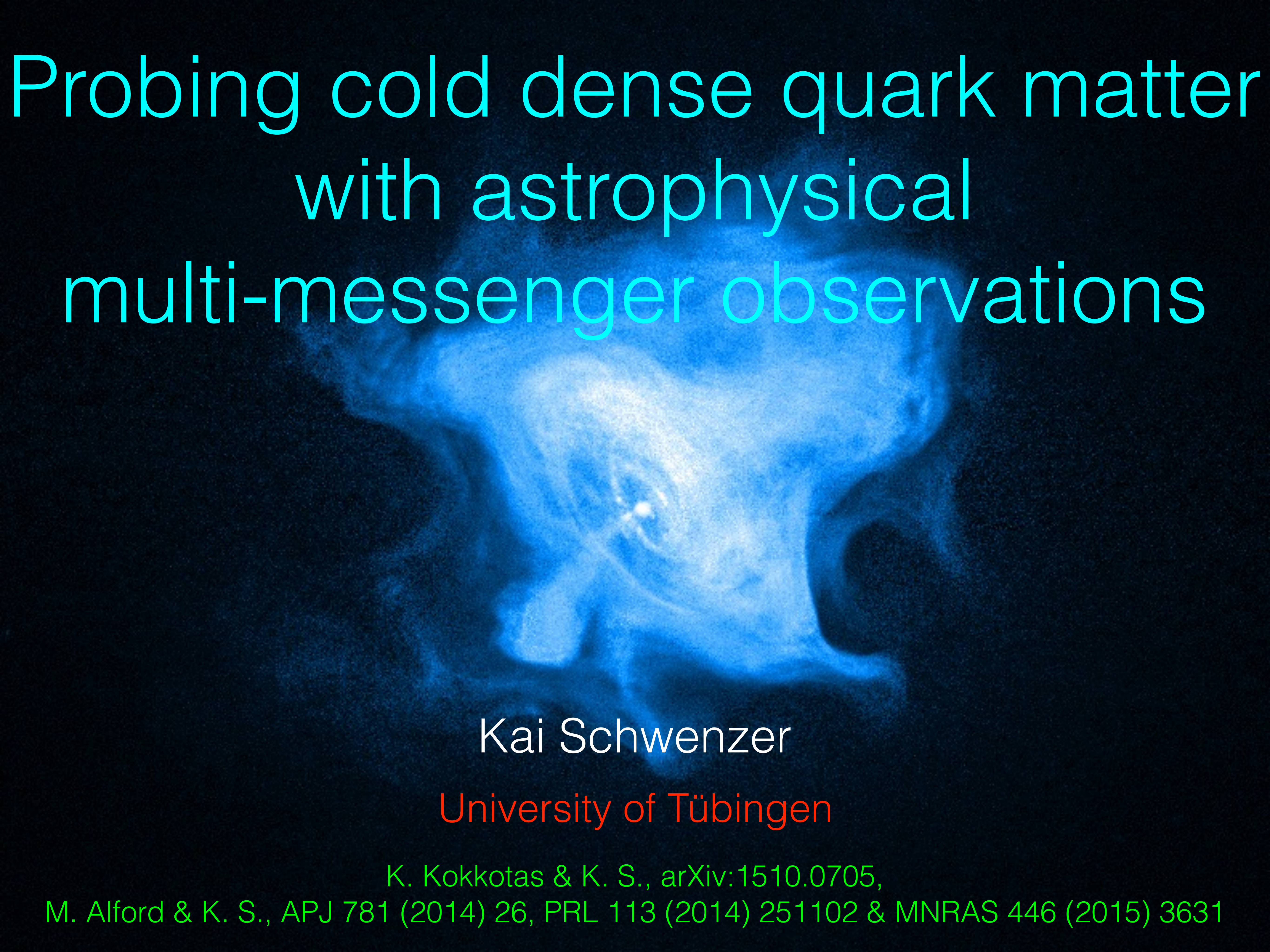
Probing cold dense quark matter with astrophysical multi-messenger observations



Kai Schwenzer

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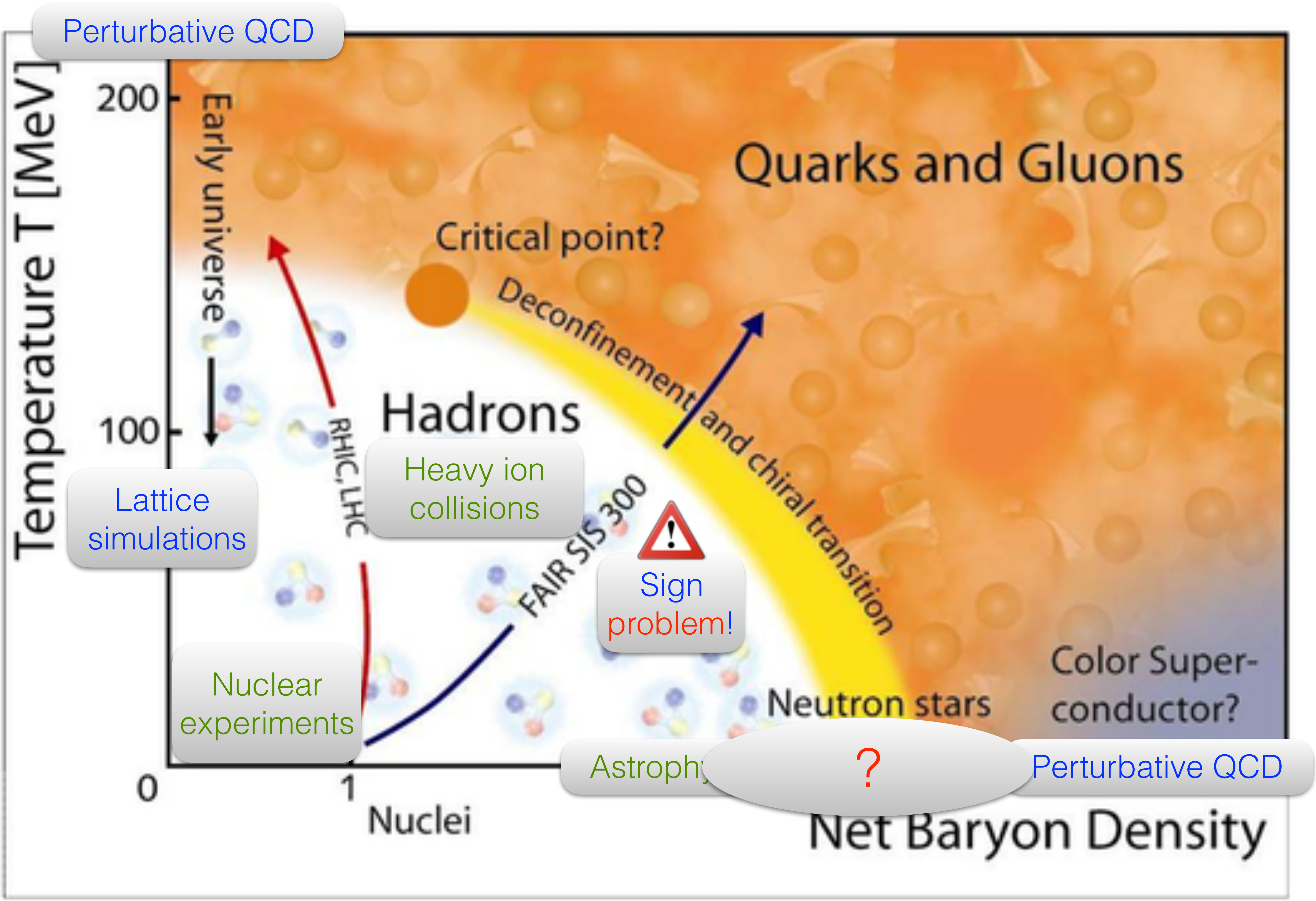
K. Kokkotas & K. S., arXiv:1510.0705,
M. Alford & K. S., APJ 781 (2014) 26, PRL 113 (2014) 251102 & MNRAS 446 (2015) 3631

QCD Phase diagram



Perturbative QCD

Lattice simulations

Heavy ion collisions

Sign problem!

Nuclear experiments

Astrophy

?

Perturbative QCD

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

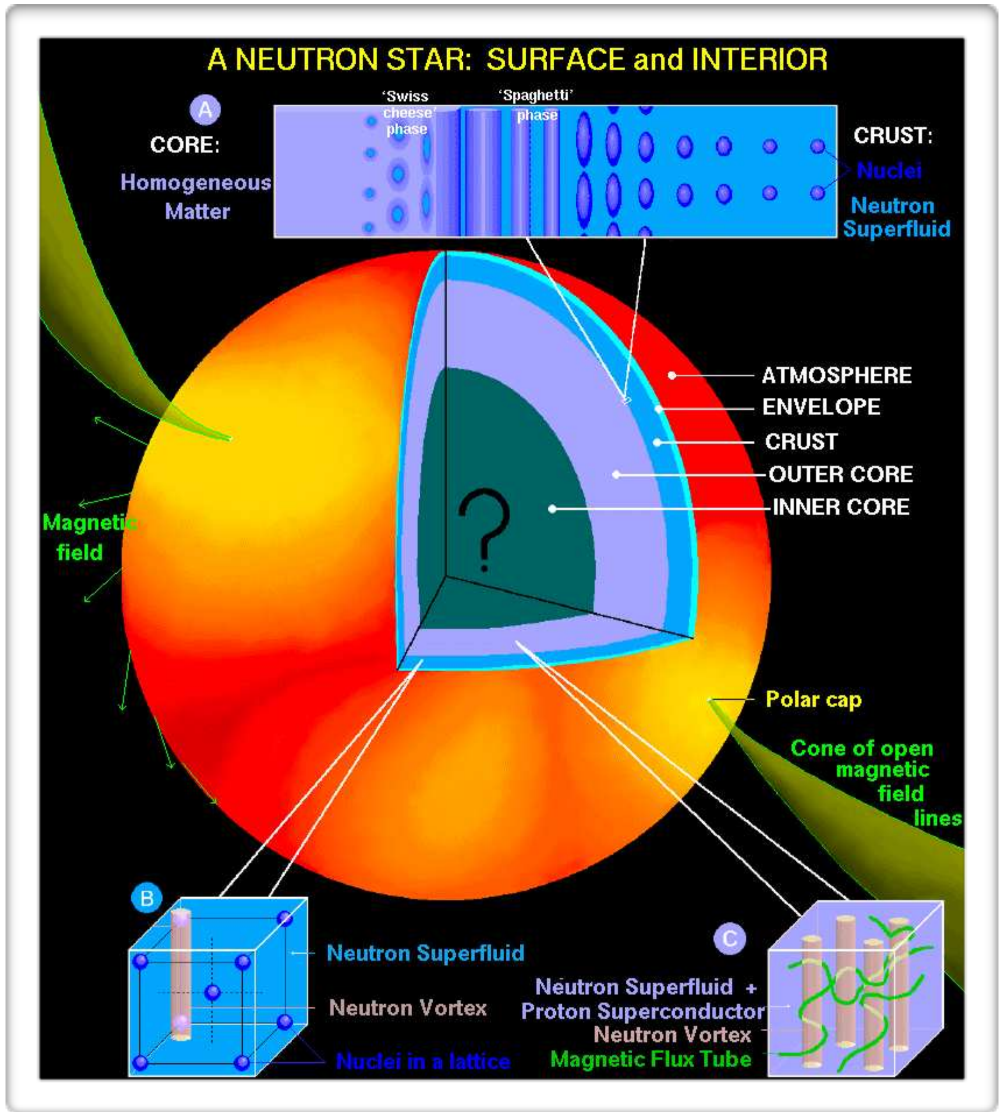


figure by D. Page

- 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

Many possibilities for dense interior …

- Classic view: neutron matter

- QCD predicts deconfinement at (very) high density

➡ Many ($\gg 10$) novel forms of matter are possible, because of:

  - many hadrons
  - many quark degrees of freedom, i.e. condensation patterns

  … these have very different properties!

Hyperons?

Meson condensates?

Mixed phases?

Quark matter?

Color super-conductivity?

Anisotropy / Inhomogeneity?

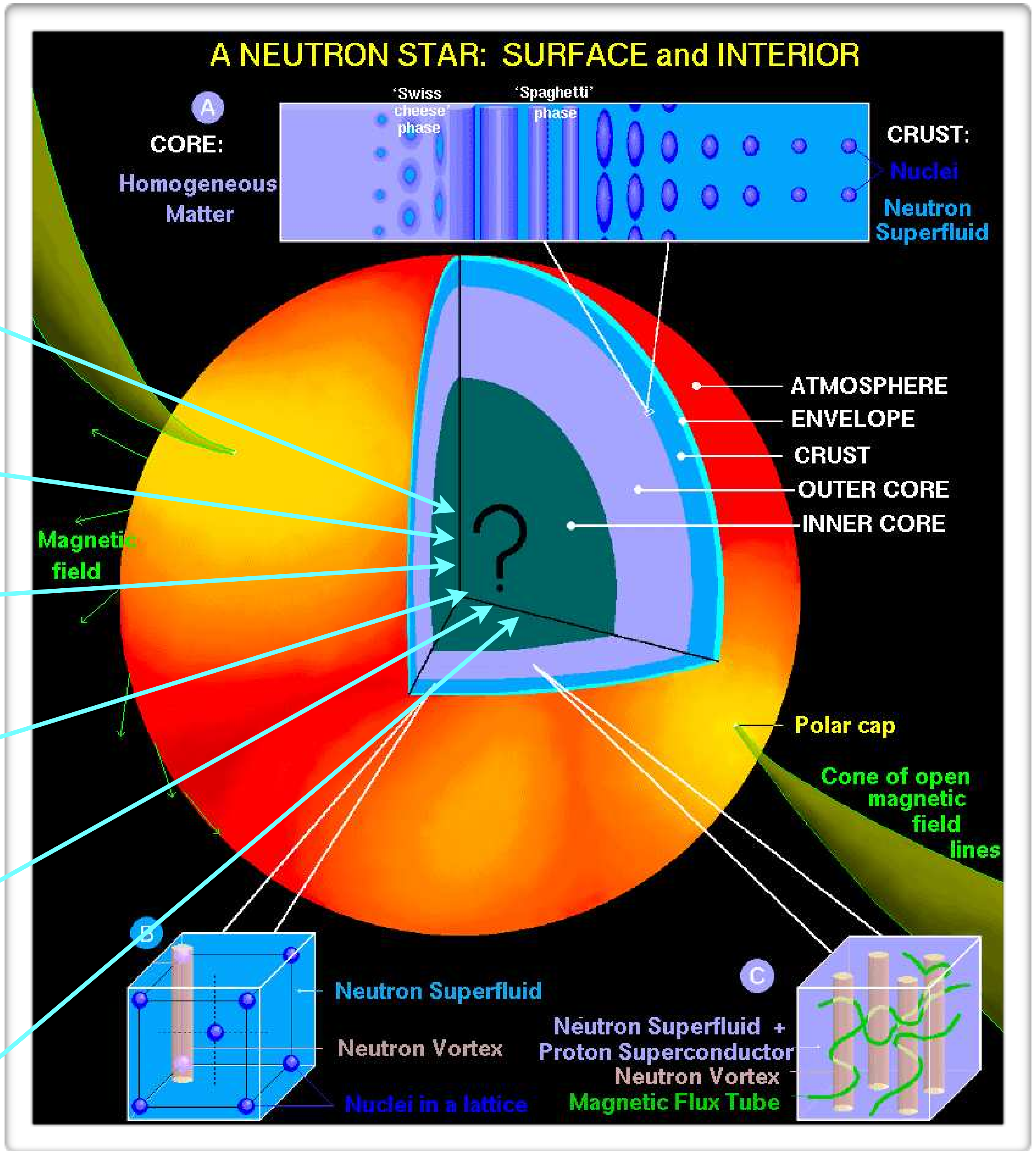
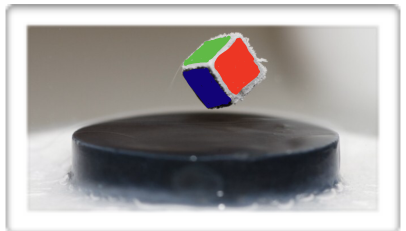


figure by D. Page

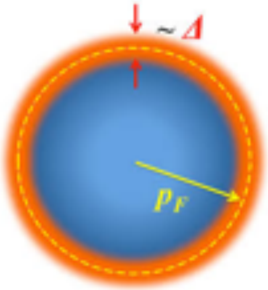
Dense matter

Properties of dense quark matter



- Dense quark matter is a cold and strongly degenerate Fermi system were at only excitations close to the Fermi surface are accessible

