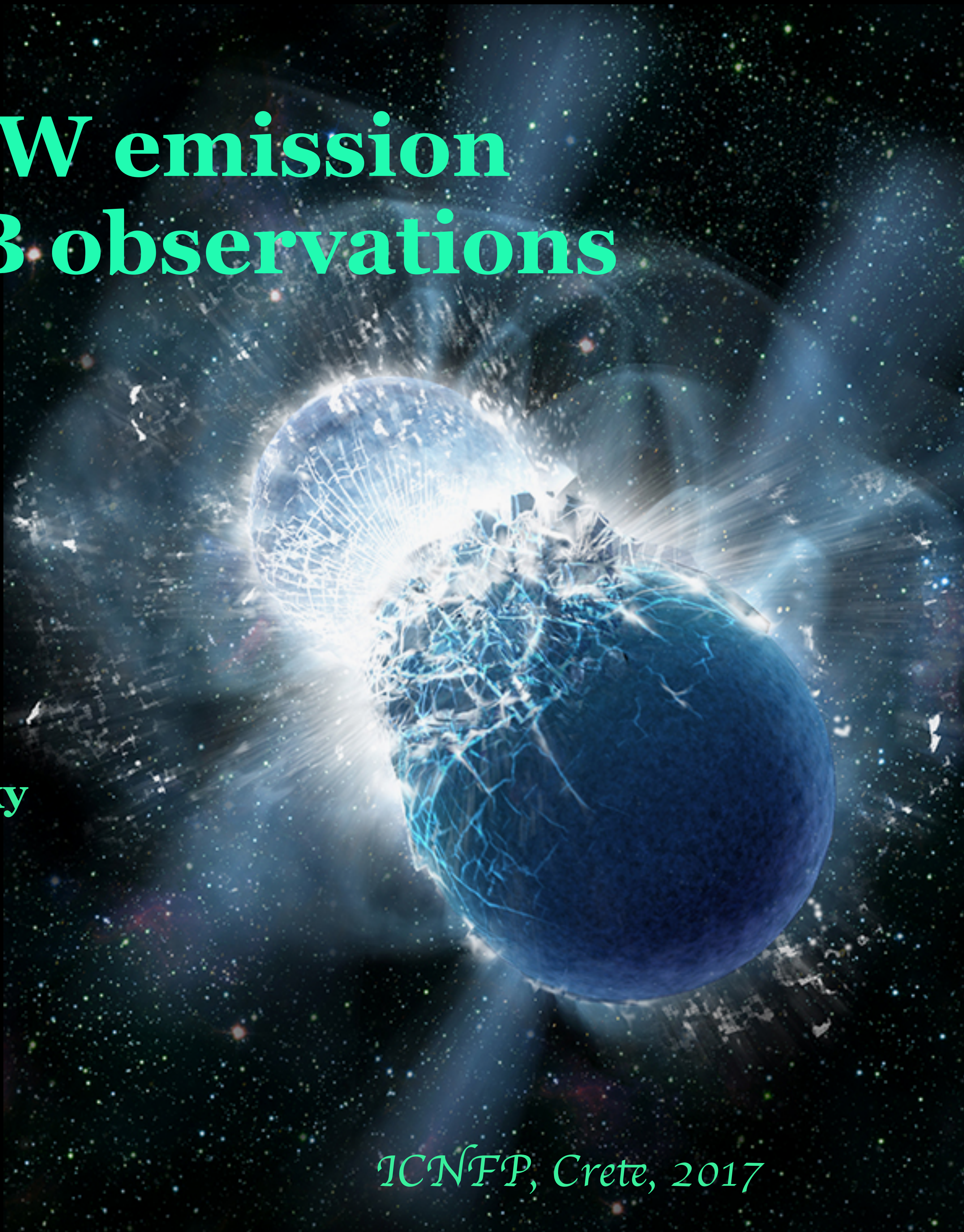
Constraining GW emission from short GRB observations

(based on MNRAS 458 2016)

