Rotation of stellar cores before gravitational collapse and prospects for gravitational wave detection

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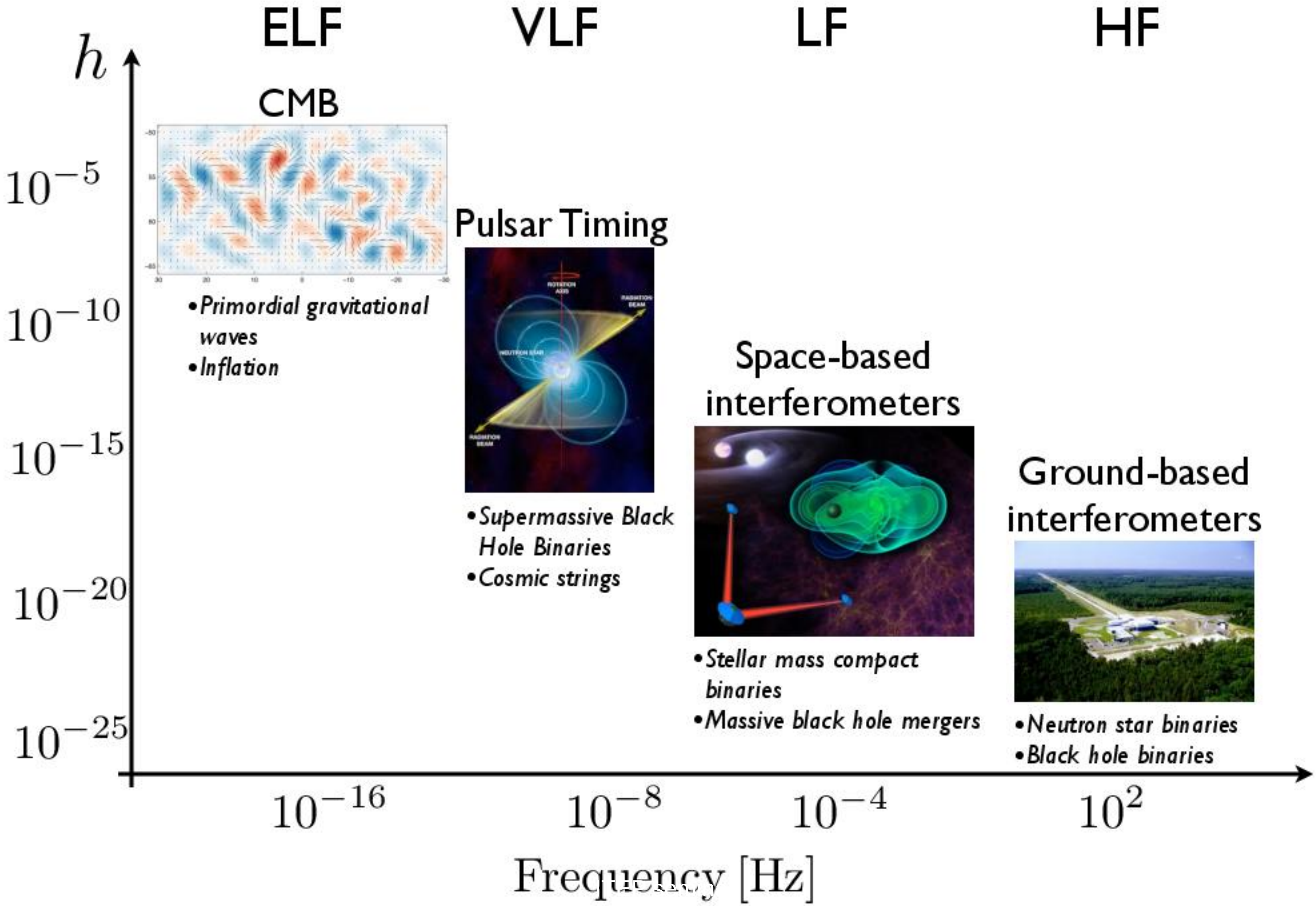
The big picture of gravitational wave astronomy



GW from core collapses

- Sources of asymmetry:
  - Large convective motions in proto-NS
  - Triaxial deformations (secular + dynamical instability (bar-mode), fragmentation)
  - r-mode instability of nascent NS
  - Fall-back accretion onto NS
  - Ringdown of produced black holes

Quadrupole formalism

$$h_{jk}^{\mathrm{TT}} = \left[\frac{2}{d}\frac{G}{c^4}\frac{d^2}{dt^2}\mathscr{I}_{jk}(t-r) + \frac{8}{3d}\frac{G}{c^5}\epsilon_{pq(j}\frac{d^2}{dt^2}\mathscr{S}_{k)p}(t-r)\boldsymbol{n}_q\right]^{\mathrm{TT}}$$

Bulk motion
(inspirals, bar-modes)

