Asteroseismology with ET

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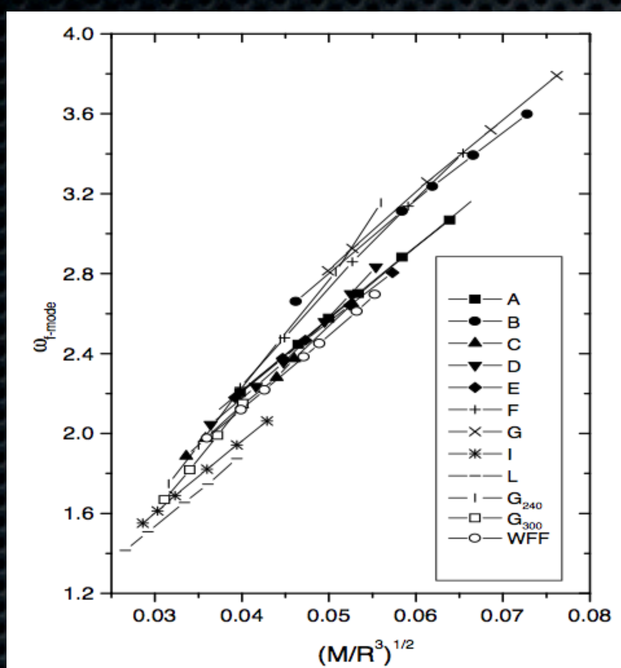
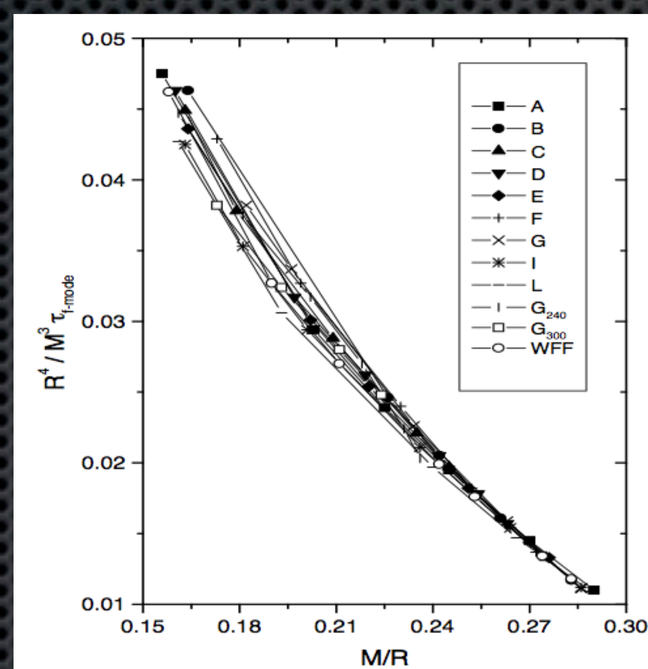
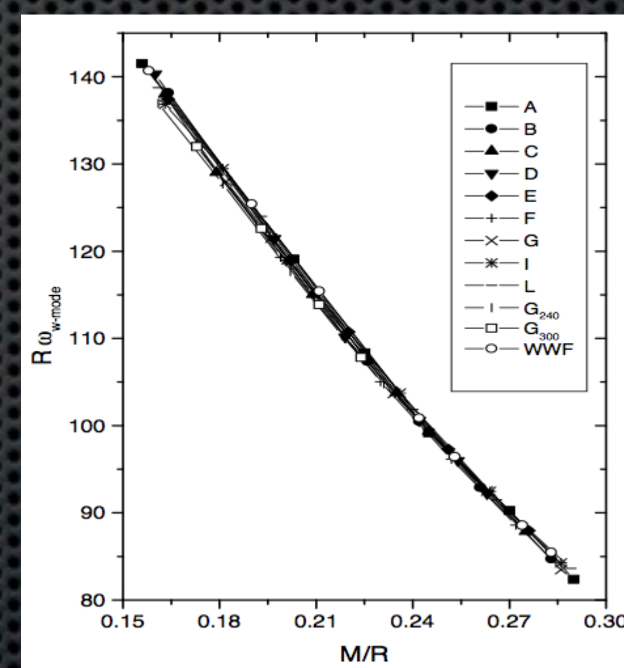
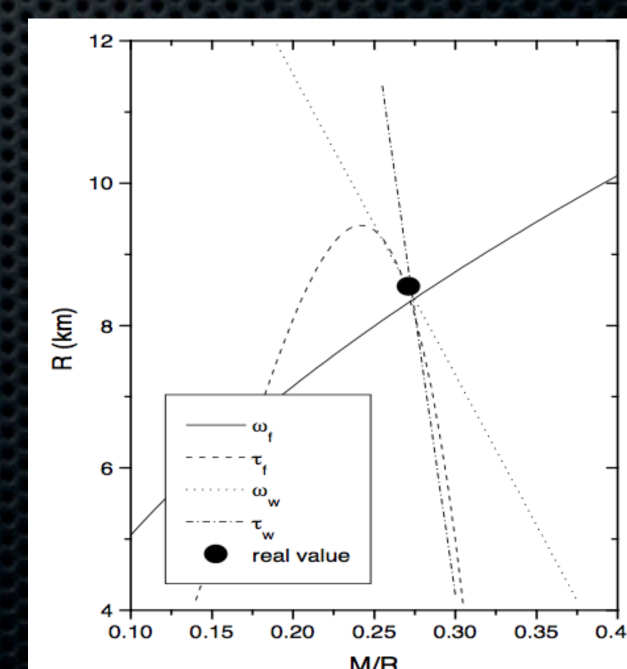
Asteroseismology with gravitational waves as a tool to probe the inner structure of NS

- neutron stars build from single-fluid, normal matter









Andersson, Kokkotas (1996, 1998)

Benhar, Berti, Ferrari(1999)

Benhar, Ferrari, Gualtieri(2004)

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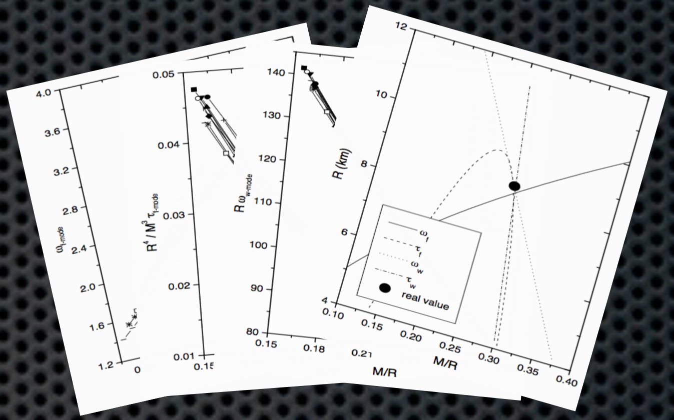
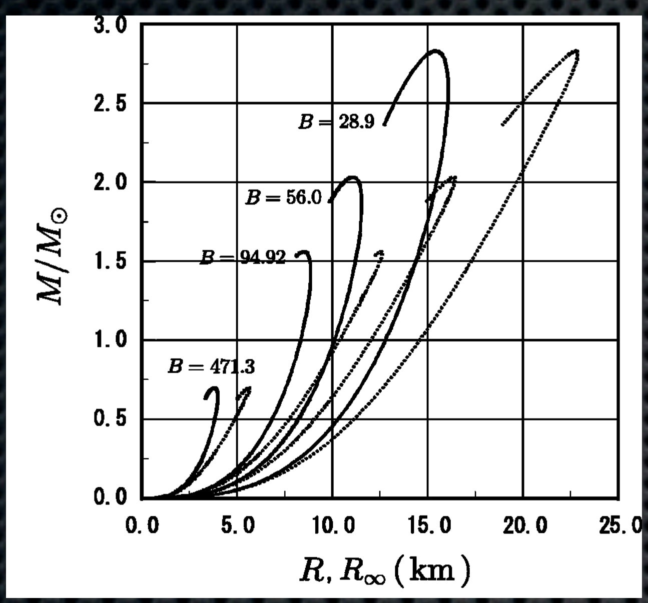
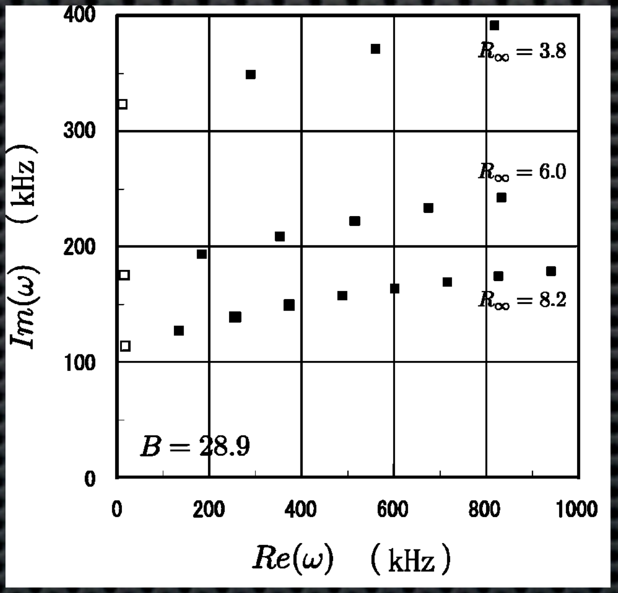
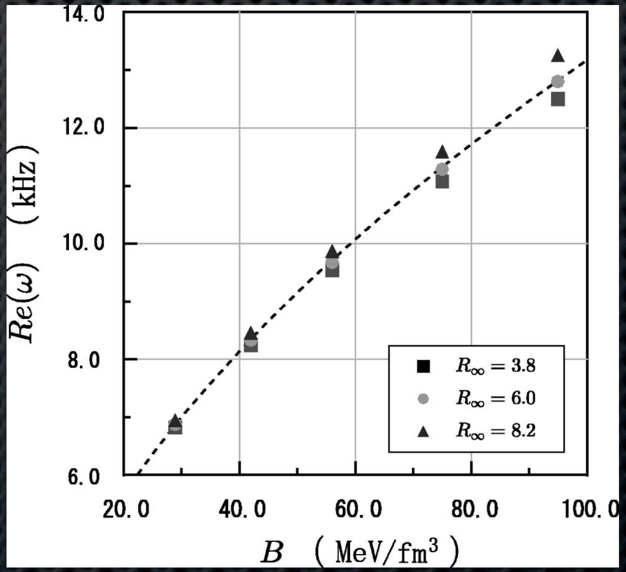
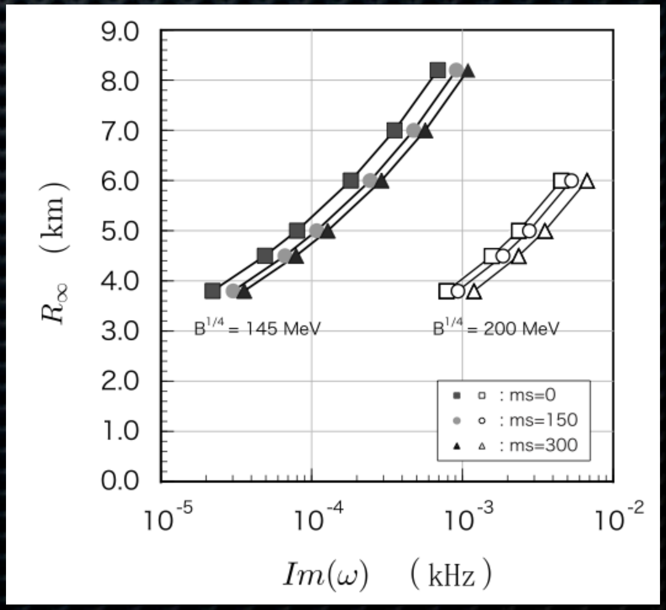
- strange stars composed of deconfined quarks











