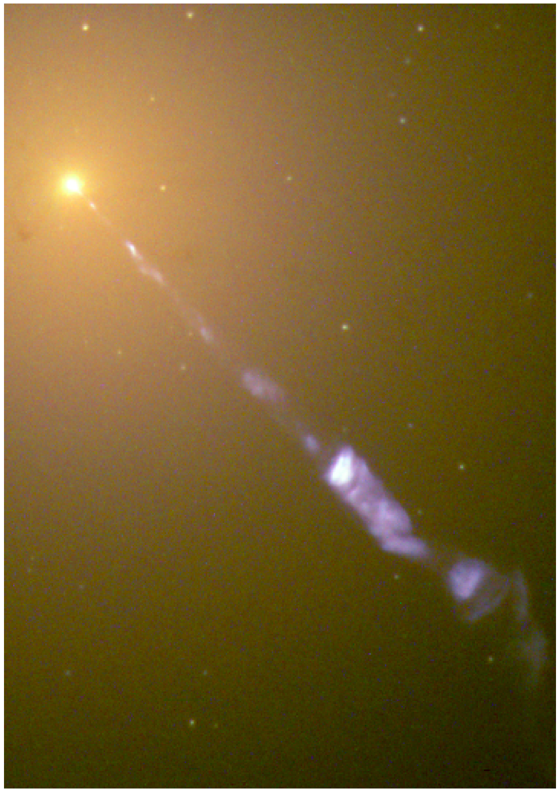
Probing Extreme Physics with Compact Objects



Dong Lai

Department of Astronomy
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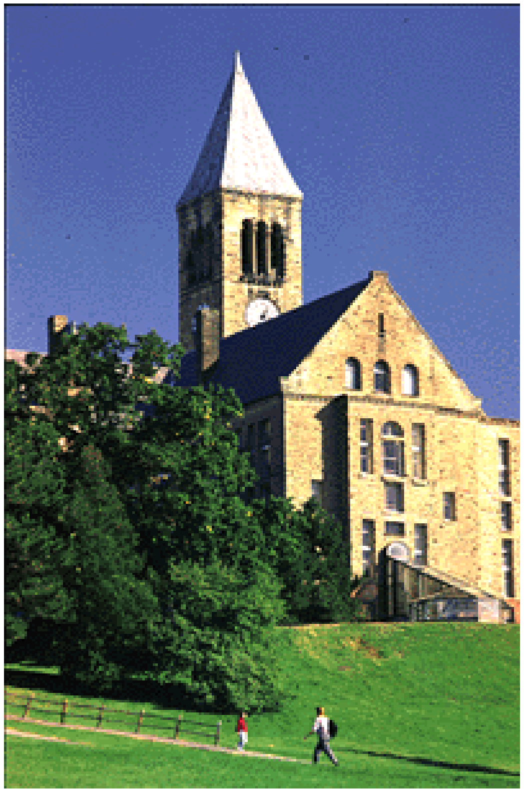

IV Workshop Challenges of New Physics in Space
Camps do Jordao - SP, Dec.11-16, 2011

“Extremes” in Astrophysics:

- Most energetic particles: 10^{20} eV
- Most energetic photons: 10^{14} eV
- Highest temperature: Big Bang
- Highest density: neutron stars
- Strongest magnet: magnetars
- Strongest gravity: black holes
-
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“Extremes” in Astrophysics:

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- Highest temperature: Big Bang
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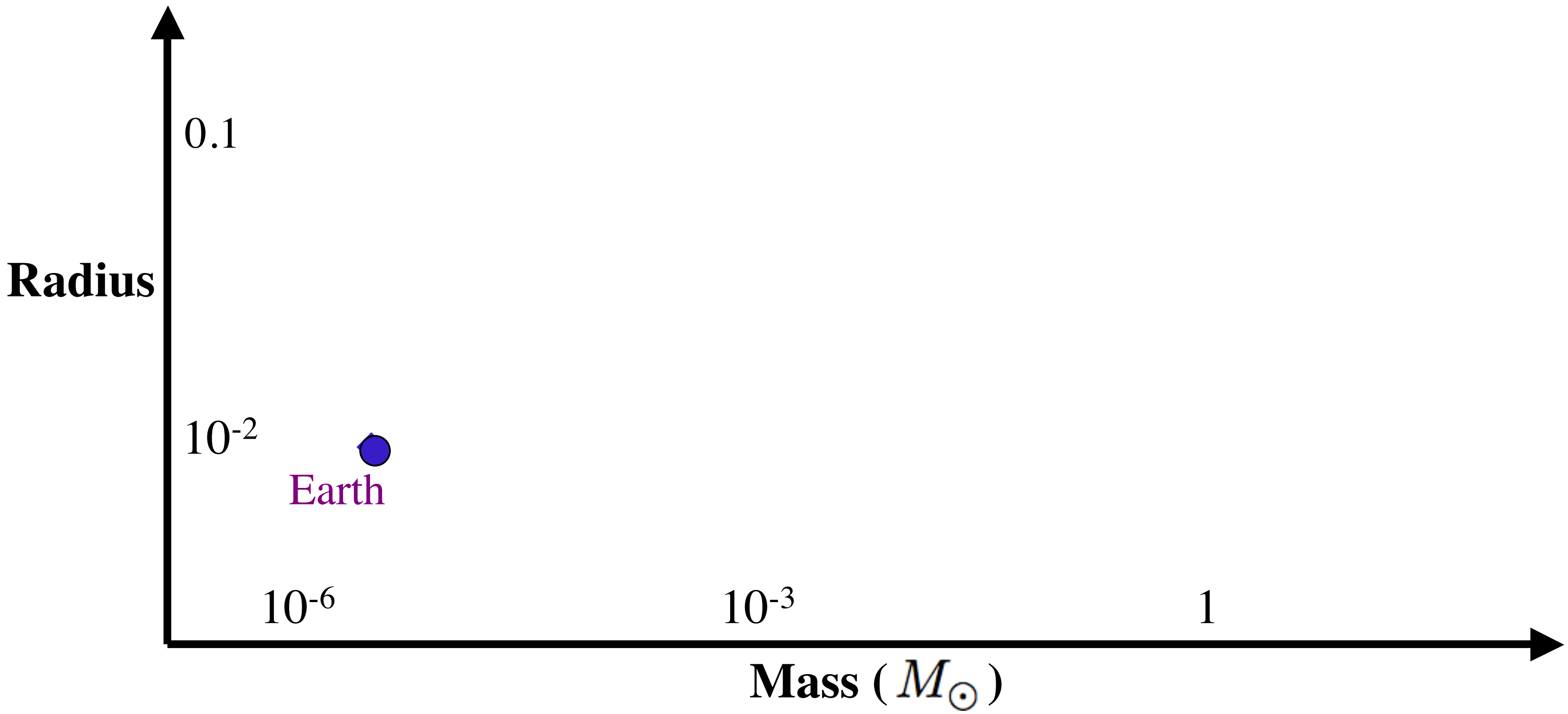
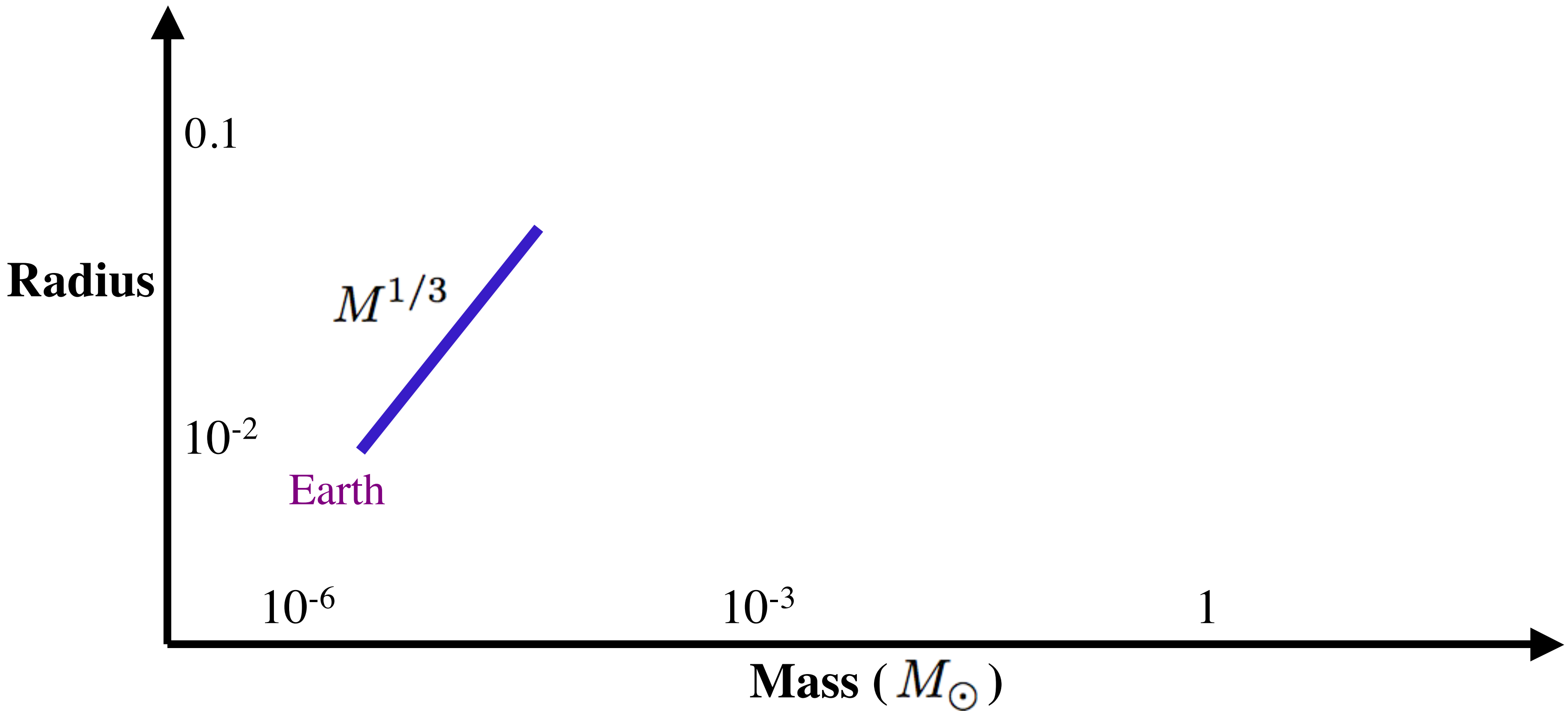
Focus of my lectures:

Compact Objects (White Dwarfs, Neutron Stars and Black Holes)

A thought experiment: Adding mass (slowly) to Earth …



A thought experiment: Adding mass (slowly) to Earth …



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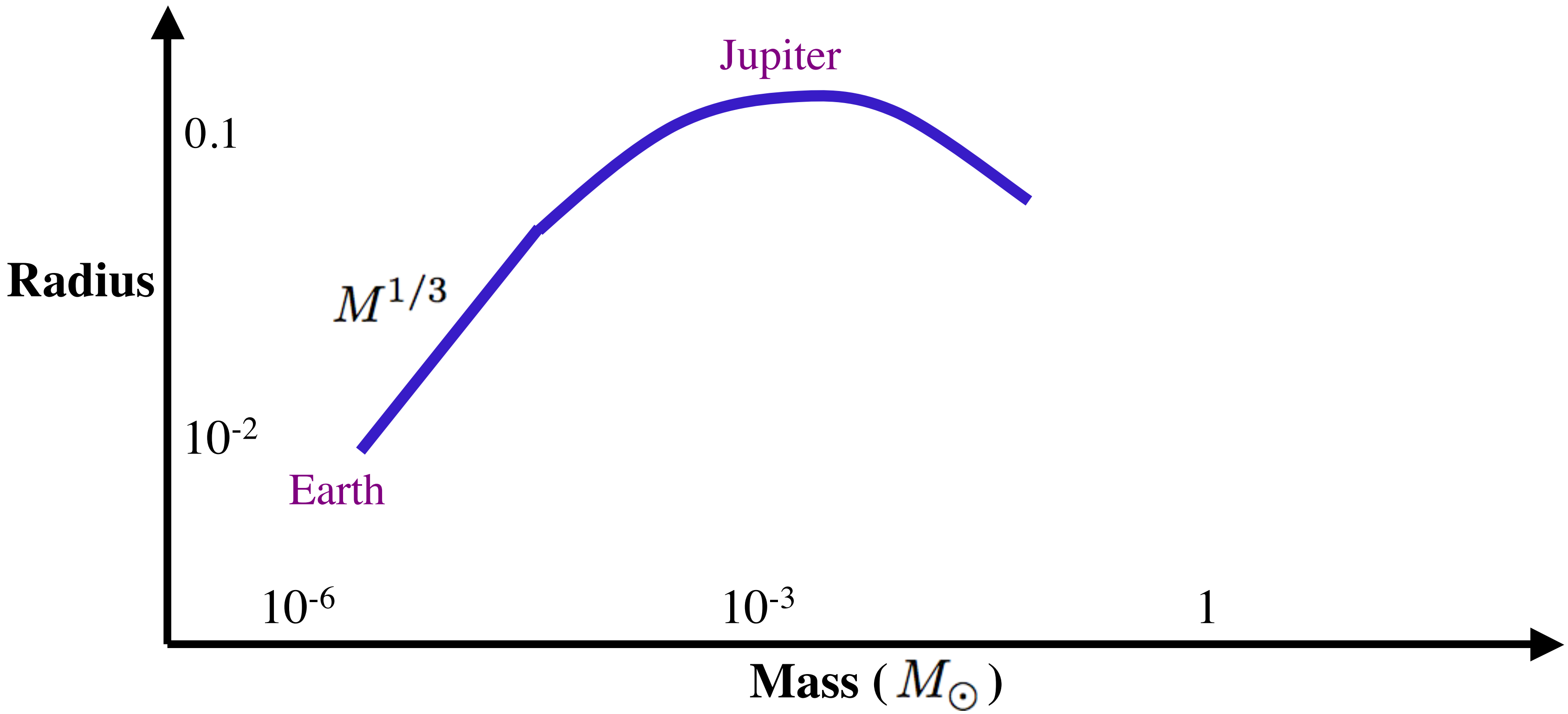
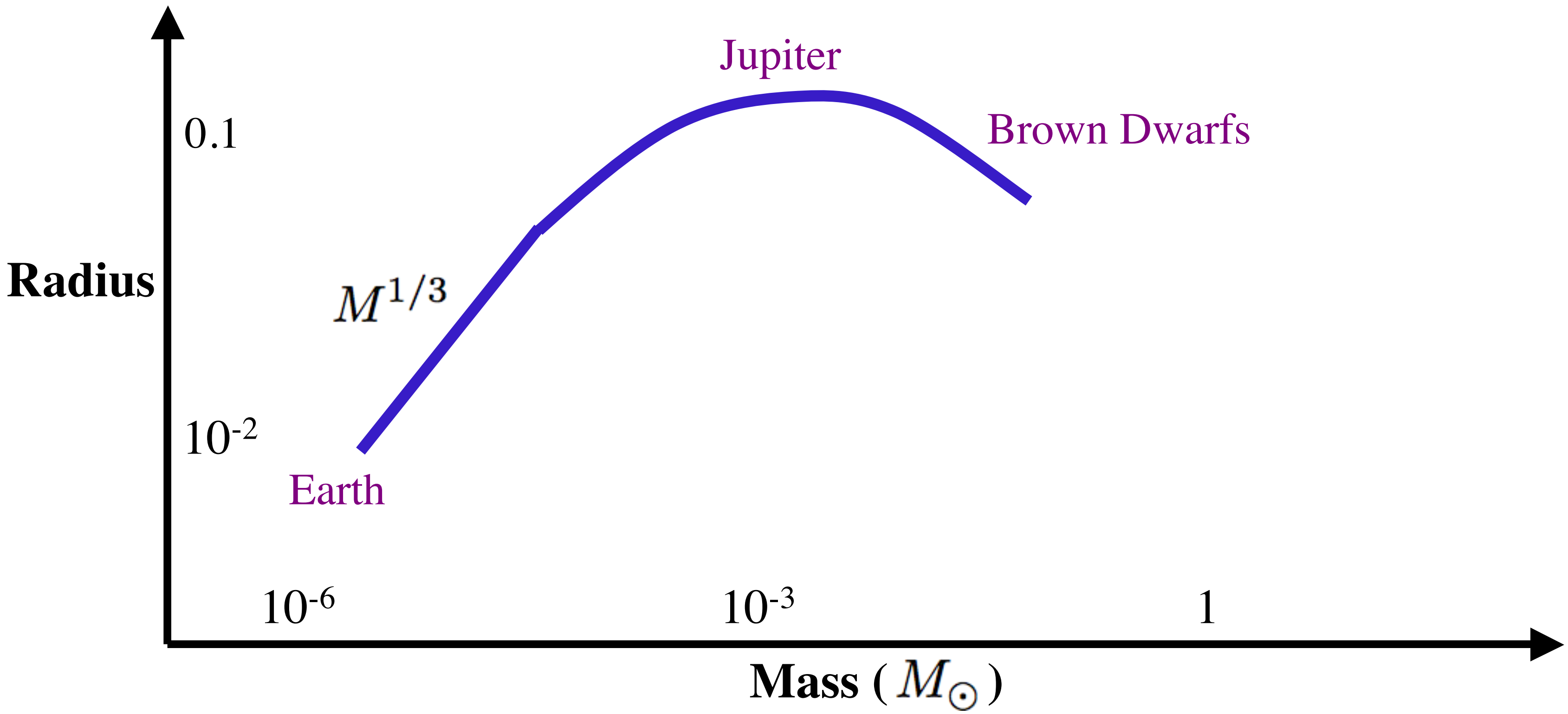


$$\frac{GMm_p}{R} \sim \frac{e^2}{r_i}, \quad R \sim \left(\frac{M}{m_p}\right)^{1/3} r_i \quad \Longrightarrow \quad M_J \sim \left(\frac{e^2}{Gm_p^2}\right)^{3/2} m_p \simeq 10^{-3} M_\odot$$

A thought experiment: Adding mass (slowly) to Earth …



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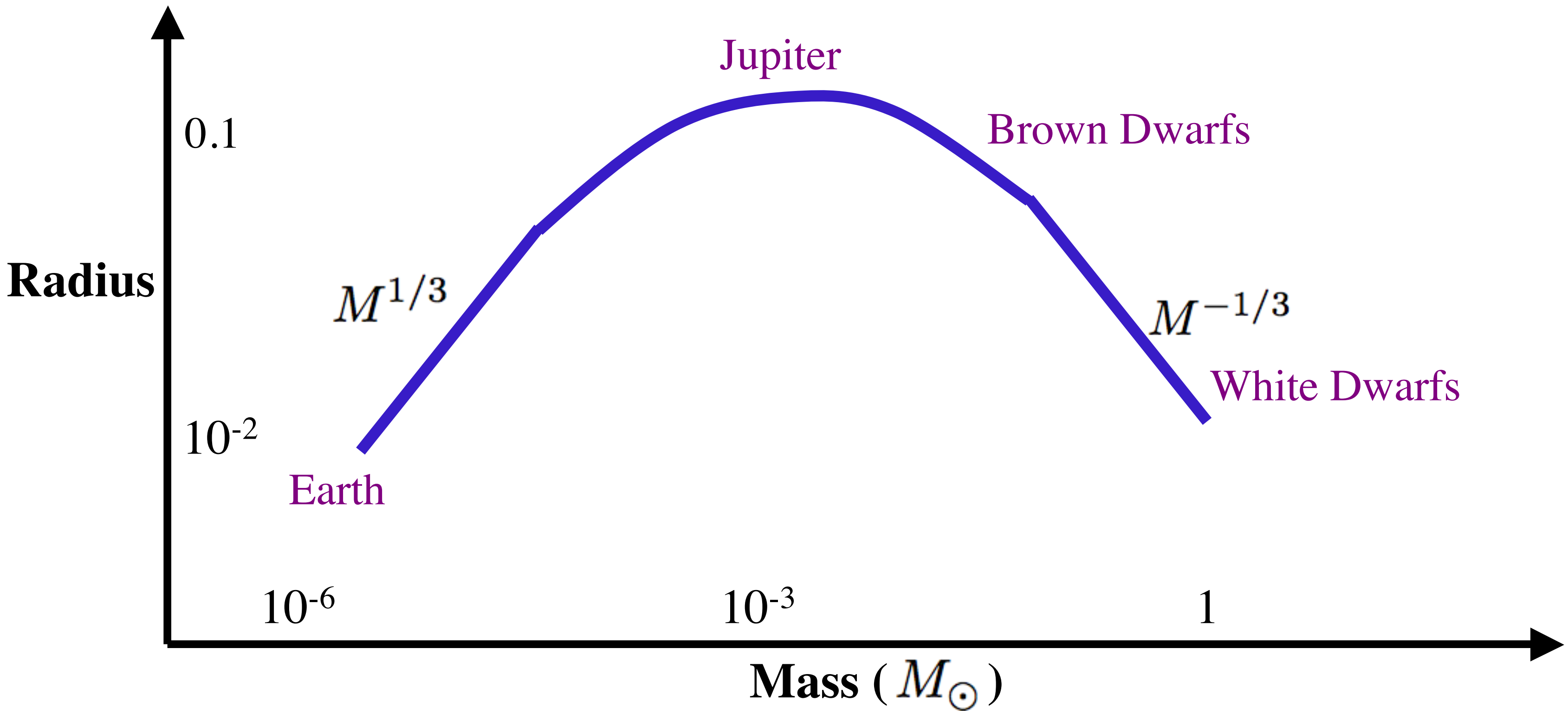
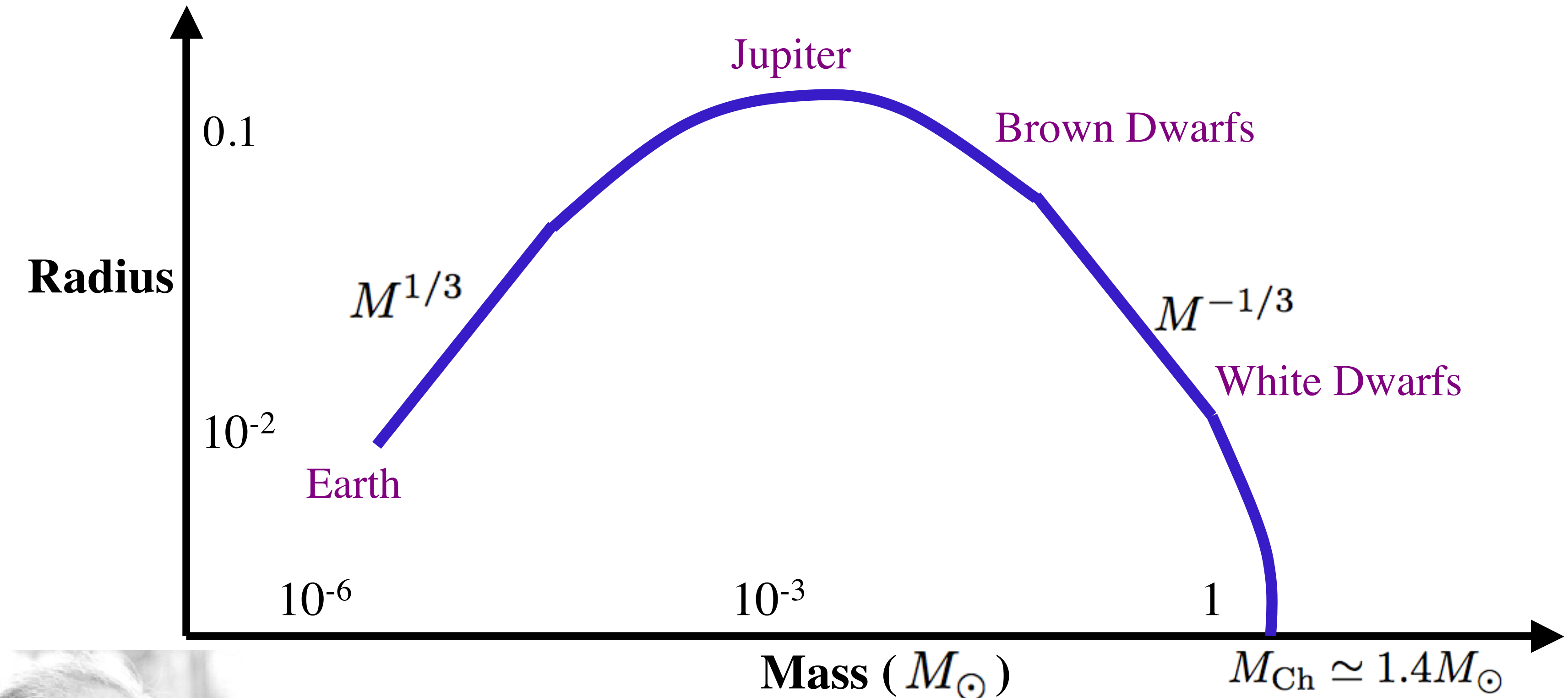
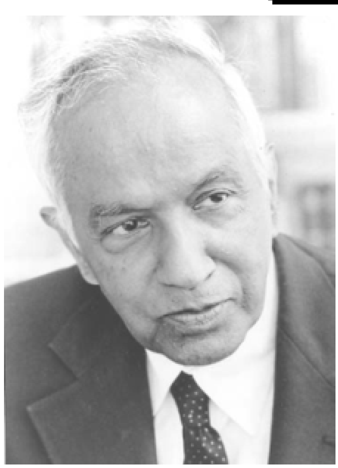


$$p \sim \frac{\hbar}{r_i}, \quad \frac{p^2}{2m_e} \sim \frac{GMm_p}{R}, \quad R \sim \left(\frac{M}{m_p}\right)^{1/3} r_i \quad \Longrightarrow \quad R \propto M^{-1/3}$$

