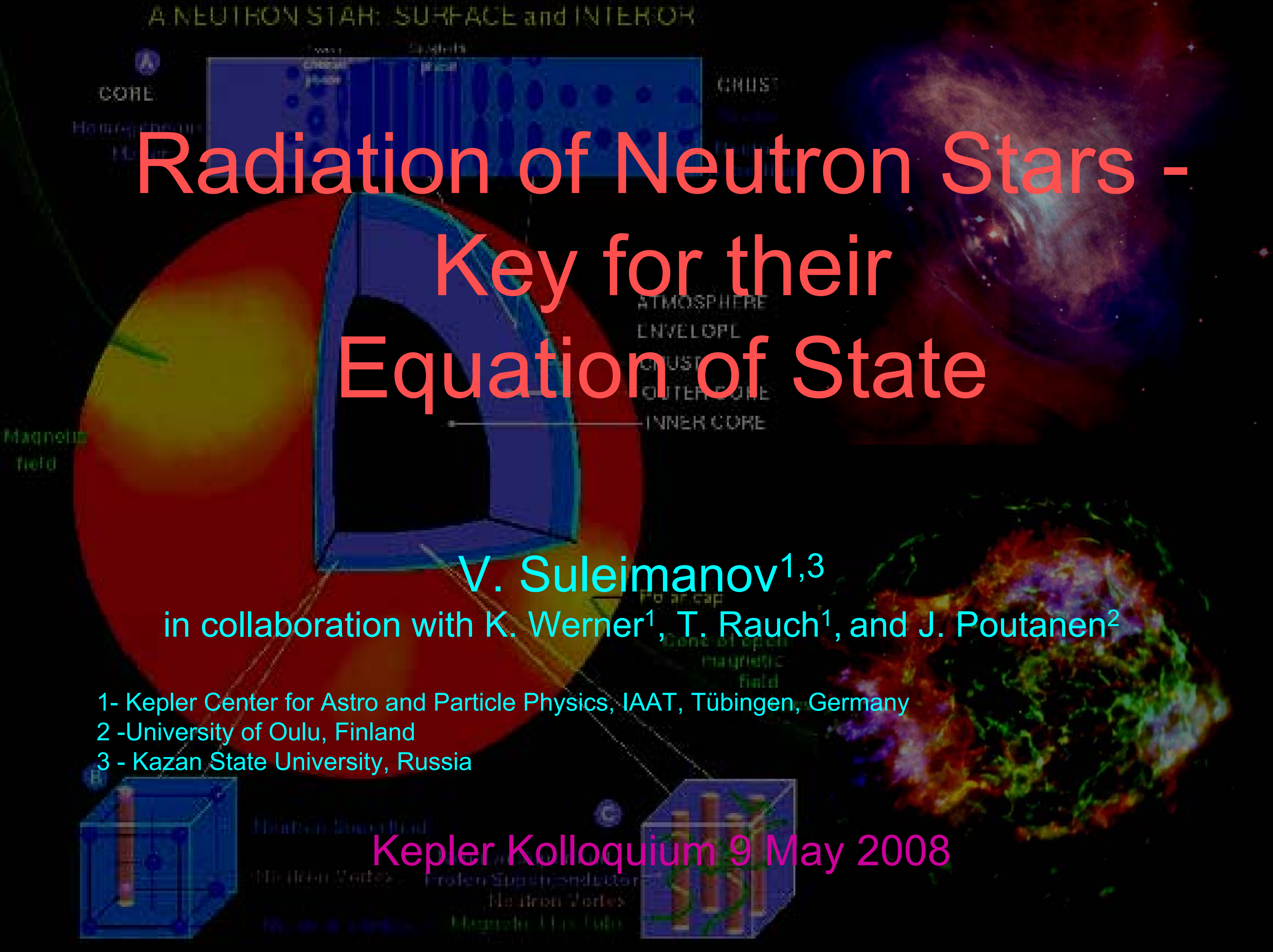


Radiation of Neutron Stars - Key for their Equation of State

V. Suleimanov[1,3]

in collaboration with K. Werner[1], T. Rauch[1], and J. Poutanen[2]

1- Kepler Center for Astro and Particle Physics, IAAT, Tübingen, Germany
2 -University of Oulu, Finland
3 - Kazan State University, Russia

Kepler Kolloquium 9 May 2008

Neutron stars – main properties and short history

$M \approx 1.4\ M_{Sun}$ $R \approx 10$ km

$E_g \approx GM^2 / R \sim 5\ 10^{53}$ erg

$\rho \approx 7\ 10^{14}$ g/cc

Pressure of degenerate neutrons

Crab nebula (*Chandra*)

First idea – L. Landau (1932)

Neutron stars arise due to Supernova outbursts

W. Baade, F. Zwicky (1934)

$E_{SN} \sim 10^{53}$ erg $\sim E_g$ (NS)

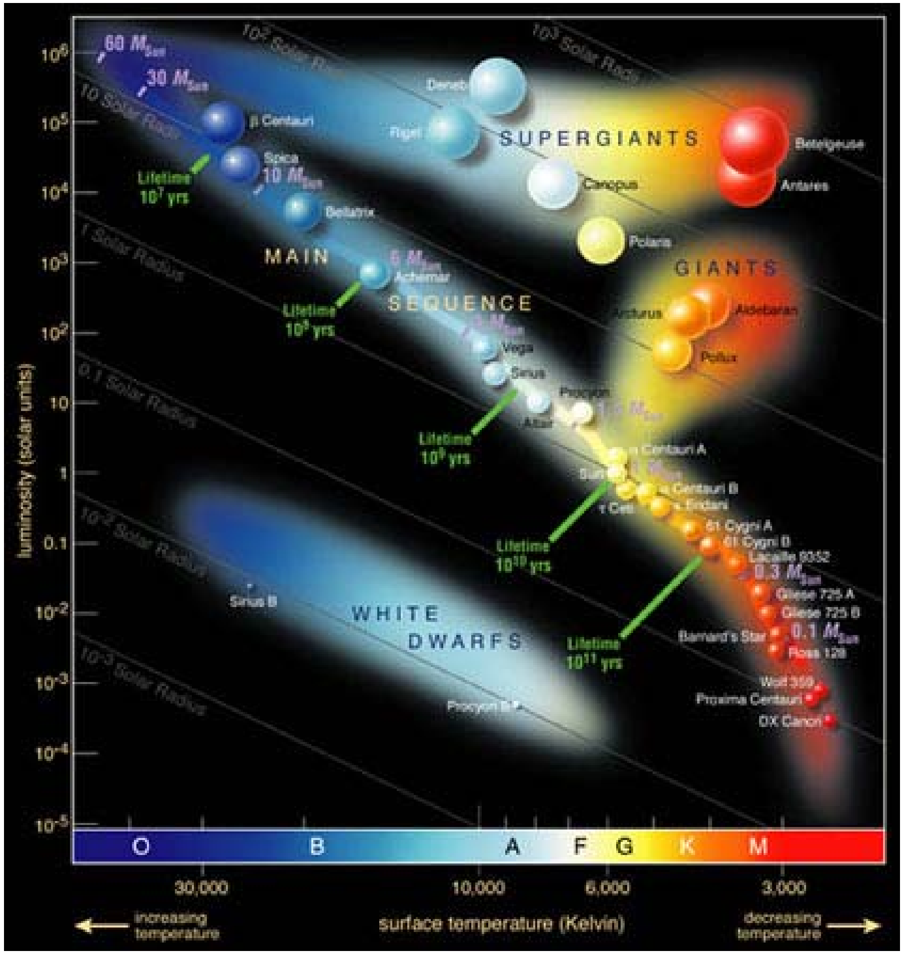
Discovery of Pulsars - A. Hewish,

Jocelyn Bell (1968)

Supernova (type II) – finale of a massive star life

Hertzsprung – Russel Diagram

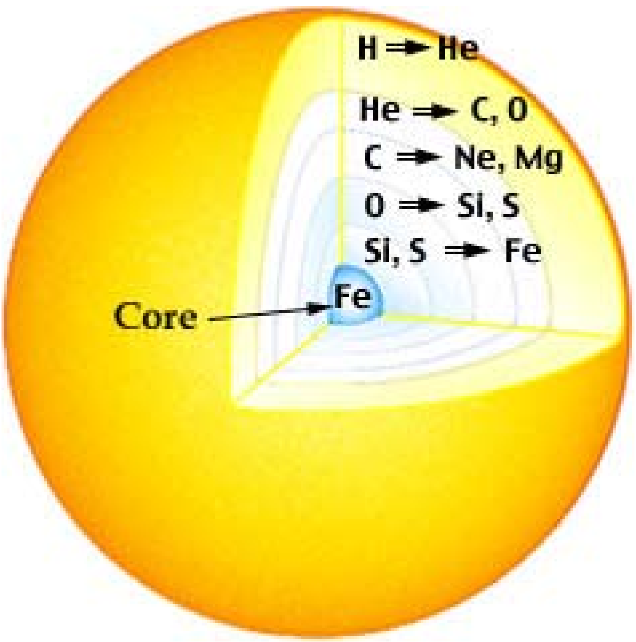
Luminosity



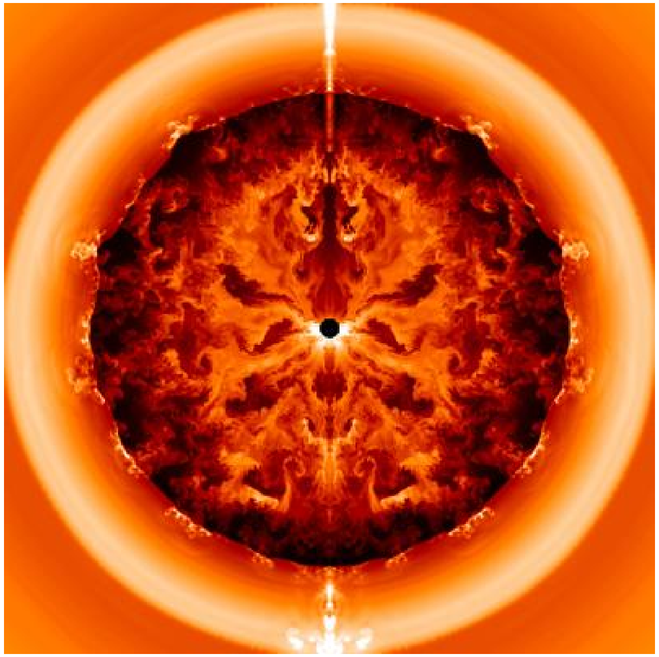
Effective temperature

Massive stars evolve along supergiant branch up to SNII explosion

Supernova (type II) – finale of a massive star life



Massive star structure before explosion



SNII explosion calculations (T. Janka, MPA)

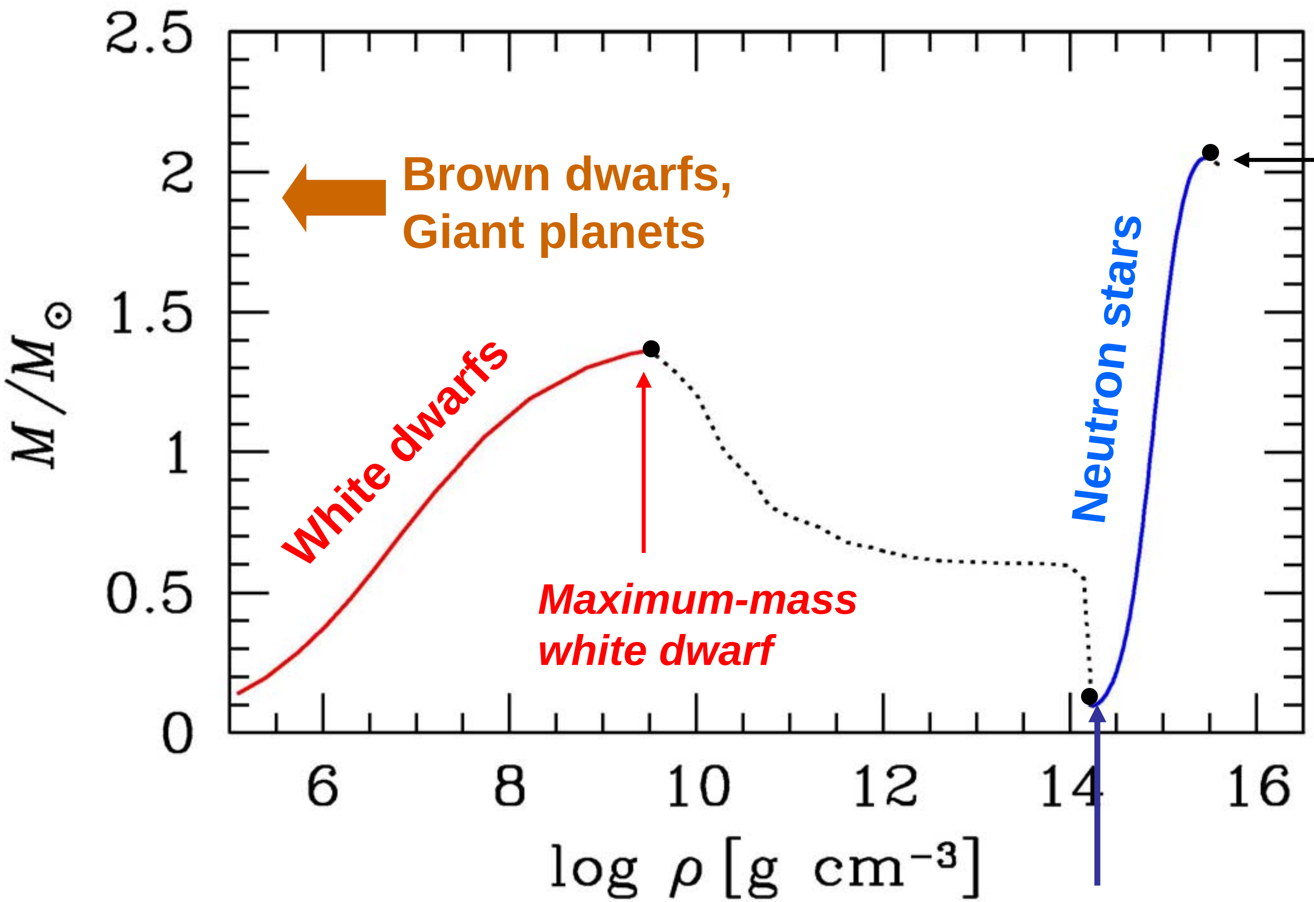
Reason – gravitational collapse of Fe core due to

