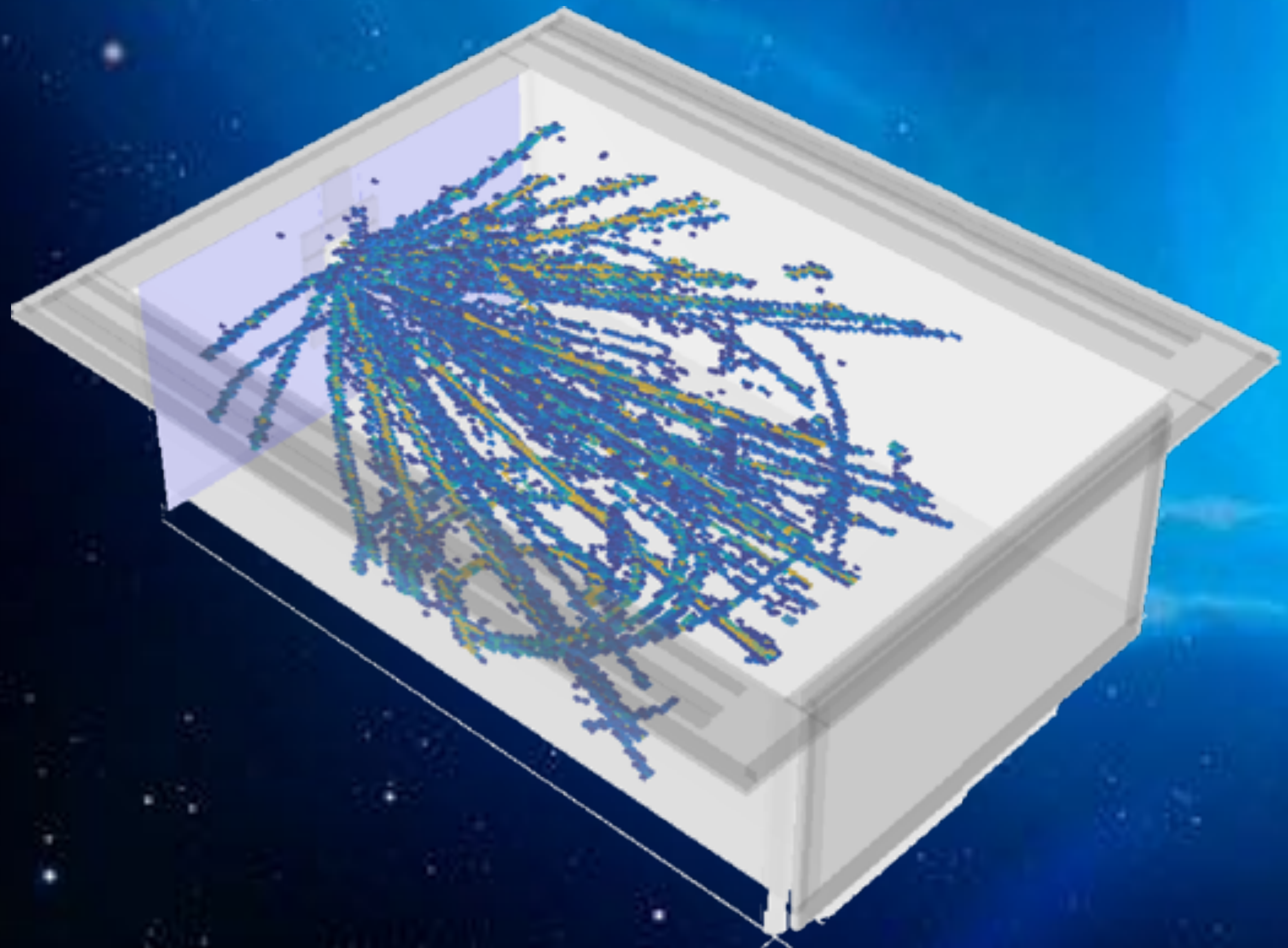
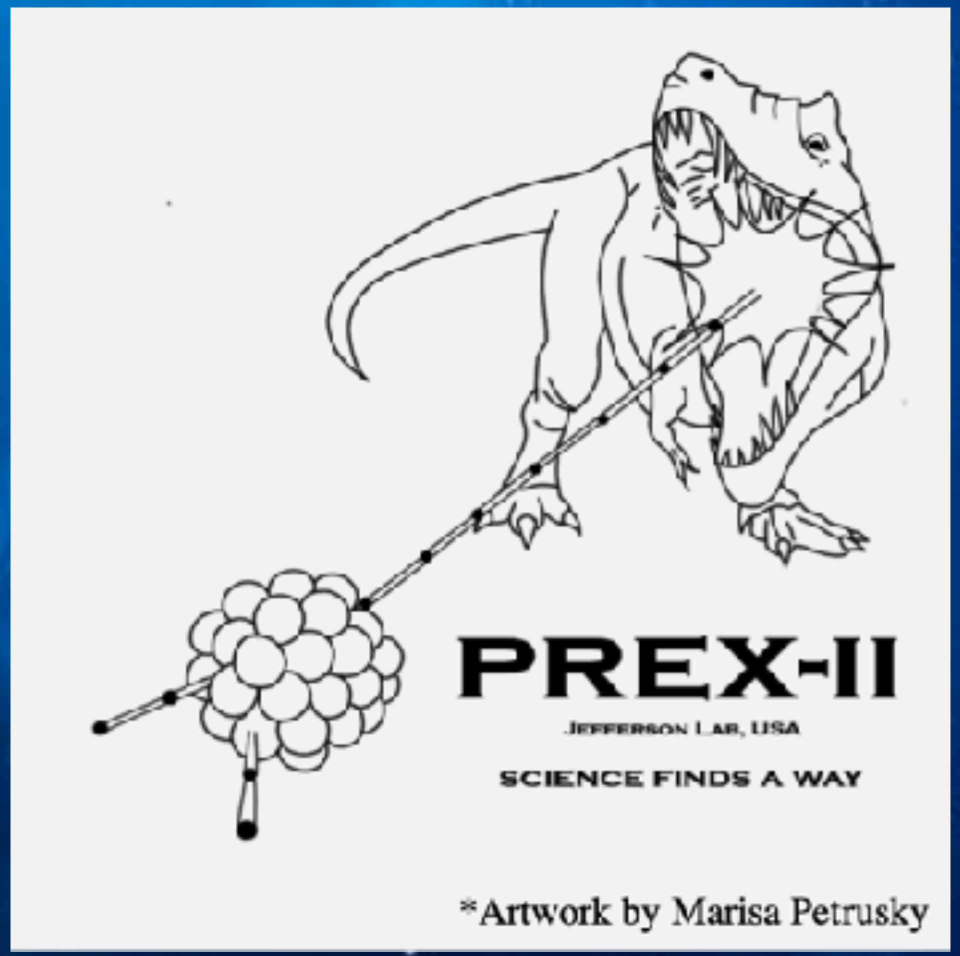
# Astronomical, nuclear structure, and HI probes of dense matter





*Artwork by Marisa Petrusky

Chuck Horowitz, Indiana U.     ECT*, Apr. 2024

# What is NATURE of dense matter?

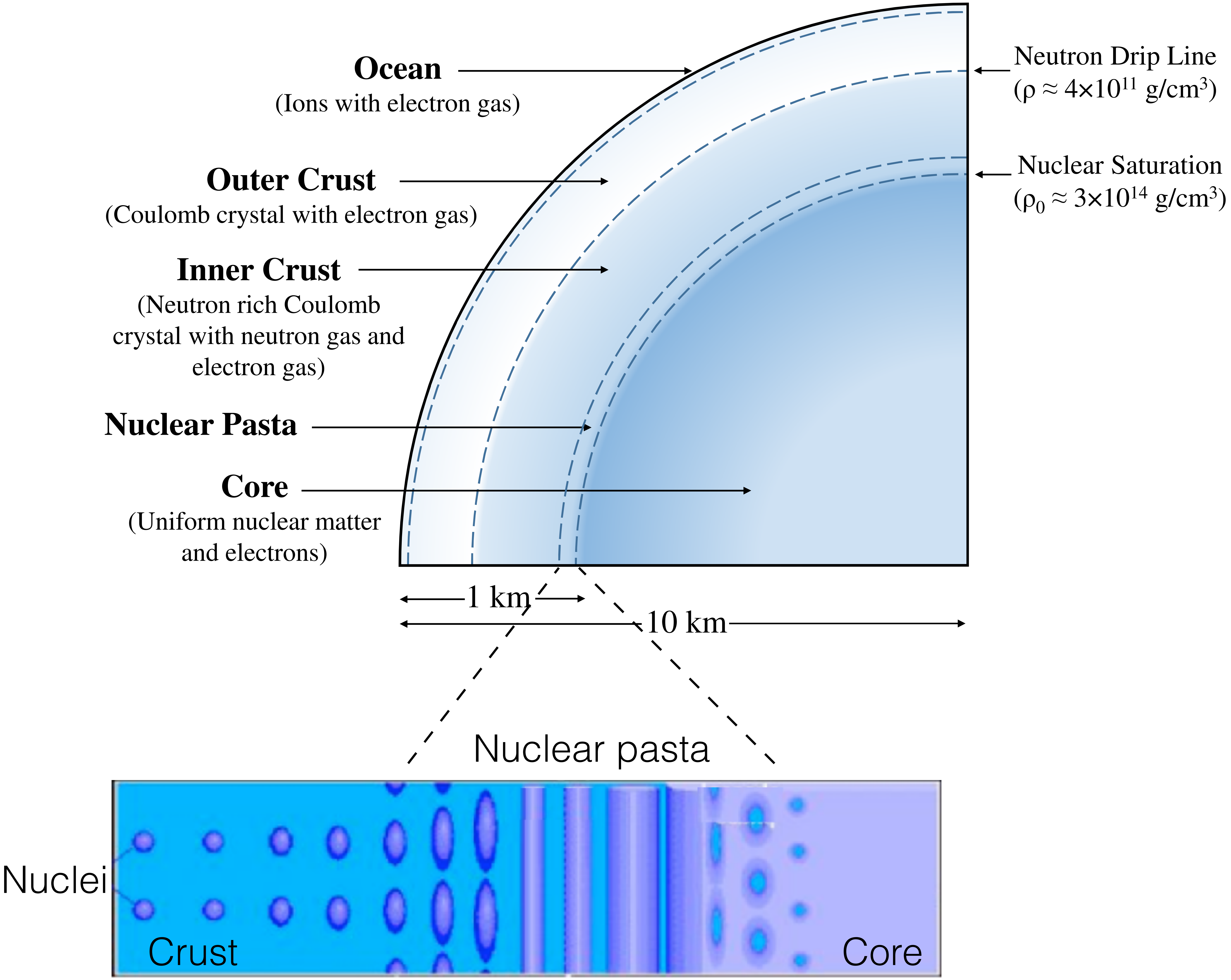
- First step: pressure vs density. p, ρ appear in stress energy tensor of Einstein eqs —> Gravitational wave observers aim to determine EOS p=p(ρ).
- EOS only gets partial credit. Need additional observables beyond NS masses, radii, and deformabilities (quadrupole polarizability).
- For example, what are NS made of? What are the degrees of freedom? (Quarks, nucleons …?)

