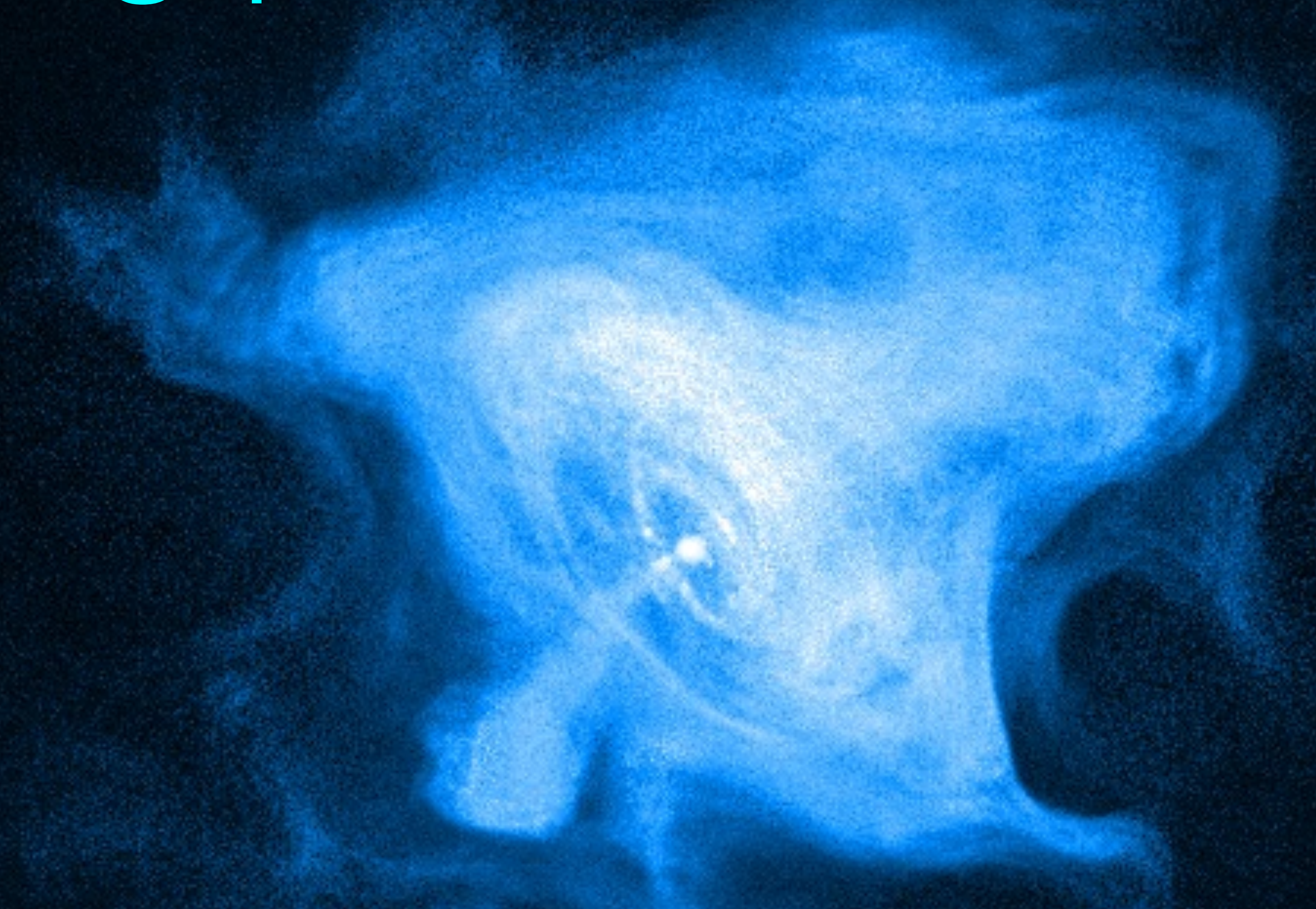
Seeing into a compact star using precise radio data



Kai Schwenzer
Washington University in Saint Louis

Alford & Schwenzer, APJ 781 (2014) 26, arXiv:1310.3524, arXiv:1403.7500

Quark matter in compact stars?

- The interior of a compact star is dense enough that it could contain various novel forms of matter … in particular quark matter

