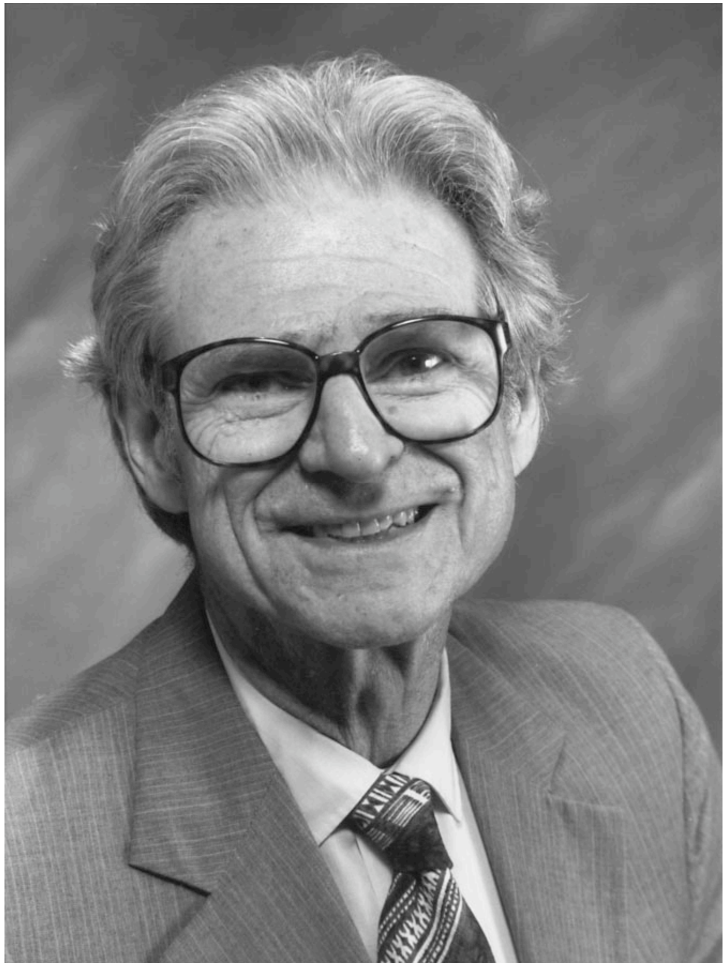
Physics of Highly Magnetized Neutron Stars

Dong Lai
Cornell University

Institut de Physique Nucleaire, Orsay, Dec. 2, 2008



Edwin E. Salpeter
1924-2008.11

Autobiography: Annual Review Astro & Astrophys. 2002, 40: 1-25

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Magnetic Field: How strong is Strong?

Electron cyclotron energy $\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = 11.6\, B_{12}$ keV

- $\hbar\omega_{ce} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B_0 = 2.35 \times 10^9$ G

When $B \gg B_0$, property of matter very different from $B=0$ case.

- $\hbar\omega_{ce} = m_e c^2 \quad \Longrightarrow \quad B_Q = \frac{B_0}{\alpha^2} = 4.4 \times 10^{13}$ G

When $B \gtrsim B_Q$, effect of Quantum Electrodynamics (QED) important

Magnetized Neutron Stars

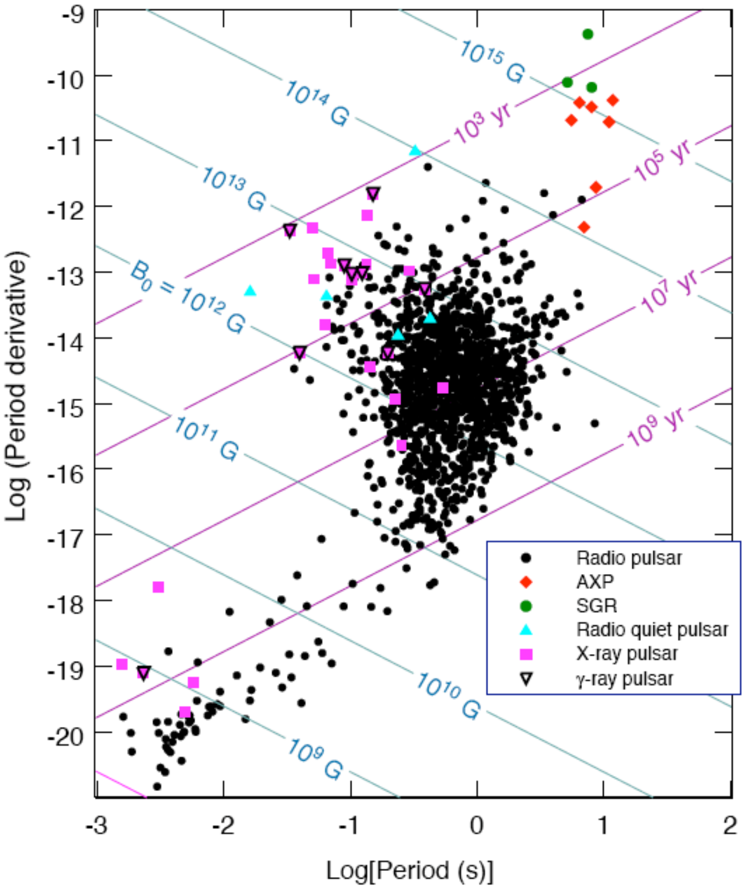
Radio pulsars

measure $P,\ \dot{P} \ \Rightarrow$ estimate $B_{\rm dipole}$

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

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

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



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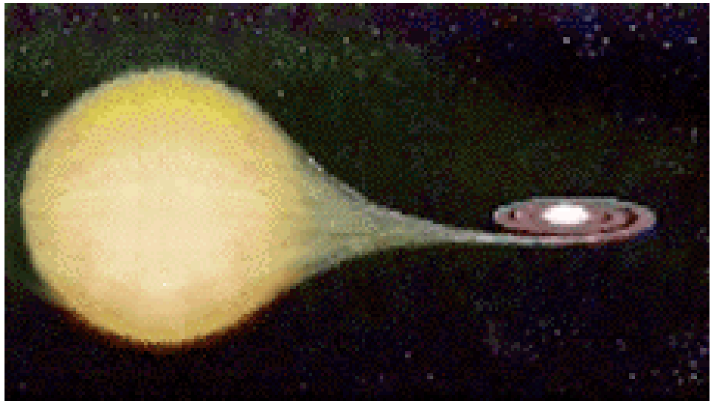
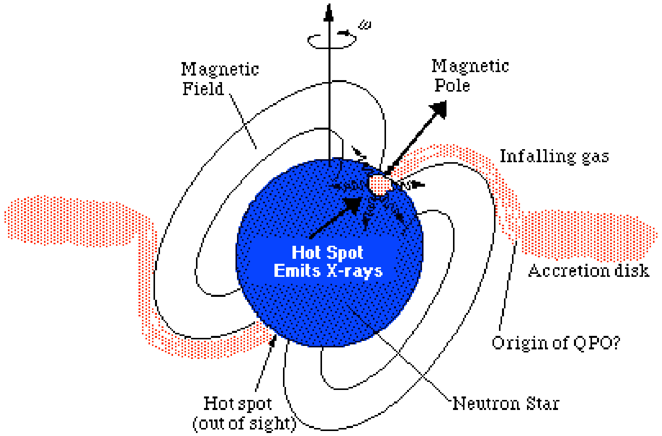
Accreting X-ray Pulsars

Cyclotron lines, spin equilibrium
$\Rightarrow B \sim 10^{12-13}$ G

accreting ms pulsars: $B \sim 10^{9}$ G





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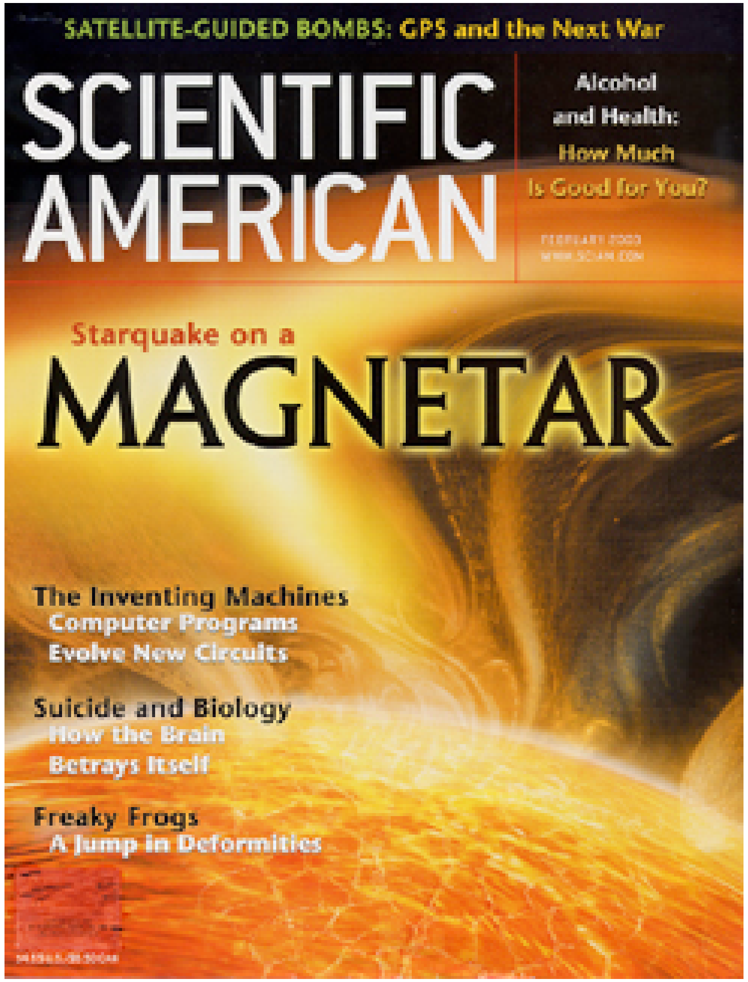
Magnetars

$B > 10^{14}$ G



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)

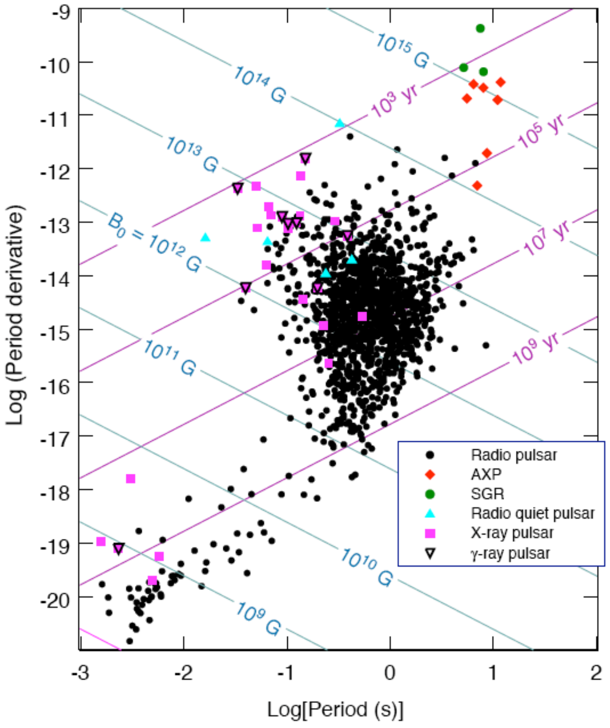
Even in quiescence, $L \sim 10^{34-36} \mathrm{erg\ s}^{-1} \gg I\Omega\dot{\Omega}$

T_s ~0.5 keV, but significant emission up to ~100 keV (==>active corona)

AXP/SGR bursts/flares
Giant flares in 3 SGRs

Magnetars do not show persistent radio emission

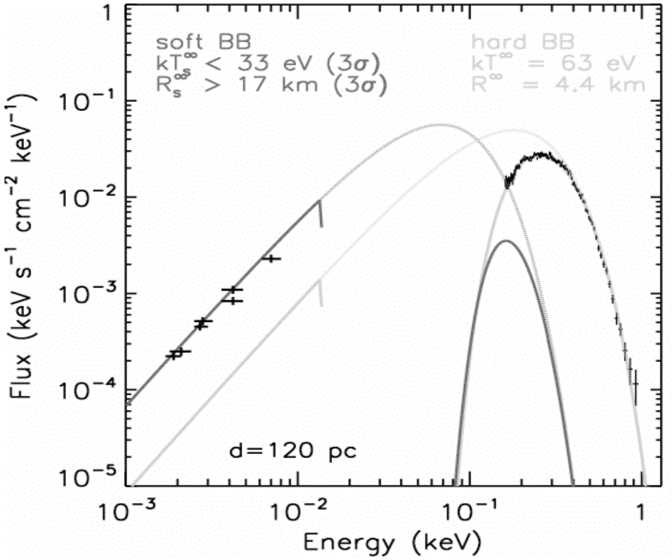
Connection with high-B radio pulsars?



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?

Note: Magnetars (in quiescence) thermal (surface) emission: T~0.5 keV.
But no absorption line detected in thermal spectrum

Magnetized Neutron Stars

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Magnetars

$B > 10^{14}$ G

This Talk:

- Radiation physics in strong magnetic fields
- Matter in strong magnetic fields

Motivation: Thermal (Surface) radiation from isolated
neutron stars

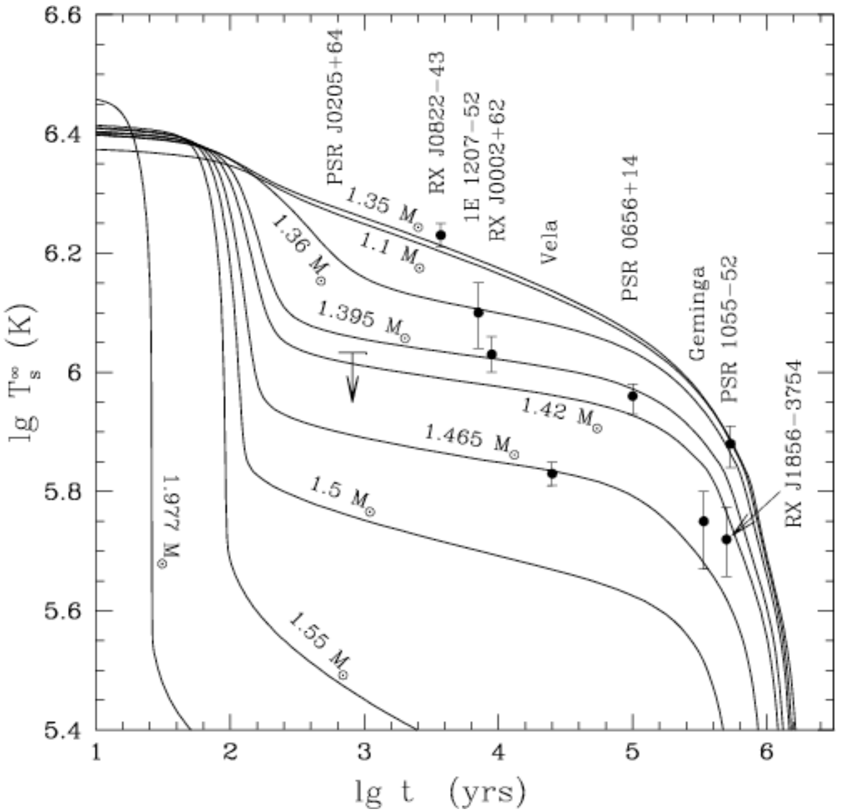
Thermal (Surface) Radiation from Isolated NSs

Has been securely detected from ~ 20 sources (Chandra, XMM-Newton)

Radio pulsars, Radio-quiet NSs,
Magnetars

Probe the near vicinity and interior of NSs:

M, R, EOS,
cooling history (exotic processes)
Ask Jerome!