Mass currents
(r-modes)

$$h = (\langle h_+^2 + h_\times^2 \rangle)^{1/2}$$

$$\mathscr{I}_{jk} = \int d^3x\rho\left(x^jx^k - \frac{1}{3}r^2\delta_{jk}\right)$$

$$P = \frac{dE}{dt} = \frac{1}{5}\frac{c^5}{G}\langle \dddot{\mathscr{I}}_{jk}\dddot{\mathscr{I}}_{\mathscr{J}\mathscr{K}}\rangle$$

$$P = \frac{\pi^2c^3}{G}f^2d^2h^2$$

- Bar-modes: β=T/|W|>0.25-0.27

$$P_{\rm bar} = \frac{32}{45}\frac{G}{c^5} m^2 r^4 \omega^6$$

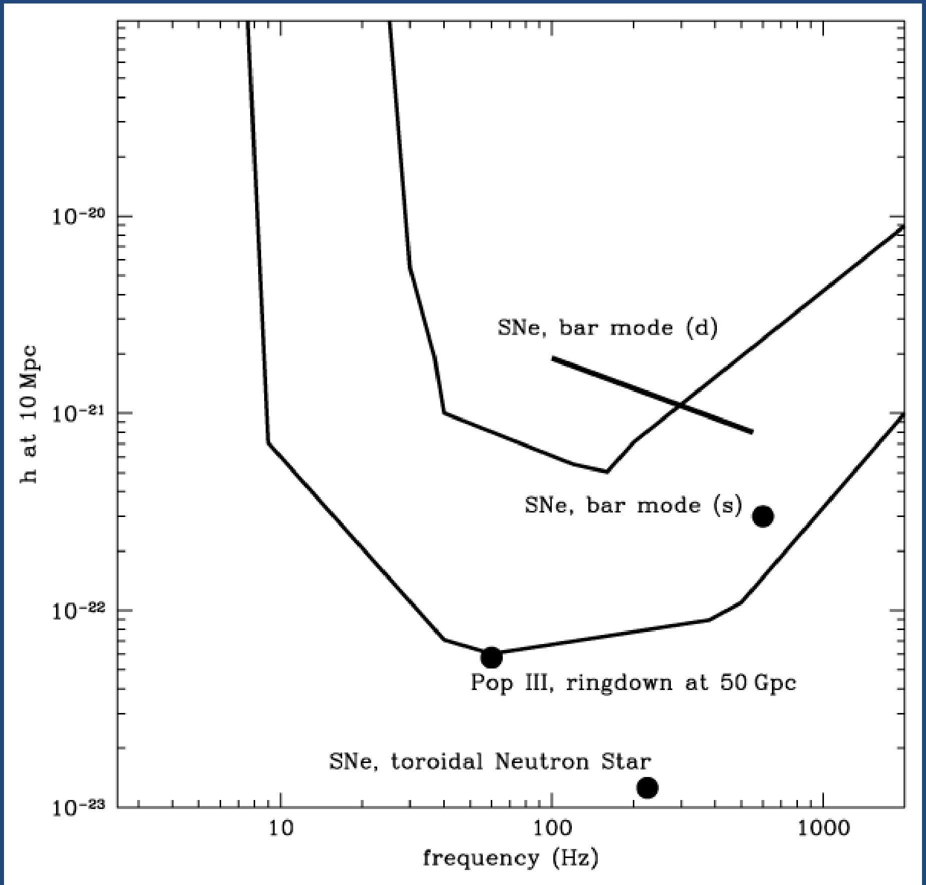
$$h_{\rm bar} = \sqrt{\frac{32}{45}\frac{G}{c^4}}\frac{mr^2\omega^2}{d}$$

- Fragmentation: e.g. binary with equal masses

$$P_{\rm bin} = \frac{128}{5}\frac{G}{c^5} m^2 r^4 \omega^6 ,$$

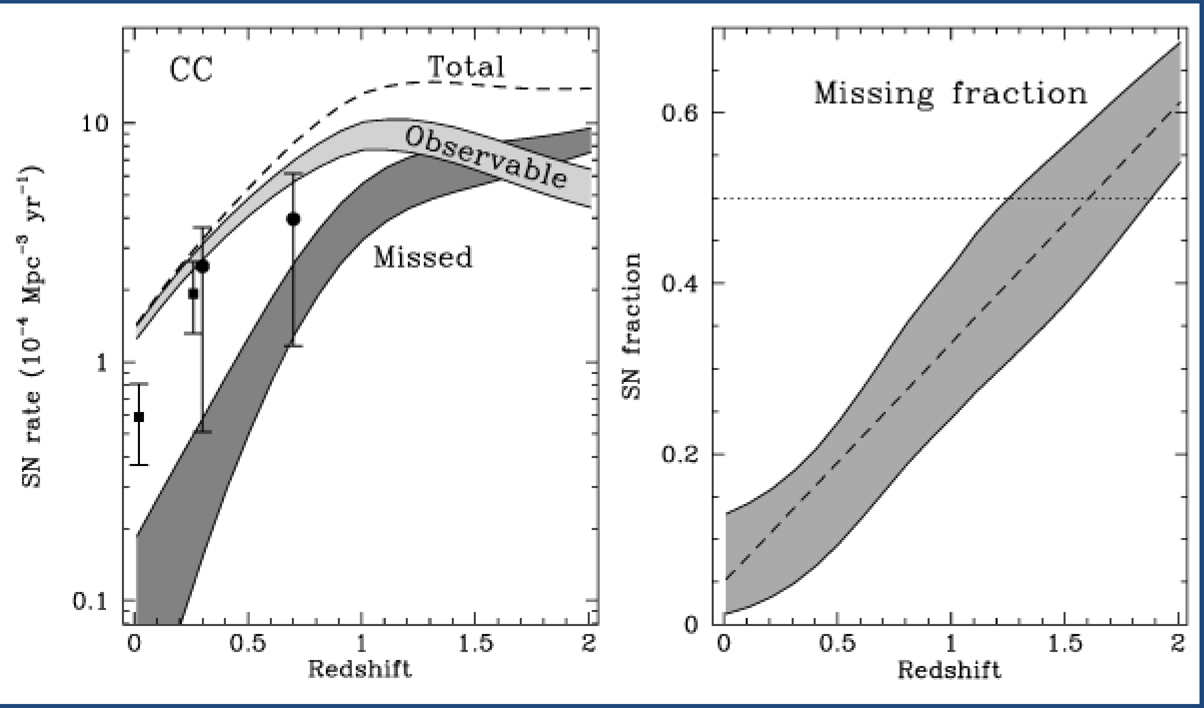
$$h_{\rm bin} = \sqrt{\frac{128}{5}\frac{G}{c^4}}\frac{mr^2\omega^2}{d} .$$

Prospects for detection



Fryer & New ’11 LRR

How high is the event rate?

