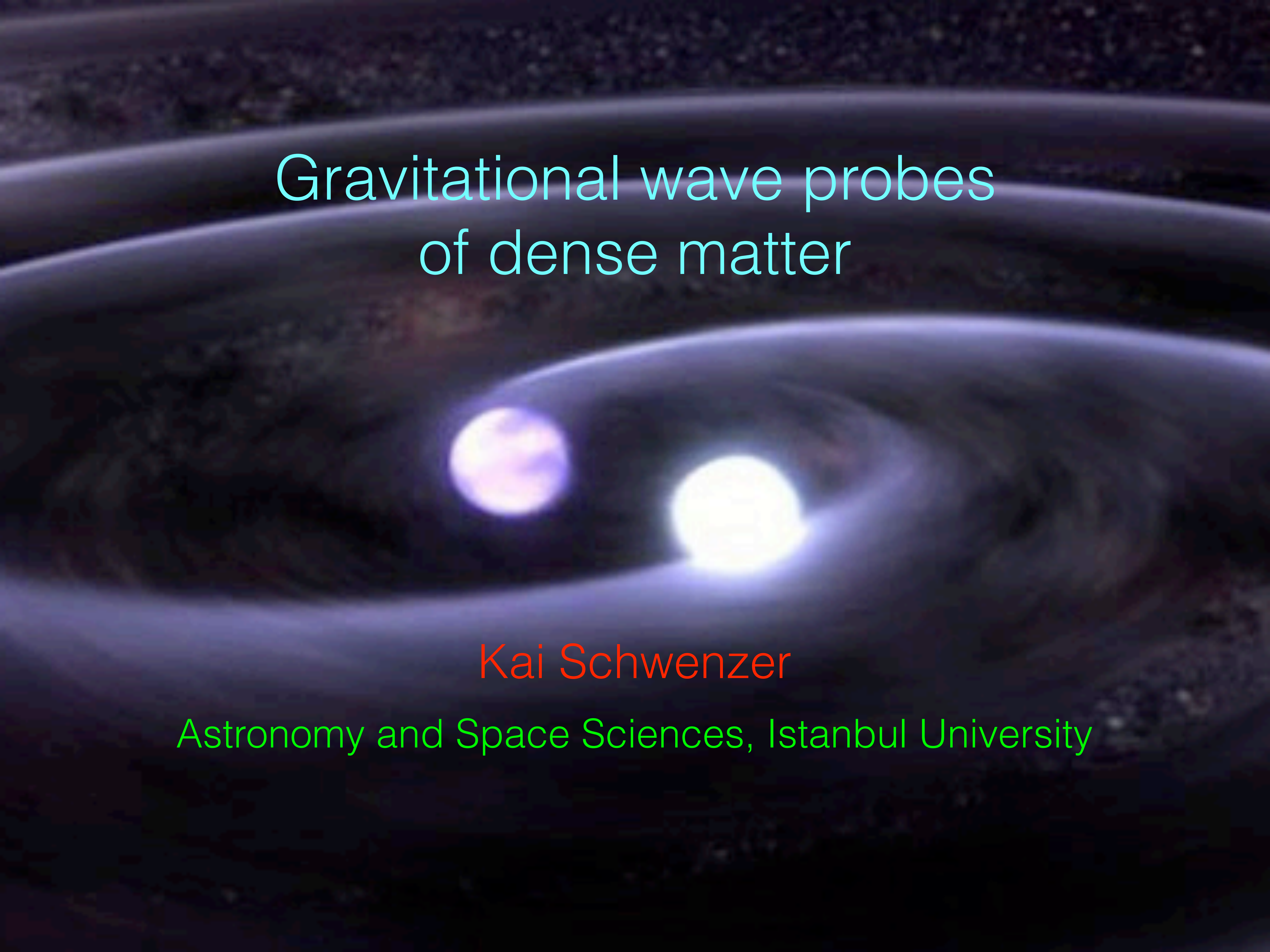


Gravitational wave probes of dense matter

Kai Schwenzer

Astronomy and Space Sciences, Istanbul University

Exciting times …

Selected for a Viewpoint in *Physics*

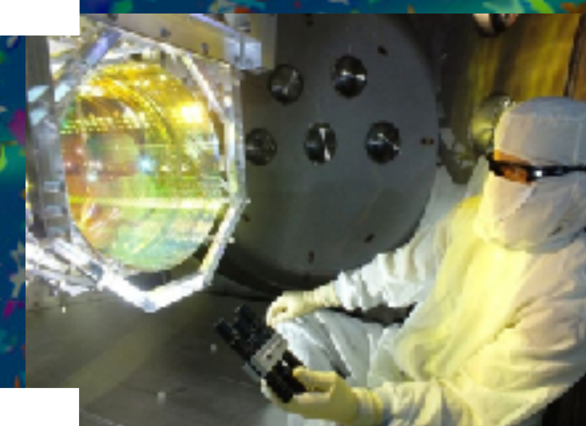
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



Selected for a Viewpoint in *Physics*

PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

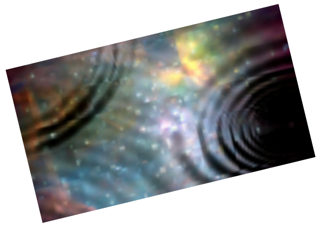
B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

… the era of GW astronomy has started!

Present & future windows to the cosmos

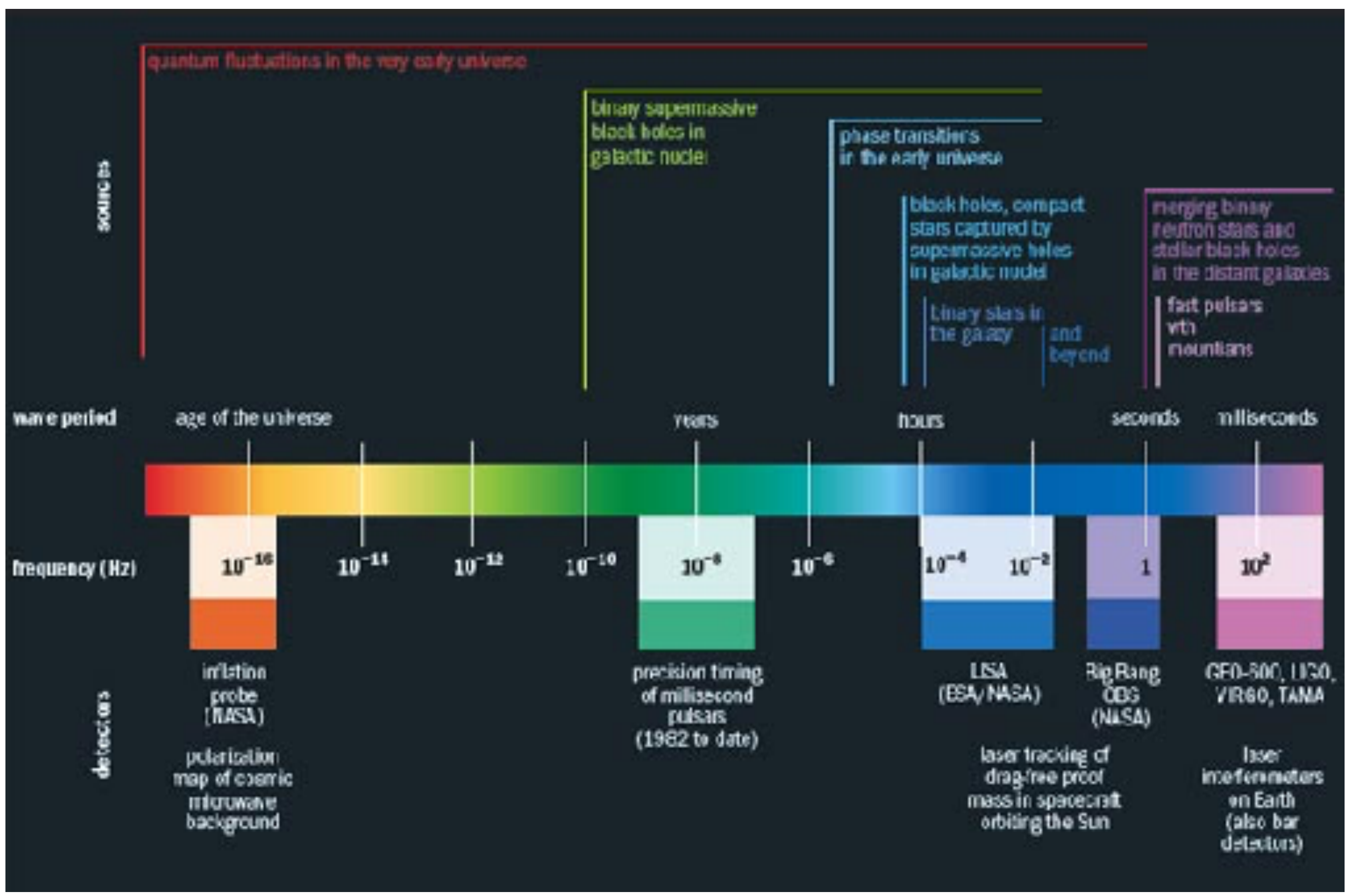


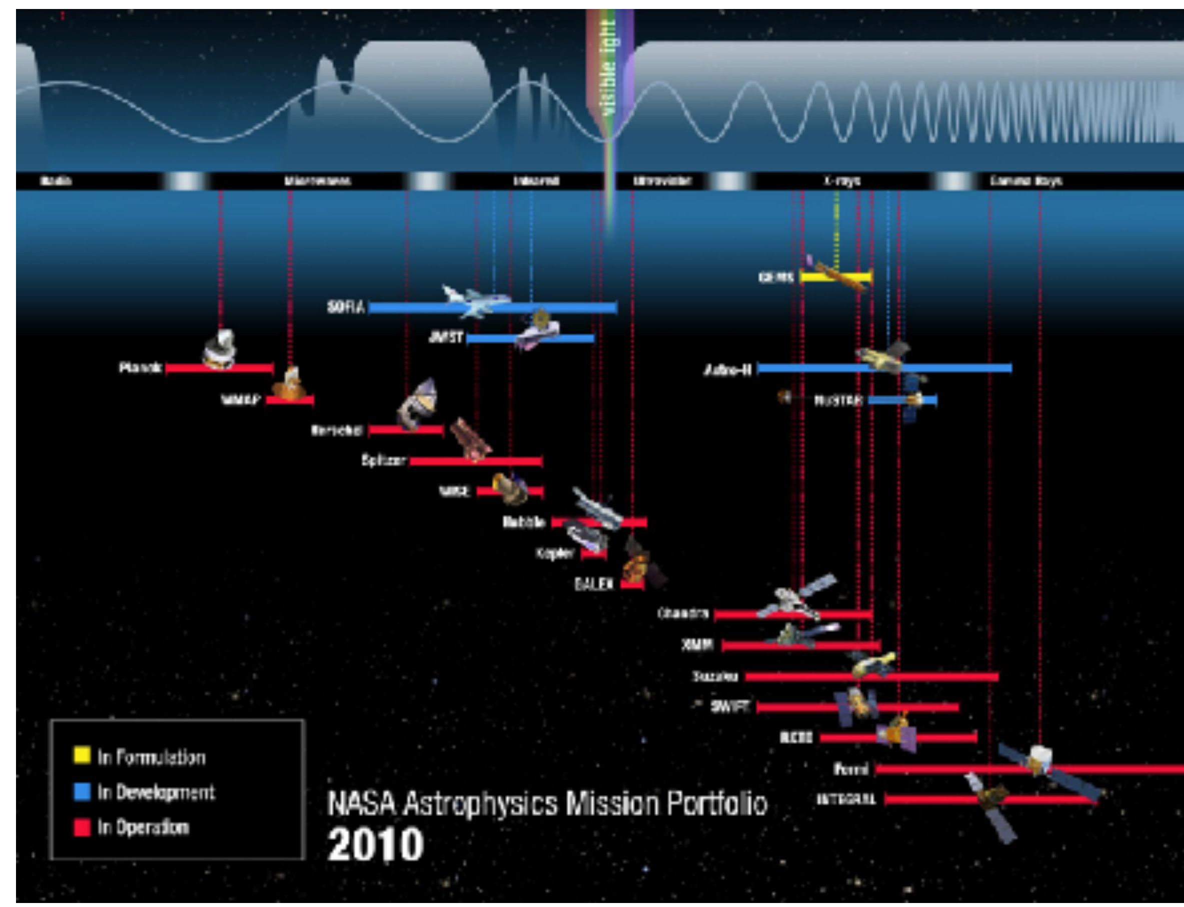
gravitational waves

- 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

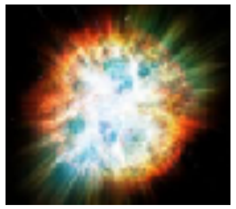




frequency

(particle rays >>)

Generic evolution of pulsars

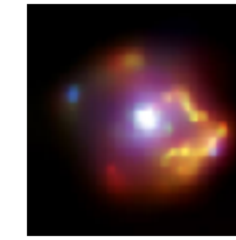


Newborn compact stars

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

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

Young compact objects



(e.g. CasA, SN1987A) no pulsation, most even undetected

Observed young pulsars

ages >1000 years & spin with surprisingly low frequencies

Why?

