Poloidal Field Instability in Magnetized Neutron Stars

RICCARDO CIOLFI

Ciolfi, Lander, Manca, Rezzolla 2011, ApJ 736, L6
Ciolfi & Rezzolla 2012, ApJ 760, 1



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Varadero, 10 May 2013

OUTLINE

Introduction and Motivation

- what is the internal magnetic field configuration in neutron stars?
- what we know so far and the issue of magnetic field stability

Poloidal Field Instability: Model and Numerical Setup

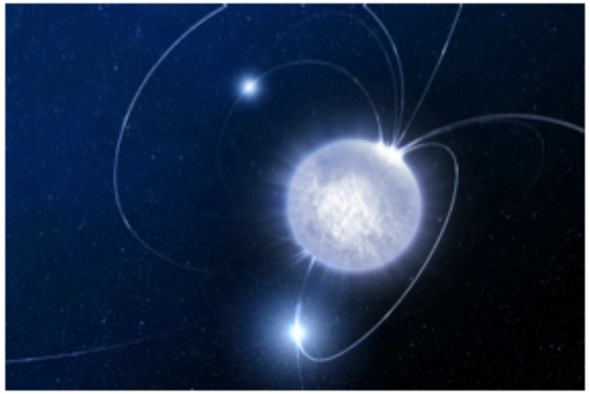
Results I - Dynamics of the Instability

- final state of the system: hints on the favoured magnetic field geometry

Results II - Magnetar Giant Flare Scenario

- electromagnetic emission, comparison with observations
- expected gravitational wave emission and detectability

INTRODUCTION

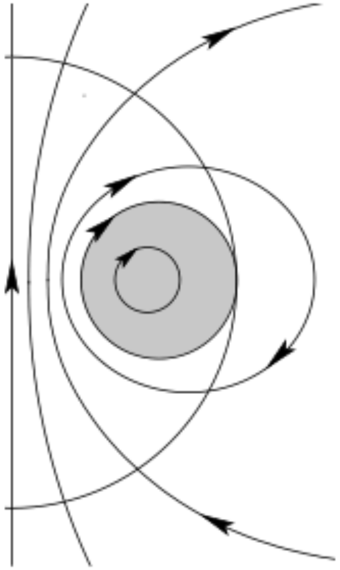


magnetic fields play a crucial role in the physiscs of NSs

- polar strenghts up to 10^{13} G , magnetars 10^{15} G
- dipole radiation, magnetar flares, structure deformations and GWs, thermal evolution, ..

[see talk by R. Perna]

what is the internal magnetic field configuration?



- equilibrium models for magnetized neutron stars
- twisted-torus MF geometry (Braithwaite & Nordlund 2006)

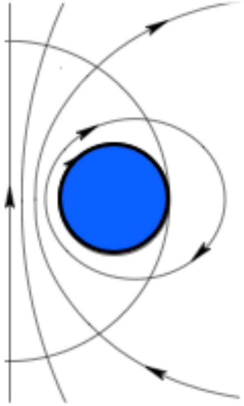
NEWT { Tomimura & Eriguchi 2005; Lander & Jones 2009, 2012; Fujisawa et al. 2012

GR { Ciolfi et al. 2009, 2010

which equilibrium configurations are stable?

INTRODUCTION

stability of magnetic field configurations studied in simple cases



- perturbative analytic work:
  purely poloidal or purely toroidal fields in non-rotating stars suffer the kink or 'Tayler' instability

Tayler 1973; Markey & Tayler 1973; Wright 1973

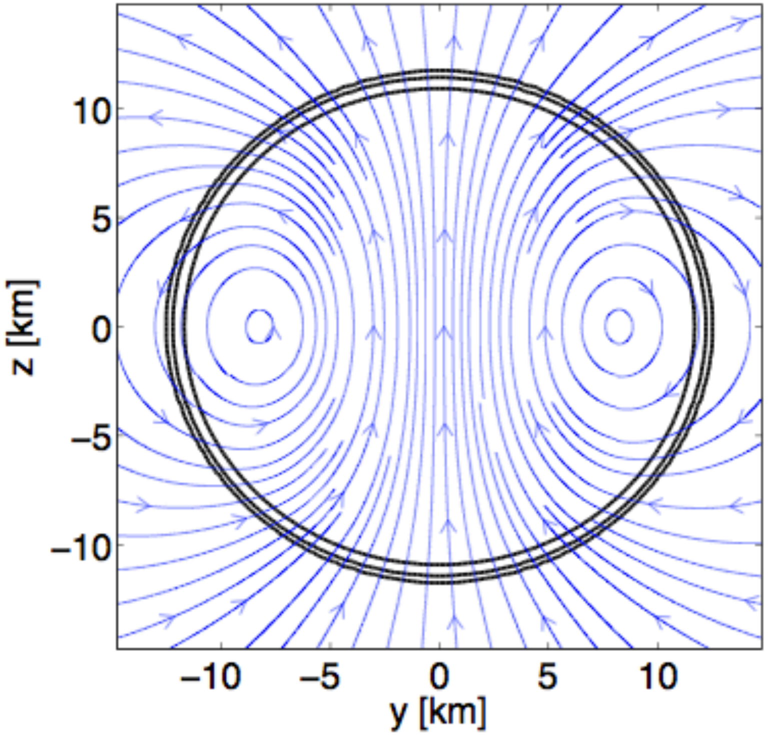
- most recently, fully 3D GRMHD simulations to study the case of purely poloidal fields:
  (i) confirm the instability
  (ii) follow the subsequent nonlinear evolution
  (iii) electromagnetic and GW emission from field rearrangement ⟶ 'test case' for giant flares

Lasky et al. 2011; Ciolfi et al. 2011

Zink et al. 2012; Lasky et al. 2012; Ciolfi & Rezzolla 2012

PHYSICAL SYSTEM and NUMERICAL SETUP

isolated non-rotating magnetized neutron star ⇨ fully 3D GRMHD simulations, Cowling approximation



LORENE initial data:

- axisymmetric equilibrium
- purely poloidal magnetic field

  $10^{16}\ \mathrm{G} < B_0 < 10^{17}\ \mathrm{G}$
- polytropic EOS $p = K\rho^{\Gamma}$

  $\Gamma = 2$ $M \sim 1.4\ \mathrm{M}_{\odot}$

  $K \sim 100$ $R^{*} \sim 12\ \mathrm{km}$

80 km of computational box, flat BCs

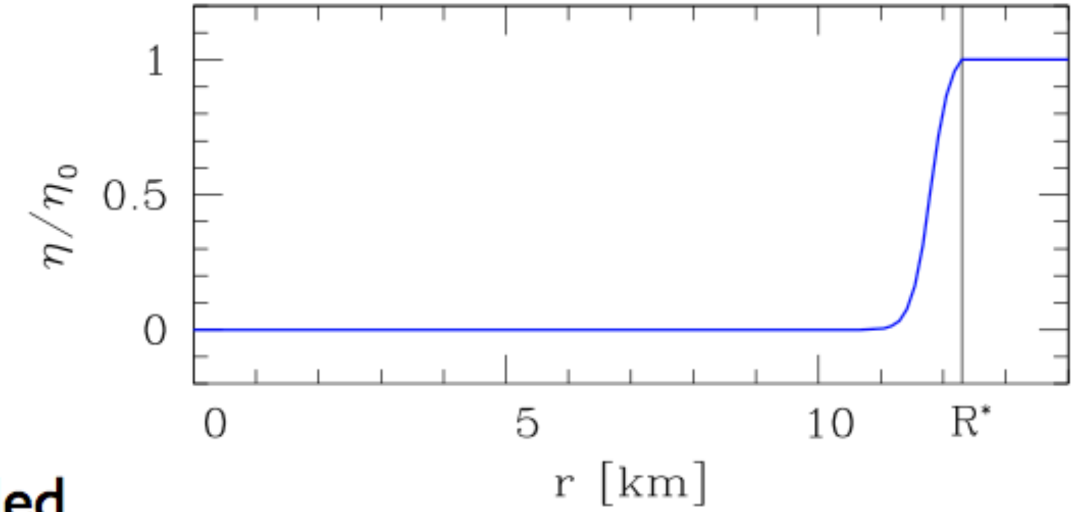
3 refinement levels, up to a resolution of $h = 0.17\ \mathrm{M}_{\odot}$

