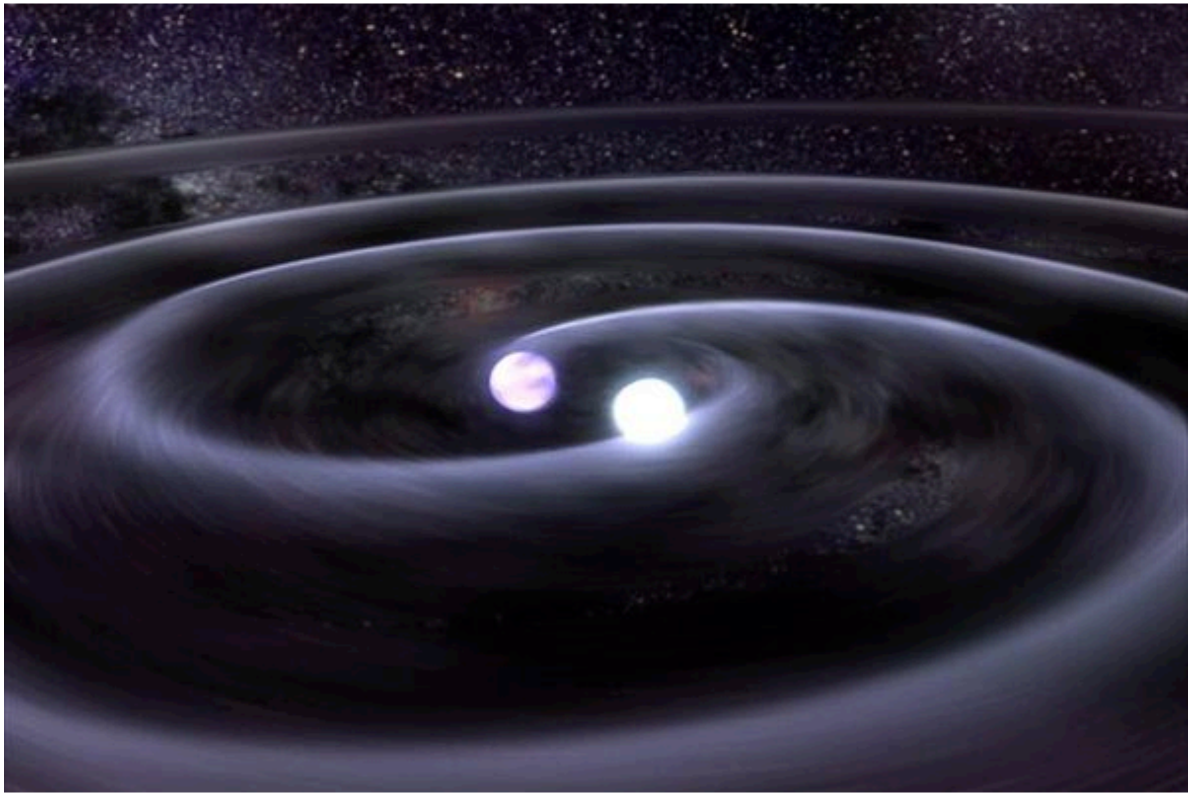
Merging Compact Binaries



Dong Lai
Cornell University

Astronomical Institute, Prague, 7/2/2013

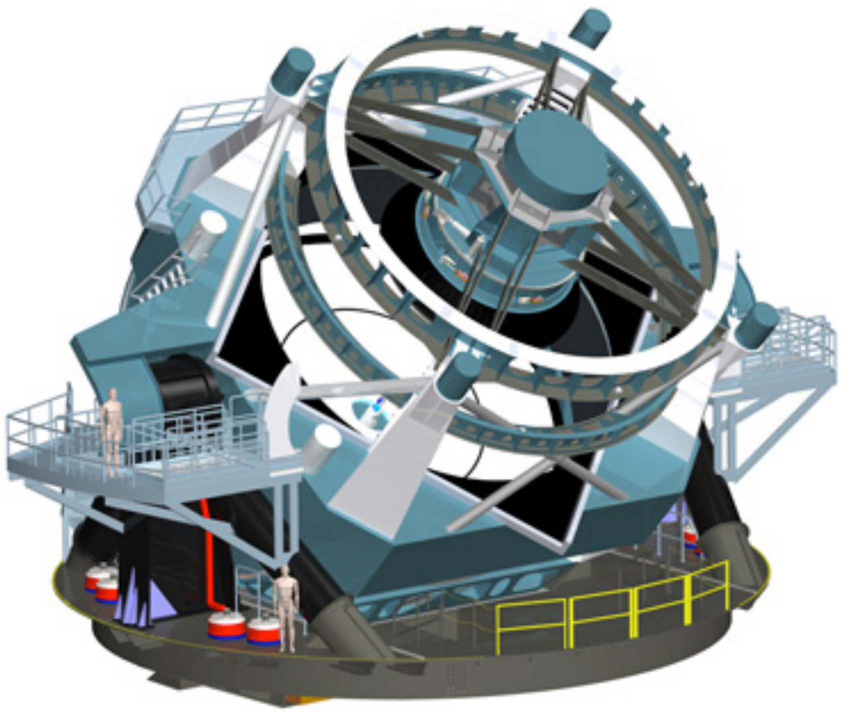
Merging Compact Binaries

1. Neutron Star/Black Hole Binaries

2. White Dwarf Binaries

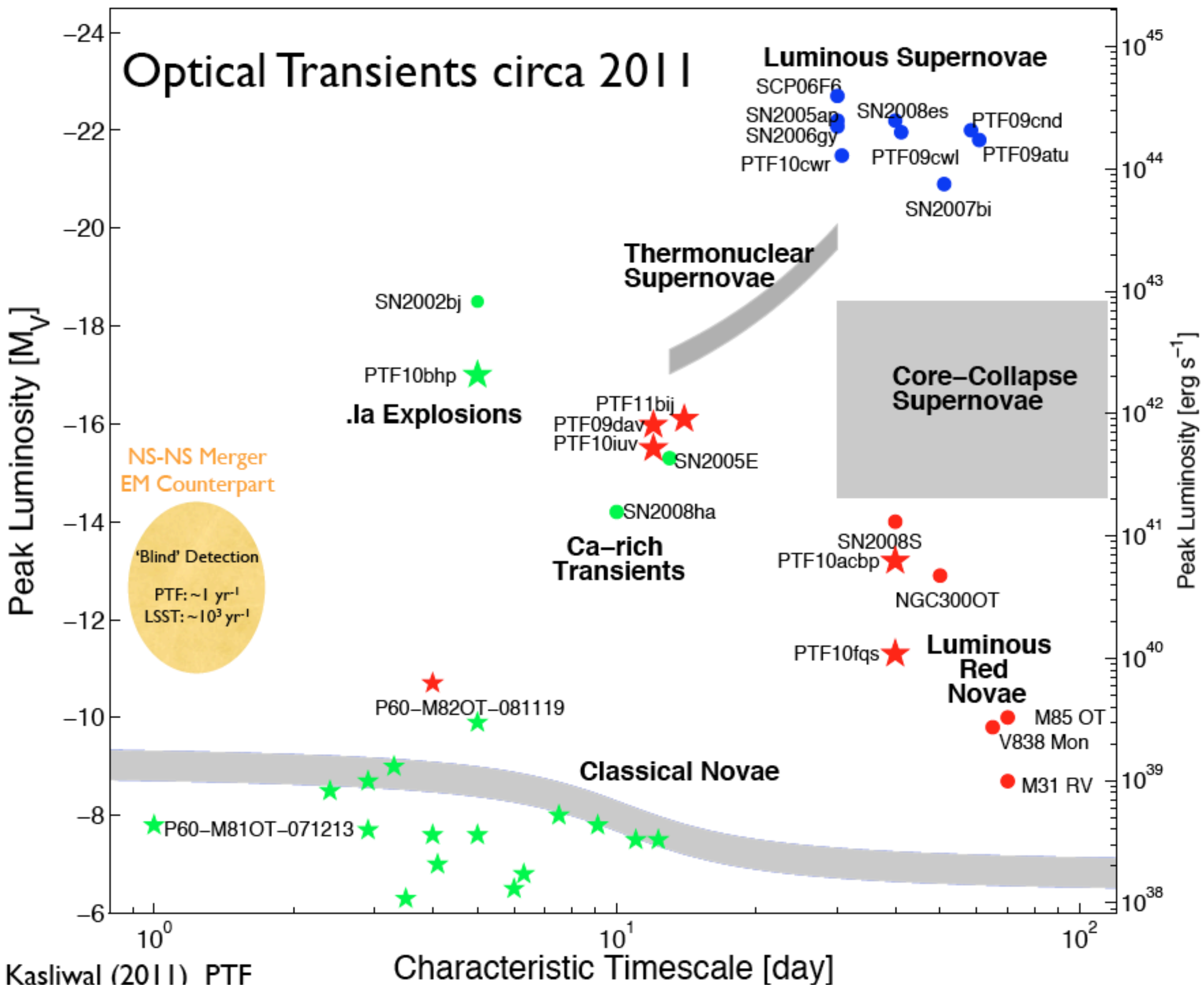
Transient & Variable Universe

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



Transient & Variable Universe

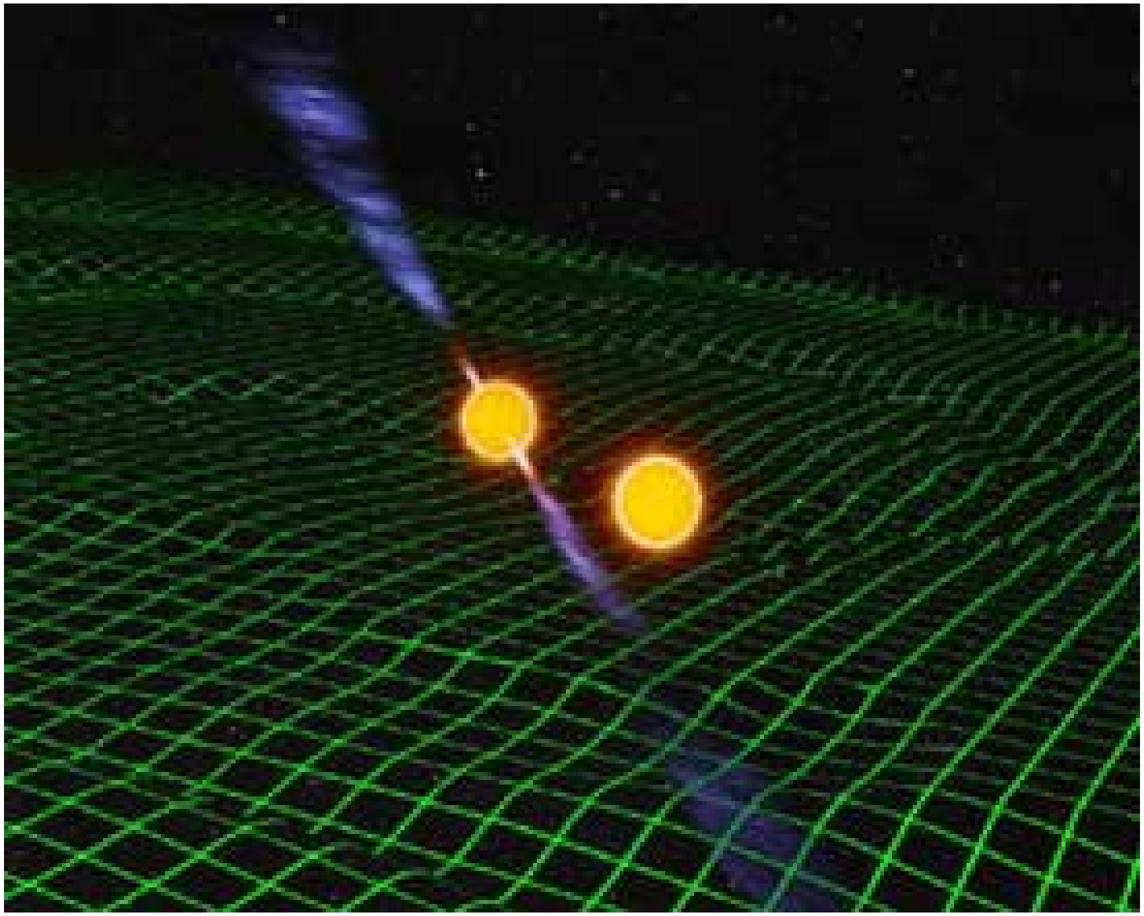
Wide-field, fast imaging telescopes in optical: **PTF, Pan-Starrs, LSST**



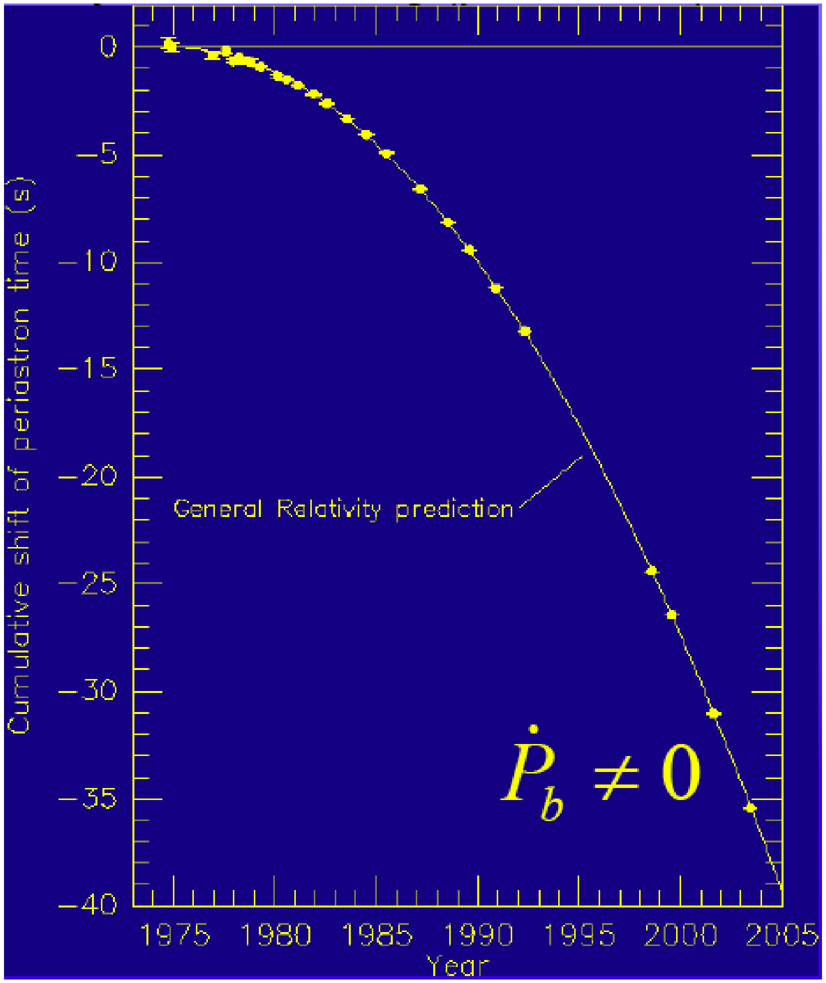
Gravitational Wave Astronomy

LIGO
VIRGO

Merging NS and BH Binaries



NS/NS Binaries: Binary Pulsars



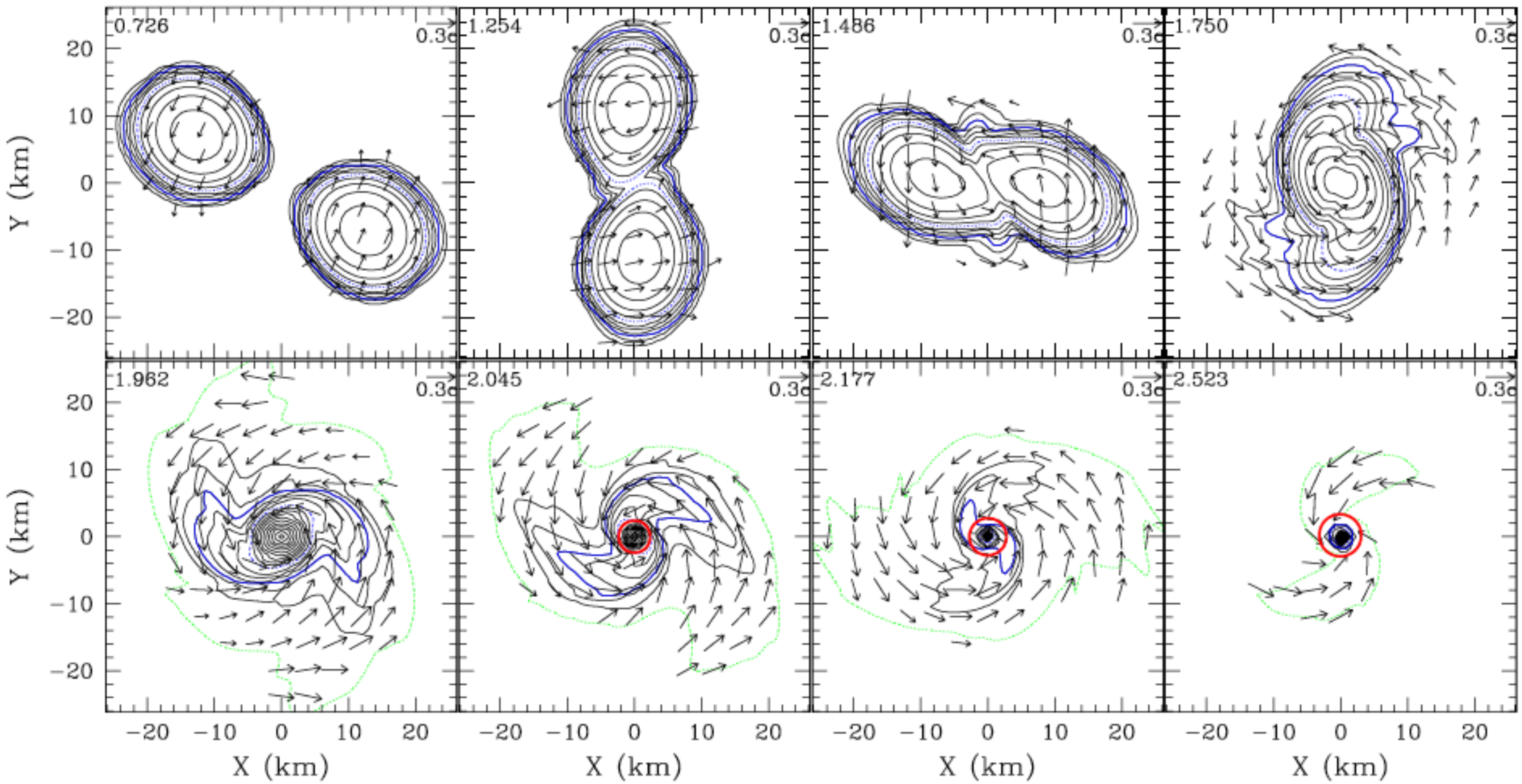
Taylor & Weisberg 2005

Nobel Prize 1993

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

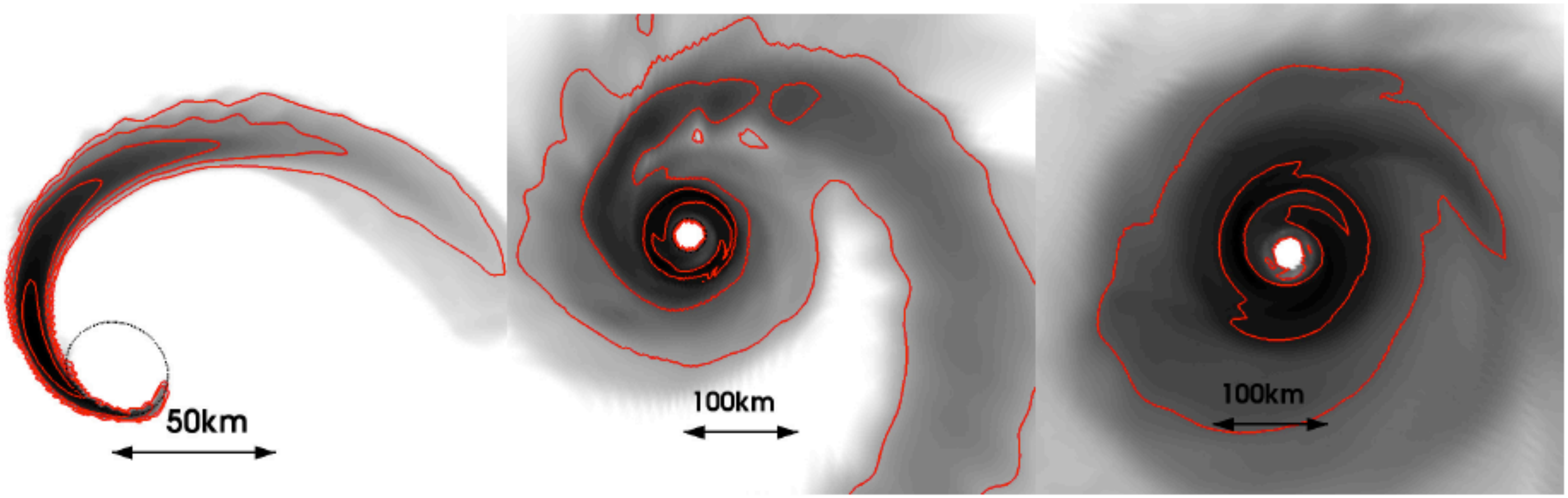
(Based on 3 systems in Galaxy that will merge within Hubble time;
No observed NS/BH and BH/BH yet !)