# Neutron star observables

- Thermal conductivity of NS crust
- Heat capacity of NS core (# of deg. of freedom)
- Neutrino emissivity (How NS cool)
- Neutrino opacity and spin response of warm unitary gas (Supernovae dominated by neutrino transport)

# Neutron stars and their crusts

- Neutron stars are formed from the collapse of a massive star in a supernova explosion.
- Mass ~1.4 $M_{sun}$, Radius ~10 km
- Solid crust ~ 1km thick over liquid core.
- Electron capture drives crust more n rich with increasing density: e + p -> n + nu.
- At ~ $10^{11}$ g/cm$^3$, n drip out of nuclei and form n gas —> inner crust.
- Nuclear pasta may be lower ~100 m of ~1km thick crust.
- Transition from crust to core involves several pasta phases.
- Dense pasta may contain half of the crust mass.



**Ocean**
(Ions with electron gas)

**Outer Crust**
(Coulomb crystal with electron gas)

**Inner Crust**
(Neutron rich Coulomb crystal with neutron gas and electron gas)

**Nuclear Pasta**

**Core**
(Uniform nuclear matter and electrons)

Neutron Drip Line
($\rho \approx 4\times10^{11}$ g/cm$^3$)

Nuclear Saturation
($\rho_0 \approx 3\times10^{14}$ g/cm$^3$)

1 km

10 km

Nuclear pasta

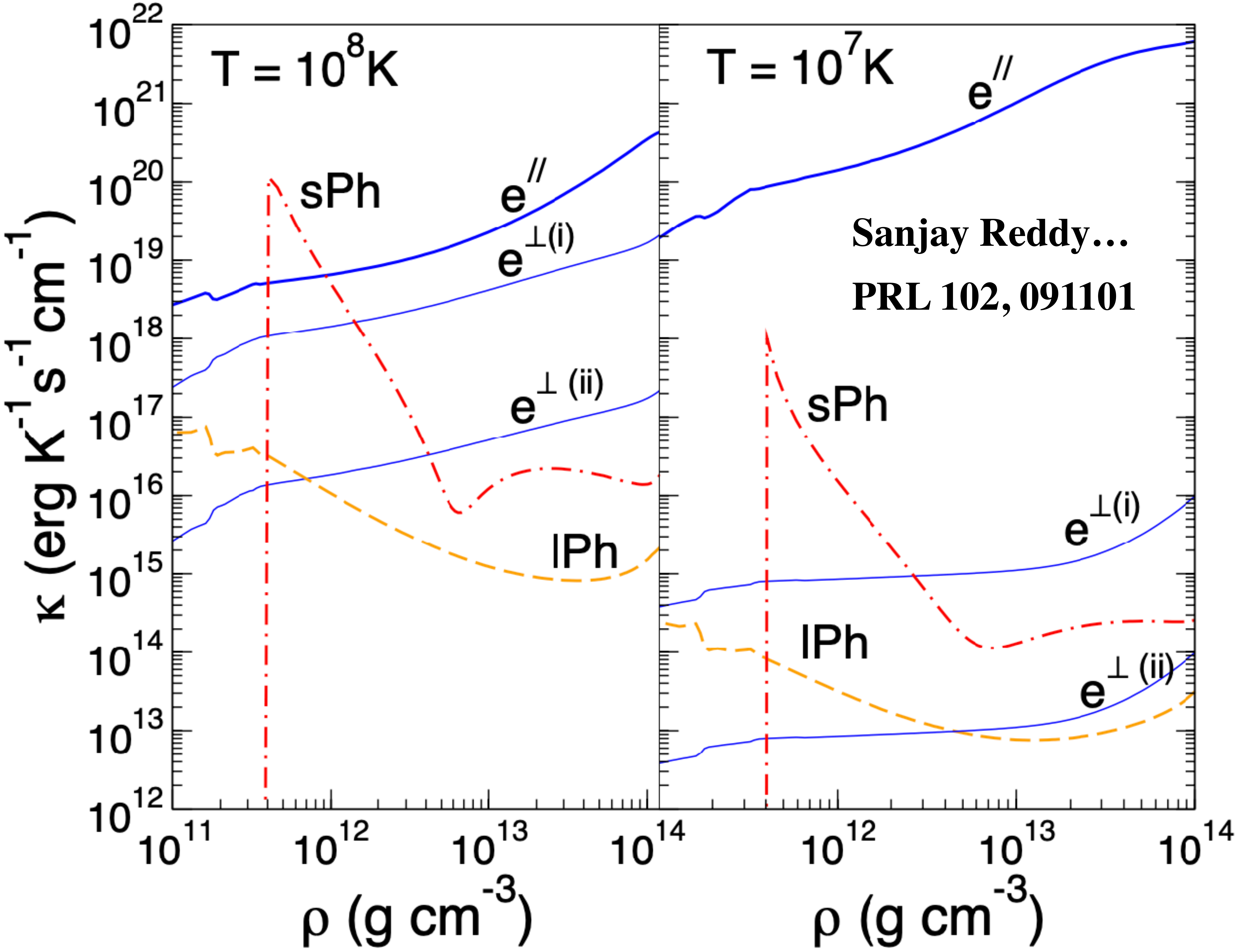
Nuclei

Crust

Core

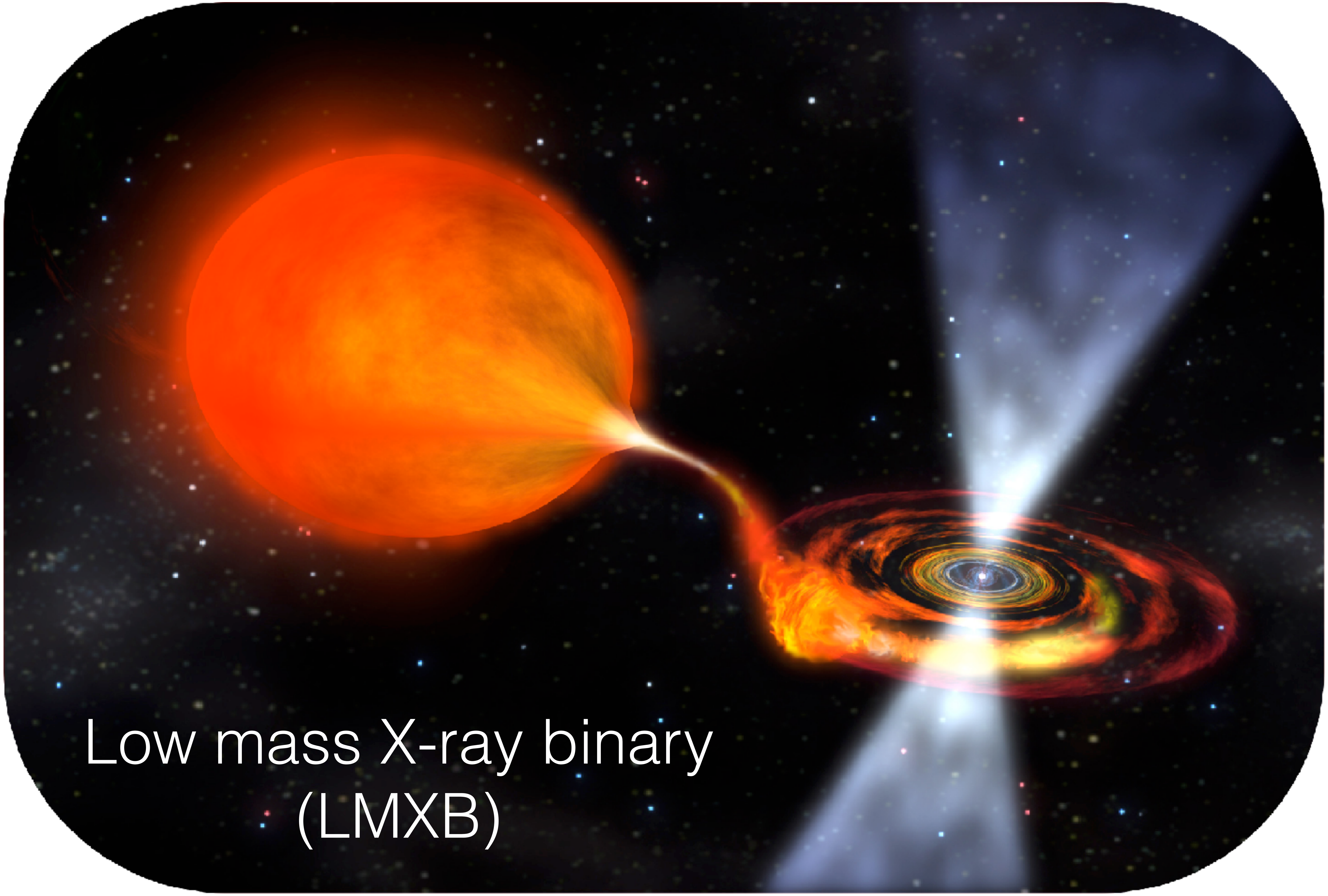
# Thermal Conductivity

- Electrons in highly degenerate Fermi gas have long MFP.
- Conductivity of NS core is high so it is nearly isothermal.
- In crust electron MFP set by e-ion scattering determined by bcc lattice static structure factor.
- Discuss crust cooling in LMXBs.



