Gravitational waves within the magnetar model of superluminous supernovae and gamma-ray bursts

Wynn C.G. Ho

University of Southampton, UK

for details, see MNRAS, in press (arXiv:1606.00454)

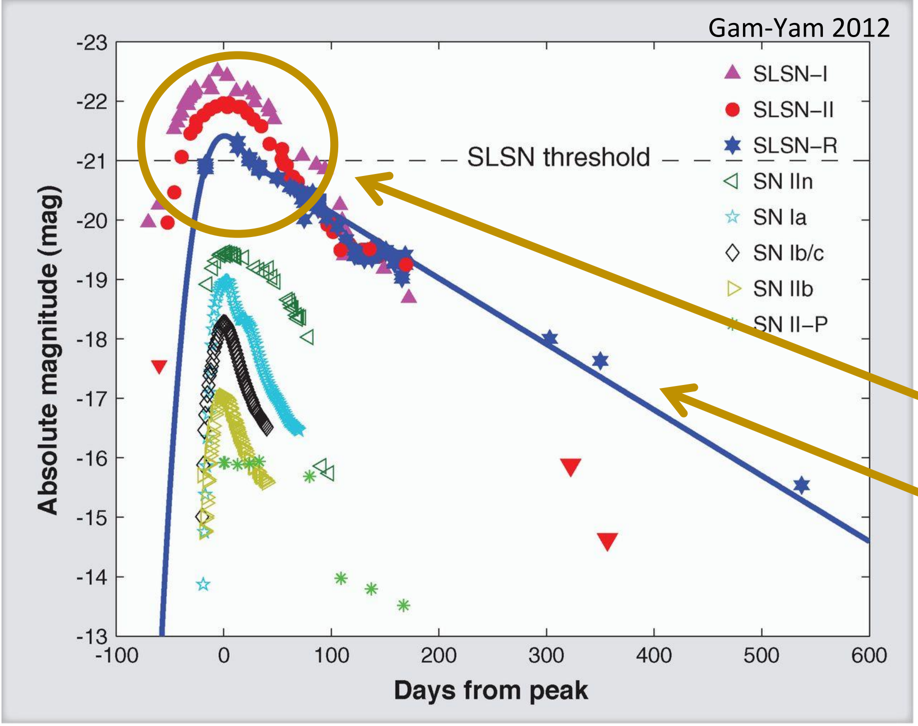
GRavitational-wave Astronomy Meeting in PAris – 29 August–2 September 2016

UNIVERSITY OF Southampton

STAG RESEARCH CENTRE

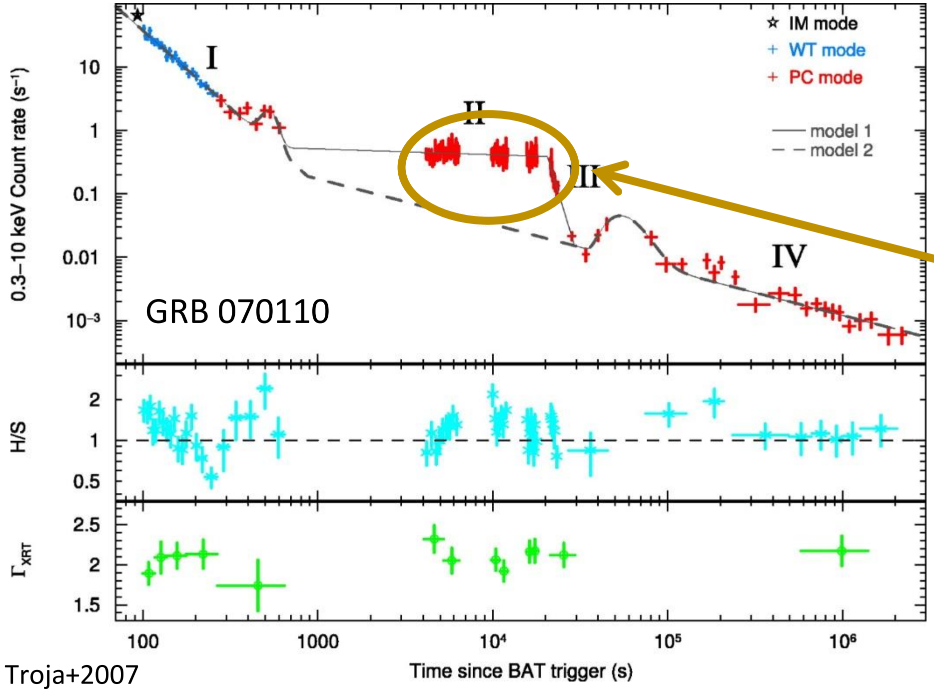
Outline

- Superluminous supernovae (SLSNe) and long-lived gamma-ray bursts (GRBs)
- Magnetars and their spin-down power and timescale
- Millisecond magnetar energy and spin evolution
- Gravitational wave (GW) emission versus electromagnetic dipole radiation
  - simple constraints
  - effect on light curve
- Conclusions



Superluminous supernovae and long-lived gamma-ray bursts

- Superluminous supernovae (SLSNe)
  - more luminous
  - bright at late times (~10–100 of days)



