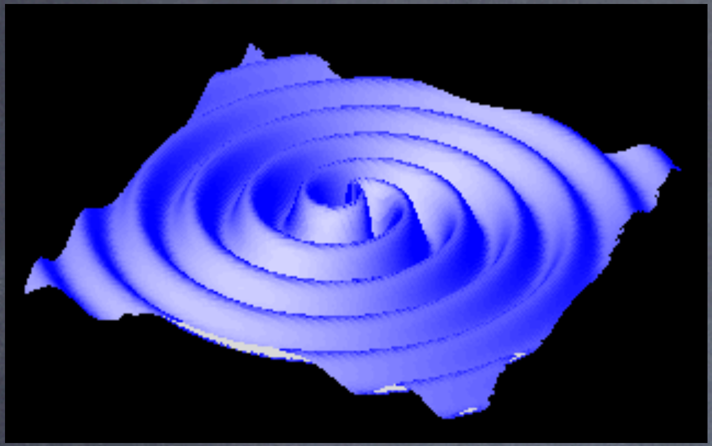
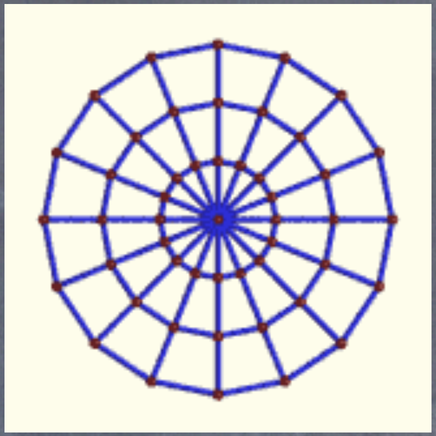
Neutron stars and magnetars vs. gravitational waves

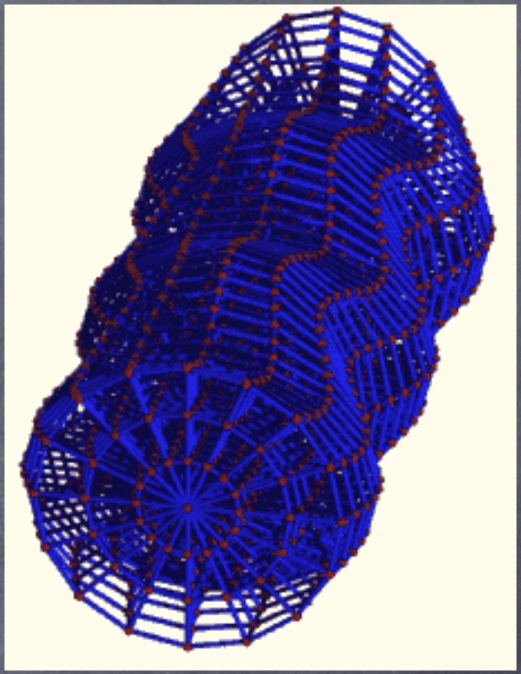
L. Stella,
INAF Osservatorio Astronomico di Roma – Italy

in collaboration with
S. Dall'Osso, R. Giacomazzo, G.L. Israel,
R. Perna, S. Shore, A. Vecchio

Gravitational Waves: space-time perturbations that propagate at c and transport energy and angular momentum







What is needed for a GW signal to be detectable ?

A mass that is:

- of order the solar mass
- extremely dense
- moving at a fraction of c
- subject to very large accelerations

Generation of GWs: Order of Magnitude

- Expand in multipole moments of source
- $h \sim 1/r$ [by energy conservation], and h dimensionless ⇒

$$h_+ \sim h_\times \sim \frac{G}{c^2}\frac{\text{mass}}{r} \;\&\; + \frac{G}{c^3}\frac{\partial(\text{mass dipole})/\partial t}{r} \;\&\; + \frac{G}{c^4}\frac{\partial^2(\text{mass quadrupole})/\partial t^2}{r} \;\&\; \ldots$$

mass; cannot oscillate

momentum; cannot oscillate

  - $\partial^2(\text{mass quadrupole})/\partial t^2 \sim$ mass x size^2/ period^2 $\sim$ (internal kinetic energy)

Strain:

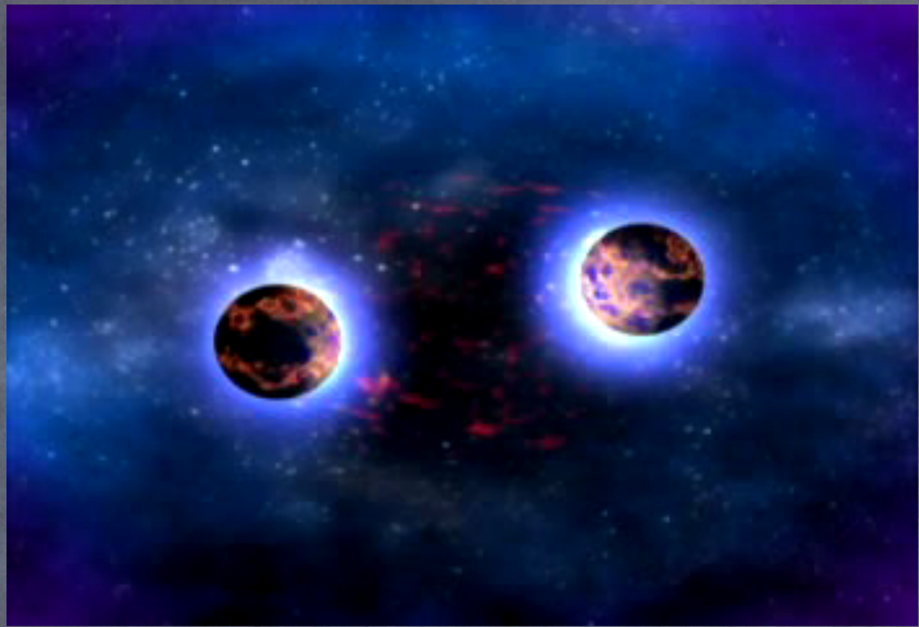
$$h_+ \sim h_\times \sim \frac{G\, E_{\rm kin}^{\rm quad}/c^2}{r} \sim 10^{-21}\left(\frac{E_{\rm kin}^{\rm quad}}{M_\odot c^2}\right)\left(\frac{100\text{Mpc}}{r}\right)$$

(Thorne)

Quadrupole formula: $-dE/dt = (G/45c^5)\, \dddot{D}^2$

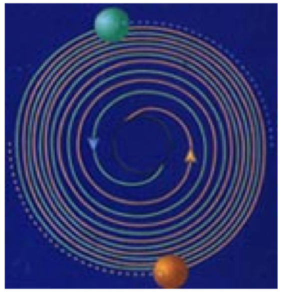
(note: constant is ~ 10^{-45} in CGS units !)