Non-pulsating compact stars

… become invisible

Low mass X-ray binaries

spinup by accretion from a companion over many millions of years

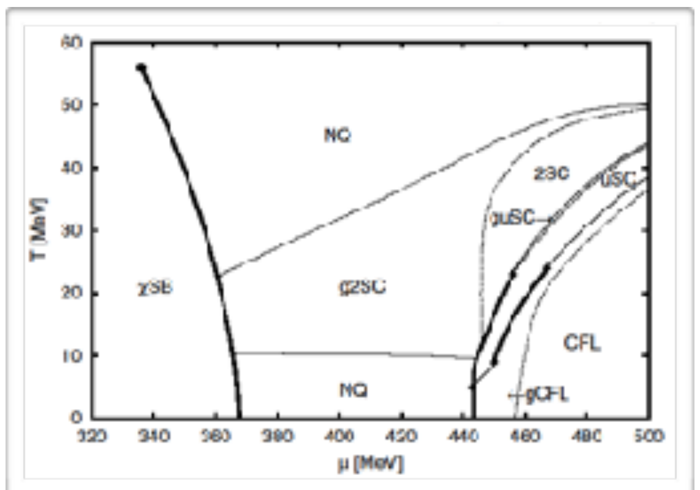
"recycling"

Millisecond pulsars

can be billions of years old and are extremely stable

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

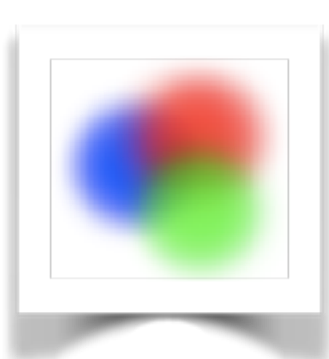
- fully gapped phases (color-flavor locking at asymptotic μ)
- partially gapped color superconducting phases (e.g. 2SC)
- inhomogeneous and anisotropic condensates (e.g. LOFF)
- ungapped quark matter

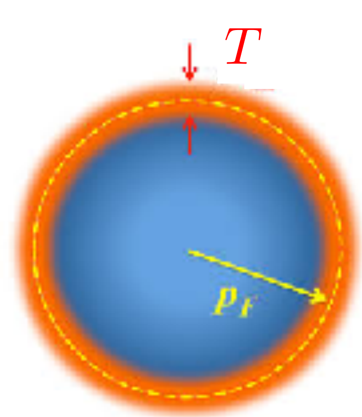
m_s

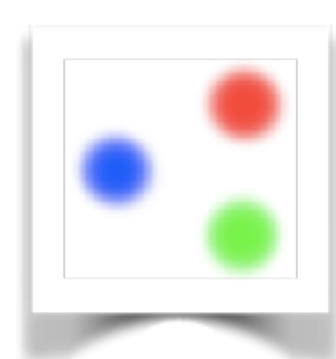
✦ Many dozens of studied phases - uncountably many potential ones!

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

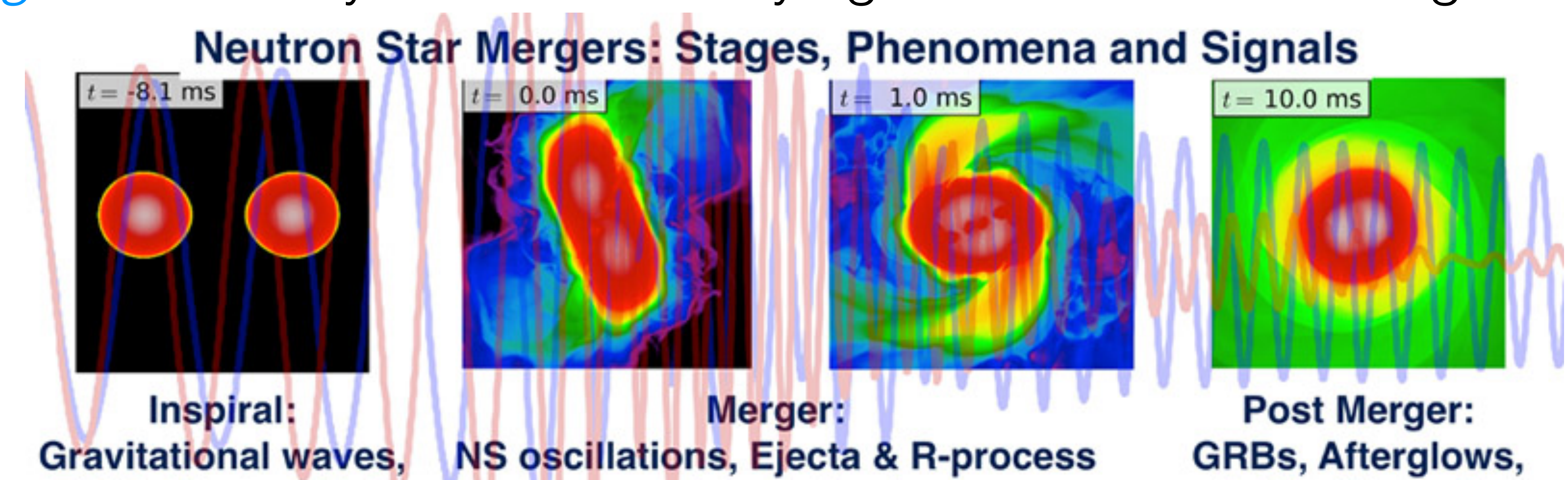
- Bulk viscosity from particle transformation (weak interaction)

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 $T/\mu\sim O(10^{-4})$

Neutron star merger phases

- *Inspiral*: Neutron stars in a binary emit gravitational radiation whereby they loose energy and approach each other
    - this process speeds up and gives a characteristic “chirp” signal
- *Merger*: Once they merge, the evolution depends on the total mass:
    - if it is very low a stable massive neutron star might form
    - if it is high it will collapse immediately to a black hole
    - at intermediate masses a metastable state forms, that is stabilized by its angular momentum (or thermal pressure), before it collapses
- *Ringdown*: Finally there is a decaying oscillation of the merged object



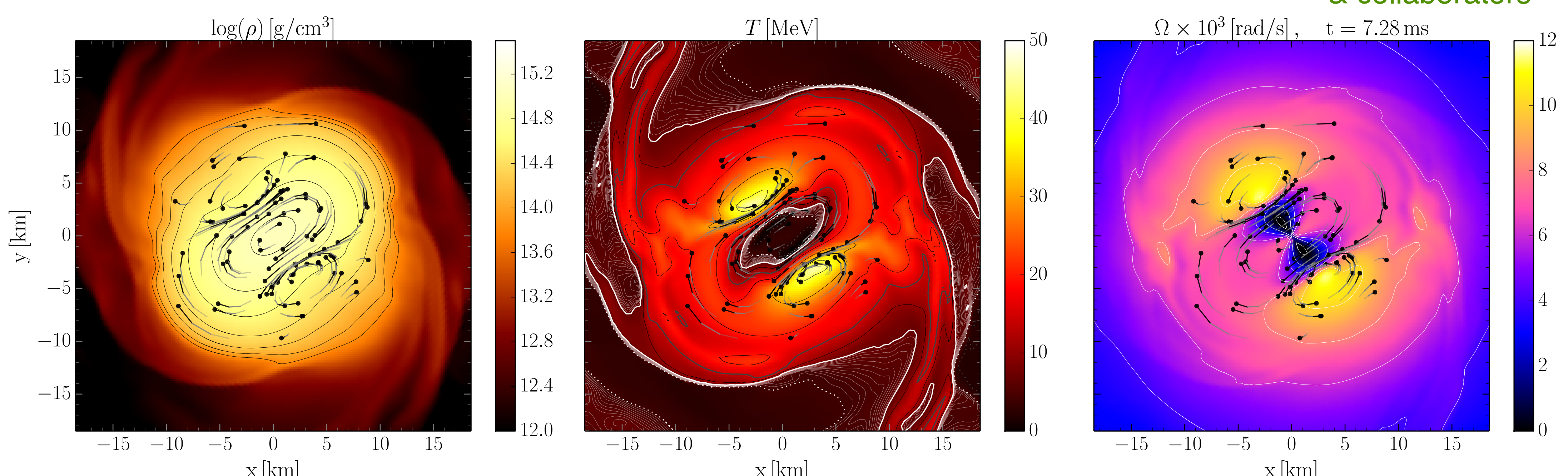
Merger dynamics

- A compact star merger produces a highly excited system with huge kinetic energy
  - can be dissipated in two different ways:
    - ✓ gravitational wave emission
    - ➡ internal dissipation?

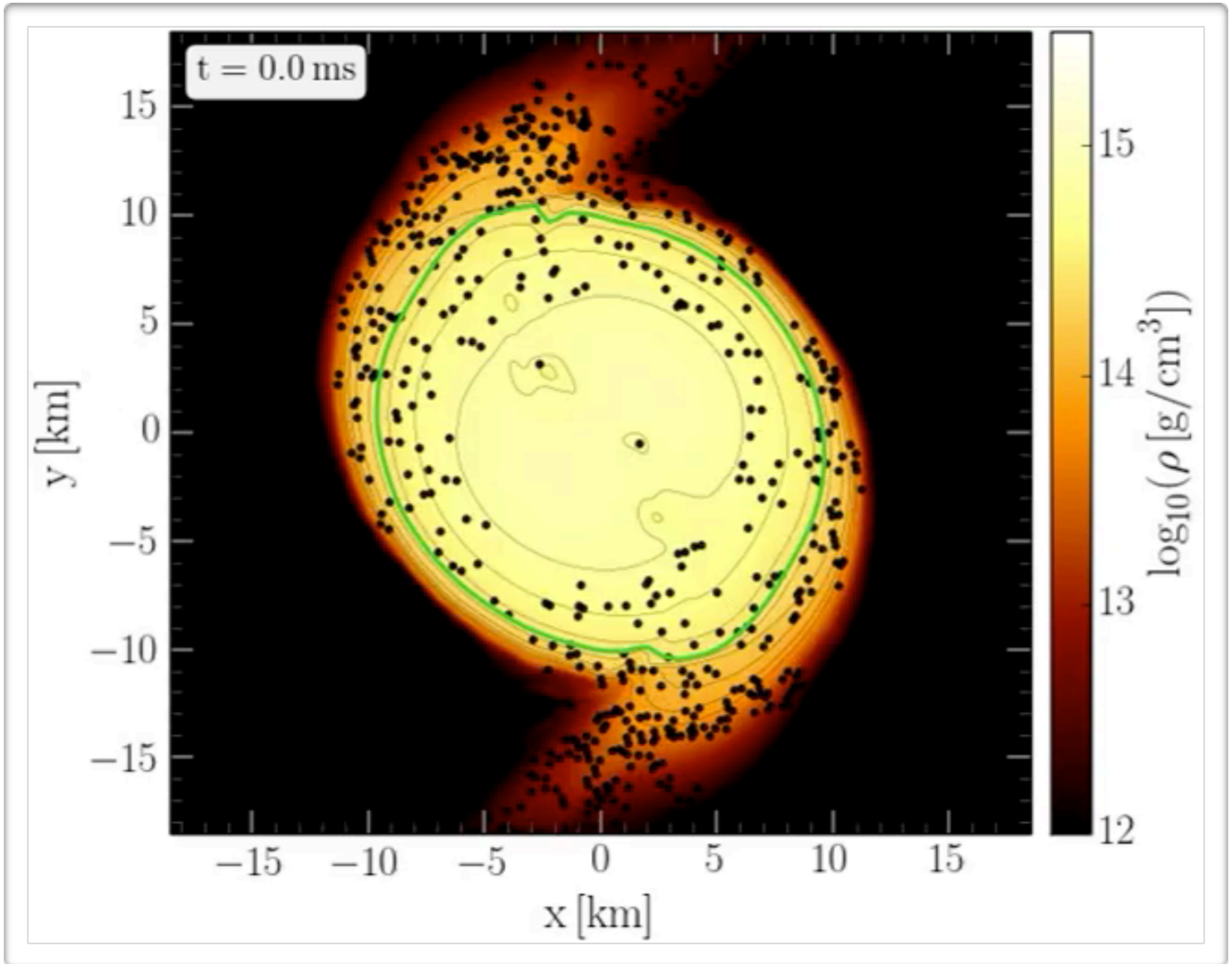
M. Alford, L. Bovard, M. Hanauske, L. Rezzolla, K. Schwenzer, PRL 120, 041101 (2018)

