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Neutron Stars

Rotational and Magnetic Field Instabilities & Gravitational Waves

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Theoretical Astrophysics

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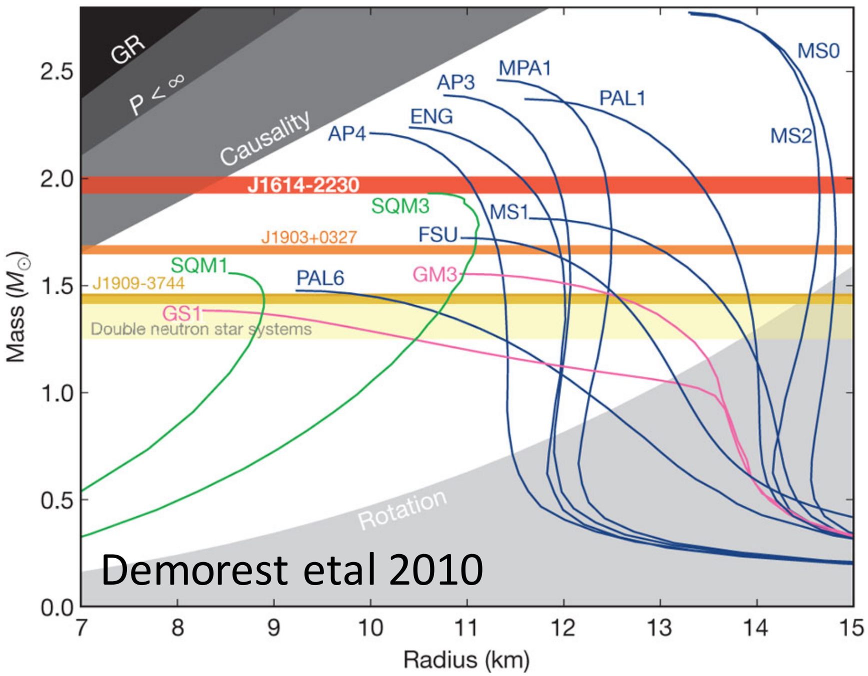
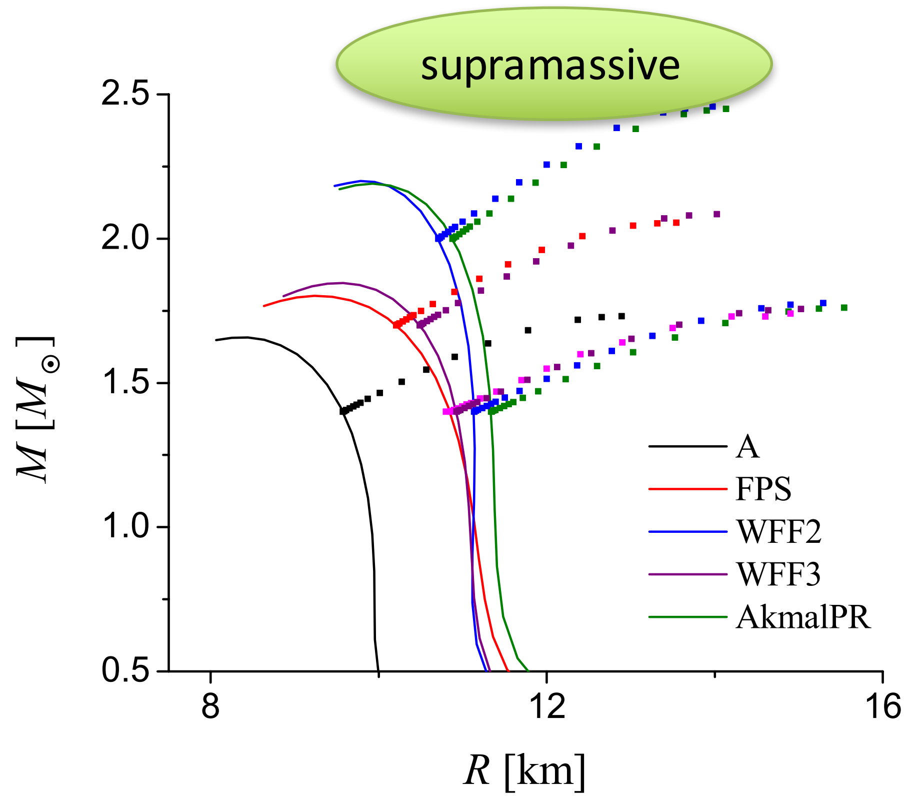
Neutron Stars: Mass vs Radius

Static Models



Rotating Models



$$M_{max} \simeq (1.1962 + 0.0108) M_{TOV}$$

Breu-Rezzolla 2015

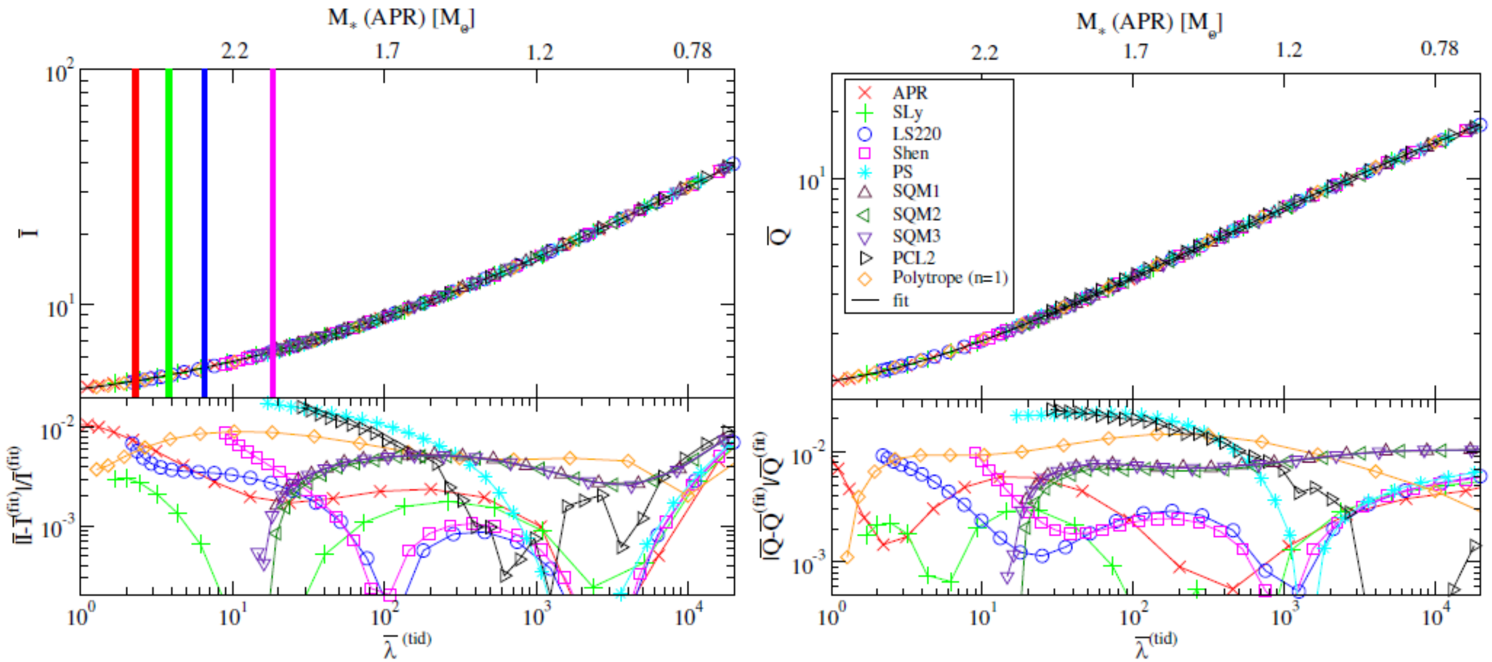
Neutron Stars & "universal relations"

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	$\lambda \sim I^2 Q$	

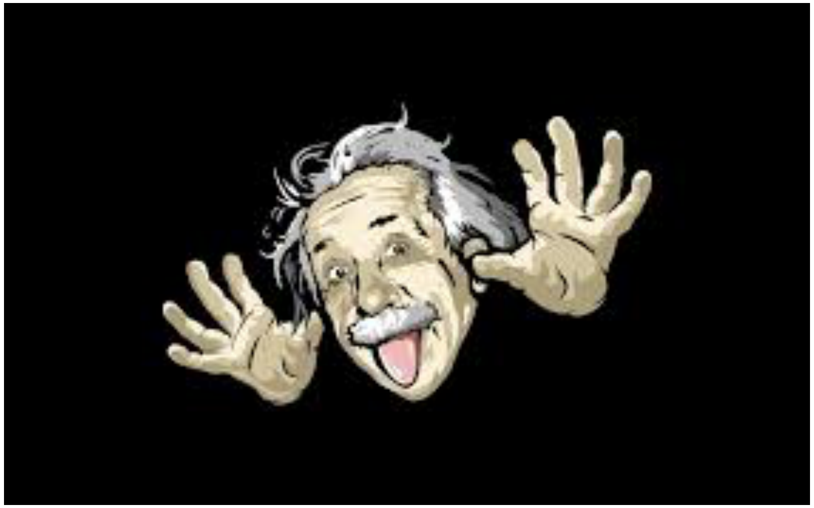
I-Love-Q relations

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

NEUTRON STARS &
ALTERNATIVE THEORIES OF GRAVITY



STT of gravity - Motivation

- The Scalar Tensor Theory (STT) is one of the most natural generalizations of the Einstein's Theory of Gravity (ETG)
- Their essence is in one or several scalar fields that are mediators of the gravitational interaction in addition to the spacetime metric of classical ETG
- Scalar fields appear in the reduction of the Kaluza-Klein theories to 4 dimensions, in string theory and in higher dimensional gravity but STT can be defined completely independently
- STT can be considered as an ETG with variable gravitational constant
- They fit to the observational data very well
- They are also an essential part of dark energy and dark matter models
- The f(R) theories are mathematically equivalent to the STT

STT of gravity – Action

- **Physical (Jordan) frame action:**

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-\tilde{g}}\left[F(\Phi)\tilde{R} - Z(\Phi)\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 2U(\Phi)\right] + S_m\left[\Psi_m;\tilde{g}_{\mu\nu}\right]$$

- **Einstein frame action (much simpler):**

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-g}\left(R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - 4V(\varphi)\right) + S_m[\Psi_m;\mathcal{A}^2(\varphi)g_{\mu\nu}]$$

  – **Coupling function**

$$\boxed{k(\varphi) = \frac{d\ln\left(A(\varphi)\right)}{d\varphi}}$$

$$A(\varphi) = e^{\frac{1}{2}\beta\varphi^2}$$

$$k(\varphi) = \beta\varphi$$

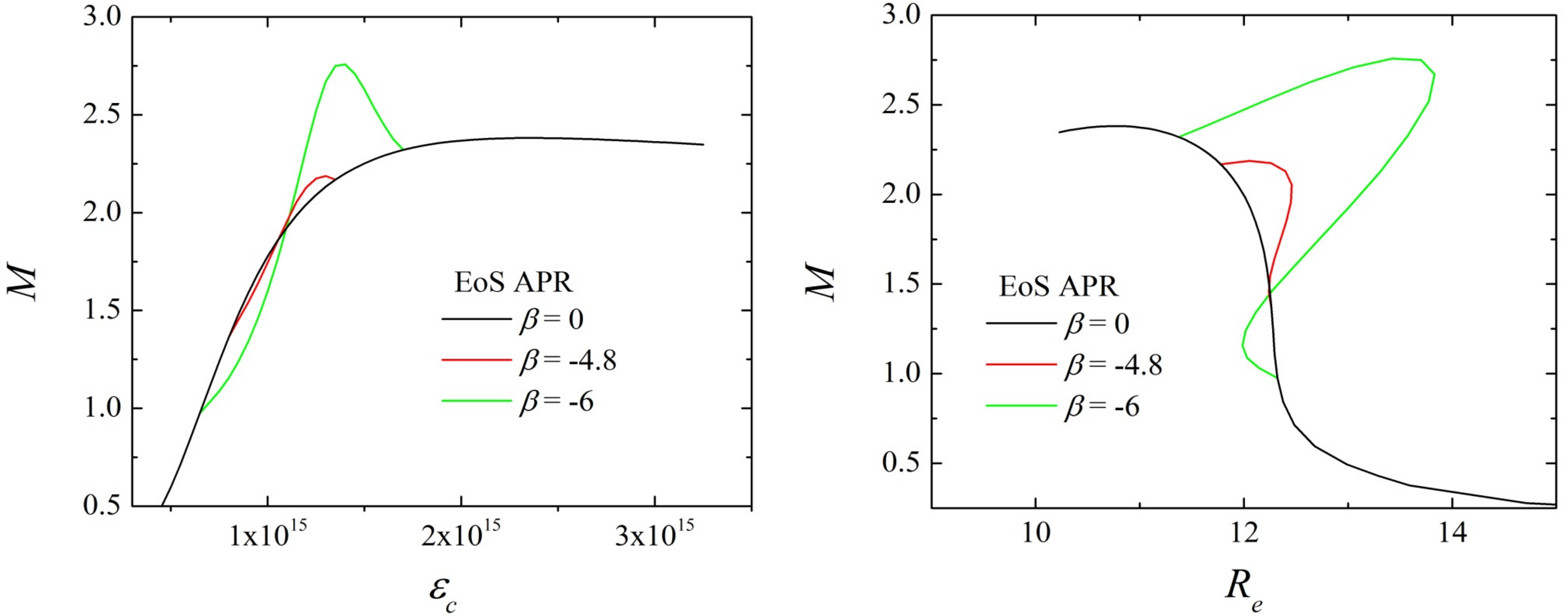
  – **We set the potential to zero**

$$\boxed{V(\varphi) = 0}$$

STT of gravity – Neutron Stars

Spontaneous Scalarizarion is possible for β<-4.35
(Damour+Esposito-Farese 1993)

Properties of the static scalarized neutron stars



The solutions with nontrivial scalar field are *energetically more favorable* than their GR counterpart (Harada 1997, Harada 1998, Sotani+Kokkotas 2004).

STT of gravity - Observations

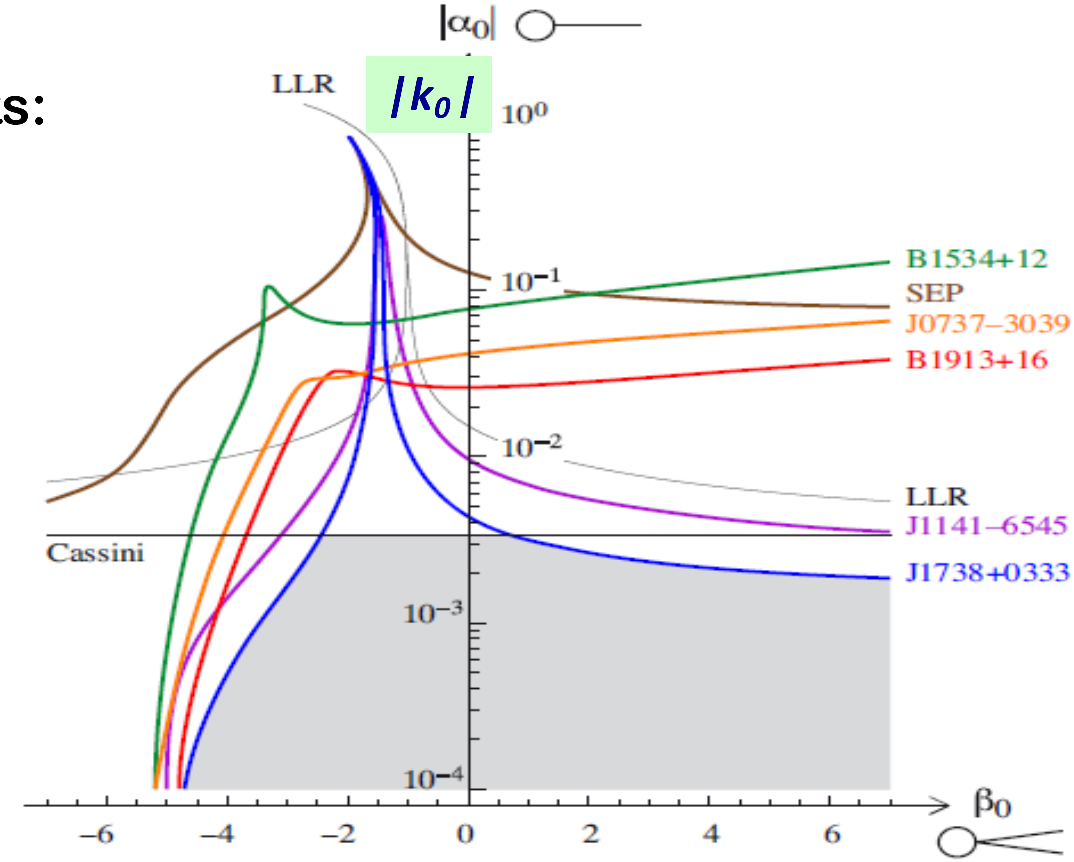
Observational constraints:

$k_0<0.004$

$\beta> -4.8$ (-4.5)

