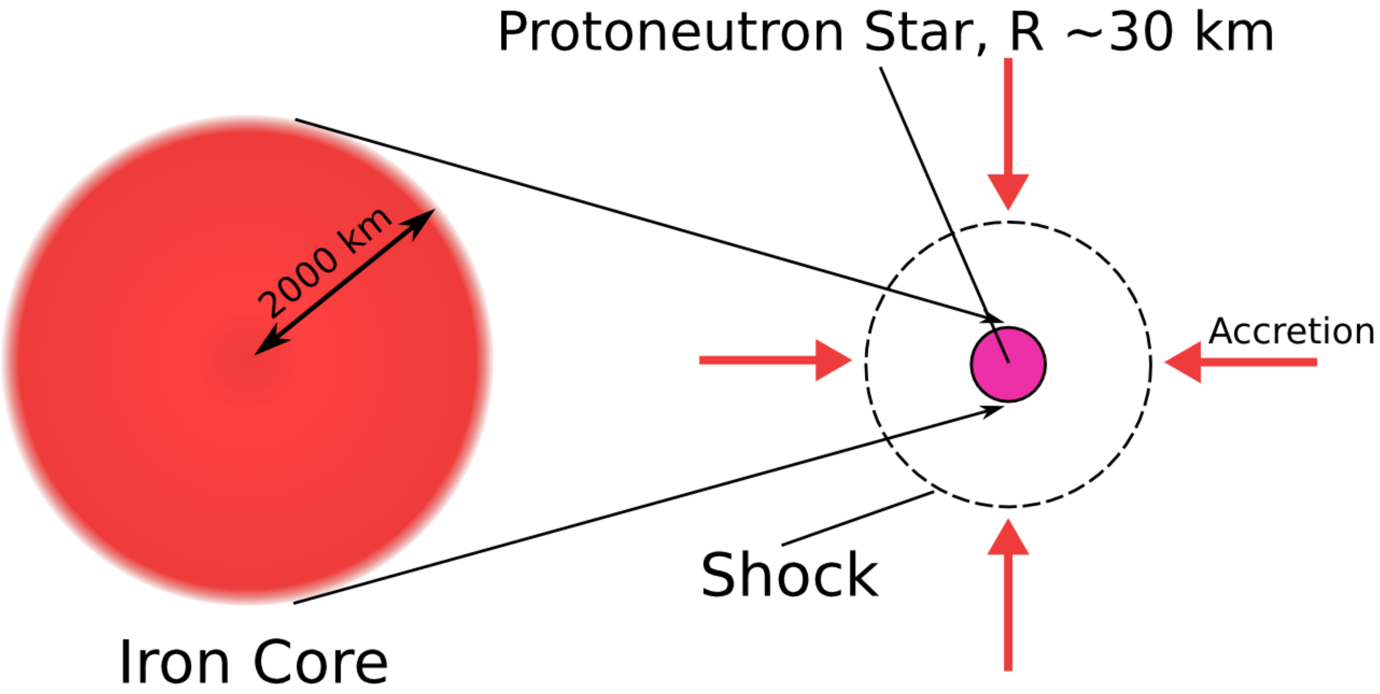
$M = M_{CH,0}$ + corrections (thermal, GR, etc.)

Collapse and Bounce

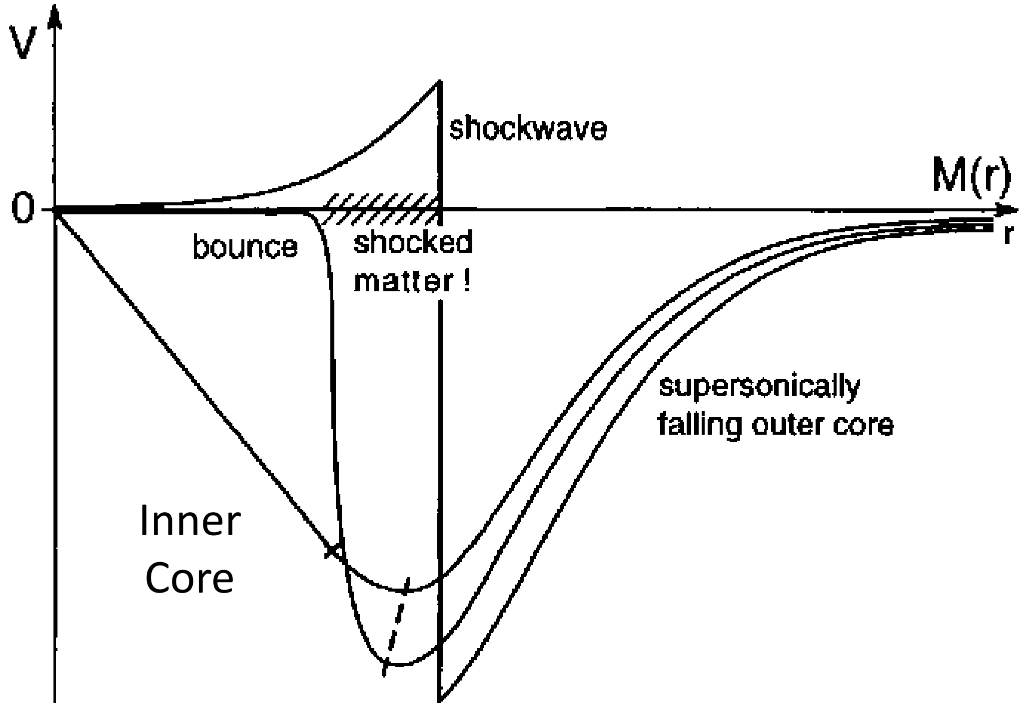


- **Inner Core** reaches ρ_{nuc}, rebounds (“bounces”) **into still infalling outer core**.

Core Bounce and Shock Formation



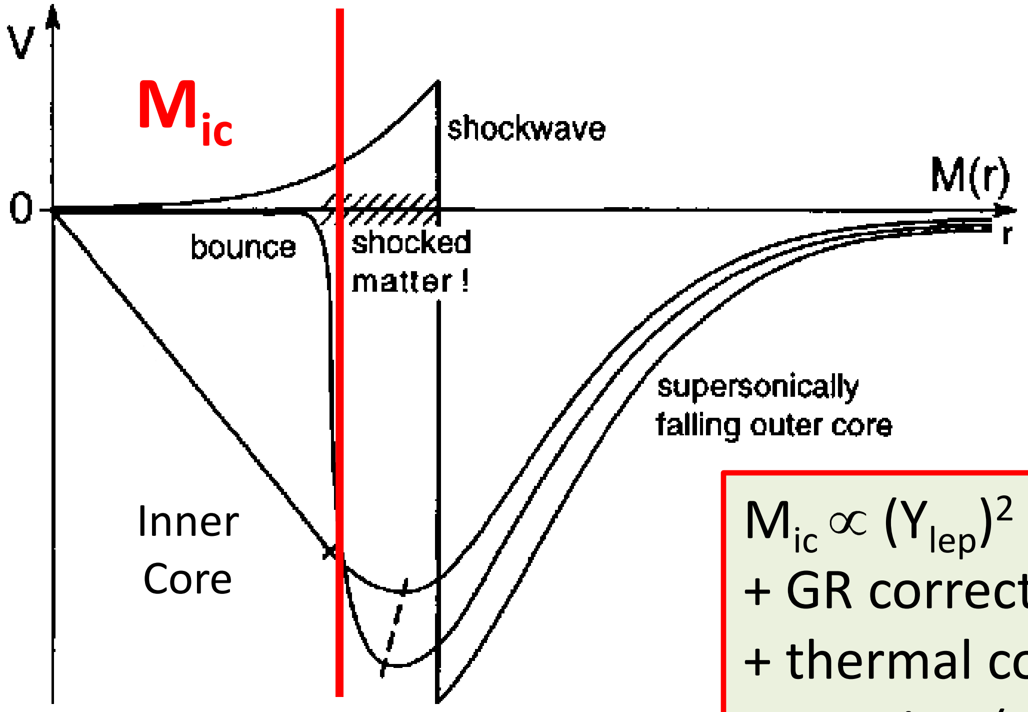
Shock Formation



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 (+)

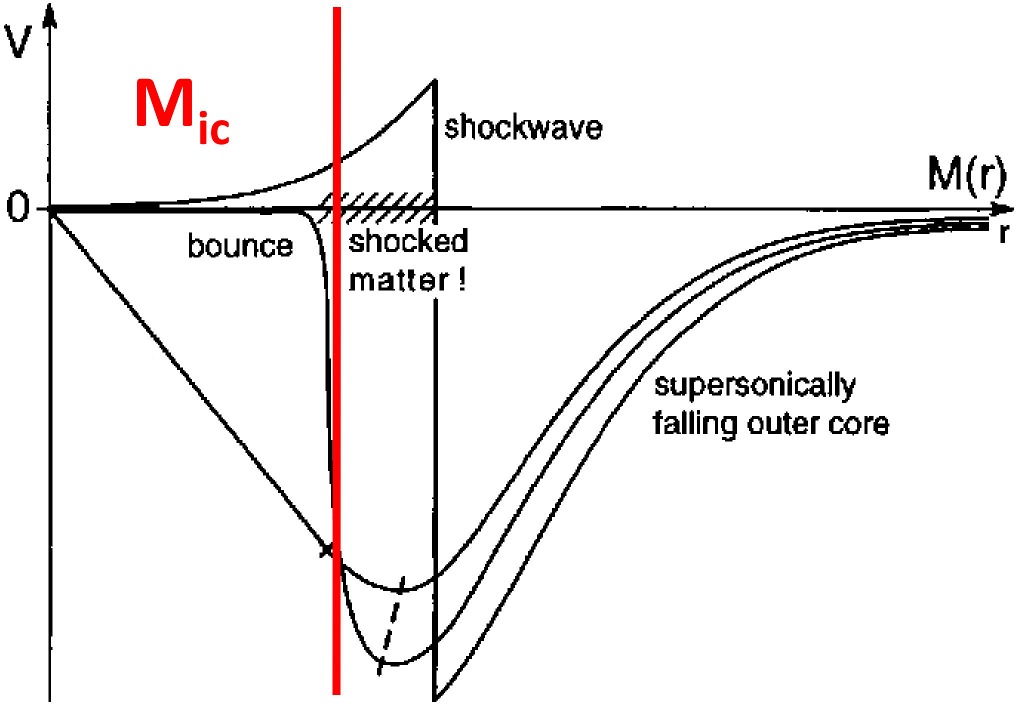
The Mass M_{ic} of the inner core at bounce is determined by nuclear physics and weak interactions, is ~0.5 M_{SUN}, and is practically independent of progenitor star mass and structure.

Stellar Collapse: Inner Core Mass

Why worry about M_{ic}?

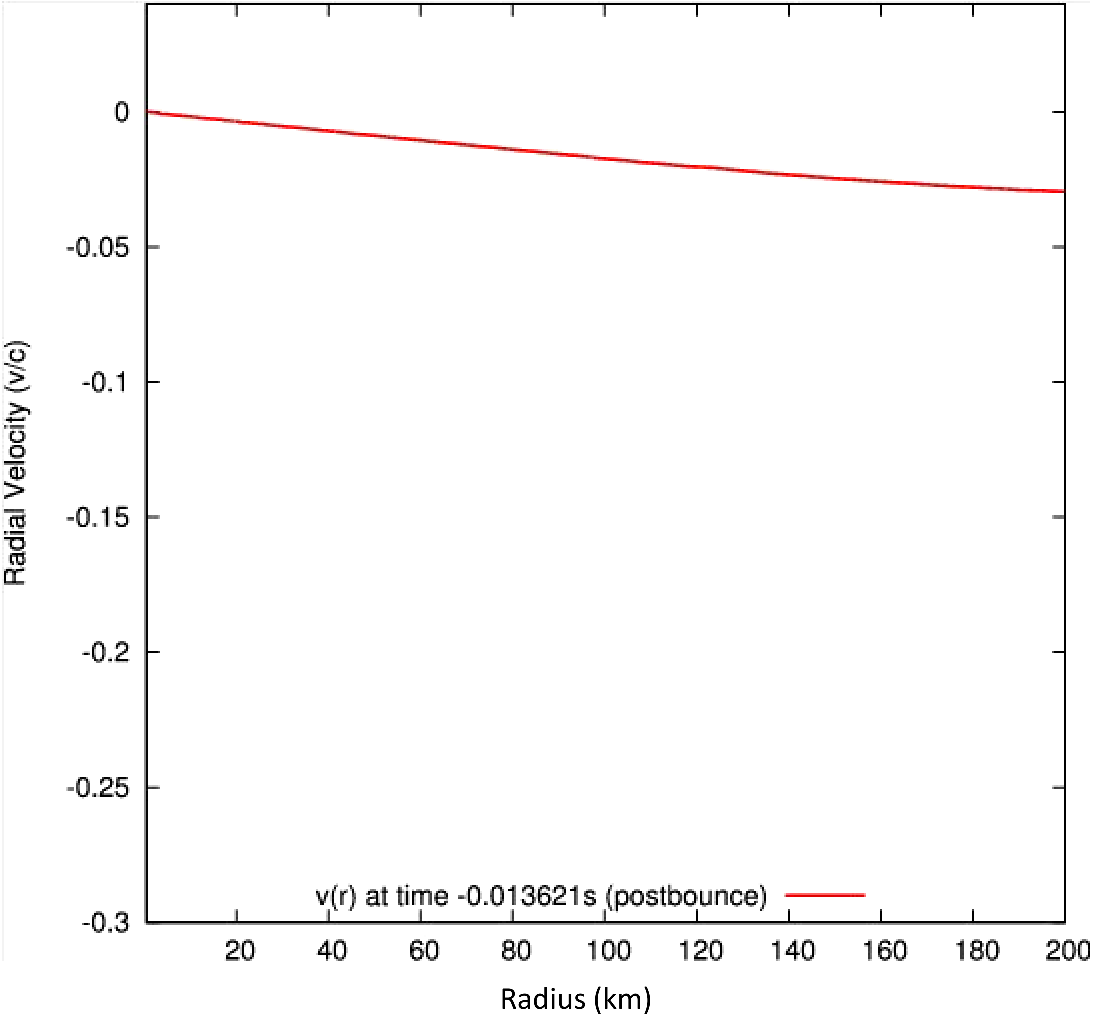
Bethe 1990!!!

