Precursors to Compact Mergers

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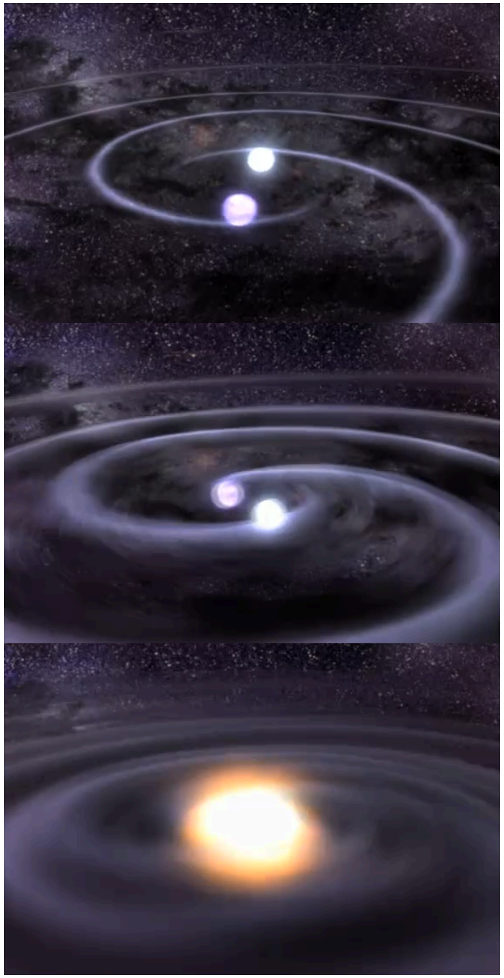
Why Precursors?



Similar advantages as postmerger transients (kilonovae, radio)

- Detection of off-axis or "unsuccessful" short GRBs

- Localization and identification of environment

Features unique to precursors

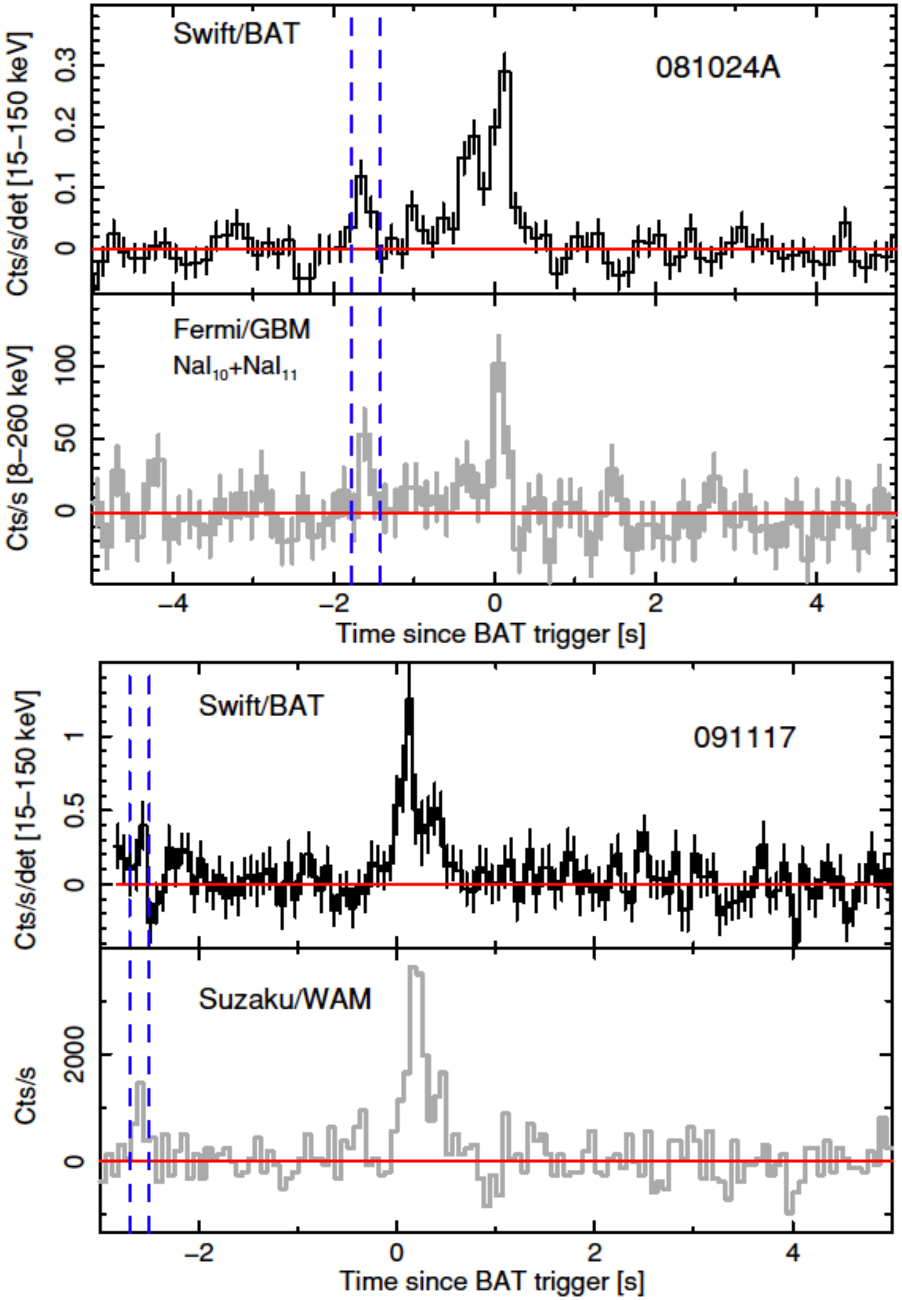
- Probes other wavelengths and timescales

