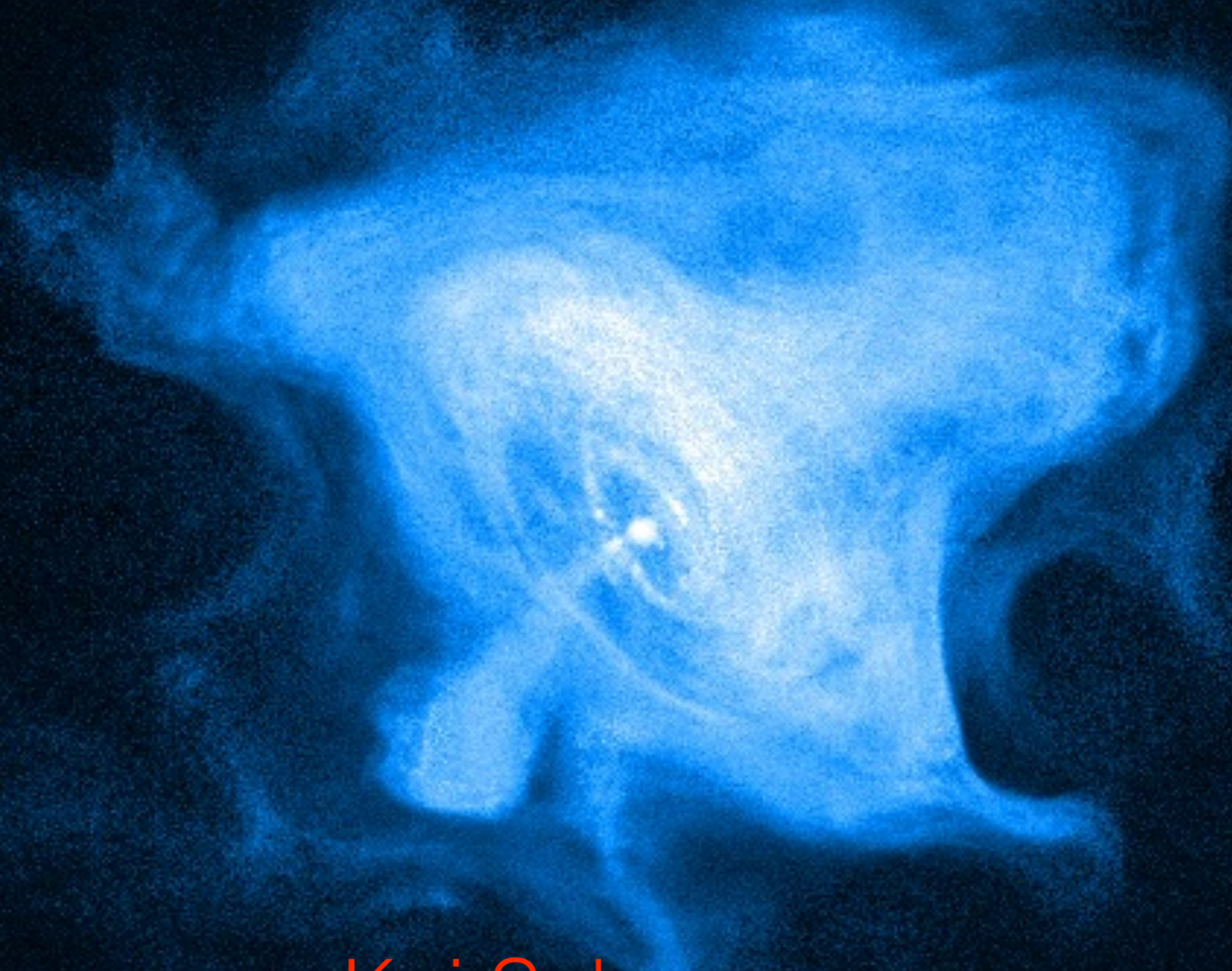


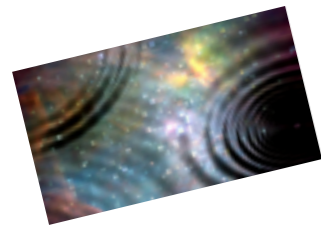
R-mode astronomy



Kai Schwitzer

University of Tübingen

Present & future windows to the cosmos



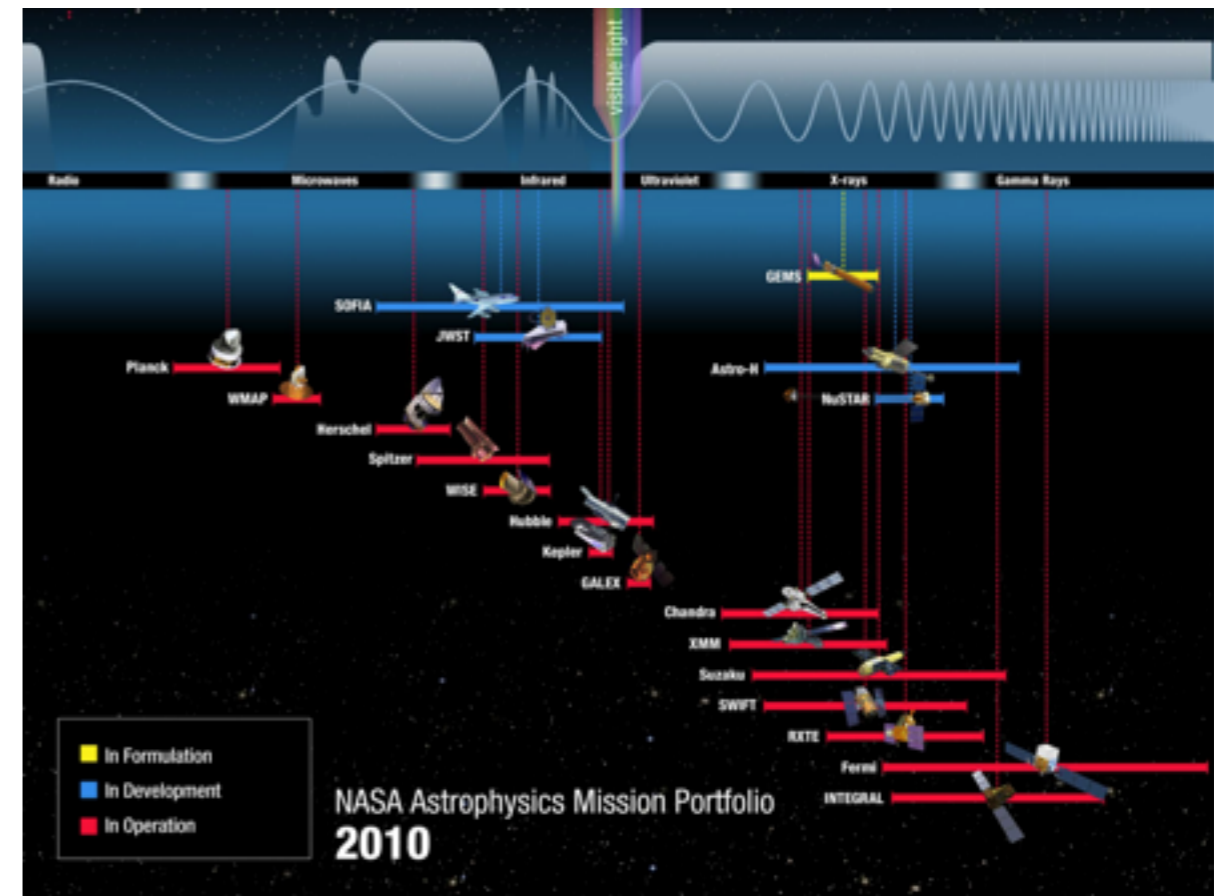
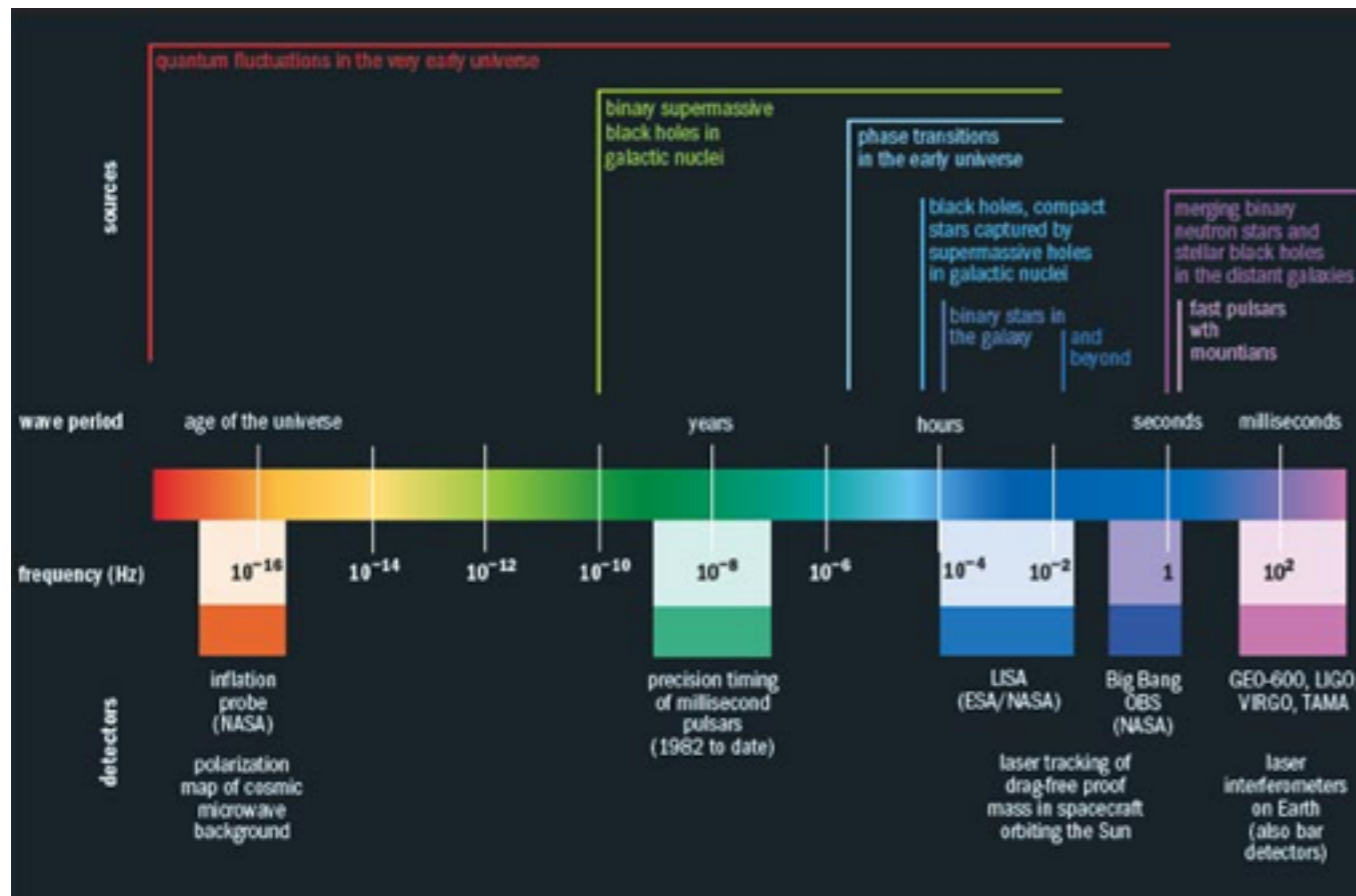
gravitational waves

- 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 >>)

Composition of compact stars

- 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

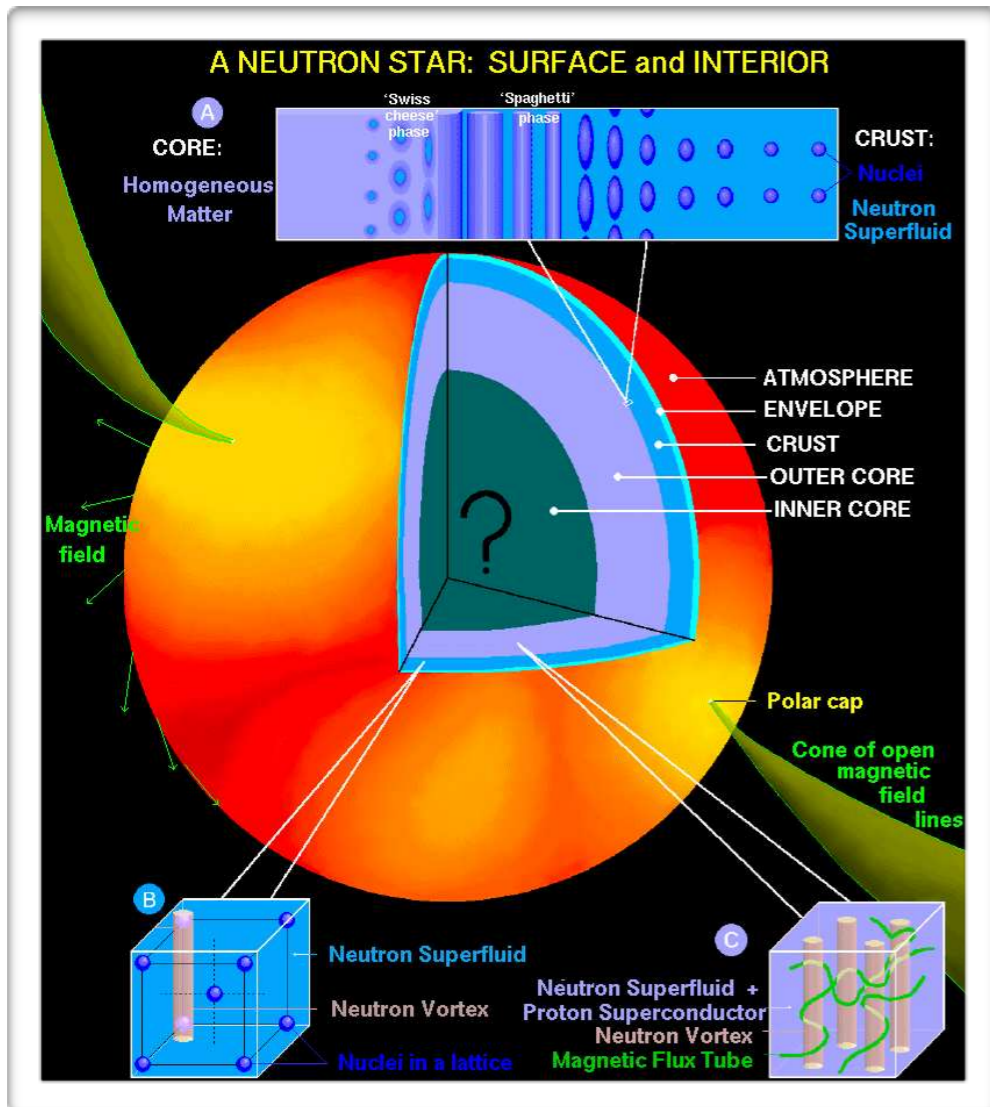
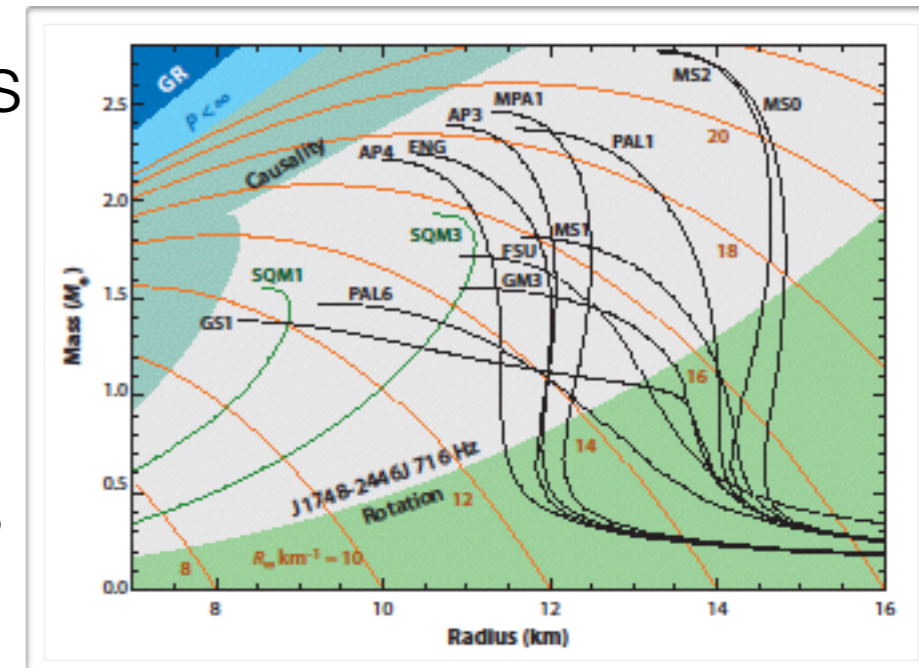


figure by D. Page

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



Dissipation in dense matter

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

candidate phase	dominant processes	shear viscosity	reference
(ungapped) nuclear matter	$e + e \rightarrow e + e$ $n + n \rightarrow n + n$	$\eta \sim (T/\mu)^{-5/3} \& (T/\mu)^{-2}$	Shternin, <i>et.al.</i> , PRD 78 (2008) 063006
hyperonic matter	$e + e \rightarrow e + e$ $n + n \rightarrow n + n$	$\eta \sim (T/\mu)^{-5/3} \& (T/\mu)^{-2}$	“
superfluid nuclear matter	$e + e \rightarrow e + e$	$\eta \sim (T/\mu)^{-3}$	Manuel, <i>et.al.</i> , PRD 84 (2011) 123007
ungapped quark matter	$q + q \rightarrow q + q$	$\eta \sim (T/\mu)^{-5/3}$	Heiselberg, <i>et.al.</i> , PRD 48 (1993) 2916
CFL quark matter	$H \rightarrow H + H$	$\eta \sim (T/\mu)^4$	Manuel, <i>et. al.</i> , JHEP 09 (2005) 76; Andersson, <i>et. al.</i> , PRD 82 (2010) 023007