- M_{ic} is the amount of matter dynamically relevant in bounce.
- M_{ic} sets kinetic energy imparted to the shock.
- M_{ic} (and IC radius) sets the angular momentum that can be dynamically relevant.
- Sets mass cut for material that the shock needs to go through.



- M_{ic} ~0.5 M_{SUN} can easily stabilized by nuclear EOS.
  No “prompt” Black Hole formation.
- M_{ic} sets the mass that must be accreted (before explosion?) to make a canonical 1.4 M_{SUN} neutron star.

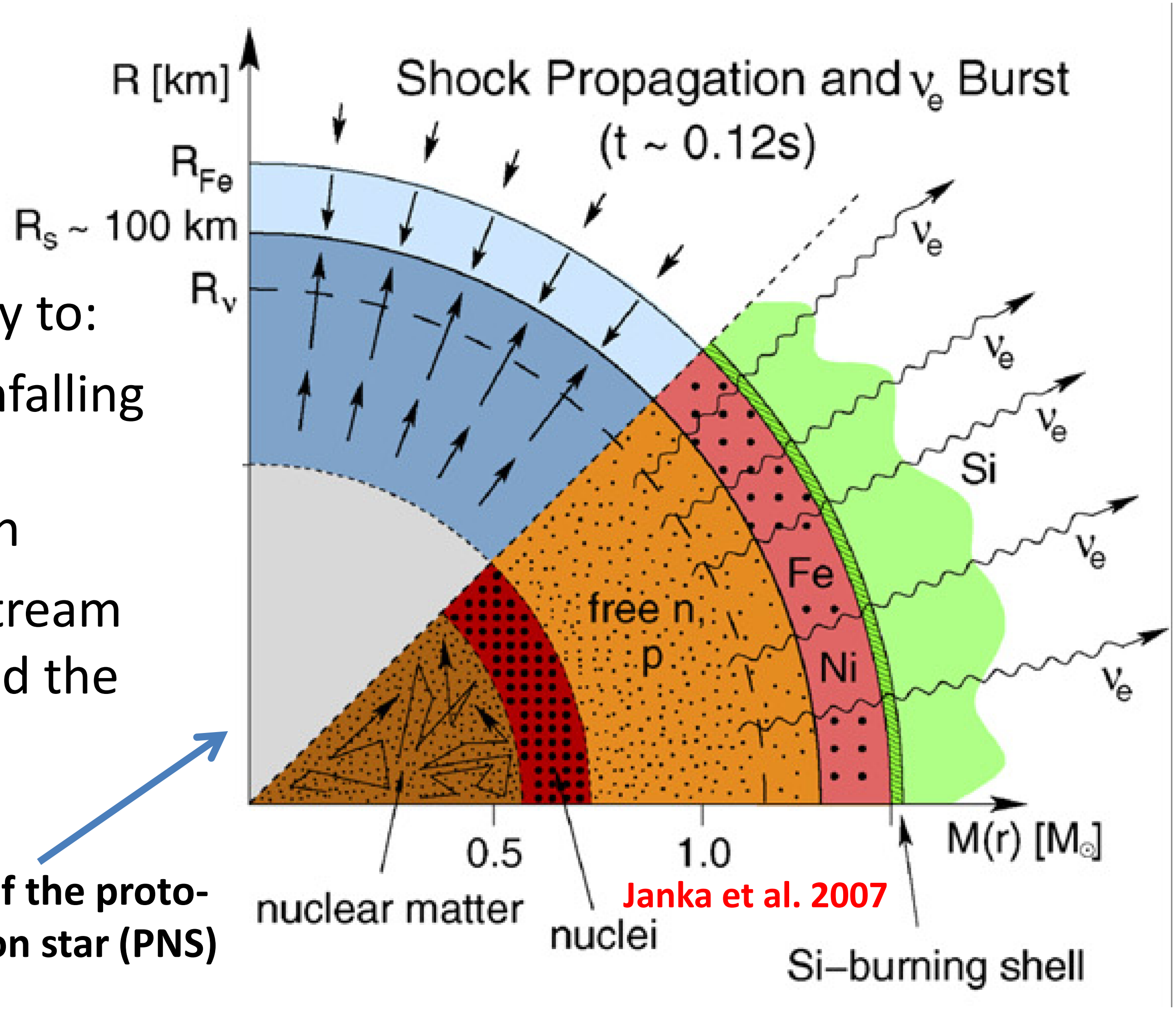
The Supernova Problem



Movie by
Evan O'Connor

Why Does the Shock Stall

- Shock loses energy to:
  - Dissociation of infalling heavy nuclei: ~8.8 MeV/baryon
  - 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

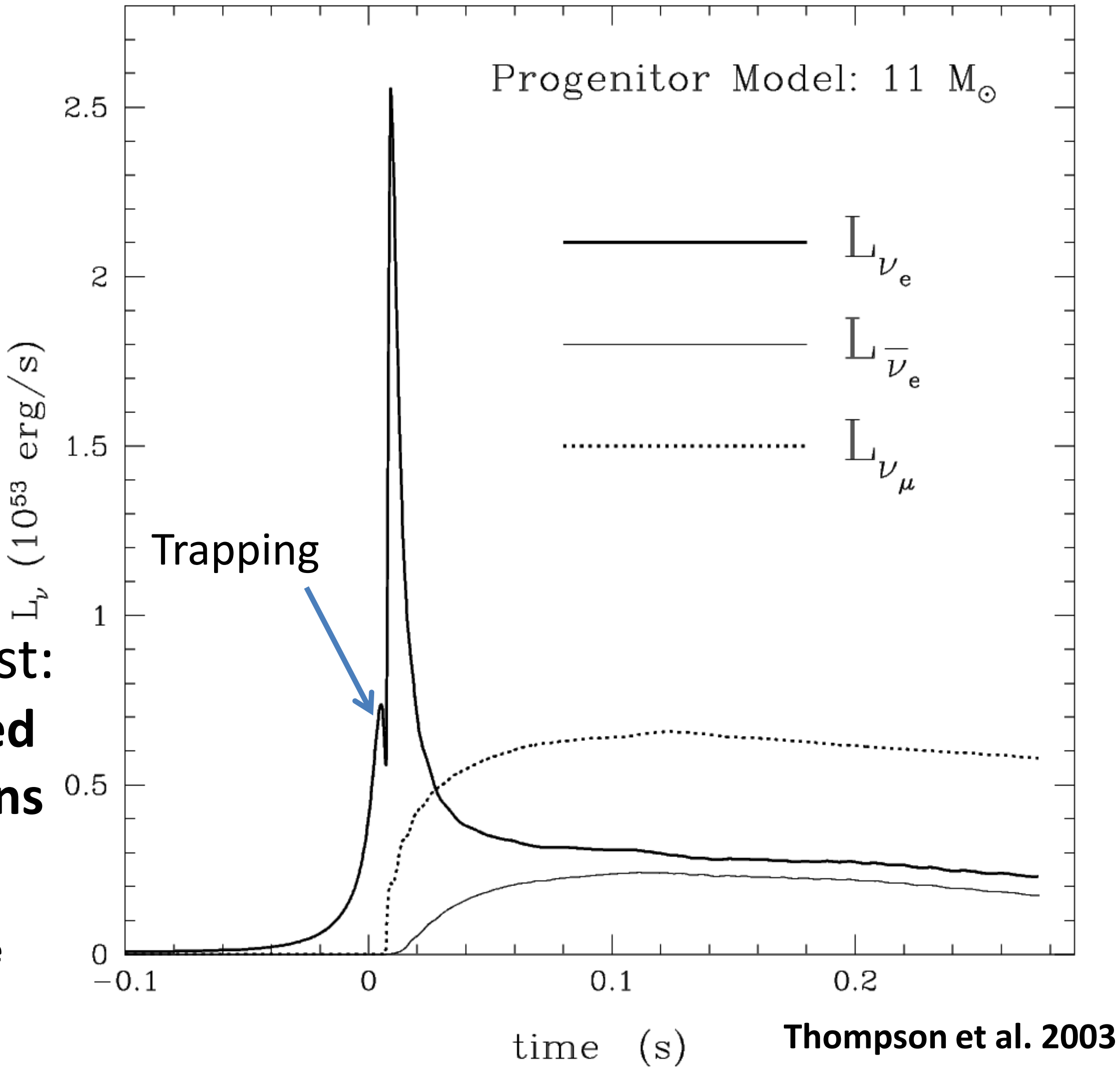
$$\tau_\nu(r) = \int_\infty^r \frac{1}{\lambda_\nu} dr'$$

- Neutrinosphere:

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

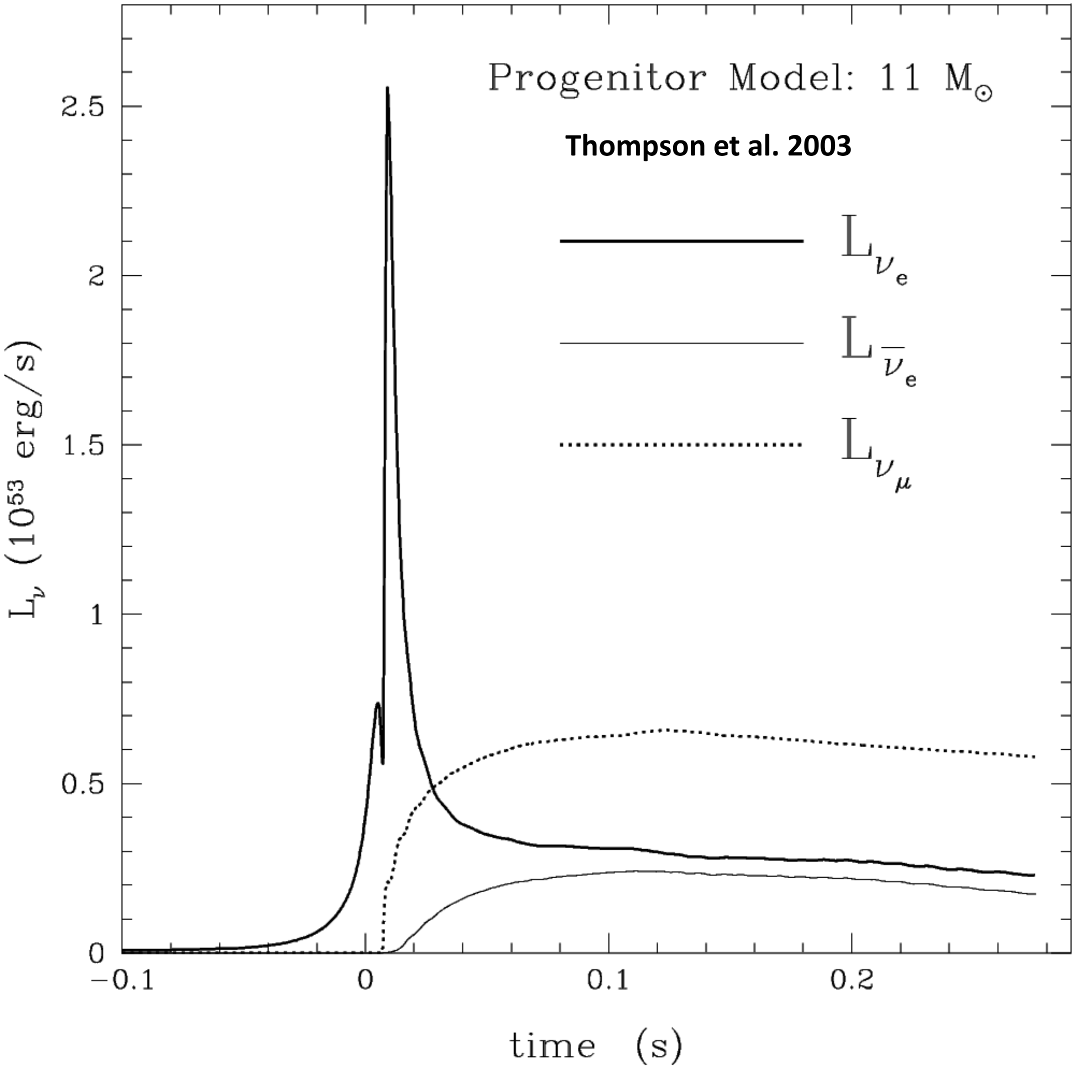
  Depends on $(\epsilon_\nu)^2$

- Postbounce neutrino burst: **Release of neutrinos created by e^- capture on free protons in shocked region when shock 'breaks out' of the ν_e neutrinospheres.**



Thompson et al. 2003

Postbounce Neutrino Emission



- Neutrinos and Anti-neutrinos of ALL species:

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

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

- Emission:

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

$$\left.\begin{aligned} e^- e^+ &\rightleftharpoons \nu_i \bar{\nu}_i \\ NN &\rightleftharpoons \nu_i \bar{\nu}_i \\ \tilde{\gamma} &\rightleftharpoons \nu_i \bar{\nu}_i \end{aligned}\right\}$$

Pair processes: hot & dense environment needed

- Accretion luminosity and diffusive luminosity.

