

Gravitational waves from a newly born accreting magnetar

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with

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Introduction

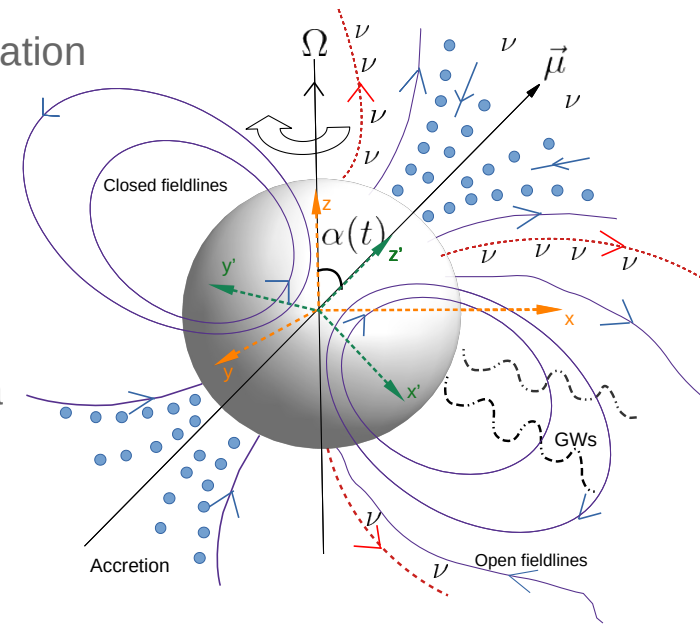
- Fallback accretion onto the magnetar with millisecond spin period ⁽¹⁾(frequency < Keplerian breakup limit).
- Magnetic moment axis inclined at an angle alpha with respect to the rotation axis.

- Two important radii, $r_m = \left(\frac{B^4 R^{12}}{GM\dot{M}^2} \right)^{1/7}$, $r_c = \left(\frac{GM}{\Omega^2} \right)^{1/3}$

Two accretion column forms when $r_m < r_c$

- Gravitational potential radiative luminosity balances neutrino cooling via electron-positron pair annihilation gives the height of accretion column
 Zhong et al PRD (2019):

$$h_{acc} = \mathcal{O}(10^4) \text{cm} M_{1.4}^{3/56} \dot{M}_2^{-25/28} B_{15}^{-5/7} R_{15}^{97/56}$$



¹Ott et al ApJS 2006

Accreting magnetar

- Mass accretion rate $\dot{M} = \eta 10^{-3} t^{1/2}$, η being the supernova explosion parameter. We consider $\eta = 10$. (1)

- Mass of accretion column $M_{acc} = 1.7 \times 10^{-7} M_{\odot} M_{1.4}^{-25/56} \dot{M}_2^{3/28} B_{15}^{-5/7} R_{15}^{125/56}$ (Zhong et.al PRD 2019)

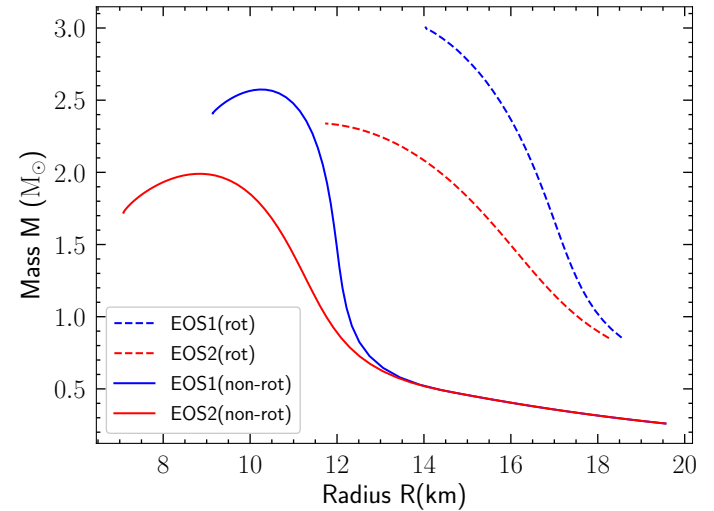
- Equation of state
$$P(\rho) = \begin{cases} k\rho^{\gamma_1} & \text{if } \rho < \rho_c \\ k'\rho^{\gamma_2} & \text{if } \rho \geq \rho_c \end{cases}$$

$$\gamma_1 = 1.663, \rho_c = 4.5 \times 10^{14} \text{ gm/cm}^3 \quad k = (3.0\pi^2)^{2/3} \hbar^2 / (5m_n^{8/3})$$

$$\gamma_2 = 3.40 \rightarrow M_{max} \sim 2.57 M_{\odot}$$

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- Fully relativistic models using RNS code (2).
- Rapid rotation allows for a higher maximum mass.
- Radius of the NS change as the NS becomes massive.
- The accretion column reduces magnetic dipole moment (Payne & Melatos MNRAS 2004)



