Modelling Neutron Star magnetic fields

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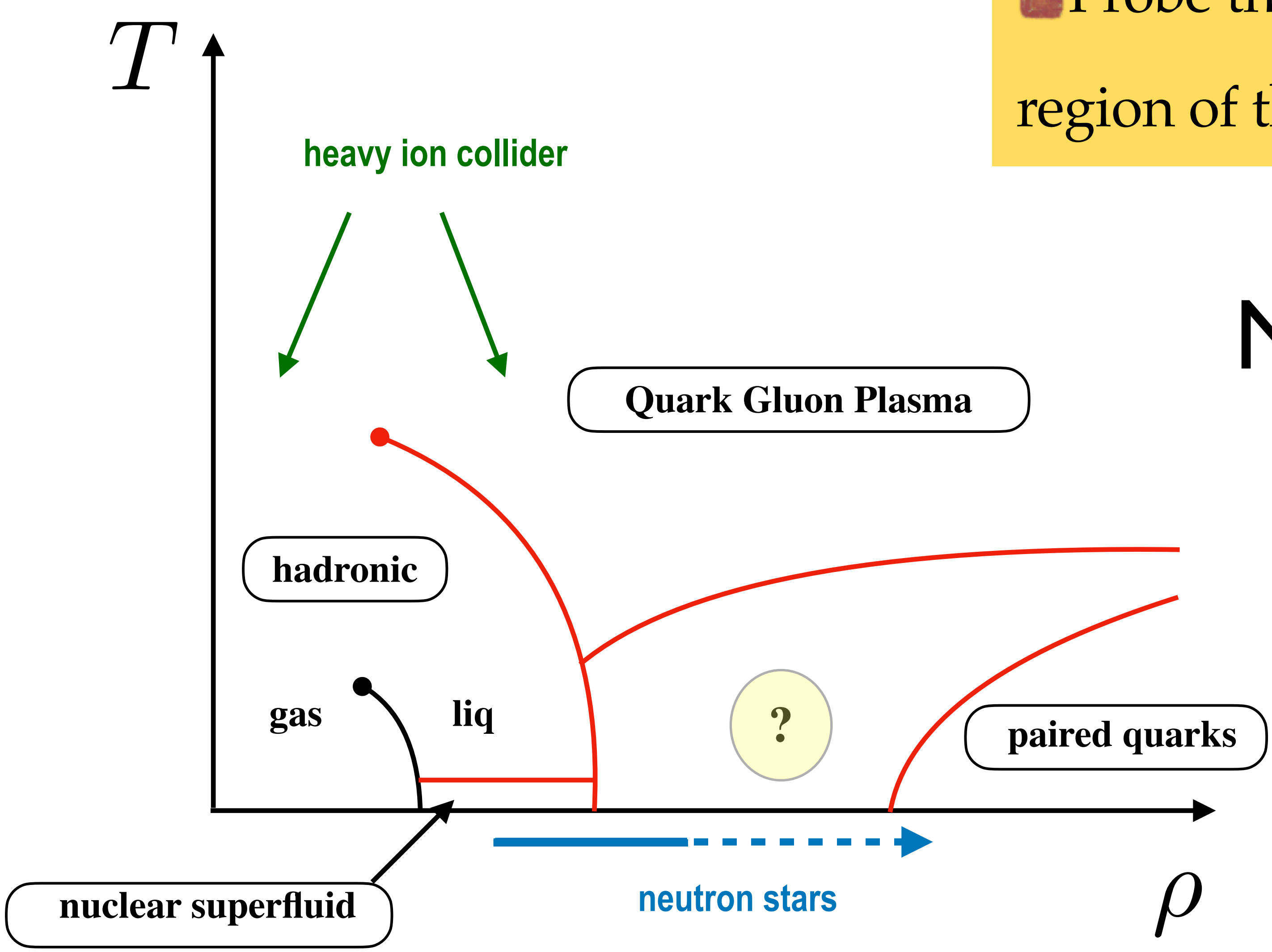
Brynmor Haskell

Polish Academy of Sciences
Nicolaus Copernicus Astronomical Center

LIGO VIRGO KAGRA

Neutron Stars - theoretical importance

What is the Equation of State of dense matter?



Probe the low-temperature high-density region of the QCD phase diagram!

Neutron Stars are cold

$$T \approx 1 \ \ \text{keV}$$

$$E_{\mathbf{Fermi}} \approx 50 \ \ \text{MeV}$$

(see Haskell & Sedrakian 2018 for a review)

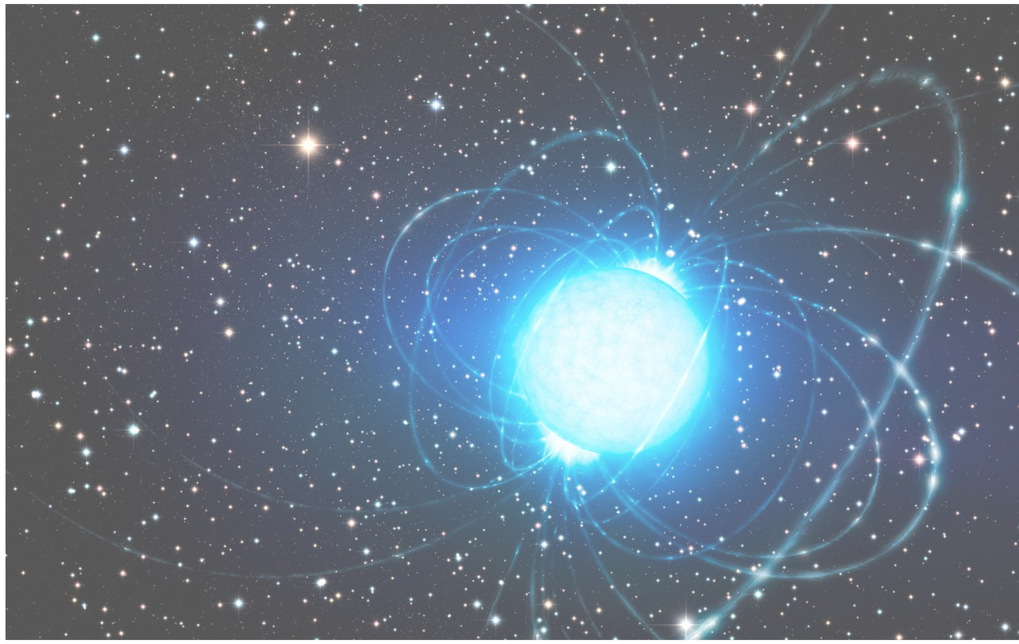
From HD to MHD: Magnetic fields

Neutron Star are strongly magnetised objects!

$$10^7\mathrm{G} \lesssim B \lesssim 10^{16}\mathrm{G}$$

In Magnetars above the QED limit

$$B > 4.4 \times 10^{13}\ \mathrm{G}$$



The field governs the emission - but also has a role in the dynamics of the star

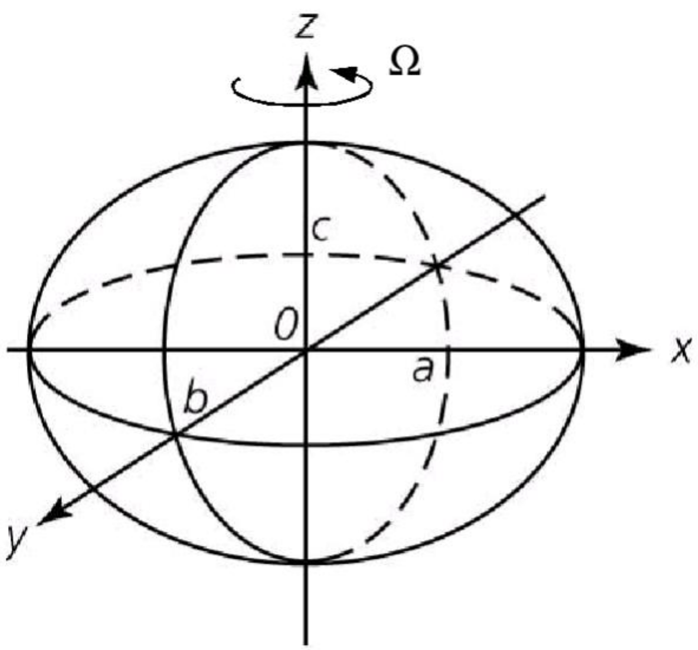
- B field couples to the thermal evolution in magnetars
- NS B field affects the pulse profile - configuration fundamental for determining EoS with NICER.
- B field governs the accretion dynamics in LMXBs