- Constrain physics through coincident GW and EM detections (before the merger)

Also see: Hansen & Lyutikov '01; Postnov & Pshirkov '09; Moortgat & Kuijpers '04; McWilliams & Levin '11; Lehner et al. '12

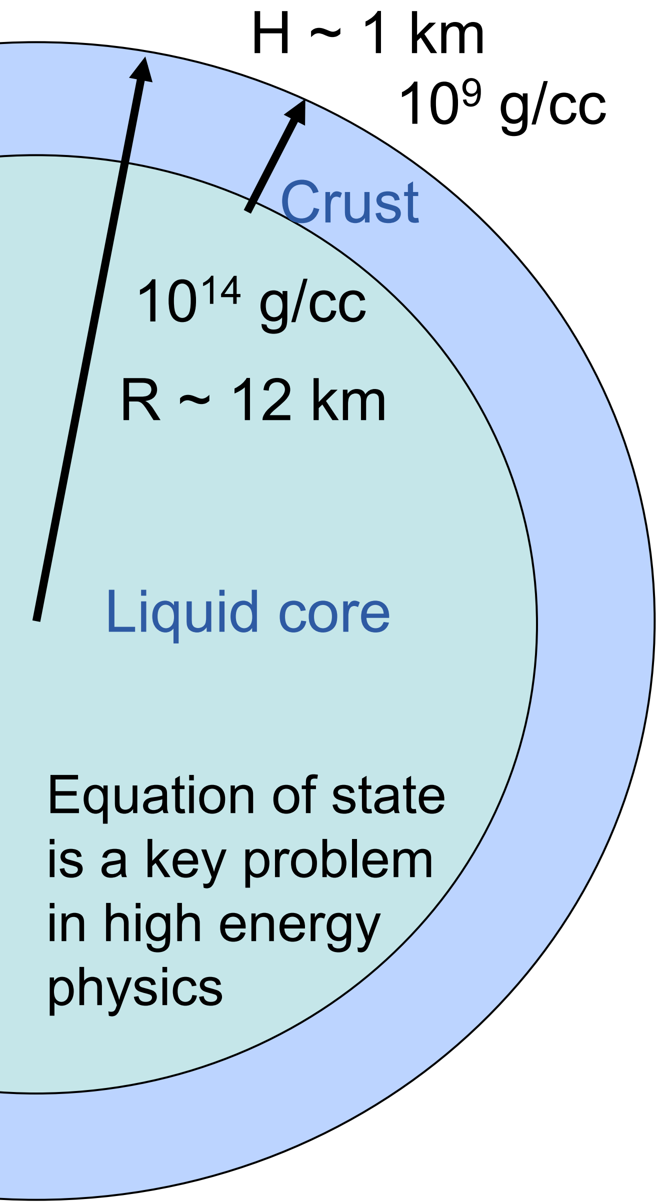
Observations

- A small fraction of short GRBs (~8-10%) show precursors at ~seconds before the main burst
- Precursor fluence is a factor of ~3-10 times less than main burst
- Seconds is a long timescale in compact binaries near merger!
- Another motivation to theoretically study precursors!



Troja et al. (2010) ApJ, 723, 1711

Crust Cracking? (Kochanek ‘92)



H ~ 1 km

10^9 g/cc

Crust

10^{14} g/cc

R ~ 12 km

Liquid core

Equation of state is a key problem in high energy physics

How much energy is stored in the crust?

$$\mu \sim \frac{(Ze)^2}{a} n_i \sim 10^{30} \text{ ergs cm}^{-3}$$

$$E_c \sim 4\pi R^2 H \mu \sim 10^{48} \text{ ergs}$$

Tides can crack the crust when δR/R~0.1 (Horowitz & Kadau 2009)

$$\frac{\delta R}{R} \sim \frac{M_1}{M_2} \left(\frac{R}{d}\right)^3 \sim 0.1 \Rightarrow d \sim \text{few} \times R$$

CONCLUSION: Lots of energy available, but the inspiral timescale is

$$\tau_{\rm gw} \sim \frac{c^5}{G^3} \frac{d^4}{M_{\rm tot} M_1 M_2} \sim \text{few} \times 10^{-3} \text{ s}$$

Too close to the main GRB to be seen!

