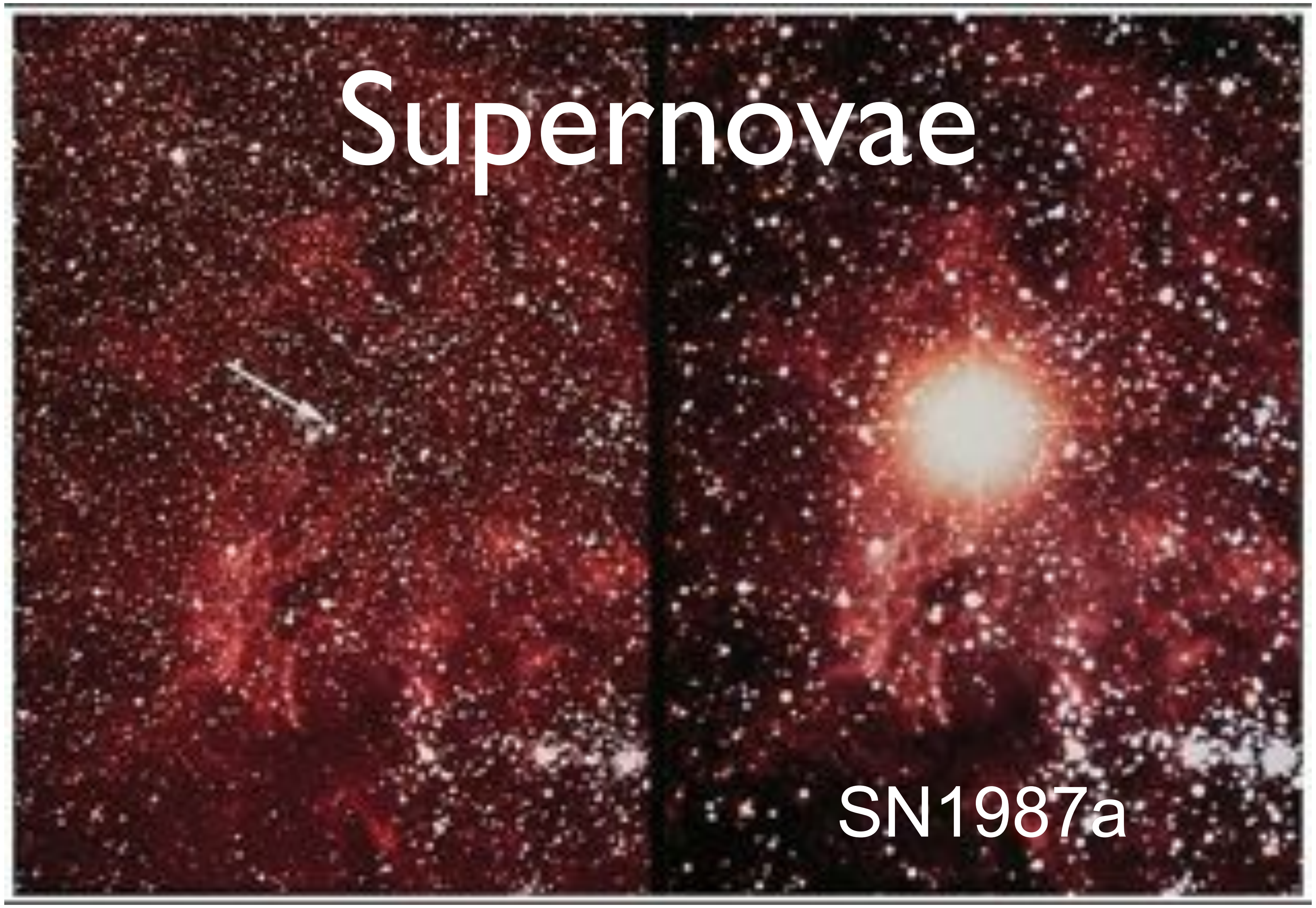
Supernovae



Lec. 1: Neutron stars and their crusts.

Lec. 2: Supernovae.

Lec. 3: Nucleosynthesis and gravitational waves

C. J. Horowitz, Indiana University, horowit@indiana.edu
National Nuclear Physics Summer School, Santa Fe, July 2012.

X-Ray observations of NS radii

- Can infer NS radii (and masses) from X-ray observations of NS.
- Note unlike mass measurements from radio observations of pulsars in binary systems, the interpretation of the X-ray observations is *model dependent*.

Observing Neutron Star Radii, Masses

- Deduce surface area from luminosity, temperature from X-ray spectrum.

$$L_\gamma = 4\pi R^2 \sigma_{SB} T^4$$

- Complications:
  - Need distance (parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
- Steiner, Lattimer, Brown [ArXiv: 1005.0811] combine observations of 6 NS in 2 classes: X-Ray bursts and NS in globular clusters.

Find EOS that is somewhat soft at medium densities so 1.4 M_{sun} star has 12 km radius.

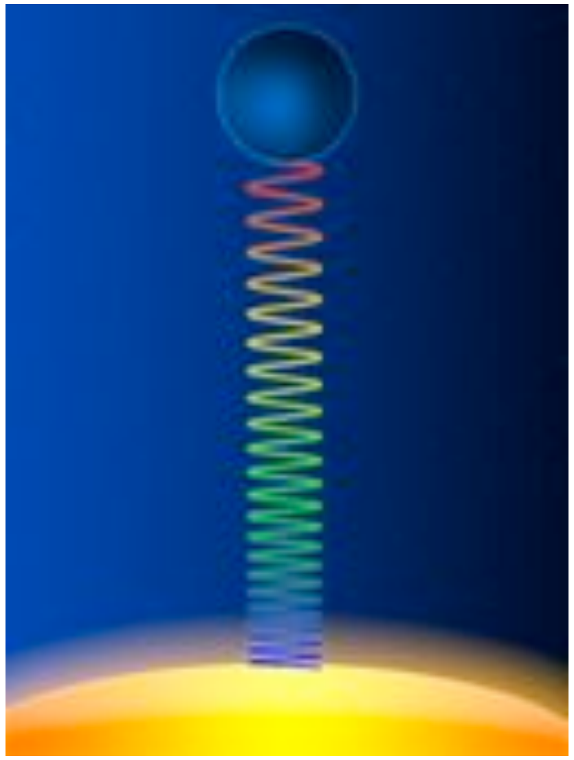
* Predict ^{208}Pb neutron skin: R_n-R_p=0.15+/- 0.02 fm.

* F. Ozel et al. get smaller radii.

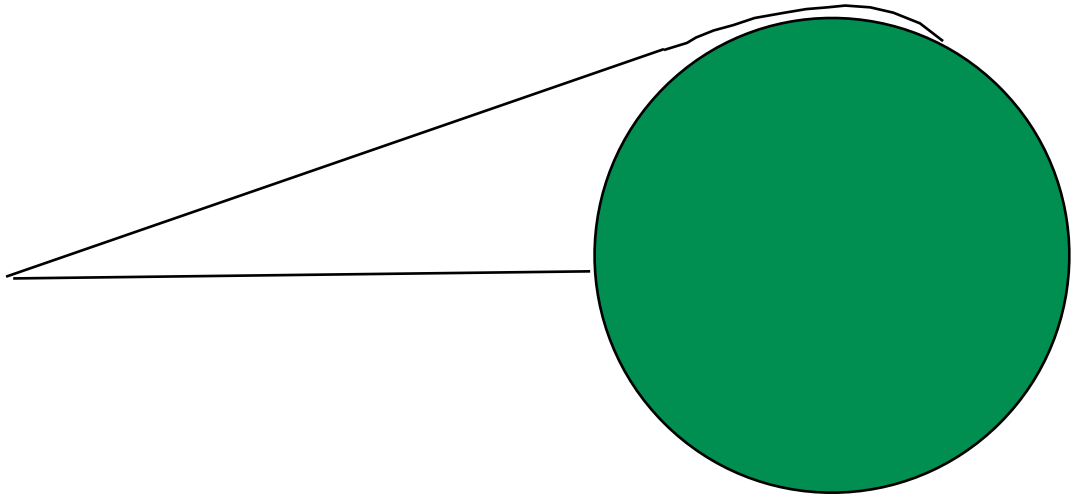
- Radio observations of PSR J1614 find M=1.97+/-0.04 M_{sun} from binary with 0.5 M_{sun} WD. Demorest et al., Nature **467** (2010) 1081.

Relativistic Corrections

- X-rays leaving a neutron star suffer a **gravitational redshift** of about 30%. Therefore the observed temperature is 30% lower than the original T.

