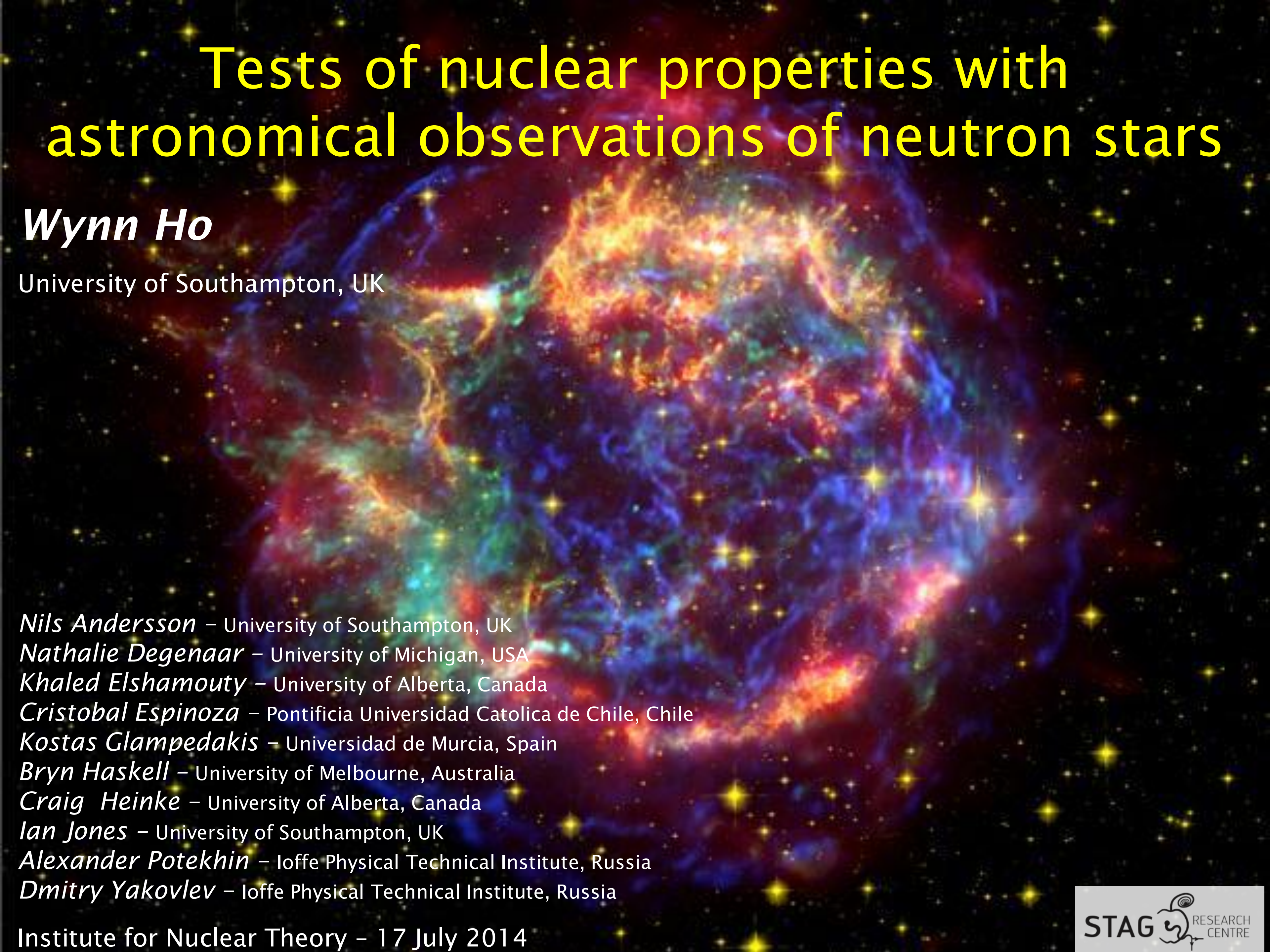

Tests of nuclear properties with astronomical observations of neutron stars

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Nathalie Degenaar – University of Michigan, USA
Khaled Elshamouty – University of Alberta, Canada
Cristobal Espinoza – Pontificia Universidad Catolica de Chile, Chile
Kostas Glampedakis – Universidad de Murcia, Spain
Bryn Haskell – University of Melbourne, Australia
Craig Heinke – University of Alberta, Canada
Ian Jones – University of Southampton, UK
Alexander Potekhin – Ioffe Physical Technical Institute, Russia
Dmitry Yakovlev – Ioffe Physical Technical Institute, Russia

Institute for Nuclear Theory – 17 July 2014

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Outline

Credit: HEASARC

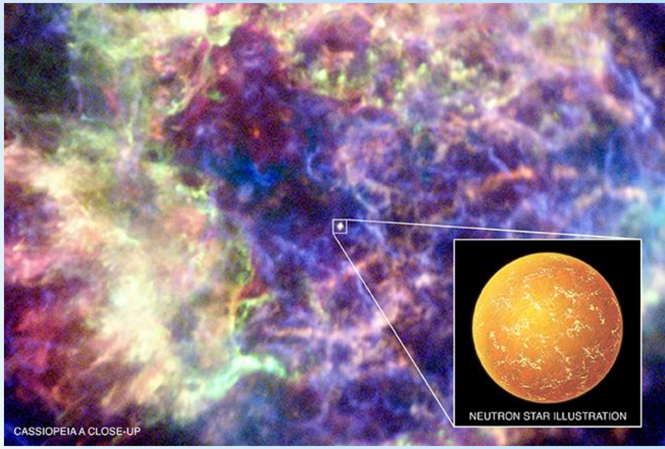
Four examples of testing of nuclear physics with neutron stars

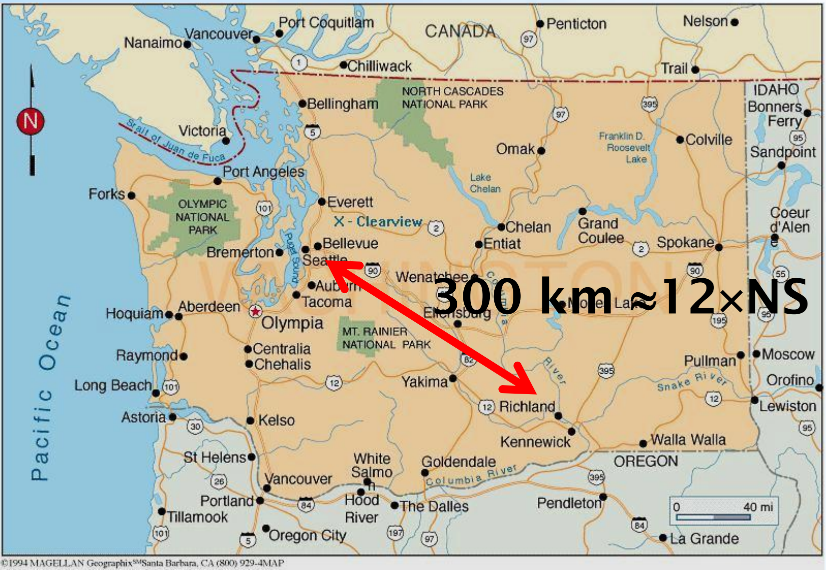
1) EOS from qLMXBs in globular clusters
   (Heinke, WH+, arXiv:1406.1497)

