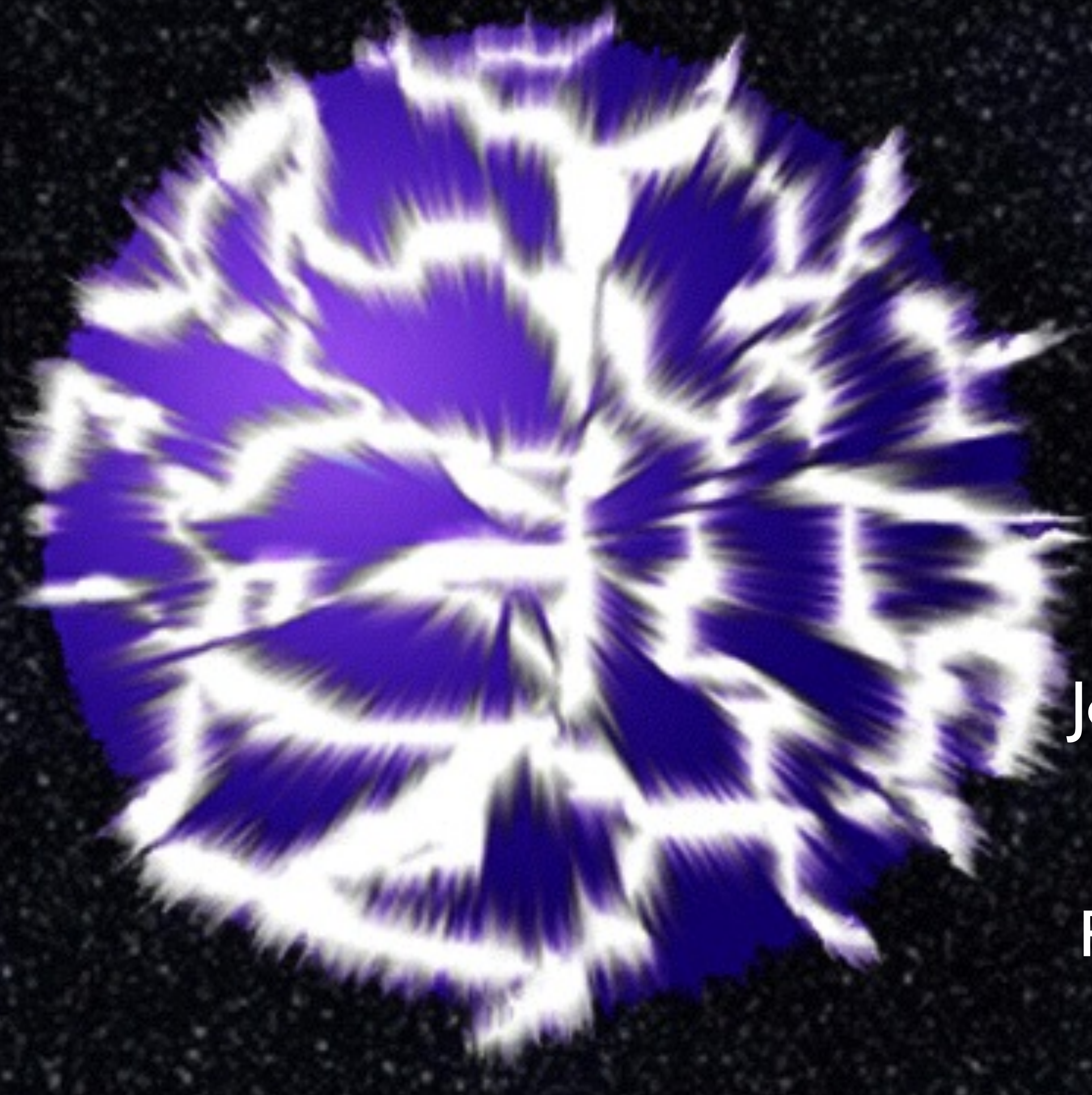
Resonant Shattering of Neutron Star Crusts

Binary Neutron Star Coalescence as a Fundamental Physics Laboratory
Institute for Nuclear Theory, UW, July 22, 2014

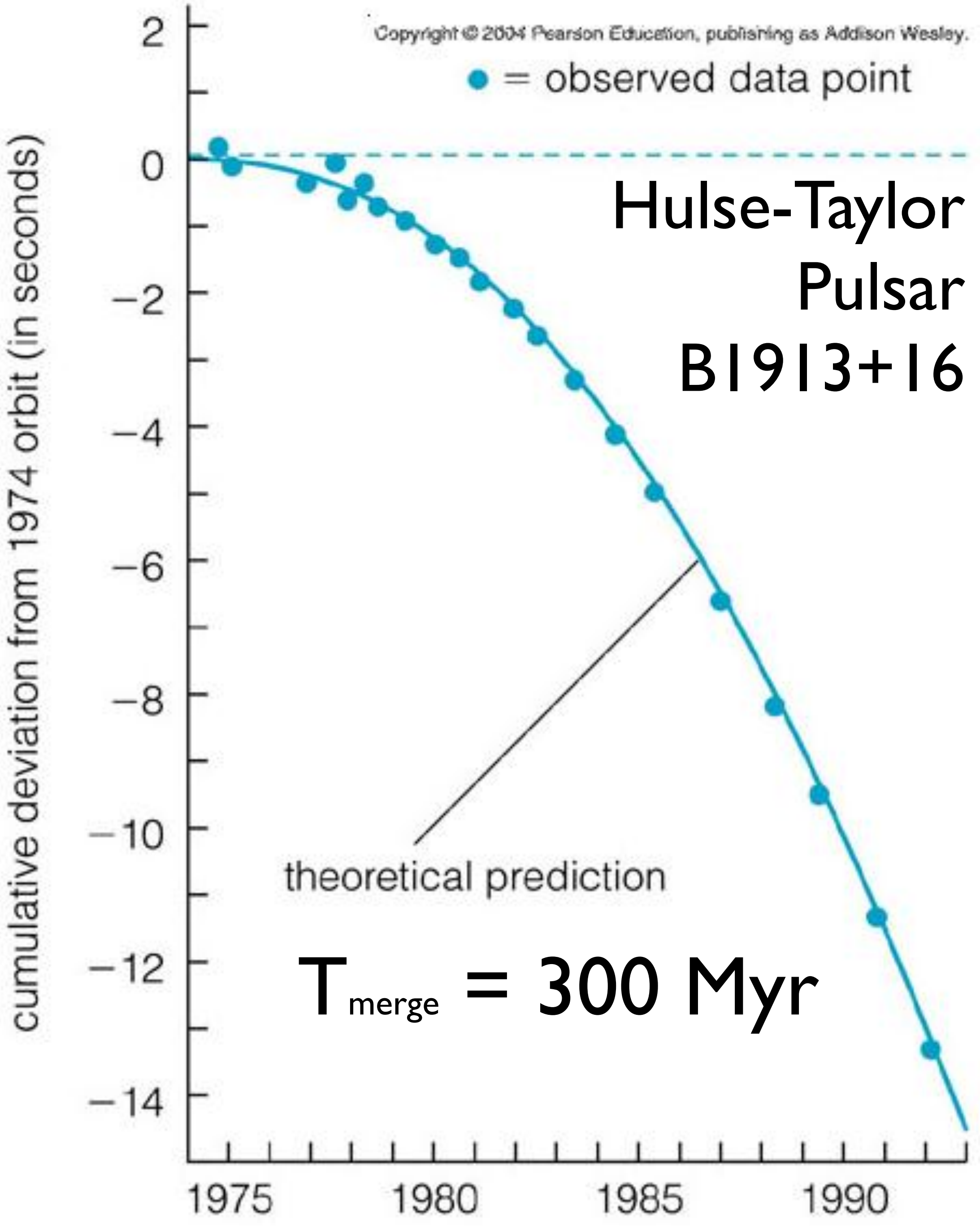


PRL 108, 011102 (2012)

David Tsang (McGill)
Jocelyn Read (Cal State Fullerton)
Tanja Hinderer (U. Maryland)
Tony Piro (Caltech)
Ruxandra Bondarescu (U. Zurich)

& DT, ApJ 777, 2, 103 (2013)

Neutron Star Binaries



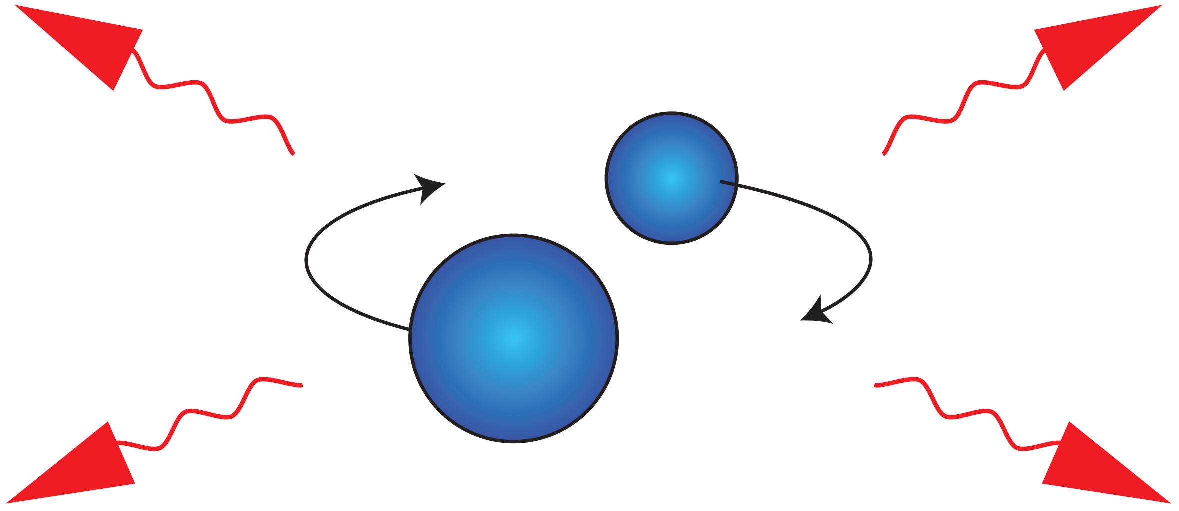
Hulse-Taylor
Pulsar
B1913+16

T_{merge} = 300 Myr

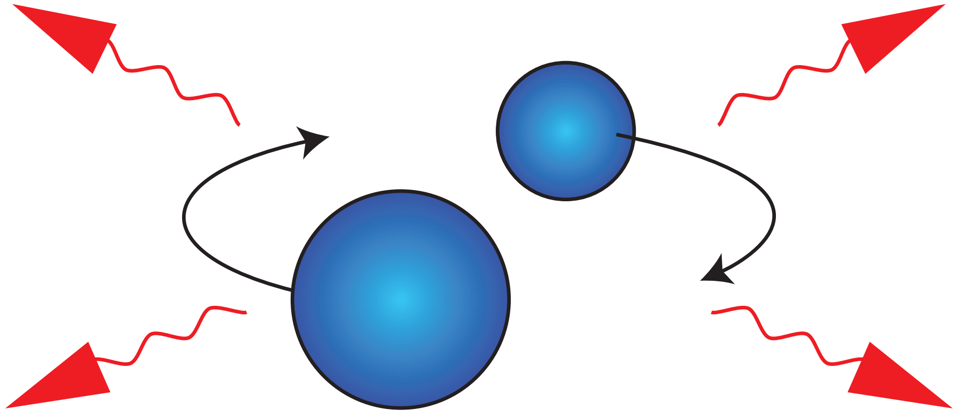
Known Galactic NS-NS binaries

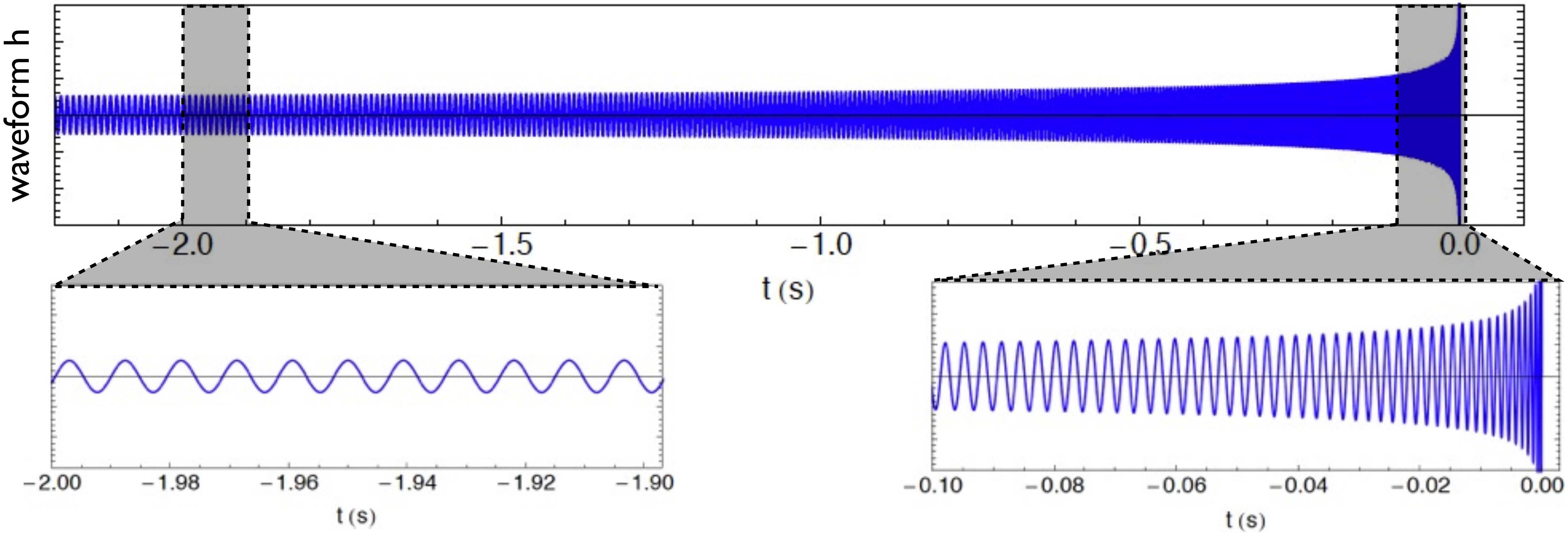
	J0737−3039	J1518+4904	B1534+12	J1756−2251	J1811−1736
P [ms]	22.7/2770	40.9	37.9	28.5	104.2
P_b [d]	0.102	8.6	0.4	0.32	18.8
e	0.088	0.25	0.27	0.18	0.83
$\log_{10}(\tau_c/[\mathrm{yr}])$	8.3/7.7	10.3	8.4	8.6	9.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	7.9	12.4	9.4	10.2	13.0
Masses measured?	Yes	No	Yes	Yes	Yes

	B1820−11	J1829+2456	J1906+0746	B1913+16	B2127+11C
P [ms]	279.8	41.0	144.1	59.0	30.5
P_b [d]	357.8	1.18	0.17	0.3	0.3
e	0.79	0.14	0.085	0.62	0.68
$\log_{10}(\tau_c/[\mathrm{yr}])$	6.5	10.1	5.1	8.0	8.0
$\log_{10}(\tau_g/[\mathrm{yr}])$	15.8	10.8	8.5	8.5	8.3
Masses measured?	No	No	Yes	Yes	Yes