Yakovlev & Pethick 2004

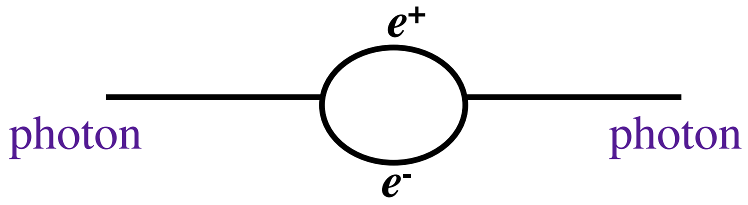
To confront theory with observations, need to understand the outermost layer of NS: **Photon propagation** and **property of matter** in strong B

Radiative Transfer in 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…

===> Vacuum is birefringent:

Dielectric Tensor $\boldsymbol{\varepsilon} = a\mathbf{I} + q\hat{\mathbf{B}}\hat{\mathbf{B}}$

Permeability Tensor $\boldsymbol{\mu} = a\mathbf{I} + m\hat{\mathbf{B}}\hat{\mathbf{B}}$

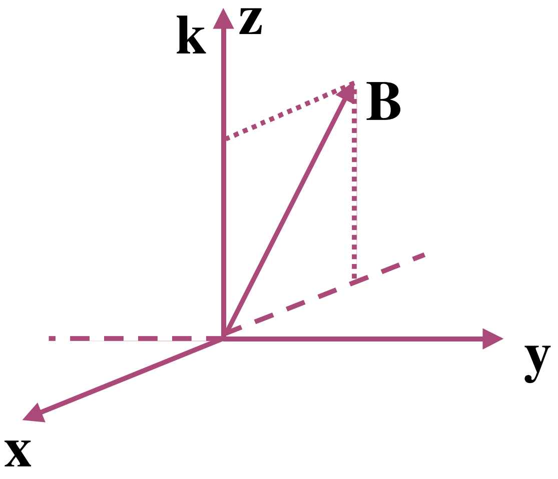
where a, q and m are functions of B

Important when B is of order or larger than

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

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

Photon Polarization Modes in a Magnetized Plasma ($\omega << \omega_{ce}$ =11.6 B_{12} keV)



Ordinary Mode (O-mode):

E nearly in the **k-B** plane

$$|K| = |E_x / E_y| >> 1$$

Extraordinary Mode (X-mode):

E nearly ⊥ **k-B** plane

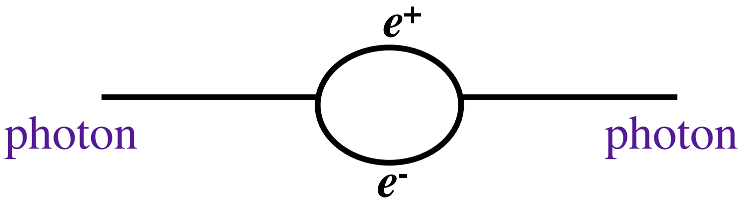
$$|K| = |E_x / E_y| << 1$$

The two modes have different opacities (scattering, absorption):

$$\kappa_{\text{(O-mode)}} \sim \kappa_{(B=0)}$$

$$\kappa_{\text{(X-mode)}} \sim \kappa_{(B=0)} \; (\omega/\omega_{ce})^2$$

Include Vacuum Polarization…



Dielectric tensor of magnetized plasma including vacuum polarization

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

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

Vacuum resonance:

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

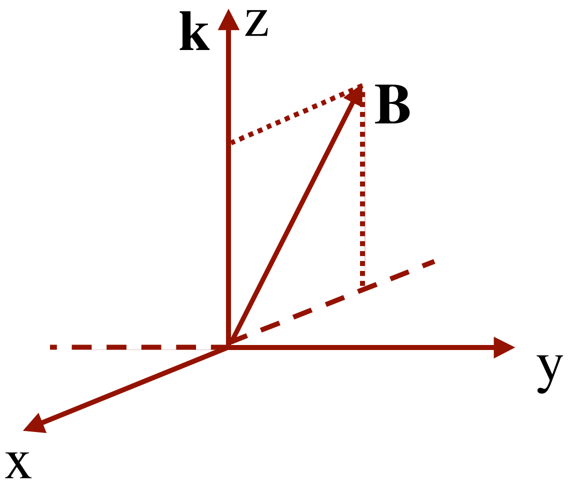
↓

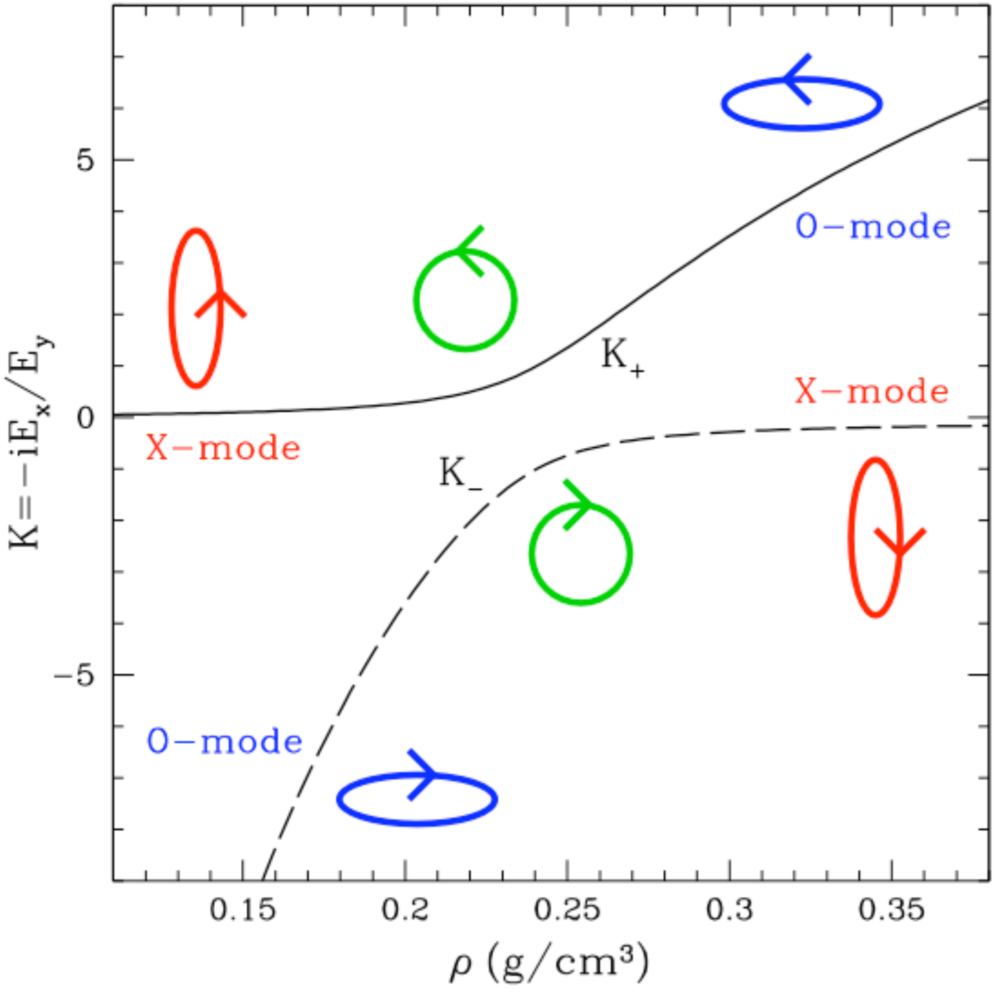
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

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

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

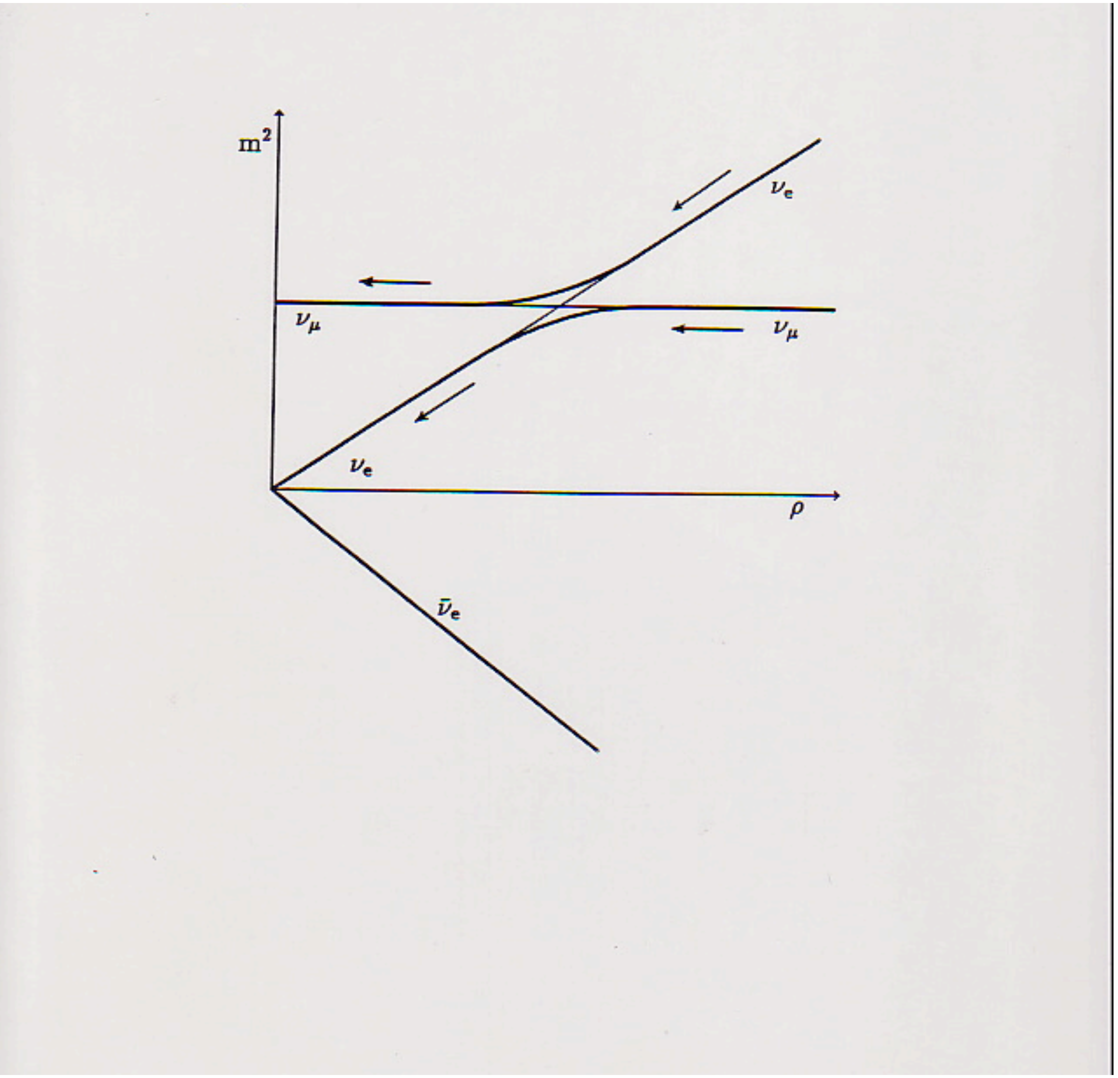
Property of photon modes



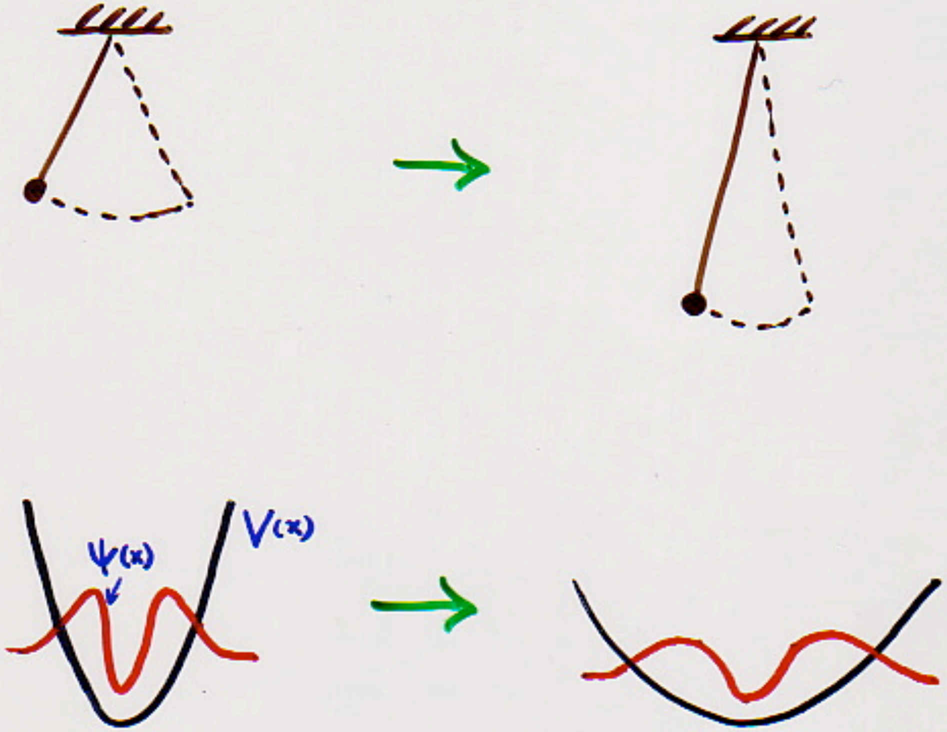


B=10^{13} G, E=5 keV, θ_B=45°

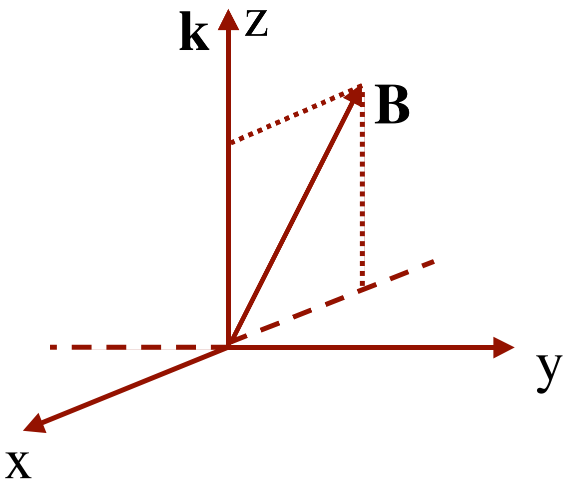
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation

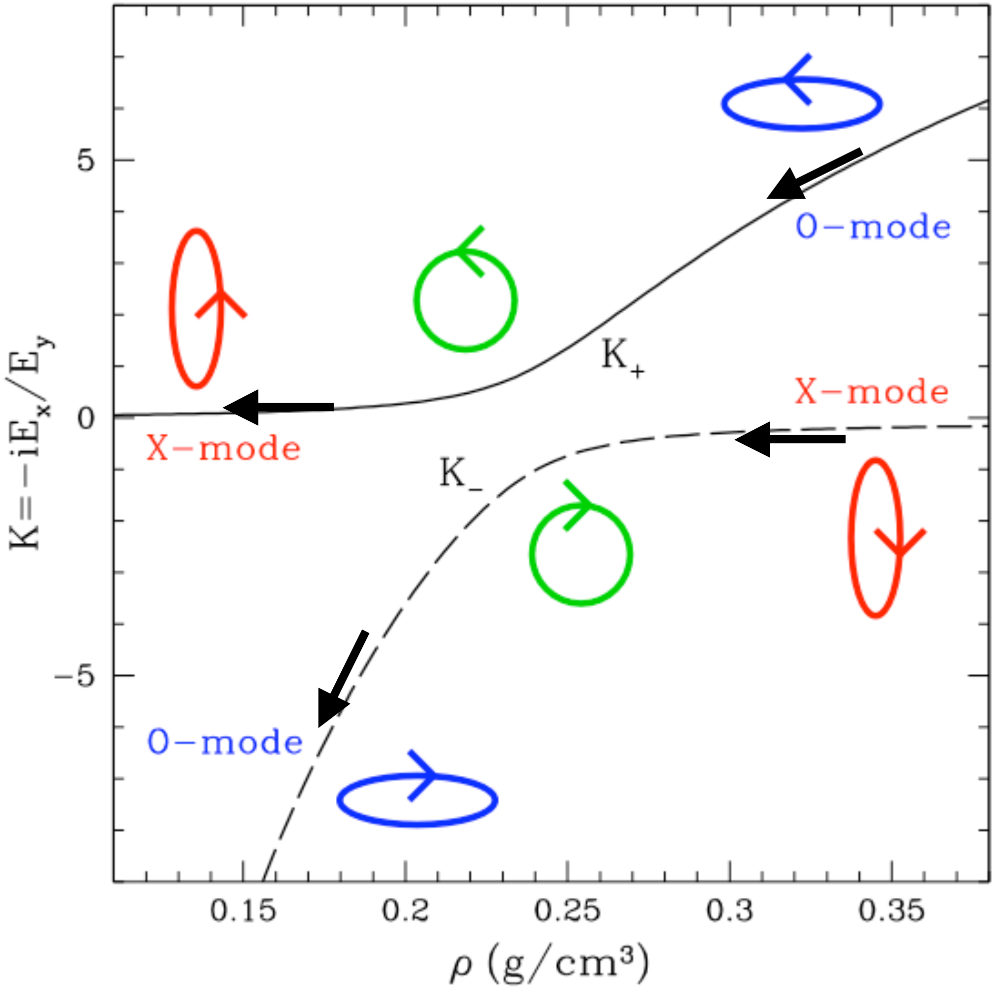


Adiabatic Evolution of a Quantum State



Property of photon modes





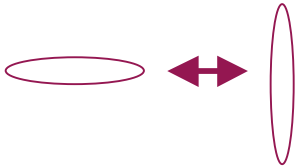
$B=10^{13}$ G, $E=5$ keV, $\theta_B=45^o$

Adiabatic Condition:

$$\left| n_1 - n_2 \right| \gtrsim (\cdots) \left| d\rho/dr \right|$$

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

Photons with E > 2 keV, mode conversion



Photons with E < 2 keV, no mode conversion

In general, nonadiabatic “jump” probability

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

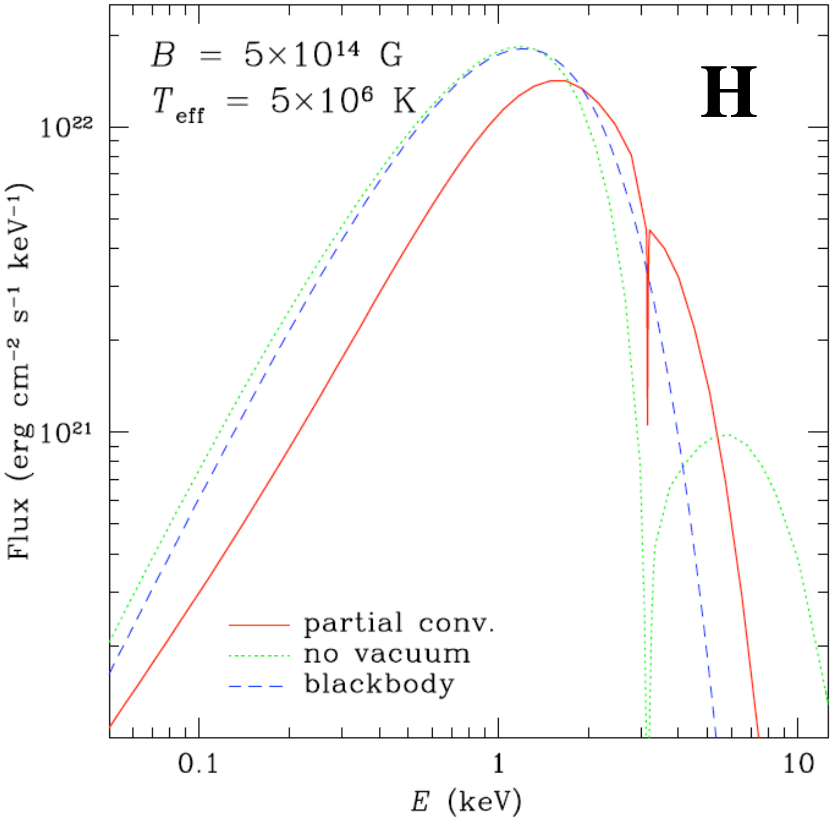
(Landau-Zener formula)

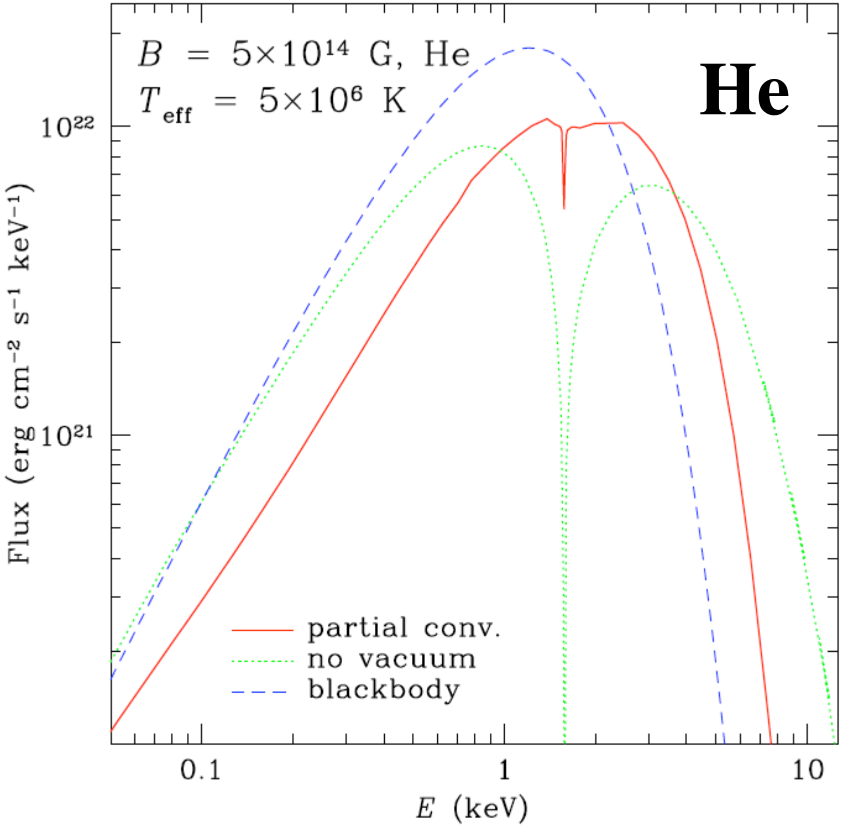
Why do we care?

The two photon modes have very different opacities

=> Mode conversion can affect radiative transfer significantly

=> Spectrum and polarization signal from the NS

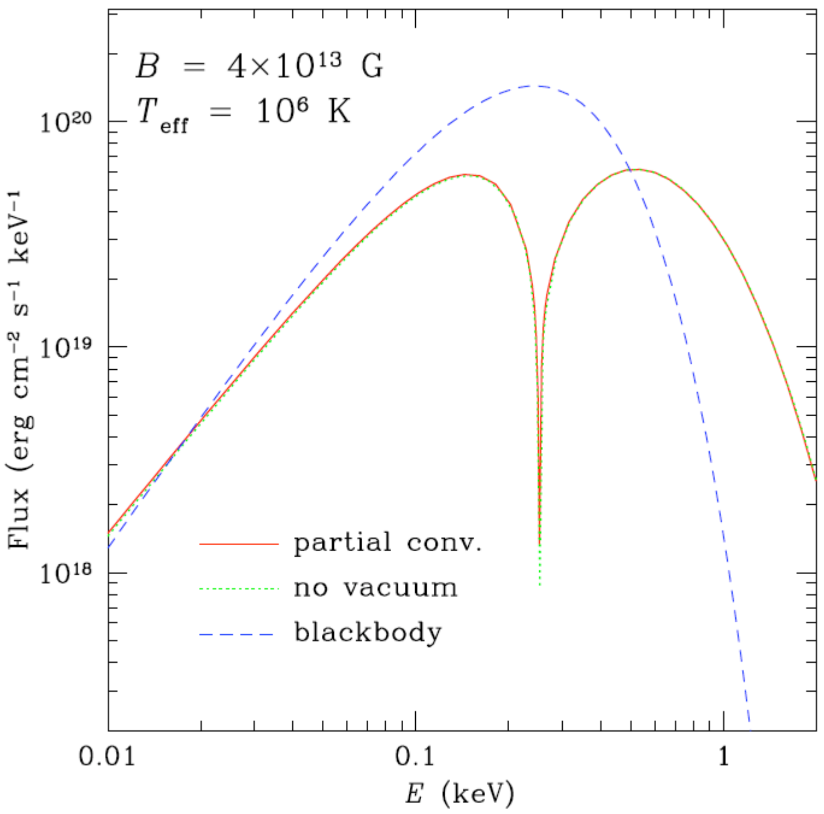


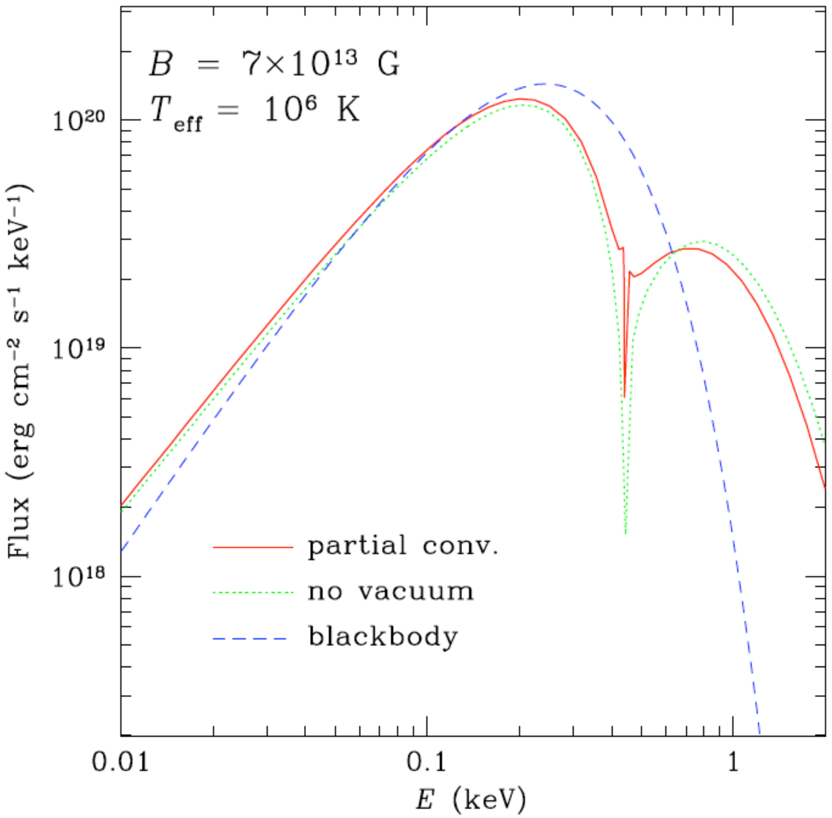


==> Magnetars do not show absorption features in thermal emission

QED at work!