Sotani, Harada (2004)

Benhar, Ferrari, Gualtieri, Marassi (2007)

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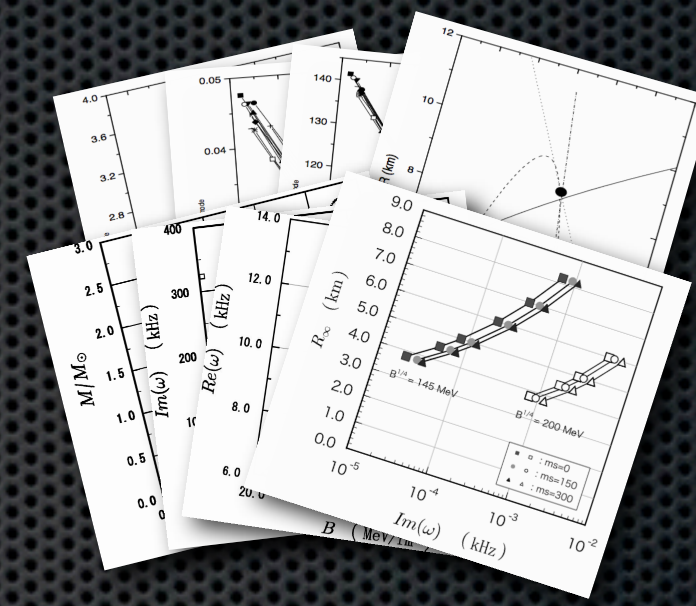
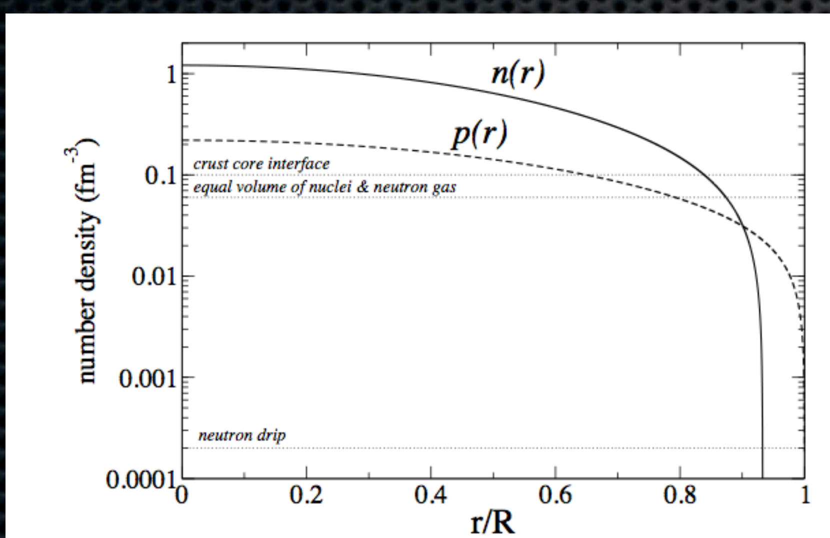
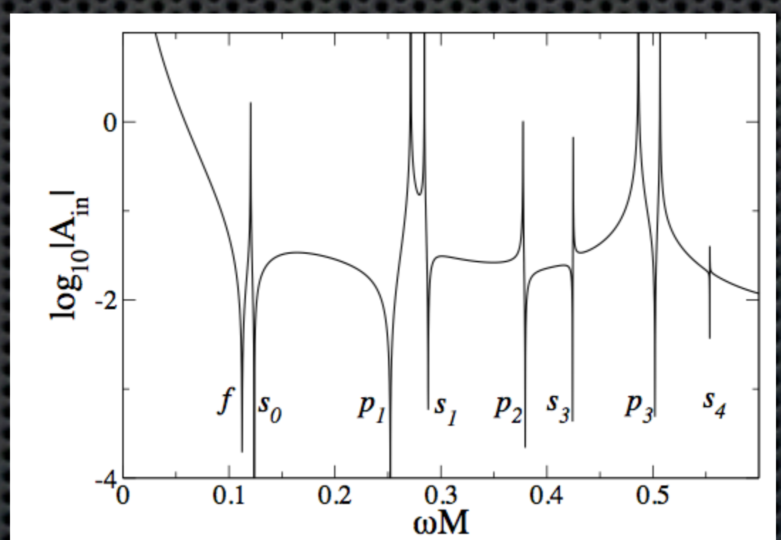
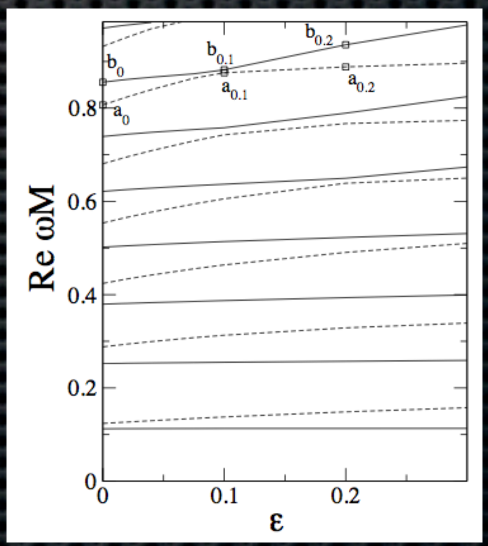
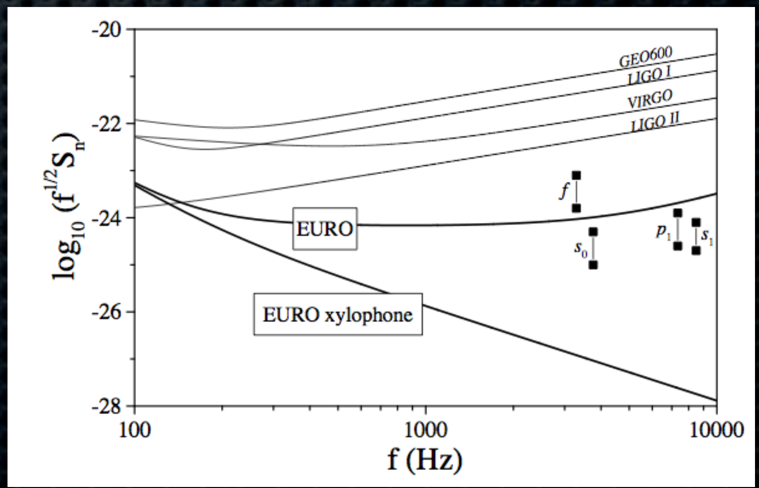


- neutron stars build from single-fluid, normal matter
- strange stars composed of deconfined quarks
- superfluid neutron stars





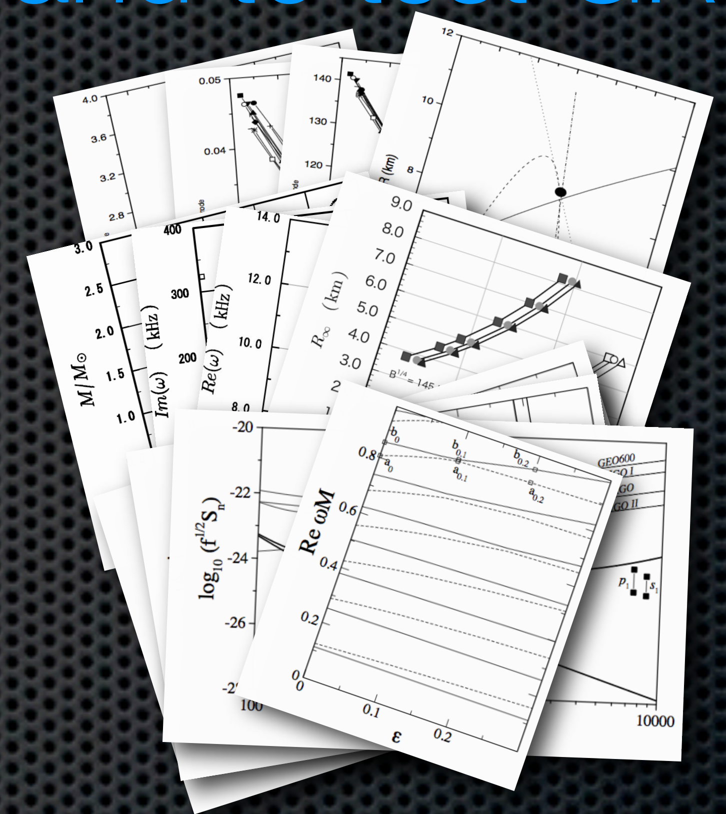




Andersson, Comer (2001)

Andersson, Comer, Langlois (2003)

Asteroseismology with gravitational waves as a tool to probe the inner structure of NS and to test GR



