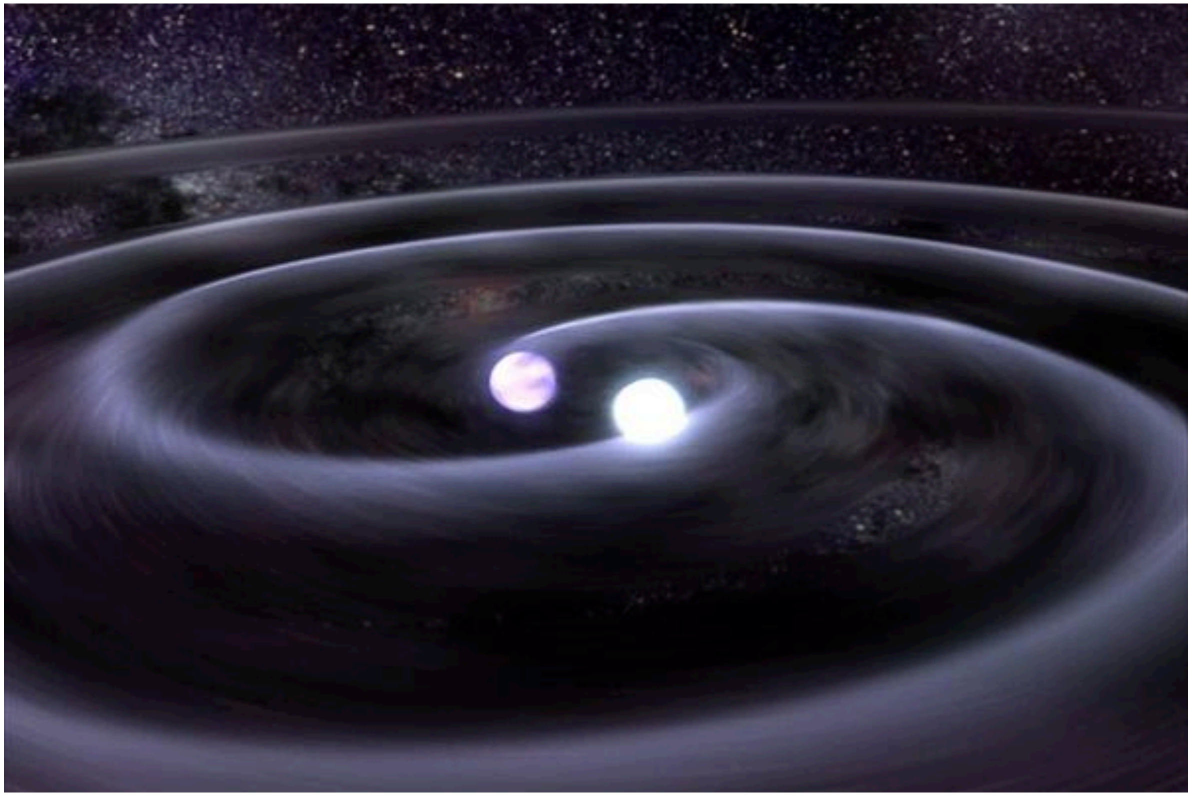
Merging Compact Binaries



Dong Lai
Cornell University

Physics & Astronomy Colloquium, Texas A&M Univ. Commerce, 3/21/2013

Merging Compact Binaries

1. Neutron Star/Black Hole Binaries
2. White Dwarf Binaries

White Dwarfs:

$$M \sim 0.6 M_\odot, \;\; R \sim 6000\,\mathrm{km}, \quad V_{\rm esc}/c \sim 10^{-2}, \quad M_{\rm MS} = (1-8) M_\odot$$

Neutron Stars:

$$M \sim 1.4 M_\odot, \;\; R \sim 10, \mathrm{km}, \quad V_{\rm esc}/c \sim 0.5, \quad M_{\rm MS} = (8 - 30?) M_\odot$$

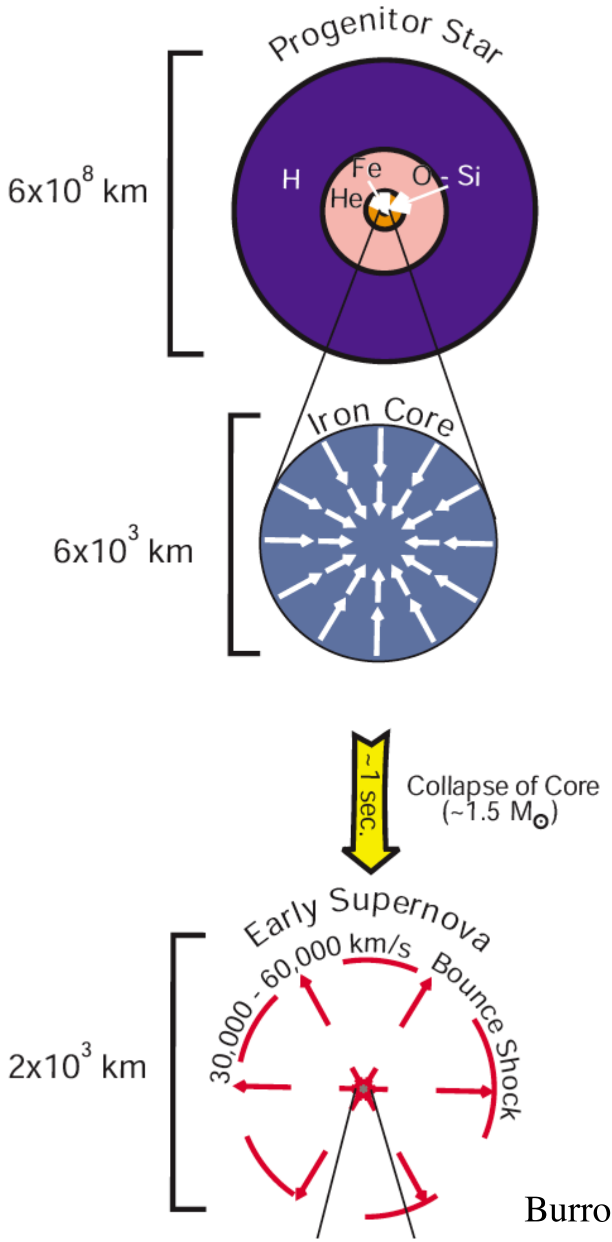
Black Holes:

$$M > 3 M_\odot, \;\; R = 2GM/c^2, \quad V_{\rm esc}/c \sim 1, \quad M_{\rm MS} = (30? {-} ?) M_\odot$$

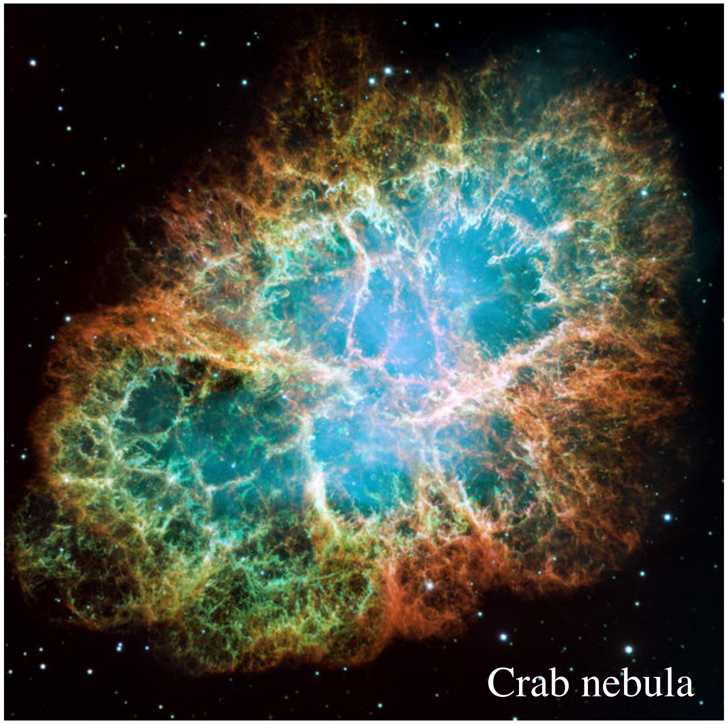
White dwarfs evolve from stars with M $\lesssim$ 8 Sun …

NGC 2392, the Eskimo Nebula (HST)

Neutron stars evolve from stars with M $\gtrsim$ 8 Sun …



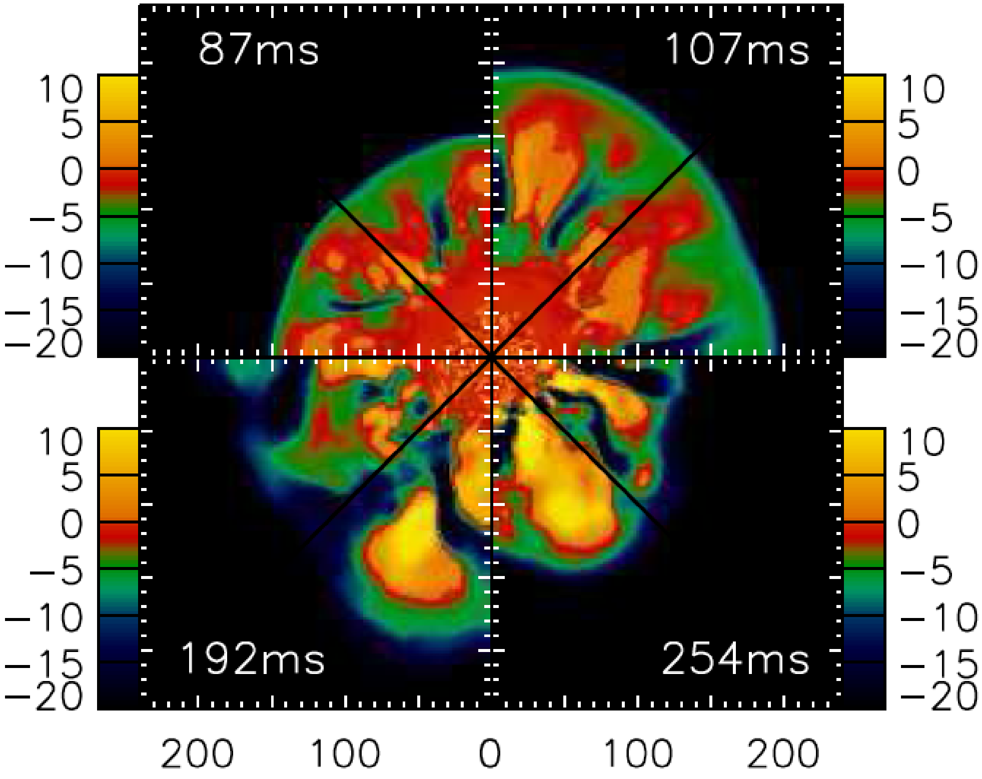
Burrows 2000



Crab nebula

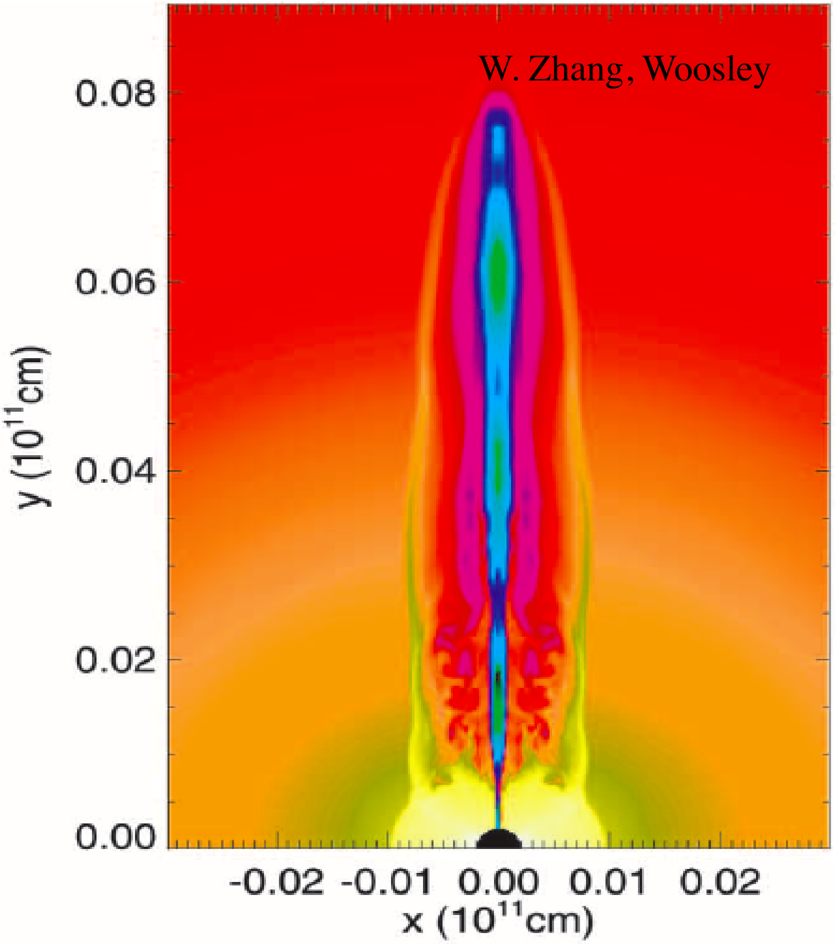
Black Holes evolve from stars with M ≳ 30 (?) Sun …

Failed bounce/explosion
==> Fall back of stellar material
==> BH formation



H-T Janka;
See O' Connor & Ott 2011

Collapse of rotating star
==> spinning BH + disk
==> Relativistic jet (?)
==> (Long) Gamma-ray bursts



White Dwarfs:

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Neutron Stars:

$$M \sim 1.4 M_\odot, \;\; R \sim 10, \mathrm{km}, \quad V_{\mathrm{esc}}/c \sim 0.5, \quad M_{\mathrm{MS}} = (8-30?) M_\odot$$

Black Holes:

$$M > 3 M_\odot, \;\; R = 2GM/c^2, \quad V_{\mathrm{esc}}/c \sim 1, \quad M_{\mathrm{MS}} = (30? - ?) M_\odot$$

Compact Objects Research Today…

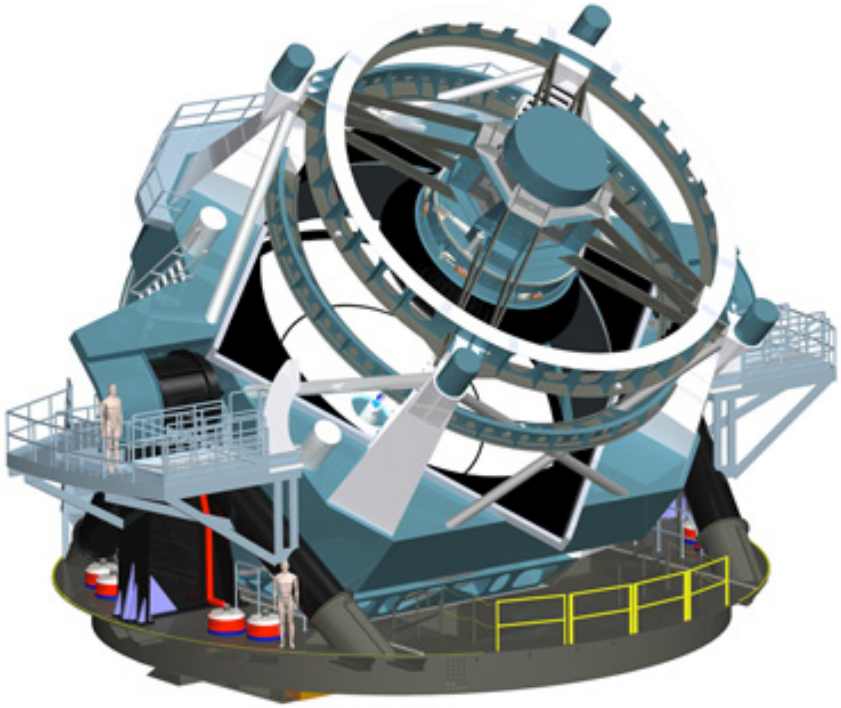
- Have become a “routine” subject of research
- Associated with extreme phenomena in the universe (e.g. SNe, GRBs)
- Interested in not just the objects themselves, but also how they interact/influence their surroundings
- Used as
  - --- an astronomy tool (e.g., expansion rate of the Universe, GWs)
  - --- a tool to probe physics under extreme conditions