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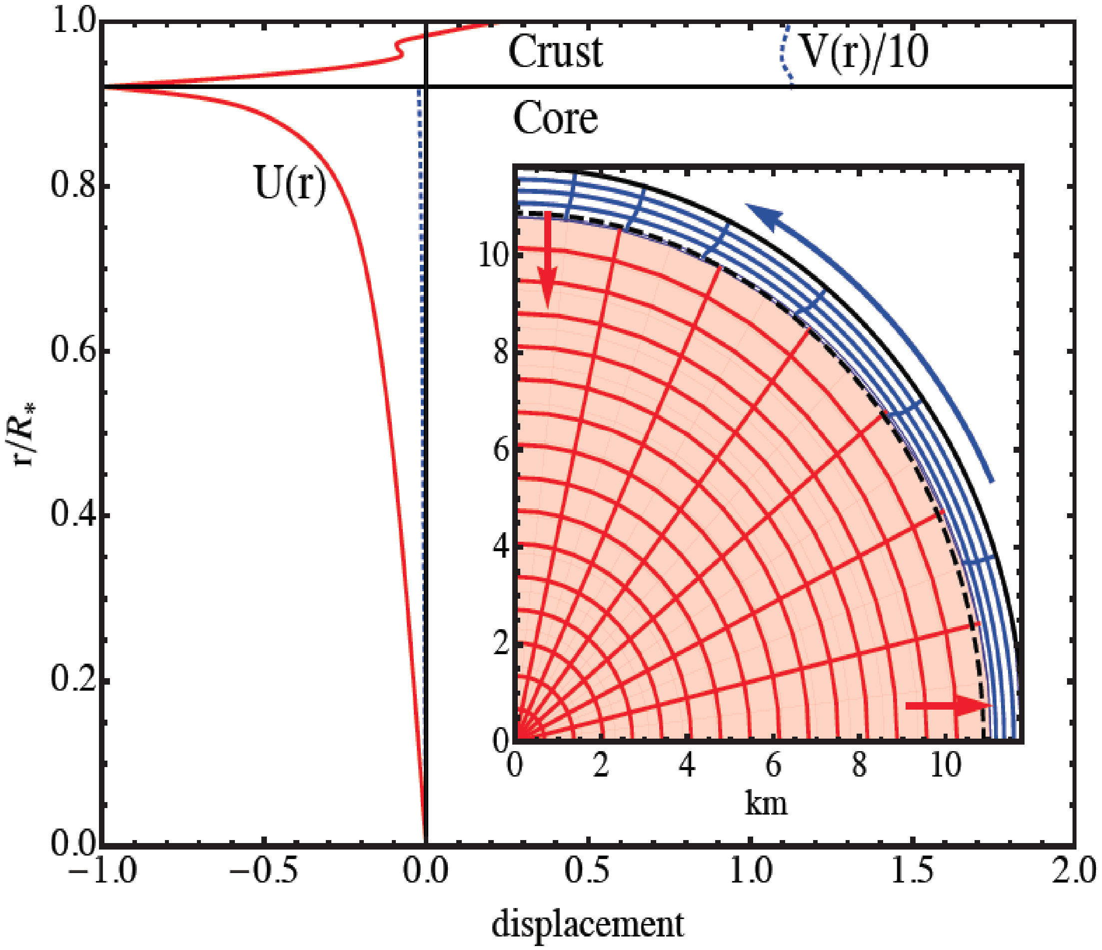
Resonant NS Crust Shattering

Tsang, Read, Hinderer, A.P., & Bondarescu (2012)