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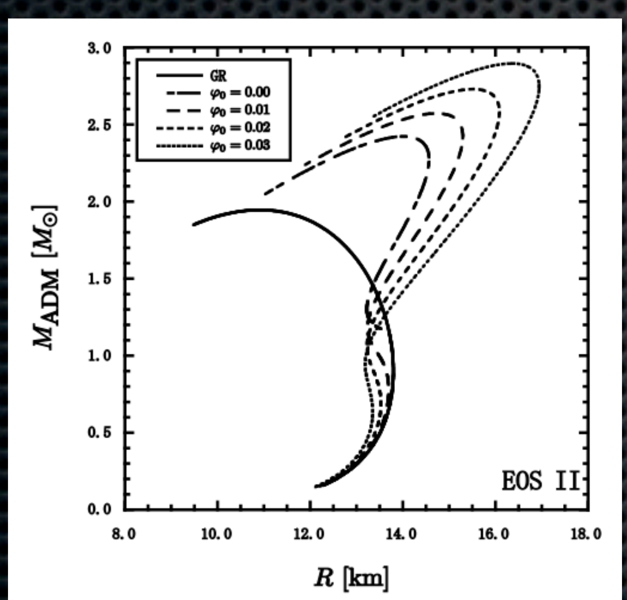
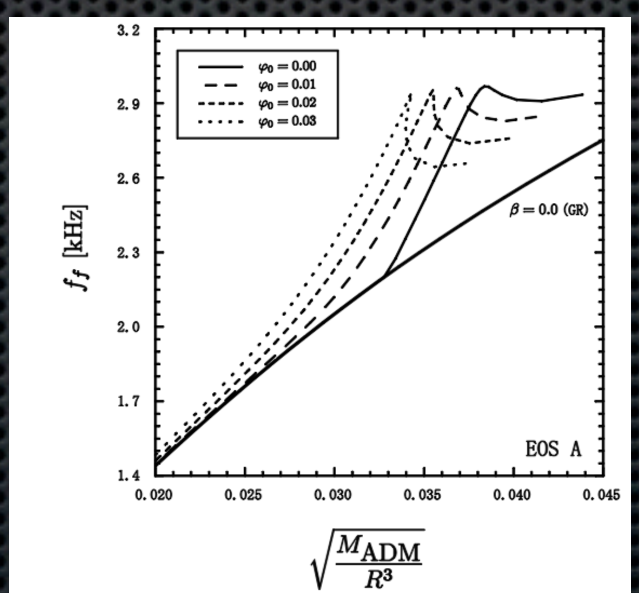
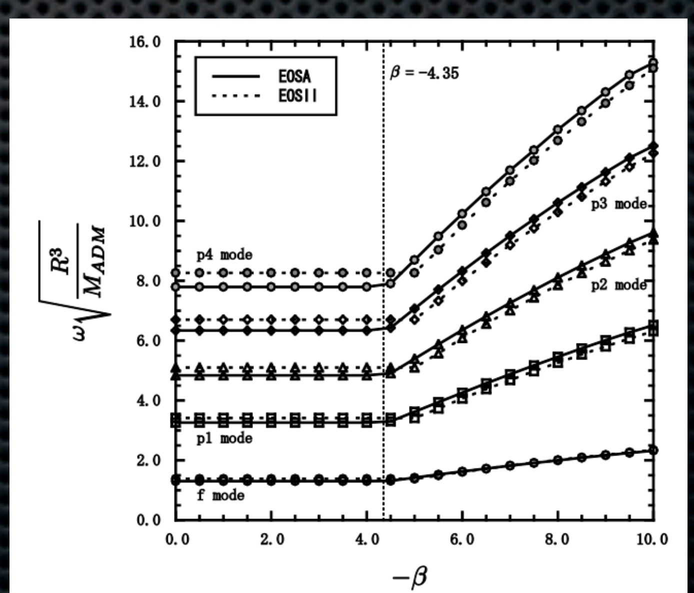
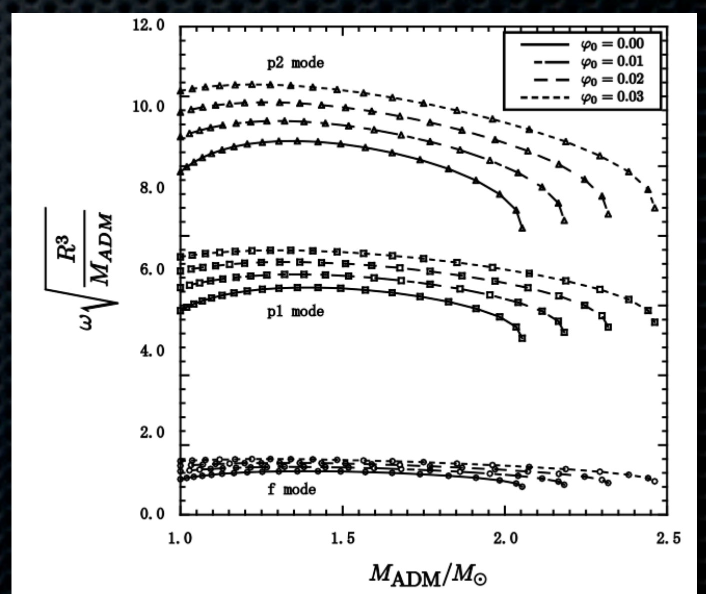
- strange stars composed of deconfined quarks
- superfluid neutron stars
- NS oscillations in TeVeS





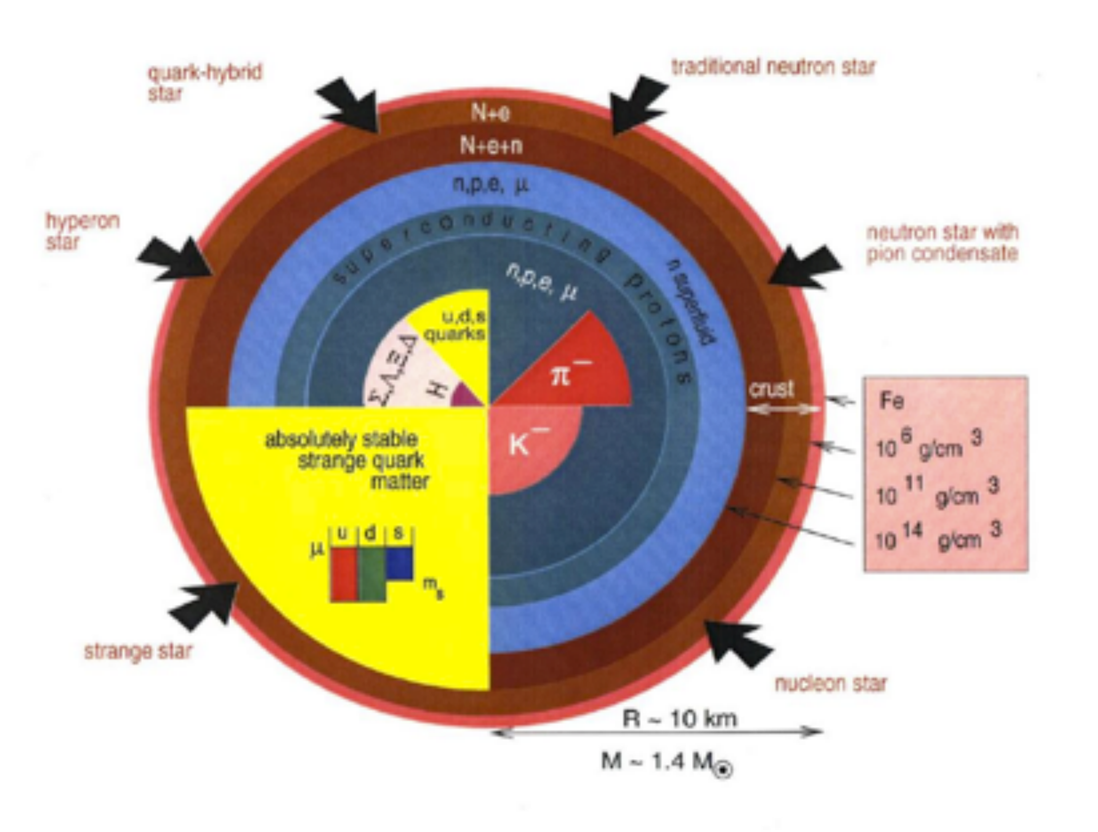




Sotani, Kokkotas (2004, 2005)

Asteroseismology with gravitational waves as a tool to probe the inner structure of NS and to test GR

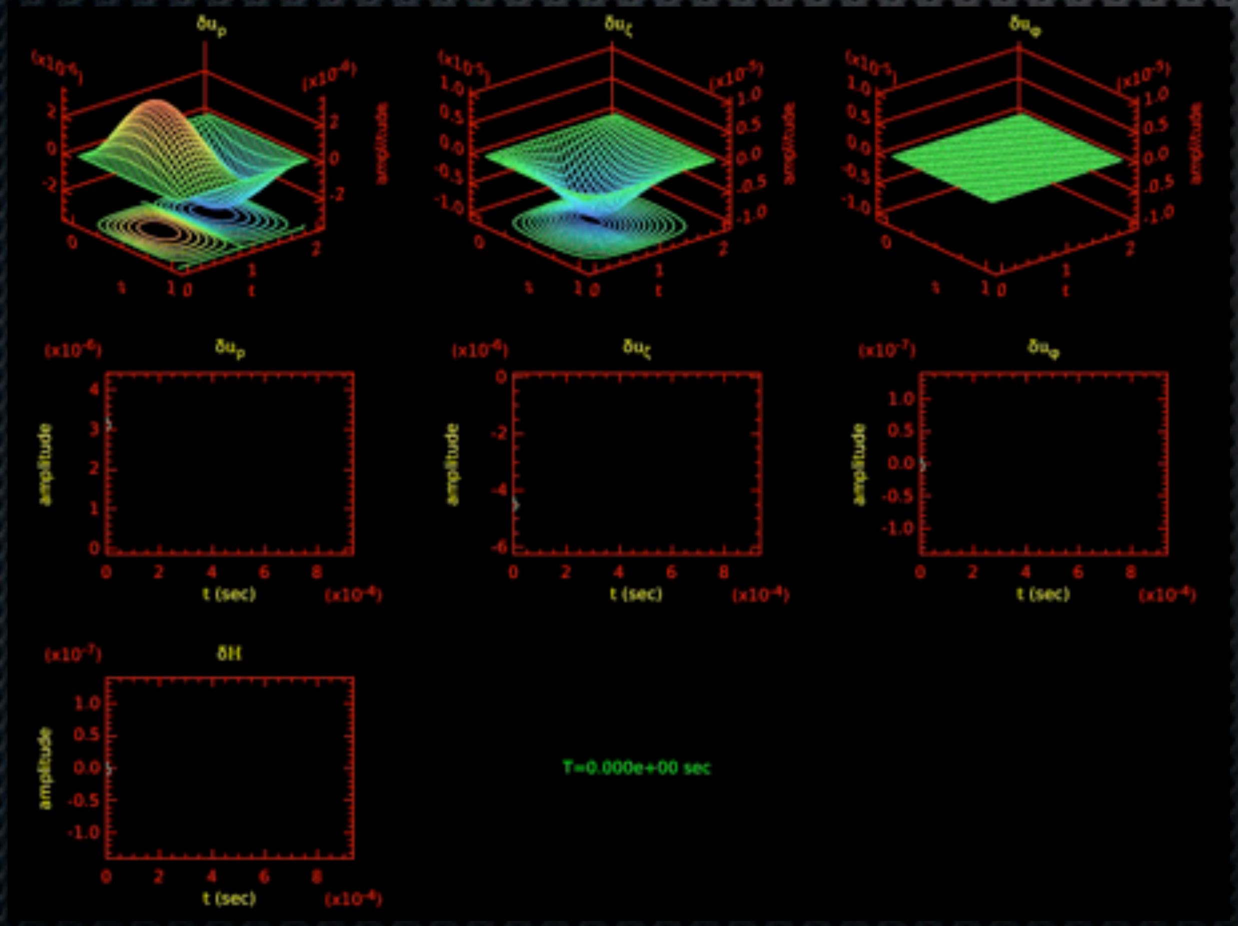
- neutron stars are the most extreme laboratories in the universe
  - rapid (differential) rotation
  - relativistic effects
  - superfluidity, superconductivity
  - strong magnetic fields
  - solid crust
  - etc...