Merging Compact Binaries

1. Neutron Star/Black Hole Binaries
2. White Dwarf Binaries

Transient & Variable Universe

Wide-field, fast imaging telescopes in optical: **PTF, Pan-Starrs, LSST**



Transient & Variable Universe

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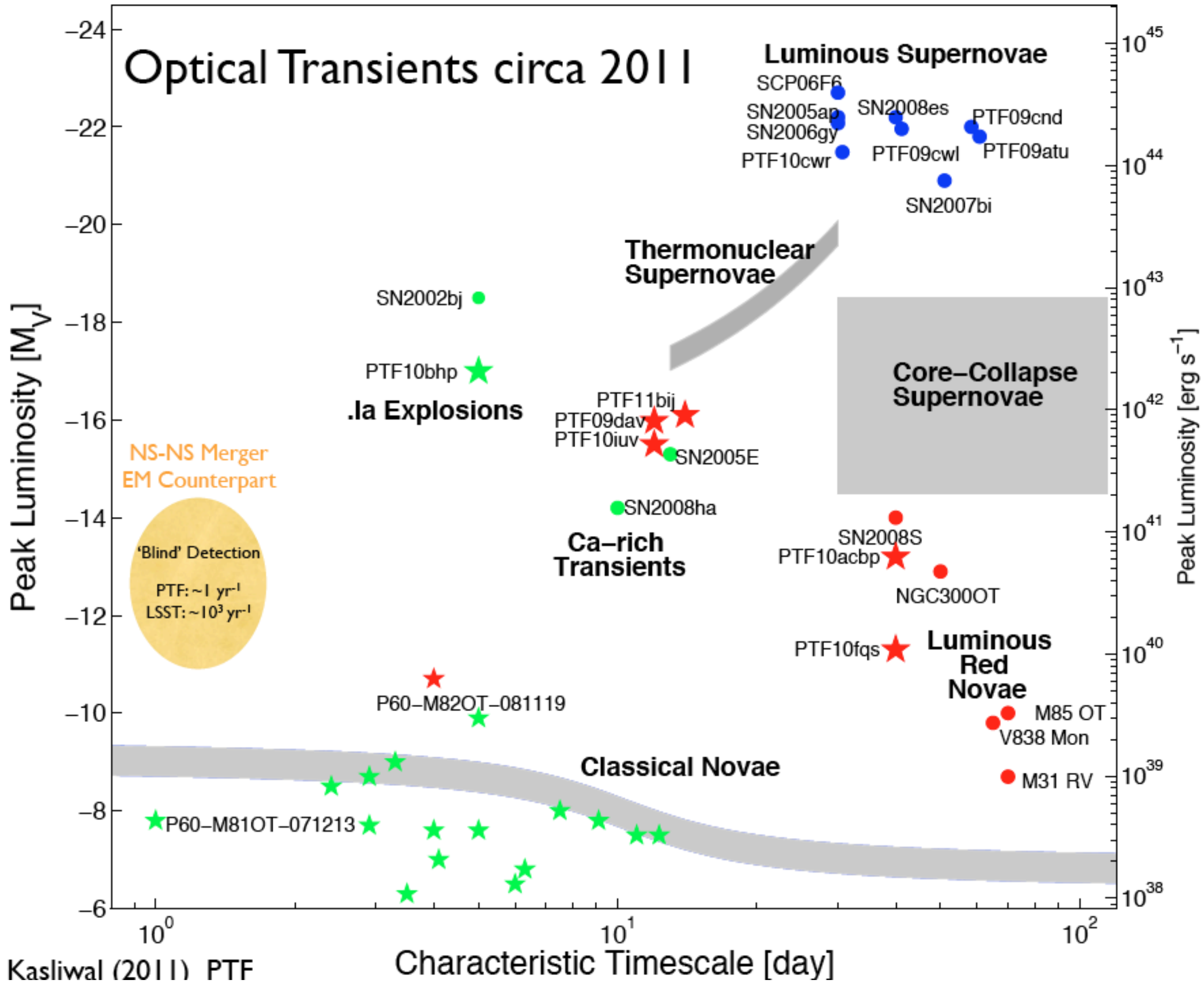
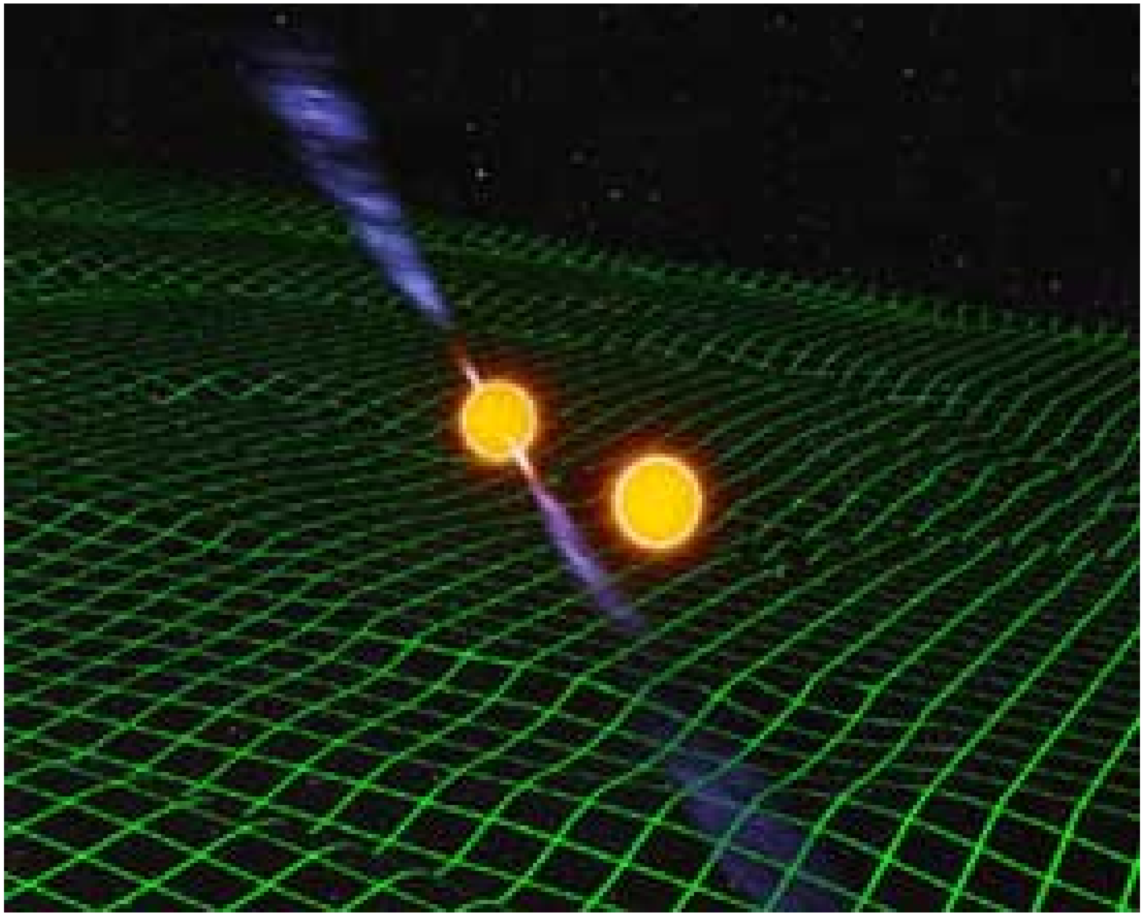


Kasliwal (2011) PTF

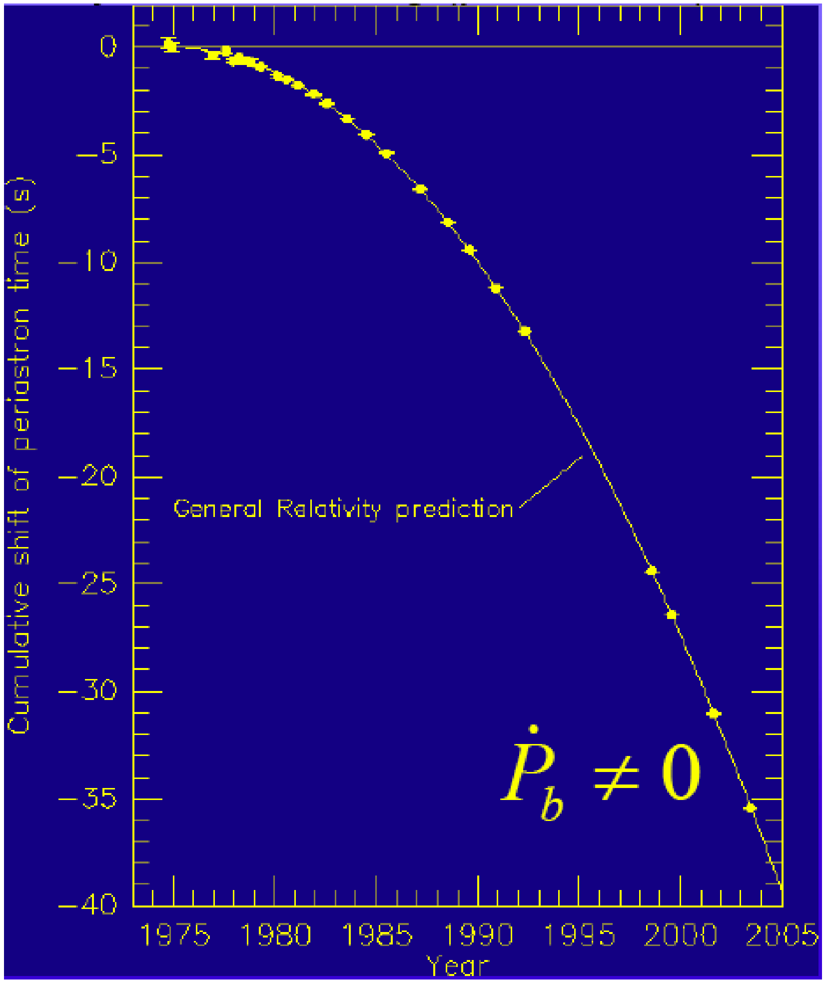
Gravitational Wave Astronomy

LIGO
VIRGO

Merging NS and BH Binaries



NS/NS Binaries: Binary Pulsars



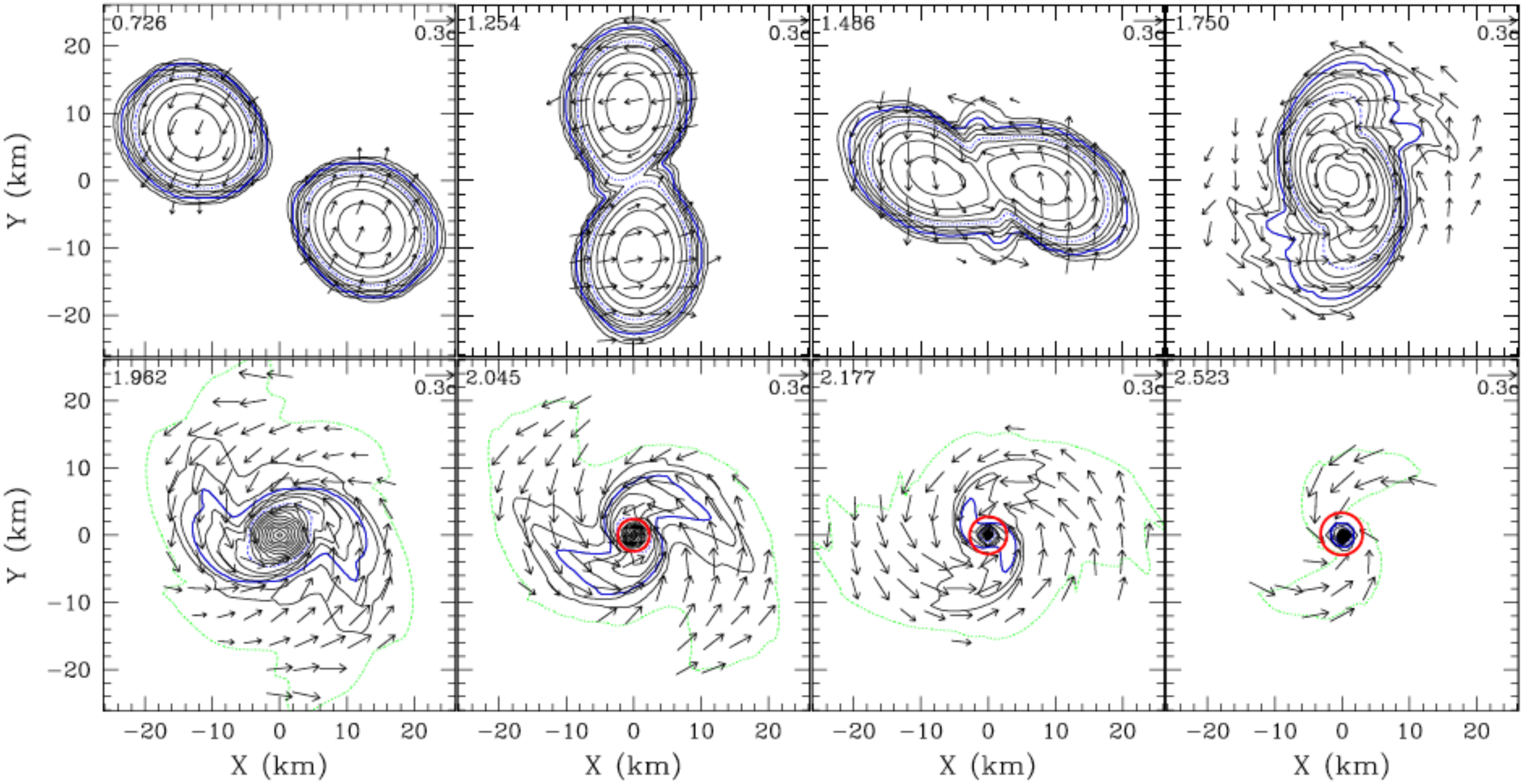
Taylor & Weisberg 2005

Nobel Prize 1993

$$\dot{N}_{\mathrm{merge}} = 10^{-5} - 3 \times 10^{-4} \mathrm{yr}^{-1} \text{ per galaxy}$$

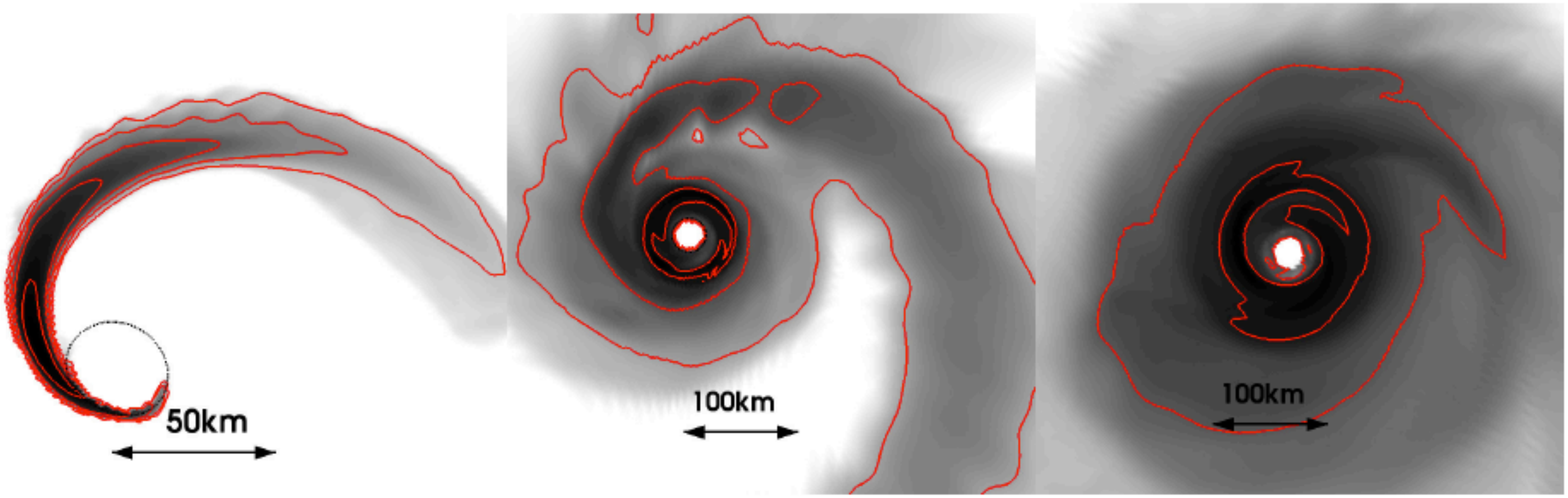
(Based on 3 systems in Galaxy that will merge within Hubble time;
No observed NS/BH and BH/BH yet !)