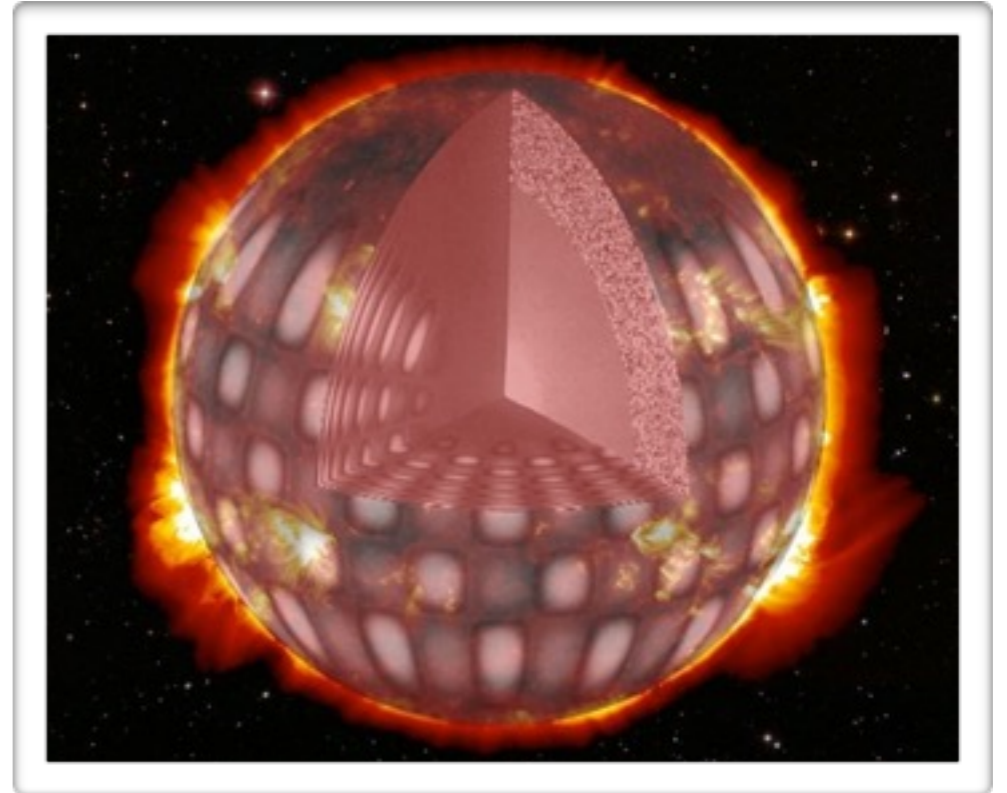
- Bulk viscosity from particle transformation (weak interaction)

candidate phase	dominant processes	bulk viscosity: low T	reference
(ungapped) nuclear matter	$n(+n) \rightarrow p(+n) + e + \bar{\nu}$ $p(+n) \rightarrow n(+n) + e + \nu$	$\zeta \sim (T/\mu)^6$ or $(T/\mu)^4$	Sawyer, PLB 233 (1989) 412; Haensel, <i>et.al.</i> , PRD 45 (1992) 4708
hyperonic matter	$n + n \rightarrow p + \Sigma^-, \dots$	$\zeta \sim (T/\mu)^2$	Haensel, <i>et. al.</i> , A&A 381 (2002) 1080
superfluid nuclear matter	$e + l \leftrightarrow \mu + l + \nu + \bar{\nu}$	$\zeta \sim (T/\mu)^7$	Alford, <i>et.al.</i> , 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	$K_0 \rightarrow H + H$	$\zeta \sim e^{-c(\mu/T)}$	Alford, <i>et.al.</i> , PRC 75 (2007) 055209

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



“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

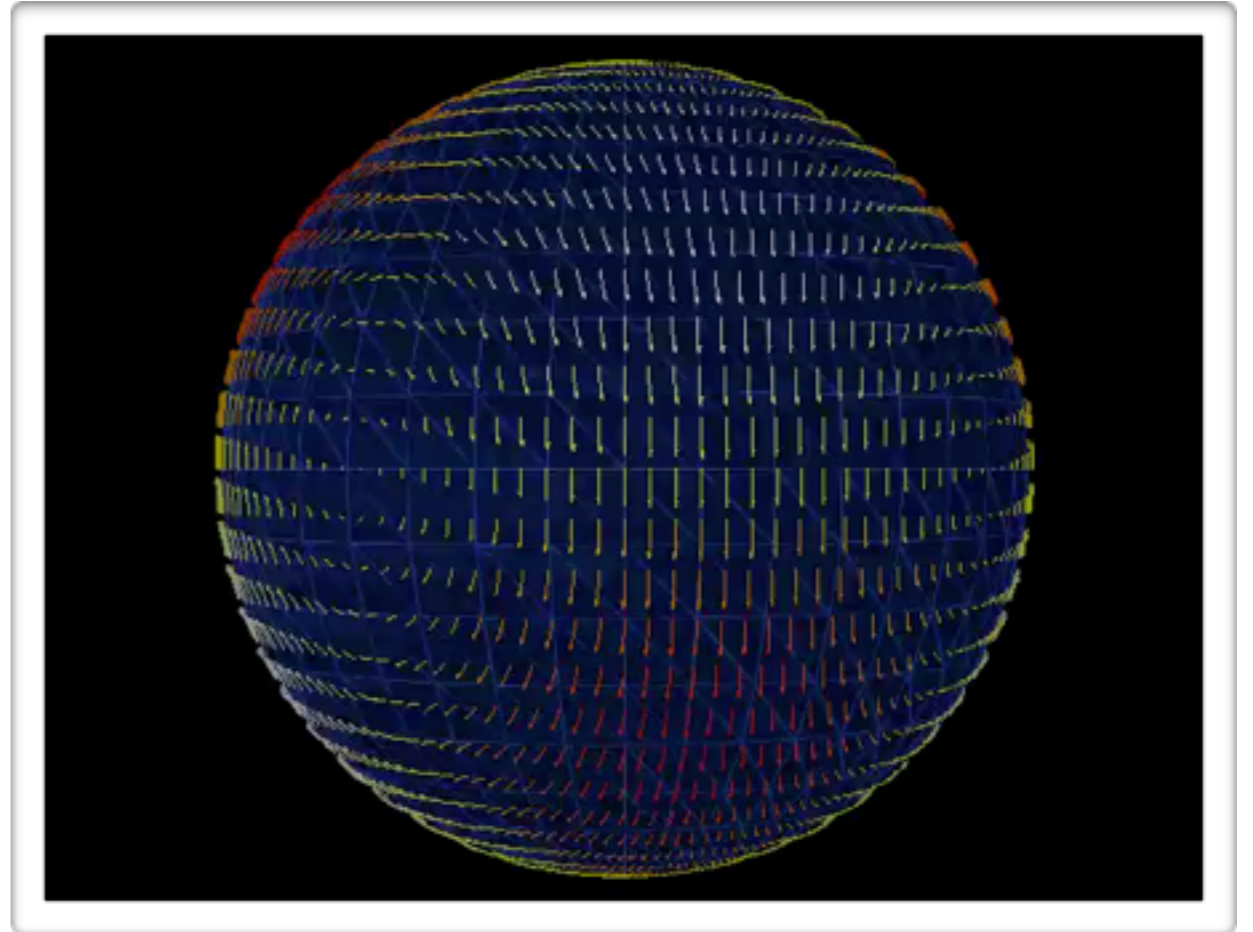
L. Lindblom, et. al., *PRL* 80 (1998) 4843,

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



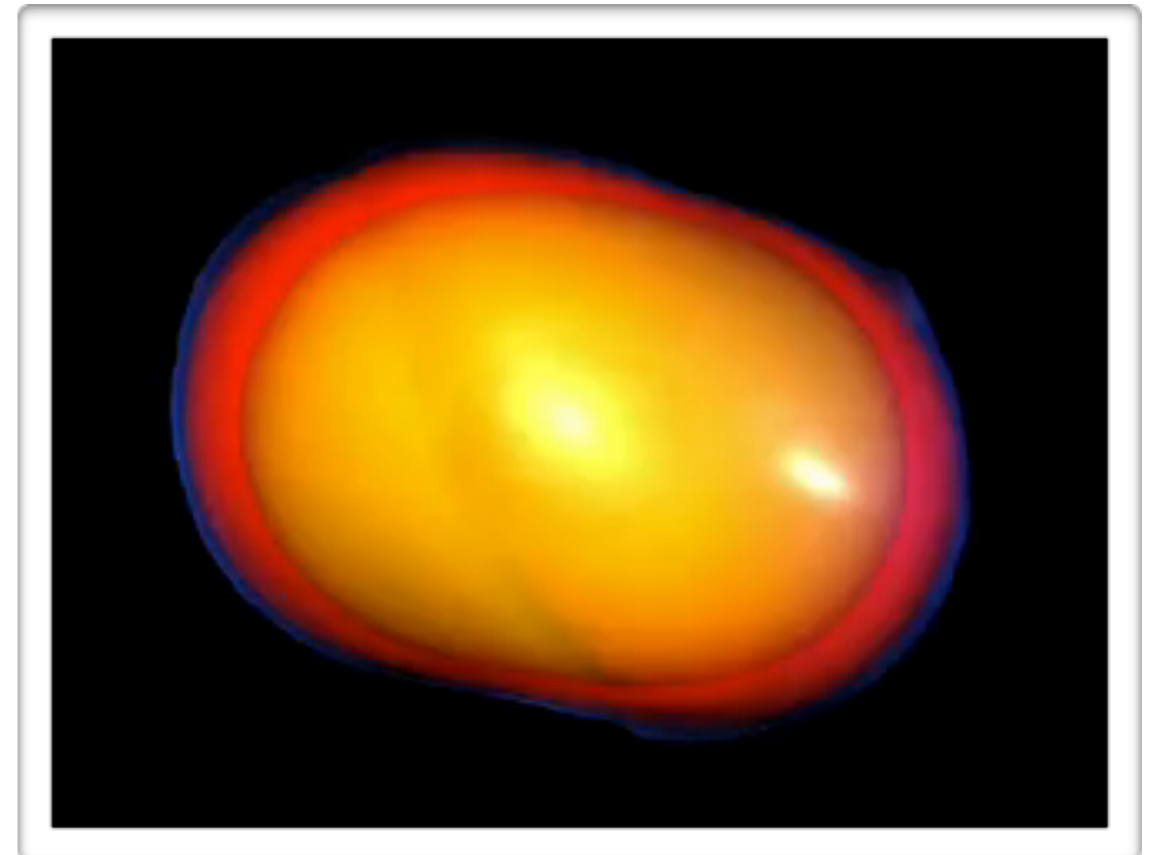
- Large amplitude r-modes could cause a quick spindown

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



Visualization by M. Beilicke

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



Simulation by L. Lindblom

R-mode oscillations

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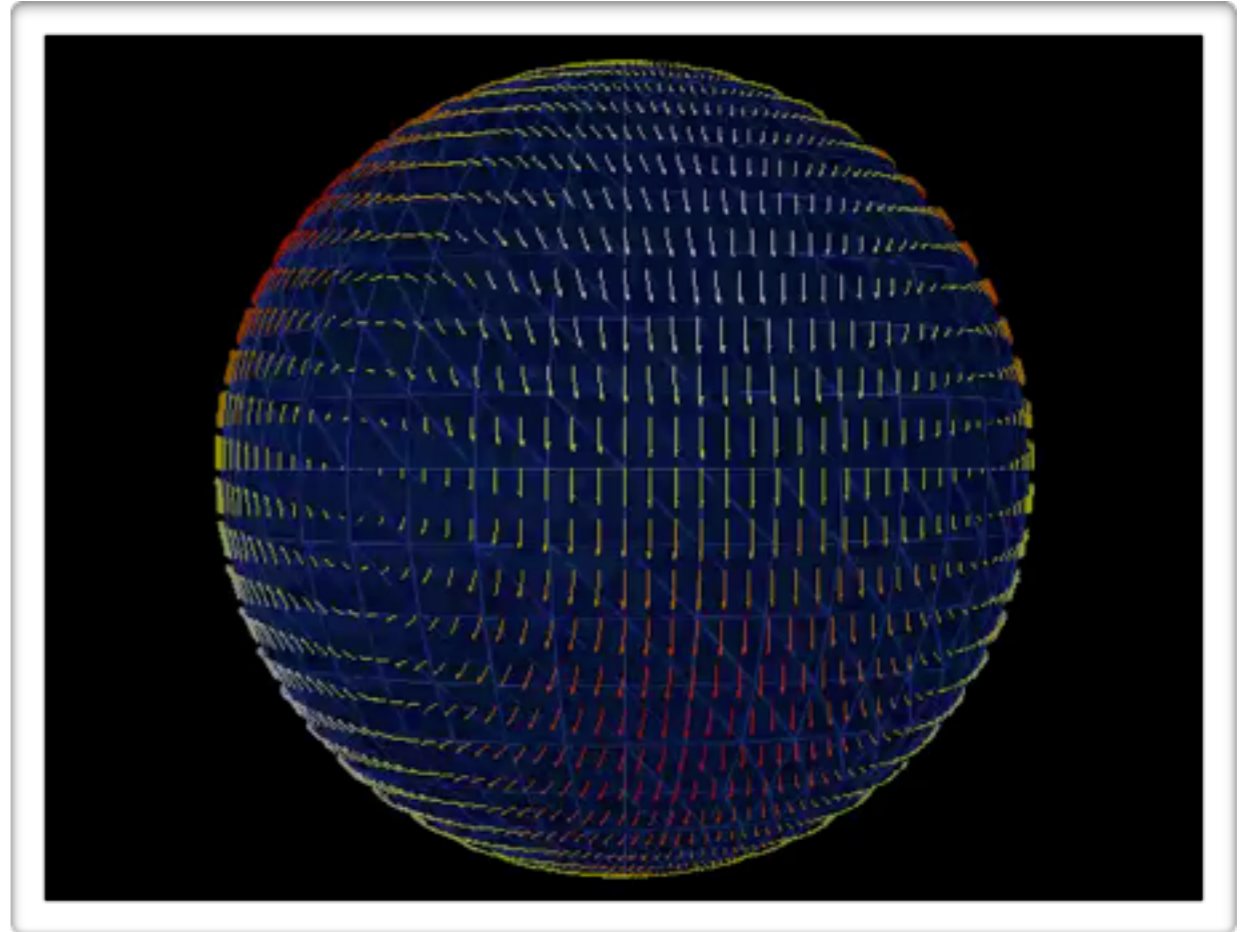
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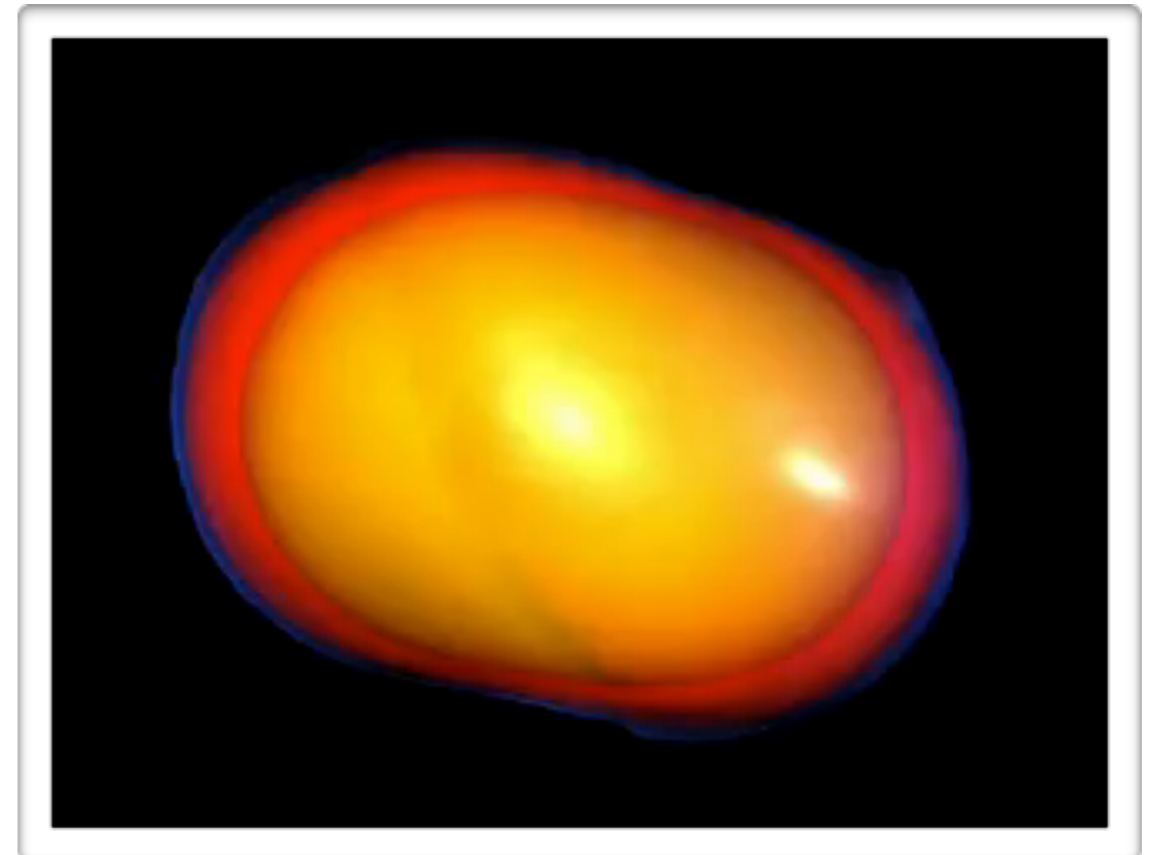
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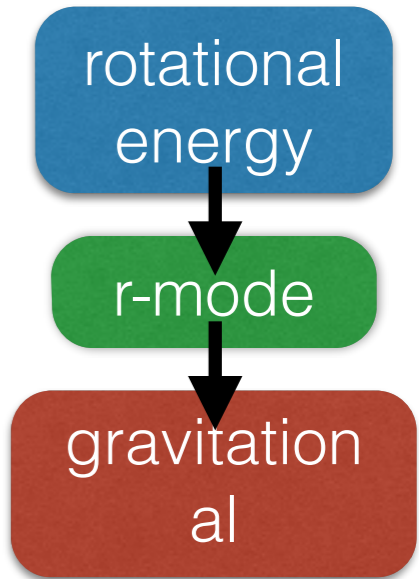
Visualization by M. Beilicke

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



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:



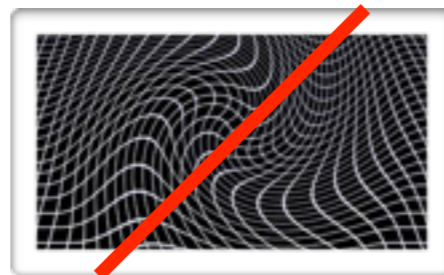
Damping

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** $\alpha_{\text{sat}} = O(1)$

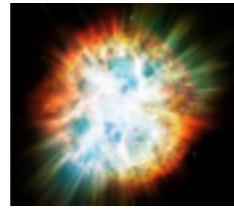
*L. Lindblom, et. al., PRL 86 (2001) 1152,
M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051*

- ▶ **mode-coupling - moderate**

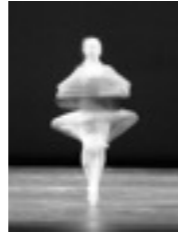
P. Arras, et. al., Astrophys. J. 591 (2003) 1129 $\alpha_{\text{sat}} = O(10^{-5})$

Generic evolution of pulsars

Newborn compact stars

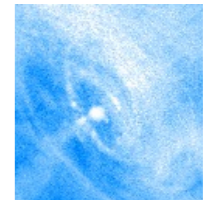


... could spin about as fast as allowed by stability ($>1\text{kHz}$)



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



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)

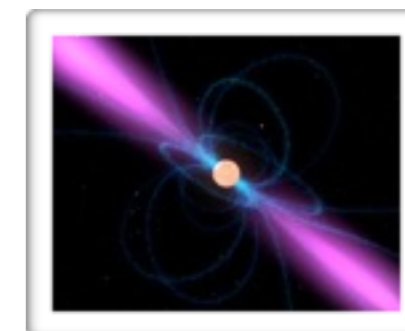


$$\langle \dot{f} \rangle > 0$$

❖ 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



$$\dot{f} < 0$$

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

❖ one of the most precise data sets in physics!

