EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Gravitational Waves
from
Neutron Stars

Kostas Kokkotas

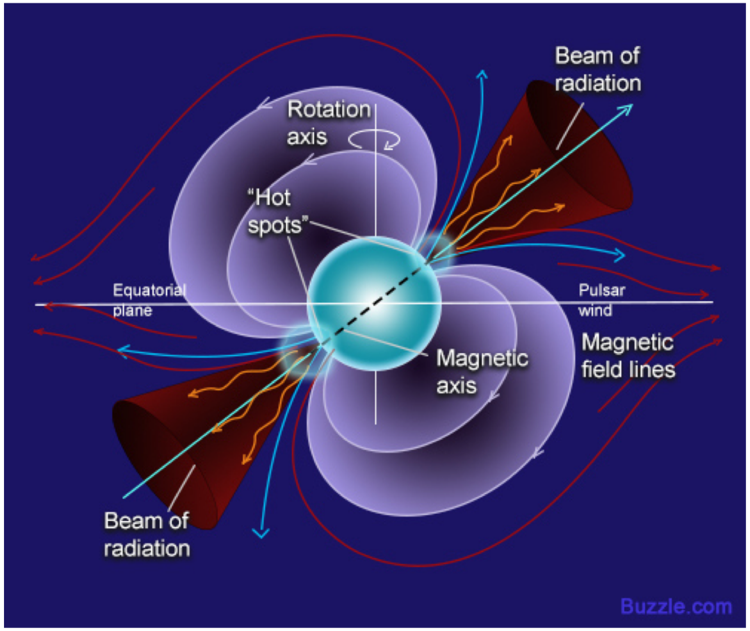
Theoretical Astrophysics

Eberhard Karls University of Tübingen

Neutron Stars

- They are the **most compact stars** known to exist in the universe.
- They have **densities equal to that of the early universe** and **gravity similar to that of a black hole.**
- Most extreme magnetic fields known in the universe up to **10^{16} G**.

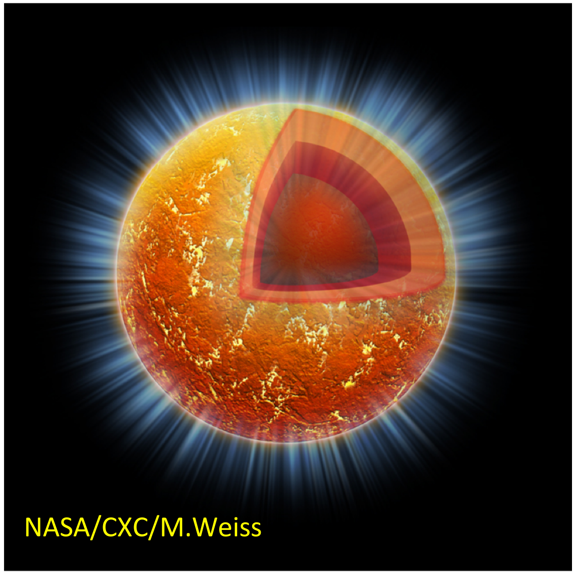
Conjectured	1931
Discovered	1967
Known	2500+
Mass	1.2–2$M_{\odot}$
Radius	8-14 km
Density	10^{15}g/cm^3
Spin	< 716 Hz
In our Galaxy	~10^8

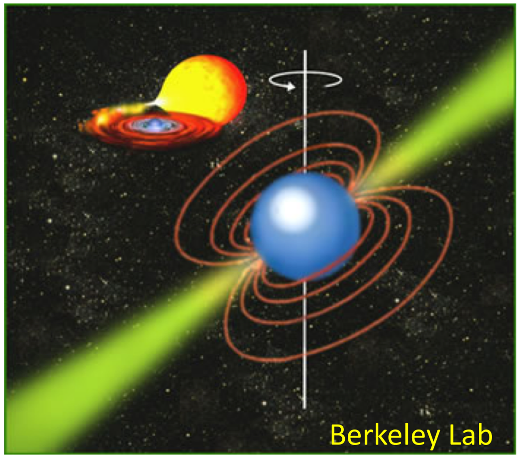


Scientific Challenge

Neutron Stars - Physics in its extremes

- **Gravity** at its maximum (which gravity?)
- **Strong interactions** more important than in any other part of the present universe
- **Electroweak interactions** drive the astronomical emission



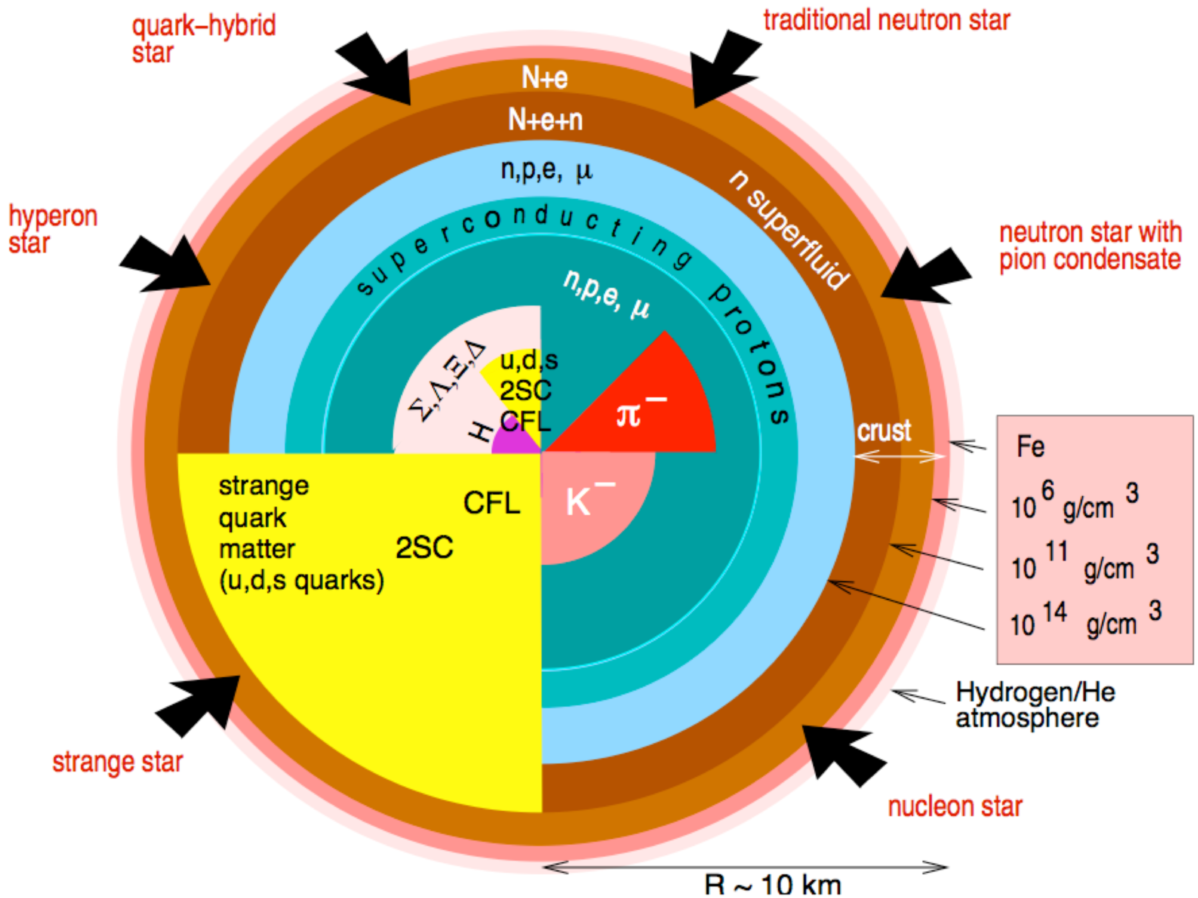


Neutron Stars - a unique interplay among

- **astrophysics**
- **gravitational physics**
- **nuclear physics**

After half a century since their discovery, we are still far from understanding the composition of matter in their cores!

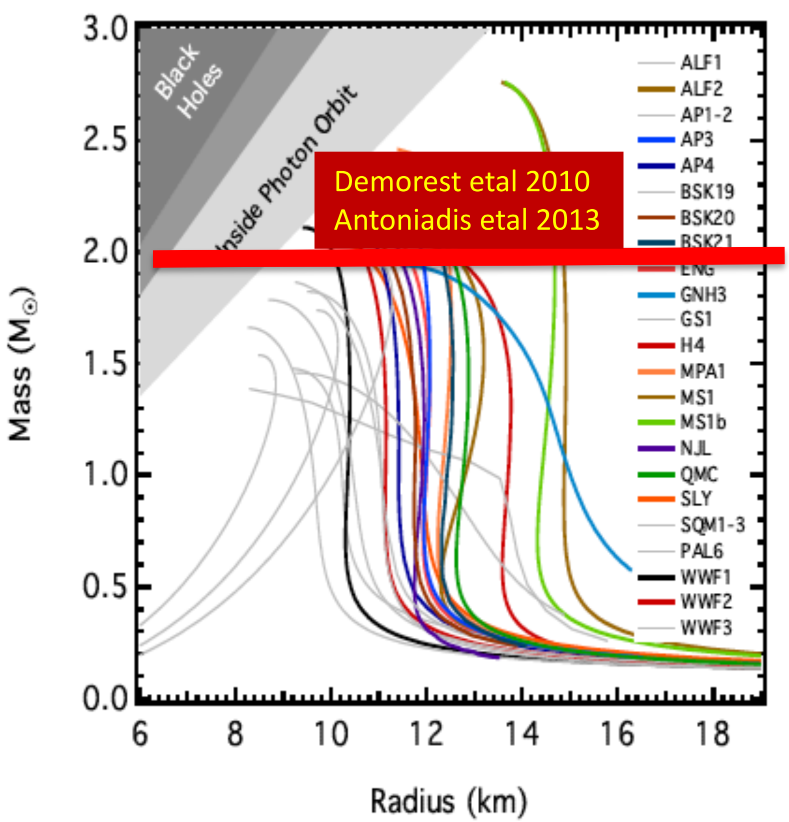
Zooming into a Neutron Star



- The holy grail of NS astrophysics… is the determination of the equation of state (EOS) of matter at supra-nuclear densities.
- The most direct way of constraining the EOS is to measure simultaneously the neutron star mass and radius.

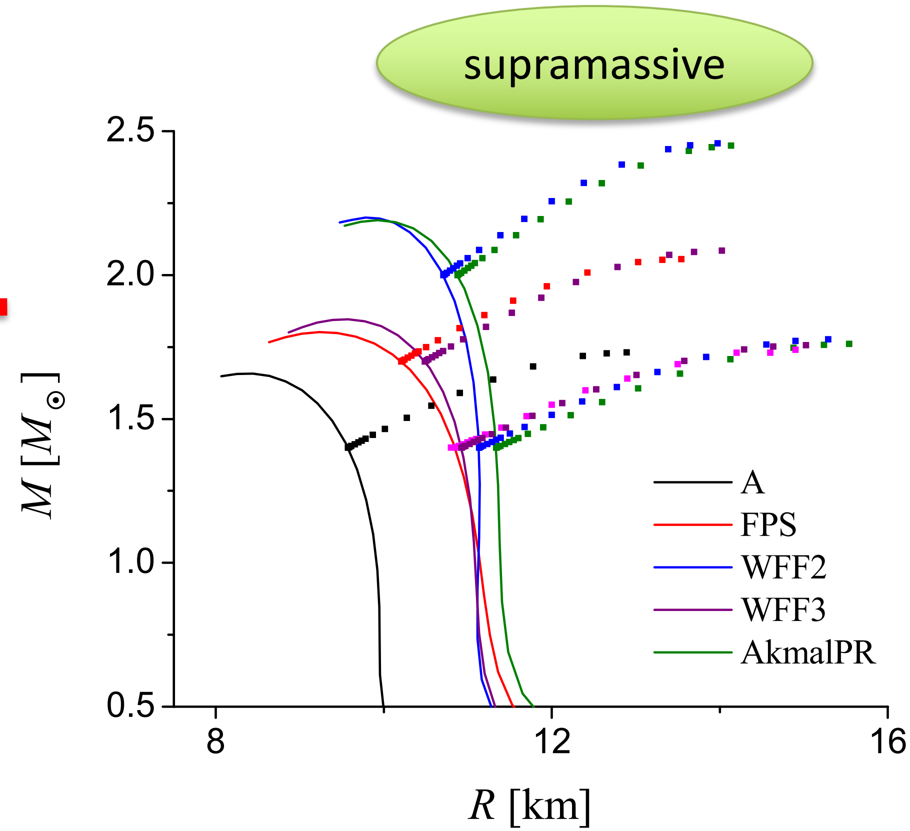
Neutron Stars: Mass vs Radius

Static Models



Özel & Freire (2016)

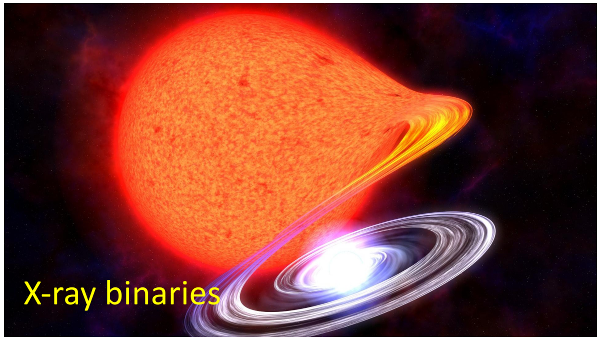
Rotating Models

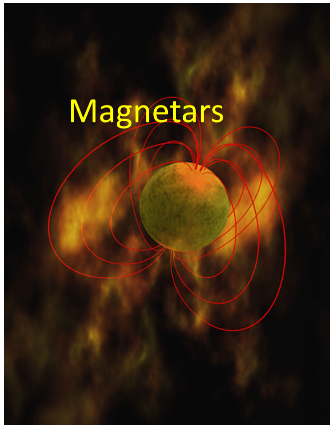


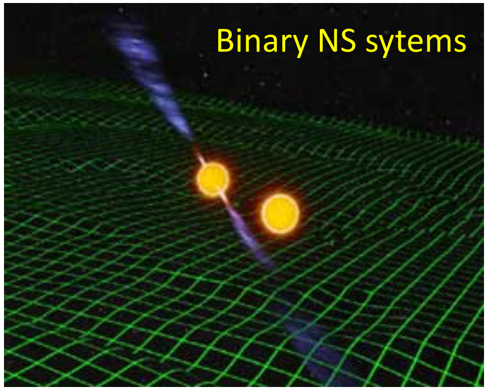
$$M_{max} \simeq 1.2\, M_{TOV}$$

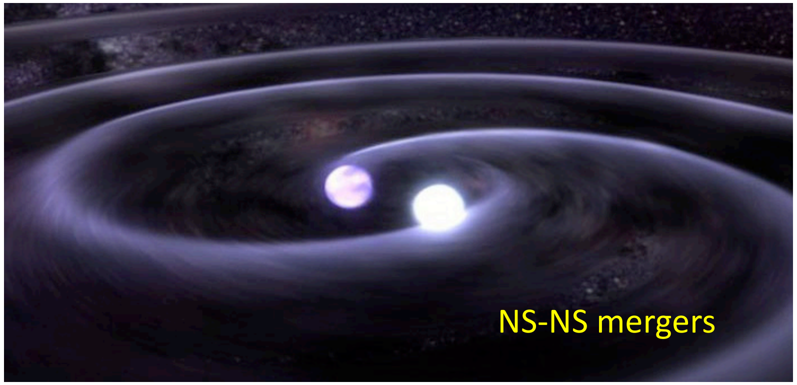
Breu-Rezzolla 2015

The Many Faces of Neutron Stars



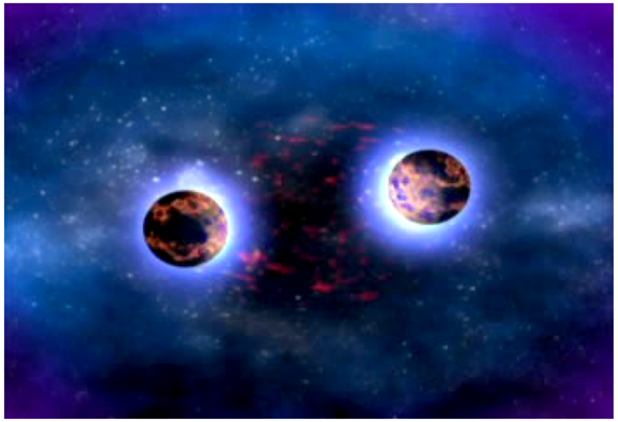




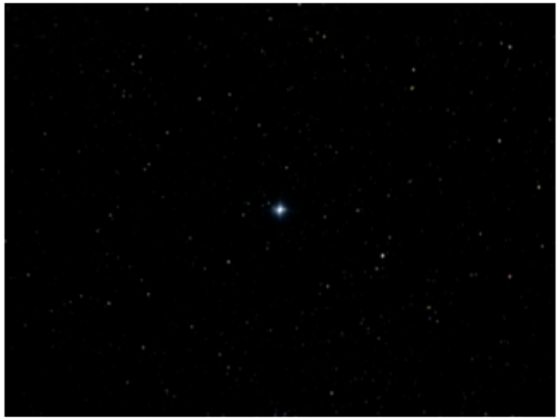


Typical masses ~1.2-2 $M_\odot$
Typical Radius ~9-14 km

Main Sources for LIGO/Virgo



BH and NS Binaries

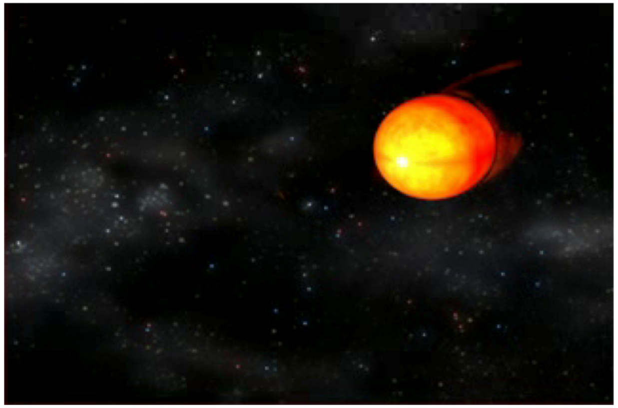


Supernovae, BH/NS formation

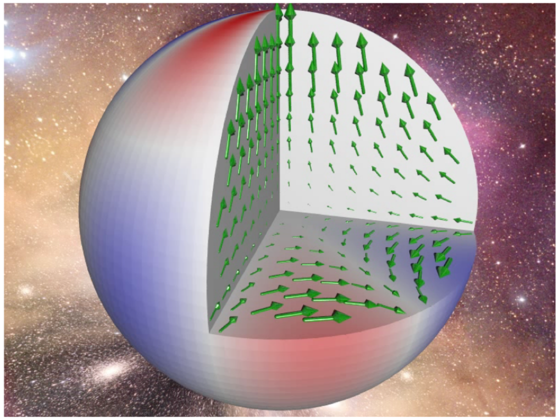
$$L_{GW} \sim \left(\frac{M}{R}\right)^5$$

$$h \sim \varepsilon \cdot \left(\frac{M}{r}\right) \cdot \left(\frac{M}{R}\right)$$

BLACK HOLES:	M/R=0.5
NEUTRON STARS:	M/R~0.2
WHITE DWRFS:	M/R~10^{-4}

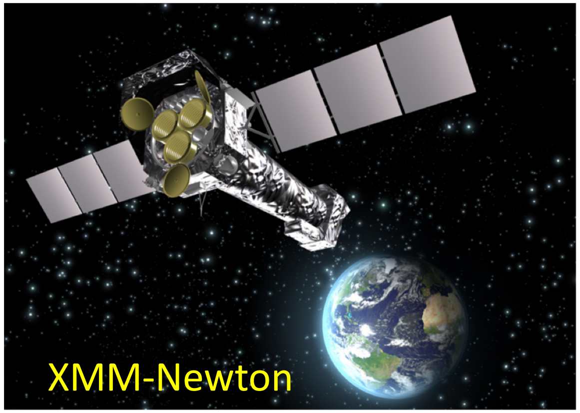


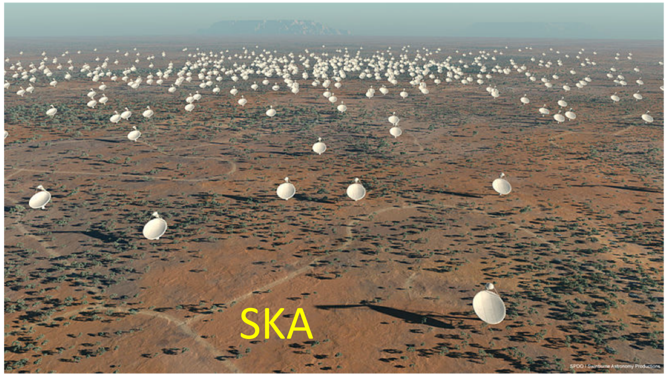
Spinning neutron stars in X-ray binaries