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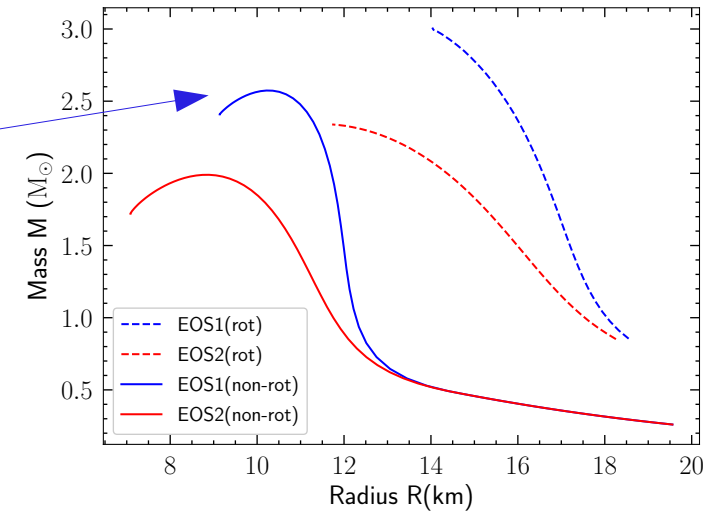
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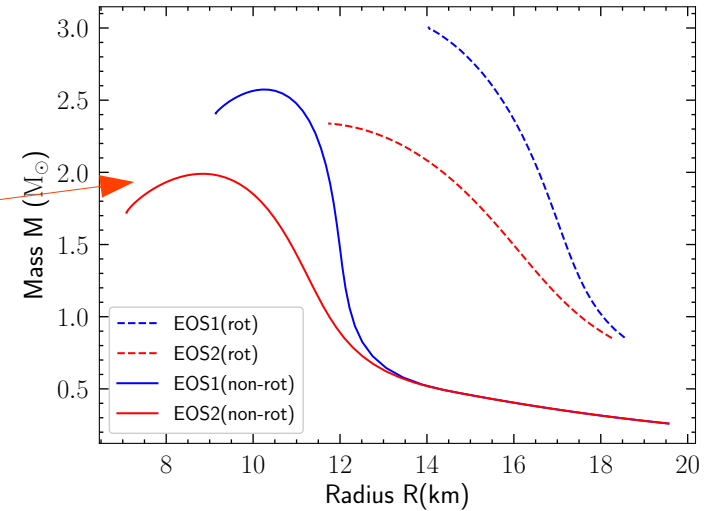
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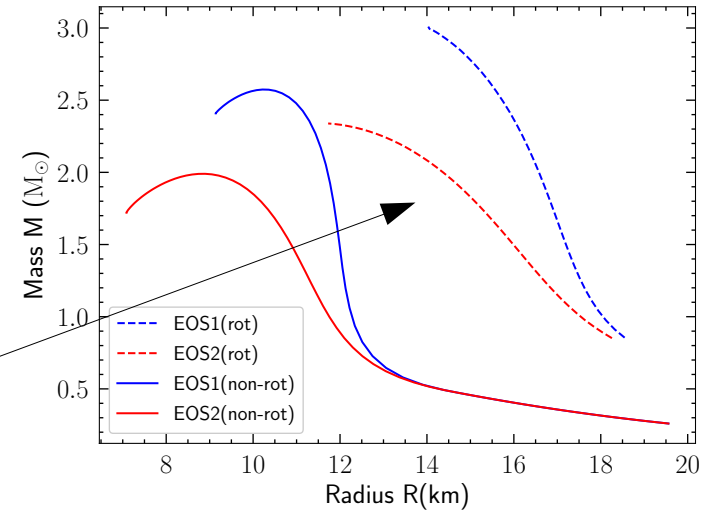
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Gravitational waves

