Different Manifestations of Neutron Stars

- Isolated (Magnetic) Neutron Stars:
  From Interior to surface to magnetosphere
- Accreting Neutron Stars
- Merging Neutron Stars

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Cornell University

"Modern Physics of Compact Stars", Yerevan, Sept 18, 2008

Isolated Neutron Stars

Radio pulsars:

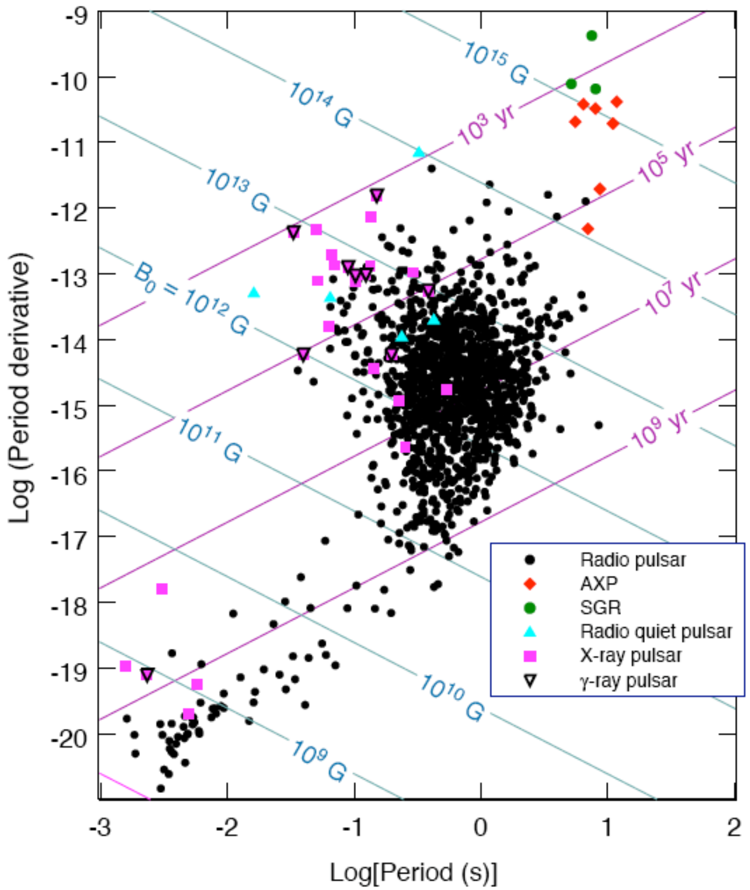
$$\text{Most pulsars}: \quad B \sim 10^{12-13}\ \text{G}$$

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

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

Radiation at all wavelengths:

radio, IR, optical, X-rays, Gamma-rays
(e.g. Fermi Gamma-Ray Telescope)



New Odd Behaviors:

- RRATs (rotating radio transients)
  radio busrts (2-30 ms), quiescence (min-hrs);
  period ~ sec (McLaughlin et al. 2006)

- Intermittent Pulsars ("Sometimes a pulsar")
  e.g. PSR B1931+24: "on" for ~ a week,
  "off" for ~ a month (Kramer et al. 06)

Magnetars

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

Soft Gamma-Ray Repeaters (SGRs) (4+1 systems)

Anomalous X-ray Pulsars (AXPs) (9+1 systems)

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

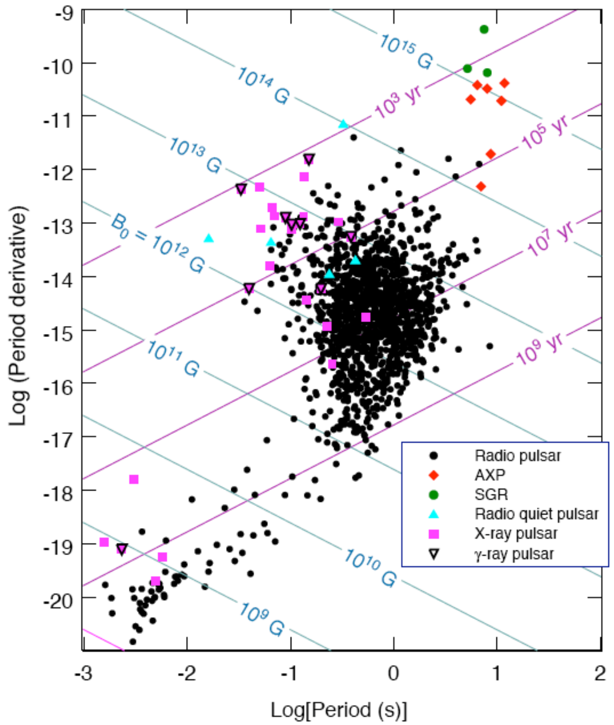
T ~0.5 keV, but significant emission up to ~100 keV (e.g. Kuiper et al.06)

AXP/SGR bursts/flares, timing behavior (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?

Radio emission triggered by X-ray outbursts

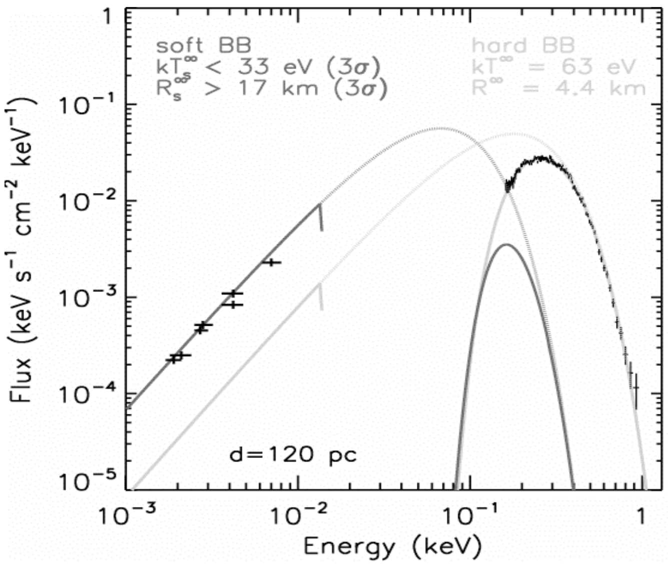
XTE J1810-197 (Camilo et al. 2006, Kramer et al.2007)

1E 1547.0=5408 (Camilo et al. 2007)

Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754



Burwitz et al. (2003)

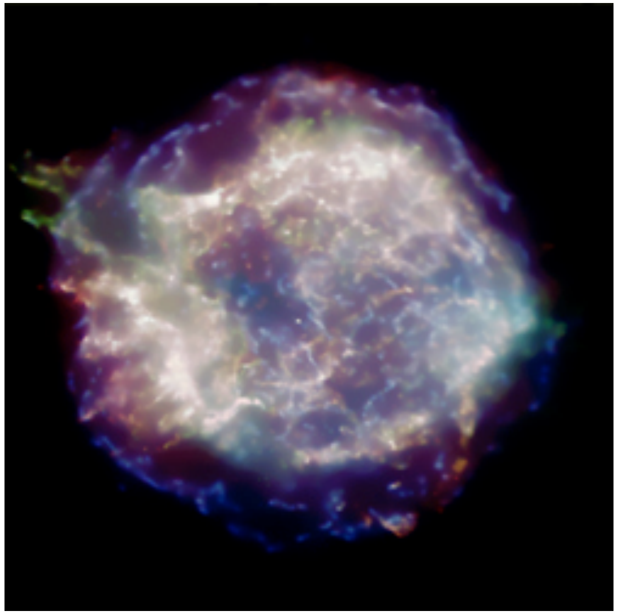
Spectral lines detected:

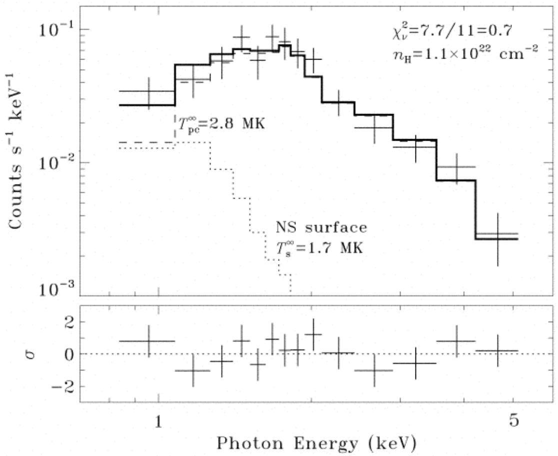
(e.g., van Kerkwijk & Kaplan 06; Haberl 06)

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





Pavlov et al. 2000

(most secure examples)

CCO	SNR	Age (kyr)	Dist. (kpc)	P (ms)	f_p^a (%)
CXOU J232327.9+584843	Cas A	0.3	4	...	< 27
RX J0822−4300	Pup A	2	3	...	< 5
CXOU J085201.4−461753	G266.1−1.2	2	2	...	< 10
CXOU J185238.6+004020	Kes 79	7	7	105	80±20
1E 1207.4−5209	PKS 1209−51/52	8	3	424	9±2
1WGA J1713.4−3949	G347.3−0.5	10	6	...	< 6

Gotthelf & Helpern 2007

PSR J1846-0258 in SNR Kes 75: P=326 ms, B=5.e13G, magnetar-like X-ray bursts (Gavrill et al 2008)

Isolated Neutron Stars

Radio pulsars

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

Magnetars

AXPs and SGRs

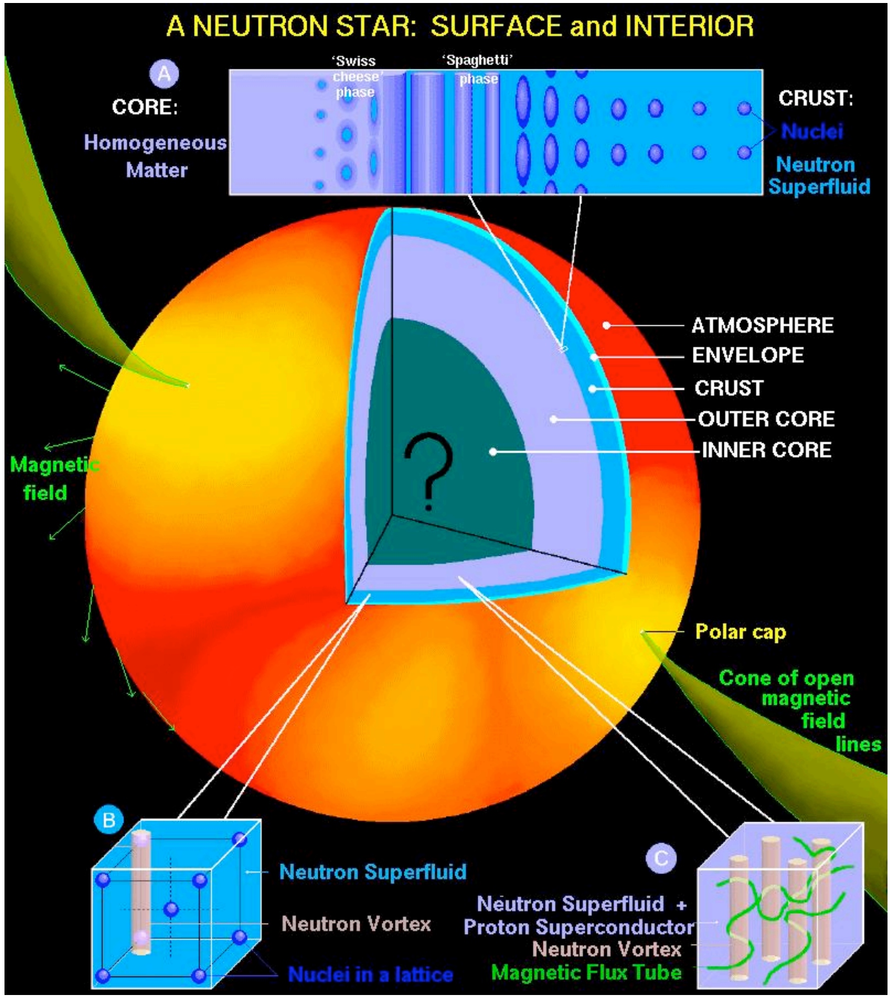
Thermally emitting Isolated NSs

Central Compact Objects in SNRs

Millisecond Magnetars (central engine of long/soft GRBs?)

Reasons for diverse NS Behaviors:
Rotation and Magnetic Fields

Neutron Star



D. Page

- Magnetosphere:
  relativstic e+e-
- Atmosphere/ocean:
  strongly coupled Coulomb plasma
- Outer crust:
  same as in WD, except neutron-rich nuclei as density increases
- Inner crust (above n drip):
  nuclei + e + n
- Liquid core (>nuclear density)

NS Crust: Some Unsolved Issues

- Composition?

  --Fully catalyzed (Fe,Ni, etc)? "Not clear" in outer layer (Shirakawa '07 PhD Thesis)

  --Accretion (inc. surface burning/weak interaction) changes compositon

  (e.g. Haensel & Zdunik 1990; Schatz et al.1999; Chang et al.2005; Horowitz et al.07)

- "Pure" Lattice (one kind of nucleus at a given density)?

  --Jones (1999,2004): Thermodynamical fluctuations at freezing leads to impure solid;

  --Horowitz et al (2008): Molecular dynamics simulations: ordered crystal

  --Important for B field dissipation and heat conduction in crust

- Inner Crust:

  --n superfluidity, vortex/lattice pinning/interactions

  --affect glitches and precession

  e.g., precessing PSR B1828-11 (Stairs et al. 2000) is a big headache for theory (Link, Wasserman)

Effects of Magnetic Field

- Cyclotron energy (Landau levels):

$$\hbar\omega_c = \hbar\frac{eB}{m_e c} = 11.6 B_{12}\ \mathrm{keV}$$

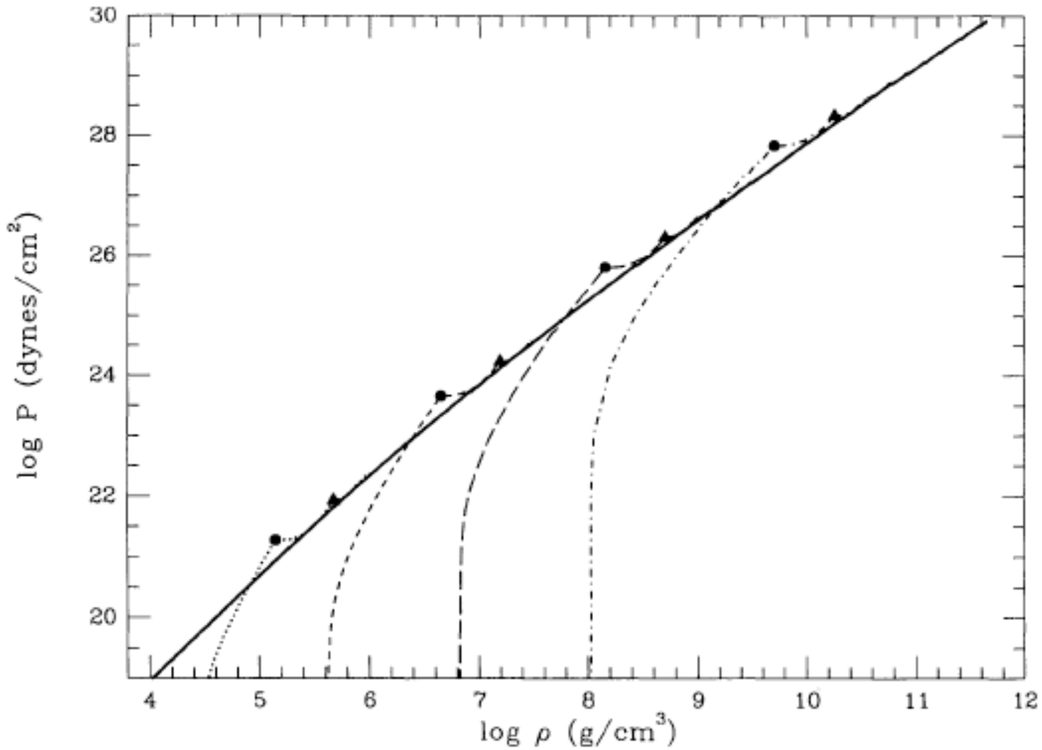
- Effects of Landau quantization on electron gas:

$$T_B = \frac{\hbar\omega_c}{k} = 1.34\times 10^8 B_{12}\ \mathrm{K}$$

$$E_{\rm Fermi} = \hbar\omega_c \Longrightarrow \rho_B = 7000\, Y_e^{-1} B_{12}^{3/2}\ \mathrm{g\ cm^{-3}}$$