NS-NS Merger



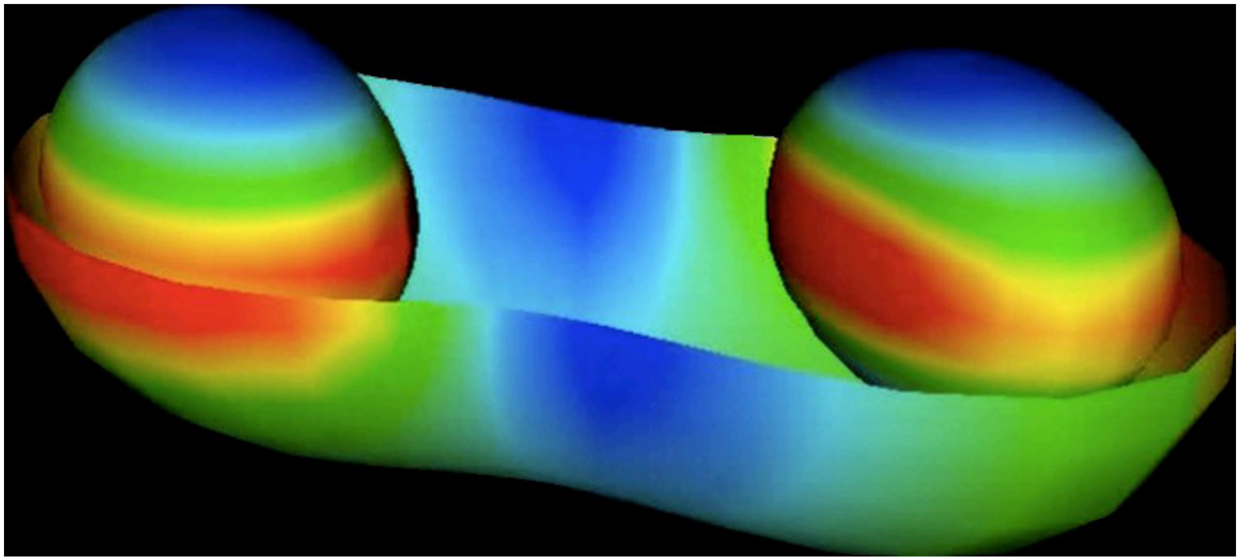
Shibata et al. 2006

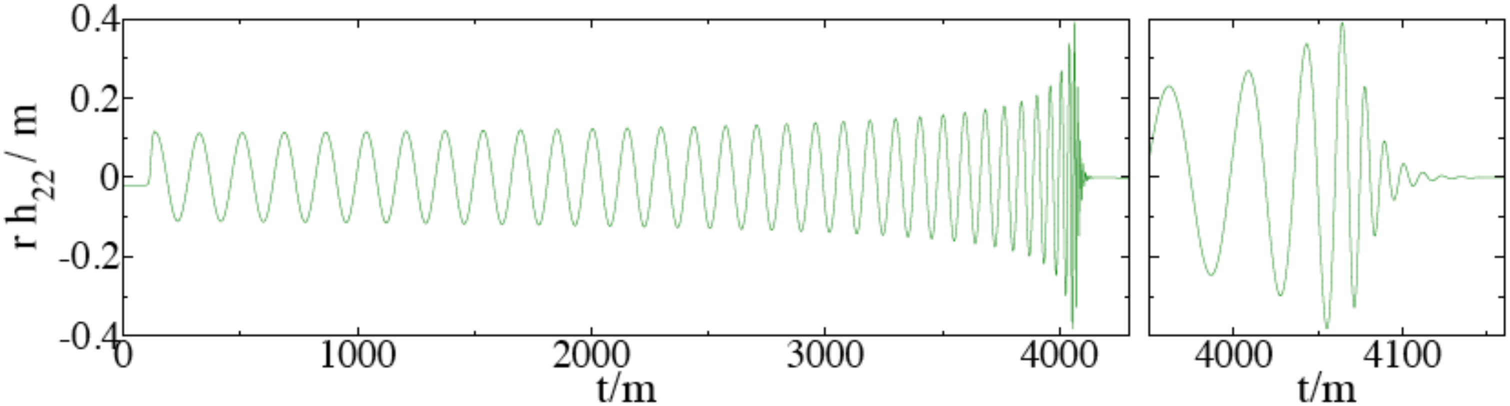
BH-NS Merger



F. Foucart et al (Cornell) 2011,13

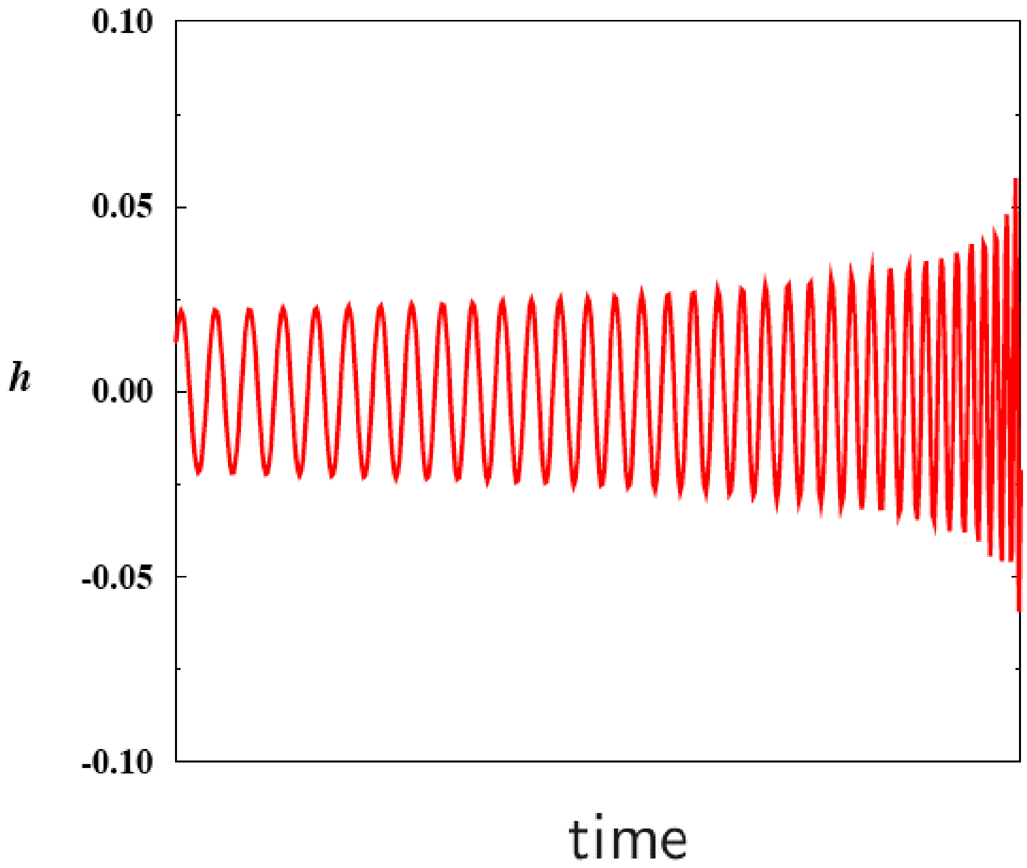
BH-BH Merger

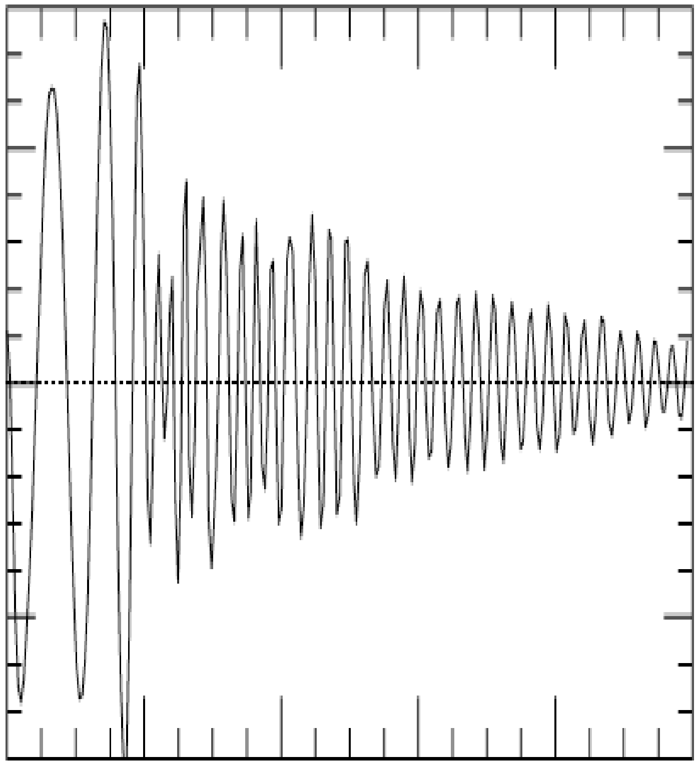


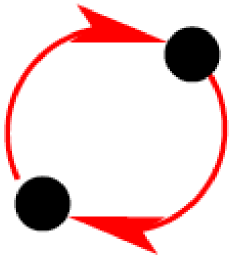


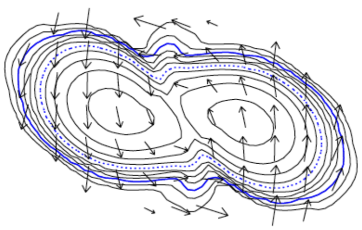
Cornell-Caltech collaboration

The last few minutes: Gravitational Waveform









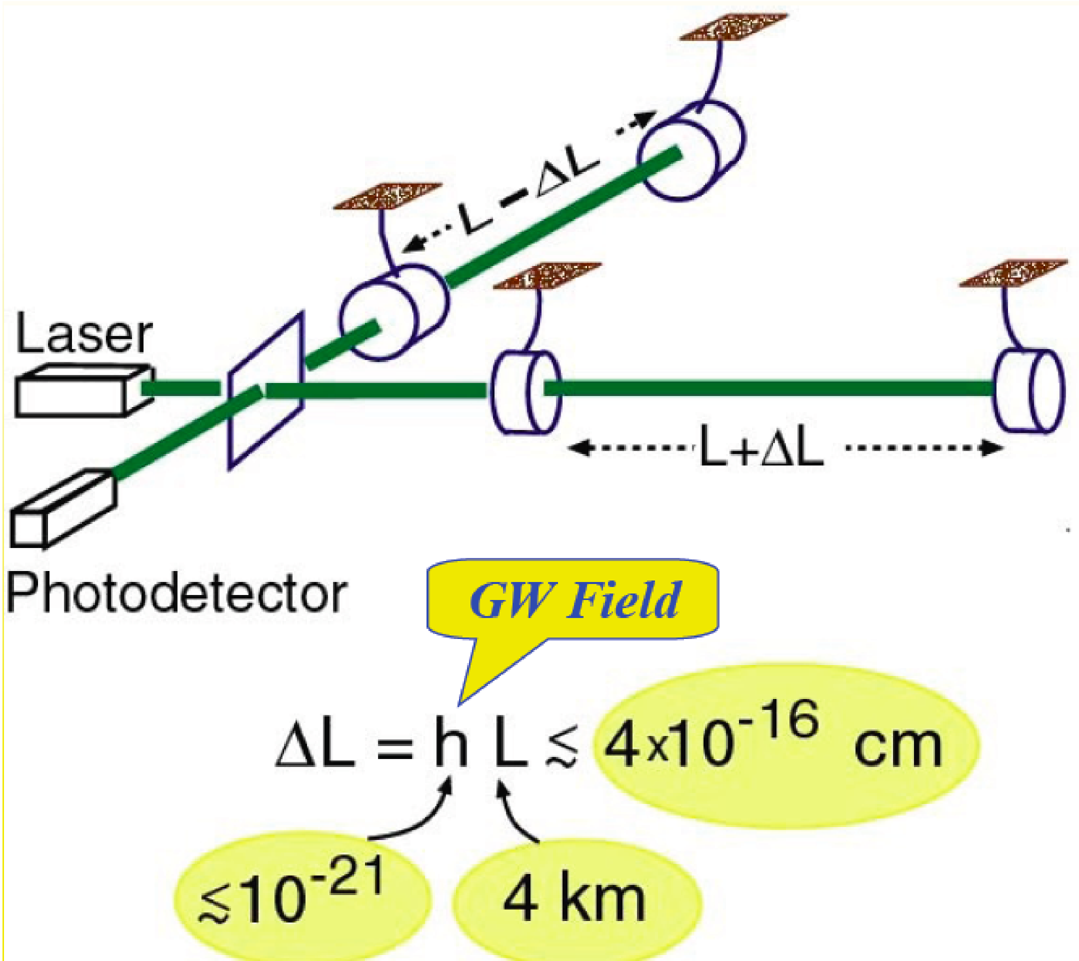
Gravitational Waves

- Warpage of Spacetime
- Generated by time-dependent quadrupoles

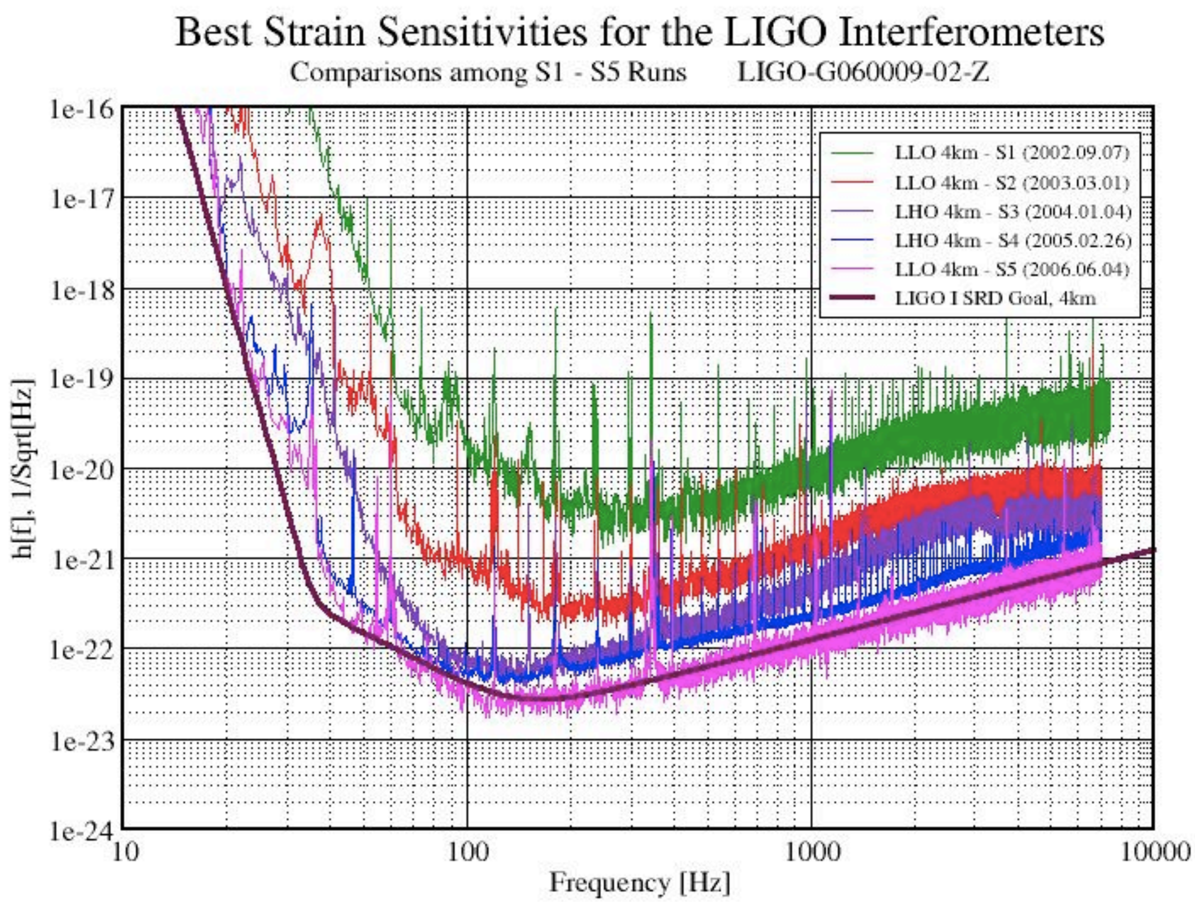
$$h \sim \frac{G}{c^4} \frac{\ddot{Q}}{D}$$

- Detector response to passage of GWs:

Gravitational Wave Interferometer



Kip Thorne



iLIGO: reached h~10^{-21} (2006)

eLIGO: h ~ 1/2 smaller (taking/analysing data)

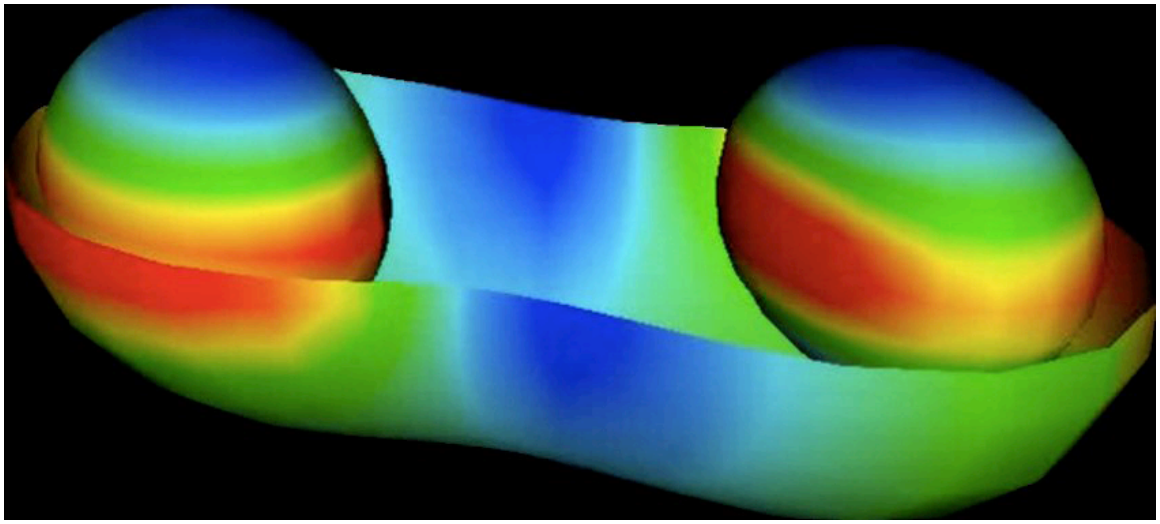
aLIGO: h ~1/10 smaller (2018?)

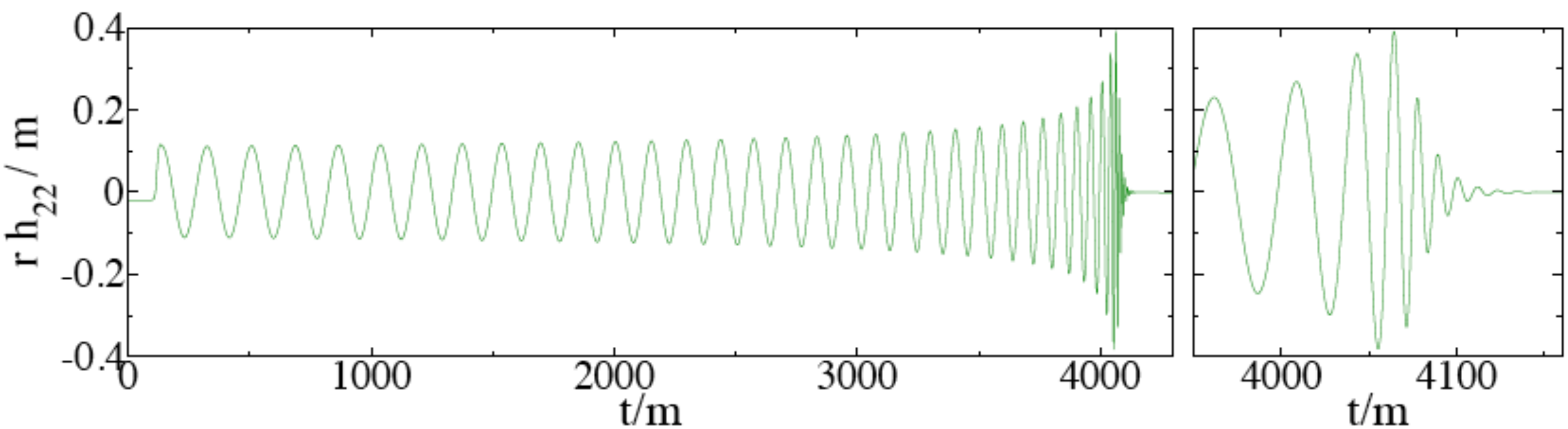
Compact Binary Inspiral Rates, yr^{-1}

	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

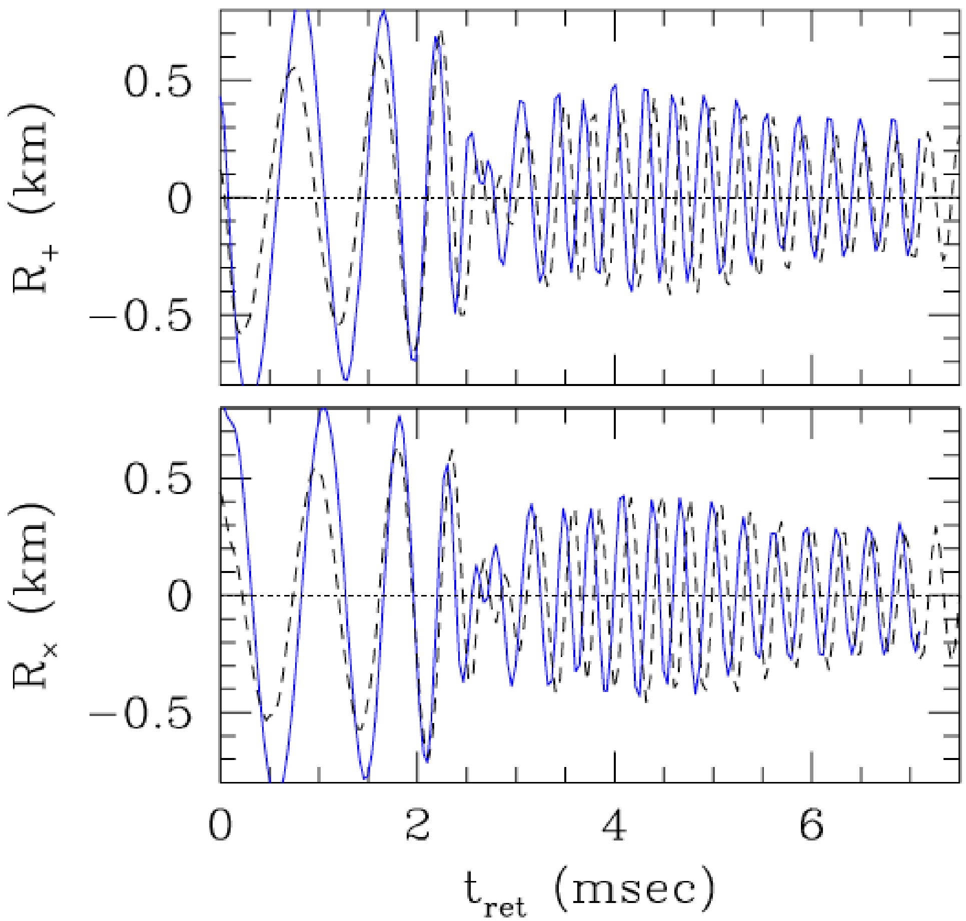
Gravitational waves probe nonlinear gravity

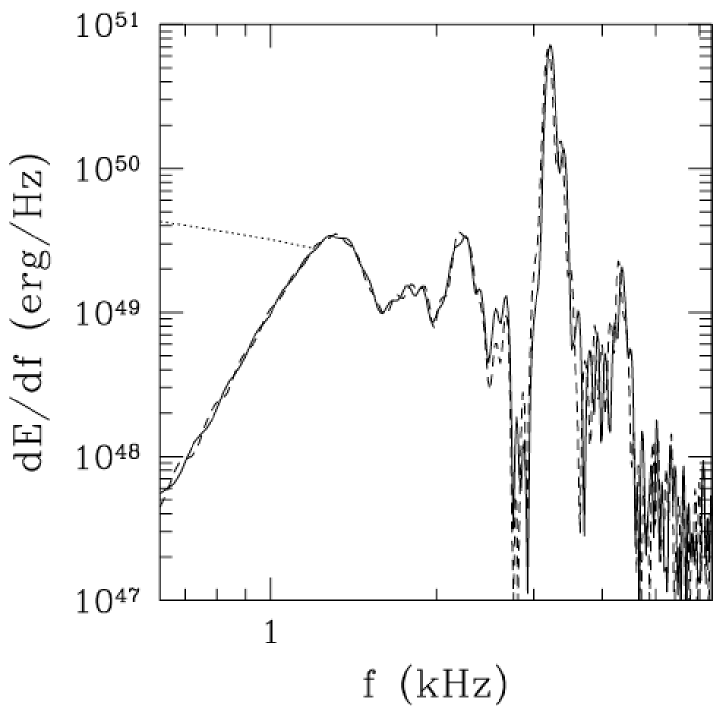




Cornell-Caltech collaboration

Gravitational waves probe NS EOS



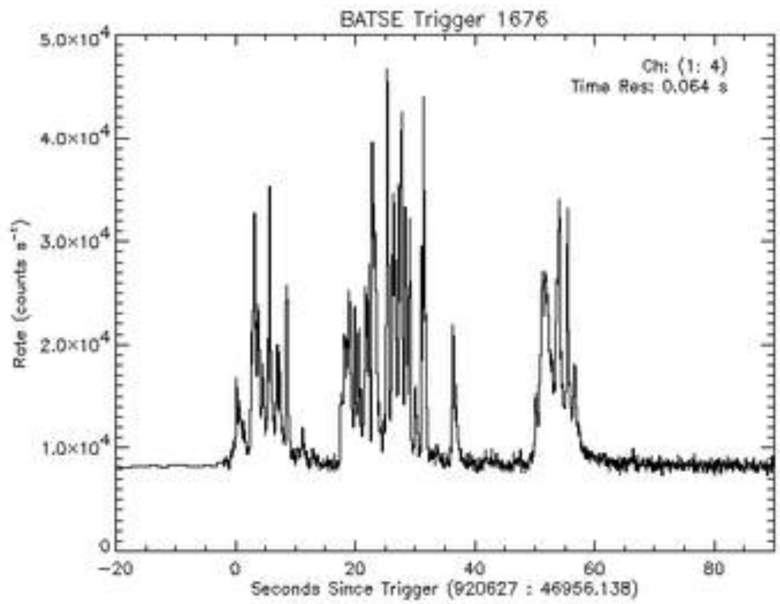


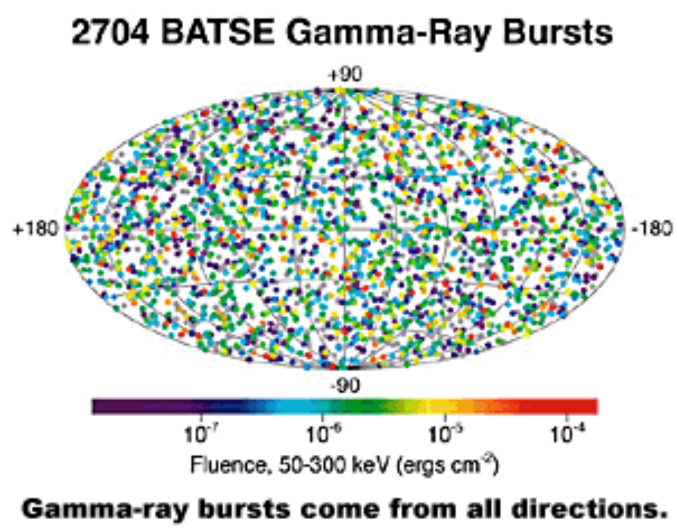
Cutler et al. '92;
DL & Wiseman '96;
Shibata et al.' 06;
…
Bauswein, Janka...' 12

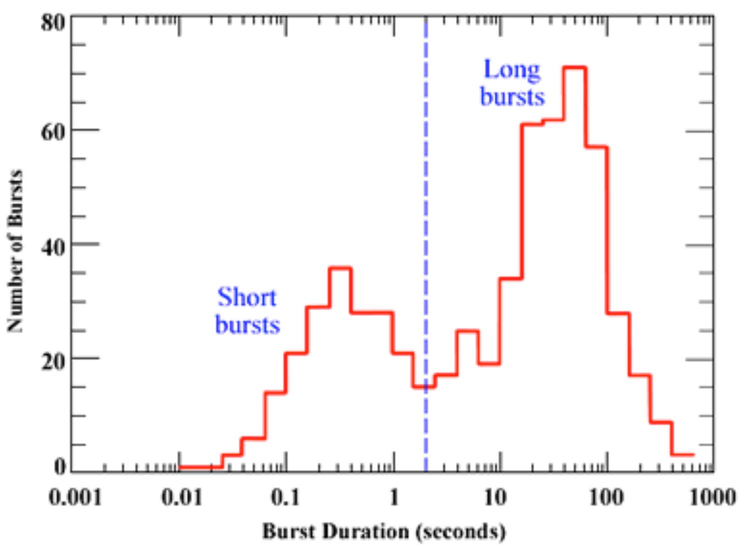
Masses well measured from inspiral waveform
Final cut-off frequency ~ $(GM/R^3)^{1/2}$

NS/NS and NS/BH Mergers: Electromagnetic Counterparts

Gamma-Ray Bursts







--Bursts of 0.1-10 MeV gamma-rays

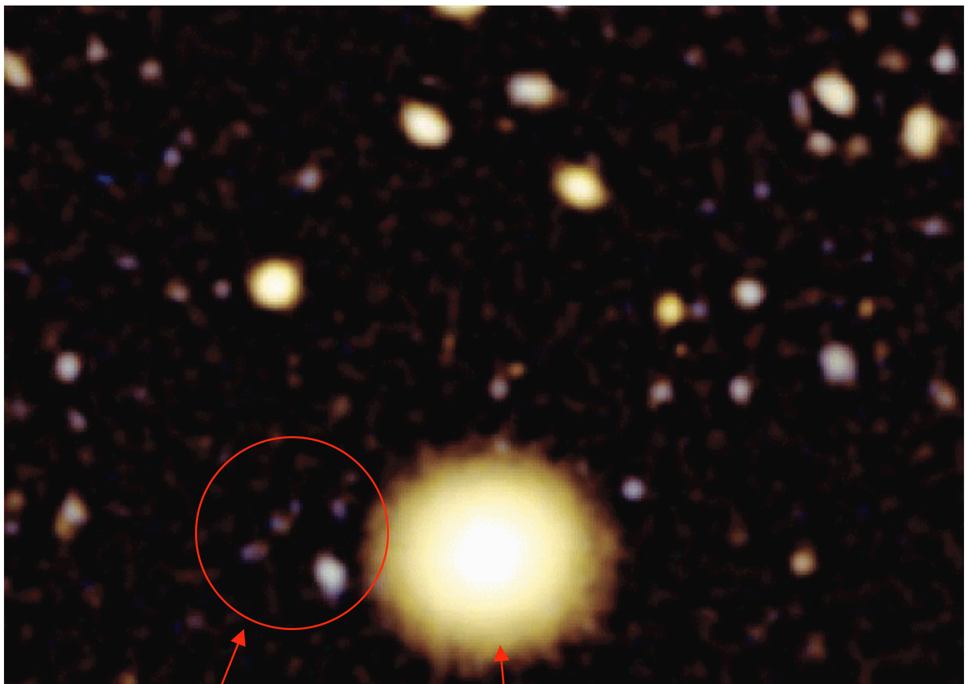
--From all directions, z~0.1-10

--Very energetic ~10^{48-55} erg

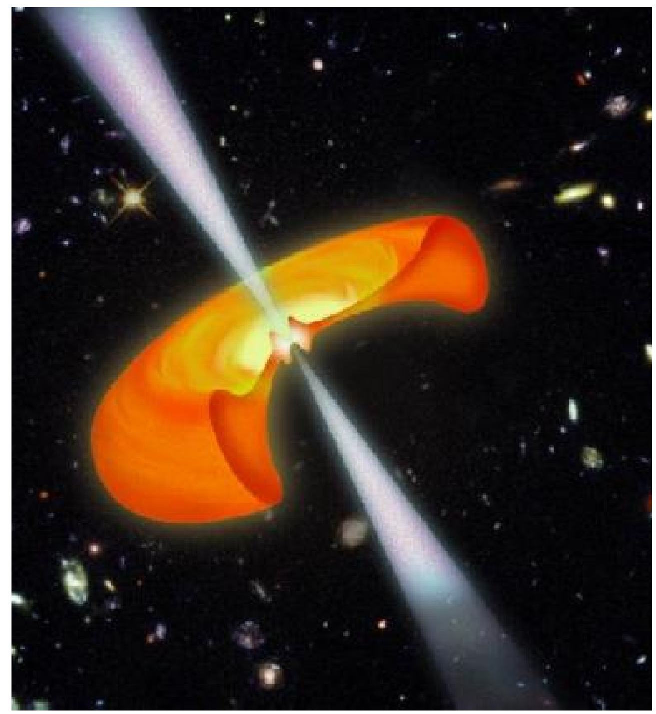
--Rare: GRB rate ~ 10^{-6}/yr/galaxy

--"Long" (~30s) and "short" (~0.3s)

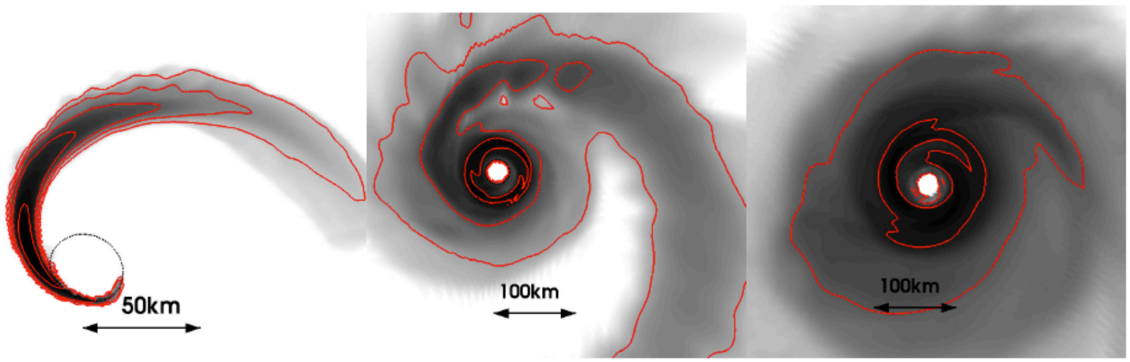
Merging NS/BH (or NS/NS?): Central Engine of Short GRBs



Bloom et al. 2006



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



Foucart et al. (Cornell-Caltech)

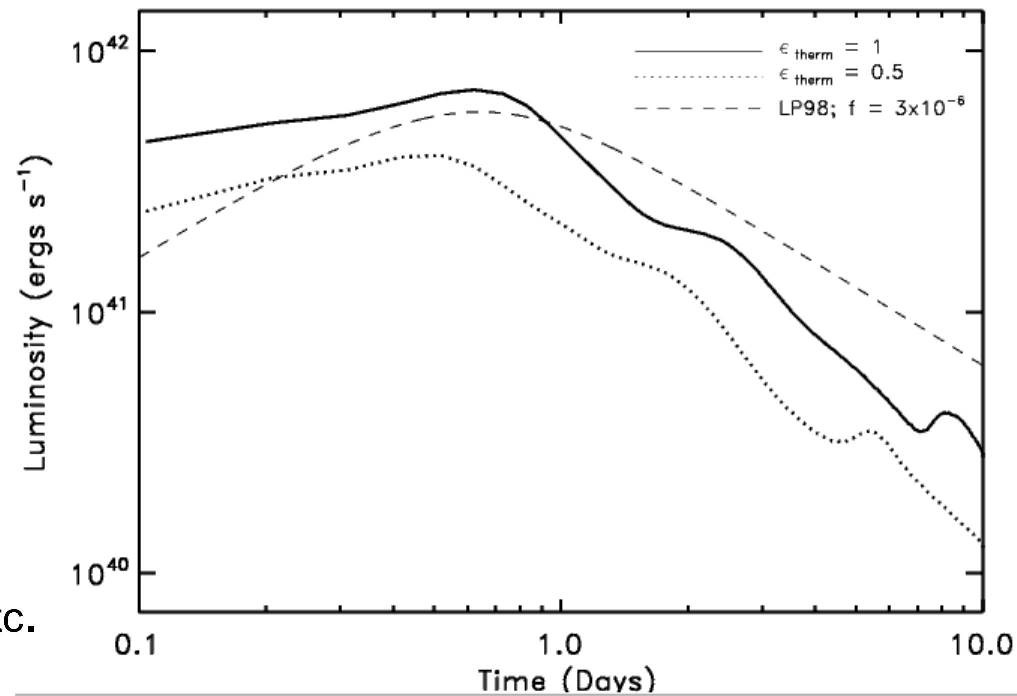
NS tidal ejecta $10^{-3} - 10^{-2} M_{\odot} (?)$

Ejecta evolution:

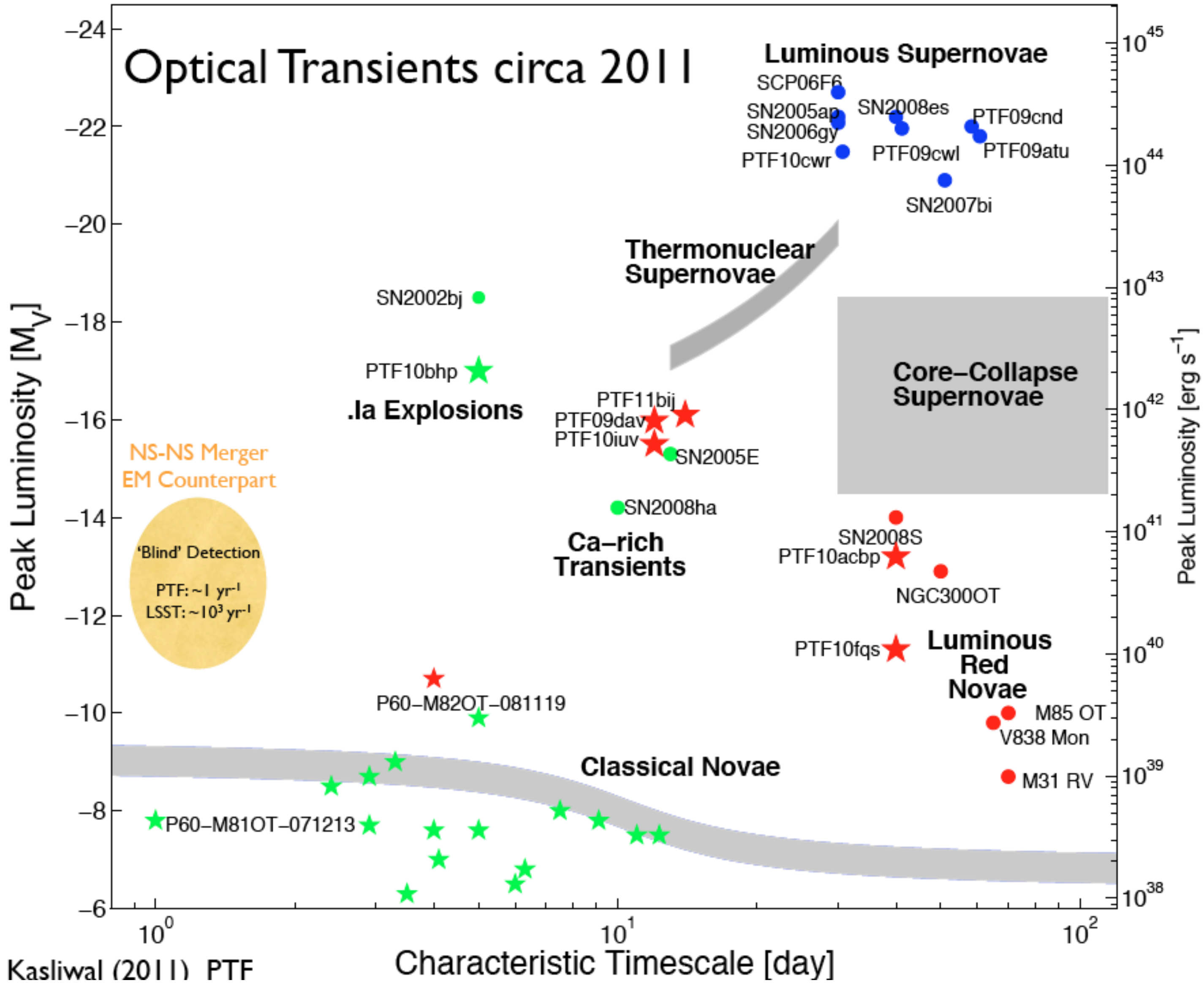
Initially mostly hot neutrons,
Decompression (cooling),
Nuclear reactions==> heating

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

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



Matzger, Quataert, 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:

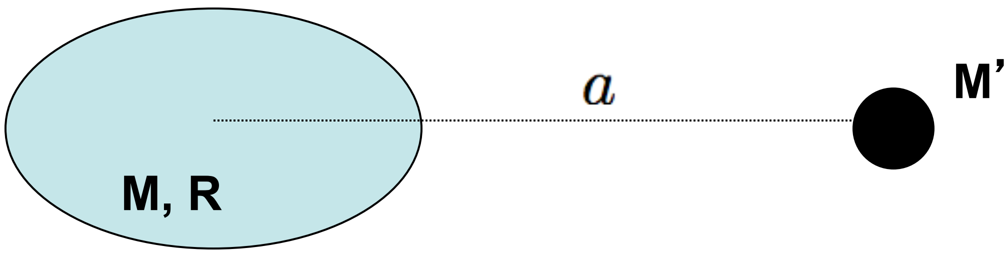
Anything interesting?

