The effect of thermal dissipation on the radial pulsations of neutron stars

PHAROS WG1+WG2 meeting

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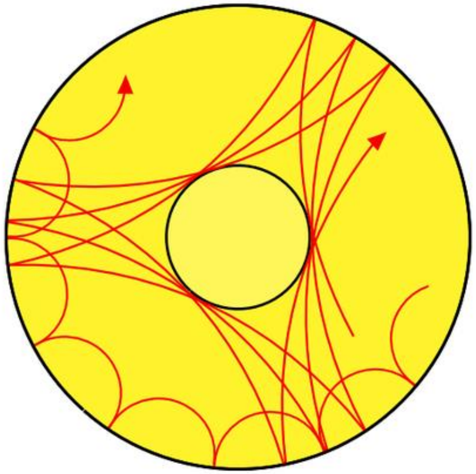
MOTIVATION

1) Constraints on the microscopic physical properties of matter at supernuclear densities rely heavily on observations of macroscopic equilibrium parameters (masses, radii, moments of inertia, etc.) of NSs. Motivation for this work comes from the possibiliy to constrain EOS though probing the interior structure of NSs by oscillations → Frequencies of NS oscillations that rely on accurate stellar models are matched to the observed frequencies.

2) We studied radial modes as the simplest oscillation modes (do not couple with GW). If the energy that goes into the radial mode leaks into other channels, that will naturally reduce the amplitude of radial oscillations.

Two leakage mechanisms:

- coupling of the radial mode to other oscillation modes (e.g. g-, f-, p- or w-modes)
- viscous or thermal dissipation



Different oscillation modes have different sensitivities to the structure of a star. By observing multiple modes, one can therefore partially infer a star's internal structure.

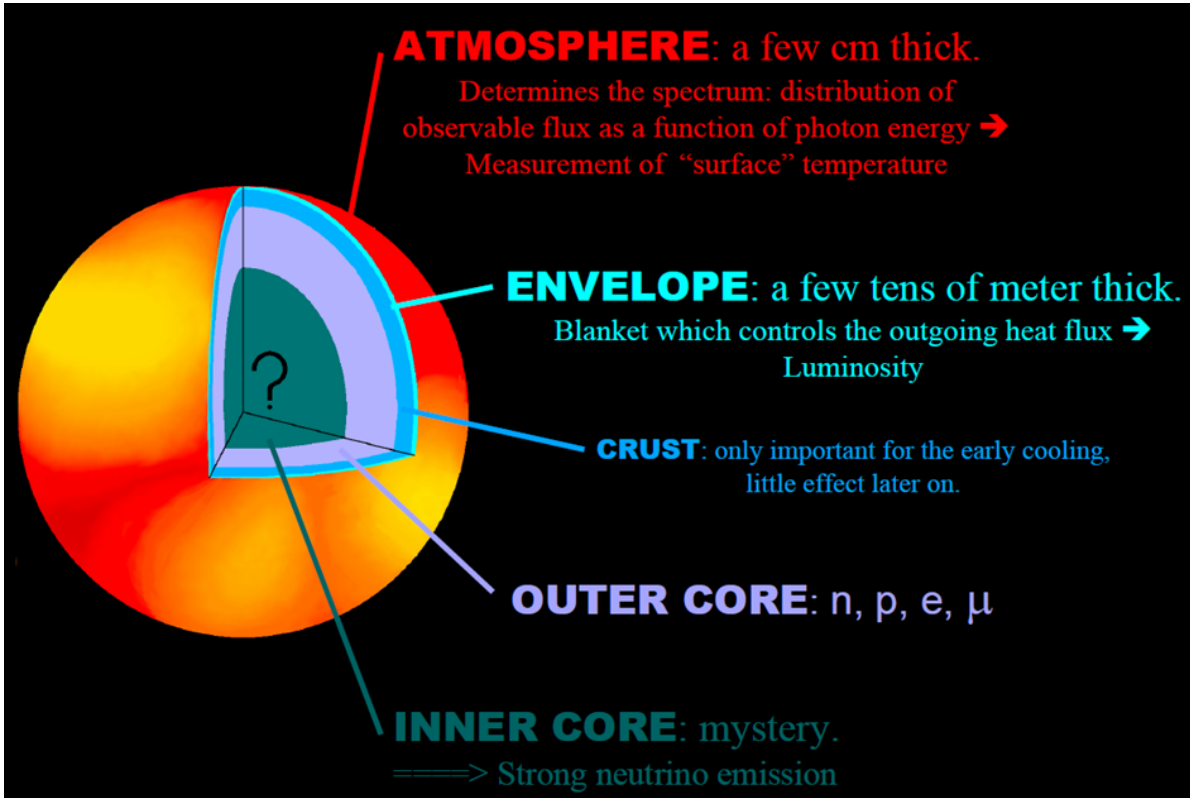
Question:

How does leakage mechanisms effect NS oscillations?

Leakage mechanism:

Whereas the earlier mechanism is unlikely to drain much energy from the originally excited radial mode (Chirenti, Gold and Miller 2017), the overwhelming majority of the energy that is deposited in this mode could be released through heat outflow via neutrino emission:

- The neutrino emission heats the crust out of thermal equilibrium with the core. After the subsequent thermal photon emission from the surface, which powers the quiescent X-ray outburst, the crust thermally relaxes toward equilibrium with the NS core.



SOURCES OF OSCILLATIONS

- **Supernova explosion: triggers all kinds of oscillation modes**

- **Starquakes caused by craks in the crust or magnetic reconfiguration**

L. Franco et al. ApJ **543** (2000) 987

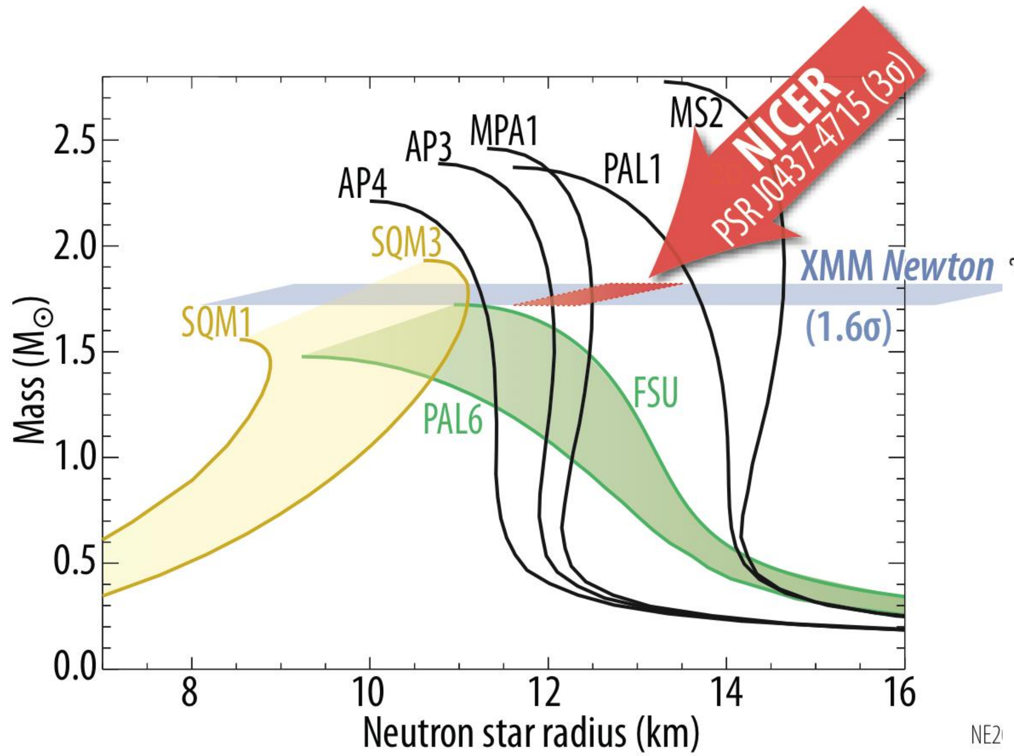
- **Accretion triggers oscillations**

- **Tidal forces in binary mergers**

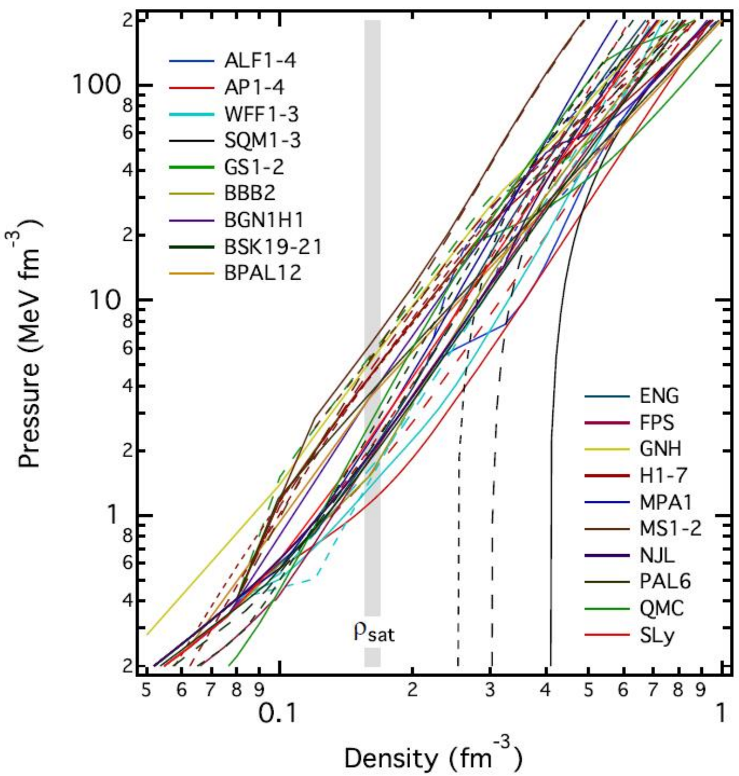
D. Tsang et al. Phys. Rev. Lett. **108**, (2012) 011102

- **Oscillation modes are *unstable* to gravitational wave emission → r-mode or f-mode oscillations**

Proposed equation of states



The mass-radius curves corresponding to the equations of state. NICER will improve radius measurements by an order of magnitude, distinguishing between proposed EOS models: ±5% uncertainty on radius measurements.

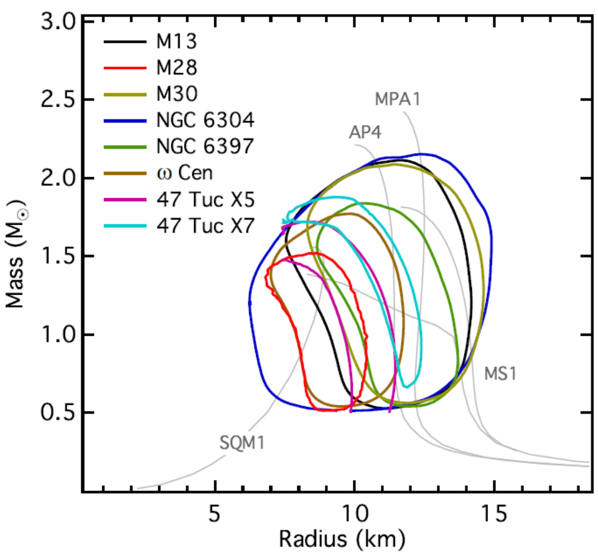


Currently proposed equations of state, spanning a density range between ~ 0.1 – 8 ρ_{sat}. F. Özel & P. Freire (2016, ARAA)