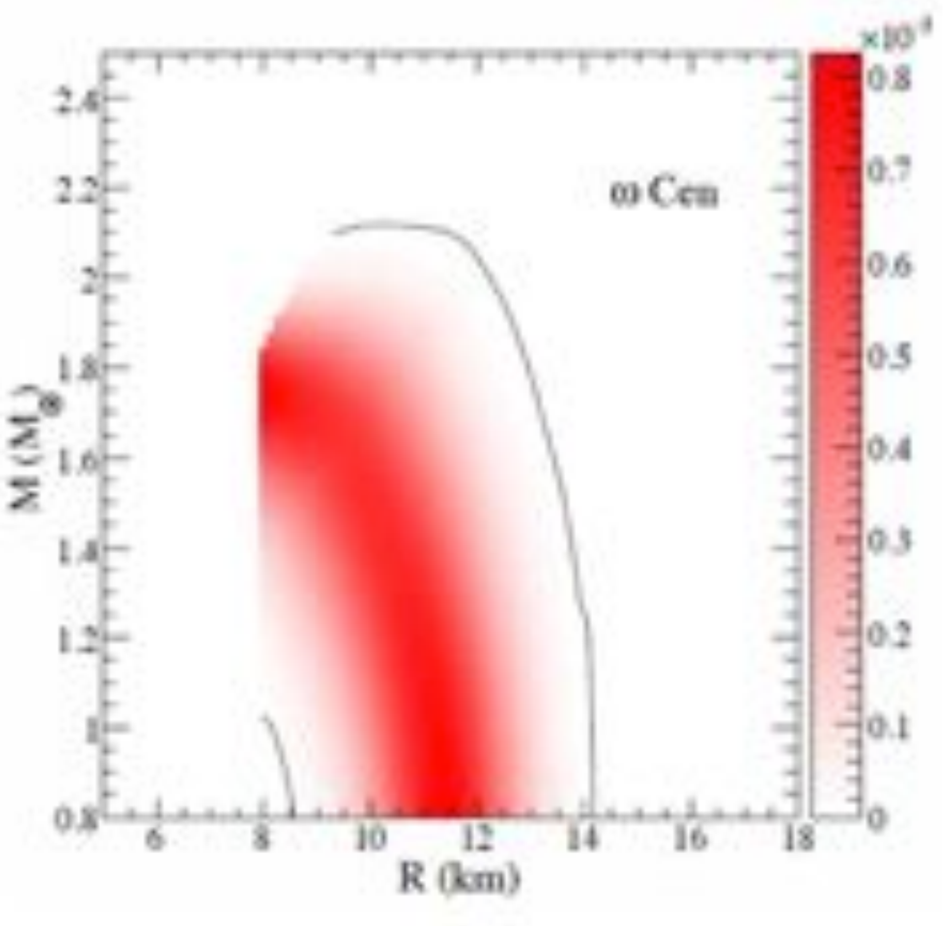


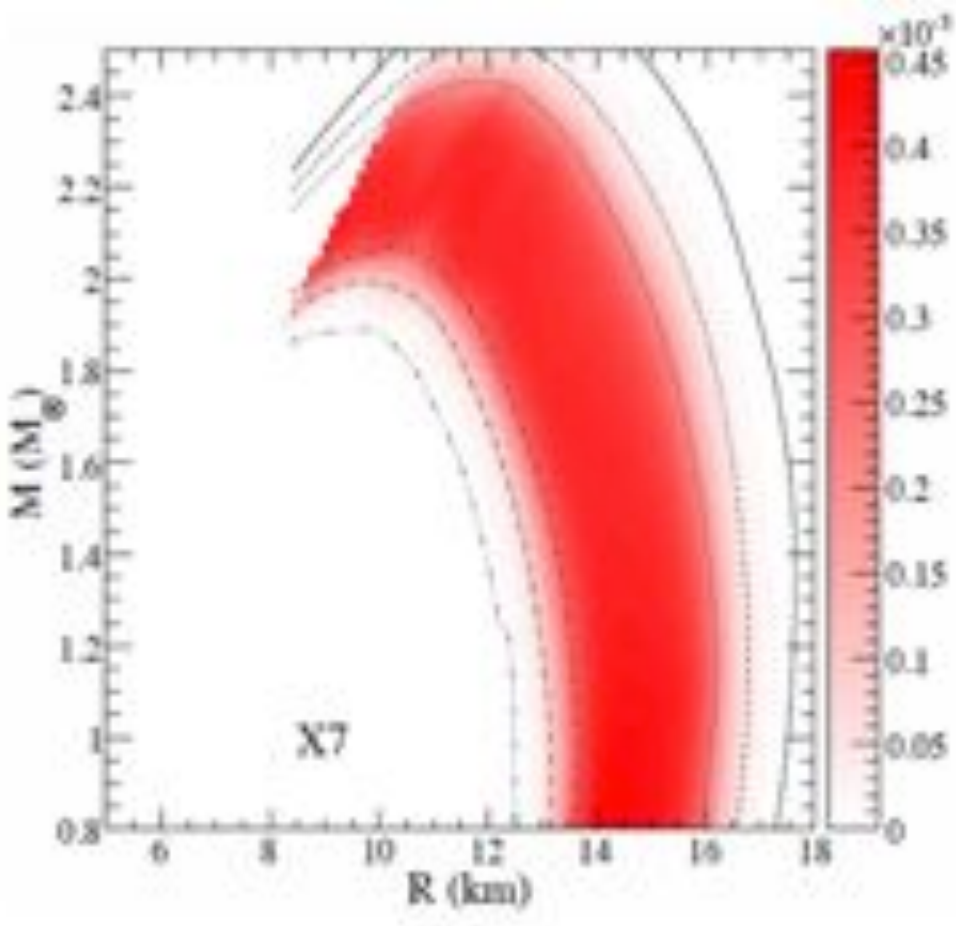
- If you look at the front of a neutron star you also see about 30% of the "back" because of the **curvature of space**.



NS in Globular Clusters

- Know distance to cluster from observing other stars.
- Crowded cluster environment -> NS have companions from which they accrete material.
- Accretion likely buried most magnetic field and contained some hydrogen, that rises to top in strong gravity.   Star has simple nonmagnetic hydrogen atmosphere.
- Globular cluster data poor because stars are far away.

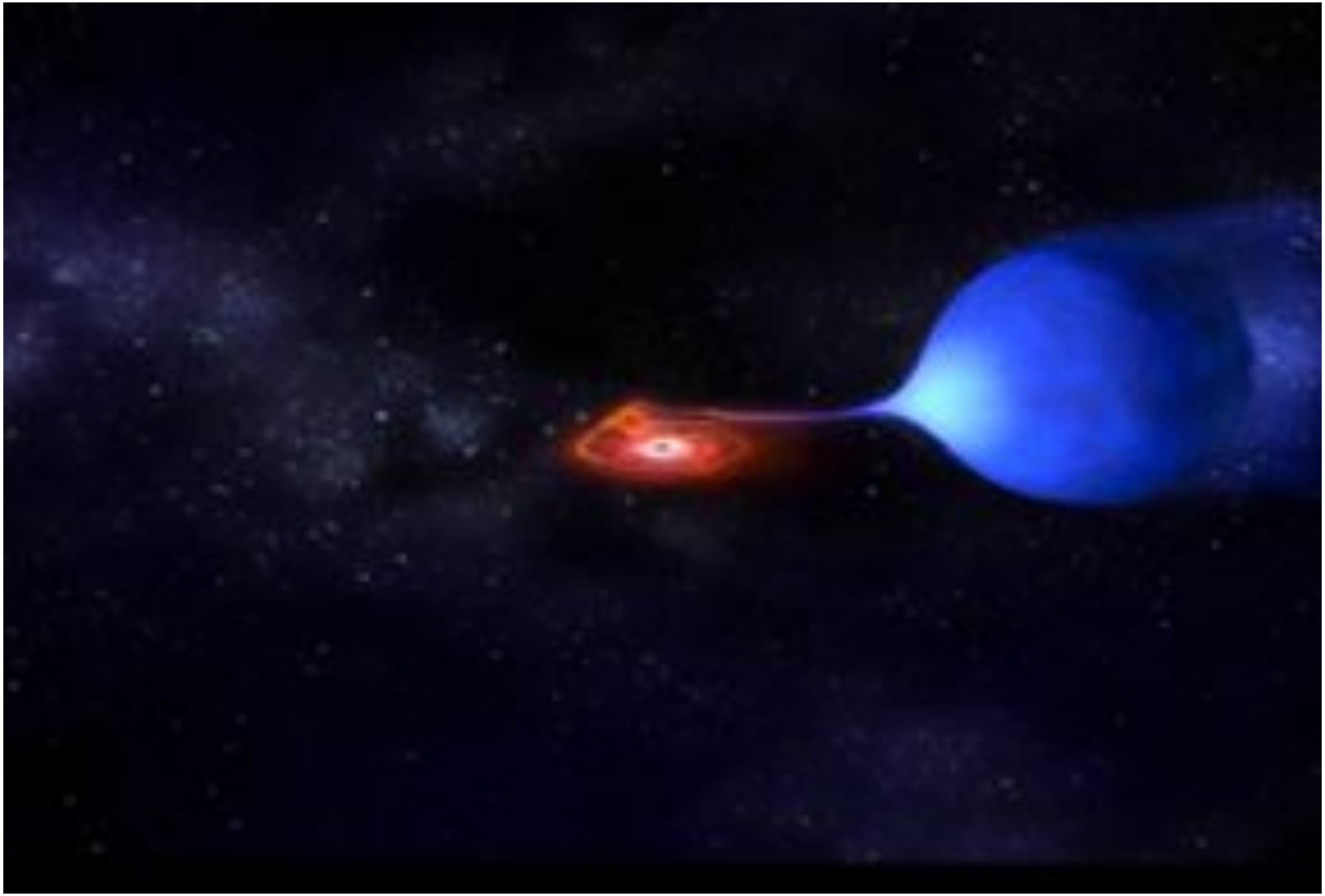




Ngc 5139 Omega Centuri

X-ray bursts

- NS accretes material from companion that ignites a runaway thermonuclear burst.
- **Eddington luminosity**: when radiation pressure balances gravity. Observe luminosity, calculate radiation pressure, and infer surface gravity (another combination of mass and radius). This additional relation gives both mass and radius separately!
- Complications: when during the burst does radiation pressure balance gravity? Uncertain non-black body NS atmosphere. Bust may be aspherical. Different bursts may have different behaviors. Which are good systems to use?
- Ozel et al get ~10km, Steiner et al find ~12 km and Suleimanov et al find ~15 km. Still model dependent!



Low Mass X-ray Binary (LMXB)

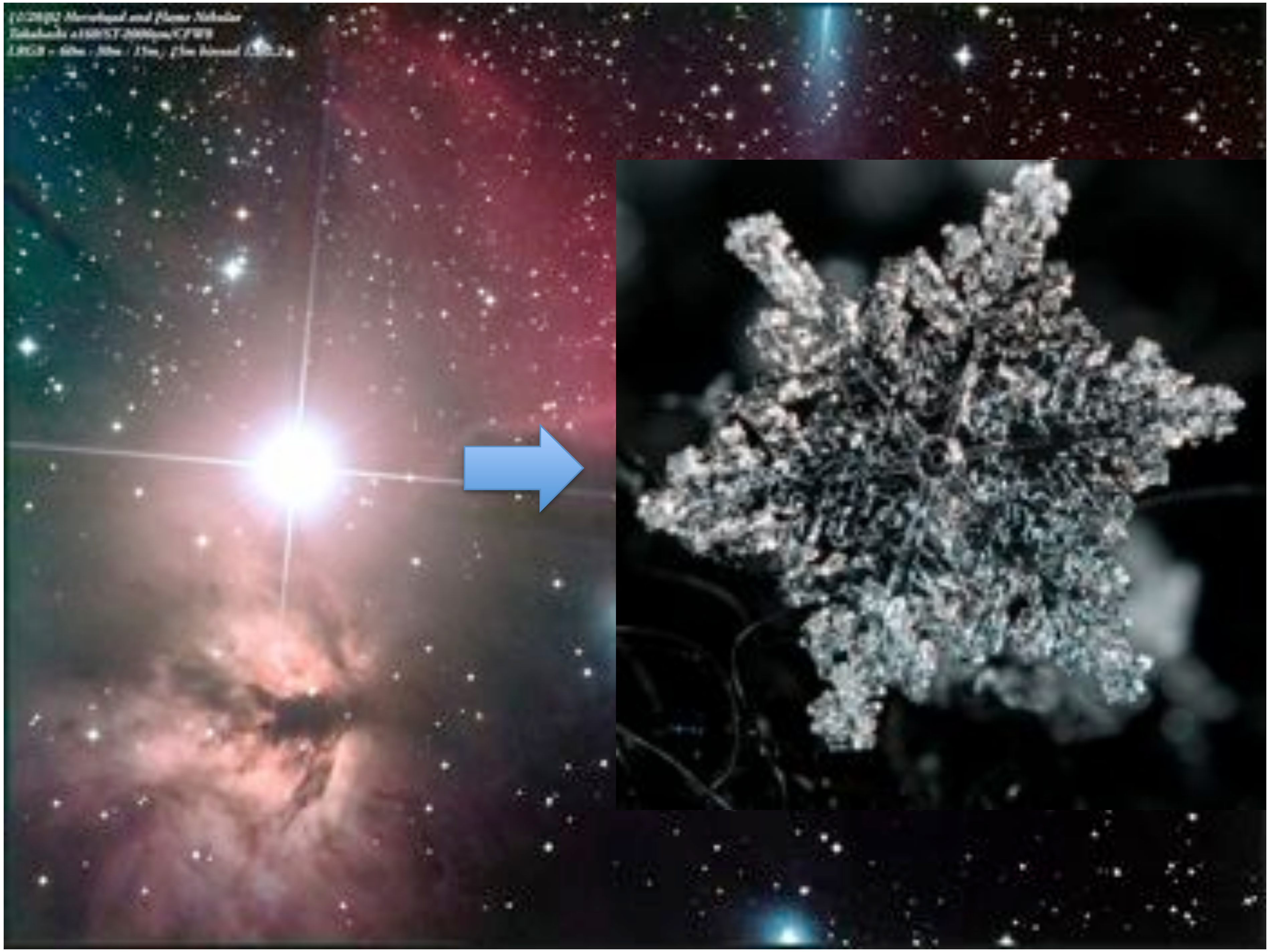
Radio and X-ray observations of NS masses and radii

- Constrain equation of state: $p=p(\epsilon)$.
- **Observation of $2M_{sun}$ NS shows p is relatively high at high density** to support star against collapse to black hole.
- However observing M and R alone do not determine composition of high density matter.
- Pressure could be high because of strongly interacting n, hyperons, or quarks...
- Nearly free quarks ruled out because p too low but not strongly interacting quarks.
- Observation of NS cooling probes composition.

