Magnetic field dynamics in isolated neutron stars and their gravitational wave signatures

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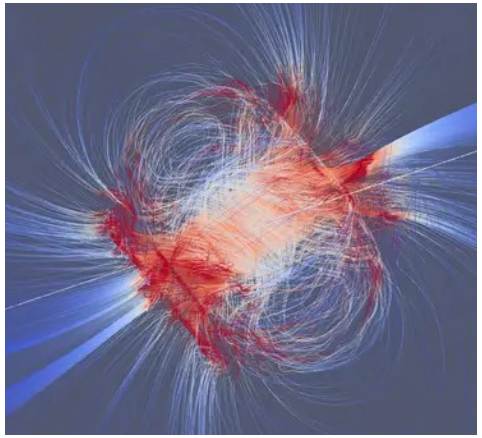
Motivation and Numerical Setup

- Neutron stars (NS) host extreme magnetic fields: impact on NS structure, dynamics and evolution.
- Effects also on observables: EM radiation, outbursts, FRBs and gravitational waves.
- Long-term equilibrium configuration unclear.
- Pulsar observations point towards a large-scale dipolar field.
- Purely poloidal fields shown to be unstable and verified via numerical simulations.

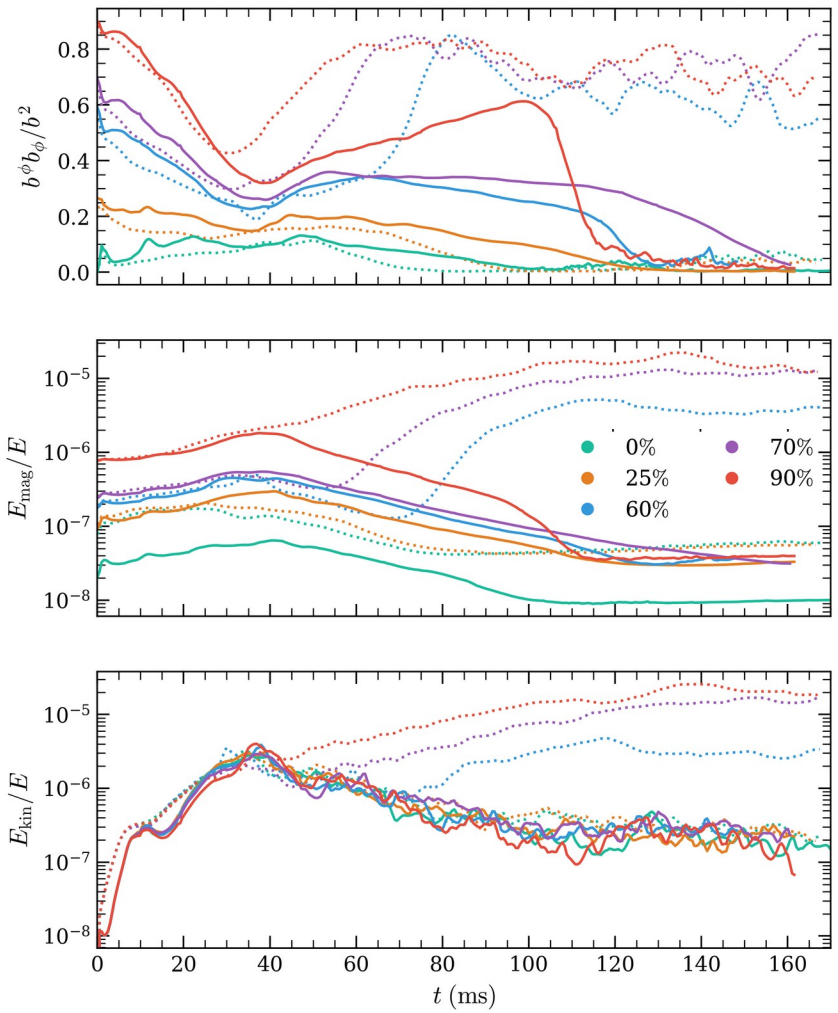
We study the stability of equilibrium configurations by performing long numerical simulations.

