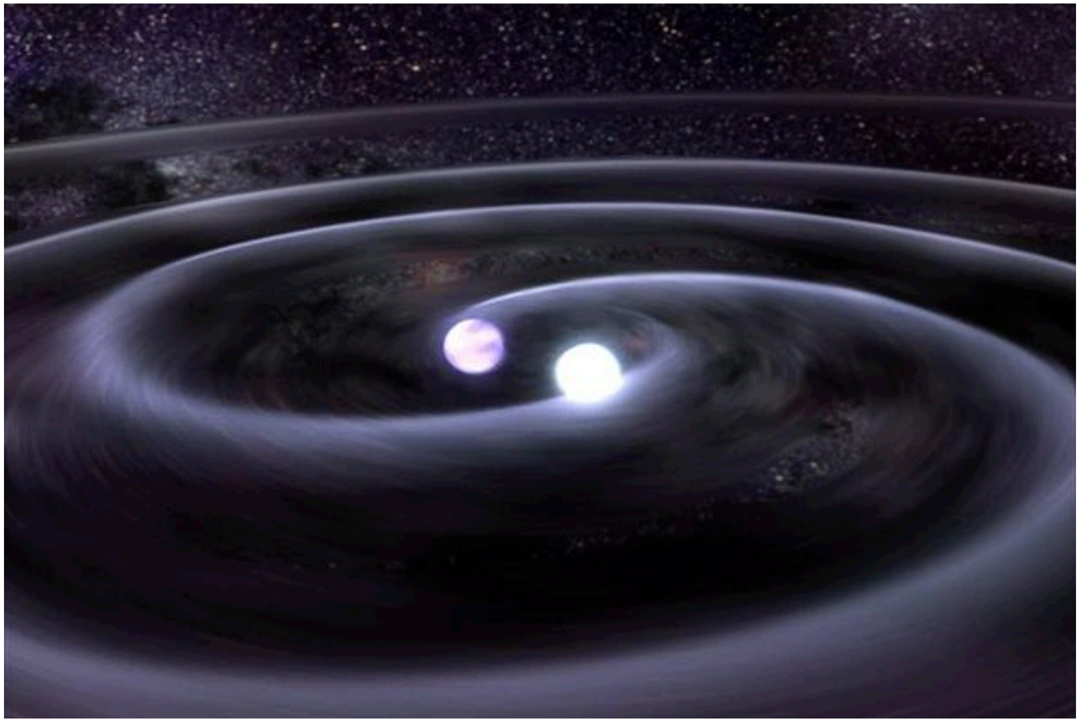
Merging Compact Binaries

From White Dwarfs, Neutron Stars to (Super)Massive BHs



Dong Lai
Cornell University

Penn State Institute for Gravitation and Cosmos, 3/27/2017

Merging Compact Binaries

1. Neutron Star/Black Hole Binaries

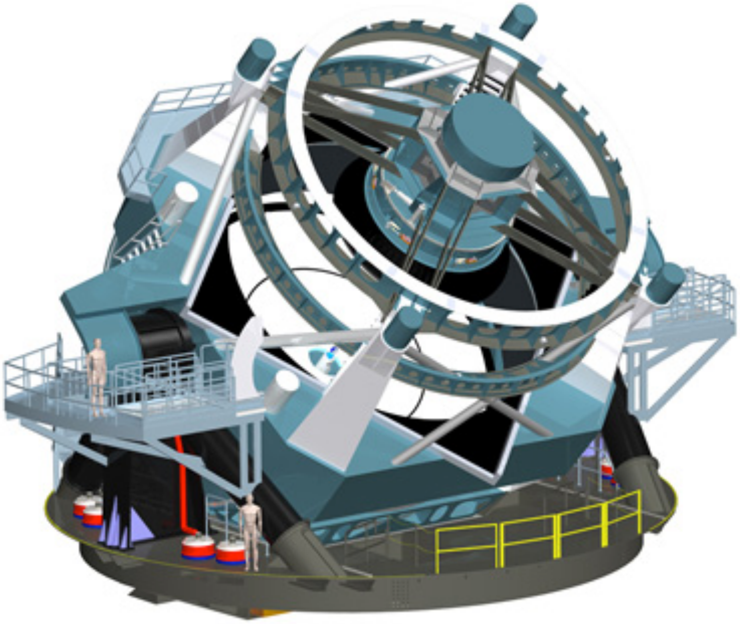
2. White Dwarf Binaries

3. Star/White Dwarf – (Super)Massive BH

Transient & Variable Universe

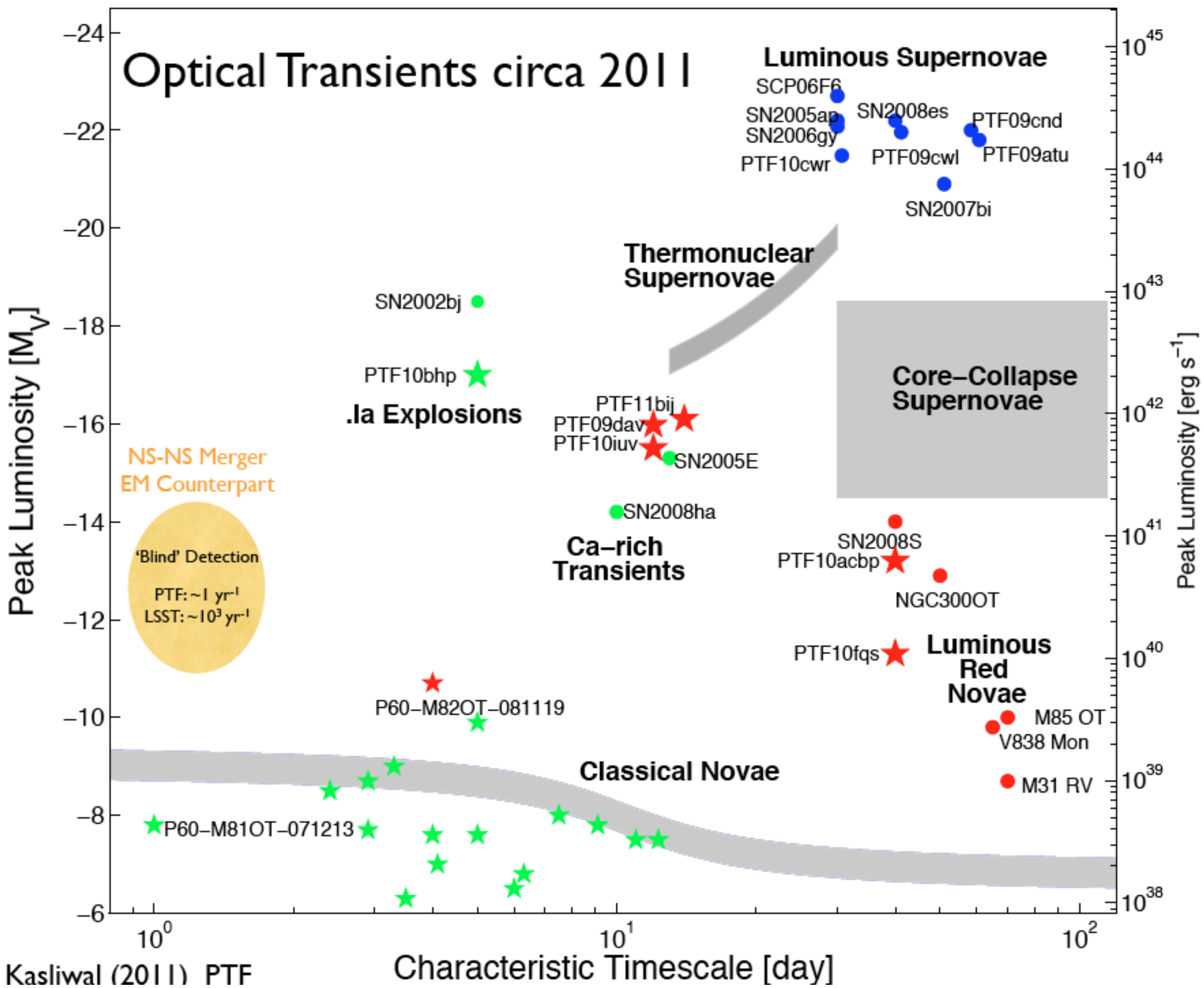
Wide-field, fast imaging telescopes in optical:

PTF(iPTF,ZTF)
Pan-Starrs
LSST



Transient & Variable Universe

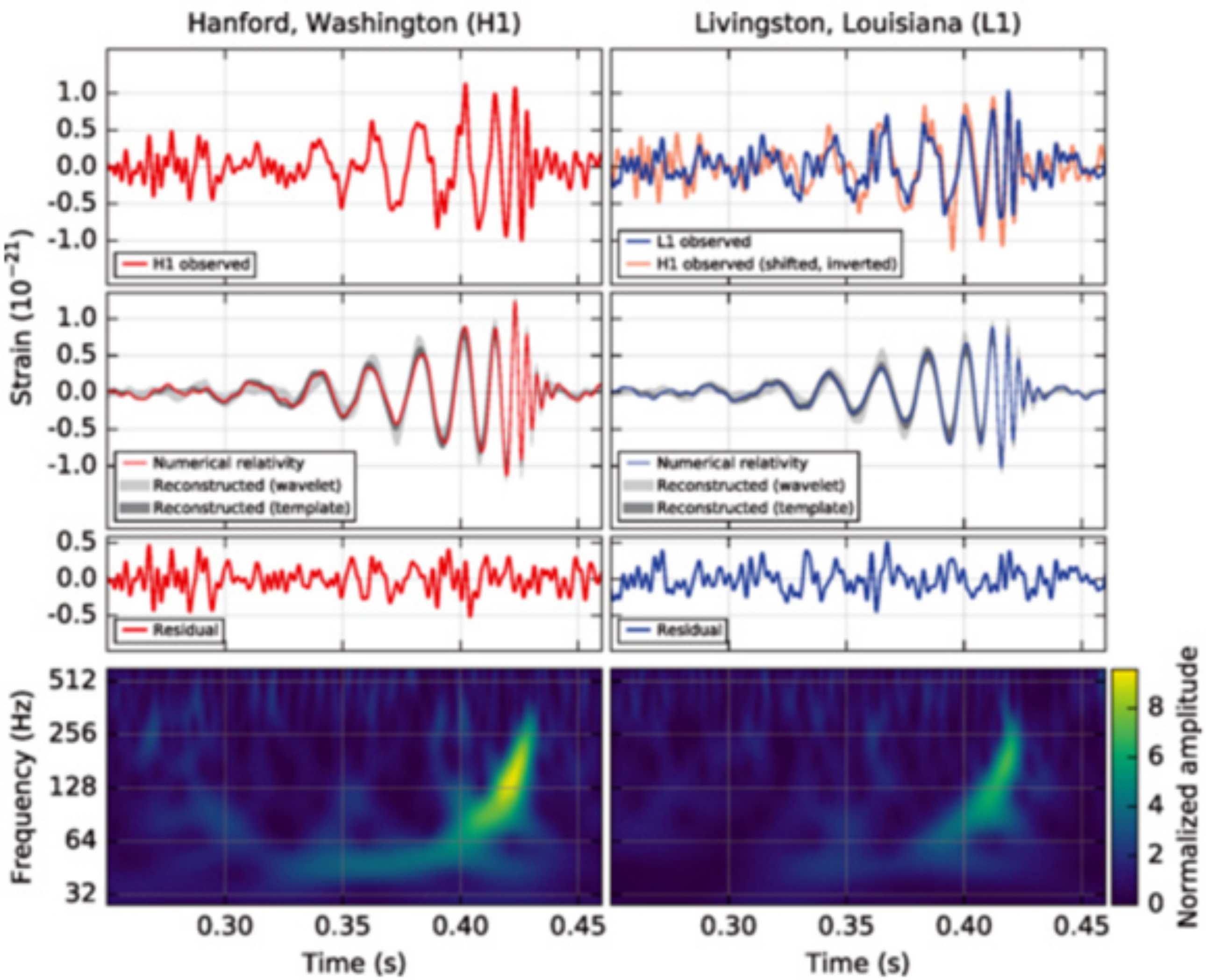
Wide-field, fast imaging telescopes in optical: **PTF, Pan-Starrs, LSST**

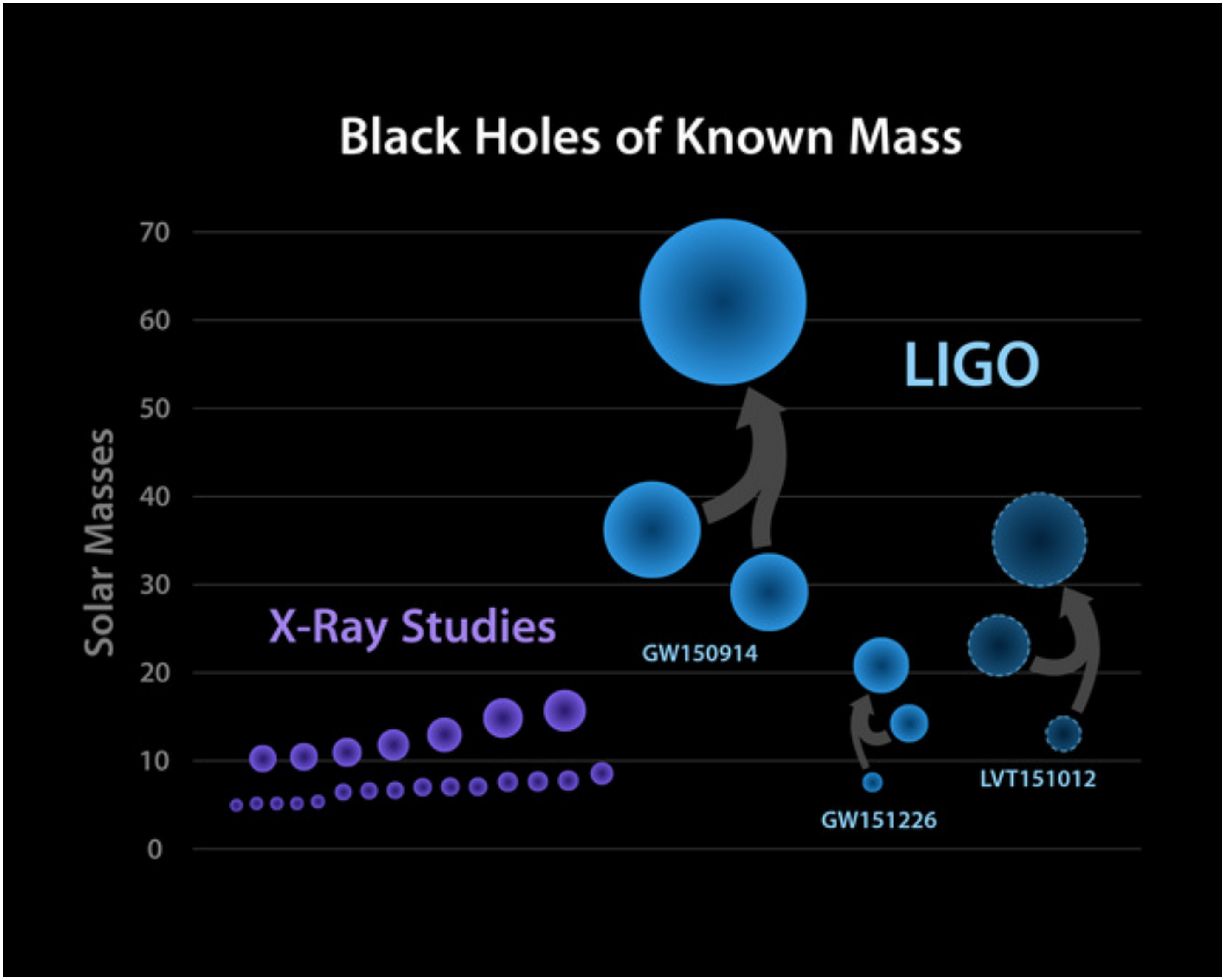


Gravitational Wave Astronomy

LIGO
VIRGO

LIGO's First Binary Black Holes:





Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012

Credit: LIGO

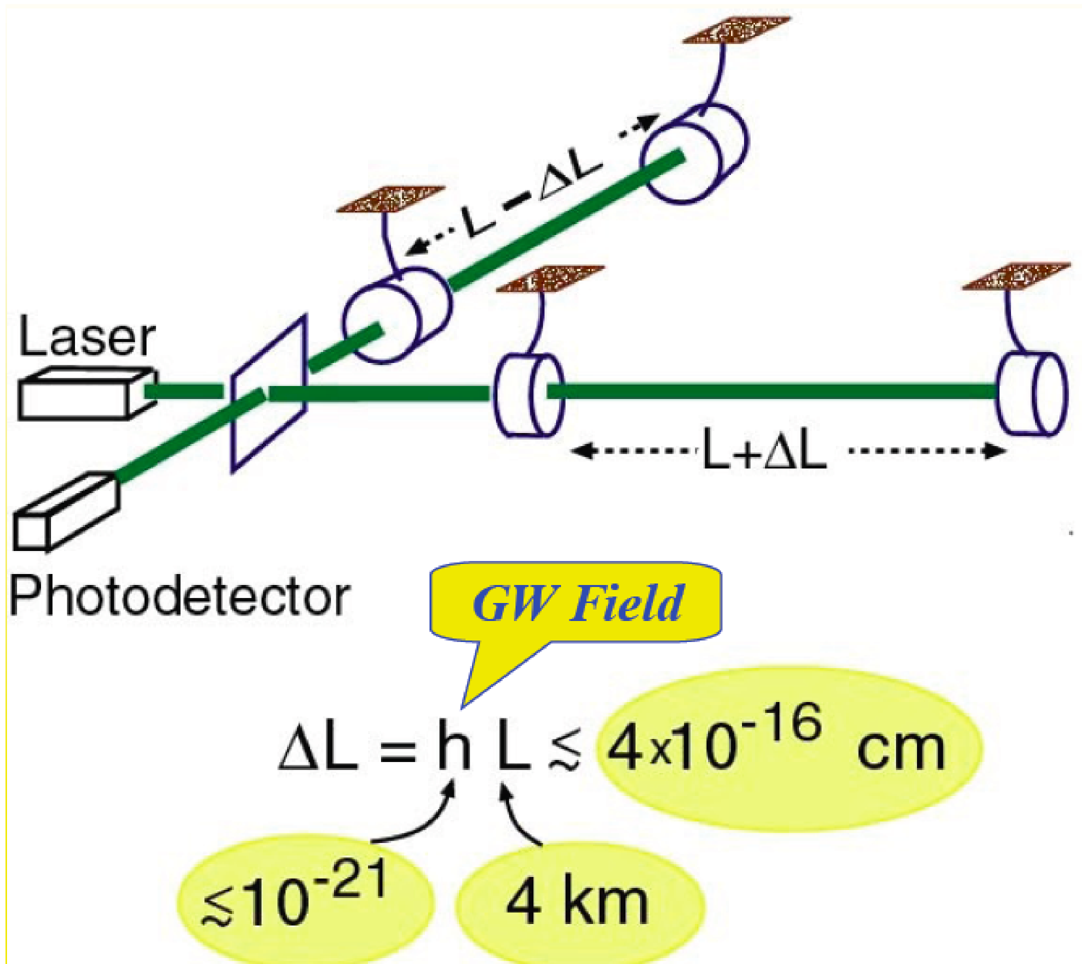
Gravitational Waves

- Warpage of Spacetime
- Generated by time-dependent quadrupoles

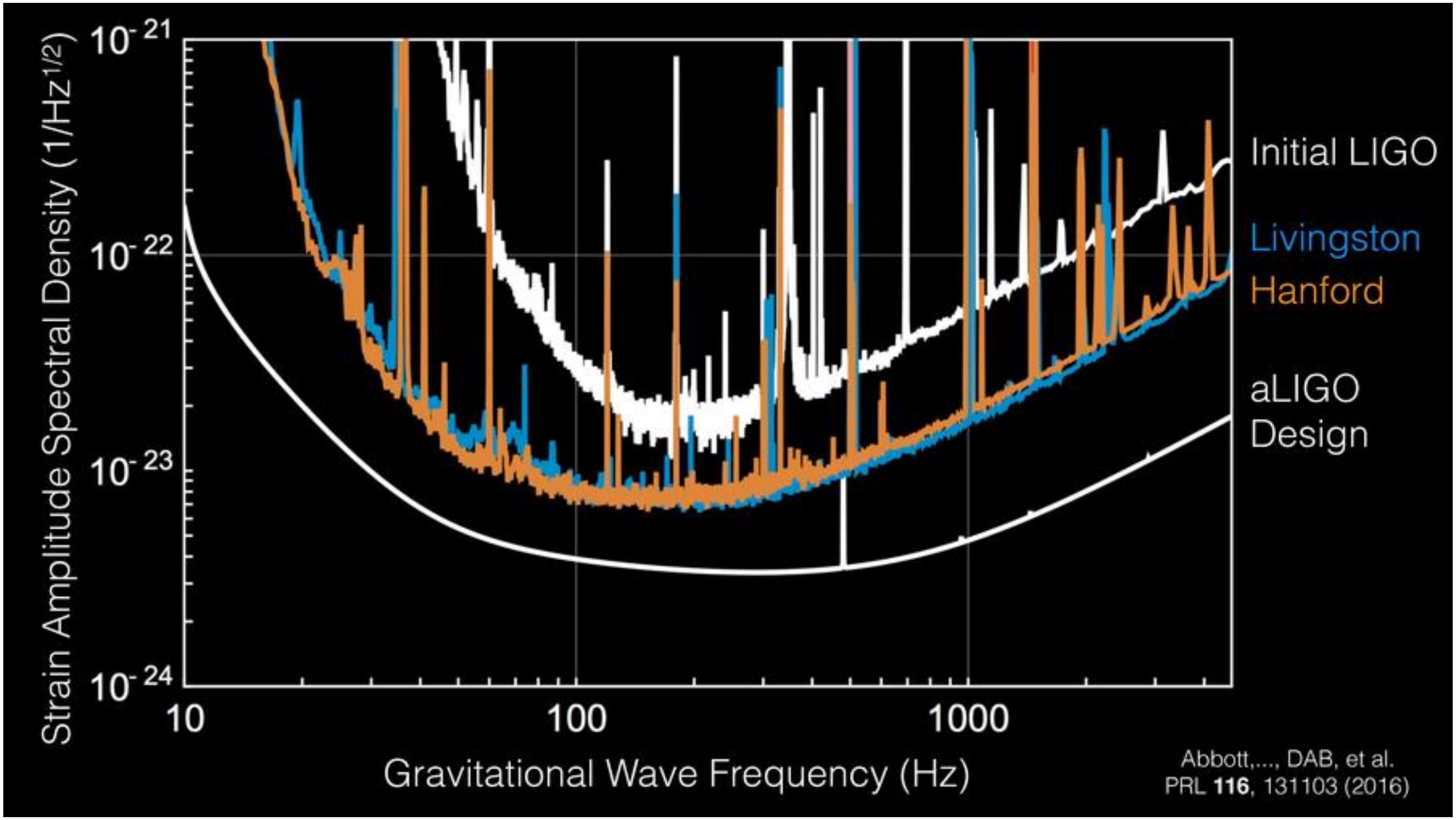
$$h \sim \frac{G}{c^4}\frac{\ddot{Q}}{D}$$

- Detector response to passage of GWs:

Gravitational Wave Interferometer

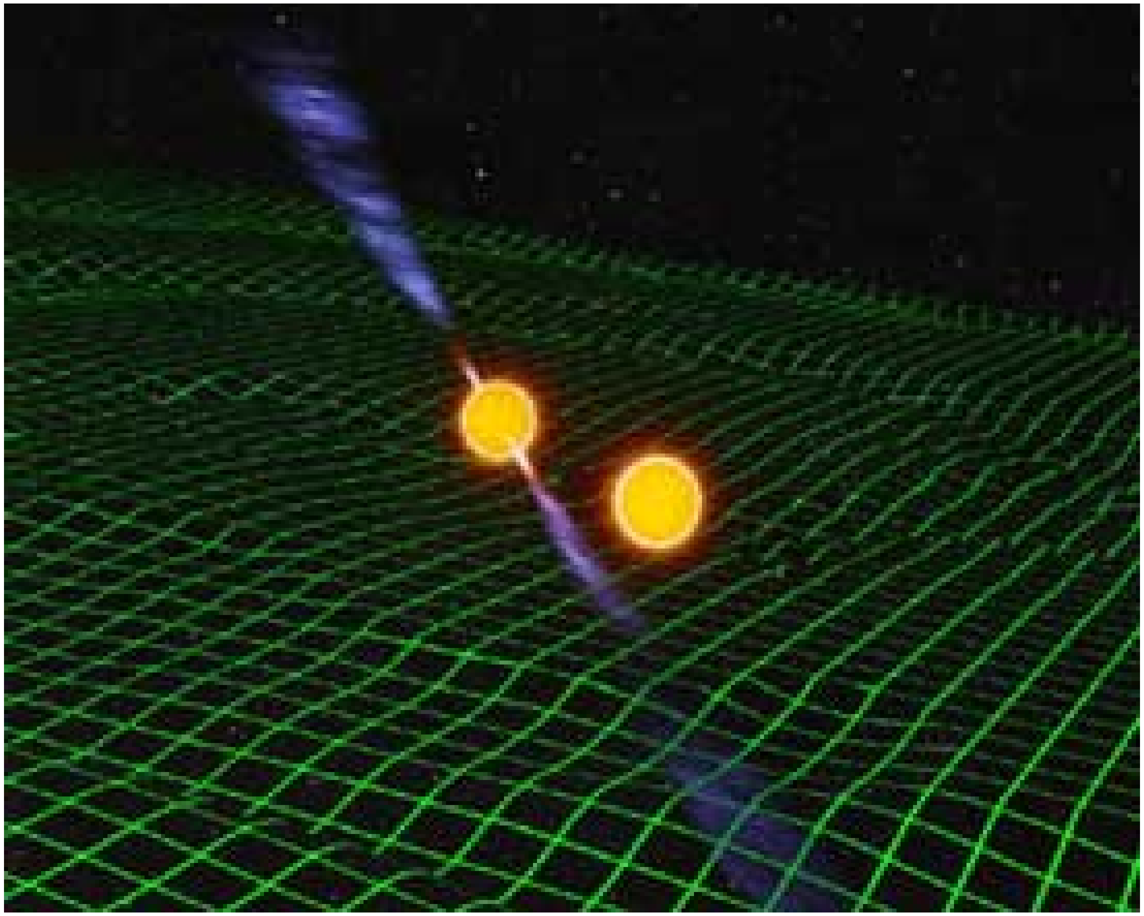


Kip Thorne

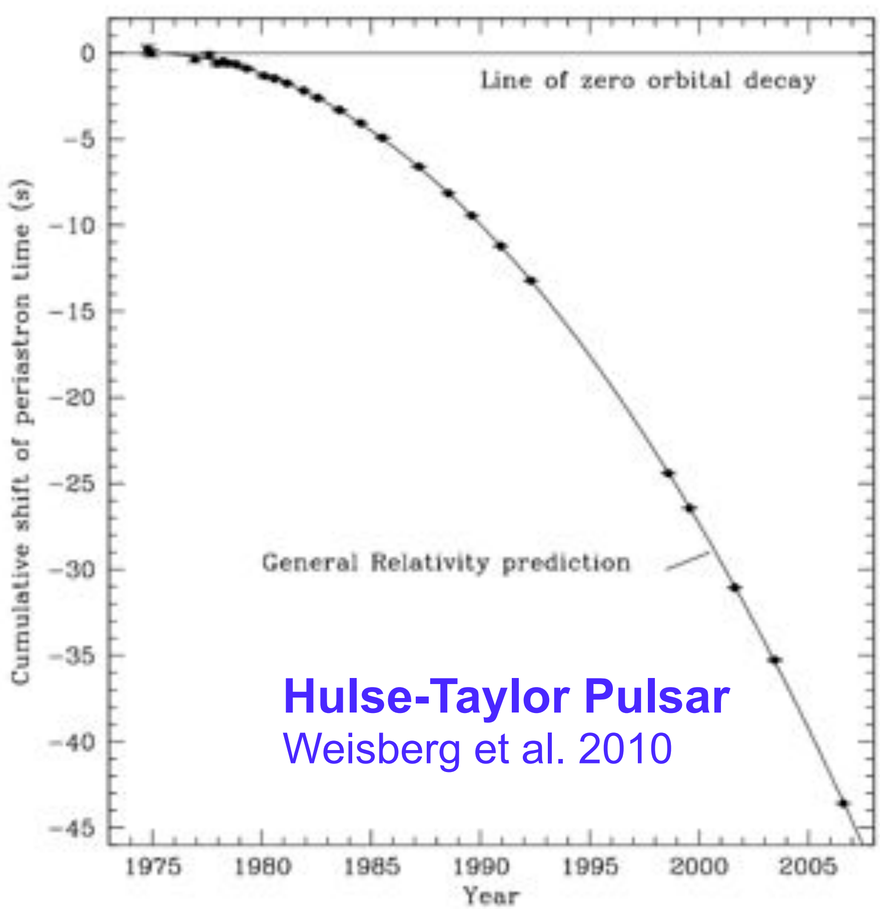


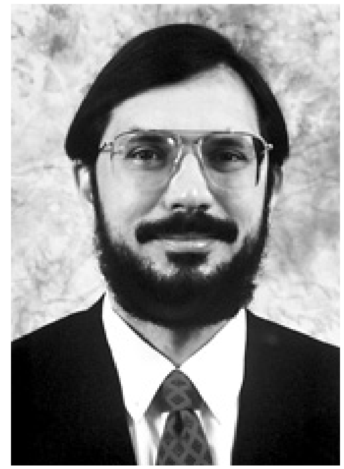
Strain Amplitude Spectral Density (1/Hz^1/2)
10^-21
10^-22
10^-23
10^-24
10
100
1000
Gravitational Wave Frequency (Hz)
Initial LIGO
Livingston
Hanford
aLIGO
Design
Abbott,..., DAB, et al.
PRL 116, 131103 (2016)