Photodisintegration and Neutronization

$$\gamma + {}^{56}Fe = 13\alpha + 4n$$

$$p + e^- \rightarrow n + \nu_e$$

Stellar remnants – White Dwarfs and Neutron Stars



Maximum -mass neutron star

$M \sim (1.5-2.5)\, M_{\rm Sun}$

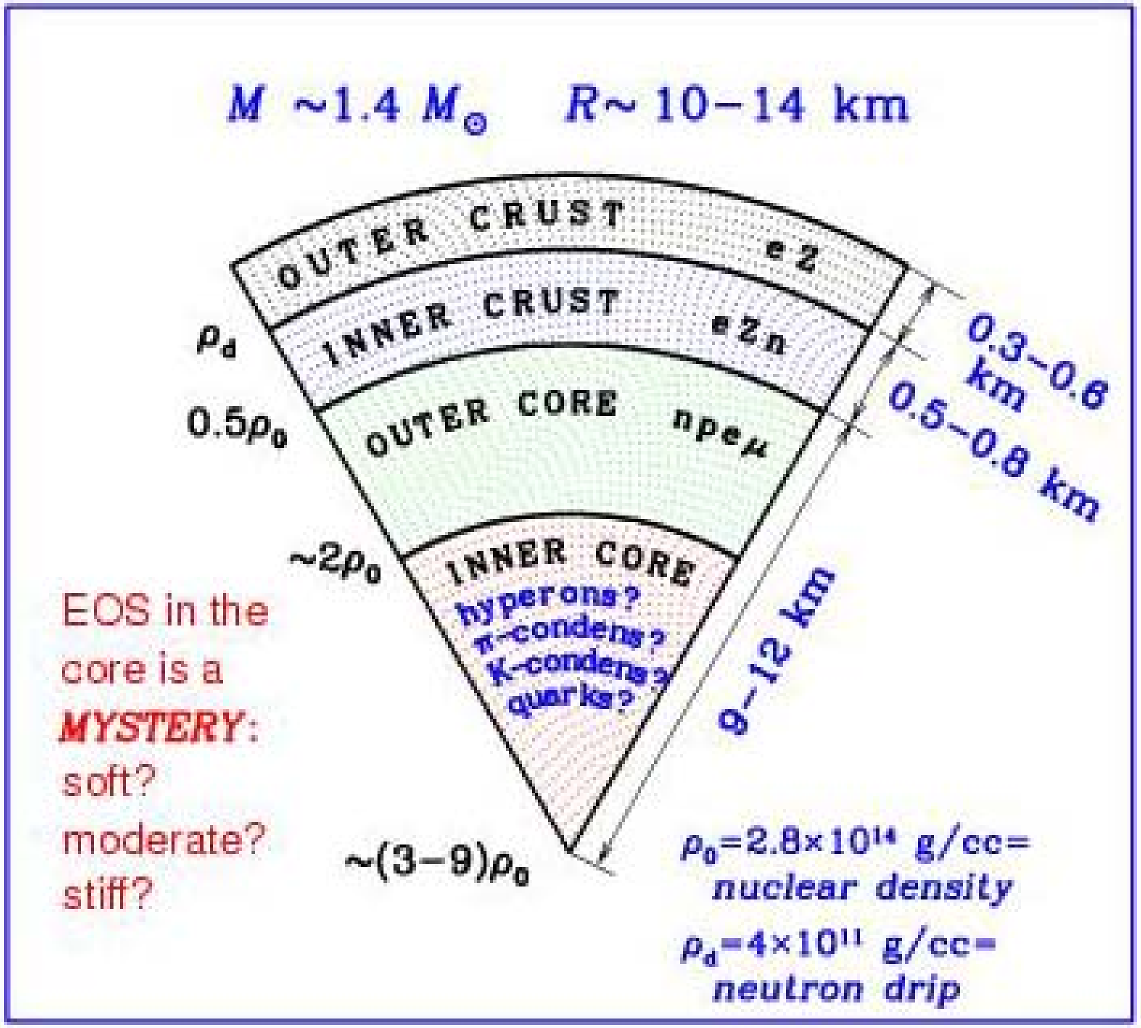
$R \sim 9-12\ \text{km}$

Minimum-mass neutron star

$M \sim 0.1\, M_{\rm Sun}$

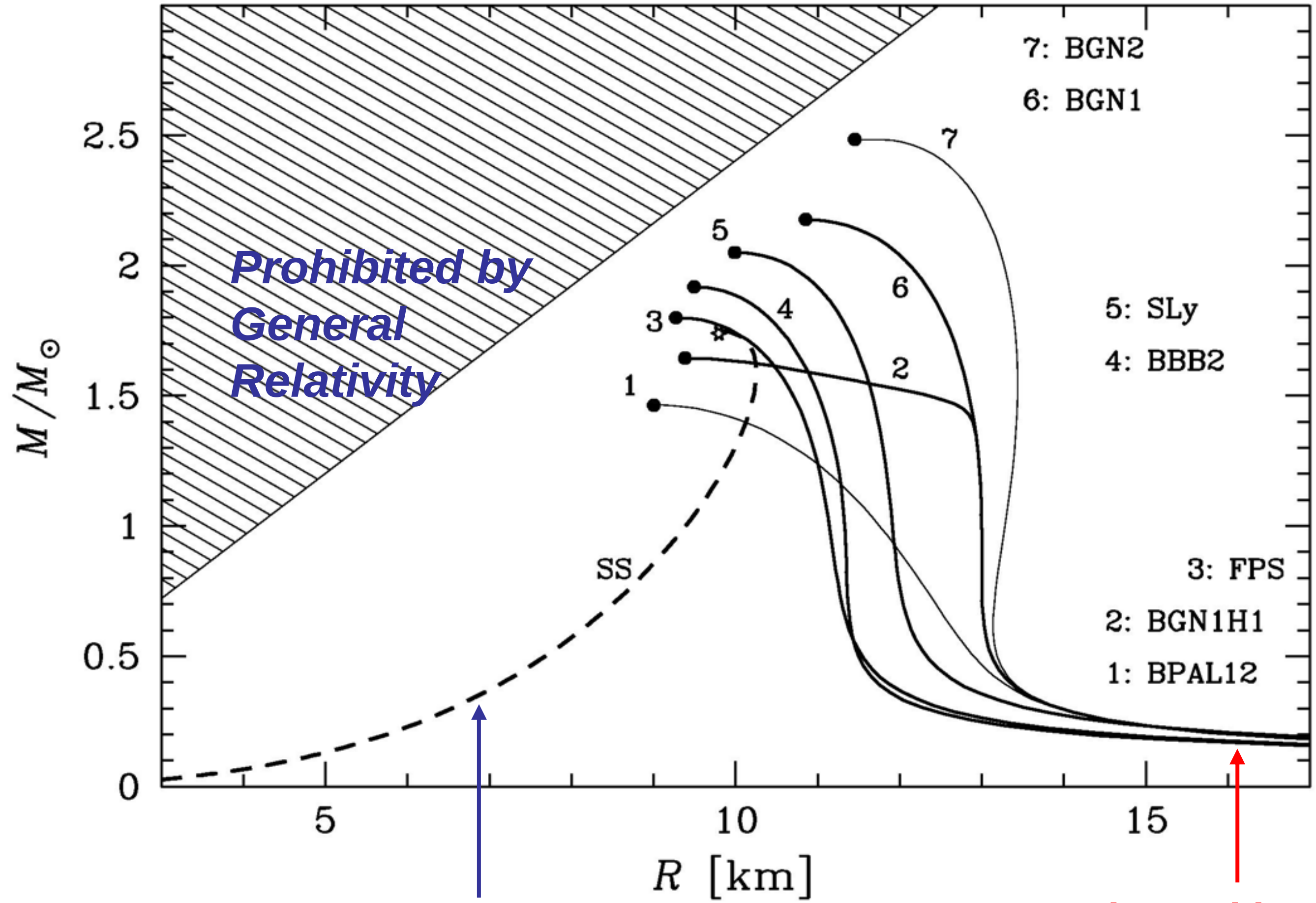
$R \sim 250\ \text{km}$

Neutron star structure



Main problem – inner core Equation of State (EoS)

Zoo of NS inner core EoS



Special family of low-mass strange stars

Universal low-mass curve

Solution – M and R from observations!

