High Frequency GW Sources

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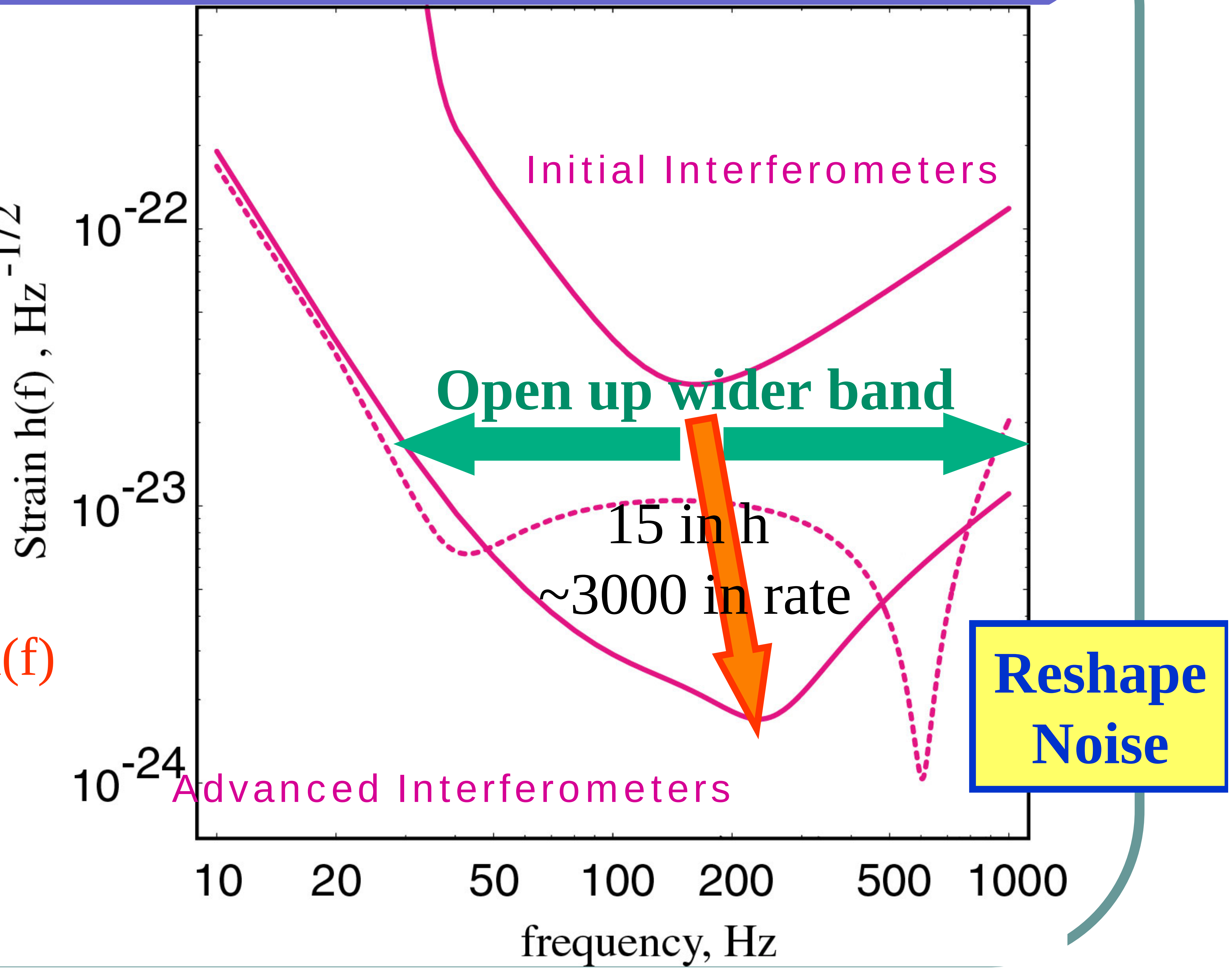
From LIGO to Advanced LIGO

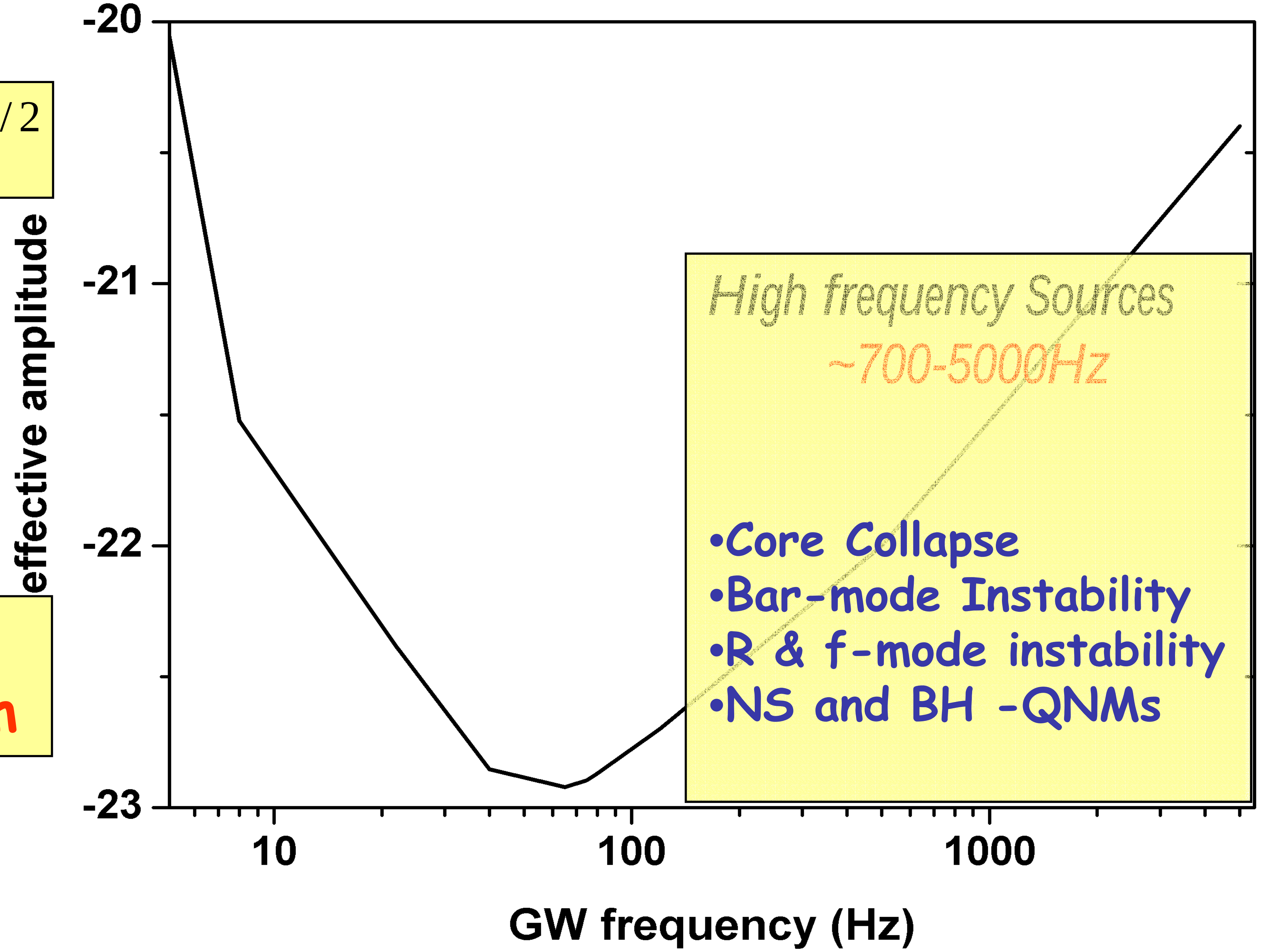


$h_{rms} = h(f)\,\sqrt{f} \sim 10\,h(f)$

The (very) high frequency window

$$f = (GM / R^3)^{1/2}$$

Mass: ~1-10M$_\odot$
Radius: ~10-30km



High Frequency Sources

- Core Collapse
  - Accretion Induced Collapse
- Bar modes
- R-modes
- BH ringing
- NS ringing
- LMXBs

Useful references:

- Fryer, Holz, Hughes, Woosley, Warren, Kalogera, Palomba
- Dimmelmeir, Font , Muller, Ruffert, Janka
- Van Putten
- Kobayasi, Meszaros
- Centrella, New, Tohline
- Shibata, Saijo, Eriguchi, Karino
- Baumgarte, Shapiro, Centrella
- Lindblom, Vallisneri, Tohline
- EU Network...