M. Alford, et. al.,
Rev. Mod. Phys. 80 (2008) 1455

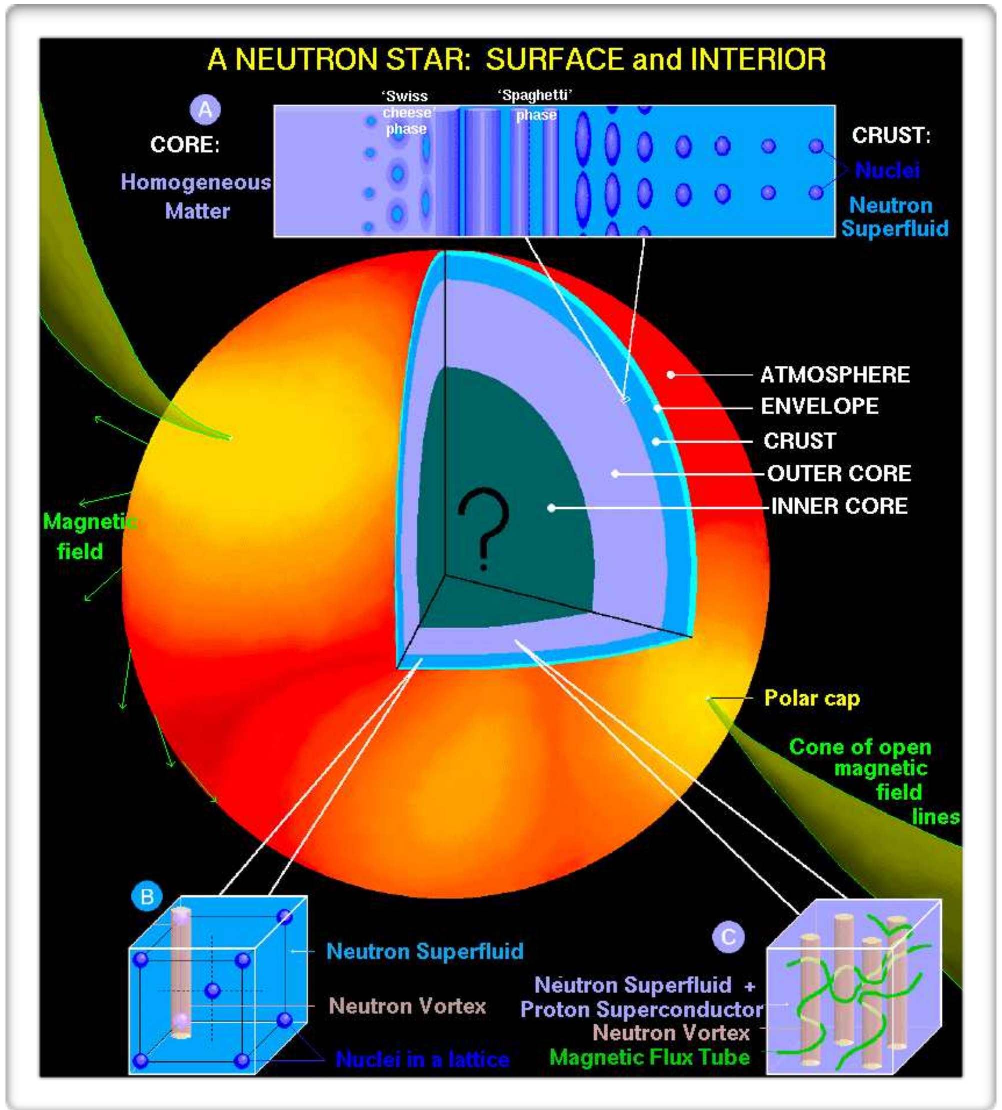
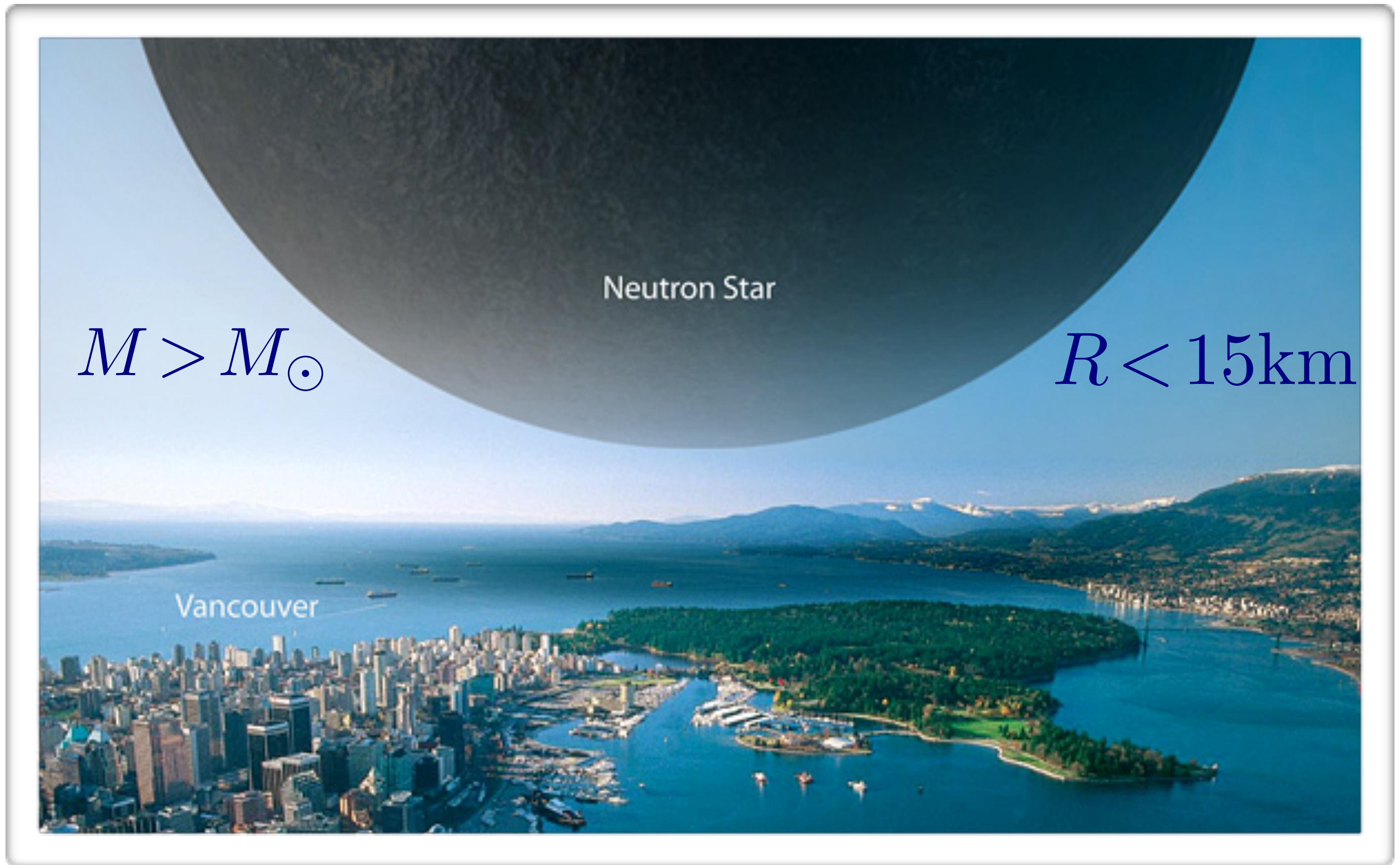
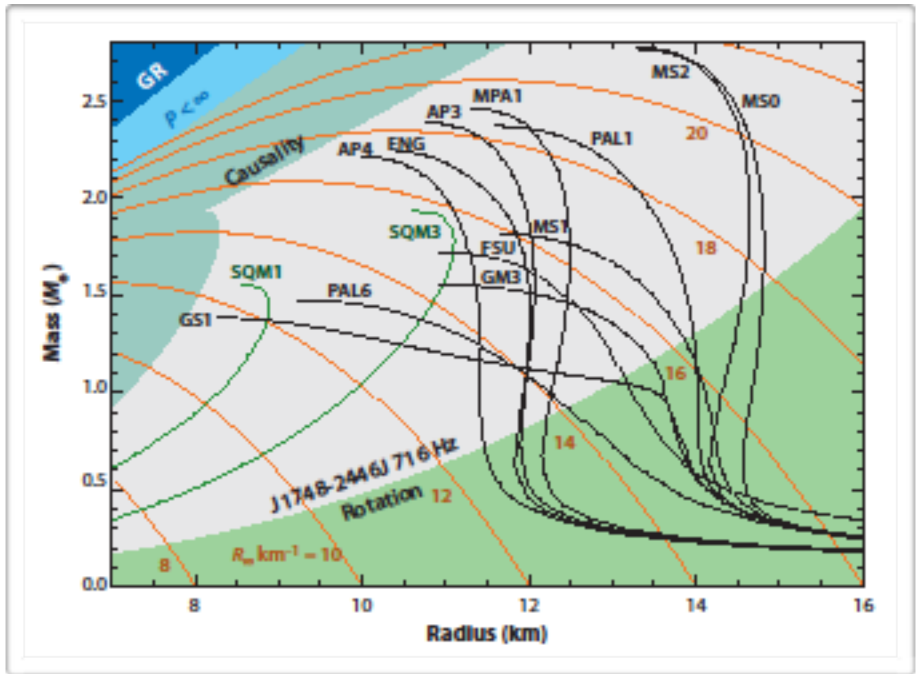


figure by D. Page

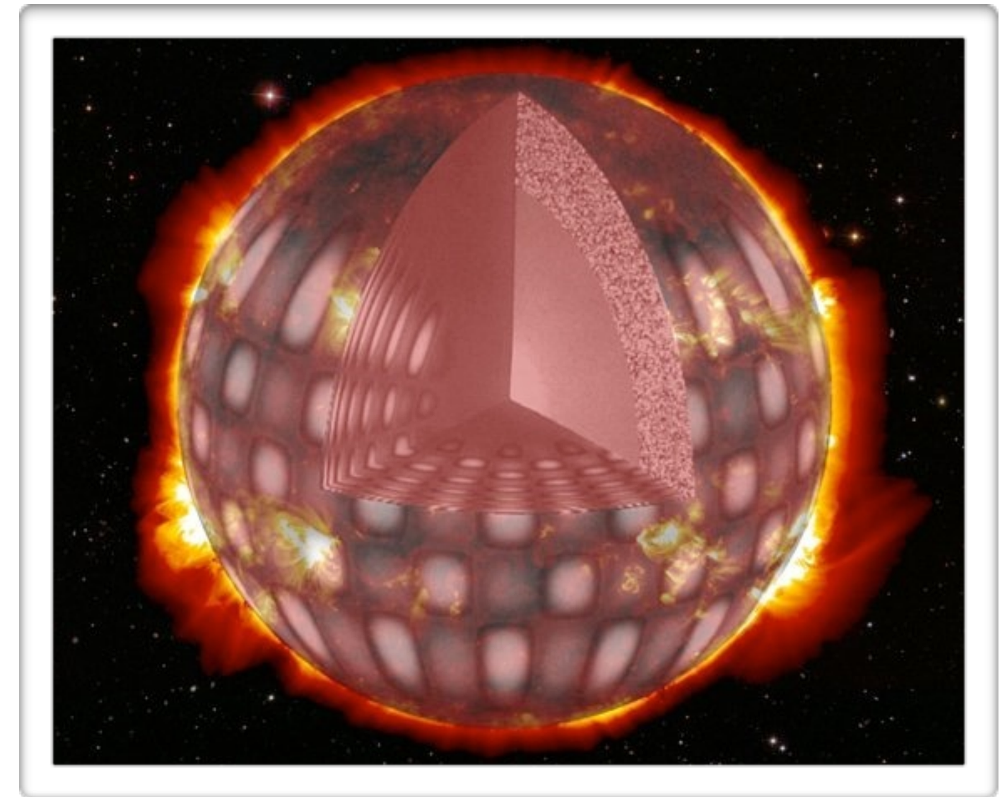


- Requires to connect observables to the microscopic properties:
- Static properties depend on EoS
- ✦ Dynamic prop. depend on low energy degrees of freedom



J. Lattimer, Ann. Rev. Nucl. Part. Sci. 62 (2012) 485

“Seeing into …
… a compact star”



- Electromagnetic radiation originates from the surface - connection to the interior very indirect
- Yet, one can use similar methods we use to learn about the interior of the earth or the sun: “Seismology”
- When non-axisymmetric oscillations are not damped away they emit gravitational waves ...
  - ✓ direct detection via gravitational wave detectors

advanced LIGO (~2015)

  - ✓ indirect detection via the spin data of pulsars

- Star oscillations are damped by viscosity, which is induced by microscopic particle interactions

… links macroscopic observables to microphysics of dense matter

Millisecond pulsars & timing data

- Gravitational waves emitted by star oscillations would generally quickly spin down a fast spinning star

- But many fast ("millisecond") pulsars are observed - they can be grouped into two classes:

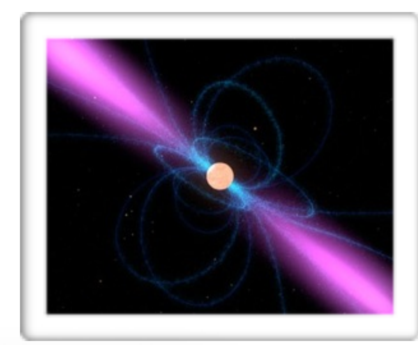
  - ms x-ray pulsars in (low mass) binaries (LMXBs) currently accrete from a companion which allows a temperature measurement (10+ sources)

$\dot{f} > 0$

e.g. Haskell, et. al., MNRAS 424 (2012) 93

    - ✤ T's involve modeling and are uncertain

  - ms radio pulsars (200+ sources) are very old and don't accrete any more, but feature extremely stable timing data



$\dot{f} < 0$

    - ✦ one of the most precise data sets in physics!

