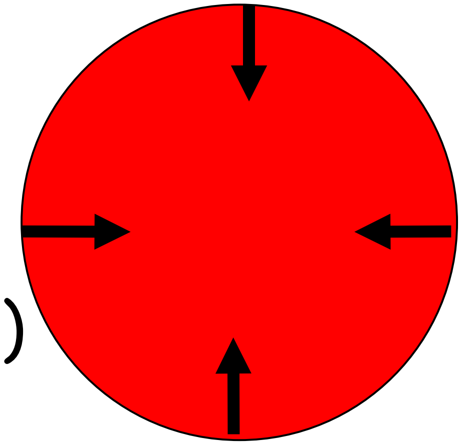
Core collapse triggered by K-captures, photodissociation

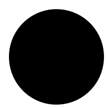
Collapse
(only core
inner ~1.5 $M_{\odot}$)
Free-fall



1000 km

10^{10} g cm^{-3}

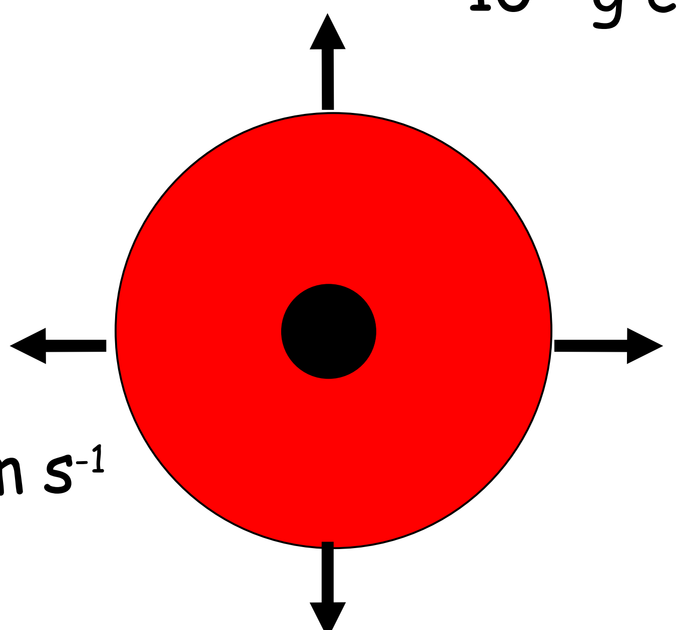
Bounce
Shock wave



30 km
nuclear dens.
~ 10^{14} g cm^{-3}

Nuclear
repulsion

Explosion



V ~ 10^{4} km s^{-1}

Collapse time scale

$$\tau_{coll} \approx \frac{R}{V_{ff}} \approx 10^{-3} \left(\frac{\rho}{10^{12}\ g\ cm^{-3}} \right)^{-1/2} \ \mathrm{s}$$

Neutrino scattering

elastic scattering of free nucleons

$$\nu + n \rightarrow \nu + n$$

$$\nu + p \rightarrow \nu + p$$

elastic scattering against nuclei (NC)

$$\nu + (Z,A) \rightarrow \nu + (Z,A)$$

inelastic scattering

$$\nu + e \rightarrow \nu + e$$

Free nucleon scattering

$$\sigma = \frac{1}{4}\sigma_0 \left(\frac{E_\nu}{m_e c^2}\right)^2$$

$$\sigma_0 = 1.76\times 10^{-44} \qquad \text{cm}^2$$

Coherent scattering off bound nucleons

$$\sigma = \frac{1}{16}\sigma_0 \left(\frac{E_\nu}{m_e c^2}\right)^2 A^2 \left[1 - \frac{Z}{A} + \frac{Z}{A}(4\, sin^2\theta_W - 1)\right] \; 2$$

$$sin^2\theta_W = 0.23 \approx 0.25$$

$$\sigma_\nu \approx \frac{1}{64}\sigma_0 \left(\frac{E_\nu}{m_e c^2}\right)^2 A^2$$

Mean free path

$$\lambda_\nu \approx 1.0\times 10^8 \left[\frac{N^2}{6\text{A}} X_{bound} + X_{nucleon}\right]^{-1} \rho_{12}^{-1} E_{MeV}^{-2} \qquad \text{cm}$$

Mean free path

$$\lambda_\nu = 2\times 10^5 \left(\frac{E_\nu}{10\ \ MeV}\right)^{-2} \rho_{12}^{-1} \qquad \text{cm}$$

diffusion time scale (random walk)

$$t_{diff} \approx \frac{\Delta R^2}{3\lambda_\nu c}$$

more exactly for spherical geometry

$$t_{diff} \approx \frac{3R^2}{\pi^2 \lambda_\nu c}$$

$$t_{diff} \approx 3.9\times 10^{-3} \left(\frac{E_\nu}{10\ \ MeV}\right)^{2} \rho_{12}^{1/3} \qquad \text{s}$$

$$t_{diff} \approx 3.9\times 10^{-3}\left(\frac{E_\nu}{10\quad MeV}\right)^2 \rho_{12}^{1/3}$$ s

Typical ν energy

$$E_\nu \approx E_F = 36.8\,\rho_{12}^{1/3}\,MeV$$ MeV

$$t_{diff} \approx 5.2\times 10^{-2}\,\rho_{12}$$ s

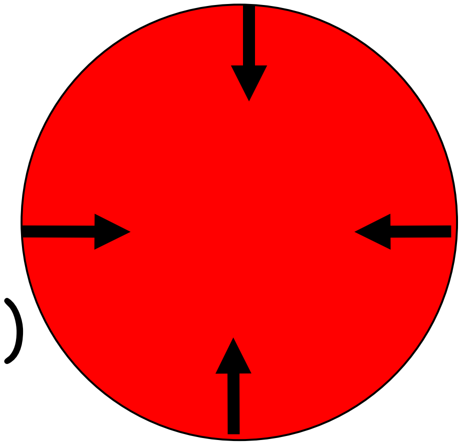
$$\frac{t_{diff}}{t_{dyn}} \approx 40\,\rho_{12}^{3/2}$$

ν:s will be trapped in collapsing core above ~ 10^{11} g cm^{-3}!

Collapse adiabatic above trapping density γ ~ 4/3

Bounce

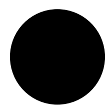
Collapse
(only core
inner ~1.5 M_O)
Free-fall