For B $\lesssim 7\times10^{13}$G, vacuum polarization has small effect on spectrum

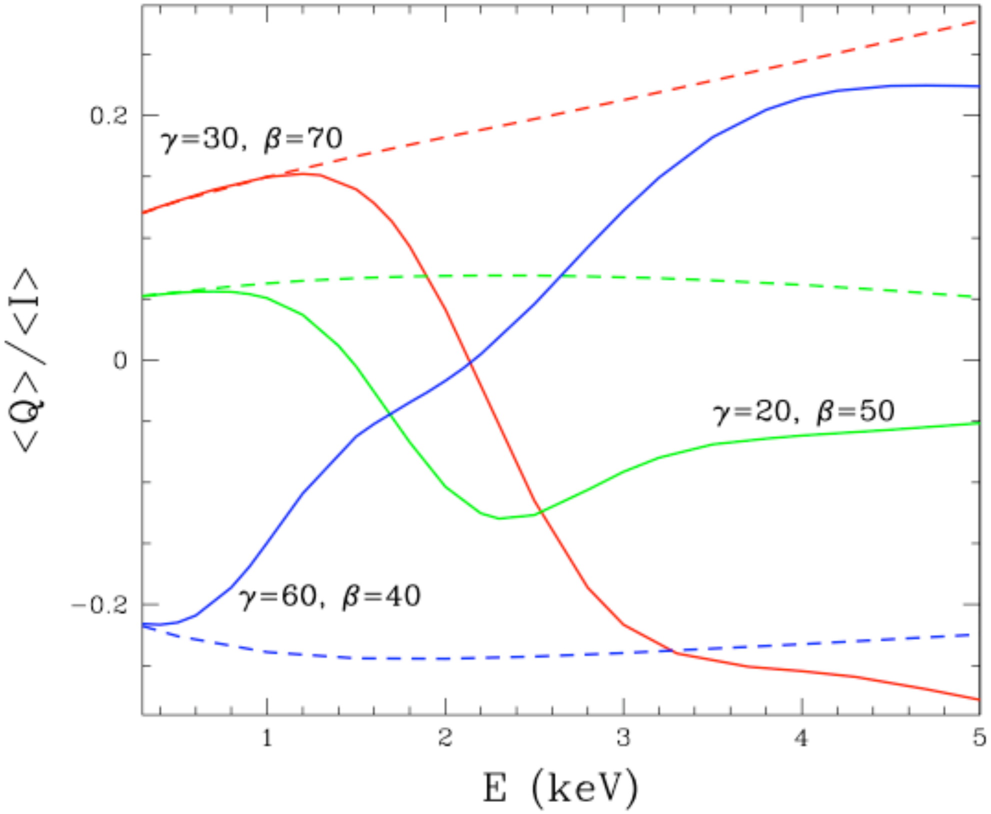




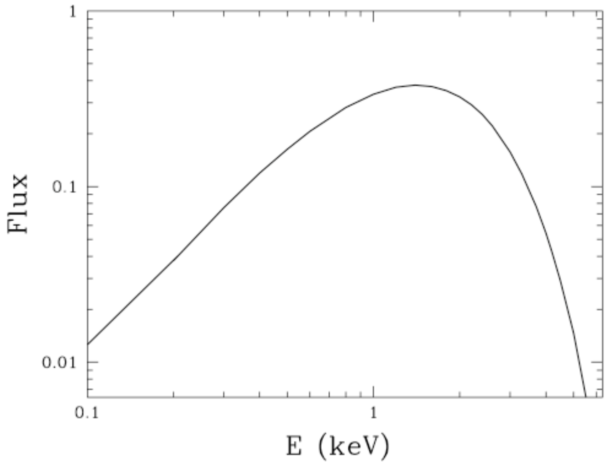
Matt Van Adelsberg & DL 2006

==> Absorption features observed in thermally emitting isolated NSs

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



B=10^{13}G



==> X-ray polarimeters (in US and Europe)

Probe strong-field QED

Matter in Strong Magnetic Fields

(atoms, molecules, condensed matter)

Critical Field:

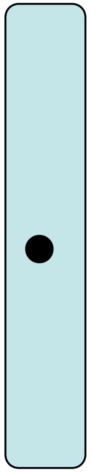
$$\hbar\omega_{ce} = \hbar\frac{eB}{m_e c} = \frac{e^2}{a_0} \quad \Longrightarrow \quad B = B_0 = 2.35 \times 10^9 \text{ G}$$

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

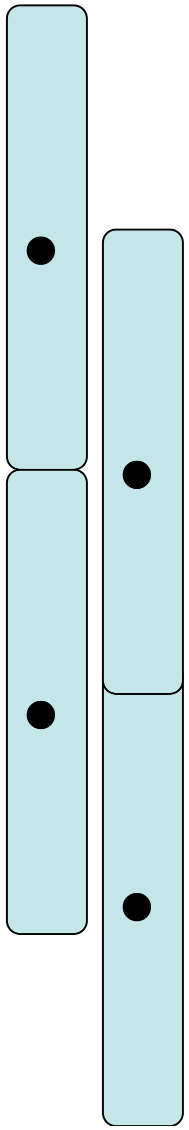
$|E| = 540 \text{ eV}$ at 10^{14}G

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

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:

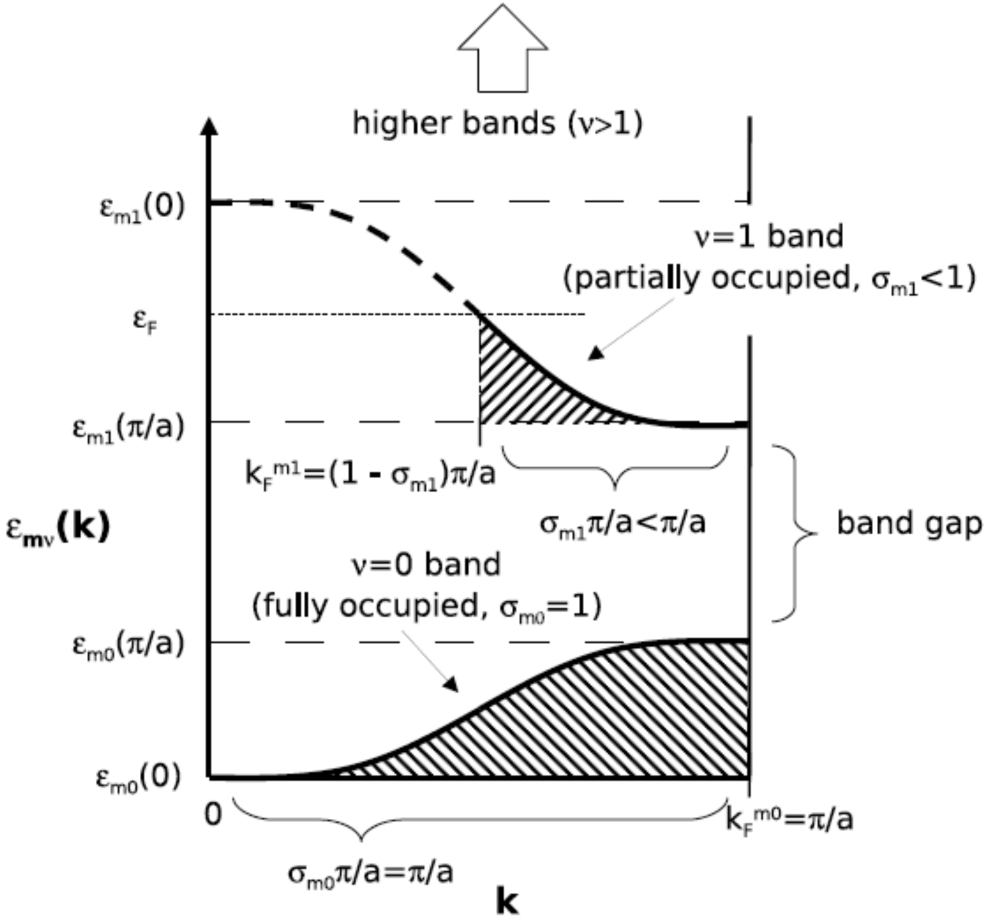
Previous calculations (P. Jones, Neuhauser et al. 1986-88) showed that

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



$$E[n] = E_K[n] + E_{eZ}[n] + E_{\mathrm{dir}}[n] + E_{\mathrm{exc}}[n] + E_{ZZ}[n]$$

$$E_{eZ}[n] = -\sum_{j=-N/2}^{N/2} Ze^2 \int_{|z|<a/2} d\mathbf{r}\, \frac{n(\mathbf{r})}{|\mathbf{r}-\mathbf{z}_j|}\,,$$

$$E_{\mathrm{dir}}[n] = \frac{e^2}{2} \iint_{|z|<a/2} d\mathbf{r}\, d\mathbf{r}'\, \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\,, \qquad E_{\mathrm{exc}}[n] = \int_{|z|<a/2} d\mathbf{r}\, n(\mathbf{r})\, \varepsilon_{\mathrm{exc}}(n)$$

$$E_{ZZ}[n] = \sum_{j=1}^{N/2} \frac{Z^2 e^2}{ja}\,.$$

$$n(\mathbf{r}) = \sum_{m\nu k} |\Psi_{m\nu k}(\mathbf{r})|^2 \qquad \Psi_{m\nu k}(\mathbf{r}) = \frac{1}{\sqrt{N}} W_m(\mathbf{r}_\perp) f_{m\nu k}(z)$$

$$W_m(\mathbf{r}_\perp) = \frac{1}{\rho_0\sqrt{2\pi m!}} \left(\frac{\rho}{\sqrt{2}\rho_0}\right)^m \exp\left(\frac{-\rho^2}{4\rho_0^2}\right) \exp(-im\phi)$$

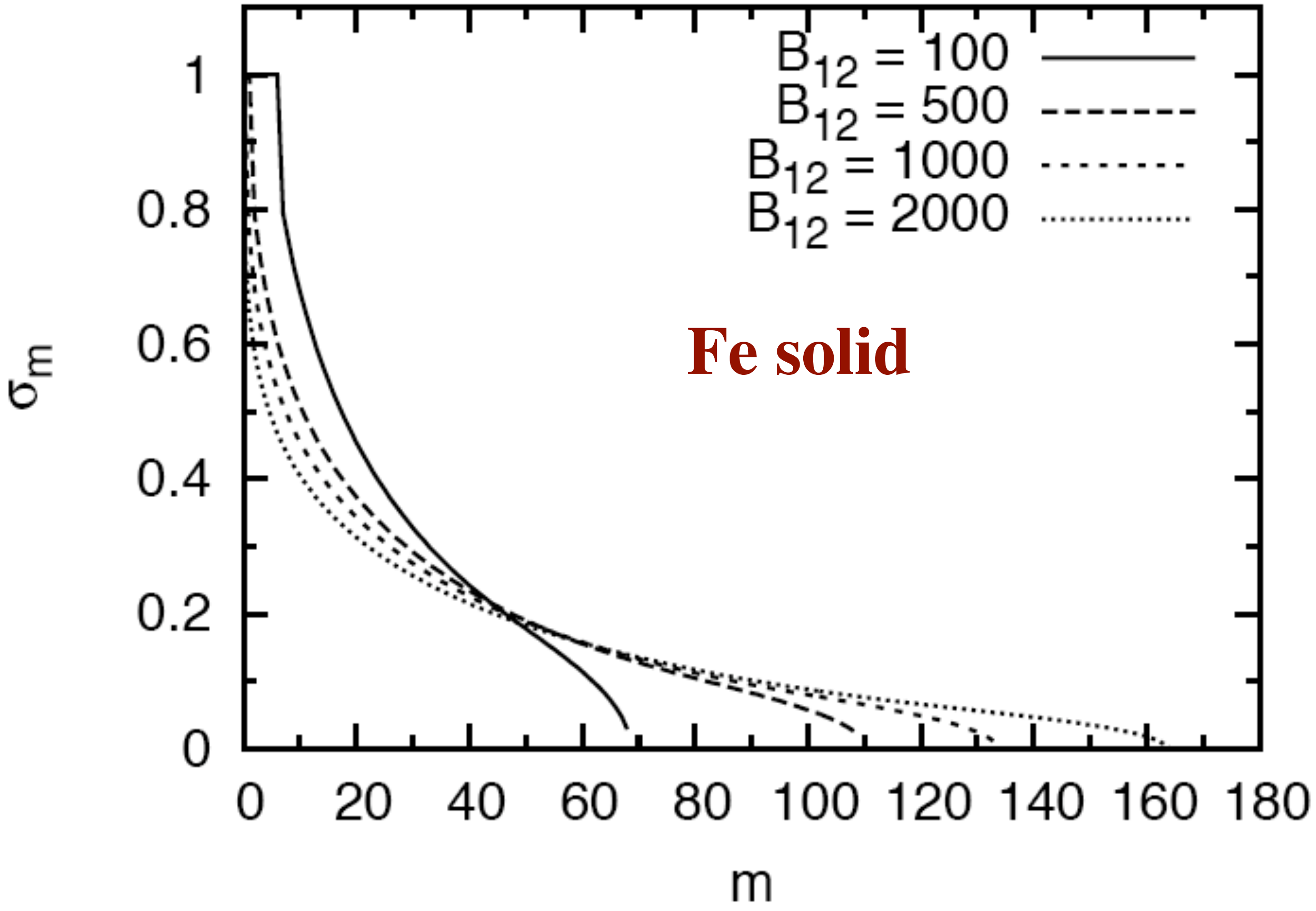
$$f_{m\nu k}(z+a) = e^{ika} f_{m\nu k}(z)$$