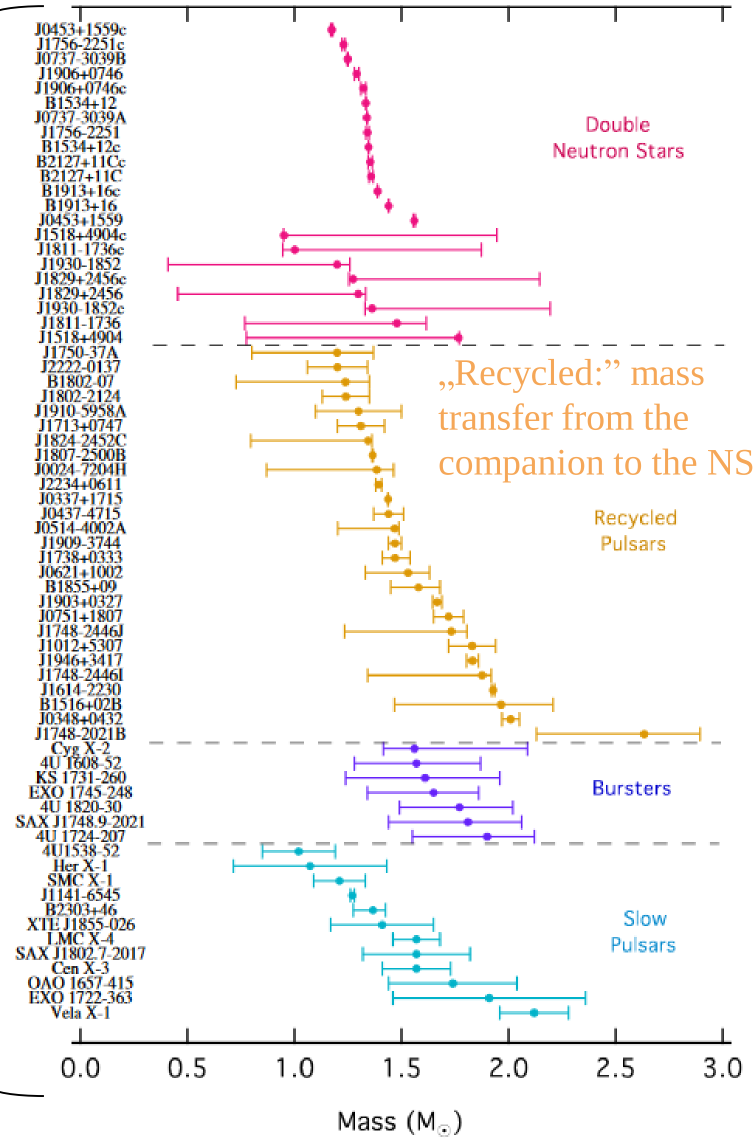
- Precise neutron star mass measurements are useful for a variety of purposes: e.g. constrain on EOS of the cold, super-dense matter at the center of a neutron star.

PULSAR MASS MEASUREMENTS

- The vast majority of the precise mass measurements from radio observations of rotation-powered pulsars.
- Currently more than 2500 pulsars (mostly radio pulsars) are known in the Galaxy (Manchester et al. 2005)
- About 90% of radio pulsars are isolated → Mass cannot be measured
- The remaining 250 pulsars are located in binary systems → info on mass →



The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from low-mass X-ray binaries F. Özel & P. Freire (2016, ARAA)



The most recent measurement of neutron star masses. Double neutron stars (magenta), recycled pulsars (gold), bursters (purple), and slow pulsars (cyan) are included.

STRUCTURE AND EVOLUION OF NEUTRON STARS

Schwarzschild metric: $$ds^2 = -e^{2\Phi}\, c^2 dt^2 + \frac{dr^2}{1-2Gm/c^2 r} + r^2 d\Omega^2.$$

Gravitational mass: $$\frac{dm}{dr} = 4\pi r^2 \rho, \qquad m(r=0)=0$$

Gravitational potential: $$\frac{d\Phi}{dr} = \frac{Gmc^2 + 4\pi G r^3 P}{c^4 r^2 (1-2Gm/c^2 r)}, \qquad e^{\Phi(R)} = \sqrt{1-\frac{2GM}{c^2 R}},$$

Hydrostatic equilibrium:
(Tolman-Oppenheimer-Volkov)
$$\frac{dP}{dr} = -(\rho c^2 + P)\frac{d\Phi}{dr} = -\frac{(\rho + P/c^2)(Gm + 4\pi G r^3 P/c^2)}{r^2(1-2Gm/c^2 r)}. \qquad P(r=0)=P_c$$