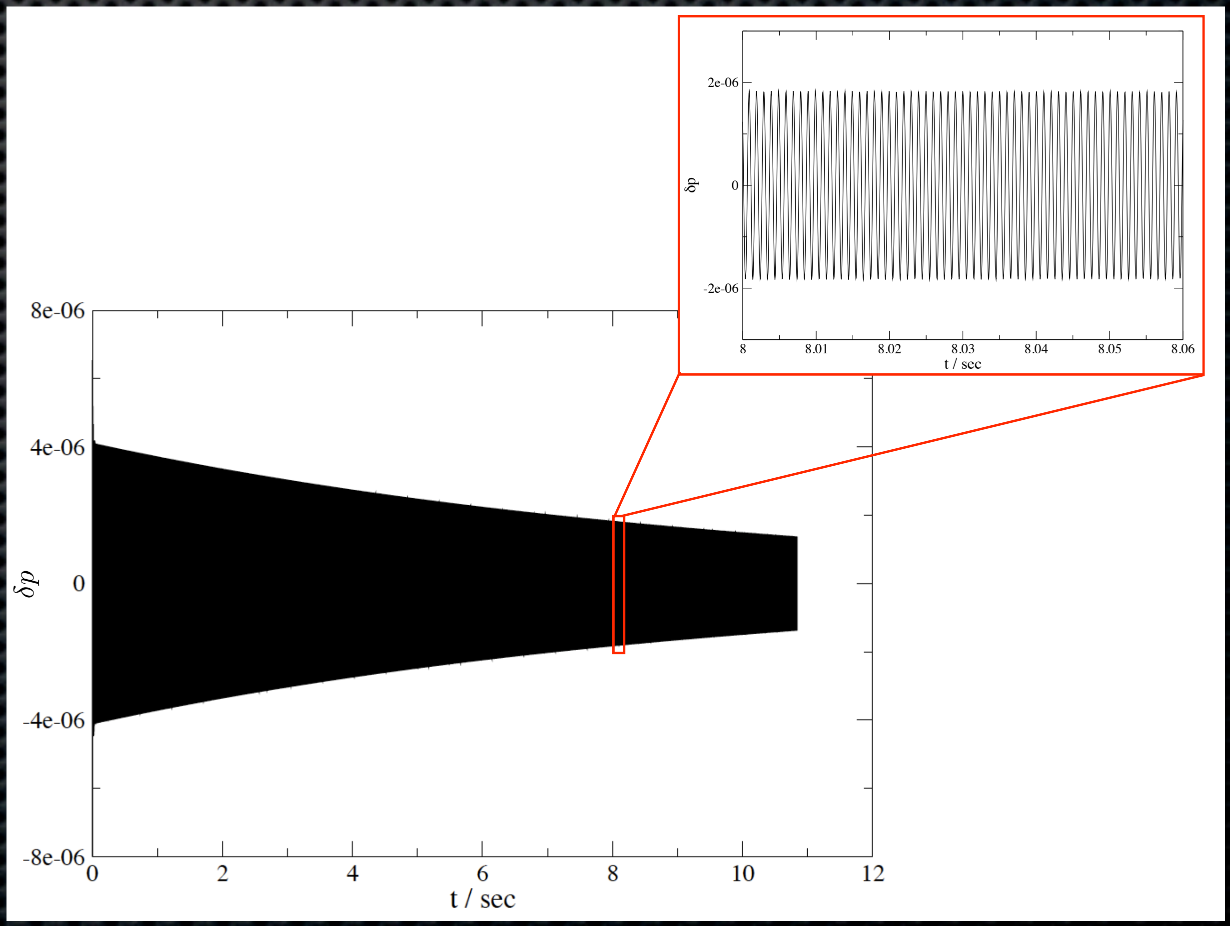


- while AdvLIGO/VIRGO most likely will detect gravitational waves for the first time, 3rd generation detectors like ET are utterly needed for high precision measurements required by asteroseismology and strong field tests

Asteroseismology and rapidly rotating NS I

- inclusion of rotational effects in linear theory posed several numerical difficulties in the past but were finally mastered two years ago
- we can now study **all** perfect fluid modes in (even differentially) rotating neutron stars up to the Kepler-limit (*p*-modes, *g*-modes, *r*-modes)

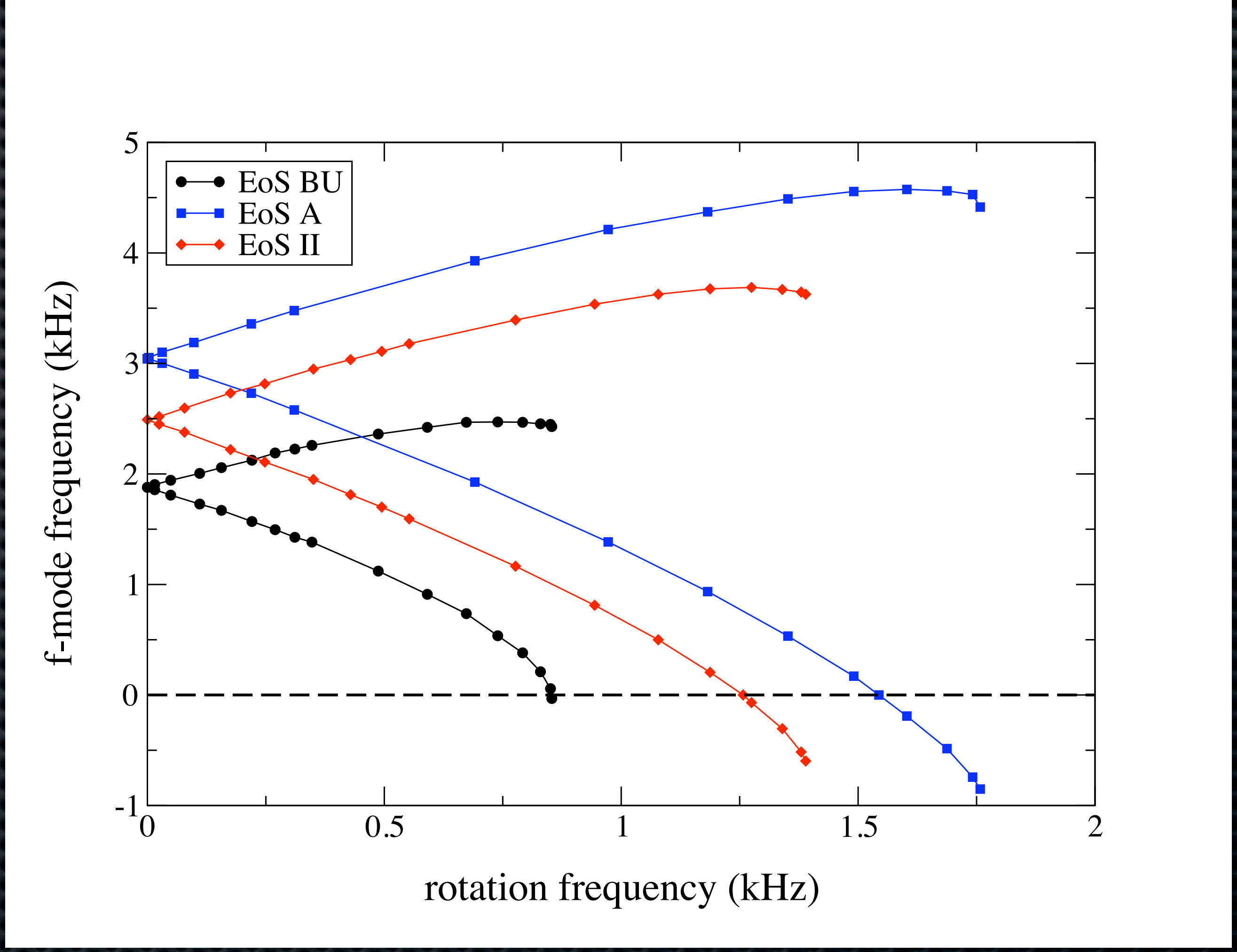




Asteroseismology and rapidly rotating NS II

- based on rotating sequences for three different EoS, we proposed simple empirical relationships for the dependence of the *f*-mode frequency on angular velocity **Gaertig, Kokkotas (2008)**

- recently, this study has been extended to a wider range of polytropic EoS and to damping times as well **Gaertig, Kokkotas (2010)**



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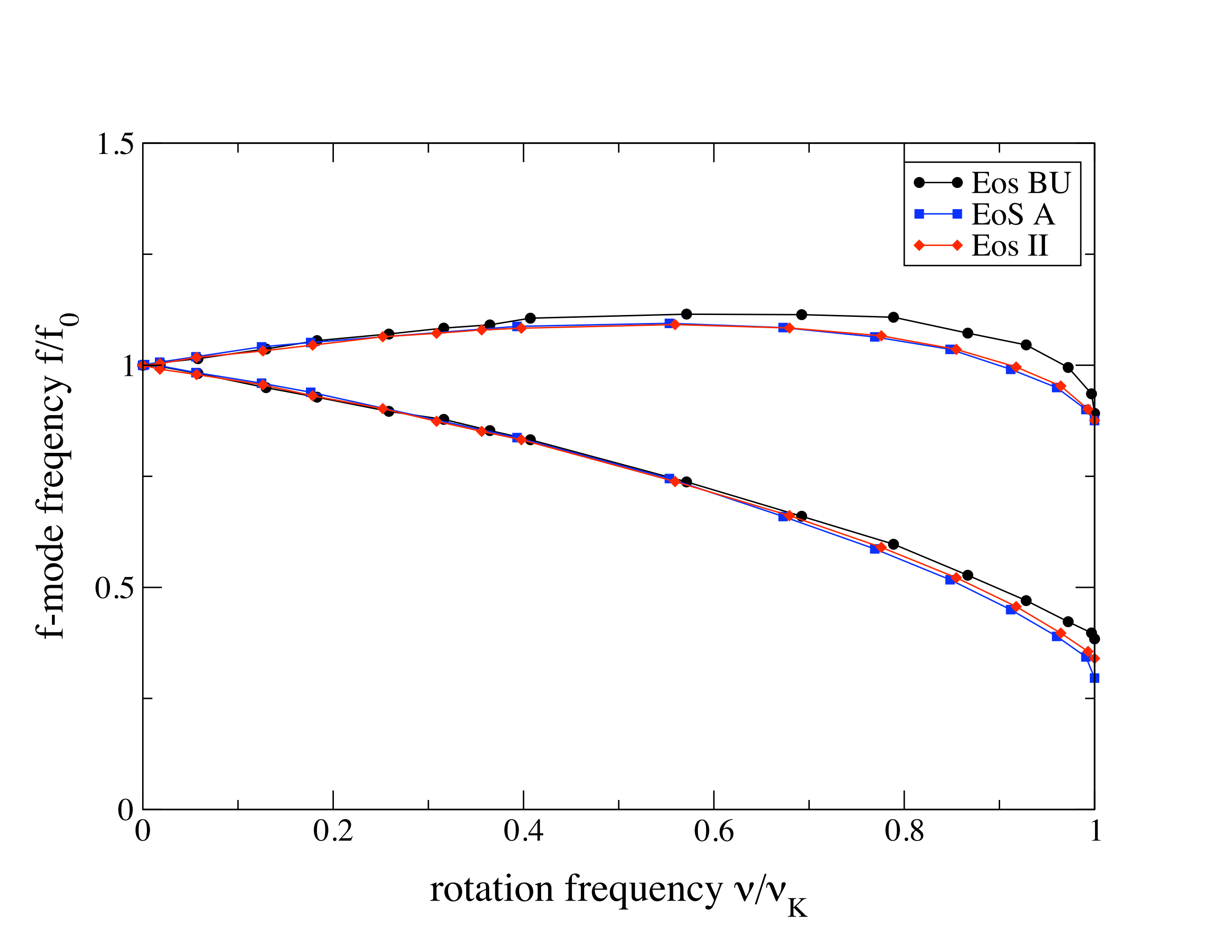