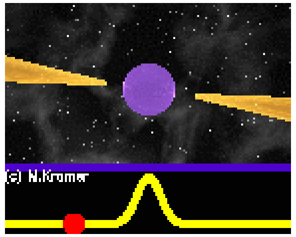
Troja+2007

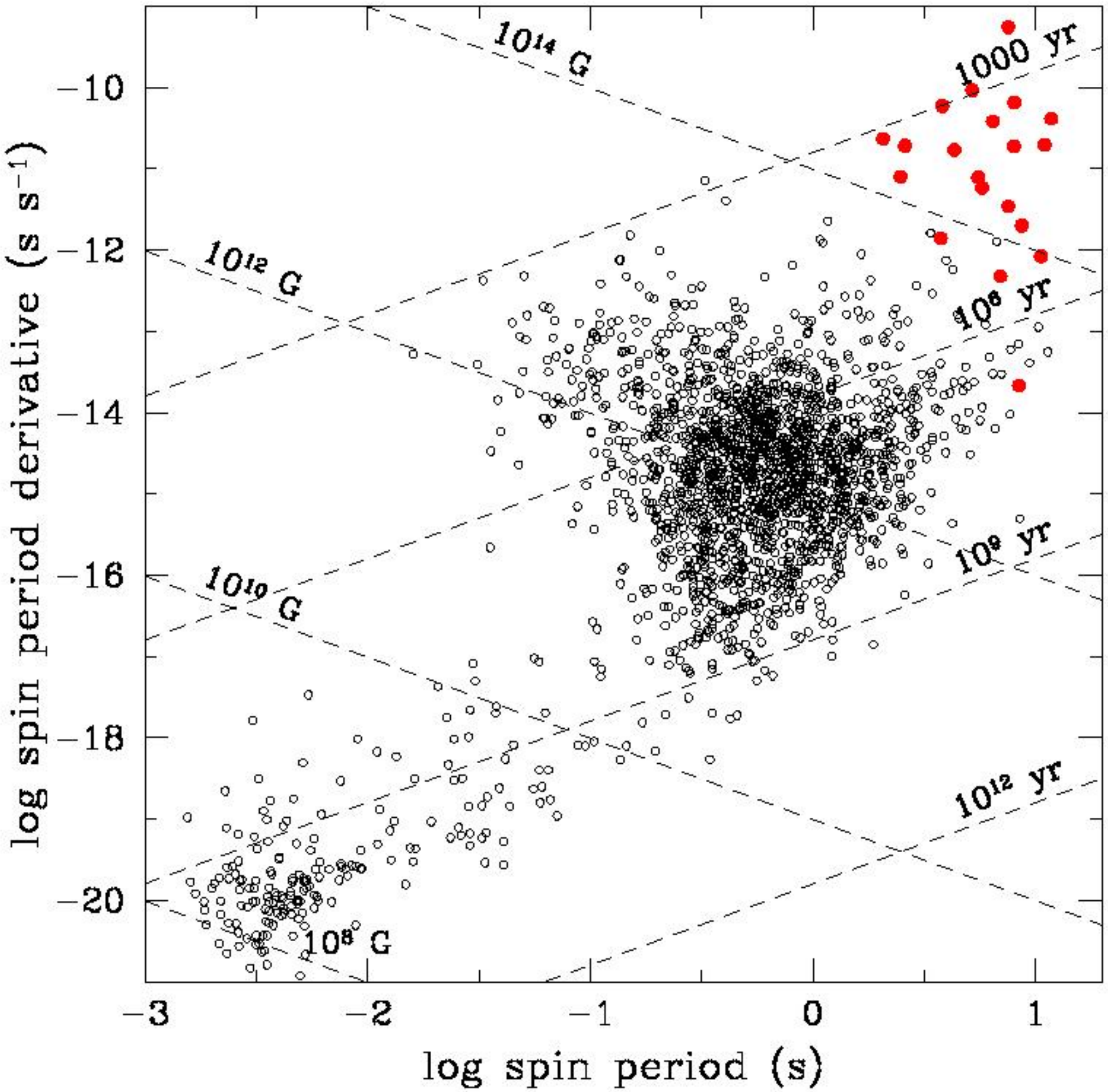
- Long-lived gamma-ray bursts (GRBs)
  - subset of short and long GRBs
  - bright late-time plateau – extra energy for prolonged time (~10^4 s)

STAG RESEARCH CENTRE

Neutron star spins and magnetic fields

see talks by Kramer and Lentati





- P–$\dot{P}$ diagram: measured spin period and time derivative
  - millisecond pulsars $B \sim 10^{8} - 10^{10}$ G
  - radio pulsars $B \sim 10^{11} - 10^{13}$ G
  - **magnetars** $\boldsymbol{B \sim 10^{13} - 10^{15}}$ **G**

- Rotational energy $E_{rot} = I\Omega^2/2 = 2\times10^{52}$ erg $(\boldsymbol{P/1\ \mathrm{ms}})^{-2}$

- Magnetic dipole radiation
  - energy loss $L_{mag} \equiv \dot{E}_{mag} \sim -\boldsymbol{B^2} R^6 \boldsymbol{\Omega^4}/c^3$
  - timescale $t_{mag} = |E_{rot}/\dot{E}_{mag}| = 2\times10^5\ \mathrm{s}\ \boldsymbol{B_{14}}^{-2}\ (P/1\ \mathrm{ms})^2$
  - infer magnetic field with $\dot{E}_{rot} \equiv I\Omega\dot{\Omega} = 4\pi^2\dot{P}/P^3 = L_{mag}$

$$\Rightarrow \quad B = 3.2\times10^{19}\ \mathrm{G}\ (P\dot{P})^{1/2}$$

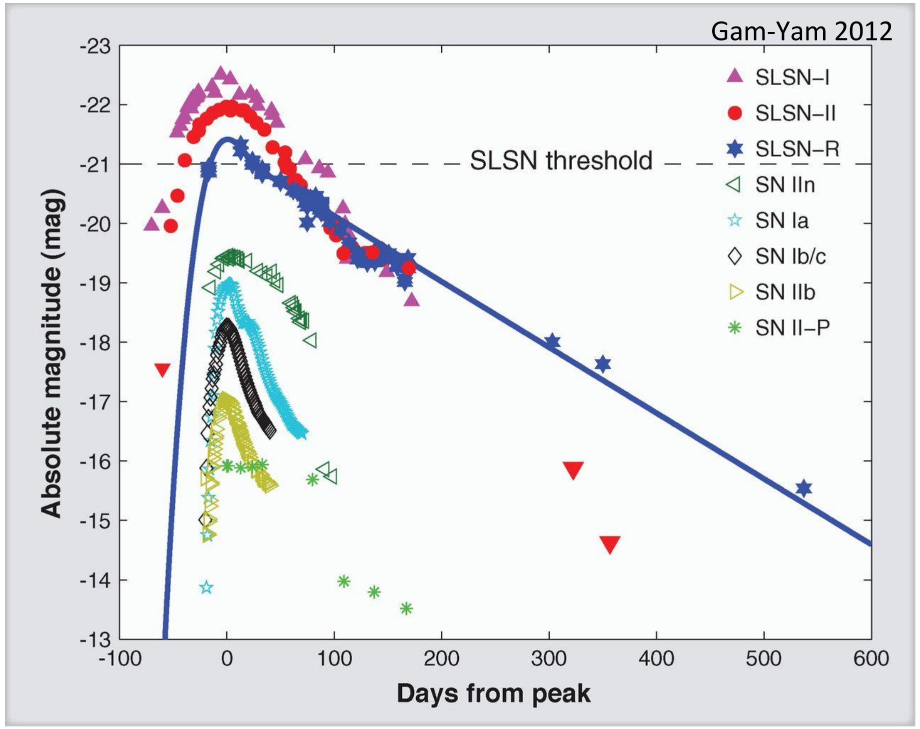
STAG RESEARCH CENTRE

Using millisecond magnetars to power SLSNe and GRBs

see also talk by Rezzolla for GRBs

Superluminous supernovae (SLSNe)