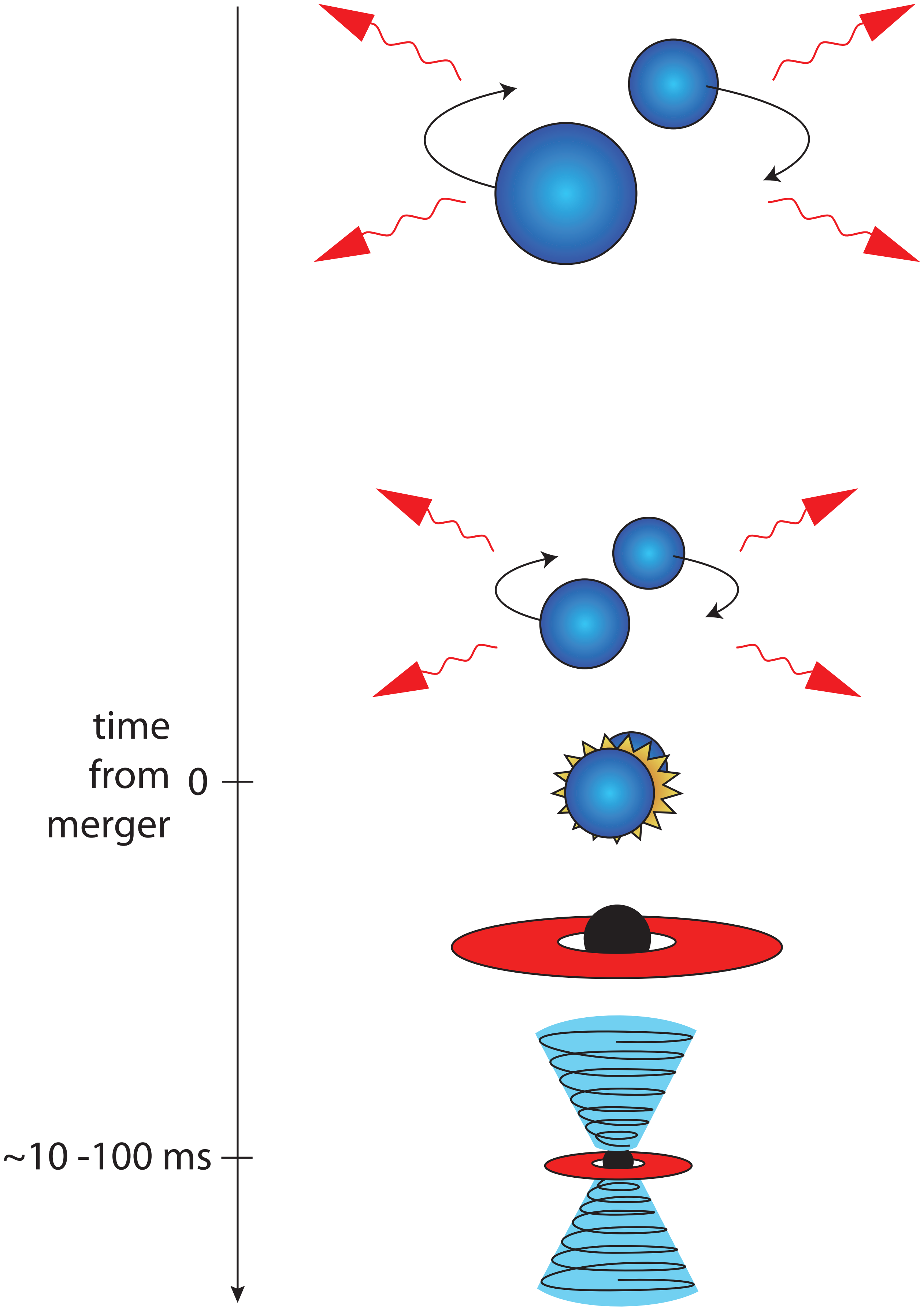


Orbit decays due to emission of gravitational waves

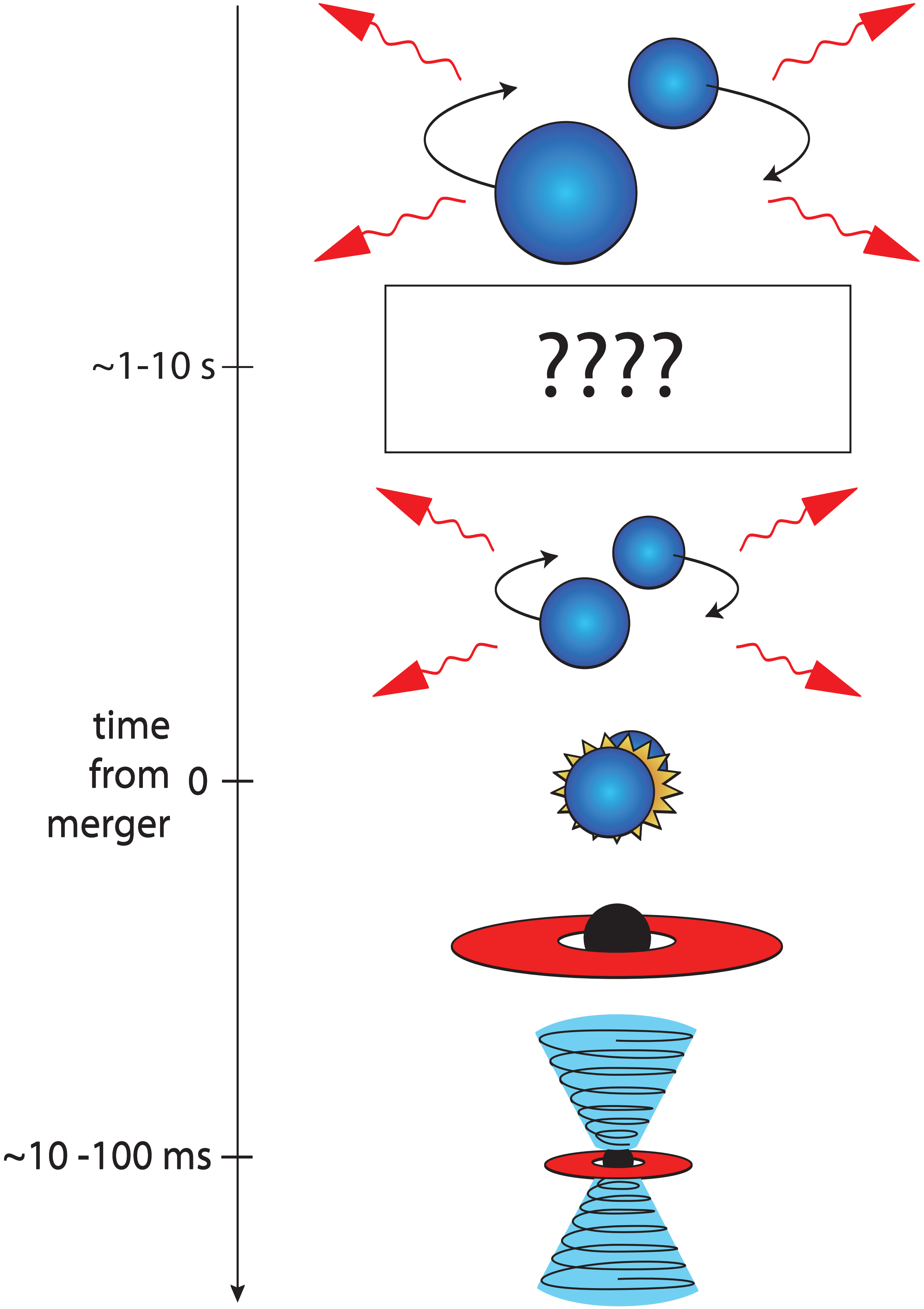


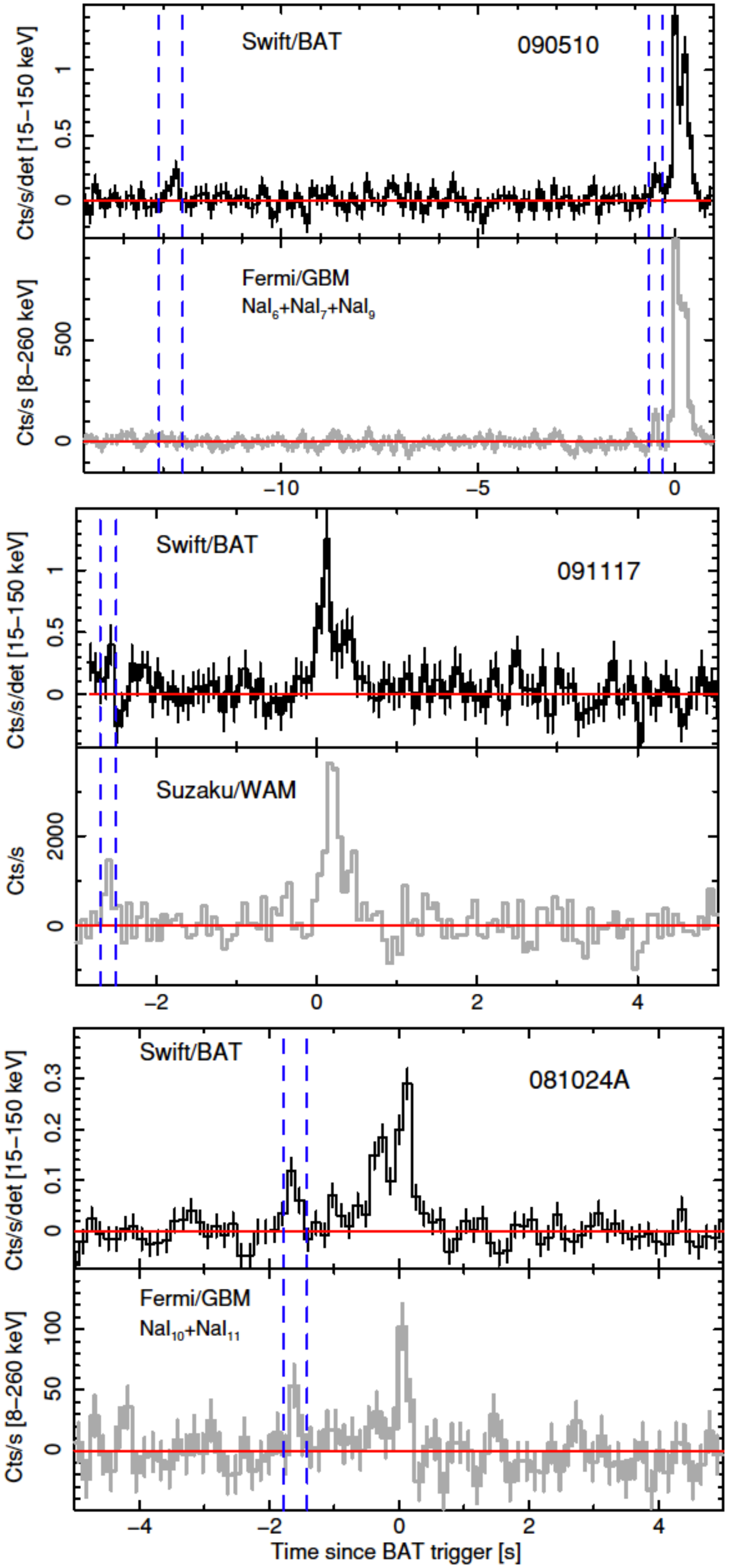

waveform h
−2.0
−1.5
−1.0
−0.5
0.0
t (s)
−2.00
−1.98
−1.96
−1.94
−1.92
−1.90
t (s)
−0.10
−0.08
−0.06
−0.04
−0.02
0.00
t (s)

Short-Hard Gamma Ray Bursts



- ☐ Short GRBs: $E \sim 10^{50} - 10^{51}$ ergs
- ☐ $T_{90} < 2$s
- ☐ Leading progenitor: NS-NS or NS-BH merger
- ☐ Swift/BAT, Fermi/GBM, Suzaku



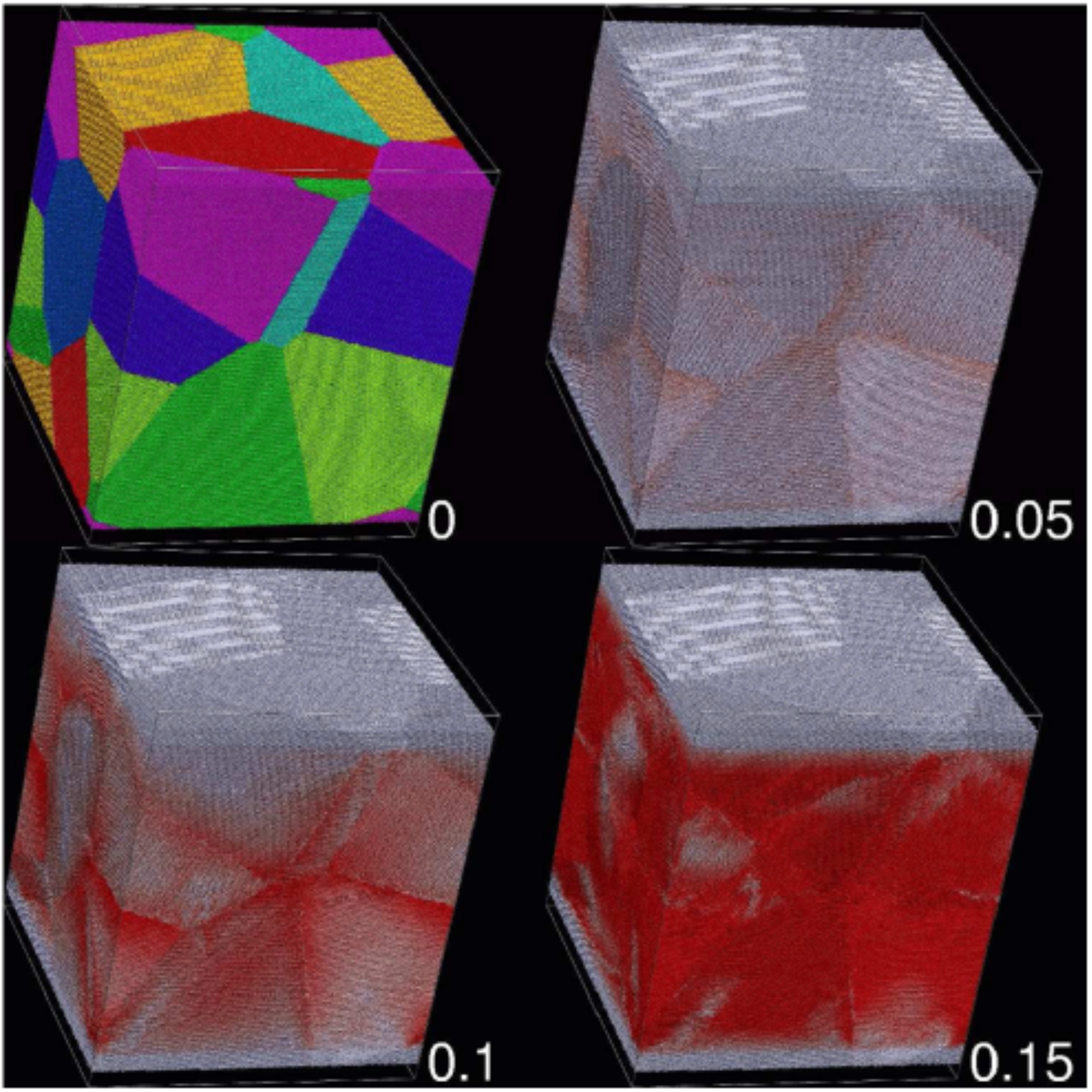


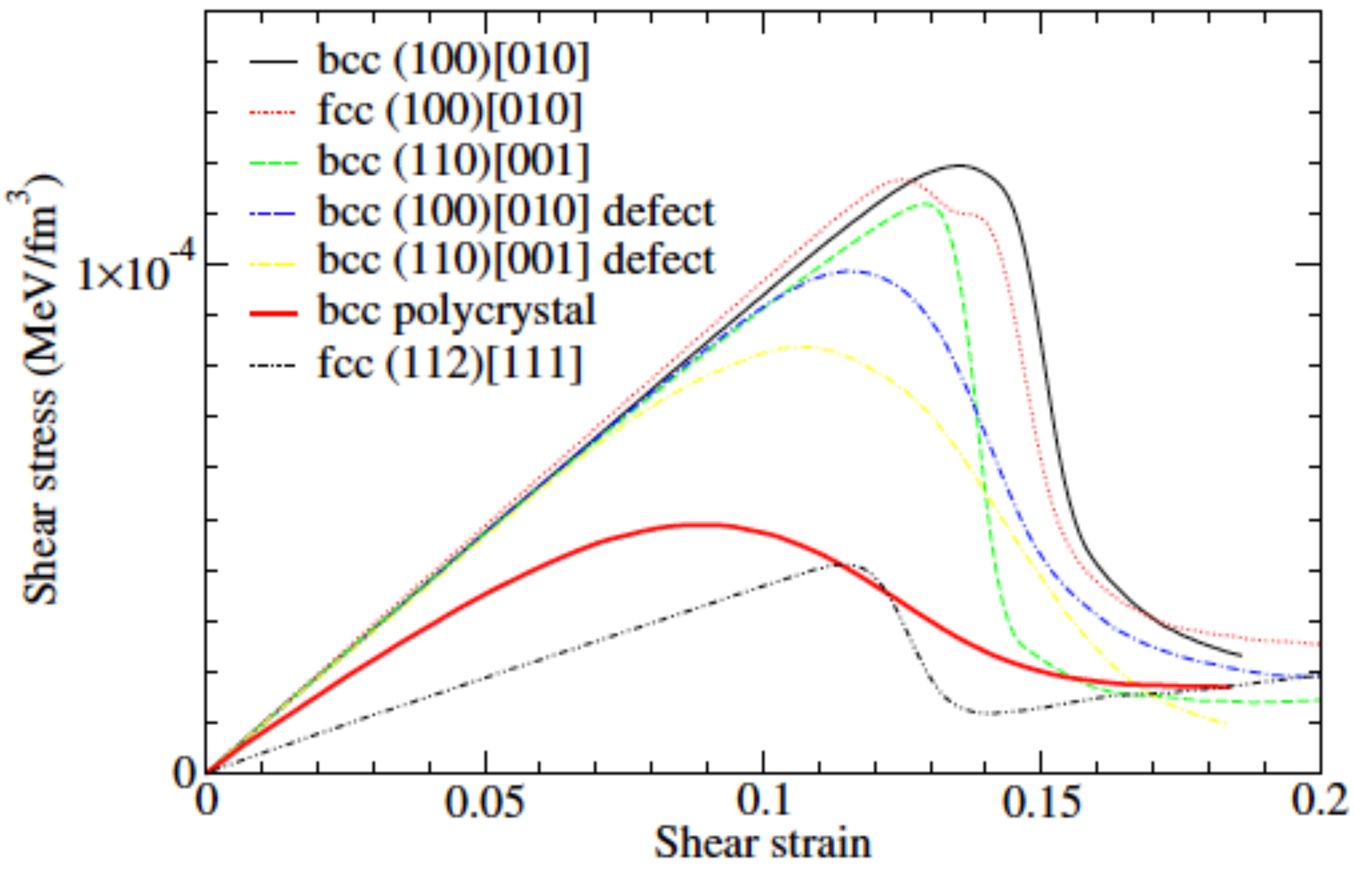
Troja et al. ApJ, 723, 1711 (2010)