- Simulations are presently treated in ideal hydrodynamics
  - gravitational wave emission for dozens of milliseconds
- Dissipation could affect both form and duration of the signal as well as the final state (compact star / black hole)

simulation by
L. Rezzolla
& collaborators

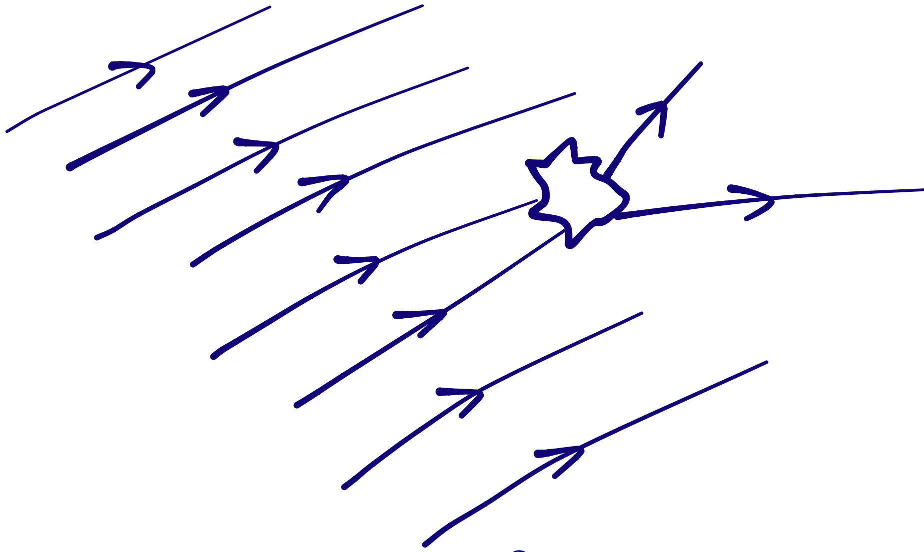


Exemplary merger simulation (density)



simulation by L. Rezzolla and collaborators

Shear dissipation timescale



- The kinetic energy density of a (Newtonian) fluid flowing in x-direction is $e_{\rm kin} = \frac{1}{2}\rho v_x^2$
- The dissipated power density due to shear is $w_{\rm shear} \approx \eta (dv_x/dz)^2$
- If the velocity changes direction on a distance scale $z_{\rm typ}$, this provides a characteristic time scale on which shear dissipation becomes relevant: $\tau_\eta \equiv e_{\rm kin}/w_{\rm shear} \approx \rho\, z_{\rm typ}^2/(2\eta)$
- At low T electrons dominate the shear viscosity $\eta^{(e)} \approx 0.2\, n_e^{14/9}/(\alpha^{5/3}T^{5/3})$ which gives

Shternin & Yakovlev, PRD 78 (2008) 063006

$$\tau_\eta^{(e)} \approx 1.6\times 10^8\,{\rm s}\left(\frac{z_{\rm typ}}{1\,{\rm km}}\right)^2 \left(\frac{T}{1\,{\rm MeV}}\right)^{\frac{5}{3}} \left(\frac{n_0}{n_B}\right)^{\frac{5}{9}} \left(\frac{0.1}{x_p}\right)^{\frac{14}{9}},$$

- However at high T neutrinos dominate $\eta^{(\nu)} \approx 0.46\, n_\nu^{4/3}/\left(G_F^2 (m_n^*)^2 n_e^{1/3} T^2\right)$ since their mean free path becomes short enough that they are trapped inside the star

Goodwin & Pethick, APJ 253 (1982) 816

$$\tau_\eta^{(\nu)} \approx 54\,{\rm s}\left(\frac{0.1}{x_p}\right)\left(\frac{m_n^*}{0.8\,m_n}\right)^2 \left(\frac{\mu_e}{2\,\mu_\nu}\right)^4 \left(\frac{z_{\rm typ}}{1\,{\rm km}}\right)^2 \left(\frac{T}{10\,{\rm MeV}}\right)^2$$

Thermal conduction timescale

- The thermal equilibration timescale can be estimated in terms of the distance $z_{\rm typ}$ of thermal gradients: $\tau_\kappa \approx c_V\, z_{\rm typ}^2/(6\kappa)$

- Thermal transport results from the movement of microscopic particles and the thermal conductivity is in kinetic theory given by

$$\kappa \propto \sum_i \kappa_i \propto \sum_i \underbrace{n_i}_{\text{particle density}} v_i \underbrace{\lambda_i}_{\text{mean free path}}$$

- At low T electrons dominate $\kappa_e \approx 1.5\, n_e^{2/3}/\alpha$ Shternin & Yakovlev, PRD 75 (2007) 103004

$$\tau_\kappa^{(e)} \approx 5\times 10^8\,{\rm s}\left(\frac{0.1}{x_p}\right)^{\frac{2}{3}}\left(\frac{m_n^*}{0.8\,m_n}\right)\left(\frac{n_0}{n_B}\right)^{\frac{1}{3}}\left(\frac{z_{\rm typ}}{1\,{\rm km}}\right)^2\left(\frac{T}{1\,{\rm MeV}}\right)$$

- However at high T neutrinos dominate $\kappa_\nu \approx 0.33\, n_\nu^{2/3}/(G_F^2 (m_n^*)^2 n_e^{1/3} T)$ since they become degenerate

Goodwin & Pethick, APJ 253 (1982) 816

$$\tau_\kappa^{(\nu)} \approx 0.7\,{\rm s}\left(\frac{0.1}{x_p}\right)^{\frac{1}{3}}\left(\frac{m_n^*}{0.8\,m_n}\right)^3\left(\frac{\mu_e}{2\,\mu_\nu}\right)^2\left(\frac{z_{\rm typ}}{1\,{\rm km}}\right)^2\left(\frac{T}{10\,{\rm MeV}}\right)^2$$

Bulk viscosity

- The bulk viscosity describes the dissipation, due to a non-adiabatic density change - resulting in a new statistical equilibrium

- In particular for a density oscillation, changing the chemical composition works by slow weak interactions and therefore lags behind a driving density oscillation

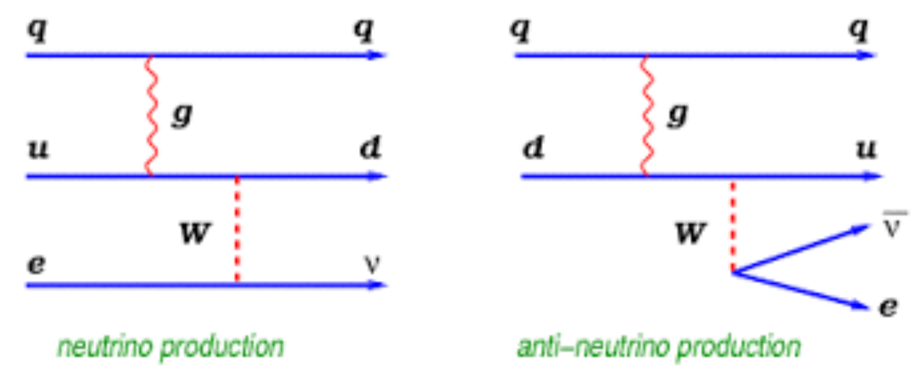
- The average bulk viscosity is maximal if the equilibration time scale matches the external oscillation time which results in a resonant behavior

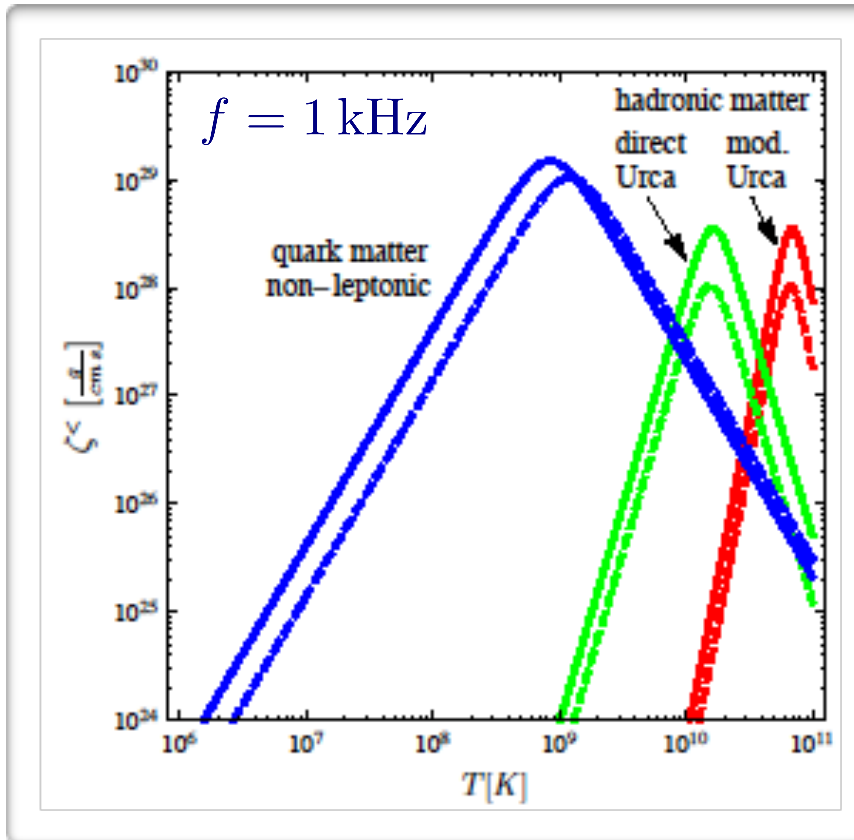
$$\zeta = \frac{C^2 \tilde{\Gamma} T^{\delta}}{\omega^2 + \tilde{\Gamma}^2 B^2 T^{2\delta}}$$

- The maximum is given by

$$\bar{\zeta}_{\max} = Y_\zeta \, \bar{n} \, t_{\rm dens} \quad , \quad Y_\zeta \equiv C^2/(4\pi B \bar{n})$$

Modified Urca interactions:
(quarks bound in baryons)



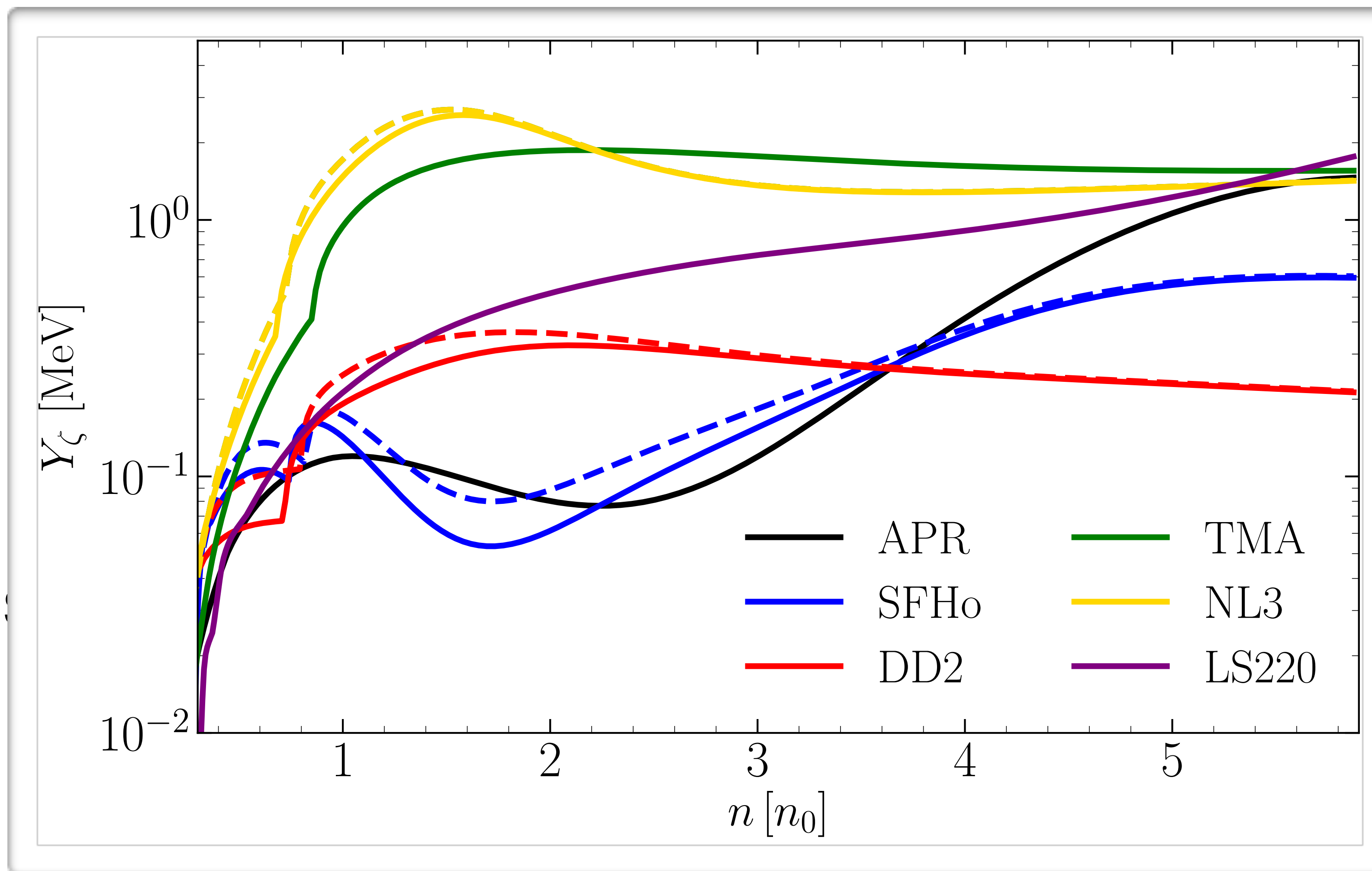


Bulk dissipation time scale

- The energy density due to compression is $\mathcal{E}_{\text{comp}} \approx K\bar{n}(\Delta n/\bar{n})^2/18$
- The dissipated power density due to bulk viscosity is for a harmonic oscillation $(d\mathcal{E}/dt)_{\text{bulk}} \approx 2\pi^2\bar{\zeta}\,(\Delta n/\bar{n})^2\,/t_{\text{dens}}^2$
- This gives the bulk timescale $\tau_\zeta \equiv \mathcal{E}_{\text{comp}}/\,(d\mathcal{E}/dt)_{\text{bulk}} \approx K\bar{n}\,t_{\text{dens}}^2/(36\pi^2\,\bar{\zeta})$
- This gives a time scale $\tau_\zeta^{\text{min}} \approx 3\,\text{ms}\left(\frac{t_{\text{dens}}}{1\,\text{ms}}\right)\left(\frac{K}{250\,\text{MeV}}\right)\left(\frac{0.25\,\text{MeV}}{Y_\zeta}\right)$
- The maximum is reached for all relevant densities and frequencies at