- more luminous →
- bright at late times (~10–100 of days) →



- Rotational energy $E_{rot} = I\Omega^2/2 = 2\times10^{52}$ erg $(P/1\ \mathrm{ms})^{-2}$
  - rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$
    where $L_{mag} \sim -B^2R^6\Omega^4/c^3$
  - on timescale $t_{mag} = 2\times10^5$ s $B_{14}^{-2}\ (P/1\ \mathrm{ms})^2$

- Energy evolution from 1st law (eg Arnett 1980)

  see also talk by Nissanke

  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$

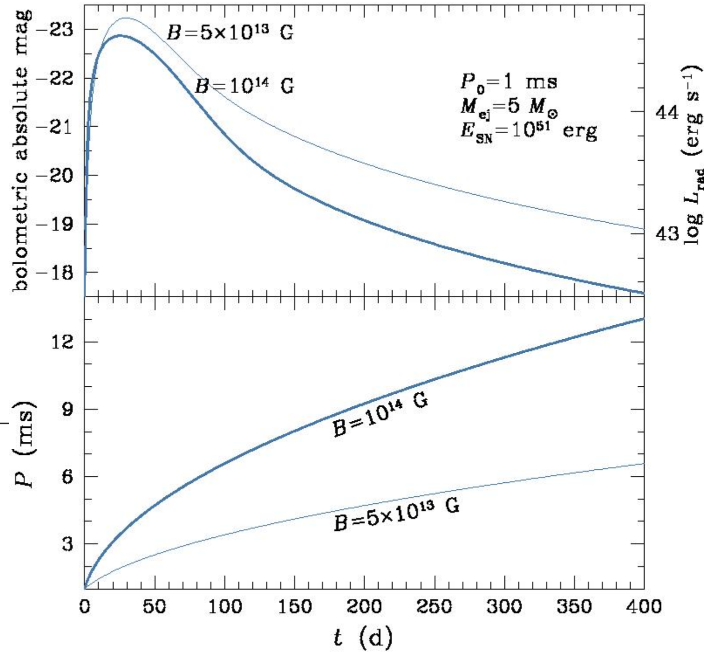
    $\frac{\partial (tE)}{\partial t} = t\,(L_{mag} - L_{rad})$

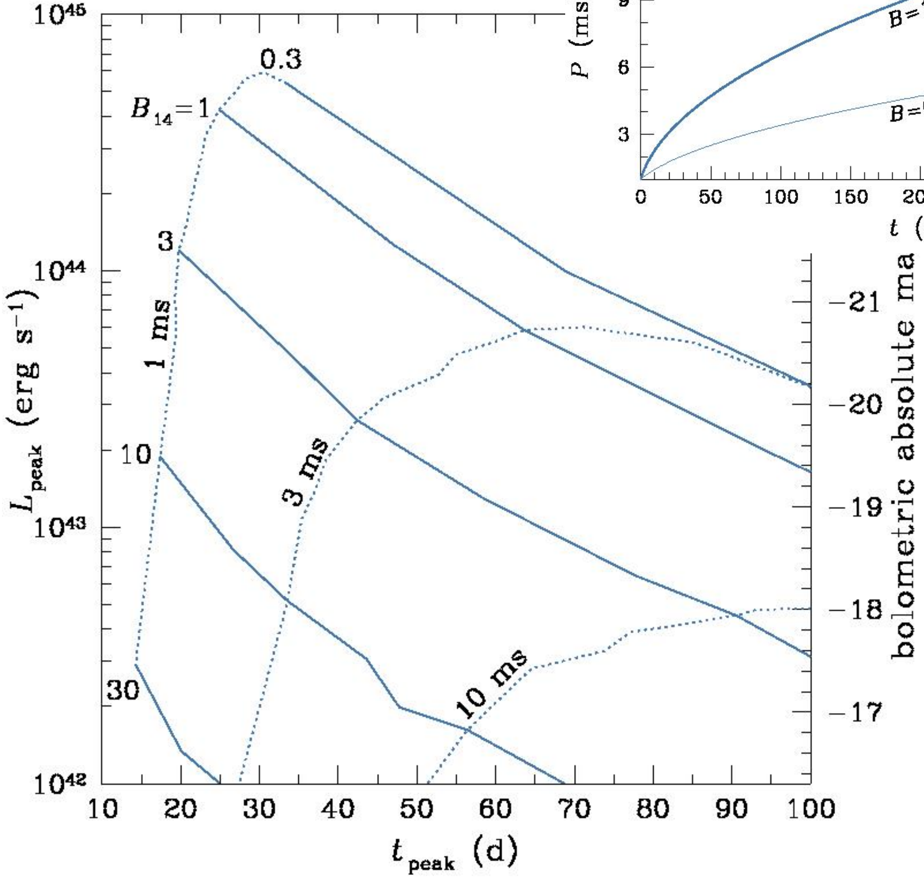
  where radiative diffusion $L_{rad} = 4\pi r^2 \frac{c}{3\kappa\rho}\frac{\partial(E/V)}{\partial r} \approx tE/t_{diff}^2$

- Coupled evolution of E and Ω (eg Kasen+Bildsten 2010)
  - light curve $L_{rad}(t)$
  - peak luminosity L_{peak} ($\equiv$ max L_{rad}) and peak time t_{peak}

STAG RESEARCH CENTRE

Using millisecond magnetars to power SLSNe and GRBs





- Rotational energy $E_{rot} = I\Omega^2/2 = 2\times10^{52}$ erg $(P/1\text{ ms})^{-2}$
  - rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$
    where $L_{mag} \sim -B^2R^6\Omega^4/c^3$
  - on timescale $t_{mag} = 2\times10^5$ s $\boldsymbol{B_{14}^{-2}\,(P/1\text{ ms})^2}$

- Energy evolution from 1st law (eg Arnett 1980)
  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$
    $\frac{\partial (tE)}{\partial t} = t\,(L_{mag} - L_{rad})$

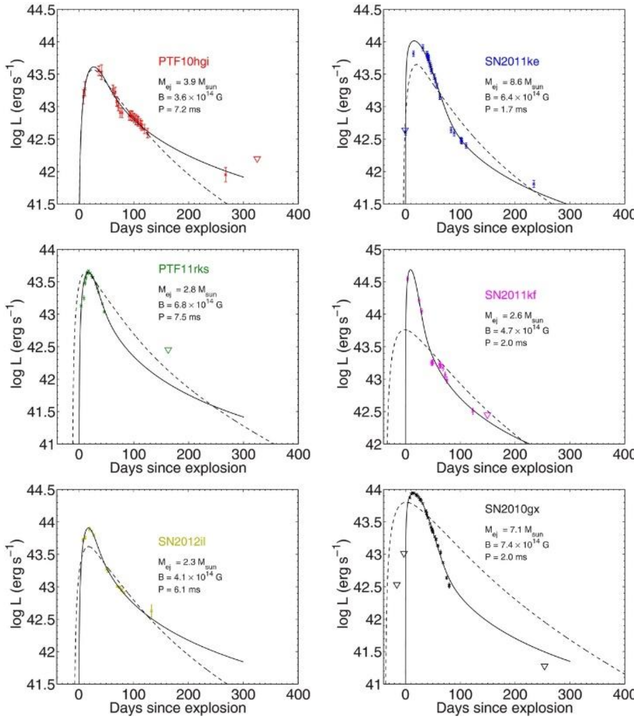
  where radiative diffusion $L_{rad} = 4\pi r^2 \frac{c}{3\kappa\rho}\frac{\partial(E/V)}{\partial r} \approx tE/t_{diff}^2$

