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GRAVITATIONAL WAVES FROM PULSATIONS OF COMPACT STARS

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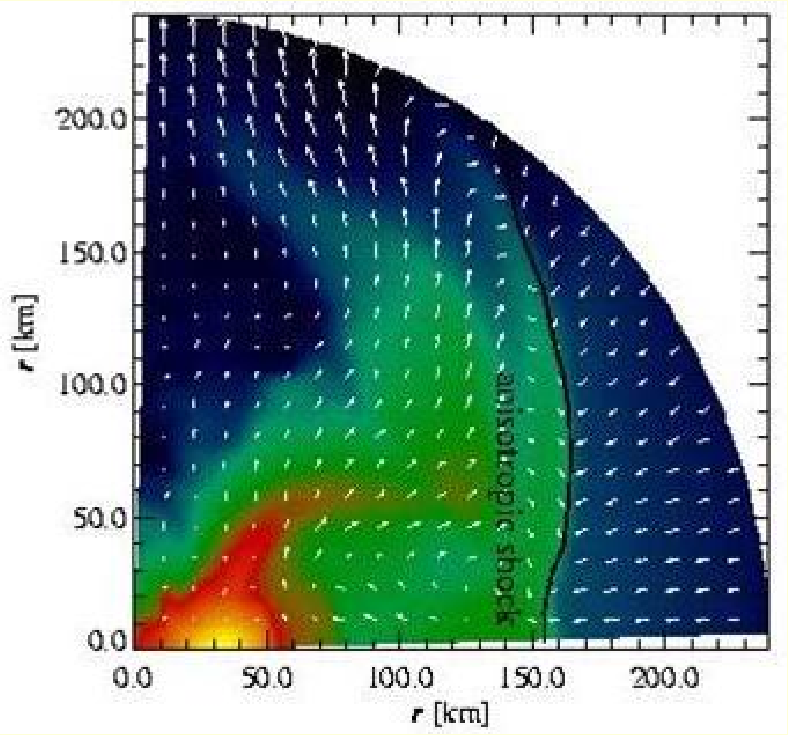
Plan of Talk

1. *Core-bounce oscillations during neutron star formation*
2. *Fall-back accretion*
3. *Phase-transition-induced mini-collapse*
4. *Resonant tidal excitation in binary systems*
5. *Gravitational-wave-driven instabilities*

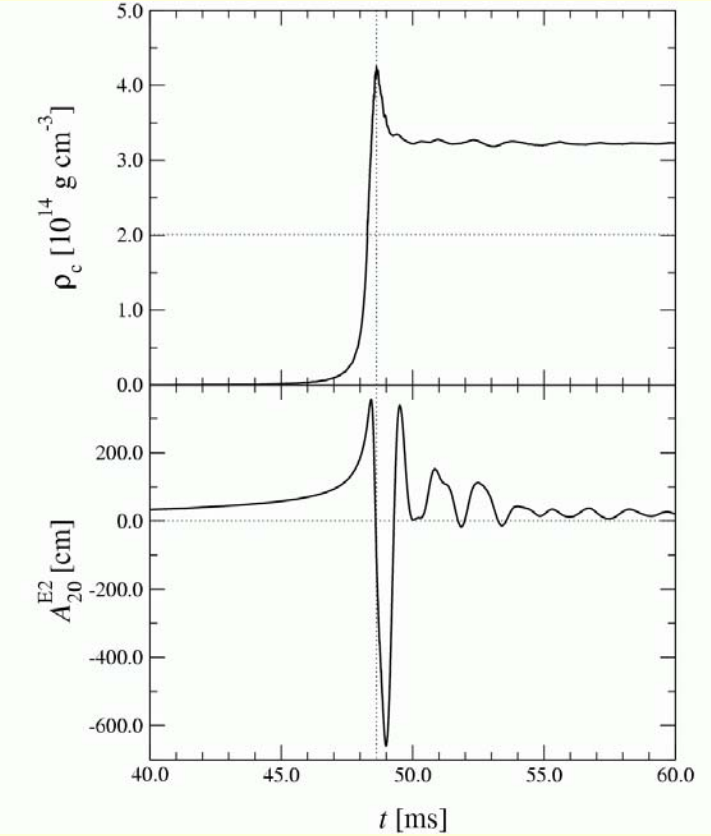
Review Articles

- Stergioulas N., “Rotating Stars in Relativity”, *Living Reviews in Relativity*, 6, 3 (2003)
- Kokkotas, K.D., Stergioulas, N., “Gravitatitional Waves from Compact Sources” (gr-qc/0506083)

1. Core-Bounce Oscillations



Dimmelmeier, Font & Mueller 2002



GW emission: mainly axisymmetric l=2 f-modes and w-modes

Energy: $10^{-8} - 10^{-6}\ M_{sun}$ => only rapidly rotating cores produce strong GWs.

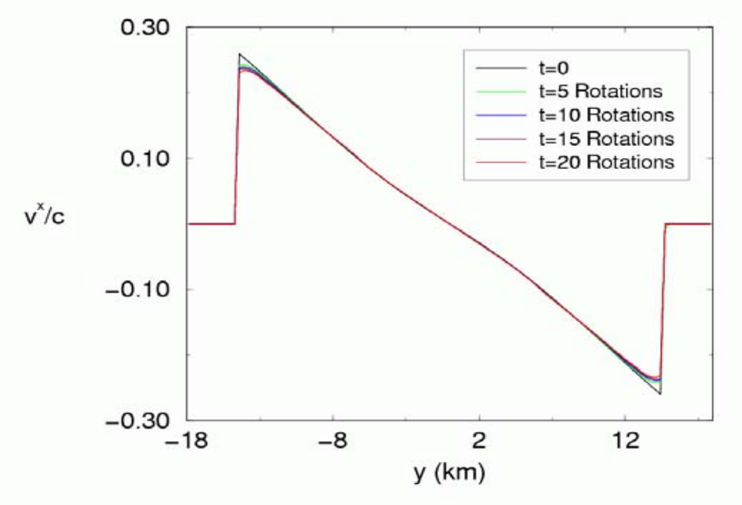
To extract information about Mass, EOS etc. need to develop GW-Asteroseismology for rotating neutron stars