2) EOS and superfluidity/superconductivity from Cassiopeia A NS
   (WH+, in preparation)

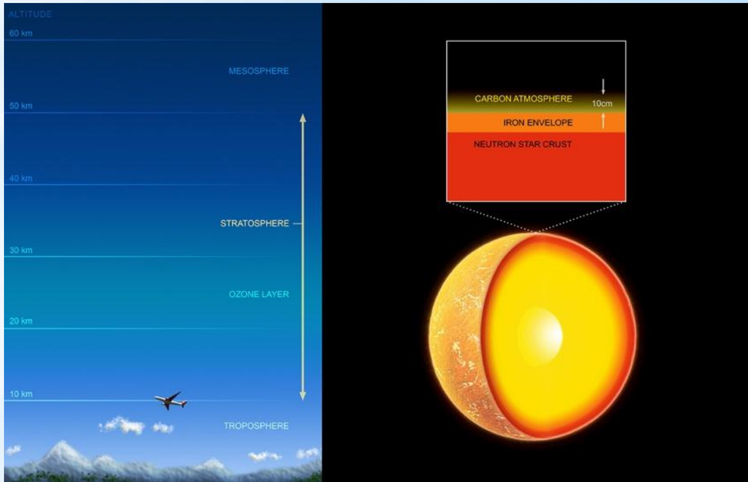
3) EOS and superfluidity from pulsar glitches
   (Andersson, WH+, 2012)

4) Gravitational wave-induced r-modes
   (WH+, 2011; Haskell, WH+, 2012; Andersson, WH+, 2014)

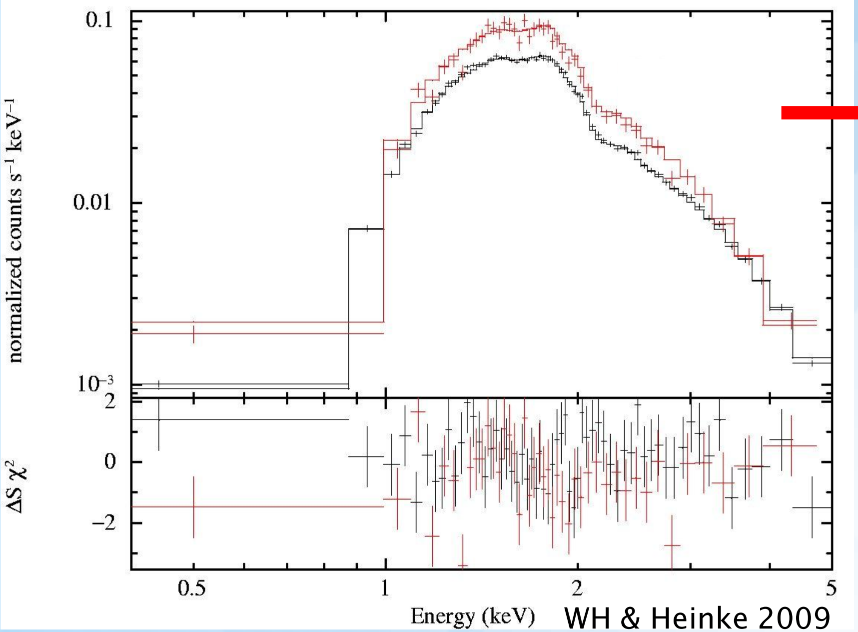




300 km ≈12×NS diameter

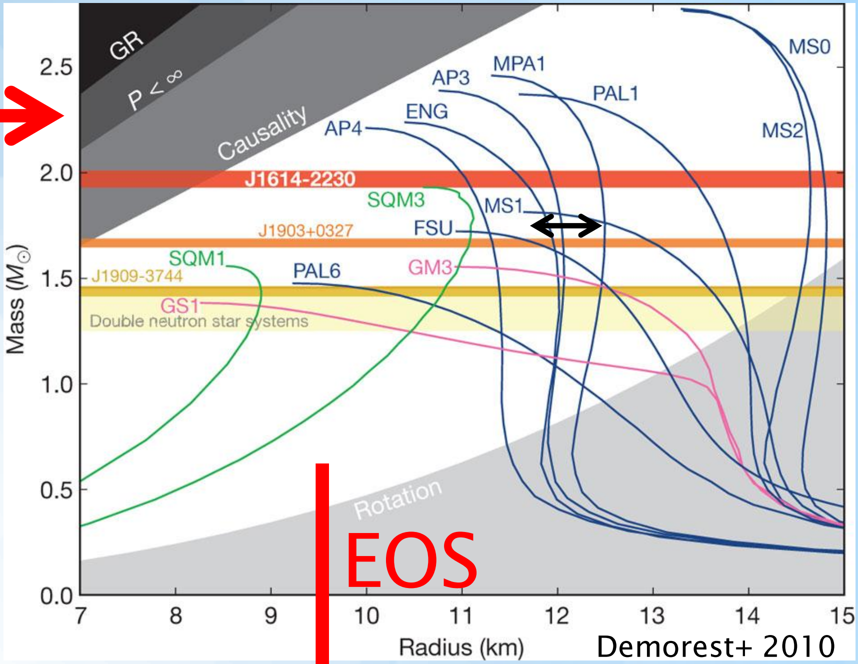


EOS from Neutron Star Surface Radiation



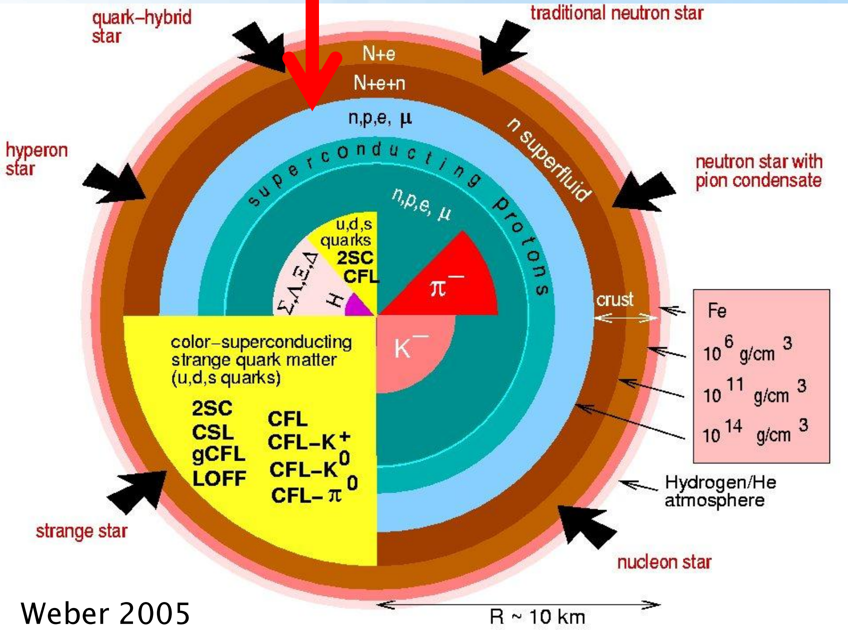
WH & Heinke 2009

M-R



Demorest+ 2010

EOS



Weber 2005

1) X-ray/UV/optical energy spectrum from telescopes (eg *Chandra*, *Hubble*, *XMM*)