- Coupled evolution of E and Ω (eg Kasen+Bildsten 2010)
  - light curve $L_{rad}(t)$
  - peak luminosity L_{peak} ($\equiv$ max L_{rad}) and peak time t_{peak}

STAG RESEARCH CENTRE

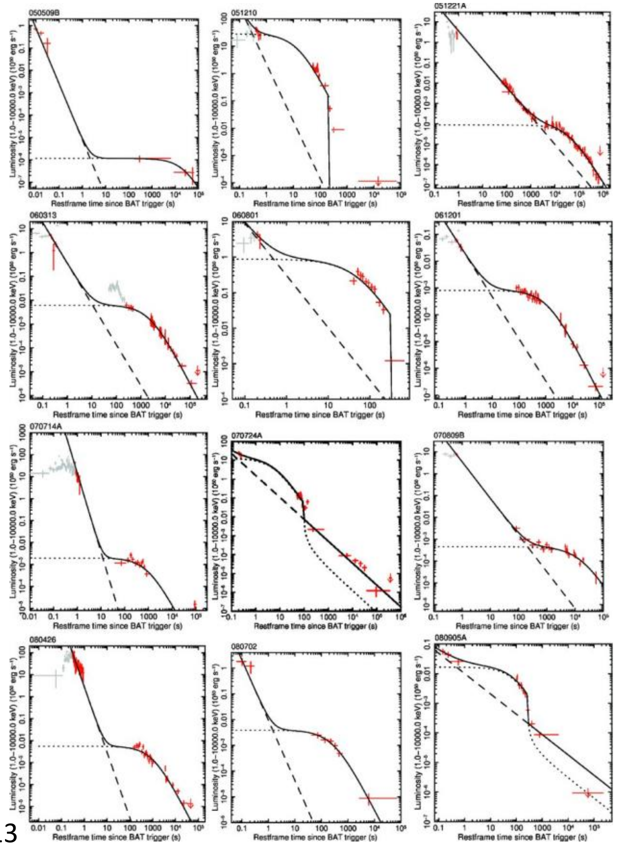
Using millisecond magnetars to power SLSNe and GRBs

SLSNe



Inserra+2013

short GRBs



Rowlinson+2013

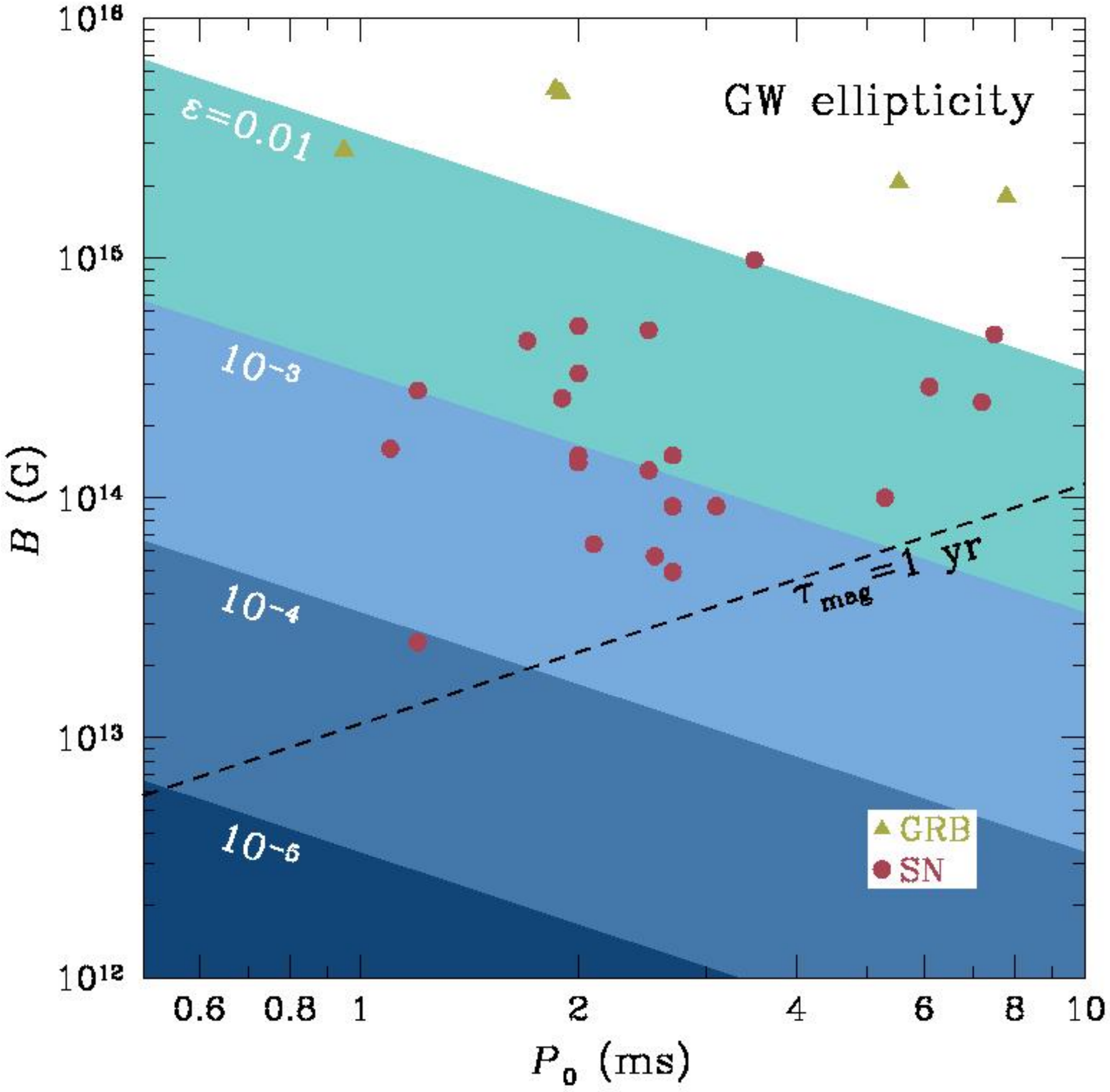
- Rotational energy $E_{rot} = I\Omega^2/2 = 2\times10^{52}$ erg $(P/1\ \mathrm{ms})^{-2}$
  - rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$
    where $L_{mag} \sim -B^2R^6\Omega^4/c^3$
  - on timescale $t_{mag} = 2\times10^5$ s $B_{14}^{-2}\ (P/1\ \mathrm{ms})^2$