Numerical Codes

Instead of using perturbative methods, one can study pulsations using fully nonlinear numerical codes:

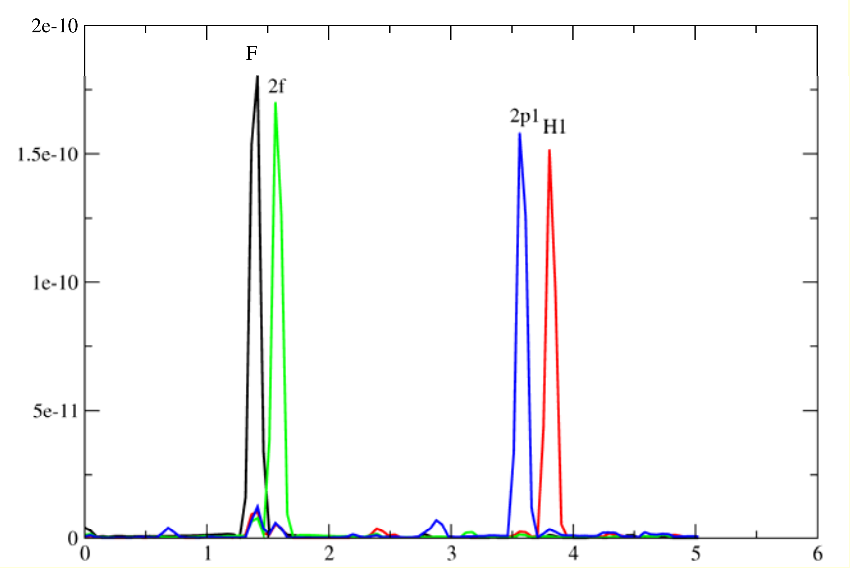
- Tonik: 2D polar, fixed spacetime (Font, N. S., Kokkotas, 2001) (N. S., Apostolatos, Font, 2004)
- Coconut: 2D polar, CFC approximation (Dimmelmeier, Font, Mueller) (Dimmelmeier, NS, Font, 2005)
- Cactus/Whisky: 3D Cartesian, full GR evolution (Baiotti, Hawke, Montero, Loeffler, Rezzolla, N.S., Font, Seidel, 2004),

Initial Data: *imported RNS models* (N.S., Friedman 1995).



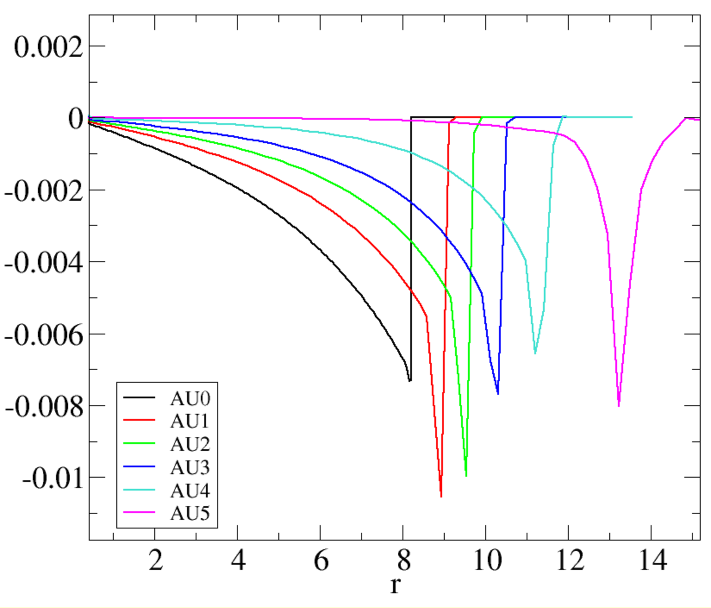
(N. S. & Font 2001)

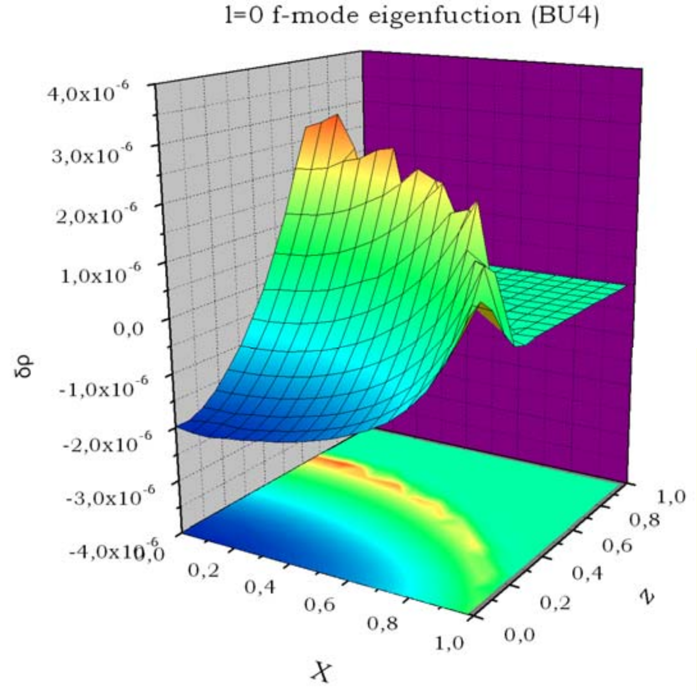
EXTRACTION OF EIGENFUNCTIONS



New Fourier Technique:

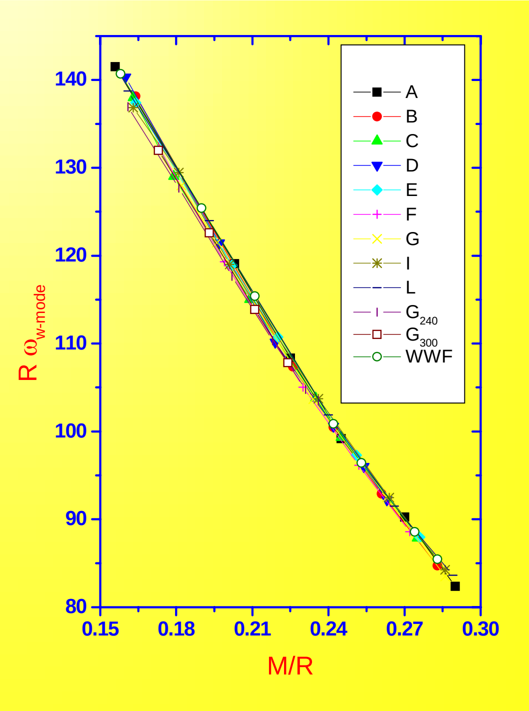
Eigenfunctions are extracted by FFT at all points – magnitude of FFT correlates with shape of eigenfunction

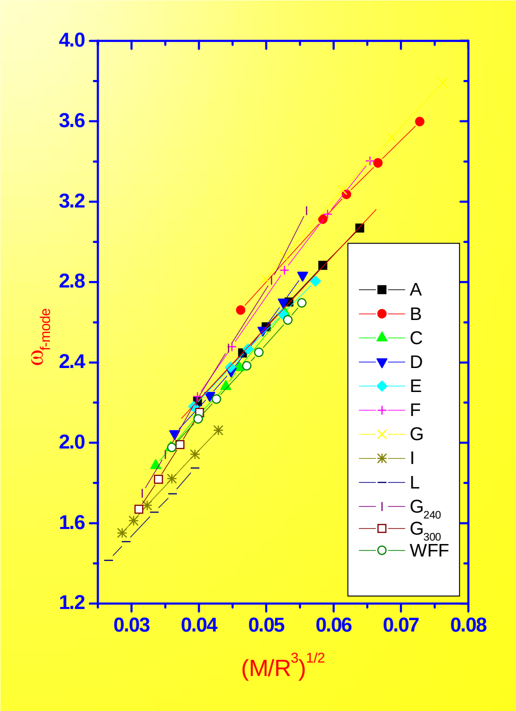




F-mode along x-axis for different rotation rates

GW Asteroseismology (Nonrotating)





$$\omega_w(kHz) \approx \frac{1}{R_{10}}\left[20.92 - 9.14\frac{M_{1.4}}{R_{10}}\right] + \delta_w m \frac{\Omega}{\Omega_K}$$

$$\omega_f(kHz) \approx 0.78 + 1.637\left(\frac{M_{1.4}}{R_{10}{}^3}\right)^{1/2} + \delta_f m \frac{\Omega}{\Omega_K}$$

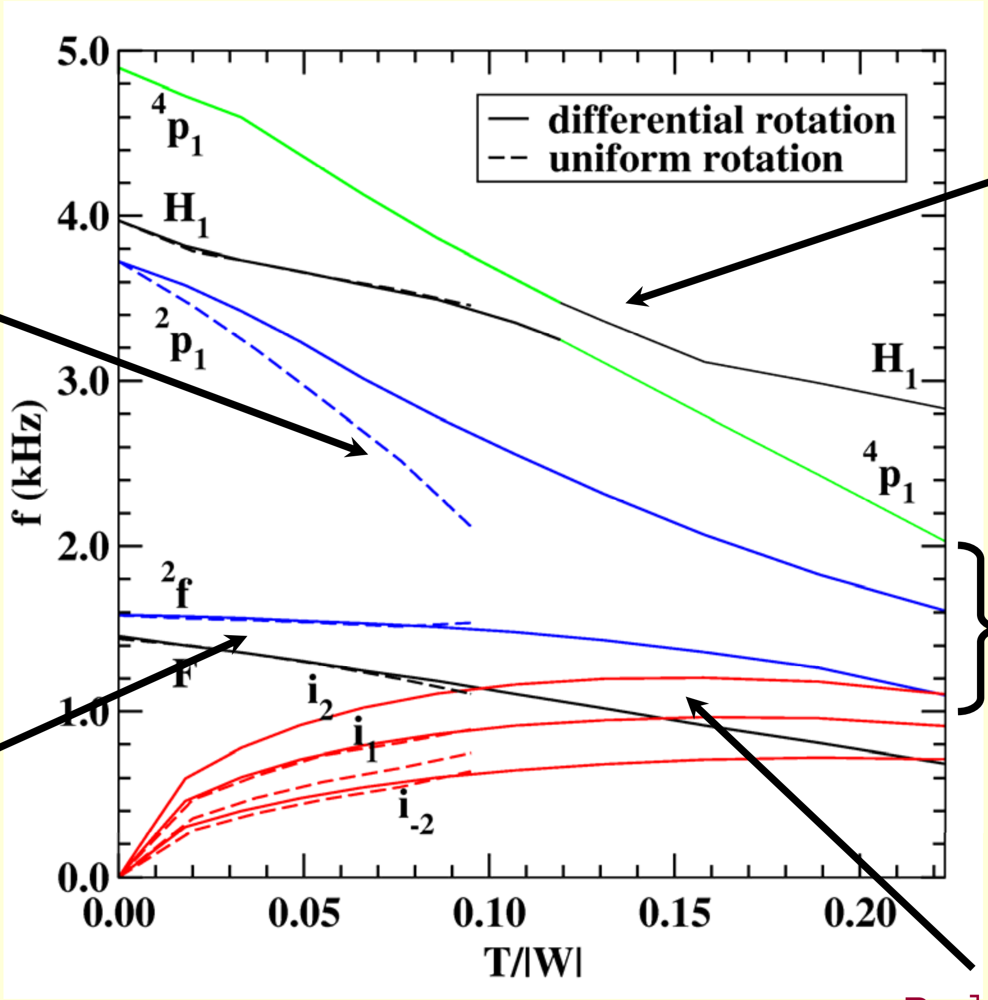
Andersson & Kokkotas (1996)
Kokkotas, Apostolatos & Andersson (2001)
Benhar, Ferrari & Gualtieri (2004)

Empirical formulas must be extended to rotating models!

