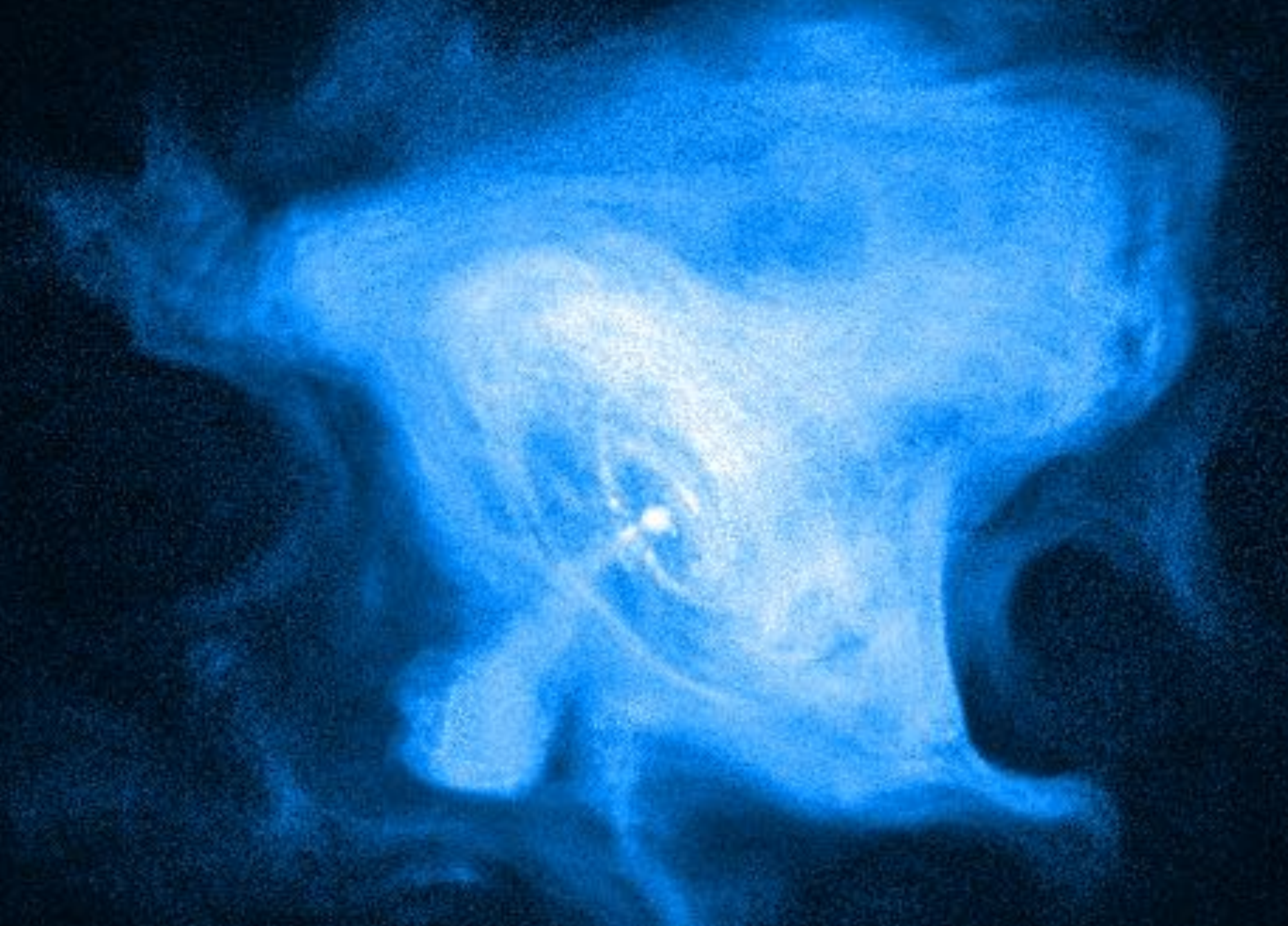
Revealing the compact star interior using dynamical properties



Kai Schwenzer

University of Tübingen

What's inside of a compact star?

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

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

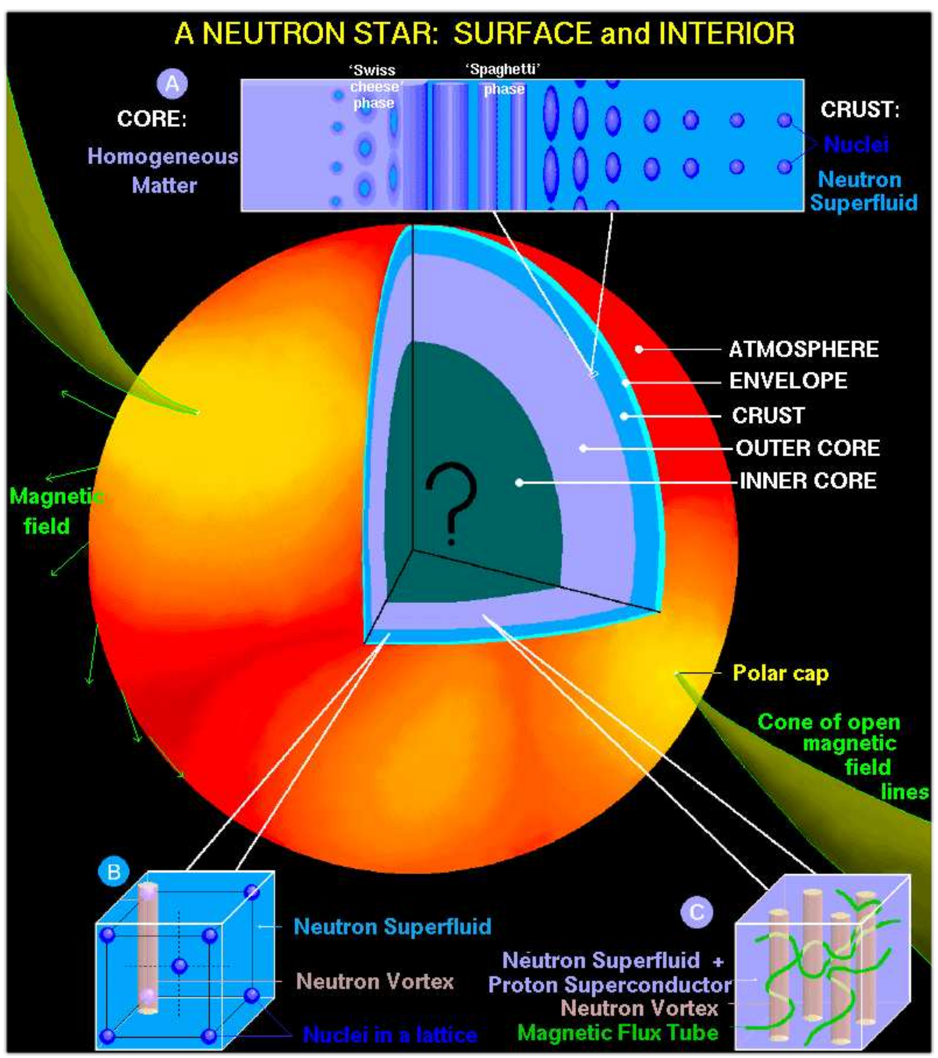
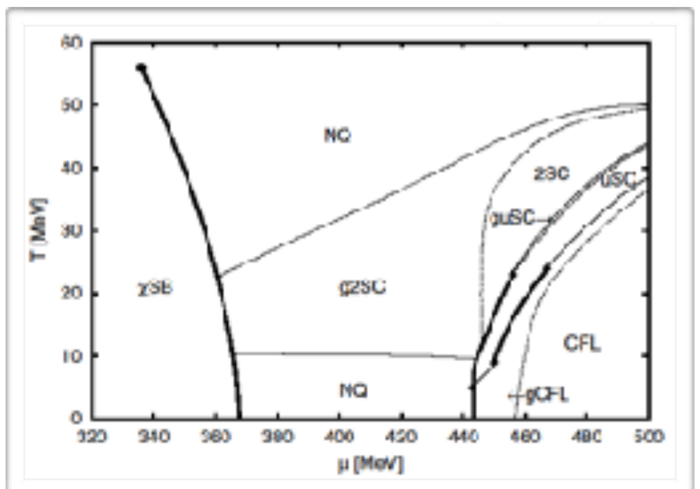


figure by D. Page

- We know the underlying theory of matter (QCD) but we simply cannot solve it at high density, yet
    - ➡ learn from astrophysical signals
- No signal we can detect (so far) escapes the opaque interior
- All signals we see come from the surface or even the magnetosphere

Forms of dense matter

- In hadronic matter there are simply many different particles: (non-relativistic) nucleons, hyperons, leptons, … and maybe mesons
- There are few quarks, but a wealth of possible condensation patterns:



S. Rüster, et. al., PRD 73 (2006) 034025

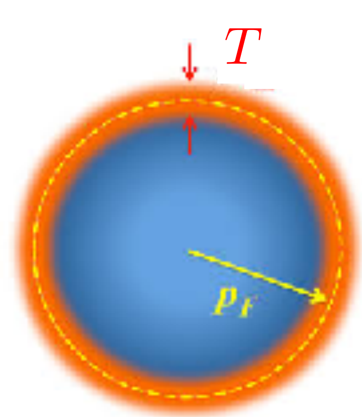
- fully gapped phases (color-flavor locking at asymptotic μ)
- partially gapped color superconducting phases (e.g. 2SC)
- inhomogenous and anisotropic condensates (e.g. LOFF)
- ungapped quark matter

m_s

✦ Many dozens of studied phases - uncountably many potential ones!

Equation of state is rather similar … for different forms of matter

Material properties, determined by low energy degrees of freedom, can be drastically different



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	$e+e \to e+e$	$\eta \sim (T/\mu)^{-3}$	Manuel, *et.al.*, PRD 84 (2011) 123007
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

—> L.Tolos's talk

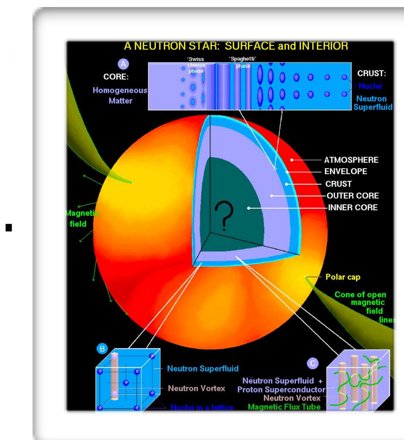
- Bulk viscosity from particle transformation (weak interaction)

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

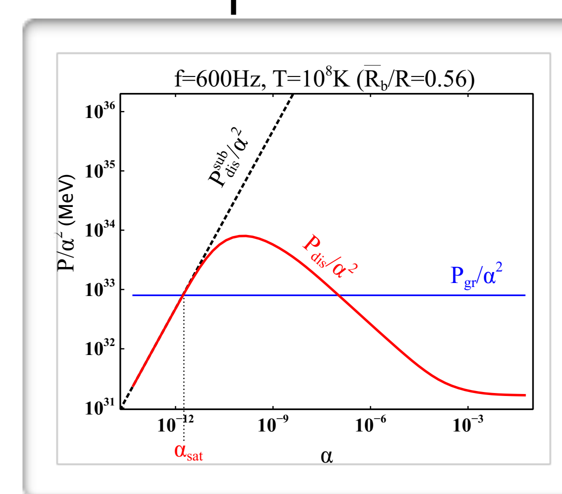
Alternative forms of matter show dramatically different damping, since $T/\mu \sim O(10^{-4})$

Dissipation at an interface in multi-component compact stars

- Ekman layer damping from shear rubbing of a fluid core along a solid crust Lindblom, *et. al.*, PRD 62 (2000) 084030
  - Damping time: $\tau_v = \frac{1}{2\Omega} \frac{2^{m+3/2}(m+1)!}{m(2m+1)!!\mathcal{I}_m} \sqrt{\frac{2\Omega R_c^2 \rho_c}{\eta_c}} \int_0^{R_c} \frac{\rho}{\rho_c} \left(\frac{r}{R_c}\right)^{2m+2} \frac{dr}{R_c}$
  - Only big if there is a sharp, i.e. cm-size, transition … … in reality there is a broad transition over >100 m! (core -> pasta phases -> inner crust -> outer curst)



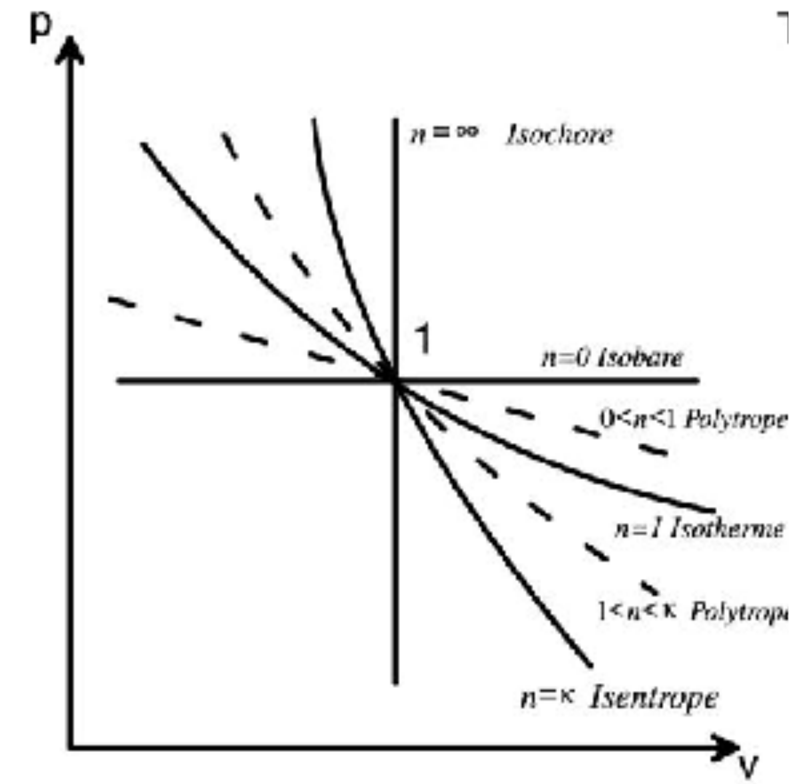
- Phase conversion dissipation between fluids in different phases with 1.order transition (e.g. quark/hadronic matter) Alford, Han & Schwenzer, arXiv:1404.5279
  - $n \leftrightarrow q$ requires strangeness changes
  - Interface slowed by weak reactions & diffusion
  - Only non-vanishing at finite amplitude, but then very strong:



Provides r-mode saturation mechanism in a hybrid star with $\alpha_{\rm sat} < O(10^{-10})$

“Transport Polytropes”

- Polytropes $p = K\rho^n$ are the swiss-army knife of neutron star physics
  - allow us to model the equation of state without direct insight into the microphysical details
  - when used piecewise they can approximate rather complicated EoS (—> Bayesian analysis)
- Goal: Can we find something similar for material and transport properties?
- Idea: Classify phases of matter by some generic properties that qualitatively distinguish different phases and determine the simple functional dependences that determine the order of magnitude of transport properties



$$\epsilon = \frac{457}{630} G_F^2 \cos^2\theta_c \, \alpha_s \, \mu_q^2 \, \mu_e \, T^6$$