Neutron Stars:
Instabilities, Deformations

Neutron Stars -Observatories





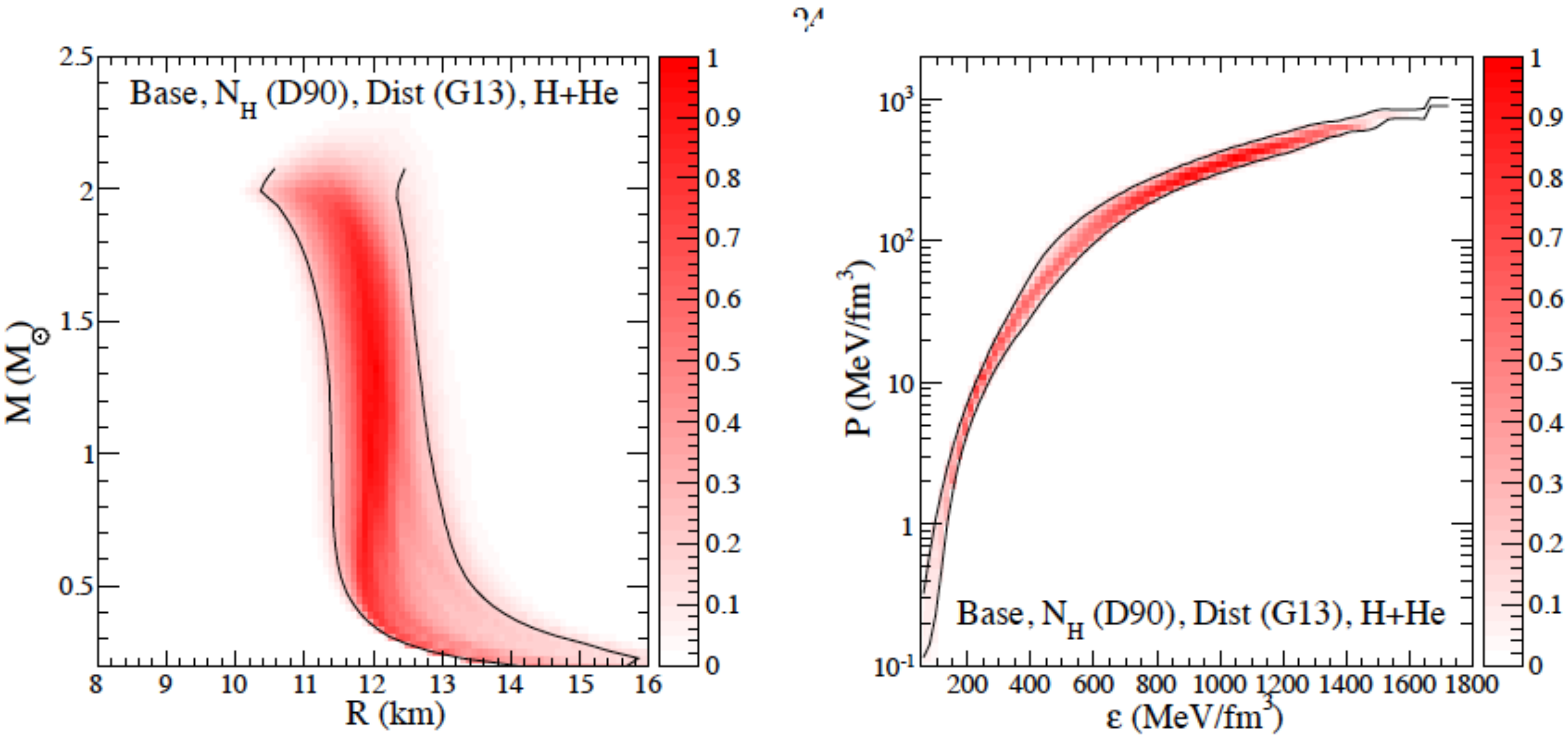
Constraints on Neutron Star Radius
GW observations

Main methods in EM spectrum:

- **Thermonuclear X-ray bursts (photospheric radius expansion)**
- **Burst oscillations (rotationally modulated waveform)**
- **Fits of thermal spectra to cooling neutron stars**
- **khZ QPOs in accretion disks around neutron stars**
- **Pericenter precession in relativistic binaries (double pulsar J0737)**

Observational Constraints on EOS

Attempts to constrain the EOS by combining observational data (LMXBs)
e.g. Lattimer-Steiner 2013



Equation of State:
Constraints from X-ray binaries / bursts

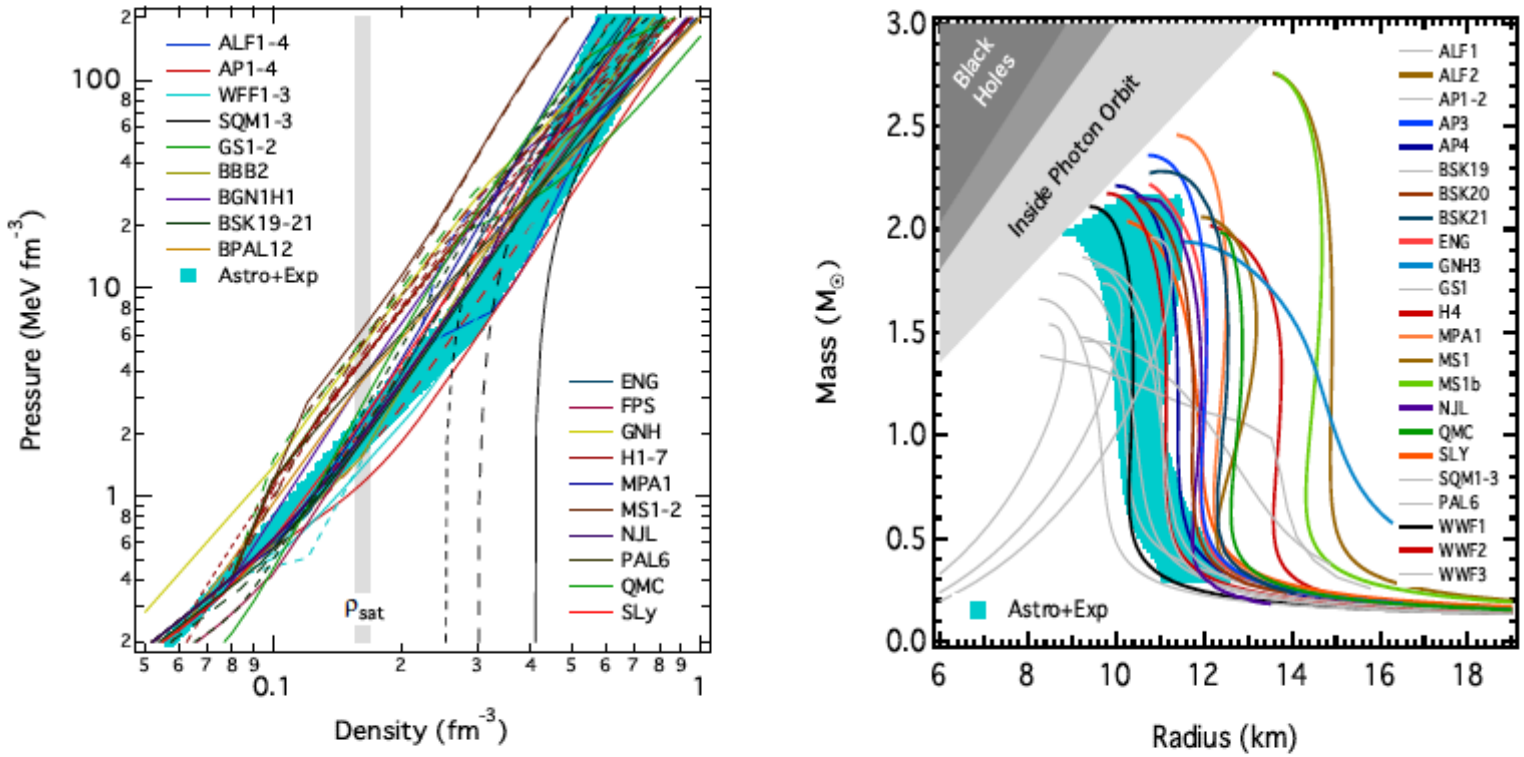


Figure 10

The astrophysically inferred (left) EoS and (right) mass-radius relation corresponding to the most likely triplets of pressures that agree with all of the neutron star radius and low energy nucleon-nucleon scattering data and allow for a $M > 1.97\ M_\odot$ neutron star mass. The light blue bands show the range of pressures and the mass-radius relations that correspond to the region of the (P_1, P_2, P_3) parameter space in which the likelihood is within e^{-1} of its highest value. Around $1.5\ M_\odot$, this inferred EoS predicts radii between 9.9 – 11.2 km.

Özel & Freire (2016)

Constraints on Neutron Star Radius
GW observations

Main methods in GW spectrum:

- **Tidal effects** on waveform during inspiral phase of NS-NS mergers
- **Tidal disruption** in BH-NS mergers
- **Oscillations** in (**early** & **late**) post-merger phase
- **Oscillation** in the post-collapse phase

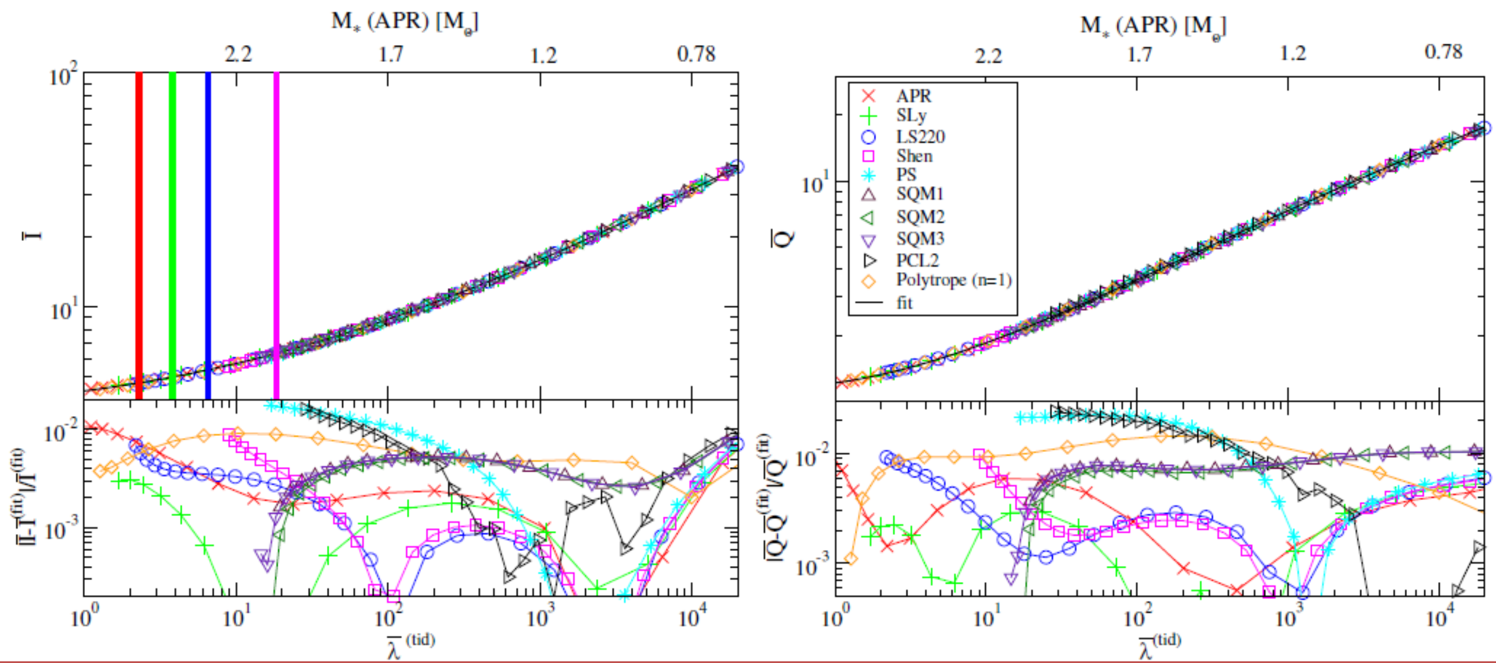
Neutron Stars & "universal relations"

Need for relations between the "observables" and the "fundamentals" of NS physics

Average Density	$\bar{\rho} \sim M / R^3$	
Compactness	$z \sim M / R$	$\eta = \sqrt{M^3 / I}$
Moment of Inertia	$I \sim MR^2$	$I \sim J / \Omega$
Quadrupole Moment	$Q \sim R^5 \Omega^2$	
Tidal Love Numbers	$\lambda \sim I^2 Q$	

I-Love-Q relations

EOS independent relations were derived by **Yagi & Yunes(2013)** for non-magnetized stars in the slow-rotation and small tidal deformation approximations.



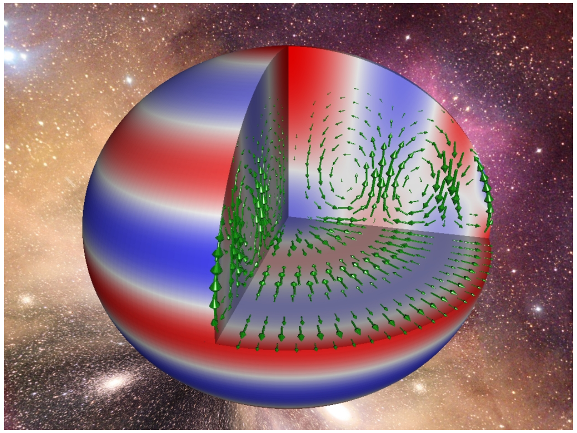
… the relations proved to be valid (*with appropriate normalizations*) even for *fast rotating* and *magnetized* stars

Latest developments: Yagi-Yunes arXiv:1601.02171 & arXiv:1608.06187

Oscillations & Instabilities

The most promising strategy for constraining the physics of neutron stars involves observing their "ringing" (oscillation modes)

- **f-mode :** scales with average density
- **p-modes:** probes the sound speed through out the star
- **g-modes :** sensitive to thermal/composition gradients
- **w-modes:** oscillations of spacetime itself.
- **s-modes:** Shear waves in the crust
- **Alfvèn modes:** due to magnetic field
- **i-modes:** inertial modes associated with rotation (r-mode)

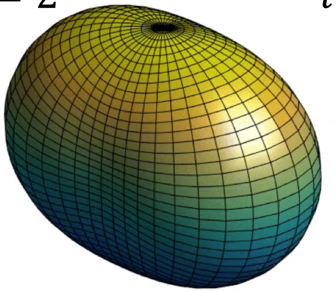


Typically **SMALL AMPLITUDE** oscillations –> weak emission of GWs

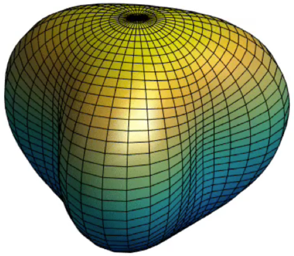
UNLESS

they become **unstable due to rotation** (r-mode & f-mode)

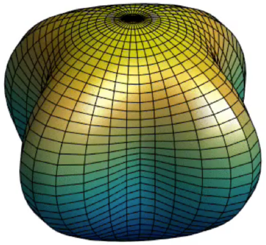
$l = 2, m = 2$



$l = 3, m = 3$



$l = 4, m = 4$



Oscillations & Instabilities

p-modes: main restoring force is the pressure (f-mode) *(>1.5 kHz)*

$$\sigma \approx \sqrt{\frac{GM}{R^3}}$$

Inertial modes: (r-modes) main restoring force is the Coriolis force

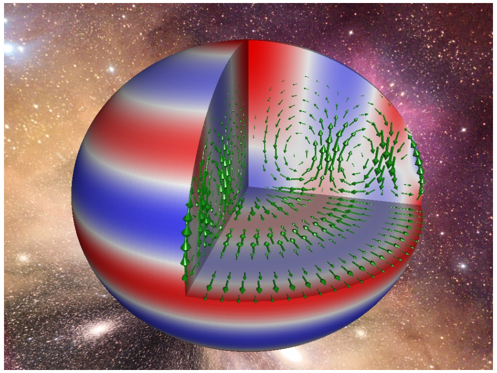
$$\sigma \approx \Omega$$

w-modes: pure space-time modes (only in GR) *(>5kHz)*

$$\sigma \approx \frac{1}{R}\left(\frac{GM}{Rc^2}\right)$$

Torsional modes (t-modes) *(>20 Hz)* shear deformations. Restoring force, the weak Coulomb force of the crystal ions.

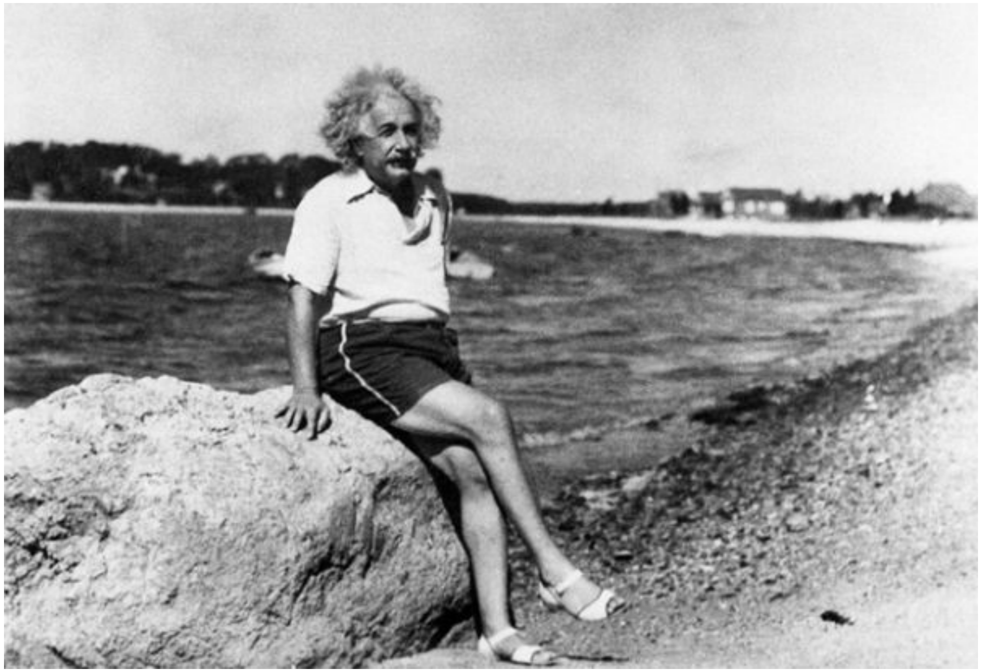
$$\sigma \approx \frac{v_S}{R} \sim 16\ \ell\ \mathrm{Hz}$$



... and many more

shear, g-, Alfven, interface, … modes

Alternative Theories of Gravity & Neutron Stars



…what if "he was not right?"

See Berti etal (2015)

The main alternative theories (ATG)

1. **Scalar-tensor theories and their generalizations.** Including multiscalar and Horndeski theories

2. **F(R) theories**

3. **Theories whose action contains terms quadratic in curvature.** Including Einstein-dilaton-Gauss-Bonnet (EdGB) and dynamical Chern-Simons (dCS) theories

4. **Lorentz-violating theories.** Including Einstein-Aether, Hořava and n-Dirac-Born-Infeld (n-DBI) gravity.

5. **Massive gravity theories**

6. **Theories involving non-dynamical fields.** Including the Palatini formulation of F(R) gravity and Eddington-inspired Born-Infeld (EiBI) gravity.