NAME	F0	F1	F2	F3
J0534+2200	30.225437	-3.862e-10	1.243e-20	-6.400e-31
J0537-6910	62.026190	-1.992e-10	6.100e-21	0
J0540-6919	19.802444	-1.878e-10	3.752e-21	0
J2022+3842	41.173009	-7.322e-11	0	0
J1513-5908	6.611515	-6.694e-11	1.919e-21	-9.139e-32
J1846-0258	3.062119	-6.664e-11	2.725e-21	2.725e-21

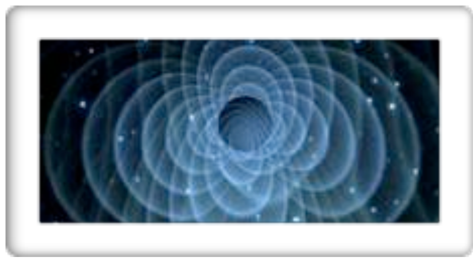
Manchester, et. al., astro-ph/0412641

- Fast pulsars are a puzzle when modes become unstable …

R-mode oscillations

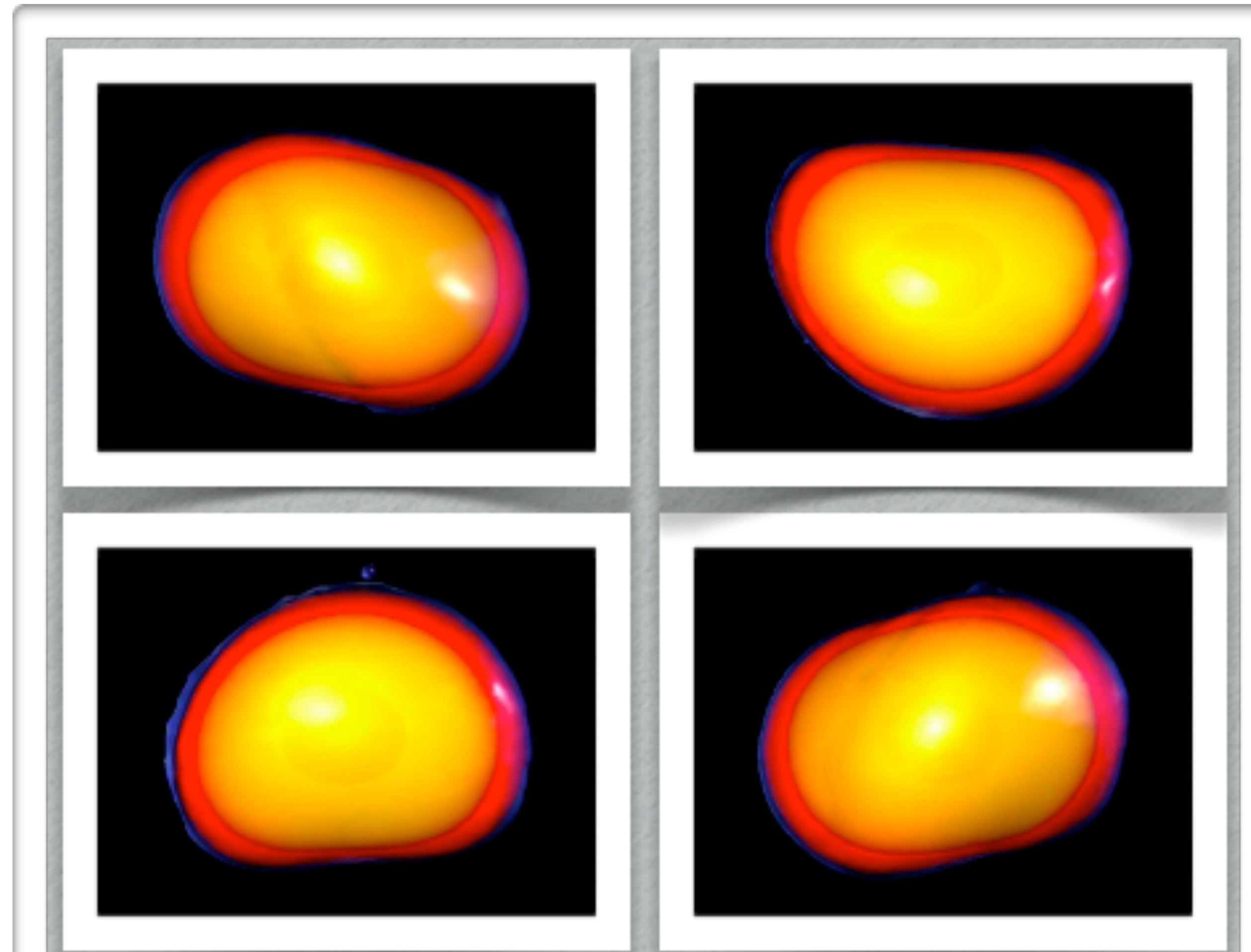
- R-mode: Eigenmode of a rotating star which is unstable against gravitational wave emission

N. Andersson, Astrophys. J. 502 (1998) 708,
L. Lindblom, et. al., PRL 80 (1998) 4843



Large amplitude r-modes could cause a quick spindown

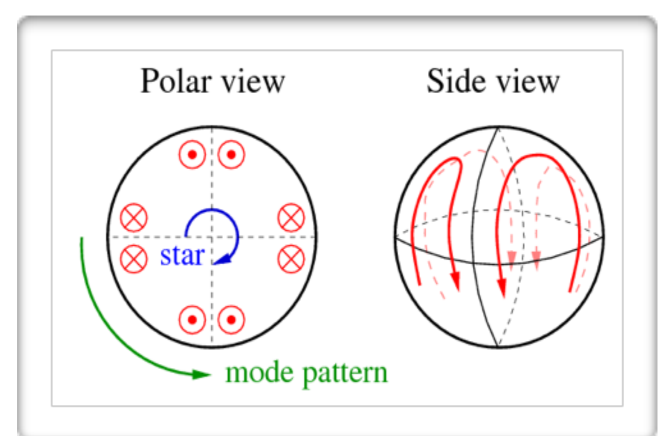
B. J. Owen, et. al.,
Phys. Rev. D 58 (1998) 084020



Simulation by L. Lindblom

- But r-mode growth has to be stopped by some non-linear damping mechanism, e.g.
  - non-linear viscous damping
    M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051
  - non-linear hydro effects - large $\alpha = O(1)$
    L. Lindblom, et. al., PRL 86 (2001) 1152,
    W. Kastaun, Phys.Rev. D84 (2011) 124036
  - mode-coupling - small $\alpha \ll 1$
    P. Arras, et. al., Astrophys. J. 591 (2003) 1129,
    R. Bondarescu, et. al., Astrophys. J. 778 (2013) 9

velocity oscillation: $\delta\vec{v} = \alpha R \Omega \left(\frac{r}{R}\right)^l \vec{Y}_{ll}^B e^{i\omega t}$



Dissipation in dense matter

- Shear viscosity from particle scattering (strong/EM interaction)

candidate phase	dominant processes	shear viscosity	reference
(ungapped) nuclear matter	$e+e \to e+e$ $n+n \to n+n$	$\eta \sim (T/\mu)^{-5/3}$ & $(T/\mu)^{-2}$	Shternin, *et.al.*, PRD 78 (2008) 063006
hyperonic matter	$e+e \to e+e$ $n+n \to n+n$	$\eta \sim (T/\mu)^{-5/3}$ & $(T/\mu)^{-2}$	“
superfluid nuclear matter	$e+e \to e+e$	$\eta \sim (T/\mu)^{-5/3}$	“
ungapped quark matter	$q+q \to q+q$	$\eta \sim (T/\mu)^{-5/3}$	Heiselberg, *et.al.*, PRD 48 (1993) 2916
CFL quark matter	$H \to H+H$	$\eta \sim (T/\mu)^{4}$	Manuel, *et. al.*, JHEP 09 (2005) 76; Andersson, *et. al.*, PRD 82 (2010) 023007