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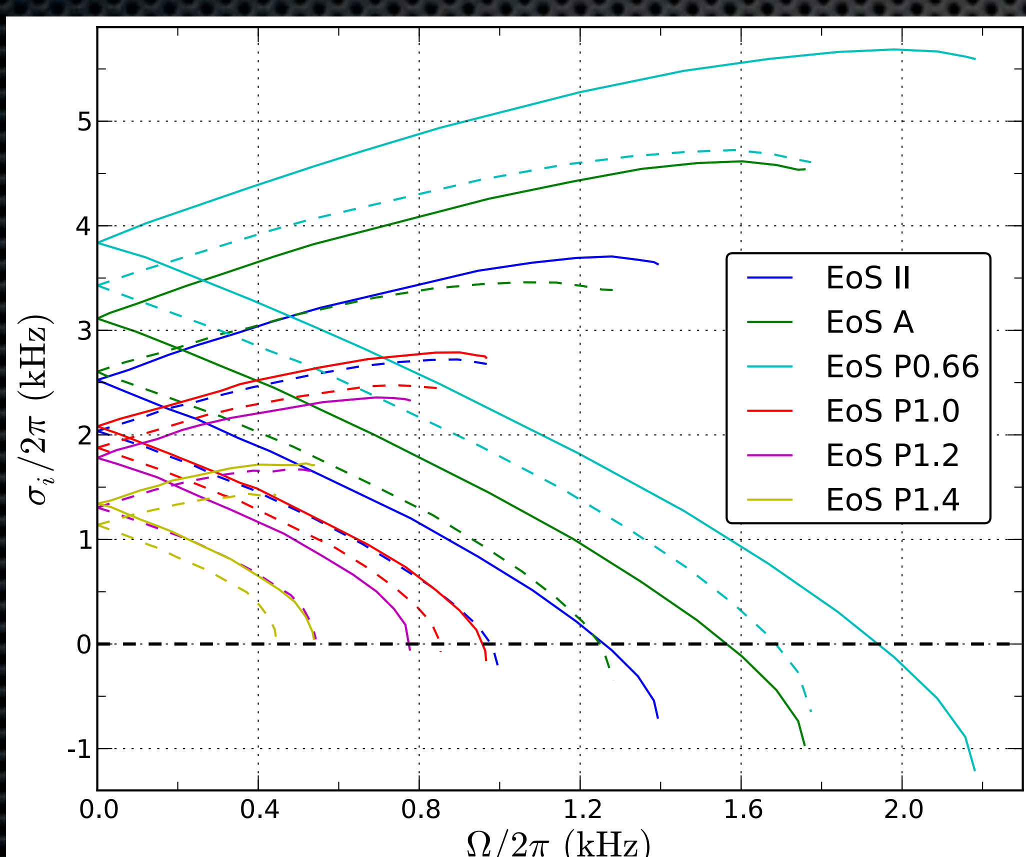

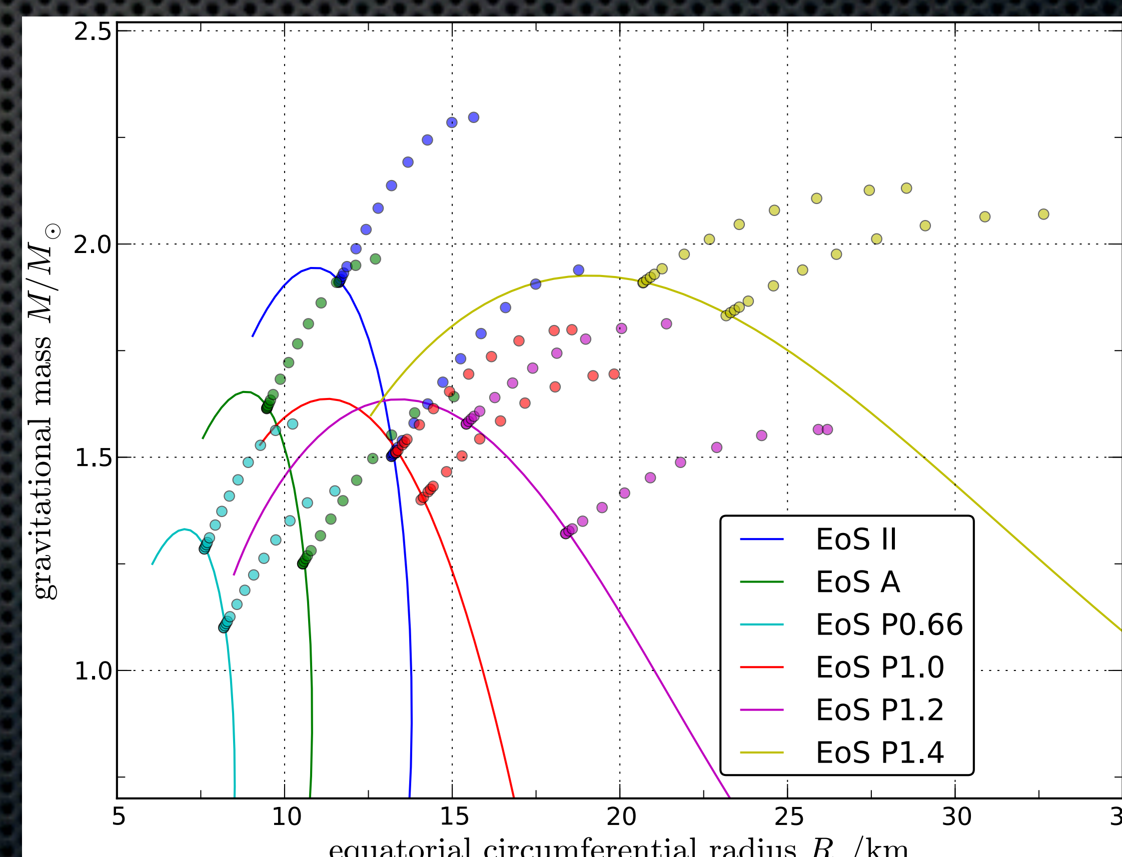

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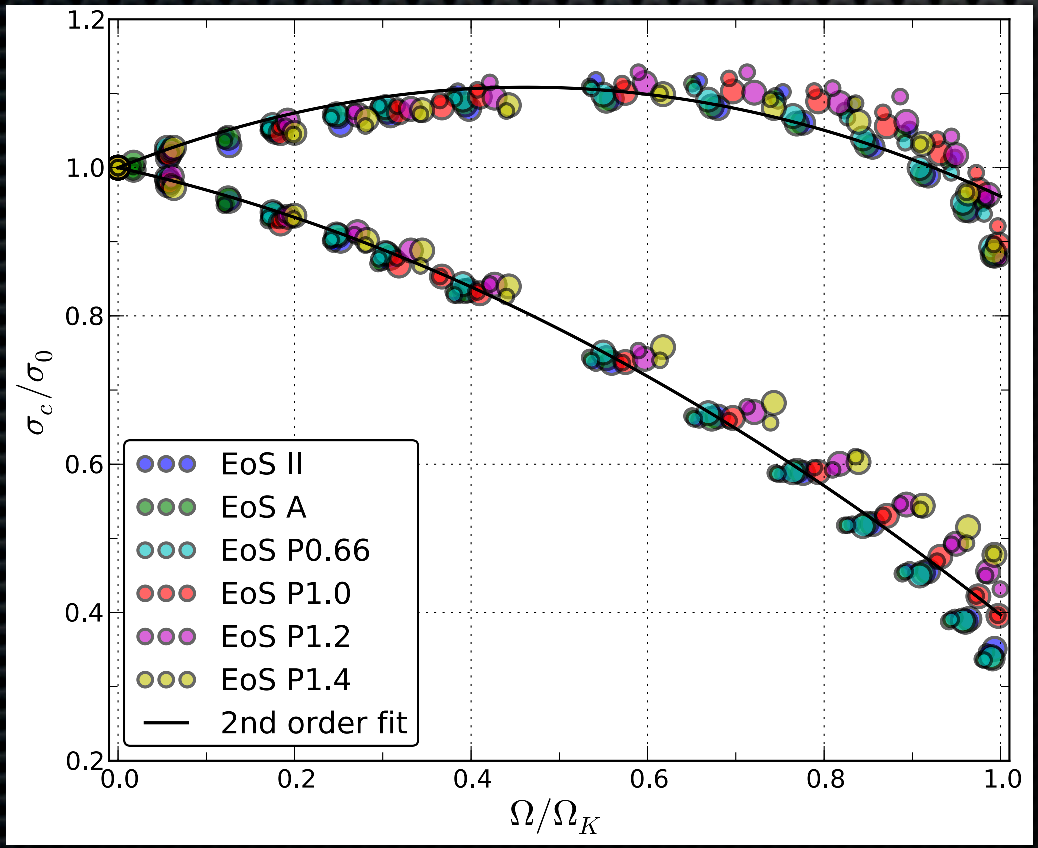
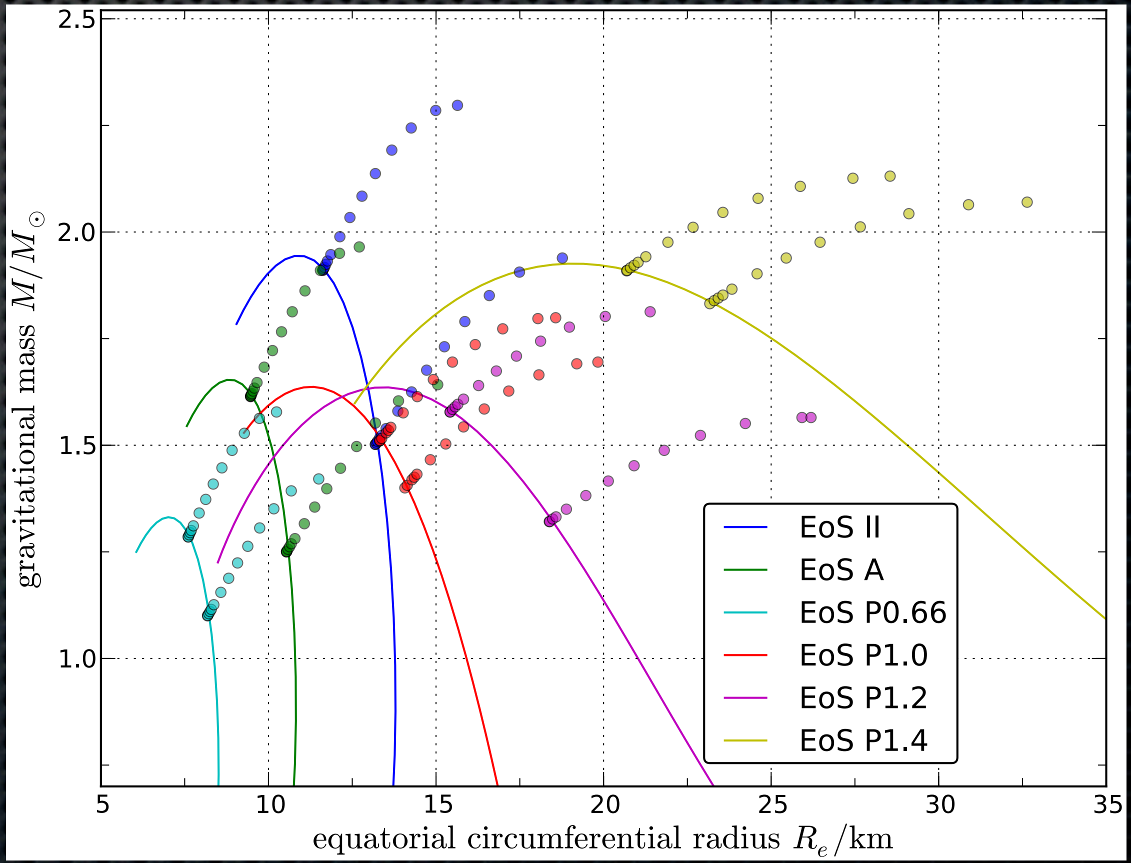
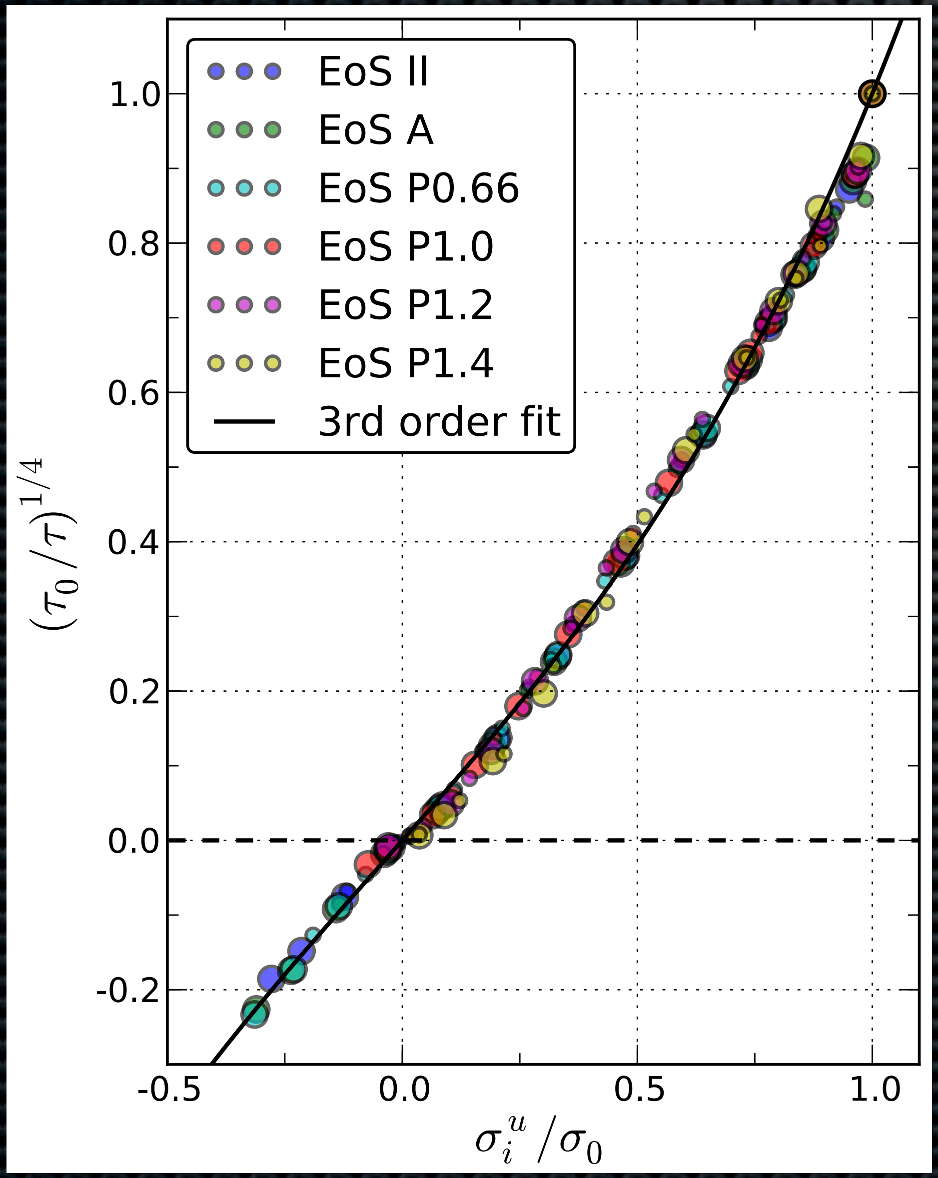