Minimum ellipticity

- **A magnetised NS (or a merger remnant) produces a 'continuous' GW signal**

  [Bonazzolla and Gourgoulhon 1996]

- Magnetic fields can support a quadrupole in the star



$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- GW emission at $2\nu_{spin}$ and ν_{spin}

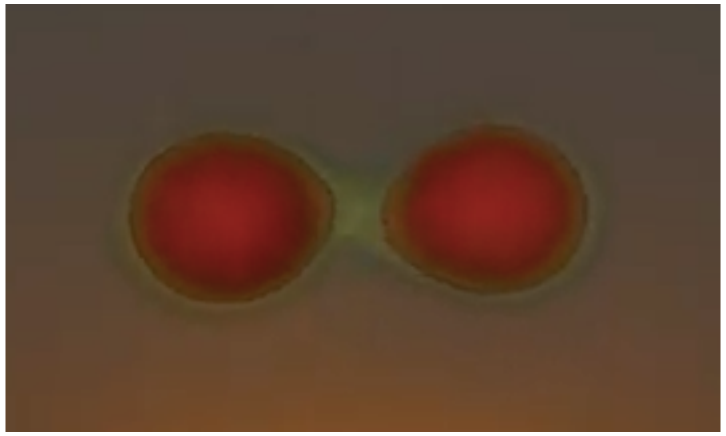
$$\epsilon \propto 10^{-11} \left(\frac{B}{10^{12} G}\right)^2$$

$$\epsilon \propto 10^{-9} \left(\frac{B}{10^{12} G}\right) \left(\frac{H_c}{10^{14} G}\right)$$

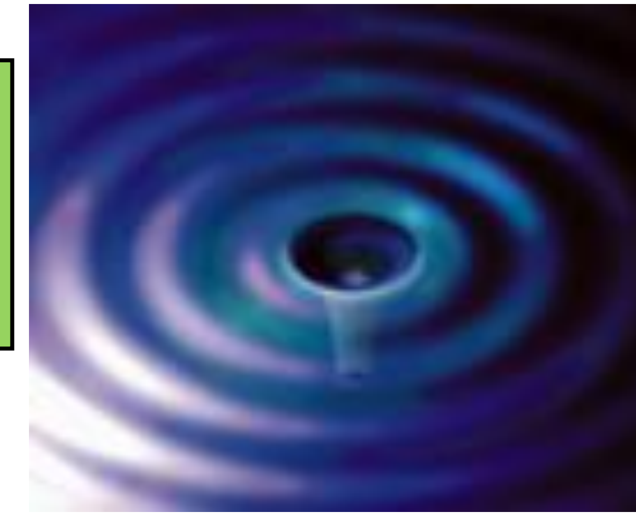
Magnetic deformation

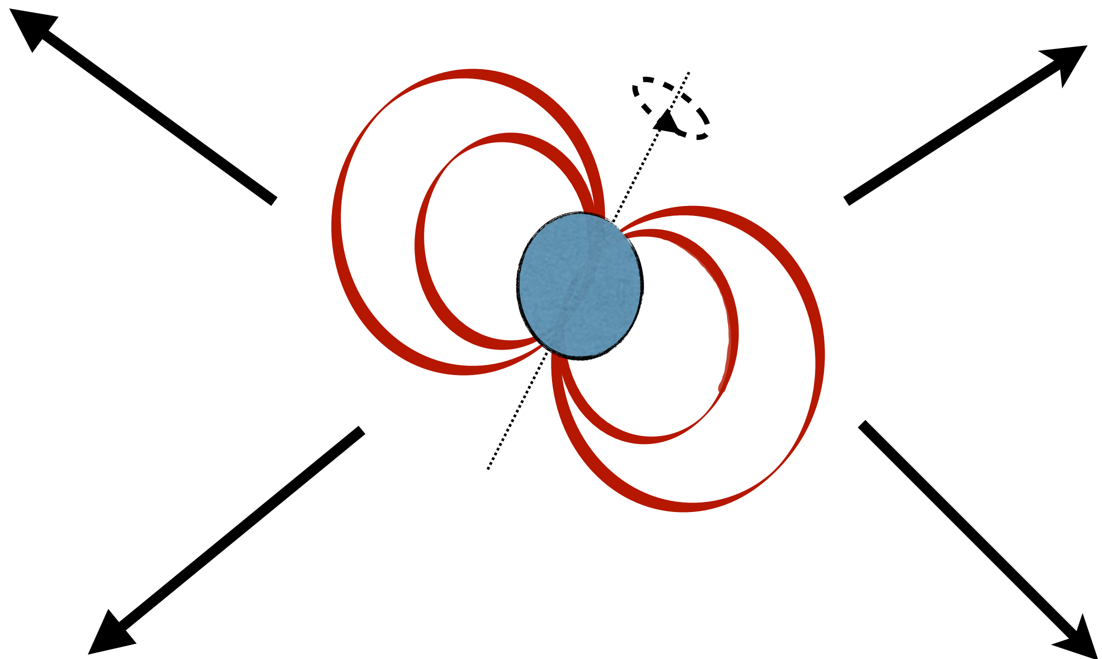
- Can lead to strong emission in new born NSs (Dall'Osso et al. 2009, 2018)

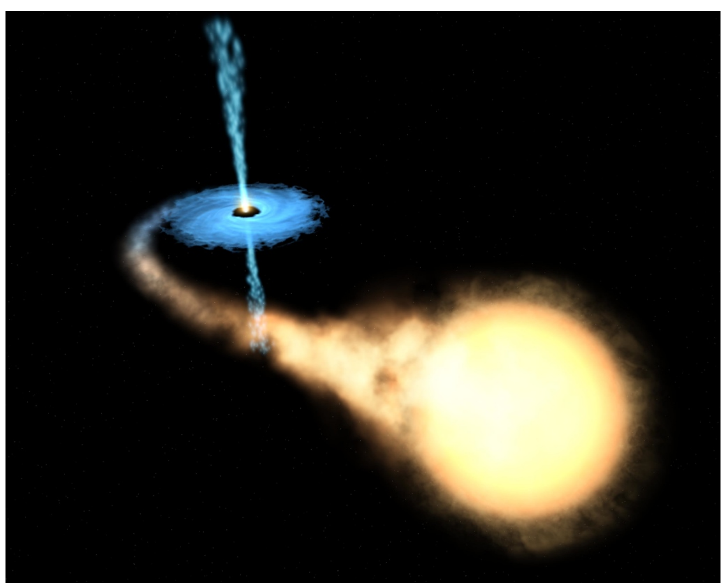
Neutron Stars - astrophysical laboratories