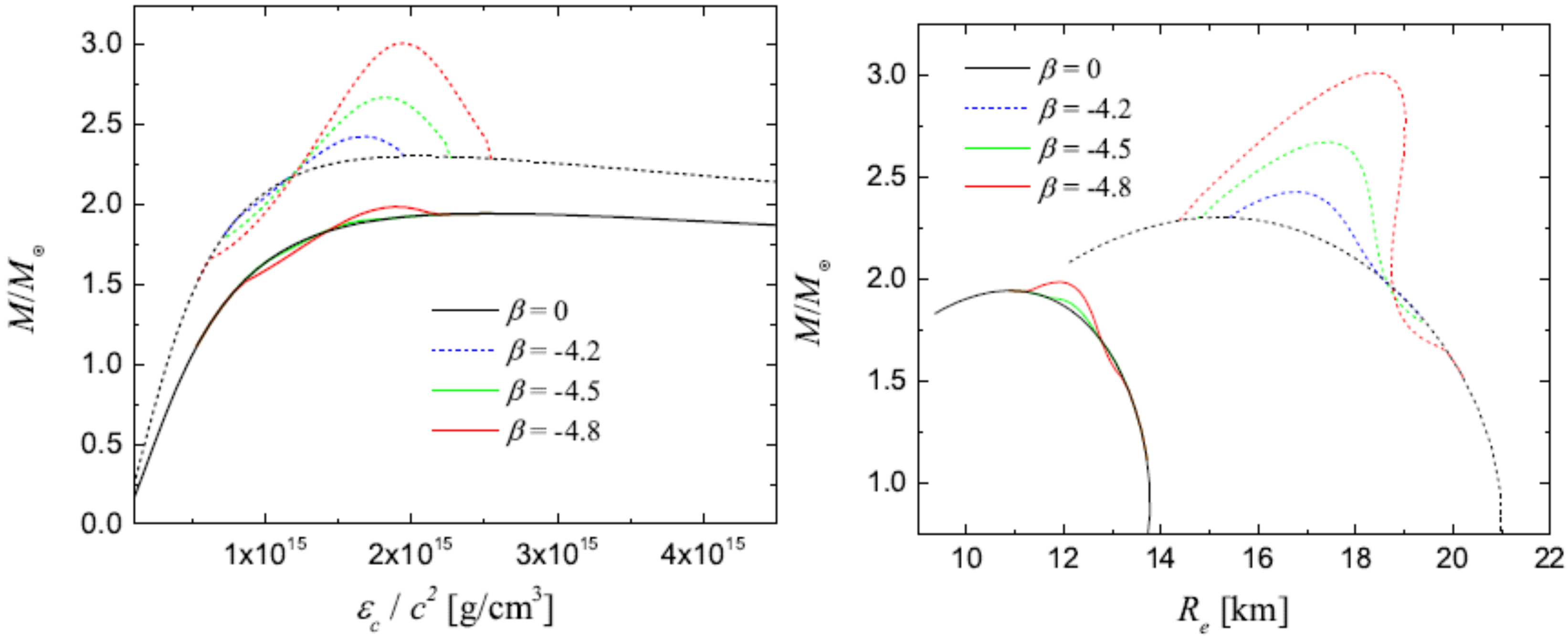
Damour & Esposito-Farese (1996, 98)

Will (2006), Freire etal (2012)



Freire at al (2012)

STT of gravity – Fast Rotating Stars



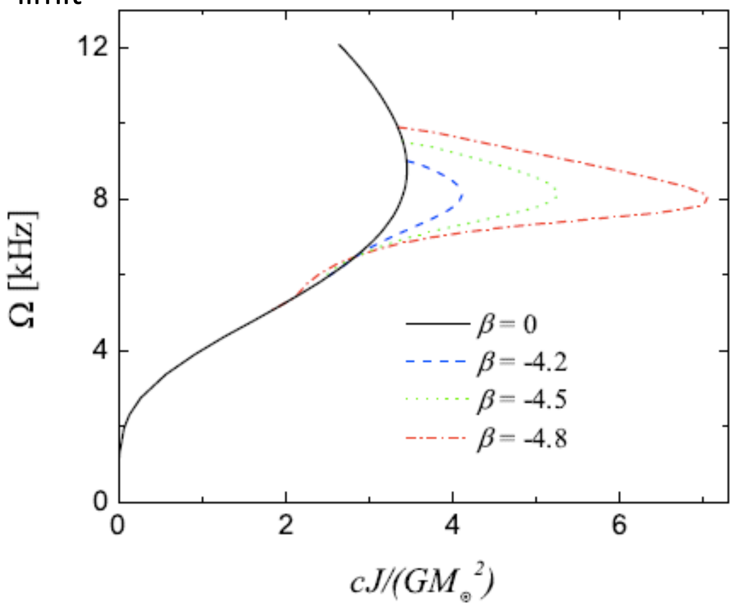
- The effect of scalarization is ***much stronger*** for fast rotation.
- Scalarized solutions exist for a ***much larger range of parameters*** than in the static case

Doneva, Yazadjiev, Stergioulas, Kokkotas 2013

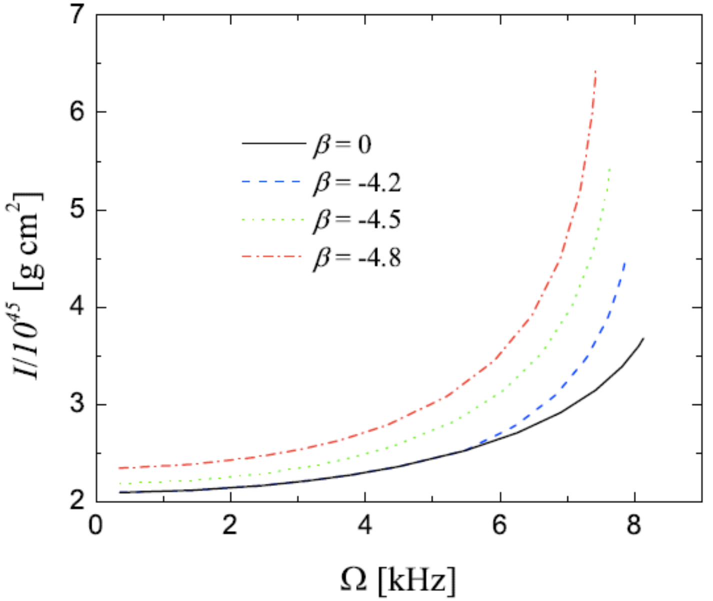
STT of gravity

Angular Momentum & Moment of Inertia

Sequences of models rotating at the Kepler limit



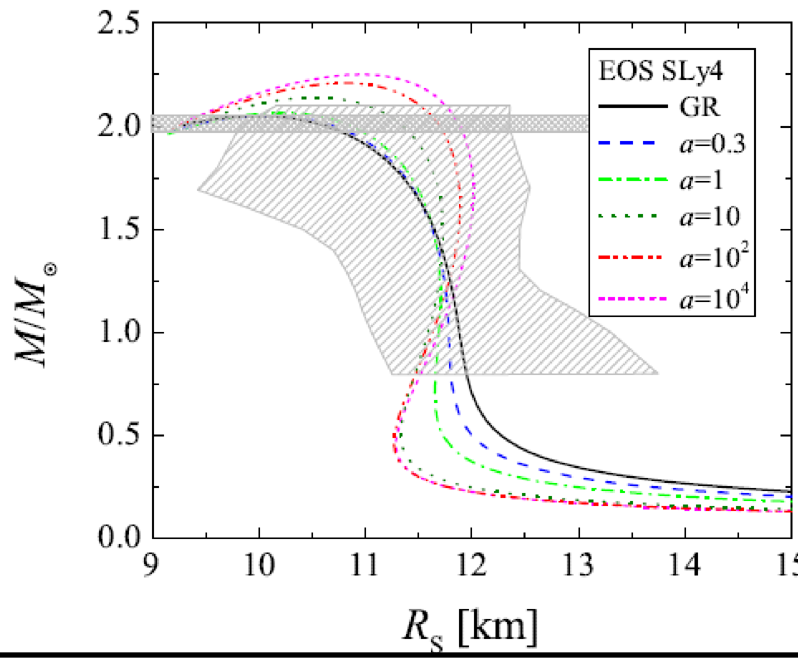
Models with constant central energy density

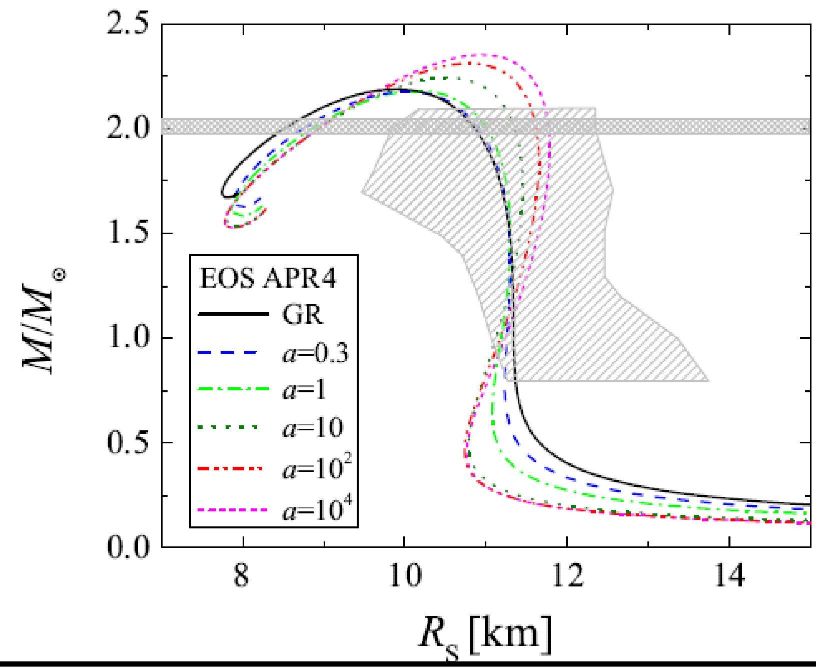


Not surprizing that both **angular momentum** and **moment of inertial** could *differ twice* for scalarized solutions

NSs in f(R)-gravity: Static Models

$$f(R) = R + aR^2$$





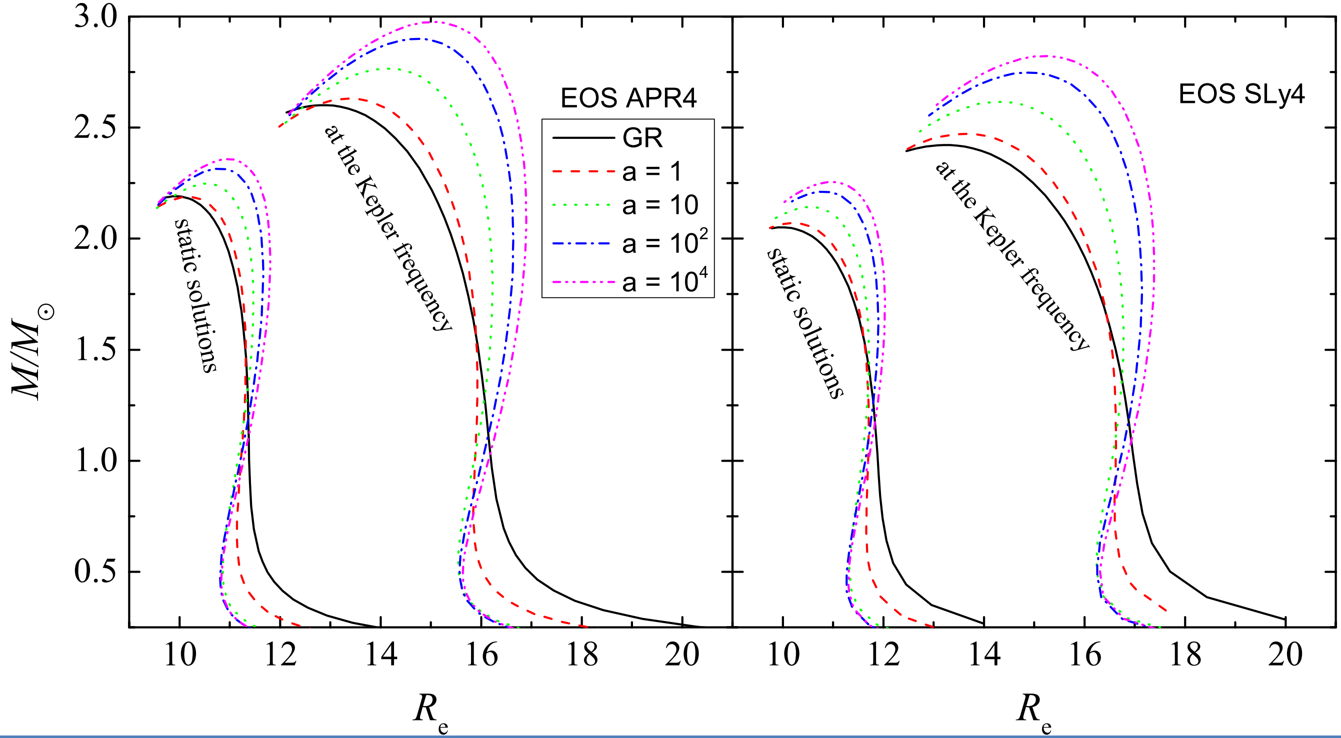
- The differences between the R^2 and GR are comparable with the uncertainties in the nuclear matter equations of state.
- The current observations of the NS masses and radii alone can not put constraints on the value of the parameters a, **unless the EoS is better constrained in the future.**

Yazadjiev, Doneva, Kokkotas, Staykov (2014)

NSs in f(R)-gravity: Fast Rotation

$$f(R) = R + aR^2$$

Mass of radius diagrams for two realistic EOS



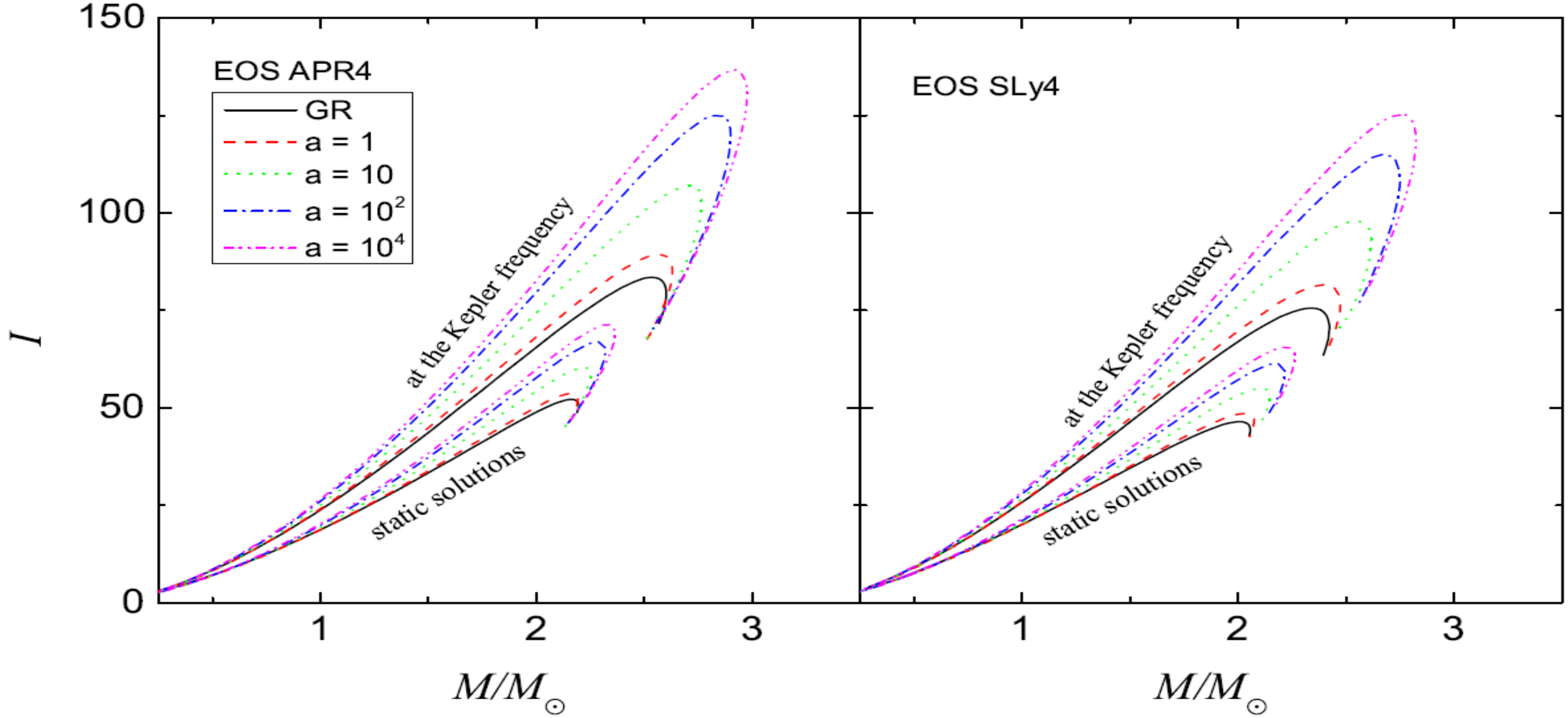
Difficult to set constraints on the *f* (*R*) theories using measurement of the neutron star **M** and **R** alone, until the EOS can be determined with smaller uncertainty.