- Bulk viscosity from particle transformation (weak interaction)

candidate phase	dominant processes	bulk viscosity: low T	reference
(ungapped) nuclear matter	$n(+n) \to p(+n)+e+\bar{\nu}$ $p(+n) \to n(+n)+e+\nu$	$\zeta \sim (T/\mu)^6$ or $(T/\mu)^4$	Sawyer, PLB 233 (1989) 412; Haensel, *et.al.*, PRD 45 (1992) 4708
hyperonic matter	$n+n \to p+\Sigma^-, \ldots$	$\zeta \sim (T/\mu)^2$	Haensel, *et. al.*, A&A 381 (2002) 1080
superfluid nuclear matter	$e+l \leftrightarrow \mu+l+\nu+\bar{\nu}$	$\zeta \sim (T/\mu)^7$	Alford, *et.al.*, PRC 82 (2010) 055805
ungapped quark matter	$d+u \leftrightarrow s+u$	$\zeta \sim (T/\mu)^2$	Madsen, PRD 46 (1992) 3290
CFL quark matter	$K_0 \to H+H$	$\zeta \sim e^{-c(\mu/T)}$	Alford, *et.al.*, PRC 75 (2007) 055209

Alternative forms of matter show dramatically different damping, since $T/\mu \sim O(10^{-4})$

“Effective Theory of pulsars”

- Observable macroscopic properties depend only on quantities that are integrated over the entire star:

$$I = \tilde{I} M R^2$$ (MOMENT OF INERTIA)

$$P_G = \frac{32\pi (m-1)^{2m} (m+2)^{2m+2}}{((2m+1)!!)^2 (m+1)^{2m+2}} \tilde{J}_m^{\,2} G M^2 R^{2m+2} \alpha^2 \Omega^{2m+4}$$ (POWER RADIATED IN GRAVITATIONAL WAVES)

$$P_S = -\frac{(m-1)(2m+1)\tilde{S}_m \Lambda_{\rm QCD}^{3+\sigma} R^3 \alpha^2 \Omega^2}{T^\sigma}$$

$$P_B = -\frac{16m}{(2m+3)(m+1)^5 \kappa^2} \frac{\Lambda_{QCD}^{9-\delta} \tilde{V}_m R^8 \alpha^2 \Omega^4 T^\delta}{\Lambda_{EW}^4 \tilde{J}_m}$$

(DISSIPATED POWER DUE TO SHEAR / BULK VISCOSITY)

$$L_\nu = 4\pi R^3 \Lambda_{EW}^4 \Lambda_{QCD}^{1-\theta} \tilde{L} T^\theta$$ (NEUTRINO LUMINOSITY)

"Effective Theory of pulsars"

- Observable macroscopic properties depend only on quantities that are integrated over the entire star:

$$I = \tilde{I} M R^2 \qquad \tilde{I} \equiv \frac{8\pi}{3MR^2}\int_0^R dr\, r^4 \rho$$

$$P_G = \frac{32\pi(m-1)^{2m}(m+2)^{2m+2}}{((2m+1)!!)^2(m+1)^{2m+2}} \tilde{J}_m{}^2 G M^2 R^{2m+2} \alpha^2 \Omega^{2m+4} \qquad \tilde{J}_m \equiv \frac{1}{MR^{2m}}\int_0^R dr\, r^{2m+2}\rho$$

$$P_S = -(m-1)(2m+1)\tilde{S}_m \frac{\Lambda_{QCD}^{3+\sigma} R^3 \alpha^2 \Omega^2}{T^\sigma} \quad \text{with} \quad \tilde{S}_m \equiv \frac{1}{R^{2m+1}\Lambda_{QCD}^{3+\sigma}}\int_{R_i}^{R_o} dr\, r^{2m}\tilde{\eta}$$

$$P_B = -\frac{16m}{(2m+3)(m+1)^5\kappa^2}\tilde{V}_m \frac{\Lambda_{QCD}^{9-\delta} R^8 \alpha^2 \Omega^4 T^\delta}{\Lambda_{EW}^4 \tilde{J}_m} \qquad \tilde{V}_m \equiv \frac{\Lambda_{EW}^4}{R^3 \Lambda_{QCD}^{9-\delta}}\int_{R_i}^{R_o} dr\, r^2 A^2 C^2 \tilde{\Gamma}\,(\delta\Sigma_m)^2$$

$$L_\nu = 4\pi R^3 \Lambda_{EW}^4 \Lambda_{QCD}^{1-\theta} \tilde{L} T^\theta \qquad \tilde{L} \equiv \frac{1}{R^3 \Lambda_{EW}^4 \Lambda_{QCD}^{1-\theta}}\int_{R_i}^{R_o} dr\, r^2 \tilde{\epsilon}$$

- Pulsar evolution for r-mode amplitude α, angular velocity Ω and temperature T are obtained from global conservation laws

✳ Universal hierarchy of evolution time scales: $\tau_\alpha \ll \tau_T \ll \tau_\Omega$

M. Alford & K. S., APJ 781 (2014) 26

✦ Semi-analytic results for the r-mode evolution …
e.g. final frequency for a neutron star:

$$f_f^{(NS)} \approx 61.4\,\mathrm{Hz}\,\frac{\Delta\tilde{S}^{\frac{3}{23}}\Delta\tilde{L}^{\frac{5}{184}}}{\Delta\tilde{J}^{\frac{29}{92}}\alpha_{sat}^{\frac{5}{92}}}\left(\frac{1.4\,M_\odot}{M}\right)^{\frac{29}{92}}\left(\frac{11.5\,\mathrm{km}}{R}\right)^{\frac{87}{184}}.$$

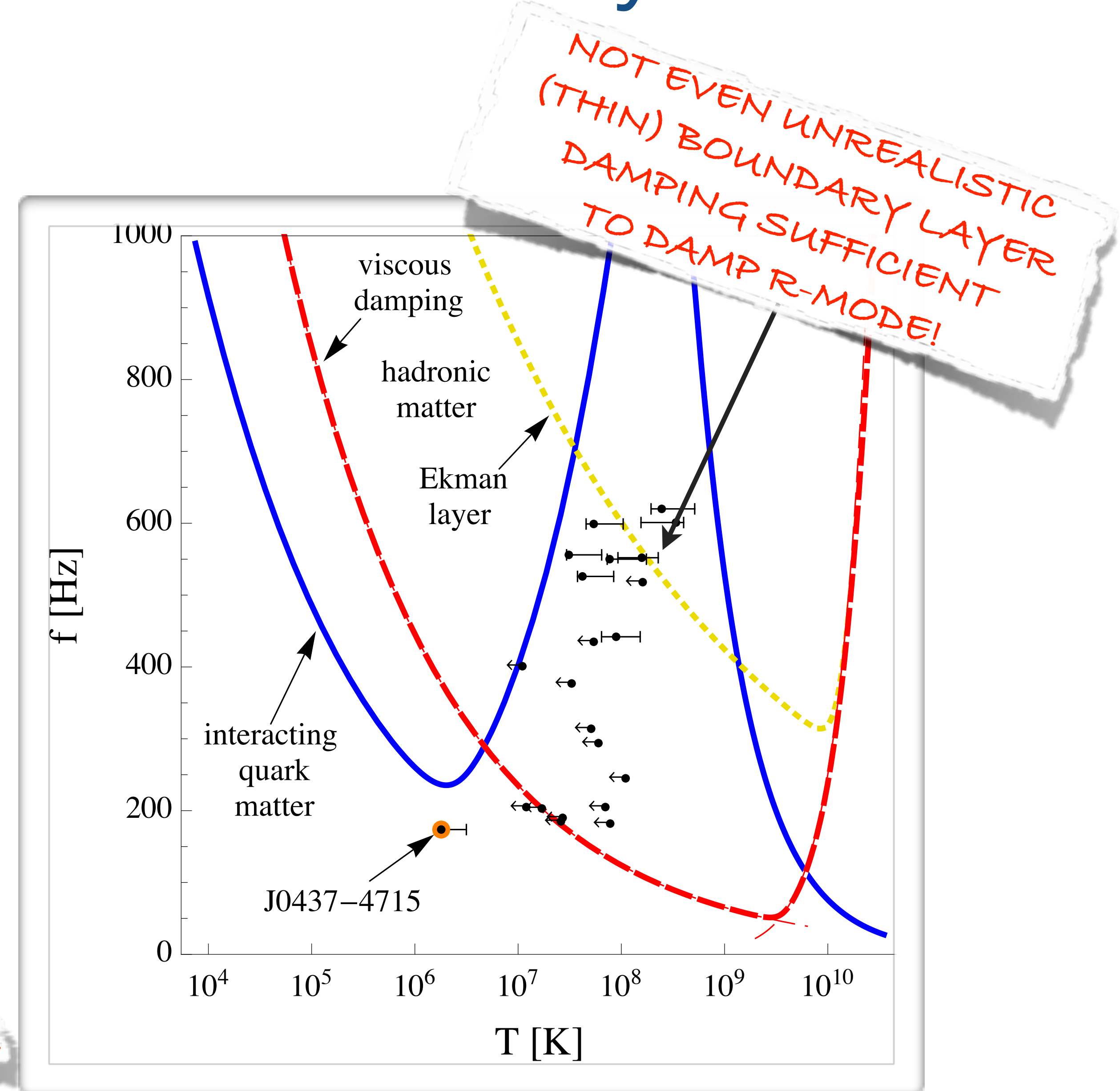
Extremely insensitive to microscopic details … but not to the form of dense matter!