Axisymmetric Modes in CFC Approximation

Spacetime evolution with Spatially Conformally Flat Condition (CFC/IWM)

Vhqvlwlyh wr#
G liihuhqwldo#
U rwdwlrq



D yrlghg#
F urvvlqj

Iuhtxhqflhv
Vkliwhg#wr
405#nK }#udqjh

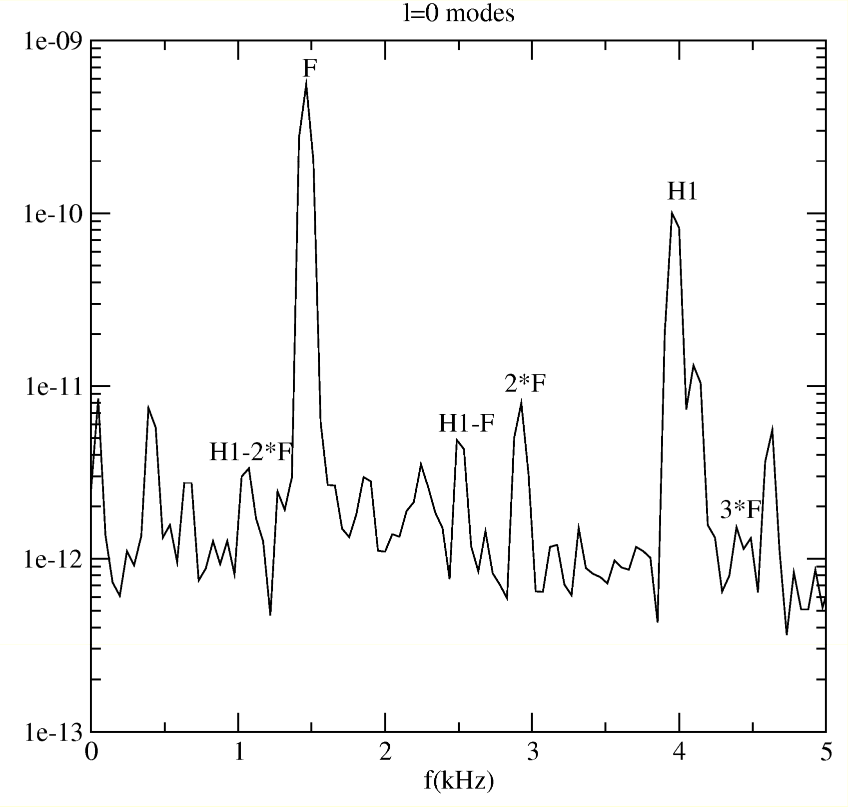
Q rwvhqvlwlyh#wr#
G liihuhqwldo#
U rwdwlrq

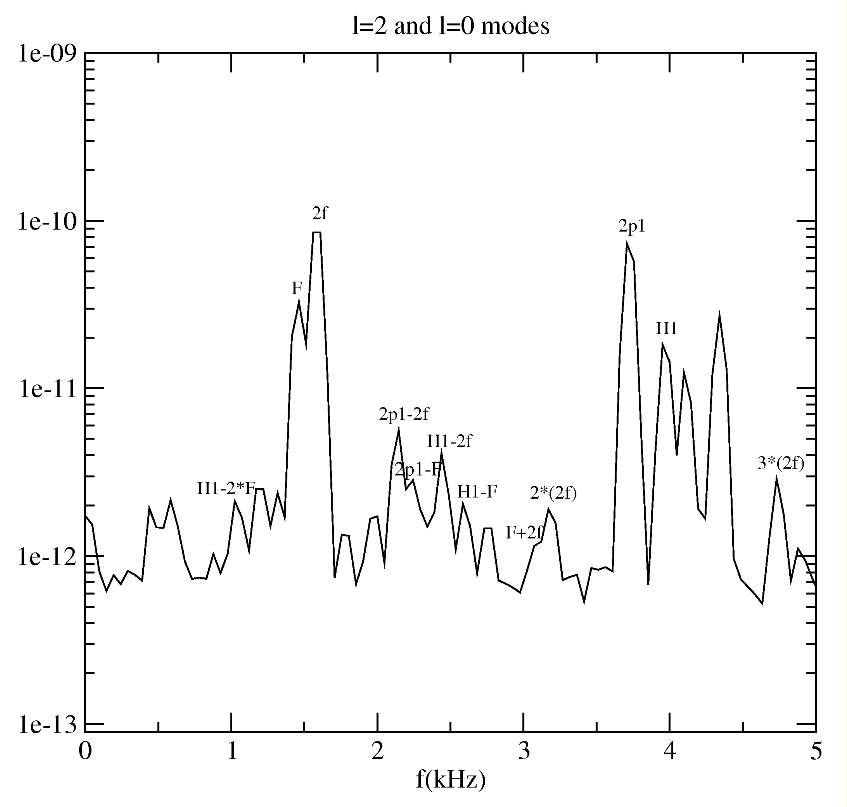
P d{lp xp
Iuhtxhqf|

Dimmelmeier, NS & Font (2006)

Nonlinear Mode Couplings

Nonlinear harmonics are also excited: linear sums and differences of linear mode frequencies.