Asteroseismology and rapidly rotating NS III

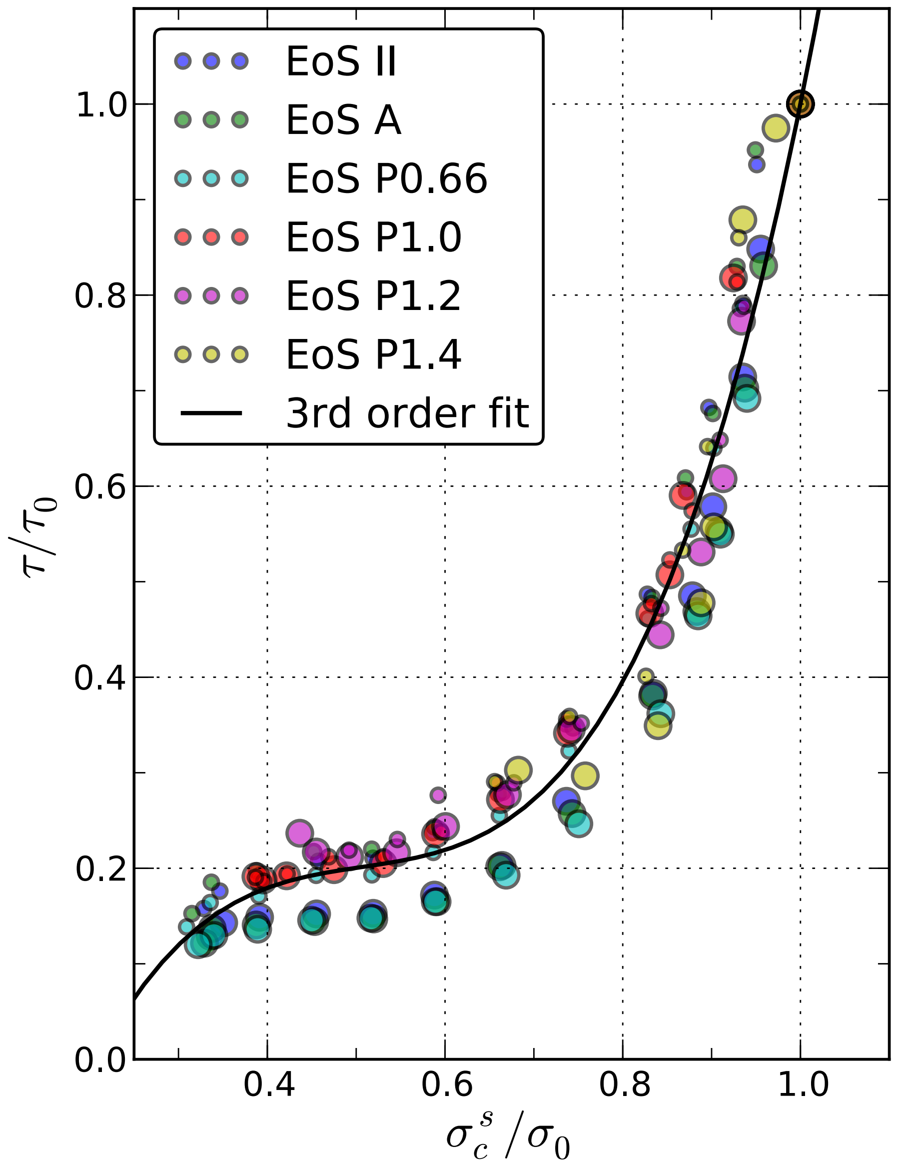
- correspondingly, EoS-independent relationships can also be found for the damping times; the key idea here: instead of using the angular velocity, use mode frequencies as measure of rotation rate



- rotation rate increases from **right** to **left**
- not all EoS become CFS-unstable, i.e. damping time grows to infinity
- fitting is done via a third order polynomial since
  - linear fit is already determined by constraints (independent of actual data)
  - quadratic fit doesn‘t match data point characteristics

Asteroseismology and rapidly rotating NS IV

- a similar approach can be made for the CFS-stable modes; keep in mind to use mode frequencies in the correct frame...



- again, rotation rate increases from **right** to **left**

- spread of the data points is somewhat larger than for the (potentially) CFS-unstable modes

- still, damping times can be fitted very well (again) with a cubic polynomial

- now, one can do asteroseismology with rotating stars!!

Asteroseismology and rapidly rotating NS V

- **example:** EoS P1.2 model rotating at 60% of the mass-shedding limit
- three unknowns (M, R, Ω, Ω_K(M, R)) vs. measurements of ($\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$, $\boldsymbol{\tau}_i$), i = 1,2
- $\mathcal{S}_i$ is a combined measurement of the triple ($\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$, $\boldsymbol{\tau}_i$), i = 1,2; i.e. two frequencies and one damping time

- accuracy of the fit: EoS P1.2

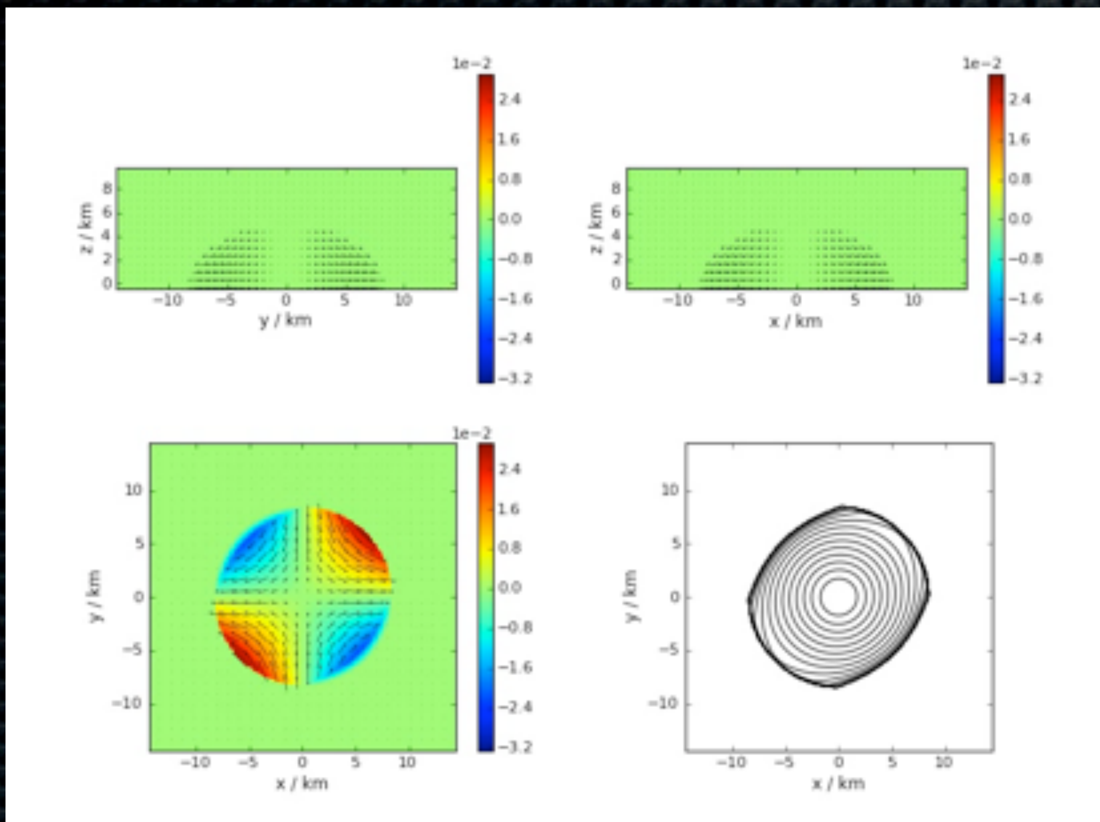
parameter	exact value	value from the fit
$\Omega_K/2\pi$	0.777	0.806
$\sigma_1/2\pi$	2.248	2.203
$\sigma_2/2\pi$	1.056	1.038
τ_1	0.161	0.136
τ_2	6.925	9.054