In collaboration with Paul Lasky

Kostas Glampedakis

UNIVERSIDAD DE MURCIA



ICNFP, Crete, 2017

Short GRBs: the basic model

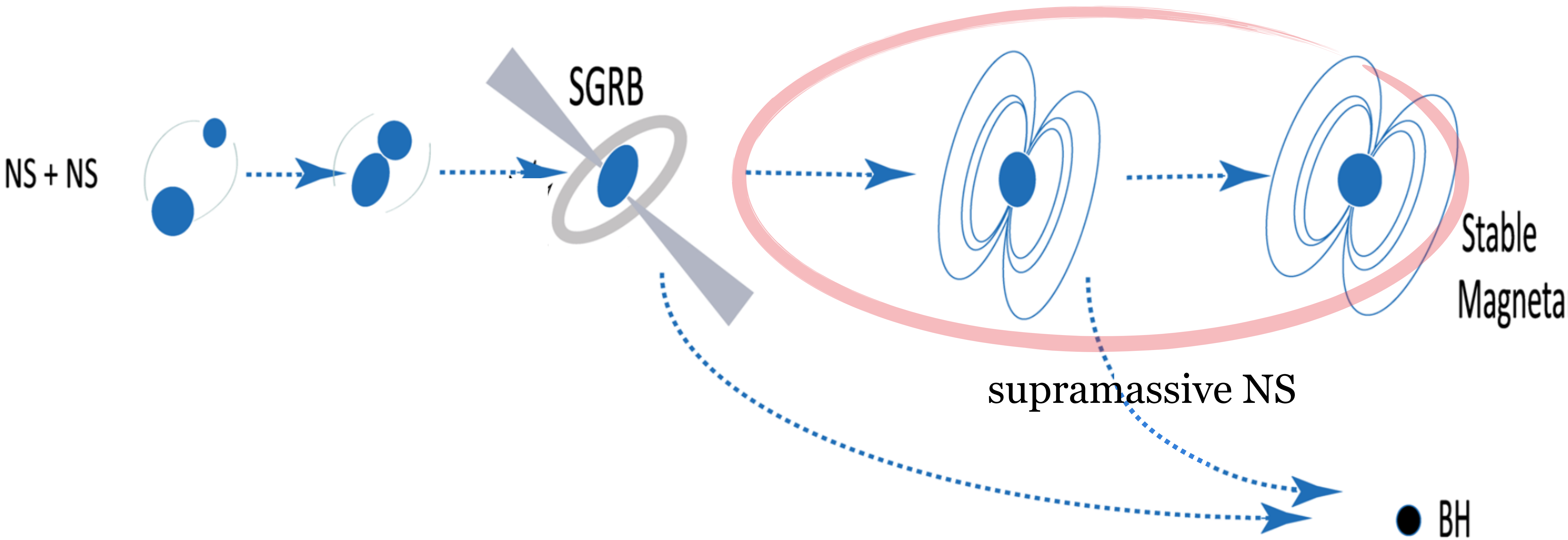
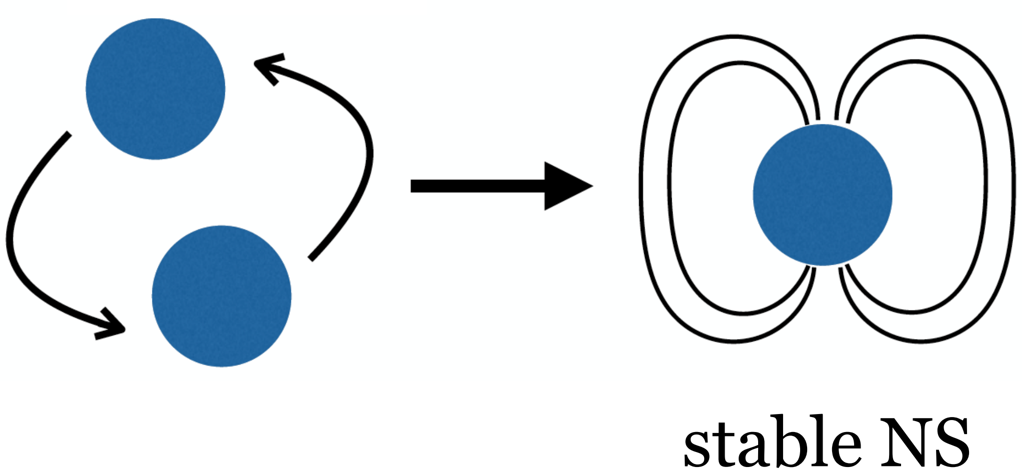
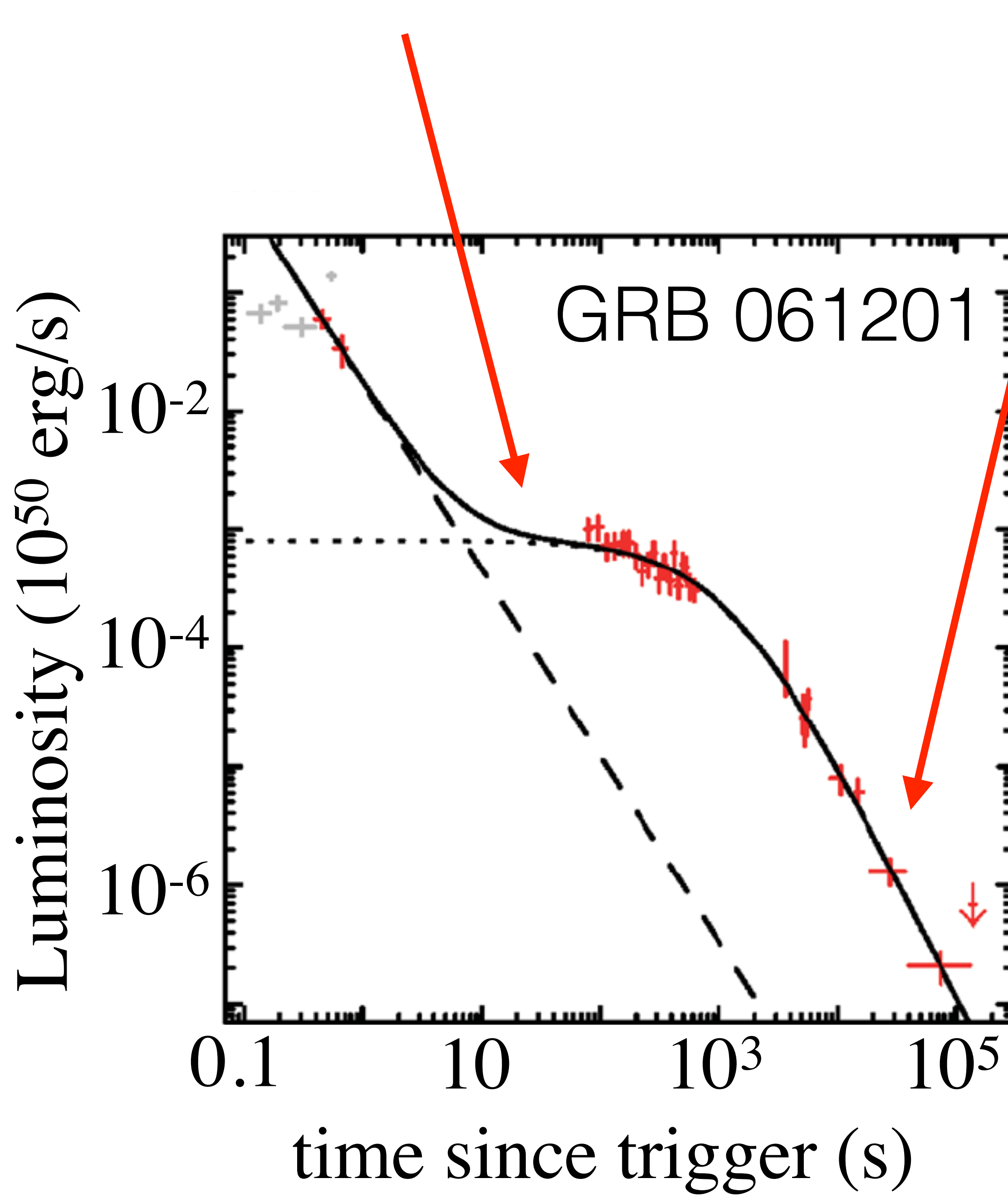


figure credit: P. Lasky

X-ray observations (I)

- Main sGRB event is followed by an X-ray “plateau” and a power-law tail.