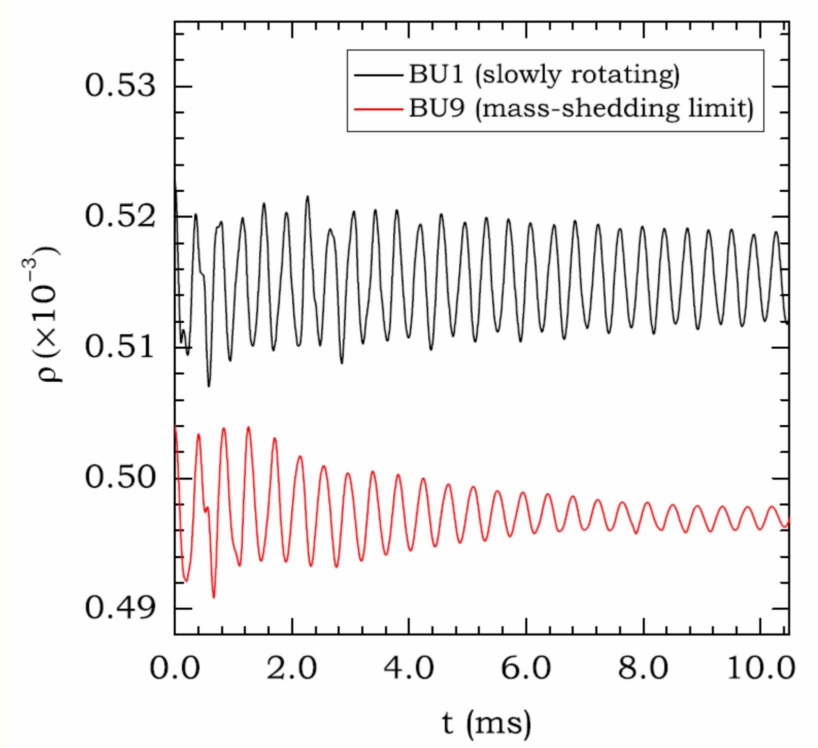
Dimmelmeier, NS, Font (2005)

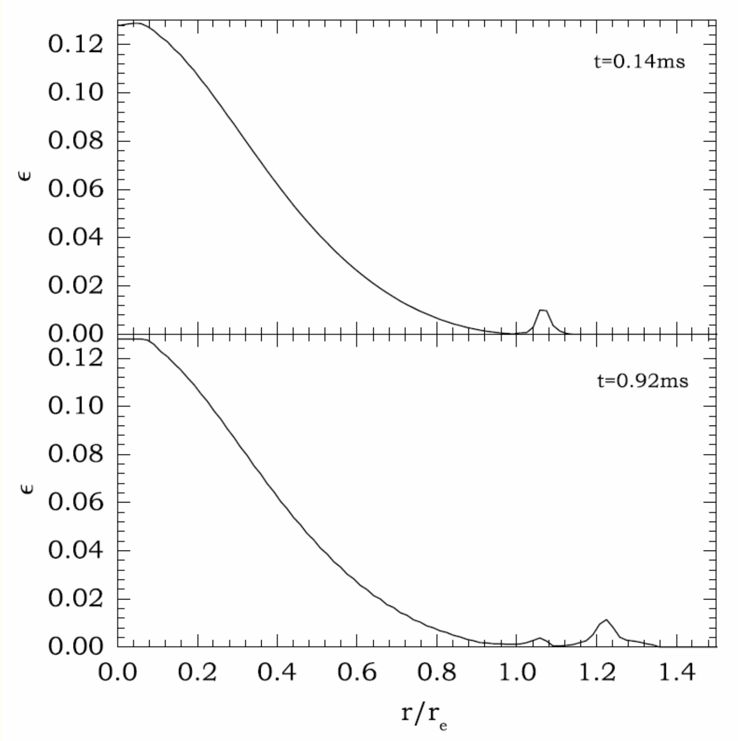
Mass-Shedding-Induced Damping

Near mass-shedding limit, fluid elements near surface are *weakly bound* (*effective gravity vanishes*).

Radial component of pulsations causes *mass-shedding* in form of *shocks.*

This could *enhance* strong damping in core-collapse oscillations and enforce *nonlinear saturation* for unstable modes.





NS, Apostolatos & Font (2004)

2. Fall-Back Accretion

If the progenitor star is sufficiently massive, then significant fall-back accretion will take place.

Depending on the nonradial structure of the fall-back material, various pulsation modes can be excited. A quadrupole shell of 0.01M produces similar GW amplitude as the core bounce signal (Nagar et al. 2004).

Delayed excitation of core g-modes: (Ott et al. 2006)

In 2D Newtonian simulations a late-time (t>400ms) excitation of g-modes in the proto-neutron-star code was observed, resulting in a strong GW signal.

Interpretation:

Supernova shock front stalls and becomes unstable with a predominantly dipolar component. Through nonlinear couplings, quadrupolar GWs are produced.

If confirmed in 3D, this would be a strong source of GWs for even slowly-rotating core collapse, underlining the importance of nonlinear effects.

3. Phase-Transition-Induced Mini-Collapse

Potentially strong excitation of quadrupole and quasi-radial modes. (Lin et al. 2006)

Typical energy release: 10^{51} ergs.

Signal strength: 10^{-22} at 10Mpc.

Delayed detection would indicate occurrence of phase transition.

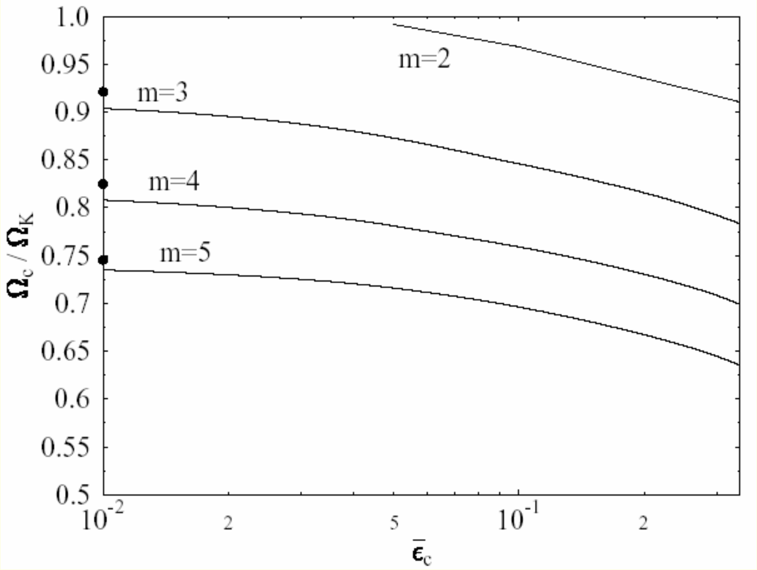
4. Resonant Tidal Excitation in Binary Systems

If there is spin-orbit misalignment, the resonant excitation of an odd-parity m=1 inertial mode can produce a significant phase shift (Lai & Wu, 2006).