Static instability regions vs. x-ray data

- R-modes are unstable at large frequencies if the damping is not sufficient
- Boundary given by $P_G = P_D|_{\alpha \to 0}$
- Requires temperature measurements which are only available for a few low mass x-ray binaries
- Two scenarios to explain data:
  "no r-mode": completely damped
  "tiny r-mode": unstable, but saturated at small α_{sat}

INTERESTING!

BORING TRIVIAL CASE



K. S., arXiv:1212.5242

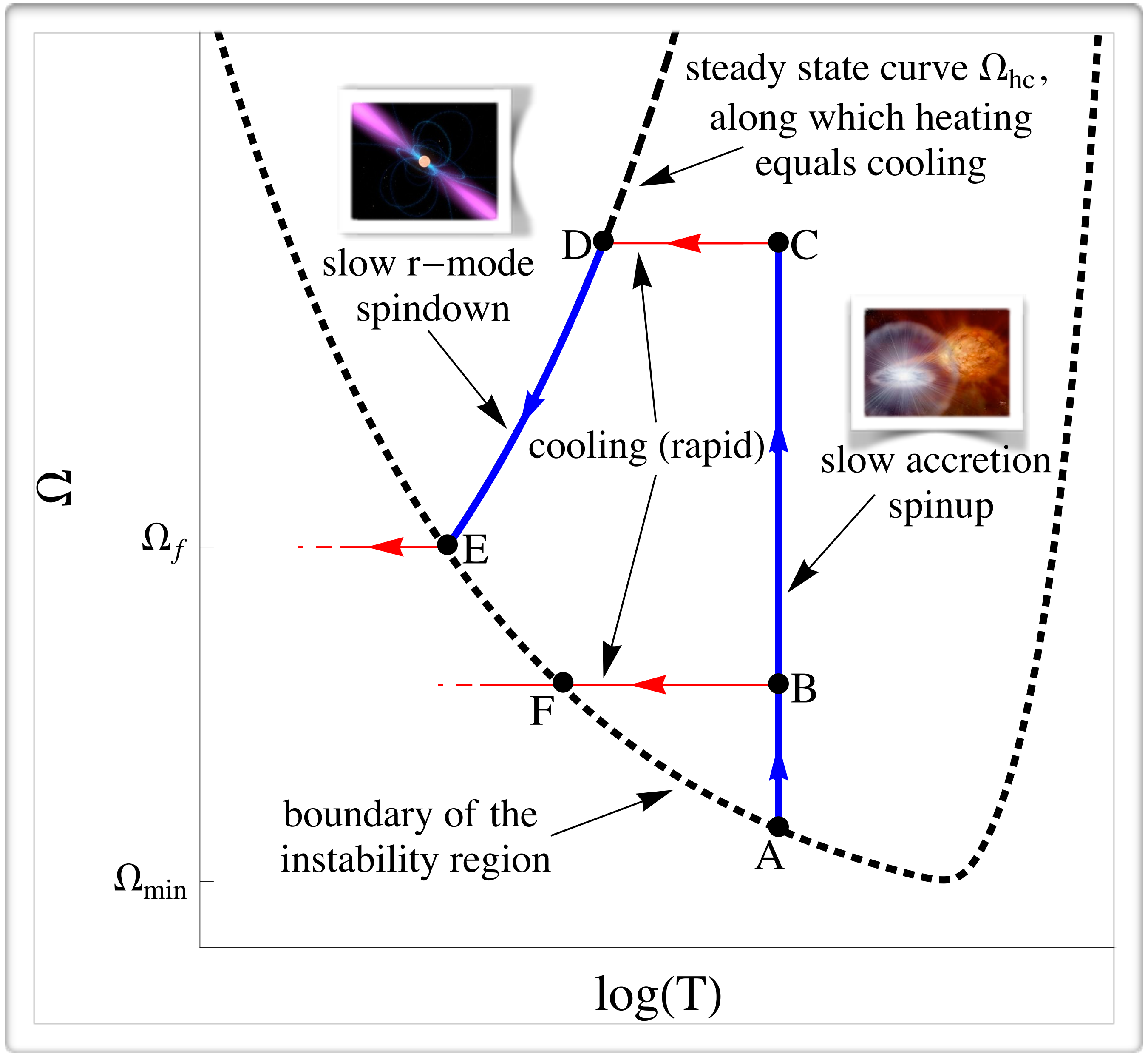
analytic result: $\Omega_{ib}(T) = \left(\hat{D} T^{\delta} \lambda^{\Delta} / \hat{G}\right)^{1/(8-\psi)}$

- Many sources are clearly within the instability region for neutron stars with standard damping (tiny r-mode scenario required)
- Quark matter (incl. gauge interactions) fully damps mode (no r-mode)

Evolution of millisecond pulsars

- Pulsars are spun up by accretion in low mass x-ray binaries (LMXBs), which heats them strongly
- When accretion stops, they cool quickly until either …
  1. they leave the instability region (low frequencies)
  2. r-mode heating balances cooling (high frequencies)

  ➡ very slow spindown along steady state curve



… without enhanced damping, fast spinning stars cannot escape the instability region