1000 km

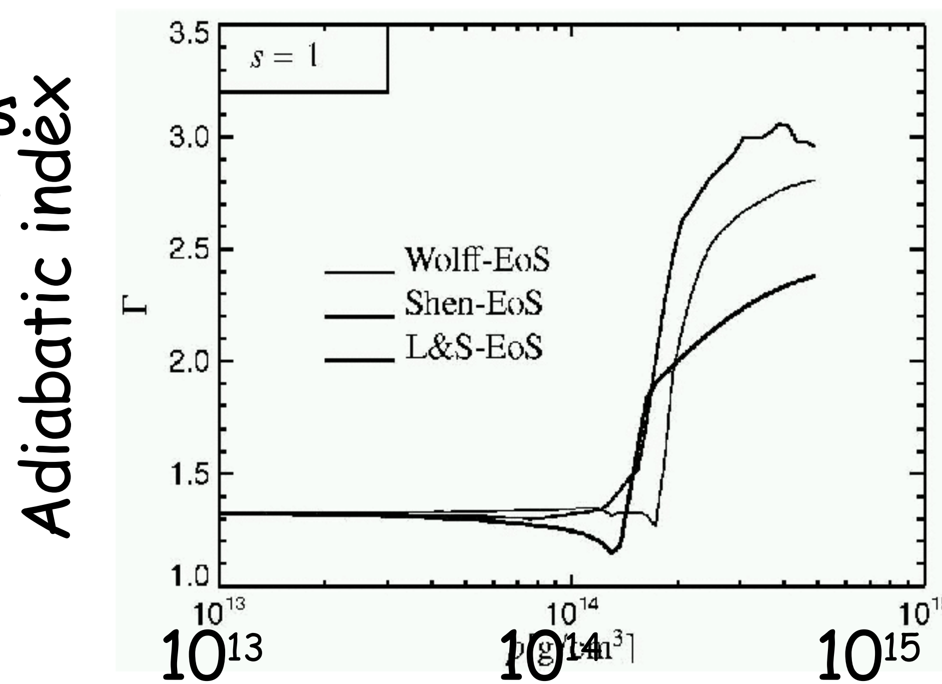
10^{10} g cm^{-3}

Bounce
Shock wave

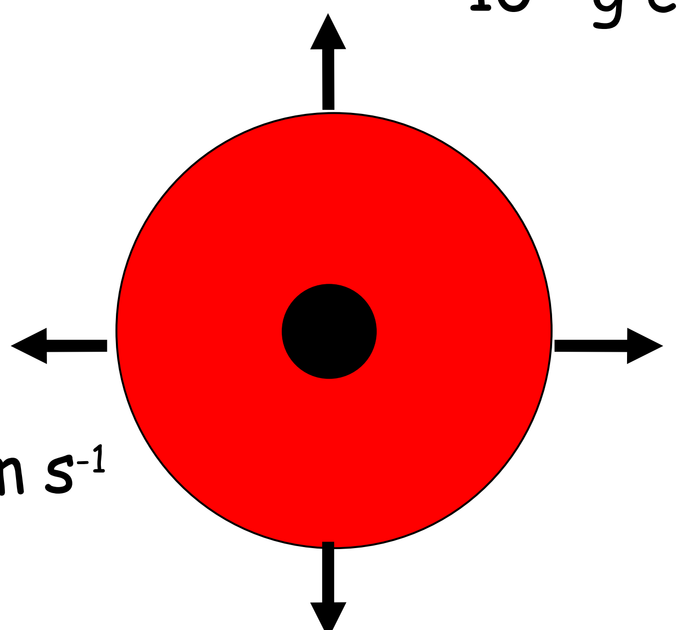


30 km
nuclear dens.
~ 10^{14} g cm^{-3}

Nuclear
repulsion

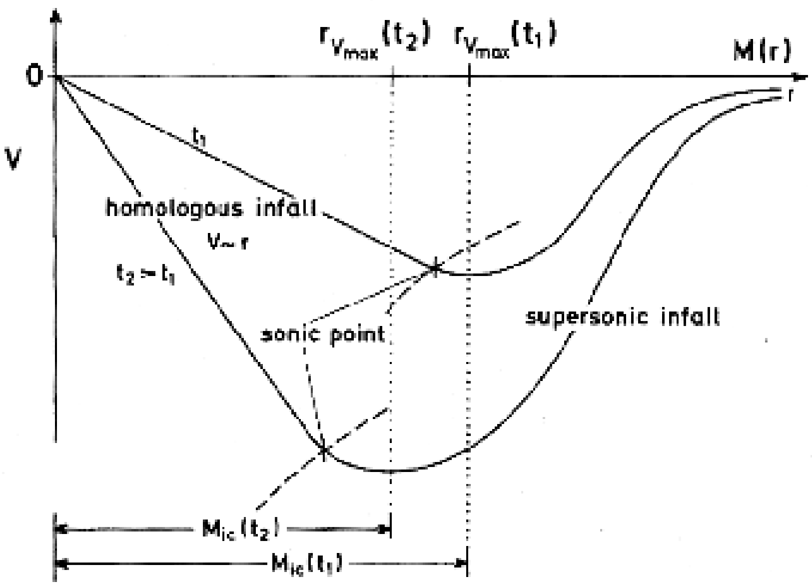


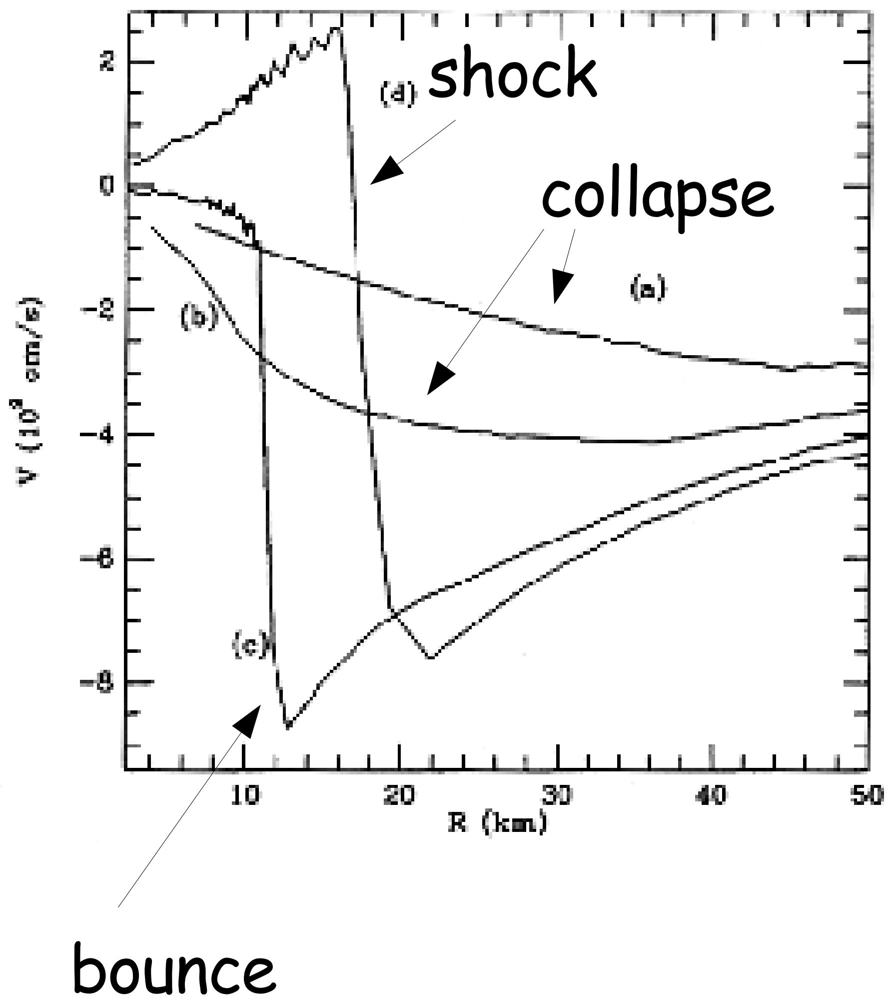
Explosion



V ~ 10^4 km s^{-1}

Collapse

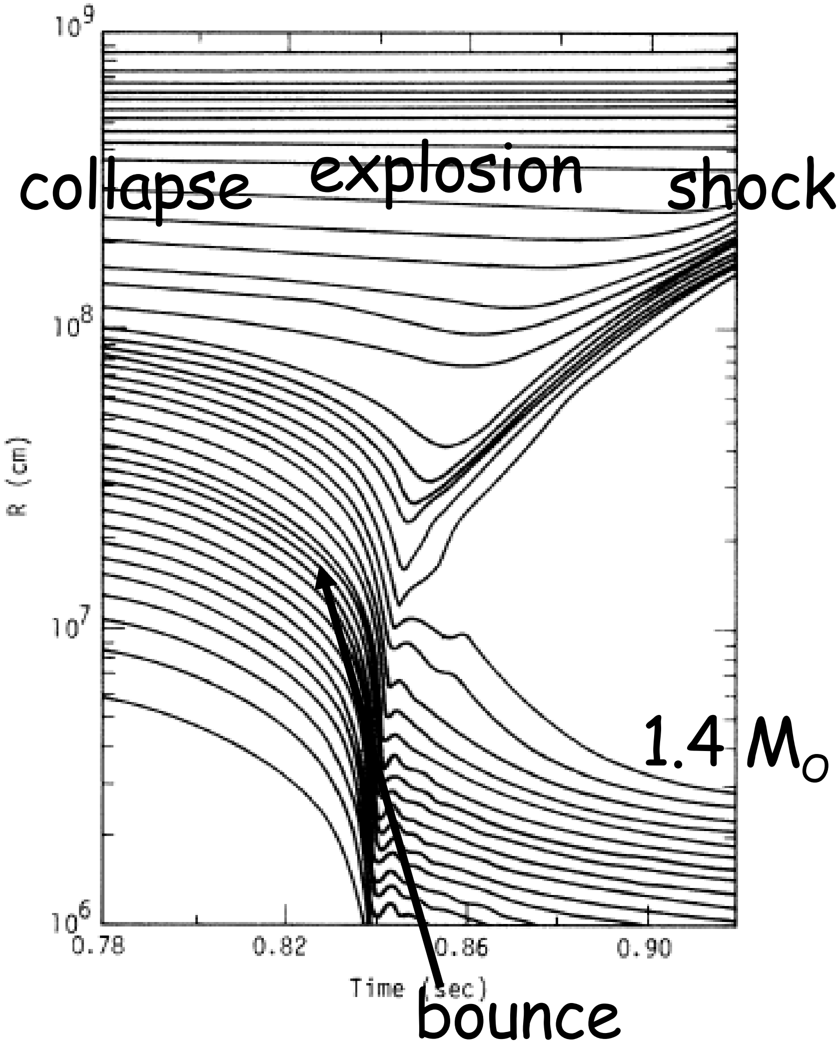




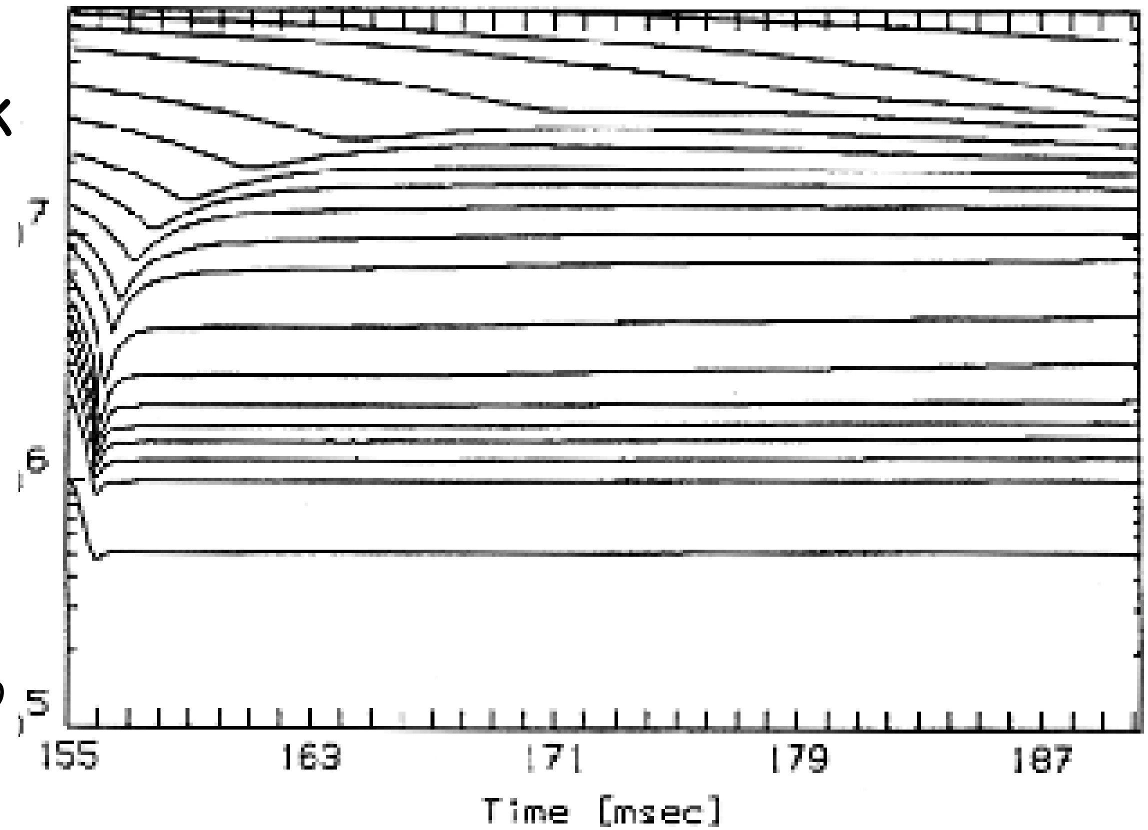
Before bounce:
Homologous inside sonic radius

Explosion?

Wilson 1974



Hillebrandt 1981

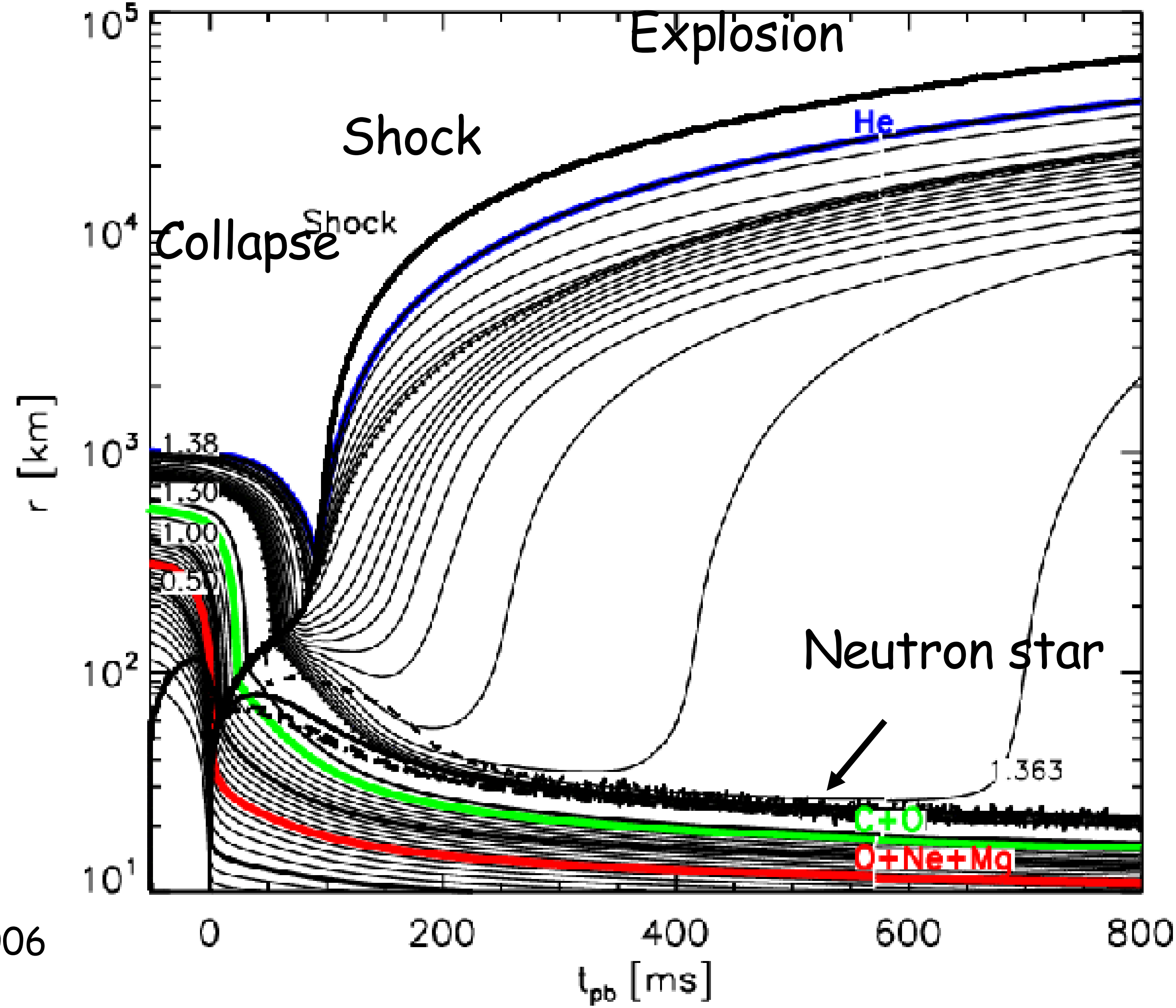


All lacking some essential physics! (neutrino transport, EOS, 2/3D….)

Success?