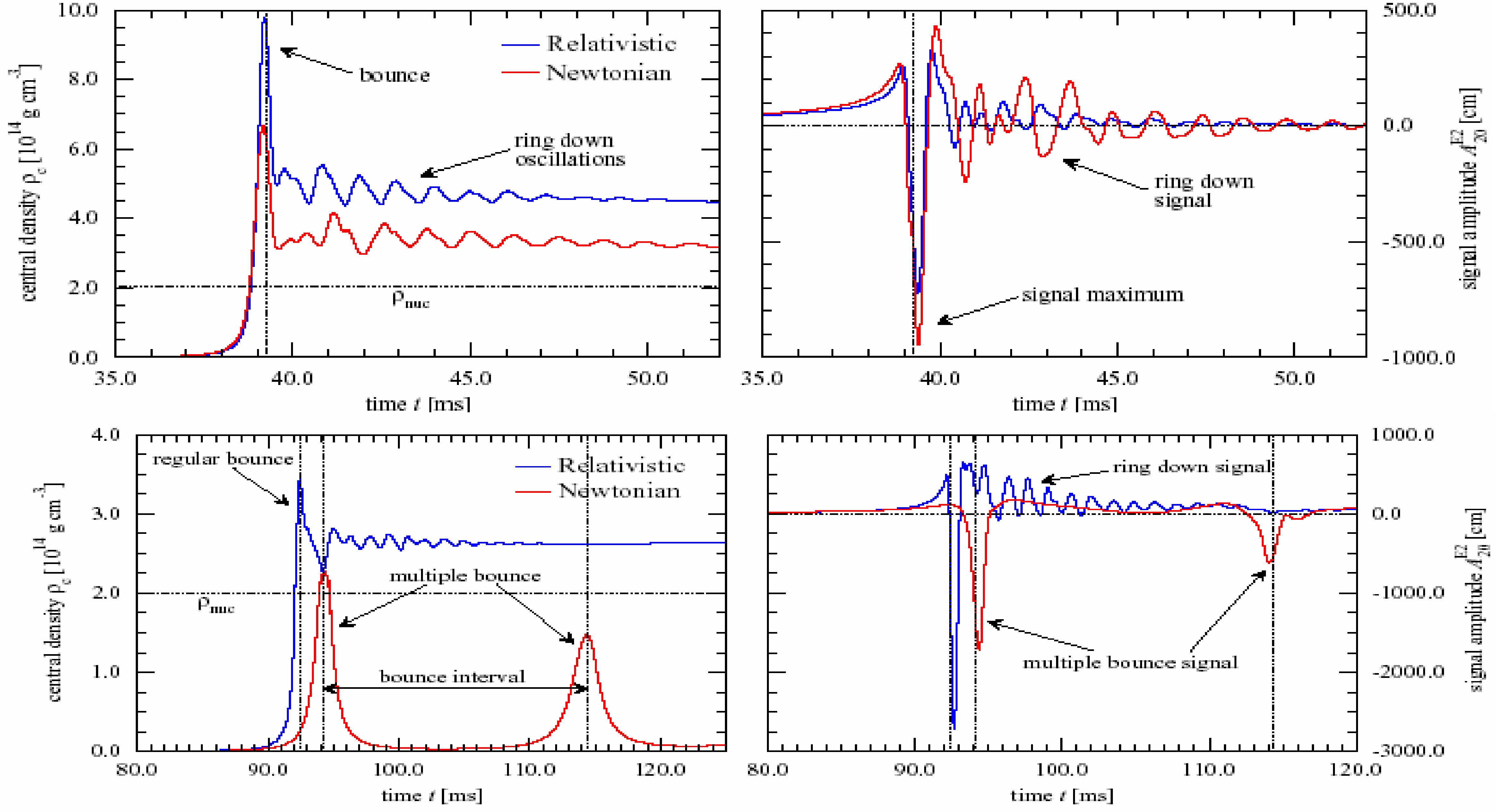
Core-Collapse Supernovae I

- Stars more massive than $\sim 8M_{\odot}$ end in core collapse ($\sim 90\%$ are stars with masses $\sim 8\text{-}20M_{\odot}$).
- ***Most of the material is ejected***
- If $M>20M_{\odot}$ more than 10% falls back and pushes the PNS above the maximum NS mass leading to the formation of BHs (type II collapsars).
- If $M>40M_{\odot}$ no supernova is launched and the star collapses to form a BH (type I collapsars)
- Formation rate:
  - 1-2 per century in the Galaxy (*Cappellaro & Turatto*)
  - 5-40% of them produce BHs through the fall back material (*Fryer & Kalogera*)
  - Limited knowledge of the rotation rate! Initial periods probably <20ms.
  - *Chernoff & Cordes* fit the initial spin with a Gaussian distribution peaked at 7ms. This means that 10% of pulsars are born spinning with millisecond periods.

Core-Collapse Supernovae II

Dimmelmeir, Font & Muller 2002

- Rotation increases strongly during the collapse.



•Multiple bounces are possible for a few models.

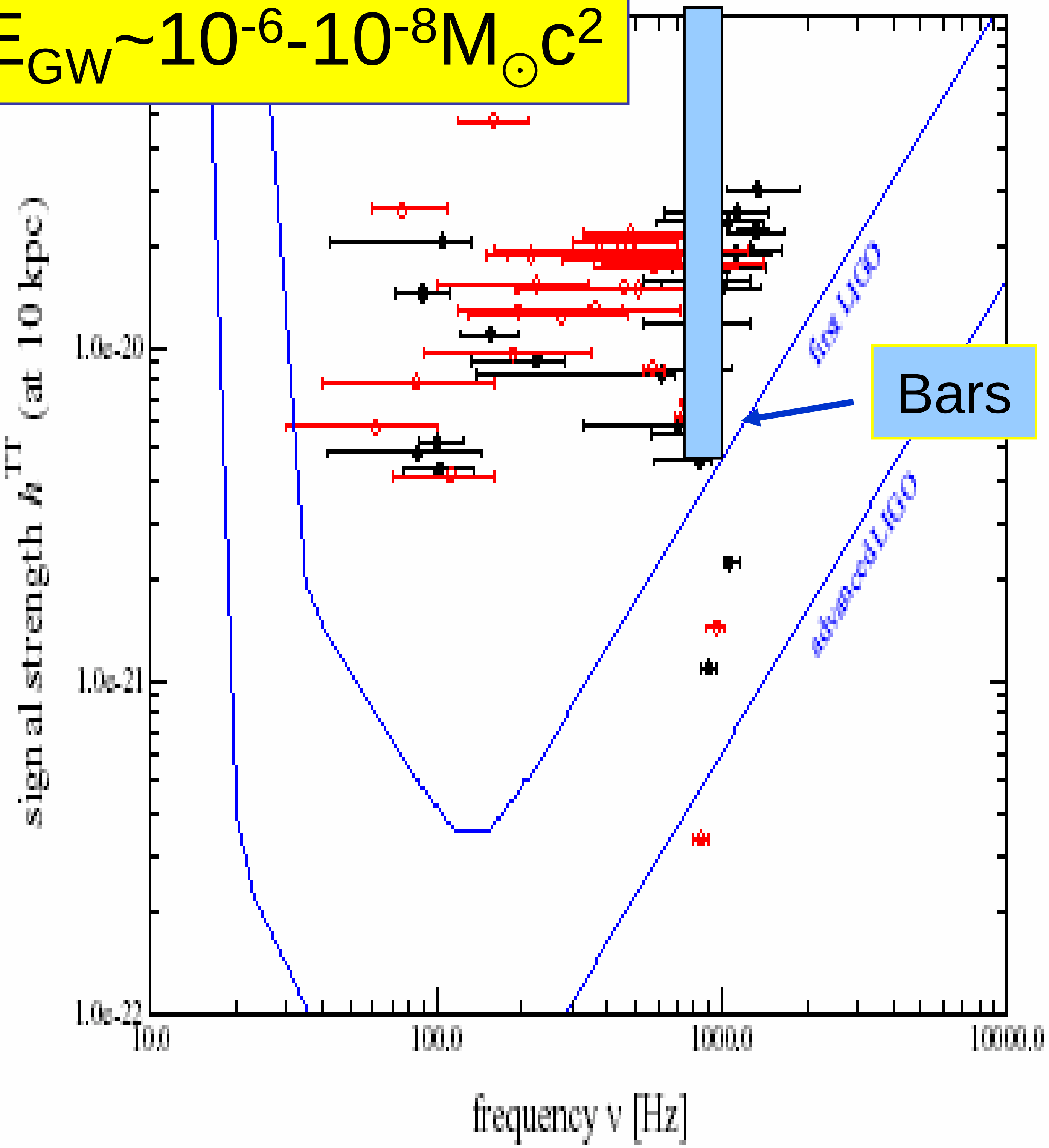
Core-Collapse Supernovae III

- GW amplitude

$$h \simeq 10^{-23} \frac{10 Mpc}{d}$$

- **Signals from Galactic supernova detectable.**
- Convective "boiling" observable to LMC
- Frequencies $\lesssim$**1 kHz**
- The numerical estimates **are not conclusive.** A number of effects *(GR, non-axisymmetric instabilities)* **have been neglected!** (2D collapse, Mathews-Wilson approximation…)
- Kicks suggest that a fraction of newly born NSs (and BHs) may be strongly asymmetric.
- Polarization of the light spectra in SN indication of asymmetry.

$E_{GW} \sim 10^{-6}$-$10^{-8} M_{\odot} c^2$



Dimmelmeir, Font & Muller 2002

Accretion Induced Collapse

When a white dwarf (WD) exceeds the Chandrasekhar limit due to accretion of material, it begins to collapse.

- The cooling via neutrino does not reduce the heating significantly and the collapsing WDs reach appropriate temperatures for ignition of nuclear burning (Type Ia supernova).
- About $0.1M_{\odot}$ material is ejected
- Since the WD is pushed over the Chandrasekhar limit due to accretion will rotate fast enough to allow various types of instabilities.
- Reheating due to the fall back of material possibly will excite the r-mode instability.
- Minimum rate at which Chandrasekhar-massed WD are produced in the Galaxy: $\sim 4\times10^{-3}$/yr.
- Galactic rate of accretion induced collapse: $\sim 10^{-5}$/yr i.e. about 1000 times rarer than core collapse SN.

Bar-mode instability

For rapidly (differentially!) rotating stars with:

$$\beta = \frac{T}{|W|} > \beta_{\rm dyn} \approx 0.27$$

the "bar-mode" grows on a dynamical timescale.

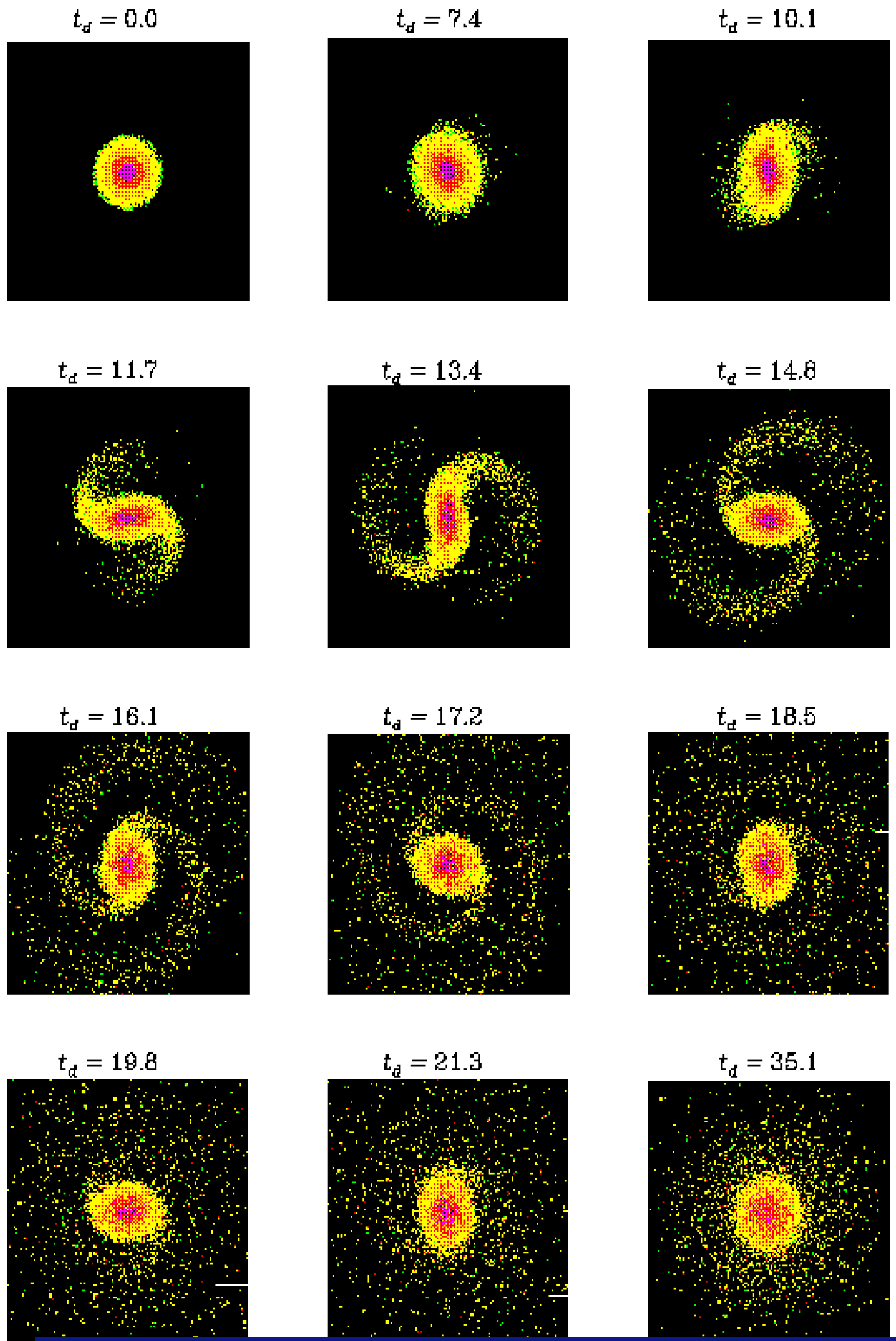
$$h \approx 10^{-22} \left(\frac{\varepsilon}{0.2}\right)\left(\frac{f}{3\ \mathrm{kHz}}\right)^2 \left(\frac{15\ \mathrm{Mpc}}{\mathrm{d}}\right) M_{1.4} R_{10}^2$$