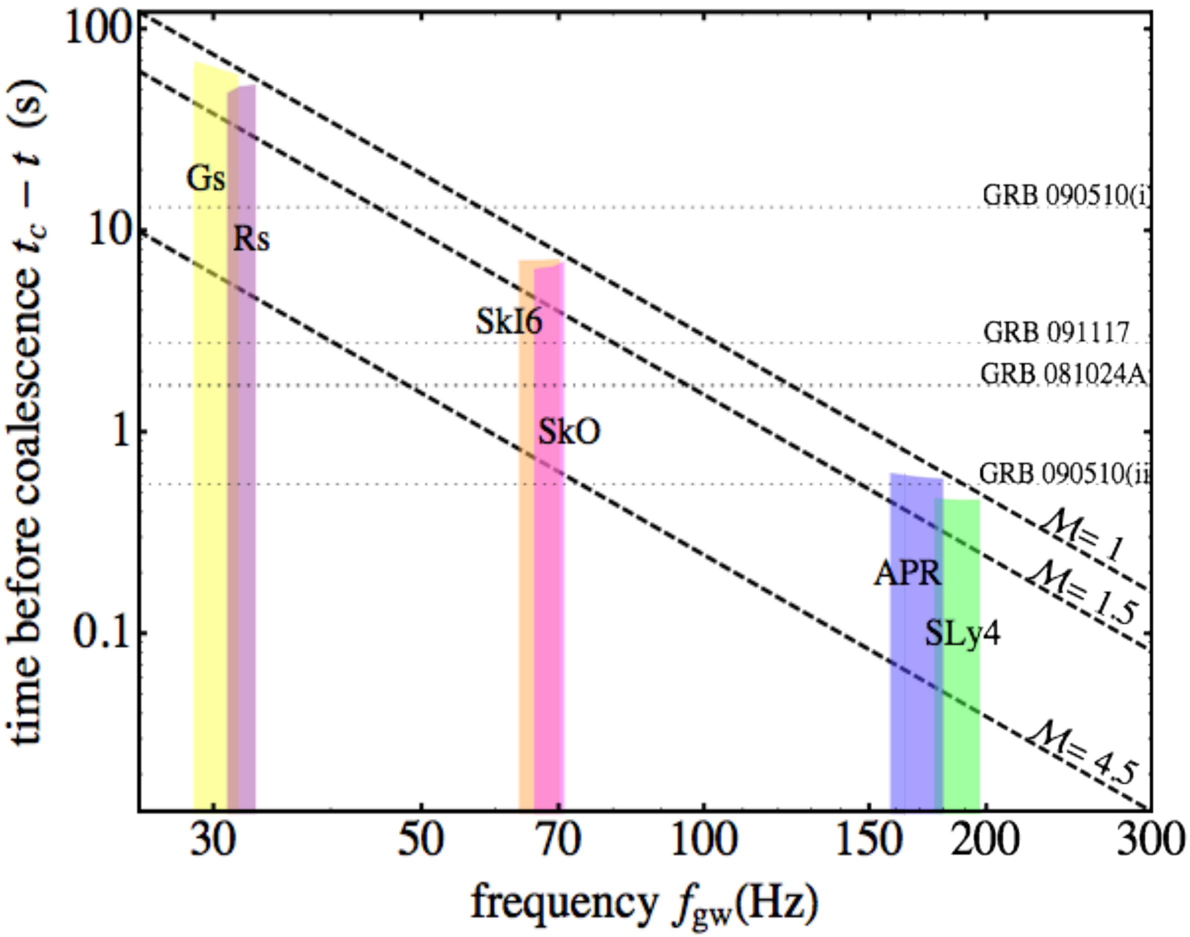
- The "crustal interface mode" has a large amplitude concentrated at the crust (first studied by McDermott et al. '88)
- Spheriodal mode, so well-coupled to the tidal potential
- Typical frequencies of

$$f \sim \frac{(\mu/\rho)^{1/2}}{H} \sim 100 \text{ Hz}$$

- Resonant excitation occurs well before merger when $2f_{orb} \sim f_{mode}$
- A more comprehensive study of tidally excited modes is in order!

Probing the crust EOS

Tsang, Read, Hinderer, A.P., & Bondarescu (2012)



- Time of crust shattering depends on the crust equation of state (EOS)
- Time of shattering complements disruption times measured from GWs that are sensitive to core EOS (Shibata 2005; Hinderer et al.)
- Emission mechanism still under study (B-fields? Thermonuclear ignition of surface material?)