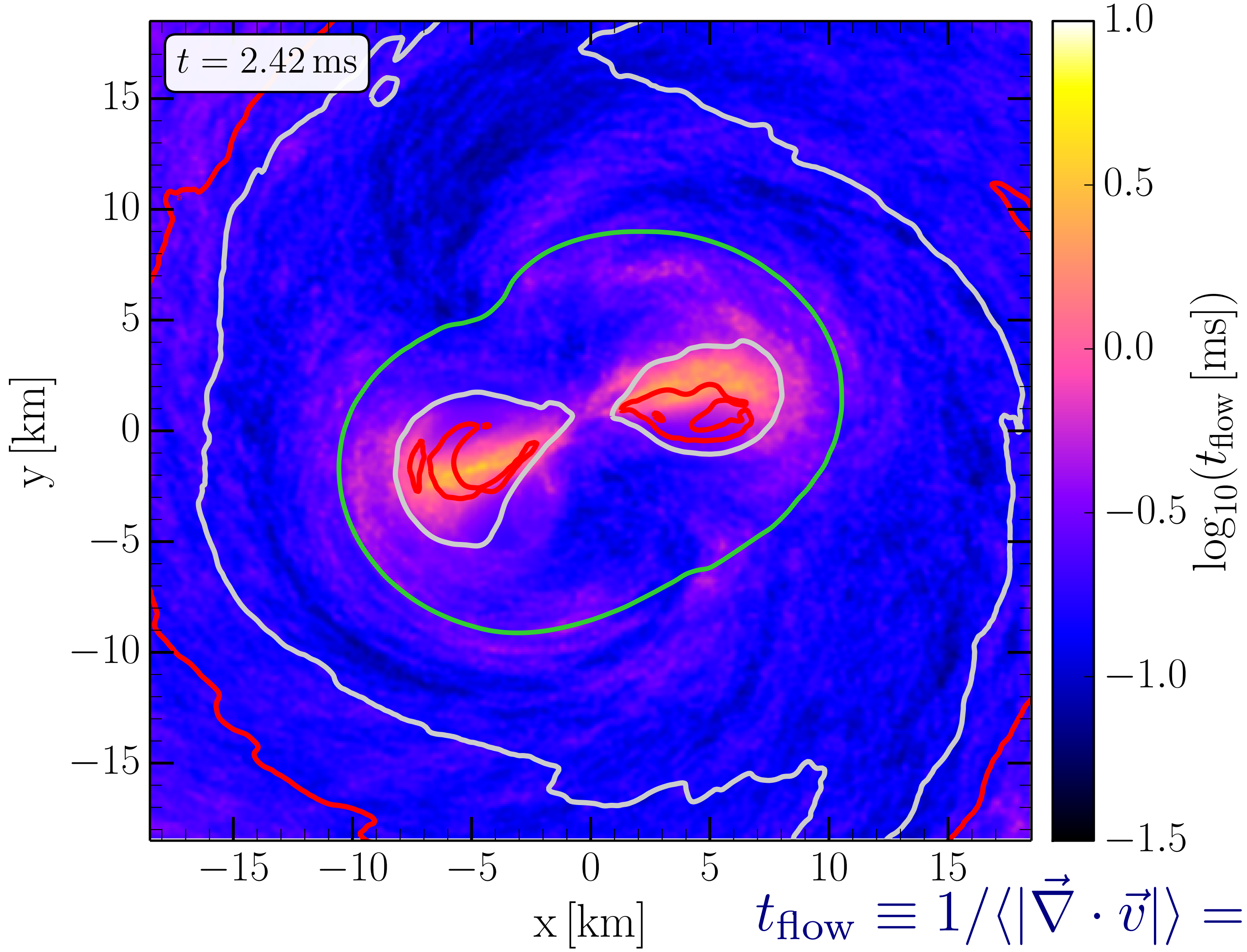
$$T_{\zeta\max}^{\text{nmU}} \approx 4-7\,\text{MeV}$$

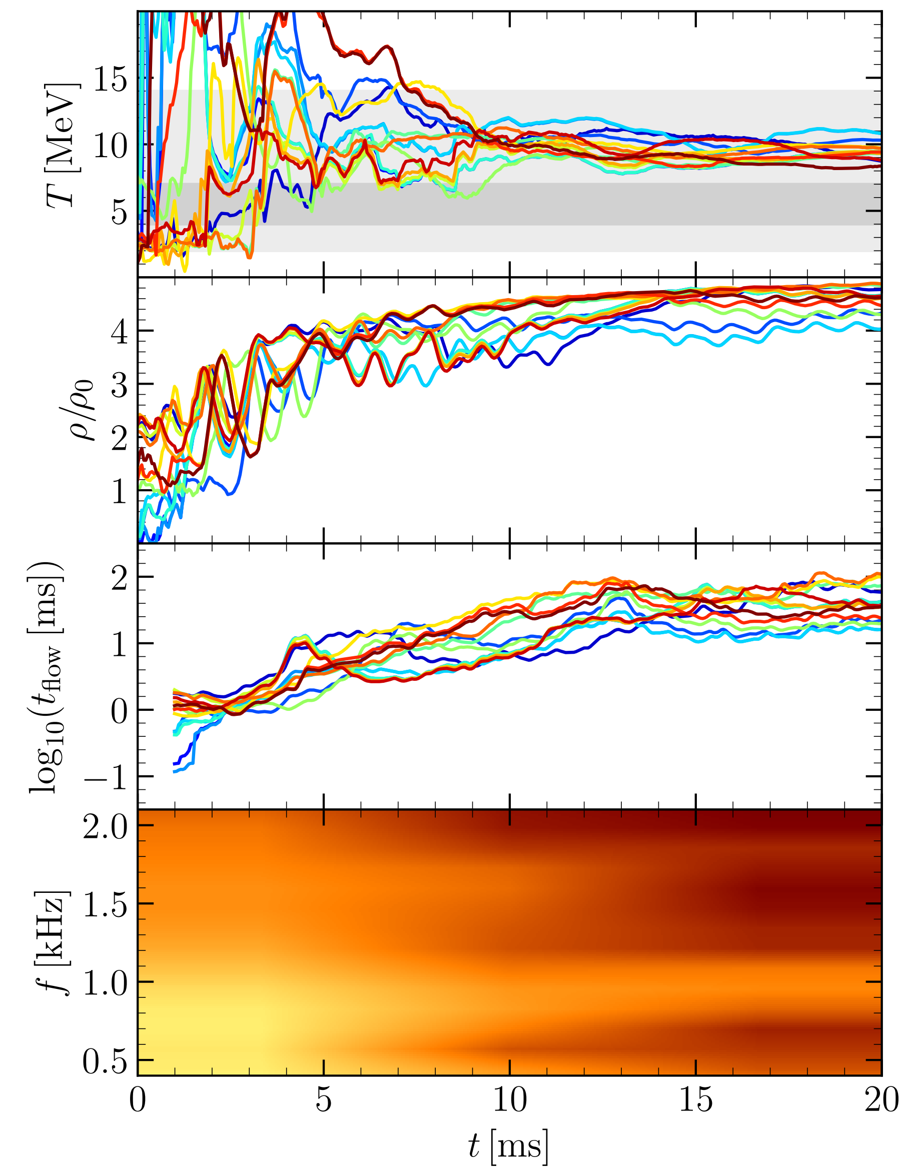
- If parts of the star are at such temperatures and undergo density oscillations on ms-timescales the damping will be huge!



Damping of density oscillations

- Very strong damping in sizable regions within the dense merger product
- Dissipation needs to be included in relativistic hydro simulations
- Could be strong enough to significantly change the evolution …





$t_{\rm dens} \approx (4\Delta n/\bar{n})t_{\rm flow} \sim t_{\rm flow}$

M. Alford, L. Bovard, M. Hanauske, L. Rezzolla, K. Schwenzer, PRL 120, 041101 (2018)

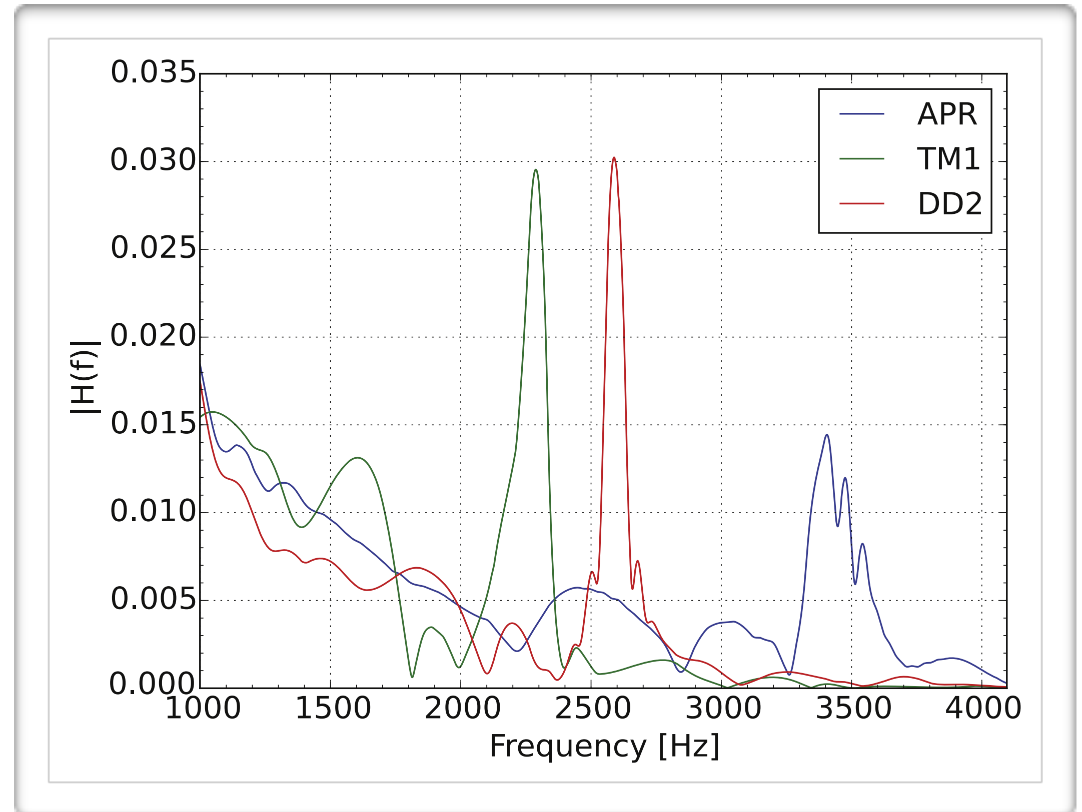
thermal dUrca opening?