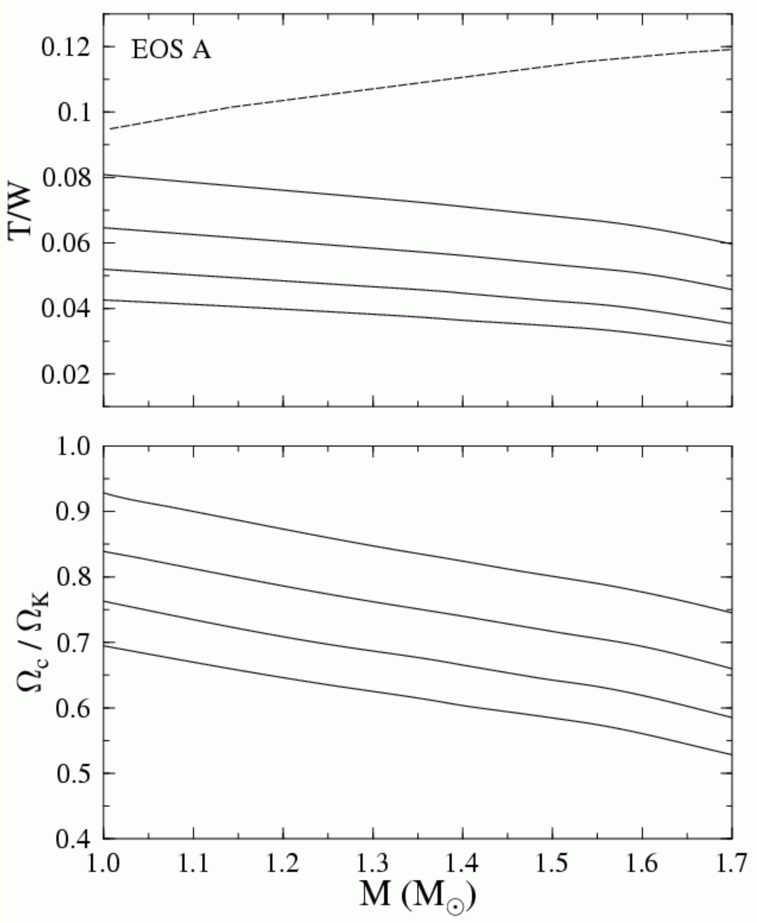
Such phase shifts need to be accurately modeled in the data analysis. There is a need for computing accurate inertial mode eigenfunctions for relativistic stars (see e.g. Boutloukos and Nollert 2006).

4. Gravitational-Wave-Driven Instabilities

F-Mode Instability (I)



(N. S. & Friedman 1998)



(Morsink, N. S. & Friedman 1998)

Onset of l=m=2 instability for:

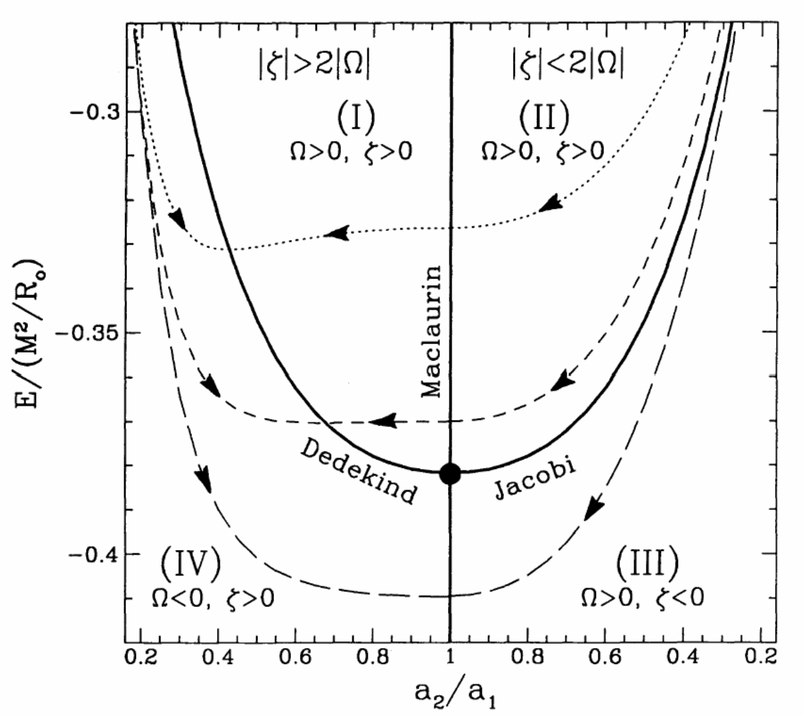
$\Omega > 0.85\Omega_K$	$\Omega > 0.95\Omega_K$
$T/W > 0.07$	$T/W > 0.14$
$N < 1.3$	$N < 0.81$
(Full GR)	(Newtonian)

F-Mode Instability (II)

The *nonlinear f-mode* modifies the background equilibrium star, inducing *differential rotation*. The modified background, in turn, modifies the f-mode, until *saturation* is reached.