Pre-Merger Phase:
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)

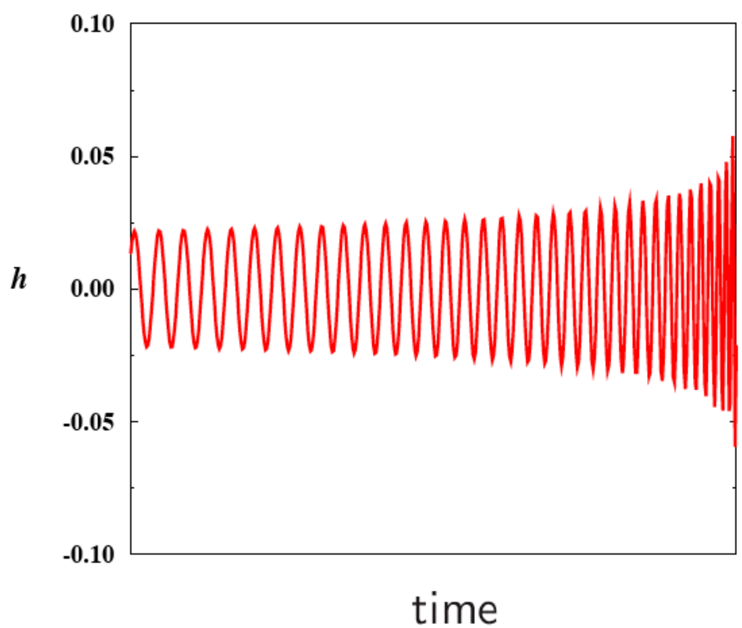
inertial modes (incl. r-modes),…

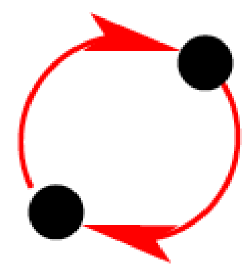
Resonance: $$\omega_\alpha = m\Omega_{\rm orb}, \quad m = 2, 3, \cdots$$

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:

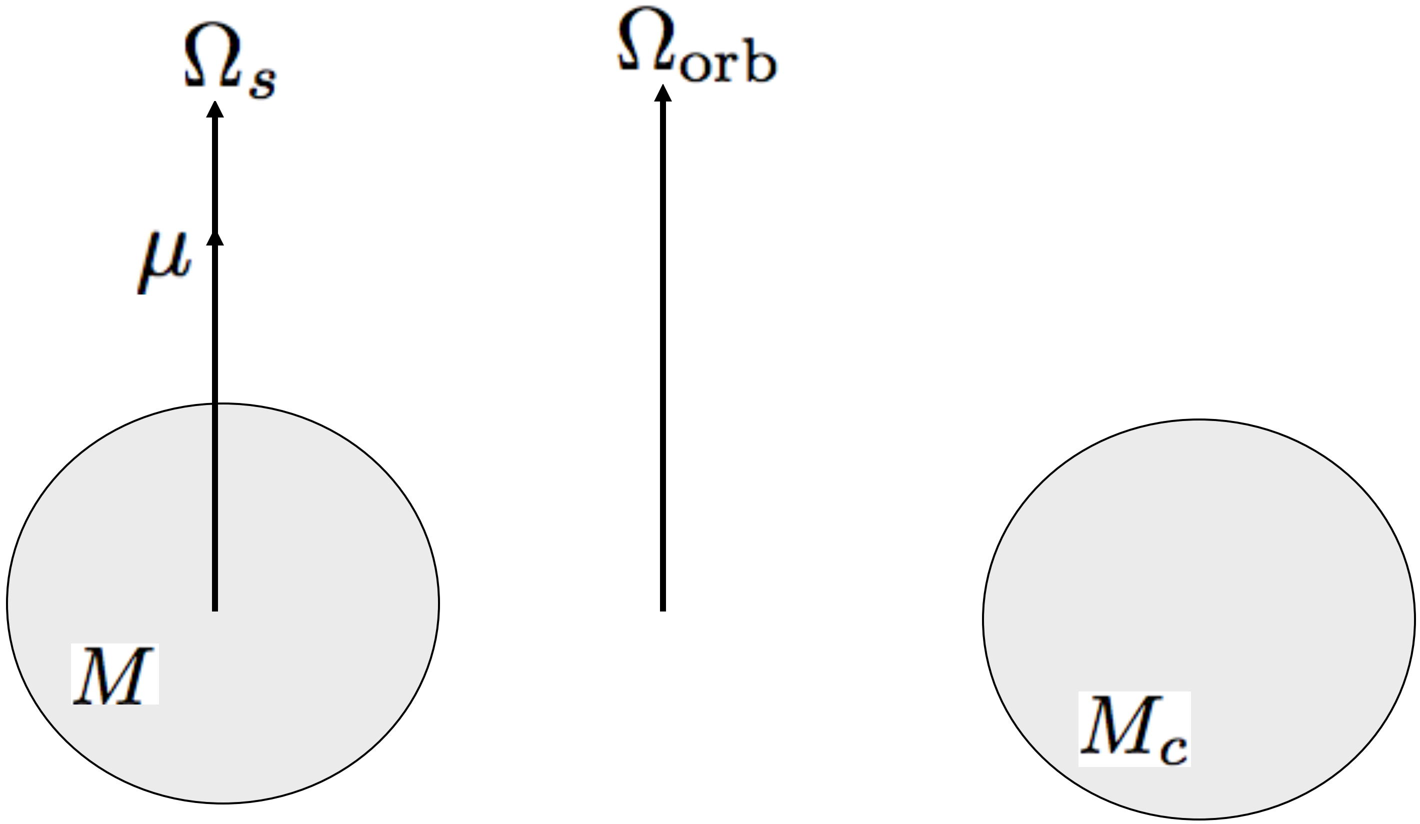
- For R=10 km NS, the number of missing cycles < 0.1, bearly measurable (unless NS is rapidly rotating)
- Number of missing cycles $\Delta N \propto R^4$ (g mode) or $R^{3.5}$ (r mode) Important for larger NS
- **G-modes:** No law that requires ΔN should be < 1 ! (Newton & DL 2013)
- **Crustal modes:** Could shatter crust, pre-cursor of short GRB (Tsang et al. 12)

Pre-Merger Phase: Magnetic NSs

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

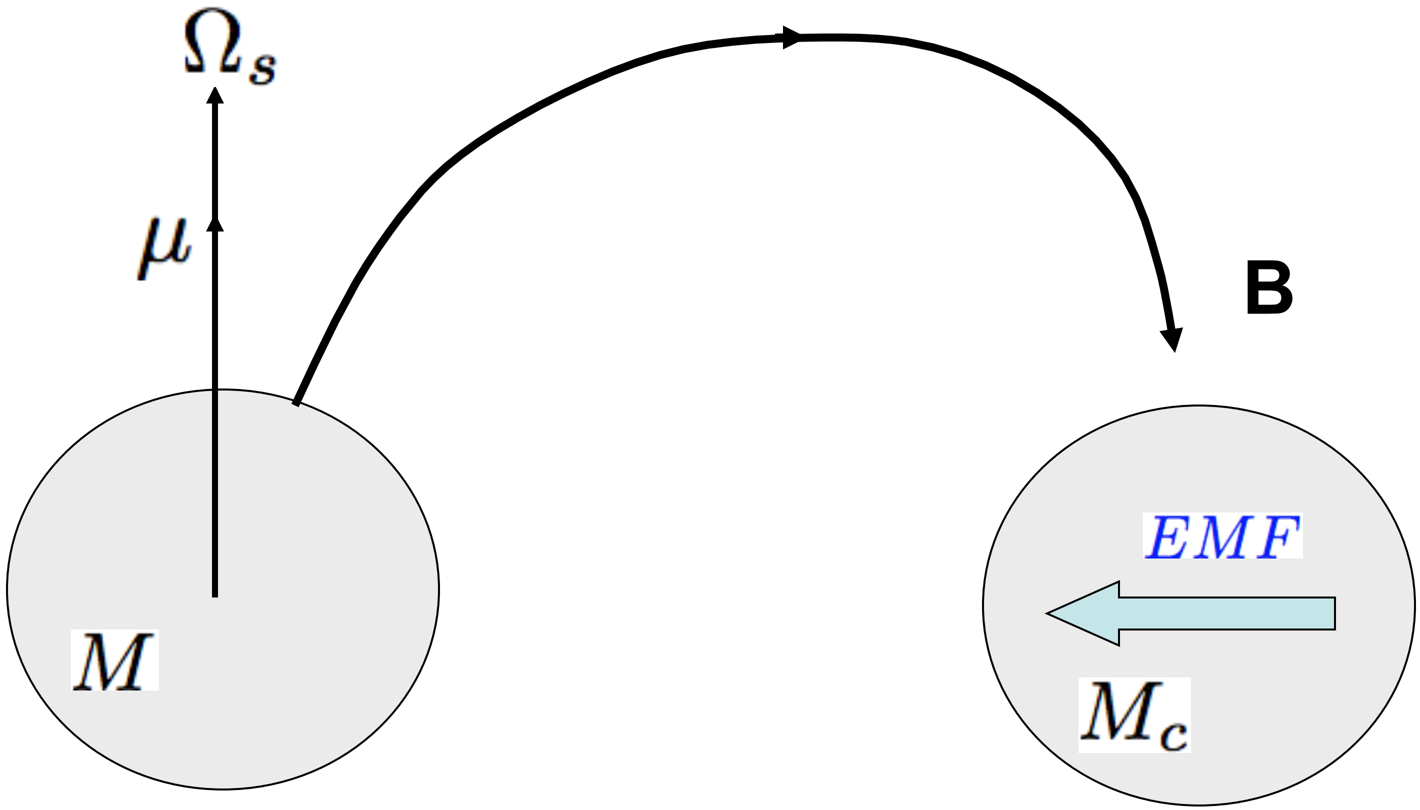
pulsar A: ~10^{10}G

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



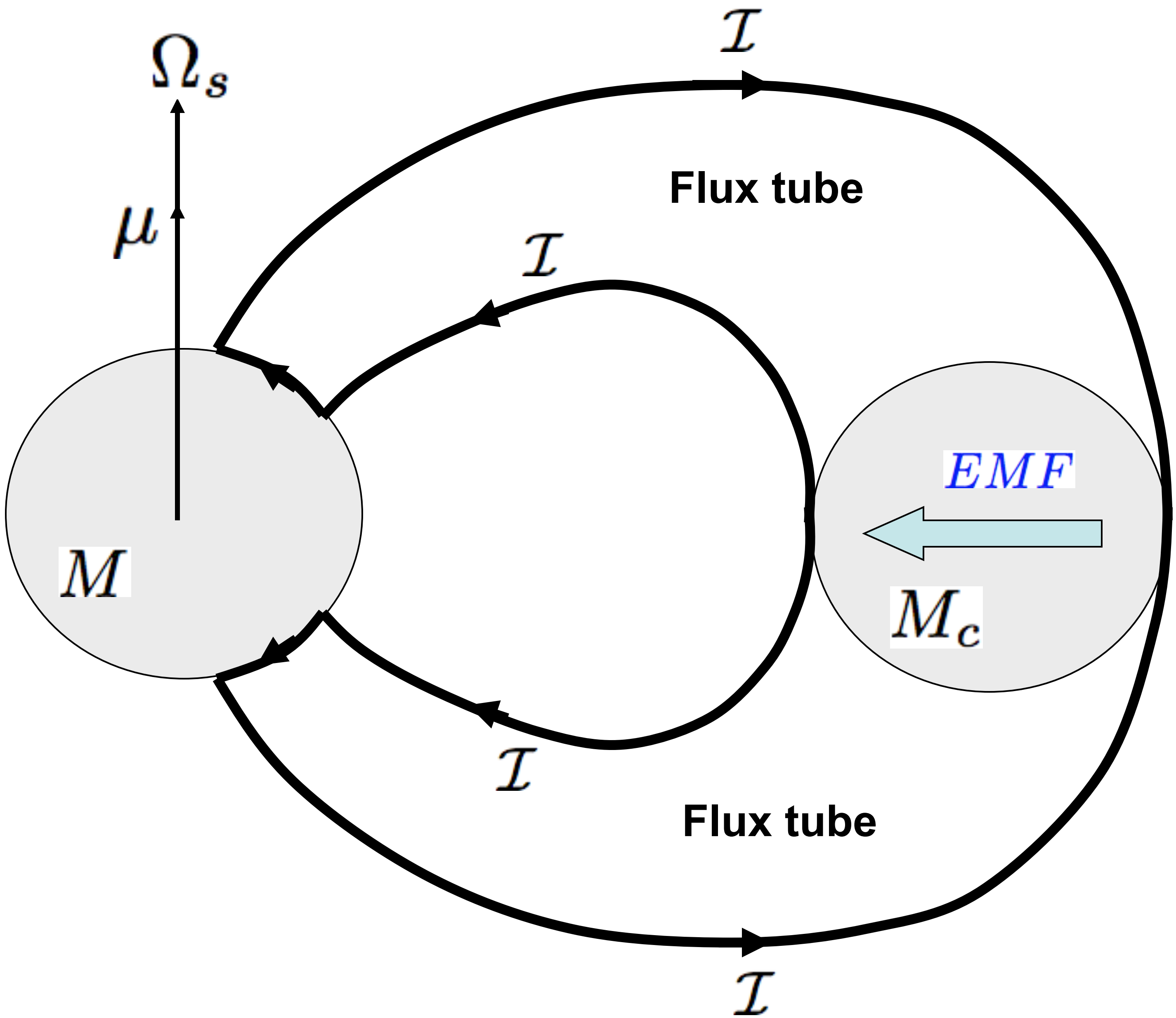
Consider a binary with

- -- magnetic NS ($>10^{12}$G) + non-magnetic NS
- -- embedded in a tenuous plasma (magnetosphere)



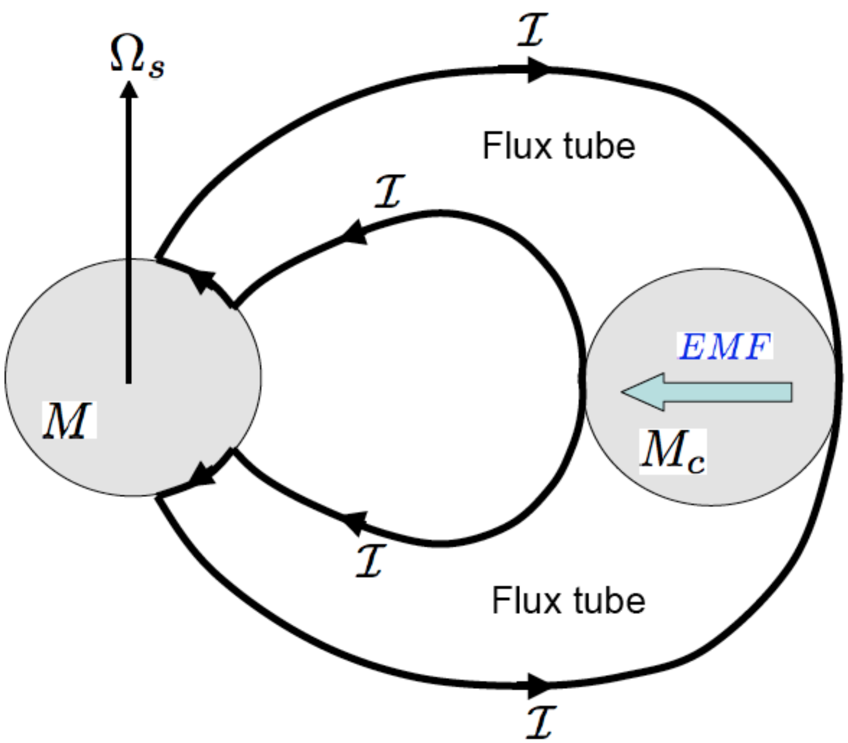
$$\text{EMF}: \quad \Phi = 2R_c \left| \frac{\mathbf{v}}{c} \times \mathbf{B} \right|$$

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



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



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

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

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

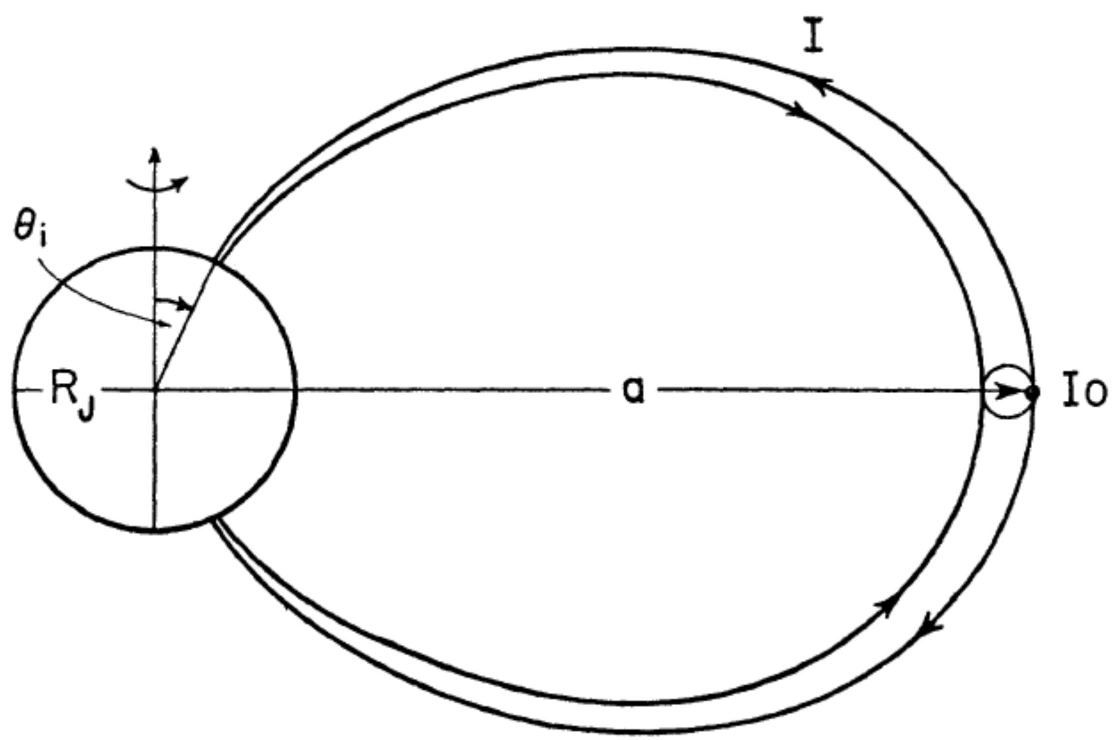
THE ASTROPHYSICAL JOURNAL, Vol. 156, April 1969

IO, A JOVIAN UNIPOLAR INDUCTOR

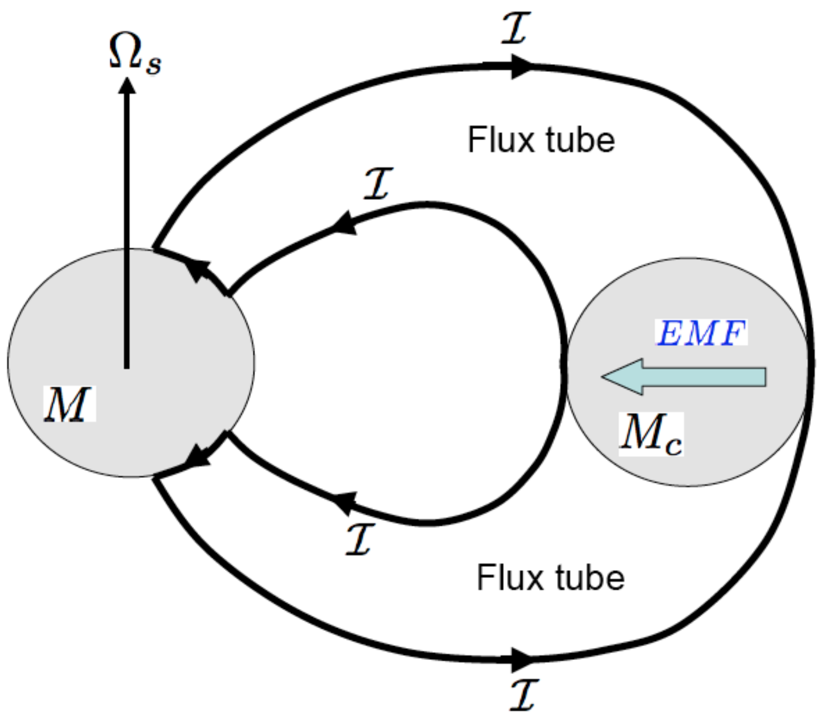
PETER GOLDREICH*
California Institute of Technology

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)

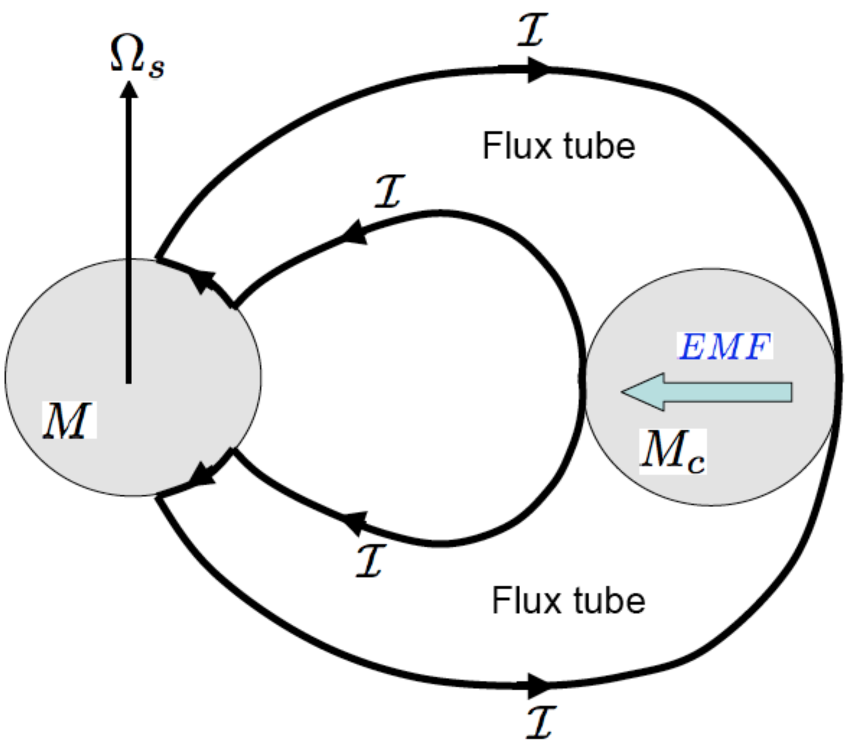
NS-NS, NS-BH Binaries

(Hansen & Lyuitikov 01; McWilliams & Levin 11; Piro 1

Exoplanetary systems (Laine & Lin 12,…)

Caution: Some of these were wrong

DC Circuit Powered by Orbital Motion



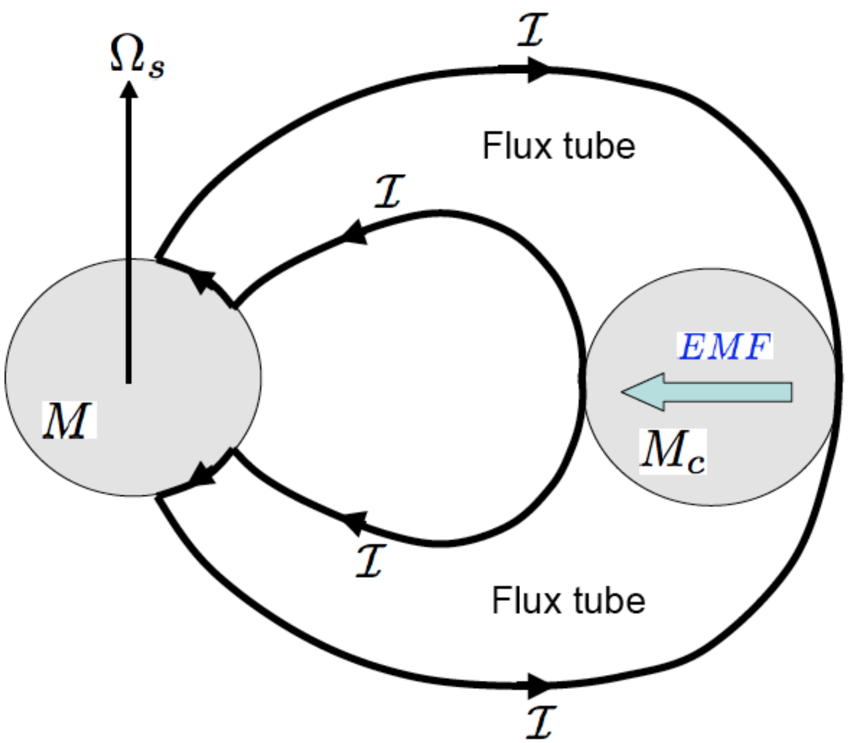
$$\text{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\text{orb}} - \Omega_s)$$

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

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

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

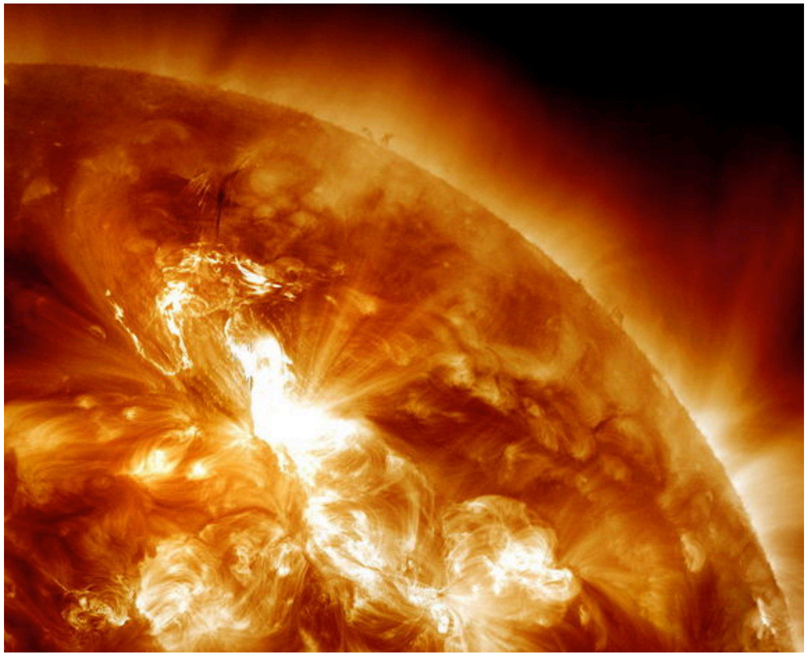
DC Circuit Powered by Orbital Motion

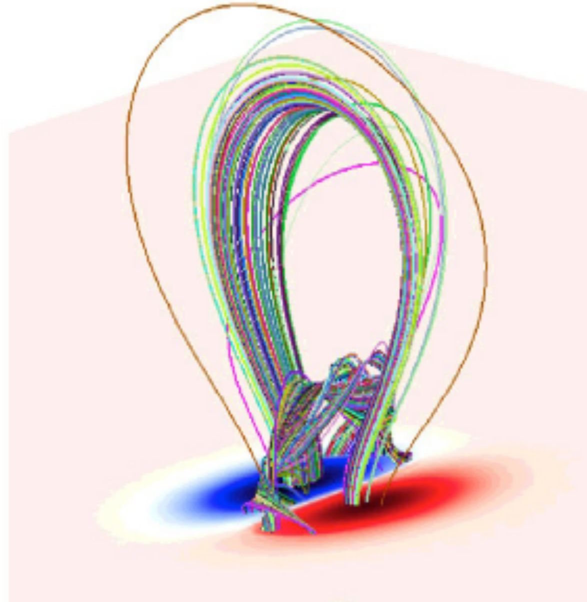


Problems with small $\mathcal{R}$ (➔large $\mathcal{I}$):