$\sim (T/\mu)^6$

Classifying phases of dense matter

- Material properties of different phases can be classified by generic features of their low energy degrees of freedom (encoded by different "flags" $s \in \{0,1\}$) …
  - degenerate (i.e. bosonic / fermionic): s_d
  - relativistic: s_r
  - strange: s_x
  - condensed: s_c

  and their interactions …
  - electromagnetic (vs. strong): s_e
  - long-range (i.e. screened / unscreened): s_l
  - kinematic restrictions that impose threshold effects: s_t

- Classification relies on several small parameters that distinguish different phases: T/μ, T/Δ, p_F/μ , $\alpha_{\rm EM}/\alpha_{\rm S}$, …

Power counting

- Material properties generally involve (collision) integrals over the phase space of the contributing interactions
  - example: direct Urca neutrino emission

$$\epsilon \sim \prod_{i=1}^{4}\left(\int \frac{d^3 p_i}{2E_i}\sum_{s_i}\right)\delta^3\left(\sum_{j=1}^{4} p_j\right)\delta\left(\sum_{k=1}^{4} E_k\right)E_\nu \mathrm{tr}\left[\left(\prod_{l=1}^{4} f_l^{(\rightarrow)}\right)\left|M^{(\rightarrow)}\right|^2+\left(\prod_{l=1}^{4} f_l^{(\leftarrow)}\right)\left|M^{(\leftarrow)}\right|^2\right]$$

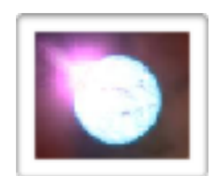
- Based on the low energy properties the size of these integrals can be estimated by mere power counting in terms of the small parameters and flags that characterize the generic low energy properties
  - example: neutrino emission

$$\epsilon \sim G_F^2 (T/\mu)^{8-2s_d(s_r+s_t)-s_c(1-s_t)}\left(1+\sigma\log\left(\Lambda/T\right)\right)^{2s_d s_l}\left(\exp(-\Delta/T)\right)^{s_c s_t}$$

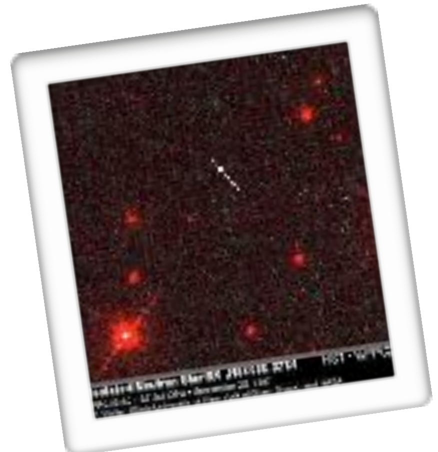
➡ classification into *slow*, *intermediate* and *fast* cooling already standardly used in this case

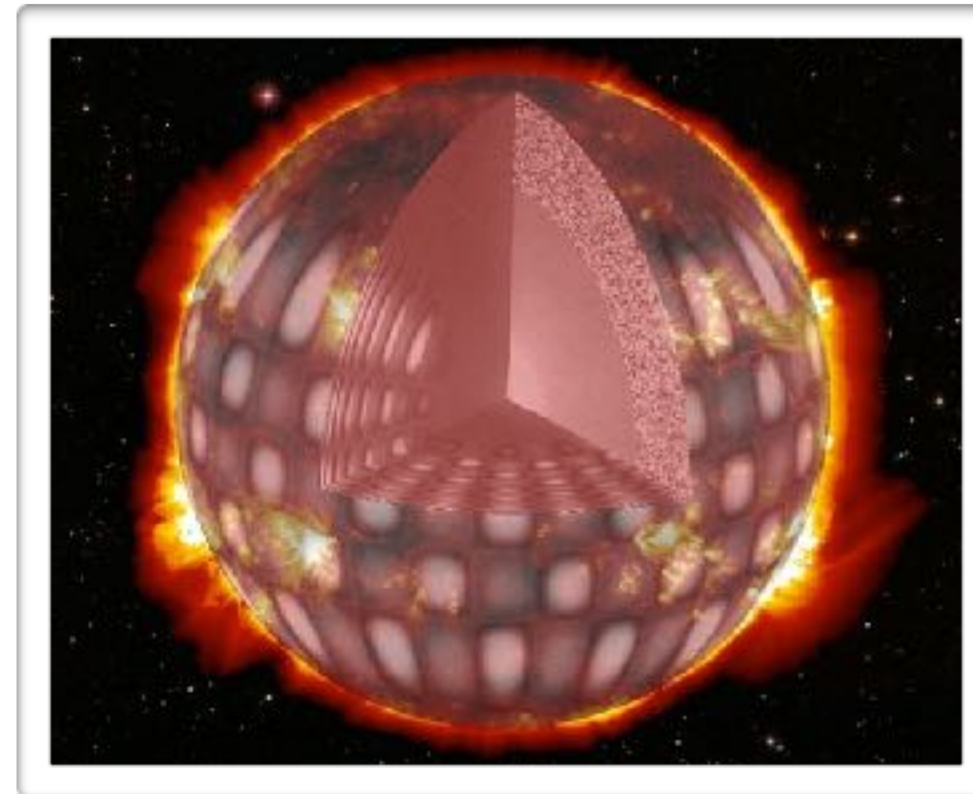
★ Huge difference between the classes ensures that they can be distinguished despite the dramatic uncertainties!

Connection to Astrophysical Observations

- The estimates for the material properties can be used to evaluate astrophysical observables, which generally depend on several transport properties, e.g. the cooling on $\epsilon/c_V \sim T^{5+2(s_d-s_r-s_t)-s_c(1-s_t)}$
- According to this the different neutron star compositions can be divided up into classes that yield different orders of magnitude for a given observable … and therefore can be distinguished despite uncertainties
- With various different astrophysical processes, relying on different observables the composition could be even better discriminated, e.g. via
  - Cooling of young stars —> X-rays 
  - Accreting sources & crust relaxation —> X-rays 
  - Neutron star mergers —> gravitational waves, … 
  - Pulsar spindown —> radio data 
  - Damping of unstable modes —> radio, X-rays, …
    & gravitational waves 

"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, spinning a star down ...
  - ✓ direct detection via gravitational wave detectors

advanced LIGO (2015)

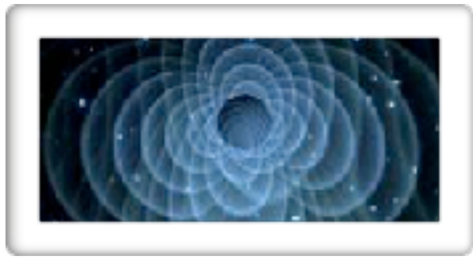
  - ✓ indirect detection via spin data of pulsar: many fast spinning sources observed!

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

… links macroscopic observables to microphysics of dense matter

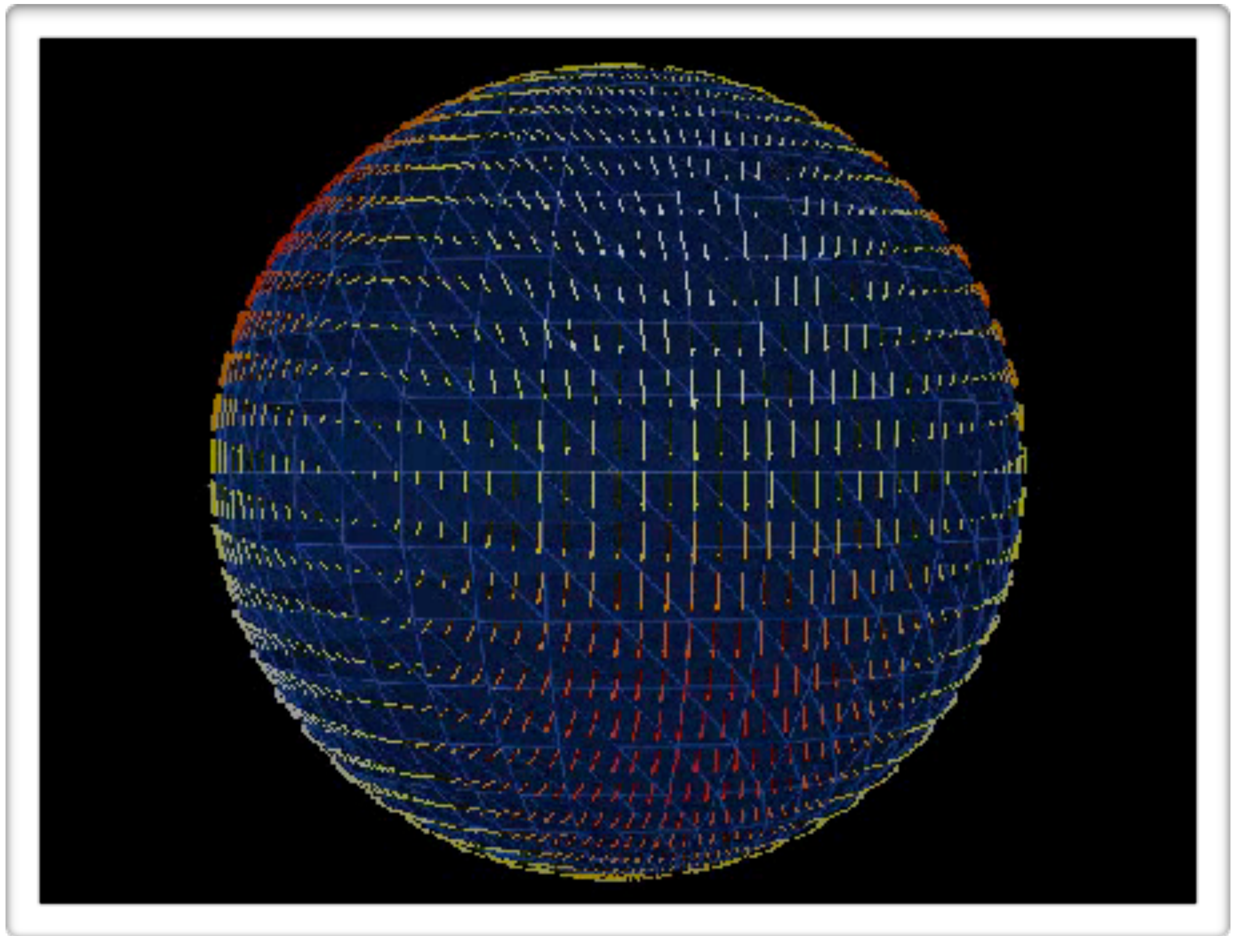
R-mode oscillations

- **R-mode**: Global oscillation eigenmode of a rotating star which emits gravitational waves
  N. Andersson, Astrophys. J. 502 (1998) 708,
  K. Kokkotas, LRR 2 (1999) 2,
  N. Andersson, K, Kokkotas, IJMP D10 (2001) 384
- Mainly an incompressible flow in individual shells, but involves density fluctuations at large frequency L. Lindblom, et. al., PRL 80 (1998) 4843,
  B. J. Owen, et. al., Phys. Rev. D 58 (1998) 084020



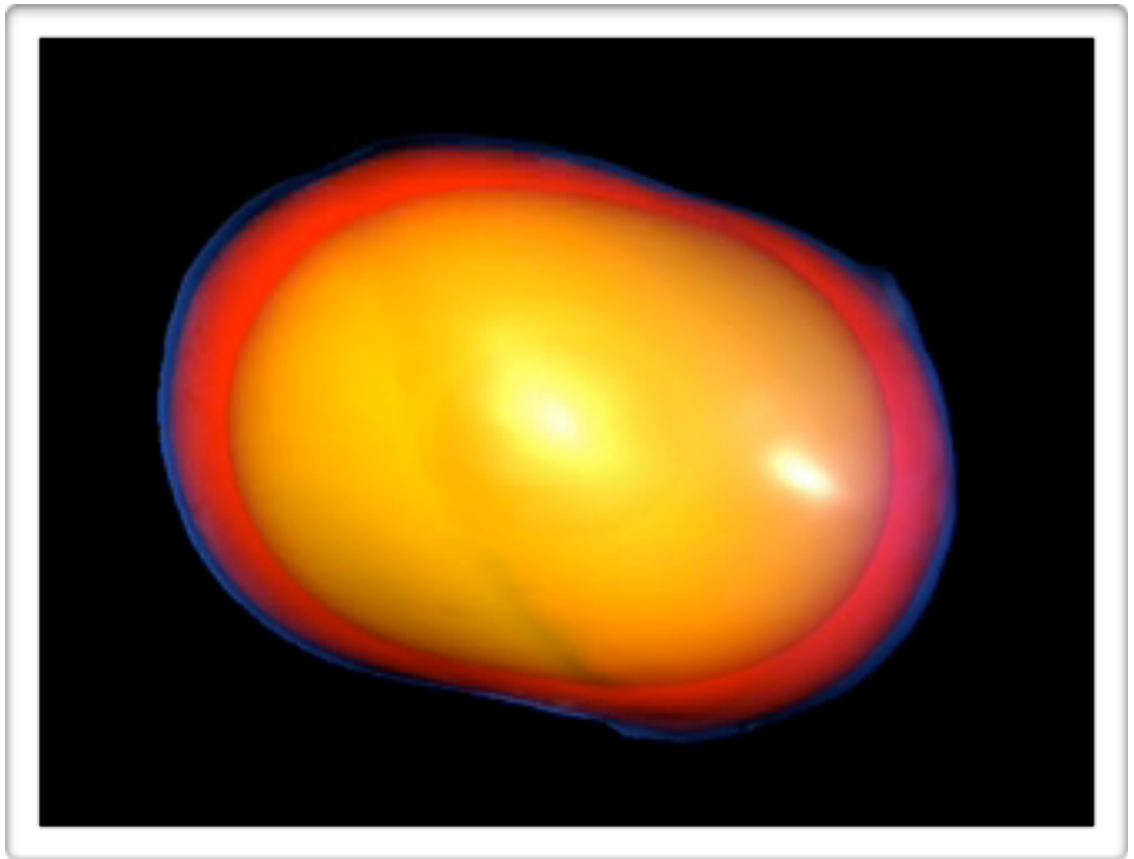
- Large amplitude r-modes could cause a quick spindown

- Yet we see very fast spinning (and slowly decelerating) sources: limits the amplitude



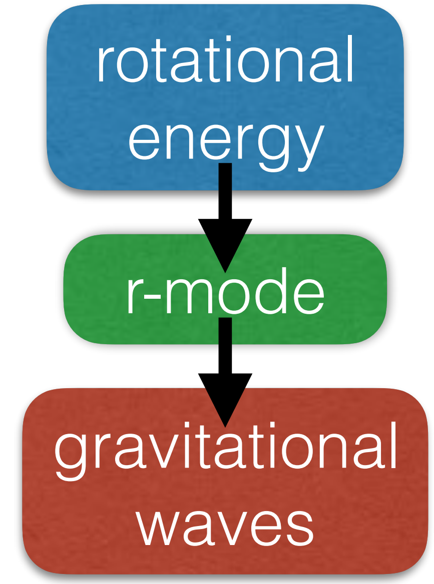
Visualization by M. Beilicke

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



Simulation by L. Lindblom

R-mode instability



- General relativity and ideal hydrodynamics predict that r-modes are unstable to gravitational wave emission