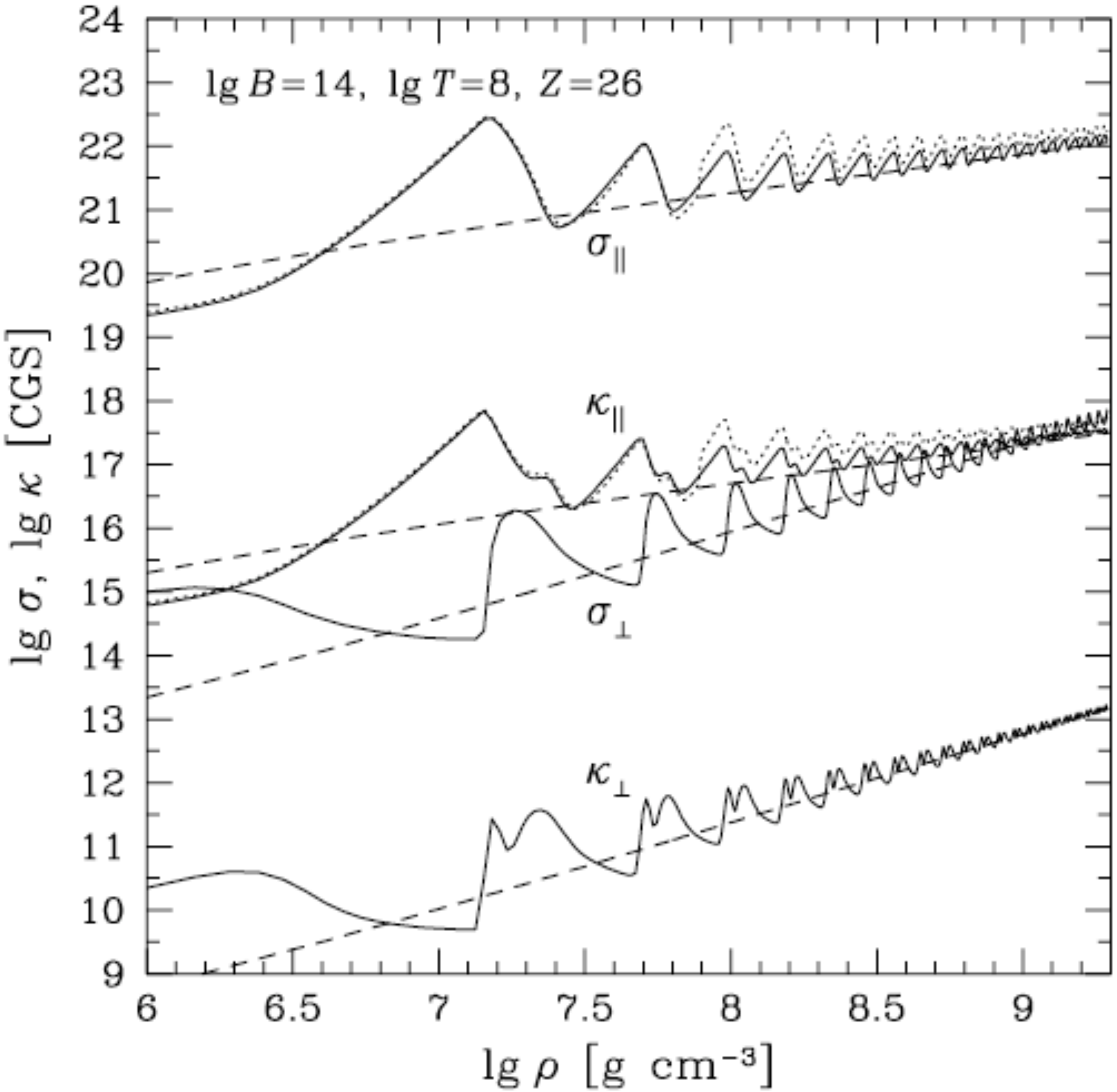
For $T \lesssim T_B$ and $\rho \lesssim \rho_B$ affects thermodynamical quantities

EOS (pressure, beta-equilibrium etc)
Rates (electron capture etc)
Electric & thermal conductivities, magnetizations, screening length, etc



$P(\rho)$ affected by B only for $\rho < 10^4 B_{12}^{3/2}$ g cm^{-3}

Heat and electric conductivities



de Haas-van Alphen oscillations

Potekhin 1999

Magnetic fields affect the transport properties

(even for nonquantizing fields, $\rho \gtrsim \rho_B$)

gyrofrequency $\omega_c^* = \dfrac{eB}{m_e^* c} \gg$ elecron collision frequency τ_0^{-1}

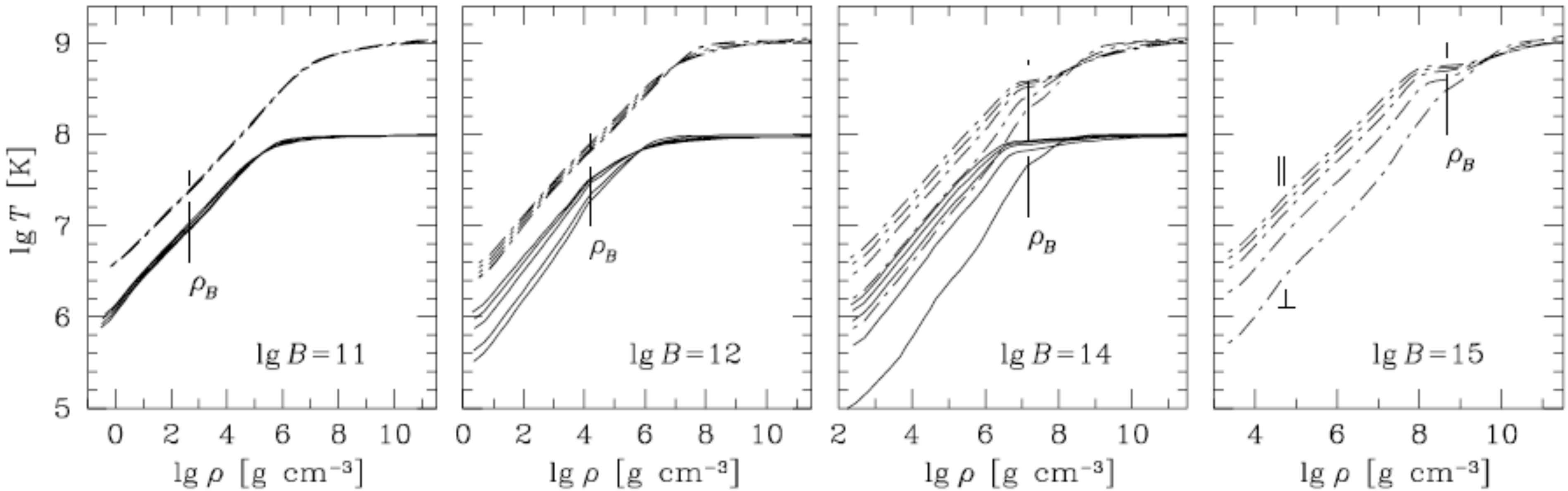
transverse conductivity suppressed by a factor of $(\omega_c^* \tau_0)^{-2}$

Affect thermal structure of NS envelope and cooling

(e.g. Hernquist, van Riper, Page, Heyl & Hernquist, Potekhin &Yakovlev etc.)

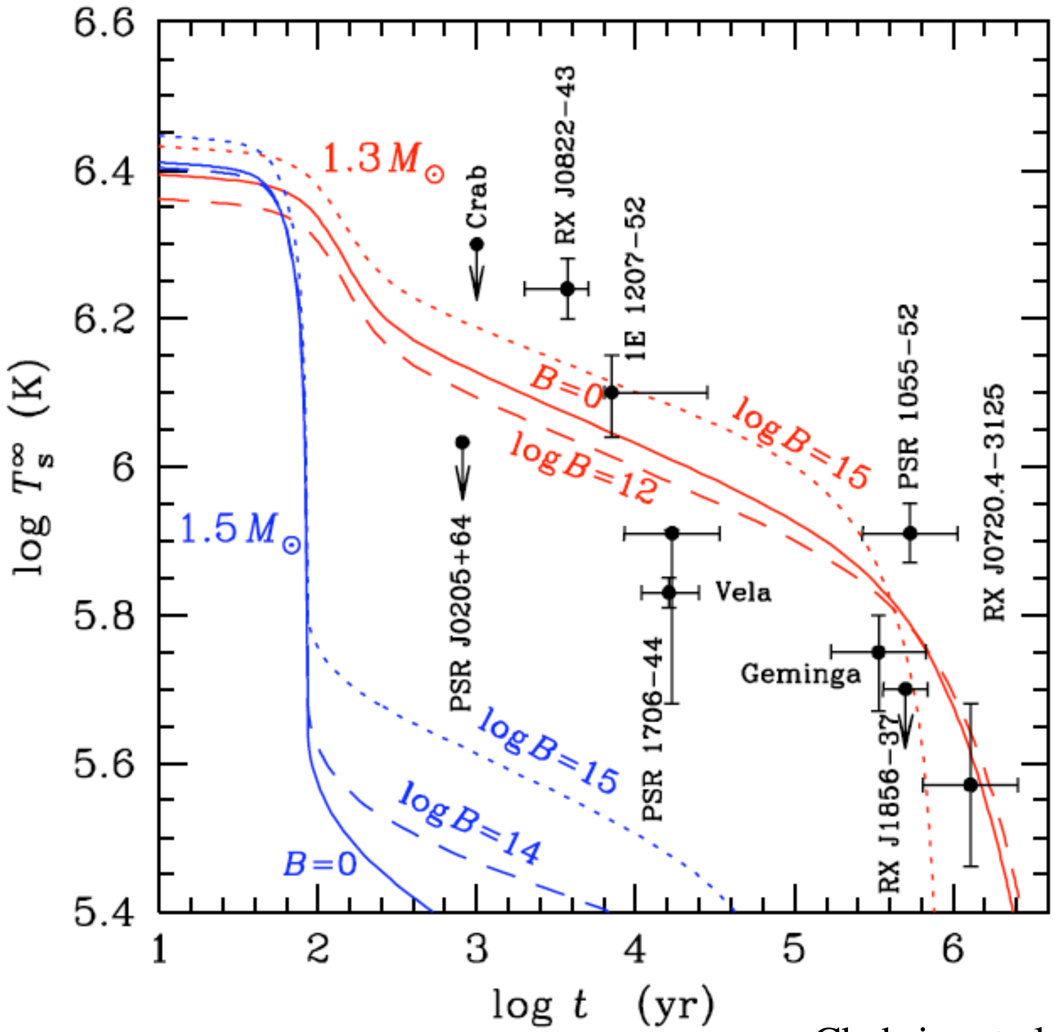
Nonuniform surface T due to anisotropic heat transport

- Region where B perpendicular to r: heat flux is reduced
- Region where B parallel to r: heat flux remains or increases (due to quantization)



Potekhin & Yakovlev 2001

Effect on (Passive) Cooling



Chabrier et al. 2006

Outermost Surface layers

- Important because:
  - --mediates emergent radiation from surface to observer
  - --boundary condition for magnetosphere model
- Composition unknown a priori
  - --hint from observations?
- Depending on B, T and composition, may be
  - --gaseous and nondegenerate, nonideal, partially ionized atmospheres: e’s, ions, atoms, molecules (small chains)
  - --condensed state (zero-pressure solid)

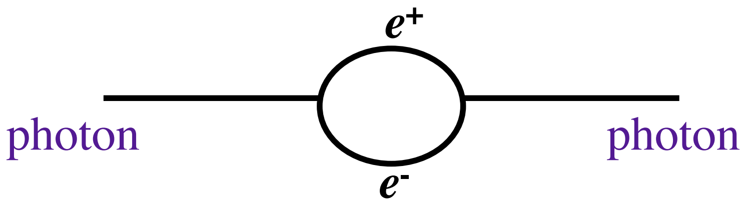
Radiative Transfer in Magnetic NS Atmospheres

Relevant to thermal emission of NSs

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



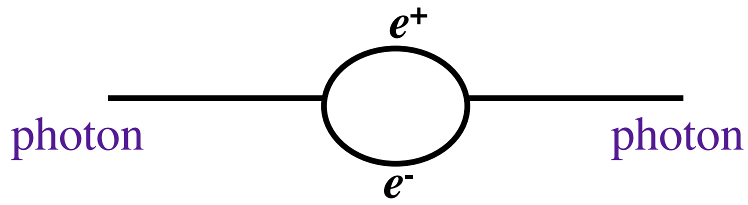
Heisenberg & Euler, Weisskopf, Schwinger, Adler…

Important when B is of order or larger than

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

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

Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
Adler…

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

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

Two photon modes:

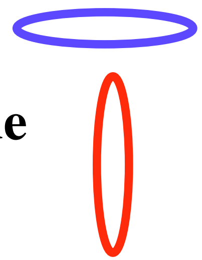
Ordinary mode (//)

Extraordinary mode (⊥)

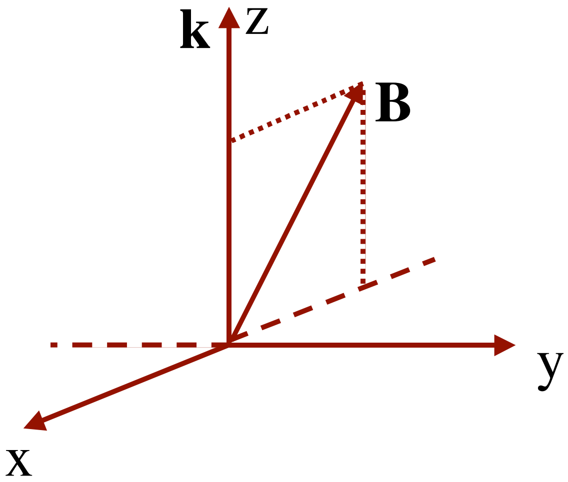
Magnetic Plasma by itself (without QED) is birefringent:

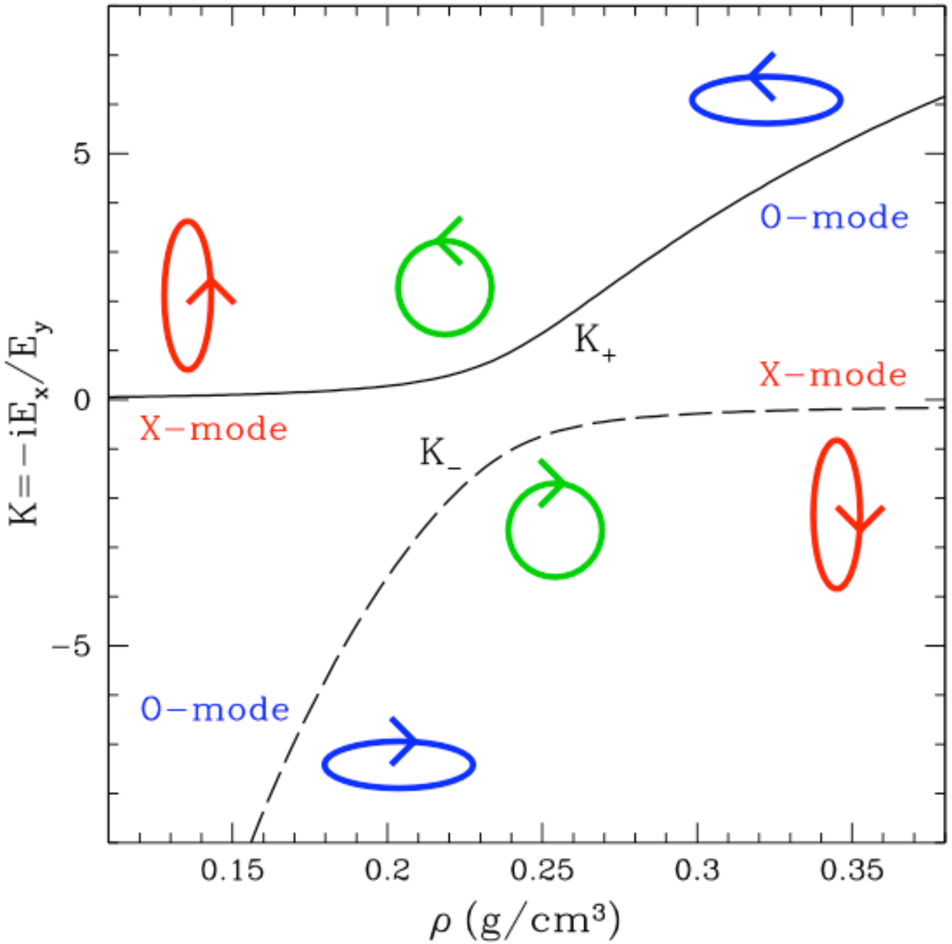
Ordinary mode

Extraordinary mode

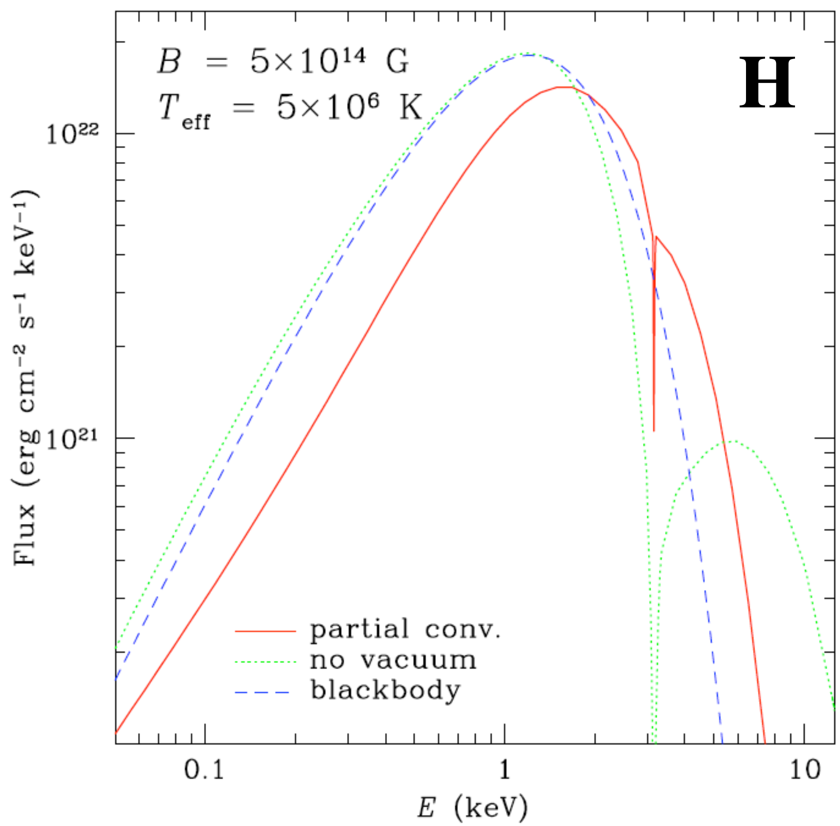


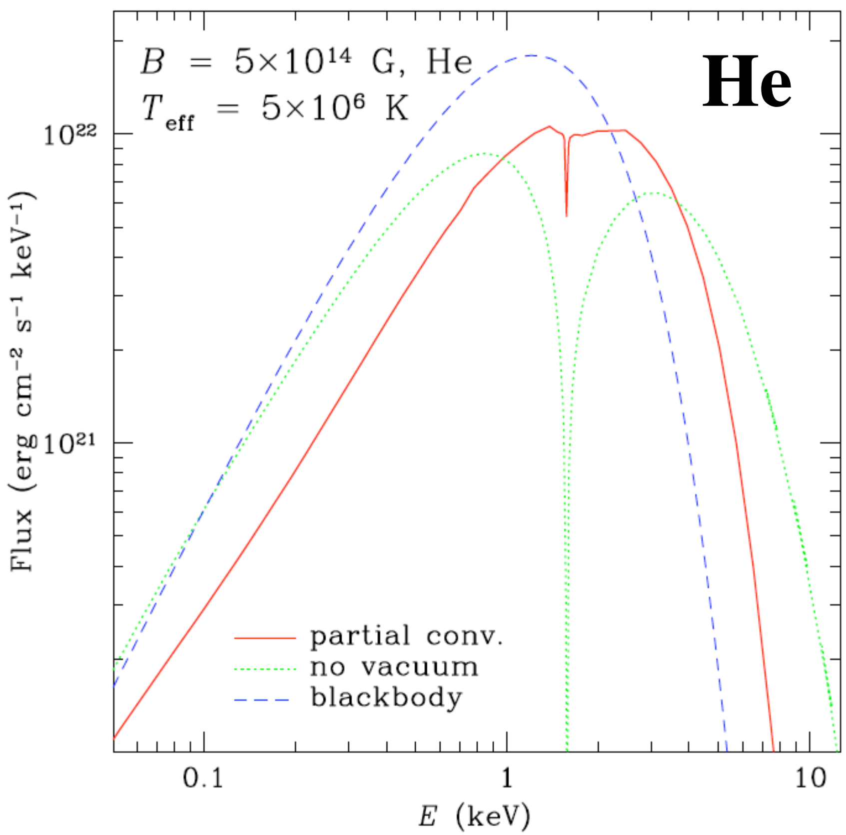
“Plasma+Vacuum” ==> Vacuum resonance





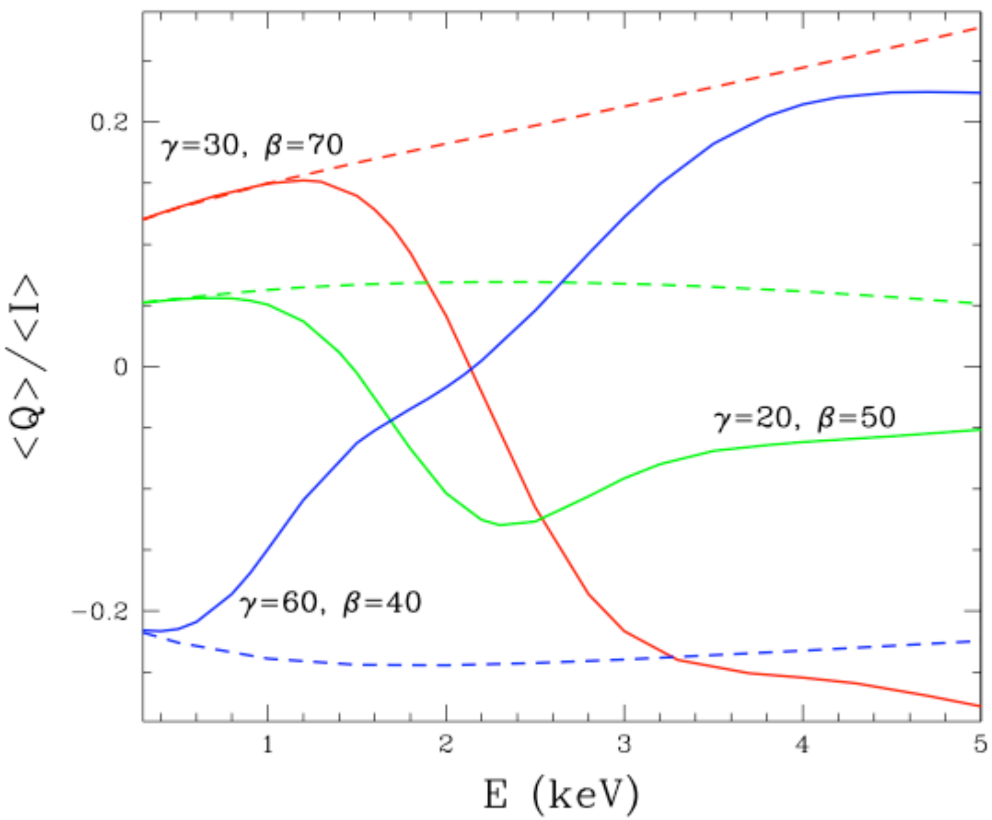
For B>10^{14}G, vacuum polarization strongly affects spectrum



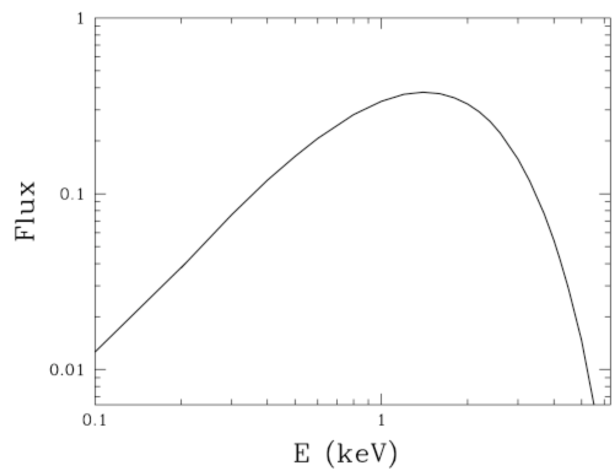


Matt Van Adelsberg & DL 2006

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

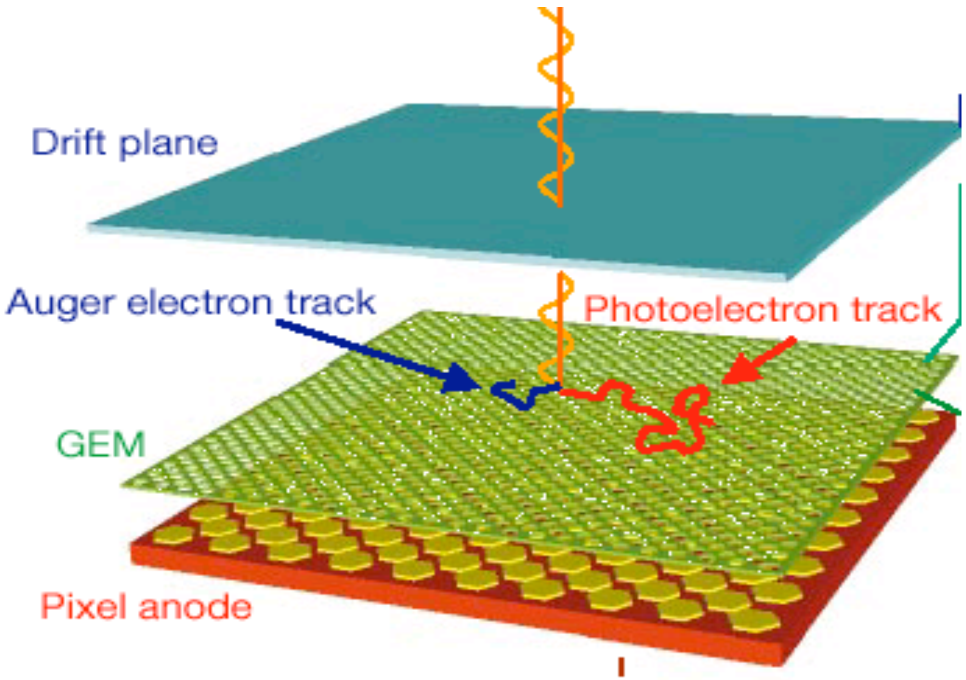
X-ray Polarimetry: Measurement Concept

Initial photo-electron direction has memory ($\cos^2\theta$) of incident polarization

Initial demonstration at INFN (Italy) Costa et al., Nature, 411, 662, (2001)

Individual photo-electron tracks are measured with a fine-spaced pixel proportional counter. The track crosses multiple pixels.

Gas filled counter can be tuned to balance length of photoelectron track and quantum efficiency



GEMS **J. Swank & T. Kallman (GSFC)**

Bound states (atoms, molecules, condensed matter) in Strong Magnetic Fields:

Critical Field:

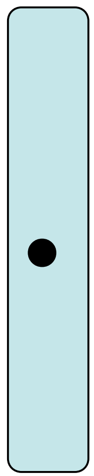
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

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

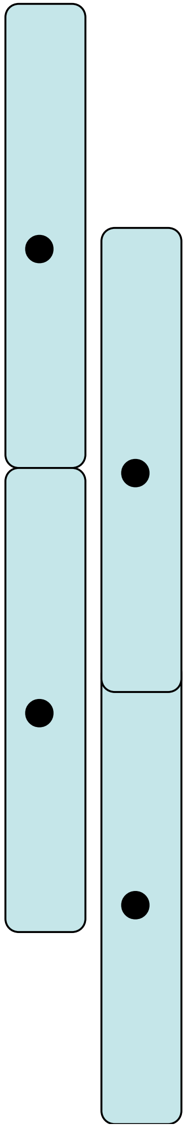
$|E| = 540 \text{ eV}$ at 10^{14}G

Atoms combine to form molecular chains:

E.g. H_2, H_3, H_4, …

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 (e.g., Ruderman, etc. 1970's)

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

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

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

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

- Quantitative Caluclations are needed:

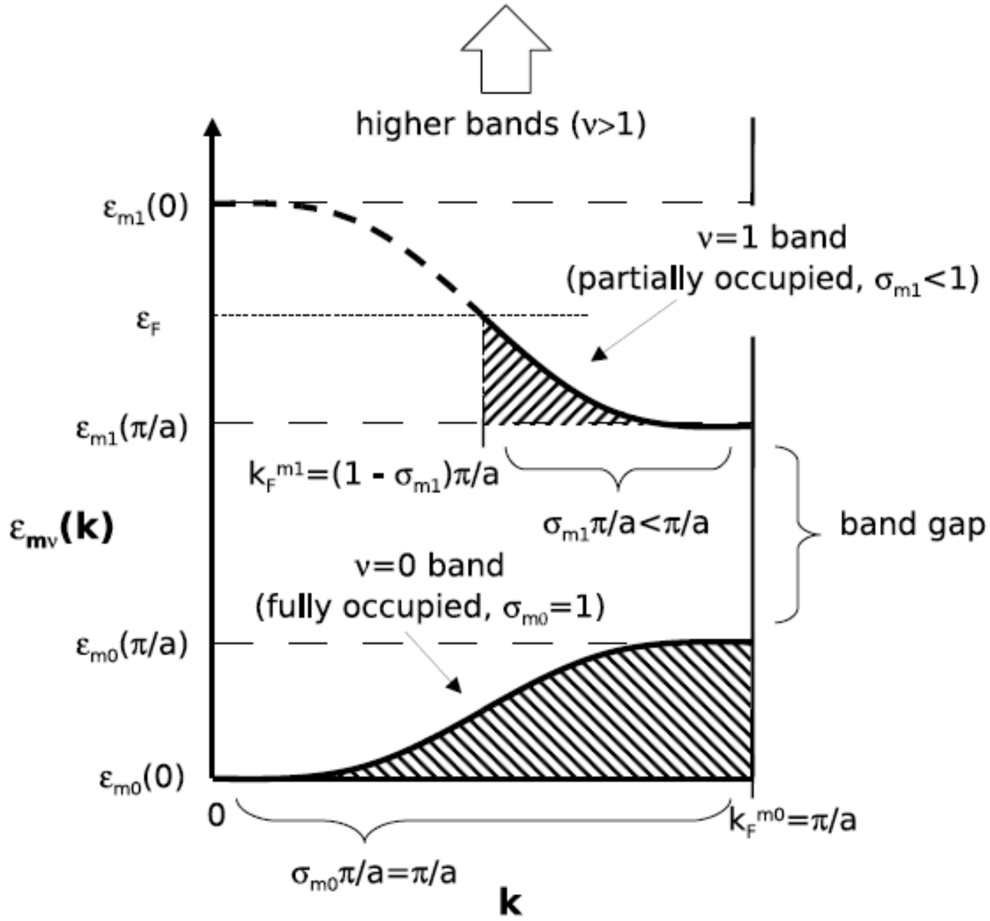
Previous calculations (P. Jones, Neuhauser et al. 1986-88) showed that

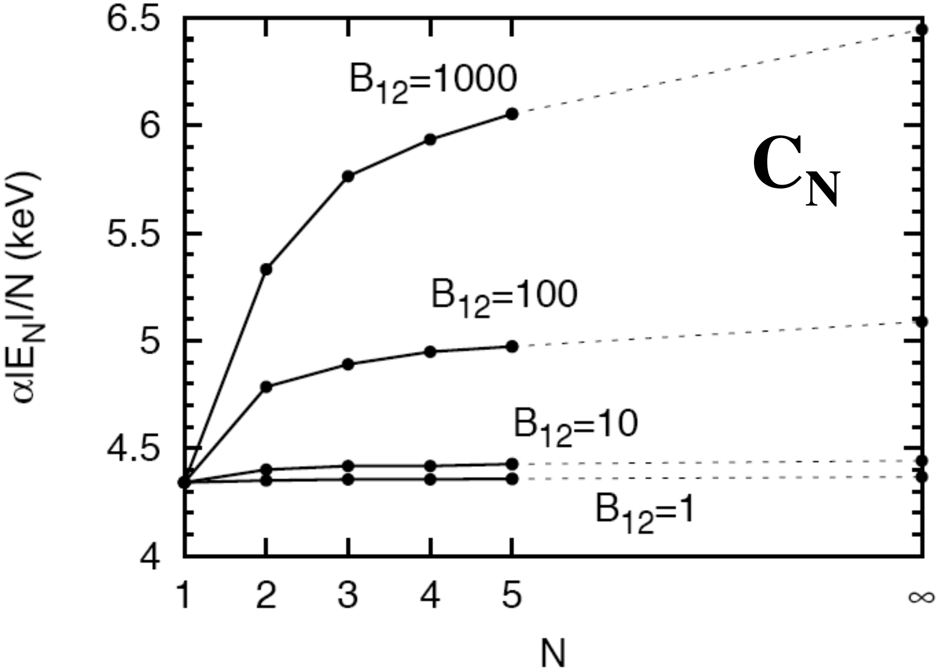
C, Fe solids are unbound (or weakly bound) at 10^{12}G;

some conflicting results.