NS-NS Merger



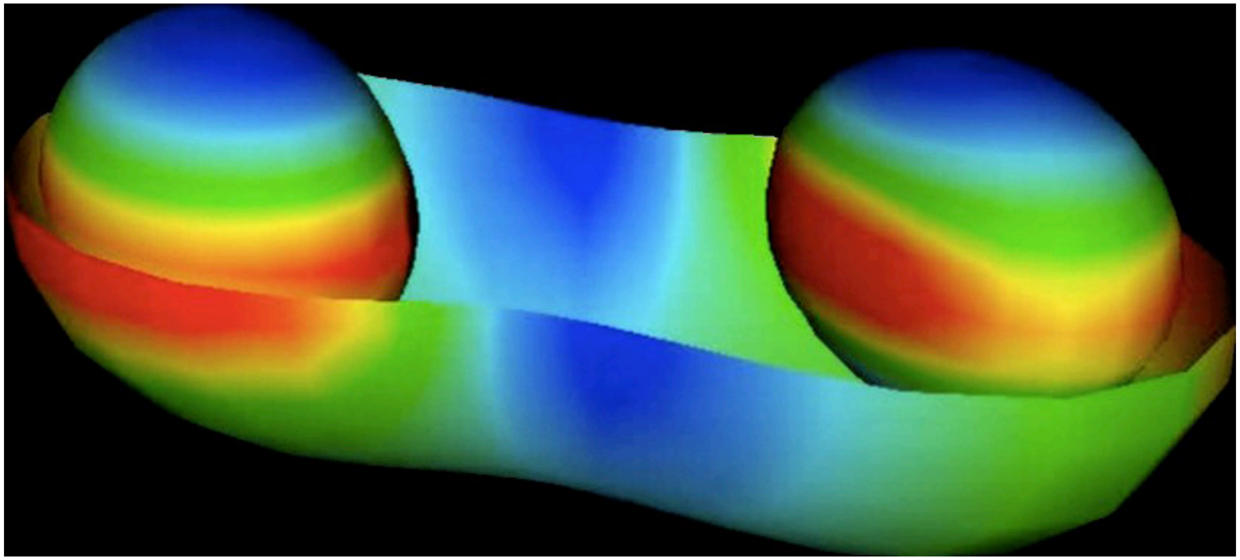
Shibata et al. 2006

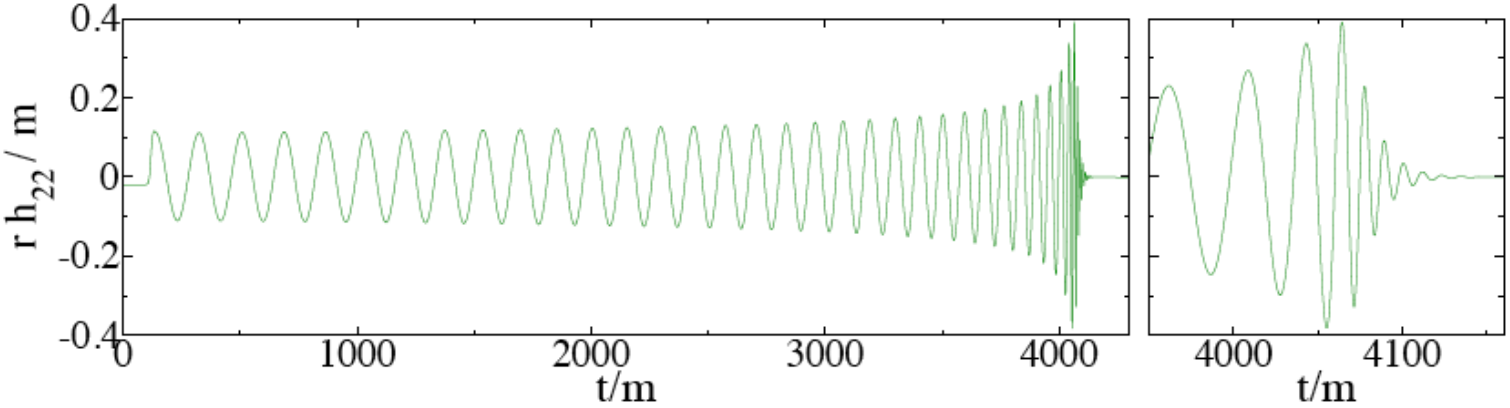
BH-NS Merger



F. Foucart et al (Cornell) 2011,13

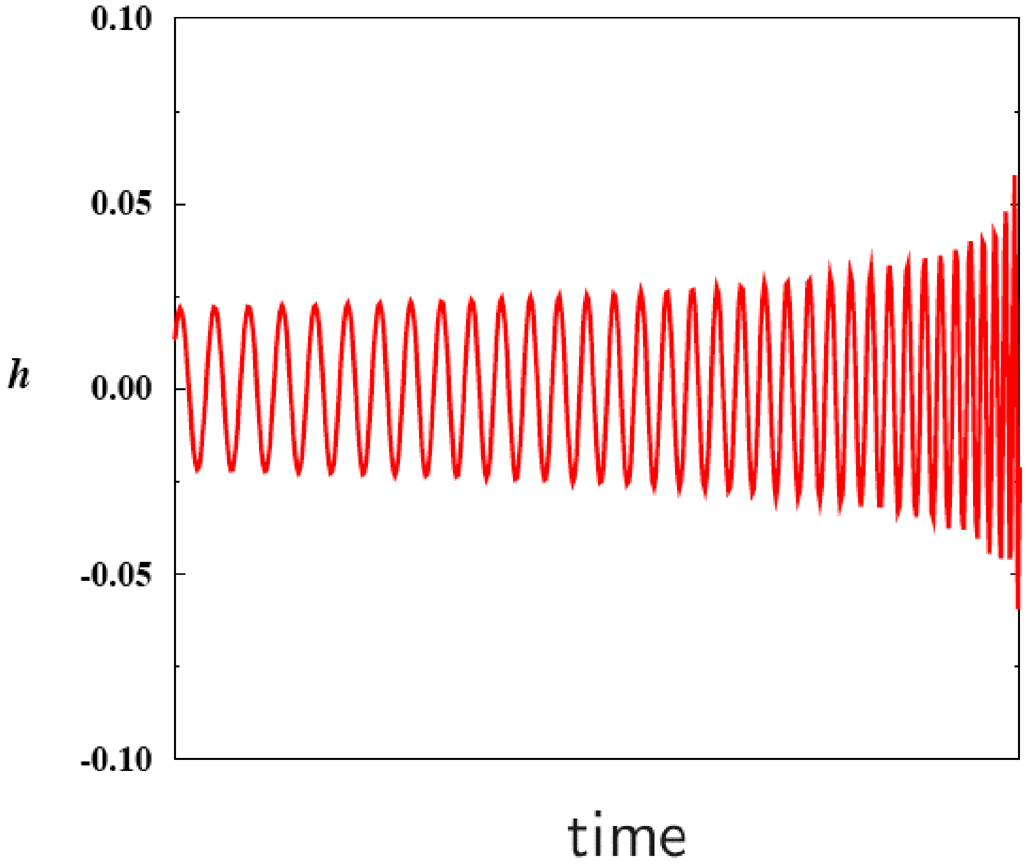
BH-BH Merger

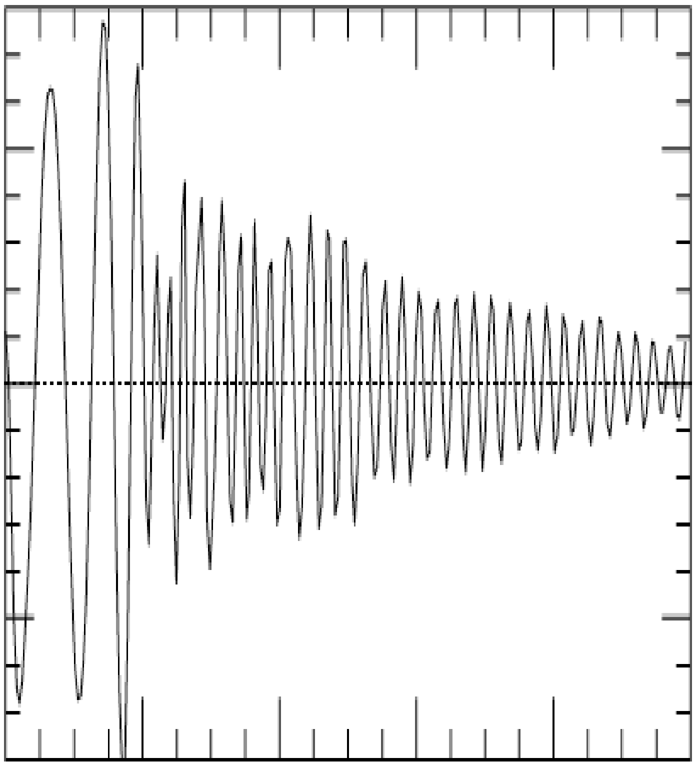


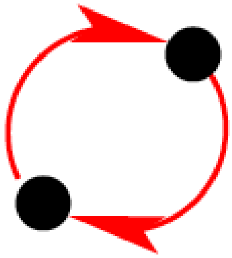


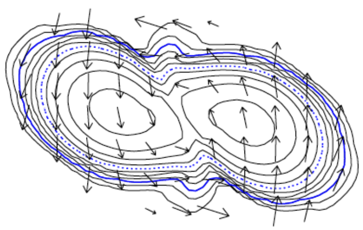
Cornell-Caltech collaboration

The last few minutes: Gravitational Waveform









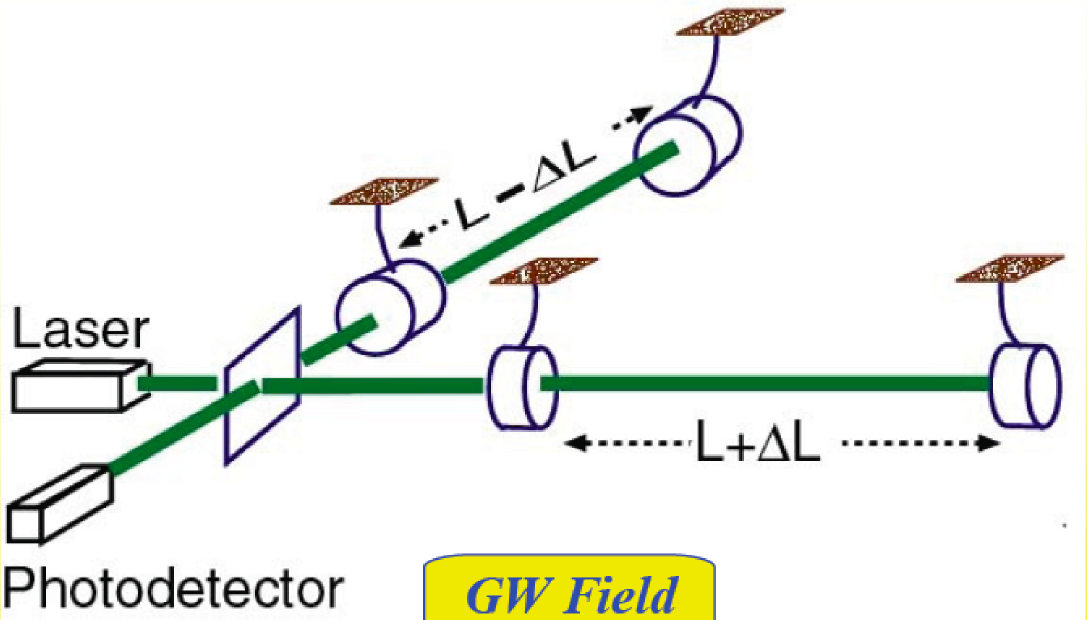
Gravitational Waves

- Warpage of Spacetime
- Generated by time-dependent quadrupoles

$$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{D}$$

- Detector response to passage of GWs:

Gravitational Wave Interferometer



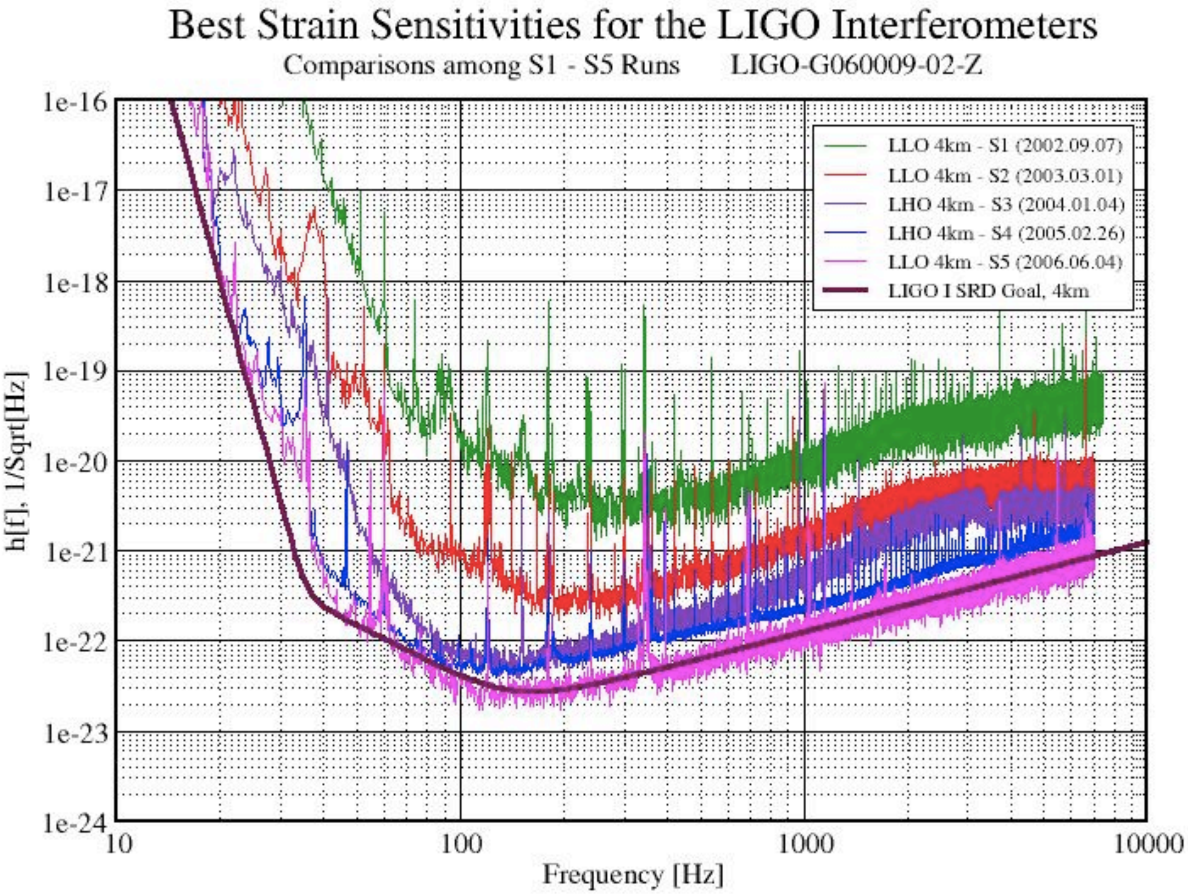
GW Field

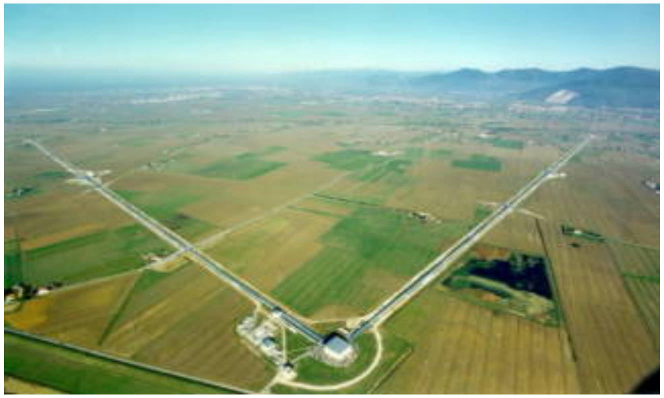
$$\Delta L = h\ L \lesssim 4\times10^{-16}\ \text{cm}$$

$\lesssim 10^{-21}$

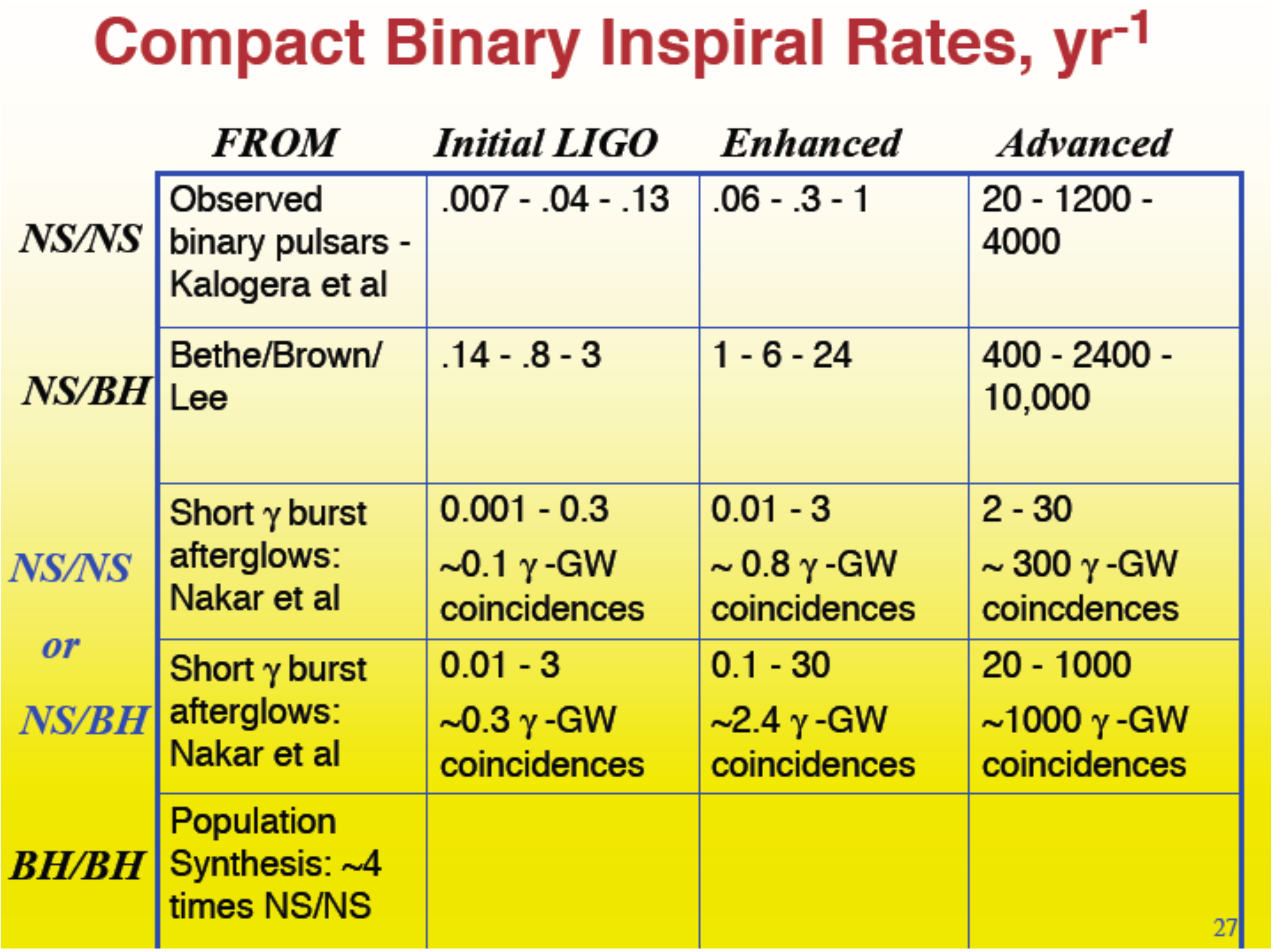
4 km

Kip Thorne





iLIGO: reached h~10^{-21} (2006)
eLIGO: h ~ 1/2 smaller (taking/analysing data)
aLIGO: h ~1/10 smaller (2018?)