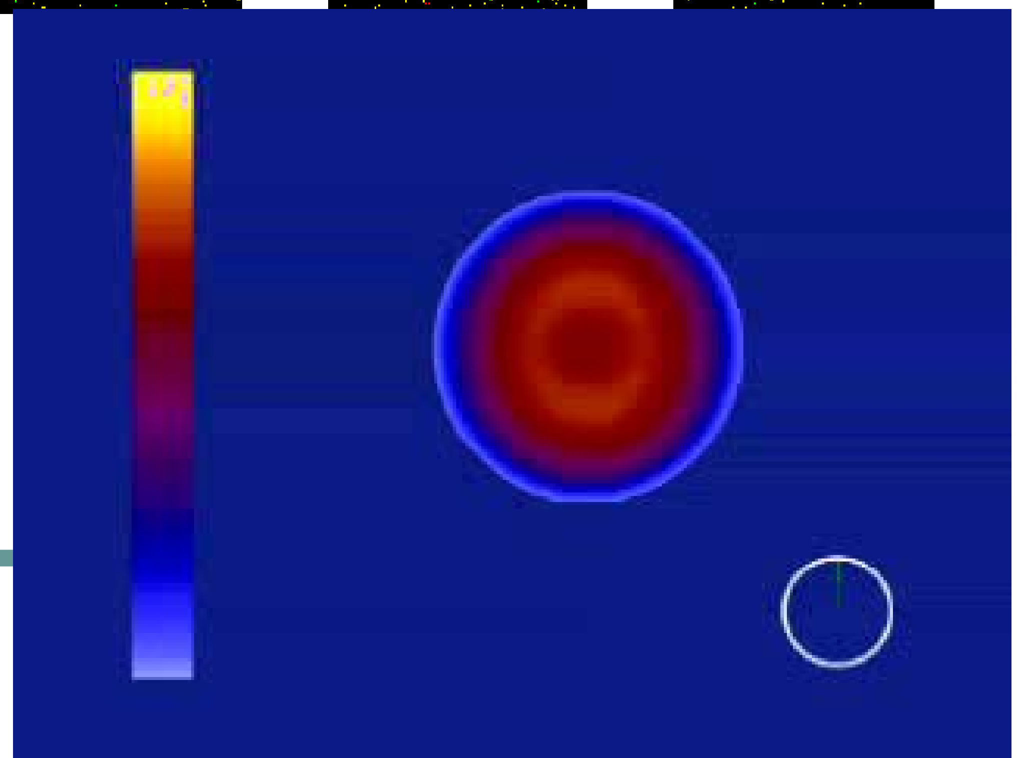
If the bar persists for many (~10-100) rotation periods, the signal will be easily detectable from at least Virgo cluster.

–A considerable number of events per year in Virgo: ***≤10⁻²/yr/galaxy***

–Frequencies ~1-3kHz

Centrella etal
Shapiro etal



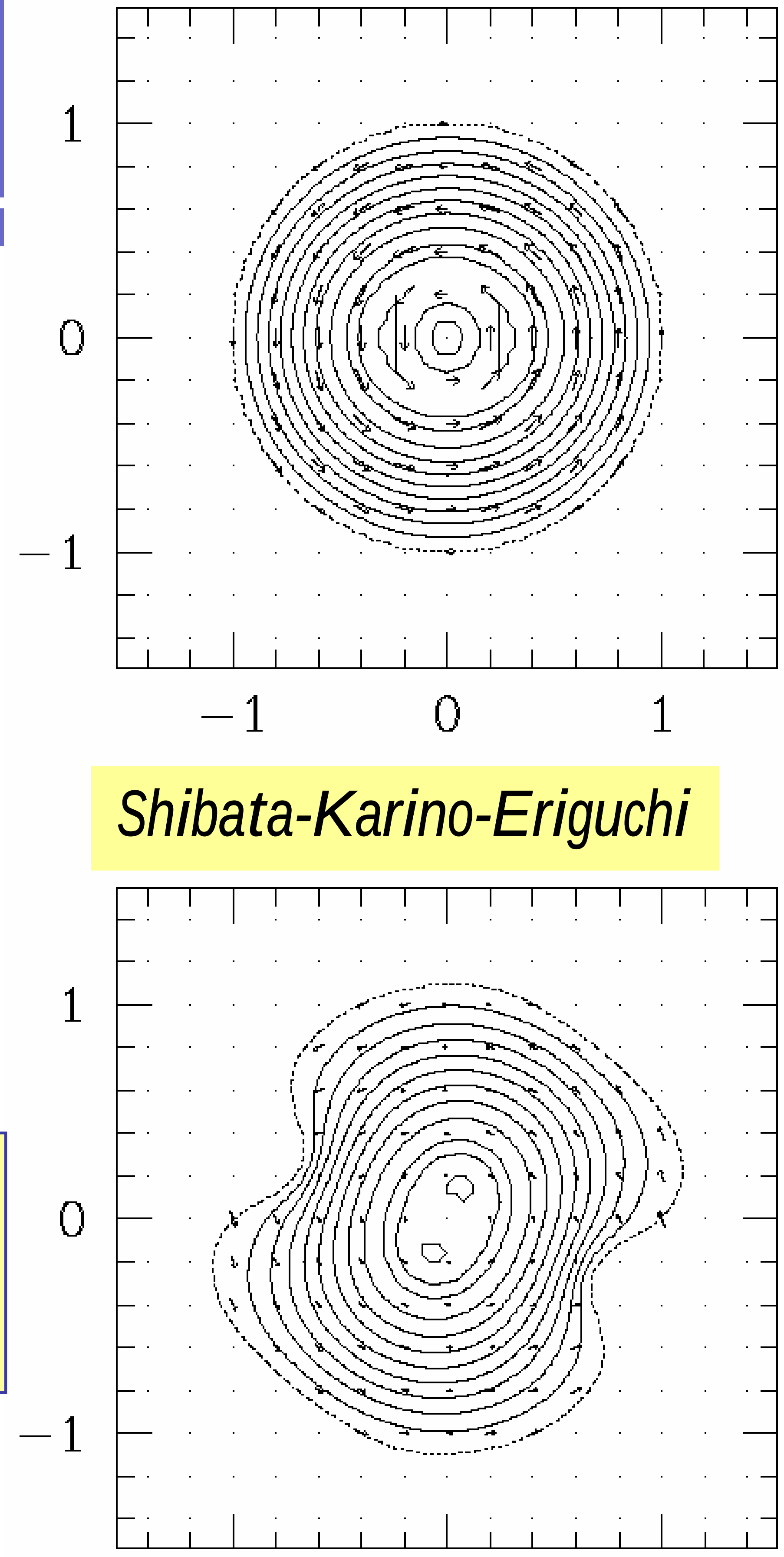


Bar Modes II

- **GR enhances the onset of the instability ($\beta_{dyn} \gtrsim 0.24$) and β decreases with increasing M/R.**
- **Bar-mode instability might happen for much smaller β if centrifugal forces produce a peak in the density off the source's rotational center.**
- **Highly differentially rotating stars are shown to be dynamically unstable for significantly lower β (even when $\beta \gtrsim 0.01$).**

$$h_{eff} \simeq 3\times10^{-22}\left(\frac{f}{800Hz}\right)\left(\frac{R_{eq}}{30km}\right)^{-1/2}\left(\frac{M}{1.4M}\right)^{3/2}\left(\frac{100Mpc}{d}\right)$$