Merging NS Binaries (NS/NS or NS/BH)



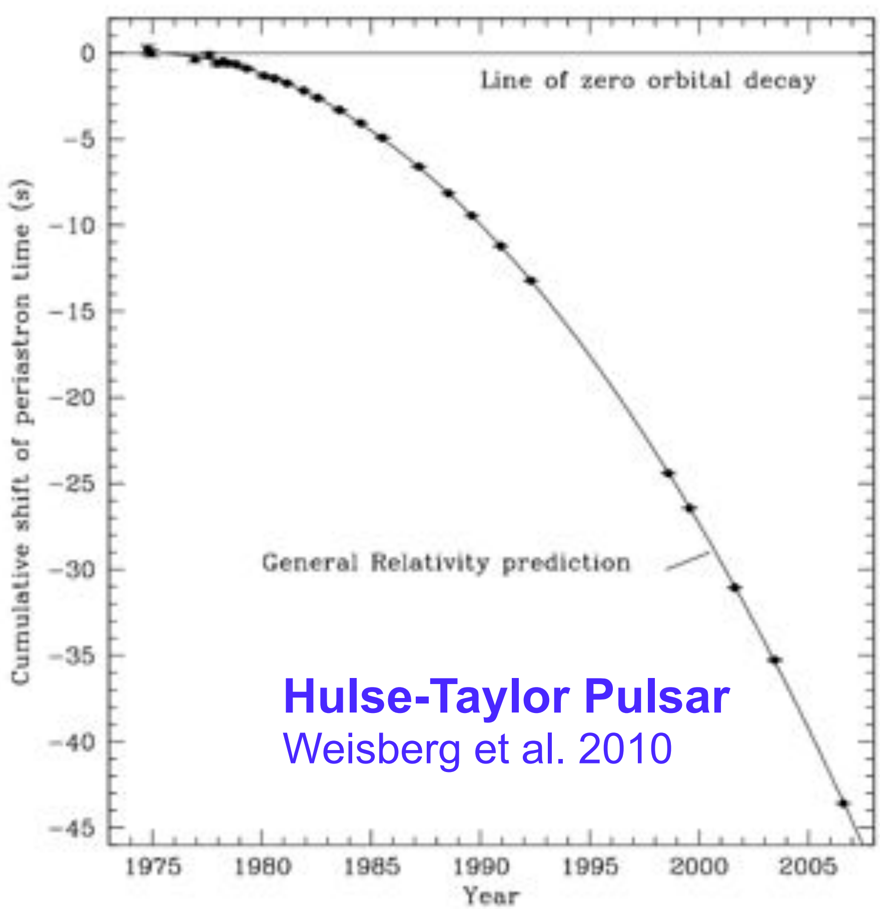
NS/NS Binaries: Binary Pulsars

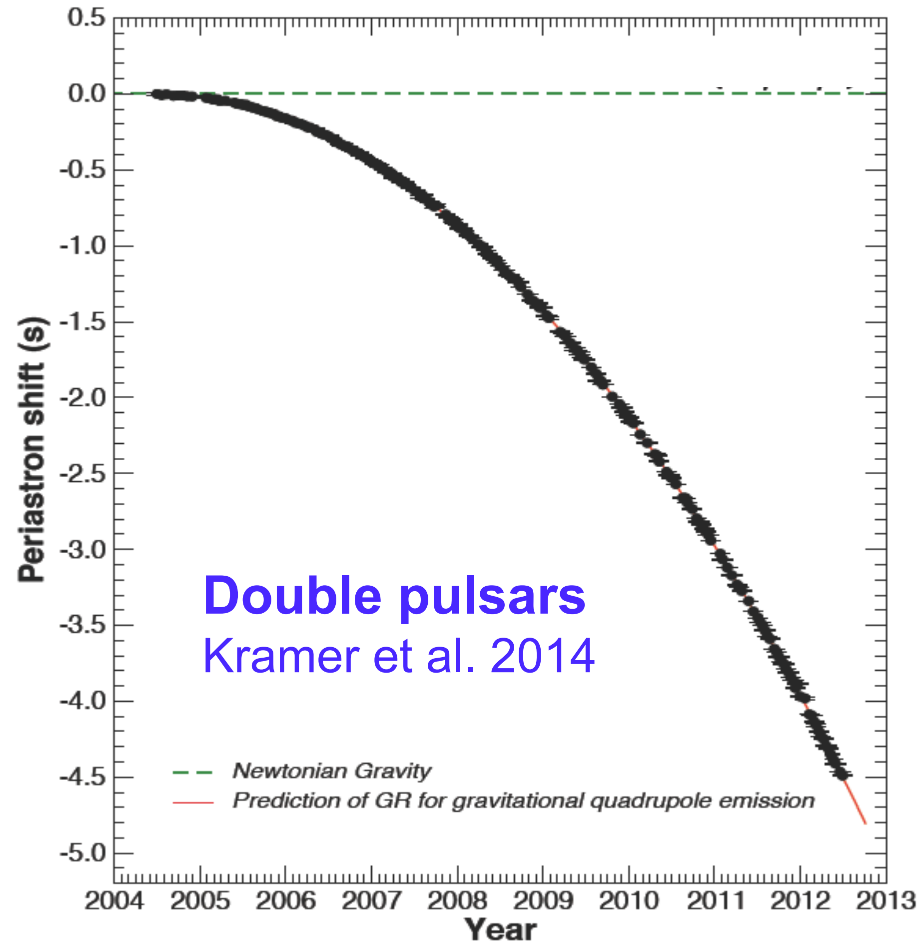




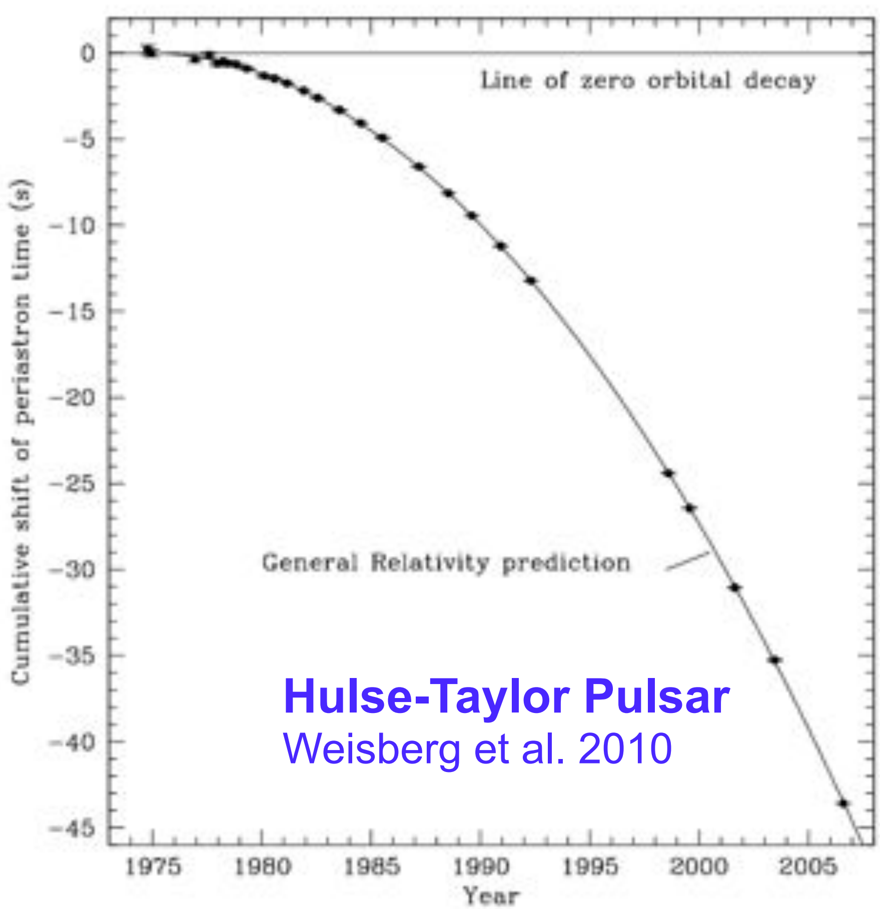

Nobel Prize 1993

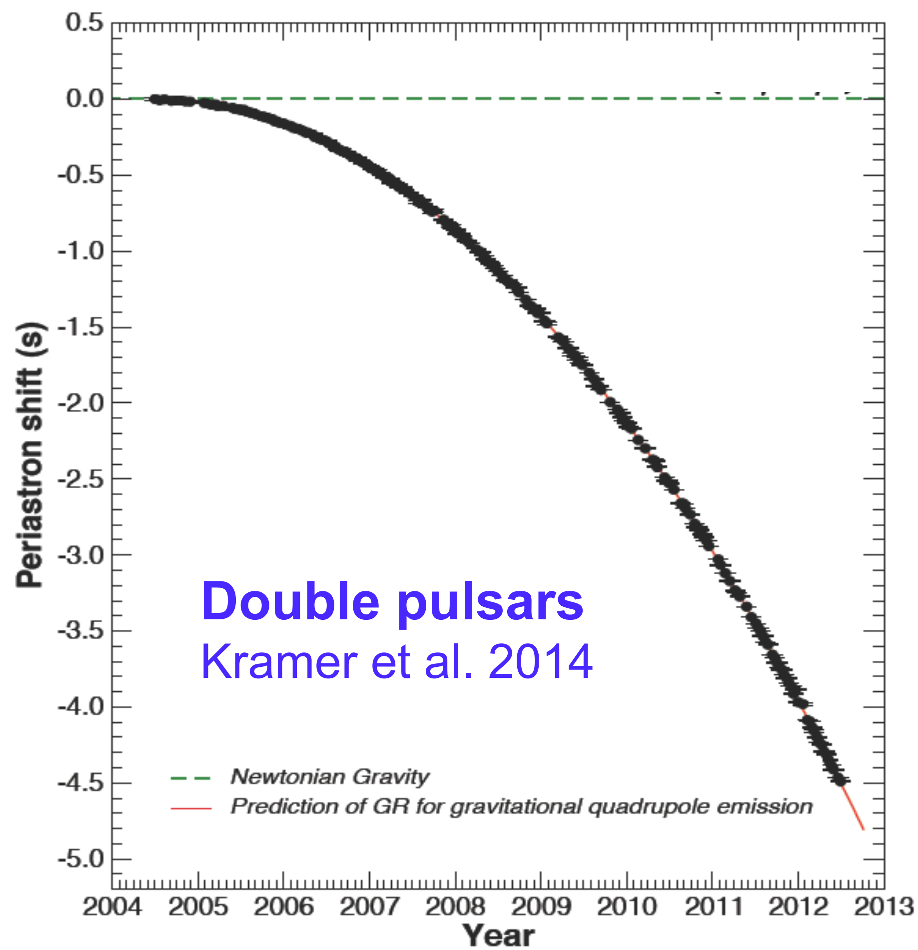
NS/NS Binaries: Binary Pulsars





NS/NS Binaries: Binary Pulsars

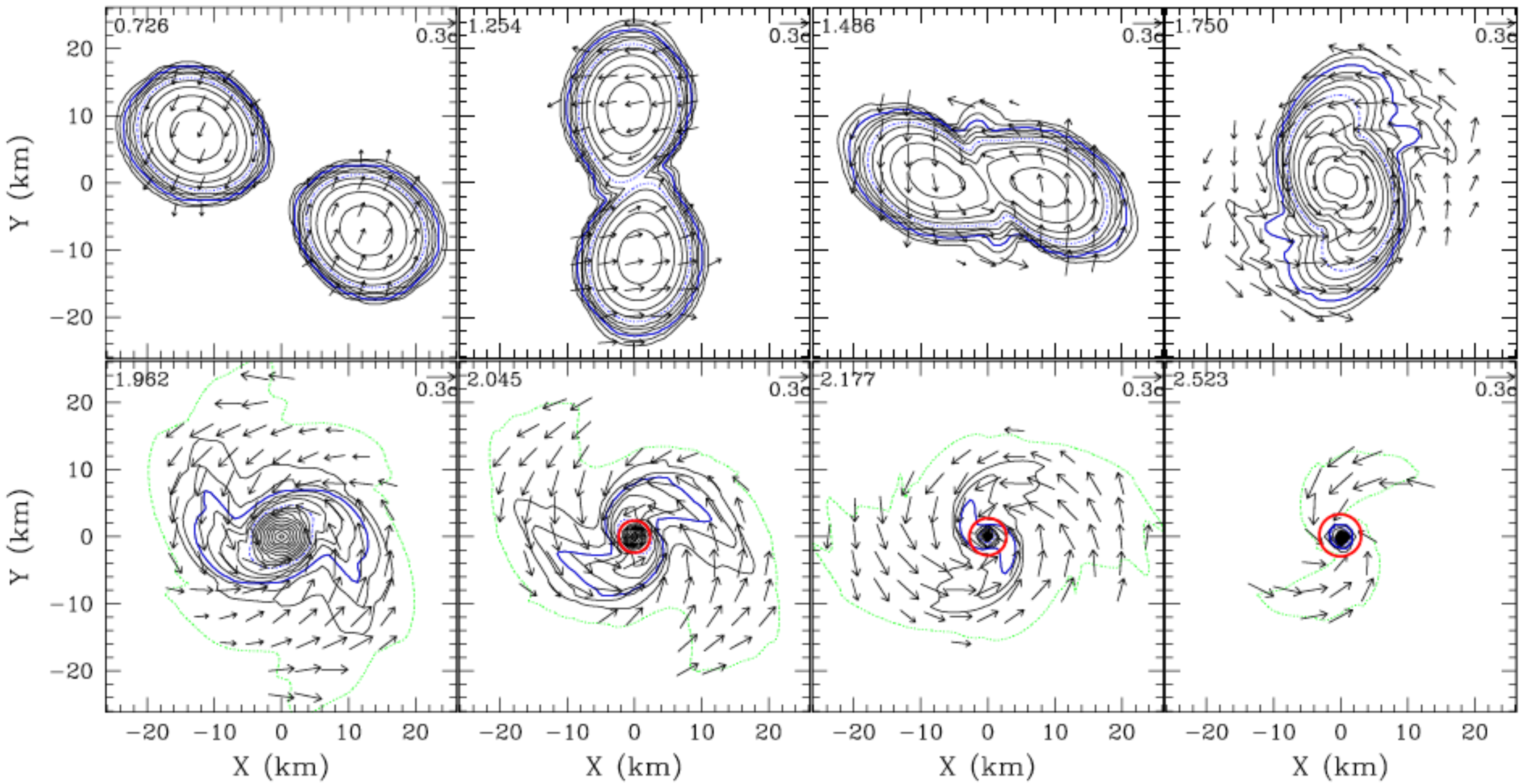




$$\dot{N}_{\rm merge} = 10^{-5} - 3 \times 10^{-4} {\rm yr}^{-1} \text{ per galaxy}$$

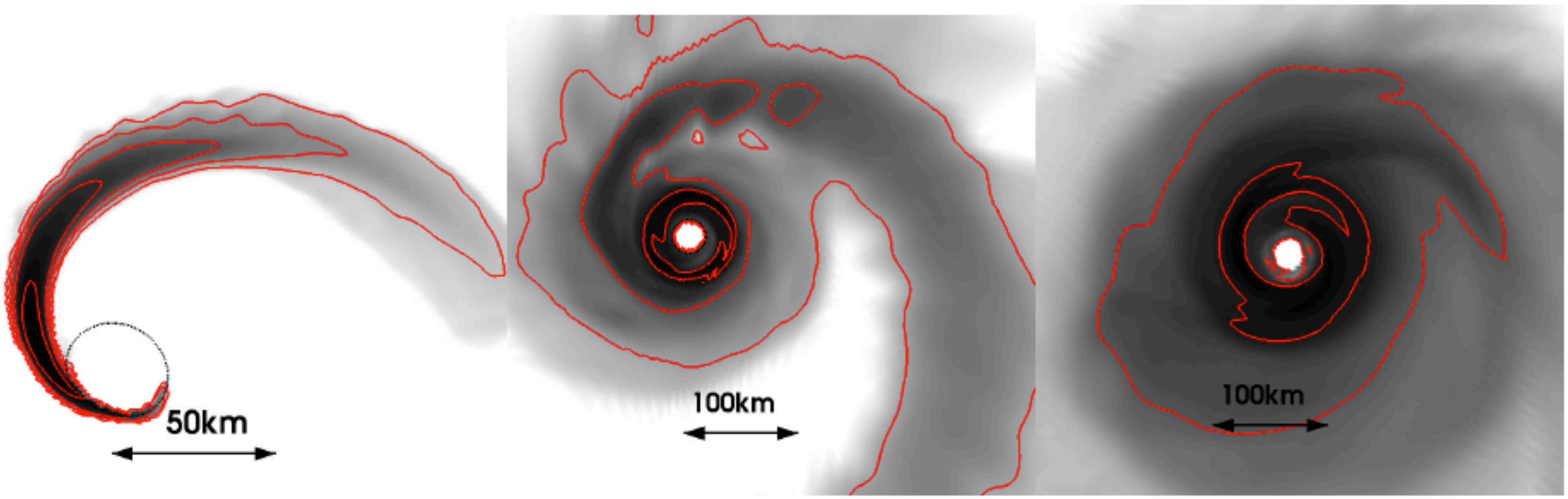
(Based on 3 systems in Galaxy that will merge within Hubble time;
No observed NS/BH yet !)

NS-NS Merger



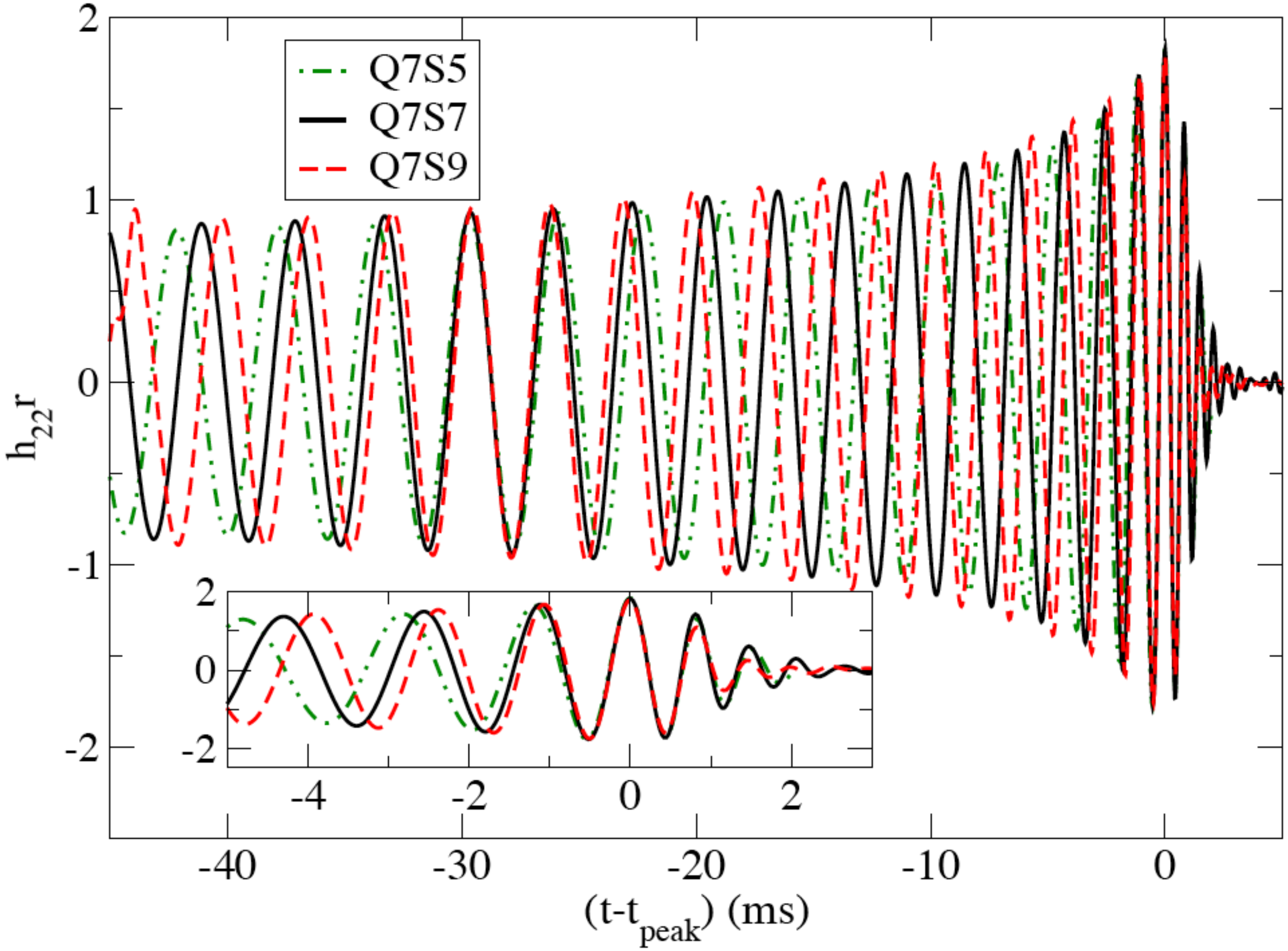
Shibata et al. 2006

BH-NS Merger



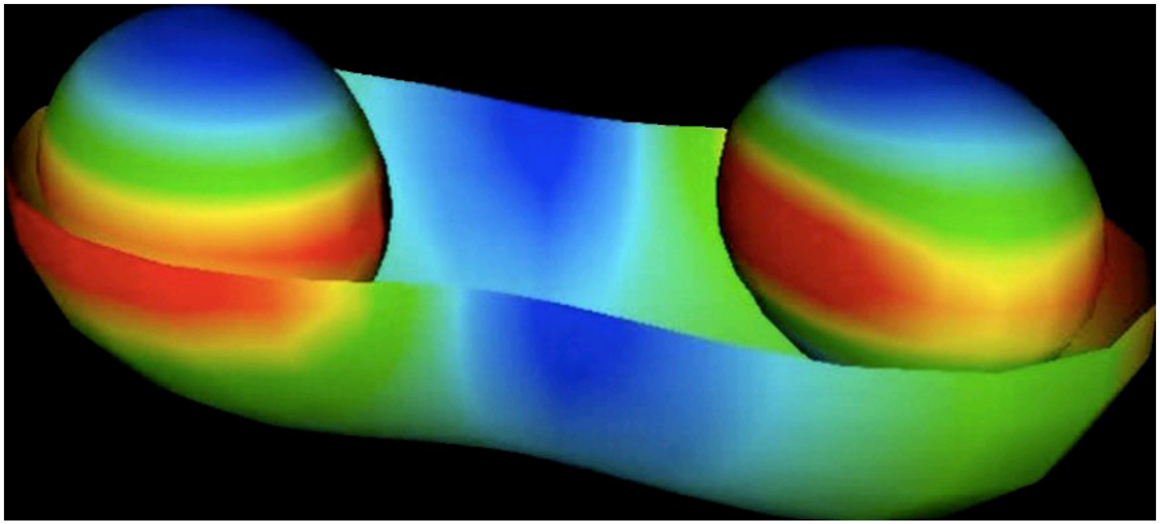
F. Foucart et al (Cornell-Caltech) 2012

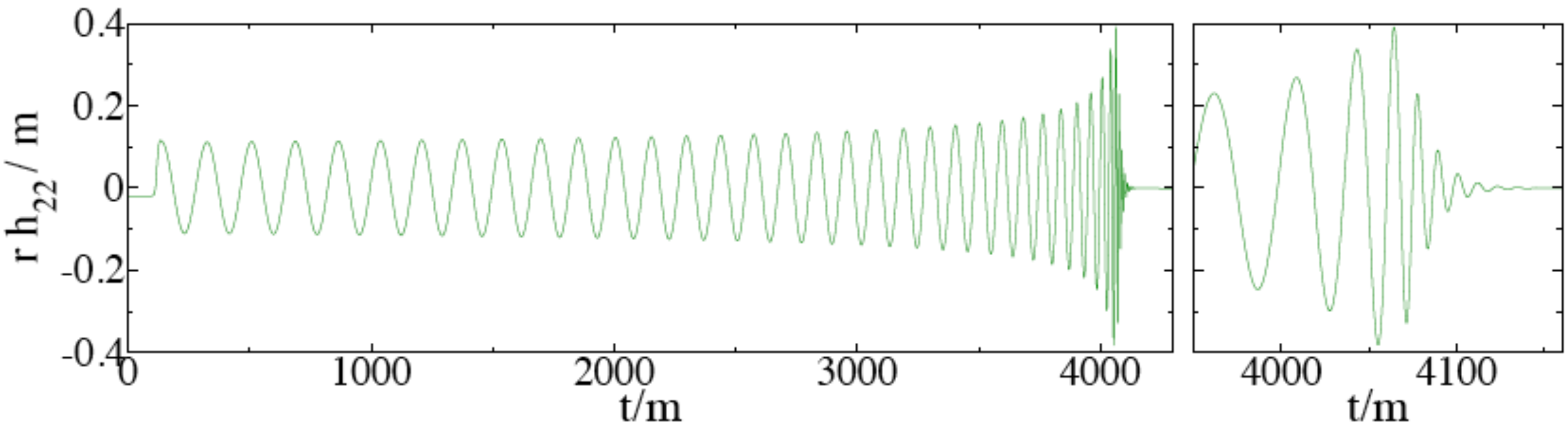
The last minutes: Gravitational Waveform