Many faces of NS

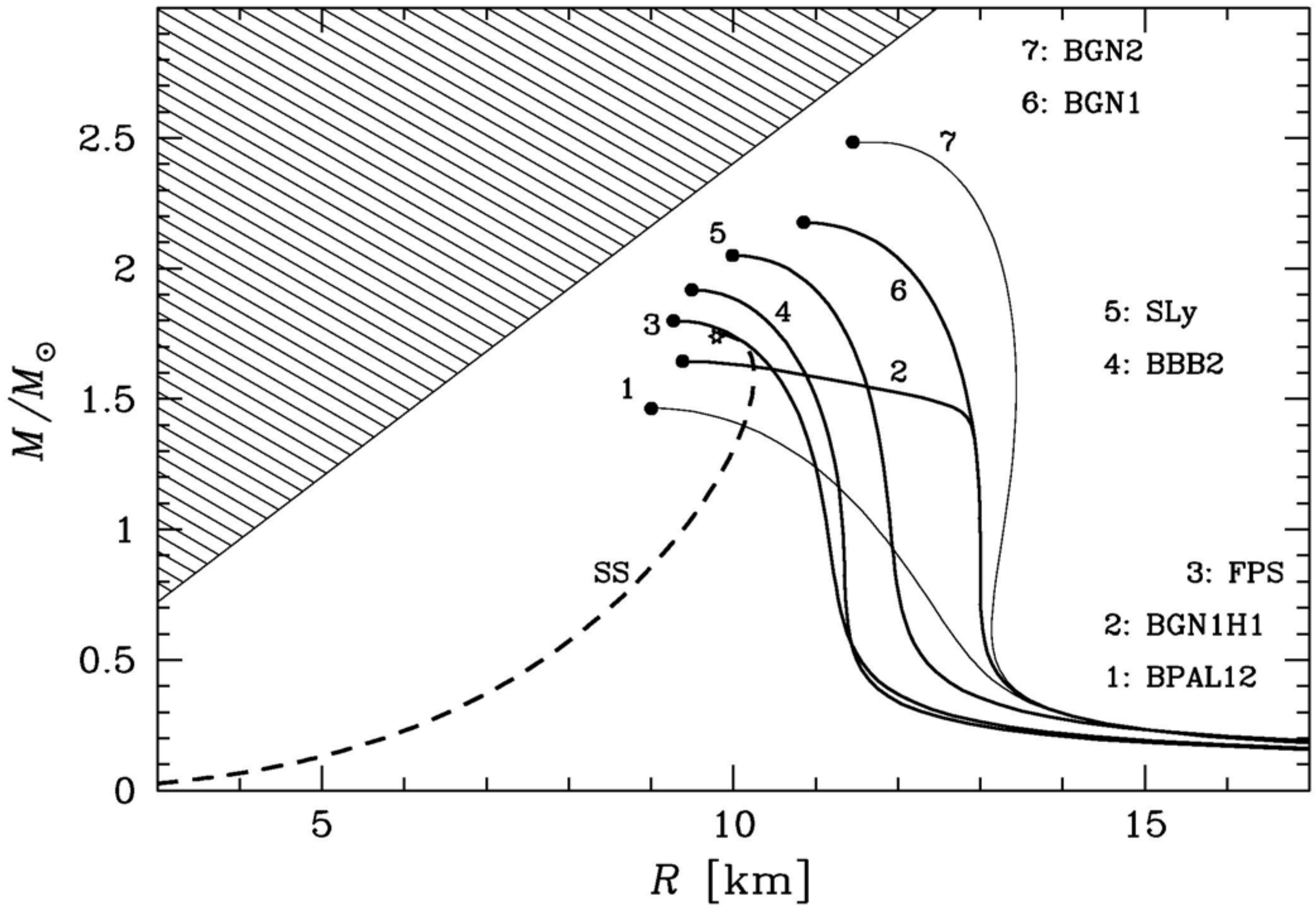
Radio Pulsars

NSs in X-ray Binaries

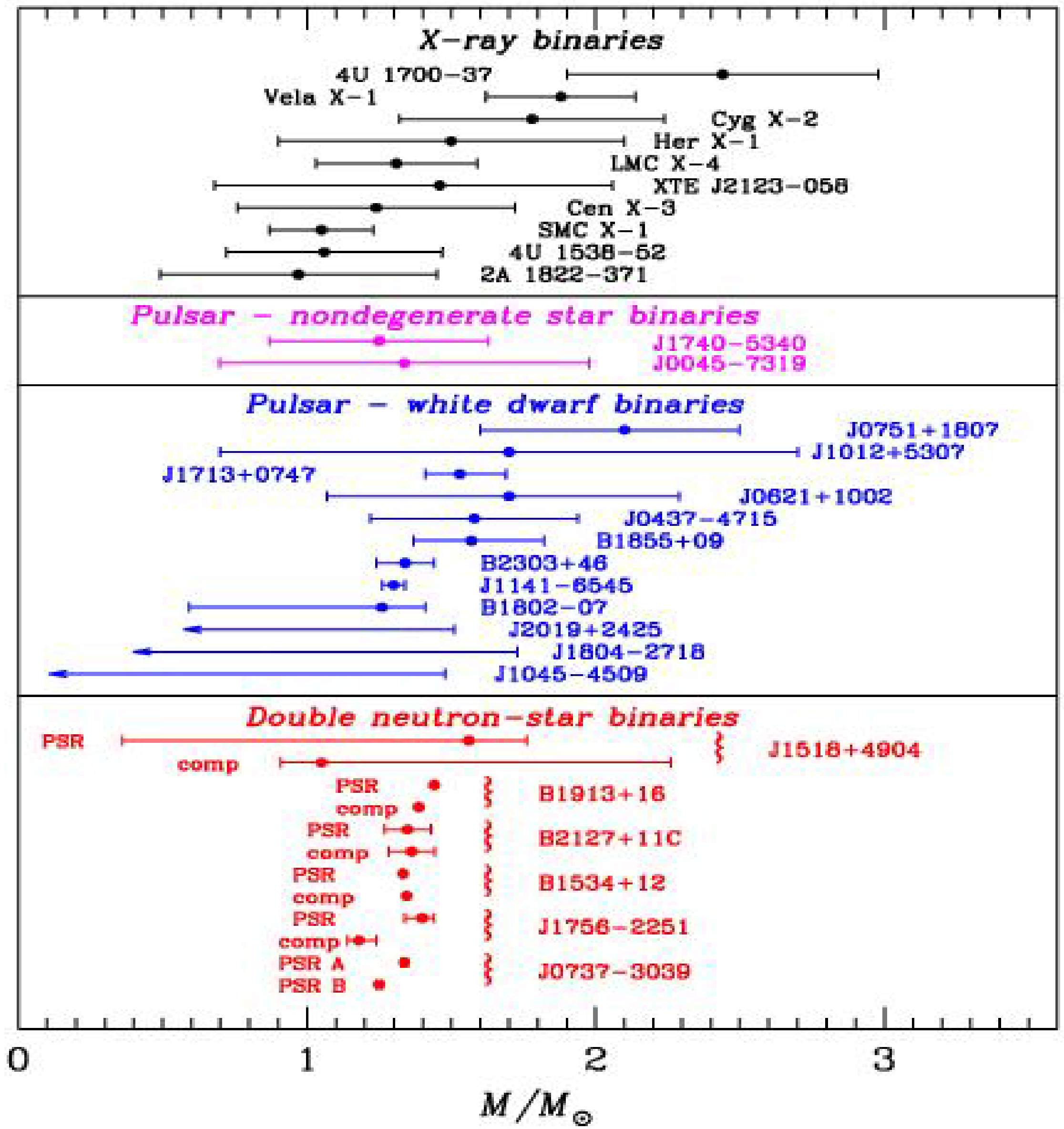
Isolated NSs

How can we find the EOS in NSs ?

1. Find the most massive NSs



Mass of NSs – from binaries



How can we find the EOS in NSs ?

1. Find the most massive NSs

2. Find the limits on the M/R relation

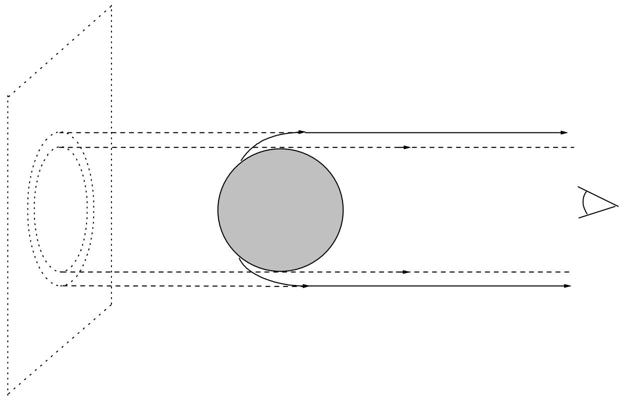
Influence of GR effects on the NS observed properties

Gravitational redshift $$1+z=\frac{1}{(1-R_S/R)^{1/2}}, \quad T_{obs}=T_{eff}(1-R_S/R)^{1/2}$$

$$L_{obs}=L(1-R_S/R)^{1/2}, \quad g=\frac{GM}{R^2(1-R_S/R)^{1/2}}, \quad R_S=\frac{2GM}{c^2}$$

Light bending

$$R_{obs}=\frac{R}{(1-R_S/R)^{1/2}}$$



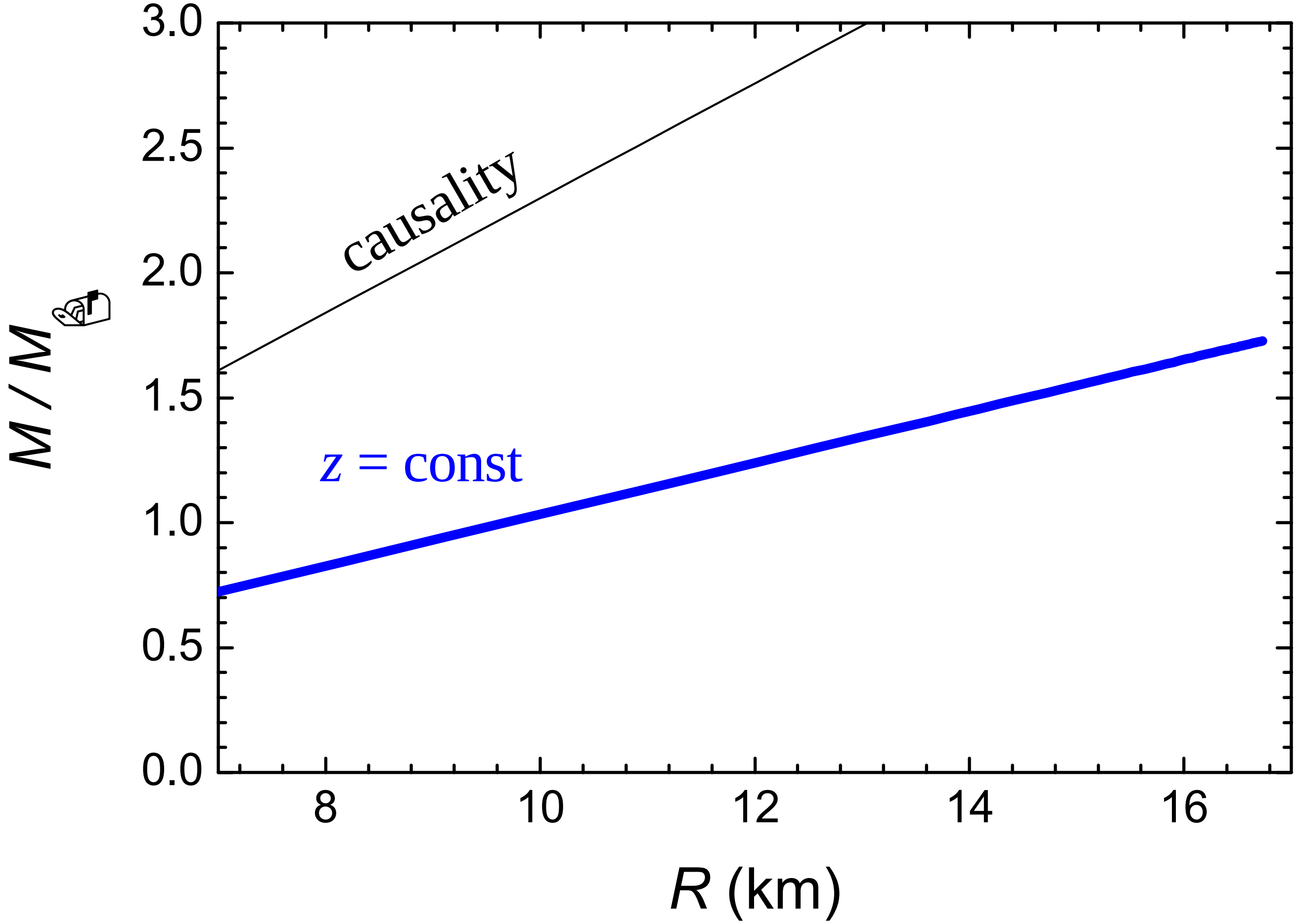
How can we find the EOS in NSs ?

1. Find the most massive NSs

2. Find the limits on the M/R relation

Gravitational redshift

$$z = \frac{\Delta\lambda}{\lambda} = \frac{1}{(1 - R_S / R)^{1/2}} - 1$$



3.0
2.5
2.0
1.5
1.0
0.5
0.0
8
10
12
14
16
R (km)
M / M☉
causality
z = const

How can we find the EOS in NSs ?