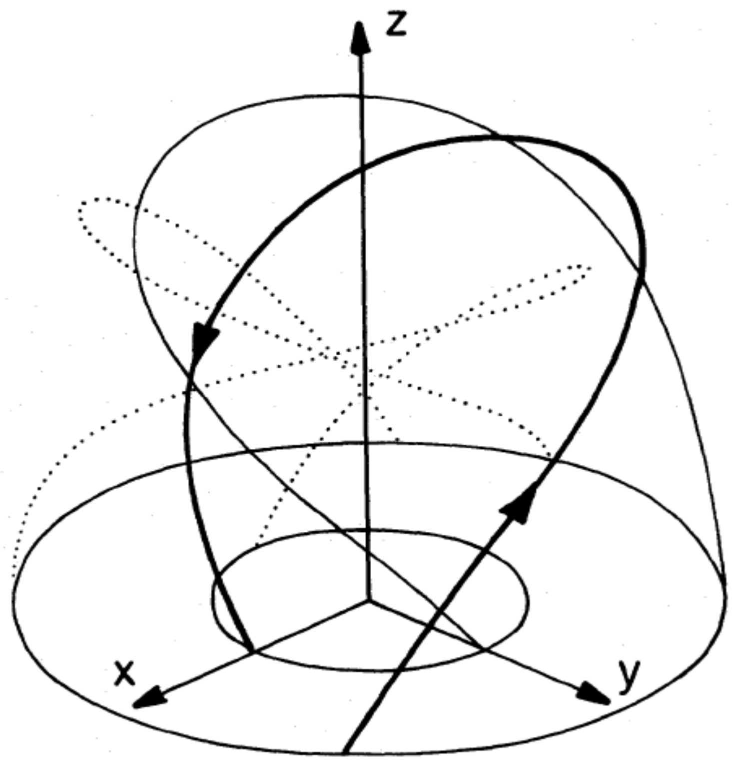
Flux tube is twisted

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

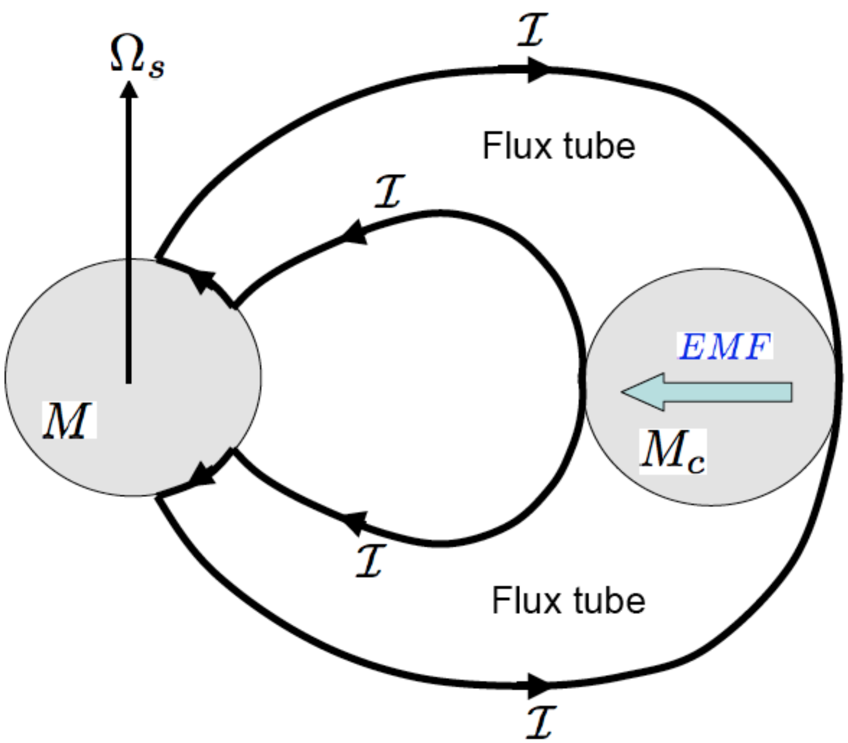




(b)



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 2012

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

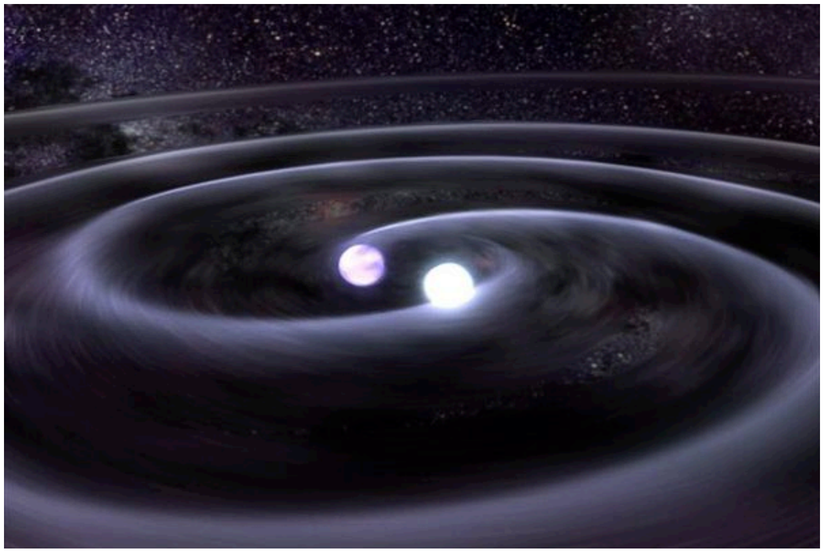
Actual dissipation rate:

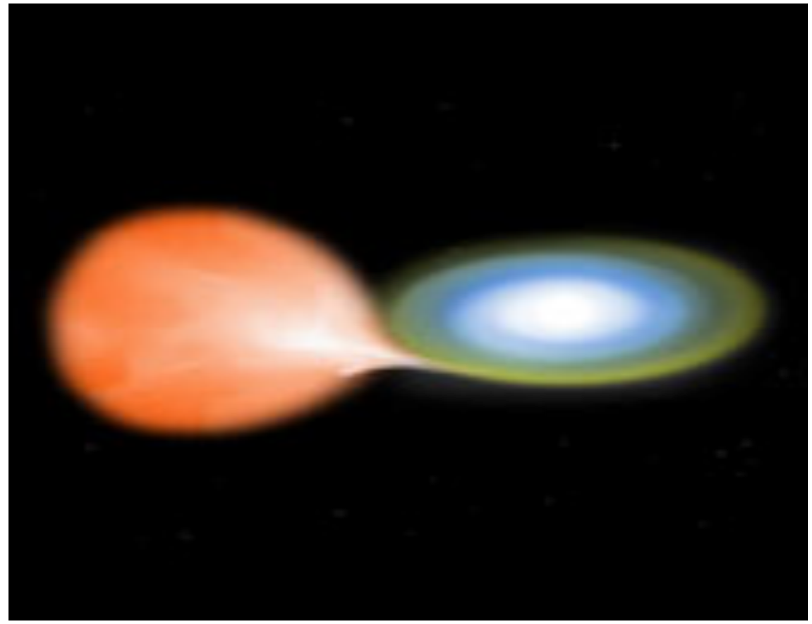
$$\dot{E} \sim 2 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{a}{30\,{\rm km}}\right)^{-7} \,{\rm erg\ s^{-1}}$$

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

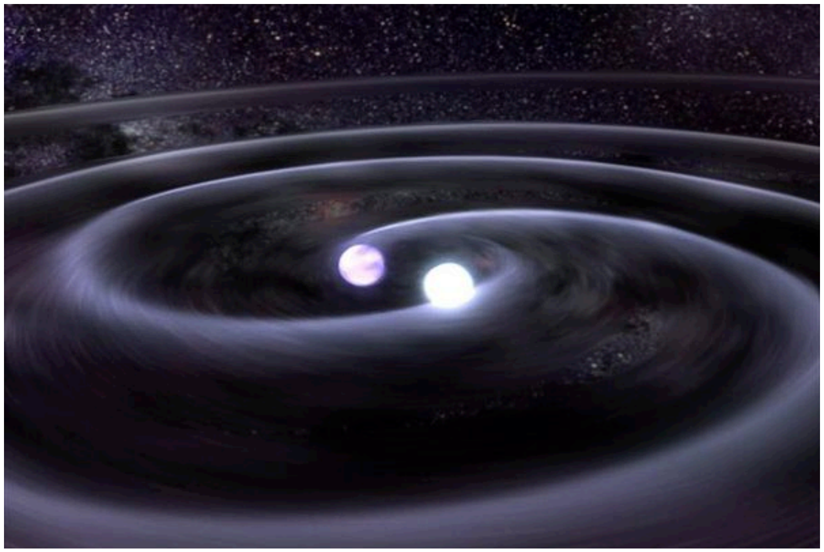
cf. isolated pulsars: $\dot{E} \simeq 10^{33} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}}\right)^2 \left(\frac{P}{1\,{\rm s}}\right)^{-4} {\rm erg\ s^{-1}}$

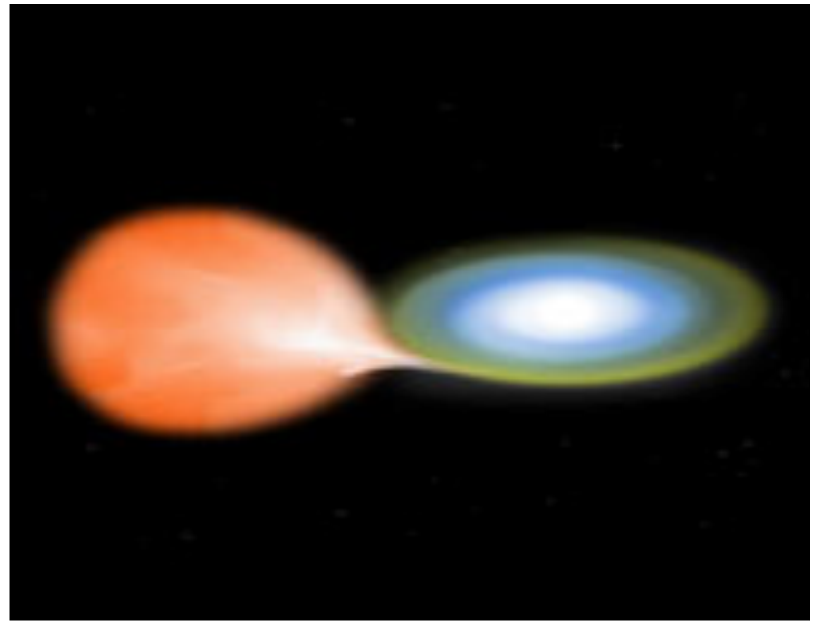
Compact White Dwarf Binaries (mins - hour)





Compact White Dwarf Binaries (mins - hour)





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

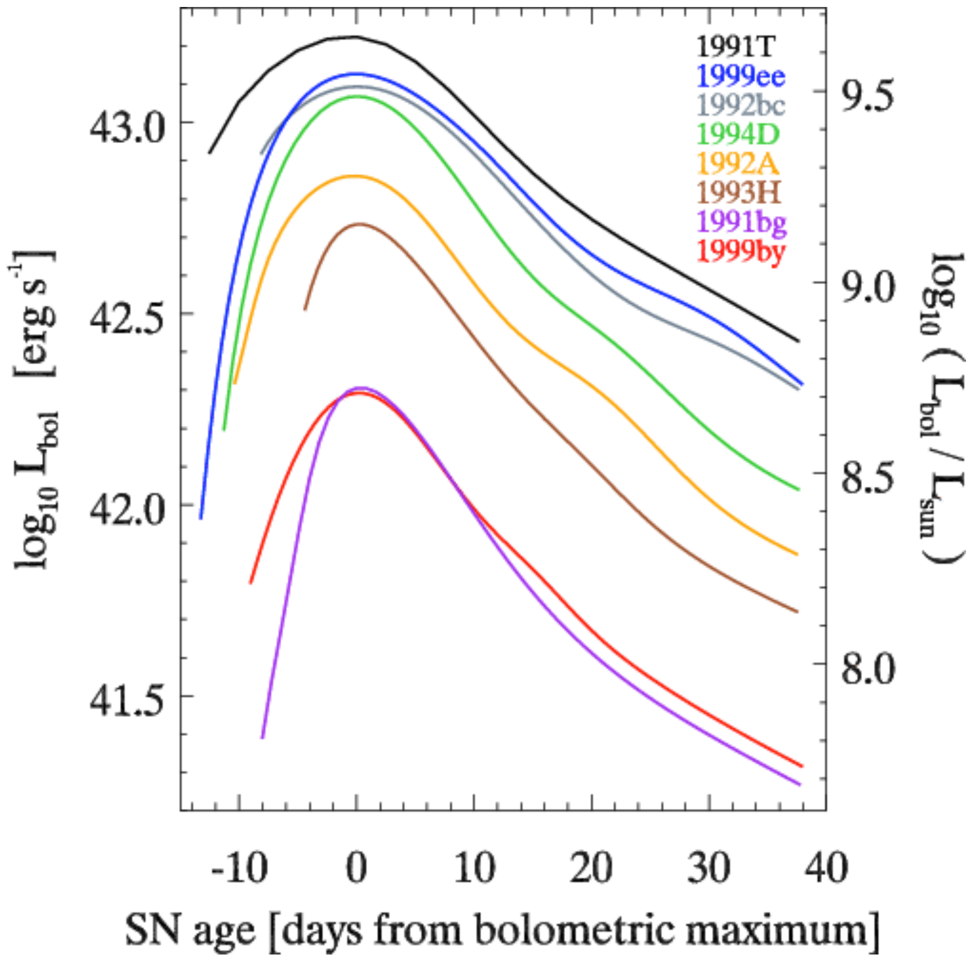
Space interferometer (eLISA-NGO??)

-- 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 ??

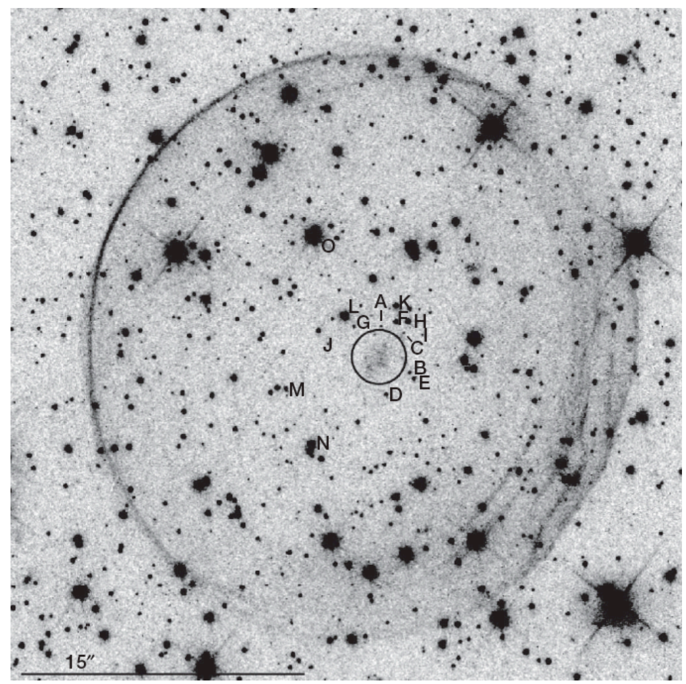
WD + non-deg. star: "Single-degenerate" Scenario
WD + WD merger: "Double-degenerate" Scenario
WD + WD collision ?

Various arguments for/against each scenario:
Rates, super-soft sources, delay time…

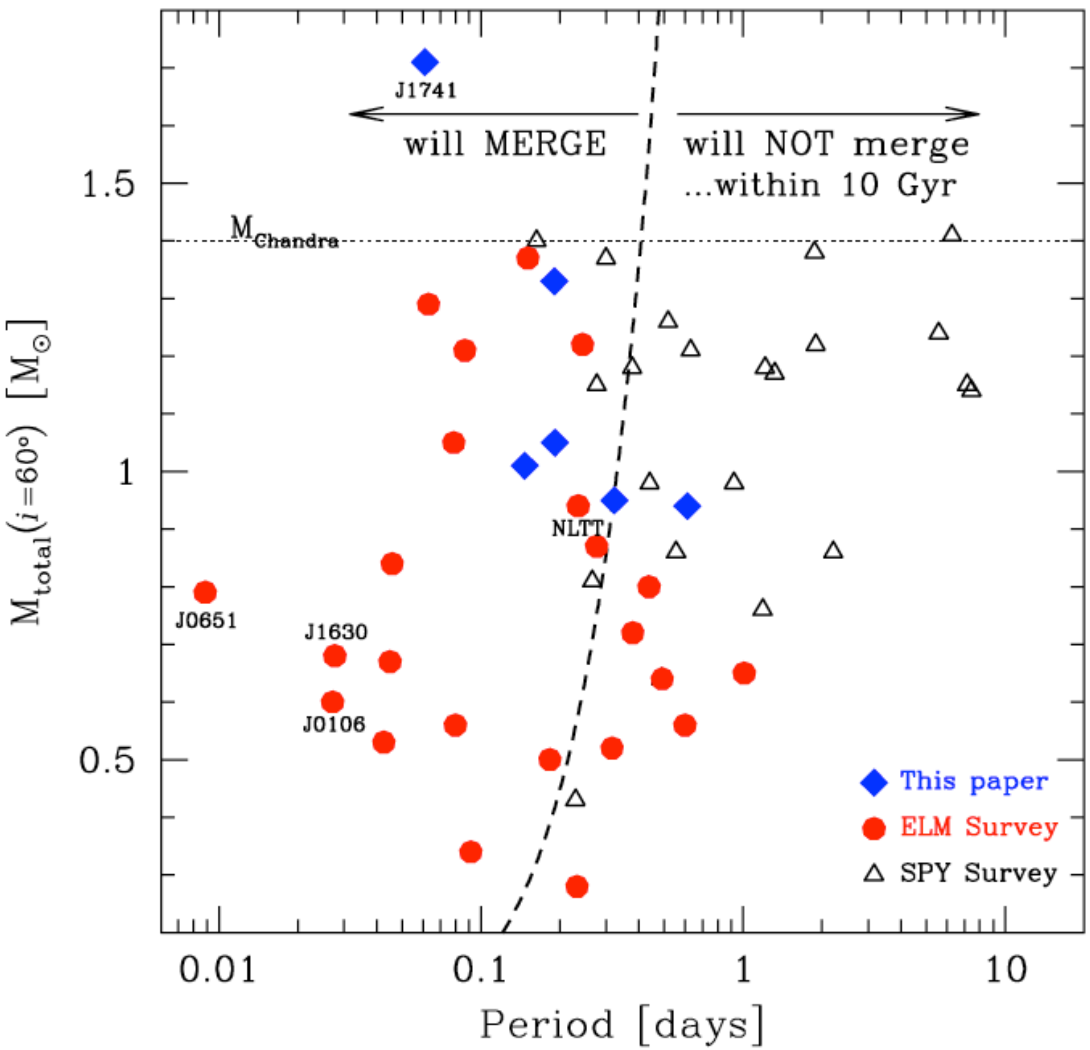
Recent observations in favor of DD:

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)

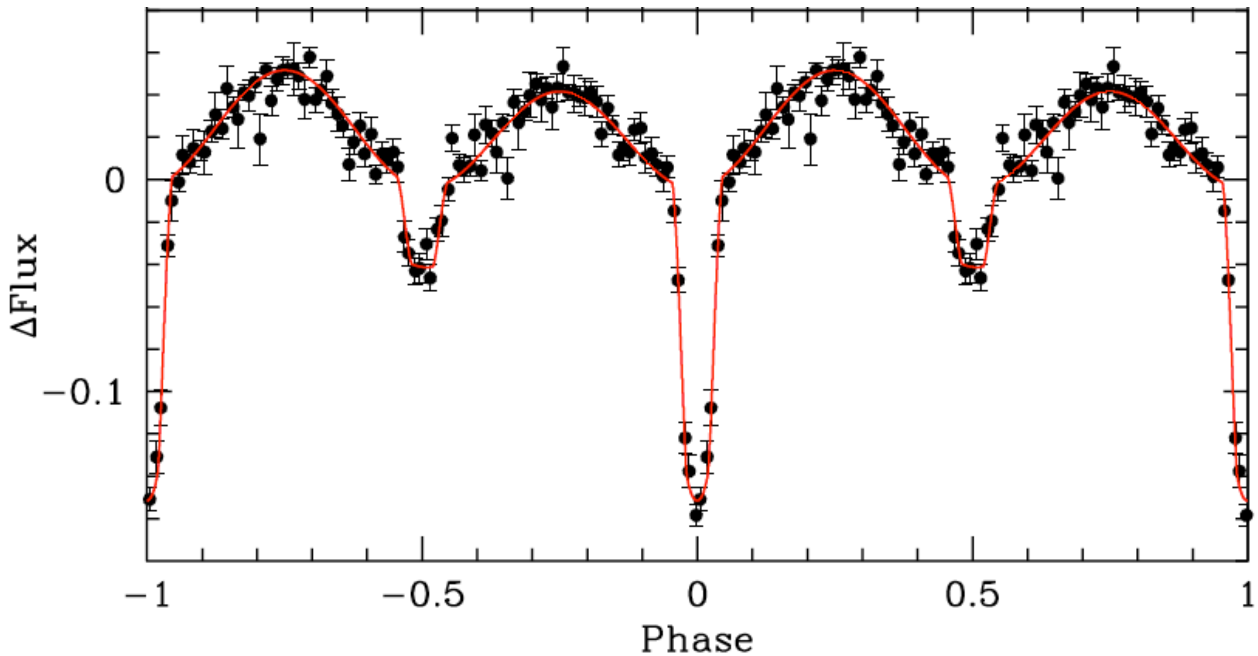


Radial Velocity Surveys of Compact WD Binaries



Brown et al. 2012

12 min orbital period double WD eclipsing binary



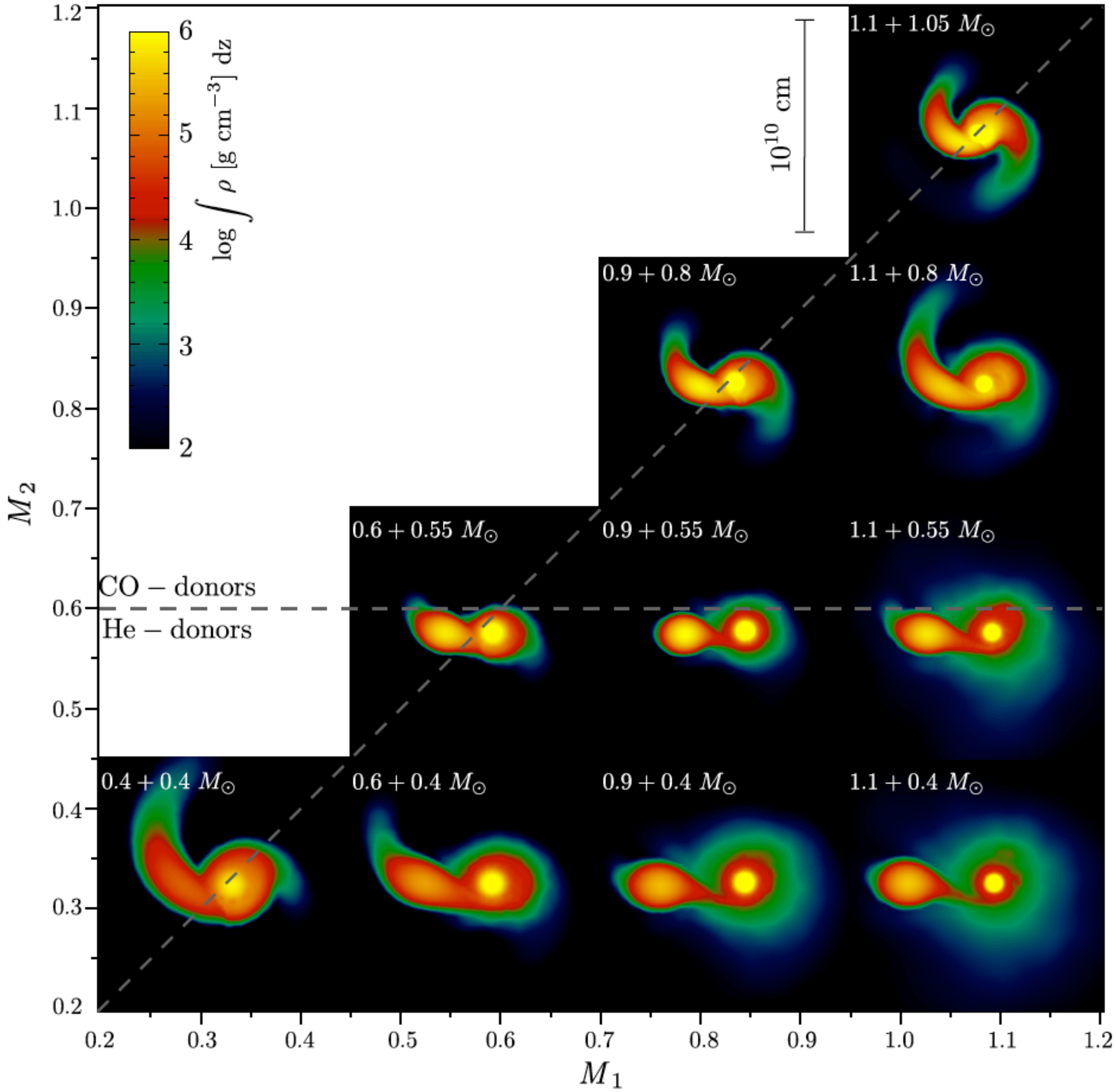
SDSS J0651+2844

Primary & secondary eclipses
Ellipsoidal (tidal) distortion
Doppler boosting

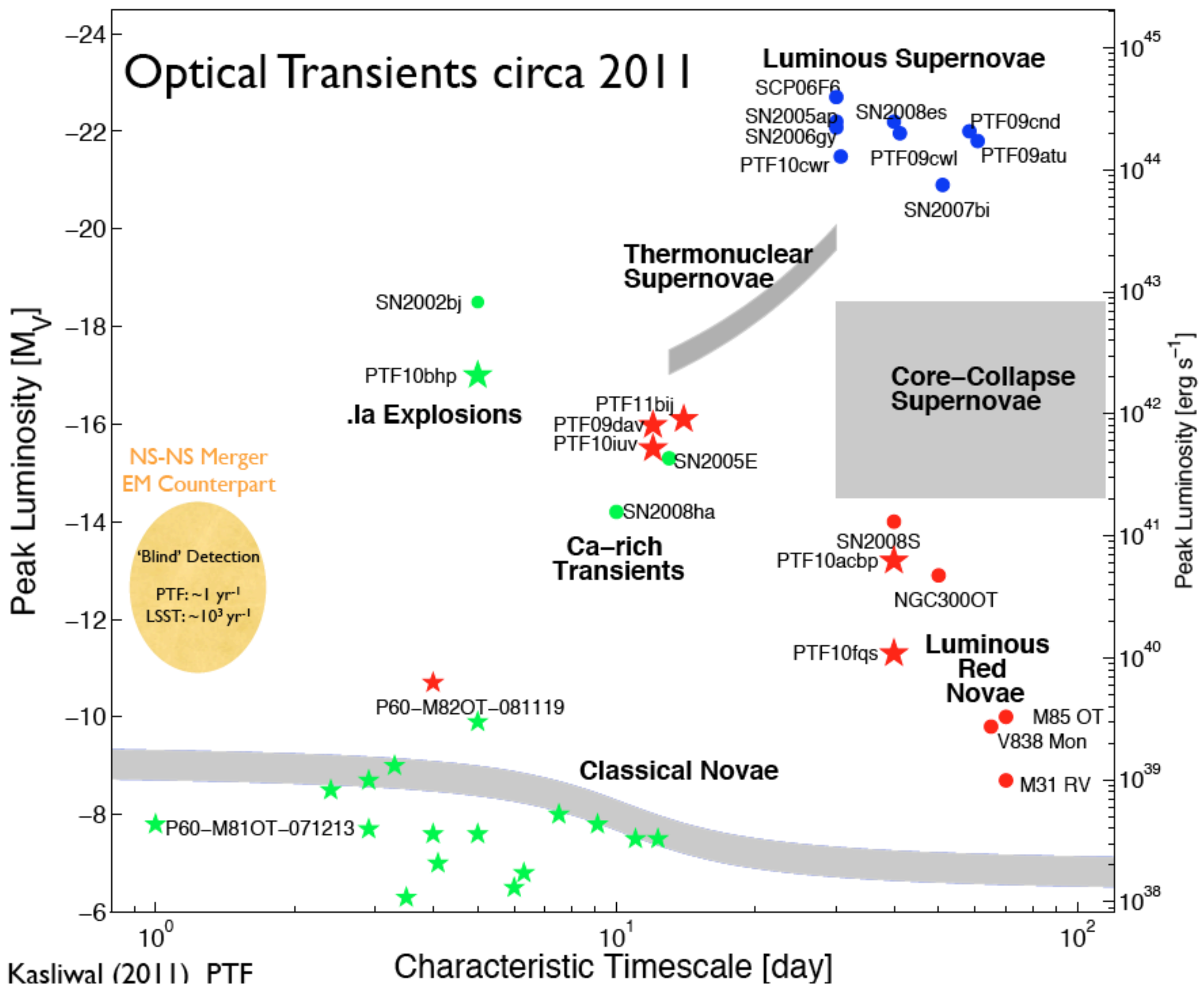
Brown et al. 2011

-- 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



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

Dynamical Tides in Compact WD Binaries

Jim Fuller & DL

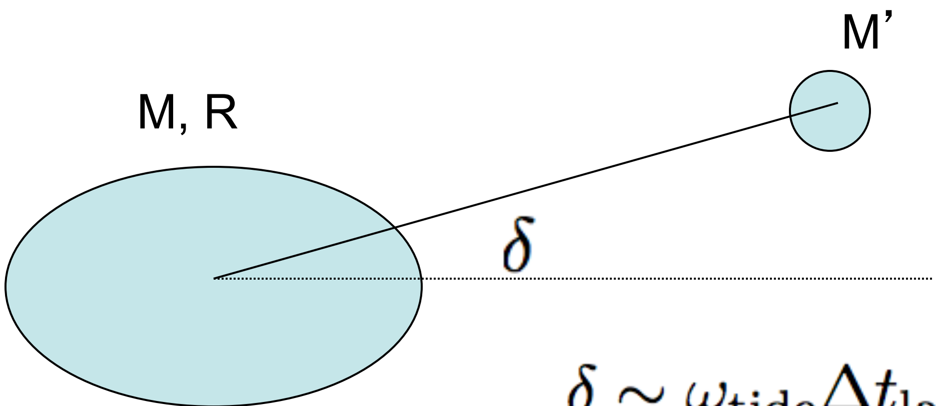
Issues:

-- Spin-orbit synchronization?