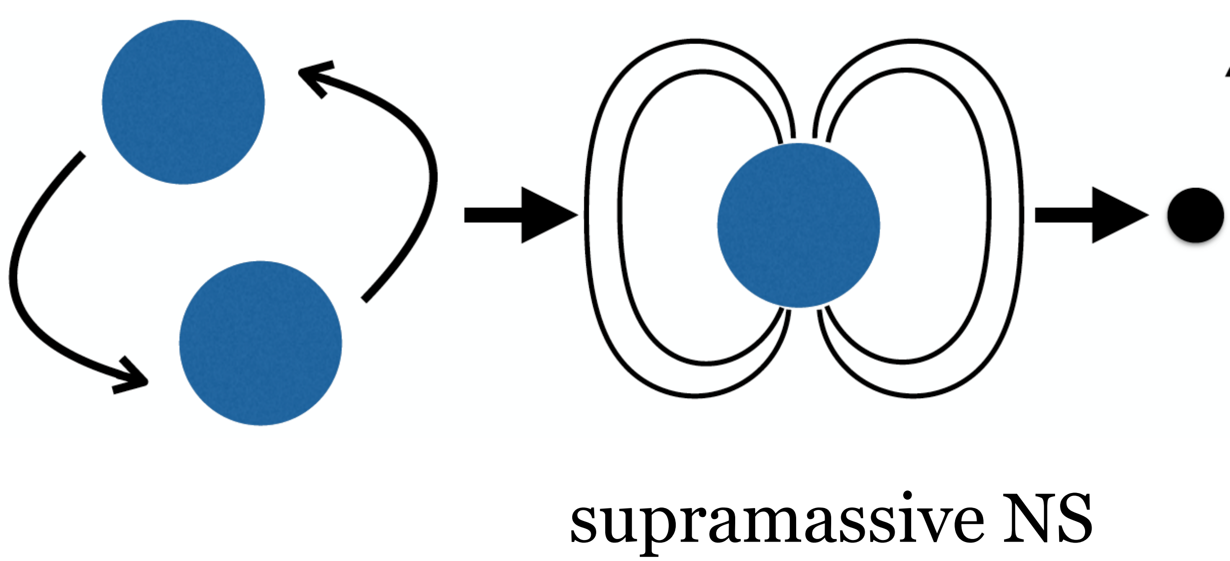


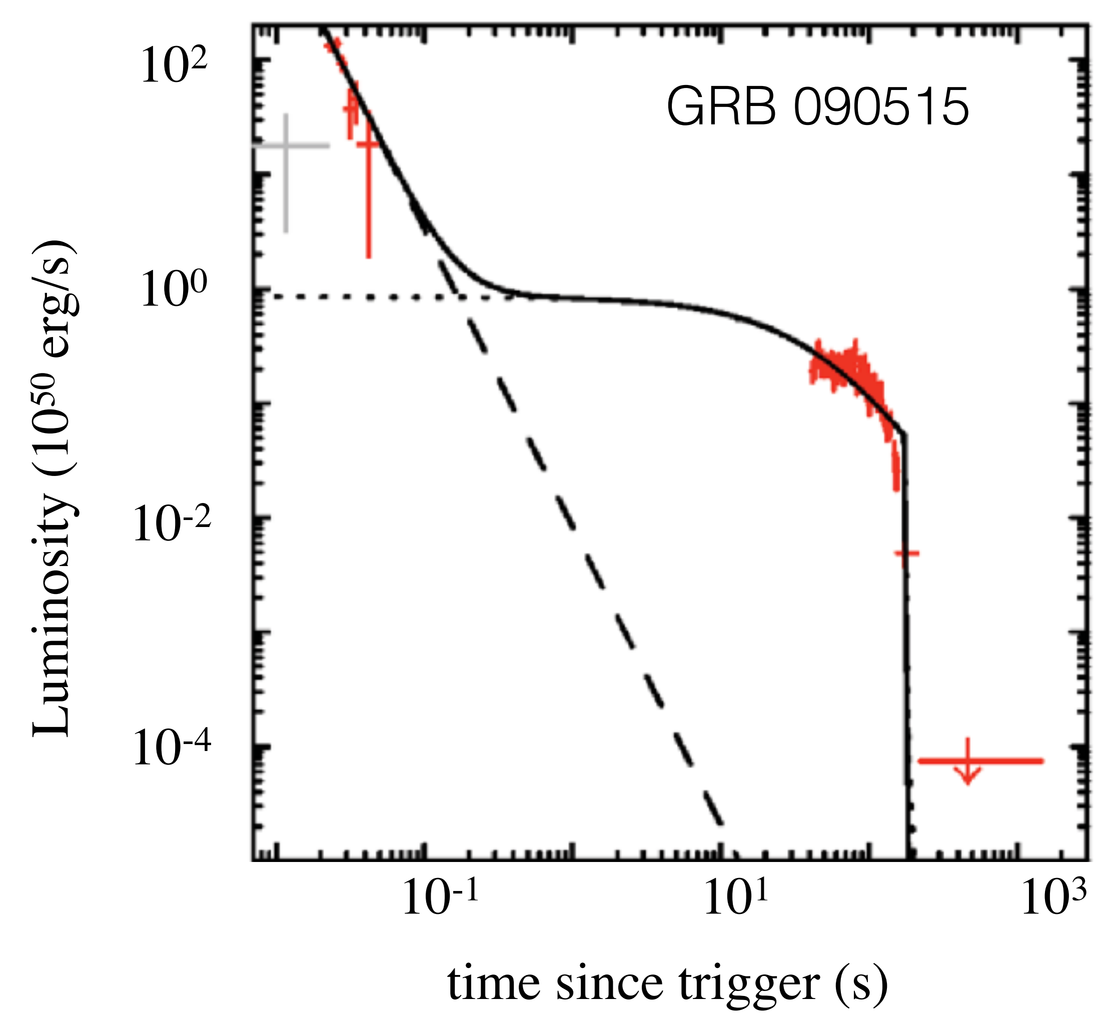


Rowlinson et al. 2013

X-ray observations (II)

- An abrupt cut-off in the signal indicates a prompt collapse to a BH.





Rowlinson et al. 2013

Post-merger remnant: spin evolution

- Spin evolution under EM + GW emission:

$$-I\Omega\dot{\Omega} = \frac{B_p^2 R^6 \Omega^4}{6c^3} + \frac{32 G I^2 \epsilon^2 \Omega^6}{5c^5}$$