Yazadjiev, Doneva, Kokkotas, (2015)

NSs in f(R)-gravity: Fast Rotation

$$f(R) = R + aR^2$$

Yazadjiev, Doneva, Kokkotas (2015) 4



- ✓ **The differences in the neutron star moment of inertia on the other hand can be much more dramatic.**
- ✓ **Large deviations can be potentially measured by the forthcoming observations of the NS moment of inertia [Lattimer-Schutz 2005, Kramer-Wex 2009] that can lead to a direct test of the R^2 gravity.**

NSs in f(R)-gravity: I-Q relations / Fast Rotation

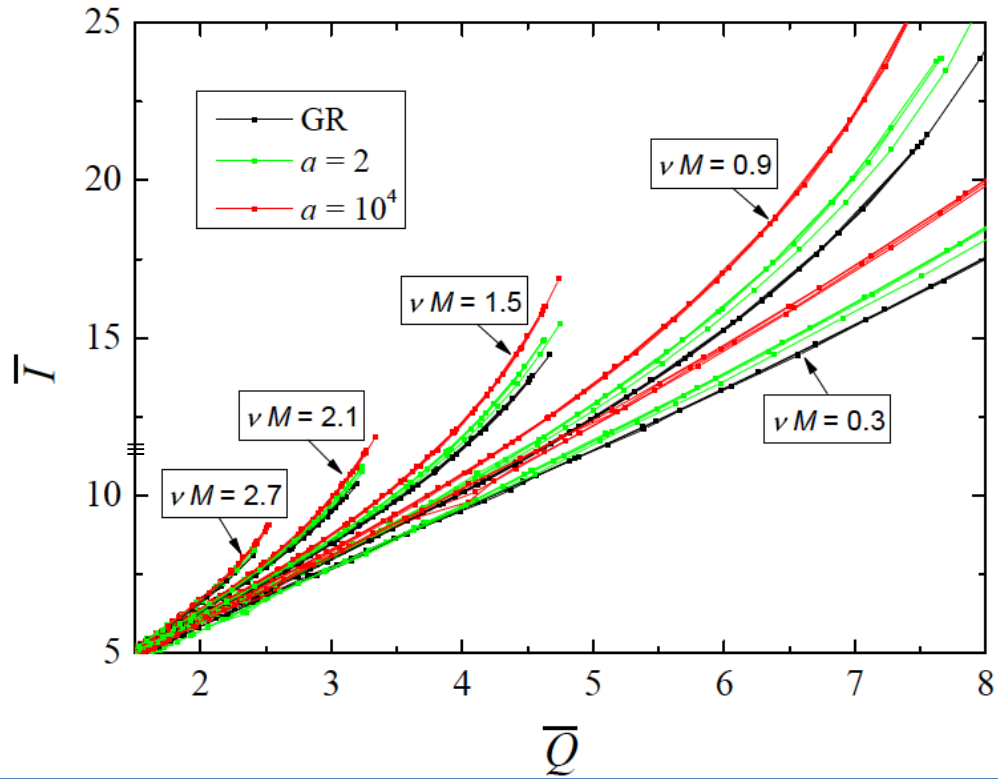
$$f(R) = R + aR^2$$

$$\bar{I} \equiv I / M^3$$

$$\bar{Q} \equiv Q / (M^3 \chi^2)$$

$$\chi \equiv J / M^2$$

ν : rot. frequency (Hz)



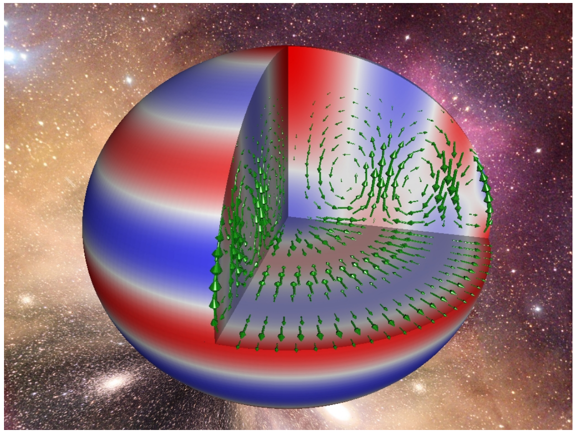
Doneva, Yazadjiev, Kokkotas (2015)

- The results show that the I-Q relation remain **nearly EoS independent** for fixed values of the normalized rotational parameter
- The differences with the pure Einstein's theory can be large reaching **above 20%** for **lower masses** and **slow rotation.**

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)

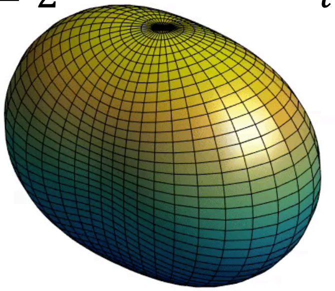


Typically **SMALL AMPLITUDE** oscillations –> weak emission of GWs

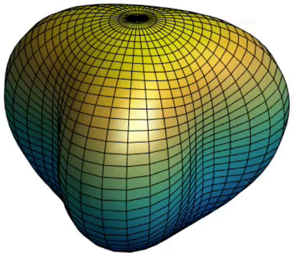
UNLESS

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

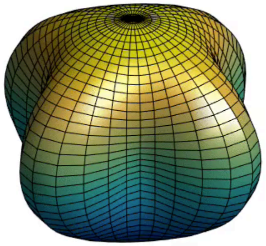
$l = 2, m = 2$



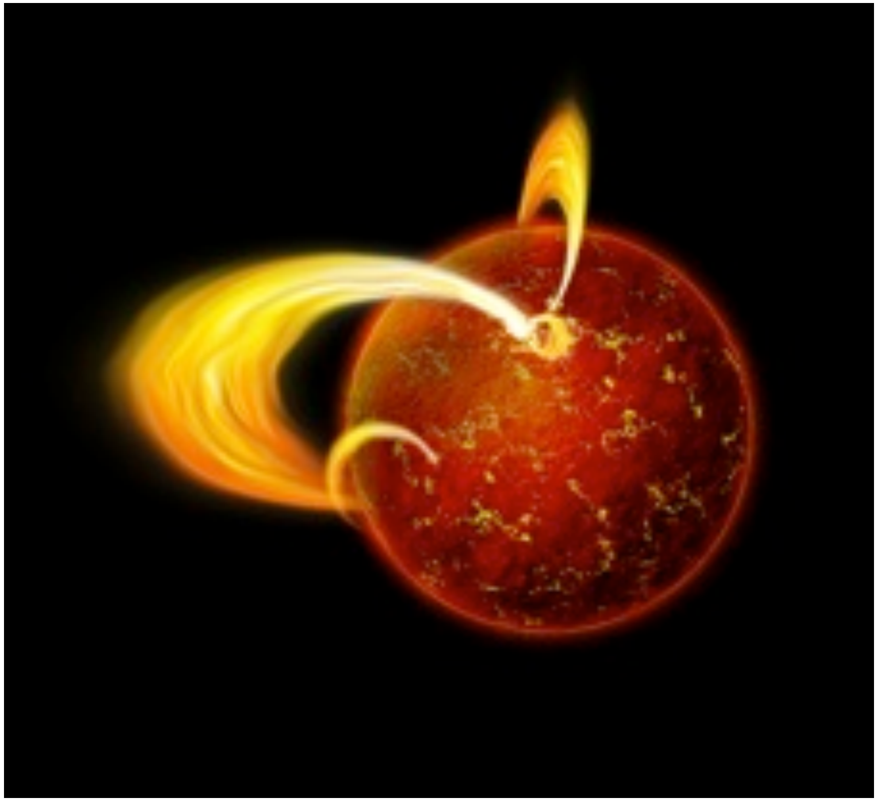
$l = 3, m = 3$

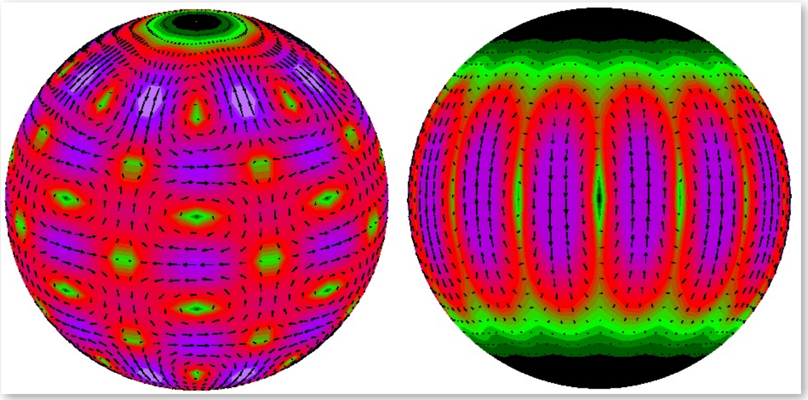


$l = 4, m = 4$



MAGNETARS:
A PROMISING CASE FOR ASTEROSEISMOLOGY





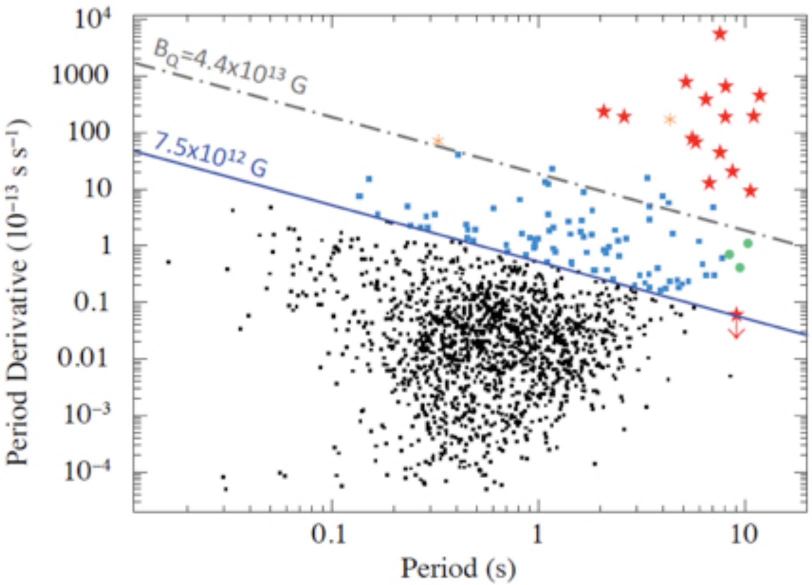
Magnetars

- **Young, slowly spinning (P~10s) systems (20+)**

- **Exhibit regular γ-ray flares**
  - Believed to be powered by magnetic field
  - Either trigger or are preceded by starquakes
  - Some linked to glitches or **anti-glitches**

- **Three giant flares observed with peak luminosities ~10^{47} erg/s**
  - March 5, 1979 : SGR 0526-66
  - August 27, 1998 : SGR 1900+14
  - December 27, 2004: SGR 1806-20
  - Recently few medium ones

- **Giant flares**
  - QPOs – 10's -100's of Hz
  - Magnetic field reconstruction



Magnetars:

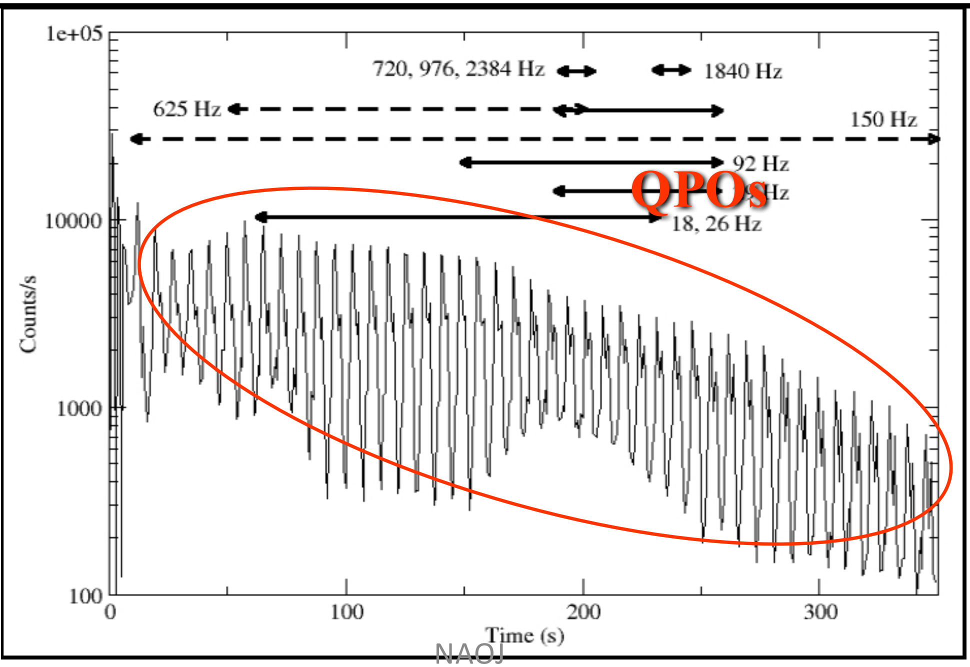
Quasi-Periodic Oscillations (QPOs)

✓ **Giant flares in SGRs**

- A decaying tail for several hundred seconds follows the flare.

✓ **QPOs in decaying tail** (Israel *et al.* 2005; Watts & Strohmayer 2005, 2006)

- SGR 1900+14 : 28, 54, 84, and 155 Hz
- SGR 1806-20 : 18, 26, 29, 92.5, 150, 626.5, 720, 976, 1837, 2384 Hz
- SGR 1806-20 : Additional frequencies 22, 16, 60, 116 Hz, also 720 & 2384 Hz; (Hambaryan, Neuhaeuser, Kokkotas 2011)



Alfven Continuum and/or Discrete oscillations

Only Crust Oscillations
- Sotani, Kokkotaa, Stergioulas 2007,2008
- Samuelsson, Andersson 2007
- Sotani, Colaiuda, Kokkotas 2008
- Steiner, Watts 2009
- …
- Sotani etal 2012-16

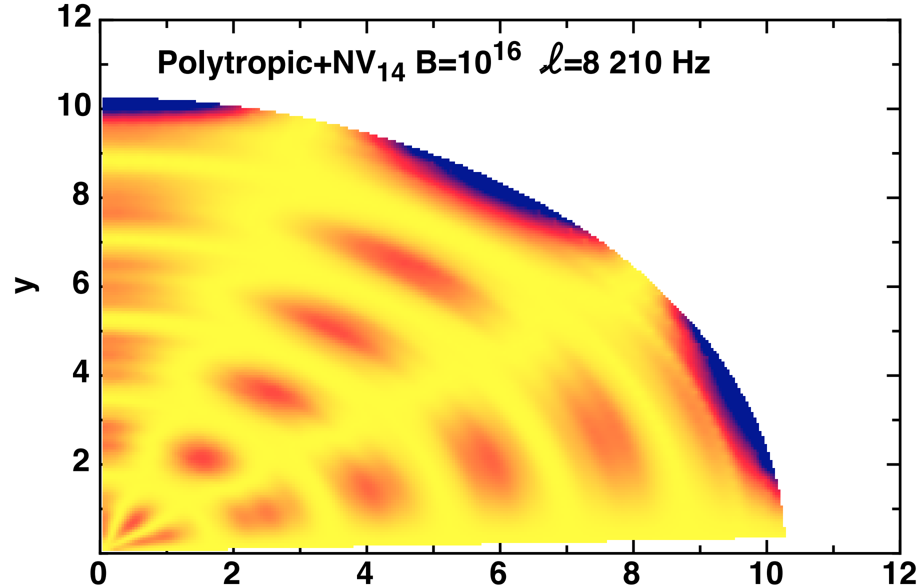
Without Crust
- Levin 2007
- Sotani, Kokkotas, Stergioulas 2008
- Colaiuda, Beyer, Kokkotas 2009
- Cerda-Duran, Stergioulas, Font 2009

Fluid + Crust
- Van Hoven, Levin 2011, 2012
- Cerda-Duran, Stergioulas, Font 2011
- Colaiuda, Kokkotas 2011
- Gabler etal 2012
- Gabler etal 2013 …

Superfluidity
- Passamonti, Lander 2012
- Sotani etal 2013
- Gabler etal 2013

Mixed axial-polar
- Colaiuda, Kokkotas 2012
- Lee, Yoshida 2015

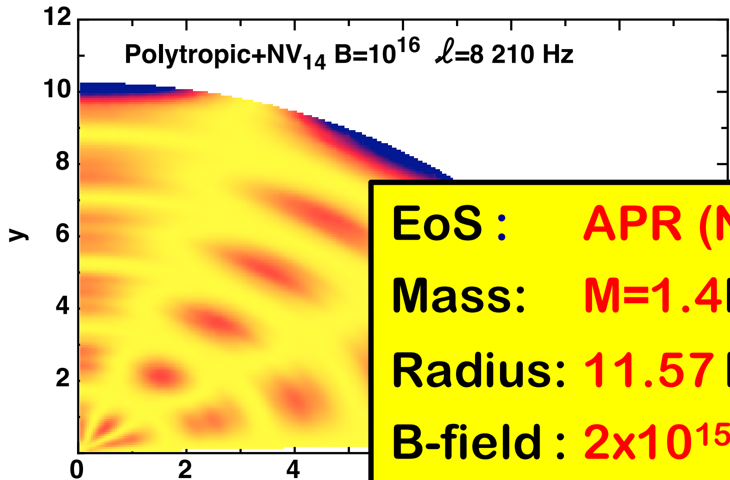
Non-axisymmetric
- Sotani, Kokkotas 2012



- ✓ The combination
  - of poloidal + toroidal magnetic fields + crust
  - leads to coupling between polar and axial modes leading to
  - PURE discrete spectrum
- ✓ The main results of the magnetar seismology remain unchanged !