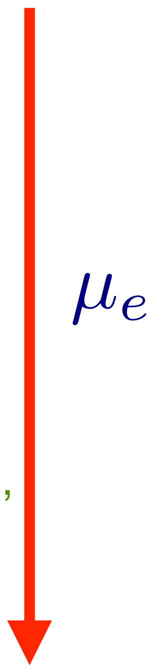
- Attraction in $\bar{3}$-channel can lead to quark pairing at high density:



Color-superconductivity … with gaps in single particle spectra

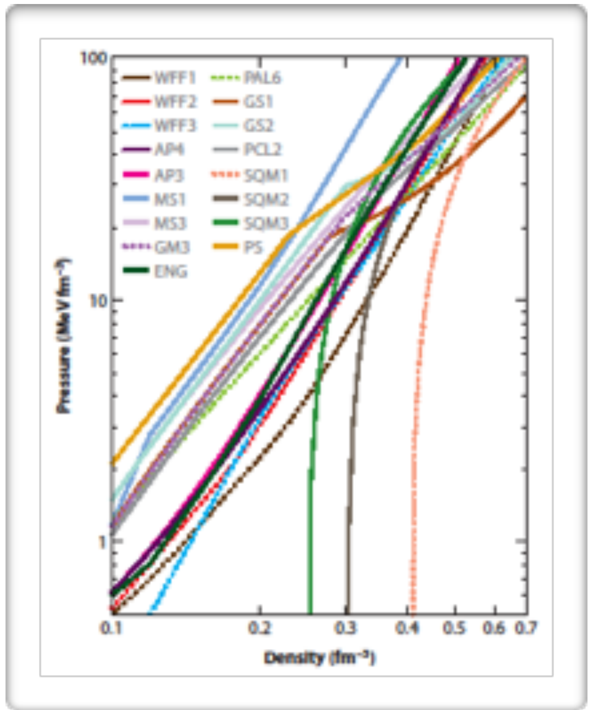
- The ground state of dense matter is in addition to the strong dynamics determined by constraints of chemical equilibrium ($d+u \leftrightarrow u+s, \begin{smallmatrix} d \to u+e^- + \bar{\nu} \\ u+e^- \to d+\nu \end{smallmatrix}$) and charge neutrality: $\mu_e = \mu_d - \mu_u \ , \quad \mu_d = \mu_s \ , \quad \frac{2n_u}{3} - \frac{n_d}{3} - \frac{n_s}{3} - n_e = 0$

- 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, …)
  - inhomogenous and anisotropic condensates (e.g. LOFF)
  - higher order condensates? (“Cooper quartets”) Alford, Schwenzer & Windisch, in preparation
  - ungapped quark matter



There is more than the equation of state …

- The equation of state completely determines *static* properties …

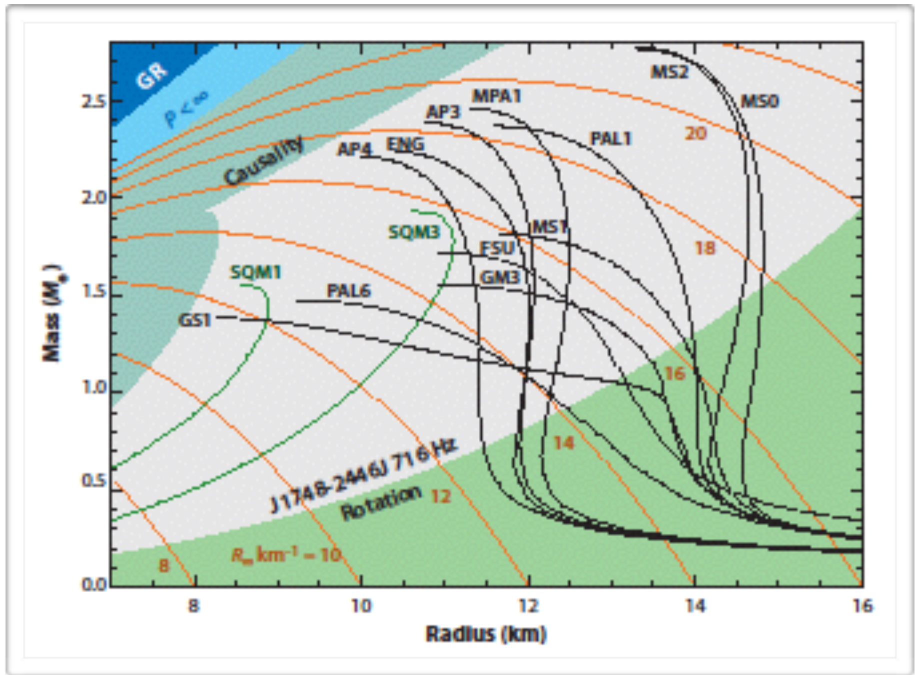


→

Oppenheimer Volkoff

←

F. Özel, G. Baym & T. Güver, PRD 82 (2010) 101301



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

… but solutions are very similar for different forms of dense matter

✦ Compact stars are (fortunately) not static:
Dynamic material properties (emissivities, viscosities, transport properties) probe the low energy degrees of freedom of matter

- ‣ fermionic vs. bosonic, strongly vs. weakly interacting, …
- ✓ power counting in small parameters T/μ, α_s/α_{em}, …
  - ➡ material properties are drastically different for many phases!

Dissipation in dense matter

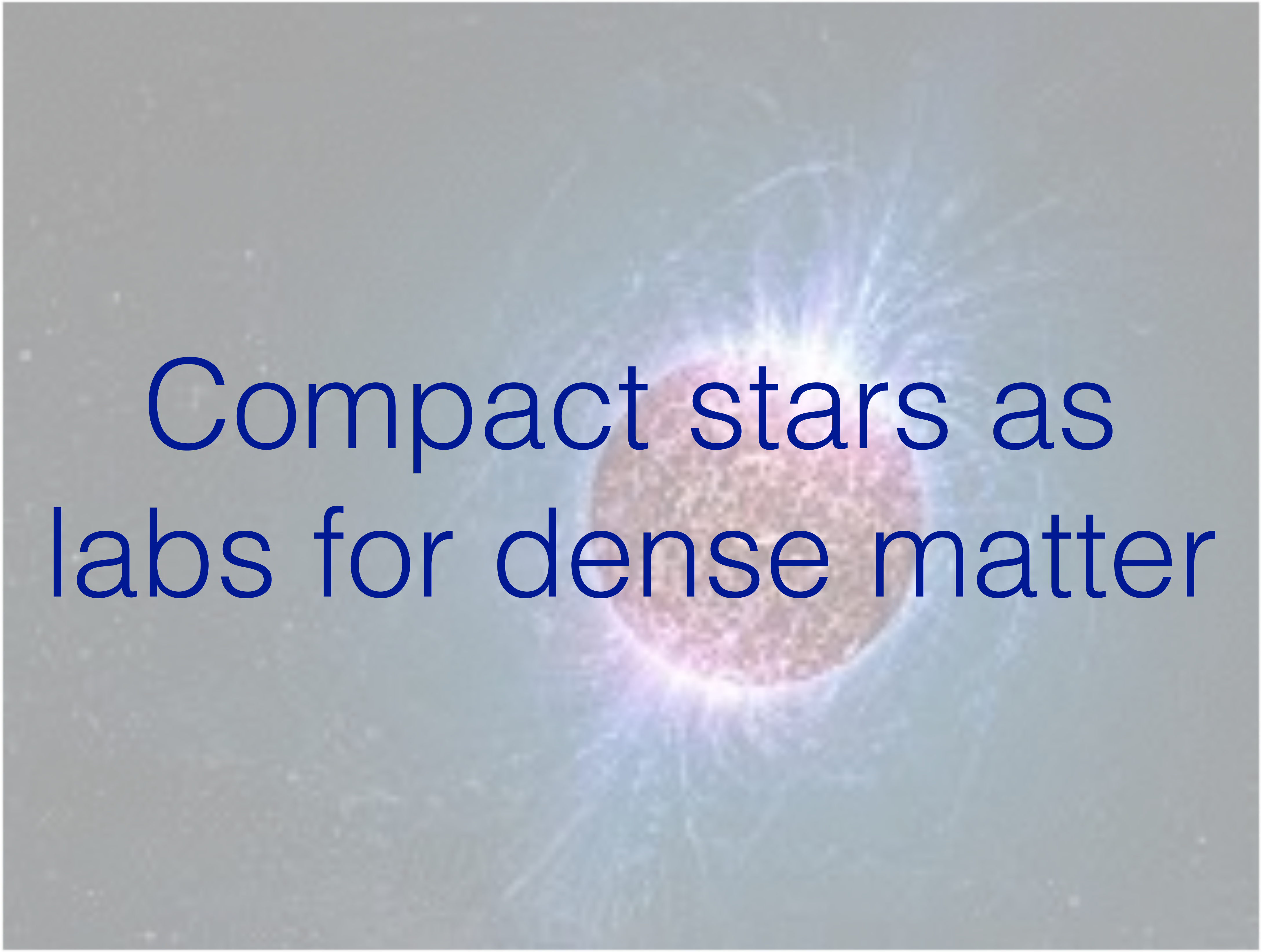
- Shear viscosity from particle scattering (strong/EM interaction)

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, *et.al.*, 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, *et.al.*, PRD 84 (2011) 123007
ungapped quark matter	$q+q\rightarrow q+q$	$\eta\sim(T/\mu)^{-5/3}$	Heiselberg, *et.al.*, PRD 48 (1993) 2916
CFL quark matter	$H\rightarrow H+H$	$\eta\sim(T/\mu)^{4}$	Manuel, *et. al.*, JHEP 09 (2005) 76; Andersson, *et. al.*, PRD 82 (2010) 023007

- Bulk viscosity from particle transformation (weak interaction)

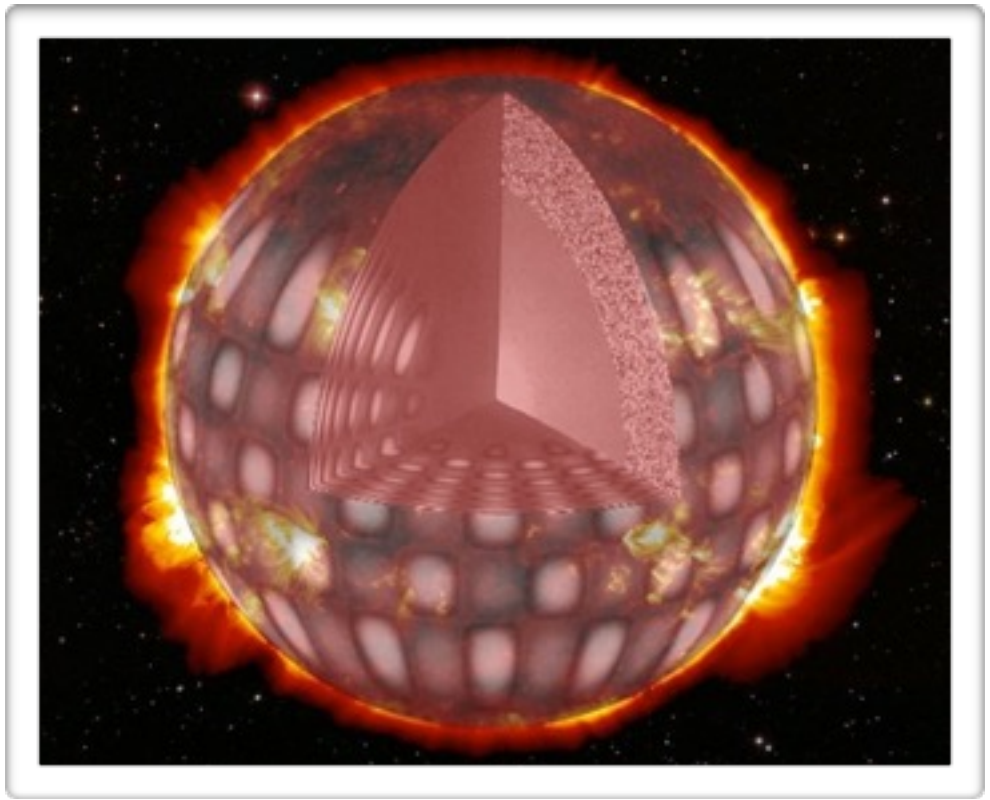
candidate phase	dominant processes	bulk viscosity: low T	reference
(ungapped) nuclear matter	$n(+n)\rightarrow p(+n)+e+\bar{\nu}$ $p(+n)\rightarrow n(+n)+e+\nu$	$\zeta\sim(T/\mu)^{6}$ or $(T/\mu)^{4}$	Sawyer, PLB 233 (1989) 412; Haensel, *et.al.*, PRD 45 (1992) 4708
hyperonic matter	$n+n\rightarrow p+\Sigma^{-},\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

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



Compact stars as labs for dense matter

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

advanced LIGO (2015)

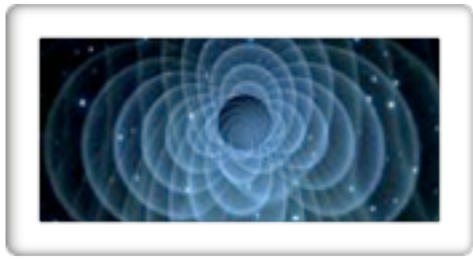
- Star oscillations are damped by viscosity, which is induced by microscopic particle interactions

… links macroscopic observables to microphysics of dense matter

R-mode oscillations

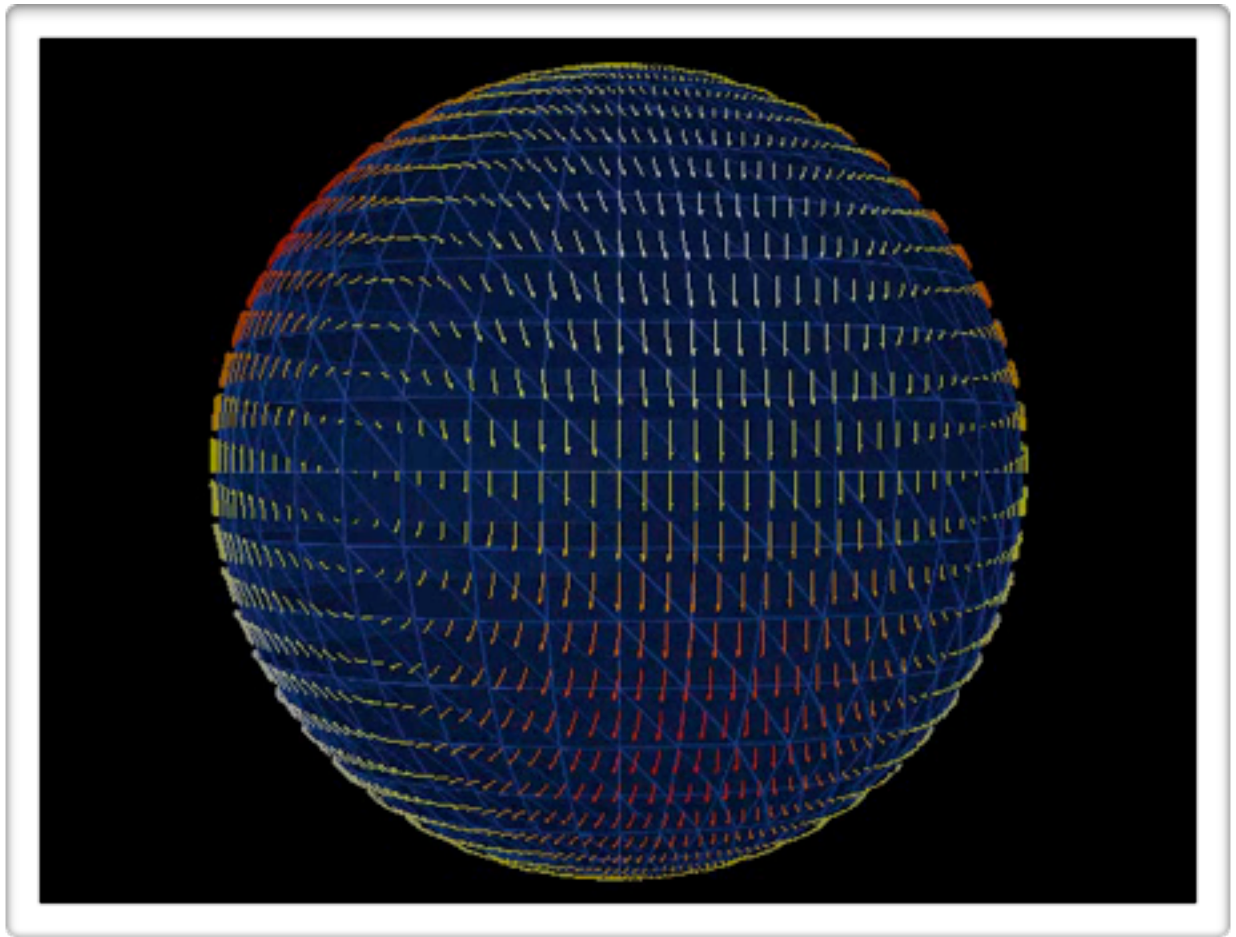
- R-mode: Eigenmode of a rotating star which is unstable against gravitational wave emission

