R-modes instability, gravitational waves and Einstein Telescope science

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Way R-modes could be interesting

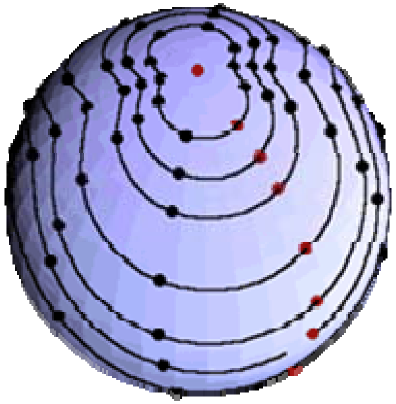
Sá and Tomé model (2005).

- R-modes can produce Gravitational waves
- The GW signals may carry information on:
  - gravitational physics
  - nuclear physics (that can't be done in other ways).

R-modes intro

- After the supernova event, the newborn neutron star may spin down during up to one year due to R-modes instability (first investigated by Owen at al.[1998])
- *R*-modes are non-radial pulsation modes of rotating stars that have the Coriolis force as restoring force.
- The characteristic frequency is comparable to the rotation speed of the star.
- These modes are driven unstable by gravitational radiation, inducing a differential rotation at second order in mode's amplitude
- Which leads the non linear evolution of the r-mode instability, making it mode difficult the GW observation.

A young neutron star
(PSR J1846-0258 pulsar)



Evolution of the *r*-mode instability: model hypothesis

Sá and Tomé model (2005).

- Model initial conditions:
  - Initial angular velocity ($\Omega_0 \approx 5.6$kHz)
  - Initial temperature ($T_0 = 10^{11}K$)
  - Initial r-modes amplitude ($\alpha_0 = 10^{-6}$)
  - Amount of differential rotation associated to the R-modes (-5/4<K<10^{13})
  - NS polytropic Equation of state → **$p=k\rho^2$**

Evolution of the *r*-mode instability:

Sá and Tomé model (2005).

- Initially the R-mode amplitude grows exponentially and after few hundred seconds saturates at:

  $\alpha_{sat}=\alpha_{sat}(K) \rightarrow (K+2)^{-0.5}$

- The star angular velocity decreases

  $\Omega(t_f) = (0.065\text{–}0.067)\ \Omega_0$

- The R-mode instability is active:
  - From $t \approx 0$
  - To $t_f=(3.6 \div 7.1)10^6$ s

R-modes Instability as gravitational waves source

- Gravitational waves from r-mode depend on the angular momentum carried away by gravitational waves

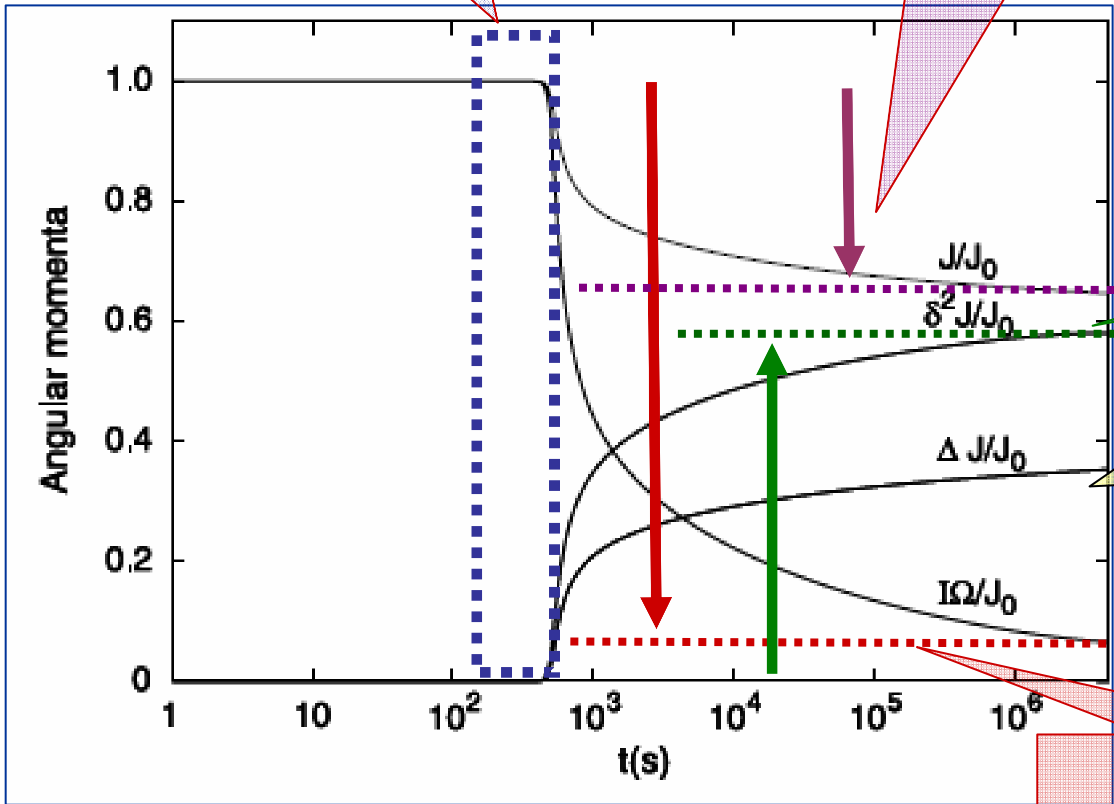
  $h \rightarrow \Delta J = J_0 - J(t)$ where $J_0 \approx I\Omega_0$ (NS Initial angular momentum)