A thought experiment: Adding mass (slowly) to Earth …





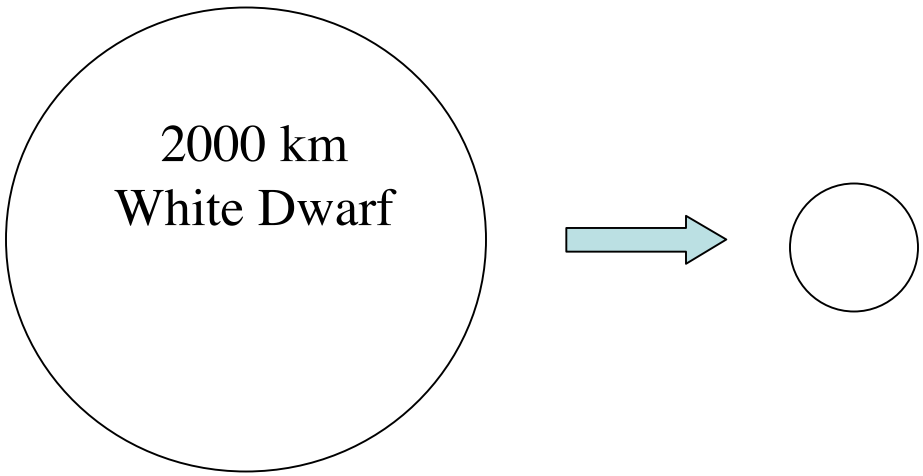
(1910-1995)

Chandrasekhar mass:

$$p \sim \frac{\hbar}{r_i}, \quad pc \sim \frac{GMm_p}{R}, \quad R \sim \left(\frac{M}{m_p}\right)^{1/3} r_i \quad \Longrightarrow M_{\rm Ch} \sim \left(\frac{Gm_p}{\hbar c}\right)^{-3/2} m_p$$

$$\simeq 1.4 M_\odot \quad \text{for C, O, Fe}$$

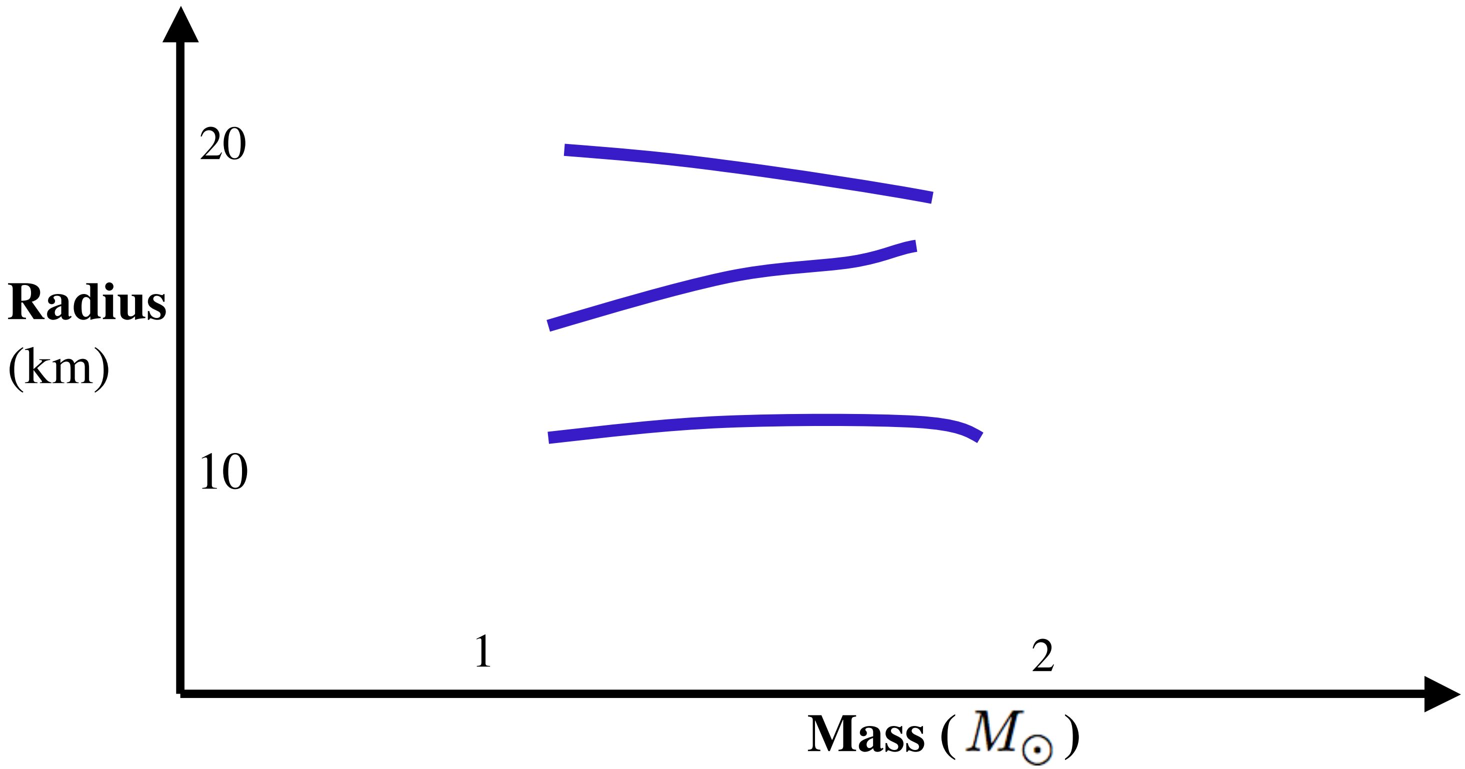
Adding mass to a white dwarf: What happens when its mass exceeds the Chandrasekhar limit?



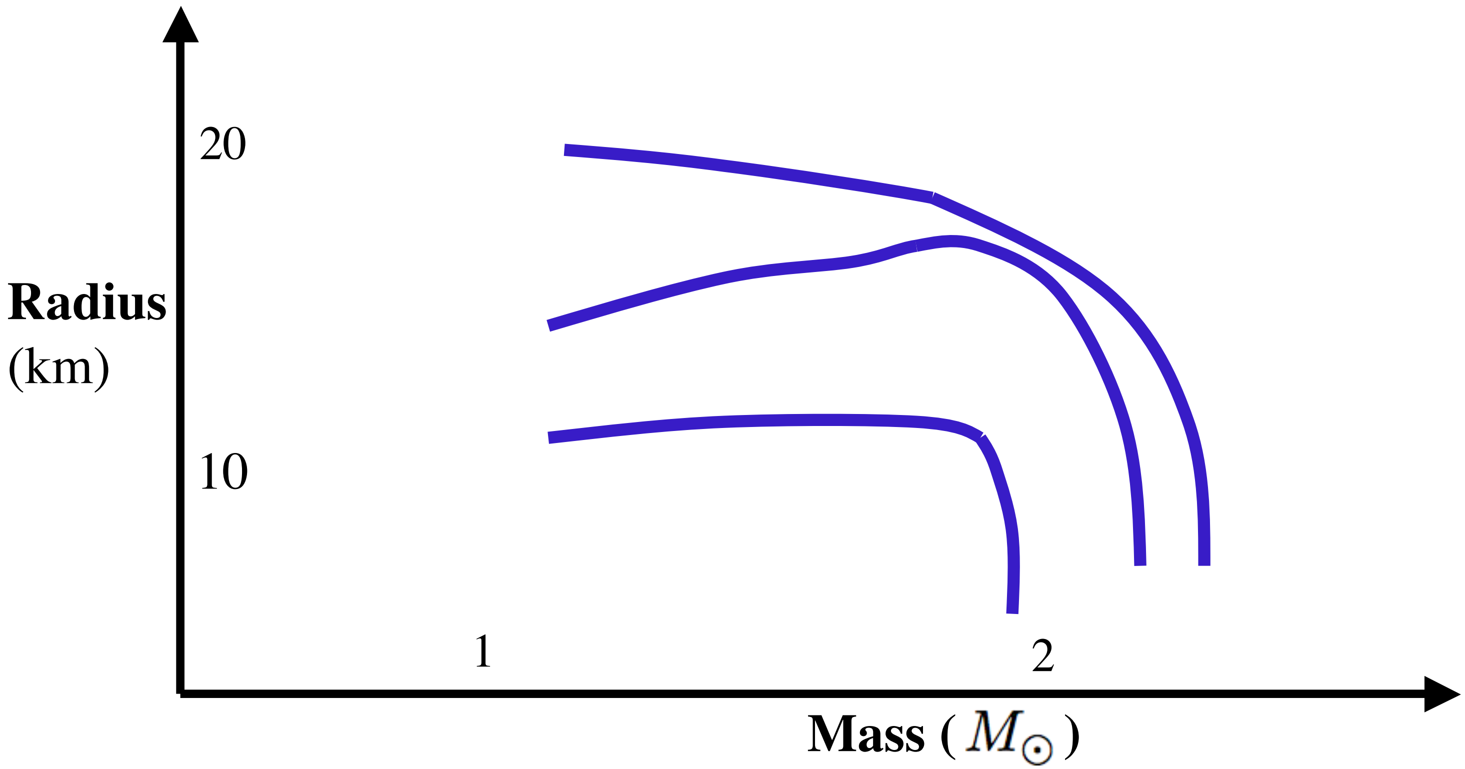
10-20 km
Neutron Star

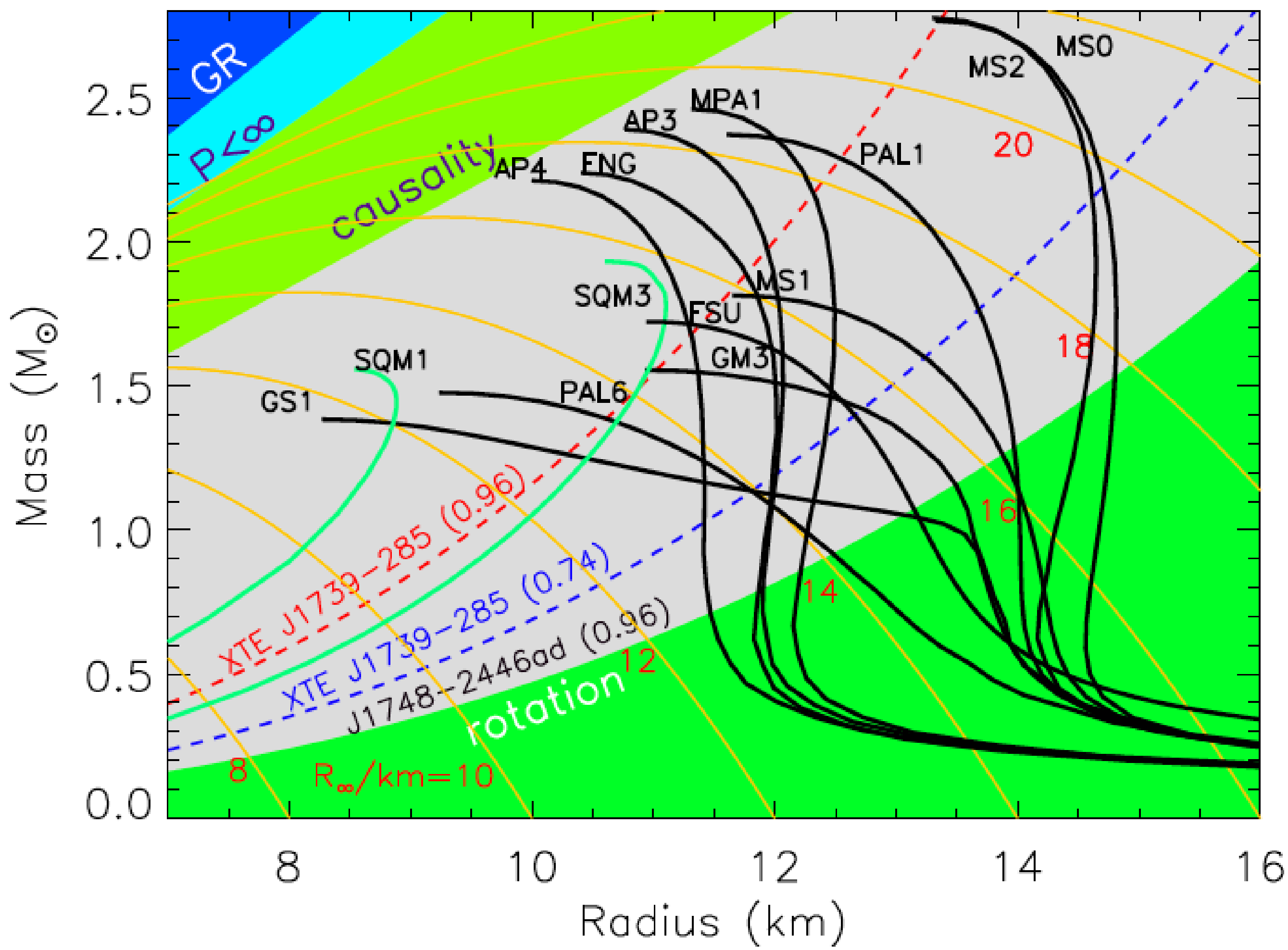
$\rho \sim$ a few $\times\, 10^{14}$ g cm^{-3}

Adding mass to a Neutron Star …



Adding mass to a Neutron Star …





Lattimer & Parkash 06

Observed $M_{\rm max} = (1.97 \pm 0.04) M_\odot$ (PSR J1914-2230)

(Demorest et al. 2010)

Why is there a maximum mass for neutron stars?

Force balance in a star:
(Newtonian)

Pressure balances **Gravity <-- M**

Why is there a maximum mass for neutron stars?

Force balance in a star:
(General relativity)

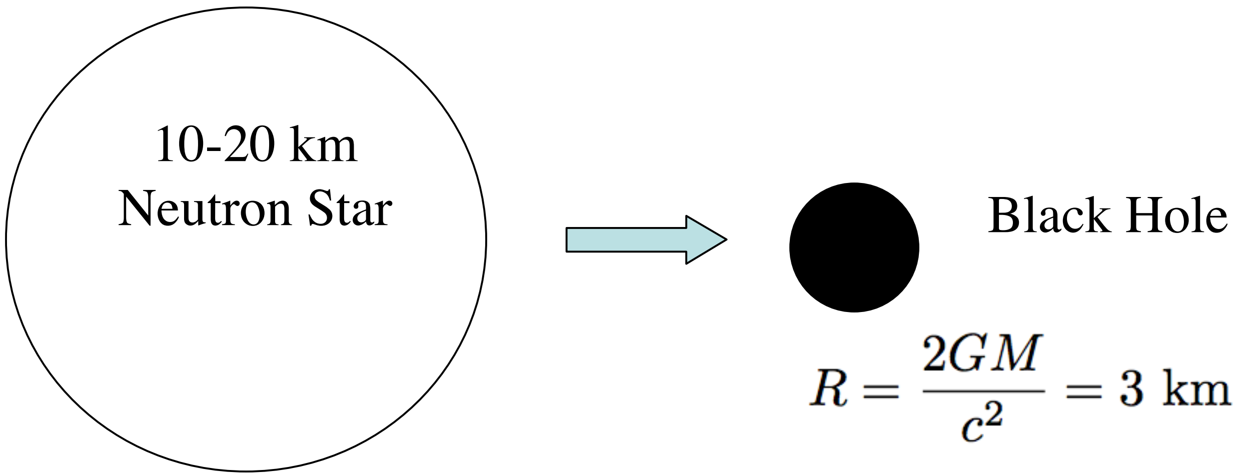
Pressure balances **Gravity <-- M, Pressure**

===> Tolman-Oppenheimer-Volkoff Limit

Tolman-Oppenheimer-Volkoff Equation:

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\rho(r)}{r^2}\left[\frac{\left(1 + P/\rho c^2\right)\left(1 + 4\pi r^2 P/mc^2\right)}{\left(1 - 2Gm/rc^2\right)}\right]$$

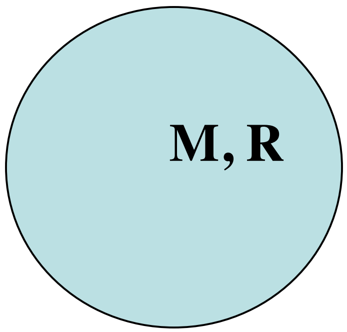
Keep adding mass to a neutron star:
What happens when its mass exceeds the maximum mass?



$$R = \frac{2GM}{c^2} = 3 \text{ km} \left(\frac{M}{1 \ M_\odot} \right)$$

First demonstrated by
Oppenheimer & Snyder (1939)

“Dark Star” Concept: John Michell (1783) Pierre Laplace (1795)



Escape velocity: $$v_{\rm esc} = \left(\frac{2GM}{R}\right)^{1/2}$$

$$v_{\rm esc} = c \quad \Longrightarrow$$

$$R = \frac{2GM}{c^2} = 3 \text{ km} \left(\frac{M}{1\ M_\odot}\right)$$

- **Although “correct” answer, derivation and interpretation are wrong.**

“Black Hole” Concept:

- **Einstein (1915): General Relativity**

  Gravity is not a force, but rather it manifests as curvature of spacetime caused by matter and energy

  Ensiten field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

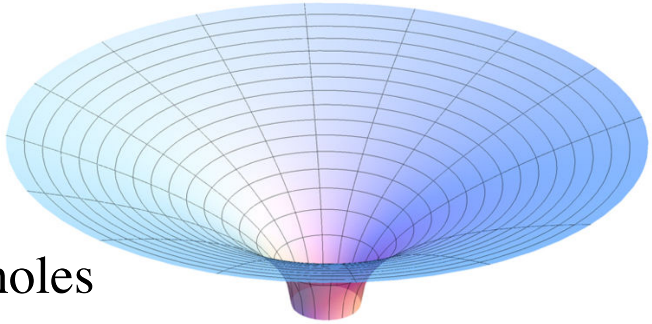
- **Karl Schwarzschild (1916):**

  The first exact solution to Einstein field equation

$$ds^2 = \left(1 - \frac{R_S}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{R_S}{r}} - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right)$$

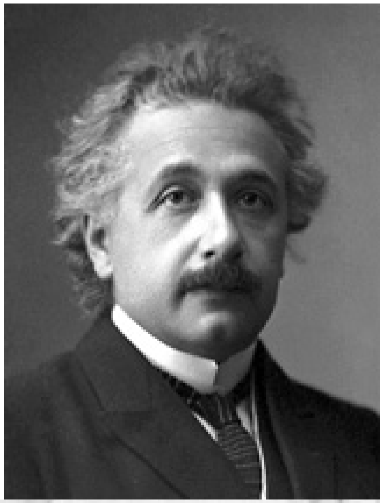
The horizon radius (Schwarzschild radius):

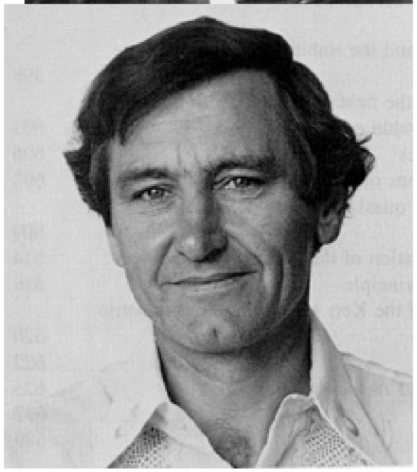
$$R_S = \frac{2GM}{c^2}$$



- **Roy Kerr (1963):**

  Solution for spinning black holes



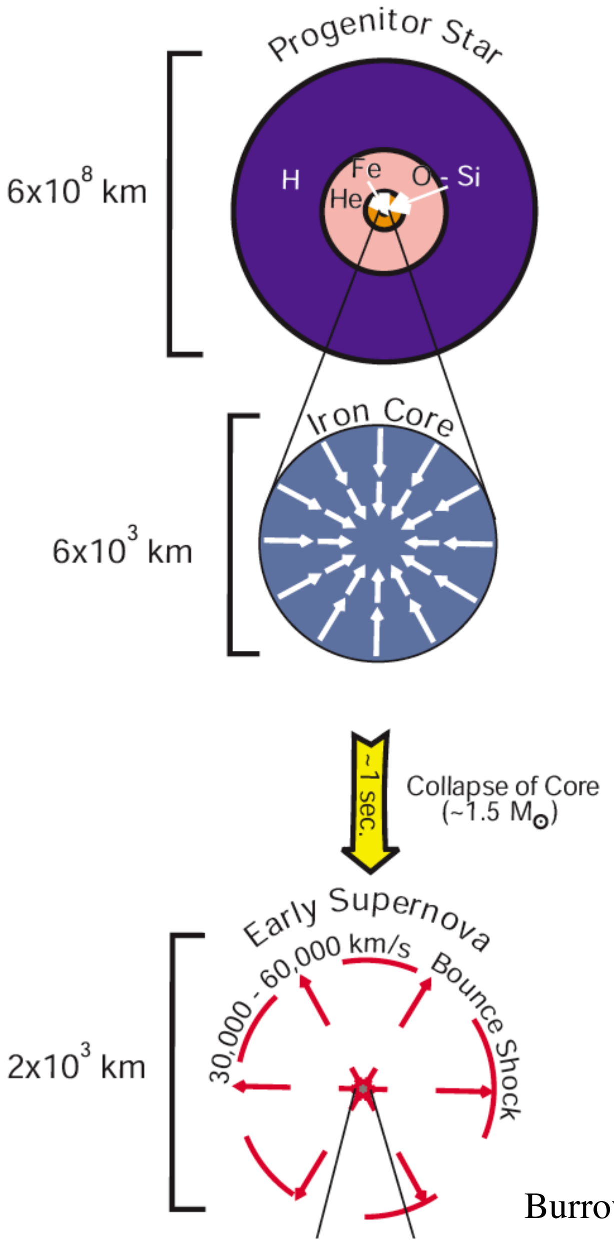


Formation of Compact Objects in Astrophysics

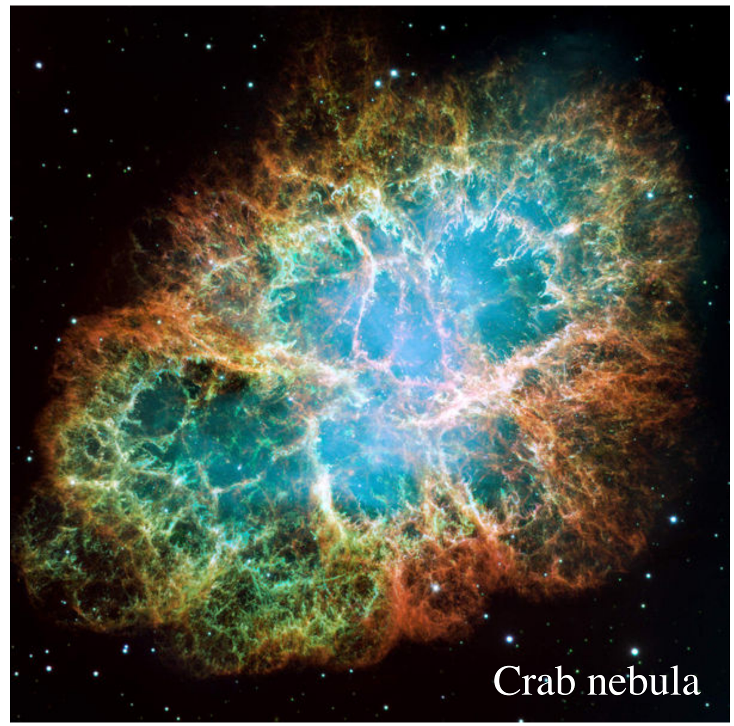
White dwarfs evolve from stars with M $\lesssim$ 8 Sun …

NGC 2392, the Eskimo Nebula (HST)