Foucart et al 2012

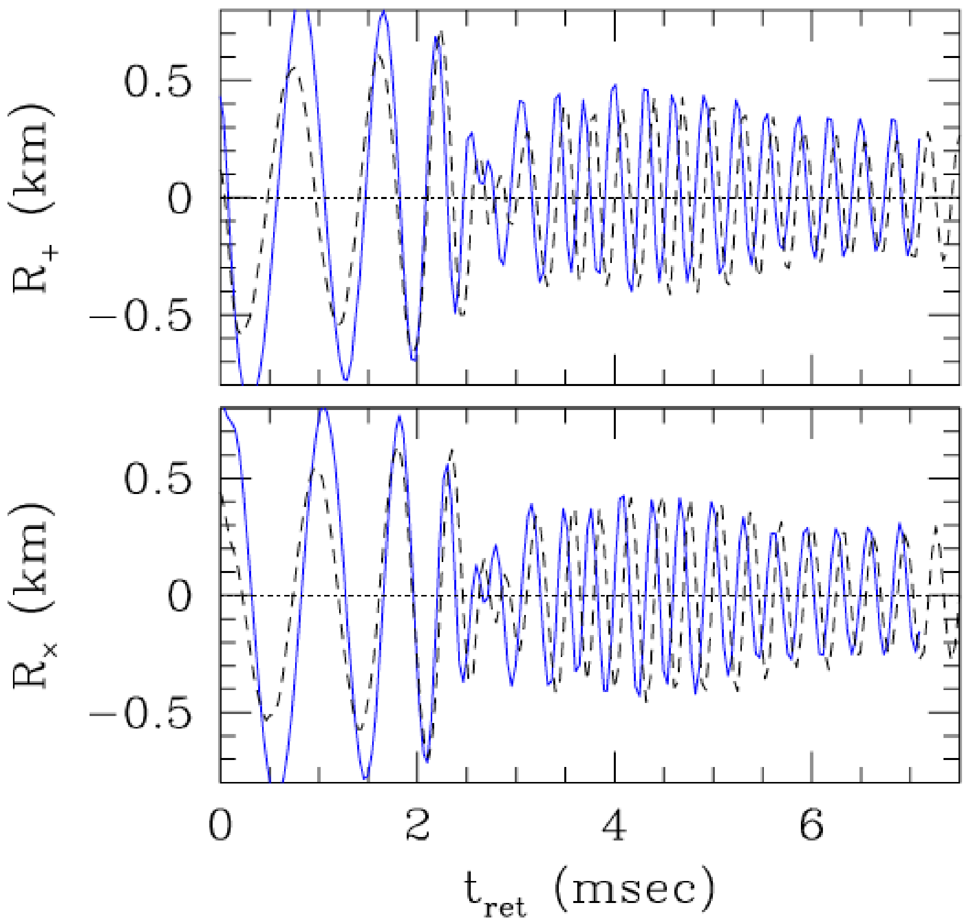
Gravitational waves probe nonlinear gravity

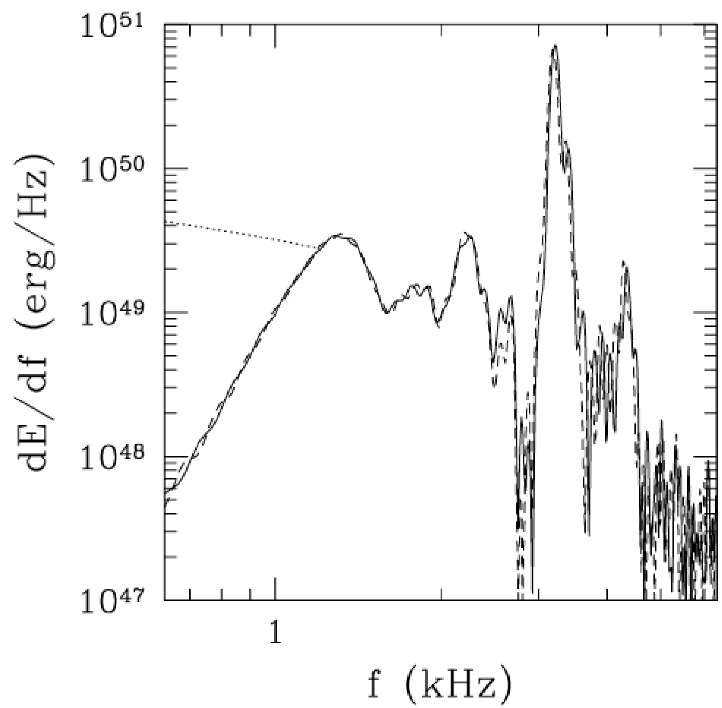




Cornell-Caltech collaboration

Gravitational waves probe NS EOS



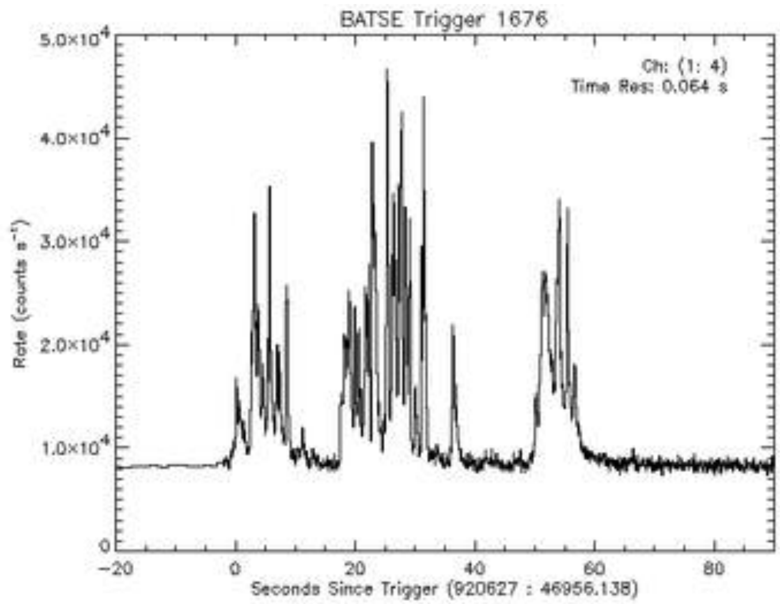


Cutler et al. ‘92;
DL & Wiseman ‘96;
Shibata et al.’ 06;
…
Bauswein, Janka, Shibata...’ 12-16

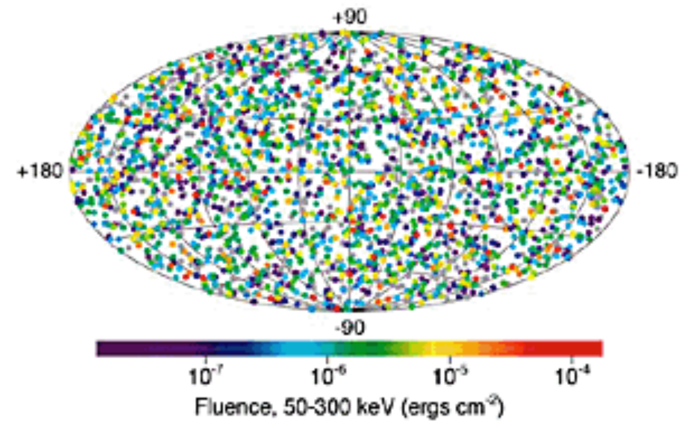
Masses well measured from inspiral waveform
Final cut-off frequency ~ $(GM/R^3)^{1/2}$

NS/NS and NS/BH Mergers: Electromagnetic Counterparts

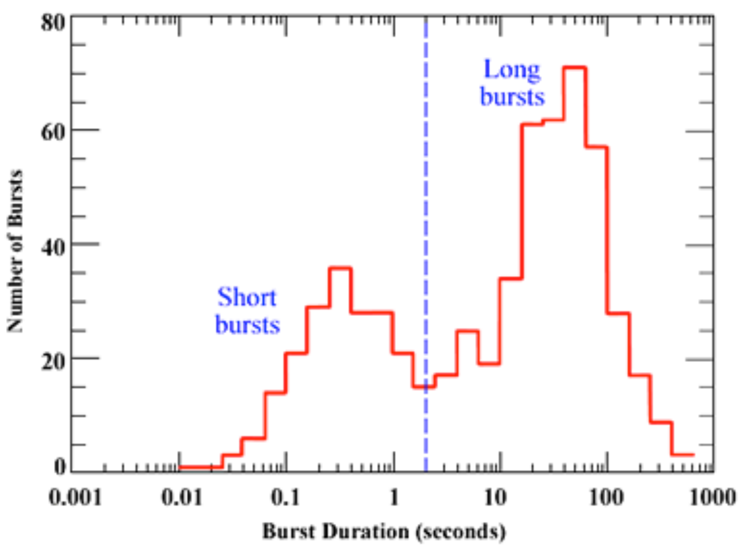
Gamma-Ray Bursts



2704 BATSE Gamma-Ray Bursts



Gamma-ray bursts come from all directions.



--Bursts of 0.1-10 MeV gamma-rays

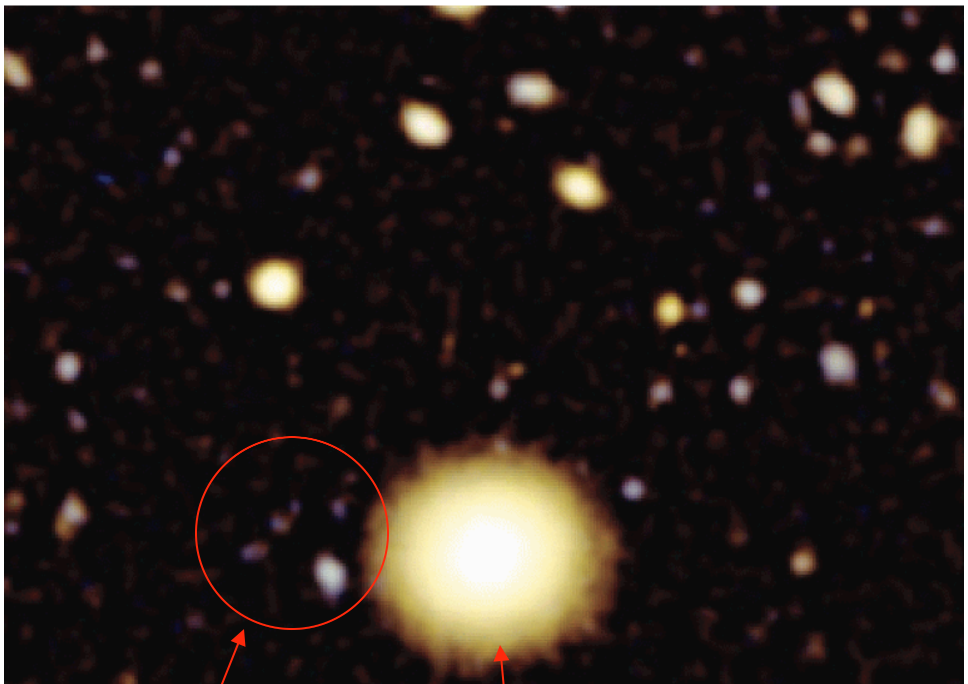
--From all directions, z~0.1-10

--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

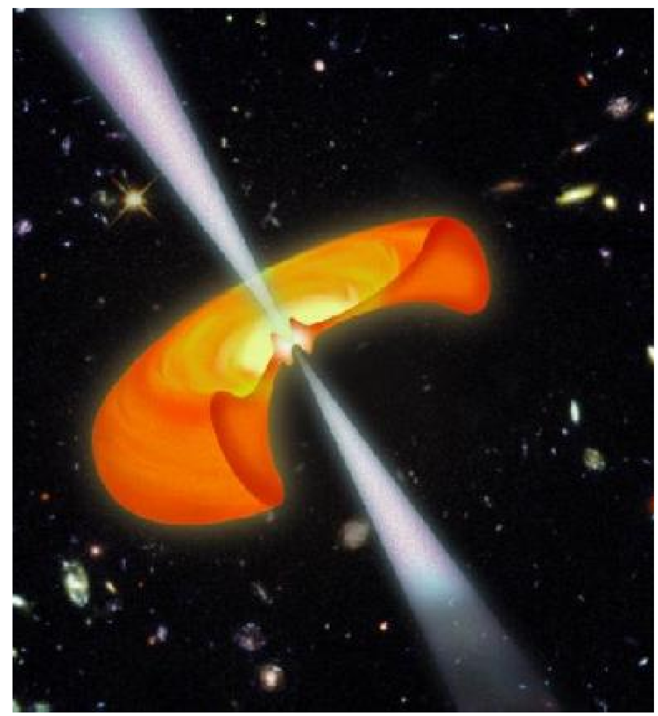


Bloom et al. 2006

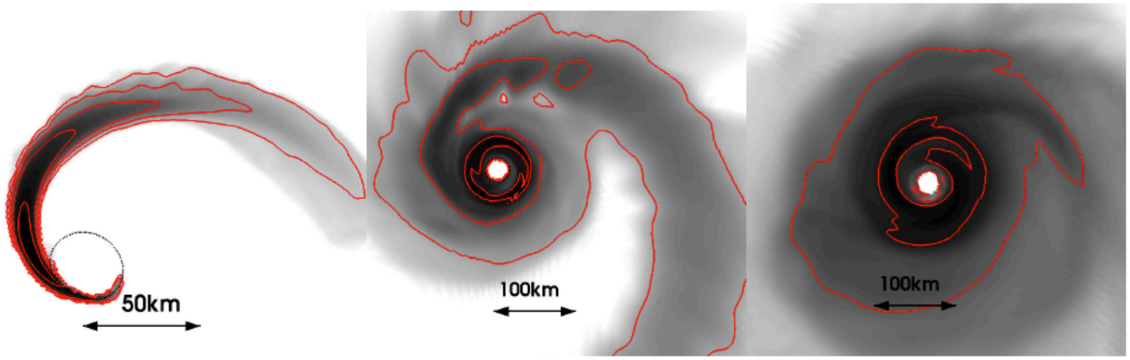
GRB

Elliptical z=0.2

Properties of host galaxies: Fong et al. 13



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:

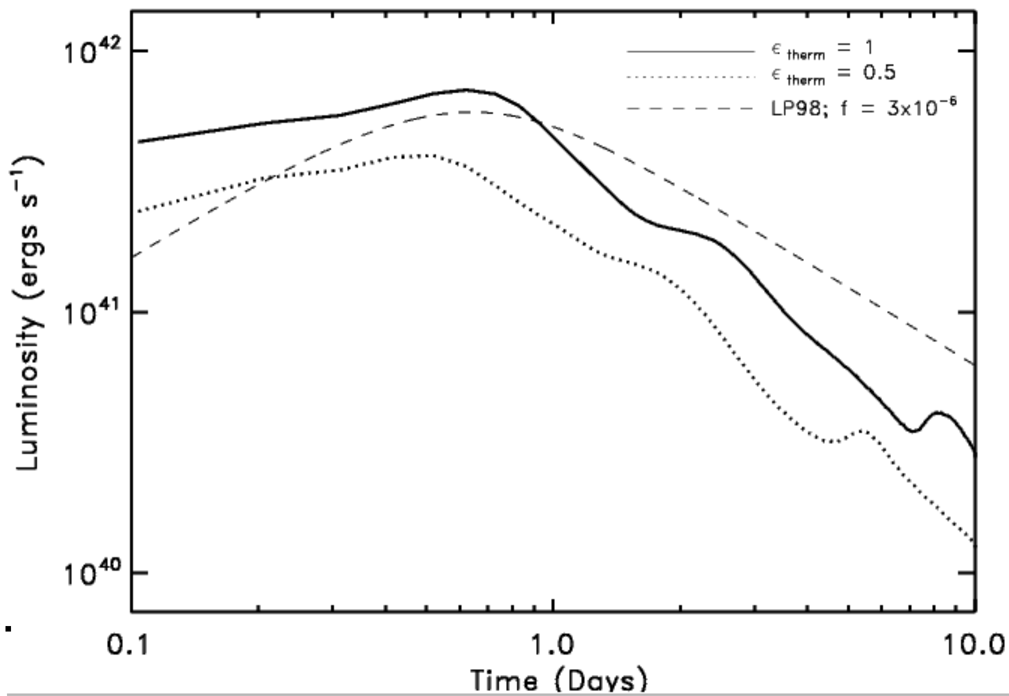
Initially mostly hot neutrons, decompression, r-process, beta decays ➔ heating

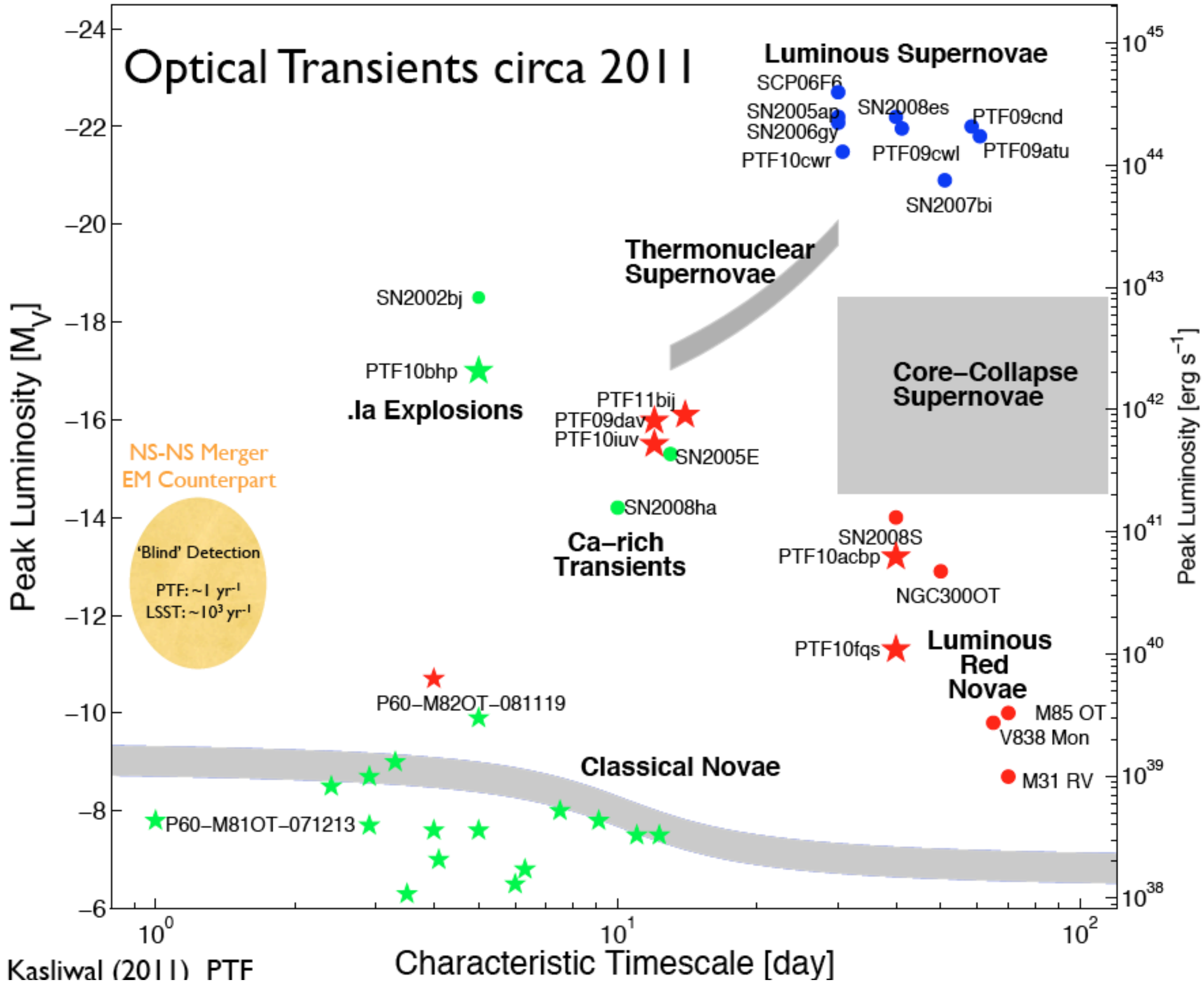
$$L \sim 3 \times 10^{41}\,\mathrm{erg\ s^{-1}} \text{ at } t \sim 1\,\mathrm{day}$$

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

Opacity effect ➔ IR transient

Matzger, Quataert, Kasen, etc.




Optical Transients circa 2011
Luminous Supernovae
SCP06F6
SN2005ap
SN2006gy
SN2008es
PTF09cnd
PTF10cwr
PTF09cwl
PTF09atu
SN2007bi
Thermonuclear Supernovae
SN2002bj
PTF10bhp
.Ia Explosions
PTF11bij
PTF09dav
PTF10iuv
SN2005E
Core–Collapse Supernovae
NS-NS Merger
EM Counterpart
'Blind' Detection
PTF: ~1 yr-1
LSST: ~10³ yr-1
SN2008ha
Ca–rich Transients
SN2008S
PTF10acbp
NGC300OT
PTF10fqs
Luminous Red Novae
P60–M82OT–081119
M85 OT
V838 Mon
Classical Novae
M31 RV
P60–M81OT–071213
Peak Luminosity [M_V]
Peak Luminosity [erg s-1]
Characteristic Timescale [day]
Kasliwal (2011), PTF

Pre-Merger Phase:

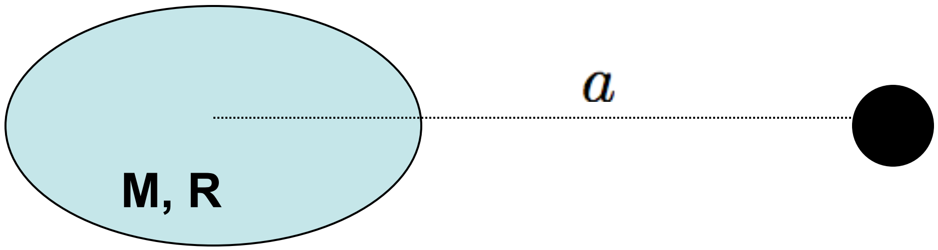
Anything interesting?