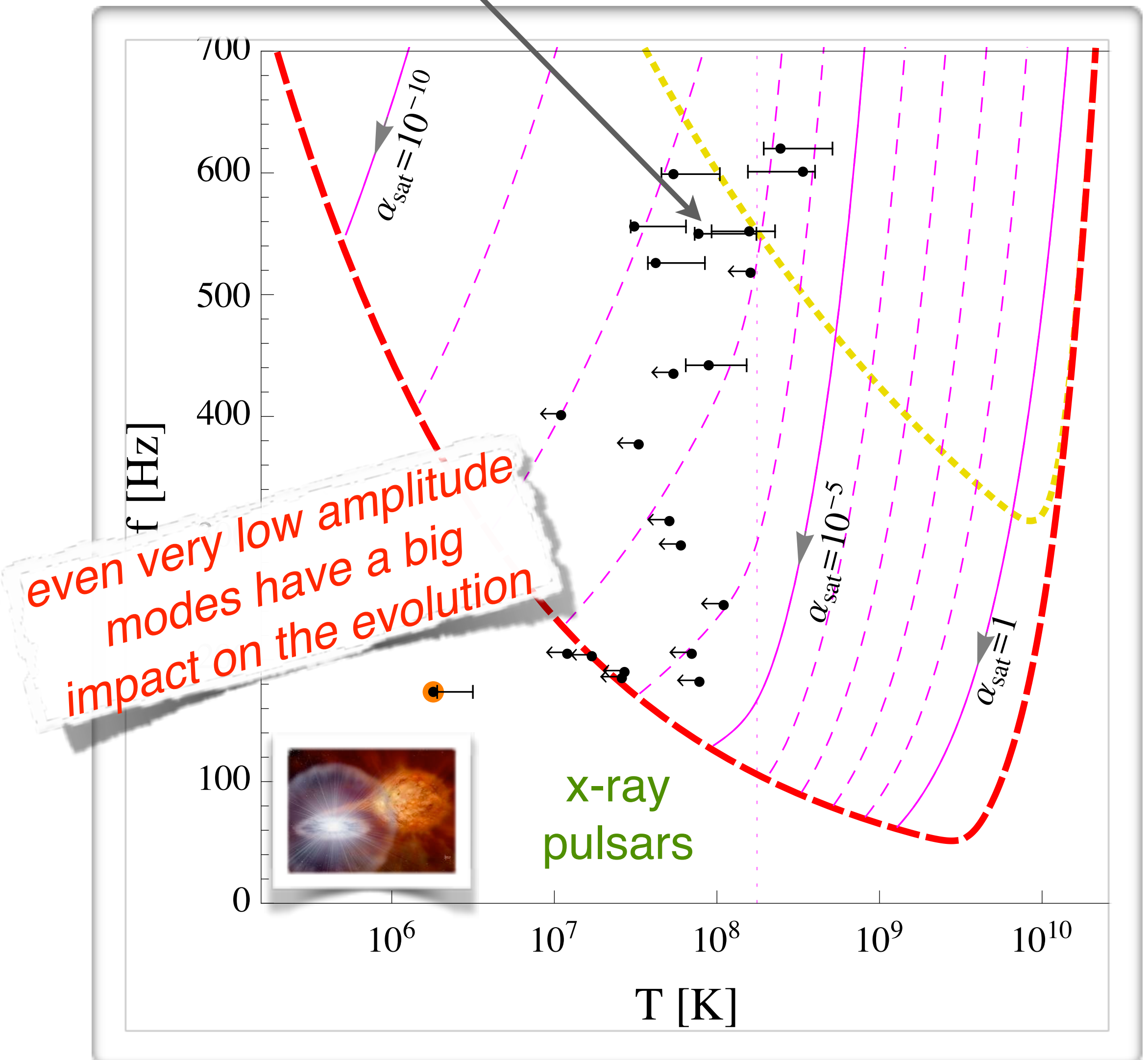
Pulsar evolution & r-mode instability

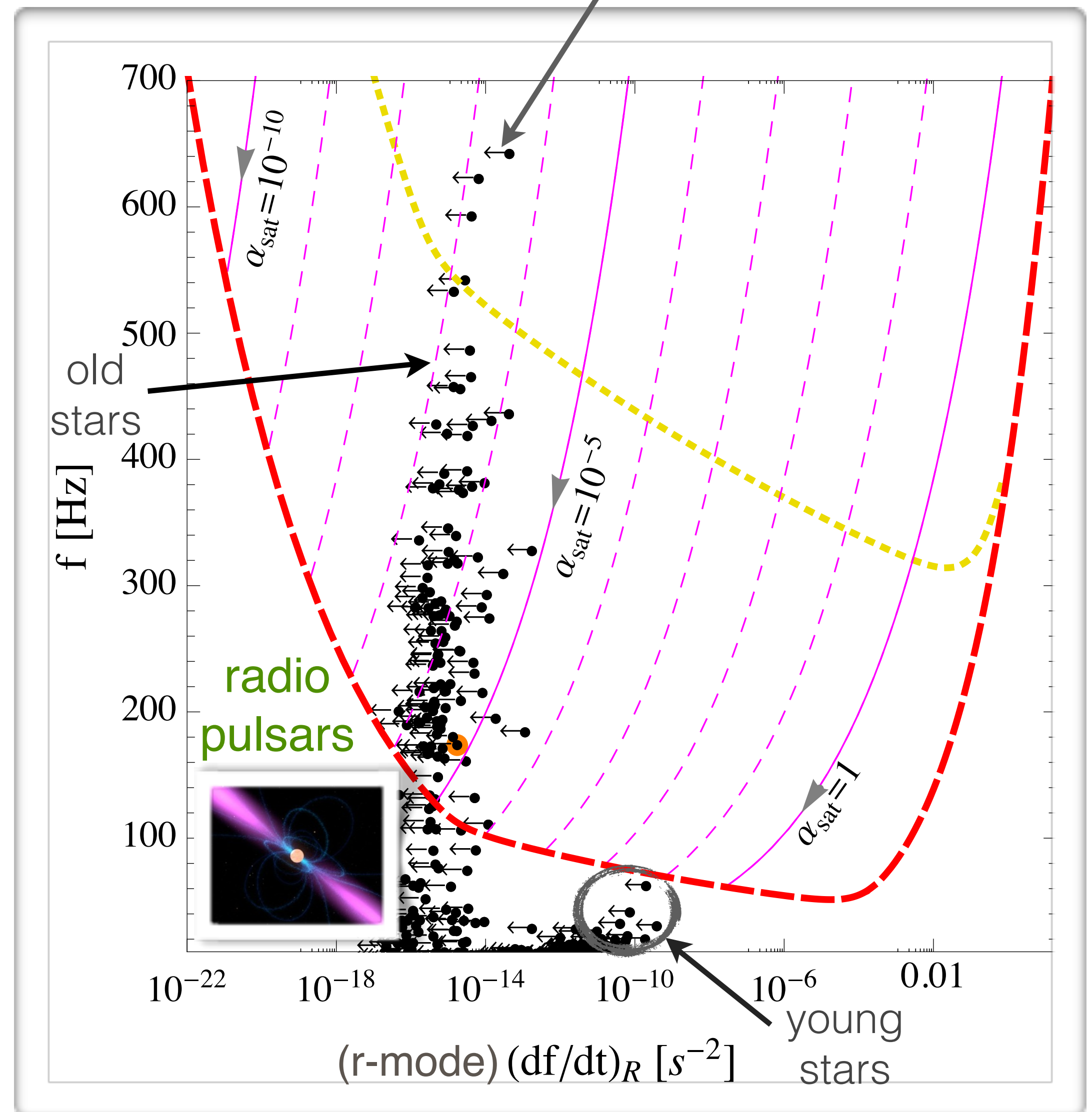
temperatures have large uncertainties

Haskell, et. al., MNRAS 424 (2012) 93

observed spindown rates are upper limits for r-mode contribution

Manchester, et. al., astro-ph/0412641





- Spindown solution allows to connect to timing data of radio pulsars …

Spindown (heating=cooling) curves depend strongly on saturation amplitude … data implies that $\alpha_{\rm sat} \lesssim O(10^{-8})$ but all proposed saturation mechanisms can only saturate at $\alpha_{\rm sat} \gtrsim O(10^{-6})$

Enhanced damping required!