NAME	F0	F1	F2	F3
J1339+2200	50.225457	-3.862e-10	1.243e-20	-0.400e-1
J1537-6910	62.026190	-1.992e-10	6.100e-21	0
J1540-6919	19.802444	-1.878e-10	3.752e-21	0
J12022+3842	41.173009	-7.322e-11	0	0
J1513-5908	6.611515	-6.694e-11	1.910e-21	-9.139e-2
J1840-0258	2.725e-21	2.725e-21	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”



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

$$\nu \approx 2f$$

R-modes

$$\nu \approx 4/3f < 2f$$

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 $\dot{\nu}$

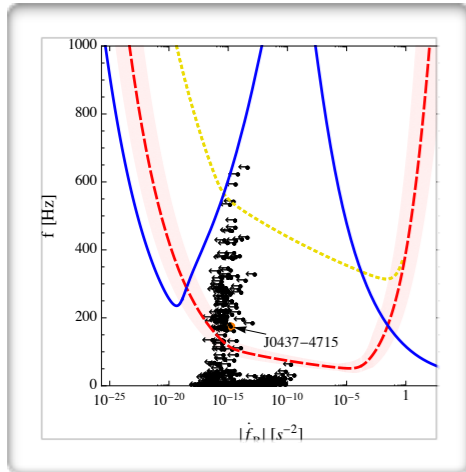
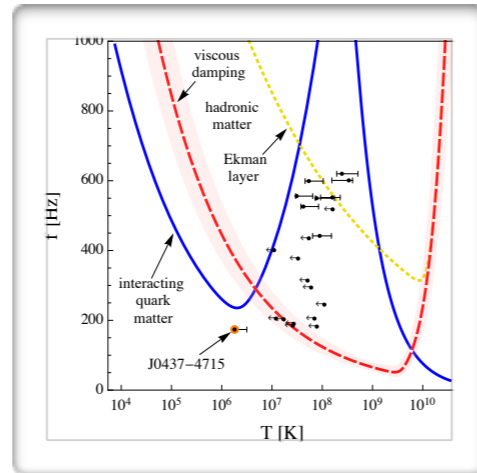
... combined
with electromagnetic data
this yields far more

Information from multi-messenger observations

Composition

Spindown Rate \dot{f}

or Temperature T



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

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}

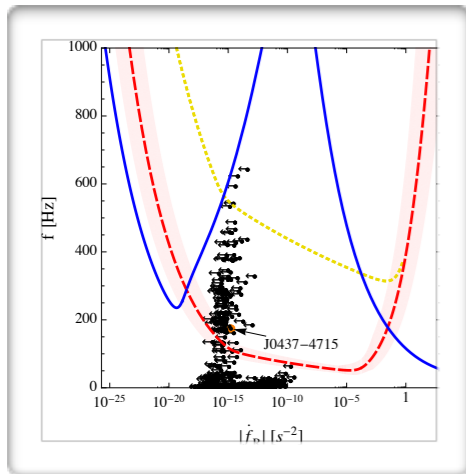
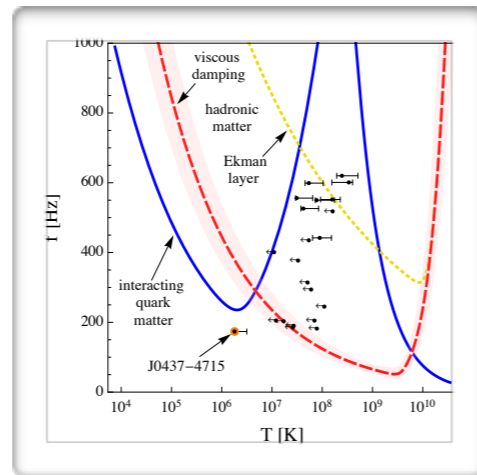
or Temperature T

Compactness

Rotation frequency f

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

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



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Information from multi-messenger observations

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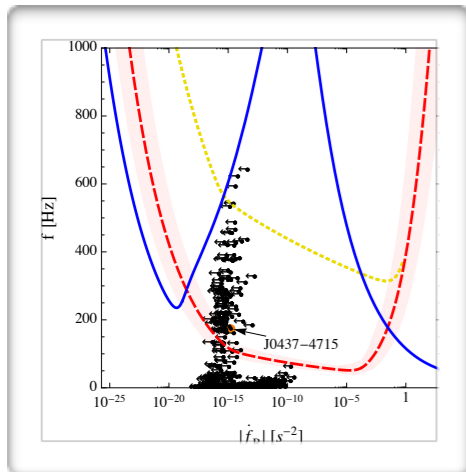
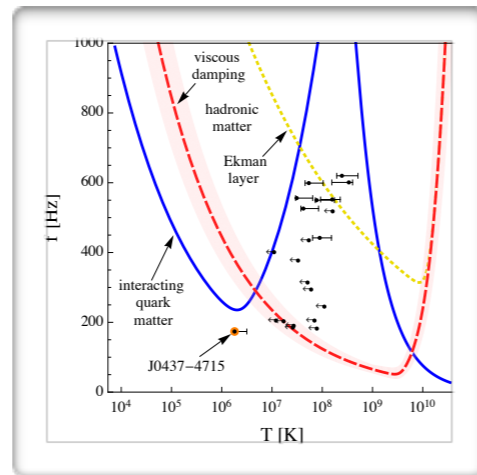
or Temperature T

Compactness

Rotation frequency f

Mass M

Radius



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

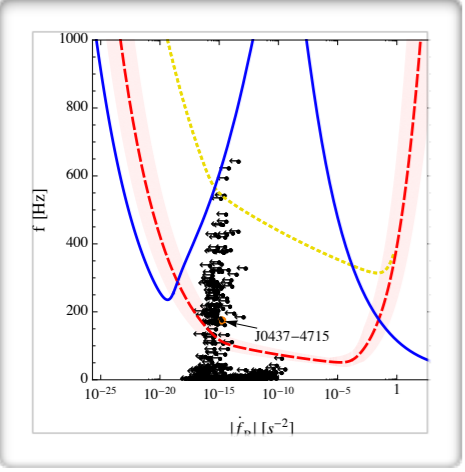
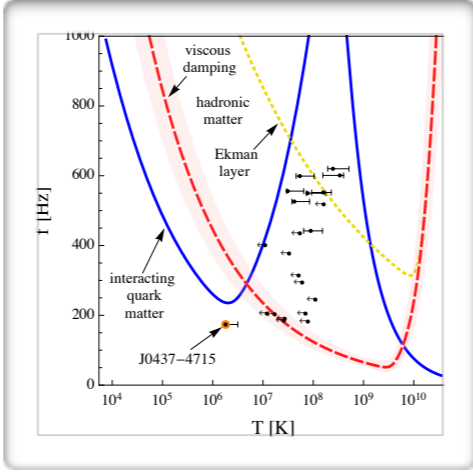
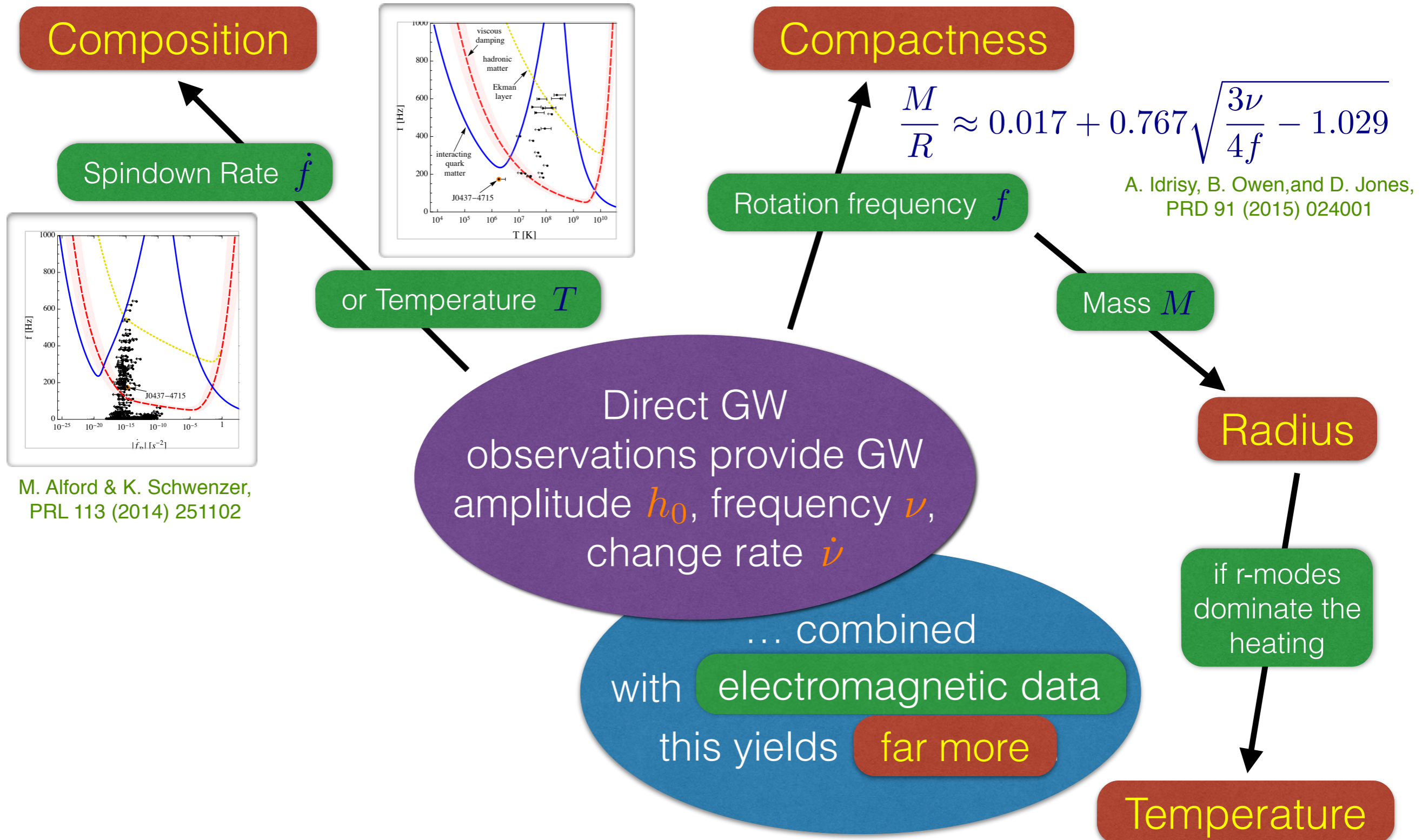
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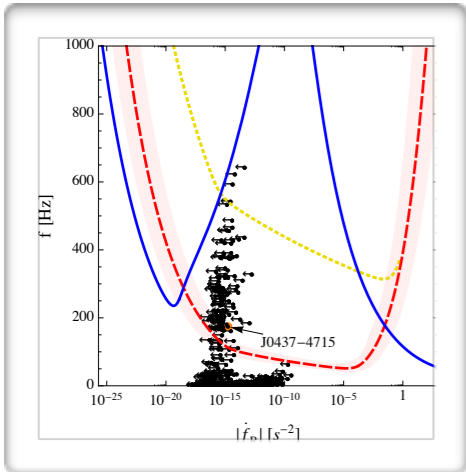
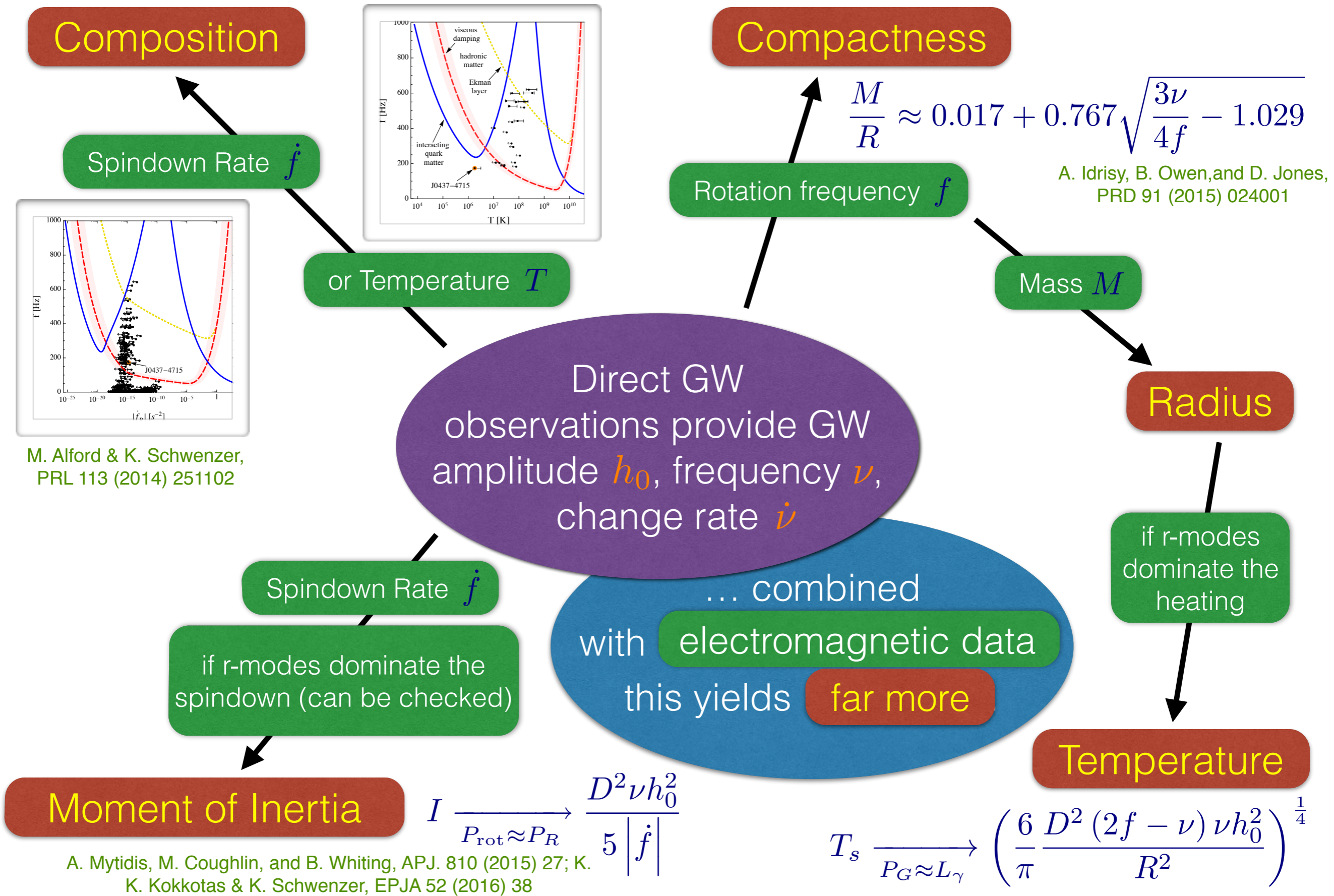
M. Alford & K. Schwenzer, PRL 113 (2014) 251102

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

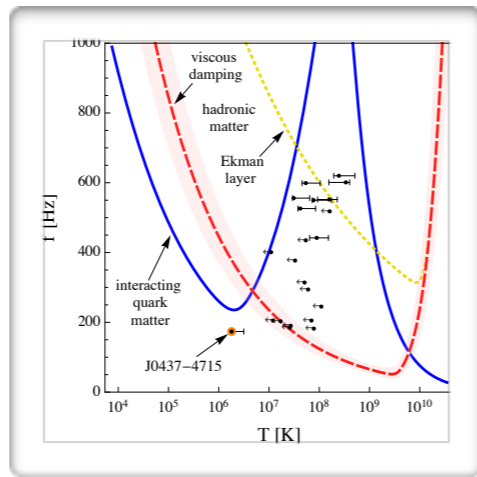
A. Idrisy, B. Owen, and D. Jones, PRD 91 (2015) 024001