Coalescence: final stages of relativistic binaries



Orbital distance decreases

$$R(t) = R_{in}\,(1 - t/t_{coal})^{1/4}$$



$$t_{coal} = \frac{5}{256}\frac{R_{in}^4}{\mu M^2}$$

$$M = M_1 + M_2$$

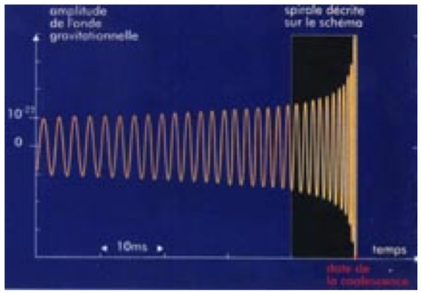
$$\mu = M_1 M_2 / M$$

the wave amplitude increases with time

Orbital frequency increases

$\nu_{GW} = 2\ \nu_{orb}$

$$\nu = \frac{1}{\pi}\left[\frac{5}{256}\,\frac{1}{\mu M^{2/3}}\,\frac{1}{(t_{coal}-t)}\right]^{3/8}$$

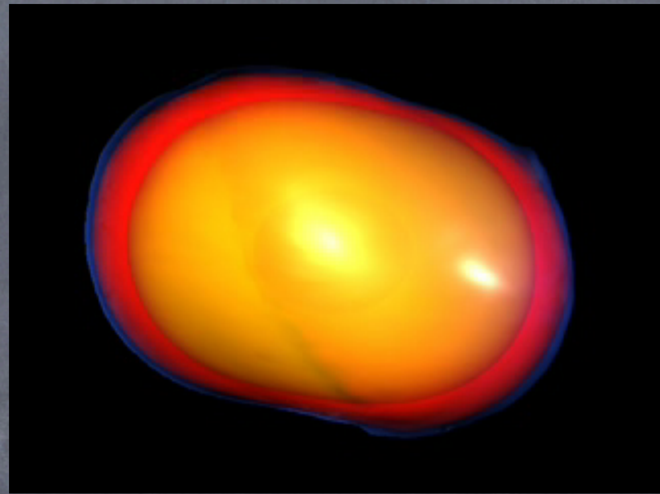


CHIRP

Ferrari

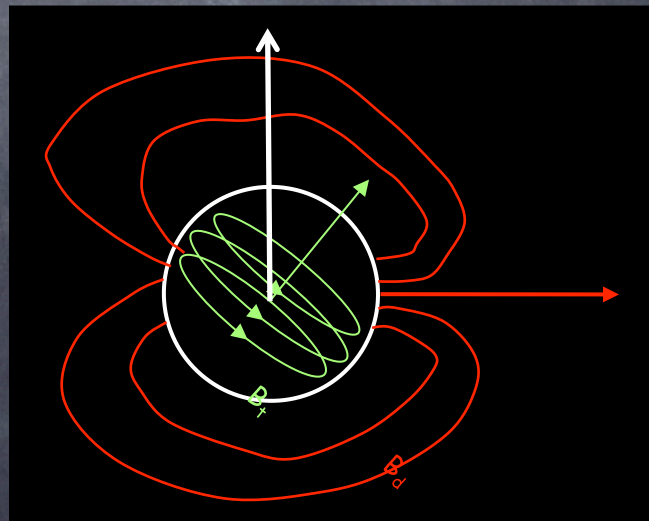
GWs from non-axially symmetric, fast spinning neutron stars

- "Mountains" (Crab [33ms] and Vela pulsars [91ms], also accreting ms pulsars in LMXB [few ms])



- Dynamical instabilities (e.g. R-modes)

- Ultra strong internal magnetic fields ($B > 10^{15}$ G; Magnetars)



Magnetar Bursts

- Concentrated in time ("outbursts")

- Broad distribution of wait times (~7 decades) and energy: similar to that of earthquakes; no waiting-time correlations

- Most bursts release ~10^{38}-10^{41} ergs

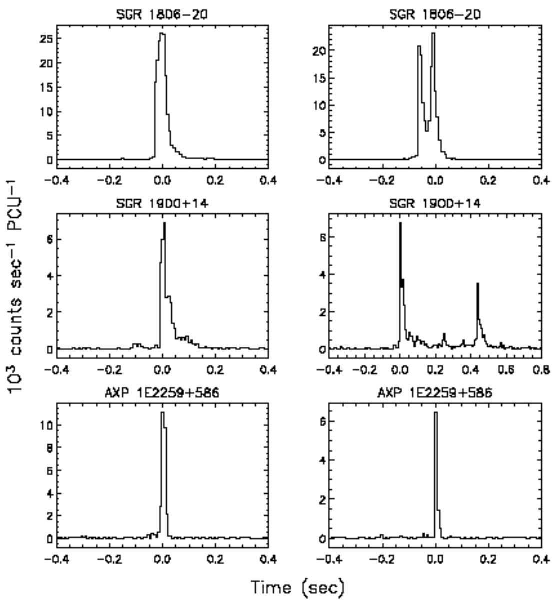
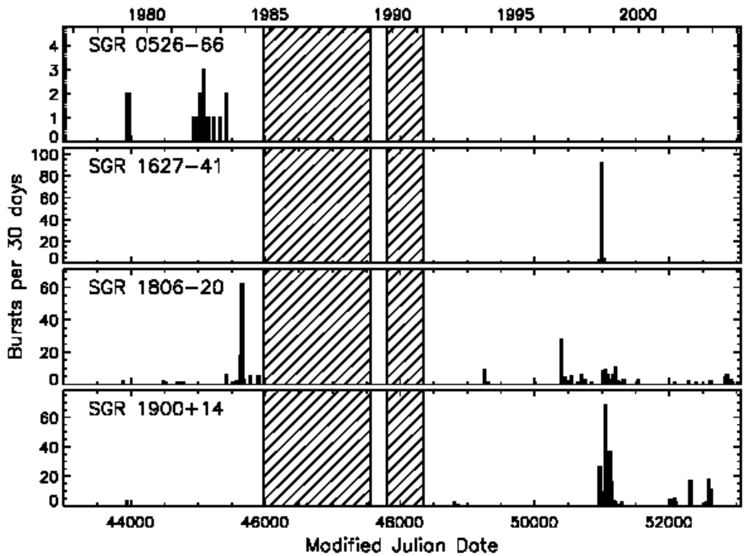
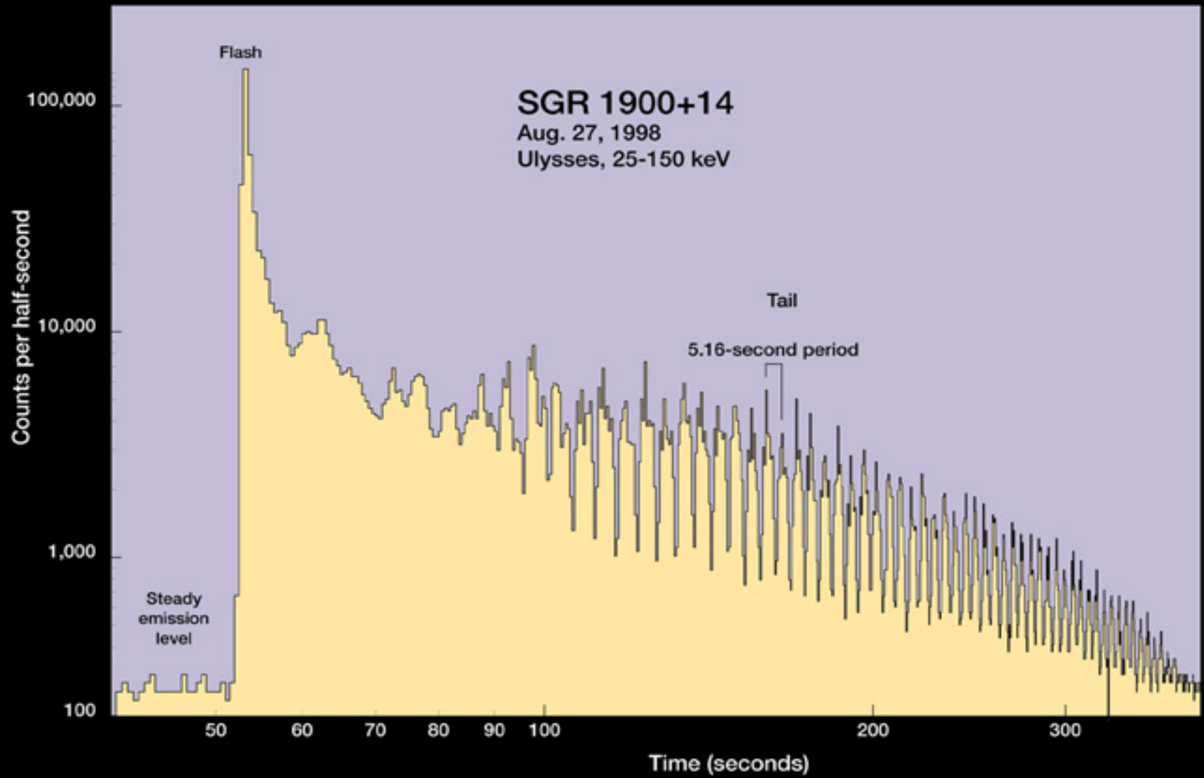