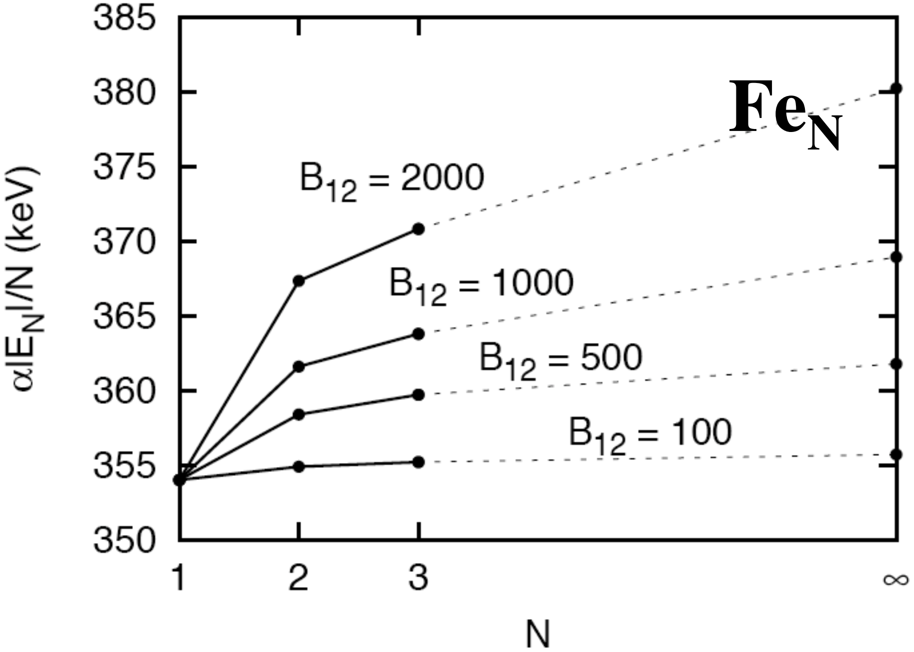
New calculations (Zach Medin & DL 2006,07)

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



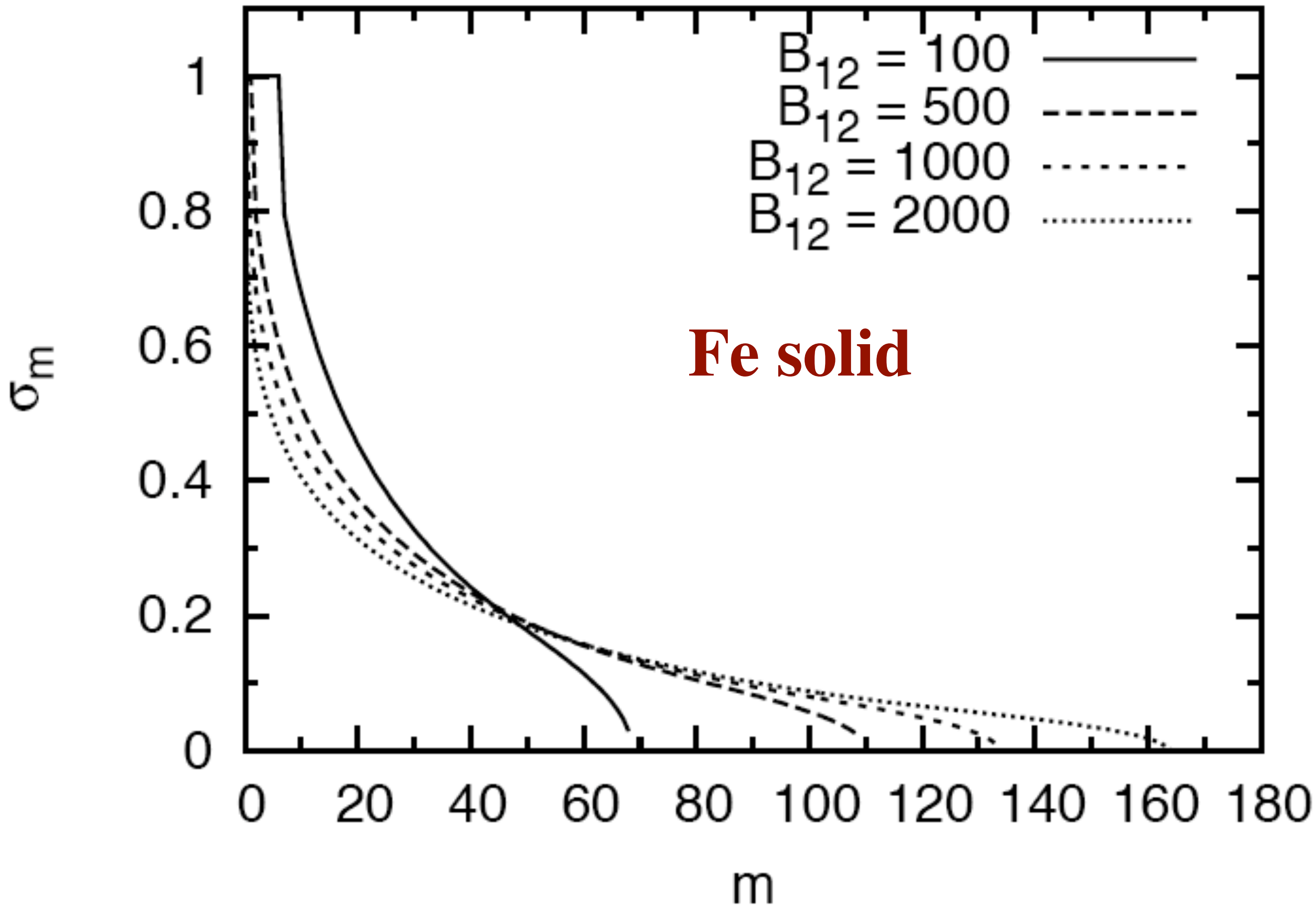


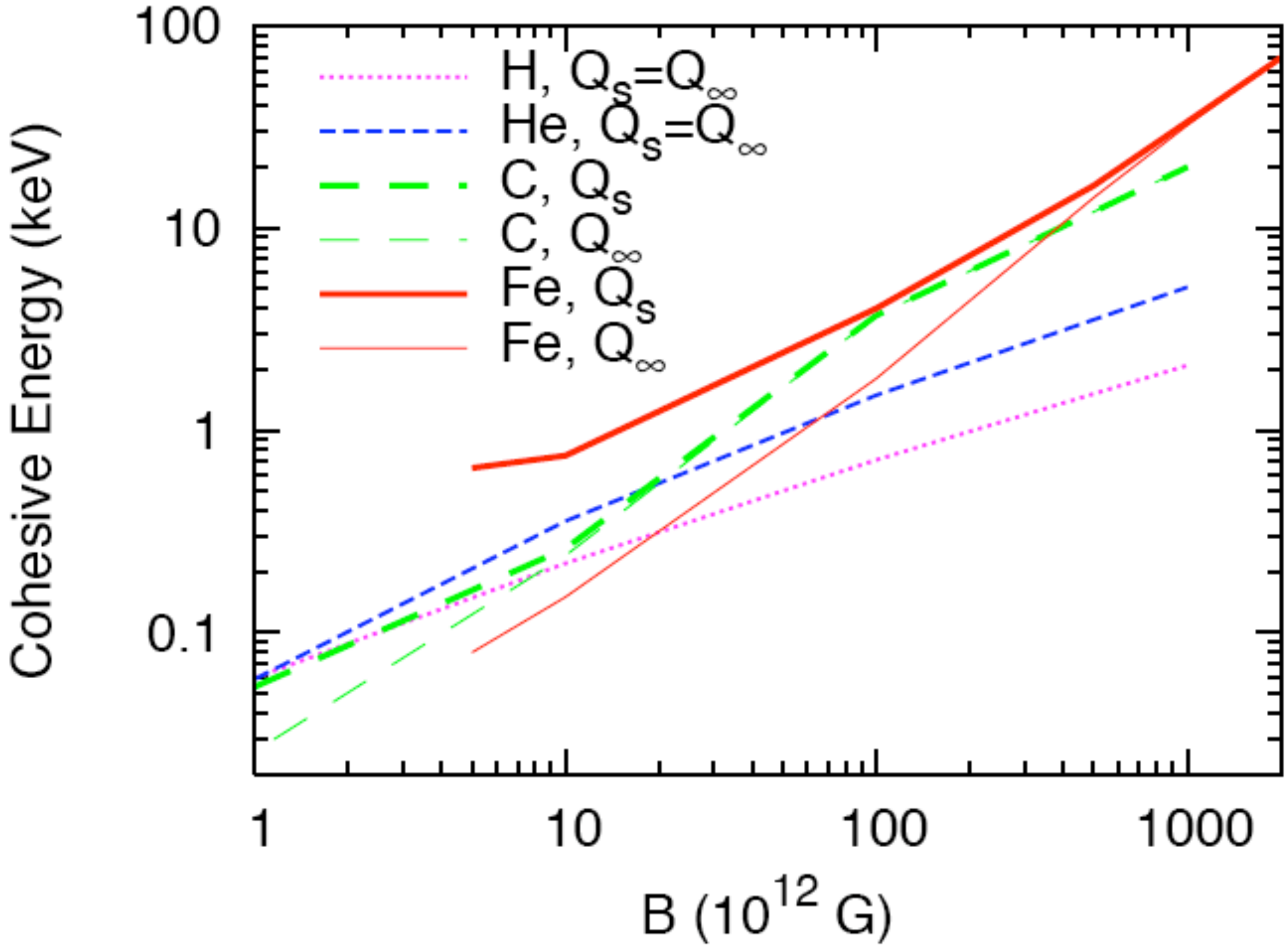
6.5
6
5.5
5
4.5
4
αIE_NI/N (keV)
B_12=1000
B_12=100
B_12=10
B_12=1
C_N
1
2
3
4
5
∞
N



385
380
375
370
365
360
355
350
αIE_NI/N (keV)
B_12 = 2000
B_12 = 1000
B_12 = 500
B_12 = 100
Fe_N
1
2
3
∞
N

Many bands (different Landau orbitals) need to be considered …



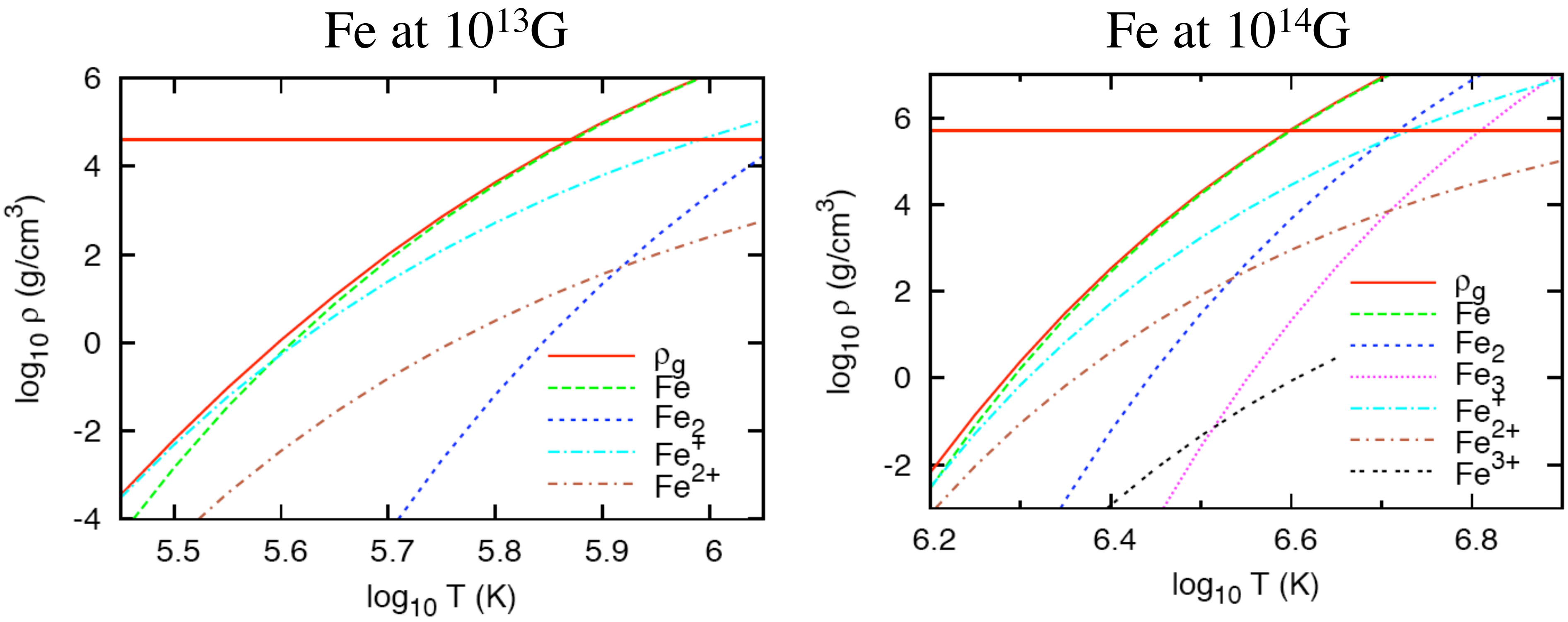


H, $Q_s=Q_\infty$
He, $Q_s=Q_\infty$
C, Q_s
C, Q_∞
Fe, Q_s
Fe, Q_∞
Cohesive Energy (keV)
B (10^{12} G)
100
10
1
0.1
1
10
100
1000

Implications…

Surface condensation of isolated NSs

Saturated Vapor of Condensed NS Surface:

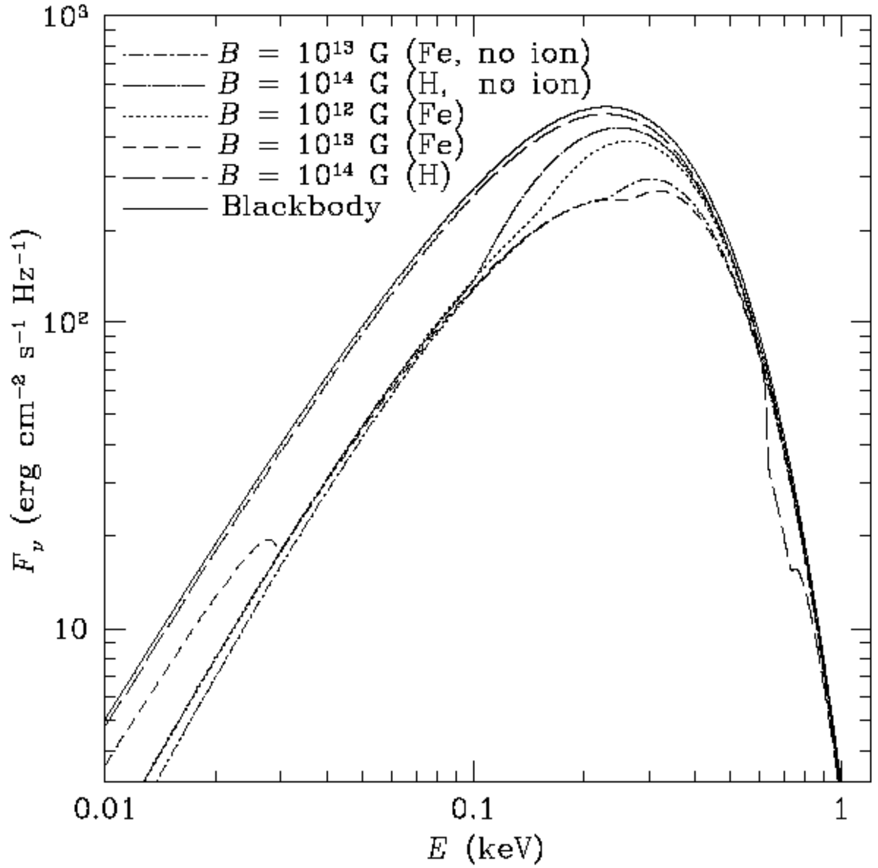


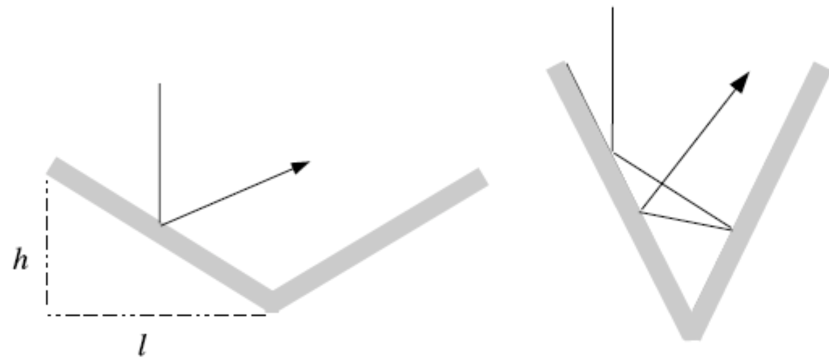
Medin & DL 2007

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





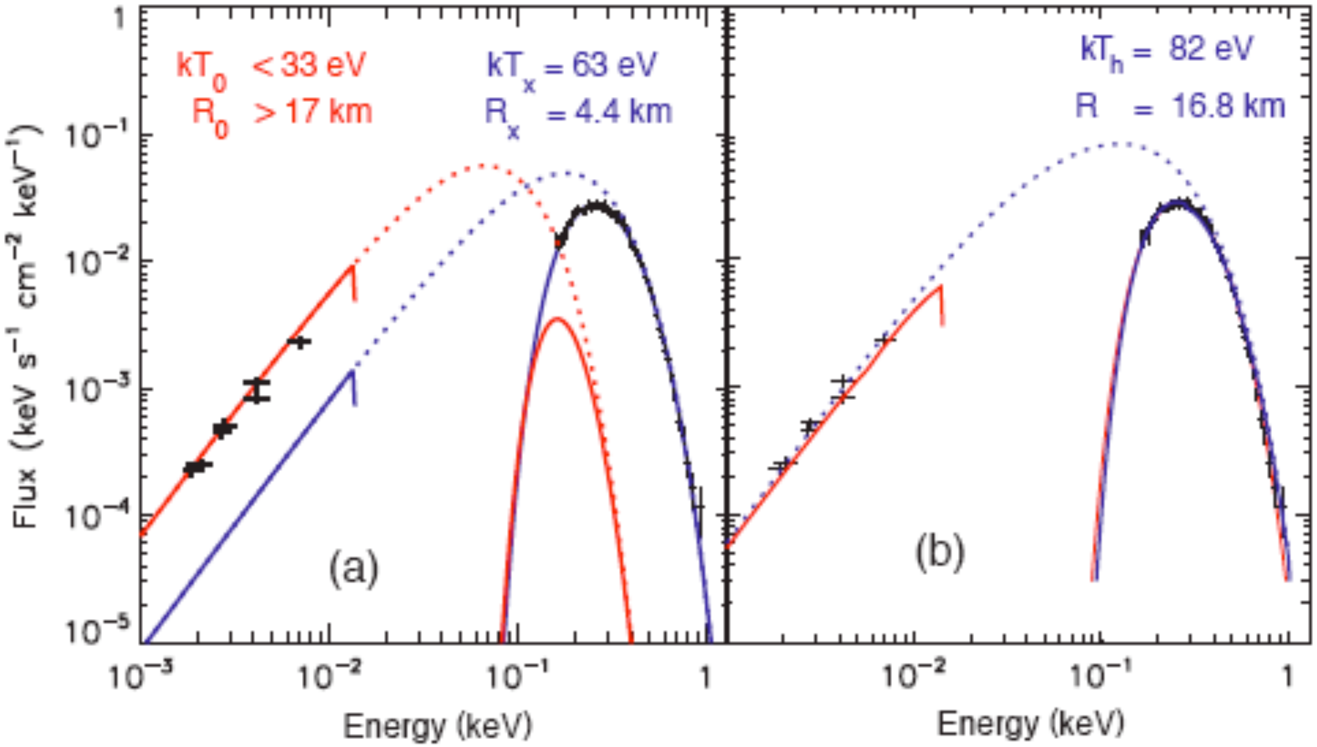
van Adelsberg, Lai, Potekhin & Arras 05

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

Particle Acceleration in Magnetosphere

The nature and efficiency of the accelerator depends on the cohesive energy of surface