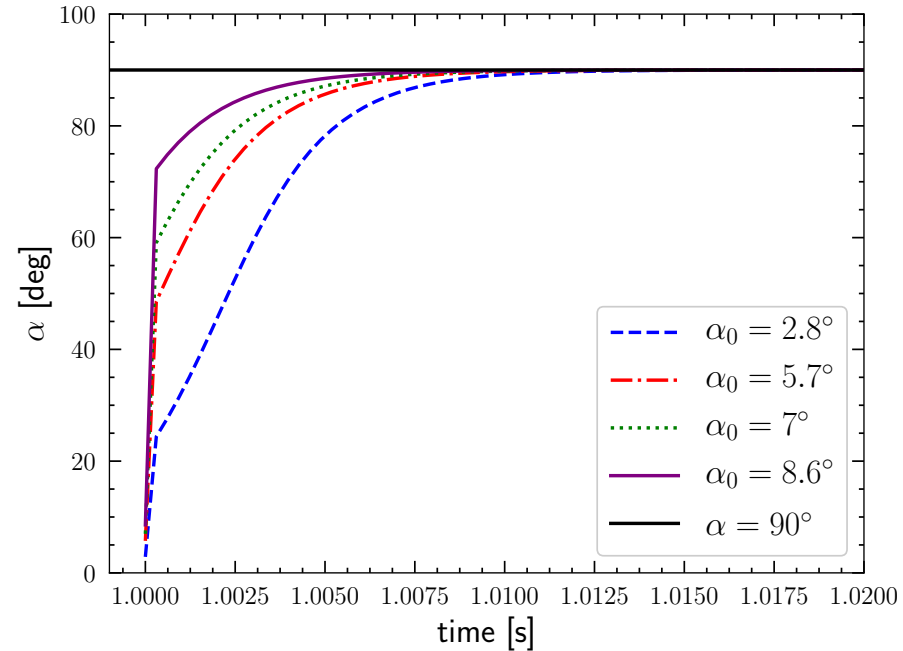
- The moment of inertia along the x' , y' , z' axes I_1 , I_2 , and I_3 respectively.
- The quadrupole moment is given by $Q = I_3 - I_1 = 2M_{acc}R^2$
- The gravitational wave luminosity is¹

$$L_{gw} = -\frac{8G}{5c^5}M_{acc}^2R^4\Omega^6\sin^2\alpha(16\sin^2\alpha+\cos^2\alpha)$$

- The gravitational wave amplitude¹ is given by

$$h_0 = \frac{4GQ\Omega^2\sin^2\alpha}{c^2d}$$

- The evolution of the inclination
- The GW amplitude is maximum



¹ Shapiro&Teuloksky

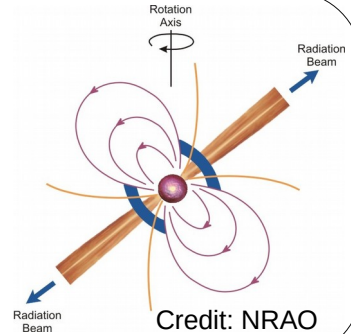
Spin evolution

The spin evolution is affected by the following torques:

Magnetic dipole radiation

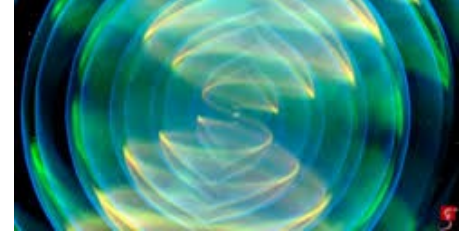
$$N_{dip} = \frac{B^2 R^6 \Omega^3}{c^3} (1 + \sin^2 \alpha)$$