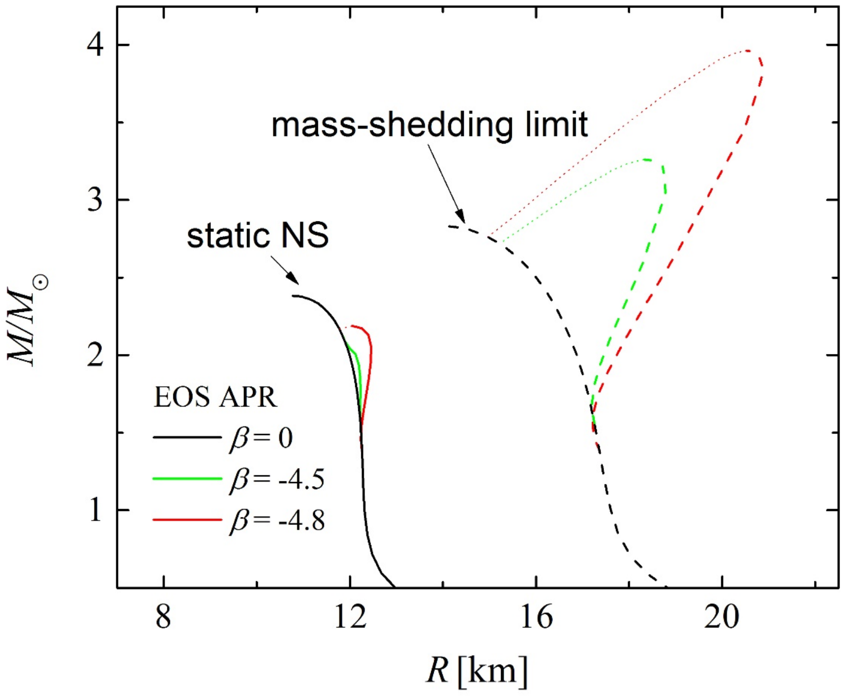
7. **…**

Berti etal (2015)

Equilibrium neutron star solutions: Scalar-Tensor Theory

- **Scalarization of neutron stars** was considered for the first time by Damour&Esposito-Farese (1993)
- **Slow rotation approximation** was also considered (Damour&Esposito-Farese (1996), Sotani (2012), Pani&Berti (2014)).
- **Rapid rotation** – changes the picture significantly (Doneva Yazadjiev, Stergioulas, Kokkotas 2014)

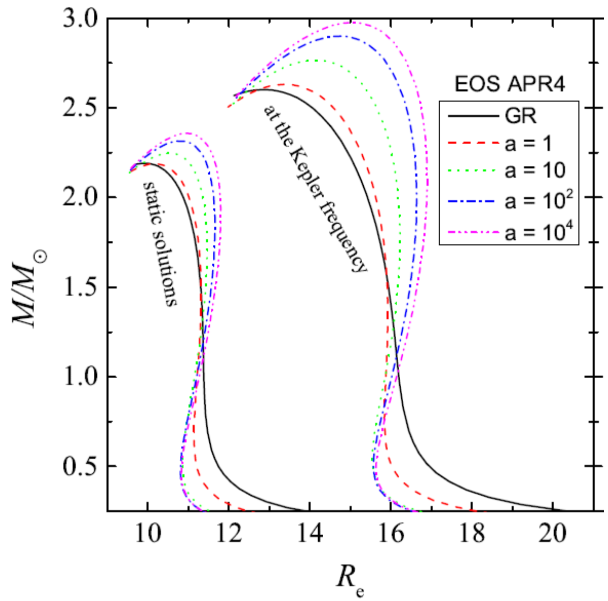
Coupling function $\alpha(\varphi) = \beta\varphi$

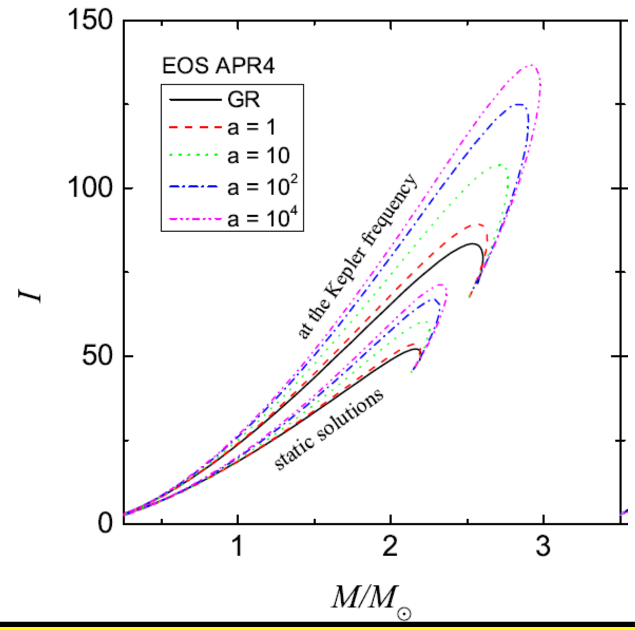


- Scalarization possible also for **positive β** and negative trace of the energy momentum tensor. Possible for stiff EOS and very massive stars, not fully studied yet (Mendes (2015), Mendes & Ortiz(2016), Palenzuela & Liebling(2015)).
- **Tensor-multi-scalar theories** (Horbatsch et al (2015)) – new interesting phenomena, still in development.

Equilibrium neutron star solutions
f(R)=R+aR²

- **Non-perturbative approach**: reported in Babichev&Langlois(2010), Jaime et al (2011), detailed studies of realistic NS models was done in Yazadjiev, Doneva, Kokkotas, Staykov (2014), Capozziello, De Laurentis, Farinelli, Odintsov (2016)
- **Rotating models** are also studied (Staykov et al (2014), Yazadjiev, Doneva, Kokkotas(2015))
- **Non-negligible deviation** for the allowed values of *a*. *The **moment of inertia** is very sensitive and can be used to set constraints on the parameters.*

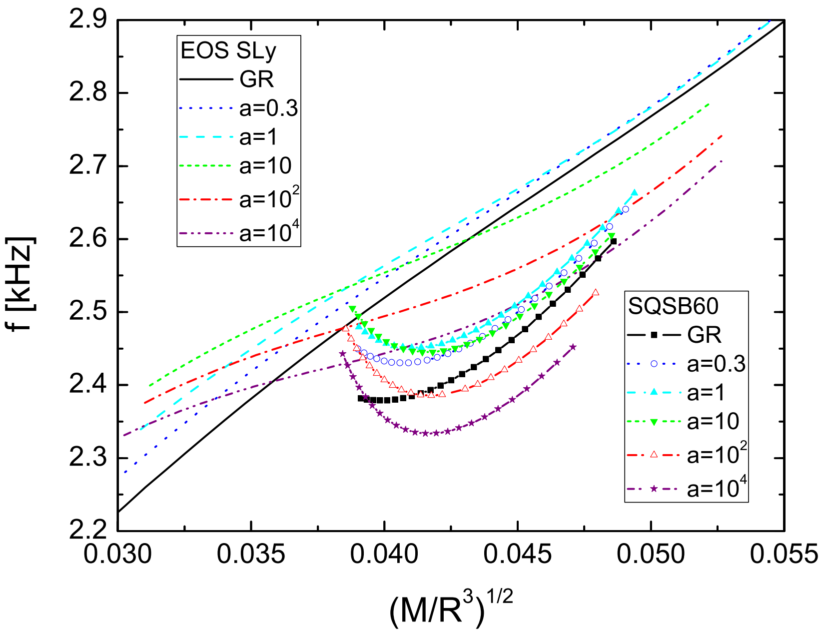


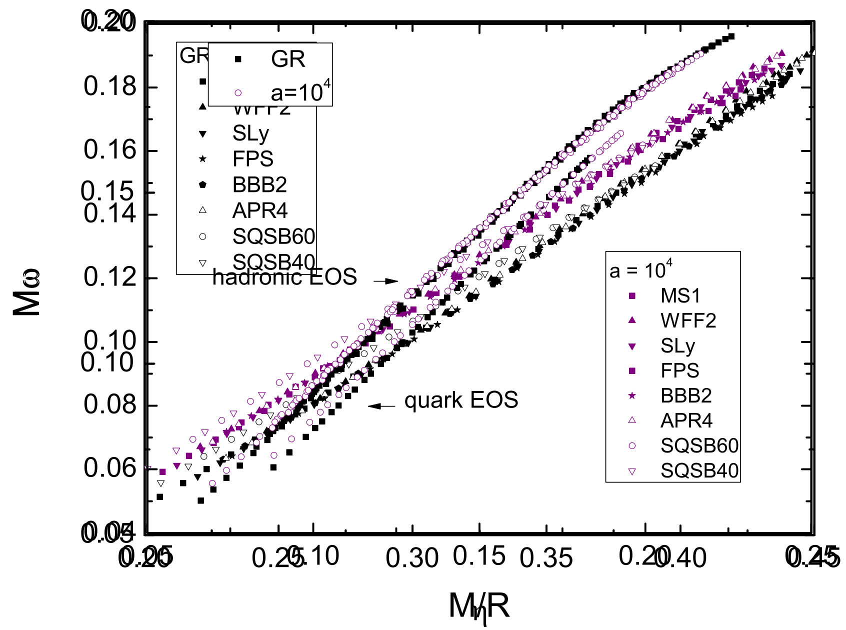


- **The differences between R^2 and GR are comparable with the uncertainties in the EOS**
- The current observations of the NS masses and radii alone can not put constraints on the value of the parameters a, **unless the EoS is better constrained in the future.**

Asteroseismology in GR and R^2 *gravity*

- **EOS independent** with suitable choice of normalization
- **Alternative normalizations show nicer relations**

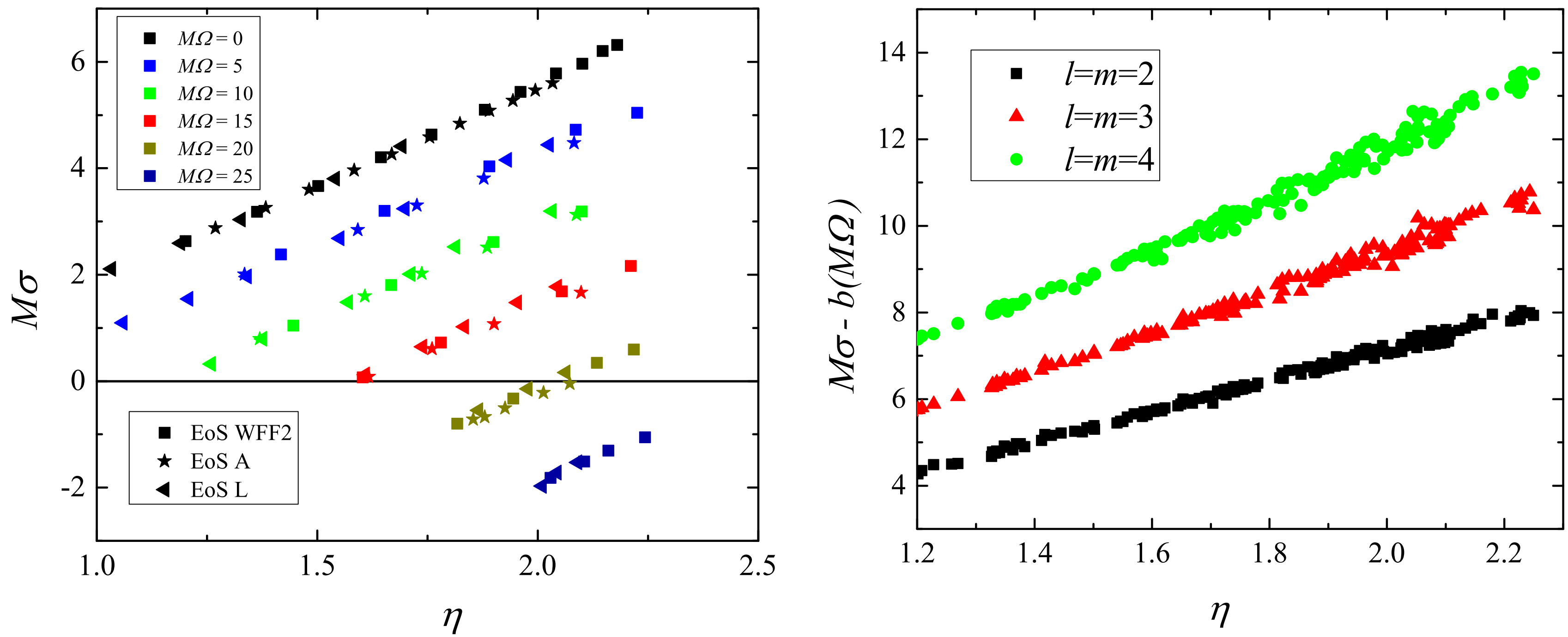




$$\eta = \sqrt{M^3 / I}$$

Asteroseismology: f-modes

$$M\sigma_i^{unst} = \left[(0.56 - 0.94\ell) + (0.08 - 0.19\ell) M\Omega + 1.2(\ell+1)\eta\right]$$



The **l = 2** f-mode oscillation frequencies as functions of the parameter η

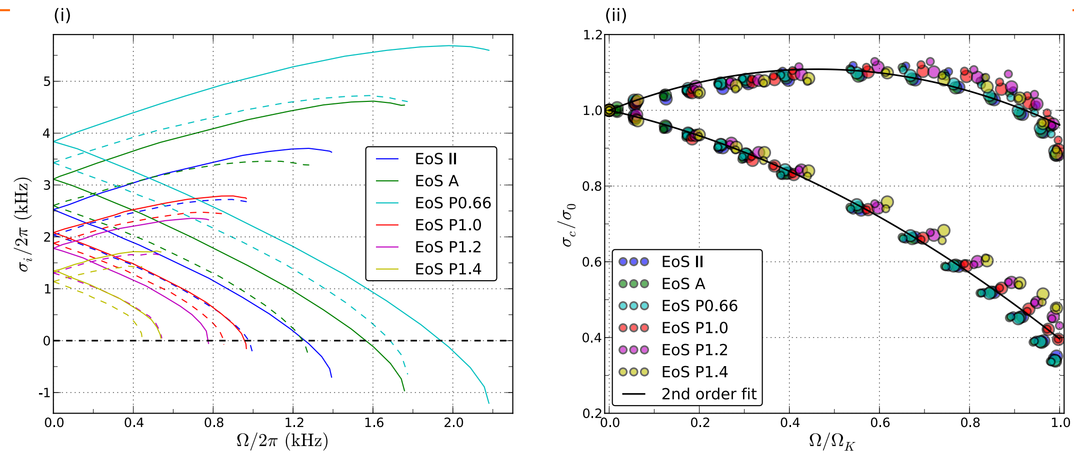
$$\eta = \sqrt{M^3 / I}$$

Doneva-Kokkotas 2015

Asteroseismology: f-modes

We can produce empirical relation relating the parameters of the *rotating neutron stars* to the observed frequencies.

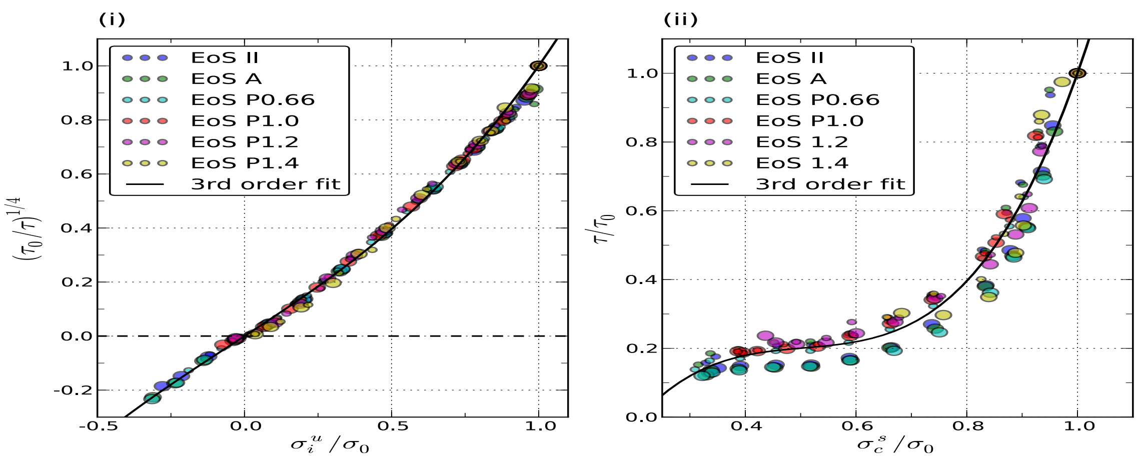
Frequency



Cowling Approximation

Gaertig-Kokkotas 2008, 2010, 2011
Doneva, Gaertig, Kokkotas, Krüger (2013)

Damping/ Growth time



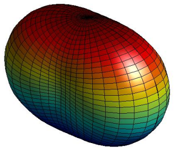
Asteroseismology: f-modes

Stable Branch

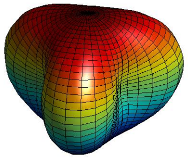
$$\frac{\omega_c^s}{\omega_0} = 1 - 0.235\left(\frac{\Omega}{\Omega_K}\right) - 0.358\left(\frac{\Omega}{\Omega_K}\right)^2$$

Unstable Branch

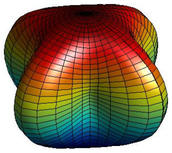
$$\frac{\omega^u_{c\ l=2}}{\omega_0} = 1 + 0.402\left(\frac{\Omega}{\Omega_K}\right) - 0.406\left(\frac{\Omega}{\Omega_K}\right)^2$$



$$\frac{\omega^u_{c\ l=3}}{\omega_0} = 1 + 0.373\left(\frac{\Omega}{\Omega_K}\right) - 0.485\left(\frac{\Omega}{\Omega_K}\right)^2$$



$$\frac{\omega^u_{c\ l=4}}{\omega_0} = 1 + 0.360\left(\frac{\Omega}{\Omega_K}\right) - 0.543\left(\frac{\Omega}{\Omega_K}\right)^2$$

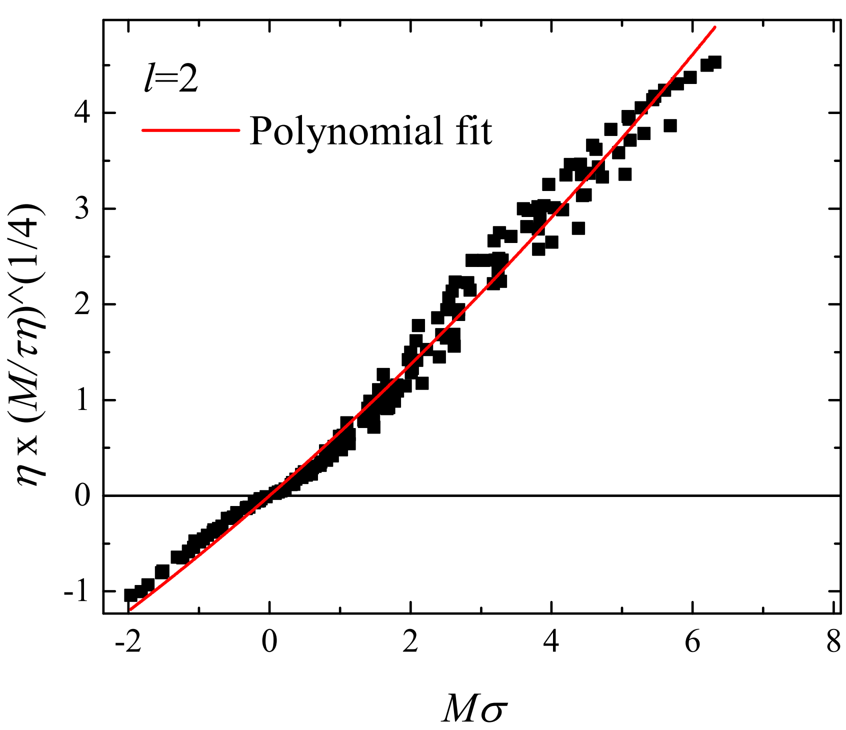


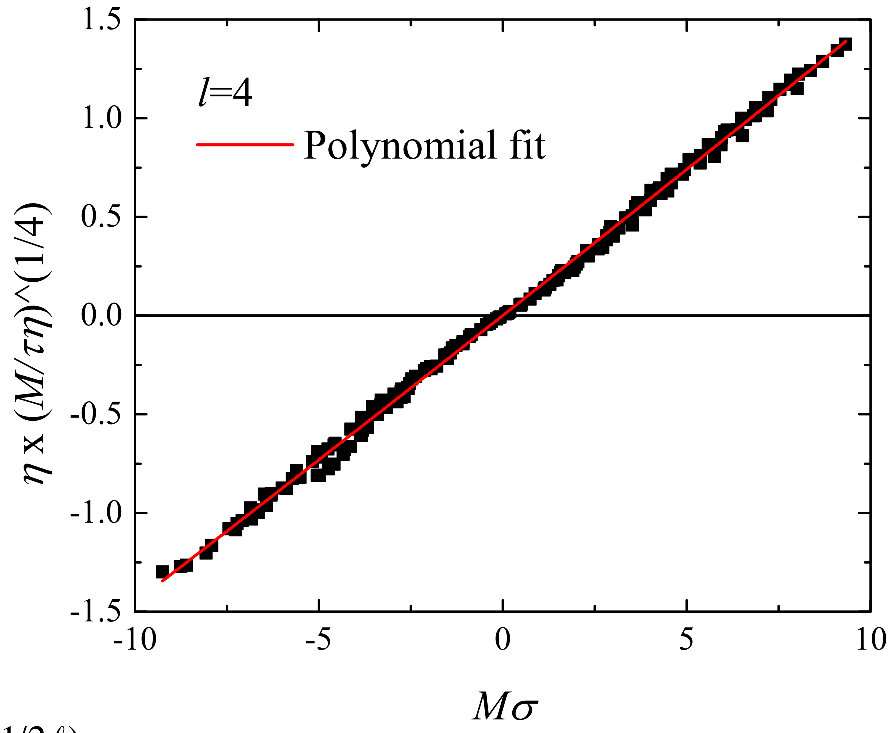
Unstable Branch

$$\frac{\tau_0}{\tau} = \mathrm{sgn}(\omega_i^u)\left(0.900\left(\frac{\omega_i^u}{\omega_0}\right) - 0.057\left(\frac{\omega_i^u}{\omega_0}\right)^2 + 0.157\left(\frac{\omega_i^u}{\omega_0}\right)^3\right)^{2l}$$