Pre-Merger Phase:
Weakly-magnetized Neutron Stars

Tides

- -- Equilibrium tides
- -- Dynamical tides

"Equilibrium" Tide (F-mode Distortion)



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

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

(Missing GW cycles)

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

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

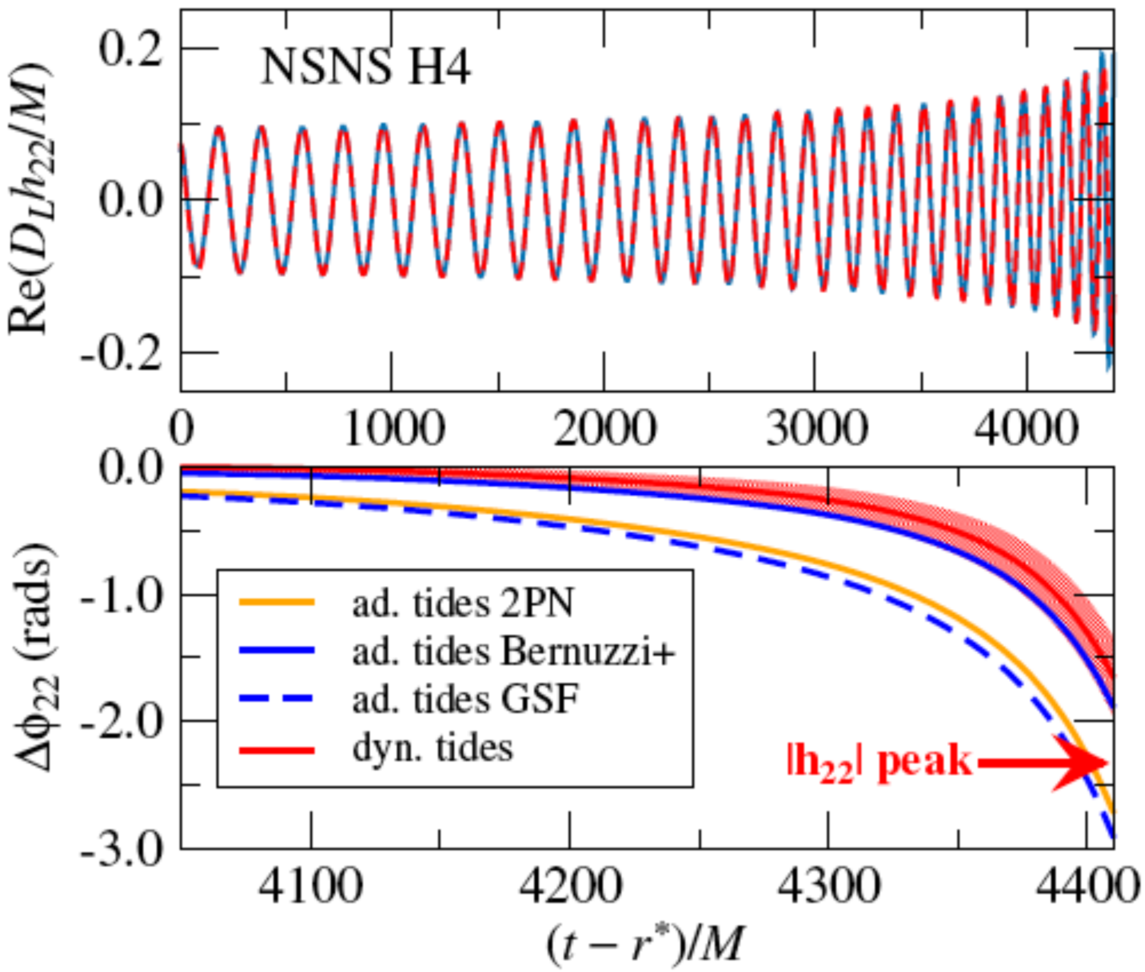
Numerical GR Quasi-equilibrium NS binary sequence

(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+)

“Equilibrium” Tide (F-mode Distortion)



Hinderer et al. 2016

Dynamical (Resonant) 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: $$\omega_\alpha = m\Omega_{\rm orb}, \quad m = 2, 3, \cdots$$

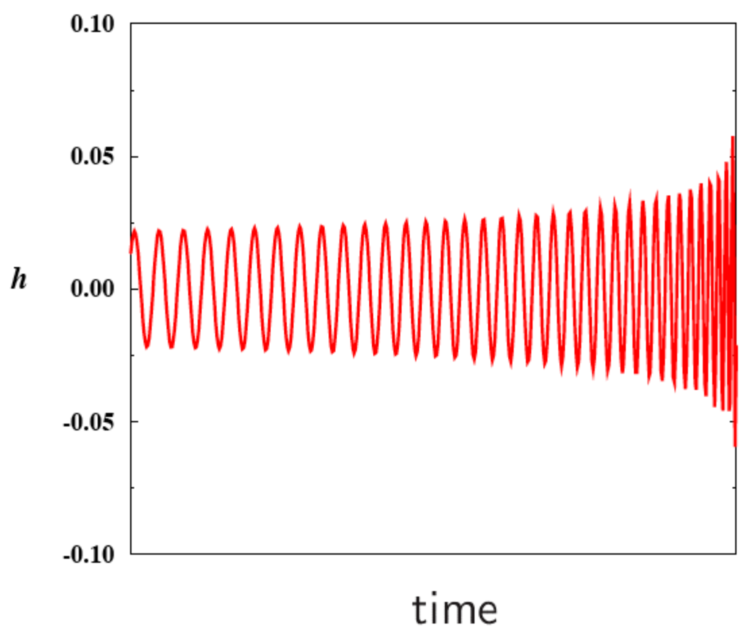
Dynamical (Resonant) Tides: Excitations of Internal Waves/Modes

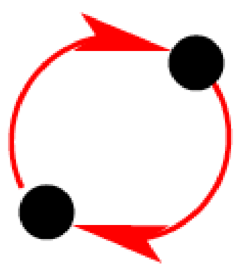
Rosonant tidal excitations of NS modes during inspiral

➔ transfer orbital energy to NS

➔ Missing GW cycles

➔ Probe NS EOS using Inspiral Waveform





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)

General Results:

- For R=10 km, 1.4 Sun NS, the number of missing cycles < 0.1, not measurable
- G-modes: Number of missing cycles $\Delta N \propto R^{3.5}/M^{4.5}$
  Important for low-mass, larger NS

Resonant Excitations of NS Oscillations During Inspiral

Rotating NS: m=1 “leading” r-mode

Wenrui Xu & DL 2017

$$\boldsymbol{\xi}(\mathbf{r}) = \xi_a(r)\,\mathbf{r}\times\nabla Y_{11}(\theta,\phi) + \left[\xi_r(r)\hat{\mathbf{r}} + \xi_\perp(r) r\nabla\right] Y_{21}(\theta,\phi)$$

$$\delta\rho(\mathbf{r}) = \delta\rho(r) Y_{21}(\theta,\phi)$$

$$\frac{\omega_\alpha}{\Omega_s} \simeq -\frac{3}{4}\hat{\Omega}_s^2 = -\frac{3}{4}\frac{\Omega_s^2}{GM/R^3}$$

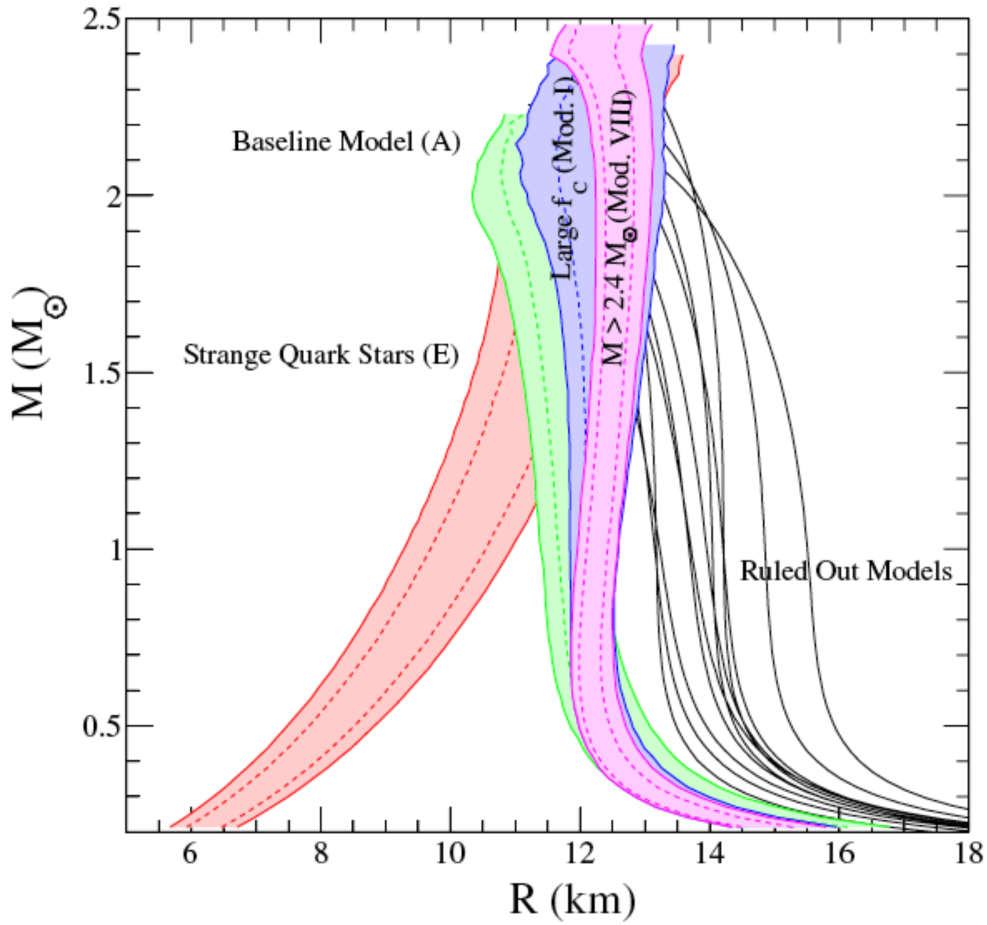
(retrograde wrt rotation)

Mode is excited for SL misaligned system at

$$\nu_{\rm gw} = 2\,\nu_{\rm orb} = |\nu_\alpha| \simeq \frac{3}{4}\hat{\Omega}_s^2\nu_s \simeq 10.2\frac{R_{10}^3}{M_{1.4}}\left(\frac{\nu_s}{400\mathrm{Hz}}\right)^3\ \mathrm{Hz}$$

$$\Delta N \simeq 26\,\frac{R_{10}^5}{M_{1.4}^5 q(1+q)}\left(\sin\frac{\Theta}{2}\right)^6\left(\cos\frac{\Theta}{2}\right)^2$$

NS Mass-Radius

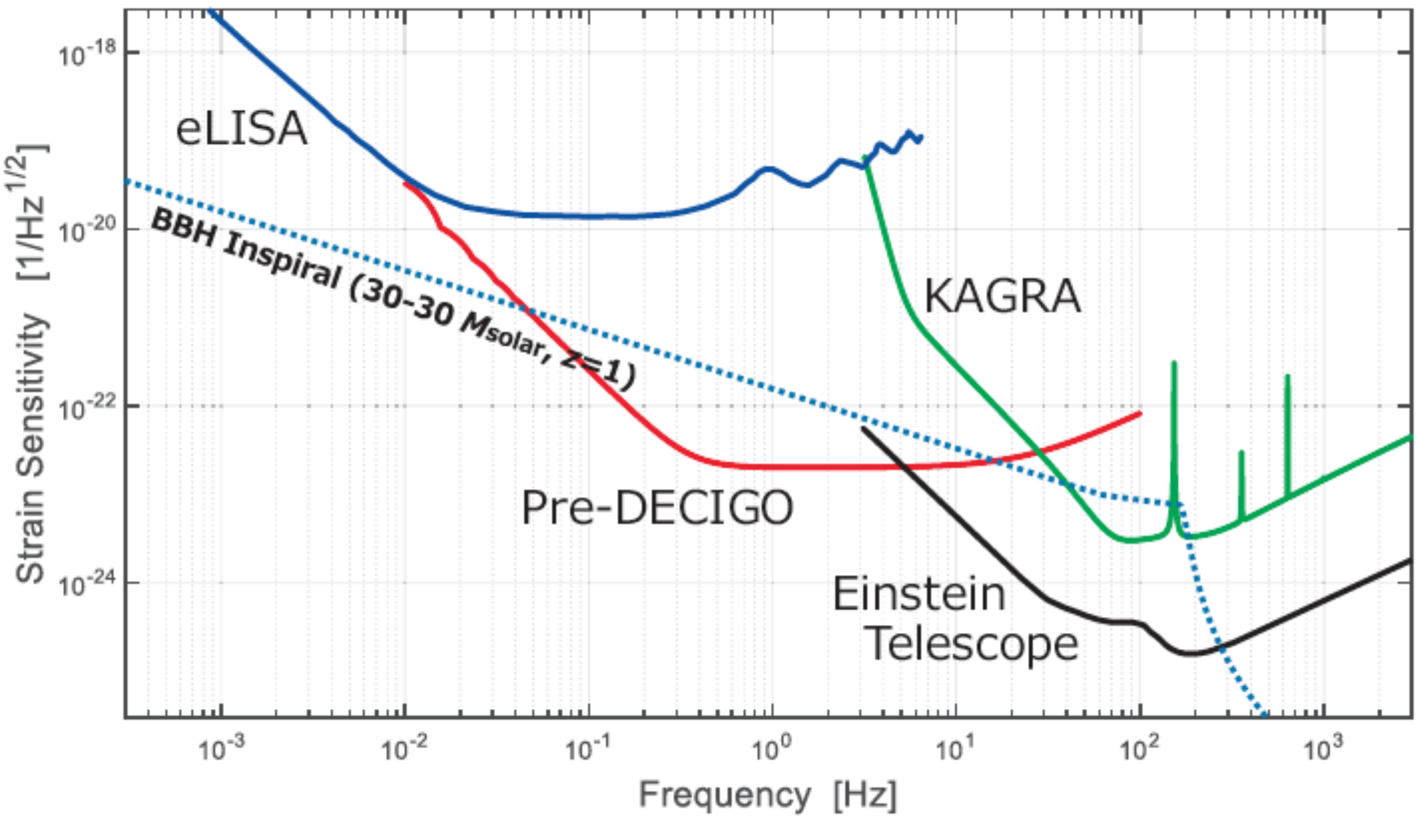


Measured NS mass:
1.17–2.0 Solar mass

Steiner et al 2013

LIGO surprise: Low-mass NSs ?
Rapidly rotation (>400 Hz) NSs ?

DECIGO (DECiHertz laser Interferometer Gravitational wave Observatory)



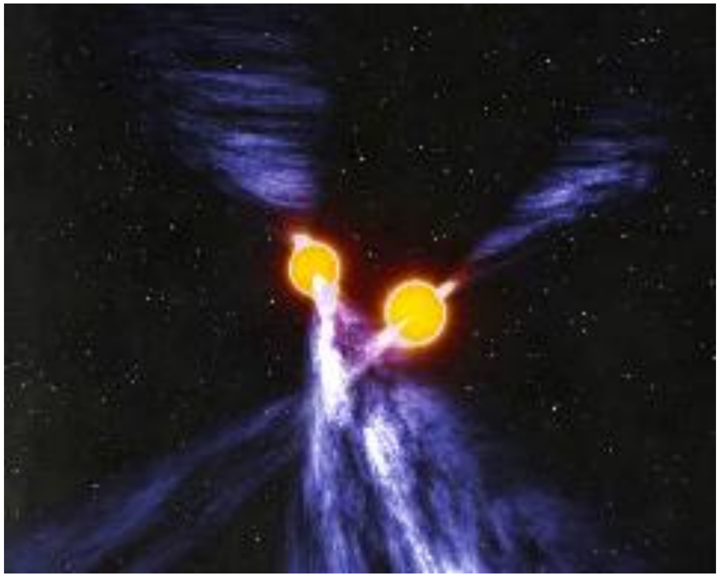
Nakamura et al. 2016

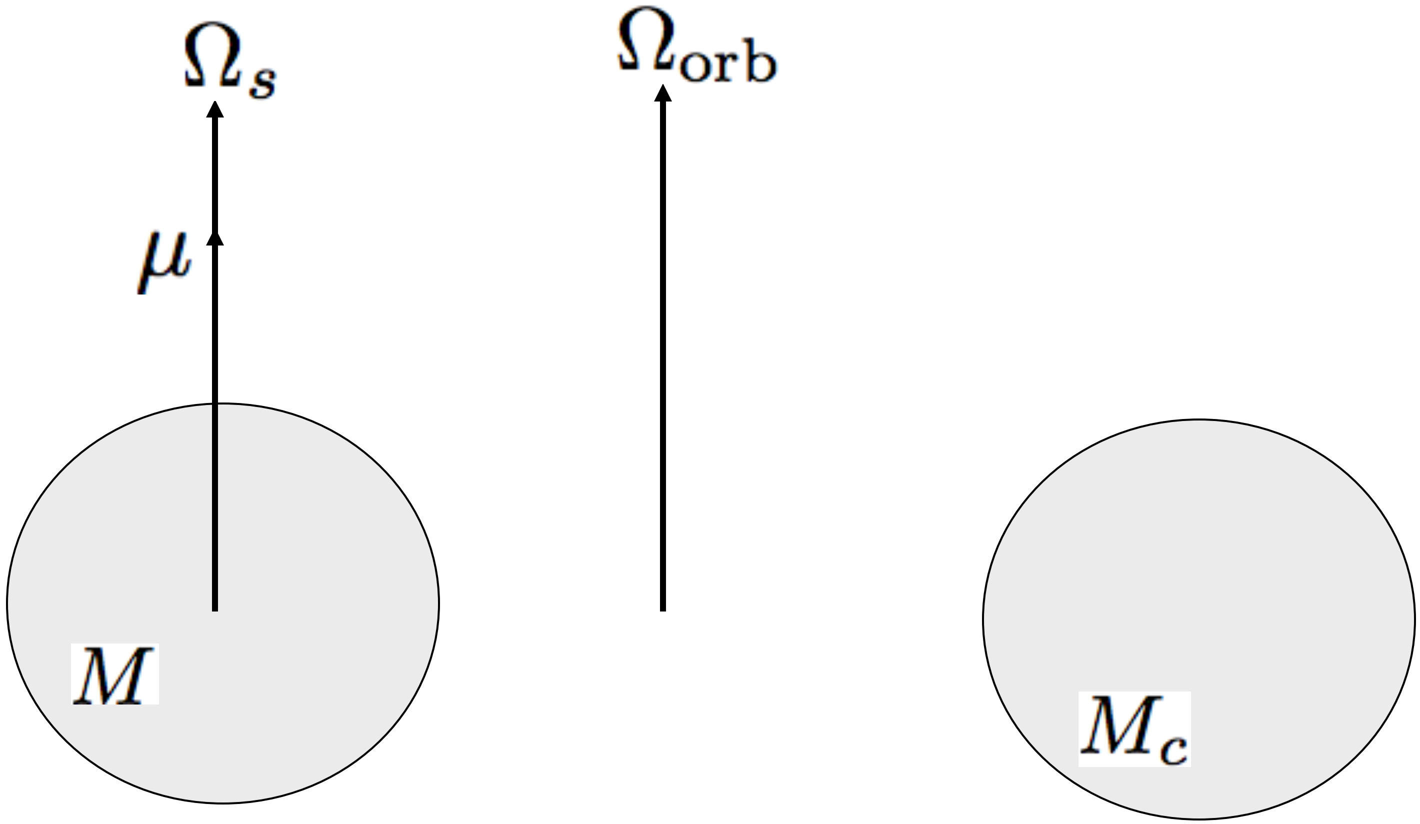
Pre-Merger Phase: Magnetic NSs

Cf. Double Pulsars: **PSR J0737-3039A,B**

pulsar A: ~10^{10}G

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

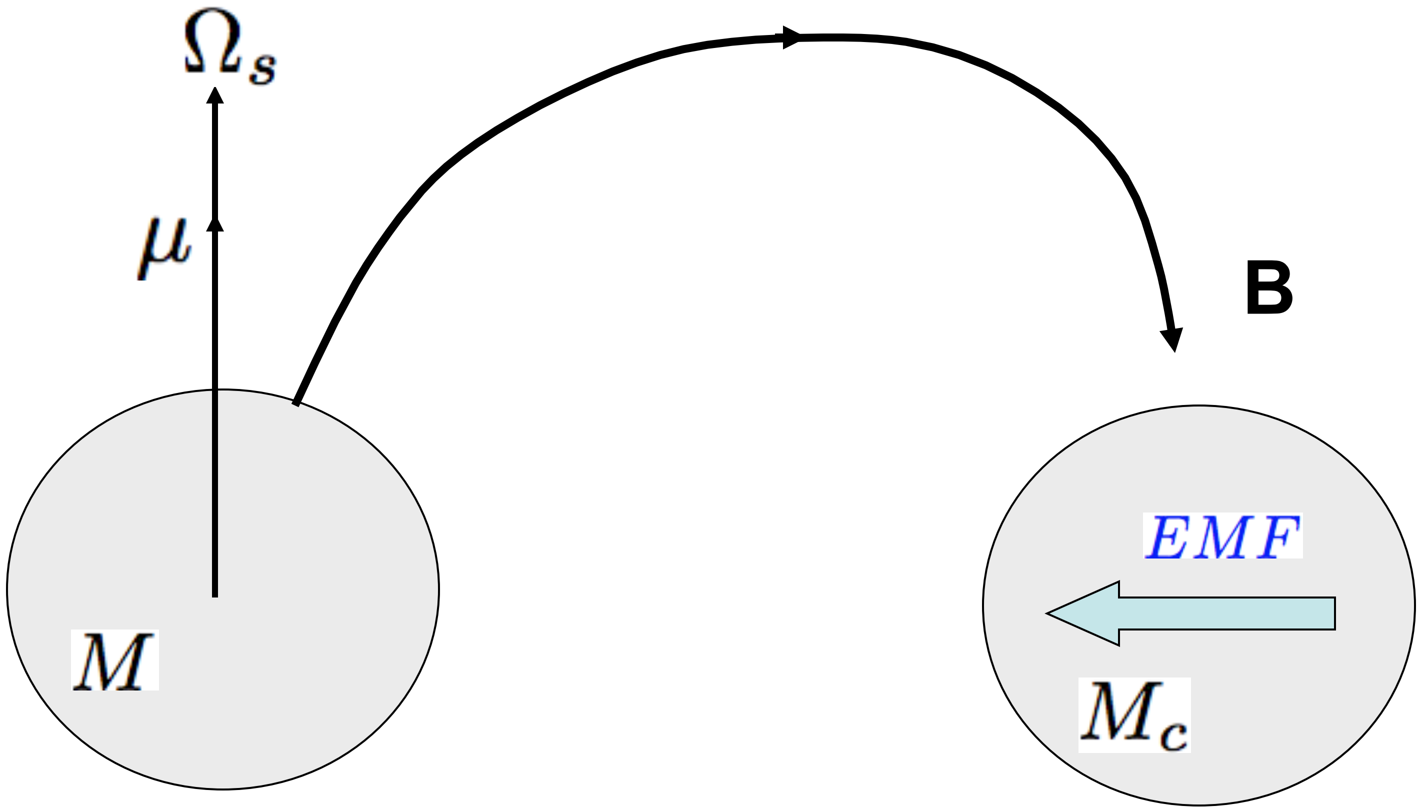




Consider a binary with

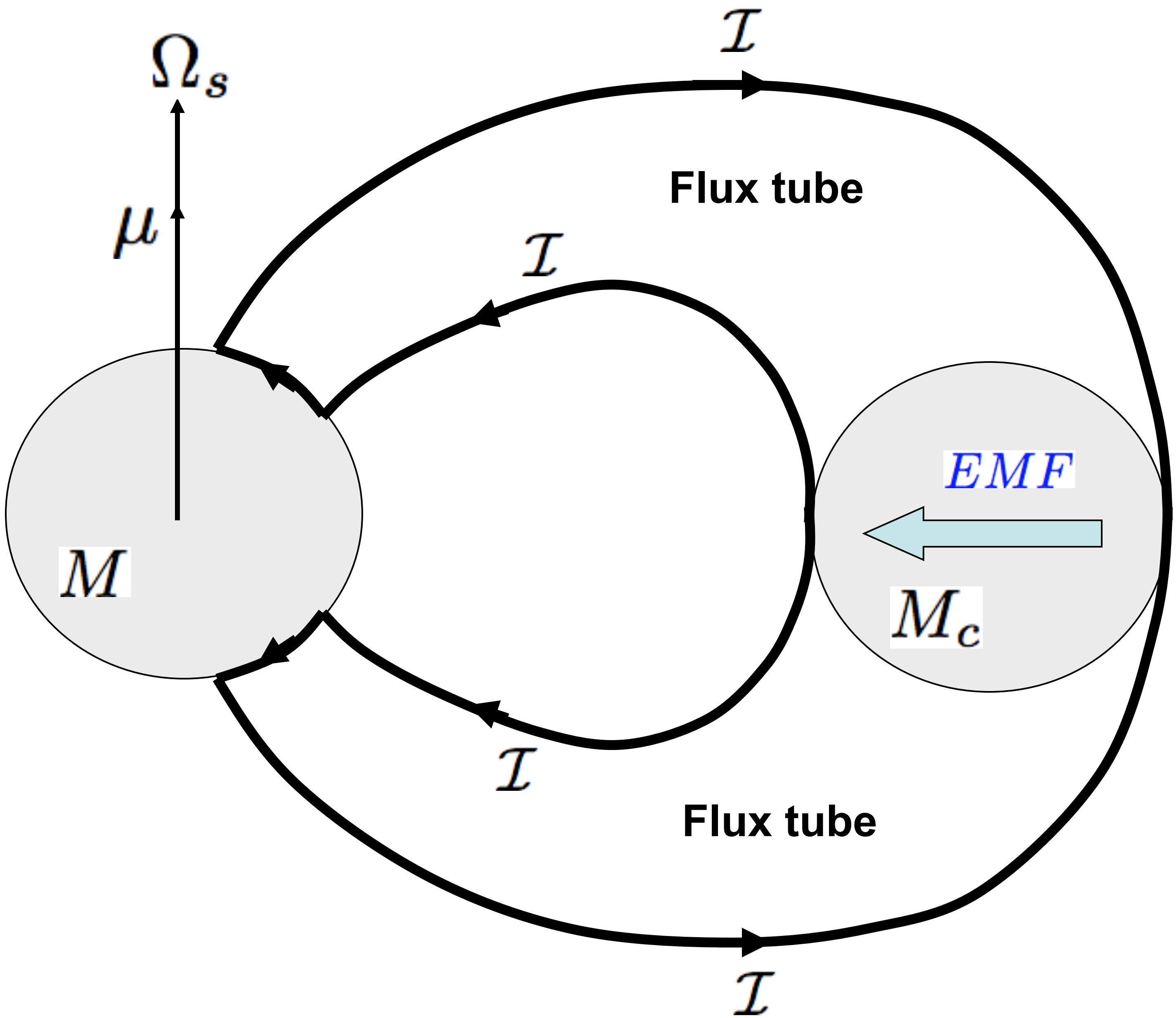
-- magnetic NS (>10^{12}G) + non-magnetic NS

-- embedded in a tenuous plasma (magnetosphere)



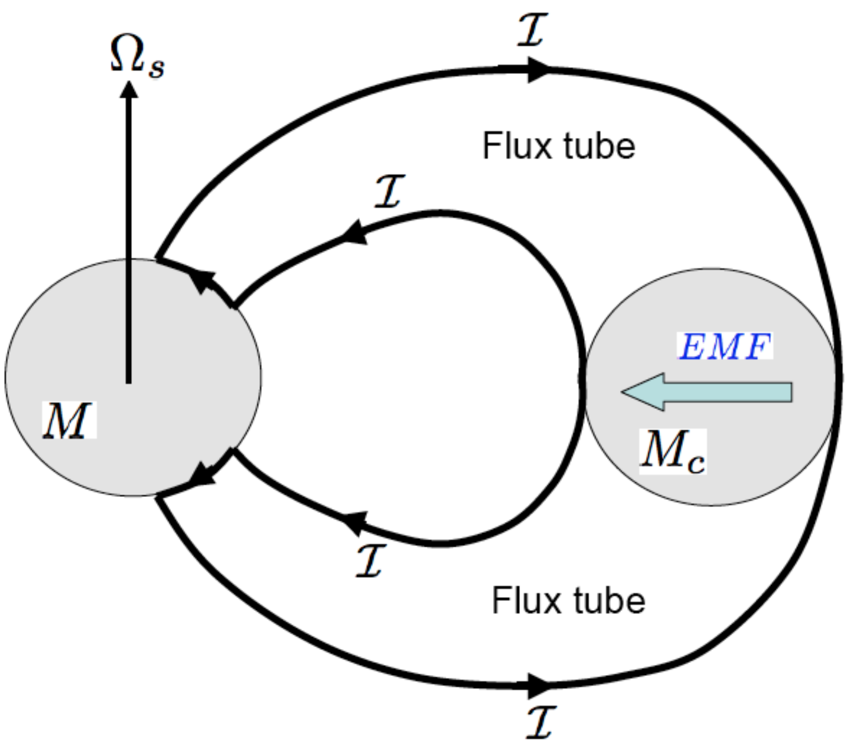
$$\text{EMF}: \quad \Phi = 2R_c \left| \frac{\mathbf{v}}{c} \times \mathbf{B} \right|$$

$$\text{e.g.} \quad \Phi \sim 10^{13}\ \text{Volt} \quad \text{at} \quad f_{\text{orb}} = 20\ \text{Hz}$$



Ω_s
μ
$\mathcal{I}$
Flux tube
$\mathcal{I}$
EMF
M
M_c
$\mathcal{I}$
Flux tube
$\mathcal{I}$

DC Circuit Powered by Orbital Motion



$$\mathrm{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\mathrm{orb}} - \Omega_s)$$

$$\mathrm{Current}: \quad \mathcal{I} = \frac{\Phi}{\mathcal{R}}$$

$$\mathrm{Dissipation}: \quad \dot{E}_{\mathrm{diss}} = \frac{\Phi^2}{\mathcal{R}}$$