  ➡ mode amplitude (fluid velocity) grows exponentially

J. Friedman, B. Schutz, APJ 221 (1978) 937

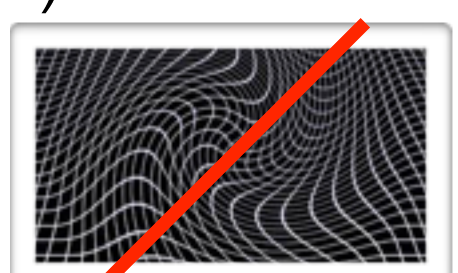
◉ Yet realistic cold dense matter is not (even close to) an ideal fluid … there are two possibilities:

Damping

Saturation

- If the viscous damping is strong enough even at low amplitude, the mode is completely damped away (does not even arise)

  ➡ no gravitational waves



- but not the case in fast pulsars

- But even if the mode is initially unstable, the growth eventually stops due to some non-linear damping mechanism, e.g.:
  - non-linear hydro or viscous damping - large $\alpha_{\mathrm{sat}} = O(1)$

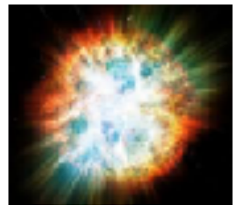
    L. Lindblom, et. al., PRL 86 (2001) 1152,
    M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051

  - mode-coupling - moderate

    P. Arras, et. al., Astrophys. J. 591 (2003) 1129 $\alpha_{\mathrm{sat}} = O(10^{-5})$

Generic evolution of pulsars

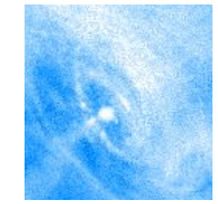
Newborn compact stars



… could spin about as fast as allowed by stability (>1kHz)

C. D. Ott, et. al., APJS, 164 (2006) 130

Observed young pulsars



with ages of thousands of years … all spin with surprisingly low frequencies

Middle-old pulsars

spindown further …

Non-pulsating compact stars

… become invisible

Low mass X-ray binaries

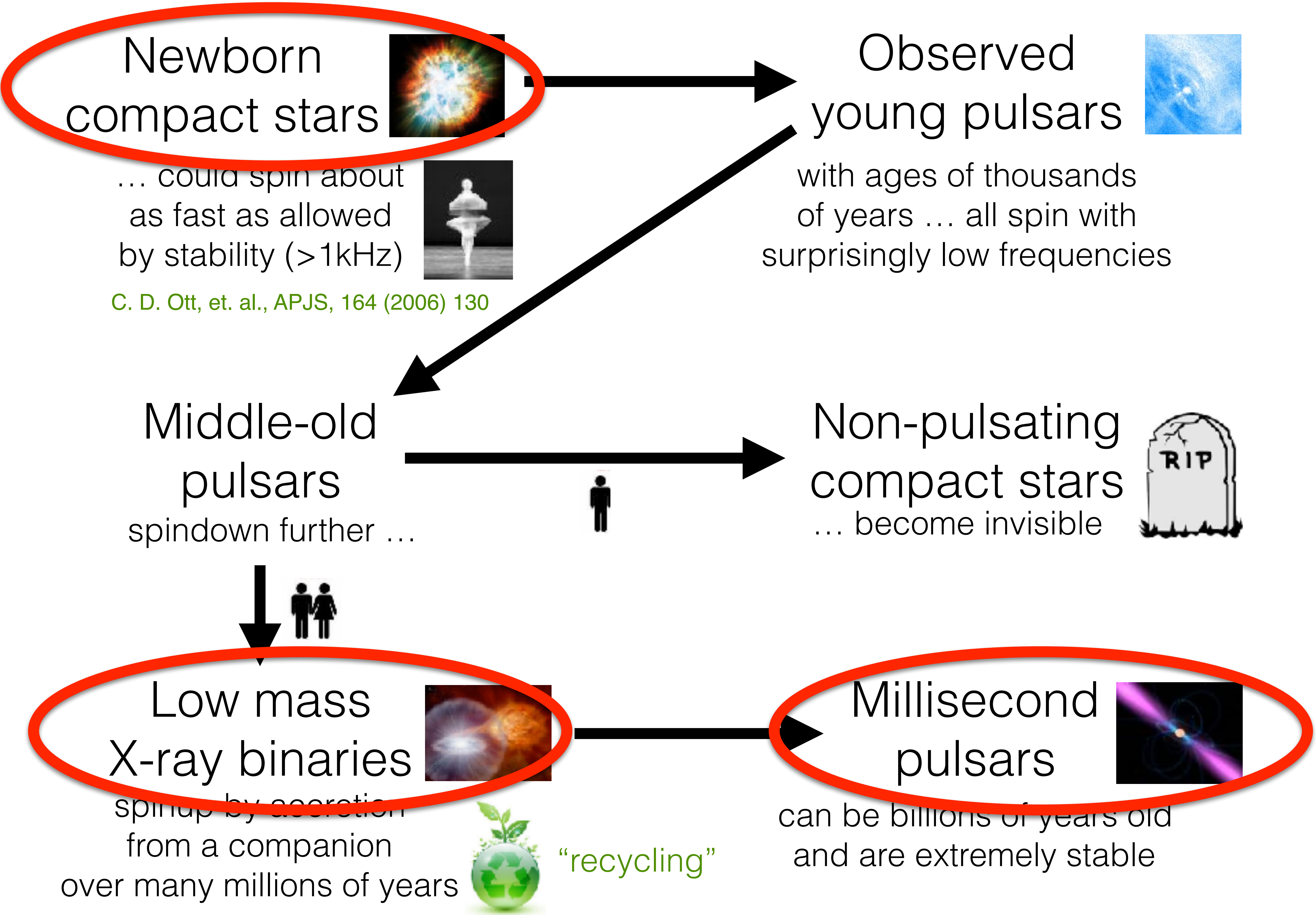
spinup by accretion from a companion over many millions of years

“recycling”

Millisecond pulsars

can be billions of years old and are extremely stable

Generic evolution of pulsars



Multi-messenger data

In electromagnetic observations many fast (“millisecond”) pulsars are observed - they can be grouped into two classes:

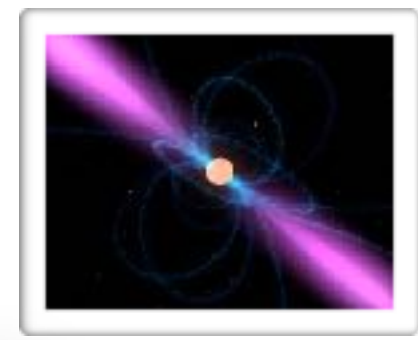
- Thermal X-ray data: ms x-ray pulsars in (low mass) binaries (LMXBs) currently accrete from a companion which allows a temperature measurement (10+ sources)

$\langle \dot{f} \rangle > 0$

  ✤ T ‘s involve modeling and are somewhat uncertain

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

- Timing data: ms radio and high energy pulsars (200+ sources) are very old and don’t accrete any more, but feature extremely stable timing data Manchester, et. al., astro-ph/0412641



$\dot{f} < 0$

  ✦ one of the most precise data sets in physics!

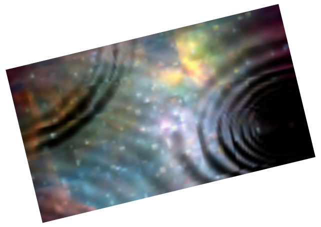
NAME	F0	F1	F2	F3
J0534+2200	30.225437	-3.862e-10	1.243e-20	-6.400e-31
J0537-6910	62.026190	-1.992e-10	6.100e-21	0
J0540-6919	19.802444	-1.878e-10	3.752e-21	0
J2022+3842	41.173009	-7.322e-11	0	0
J1513-5908	6.611515	-6.694e-11	1.919e-21	-9.139e-32
J1846-0258	3.062119	-6.664e-11	2.725e-21	2.725e-21

- (Future) Gravitational waves:

  ★ only direct way to probe the star’s interior

  ✓ GW astronomy could even detect “hidden sources”

Present & future windows to the cosmos

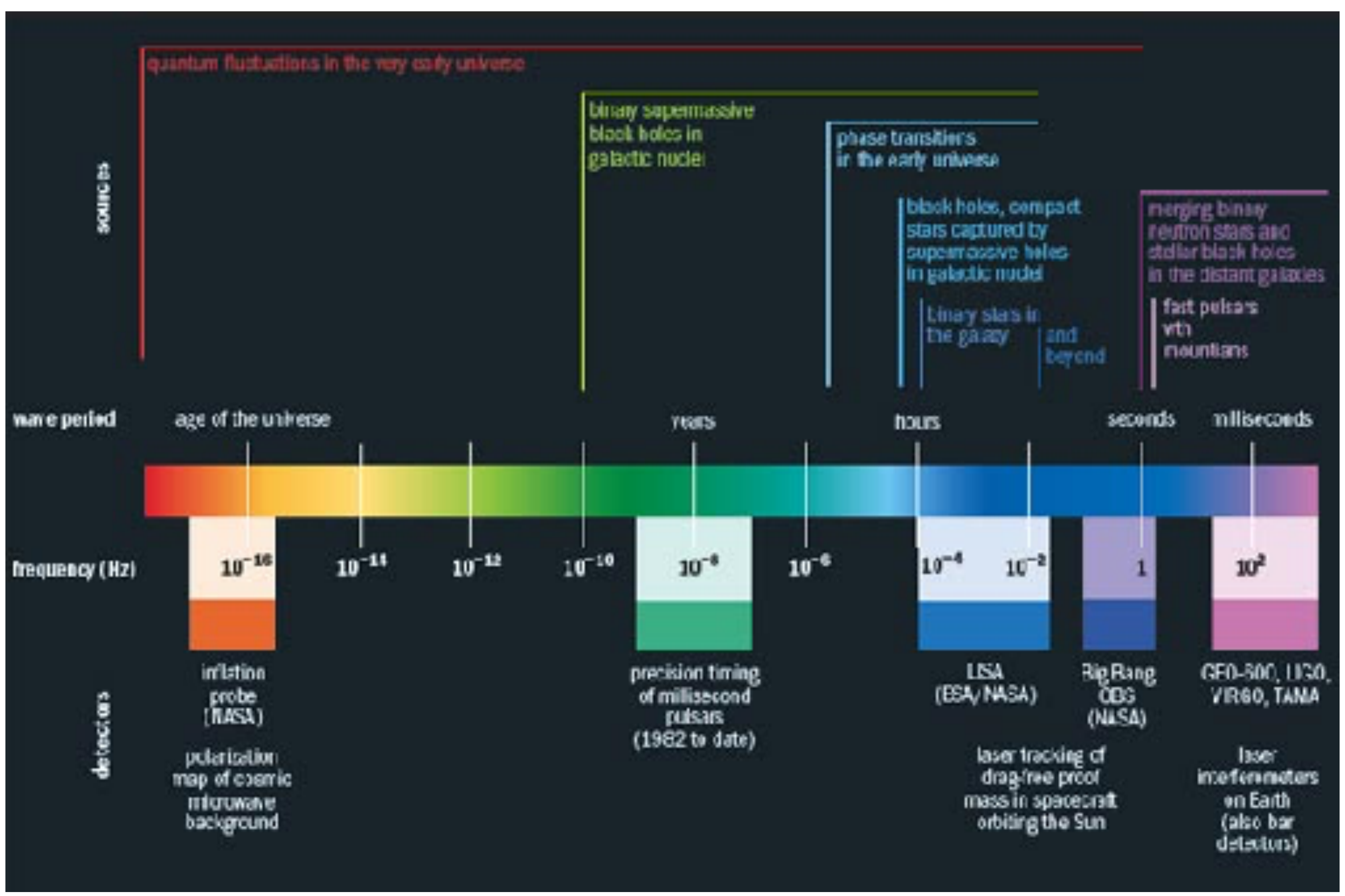


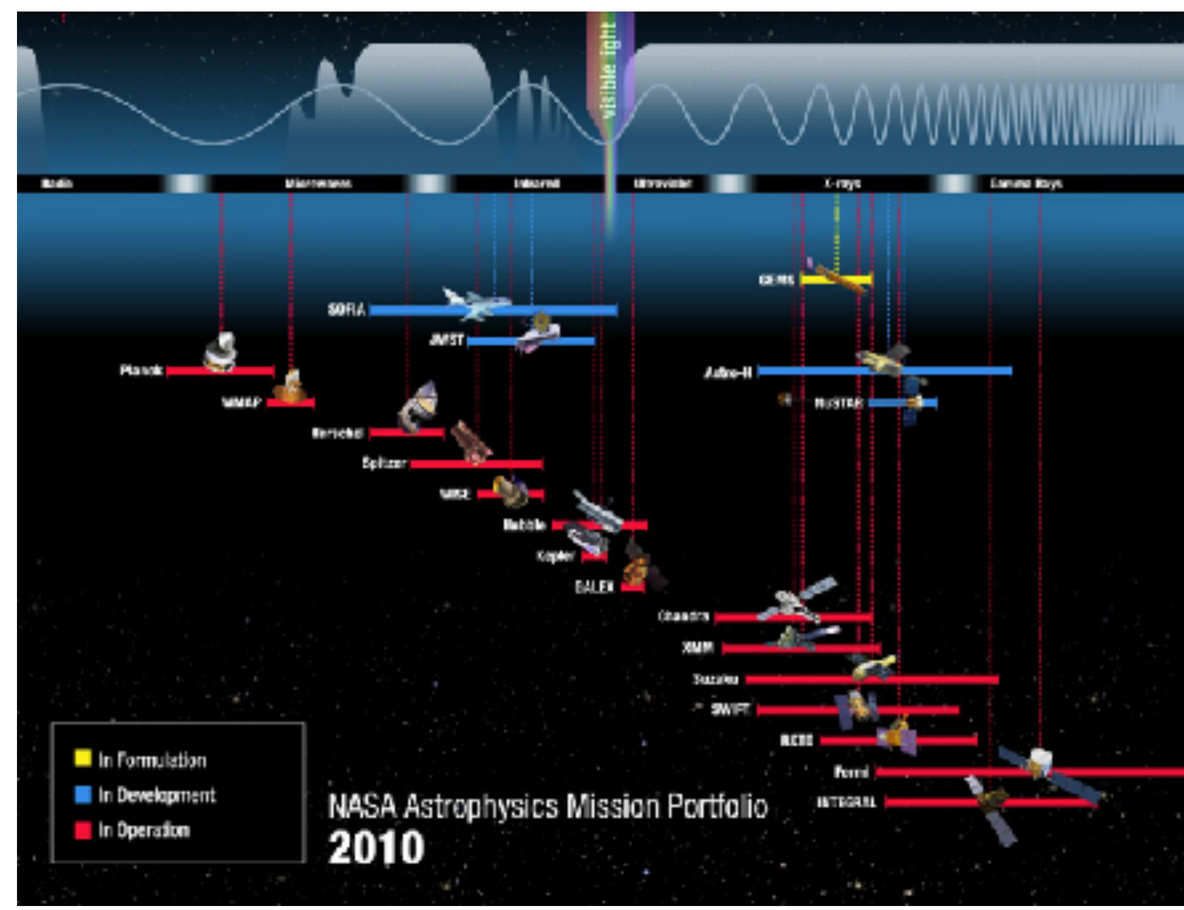
gravitational waves

- Emitted by huge and quickly moving masses
- Hardly absorbed by matter
- Probe the interior of dense objects

electromagnetic radiation

- Emitted by (thermally) moving charges
- Generally easily absorbed by matter
- Probe the surface of dense objects





frequency

(particle rays >>)

GW identification and direct Information

- Direct observables from the gravitational wave data are

GW amplitude h_0, GW frequency ν ,GW spindown rate $\dot{\nu}$ …

- If the rotation frequency is known r-mode gravitational wave emission can be clearly identified

Ellipticity	R-modes	
$\nu \approx 2f$	$\nu \approx 4/3 f < 2f$	general relativistic and rotation corrections

- The most important information is …

… that r-mode GW emission is present!