- Energy evolution from 1st law (eg Arnett 1980)
  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$
    $\frac{\partial (tE)}{\partial t} = t\,(L_{mag} - L_{rad})$

  where radiative diffusion $L_{rad} = 4\pi r^2 \frac{c}{3\kappa\rho}\frac{\partial(E/V)}{\partial r} \approx tE/t_{diff}^2$

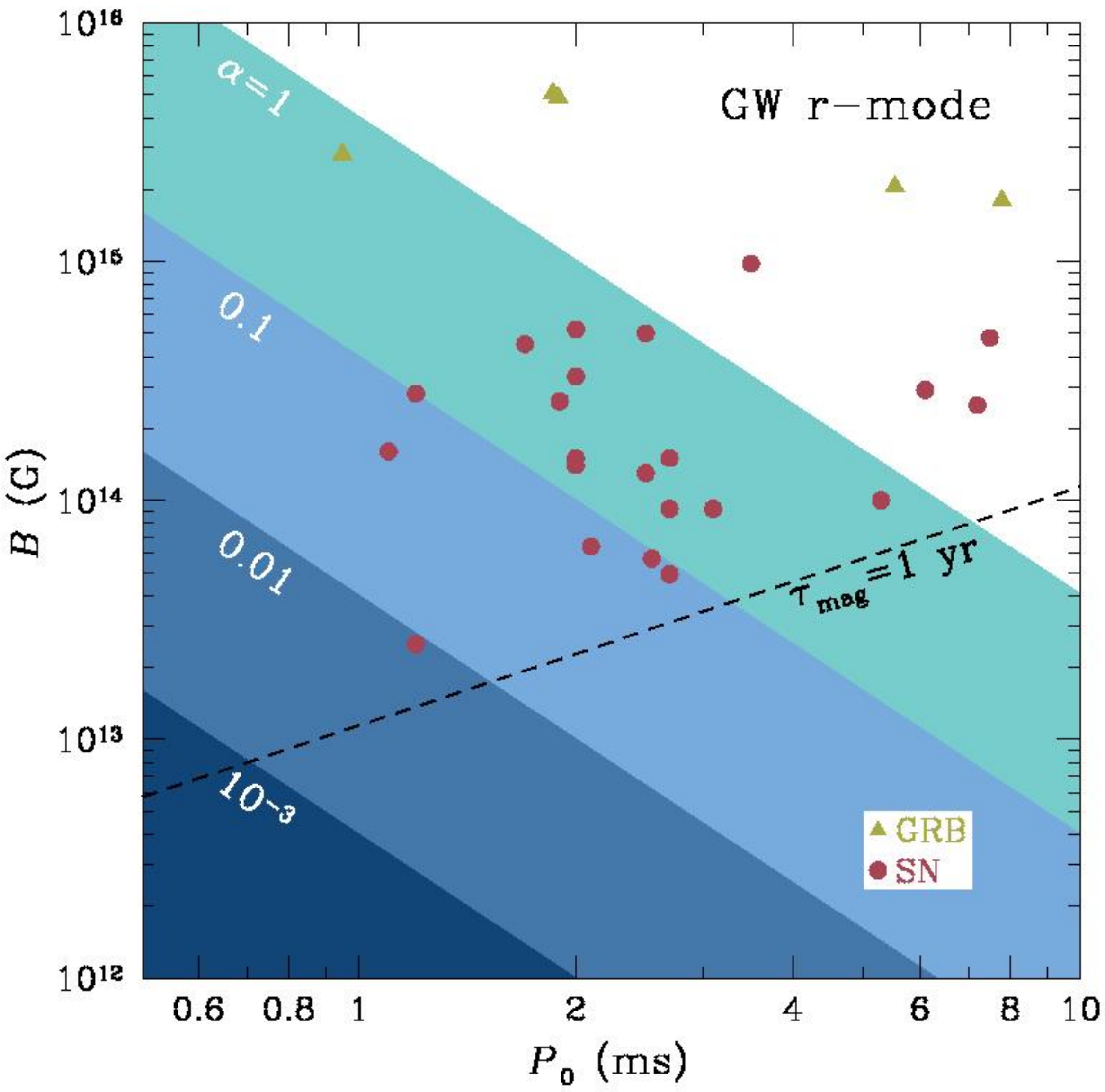
- Coupled evolution of E and Ω (eg Kasen+Bildsten 2010)
  - light curve $L_{rad}(t)$
  - peak luminosity L_{peak} ($\equiv$ max L_{rad}) and peak time t_{peak}

Simple constraints on amplitudes of ellipticity and r-mode



- Magnetic dipole radiation $L_{\mathrm{mag}} \sim \boldsymbol{B^2\Omega^4} R^6/c^3$
  - energy loss time
    $t_{\mathrm{mag}} = |E_{\mathrm{rot}}/\dot{E}_{\mathrm{mag}}| = 2\times10^5\ \mathrm{s}\ B_{14}^{-2}\ (P/1\ \mathrm{ms})^2$
- GW from ellipticity $L_{\mathrm{gw}} \sim \boldsymbol{\varepsilon^2\Omega^6} GI^2/c^5$
  - energy loss time
    $t_{\mathrm{gw}} = |E_{\mathrm{rot}}/L_{\mathrm{gw}}| = 2\times10^4\ \mathrm{s}\ (\varepsilon/10^{-3})^{-2}(P/1\ \mathrm{ms})^4$
- GW from r-mode oscillation $L_{\mathrm{gw,r}} \sim \boldsymbol{\alpha^2\Omega^8} GIMR^4/c^7$
  - energy loss time
    $t_{\mathrm{gw,r}} = |E_{\mathrm{rot}}/L_{\mathrm{gw,r}}| = 1\times10^5\ \mathrm{s}\ (\alpha/0.03)^{-2}(P/1\ \mathrm{ms})^6$
- GW constraints if t_{gw} or $t_{\mathrm{gw,r}} < t_{\mathrm{mag}}$
- Rotational energy loss $I\Omega\dot{\Omega} = L_{\mathrm{mag}} + L_{\mathrm{gw}}$