Spitkovsky ApJL 2006



GW radiation

$$N_{gw} = L_{gw} / \Omega$$

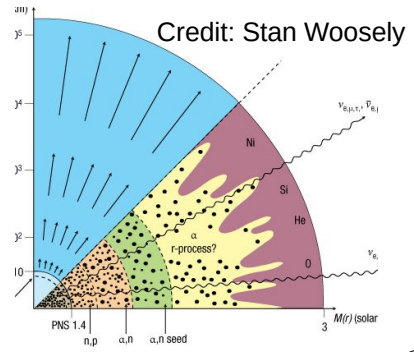


Credit: AEI Potsdam / LIGO

Neutrino torque ⁽¹⁾

$$L_\nu = \left(\frac{B^2 R^6 \Omega^4}{\dot{M}_\nu} \right)^{2/5} \dot{M}_\nu$$

$$N_\nu = L_\nu / \Omega$$

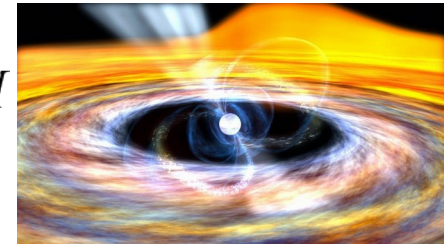


Accretion torque ⁽¹⁾

$$N_{acc} = n(\omega) (GM r_m)^{1/2} \dot{M}$$

Fastness parameter ⁽²⁾

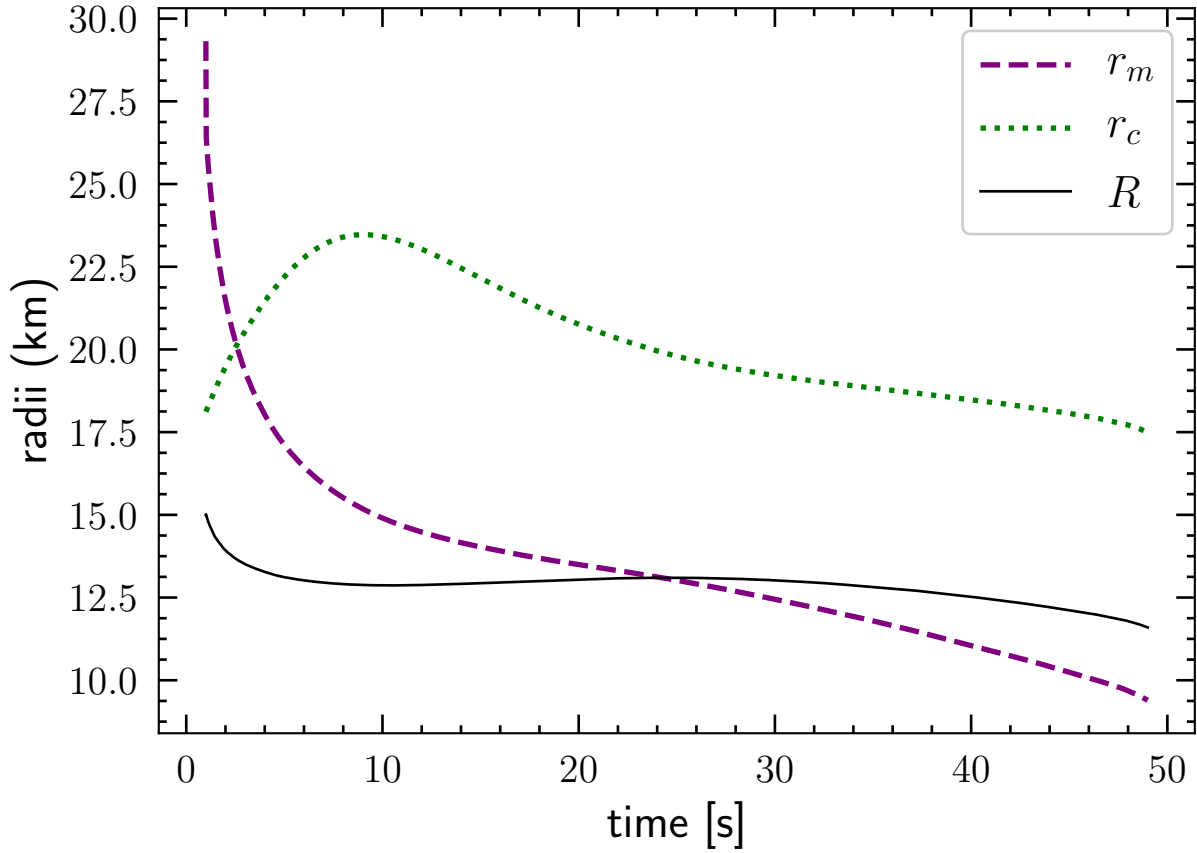
$$n(\omega) = (1 - \omega), \quad \omega = (r_m / r_c)^{3/2}$$