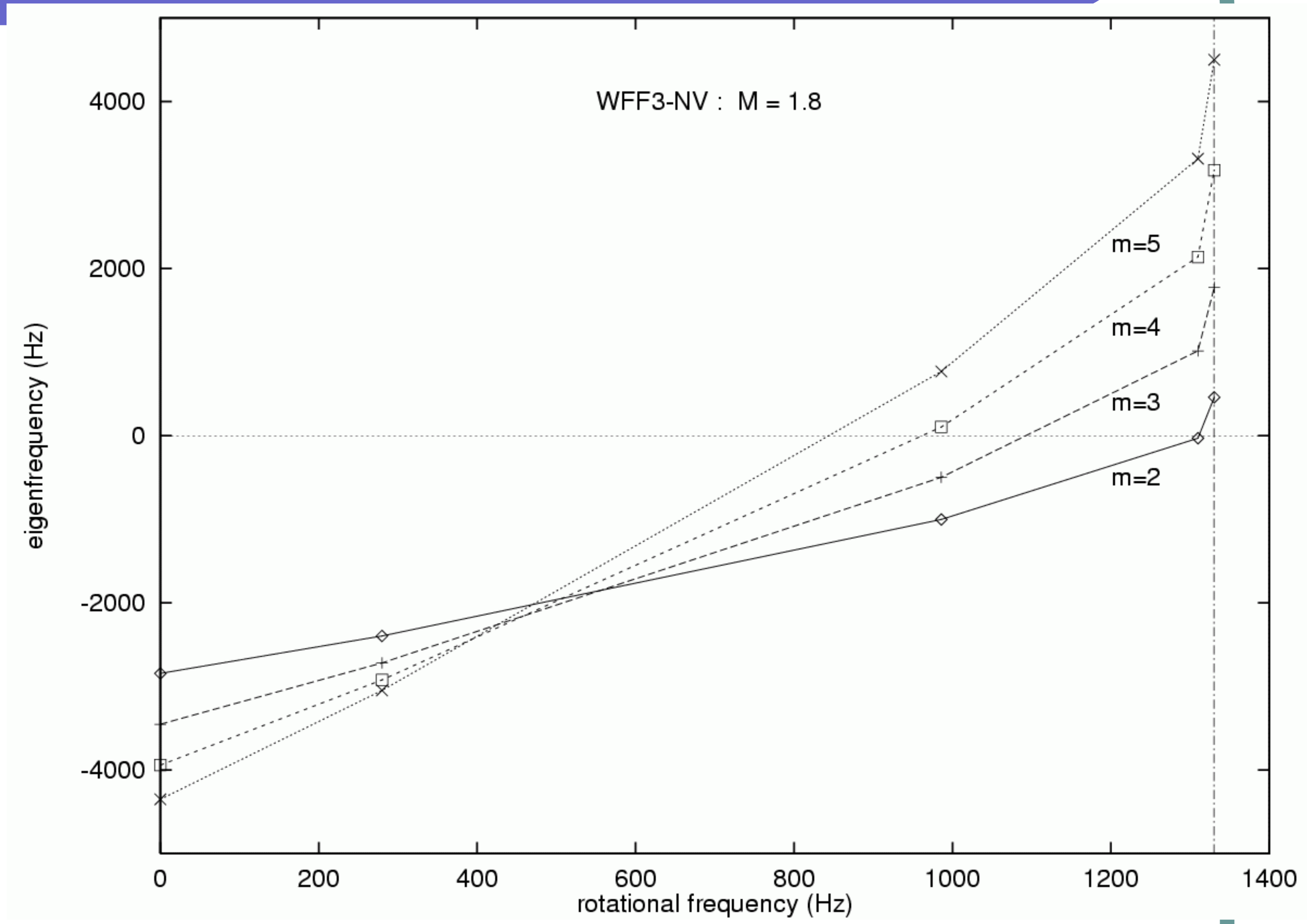
- **Bars can be also created during the merging of NS-NS, BH-NS, BH-WD and Collapsars (type II).**



Shibata-Karino-Eriguchi

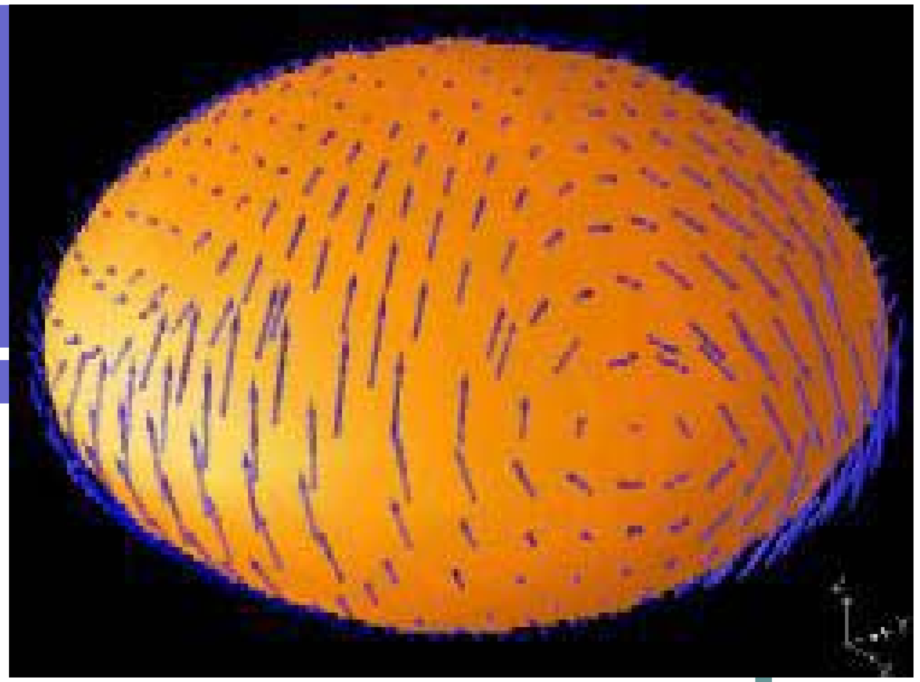
CFS Instability: F-modes

- **F-mode - dominated by density variations**
- Large *m* modes go unstable first but their growth times are unphysically large.
- Excellent source
- Signal detectable from Virgo cluster even with LIGO-I sensitivity
- Spans a wide range of frequencies: 1000->100Hz
- Excitation, for $\Omega \gtrsim 0.85\Omega_K$
- Viscosity might suppresses instability.



$$\omega_{\text{inert}} = \omega_{\text{rot}} - m\Omega < 0$$

CFS instability: r-modes



In a frame rotating with the star, the r-modes have frequency *(l=m=2)*

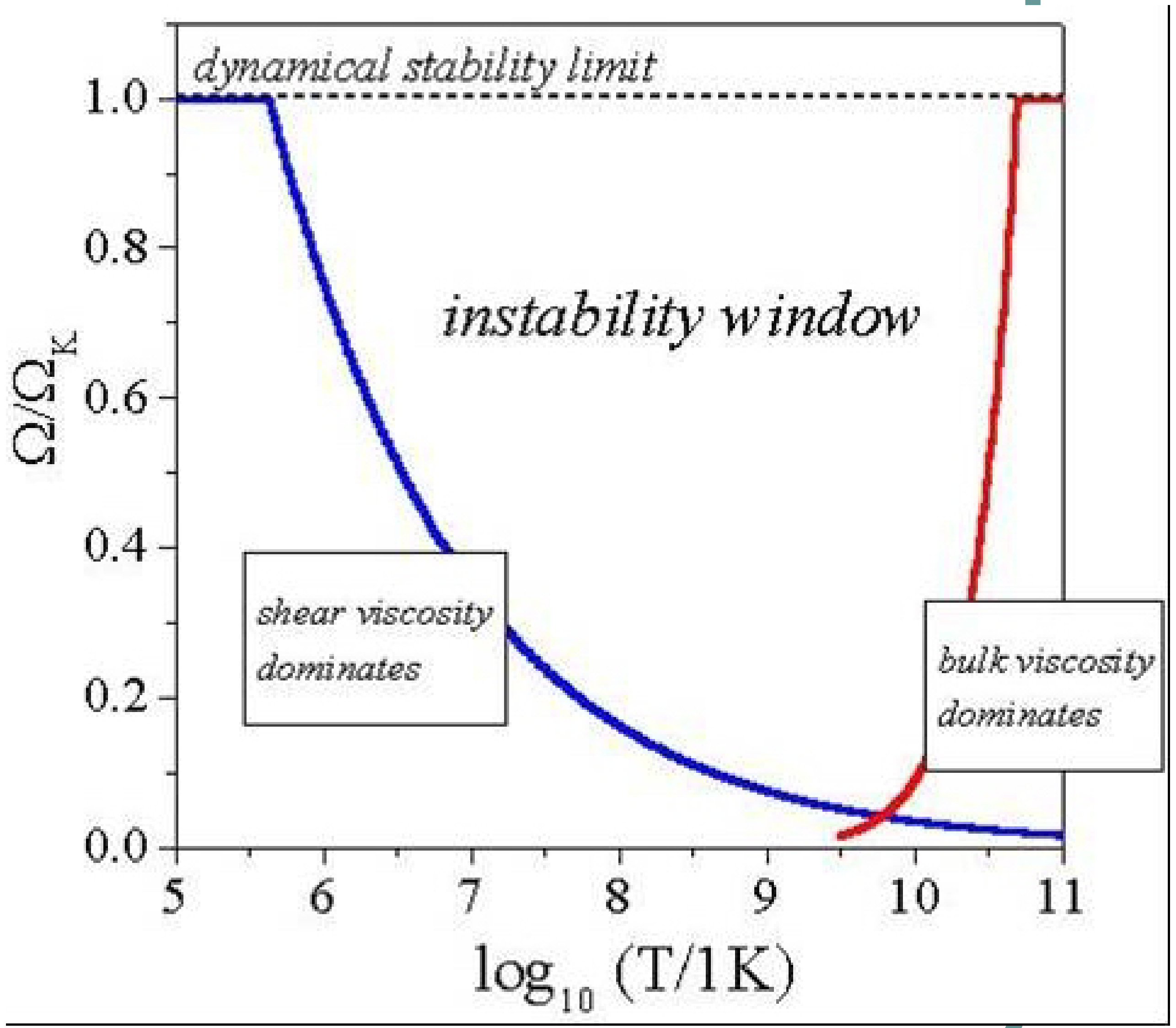
$$\omega = -\frac{2}{3}\Omega$$

Meanwhile in the inertial frame

$$\omega = -\frac{4}{3}\Omega$$

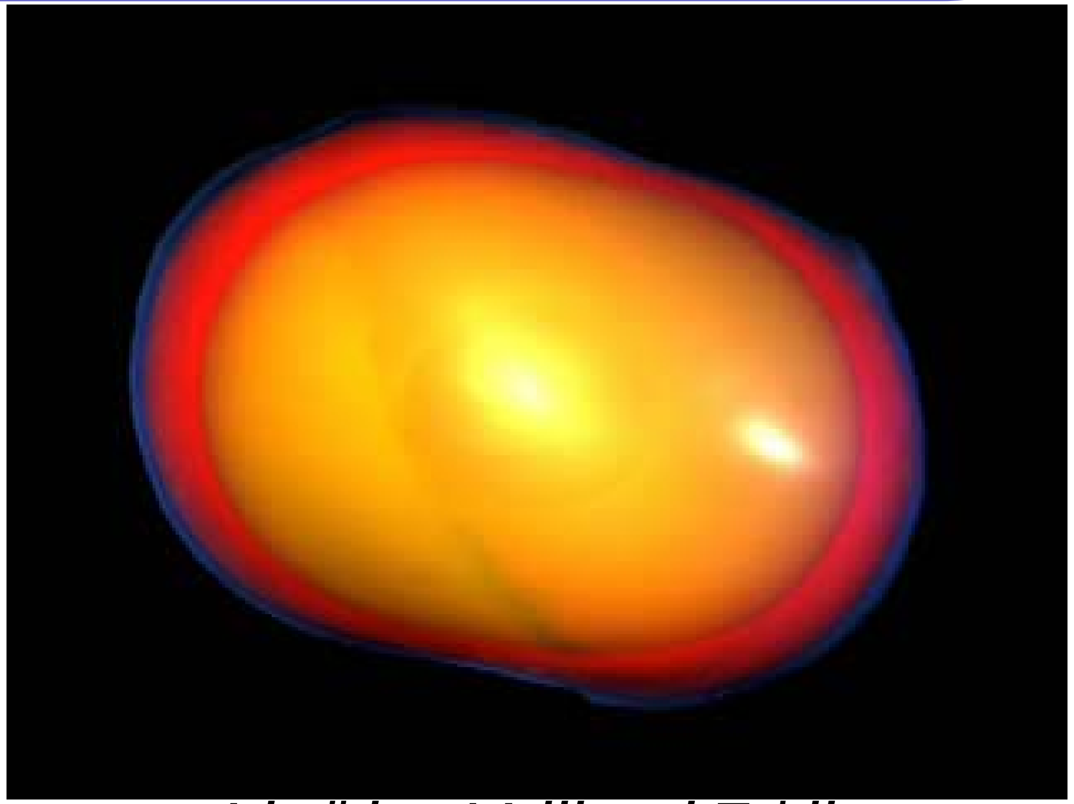
The r-modes are unstable to the emission of GWs at all rotation rates!