N. Andersson, Astrophys. J. 502 (1998) 708,
K. Kokkotas, LRR 2 (1999) 2,
N. Andersson, K, Kokkotas, IJMP D10 (2001) 384



Large amplitude r-modes could cause a quick spindown

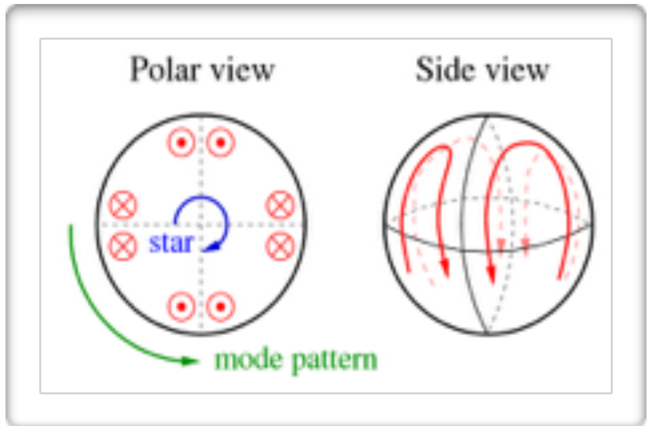
L. Lindblom, et. al., PRL 80 (1998) 4843,
B. J. Owen, et. al., Phys. Rev. D 58 (1998) 084020



Visualization by M. Beilicke

- But r-mode growth has to be stopped by some non-linear damping mechanism, e.g.:
  - non-linear hydro effects - large $\alpha_{\rm sat} = O(1)$
    L. Lindblom, et. al., PRL 86 (2001) 1152,
    W. Kastaun, Phys.Rev. D84 (2011) 124036
  - non-linear viscous damping
    M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051
  - mode-coupling - moderate $\alpha_{\rm sat} = O(10^{-5})$
    P. Arras, et. al., Astrophys. J. 591 (2003) 1129,
    R. Bondarescu, et. al., Astrophys. J. 778 (2013) 9
  - vortex-fluxtube cutting
    B. Haskell, K. Glampedakis and N. Andersson, MNRAS 441 (2014) 1662

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



Multi-messenger data

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

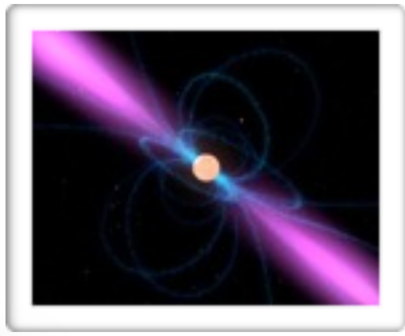
- Thermal X-ray data: ms x-ray pulsars in (low mass) binaries (LMXBs) currently accrete from a companion which allows a temperature measurement (10+ sources)

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

  - ✤ T ‘s involve modeling and are somewhat uncertain

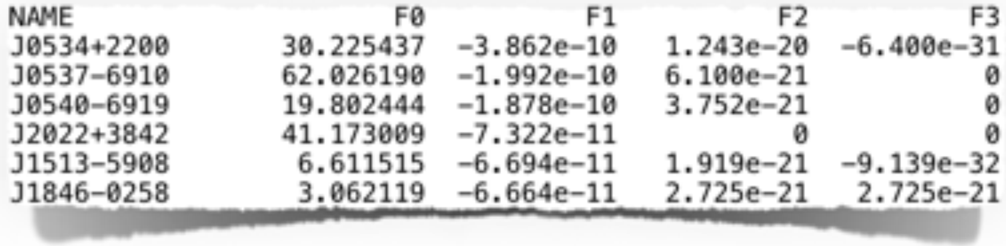
e.g. Haskell, et. al., MNRAS 424 (2012) 93