2) Fit spectrum with model:

   - blackbody: *T*, *R/d*

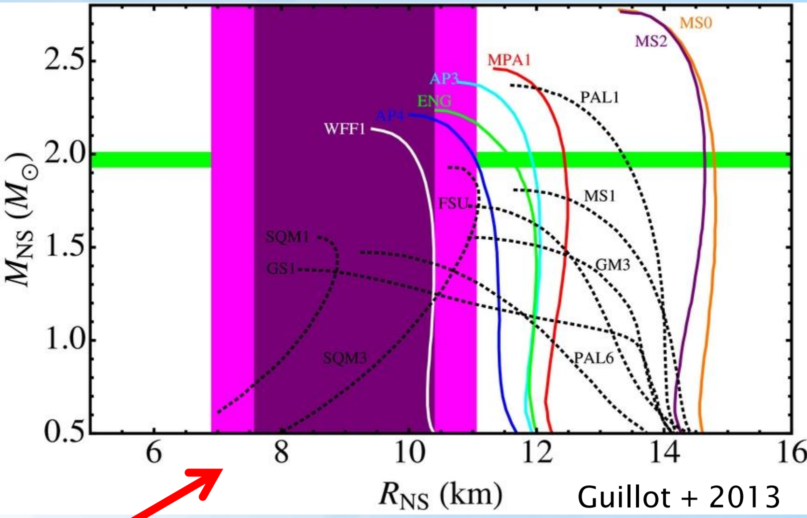
   - atmosphere: redshift $\propto M/R$, surface gravity $\propto M/R^2$, composition, magnetic field

3) Constrain EOS

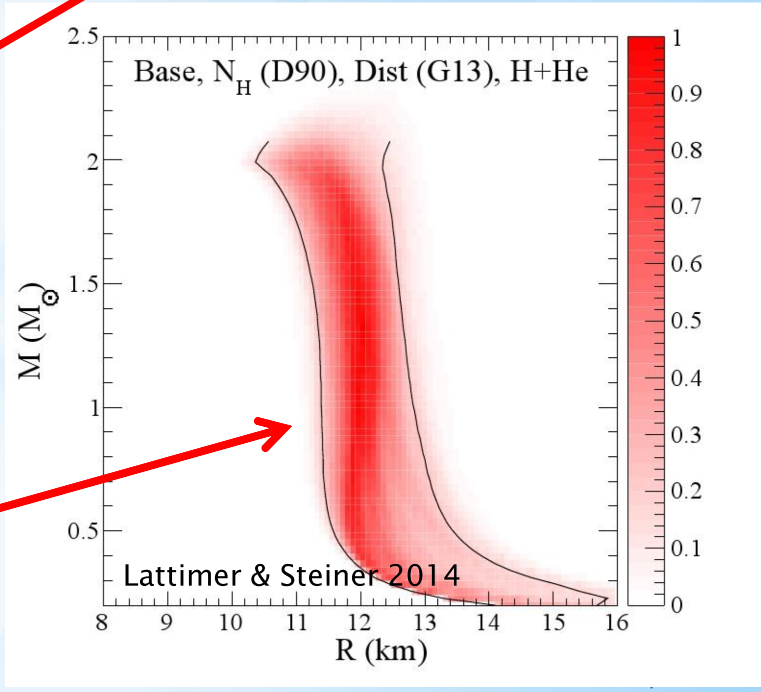
Neutron star radii from quiescent low-mass X-ray binaries (qLMXBs) in globular clusters

- qLMXBs in globular clusters
  - binary star system with NS accreting from low-mass companion, thus X-ray bright
  - globular cluster – mini-galaxy orbiting Milky Way with well-determined distance
  - spectral fit depends on *R/d*

- Radius constraints using five qLMXB in GC
  - Guillot+ (2013): $R = 9.1_{-1.5}^{+1.3}$ km
    - NGC 6397: $R \approx 6.6 \pm 1.2$ km
    - ω Cen: $R \approx 20.1 \pm 7.3$ km
    - other three: $R \sim 10 \pm 3$ km
    - exclude NGC 6397: $R = 10.7_{-1.4}^{+1.7}$ km
  - Lattimer & Steiner (2014): $R \approx 12 \pm 1$ km



Guillot + 2013

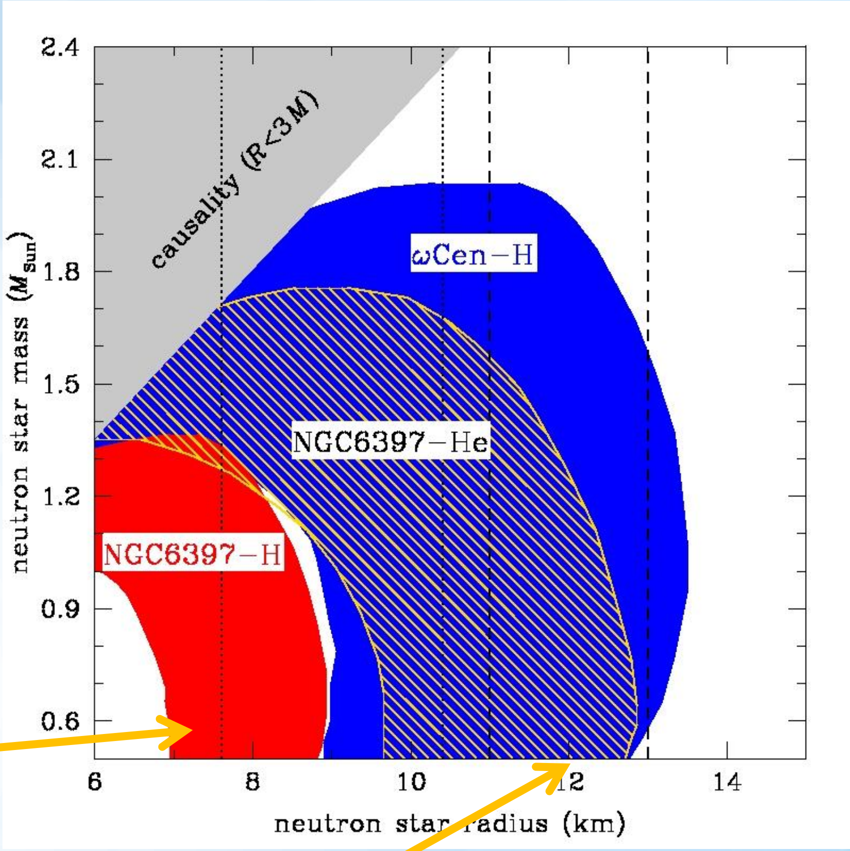


Lattimer & Steiner 2014

Neutron star radii from qLMXBs in globular clusters

Heinke, WH+, arXiv:1406.1497

- NGC 6397
  - *Hubble* observations place upper limit on hydrogen on companion
    - ⇒ possible helium white dwarf
    - ⇒ **NS has helium surface (?)**



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Cassiopeia A neutron star and APR and BSk EOSs