AAS Nova

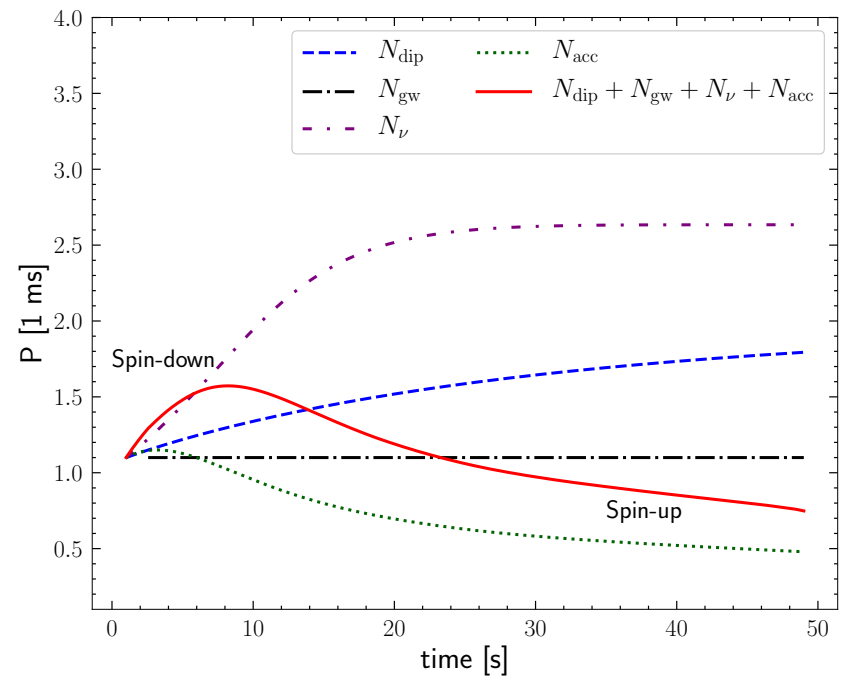


Different Radii

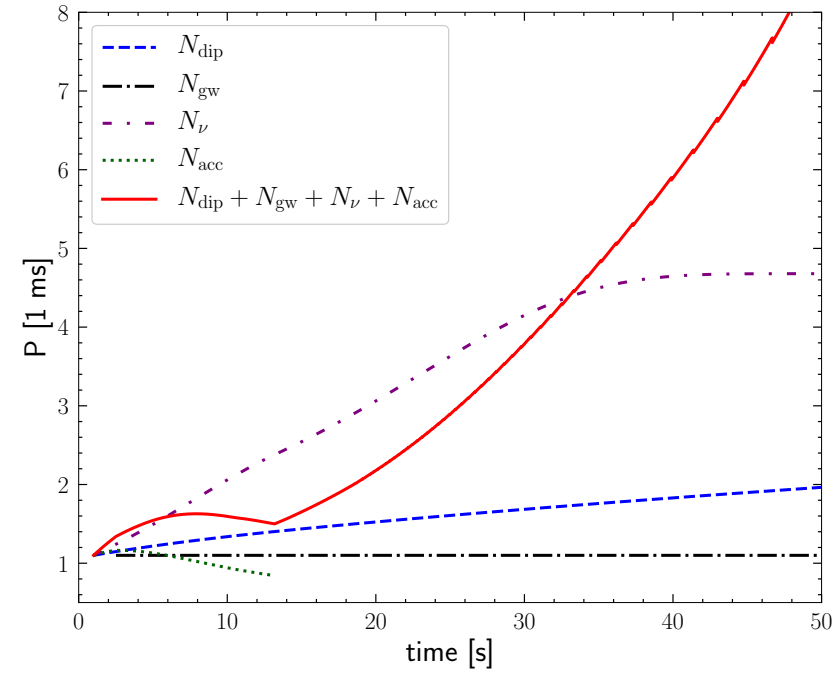


Results: Spin

Core-collapsed supernovae (CCS)



Binary neutron star merger (BNS)



Fallback accretion, the star becomes massive with $M_g = 2.73M_{\odot}$ before becoming a black hole.