Precursor Mechanisms

- Magnetic Field Interaction? Hansen & Lyutikov (2001), MNRAS, 322, 695
    - $L \simeq 7 \times 10^{45}\,\mathrm{erg\,s^{-1}} \left(\frac{B}{10^{15}\mathrm{G}}\right)^2 \left(\frac{a}{10^7\mathrm{cm}}\right)^{-7}$
    - B-field needs to be > Magnetar Strength
- Early Central Engine?
- Hyper-massive Magnetar?
- What about crust cracking? Kochanek (1992), APJ, 398, 234

Direct Tidal Crust Cracking





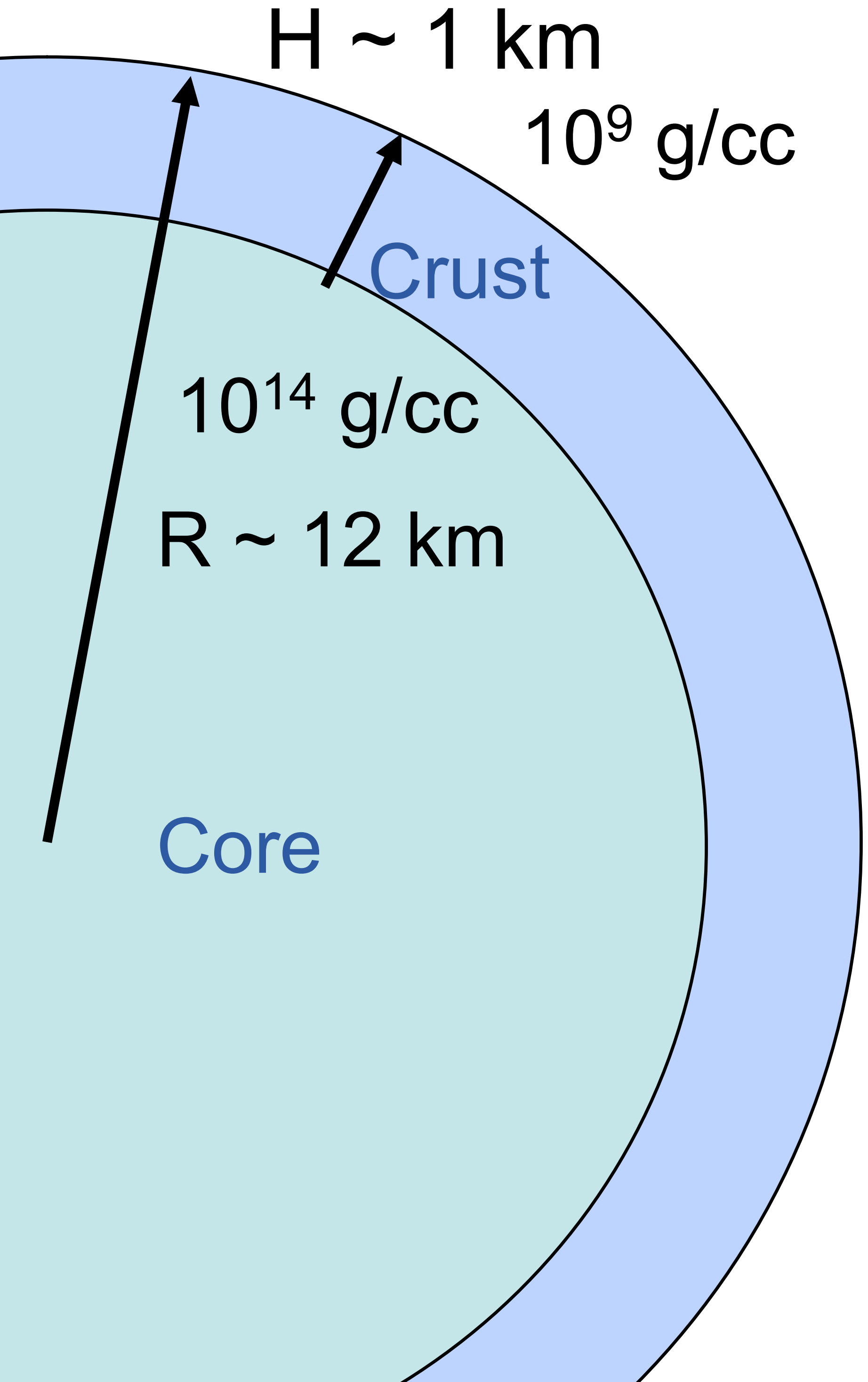
Horowitz & Kadau (2009), PRL, 102, 191102

For tidal crust cracking we need $\delta R/R \simeq \epsilon_{\rm break} \sim 0.1$

Direct Tidal Crust Cracking

How much energy can you get out of the crust?

Energy stored in crust:



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

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

Fracture when dR/R ~ 0.1:

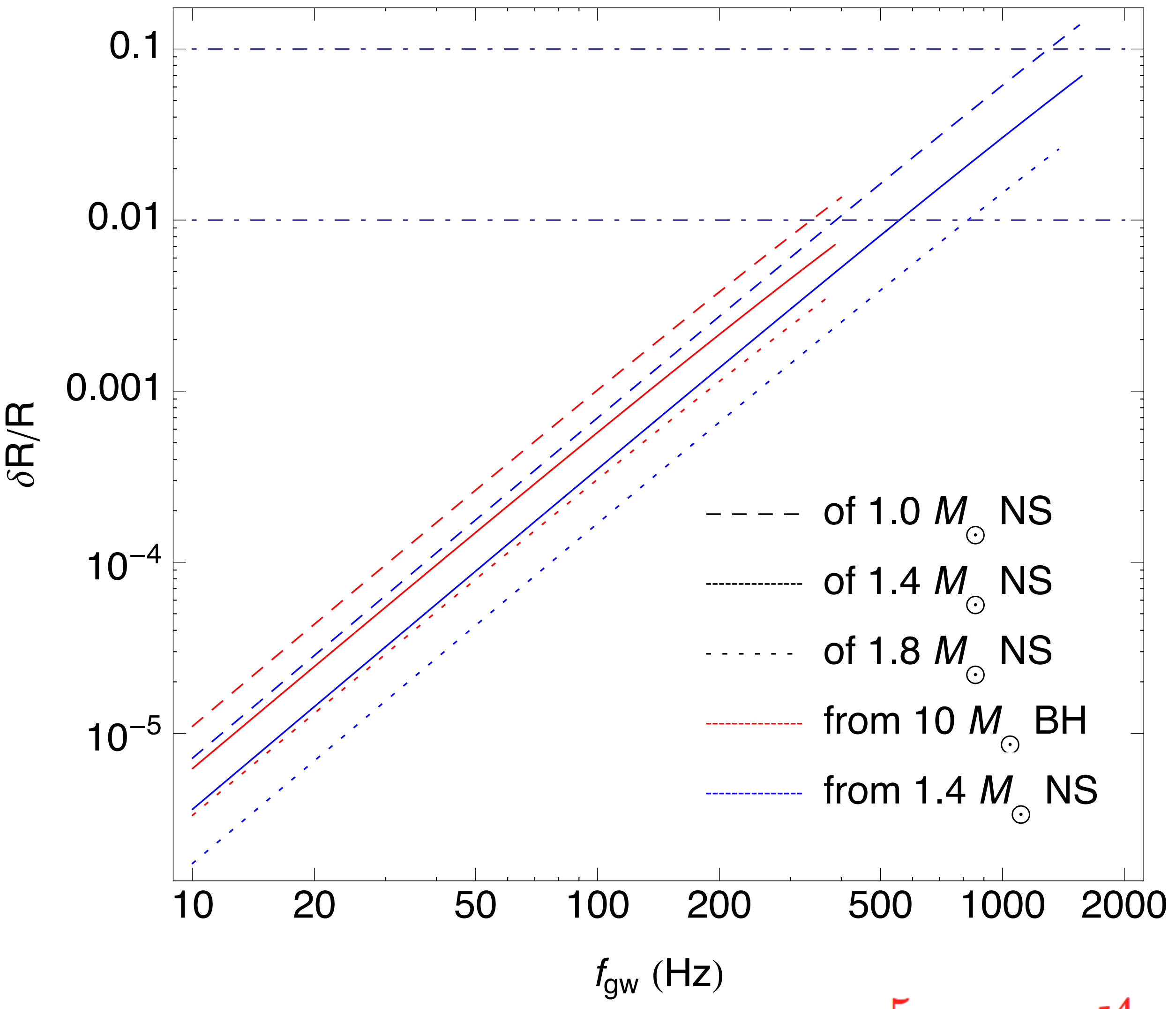
$$\frac{\delta R}{R} \sim \frac{M_1}{M_2}\left(\frac{R}{d}\right)^3 \sim 0.1 \Rightarrow d \sim \text{few} \times R$$

Releasing energy:

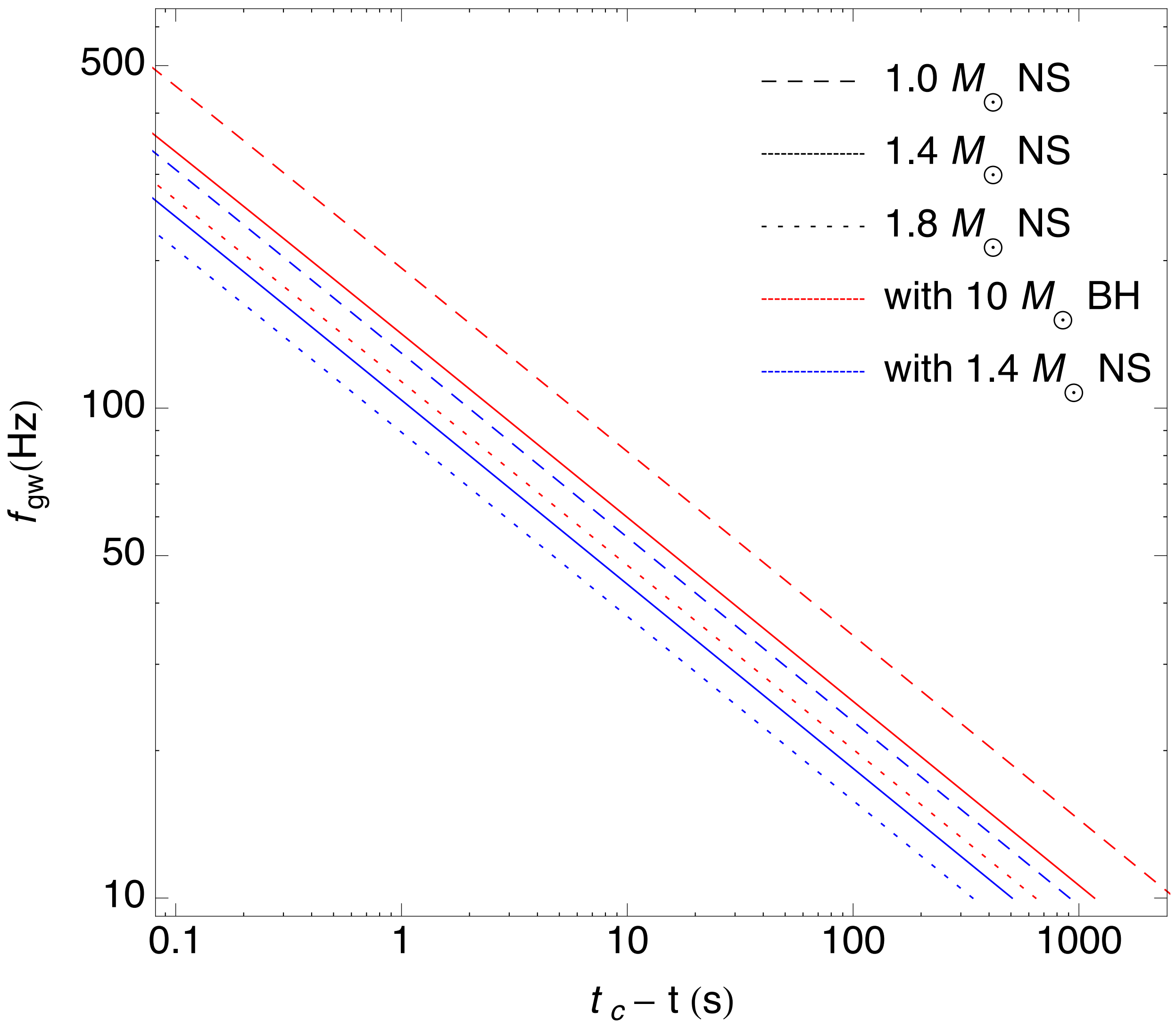
$$E_{\text{tide}} \sim 4\pi(\delta R)^2 H\mu \sim 10^{46} - 10^{47} \text{ ergs}$$

When does this happen?

Direct Tidal Crust Cracking



Surface deformation in inspiral



Frequency at time before merger

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

Direct crust cracking doesn’t happen until just before merger (if at all). What else?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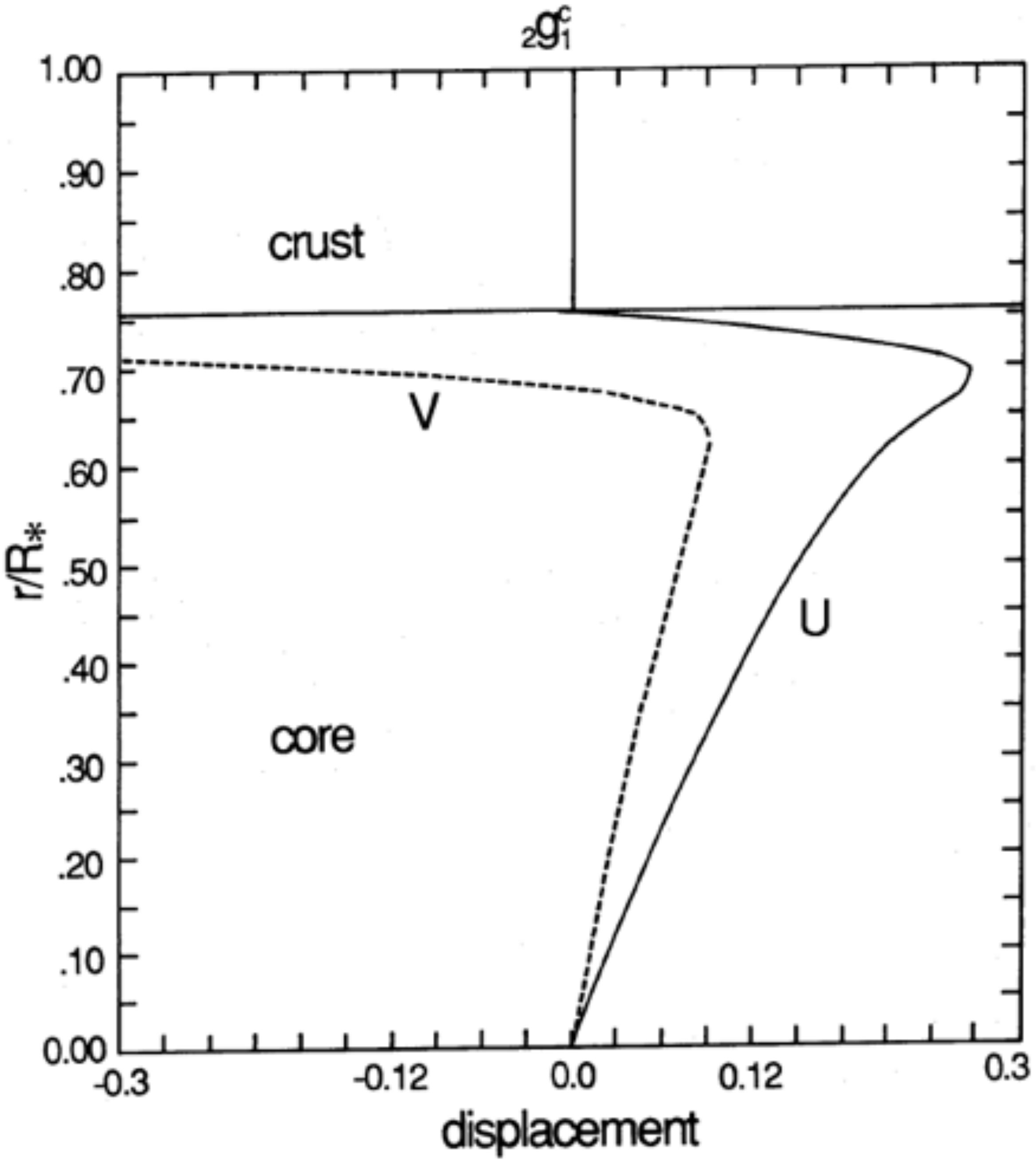
Tidal Resonance

- NSs have normal modes
- Tidal resonance can transfer huge amounts of energy
- Need a mode that:
  - strains the crust
  - couples to the tidal field (l=2, spheroidal)
  - hits a resonance well before merger (f < 1 kHz)
- We treat perturbations with McDermott et al (1988) and Reisenegger & Goldreich (1994), using modern backgrounds