Polar Gap Accelerator in Magnetosphere

Coulomb's law in rotating frame:

$$\nabla \cdot \mathbf{E} = 4\pi(\rho_e - \rho_{\mathrm{GJ}})$$

$$\rho_e = \text{actual charge density}$$

$$\rho_{\mathrm{GJ}} = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}$$ (Goldreich-Julian density)

$E_{||} \neq 0$ (gap) exists when $\rho_e \neq \rho_{\mathrm{GJ}}$

If cohesive energy is large:

$\rho_e = 0$ above polar cap ==> Vacuum Gap Accelerator

If cohesive energy is small:

Space charge limited flow (SCLF)

ρ_e close to but not thesame as $\rho_{GJ} = -\dfrac{\mathbf{B} \cdot (\mathbf{\Omega} - \mathbf{\Omega}_{\mathrm{FD}})}{2\pi c}$

==> SCLF accelerator (less efficient)

Existence of polar (vacuum) gap requires:

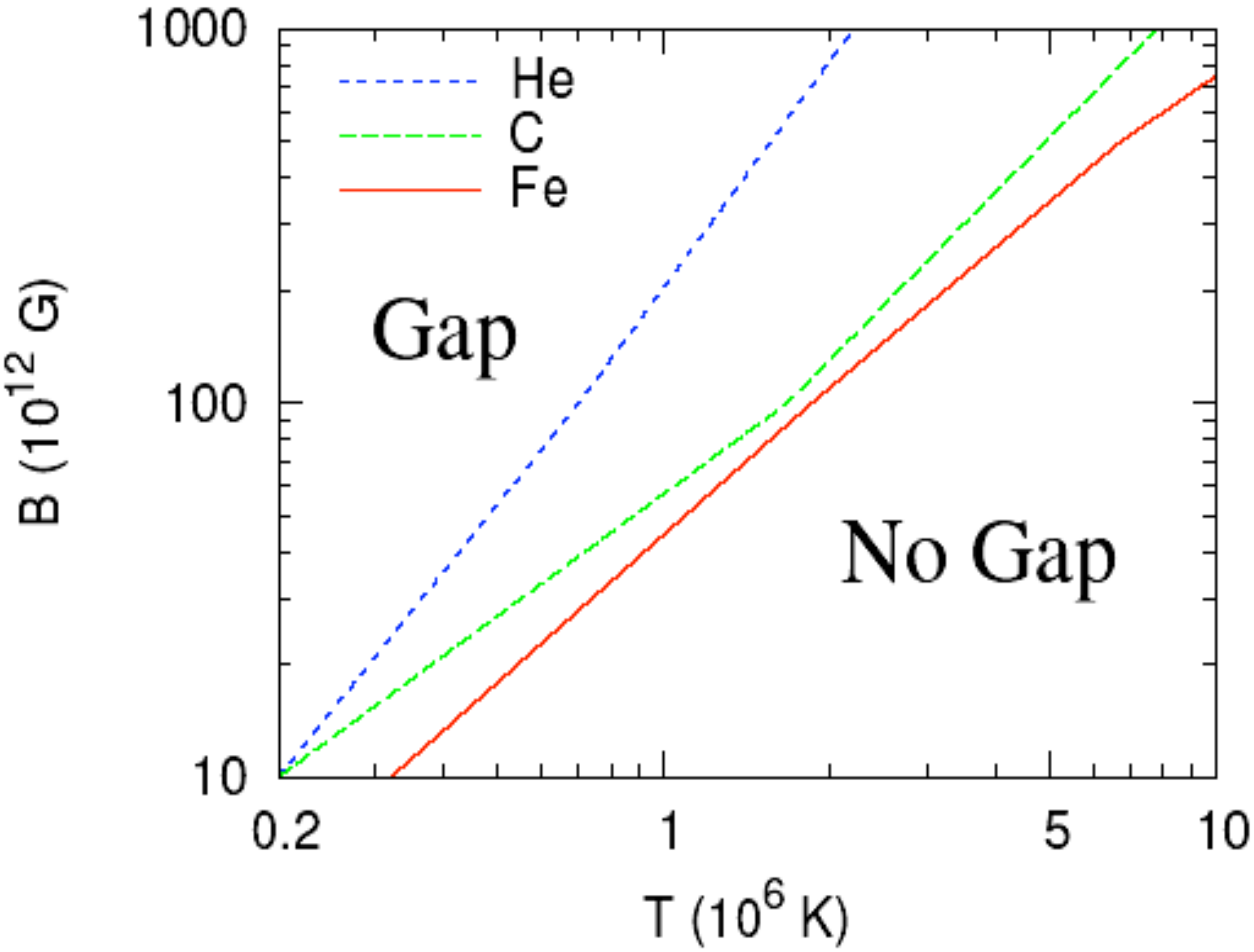
surface does not efficiently supply charges to magnetospheres

Ion emission from condensed surface:

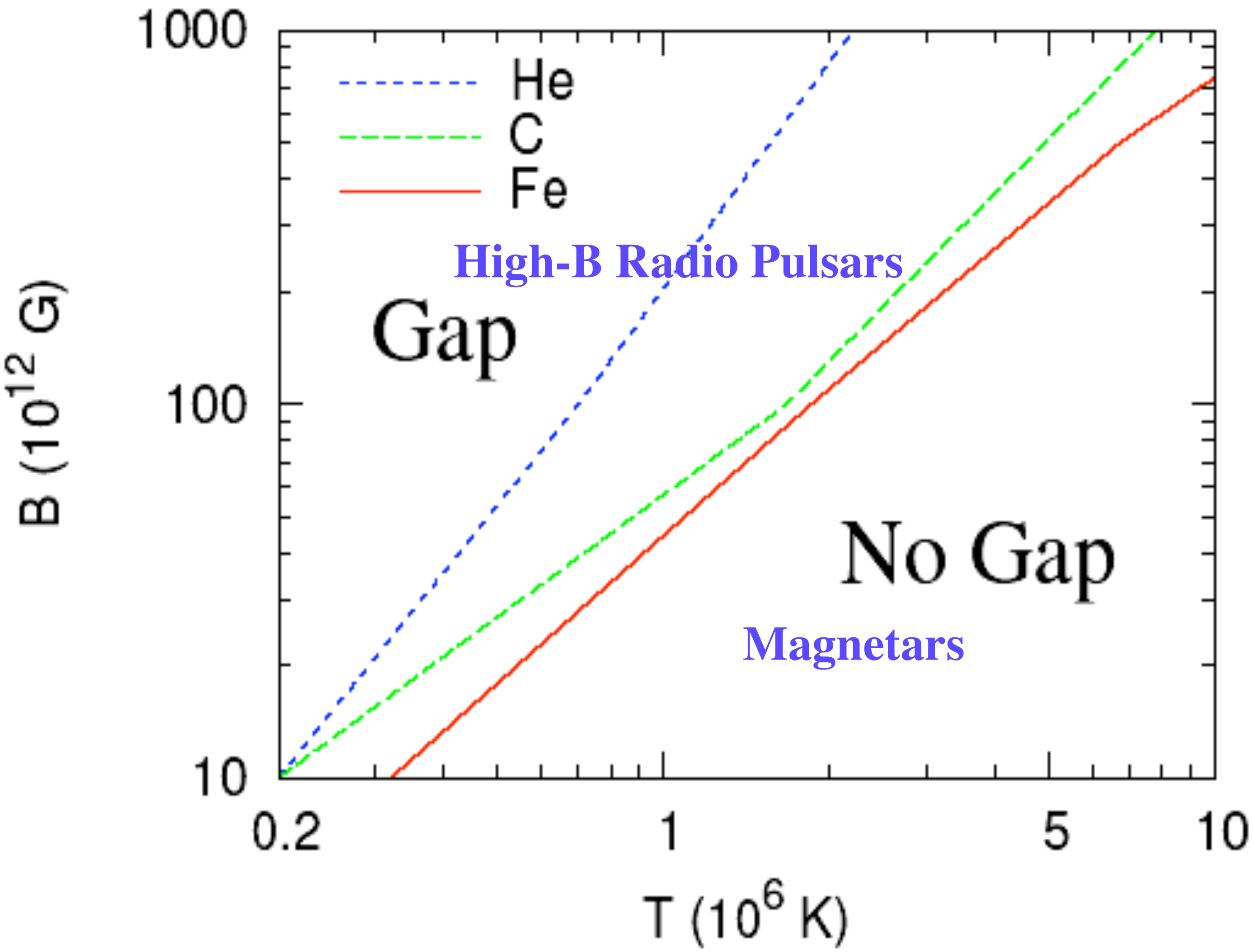
Energy barrier $E_B = E_{\rm coh} + I - ZW$

Emission rate per surface "atom" $\sim \omega_{\rm vib} \exp(-\mathrm{E_B}/\mathrm{kT})$

Note: mainly thermal evaporation: electric field helps, but not dominant

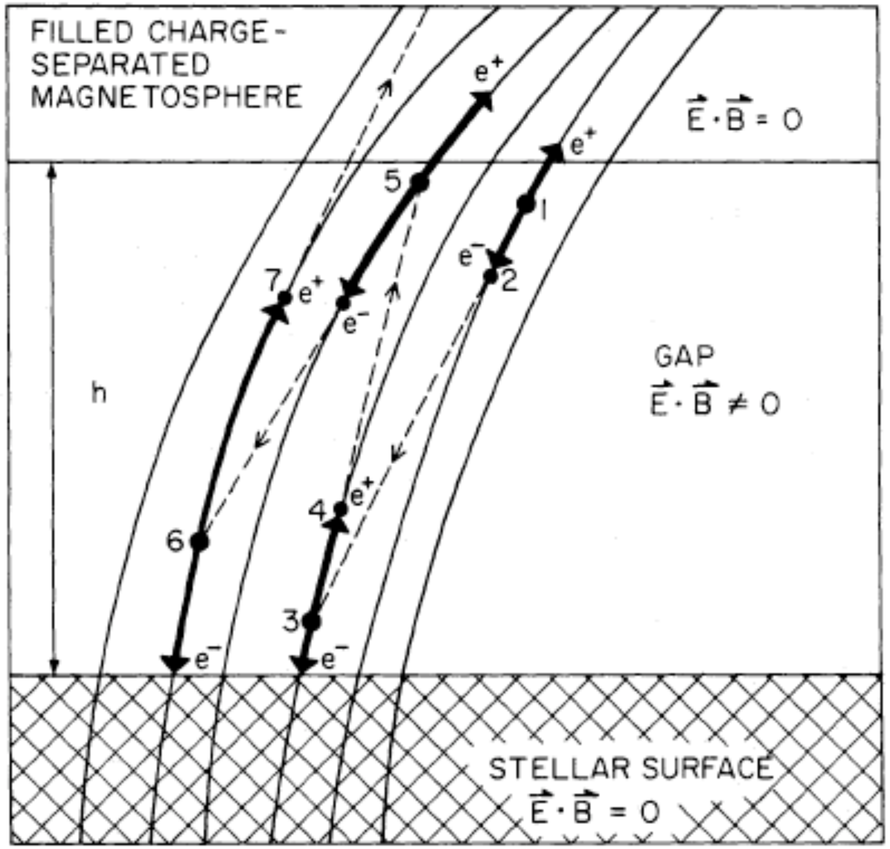


Medin & DL 2007



Suggest pulsar activity depends on T (in addition to P and B)?

Polar Gap Accelerator
(vacuum gap or SCLF gap)



Ruderman & Sutherland 1979

Pair Cascade in Polar Gap

- e^-/e^+ acceleration across the gap (efficiency depends on VG or SCLF)
- Photon emission
  -- Curvature radiation $\epsilon \sim \gamma^3 \hbar c/\mathcal{R}_c$

  -- Resonant inverse Compton Scatterings

$$\epsilon = \left[1 - \left(1 + 2\frac{B}{B_Q}\right)^{-1/2}\right]\gamma m_e c^2$$

- One-photon pair production

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

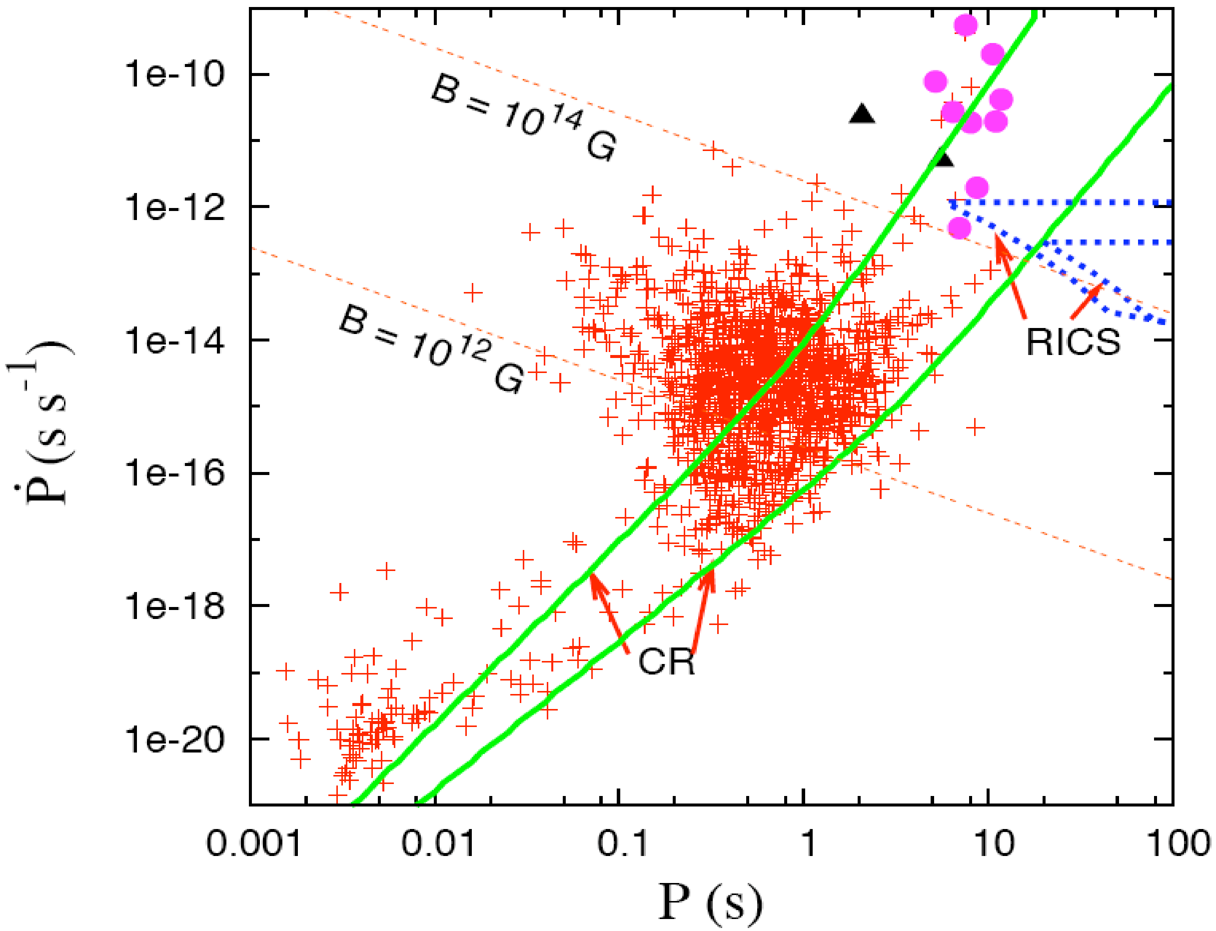
To initiate pair cascade in the gap, requires

-- N_{ph} > a few

-- $l_{ph} < h$

Note: New features in super-QED field regime:
e.g., For $B>4B_Q$, RICS photon can produce pairs immediately;
Possibility of photon splitting before pair production.