Fig. 14.1. A selection of common burst morphologies recorded from SGR 1806−20, SGR 1900+14 and 1E 2259+586, as observed with the *RXTE* PCA. All light curves display counts in the energy range 2−20 keV, with a time resolution of 7.8 ms. See text for further details.



Magnetar Giant Flares

- 1979 March 5 from SGR 0526−66: energy released ~10^{44} ergs
- 1998 August 27 from SGR1900+14: energy released ~10^{44} ergs



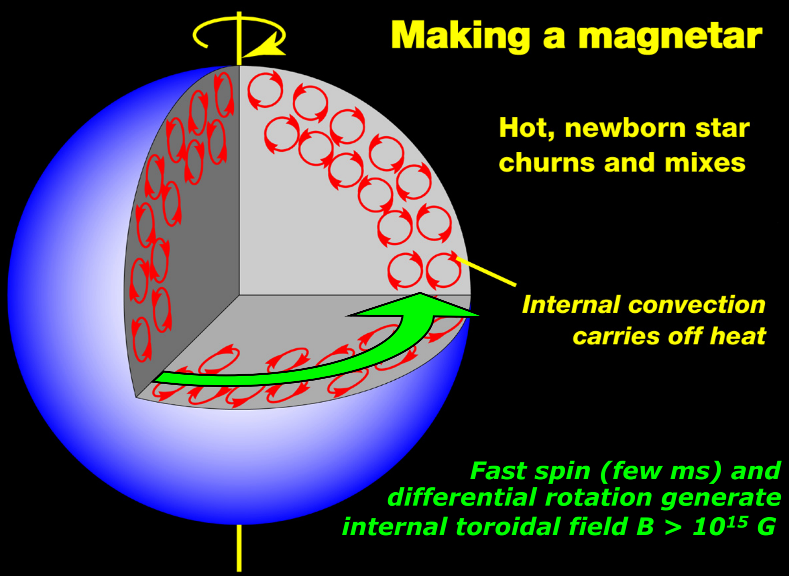
Two classes of galactic high energy sources contain magnetars
(~20 objects so far)

	Soft Gamma Repeaters SGRs (1987)	Anomalous X-ray Pulsars AXPs (1995)
• Spin Period	5-10 s	2-12 s
• Period Derivative	$\sim 10^{-11}$ s/s	$\sim 10^{-11}$-5×10^{-13} s/s
• Recurrent Bursts	$\sim 10^{38}$-10^{41} erg/s	$\sim 10^{37}$-10^{38} erg/s
• Giant Flares	yes	no ?
• Persistent emission	$\sim 10^{35}$ erg/s	$\sim 10^{34}$-10^{35} erg/s
• Transient behaviour	yes	yes
• Association to SNRs	?	in some cases
• Radio pulsations	?	in some cases

Magnetars: neutron stars powered by magnetic energy

- "Magnetars" (MAGNEtic sTARS): neutron stars with very high magnetic fields ($B > 10^{14}$G)
  Why powered by magnetic energy ?

  Persistent luminosity 10-100 times higher than spin down power
  -> rotational energy ruled out
  Recurrent flares reach 10^{41} erg/s ~ 1000 L_{Edd} , giant flares 10^{44} erg/s ~ 10^6 L_{Edd}
  -> accretion energy ruled out



Interest in Magnetars

* Original idea predates the discovery of neutron stars (Woltjer 1964)

* Modern theory developed in late ninties (Thompson & Duncan 96 ->)

* In the last ~ 10 years a lot of the interest in magnetars

  - different channels have been described to form magnetars.