Rough Supernova Energetics

- Supernova problem: What revives the shock?
- Precollapse iron core gravitational energy:

$$E_{\mathrm{grav,Fe(1.5M_\odot)}} \approx 5 \times 10^{51}\,\mathrm{erg} = 5\ \mathrm{B}$$

- Binding energy of a cold 1.5 M_{SUN} NS, R=12.5 km -> **Energy Reservoir**

$$E_{\mathrm{grav,NS}} \approx -\frac{3}{5}G\frac{M^2}{R} \approx -3 \times 10^{53}\,\mathrm{erg} = -3 \times 10^{46}\mathrm{J} = -300\,[\mathrm{B}]\mathrm{ethe}$$

- Initial shock energy: $E_{\mathrm{shock,0}} = \frac{1}{2}Mv^2 \approx 1.2 \times 10^{51}\,\mathrm{erg} = 1.2\,\mathrm{B}$

(Shock formation at ~0.55 M_{SUN}, v ~ 0.05 c)

- Dissociation:

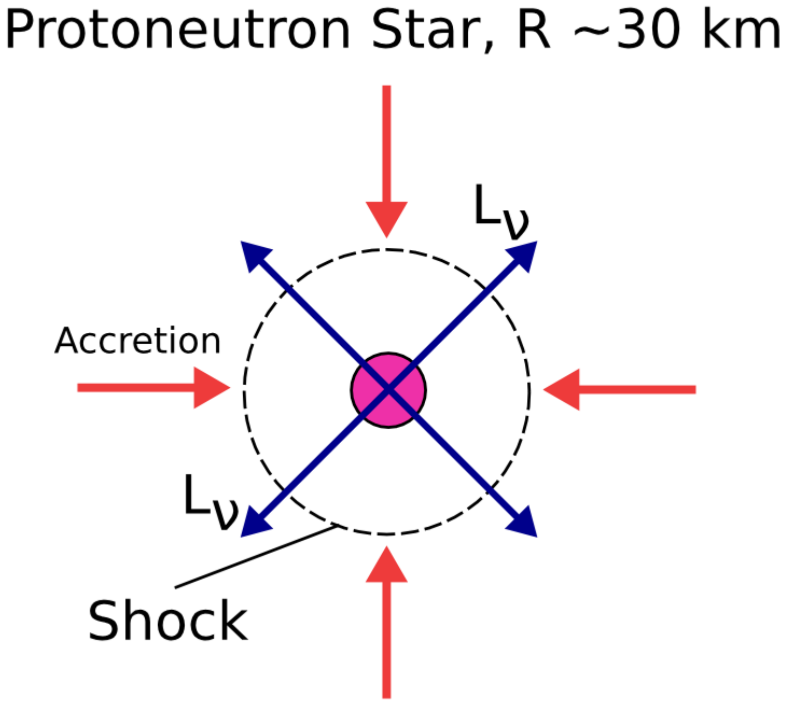
$$E_{\mathrm{diss}} = 17\left(\frac{M}{M_\odot}\right)\mathrm{B}$$

-> Shock stalls "after" ~0.1 M_{SUN}.

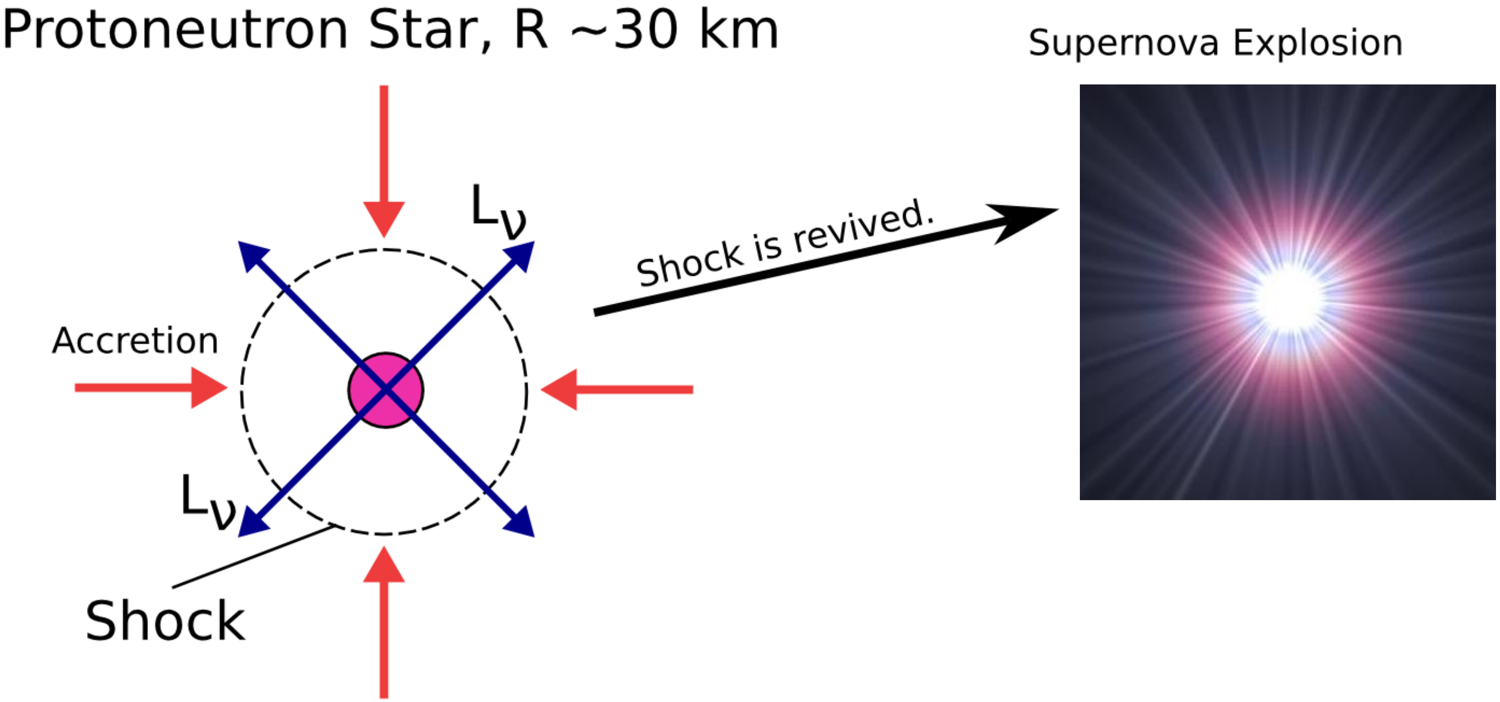
- Neutrinos: initially up to $L_{\nu,\mathrm{total}} \sim 100\,\mathrm{B/s}$
- Binding energy of the mantle (12-M_{SUN} star): $E_{\mathrm{bind,0.6-12\,M_\odot}} = -3.7\,\mathrm{B}$

-> need multiple Bethes to blow up the star!

The General Picture



The General Picture



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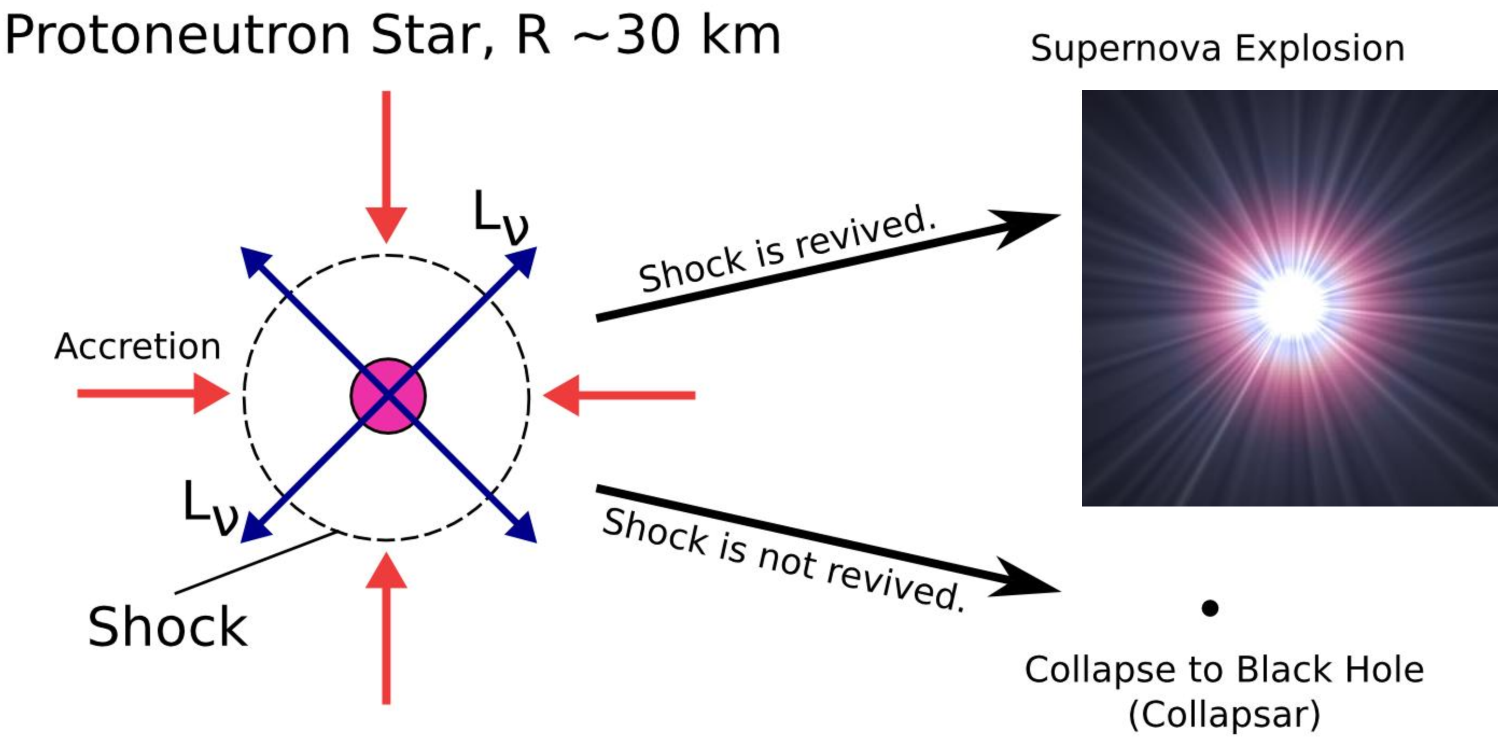


Protoneutron Star, R ~30 km

Accretion

L_ν

L_ν

Shock

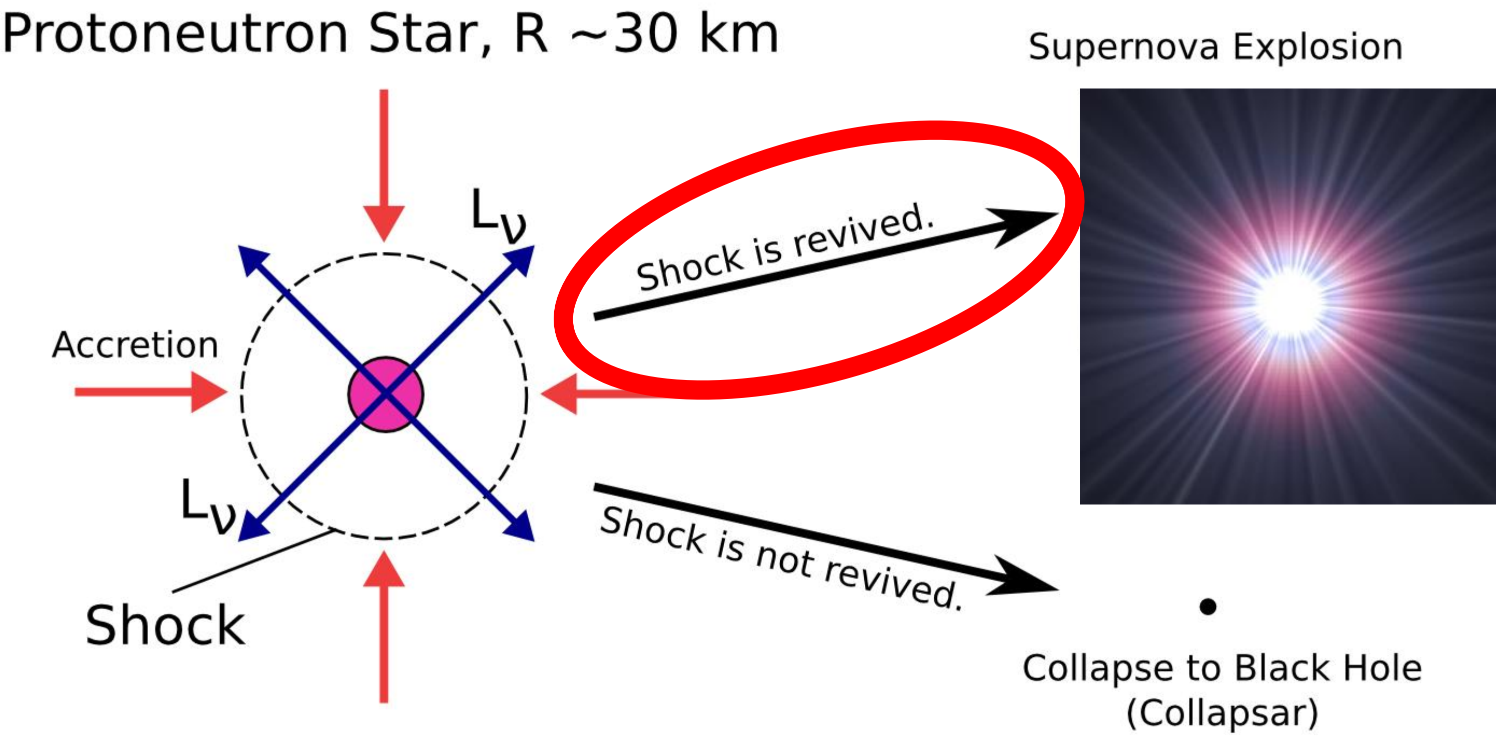
Shock is revived.