★ yields direct information on the damping in the interior

➡ for the different classes of sources this directly distinguishes different phases of dense matter

Information from multi-messenger observations

Direct GW observations provide GW amplitude h_0, frequency ν, change rate $\dot{\nu}$

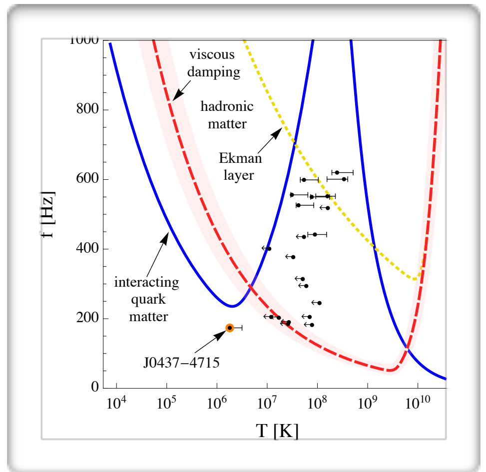
… combined with electromagnetic data this yields far more

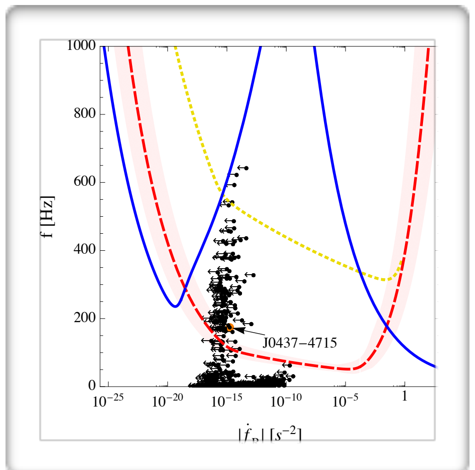
Information from multi-messenger observations

Composition

Spindown Rate $\dot{f}$

or Temperature T





M. Alford & K. Schwenzer, PRL 113 (2014) 251102

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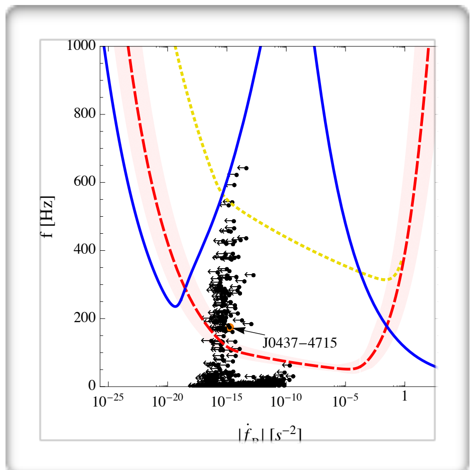

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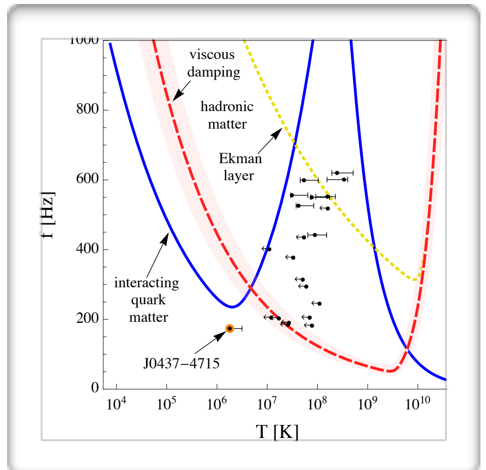

or Temperature T

Compactness

$$\frac{M}{R} \approx 0.017 + 0.767\sqrt{\frac{3\nu}{4f} - 1.029}$$

A. Idrisy, B. Owen, and D. Jones, PRD 91 (2015) 024001

Rotation frequency f

Direct GW observations provide GW amplitude h_0, frequency ν, change rate $\dot{\nu}$

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Information from multi-messenger observations

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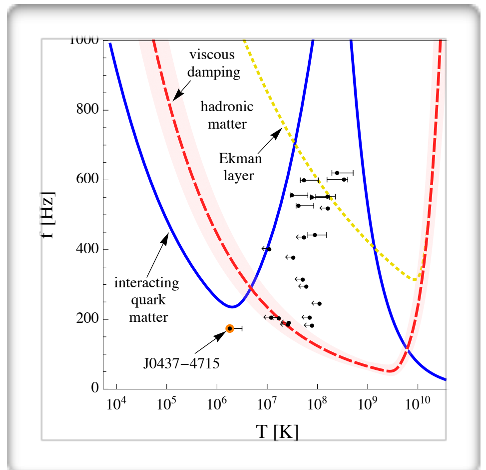

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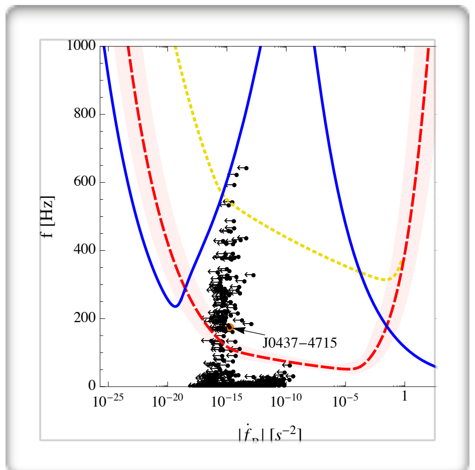

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Rotation frequency f

Mass M

Radius

Direct GW observations provide GW amplitude h_0, frequency ν, change rate $\dot{\nu}$

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Information from multi-messenger observations

Composition

Spindown Rate $\dot{f}$

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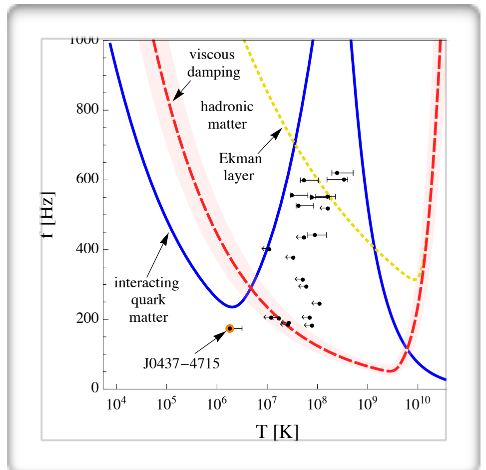

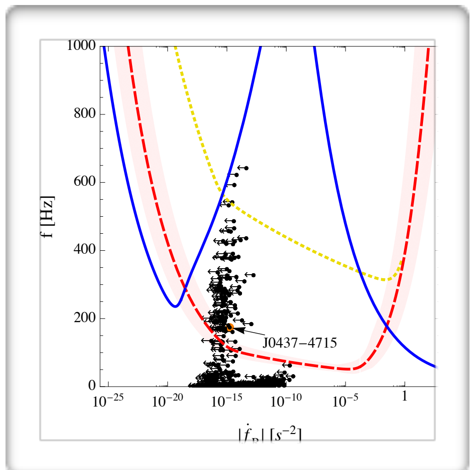

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Rotation frequency f

Mass M

Radius

if r-modes dominate the heating

Temperature

$$T_s \xrightarrow[P_G \approx L_\gamma]{} \left(\frac{6}{\pi} \frac{D^2 \left(2f - \nu\right) \nu h_0^2}{R^2} \right)^{\frac{1}{4}}$$

Direct GW observations provide GW amplitude h_0, frequency ν, change rate $\dot{\nu}$

… combined with electromagnetic data this yields far more

Information from multi-messenger observations

Composition

Spindown Rate $\dot{f}$

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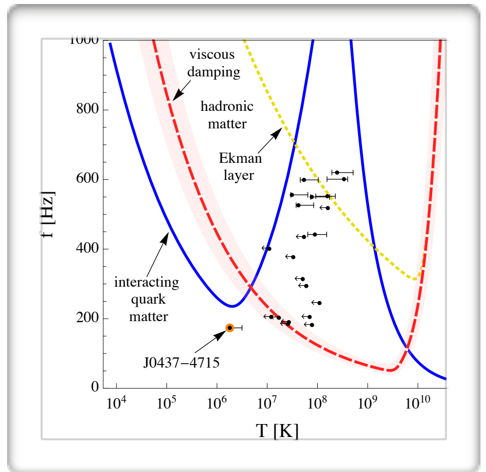

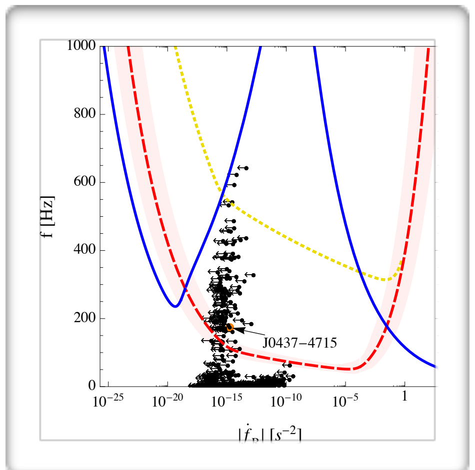

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… combined with electromagnetic data this yields far more

if r-modes dominate the heating

Temperature

$$T_s \xrightarrow[P_G \approx L_\gamma]{} \left(\frac{6}{\pi} \frac{D^2 \left(2f - \nu\right) \nu h_0^2}{R^2} \right)^{\frac{1}{4}}$$

Spindown Rate $\dot{f}$

if r-modes dominate the spindown (can be checked)

Moment of Inertia

$$I \xrightarrow[P_{rot} \approx P_R]{} \frac{D^2 \nu h_0^2}{5\left|\dot{f}\right|}$$

A. Mytidis, M. Coughlin, and B. Whiting, APJ. 810 (2015) 27; K. Kokkotas & K. Schwenzer, EPJA 52 (2016) 38

Gravitational waves from old ms-pulsars

- In addition to the standard case of deformations r-modes are a promising continuous GW-source

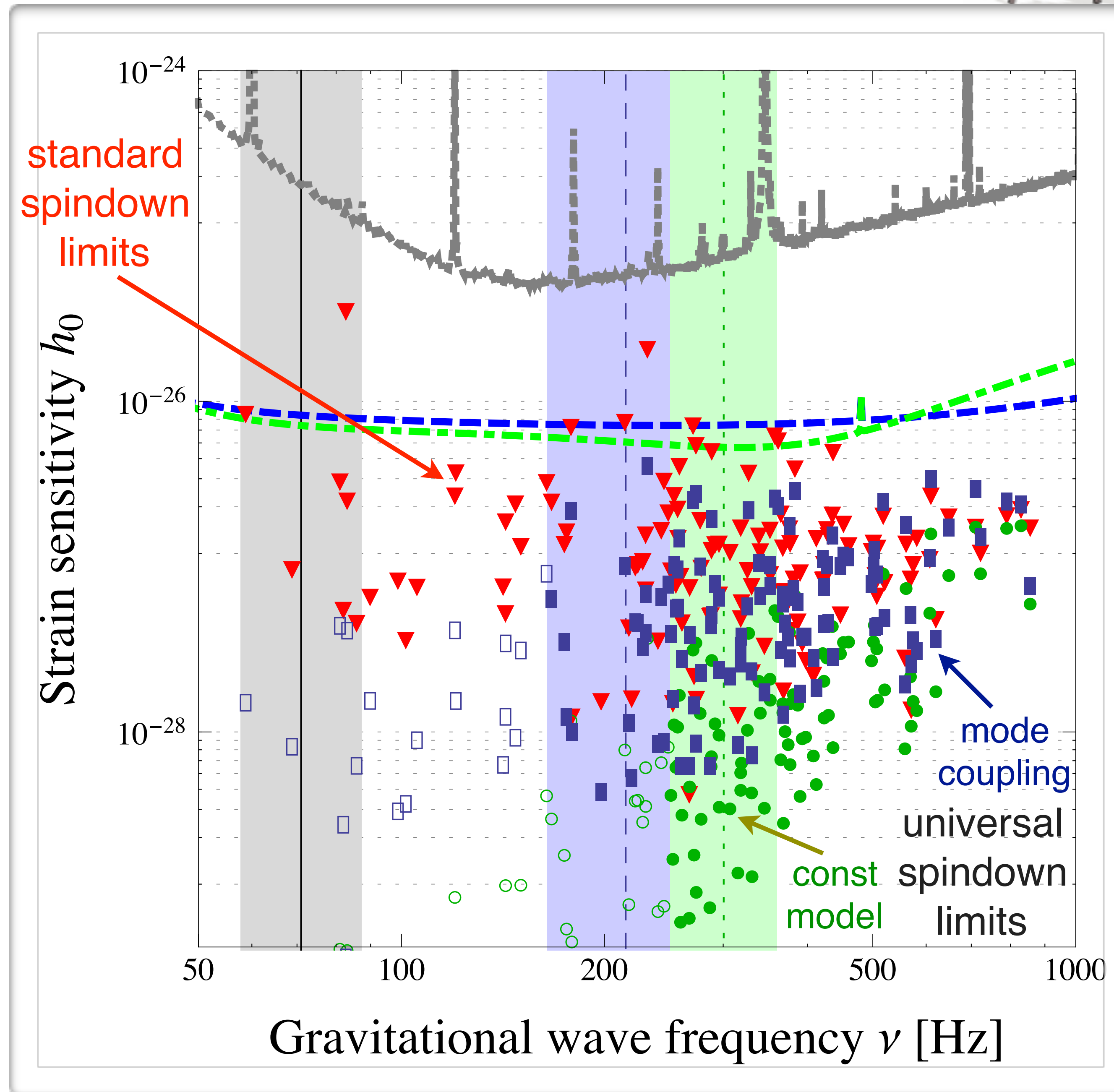
Aasi, *et. al.*, arXiv:1309.4027

- The r-mode saturation mechanism should operate in all sources …

  ✦ novel universal spindown limit for the GW signal

➡ Millisecond pulsars are below the aLigo sensitivity

✓ However they could be detectable with further improvements or 3. generation detectors