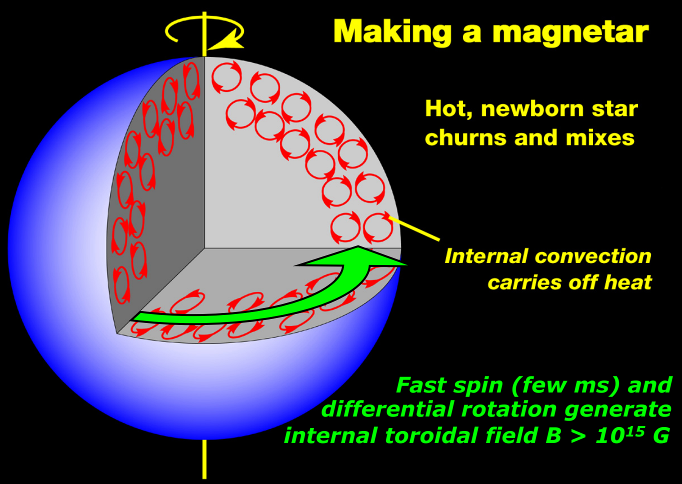
  - magnetars to interpret:
    - Fast Radio Bursts,
    - Some SuperLuminous SuperNovae
    - Ultrahigh energy neutrinos
    - Central engine of both long and short GRBs,
    - Gravitational wave sources detectable by Advanced LIGO/Virgo

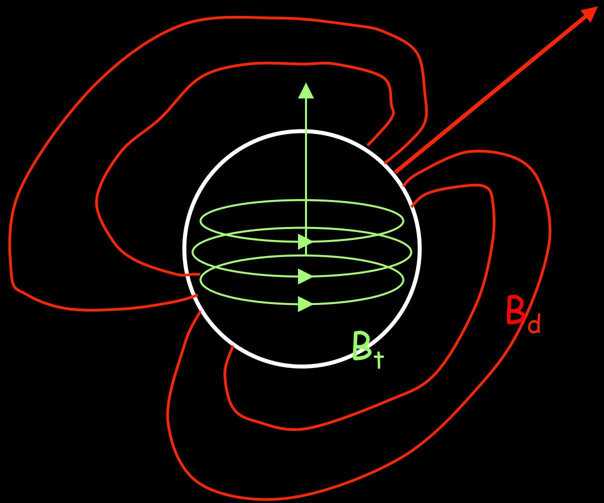
The B-field of Magnetars

Very strong internal *B*-fields in a newborn differentially rotating fast-spinning neutron star

For initial spin periods of P_i~1–2 ms, differential rotation can store ~$10^{52}(Pi/1\ ms)^2$ ergs, that can be converted into a magnetic field of up to $3\times10^{17}\ (P_i/1ms)^{-1}$ G.
(efficient dynamo might be limited to ~3×10^{16} G)

(Duncan & Thompson 1992)





B_d ~ $10^{14\text{-}15}$ G outer dipole field (spin-down, pulsations) inferred from spin-down rate (and confirmed through the energetics and fast variability properties of the "ringing tail" of Giant Flares from SGRs)

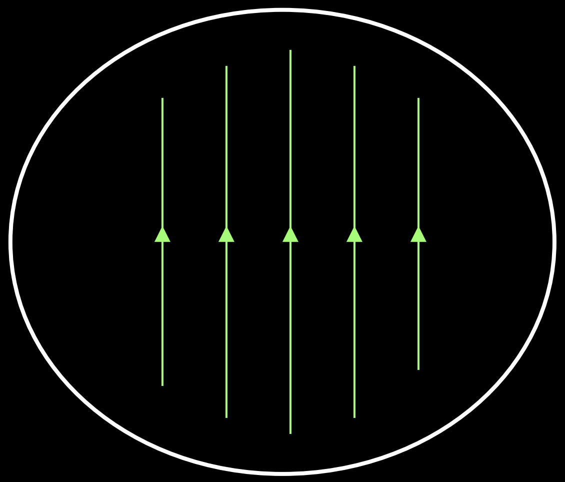
B_t > 10^{15} G inner toroidal field (energy reservoir): lower limit from: L(persistent) x age ~ 10^{47} ergs

Shape of a highy magnetic star

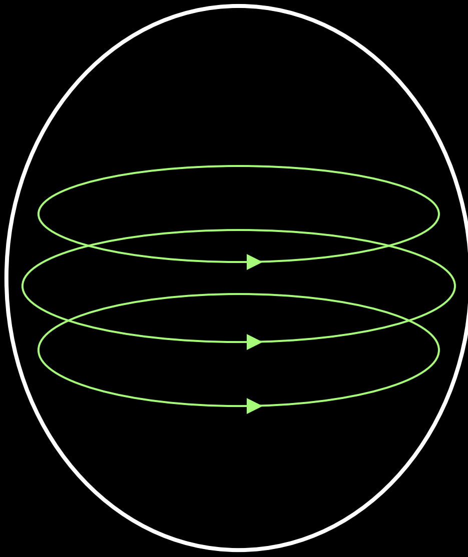
Star with a constant inner B-field cannot be spherical

(Chandrasekhar & Fermi 1953)

Poloidal inner B-field : Oblate star



Toroidal Innar B-field : Prolate star



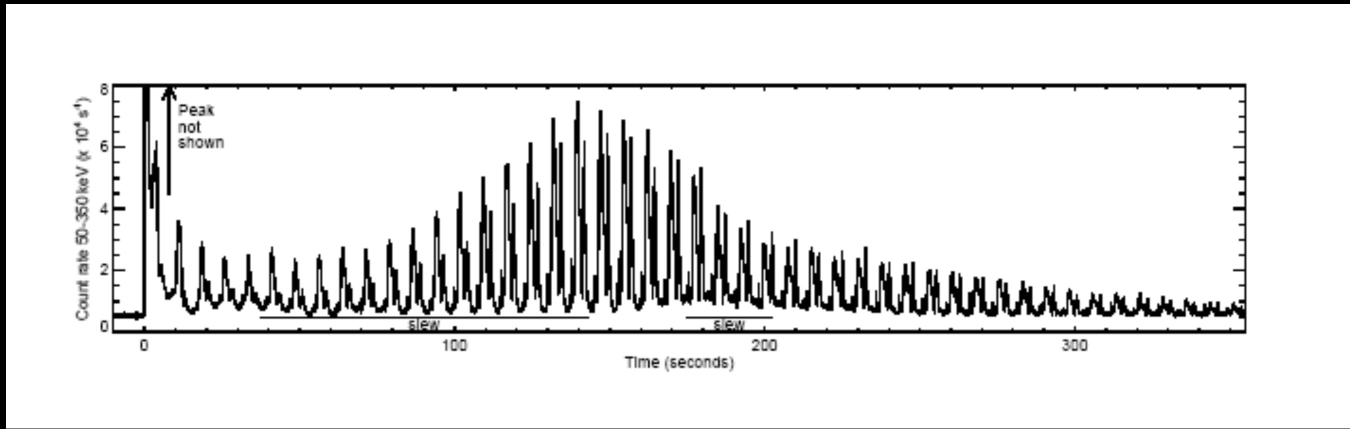
Magnetically induced distortion and gravitational wave emission

- An old idea, considered mainly in relation to young radio pulsars such as the Crab (e.g. review by Cutler & Thorne 2002)