The $l=m=2$ r-mode grows on a timescale of 20-50secs



CFS instability: r-modes

- GW amplitude depends on α (the saturation amplitude).
- Mode coupling might not allow the growth of instability to high amplitudes *(Schenk etal)*
- The existense of *crust*, hyperons in the core, magnetic fields, affect the efficiency of the instability.
- For newly born neutron stars might be quite weak ; unless we have the creation of a strange star
- Old accreting neutron (or strange) stars, probably the best source! (400-600Hz)



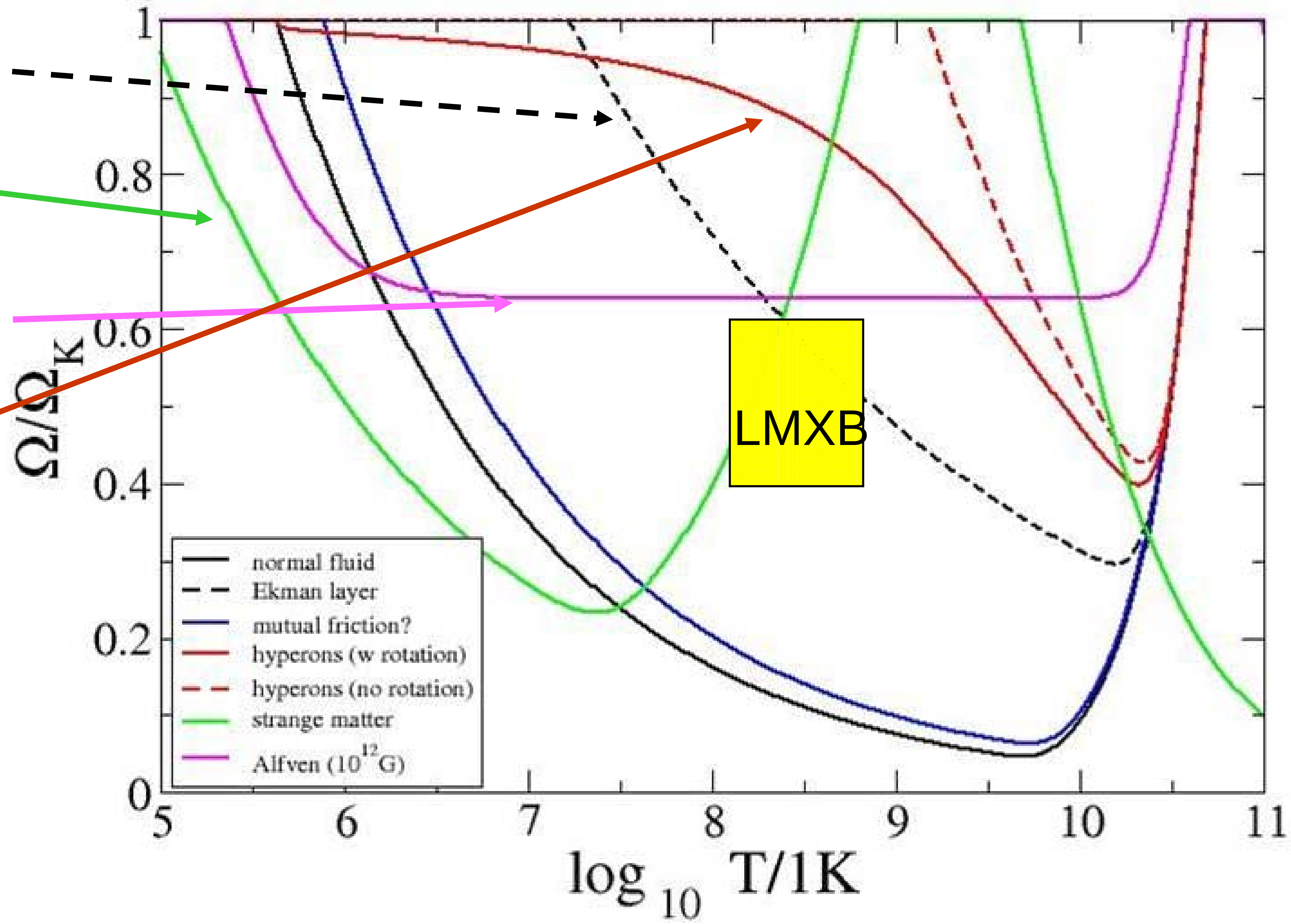
Lindblom-Vallisneri-Tohline

$$h(t) \approx 10^{-22} \alpha \left(\frac{\Omega}{1\ \mathrm{kHz}} \right) \left(\frac{1\mathrm{Mpc}}{d} \right)$$

$$\alpha \simeq 10^{-2} - 10^{-3}$$

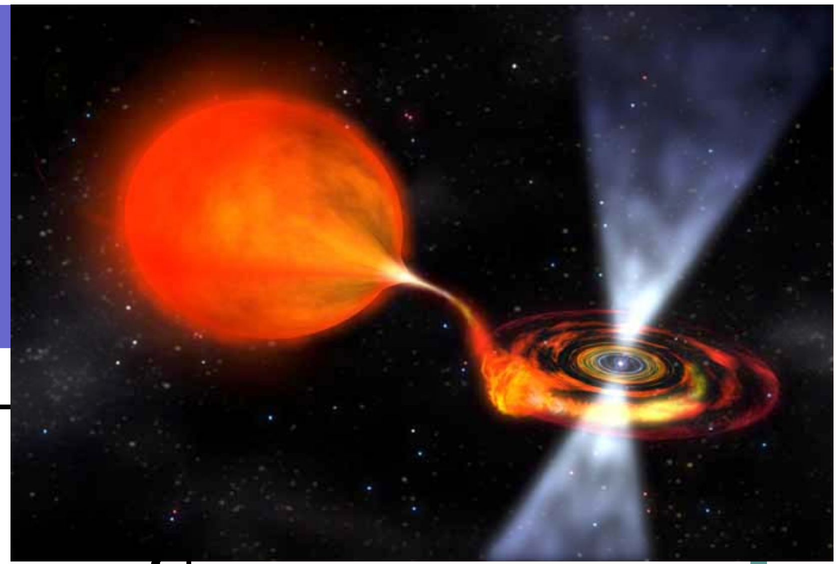
R-mode instability vs EOS

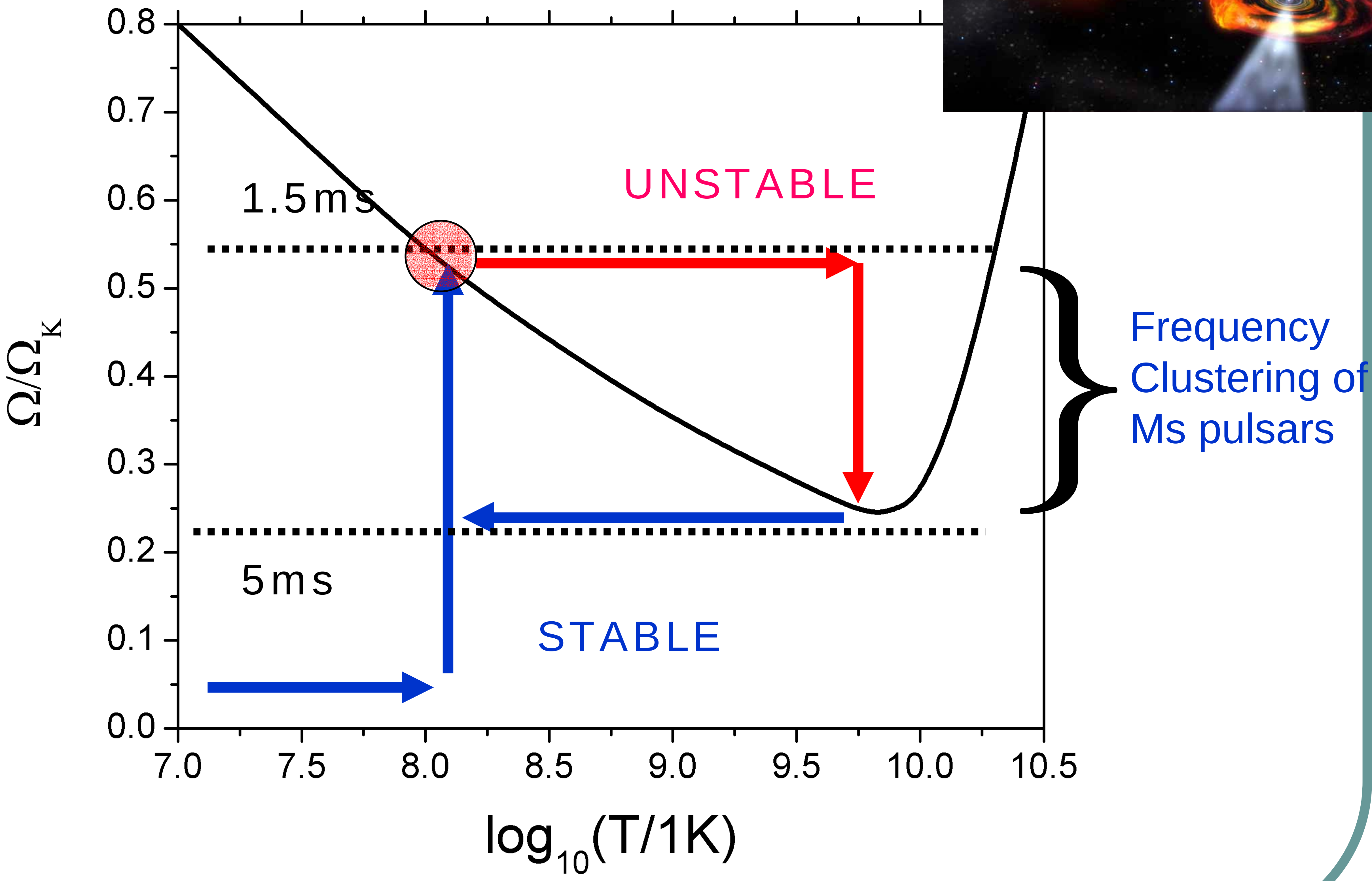
- Crust
- Strange star
- Magnetic field
- Hyperon core