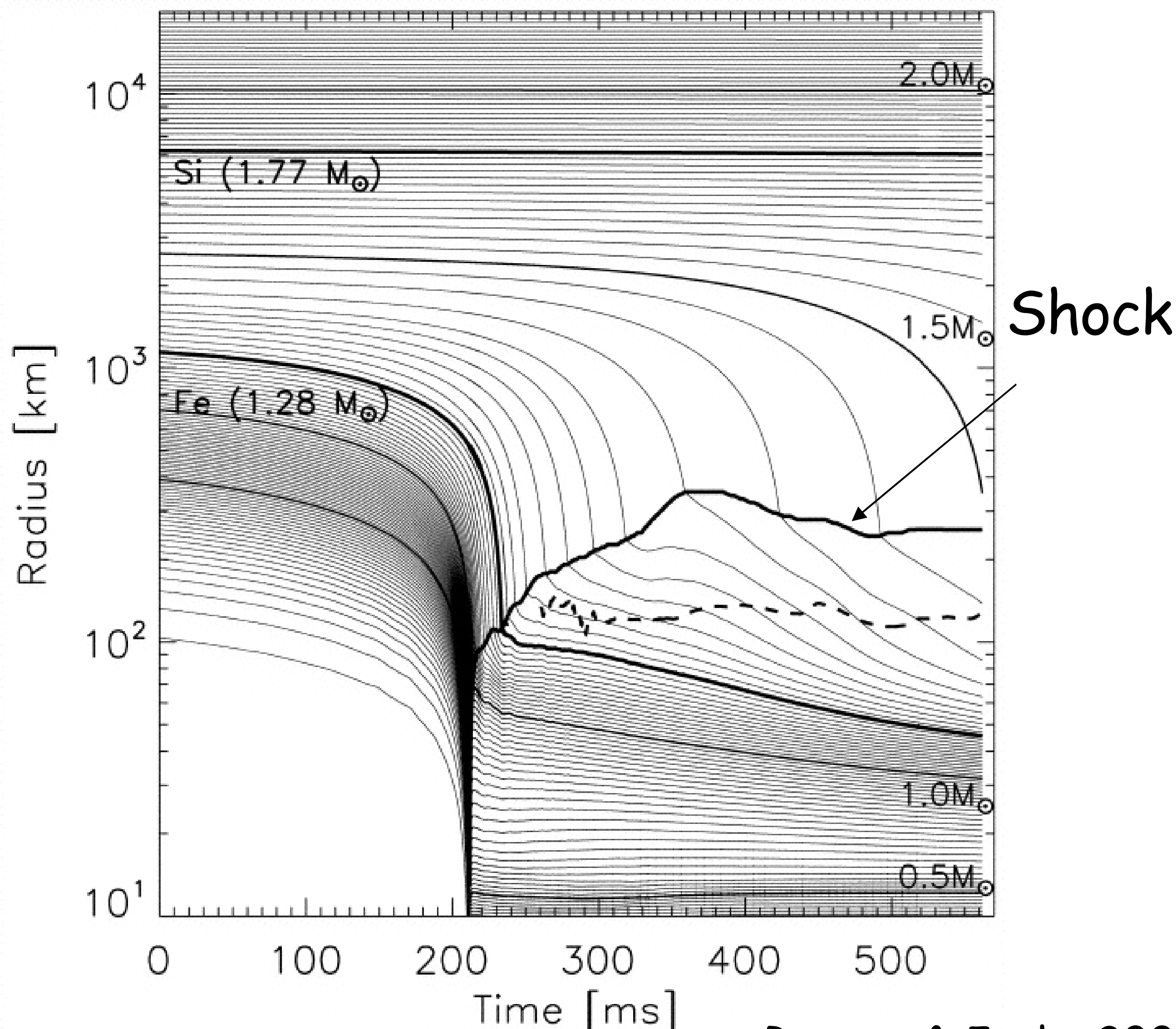
Progenitor

11 M_O



Kitaura et al 2006

Black holes in most cases!



Rampp & Janka 2000

Photodissociation of Fe

$^{56}Fe + \gamma \rightarrow 13\alpha + 4\,n$

ν-losses

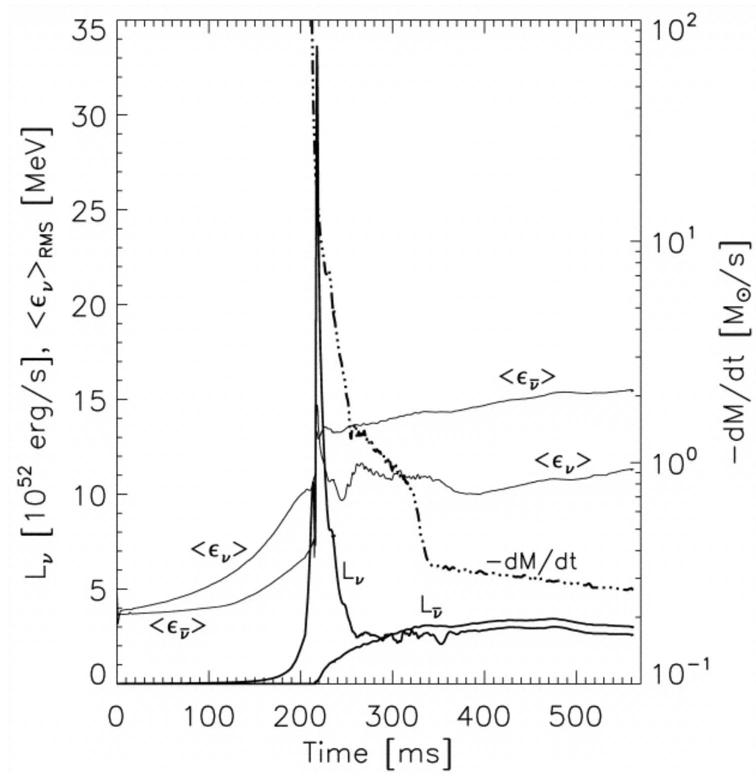
Except for low mass stars (< 12 $M_\odot$) shock stalls and collapse continues

Total energy = binding energy of neutron star

$$E \approx \frac{GM_{core}^2}{R_n} \approx 3\times 10^{53} \quad \text{ergs}$$

Release time scale ≈ ν diffusion time scale

$$\tau_{diff} \approx 5 \left(\frac{\rho}{\rho_{nuclear}} \right) \quad \text{s}$$

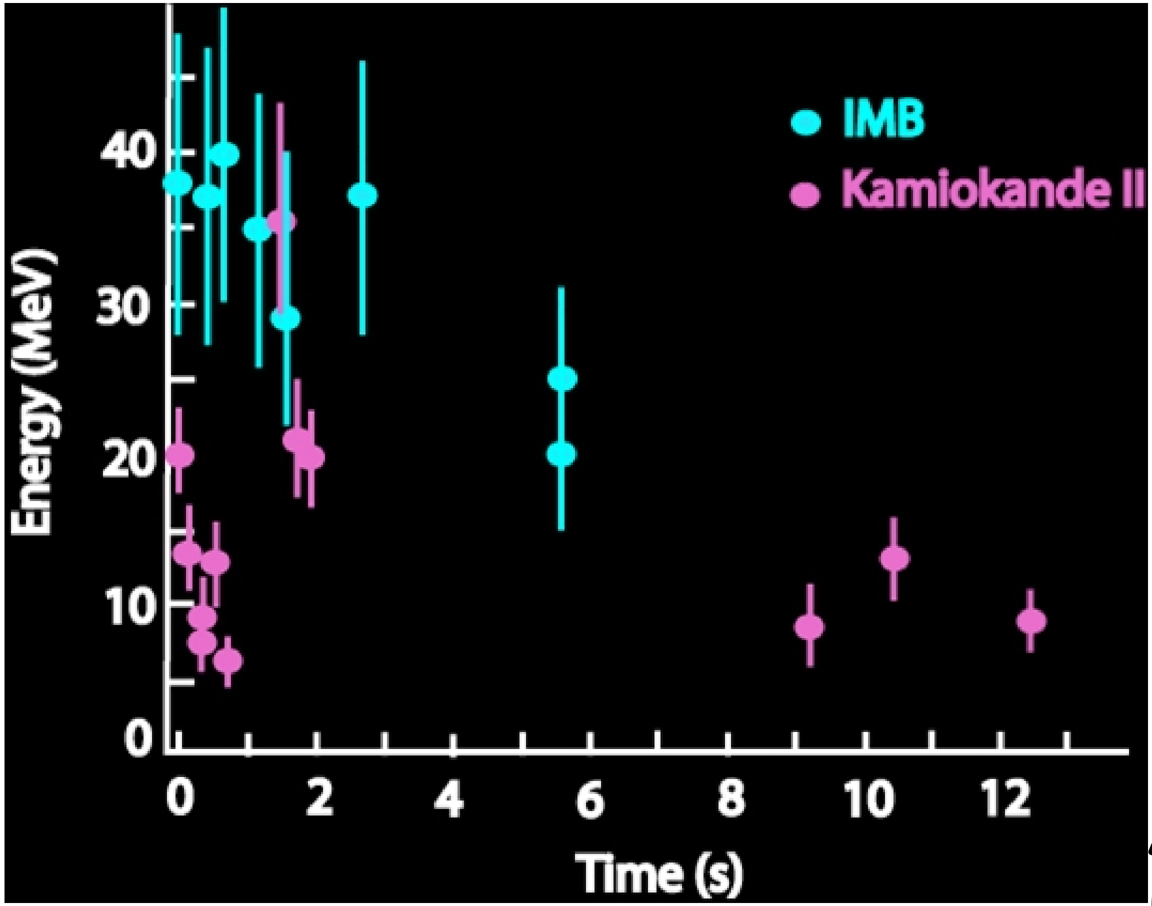


Mean energy 10-15 MeV

Trapping equilibrium creation of all neutrino species

Neutrinos

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



Also ~5 νs from Baksan

E($\bar{\nu}_e$) ~ 6x10^{52} ergs. Equal amounts of all 6 ν:s ⇒

E_{tot} ~ (3-4)x10^{53} ergs τ ~ 5 s Mean energy ~ 15 MeV

A history of failures....

1965 Colgate & White neutrino heating

1970-1980 Arnett, Bethe, Brown, Wilson

EOS, neutrino transport prompt explosion. No!

198? J. Wilson Late neutrino heating

Woosley, Nomoto: progenitor models: Fe core mass.........

1990 Janka, Burrows... neutrino convection 2D, 3D

2000 - Large scale instabilities, rotation, 2D, 3D........