Color superconductors

- Asym. freedom suggests nearly free quarks at high density with weak gluon interactions.
- Gluon interaction between two quarks is attractive in some spin-color-flavor states--> form cooper pairs of quarks called--> a color superconductor.
- Now know that interactions at neutron star densities are not weak but strongly increase pressure.
- Therefore we don’t have a weakly interacting color superconductor in NS.
- Can something of color quark pairing remain in strongly interacting system? Maybe, we can’t calculate. (ask Sanjay Reddy next week)

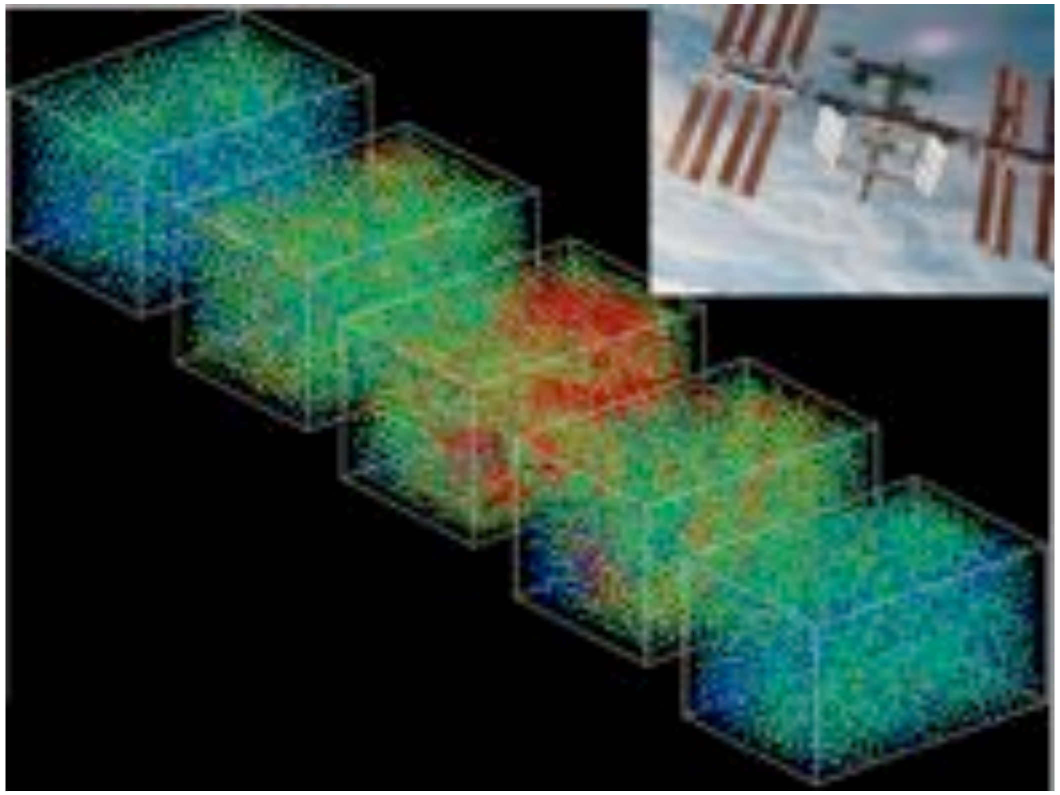
How Stars Freeze



What is the origin of neutron star crust?

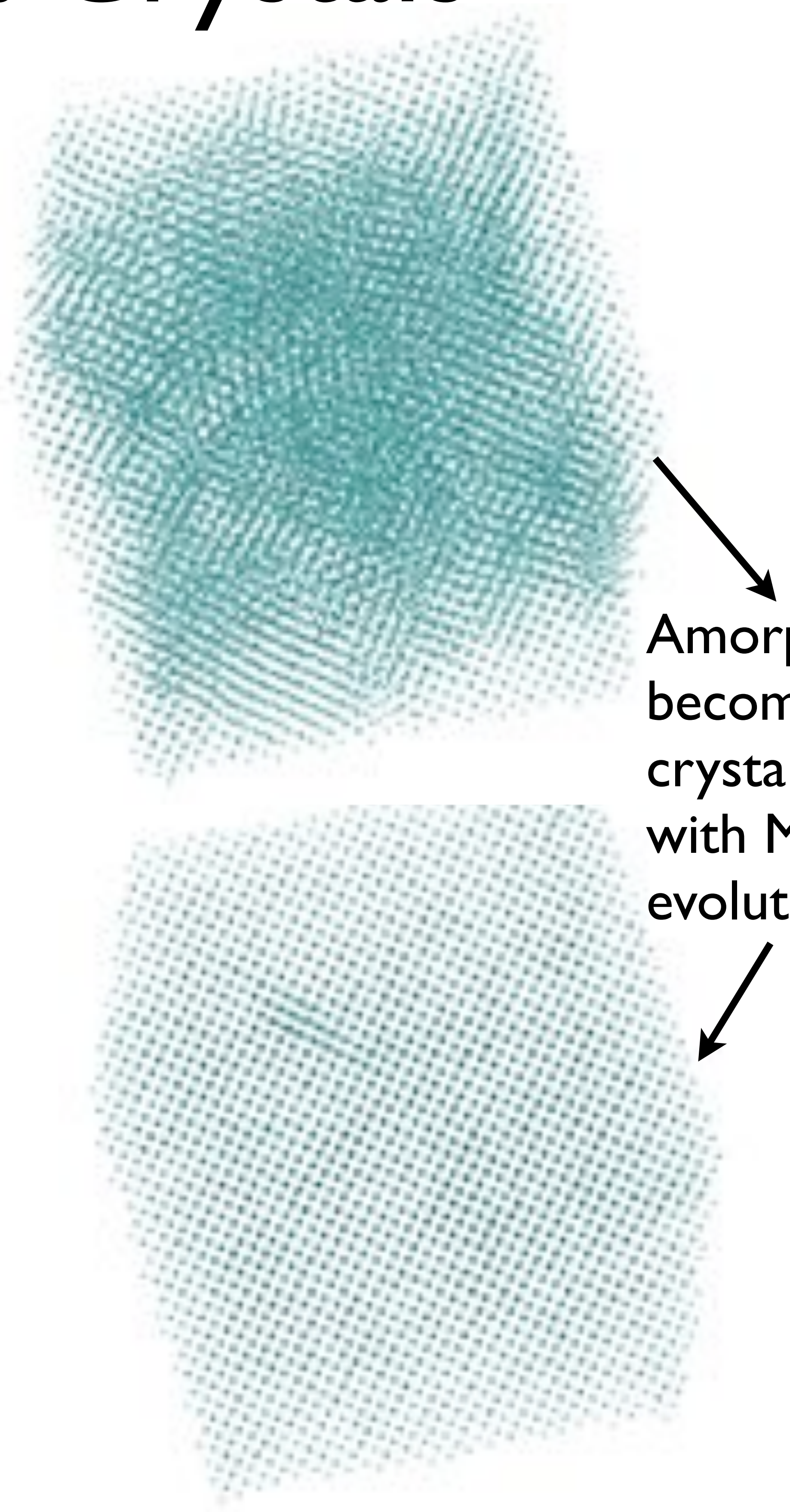
How stars freeze: plasma crystals

- Stars are plasmas, however interior of white dwarfs and crust of neutron stars are so dense that they can freeze.
- In stars, plasma consists of ions plus very degenerate (relativistic) electron gas. Electrons slightly screen ion-ion interactions $V(r)=Z^2e^2/r \exp(-r/\lambda)$ with screening length λ.
- In lab. complex (or dusty) plasmas made of micron sized microparticles in weakly ionizing gas.
- Two dim. plasma crystals first observed in lab in 1994.
- In microgravity on space station 3D system freezes (center) and melts (right) as control voltage changed.
- B. A. Klumov, Physics-Uspekhi, 53, 1053 (2010)



Diffusion in Plasma Crystals

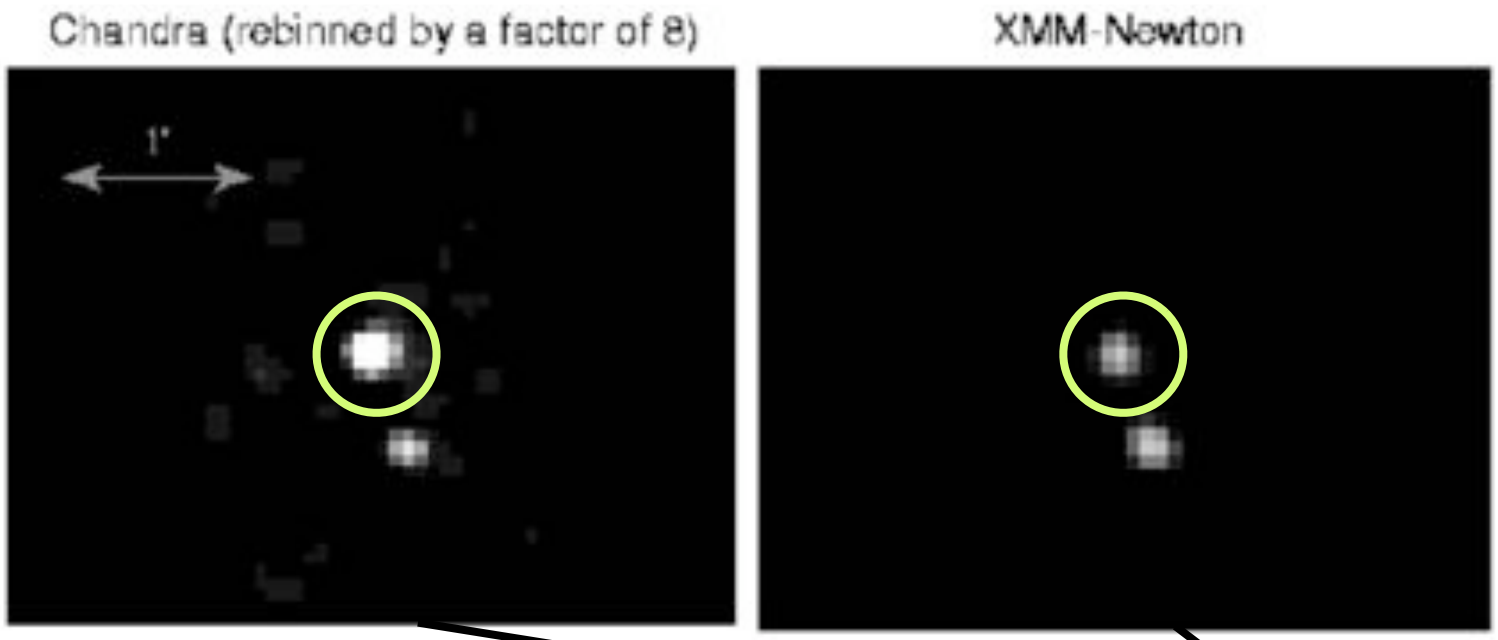
- Ions have soft screened coulomb interactions, 1/r, without hard cores!
- Diffusion much faster than in conventional materials because ions can move past one another.
- Example: quench a liquid configuration of 27648 ions by reducing T by a factor of 2.9. Then evolve amorphous system with MD for long time. System spontaneously crystallizes.
- Fast diffusion suggests *WD interiors and neutron star crust are remarkably perfect crystals with few defects*.
- Observations of rapid crust cooling in LMXBs after extended outbursts strongly favors high thermal conductivity of crystalline rather than amorphous crust.
- With J Hughto and A. Schneider