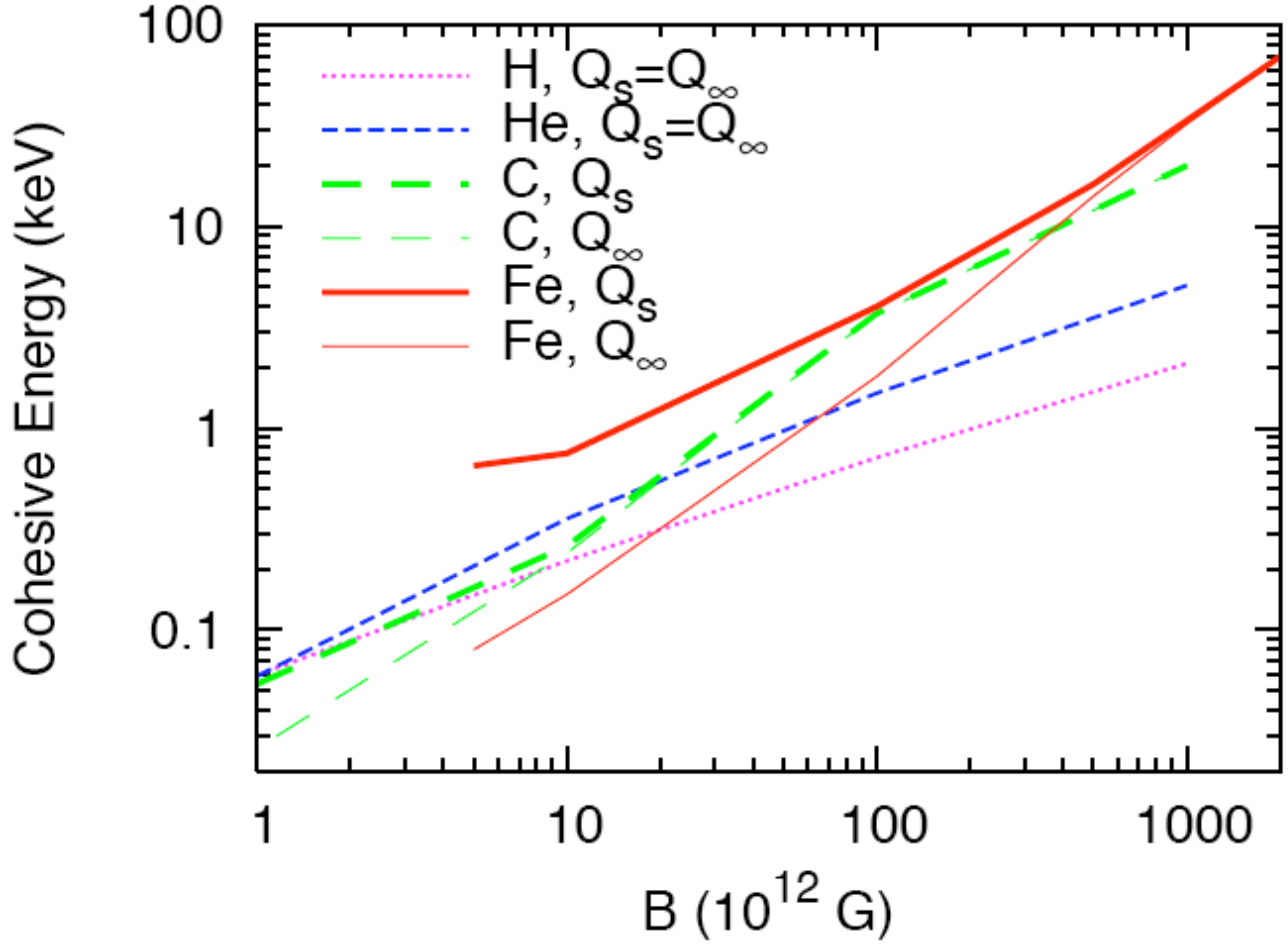
$$\left[-\frac{\hbar^2}{2m_e}\nabla^2 + V_{\mathrm{eff}}(\mathbf{r})\right] \Psi_{m\nu k}(\mathbf{r}) = \varepsilon_{m\nu}(k) \Psi_{m\nu k}(\mathbf{r})$$

$$V_{\mathrm{eff}}(\mathbf{r}) = -\sum_{j=-N/2}^{N/2} \frac{Ze^2}{|\mathbf{r}-\mathbf{z}_j|} + e^2 \int d\mathbf{r}'\, \frac{n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} + \mu_{\mathrm{exc}}(n) \qquad \mu_{\mathrm{exc}}(n) = \frac{\partial(n\varepsilon_{\mathrm{exc}})}{\partial n}$$

$$\begin{aligned} E_\infty \;=\; & \frac{a}{2\pi} \sum_{m\nu} \int_{I_{m\nu}} dk\, \varepsilon_{m\nu}(k) - \frac{e^2}{2} \iint_{|z|<a/2} d\mathbf{r} d\mathbf{r}'\, \frac{n(\mathbf{r})n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \\ & + \int_{|z|<a/2} d\mathbf{r}\, n(\mathbf{r}) [\varepsilon_{\mathrm{exc}}(n) - \mu_{\mathrm{exc}}(n)] + \sum_{j=1}^{N/2} \frac{Z^2 e^2}{ja}\,, \end{aligned}$$

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



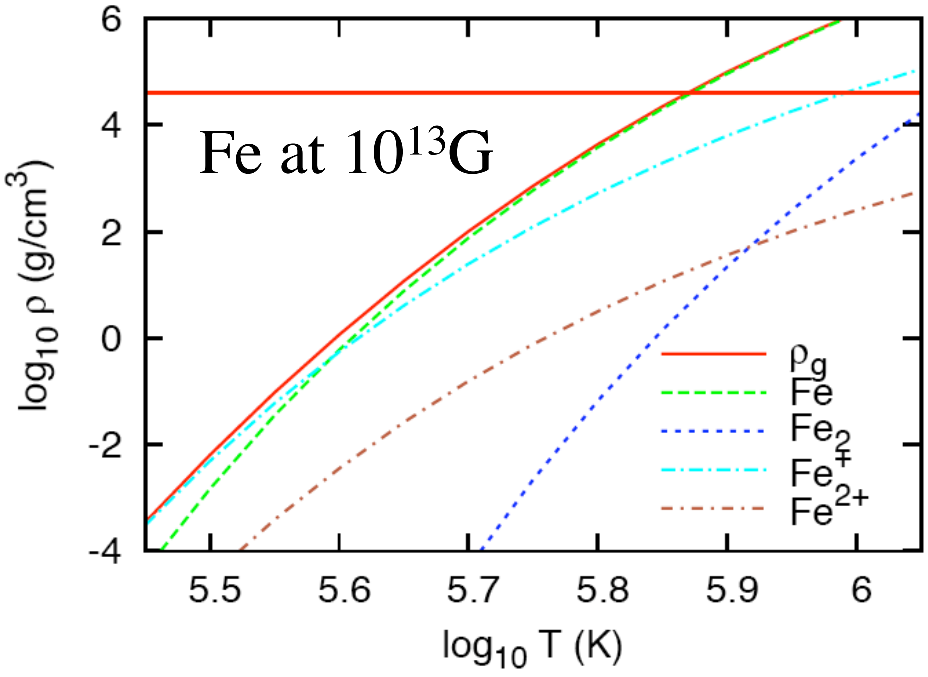

H, Q_s=Q_∞
He, Q_s=Q_∞
C, Q_s
C, Q_∞
Fe, Q_s
Fe, Q_∞
Cohesive Energy (keV)
100
10
1
0.1
1
10
100
1000
B (10^{12} G)

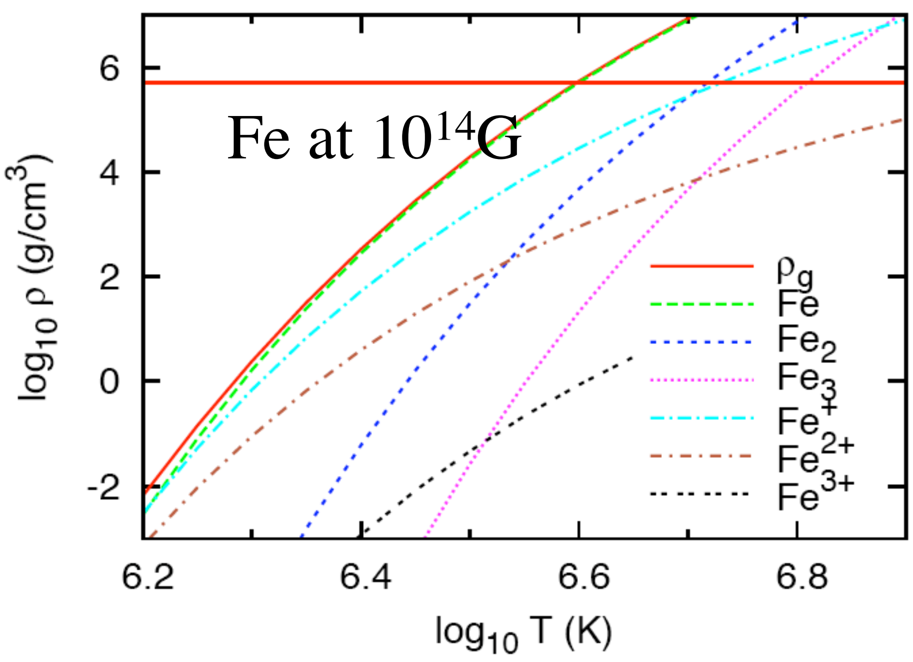
Why Do We Care?

Surface condensation of isolated NSs

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

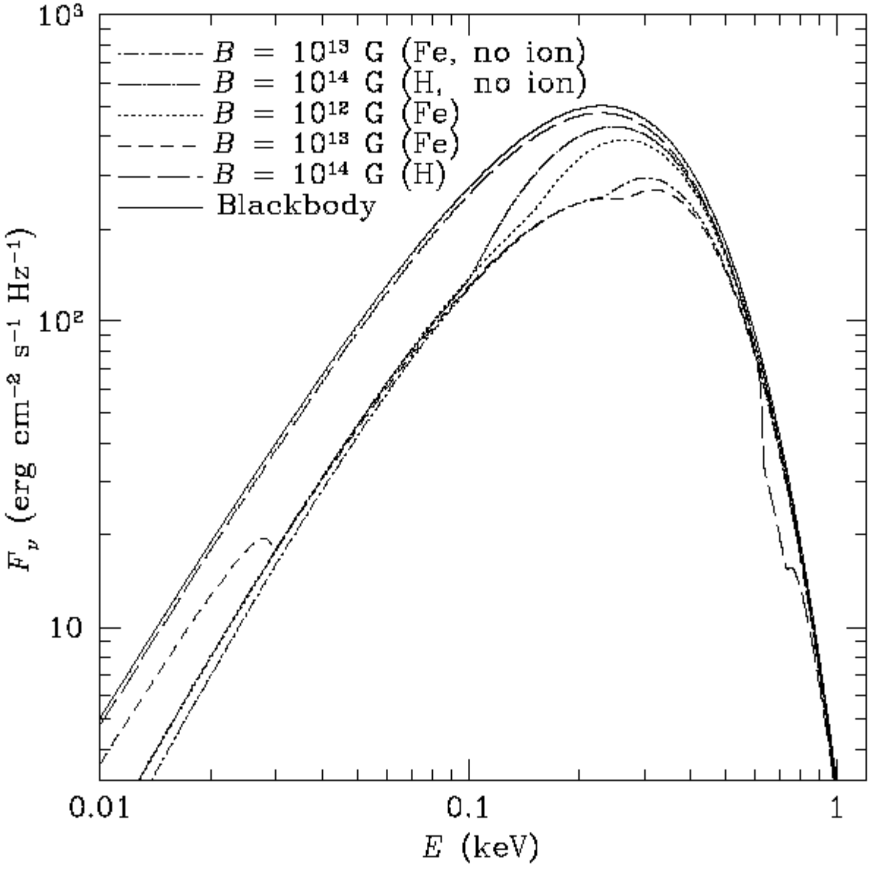
NS surface is in condensed form (with little vapor above)





Emission from condensed NS surface resembles a featureless blackbody

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



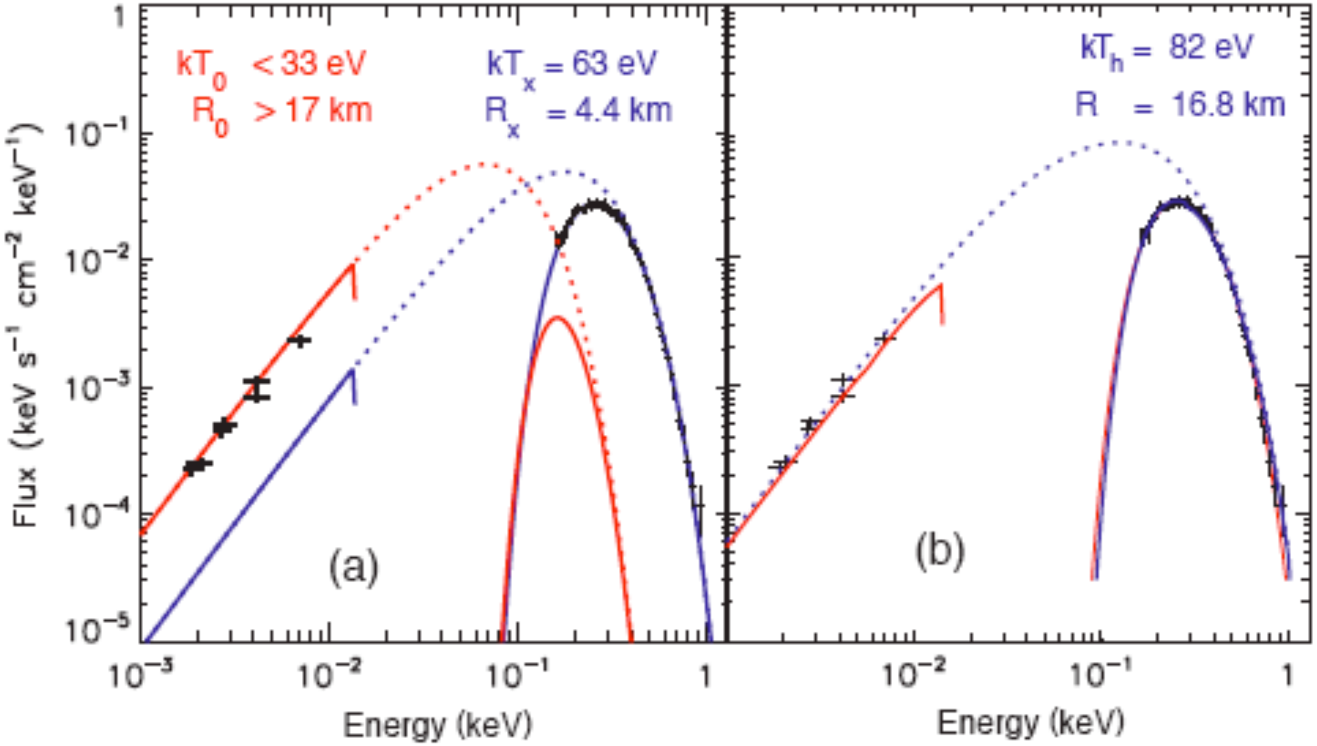
van Adelsberg, Lai, Potekhin & Arras 05

Thermally Emitting Isolated NSs

“Perfect” X-ray blackbody:

RX J1856.5-3754

(T ~ 60 eV)

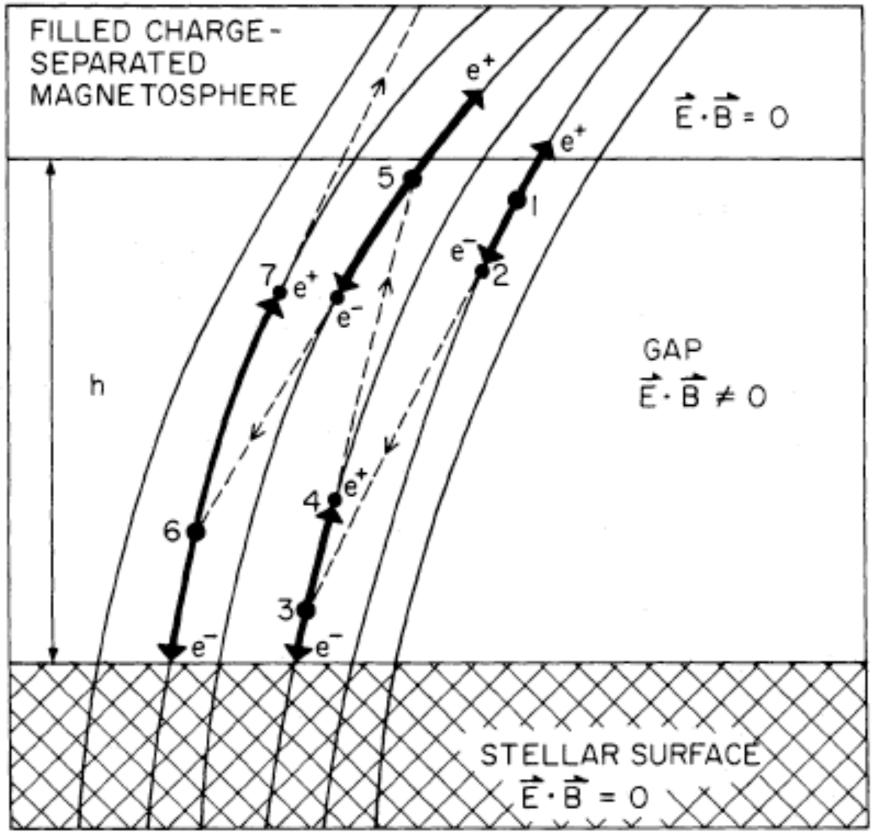


Burwitz et al. 03, Trumper et al 04

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

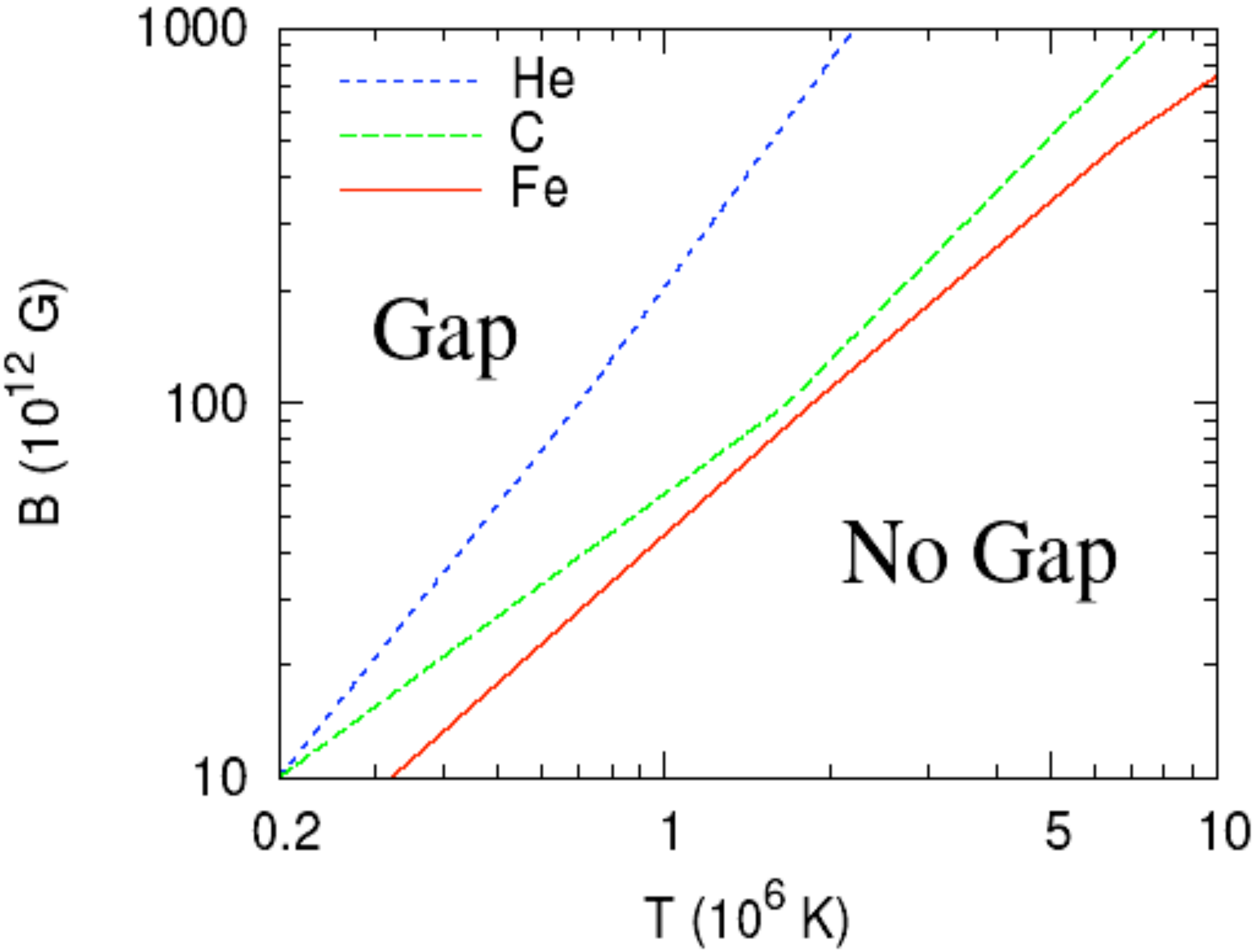


Large cohesive energy

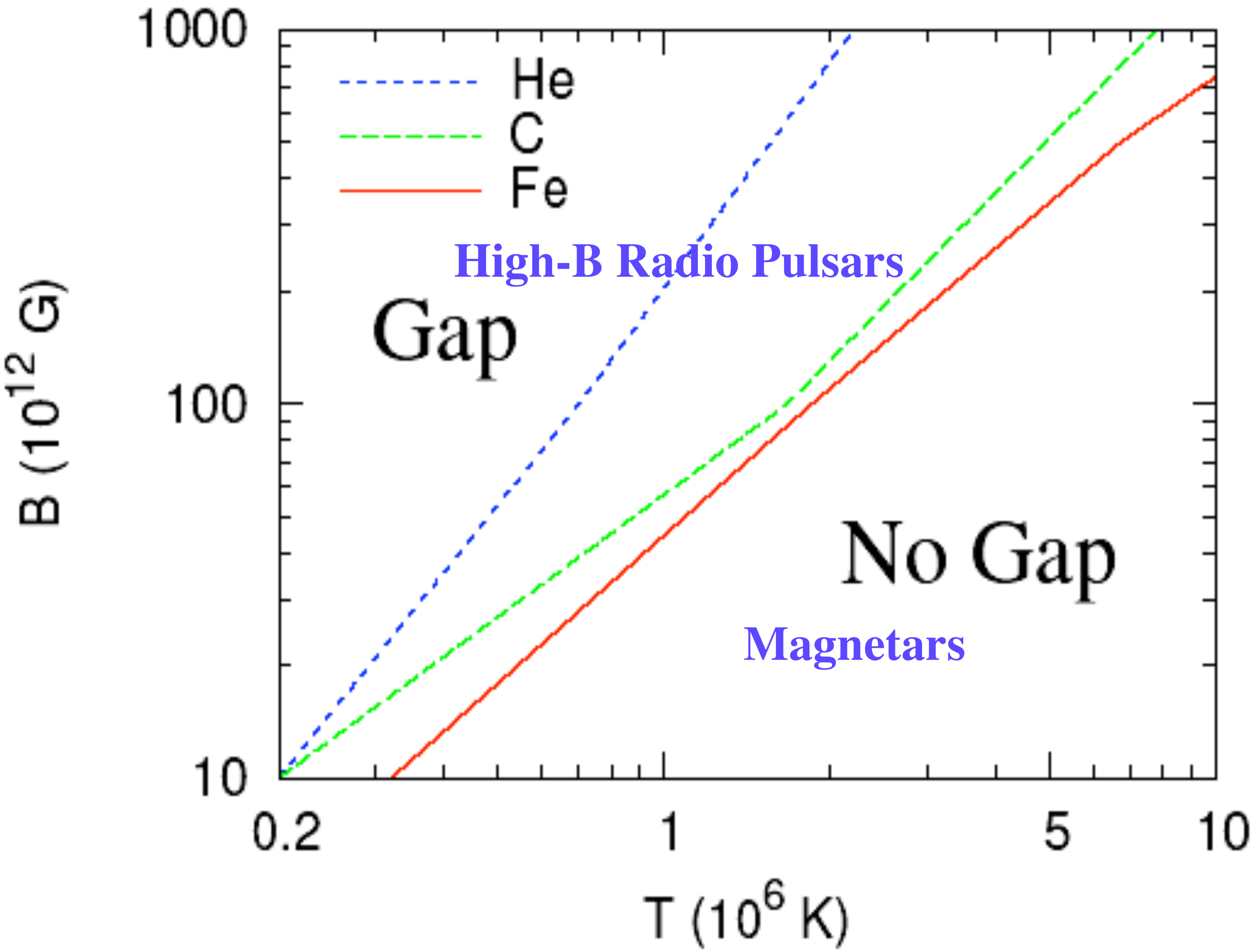
===> charged particle cannot come out of the surface

===> Vacuum gap above the surafce

(very efficient acclerator)



Medin & DL 2007



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

Summary

- **Magnetic NSs have many different manifestations**
  (pulsars, magnetars, thermal emitters, transients/RRATs, accreting NSs etc)

- **Many recent observational surprises/puzzles**

  (Evolution/connection of different types of NSs, high-B radio pulsars vs magnetars, giant flares, perfect blackbody vs spectral lines, etc)

- **Theoretical problems (2 examples):**

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  QED effect on spectrum and polarization

  * **Matter in string B-fields:**
  Condensed NS surface: Implication for black-body surface emission?
  Particle acceleration in magnetosphere

Neutron stars as (nuclear) physics laboratory

Many ways to probe/constrain nuclear physics with NSs:

- NS cooling
- NS mass measurement (from radio and X-ray pulsars in binaries).
- Measure radius from thermal emission
- Gravitational red-shifted lines (==> M/R relation)
- Rotation rate (sub-ms pulsars?)
- Variability (QPOs) of X-ray flux from NS in LMXBs
- QPO in magnetar giant flares
- Pulsar Glitches: probe of superfluidity of nucelar matter
- Precession?
- Measure moment of inertia from double pulsars system

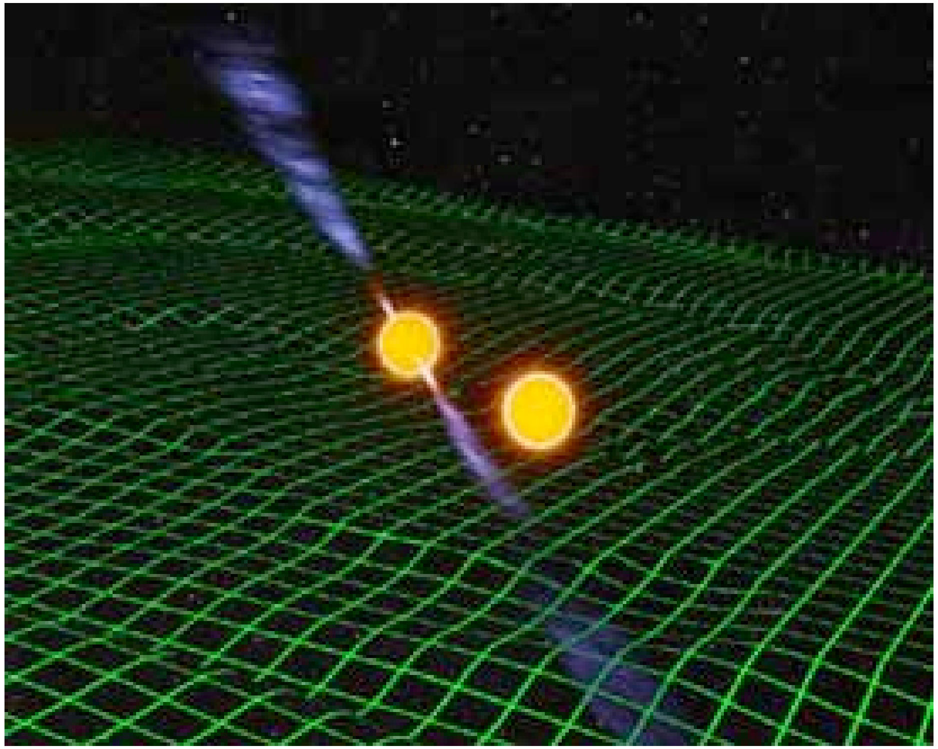
Other important applications of pulsars:

- Test GR
- Probe ISM (electron density and B fields)
- Probe GW background

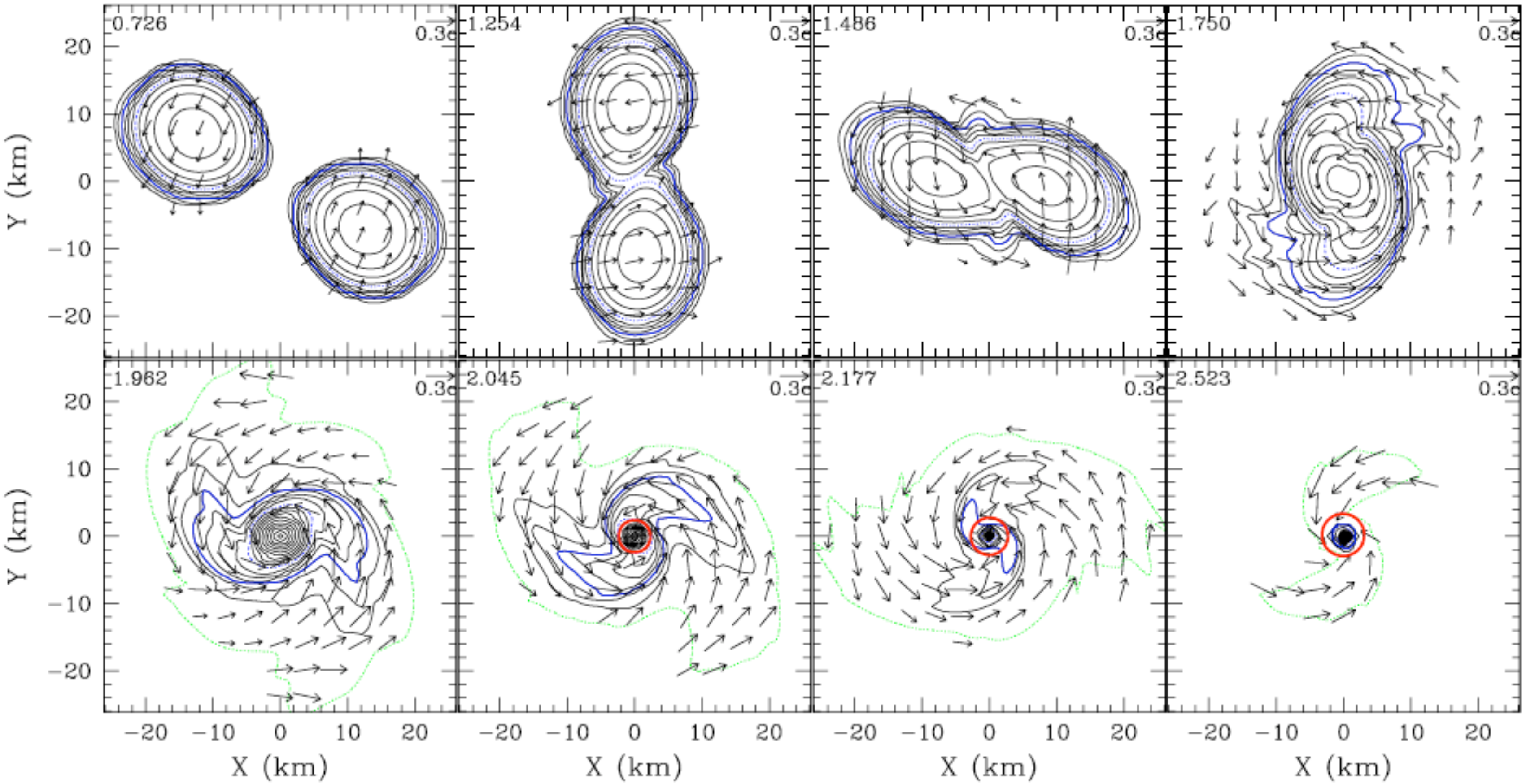
Two topics:

- Probing nuclear physics with coalescing NS binaries
- Probing axions with magnetic NSs

Probing Nuclear Physics with Merging NS/NS or NS/BH

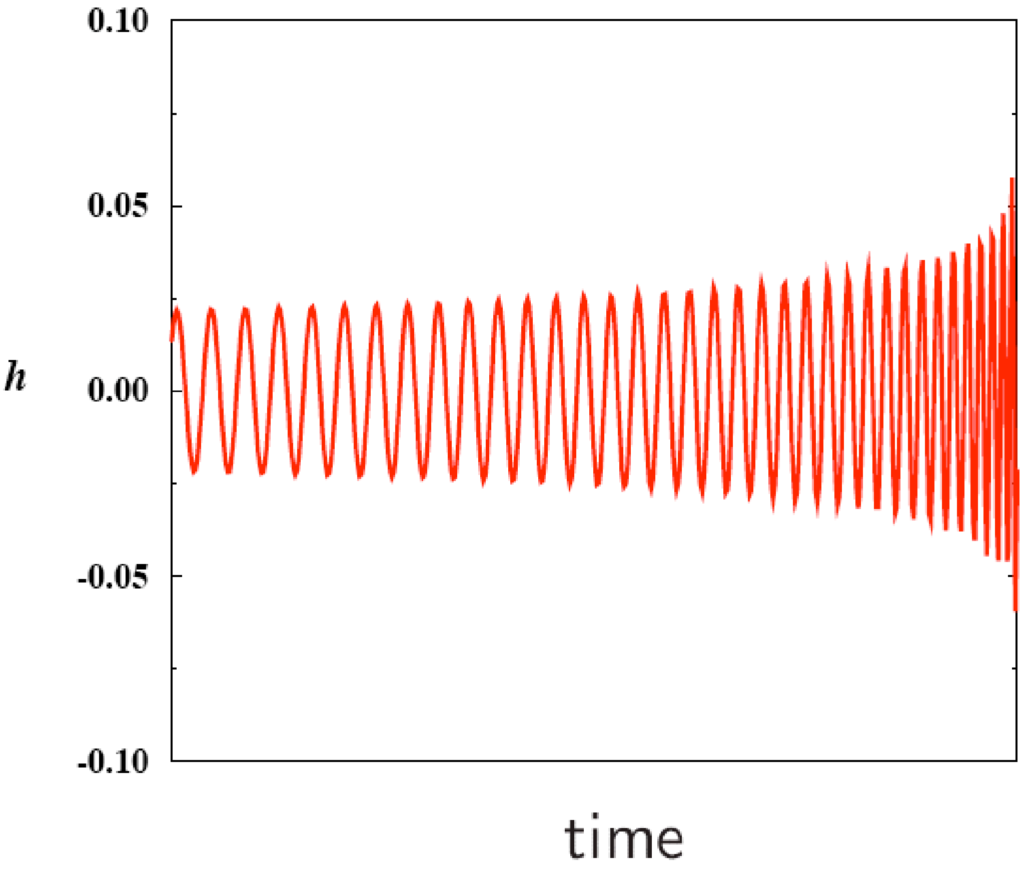


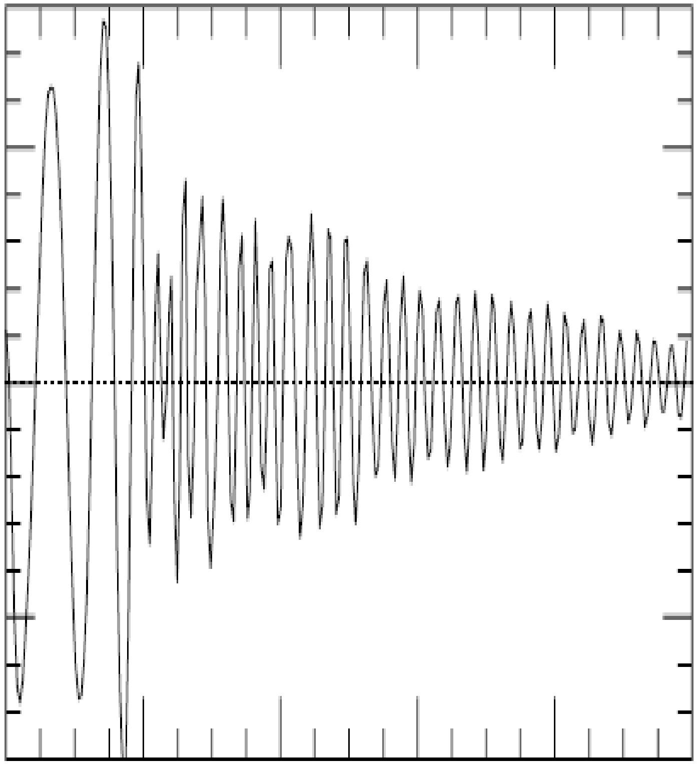
Binary pulsars

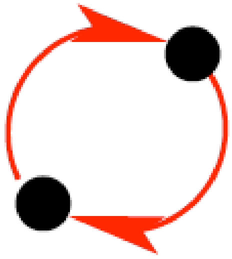


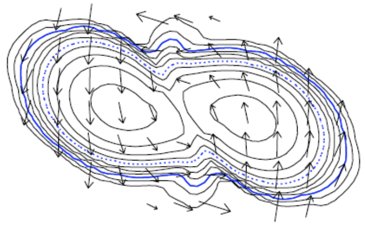
Shibata et al. 2006

The last three minutes: Gravitational Waveform

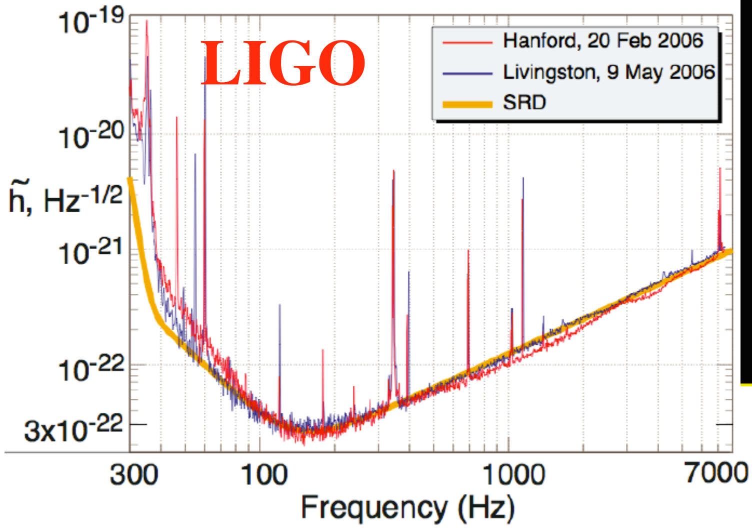









Hanford Washington


LIGO
Hanford, 20 Feb 2006
Livingston, 9 May 2006
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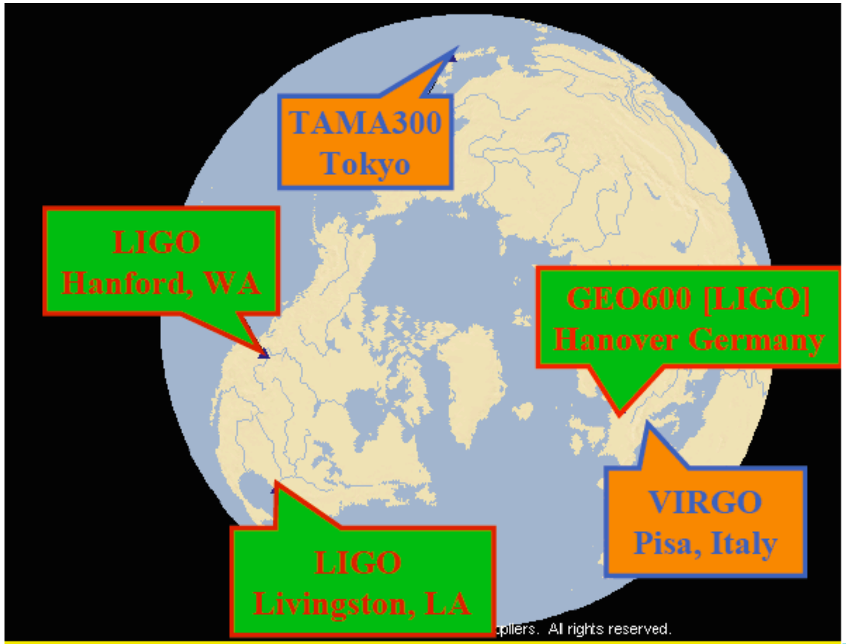
Frequency (Hz)


Livingston,
Louisiana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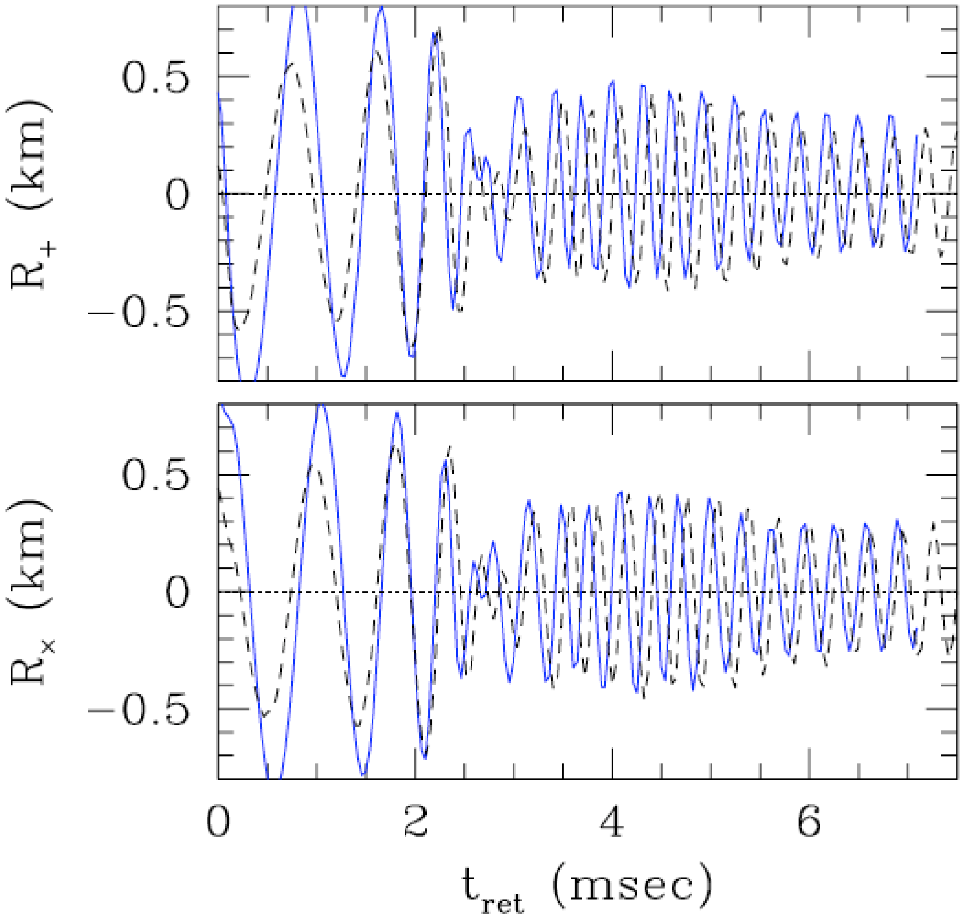
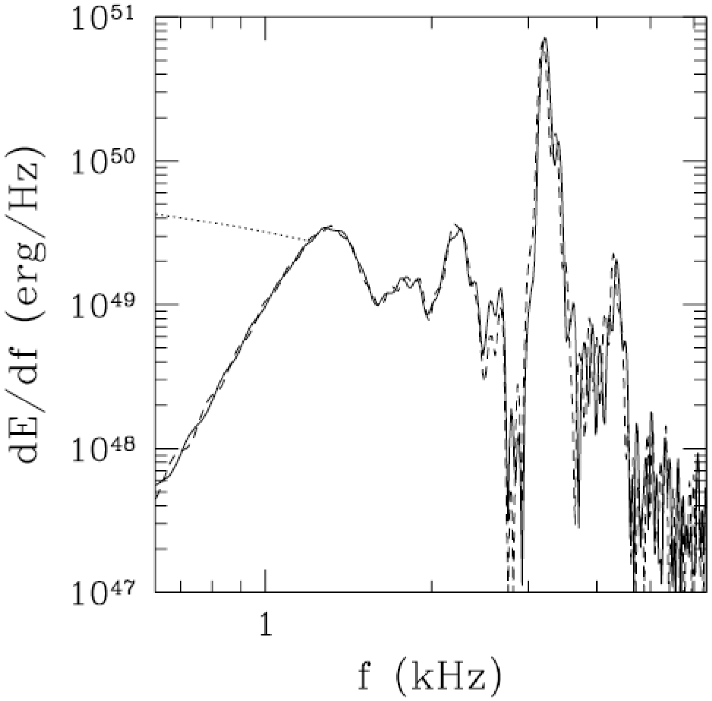
VIRGO