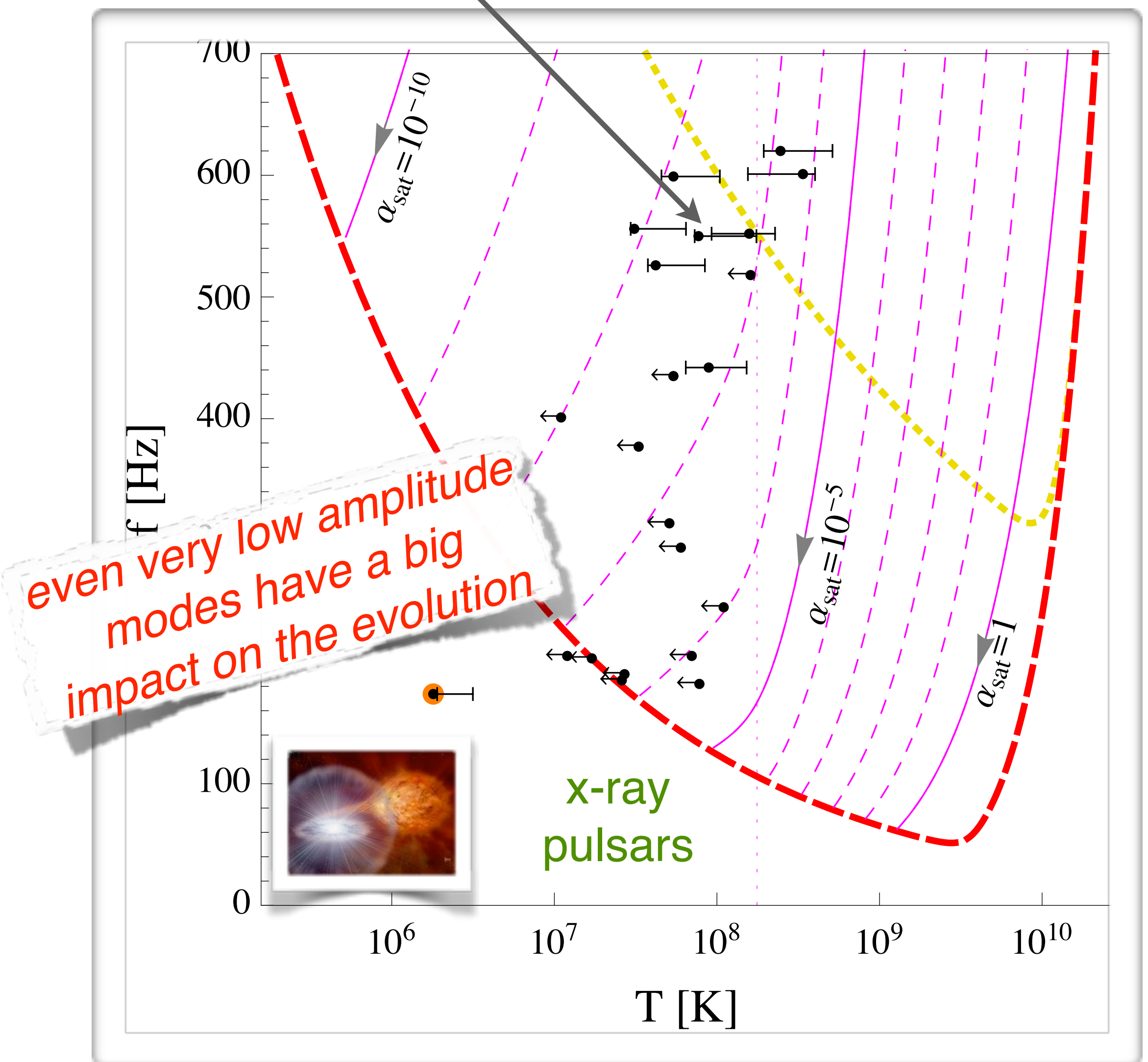
Pulsar evolution & r-mode instability

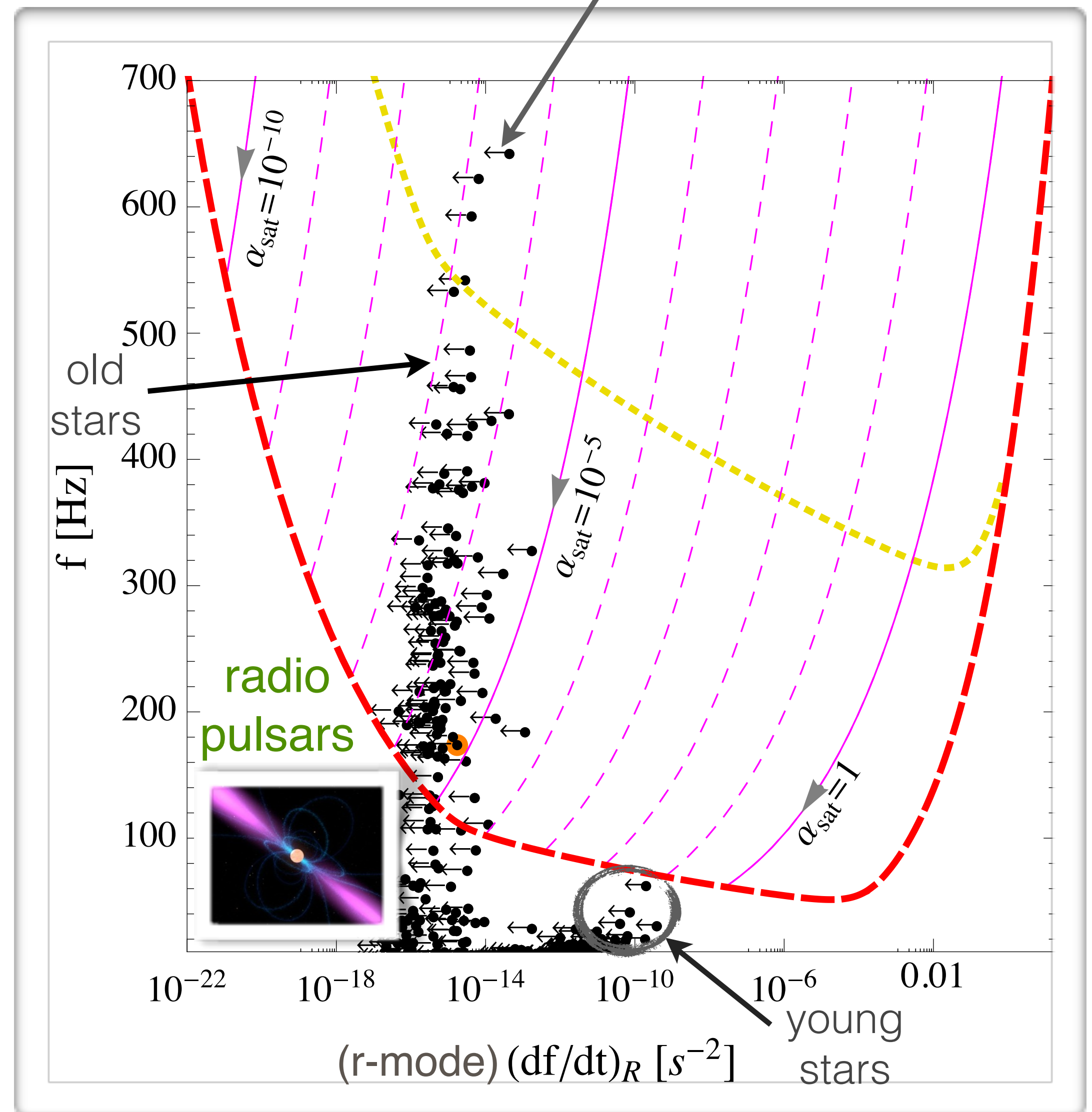
temperatures have large uncertainties

Haskell, et. al., MNRAS 424 (2012) 93

observed spindown rates are upper limits for r-mode contribution

Manchester, et. al., astro-ph/0412641



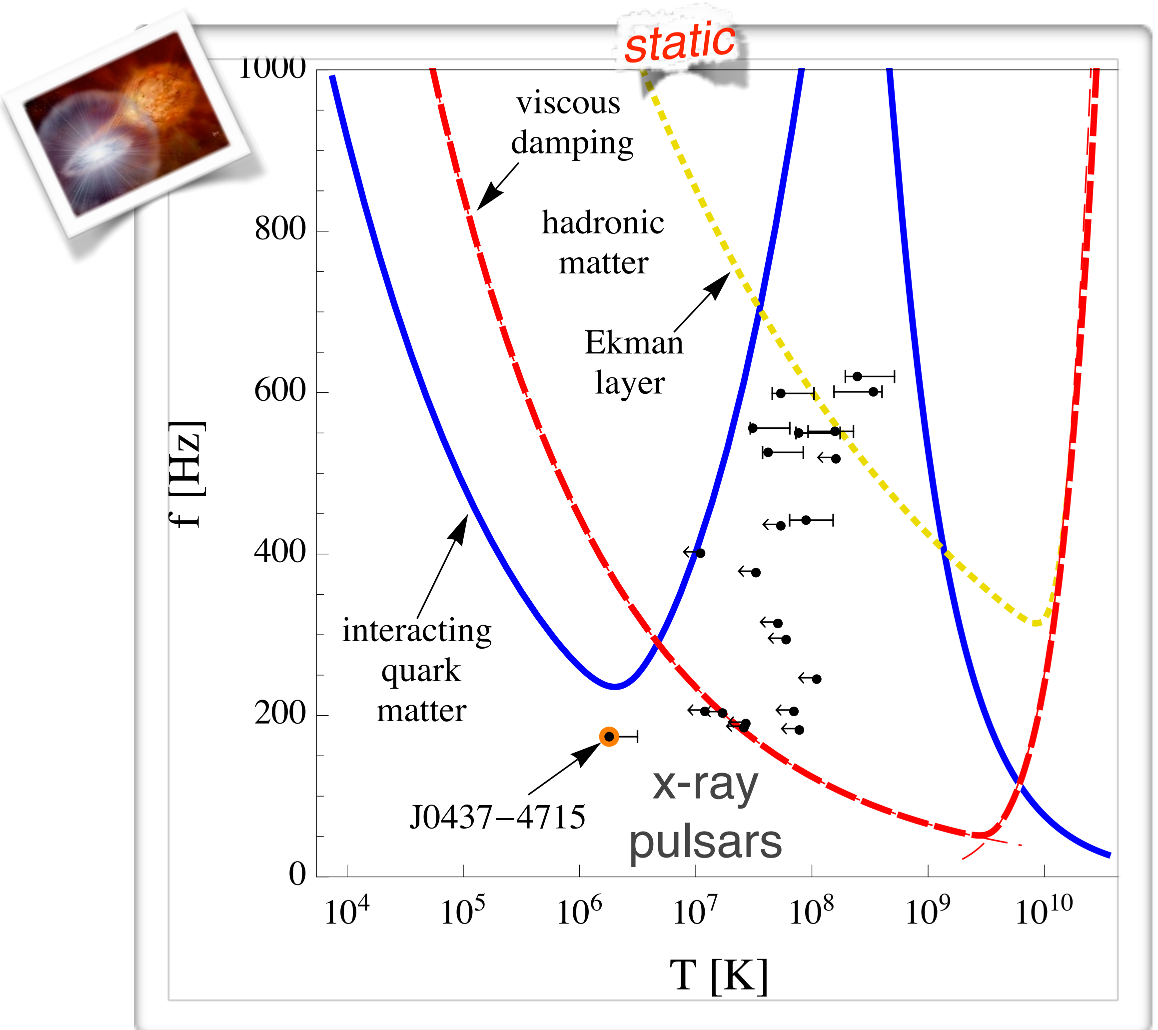


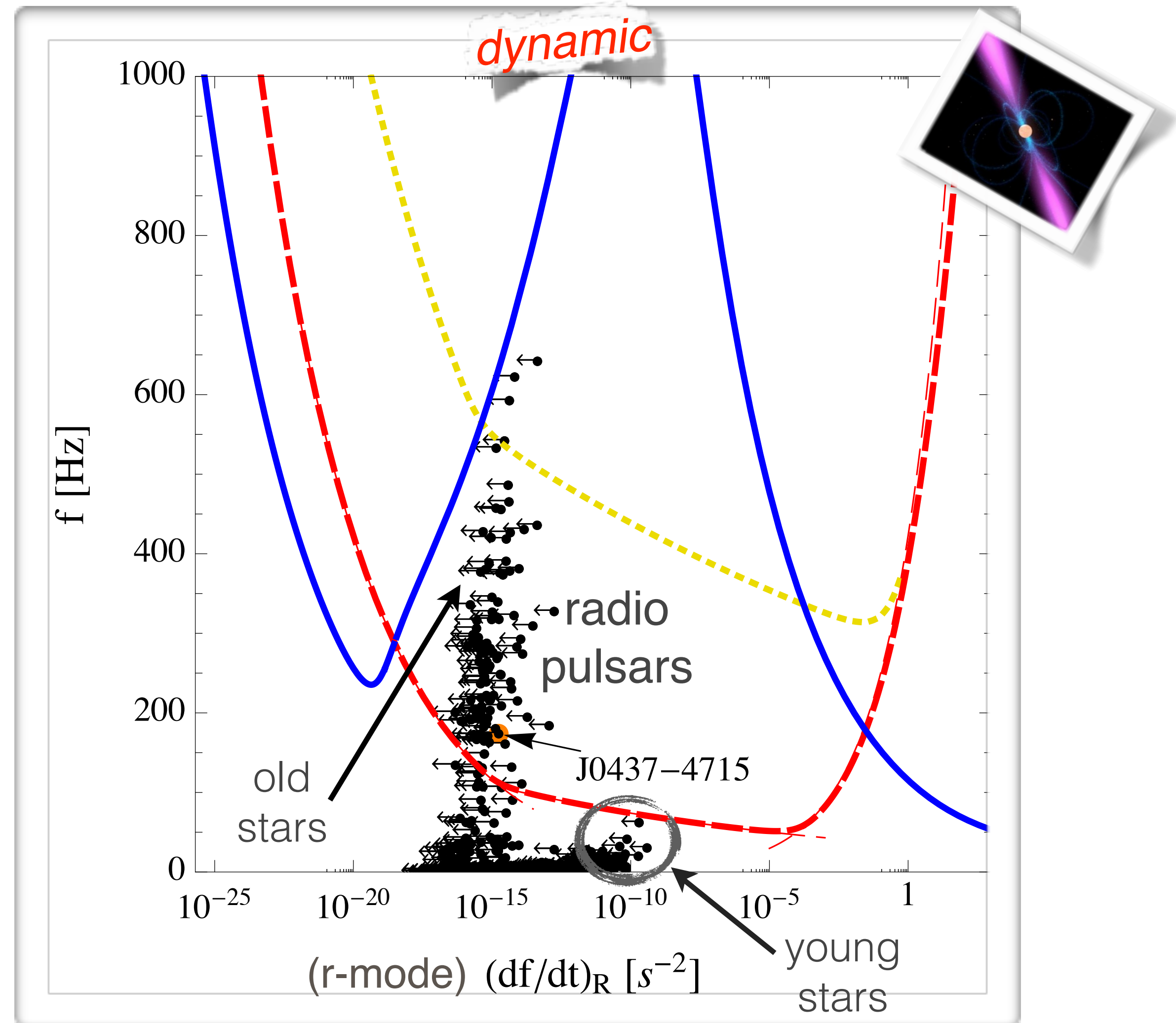
We only measure the total spindown rate which can stem from various mechanisms, so that the sources could be outside of the instability region …

- However, to cool out of the instability region would even require $\alpha_{\rm sat} \lesssim O(10^{-10})$

Spindown data is restrictive despite our ignorance what fraction is due to r-modes!

R-mode instability regions vs. thermal x-ray & radio timing data





M. Alford & K. S., arXiv:1310.3524

Dynamic Instability boundaries in timing parameter space:

$$\Omega_{ib}\left(\dot{\Omega}\right) = \left(\hat{D}^{\theta} I^{\delta} |\dot{\Omega}|^{\delta} / \left(3^{\delta} \hat{G}^{\theta} \hat{L}^{\delta}\right)\right)^{1/((8-\psi)\theta-\delta)}$$

independent of saturation physics!

Interacting quark matter consistent with both x-ray and radio data (no r-mode scenario)

"R-mode temperatures"

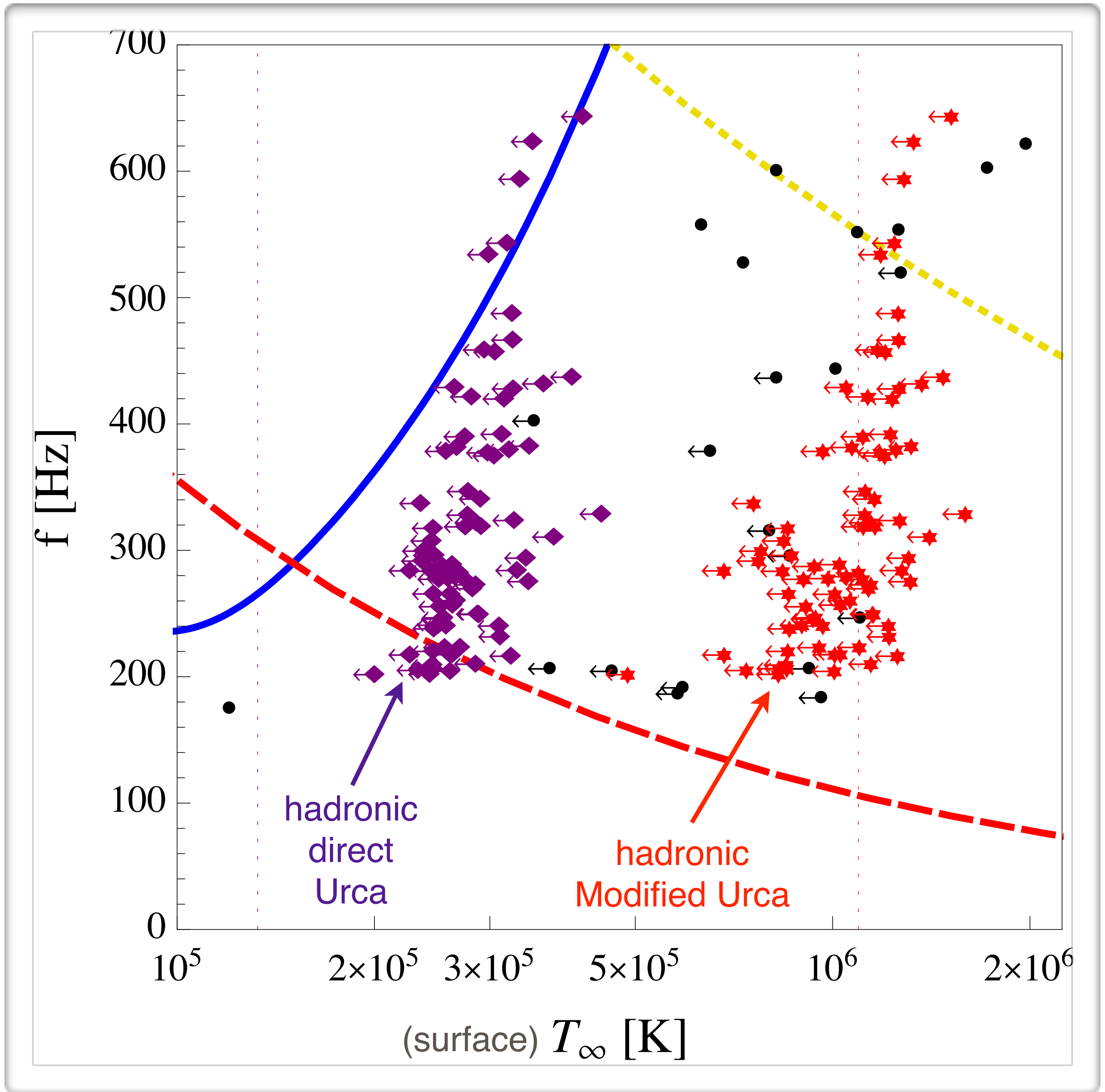