Doneva, Gaertig, KK, Krüger (2013)

Asteroseismology: f-modes

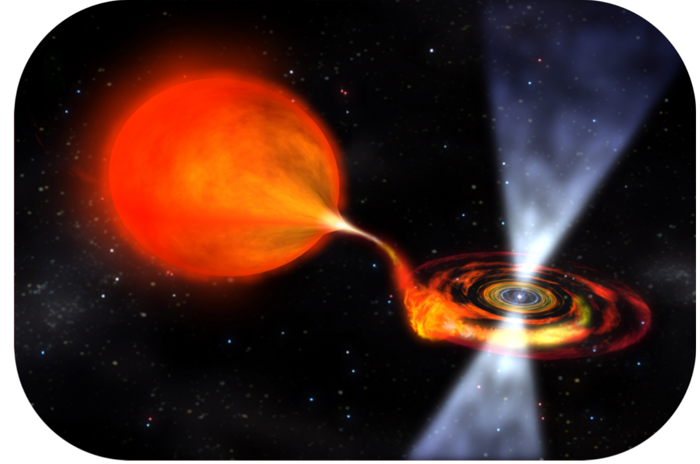




The **normalized damping time** $\eta\left(\frac{M}{\tau\eta^2}\right)^{(1/2\ell)}$ where $\eta = \sqrt{M^3/I}$

as a function of the normalized oscillation frequency ***Mσ*** for l = m = 2 & l = m = 4 f-modes.

Doneva-KK 2015



Neutron Stars
as
Continuous GW Sources

- Haskell, Andersson, D‘Angelo, Degenaar, Glampedakis, Ho, Lasky, Melatos, Oppenoorth, Patruno, Priymak (arXiv:1407.8254)
- Kokkotas, Schwenzer EPJA (2016) (arXiv:1510.07051)
- …and referenceces therein

NS as Continuous Sources
r-modes & "mountains"

"Mountains": Deformations that are static (at dynamical timescales) typically in the crust. *The finite shear modulus of the crystalline crust offers the possibility of supporting a deformation* (Bildsten 1998)

- **Strong magnetic fields** can also confine material and lead to deformations that could be quite large (magnetars).
- In LMXBs **accretion process** can lead to material spreading equatorially and compressing the field making it locally strong enough to sustain sizable mountains.

- **Modes of oscillations** can grow to large amplitude and lead to GWs.
- The prime candidate in LMXBs is the **r-mode** (restoring force the Coriolis force).
- Primarily toroidal perturbations and the Eulerian velocity perturbation is:

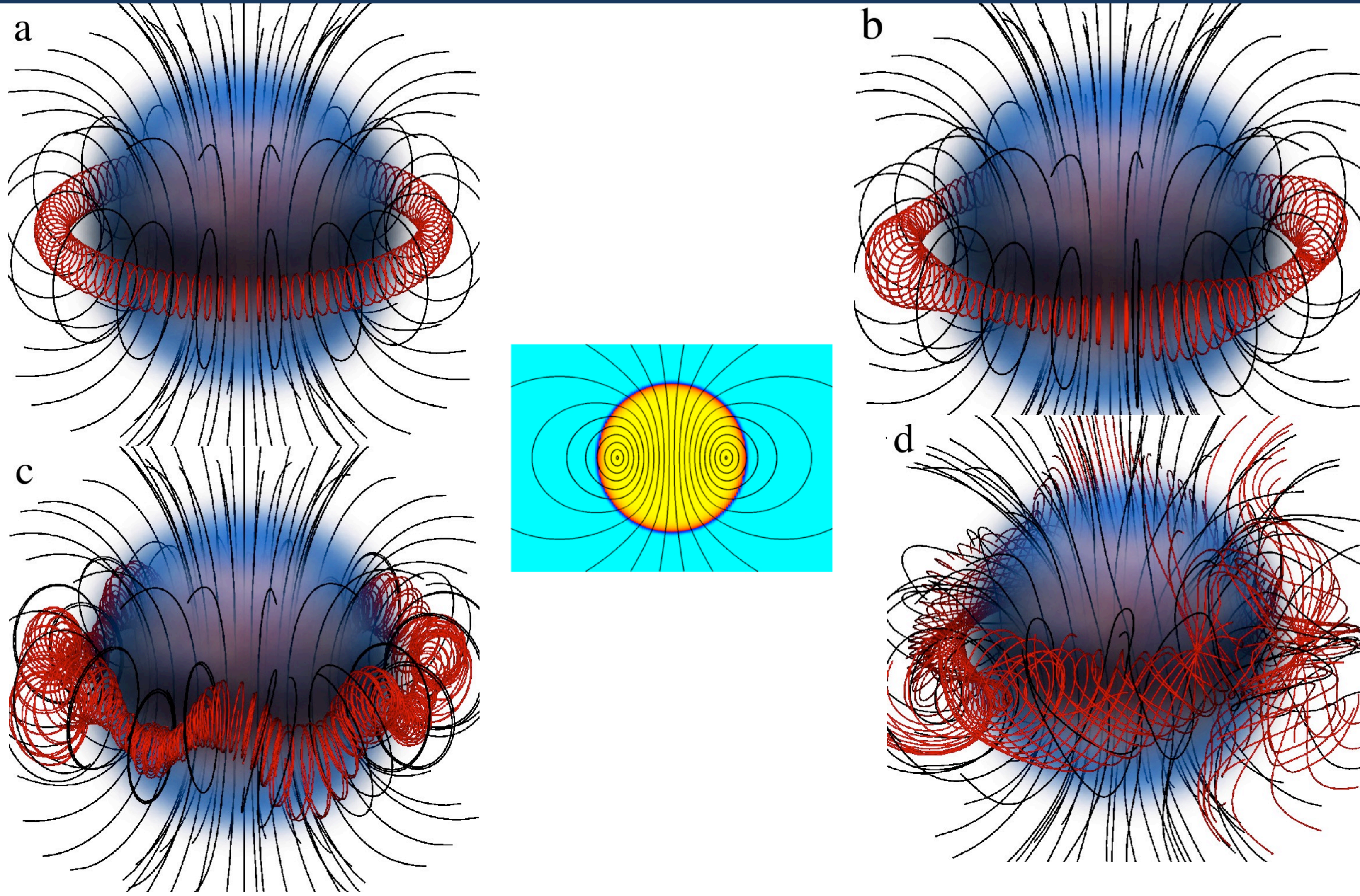
$$\delta \mathbf{v} = \alpha \left(\frac{r}{R}\right)^l R\Omega \mathbf{Y}^B_{lm} e^{i\omega t}$$

Observational constraints for ellipticity : $\sim \mathbf{8.5 \times 10^{-6}}$

Abbot at al arXiv:1607.02216

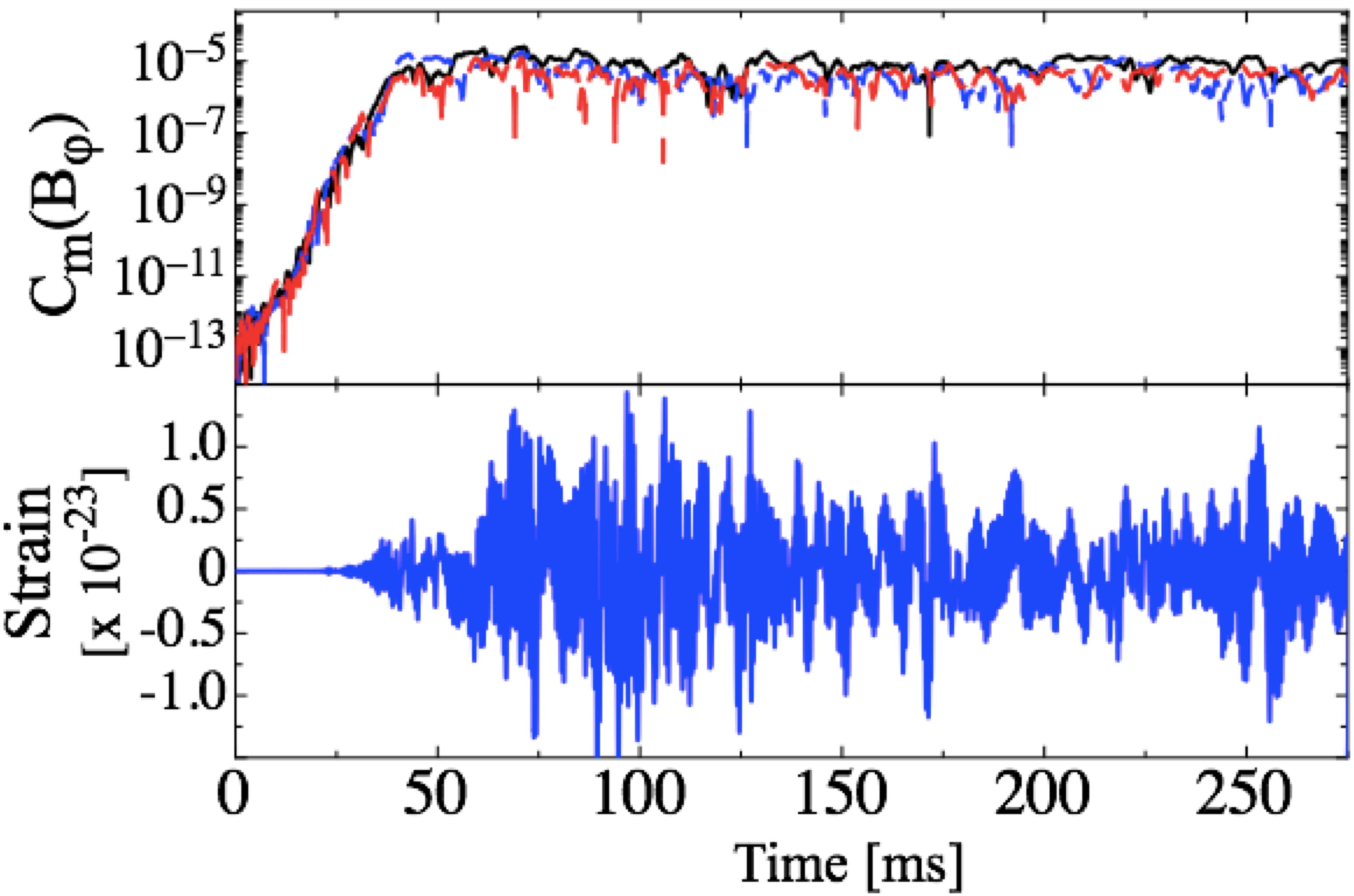
Simulation of Magnetic Field Instability

Lasky, Zink, Kokkotas, Glampedakis (2011-13)
Ciolfi, Lander, Manca, Rezzolla (2011-12)



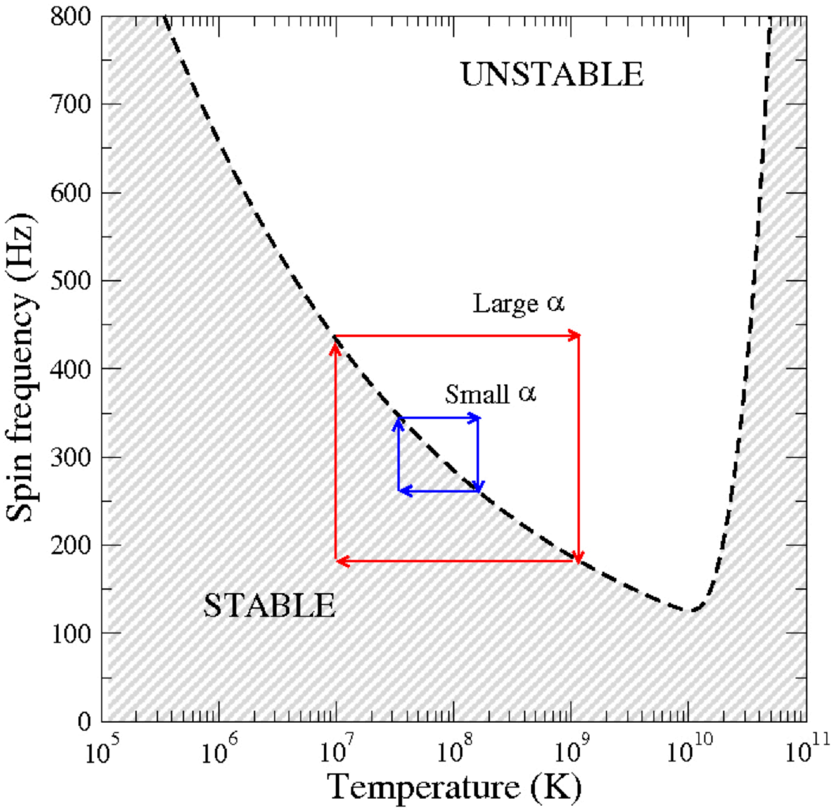
Gravitational Waves from Magnetars

Lasky, Zink, Kokkotas (2012), Ciolfi, Rezzolla (2012)



Neutron Stars as Continuous Sources
r-modes

The classical instability window



- **Large α**: the system enters into the unstable region with very short duty cycle ~1%.
- **Small α** (~10^{-5}): the duty cycle much longer but the system will never depart from the instability curve.

In both cases it is **highly unlikely** to observe a system in the unstable region

Andersson, Kokkotas, Stergioulas, 1999
Levin Y. 1999
Andersson, Jones, Kokkotas, Stergioulas, 2001
Andersson-Kokkotas 2001
Heyl 2002
…

Saturation of the Instability
Parametric Resonance

$$\dot{Q}_\alpha = \gamma_\alpha Q_\alpha + i\omega_\alpha \mathcal{H}\, Q_\beta Q_\gamma\, e^{-i\Delta\omega t}$$
$$\dot{Q}_\beta = \gamma_\beta Q_\beta + i\omega_\beta \mathcal{H}\, Q_\gamma^* Q_\alpha\, e^{i\Delta\omega t}$$
$$\dot{Q}_\gamma = \gamma_\gamma Q_\gamma + i\omega_\gamma \mathcal{H}\, Q_\alpha Q_\beta^*\, e^{i\Delta\omega t}$$

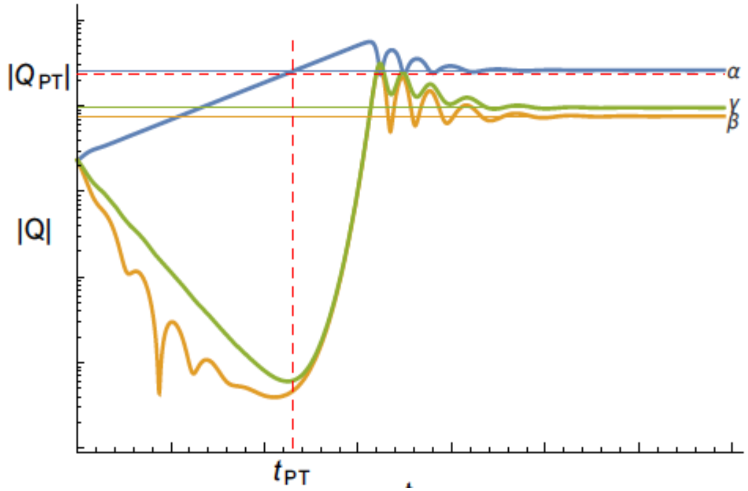
Detuning $\Delta\omega$

Coupling coefficient $\mathcal{H}$

Growth/damping rates γ_i

Detuning $\Delta\omega \equiv \omega_\alpha - \omega_\beta - \omega_\gamma \approx 0$ **resonance condition**

Parametric resonance: $\mathcal{H} \neq 0$ and $\Delta\omega \approx 0$



- Parent feeds daughters and makes them grow
- *Parametric threshold:* daughters grow when

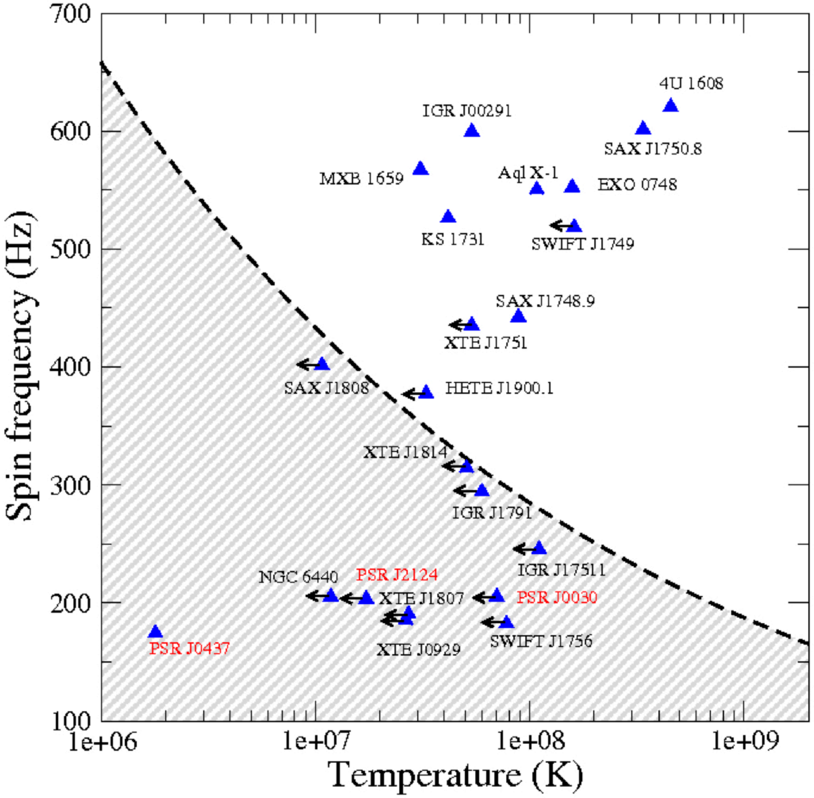
$$|Q_\alpha|^2 > |Q_{\rm PT}|^2 \equiv \frac{\gamma_\beta\gamma_\gamma}{\omega_\beta\omega_\gamma\mathcal{H}^2}\left[1 + \left(\frac{\Delta\omega}{\gamma_\beta + \gamma_\gamma}\right)^2\right]$$

- $|Q_\alpha^{\rm sat}| \approx |Q_{\rm PT}|$

Pnigouras, Kokkotas (2015,16)