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



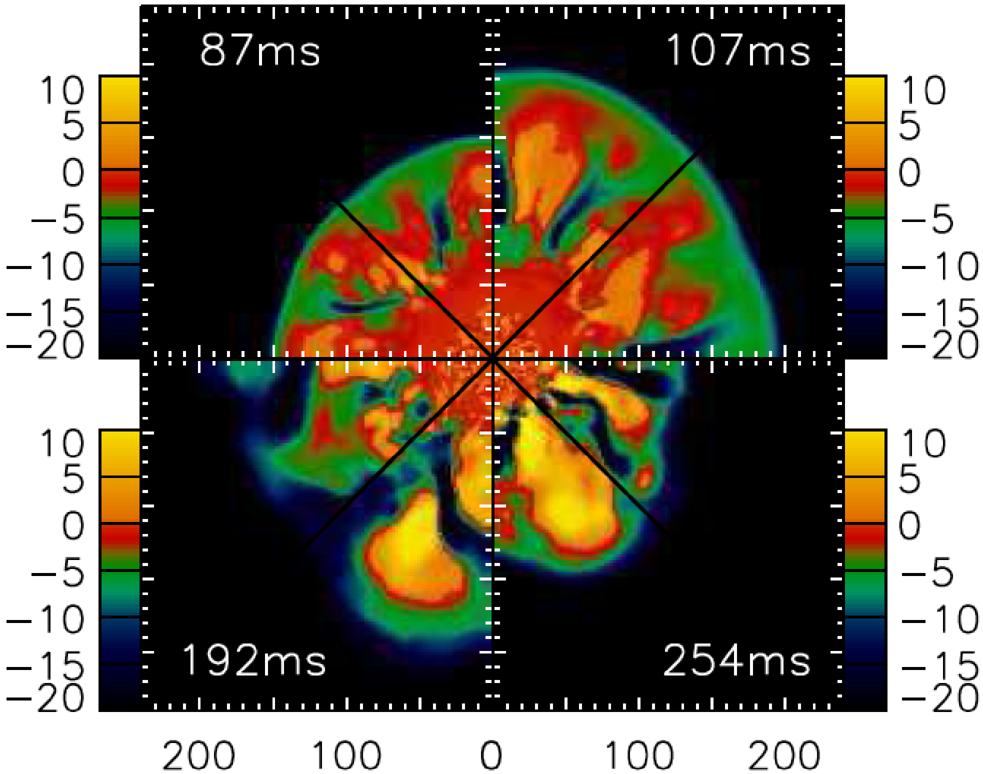
Burrows 2000



Crab nebula

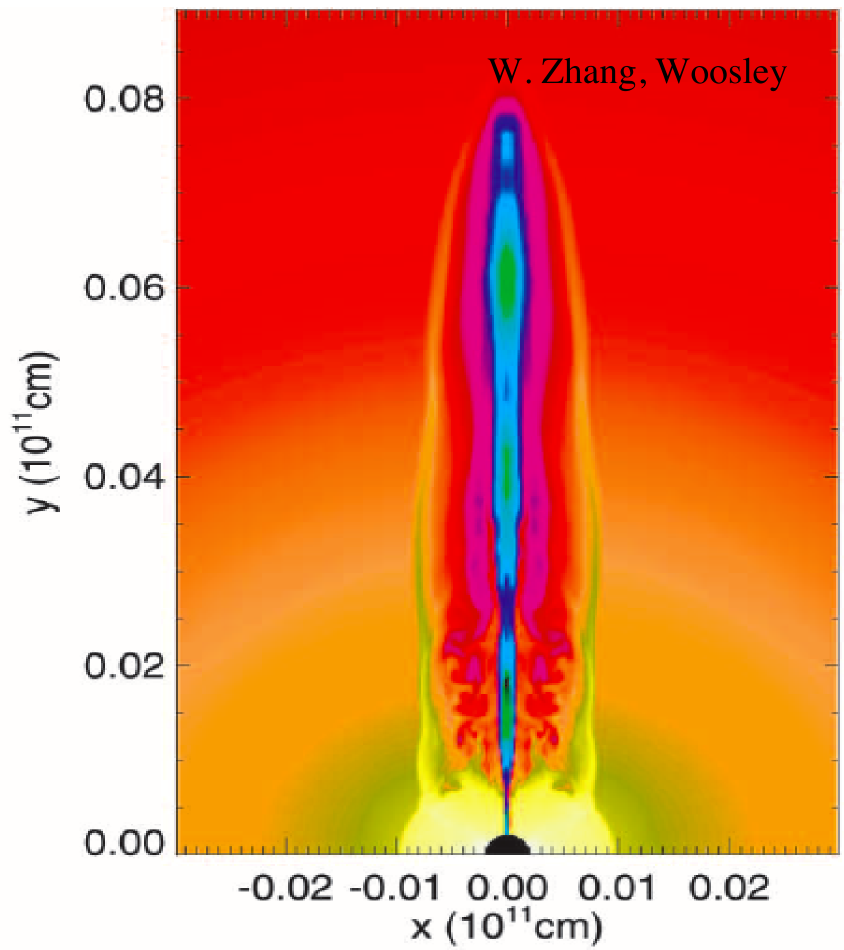
Black Holes evolve from stars with M ≳ 30 (?) Sun …

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



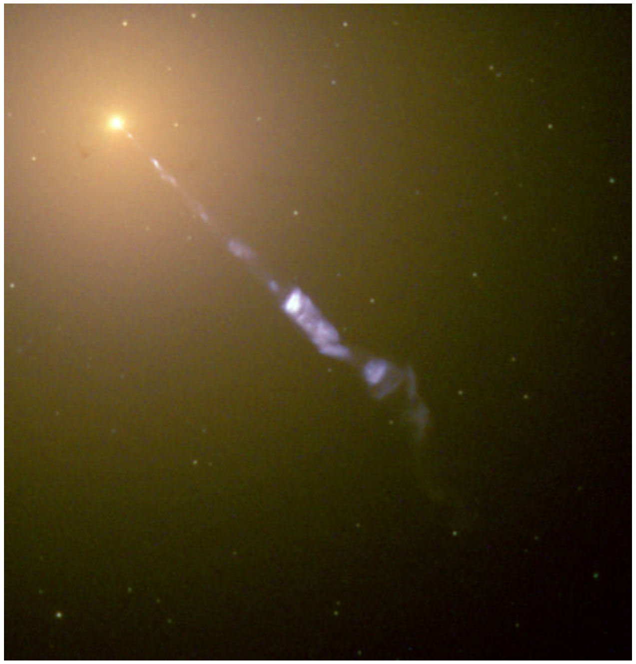
H-T Janka;
See O'Connor & Ott 2011

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



Supermassive Black Holes (10^6-10^{10} Sun)

- Have been found at the center of most galaxies.
  Responsible for violent activities associated with AGNs and Quasars (e.g., relativistic jets)
- Not really compact: mean density with the horizon ~ 1 g/cm^3 for $M=10^8$ Sun



- How do supermassive BHs form?
  --- Merger of smaller black holes in galaxy merger
  --- Collapse of supermassive stars followed by gas accretion

Intermediate-Mass BHs (~10^2-10^4 sun) ?

Tentative evidence : Ultra-Luminous X-ray Sources

Compact Objects Research Today…

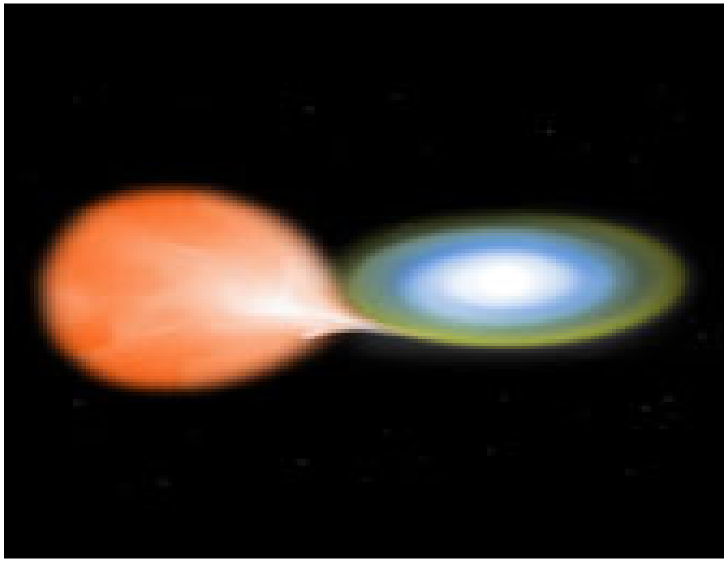
- Have become a "routine" subject of research
- Associated with extreme phenomena in the universe (e.g. SNe, GRBs)
- Interested in not just the objects themselves, but also how they interact/influence their surroundings
- Used as

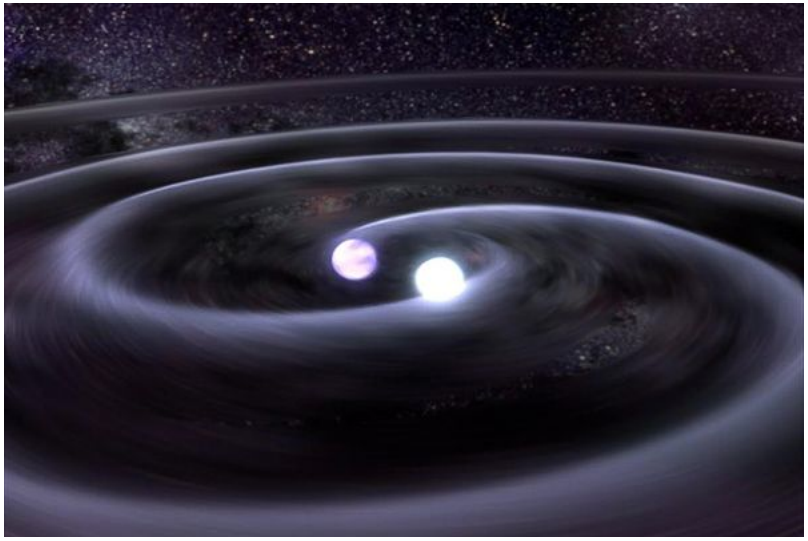
  --- an astronomy tool (e.g., expansion rate of the Universe, GWs)

  --- a tool to probe physics under extreme conditions

White Dwarfs

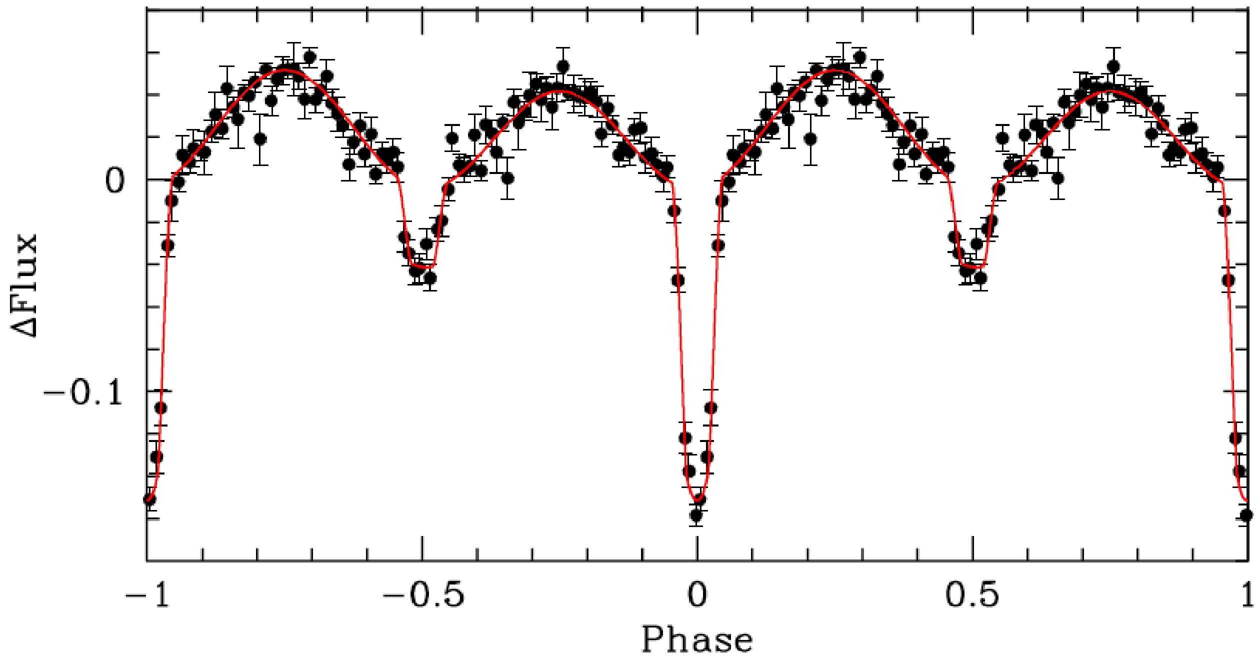
A "Challenge" Problem:
Fate of Accreting and Merging WD Binaries





-- may lead to various outcomes: SN Ia, transients, AICs, etc
-- SN Ia: single vs double-WDs ? Sub-Chandra Mass ?
explosion mechanism ?

12 min orbital period double WD eclipsing binary



Primary & secondary
eclipses
Ellipsoidal (tidal) distortion
Doppler boosting

Brown et al. 2011

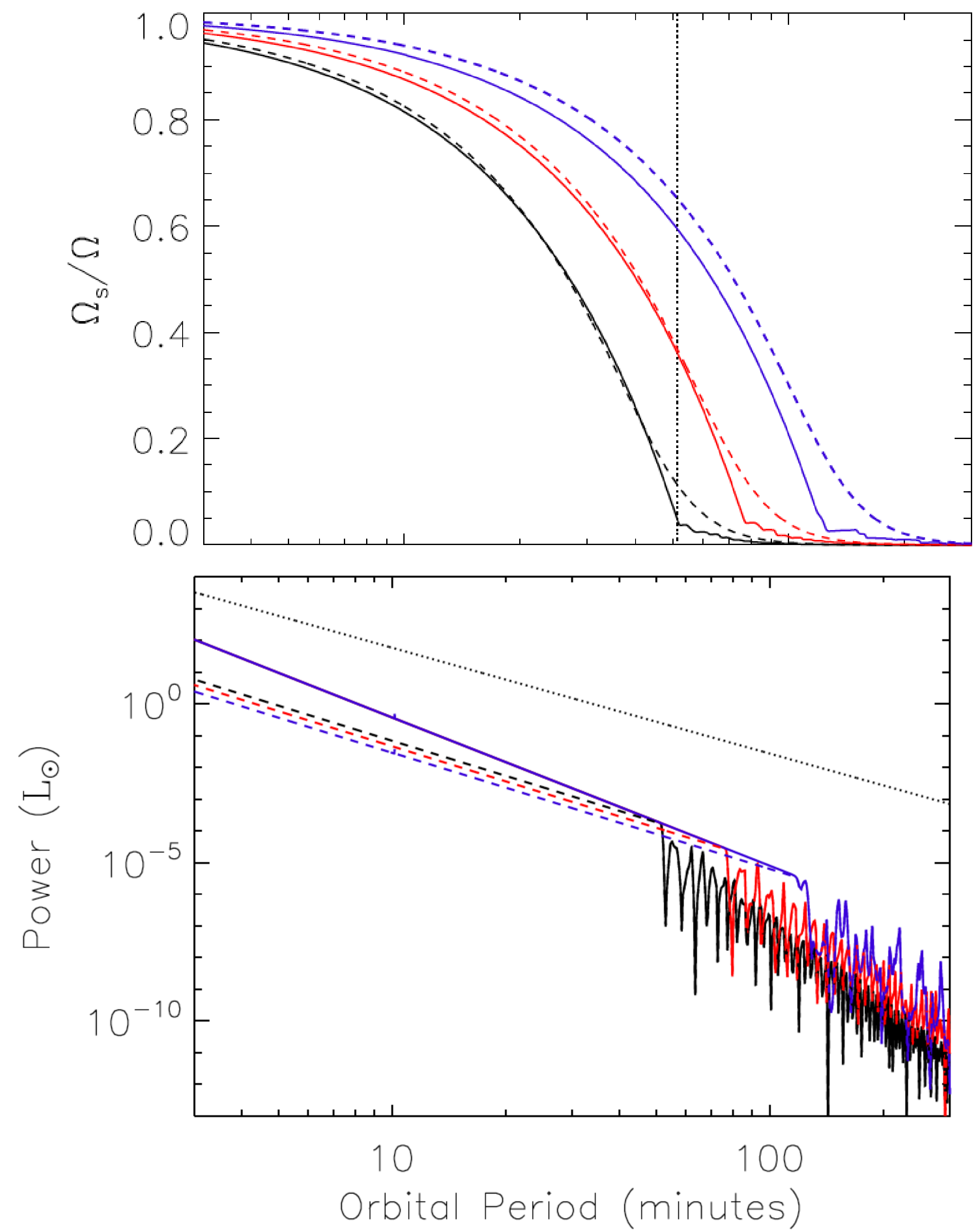
-- will merge in 0.9 Myr
-- large GW strain ==> LISA
-- orbital decay measurable from eclipse timing

Dynamical Tides in Merging WD Binary

Jim Fuller & DL 2011

-- Spin-orbit synchorinzation

-- Tidal heating



Neutron Stars:

Different Observational Manifestations

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

Isolated Neutron Stars

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

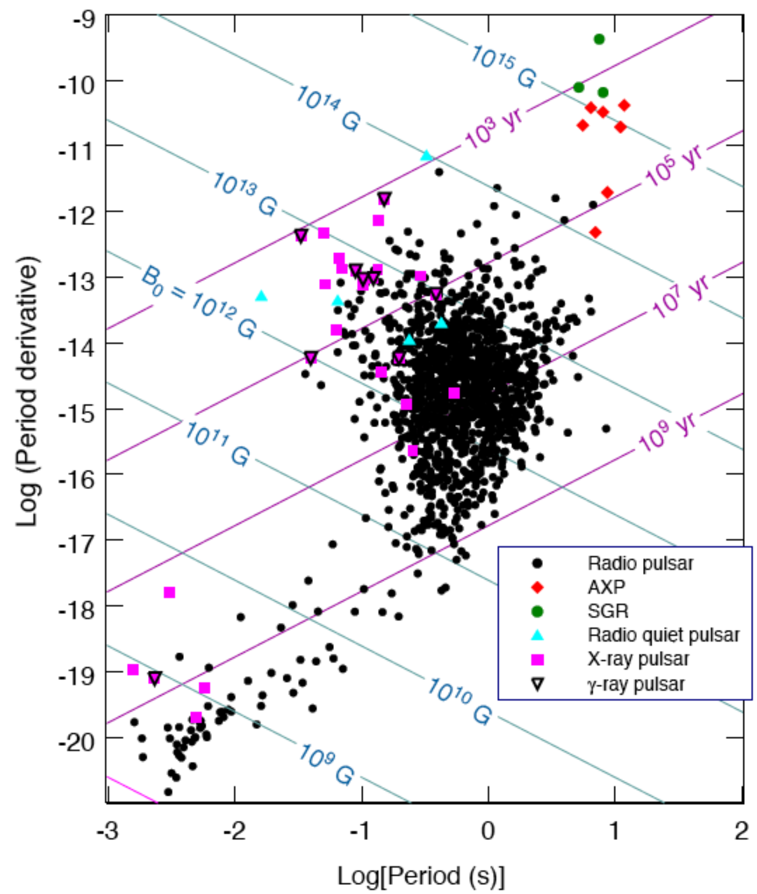
$\text{Most pulsars}: \ B \sim 10^{12-13} \text{ G}$

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

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

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

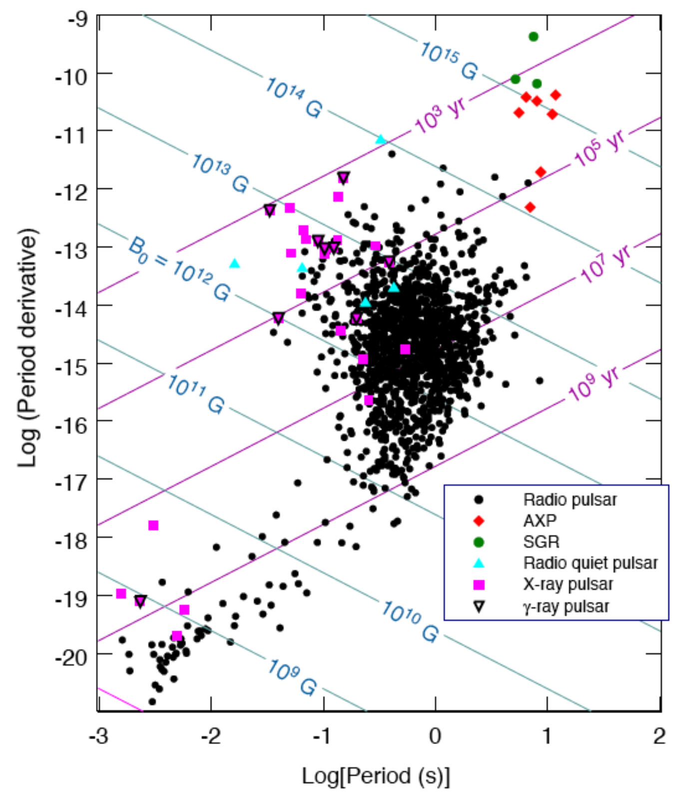
T ~0.5 keV, but significant emission up to ~100 keV (e.g. Kuiper et al.) => Magnetar corona

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:

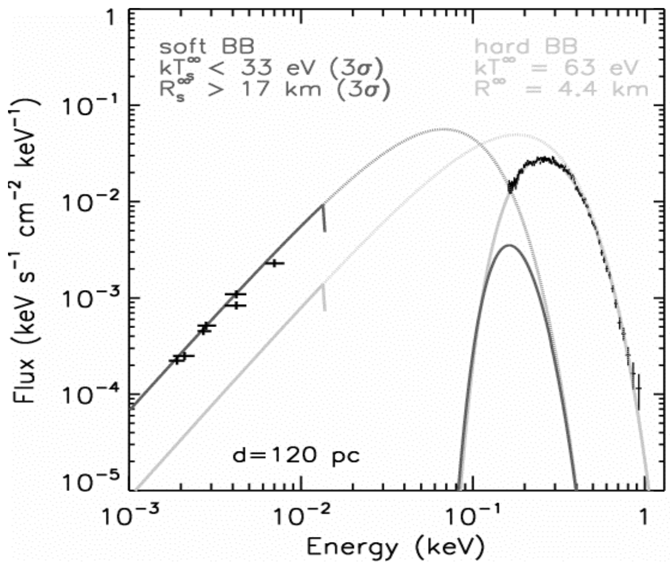
-- Transient magnetars: Radio emission triggered by X-ray outbursts
XTE J1810-197, 1E 1547.0-5408 (Camilo et al. 2007)

-- PSR J1622-4950 has $B\sim 3.10^{14}$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)

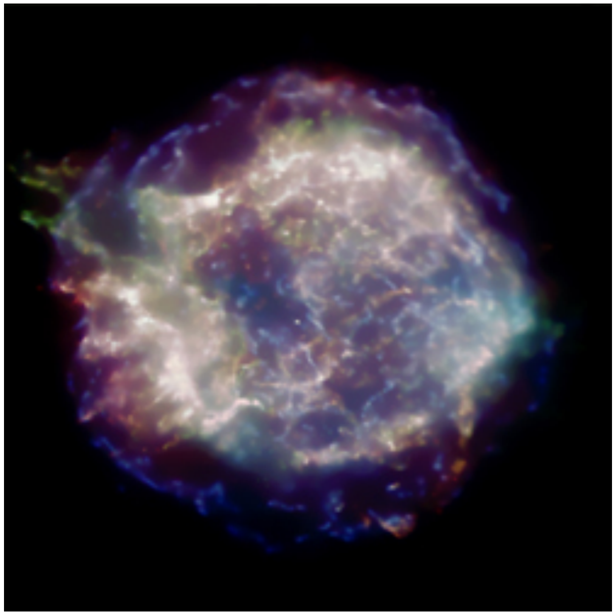
Spectral lines detected:

(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



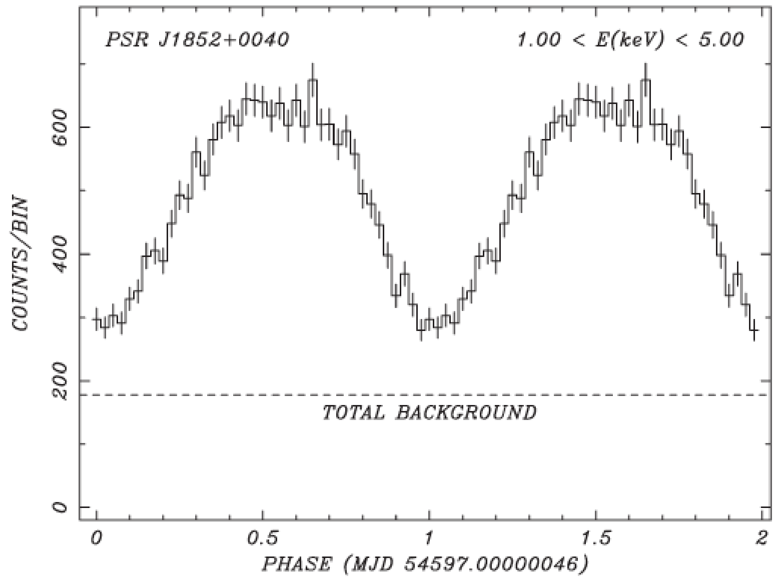
CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)
RX J0822.0 − 4300	Puppis A	3.7	2.2	0.112	11	<9.8
CXOU J085201.4 − 461753	G266.1 − 1.2	1	1	...	<7	...
1E 1207.4 − 5209	PKS 1209 − 51/52	7	2.2	0.424	9	<3.3
CXOU J160103.1 − 513353	G330.2 + 1.0	$\gtrsim$3	5	...	<40	...
1WGA J1713.4 − 3949	G347.3 − 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"?)

Hidden Magnetic Fields of Neutron Stars

- NS in Kes 79 SNR has $B_{\rm dipole} \simeq 3 \times 10^{10}$ G, but large pulse fraction 60%



(Halpern & Gotthelf 2010)

==> $B_{\rm crust} \sim$ a few $\times 10^{14}$ G

(**Natalia Shabaltas** & DL 2011)

- SGR 0418+5729, with $B_{\rm dipole} \simeq 4 \times 10^{12}$ G (Rea et al. 2010)

==> Internal field is much larger (Turolla et al 2011)

Isolated Neutron Stars

Radio pulsars

Normal/millisecond pulsars, high-B pulsars
Gamma-ray pulsars, Radio bursters, RRATs etc

Magnetars

AXPs and SGRs

Thermally emitting Isolated NSs

Central Compact Objects in SNRs

Goals of NS Astrophysics:

-- Understand the evolutionary connections
(B field origin & evolution?)