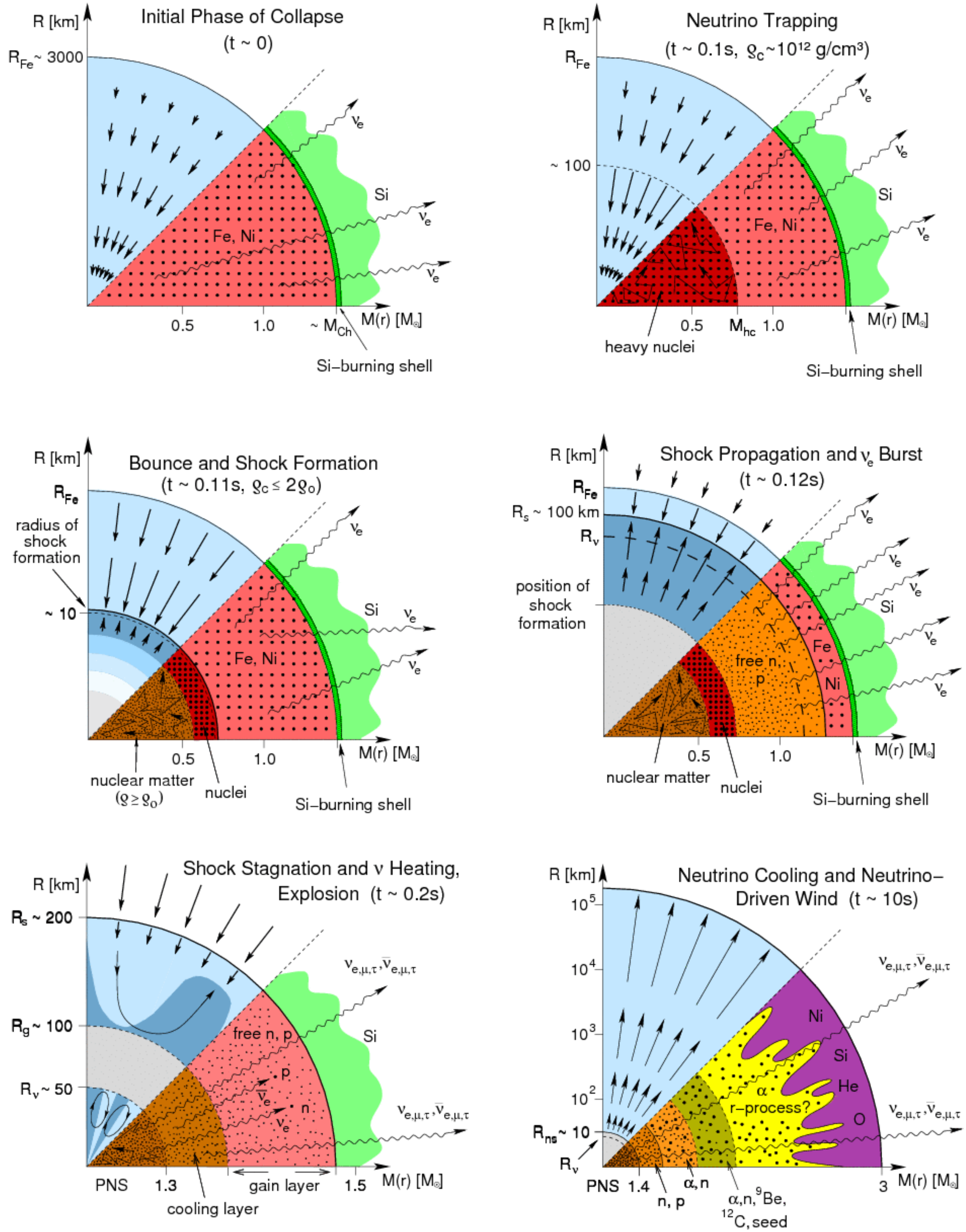
collapse

ν-trapping

bounce shock

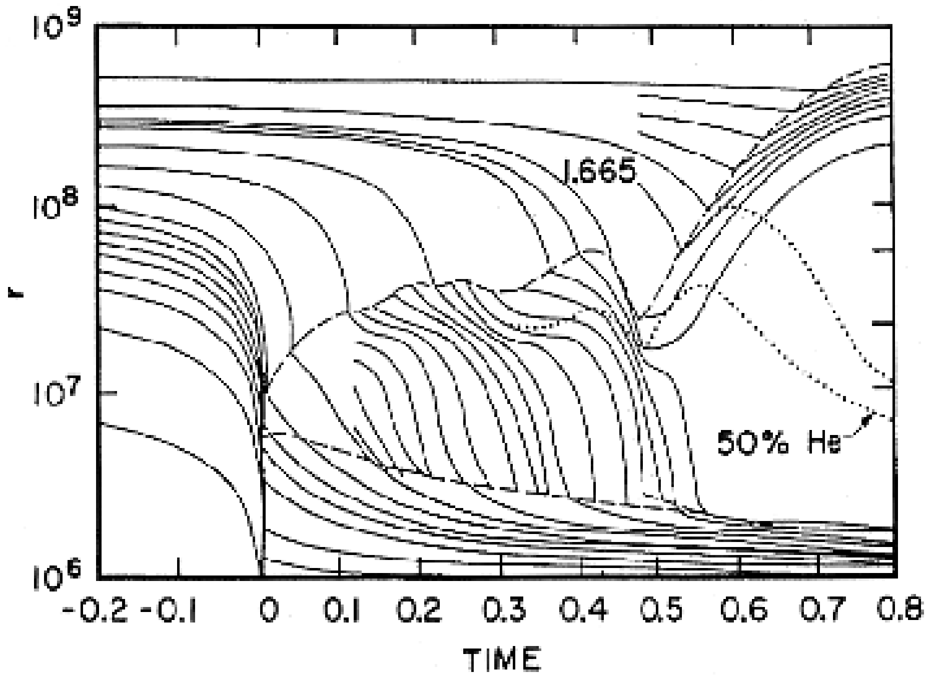
ν-heating

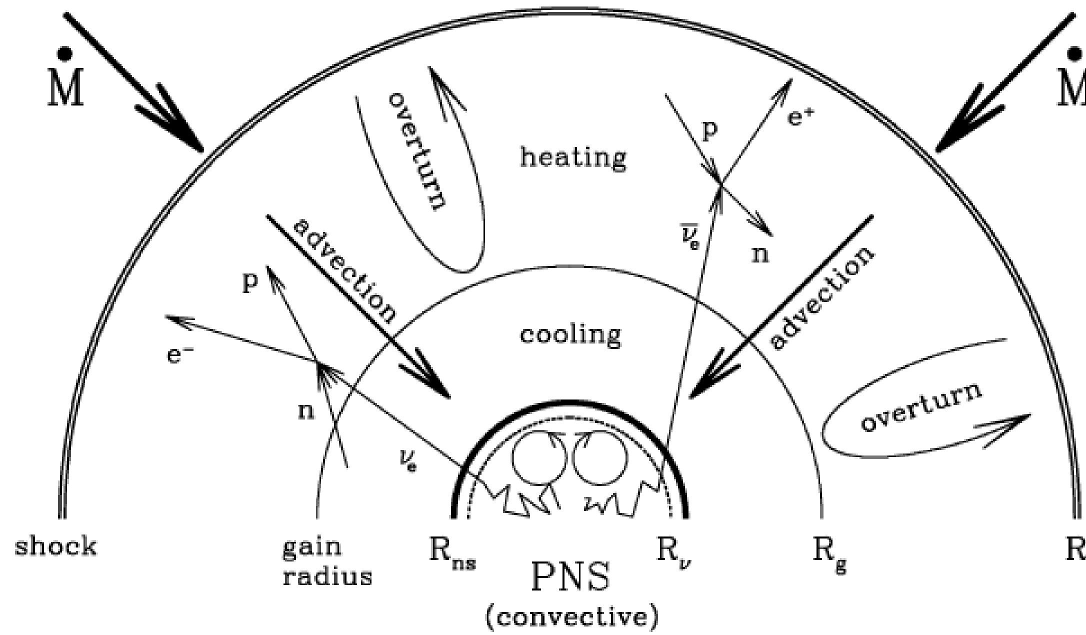
Explosion, ν driven wind



Janka et al 2006

Delayed neutrino heating?





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

J. Wilson + H. Bethe 1985

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

Neutrino heating

$$\bar{\nu} + p \rightarrow e^{+} + n$$

$$\nu + n \rightarrow e^{-} + p$$

Heating rate

$$H_{\nu}(r) = \frac{4\pi}{(c\,h)^3} \int c\,\sigma(E_{\nu})\,E_{\nu}\,W(r)\,f(E_{\nu})\,E_{\nu}^2\,dE_{\nu}$$

$$f(E_{\nu}) = \frac{1}{e^{E_{\nu}/kT\,\nu} + 1}$$

Dilution factor

$$W(r) = \frac{1}{2}\left[1 - \sqrt{1 - (R_{\nu}/r)^2}\right]$$

radius of 'neutrinosphere'

For cooling we need

$$\sigma_{e^- + p \rightarrow \nu + n}$$

Detailed balance

$$\sigma_{i \rightarrow f} \quad g_i \, p_i^2 = \sigma_{f \rightarrow i} \quad g_f \, p_f^2$$

$$g_\nu = 1 \qquad g_e = 2 \qquad p_\nu = E_\nu / c \qquad p_e \approx E_e / c$$

¿

$$E_\nu^2 \quad \sigma_{\nu + n \rightarrow e^- + p} = 2 \, E_e^2 \quad \sigma_{e^- + p \rightarrow \nu + n}$$

Earlier

$$\sigma_{\nu + n \rightarrow e^- + p} = \frac{1}{4} \sigma_0 \left(\frac{E_\nu}{m_e c^2} \right)^2$$

$\Rightarrow$

$$\sigma_{e^- + p \rightarrow \nu + n} = \frac{1}{8} \sigma_0 \left(\frac{E_e}{m_e c^2} \right)^2$$

¿

¿

¿

Cooling rate

$$C_\nu(r) = \frac{\pi \sigma_0 c}{2(c h)^3} \int E^5 f(E) dE$$

$$C_\nu(r) = \frac{31 \pi^7}{252} \frac{m_e^4 c^6}{h^3} \sigma_0 \left(\frac{k T}{m_e c^2} \right)^6$$

¿

$$H_\nu(r) = \frac{31 \pi^7}{252} \frac{m^4 c^6}{h^3} \sigma_0 [W(r) T_\nu^6 - \frac{1}{2} T^6]$$

¿

Net neutrino heating rate

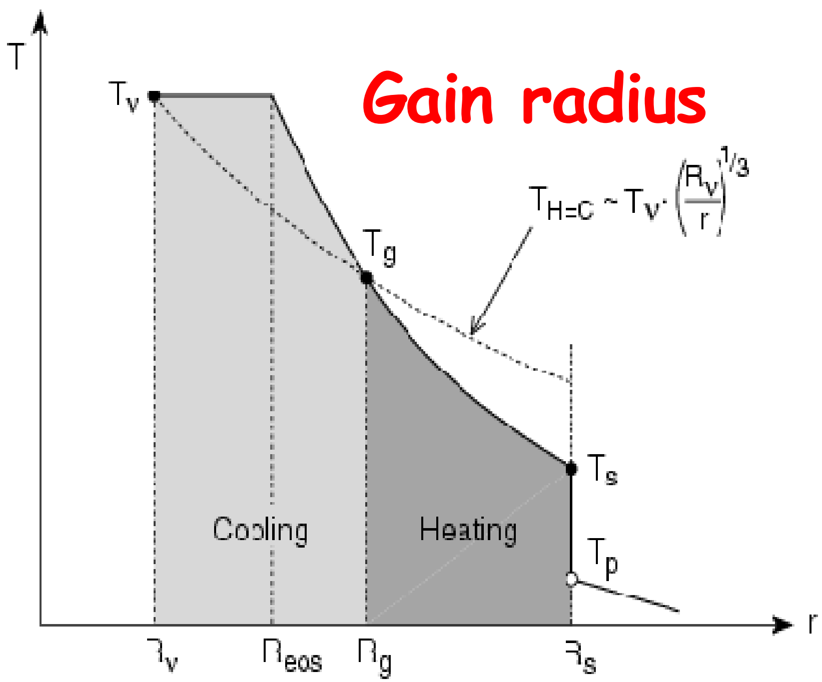
$$H_\nu(r) = \frac{31\pi^7}{252}\frac{m^4c^6}{h^3}\sigma_0[W(r)T_\nu^6 - \frac{1}{2}T^6]$$

Temperature of nucleons set by energy loss due to photodiss.

$$\frac{GMm_p}{r} = E_{bind} + \frac{3}{2}kT$$

Fe to α-particles ~ 2 MeV/nucleon

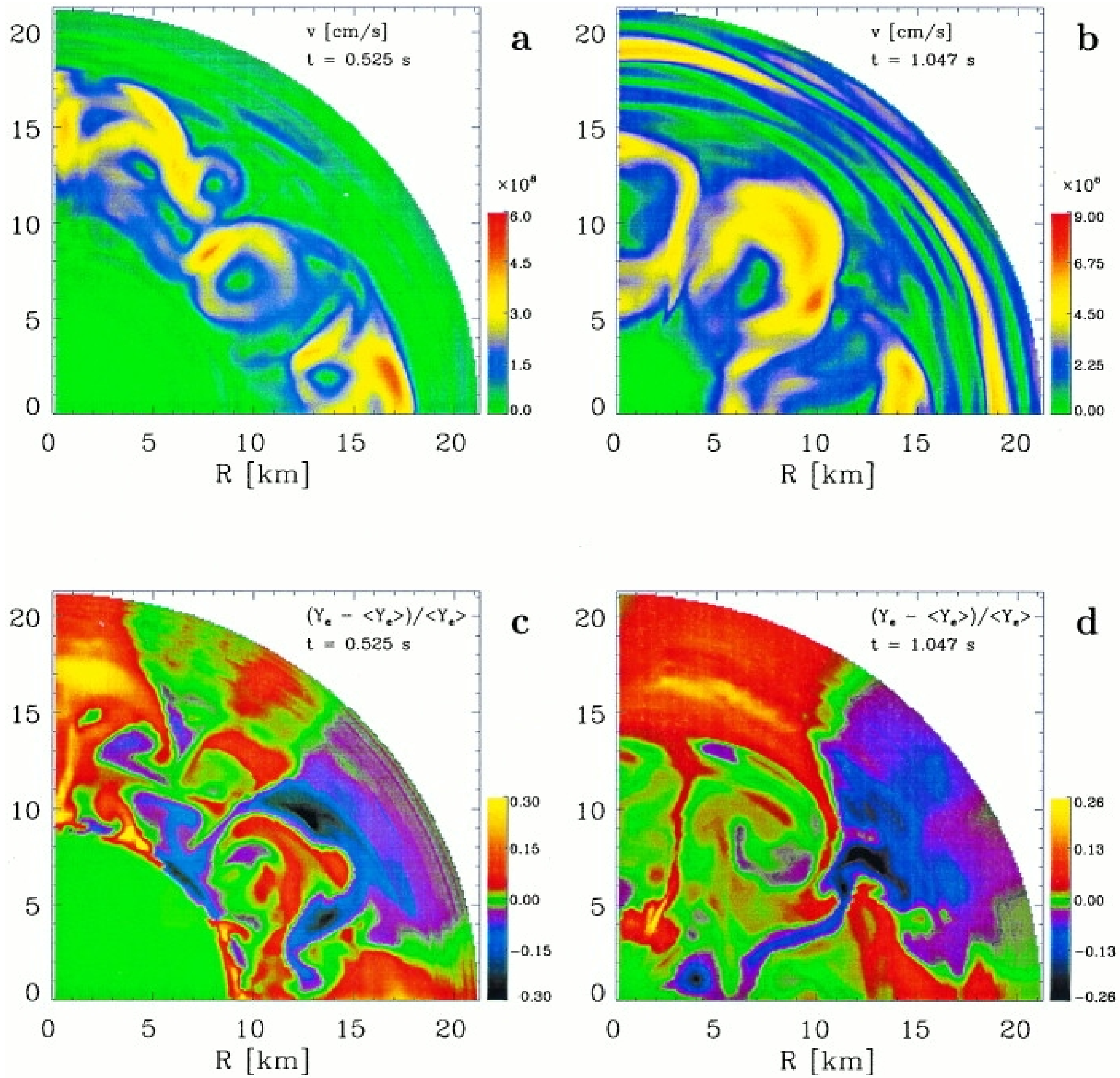
$$T \approx \frac{15}{r_7} - 1.3 \quad MeV$$