Shock is not revived.

Supernova Explosion

Collapse to Black Hole
(Collapsar)

The Supernova Problem



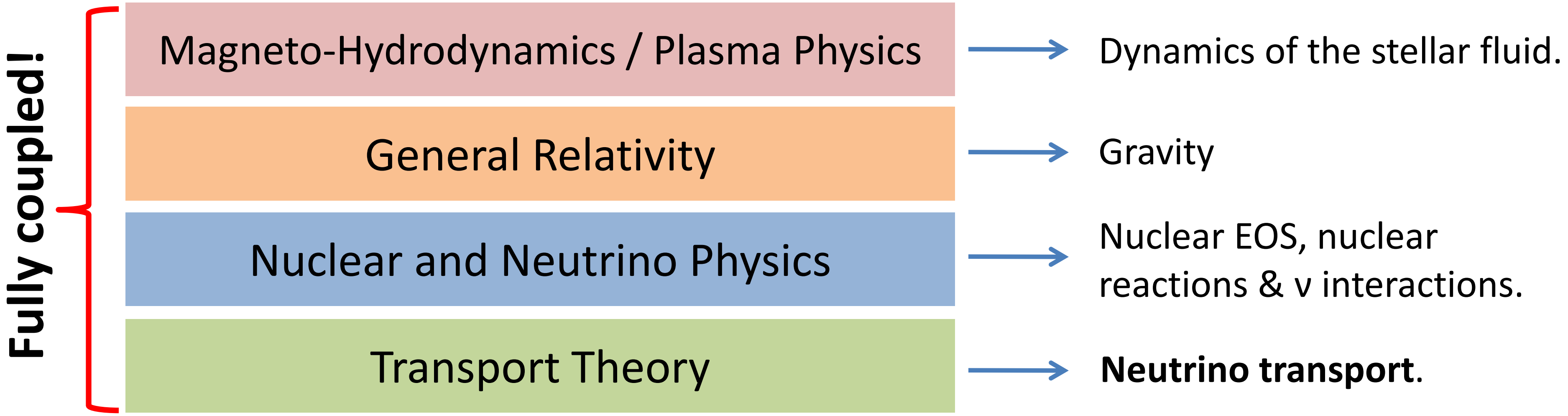
What is the Mechanism of shock revival?

The Essence of any Supernova Mechanism

- Collapse to neutron star:
  $\sim$3 x 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

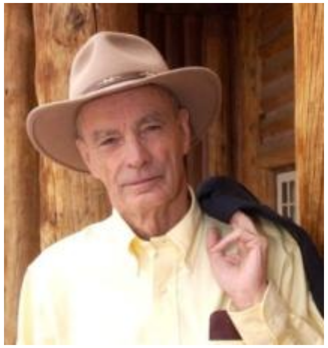


Fully coupled!

- 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: **The Multi-D Nature of the Beast**
  - 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

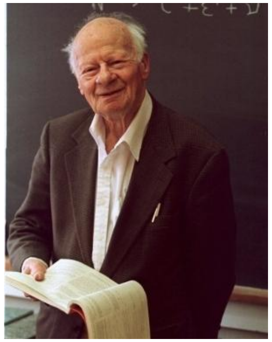


Stirling Colgate

Colgate & White 1966

Dave Arnett

Arnett 1966



Hans Bethe

Jim Wilson

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

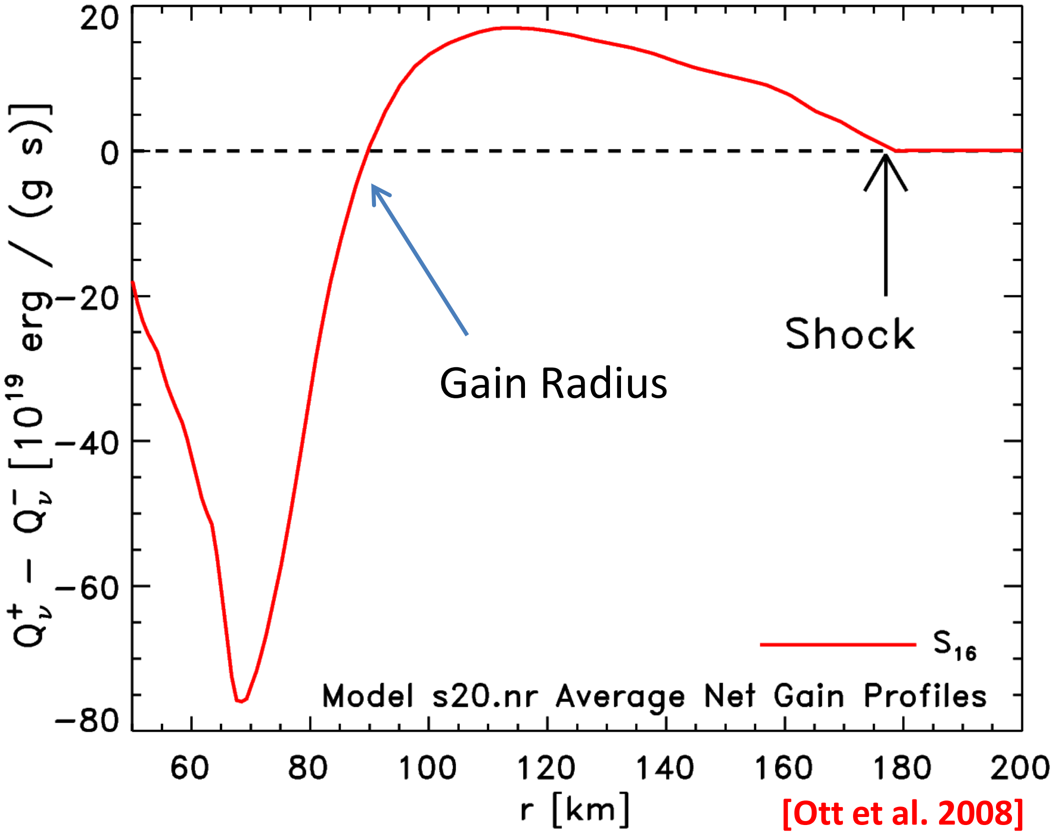
Neutrino cooling: $Q_\nu^- \propto T^6$

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

$\text{Net heating where:}$

$Q_\nu^+ > Q_\nu^-$

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



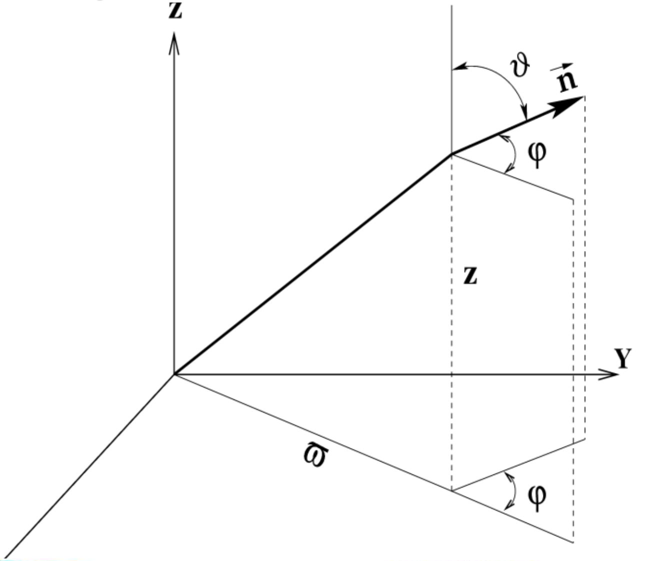
[Ott et al. 2008]

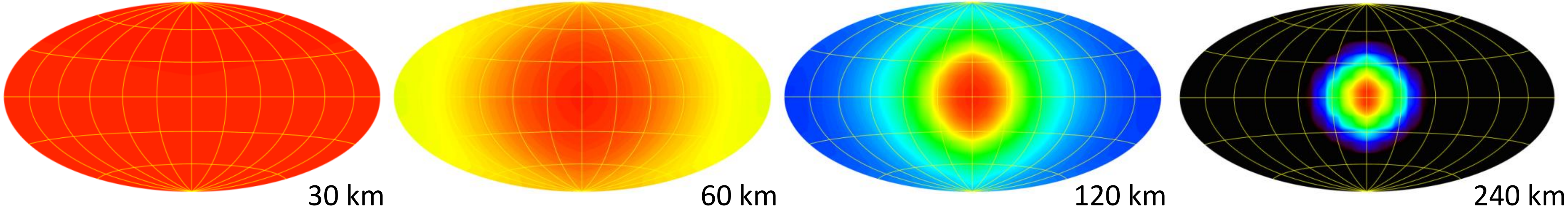
A few Words on Neutrino Transport

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

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

- 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)





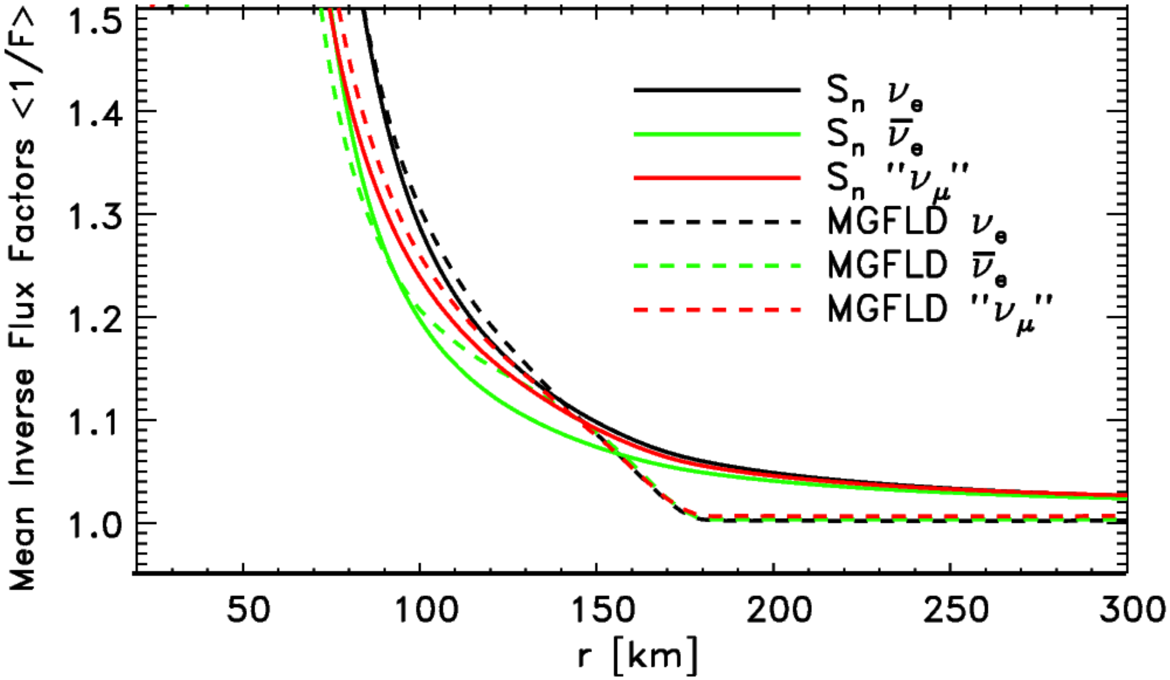
Neutrino Transport in Core-Collapse SNe

- Main complication: Need to track radiation field from complete isotropy to full free streaming over many orders of magnitude of τ.
- Neutrino heating depends on details of the radiation field:

$$Q^+_{\nu_e/\bar{\nu}_e} = 4\pi \int_0^\infty d\epsilon_\nu\, \kappa_{\mathrm{a},\nu_e/\bar{\nu}_e} J_\nu = \frac{1+3g_\mathrm{A}^2}{4} \frac{\sigma_0 N_\mathrm{A} X_{\mathrm{n/p}}}{(m_\mathrm{e}c^2)^2} \boxed{\langle \epsilon_\nu^2 \rangle} \frac{\boxed{L_{\nu_e/\bar{\nu}_e}}}{4\pi r^2} \boxed{\left\langle \frac{1}{\mathsf{F}} \right\rangle}$$

- Inverse Flux factor:

$$\left\langle \frac{1}{\mathbf{F}_{\nu_i}} \right\rangle = \frac{c \int d\varepsilon_\nu E(\varepsilon_\nu, \nu_i)}{\int d\varepsilon_\nu F_r(\varepsilon_\nu, \nu_i)}$$



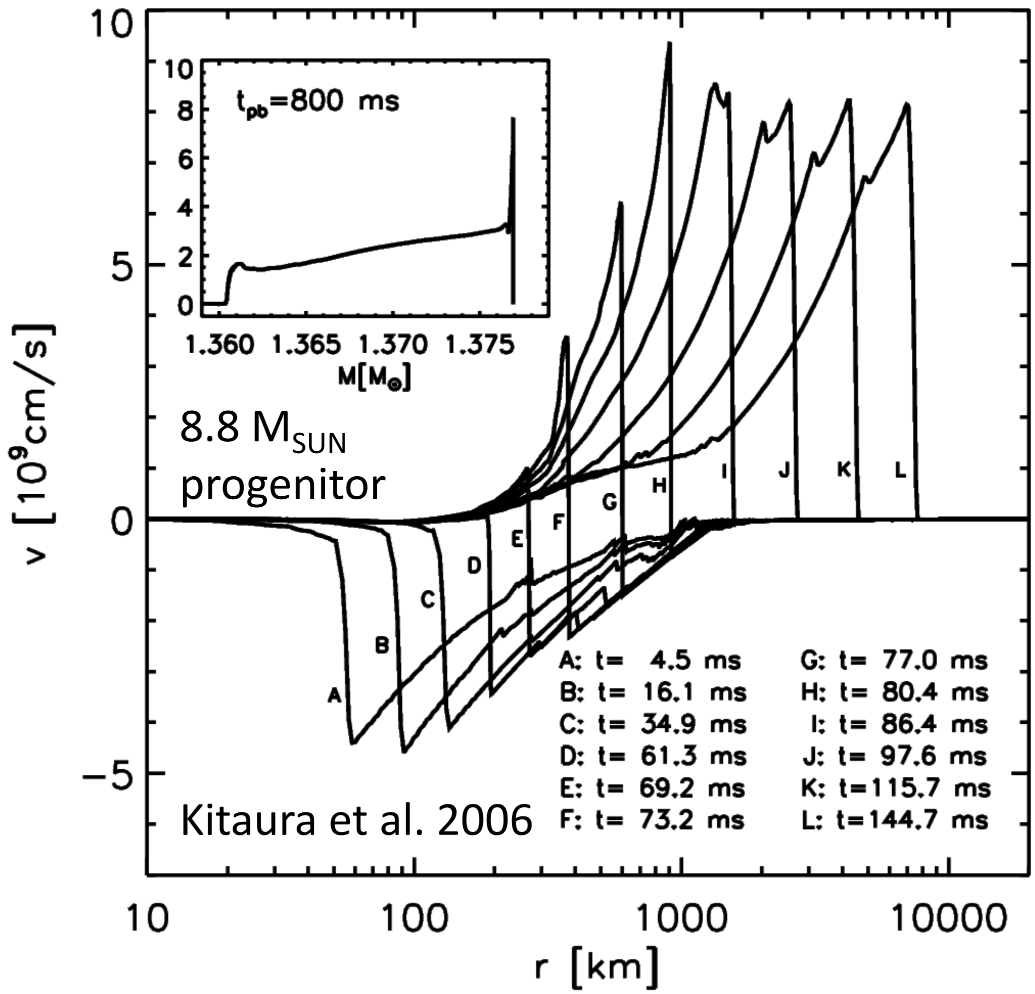
Stellar Collapse: Neutrino Mechanism

Does it work?