Alford, Harris, arXiv:1803.00662

$t_{\rm flow} \equiv 1/\langle|\vec{\nabla}\cdot\vec{v}|\rangle = \rho/D_t\rho$

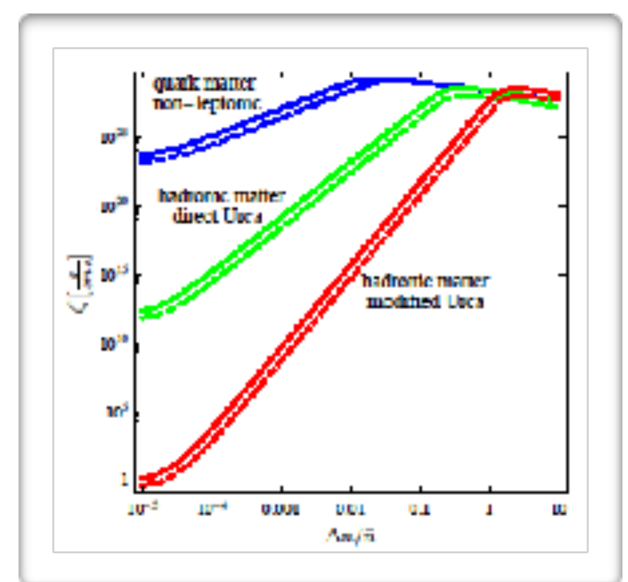
Expected impact on the GW signal

- A significant damping on ms-timescales will will drain energy and thereby shorten the gravitational wave signal
  - ✓ should be observable due to characteristic oscillations



J. Clark, et. al. Class. Quantum Grav. 33 (2016) 085003

- If the dissipated heat will not be efficiently distributed, the additional pressure could stabilize the remnant and will change the large scale flow as well as the GW signal
- To compare to future GW data requires realistic simulations that include dissipative effects
  - hard to implement (non-linearities)
- Bulk viscosity is even enhanced at large amplitudes and methods to include bulk viscosity are currently developed …

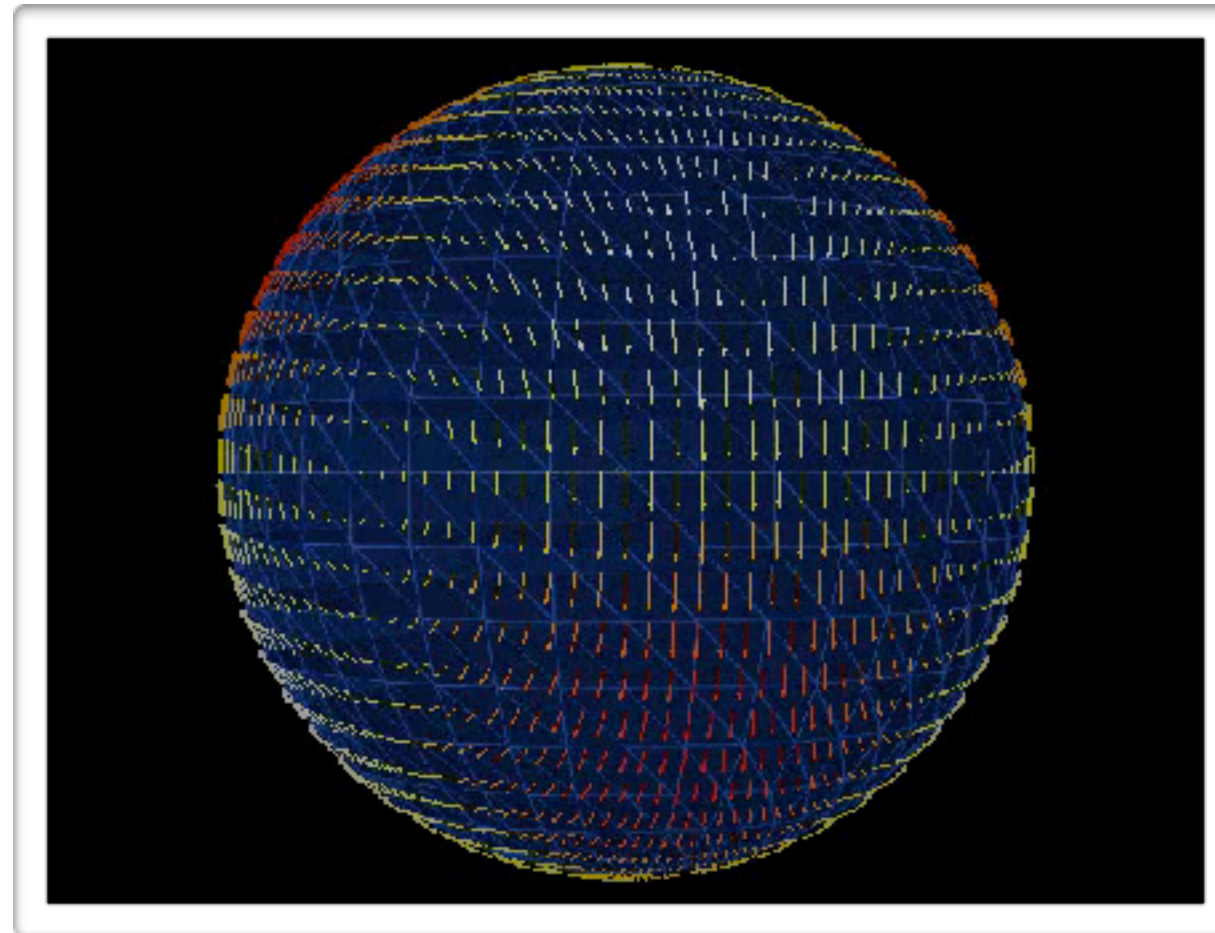


Mergers are like falling stars …

… but there could be literally billions of continuous compact gravitational wave sources!

R-mode oscillations

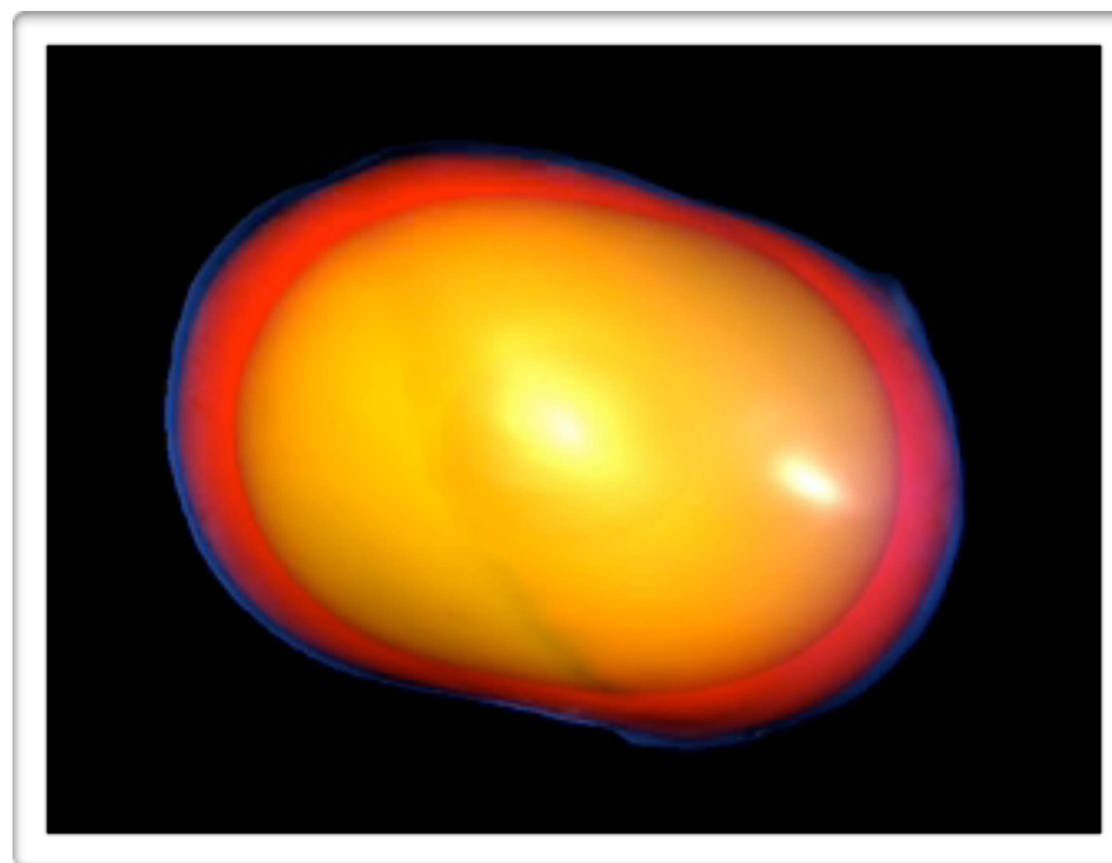
- **R-mode**: Global oscillation eigenmode of a rotating star which emits gravitational waves
  N. Andersson, Astrophys. J. 502 (1998) 708,
  K. Kokkotas, LRR 2 (1999) 2,
  N. Andersson, K, Kokkotas, IJMP D10 (2001) 384
- Mainly an incompressible flow in individual shells, but involves density fluctuations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



Visualization by M. Beilicke

r-mode spectrum: $\omega = -4/3\chi\Omega$

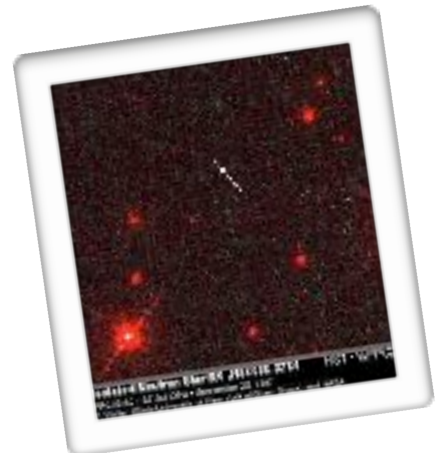
- Large amplitude r-modes could cause a quick spindown

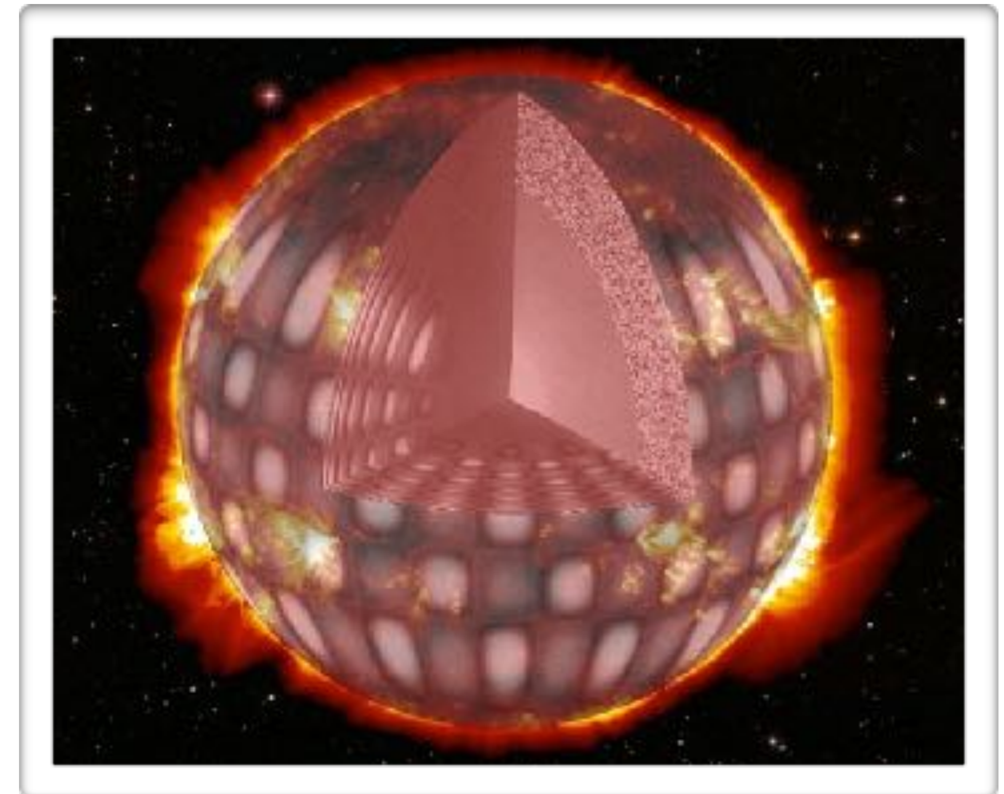


Simulation by L. Lindblom

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

"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

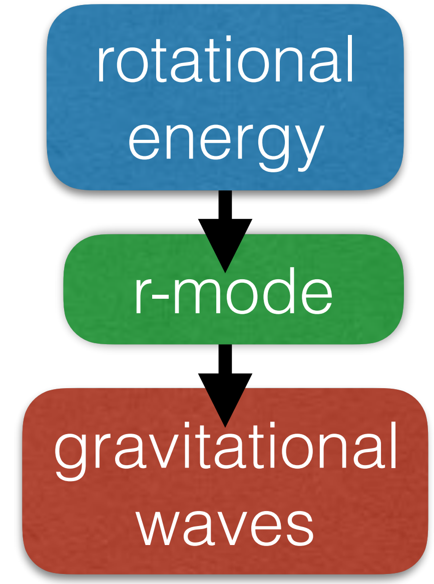
advanced LIGO

  - ✓ 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 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