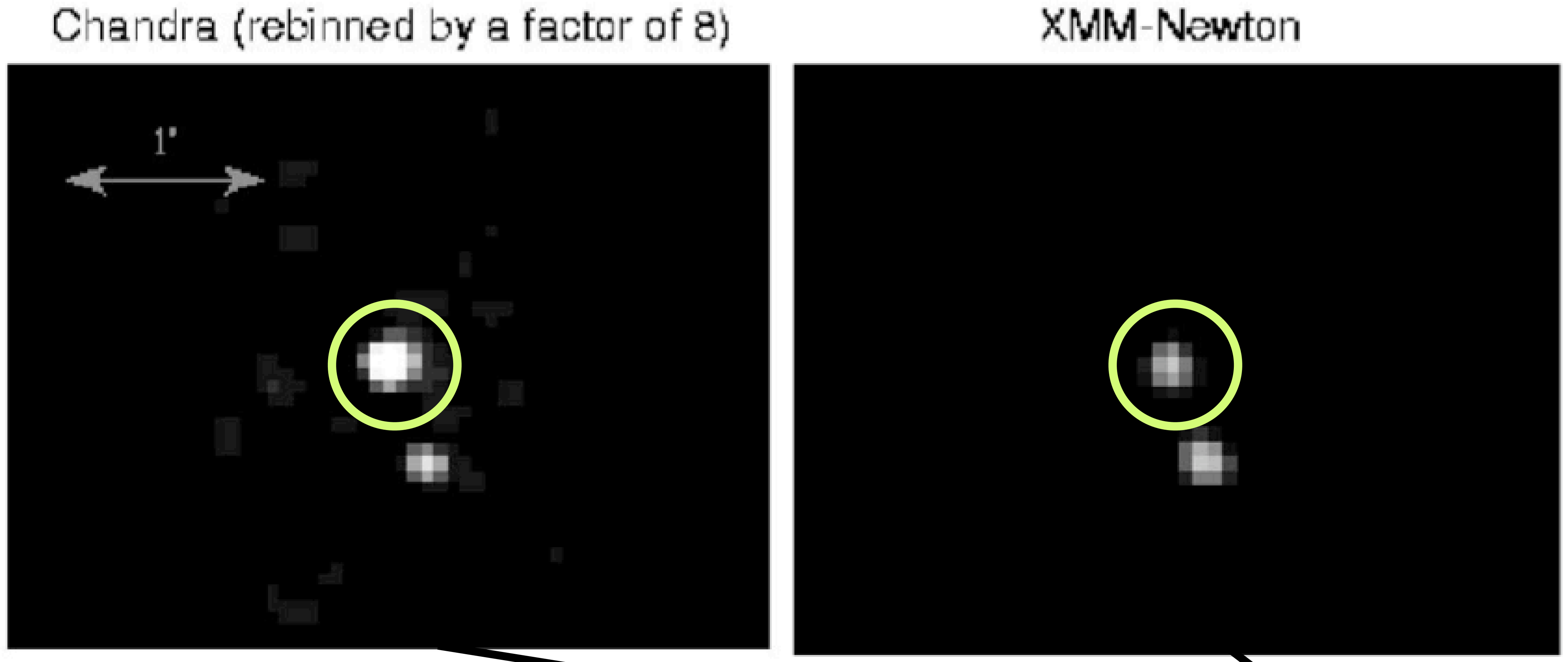
**Sanjay Reddy…**

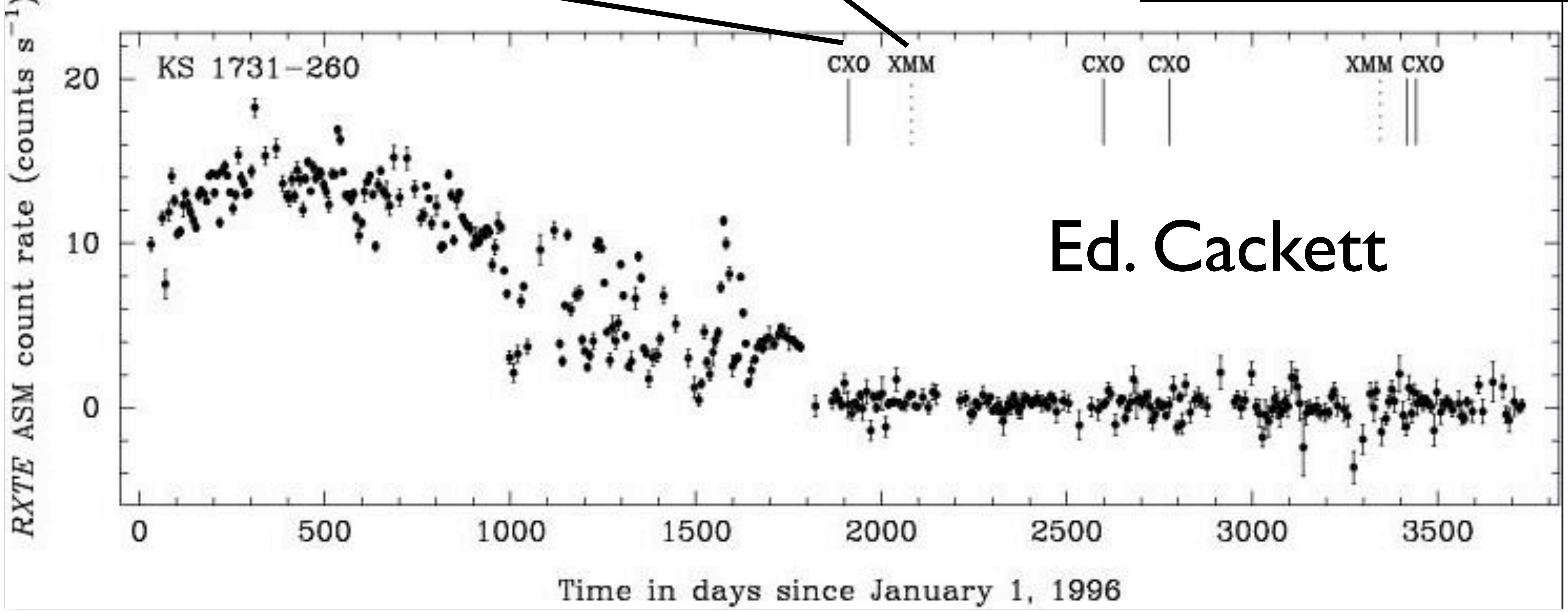
**PRL 102, 091101**



Low mass X-ray binary
(LMXB)

# Cooling of crust of KS 1731-260





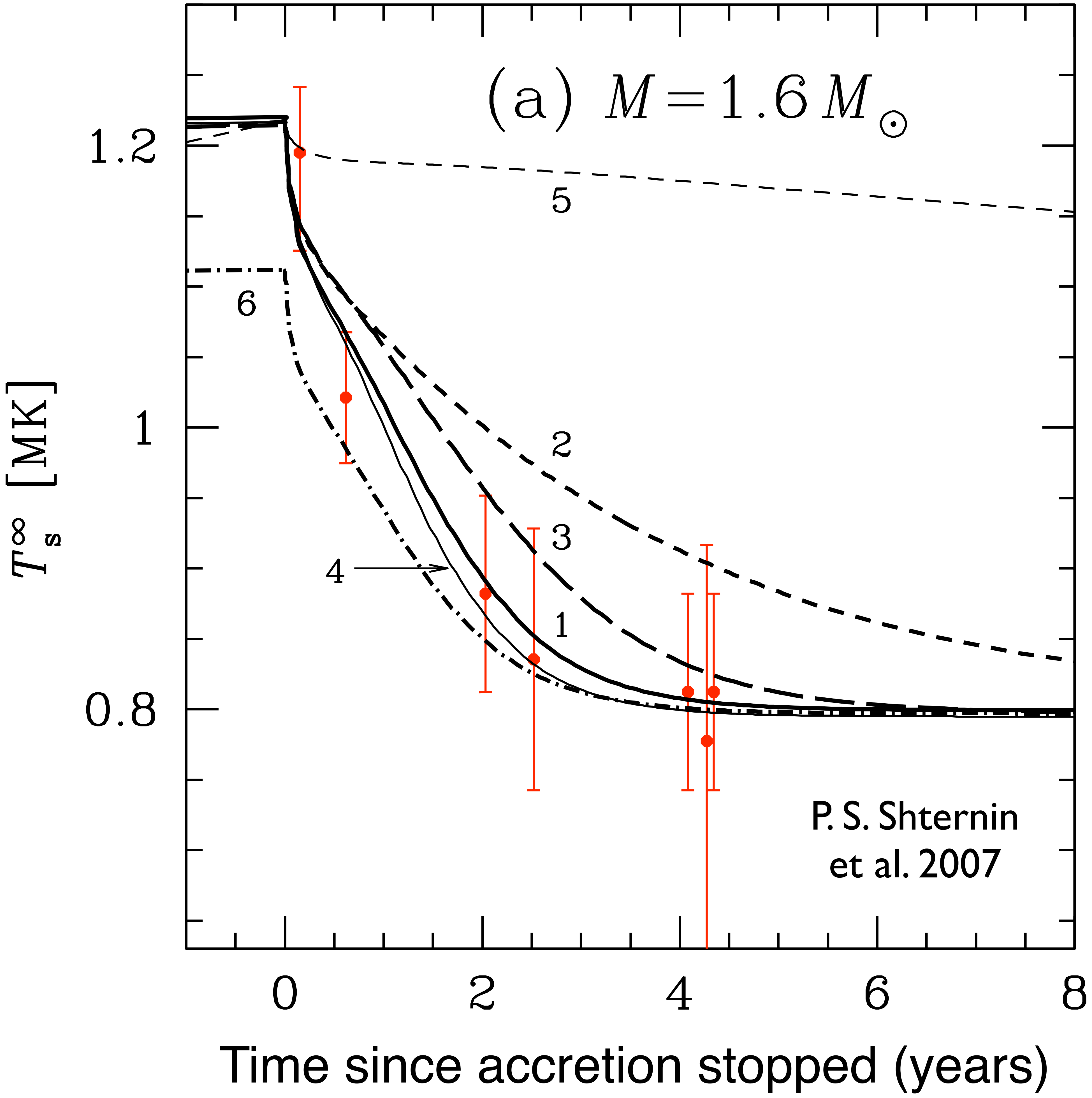
Ed. Cackett

# Cooling of KS 1730-260 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)

Rapid cooling strongly suggests crust is a clean crystalline solid with high thermal conductivity.