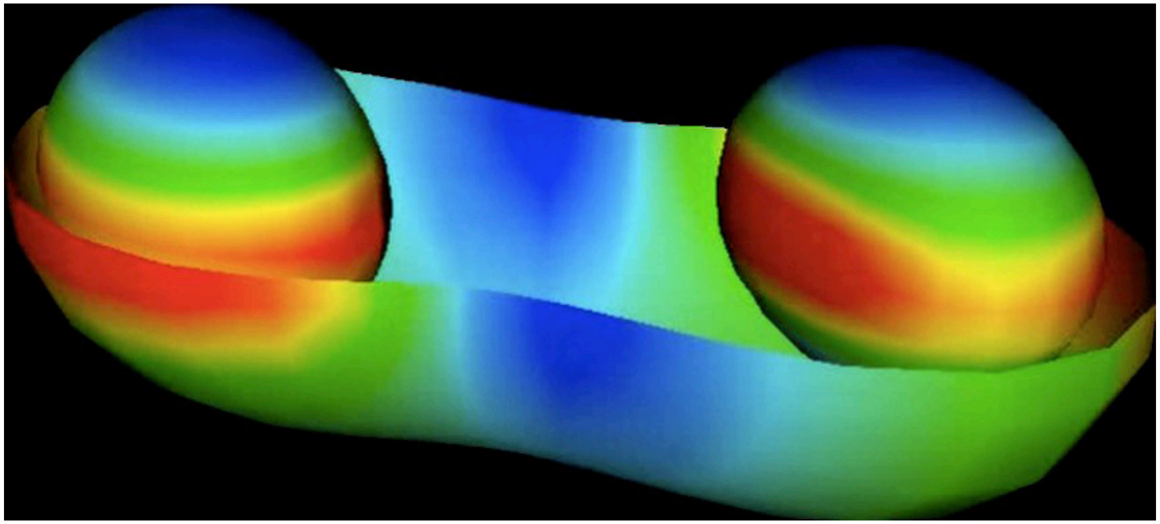


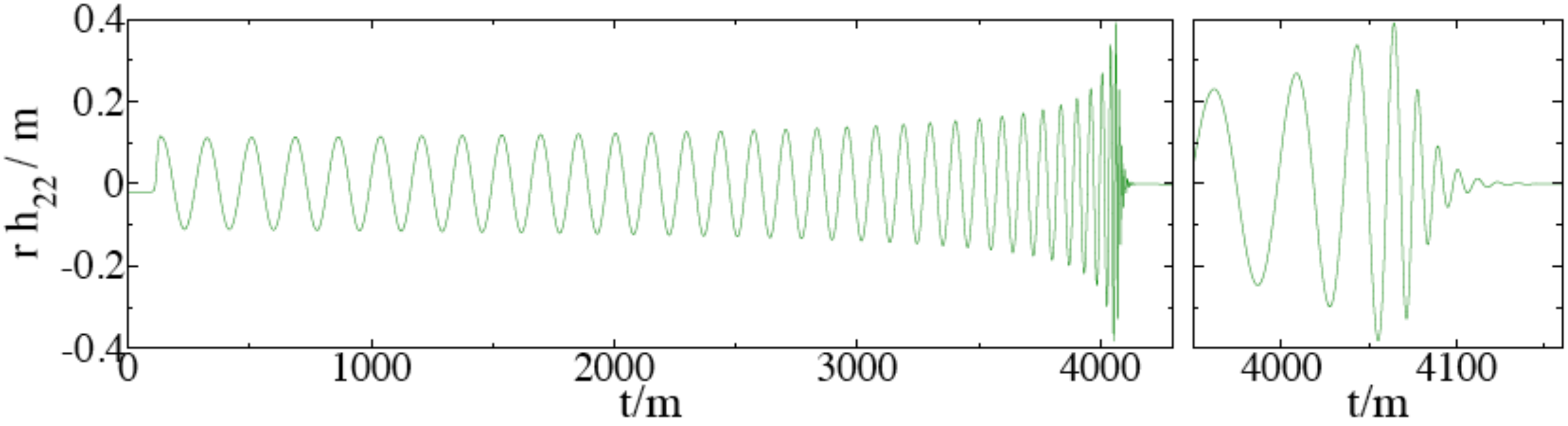
Compact Binary Inspiral Rates, yr^{-1}

	FROM	*Initial LIGO*	*Enhanced*	*Advanced*
NS/NS	Observed binary pulsars - Kalogera et al	.007 - .04 - .13	.06 - .3 - 1	20 - 1200 - 4000
NS/BH	Bethe/Brown/ Lee	.14 - .8 - 3	1 - 6 - 24	400 - 2400 - 10,000
NS/NS ***or***	Short γ burst afterglows: Nakar et al	0.001 - 0.3 ~0.1 γ -GW coincidences	0.01 - 3 ~ 0.8 γ -GW coincidences	2 - 30 ~ 300 γ -GW coincdences
NS/BH	Short γ burst afterglows: Nakar et al	0.01 - 3 ~0.3 γ -GW coincidences	0.1 - 30 ~2.4 γ -GW coincidences	20 - 1000 ~1000 γ -GW coincidences
BH/BH	Population Synthesis: ~4 times NS/NS			

Kip Thorne

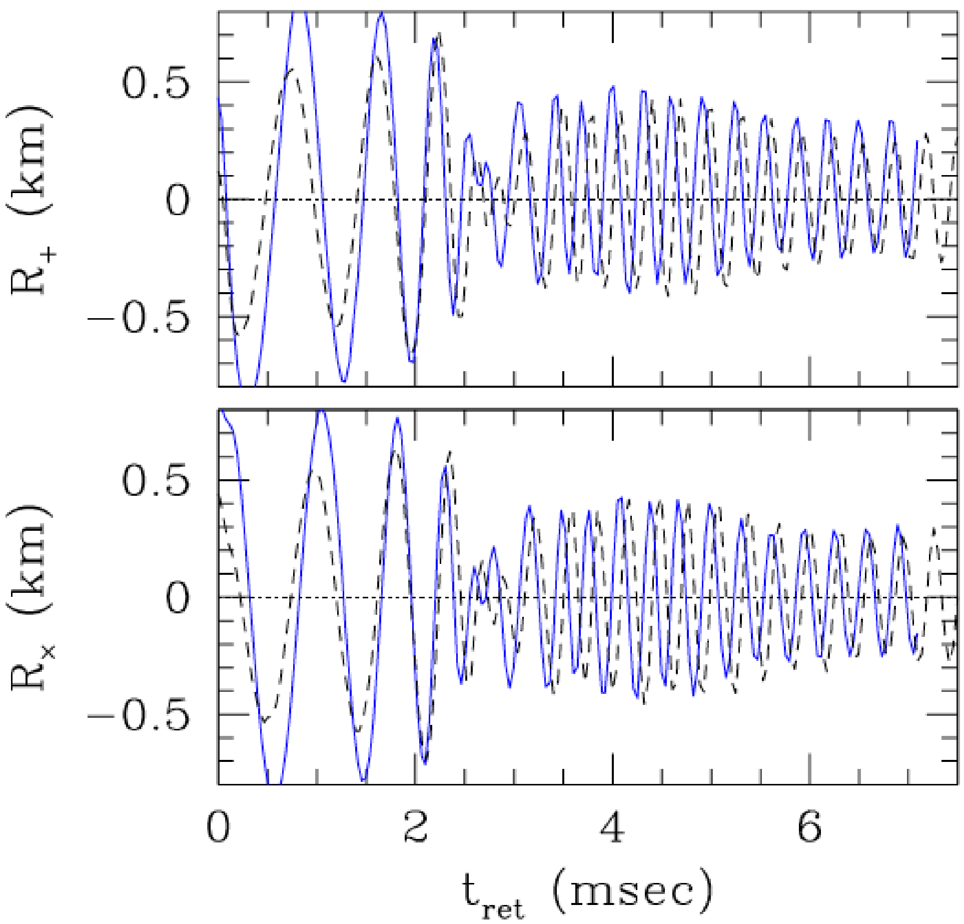
Gravitational waves probe nonlinear gravity

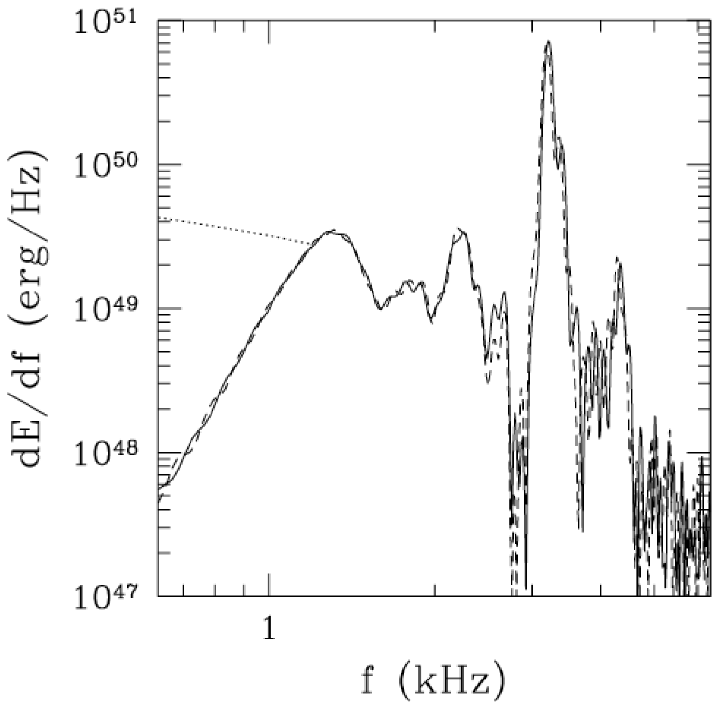




Cornell-Caltech collaboration

Gravitational waves probe NS EOS



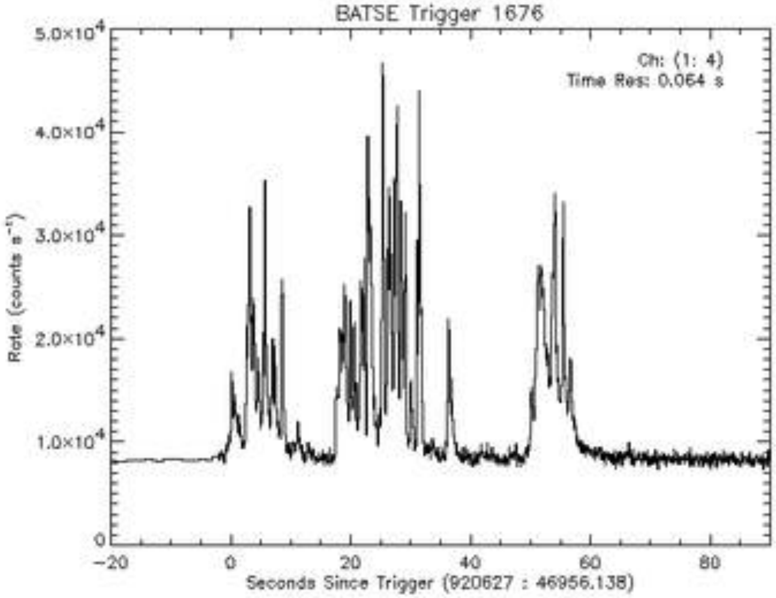


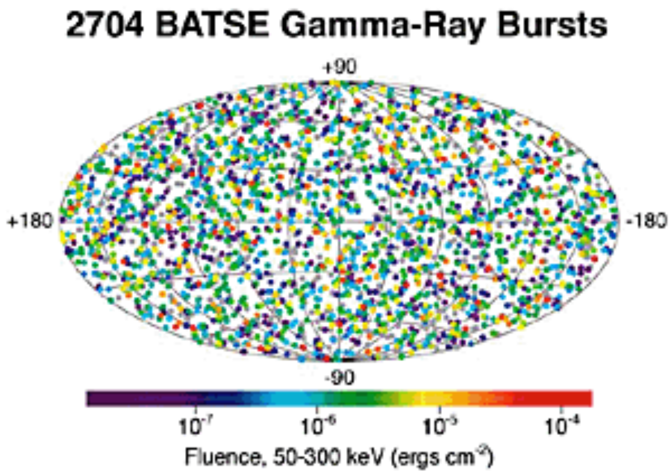
Masses well measured from inspiral waveform
Final cut-off frequency ~ $(GM/R^3)^{1/2}$

Cutler et al. ‘92;
DL & Wiseman ‘96;
Shibata et al.’ 06;
…
Bauswein, Janka...’ 12

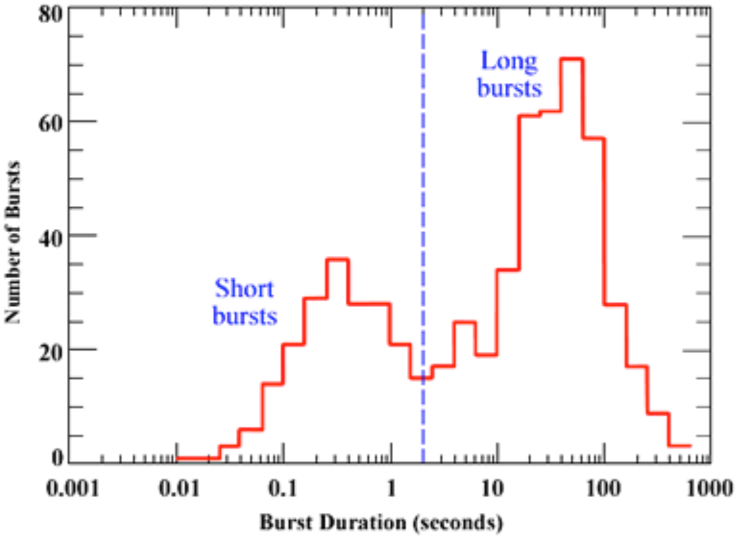
NS/NS and NS/BH Mergers: Electromagnetic Counterparts

Gamma-Ray Bursts





Gamma-ray bursts come from all directions.



--Bursts of 0.1-10 MeV gamma-rays

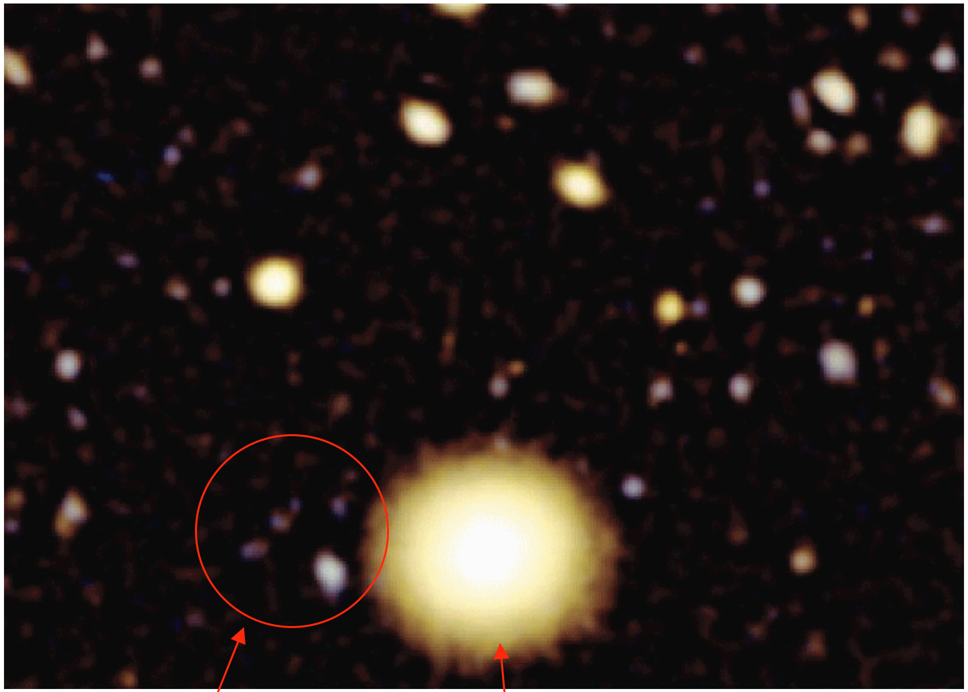
--From all directions, z~0.1-10

--Very energetic ~$10^{48\text{-}55}$ erg

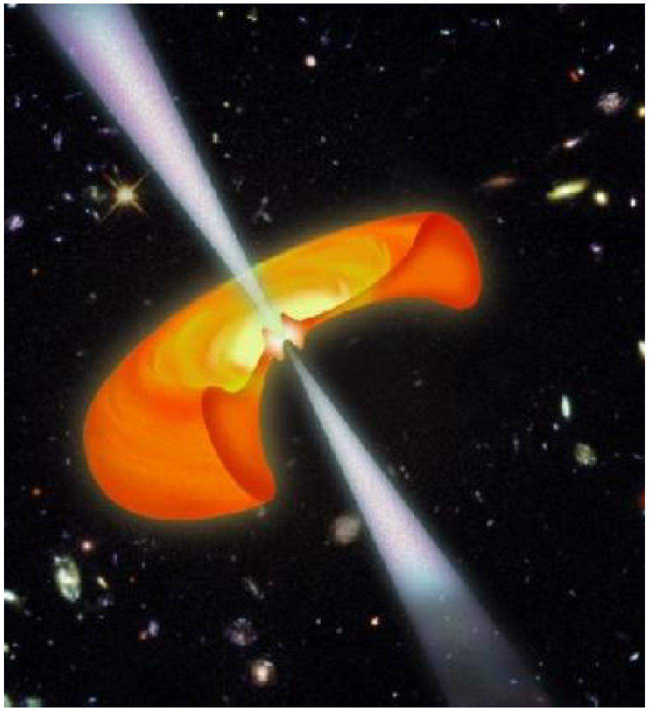
--Rare: GRB rate ~ 10^{-6}/yr/galaxy

--”Long” (~30s) and “short” (~0.3s)

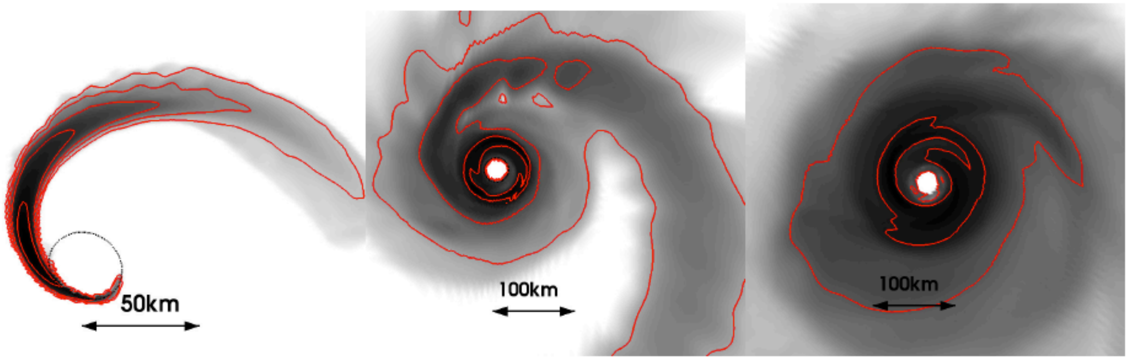
Merging NS/BH (or NS/NS?): Central Engine of Short GRBs



Bloom et al. 2006



Merging NS/BH and NS/NS: Optical/IR Transients (?)