(Colaiuda-Kokkotas 2012)

Magnetars: SGR 1806-20



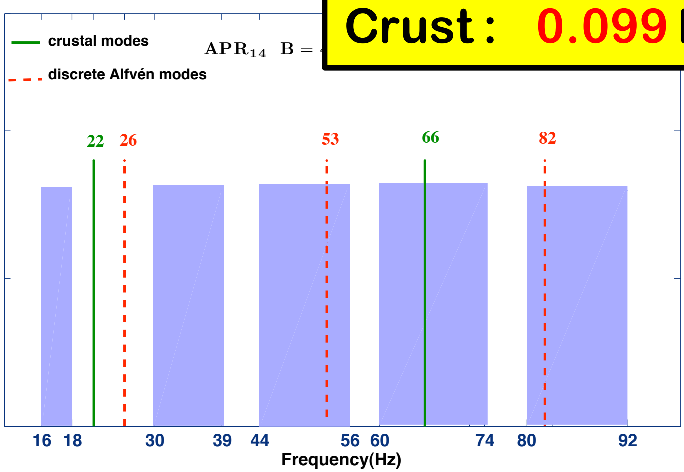
EoS : APR (NV)

Mass: $M=1.4M_\odot$

Radius: 11.57 km

B-field : $2x10^{15}$ G

Crust : 0.099 R



Colaiuda, Kokkotas (2011-12)

2005-6 Israel etal Watts & Strohmayer	2010-12 Colaiuda-KK	2011 Hambaryan, Neuhaüser, KK	2013-15
	16	16	
18	18		
	22	22	
26	26		
29.5	30		
	39	37	
	44		
	53		
	56		56
	60	59 &61	
	66		
	74		
	80		
	82		
92	**92**		92

Magnetars: Open Questions

Do we understand how the QPOs are excited?
The answer is NO! (at least partially)

Great progress in the last 7-8 years

- ✓ **BUT mainly AXISYMMETRIC oscillations used to explain the observed QPOs**
- ✓ **For NON-Axisymmetric oscillations both poloidal & toroidal B-fields are unstable!**

A new event of the type of SGR 1806-20, might be catalytic for understanding:

- The mechanism that triggers the hyperflares
- The QPOs in the decaying tail
- The EOS, the Mass, Radius, B-field of magnetars

The Tayler Instability

Toroidal Fields

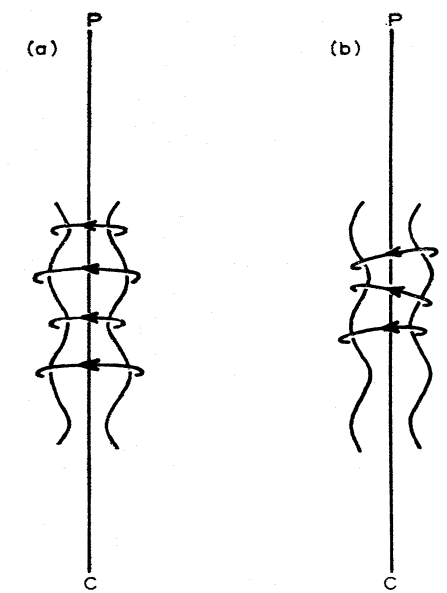
Bernstein etal (1958) showed that the stability of an ideally conducting system depends on the sign of the change of potential energy of the system for an arbitrary perturbation ξ(x,t):

$$\delta W = \frac{1}{2}\int\left[\vec{Q}^2 - \vec{j}\cdot\vec{Q}\times\vec{\xi} + \gamma P(\mathrm{div}\vec{\xi}) + \vec{\xi}\cdot\mathrm{grad}P\,\mathrm{div}\vec{\xi} + \vec{\xi}\cdot\mathrm{grad}\Phi\,\mathrm{div}\rho\vec{\xi}\right]d\tau$$

$$\vec{Q} = \mathrm{curl}\left(\vec{\xi}\times\vec{B}\right)$$

For a **toroidal field** the m=0 and the m=1 will look like:

Rotation or/and a strong poloidal field can potentially work against this instability



Magnetic Field Stability: Semianalytic Approach

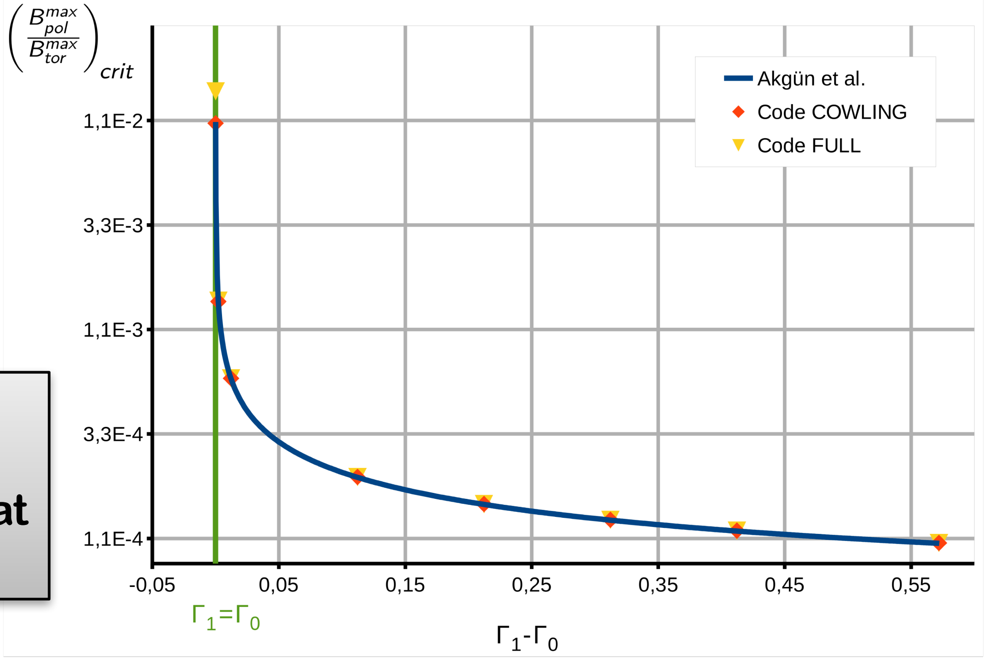
Herbrick+KK 2015

$$\delta W = \int_V \left[\delta W_B + \delta W_{fluid} + \delta W_{grav} \right] dV$$

- ✓ Pure poloidal
- ✓ Pure toroidal
- ✓ Mixed field + stratification

The pure toroidal field would be unstable but can be stabilized by the contribution from the poloidal field that is positive in this area.

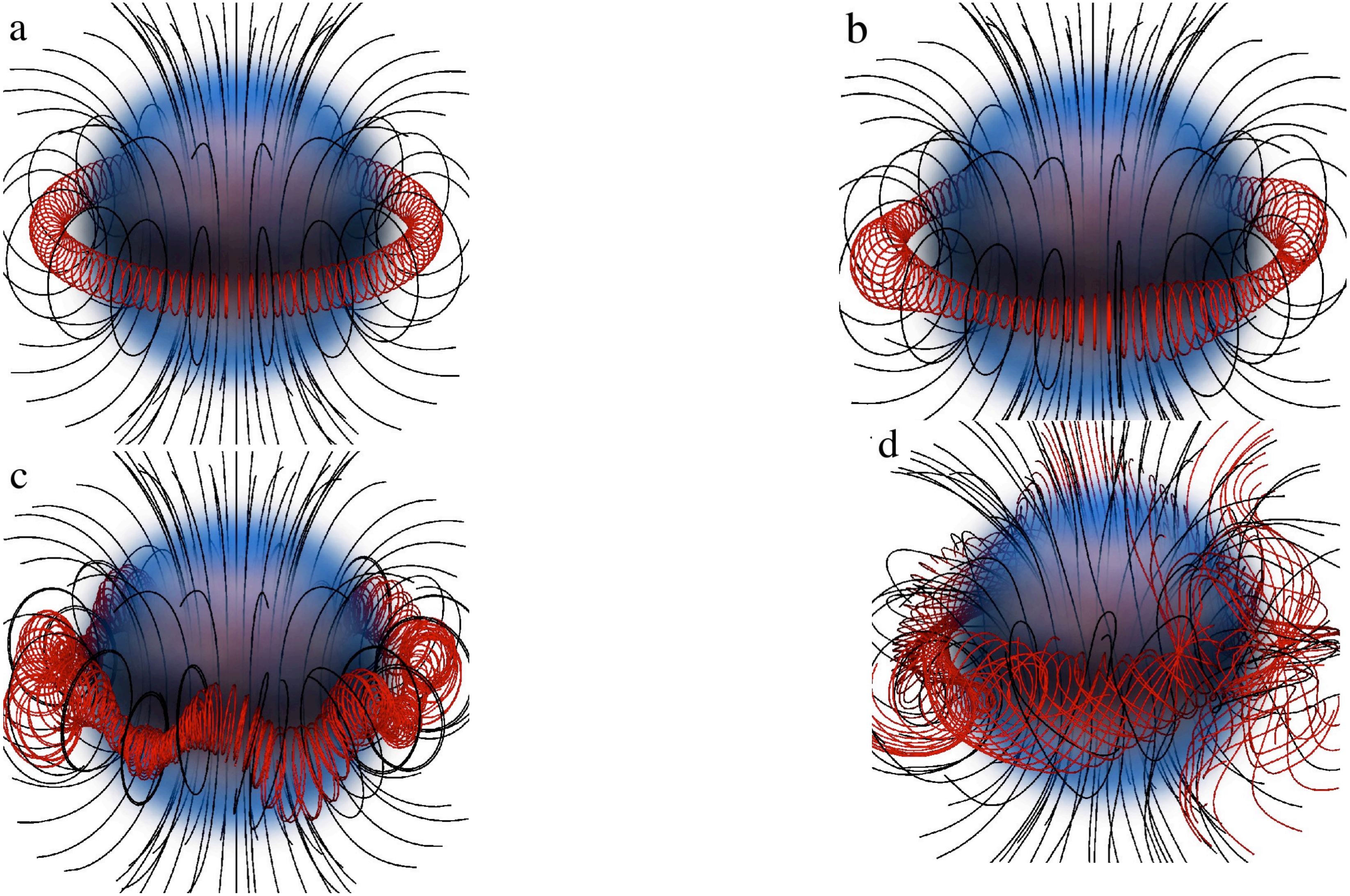
In agreement with Akgün etal (2013)



- ✓ Constraining realistic magnetic field structures by parametrisation
- ✓ Adding more realistic features e.g. crust, superconductivity,…
- ✓ Constructing arbitrary displacement fields
- ✓ Eventually providing a GR criterion of stability

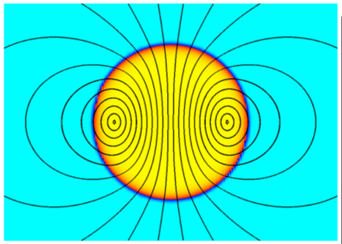
Simulation of Magnetic Field Instability

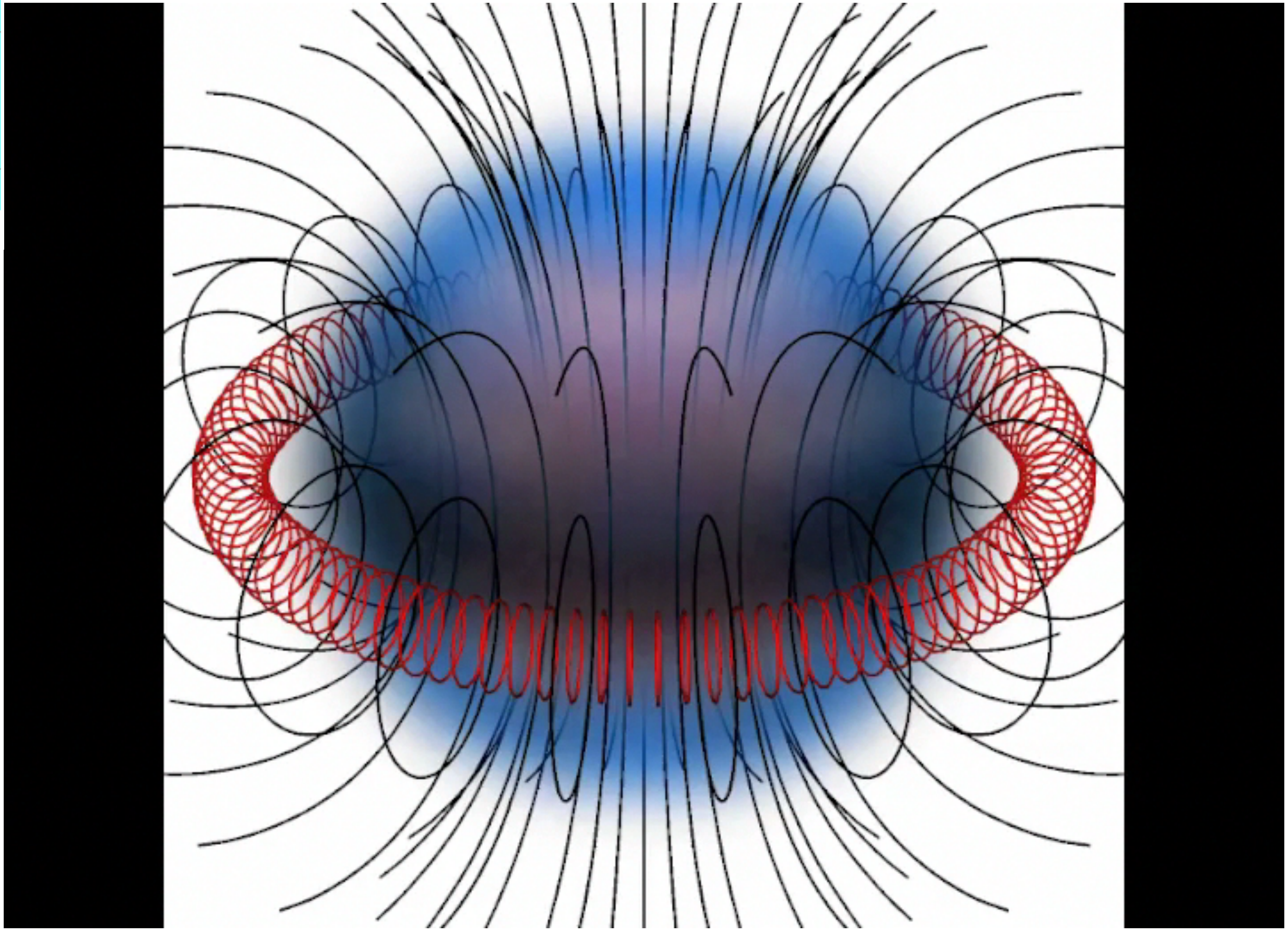
Lasky, Zink, Kokkotas, Glampedakis ApJL (2011)



Simulation of Magnetic Field Instability

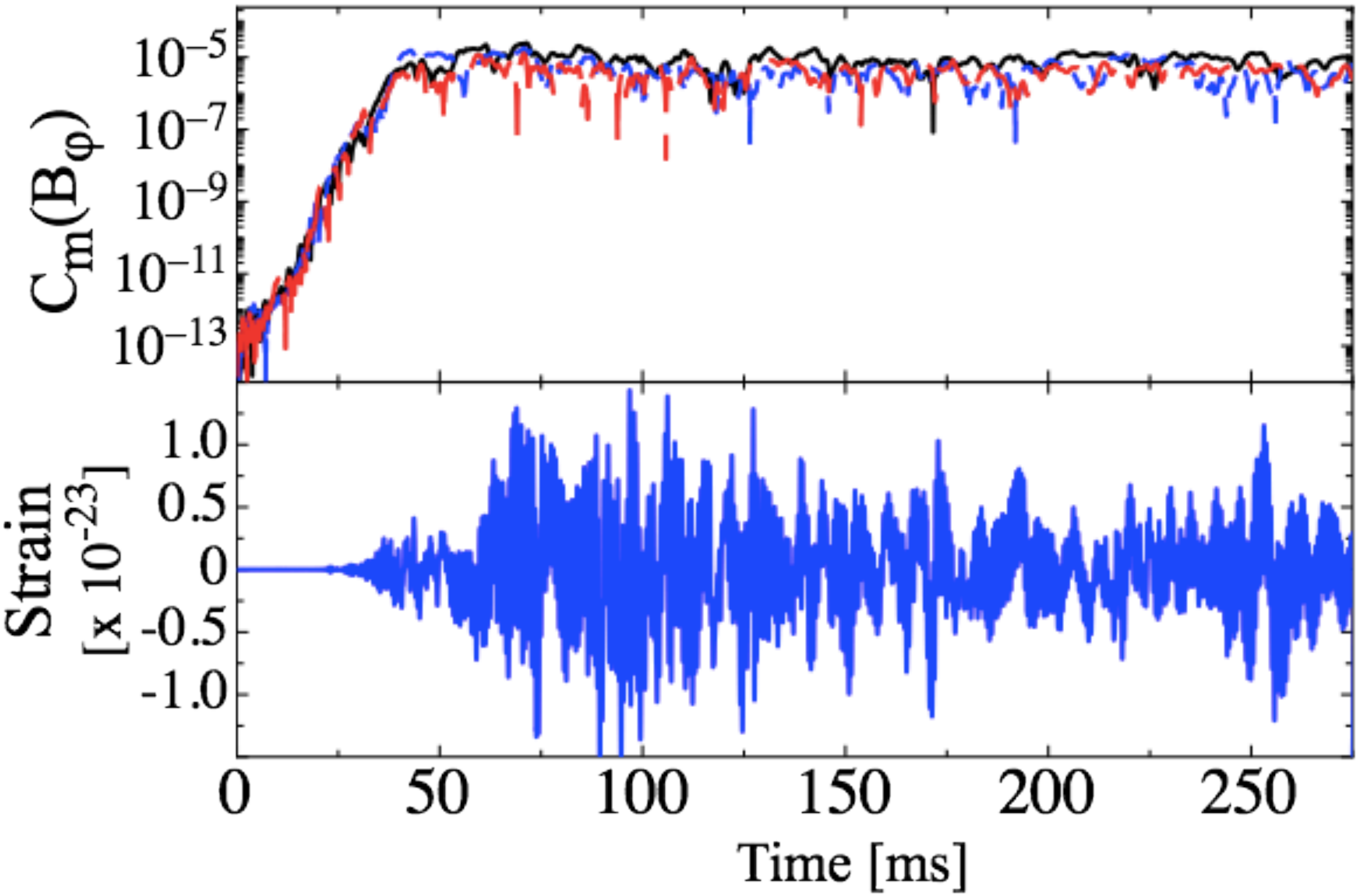
Lasky, Zink, Kokkotas, Glampedakis ApJL (2011)





Gravitational Waves from Magnetars

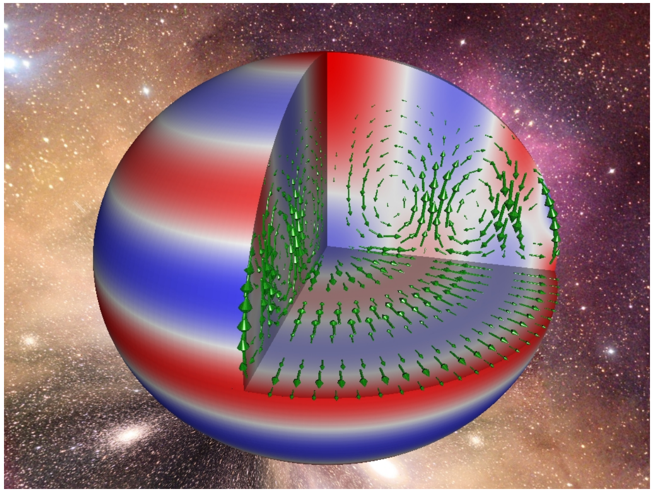
Zink, Lasky, KK (2012)