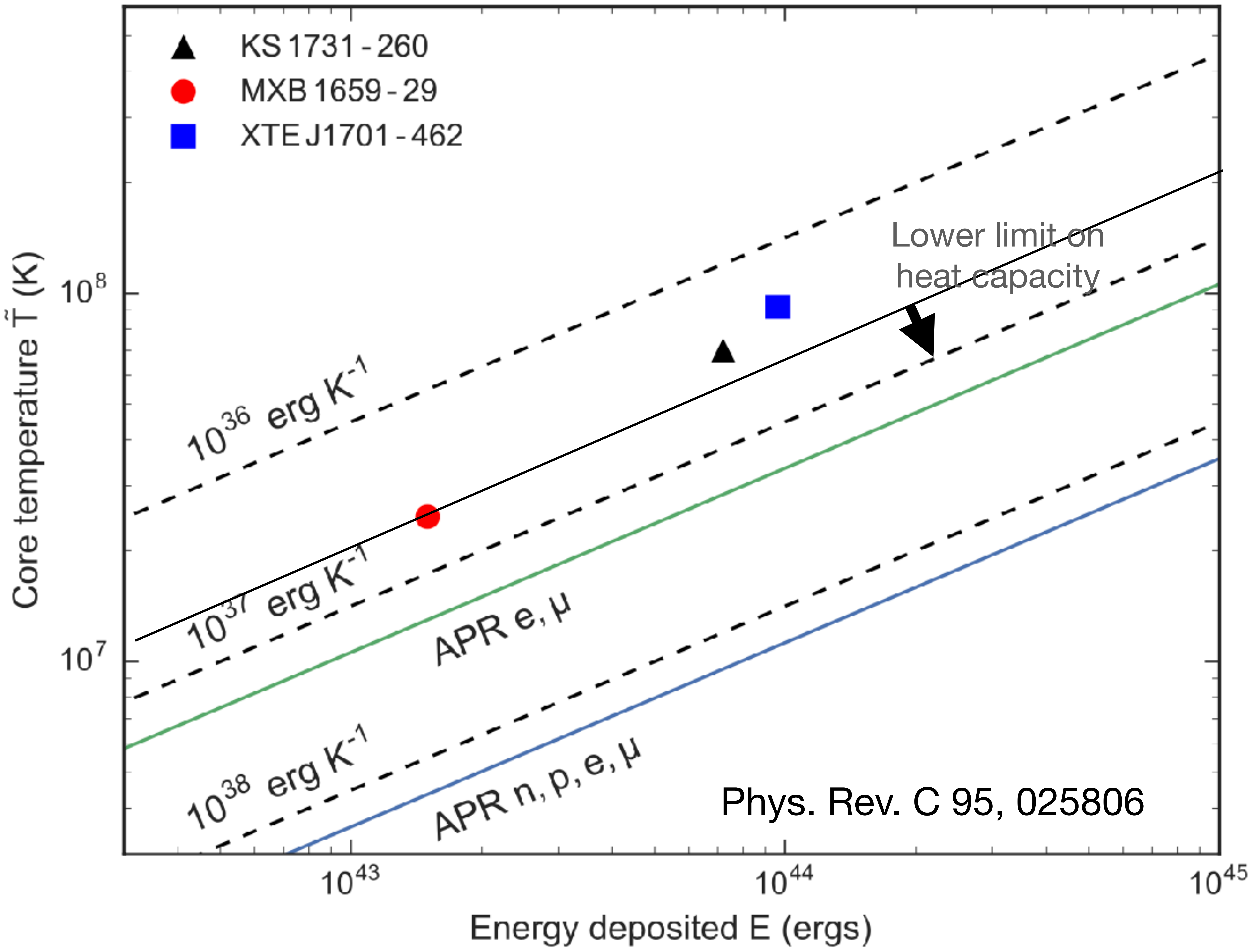


P. S. Shternin et al. 2007

# Heat capacity of NS core

# Core heat capacity

- Star absorbs energy E during outburst and has final core T.
- Heat capacity must be greater than 5x$10^{36}$ erg/K else final T would be higher even if initial T=0.
- Rules out extreme color superconductor phase with low transition density.
- CFL color superconductor has paired quarks and no electrons.



Lower limit on heat capacity

Phys. Rev. C 95, 025806

# Neutrino emissivity

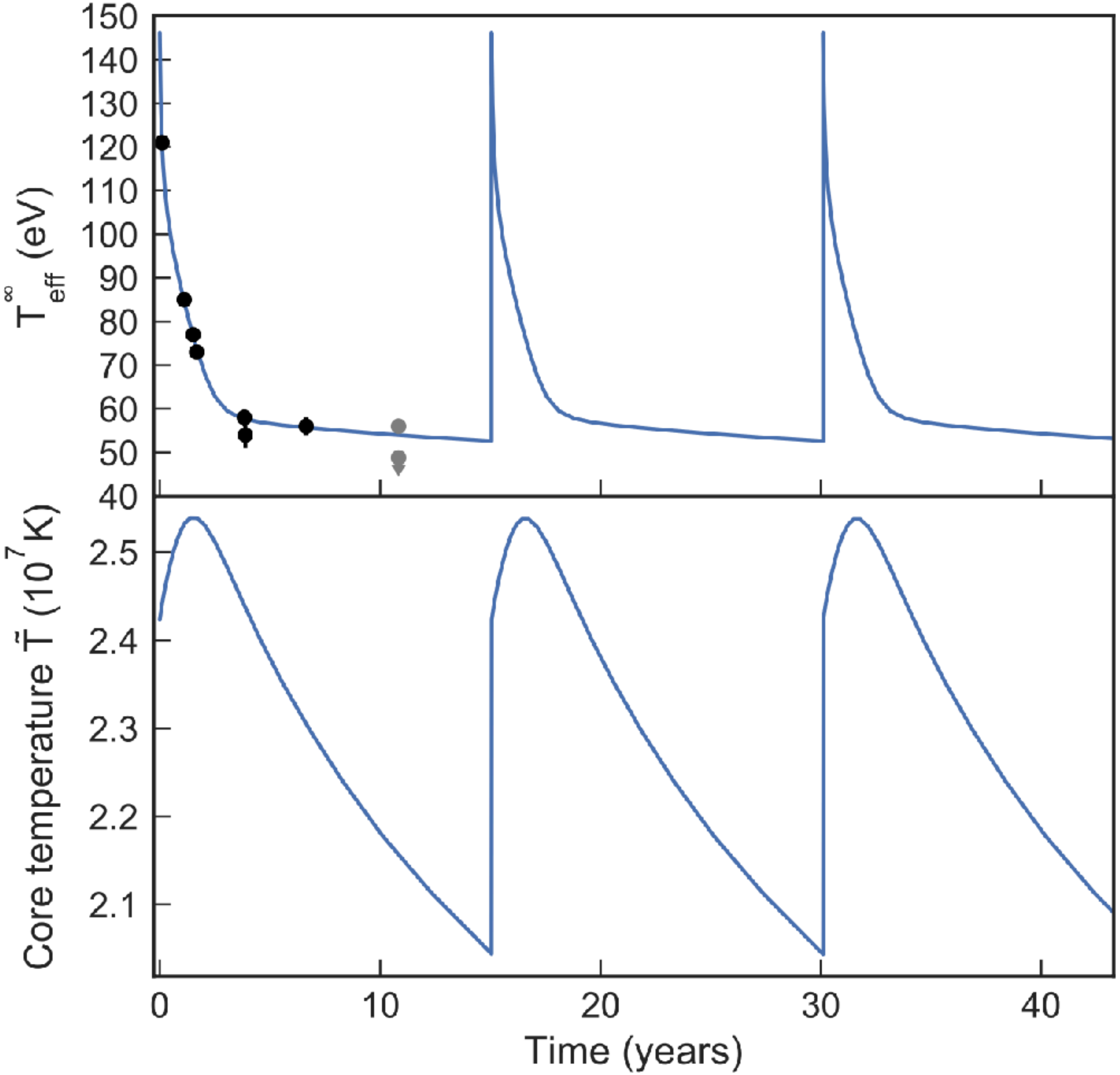
# NS Cooling

- Many stars appear to cool via **modified URCA** reactions n+n -> n+p+e+anti-$\nu$ followed by e+p+n -> n+n+$\nu$. Cools star by radiating $\nu$ anti-$\nu$ pair. Need 2nd nucleon to conserve momentum and energy. This slows rate.
- If proton fraction is high, star can rapidly cool via **direct URCA** n->p+e+anti-$\nu$ followed by e+p-> n+$\nu$. Need $k_{Fe} + k_{Fp} > k_{Fn}$ to conserve momentum. Proton fraction $Y_p$>~1/9.
- If hyperions, pions, quarks, … are present they can also beta decay to cool star.

# MXB 1659-29

- Large 2.5 yr outburst after 15 yr in quiescence. Final surface T very low ~50 eV
- If system in steady state, has high neutrino luminosity to radiate outburst heat over 15 yr.
- First NS with well measured surface T showing direct URCA like cooling. Perhaps star more massive than slower cooling ones.

Phys. Rev. Lett. **120**, 182701 (2018)



# Neutrino opacity

# Supernovae

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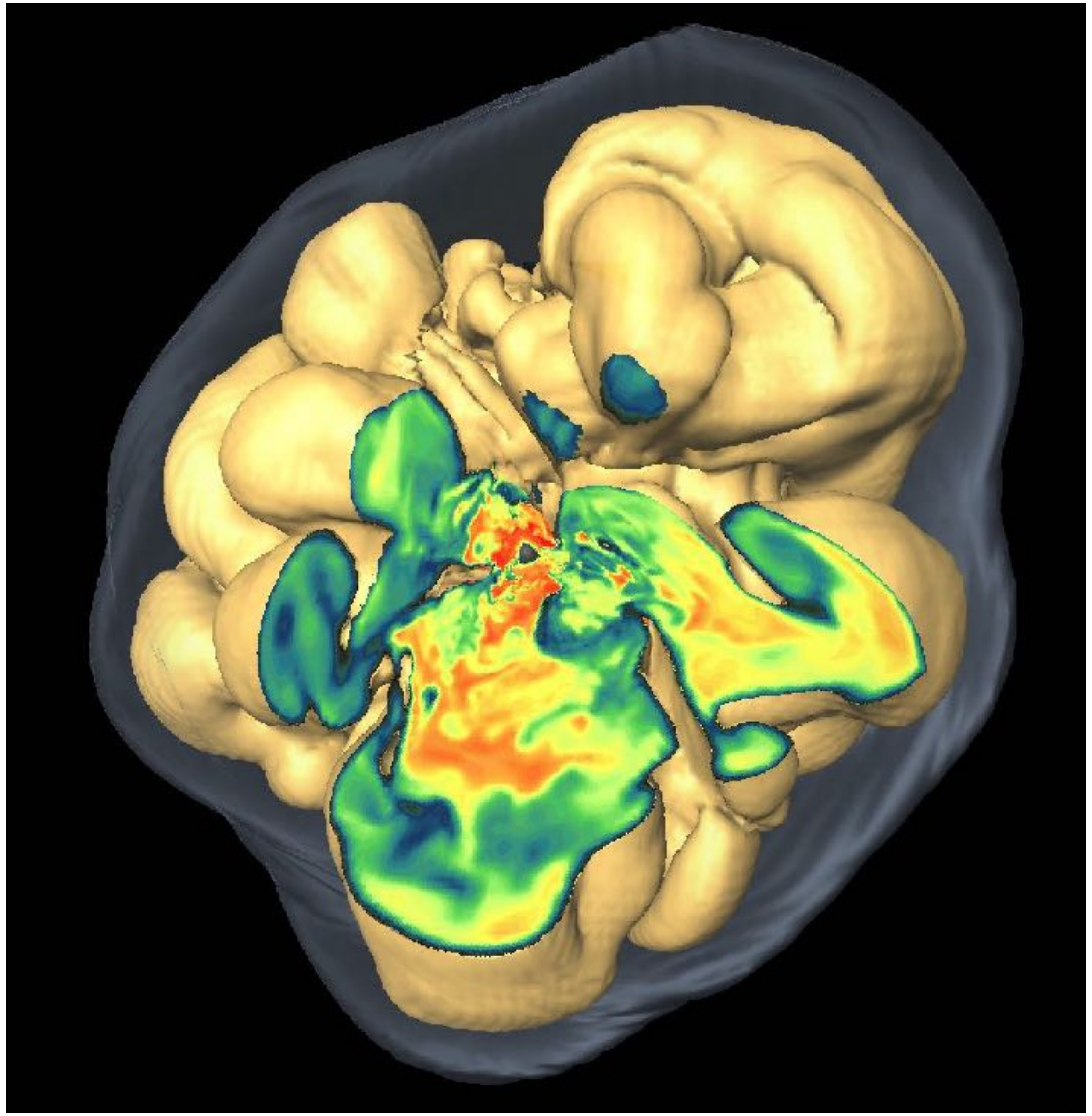
- Detected ~20 neutrino events from SN1987A

# Neutrinos help supernovae explode

- Gravitational binding E of NS $10^{53}$ ergs radiated as $10^{58}$ neutrinos
- Kinetic energy of ejecta $10^{51}$ ergs helped by rare neutrino interactions.
- Neutrinos come from neutrino-sphere where mean free path ~ size of system. $10^{11}$-$10^{12}$ g/cm$^3$ and T ~ 5 MeV



# $\nu$ interactions in SN matter

| $\nu_e$ + n —> p + e (Charged current capture rxn) |
|---|
| $\nu$ + N —> $\nu$ + N (Neutral current elastic scattering, important opacity source for mu and tau $\nu$) |

- Neutrino-nucleon neutral current cross section in SN is modified by axial or spin response $S_A$, and vector response $S_V$, of the medium.

$$\frac{1}{V}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\Big(g_a^2(3-\cos\theta)(n_n+n_p)S_A + (1+\cos\theta)n_n S_V\Big)$$

- Responses $S_A$, $S_V$ —> 1 in free space. Normally $S_A$ dominates because of $3g_a^2$ factor.
- Dynamical spin response $S_A(q,\omega)$ -> Static $S_A(q)$ -> $S_A(q\to 0)$

# Neutrinosphere as unitary gas

- Much of the action in SN at *low densities* near neutrinosphere at $n \sim n_0/100$ (nuclear density $n_0$).