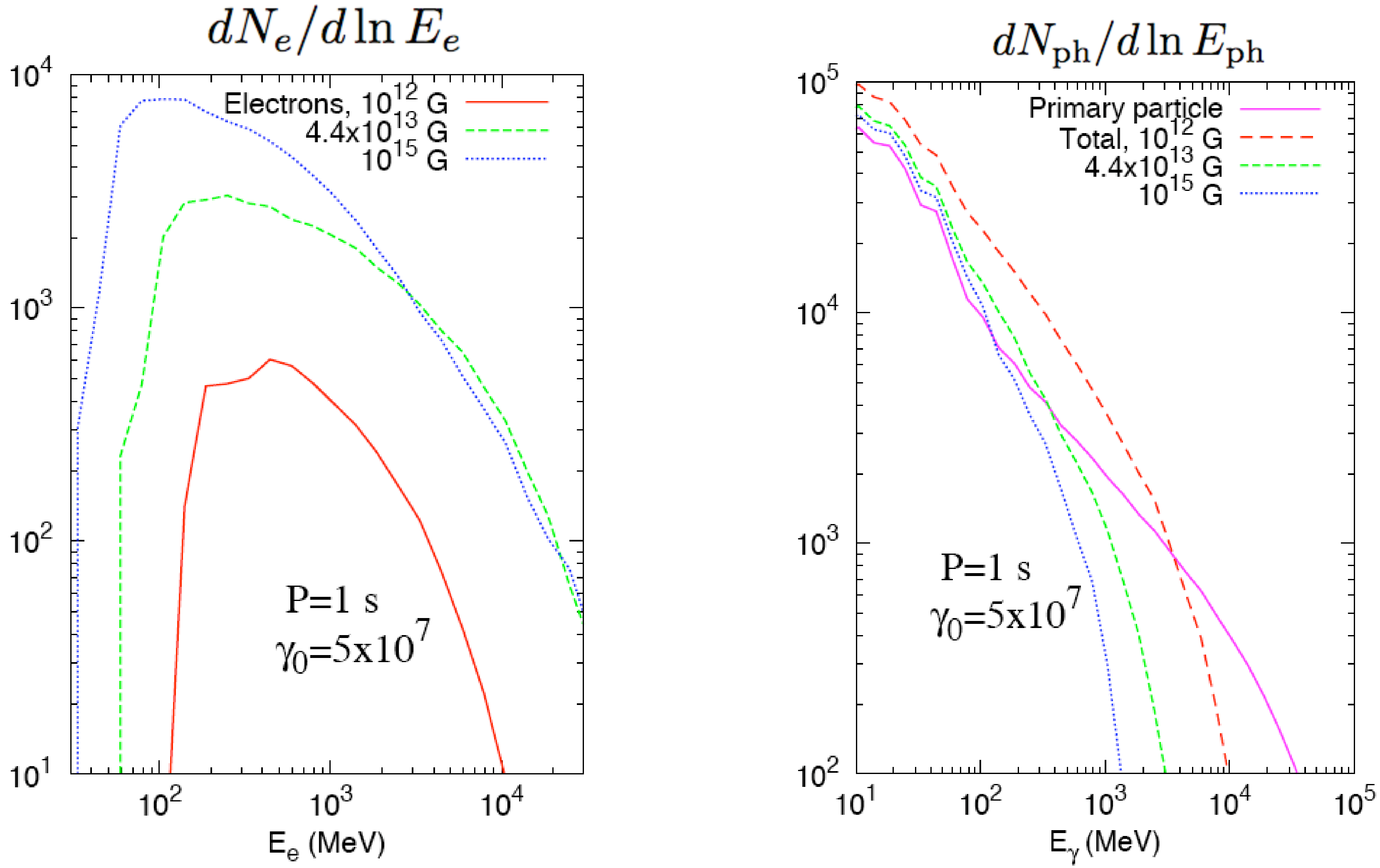
Minimum condition for gap cascade (Pulsar death line/boundary)



- Multipole field is needed to explain slow pulsars
- Inverse Compton scatterings are not effective in cascade

Medin & DL 2007,08

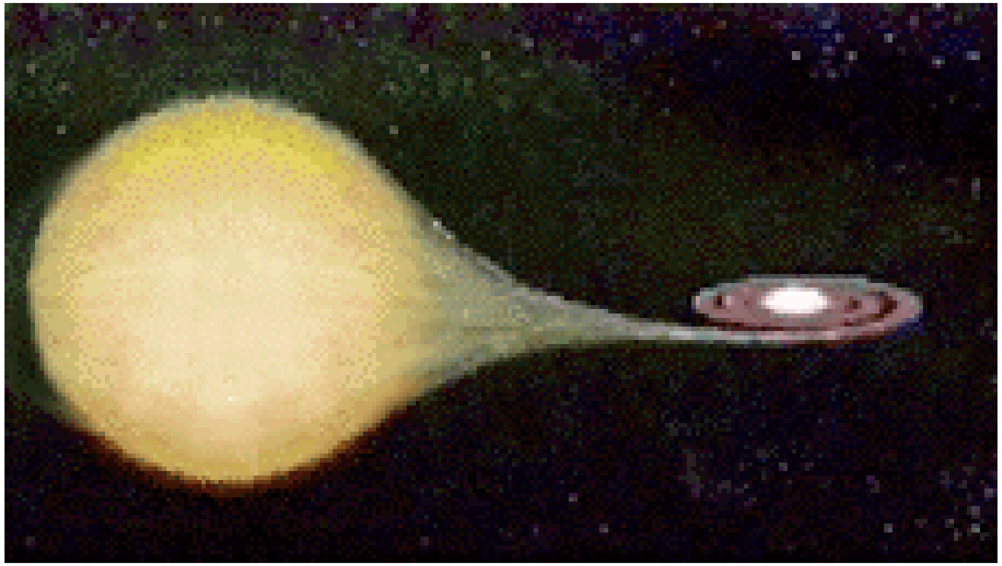
Full cascade simulations: Comparison of normal-B vs High-B NSs



High-B NS has higher multiplicity (==> hard radio spectrum?)

Medin & Lai 2008

Accreting Neutron Stars

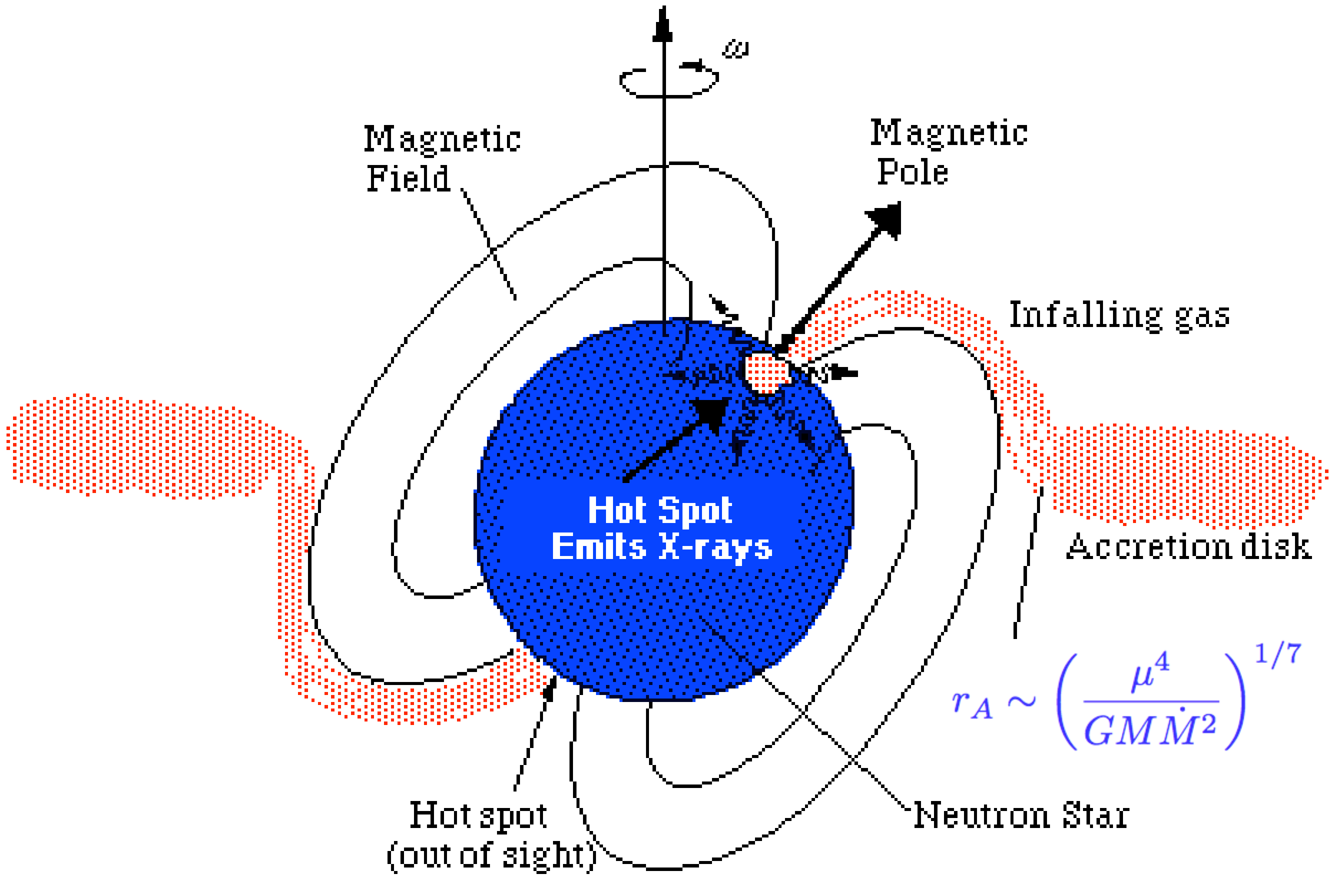


NASA

High-mass X-ray binaries: X-ray pulsars (period > seconds)

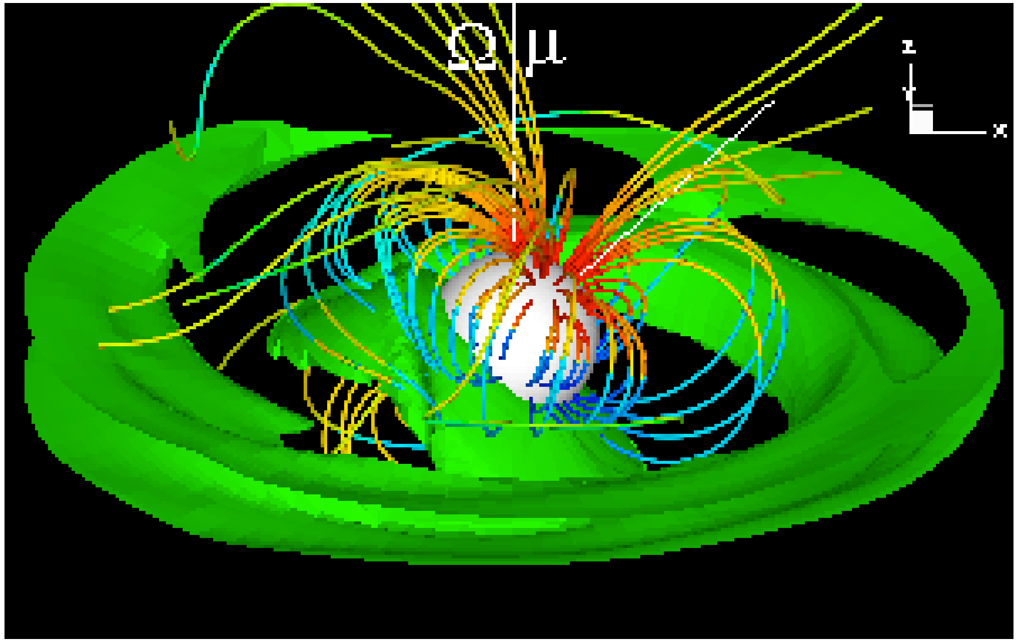
Low-mass X-ray binaries: ~150 known
8 Accreting millisecond pulsars

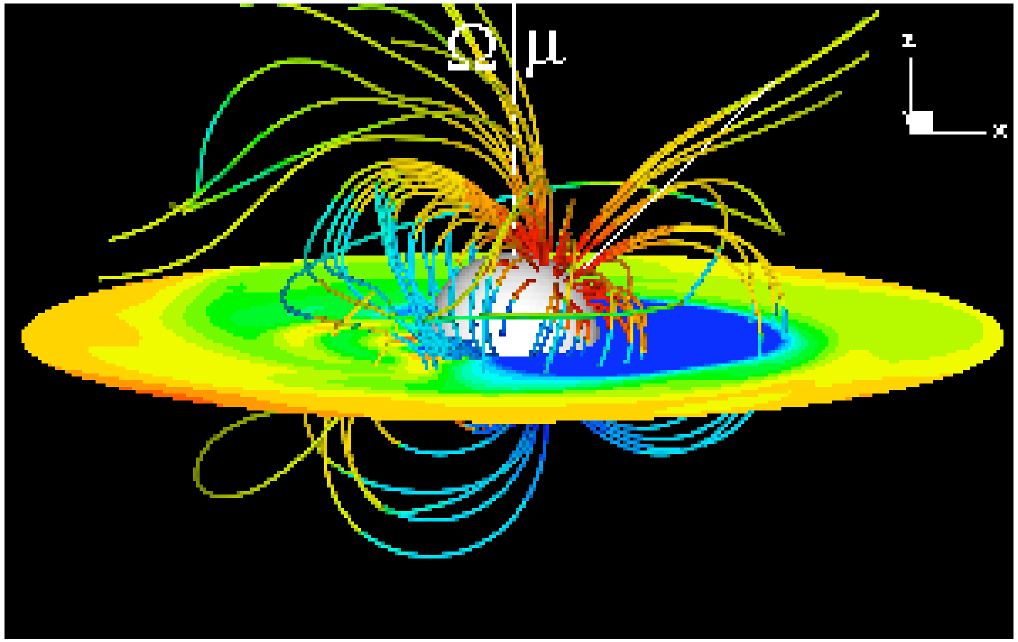
Accretion onto Magnetic (Neutron) Stars



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

NASA

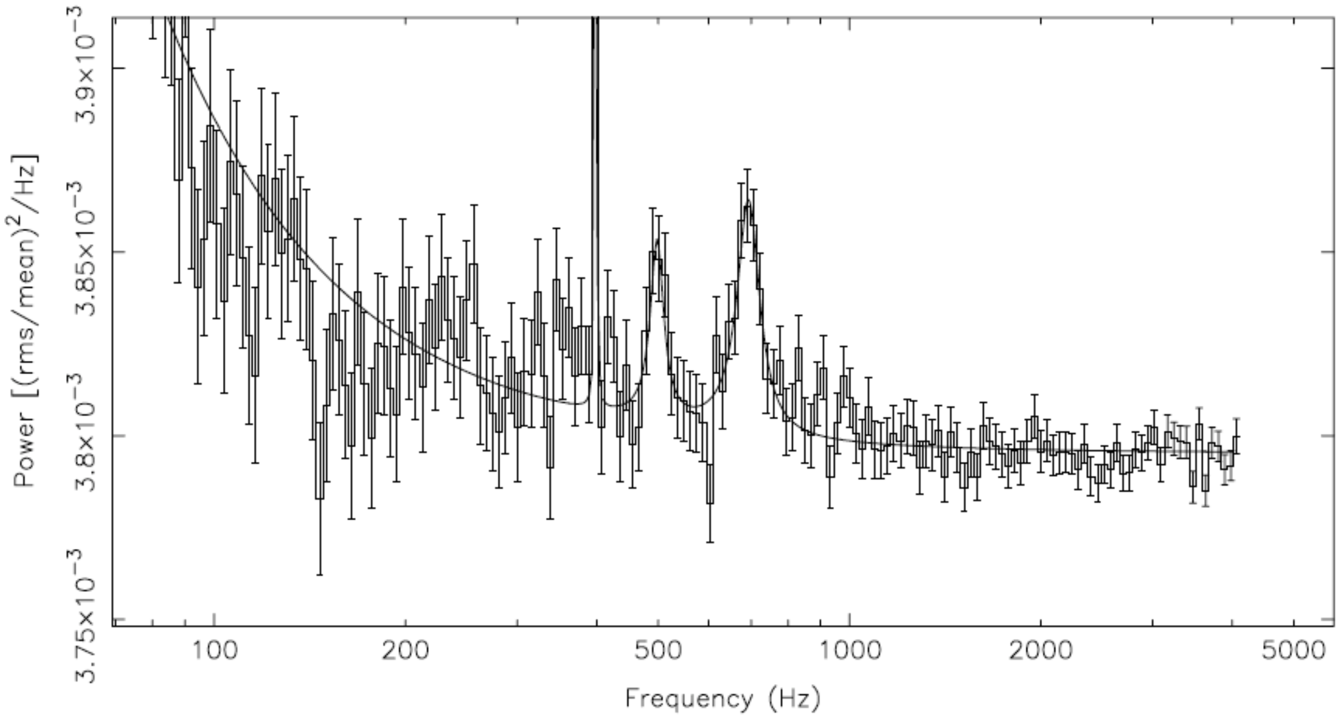




Long, Romanova & Lovelace 2008

Quasi-Periodic Oscillations (QPOs)

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



Van der Klis 2005

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

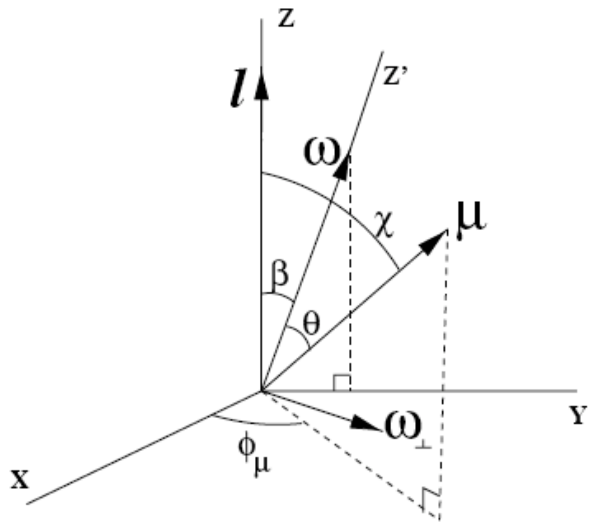
XTE J1807.4-294: $\nu_s = 191\ \text{Hz},\ \ \nu_h - \nu_l \simeq \nu_s$