Neutron Stars as Continuous Sources
r-modes

The classical instability window



Haskell et al 2012
Mahmoodifar-Strohmayer 2013
Ho et al 2011

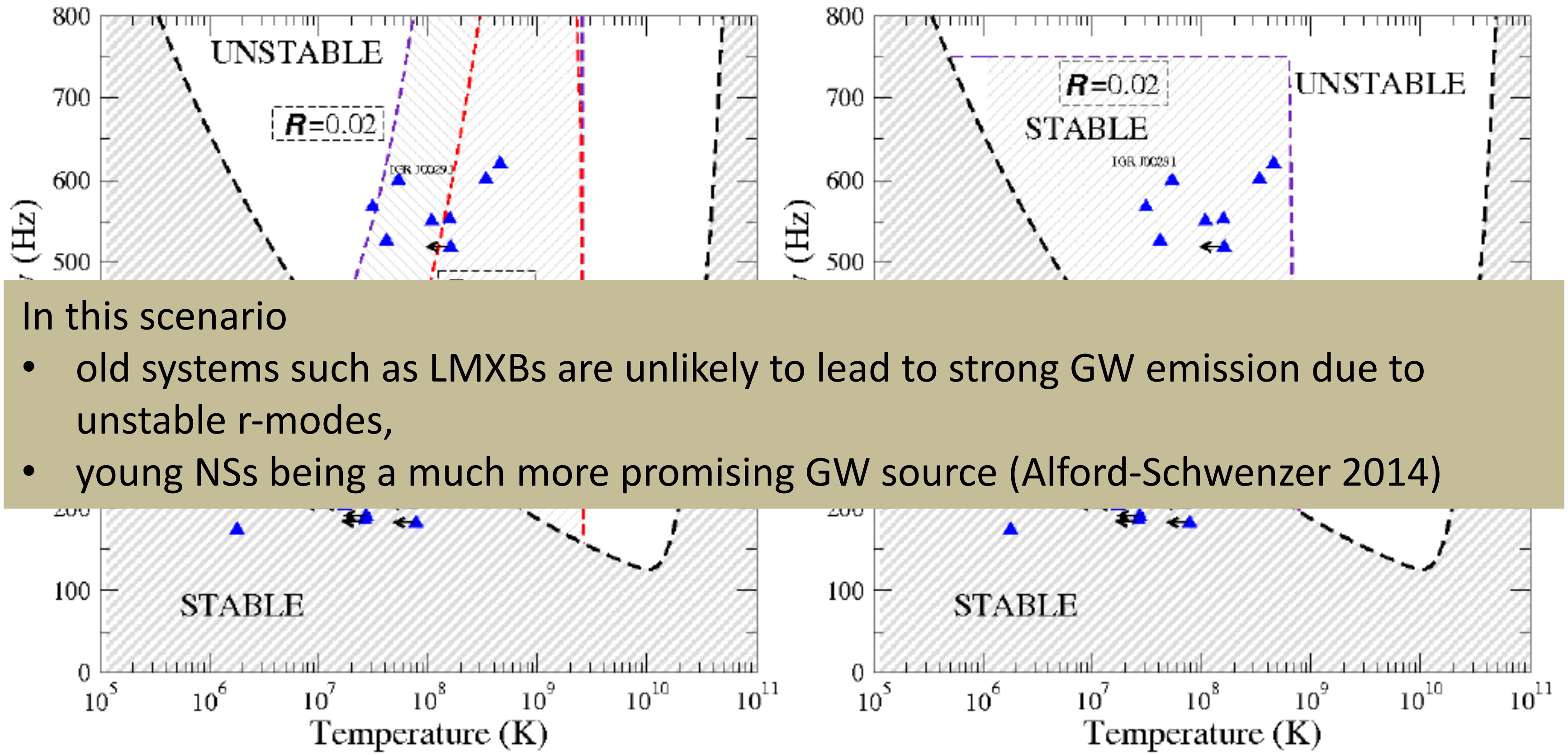
Observational data suggest that many systems would sit inside the instability window !!

The "minimal" NS model described earlier is not consistent with observations.

Either
we should include extra sources of damping (hyperons, deconfined quarks, mode coupling, torsional crust oscillations, magnetic braking**, superfluid mutual friction)**
OR
The r-mode amplitude is too **small** that although the NS is indeed unstable does'n affect impact on the thermal and spin evolution.

NS as Continuous Sources
r-modes

The r-mode instability windows assuming a superfluid core.
The dimensionless drag parameter $\mathcal{R}$ represents the strength of the mutual friction.



In this scenario

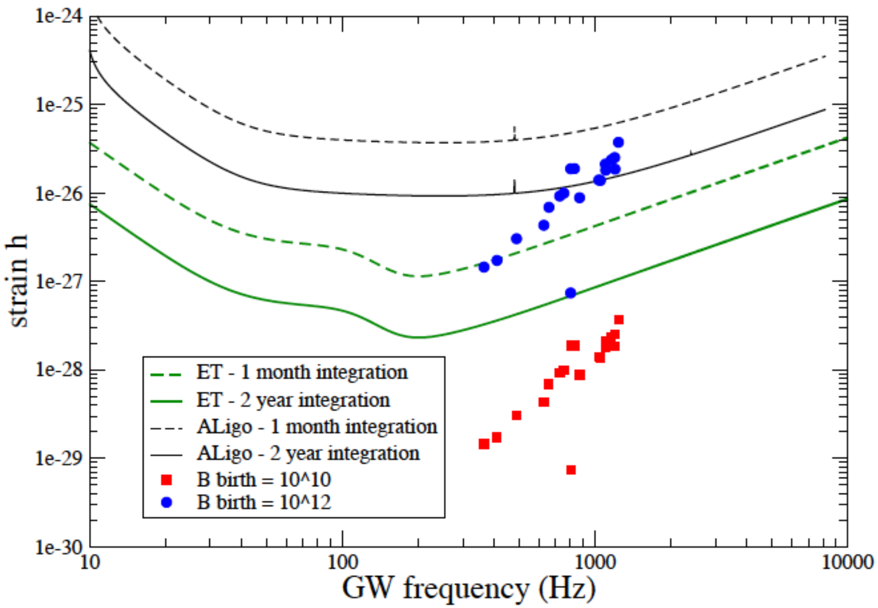
- old systems such as LMXBs are unlikely to lead to strong GW emission due to unstable r-modes,
- young NSs being a much more promising GW source (Alford-Schwenzer 2014)

Haskell etal 2015

NS as Continuous Sources
Magnetic Mountains

- **Accretion** does not only lead to thermal perturbations in the crust, but also **perturbs the magnetic field structure.**
- After matter is accreted at the magnetic poles it spreads towards the equator, compressing the field and leading to an overall suppression of the large-scale dipolar structure, but also to local enhancements that can support a sizeable mountain (Melatos et al 2004,2005, 2009,…)
- The mass quadrupole $Q_{22}(\approx 10^{39} - 10^{40} g\ cm^2$ [Haskell et al 2006, Johnson-McDaniel, Owen 2013]) depends on the accreted matter M_a and the critical mass M_c at which the process saturates and both of them (Q_{22} and M_c) on the EOS.

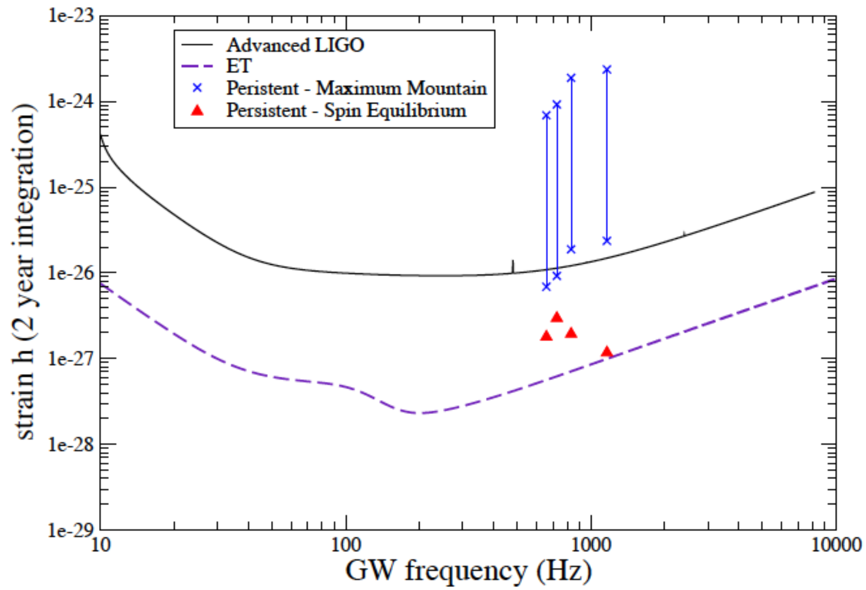
- Predictions [Haskell et al. 2015] for the GW emission from *known LMXBs*, given a magnetic mountain with a background magnetic field of **B = 10^{10} G** or **B = 10^{12} G**.
- Here *the mountain is assumed to* ***be stable in-between outbursts*** *and can thus be built gradually over the life time of the system.*



NS as Continuous Sources
Thermal Mountains on NSs

- In the the thermal case the mountain arises as the crust is heated by reactions that occur as accreted material is submerged deep into the crust.
- As it reaches higher densities several pycnonuclear reactions occur, which heat the star locally.
- If part of this heating is asymmetric, and quadrupolar in particular, this can lead to a mass quadrupole

The LIGO and ET sensitivity curves compared to the GW amplitude for persistent LMXBs (Haskell et al 2015)



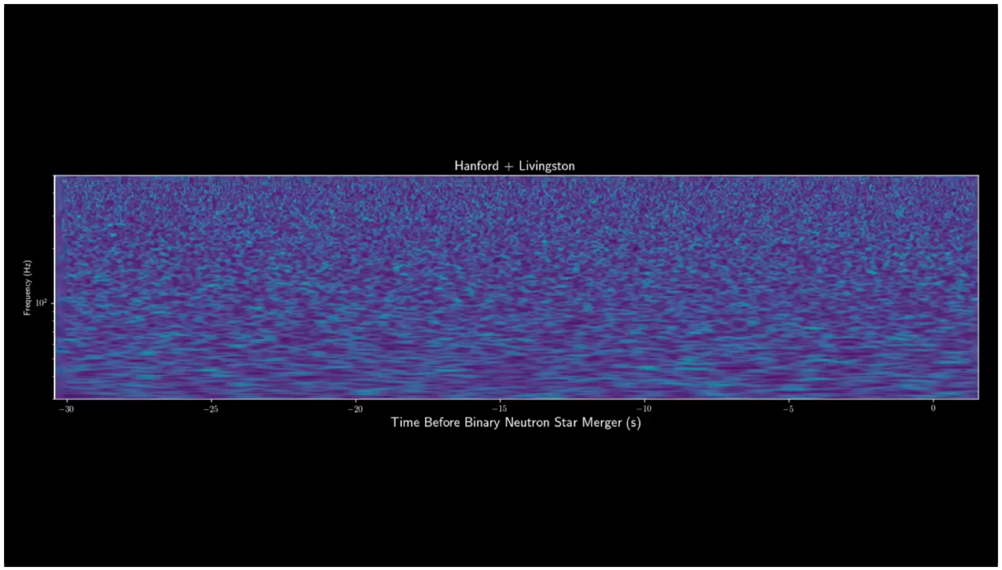
- Here was assumed the **maximum deformation** that the crust can sustain
- The error bars account for **uncertainties** in mass and EOS.
- For comparison it is shown the GW amplitude that would be needed for torque balance.

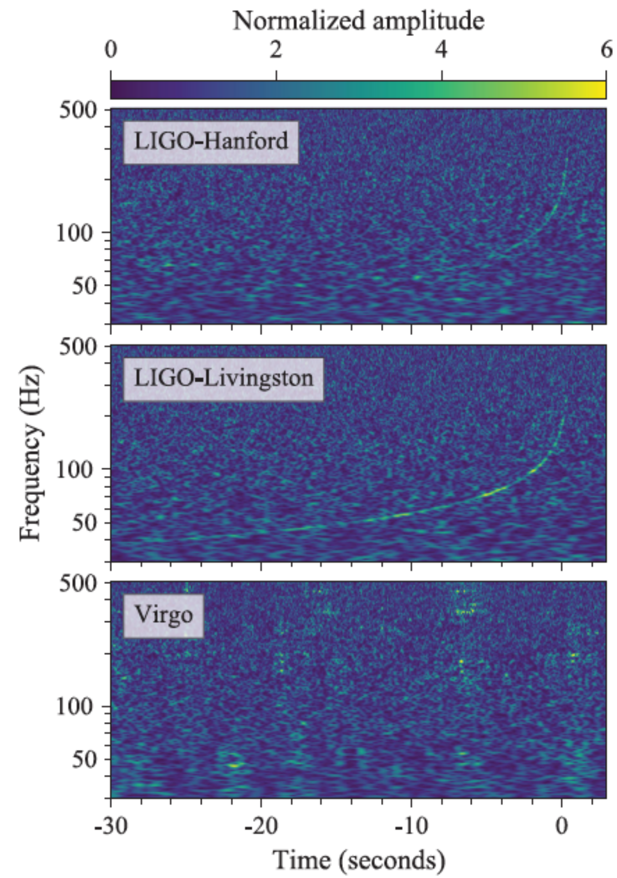
- No cyclotron lines have been detected
- The magnetic fields are much weaker ~10^8G

Prepare for the Unexpected

GW170817

Neutron Star Mergers
GW170817





M1~1.36-1.60 $M_\odot$
M2~1.17-1.36 $M_\odot$
Radiated energy ~0.025 $M_\odot$ c^2
Luminosity distance~ 40 Mpc

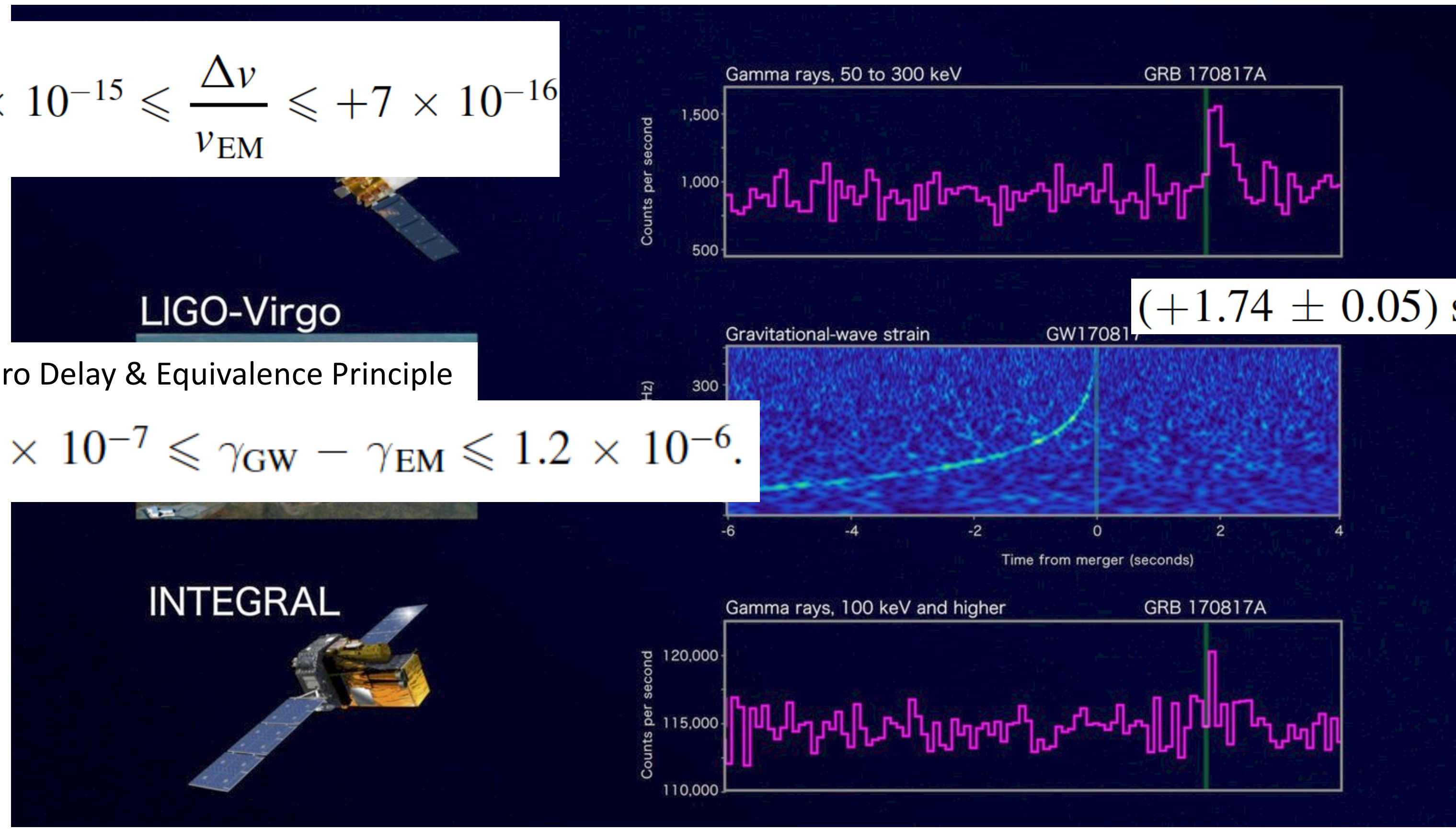
Neutron Star Mergers
constraining the speed of gravity

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}$$

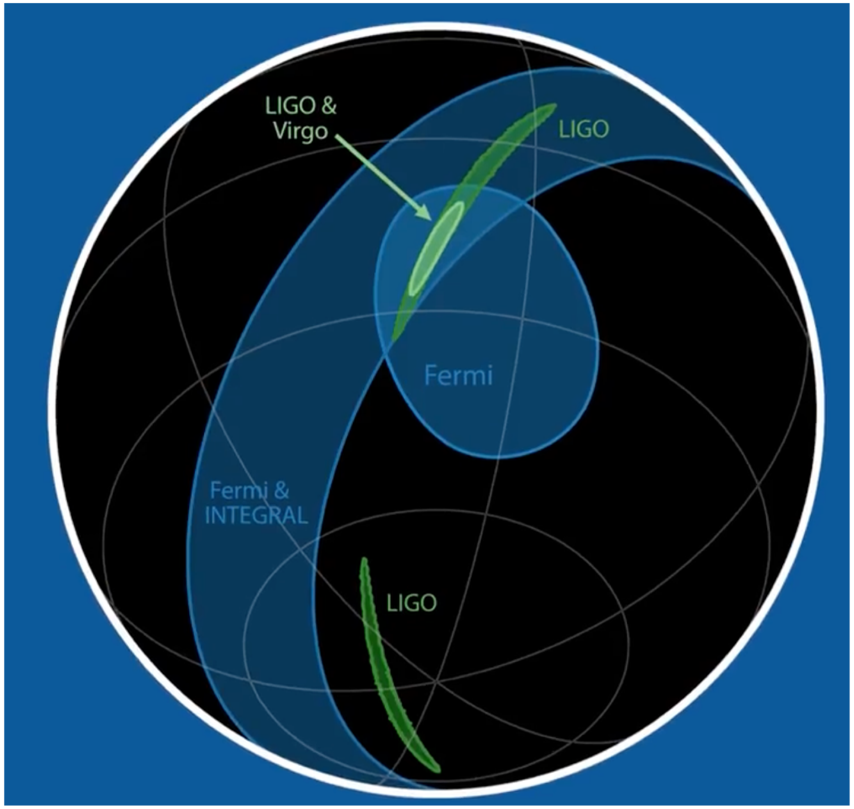
$(+1.74 \pm 0.05)$ s

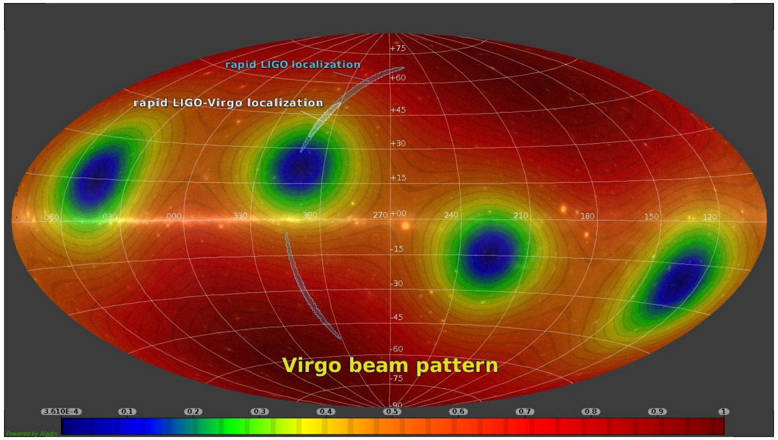
Shapiro Delay & Equivalence Principle

$$-2.6 \times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2 \times 10^{-6}.$$