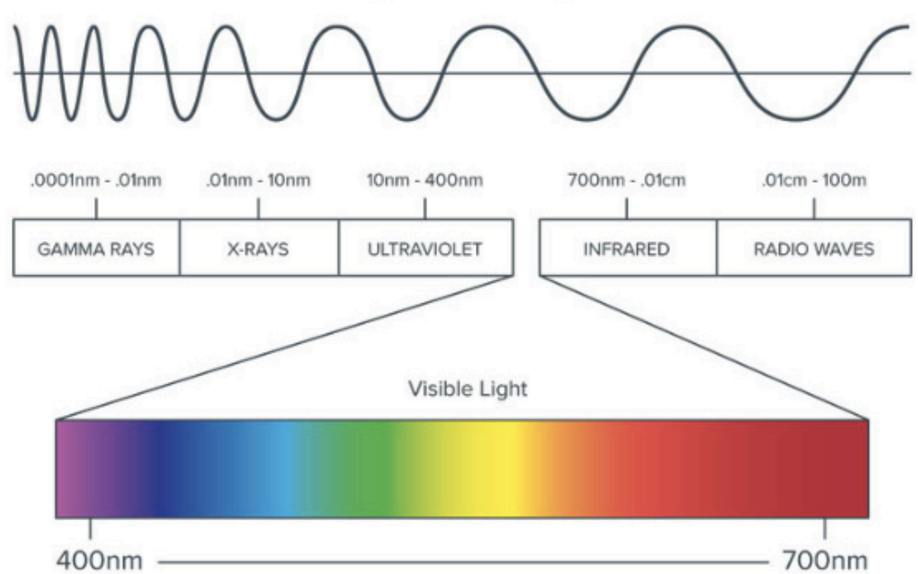
Gravitational waves

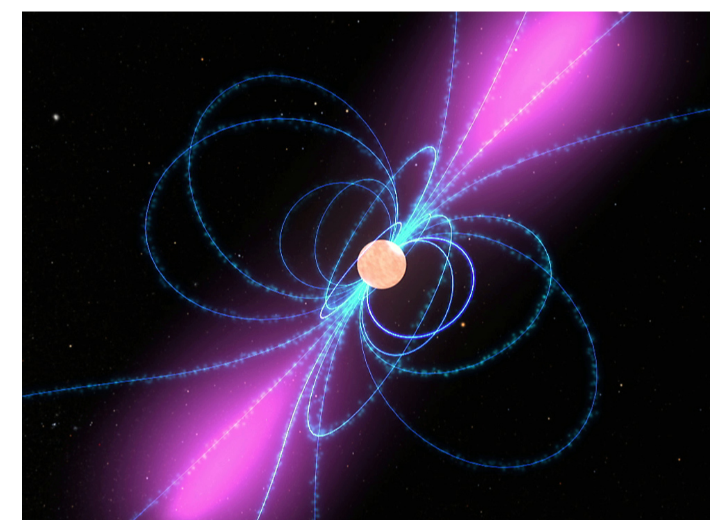






Neutrinos?





Electromagnetic waves

EM observations

- Evidence cutoff in the P-Pdot diagram

  (Woan, Pitkin, BH, Jones & Lasky 2018)

  $\epsilon \approx 10^{-9}$

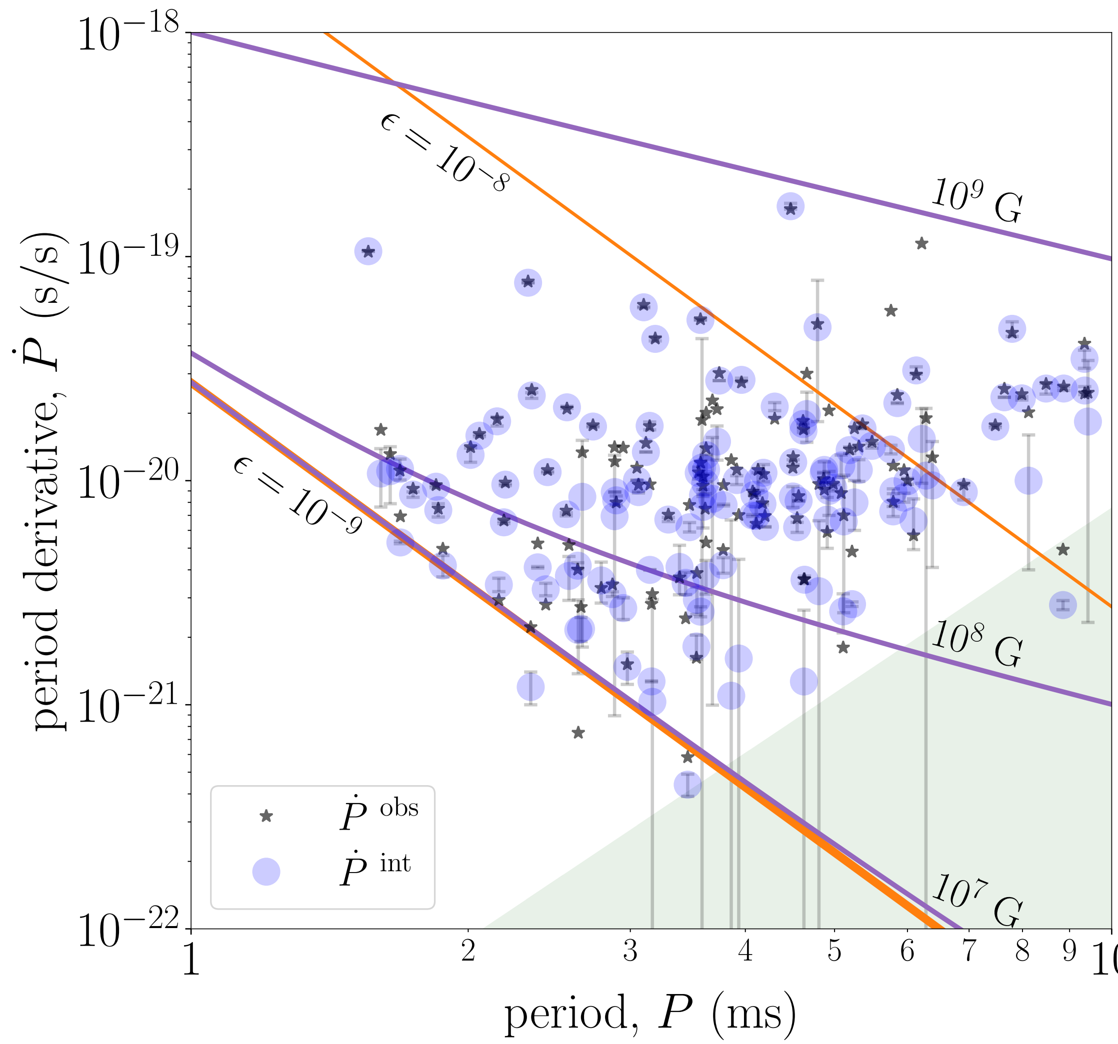
- Buried B field in type II superconductor?

- Deformations expected also in young NSs (up to $\epsilon \approx 10^{-6}$)

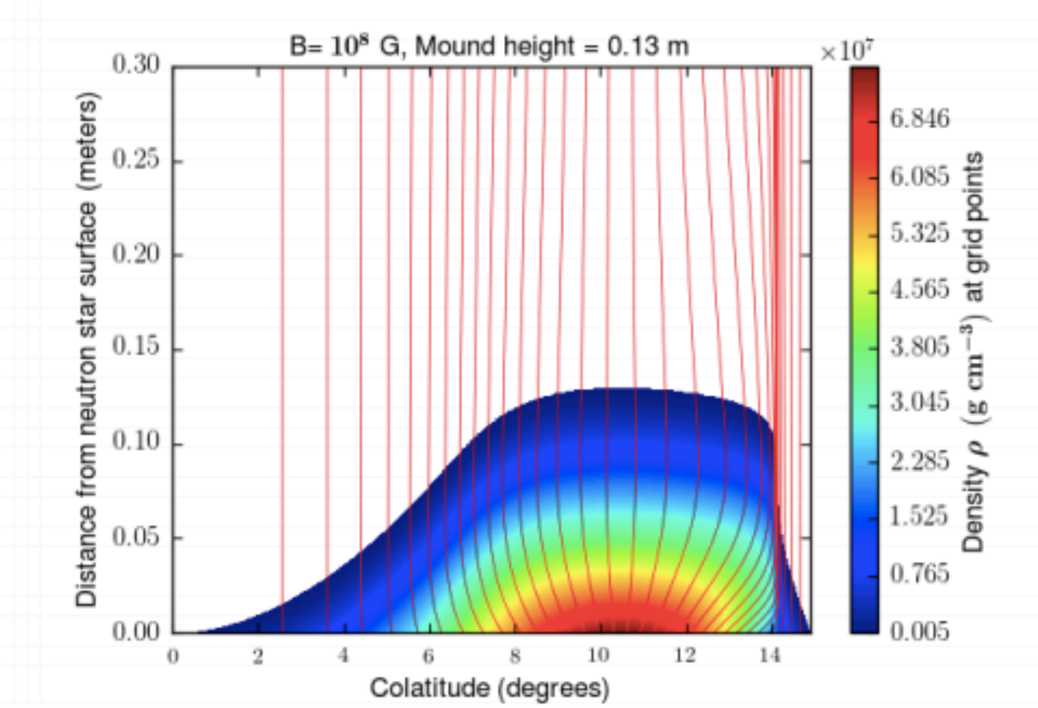
  (Suvorov et al. 2016)

- Lack of sub-millisecond pulsars?