Foucart et al. (Cornell-Caltech)

NS tidal ejecta $10^{-3} - 10^{-2} M_{\odot} (?)$

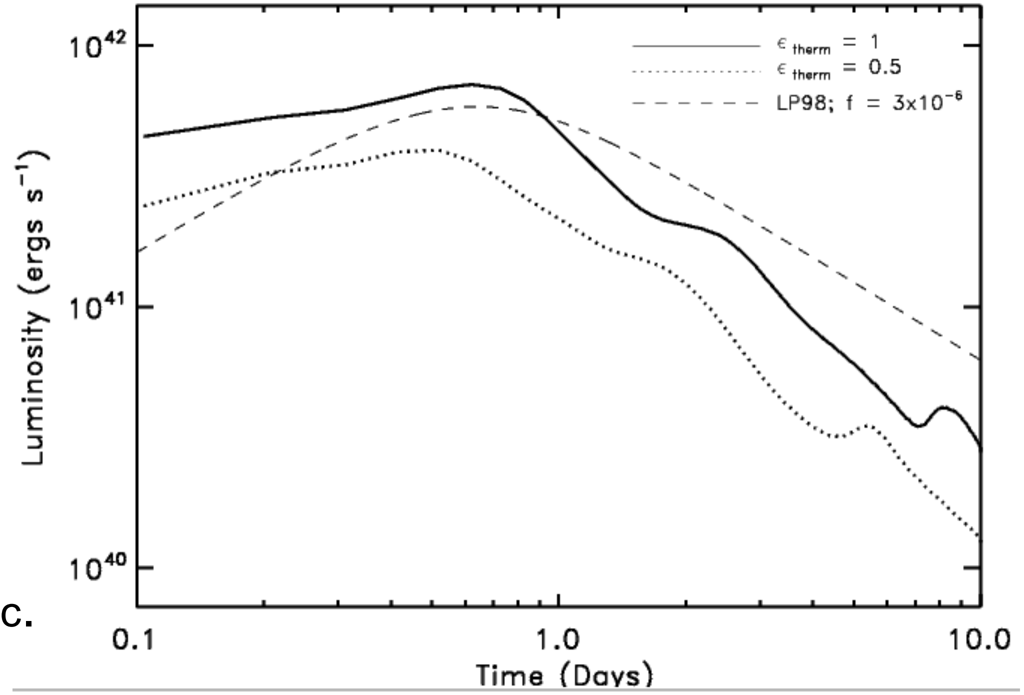
Ejecta evolution:

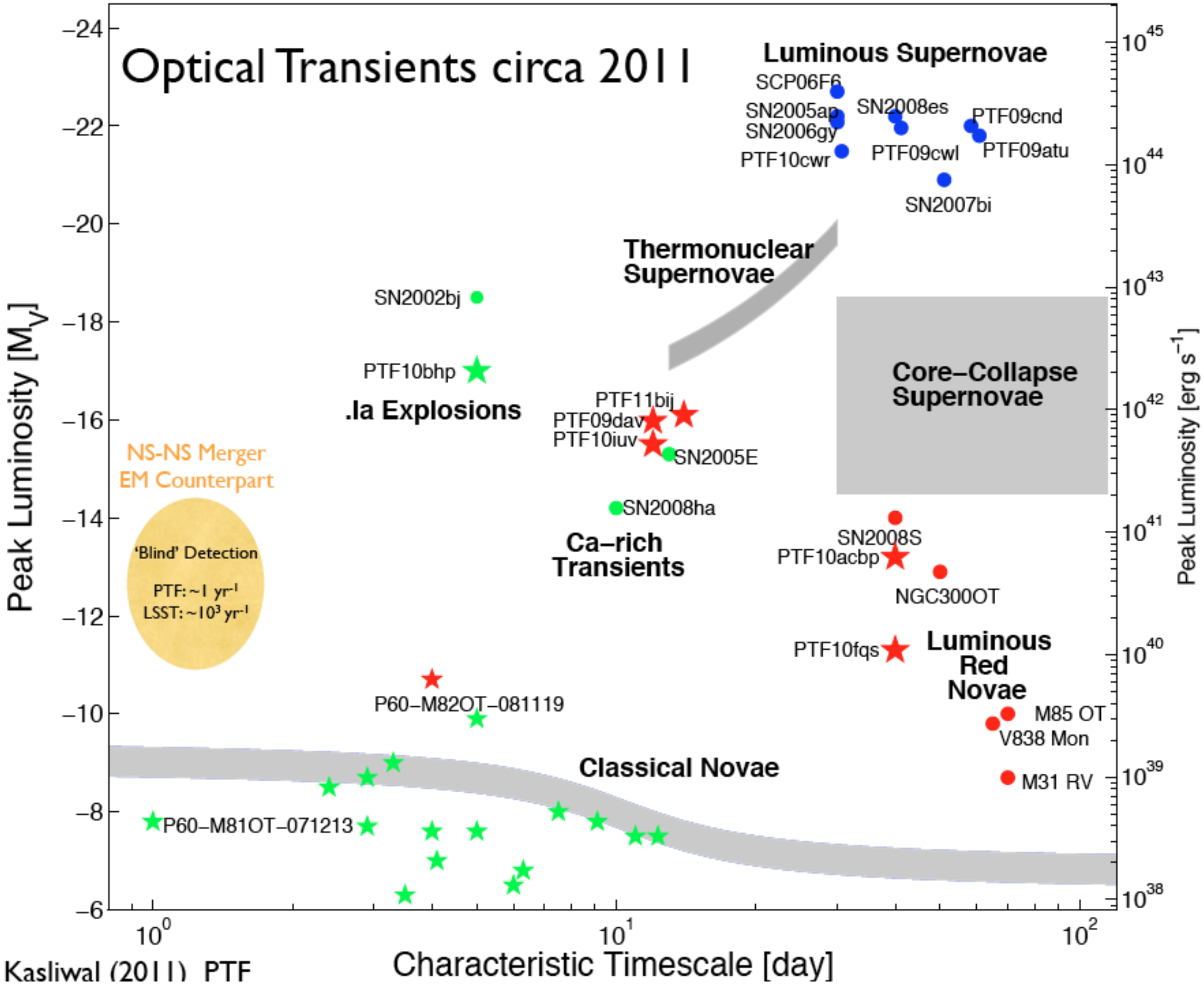
Initially mostly hot neutrons,
Decompression (cooling),
Nuclear reactions==> heating

$$L \sim 3 \times 10^{41}\,\mathrm{erg\ s^{-1}} \quad \text{at} \quad t \sim 1\,\mathrm{day}$$

$$T \sim 10^4\,\mathrm{K} \quad (\text{optical})$$

Matzger, Quataert, etc.





Kasliwal (2011) PTF

Pre-Merger Phase:

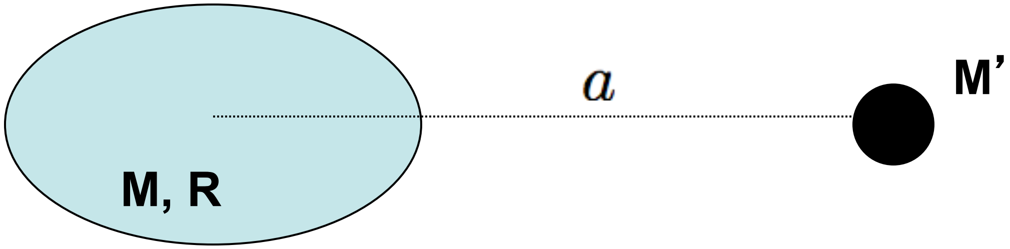
Anything interesting?

Pre-Merger Phase:
Non-magnetic Neutron Stars

Tides

-- Equilibrium tides
-- Dynamical tides

Equilibrium Tide



$$V = -\frac{MM'}{a} - \mathcal{O}\left(k_2 \frac{M'^2 R^5}{a^6}\right)$$

$k_2 =$ Love number

$$dN_{\rm GW} = dN_{\rm GW}^{(0)}\left[1 - \mathcal{O}\left(k_2 \frac{M' R^5}{M a^5}\right)\right]$$

(Missing GW cycles)

==> Important only at small separation (just prior to merger)

(Bildsten & Cutler 1992; Kochenek 92; DL, Rasio & Shaipro , etc)

Numerical GR Quasi-equilibrium NS binary sequence

(Baumgarte, Shapiro, Teukolsky, Shibata, Meudon group, etc. 1990s--200x)

Recent (semi-analytic) GR calculation of tidal effect

(Hinderer, Flanagan, Poisson, Damour, Penner, Andersson, Jones, etc., 2008+)

Dynamical Tides:
Excitations of Internal Waves/Modes

NS has low-frequency oscillation modes:

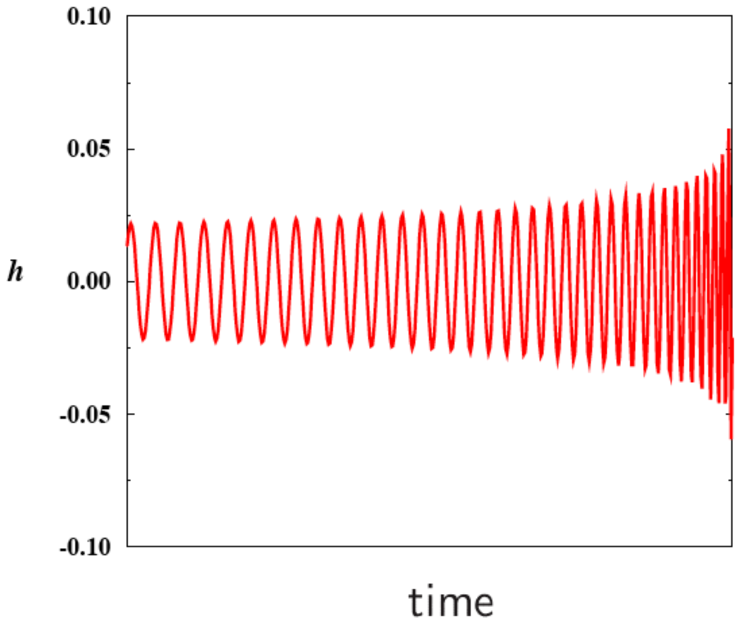
- **g-modes (~100 Hz) (depends on symmetry energy)**
- **inertial modes (incl. r-modes),…**

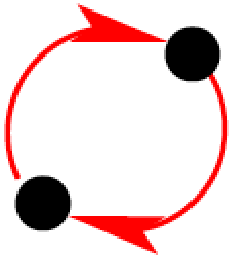
Resonance: $$\omega_\alpha = m\Omega_{\rm orb}, \quad m = 2, 3, \cdots$$

Dynamical Tides:
Excitations of Internal Waves/Modes

==> Probe NS EOS using Inspiral Waveform

Rosonant tidal excitations of NS modes during inspiral
==> transfer orbital energy to NS
==> Missing GW cycles





Resonant Excitations of NS Oscillations During Inspiral

Non-rotating NS:

G-mode (Reisenegger & Goldreich 94; Shibata 94; DL 94)

Rotating NS:

G-mode, F-mode, R-mode (Ho & DL 99)
Inertial modes (DL & Wu 06)
R-mode (excited by gravitomagnetic force; Racine & Flanagan 06)

Results:

- For R=10 km NS, the number of missing cycles < 0.1, bearly measurable (unless NS is rapidly rotating)
- Number of missing cycles $\Delta N \propto R^4$ (g mode) or $R^{3.5}$ (r mode)
  Important for larger NS
- **G-modes:** No law that requires ΔN should be < 1 !
- **Crustal modes:** Could shatter crust, pre-cursor of short GRB (**Tsang** et al. 12)

Pre-Merger Phase: Magnetic NSs

Cf. Double Pulsars: **PSR J0737-3039**

pulsar A: ~10^{10}G
pulsar B: ~a few x10^{12}G

Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

DL 2012

$$\dot{E}_{\rm max} \simeq 7 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}} \right)^2 \left(\frac{a}{30\,{\rm km}} \right)^{-13/2} {\rm erg~s^{-1}}$$

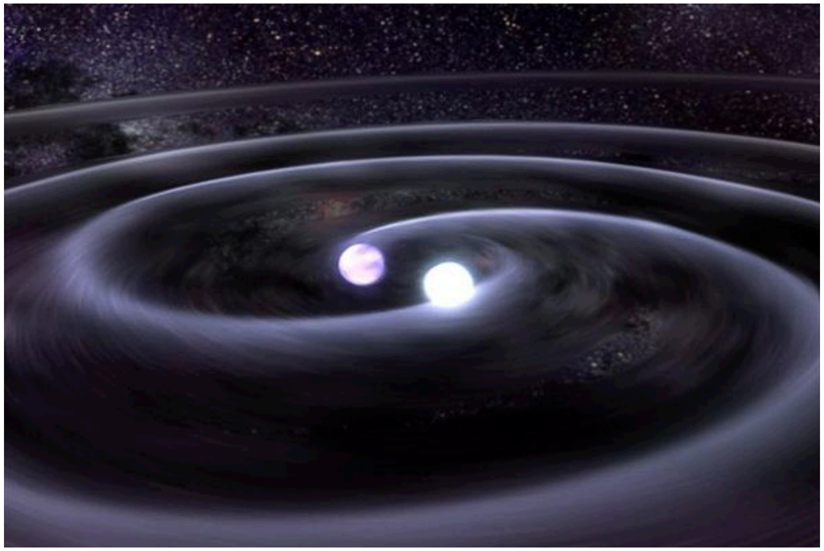
Actual dissipation rate:

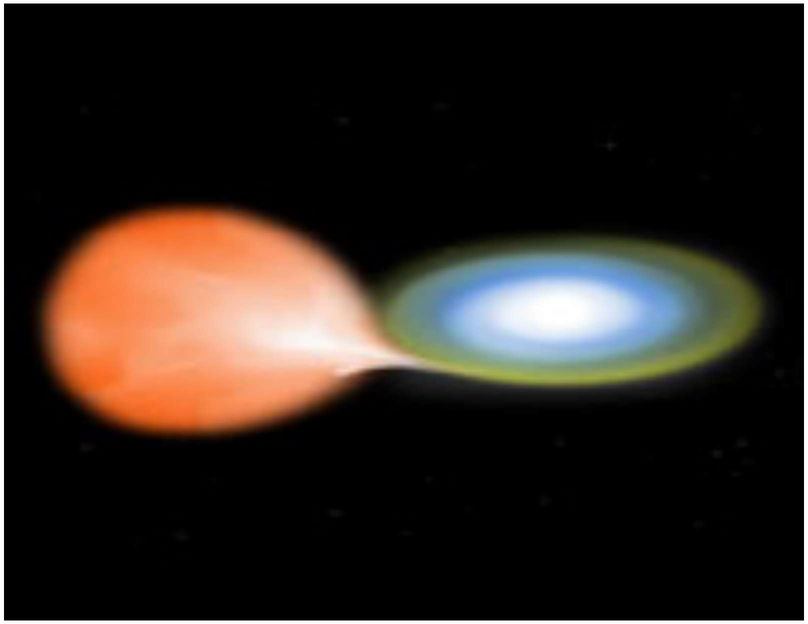
$$\dot{E} \sim 2 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}} \right)^2 \left(\frac{a}{30\,{\rm km}} \right)^{-7} {\rm erg~s^{-1}}$$

- This Edot will not affect orbital decay rate (GW signal)
- Radio emission prior to binary merger (?) **cf. Vietri 96; Hansen & Lyutikov 01**

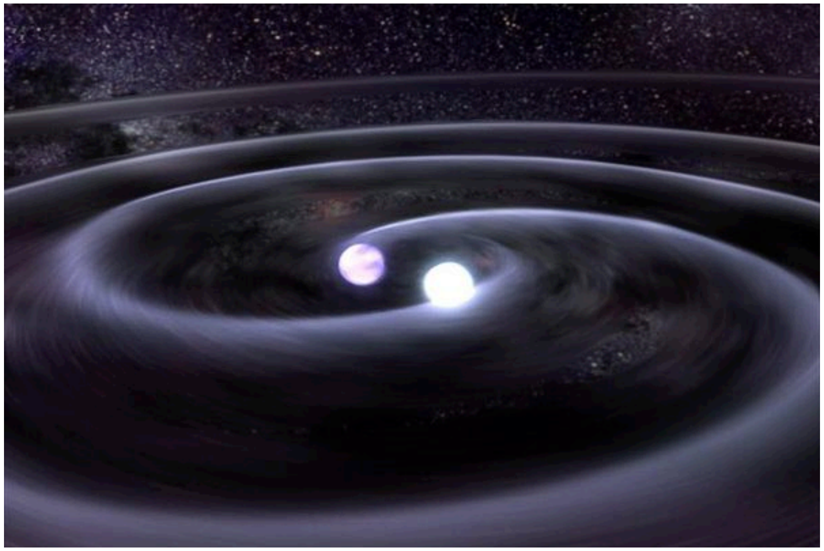
cf. isolated pulsars: $\dot{E} \simeq 10^{33} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}} \right)^2 \left(\frac{P}{1\,{\rm s}} \right)^{-4} {\rm erg~s^{-1}}$

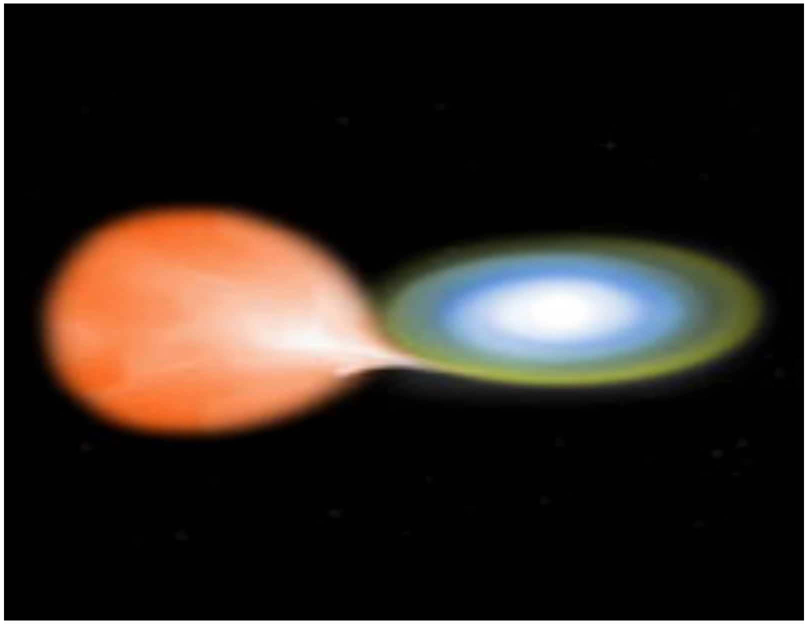
Compact White Dwarf Binaries (mins - hour)