1. Find the most massive NSs

2. Find the limits on the M/R relation

Gravitational redshift

$$z = \frac{1}{(1 - R_S / R\ )^{1/2}} - 1$$

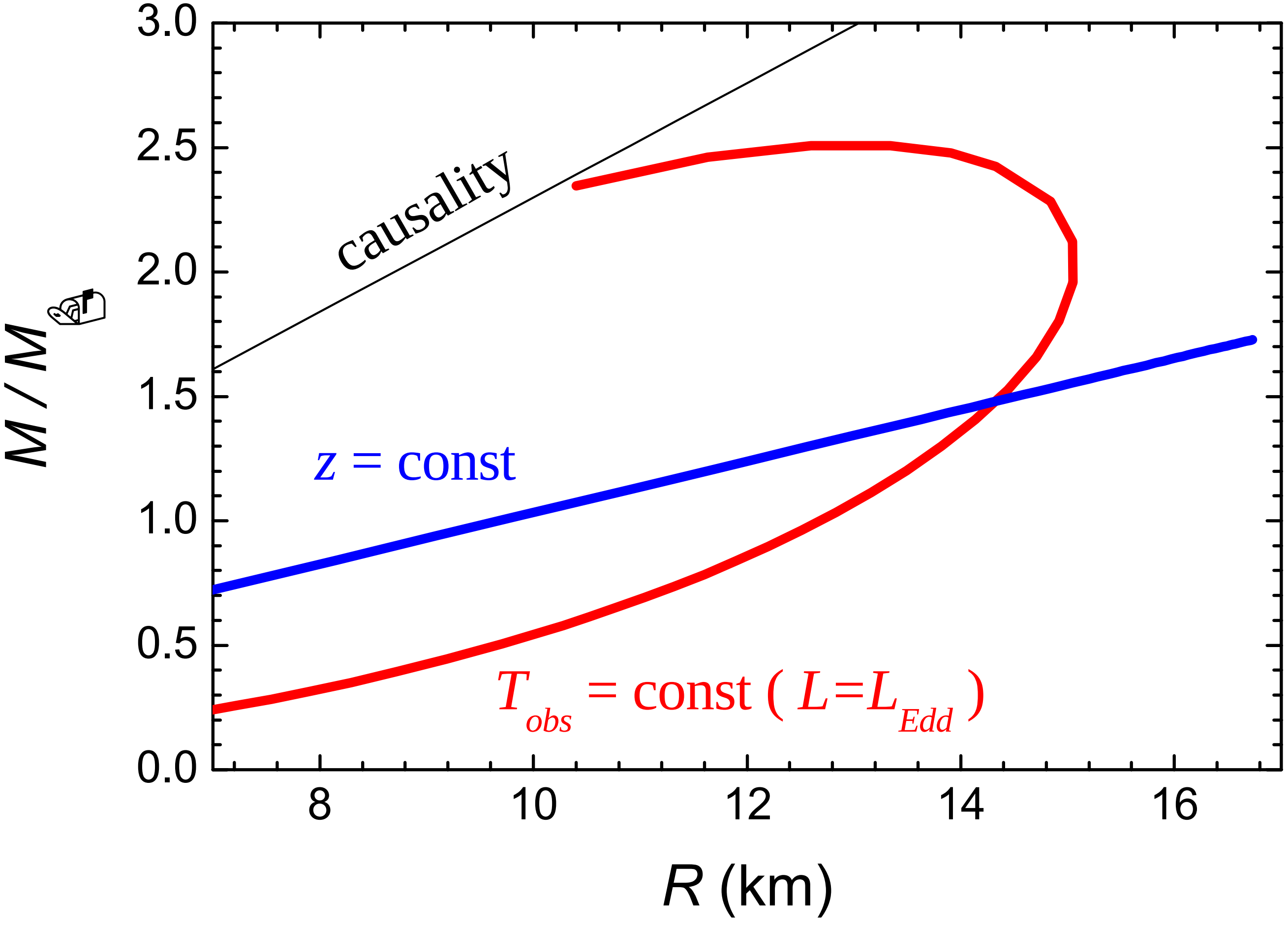
Observed color temperature of objects close to the Eddington limit

Eddington limit

$$g_{grav} = g_{rad} \quad \Rightarrow \quad \frac{GM}{R^2 (1 - R_S / R)^{1/2}} = 0.2(1 + X\ ) \frac{\sigma T_{Edd}^4}{c}$$

Problems: chemical composition (X– mass fraction of hydrogen)

$T_c = f_c T_{Edd}, \quad f_c \approx 1.5 \div 1.9$ - hardness factor



3.0
2.5
2.0
1.5
1.0
0.5
0.0
8
10
12
14
16
R (km)
M / M
causality
z = const
T obs = const (L=L Edd)

How can we find the EOS in NSs ?

1. Find the most massive NSs

2. Find the limits on the M/R relation

Gravitational redshift

$$z = \frac{1}{(1 - R_S / R\ )^{1/2}} - 1$$

Observed color temperature of objects close to the Eddington limit

Eddington limit

$$g_{grav} = g_{rad} \quad \Rightarrow \quad \frac{GM}{R^2 (1 - R_S / R)^{1/2}} = 0.2(1 + X\ ) \frac{\sigma T_{Edd}^4}{c}$$

Problems: chemical composition (*X*– mass fraction of hydrogen)

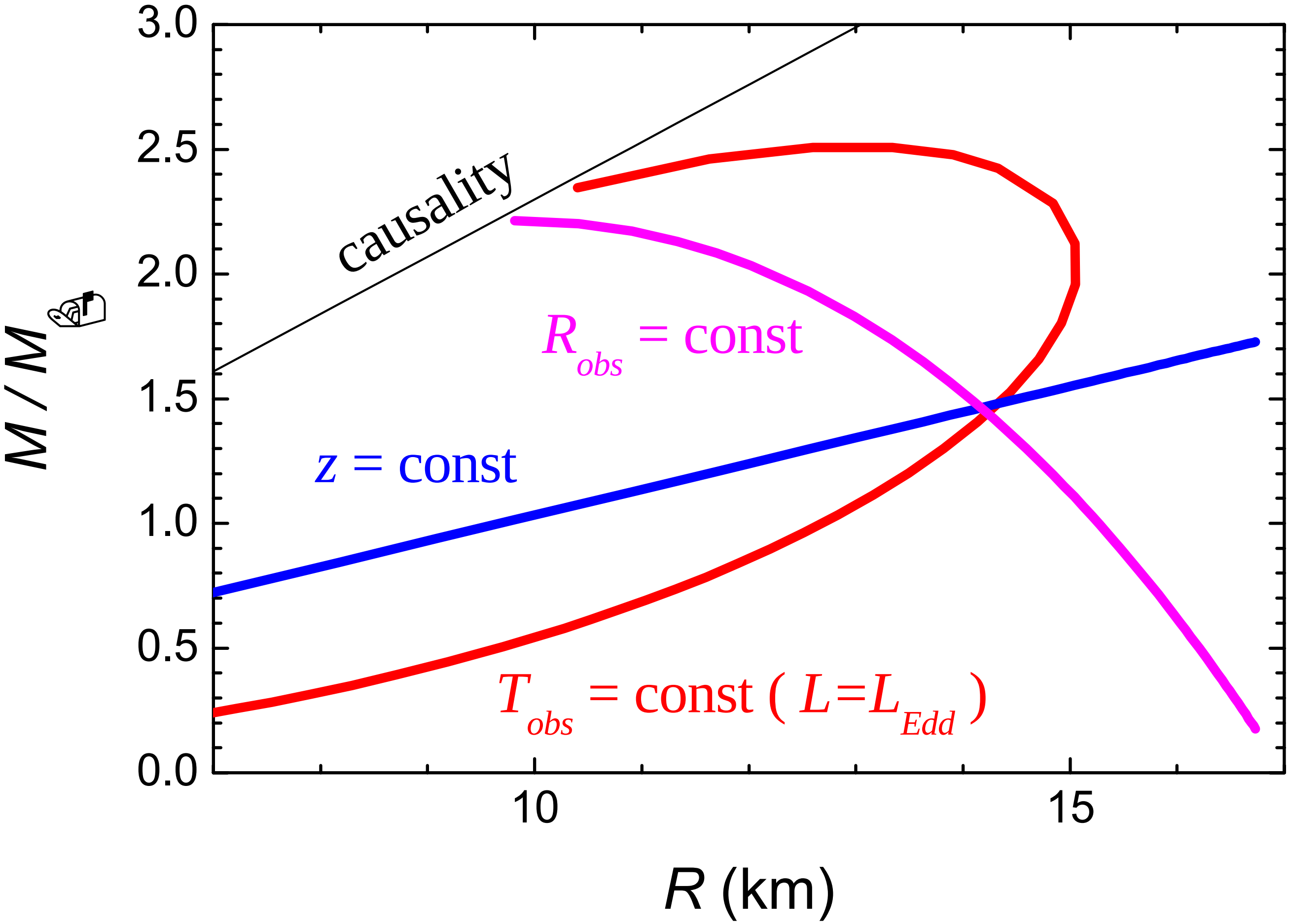
$T_c = f_c T_{Edd}, \quad f_c \approx 1.5 \div 1.9$ - hardness factor

Observed size of isolated NSs

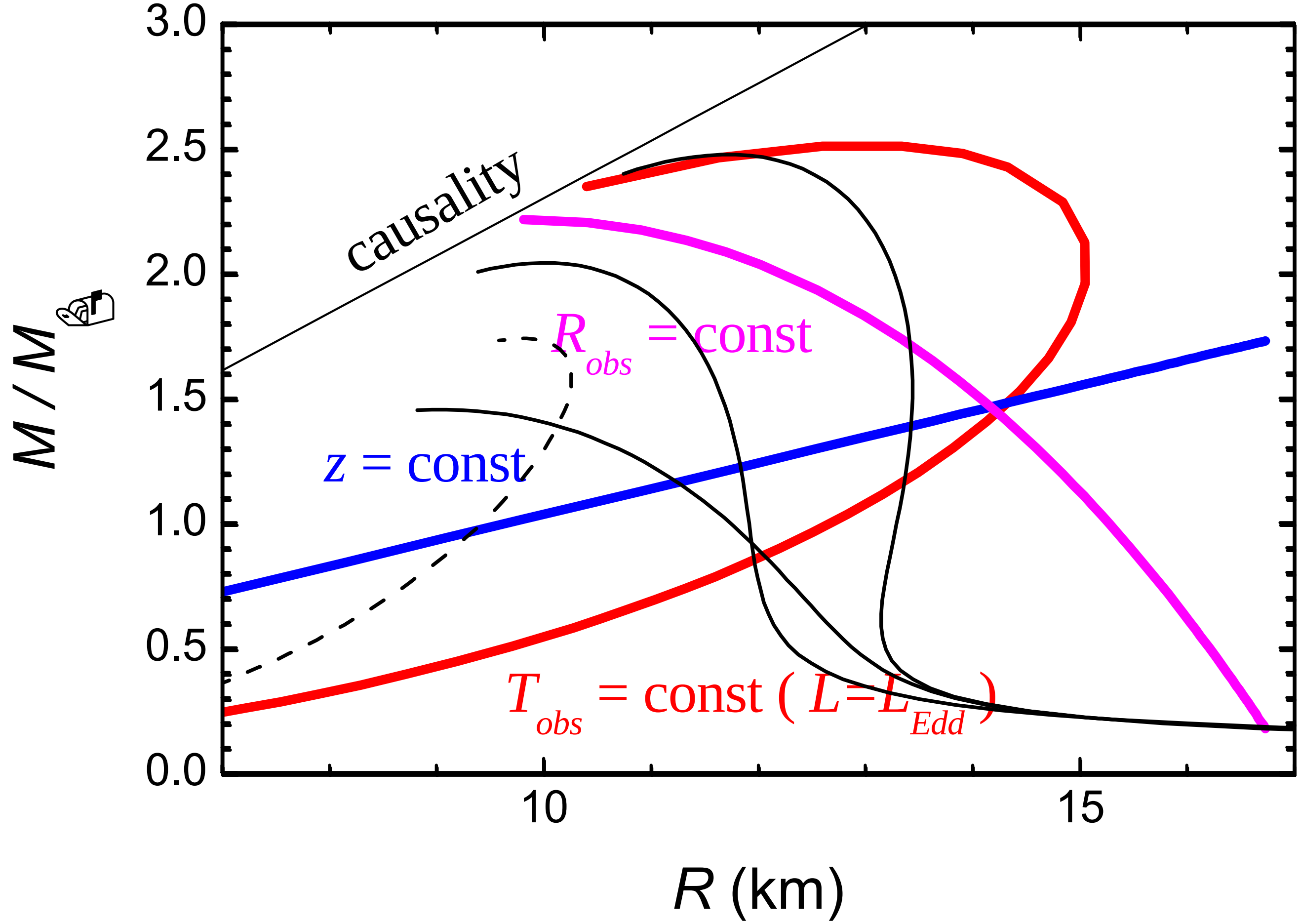
$$F_{obs} = \sigma T_{obs}^4 \frac{R_{obs}^2}{d^2}$$

Problems: distance *d*

T_{eff} from observed spectrum (chemical composition etc.)