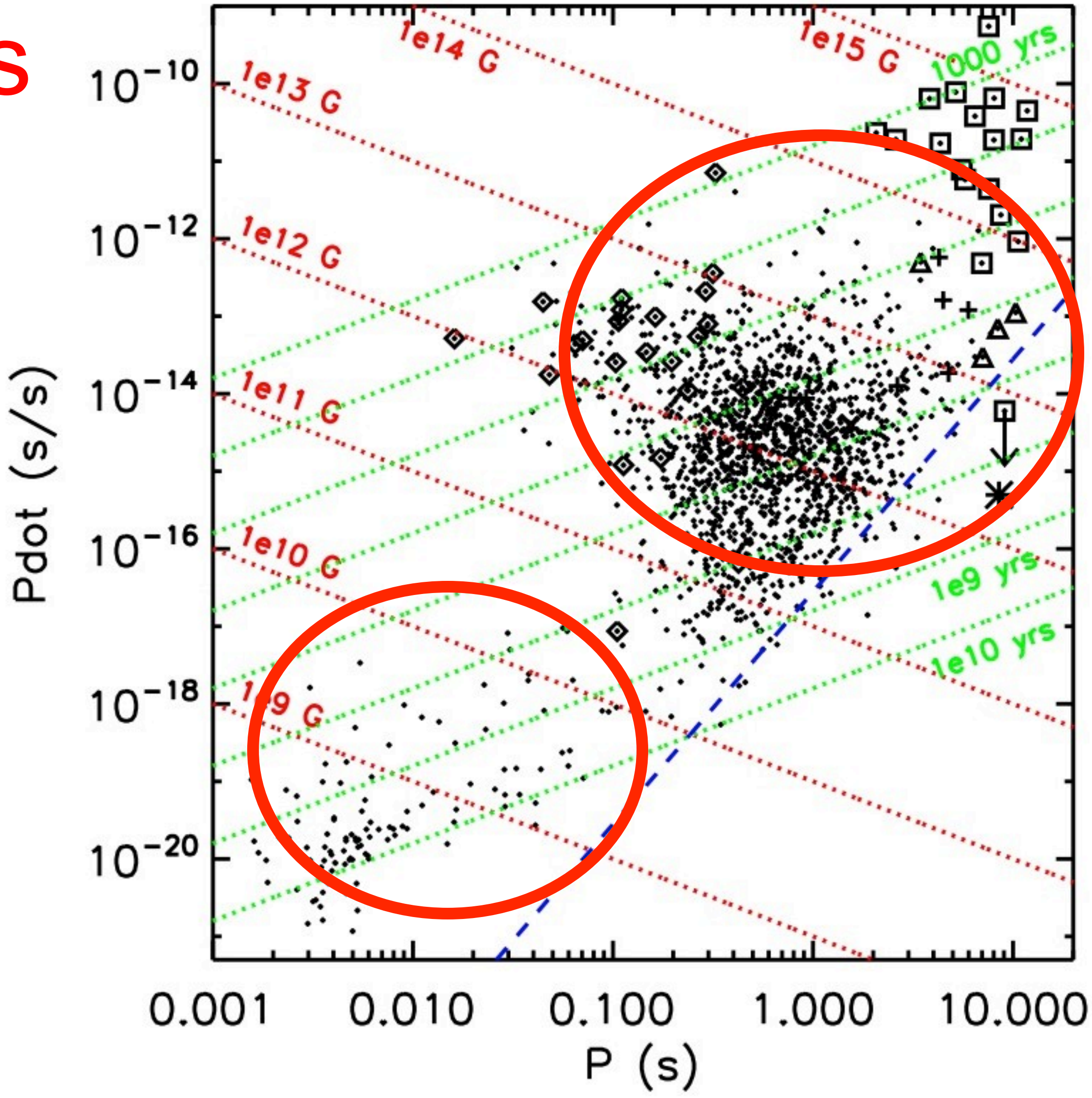
Neutron Star Magnetic Fields

- NS generally have B-fields from ~10^8-10^{15} G

$$B \propto \sqrt{P\dot{P}}$$

- On evolutionary grounds it is expected that NS binaries should have one strong B-field (>10^{12} G) and one weak B-field (~10^9 G) (Bhattacharya & van den Heuvel 1991)

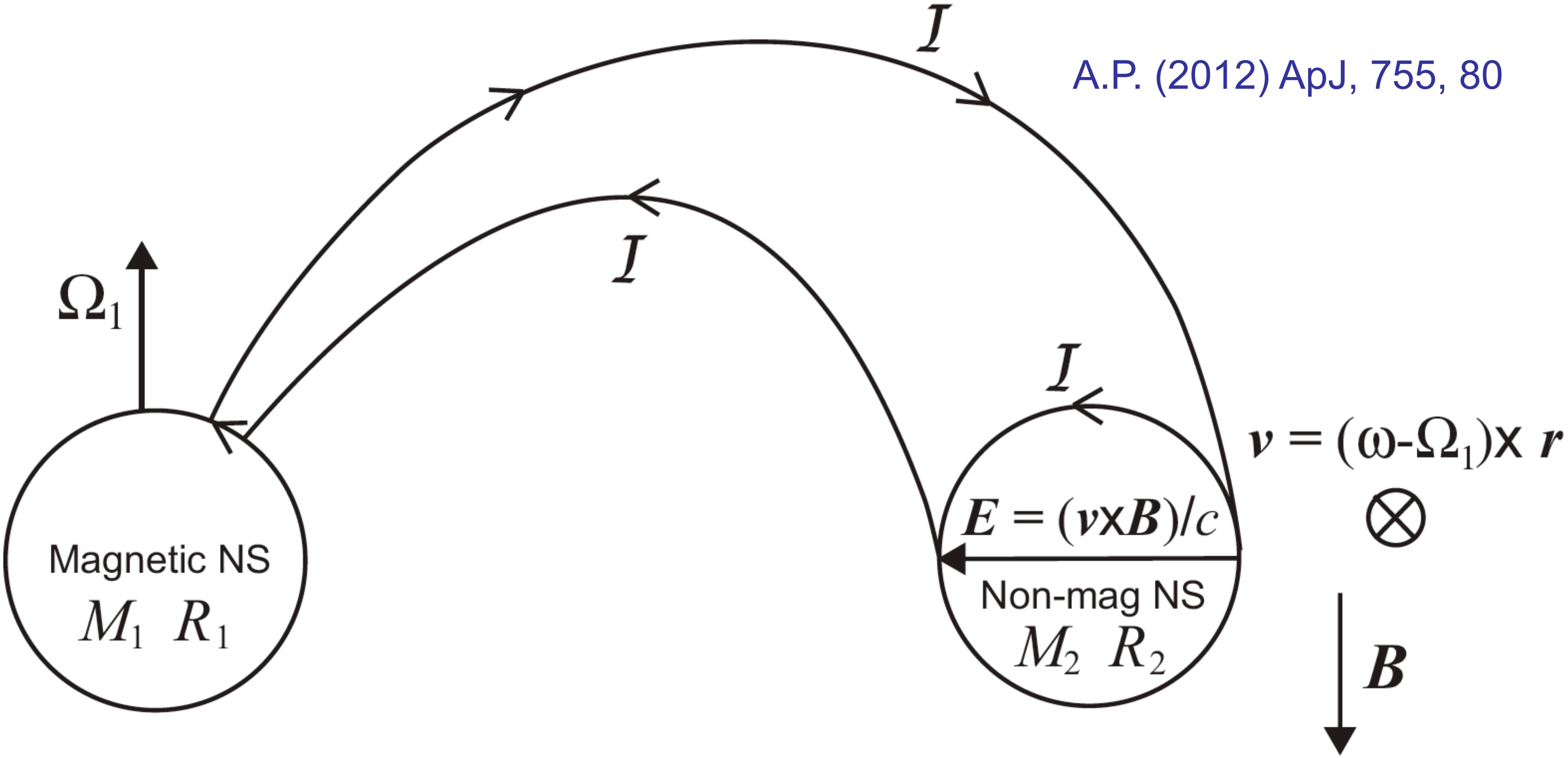
- This expected hierarchy has been confirmed in at least one case (binary double pulsar, J0737)