Compact White Dwarf Binaries (mins - hour)





-- Dominant sources of gravitational waves (10^{-4}-0.1 Hz)

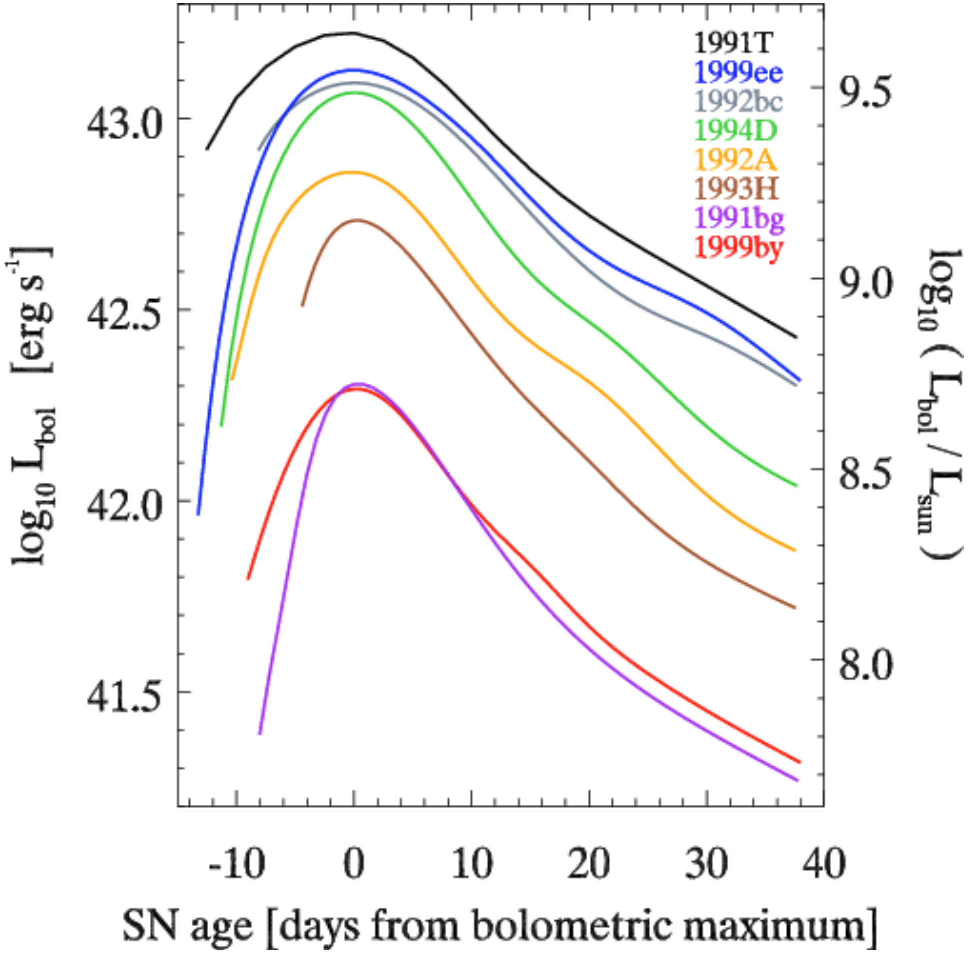
Space interferometer (eLISA-NGO??)

-- Lead to various outcomes:

R CrB stars, AM CVn binaries, transients

If total mass ~ $1.4M_{sun}$: AIC => NS or SN Ia

Type Ia Supernovae



Type Ia Supernovae

Thermonuclear explosion of CO white dwarfs of ~1.4M_{sun}

Progenitors ??

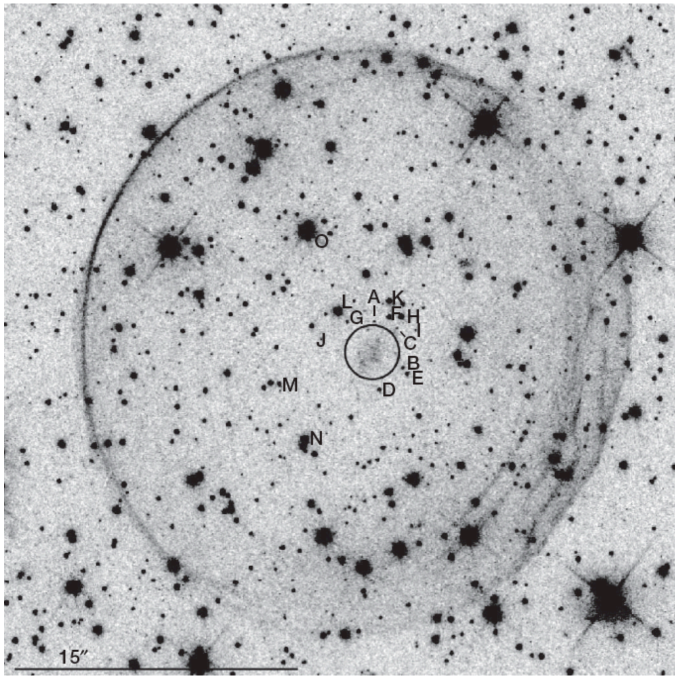
WD + non-deg. star: “Single-degenerate” Scenario
WD + WD merger: “Double-degenerate” Scenario
WD + WD collision ?

Various arguments for/against each scenario:

Rates, super-soft sources, delay time…

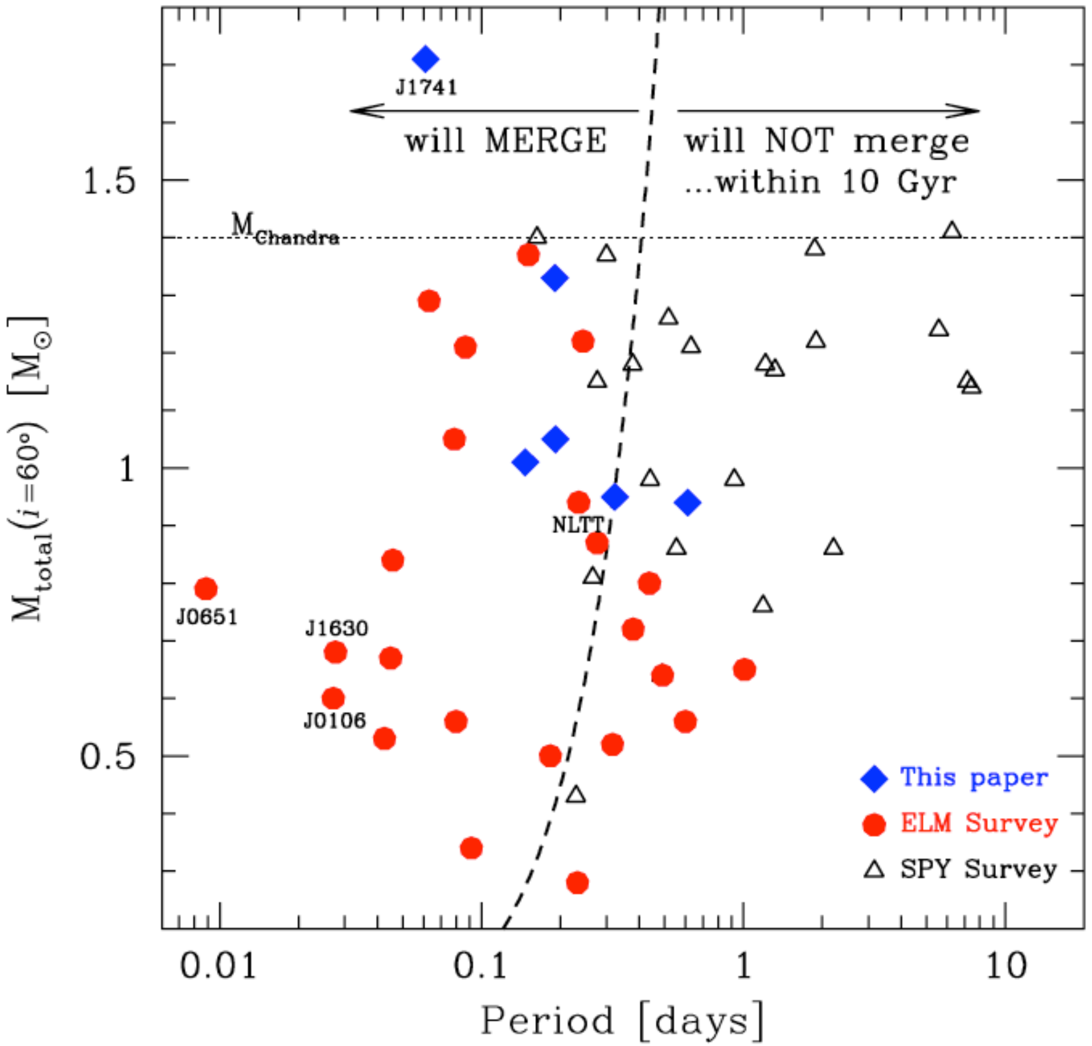
Recent observations in favor of DD:

e.g., Absence of ex-companion stars
in SN Ia remnant SNR 0509-67.5
==> rule out V=26.9



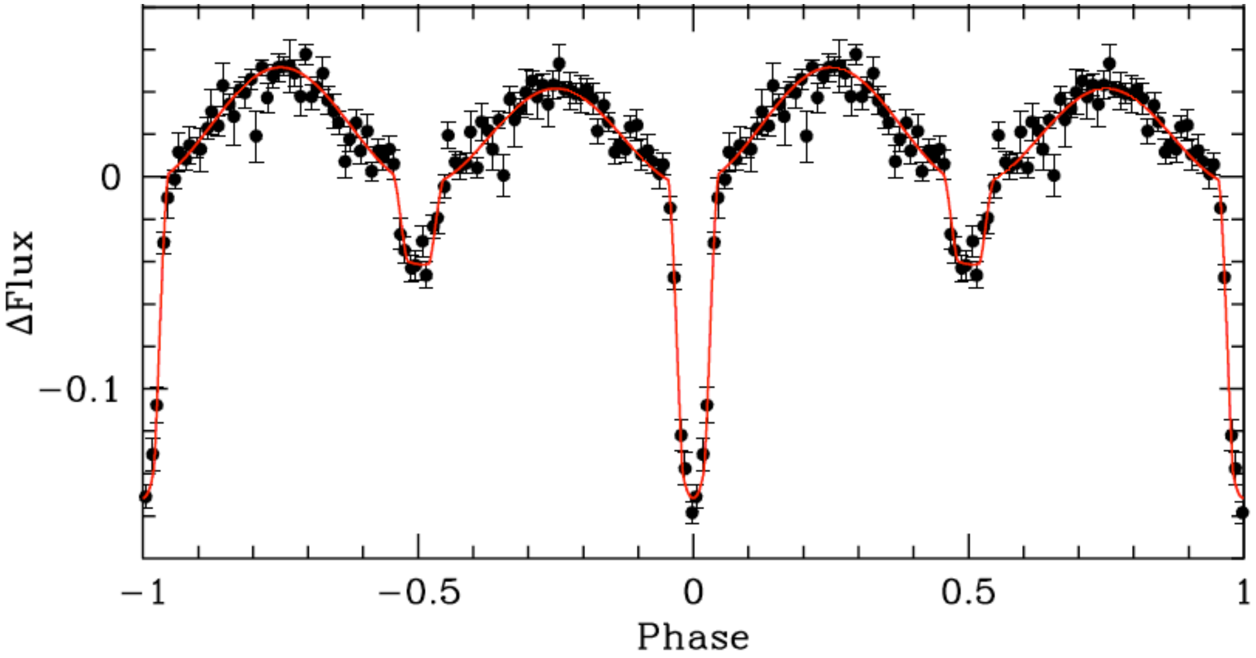
Schaefer & Pagnotta 2012
(cf Di Stefano & Kilic 2012)

Radial Velocity Surveys of Compact WD Binaries



Brown et al. 2012

12 min orbital period double WD eclipsing binary



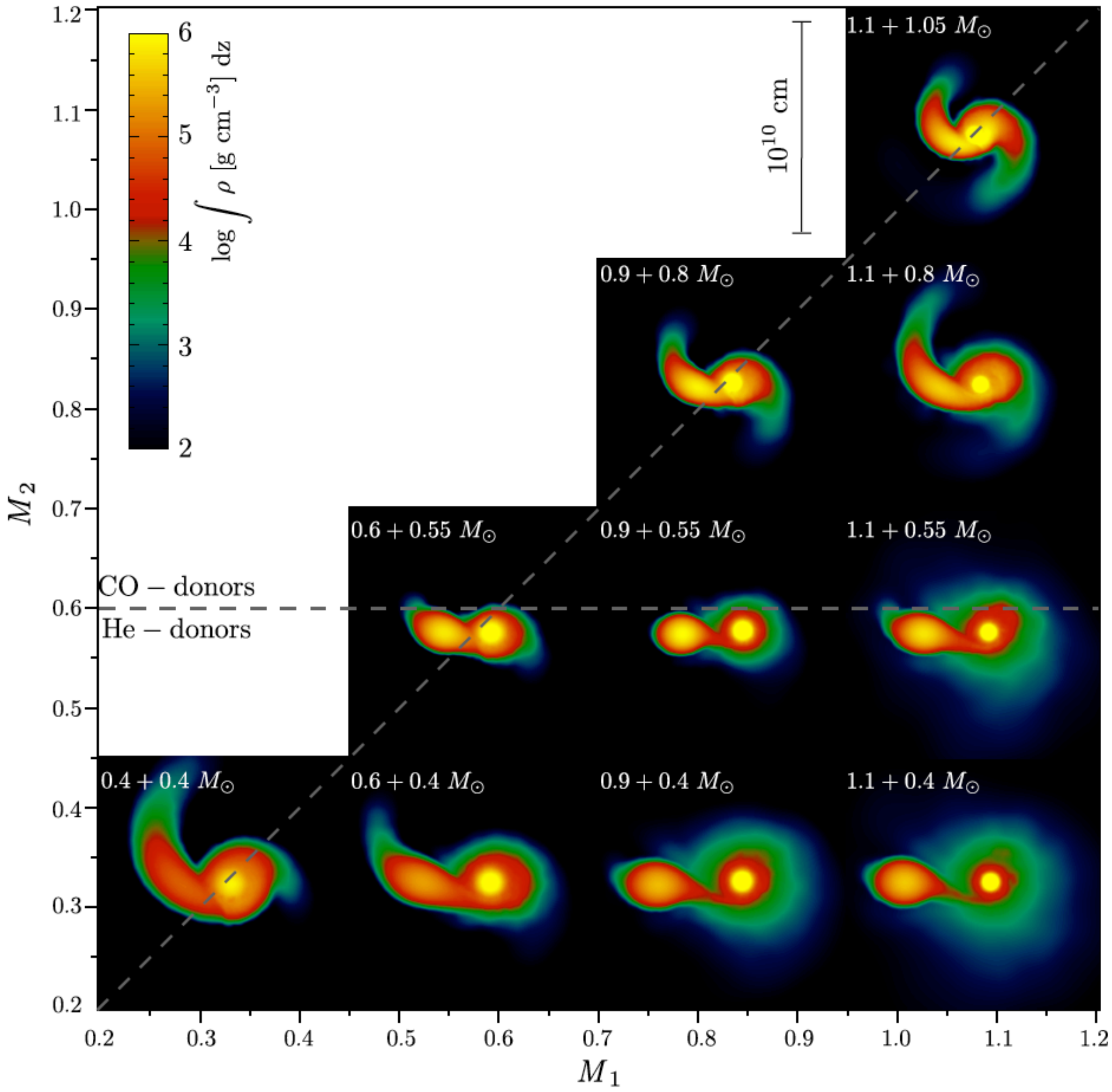
SDSS J0651+2844

Primary & secondary
eclipses
Ellipsoidal (tidal) distortion
Doppler boosting

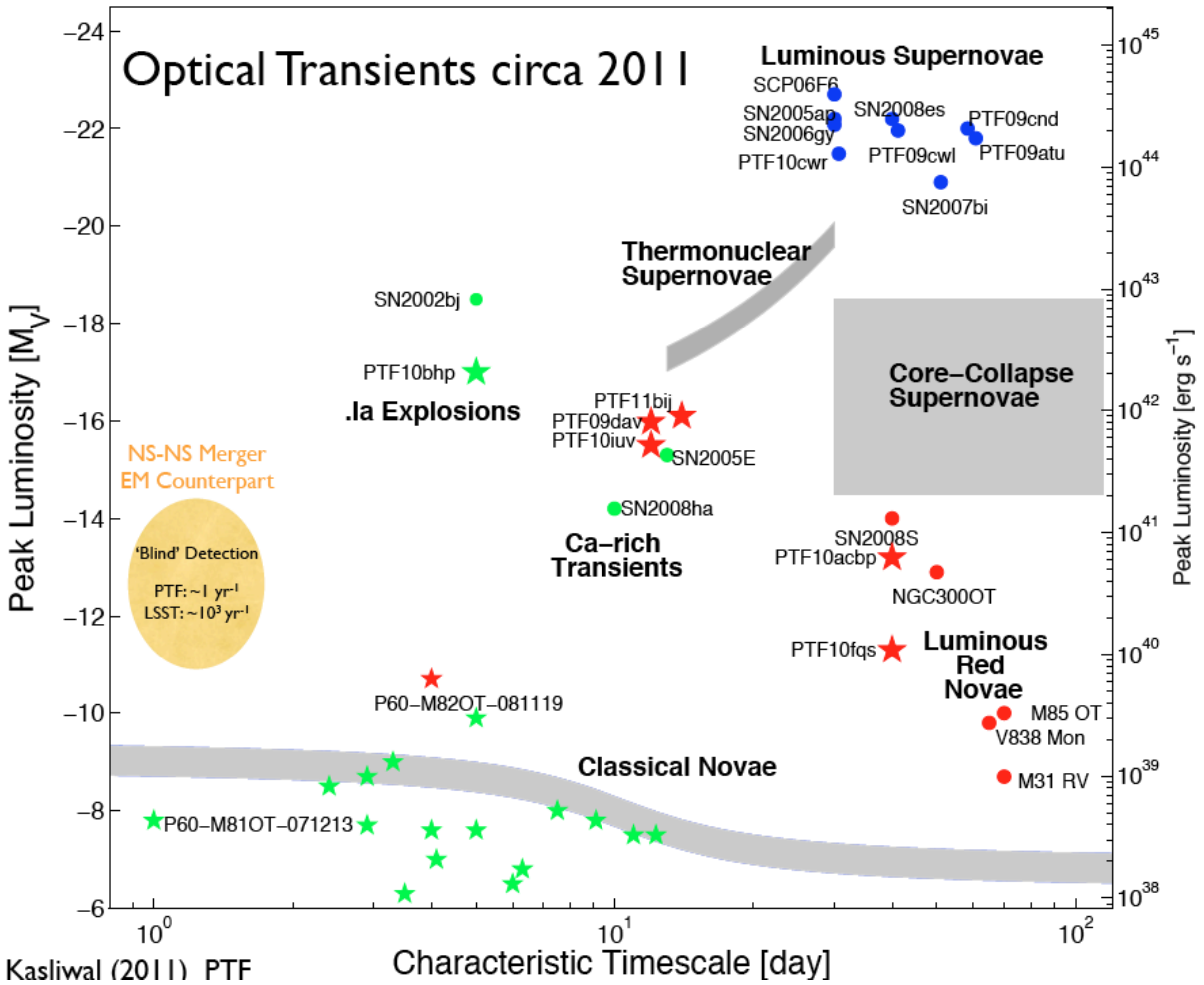
Brown et al. 2011

-- will merge in 0.9 Myr
-- large GW strain ==> (LISA)
-- orbital decay measurable from eclipse timing (Hermes et al 2012)