- 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



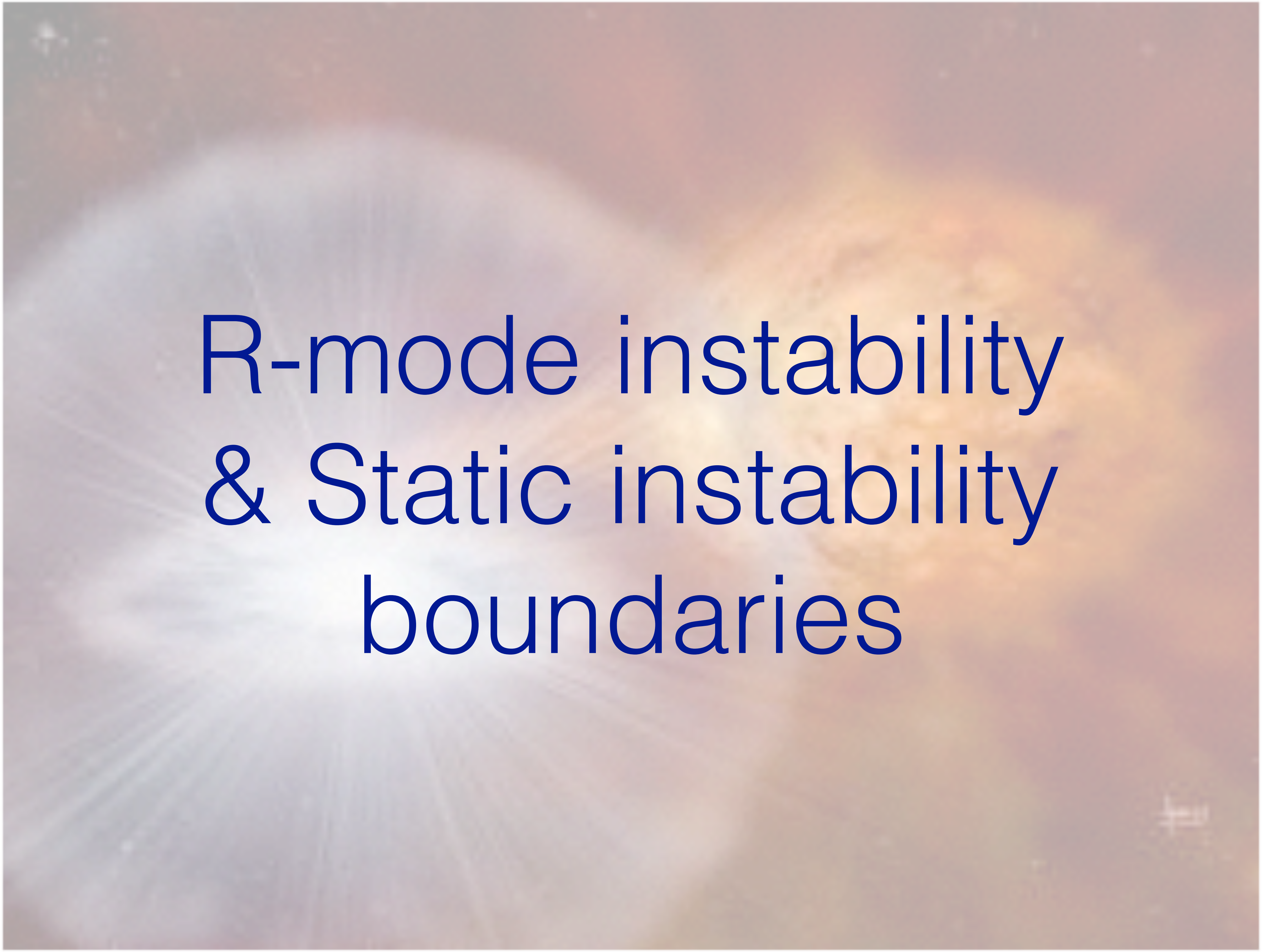
$\dot{f} < 0$

  - ✦ 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
```

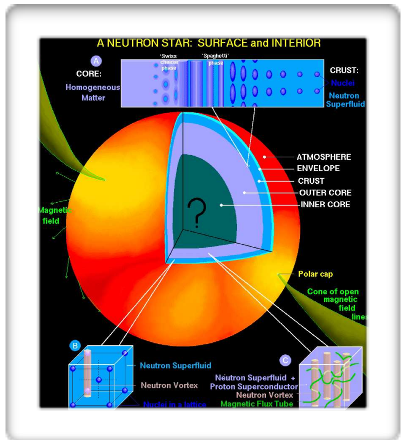
- (Future) Gravitational waves:
  - ★ only direct way to probe the star’s interior
  - ✓ GW astronomy could even detect “hidden sources”



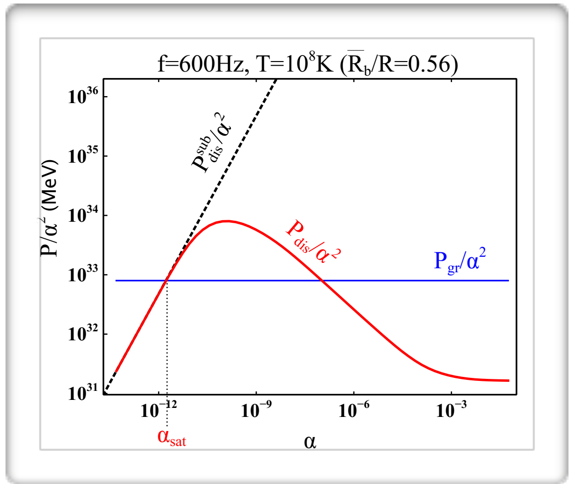
R-mode instability & Static instability boundaries

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 $\alpha_{\text{sat}} < O(10^{-10})$

“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:

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

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

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

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

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

with

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

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

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

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

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

- 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:

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

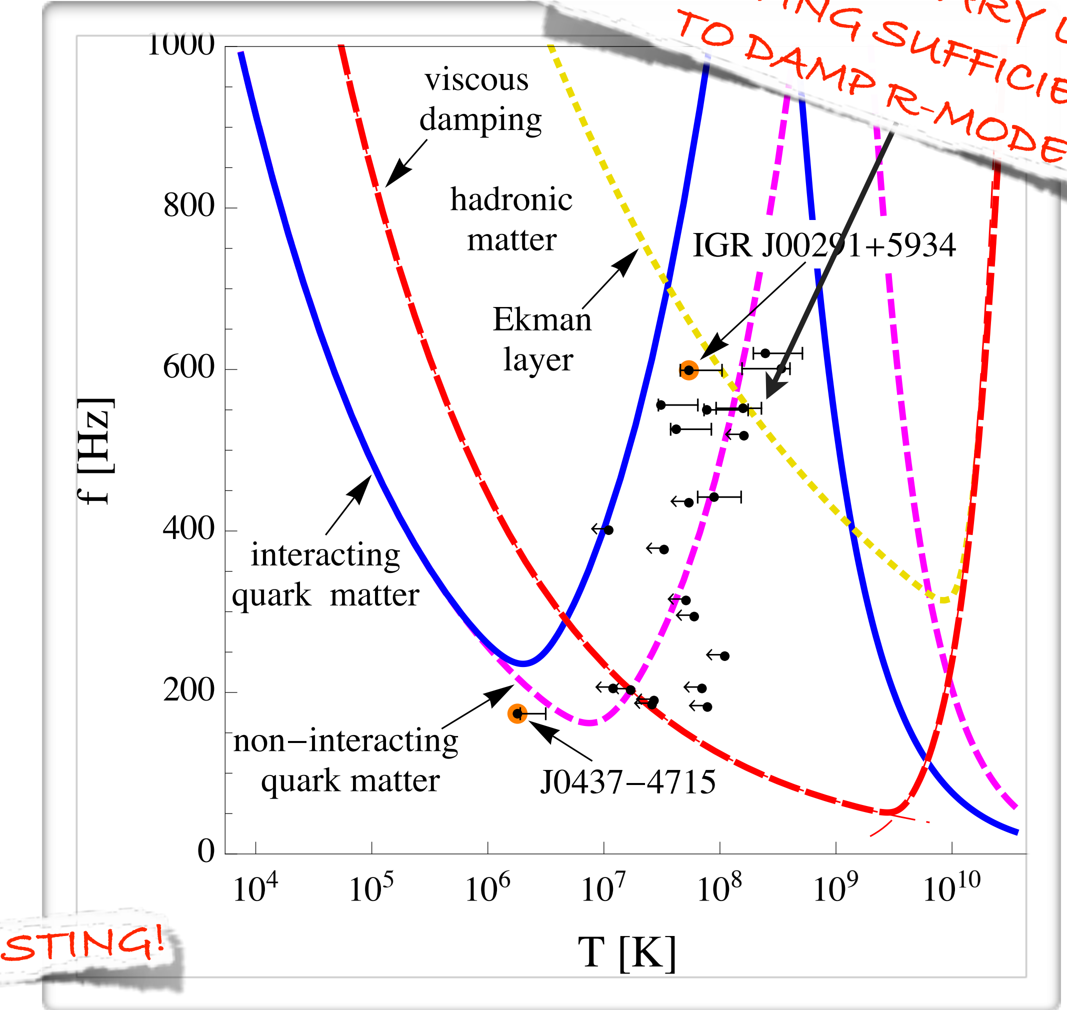
Extremely insensitive to microscopic details … but not to the form of dense matter!

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!

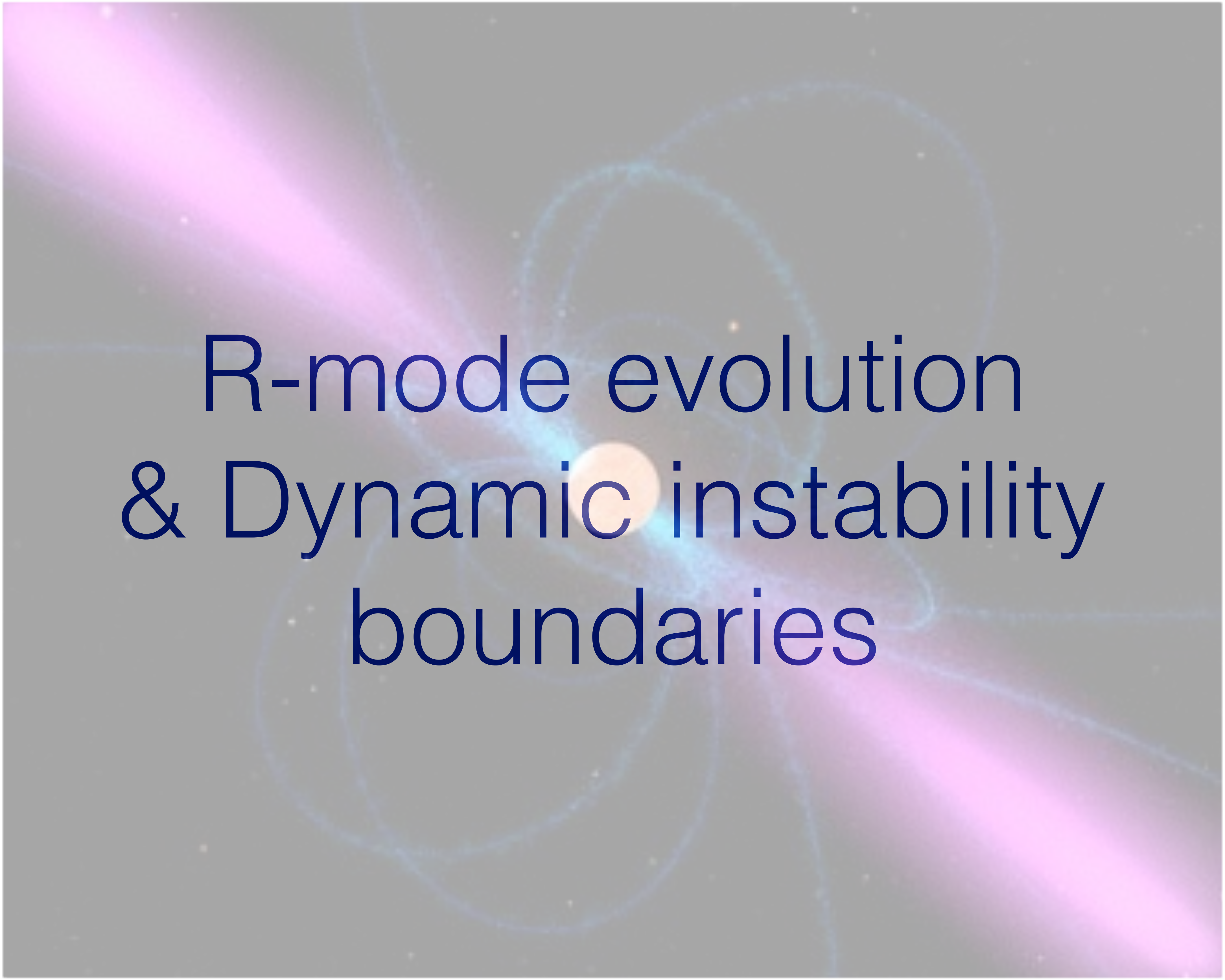
BORING TRIVIAL CASE



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)



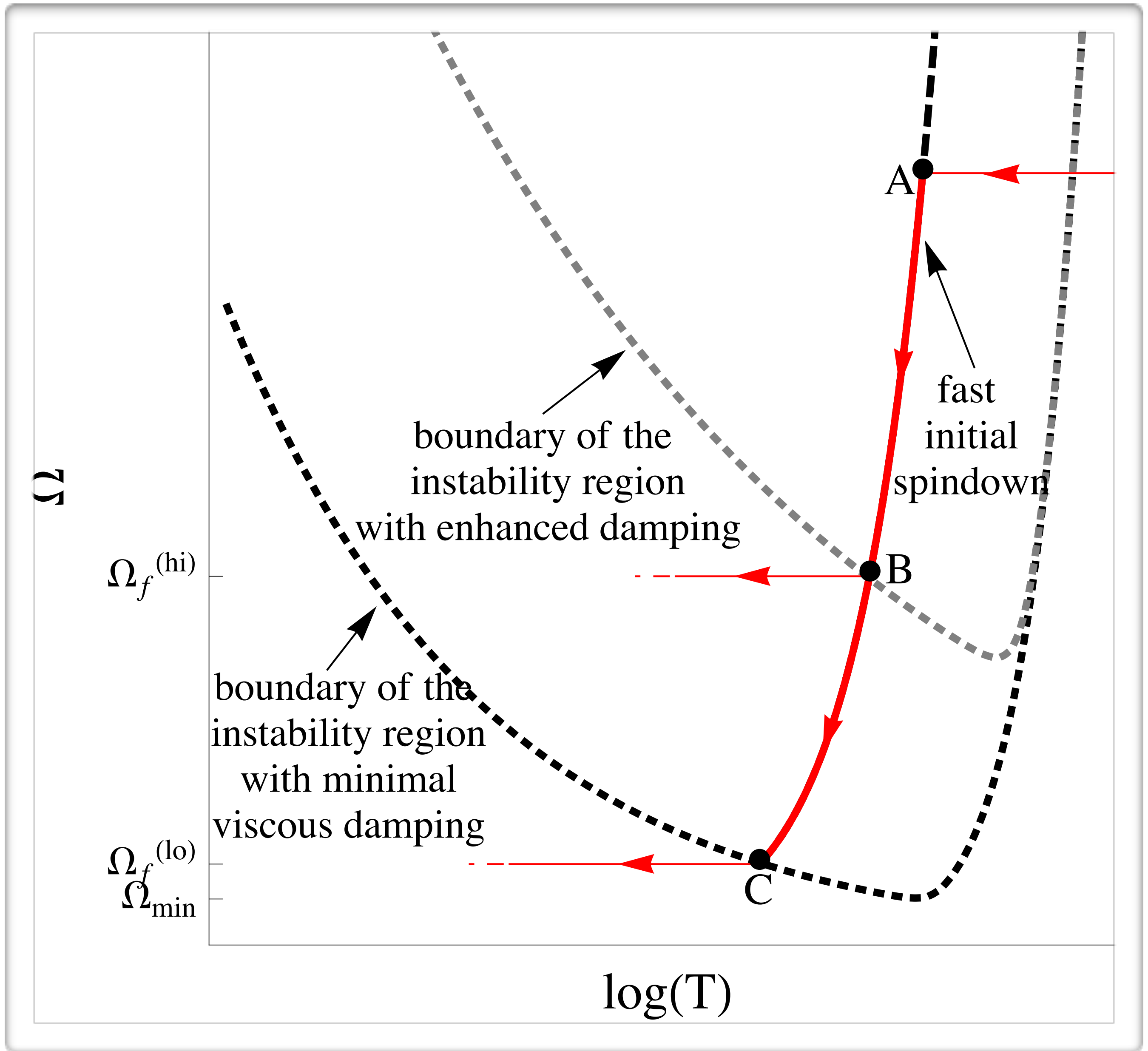
R-mode evolution & Dynamic instability boundaries

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

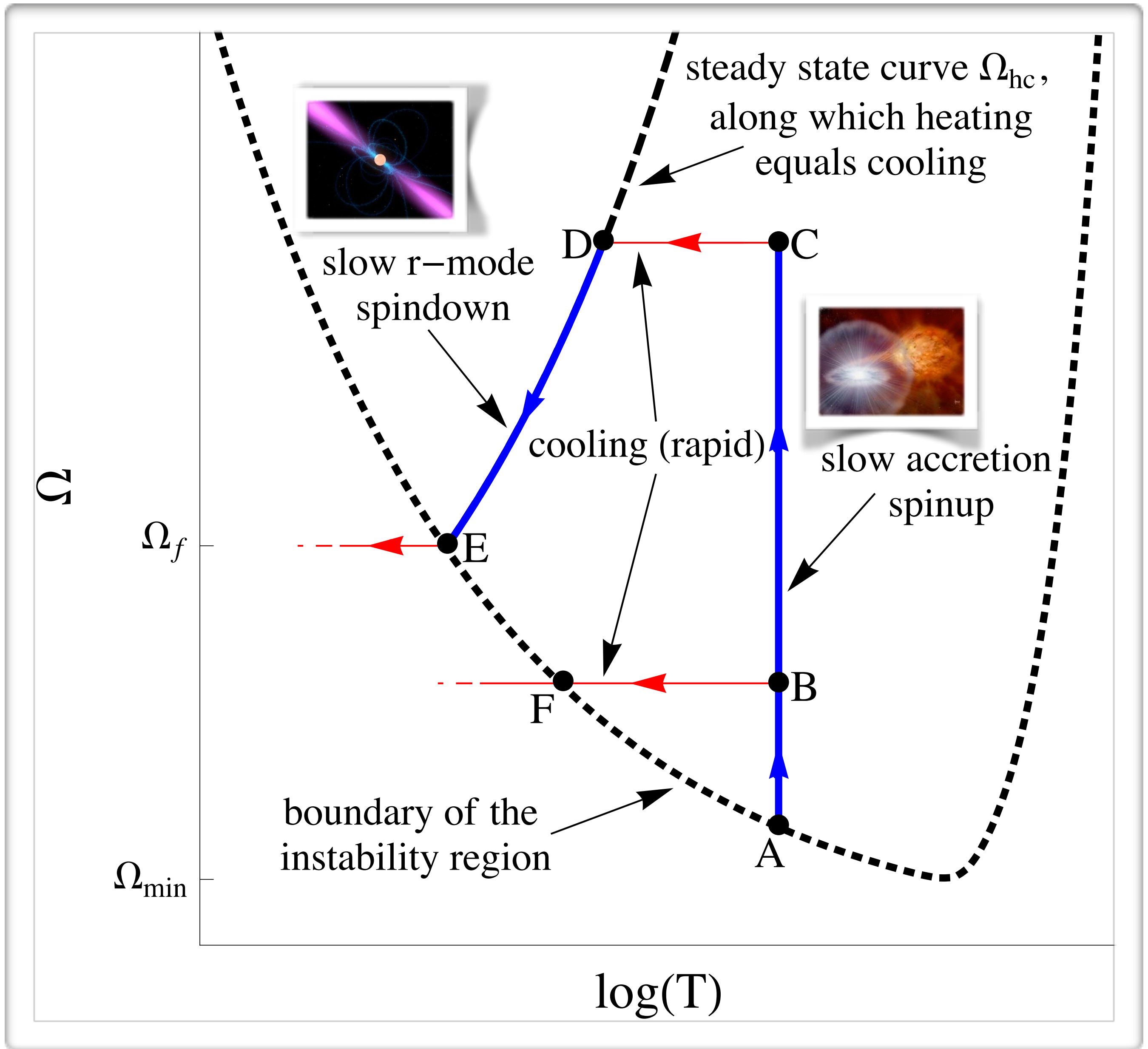
- Pulsars can be spun up to high frequencies (so far $716\,\mathrm{Hz}$) by accretion in low mass x-ray binaries (LMXBs): “Recycling”, which heats them strongly

- 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

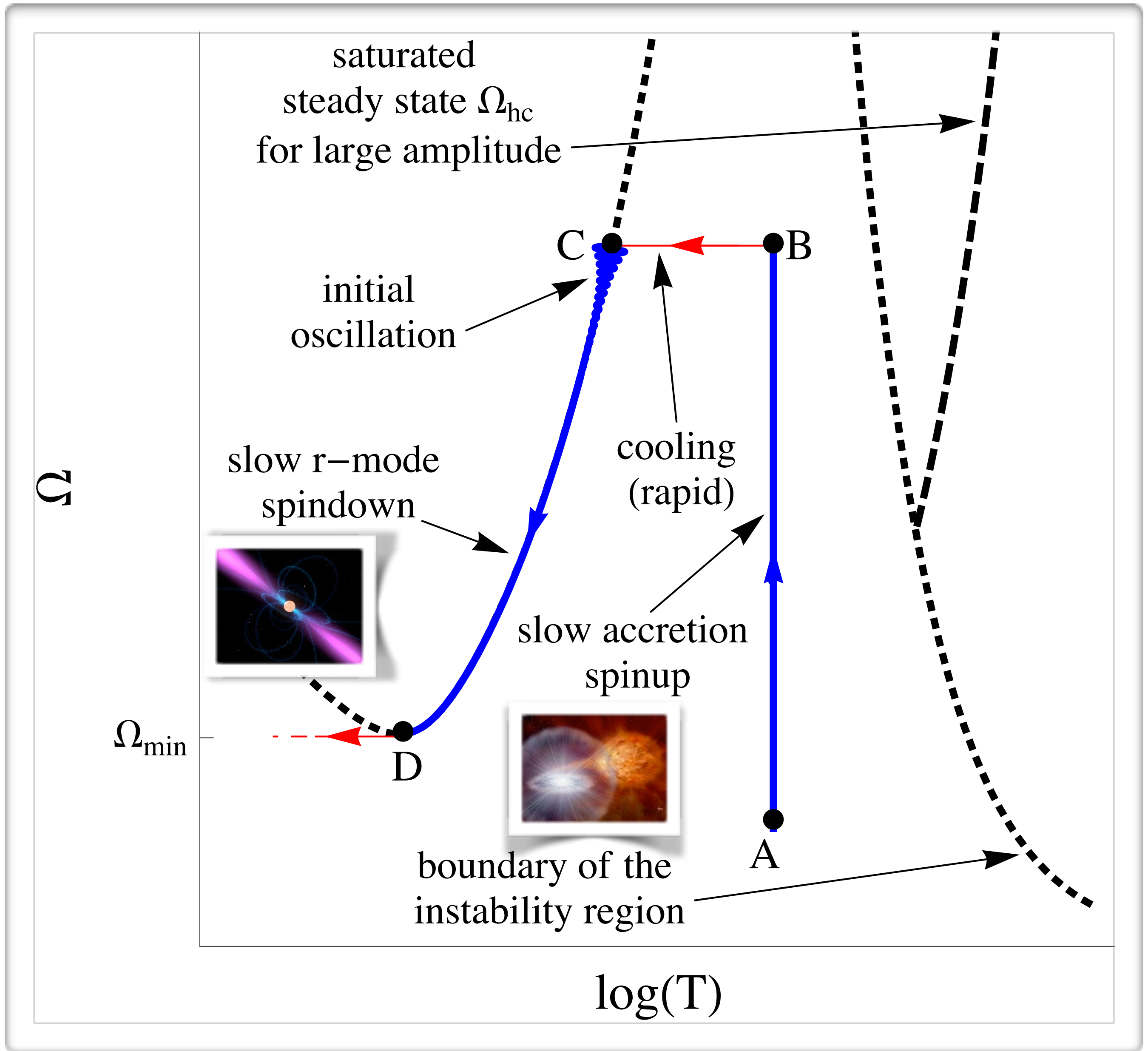
Pulsar evolution with enhanced damping

- 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



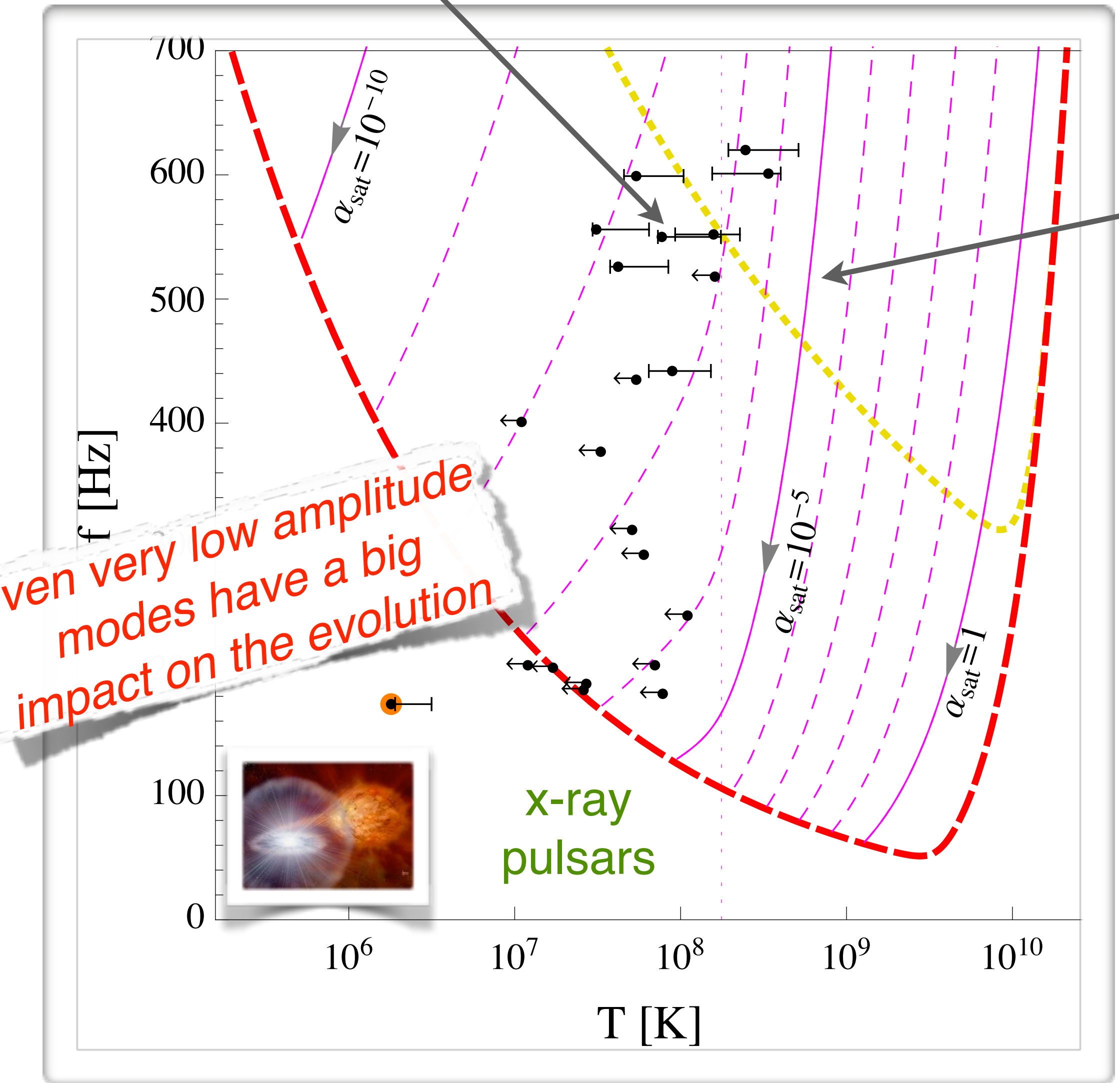