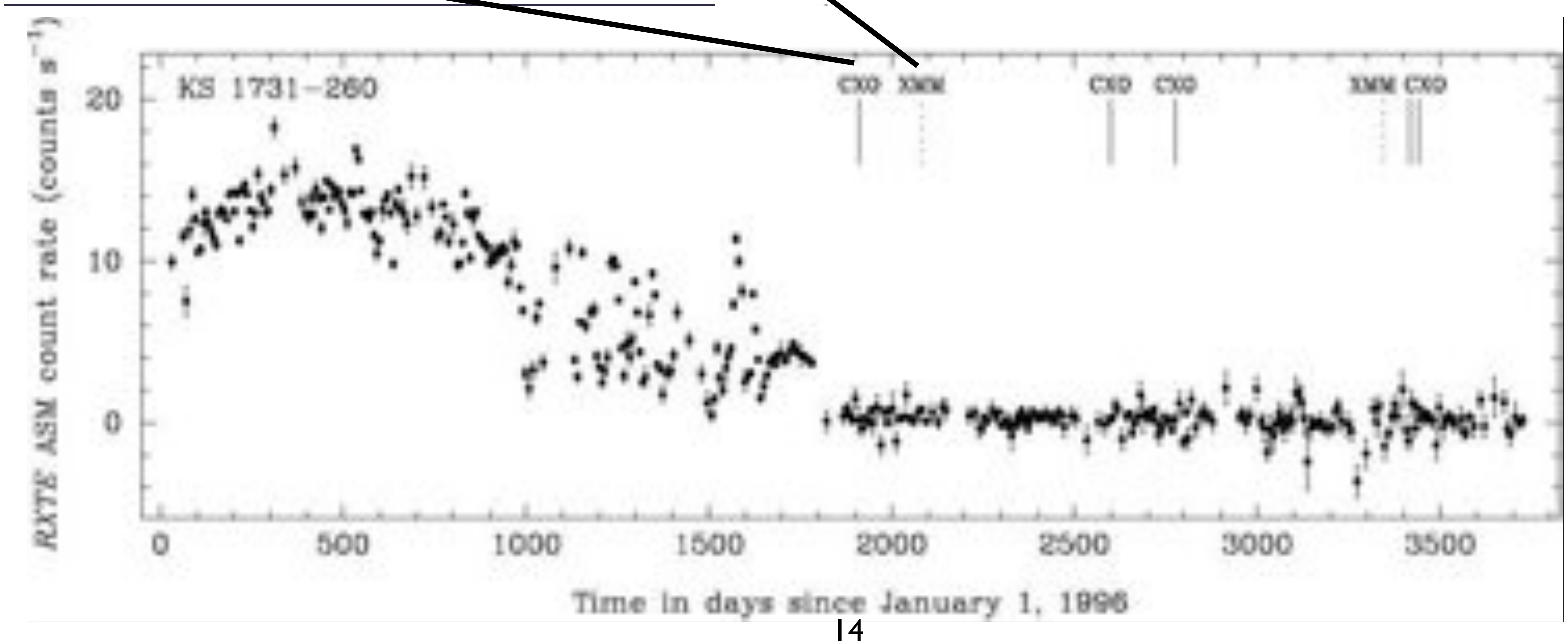
Amorphous becomes crystalline with MD evolution

Phys Rev E **84**, 016401 (2011)

Cooling of crust of KS 1731-260



X-ray observations of a NS cooling after long outburst.
--Ed. Cackett



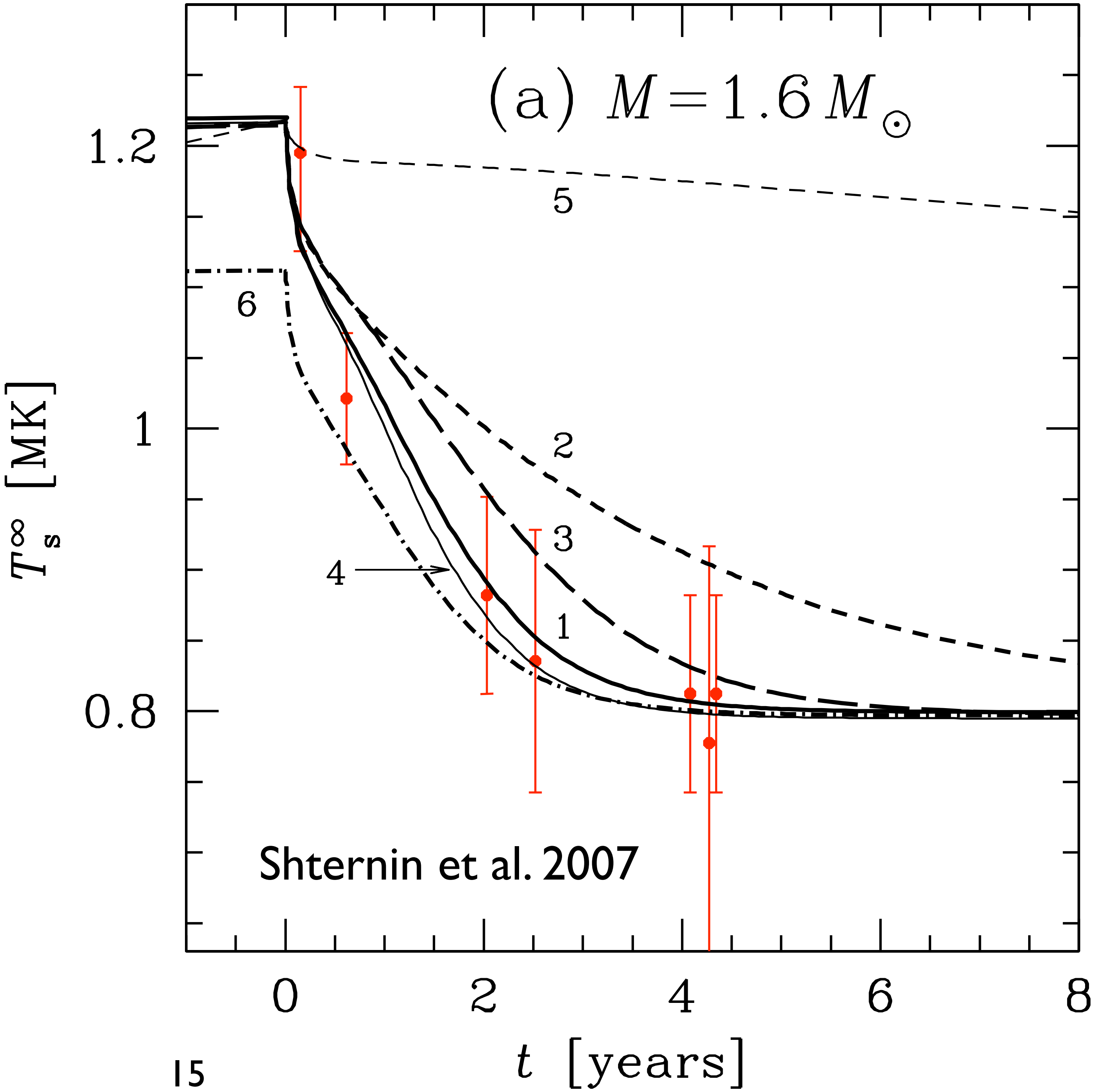
Cooling of KS 1730-260 Surface After Extended Outburst

Rutledge et al. suggested cooling would measure crust properties.

Also calculations by E. Brown and A. Cumming.

Curves 1-4 use high crust thermal conductivity (regular lattice) while 5 uses low conductivity (amorphous)

Data favor high conductivity!



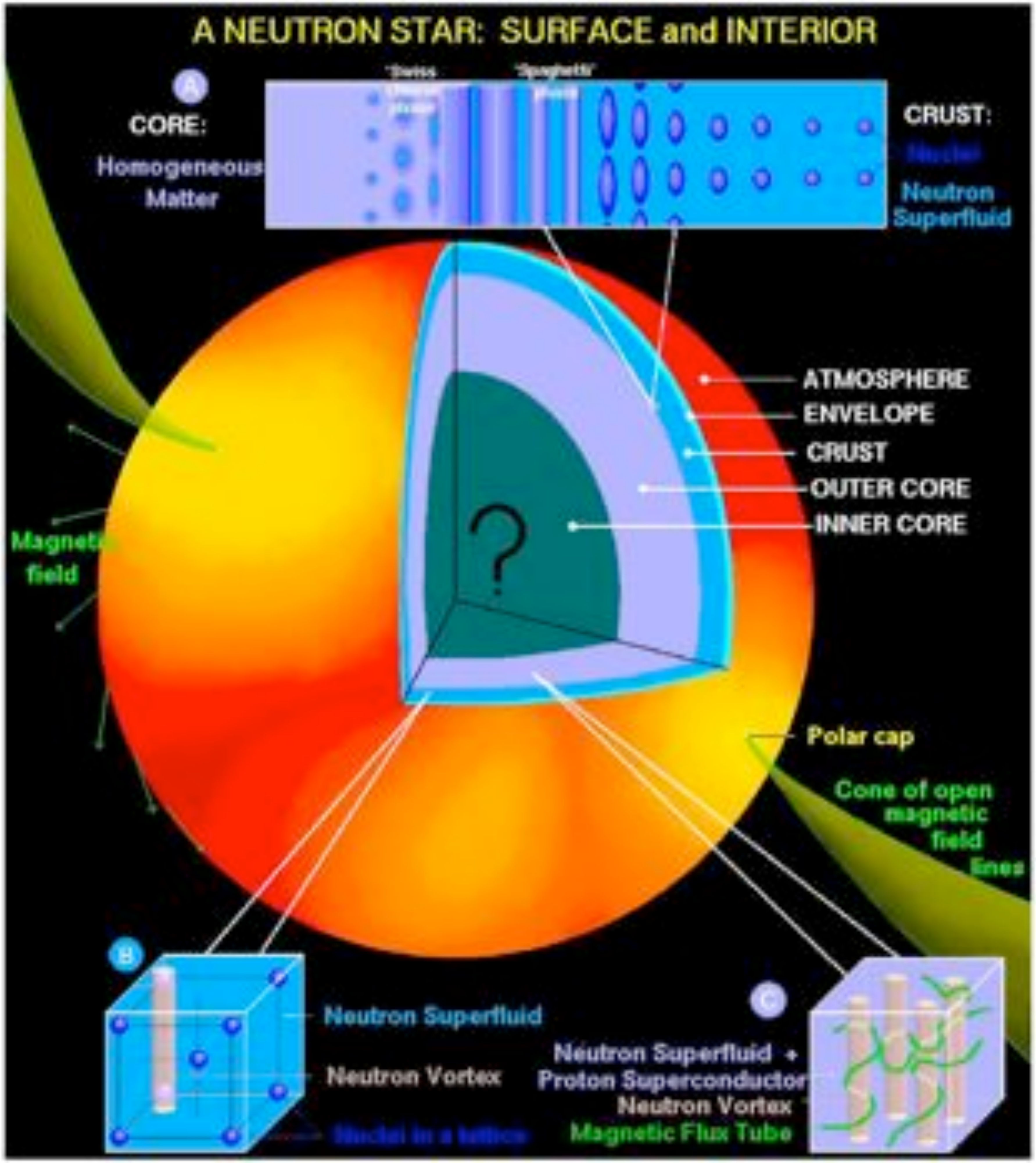
Shternin et al. 2007

Neutron drip

- Outer crust about 300 meters thick crystal lattice of neutron rich nuclei and degenerate electrons.
- When $\rho \sim 3 \times 10^{11}$ g/cm^3 high e Fermi energy drives n Fermi energy positive. $E_F^e + E_F^p = E_F^n > 0$. This leads to unbound n.
- Inner crust about 700 meters thick crystal lattice of neutron rich nuclei, nearly free n (superfluid), and degenerate e gas.
- Near 10^{14} g/cm^3 transition from nonuniform inner crust to uniform core liquid of n rich matter. This likely involves complex nuclear pasta intermediate phases.