- The connection between the spindown curves allows to determine the R-mode temperature of a star with saturated r-mode oscillations (tiny r-mode scenario) for given timing data

$$T_{rm} = \left(I\Omega\dot{\Omega}/\left(3\hat{L}\right)\right)^{1/\theta}$$

- Independent of the saturation mechanism ... but depends on the cooling
- Temperatures only upper bounds since the observed spindown rate can also stem from electromagnetic radiation

✦ Measurements of temperatures (or bounds) of fast nearby radio pulsars would allow us to test if saturated r-modes can be present

➡ falsifiable scenario!



M. Alford & K.S., arXiv:1310.3524

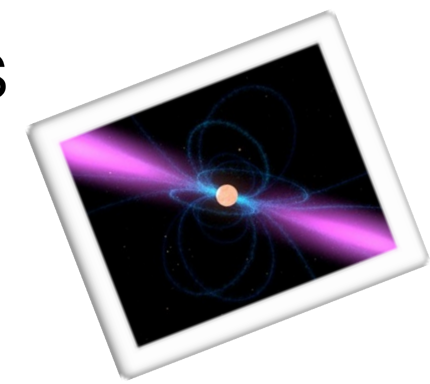
If radio pulsars spin down by r-mode emission, they would be warm enough to observe thermal x-rays

Conclusions and Outlook

- ✦ Timing data of radio pulsars …
  can be used to probe the interior of compact stars

- ✤ Standard neutron stars cannot damp r-modes in LMXBs and cannot explain the radio pulsar data for proposed r-mode saturation mechanisms

  - ★ Quark matter can simultaneously explain the data on LMXBs and radio pulsars



- ➡ Thermal x-ray or gravitational wave measurements for nearby millisecond pulsars would tell us which scenario is realized

- ➡ Need to rule out other possible mechanisms of enhanced damping (crust, superfluidity, …)