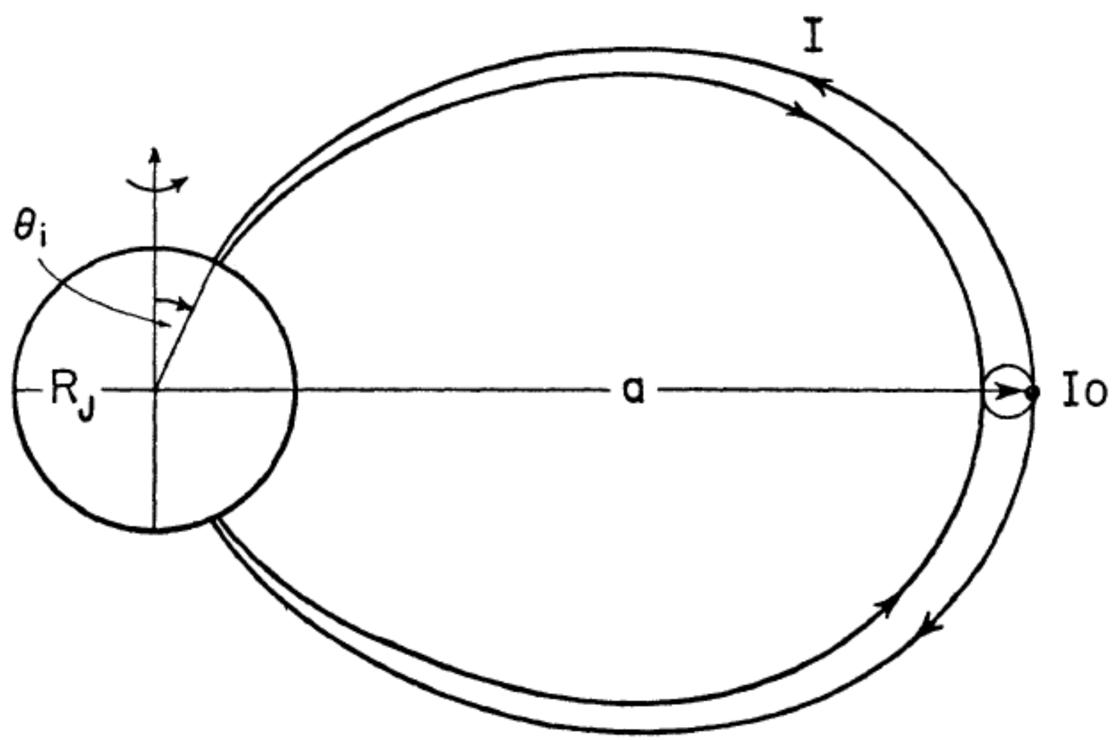
THE ASTROPHYSICAL JOURNAL, Vol. 156, April 1969

IO, A JOVIAN UNIPOLAR INDUCTOR

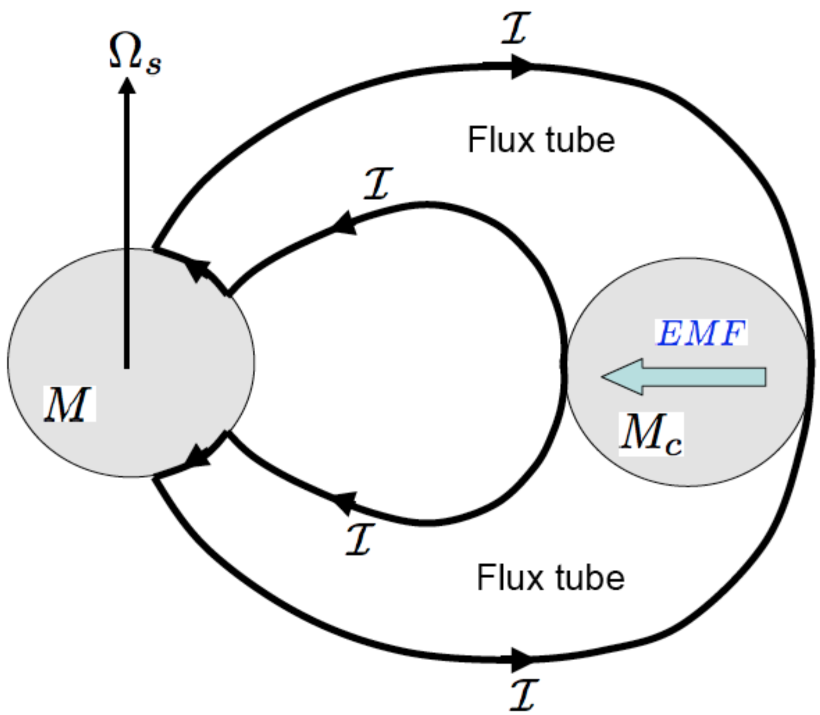
PETER GOLDREICH*
California Institute of Technology

AND

DONALD LYNDEN-BELL
Royal Greenwich Observatory



DC Circuit Powered by Orbital Motion



Applications to:

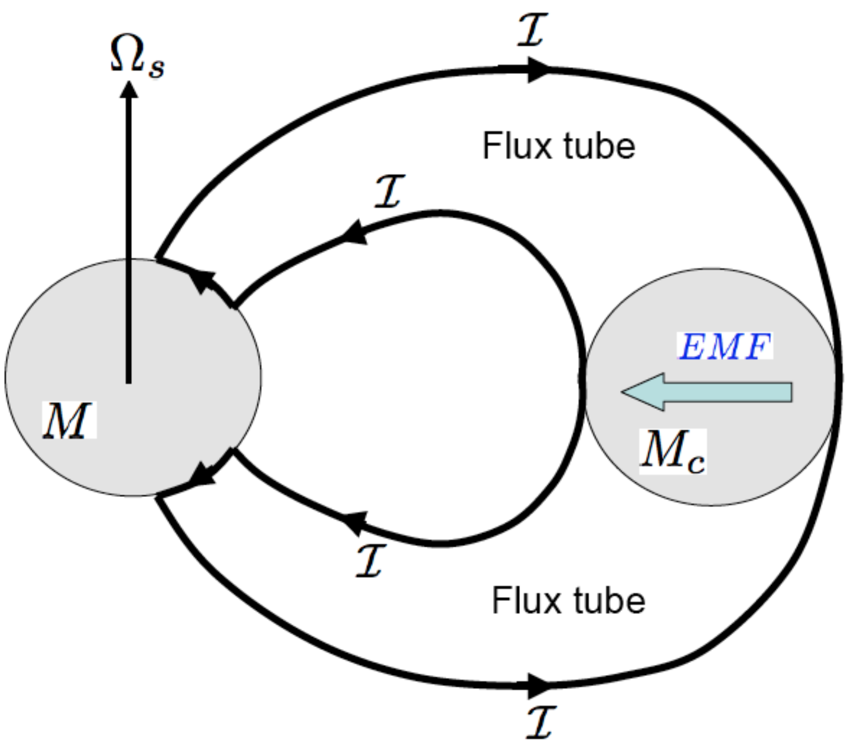
WD-WD Binaries
(K.Wu et al. 02,09; Dall'Osso, Israel, Stella 06,07)

NS-NS, NS-BH Binaries
(Hansen & Lyuitikov 01; McWilliams & Levin 11; Piro 12)

Exoplanetary systems (Laine & Lin 12,…)

Caution: Some of these were wrong

DC Circuit Powered by Orbital Motion



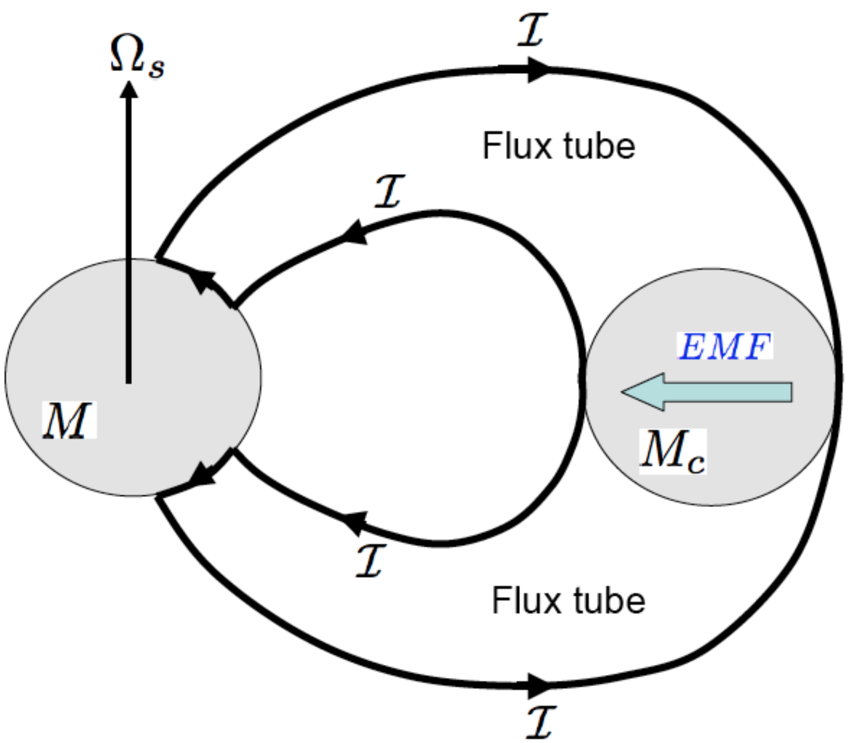
$$\text{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\text{orb}} - \Omega_s)$$

$$\text{Current}: \quad \mathcal{I} = \frac{\Phi}{\mathcal{R}}$$

$$\text{Dissipation}: \quad \dot{E}_{\text{diss}} = \frac{\Phi^2}{\mathcal{R}}$$

Results depend on the resistance: $\mathcal{R}$

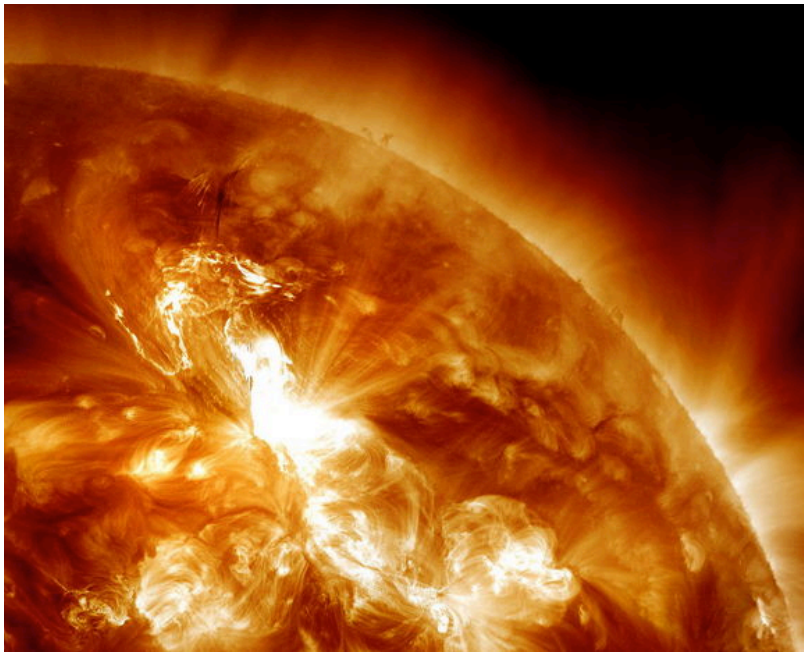
DC Circuit Powered by Orbital Motion

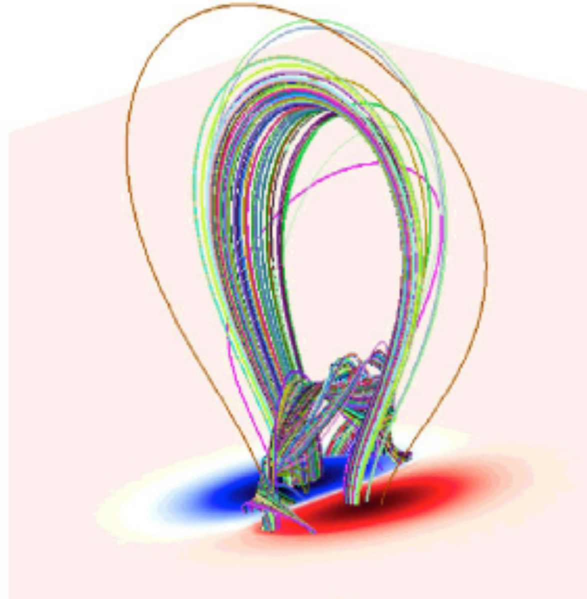


Problems with small $\mathcal{R}$
(➔large $\mathcal{I}$):

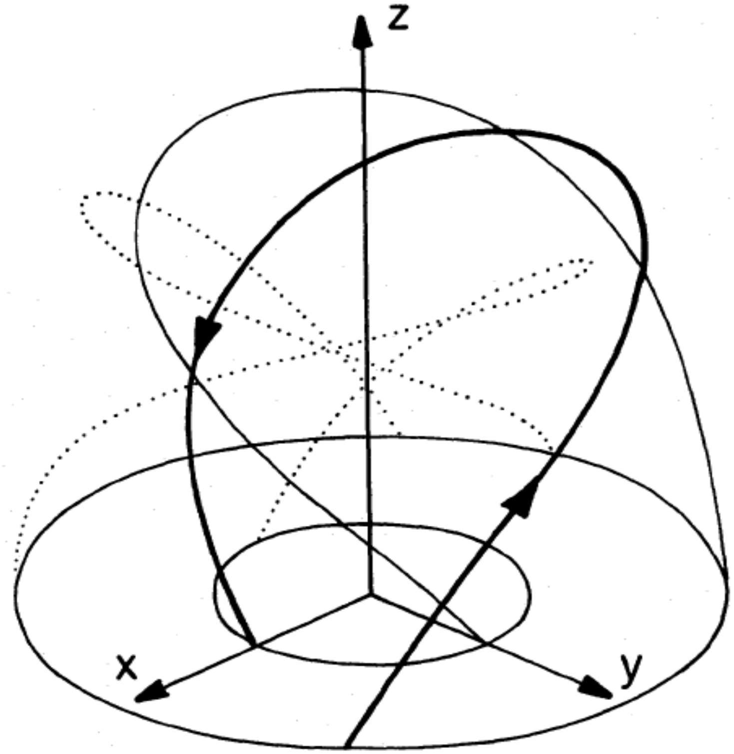
Flux tube is twisted

$$\frac{|B_\phi|}{|B_z|} \sim \frac{16\, v/c^2}{\mathcal{R}}, \quad v = (\Omega_{\rm orb} - \Omega_s)a$$

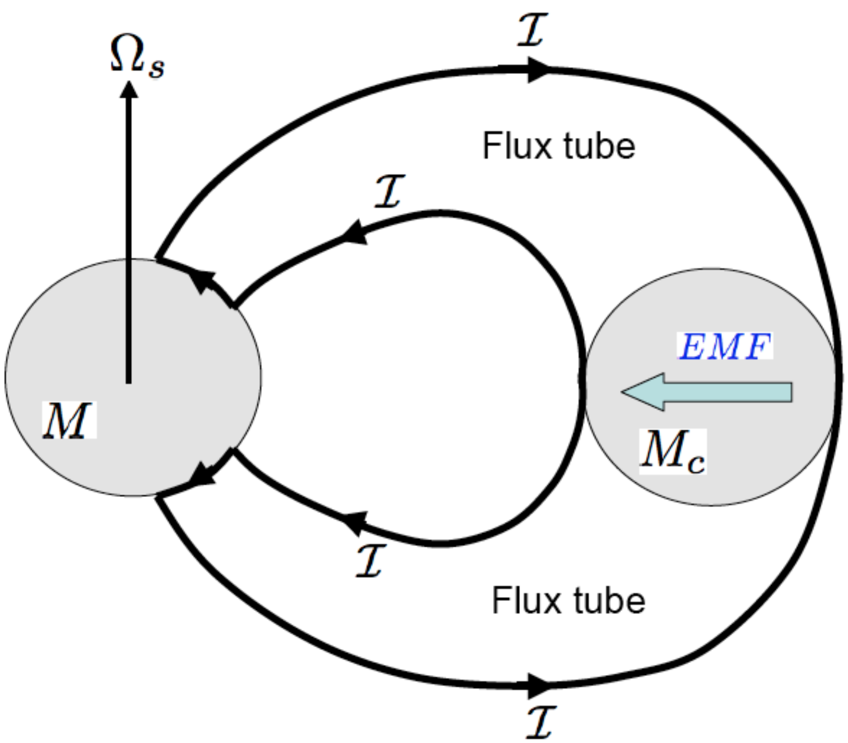




(b)



DC Circuit Powered by Orbital Motion



$$\frac{|B_\phi|}{|B_z|} \sim \frac{16\, v/c^2}{\mathcal{R}}, \quad v = (\Omega_{\rm orb} - \Omega_s)a$$

Circuit will break when $|B_\phi|/|B_z| \gtrsim 1$

Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

DL 2013

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

Actual dissipation rate:

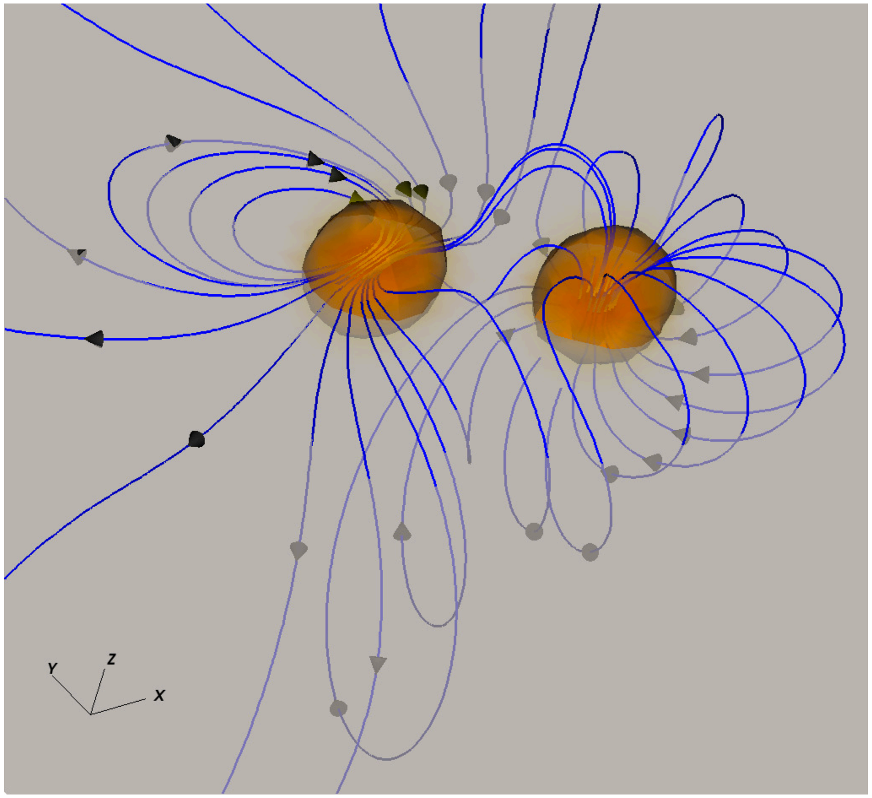
$$\dot{E} \sim 2 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{a}{30\,{\rm km}}\right)^{-7} {\rm erg~s^{-1}}$$

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

Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

Q: What happens if both NSs are magnetic?



Ponce… Lehner …2014-16

Summary (I)

Merging NS and BH Binaries:

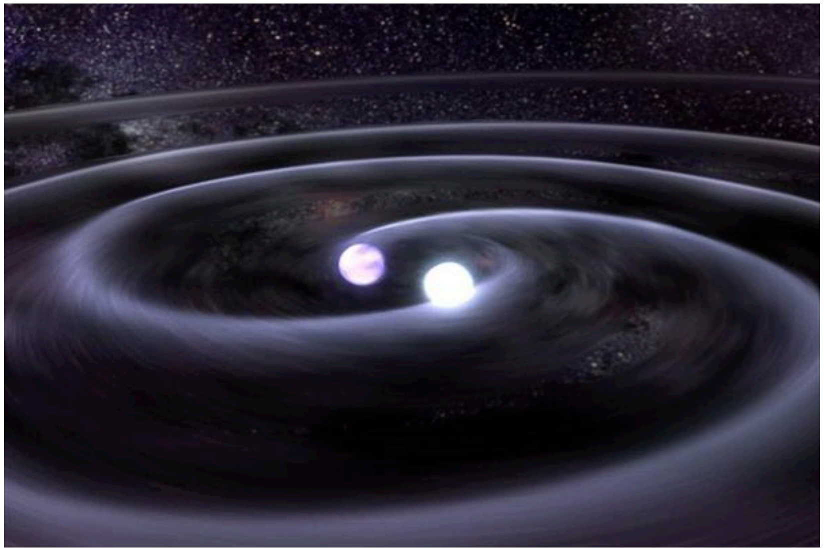
-- Should be detected (soon!) by advanced LIGO/VIRGO

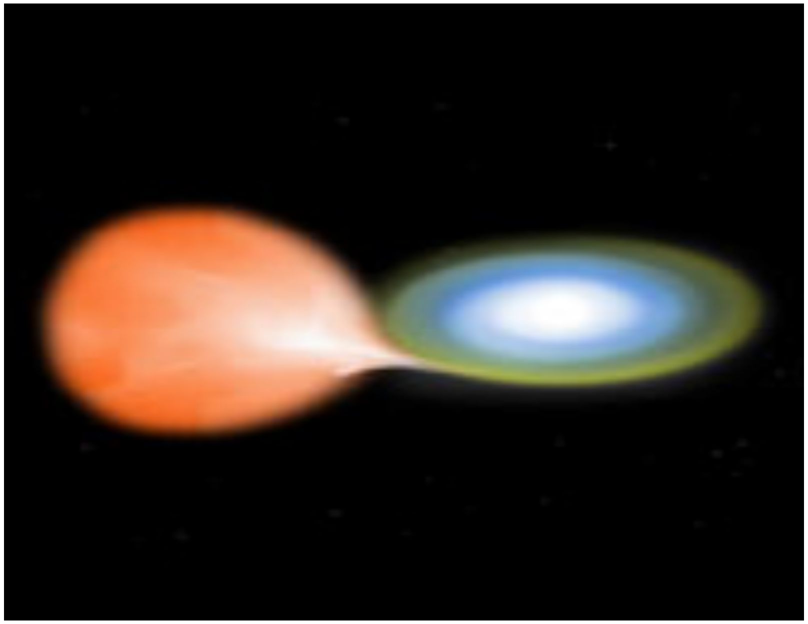
-- Probe NS EOS: Resonant excitations of modes

-- EM counterparts: GRBs, kilonovae (Optical/IR)

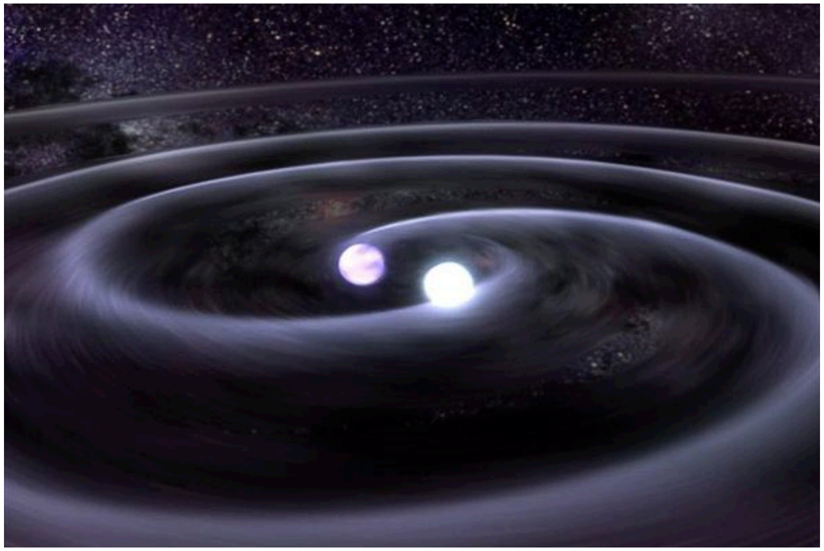
pre-merger magnetic interactions → precursors (?)