“Boundary straddling scenario”

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

x-ray pulsars

Pulsar evolution & r-mode instability

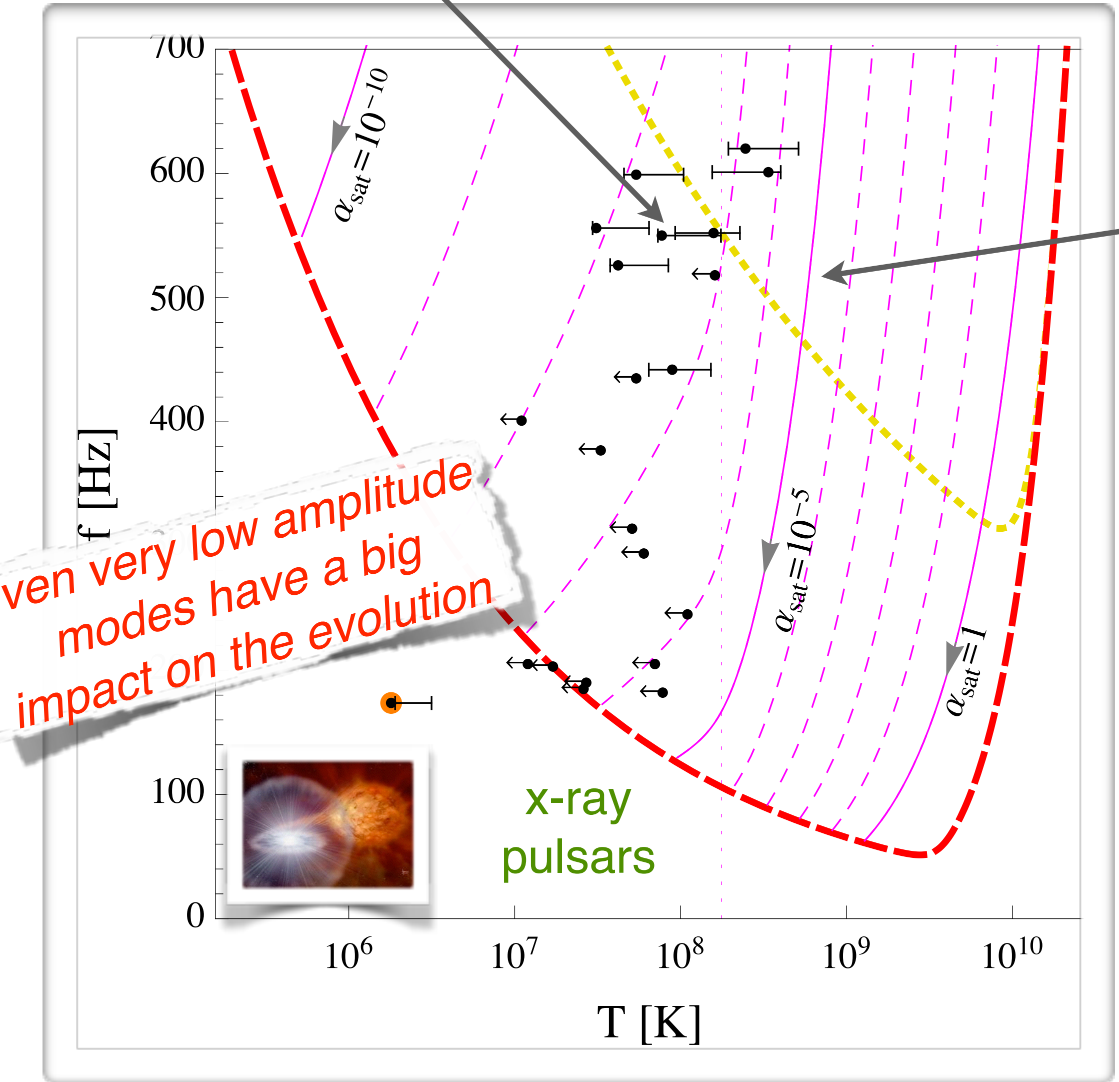
temperatures have large uncertainties

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

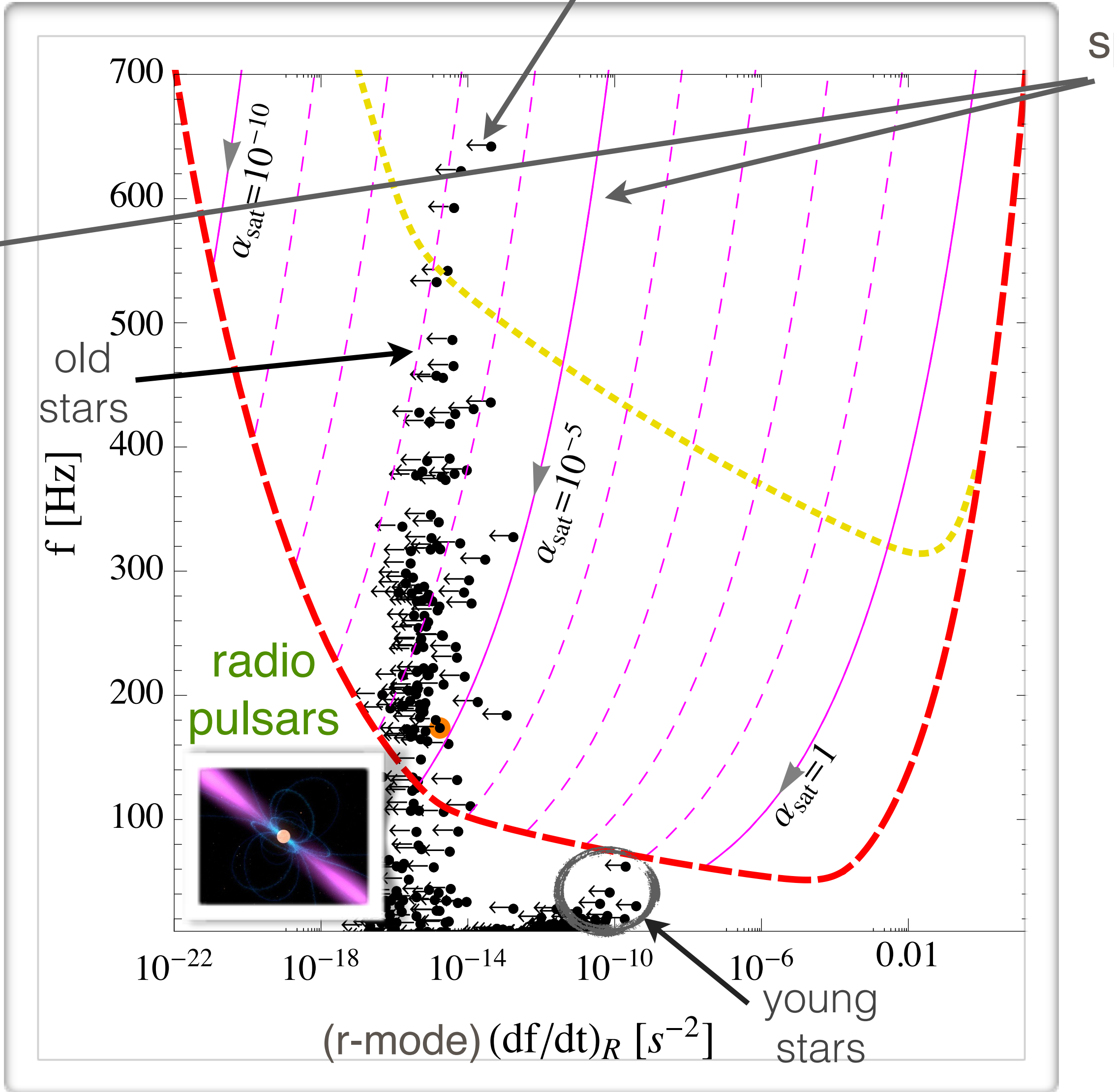
observed spindown rates are upper limits for r-mode contribution

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

spindown curves



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



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

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

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

Enhanced damping required!

Pulsar evolution & r-mode instability

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

observed spindown rates are
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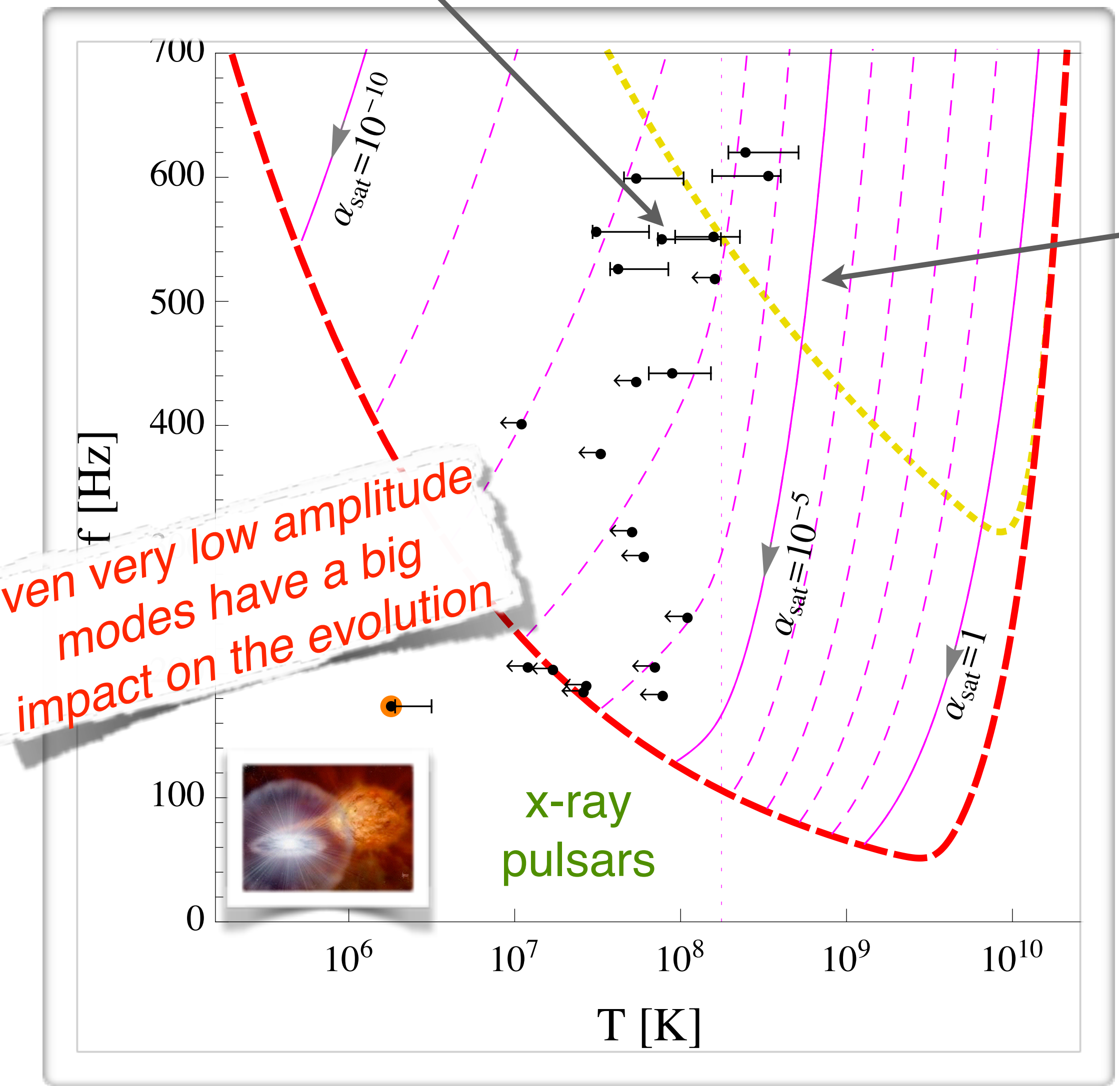
Manchester, et. al.,
astro-ph/0412641

spindown
curves



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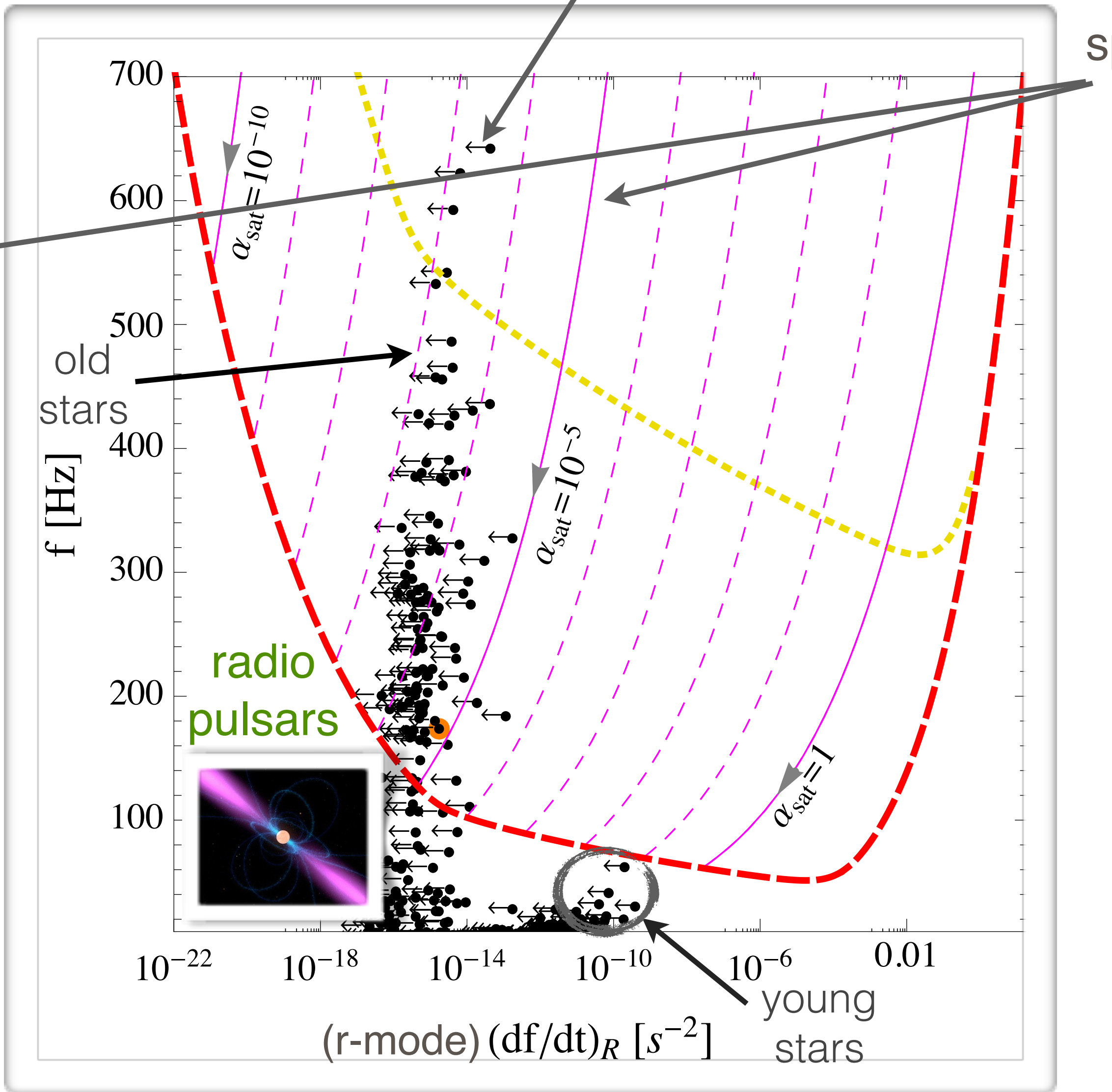
modes have a big
impact on the evolution

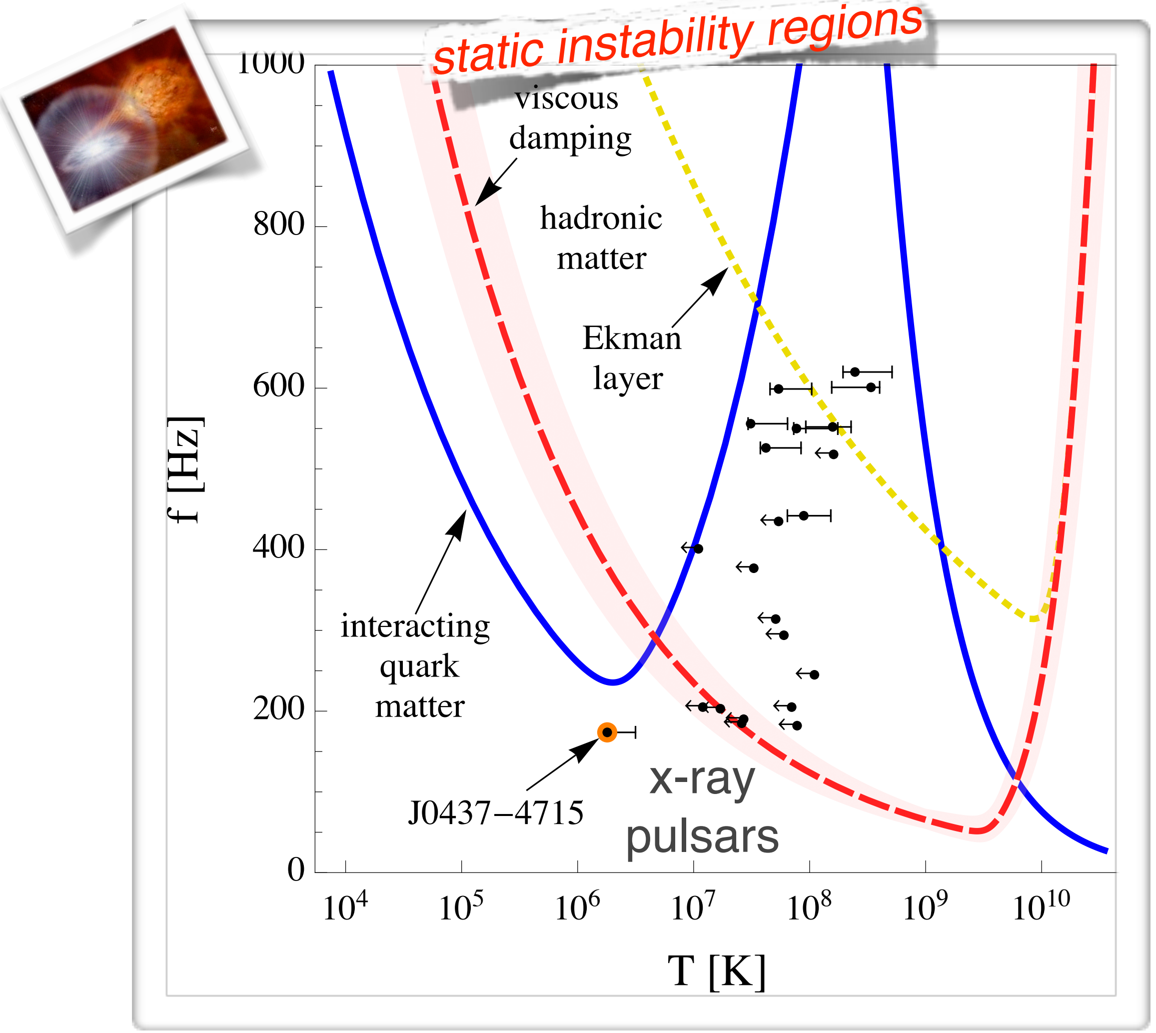


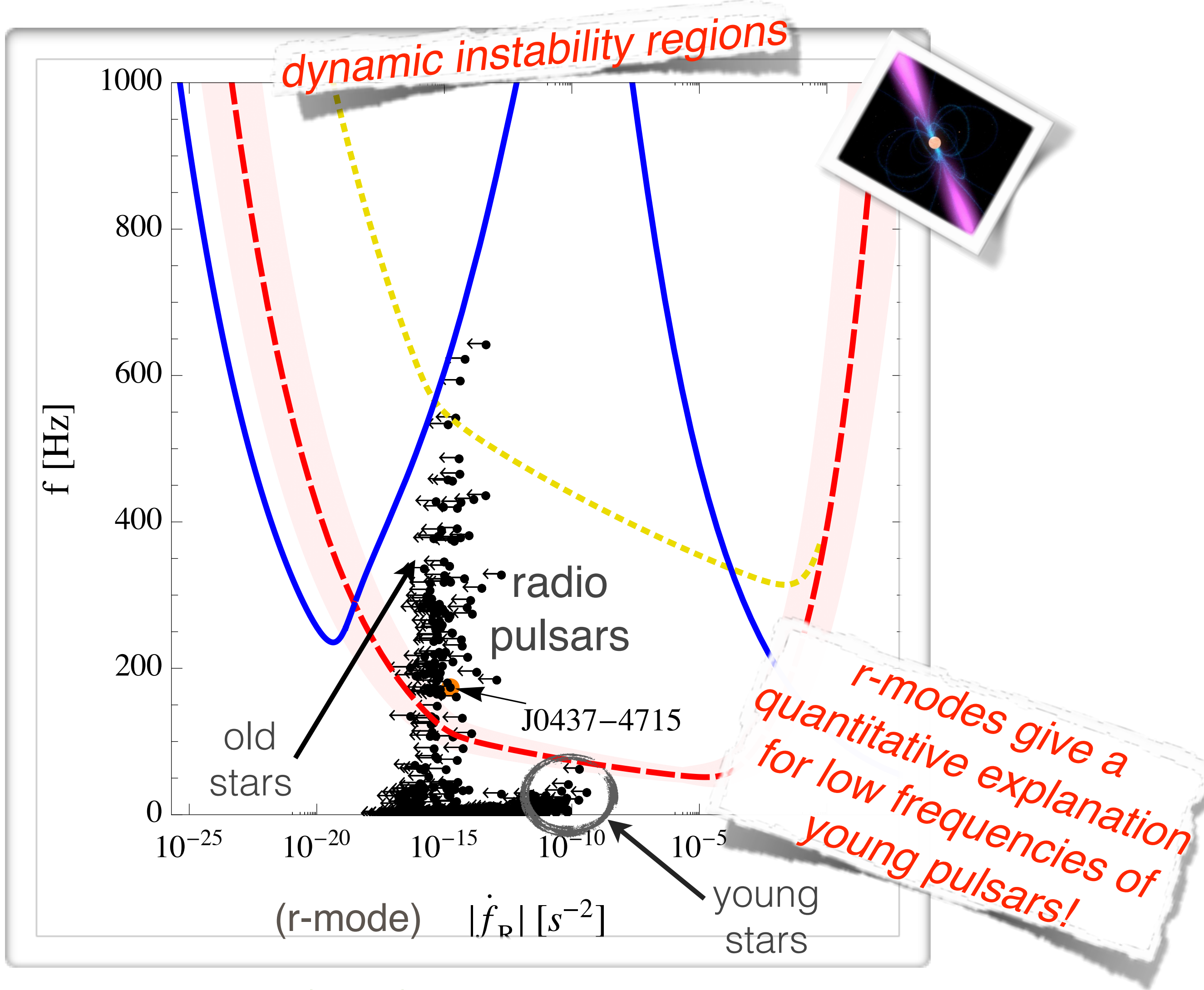
⚠ We only measure the total spindown rate which can stem from various mechanisms, so that the sources could be outside of the instability region …

- 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


static instability regions


dynamic instability regions

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

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 temperatures“

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

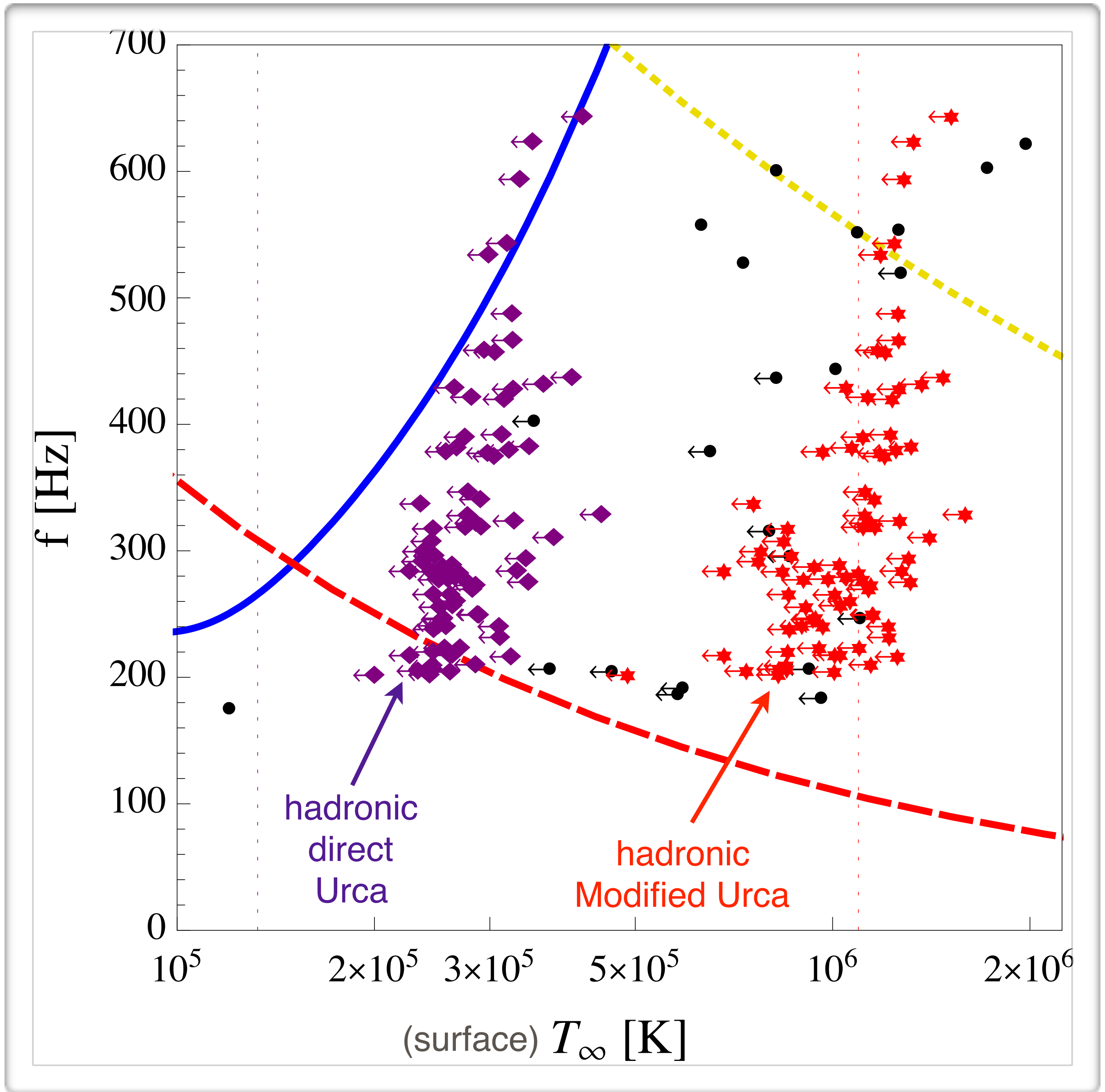
$$T_{rm} = \left(I\Omega\dot{\Omega}/\left(3\hat{L}\right)\right)^{1/\theta}$$

- 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., PRL 113 (2014) 251102

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

Constraints on dense quark matter

- When quark matter with enhanced damping is present 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: $\frac{\tilde{V}^3 \tilde{I} R^2}{\tilde{J}^6 \tilde{L} M^5} \geq \frac{2^{54} 7^3 \pi^{14}}{3^{14} 5^6} \frac{\Lambda_{EW}^8 G^3}{\Lambda_{QCD}^{18}} \frac{f_0^{11}}{\left|\dot{f}_0\right|}$