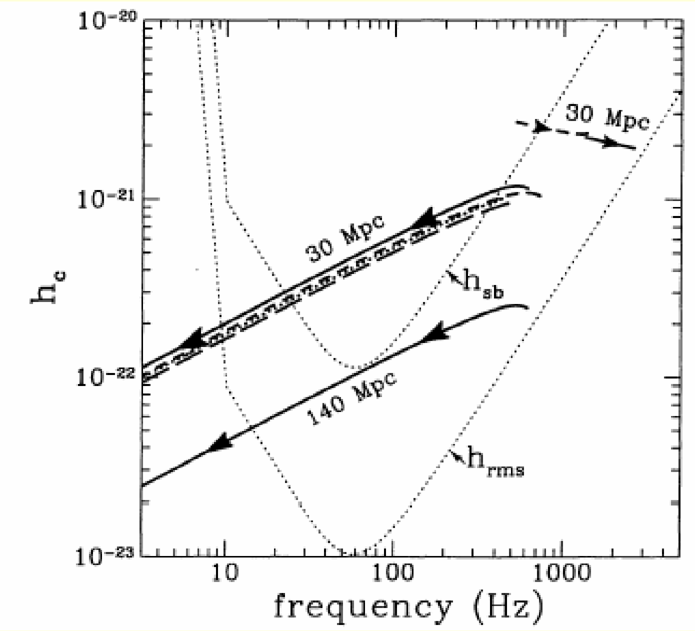
A uniformly rotating *Maclaurin spheroid* is driven along a sequence of *Riemann-S ellipsoids* towards a *stationary Dedekind ellipsoid*.

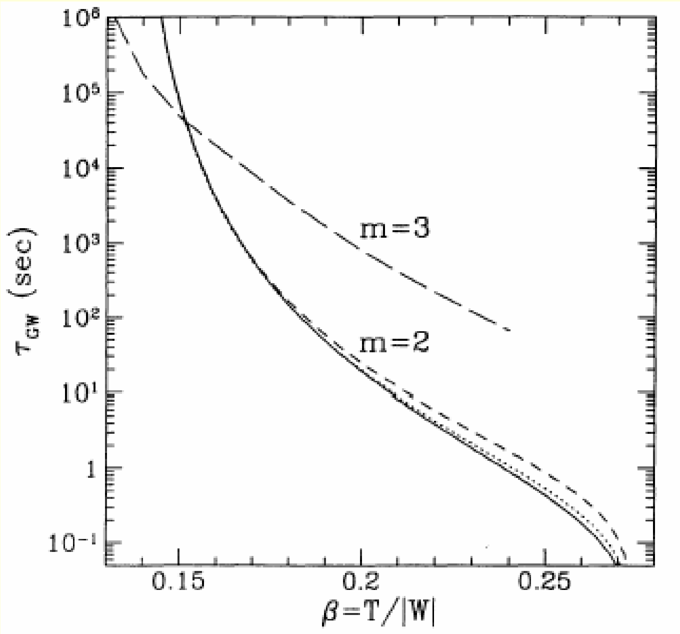
Gravitational waves are *strongest* during the *Riemann-S ellipsoid* phase.



Lai & Shapiro, 1995

F-Mode Instability (III)





Lai & Shapiro, 1995

In the *best-case scenario*, the GWs are easily detectable out to 140 Mpc !

<u>Major uncertainties:</u>

1. Relativistic growth times
2. Nonlinear saturation
3. Initial rotation rates of protoneutron stars – event rate
4. Effect of magnetic fields