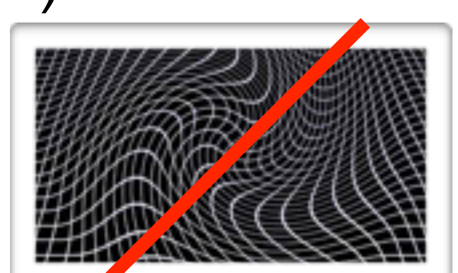
◉ Yet realistic cold dense matter is not (even close to) an ideal fluid … there are two possibilities:

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 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 $\alpha_{\text{sat}} = O(10^{-5})$

    P. Arras, et. al., Astrophys. J. 591 (2003) 1129

"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 DRIVING THE R-MODE)

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

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

(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:

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

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

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

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

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

- Damping is strongly temperature dependent and r-modes strongly heat a source, which requires to consider the thermal evolution

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

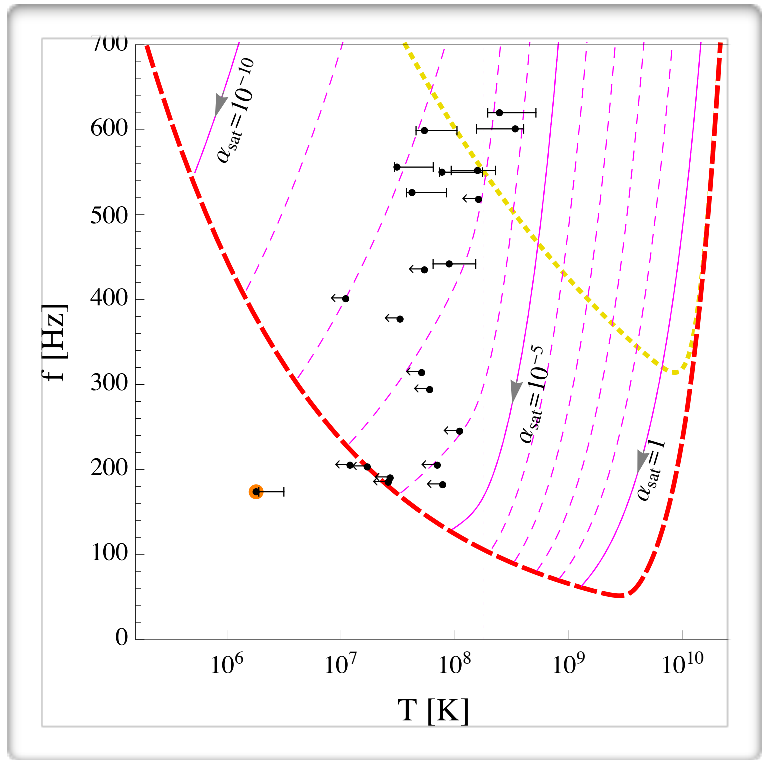
B. J. Owen, et. al., Phys. Rev. D 58 (1998) 084020

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

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

✦ Pulsar evolution decouples and allows semi analytic results

Effective r-mode spindown



- The r-mode saturation mechanism is unknown and the amplitude generally depends in on powers of temperature and frequency

$$\alpha_{\rm sat} = \hat{\alpha} T^{\beta} \Omega^{\gamma}$$

- Due to the scale hierarchy, the r-mode spindown proceeds along thermal steady state trajectories with an altered spindown law

$$\frac{d\Omega}{dt} = -\frac{3}{I}\left(\frac{\chi^{5\theta}\,(3-2\chi)^{2\beta}\,\hat{G}^{\theta}\hat{\alpha}_{sat}^{2\theta}}{\hat{L}^{2\beta}}\right)^{\frac{1}{\theta-2\beta}}\Omega^{n_{\rm rm}} \qquad n_{\rm rm} \equiv \frac{(7+2\gamma)\,\theta+2\beta}{\theta-2\beta}$$

➡ in terms of an effective r-mode braking index

- e.g. mode coupling: $n_{\rm rm}^{(\rm mc)} = 4$, vortex-fluxtube-cutting: $n_{\rm rm}^{(\rm vfc)} = 1$

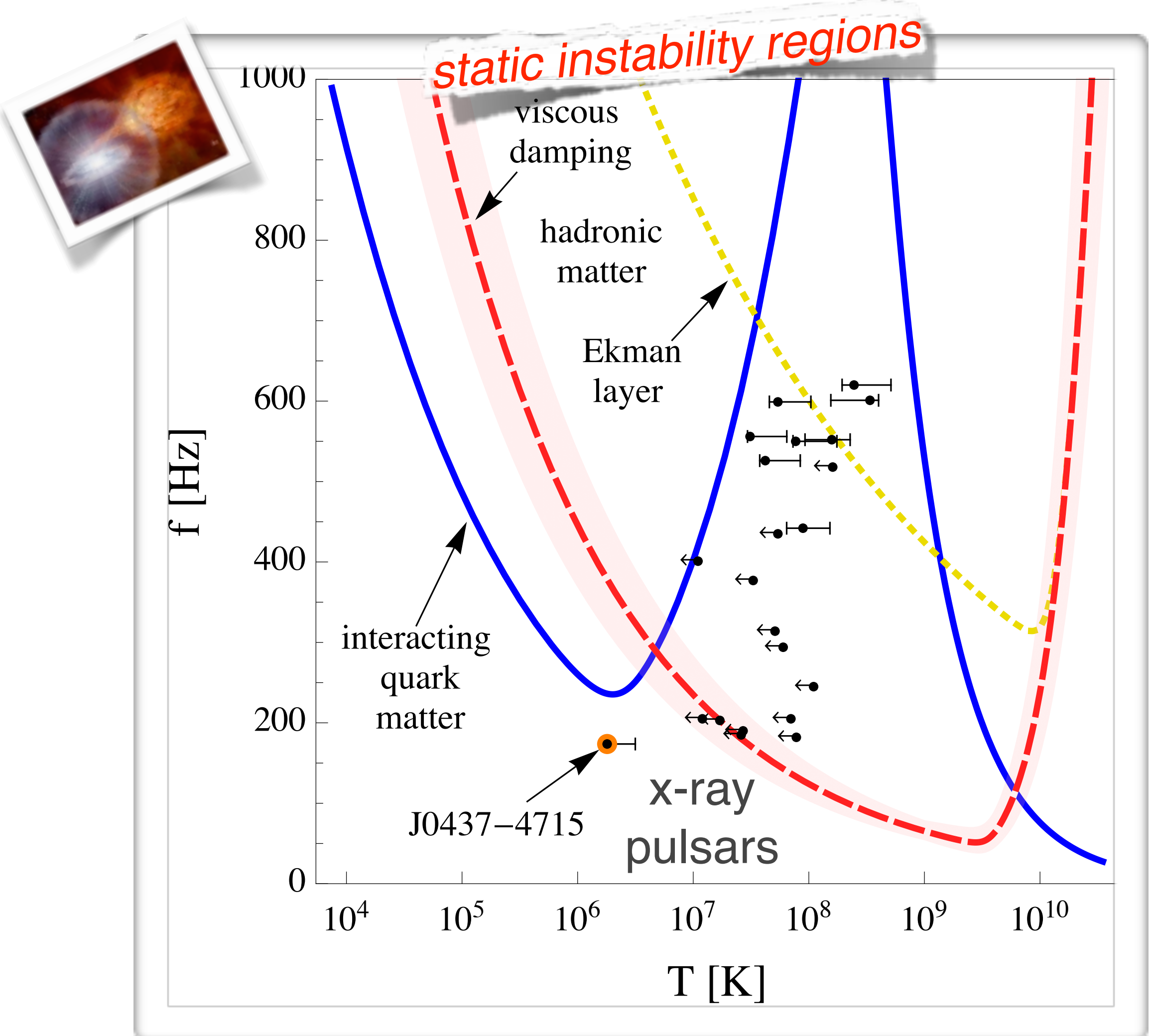
P. Arras, et. al., Astrophys. J. 591 (2003) 1129 B. Haskell, K. Glampedakis, N. Andersson, MNRAS 441 (2014) 1662

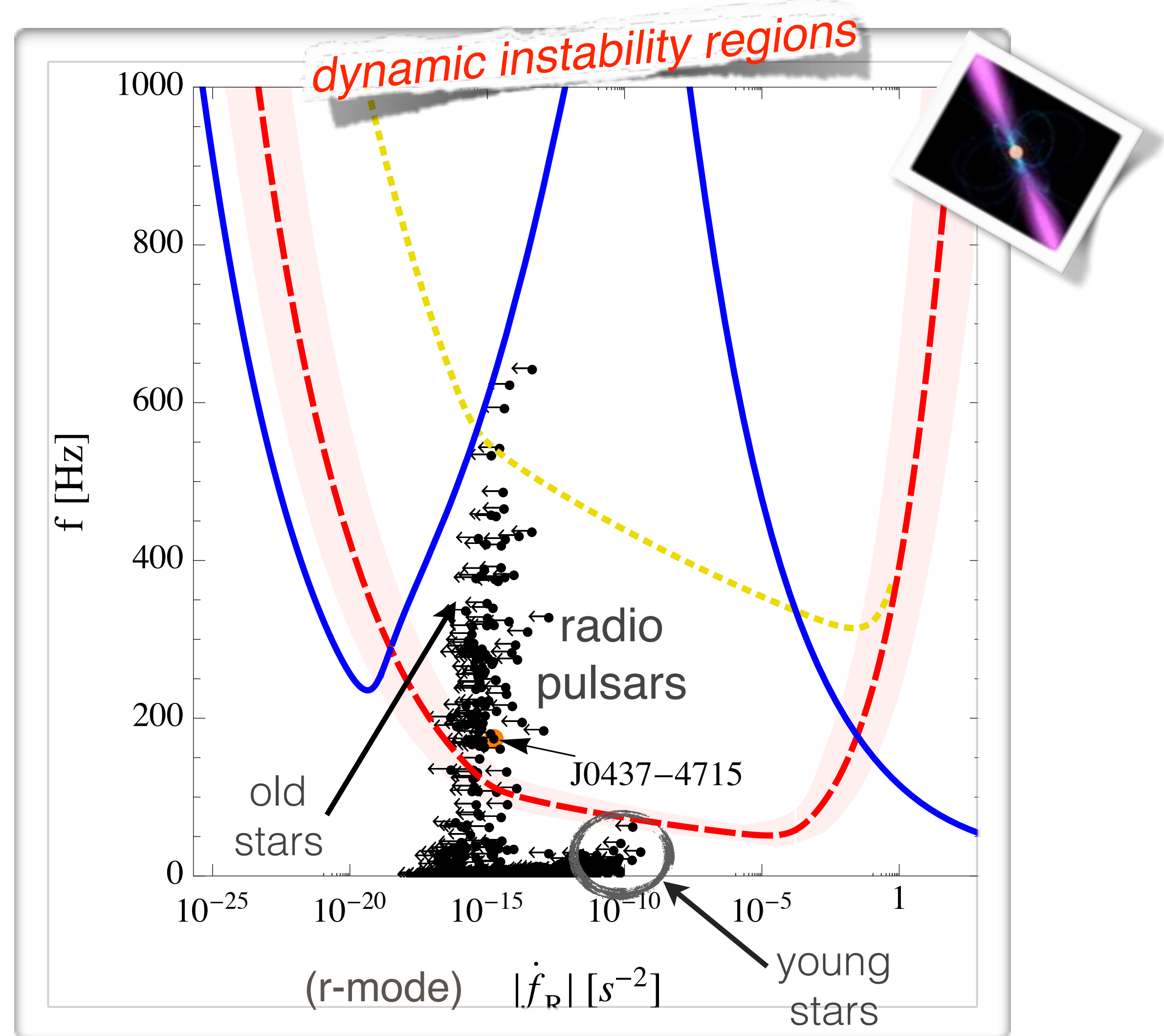
- Semi-analytic results for the entire r-mode evolution … e.g. final frequency for a neutron star:

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

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

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





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

Instability boundaries in temperature & timing space:

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

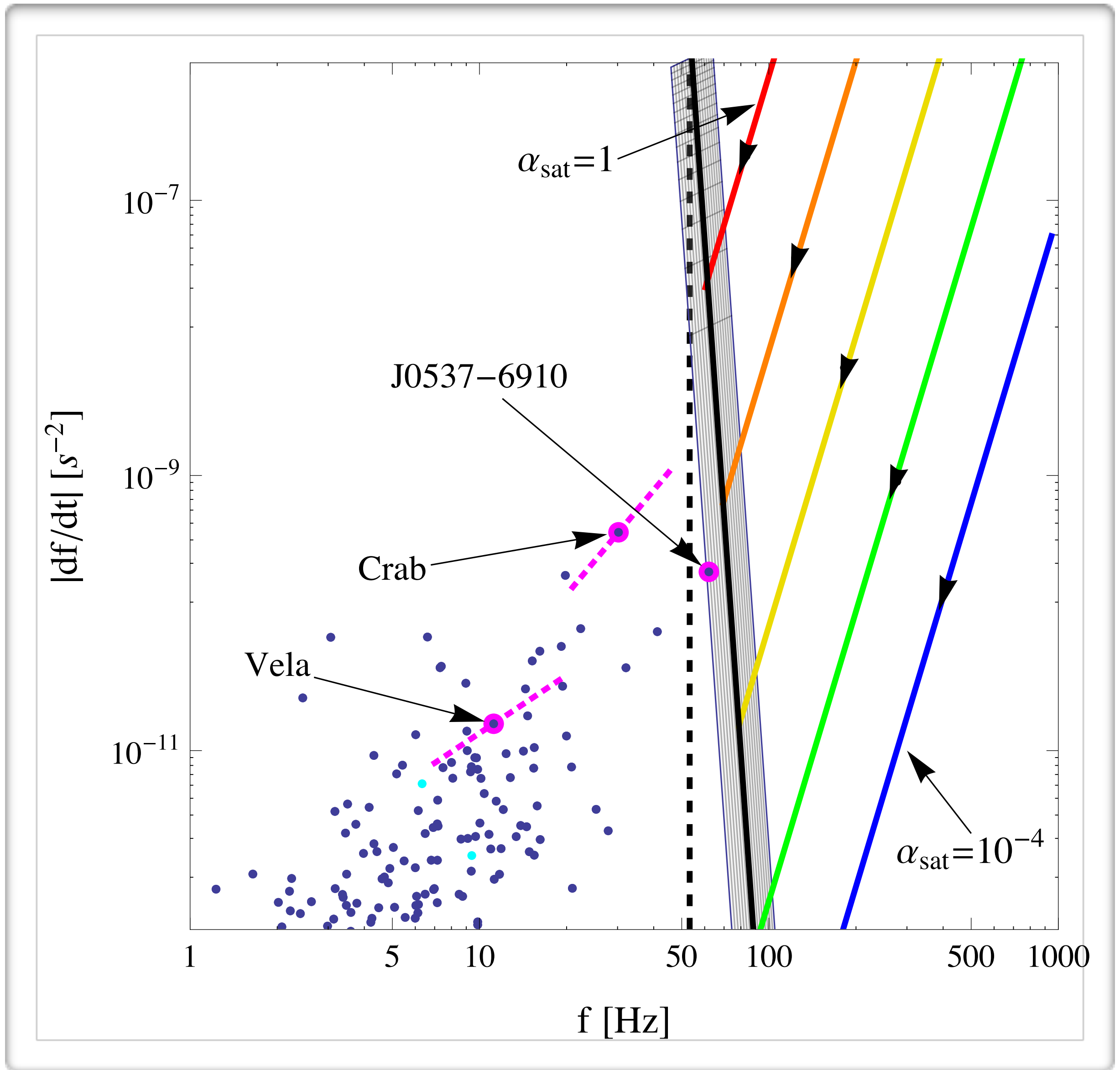
independent of saturation physics!

Standard neutron matter cannot damp r-modes in theses sources!

Quantitative explanation of low pulsar frequencies

- r-mode emission can *quantitively* explain the low rotation frequencies of young pulsars (which already spin too slow to emit GWs),

  ➡ Even younger sources are promising GW targets!



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

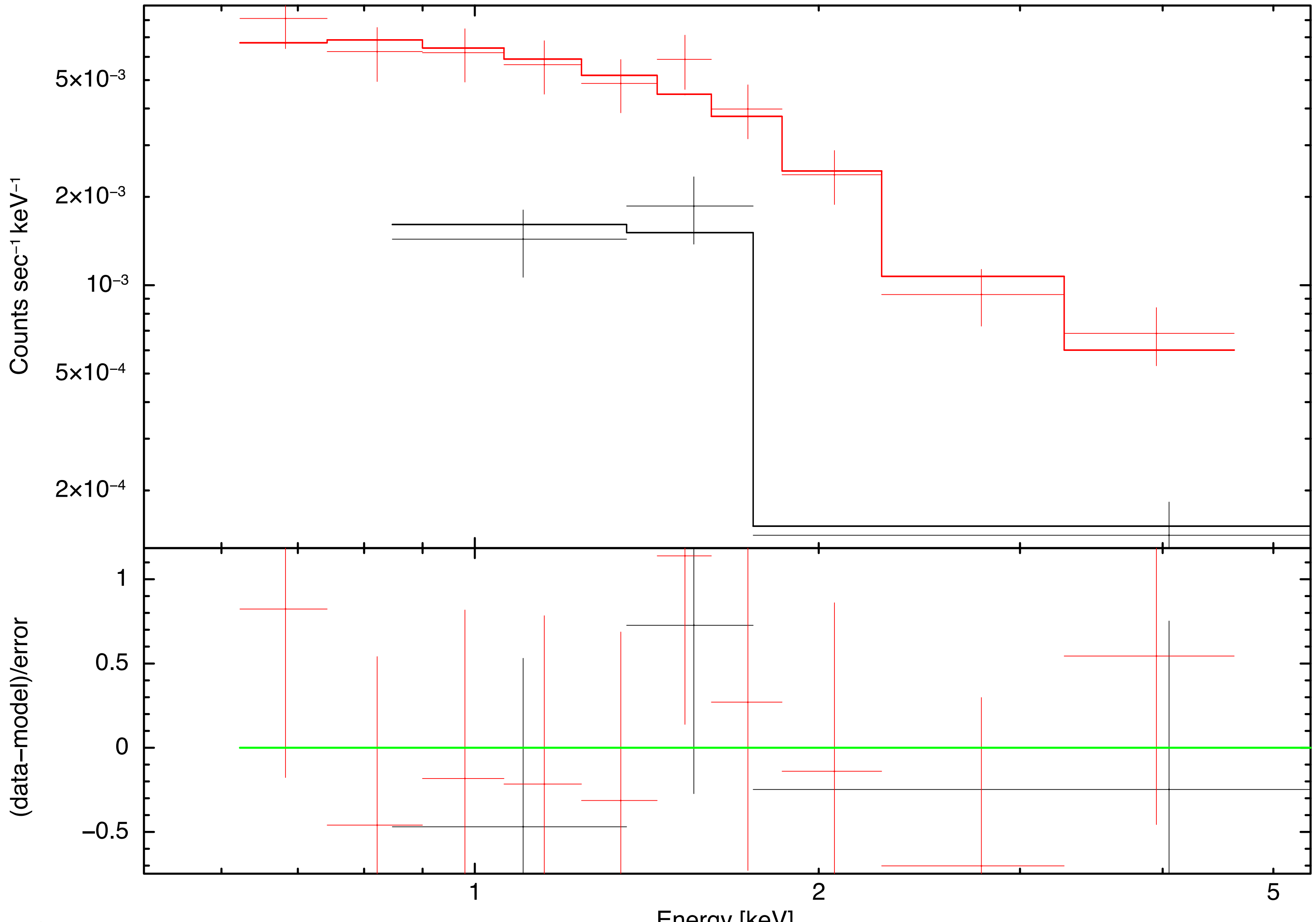
Temperature bounds on ms-pulsars

- r-modes strongly heat a source
  - ✦ temperature bounds impose r-mode amplitude bounds

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

K. S., T. Boztepe, T. Güver, E. Vurgun, MNRAS 446 (2017) 2560
S. Bhattacharya, C. Heinke, A. Chugunov;
P. Freire, A. Ridolfi, S. Bogdanov, arXiv:1709.01807

- Although most millisecond pulsars are too faint to measure their temperature, X-ray luminosity measurements impose upper bounds on the temperature …
- New dedicated XMM-Newton observation of J1810+1744 (f=602Hz)
- Spectral fit does not require surface comp. (hotspot + power law)
- Bound from checking at which temperature, a surface component would invalidate the fit



K. S., T. Boztepe, T. Güver, E. Vurgun, MNRAS 446 (2017) 2560

T. Boztepe, T. Güver & K. S. in preparation

r-mode amplitude bounds

- Temperature bounds impose tight bounds on the r-mode amplitude

$$\alpha_{\rm sat} \leq \sqrt{\frac{3^7 5}{2^{25}\pi^6 (3-2\chi)\,\chi^5 G\,\tilde{J} M R^2}} \left(1-\frac{2GM}{R}\right)^{-1} \frac{T_\infty^2}{f^4}$$

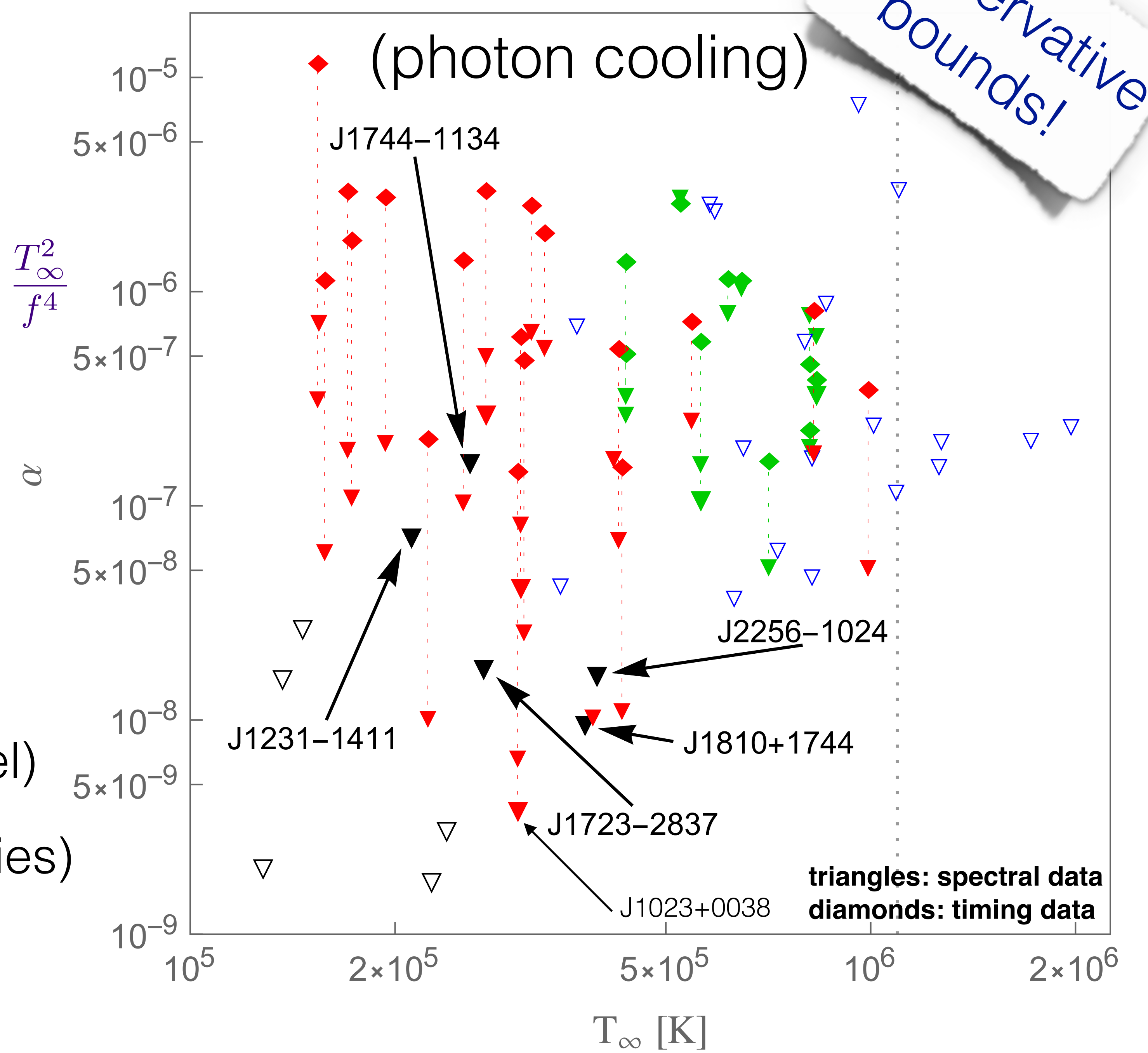
T. Boztepe, T. Güver & K. S. in preparation

- New bound on J1810+1744 (f = 602 Hz), sets the lowest bound, yet:

$\alpha_{\rm sat} \lesssim 2 \times 10^{-9}$ (standard NS model)

$\alpha_{\rm sat} \lesssim 10^{-8}$ (including uncertainties)

- Close to completely ruling out r-modes in these sources!