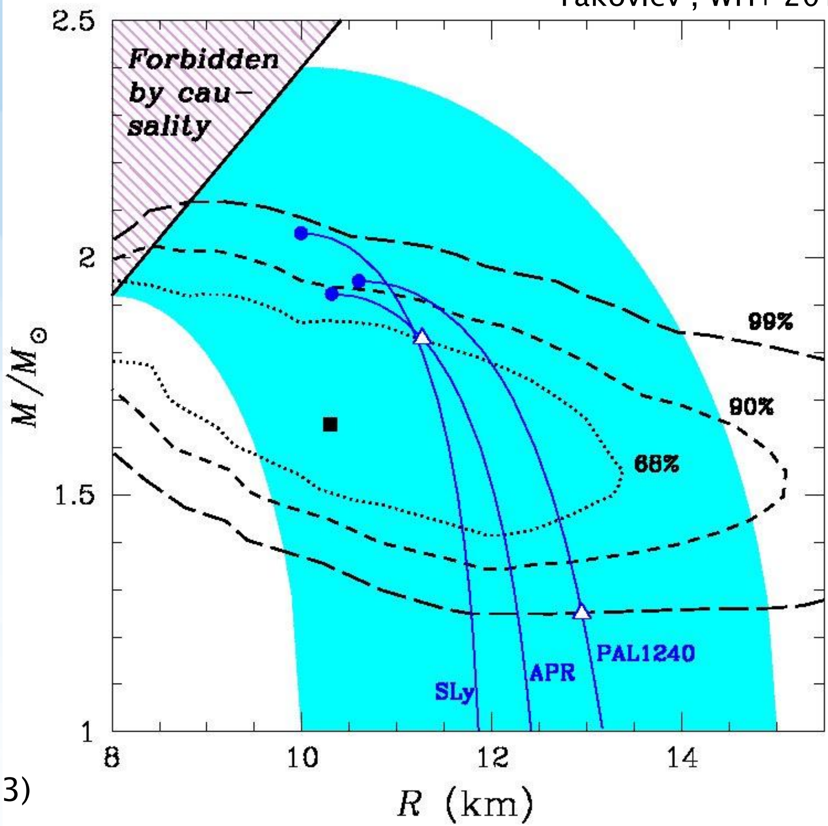
- Mass and radius from X-ray spectrum
  - redshift – M/R
  - brightness – R^2
  - surface gravity – M/R^2

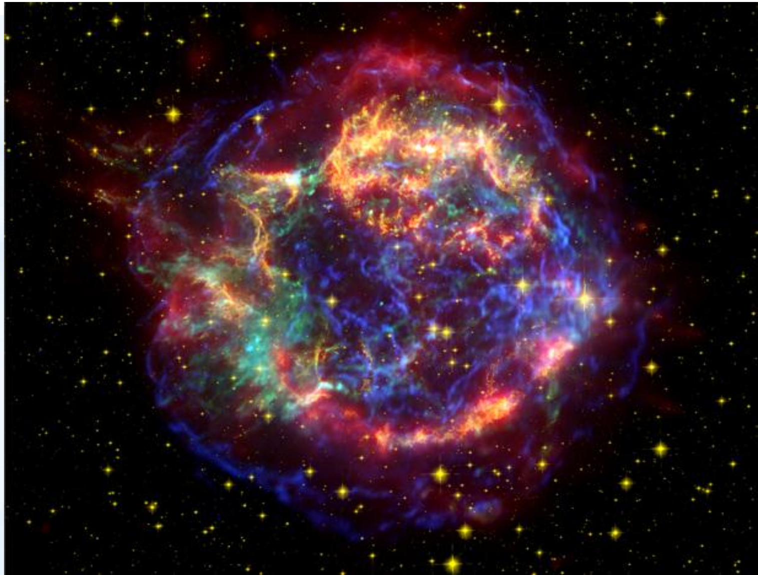
- Neutron star cooling
  - detailed EOS info (eg particle abundances)
  - superfluid & superconducting gap energies

- Detailed constraints from using specific EOS
  - APR (A18+δv+UIX*) – $M_{\mathrm{dU}} > 1.96\ M_{\mathrm{sun}}$
  - BSk20
  - BSk21 – $M_{\mathrm{dU}} > 1.59\ M_{\mathrm{sun}}$ (BSk: Potekhin, Chamel+ 2013)

- Not consider other causes of Cas A cooling
  - r-mode (Yang+2011)
  - medium modified (Blaschke+ 2012; 2013)
  - rotation-induced transition (Negreiros+ 2013)
  - pasta and symmetry energy (Newton+ 2013)
  - quark transition (Noda+ 2013; Sedrakian 2013)
  - Joule heating (Bonanno+2014)
  - detector/SNR (Posselt+ 2013)

Yakovlev , WH+ 2011





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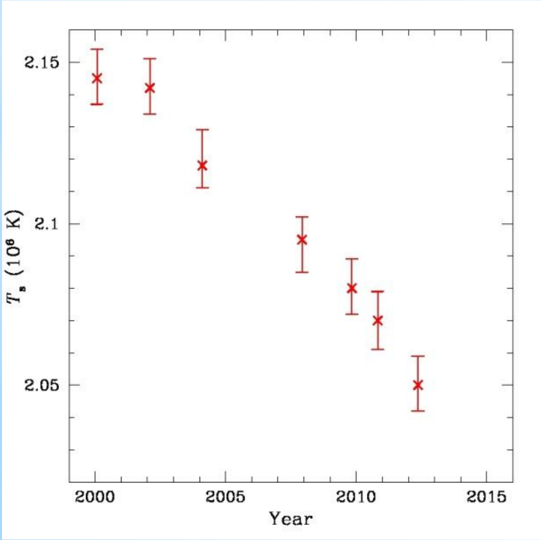