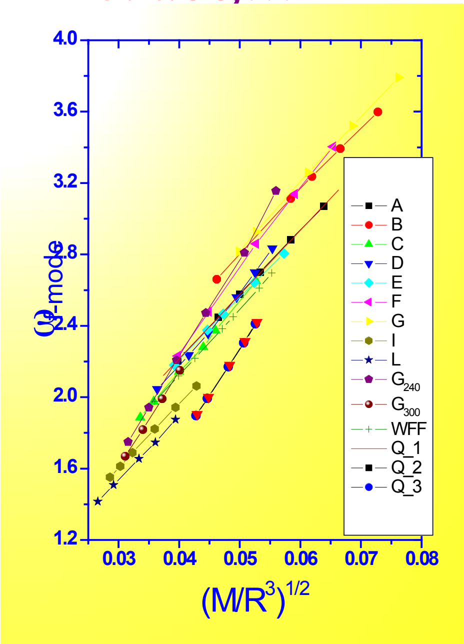
Gravitational Wave Asteroseismology

Oscillation patterns can reveal the internal structure of neutron stars :

- ✓ **mass,**
- ✓ **radius,**
- ✓ **EoS,**
- ✓ **rotation,**
- ✓ **B-field,**
- ✓ **crust,…**



Andersson,Kokkotas 1996,1998,2001



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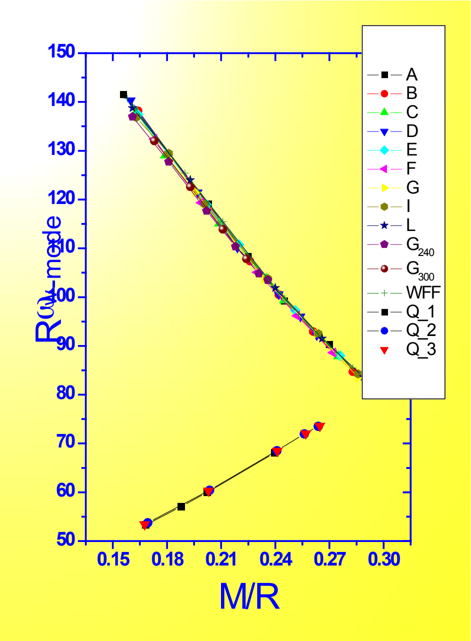
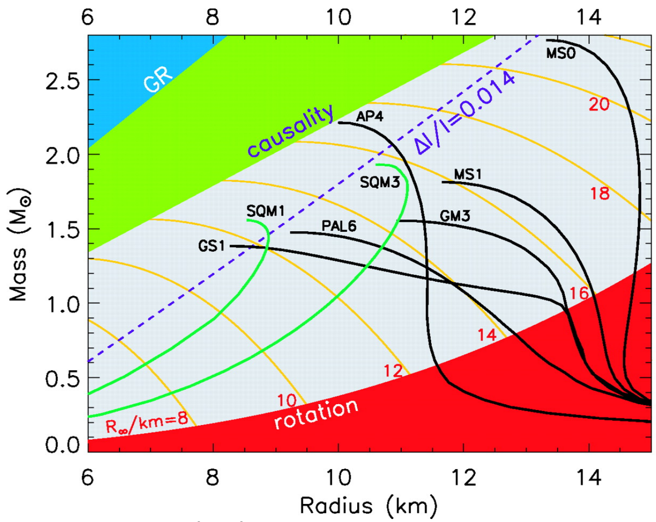




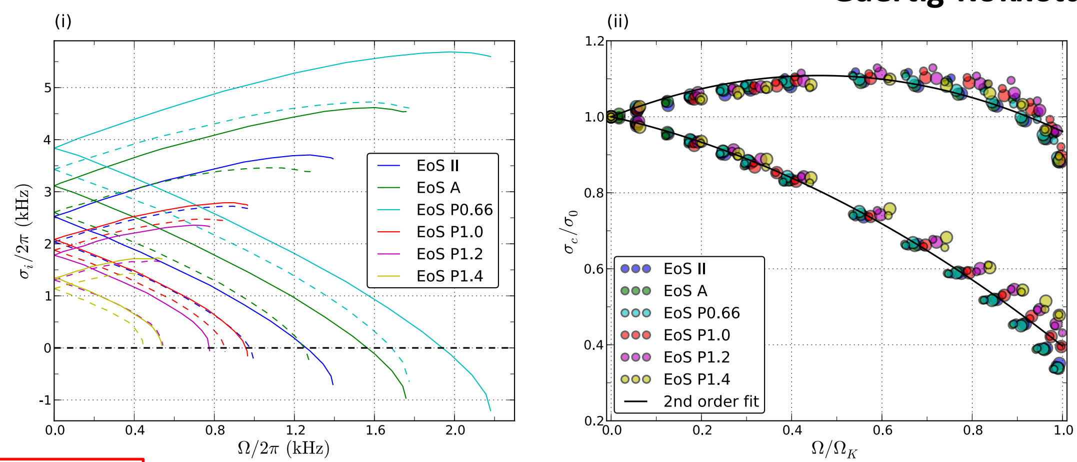
Lattimer+Prakash 2007

f-modes: Asteroseismology

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

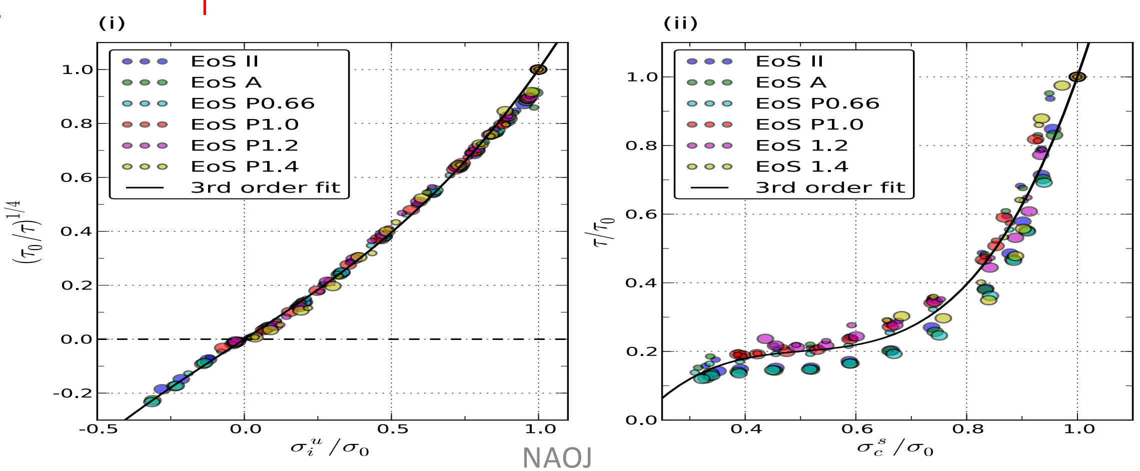
Gaertig-Kokkotas 2008, 2010, 2011

Frequency



Cowling Approximation

Damping/Growth time



Asteroseismology: Realistic EoS

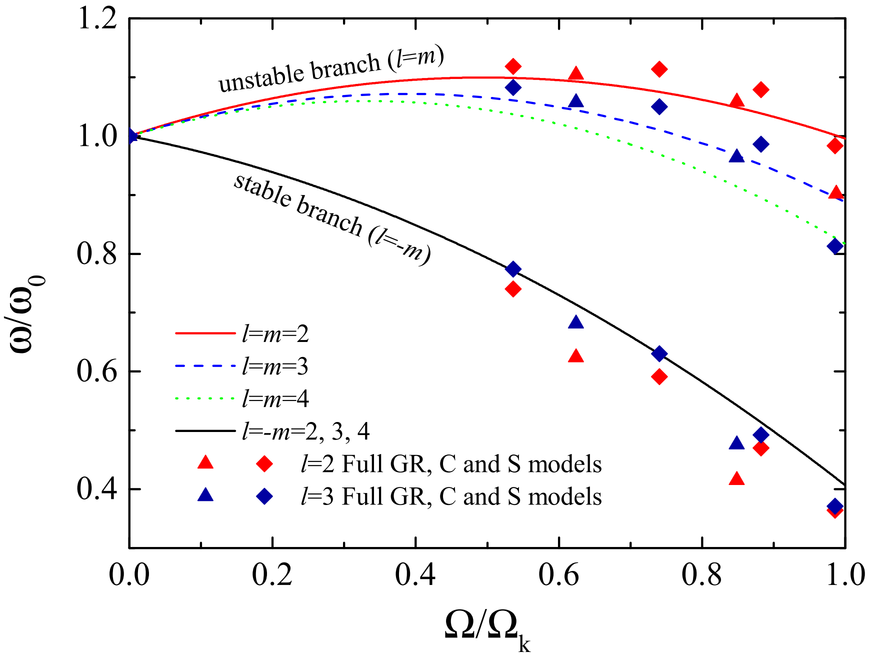
Doneva, Gaertig, KK, Krüger (2013)

$$\left(\frac{\omega_c}{\omega_0}\right)_{\ell=2,3,4} \approx f\left(\frac{\Omega}{\Omega_K}\right)$$

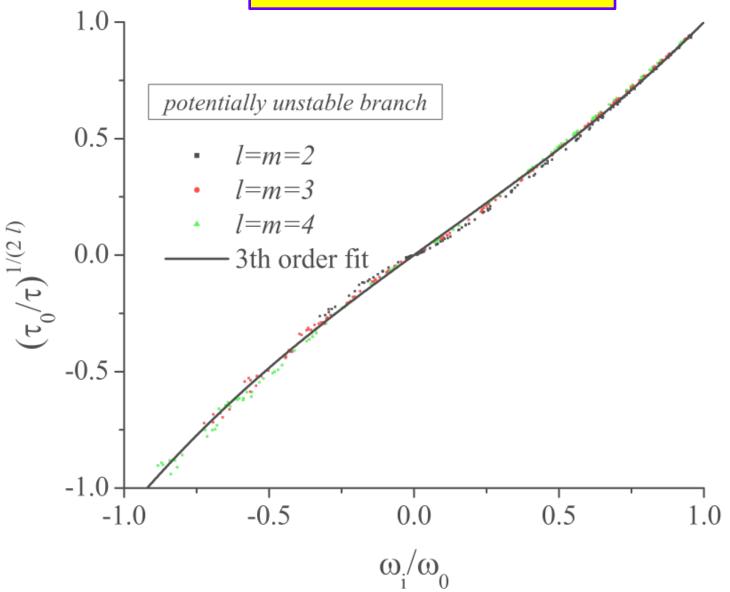
Nearly "universal" fitting formulae for :

- **the frequencies**
- **the damping times**
- **Independent of GR or Cowling**

$$\left(\frac{\tau_0}{\tau}\right)^{1/2\ell} \approx f\left(\frac{\omega_i}{\omega_0}\right)$$



Oscillation frequencies



Damping/Growth Times

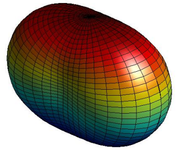
Asteroseismology

Stable Branch

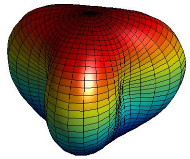
$$\frac{\omega_c^s}{\omega_0} = 1 - 0.235\left(\frac{\Omega}{\Omega_K}\right) - 0.358\left(\frac{\Omega}{\Omega_K}\right)^2$$

Unstable Branch

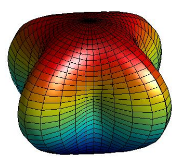
$$\frac{\omega_{c\ l=2}^u}{\omega_0} = 1 + 0.402\left(\frac{\Omega}{\Omega_K}\right) - 0.406\left(\frac{\Omega}{\Omega_K}\right)^2$$



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



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



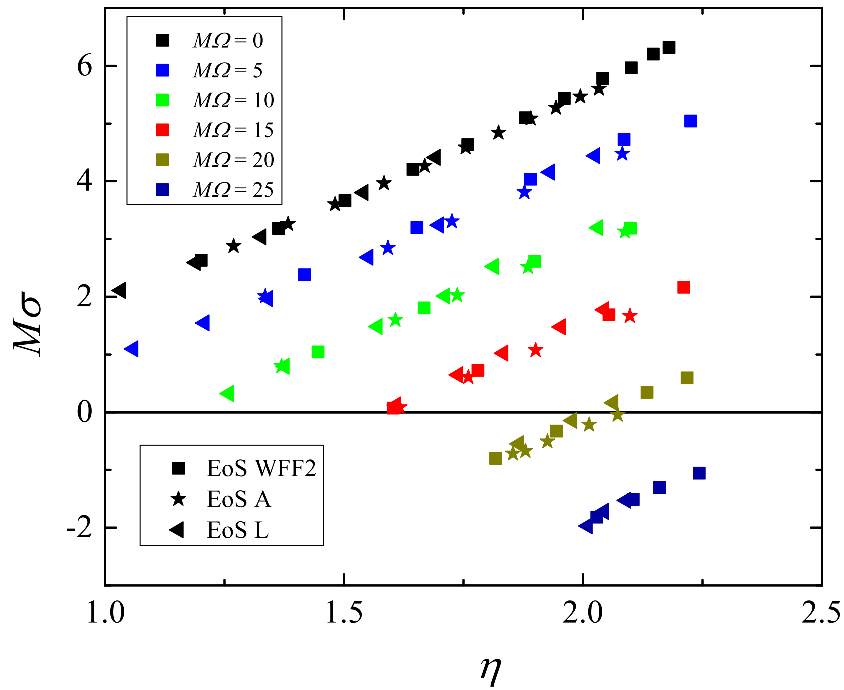
Unstable Branch

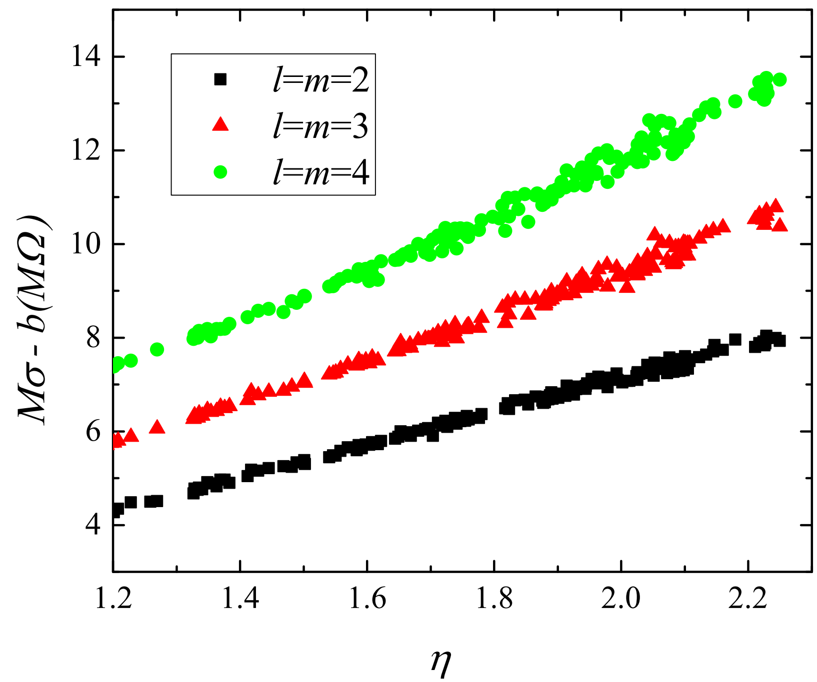
$$\frac{\tau_0}{\tau} = \mathrm{sgn}(\omega_i^u)\left(0.900\left(\frac{\omega_i^u}{\omega_0}\right) - 0.057\left(\frac{\omega_i^u}{\omega_0}\right)^2 + 0.157\left(\frac{\omega_i^u}{\omega_0}\right)^3\right)^{2l}$$

Doneva, Gaertig, KK, Krüger (2013)