The Unipolar Inductor Model

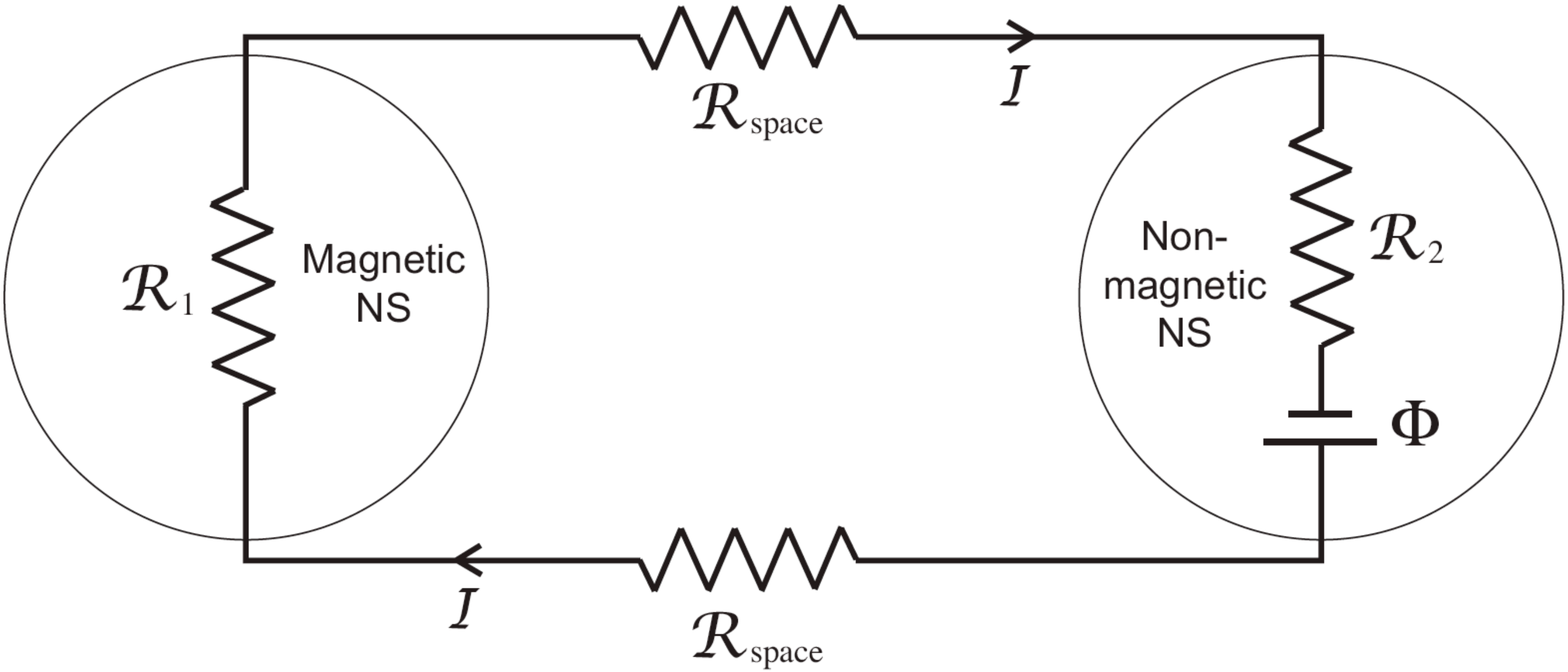
Goldreich & Lynden-Bell 1969; Wu et al. 2002; Dall’ Osso et al. 2006; McWilliams & Levin 2011; Lyutikov 2011; Laine & Lin 2012; Lai 2012