PHYSICAL SYSTEM and NUMERICAL SETUP

MHD evolution performed with the WhiskyMHD code

Giacomazzo & Rezzolla 2007; Pollney et al. 2007; Giacomazzo et al. 2009, 2011

ATMOSPHERE

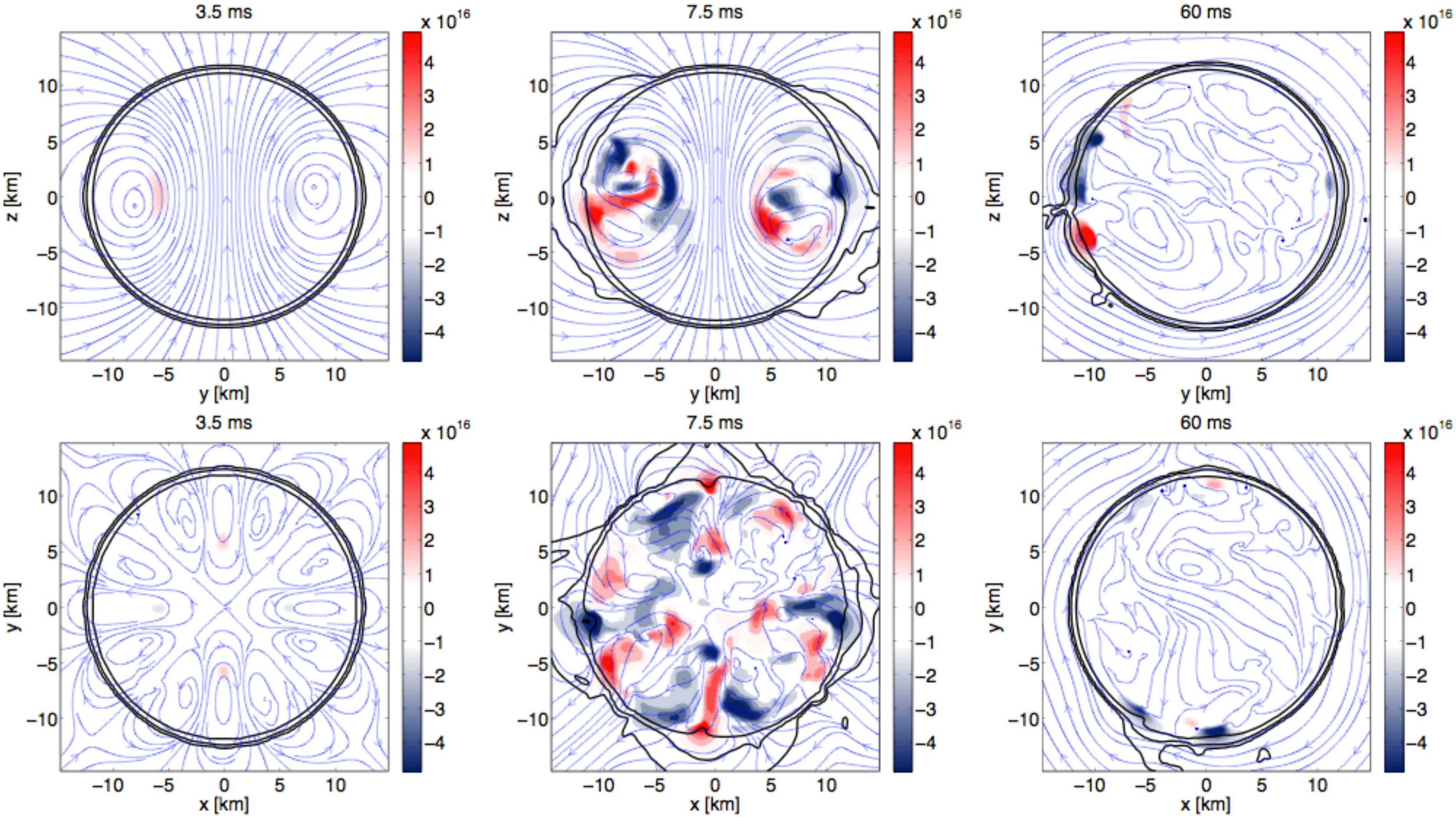


- densities are reset to a minimum value and fluid velocity is set to zero
- non-ideal MHD term added in the induction equation →

$$\partial_t \vec{A} = \vec{v} \times \vec{B} + \boxed{\eta \Delta \vec{A}}$$

- with the chosen profile we retain ideal MHD inside the star and allow for magnetic field evolution outside
- we avoid errors at the stellar surface and simulations are long-lived

INSTABILITY OF POLOIDAL FIELDS IN NEUTRON STARS: OUR SIMULATIONS



$$B_p = 6.5 \times 10^{16}\ \mathrm{G}$$

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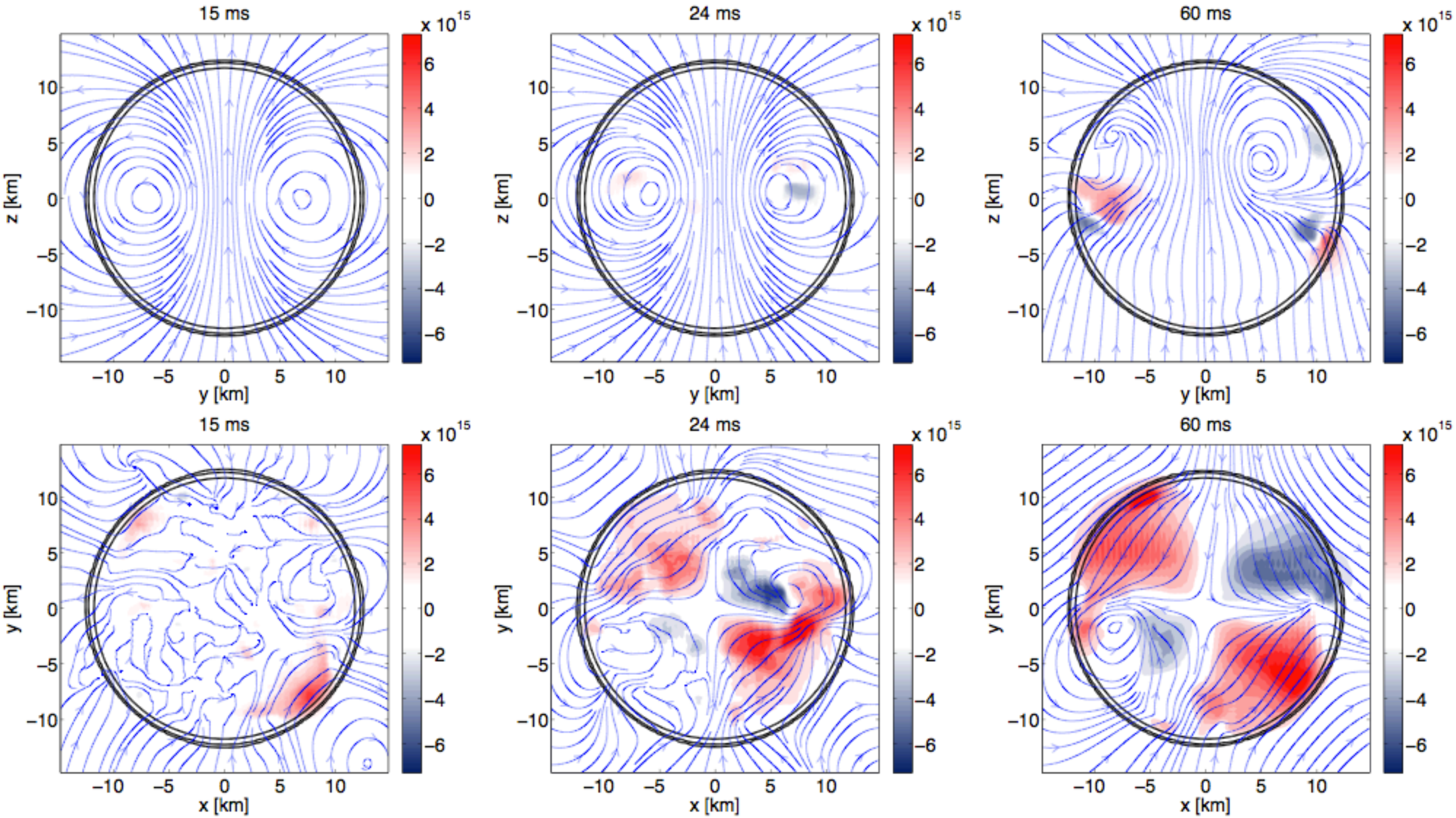
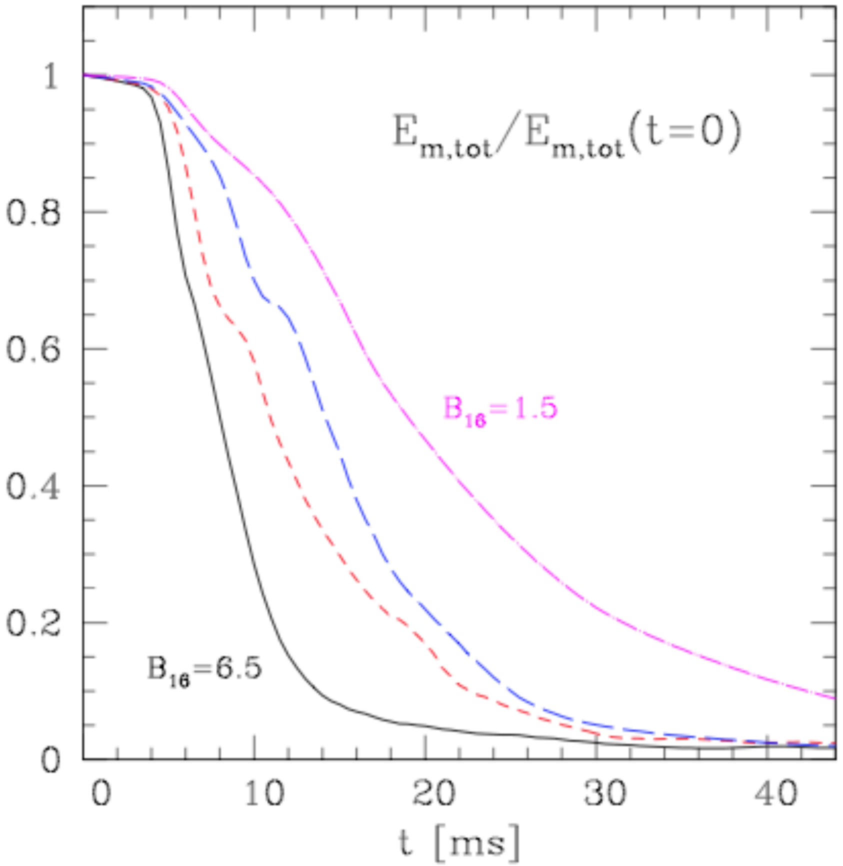
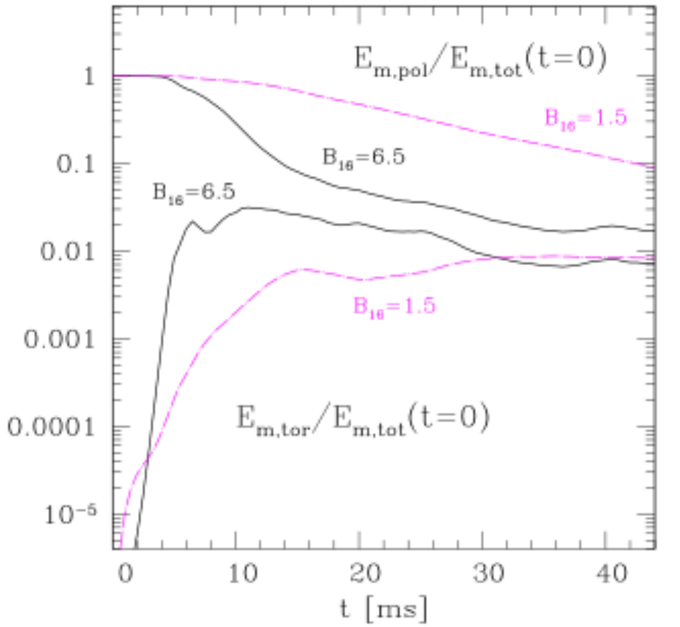
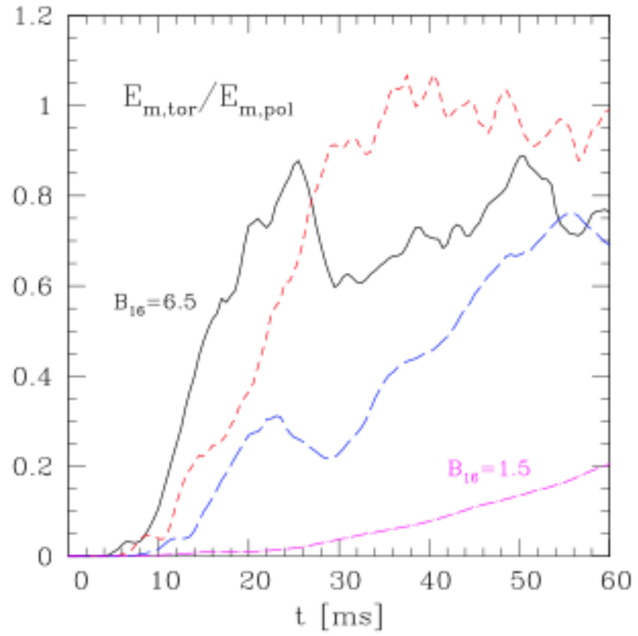