-- Tidal dissipation and heating?

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

Equilibrium Tide



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

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

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

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

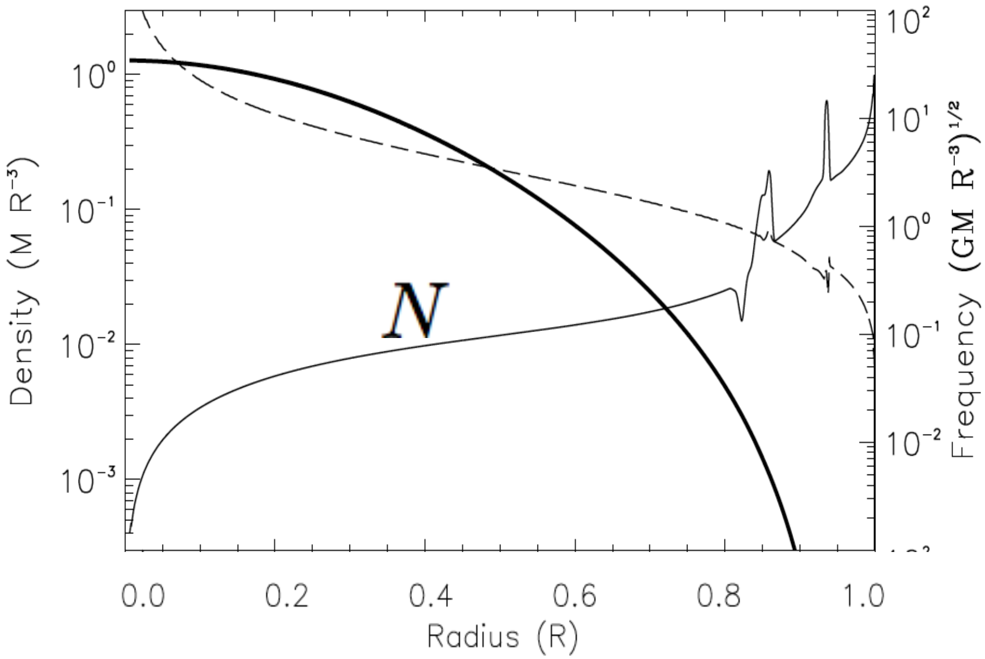
Problems:

-- Parameterized theory

-- The physics of tidal dissipation is more complex:

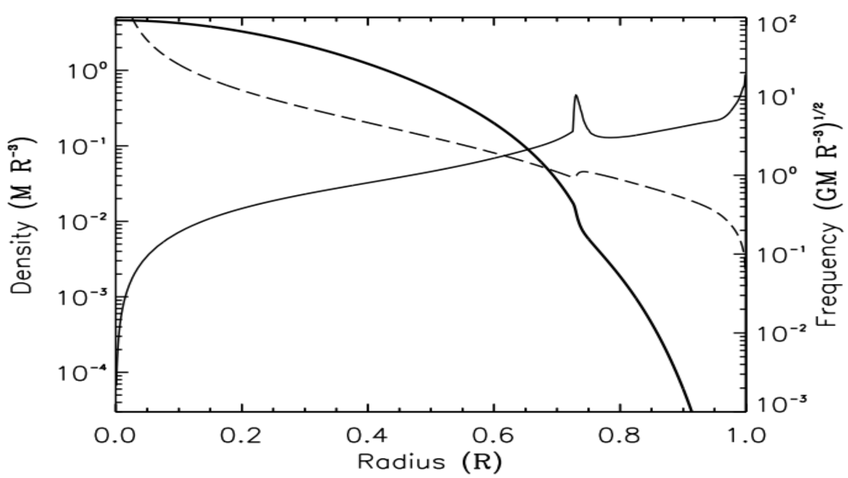
Excitation/damping of internal waves/modes (Dynamical Tides)

Wave Propagation inside White Dwarf



CO WD

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

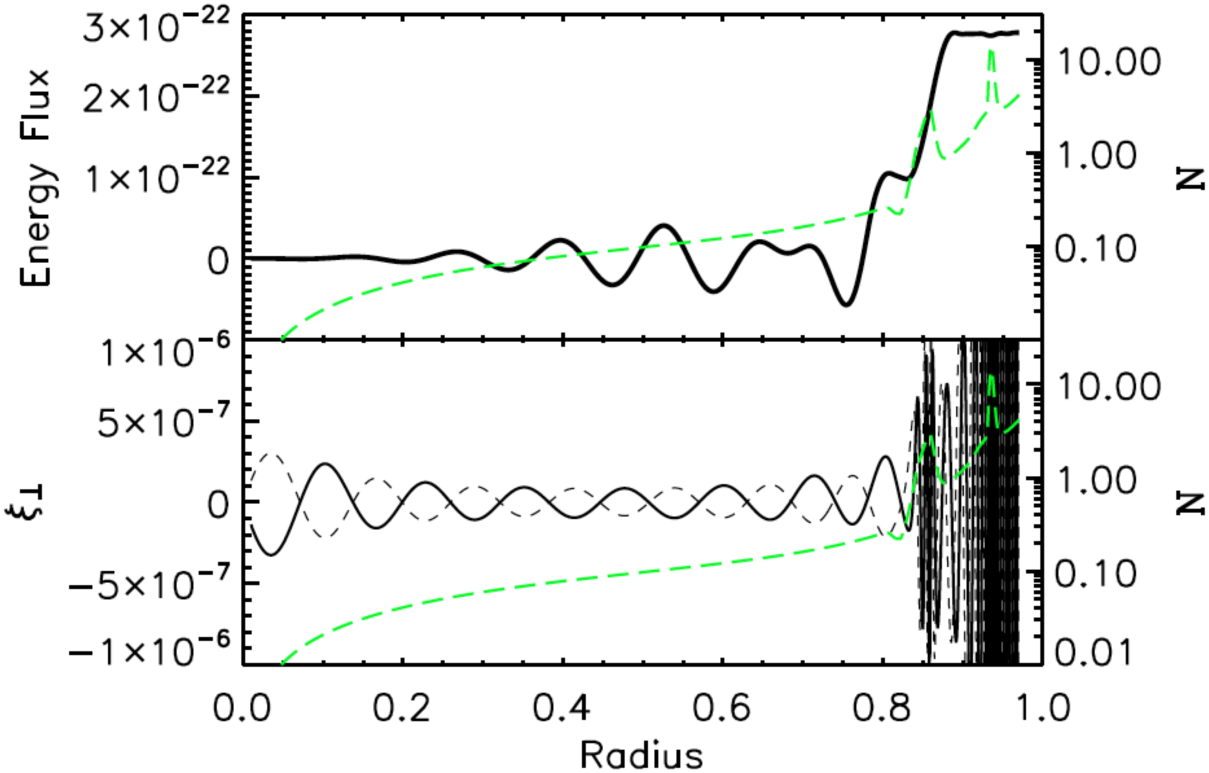


He-core WD

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

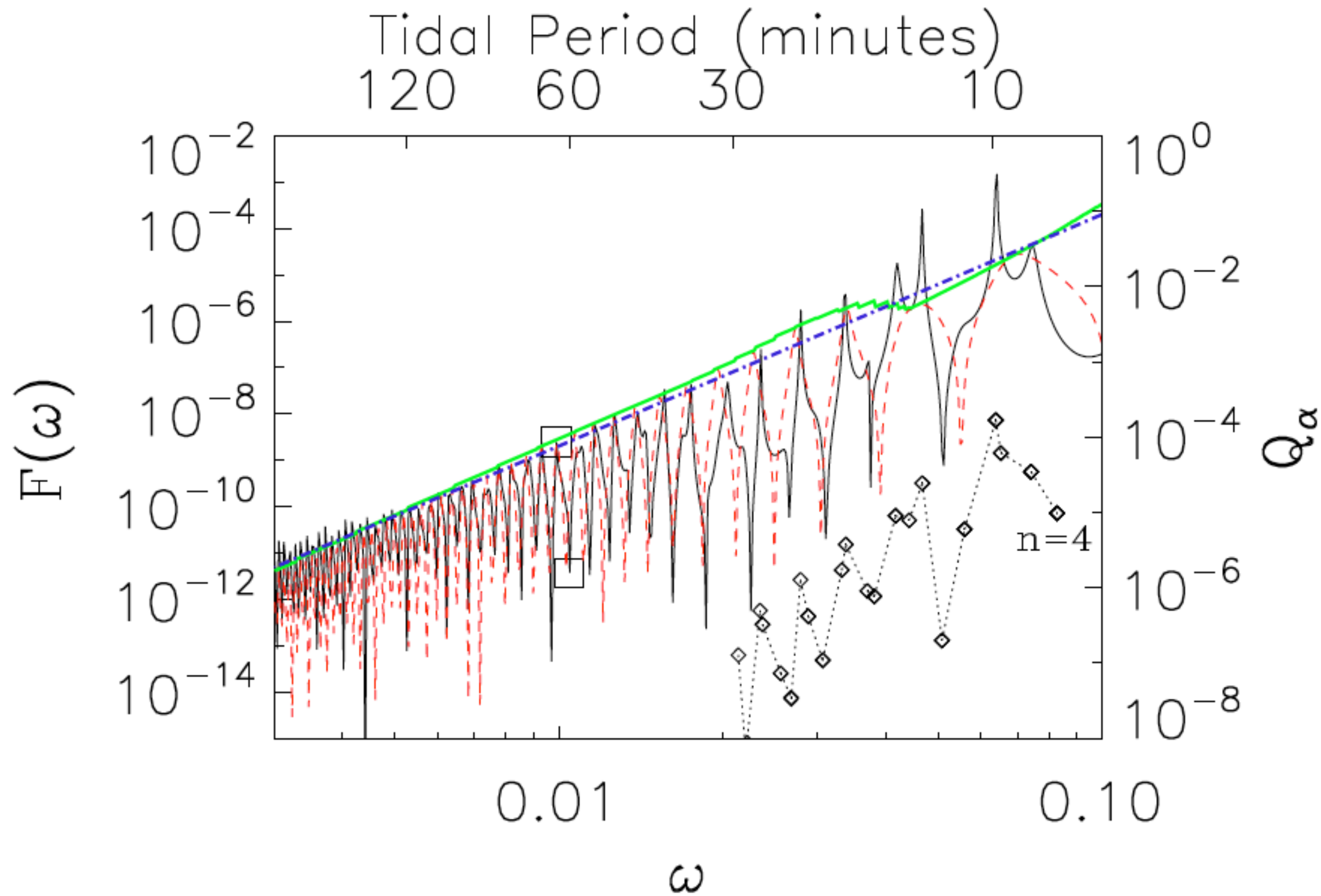
"Continuous" Excitation of Gravity Waves

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

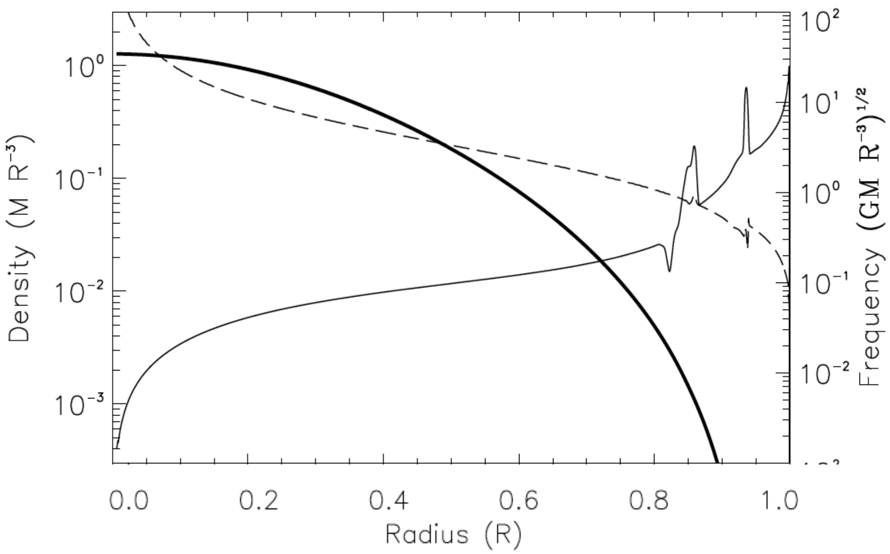


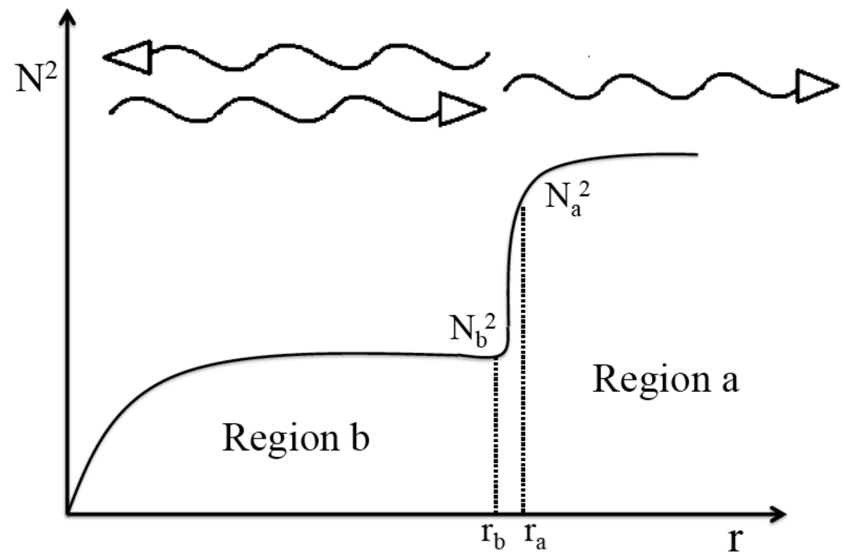
$$M = 0.6M_{\odot}, \quad \omega = 0.01$$

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

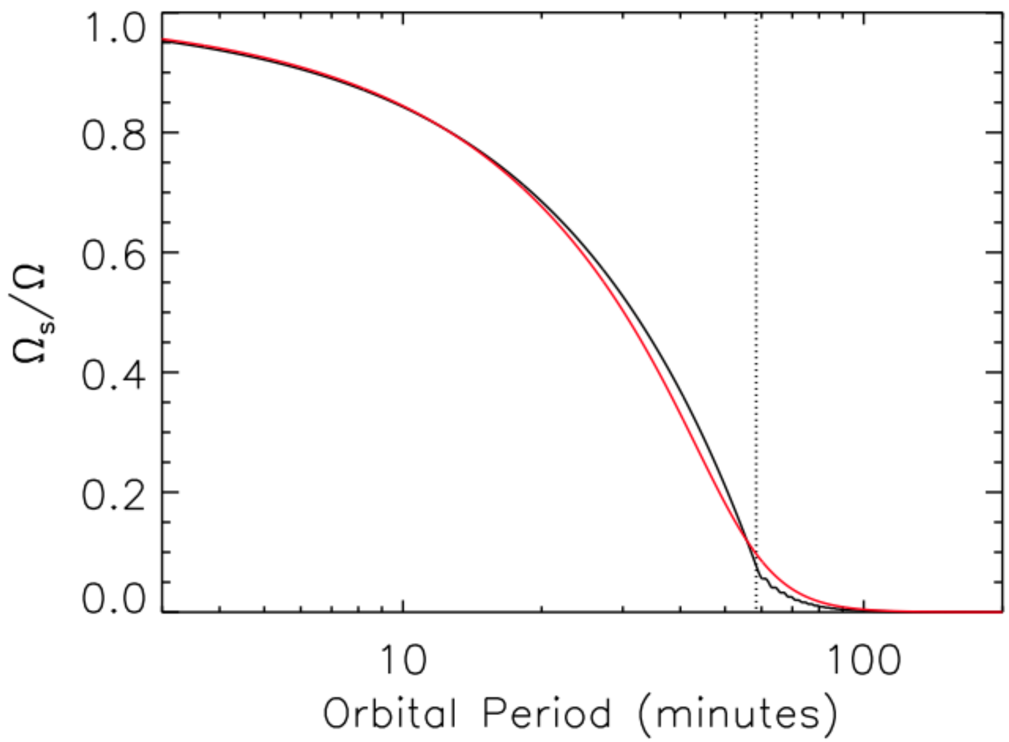


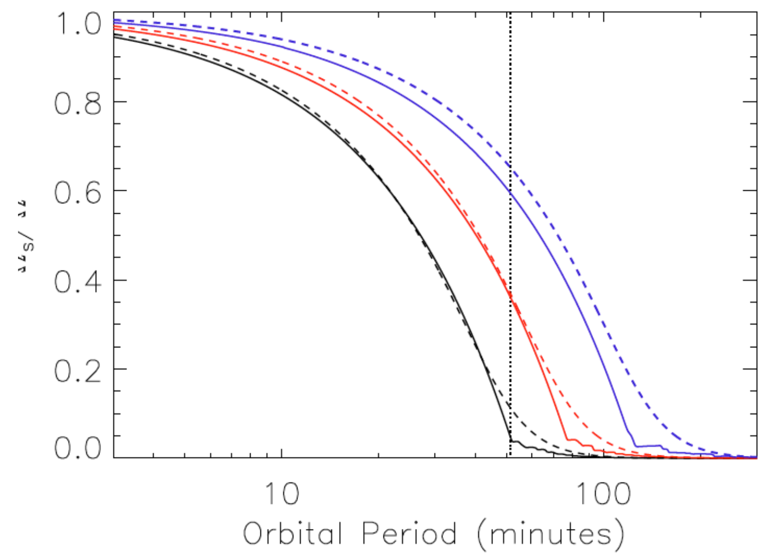
Why is $F(\omega)$ not smooth ?





Spin-Orbit Synchronization



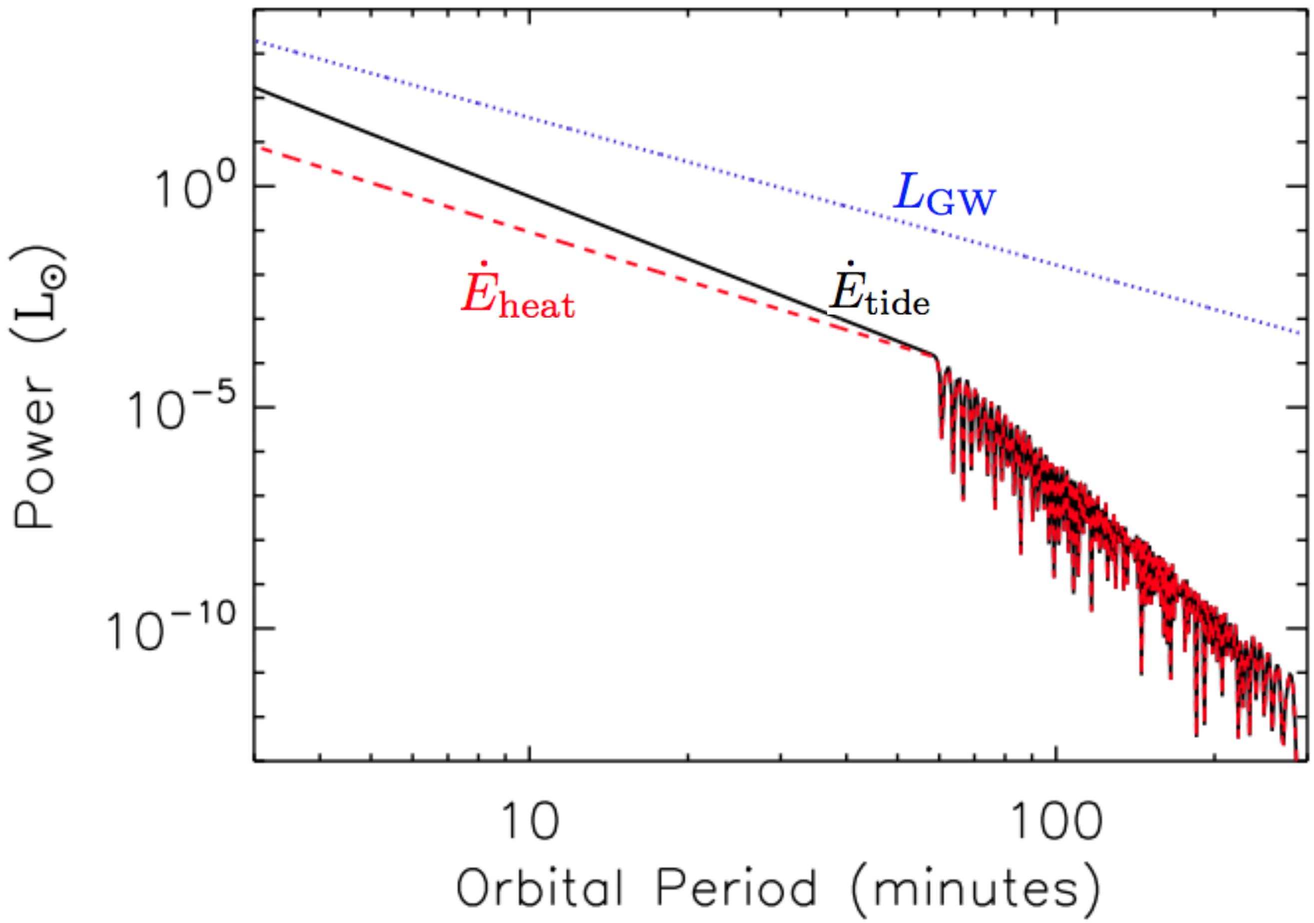


Critical orbital Ω_c : $\quad \dot{\Omega}_s = \dfrac{\text{Torque}}{I} \simeq \dot{\Omega}_{\rm orb} = \dfrac{3\Omega_{\rm orb}}{2t_{\rm GW}}$

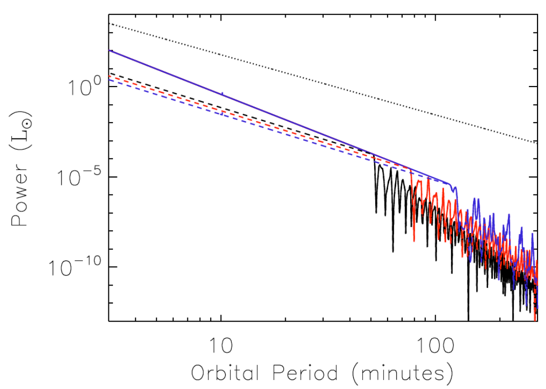
For $\Omega_{\rm orb} > \Omega_c$: $\quad \dot{\Omega}_s > \dot{\Omega}_{\rm orb}$

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

Tidal Heating Rate



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



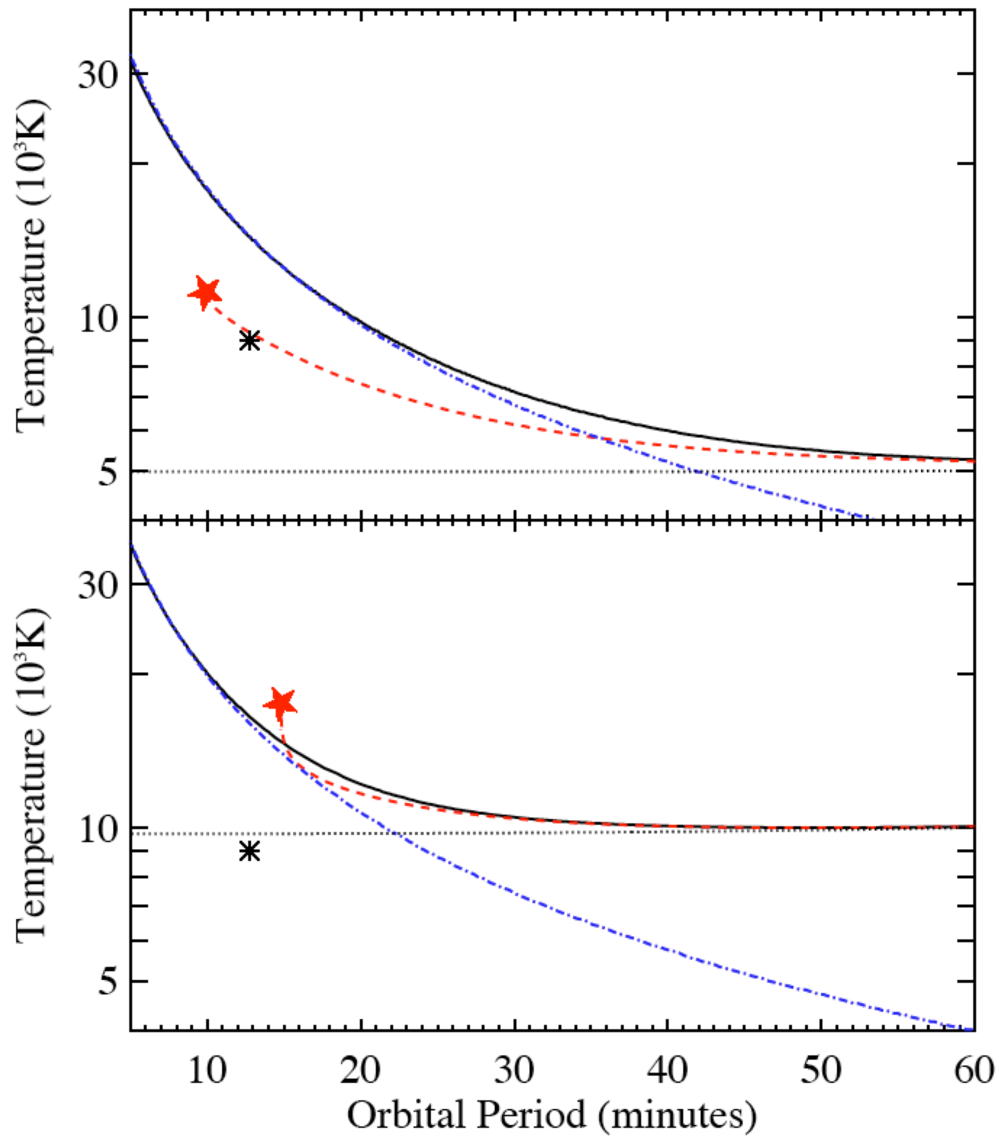
Consequences of Tidal Heating

Depend on where the heat is deposited …

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

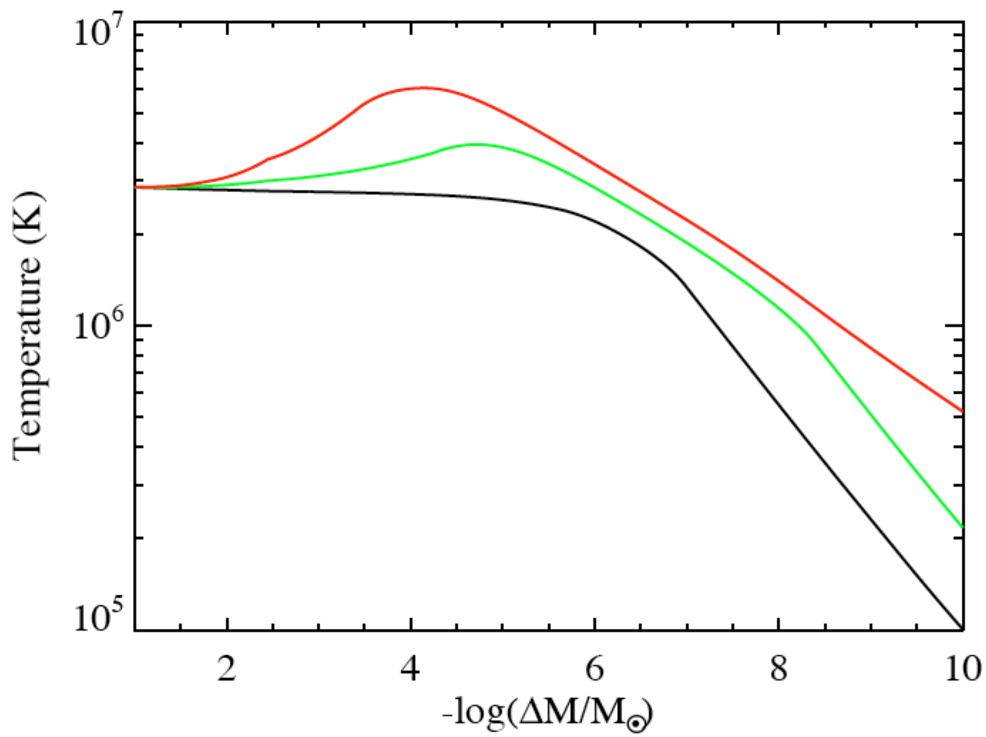
If deposited in deeper layer:
  thermal time longer than orbital
  ==> nuclear flash

"Tidal Nova" !