Basic point:

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

A generic toy model of magnetic force on disk:

$$
\begin{aligned}
B_r &= \frac{2\mu}{r^3}\sin\chi\cos(\varphi-\varphi_\mu) \pm \frac{4\mu}{\pi r^3\mathcal{D}}\sin\beta\sin\theta\sin\omega_s t \\
B_\varphi &= \frac{\mu}{r^3}\sin\chi\sin(\varphi-\varphi_\mu) \pm \zeta\frac{\mu}{r^3}\cos\beta\cos\theta, \\
B_z &= -\frac{\mu}{r^3}\cos\beta\cos\theta,
\end{aligned}
$$



===>

$$
F_z = -\frac{4\mu^2}{\pi^2 r^6\mathcal{D}}\sin\beta\sin\theta\sin\omega t\sin\chi\cos(\varphi-\varphi_\mu) - \frac{\zeta\mu^2}{2\pi r^6}\cos\beta\cos\theta\sin\chi\sin(\varphi-\varphi_\mu)
$$

Look at different frequency components …

Magnetic force per unit area:

$$F_z = \mathrm{Re} \sum_{\omega_f} F_{\omega_f}(r) \exp(i\phi - i\omega_f t)$$

$$\begin{aligned}
F_0(r) &= i\mathcal{F}_D \sin^2\theta \sin 2\beta + \mathcal{F}_T \cos^2\theta \sin 2\beta, \\
F_{\omega_s}(r) &= \mathcal{F}_D \sin 2\theta \sin^2\beta + \frac{1}{2} i\mathcal{F}_T \sin 2\theta \cos\beta(1 + \cos\beta), \\
F_{-\omega_s}(r) &= -\mathcal{F}_D \sin 2\theta \sin^2\beta + \frac{1}{2} i\mathcal{F}_T \sin 2\theta \cos\beta(1 - \cos\beta) \\
F_{2\omega_s}(r) &= -i\mathcal{F}_D \sin^2\theta \sin\beta\,(2 + \cos\beta), \\
F_{-2\omega_s}(r) &= i\mathcal{F}_D \sin^2\theta \sin\beta\,(2 - \cos\beta),
\end{aligned}$$

$$\mathcal{F}_D \equiv \frac{\mu^2}{\pi^2 r^6 \mathcal{D}}$$

$$\mathcal{F}_T \equiv \frac{\zeta\mu^2}{4\pi r^6}$$

Time-independent component:

$$F_z(r, \phi, t) = (\cdots) \cos\phi + (\cdots) \sin\phi$$

===> Disk warping and precession driven by magnetic forces

With timescale:

LMXBs: ~ Hz

HMXBs: ~ mHz

Lai 1999
Shirakawa & Lai 2002
Pfeiffer & Lai 2004

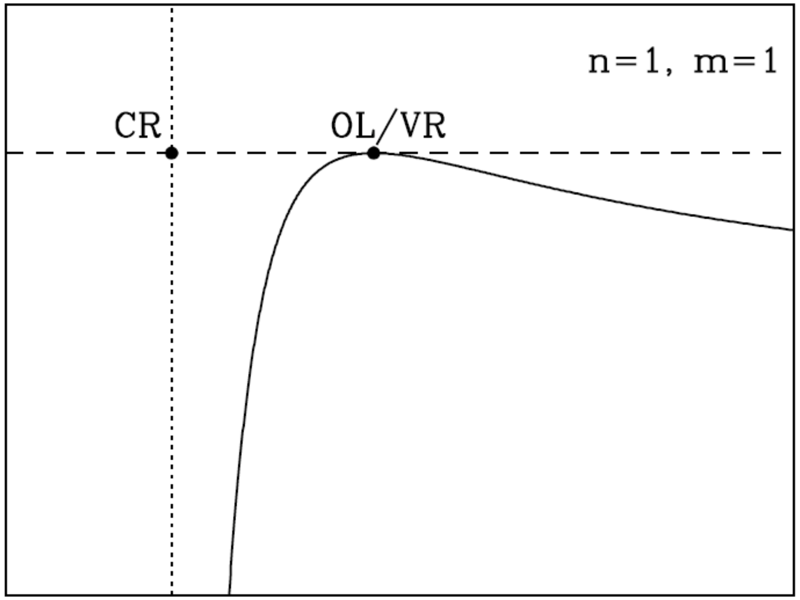
Time-varying component:

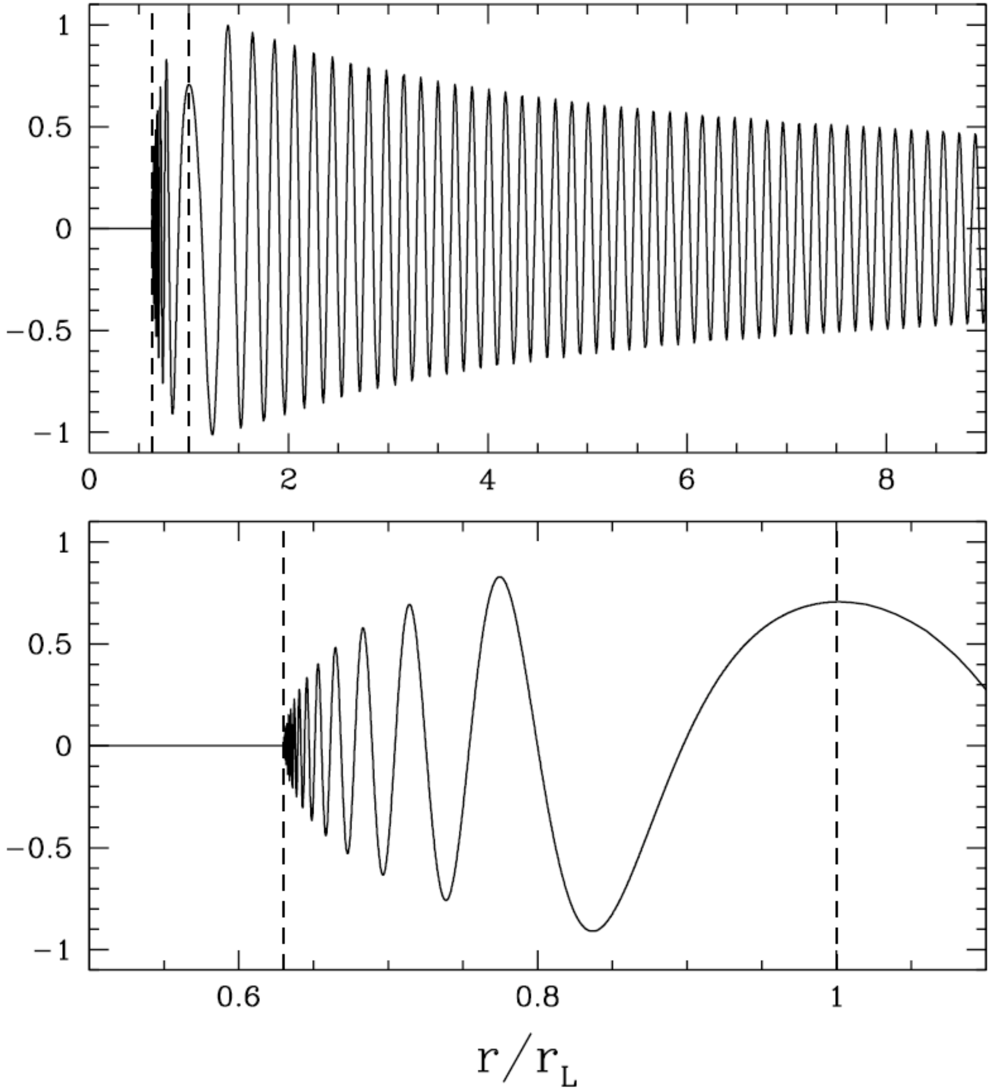
$$F_z(r, \varphi, t) = F_\omega(r) \exp(im\varphi - i\omega t)$$

$$m = 1,\ \omega = \omega_s, 2\omega_s$$

===> Excitation of Bending waves in disks

Excitation of bending wave by magnetic force:





Lindblad/Vertical Resonance:

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

===> $\omega \simeq 2\Omega(r_L)$

DL & Zhang 2008

Magnetically Driven Bending Waves in Disks

- Perturbations most "visible" at Lindblad/Vertical Resonance

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

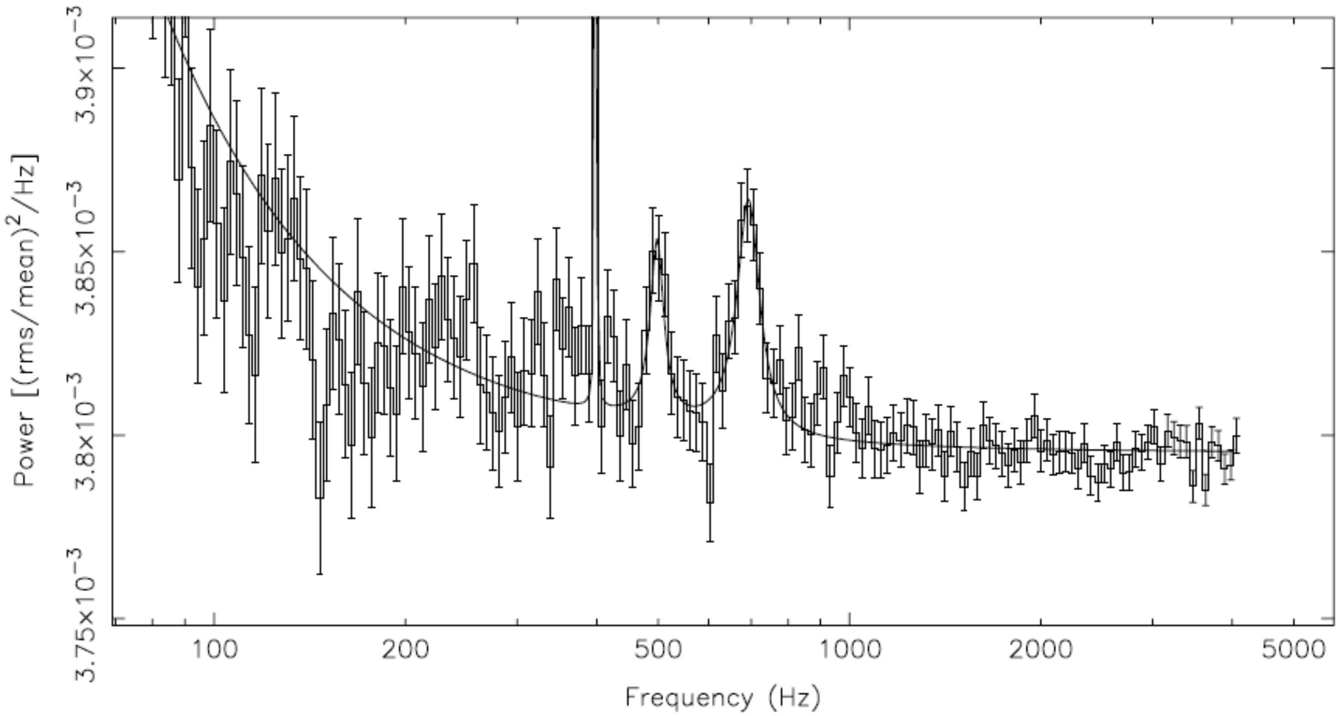
$$\Longrightarrow \quad \Omega(r_L) = \frac{1}{2}\omega = \frac{\omega_s}{2}, \ \omega_s$$

- 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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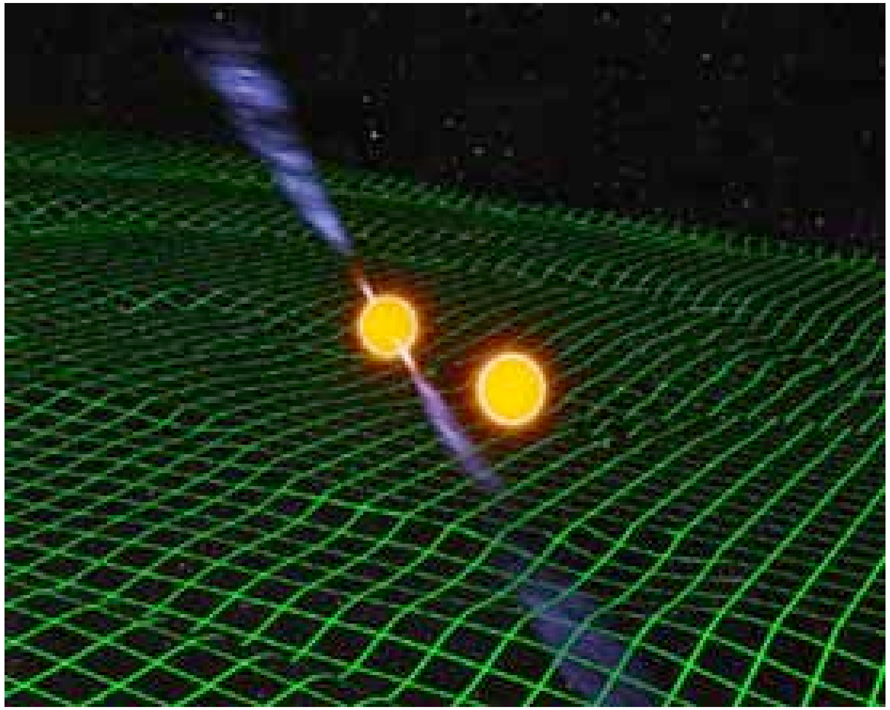
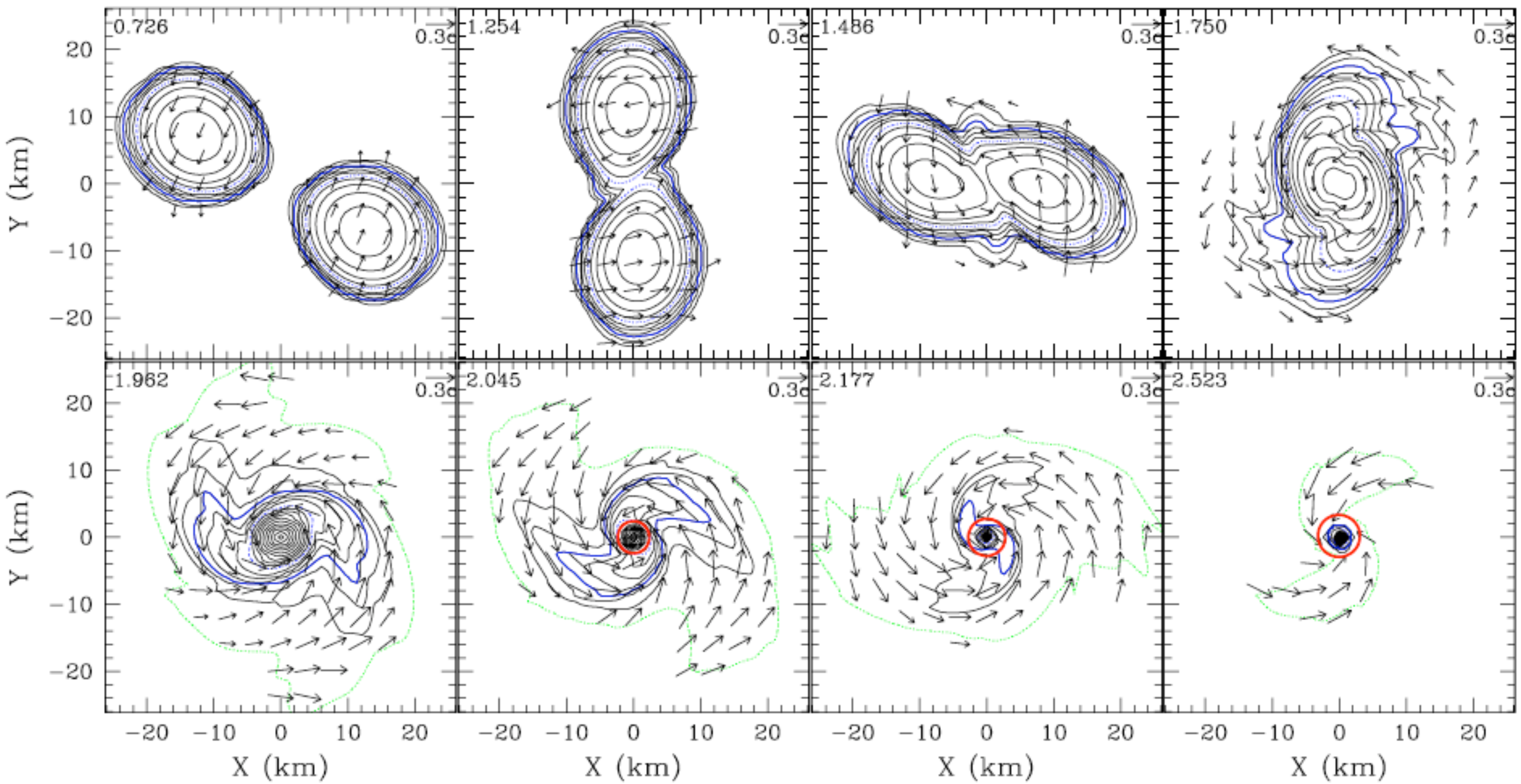
Merging Neutron Stars