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

Information from multi-messenger observations



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

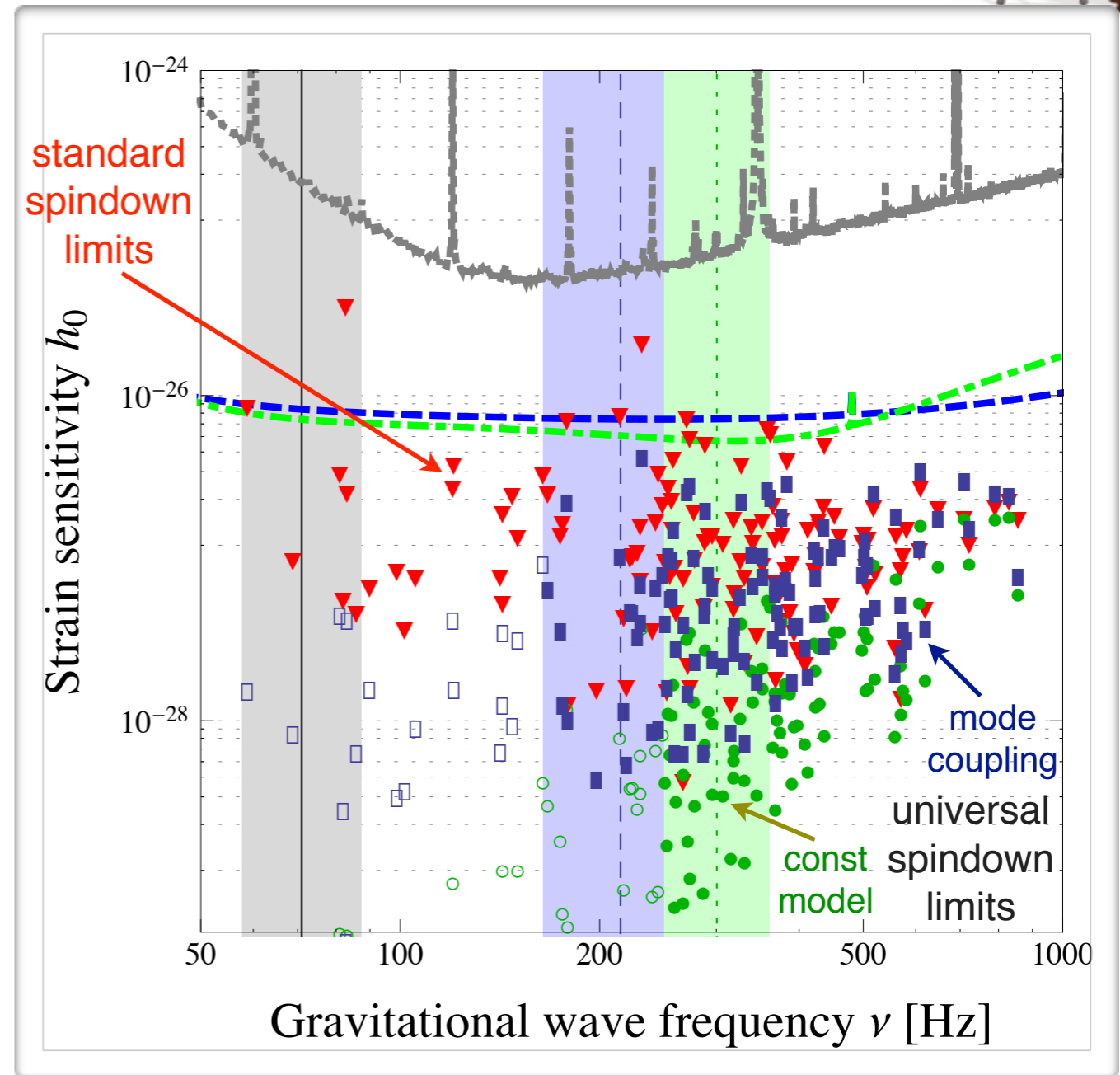


or Temperature T

Gravitational waves from old ms-pulsars



- In addition to the standard case of deformations Aasi, et. al., arXiv:1309.4027 r-modes are a promising continuous GW-source
- 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 should be detectable with further improvements or 3. generation detectors



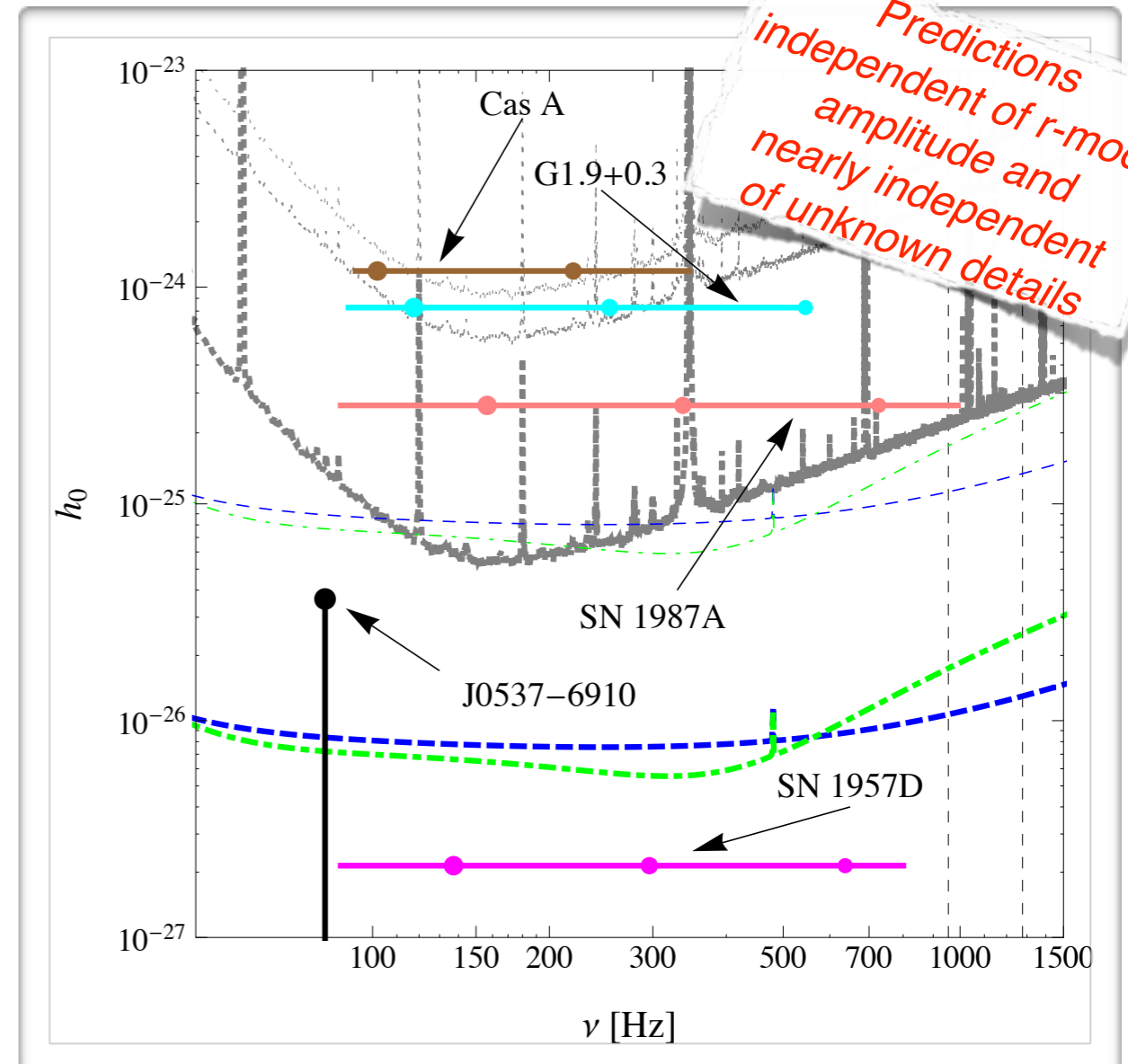
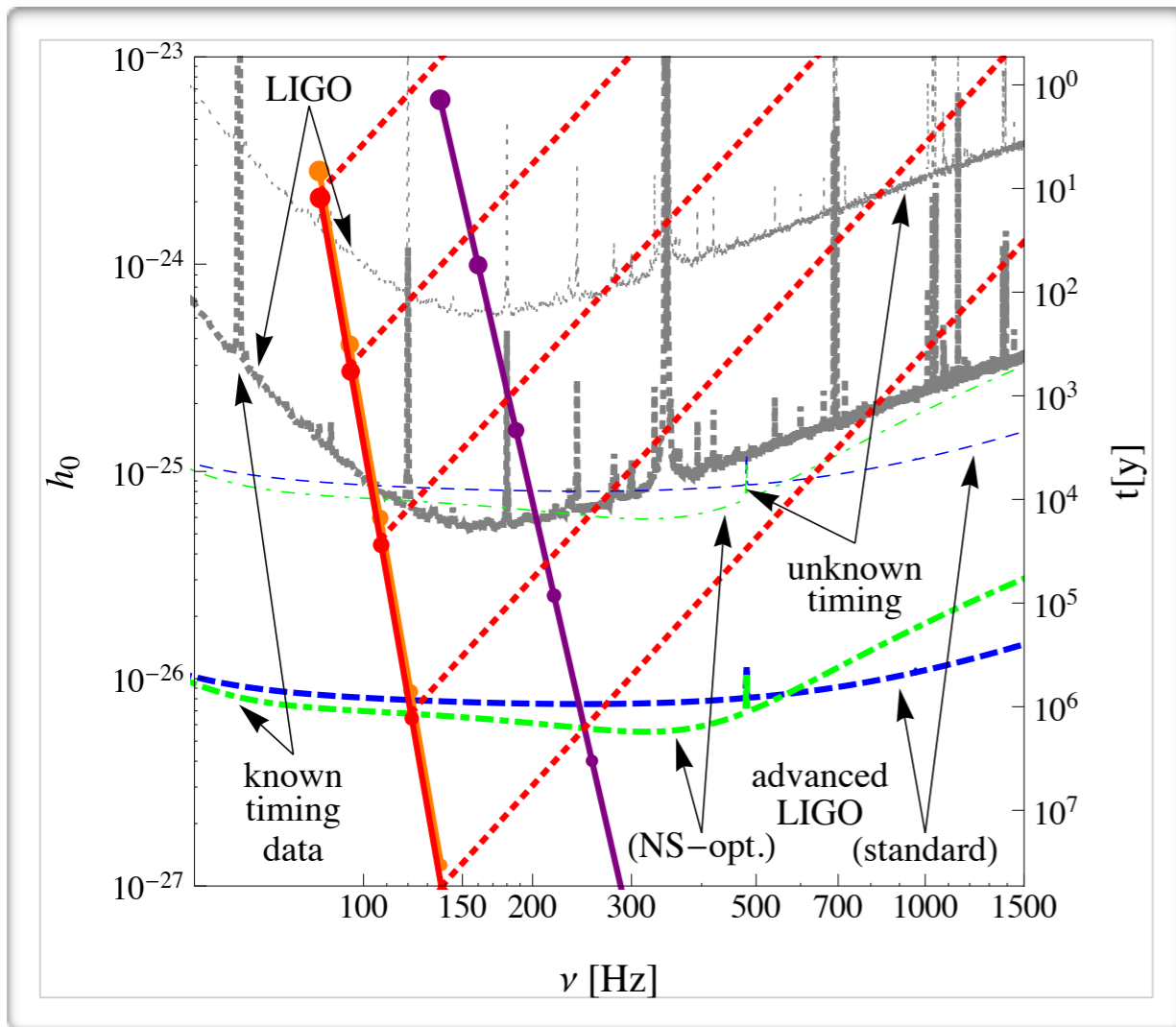
$$h_0^{(\text{usl})} = \sqrt{\frac{15}{4} \frac{GI}{D^2 f_0} \left| \dot{f}_0 \right|} \left(\frac{\hat{\alpha}_{\text{sat}}^{(\text{mac})}}{\hat{\alpha}_{\text{sat},0}^{(\text{mac})}} \right)^{\frac{1}{1-2\beta/\theta}} \left(\frac{f}{f_0} \right)^{\frac{3+\gamma+2\beta/\theta}{1-2\beta/\theta}}$$

(“universal spindown limit”)

Gravitational wave emission of young sources



- Since r-mode emission can *quantitatively* 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 $h(t) \xrightarrow{\Omega \ll \Omega_i} \sqrt{\frac{3 CGI}{40 D^2 t}}$

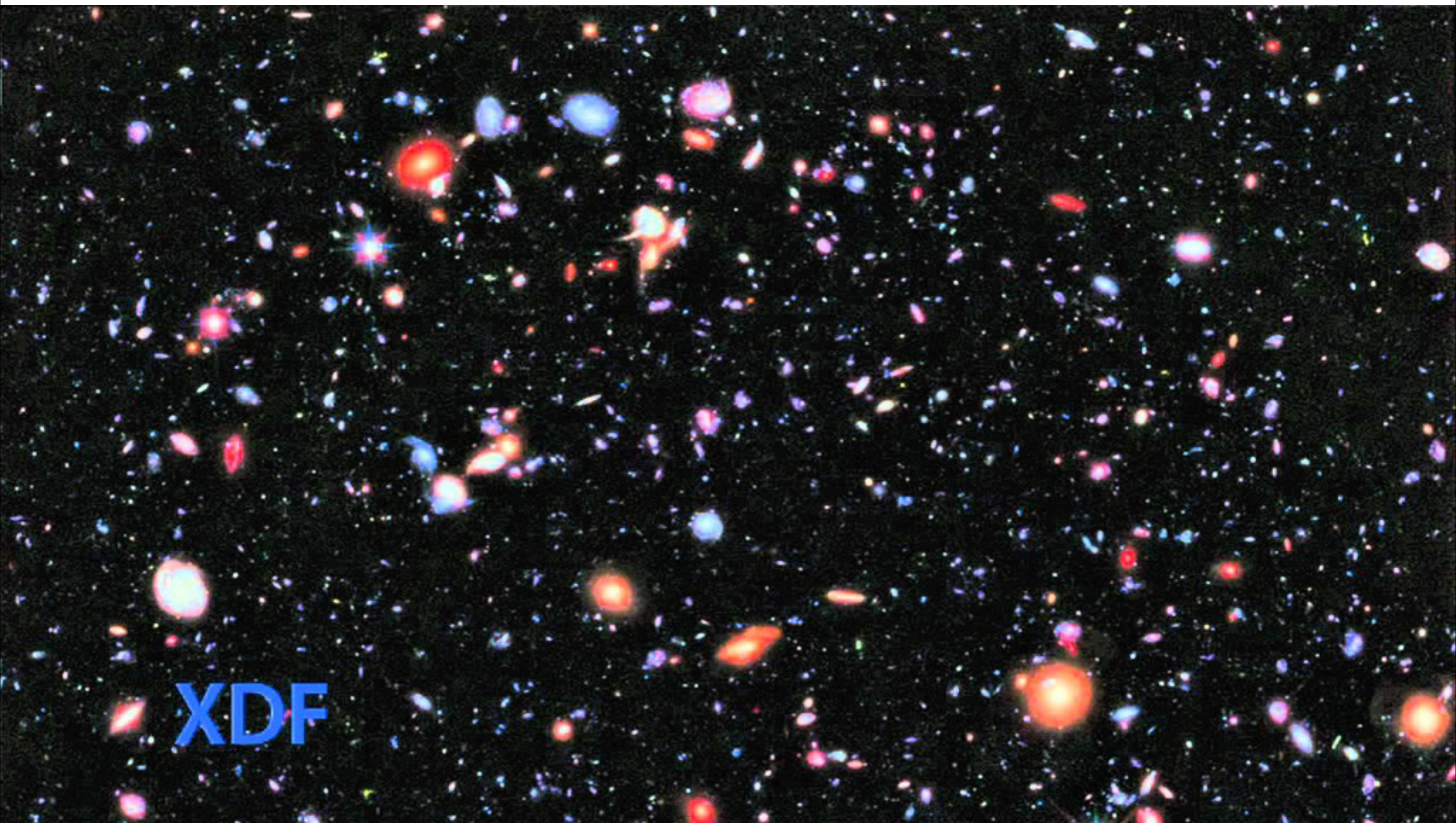


Several potential sources in reach of aLigo

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:

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

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

$$P_S = -\frac{(m-1)(2m+1)\tilde{S}_m \Lambda_{\text{QCD}}^{3+\sigma} R^3 \alpha^2 \Omega^2}{T^\sigma} \quad (\text{DISSIPATED POWER DUE TO SHEAR / BULK VISCOSITY})$$

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

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

“Effective Theory of pulsars”

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

$$I = \tilde{I} M R^2$$

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

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

$$\tilde{J}_m \equiv \frac{1}{MR^{2m}} \int_0^R dr r^{2m+2} \rho$$

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

$$\tilde{S}_m \equiv \frac{1}{R^{2m+1} \Lambda_{\text{QCD}}^{3+\sigma}} \int_{R_i}^{R_o} dr r^{2m} \tilde{\eta}$$

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

$$\tilde{V}_m \equiv \frac{\Lambda_{\text{EW}}^4}{R^3 \Lambda_{\text{QCD}}^{9-\delta}} \int_{R_i}^{R_o} dr r^2 A^2 C^2 \tilde{\Gamma} (\delta \Sigma_m)^2$$

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

$$\tilde{L} \equiv \frac{1}{R^3 \Lambda_{\text{EW}}^4 \Lambda_{\text{QCD}}^{1-\theta}} \int_{R_i}^{R_o} dr r^2 \tilde{\epsilon}$$

- 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 ...