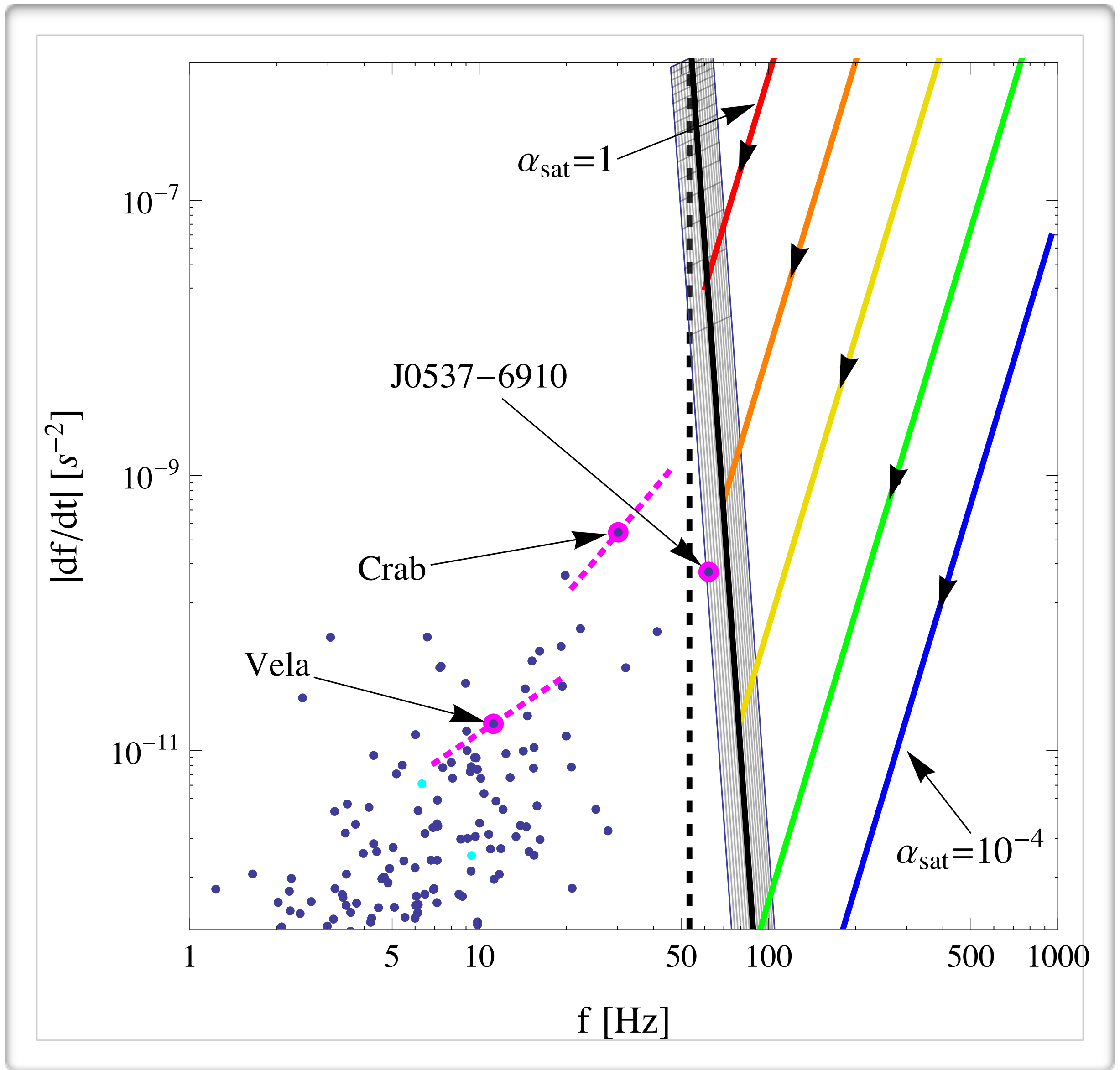
$$h_0^{(\mathrm{usl})} = \sqrt{\frac{15}{4}\frac{GI\left|\dot{f}_0\right|}{D^2 f_0}} \left(\frac{\hat{\alpha}_{\mathrm{sat}}^{(\mathrm{mac})}}{\hat{\alpha}_{\mathrm{sat},0}^{(\mathrm{mac})}}\right)^{\frac{1}{1-2\beta/\theta}} \left(\frac{f}{f_0}\right)^{\frac{3+\gamma+2\beta/\theta}{1-2\beta/\theta}}$$

("universal spindown limit")

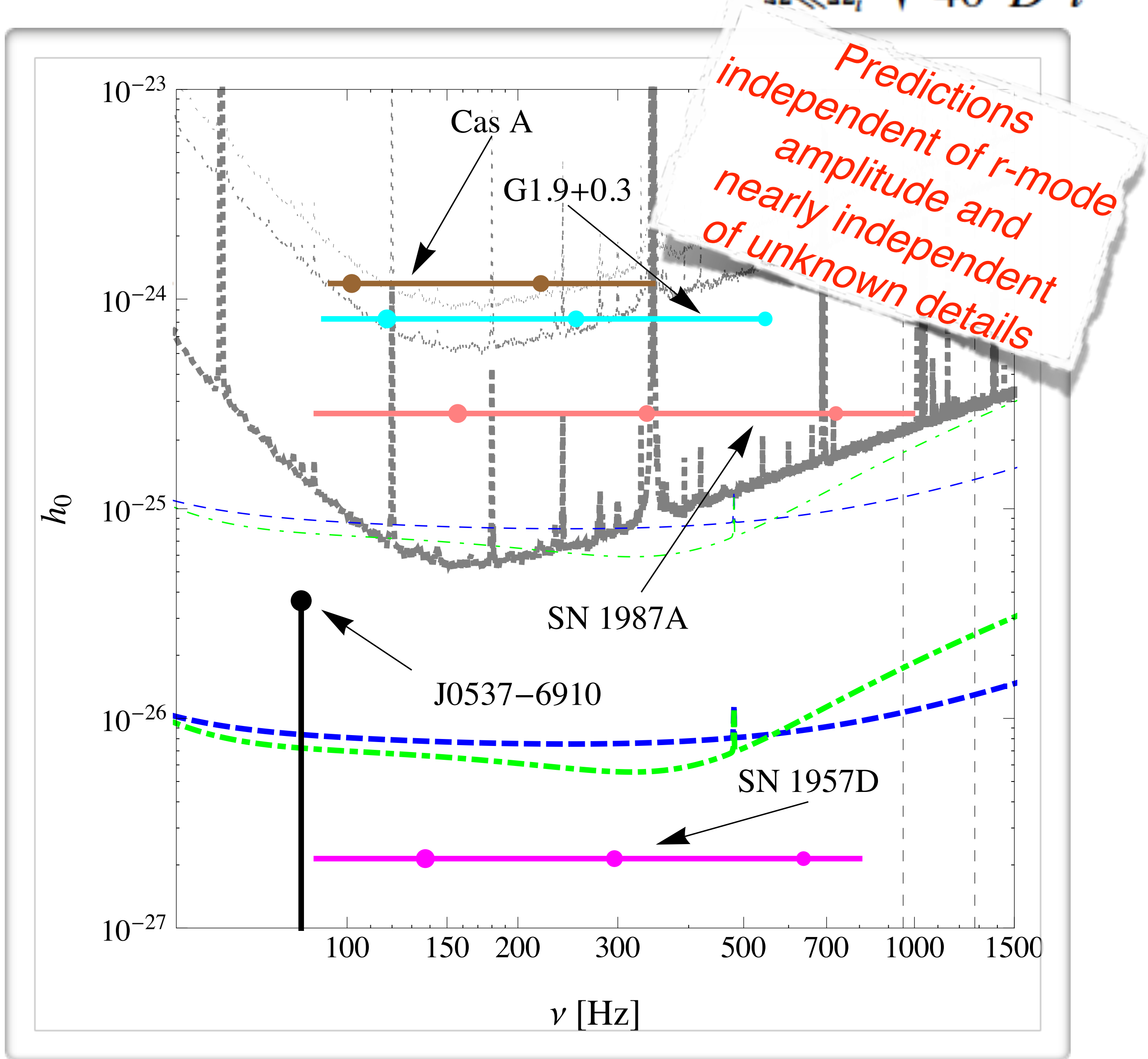
M. Alford & K. S., MNRAS 446 (2015) 3631

Gravitational wave emission of young sources

- Since r-mode emission can *quantitively* explain the low rotation frequencies of young pulsars (which already spin too slow to emit GWs), very young sources are promising targets
- GW strain depends basically only on age and distance $h(t) \xrightarrow[\Omega \ll \Omega_i]{} \sqrt{\frac{3}{40}\frac{CGI}{D^2 t}}$



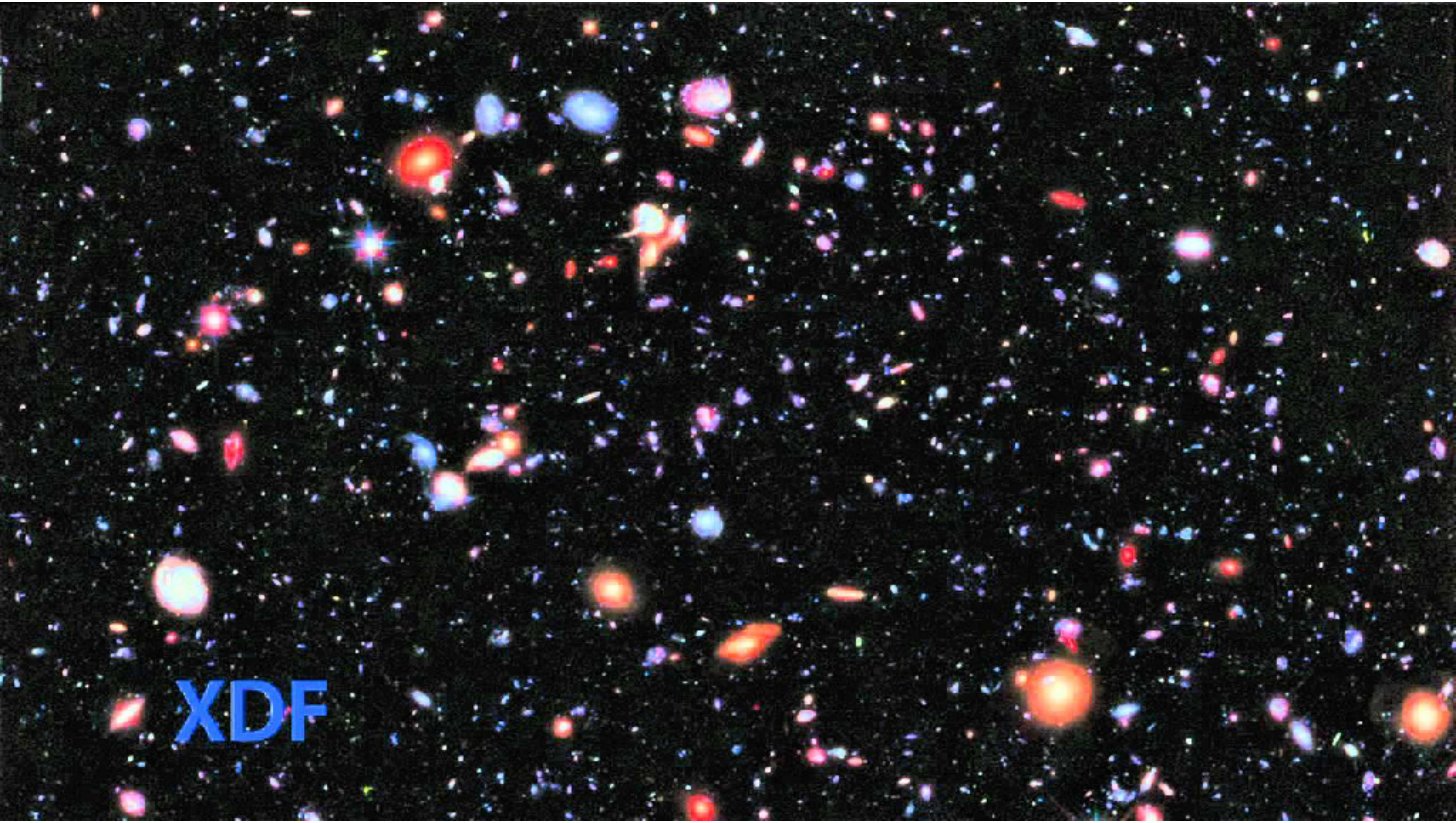
M. Alford & K. S., Astrophys. J. 781 (2014) 26
data: Manchester, et. al. astro-ph/0412641



Several potential sources in reach of aLigo

So far we are at the beginning …

… but it could be only a matter of sensitivity



"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)

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

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

(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

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

✳ 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 complete r-mode evolution …
e.g. final frequency for a neutron star:

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

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

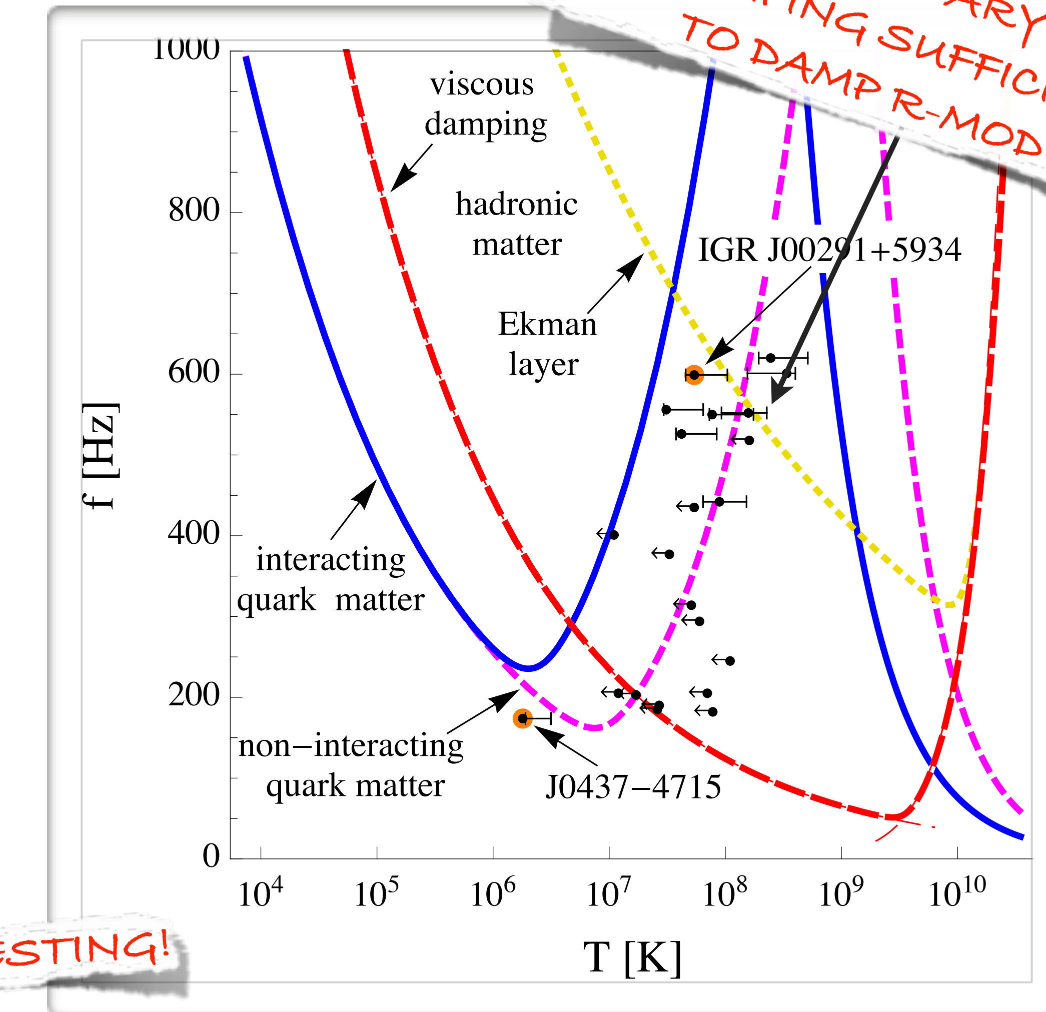
Static instability regions vs. x-ray data

- 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 the data:
  "no r-mode": completely damped
  "saturated r-mode": unstable, but saturated at small α_{sat}

INTERESTING!