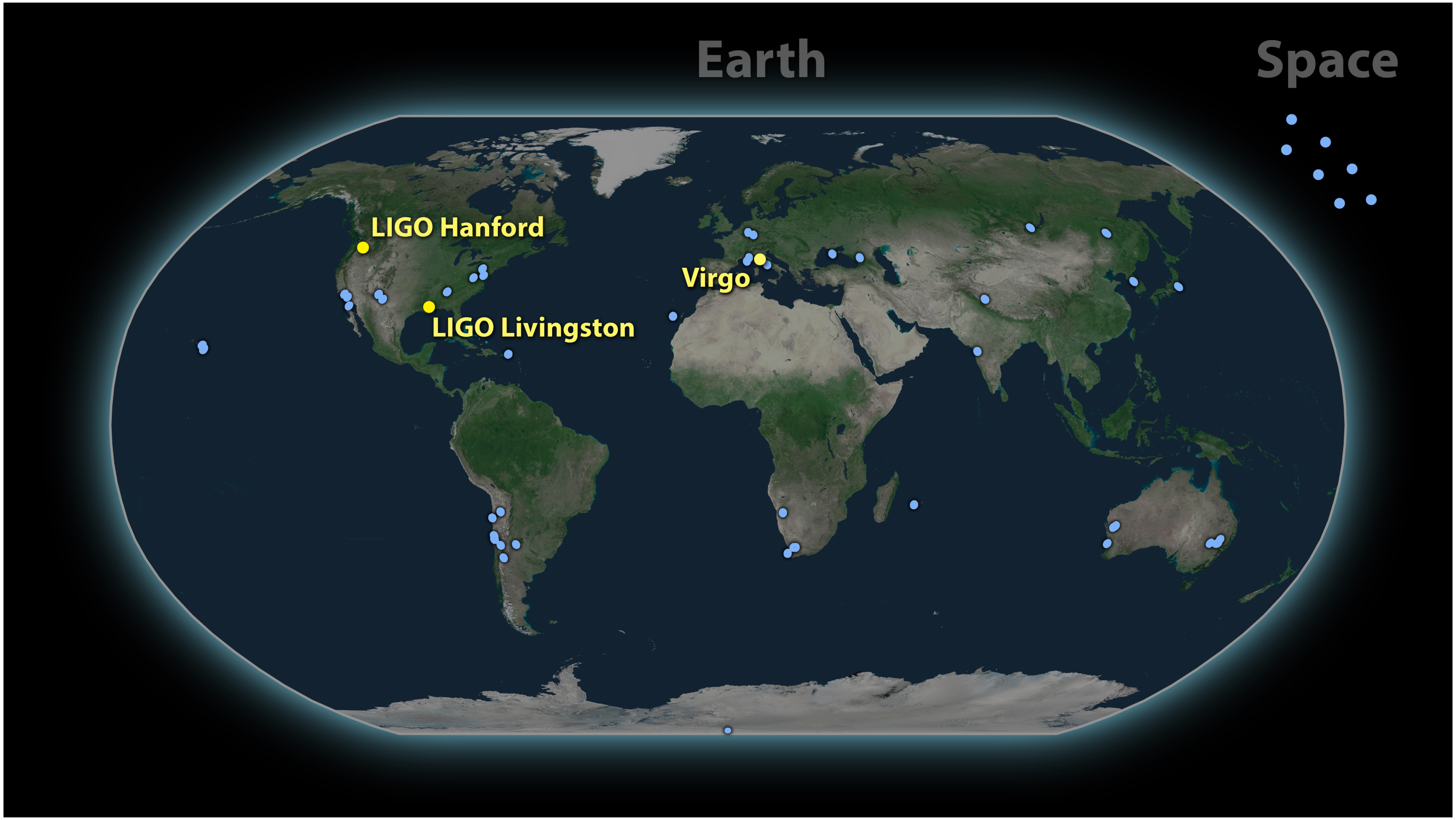
Neutron Star Mergers
Positioning the source





Neutron Star Mergers

GW - EM Observatories

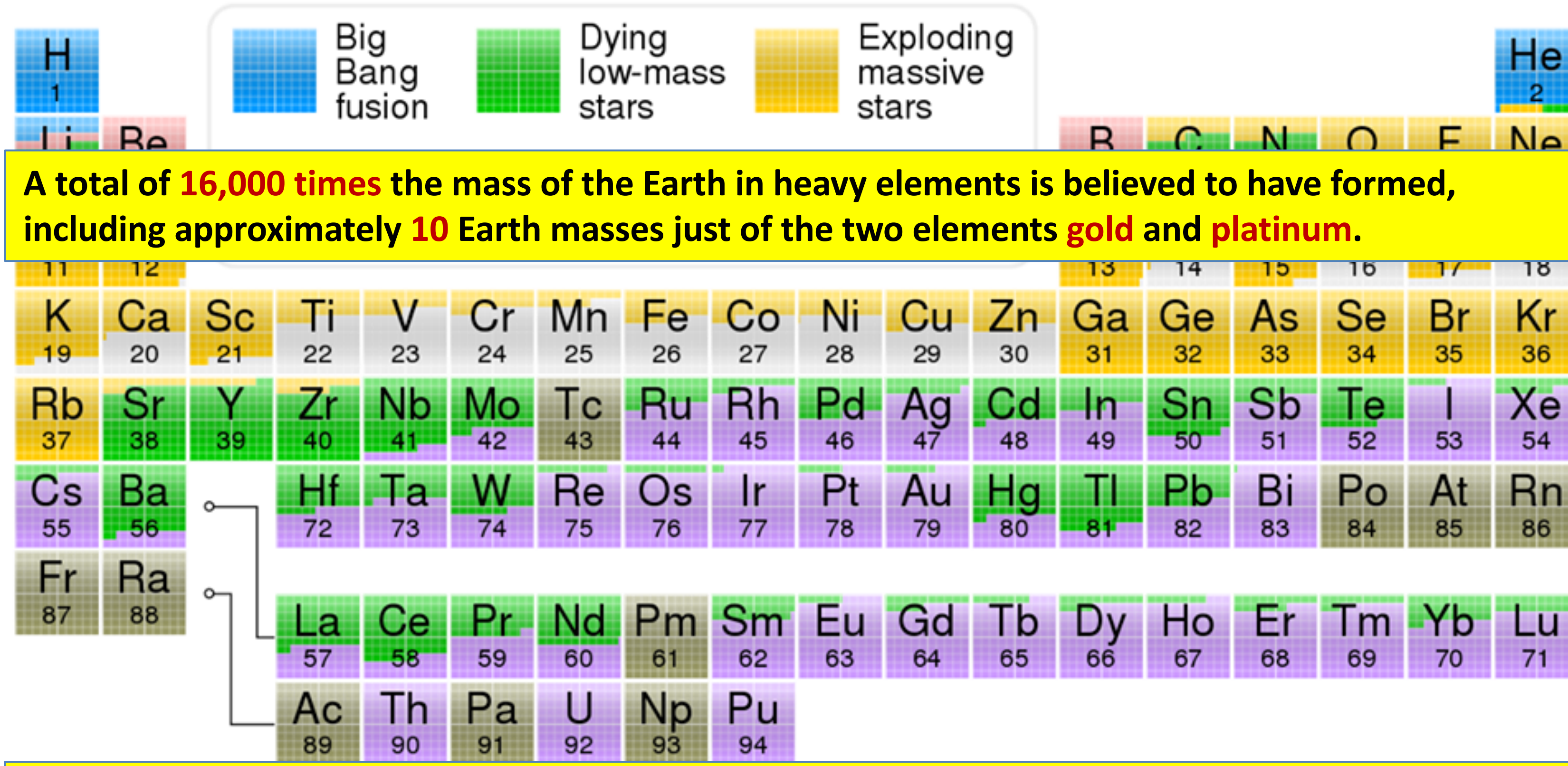


Neutron Star Mergers
Sequence of Events

12:41:04 UTC	A **Gravitational Wave** from binary NS merger is detected
+2 sec	A **Short Gamma ray** burst is detected
	GW + EM from the same source provide compelling evidence that **GWs travel with the speed of light**
	The two events allow for the **measure of the expansion rate of the Universe**
	Kilonova: neutron star mergers responsible for the production of heavy elements in the universe.
+10 h **52** min	A new bright source of **optical light** is detected in a galaxy called NGC 4993 (constellation of Hydra)
+11 h **36** min	**Infrared emission** observed
+15 h	**Bright ultraviolet** emission detected
+9 days	**X-ray** emission detected
+16 days	**Radio** emission detected

Neutron Star Mergers

Alchemy or Heavy Element Production



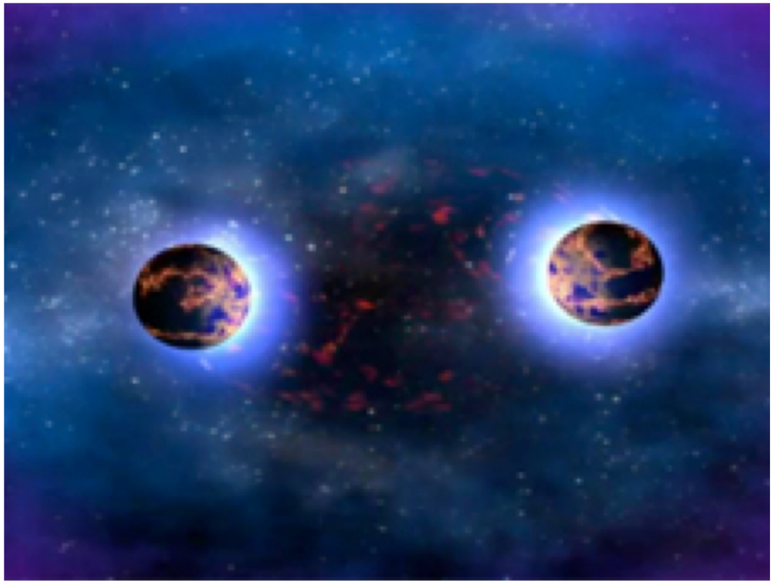
A total of 16,000 times the mass of the Earth in heavy elements is believed to have formed, including approximately 10 Earth masses just of the two elements gold and platinum.

Light emitted after a neutron star collision showed signs of heavy elements present in the aftermath, confirming that certain elements (purple) are produced in such mergers

Binary Neutron Star Mergers

Astrophysical goals:

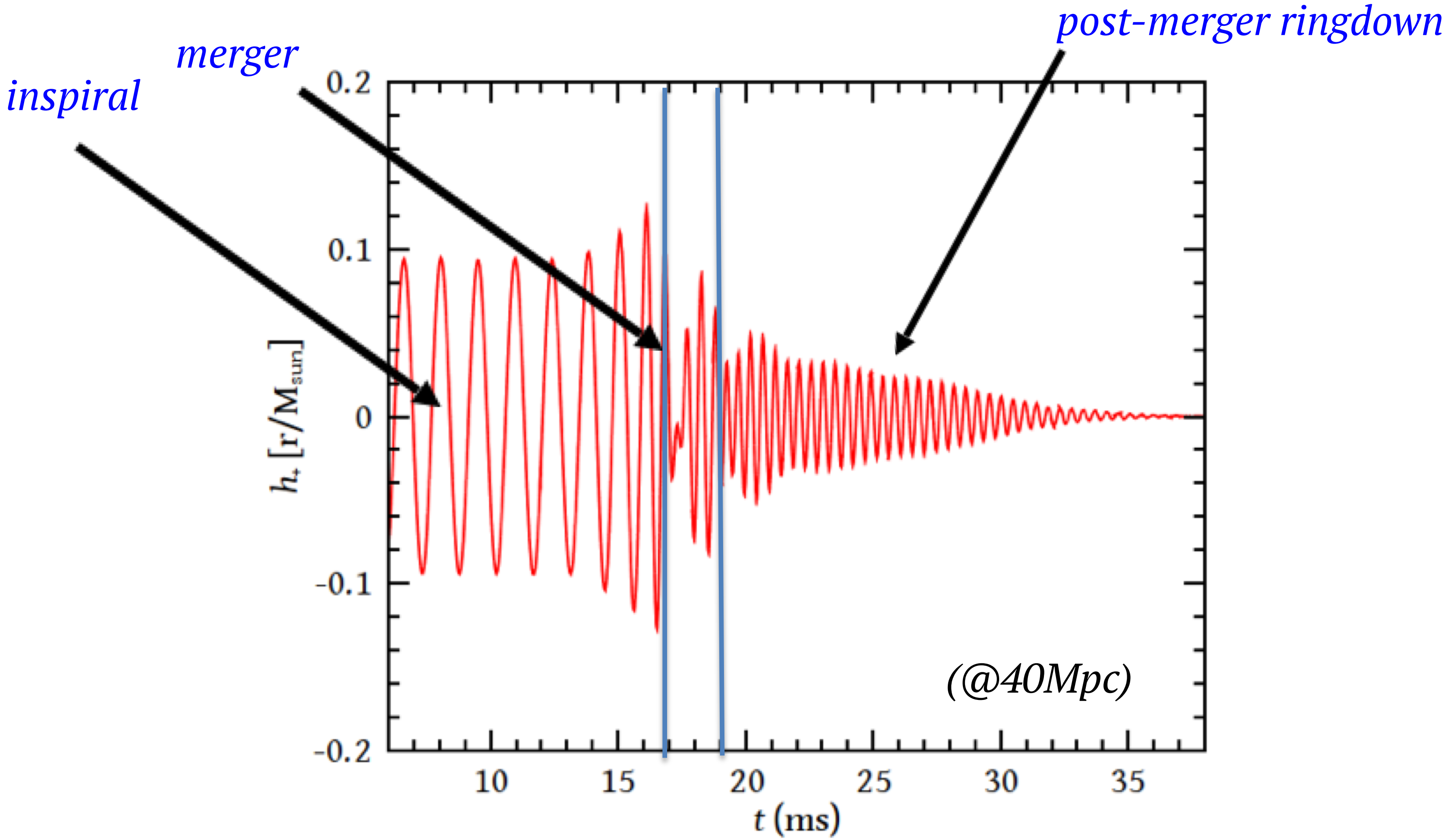
- Constrain the neutron star internal structure, i.e. its EOS
- Gain information on the nature of short gamma-ray bursts



Baiotti, Rezzolla arXiv:1607.03540 (REVIEW)
Bernuzzi,Radice, Ott, Roberts, Mösta, Galeazzi PRD 94, 024023 (2016)
Rezzolla, Takami PRD 93, 124051 (2016)
Lehner, Liebling, Palenzuela, Motl PRD 94, 043003 (2016)
De Pietri, Feo, Maione, Löffler PRD 93, 064047 (2016)
Hotokezaka, Kyutoku, Sekiguchi, Shibata4 PRD 93, 064082 (2016)
Clark, Bauswein, Stergioulas, Shoemaker CQG 33 (2016) 085003
Lehner, Liebling, Palenzuela, Caballero, O'Connor, Anderson, Neilsen CQG 33 (2016) 184002
Maione, De Pietri, Feo, Löffler CQG 33 (2016) 175009 (30pp)
Feo, De Pietri, Maione, Löffler arXiv:1608.02810
Paschalidis, Stergioulas Liv.Reviews arXiv:1612.03050

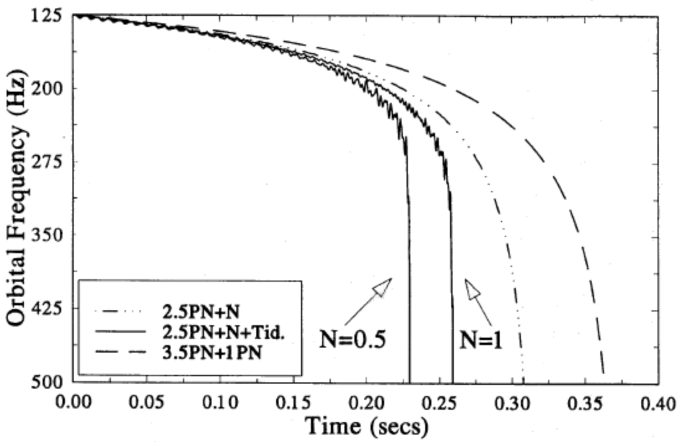
Binary Neutron Star Mergers
the standard scenario

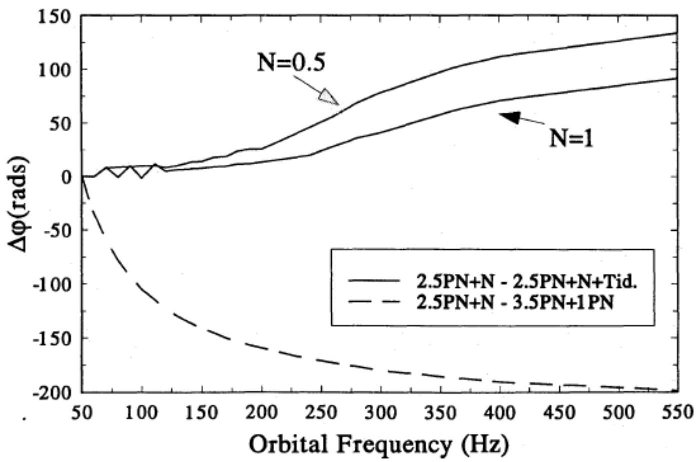
The GW signal can be divided into **three distinct phases**



Binary Neutron Star Mergers
Tidal Interaction

Tidal interactions affect the last part of the inspiral, modifying the orbital motion and the GW emission.