WD Binary Merger



Dan, Rosswog,et al. 2012



Optical Transients circa 2011

Kasliwal (2011) PTF

WD binary merger: Outcome depends on WD masses, composition, and pre-merger conditions

Dynamical Tides in Compact WD Binaries

Jim Fuller & DL

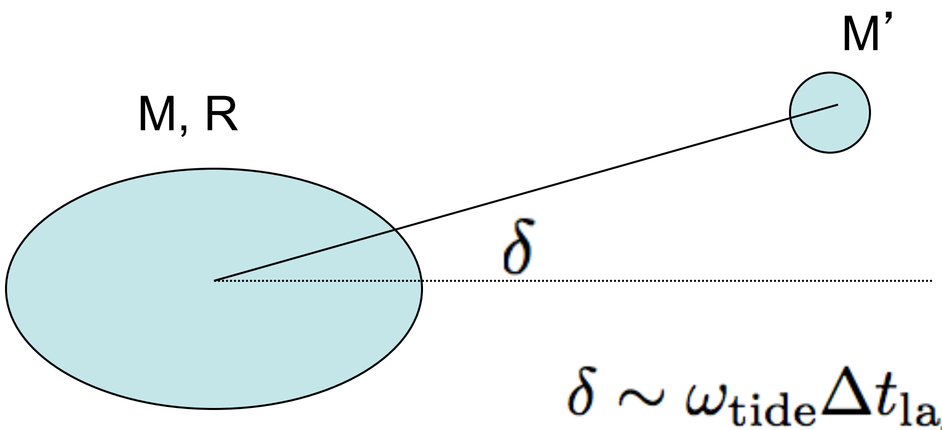
Issues:

-- Spin-orbit synchronization?

-- Tidal dissipation and heating?

-- Effect on orbital decay rate? (e.g. eLISA-NGO)

Equilibrium Tide



$$\delta \sim \omega_{\rm tide}\Delta t_{\rm lag} \sim 1/Q$$

$$\omega_{\rm tide} = 2(\Omega_{\rm orb} - \Omega_s)$$

$$\text{Torque} \sim G\left(\frac{M'}{a^3}\right)^2 R^5\,\delta$$

$$\dot{E}_{\rm tide} = \text{Torque}\cdot\Omega$$

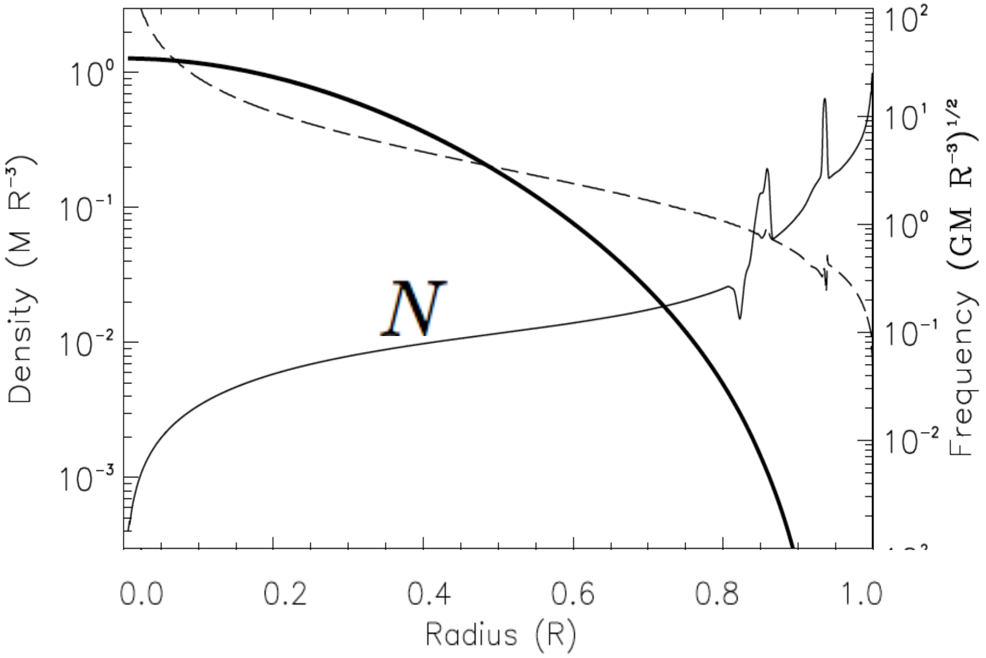
Problems:

-- Parameterized theory

-- The physics of tidal dissipation is more complex:

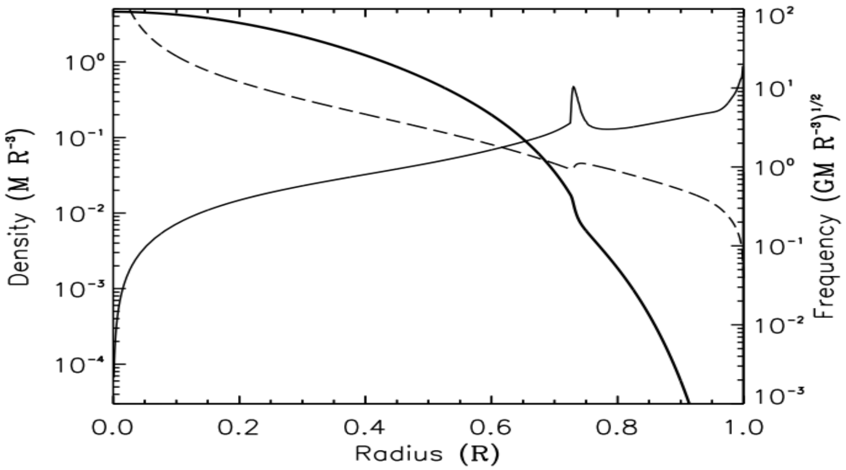
Excitation/damping of internal waves/modes (Dynamical Tides)

Wave Propagation inside White Dwarf



CO WD

$0.6M_\odot,\ 8720\,\mathrm{K}$

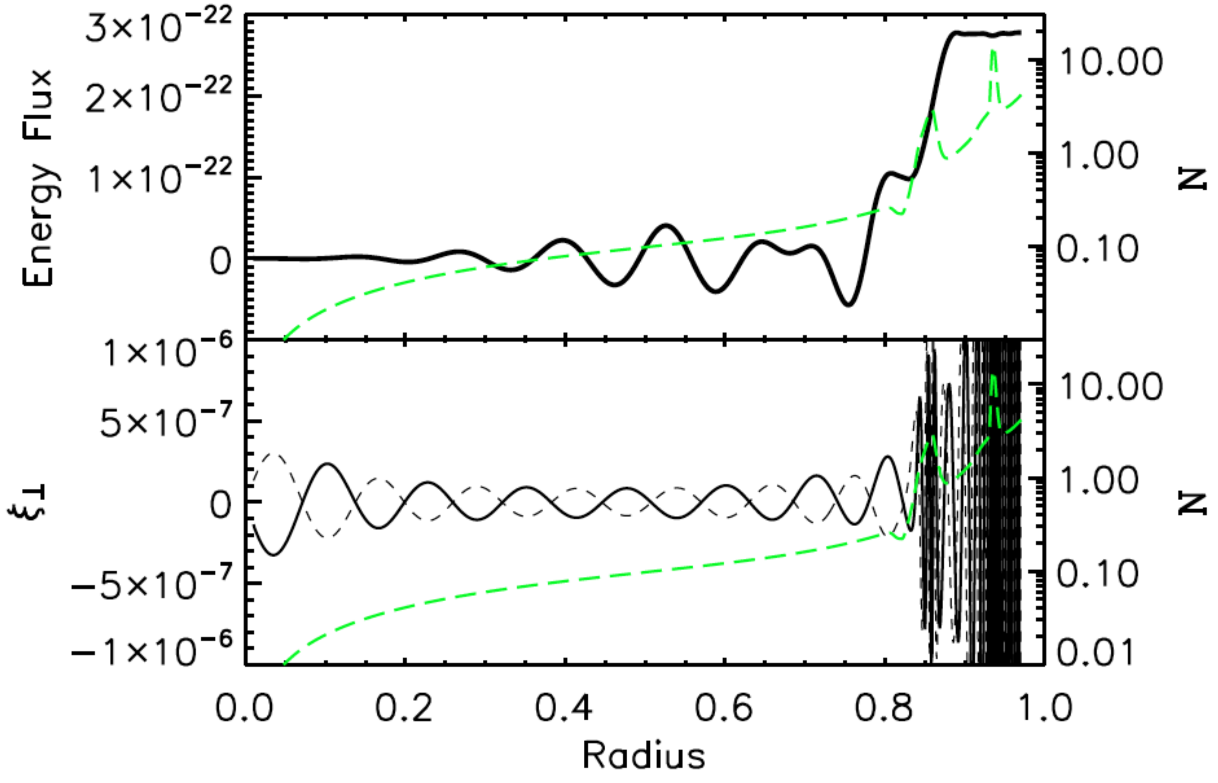


He-core WD

$0.3M_\odot,\ 12000\,\mathrm{K}$

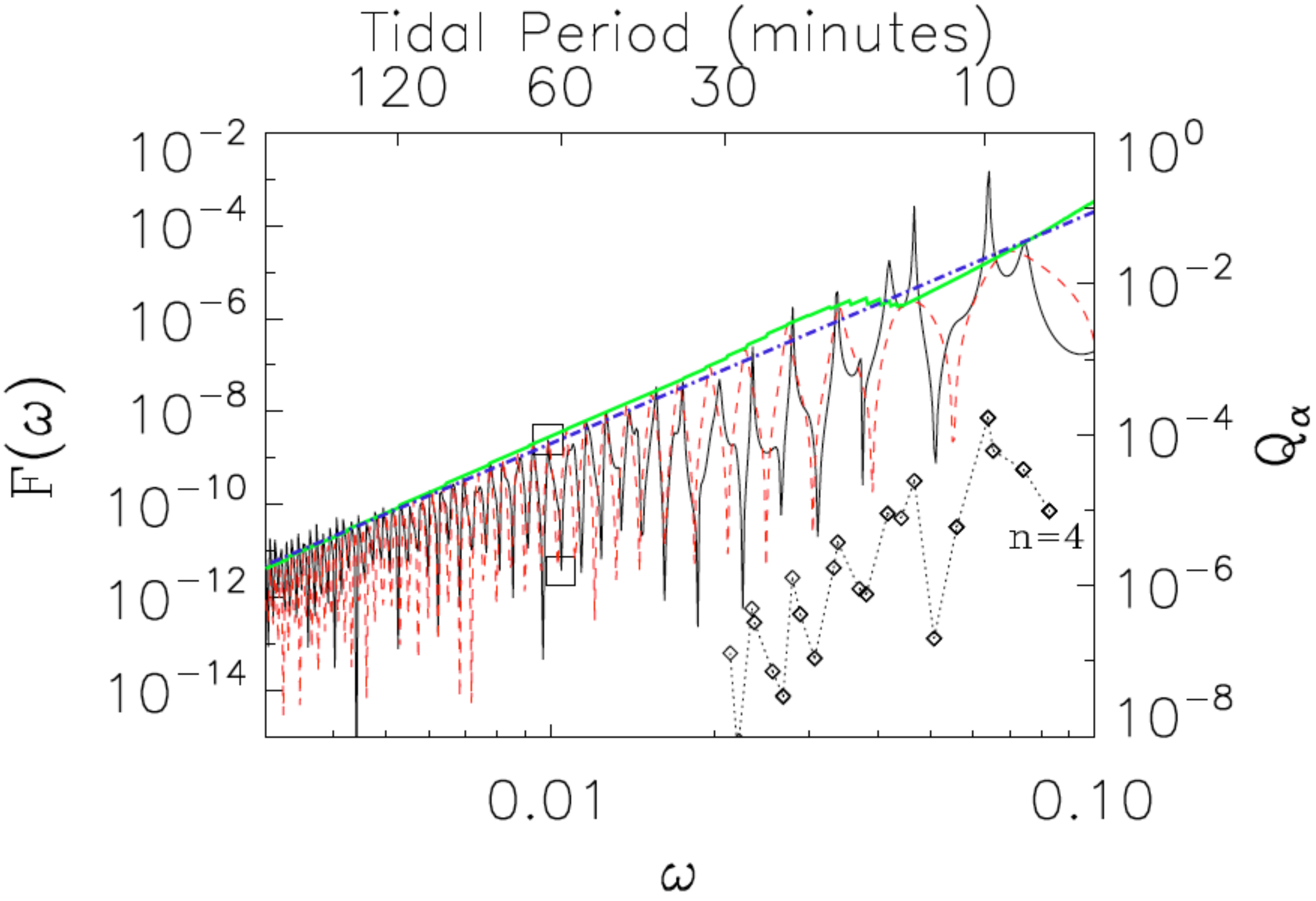
"Continuous" Excitation of Gravity Waves

Waves are excited in the interior/envelope, propagate outwards
and dissipate near surface