BORING TRIVIAL CASE

NOT EVEN UNREALISTIC (THIN) BOUNDARY LAYER DAMPING SUFFICIENT TO DAMP R-MODE!



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

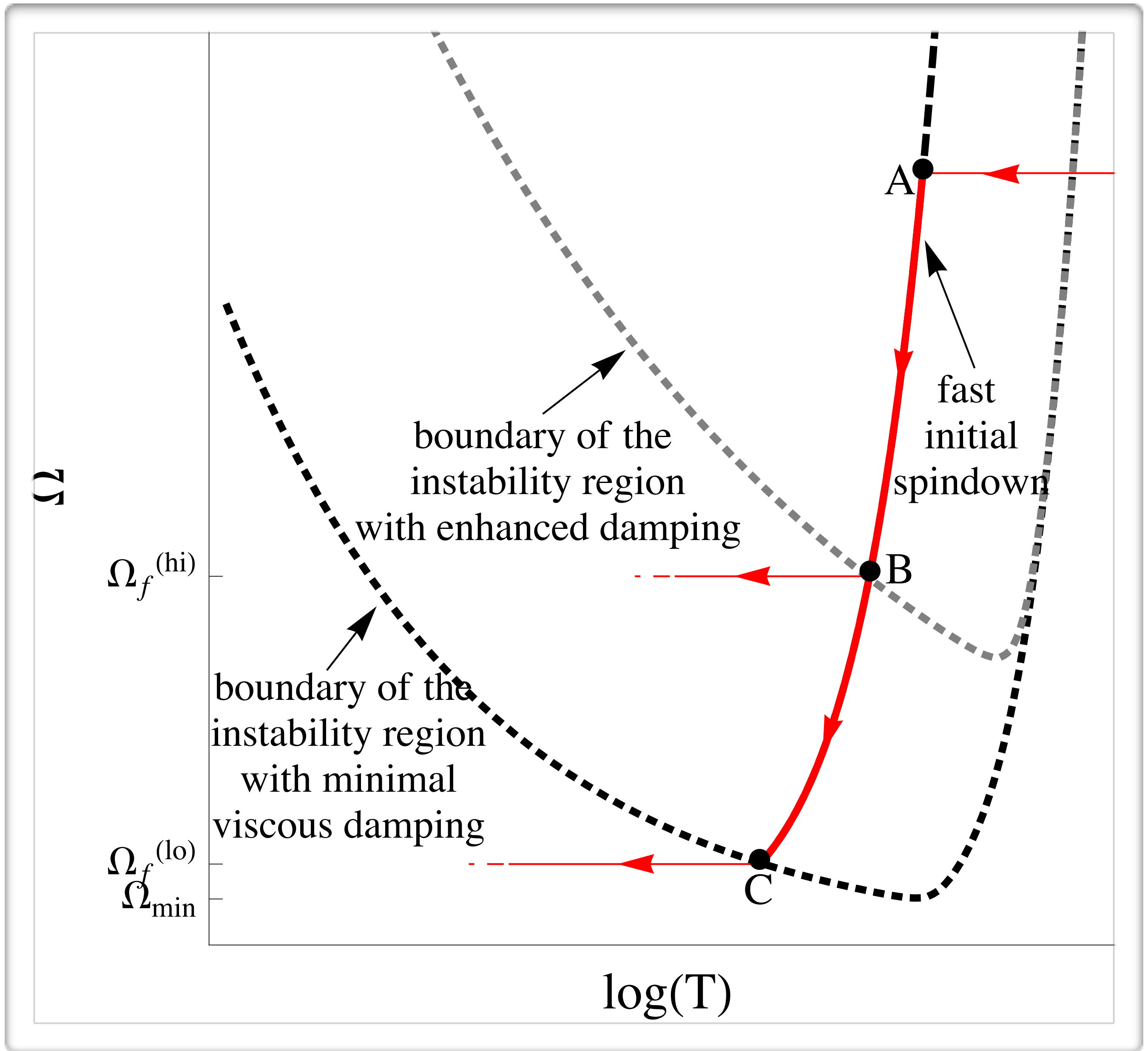
- Many sources are clearly within the instability region for neutron stars with standard damping (saturated r-mode scenario required)
- (Incl. interactions) quark matter fully damps mode (no r-mode scenario)

Evolution of young pulsars

- Observed young pulsars spin with very low frequencies, but newly formed pulsars should spin with huge frequencies

C. D. Ott, et. al., APJS, 164 (2006) 130

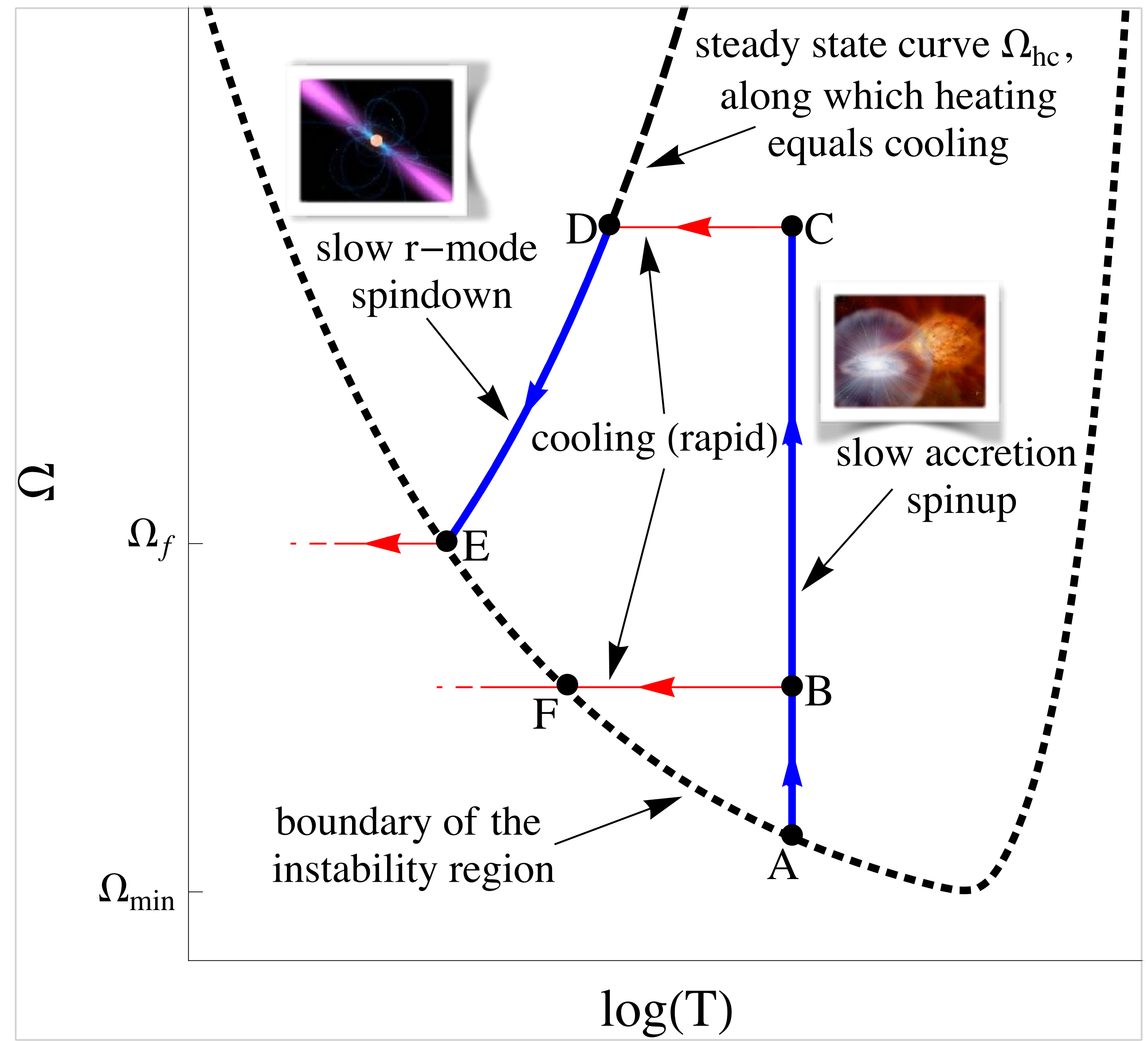
- They cool until r-modes become unstable and saturate at a finite amplitude
- R-modes heat the source and the GW emission spins it down along a steady state curve where heating balances cooling
- Afterwards they leave the instability region, r-modes decay and these sources cool and spindown



Evolution of recycled pulsars

- Pulsars can be spun up to high frequencies (so far $716\,\mathrm{Hz}$) by accretion in low mass x-ray binaries (LMXBs): “Recycling”, 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



“Saturated r-mode scenario”

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

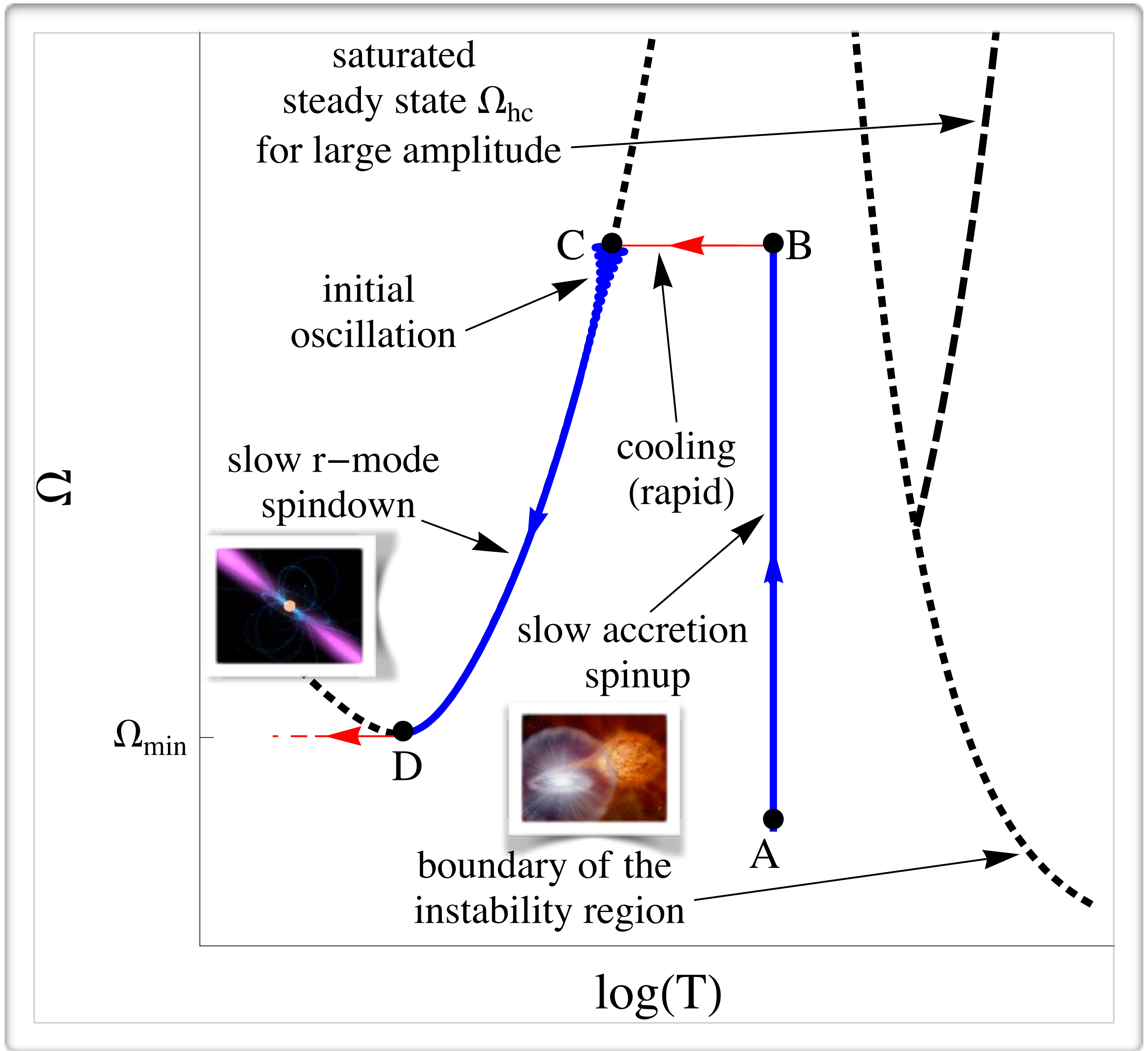
Pulsar evolution with enhanced damping

- Enhanced damping can lead to a stability window where the mode is stable up to large Ω
- When accretion stops, source
  1. cools into the instability region and …
  2. is pushed out of it again by strong r-mode heating
- Decaying oscillation around the instability boundary

N. Andersson, D. Jones and K. Kokkotas, MNRAS 337 (2002) 1224

➡ dynamic steady state and slow spindown along the boundary

Reisenegger and Bonacic, PRL 91 (2003) 201103



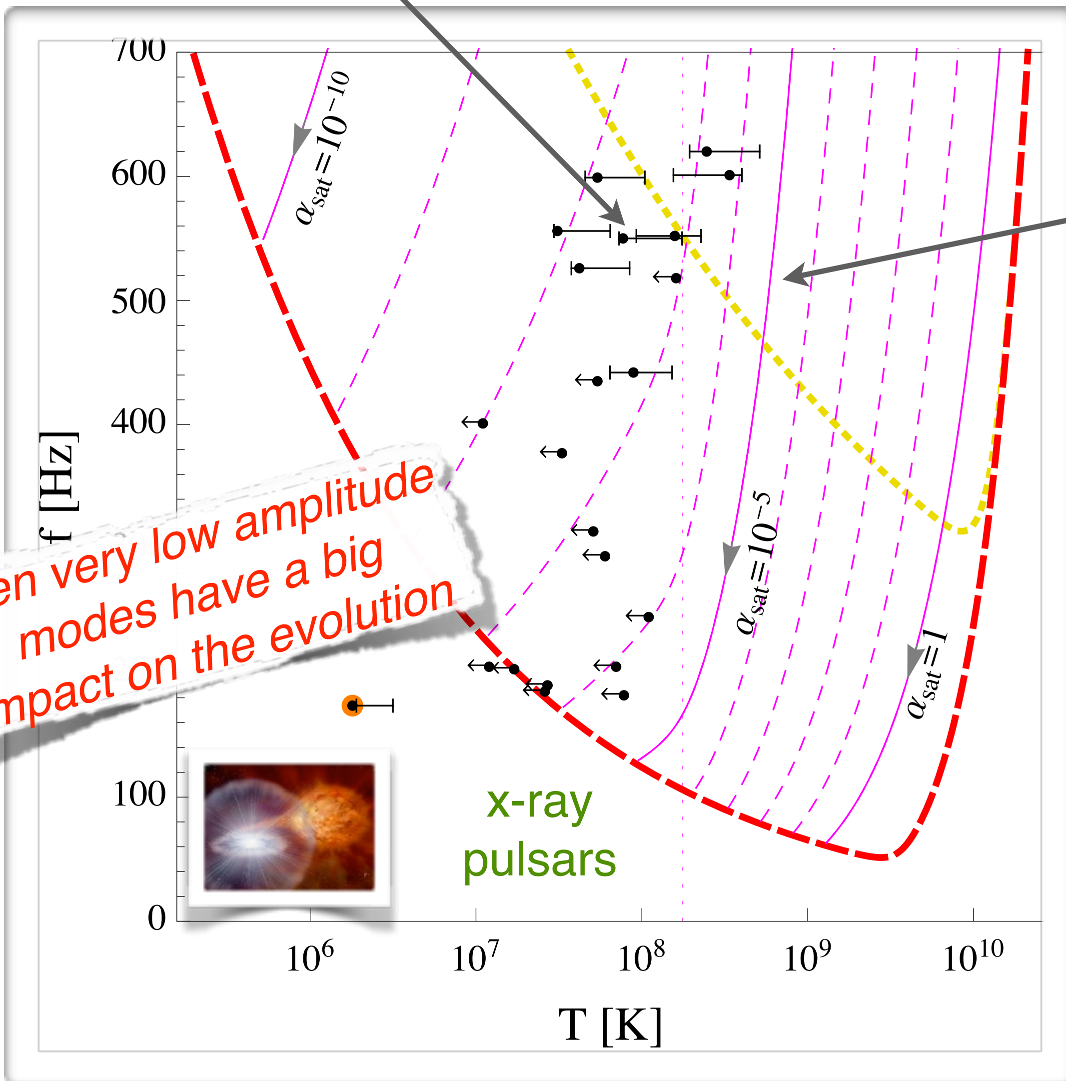
“Boundary straddling scenario”