STRUCTURE

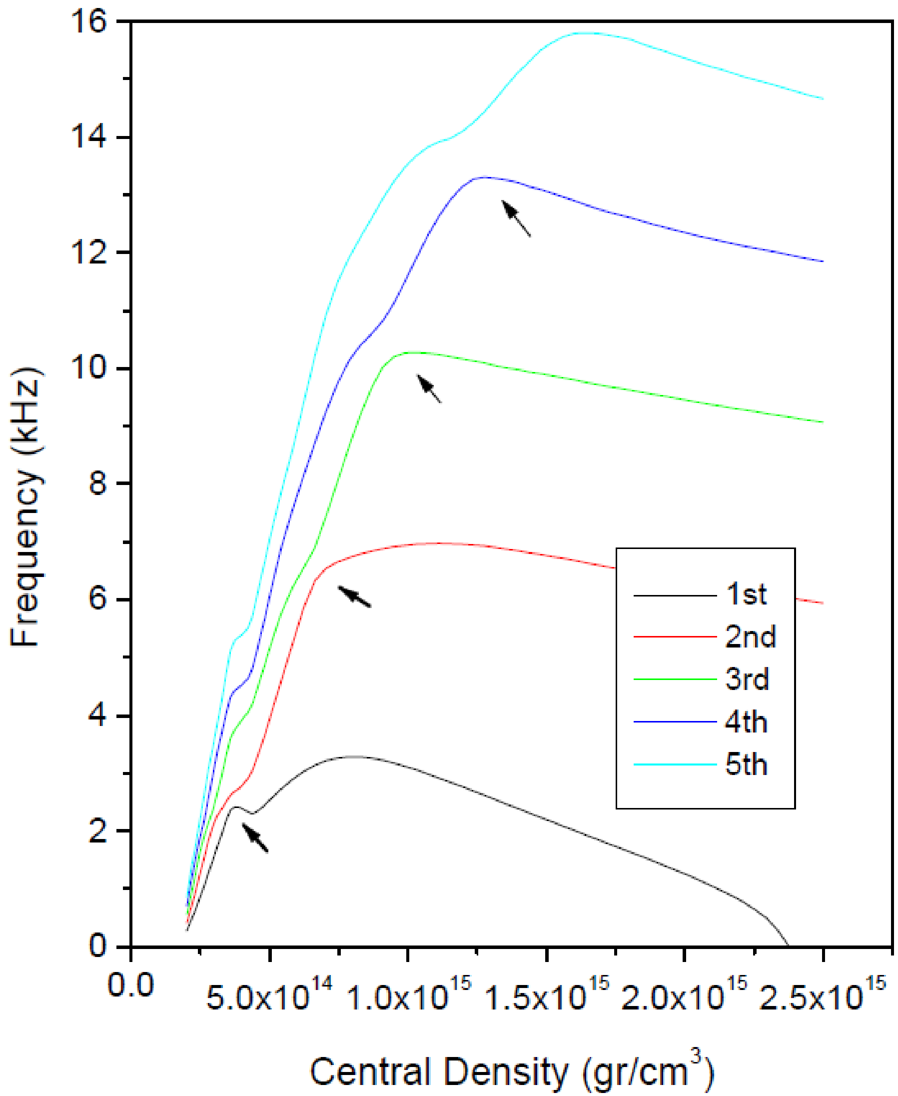
Energy conservation: $$\frac{d(Le^{2\Phi})}{dr} = -\frac{4\pi r^2 n e^{\Phi}}{\sqrt{1-2Gm/c^2 r}}\left(\frac{d\epsilon}{dt} + e^{\Phi}(q_\nu - q_h)\right) \qquad L(r=0)=0$$

EVOLUTION

$$\frac{d\epsilon}{dt} = \frac{d\epsilon}{dT}\cdot\frac{dT}{dt} = c_v \cdot \frac{dT}{dt}$$

Heat transport: $$\frac{d(Te^{\Phi})}{dr} = -\frac{3}{16\sigma_{SB}}\frac{\kappa\rho}{T^3}\frac{Le^{\Phi}}{4\pi r^2\sqrt{1-2Gm/c^2 r}} \qquad T_b = T_b(L_b)$$

Radial mode frequencies (non-dissipative case: no cooling)



1. The five radial modes as a function of the central density for the EOS APR1 (Akmal et al. (1998)).
2. The frequency of the fundamental mode goes to zero at a density of about 2.5×10^{15} g/cm^3, which indicates the onset of radial instability with respect to collapse to a black hole.
3. The arrows indicate the avoided crossings between the different modes.