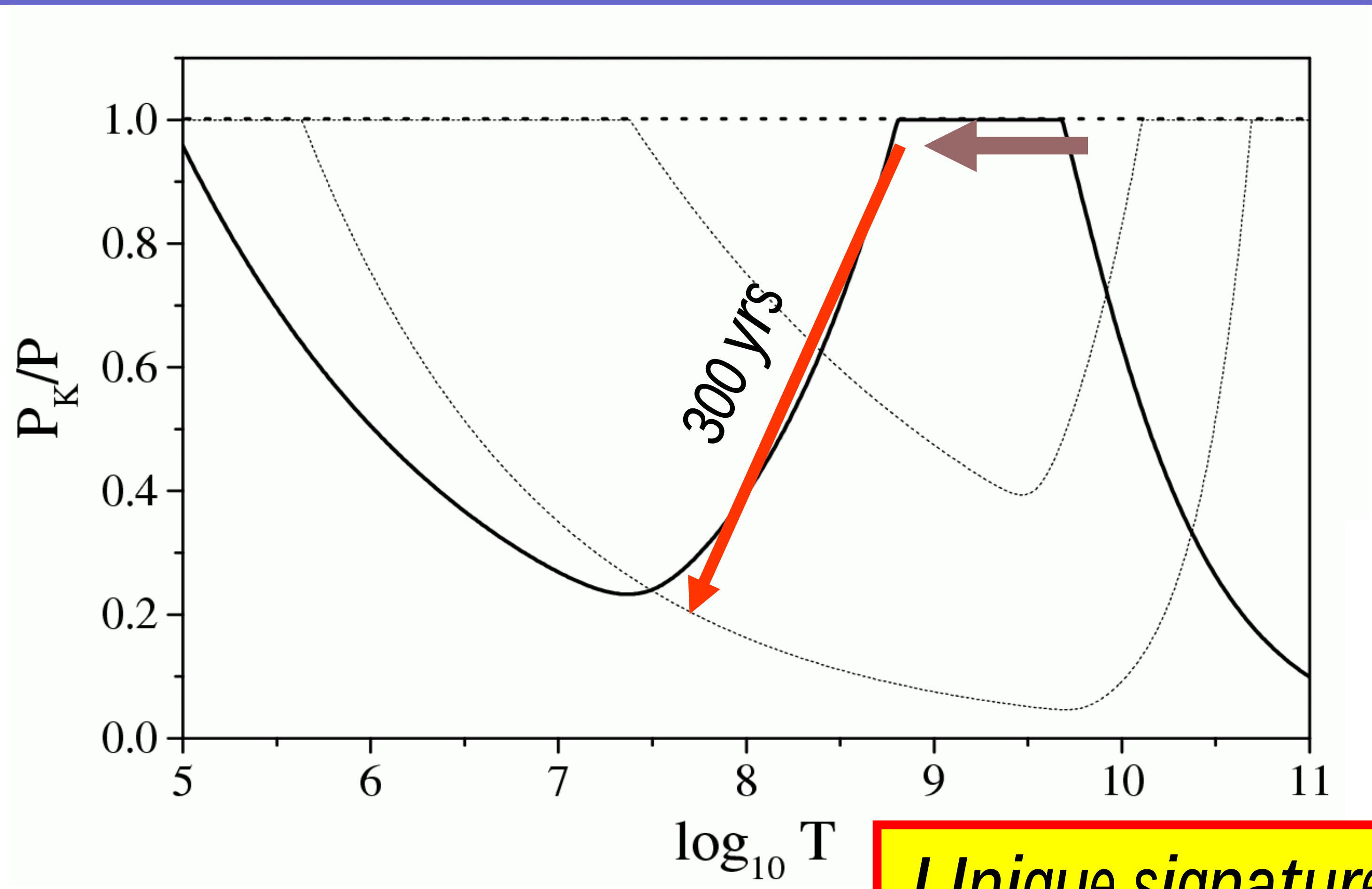
LMXBs & r-modes

LMXBs & r-modes

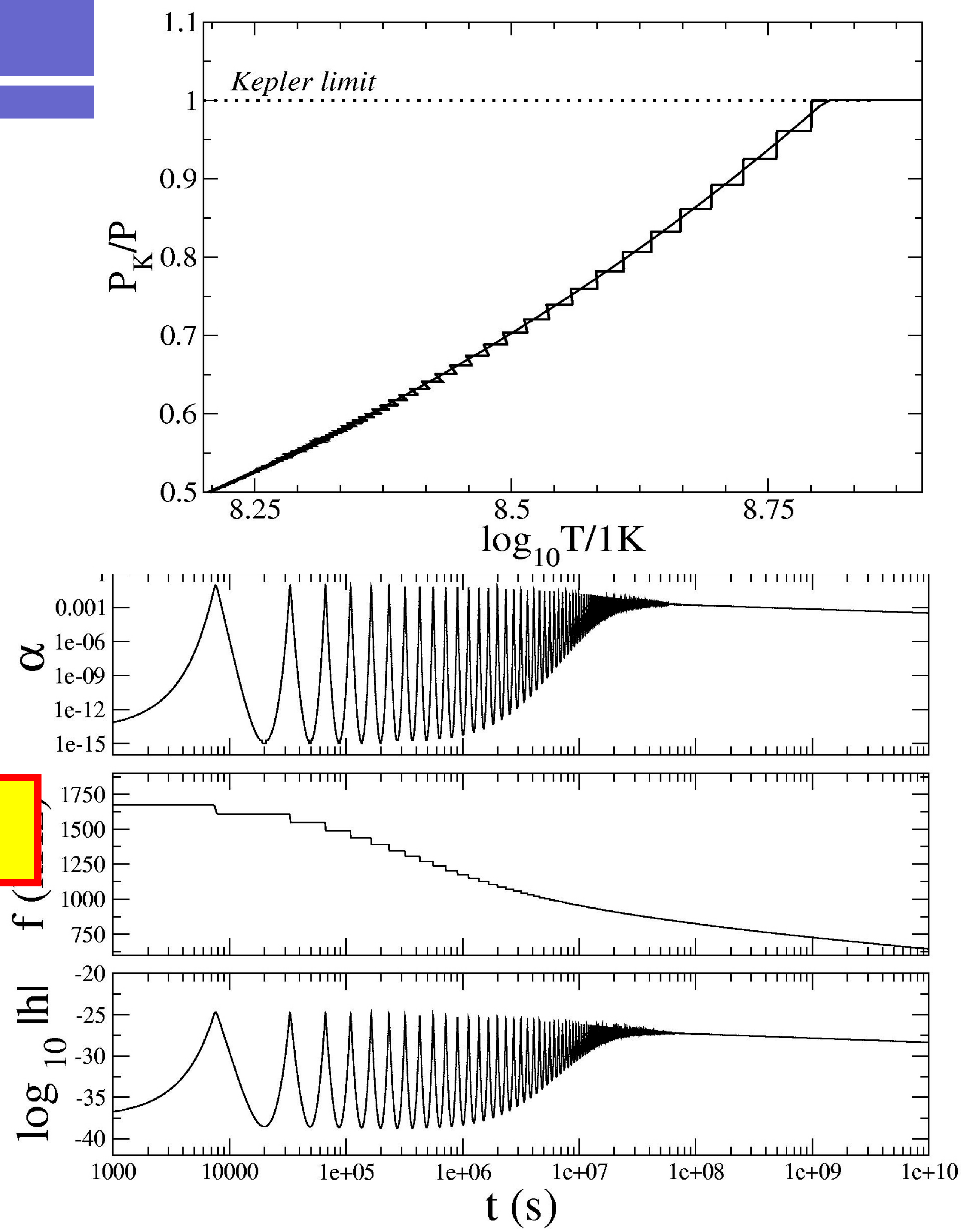




R-modes in young strange stars



Unique signature



- Lasts more than ~ 300yrs
- A few weeks: $h_{eff} \sim 10^{-21}$ (r~10kpc)
- 5-10 might be active in our Galaxy!