- the inverse problem: EoS P1.2

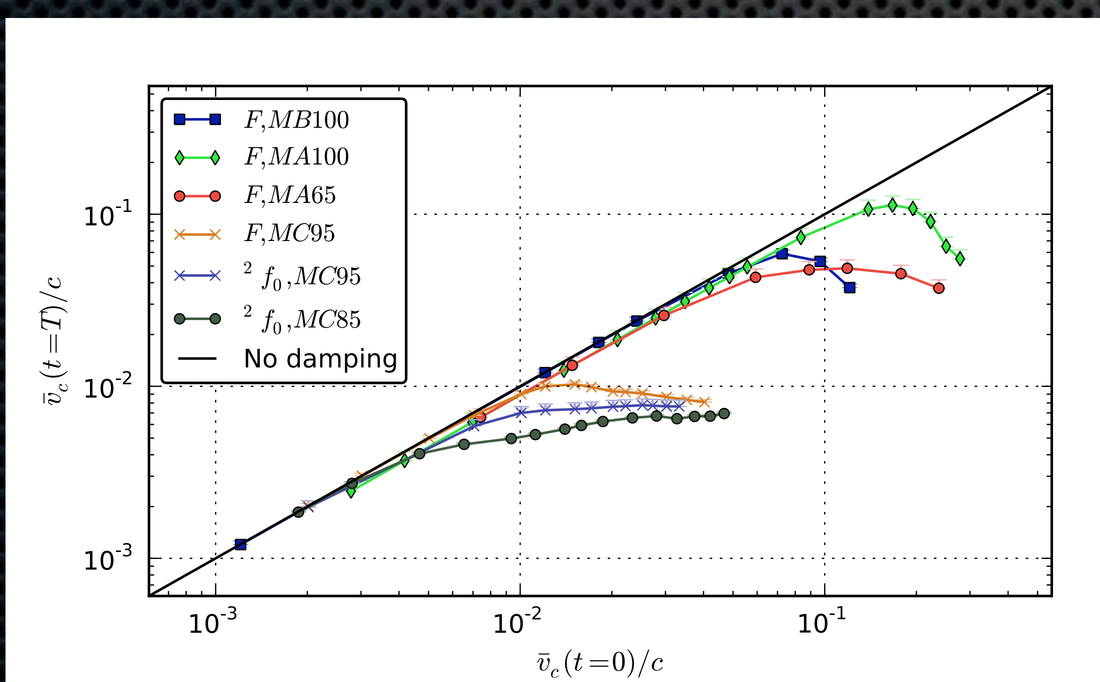
	M	R	$\Omega/2\pi$	$\Omega_K/2\pi$
exact	1.58	15.42	0.464	0.777
using $\mathcal{S}_1$	1.09	13.88	0.470	0.792
using $\mathcal{S}_2$	1.64	15.80	0.470	0.792

- the estimated values for M, R, Ω can restrict the range of allowed EoS

Nonlinear Saturation and Detectability



Kastaun, Willburger, Kokkotas (2010)



- growth-phase of the *f*-mode instability is constrained by other viscous effects but also by nonlinear saturation
- high-amplitude oscillations are damped by
  - shock-formation
  - wave-breaking at the surface
  - mode coupling to inertial-modes

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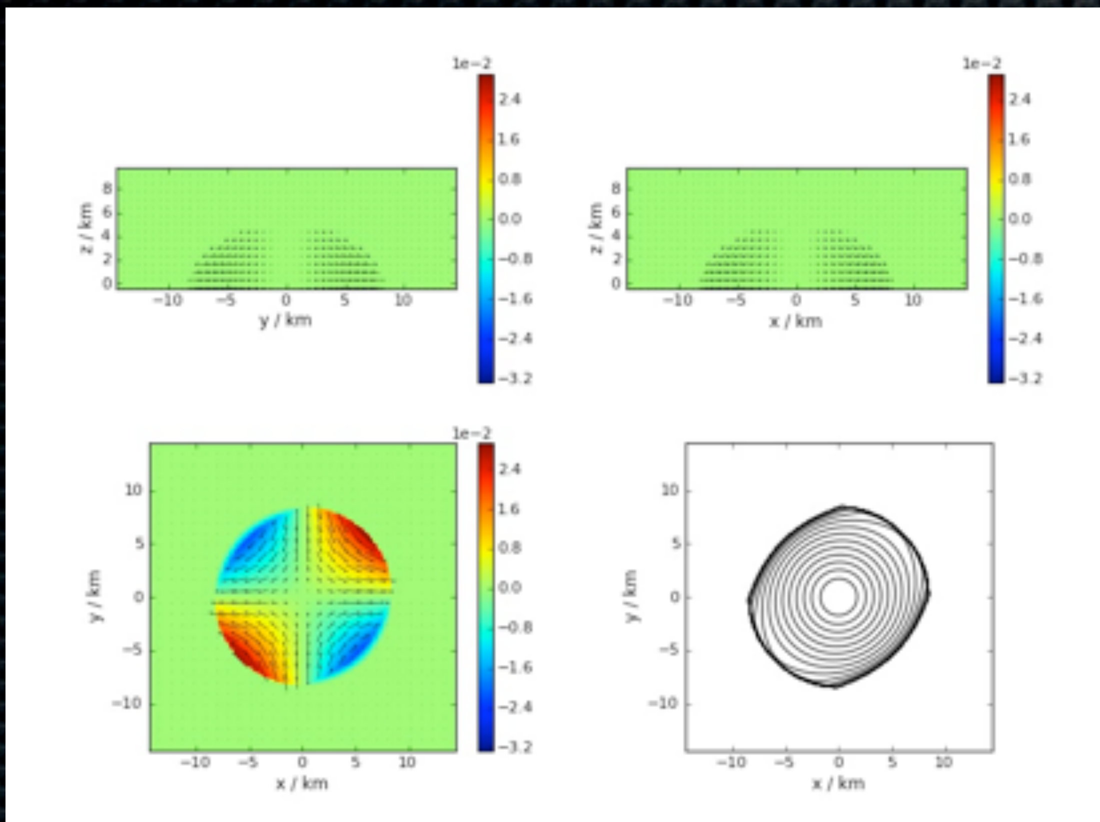

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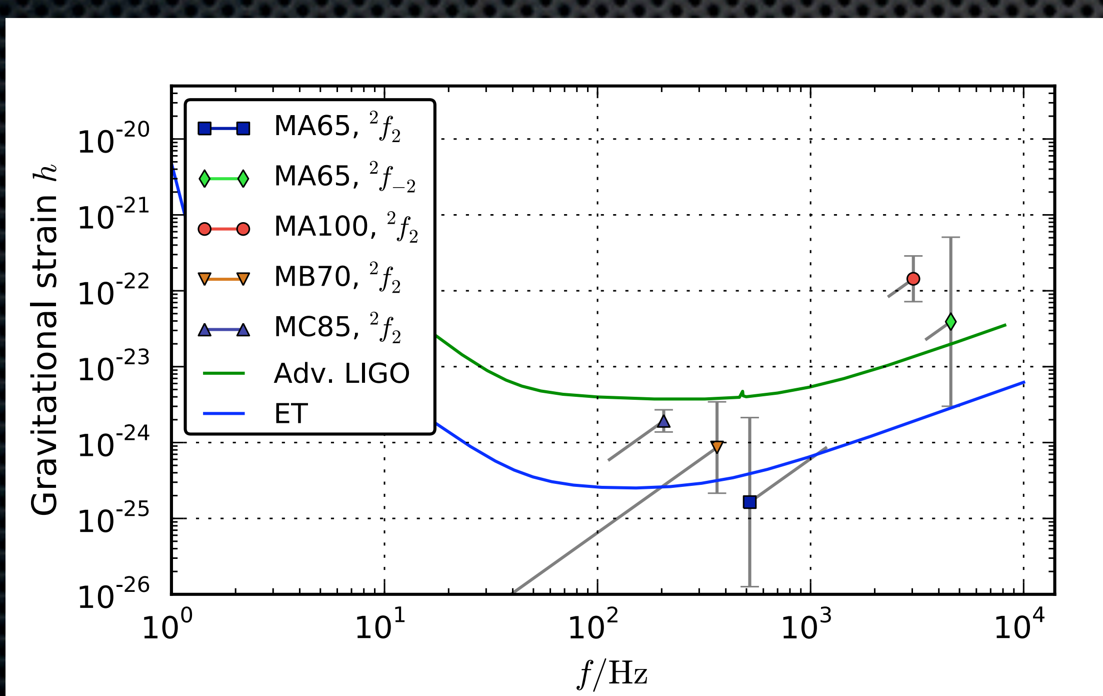
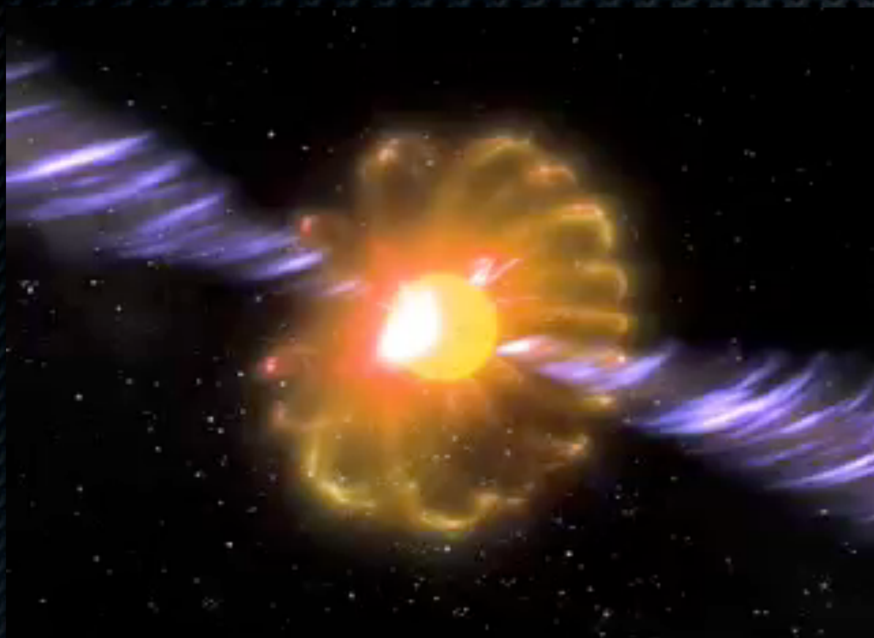
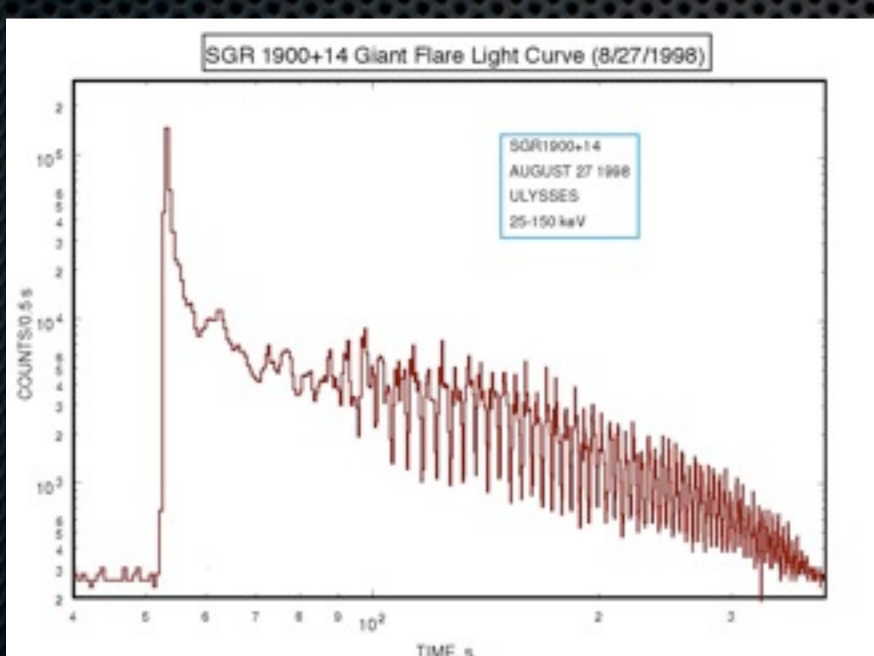


- growth-phase of the *f*-mode instability is constrained by other viscous effects but also by nonlinear saturation
- high-amplitude oscillations are damped by
  - shock-formation
  - wave-breaking at the surface
  - mode coupling to inertial-modes
- instability saturates at an amplitude which is detectable at least from Virgo Cluster
- detailed study in progress (improved surface treatment, more accurate mode-coupling, ...)