$\epsilon =$ ellipticity

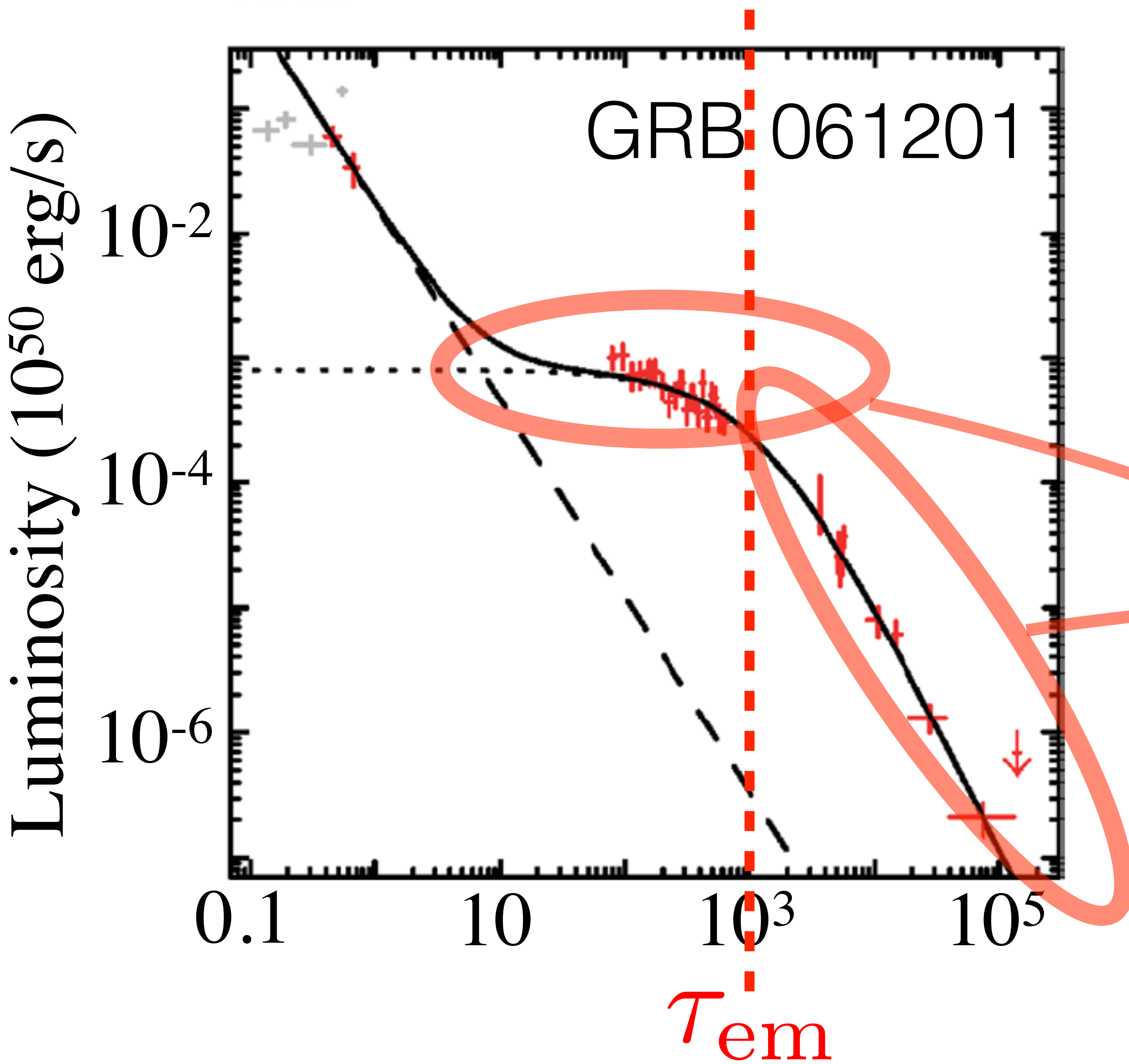
$B_{\rm p} =$ polar magnetic field

- EM spin-down powers X-ray flux: $L(t) = \eta \frac{B_{\rm p}^2 R^6 \Omega(t)^4}{6c^3}$

efficiency
$\eta \sim 0.1$

EM dominates spin-down	GWs dominates spin-down:
$L(t) = L_{\rm em,0}\left(1 + \frac{t}{\tau_{\rm em}}\right)^{-2}$	$L(t) = L_{\rm em,0}\left(1 + \frac{t}{\tau_{\rm gw}}\right)^{-1}$
$L_{\rm em,0} = \eta \frac{I\Omega_0^2}{2\tau_{\rm em}}$ $\quad \tau_{\rm em} = \frac{3c^3 I}{B_{\rm p}^2 R^6 \Omega_0^2}$	$\tau_{\rm gw} = \frac{5c^5}{128 G I \epsilon^2 \Omega_0^4}$

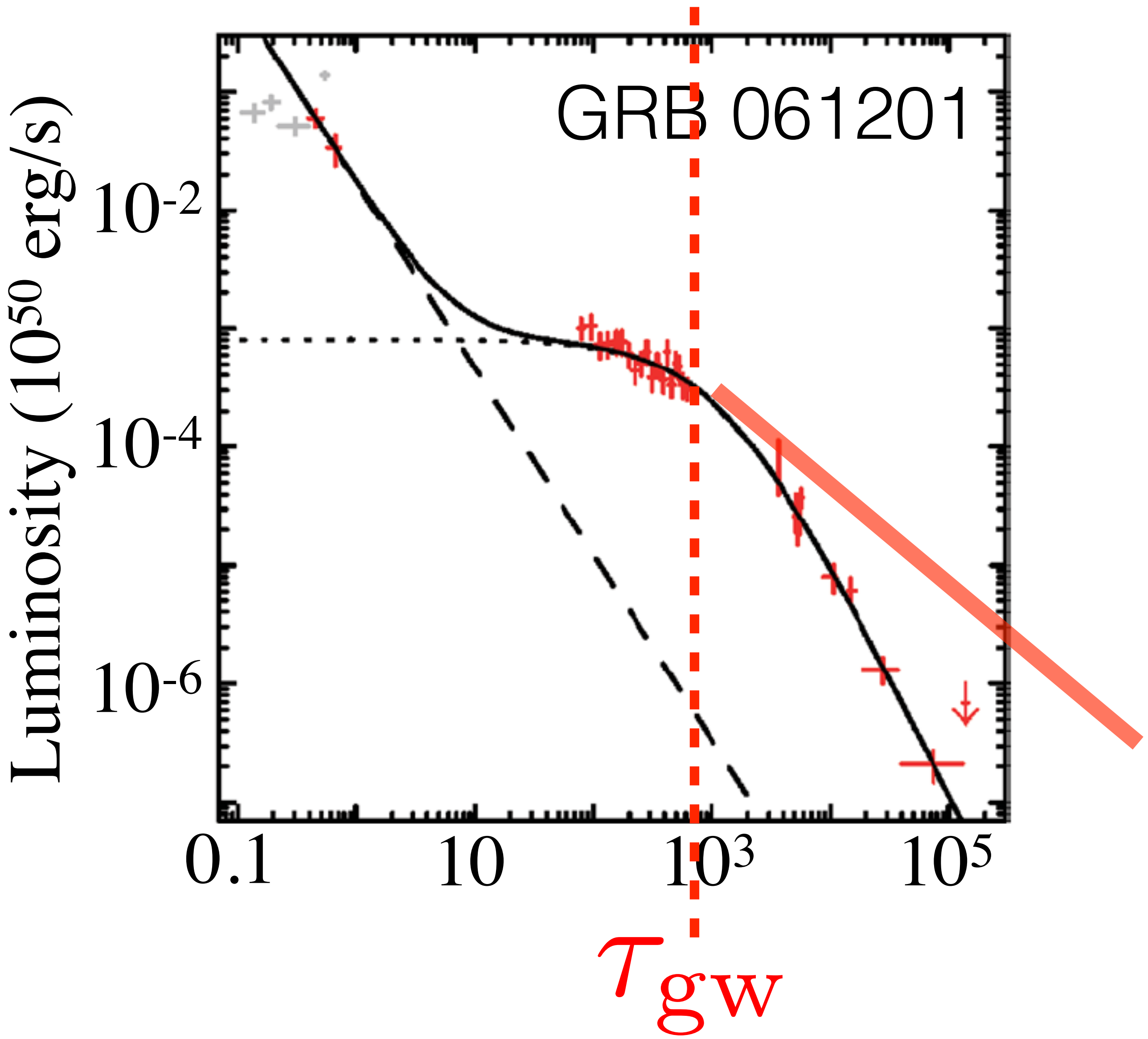
X-ray tail: EM or GW spin-down?



$$L(t) = L_{\rm em,0}\left(1 + \frac{t}{\tau_{\rm em}}\right)^{-2}$$

→ Late time spin-down is due to magnetic dipole radiation

X-ray tail: EM or GW spindown?