$$B_p = 1.5 \times 10^{16}\ \mathrm{G}$$

MAGNETIC ENERGIES AND TIMESCALES



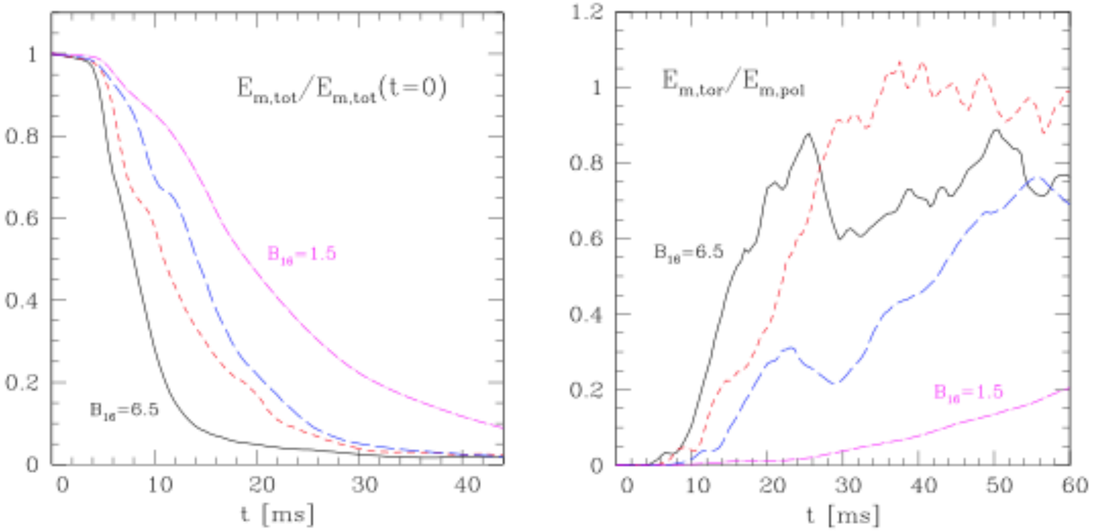


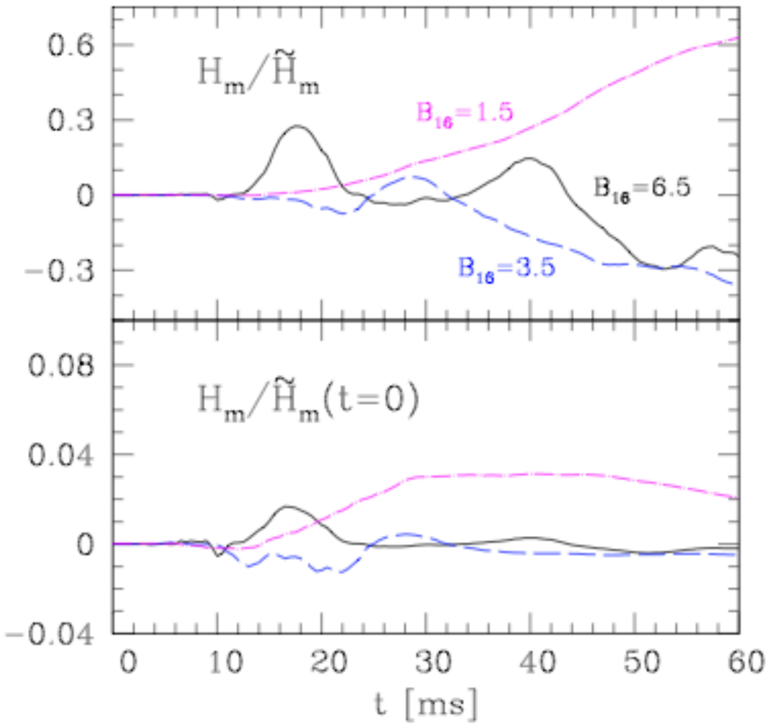


- 90% of magnetic energy is lost in few Alfven timescales!
- toroidal-to-poloidal energy ratio tends to equipartition