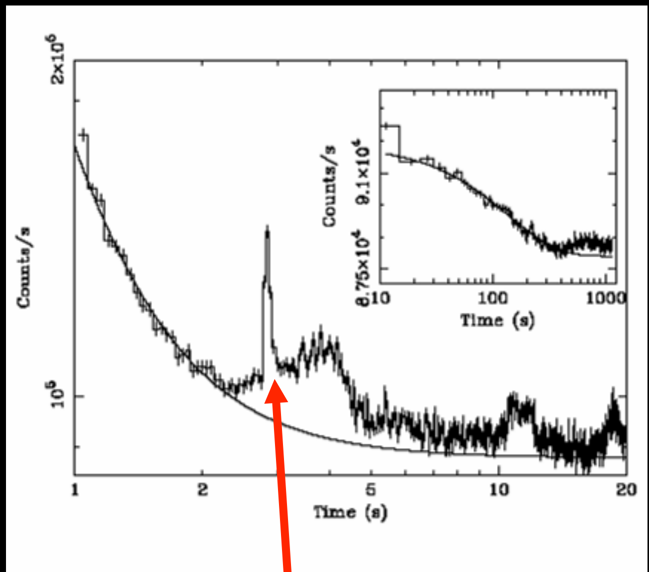
- Renewed interest in highly magnetic (~10^{14}-10^{15} G) newly-formed neutron star in our Galaxy.
  Problem: expected recurrence times are long (> 100 yr at the best) (e.g. review by Bonazzola & Marck 1994)

- Detailed studies of gravitational wave emission properties (Gourgoulhon & Bonazzola 1996, Konno 2001, Palomba 2001)
  and early evolution (Cutler 2002)

SGR 1806-20: Giant Flare of 2004 Dec 27



(Palmer et al. 2005
Hurley et al. 2005)



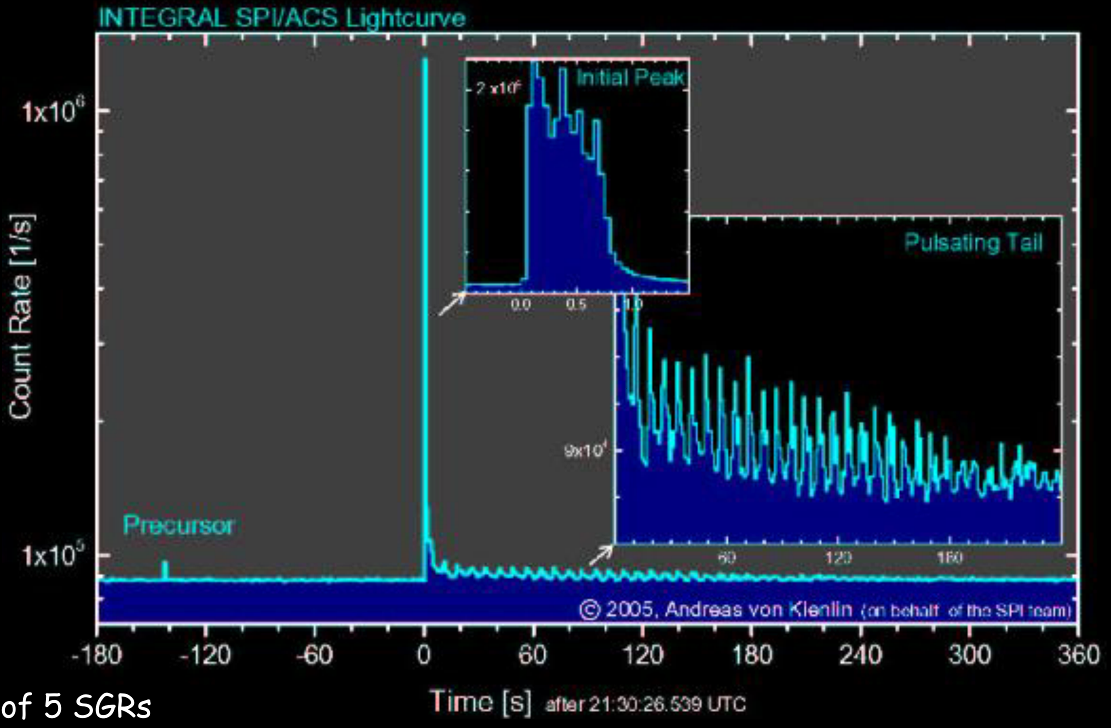
Moon reverberation seen !

Giant Flare Source Assumed distance	March 5, 1979 SGR 0526–66 55 kpc	August 27, 1998 SGR 1900+14 10 kpc	December 27, 2004 SGR 1806–20 15 kpc
Initial Spike			
Duration (s)	$\sim$0.25	$\sim$0.35	$\sim$0.5
Peak luminosity (erg s^{-1})	3.6 10^{44}	>3.7 10^{44}	(2÷5) 10^{47}
Fluence (erg cm^{-2})	4.5 10^{-4}	>5.5 10^{-3}	0.6÷2
Isotropic Energy (erg)	1.6 10^{44}	>6.8 10^{43}	(1.6÷5) 10^{46}
Pulsating tail			
Duration (s)	$\sim$200	$\sim$400	$\sim$380
Fluence (erg cm^{-2})	1 10^{-3}	4.2 10^{-3}	5 10^{-3}
Isotropic Energy (erg)	3.6 10^{44}	5.2 10^{43}	1.3 10^{44}
Spectrum	kT$\sim$30 keV	kT$\sim$20 keV	kT$\sim$15–30 keV
Pulse Period (s)	8.1	5.15	7.56

(Mereghetti et al. 2005)

The 2004 Dec 27 Event and the Internal B-field of Magnetars

- Energy of ~ 5x 10^{46} ergs released in initial 0.6 s long spike (Terasawa et al. 2005; Hurley et al. 2005)



- 1 such event in ~30 yr of monitoring of 5 SGRs
  -> Recurrence time ~ 150 yr/magnetar

- ~70 events like the 2004 Dec 27 event expected in ~10^4 yr (SGR lifetime)
  -> Total energy release (independent of beaming) ~4×10^{48} ergs