  (Bildsten 1998, Patruno et al. 2017, BH et al. 2019)



Old NSs - accreting NSs in LMXBs



(Singh et al. 2020)

Fastest Neutron Star: 716 Hz

[Chakrabarty et al 2003, Patruno 2010, Papitto et al. 2014, Patruno, BH and Andersson. 2017]

- Spin up halted well before breakup frequency

(Theoretical lower limit on max breakup f ~1200 Hz - **BH et al. 2018**)

- GWs!: magnetic deformations from accretion

$$\epsilon \approx 10^{-7}$$

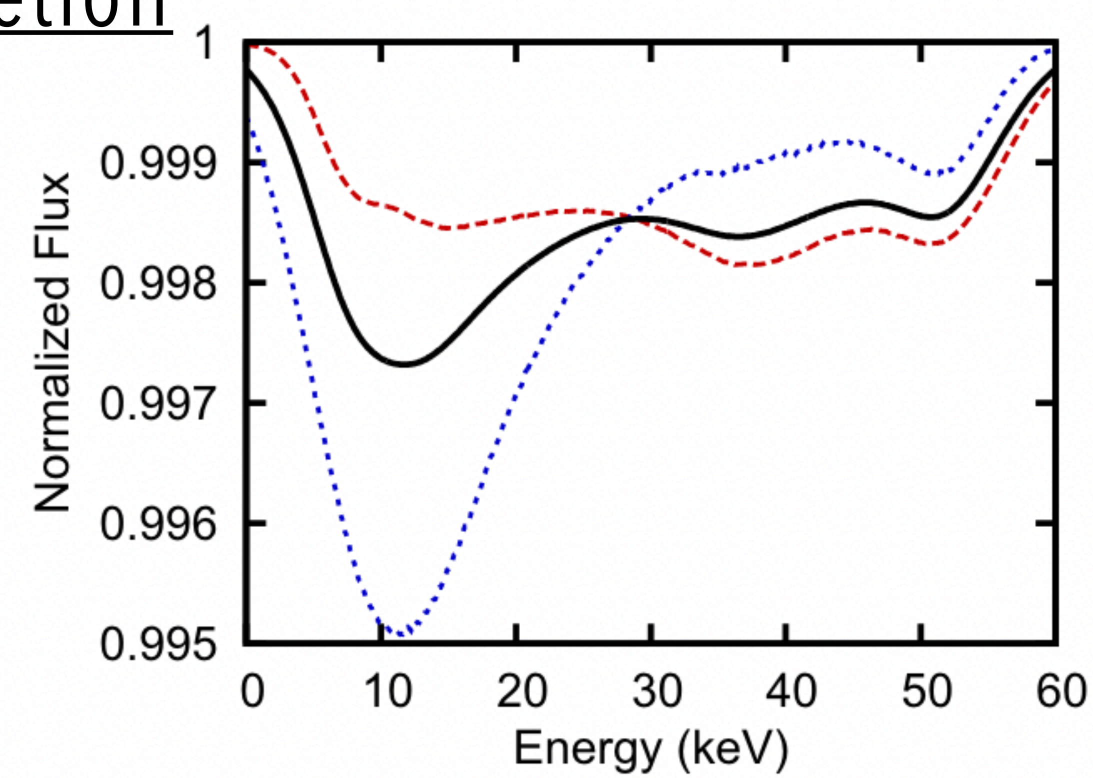
[Payne & Melatos 2005]

- Cyclotron features possible

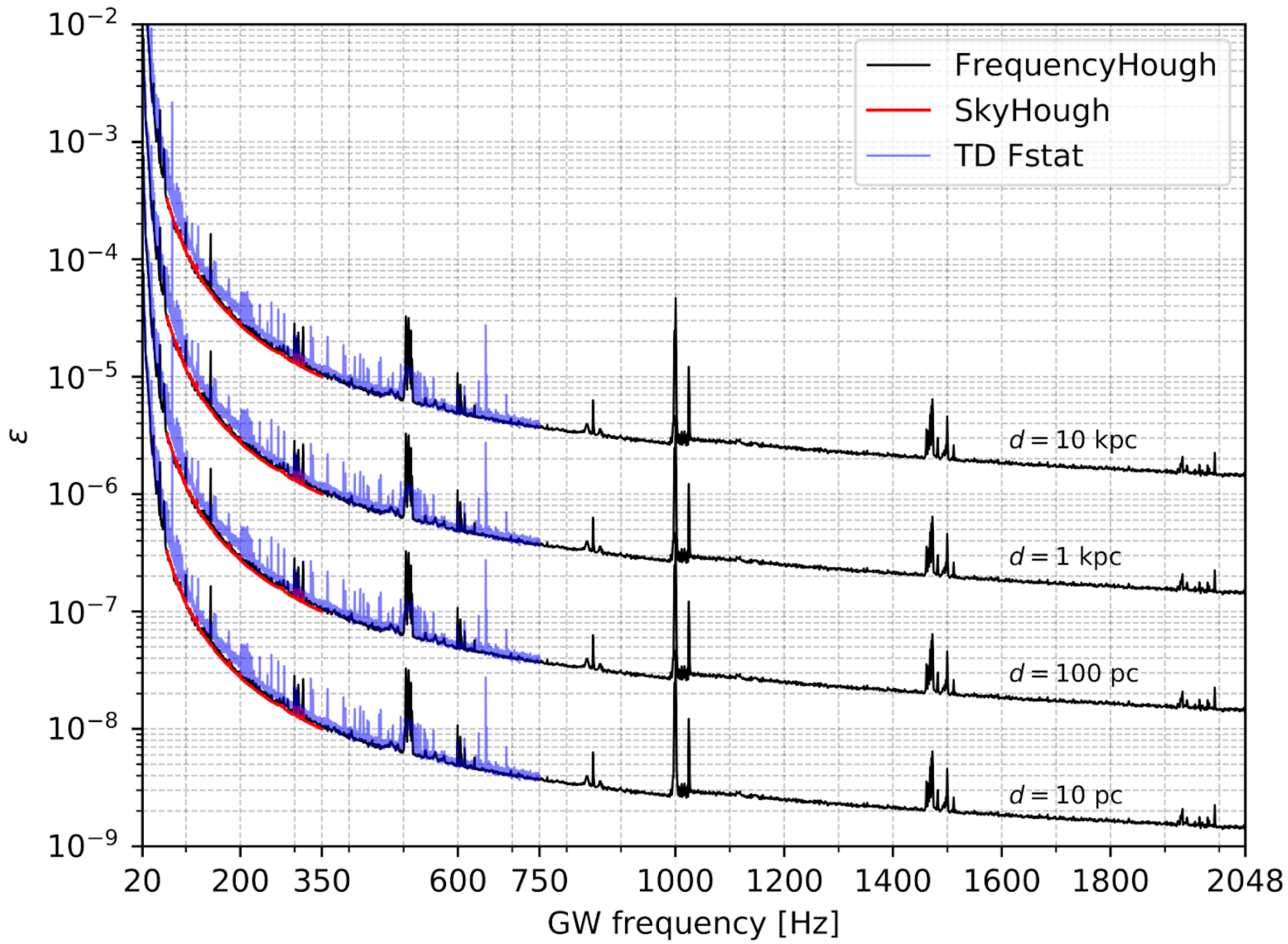
[BH et al. 2015]

- At work in transitional pulsars?

[BH + Patruno 2017, Singh et al. 2020]



CW searches in the O3 run of the LVK



- Reach of 'blind' searches

Abbott et al. Phys. Rev. D 103, 064017 (2021)

Abbott et al. Phys. Rev. D 106, 102008 (2022)