FINAL MAGNETIC FIELD CONFIGURATION

no evidence for a stable equilibrium





- system tends to equipartition of toroidal and polidal magnetic energies
- significant magnetic helicity produced (initially zero)

likely features of a stable equilibrium configuration

HYDROMAGNETIC INSTABILITIES AND MAGNETAR GIANT FLARES

- the violent, global rearrangement of magnetic fields induced by hydromagnetic instability proposed as trigger mechanism for magnetar Giant Flares Thompson & Duncan 1995, 2001

electromagnetic emission

- our system represents a test case for this scenario: we can estimate electromagnetic luminosity and duration of the process and compare with the observed Giant Flares
(up to now, only simple analytic estimates)

gravitational wave emission

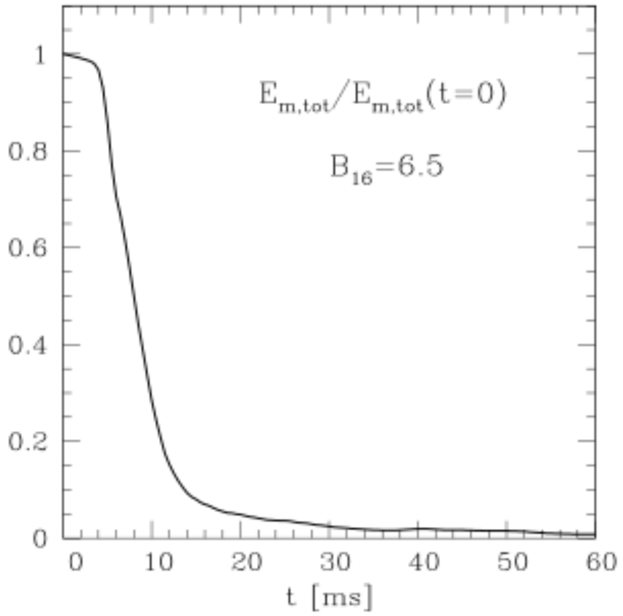
- in this scenario, magnetar flares are likely accompanied by f-mode oscillations and GW emission; this motivated recent LIGO/Virgo search for GWs in coincidence with SGR flares e.g. Abadie et al. 2011
- we can provide a realistic estimate of the amplitude of such GW signal, and establish its level of detectability with next future detectors

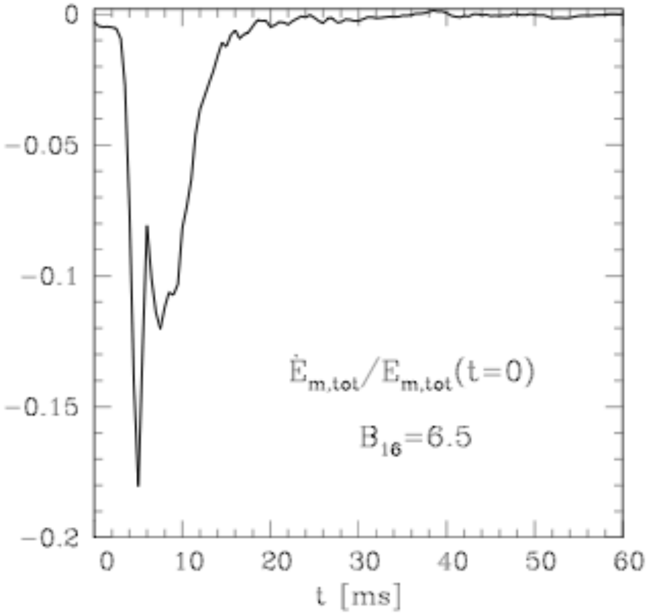
ELECTROMAGNETIC EMISSION

- most of the magnetic energy is lost, mainly due to em radiation
- initial ~90% drop of magnetic energy corresponds to a spike in luminosity
- scaling laws: $\tau_{em} \propto 1/B$

$$E_m \propto B^2$$

$$L_{em} \propto B^3$$





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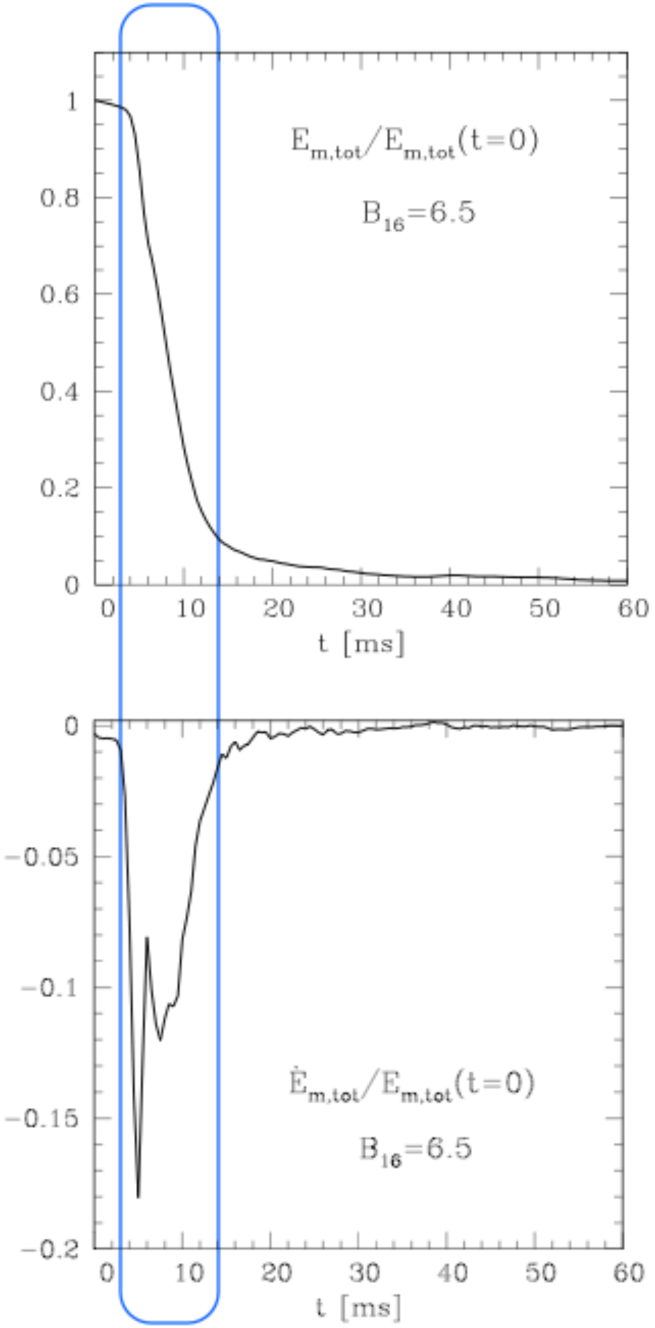