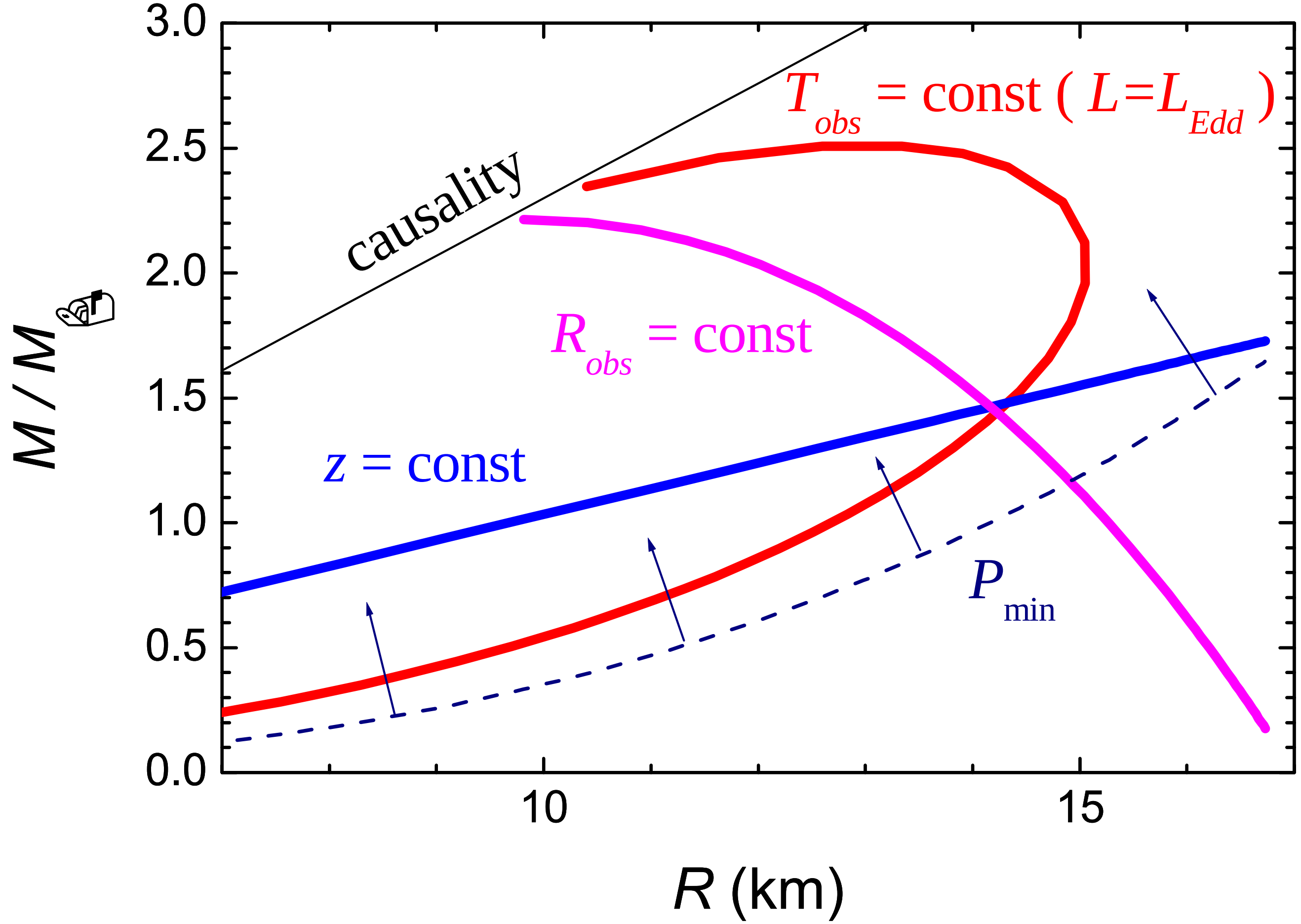


causality
R_obs = const
z = const
T_obs = const (L=L_Edd)
M / M
R (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
10
15



In any case it is necessary to model emergent radiation spectra (spectral energy distribution)

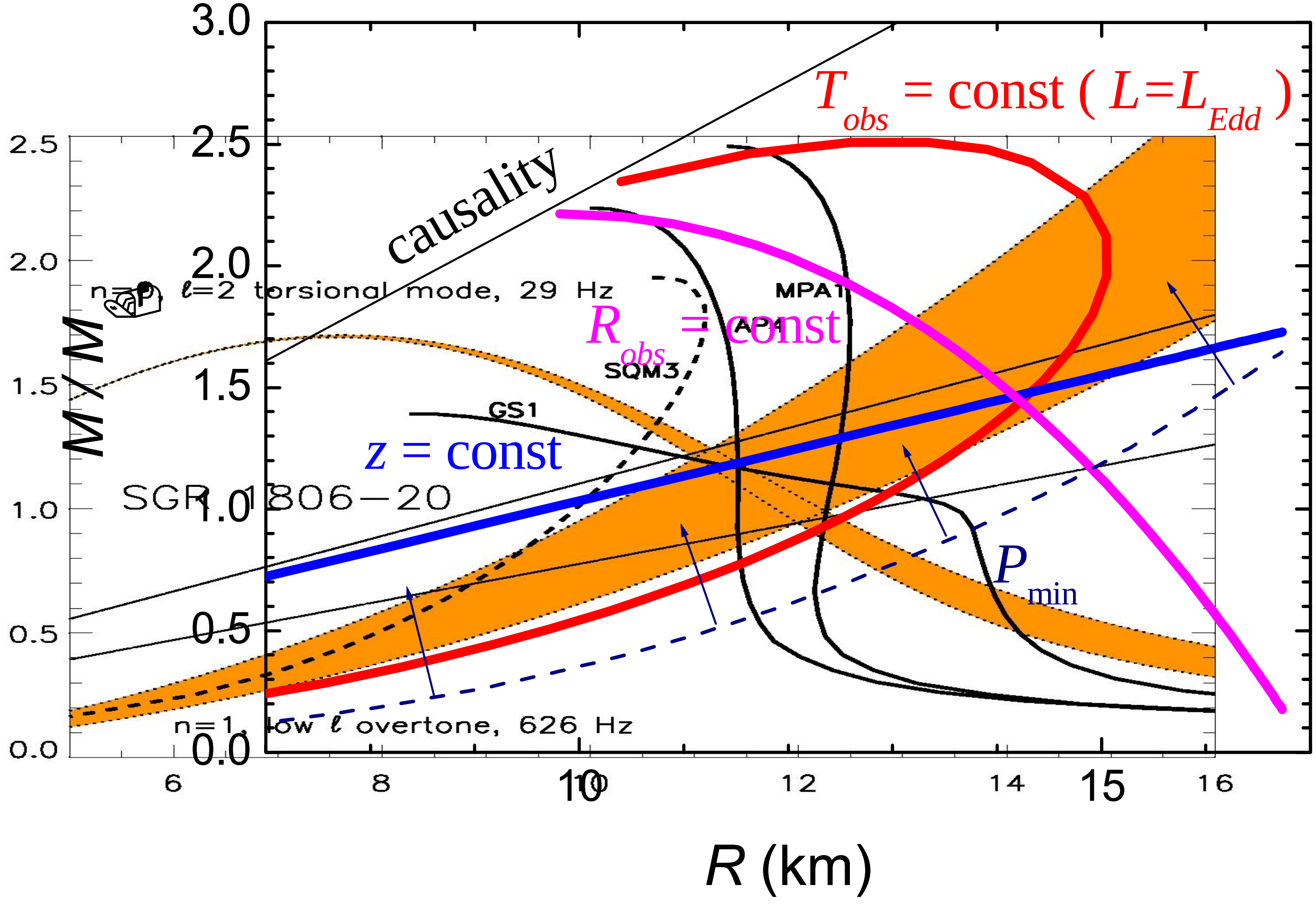
Other possibilities: minimum NS spin period (Kepler with GR corr.)



$$\frac{M}{M_{sun}} \geq 0.92 \left(\frac{R}{10km} \right)^3 P_{ms}^{-2}$$

From Lattimer & Prakash (2007)

Other possibilities:
NS oscillations during SGR bursts



From Lattimer & Prakash (2007)

It is necessary to model emergent radiation spectra (spectral energy distributions)

METHOD - Stellar atmosphere modeling

Parameters: T_{eff}, $g = \frac{GM}{R^2(1-R_S/R)^{1/2}}$, chemical composition

Hydrostatic equilibrium
$$\frac{1}{\rho}\frac{dP_{gas}}{dz} = -g + \frac{4\pi}{c}\int H_\nu(\sigma_e + k_\nu)\,d\nu$$

Radiation transfer
$$\cos\vartheta \frac{\partial I_\nu}{\partial \tau_\nu} = I_\nu - S_\nu$$

Energy conservation
$$\int k_\nu (J_\nu - B_\nu)\,d\nu = 0$$

Equation of state
$$P_{gas} = N_{tot}\,kT$$

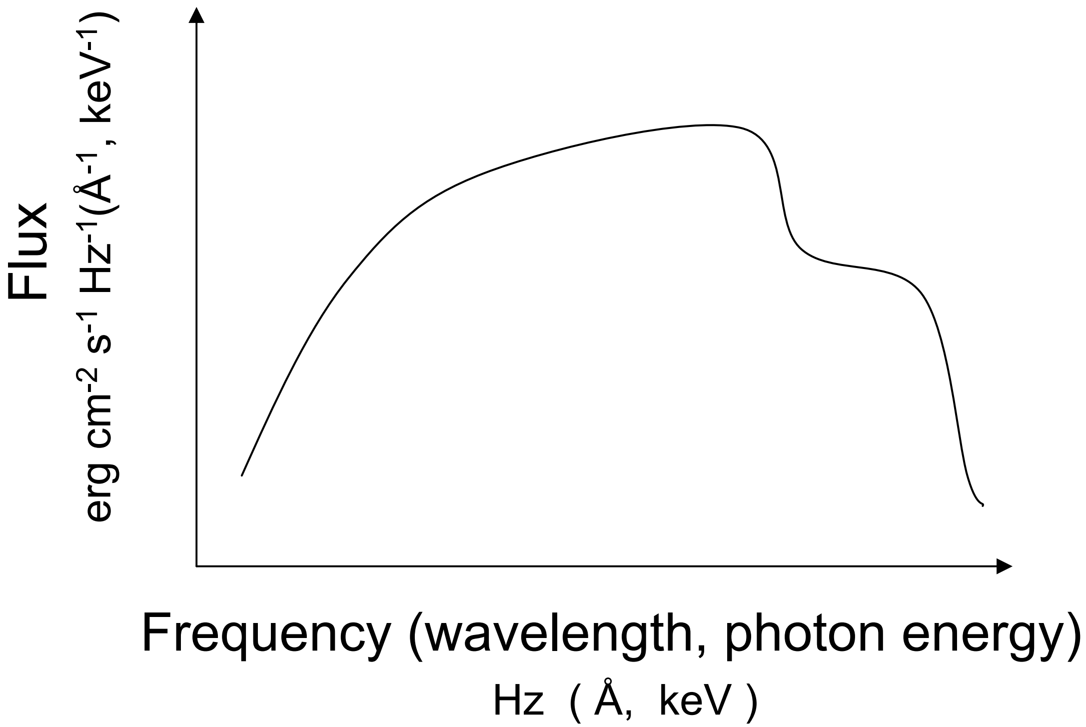
Conservation of charges, number of particles

METHOD - Stellar atmosphere modeling

It is necessary to take into account ~ 25 most abundant chemical elements and ~ 10^4 – 10^8 spectral lines → ~ 30 000 frequencies

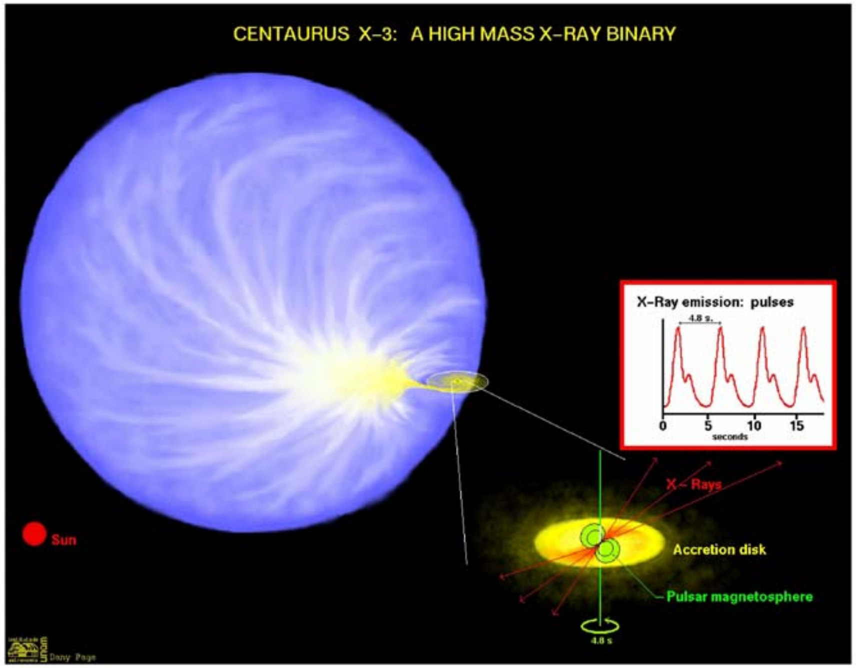
Large computer codes

Main results – a model atmosphere and a spectral energy distribution



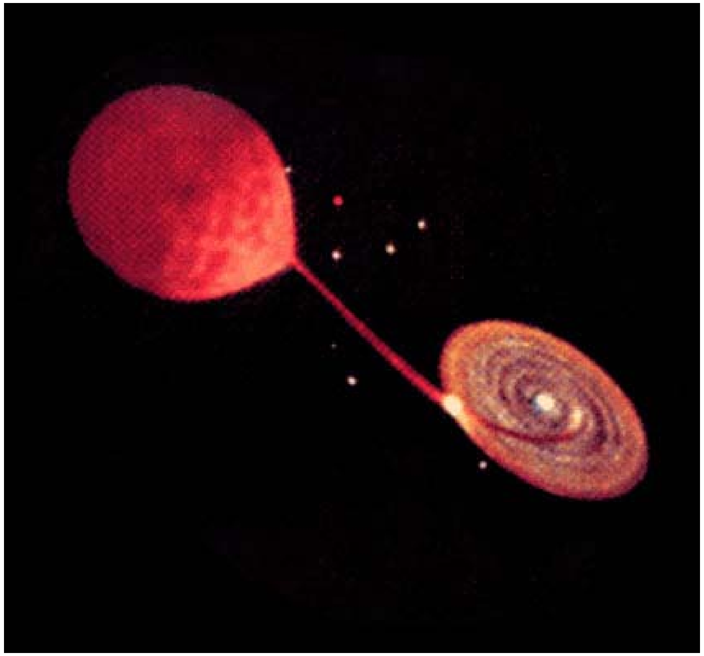
X-ray Binaries

High Mass



$M_2 >> M_{Sun}$
Young systems (Pop. I)
Accretion from wind
X-ray Pulsars

Low Mass



$M_2 < M_{Sun}$
Old systems (Pop. II)
Secondary overfilled of the Roche lobe
Atoll- and Z-sources, Bursters,
Millisecond X-ray Pulsars