  … completely general but not very focussed

- A self bound strange star (and to some extend also the core of a hybrid star) has approximately constant density, which yields a direct bound on the material parameters: $\frac{A^6 C^6 \tilde{\Gamma}^3}{\tilde{\epsilon}} \gtrsim \frac{2^{41} \pi^8}{3^3 5^5 7^3} \frac{G^3 M^5}{R^2} \frac{f_0^{11}}{\left|\dot{f}_0\right|}$

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

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

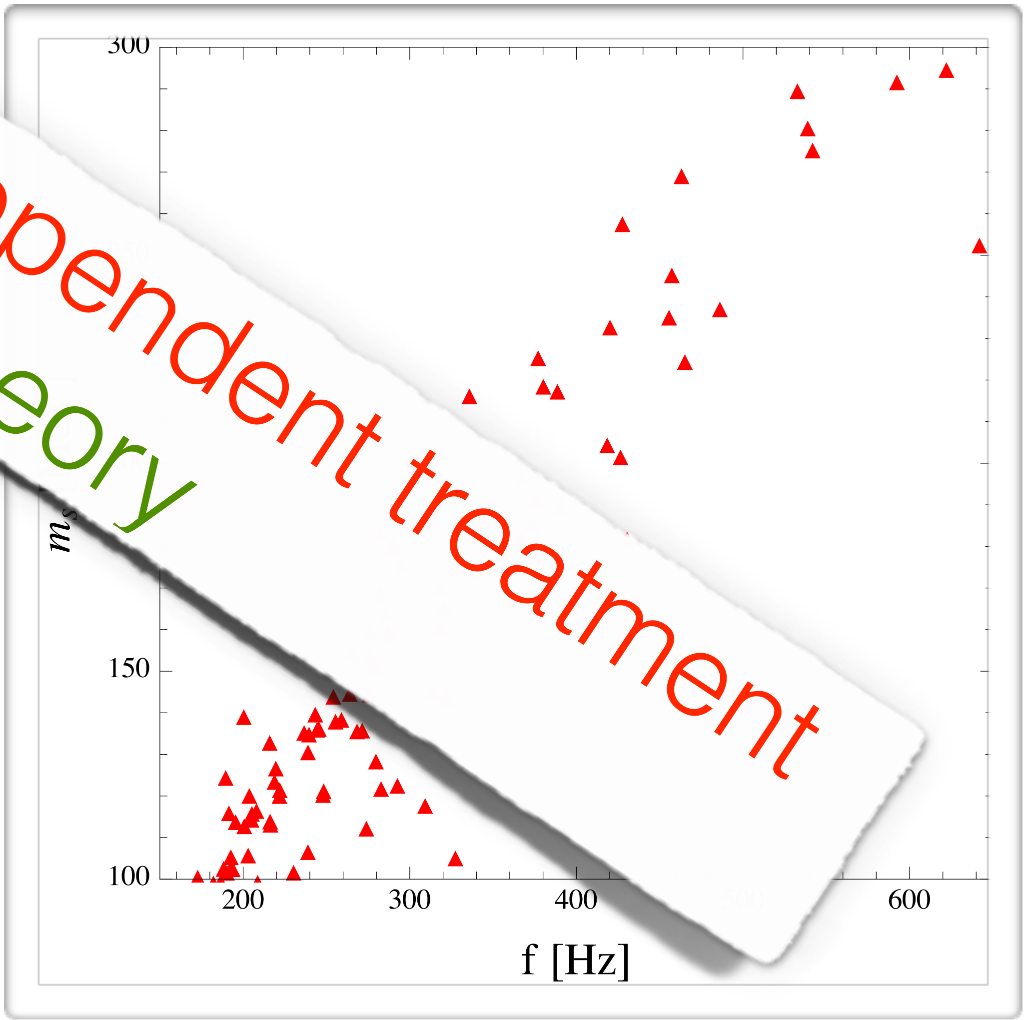
★ Goal: Connection to microscopic particle properties

Direct constraints on CSC phases

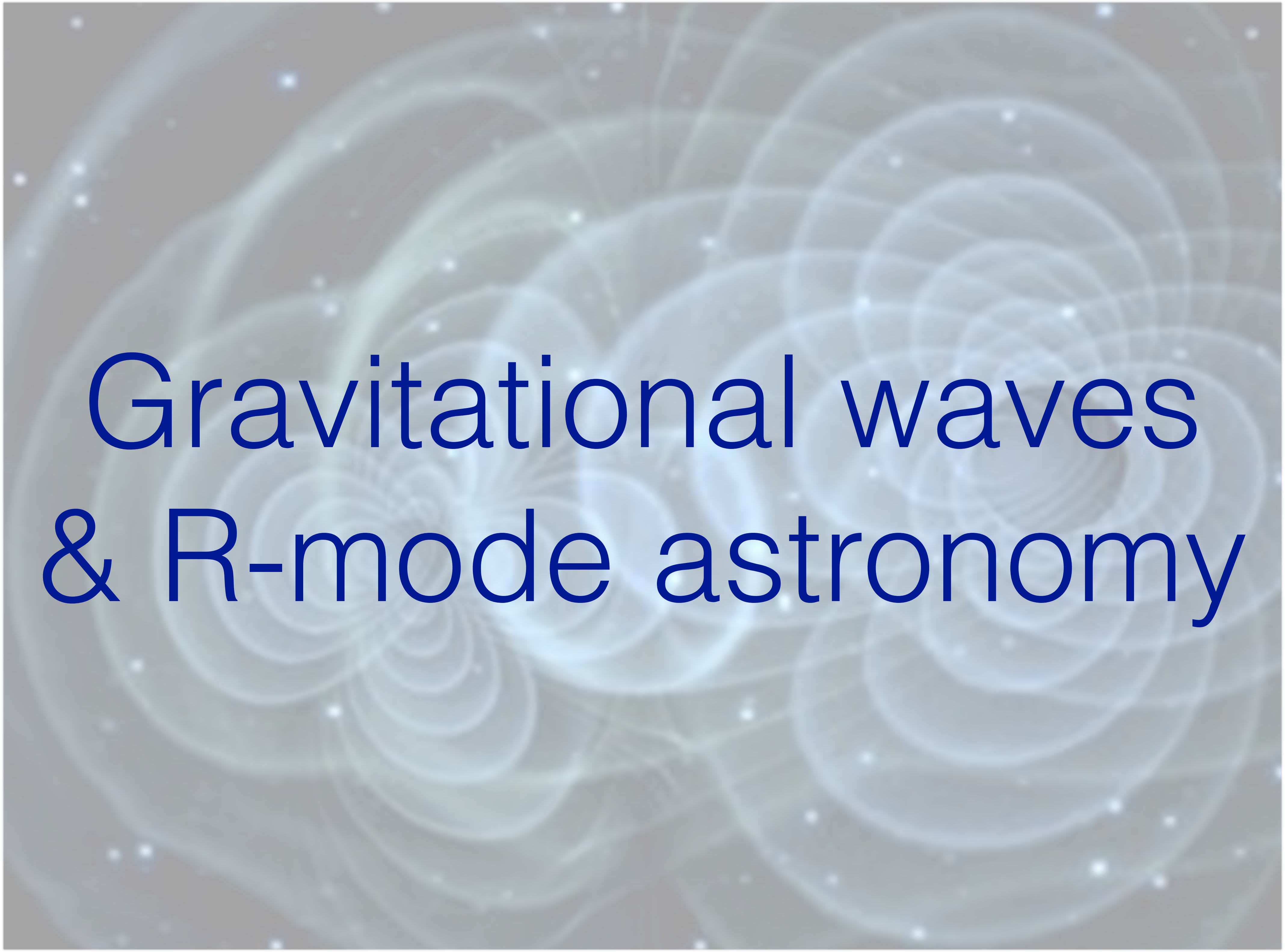
- Evaluating these expressions for partially paired color-super ucting phases (e.g. 2SC) in a perturbative approximation give s a bound on the strang s:

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

- Rather inse itive to roperties except for the frequency …
  - ➡ bound arises me act that we see very fast pulsars!
- Using conservative estima
  $M \geq M_\odot\,,\quad R > 10\,\mathrm{km}\,,\quad \alpha_s > \alpha_s(m_Z)$
  yields quantitative bounds from the pulsar data with result: $m_s \gtrsim 296\,\mathrm{MeV}$
- Imposes chemical potential $\mu_e \gtrsim 69\,\mathrm{MeV}$
- Very restricting constraint since this would require $\Delta > 100\,\mathrm{MeV}$, which is not provided by microscopic models!

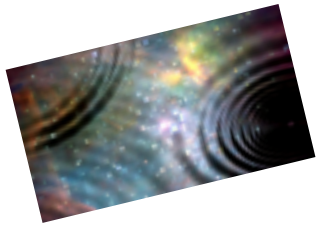


Outlook: proper model-independent treatment in Fermi liquid theory



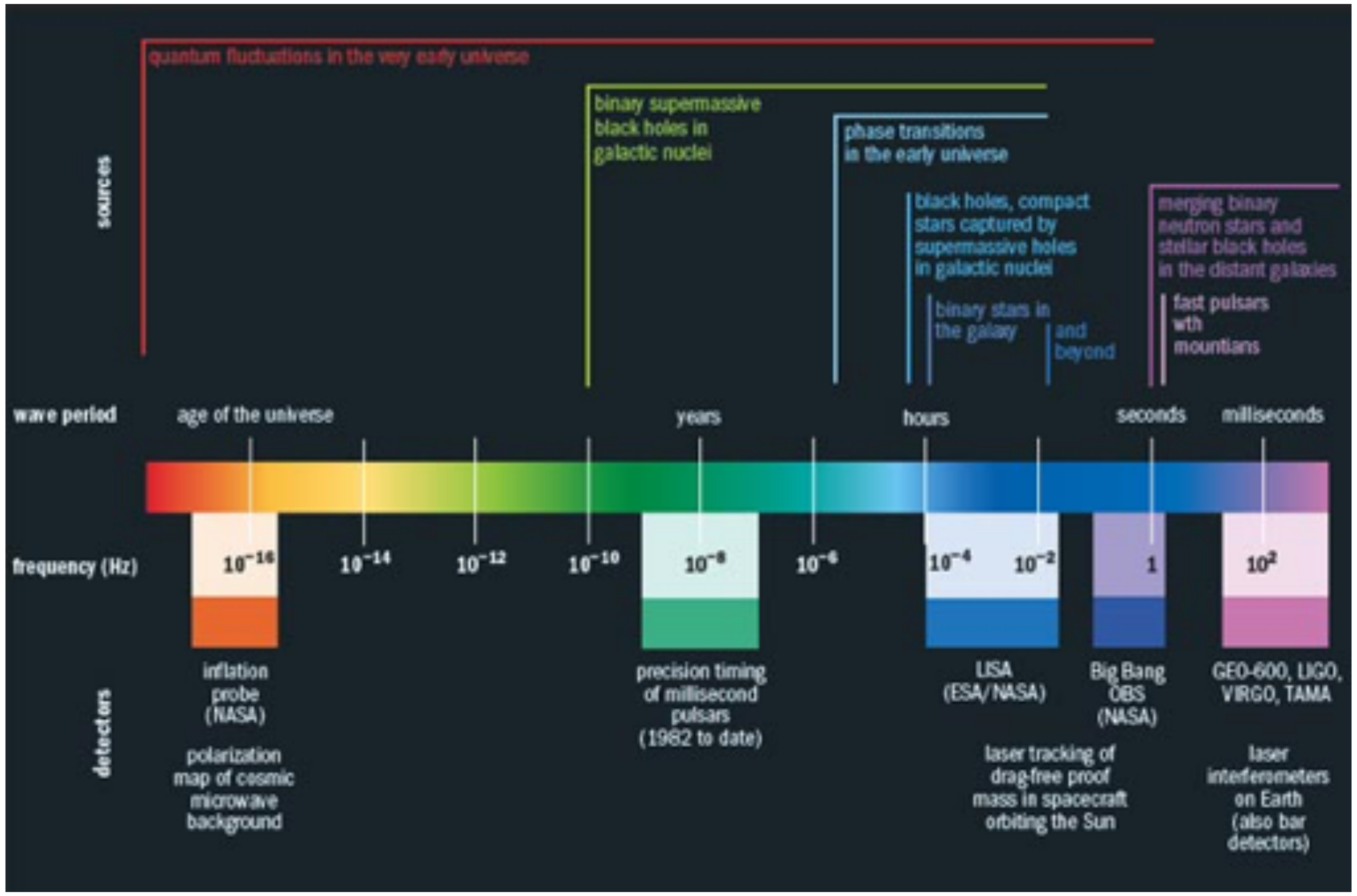
Gravitational waves & R-mode astronomy

Present & future windows to the cosmos



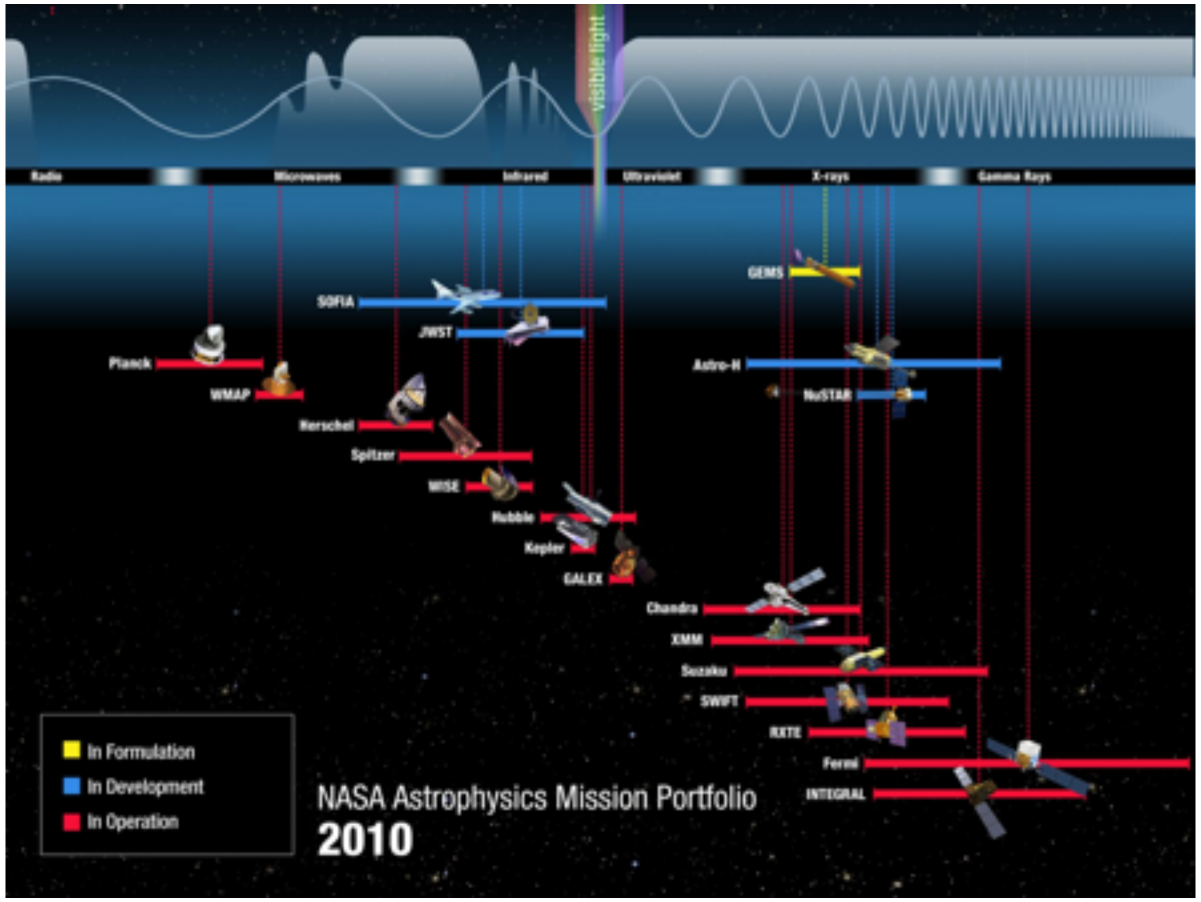
gravitational waves

- 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 >>)

Gravitational Wave Detectors

- Extremely hard to detect
  … and not directly detected, yet!

  ➡ huge interferometers required

- Present facilities:

  LIGO (4km; Hanford WA & Livingston LA)
  Virgo (3km; Cascina, Italy)
  GEO (600m; Hannover, Germany)

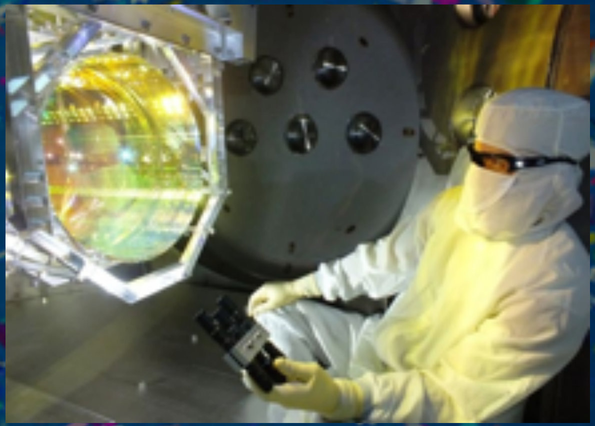
- Future facilities:

  advanced LIGO (~10-times LIGO sensitivity)