THE EQUATIONS OF NEUTRON STAR COOLING

Most of it is just energy balance:

$$\boxed{\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma}$$

E_{th} = Total thermal energy content [erg]

C_V = specific heat [erg K^{-1}]

L_ν = neutrino luminosity [erg s^{-1}]

L_γ = photon luminosity [erg s^{-1}]

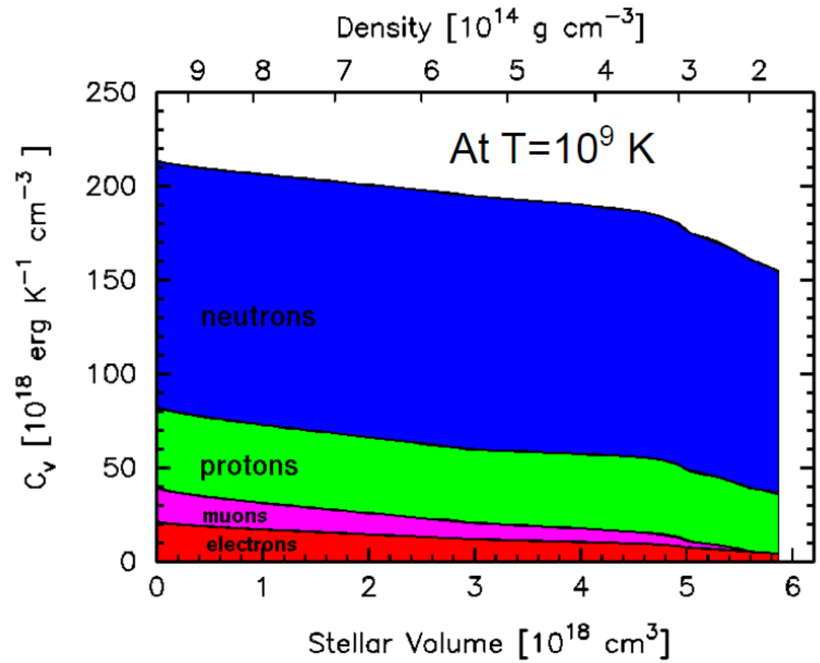
$$\boxed{\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma + H}$$

H = Heating rate [erg s^{-1}]

Distribution of C_v in the core among constituents:

$$C_V = N(0) \frac{\pi^2}{3} k_B^2 T$$

$$N(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$



BASIC COOLING: NEUTRINO VS PHOTON COOLING

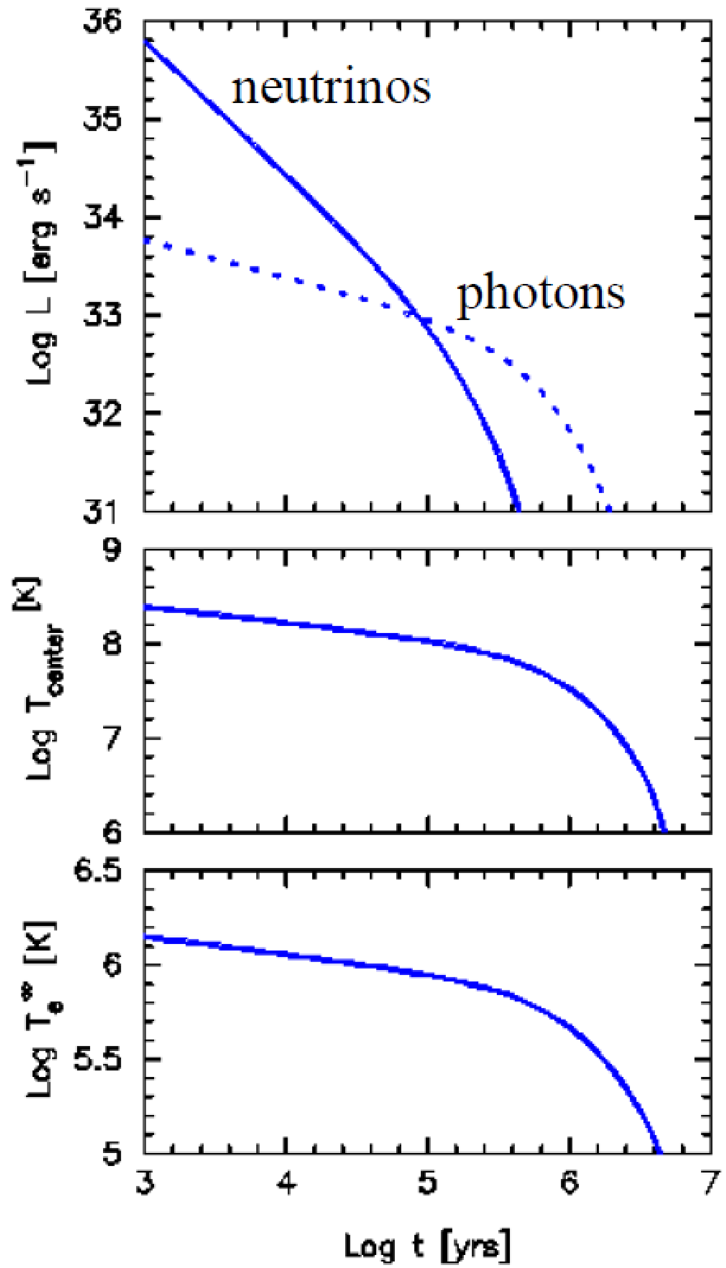
$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

Neutrino Cooling era: $L_\nu >> L\gamma$

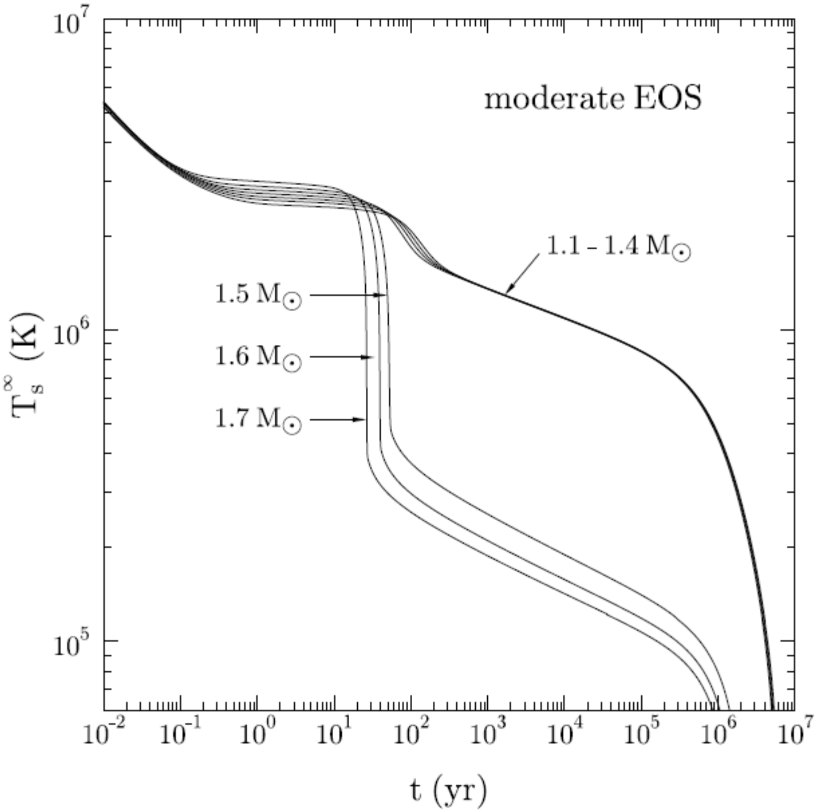
$$\frac{dT}{dt} = -\frac{q_{\nu 0}}{c_{V0}} \times T^7 \Rightarrow t - t_0 = A\left[\frac{1}{T^6} - \frac{1}{T_0^6}\right] \quad \Rightarrow \quad T \propto t^{-1/6}$$