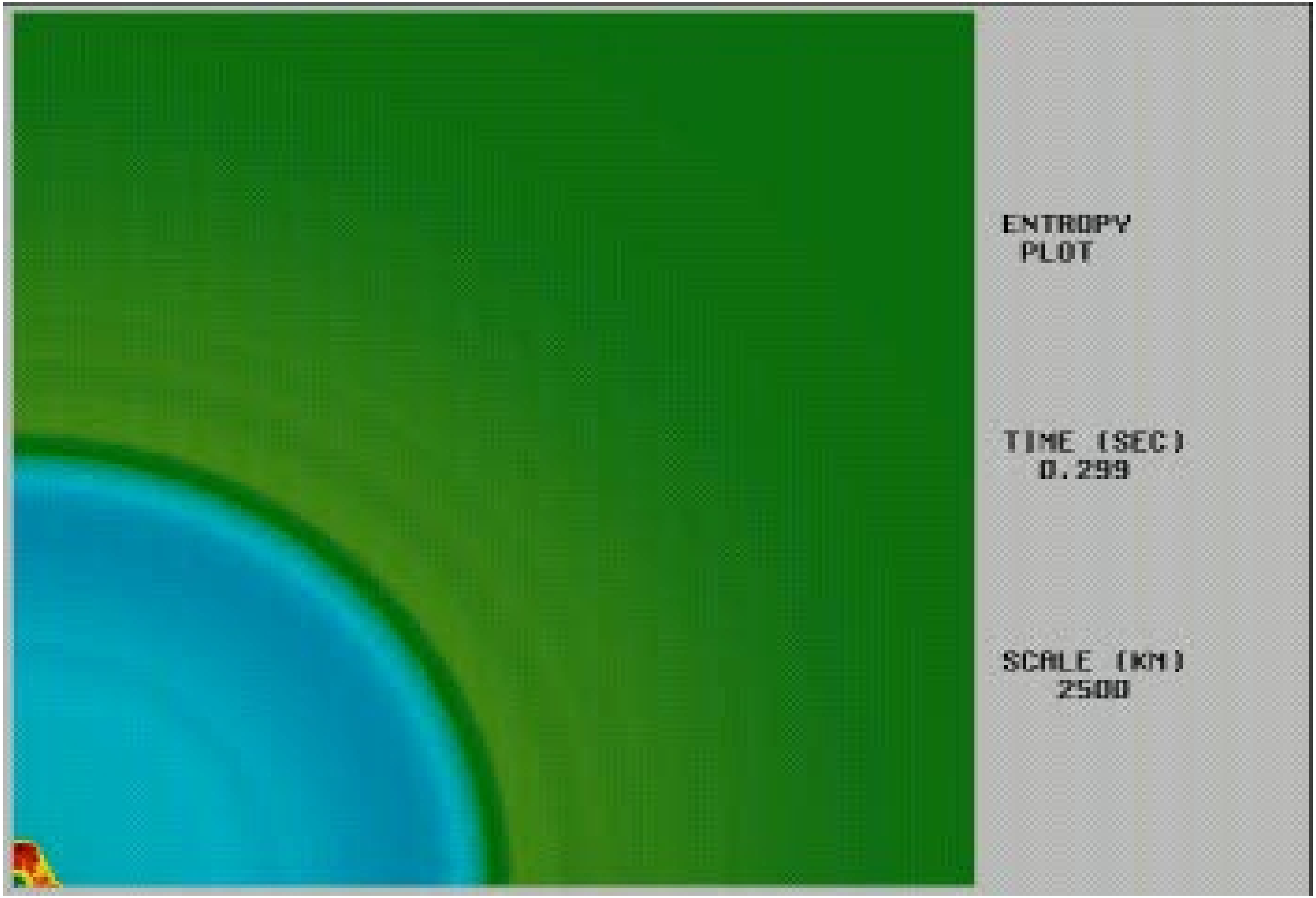


$$W \approx \frac{1}{2}\left(\frac{R_\nu}{r}\right)^2$$

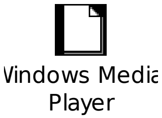
$$T_{H=C} \approx T_\nu\left(\frac{R_\nu}{r}\right)^{1/3}$$

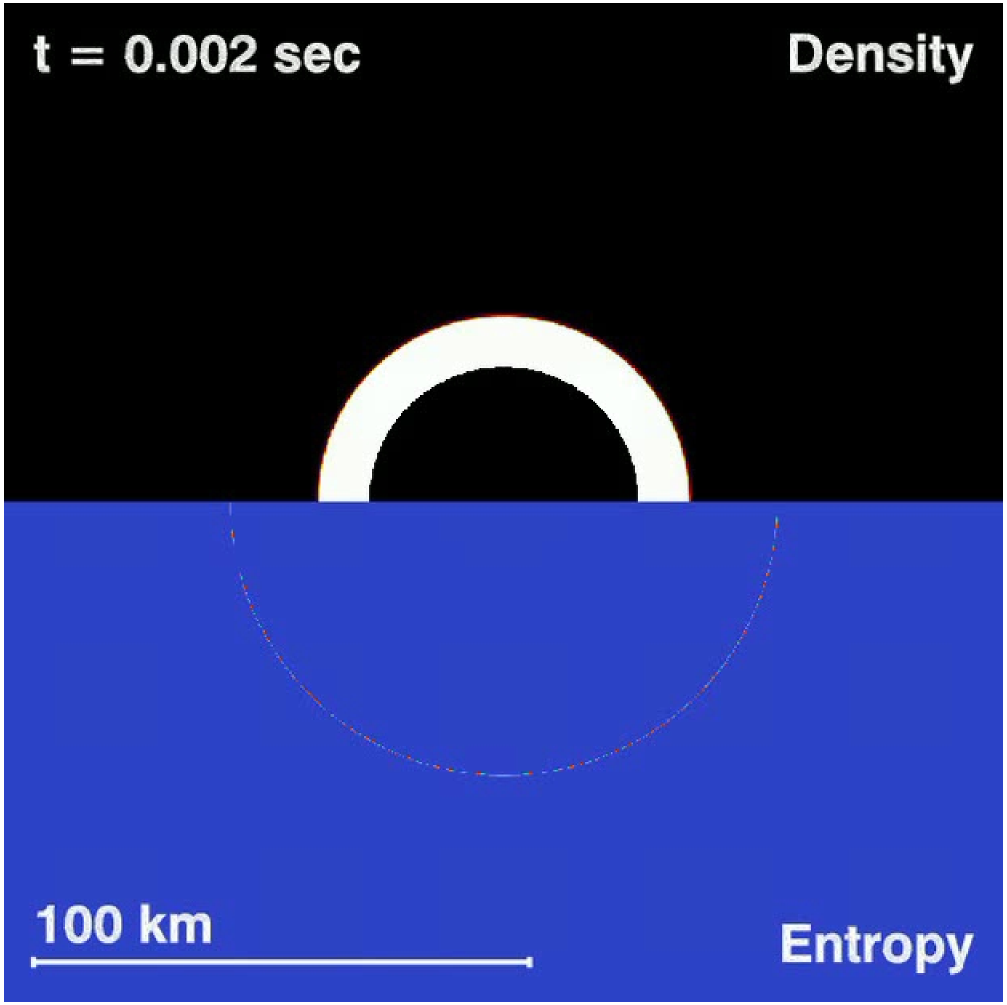
Convection in proto neutron star increases neutrino flux





A. Burrows


Windows Media Player


t = 0.002 sec
Density
100 km
Entropy

Latest ingredient: Large scale shock instabilities

Accretion shock unstable to large scale modes

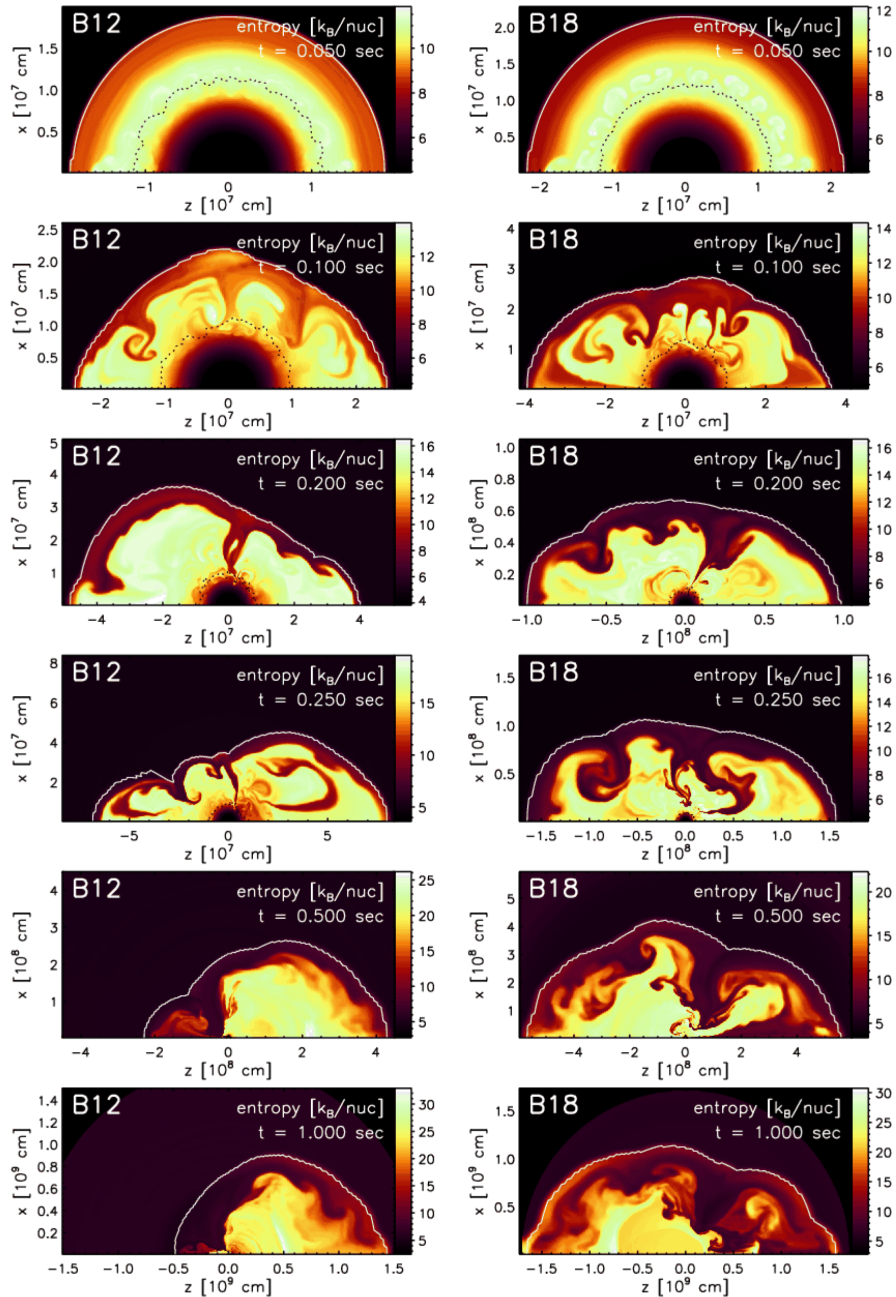
l=1,2

SASI mechanism

Standing Accretion Shock Instability

Proto-neutron star oscillations excited by accretion?