Tidal Resonance

- Need a mode that:
  - strains the crust ✗
  - couples to the tidal field (l=2, spheroidal) ✓
  - hits a resonance well before merger (f < 1 kHz) ✓



McDermott, Van Horn & Hansen, ApJ, 325, 725, 1988

Tidal Resonance

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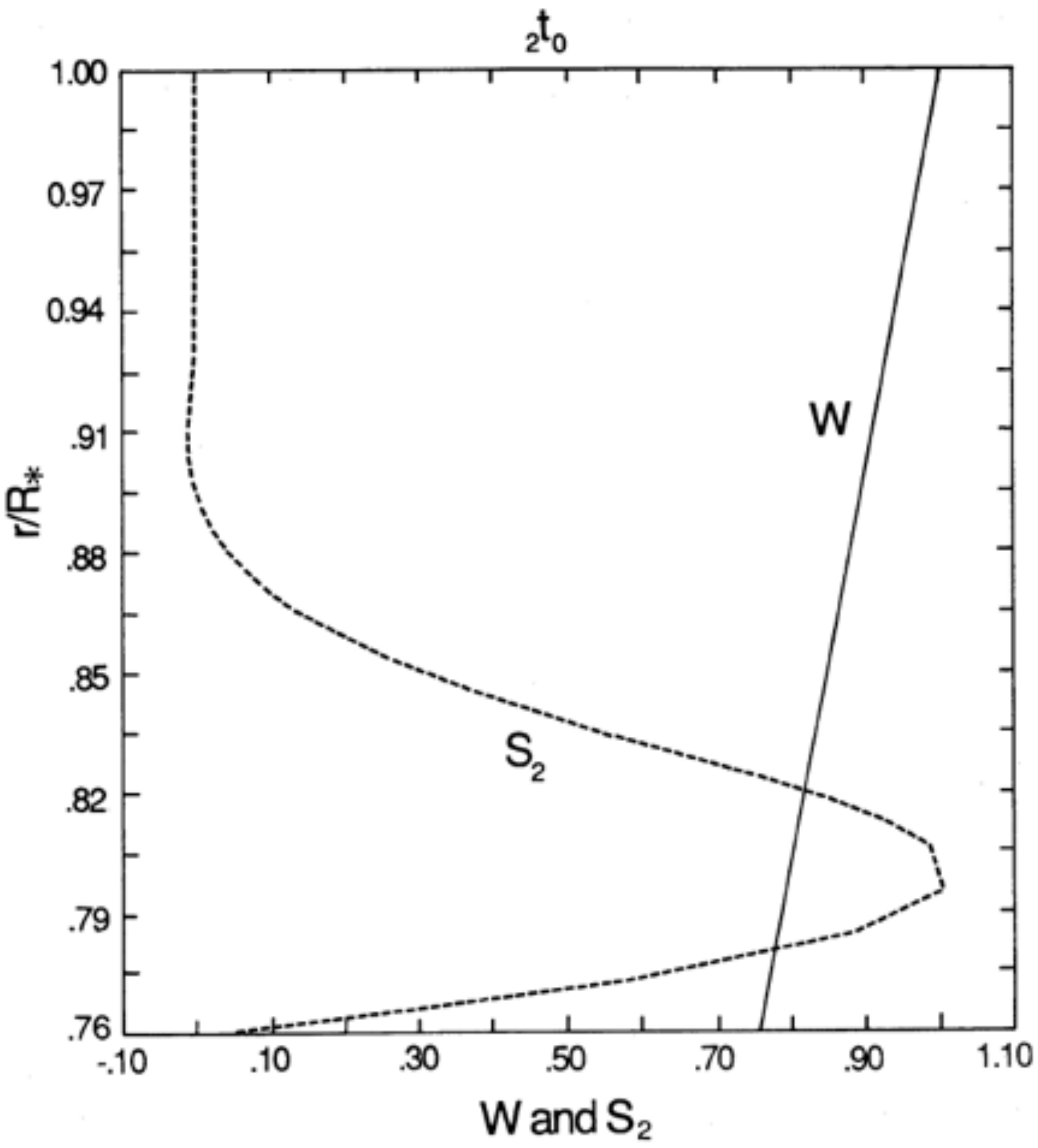

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Tidal Resonance

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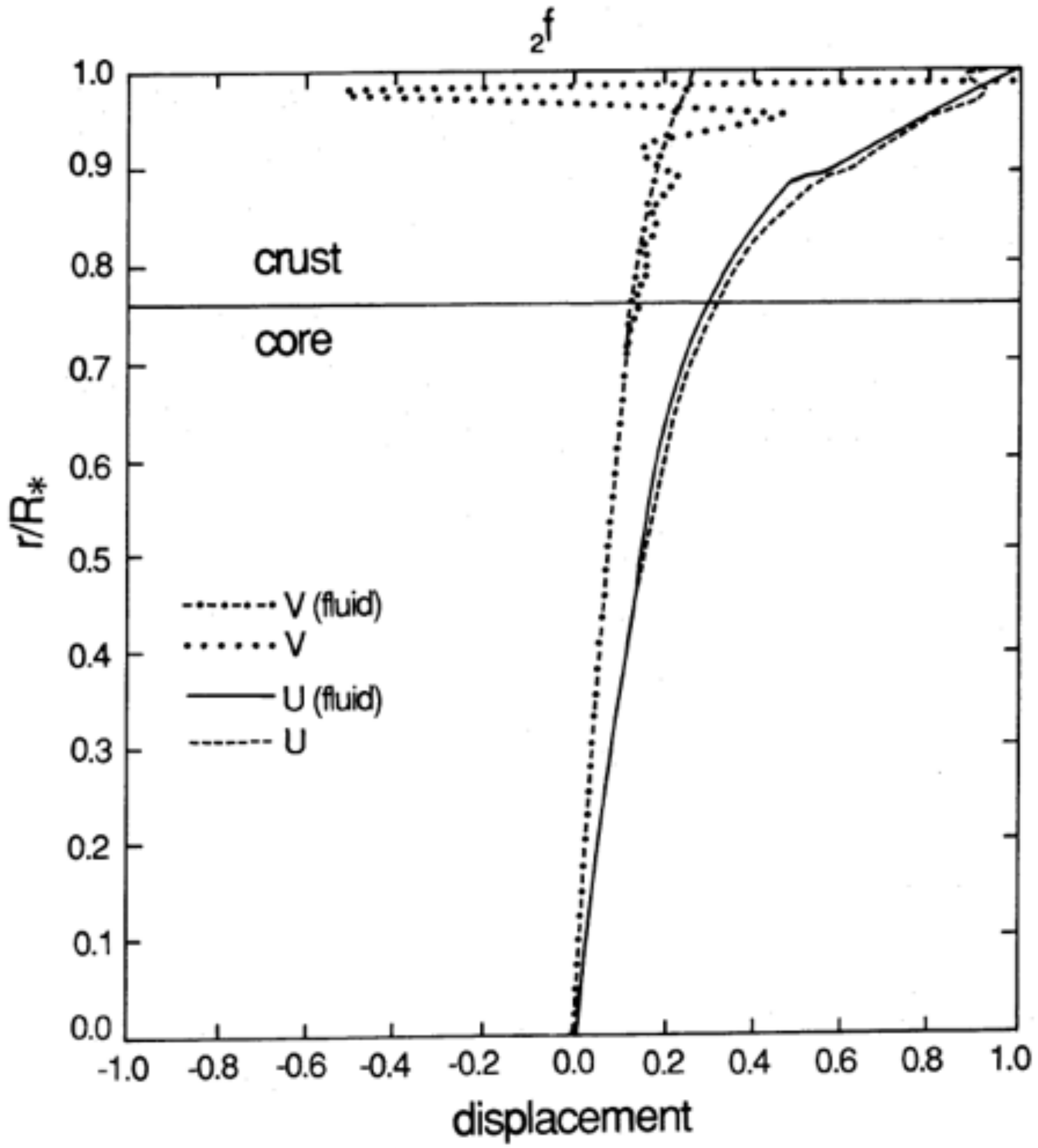

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Tidal Resonance

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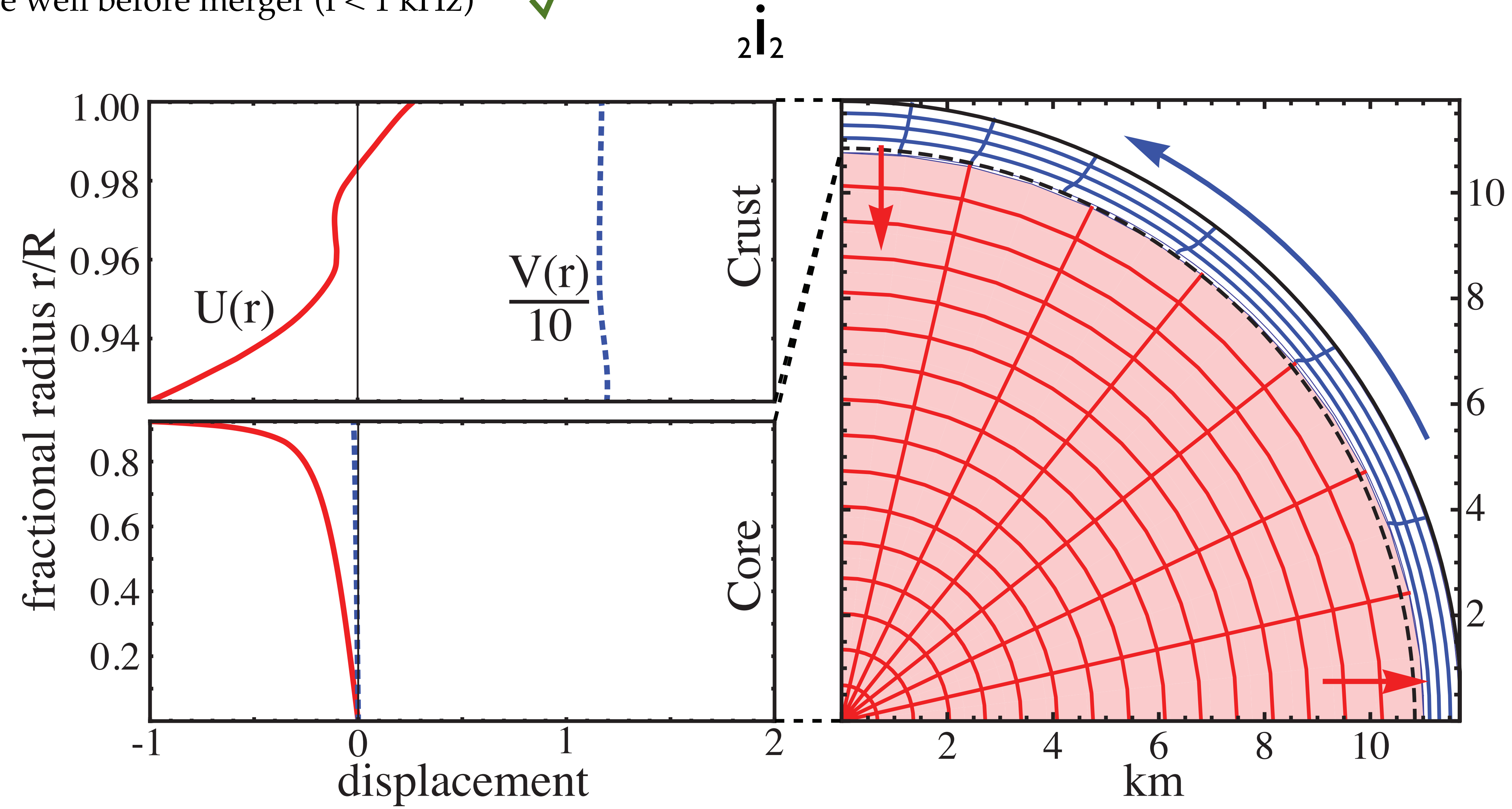


☐ How does the i-mode couple to the tidal field?

$$Q \equiv \frac{1}{MR^2} \int d^3x\rho \, \boldsymbol{\xi}^* \cdot \boldsymbol{\nabla}[r^2 \mathrm{Y}_{2,\pm 2}(\theta, \phi)] \simeq 0.025$$

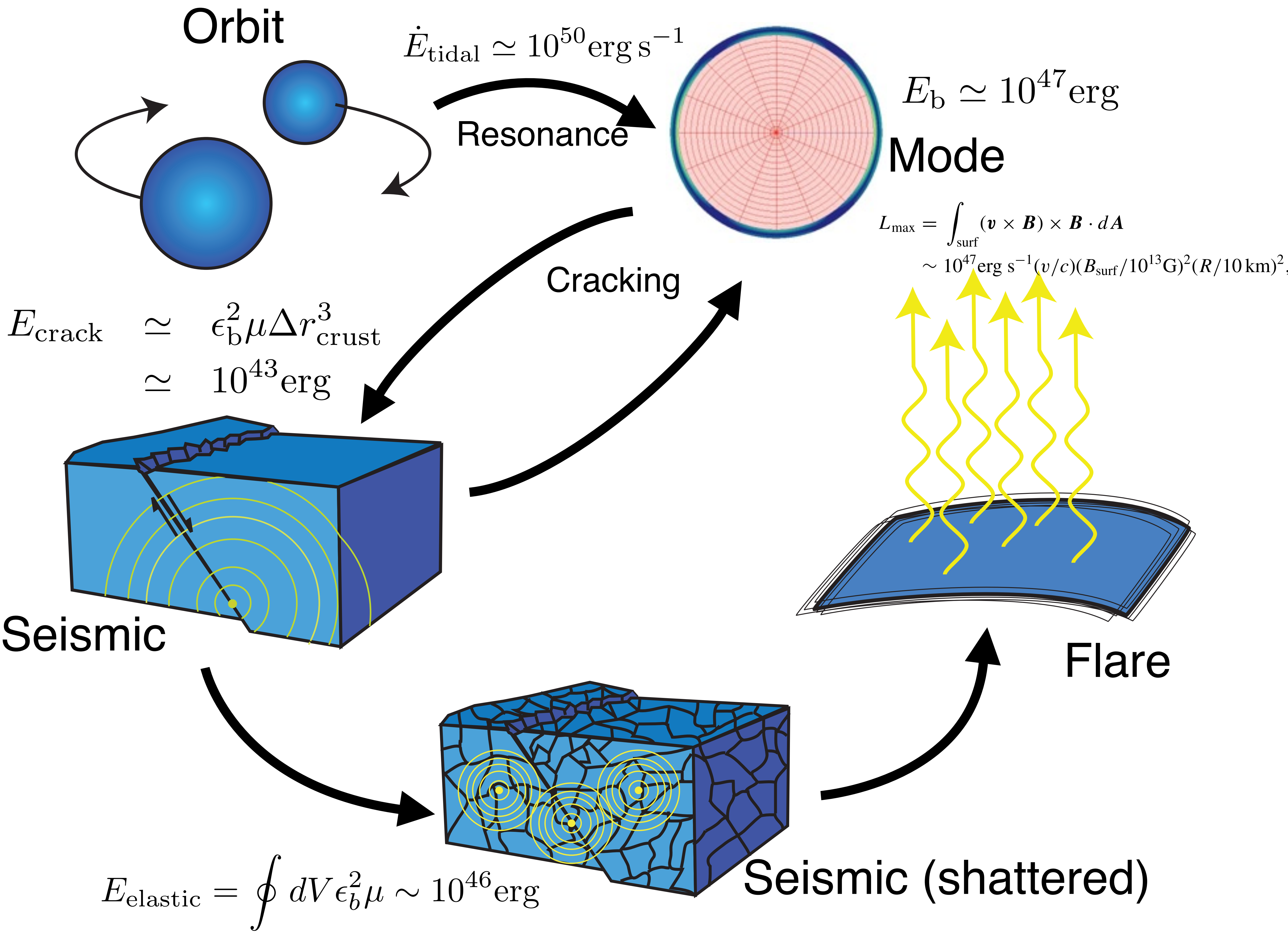
☐ How much energy can be transferred tidally?

$$E_{\max} \simeq 3 \times 10^{50} \text{ erg} \, f_{185}^{1/3} Q_{0.03}^2 M_{1.4}^{-2/3} R_{12}^2 \, q \left(\frac{2}{1+q} \right)^{5/3}$$

☐ How much energy does it take to break the crust?

$$E_{\mathrm{b}} = (2\pi f_{\mathrm{mode}})^2 \int d^3x \, \rho \, \boldsymbol{\xi}_{\mathrm{b}}^* \cdot \boldsymbol{\xi}_{\mathrm{b}} \simeq 5 \times 10^{46} \mathrm{erg} \, \epsilon_{0.1}^2$$

☐ What happens next?