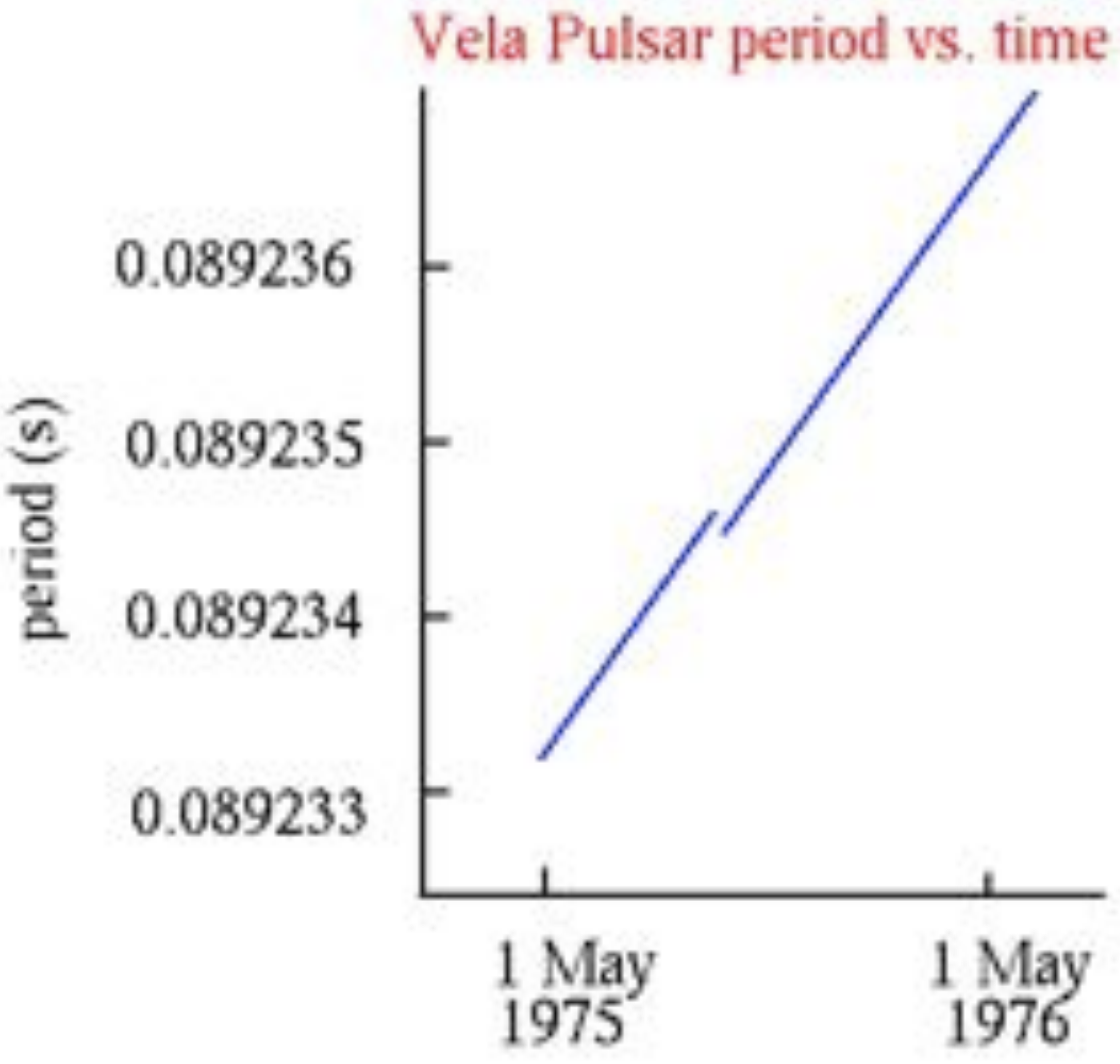
Superfluid gas of neutrons

- Low density neutron gas: Inter-particle spacing >> range of neutron-neutron interaction 2.7fm.
- Scattering length ~ -18 fm is very long (almost have a zero energy $^1S_0$ n-n bound state).
- Attractive n-n interaction forms Cooper pairs with ~ 1MeV binding E or critical T.
- Rotating NS--> rotational vortices.

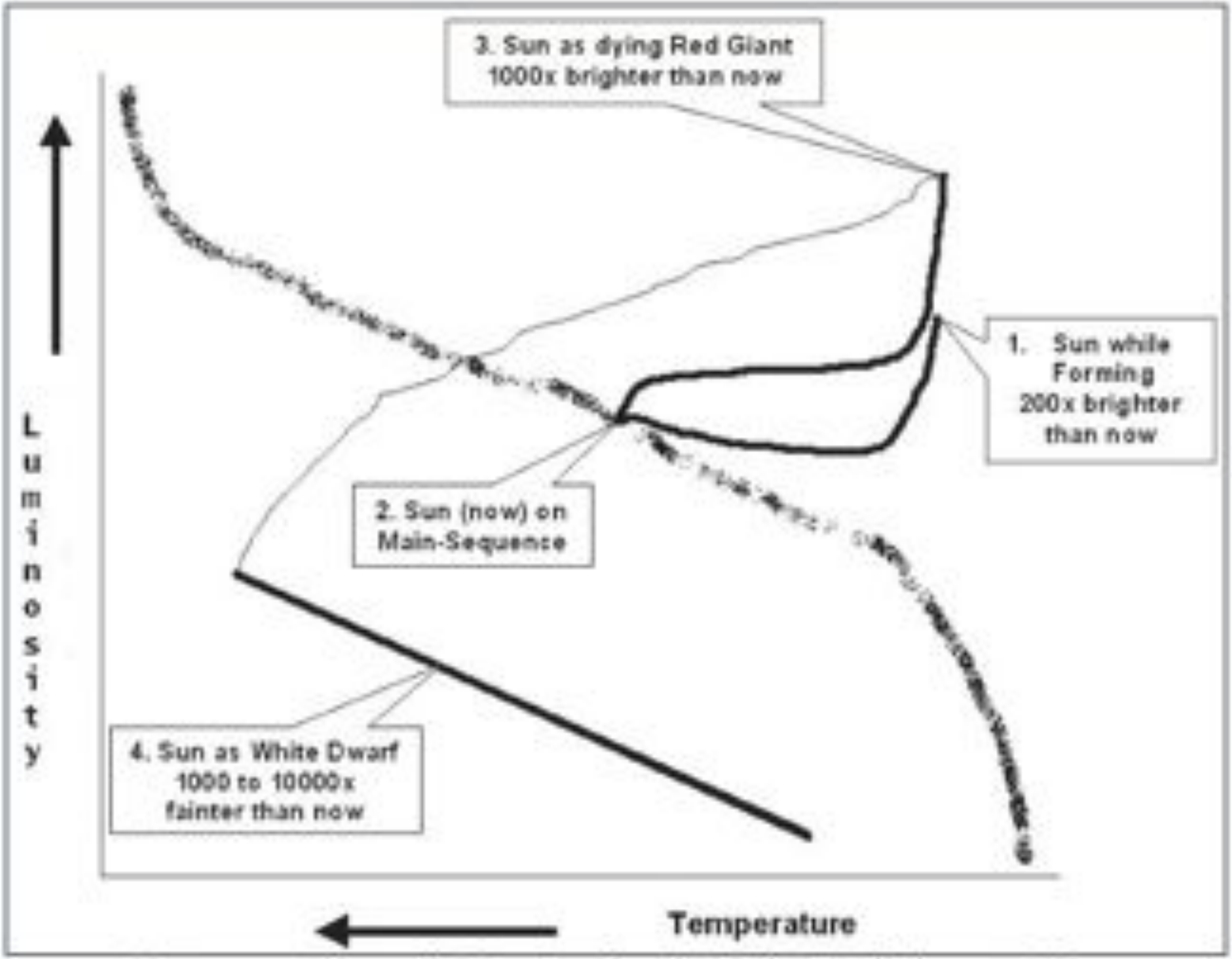
A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
"Swiss cheese" phase
"Spaghetti" phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube

NS spin glitches

- Spin very gradually slows due to E+M radiation.
- Sometimes see abrupt change in spin period.
- Some part of angular momentum carried by superfluid vortices.
- Vortices may pin to crust lattice allowing superfluid to "spin" at different rate from crust.
- At some point many vortices unpin and rapidly change moment of inertia causing glitch.



Supernovae



Hertzsprung-Russell Diagram Showing Solar Evolutionary Path, and Brightness at Different Stages of its Evolution

Chandrasekhar Limit

- Consider a uniform density extremely relativistic star where $k_F \gg m_e$.
- A=#of baryons, N=#of e = $A\,Y_p$.
- Energy of rel. Fermi gas $E/N = \mathbf{3/4\ k_F}$
- $n = k_F^3/3\pi^2 = N/V = AY_p/V$, $V = 4\pi R^3/3$
- $E/A = (3Y_p/4)(9\pi AY_p/4)^{1/3}(\mathbf{1/R})$
- Grav. total E = $-3/5\ G\ M^2/R$, $M = Am_n$.
- Grav $E/A = -(3/5)\ GMm_n/\mathbf{R}$
- $E/A = [(3Y_p/4)(9\pi AY_p/4)^{1/3} - (3/5)\ GMm_n]\mathbf{1/R}$
- For large enough M, [] will be <0 and star will collapse towards R--> 0.
- This mass is called Chandrasekhar limit ~ $1.4M_{sun}$.
- White dwarfs above Chandrasekhar limit collapse.