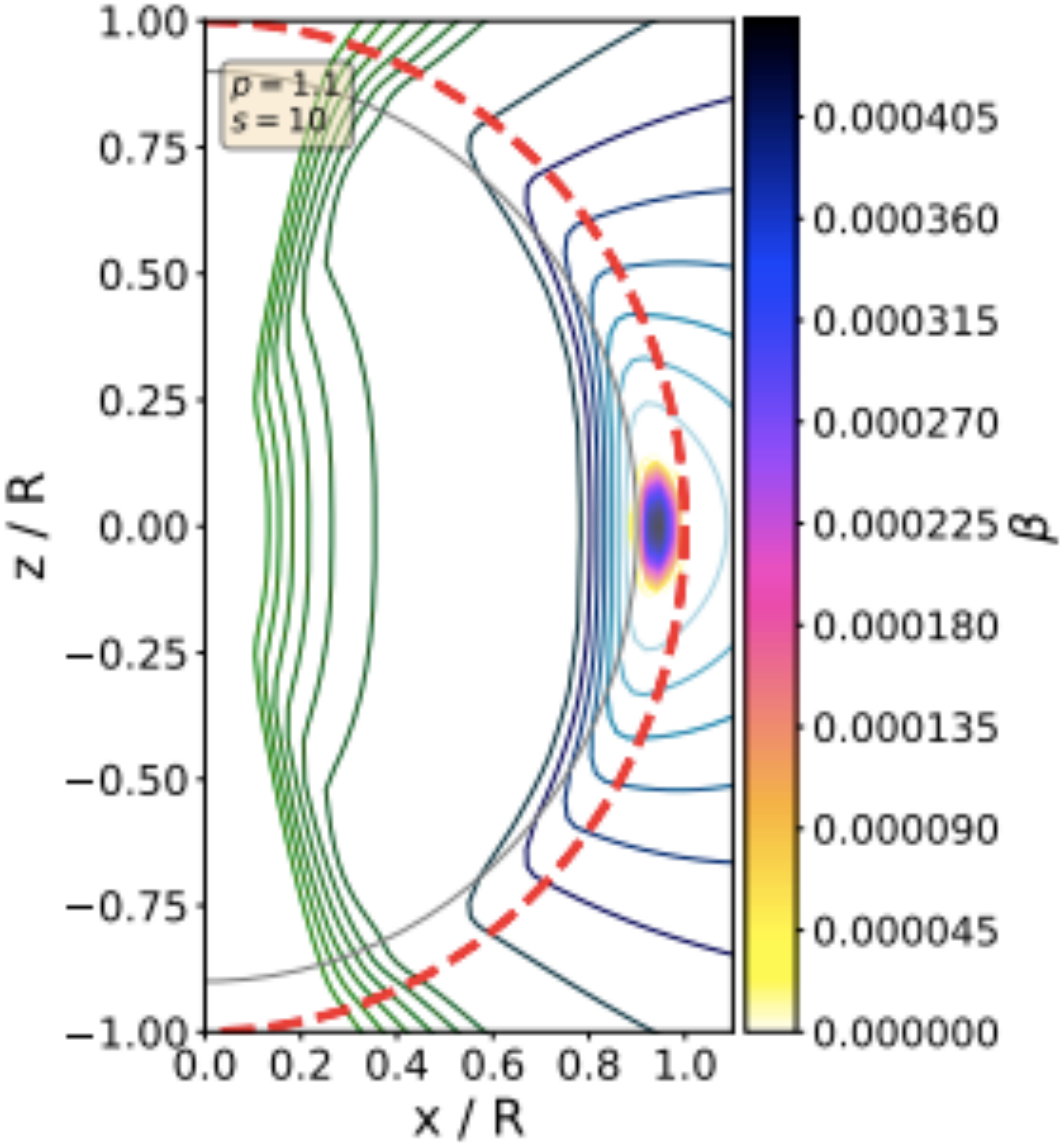
- Probing NS in the galaxy - next runs exciting
- Searches beat the spin-equilibrium limit for the LMXB SCO X-1

Abbott et al. ApJ Letters 941, L30 (2022)

- Next generation instruments (ET, Cosmic Explorer) can probe these models

(Woan, Pitkin, BH, Jones & Lasky 2018)

What is the B field configuration?



[Sur and Haskell 2021]

- Purely poloidal or toroidal are unstable ⟶ twisted torus?
- What is the ratio of the components? (Can I have a much stronger field inside, and a much larger deformation? [Ciolfi & Rezzolla 2014]
- Several effects must be included (e.g. superconductivity, Hall effect..)
- Is stratification needed? [Becerra+ 22, Moraga+24]
- Equilibrium models have been constructed by several groups

[BH et al 2009, Lander 2012, 2014, Suvorov et al 2016, Sur et al. 2021]

From HD to MHD: Magnetic fields

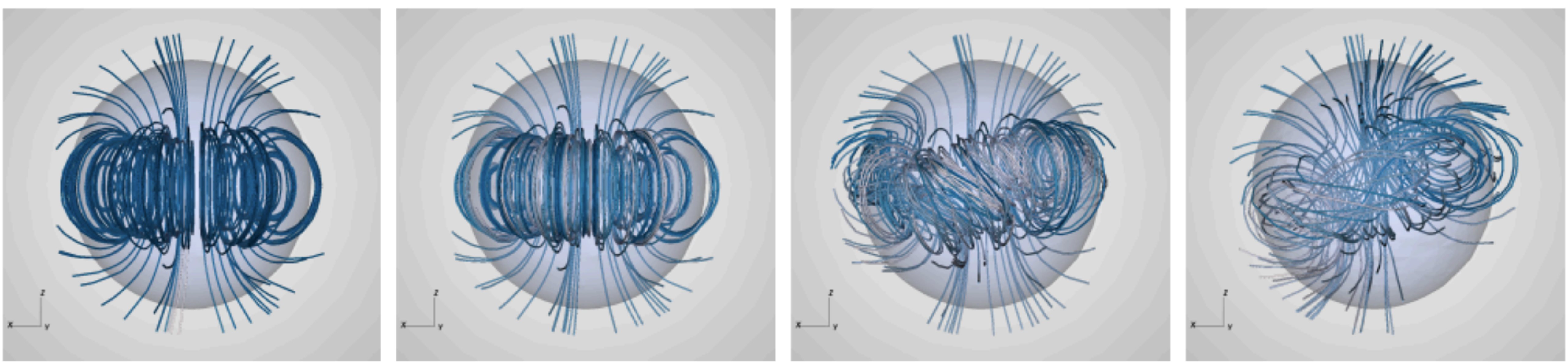
- Which is a stable B field configuration? - Equilibrium models can be constructed, but are they stable?

- Can the toroidal field be much stronger than the poloidal field? (Stronger GWs)

[Ciolfi & Rezzolla 2014]

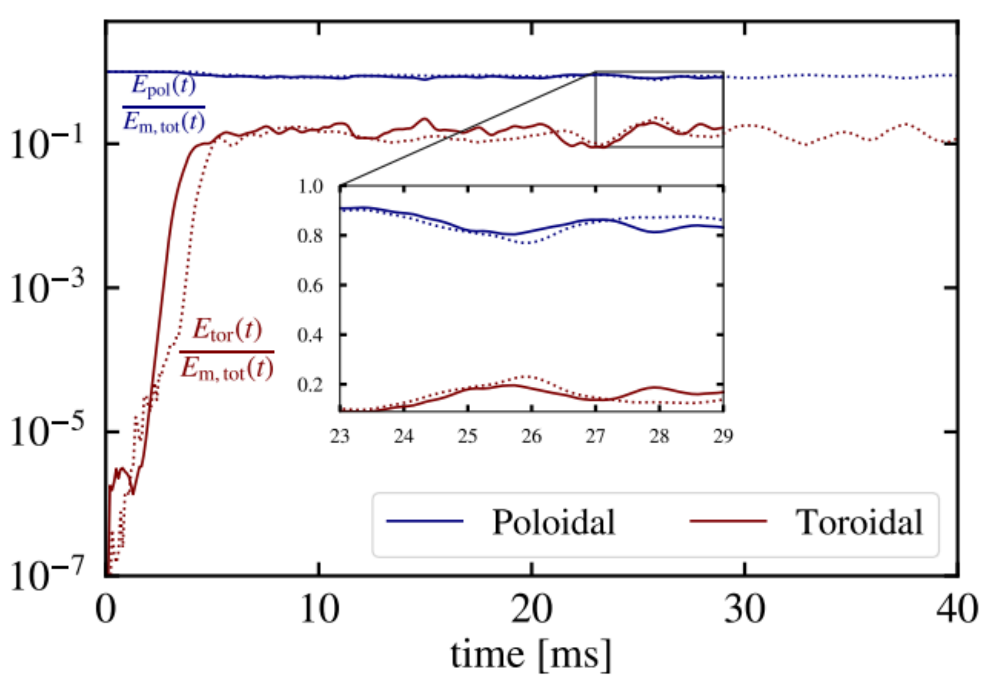
- Try to understand with time evolutions with PLUTO and ATHENA++