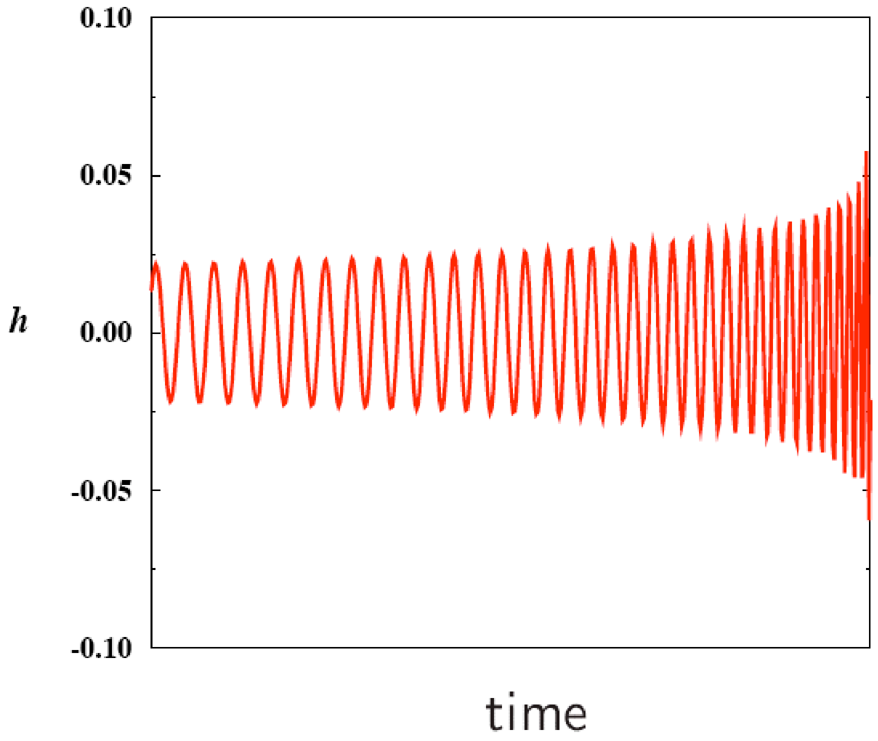
Final merger waveform probes NS EOS

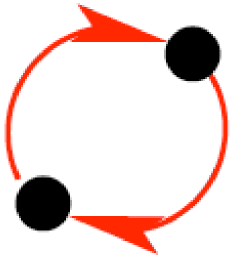




Shibata et al 2006

Another Way: 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 (e.g. 13-15 km) NS

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

Merger of Binary Strange/Quark Stars?

How is a strange star disrupted by a black hole?

Is there unique signature of strange star merger?

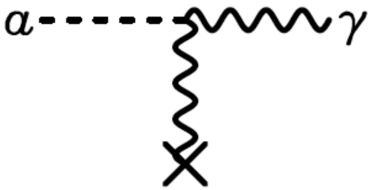
Probing Axions with Magnetic Neutron Stars

Probing Axions with Magnetic NSs

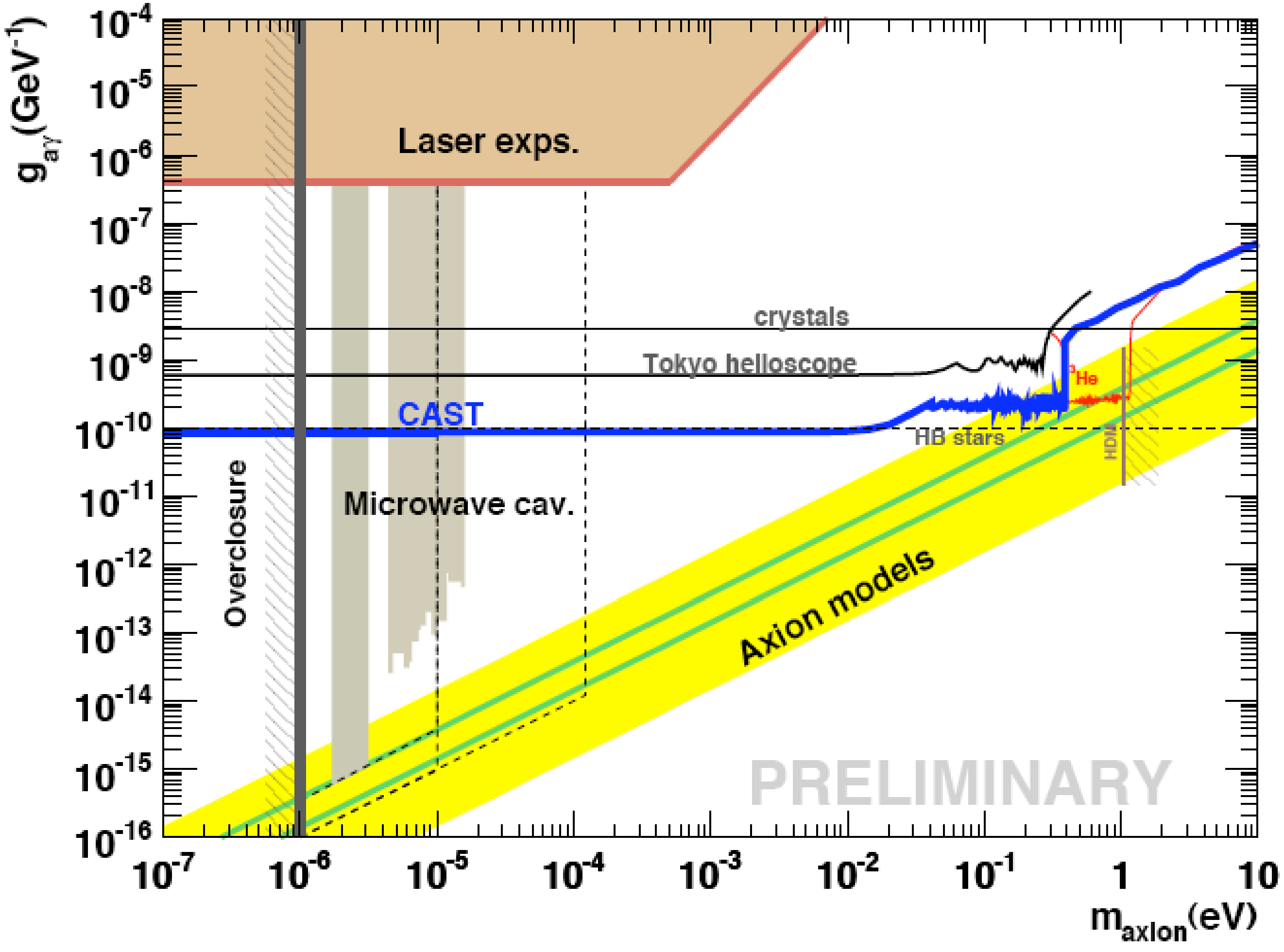
Axions: pseudoscalar particles, arise in the Peccei-Quinn solution of the strong CP problem; could be dark matter candidates

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

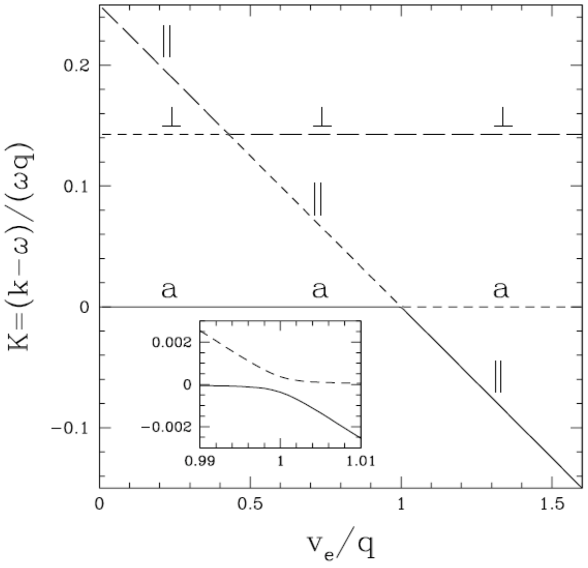


arXiv:0810.1874 (CAST collaboration)

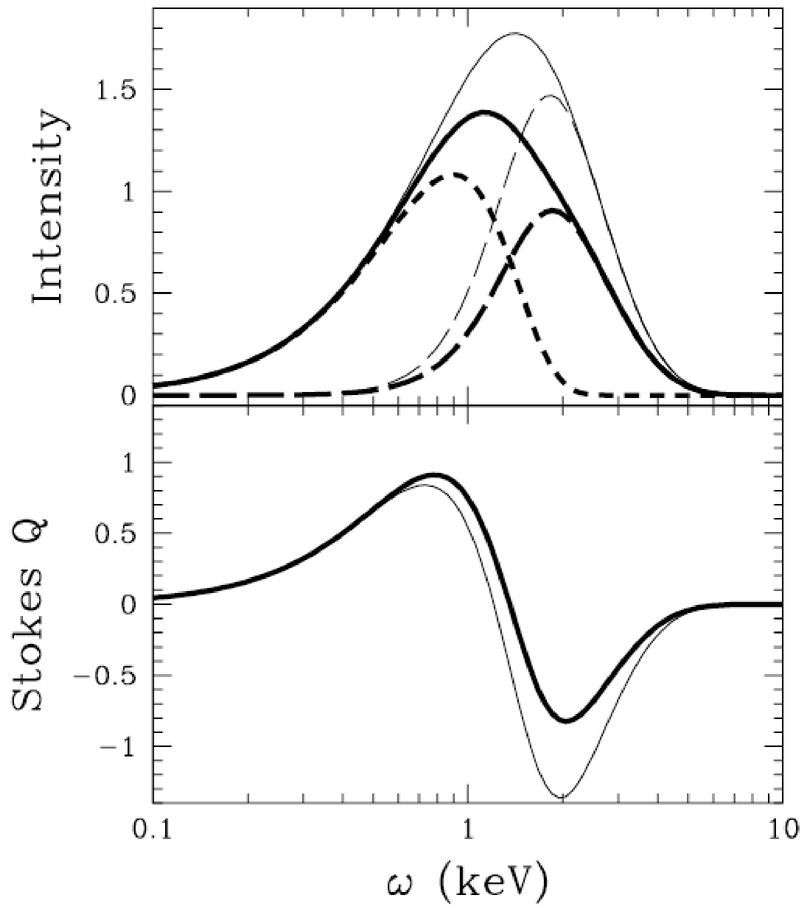
Photon-Axion Conversion in Magnetic Neutron Stars

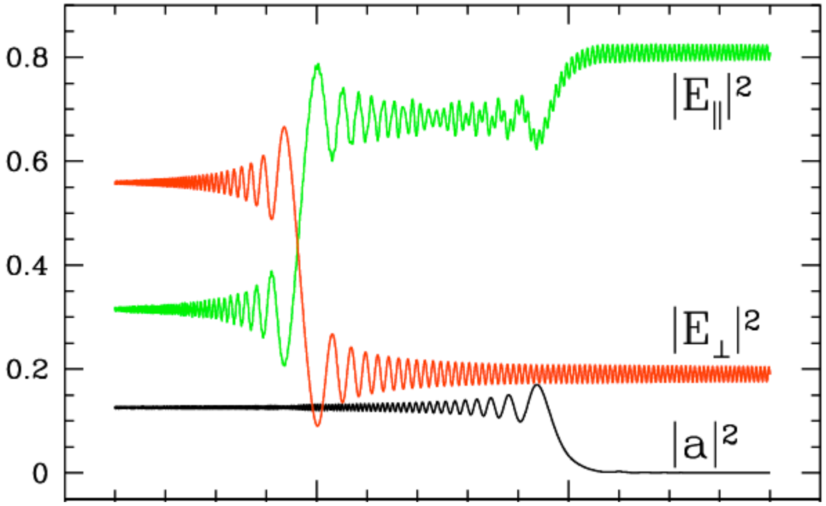
In the magnetized plasma of NSs, photons (//-polarization component) can convert (resonantly a la MSW) into axions

===> modify radiation spectra and polarization signals



DL & Heyl 2007





The End….Merci Beaucoup!

Summary

- **Magnetic NSs have many different manifestations**

  (pulsars, magnetars, thermal emitters, transients/RRATs, accreting NSs etc)

- **Many recent observational surprises/puzzles**

  (Evolution/connection of different types of NSs, high-B radio pulsars vs magnetars, giant flares, perfect blackbody vs spectral lines, etc)

- **Theoretical problems (2 examples):**

  * **Photon propagation in NS atmospheres:**

  QED effect on spectrum and polarization

  * **Matter in string B-fields:**

  Condensed NS surface: Implication for black-body surface emission?

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- **Using NSs to probe nuclear/particle physics**