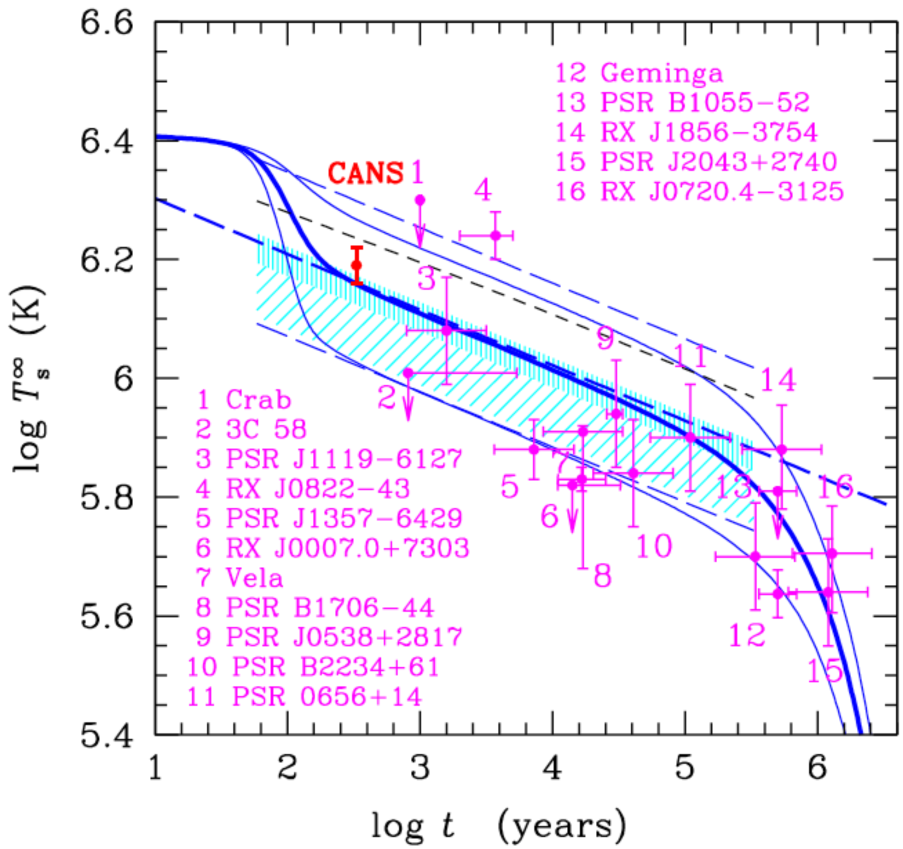
-- Probe physics under extreme conditions

Highlight #1:
Constrain NS Interior physics by Cooling

Surface emission has been
Detected in ~20 NSs

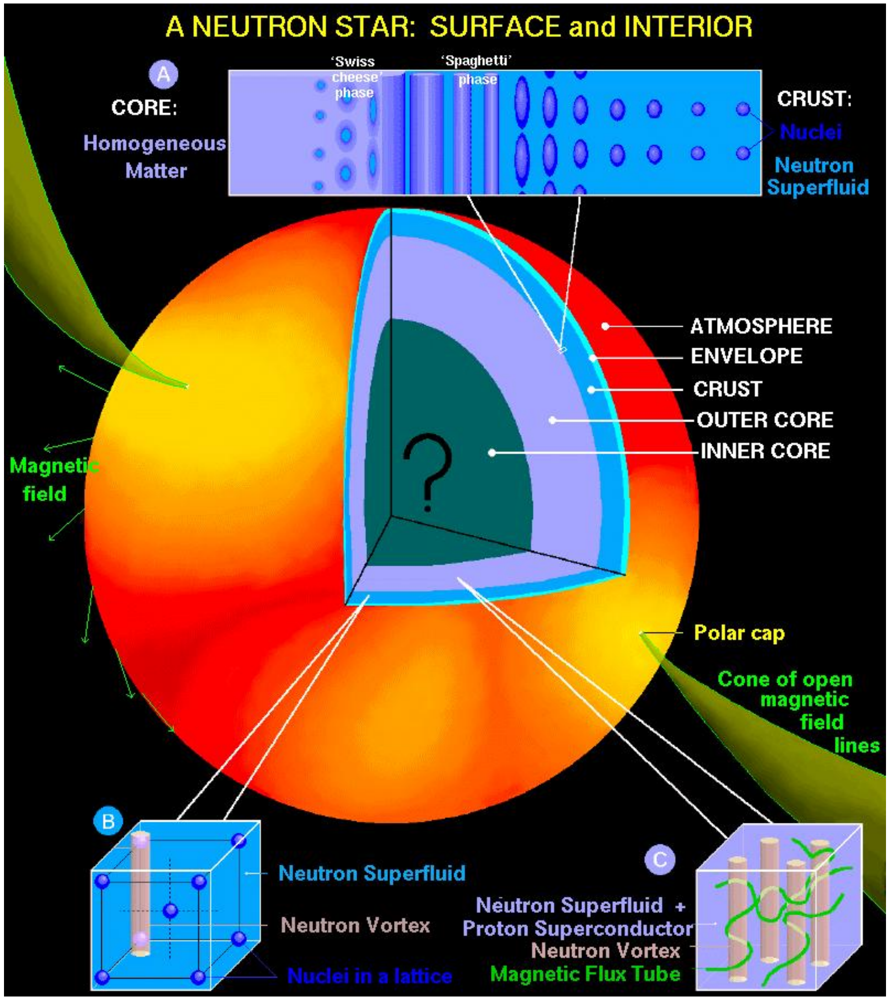
Probe the interior of NS
(EOS, exotic processes)

Difficuities:
Many parameters and theoretical
Models/processes…



Yakovlev et al. 2011

Neutron Star Structure



D. Page

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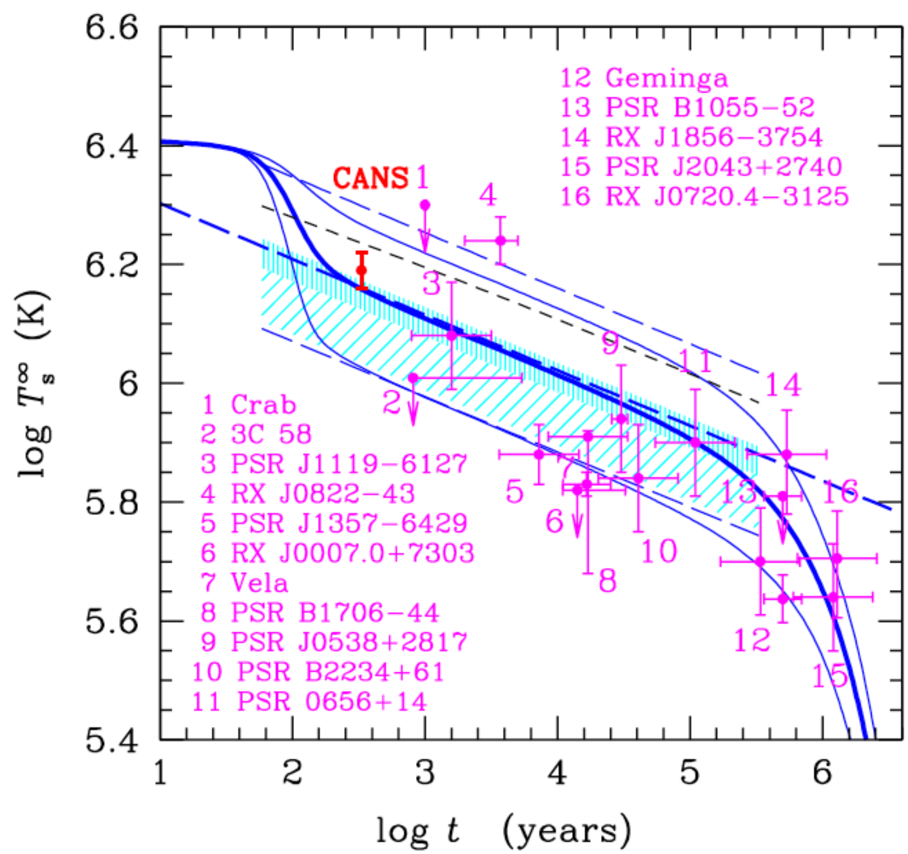
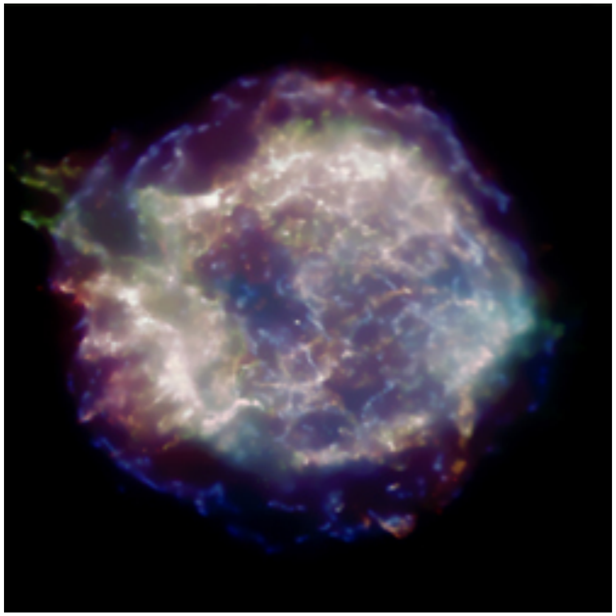


Yakovlev et al. 2011

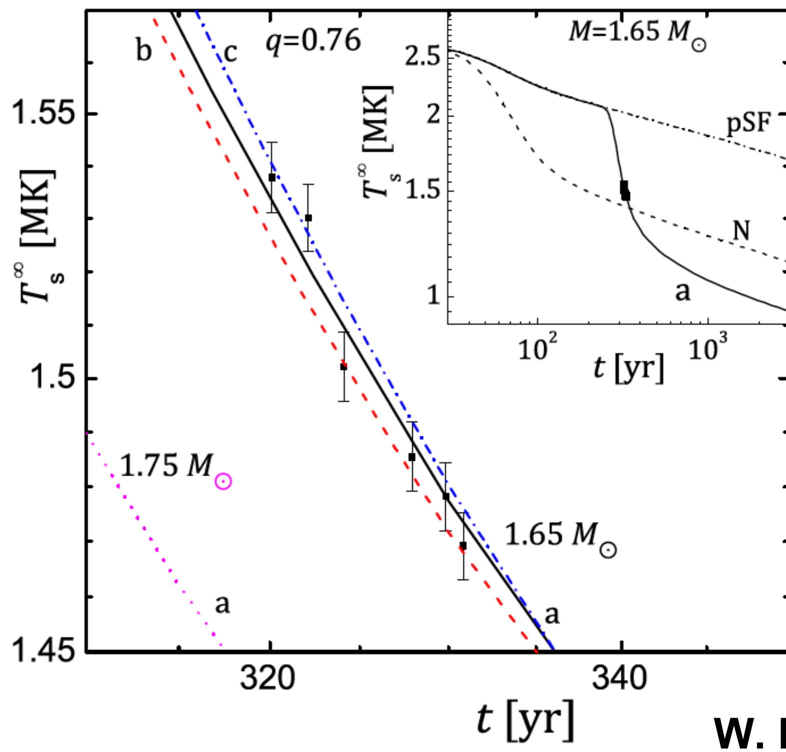
NS in Cas A SNR: Evidence of Superfludity



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

CCO (NS) first discovered in 1999

Many observations since then…



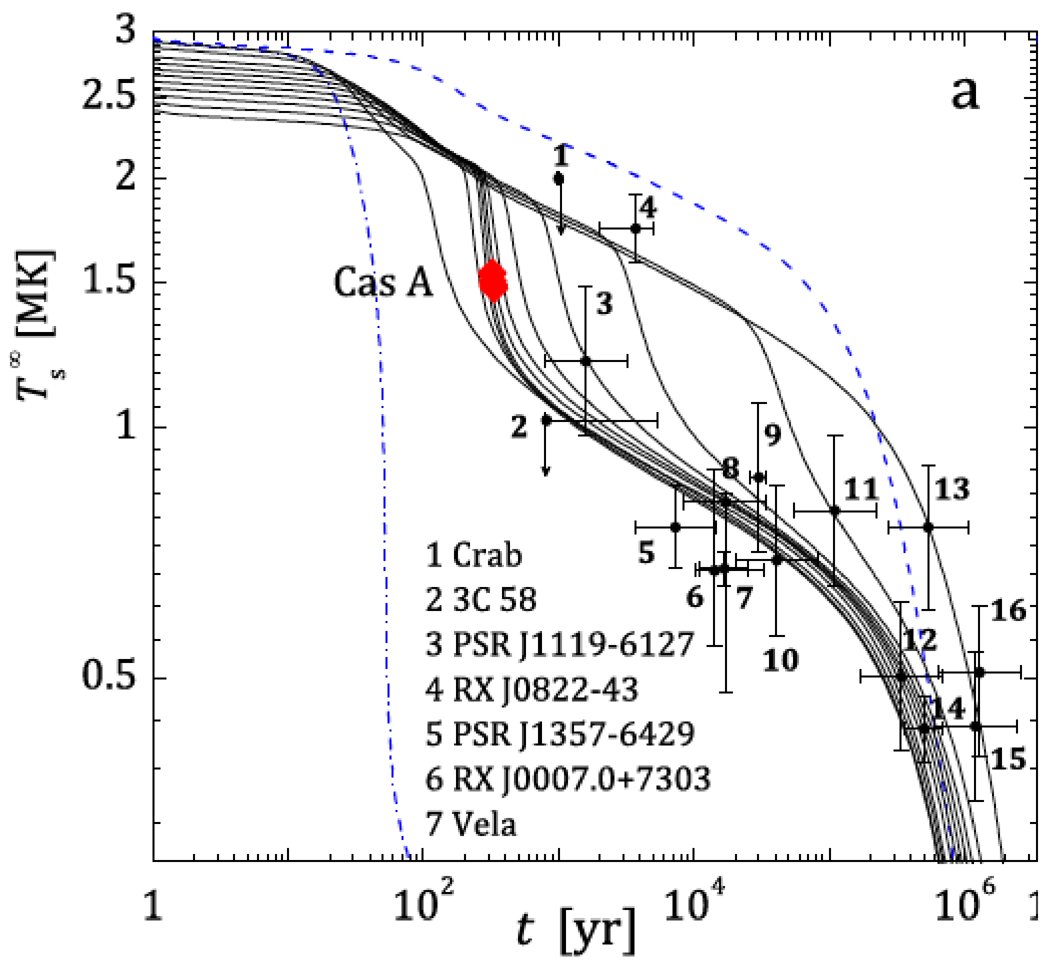
W. Ho & Heinke 2010

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

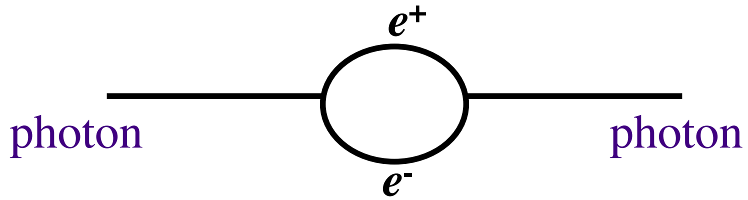
- One photon pair production:

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

- Photon splitting:

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

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

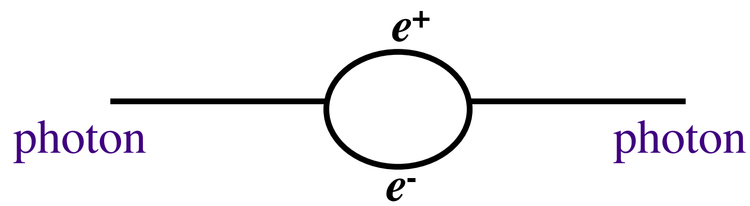


Context:
Modeling Radiation from Magnetic NS Atmospheres

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



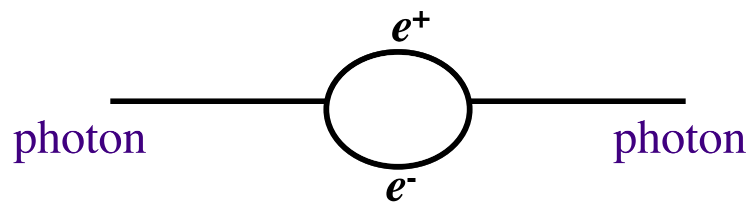
Heisenberg & Euler, Weisskopf, Schwinger, Adler…

Important when B is of order or larger than

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

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

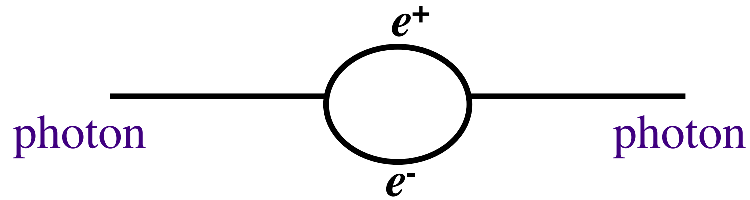
$$|\Delta\varepsilon_{\mathrm{vac}}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4 \times 10^{13}\ \mathrm{G}$$

Two photon modes:

Ordinary mode (//)

Extraordinary mode (⊥)

Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
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Dielectric tensor: $$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\mathrm{vac}}$$

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

Two photon modes:

Ordinary mode (//)

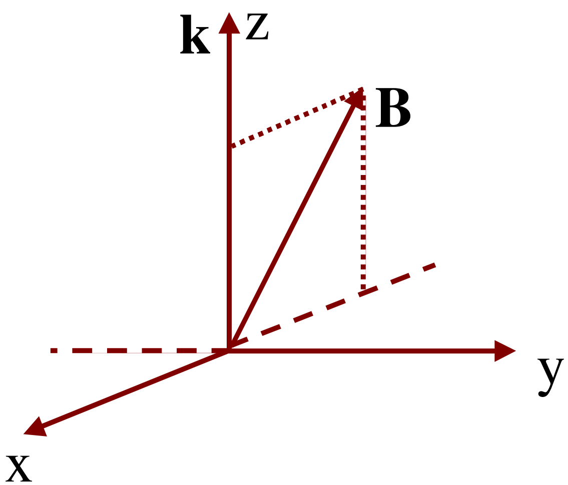
Extraordinary mode (⊥)

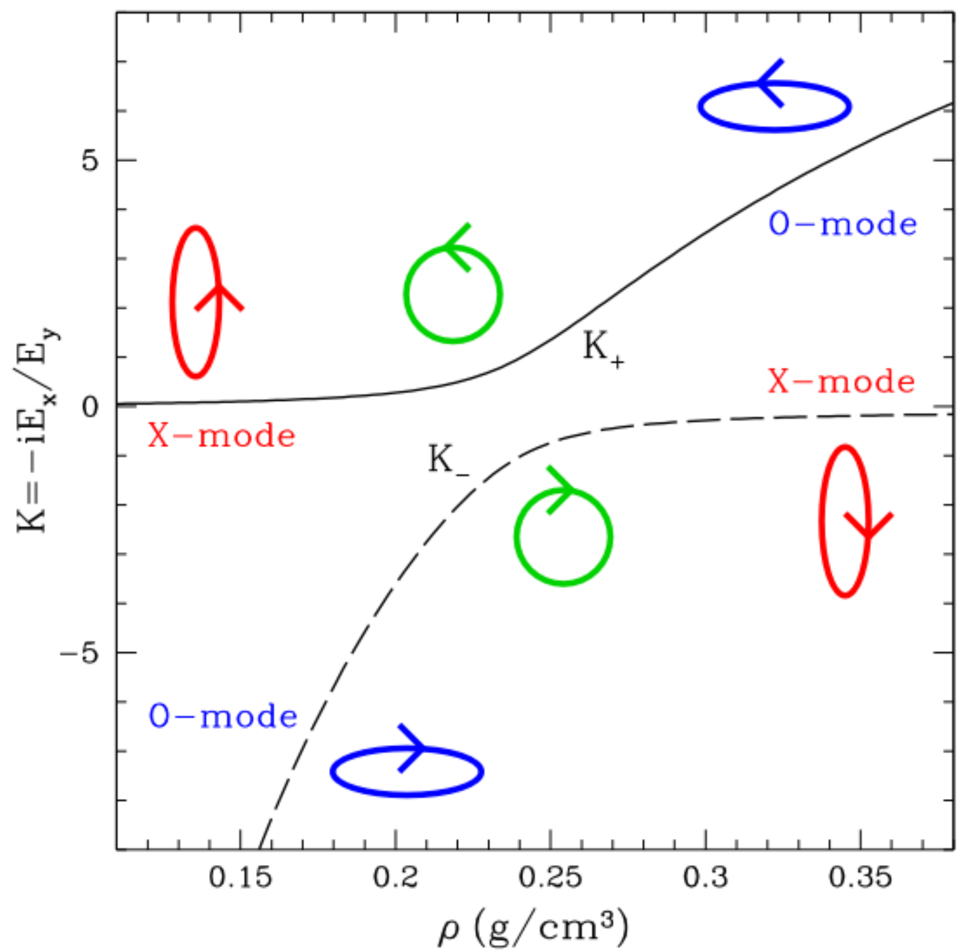
On the other hand…
Magnetic Plasma by itself (without QED) is birefringent:

Ordinary mode 

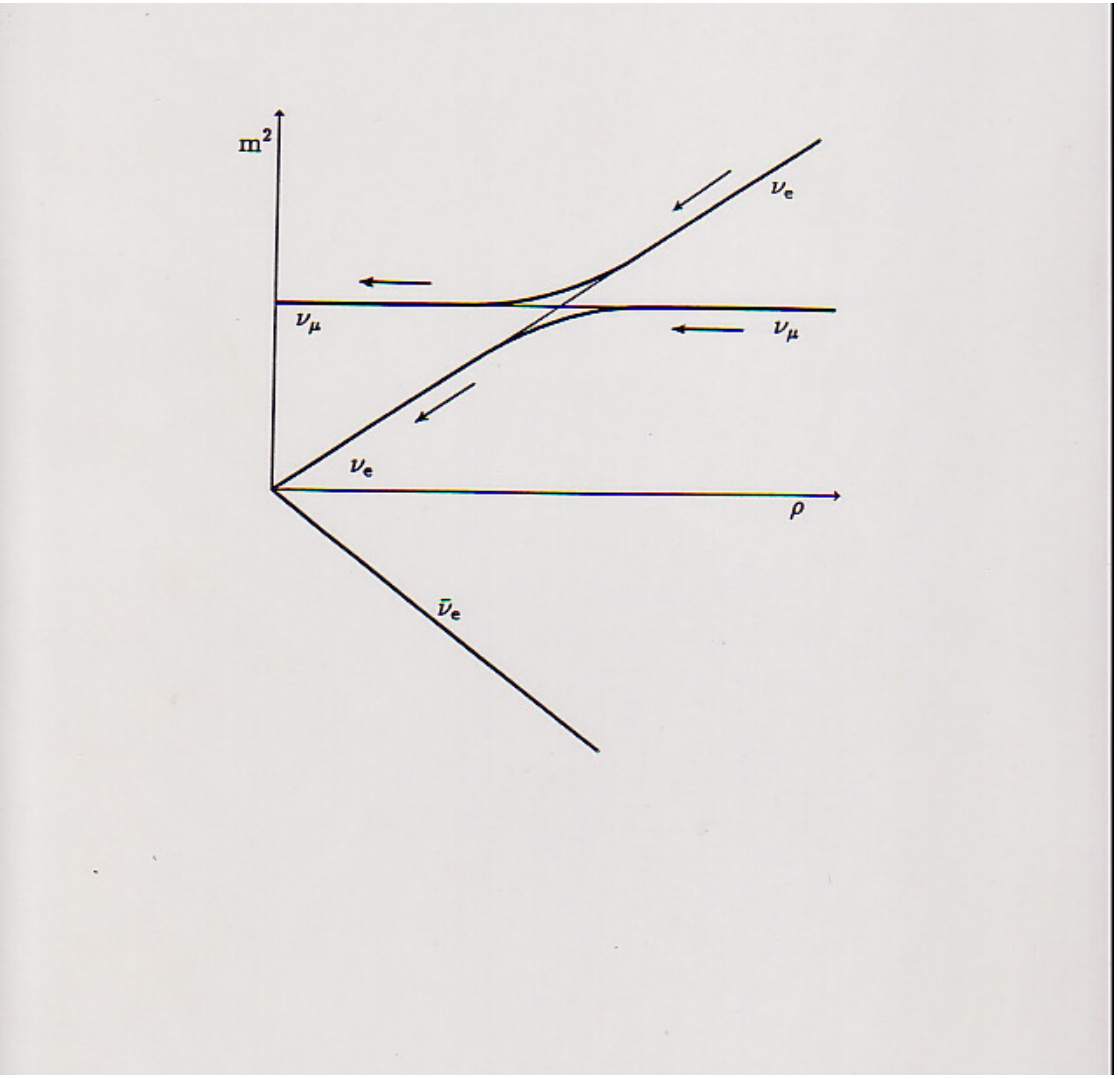
Extraordinary mode 

“Plasma+Vacuum” ==> Vacuum resonance

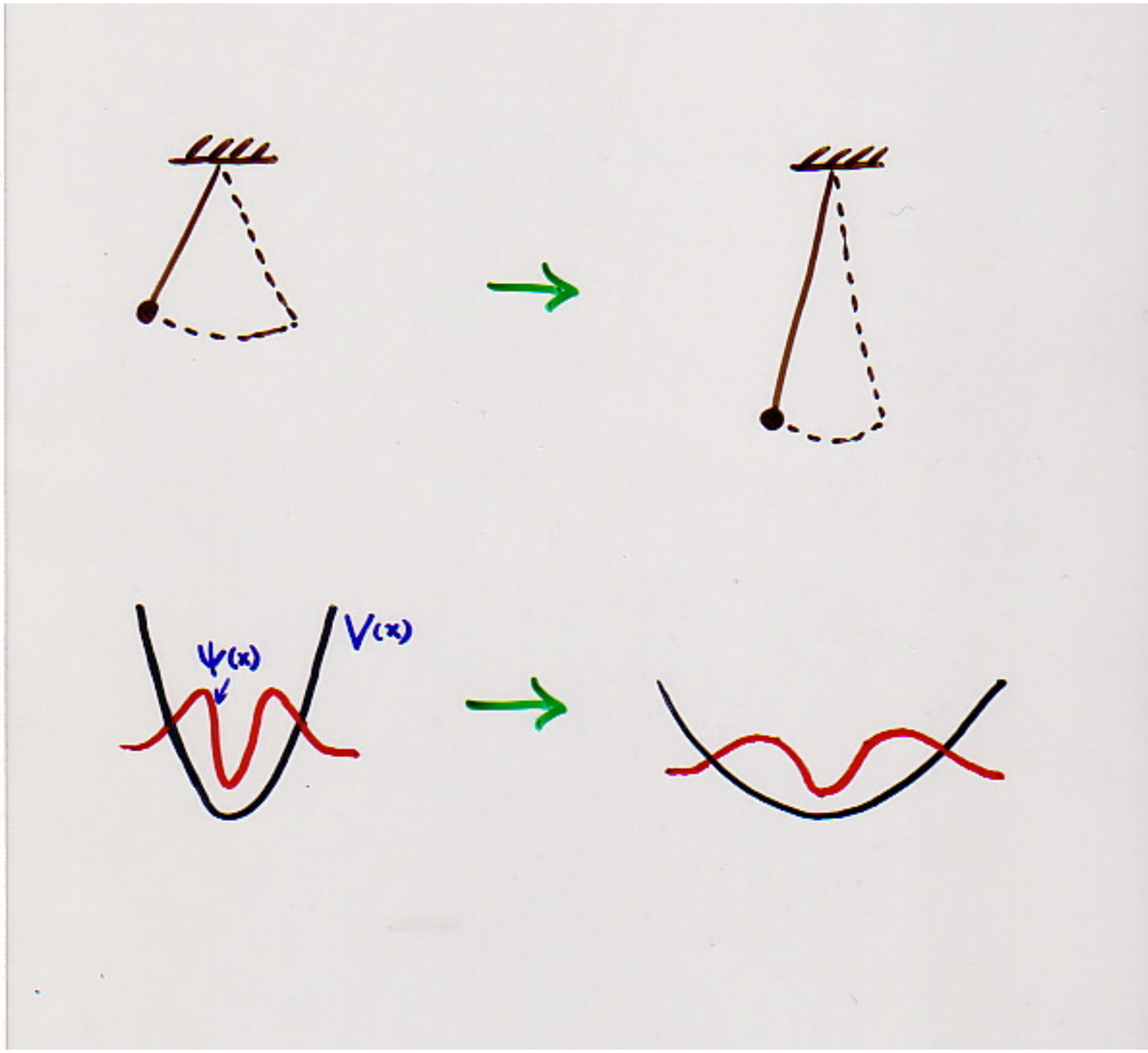




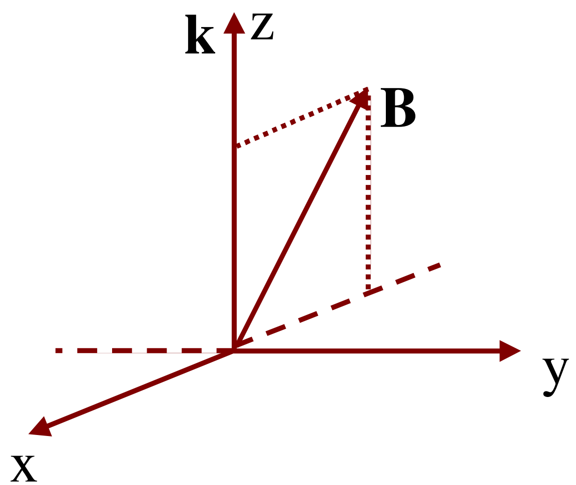
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation

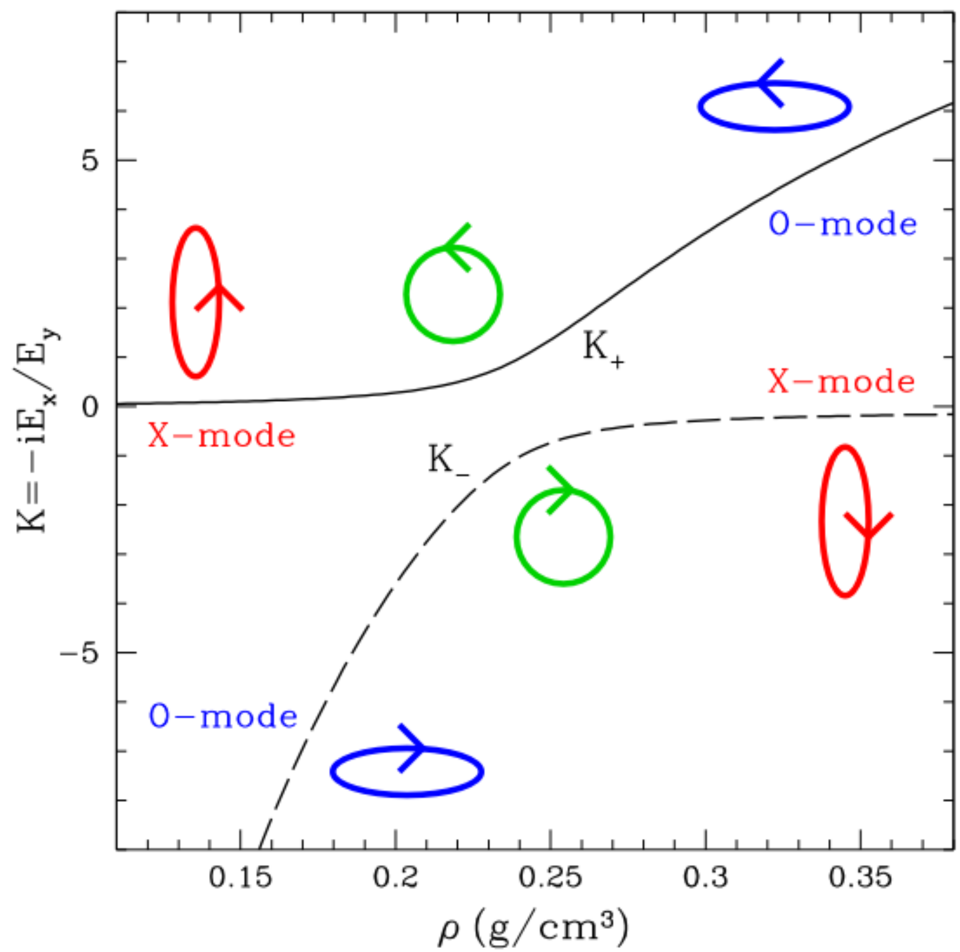


Adiabatic Evolution of a Quantum State



“Plasma+Vacuum” ==> Vacuum resonance





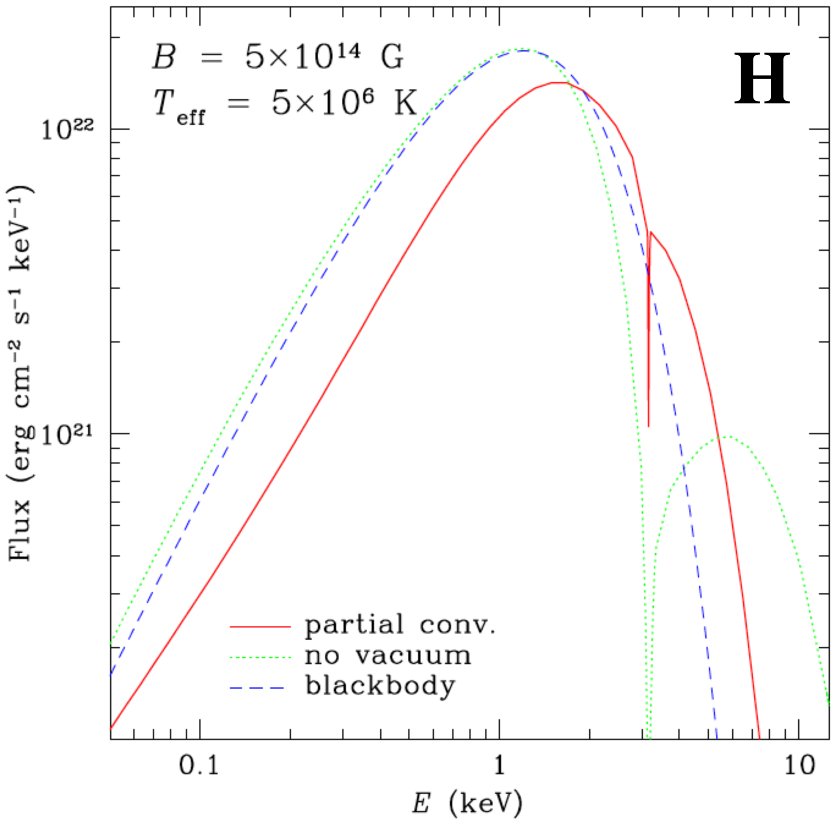
Why do we care?

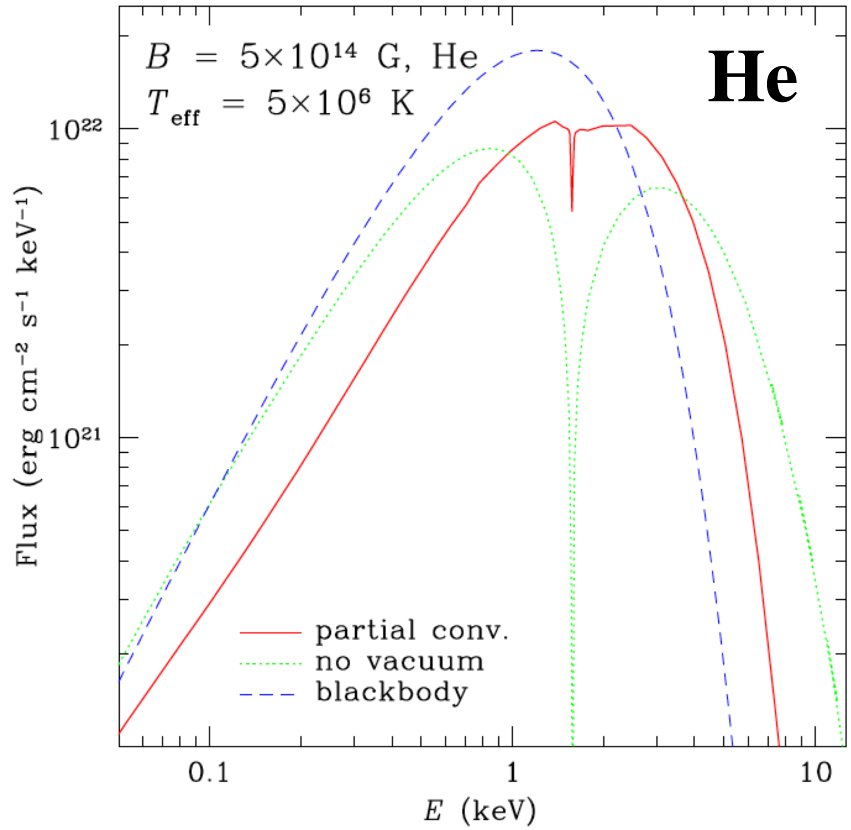
The two photon modes have very different opacities

=> Mode conversion can affect radiative transfer significantly

=> Spectrum and polarization signal from the NS

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



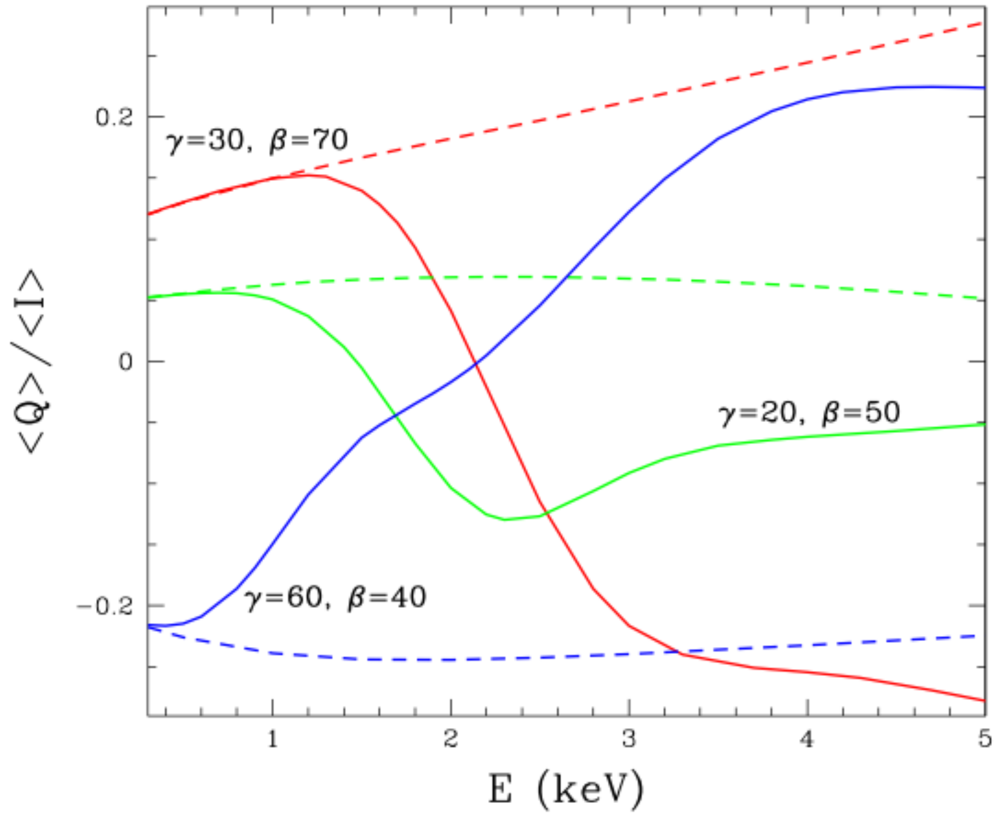


Matt Van Adelsberg & DL 2006

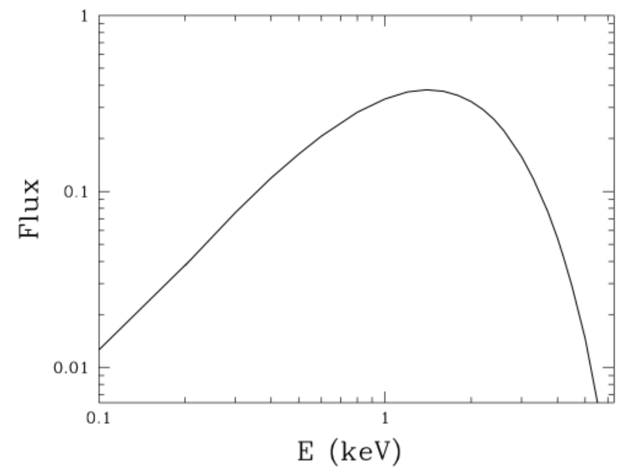
==> Magnetars do not show absorption features in thermal emission

QED at work!

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

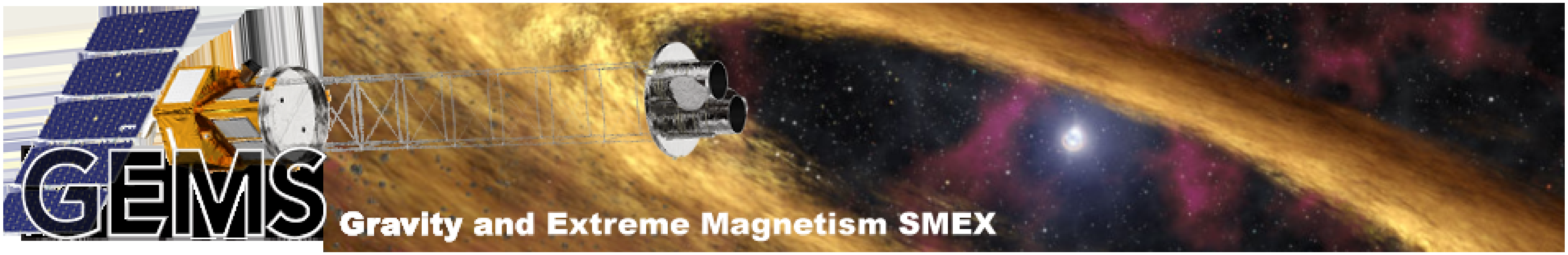


B=10^{13}G

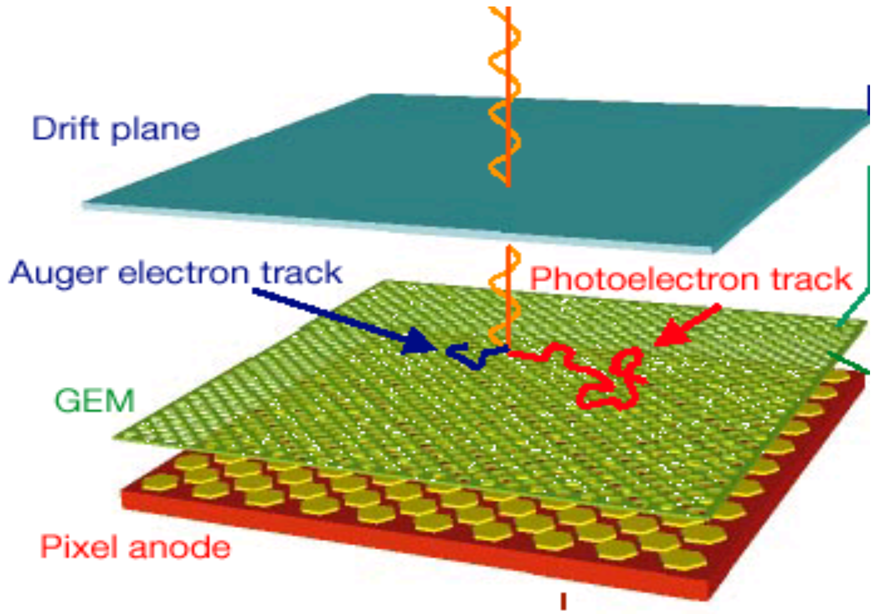


"boring" spectrum & lightcurve,
but interesting/nontrivial polarization spectrum!

==> X-ray polarimeters



X-ray polarization
Measurement:



GEMS: J. Swank, GSFC (PI); launch 2013-2014

Technical slides:
QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

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

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

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

Vacuum resonance:

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

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

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

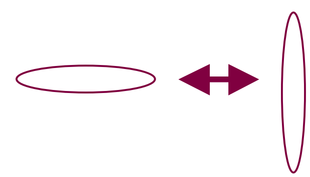
At resonance, X-mode and O-mode are “similar”

Adiabatic Condition:

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

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

Photons with E > 2 keV, mode conversion



Photons with E < 2 keV, no mode conversion

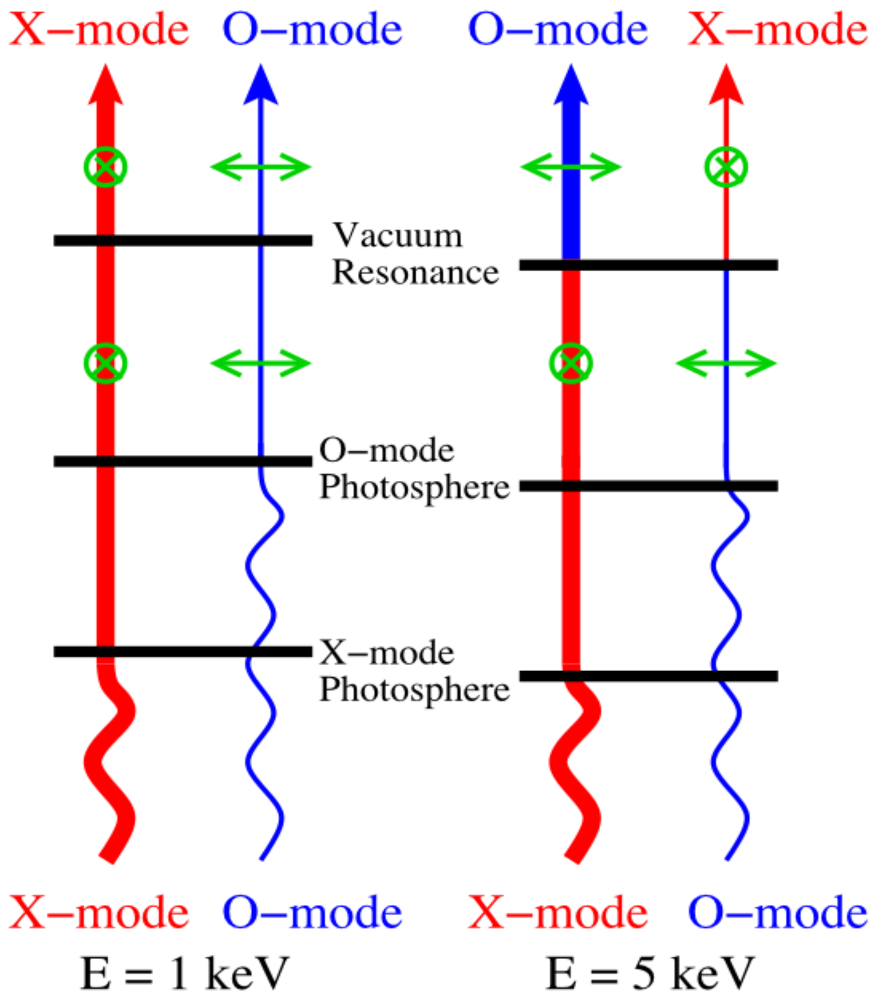
In general, nonadiabatic "jump" probability

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

(Landau-Zener formula)

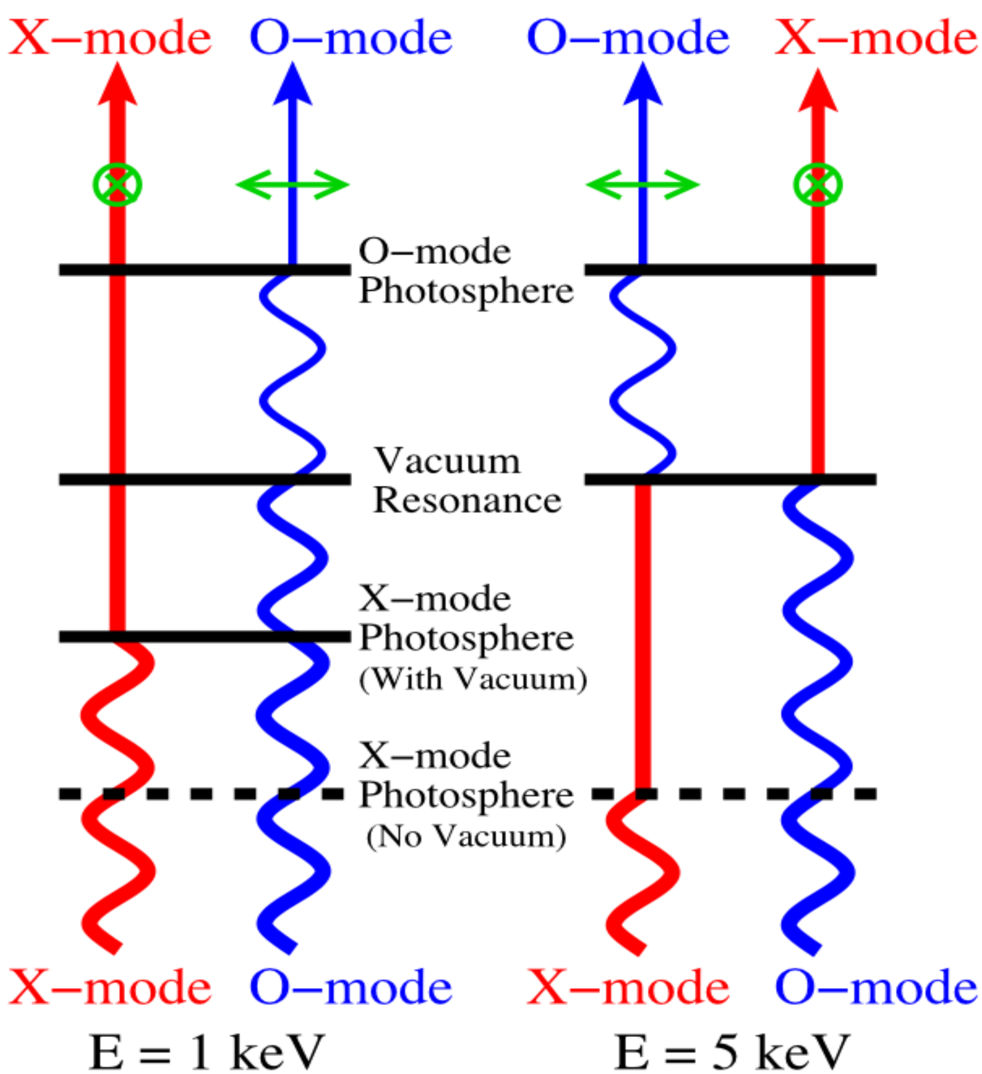
For B < $7\times10^{13}\ T_6^{-1/8}\ E_1^{-1/4}$ G:

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:

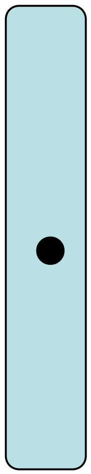
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

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

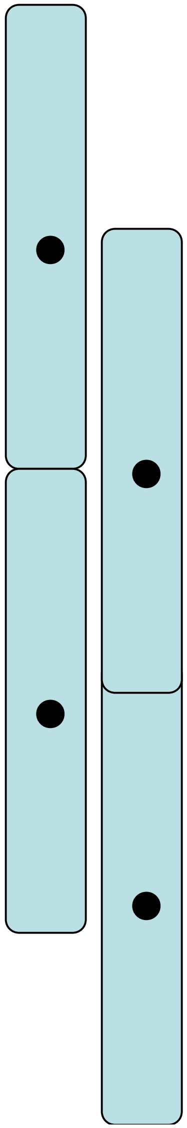
$|E| = 540 \text{ eV}$ at 10^{14}G

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

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

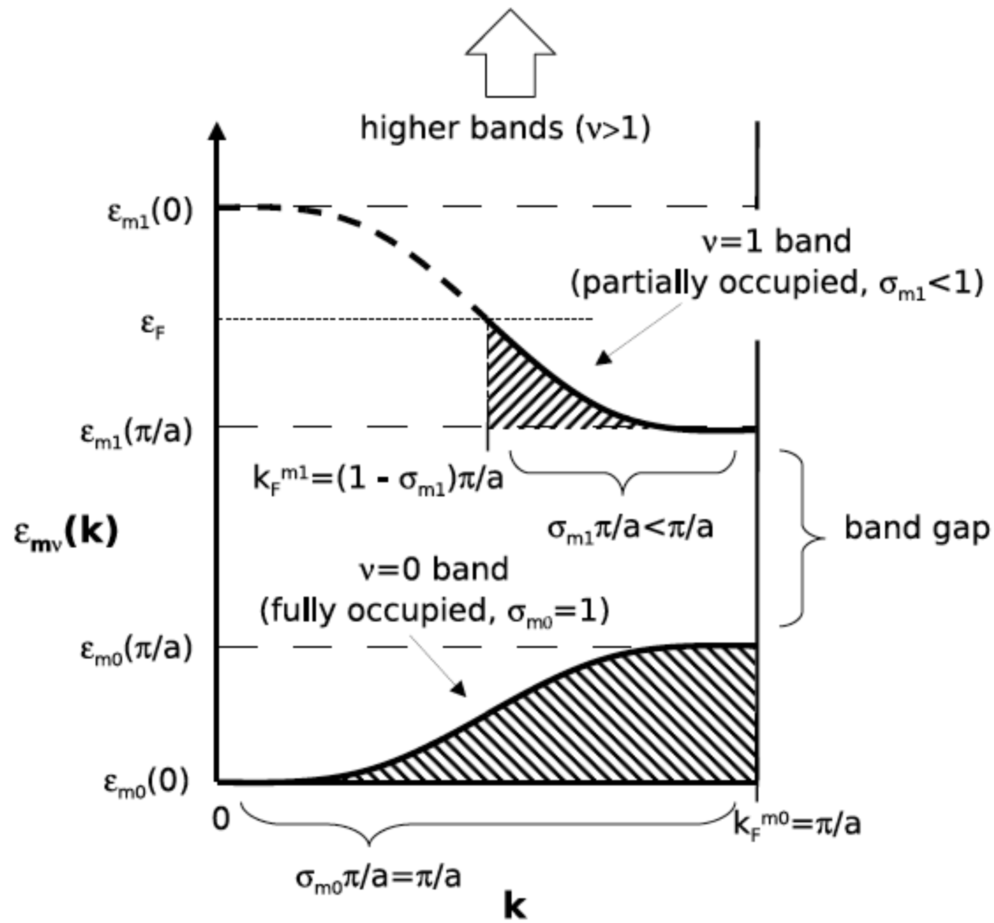
Energy of zero-pressure solid: $\sim b^{0.4}$