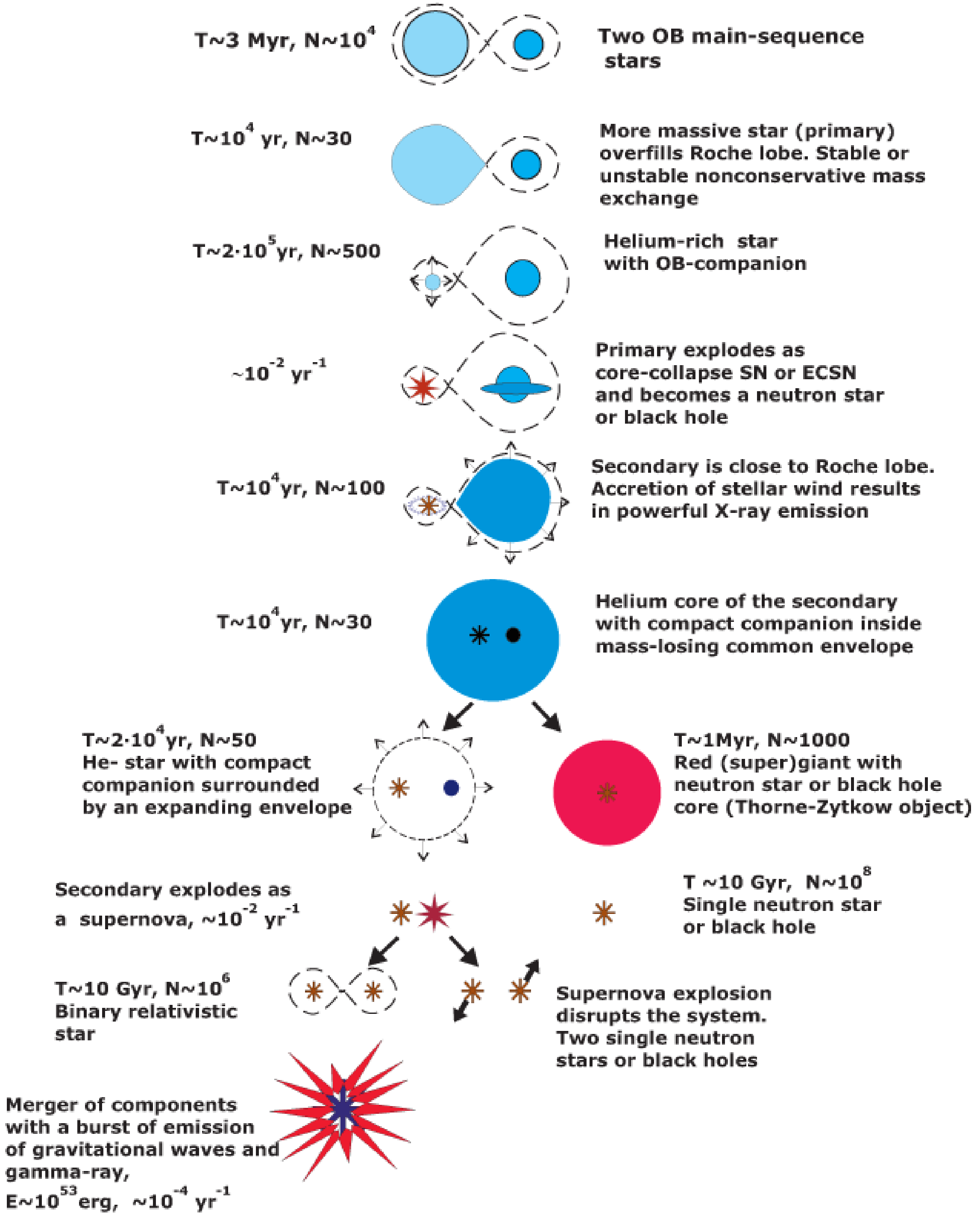


- CC SNe ~1/30 yrs in Milky Way
- 2-3 a year per cubic Mpc in the local Universe
- ~10^3 CC SNe a year within 10 Mpc (visibility horizon of first aLIGO)

- **What is the fraction of rapidly rotating iron cores?**

Method: Population synthesis

- Take binary evolution scenario
- Take initial distributions (masses, semi-major axes, rotations…)
- MC calculation (modified BSE code Hurley+'00,'02)



Initial rotation of components

- Initial star rotation

$$v_{rot}(M) = \frac{330M^{3.3}}{15.0 + M^{3.45}}\, km\ s^{-1}$$

Connection with envelope

- Rotation of the core is coupled with rotation of the envelope (e.g. magnetic coupling, Spruit & Phinney 1998). Effective description:

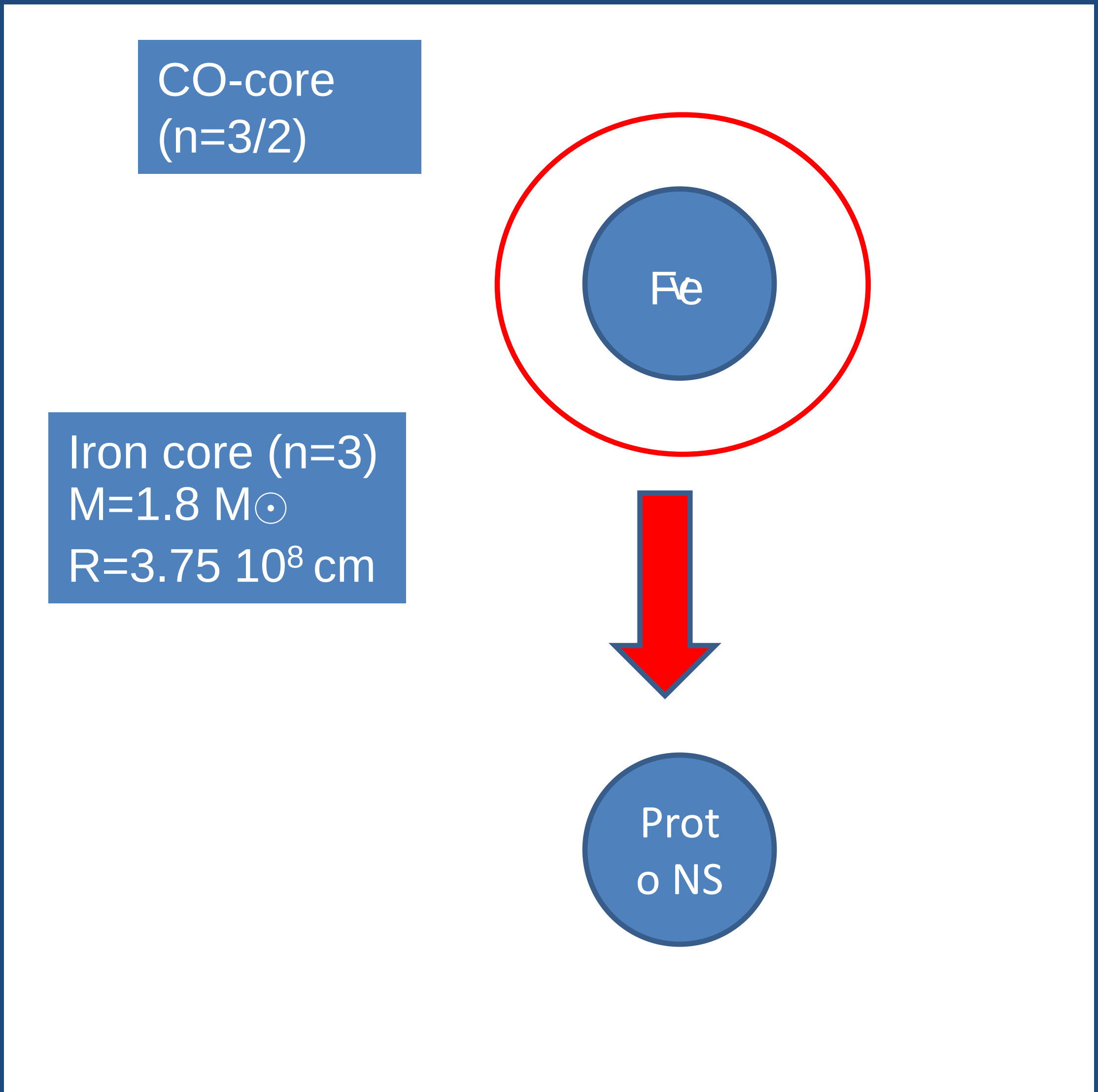
$$\frac{dJ_c}{dt} = \frac{I_c I_e}{I_c + I_e} \frac{\Omega_e - \Omega_c}{\tau}$$

- In a binary: tidal synchronisation (as in BSE code); RLOF → corotation with orbital period