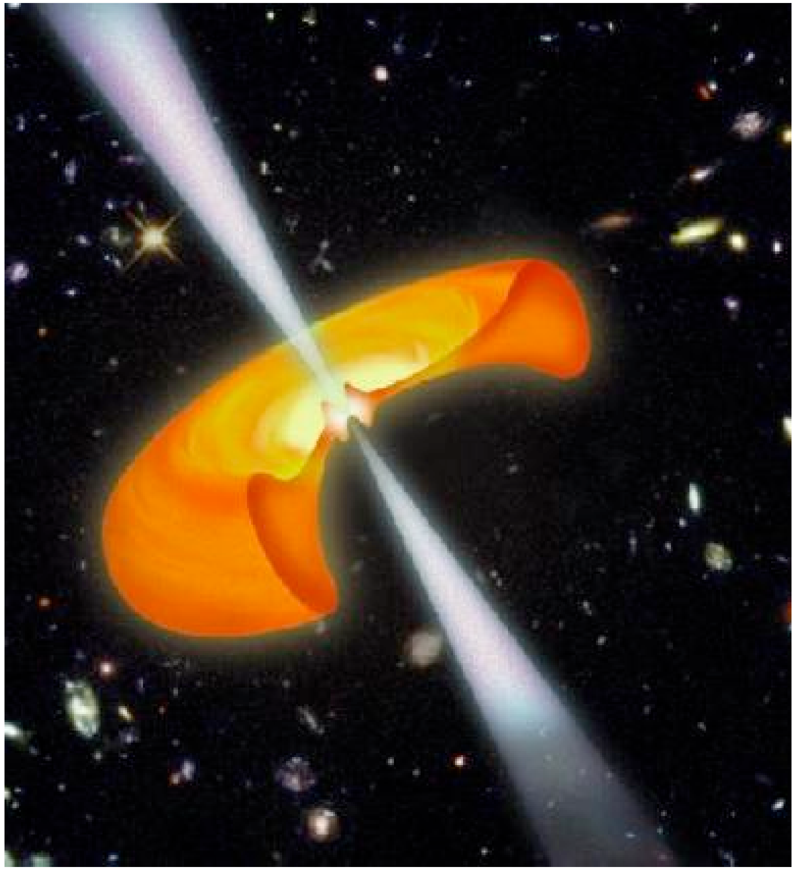


Binary pulsars

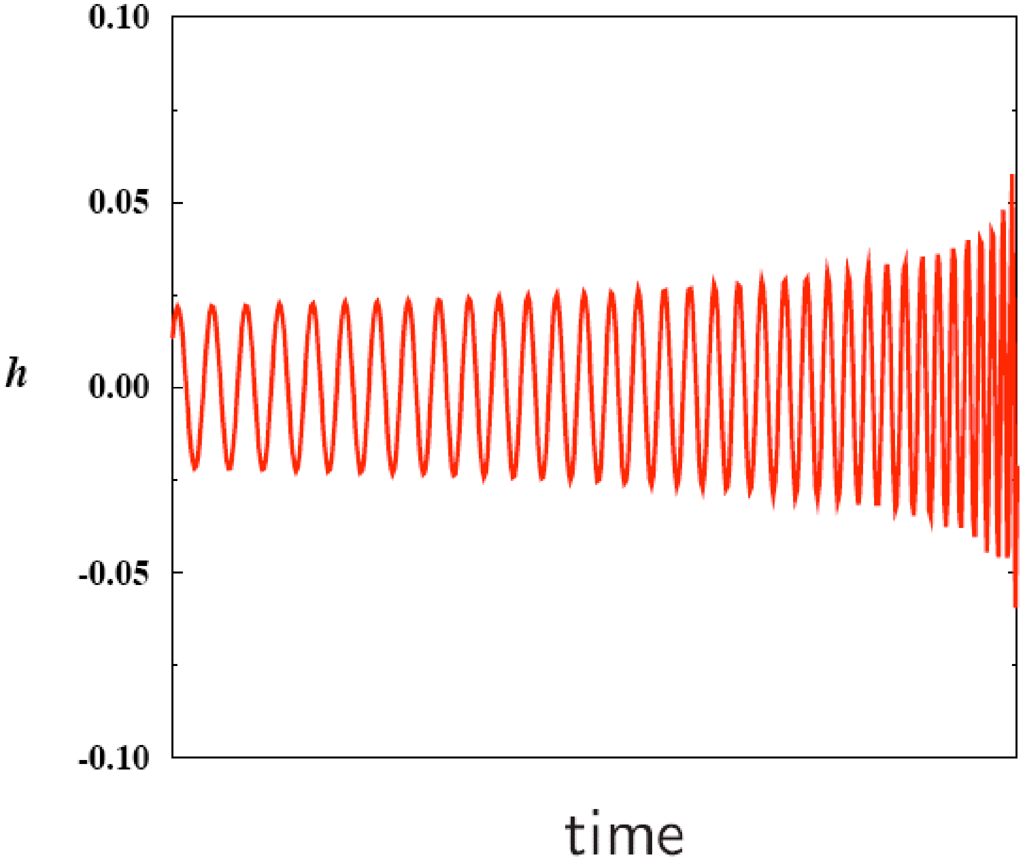


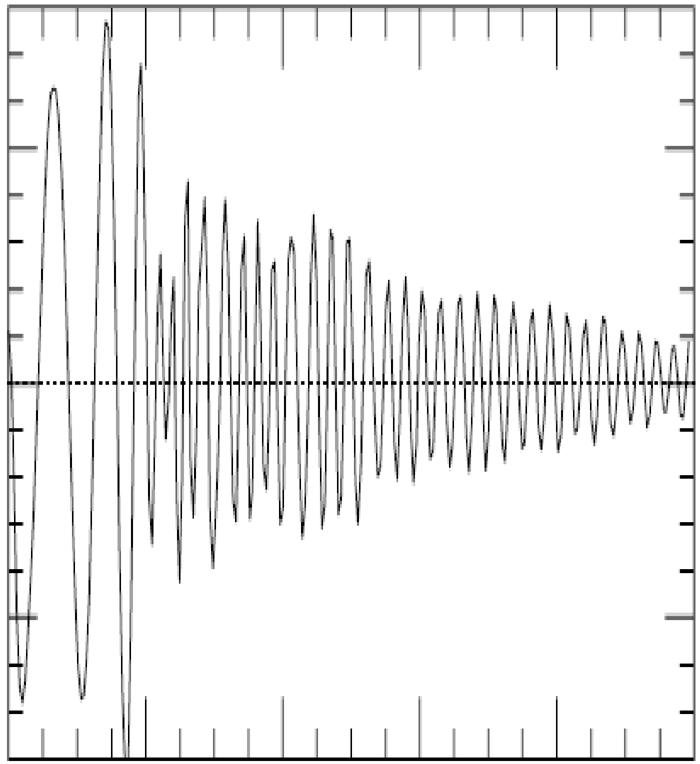
Shibata et al. 2006

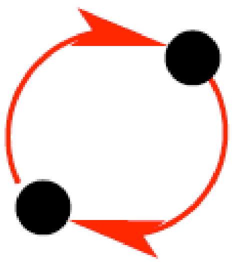
Merging NSs (NS/BH or NS/NS) as Central Engine of (short/hard) GRBs

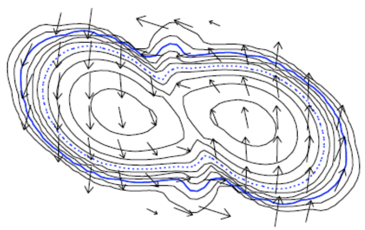


The last three minutes: Gravitational Waveform



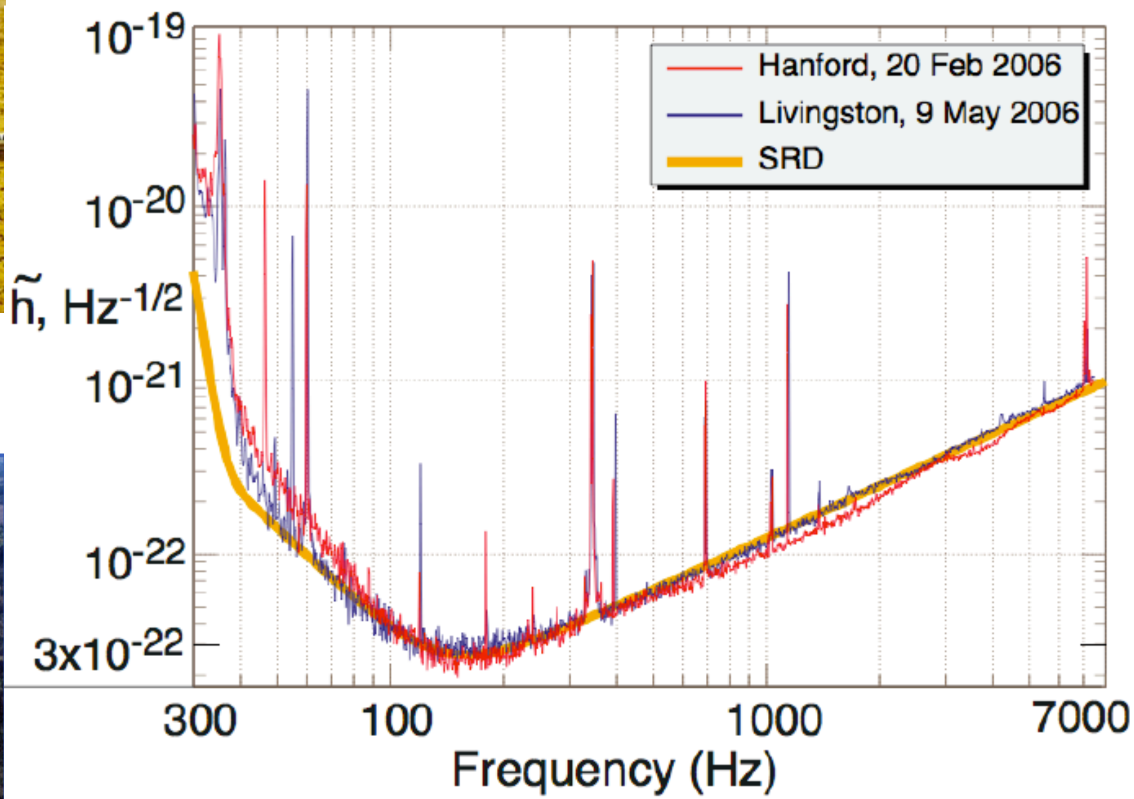




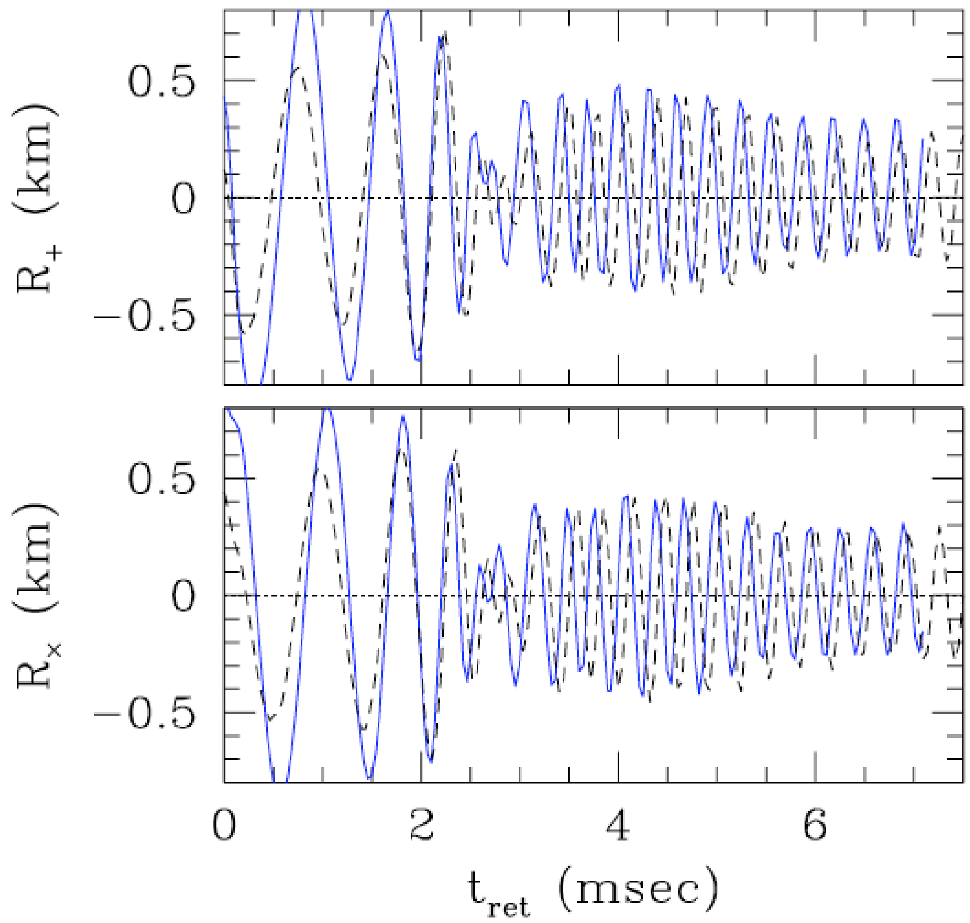


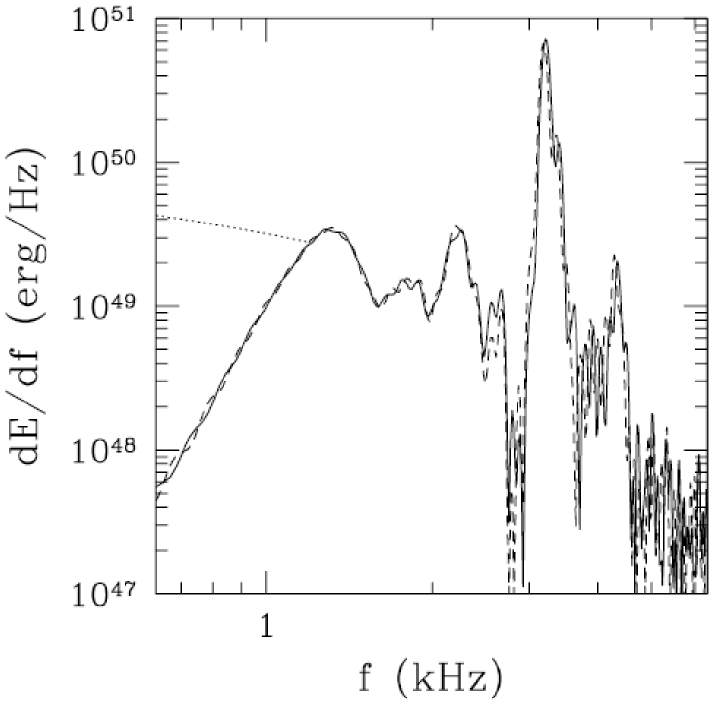

Hanford Washington


Livingston,
Louisiana


Hanford, 20 Feb 2006
Livingston, 9 May 2006
SRD
10^{-19}
10^{-20}
$\tilde{h}$, $Hz^{-1/2}$
10^{-21}
10^{-22}
$3x10^{-22}$
300
100
1000
7000
Frequency (Hz)

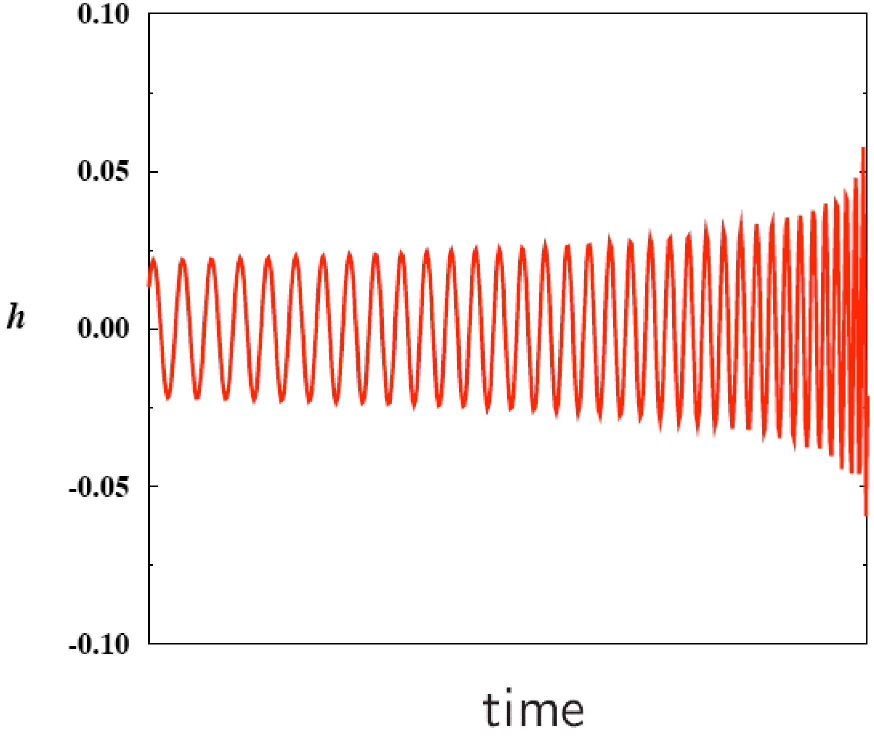
Final merger wave form probes NS EOS

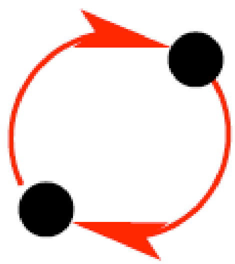




Shibata et al 2006

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

Note: For WD/WD binaries (LISA source), the effect is very large

Summary

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

- **Diverse observational manifestations:**

  * **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