When mass available for accretion $\sim 0.2 M_{\odot}^{(1,2)}$



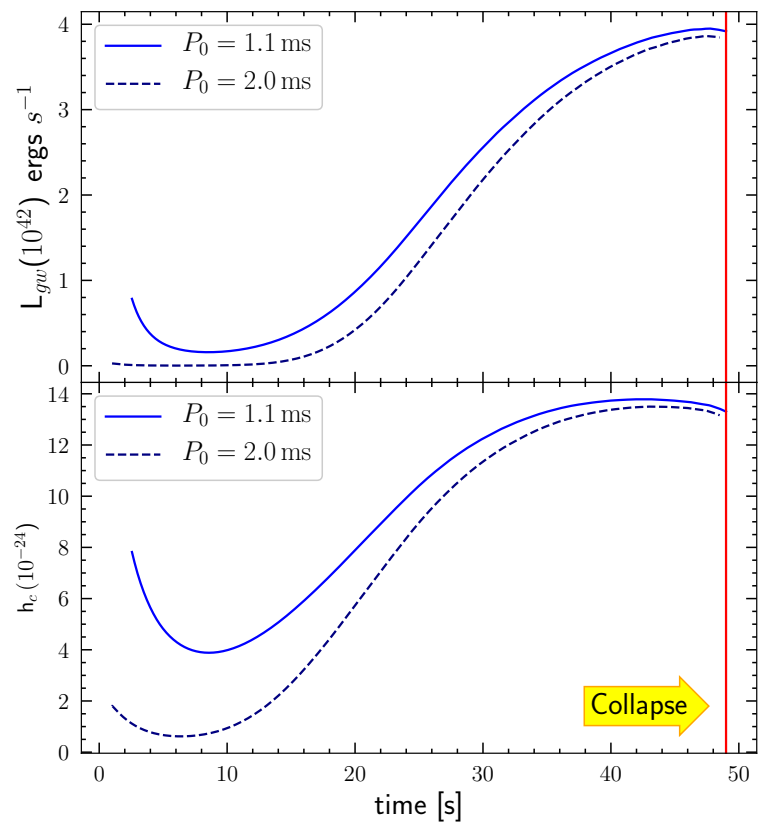
¹Radice et al. ApJ 2018

²Bernuzzi et al. MNRAS 2020

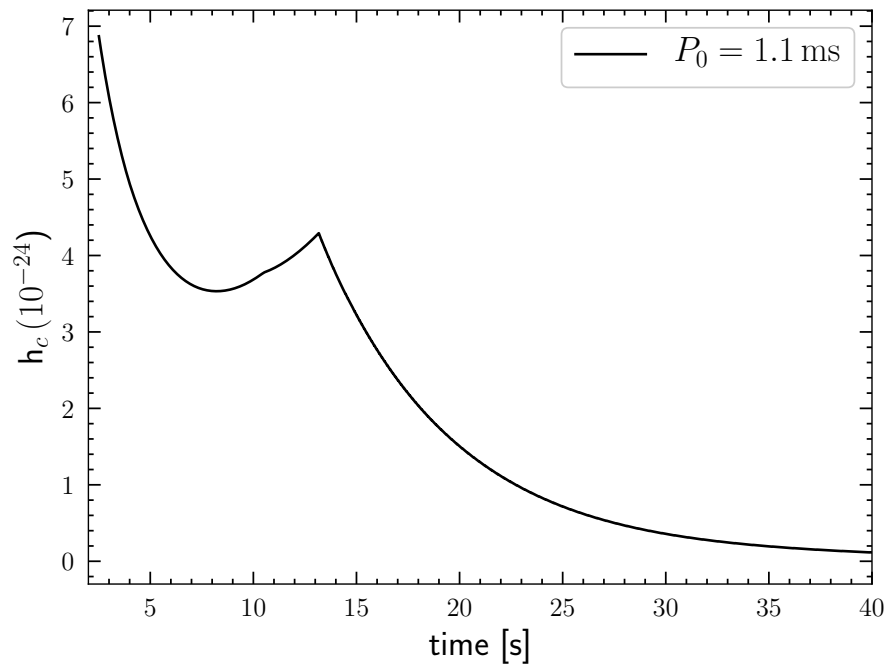
Sur&Haskell (in prep)

Results: GW strain

Core-collapsed supernovae (CCS)