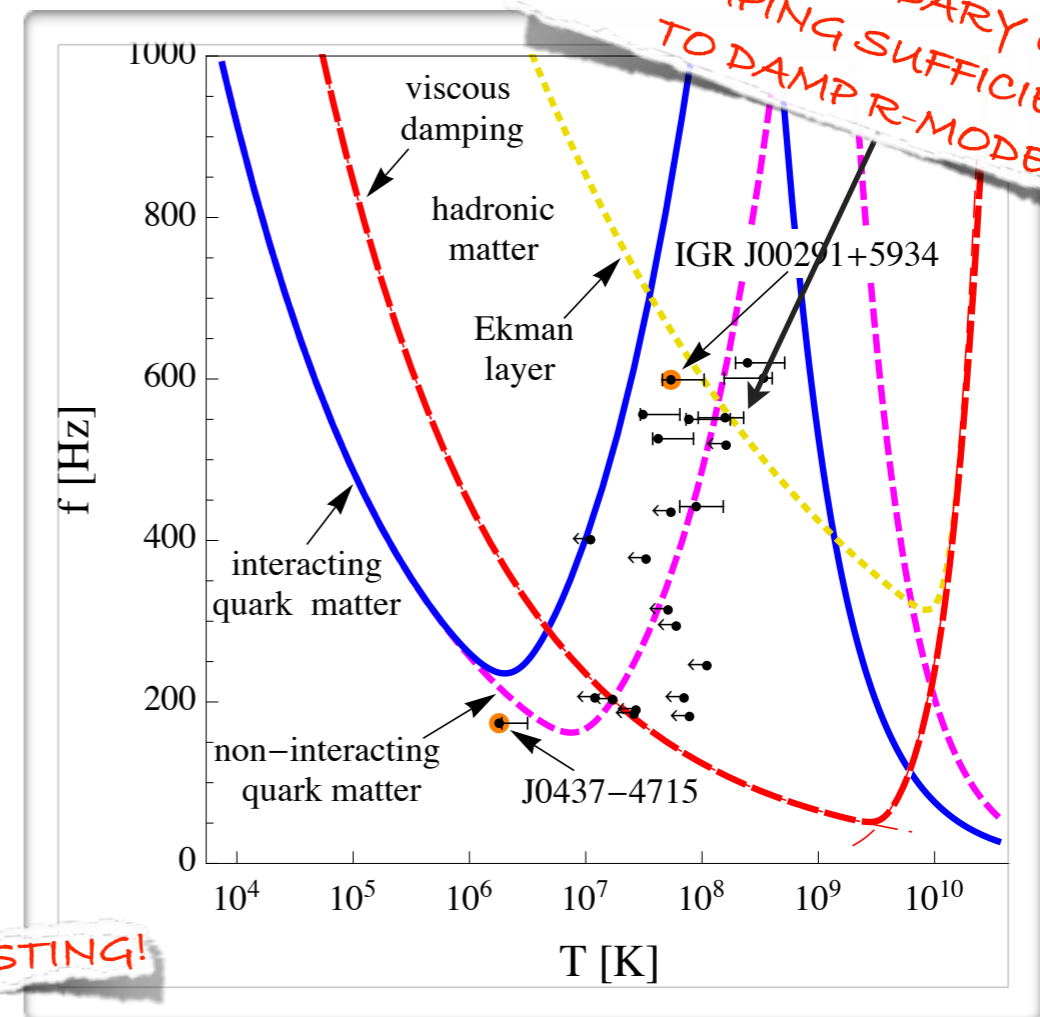
e.g. final frequency for a neutron star:

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

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 $P_G = P_D|_{\alpha \rightarrow 0}$
- 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,



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

but saturated at small α_{sat}

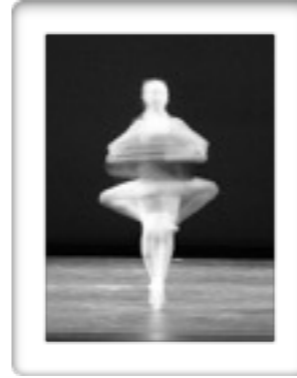
BORING TRIVIAL CASE

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)

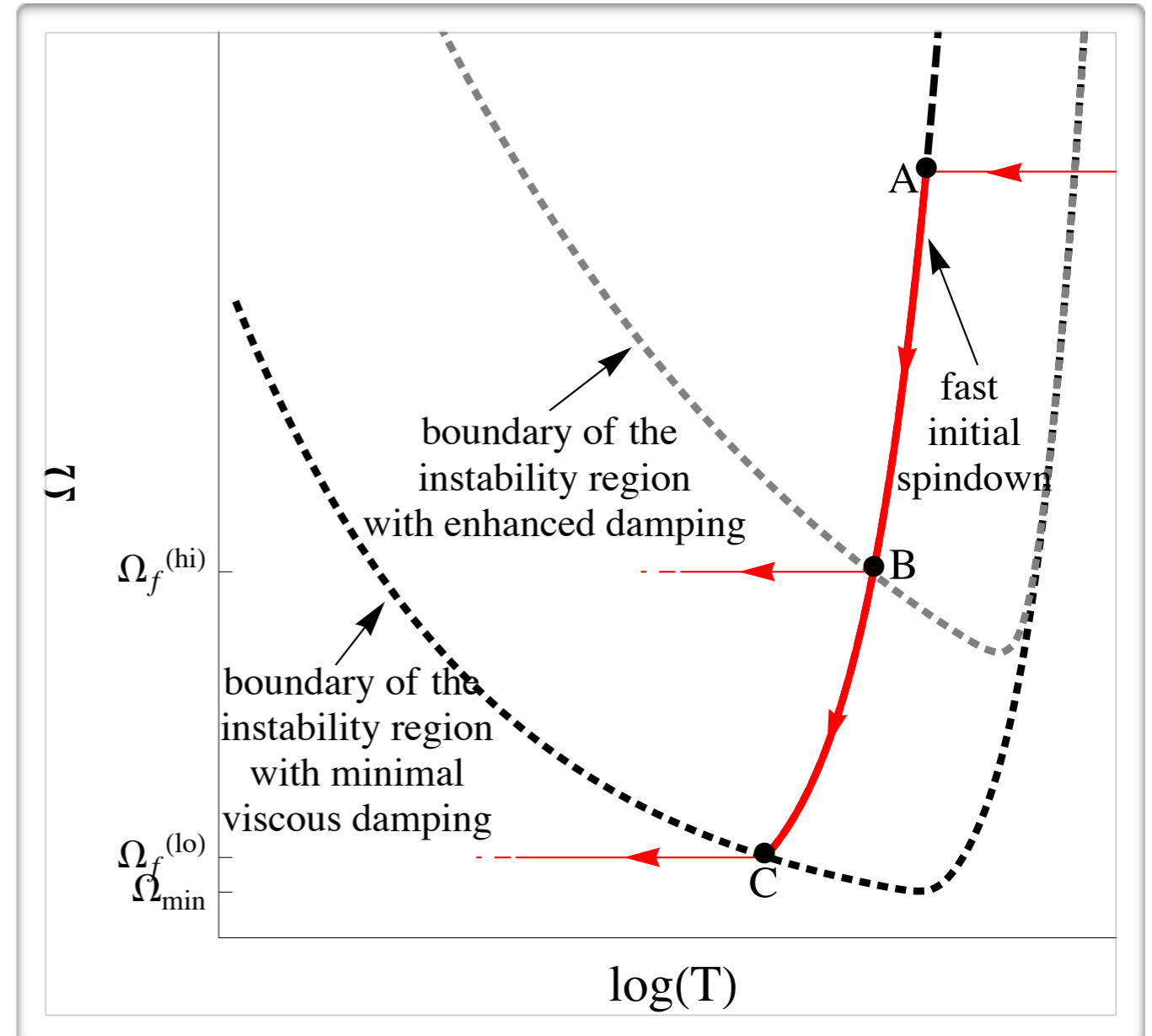
Evolution of young pulsars

- 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

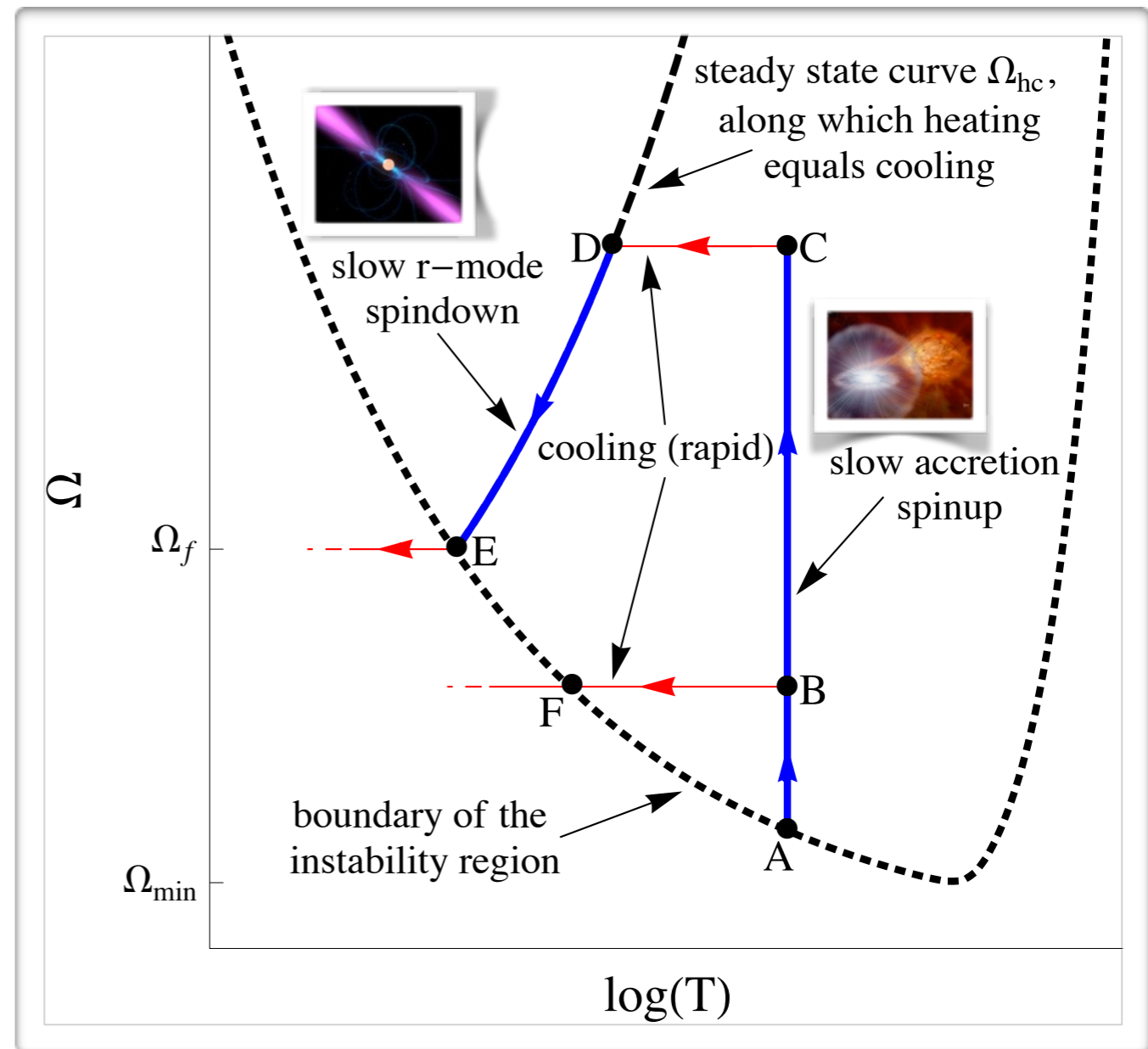
- They cool until r-modes become unstable and saturate at a finite amplitude
- R-modes heat the source and the GW emission spins it down along a steady state curve where heating balances cooling
- Afterwards they leave the instability region, r-modes decay and these sources cool and spindown



Evolution of recycled pulsars



- Pulsars can be spun up to high frequencies (so far **716 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

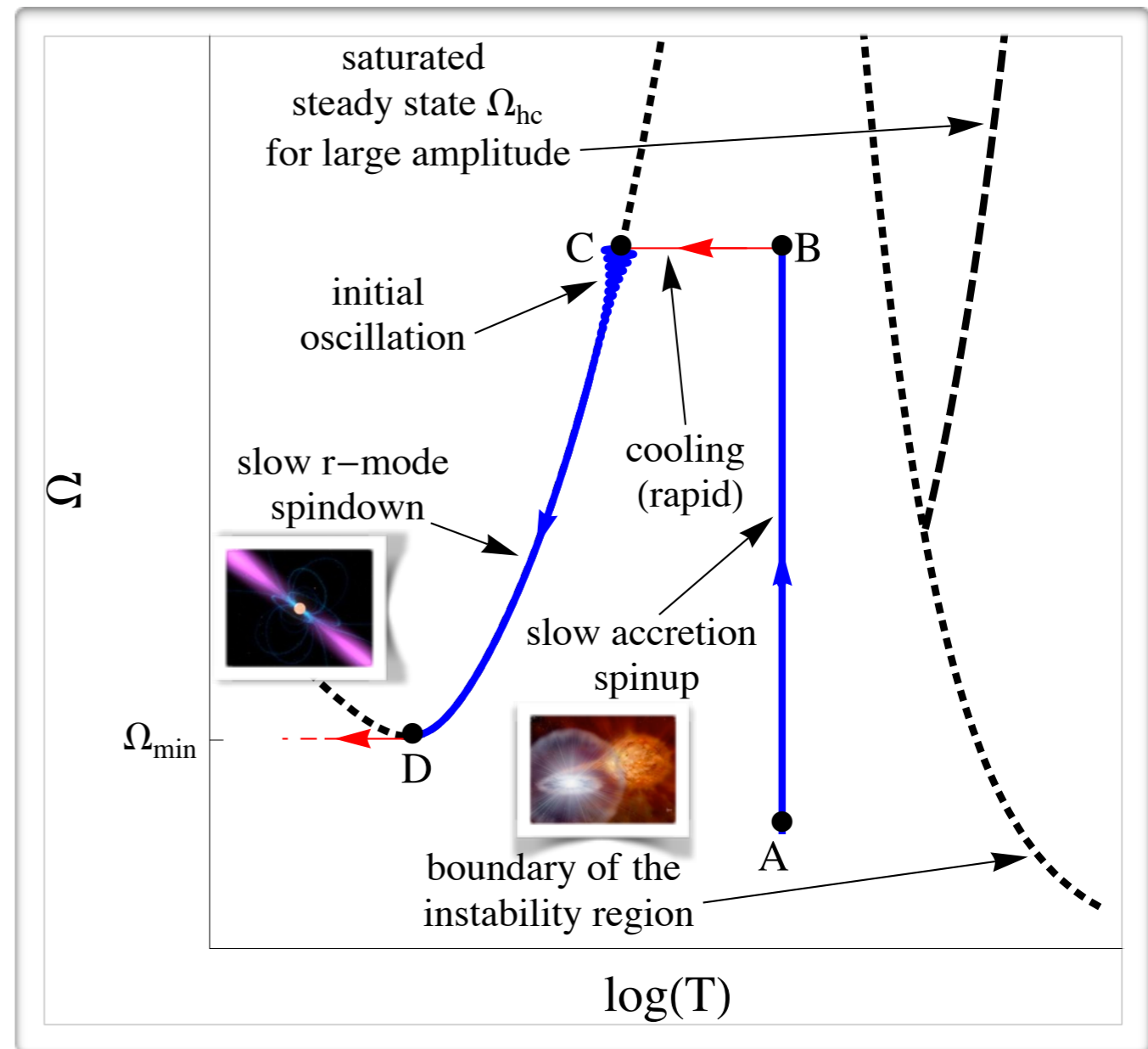
Pulsar evolution with enhanced damping

- 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



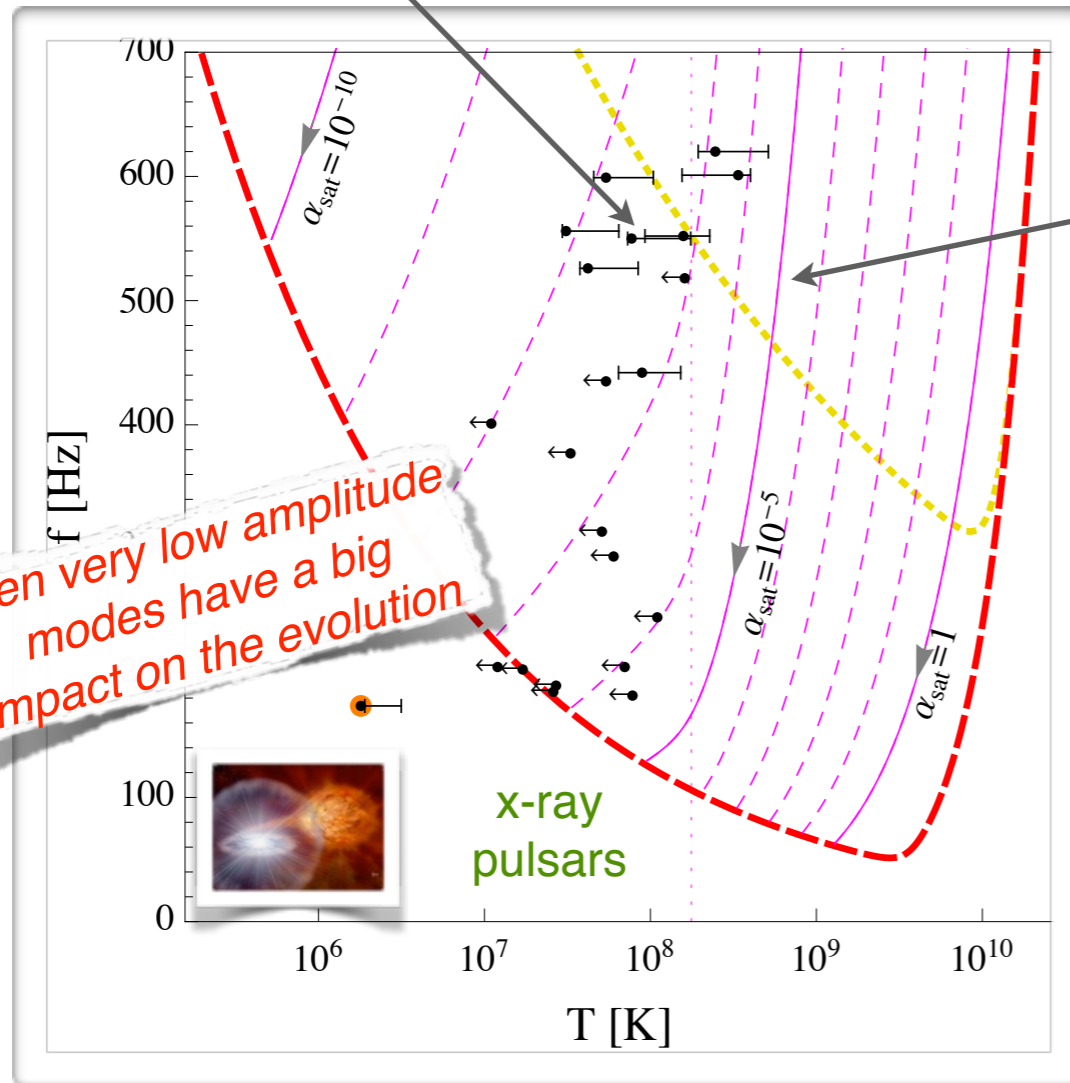
"Boundary straddling scenario"