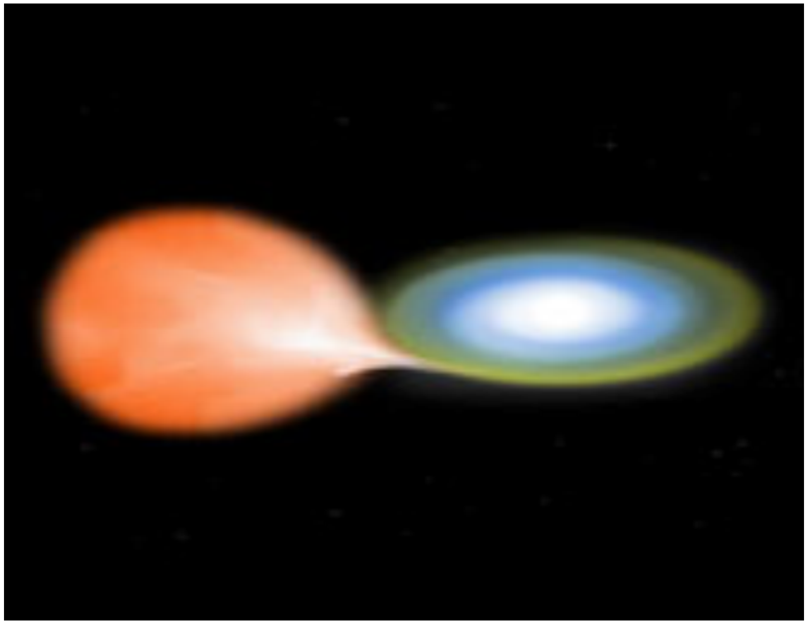
Compact White Dwarf Binaries (mins - hour)





Compact White Dwarf Binaries (mins - hour)





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

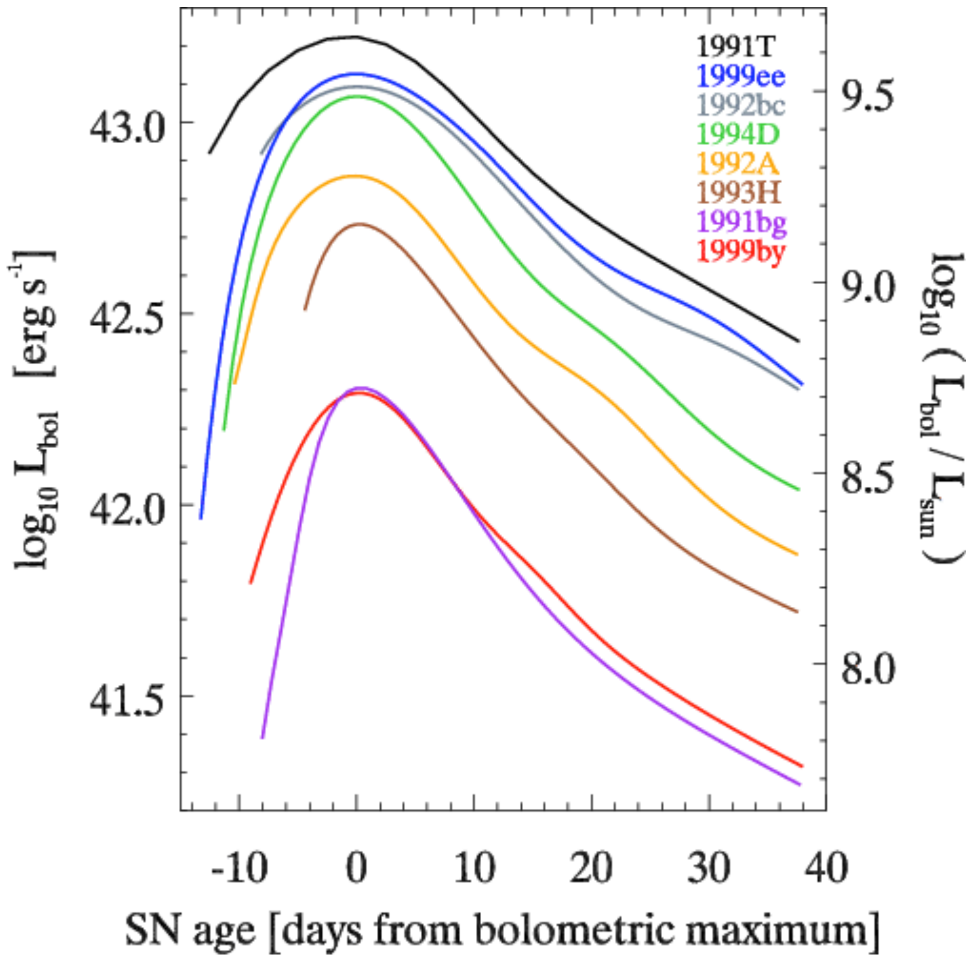
Space interferometer (LISA)

-- **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 ~$1.4M_{sun}$

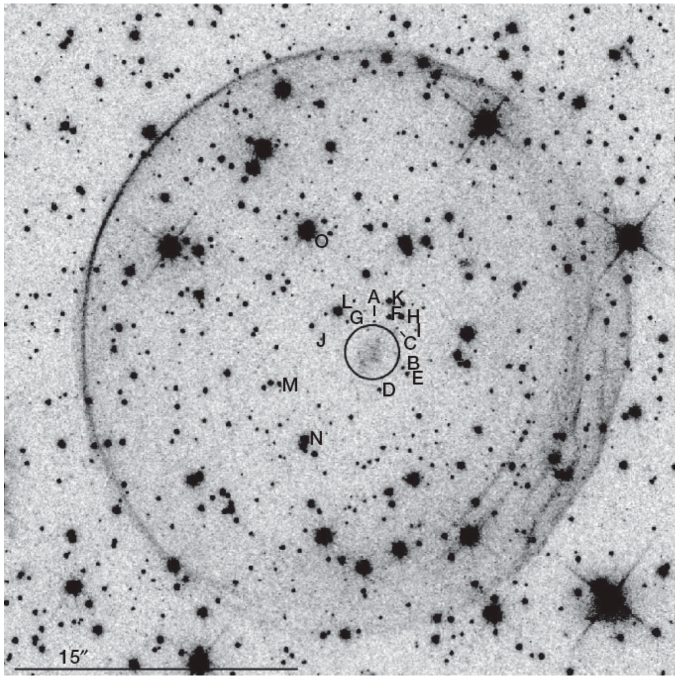
Progenitors ??

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…

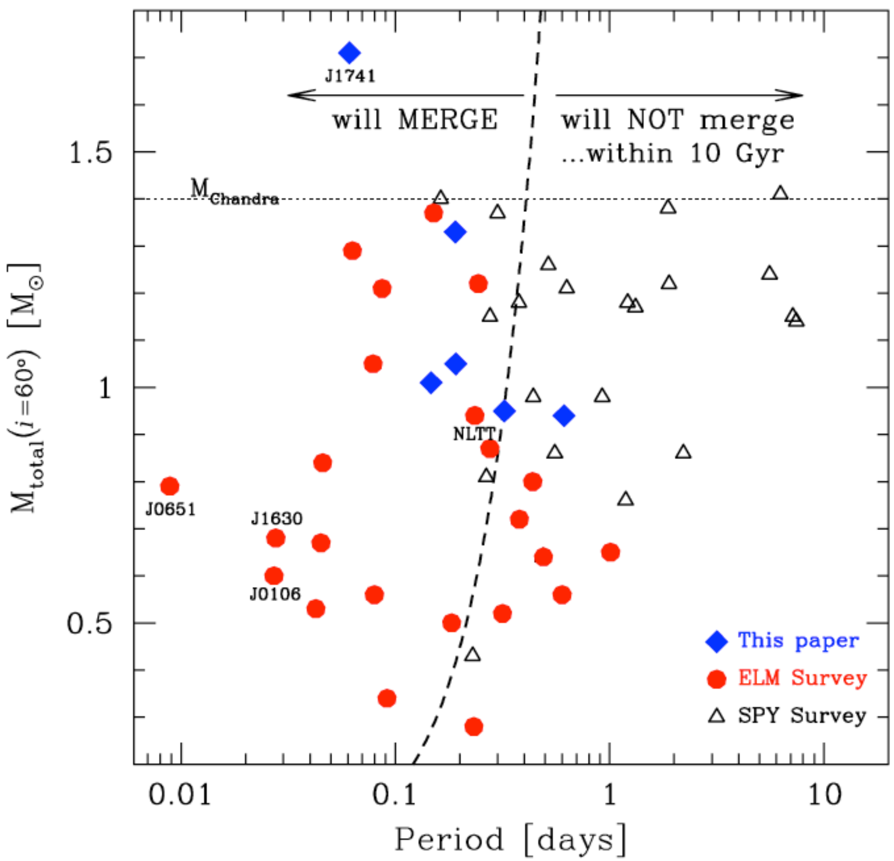
Recent observations in favor of DD:

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

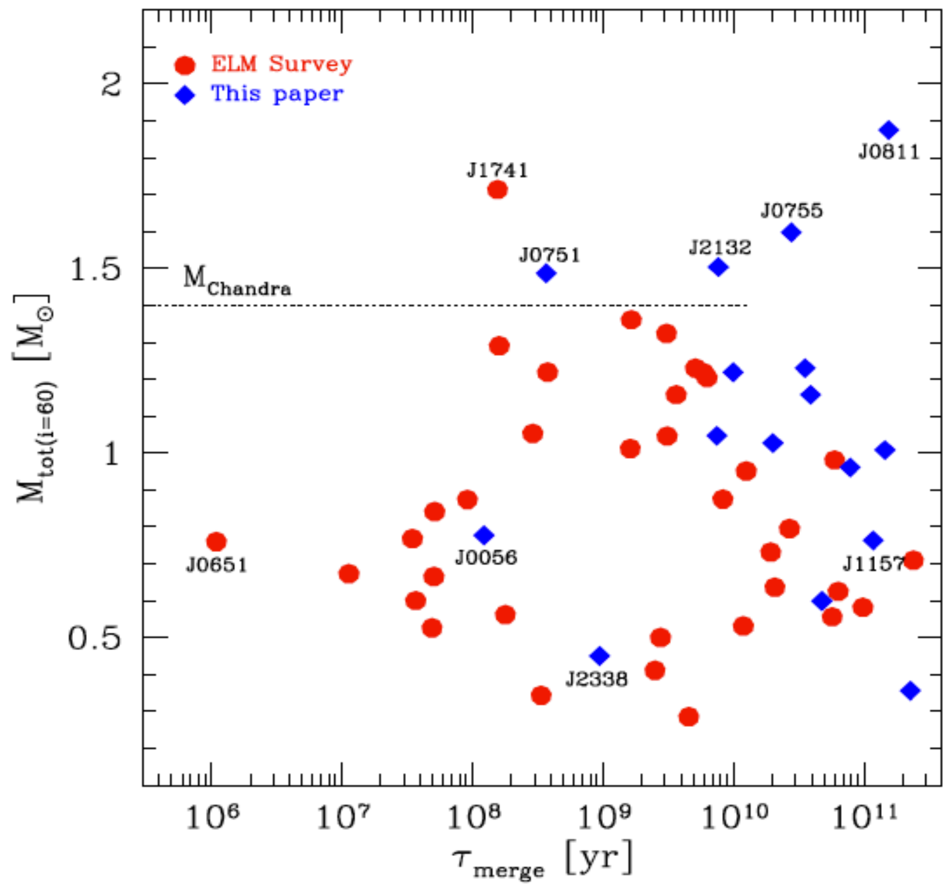


Schaefer & Pagnotta 2012
(cf Di Stefano & Kilic 2012;
Shen et al.13)

Radial Velocity Surveys of Compact WD Binaries

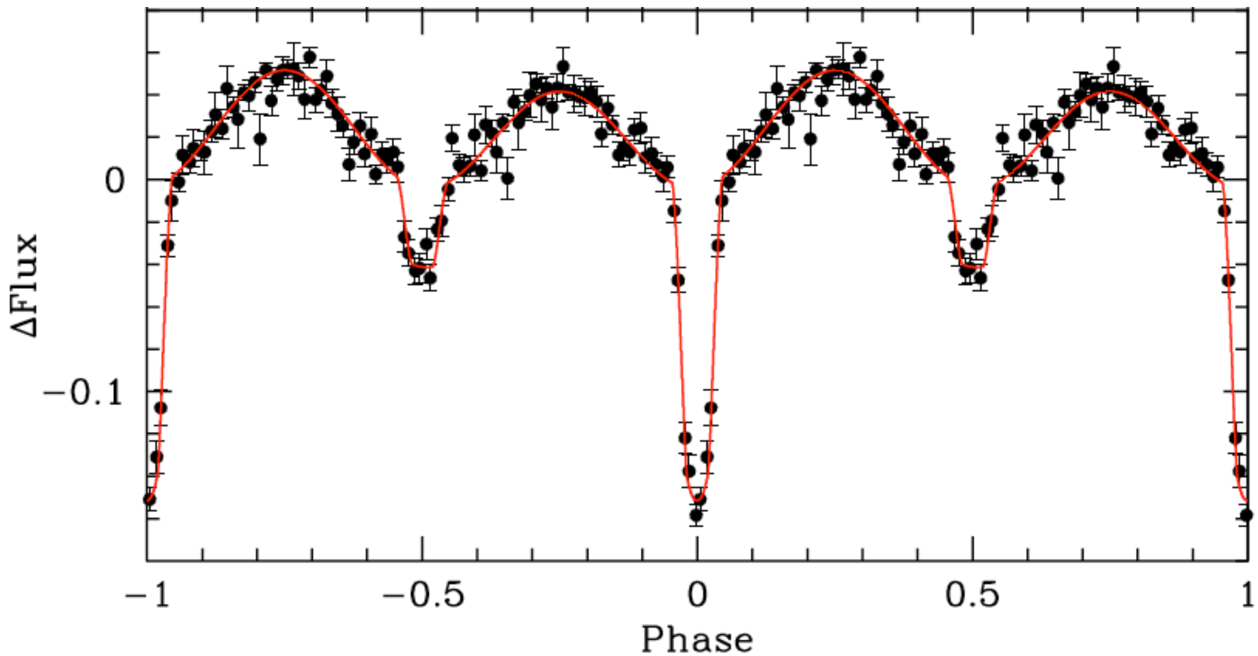


Brown et al. 2012



Brown et al. 2013
Gianninas et al. 2015

12 min orbital period double WD eclipsing binary



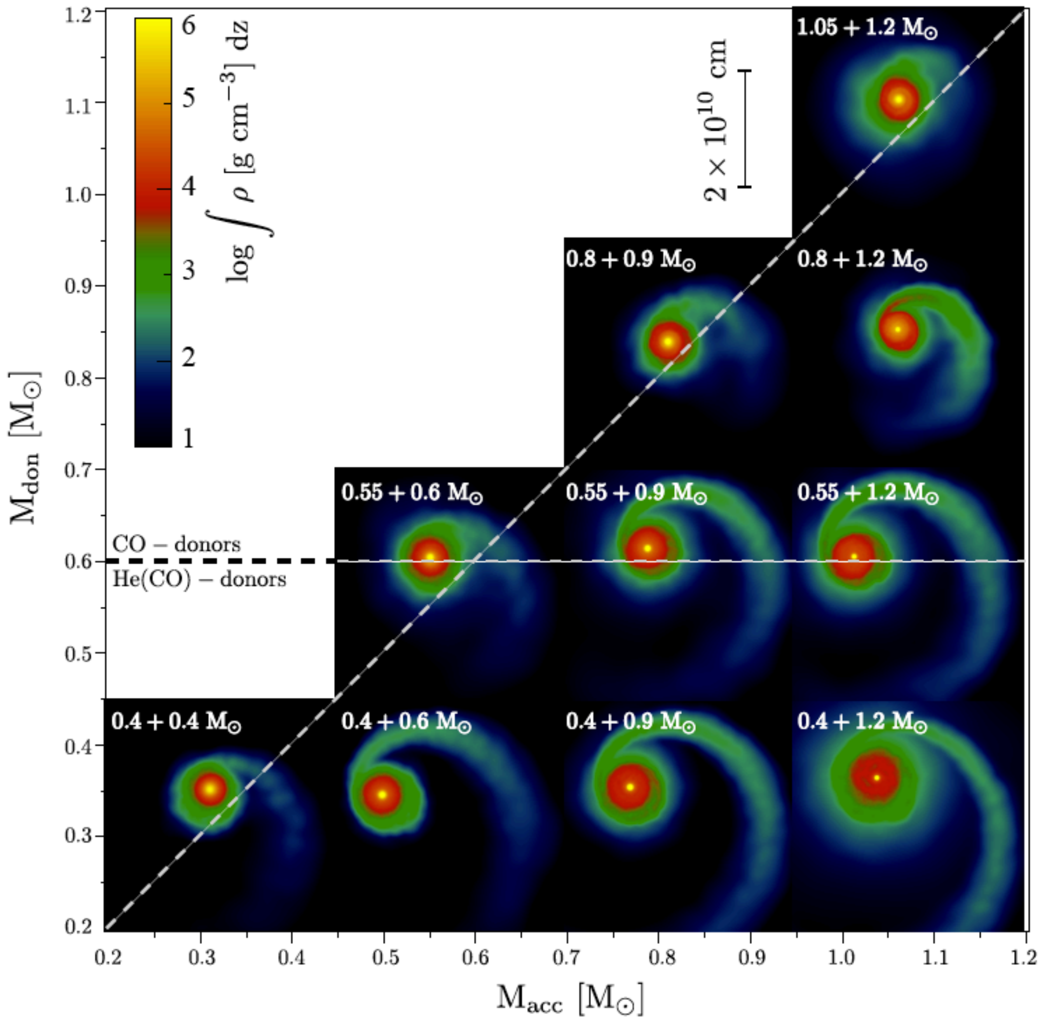
SDSS J0651+2844

Primary & secondary eclipses
Ellipsoidal (tidal) distortion
Doppler boosting

Brown et al. 2011

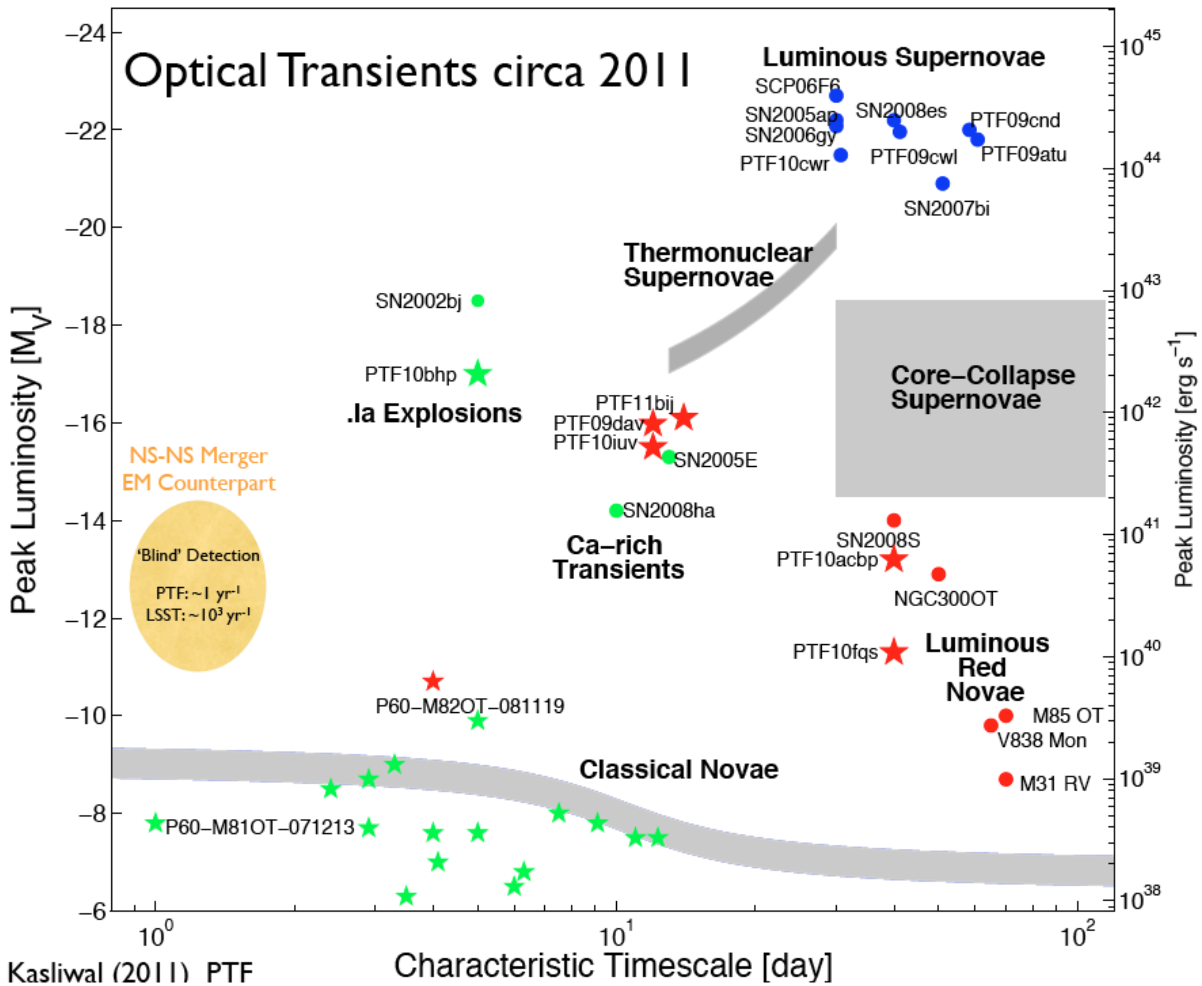
-- will merge in 0.9 Myr
-- large GW strain → (eLISA verification source)
-- orbital decay measurable from eclipse timing (Hermes et al 2012)

WD Binary Merger

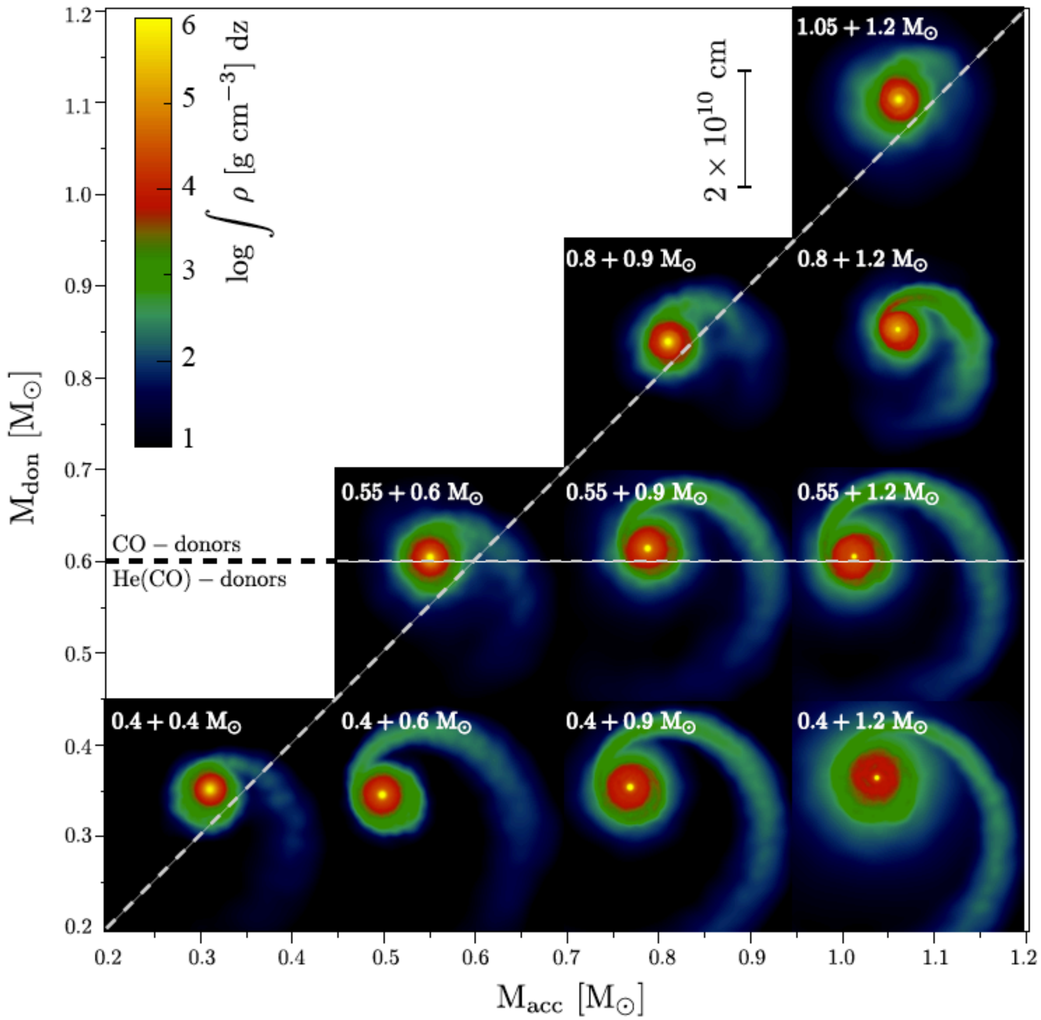


Dan, Rosswog,et al. 14

WD Binary Merger ➔ Transient sources



WD Binary Merger



Dan, Rosswog,et al. 14

Outcome depends on WD masses, composition, and pre-merger conditions (temperature, rotation)

Dynamical Tides in Compact WD Binaries

with Jim Fuller
(Ph.D. 2013; now at Caltech)

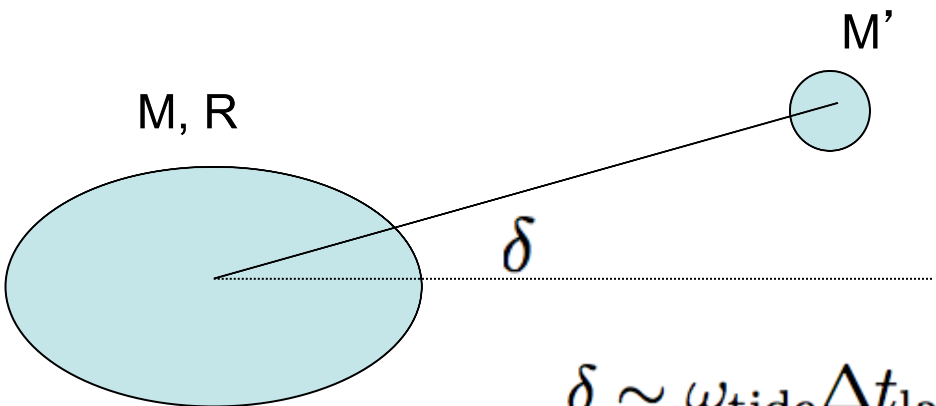
Issues:

-- Spin-orbit synchronization?

-- Tidal dissipation and heating?