- **Yes!**
  BUT:
  Only for lowest-mass massive stars.

  (Kitaura et al. 2006, Burrows 1988, Burrows, Livne, Dessart 2007)

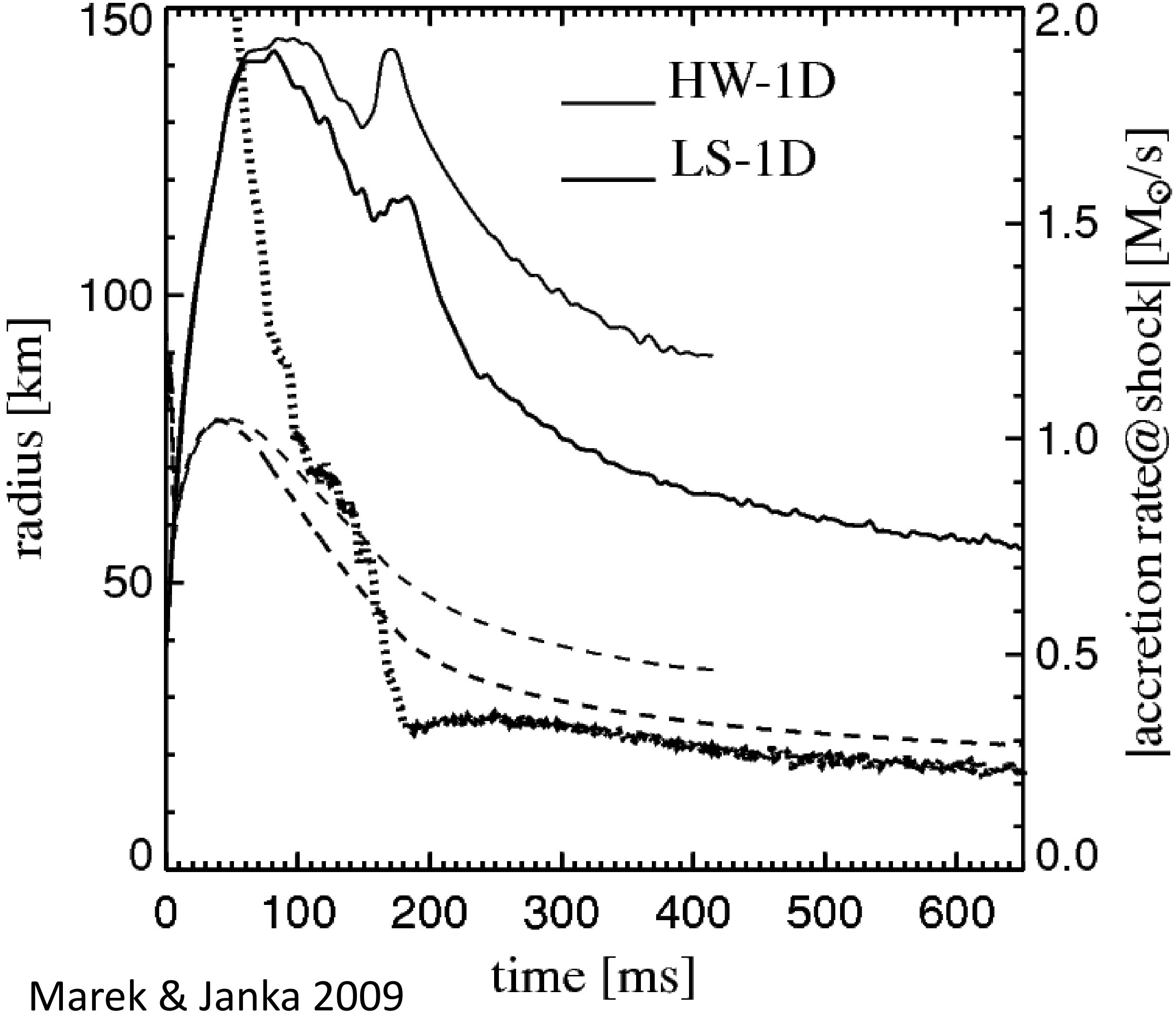
- **FAILS in spherical symmetry (1D) for garden-variety massive stars (~15 M_{SUN}) in simulations with best neutrino physics and neutrino transport**



8.8 M_{SUN} progenitor

Kitaura et al. 2006

Failure of the Neutrino Mechanism in 1D

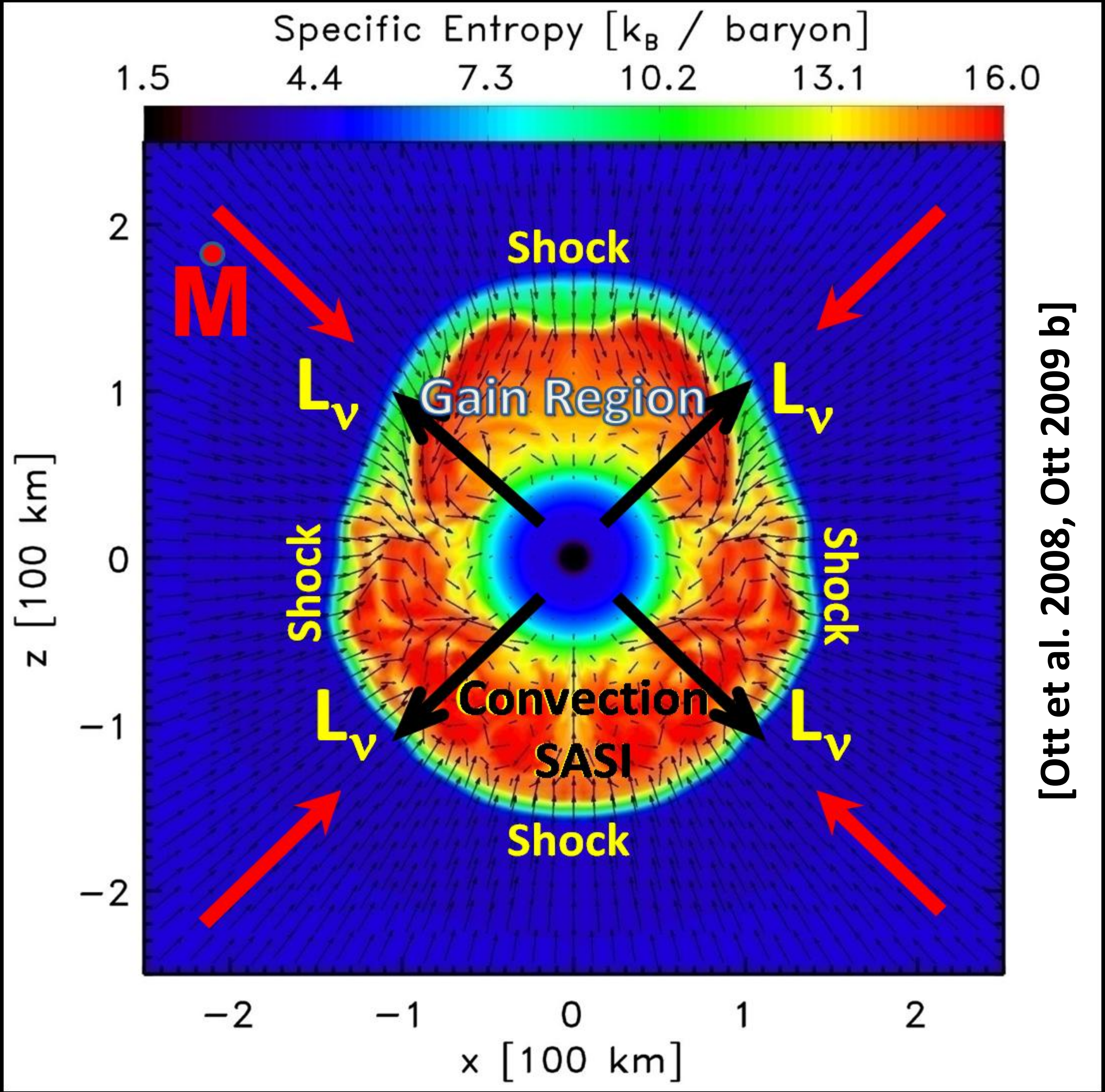


Marek & Janka 2009

Anyway... What next?

- Why does the neutrino mechanism fail in 1D?
- Is dimensionality an issue? What is 1D missing?
  - Rotation and magnetohydrodynamics (MHD)
  - Convection/Turbulence
  - Other multi-D processes; e.g., pulsations
- First multi-D radiation-hydrodynamics simulations:
  - early to mid 1990s:
    Herant et al. 1994, Burrows et al. 1995, Janka & Müller 1996.

A Look at the Beast:



[Ott et al. 2008, Ott 2009 b]

Convection

Convection

- Ledoux criterion for instability:

$$C_L \equiv \left(\frac{\partial\rho}{\partial s}\right)\Bigg|_{Y,p} \frac{ds}{dr} + \left(\frac{\partial\rho}{\partial Y}\right)\Bigg|_{s,p} \frac{dY}{dr}$$