ELECTROMAGNETIC EMISSION

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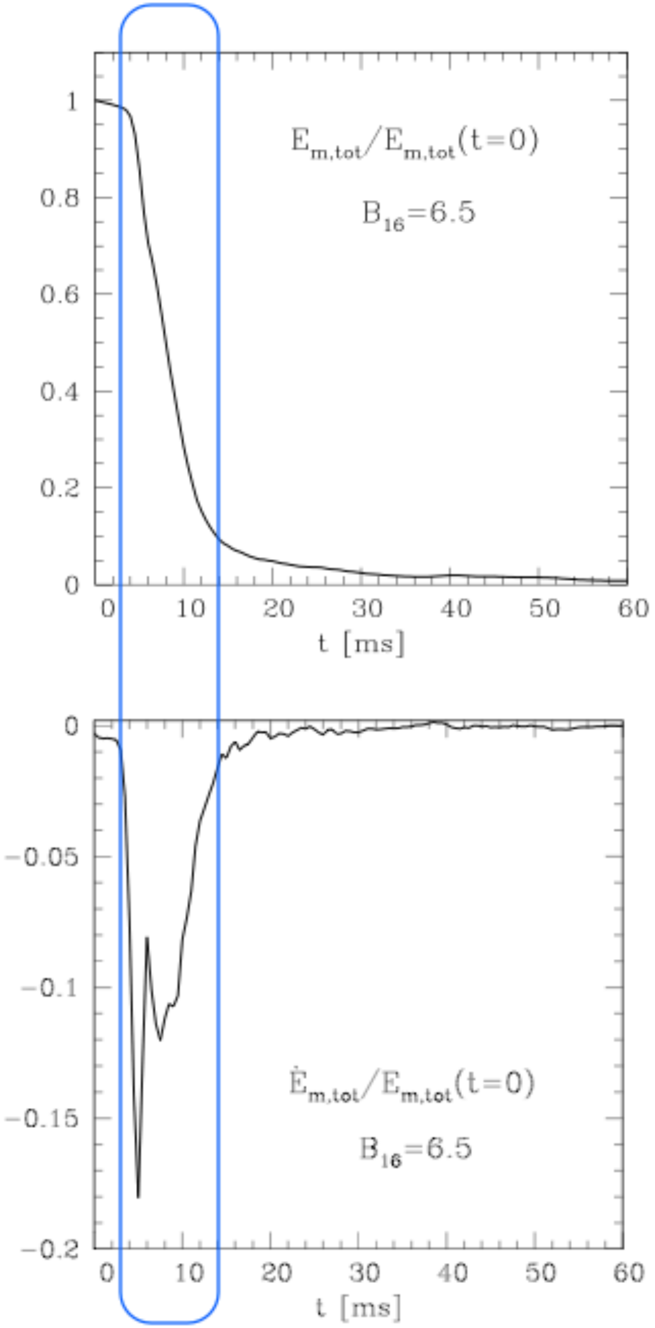
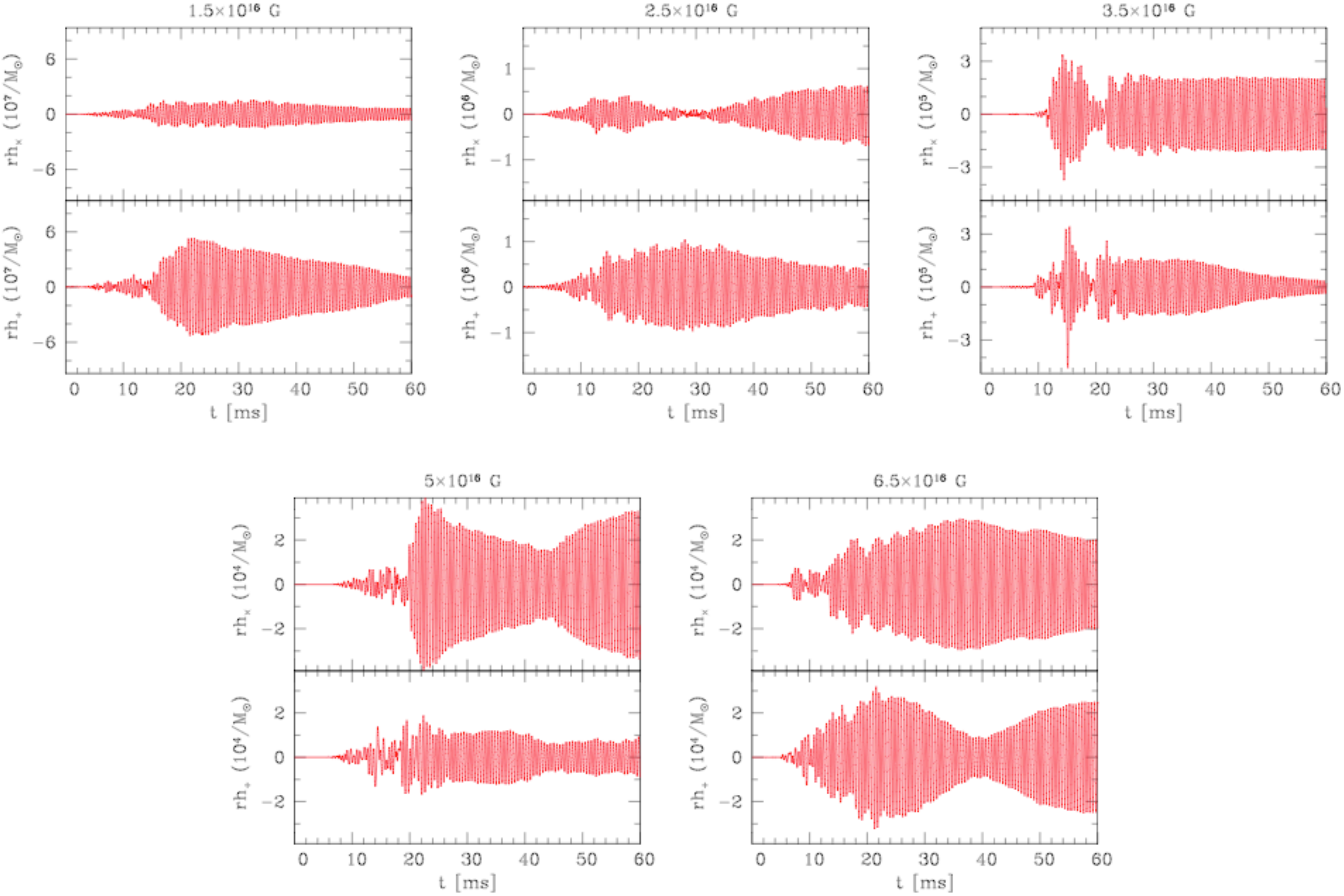
- initial ~90% drop of magnetic energy corresponds to a spike in luminosity

	τ_{em} [s]	$\langle L_{em} \rangle$ [erg/s]
our result @ 10^{15} G	~ 0.7	1.9×10^{48}
1806-20 (2004)	~ 0.5	$(0.3 - 1) \times 10^{47}$
1900+14 (1998)	~ 0.35	$> 4.3 \times 10^{44}$
0526-66 (1979)	~ 0.25	6.4×10^{44}

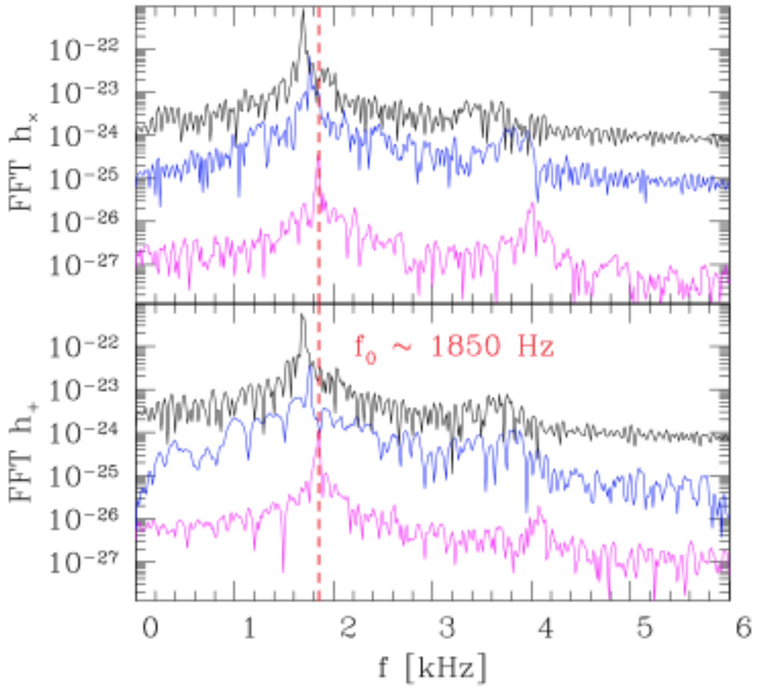
Mereghetti 2008



GW SIGNALS


1.5×10¹⁶ G
2.5×10¹⁶ G
3.5×10¹⁶ G
5×10¹⁶ G
6.5×10¹⁶ G
$rh_\times$ $(10^7/M_\odot)$
rh_+ $(10^7/M_\odot)$
$rh_\times$ $(10^6/M_\odot)$
rh_+ $(10^6/M_\odot)$
$rh_\times$ $(10^5/M_\odot)$
rh_+ $(10^5/M_\odot)$
$rh_\times$ $(10^4/M_\odot)$
rh_+ $(10^4/M_\odot)$
6
0
−6
1
0
−1
3
0
−3
2
0
−2
0
10
20
30
40
50
60
t [ms]

SIGNAL-TO-NOISE RATIO AND DETECTABILITY



$f_0 \sim 1.55$ kHz (Cowling correction)

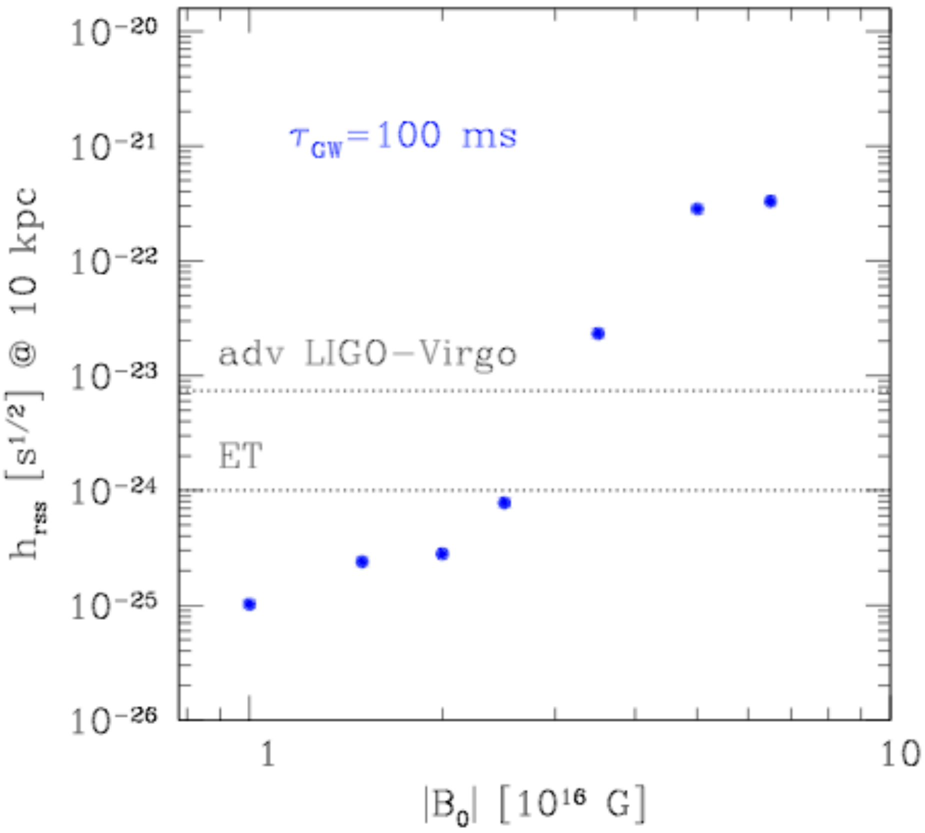
$$\frac{S}{N} = \frac{h_{rss}}{\sqrt{S_h(f_0)}} \qquad h_{\rm rss} = \left[\int_{-\infty}^{+\infty} h(t)^2\, dt\right]^{1/2}$$