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

Equilibrium Tide



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

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

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

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

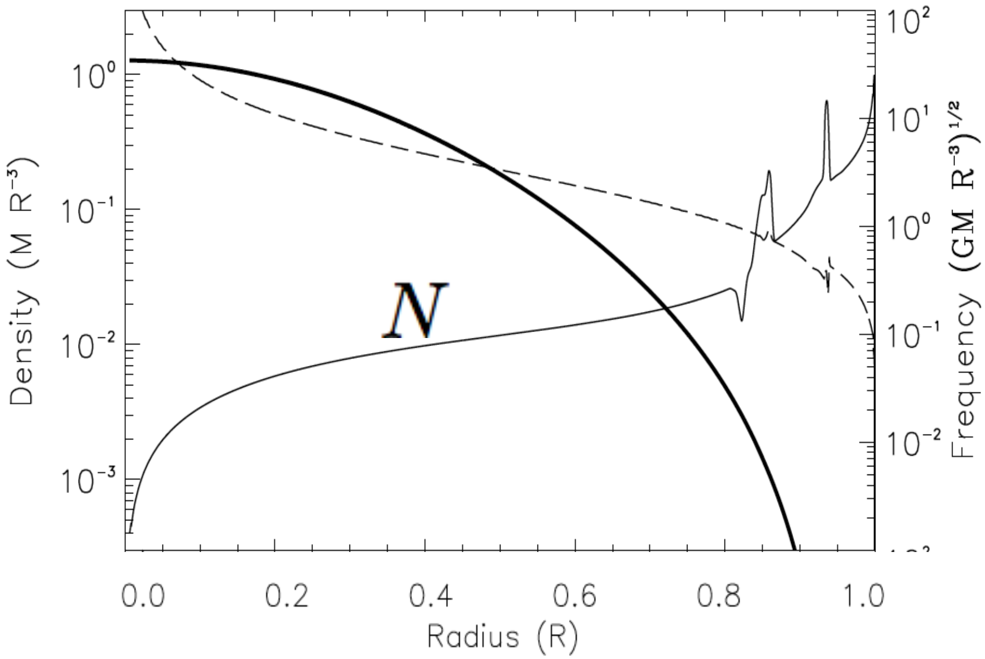
Problems:

-- Parameterized theory

-- The physics of tidal dissipation is more complex:

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

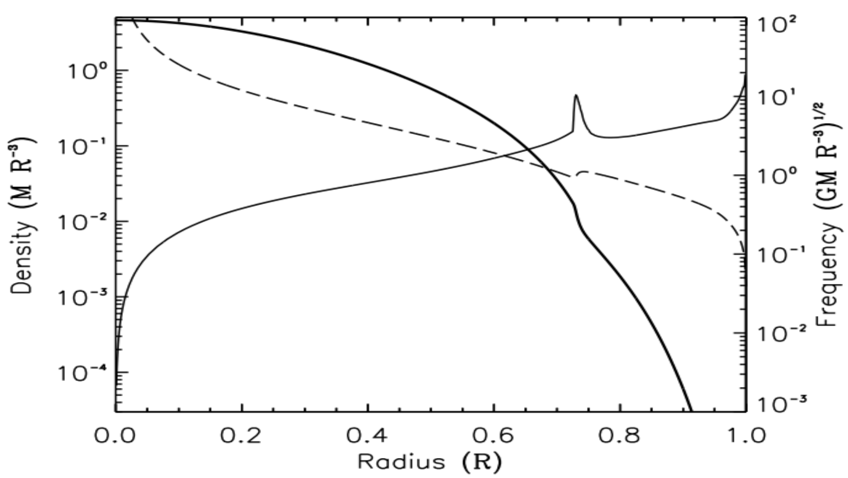
Wave Propagation inside White Dwarf



N = Local Buoyancy Freq

CO WD

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



He-core WD

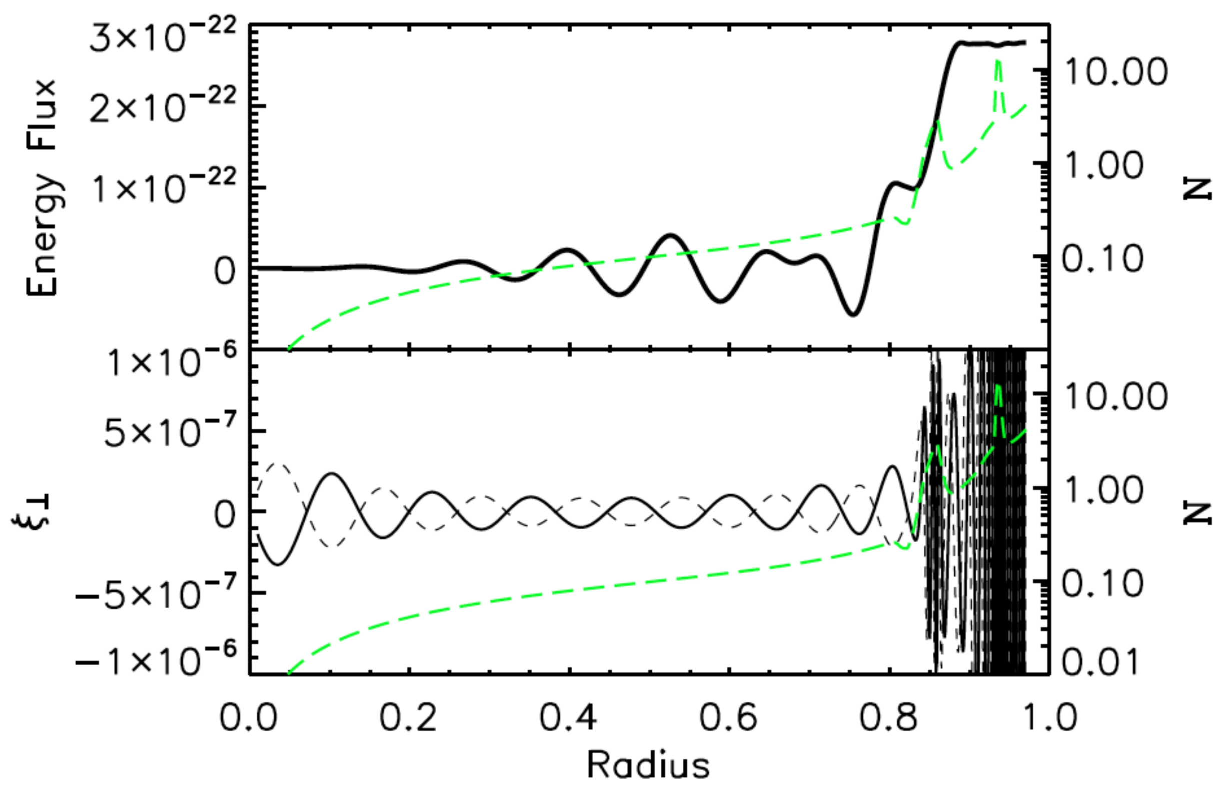
$0.3 M_\odot,\ 12000\,\mathrm{K}$

“Continuous” Excitation of Gravity Waves

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

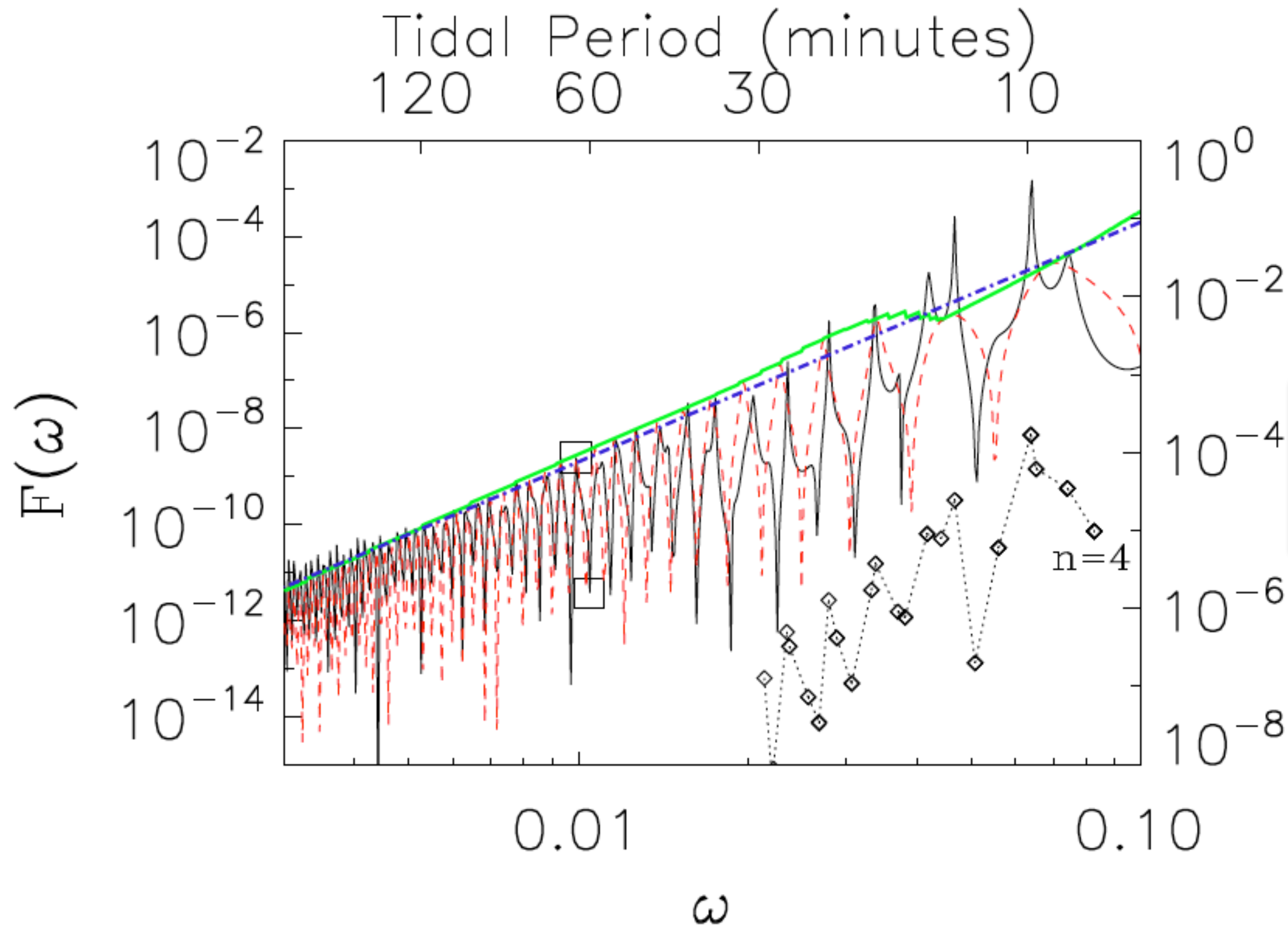
"Continuous" Excitation of Gravity Waves

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

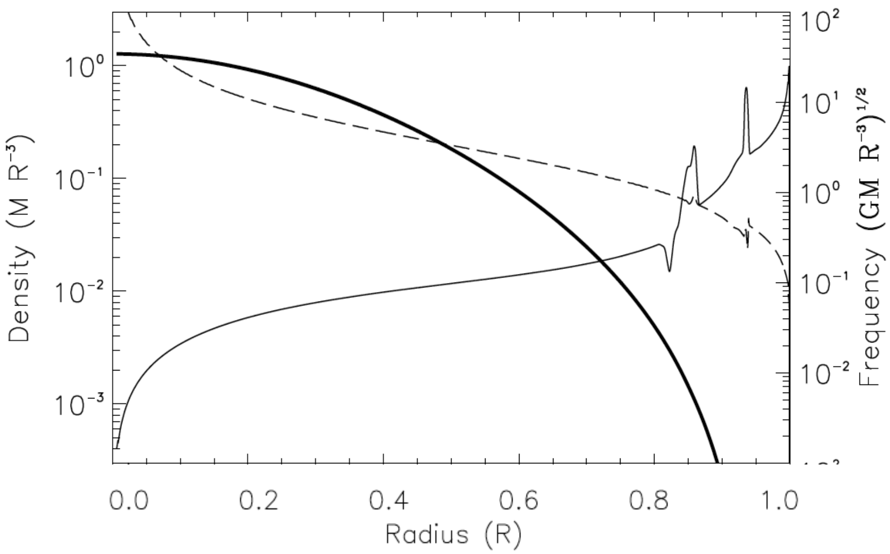


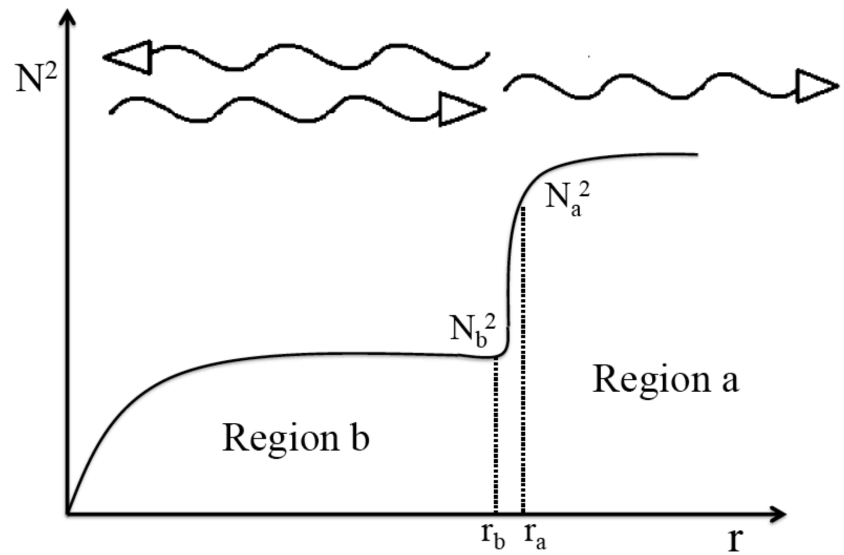
$$M = 0.6 M_\odot, \quad \omega = 0.01$$

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

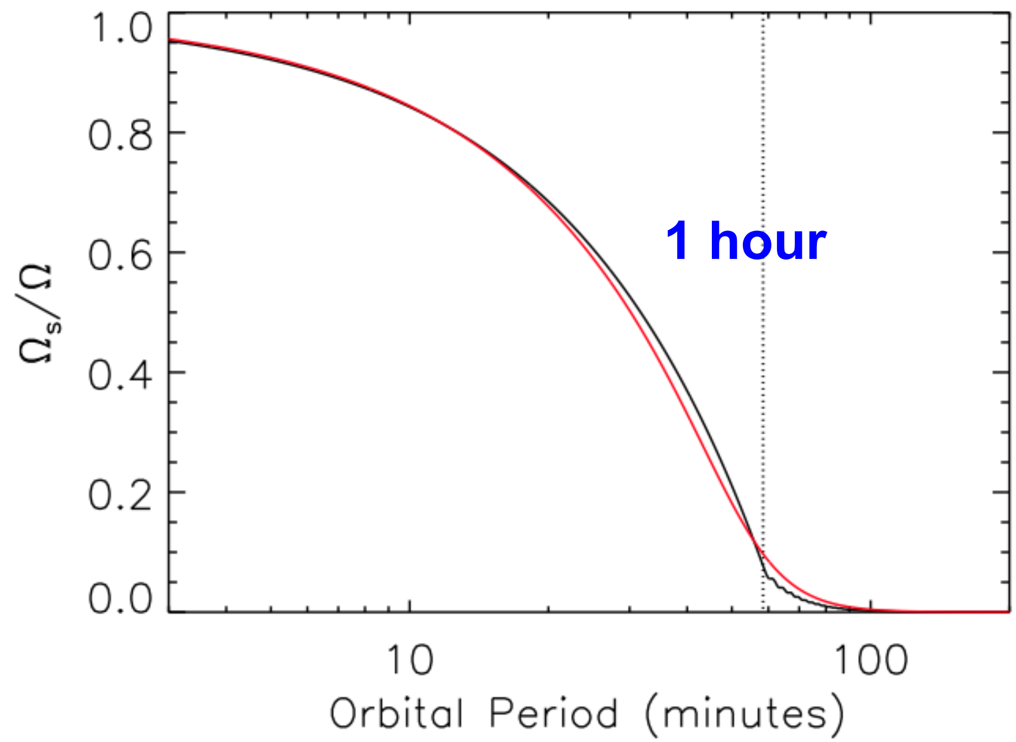


Why is $F(\omega)$ not smooth ?





Spin-Orbit Synchronization

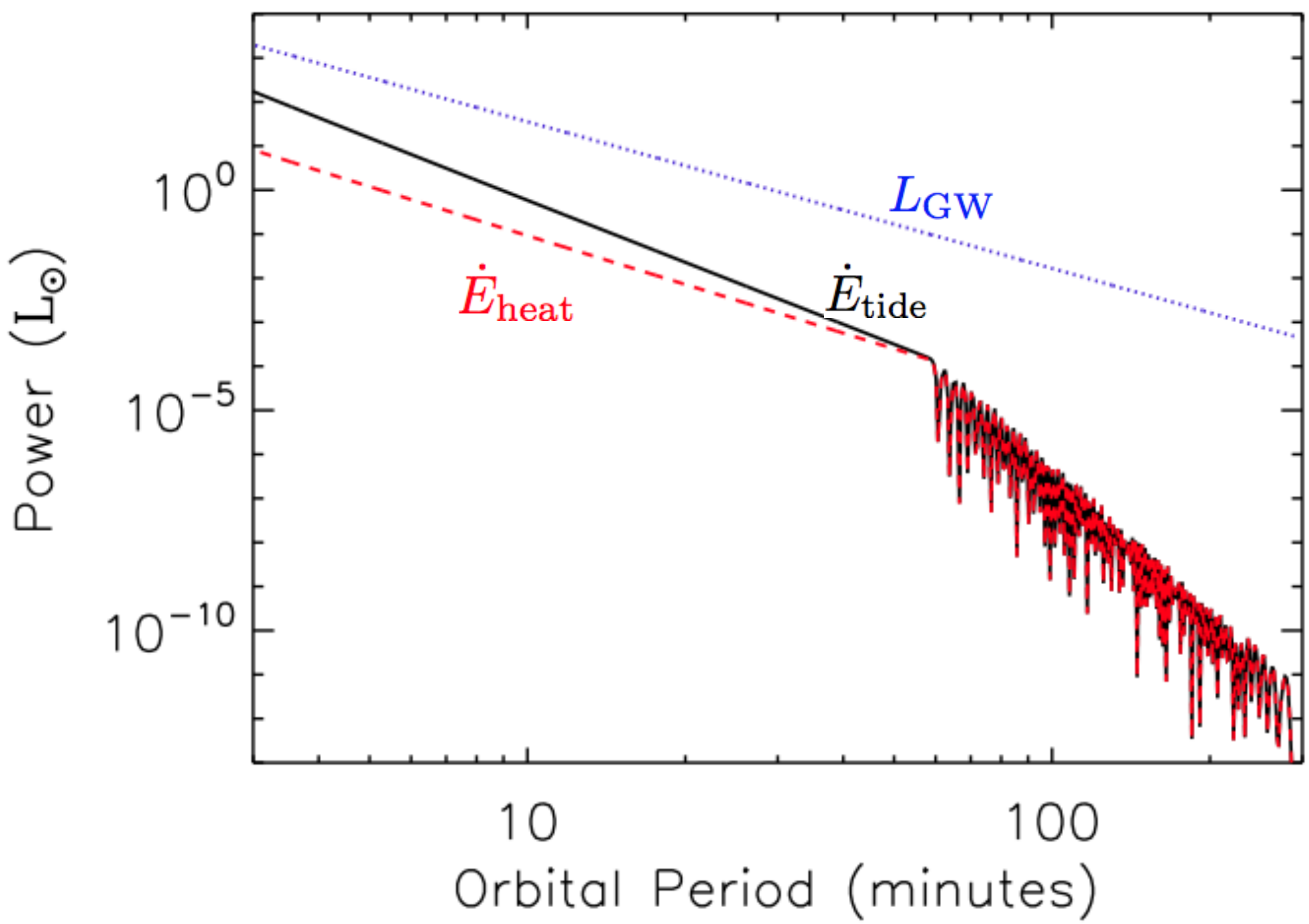


$$\text{Critical orbital } \Omega_c : \quad \dot{\Omega}_s = \frac{\text{Torque}}{I} \simeq \dot{\Omega}_{\text{orb}} = \frac{3\Omega_{\text{orb}}}{2t_{\text{GW}}}$$

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

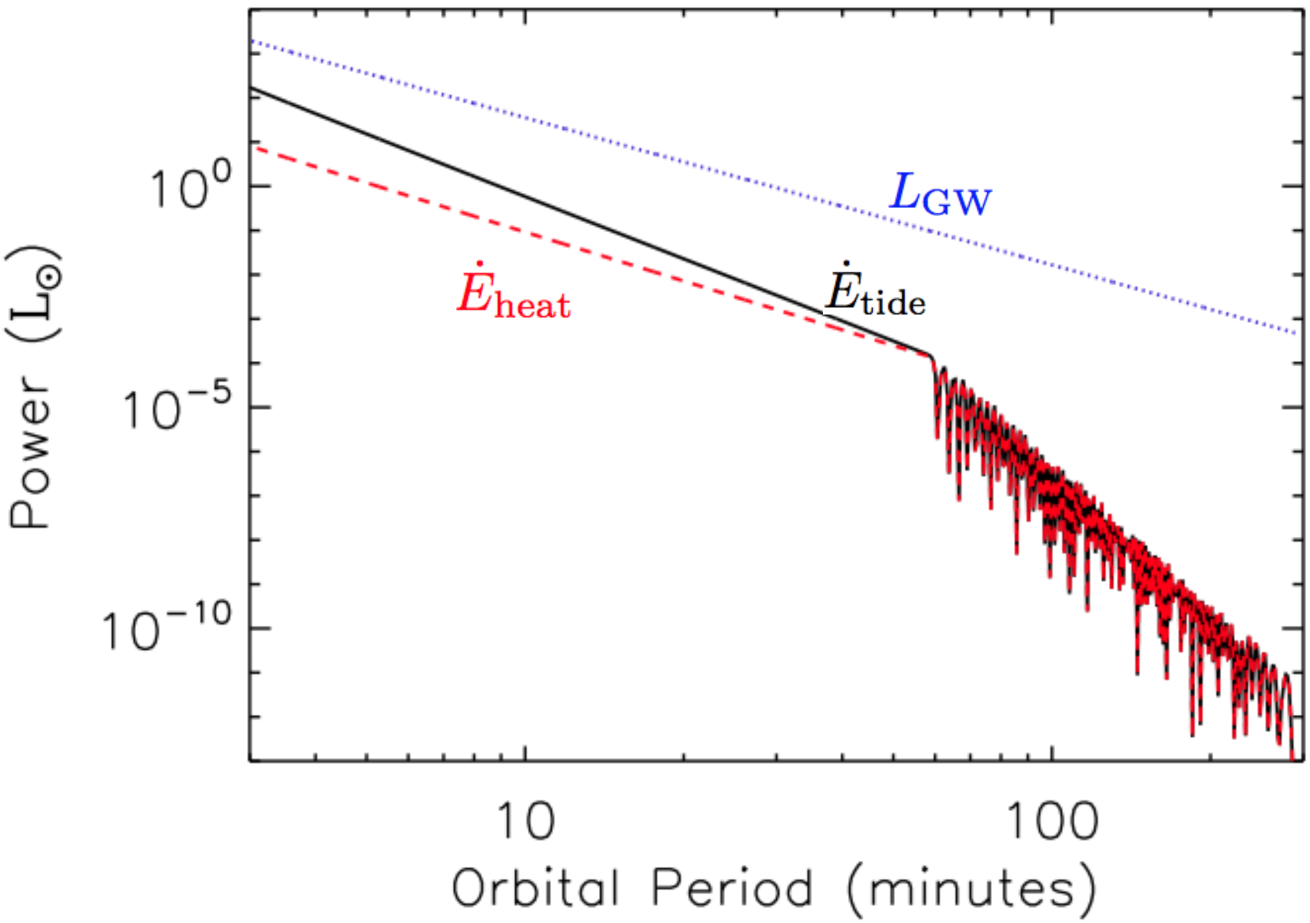
$$\dot{\Omega}_s - \dot{\Omega}_{\text{orb}} \ll \dot{\Omega}_{\text{orb}} \Longrightarrow \dot{E}_{\text{tide}} = \Omega_{\text{orb}} T \simeq \frac{3I\Omega_{\text{orb}}^2}{2t_{\text{GW}}}$$

Tidal Dissipation (energy transfer from orbit to star)



$$\dot{E}_{\rm tide} \lesssim 0.03 L_{\rm GW}$$

Tidal Heating Rate



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

Consequences of Tidal Heating

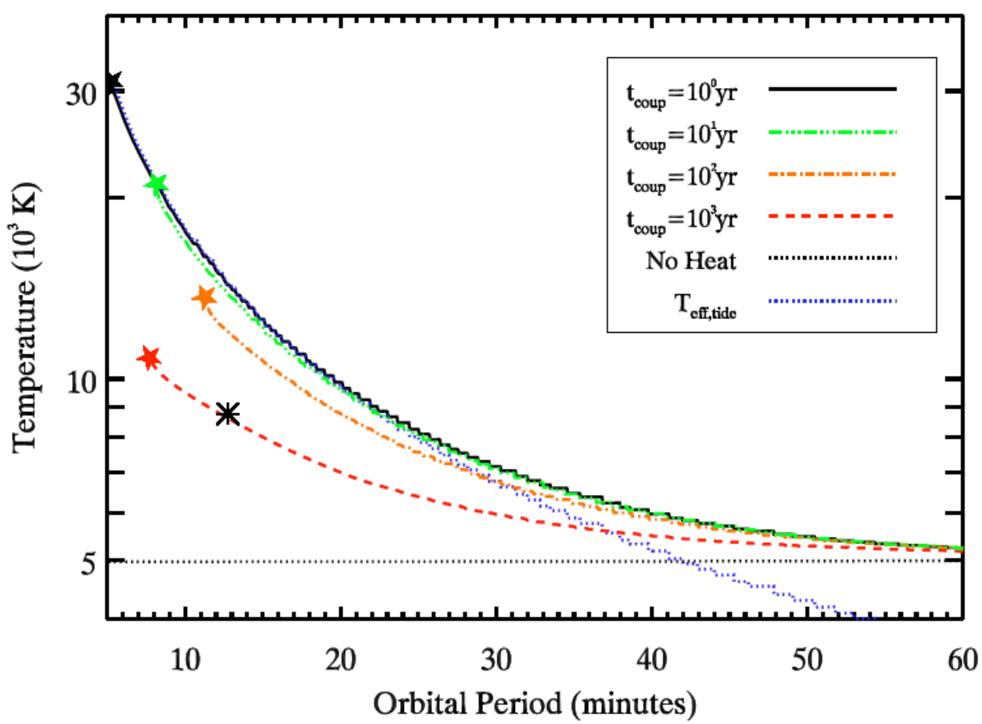
Depend on where the heat is deposited …

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

Explain SDSS J0651+2844

If deposited in deeper layer:
(common: critical layer…)
thermal time longer than orbital
==> Nuclear flash

* **“Tidal Nova”**



Summary (II)

Merging WD Binaries:

-- Produce various outcomes (e.g. SN Ia), transient sources (PTF/ZTF, LSST)

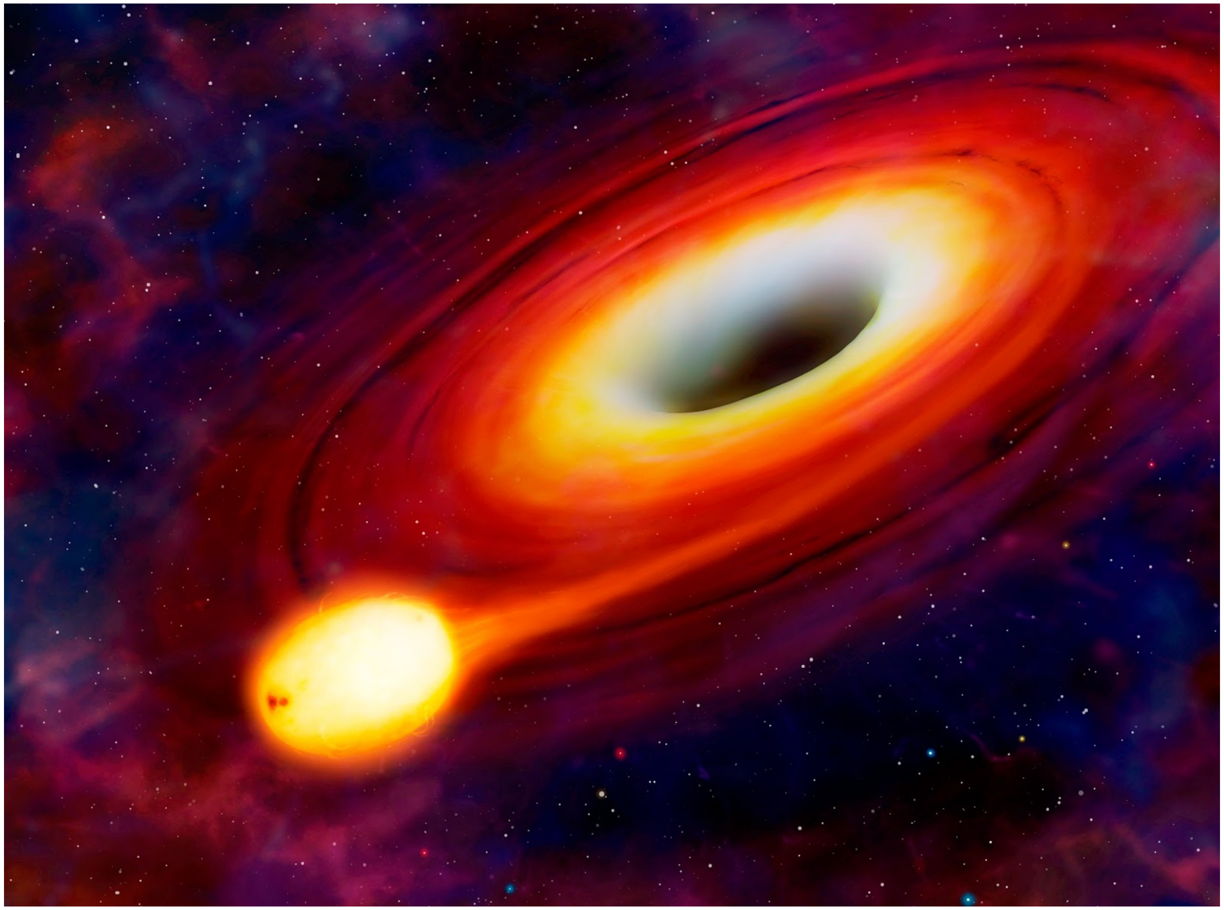
-- Pre-merger phase important/interesting:

dynamical tides: Continuous excitations of waves, nonlinear breaking

spin synchronization, tidal heating → Tidal nova

-- Low-frequency GWs (LISA)