Nonlinear Simulation F-Mode Instability

Shibata & Karino, 2004

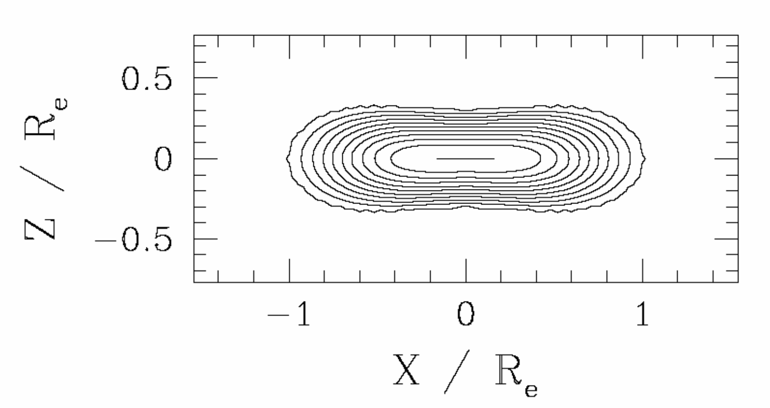
Newtonian + accelerated g-r-r

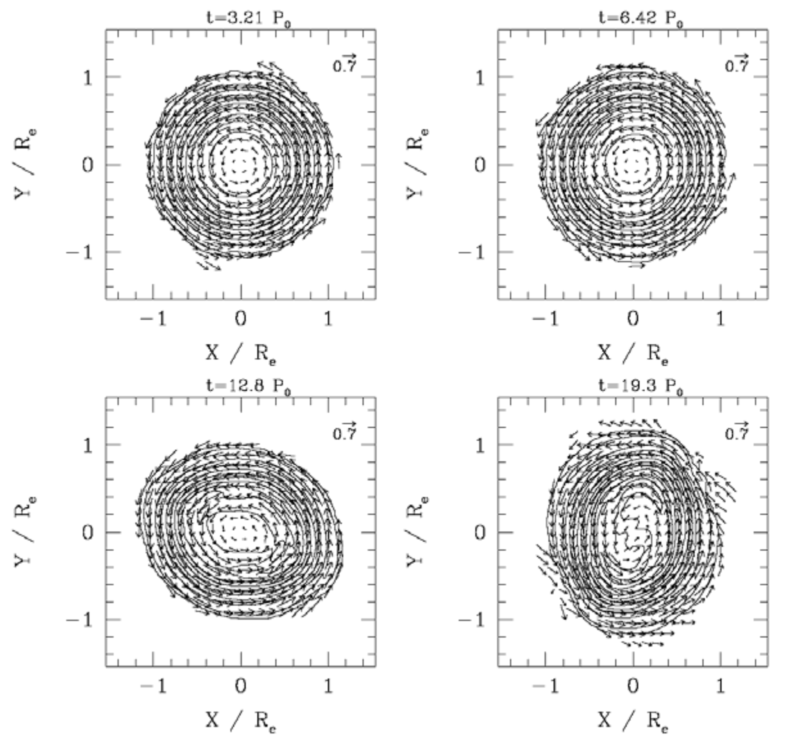
N=1 polytrope

Differentially rotating

T/W~0.27

-> *star becomes like Riemann-S ellipsoid*





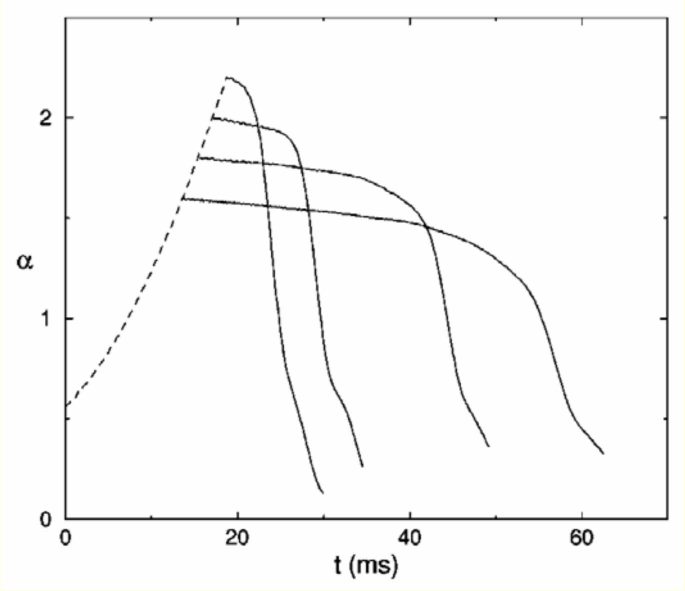
Agrees with basic conclusions of Lai & Shapiro.

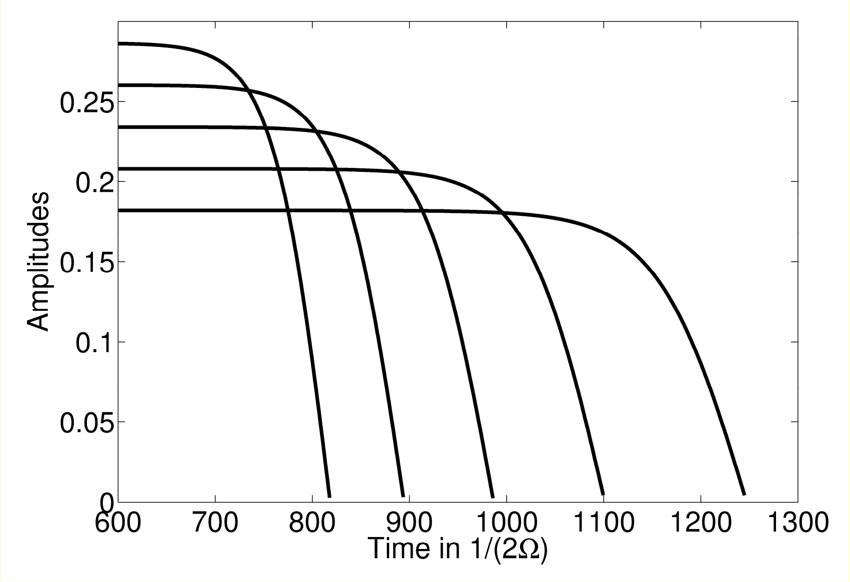
Major uncertainty:

Nonlinear saturation.

Saturation of Nonlinear R-Modes

Long-term nonlinear evolution of r-modes using two different methods:



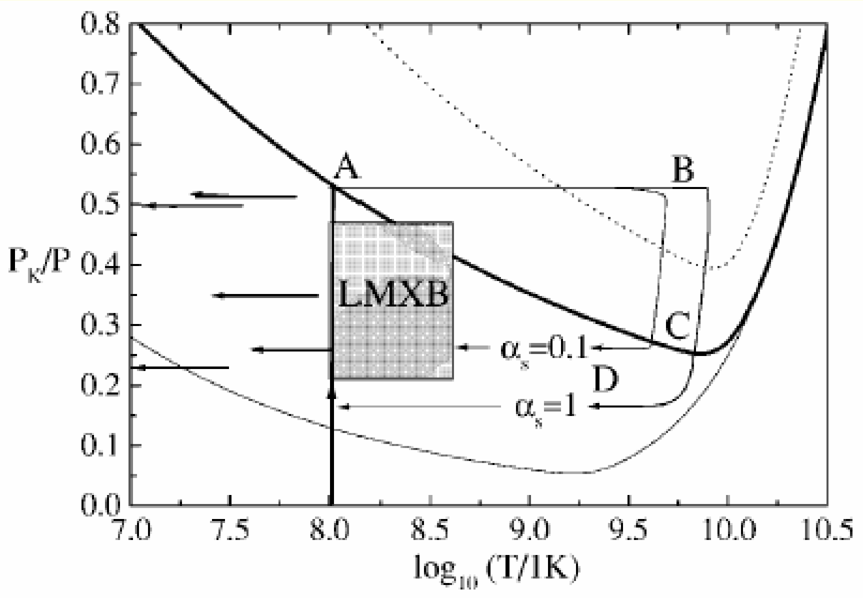


Gressman, Lin, Suen, N. S. & Friedman (2002)

Morsink (2002)
Schenk, Arras, Flanagan, Teukolsky, Wasserman (2002)
Arras, Flanagan, Morsink, Schenk, Teukolsky, Wasserman (2003)
Brink, Teukolsky, Wasserman (2004a, 2004b)

When scaled to same resolution, both methods agree that saturation amplitude is small, of $O(10^{-3})$.

R-Mode Instability in LMXBs



Andersson, Kokkotas, N.S., 1999

Even with a small saturation amplitude, the r-mode instability can operate in LMXBs, balancing the accretion torque.

The signal is nearly monochromatic and if persistent, it could be detected with a few weeks of signal integration for galactic sources.

To reduce computational costs in the search, accurate *r*-mode frequencies are needed (work in progress).