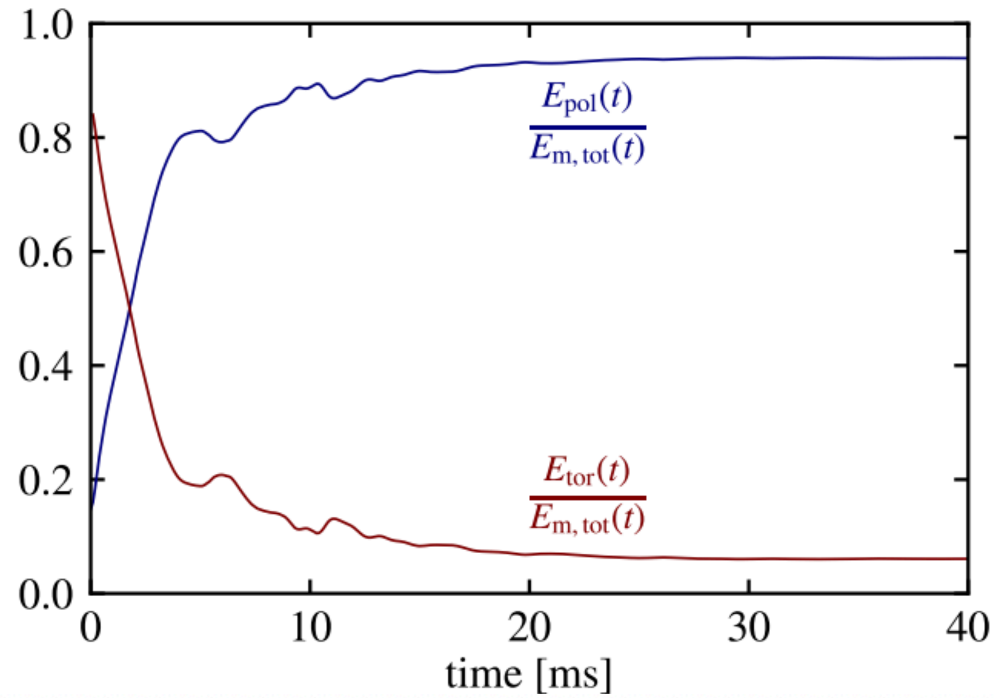
[Sur, Haskell and Kuhn 2020, Sur et al. 2021]



Magnetic fields configurations

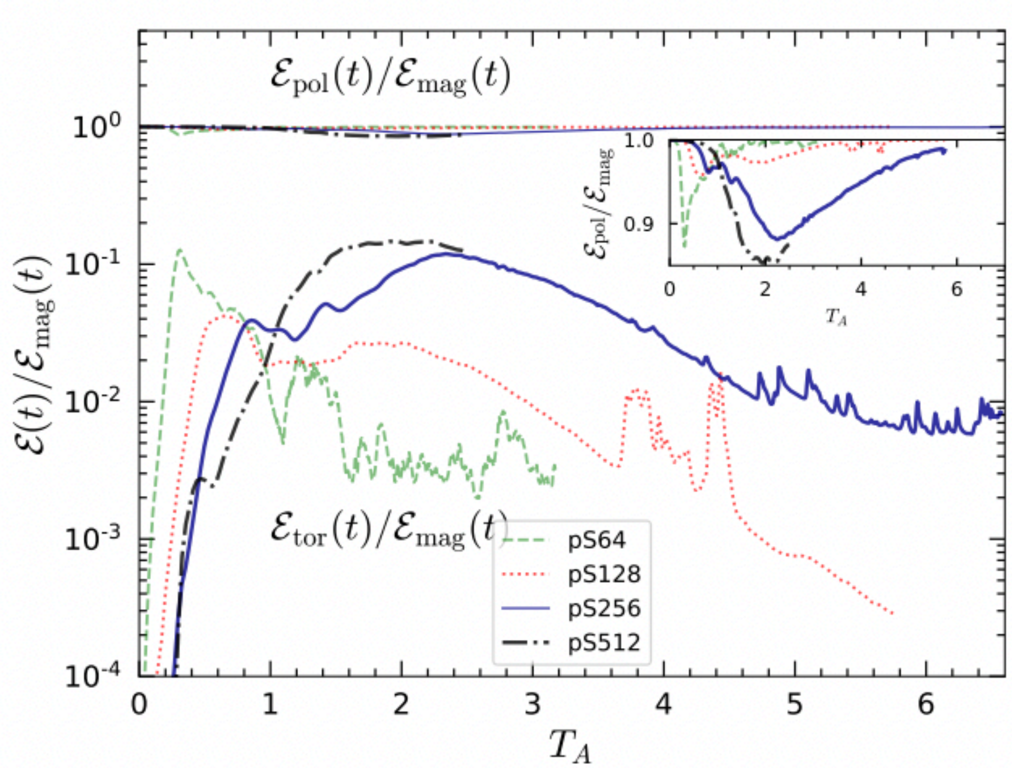
- Large scale configuration 'mixed' - 20% toroidal roughly
- Still unclear what the field settles down to: field must be helical

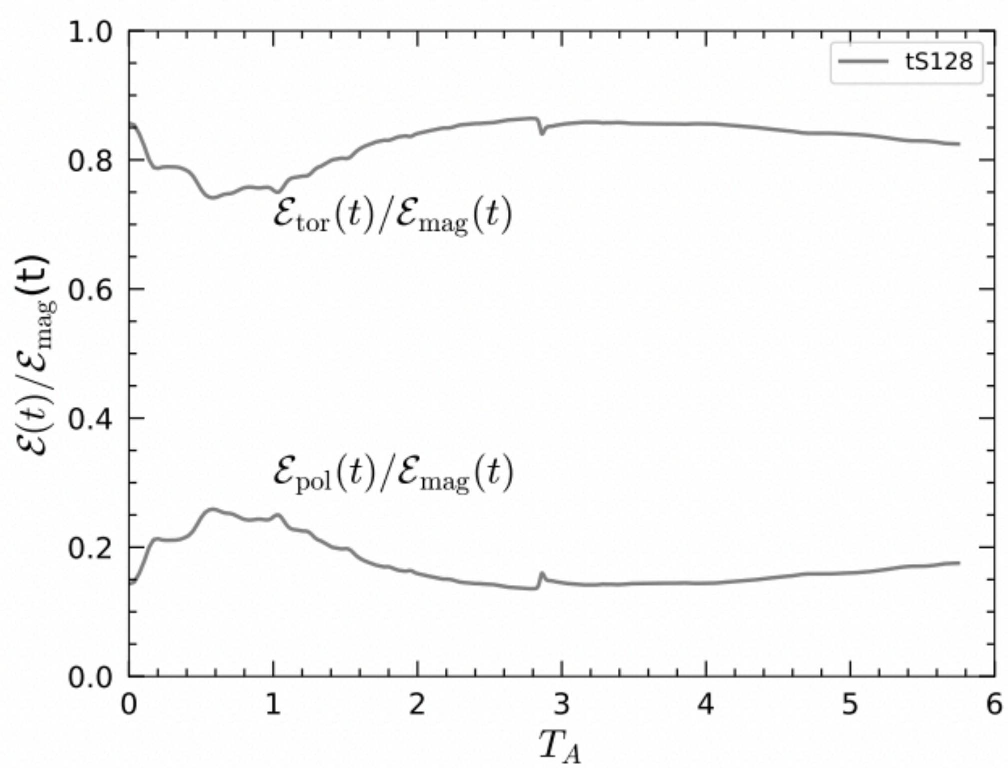




[Sur et al 2020, PLUTO]

Dipole at boundary

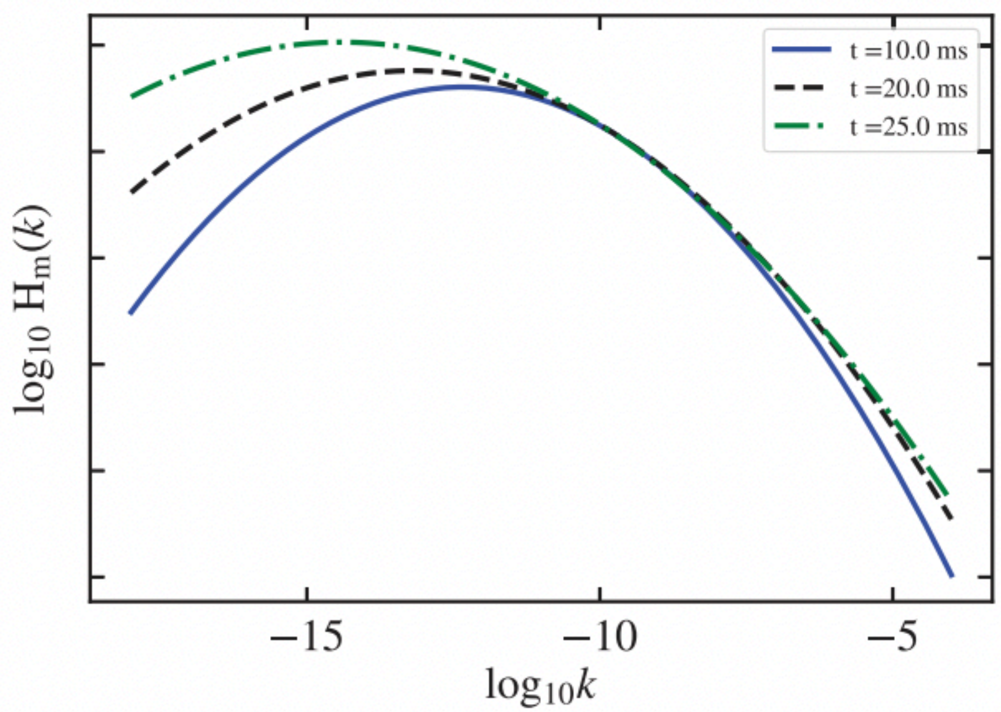




[Sur et al 2021, ATHENA++]