$$h^2(t) = h_\times^2(t) + h_+^2(t)$$

what is the expected scaling law for h_{rss}? →

$$h_{rss} \propto B^2$$

Levin & van Hoven 2011



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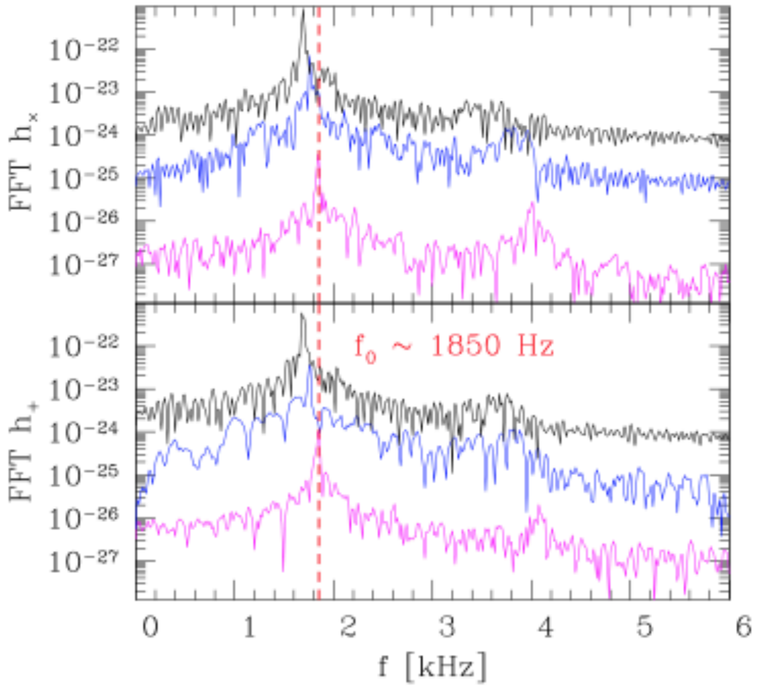

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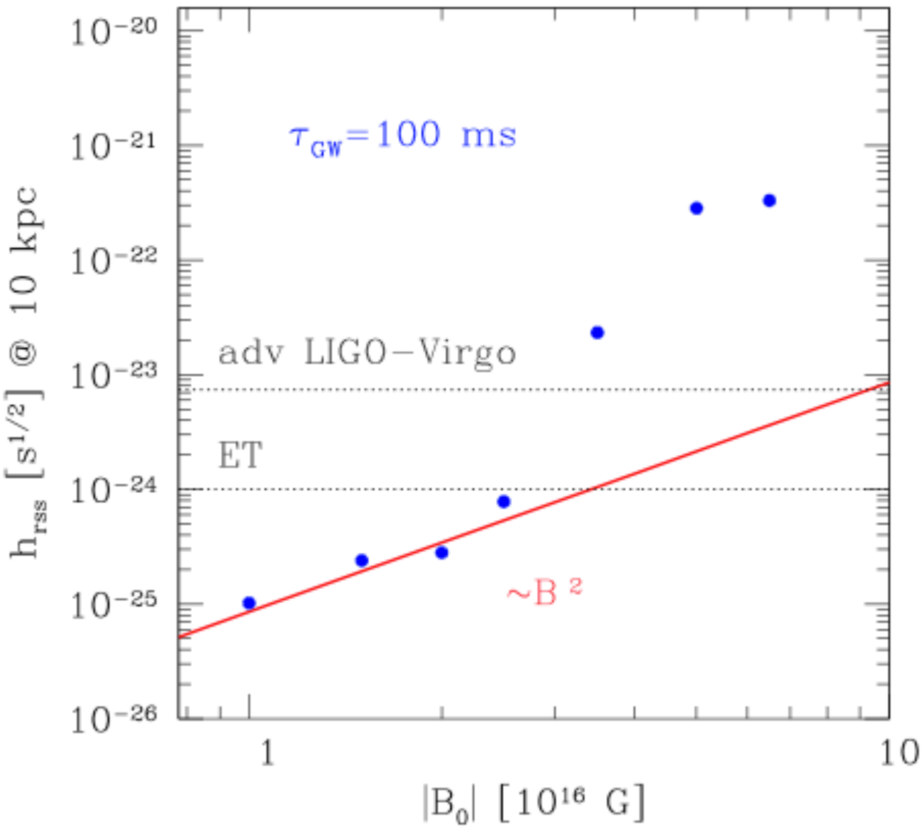
Levin & van Hoven 2011

in agreement with our results!



SIGNAL-TO-NOISE RATIO AND DETECTABILITY

..quadratic extrapolation gives

$$\frac{S}{N}(\mathrm{AdvLIGO\text{-}Virgo}) \simeq 1.6 \times 10^{-4} \times \left(\frac{B_0}{10^{15}\ \mathrm{G}}\right)^2$$

$$\frac{S}{N}(\mathrm{ET}) \simeq 1.2 \times 10^{-3} \times \left(\frac{B_0}{10^{15}\ \mathrm{G}}\right)^2$$

hardly detectable by present and near future GW detectors

$$E_{GW} = \frac{2\pi^2 f_0^2 c^3}{G} r^2 h_{rss}^2 \simeq 4.5 \times 10^{37}\ \mathrm{erg} \times \left(\frac{B_0}{10^{15}\ \mathrm{G}}\right)^4 \times \left(\frac{\tau_{GW}}{100\ \mathrm{ms}}\right)$$

$E_{GW} \sim E_m$ would give
$S/N\ (\mathrm{advLIGO}) \sim 50\ !$ →

Corsi & Owen 2011

but only a very small fraction of available energy is pumped into f-mode, confirming expectation of Levin & Van Hoven 2011

SUMMARY

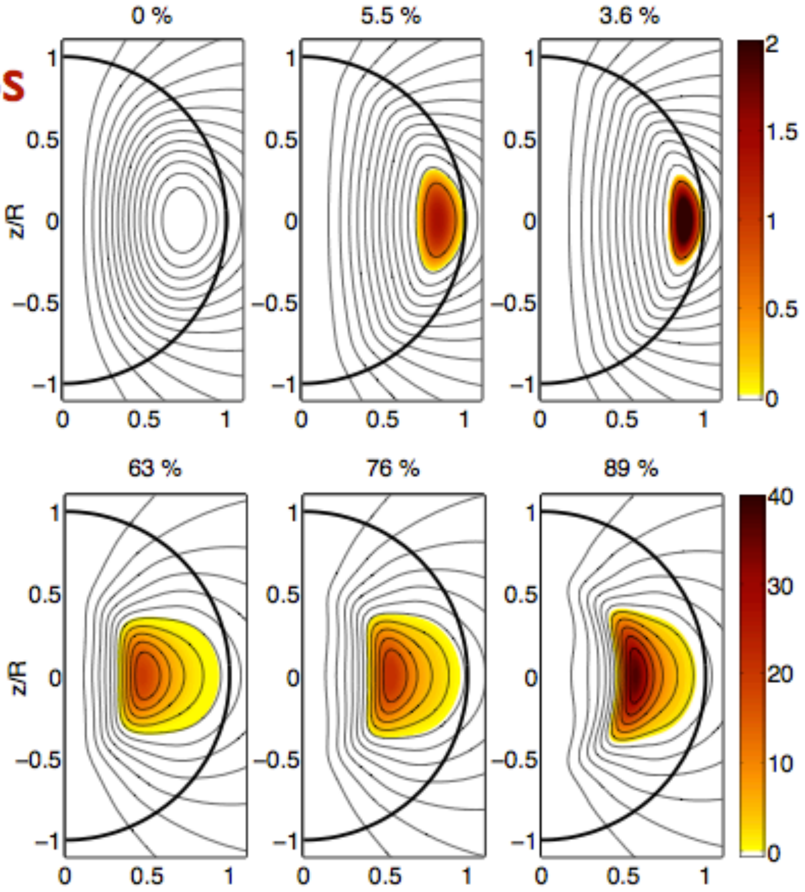
- GRMHD simulations of a non-rotating magnetized NS with purely poloidal magnetic field ⟶ evolution triggered by the poloidal field instability
- we confirm all the expectations from earlier perturbative work on the onset of the instability, and follow the subsequent field rearrangement
- at the the final stages, most of MF energy is lost;
  toroidal-to-poloidal energy ratio tends to unity and significant amount of magnetic helicity is produced
- our system represents a test case for the internal rearrangement scenario of magnetar giant flares:
  I - we estimate the electromagnetic luminosity and find compatibility with the observations
  II - we establish that GW emission in giant flares is hardly detectable