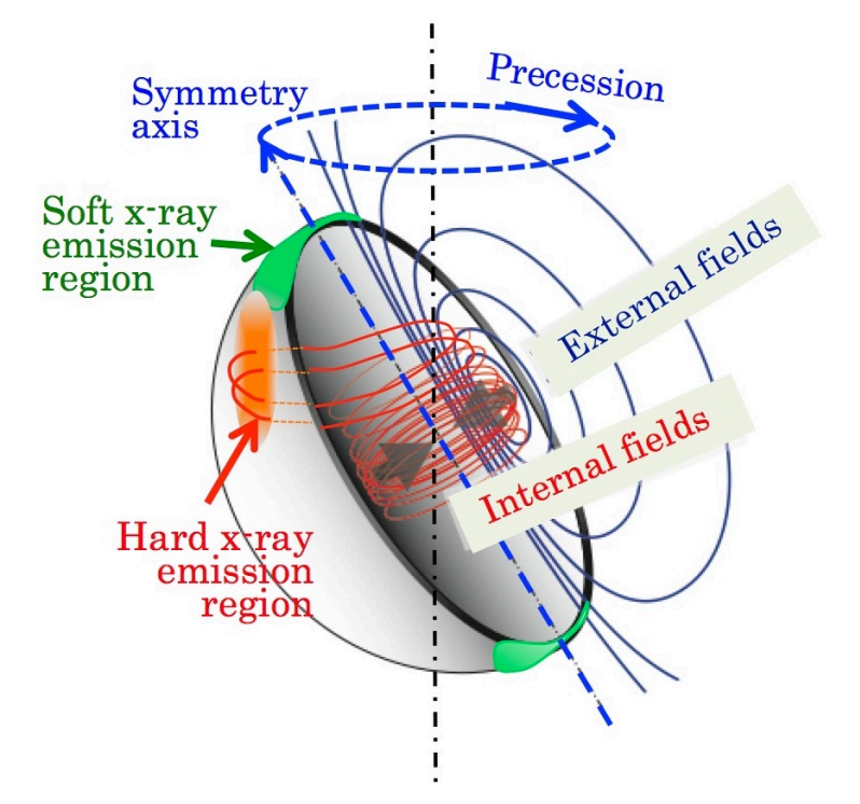
If internal field is the energy source, then $B > 10^{15.7}$ G

Including total neutrino energy release: $B > 10^{15.9}$ G   New limit on B_t

(Stella et al 2005)

GWS FROM NEWLY BORN MAGNETARS

TOROIDAL B-FIELD → **PROLATE DISTORTION**



$\chi \neq 0$ **Excites free body precession**

$\omega = \epsilon_B \Omega \cos\chi$ Mestel & Takhar (1972)

$\epsilon_B \sim 10^{-3} B_{16}^2$ cf. Cutler (2002)