B=0 exterior

Turbulence in Magnetic fields

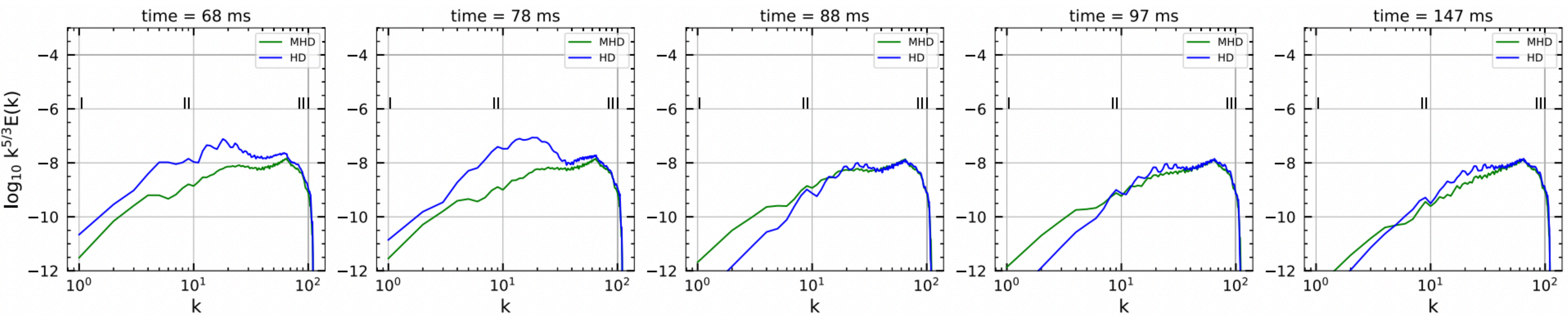


- Turbulence plays a role, but higher resolution needed for the atmosphere

  [Sur, Cook, Radice, BH & Bernuzzi 2021]
  [Sur et al. 2020]

- Stratification could stabilise the field

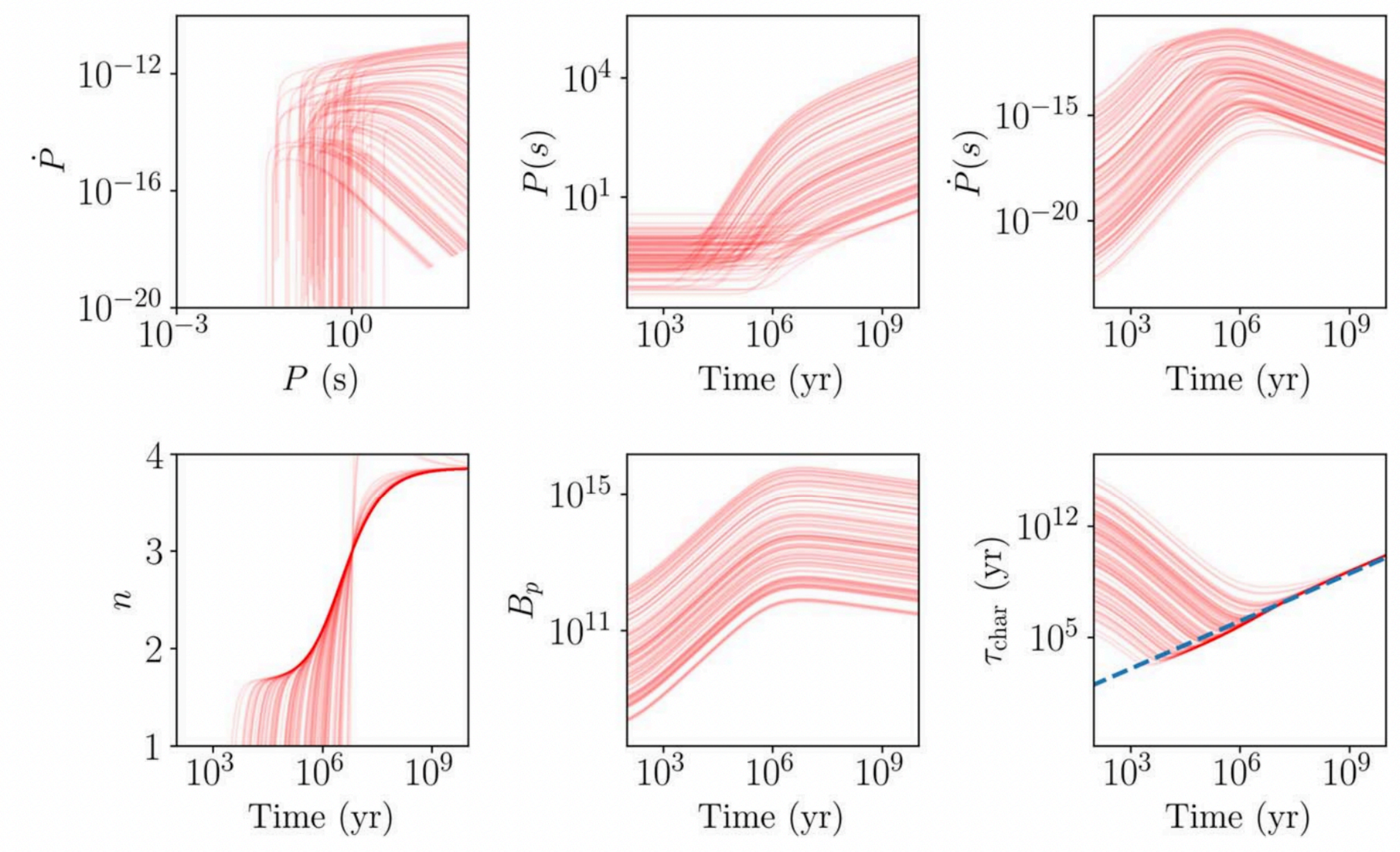
  [Becerra et al. 2022]



Helical turbulence in a box

- Magnetic field could grow in young pulsars due to inverse Hall cascades - leads to evolution of braking index
  [Gourgouilatos & Cummings 2015]