- Average distance between two neutrons near neutrinosphere is less than NN scattering length.

←— 19 fm —→ nn scattering length

←— 8.5 fm —→ Average distance between two neutrons at $n_0/100$

←→ 1.4 fm Range of NN force. (Effective range 2.8 fm)

- Because of the long scattering length one can have important correlations even at low densities.

- Two neutrons are correlated into spin zero $^1S_0$ state that reduces spin response $S_A<1$. **Do the spin correlations of a unitary gas help a SN explode?**

# Can the spin response of a unitary gas help a supernova explode?

- Well posed question.

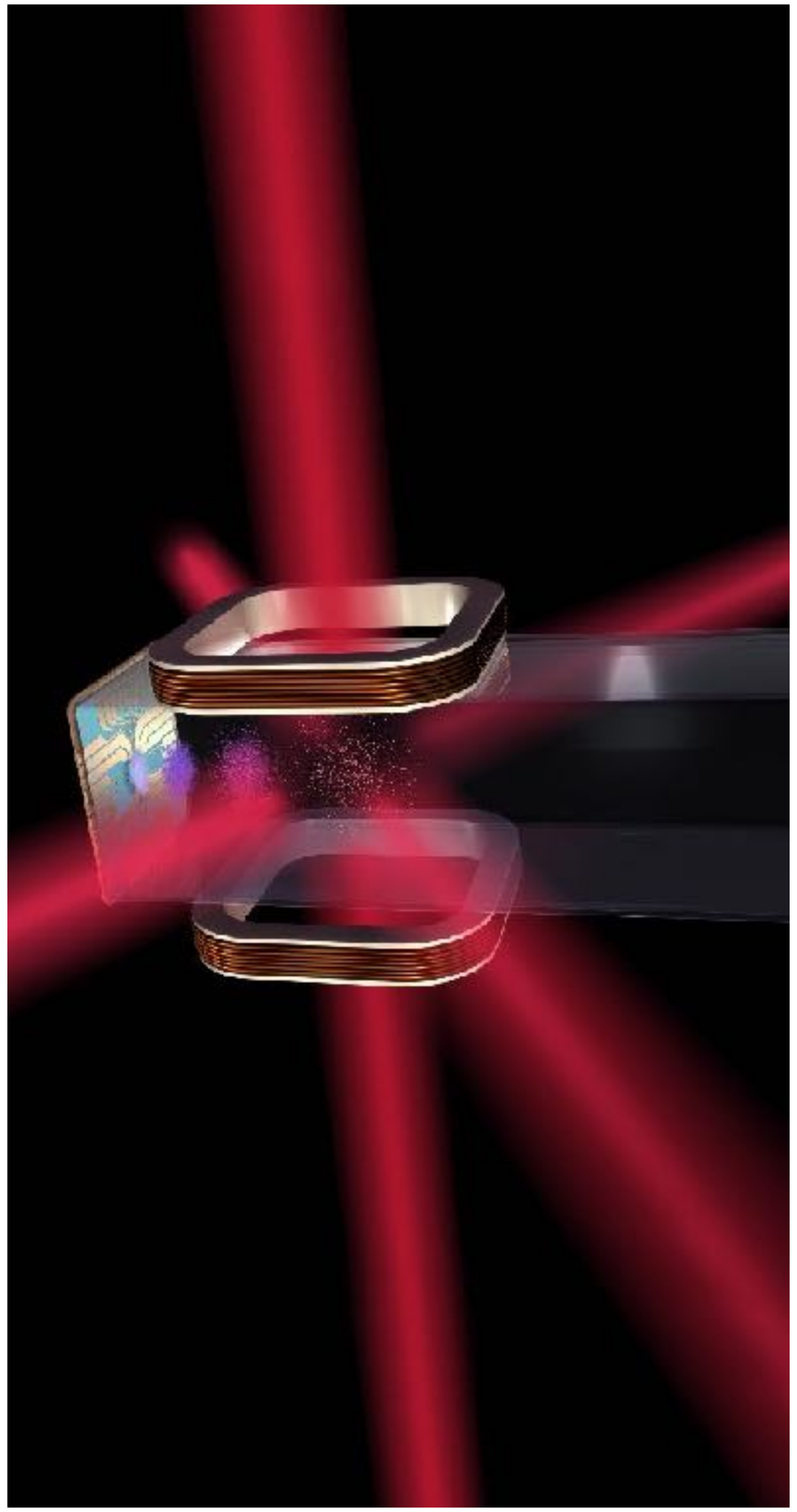
- Helpful to think of neutrinos interacting with a unitary gas as a special reference system for nuclear matter. Better to model neutrinosphere region as a unitary gas instead of a free (Fermi) gas as is often done.

- Many theoretical results for a unitary gas and many **experimental results** for cold atoms.

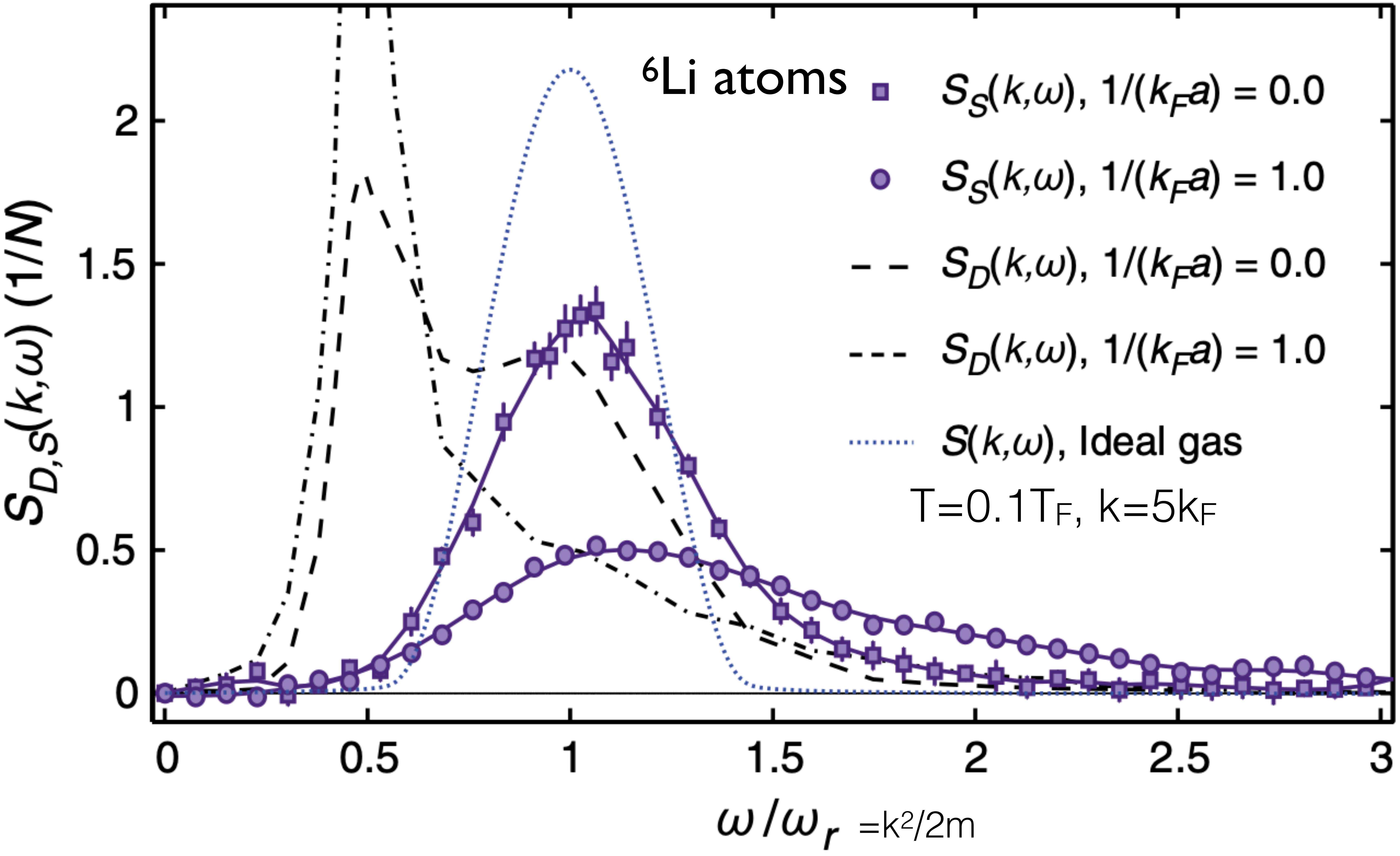
- Spin response <1 reduces scattering opacity.

- Effect may be important even at low ~$10^{12}$ g/cm$^3$ densities because of the large scattering length.

- Probably helps 2D (and 3D?) simulations explode perhaps somewhat earlier???