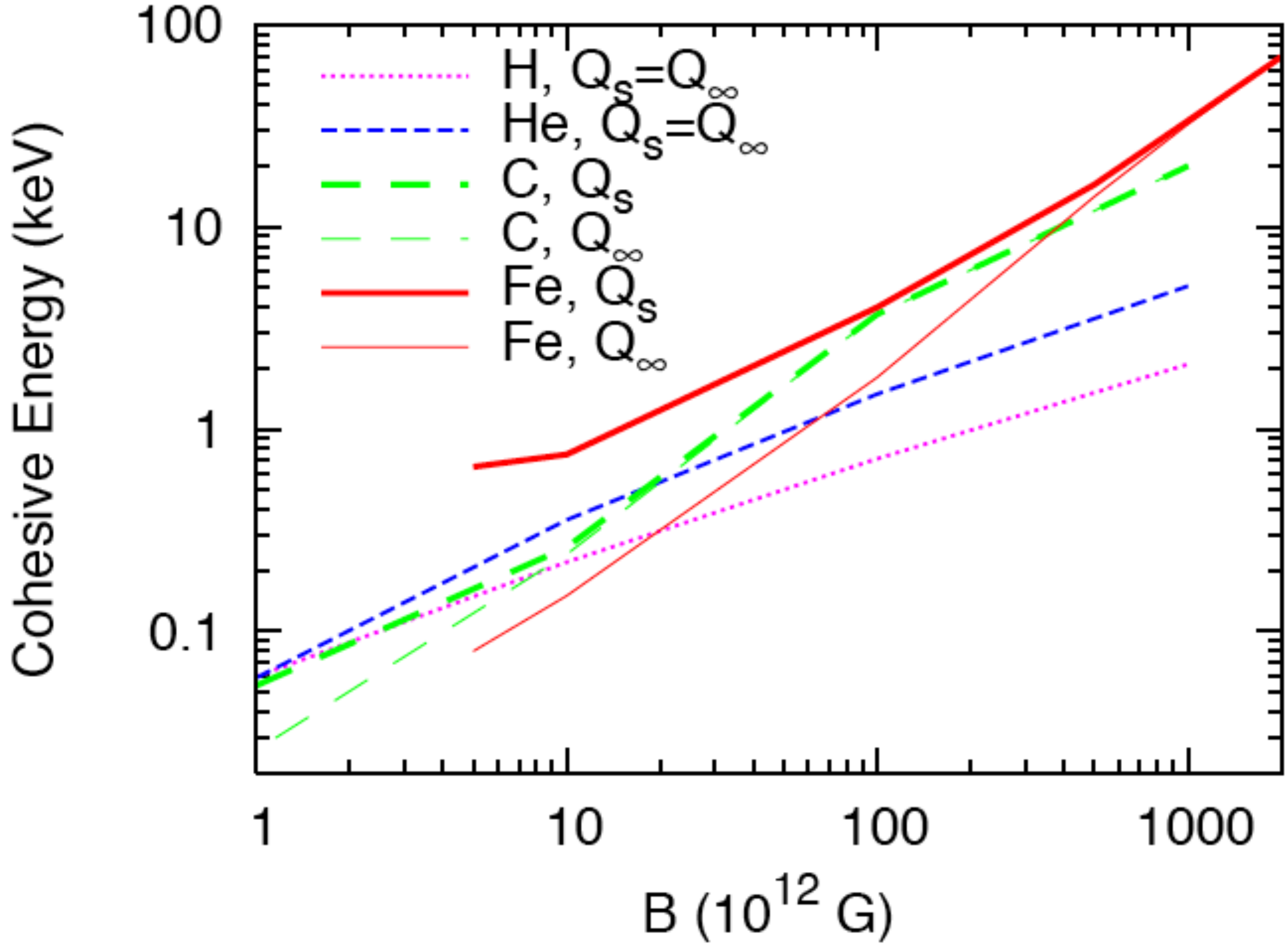
==> **Expect condensed solid to have large cohesive energy**

- 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





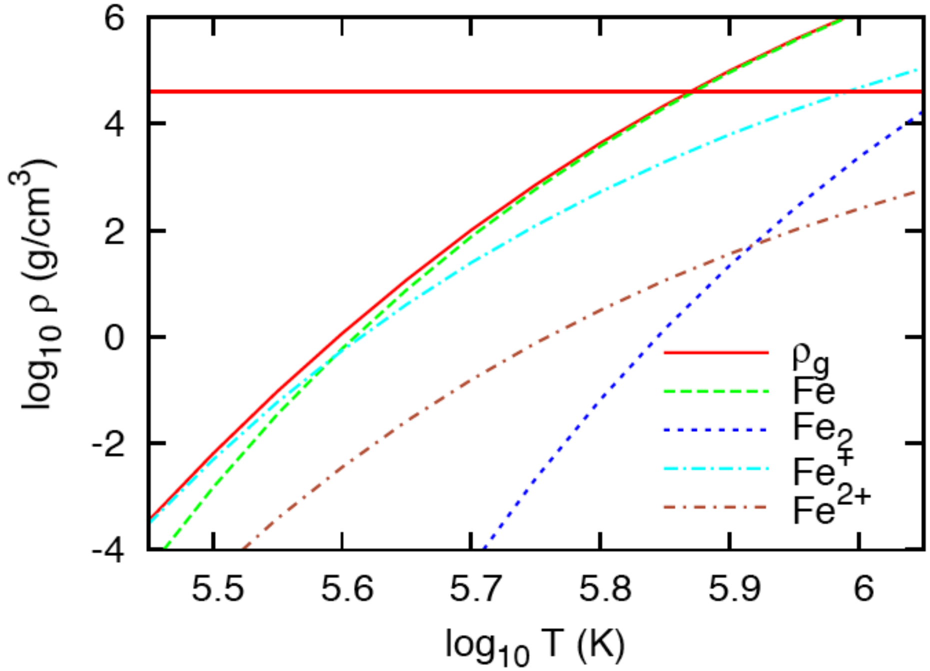
Cohesive Energy (keV)
B (10^{12} G)
H, $Q_s=Q_\infty$
He, $Q_s=Q_\infty$
C, Q_s
C, Q_∞
Fe, Q_s
Fe, Q_∞
100
10
1
0.1
1
10
100
1000

Implications…

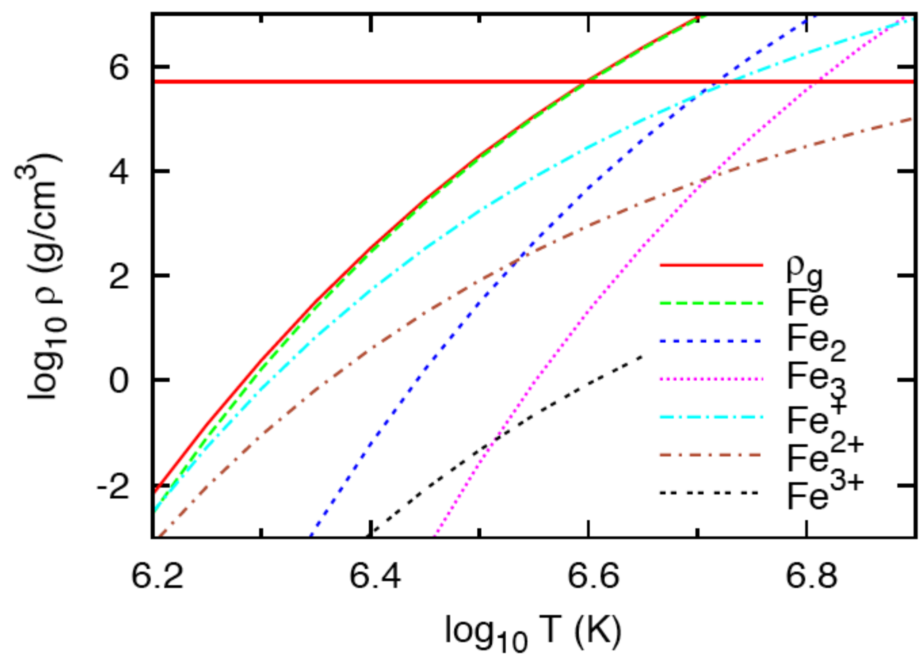
Surface condensation of isolated NSs

Saturated Vapor of Condensed NS Surface:

Fe at 10^{13}G



Fe at 10^{14}G



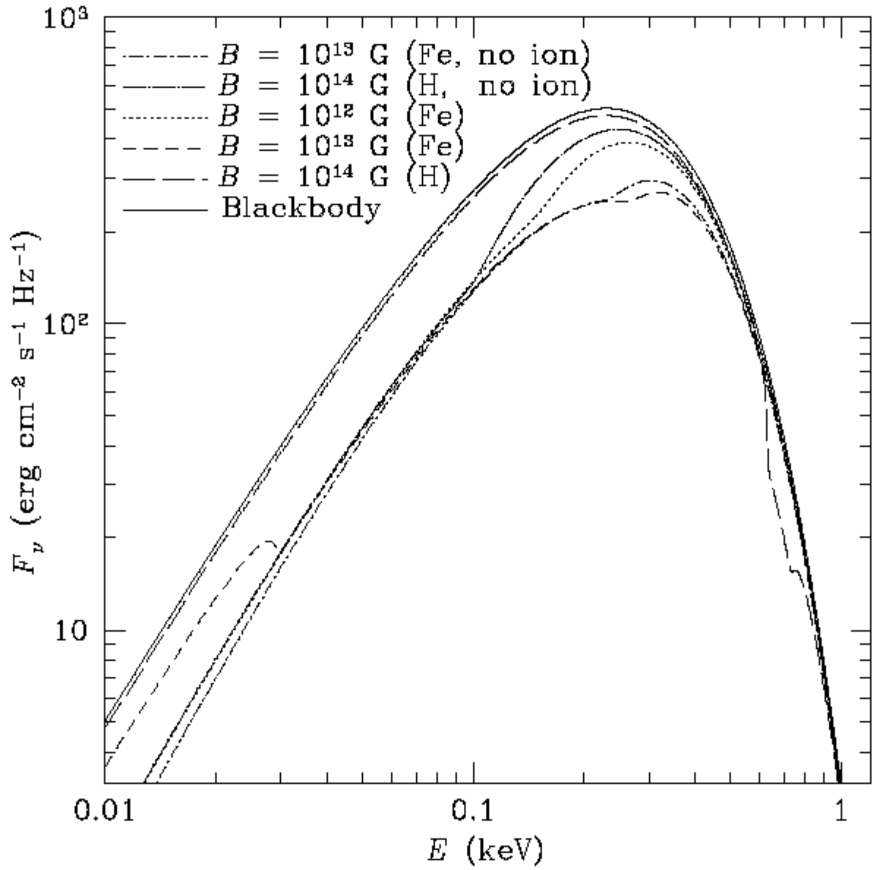
Zach Medin & DL 2007

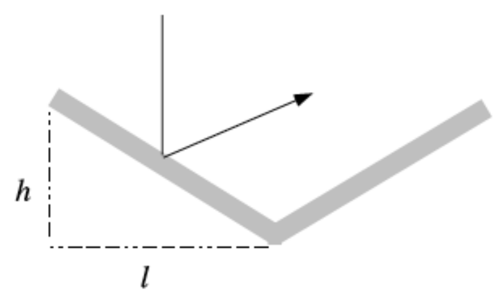
For a given B, below T_{crit}(B),

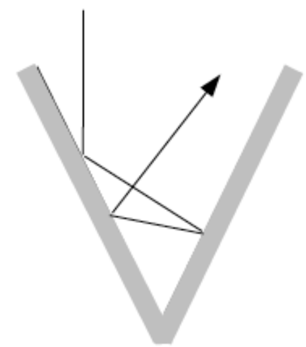
NS surface is in condensed form (with little vapor above)

Emission from condensed NS surface resembles a featureless blackbody

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







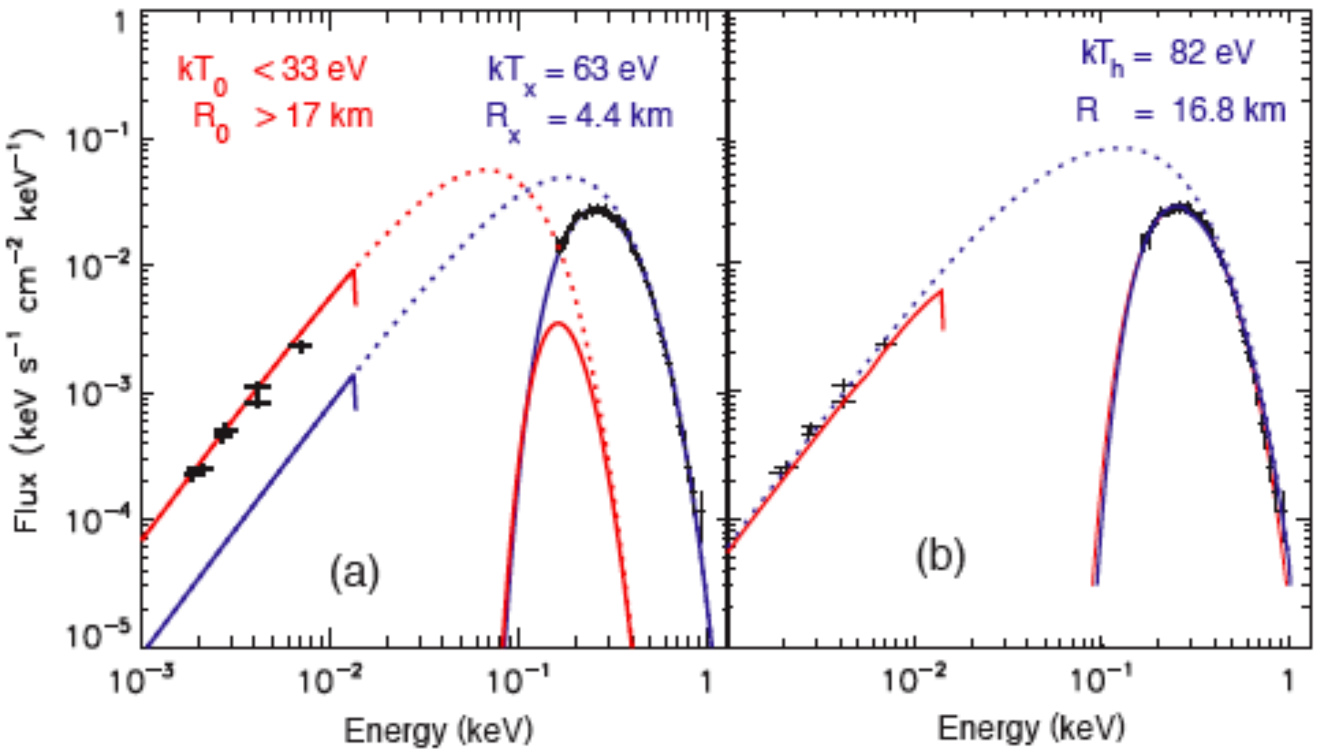
van Adelsberg, Lai, Potekhin & Arras 05

Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754

(T ~ 60 eV)



Burwitz et al. 03, Trumper et al 04

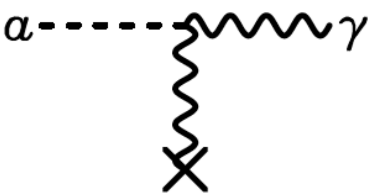
May be explained by emission from condensed surface

Highlight #4: Probing Axions with Magnetic NSs

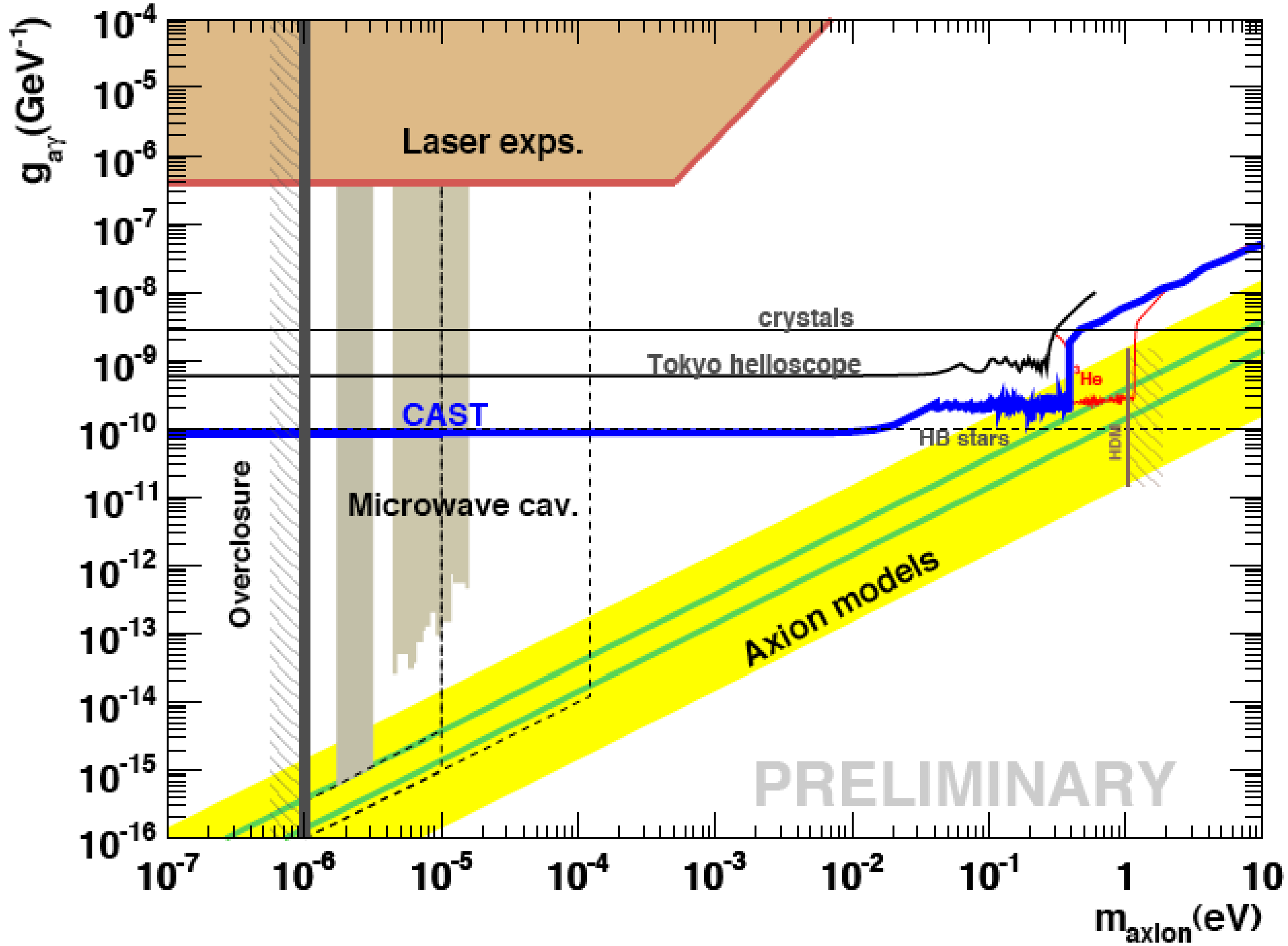
Axions: pseudoscalar particles, arise in the Peccei-Quinn solution of the strong CP problem; could be dark matter candidates

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

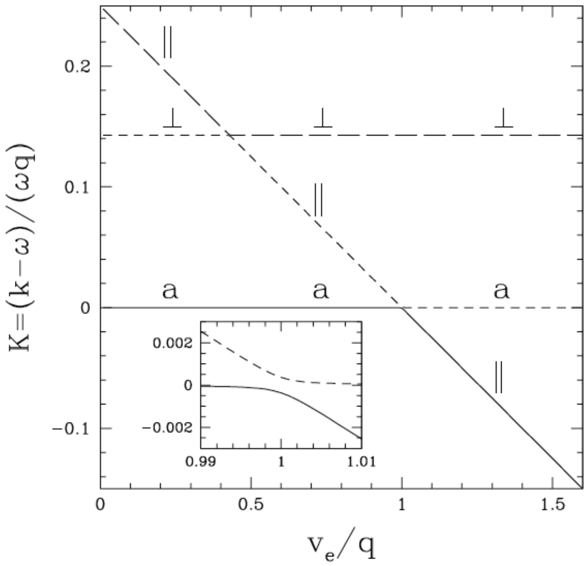


arXiv:0810.1874 (CAST collaboration)

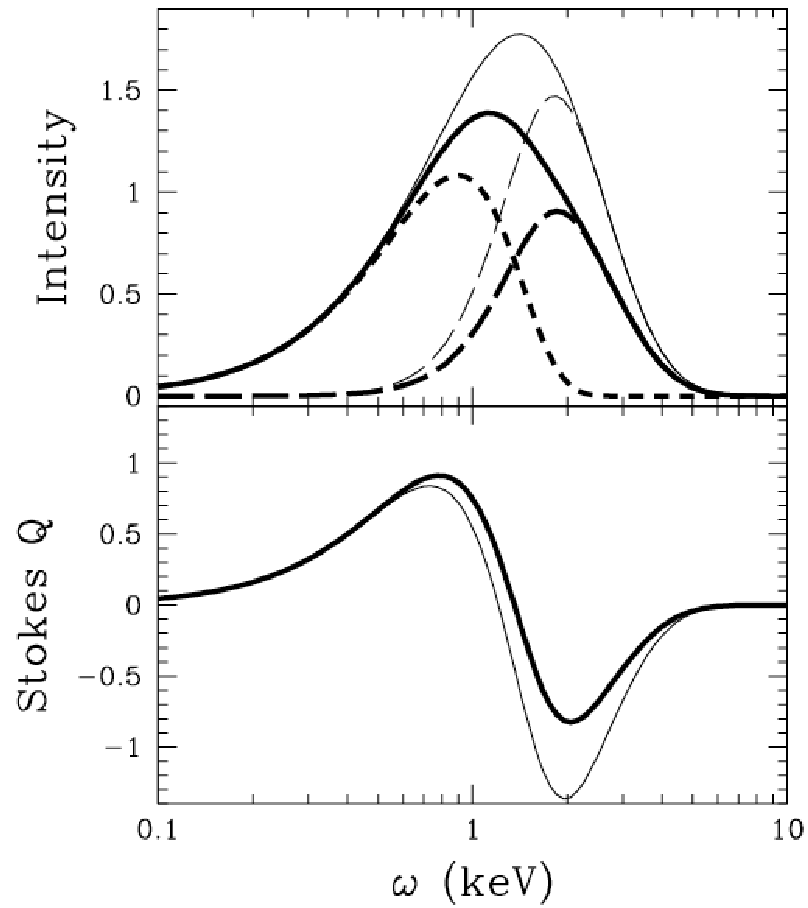
Photon-Axion Conversion in Magnetic Neutron Stars

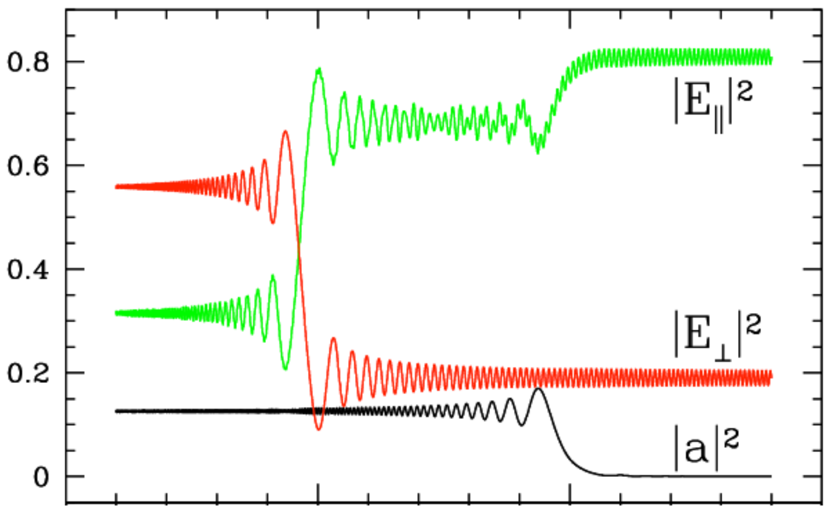
In the magnetized plasma of NSs, photons (//-polarization component) can convert (resonantly a la MSW) into axions