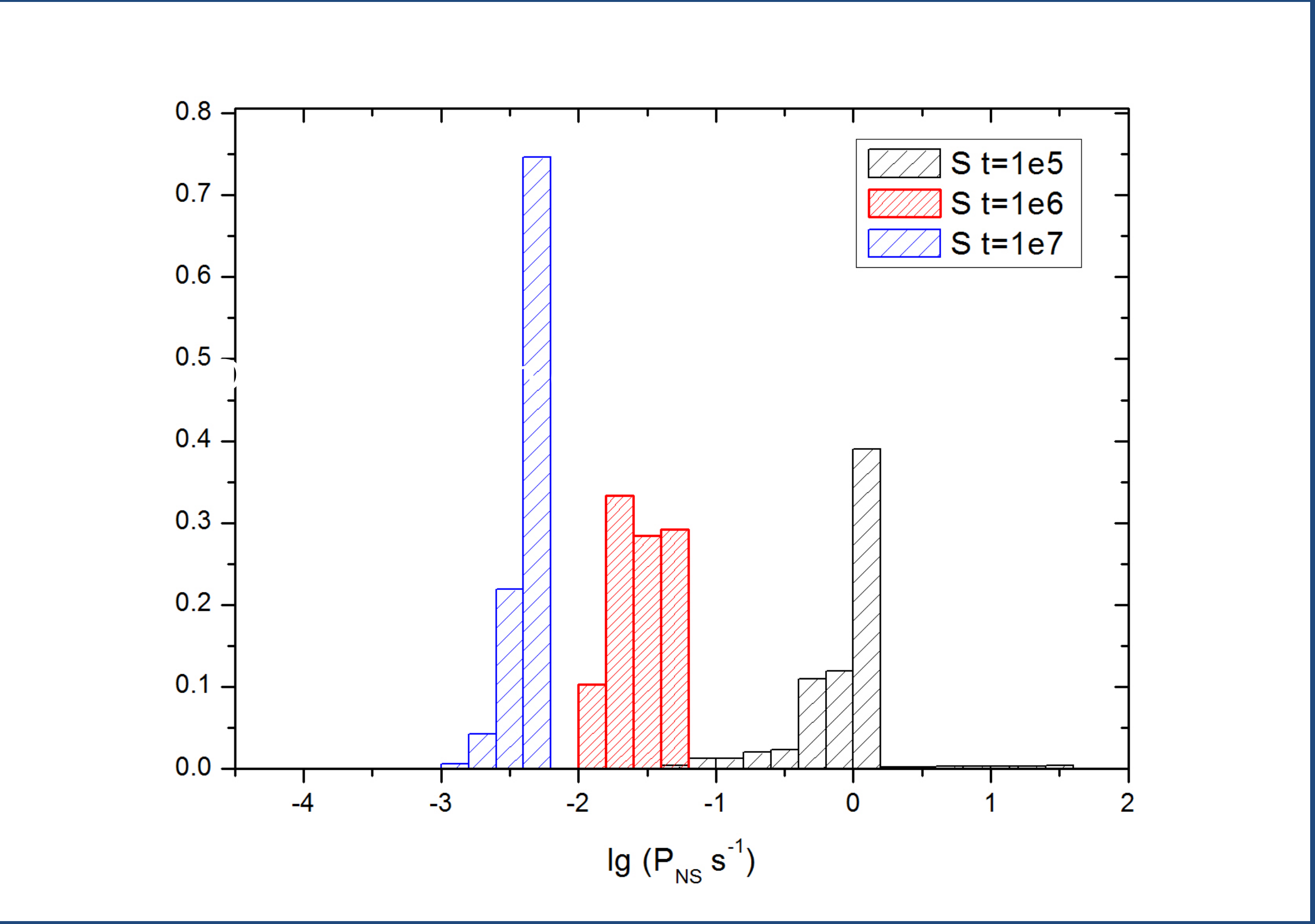
Evolution of the core rotation

J_{Fe}=const

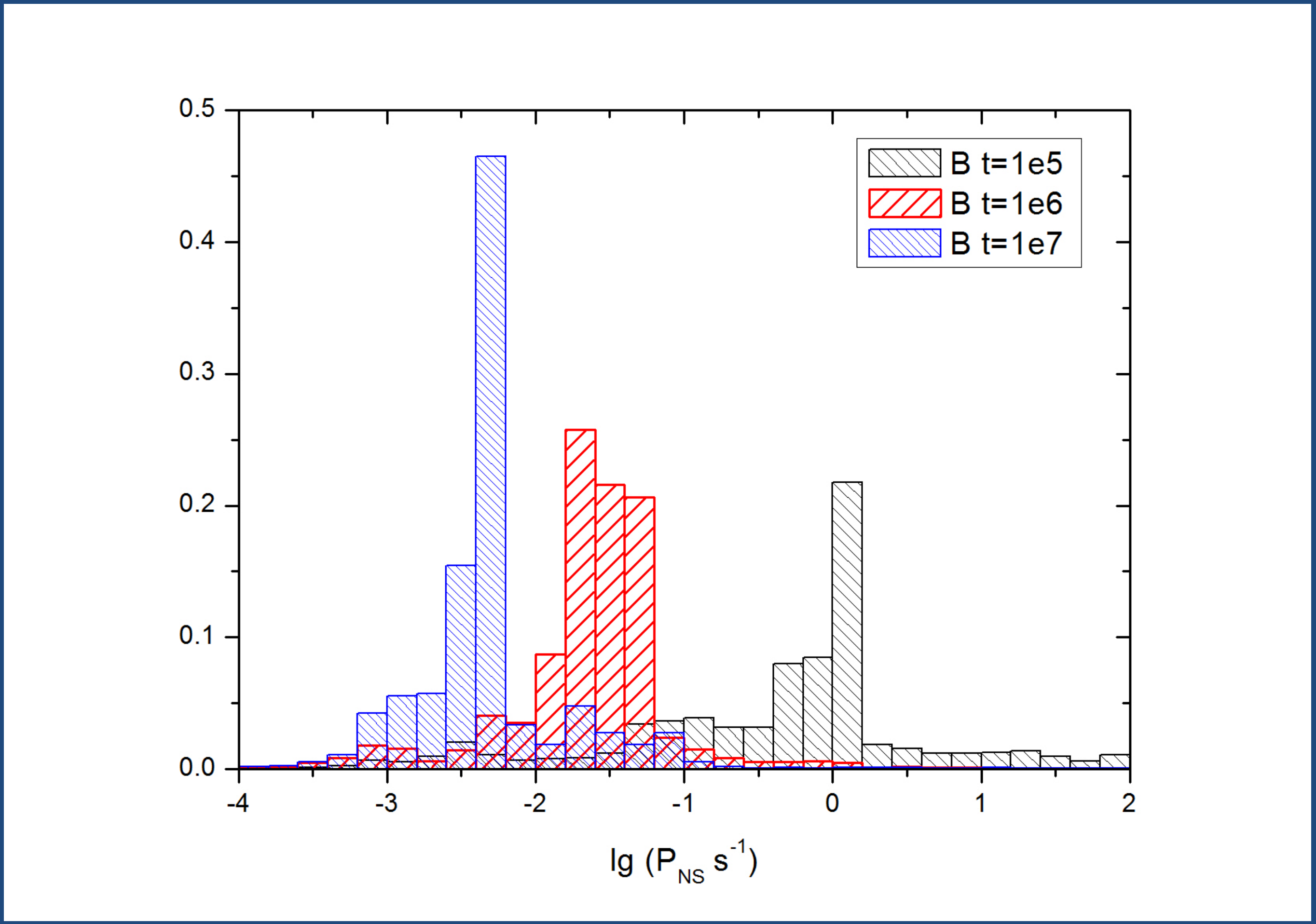
R_{NS}/R_{Fe}= 1/100