A.P. (2012) ApJ, 755, 80



The Binary NS Circuit

A.P. (2012) ApJ, 755, 80

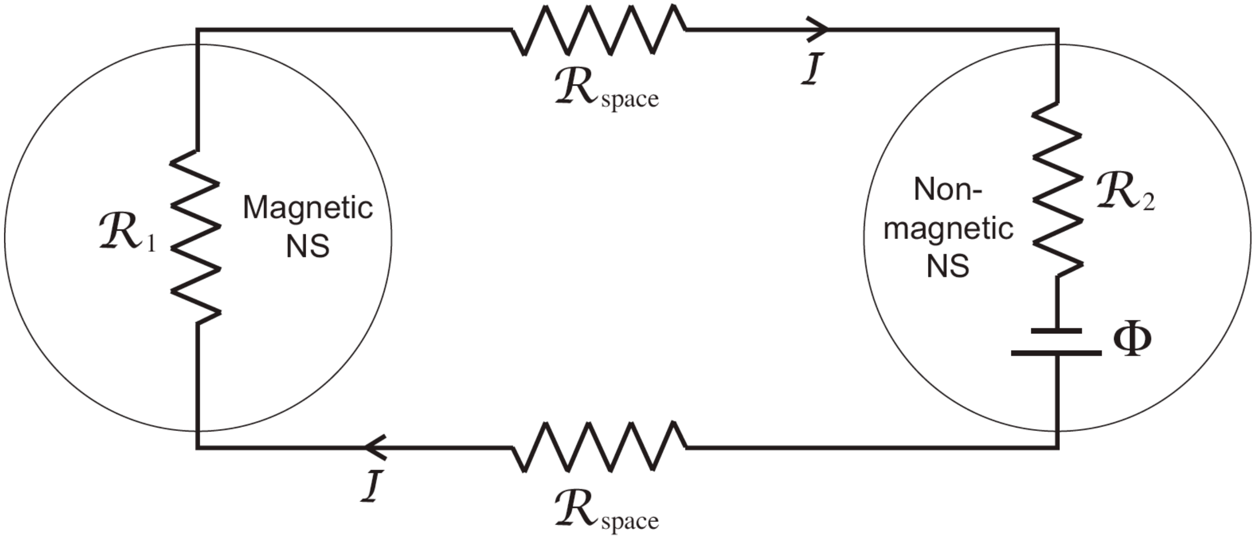


- R_1 and R_2 are understood from microphysics of the NS surfaces
- $R_{\rm space}$ is dominated by complicated processes (particle acceleration, pairs production, dissipation of currents, radiative processes, etc)
- Therefore the plan is to consider $R_{\rm space}$ as a free parameter and explore the consequences as it is varied

NS Circuit Analysis

A.P. (2012) ApJ, 755, 80

- Simple circuit with voltage set by non-magnetic NS and 4 resistors in series



- Current depends on the sum of the resistors:

$$\mathcal{I} = \Phi/(\mathcal{R}_1 + \mathcal{R}_2 + 2\mathcal{R}_{\text{space}})$$

- Associated electrical dissipation in each location:

$$\dot{E}_1 = \Phi^2\mathcal{R}_1/(\mathcal{R}_1 + \mathcal{R}_2 + 2\mathcal{R}_{\text{space}})^2$$