Planetary Nebula

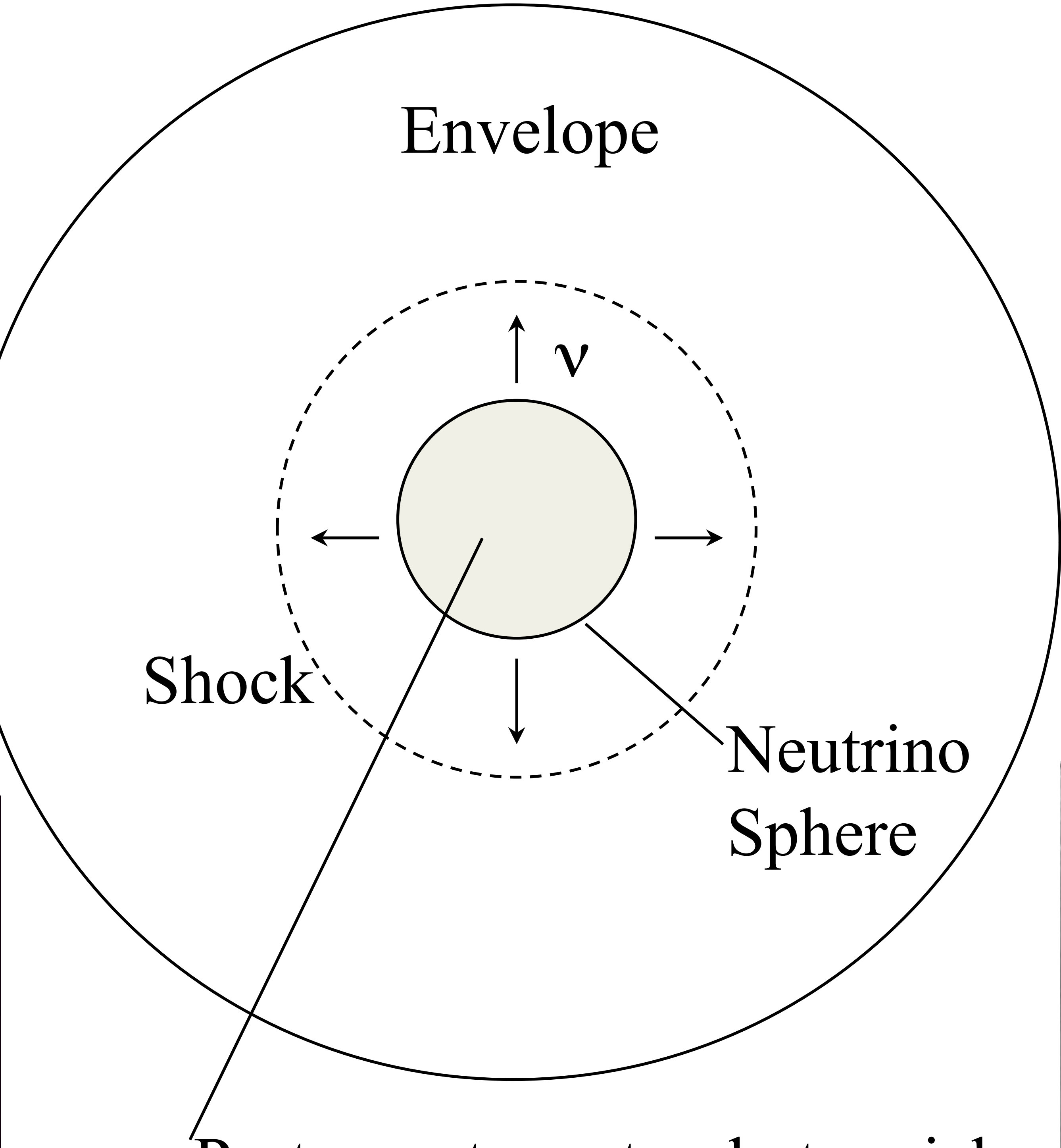
- Many stars above 1.4M_{sun} lose enough mass in stellar winds at end of giant phase to wind up as a WD below limit.

Supernovae

- Type IA are thermonuclear explosions that arise when a WD(s) accretes material and exceeds Chandrasekhar mass. *Energy from burning large amounts of C and O* to Fe. Either merger of two WD or single WD accreting material from normal star. SN IA useful in cosmology as standard candles.
- Type II involve core collapse when the core of a $M>8M_{sun}$ star exceeds Chandrasekhar mass and collapses. *Energy from gravitational binding E* of newly formed NS released in neutrinos.
- Binding E of NS $\sim 3/5\, GM^2/R \sim 0.1$ to $0.2\, M_{sun}c^2$! This is $\sim 10^{53}$ ergs and is radiated as $\sim 10^{58}$ neutrinos.
- Kinetic energy of SN remnant $\sim 10^{51}$ ergs.

NS Born in Core Collapse Supernovae

Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.