Asteroseismology: alternative scalings

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



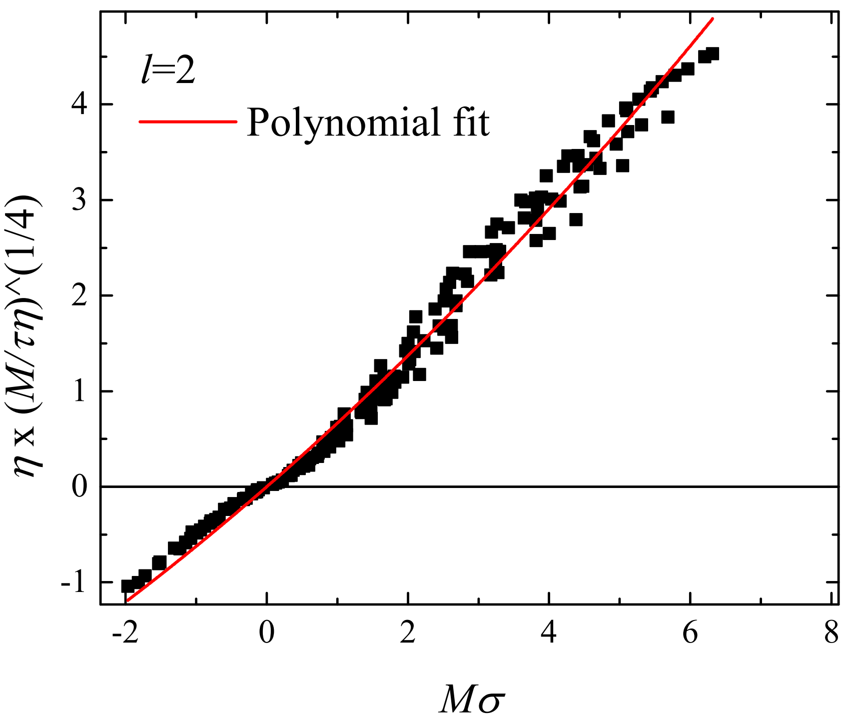


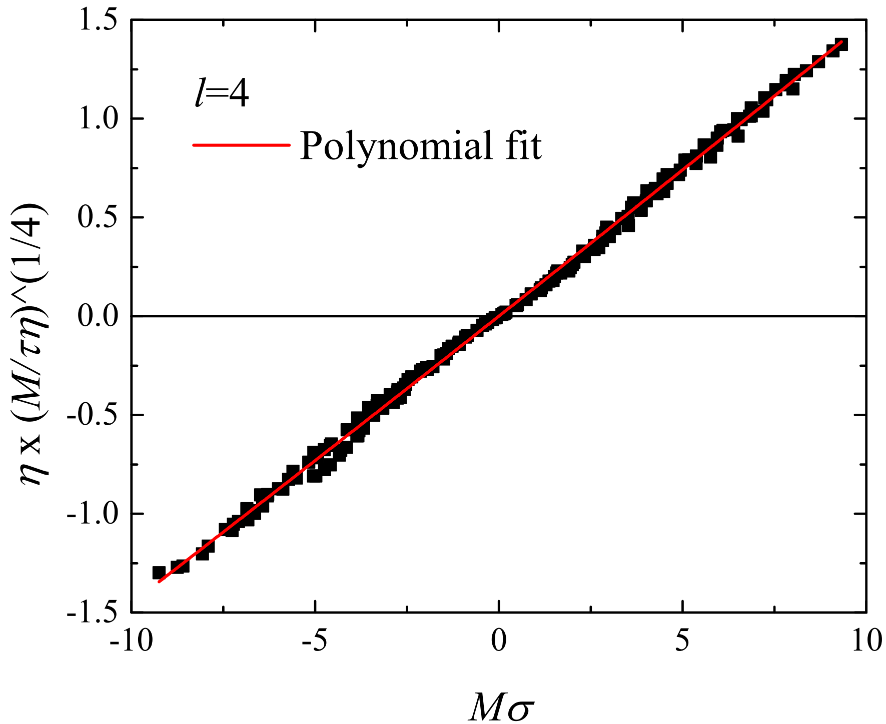
The l = 2 f-mode oscillation frequencies as functions of the parameter η

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

Doneva-Kokkotas 2015

Asteroseismology: alternative scalings



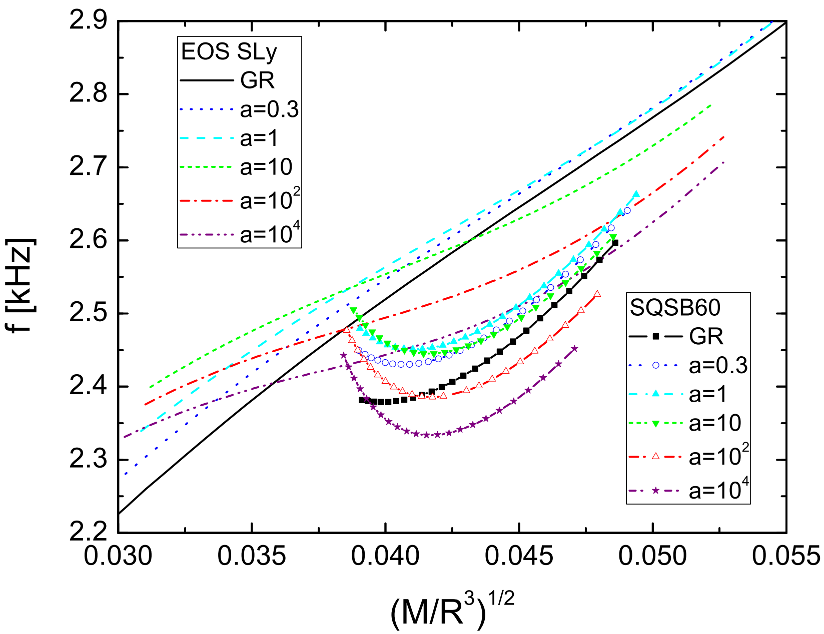


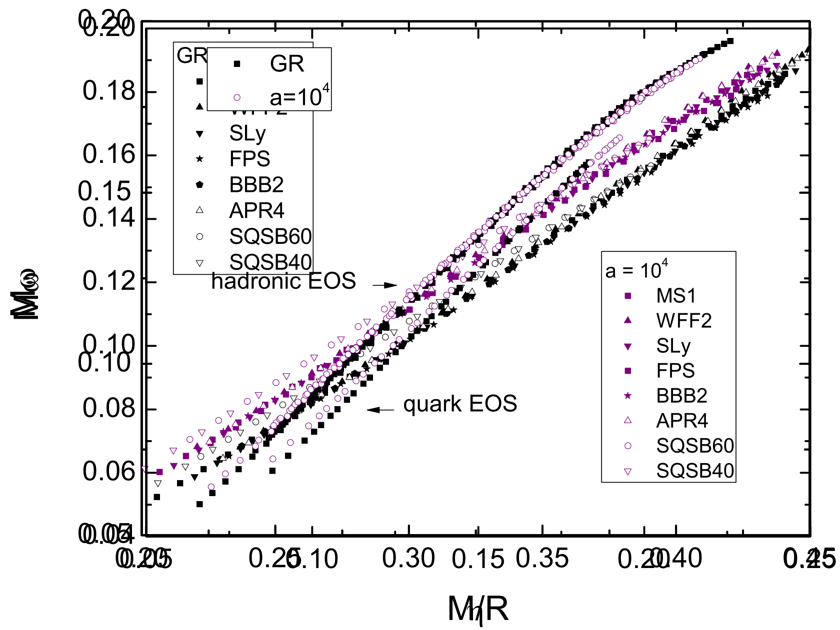
The **normalized damping time** $\eta\left(\frac{M}{\textcolor{red}{\tau}\eta^2}\right)^{(1/2\ell)}$ where $\eta = \sqrt{M^3 / I}$

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

Doneva-KK 2015

Asteroseismology:
Alternative Theories of Gravity





- The maximum deviation between the f-mode frequencies in GR and R^2 gravity is up to 10% and depends on the value of the R^2 gravity parameter *a*.
- Alternative normalizations show nicer relations

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

The CFS instability

Chandrasekhar 1970: Gravitational waves lead to a secular instability

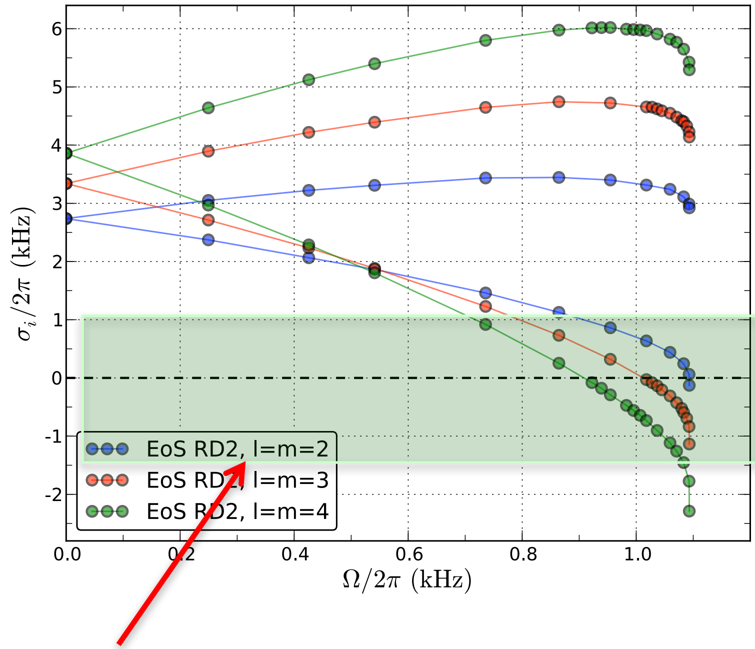
Friedman & Schutz 1978: The instability is generic, modes with sufficiently large *m* are unstable.

A neutral mode of oscillation signals the onset of CFS instability

- ✓ Radiation drives a mode unstable if the mode pattern moves backwards according to an observer on the star *($J_{rot}<0$)*, but forwards according to someone far away *($J_{rot}>0$)*.
- ✓ They radiate positive angular momentum, thus in the rotating frame the angular momentum of the mode increases leading to an increase in mode's amplitude.

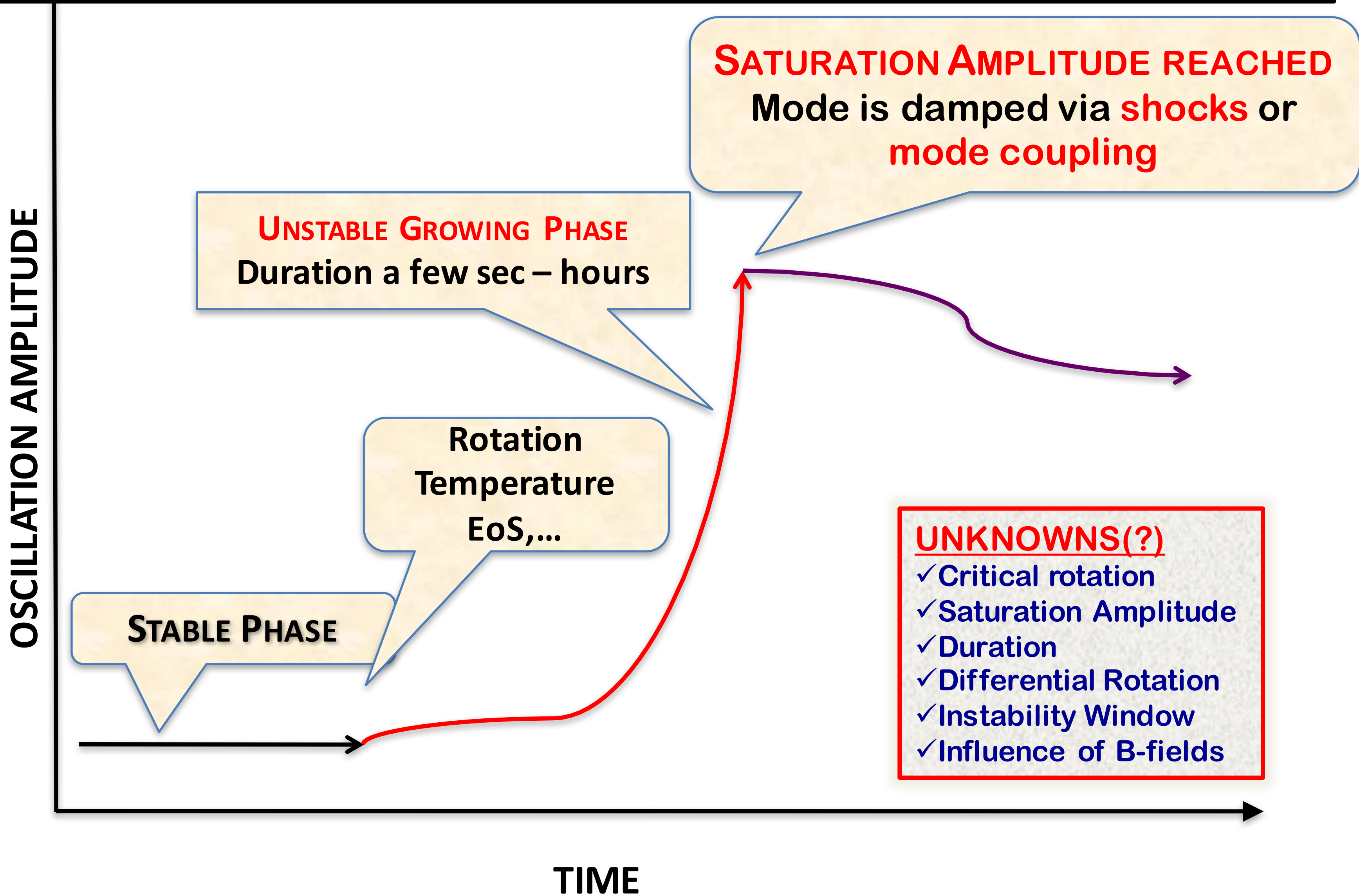
$$\frac{\omega_{\text{in}}}{m} = -\frac{\omega_{\text{rot}}}{m} + \Omega$$

Gaertig+Kokkotas 2008



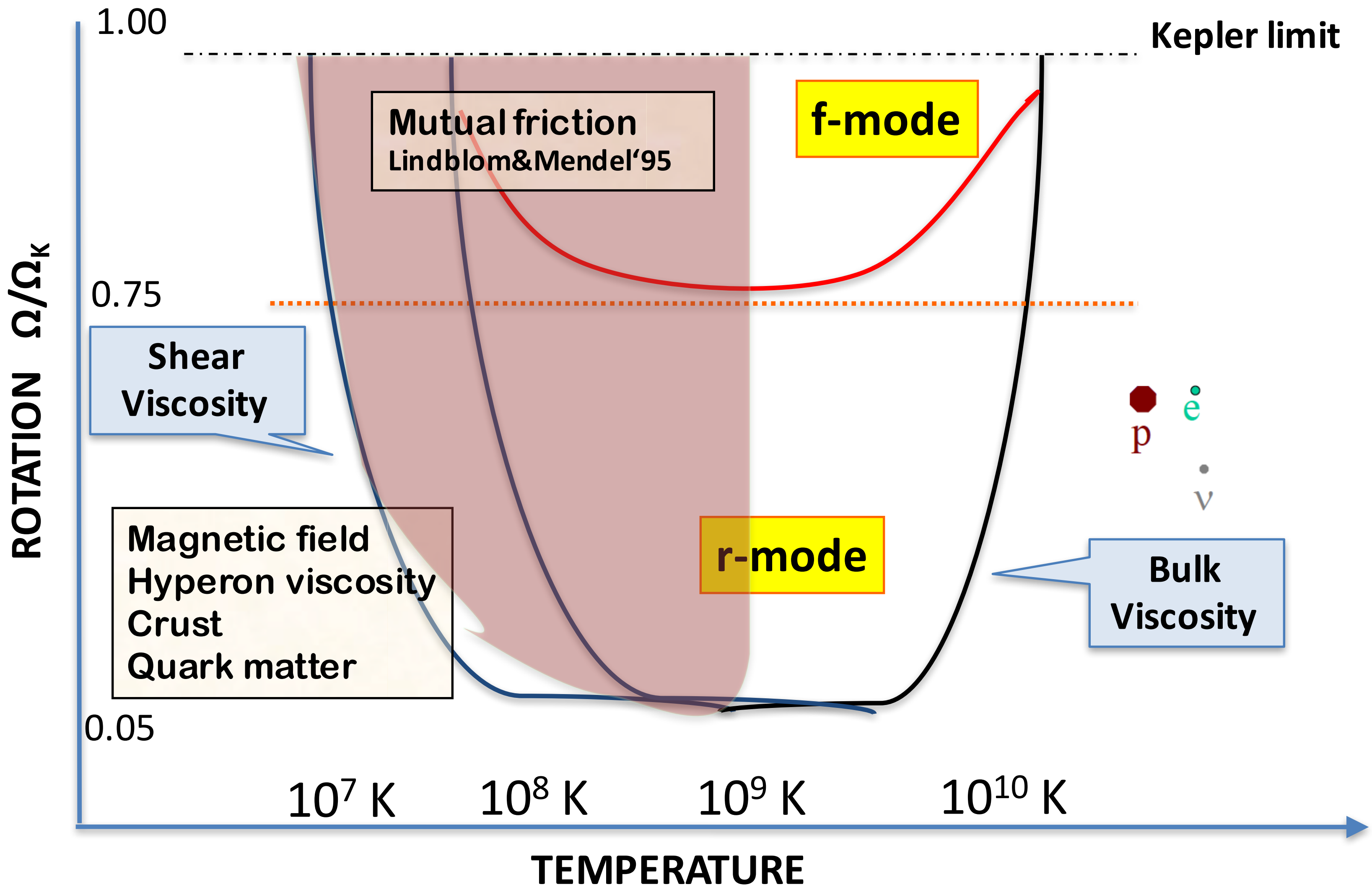
LIGO/Virgo/GEO/KAGRA/ET band

The Excitation of Secular Instabilities



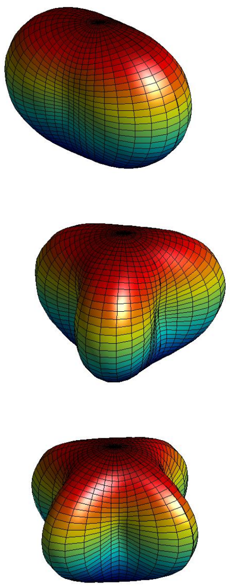
UNKNOWNS(?)
- ✓Critical rotation
- ✓Saturation Amplitude
- ✓Duration
- ✓Differential Rotation
- ✓Instability Window
- ✓Influence of B-fields