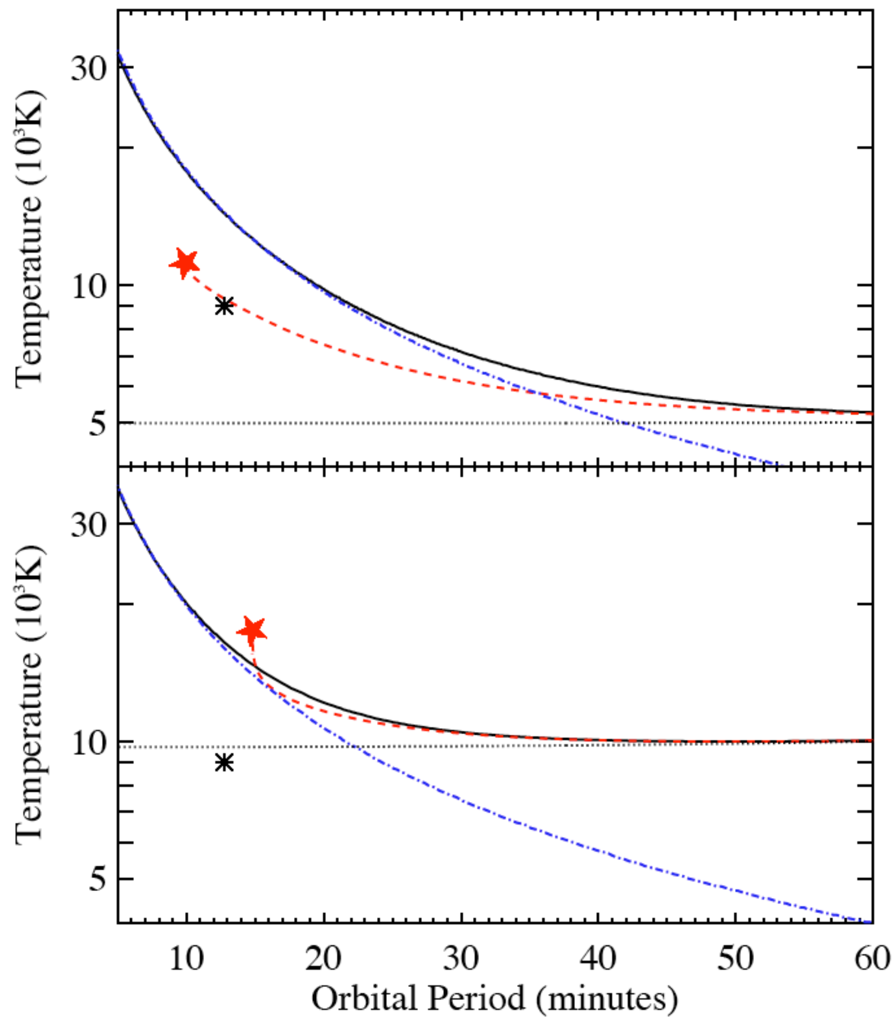


Fuller & DL 2012

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??)

Neutron Stars:

Different Observational Manifestations

-- Isolated NSs
-- Accreting NSs
-- Merging NSs

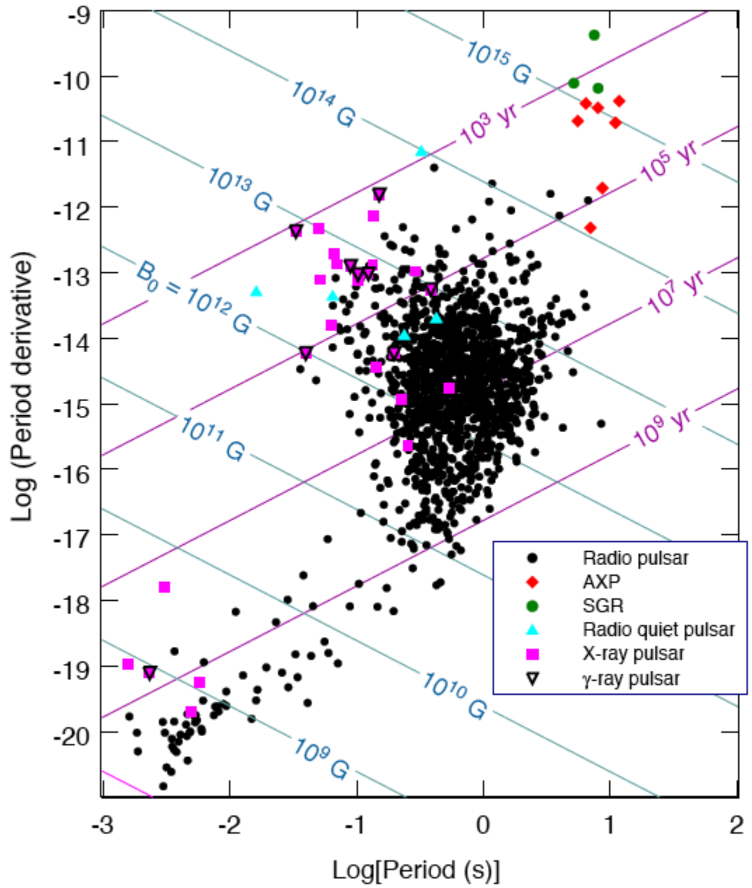
Isolated Neutron Stars

Radio pulsars: $P, \dot{P} \Rightarrow$

$\text{Most pulsars}: \ B \sim 10^{12-13} \text{ G}$

$\text{Millisecond pulsars}: \ B \sim 10^{8-9} \text{ G}$

$\text{High} - \text{B radio pulsars}: \ B \sim 10^{14} \text{ G}$



Radiation at all wavelengths:

radio, IR, optical, X-rays, Gamma-rays

New Odd Behaviors:

- RRATs (rotating radio transients)
  radio busrts (2-30 ms), quiescence (min-hrs);
  period ~ sec

- Intermittent Pulsars ("Sometimes a pulsar")
  e.g. PSR B1931+24: "on" for ~ a week,
  "off" for ~ a month

Magnetars

Neutron stars powered by superstrong magnetic fields ($B>10^{14}$G)

Soft Gamma-Ray Repeaters (SGRs) (7+4 systems)
Anomalous X-ray Pulsars (AXPs) (9+3 systems)

Even in quiescence, $L \sim 10^{34-36}\mathrm{erg\ s}^{-1} \gg I\Omega\dot{\Omega}$

T ~0.5 keV, but significant emission up to ~100 keV (e.g. Kuiper et al.) => Magnetar corona

AXP/SGR bursts/flares (e.g. Kaspi, Gavriil, Kouveliotou, Woods, etc)

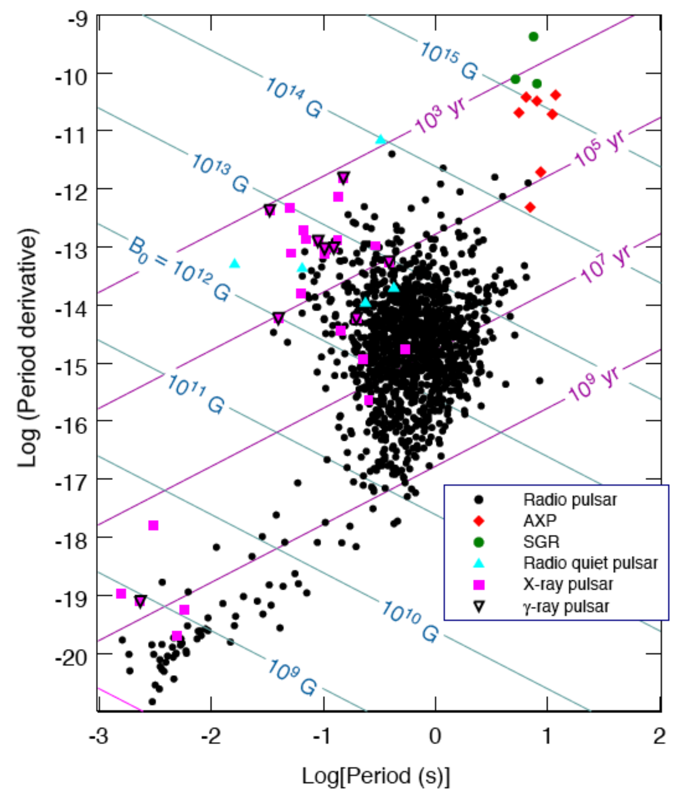
Giant flares in 3 SGRs

12/04 flare of SGR1806-20 has $E>10^{46}$erg

QPOs during giant flares (e.g Israel, Strohmayer, Watts, etc)

Magnetars do not show persistent radio emission

Connection with high-B radio pulsars?



Note:

-- Transient magnetars: Radio emission triggered by X-ray outbursts

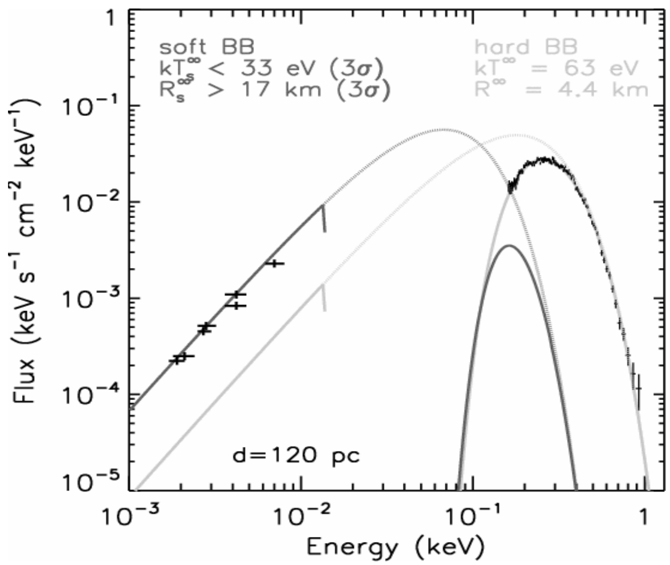
XTE J1810-197, 1E 1547.0-5408 (Camilo et al. 2007)

-- PSR J1622-4950 has $B\sim3.10^{14}$G, but $L_x \sim L_{sd}/4$ (Levin et al 2010)

Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754



Burwitz et al. (2003)

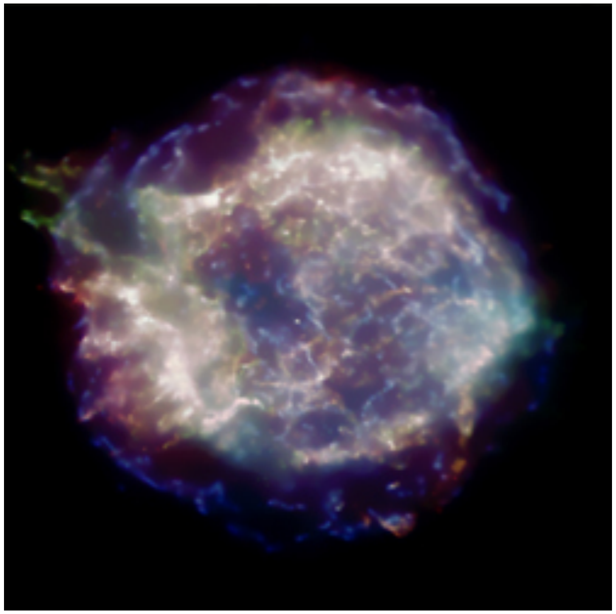
Spectral lines detected:

(e.g., van Kerkwijk & Kaplan 06; Haberl 06)

RXJ1308+2127 (0.2-0.3 keV)
RXJ1605+3249 (~0.45 keV)
RXJ0720-3125 (~0.3 keV)
RXJ0420-5022 (~0.3 keV)?
RXJ0806-4123 (~0.5 keV)?
RBS 1774 (~0.7 keV)?

$\Longrightarrow B \sim 10^{13-14}$G? magnetar descendant & off-beam radio pulsar?

Central Compact Objects (CCOs) in SNRs

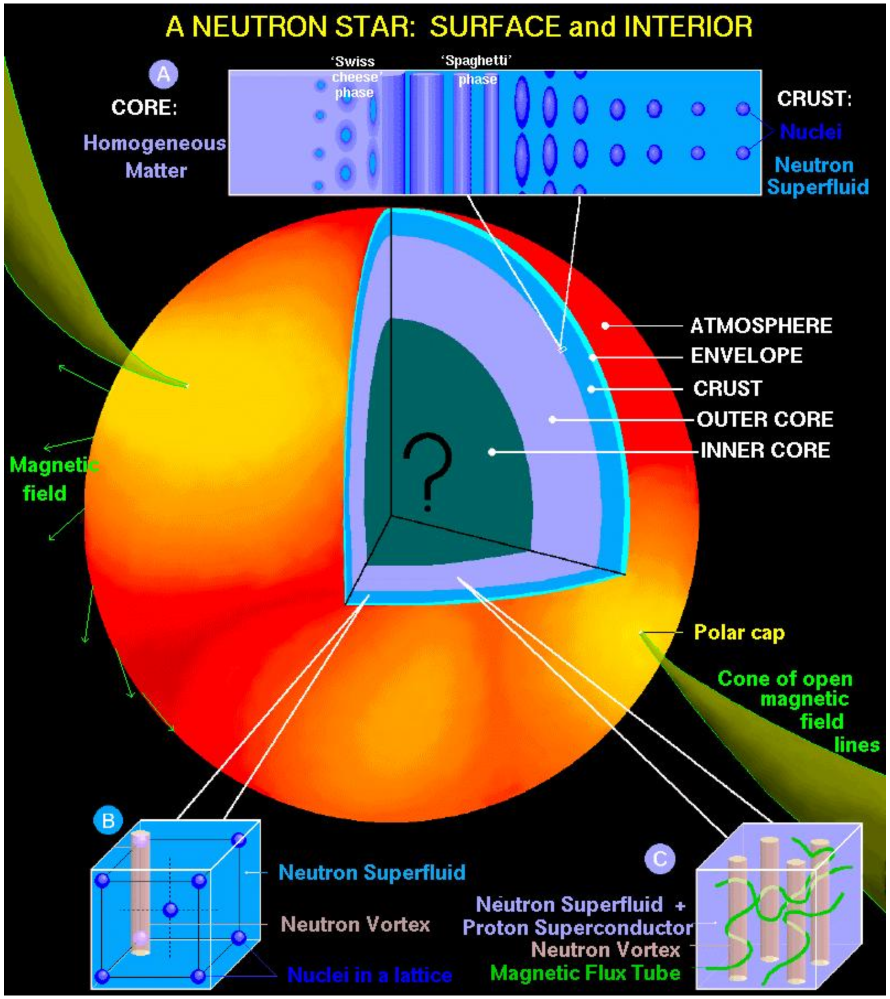


CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)
RX J0822.0 − 4300	Puppis A	3.7	2.2	0.112	11	<9.8
CXOU J085201.4 − 461753	G266.1 − 1.2	1	1	⋯	<7	⋯
1E 1207.4 − 5209	PKS 1209 − 51/52	7	2.2	0.424	9	<3.3
CXOU J160103.1 − 513353	G330.2 + 1.0	$\gtrsim$3	5	⋯	<40	⋯
1WGA J1713.4 − 3949	G347.3 − 0.5	1.6	1.3	⋯	<7	⋯
CXOU J185238.6 + 004020	Kes 79	7	7	0.105	64	0.31
CXOU J232327.9 + 584842	Cas A	0.33	3.4	⋯	<12	⋯

Halpern & Gotthelf 2010

Small surface dipole field …   (are they "anti-magnetars"?)

Neutron Star Structure



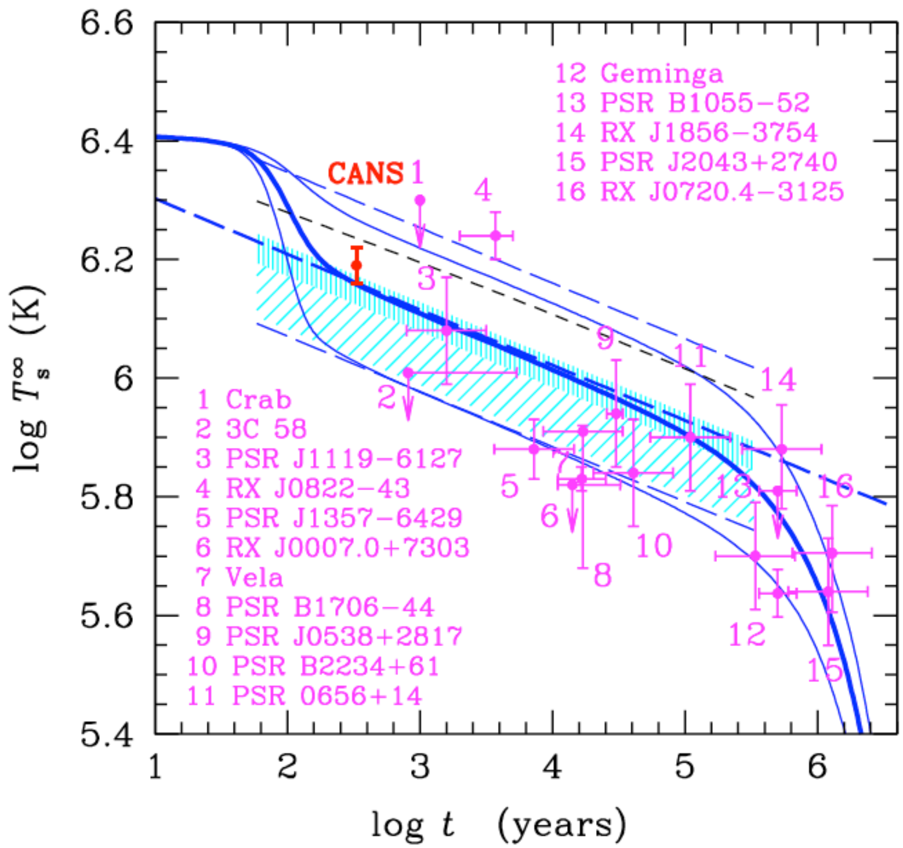
D. Page

Highlight #1:
Constrain NS Interior physics by Cooling

Surface emission has been
Detected in ~20 NSs

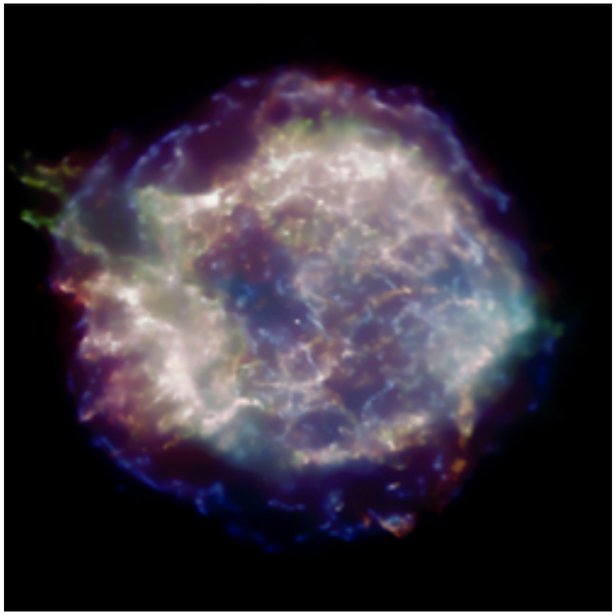
Probe the interior of NS
(EOS, exotic processes)

Difficuities:
Many parameters and theoretical
Models/processes…



Yakovlev et al. 2011

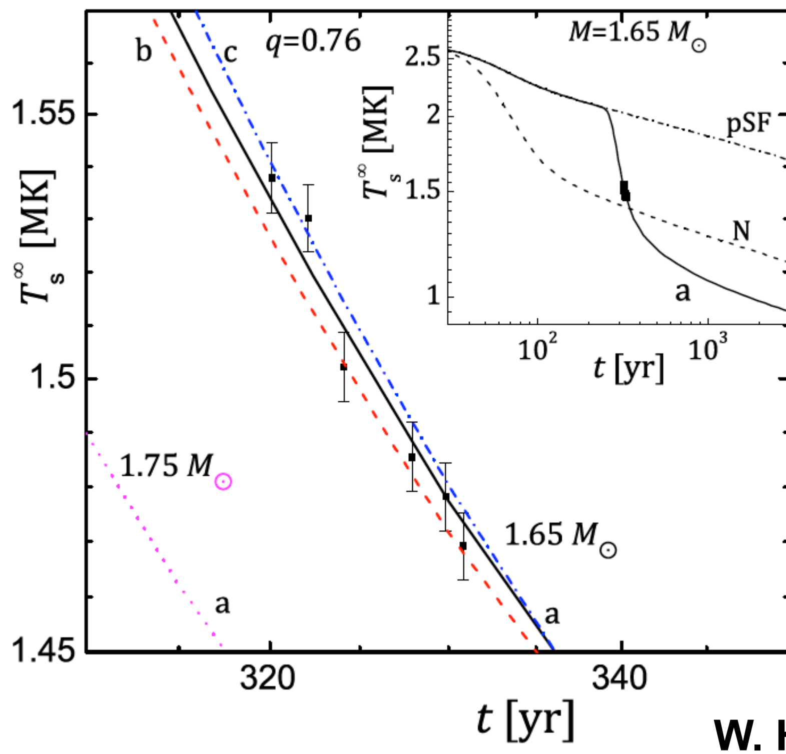
NS in Cas A SNR: Evidence of Superfludity



Cas A SNR: age 330 yr**s**

CCO (NS) first discovered in 1999

Many observations since then…



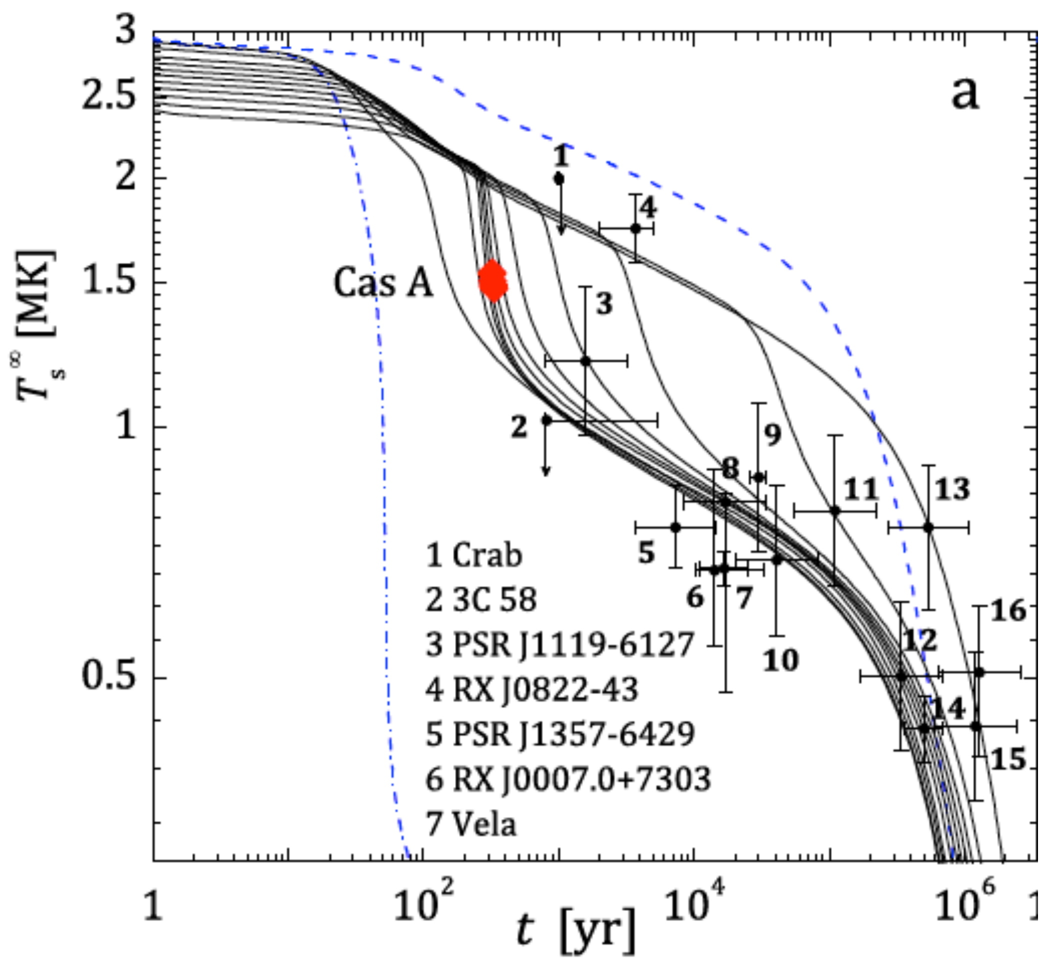
W. Ho & Heinke 2010

Shternin et al. 2011

NS in Cas A SNR: Evidence for Superfluidity

Decline in T is quite large for t~300 yrs.

Solution: Internal T drops below T_{crit} at 300 yrs ==> neutrons become superfluid at 300 yrs, leading to sudden Cooling.



Strongest evidence of neutron superfluidity in NS core.