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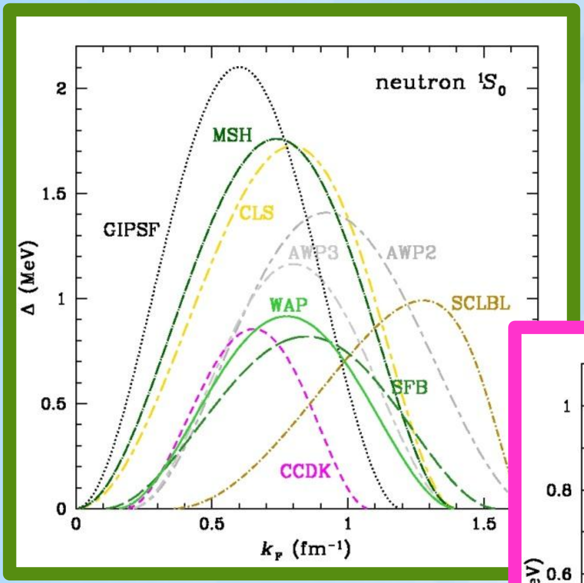
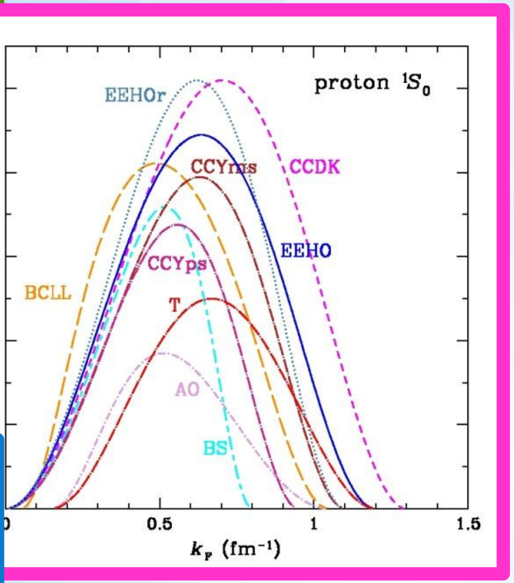
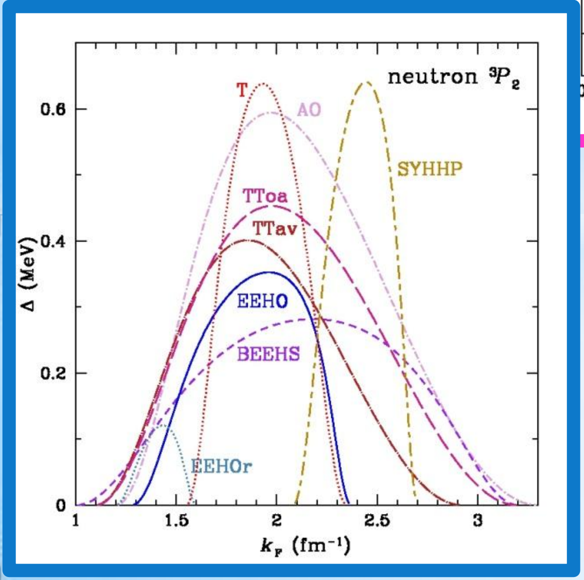
Superfluid and Superconductor Gap Energies

GIPSF: Gandolfi, Illarionov, Pederiva, Schmidt, Fantoni (2009); also used GIPSF for to obtain CLS, MSH







- sf/sc characterized by energy $\Delta(k_F)$ where $k_F \propto n^{1/3}$
- Matter becomes sf/sc when $T < T_c(\Delta)$
- 3 sf/sc (pairing) types in NS:
  - inner crust-core – n singlet $^1S_0$
  - core – proton singlet $^1S_0$
  - core – neutron triplet $^3P_2$-$^3F_2$
- Parameterize theoretical models by (see Kaminker et al 2001; Andersson et al 2005)

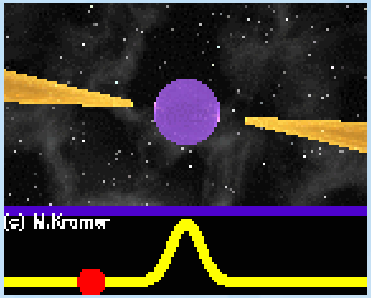
$$\Delta = \Delta_0 \, (k_F - k_0)^2 \, / \, [(k_F - k_0)^2 + k_1] \times (k_F - k_2)^2 \, / \, [(k_F - k_2)^2 + k_3]$$

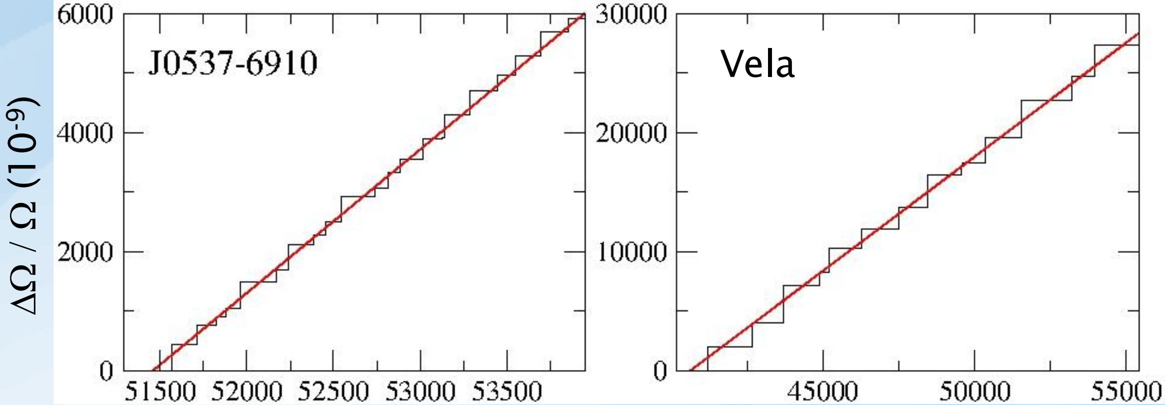
  - 9 neutron singlet models
  - 9 proton singlet models
  - 8 neutron triplet models

Preliminary Conclusions

Pulsar Glitches: The Crust is Not Enough

Andersson, WH+, PRL, 109, 241103 (2012); see also Chamel (2013)

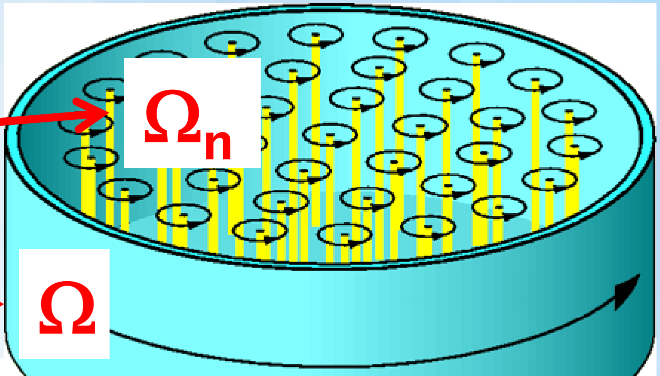




- Track spin evolution of 11 pulsars

- Model: Two-component moment of inertia
  1. inner crust superfluid
     - no spin-down since vortices pinned
  2. outer crust (+ core)
     - spin-down by EM radiation

     $\Rightarrow$ glitch when $\Delta\Omega / \Omega$ too big

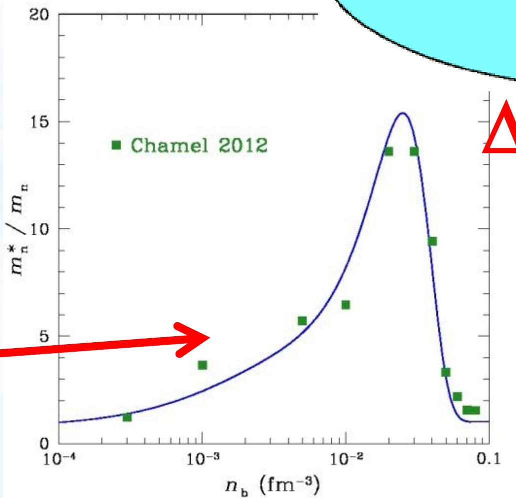


$\Delta\Omega \propto \Omega_n - \Omega$

- Requires angular momentum/moment of inertia reservoir
  - $I_{crust} / I_{total} \approx [-\Omega/(d\Omega/dt)]\ (\Sigma\ \Delta\Omega^i/\Omega)/t_{obs}$

    $= 2\ \tau_c\ A\ \ \langle m_n^*\rangle/m_n$

  superfluid entrainment (Chamel 2005; 2012)