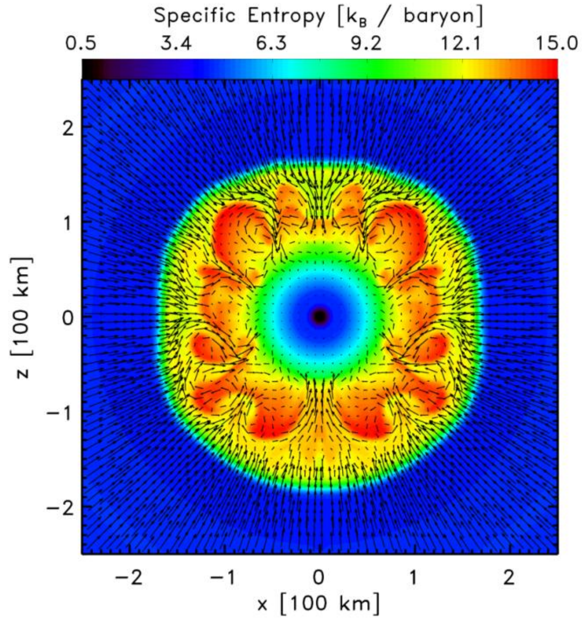
< 0

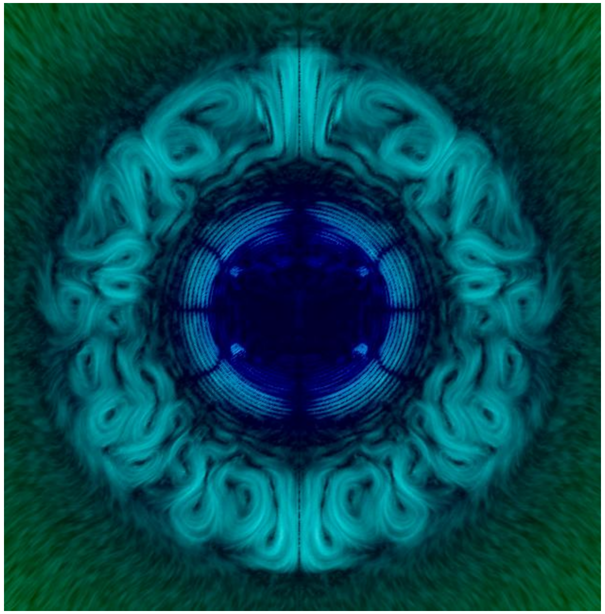
Entropy Gradient

< 0

Lepton Gradient

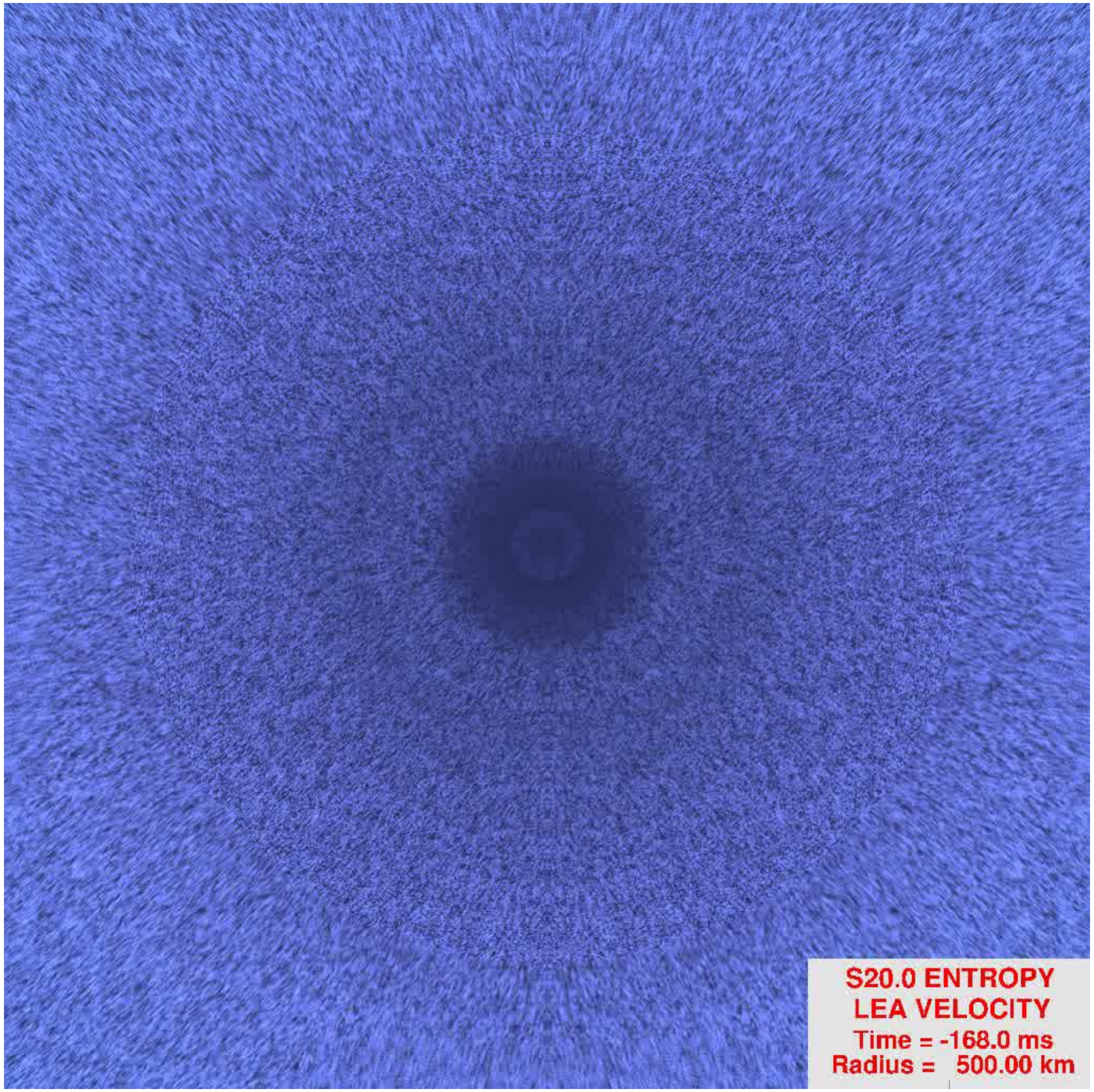
- $C_L > 0$ -> convective instability.
- Postbounce supernova cores:
  - Negative entropy gradient in postshock region -> convection
  - Negative entropy region inside the neutrinosphere in the PNS -> convection
- **Important effect of convection:**
  - "Dwell time" of material in the heating ("gain") region is increased -> leads to more favorable ratio $\tau_{\text{advect}} / \tau_{\text{heat}}$.
    (alternative interpretation: Pejcha & Thompson '11)





Standing Accretion Shock Instability

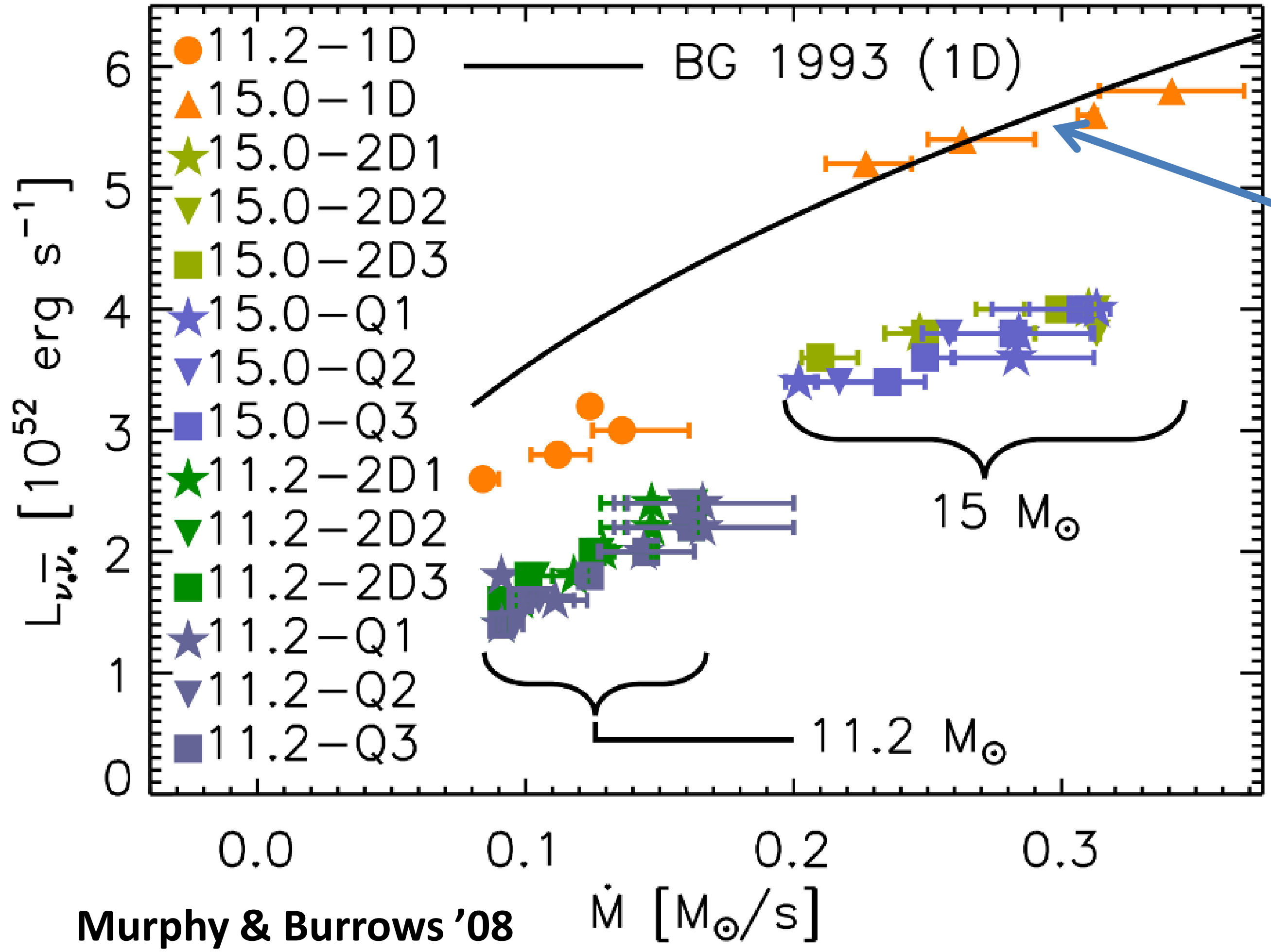
[Blondin et al. ‘03,’06; **Foglizzo et al. ‘06**, Scheck et al. ‘06, ‘07, Burrows et al. ‘06, ’07]



Advective-acoustic cycle drives shock instability.

Seen in simulations by all groups!

1D -> 2D

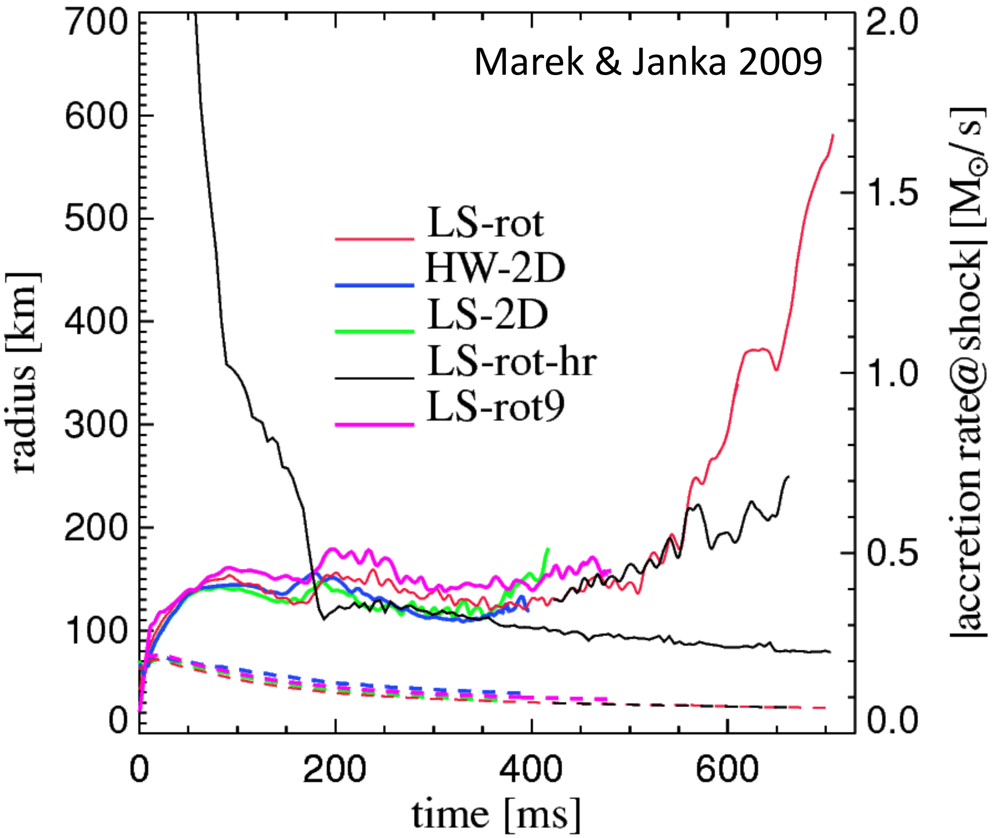


Murphy & Burrows '08

Simple analytic/ODE model of Burrows & Goshy 1993. "Critical Curve" – Luminosity required to explode at given accretion rate.

Status of the Neutrino Mechanism

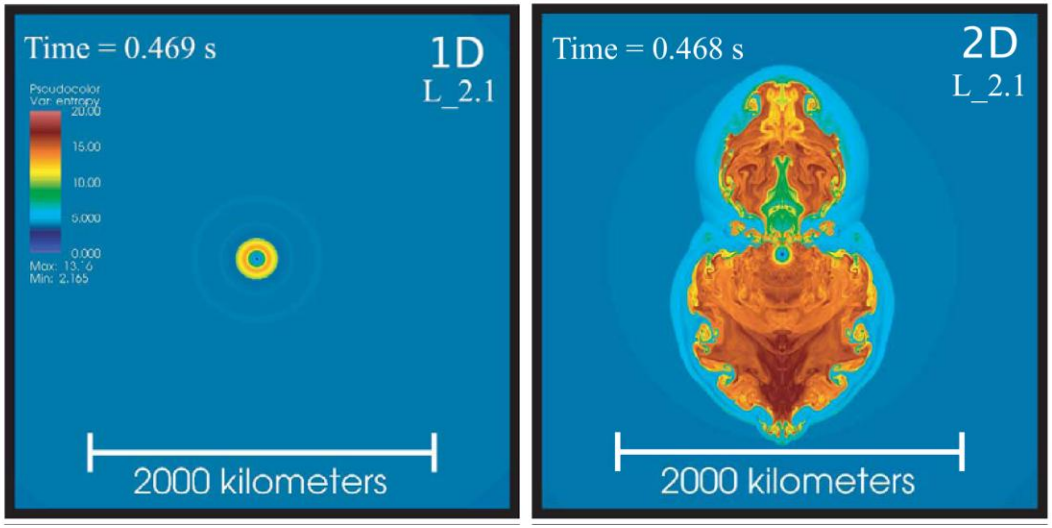
- Best simulations are still in 2D.
- Things look better in 2D, some models explode under special circumstances.
- No robust explosions.
- Crucial conditions (?):
  General relativity
  Soft nuclear EOS
- **Robust explosions in 3D?**



First 3D Simulations

Nordhaus, Burrows, Almgren, Bell 2010

- 1D/2D/3D simulations with the CASTRO code.
- H. Shen EOS, Simple neutrino cooling/heating treatment, 1D gravity.