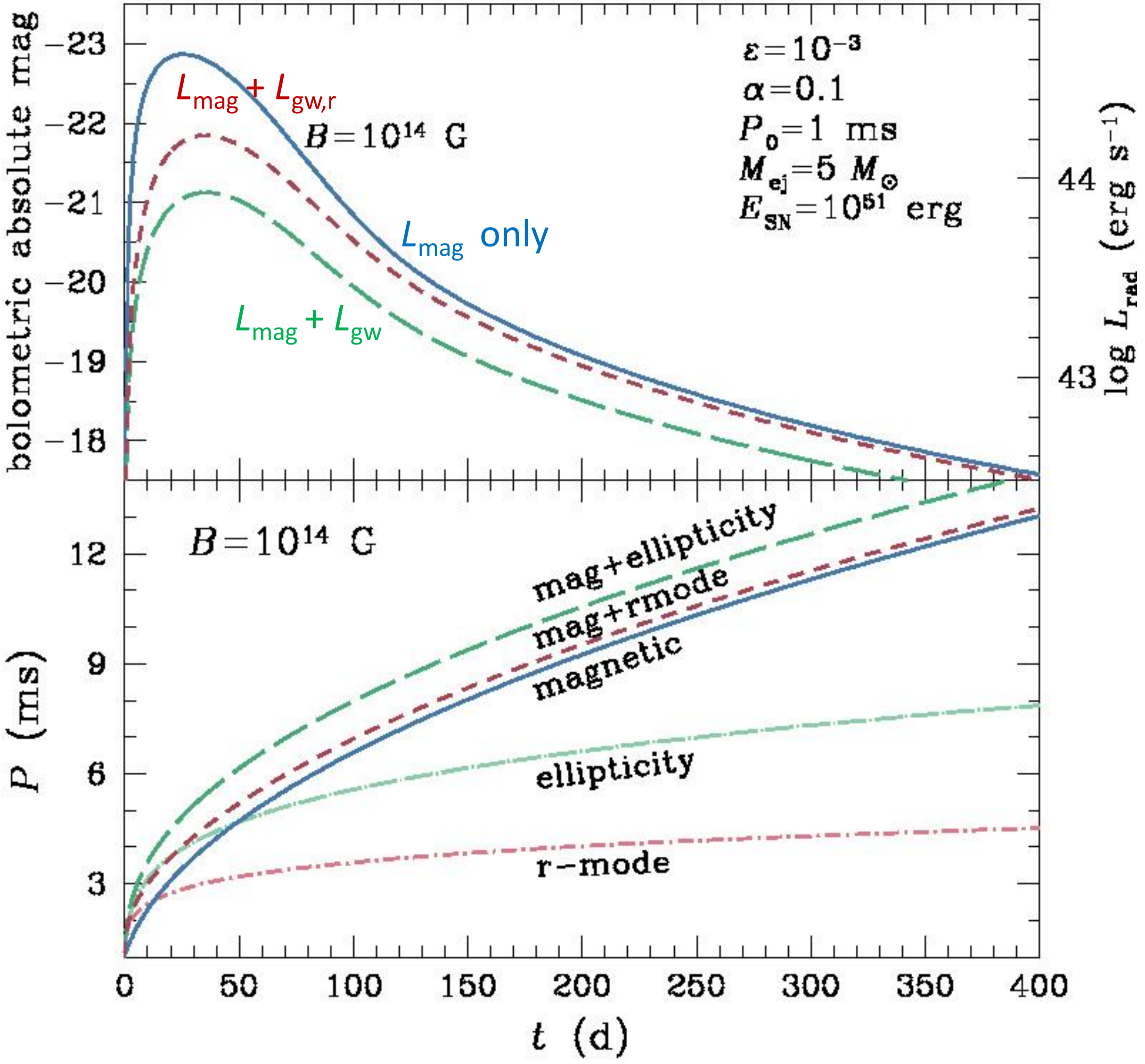
Simple constraints on amplitudes of ellipticity and r-mode



- Magnetic dipole radiation $L_{mag} \sim \boldsymbol{B^2\Omega^4} R^6/c^3$
  - energy loss time
    $t_{mag} = |E_{rot}/\dot{E}_{mag}| = 2\times10^5\ \mathrm{s}\ B_{14}^{-2}\ (P/1\ \mathrm{ms})^2$
- GW from ellipticity $L_{gw} \sim \boldsymbol{\varepsilon^2\Omega^6} GI^2/c^5$
  - energy loss time
    $t_{gw} = |E_{rot}/L_{gw}| = 2\times10^4\ \mathrm{s}\ (\varepsilon/10^{-3})^{-2}(P/1\ \mathrm{ms})^4$
- GW from r-mode oscillation $L_{gw,r} \sim \boldsymbol{\alpha^2\Omega^8} GIMR^4/c^7$
  - energy loss time
    $t_{gw,r} = |E_{rot}/L_{gw,r}| = 1\times10^5\ \mathrm{s}\ (\alpha/0.03)^{-2}(P/1\ \mathrm{ms})^6$
- GW constraints if t_{gw} or $t_{gw,r} < t_{mag}$
- Rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$

STAG RESEARCH CENTRE

Effect of GWs on SN/GRB light curve



- Energy evolution from 1st law (eg Arnett 1980)
  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$
- Rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$
- Magnetic dipole radiation $L_{mag} \sim B^2\Omega^4 R^6/c^3$
  - energy loss time $t_{mag} = 2\times10^5$ s $B_{14}^{-2}\,(P/1\text{ ms})^2$
- GW from ellipticity $L_{gw} \sim \varepsilon^2\Omega^6\, GI^2/c^5$
  - energy loss time