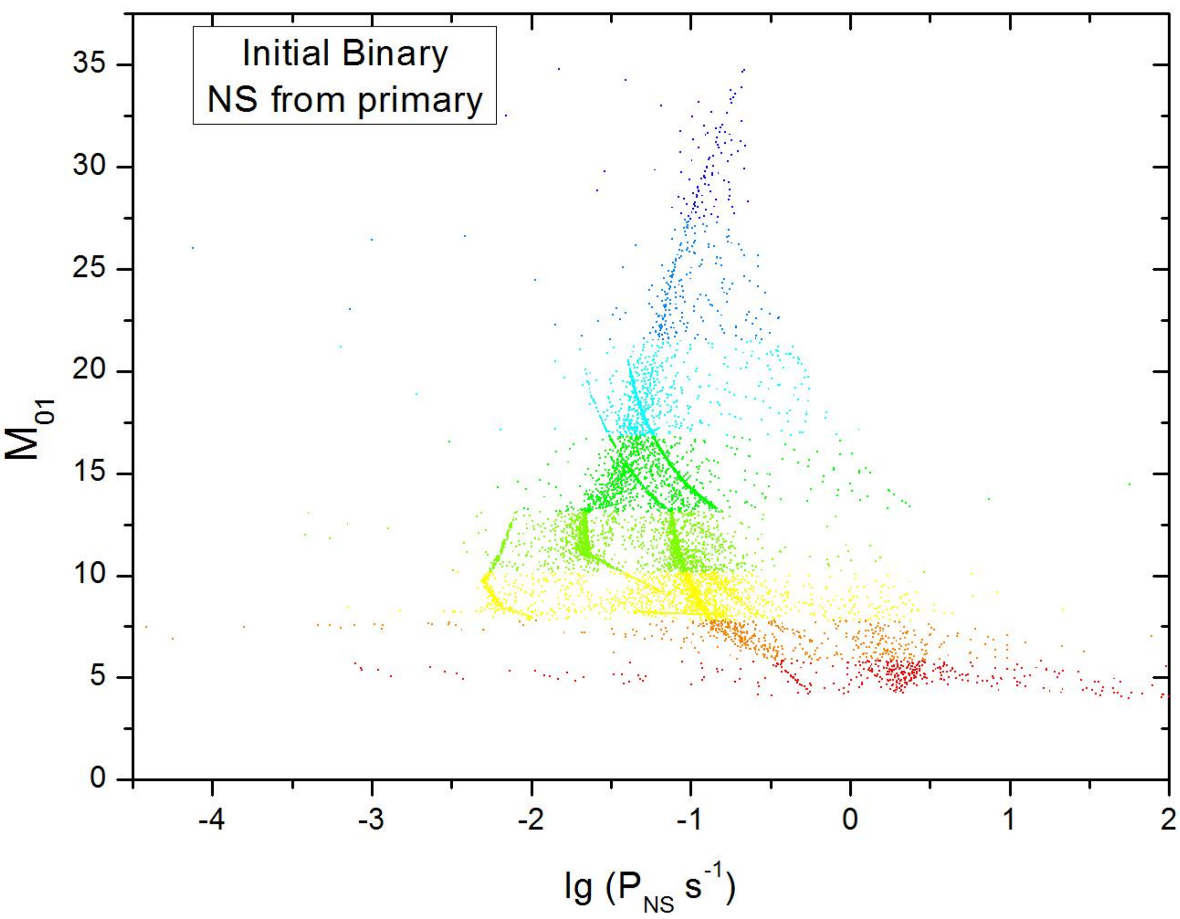


Dependence on coupling strength: single stars



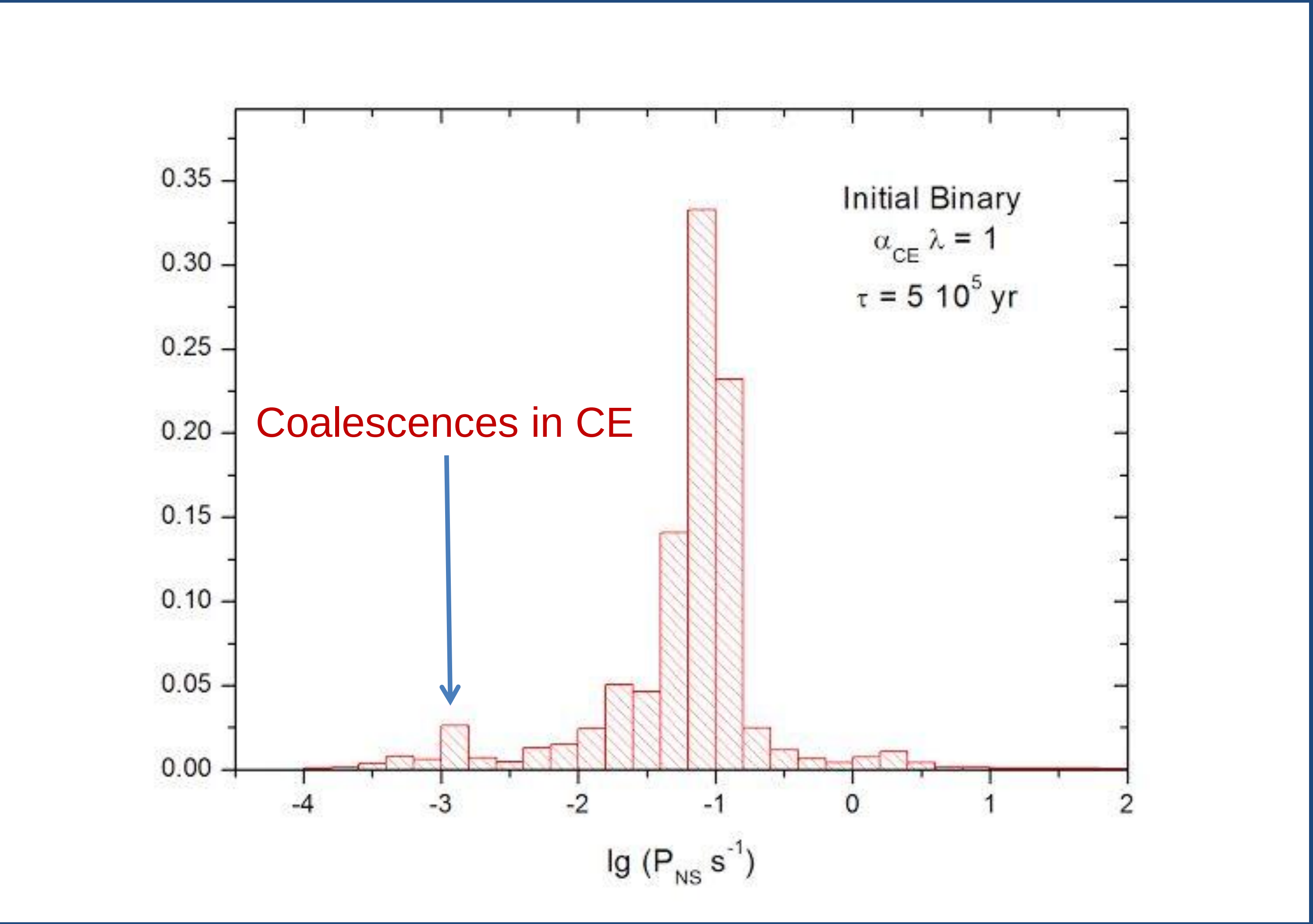
Dependence on coupling strength: binaries