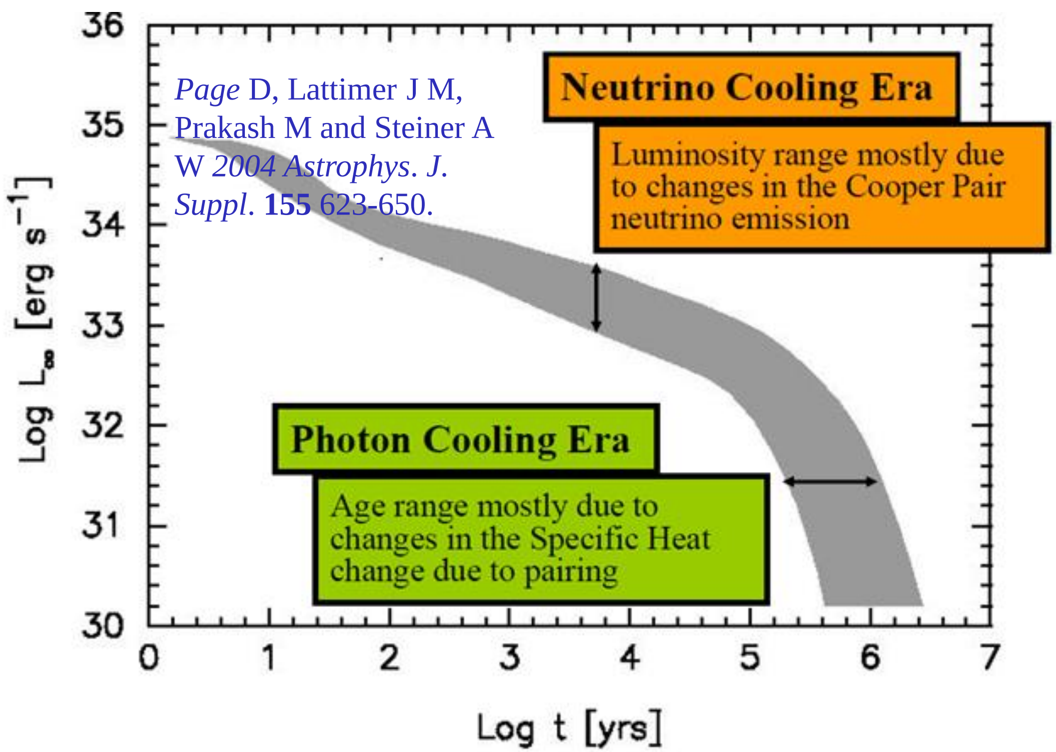
Photon Cooling era: $L_\nu << L\gamma$

$$\frac{dT}{dt} \propto -T^{1+\alpha} \Rightarrow t - t_0 = B\left[\frac{1}{T^\alpha} - \frac{1}{T_0^\alpha}\right] \quad \Rightarrow \quad T \propto t^{-1/\alpha}$$



NEUTRON VS PHOTON COOLING ERA





- The theoretical cooling curves depend on the adopted physical models of the stellar interior, especially the neutrino emission and heat capacity, as well as the superfluidity of neutrons and protons in the core.
- In the low-mass models, $M < 1.44\, M_\odot$, the direct Urca process is forbidden. These stars follow the standard cooling scenario and the cooling curves are almost independent of M.
- The high-mass models go through the fast cooling scenario and demonstrate a spectacular drop of the surface temperature at the end of the thermal relaxation epoch, $t \sim 50$ yr, due to the emergence of the cooling wave on the surface.

Preliminary results:

- We have given the first five radial modes as a function of the central density for some common EOS (APR1, GNH3, H1-7, MPA1, SLy)**:** We could compute the eigenfrequencies up to arbitrary precision, but the overall accuracy of the frequencies is limited by the number of tabulated values of the equation of state (not by the machine precision)

- Prominent feature is the occurrence of a series of avoided crossings between the various modes. (First shown by Kokkotas & Ruoff (2001, A&A))

Further work: include NS cooling scenarios

Thank you very much for your kind attention!