Effective dynamic saturation mechanism without amplitude-dependent dissipation

Pulsar evolution & r-mode instability

temperatures have large uncertainties

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



spindown curves

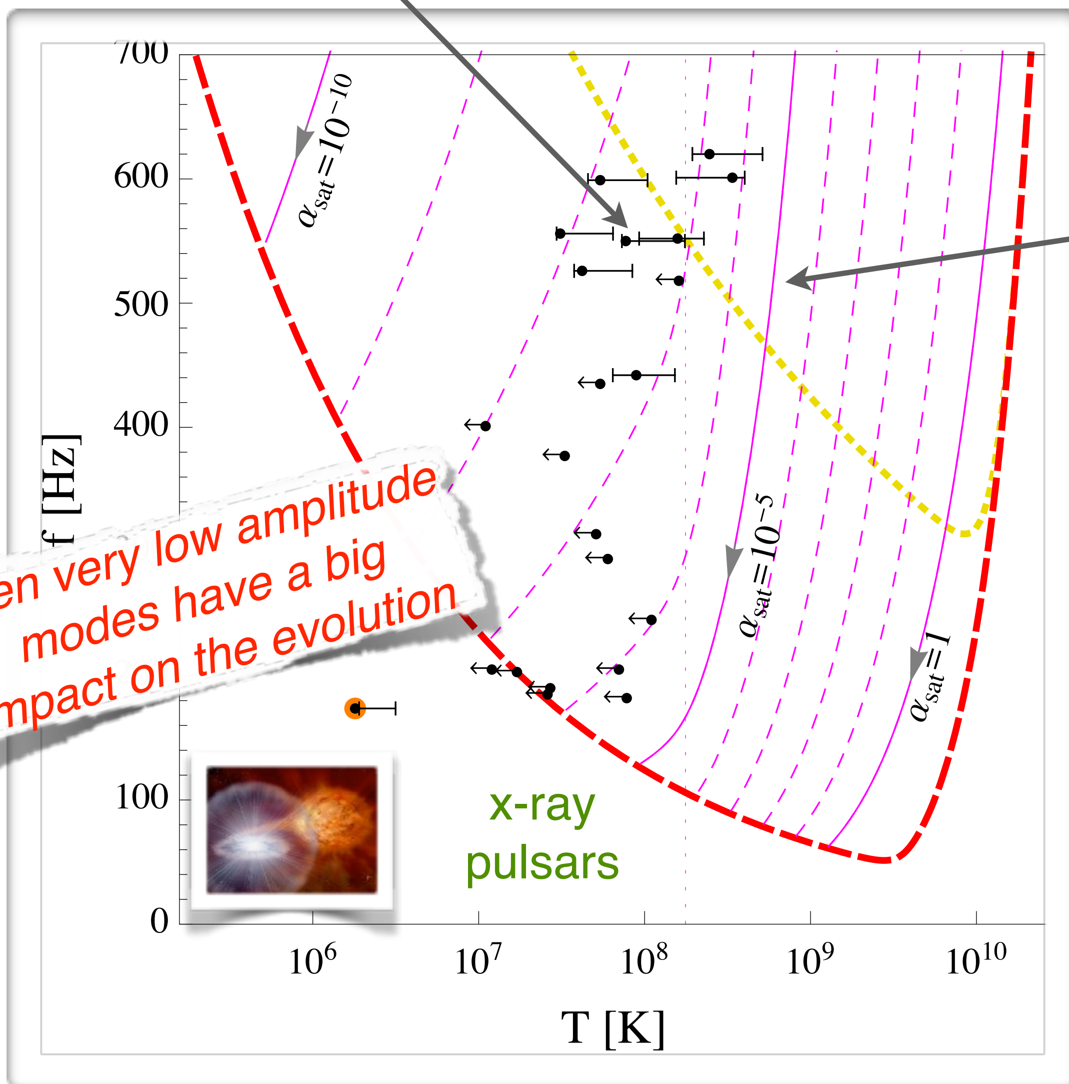
even very low amplitude modes have a big impact on the evolution

Pulsar evolution & r-mode instability

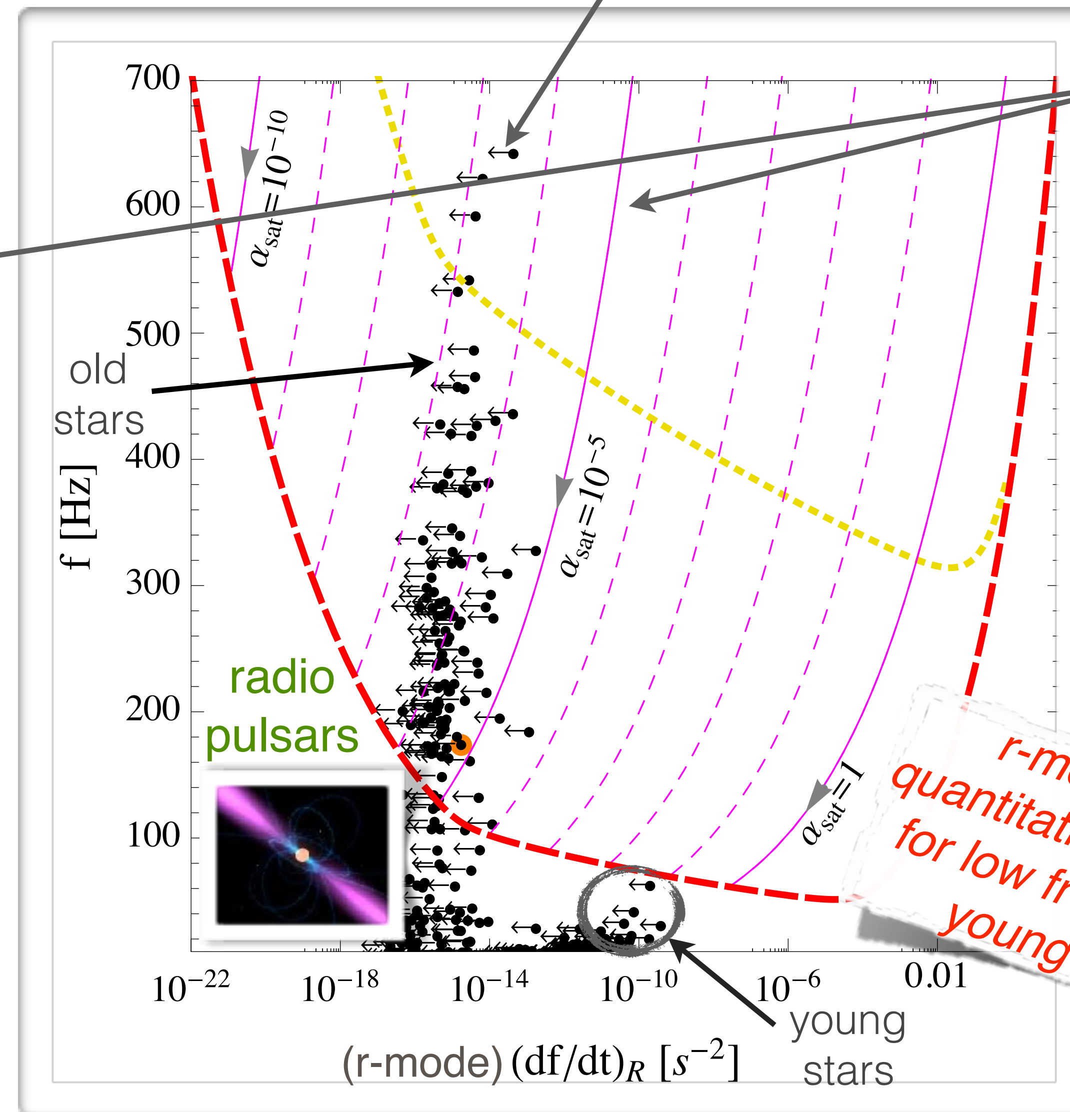
temperatures have large uncertainties
Haskell, et. al., MNRAS 424 (2012) 93

observed spindown rates are upper limits for r-mode contribution
Manchester, et. al., astro-ph/0412641

spindown curves



even very low amplitude modes have a big impact on the evolution



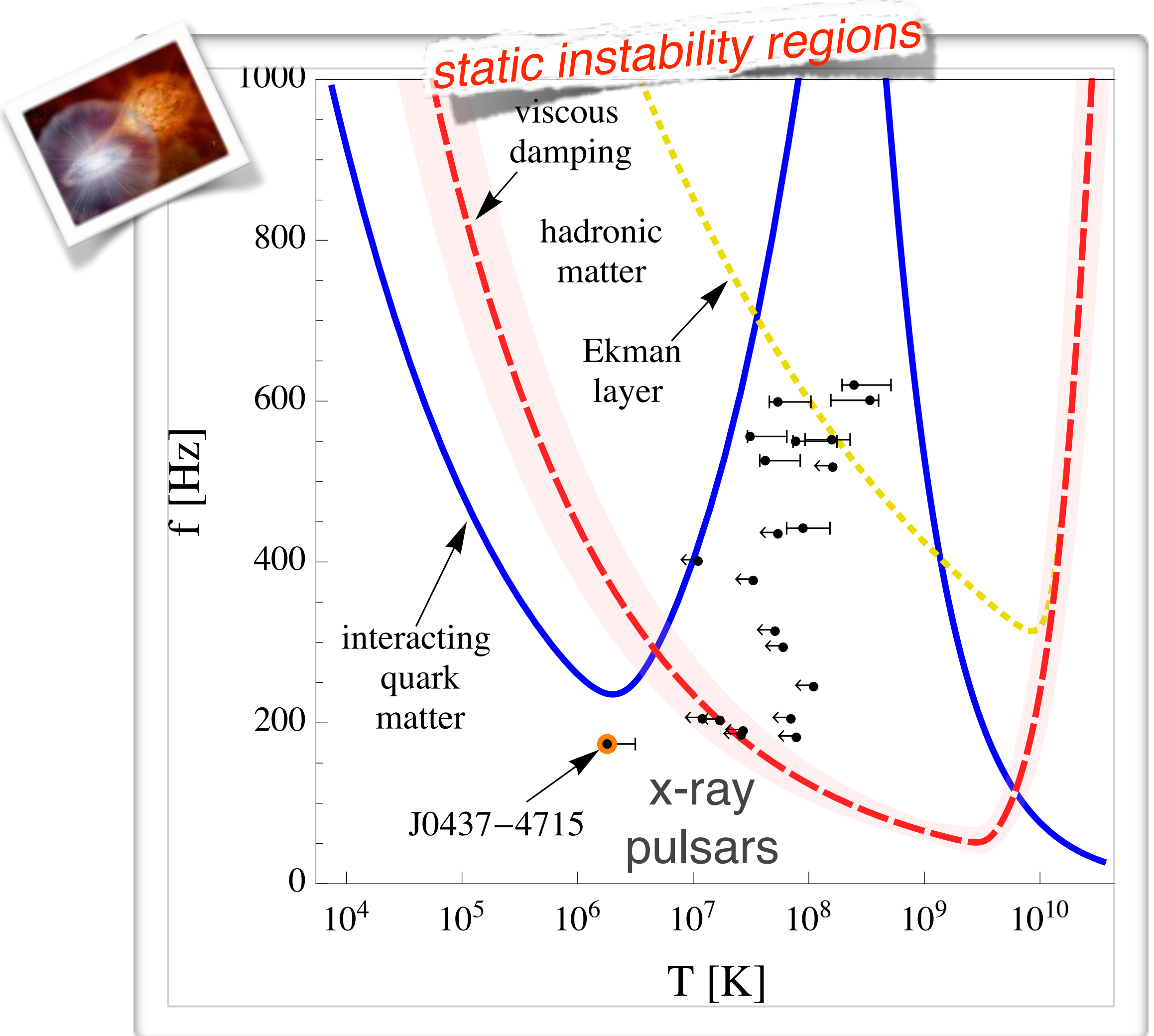
r-modes give a quantitative explanation for low frequencies of young pulsars!