FUTURE WORK

understanding the Giant Flare trigger mechanism

- repeat the evolutions with a fully resistive MHD version of the Whisky code
- explore the electromagnetic emission in more detail, provide full support to the internal rearrangement scenario of giant flares

looking for stable equilibria in magnetized NSs



- test the stability of different magnetic field configurations, in particular twisted-torus geometries
- known twisted-torus solutions are poloidal dominated and likely unstable

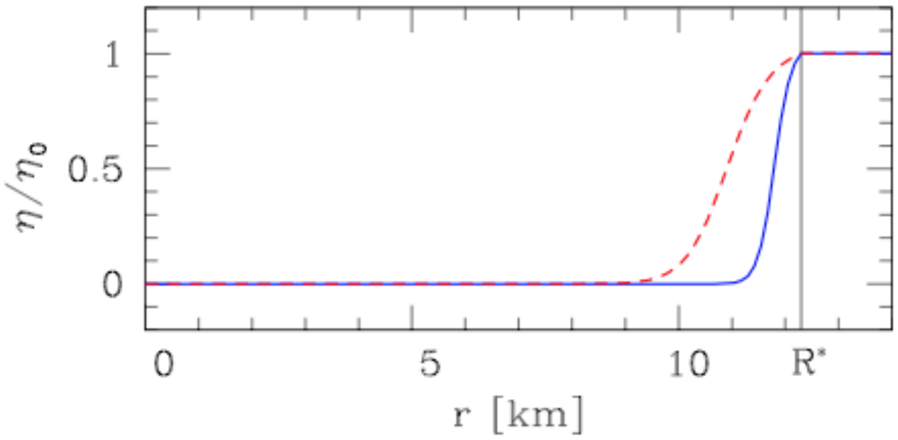
Braithwaite 2009, Lander & Jones 2012

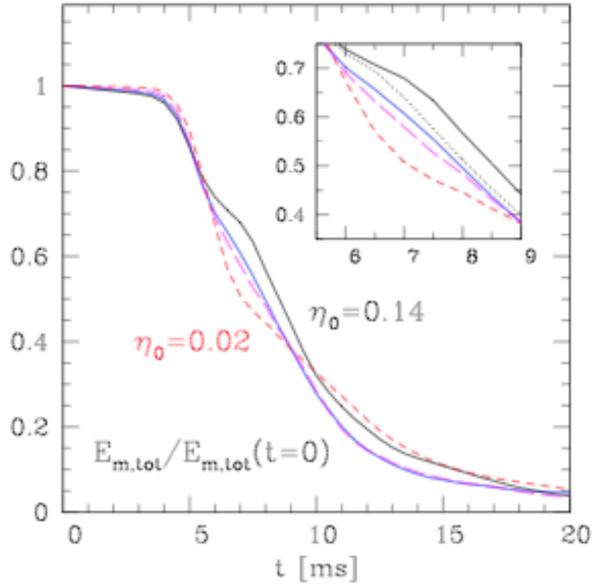
- we recently obtained higher energy in toroidal fields (up to 90%), these configurations could be stable!