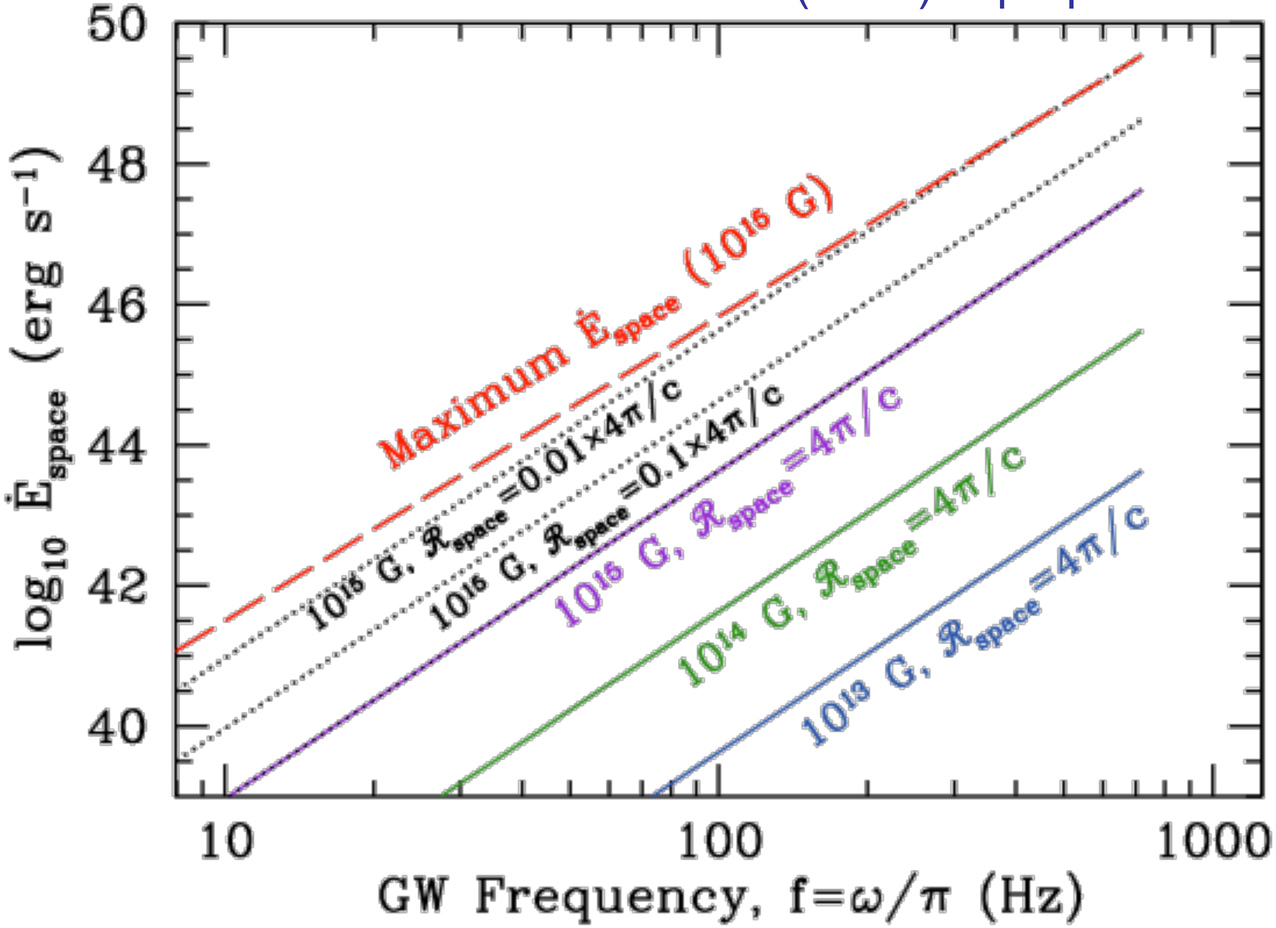
$$\dot{E}_{\text{space}} = \Phi^2\mathcal{R}_{\text{space}}/(\mathcal{R}_1 + \mathcal{R}_2 + 2\mathcal{R}_{\text{space}})^2$$

Magnetospheric Dissipation Rates

- Dissipation in magnetosphere dominates over NS surface dissipation

- Independent of $\mathcal{R}_{\rm space}$, there is a maximum dissipation rate set by $B_\phi \sim B_{\rm dipole}$ (Lai 2012)

- In saturated regime emission is likely flared as currents build up and then released as magnetic field lines open up.


A.P. (2012) in preparation

~10^{42}-10^{48} erg/s dissipated in magnetosphere, but what are the observable signatures?

Emission Mechanisms (speculative!)

Also see discussions in Hansen & Lyutikov 2001,
Pshirkov & Postnov 2010, McWilliams & Levin 2011

Particle acceleration between NSs easily gets to energies required for pair production

- Dissipation dominated by production of a dense, pair plasma
- May lead to a precursor flare similar to soft gamma-ray repeater outbursts (Thompson & Duncan 2005)
- Thermal wind with energies of ~50 keV to ~MeV with a softer ~keV component from magnetically trapped plasma

Radio emission in analogy with radio pulsars

- Is coherent radio emission some fraction of the total magnetospheric luminosity? Primary beam luminosity?
- Estimates of ~10^{-3} to a few Jansky at ~100 MHz at ~200 Mpc depending on assumptions (LOFAR?)

Summary

NS Crust Shattering

- Resonant excitation may shatter crust, releasing ~10^{46}-10^{47} erg ~1-100 sec before merger
- Probes the NS crust EOS (complementary to core EOS studies)
- Emission mechanisms? Detailed dynamical tide analysis?

Magnetic Interactions

- Magnetic interactions drive a strong current between NSs
- Magnetospheric dissipation may produce hard X-rays, gamma-rays and radio, but requires further study

Conclusion: There is good motivation to search for NS merger precursors (we even see some!), and it deserves more in depth theoretical study!