X-ray bursting neutron stars

- X-ray bursting NSs – LMXBs with thermonuclear explosions at the neutron star surface
- Close to Eddington limit during the burst
- Burst duration ~10 sec, time between bursts ~1 day

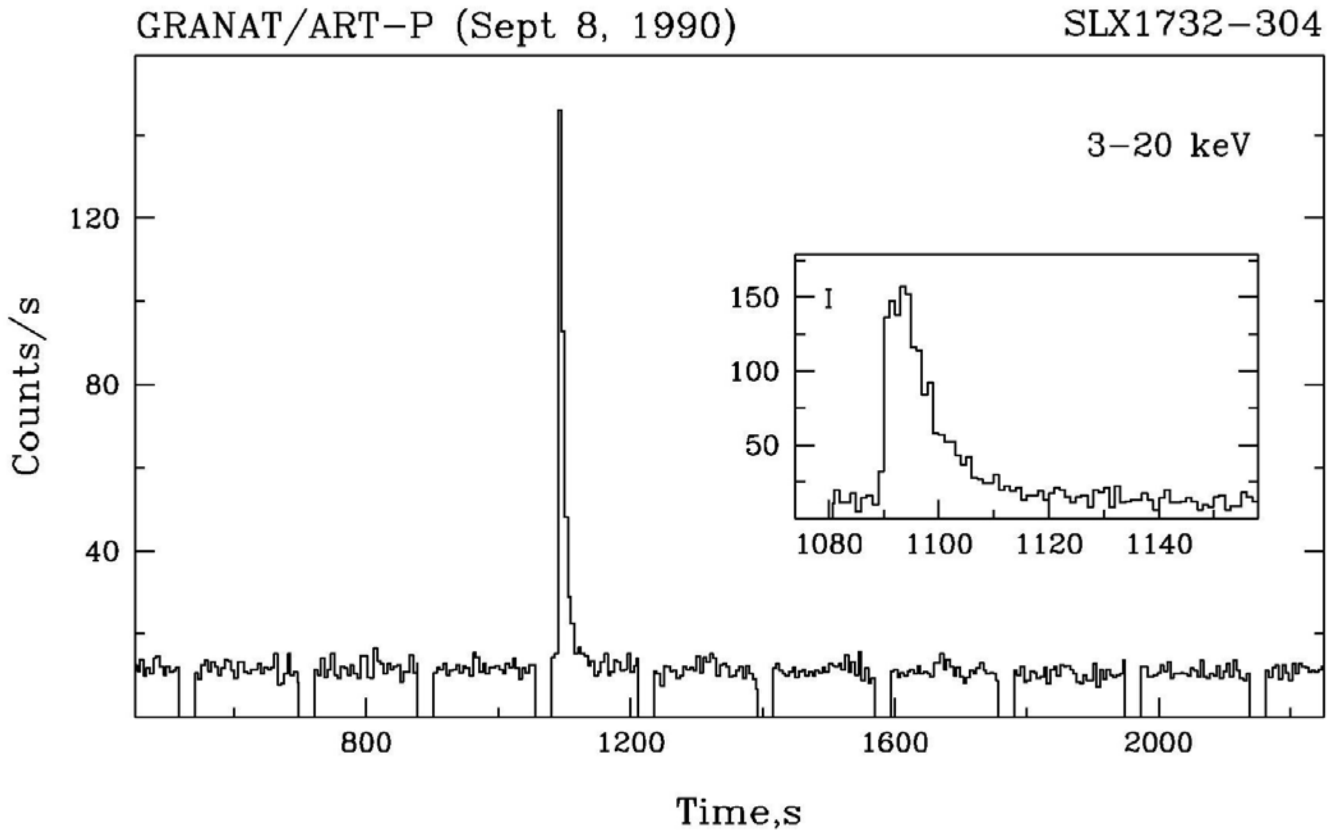
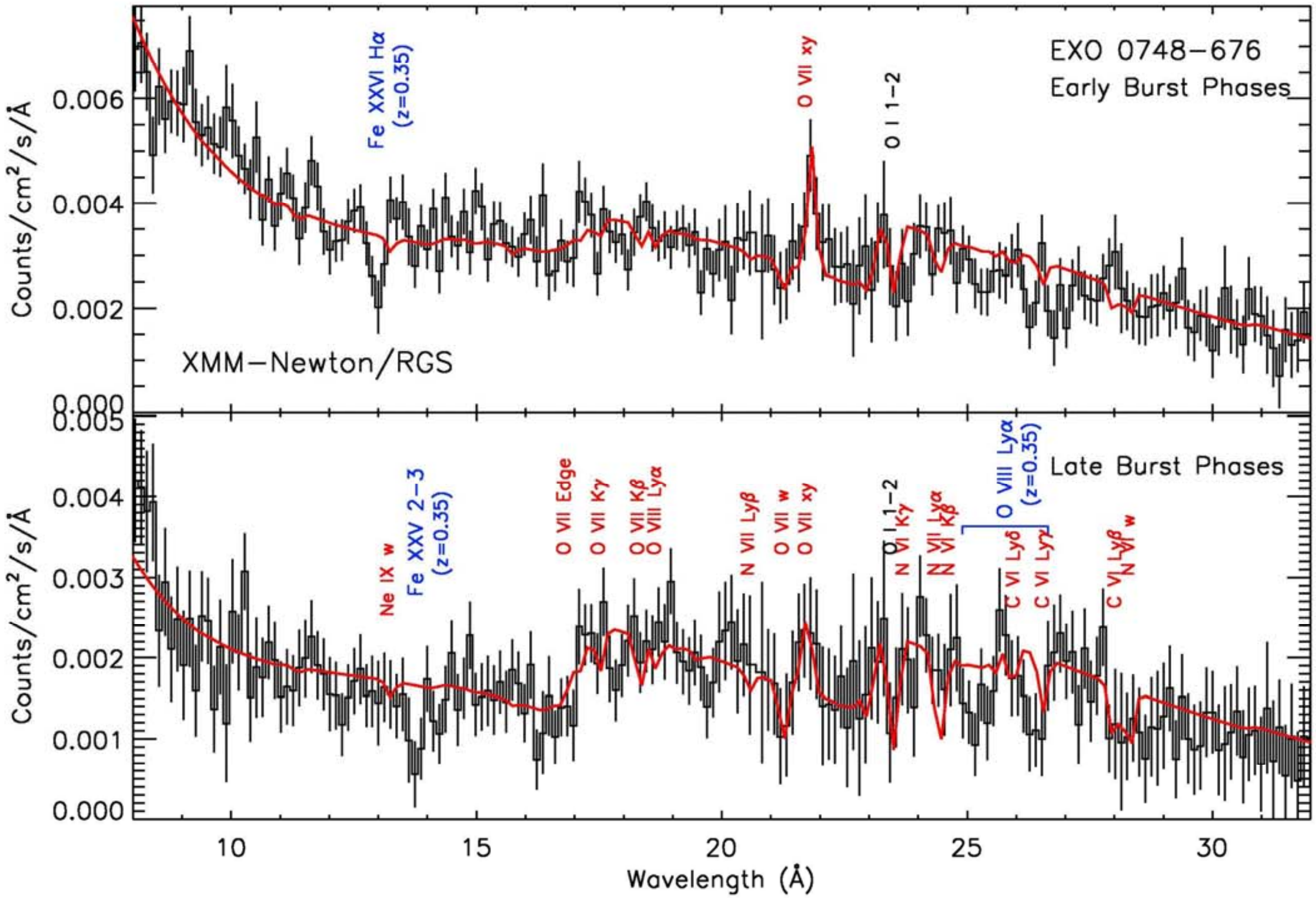


Figure from Pavlinsky et al (2001)

13

Gravitational redshift

Absorption lines in the spectra of EXO 0748-676 during outburst ?
Cottam et al. 2002, Cottam et. al 2008