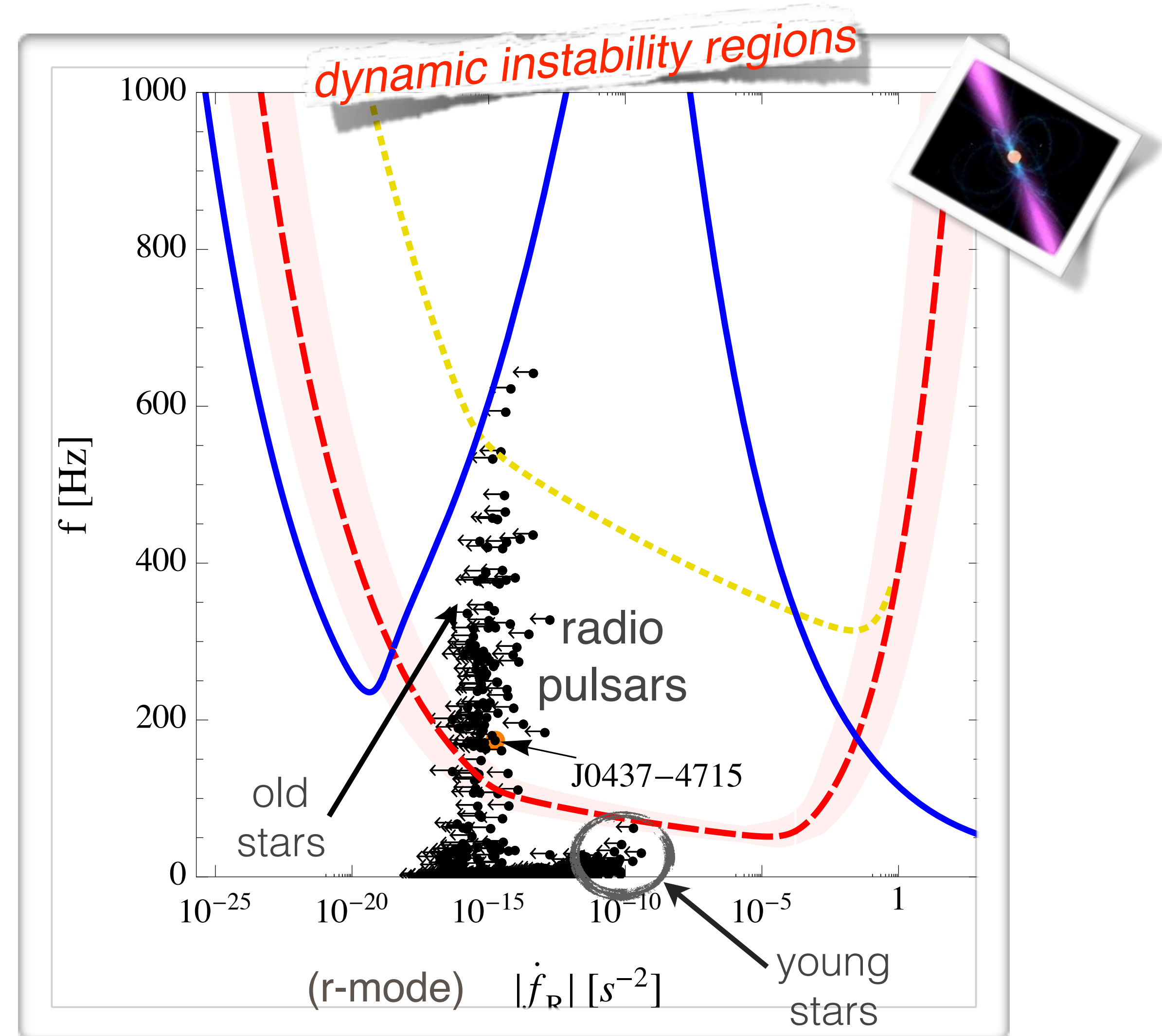
We only measure the total spindown rate which can stem from various mechanisms, so that the sources could be outside of the instability region …

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

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., PRL 113 (2014) 251102 & NPA 931 (2014) 740

Dynamic Instability boundaries in timing parameter space:

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

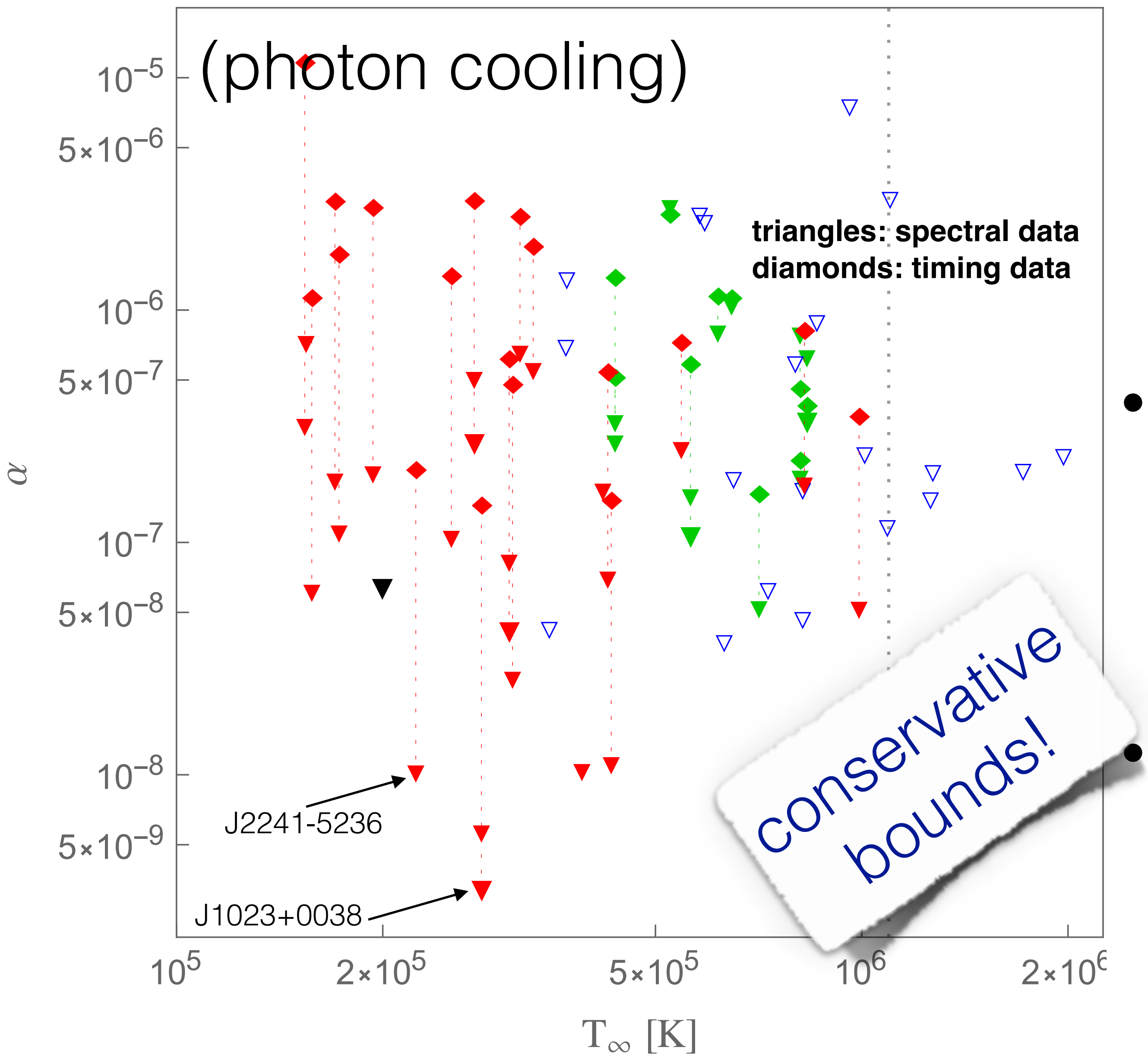
independent of saturation physics!

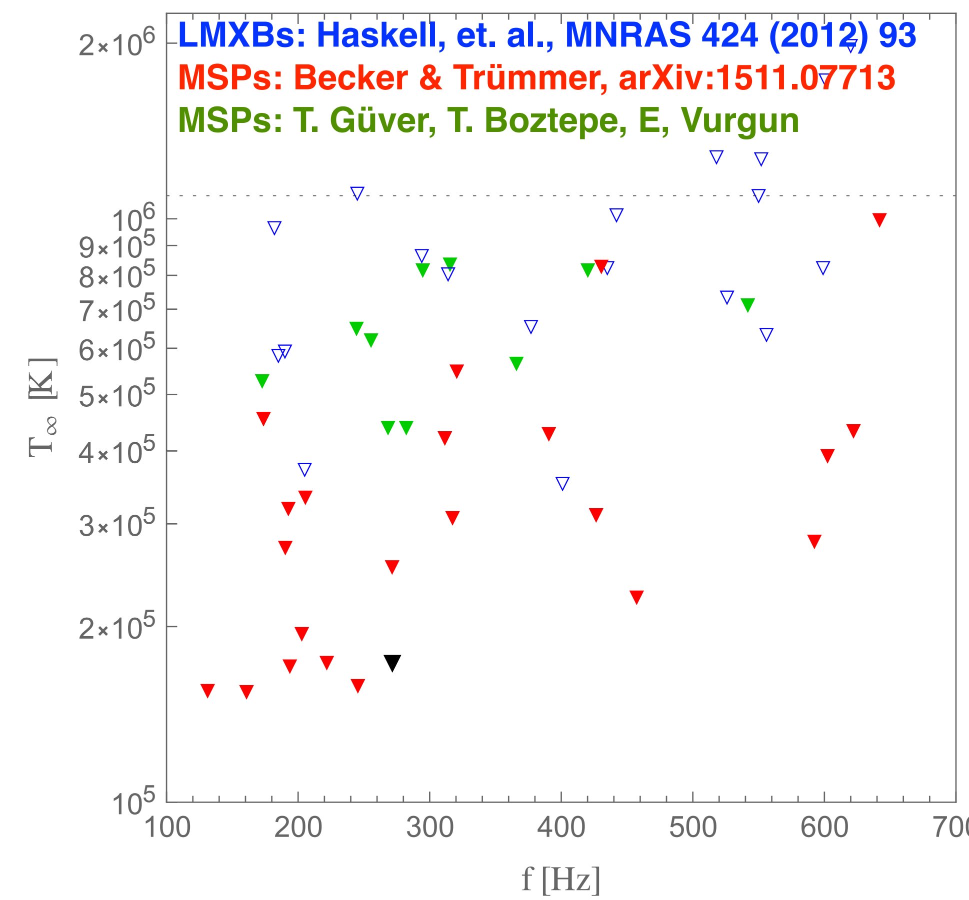
Interacting quark matter consistent with both x-ray and radio data (no r-mode scenario)

R-mode amplitude bounds

- Although most millisecond pulsars are too faint to measure their temperature, X-ray luminosity measurements impose upper bounds on the temperature …

S. Mahmoodifar and T. Strohmayer,APJ 773 (2013) 140





K. S., T. Boztepe, T. Güver, E. Vurgun, arXiv:1609.01912

- R-modes strongly heat a source
  - ✦ temperature bounds impose r-mode amplitude bounds
- Millisecond pulsars impose the lowest amplitude bounds $\alpha < 10^{-8}$
  - ✦ requires very strong dissipation!

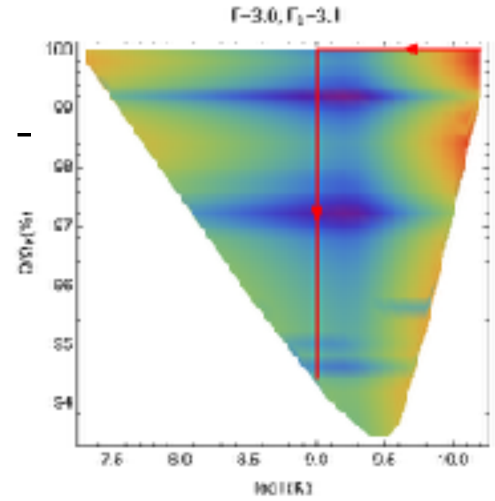
Standard damping mechanisms

What could saturate r-modes at such low amplitudes $\alpha < 10^{-8}$?

- ~~Ekman damping~~ —> "pasta" L. Bildsten, G. Ushomirsky, APJ 529 (2000) 33, L. Lindblom, B. Owen, G. Ushomirsky, PRD 62 (2000) 084030
- ~~Non-linear hydro~~ $\alpha_{\rm sat} = O(1)$ L. Lindblom, et. al., PRL 86 (2001) 1152, W. Kastaun, Phys.Rev. D84 (2011) 124036
- ~~Non-linear viscosity~~ $\alpha_{\rm sat} = O(1)$ M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051
- ~~Mode coupling~~ $\alpha_{\rm sat} > 10^{-6}$ (1. parametric instability theshold - best estimate!)

  P. Arras, et. al., Astrophys. J. 591 (2003) 1129, R. Bondarescu, et. al., Astrophys. J. 778 (2013) 9

  - complicated since there are many modes …



P. Pnigouras, K. Kokkotas, 1607.03059

(f-mode)

- Magnetic fields generated by ~~Differential rotation~~

  L. Rezzolla, F. Lamb, S. Shapiro, APJ 531 (1999) 139, J. Friedman, L. Lindblom, K. Lockitch, PRD 93 (2016) 024023

  - pulsars have "tiny" magnetic fields $B = 10^8 - 10^9 {\rm G}$

- ~~Mutual friction~~ B. Haskell, N. Andersson, A. Passamonti, MNRAS 397 (2009) 1464

➡ All "standard mechanisms", that are independent of the composition and could be present in minimal neutron stars, face big challenges!

This is getting interesting …

There are several composition-dependent mechanisms in more interesting forms of matter (random selection):

- Completely ungapped quark matter (non-Fermi liquid interactions)

  M. Alford & K. S., PRL 113 (2014) 251102 & NPA 931 (2014) 740

  - spindown along a stability window (dynamic saturation)

- Hyperonic matter

  L. Lindblom, B. Owen,, PRD 65 (2002) 063006

- Resonance coupling in superfluids (not quantitative, yet)

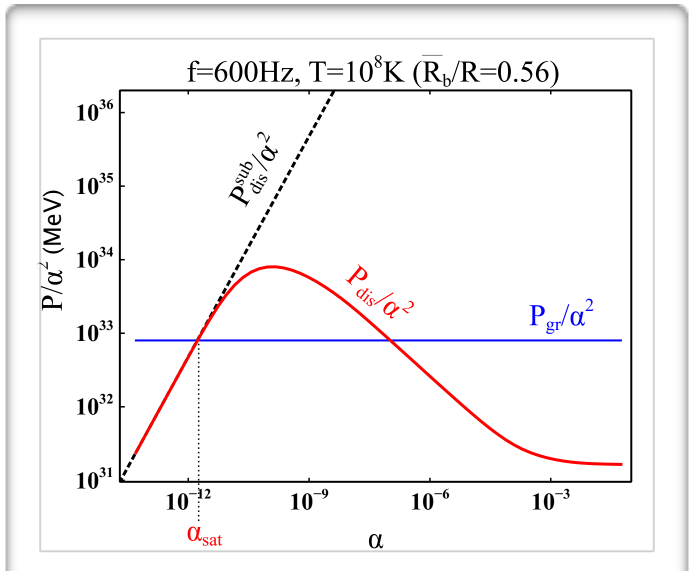
  M. Gusakov, A. Chugunov, E. Kantor, PRL 112 (2014) 151101

- Pasta phases ???

- Phase conversion in hybrid stars

  M. Alford, S. Han & K. S., PRC 91 (2015) 055804

  ★ Strongest saturation mechanism $\alpha_{\rm sat} < 10^{-10}$



- Or something we haven't even thought about …

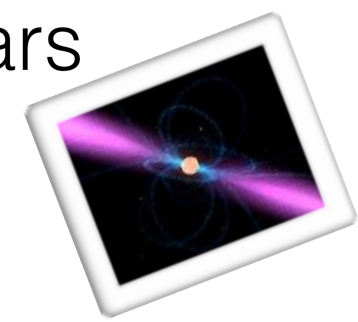
Conclusions and Outlook

- Electromagnetic observations actually start to constrain the interior physics of compact stars via r-mode astroseismology

  ✤ "Minimal" neutron stars cannot damp r-modes in MSPs and LMXBs and therefore have problems to explain the pulsar data for know saturation mechanisms

  ★ Unpaired quark matter can simultaneously explain the data on LMXBs and radio pulsars

THERMAL X-RAYS AND GRAVITATIONAL WAVES EXPECTED!



  ✦ Hybrid stars can saturate r-modes at insignificantly low amplitudes

"NO X-RAYS" AND NO GRAVITATIONAL WAVES

✳ Gravitational wave detection would open a novel window into the star interior and provide detailed information on star properties

➡ Classification scheme required to combine different observational data sets to clearly discriminate different forms of dense matter