Orbit

$\dot{E}_{\rm tidal} \simeq 10^{50} {\rm erg\,s^{-1}}$

Resonance

Mode

$E_{\rm b} \simeq 10^{47} {\rm erg}$

$$\begin{aligned} L_{\rm max} &= \int_{\rm surf} (\boldsymbol{v} \times \boldsymbol{B}) \times \boldsymbol{B} \cdot d\boldsymbol{A} \\ &\sim 10^{47} {\rm erg\ s^{-1}} (v/c)(B_{\rm surf}/10^{13}{\rm G})^2 (R/10\,{\rm km})^2, \end{aligned}$$

Cracking

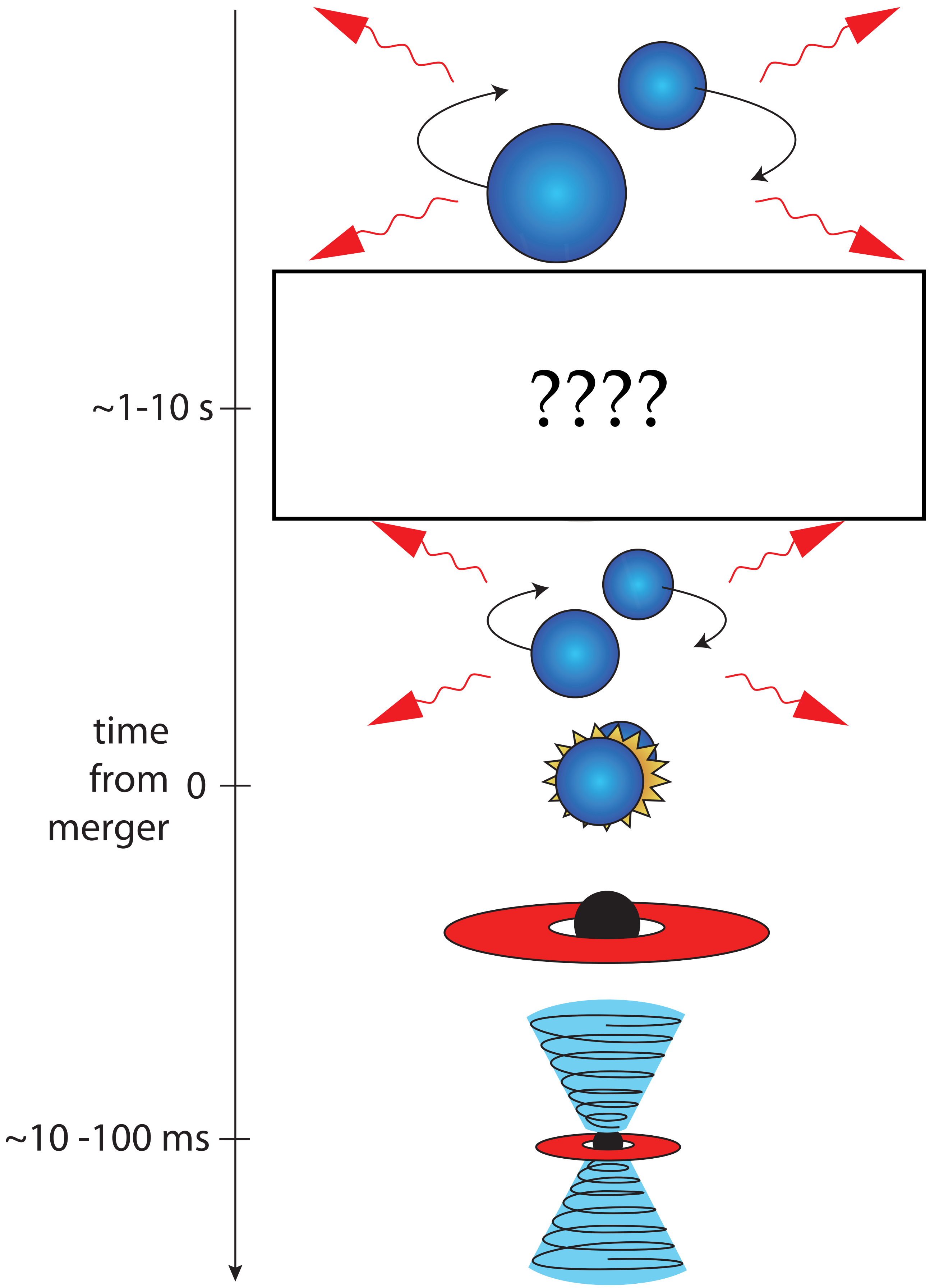
$$\begin{aligned} E_{\rm crack} &\simeq \epsilon_{\rm b}^2 \mu \Delta r_{\rm crust}^3 \\ &\simeq 10^{43} {\rm erg} \end{aligned}$$

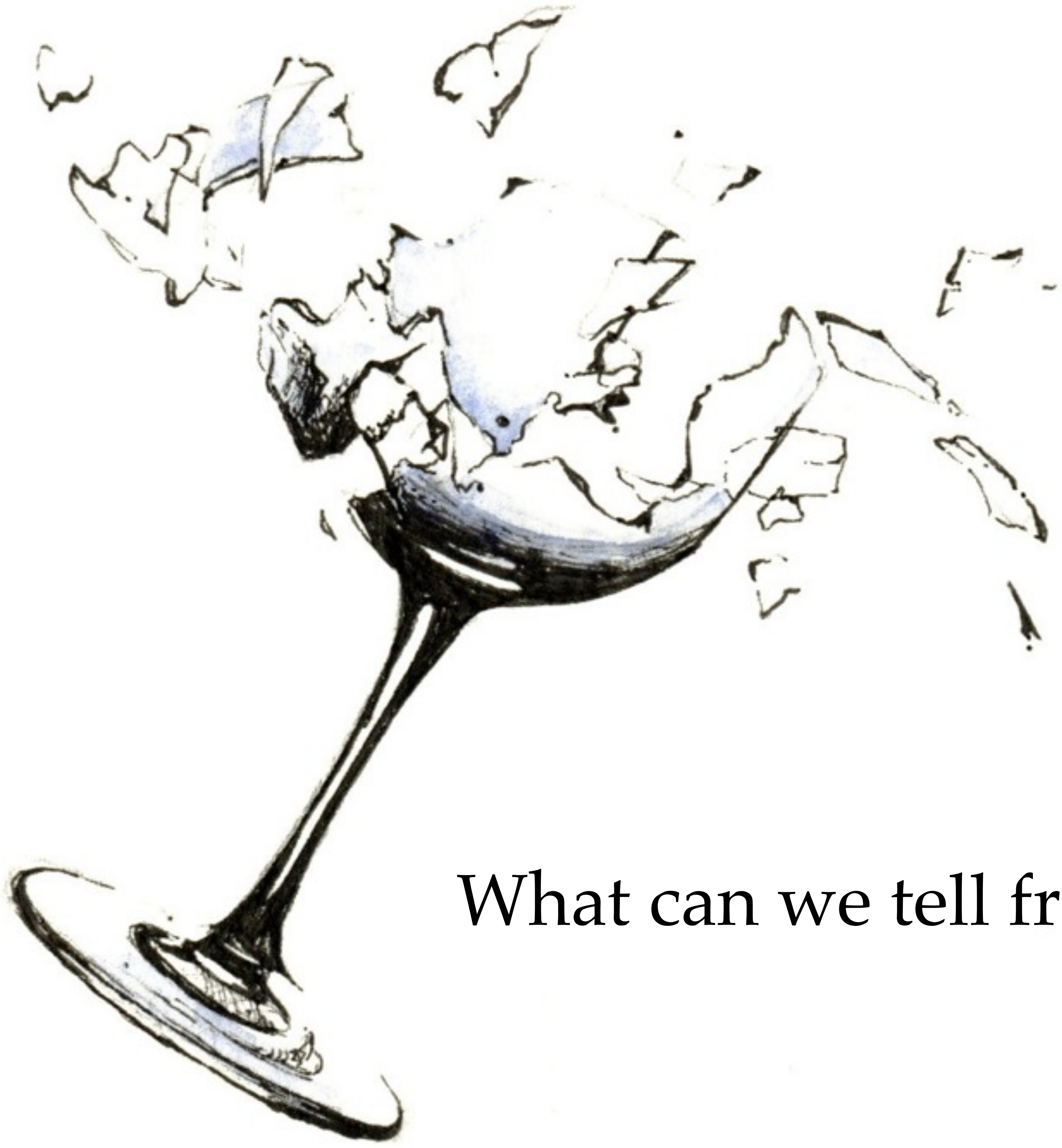
Seismic

Seismic (shattered)

$$E_{\rm elastic} = \oint dV \epsilon_b^2 \mu \sim 10^{46} {\rm erg}$$

Flare


????
~1-10 s
time
from
merger
0
~10 -100 ms



What can we tell from shattering?

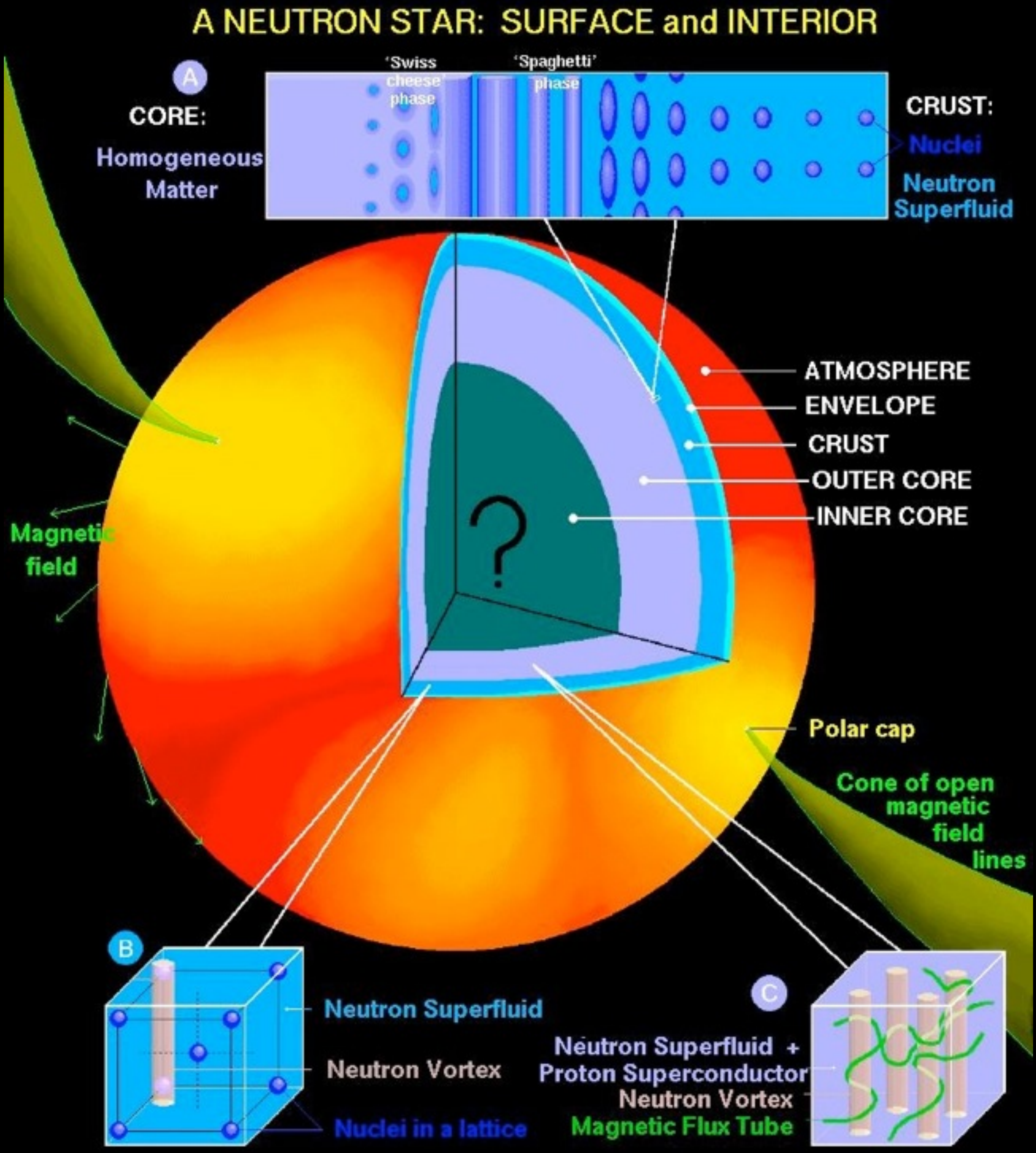
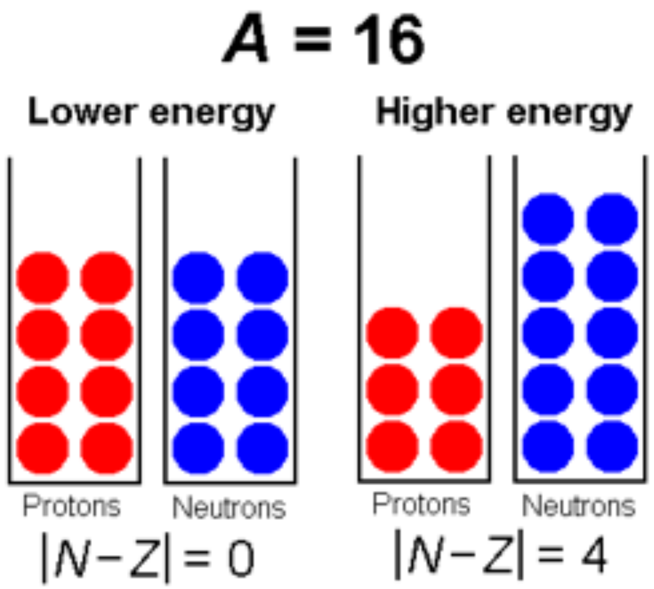
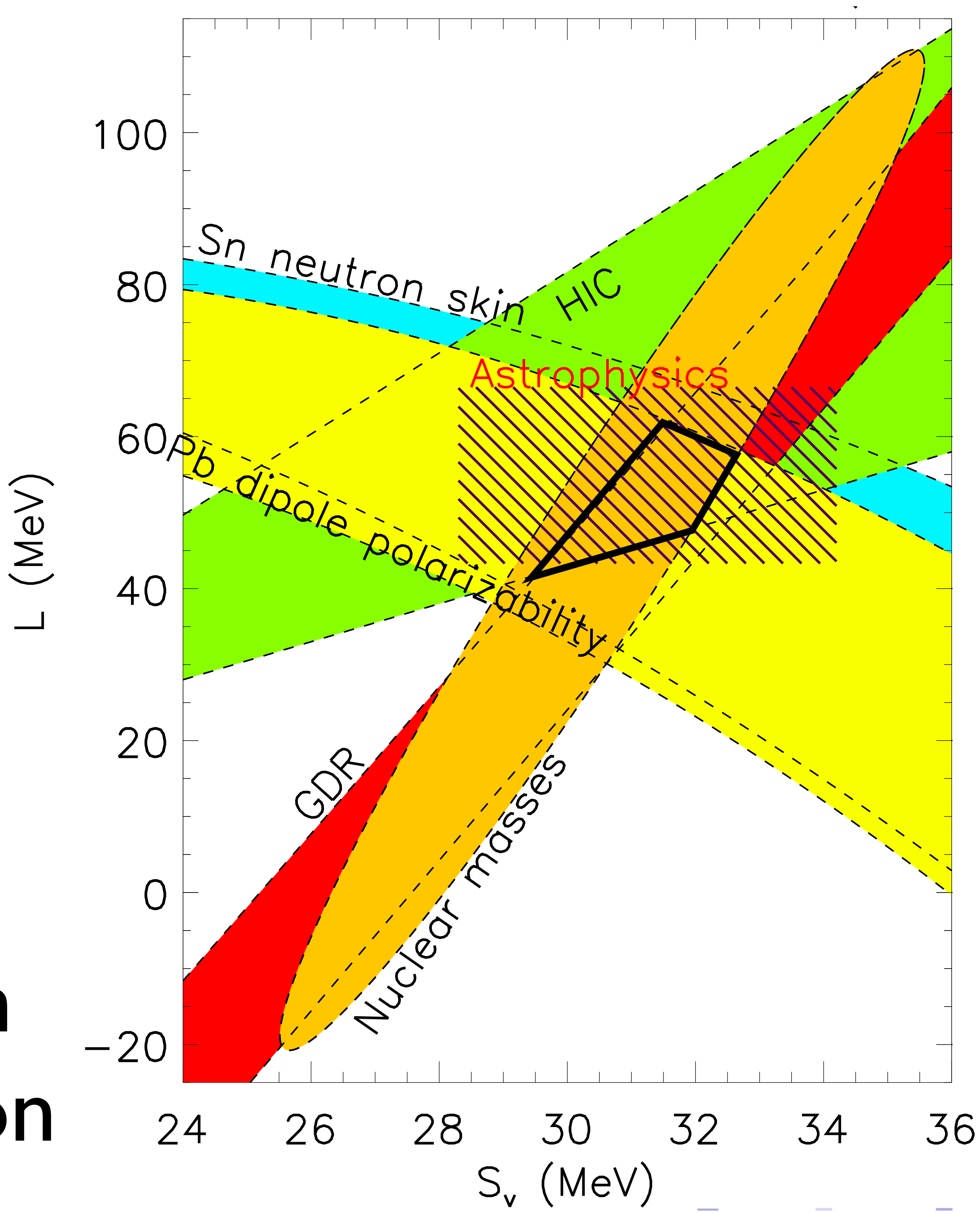