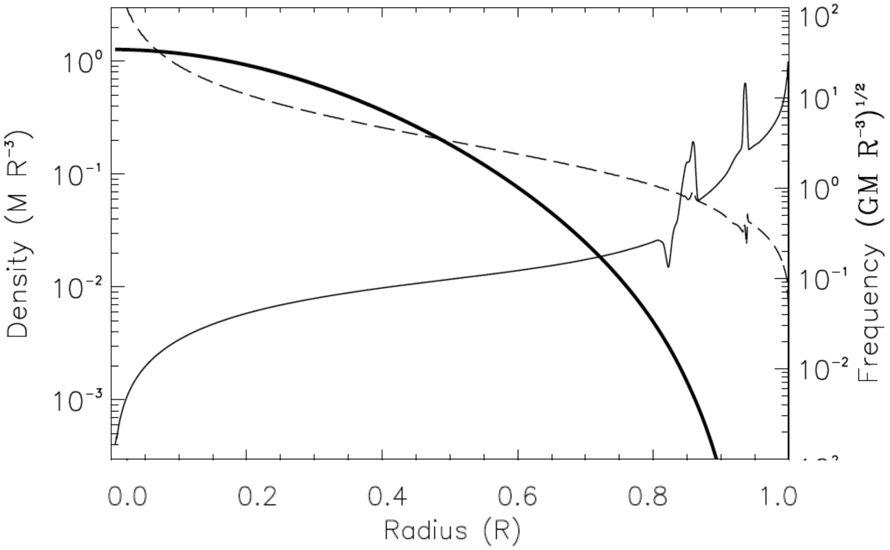


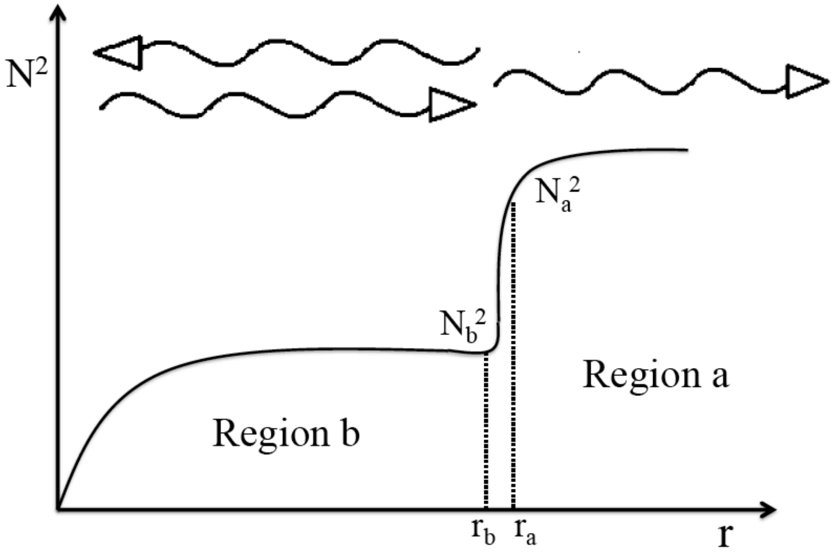
$M = 0.6 M_\odot, \quad \omega = 0.01$

$$\text{Torque} = G\left(\frac{M'}{a^3}\right)^2 R^5\ F(\omega)$$

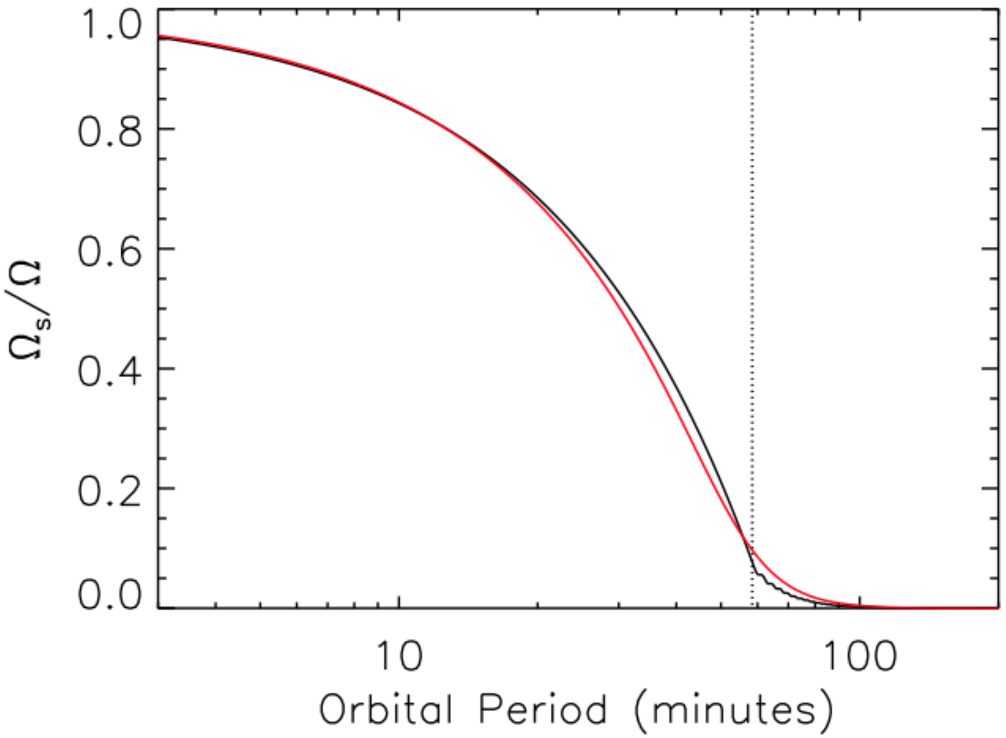


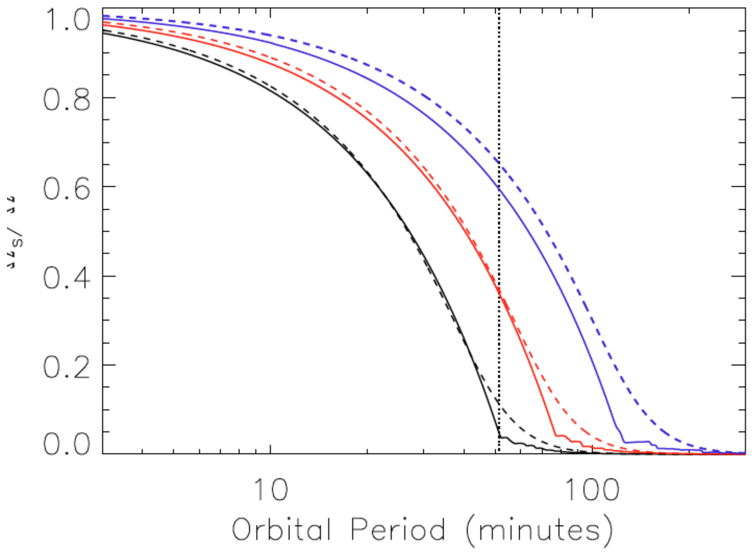
Why is $F(\omega)$ not smooth ?





Spin-Orbit Synchronization



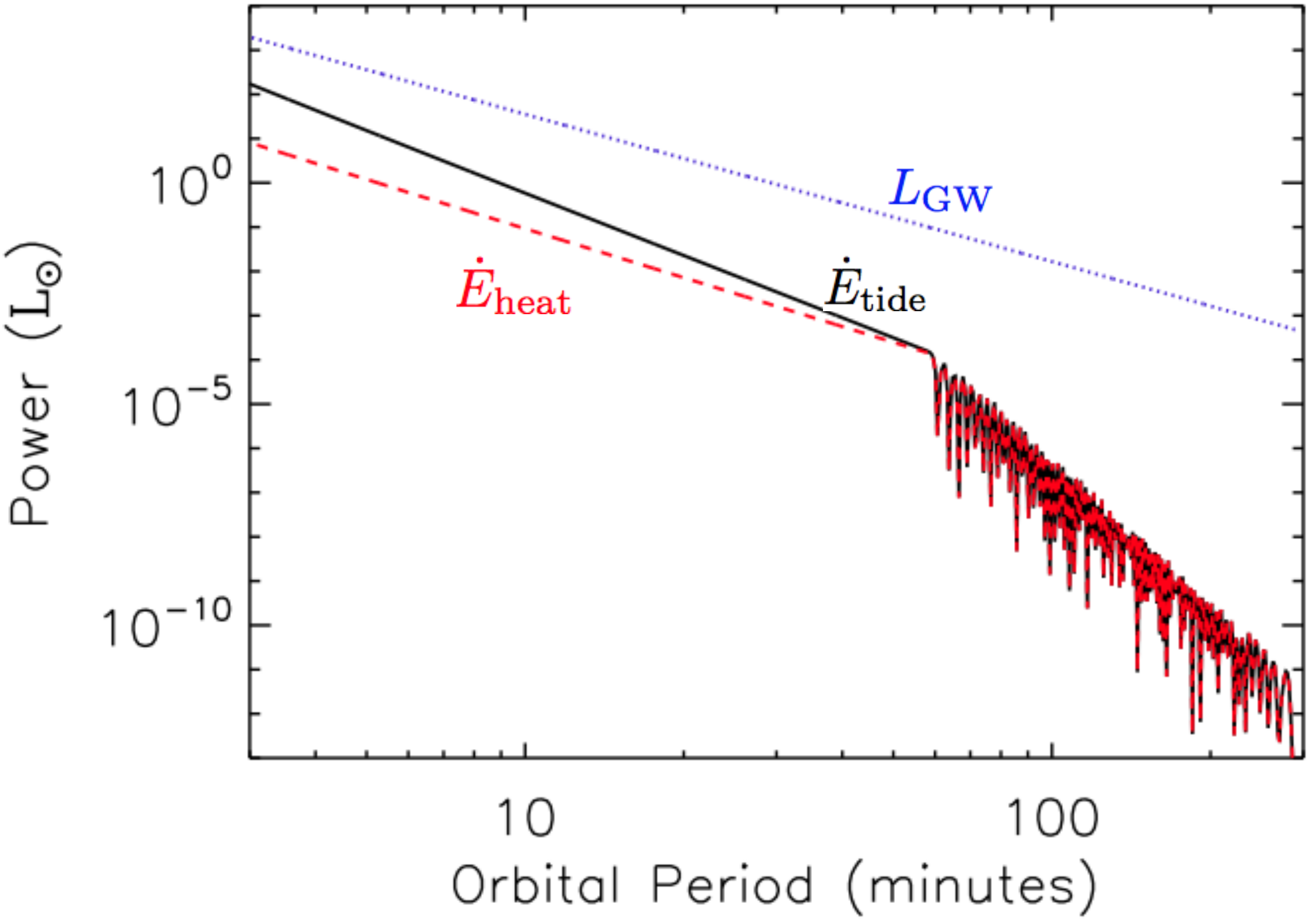


Critical orbital Ω_c : $\dot{\Omega}_s = \frac{\text{Torque}}{I} \simeq \dot{\Omega}_{\rm orb} = \frac{3\Omega_{\rm orb}}{2t_{\rm GW}}$

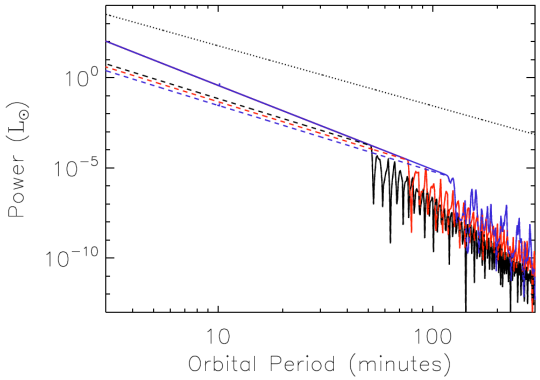
For $\Omega_{\rm orb} > \Omega_c$: $\dot{\Omega}_s > \dot{\Omega}_{\rm orb}$

$$\dot{\Omega}_s - \dot{\Omega}_{\rm orb} \ll \dot{\Omega}_{\rm orb} \Longrightarrow \dot{E}_{\rm tide} = \Omega_{\rm orb} T \simeq \frac{3I\Omega_{\rm orb}^2}{2t_{\rm GW}}$$

Tidal Heating Rate



$$\dot{E}_{\rm heat} = \dot{E}_{\rm tide}\left(1 - \frac{\Omega_s}{\Omega_{\rm orb}}\right)$$



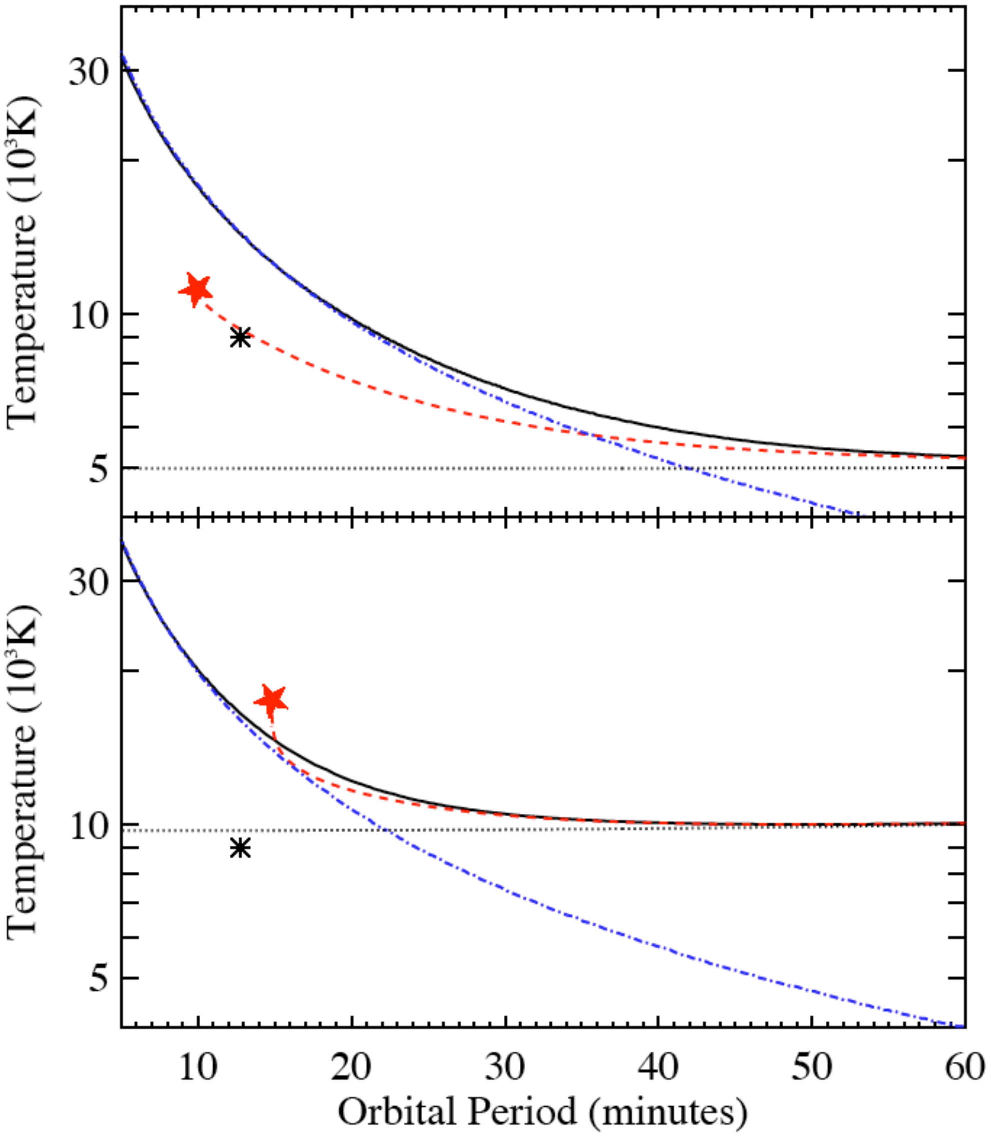
Consequences of Tidal Heating

Depend on where the heat is deposited …

If deposited in shallow layer:
  thermal time short
  ==> change T_{eff}

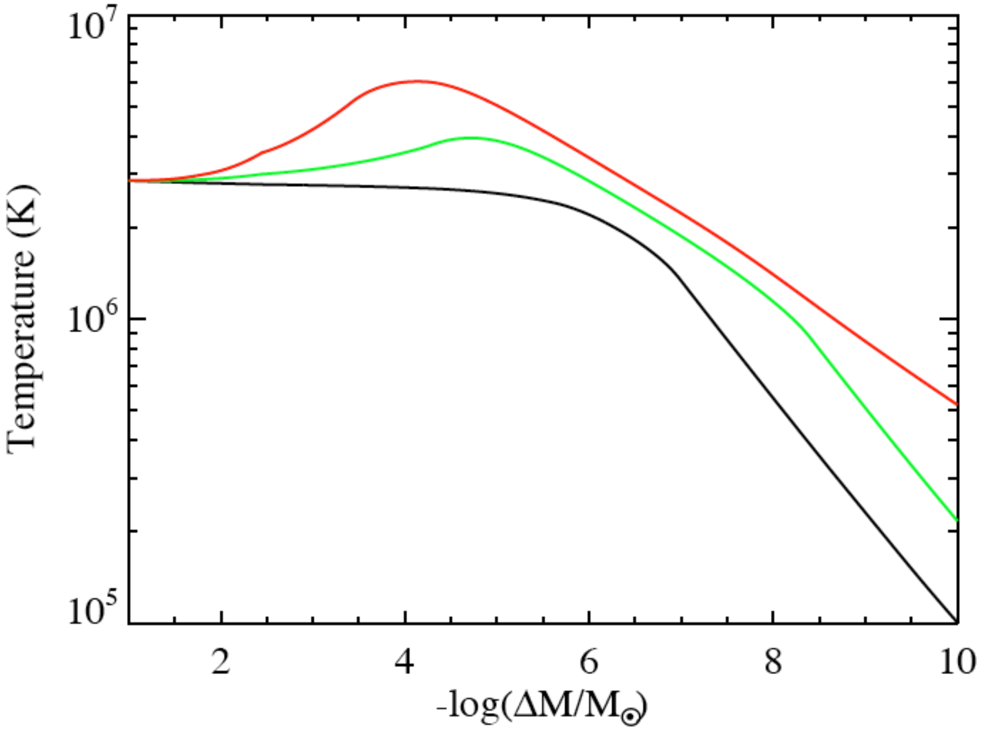
If deposited in deeper layer:
  thermal time longer than orbital
  ==> nuclear flash

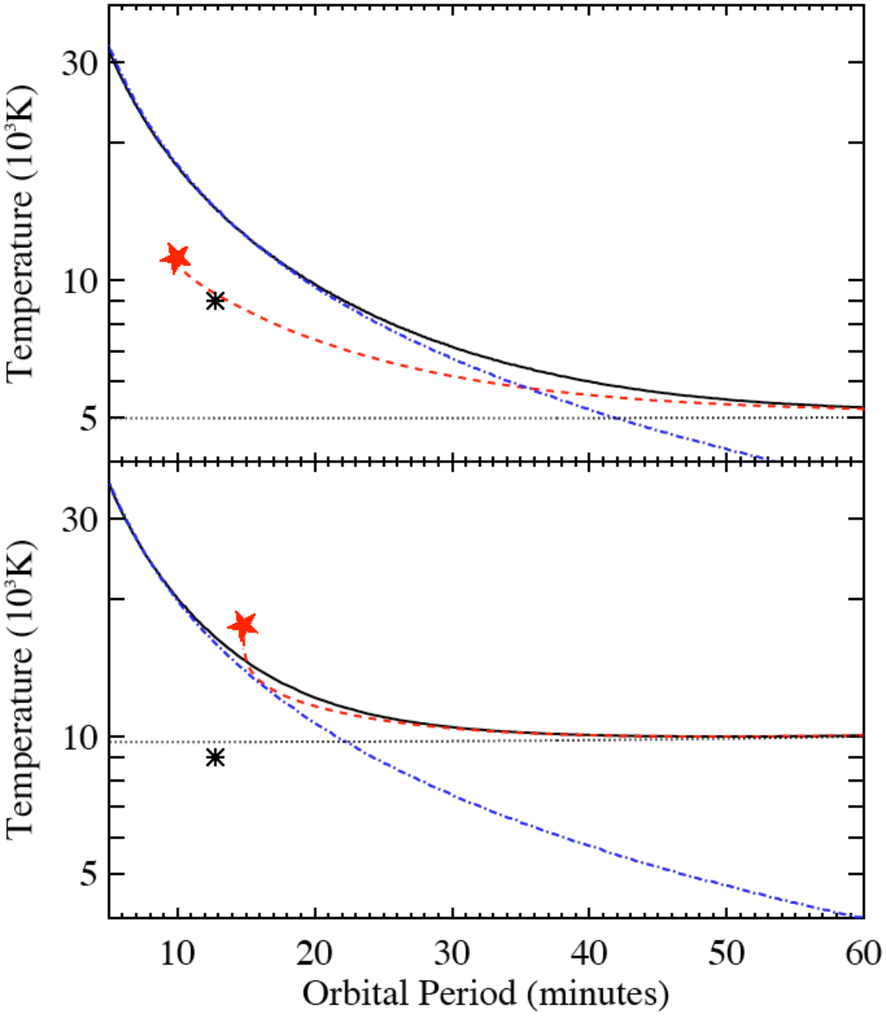
"Tidal Nova" !



Fuller & DL 2012

Tidal Nova


10^7
10^6
10^5
Temperature (K)
2
4
6
8
10
$-\log(\Delta M/M_\odot)$


30
10
5
Temperature (10^3K)
30
10
5
Temperature (10^3K)
10
20
30
40
50
60
Orbital Period (minutes)

Summary

- **Merging NS and BH Binaries:**

  -- will likely be detected this decade by LIGO/VIRGO

  -- Most severe test of gravity; also probe NS EOS

  -- EM counterparts: GRBs, Optical/IR detectable by LSST (?),
  Precusors (??)

- **Merging WD Binaries:**

  -- Being detected in recent/ongoing surveys

  -- Produce various outcomes: e.g., SN Ia

  -- Transient sources (PTF, LSST)

  -- Pre-merger: Tidal Nova

  -- Low-frequency GW sources (LISA??)