  advanced Virgo
  KAGRA (3km; Kamioka, Japan)

  … Einstein Telescope (~100-times sensitivity)

Exciting times … the future just started

Advanced LIGO started this fall!



1916.　№ 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

During the Einstein centennial!

(there are first rumors about a detection …)

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

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

- 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

Gravitational waves from old ms-pulsars

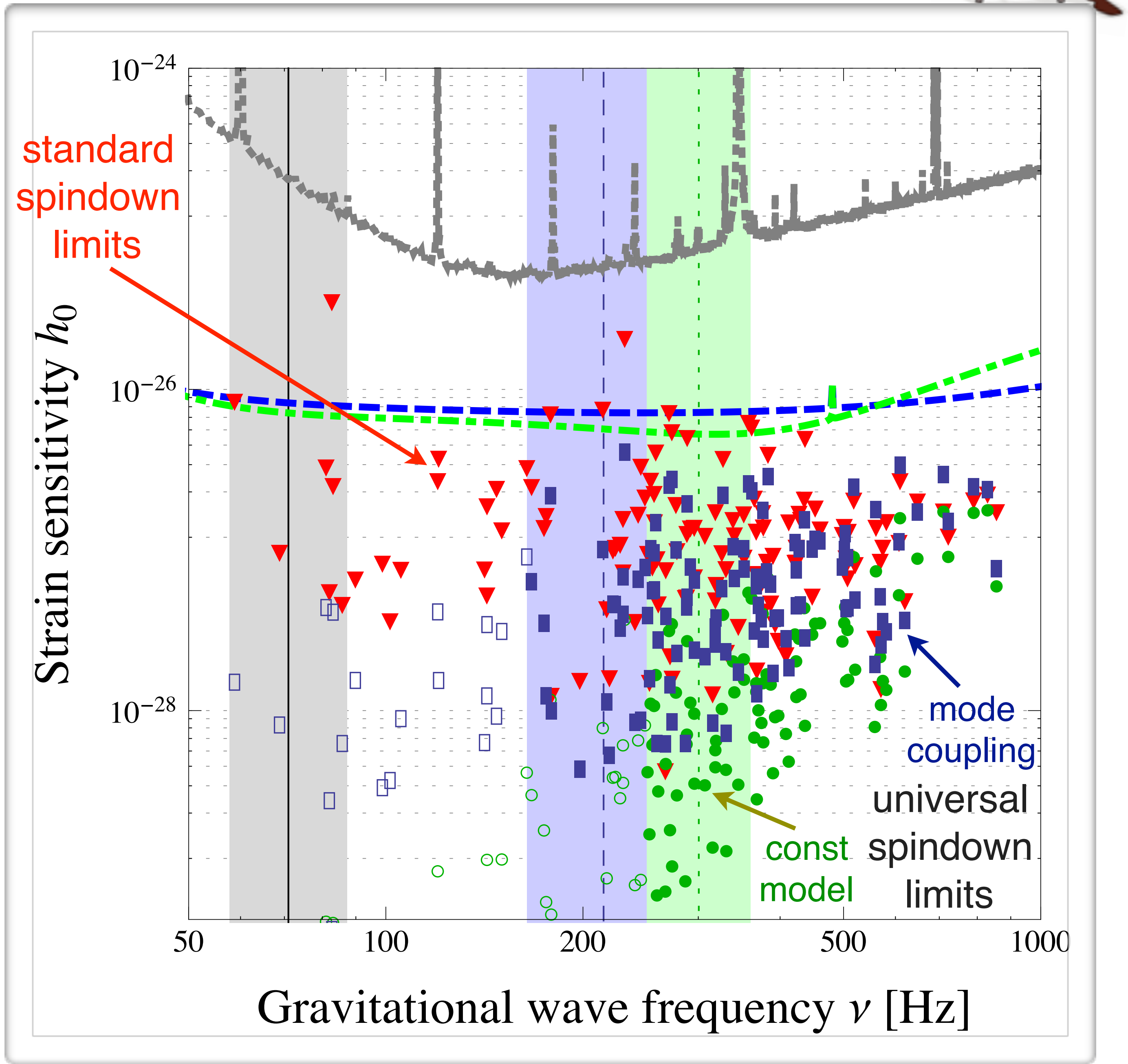
- In addition to the standard case of deformations r-modes are a promising continuous GW-source

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 should be detectable with further improvements or 3. generation detectors



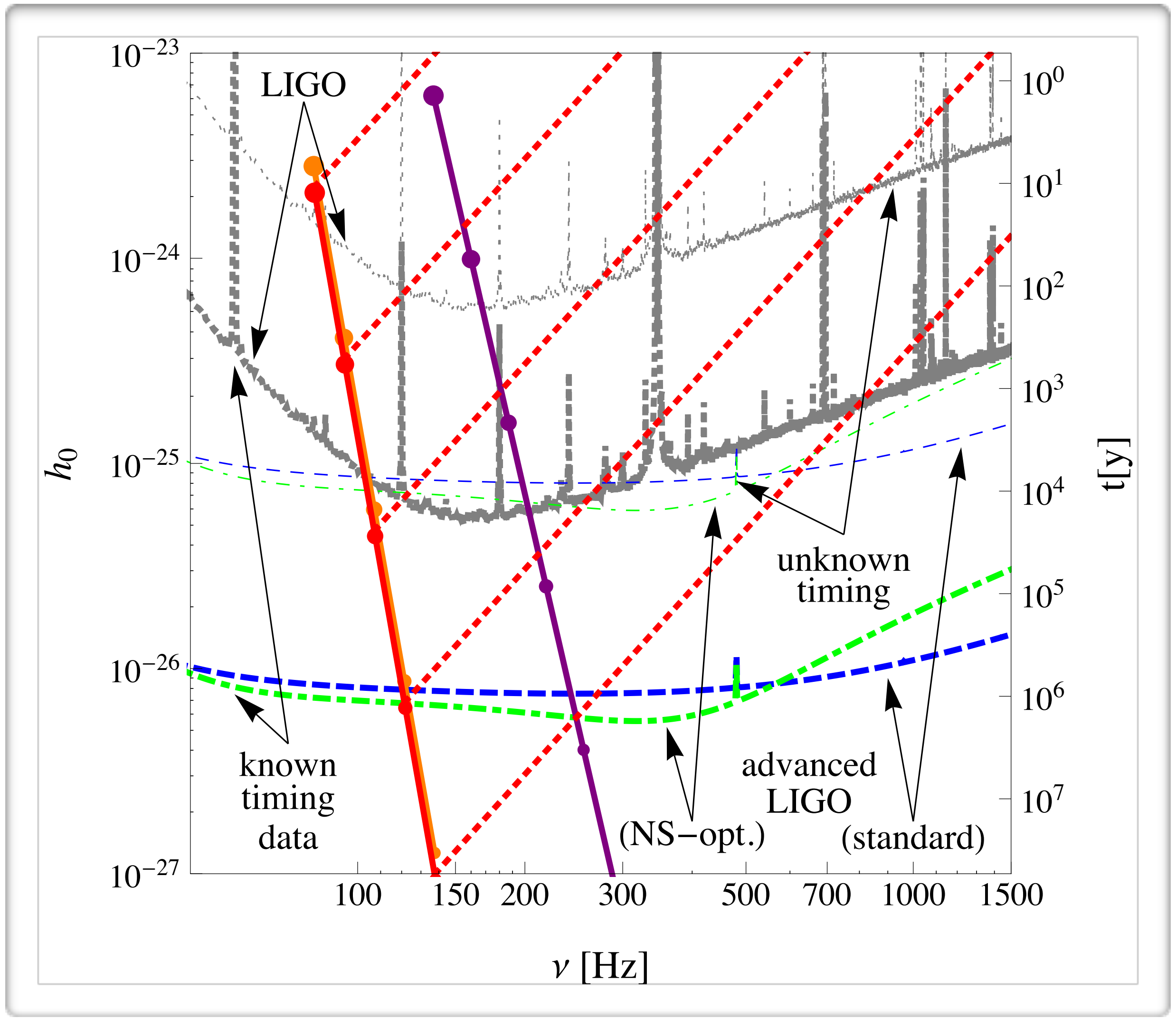
$$h_0^{(\mathrm{usl})} = \sqrt{\frac{15}{4}\frac{GI\left|\dot{f}_0\right|}{D^2 f_0}}\left(\frac{\hat{\alpha}^{(\mathrm{mac})}_{\mathrm{sat}}}{\hat{\alpha}^{(\mathrm{mac})}_{\mathrm{sat},0}}\right)^{\frac{1}{1-2\beta/\theta}}\left(\frac{f}{f_0}\right)^{\frac{3+\gamma+2\beta/\theta}{1-2\beta/\theta}}$$

("universal spindown limit")

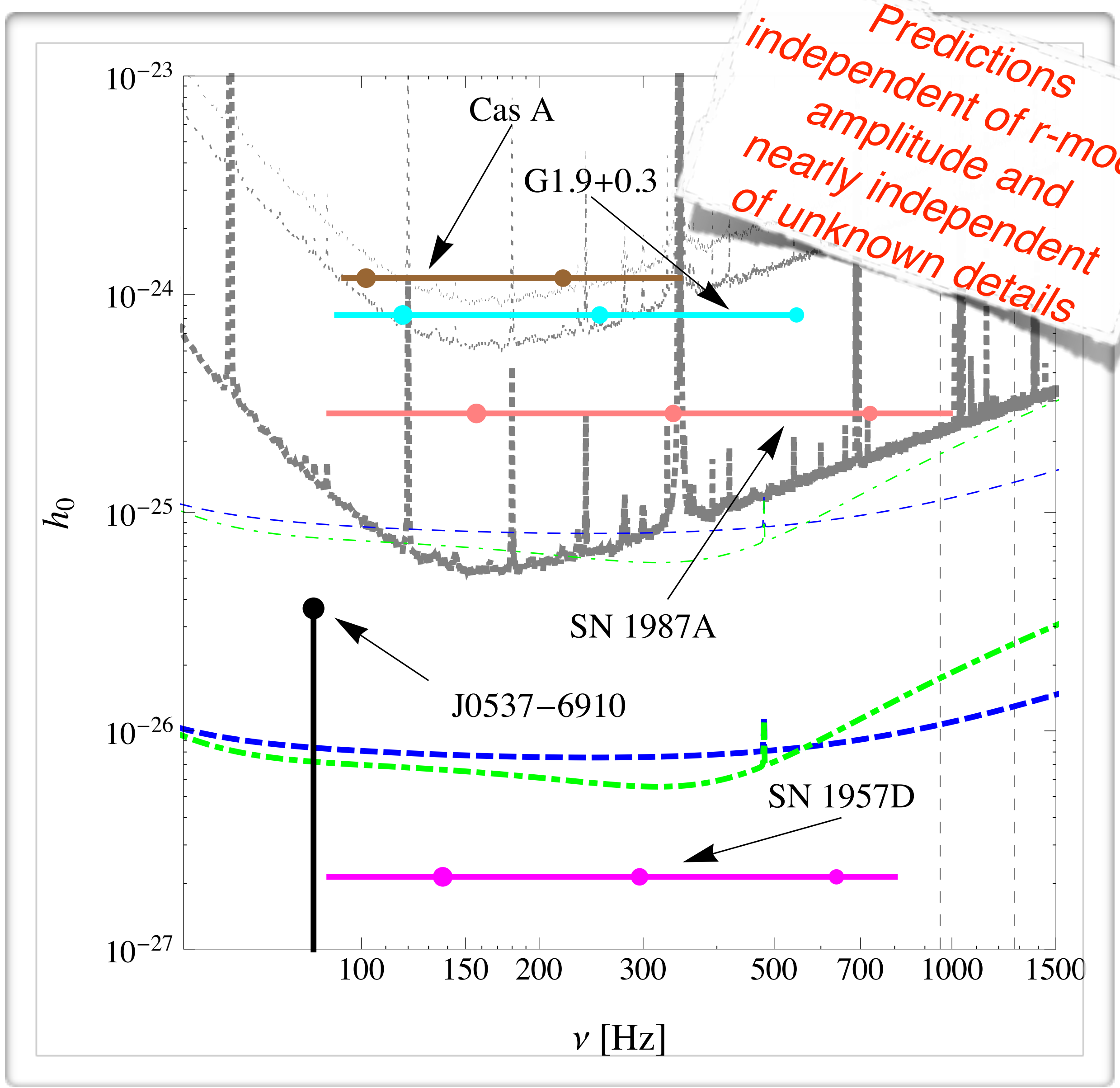
M. Alford & K. S., MNRAS 446 (2015) 3631

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 $h(t) \xrightarrow[\Omega\ll\Omega_i]{} \sqrt{\frac{3}{40}\frac{CGI}{D^2 t}}$



Several potential sources in reach of aLigo



Predictions independent of r-mode amplitude and nearly independent of unknown details

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

Information from multi-messenger observations

- For pulsars we know the … Rotation Frequency f
- From the numerical result for the gravitational wave/rotation frequency connection that is nearly independent to the equation of state, one obtains a result for the … Compactness parameter

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

& for known mass the … Radius

  - Stems presently from a numerical fit but a controlled result in a post-Newtonian and slow-rotation expansion could be derived!

- For many pulsars we also know the … Spindown Rate $\dot{f}$