Image due to Dany Page

Nuclear Symmetry Energy

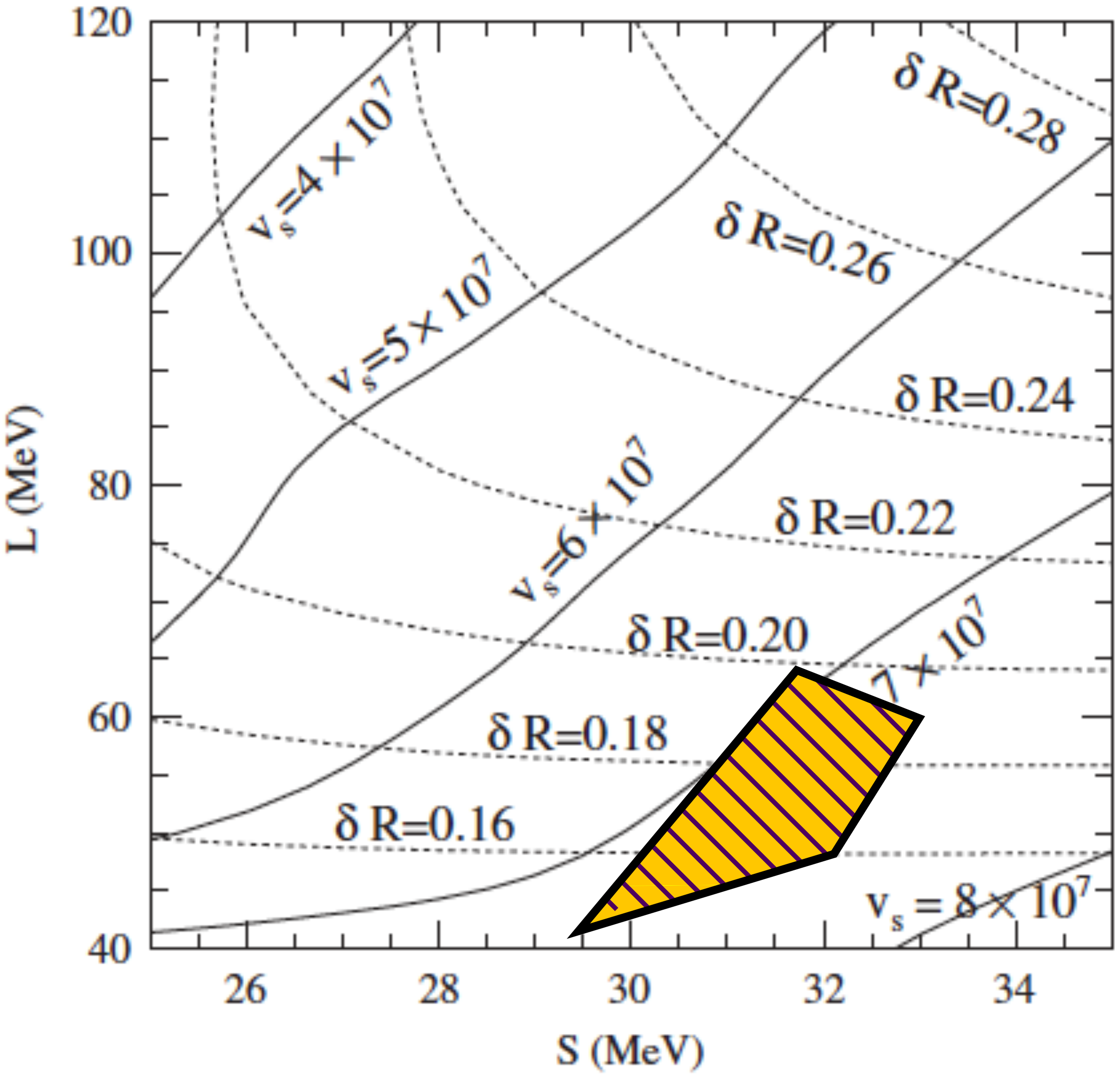
$$E(\rho_n, \rho_p) = E_o(\rho) + S(\rho) \left(\frac{\rho_n - \rho_p}{\rho} \right)^2 + \ldots$$



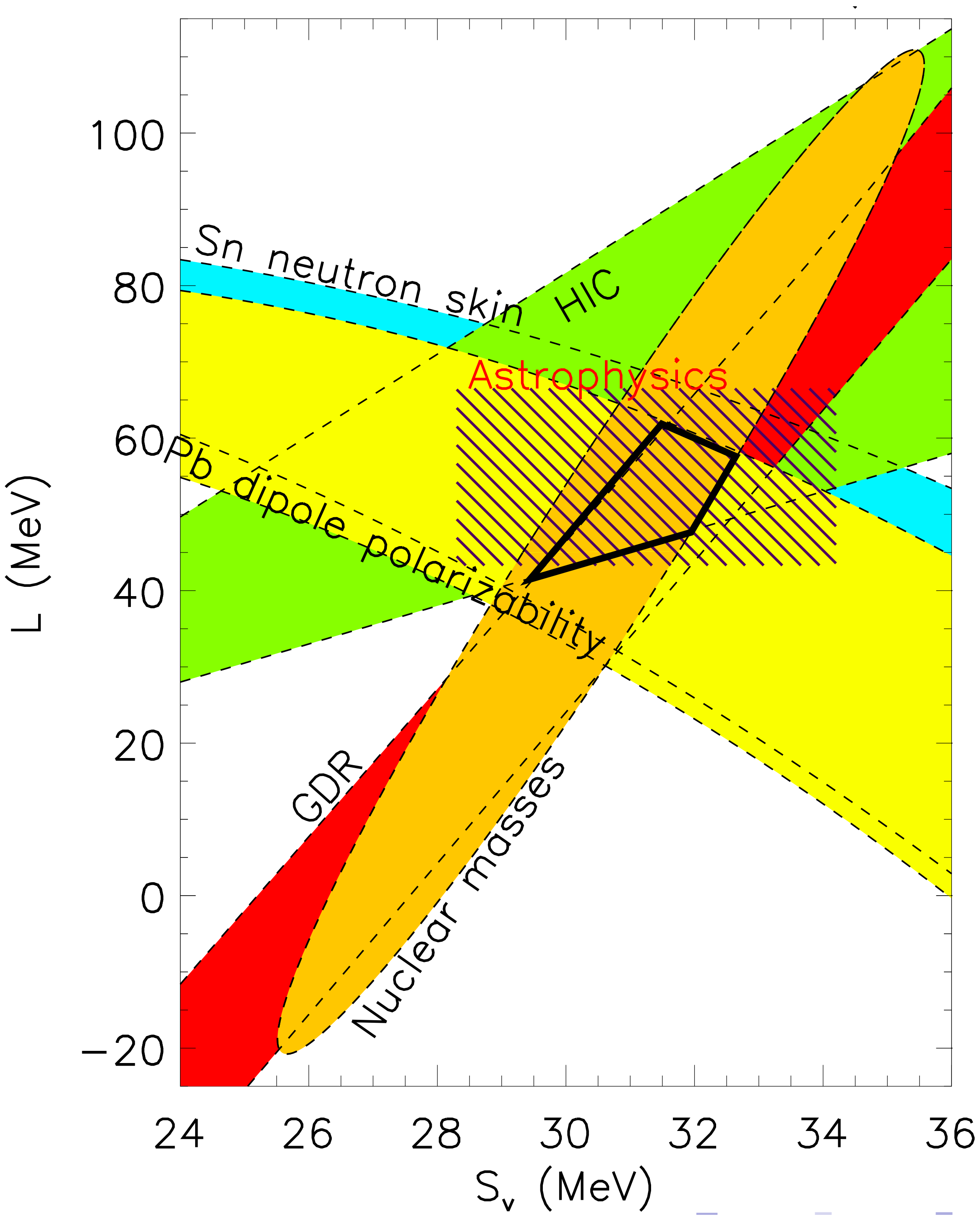


(Courtesy Jim Lattimer)

Experimental constraints on S(ρ), L(ρ) at nuclear saturation density



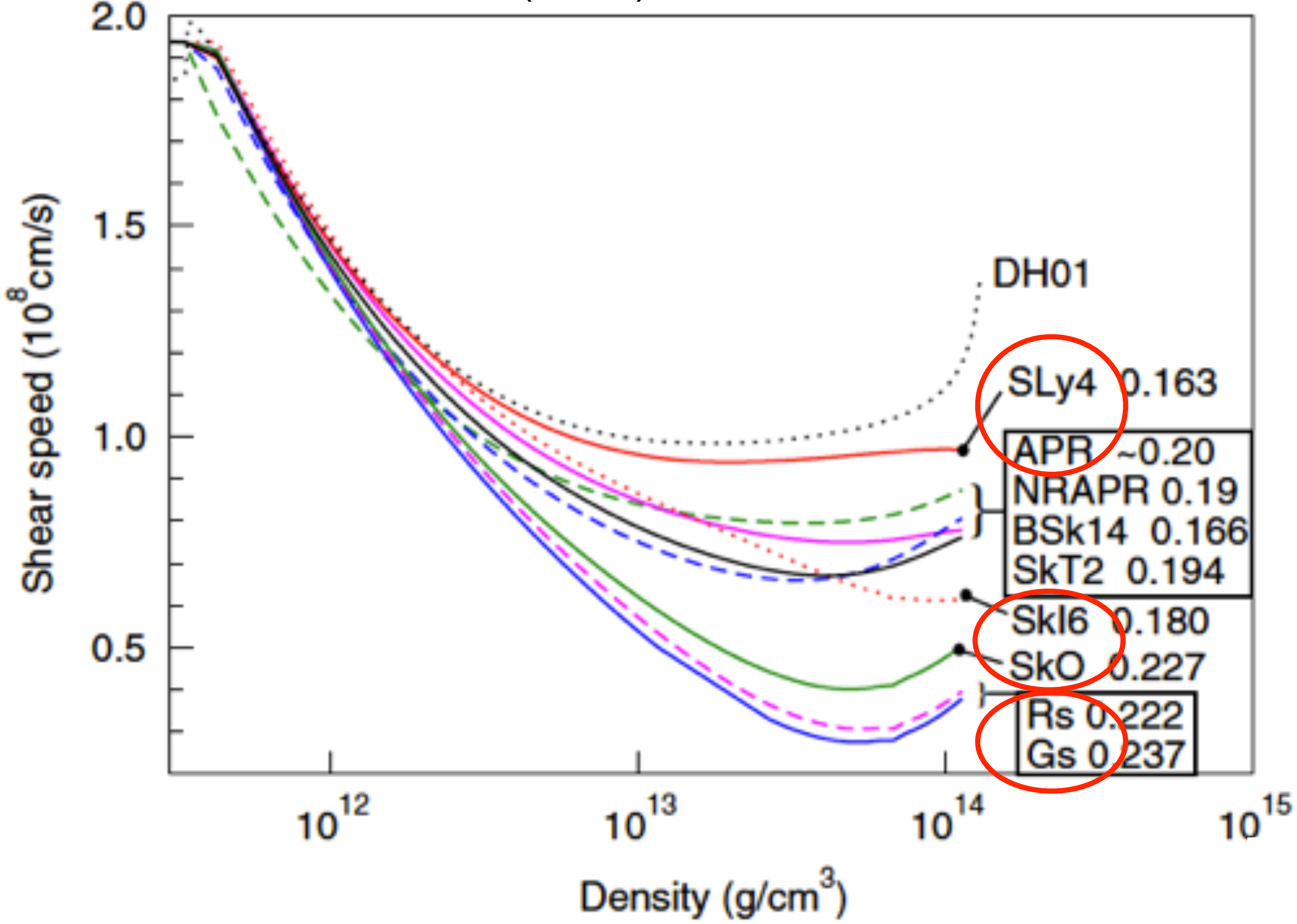
Steiner & Watts, (2009), PRL, 103, 181101



(Courtesy Jim Lattimer)

Magnetar Flares and Shear Modes

Steiner & Watts (2009) constrained equation of state based using QPOs from 2004 giant flare



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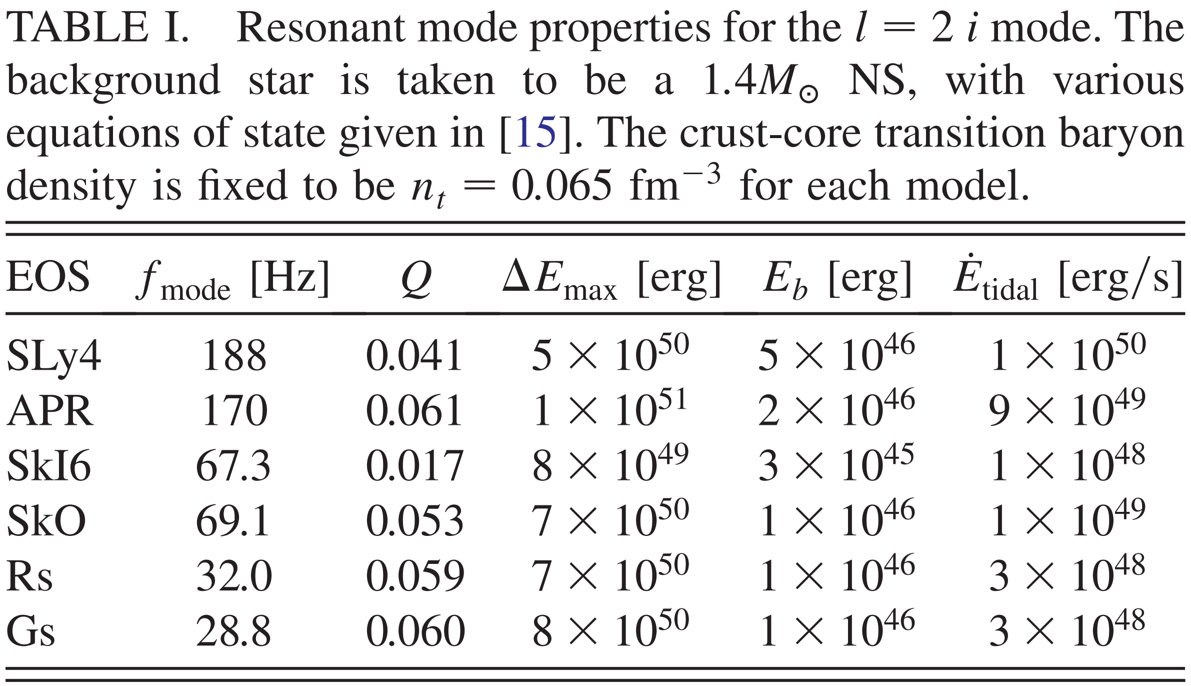
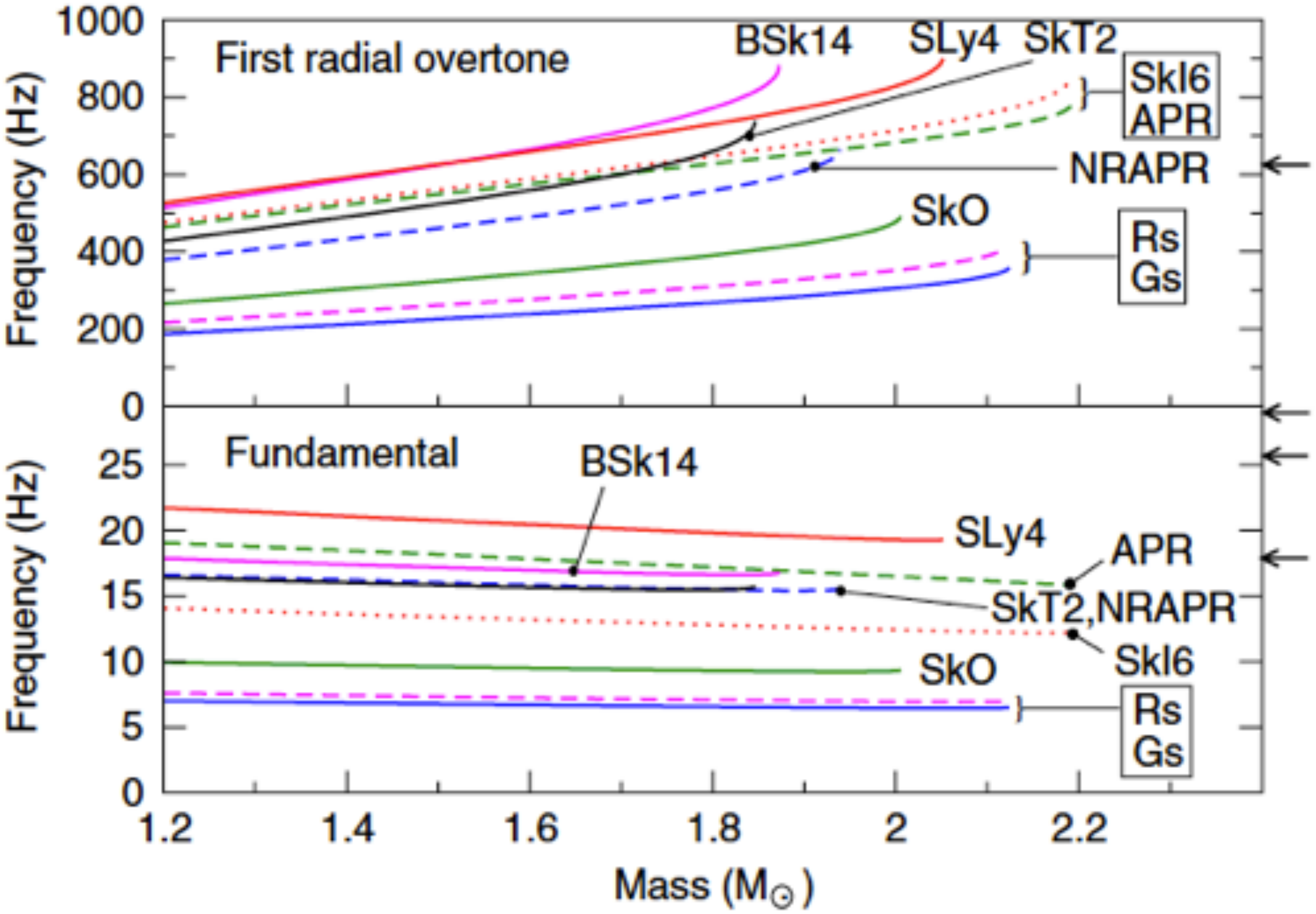
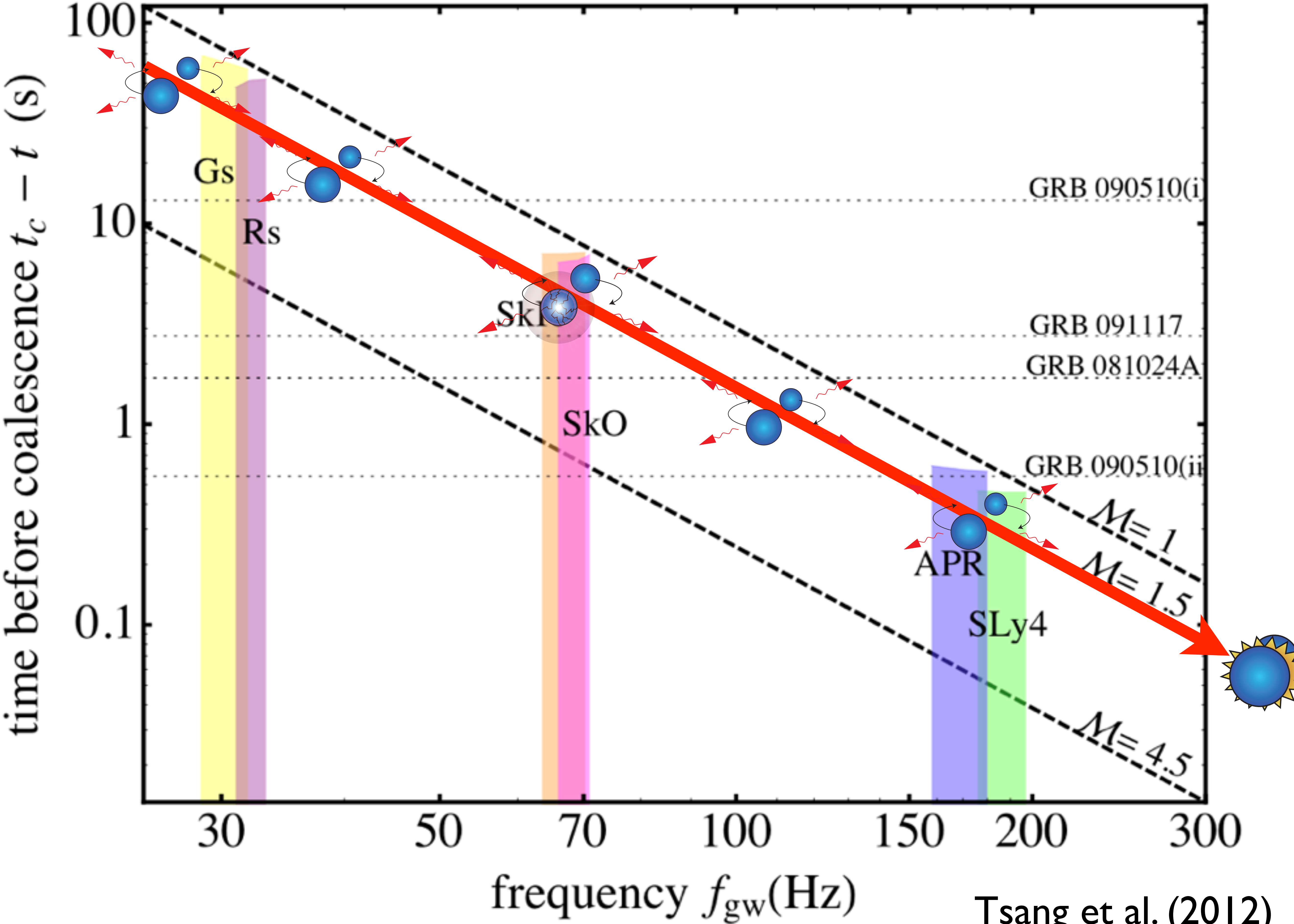