# Dynamic Spin Response of a Strongly Interacting Fermi Gas
# [S. Hoinka, PRL **109**, 050403]



$S_A$(k,w) is solid line and squares, while dashed line is $S_V$(k,w)

# Virial Expansion for Unitary Gas

- In high T and or low density limit, expand P in powers of fugacity z=Exp[chemical pot/T]

$$P = \frac{2T}{\lambda^3} \sum_{n=1}^{4} b_n z^n \qquad\qquad n = \frac{z}{T} \frac{dP}{dz}$$

- Long wavelength response:

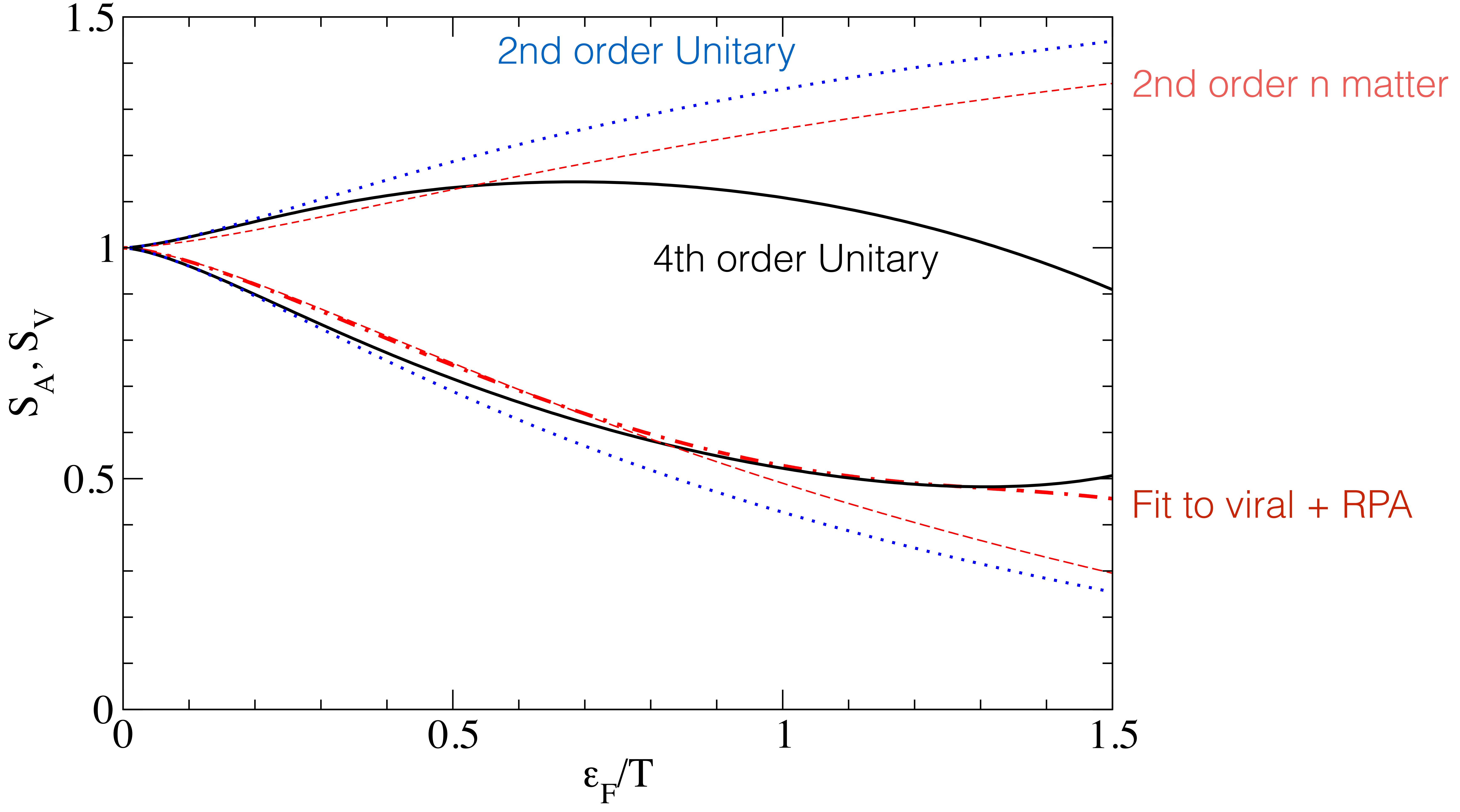
$$S_V(q \to 0) = T/(\partial P/\partial n)_T = z(\partial n/\partial z)/n,$$

$$S_V(q \to 0) = \frac{1 + 4zb_2 + 9z^2 b_3 + 16z^3 b_4}{1 + 2zb_2 + 3z^2 b_3 + 4z^3 b_4}$$

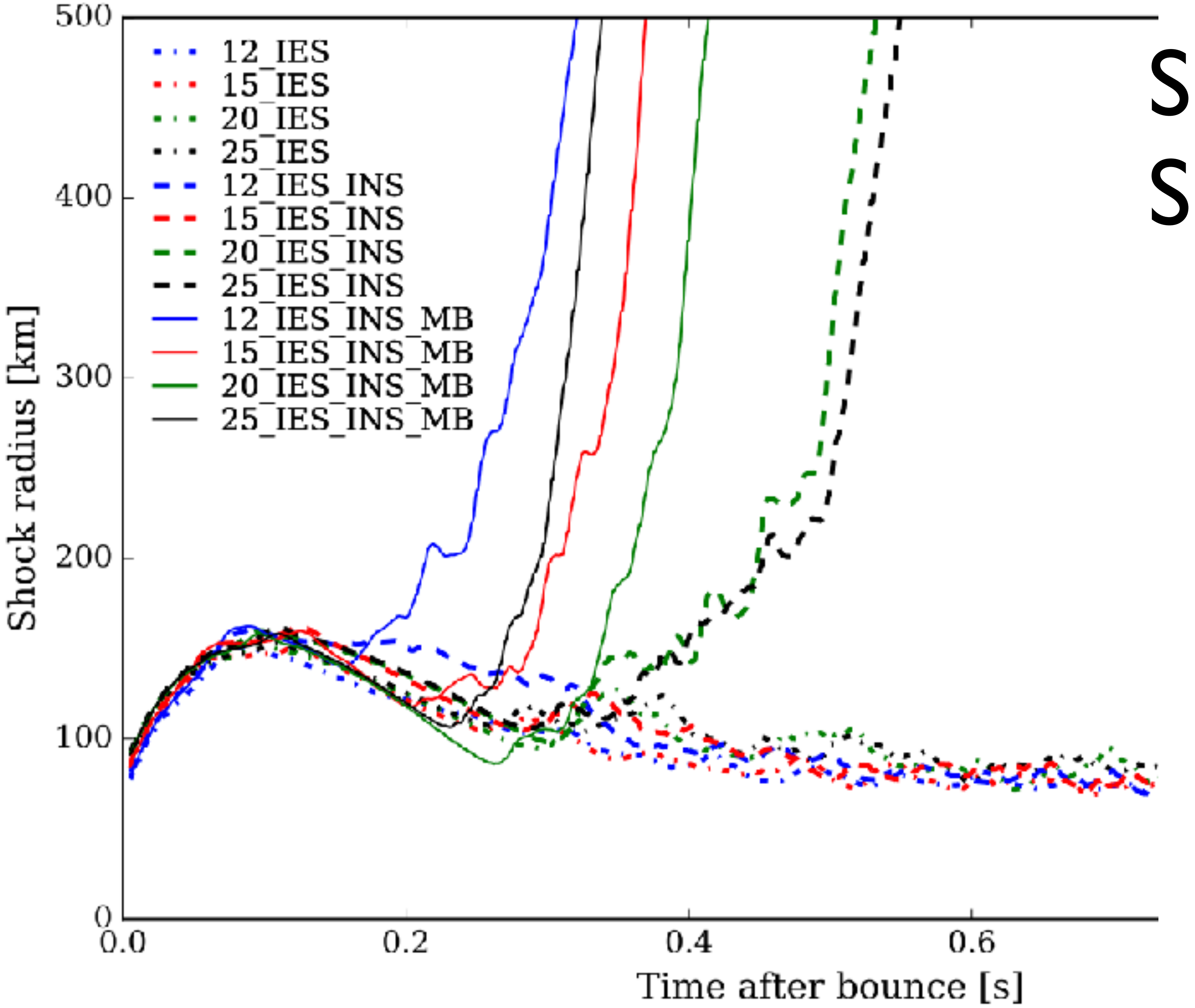
- Axial response: $S_A(q \to 0) = \frac{2z}{n} \frac{\partial}{\partial(z_1 - z_2)} (n_1 - n_2)\big|_{z_1 = z_2}$

# Unitary gas response

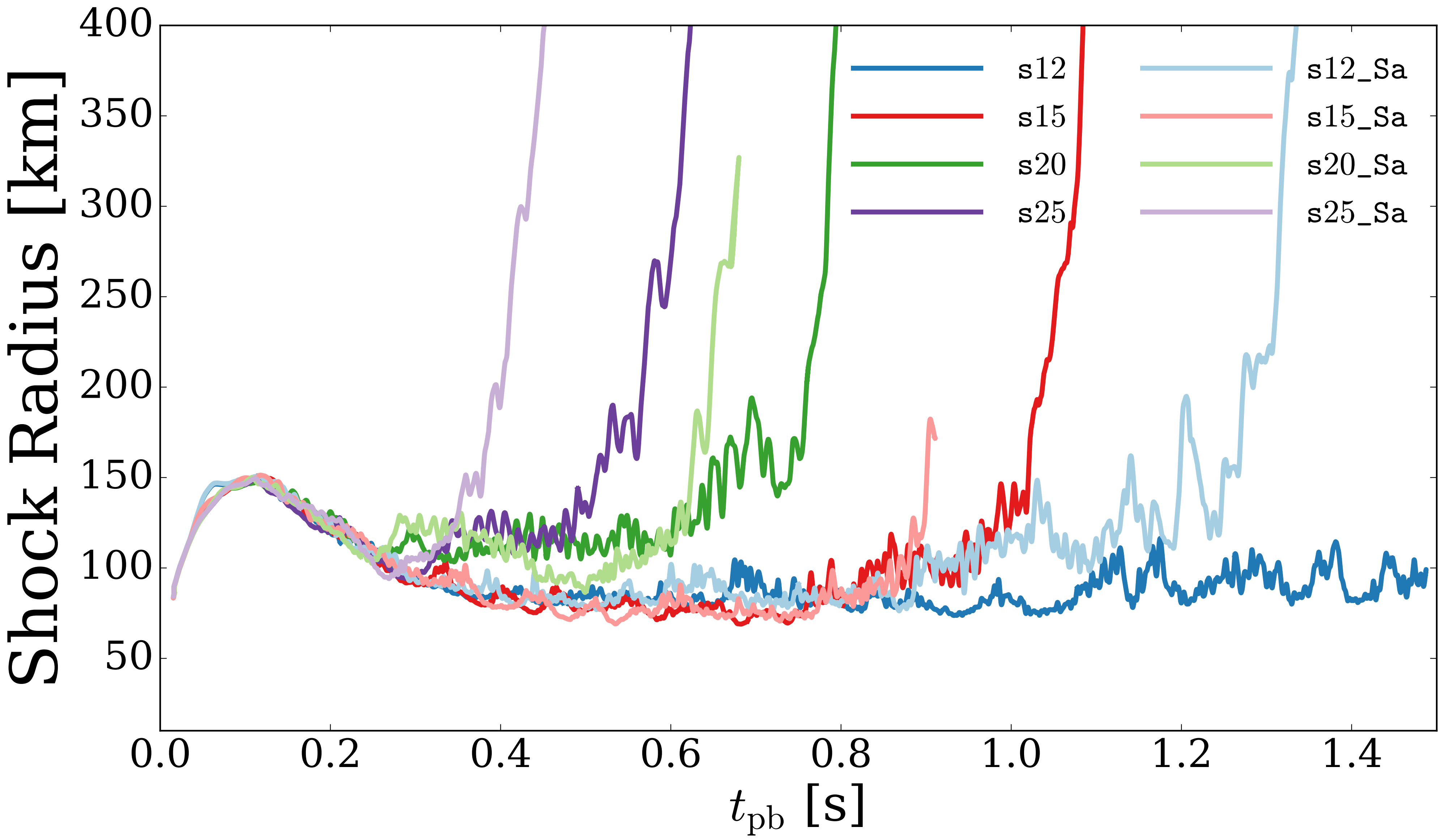
arXiv:1708.01788



# Shock radius vs time for 2D SN simulations



All 2-D SN simulations by Burrows et al [arXiv:1611.05859] with correlations ($S_A$<1) explode (solid lines) while 12 and 15 $M_{sun}$ stars fail to explode, and 20, 25 $M_{sun}$ explode later, without correlations ($S_A$=1).