- For this model the star total angular momentum is function of only two variables: (Ω , α)

Total Angular Momentum (J) evolution

NS formation

Total Angular momentum (J) decrease to 65%



R-mode perturbation angular momentum increase up to 58%

35 % Angular momentum $\Delta J/J0$ carried away by gravitational waves

Unperturbed start Angular momentum($I\Omega/J_0$) decrease to 7%

Total Angular Momentum (J) evolution

- Unperturbed star angular momentum is reduced to **7%**
- **58%** of the initial angular momentum is transferred to the r-mode
- About **35%** of the initial angular momentum is carried away **by gravitational waves**
- This is **for K=0**
- **For K >100** the initial angular momentum carried away decreases: Δ**J/J0 < 1%**

R-mode Gravitational waves characterization

- The frequency of these waves is related to the angular velocity by:

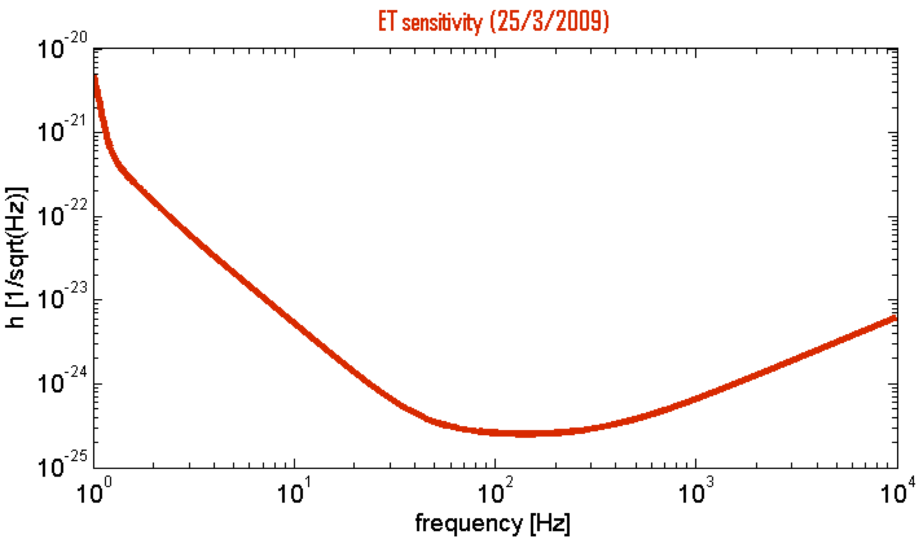
  $f=2\Omega/(3\pi)$
- The frequency bound is given:
  - $\mathbf{f_{max}} \approx$ **1200 Hz**, it depends on the initial value of the angular velocity Ω_0
  - $\mathbf{f_{min}} \approx$ **[77÷80] Hz**, it depends on the final value of the angular velocity $\Omega(\mathbf{t_f})$ and K
- The GW duration we recall that is roughly:
  - $\mathbf{t_f = (3.6 \div 7.1) 10^6\ s}$