Envelope

ν

Shock

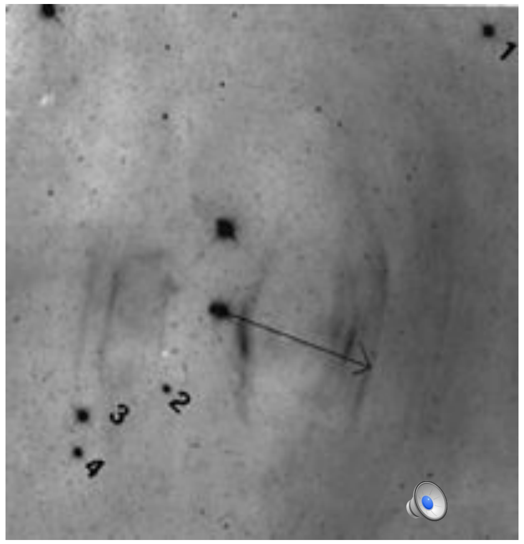
Neutrino Sphere

Proto-neutron star: hot, e rich

July 5, 1054

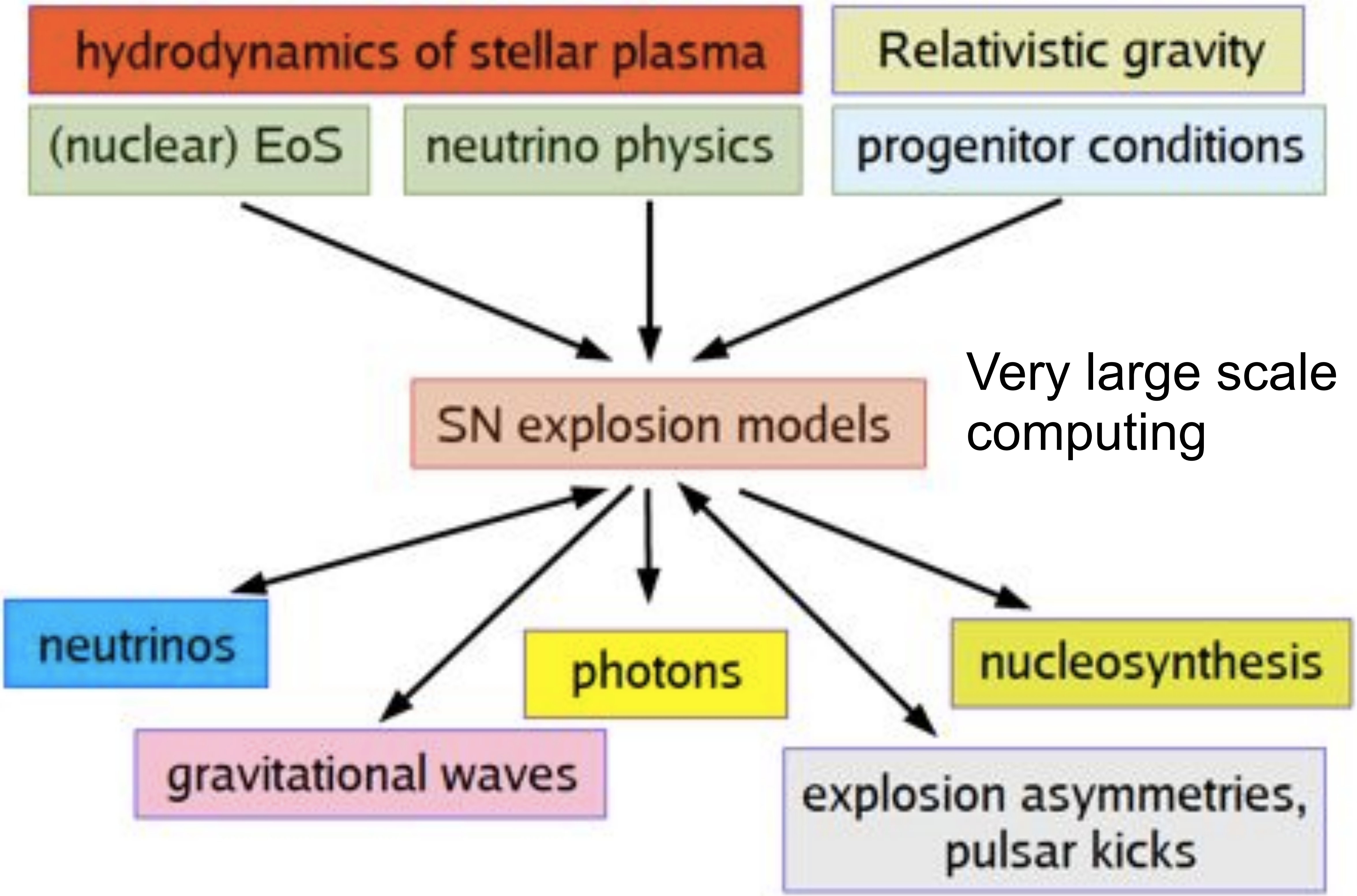
Crab nebula

Crab Pulsar



Hubble ST

Predictions of Signals from SN Core



hydrodynamics of stellar plasma

Relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

Very large scale computing

neutrinos

photons

nucleosynthesis

gravitational waves

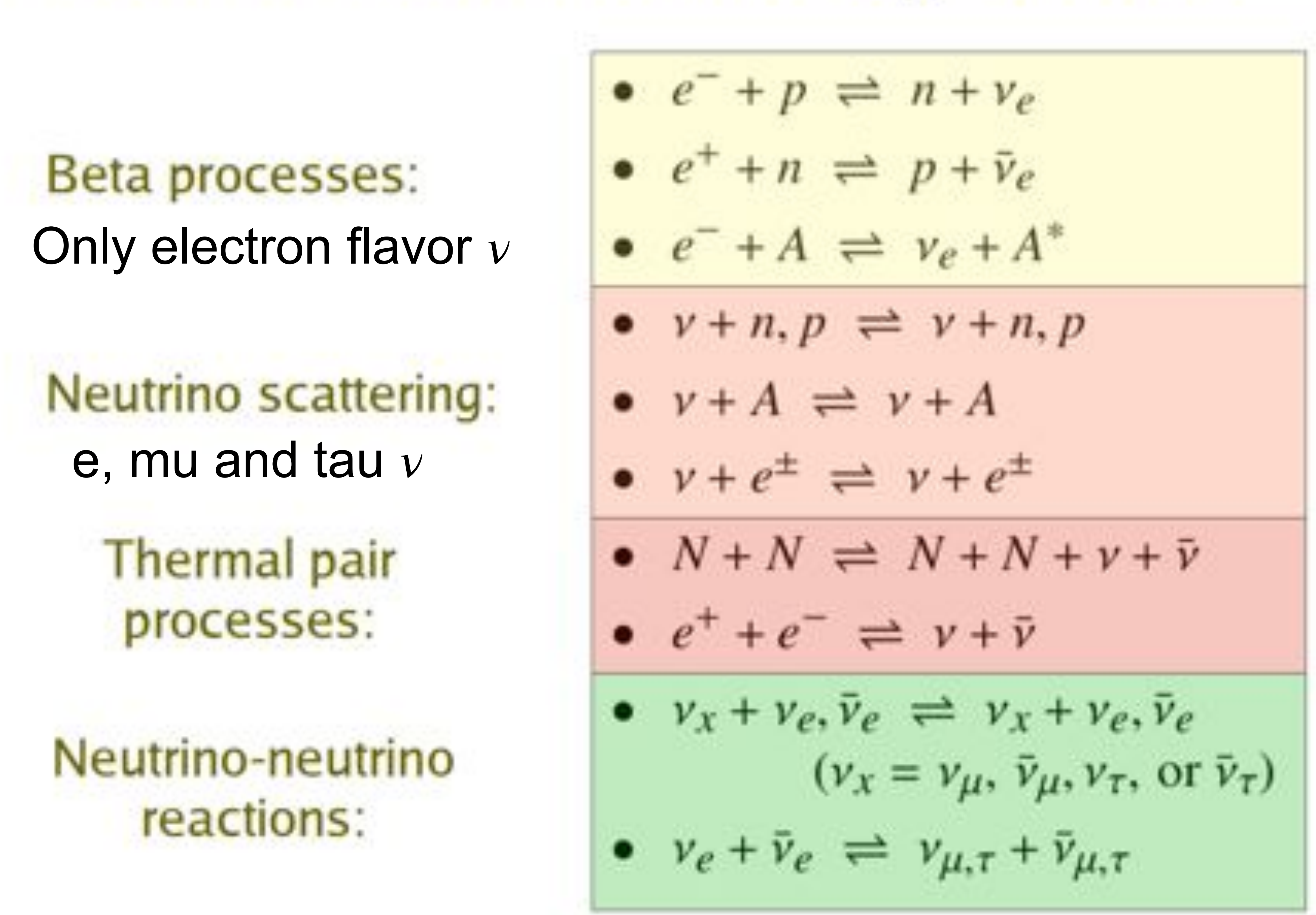
explosion asymmetries, pulsar kicks

NS properties mass, spin, magnetic field...

Equation of state for SN

- Now need full finite temperature EOS for matter at arbitrary Y_p that is not in beta equilibrium.
- $P = P(n,T,Y_p)$
- Need EOS over large range of density from $\sim 10^6$ to $>10^{15}$ g/cm^3.
- Temperatures from 0 to as high as 35 to 50 MeV (even hotter for black hole formation).
- Y_p from 0 to ~ 0.6.
- Need 3 Dim table with finely spaced grid so thermodynamic derivatives can be calculated consistently. [Otherwise interpolation errors can artificially generate entropy.]
- Table could have up to one million entries.
- Example: Gang Shen et al EOS (2011) based on virial expansion at low density and large scale relativistic mean field calculations at high density.

Neutrino Reactions in Supernovae



Beta processes:

Only electron flavor ν

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

Neutrino scattering:

e, mu and tau ν

- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$

Thermal pair processes:

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

Neutrino-neutrino reactions:

- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Cross sections modified in medium in way consistent with EOS

Neutrinosphere

- Mean free path $\lambda \sim 1/\sigma n$
- Typical nu-nucleon cross section: $\sigma \sim G^2 E_\nu^2$ with $E_\nu \sim 10\mathrm{MeV}$, G=Fermi constant ($=10^{-5}/m_n^2$).
- Neutrinosphere (surface of last scattering) where $\lambda = R \sim 20$ km. Density $n = 1/\sigma R \sim 10^{11}$ g/cm^3. This is 1/1000 of nuclear density.
- Much of the "action" in SN occurs at low density near the neutrinosphere.

Diffusion time

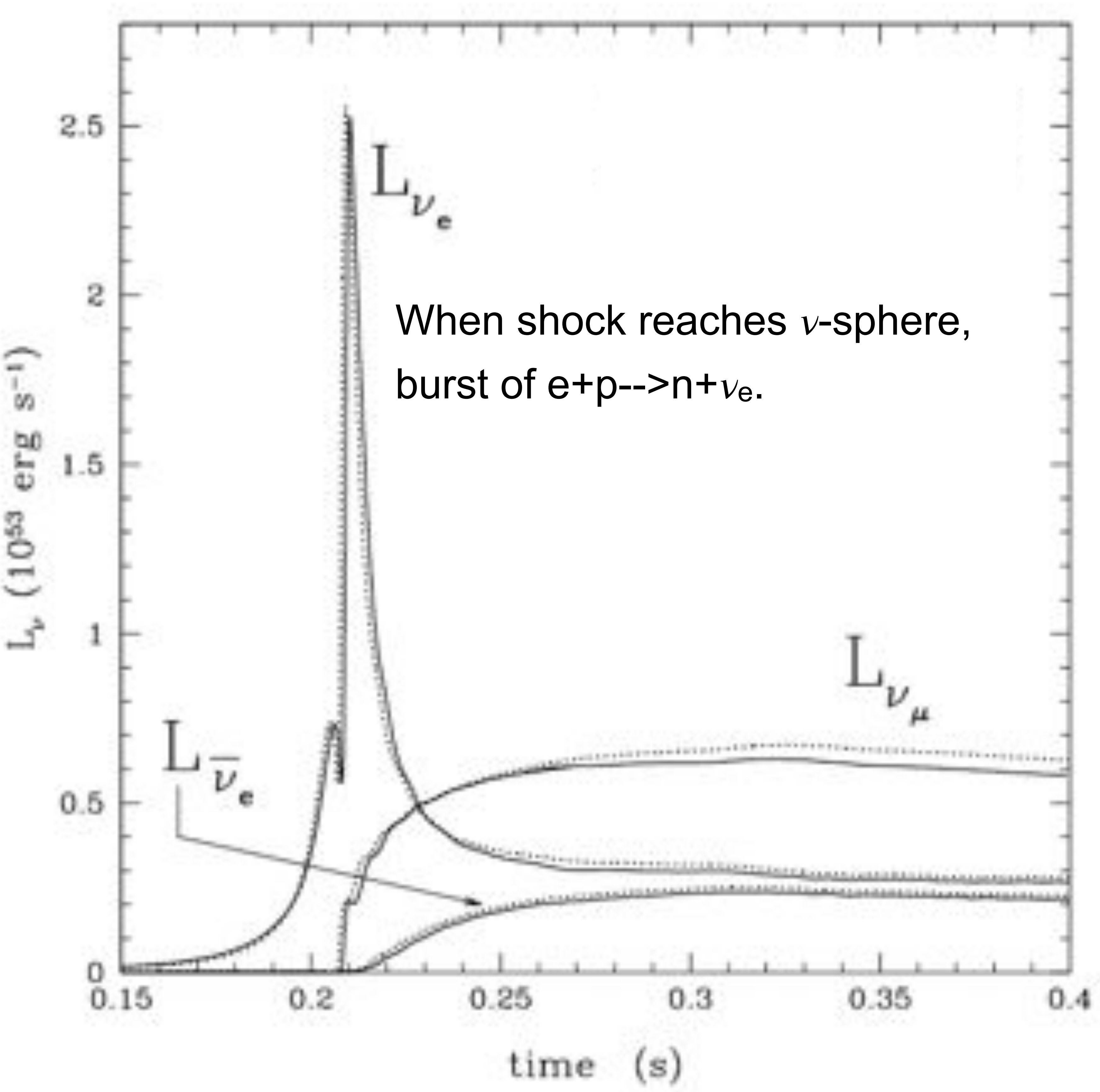
- Neutrinos well inside neutrinosphere diffuse and scatter many times before escaping.
- Diffusion time $\tau \sim (R/c)\,(R/\lambda)$
- Inside T~10 MeV, E_ν=3T=30 MeV.

  Average density of order nuclear density so λ~1 meter, R~20km --> $\tau \sim 1$ second.
- Expect neutrino signal to last few seconds.

Neutrino spectrum

- Neutrinos are radiated with a spectrum that reflects temperature at neutrinosphere. For a blackbody spectrum <E> = 3T.
- Electron neutrinos (and antineutrinos) have both charged current and neutral current interactions. Mu and Tau neutrinos only have neutral current interactions. Expect mu and tau neutrinosphere to occur at higher density than e neutrinosphere.
- Electron neutrinos capture on neutrons ν_e+n->p+e while antineutrinos capture on protons. Neutrinosphere region is neutron rich. Therefore neutrinosphere for anti-ν_e occurs at higher density than for ν_e.
- Supernova is hotter inside --> Expected average energies
- E(ν_x) ~ 18 MeV, E(anti-ν_e) ~ 15 MeV, E(ν_e) ~ 12 MeV.
- Recent simulations tend to have more nearly equal energies.

Neutrino luminosity

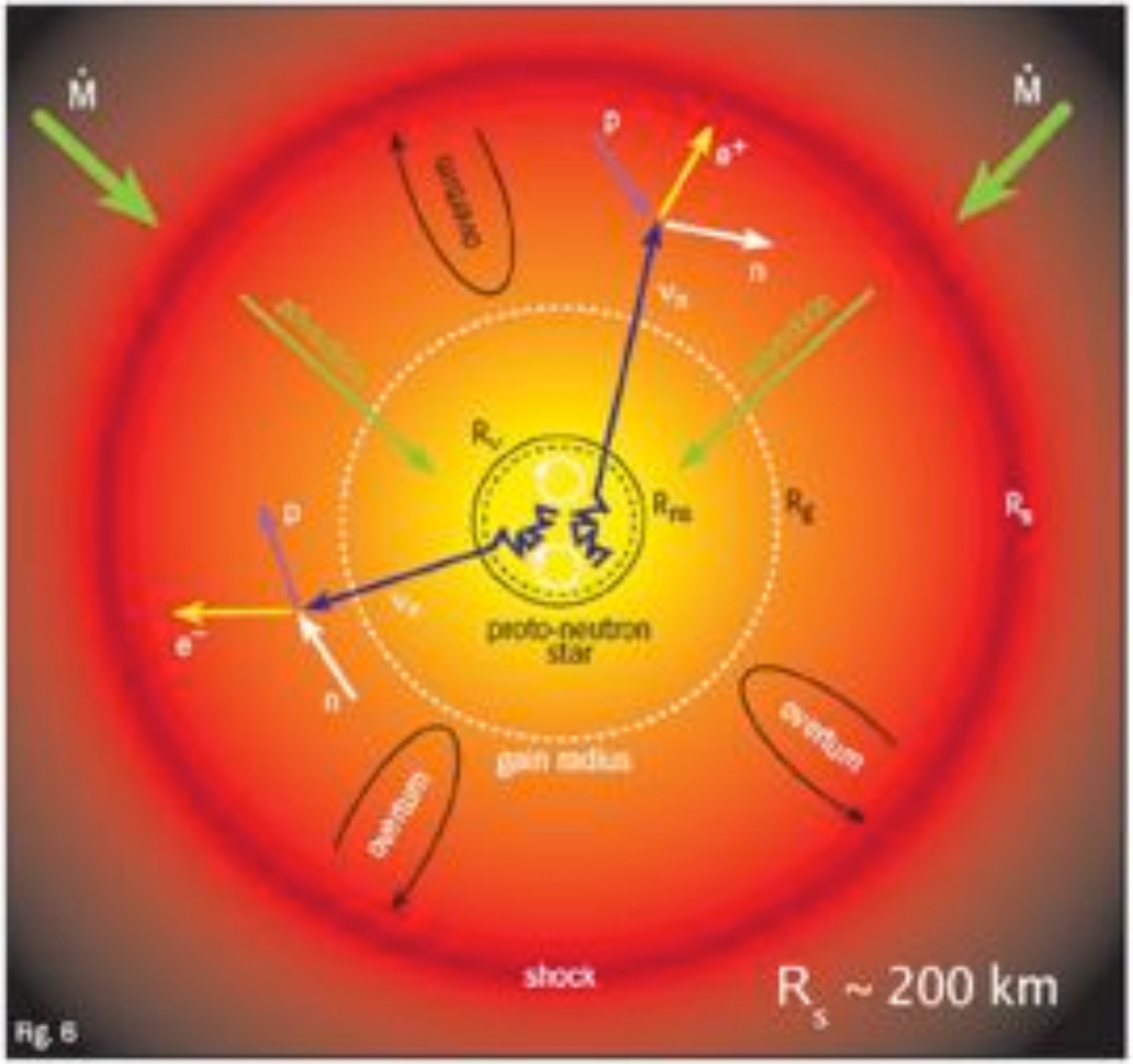


When shock reaches ν-sphere, burst of $e+p \rightarrow n+\nu_e$.