- If the observed spindown power $P_{\mathrm{rot}} = I\Omega\dot{\Omega}$ roughly agrees with the r-mode spindown torque P_R, r-modes dominate the spindown and in this case one obtains a direct measurement for the …

Moment of Inertia

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

A. Mytidis, M. Coughlin, and B. Whiting, arXiv:1505.03191

✦ Precise measurement would rule out most of the current EoS!

Accreting sources

- For accreting sources in LMXBs other observables are known:

Temperature T_∞ and thermal photon flux J_γ

- The ratio of the r-mode heating power and the thermal photon luminosity takes the simple form (the distance drops out)

$$\frac{P_G}{L_\gamma} = \frac{\pi}{10}\frac{(2f-\nu)\,\nu h_0^2}{J_\gamma}\left(1-2G\frac{M}{R}\right)$$

… which depends only on precisely known observables!

- If this is quantity is one (as is likely for colder sources!), r-modes dominate the heating and photon emission the cooling and this gives an expression in terms of gravitational wave observables for the …

LMXBs could become “standard sirens” for astronomy …

Thermal luminosity

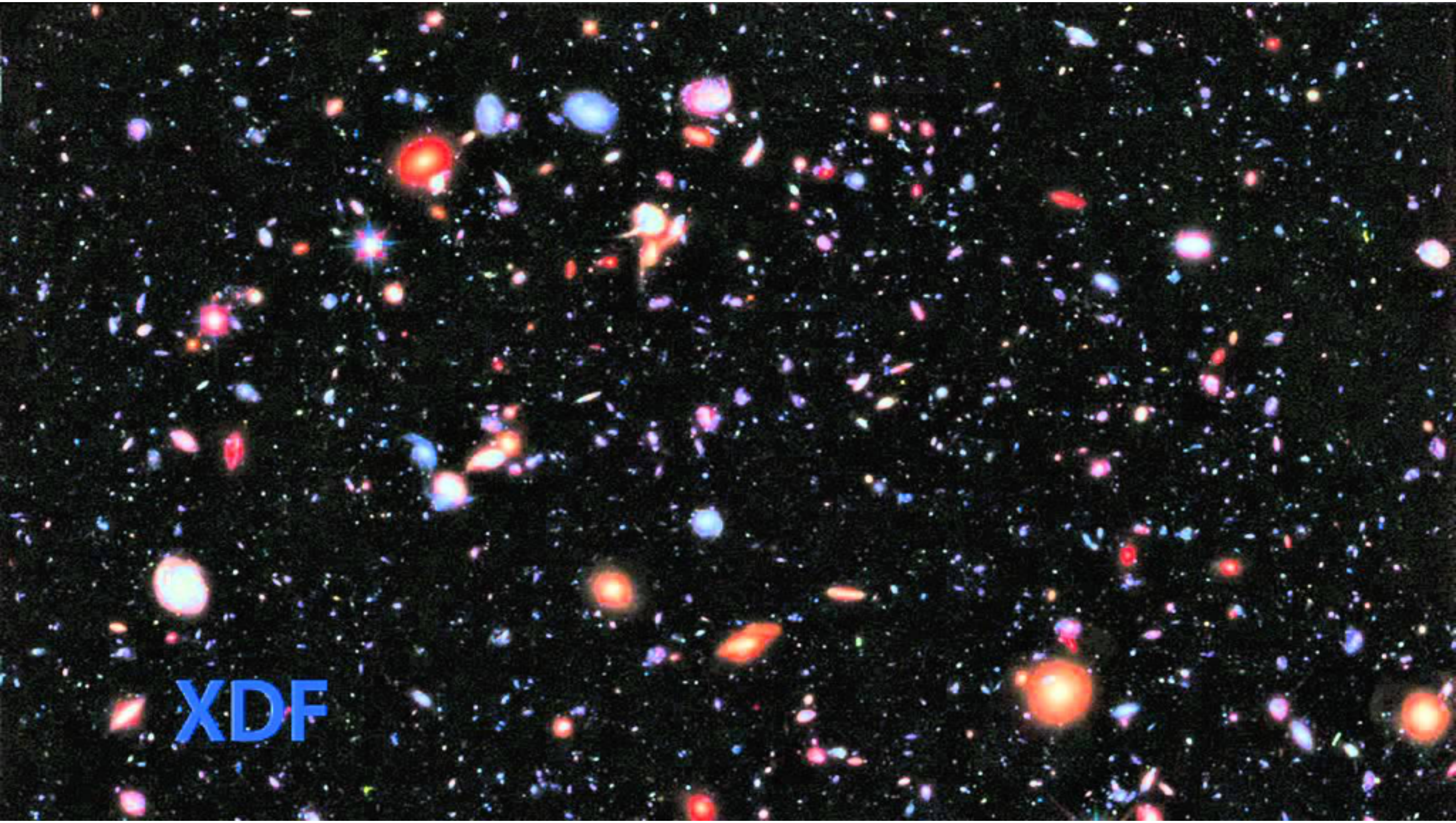
$$L_\gamma = \frac{2\pi^2}{5} D^2\,(2f-\nu)\,\nu h_0^2$$

★ If the radius is independently measured by a precise mass measurement and the compactness ratio this gives the **Distance**

$$D \xrightarrow[L_\gamma \gg L_\nu,\, P_G \gg P_{\rm acc}]{} \sqrt{\frac{\pi}{6}\frac{R^2 T_\infty^4}{(2f-\nu)\,\nu h_0^2}\left(1-2G\frac{M}{R}\right)^2}$$

So far we are at the beginning …

… but it could be only a matter of sensitivity



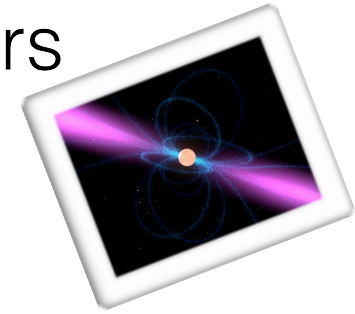
Conclusions and Outlook

- Thermal X-ray data of LMXBs and timing data of radio pulsars …
  can be used to probe the interior of compact stars

  ✤ “Minimal” neutron stars cannot damp r-modes in LMXBs and 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

  ◉ Partially gapped color superconducting phases (e.g. 2SC phase) have big problems to explain the pulsar data

- Thermal x-ray or for nearby millisecond pulsars could tell us which scenario is realized

✳ Gravitational wave astronomy opens a novel window to the star interior