Andersson, Jones, KK

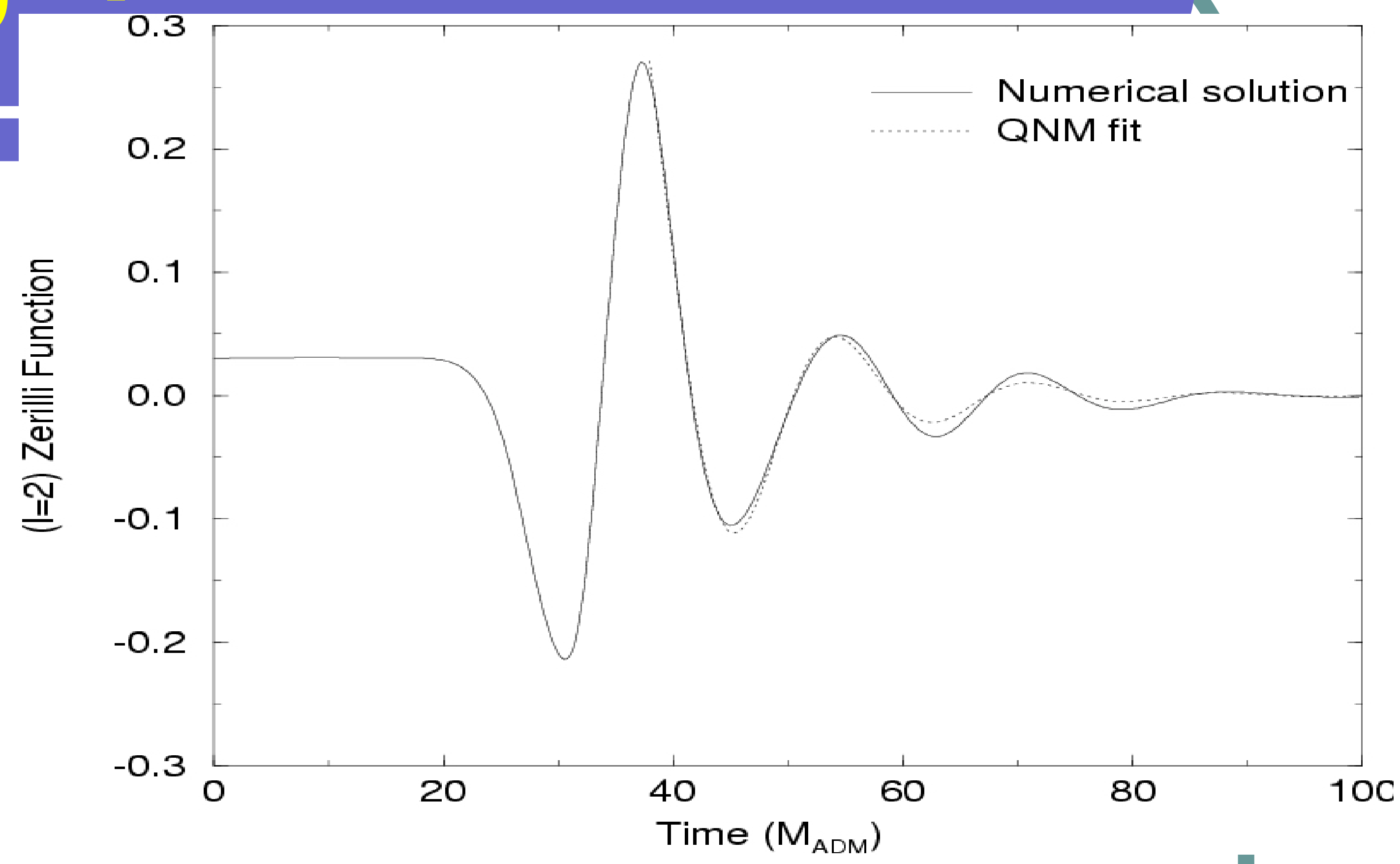
Fragmentation and Fallback

- A significant amount of remnants can fallback, subsequently spinning up and reheating the nascent NS.
- Instabilities can be excited again during such a process.
- BH-QNMs can be excited for as long as the process lasts.
- "Collapsars" accrete initially (for about ~2-3s) at rates ~1-2$M_\odot$/sec ! Later at a rate ~0.1$M_\odot$ /sec for a few tenths of secs.
- Typical frequencies: ~2kHz.
- If disk mass is :~1$M_\odot$ self-gravity becomes important and gravitational instabilities (spiral arms, bars) might develop and radiate GWs *(Davies et al 2002, Fryer et al 2002)*
- The collapse material might fragments into clumps, which orbit for some circles like a binary system (Fragmentation Instability). *Needs density distribution to peaks off the center (maybe in Population III stars).*

Black-Hole Ringing I

- The newly formed BH is ringing till settles down to the stationary Kerr state (QNMs).
- The ringing due to the excitation by the fallback material might last for secs
- Typical frequencies: ~1-3kHz
- The amplitude of the ringdown waves and their energy depends on the distortion of the BH.
- The energy emitted in GWs by the falling material is:

$\Delta E \gtrsim 0.01 \mu c^2 (\mu / M)$.

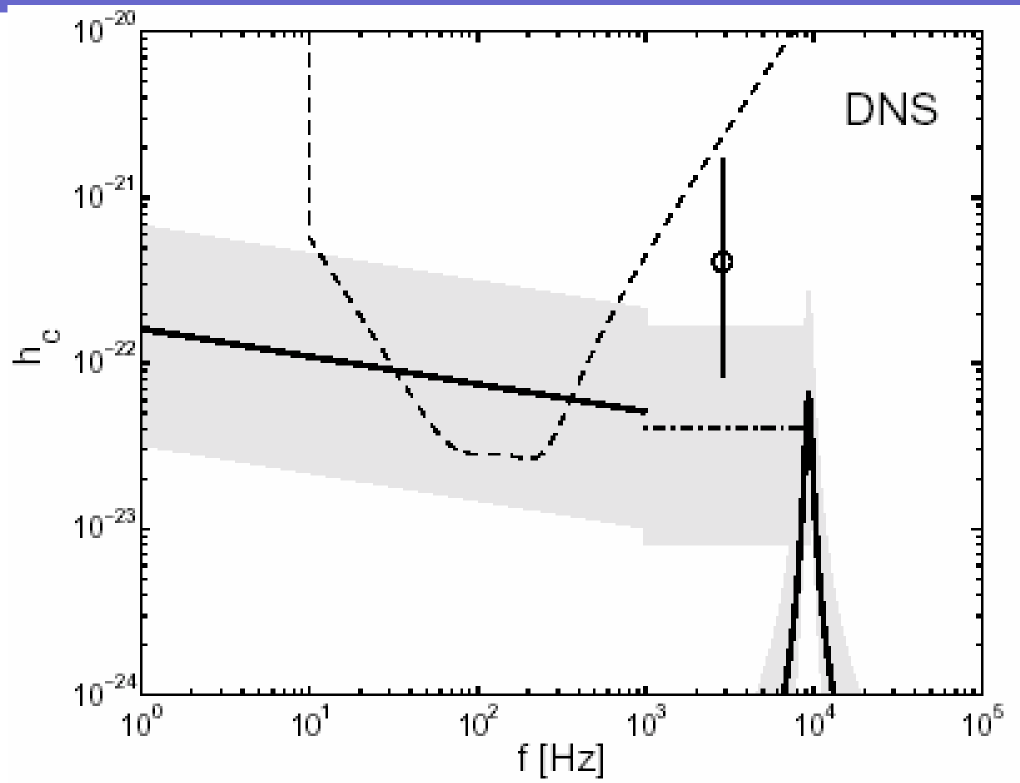


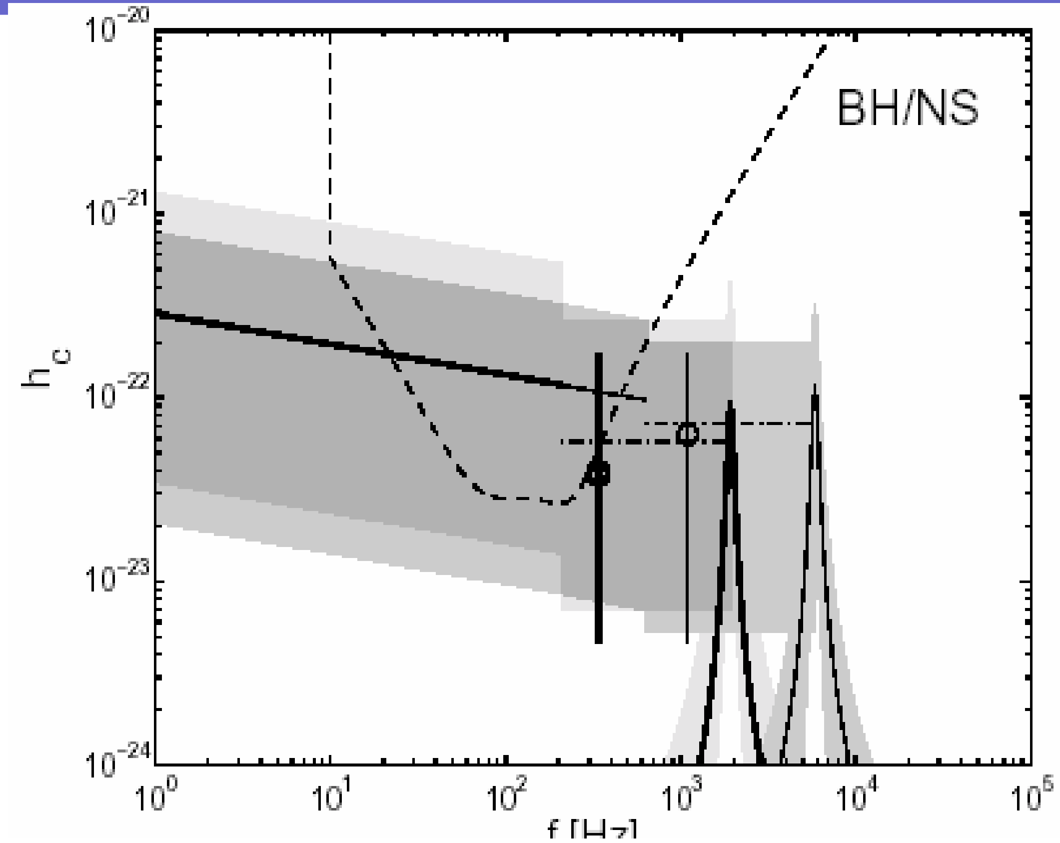
$$f \simeq 3.2\text{kHz}\ M_{10}^{-1}[1-0.63(1-a/M)^{3/10}]$$

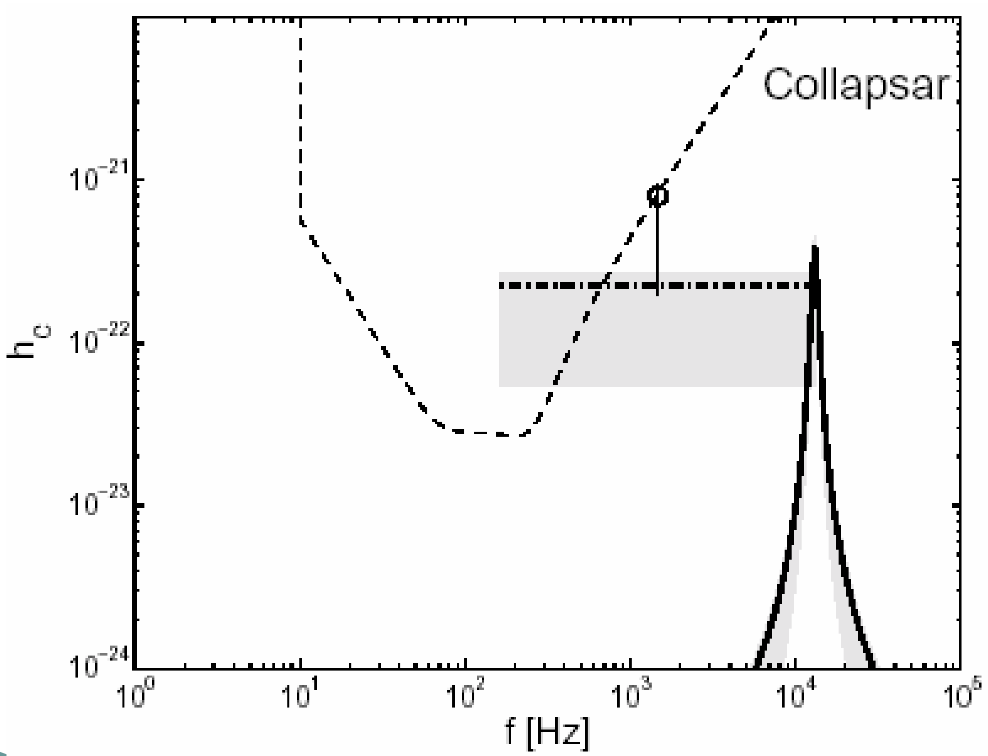
$$Q = \pi f \tau \approx 2(1-a)^{-9/20}$$

$$h_{\text{eff}} \approx 2\times 10^{-21}\left(\frac{\varepsilon}{0.01}\right)\left(\frac{d}{10\text{Mpc}}\right)^{-1}\left(\frac{\mu}{M_\odot}\right)$$