(Shternin et al. 2011; Page et al 2011)

Highlight #2:
Probing QED Processes in Superstrong B Fields

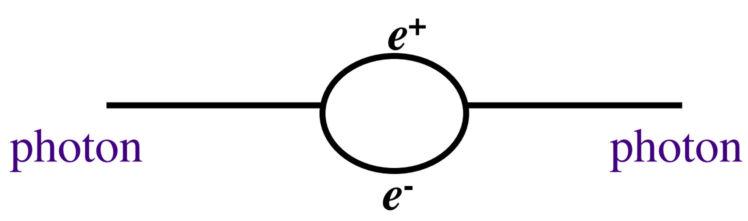
- One photon pair production:

$$\gamma \longrightarrow e^{+} + e^{-}$$

- Photon splitting:

$$\gamma \longrightarrow \gamma + \gamma$$

- **Vacuum birefringence:**
  (photon propagation affected by B field)

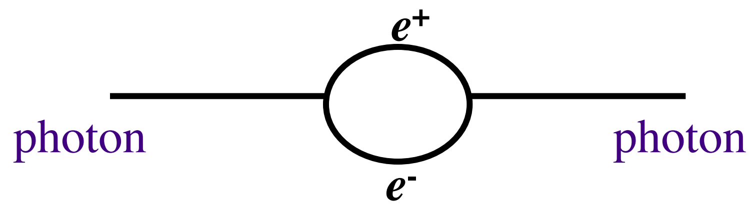


Context:
Modeling Radiation from Magnetic NS Atmospheres

NS Atmospheres:

- Outermost ~cm of the star
- Density 0.1-10^3 g/cm^3: nonideal, partially ionized, magnetic plasma
- **Effect of QED: Vacuum polarization**

Vacuum Polarization in Strong B



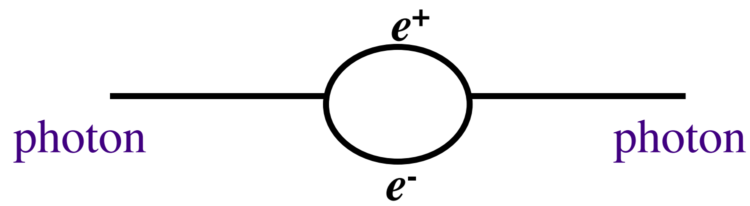
Heisenberg & Euler, Weisskopf, Schwinger, Adler…

Important when B is of order or larger than

$$B_Q = 4.4 \times 10^{13}\ \mathrm{G}$$

at which $\hbar\omega_{ce} = \hbar \dfrac{eB}{m_e c} = m_e c^2$

Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
Adler…

Dielectric tensor: $$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\mathbf{vac}}$$

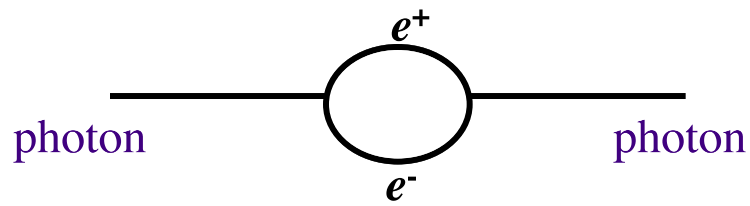
$$|\Delta\varepsilon_{\rm vac}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4\times10^{13}\ \mathrm{G}$$

Two photon modes:

Ordinary mode (//)

Extraordinary mode (⊥)

Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
Adler…

Dielectric tensor: $$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\mathrm{vac}}$$

$$|\Delta\varepsilon_{\mathrm{vac}}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4 \times 10^{13}\ \mathrm{G}$$

Two photon modes:

Ordinary mode (//)

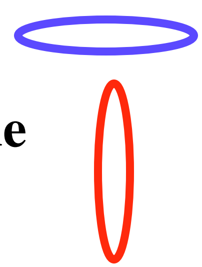
Extraordinary mode (⊥)

On the other hand…

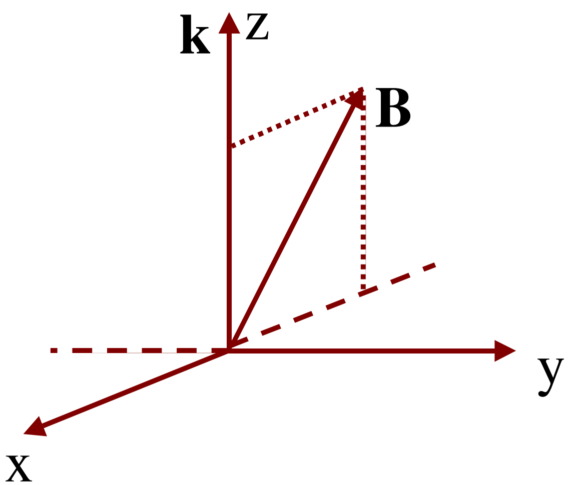
Magnetic Plasma by itself (without QED) is birefringent:

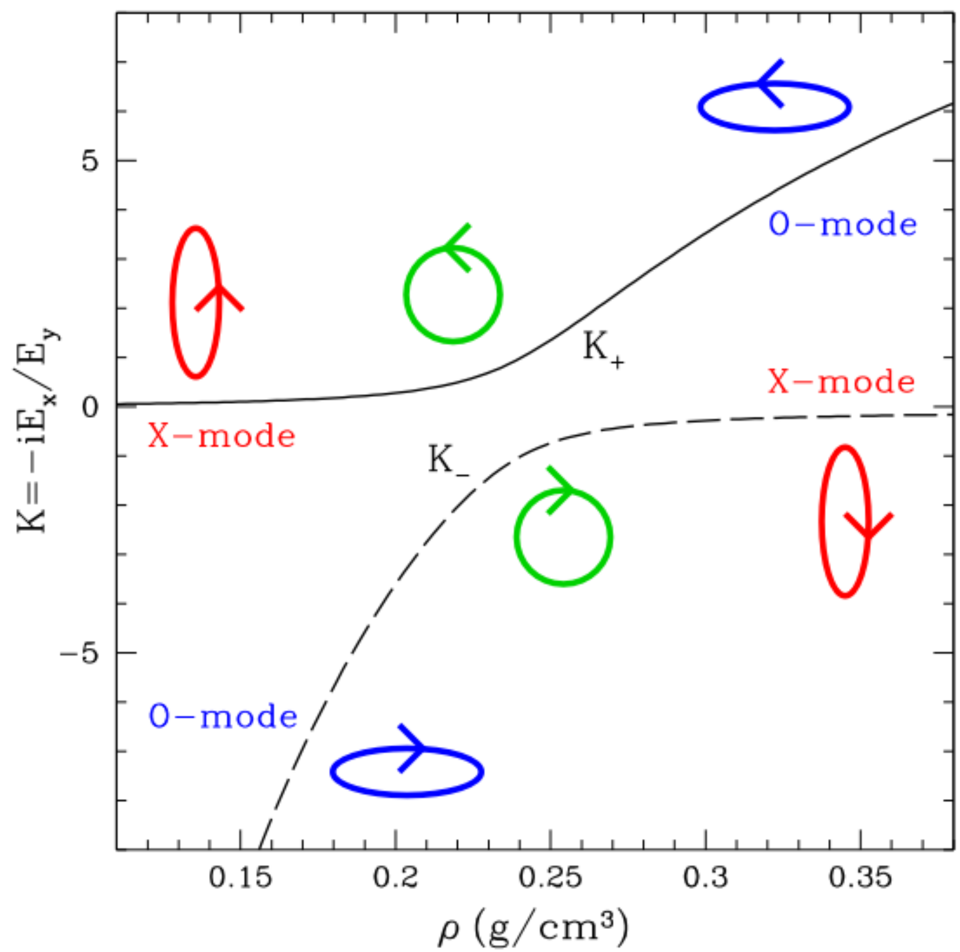
Ordinary mode

Extraordinary mode

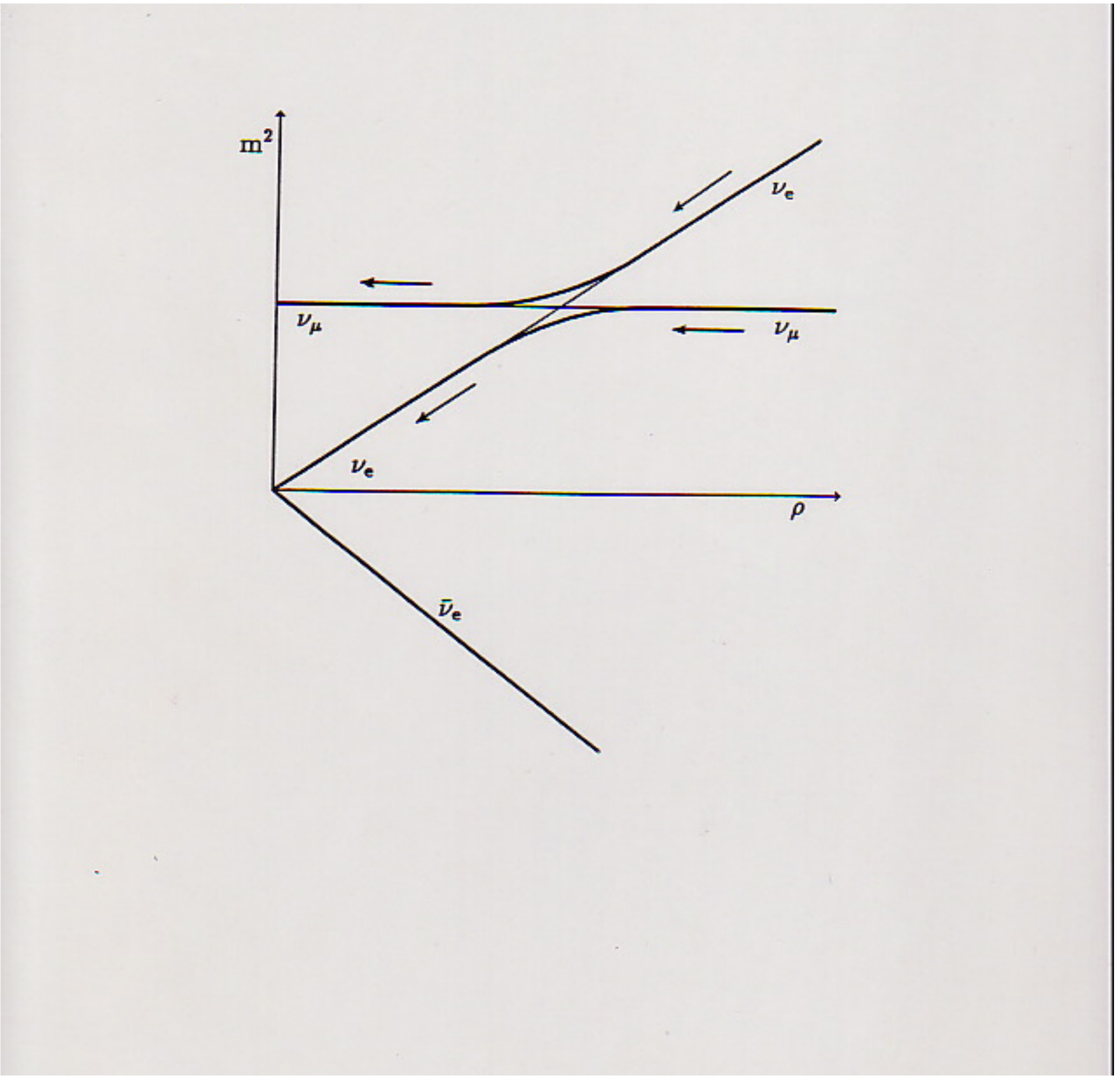


“Plasma+Vacuum” ==> Vacuum resonance

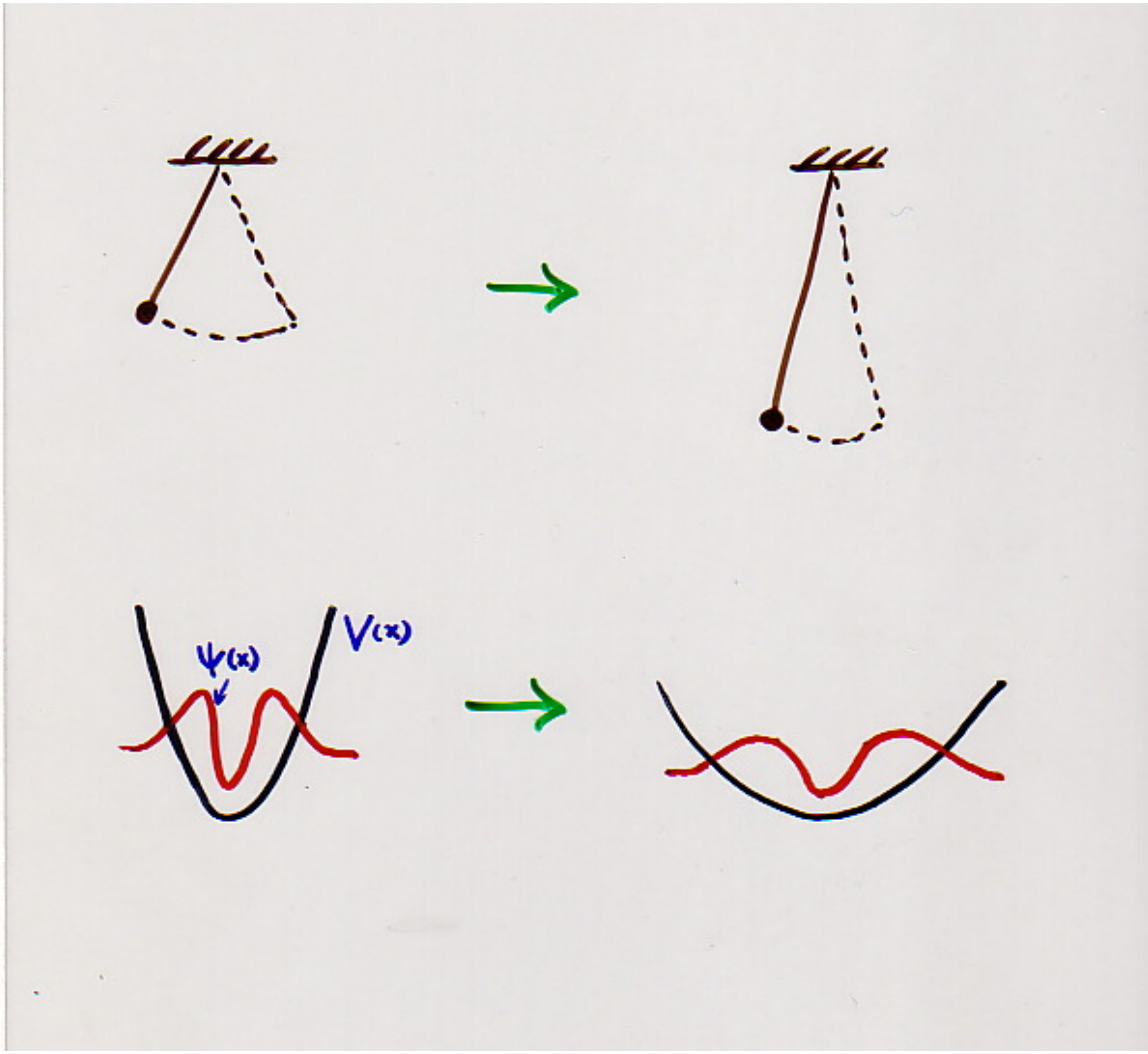




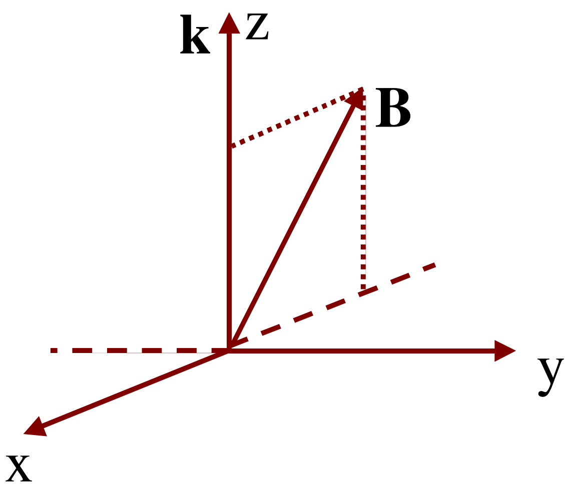
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation

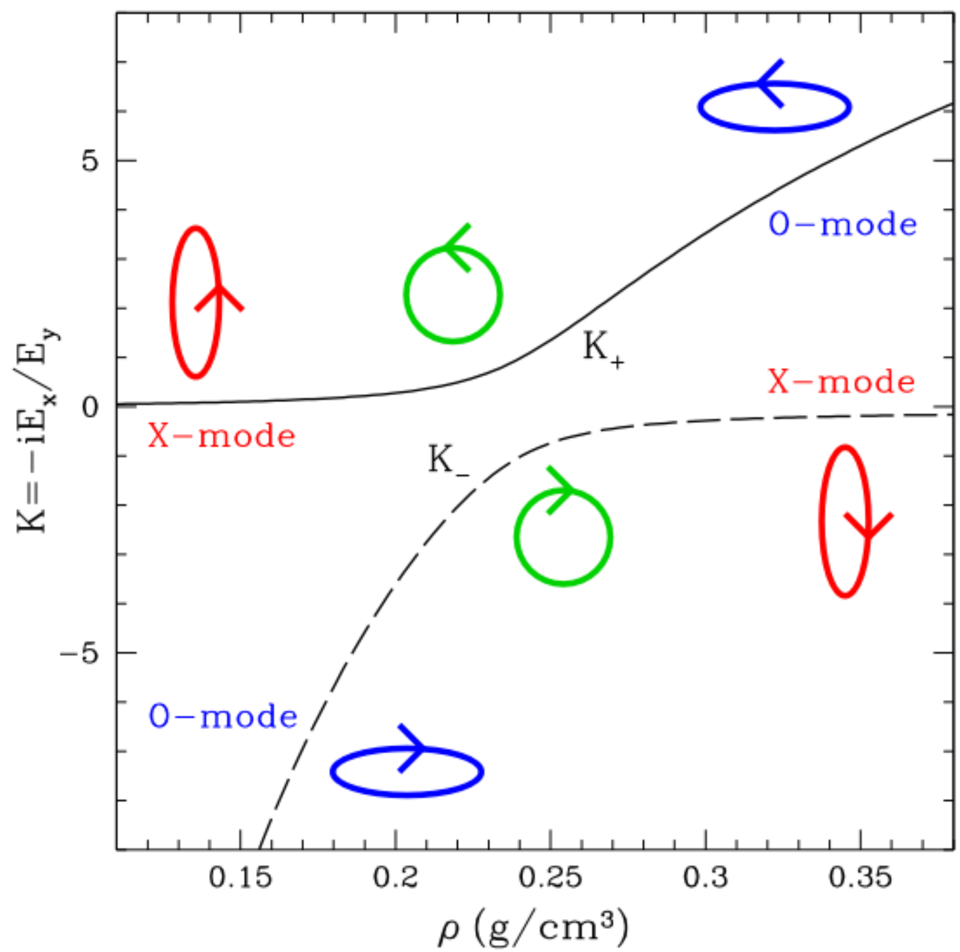


Adiabatic Evolution of a Quantum State



"Plasma+Vacuum" ==> Vacuum resonance





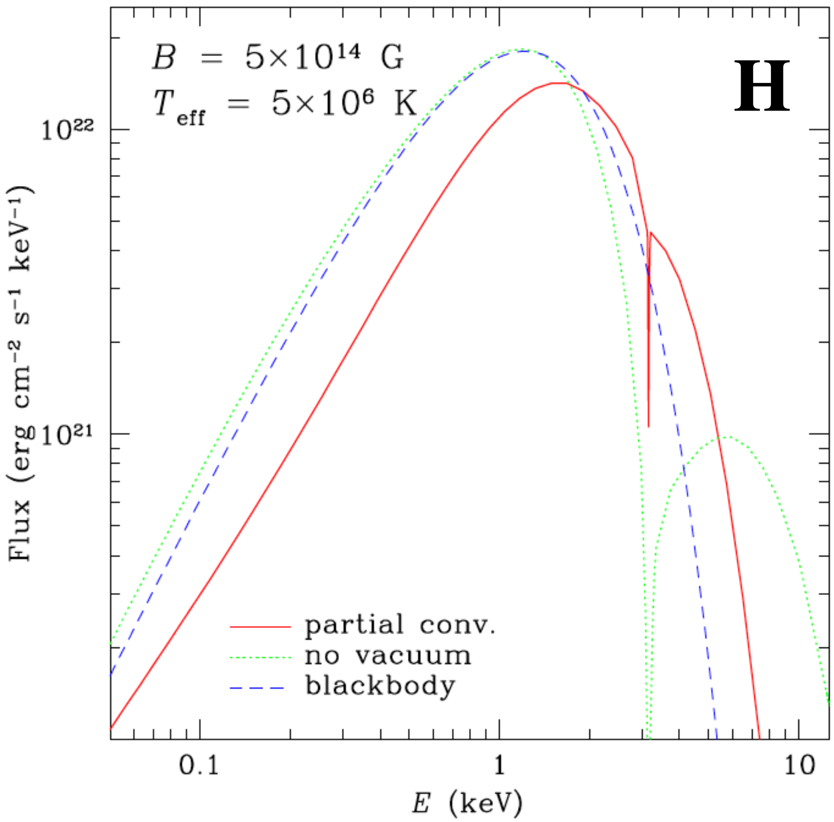
Why do we care?

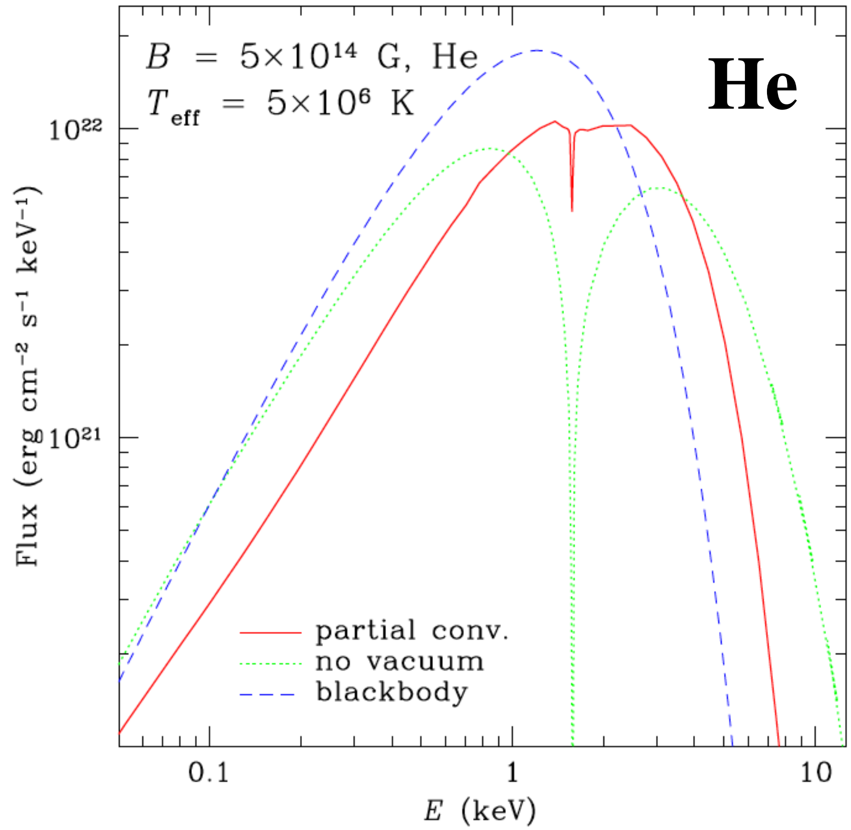
The two photon modes have very different opacities

=> Mode conversion can affect radiative transfer significantly

=> Spectrum and polarization signal from the NS

For B>10^{14}G, vacuum polarization strongly affects spectrum



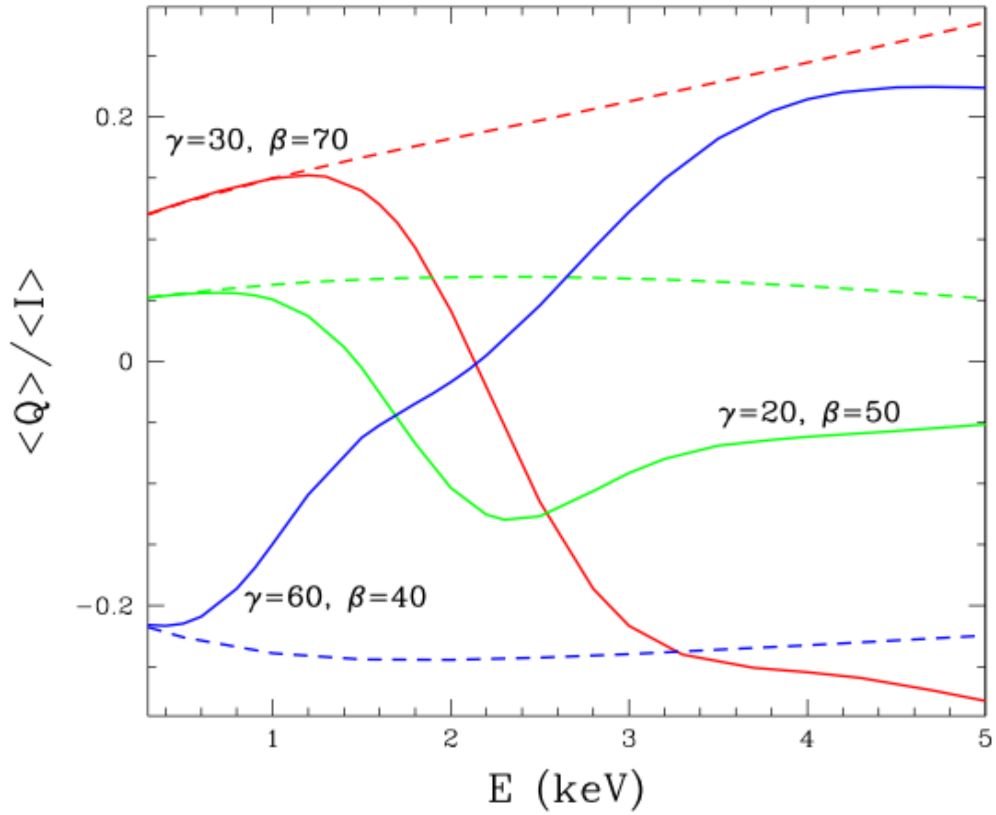


Matt Van Adelsberg & DL 2006

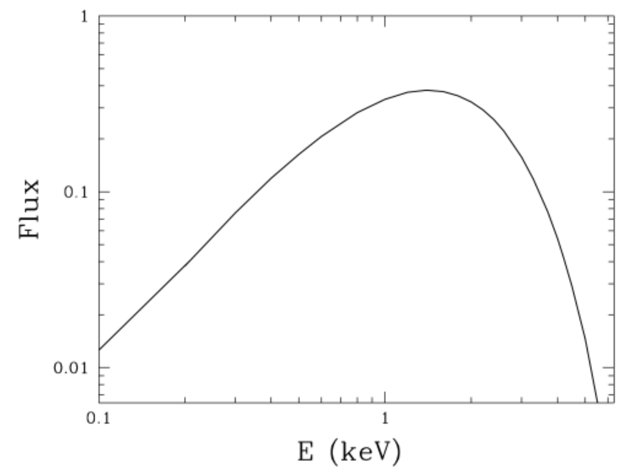
==> Magnetars do not show absorption features in thermal emission

QED at work!

Even for modest B's, vacuum resonance produces unique polarization signals

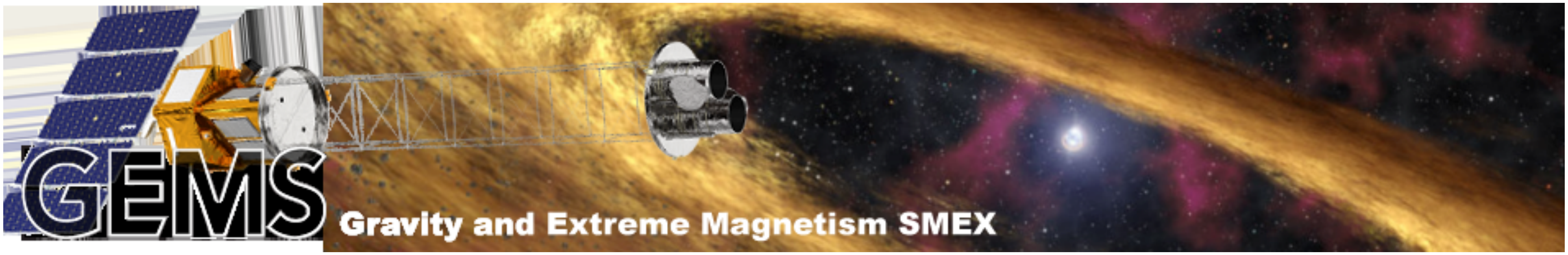


$B = 10^{13}$G

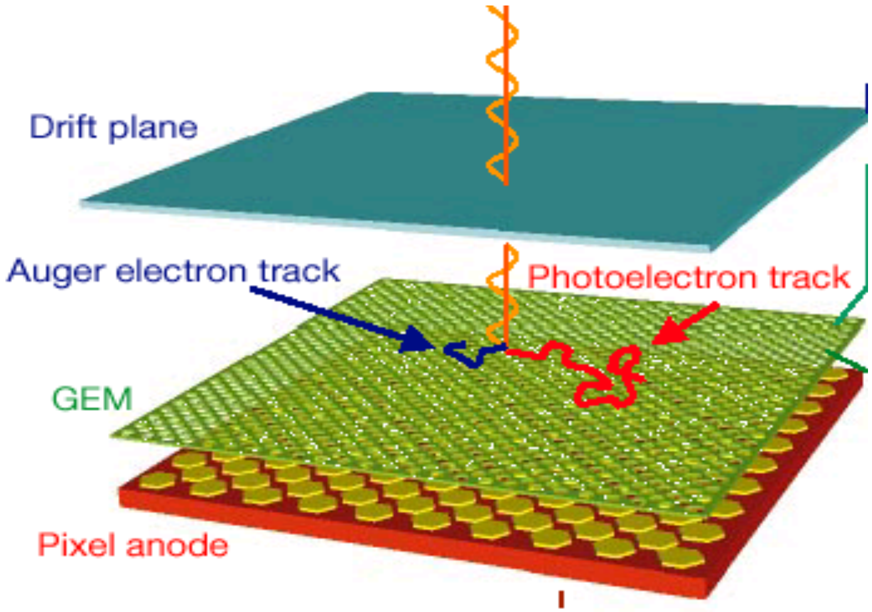


"boring" spectrum & lightcurve,
but interesting/nontrivial polarization spectrum!