Asteroseismology and Magnetar QPOs I



- magnetars are neutron stars with huge magnetic fields ($B > 10^{14}$ G) and they come (mainly) in two flavours:
  - anomalous x-ray pulsars (high x-ray flux, narrow range of spin periods)
  - soft gamma repeaters (giant flare eruptions, fine-structured, decaying tail)

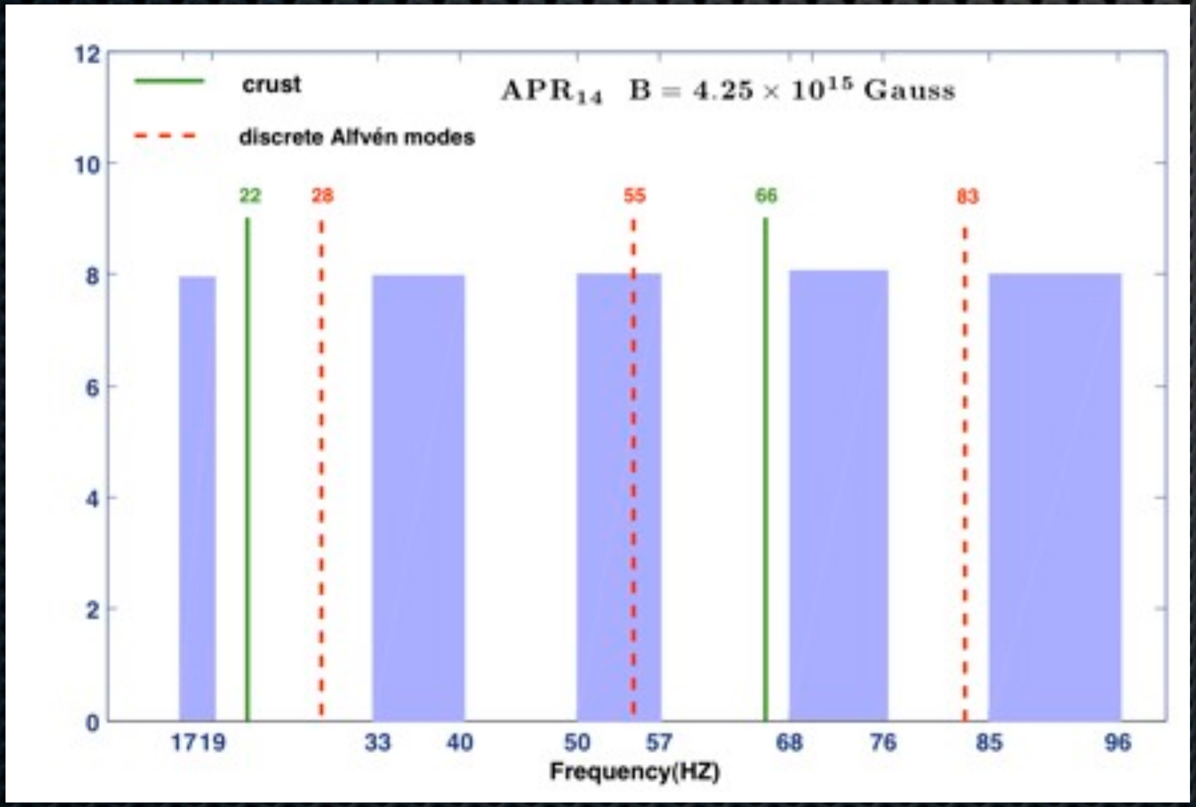


- connecting observed frequencies with theoretical models can tell us
  - mass and radius of the star
  - magnetic field strength and field topology
  - better understanding of the stellar composition

Asteroseismology and Magnetar QPOs II

- earlier studies dealt with pure crustal oscillations or used a toy model to study global oscillations (crust + core) in a uniform magnetic field [*Sotani et al. (2007), Glampedakis et al. (2006)*]

- recently, these studies were extended to handle solid crust - fluid core oscillations with poloidal/toroidal field topology [*Gabler et al. (2010), Colaiuda&Kokkotas (2010 in prep.)*]



Colaiuda, Kokkotas(2010)

- the continuous spectrum is still present in the core
- the frequencies in the crust are discrete
- the crust transfers its energy rapidly to the core
- discrete Alfvén-modes at the crust-core interface

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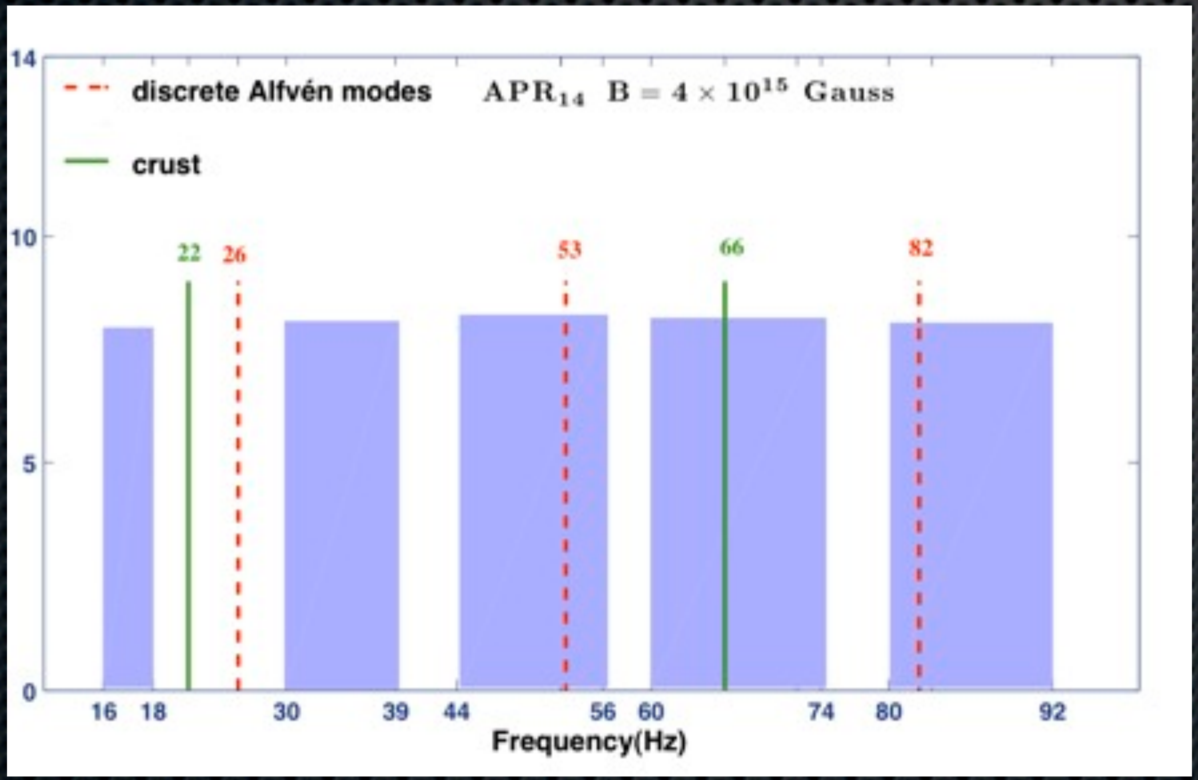

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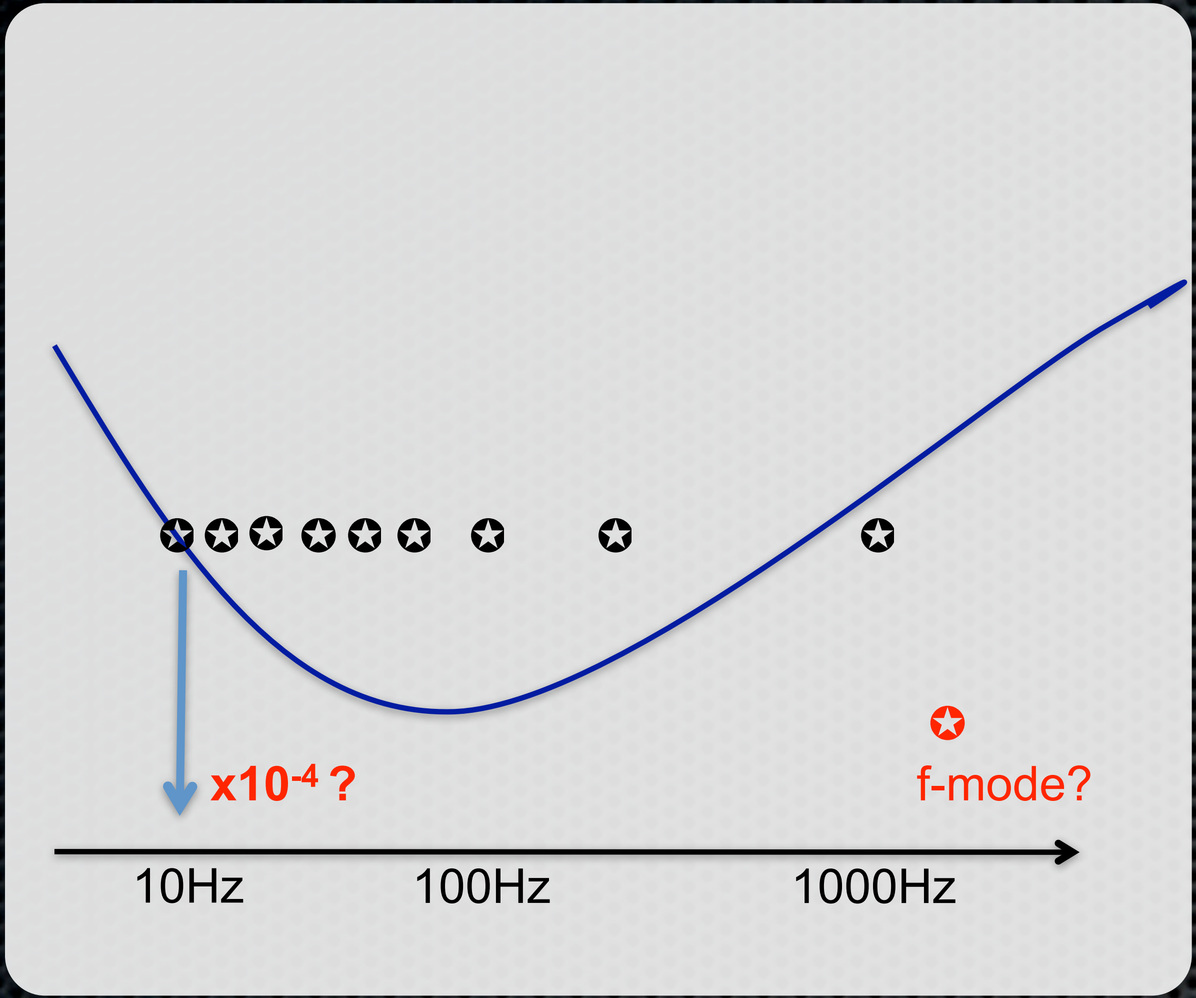
Magnetars and Gravitational Waves



- many mode frequencies in the optimal band of GW detectors
- ideal source for multi-messenger astronomy
- is it possible to excite density-perturbations?
  - $E_{mode} \approx 10^{-??} E_{burst}$
- amplitude of GWs unknown

- smaller and more frequently excited flares also carry information
- can one use them to reveal SGR-parameters and detect GWs?