Free precession in 4U 0142+61
B~10^16 G Makishima et al. 2014

$E_{spin} \sim 0.015\, P^{-2}_{ms} M_\odot c^2$

External (dipole) B ~ 10^{14}-10^{15} G

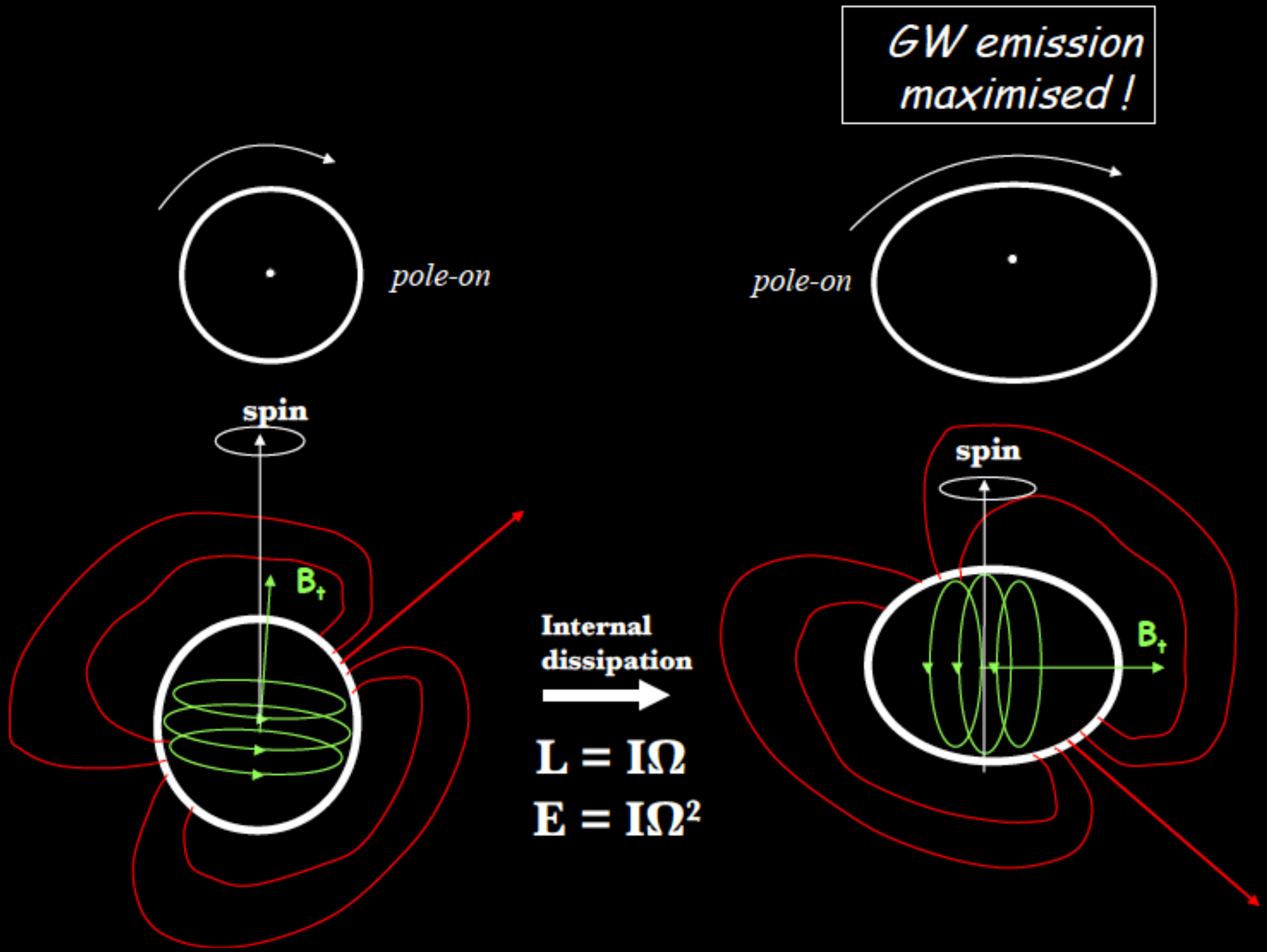
Internal (toroidal) B ~ 10^{16} G

} → **Magnetic dipole emission**

GW emission

Dall'Osso et al 2009, 2015 ,2017

GWS FROM NEWLY BORN MAGNETARS

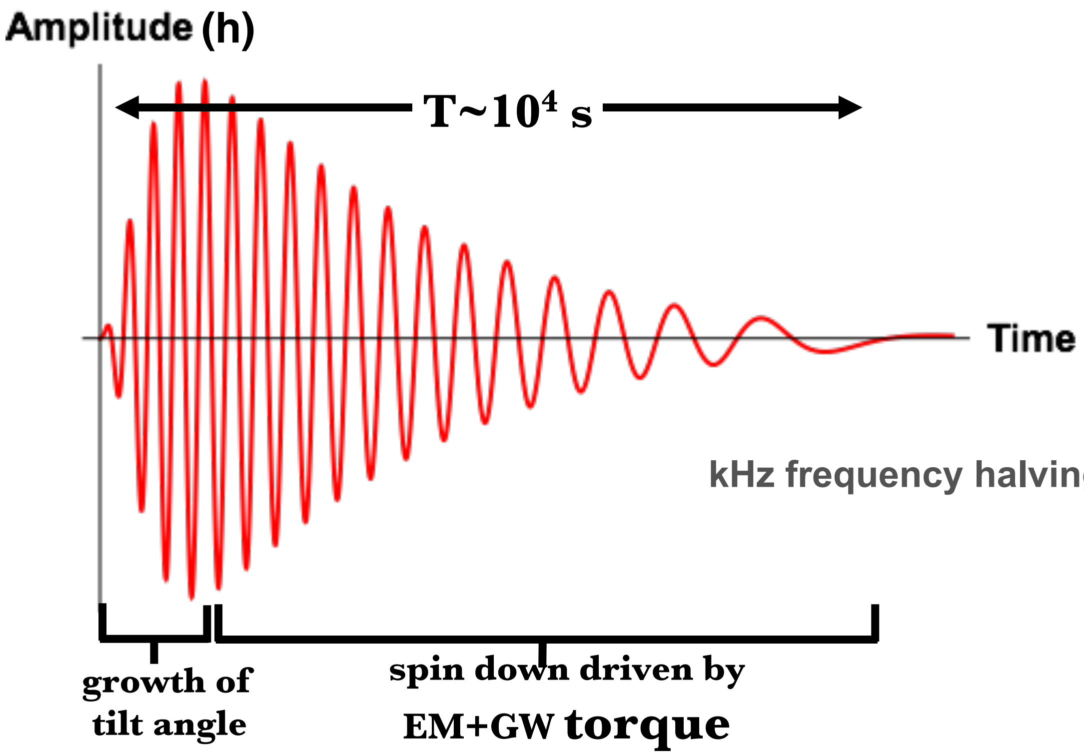


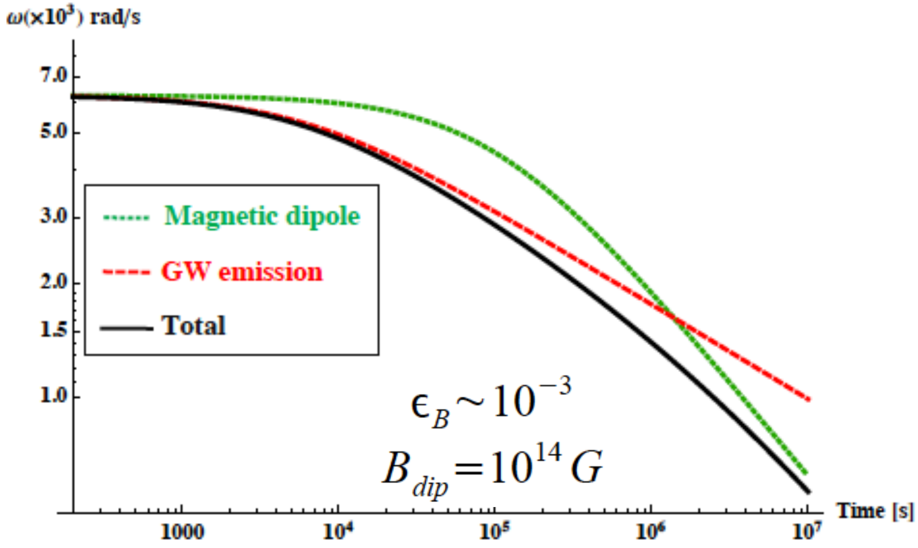
BULK VISCOSITY:

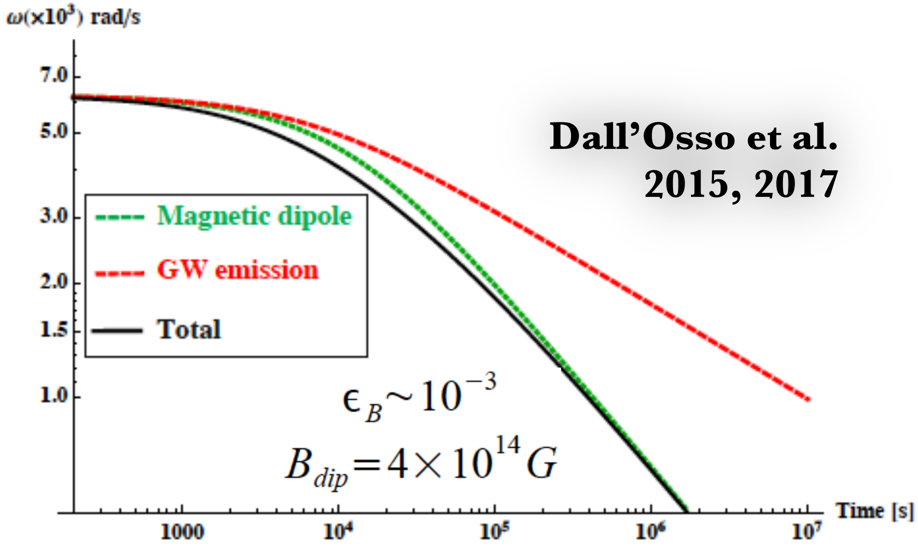
depends on chemical composition and EoS

(**Prakash 1998, Haensel et al. 2001, Dall'Osso et al. 2017**)