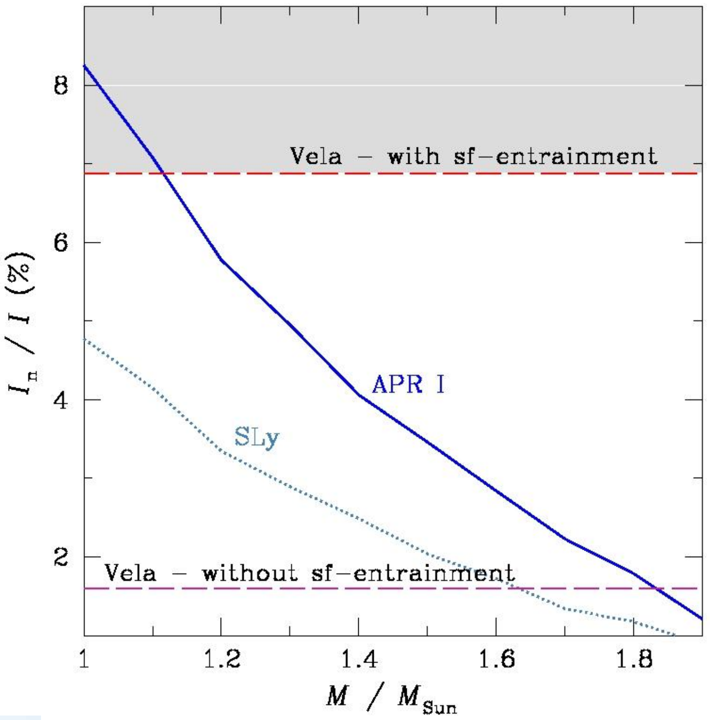


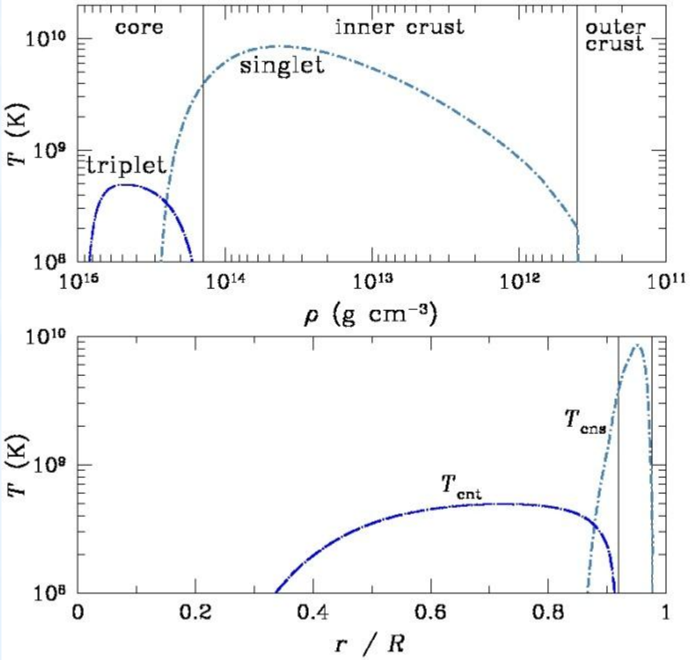
The Crust is Not Enough

Andersson, WH+, PRL, 109, 241103 (2012)

- Superfluid entrainment increases neutron effective mass (Chamel 2005; 2012)
- Glitches need mom of inertia reservoir 4-8% e.g., Vela: 7%
- NS models provide < 8%

- Possible solutions:
  - ○ stiff EOS and low NS mass
  - ○ crust superfluid extends into core
  - ○ core superfluid
  - ○ crust EOS and superfluid effective mass (see talk tomorrow by Chamel)
  - ○ crust may be enough: extremely stiff EOS (Piekarewicz, Horowitz+ 2014; Steiner, Gandolfi+ 2014)





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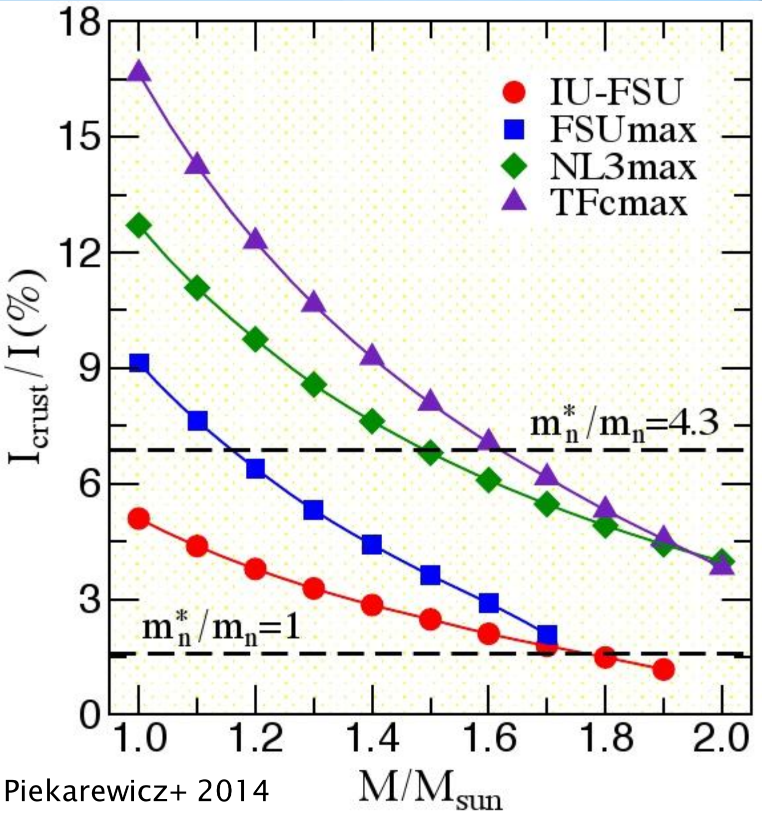
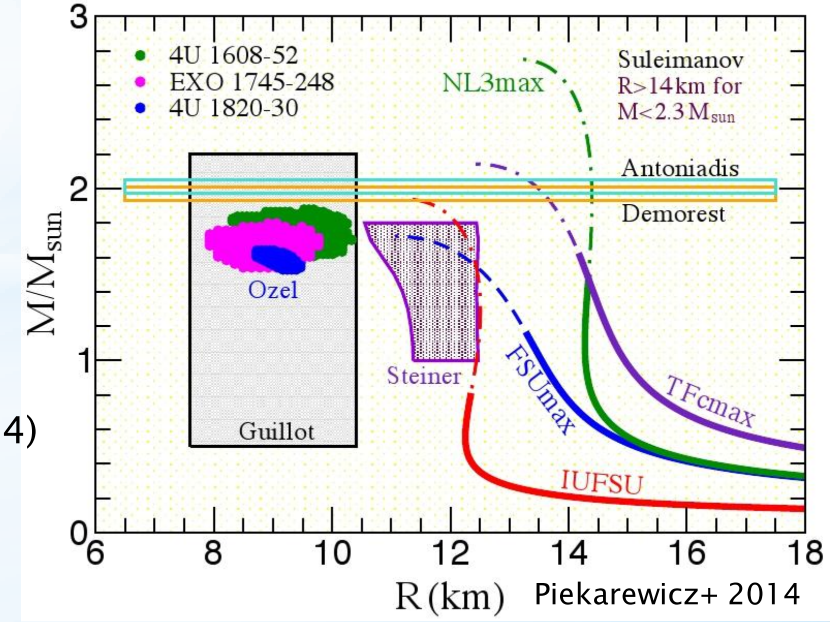
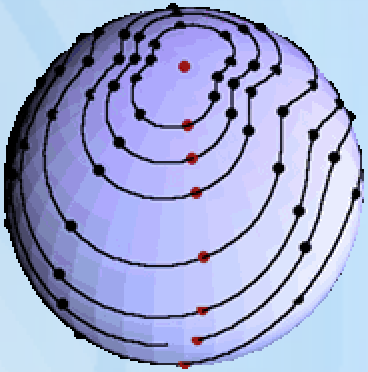