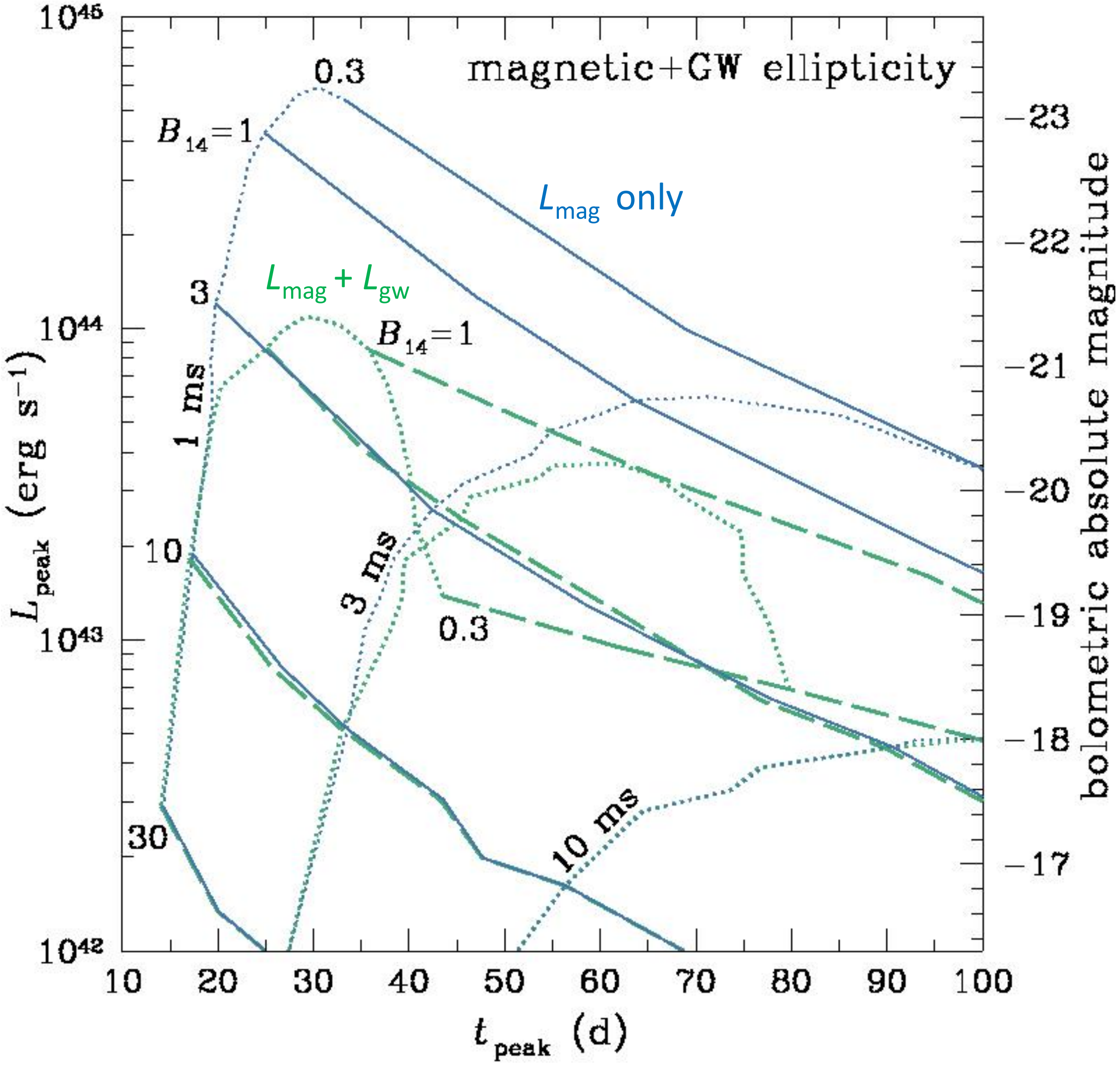
    $t_{gw} = |E_{rot}/L_{gw}| = 2\times10^4$ s $(\varepsilon/10^{-3})^{-2}(P/1\text{ ms})^4$
- GW from r-mode oscillation $L_{gw,r} \sim \alpha^2\Omega^8\, GIMR^4/c^7$
  - energy loss time

    $t_{gw,r} = |E_{rot}/L_{gw,r}| = 1\times10^5$ s $(\alpha/0.03)^{-2}(P/1\text{ ms})^6$

see Kashiyama et al 2016, for more detailed calculation with GW constraints

STAG RESEARCH CENTRE

Effect of GWs on SN/GRB light curve



- Energy evolution from 1st law (eg Arnett 1980)
  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$
- Rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$

- Magnetic dipole radiation $L_{mag} \sim \mathbf{B^2\Omega^4} R^6/c^3$
  - energy loss time $t_{mag} = 2\times10^5$ s B_{14}^{-2} $(P/1\text{ ms})^2$

- GW from ellipticity $L_{gw} \sim \boldsymbol{\varepsilon^2\Omega^6} GI^2/c^5$
  - energy loss time

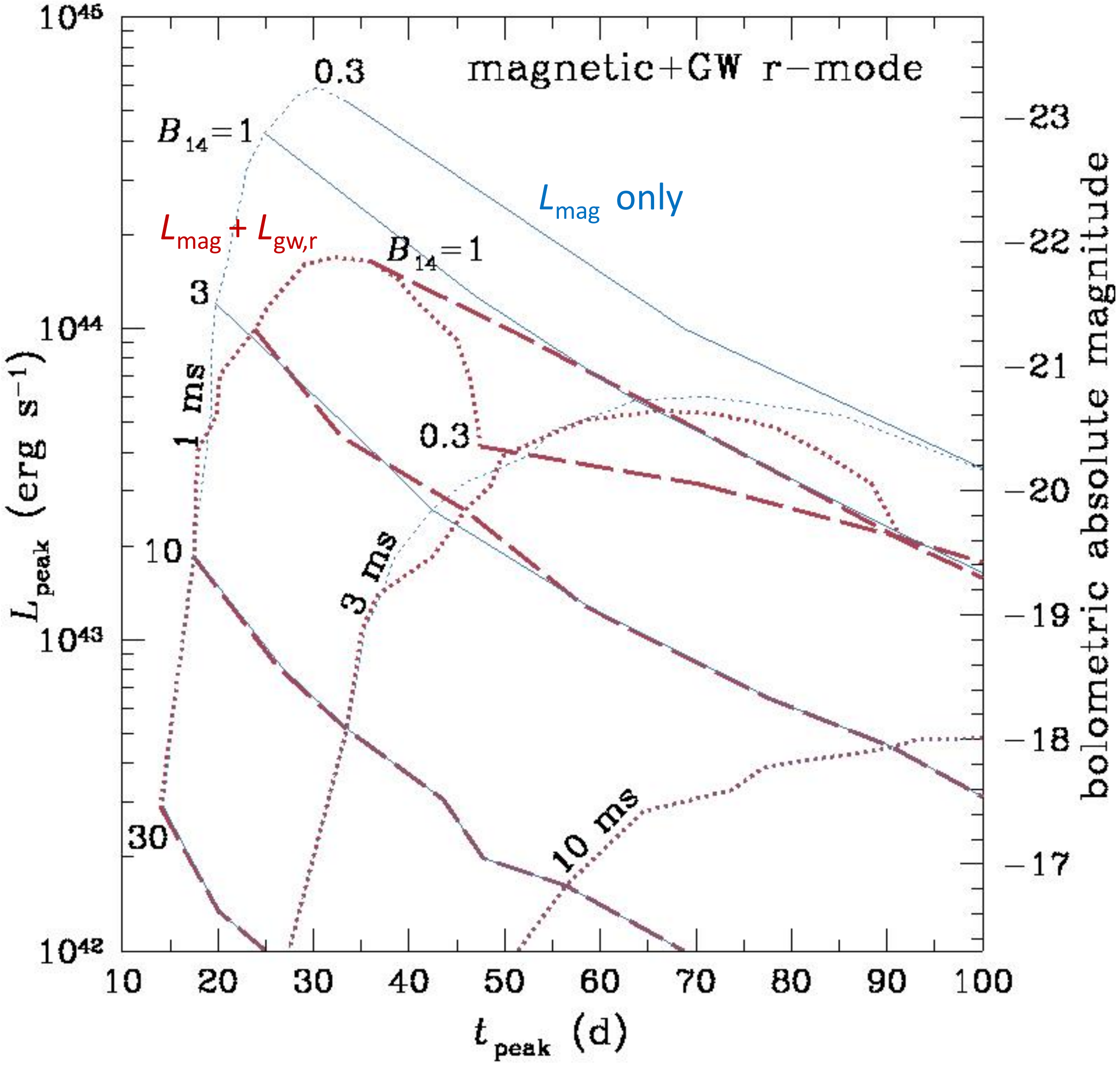
    $t_{gw} = |E_{rot}/ L_{gw}| = 2\times10^4$ s $(\varepsilon/10^{-3})^{-2}(P/1\text{ ms})^4$