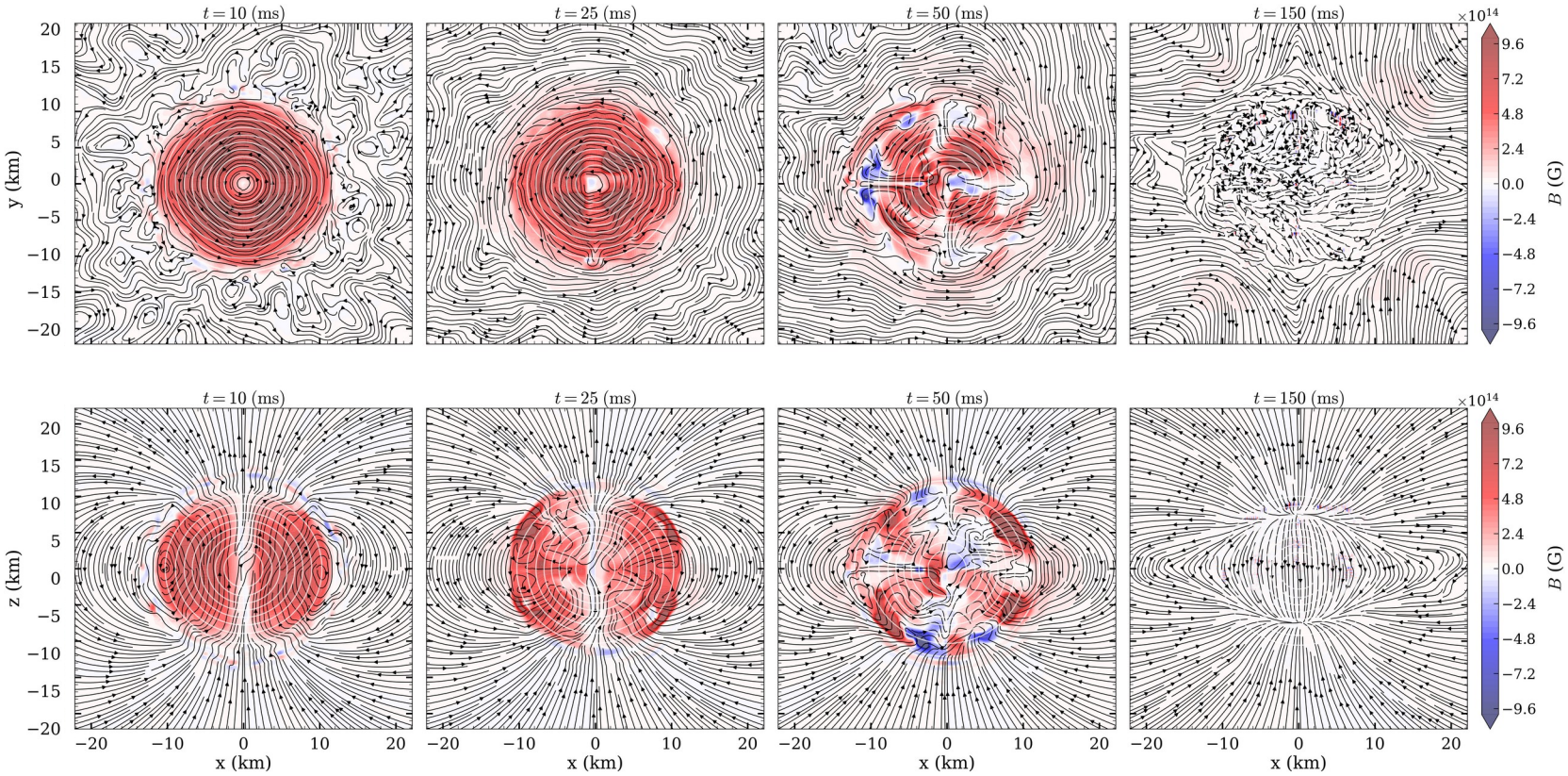


- TOV star with full ideal GRMHD evolution with `Athenak`[1].
- 3D domain of ±470 km and 230 m resolution.
- Dipole external field with maximum strength $B = 10^{15}$ G at the surface. In the star's interior, varying toroidal magnetic energy B_{tor} .

[1] Publically available at: https://github.com/IAS-Astrophysics/athenak

Results: Energetics





Our simulations show that the toroidal magnetic energy decays to $\lesssim 10\%$ of the total magnetic energy, **independently** of the initial BE_{tor}/BE_{pol} ratio.
This suggests a consistent **quasi-equilibrium end state** and a correlation with the presence of an external dipole field.

Results: GW signatures

- GW amplitude grows during the magnetic instability, reaching a peak at ~25 ms, consistent with the growth of magnetic and kinetic energies.
- Magnetized models show an additional early-time spectral peak, identified as the nonlinear coupling of fundamental pressure mode and the first quasiradial overtone.
- Key conclusion: Magnetic instabilities leave distinct GW fingerprints through nonlinear mode coupling, offering potential probes of neutron star magnetic dynamics.