R-mode Gravitational waves and Einstein Telescope sensitivity

- Gravitational waves strain h(f) generated by R-mode (Sà and Tomé model) is:

$$|\tilde{h}(f)| = \frac{4.6 \times 10^{-25}}{\sqrt{K+2}} \sqrt{\frac{f_{\max}}{f}} \frac{20 \text{ Mpc}}{D} \text{ Hz}^{-1}.$$

- The Einstein Telescope design sensitivity used in this talk:



Estimation of R-Mode GW Signal-to-Noise ratio for ET case (preliminary)

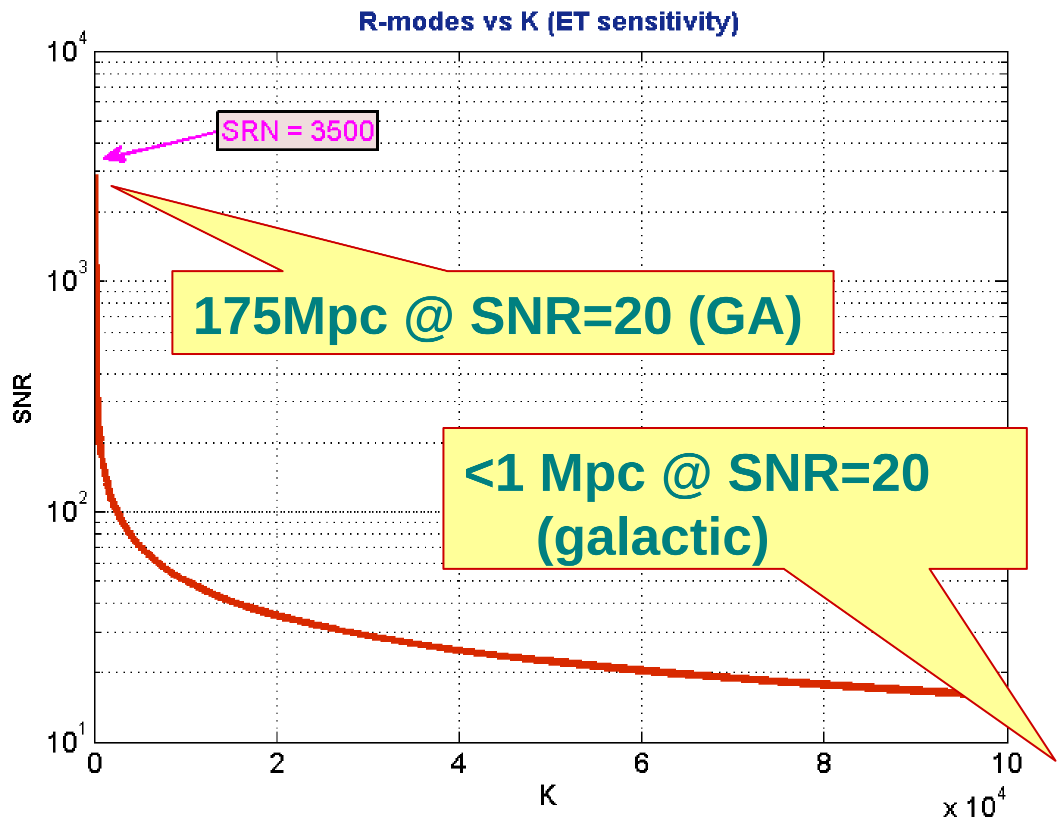
- The <u>optimal</u> Signal-to-Noise ratio for Einstein Telescope has been estimated, and it is given by the formula:

$$\frac{S}{N} = \frac{250}{\sqrt{2+K}} \, \frac{20\ \text{Mpc}}{D}$$

- The SNR dependence on K is show in figure:

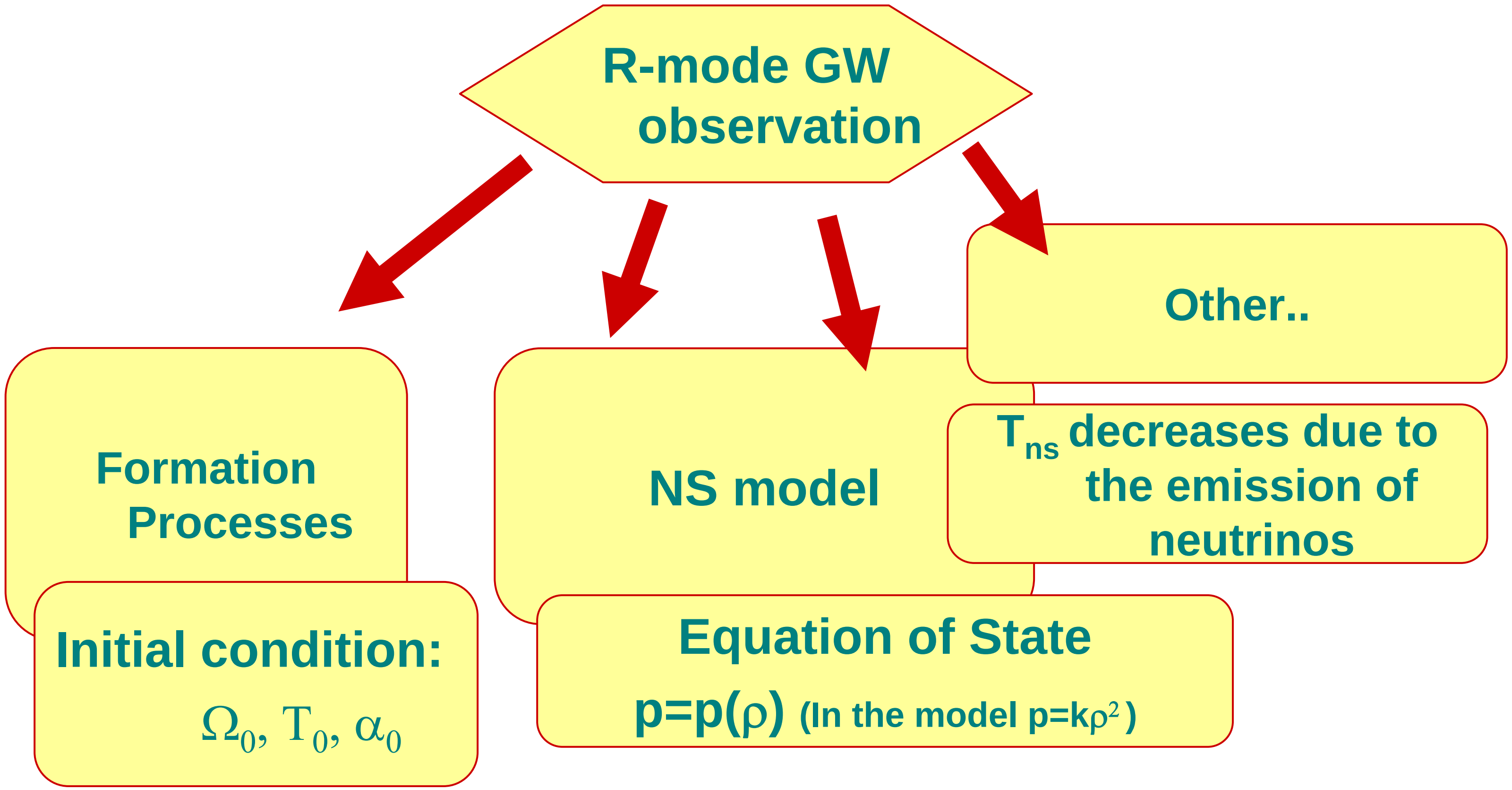
- Pessimistic case is for very high K, when NS born with substantial differential rotation:

  $K \approx [10^5 \div 10^6] \rightarrow$ SNR is [5-15] @1Mpc



R-modes GW, ET science case and nuclear physics

- R-mode gravitational wave observation can produce important and unique correlation with the nuclear physics of the neutron star and formation processes.



Conclusions

- The r-mode GW optimal Signal-to-Noise ratio for Einstein Telescope has been estimated
- r-mode GW could be observed by ET with SNR>20
- GW signals may carry information on:
  - gravitational physics
  - nuclear physics
- This signals could be an opportunity to know the NS nuclear physics, that maybe can't be done in other ways.

What next

- Correlate ET SNR with the Expected newborn Neutron
  - Our galaxy
  - Up to 150Mpc
- Take a look on the detection algorithms, parameters reconstruction and computational requirements for the sub-optimal case
- Compile the science opportunity list, given by this type of signal for ET

References

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- ***"Gravitational waves from the r-modes of rapidly rotating neutron stars" Owen B.J. -*** *Gravitational Waves, AIP Conference Proceedings, Vol. 523. New York: AIP Press, 2000., p.55*
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