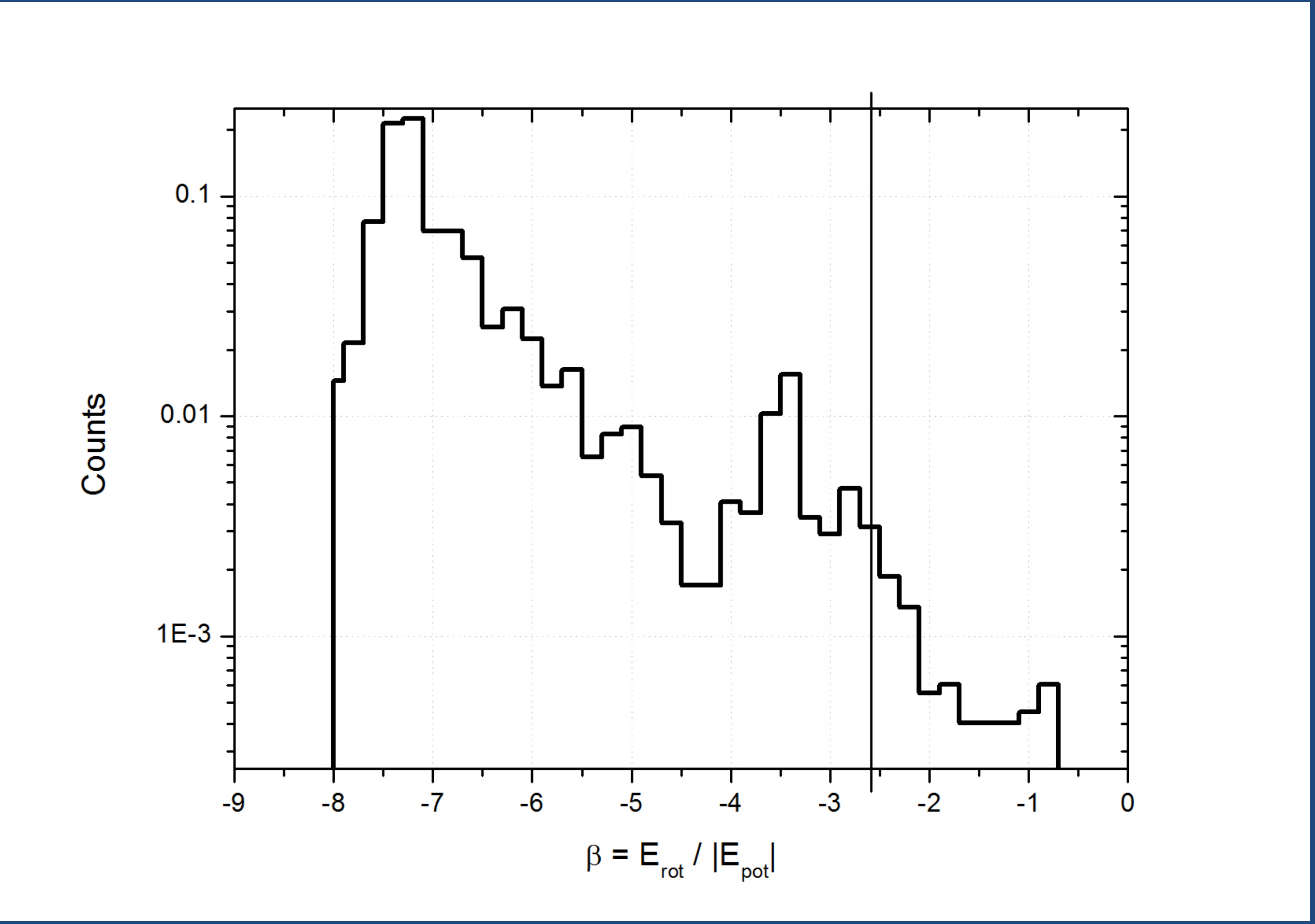


Initial Binary
NS from primary
35
30
25
20
15
10
5
0
-4
-3
-2
-1
0
1
2
M_{01}
lg (P_{NS} s^{-1})