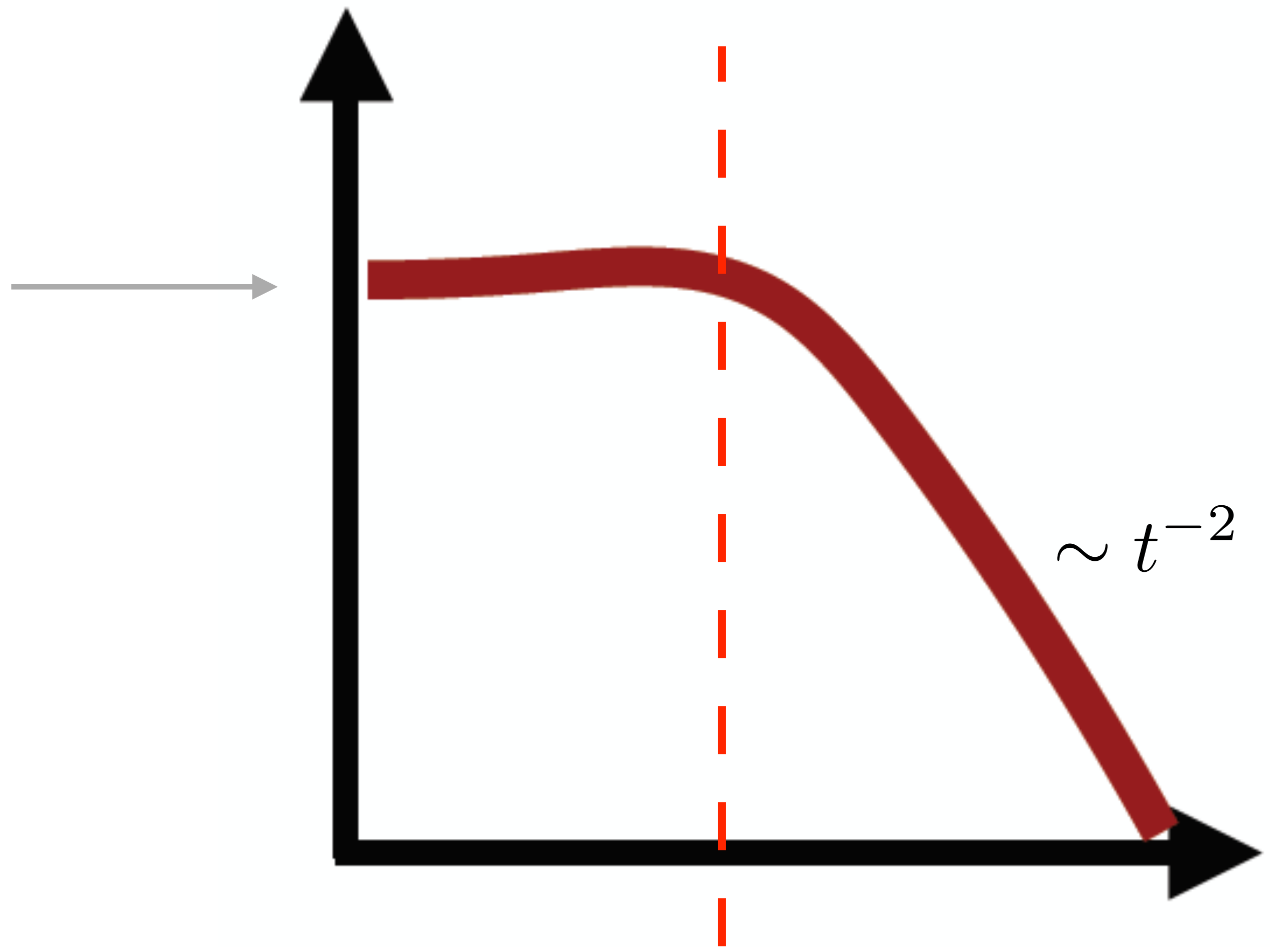
$$L(t) \propto \left(1 + \frac{t}{\tau_{\rm gw}}\right)^{-1}$$

→ GWs can only dominate *early* spin-down

Constraining the NS ellipticity

observable 1:
plateau flux

$$L_{\mathrm{em},0} = \eta \frac{I\Omega_0^2}{2\tau_{\mathrm{em}}}$$



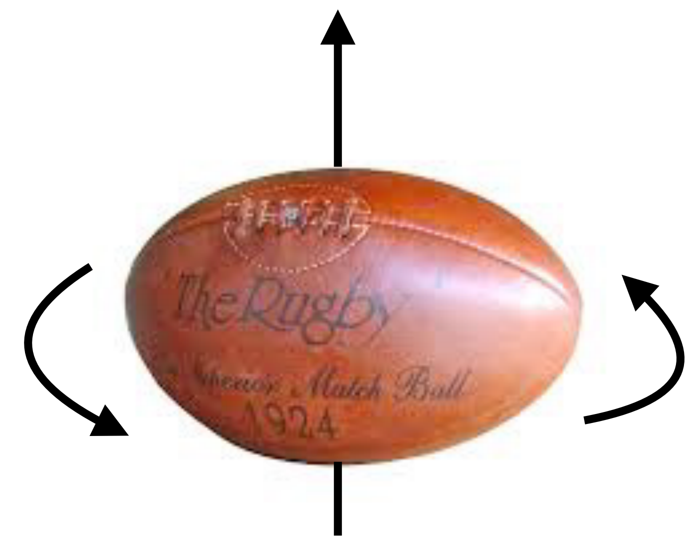
observable 2: plateau duration $t_b \approx \tau_{\mathrm{em}}$

$$\tau_{\mathrm{gw}} \gtrsim t_b \quad \Rightarrow \quad \epsilon_{\mathrm{obs}} \leq 0.33\eta \left(\frac{I}{10^{45}\,\mathrm{g\,cm^2}}\right)^{1/2} \left(\frac{L_{\mathrm{em},0}}{10^{49}\,\mathrm{erg\,s^{-1}}}\right)^{-1} \left(\frac{t_{\mathrm{b}}}{100\,\mathrm{s}}\right)^{-3/2}$$

Modelling GW emission

- Mechanisms for generating NS ellipticity:

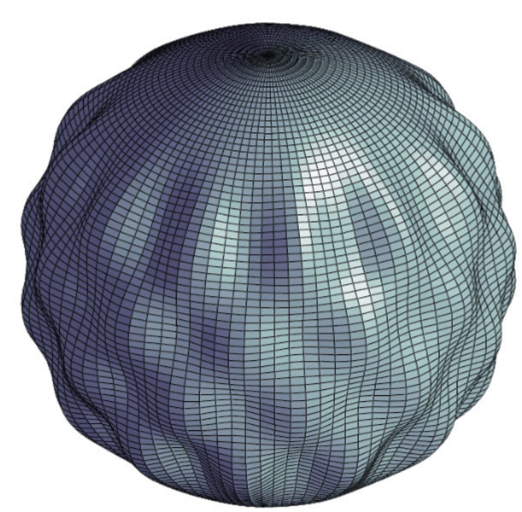
a non-axisymmetric quadrupolar deformation in the stellar shape (NS “mountain”)



in our case, the “mountain” is sustained by magnetic forces

the secular *f*-mode instability

(aka the bar-mode instability)



GW-driven *f*-mode instability

- The instability's growth rate is vastly enhanced in a supramassive NS.

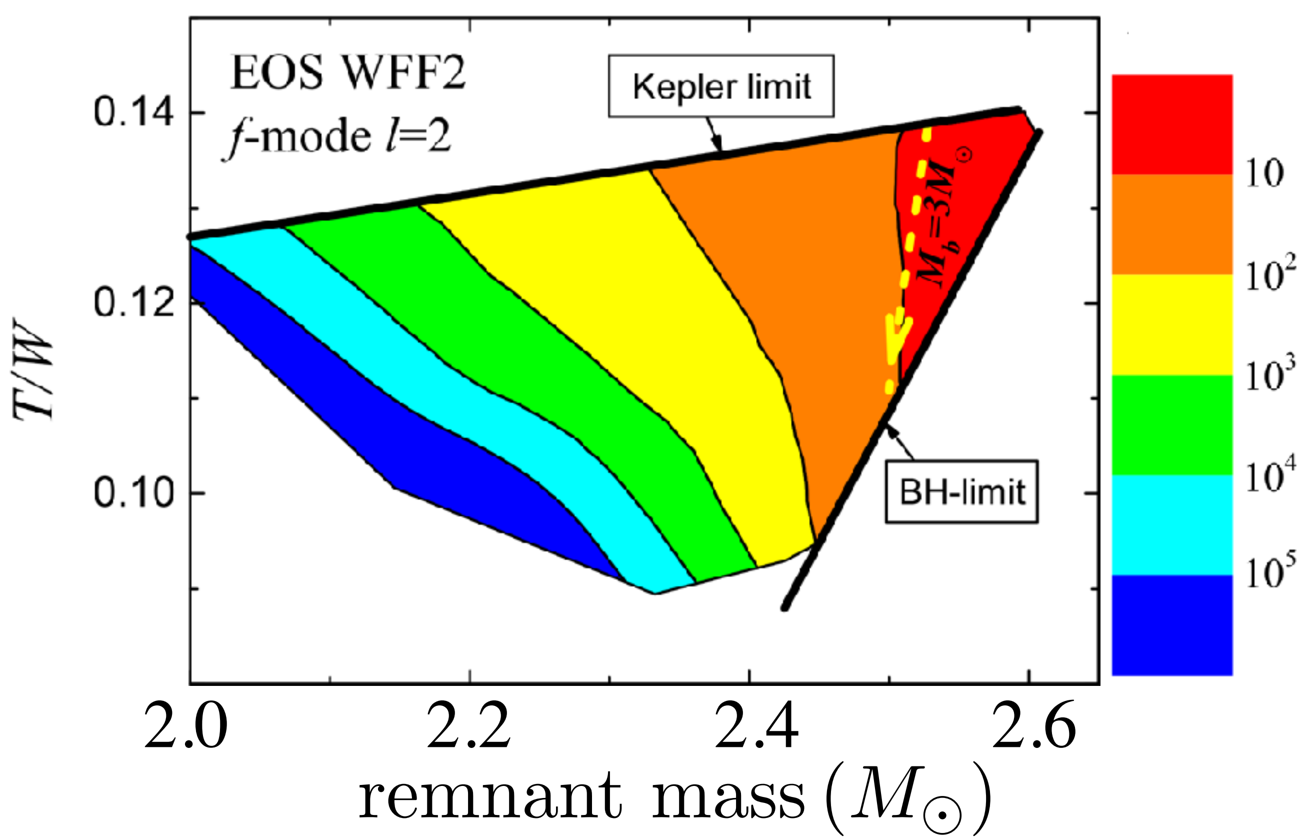
- The associated ellipticity is:

$$\epsilon_f \approx \frac{2\delta R}{R} \sim \left(\frac{E_{\rm mode}}{Mc^2}\right)^{1/2} \left(\frac{c^2 R}{GM}\right)^{1/2}$$

Maximum value:

$$\epsilon_f \approx 10^{-3}$$

GW growth timescale



Doneva et al. 2015

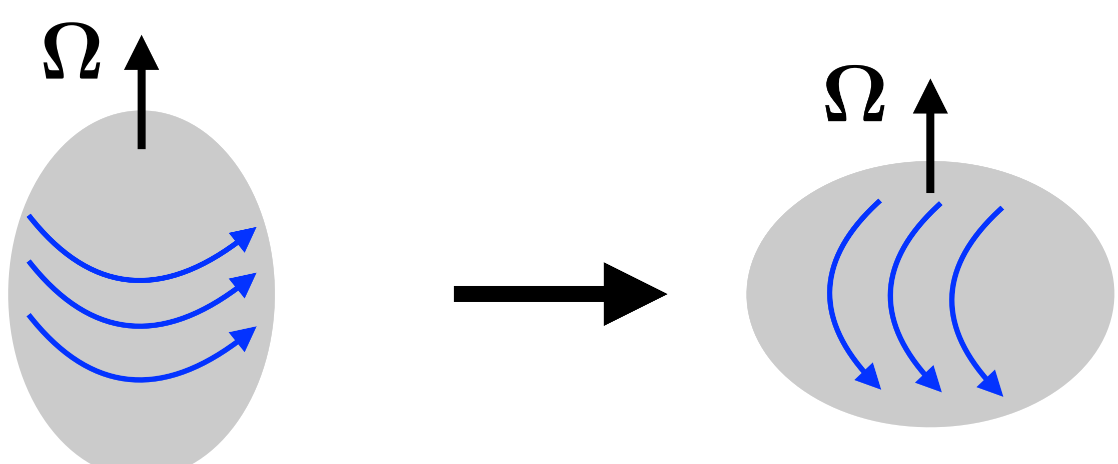
Magnetic deformation & "spin-flip"

- The magnetic deformation is expected to be dominated by the post-merger generated *toroidal* field:

$$\epsilon_B \approx 10^{-6} \left(\frac{\langle B_{\rm t} \rangle}{10^{15}\,{\rm G}} \right)^2 \qquad\qquad B_{\rm t} \sim (1-10) B_{\rm p}$$

- The initial B-field is likely to be nearly symmetric with respect to the spin axis → GW emission minimised

- But: a dominantly toroidal B-field undergoes a "spin-flip" instability where the spin and magnetic axes become orthogonal.