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

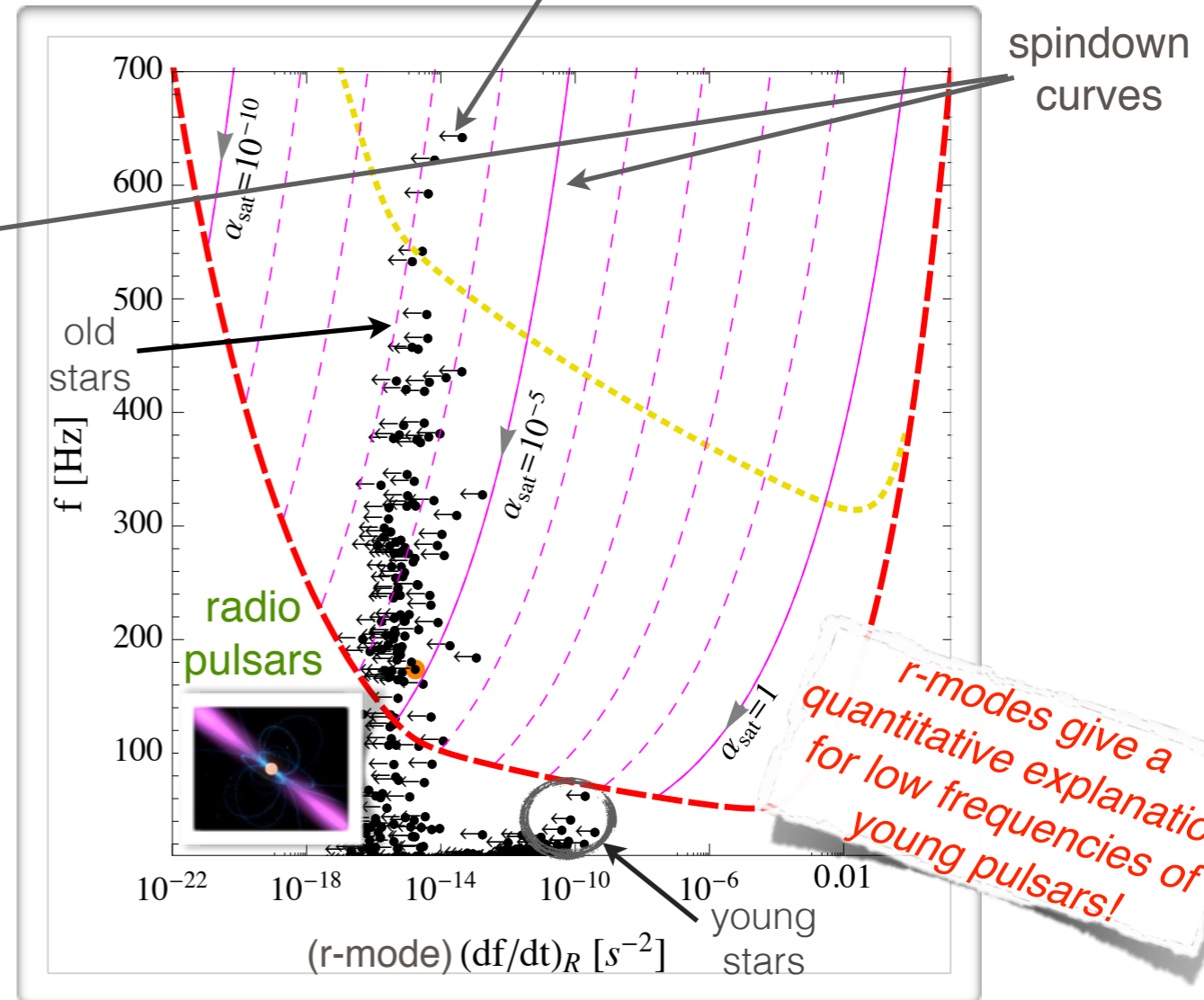
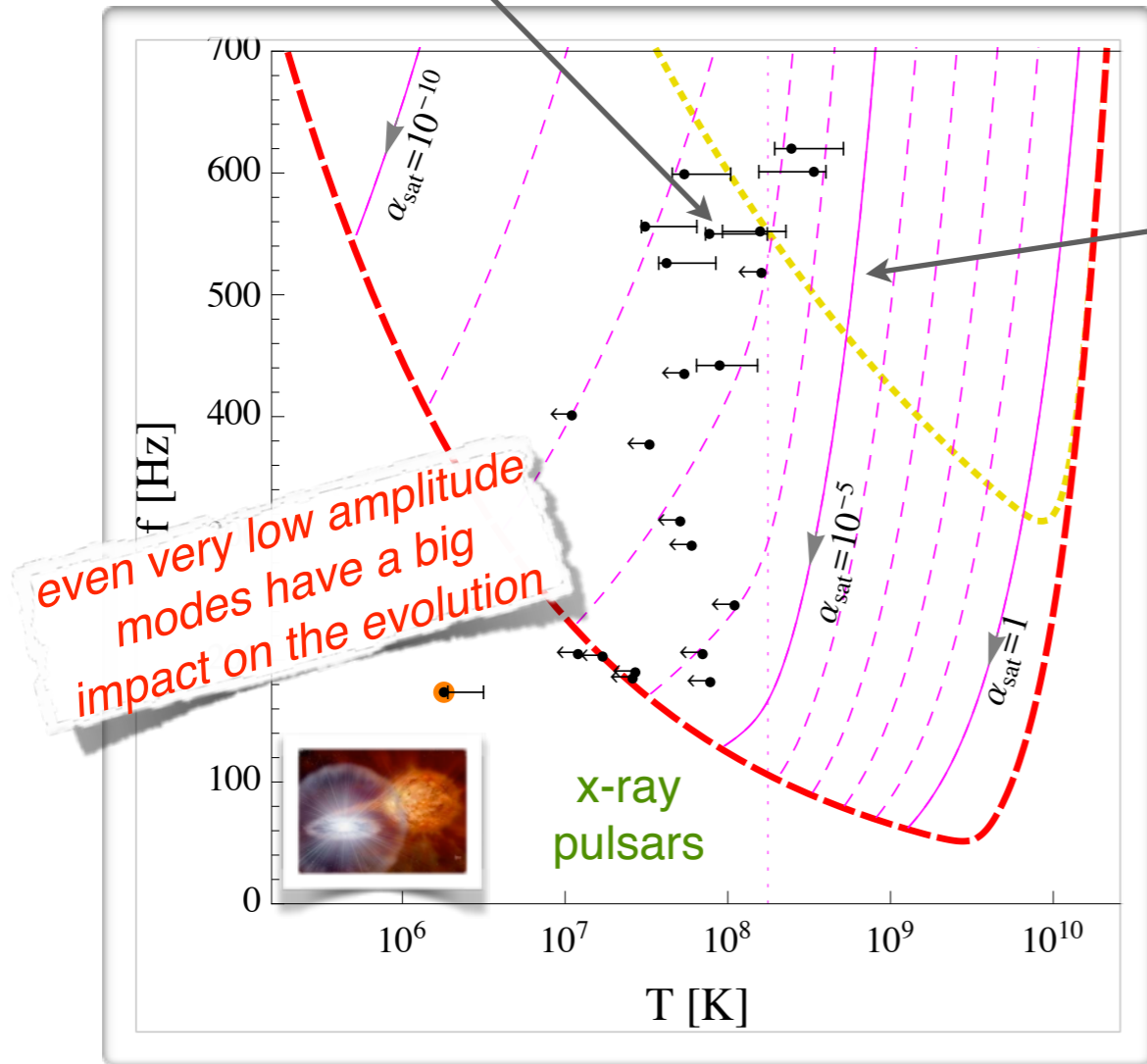
even very low amplitude
modes have a big
impact on the evolution

x-ray
pulsars

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

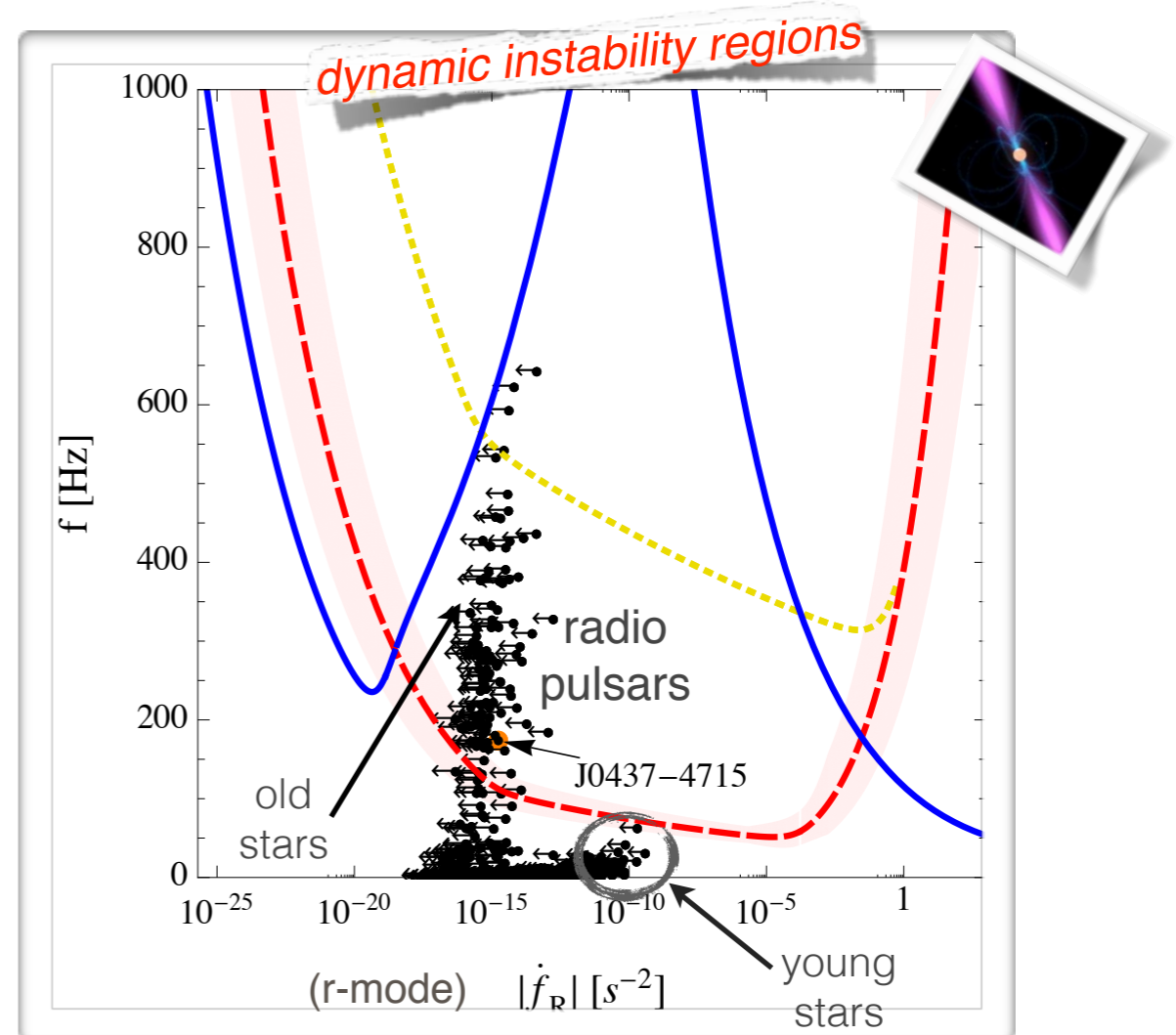
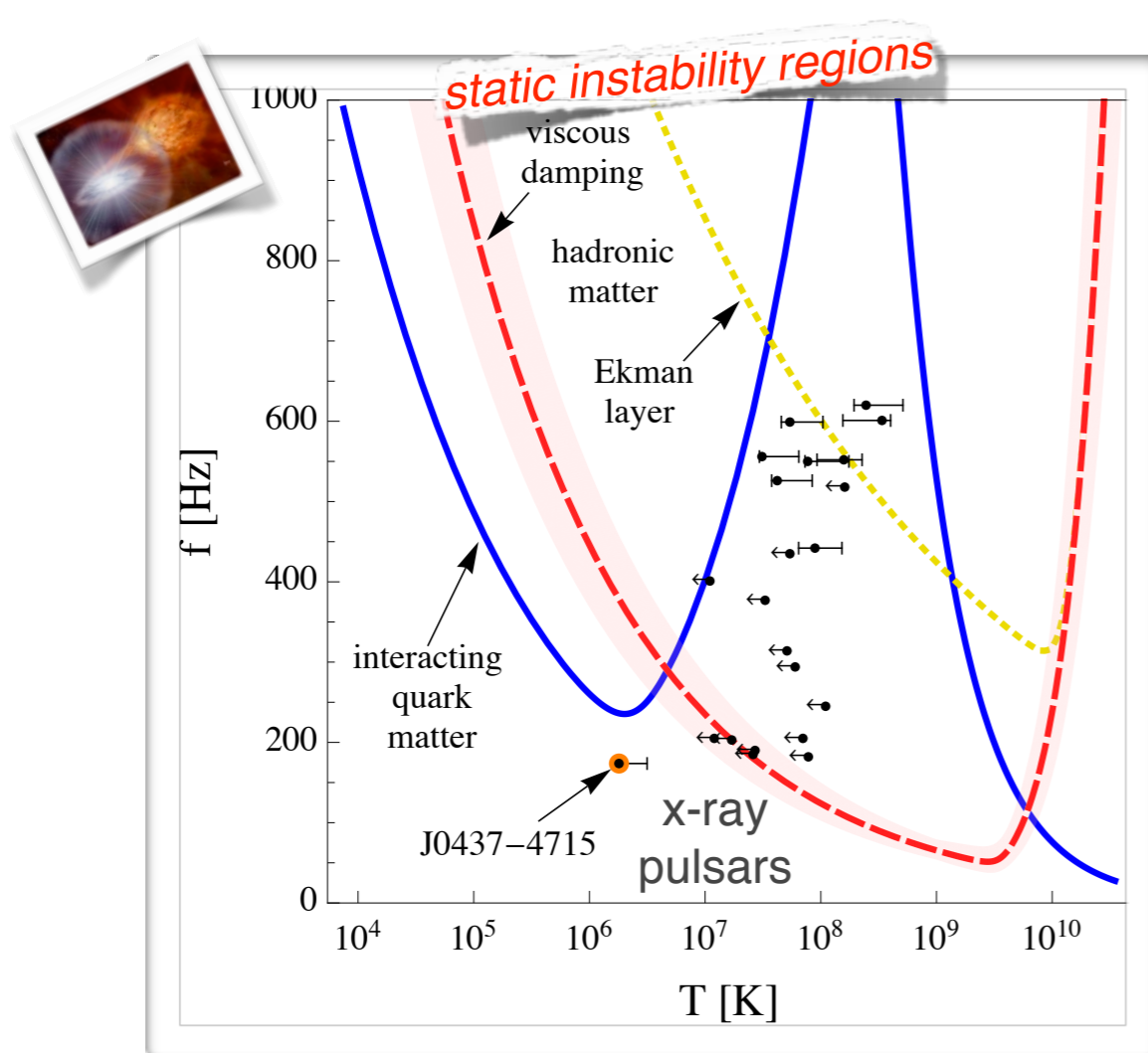


We only measure the total spindown rate which can stem from various mechanisms, so that the sources could be outside of the instability region ...

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

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:

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

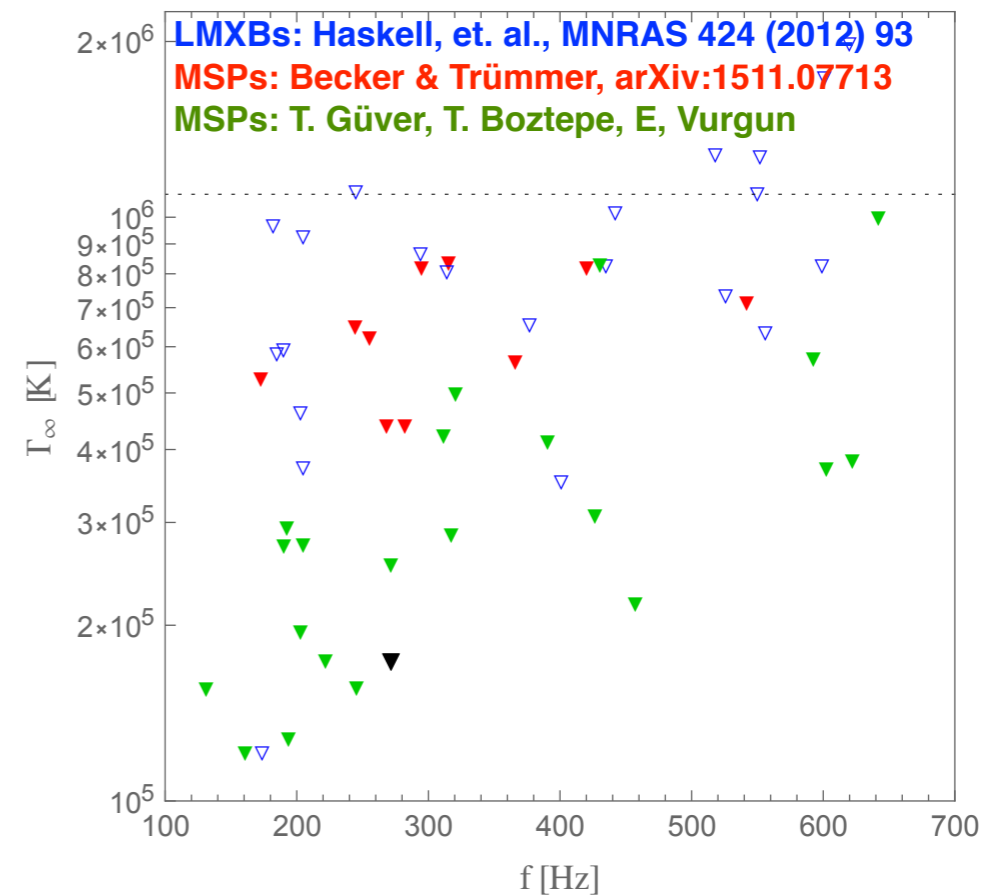
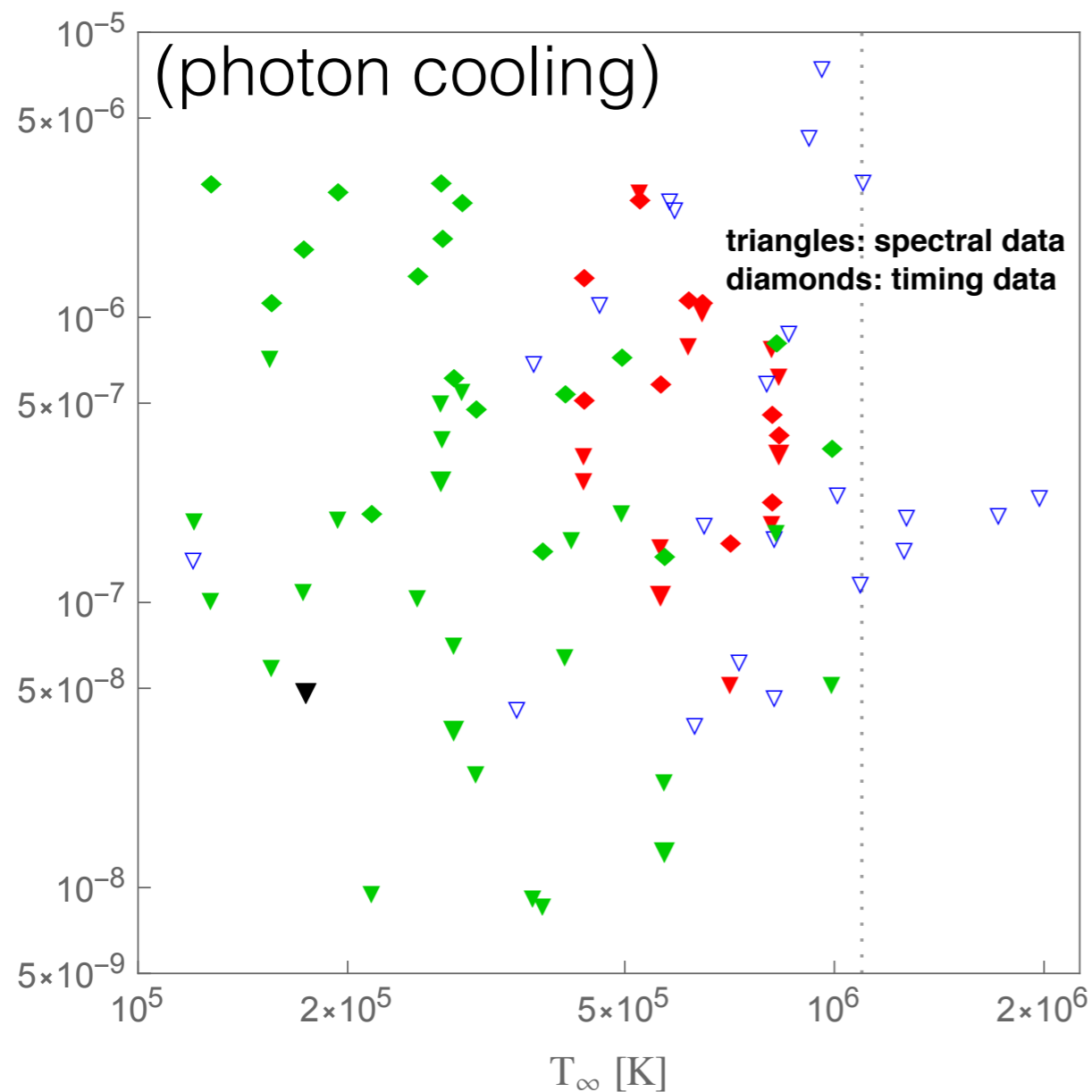
independent of saturation physics!

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

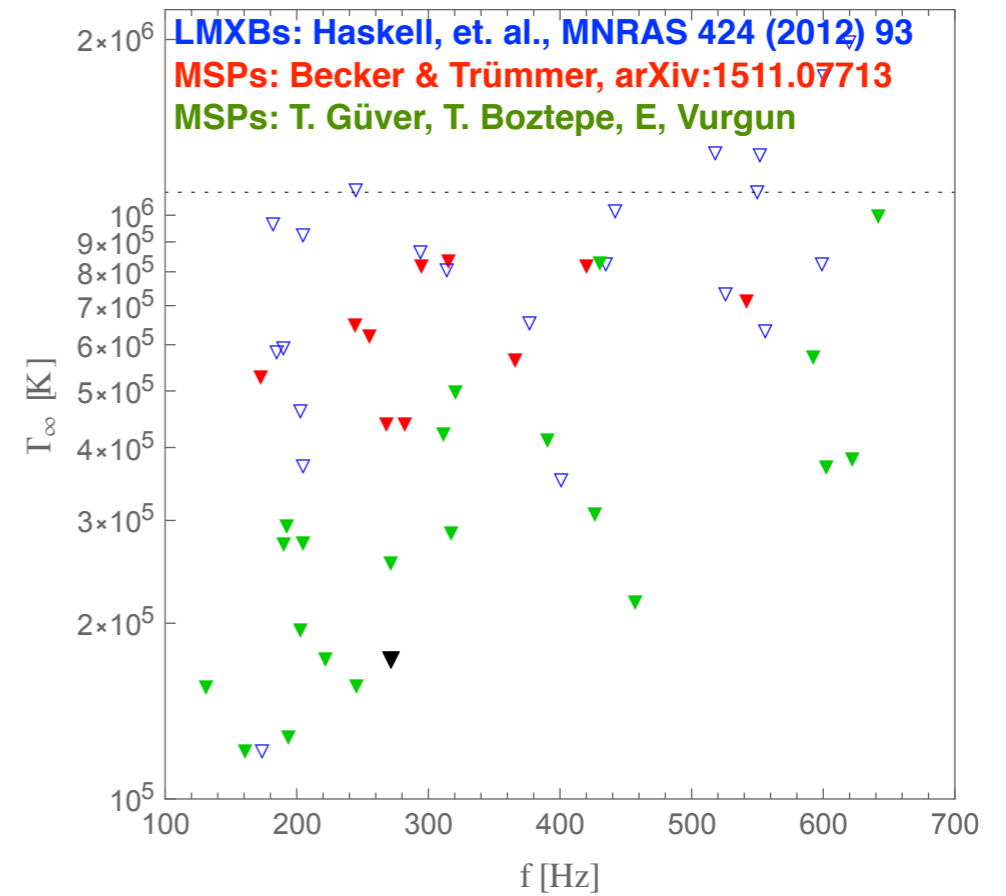
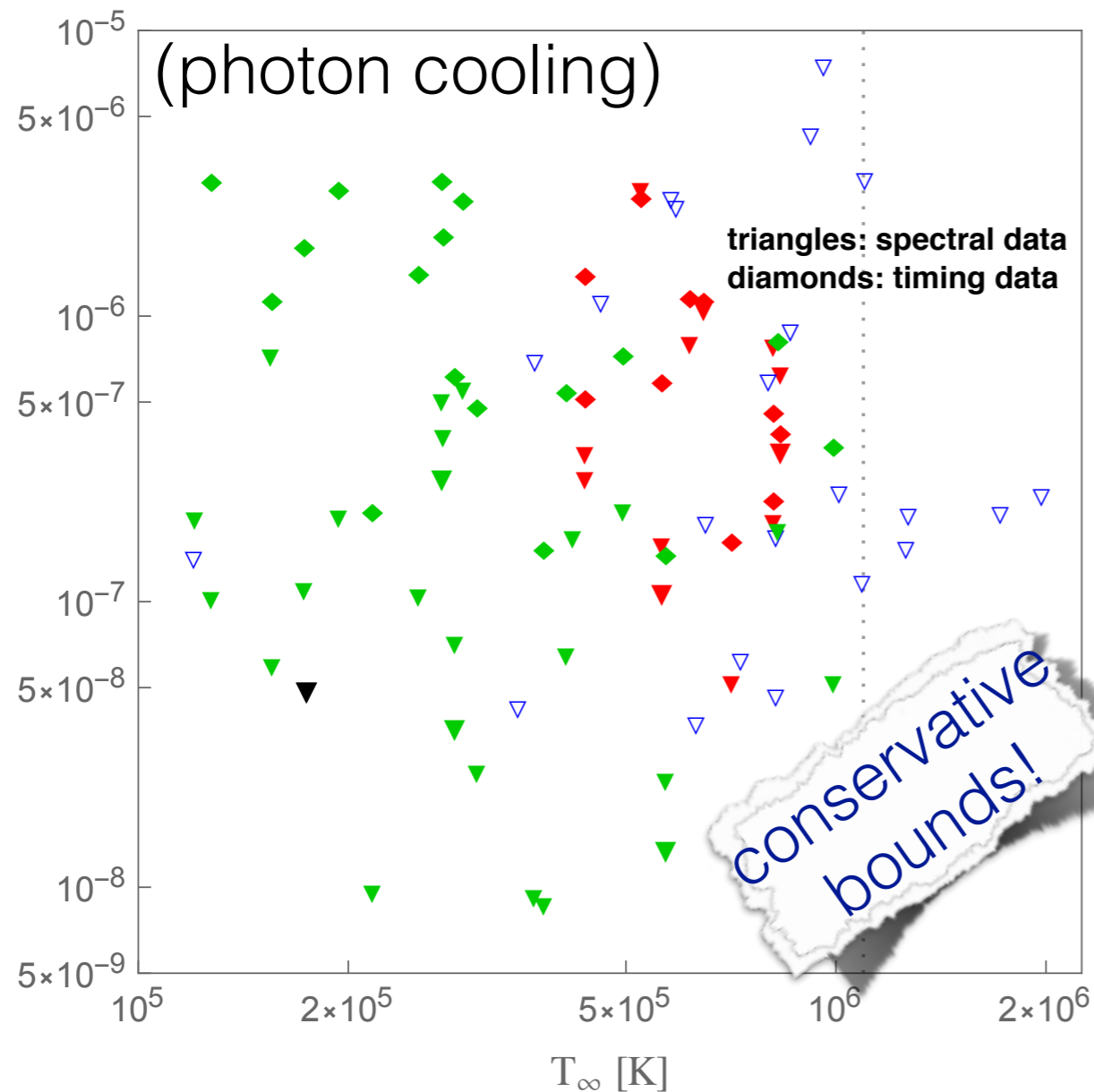


- R-modes strongly heat a source
 - ◆ temperature bounds impose r-mode amplitude bounds
- Millisecond pulsars impose the lowest amplitude bounds $\alpha < 10^{-8}$
 - ◆ requires very strong

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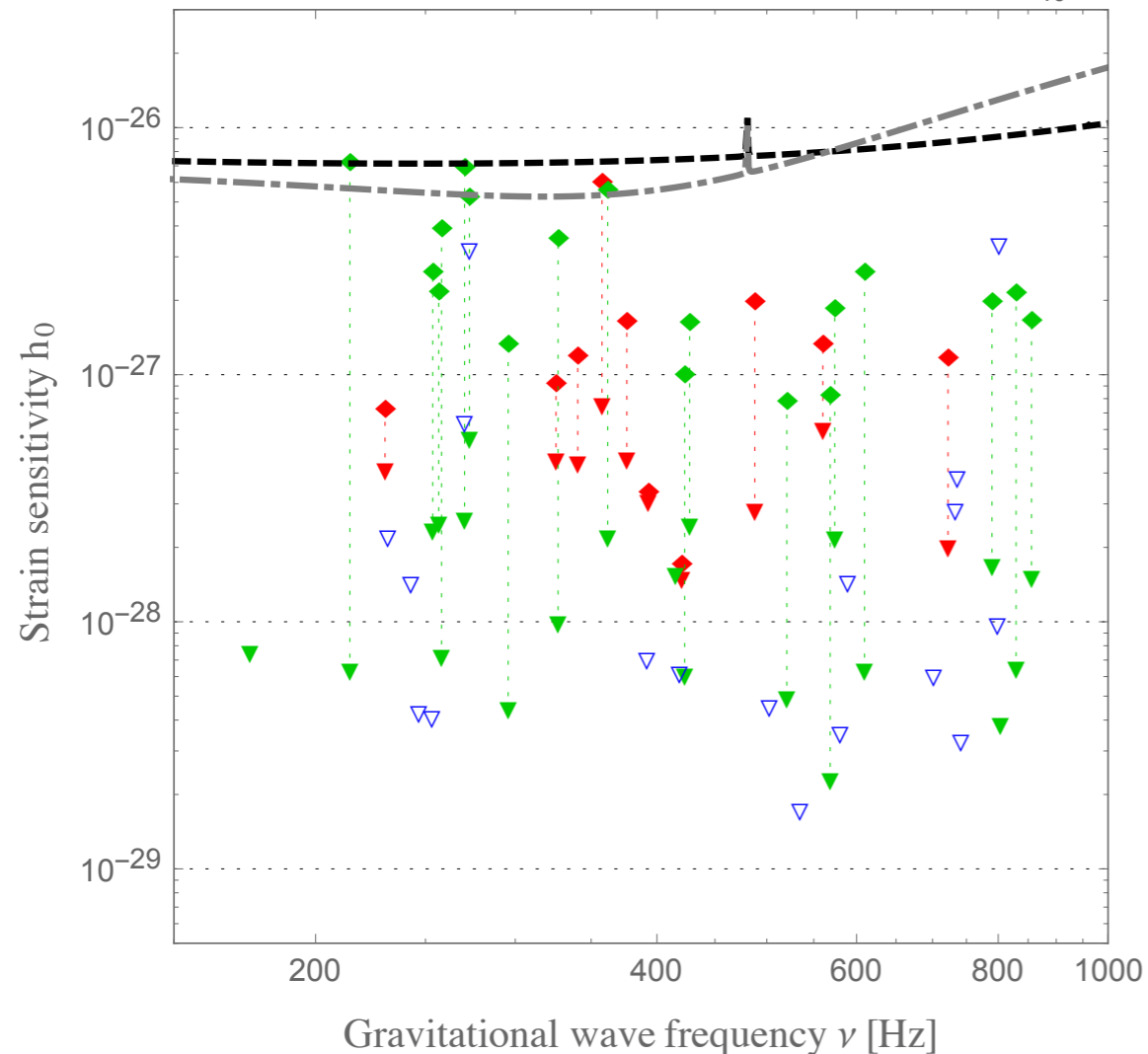
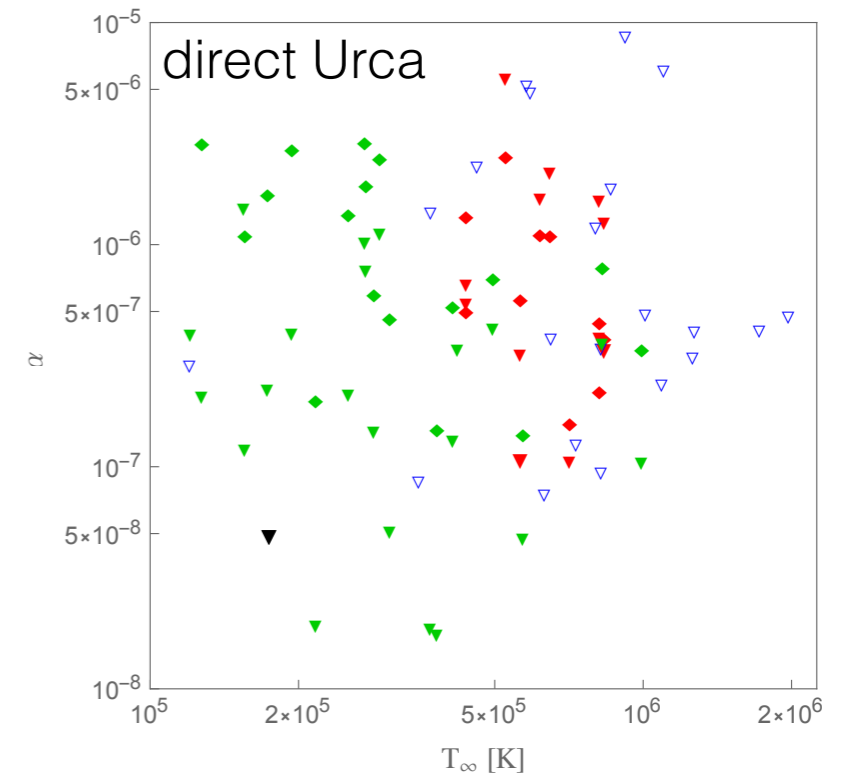
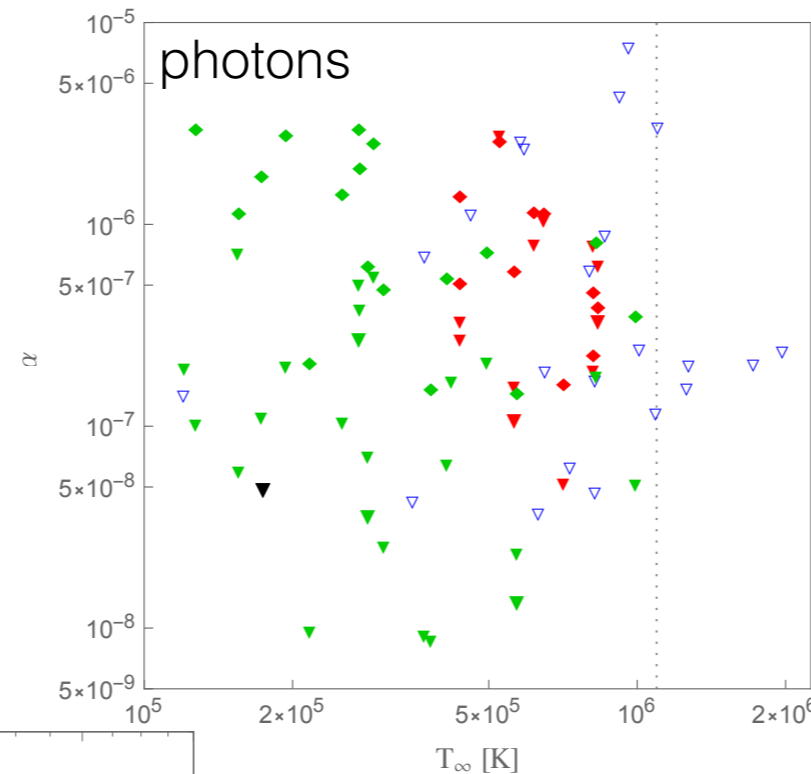
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Impact of cooling and gravitational waves

- When fast neutrino cooling is present it dominates even at low temperatures
- ✓ but the bounds are hardly affected



- Also imposes lower bounds on the gravitational wave strain
- Bad news for gravitational wave astronomy: detection of these sources with aLIGO is not possible
- But very good news for “optical r-mode astronomy” ...