Black-Hole Ringing II et al







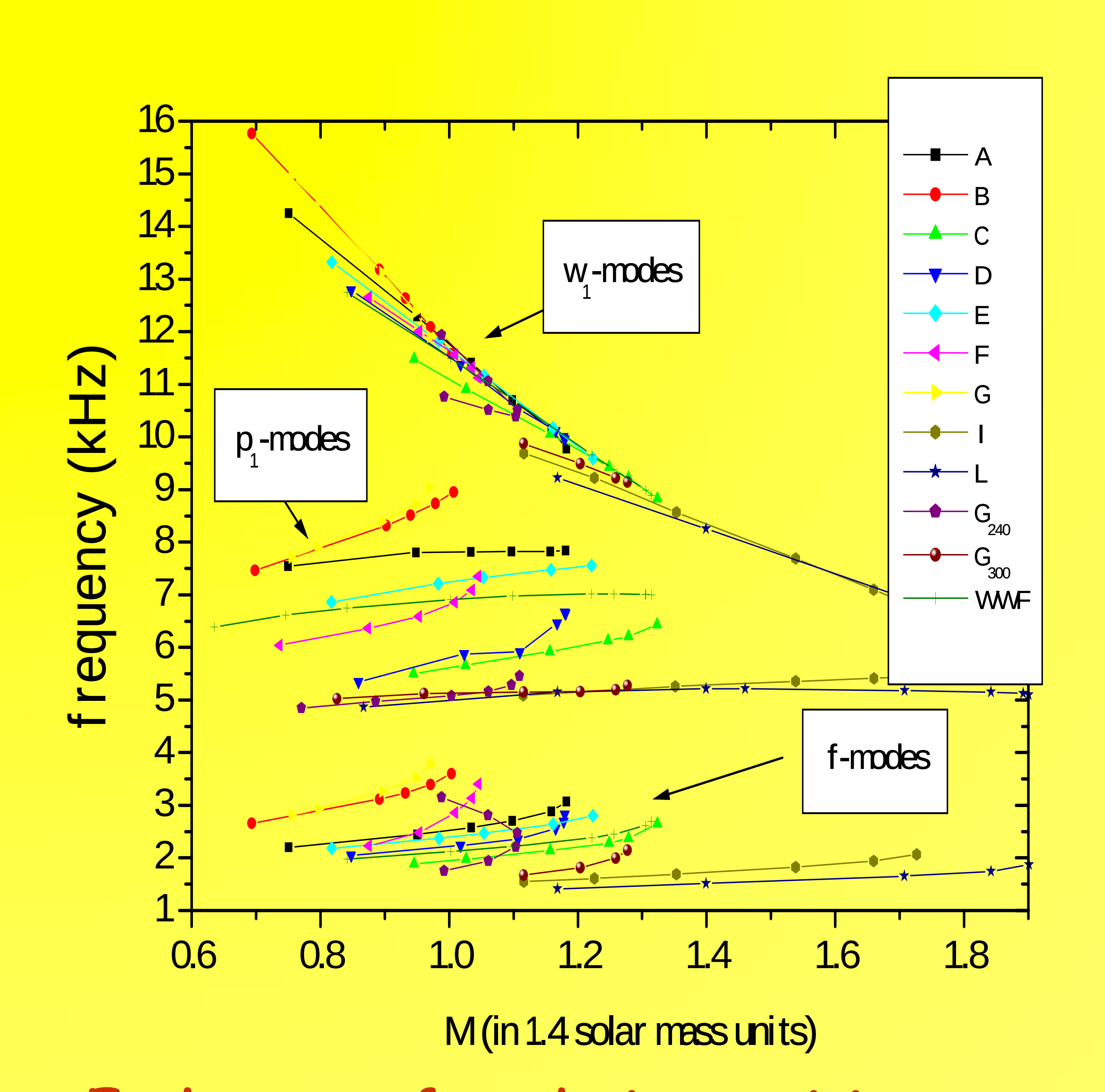
Kobayasi & Meszaros 2003

DNS : 220Mpc
BH/NS: 170 & 280 Mpc
Collapsar: 27 Mpc

Bar rotates: 10 times

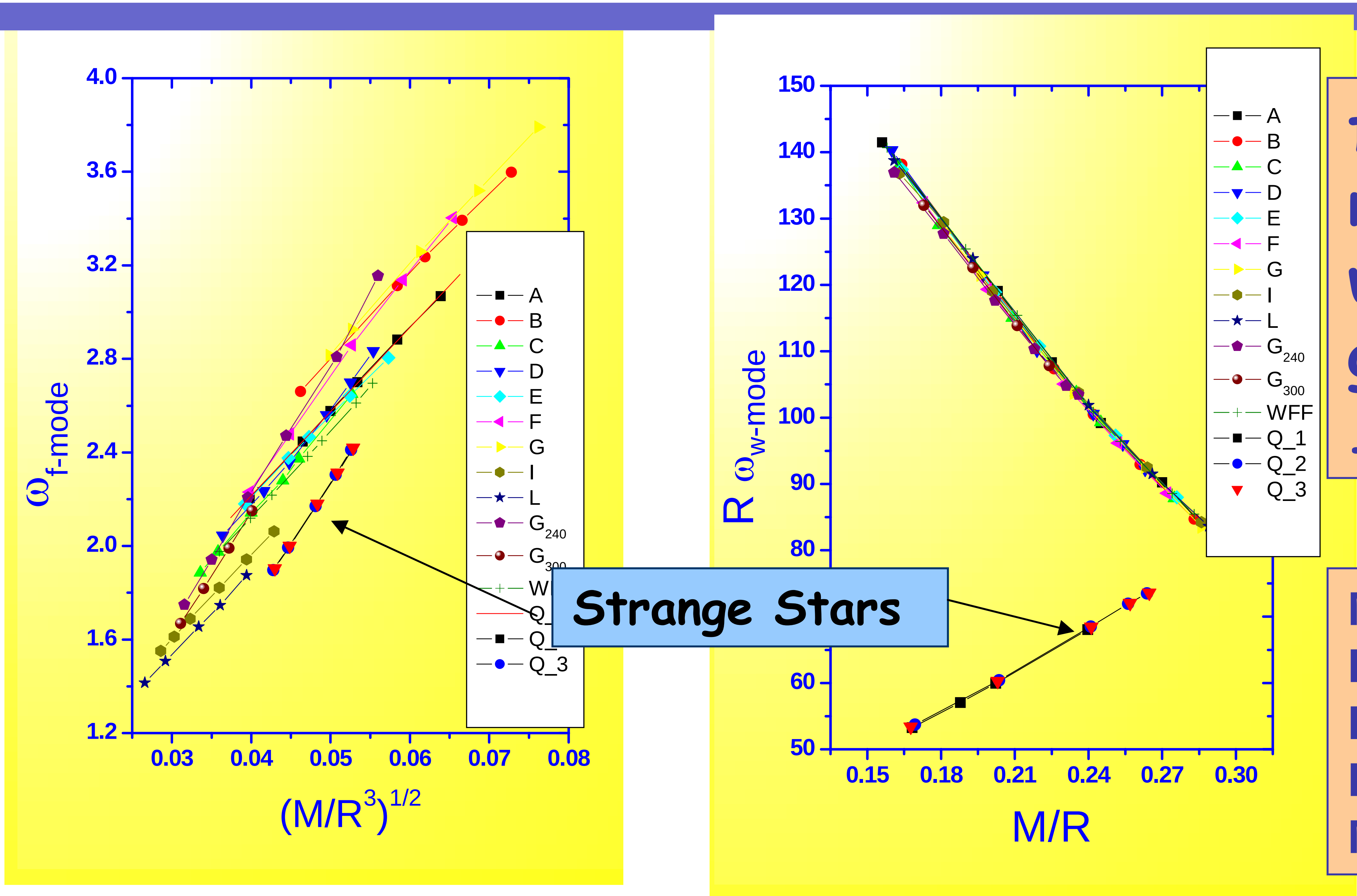
NS ringing : Stellar Modes

- **P-modes**: main restoring force is the **pressure**
- **G-modes:** main restoring force is the **buoyancy force** *(can become unstable)*
- **F-mode**: has an inter-mediate character of p- and g-mode *(can become unstable)*
- **W-modes:** pure **space-time modes** (only in GR) *(can become unstable)*
- **Inertial modes (r-modes)** :main restoring force is the **Coriolis force** *(can become unstable)*
- **Superfluid modes**: Deviation from chemical equilibrium provides the main restoring agent *(can become unstable)*



Each type of mode is sensitive to the physical conditions where the amplitude of the mode is greatest.

Grav. Wave Asteroseismology



f-modes
r-modes
w-modes
g-modes
…

Mass
Radius
EoS
Rotation Rate
Magnetic field

$$\omega_f\,(\mathrm{kHz}) \approx 0.78 + 1.637\left(\frac{M_{1.4}}{R_{10}^{\ 3}}\right)^{1/2} + \delta_1 m\Omega$$

$$\omega_w\,(\mathrm{kHz}) \approx \frac{1}{R_{10}}\left[20.92 - 9.14\frac{M_{1.4}}{R_{10}}\right] + \delta_2 m\Omega$$

Merging phase: NS/NS & BH/NS

- Tidal disruption of a NS by a BH *(Vallisneri)*
  - GWs could carry information about the EOS of NS eg. estimation of NS radius (15% error).
  - The disruption waves lie in the band 300-1000Hz
  - A few events per year at 140Mpc (LIGO-II)

- Merging of two Neutron Stars (*Rasio et al*)
  - Imprint of the NS radii just before merging (**$f \lesssim 1$kHz**)
  - During the merging we could get important information about the EOS (**$f \gtrsim 1$kHz**)

The high-frequency window