→ GW emission maximised

Spin-flip physics (I)

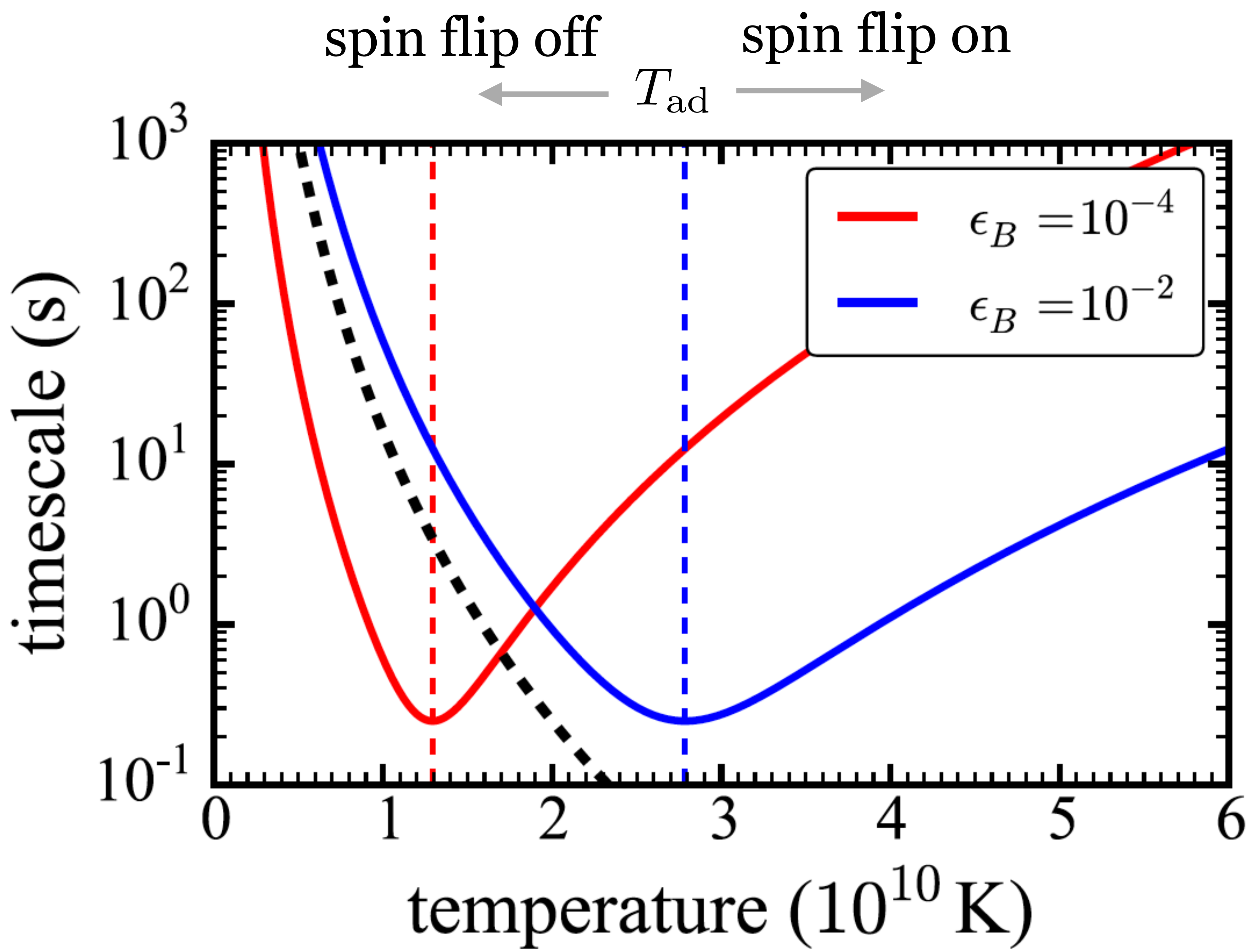
- The spin-flip timescale depends on viscosity — for the system at hand this is bulk viscosity.
- The spin-flip is *suppressed* below a temperature threshold because bulk viscosity reactions become too slow with respect to fluid motion.

$$T_{\rm ad} \approx 9 \times 10^9 \left(\frac{\rho}{10^{15}\,{\rm g\,cm^{-3}}}\right)^{1/9} \left(\frac{P}{1\,{\rm ms}}\right)^{-1/6} \left(\frac{\epsilon_B}{10^{-5}}\right)^{1/6} {\rm K}$$

- When combined with standard cooling, this constraint leads to a *maximum* magnetic mountain ellipticity that spin-flips:

$$\epsilon_{\rm sf} \approx 5 \times 10^{-3} \left(\frac{\rho}{10^{15}\,{\rm gr\,cm^{-3}}}\right) \left(\frac{P}{1\,{\rm ms}}\right)^{-2} \left(\frac{R}{10\,{\rm km}}\right)^{-2}$$

Spin-flip physics (II)