===> modify radiation spectra and polarization signals

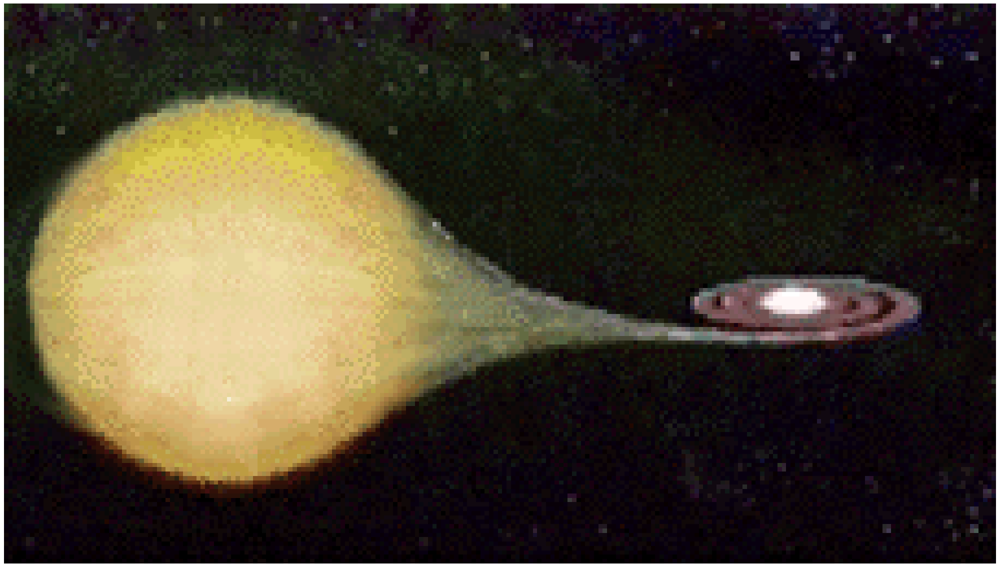


DL & Heyl 2007; Perna et al. 2011





Accreting Neutron Stars



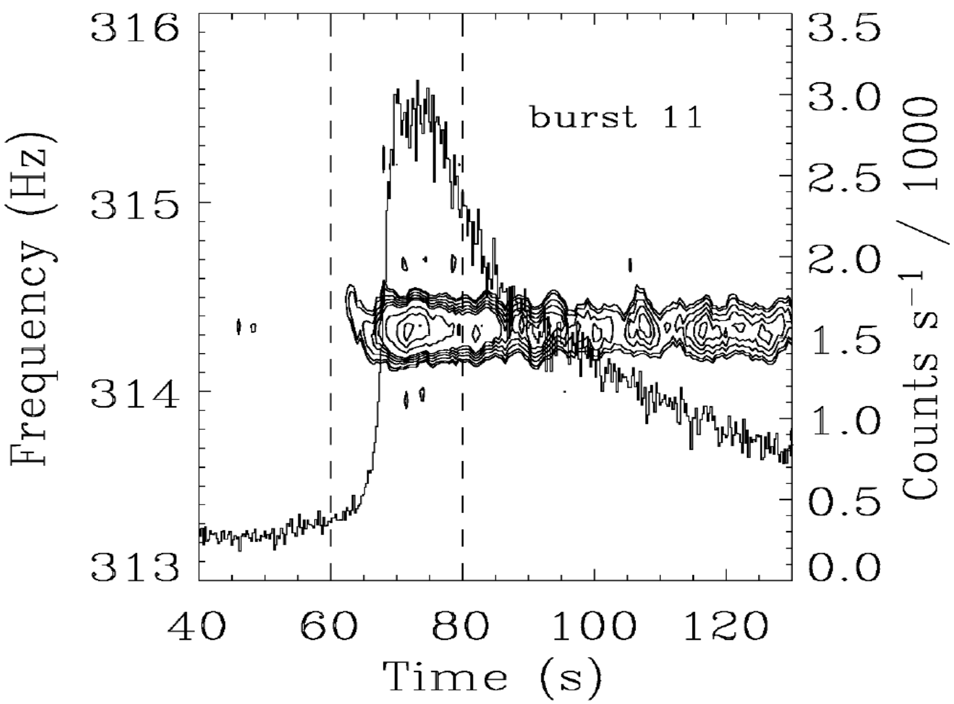
-- Non- or weakly magnetized NSs (LMXBs)

-- Highly magnetized NSs (HMXBs)

Accretion onto non- or weakly magnetized NSs

Unstable surface nuclear burning ==> X-ray bursters

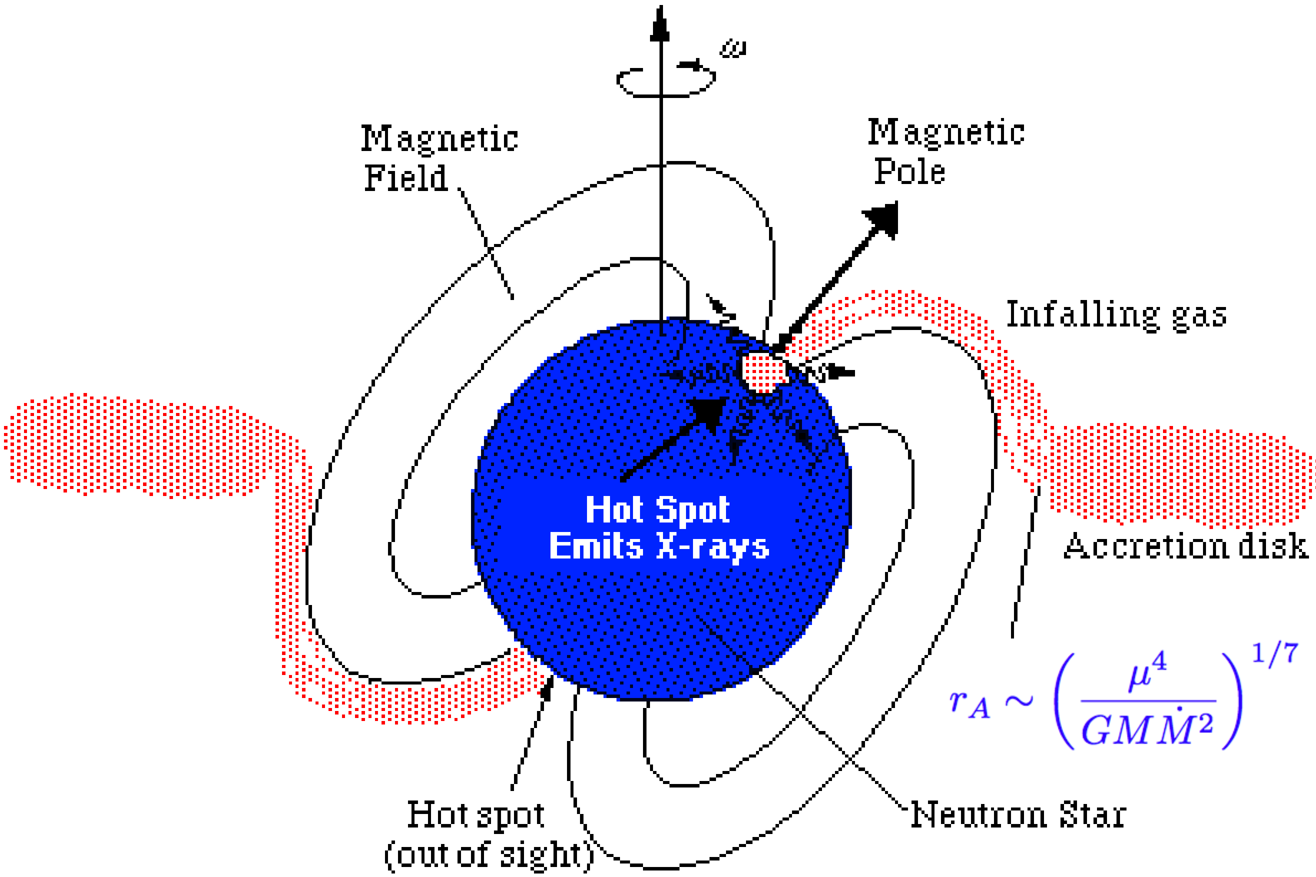
Burst oscillations (due to rotating hot spot)



Strohmayer et al 2003

Modeling burst lightcurve can constrain M/R (self-lensing by NS)

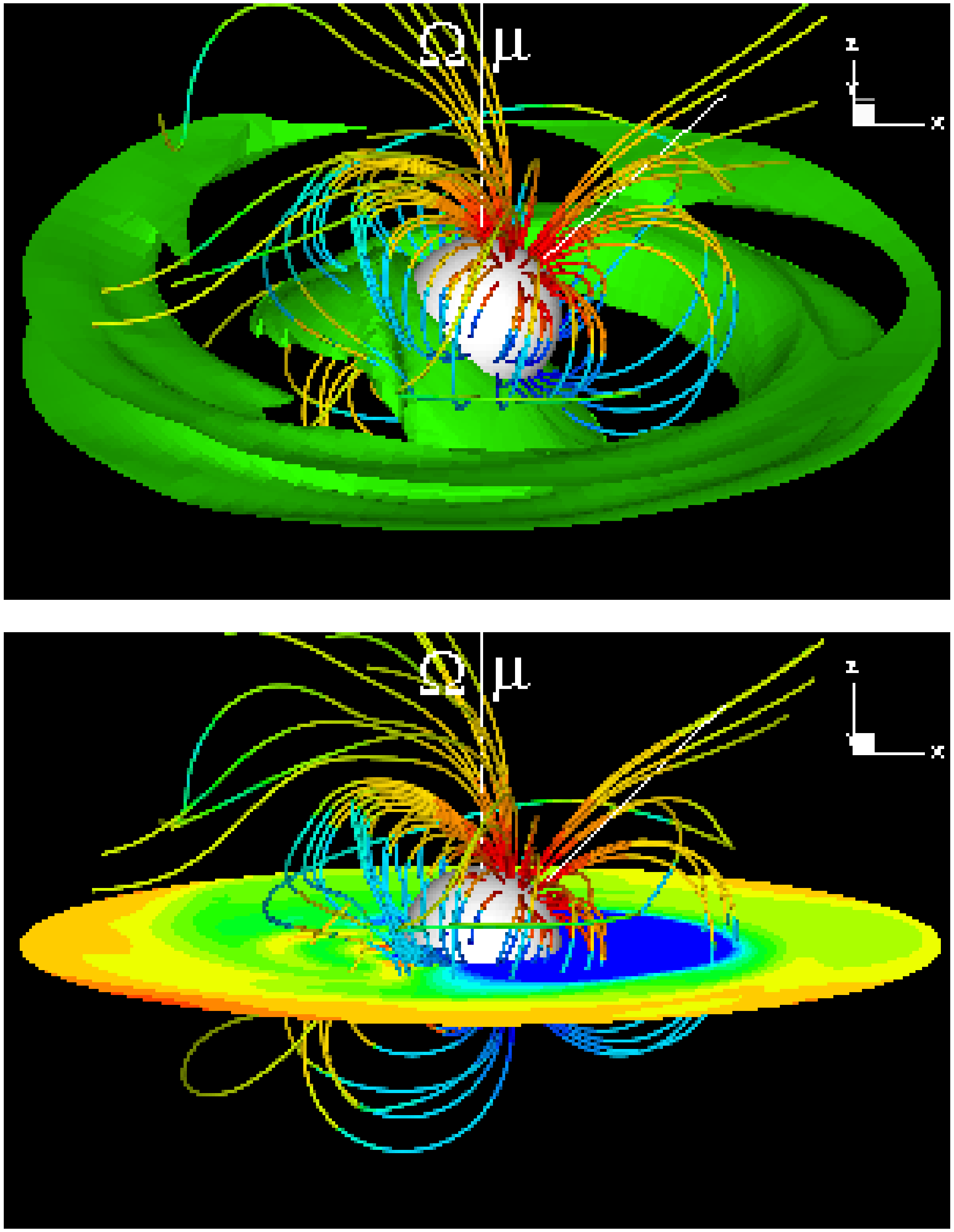
Accretion onto Magnetic NSs



$$r_A \sim \left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7}$$

NASA

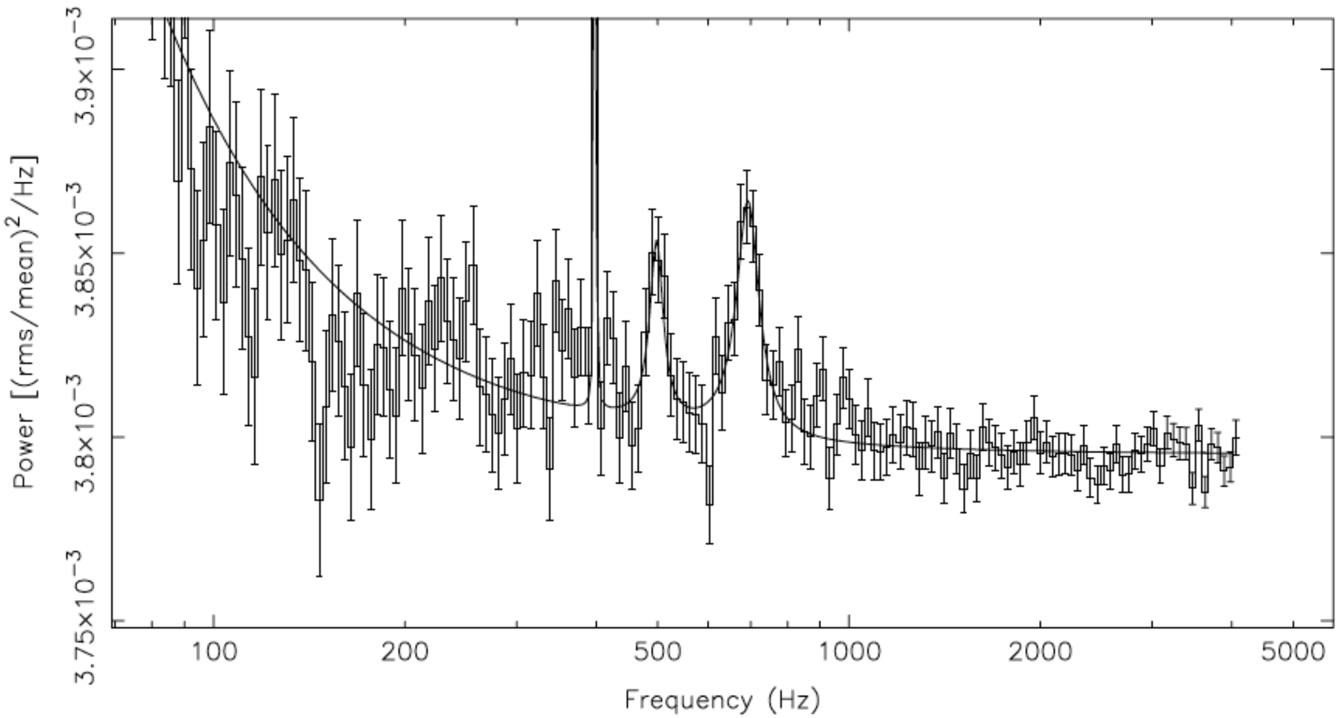
Similar physics as accreting protostars…



Simulations by Cornell group:
M. Romanova, Lovelace, etc

Quasi-Periodic Oscillations (QPOs)

Power density spectrum of x-ray flux variations of accreting millisecond pulsars



Van der Klis 2005

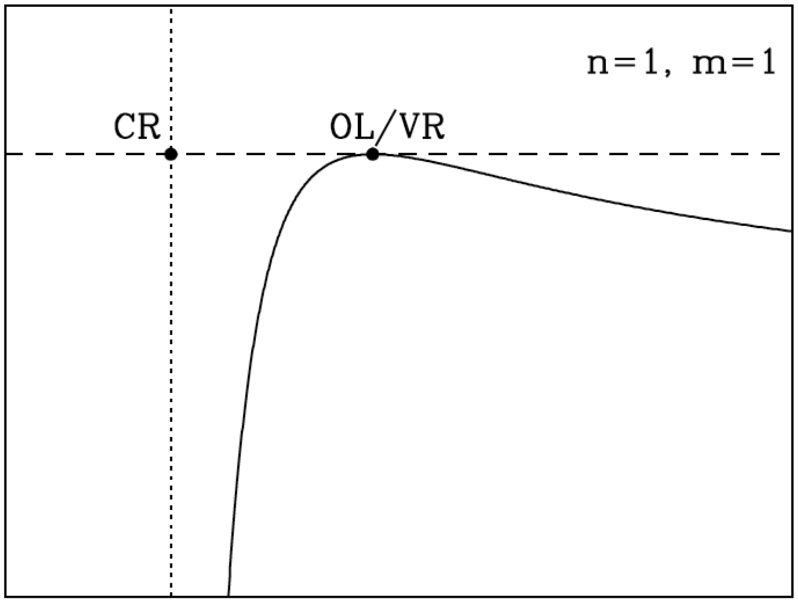
SAX J1808.4-3658: $\nu_s = 401$ Hz, $\nu_h - \nu_l \simeq \nu_s/2$ ($\pm$a few Hz)

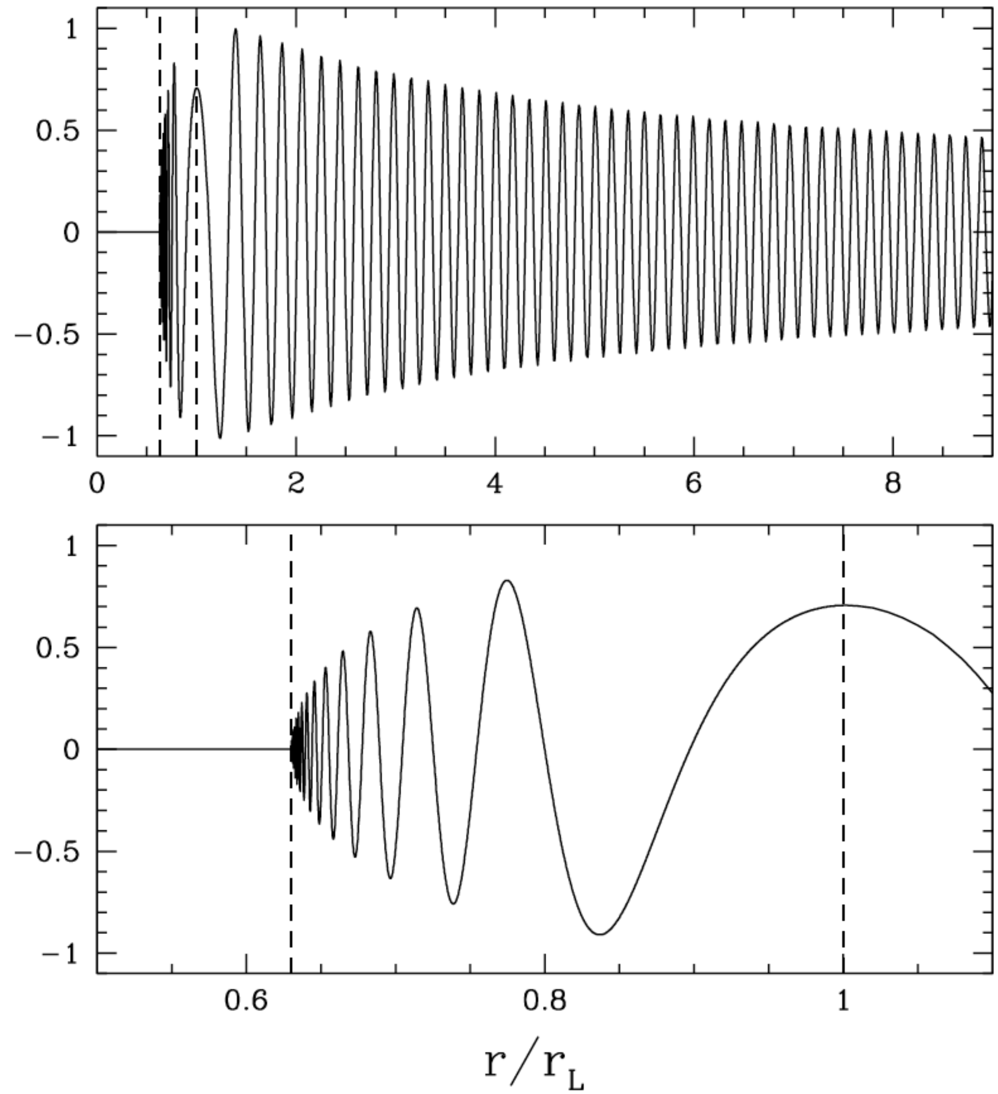
XTE J1807.4-294: $\nu_s = 191$ Hz, $\nu_h - \nu_l \simeq \nu_s$

A possible (promising) model:

A misaligned rotating dipole magnetic field can excite bending waves in disk, which can modulate X-ray flux.

Excitation of bending wave by magnetic force:





Lindblad/Vertical Resonance:

$$\omega - \Omega = \Omega_{\perp} \simeq \Omega$$

$$\Longrightarrow \quad \omega \simeq 2\Omega(r_L)$$

DL & H. Zhang 2008

Details: Magnetically Driven Bending Waves in Disks

- Perturbations most "visible" at Lindblad/Vertical Resonance

$$\omega - \Omega = \Omega_\perp \simeq \Omega$$

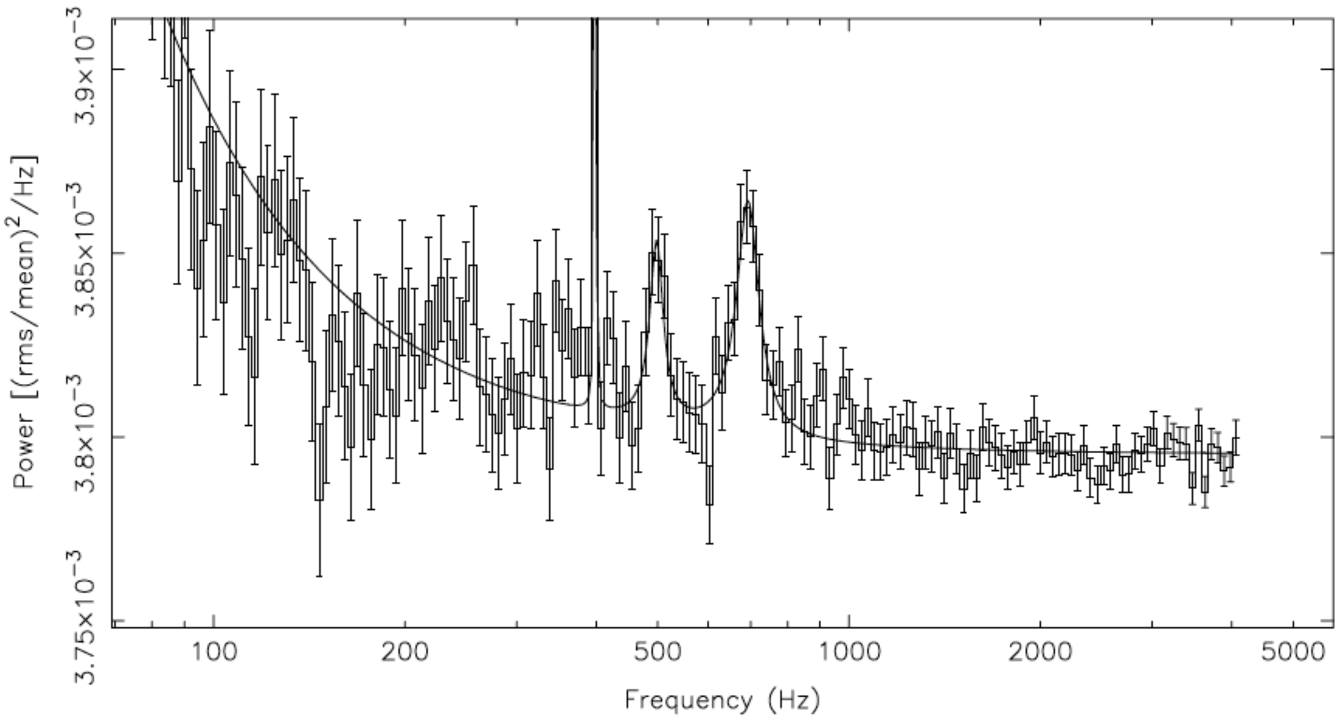
$$\Longrightarrow \quad \Omega(r_L) = \frac{1}{2}\omega = \frac{\omega_s}{2},\ \omega_s$$

- Dimensionless perturbation amplitude reaches a few %

- Beating of high-freq. QPO with perturbed fluid at L/VR produces low-freq. QPO?