==> X-ray polarimeters



X-ray polarization
Measurement:



GEMS: J. Swank, GSFC (PI)

Technical slides:
QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

$$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}^{(\text{plasma})} + \Delta\boldsymbol{\varepsilon}^{(\text{vac})}$$

where $\Delta\boldsymbol{\varepsilon}^{(\text{vac})} \sim 10^{-4}\,(B/B_Q)^2 f(B)$, with $B_Q = 4.4\times10^{13}\,\text{G}$, $f(B) \sim 1$

cf. Gnedin, Pavlov & Shibanov 1978;
Meszaros & Ventura 1978, etc

Vacuum resonance:

$$\Delta\boldsymbol{\varepsilon}^{(\text{plasma})} + \Delta\boldsymbol{\varepsilon}^{(\text{vac})} \sim 0$$

depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

$$\Rightarrow \quad \rho_{\text{vac}} = 1.0\, B_{14}^2\, f(B)^{-1}\, (E/1\ \text{keV})^2\ \text{g cm}^{-3}$$

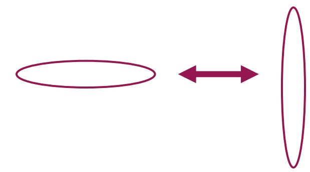
At resonance, X-mode and O-mode are "similar"

Adiabatic Condition:

$$\left| n_1 - n_2 \right| \gtrsim (\cdots) \left| \mathrm{d}\rho/\mathrm{d}r \right|$$

$$\Longrightarrow \quad E \gtrsim E_{\mathrm{ad}} = 2.5\,(\tan\theta_B)^{2/3} \left(\frac{1\,cm}{H}\right)^{1/3} \mathrm{keV}$$

Photons with E > 2 keV, mode conversion



Photons with E < 2 keV, no mode conversion

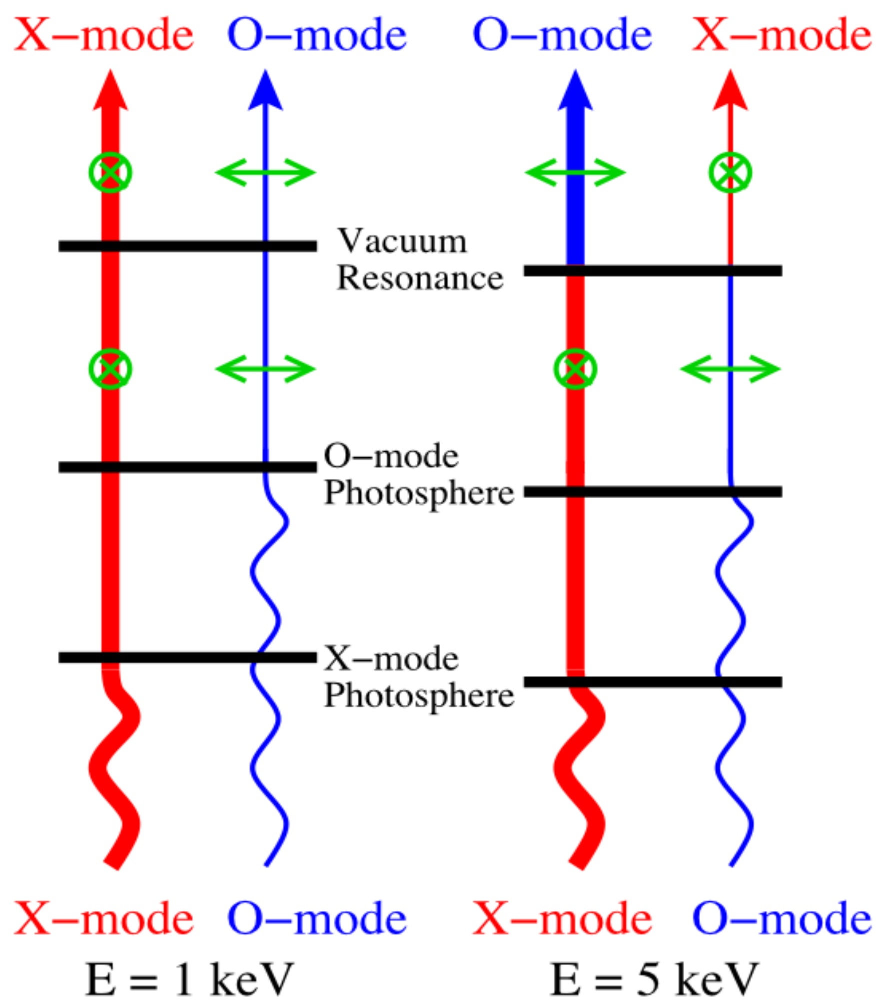
In general, nonadiabatic "jump" probability

$$P_{\mathrm{jump}} = \exp\,[-\,(\pi/2)\,(E/E_{\mathrm{ad}})^3]$$

(Landau-Zener formula)

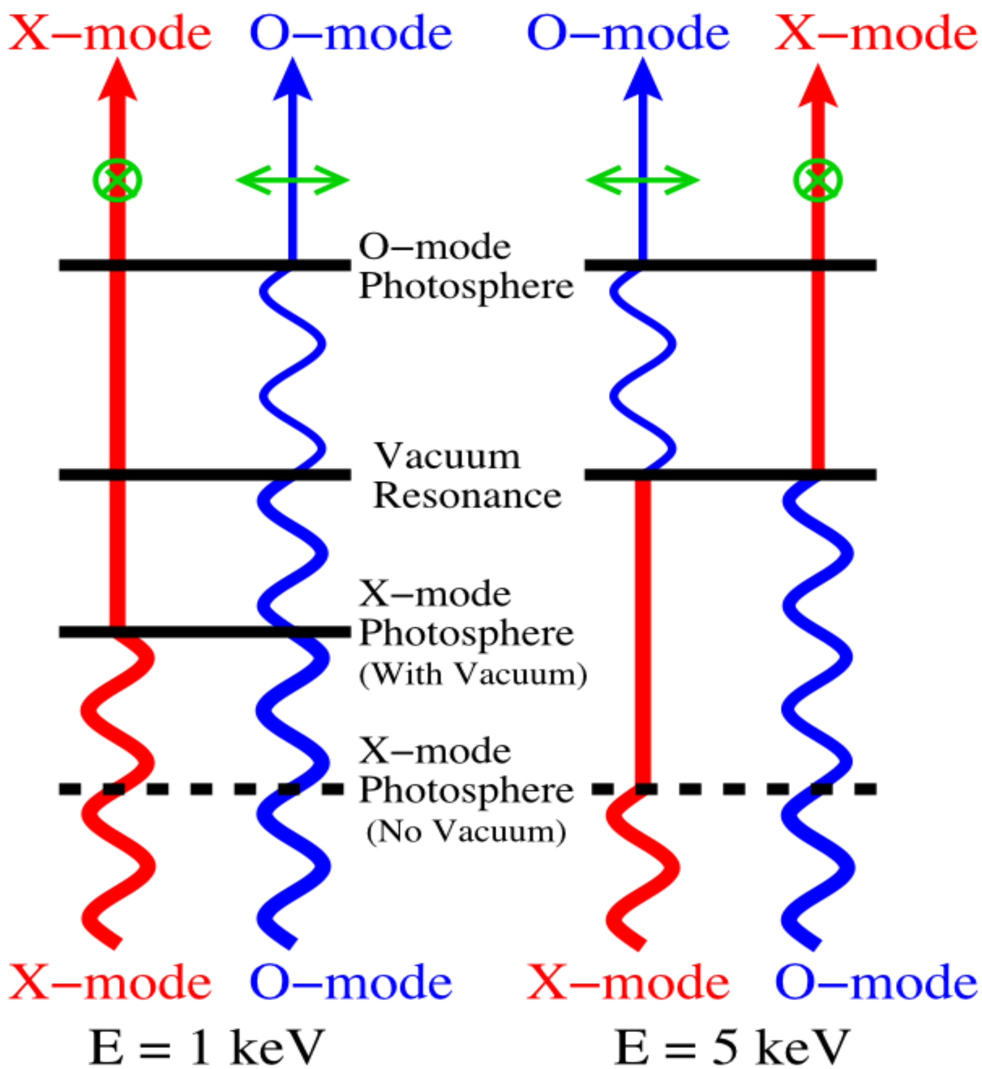
For B < $7\times10^{13}\, T_6^{-1/8}\, E_1^{-1/4}$ G:

Vacuum resonance lies outside both photospheres



For B > $7\times10^{13}\,T_6^{-1/8}\,E_1^{-1/4}$ G:

Vacuum resonance lies between the two photospheres



Highlight #3:
Matter in Strong Magnetic Fields

Critical Field:

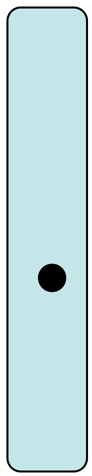
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

Strong field: $B \gg B_0$

Property of matter is very different from zero-field

Atoms and Molecules

Strong B field significantly increases the binding energy of atoms



For $b = \dfrac{B}{B_0} \gg 1, \quad B_0 = 2.35 \times 10^9 \text{ G}$

$$|E| \propto (\ln b)^2$$

E.g. $|E| = 160 \text{ eV}$ at 10^{12}G

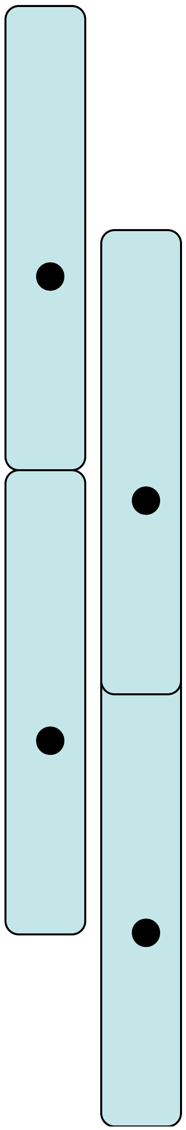
$|E| = 540 \text{ eV}$ at 10^{14}G

Atoms combine to form molecular chains:

E.g. $H_2, H_3, H_4, \ldots$

Condensed Matter

Chain-chain interactions lead to formation of 3D condensed matter



Binding energy per cell $|E| \propto Z^{9/5} B^{2/5}$

Zero-pressure density

$$\simeq 10^3 A Z^{3/5} B_{12}^{6/5} \text{ g cm}^{-3}$$

Cohesive energy of condensed matter:

- Strong B field increases the binding energy of atoms and condensed matter

For $b = \dfrac{B}{B_0} \gg 1, \quad B_0 = 2.35 \times 10^9 \text{ G}$

Energy of atom: $\sim (\ln b)^2$

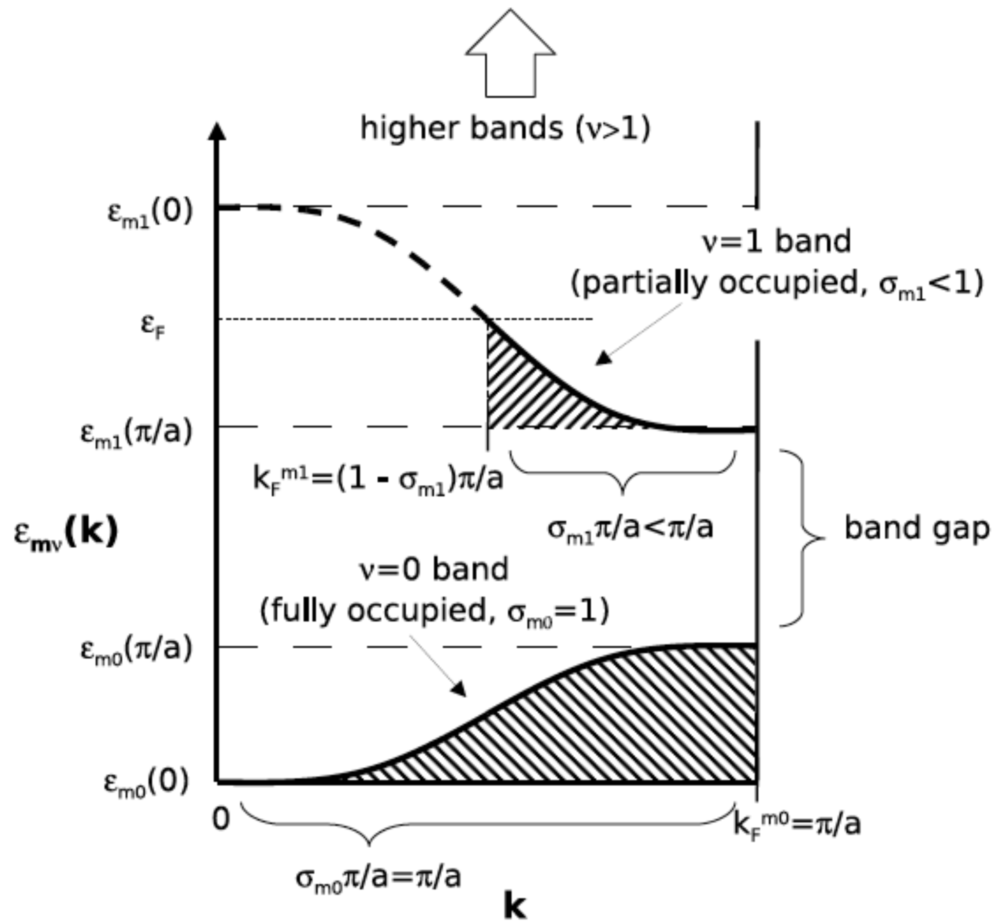
Energy of zero-pressure solid: $\sim b^{0.4}$

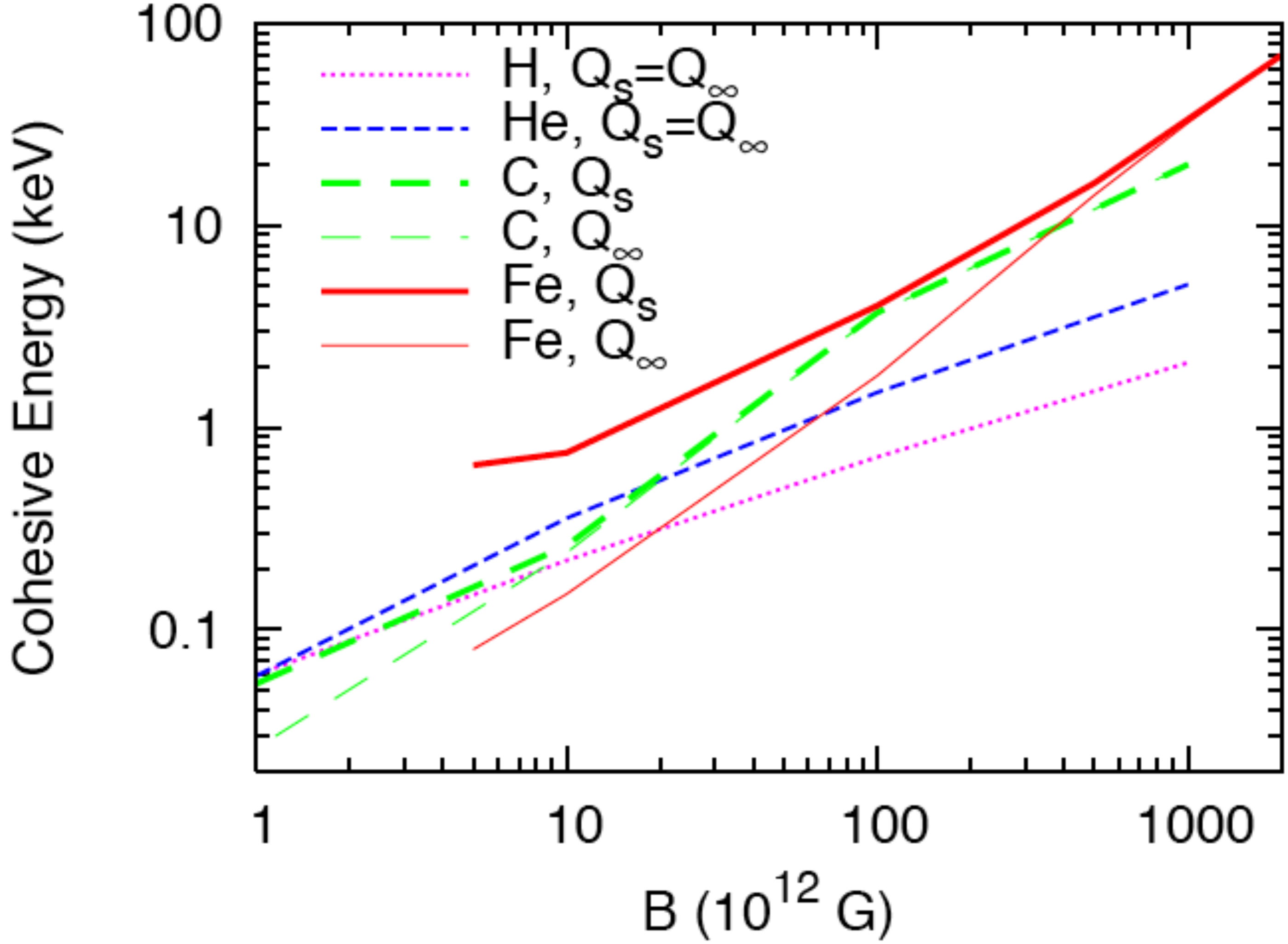
==> **Expect condensed solid to have large cohesive energy**

- Quantitative Calculations are needed …

New calculations (Zach Medin & DL 2007)

- Density functional theory
- Accurate exchange-correlation energy
- Accurate treatment of band structure
- Extend to $\sim 10^{15}$G





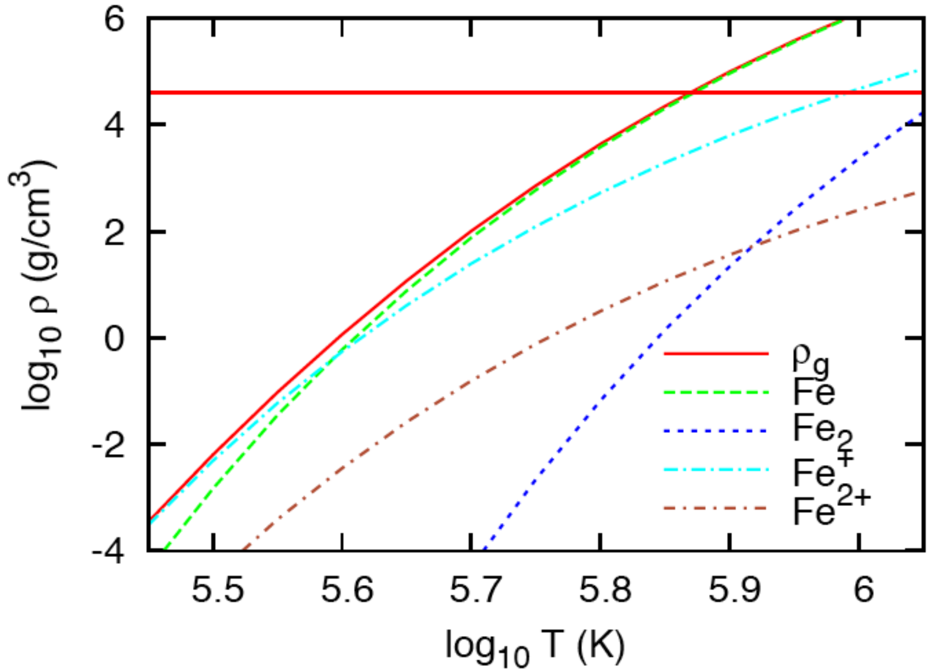
Cohesive Energy (keV)
B (10^{12} G)
100
10
1
0.1
1
10
100
1000
H, Q_s=Q_∞
He, Q_s=Q_∞
C, Q_s
C, Q_∞
Fe, Q_s
Fe, Q_∞

Implications…

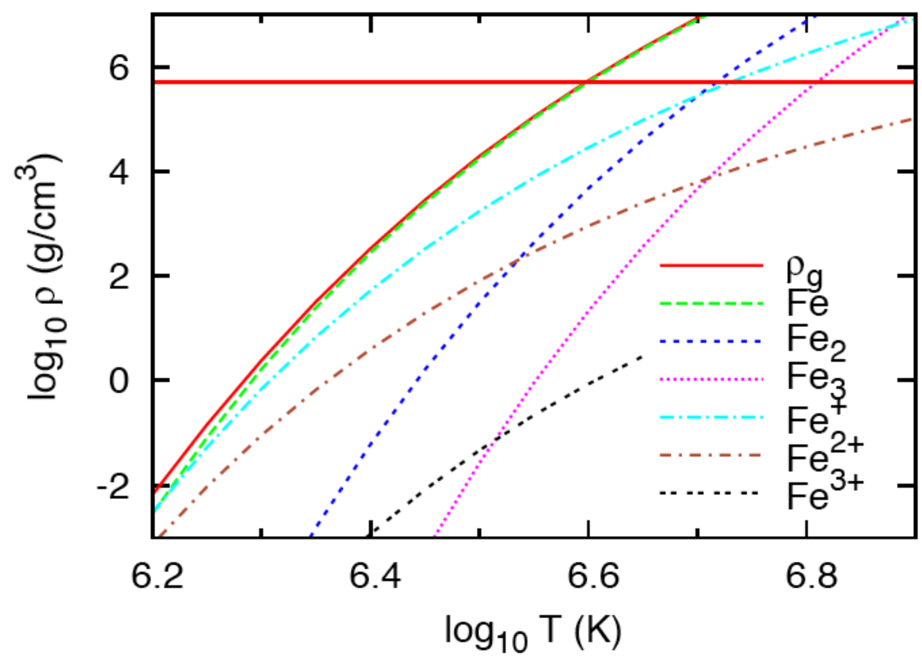
Surface condensation of isolated NSs

Saturated Vapor of Condensed NS Surface:

Fe at 10^{13}G



Fe at 10^{14}G

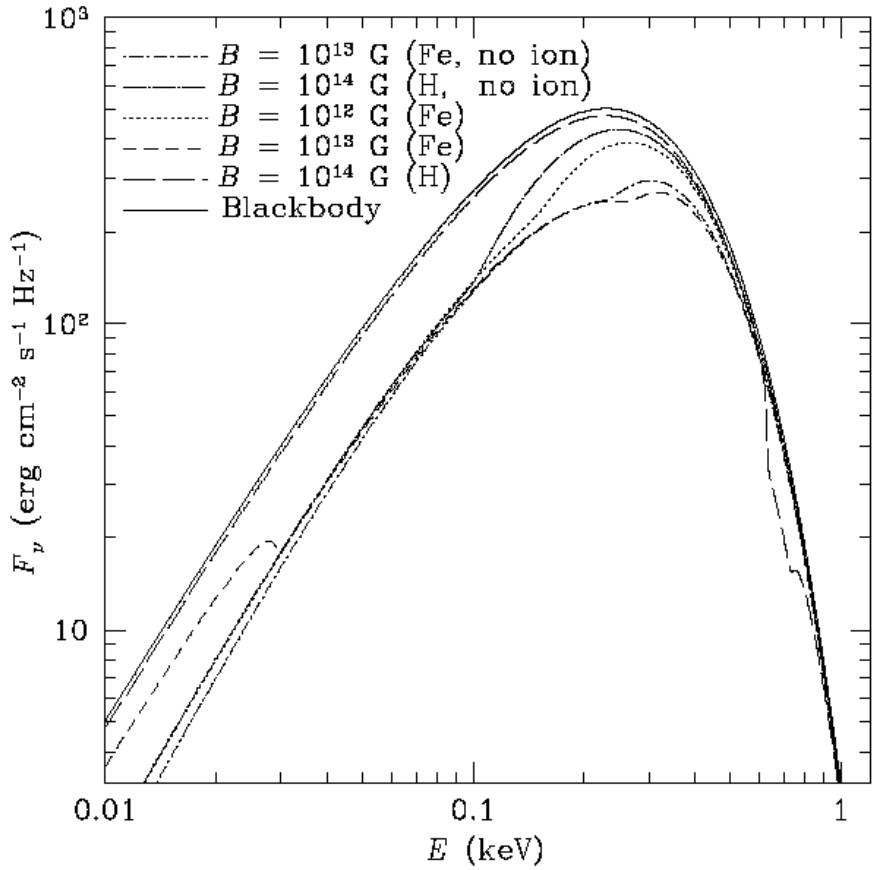


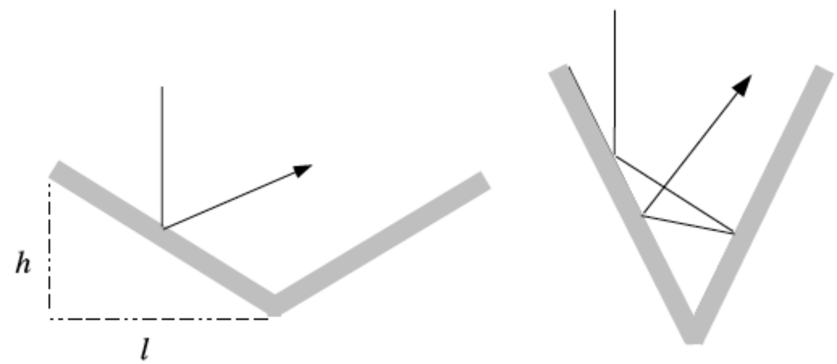
Zach Medin & DL 2007

For a given B, below T_{crit}(B),
NS surface is in condensed form (with little vapor above)

Emission from condensed NS surface resembles a featureless blackbody

Reflectivity R_E Emission $I_E=(1-R_E)B_E(T)$





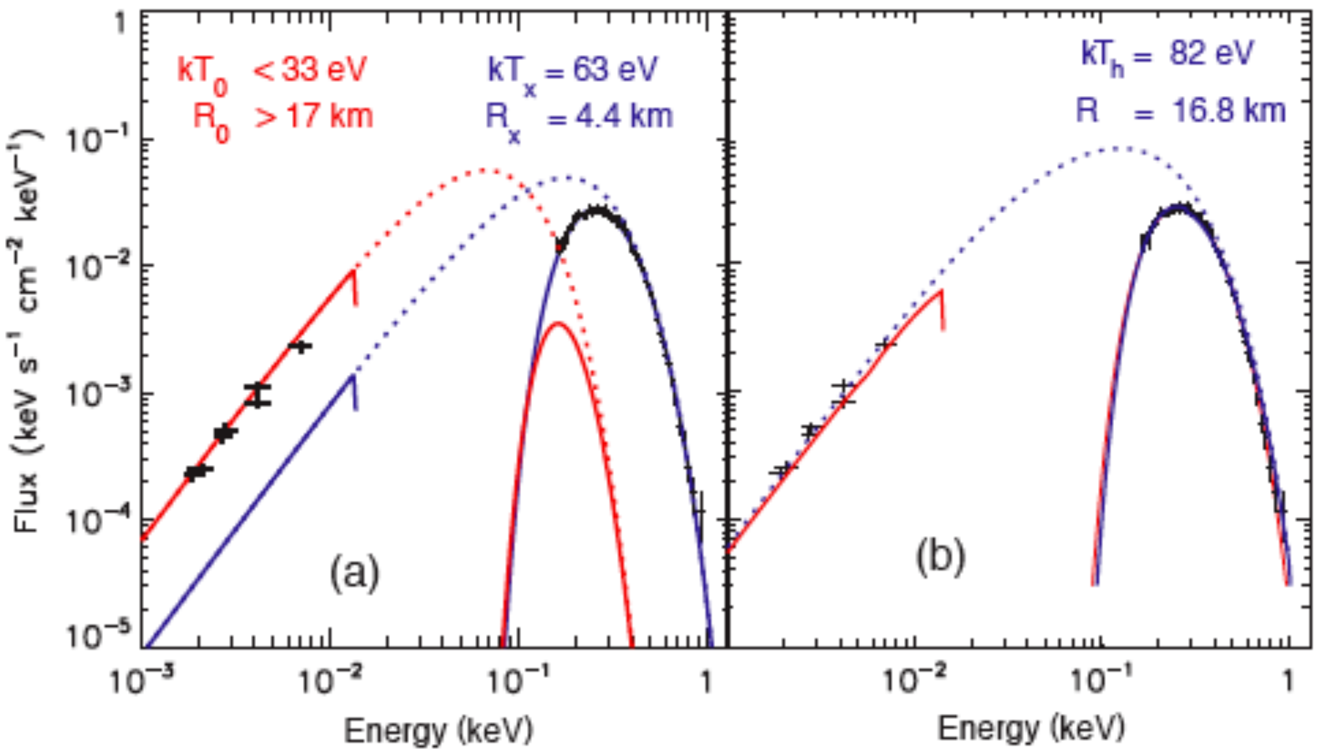
van Adelsberg, Lai, Potekhin & Arras 05

Thermally Emitting Isolated NSs

“Perfect” X-ray blackbody:

RX J1856.5-3754

(T ~ 60 eV)



Burwitz et al. 03, Trumper et al 04

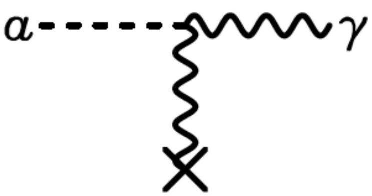
May be explained by emission from condensed surface

Highlight #4:
Probing Axions with Magnetic NSs

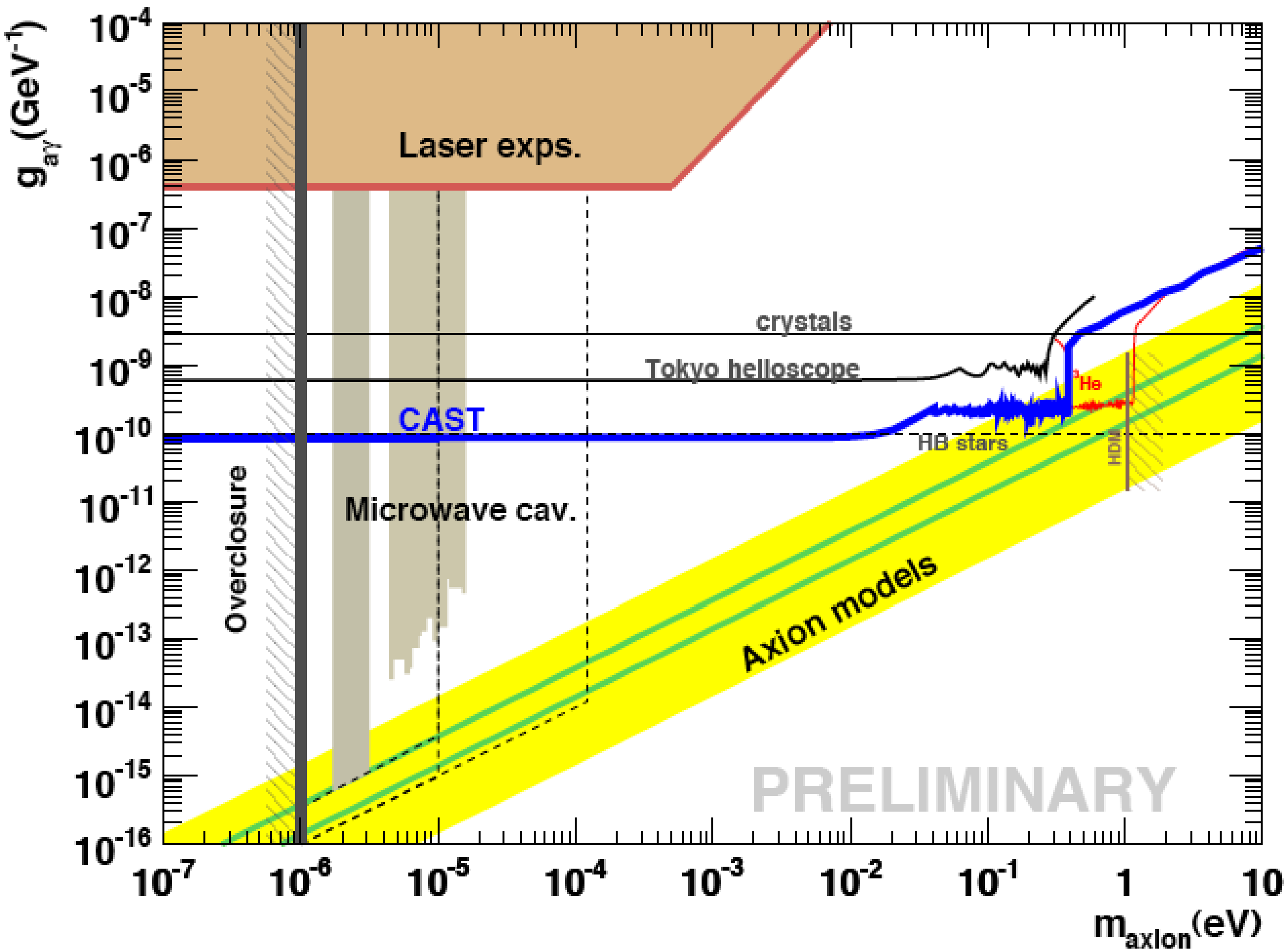
Axions: pseudoscalar particles, arise in the Peccei-Quinn solution of the strong CP problem; could be dark matter candidates

Can be produced or detected through the **Primakoff process:**

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\ \mathbf{E}\cdot\mathbf{B}\, a$$



Current constraints on axion mass and coupling parameter



arXiv:0810.1874 (CAST collaboration)

Photon-Axion Conversion in Magnetic Neutron Stars

In the magnetized plasma of NSs, photons (//-polarization component) can convert (resonantly a la MSW) into axions

===> modify radiation spectra and polarization signals

DL & Heyl 2007; Perna et al. 2011