cooling

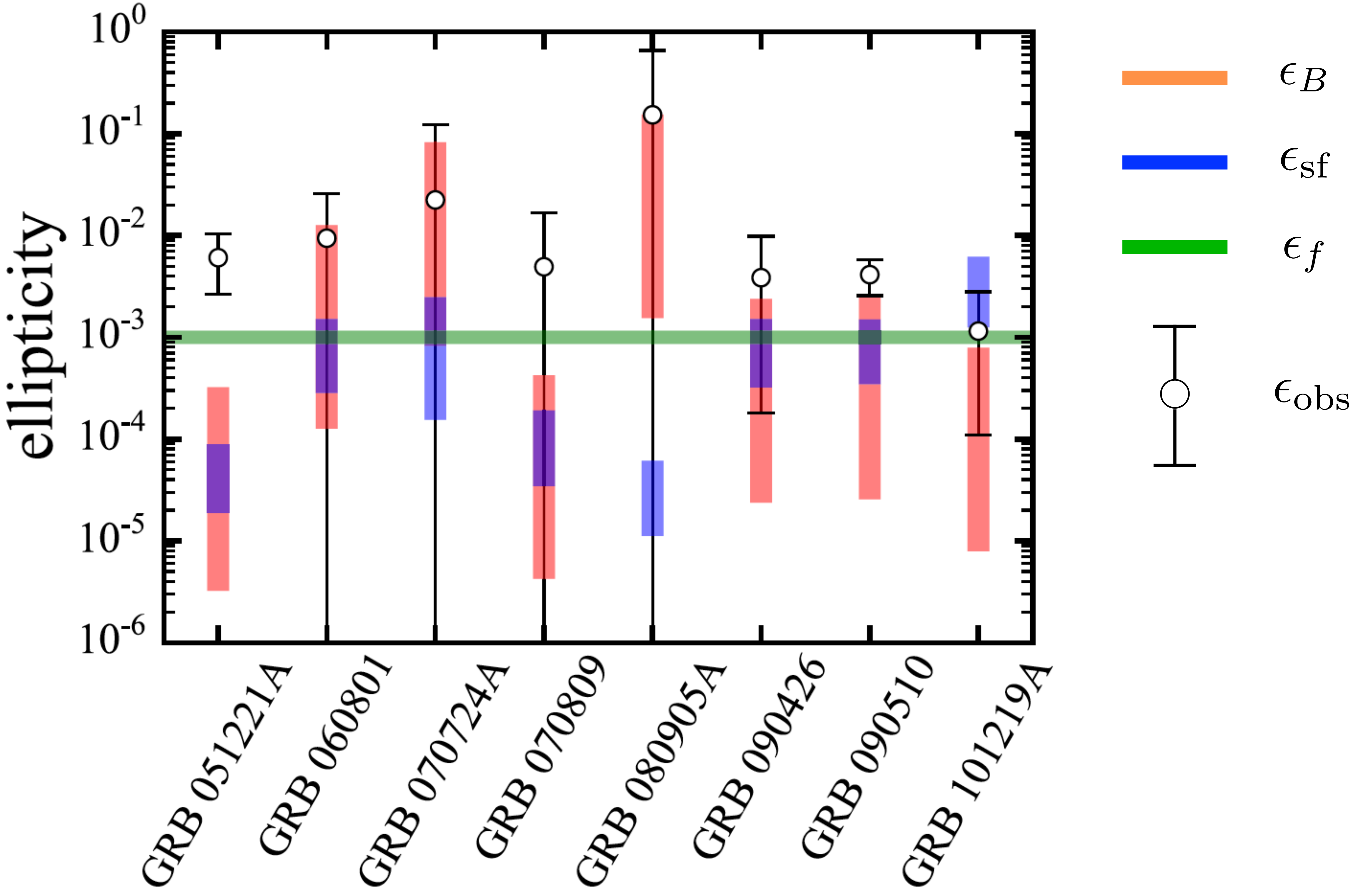
$\epsilon_B > \epsilon_{\rm sf}$

spin flip ✗

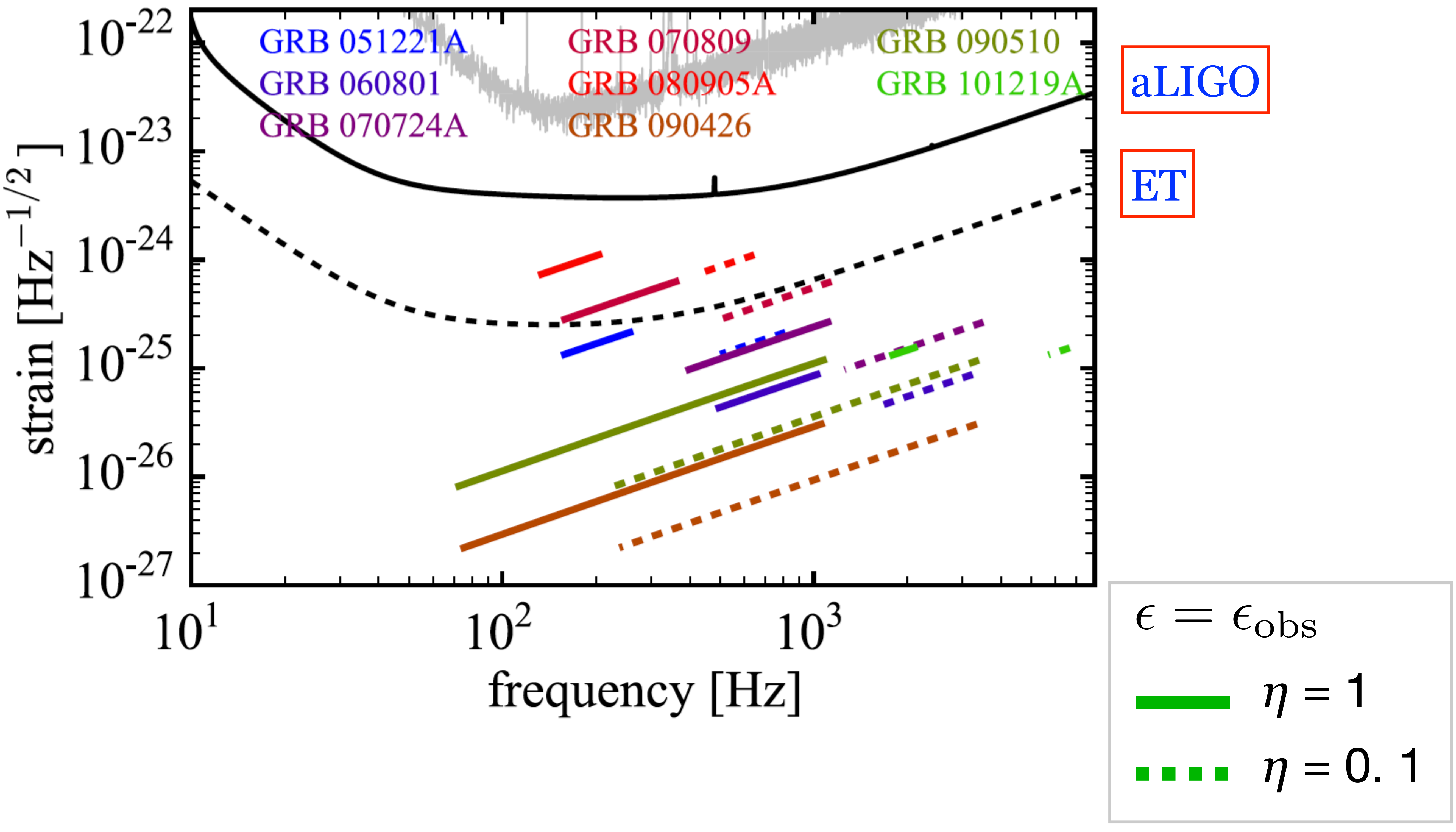
$\epsilon_B < \epsilon_{\rm sf}$

spin flip ✓

Observational bounds on ellipticity



GW detectability of short GRBs



Summary

- X-ray light curves from short GRBs can constrain GW emission from these systems.

- Constraints on NS ellipticity: “reasonable” and compatible with theoretical predictions.

- GW emission from the spin down of short GRB remnants unlikely to be detectable from aLIGO — slightly better prospects for ET.