Supernova Quantum Numbers

	Pre-SN Core	Proto-N Star	Neutron Star
Mass (M_{sun})	1.6	1.6 --> 1.4	1.4
ν radiated	small	10^{58}	small
Baryon #	10^{57}	10^{57}	10^{57}
Electron #	10^{57}	10^{57}-->10^{56}	10^{56}
Muon #	small	10^{55}	10^{55}
Tau #	small	10^{54}	small
Strangeness	small	?	?

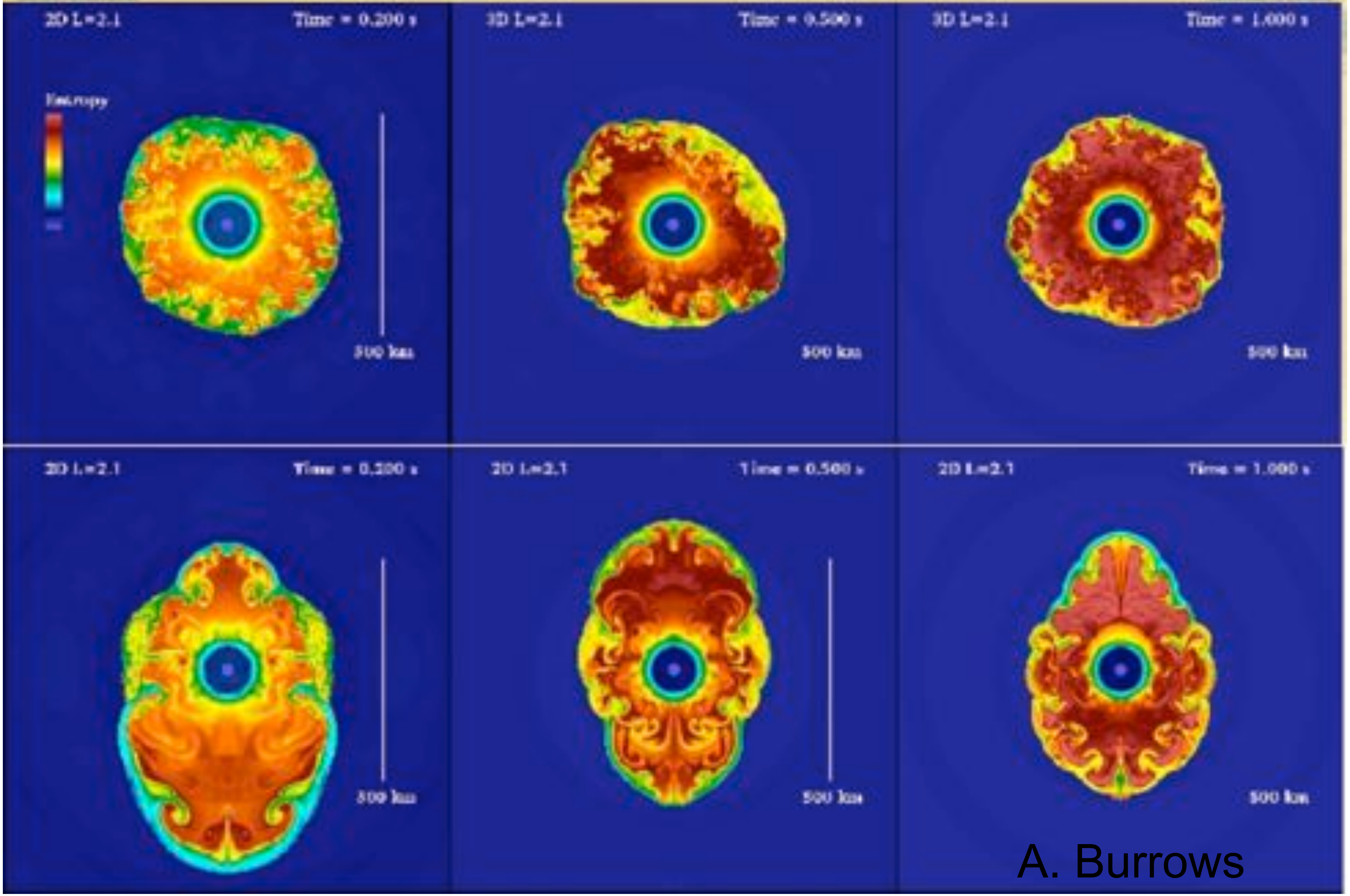
Neutrinos & SN Explosion Mechanism



Paradigm: Explosions by the neutrino-heating mechanism, supported by hydrodynamic instabilities in the postshock layer

- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities support the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08).

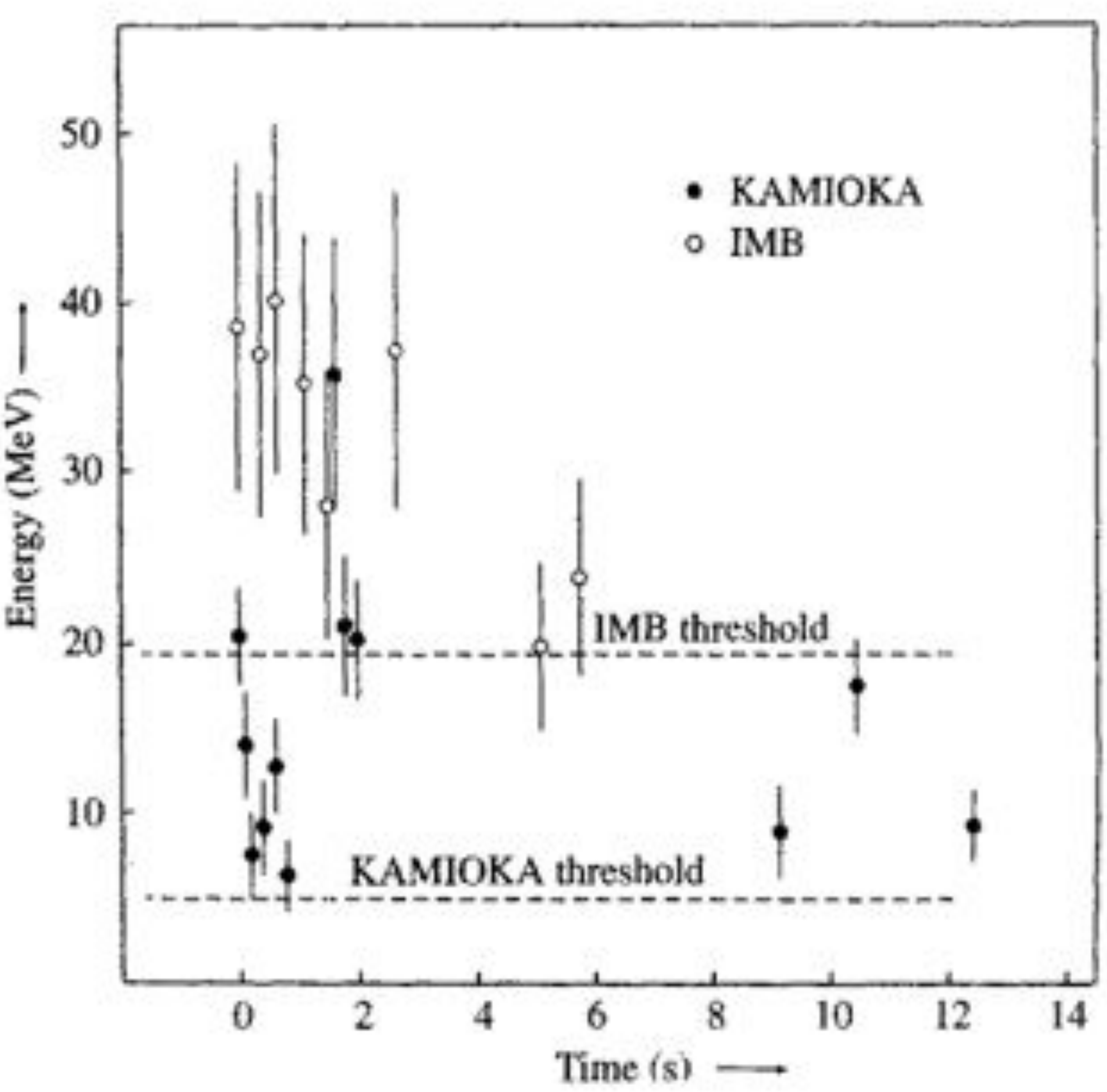
Comparison of 2D with 3D



A. Burrows

A. Burrows

Neutrinos from SN1987a



Neutrino Oscillations

- Solar neutrinos and reactor antineutrinos are observed to oscillate from electron to mu or tau flavor...
- Neutrino oscillations depend on mass differences between neutrino states, mixing angles, and interaction potentials between neutrinos and background particles.
- Supernovae have high densities of both electrons and neutrinos that produce important interaction potentials. --> Neutrino oscillations are complicated in supernovae.
- Not such large differences between energies and fluxes for different neutrino flavors. This may limit the effect of neutrino oscillations.

Next galactic supernova

- Very detailed electromagnetic observations.
- Likely detect gravitational wave signal.
- Detailed neutrino observations involving tens of thousands of events (SN1987a ~20 events).
- Learn about the explosion mechanism, for example how long was the delay to explosion?
- Learn about nucleosynthesis (next lecture)
- Learn about neutrinos and neutrino oscillations and other possible weakly interacting particles. Example protoneutron star cooling sensitive to any other even very weakly interacting particles.
- Can there be superluminal neutrinos???

Next galactic supernova

- Has all ready occurred! (One just needs to view galaxy in correct reference frame.)
- “Check is in the mail”.
- As I speak today, astronomical numbers of neutrinos are racing towards earth at all but the speed of light.

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National Nuclear Physics Summer School, Santa Fe, July 2012.