TABLE I. Resonant mode properties for the $l = 2$ i mode. The background star is taken to be a $1.4 M_\odot$ NS, with various equations of state given in [15]. The crust-core transition baryon density is fixed to be $n_t = 0.065$ fm^{-3} for each model.

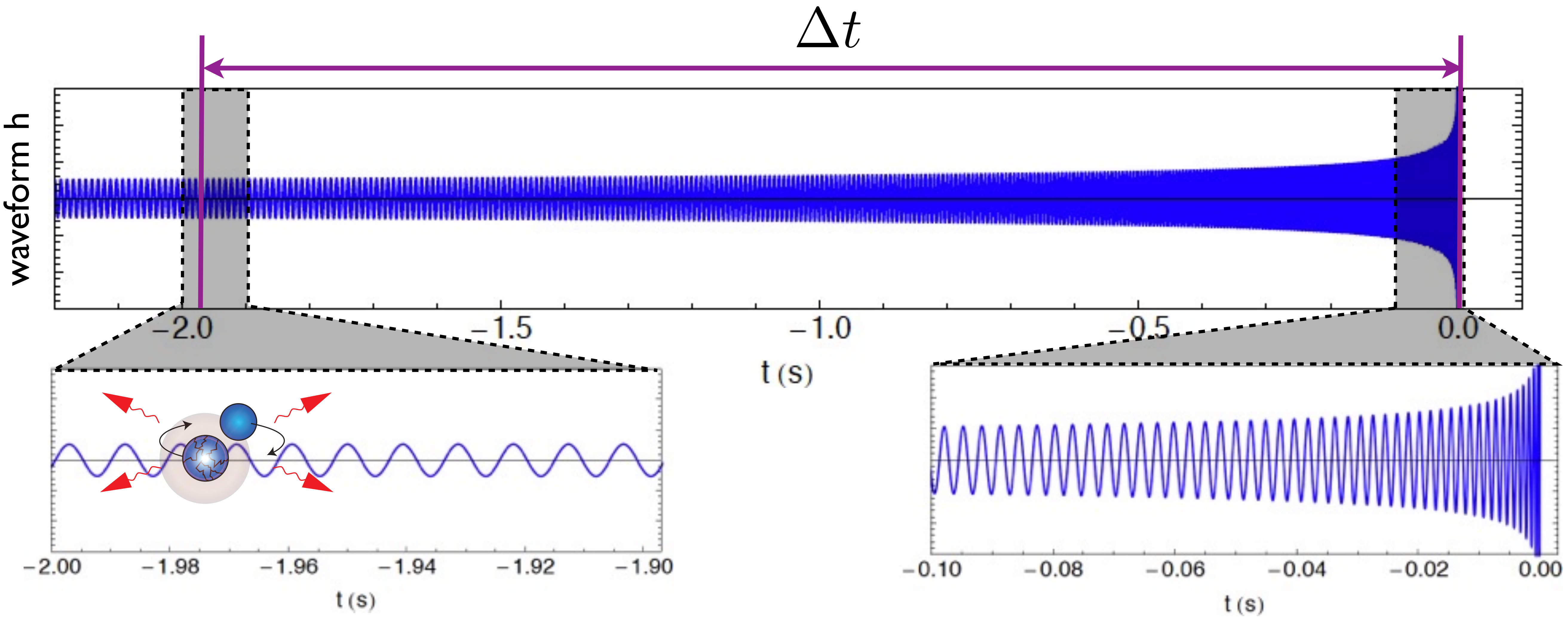
EOS	$f_{\rm mode}$ [Hz]	Q	$\Delta E_{\rm max}$ [erg]	E_b [erg]	$\dot{E}_{\rm tidal}$ [erg/s]
SLy4	188	0.041	5×10^{50}	5×10^{46}	1×10^{50}
APR	170	0.061	1×10^{51}	2×10^{46}	9×10^{49}
SkI6	67.3	0.017	8×10^{49}	3×10^{45}	1×10^{48}
SkO	69.1	0.053	7×10^{50}	1×10^{46}	1×10^{49}
Rs	32.0	0.059	7×10^{50}	1×10^{46}	3×10^{48}
Gs	28.8	0.060	8×10^{50}	1×10^{46}	3×10^{48}

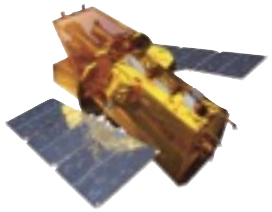
DT et al (2012)





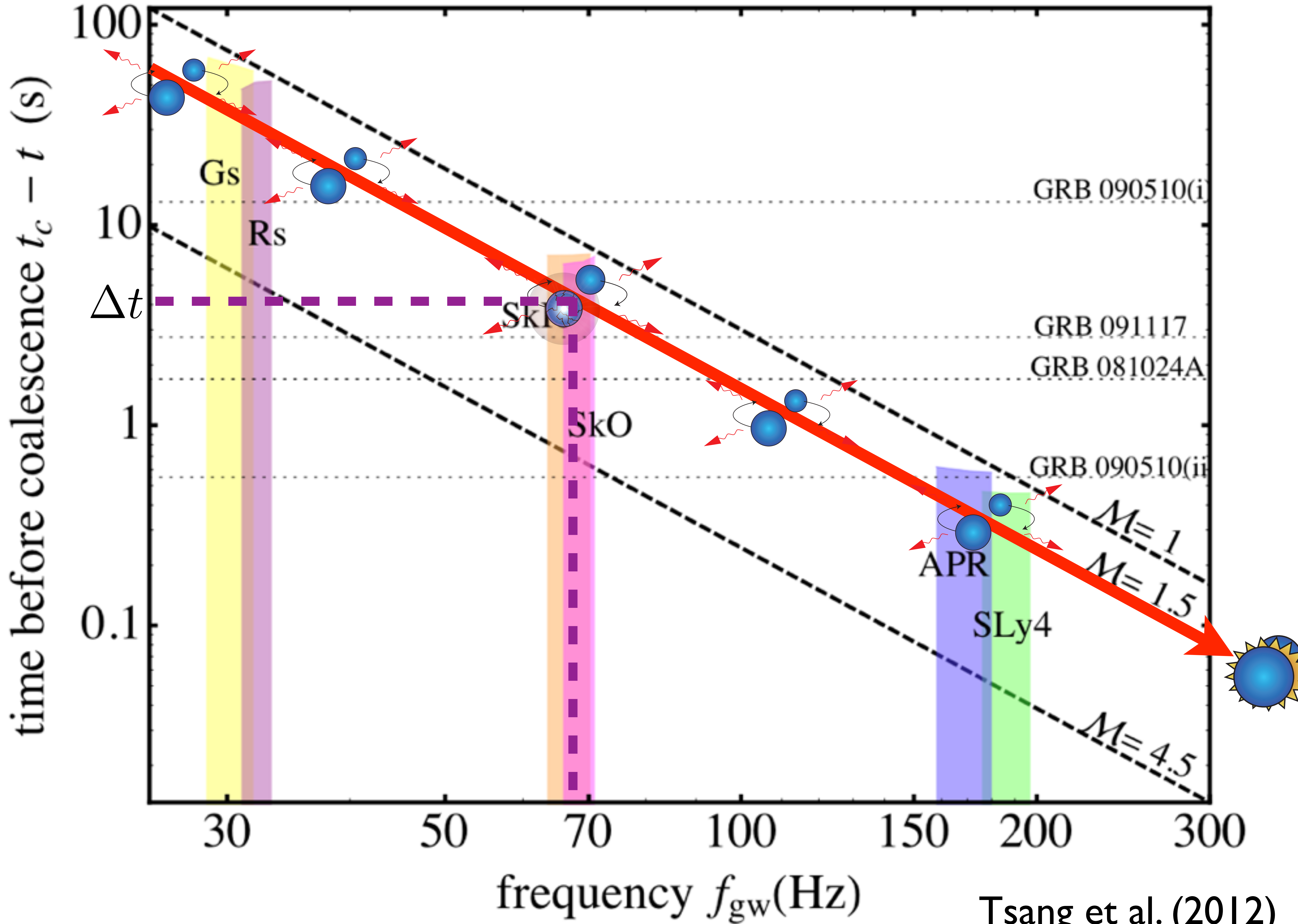
Tsang et al. (2012)





GW phase change too small to measure

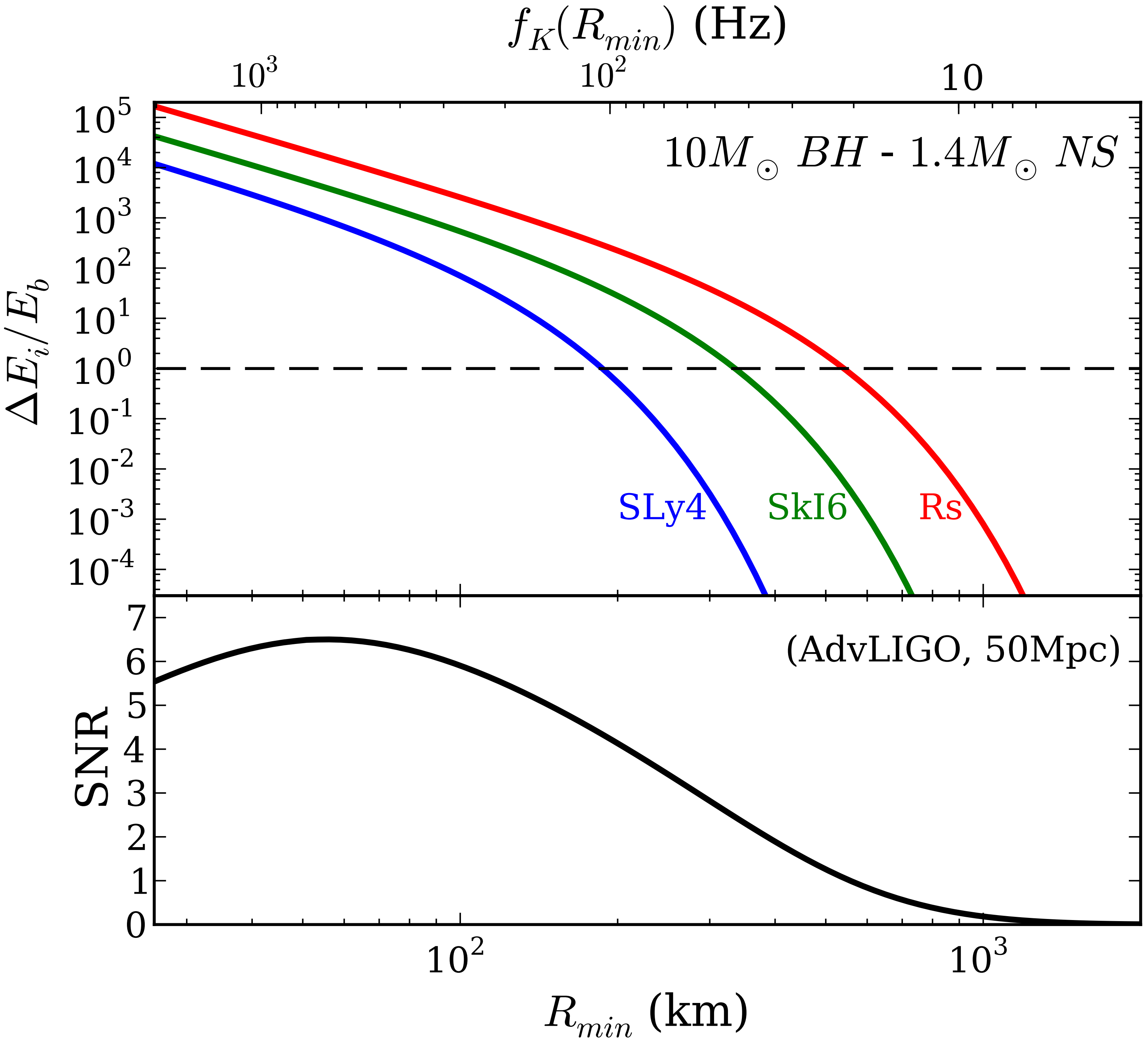
$$\Delta\phi \sim \frac{t_{rr}E_b}{t_{orbit}E_{orbit}} \sim 10^{-3} rad$$



Tsang et al. (2012)

Parabolic/Eccentric Encounters

- If encounter is close enough shattering flare can occur
- Emission similar to circular case
- Eccentric captures may lead to multiple bursts
- Possible EM/GW signal!
- Rates are not very good…(~100x less than Lee et al, 2010; O'Leary, Kocsis & Loeb, 2009)