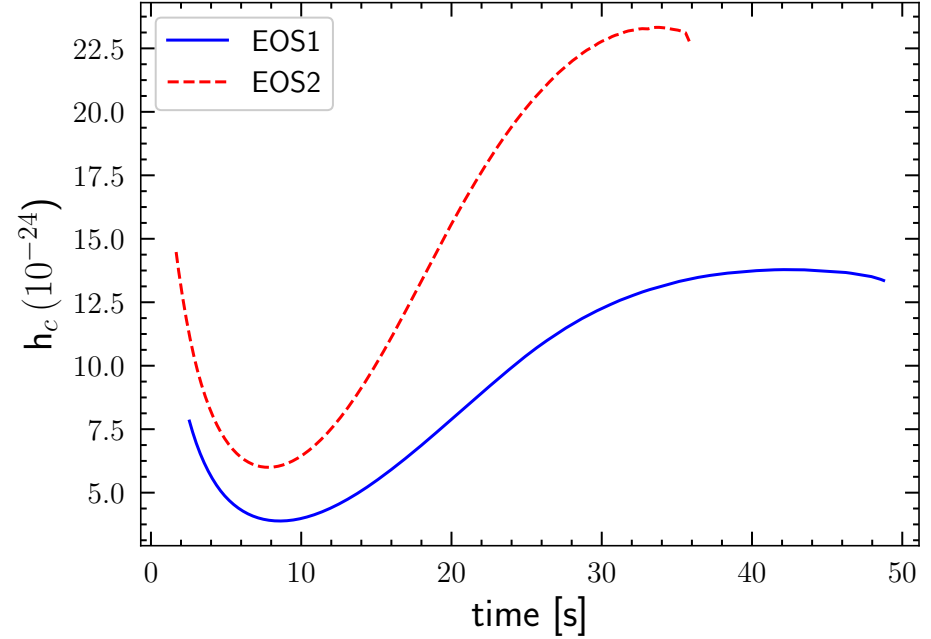
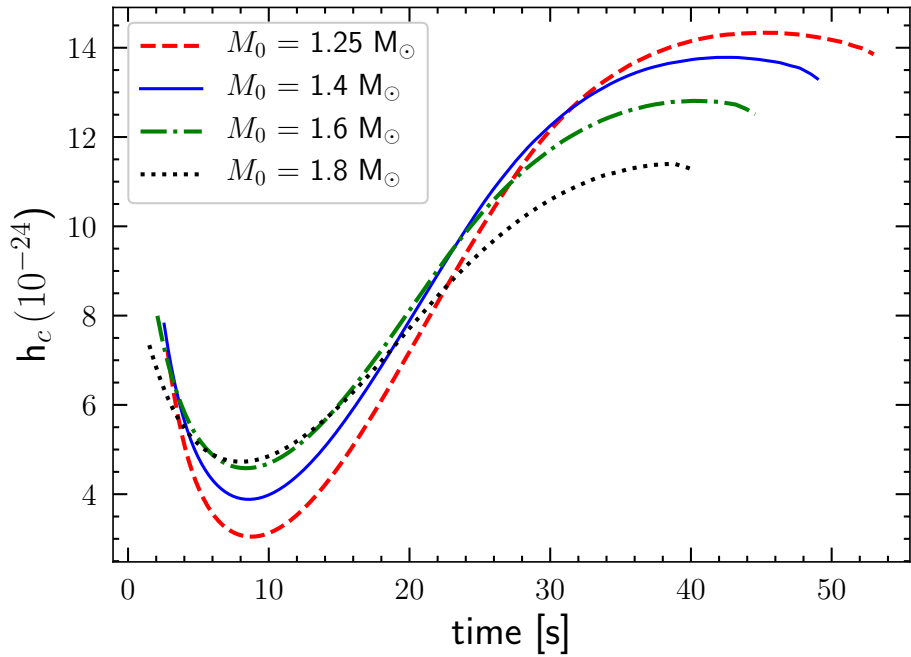
Binary neutron star merger (BNS)



$$h_c = h_0 \sqrt{ft_{sur}} = \mathcal{O}(10^{-24}) M_{1.4}^{-25/56} \dot{M}_{-2}^{3/28} B_{15}^{-5/7} R_{15}^{237/56} P^{-2} D_{Mpc}^{-1}$$



Results: GW strain



Changing the initial mass or the EOS does not change the GW strain significantly.