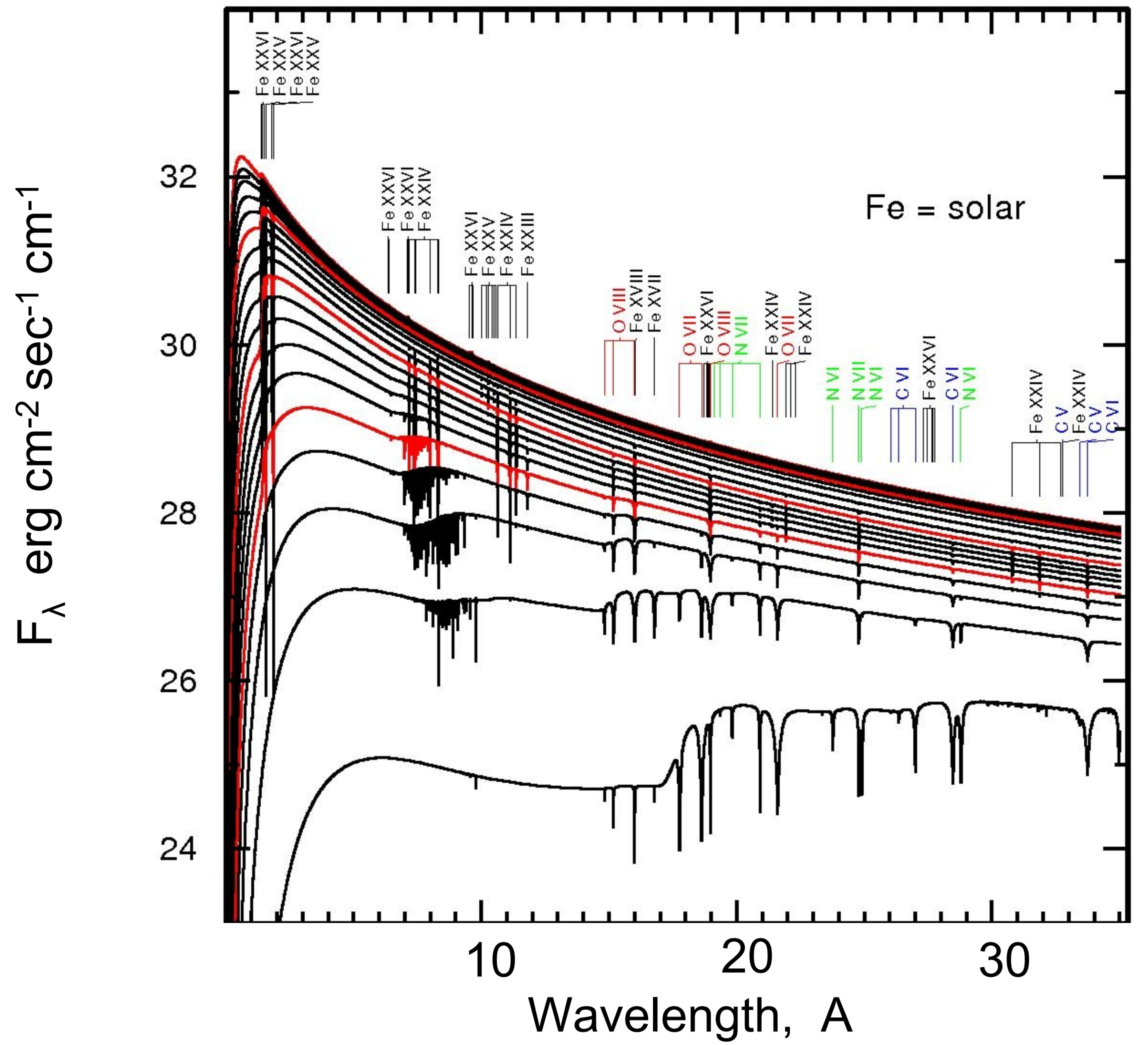


$T_{obs} \approx 1.8$ keV

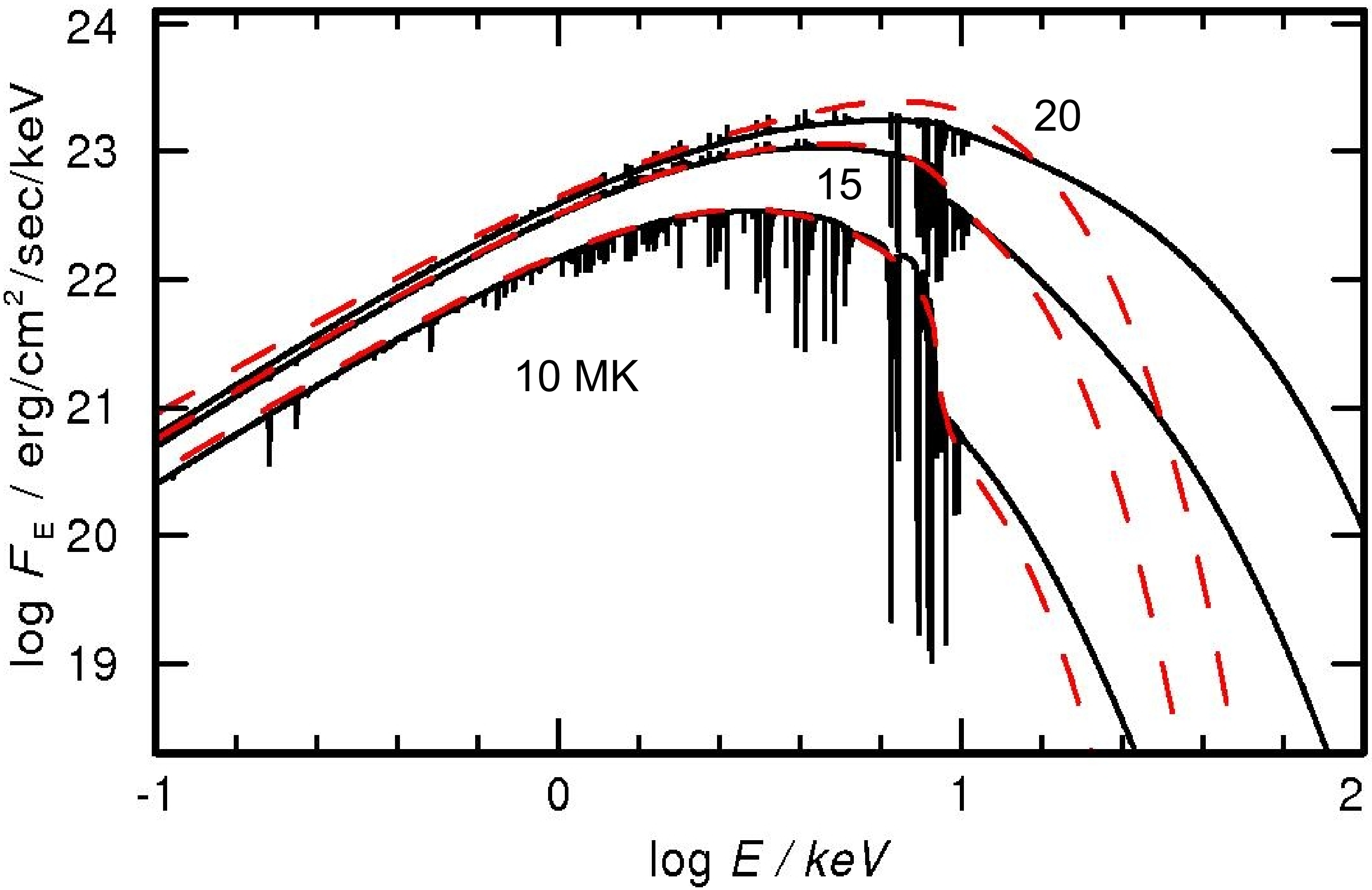
$T_{obs} \leq 1.5$ keV

Cottam et al. 2002

Grids of non-LTE NS model atmospheres (T_{eff} from 1 to 20 MK, log g = 14.39) with various Fe abundances (solar, 30%, 99% mass fractions) have been calculated.

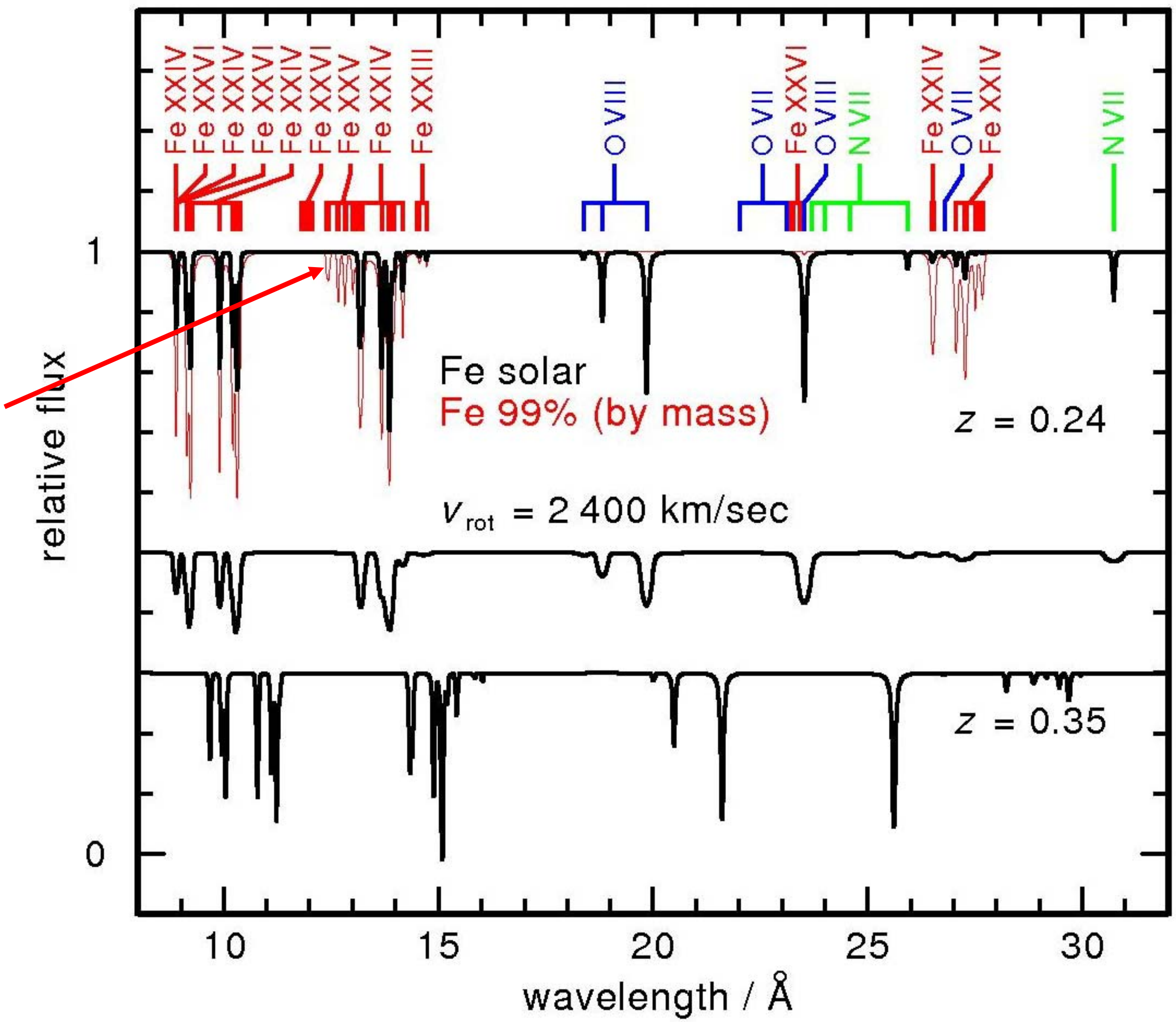


Importance of Compton scattering



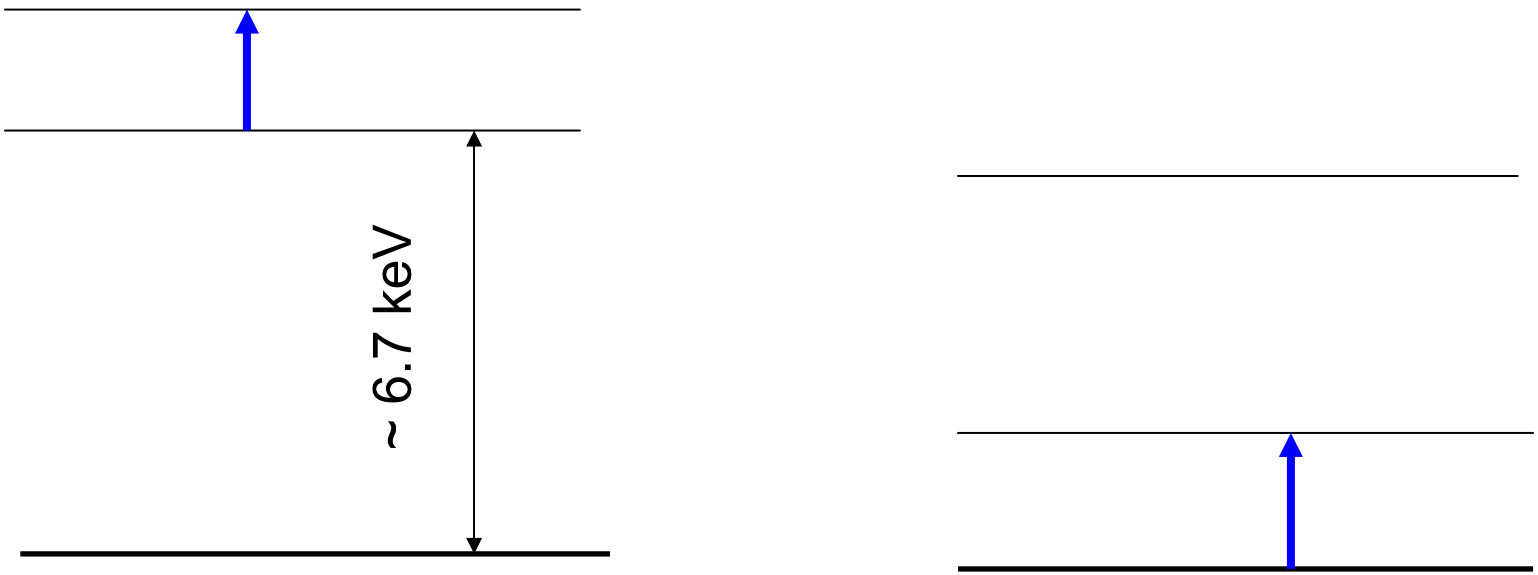
Identification of lines

Cottam et al. (2002) suggested that they observed this line



Why FeXXV lines so weak?