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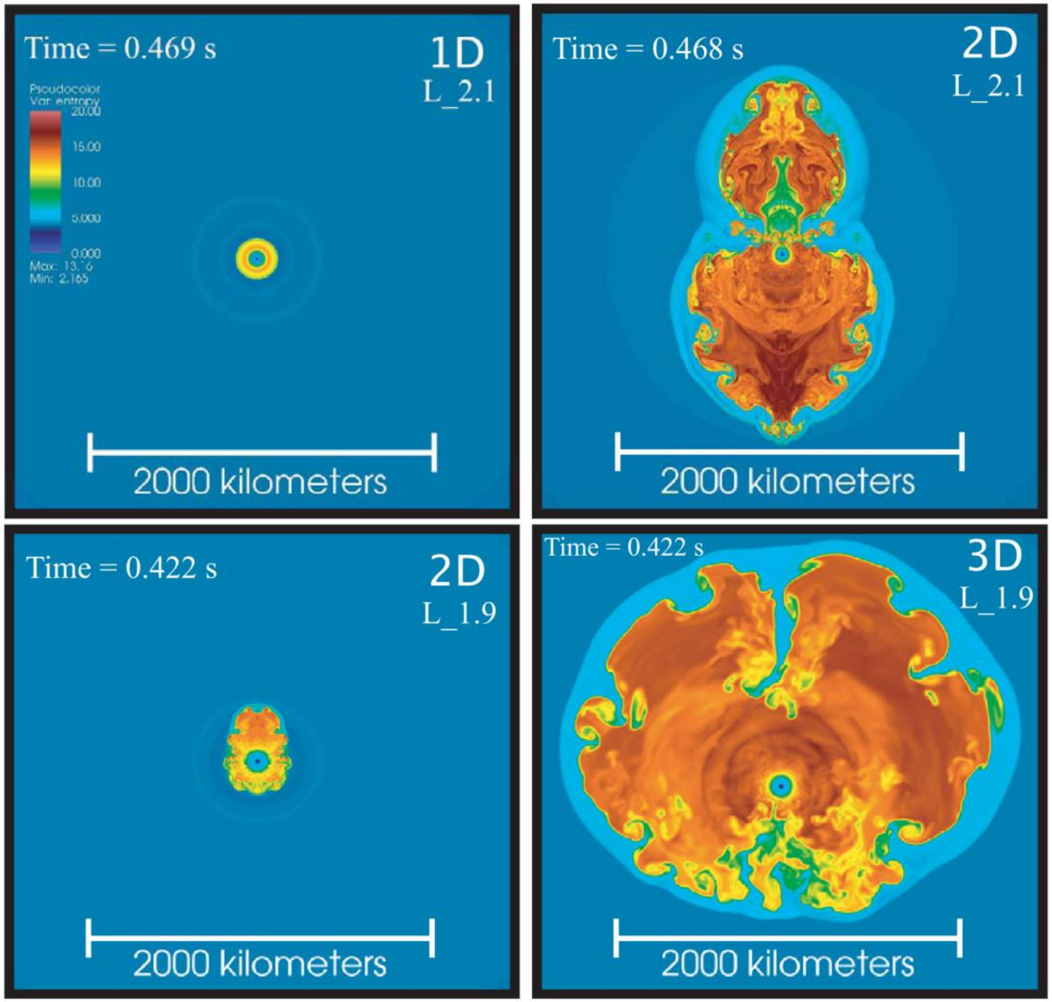

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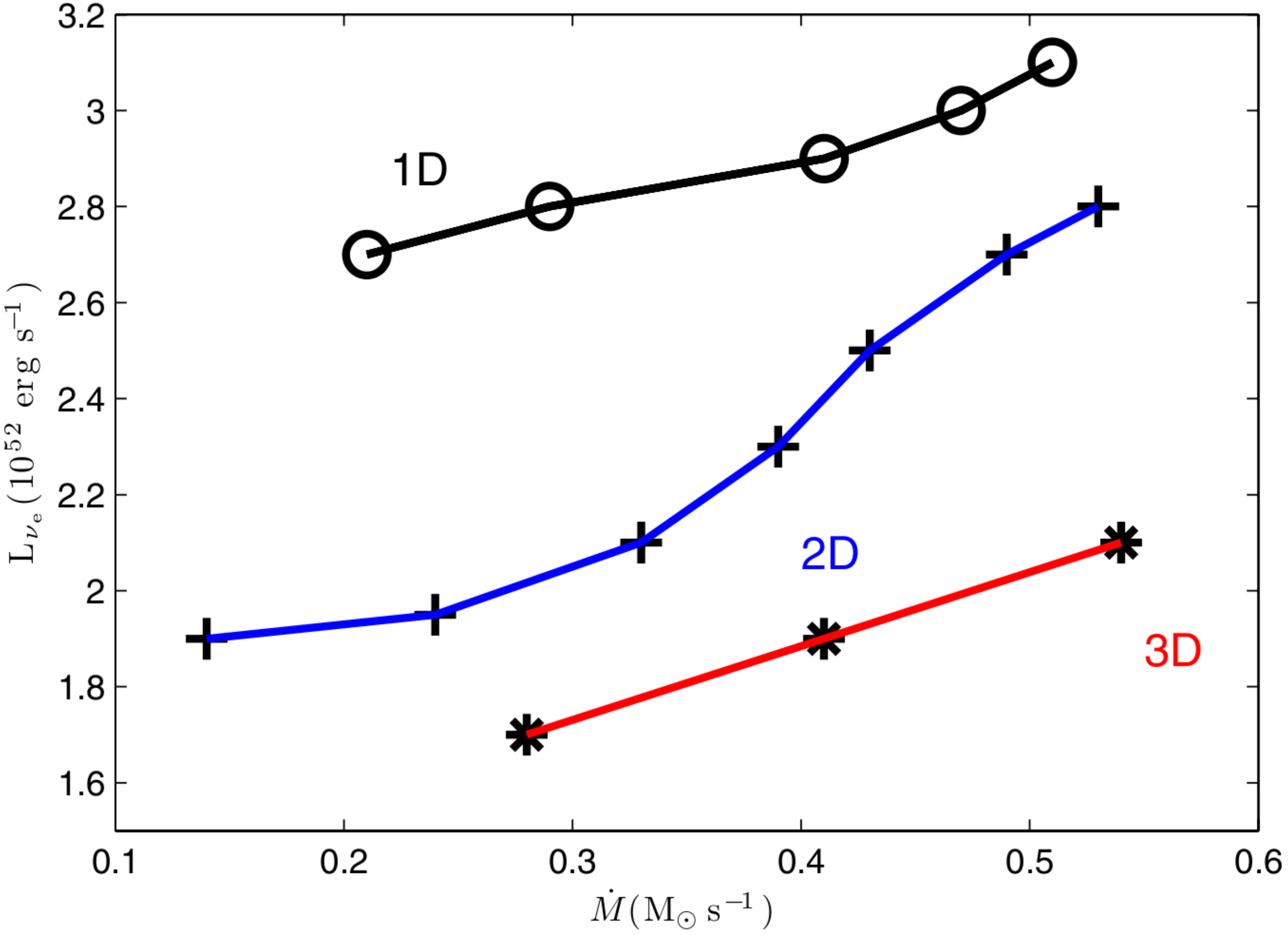
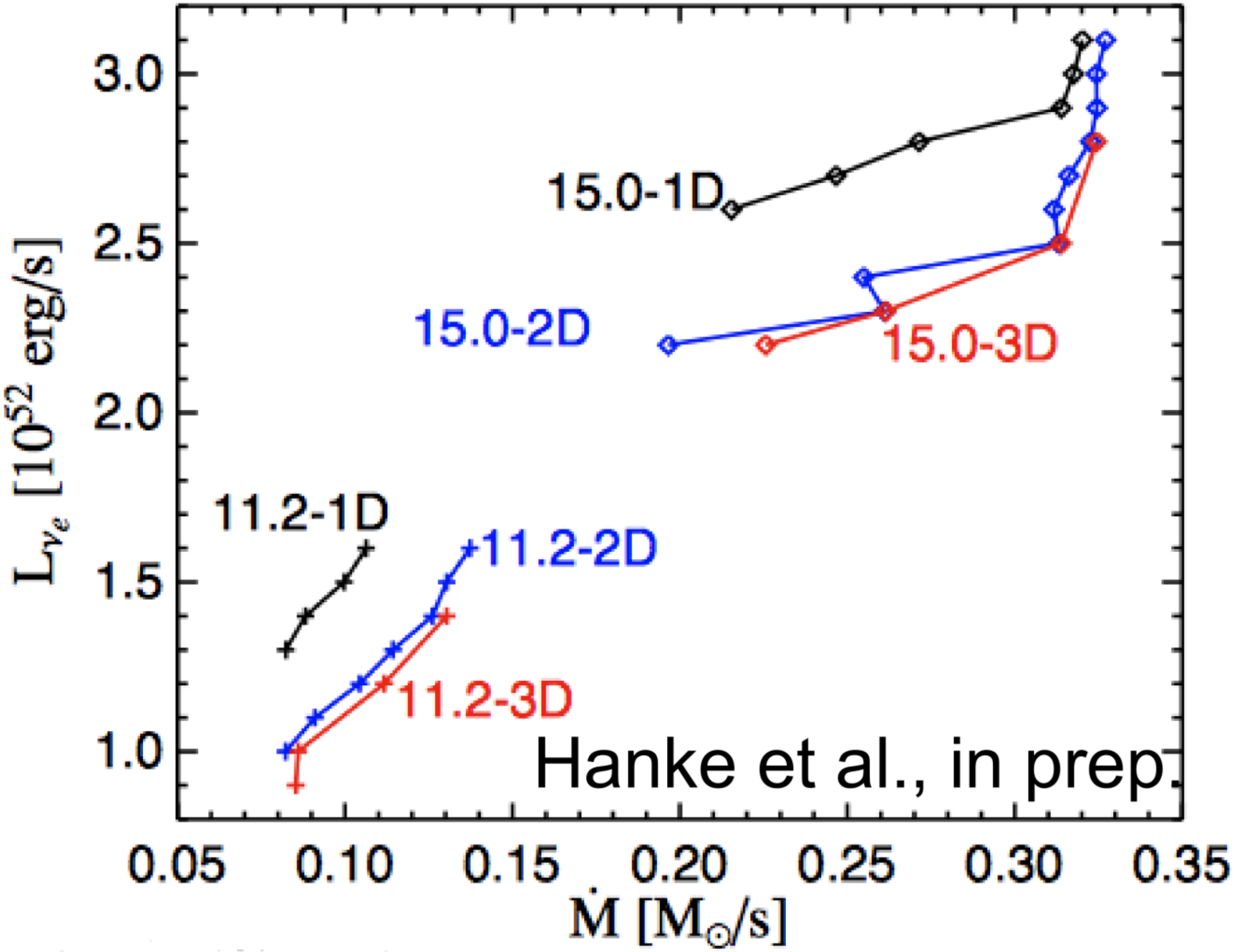


Hanke, Janka, Müller et al. in prep.

- Repeated Nordhaus et al. study
- Results inconsistent. Why?



Alternatives to the Neutrino Mechanism

Magnetorotational Mechanism

[LeBlanc & Wilson 1970, Bisnovatyi-Kogan et al. 1976, Meier et al. 1976, Symbalisty 1984]

Acoustic Mechanism

[proposed by Burrows et al. 2006, 2007; not (yet?) confirmed by other groups/codes]