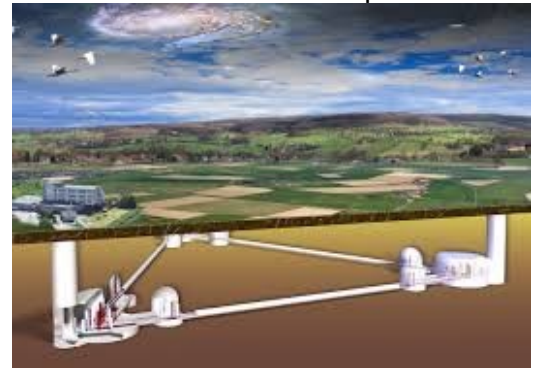


Detectability

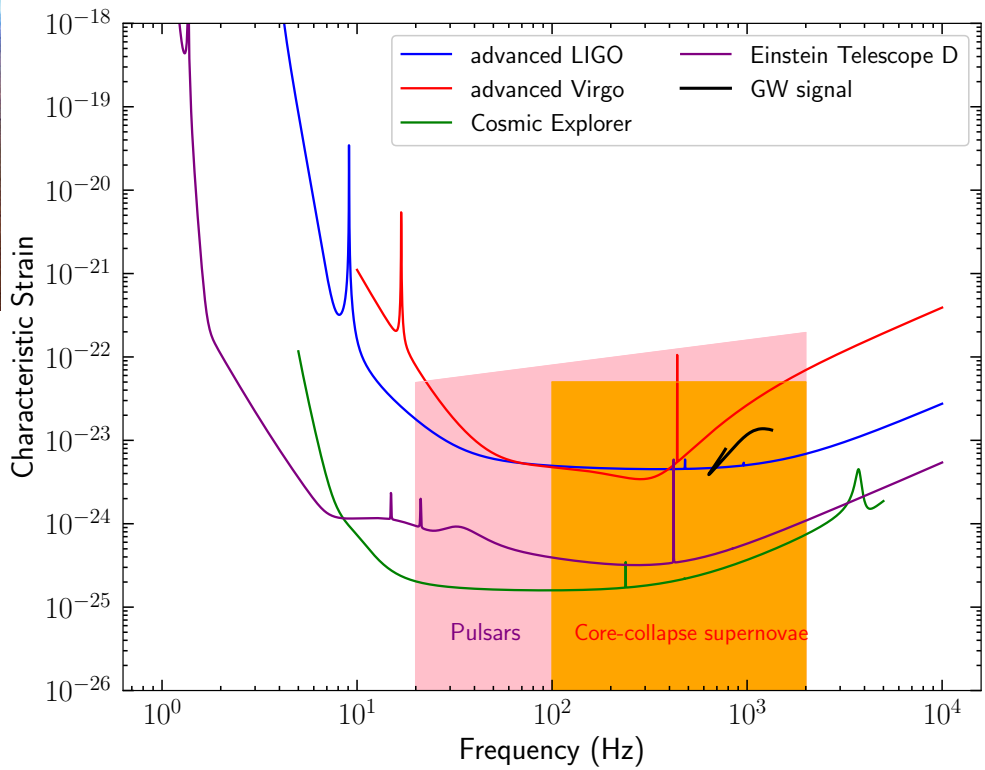
Advanced LIGO



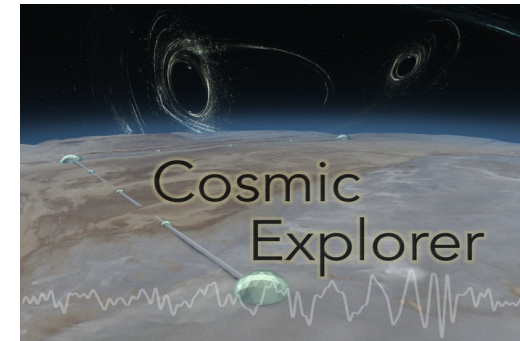
Einstein Telescope



(Credit: Marco Kraan, Nikhef)



Advanced Virgo



<https://cosmicexplorer.org/>



Summary

- We studied how a newly born magnetar could form accretion mountains.
- The magnetic moment axis becomes orthogonal to the rotation axis in few ms.
- Spin evolution is dominated by the neutrino and the accretion torques.
- Gravitational wave strain does not depend on the initial spin, initial mass or the EOS but it does depend on the mass available for accretion.
- Potential targets for future observatories.



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THANK YOU