- GW from r-mode oscillation $L_{gw,r} \sim \boldsymbol{\alpha^2\Omega^8}$ $GIMR^4/c^7$
  - energy loss time

    $t_{gw,r} = |E_{rot}/ L_{gw,r}| = 1\times10^5$ s $(\alpha/0.03)^{-2}(P/1\text{ ms})^6$

STAG RESEARCH CENTRE

Effect of GWs on SN/GRB light curve



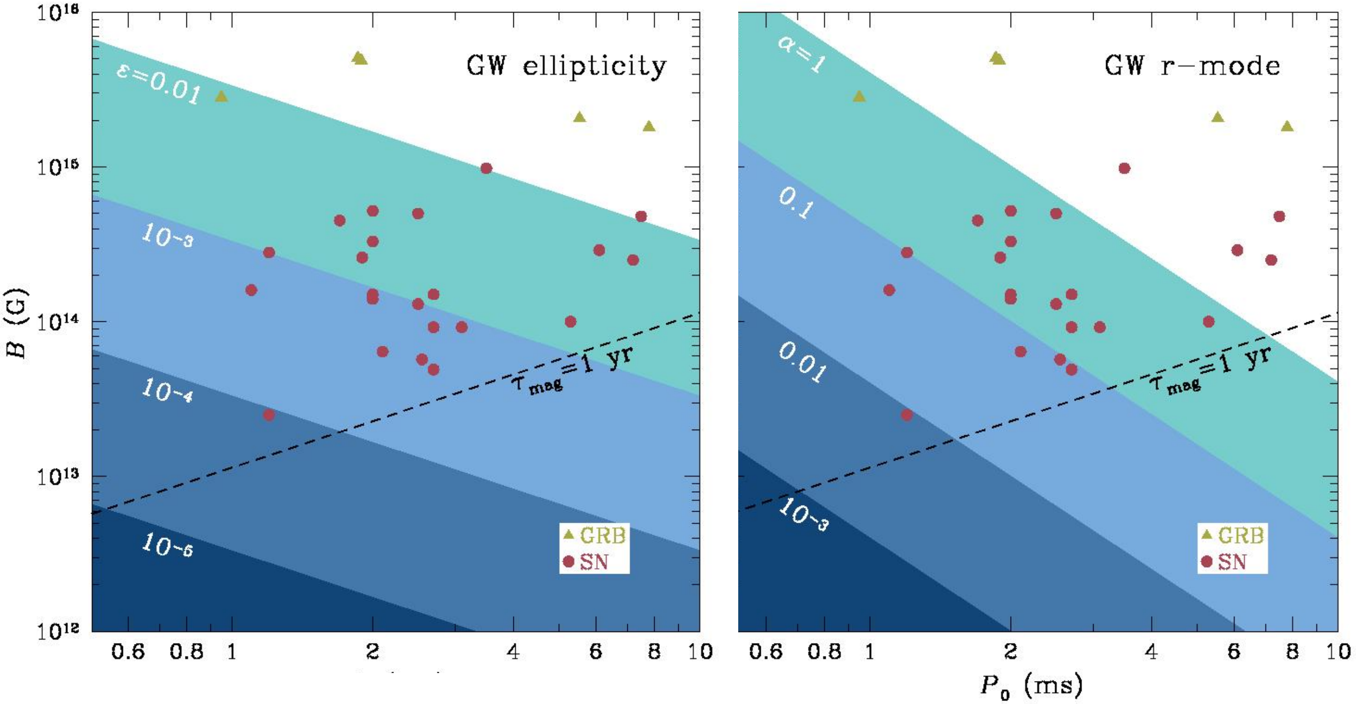
- Energy evolution from 1st law (eg Arnett 1980)
  - $\frac{\partial E}{\partial t} = -p\frac{\partial V}{\partial t} + L_{mag} - L_{rad}$
- Rotational energy loss $I\Omega\dot{\Omega} = L_{mag} + L_{gw}$
- Magnetic dipole radiation $L_{mag} \sim \boldsymbol{B^2\Omega^4} R^6/c^3$
  - energy loss time $t_{mag} = 2\times10^5$ s B_{14}^{-2} $(P/1\text{ ms})^2$
- GW from ellipticity $L_{gw} \sim \boldsymbol{\varepsilon^2\Omega^6} GI^2/c^5$
  - energy loss time

    $t_{gw} = |E_{rot}/L_{gw}| = 2\times10^4$ s $(\varepsilon/10^{-3})^{-2}(P/1\text{ ms})^4$
- GW from r-mode oscillation $L_{gw,r} \sim \boldsymbol{\alpha^2\Omega^8} GIMR^4/c^7$
  - energy loss time

    $t_{gw,r} = |E_{rot}/L_{gw,r}| = 1\times10^5$ s $(\alpha/0.03)^{-2}(P/1\text{ ms})^6$

STAG RESEARCH CENTRE

Conclusions



GW effect on magnetar model of SNe/GRBs if

- ellipticity $\varepsilon > 10^{-4}$, but theory/observation $< 10^{-3}$
- r-mode $\alpha > 0.01$, but theory/observation $< 10^{-3}/0.1$ (see also talk by Andersson)

$\Rightarrow$ magnetar model is ok for SNe/GRBs without GWs