Piekarewicz+ 2014



Piekarewicz+ 2014

R-mode oscillations and X-ray detection(?)



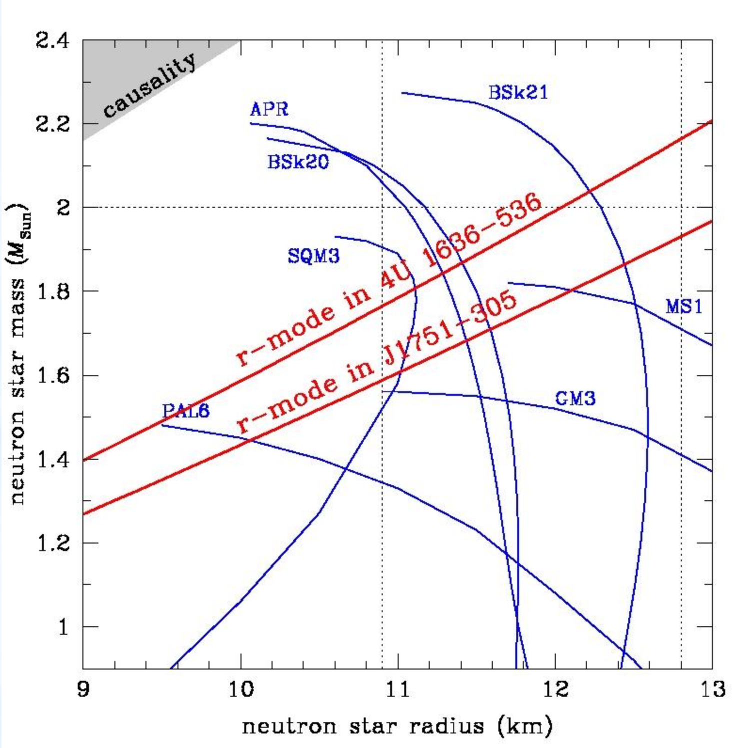
- Fluid oscillations in rotating stars with quadrupolar (corotating) frequency

$$\nu = (2/3)\times\Omega_s$$

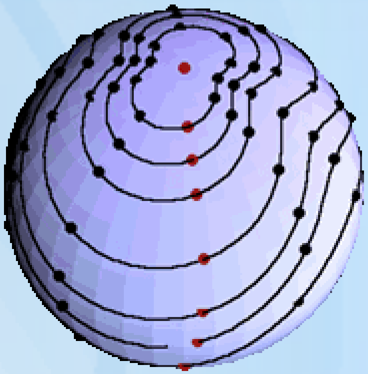
- Observed in XTE J1751-305 (& 4U 1636-536) (Strohmayer & Mahmoodifar 2014)

$$\nu = 0.5727597\times\Omega_s \quad \text{for J1751-305}$$
$$\nu = 0.56454\times\Omega_s \quad \text{for 4U 1636-536 if r-mode}$$

- Andersson, WH+, MNRAS, 442, 1786 (2014):
  - Relativistic corrections to mode frequency
  - Observed oscillation amplitude and spin evolution inconsistent with r-mode theory for XTE J1751-305

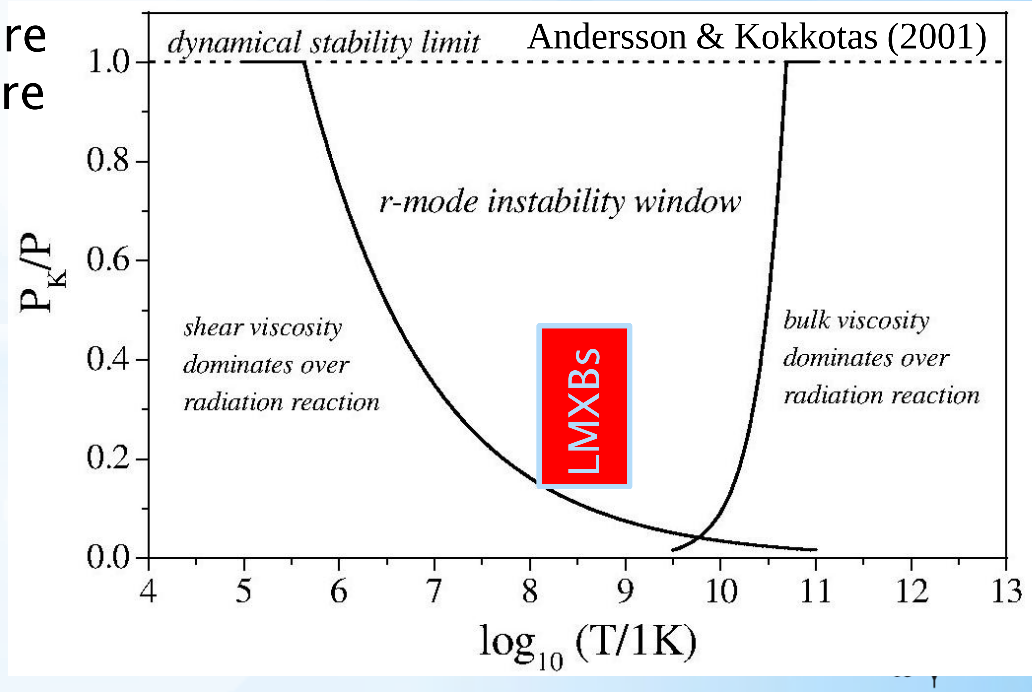


R-mode instability and emission of gravitational waves



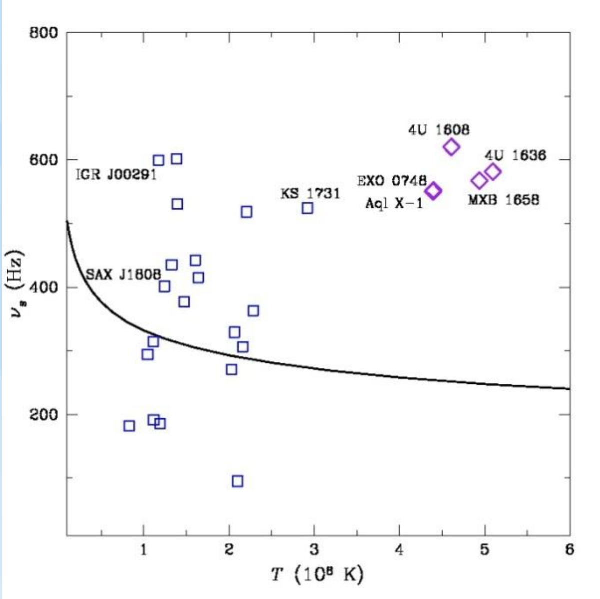
- Fluid oscillations in rotating stars
- Generically unstable
  (Andersson 1998; Friedman & Morsink 1998):
  - GW emission drives r-mode growth
  - Viscosity damps r-mode
    - shear viscosity at low temperature
    - bulk viscosity at high temperature
  - R-mode (in)stability criterion

$$t_{\mathrm{gw}}\,(\nu_s) = t_{\mathrm{visc}}\,(\nu_s\,, T)$$



Physics of r-mode instability

WH+, PRL, 107, 101101 (2011);
Haskell, WH+, MNRAS, 424, 93 (2012)