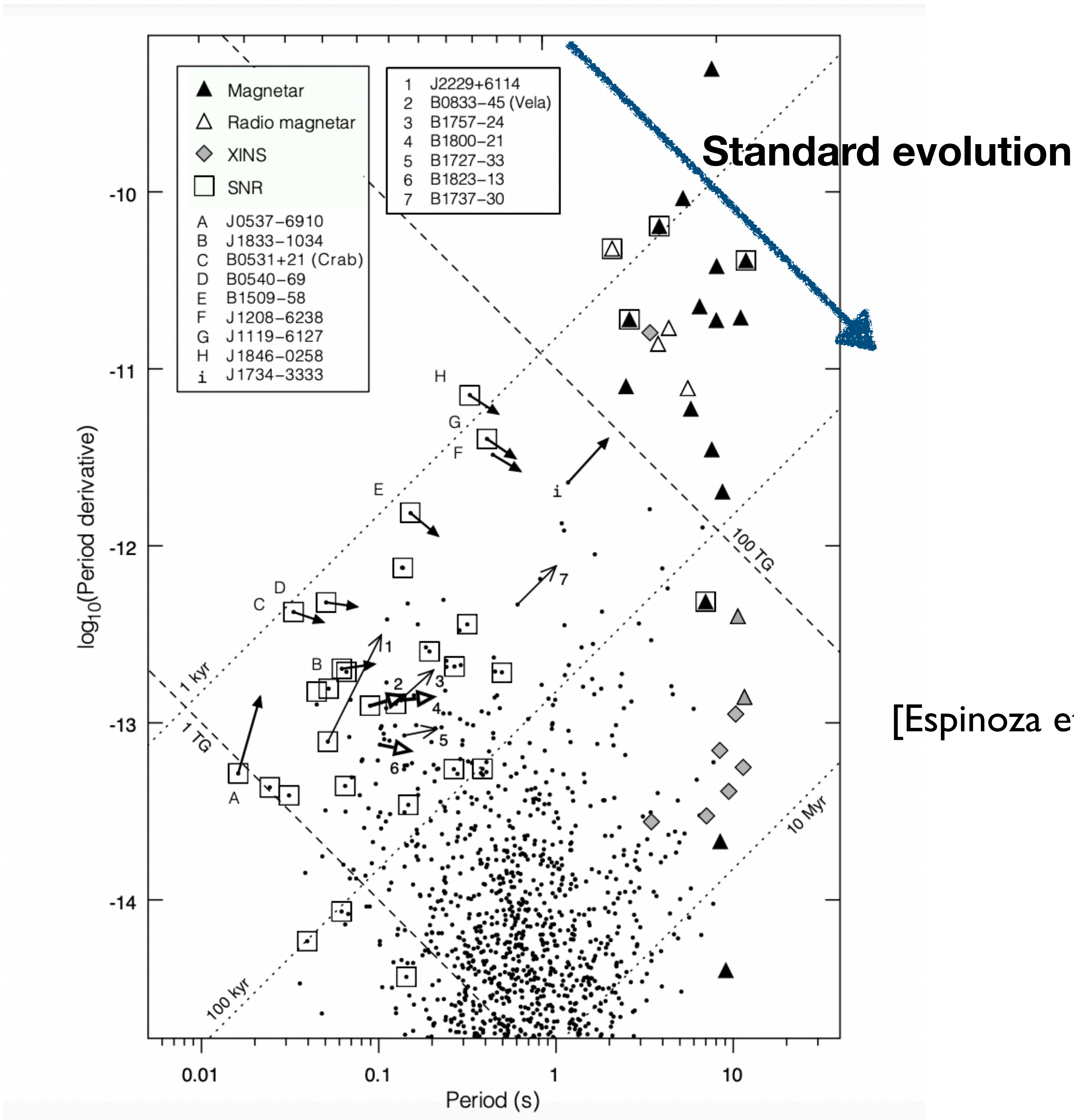
- Small scale simulations of helical MHD turbulence show growth of the large scale magnetic field from an initial random field $B_{\rm LS} \propto B_{\rm rms}^{-5} \propto t$ [Brandenburg 2020]



- Assume birth B field small scale and turbulent

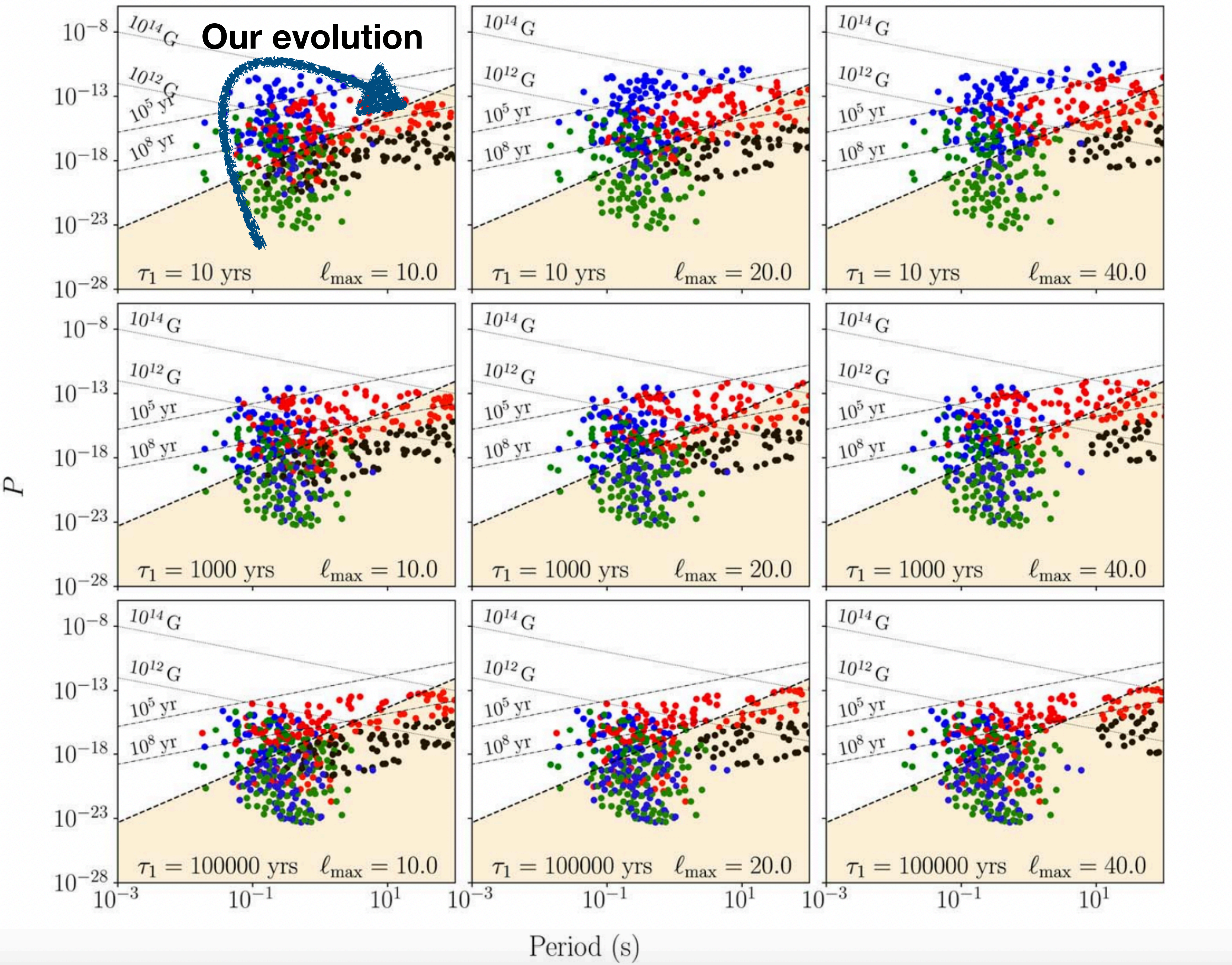
[Sarin, Brandenburg & BH, 2023]

Pulsar evolution



[Espinoza et al. 2016]

[Sarin, Brandenburg & BH, 2023]



From helical turbulence in a box to pulsars

- Explains anomalous braking index
- Magnetars older than expected
- To explain observations we need a very thin resistive layer in the crust - pasta? [Pelicer et al., 2023]
- Explains also the absence of long-period isolated X-ray pulsars [Pons, Vigano' & Rea, 2013]
- This is MHD turbulence - Quantum turbulence may play a role in the interior - it can be investigated with pulsar glitches! [BH, Antonopoulou & Barenghi, 2020]

Bulk viscosity

- Reactions on finite timescales affect the magnetic field structure and give rise to bulk viscosity [Becerra et al. 2021]

- GR formulation needed. Must be causal to be stable

  [Gavassino, Antonelli & BH 2022, Gavassino 2022]

'Slow' degrees of freedom

$$\mathcal{U} = \mathcal{U}(s, n, n_A) \qquad d\mathcal{U} = \Theta ds + \mu dn - \sum \mathcal{A}^A dn_A$$

$$\Pi = \zeta \nabla_\nu u^\nu + \tau_M \dot{\mathcal{A}} \frac{\partial {x_p}^{eq}}{\partial v}$$

[Gavassino et al. 2020]

- Implementing the evolution for individual components and reactions guarantees a causal formulation

[Camelio, Gavassino, Antonelli, Bernuzzi & BH 2023a, 2023b]

Conclusions

- Need to go beyond equilibrium models
- Origin of the field linked to turbulence and dynamo
- Field evolution, linked to thermal and chemical evolution
- GWs will help solve some of the puzzle
- We have a new joint NCN-DFG grant - MERLIN - to study MHD evolutions of B-fields - PIs: Haskell (Warsaw), Bernuzzi (Jena)