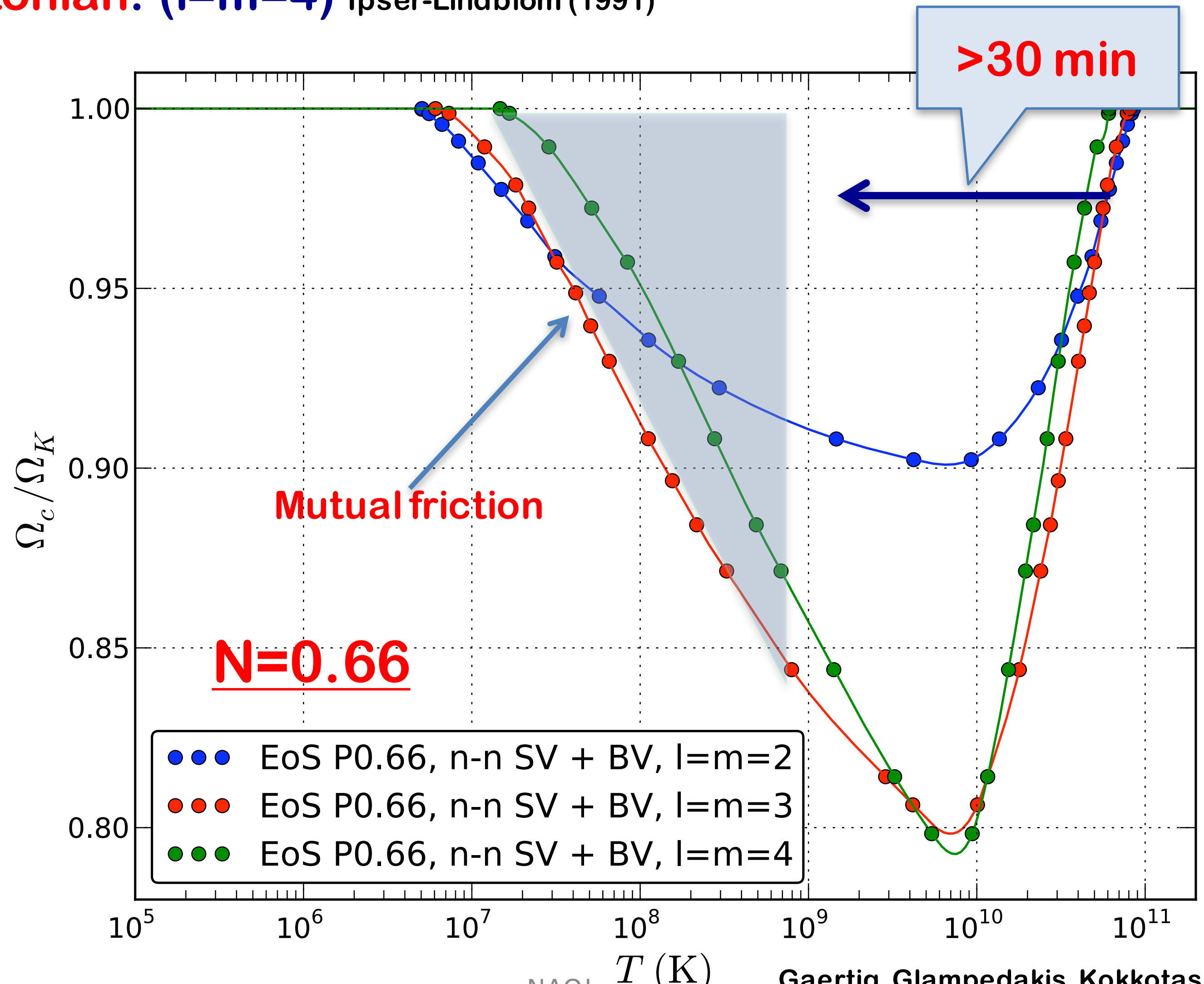
The CFS Instability Window



Instability Window

- ✓ For the first time we have the window of f-mode instability in GR
- ✓ Newtonian: (l=m=4) Ipser-Lindblom (1991)





Gaertig, Glampedakis, Kokkotas, Zink (2011)

Saturation of the Instability

Parametric Resonance

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

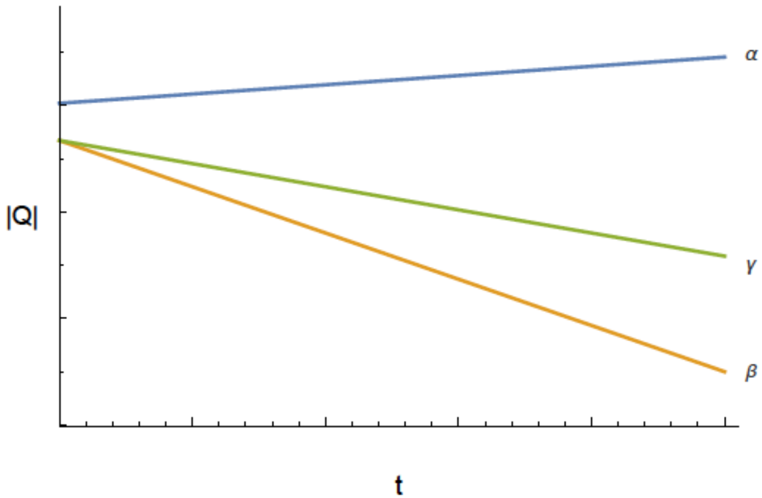
Detuning $\Delta\omega$

Coupling coefficient $\mathcal{H}$

Growth/damping rates γ_i

Detuning $\Delta\omega \equiv \omega_\alpha - \omega_\beta - \omega_\gamma \approx 0$ $\boxed{\text{resonance condition}}$

No mode coupling: $\mathcal{H} = 0$ or $\Delta\omega \gg 0$



- Modes evolve independently
- No non-linear interaction

$$\dot{Q}_\alpha = \gamma_\alpha Q_\alpha$$
$$\dot{Q}_\beta = \gamma_\beta Q_\beta$$
$$\dot{Q}_\gamma = \gamma_\gamma Q_\gamma$$

Pnigouras, Kokkotas (2015)

Saturation of the Instability

Parametric Resonance

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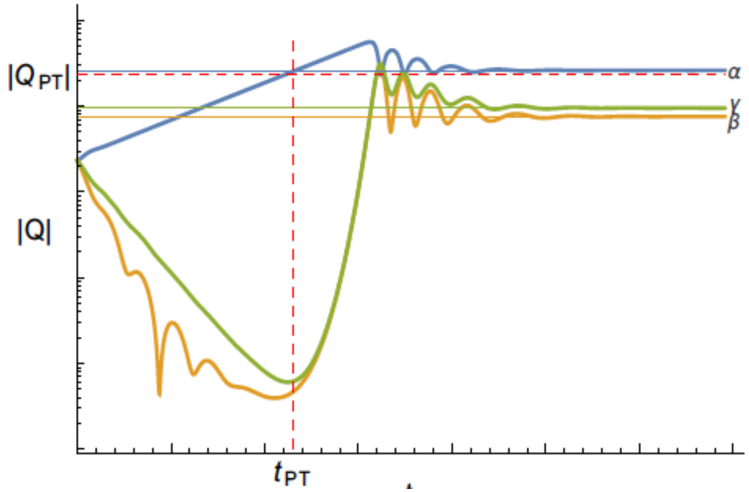
Coupling coefficient $\mathcal{H}$

Growth/damping rates γ_i

Detuning $\Delta\omega \equiv \omega_\alpha - \omega_\beta - \omega_\gamma \approx 0$ $\boxed{\text{resonance condition}}$

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)

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 $\Delta\omega$

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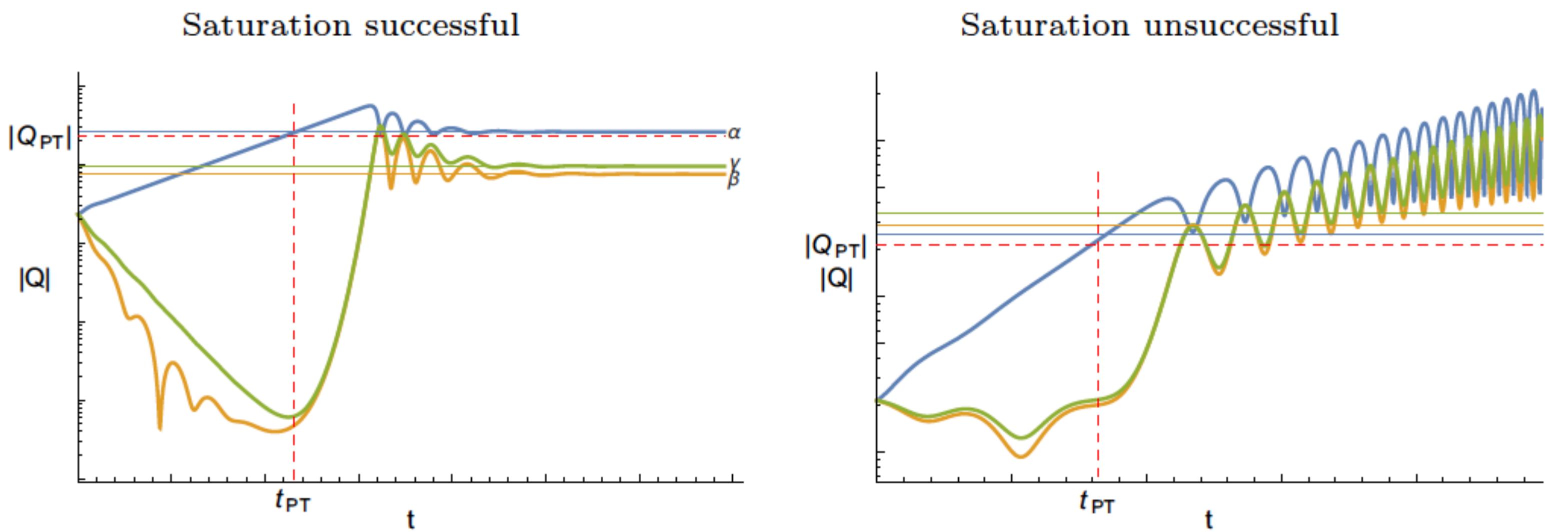
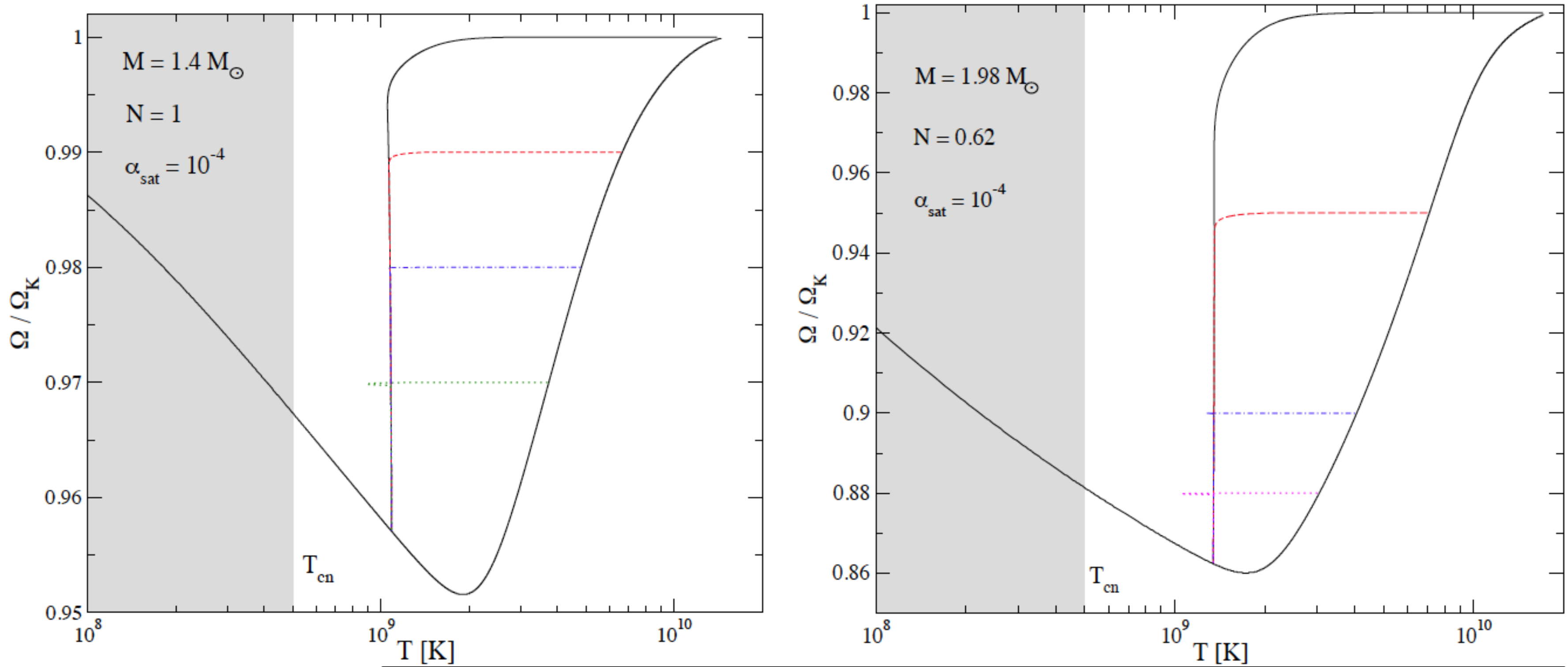


Pnigouras, Kokkotas (2015)

Evolution of a nascent (unstable) NS

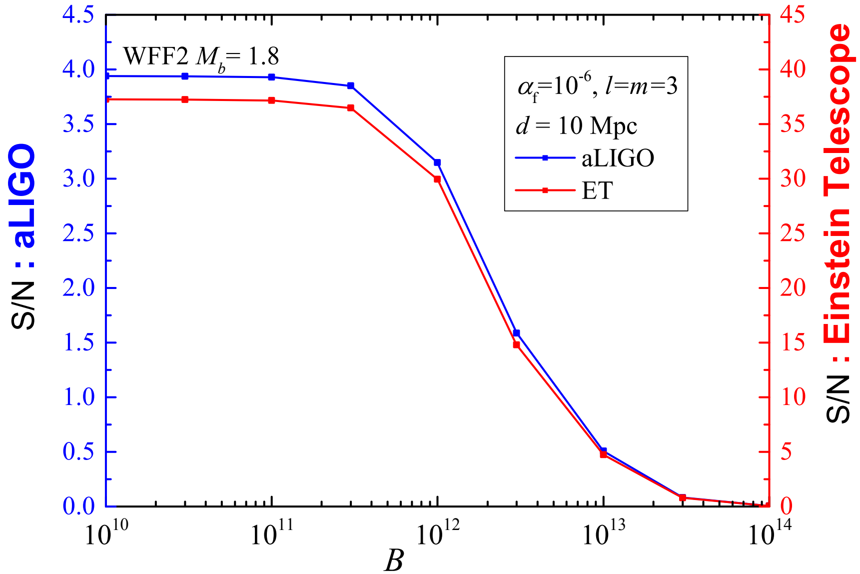


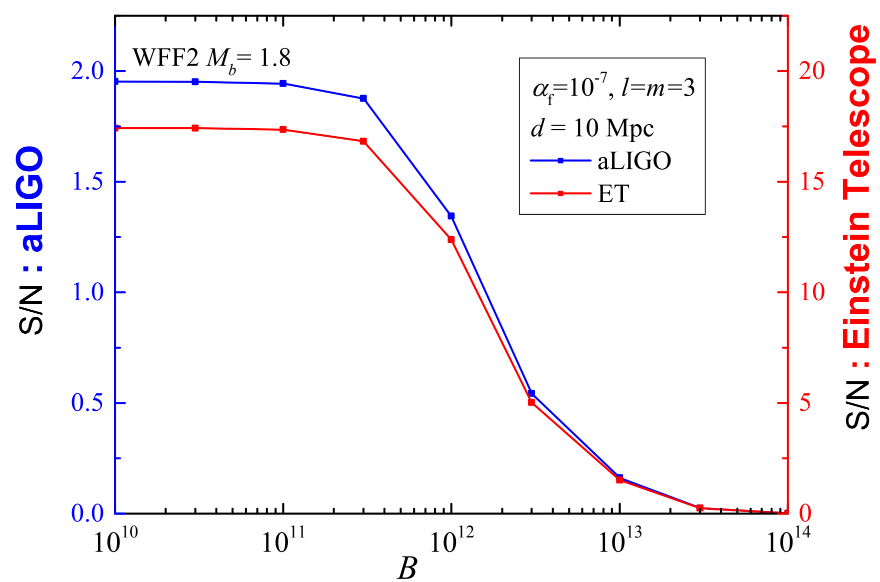
Mutual Friction plays NO ROLE for the f-mode instability

Procedure as described in Owen etal 1998 & Anderson, Jones, KK 2002

Passamonti-Gaertig-KK-Doneva (2013)

Evolution of a nascent (unstable) NS





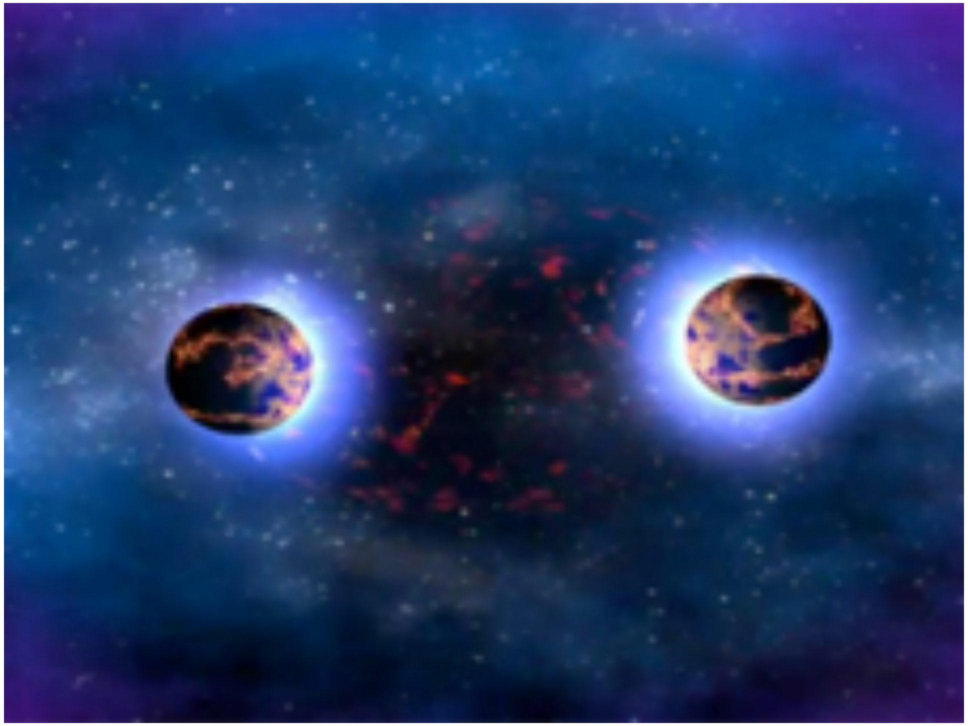
The instability can be potentially observed by events in Virgo cluster