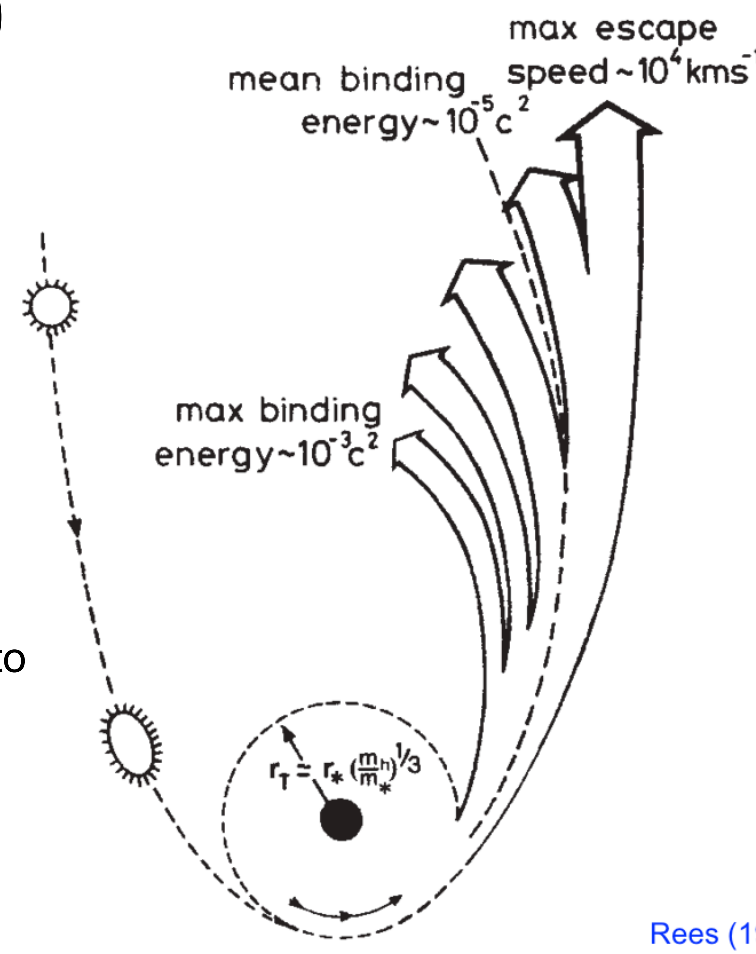
Star (WD) – Massive BH Binaries:
Eccentric Path to Tidal Disruption



Tidal Disruption of Star by Supermassive BH

$$r_{\rm bh} \lesssim r_{\rm peri} \lesssim r_{\rm tide}$$

$$r_{\rm bh} \simeq \frac{2GM_{\rm bh}}{c^2} \qquad r_{\rm tide} \simeq R_\star \left(\frac{M_{\rm bh}}{M_\star}\right)^{1/3}$$

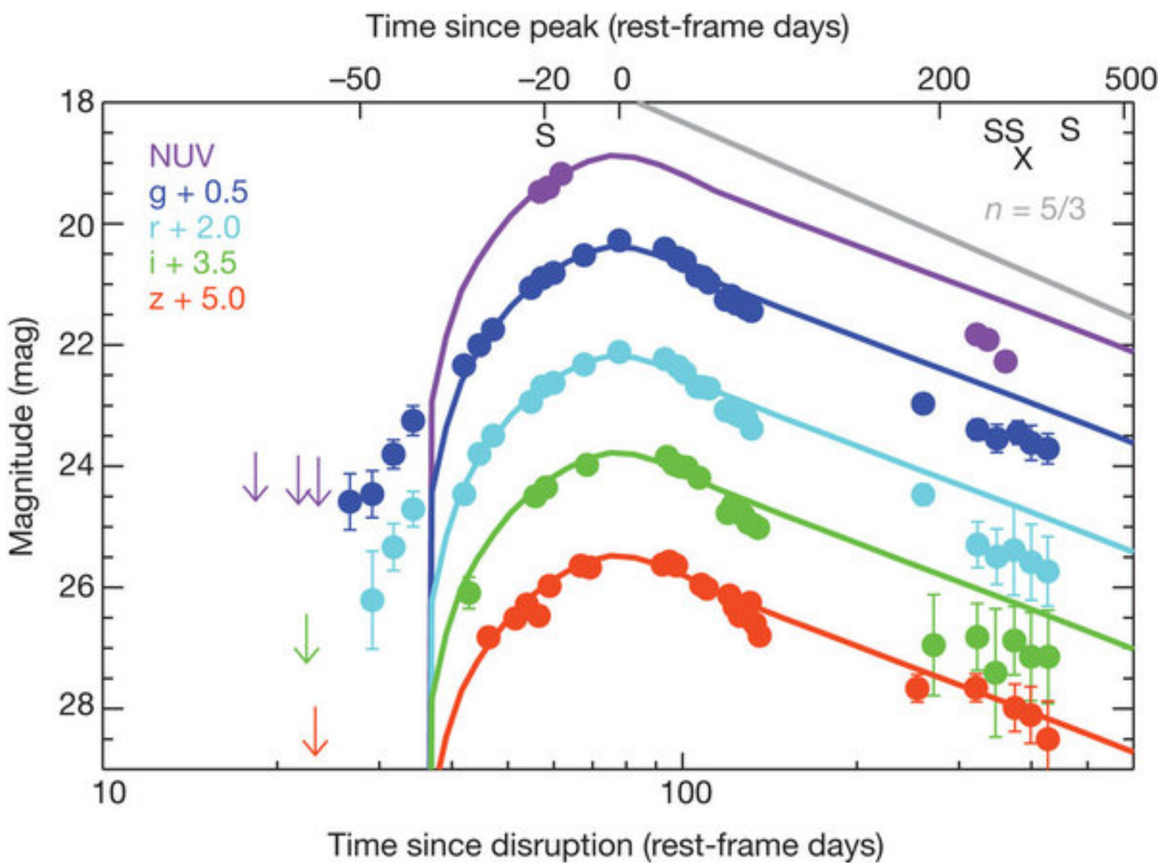


Disrupted stellar debris falls back onto an accretion disk
➔ Flares followed by $t^{-5/3}$ decay

Rees (1988)

Tidal Disruption Events (TDEs)

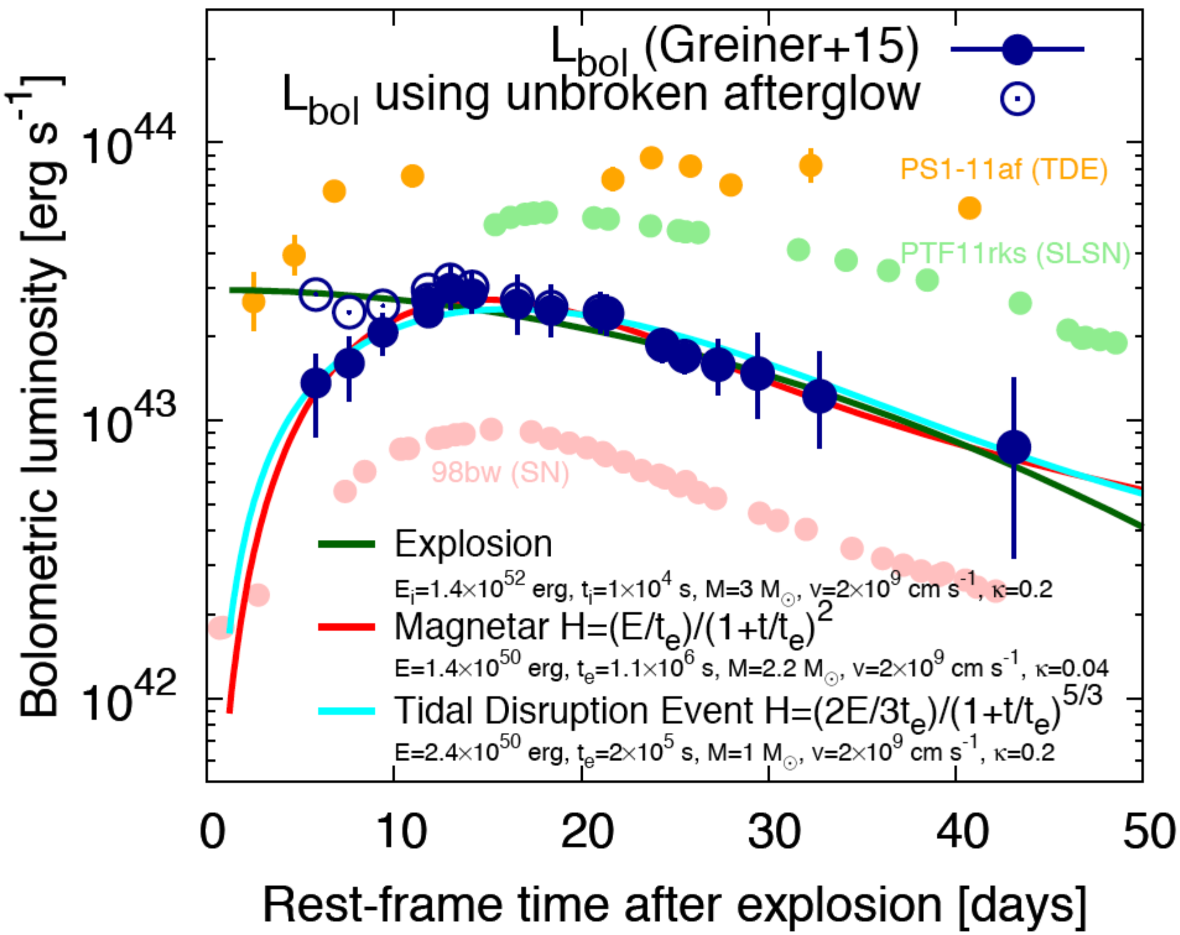
~70 candidates so far (Auchettl et al 2017)
optical/UV, soft x-rays (hard x-rays for jetted TDEs)



Gezari et al. 2012

Tidal Disruption Events (TDEs)

White Dwarf -TDEs ? (ultra-long 10^4 s GRBs?)



WD-TDEs require
$M_{\rm bh} \lesssim 10^5 M_\odot$

Ioka, Hotokezaka & Piran 2017

See also Shcherbakov et al.13; Levan et al.14

What will happen when a star (WD) is captured into an orbit with $r_{peri} = (3\text{-}20) \times r_{tide}$?

WD – Massive BH Binaries:
Eccentric Path to Tidal Disruption

with Michelle Vick

Issues:

-- **Gravitational radiation (GR) vs tidal dissipation ?**

GR reduces a, e and r_{peri}

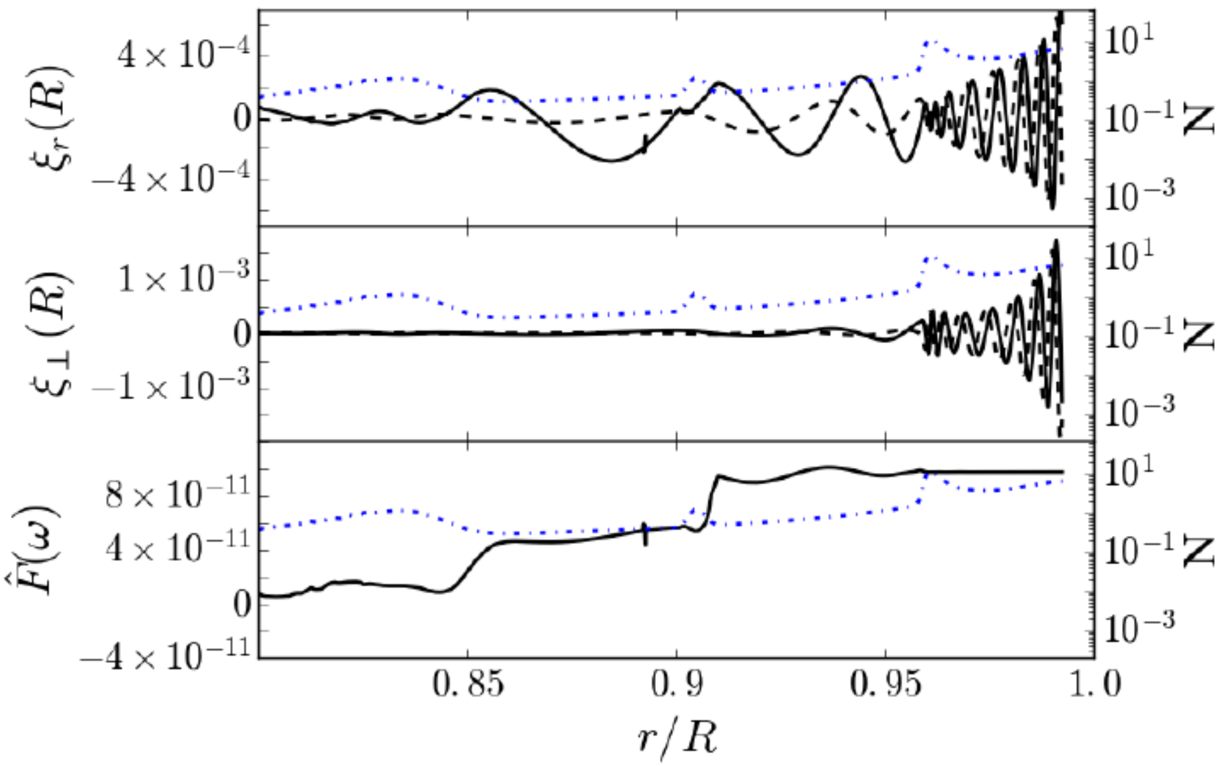
Tide reduces a, e but increases r_{peri}

-- **Rotational state of WD ?**

-- **Tidal heating of WD?**

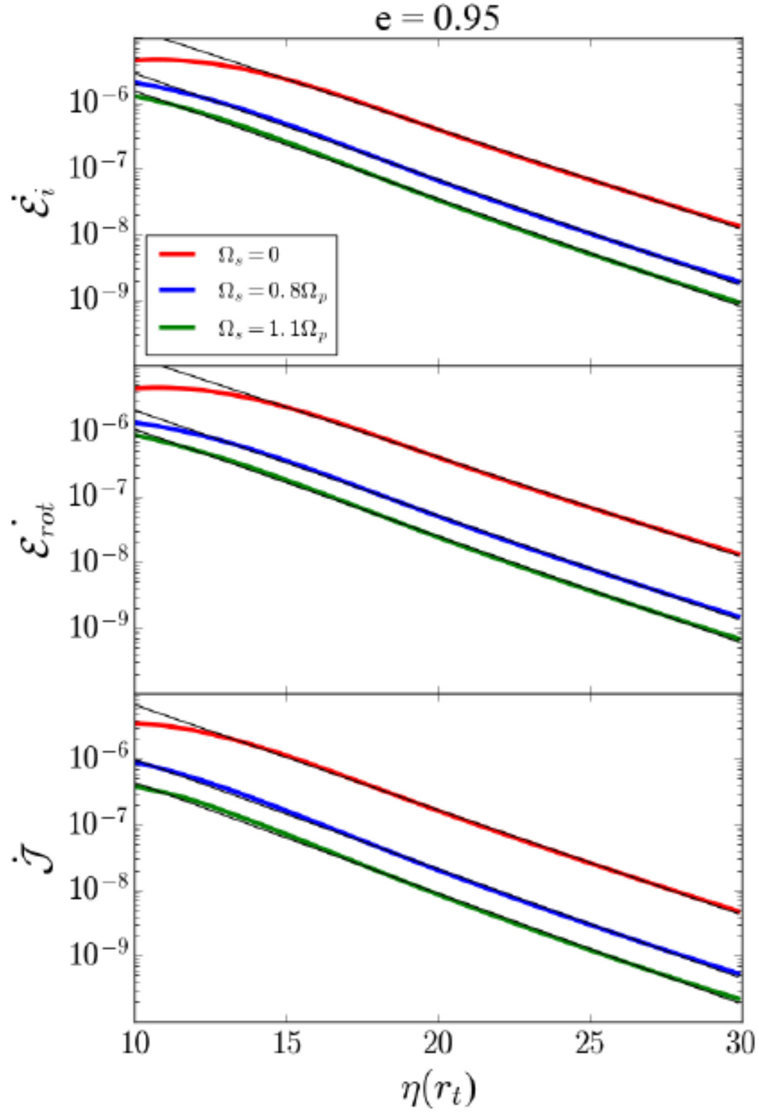
Physics of Dynamical Tides in Eccentric WD-BH Binaries

-- Tidal excitation of gravity waves inside WD, nonlinear damping in envelope
-- Eccentric orbits: for each a,e, a spectrum of gravity waves are excited



Vick, DL & Fuller 2017

Tidal energy and angular momentum transfer rates



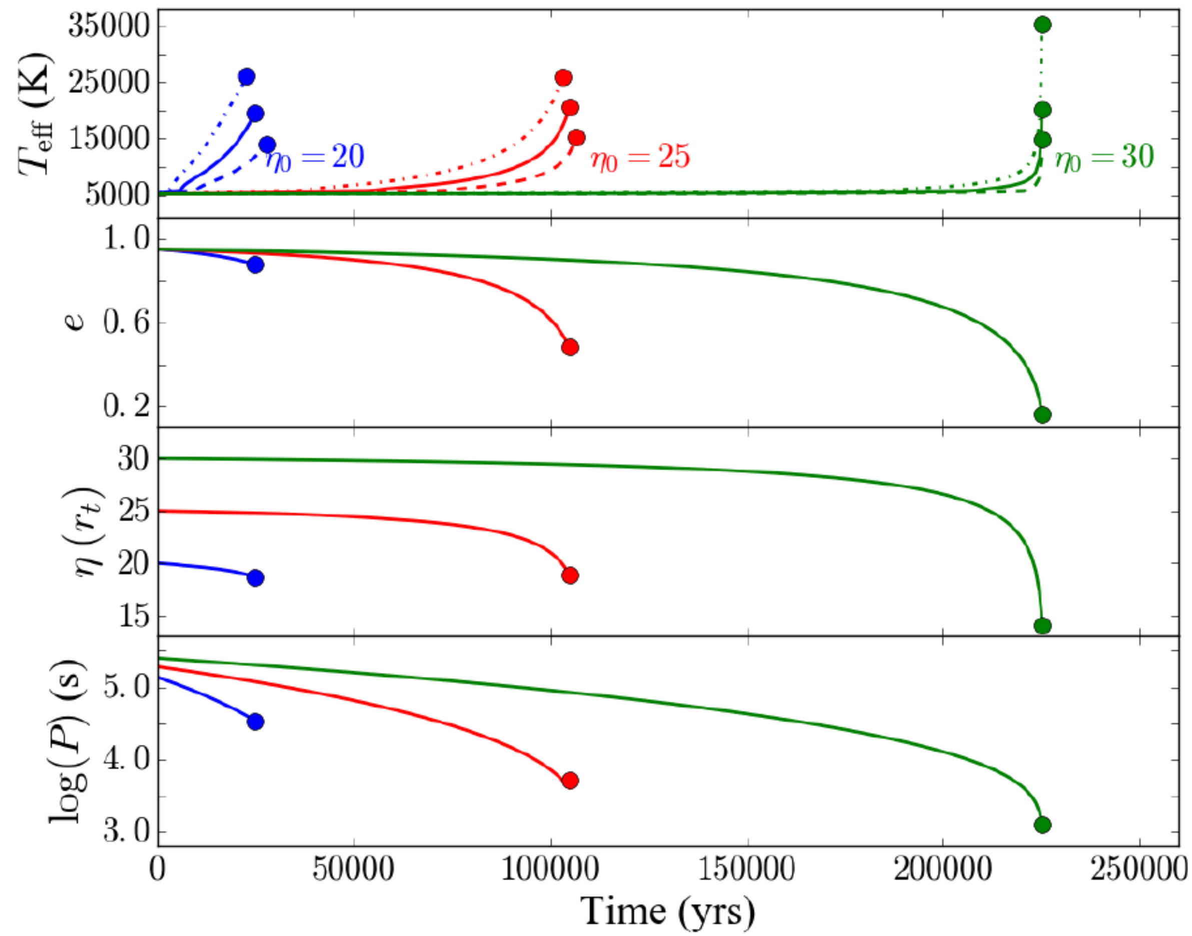
$$\dot{J}_{\rm tide} = \frac{GM_{\rm bh}^2 R^5}{r_{\rm p}^6}(1-e)^{3/2}\dot{\mathcal{J}}$$

$$\dot{E}_{\rm tide,in} = \frac{GM_{\rm bh}^2 R^5}{r_{\rm p}^6}\Omega\,\dot{\mathcal{E}}_{\rm in}$$

$$\dot{E}_{\rm tide,rot} = \dot{E}_{\rm tide,in} - \Omega_{\rm s}\dot{J}_{\rm tide} = \frac{GM_{\rm bh}^2 R^5}{r_{\rm p}^6}\Omega\,\dot{\mathcal{E}}_{\rm rot}$$

➔ Gravitational Radiation dominates over tide

Tidal Heating of WD during circularization



Tidal brightening of WD

Tidal nova ➔ ejection of H envelope

Summary

Merging NS and BH Binaries:

-- Should be detected (soon!) by advanced LIGO/VIRGO
-- Probe NS EOS: Resonant excitations of modes
-- EM counterparts: GRBs, kilonovae (Optical/IR)
pre-merger magnetic interactions → precursors (?)

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-- Pre-merger phase important/interesting:
dynamical tides: Continuous excitations of waves, nonlinear breaking
spin synchronization, tidal heating → Tidal nova
-- Low-frequency GWs (LISA)

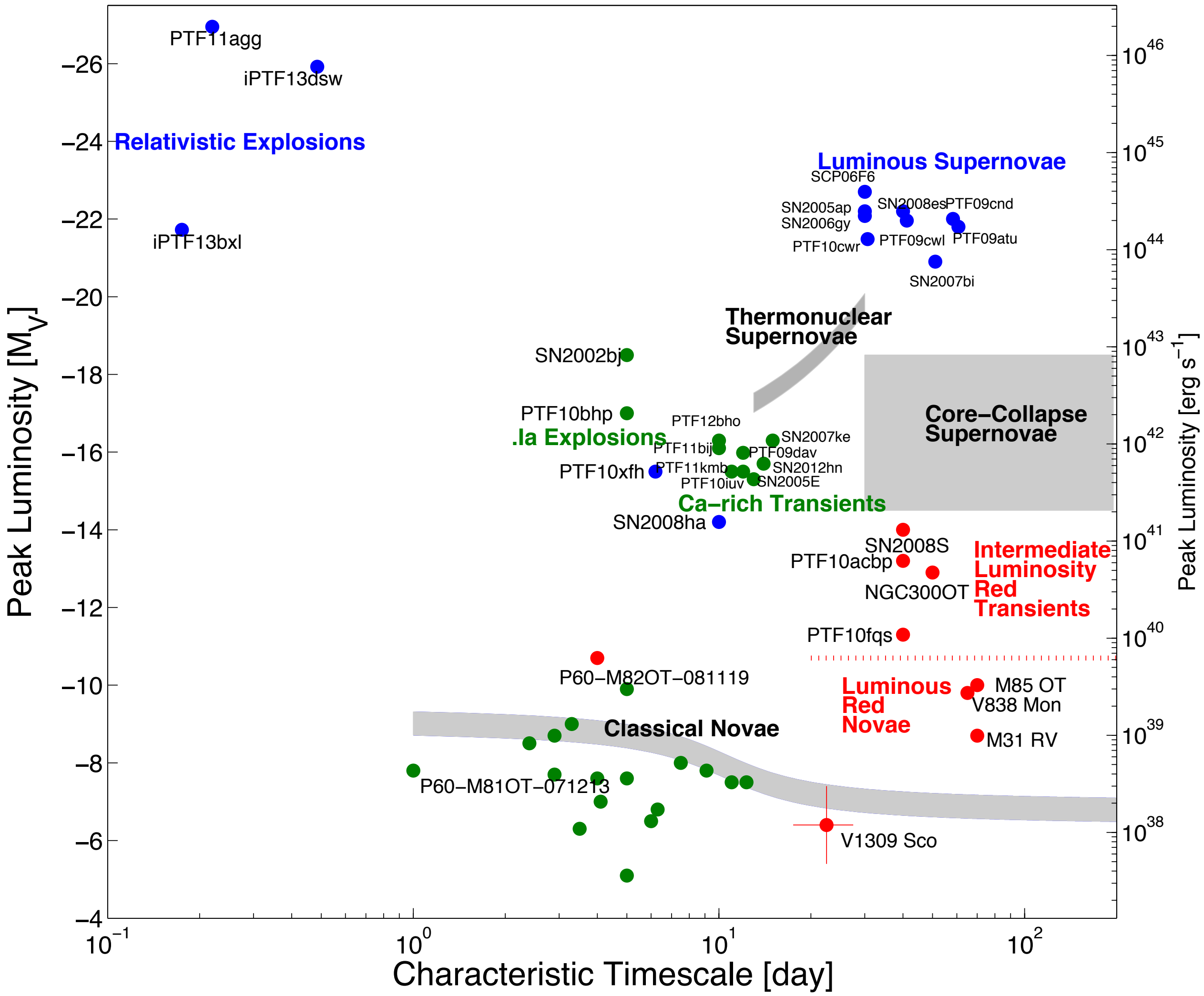
Eccentric Star(WD)/Massive BH Binaries:

-- Possible precursors to TDEs
-- Dynamical tides cannot compete with GR for orbital evolution
-- Tidal heating is important

Thanks!

Transient & Variable Universe

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



Kasliwal 2014