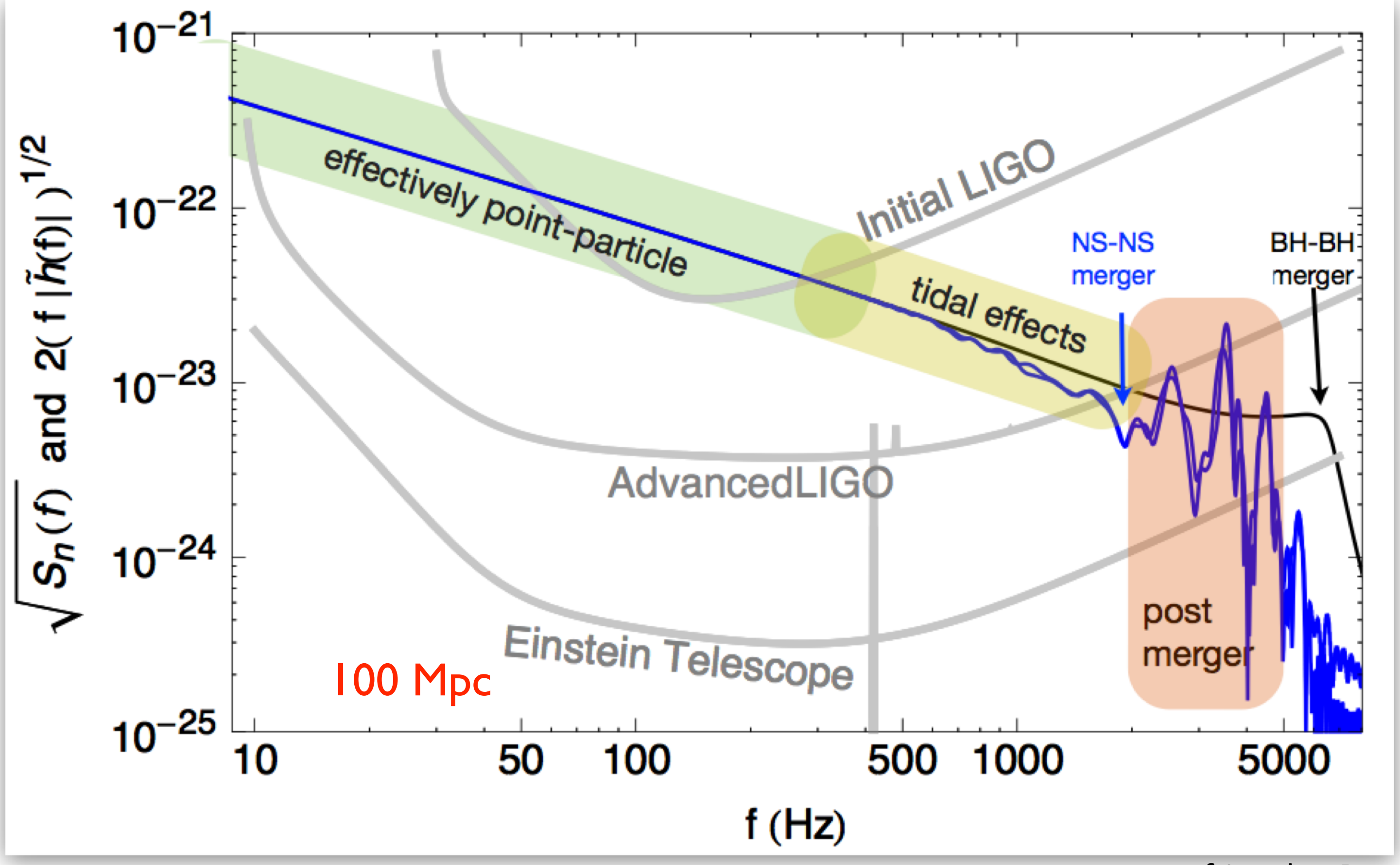


Kokkotas-Schaefer MNRAS 1995

Bildsten-Cutler 1992
Lai et al 1993,1994
Kokkotas-Schaefer 1993-5
Shibata 1994
Flanagan 1998
Ho-Lai 1999
…

Binary Neutron Star Mergers
Tidal Interaction

Tidal interactions affect the last part of the inspiral, modifying the orbital motion and the GW emission.



courtesy of Jocelyn Read

Binary Neutron Star Mergers
Tidal Love numbers

The last part of the inspiral signal carries the imprint of the quadrupole tidal deformability $\lambda = -\frac{Q_{ij}}{E_{ij}} = \frac{2}{3} k_2 R^5$ Read et al. (2013), Hotozaka et al (2013)…

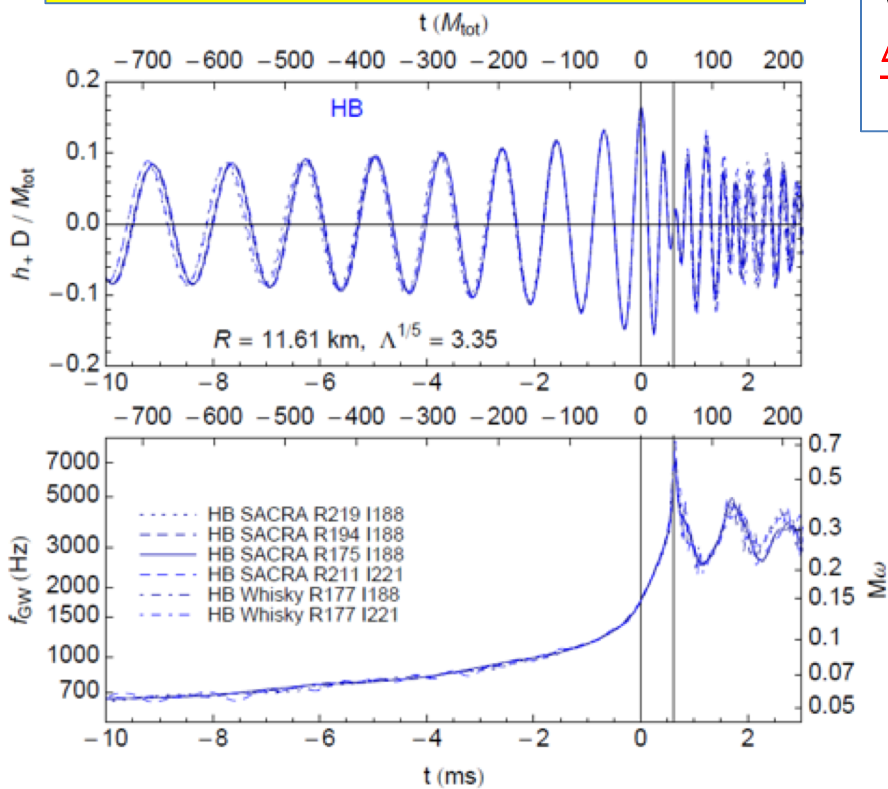
k_2 : tidal Love number

Dimensional tidal deformability $\Lambda \equiv \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$

Measurements of M_{NS} and Λ would be helpful to constrain the NS EOS

With aLIGO

$\frac{\Delta R}{R} \sim 10\%$ at 100Mpc



Hinderer, ApJ 677 1216 (2008)
Vines et al. PRD 83 084051 (2011)
Bennington & Poisson, PRD 80 084018 (2009)
Damour & Nagar, PRD 80 084035 (2009)
Damour & Nagar, PRD 81 084016 (2009)
Vines & Flanagan PRD 88 024046 (2013)…

Modeling

Flanagan & Hinderer, PRD 77 021502 (2008)
Hinderer et al., PRD 81 123016 (2010
Pannarale et al. PRD 84 103017 (2011)
Damour et. al., PRD 85 123007 (2012)
Maselli et al. , PRD 88 104040 (2013)
Read et al., PRD 88 044042 (2013)…

Detectability

Steinhoff et al., 1608.01907
Weinberg et al, 2012-16

Dynamical

Binary Neutron Star Mergers
the standard scenario

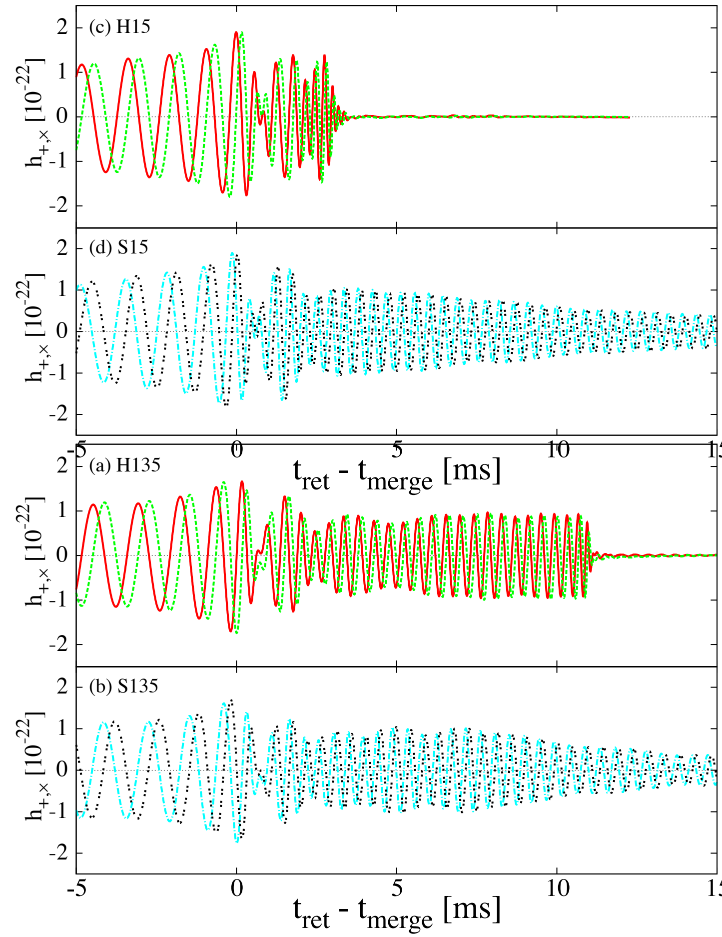
I. After the merging the final body most probably will be a supramassive NS (2.5-3 $M_{\odot}$)

II. The body will be **initially** differentially rotating

III. The "averaged" magnetic field will amplified due to magnetic field instabilities (up to 2-3 orders of magnitude)

IV. The strong magnetic field and the emission of GWs will drain rotational energy

V. This phase will last only a few tenths of msecs and can potentially provide information for the EOS



Kiuchi, Sekiguchi, Kyutoku, Shibata2012

Binary Neutron Star Mergers
the post-Merger scenario

I. Direct collapse to BH if

$$\mathrm{M_{TOT}} > \mathrm{M}_{max}(\Omega)$$

II. Formation of an "unstable" NS if

$$M_{max}(\Omega) > M_{\mathrm{TOT}} > M_{max}$$

III. Formation of a "stable" NS if

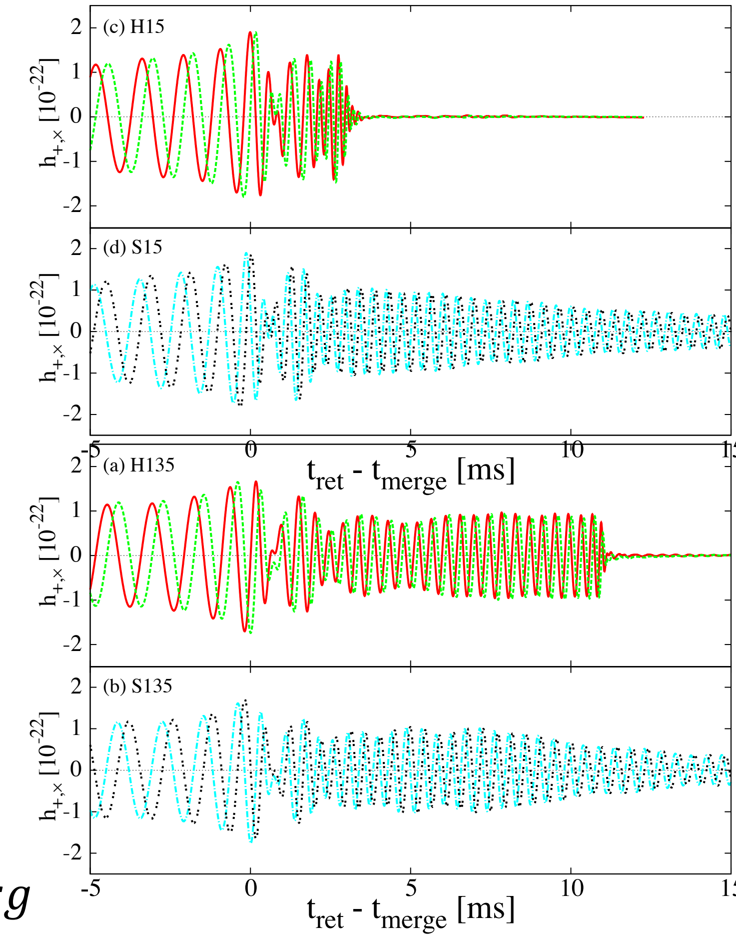
$$\mathrm{M_{TOT}} < \mathrm{M}_{max}(\Omega)$$

- NS-NS mergers will produce: Gao, Zhang, Lü 2016
  - ~40% prompt BHS
  - ~30% supramassive NS -> BH
  - ~30% Stable NS
- Initial spin near breakup limit ~1ms

Differential rotation/turbulence -->

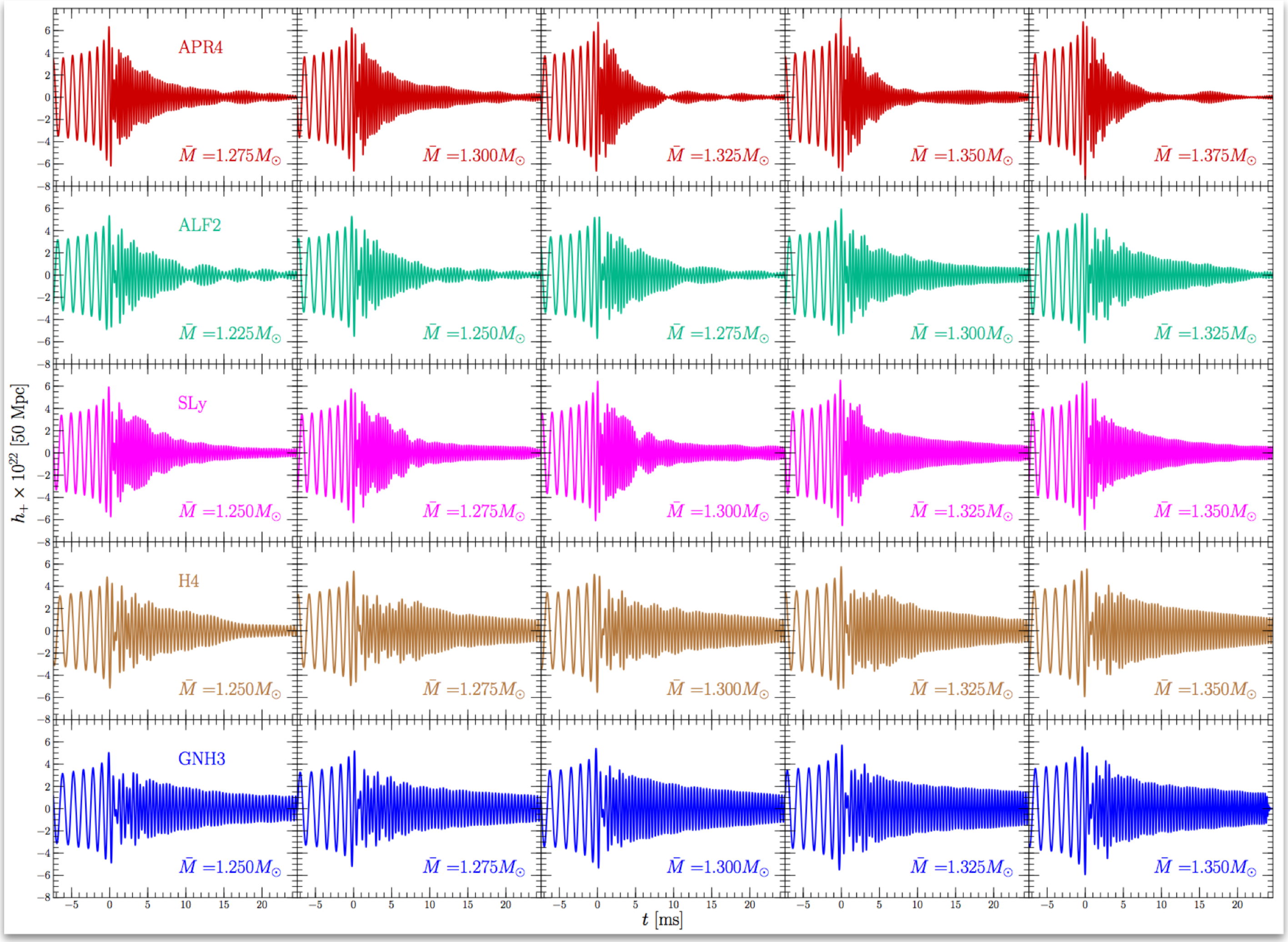
strongly twisted internal field $E_B \geq 10^{50} erg$

e.g. Rosswog etal (2003), Rezzolla etal 2011, Kiuchi etal 2012, Giacomazzo & Perna 2013, Giacomazzo etal 2015, Kyotoku etal 2015,...



Kiuchi, Sekiguchi, Kyutoku, Shibata 2012

Binary Neutron Star Mergers
the post-Merger scenario



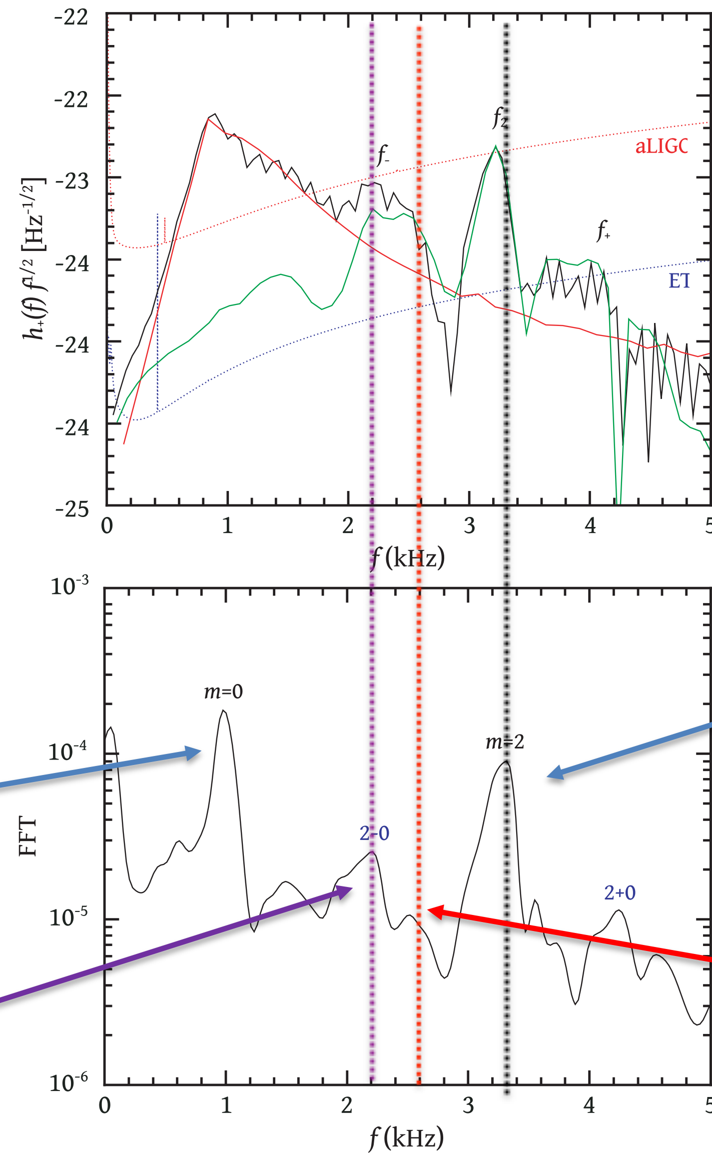
Takami, Rezzola, Baiotti (2014, 2015), Rezzola etal (2016

Binary Neutron Star Mergers

Post-merger Oscillations & GWs

GRAVITATIONAL WAVES

Stergioulas et al. (2011)
Bauswein, Stergioulas (2015)
…
Similar results from all groups



NEUTRON STAR OSCILLATIONS

l=m=0 linear quasi-radial mode

Quasi-linear combination frequency (f_{2-0})

l=m=2
linear f-mode (f_{peak})

nonlinear spiral frequency

Equation of State:
Constraints from GW170817 (Bauswein etal)

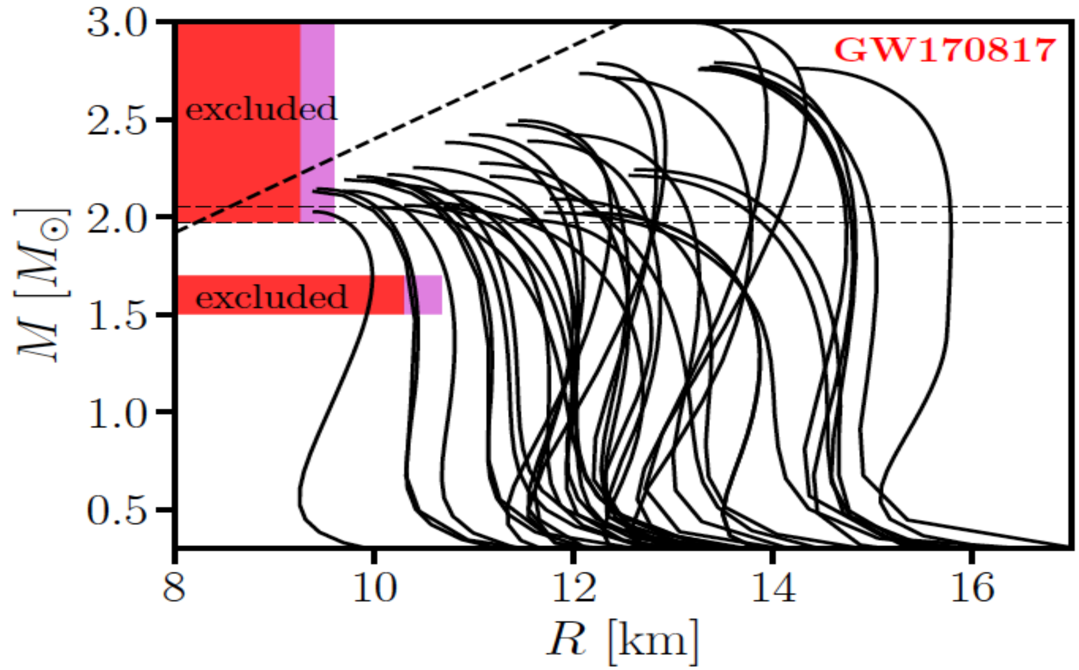


Figure 2. Mass-radius relations of different EoSs with very conservative (red area) and "realistic" (cyan area) constraints of this work for $R_{1.6}$ and $R_{\max}$. Horizontal lines display the limit by Antoniadis & et al. (2013). The dashed line shows the causality limit.