DT (2013) ApJ, 777, 2, 103

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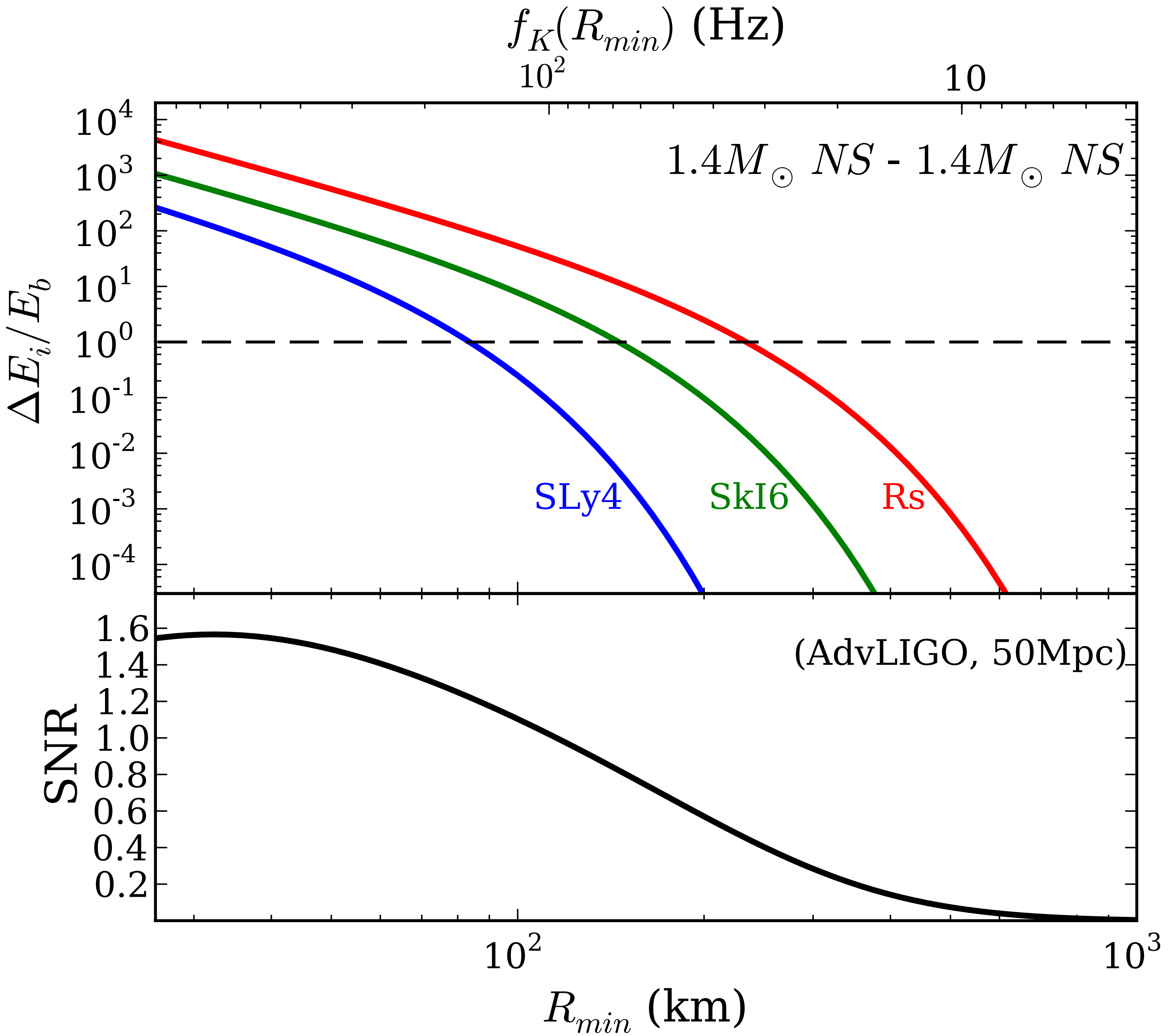

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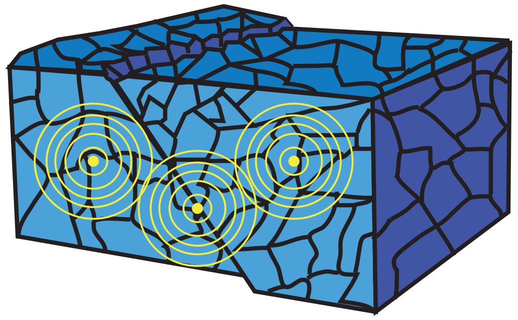
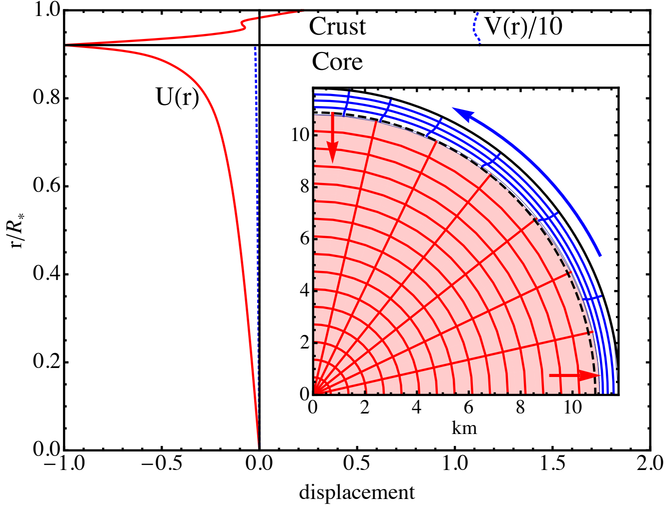
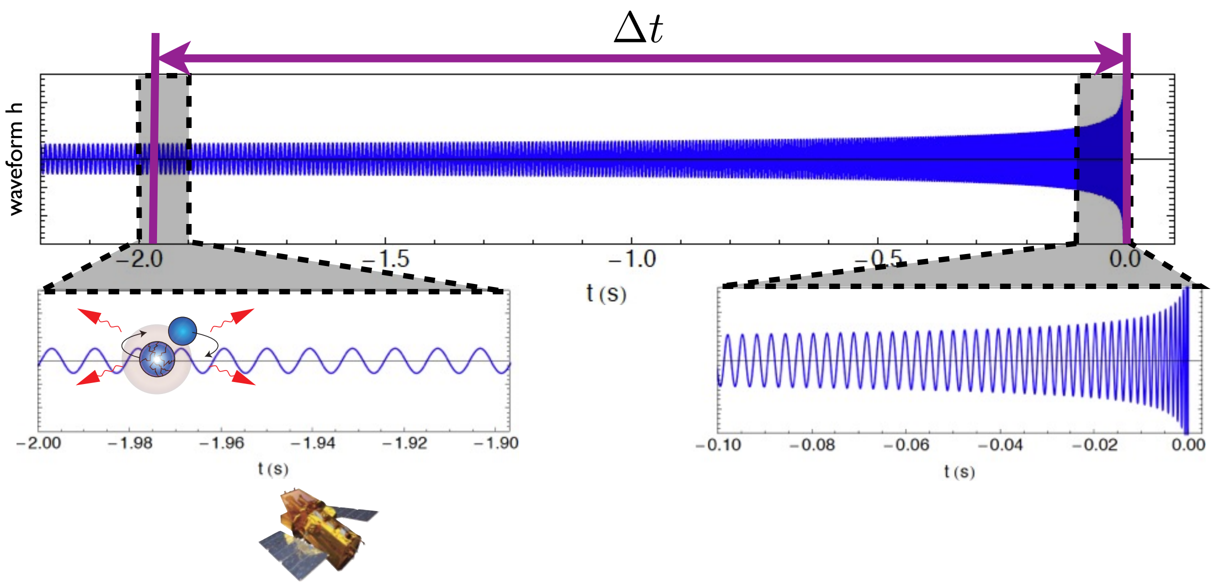


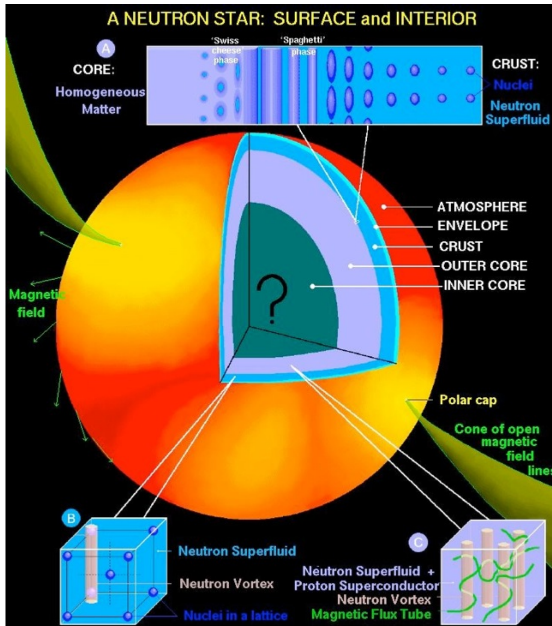
Summary/Future Work



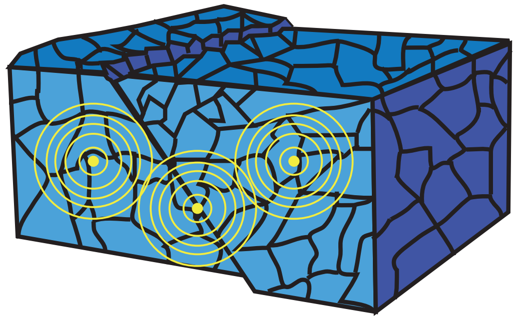
- Precursor flares are seen before some SGRBs
- Shattering flare caused by tidal resonant excitation of the i-mode
- Coincident timing of precursor w/ GW inspiral determine mode freq.
- Can provide constraints on shear speed/nuclear physics at base of crust
- Total fluence can constrain breaking strain

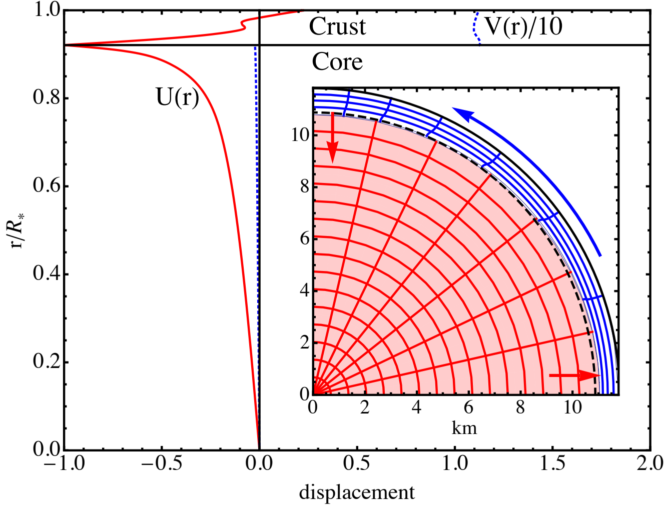
- Parabolic/Eccentric Encounters in Globular/Nuclear Clusters
- Details of EM coupling/Emission mech.
- More realistic EOS
- Better oscillation/elasticity model
- Pasta??
- Elastic vs Plastic





Summary/Future Work





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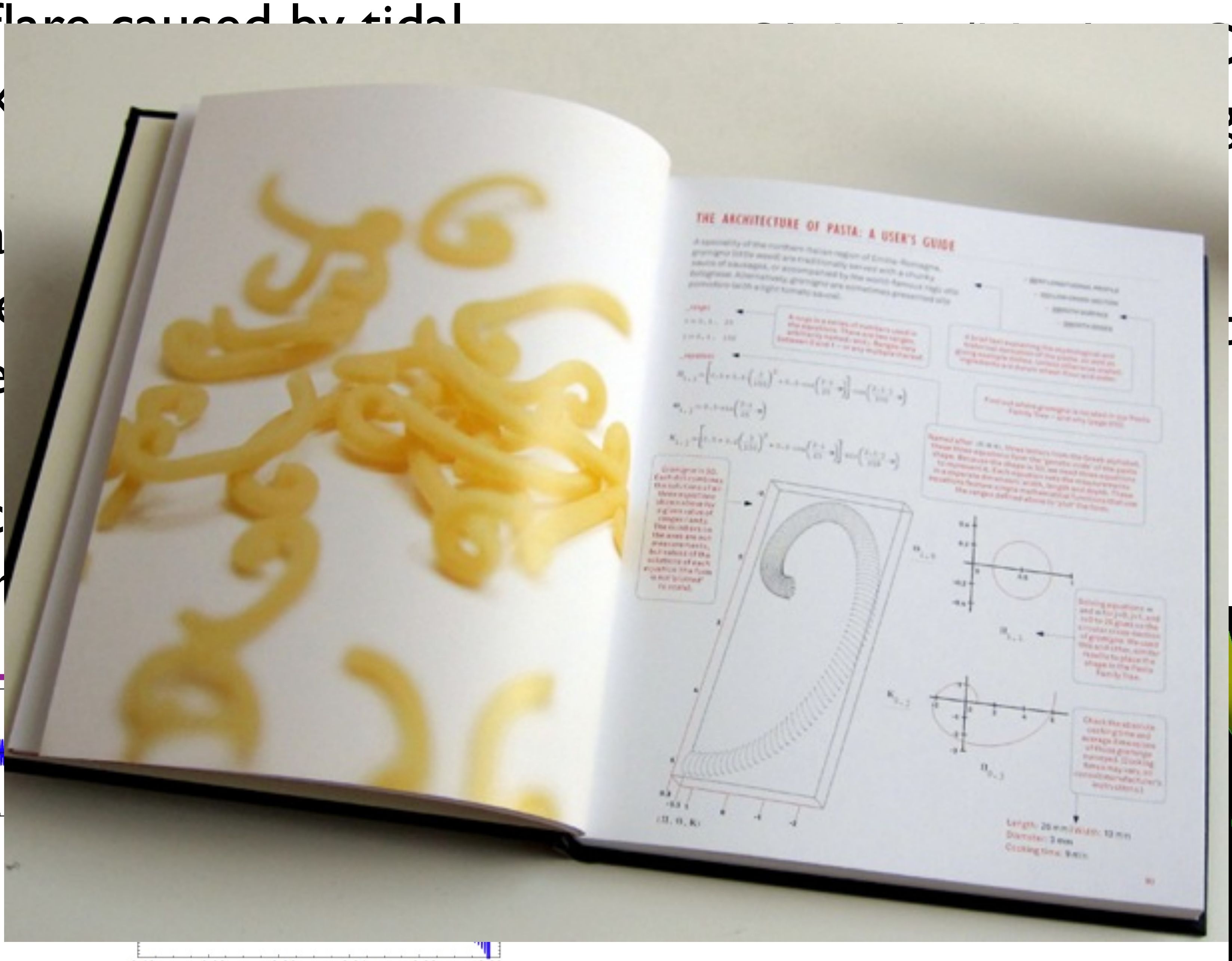
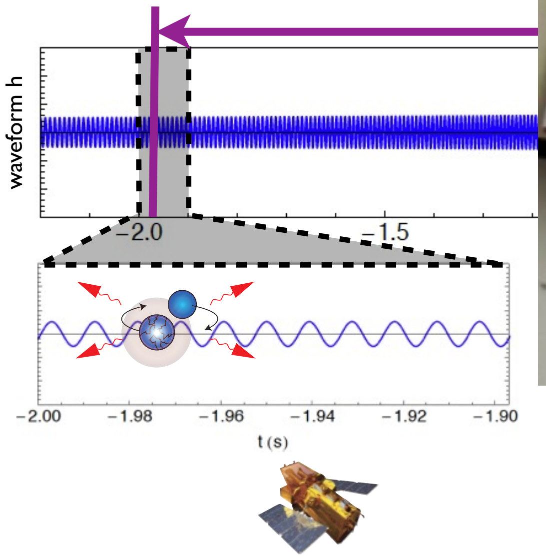
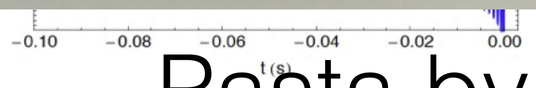
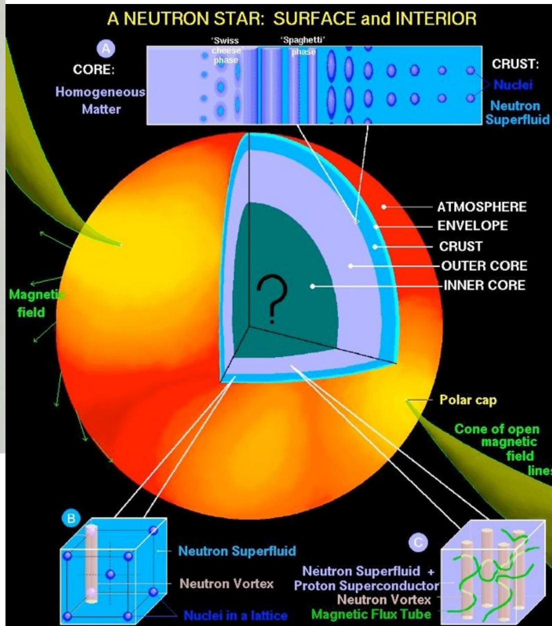


THE ARCHITECTURE OF PASTA: A USER'S GUIDE

Pasta by Design (Legendre)







The End