Scheck et al



0.05 s

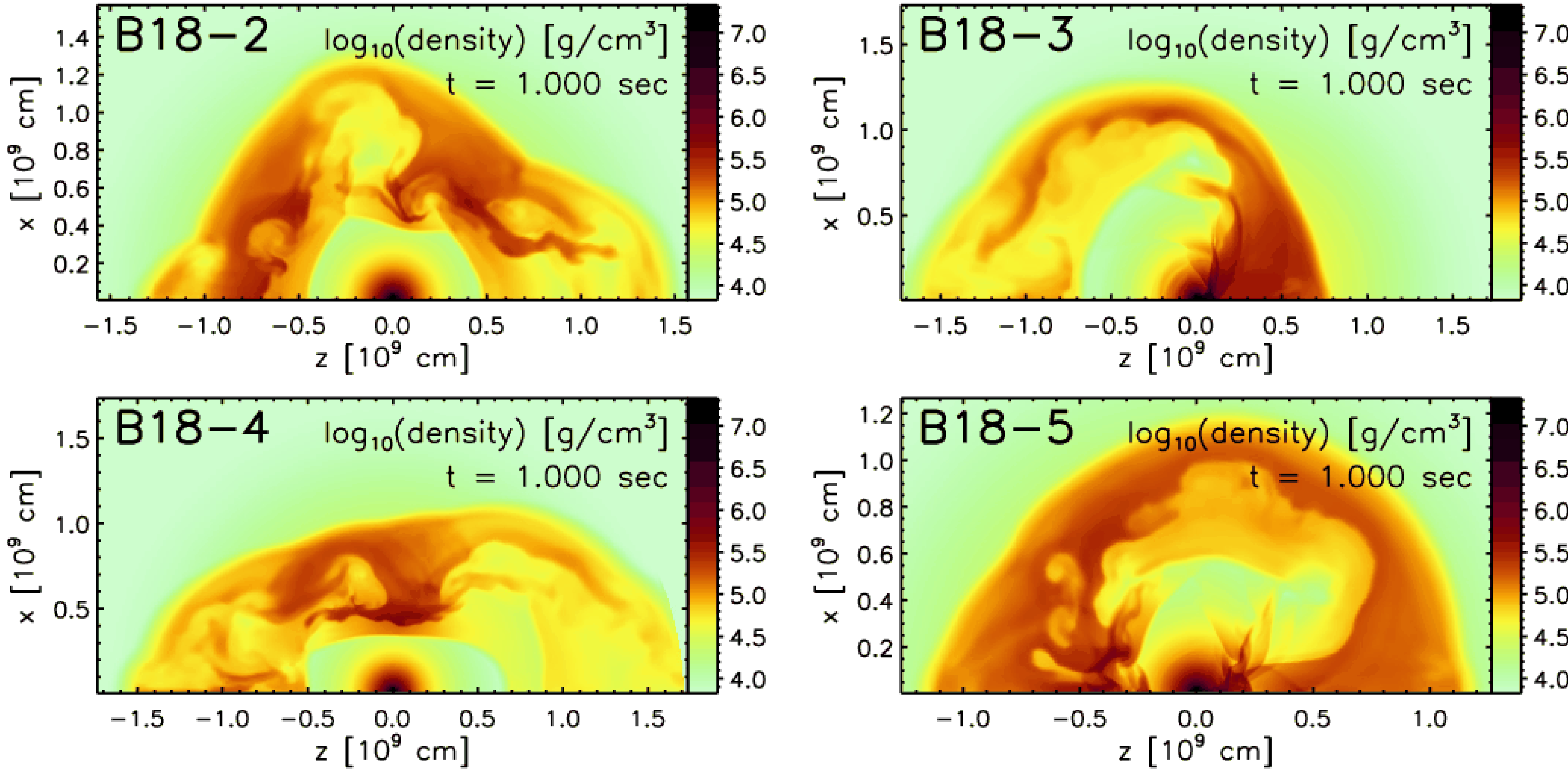
0.1

0.2

0.25

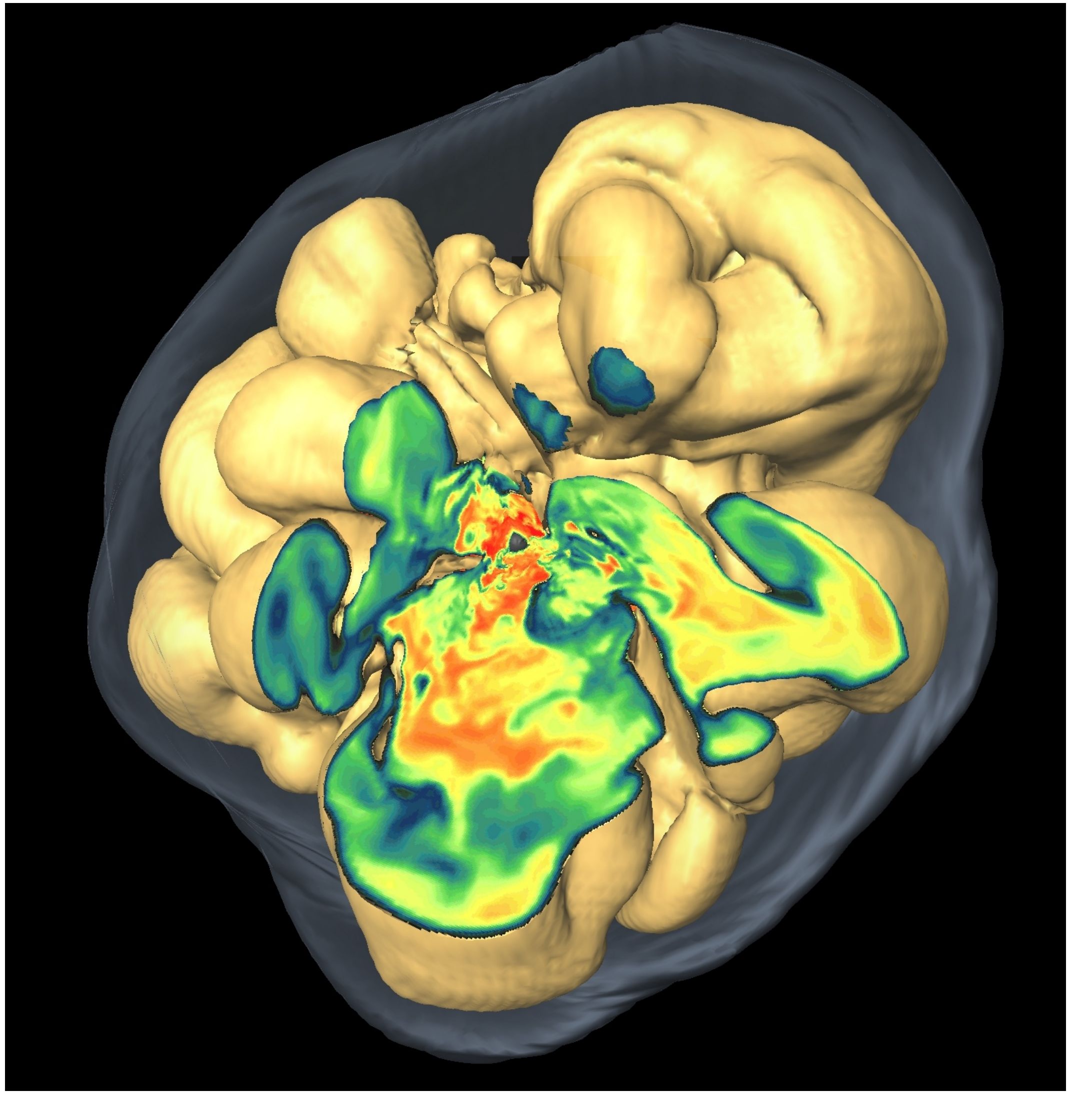
0.5

1.0 s



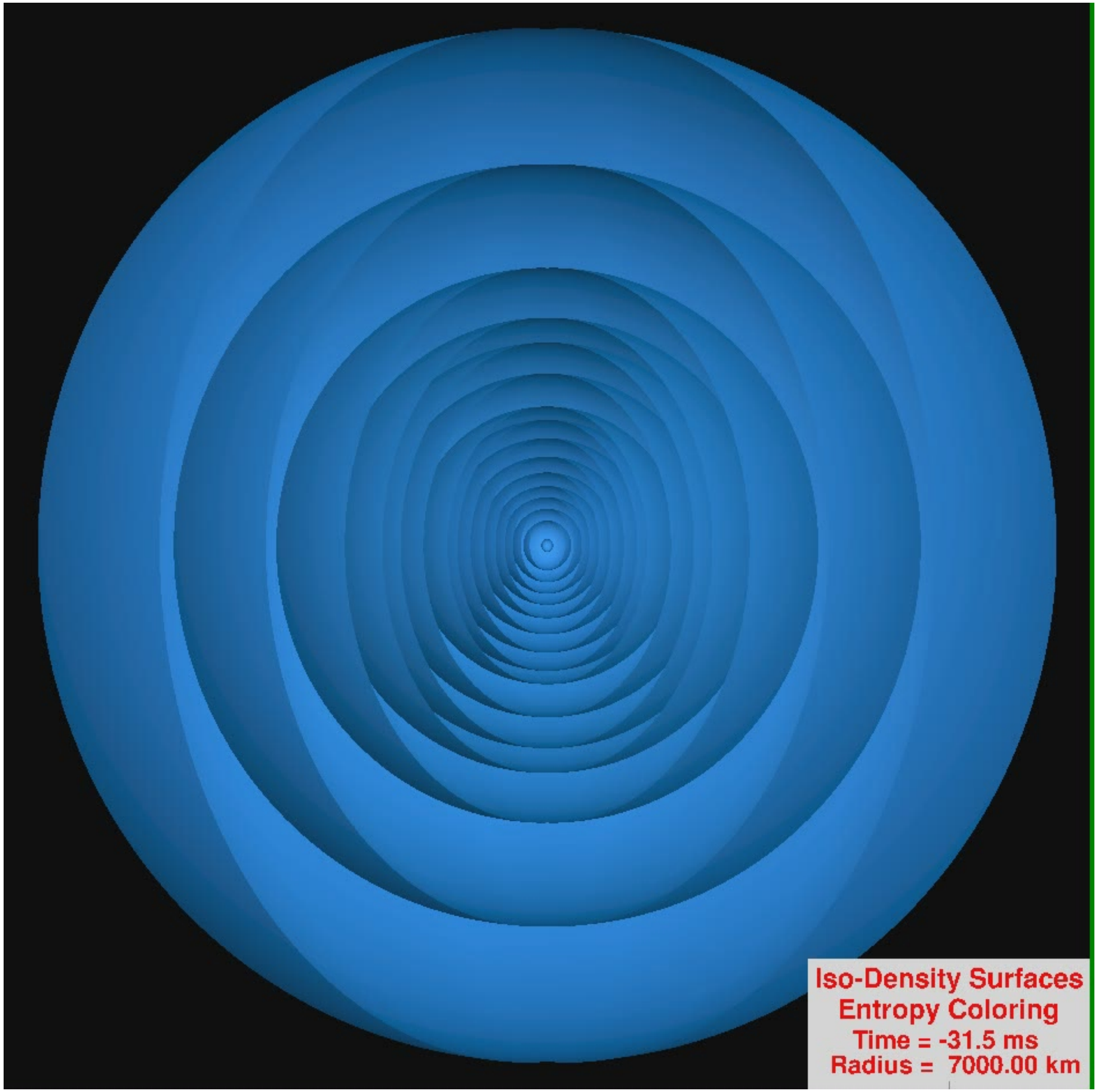
B18−2
log10(density) [g/cm3]
t = 1.000 sec
B18−3
log10(density) [g/cm3]
t = 1.000 sec
B18−4
log10(density) [g/cm3]
t = 1.000 sec
B18−5
log10(density) [g/cm3]
t = 1.000 sec
x [10^9 cm]
z [10^9 cm]

3 D simulation



Scheck et al 2006

Oscillations in proto-neutron star



Burrows et al

Pulsar kicks

Pulsars = isolated neutron stars: Space velocities up to 1000 km/s.