K. S., T. Boztepe, T. Güver, E. Vurgun, MNRAS 446 (2017) 2560, T. Boztepe, T. Güver & K.S., in preparation

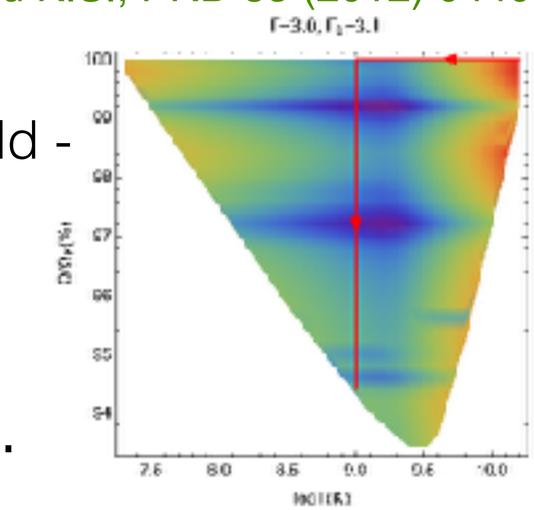
r-modes have a strong impact on the thermal evolution, even when they are irrelevant for the spindown!

$$\alpha_{\rm sat} < 1.4 \times 10^{-9} \left(\frac{T_\infty}{10^5\,{\rm K}}\right)^2 \left(\frac{500\,{\rm Hz}}{f}\right)^4$$

Standard damping mechanisms

What could saturate r-modes at such low amplitudes $\alpha \lesssim 10^{-9} - 10^{-8}$?

- ~~Ekman damping~~ —> "pasta" L. Bildsten, G. Ushomirsky, APJ 529 (2000) 33, L. Lindblom, B. Owen, G. Ushomirsky, PRD 62 (2000) 084030
- ~~Non-linear hydro~~ $\alpha_{\text{sat}} = O(1)$ L. Lindblom, et. al., PRL 86 (2001) 1152, W. Kastaun, Phys.Rev. D84 (2011) 124036
- ~~Non-linear viscosity~~ $\alpha_{\text{sat}} = O(1)$ M. Alford, S. Mahmoodifar and K.S., PRD 85 (2012) 044051
- ~~Mode coupling~~ $\alpha_{\text{sat}} > 10^{-6}$ (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; A. Chugunov, J. Friedman, L. Lindblom, L. Rezzolla, arXiv:1712.09224
  - not relevant since the mechanism is weaker than estimated
- ~~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)
  - spindown along a stability window (dynamic saturation)

N. Andersson, I. Jones, K. D. Kokkotas, MNRAS 337 (2002) 1224,
M. Alford & K. S., PRL 113 (2014) 251102 & NPA 931 (2014) 740

- Hyperonic matter

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

- Resonance coupling in superfluids

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

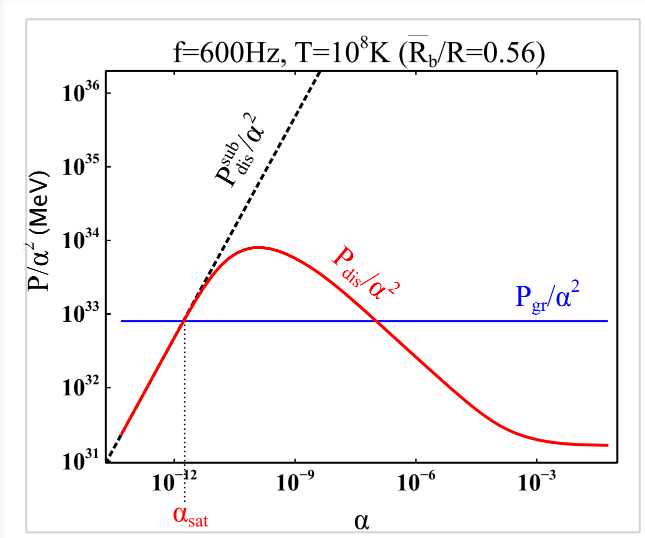
- Vortex / fluxtube cutting? $\alpha_{\rm sat} \approx 10^{-7} - 10^{-6}$

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

- Phase conversion in hybrid stars

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

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



- Pasta phases?? … or something we haven't even thought about …

aLIGO search for continuous waves

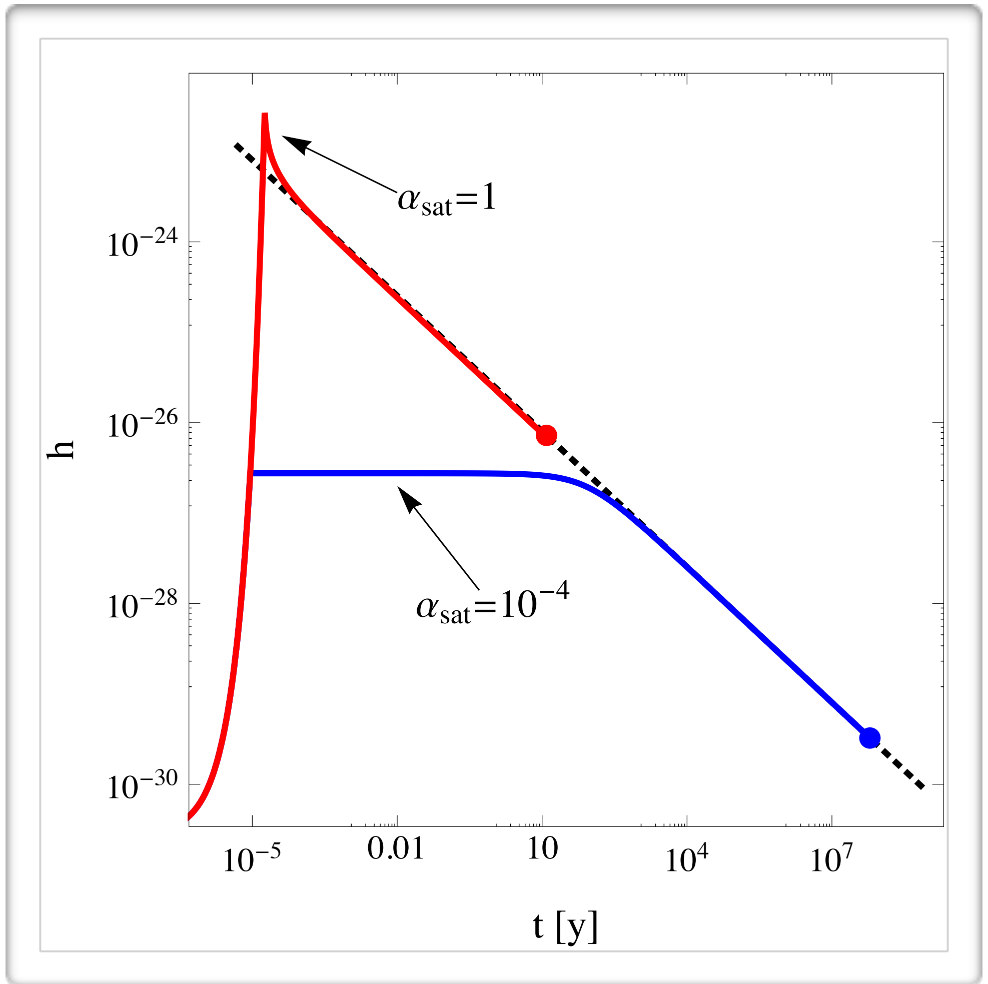
- First aLIGO all-sky search for continuous gravitational waves: O1 data (2015)
  B. P. Abbott, et. al., PRD 96 (2017) 6 & arXiv:1802.05241
  - (semi-coherent) all-band: 10-2000 Hz
    - very promising for r-modes
  - ➡ NO signal detected!

- Search not specifically tailored towards r-mode gravitational waves, but should be applicable …
  - un-targeted search (frequencies unknown)
  - linear spindown model (braking index enters only at quadratic order)
  - wide range of spindown rates:

$$-10^{-8}\,\mathrm{Hz/s} \leq \dot{\nu} \leq +10^{-9}\,\mathrm{Hz/s}$$

Gravitational strain of young sources

- r-mode evolution has three stages
  - mode growth
  - early stage (frequency constant)
  - late time stage (independent of initial conditions)



- Intrinsic strain in the late-time stage:

B. Owen, PRD 82 (2010) 104002

saturation mechanism

$$h_0 \xrightarrow[\Omega \ll \Omega_i]{} \sqrt{\frac{5\mathcal{C}GI}{8\chi D^2 t}} \qquad \mathcal{C} \equiv \frac{1-2\beta/\theta}{1+\gamma/3+2\beta/(3\theta)}$$

$(\alpha_{sat} = \hat{\alpha} T^{\beta} \Omega^{\gamma}\ ,\ L = \hat{L} T^{\theta}\ )$

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

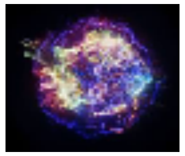
K. S. in preparation

r-mode spectrum $\omega = -4/3\chi\Omega$

- Allows to take into account the uncertainties in the analysis, which is important to abstract information from gravitational wave data

GW emission from young, nearby sources

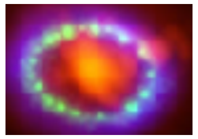
- A handful of "recent" historic SN remnants are known in our local group LIGO Col., arXiv:1412.5942
  - Cas A (~335 years, Milky way)



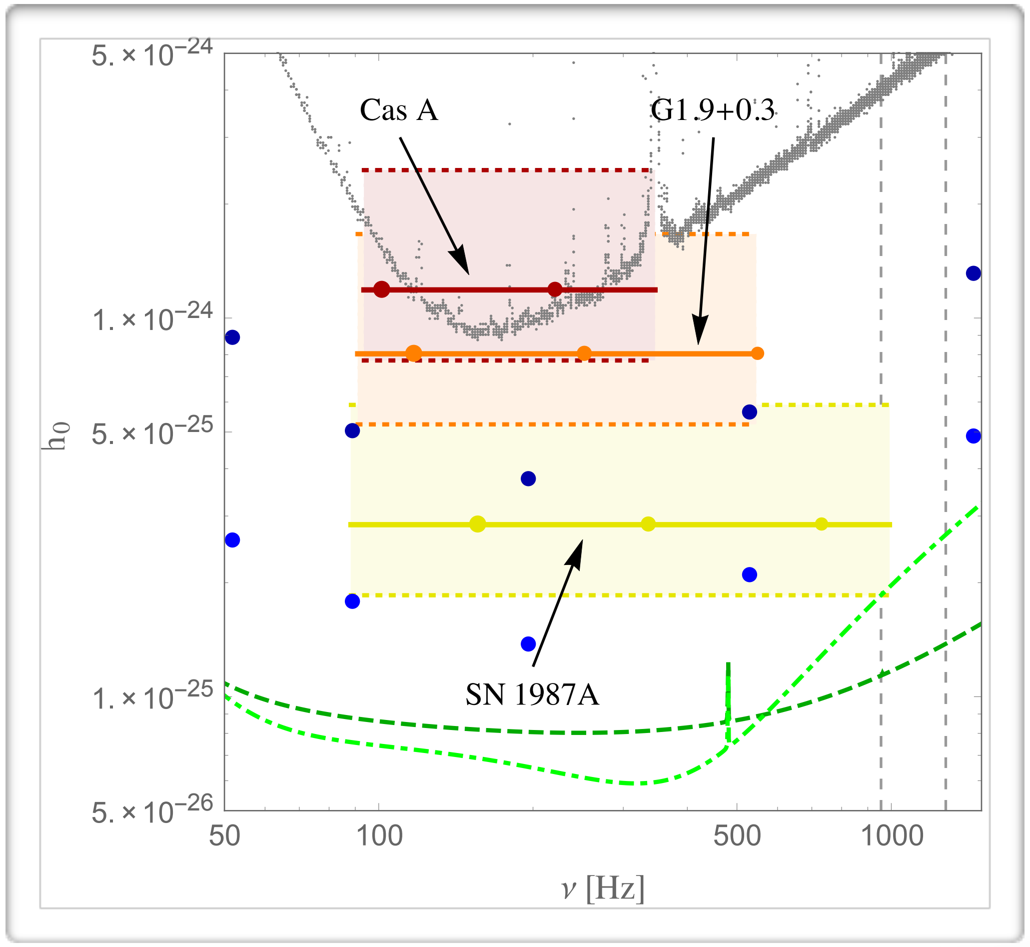
LIGO Col., APJ 722 (2010) 1504

  - G1.9+0.3 (~145 years, Milky way)

  - SN 1987A (Large Mag. Cloud)



- Including uncertainties Cas A & G1.9+0.3 should have been above the background!



K. S. in preparation

★ No sizable r-modes in these sources

work in progress

- dissipation could either be strong, so that $\alpha \lesssim 10^{-3}$
- or the amplitude is large, $\alpha^{(\text{Cas A})} \gtrsim 0.1$ and $\alpha^{(\text{G1.9+0.3})} \gtrsim 0.2$, so that the r-mode spindown phase is already over

- Should exclude r-mode amplitudes $10^{-3} \lesssim \alpha \lesssim 0.1$, if these sources were born quickly rotating

So far we are at the beginning …

… but it could be only a matter of sensitivity