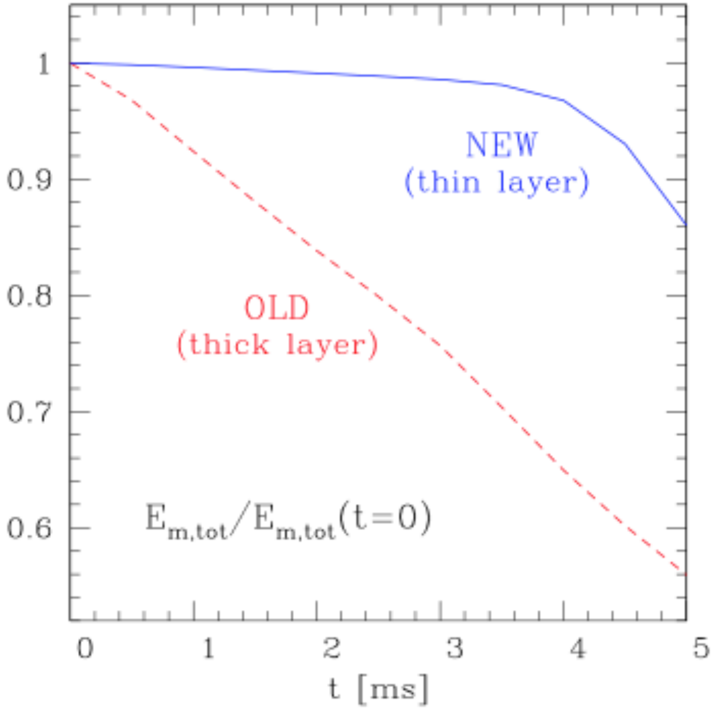
Ciolfi & Rezzolla , in preparation

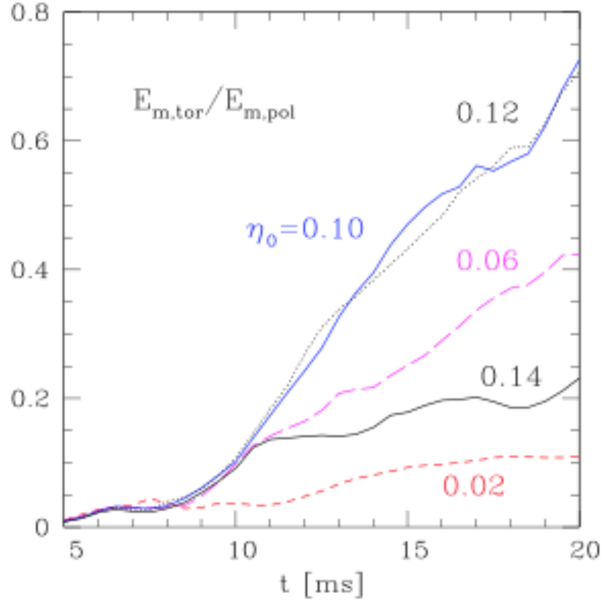
BACKUP SLIDES

TREATMENT OF THE ATMOSPHERE

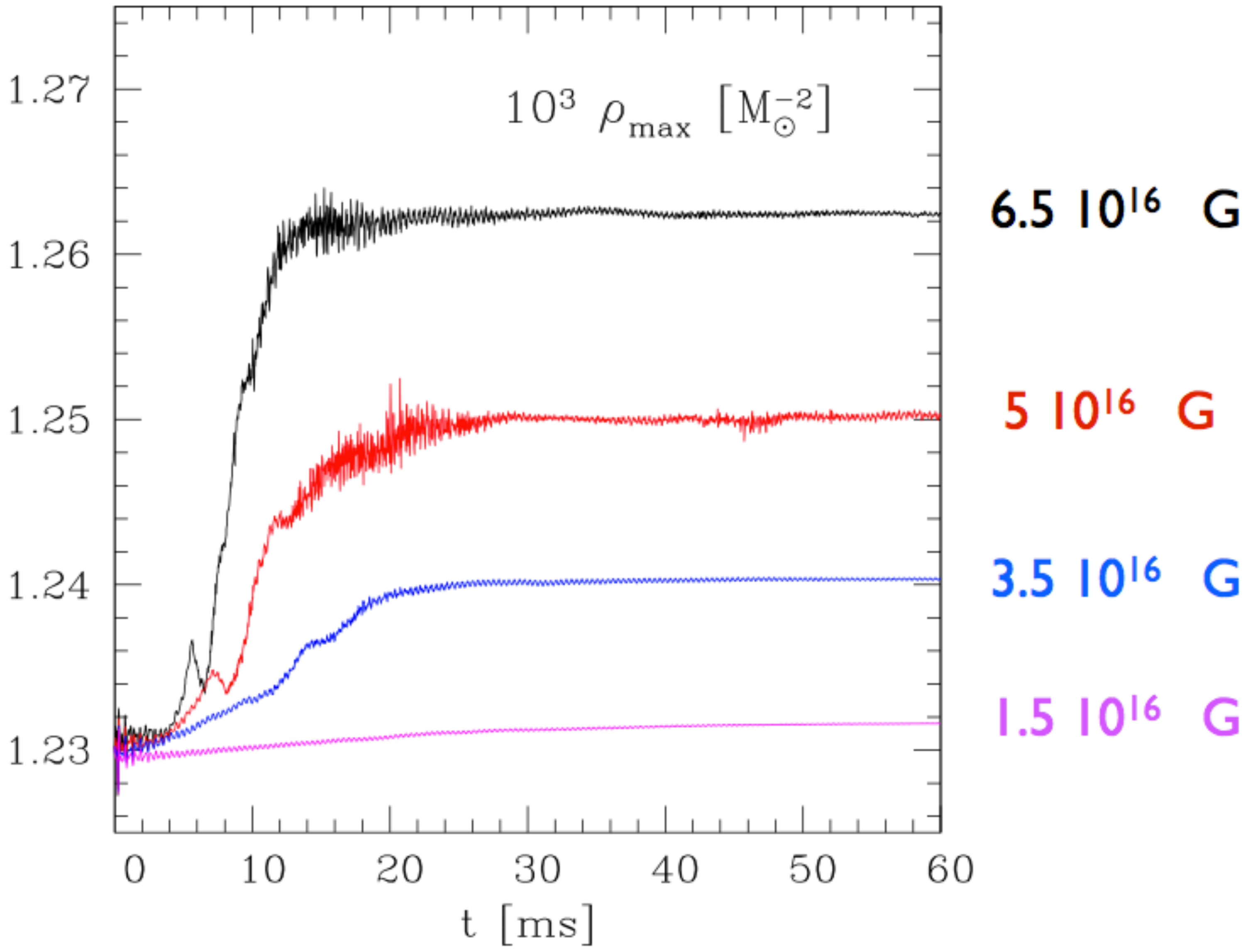








CENTRAL DENSITY



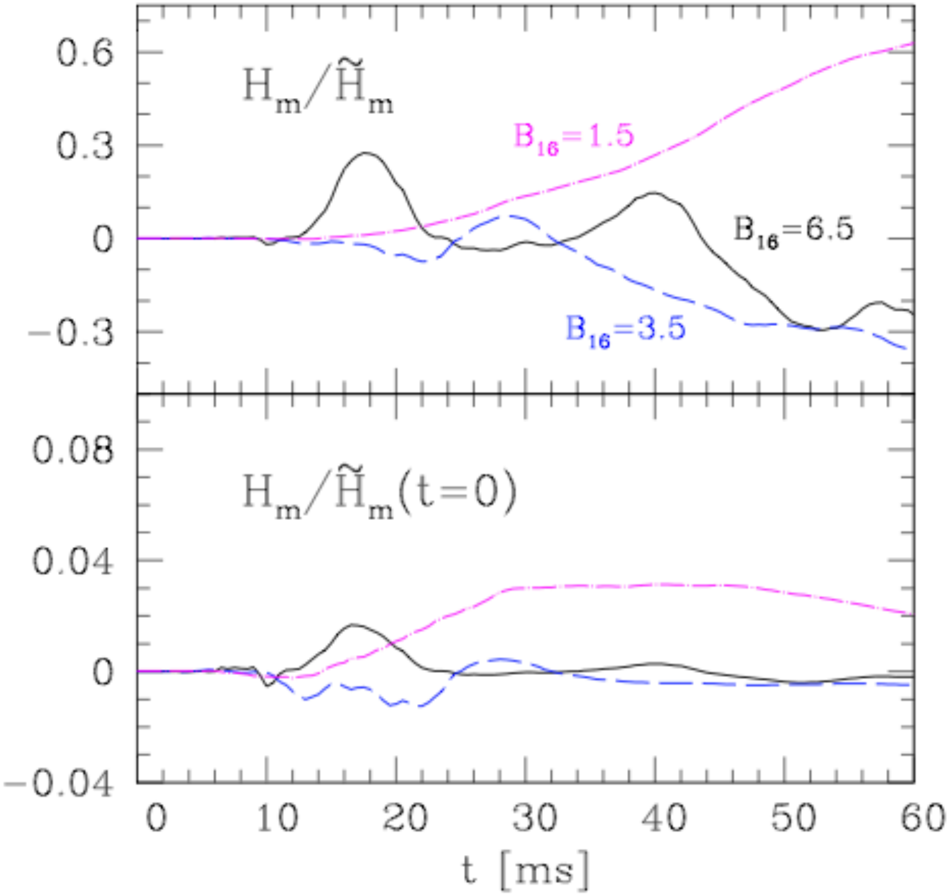
MAGNETIC HELICITY

$$H_m = \int_{\Sigma_t} H_m^0 \sqrt{-g}\, d^3x$$

$$H_m^\alpha = {}^*F^{\alpha\beta} A_\beta$$

$$|\tilde{H}_m| \sim R_N \times \sqrt{E_{pol}\, E_{tor}}$$

$$= R_N \times E_m/2$$



$|H_m/\tilde{H}_m| \ll 1$ → small magnetic helicity

$|H_m/\tilde{H}_m| \sim 1$ → significant amount of magnetic helicity

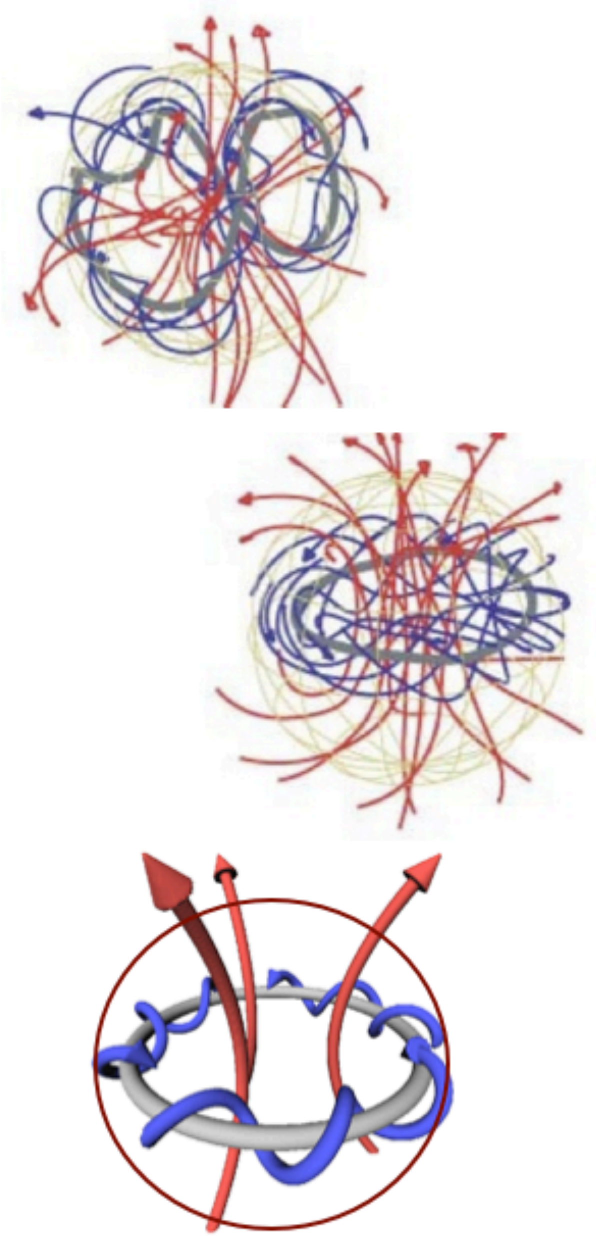
EQUILIBRIUM MODELS OF MAGNETARS

a theoretical explanation of magnetar observations relies on a good description of magnetar equilibrium configurations

- Braithwaite et al. (2004, 2006): stable magnetic field equilibrium configuration found in 3D newtonian magnetohydrodynamical simulations

↓

Twisted-torus configuration



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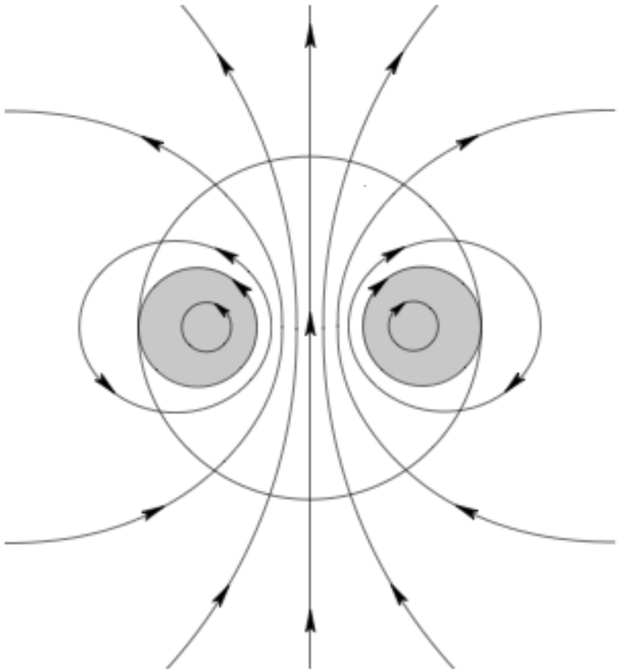

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