Large scale anisotropy ⇒ 'kicks' ⇒ high space velocities

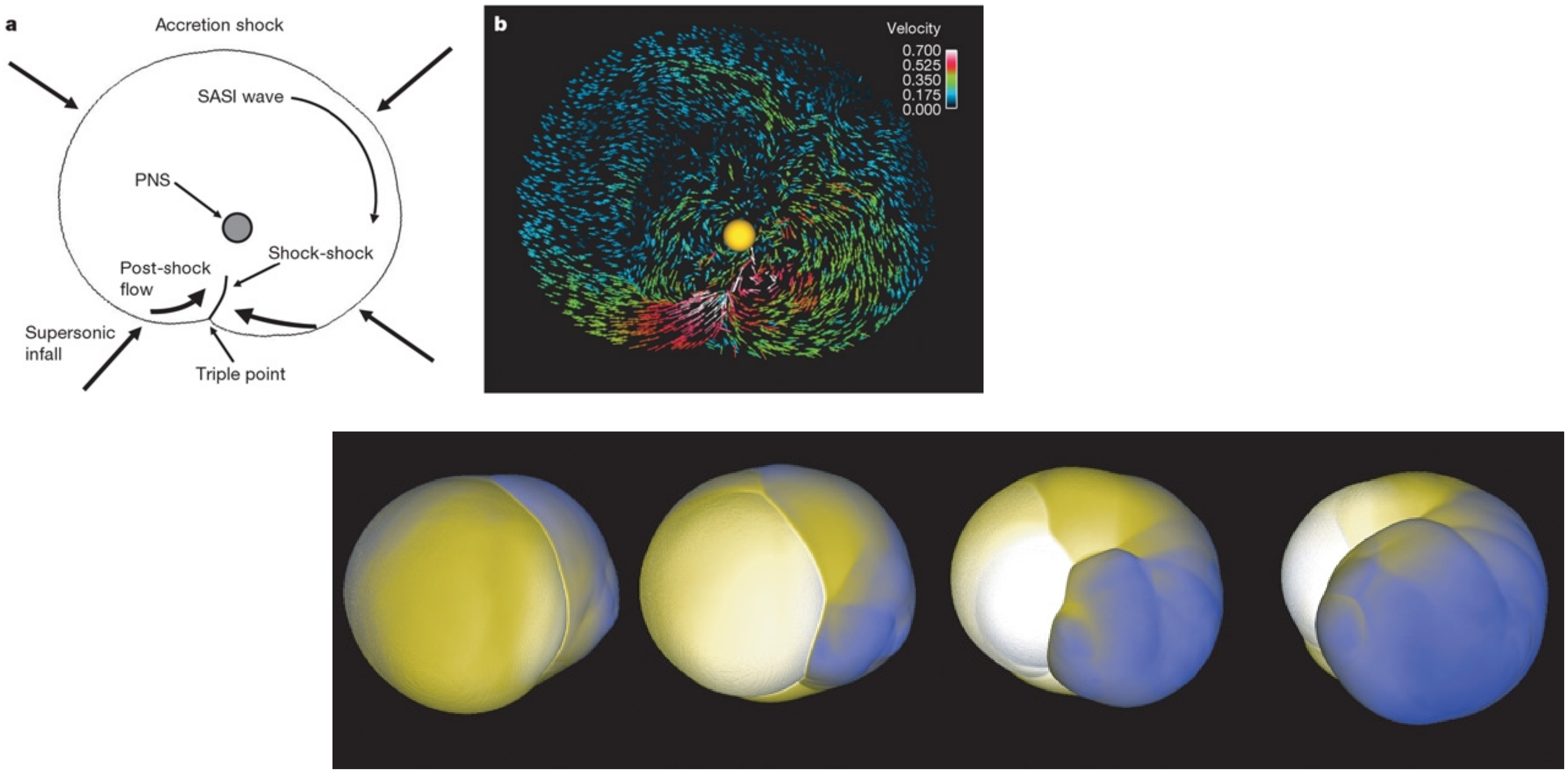
pulsar

Guitar nebula

Pulsar spins

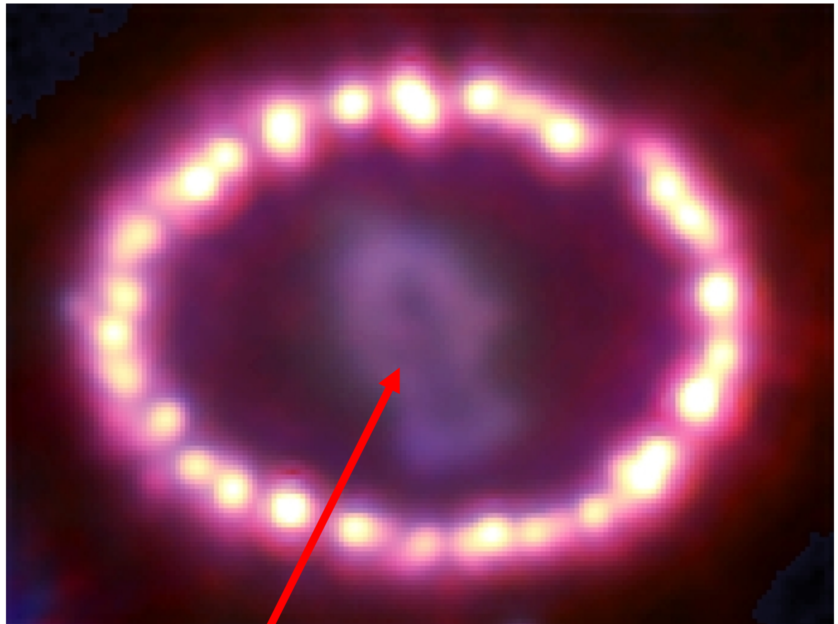
Pulsars: Rotation periods 20 ms to ~10 s

'Spiral' wave m = 1 ⇒ pulsar spins



Blondin & Mezzacappa

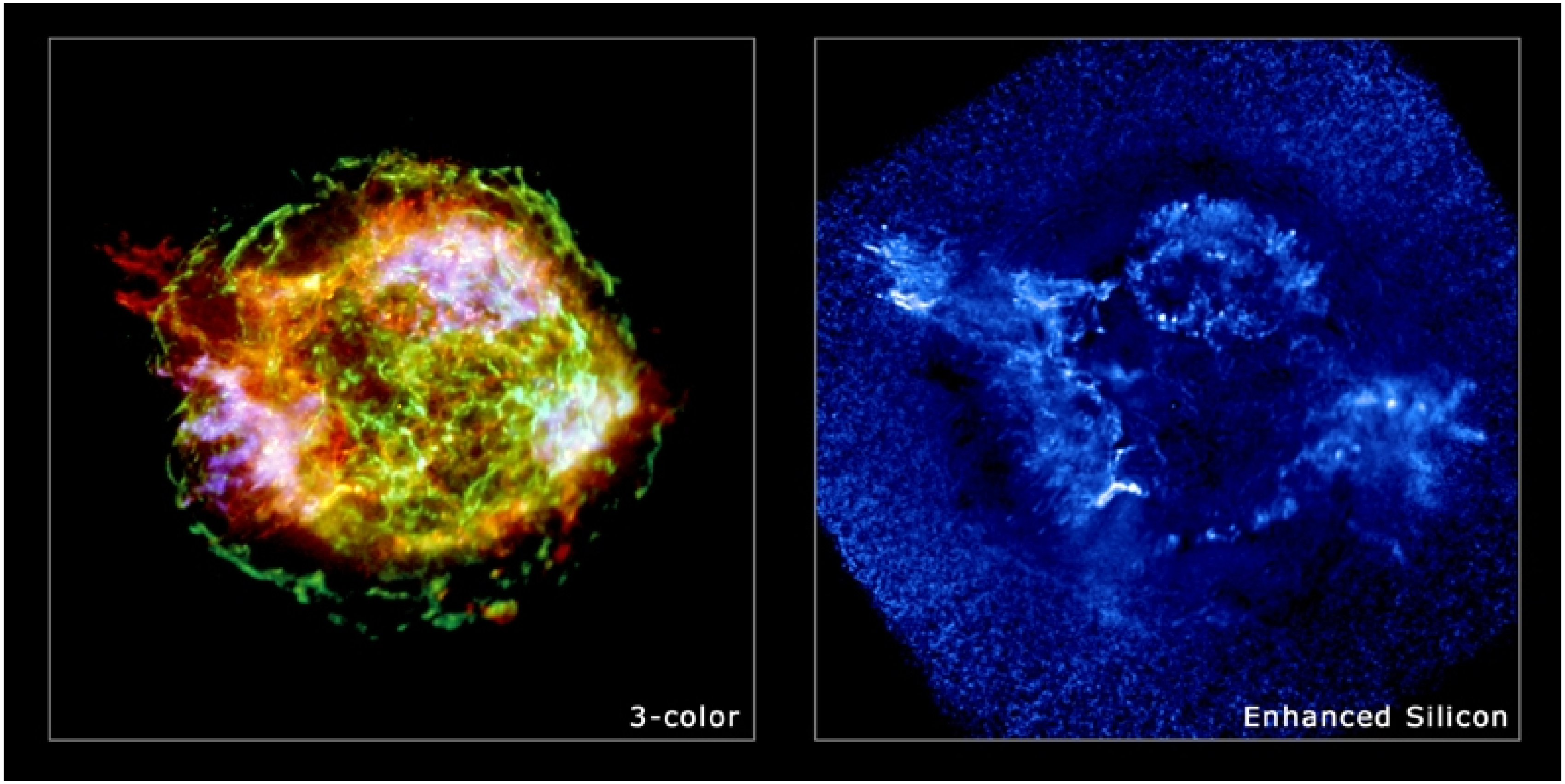
Asymmetries, element mixing common



SN ejecta

SN 1987A

Asymmetries, element mixing common



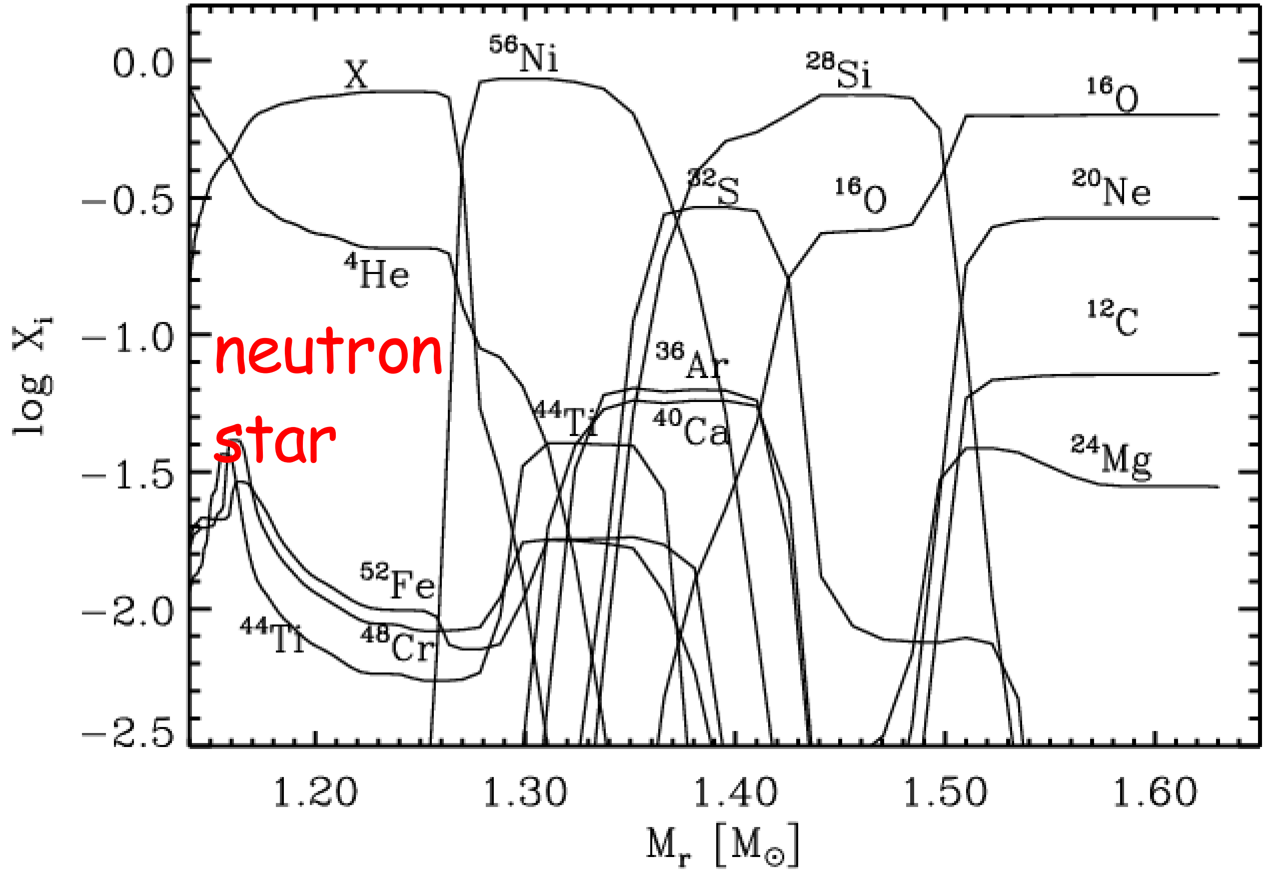
Chandra

Red = Si

Cas A (~ 340 years)

Blue = Fe

Explosive nucleosynthesis by shock wave



Kifonidis et al

r-process in neutrino driven wind during first seconds

n-capture

$(Z,A) + n \rightarrow (Z,A+1) + \gamma$ n-capture

1. $(Z,A+1) + n \rightarrow (Z,A+2) + \gamma$

2. $(Z,A) \rightarrow (Z+1,A+1) + e^- + \nu$ β-decay

Time scale for β-decay seconds to days (short compared to evolutionary time scale)

s-process: β-decay before new n-capture

r-process: new n-capture before β-decay

r-process

$(Z,A) \quad + n \rightarrow (Z,A+1) + \gamma$ n-capture

$(Z,A+1) + n \rightarrow (Z,A+2) + \gamma$

$(Z,A+2) + n \rightarrow (Z,A+3) + \gamma$

....