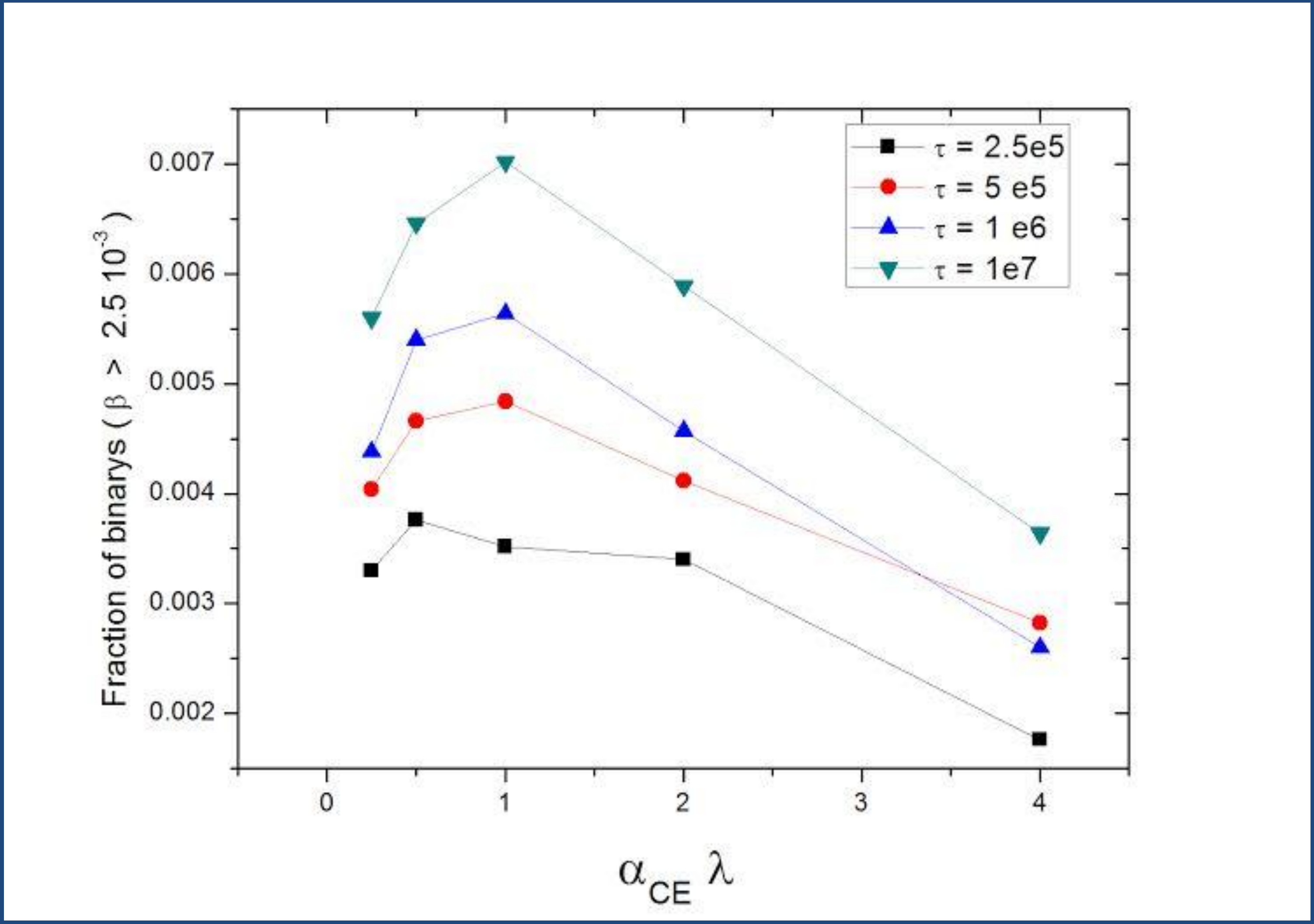
Expected NS spin periods for best-fit τ=5 10^5 yrs



Rotating iron cores before collapse for τ=5 10^5 yrs



Fraction of rapidly rotating cores



Conclusions

- Population synthesis of rotation of stellar cores with effective description of coupling between the stellar CO core and the envelope in single and binary stars allows the determination of effective coupling $\tau \sim 5\ 10^5$yrs from comparison with initial NS periods
- with this coupling, rotation of pre-collapse iron cores in binary systems is calculated
- In 0.2-0.7% cases, iron cores rotate with $\beta > 0.0025$
- Assuming angular momentum conservation, this core rotation leads to proto-NS with $\beta > 0.25$ which may lead to dynamical bar instability and possible fragmentation
- With current aLIGO sensitivity, GW emission can be observed from 0.2-0.7% of core collapses, which is ~ a few events per year, comparable to expected NS-NS coalescence rate!