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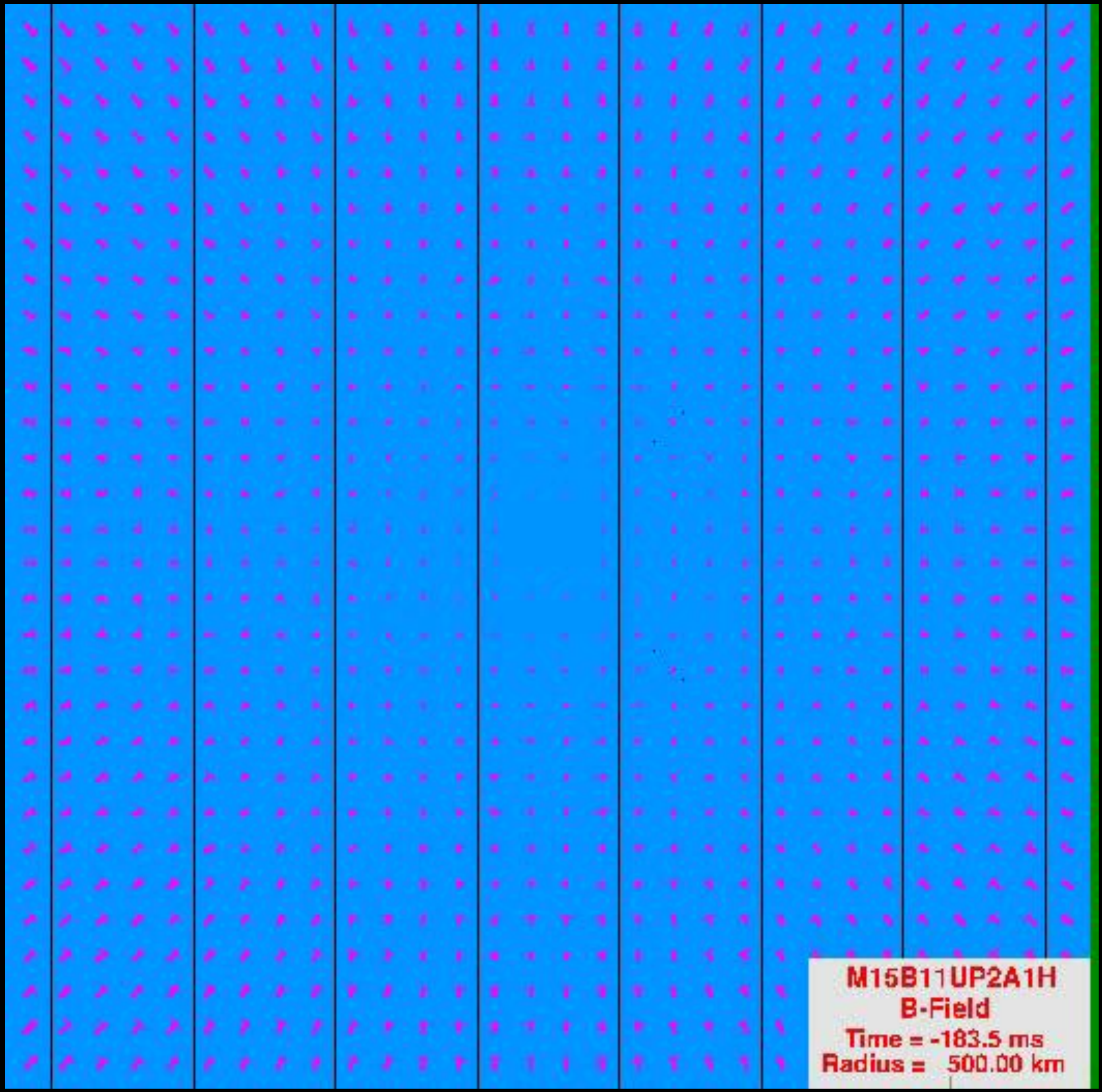
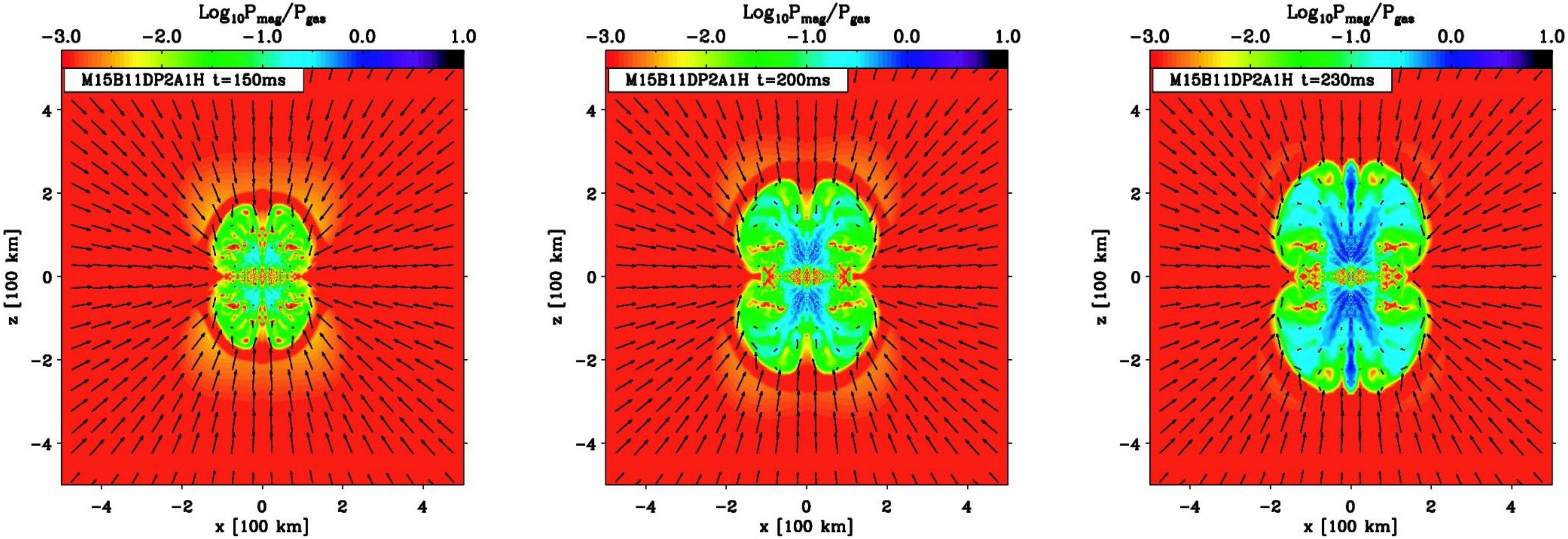
MHD-driven Explosions

[e.g., Burrows et al. 2007, Dessart et al. 2008, Kotake et al. 2004, Yamada & Sawai 2004, Sawai et al. 2008, Takiwaki et al. 2009]

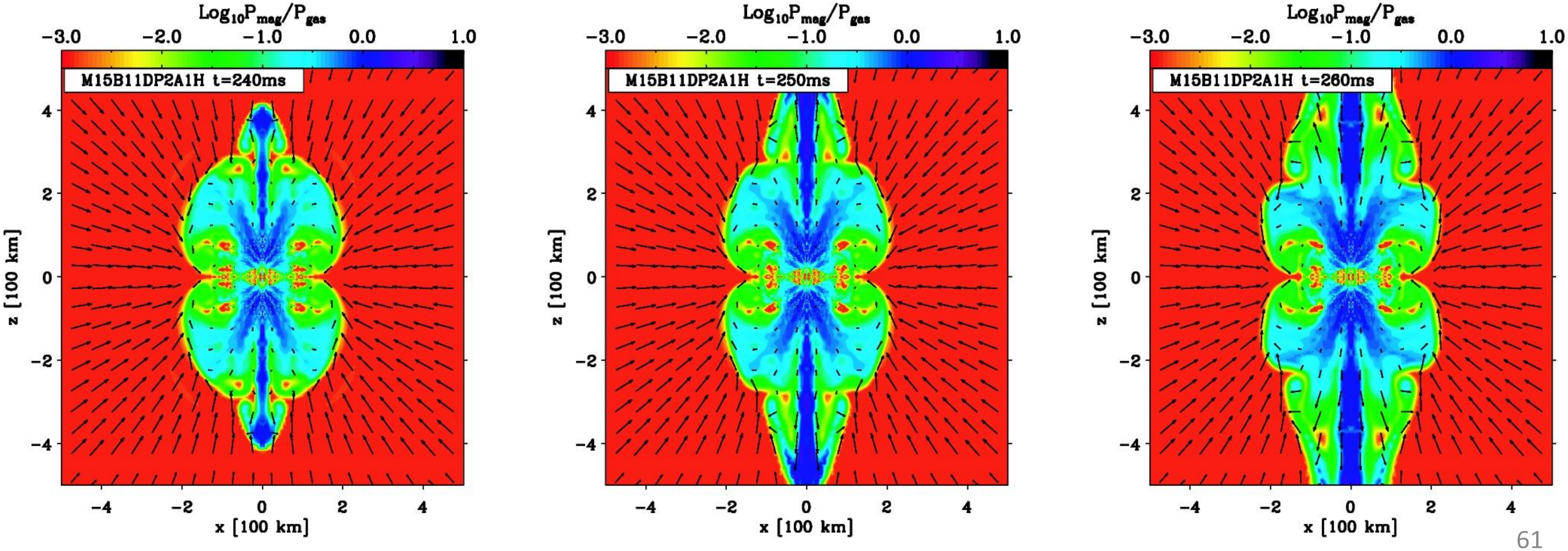
- **Rapid rotation**:
  $P_0 < 4\text{-}6$ s
  -> millisecond PNS
- PNS rotational energy: ~10 B
- Amplification of B fields up to equipartition:
  - compression
  - dynamos
  - magneto-rotational instability (MRI)
- Jet-driven outflows.
- MHD-driven explosion may be GRB precursor.



VULCAN 2D R-MHD code, Livne et al. 2007, Burrows et al. 2007.



MHD jet/explosion launched when $P_{mag} / P_{gas} \sim 1$



Features/Limitations of the Magnetorotational Mechanism

[Burrows et al. 2007]

- Jet powers up to 10 B/s (10^{52} erg/s).
- **Simultaneous explosion and accretion**.
- **Hypernova** energies (> 10 B) attainable.
- MHD mechanism inefficient for cores with precollapse $P_0 > 4$ s, but stellar evolution + NS birth spin estimates: **$P_0 > 30$ s in most cores**.

  [Heger et al. 2005, Ott et al. 2006]
- MHD explosion — a GRB precursor?
- Limitations: Resolution does not allow to capture Magnetorotational Instability;
  Simulations 2D and Newtonian.

Alternatives to the Neutrino Mechanism

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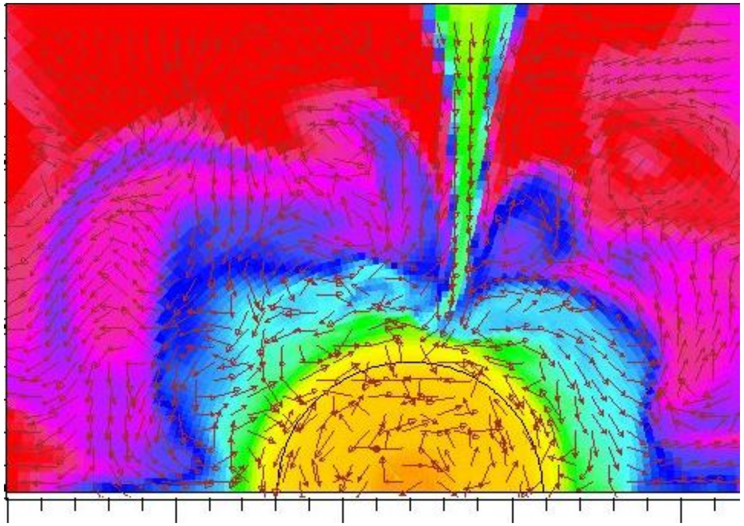
[LeBlanc & Wilson 1970, Bisnovatyi-Kogan et al. 1976, Meier et al. 1976, Symbalisty 1984]

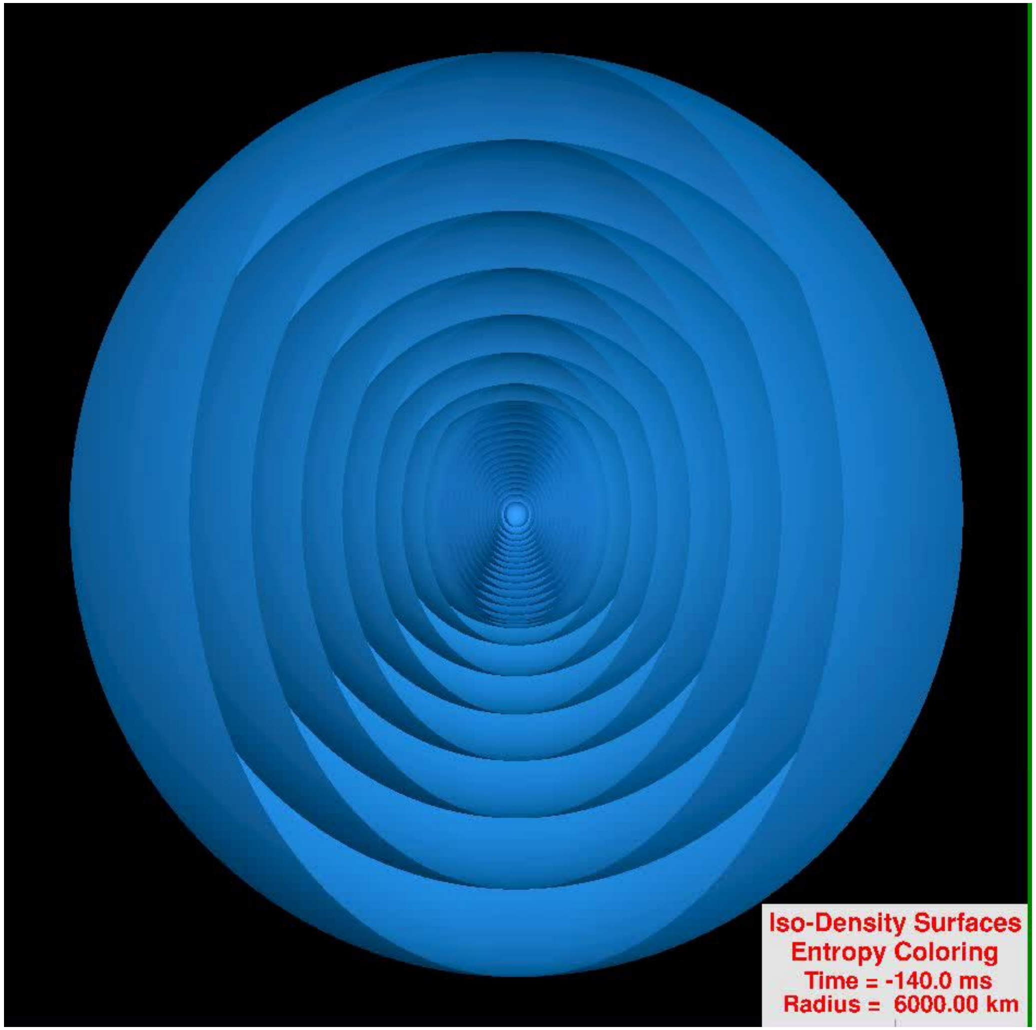
Acoustic Mechanism

[proposed by Burrows et al. 2006, 2007; not (yet?) confirmed by other groups/codes]

Alternatives: The Acoustic Mechanism

SASI-modulated supersonic accretion streams and SASI generated turbulence excite lowest-order (l=1) g-mode in the PNS. f $\approx$ 300 Hz.





- g-modes reach large amplitudes ~500 ms —1 s after bounce.
- Damping by strong sound waves that steepen into shocks; deposit energy in the stalled shock.
- ~1 B explosions at late times.
- (1) hard to simulate; unconfirmed, (2) **possible parametric instability, limiting mode amplitudes** (Weinberg & Quataert '08).

Summary and Take-Home Messages (Part I)

- Core-Collapse Supernovae are **Gravity Bombs**.
  CCSNe are the most energetic explosive events in the universe.
  CCSNe are rare events in the local group of galaxies.

- **The Core-Collapse Supernova Problem**:
  The shock always stalls and must be revived.

- There are multiple possible supernova mechanisms:
  Neutrino, magnetorotational, and acoustic mechanism.

- What I did not talk about:
  CCSN postbounce dynamics can be observed directly in neutrinos and gravitational waves!
  -> next galactic CCSN will provide answers.

“I like things that explode –

nukes, supernovae, and orgasms.”

– attributed to Stirling Colgate