neutron capture cross section decreases with N

photodisintegration increases with N

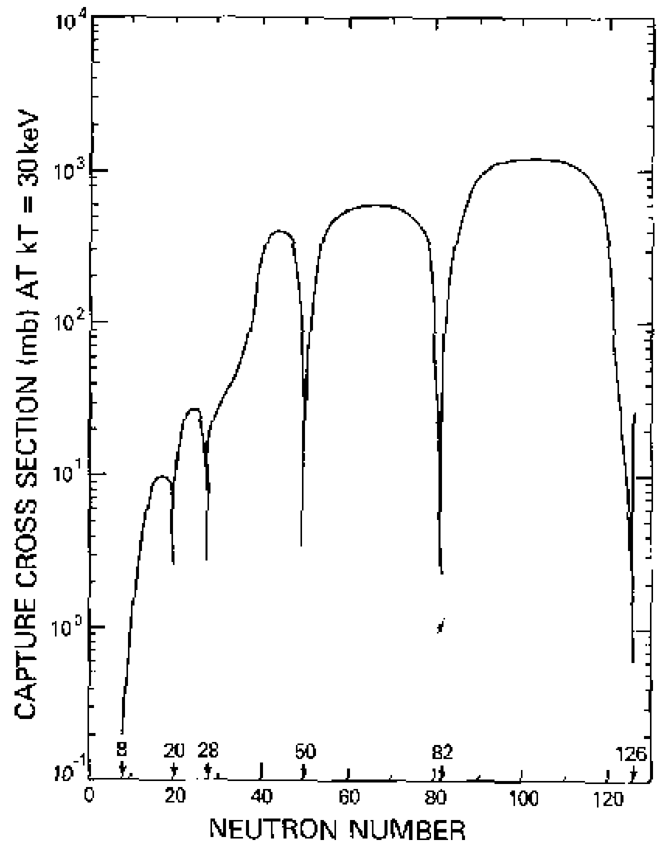
n-capture continues until equlibrium between

n-capture = photodis. from this β-decay $\Rightarrow (Z+1,A)$

r-process

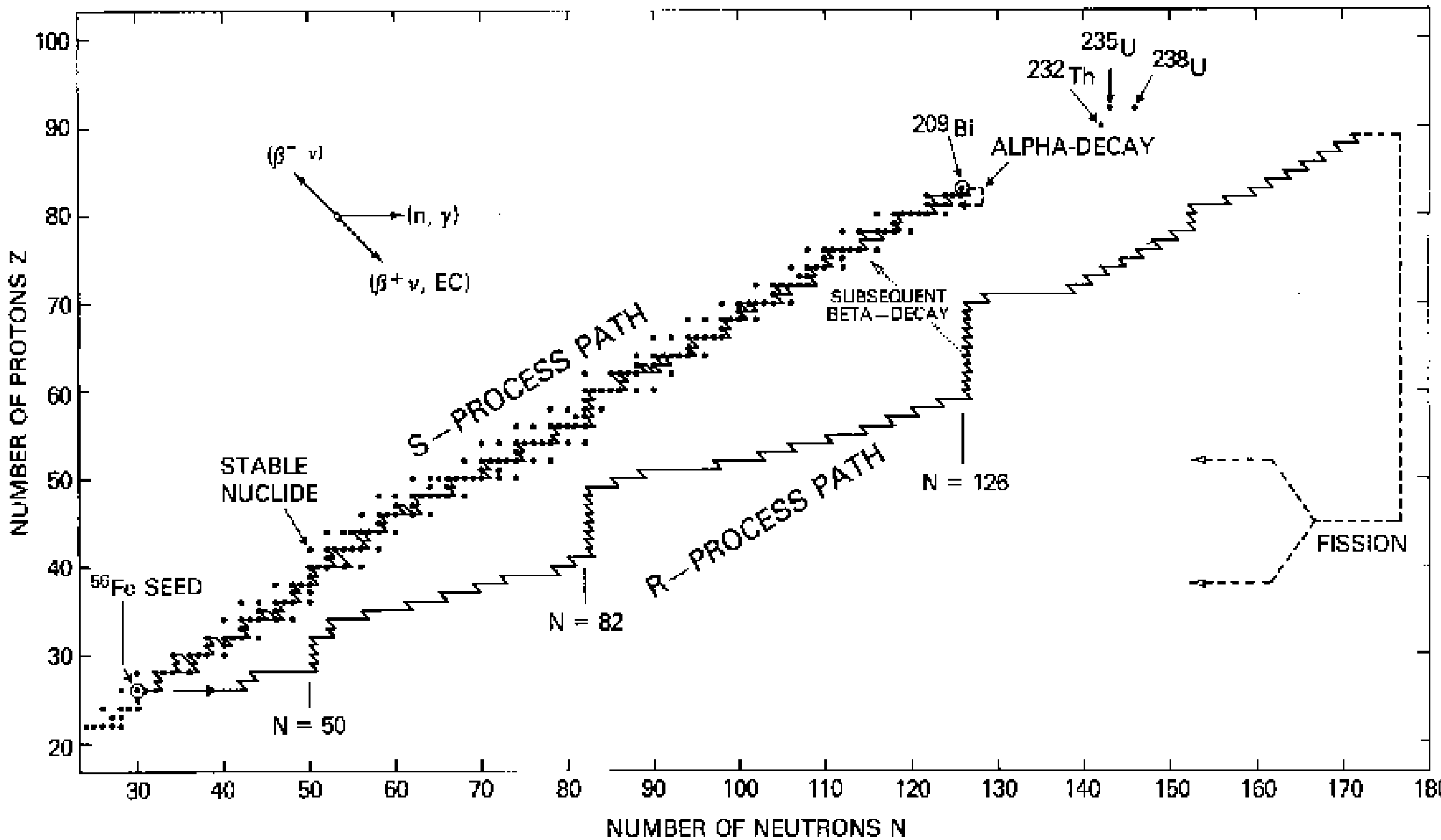
Photodisintegration cross section large above magic n-numbers

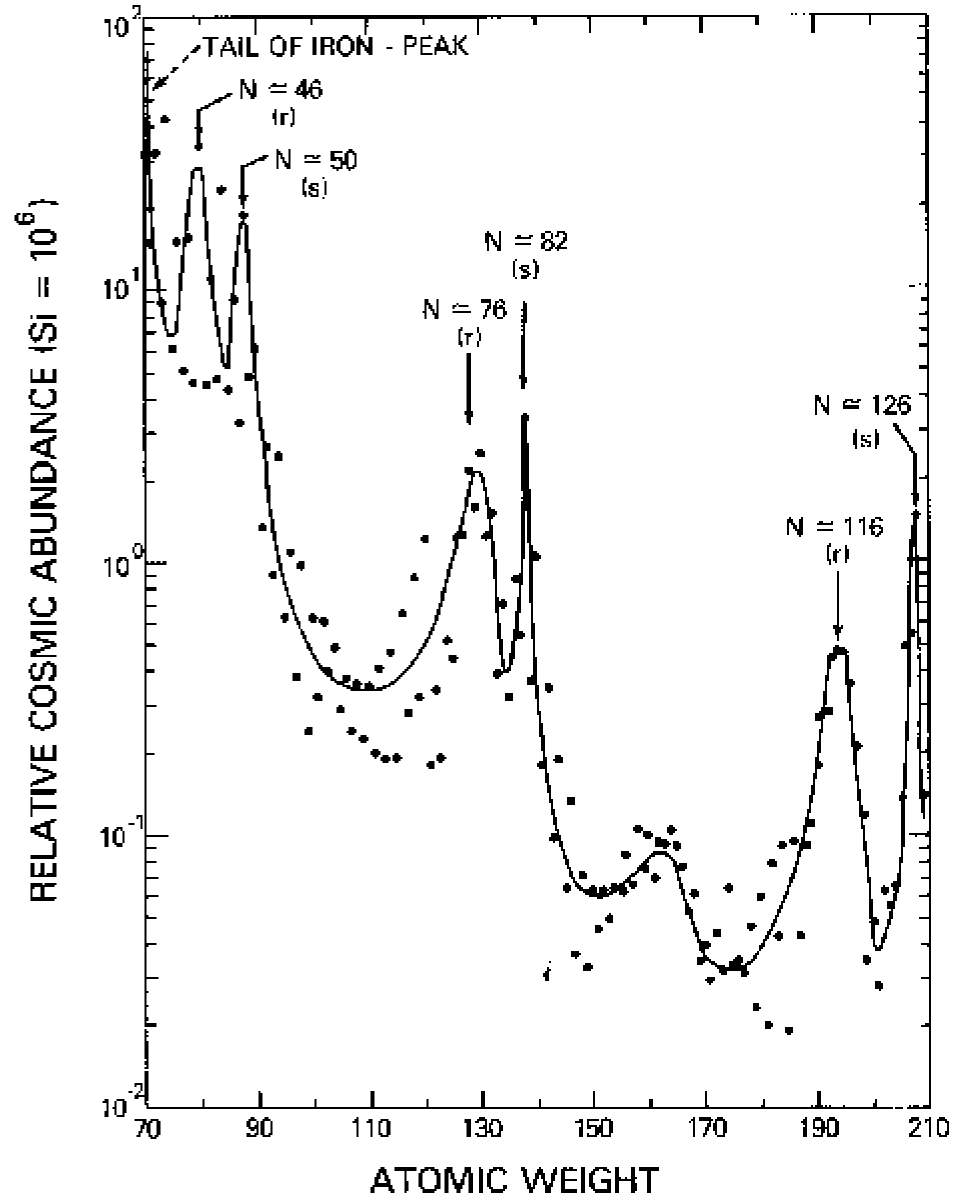
(N=8, 20, 28, 50, 82, 126, 184) ⇒ pile up at magic n-numbers



r-process

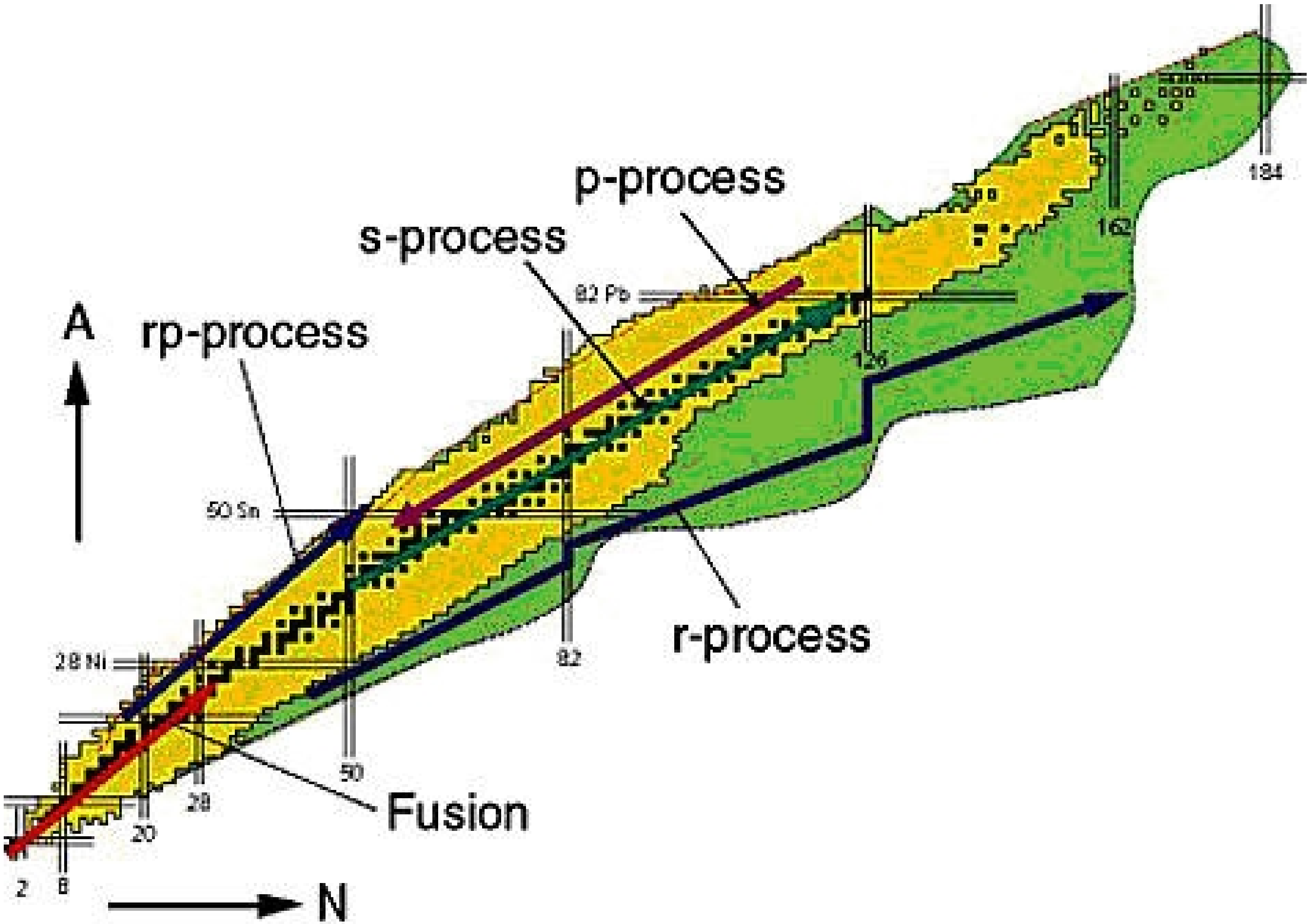
⇒ pile up at magic n-numbers





TAIL OF IRON - PEAK
N ≃ 46
(r)
N ≃ 50
(s)
N ≃ 82
(s)
N ≃ 76
(r)
N ≃ 126
(s)
N ≃ 116
(r)
RELATIVE COSMIC ABUNDANCE (Si = 10^6)
10^2
10^1
10^0
10^-1
10^-2
70
90
110
130
150
170
190
210
ATOMIC WEIGHT

r-process



p-process
s-process
rp-process
A
82 Pb
50 Sn
28 Ni
184
162
126
82
50
28
20
2
8
r-process
Fusion
N

Site of r-process

Needed: High density of neutrons during a short period

Region close to neutron star during explosion ideal:

High neutron density from inverse beta decays (K-captures)

Many heavy seed nuclei from NSE (^{56}Ni, ^{56}Fe ....)

Correct abundance pattern? Not yet clear