Equation of State:

Constraints from GW170817 (Rezzolla etal)

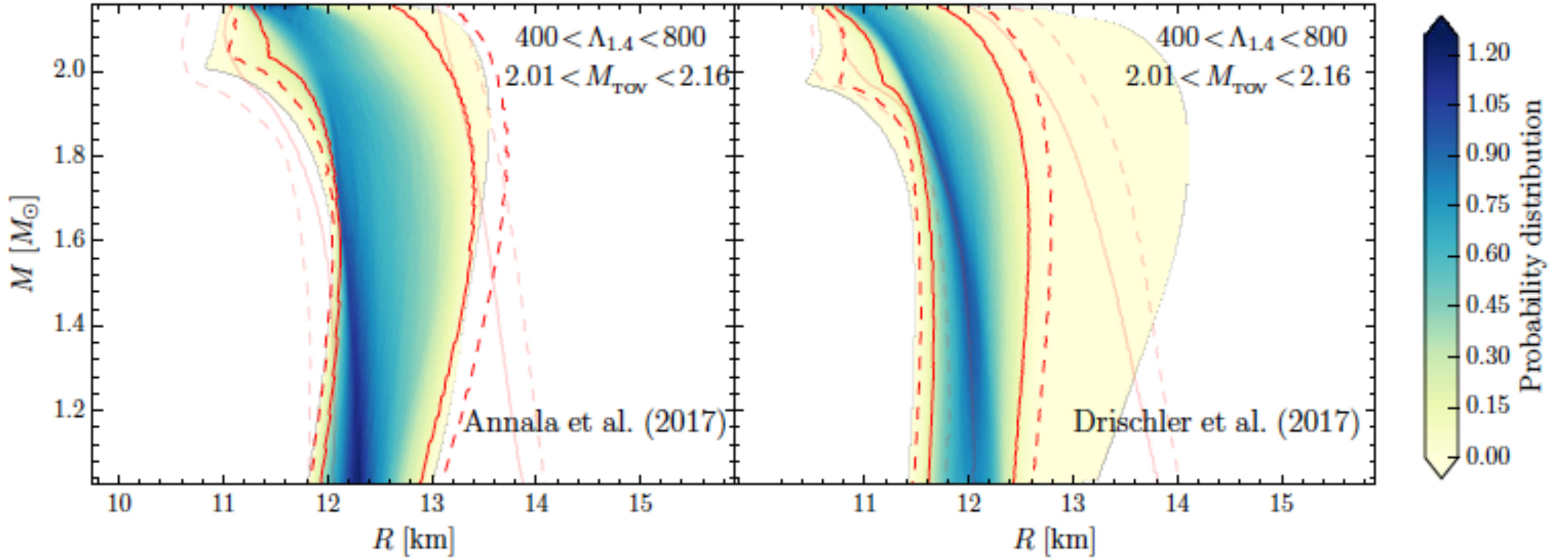
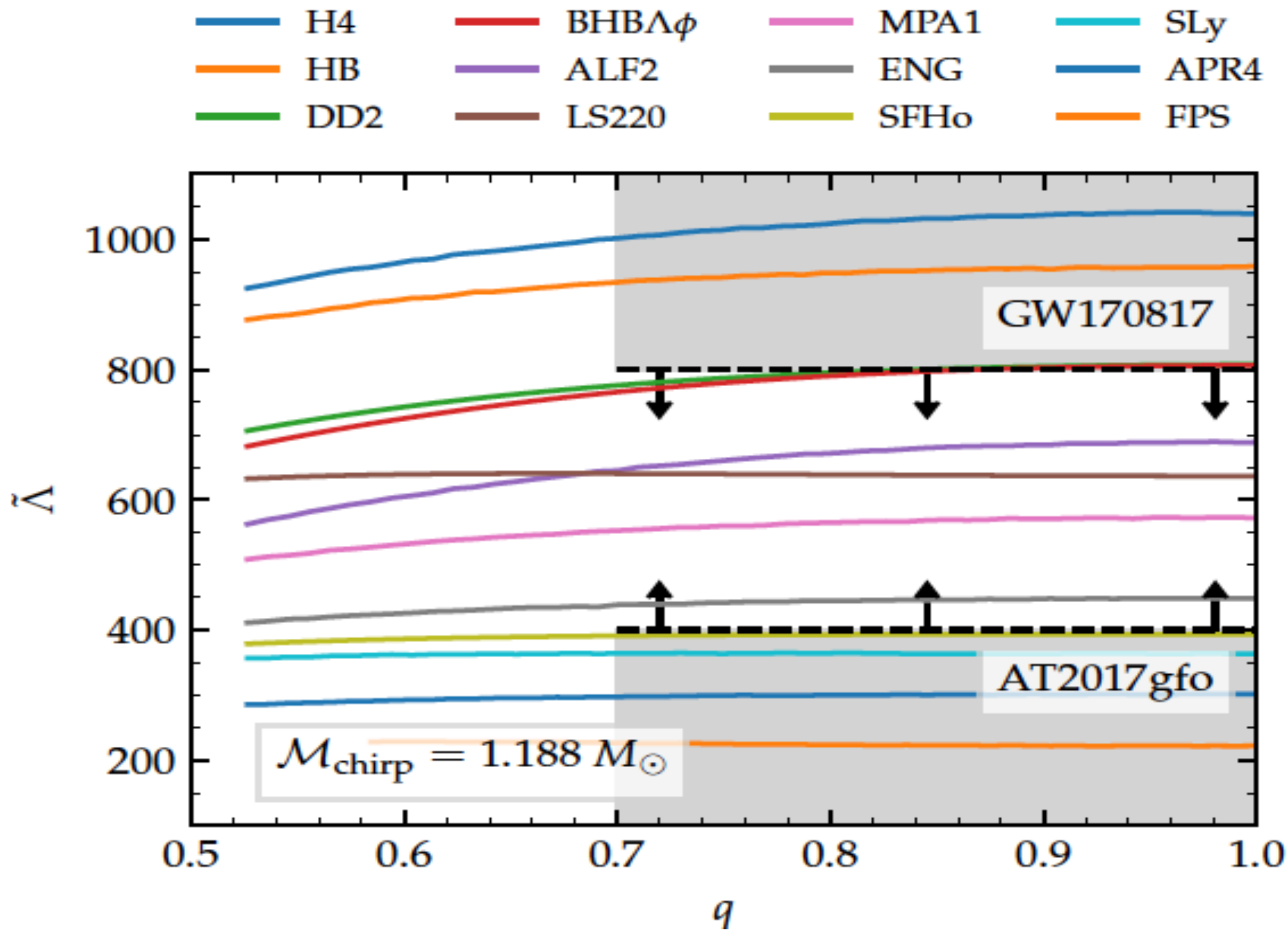


FIG. 4. *Left panel:* The same as in bottom-right panel of Fig. 1, but when the neutron matter in the outer core is treated following the approach of [11]. *Right panel:* The same as in the left panel but when considering the more recent prescription of [29] for the outer core. Shown as light shaded lines are the $2/3$-σ values reported in the bottom-right panel of Fig. 1.

Equation of State:
Constraints from GW170817 (Radice etal)

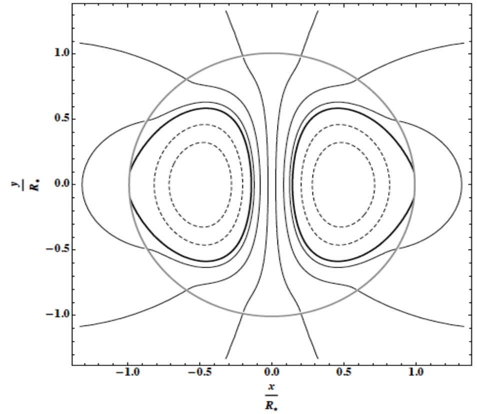


Binary Neutron Star Mergers
Formation of a “stable” NS

Slowdown due to three competing mechanisms:

I. Typical dipole B-field spindown

$$t_{sd} \approx 7 \left(\frac{B_d}{10^{15} G}\right)^{-2} \left(\frac{P}{1ms}\right)^{2} hr$$



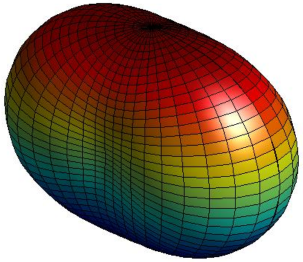
II. Deformed Magnetar Model

Dall’Osso-Giacomazzo-Perna-Stella 2015

III. Rotational Instabilities

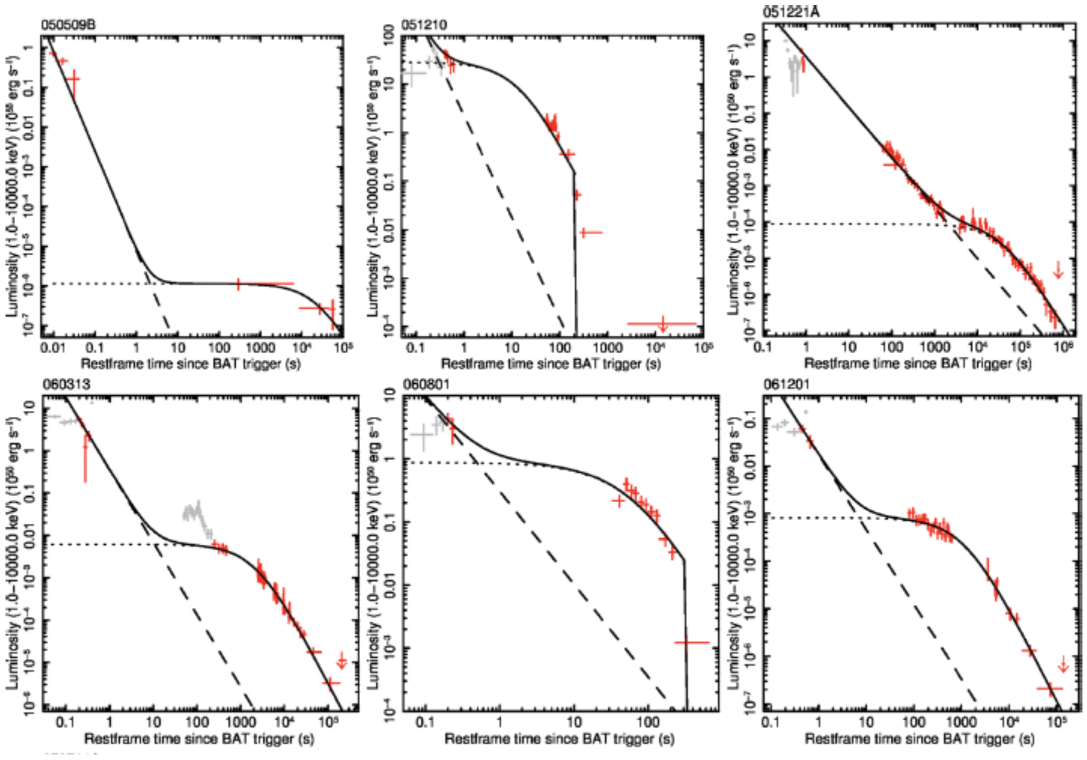
Doneva-Kokkotas-Pnigouras 2015

$$l = 2, m = 2$$



Binary Neutron Star Mergers
Short γ-ray light curves

- The favored progenitor model for SGRBs is the merger of two NSs that triggers an explosion with a burst of collimated γ-rays.
- Following the initial prompt emission, some SGRBs exhibit a plateau phase in their X-ray light curves that indicates additional energy injection from a central engine, believed to be a rapidly rotating, highly magnetized neutron star.
- The collapse of this "protomagnetar" to a black hole is likely to be responsible for a steep decay in X-ray flux observed at the end of the plateau.

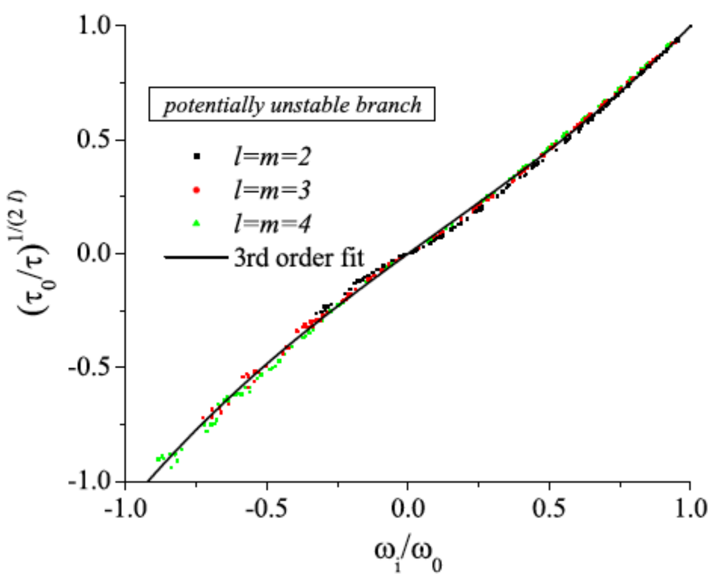


Rowlinson, O'Brien, Metger, Tanvir, Levan 2013

Post-Merger NS:
Secular instability

The post-merger object **is still stable** and rotates at nearly Kepler **periods < 1ms**

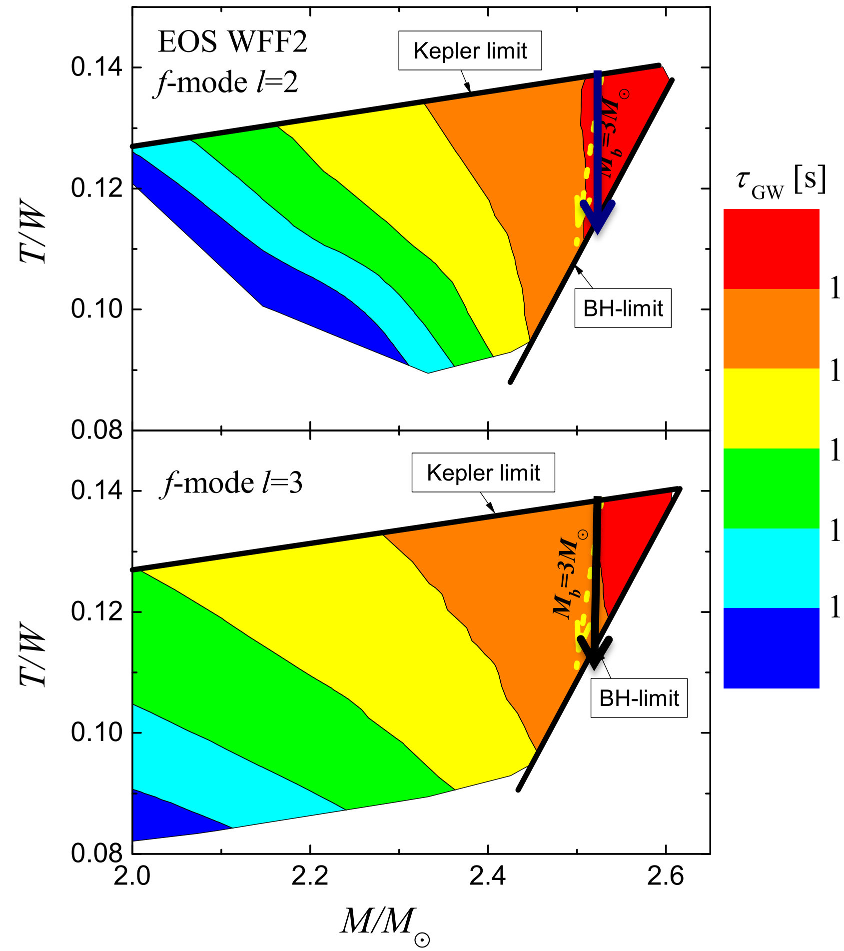
Growth time of the f-mode instability:



Approximate relation Lai-Shapiro 1994-5

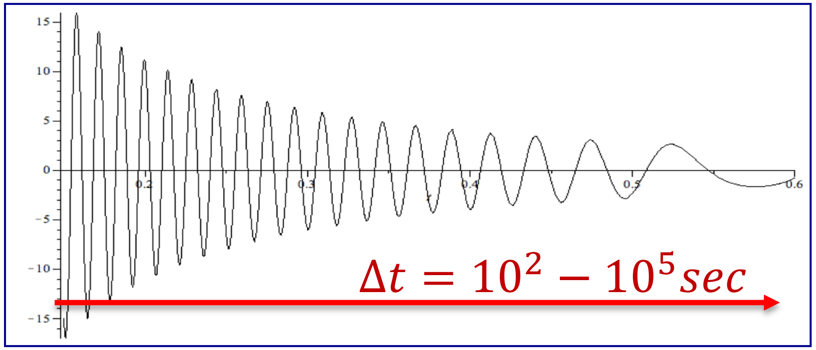
$$\tau_{\rm GW} \approx 2\times 10^5 \left(\frac{1.4M_\odot}{M}\right)^3 \left(\frac{R}{10{\rm km}}\right)^4 \frac{1}{(\beta-\beta_{\rm sec})^5}{\rm sec}$$

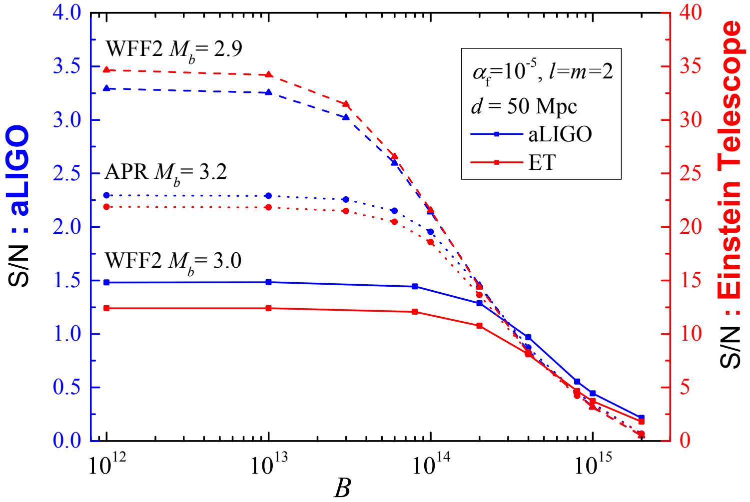
$$\beta = \frac{T}{W}$$

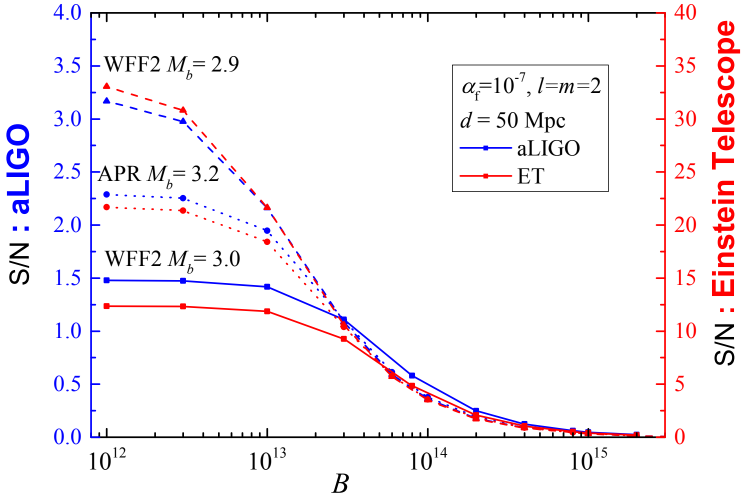


Doneva-Kokkotas-Pnigouras 2015

Post-Merger NS:
F-mode instability vs Magnetic field







Competition between the B-field and the secular instability

GW frequencies:
WW2a: 920-1000 Hz
APR: 370–810 Hz
WFF2b: 600–780 Hz

Doneva-Kokkotas-Pnigouras 2015

Conclusions

✓ **Continuous Sources (mountains & R-modes)**

- ❖ The details and nature of deformation (microphysics) need further study
- ❖ Weak galactic sources for present generation detectors

✓ **Binary Mergers**

- ❖ **Tidal effects very promising, may be the first to be measured**
- ❖ **Early post-merger phase**
  - Ideal field for asteroseismology and constraining the EOS
  - Towards the **end of next decade** will provide a wealth of information (earlier detection also possible).
- ❖ **Late post-merger phase**
  - The GW emission depends strongly on the strength of the dipole component of the magnetic field ($\gtrsim 10^{14}$ Gauss)
  - All 3 cases (*boring* **B-field spindown**, **deformed magnetar** and **f-mode instability**) maybe observed towards the end of next decade.

THANK YOU