BUT

- Event rate is unknown
- Competition with r-mode and magnetic field slow-down
- Saturation amplitude is varying during the procces

Passamonti-Gaertig-Kokkotas-Doneva (2013)

A GRAVITATIONAL WAVE AFTERGLOW IN BINARY NEUTRON STAR MERGERS



Binary Neutron Star Mergers
the standard scenario

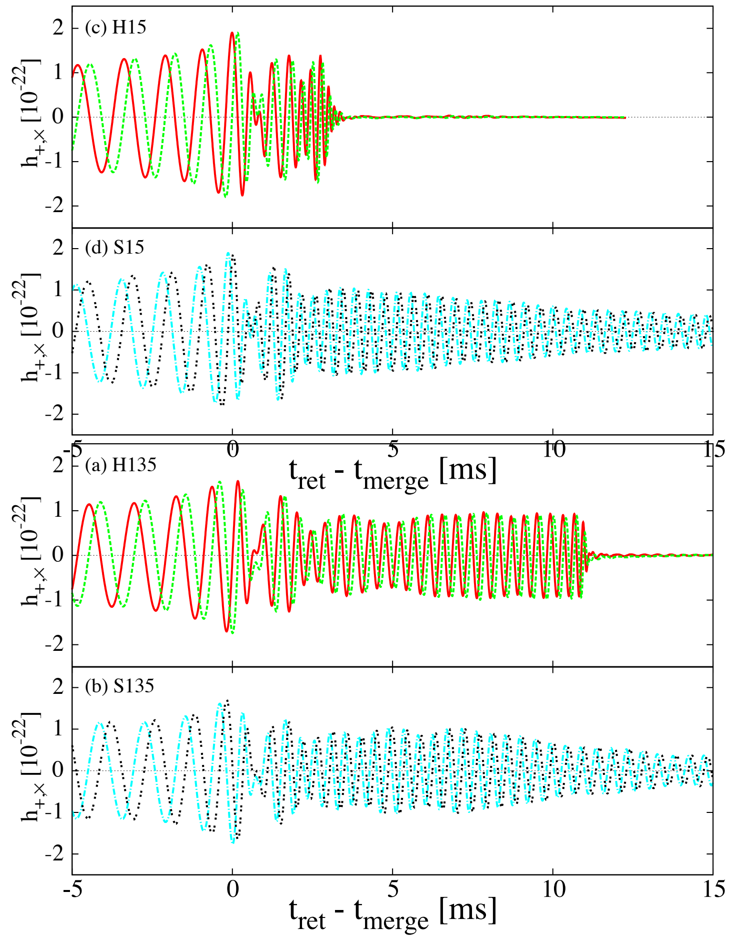
I. After the merging the final body most probably will be a supramassive NS (2.5-3 $M_\odot$)

II. The body will be differentially rotating

III. The “averaged” magnetic field will amplified due to magnetic field instabilities (up to 3-4 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 Equation of State (EOS)

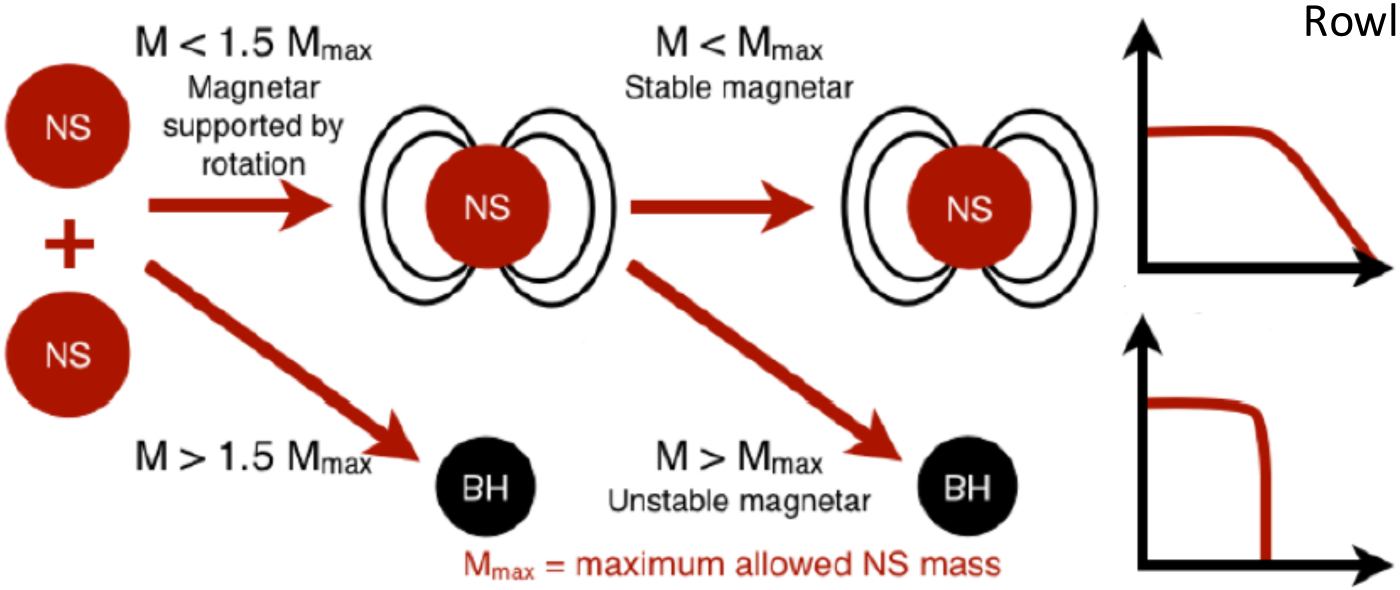


Kiuchi, Sekiguchi, Kyutoku, Shibata2012

Post-Merger Scenario

Three different outcomes of the merger of a BNS merger

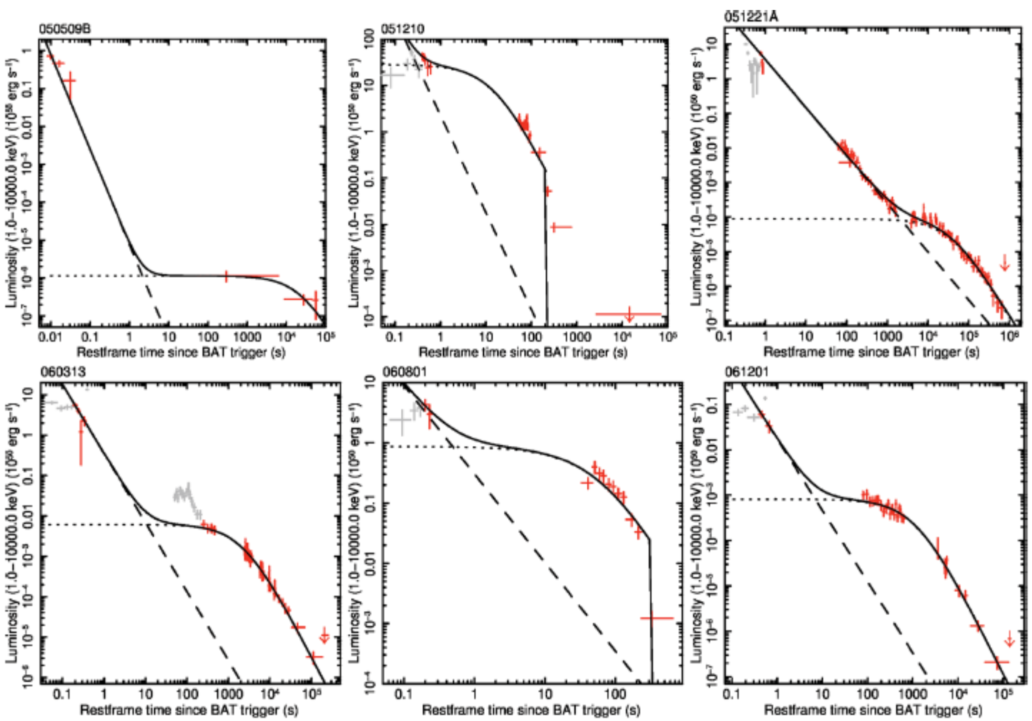
Rowlinson 2013



- ✓ The outcome is dependent upon the mass (M) of the central object formed and the maximum possible mass of a neutron star (M_{max}).
- ✓ On the right are sketches of the expected light-curves if a stable (top) or an unstable magnetar (bottom) is formed.

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.

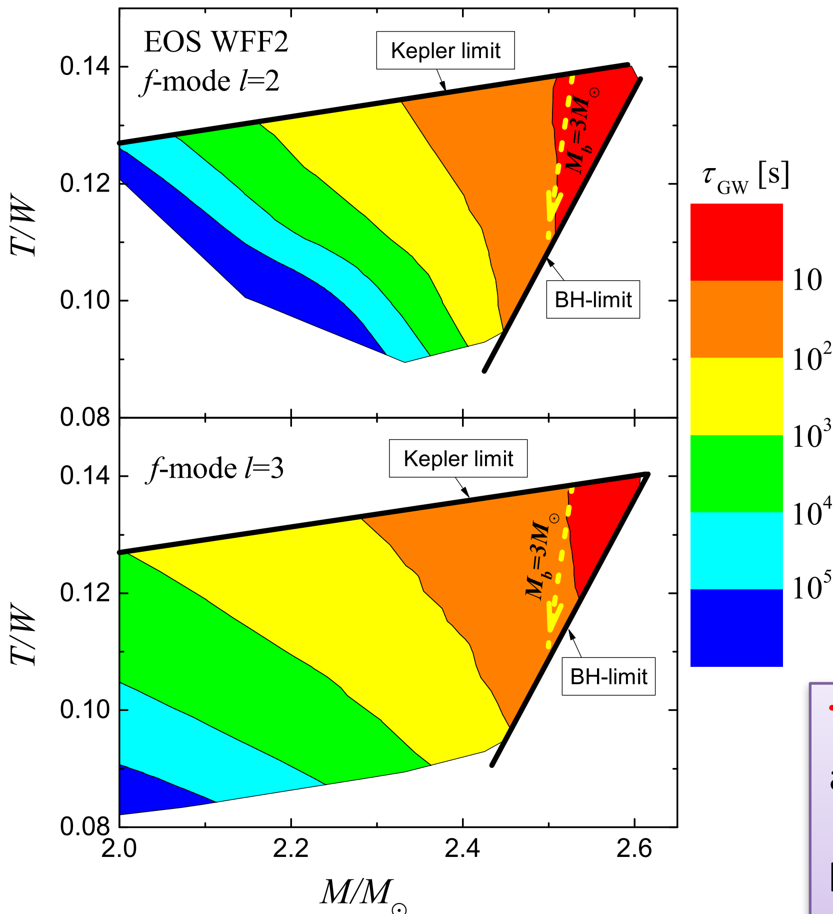


Rowlinson, O’Brien, Metger, Tanvir, Levan 2013

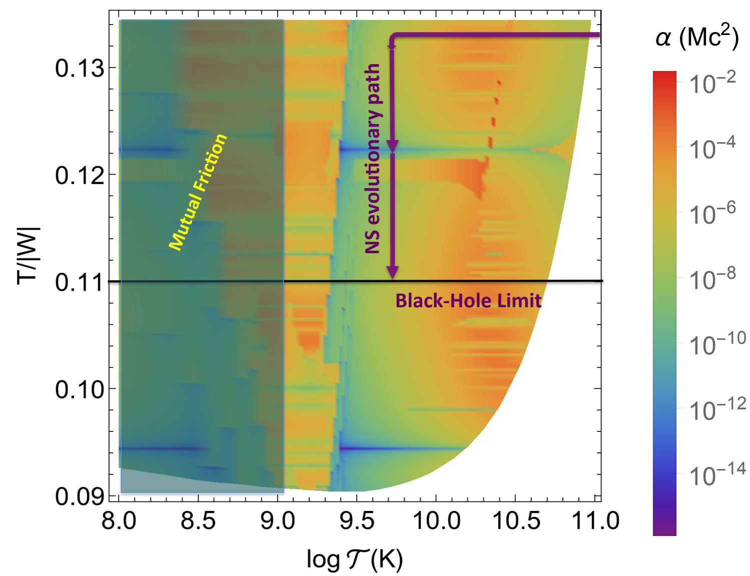
Post-Merger NS: secular instability

Doneva-KK-Pnigouras 2015

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



The evolution into the instability window



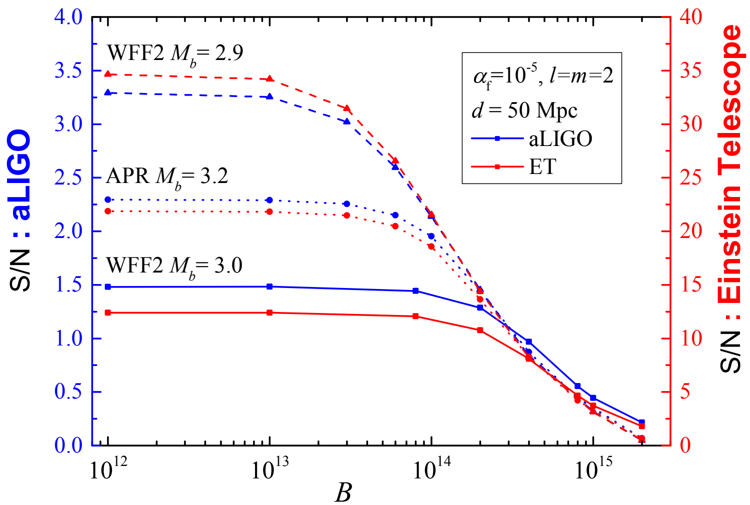
The detailed evolution depends:

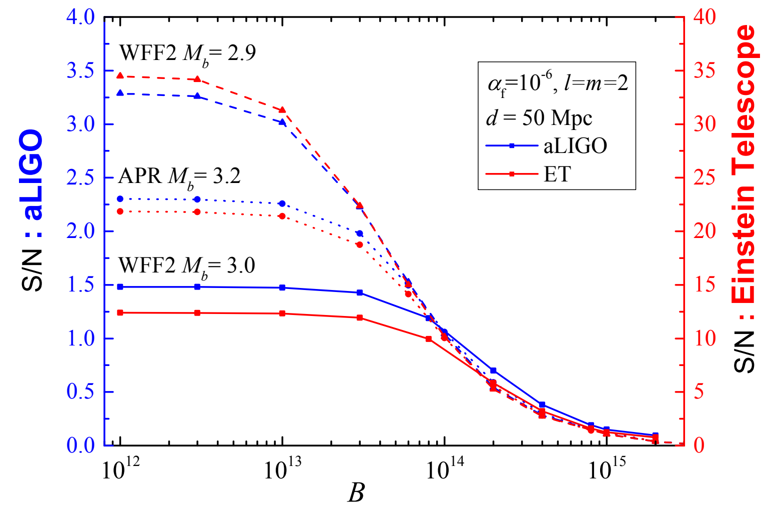
a) Strength of the **magnetic field** (averaged may reach $10^{15\text{-}16}$ G !)

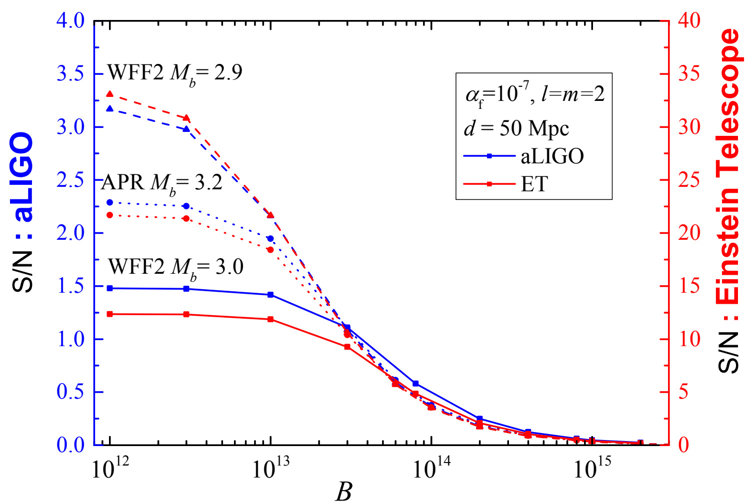
b) Equation of state of the post-merger neutron star

c) Fine details of **the non-linear dynamics** (three mode coupling, shock waves, wave breaking)

Post-Merger NS: secular instability







Competition between the B-field and the secular instability

GW frequencies:

WW2a: 920-1000 Hz

APR: 370–810 Hz

WFF2b: 600–780 Hz

Doneva-KK-Pnigouras 2015

Conclusions

- ✓ The influence of alternative/extended theories of gravity on NS parameters is much more pronounced for fast rotation.
- ✓ Difficult to set constraints on theories using measurement of the neutron star M and R alone, until the EOS can be determined with smaller uncertainty.

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- ✓ Asteroseismology for fast rotating stars is possible
- ✓ Asteroseismology for magnetars is promising (!)

Conclusions

- ✓ The influence of alternative/extended theories of gravity on NS parameters is much more pronounced for fast rotation.
- ✓ Difficult to set constraints on theories using measurement of the neutron star M and R alone, until the EOS can be determined with smaller uncertainty.

- ✓ Asteroseismology for fast rotating stars is possible
- ✓ Asteroseismology for magnetars is promising

- ✓ f-mode instability can be potentially a good source for GWs for supramassive NS
- ✓ The efficincy depends on the saturation amplitude and strength of B-field.