GWS FROM NEWLY BORN MAGNETARS





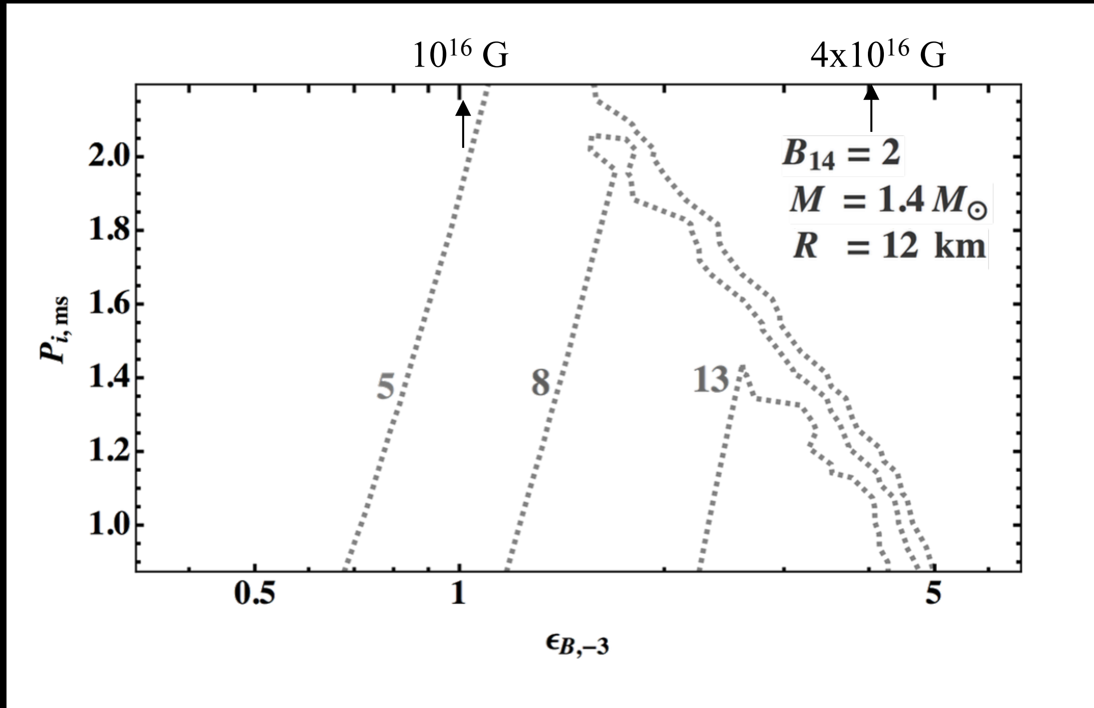


Dall'Osso et al. 2015, 2017

Signal to Noise ratio with Advanced LIGO/Virgo

(for Virgo Cluster distance, 20 Mpc)

Most promising region is
$B_t \sim 10^{16}$ G and $B_d \sim 10^{14}$ G



- Expected magnetar birth rate at Virgo distances: $\sim 1\ yr^{-1}$!

Potentially Interesting GW Event Rate in Advanced LIGO/Virgo

Association with Supernovae -> e.m. counterpart of GW event

Merging neutron star binaries:
GW sources + central engines of short GRBs (?)

Massive Neutron Stars

- A few neutron stars discovered with mass ~ 2Mo:
  -> equation of state must be stiff enough to sustain them !

(Demorest et al. 2010; Antoniadis et al. 2013)

- Merging neutron stars may lead to the formation of a massive, very fast spinning NS, rather than a BH (Giacomazzo & Perna 2013)

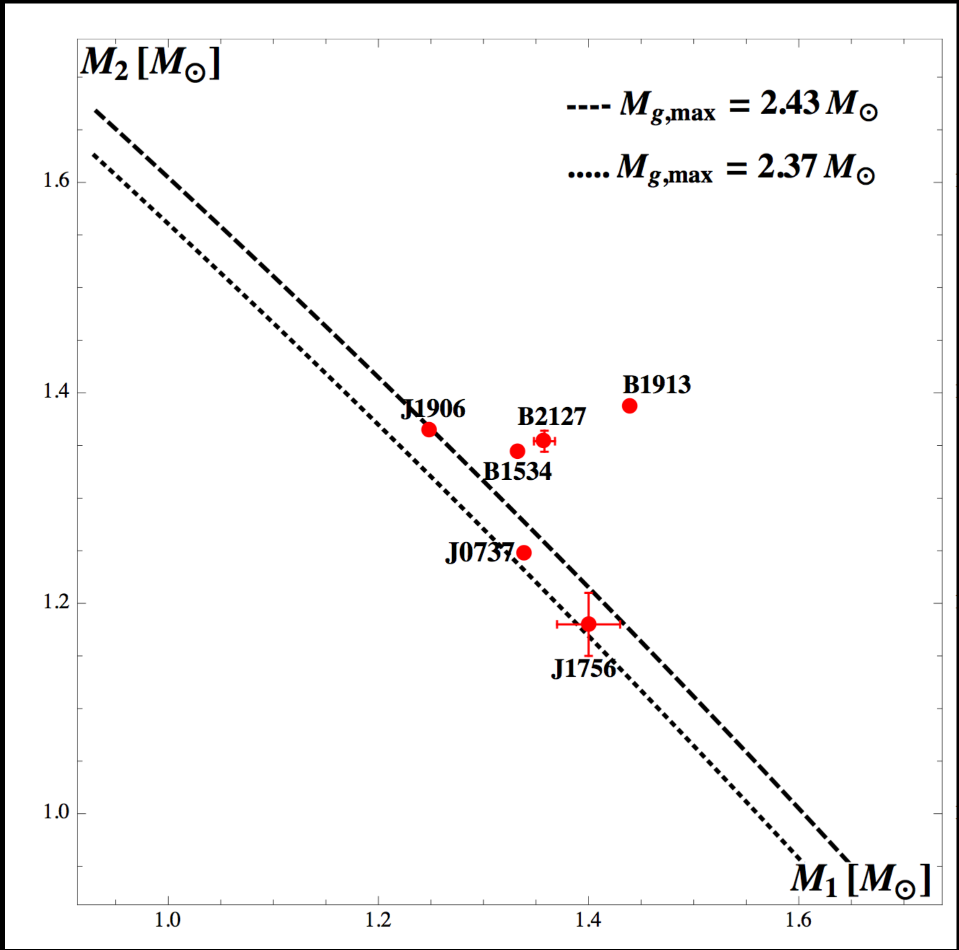
Post-Merging Neutron Stars:
- Stable: M<M(max)
- Supramassive: stabilised by rotation
- Hypermassive: stabilised by differential rotation

Differential rotation amplifies the B field to magnetar values with very strong toroidal component

(Zrake & MacFadyen 2013, Giacomazzo + 2014)

Neutron star binary systems with known masses:

how many would give rise to a post merging neutron star ?



- Fraction depends on EoS, but it might be high (~30%)
- Similar value obtained from mass distribution of all NSs

GW signal:

- merging binary NS signal followed by a weaker week-long signal from fast spinning massive magnetar

The latter can be detectable in ~1% of the cases
(range of ~ 35 Mpc).

Detection would provide crucial info on:

- EoS
- Short GRB engine

Summary

- We have astrophysical evidence that magnetars have internal, mainly toroidal magnetic fields ~ 10^{16} Gauss.

- Magnetars are born fast-spinning and can be very powerful GWs sources for days-weeks

  * The magnetar birth rate in core-collapse SN is ~ 1/yr at Virgo cluster distances:
    detectable GW signal by Advanced Virgo/LIGO for a range of parameters plus association to a SN !

  * When formed in merging binaries:
    (massive) magnetars would be detectable by Advanced Virgo/LIGO up to R ~35 Mpc.
    Rates ~1% of merging NS rate.