Quasi-Periodic Oscillations (QPOs)

Power density spectrum of x-ray flux variations of accreting millisecond pulsars



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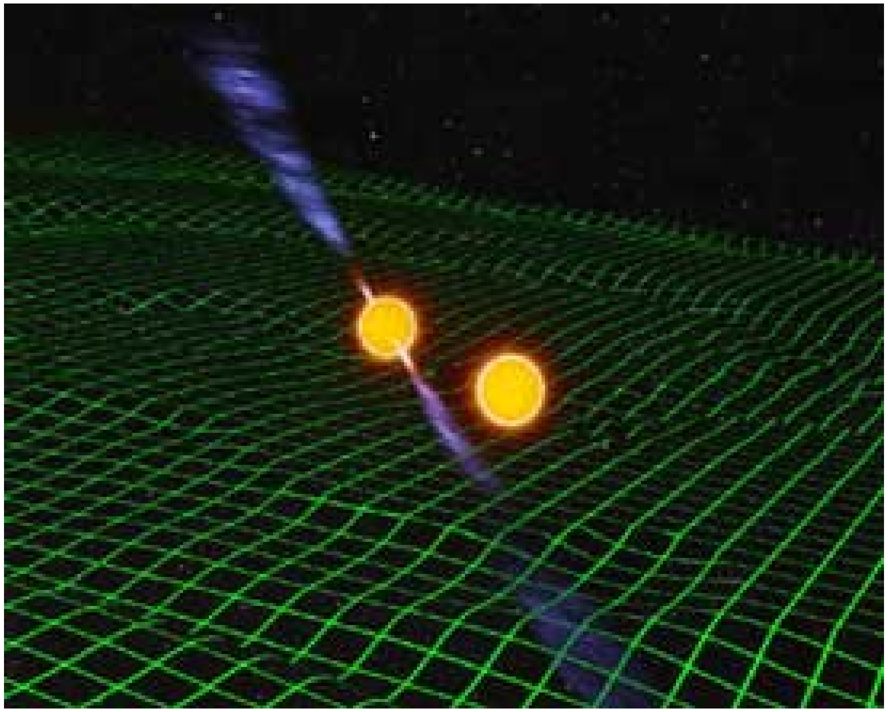
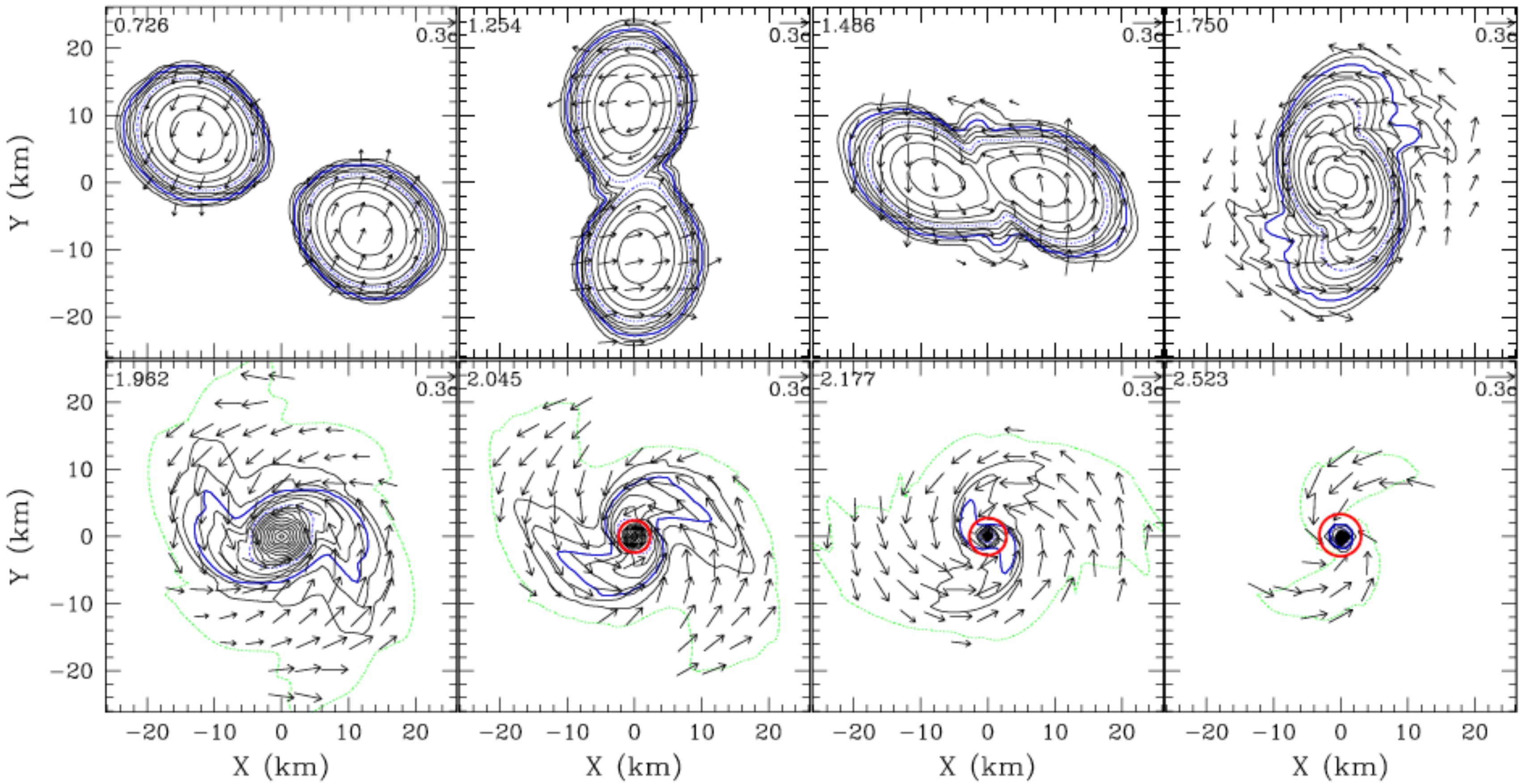
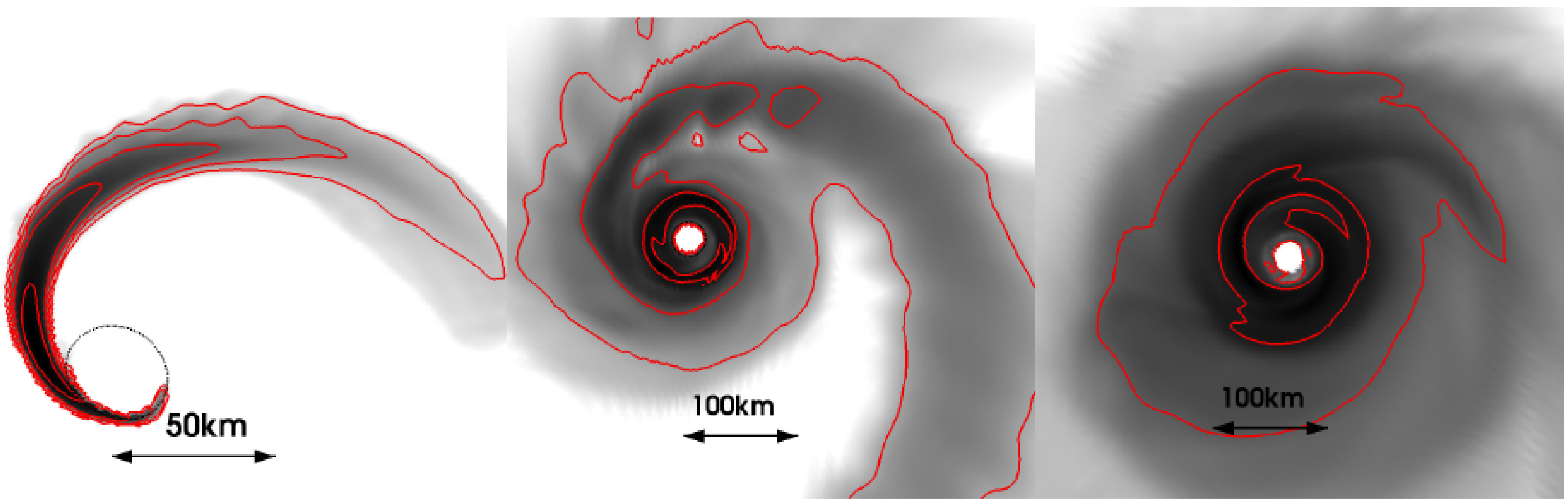
Merging Neutron Stars



Binary pulsars

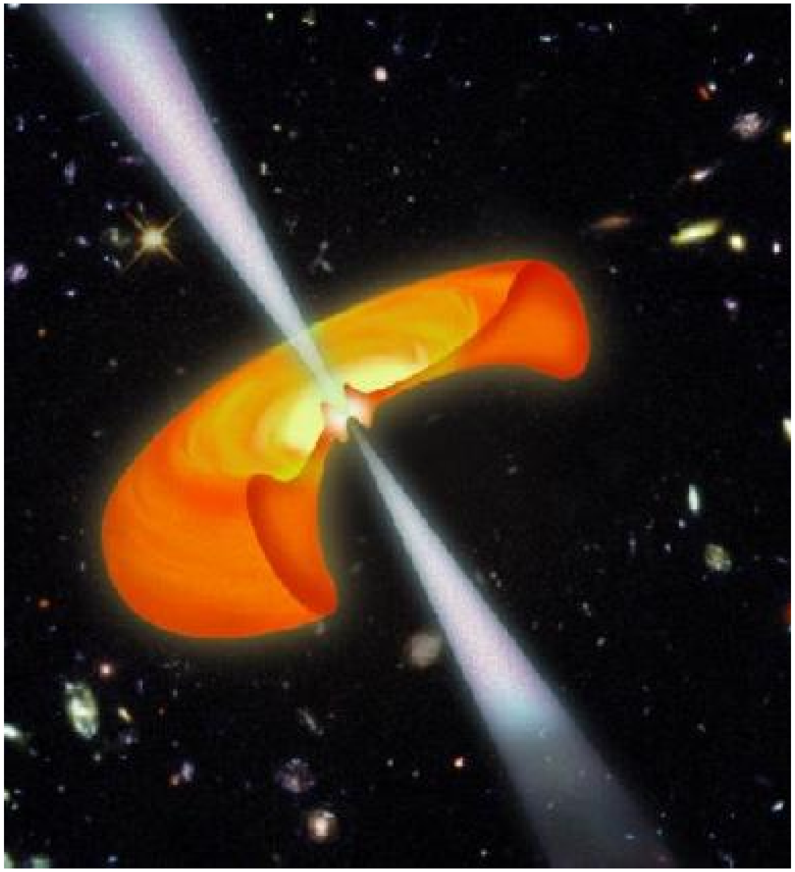


Shibata et al. 2006

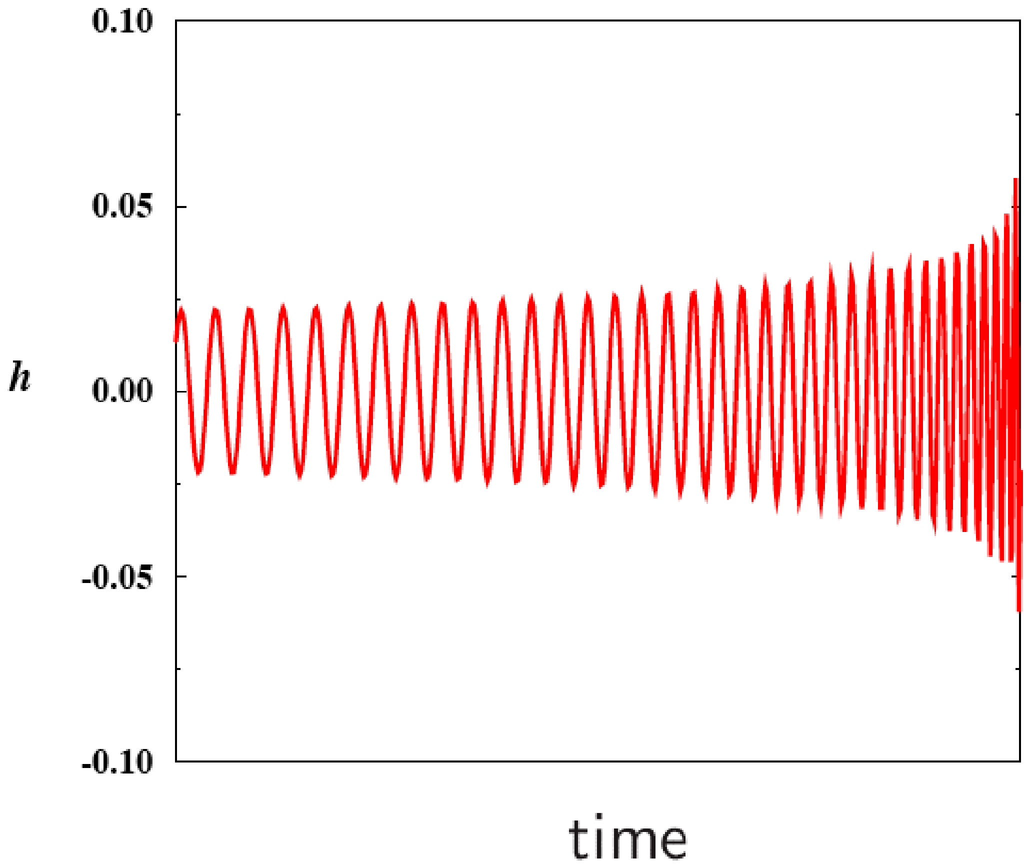


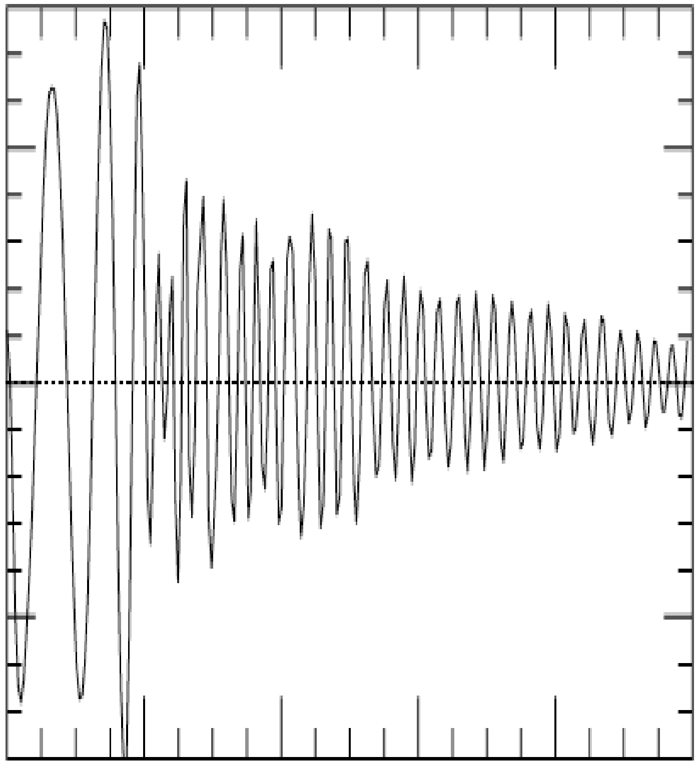
F. Foucart et al (Cornell) 2011

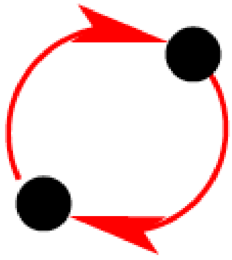
Merging NSs (NS/BH or NS/NS) as Central Engine of (short/hard) GRBs

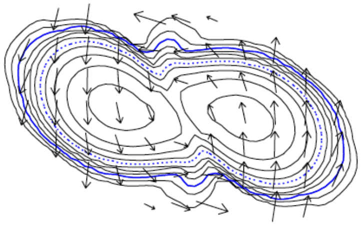


The last three minutes: Gravitational Waveform



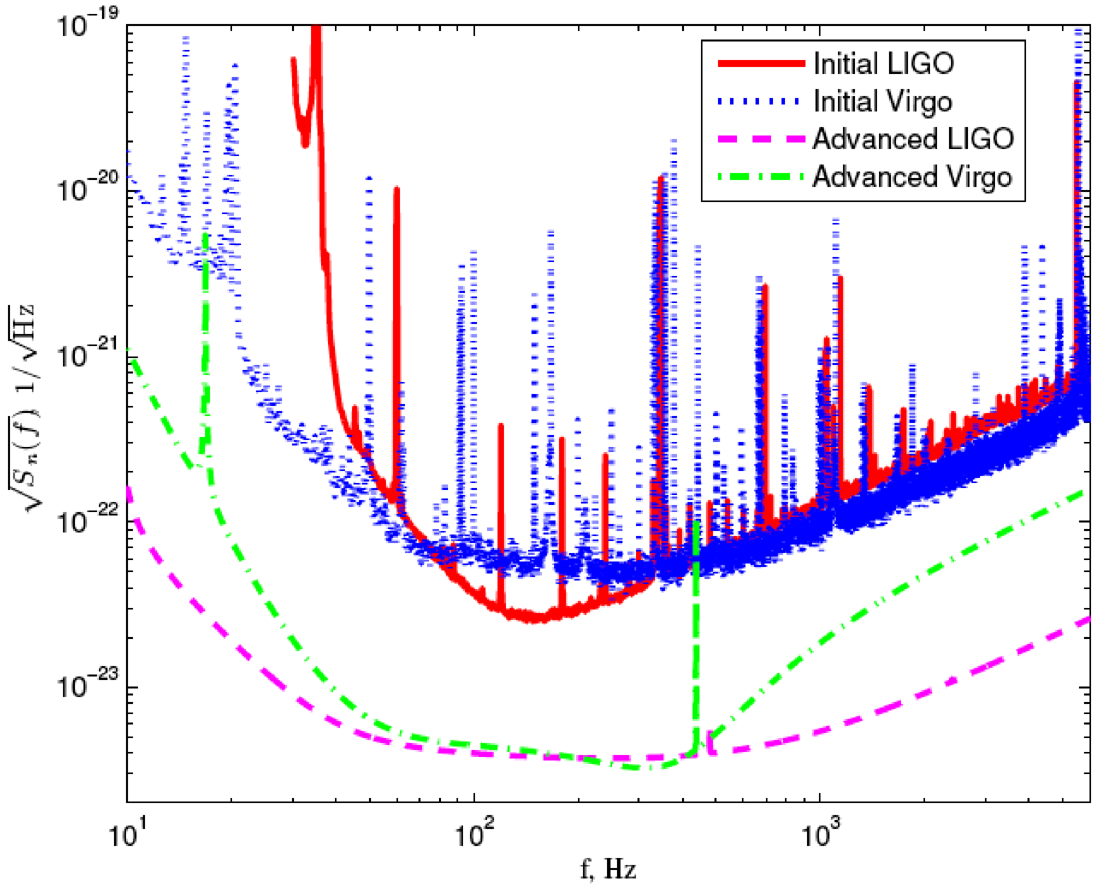




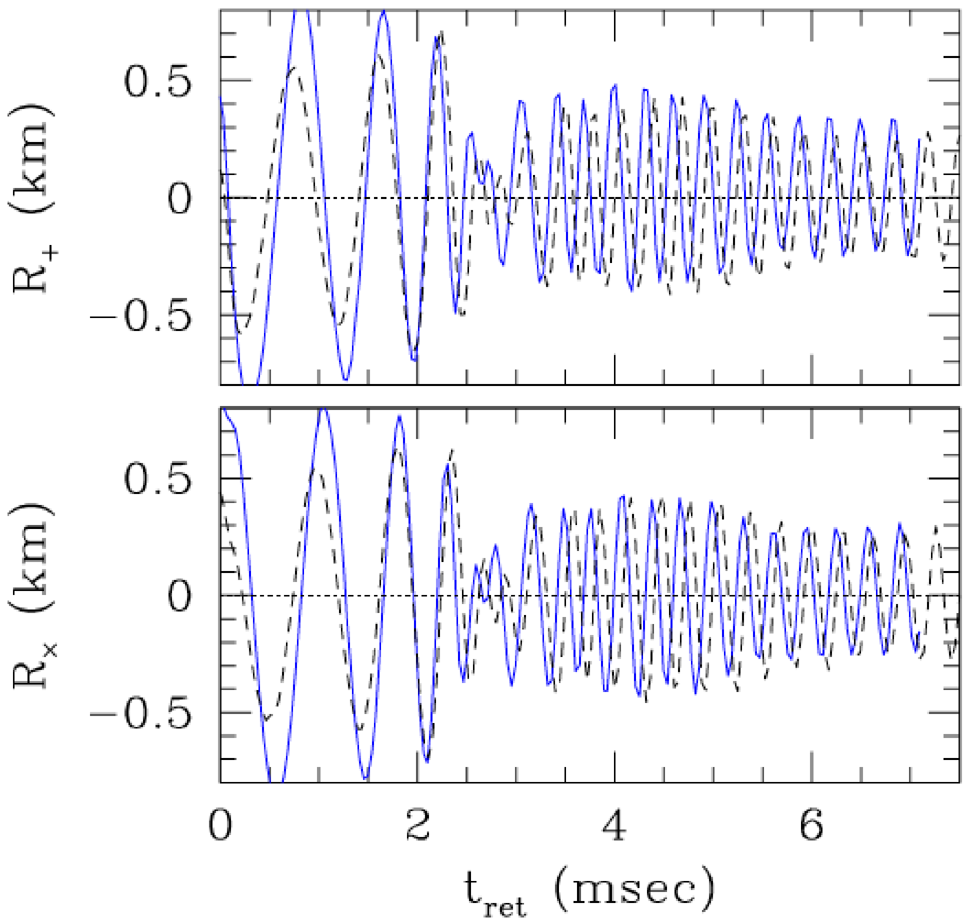


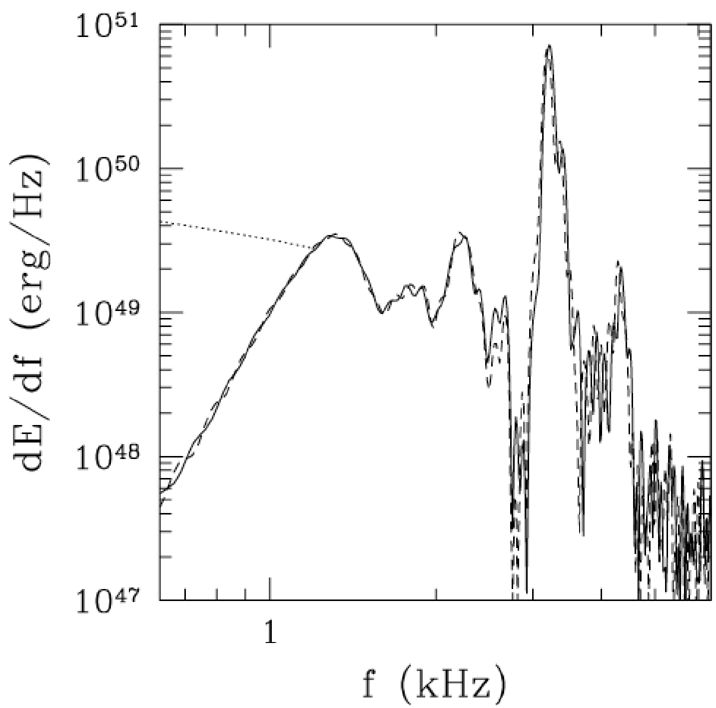

Hanford Washington


Livingston,
Louisiana


Initial LIGO
Initial Virgo
Advanced LIGO
Advanced Virgo
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
$\sqrt{S_n(f)}\ 1/\sqrt{\mathrm{Hz}}$
10^{1}
10^{2}
10^{3}
f, Hz

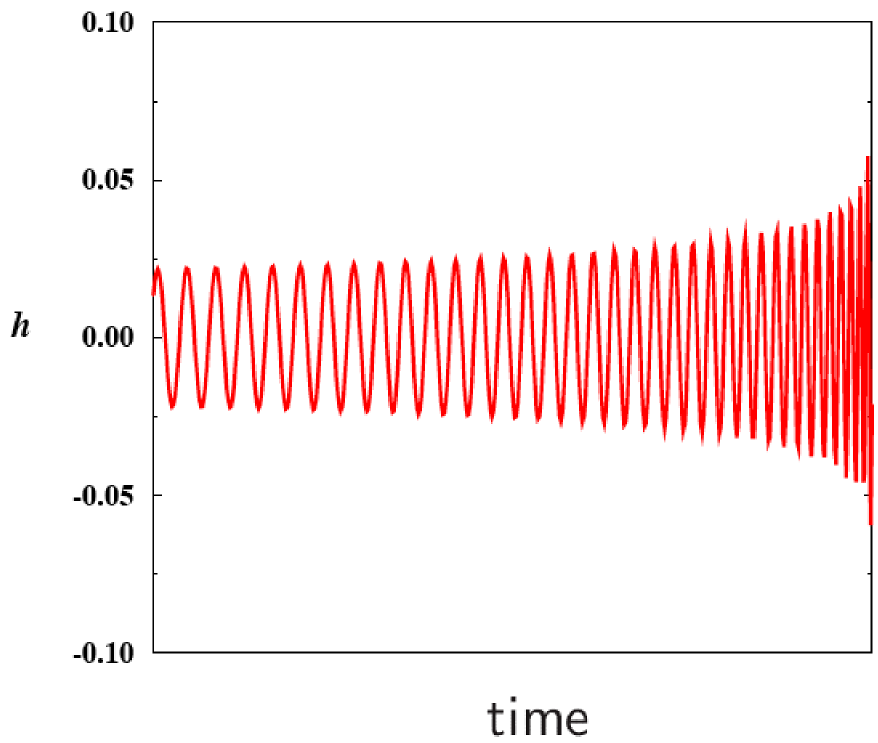
Final merger wave form probes NS EOS

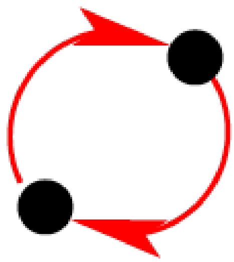




Shibata et al 2006

Probe NS EOS using Inspiral Waveform





Idea:

- For point masses, the number of GW cycles is known exactly

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

Resonant Excitations of NS Modes During Binary Inspiral

Non-rotating NS:

G-mode (Reisenegger & Goldreich 1994; DL 1994)

Rotating NS:

G-mode, F-mode, R-mode (Wynn Ho & DL 1999)
Inertial modes (DL & Yanqin Wu 2006)
R-mode (excited by gravitomagnetic force; Racine & Flanagan 2006)

Results:

- For R=10 km NS, the number of missing cycles < 0.1, unlikely 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
- Crustal modes: important? Could shatter crust, pre-cursor of short GRB (D. Tsang et al. 2011)

Summary

- **Compact Objects present a rich set of astrophysics/physics problems:**
  Ideal laboratory for probing physics under extreme conditions

- **Diverse observational manifestations:**
  * **Binary WDs**
  * **Isolated NSs** (powered by rotation, magnetic fields, or internal heats)
    Effects of magnetic fields: crust, surface, matter in strong B, magnetosphere processes
  * **Accreting NSs** (powered from outside): QPOs, disk warping, precession, wave excitations
  * **Merging NSs:** Possible central enegine of short GRBs; primary sources of gravitational waves; tidal effect; probe of NS EOS