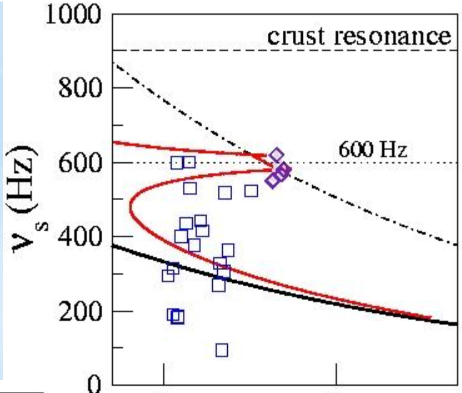


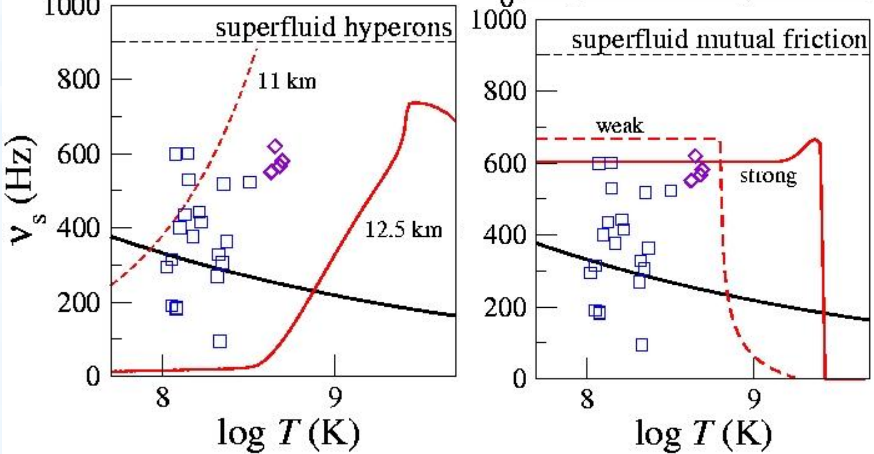
- Instability window for GWs is uncertain

- GW sources counter to expectations

- Rich physics arena
  - core temperature estimates:
    - envelope composition
    - thermal conductivity (e.g., Page & Reddy 2013)
    - neutrino emission (e.g., Schatz, Steiner+ 2014)

  - window shape:
    - crust-core transition/elasticity
    - superfluidity (critical temperature, hyperons, mutual friction)
    - EOS (strange matter, quarks)
    - magnetic field (damping and strength)
    - non-linearity and saturation



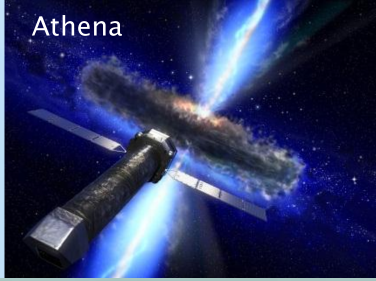


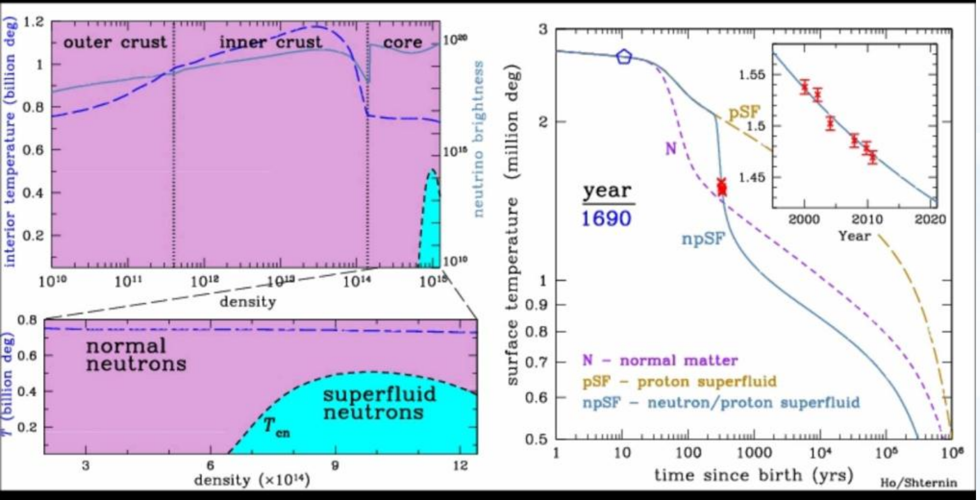
Summary

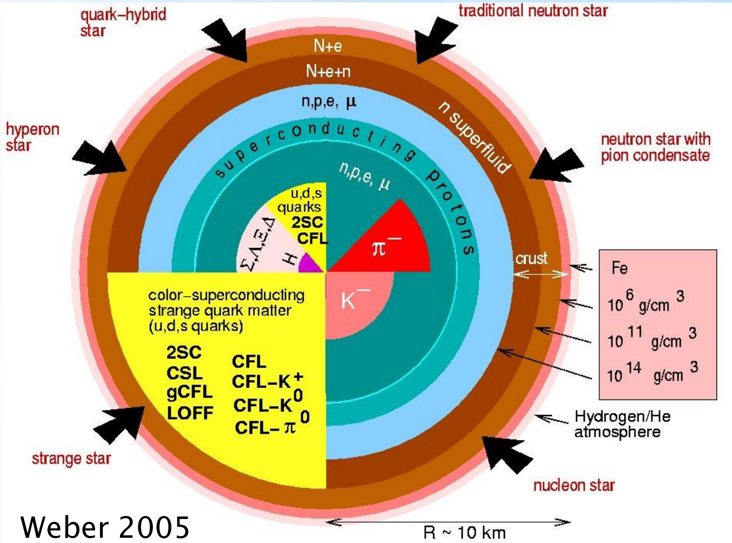
- Neutron stars are unique astronomical tool for nuclear physics (EOS, sf/sc gaps, transport)
  - quiescent low-mass X-ray binaries
  - Cas A X-ray spectra and cooling
  - radio pulsar glitches
  - r-modes and gravitational waves

- Request for astrophysically-useful parameterization of nuclear properties

- **By studying the big and far, we can understand the small and near.**







Weber 2005