Standard damping mechanisms

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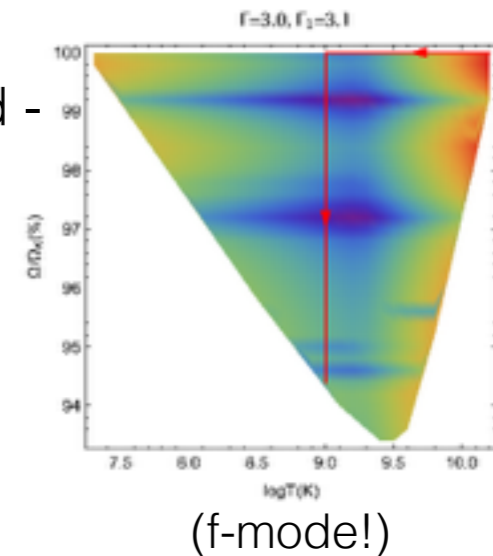
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► complicated since there are many modes ...



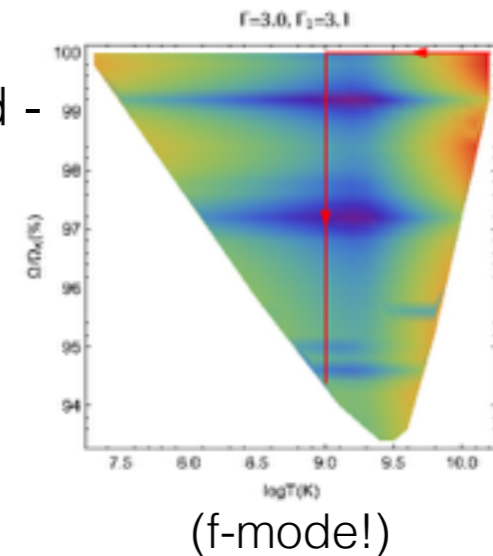
P. Pnigouras,
K. Kokkotas,
1607.03059

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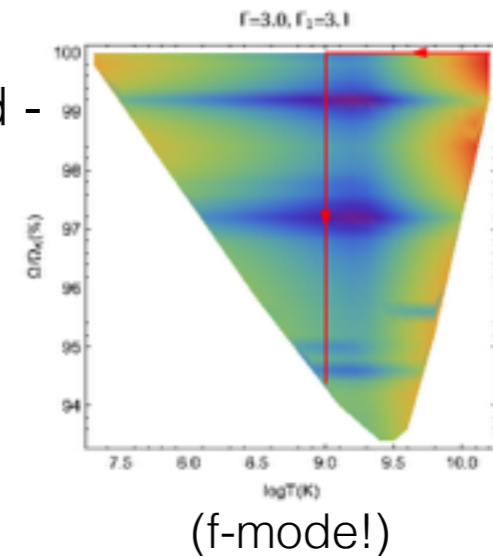


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 - L. Rezzolla, F. Lamb, S. Shapiro, APJ 531 (1999) 139,
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L. Rezzolla, in preparation
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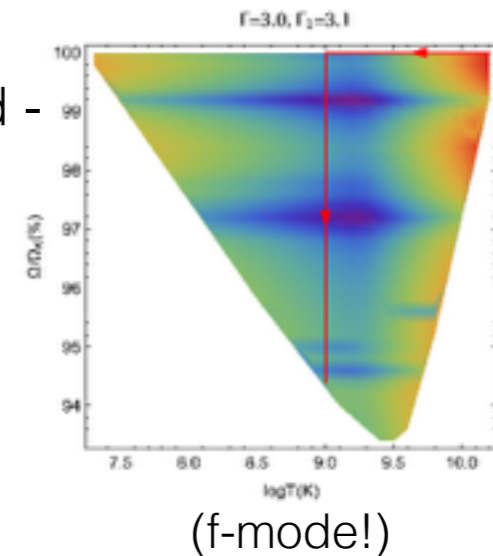


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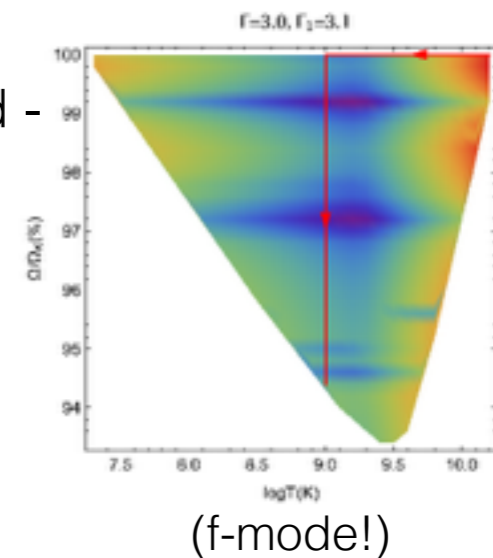
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P. Pnigouras,
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1607.03059

\rightarrow 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 exotic 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)

- **Resonance coupling** in superfluids M. Gusakov, A. Chugunov, E. Kantor, PRL 112 (2014) 151101

- **Vortex / fluxtube cutting** $\alpha_{\text{sat}} \approx 10^{-7} - 10^{-6}$

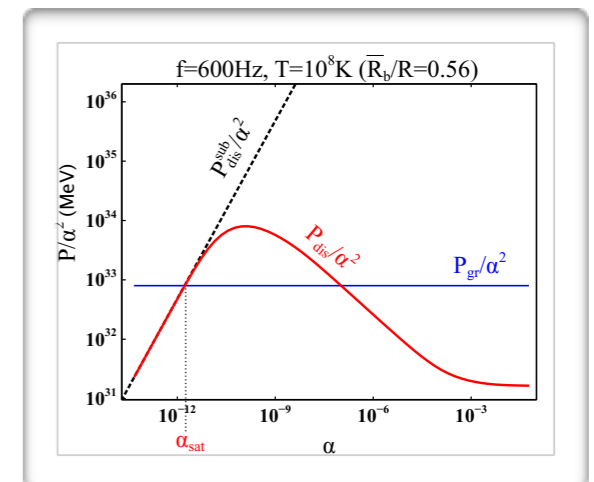
B. Haskell, K. Glampedakis and N. Andersson, MNRAS 441 (2014) 1662

- **Phase conversion in Hybrid stars**

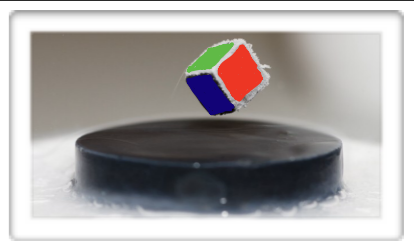
M. Alford, S. Han & K. S., PRC 91 (2015) 055804

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

- Gapped quark matter ... ?



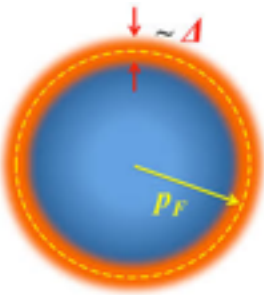
Properties of dense quark matter



- Dense quark matter is a cold and strongly degenerate Fermi system where only excitations close to the Fermi surface are accessible
- Attraction in $\bar{3}$ -channel can lead to quark pairing at high density:

Color-superconductivity

... with gaps in single particle spectra



- The ground state of dense matter is in addition to the strong dynamics determined by constraints of chemical equilibrium ($d+u \leftrightarrow u+s$, $d \rightarrow u+e^- + \bar{\nu}$, $u+e^- \rightarrow d+\nu$) and charge neutrality: $\mu_e = \mu_d - \mu_u$, $\mu_d = \mu_s$, $\frac{2n_u}{3} - \frac{n_d}{3} - \frac{n_s}{3} - n_e = 0$
- Wealth of possible condensation patterns (depends on “mismatch” μ_e):
 - fully gapped phases (e.g. color-flavor locking at asymptotic μ)
 - partially gapped phases (e.g. 2SC, CSL, ...)
 - inhomogeneous and anisotropic condensates (e.g. LOFF)

R. Sharma's talk
 - higher order condensates? (“Cooper quartets”)

M. Alford, K. S. & A. Windisch,
in preparation
 - ungapped quark matter

μ_e



Constraints on dense quark matter

- When matter with enhanced damping is present (e.g. quarks) a star spins down along the boundary of the instability region

- Due to other potential mechanisms the observed spindown rate has to be larger than the part due to r-modes, which yields the **general bound** on the **star parameters**:

$$\frac{\tilde{V}^3 \tilde{I} R^2}{\tilde{J}^6 \tilde{L} M^5} \geq \frac{2^{54} 7^3 \pi^{14}}{3^{14} 5^6} \frac{\Lambda_{EW}^8 G^3}{\Lambda_{QCD}^{18}} \frac{f_0^{11}}{|\dot{f}_0|}$$

... completely general but not very focussed

- A self bound **strange star** (and to some extent also the core of a hybrid star) has approximately constant density, which yields a

direct bound on the **material parameters**:

$$\frac{A^6 C^6 \tilde{\Gamma}^3}{\tilde{\epsilon}} \gtrsim \frac{2^{41} \pi^8}{3^3 5^5 7^3} \frac{G^3 M^5}{R^2} \frac{f_0^{11}}{|\dot{f}_0|}$$

where: $A \equiv \frac{\partial \epsilon}{\partial p}$, $C \equiv n_B \frac{\partial \mu_K}{\partial n_B}$, $\Gamma \equiv -\tilde{\Gamma} T^2 \mu_K$, $\epsilon \equiv \tilde{\epsilon} T^6$ and $\mu_K = \mu_d - \mu_s$

are susceptibilities, the non-leptonic weak rate and the emissivity

- ★ Goal: Connection to microscopic particle properties

Direct constraints on CSC phases

- Evaluating these expressions for partially paired color-superconducting phases (e.g. 2SC) in a perturbative approximation

gives a **direct bound on the strange quark mass**:

$$m_s \geq \left(\frac{2^{20} \pi^{15} 457}{3^3 5^3 7^4} \frac{G^3 \alpha_s M^3 R^4 f_0^{11}}{G_F^4 \sin^6 \theta_c \cos^4 \theta_c |\dot{f}_0|} \right)^{\frac{1}{10}}$$

- Rather insensitive to star properties except for the frequency ...
- ➔ bound arises merely from the fact that we see very fast pulsars!

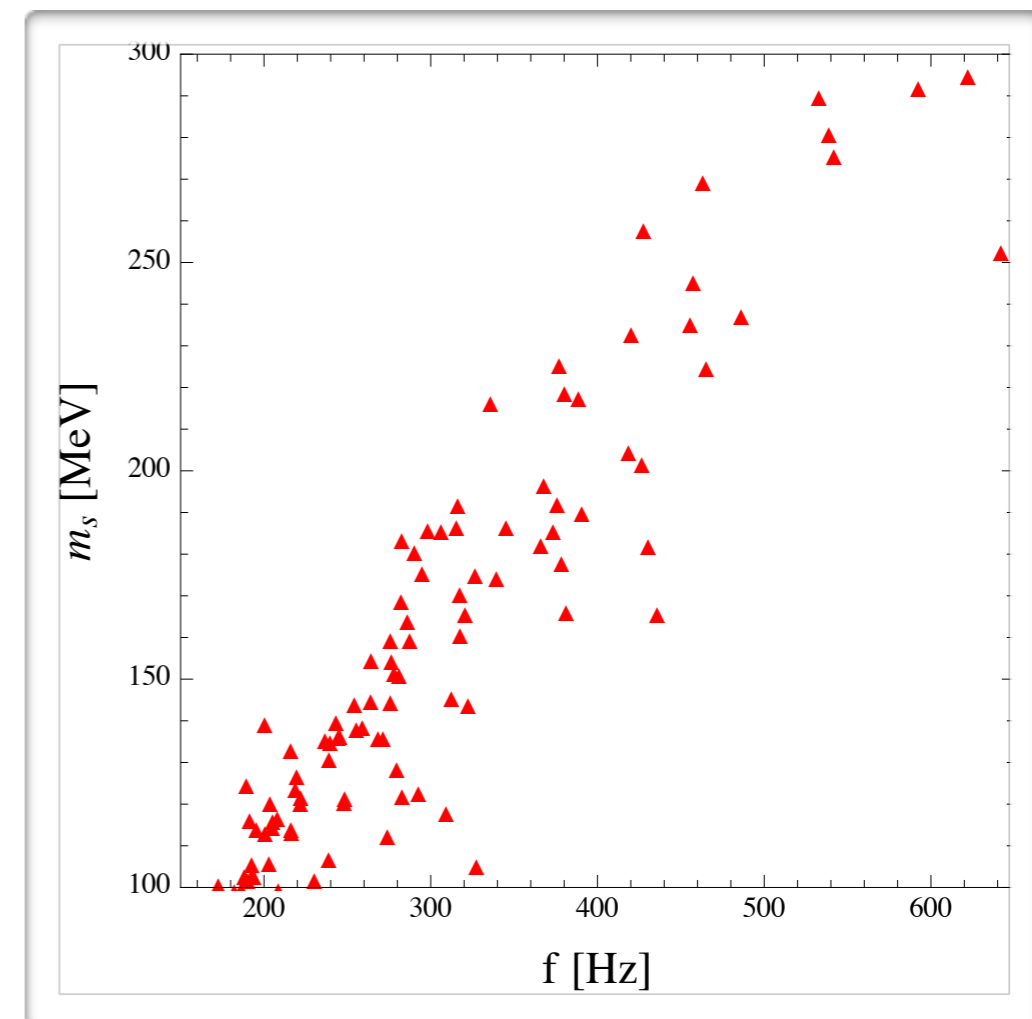
- Using conservative estimates

$$M \geq M_\odot, \quad R > 10 \text{ km}, \quad \alpha_s > \alpha_s(m_Z)$$

yields quantitative bounds from the pulsar data with result:

$$m_s \gtrsim 296 \text{ MeV}$$

- Imposes chemical potential $\mu_e \gtrsim 69 \text{ MeV}$
- Very restricting** constraint since this would require $\Delta > 100 \text{ MeV}$, which is not provided by microscopic models!



Direct constraints on CSC phases

- Evaluating these expressions for partially paired color-superconducting phases (e.g. 2SC) in a perturbative approximation

give a lower bound on the strange quark mass:

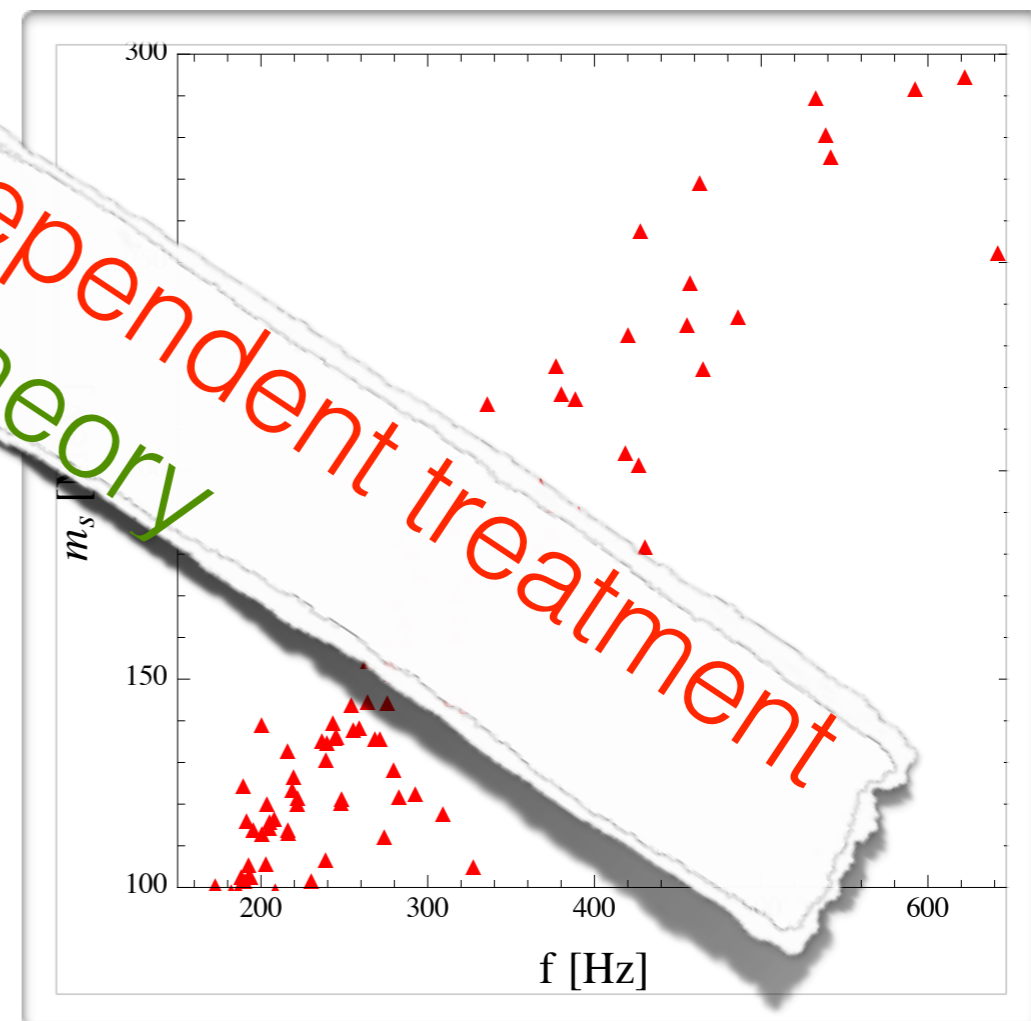
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Outlook: proper model-independent treatment in Fermi liquid theory

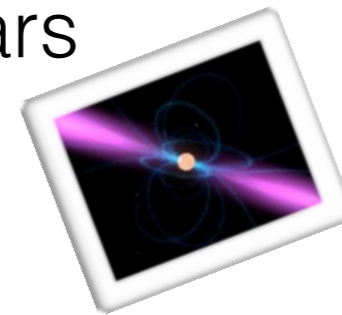
Conclusions and Outlook

- 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 known 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

- ◉ Partially gapped color superconducting phases (e.g. 2SC phase) face big problems to explain the pulsar data
- * Actual gravitational wave detection would open a novel window into the star interior and provide detailed information on star properties