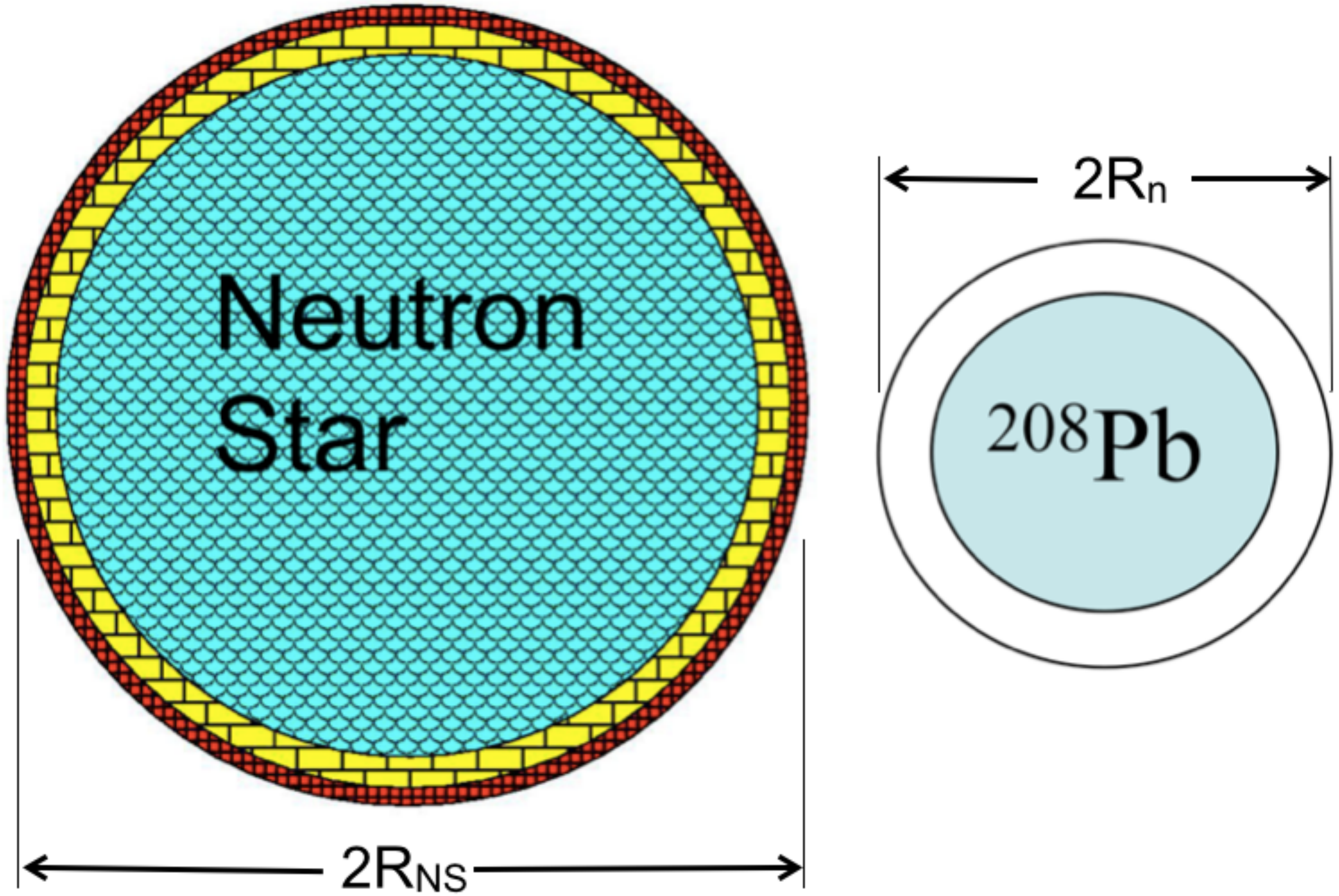
Preliminary 2D SN simulations by Evan O'Connor for 12 to 25 $M_{sun}$ stars explode earlier (lighter color) if correlations ($S_A$<1) included.

Sensitivity of SN dynamics motivates better treatments of neutrino interactions and NN correlations.

# Neutron skins of finite nuclei

# Radii of $^{208}$Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> $R_n$-$R_p$ of $^{208}$Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of $R_n$ ($^{208}$Pb) in laboratory PREX-II has important implications for the structure of neutron stars.



Neutron star is 18 orders of magnitude larger than Pb nucleus but both involve neutron rich matter at similar densities with the same strong interactions and equation of state.

# PREX uses Parity V. to Isolate Neutrons

- In Standard Model $Z^0$ boson couples to the weak charge.
- Proton weak charge is small:

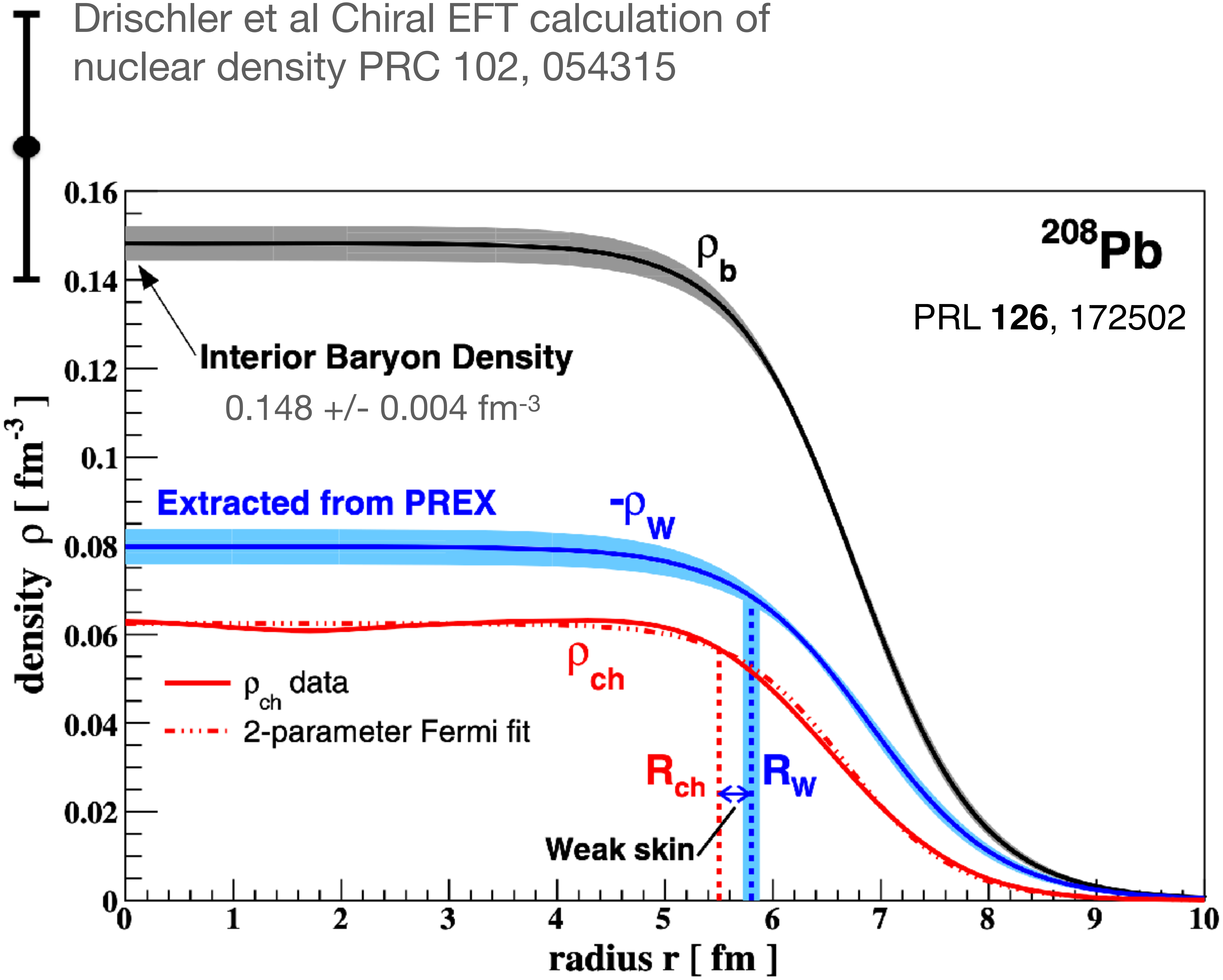
$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

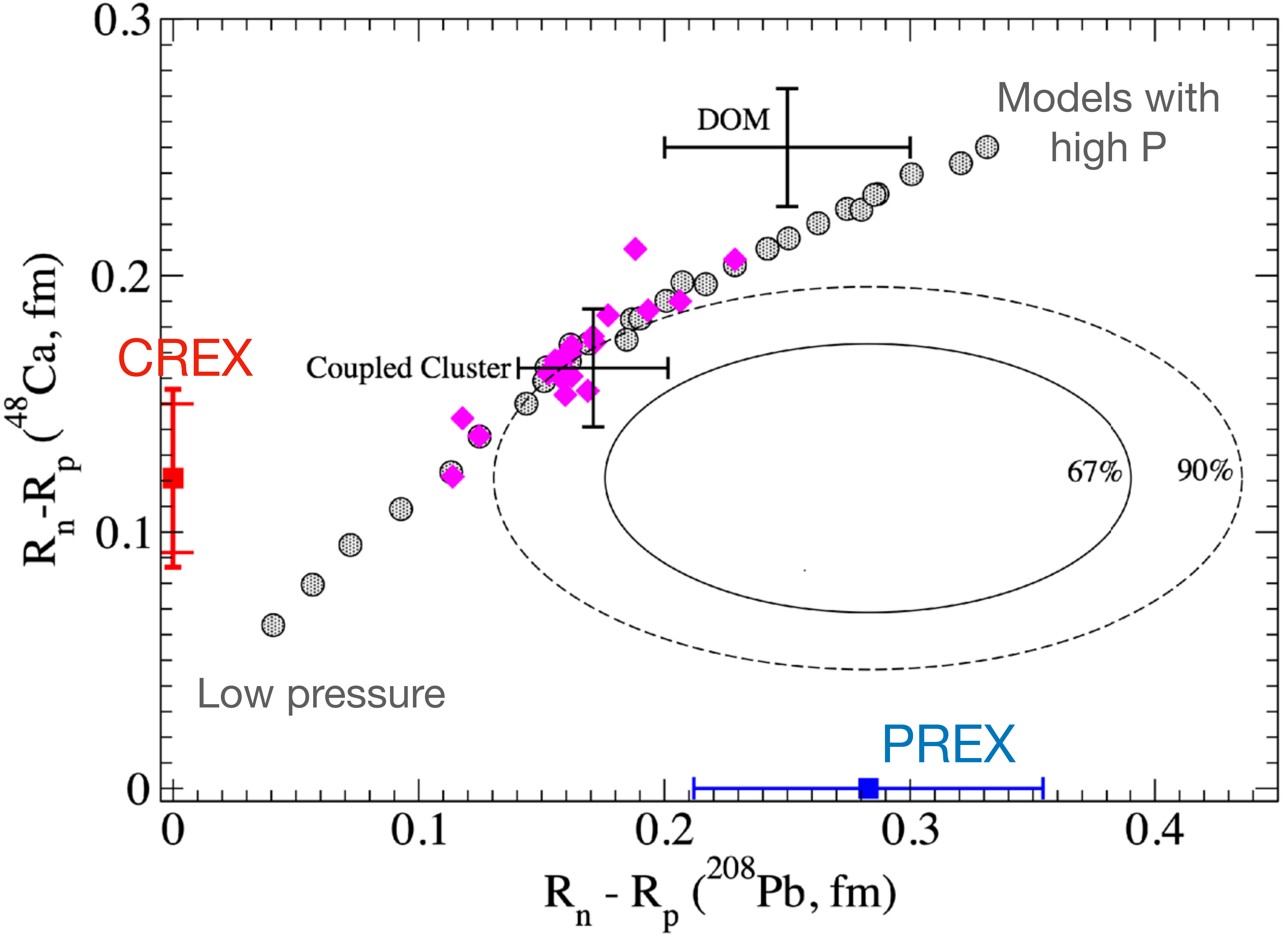
- Neutron weak charge is big:

$$Q_W^n = -1$$

- Weak interactions, at low $Q^2$, probe neutrons.
- Parity violating asymmetry $A_{pv}$ is cross section difference for positive and negative helicity electrons

Drischler et al Chiral EFT calculation of nuclear density PRC 102, 054315





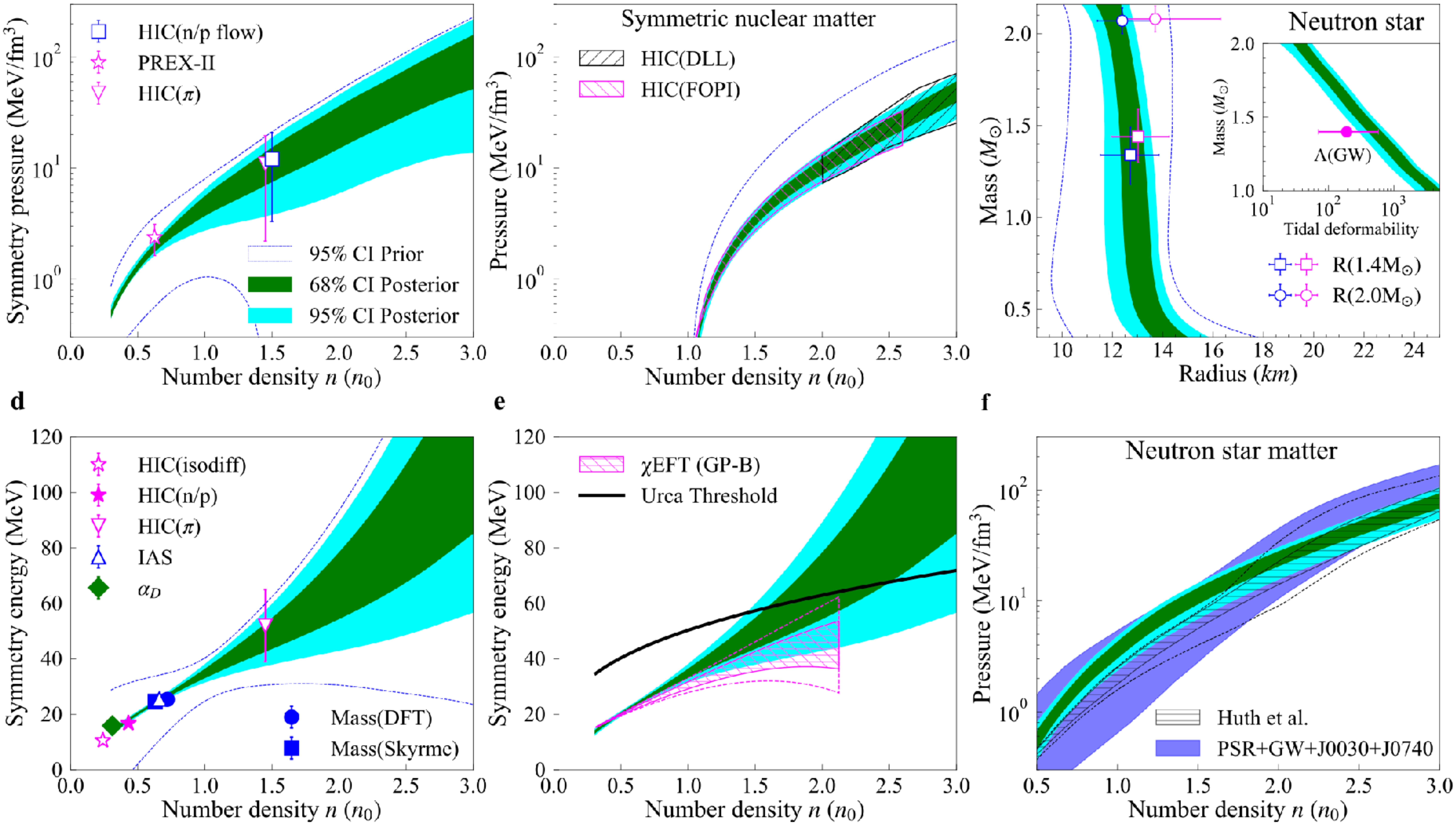
Symmetry energy describes how E rises when one goes away from N=Z. Rapid density dependence of symmetry energy (L) pushes excess n out of center into skin

Brendan Reed

# Heavy Ion Collisions

# The Equation of State from Nuclear Experiments and Neutron Star Observations

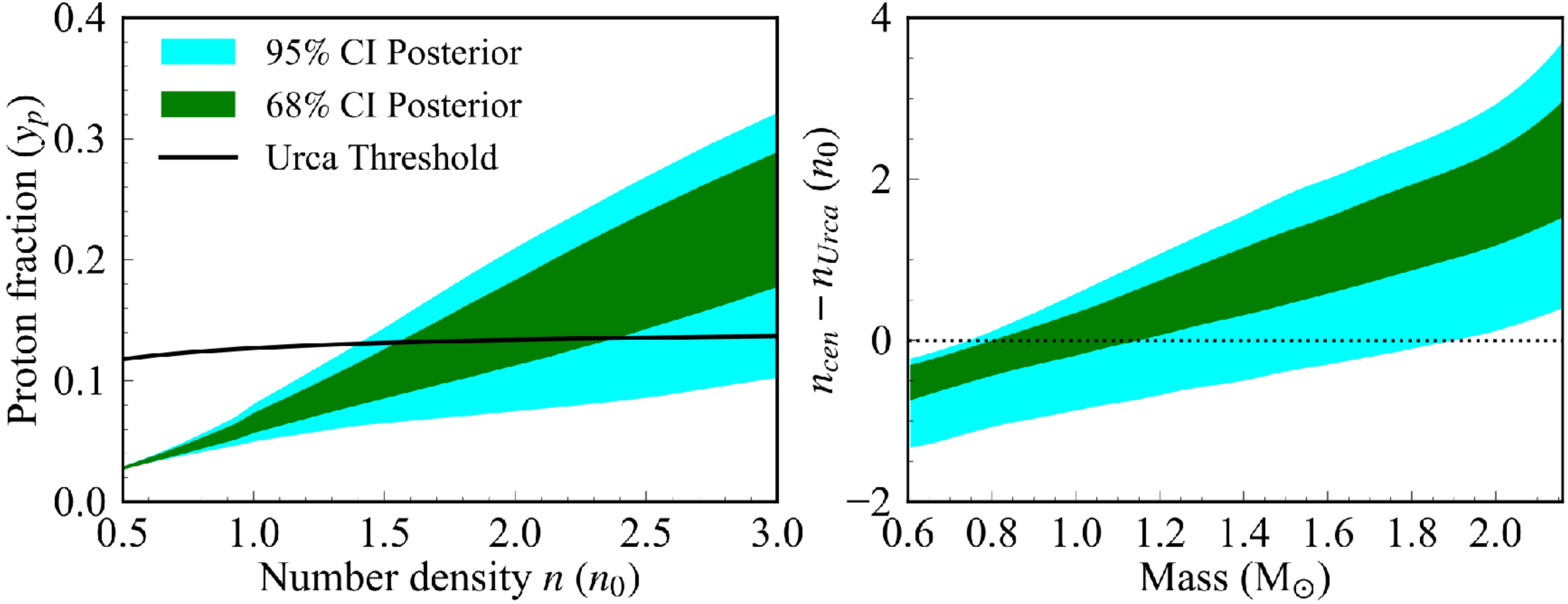
- Chun Yuen Tsang, Man Yee Betty Tsang, William G. Lynch, Rohit Kumar and Chuck Horowitz, Nature Astronomy **8**, 328 (2024).
- Determine EOS from nuclear structure and heavy ion collision experiments and gravitational wave and X-ray observations of neutron stars.
- Provides clean test of Chiral EFT calculations of EOS.
- Include data for both symmetric matter and neutron matter.


HIC(n/p flow)
PREX-II
HIC(π)
95% CI Prior
68% CI Posterior
95% CI Posterior
Symmetry pressure (MeV/fm³)
Number density n (n₀)
Symmetric nuclear matter
HIC(DLL)
HIC(FOPI)
Pressure (MeV/fm³)
Number density n (n₀)
Neutron star
Mass (M⊙)
Tidal deformability
Λ(GW)
R(1.4M⊙)
R(2.0M⊙)
Mass (M⊙)
Radius (km)
d
HIC(isodiff)
HIC(n/p)
HIC(π)
IAS
α_D
Mass(DFT)
Mass(Skyrme)
Symmetry energy (MeV)
Number density n (n₀)
e
χEFT (GP-B)
Urca Threshold
Symmetry energy (MeV)
Number density n (n₀)
f
Neutron star matter
Huth et al.
PSR+GW+J0030+J0740
Pressure (MeV/fm³)
Number density n (n₀)

# Heavy ion collisions+FRIB

- Symmetry E near $2n_0$ is lab observable most closely related to neutron star structure.
- FRIB gives HI with range of N/Z. Measure sym. E AND p of symmetric matter.
- **What are neutron stars made of?** [EOS is steam table]
- Measure S(n) and infer proton fraction in beta equilibrium.

$$[4S(n)(1-2y_p)]^3+\left\{[4S(n)(1-2y_p)]^2-m_\mu^2\right\}^{3/2}=3\pi^2 n y_p$$



Can infer proton fraction $y_p$ from HI data for symmetric nuclear matter and astronomical data for neutron rich matter!