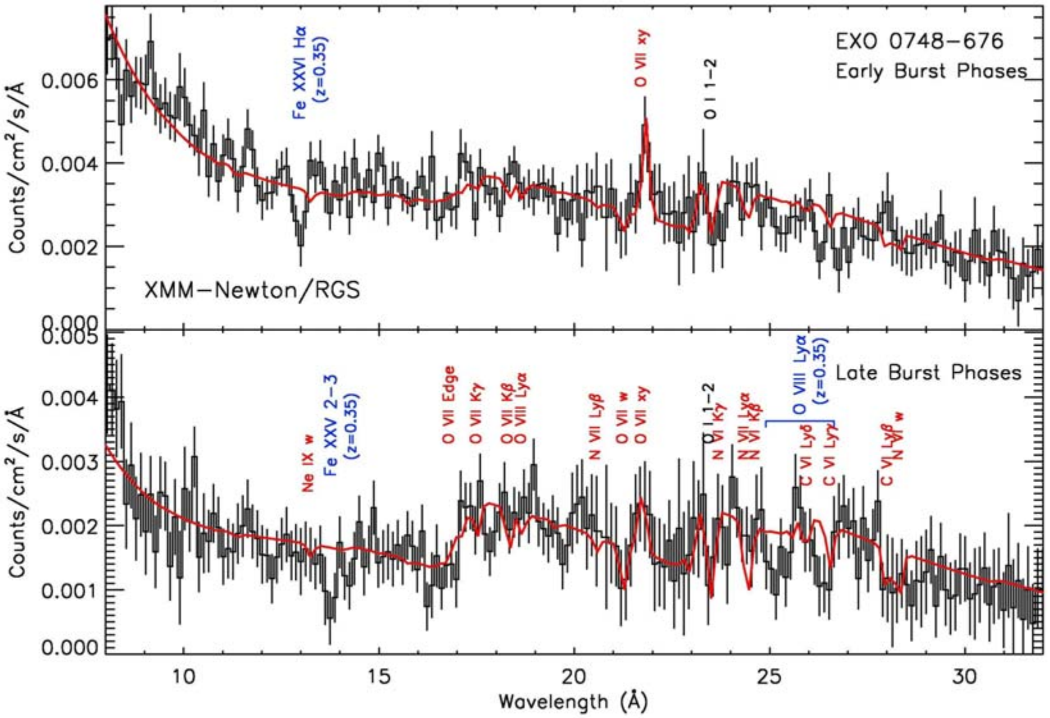
Line intensity depends on low energy level number density

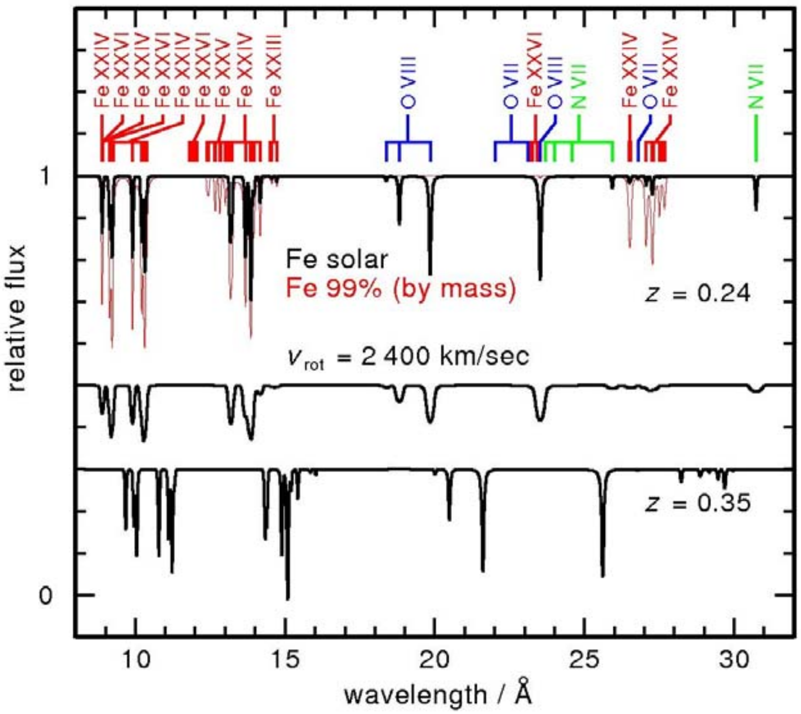


FeXXV FeXXIV

$$N_{FeXXV} \exp(-6.7\ keV/1\ keV) \ll N_{FeXXIV}$$

Comparison with observations.





Conclusions for gravitational redshift

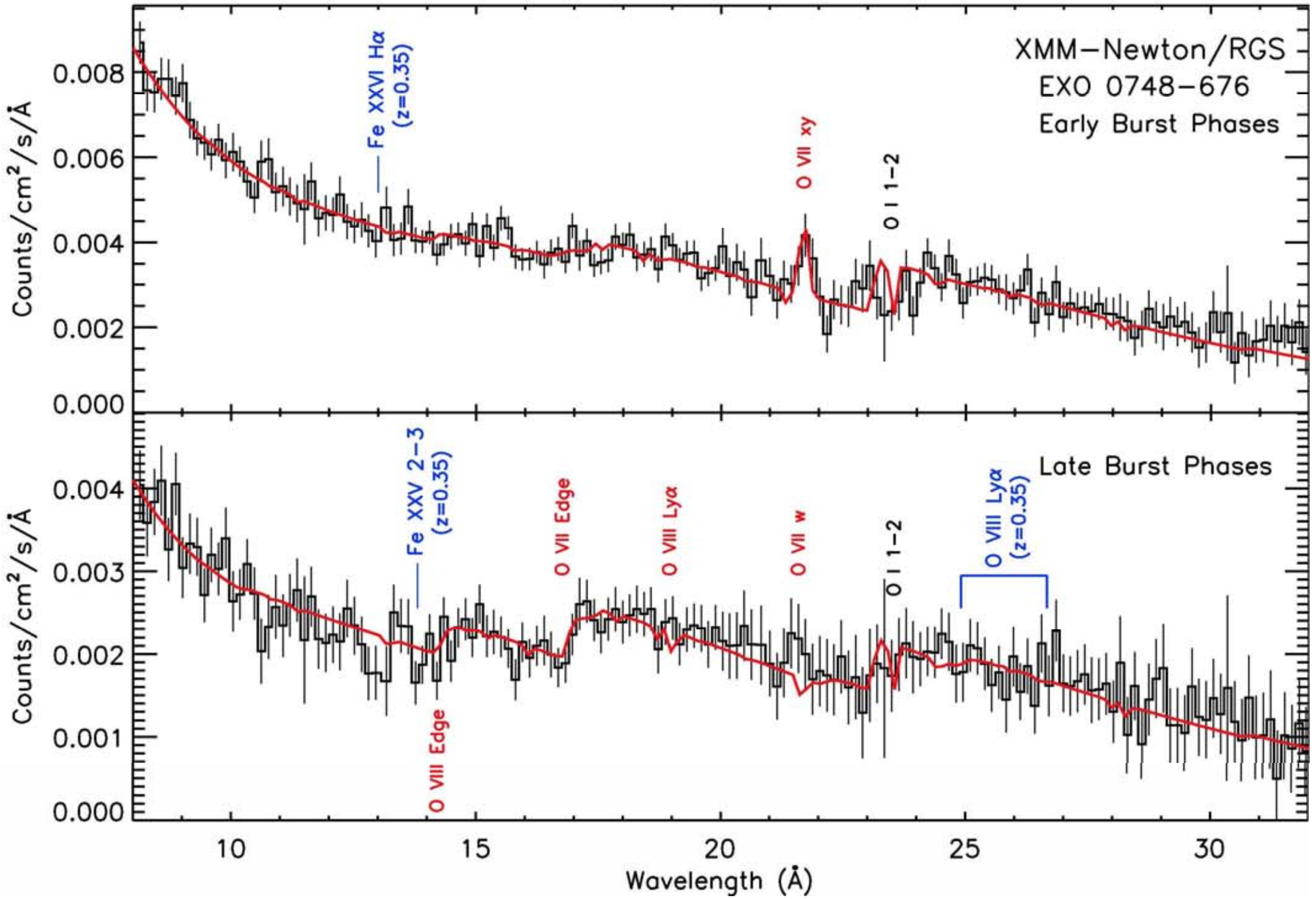
1. The lines have been wrongly identified.
   The Fe XXV lines are too weak to be observed.
   They have to be Fe XXIV lines. In this case z=0.24 instead of z = 0.35.

2. Predicted relative depth of the absorption lines (FeXXIV) are too small to be observed.

3. At the moment our knowledge about gravitational redshift is ambiguous.

By the way ….

Absorption lines in the spectra of EXO 0748-676 during outburst ?
Cottam et al. 2002, Cottam et. al 2008



Cottam et al. 2008 NO LINES !!!!

Observed color temperature of objects close to the Eddington limit

Bursters – luminosity near the Eddington limit

(see Lewin et al. 1993, Galloway et al. 2007, …)

Problems – hardness factor f_c, chemical composition…

Our Attempt

Boundary Layers between accretion disc and NS in Low Mass X-ray Binaries

(Suleimanov & Poutanen 2006)

Boundary layer (BL)

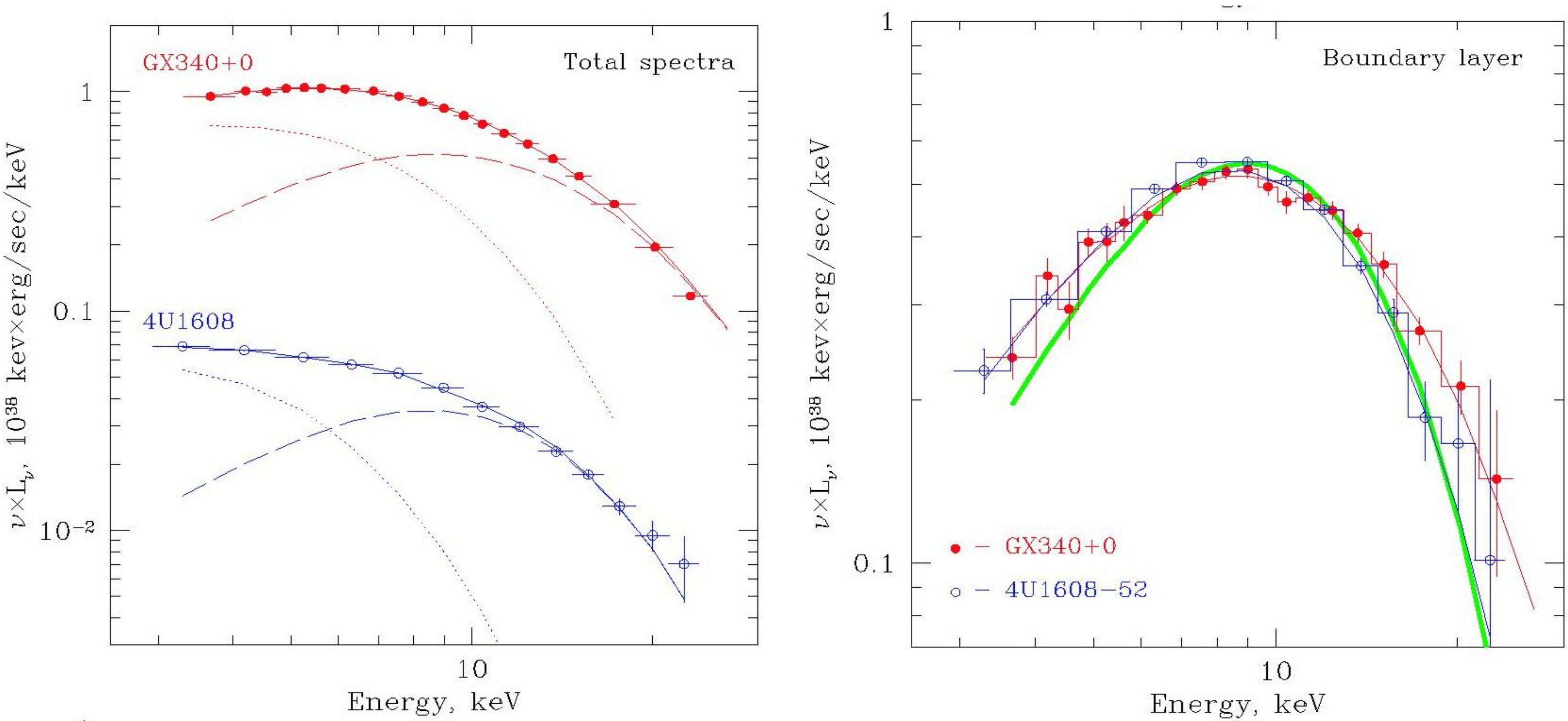
- Region between an accretion disk and a neutron star
- In BL fast rotating (with the Keplerian velocity) accretion disk matter is decelerated to the neutron star rotation velocity.
- Luminosity of the BL comparable to the accretion disk luminosity

$$L_{BL} \sim \dot{M} \frac{V_K^2}{2} = \frac{1}{2} \dot{M} \frac{GM_{NS}}{R_{NS}} \sim L_{AD}$$

Size of BL is smaller than the accretion disk size. Therefore, effective temperature of BL is larger than the effective temperature of accretion disk.

Hard black body component in the soft state of LMXB –
a boundary layer spectrum ?

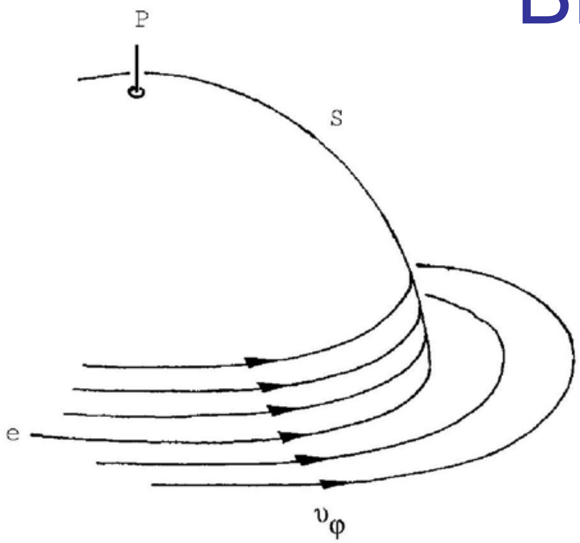
Spectra of Boundary Layers



Figures taken from Gilfanov, Revnivtsev and Molkov (2003). They have shown that the shape of boundary layer spectra is independent of luminosity.

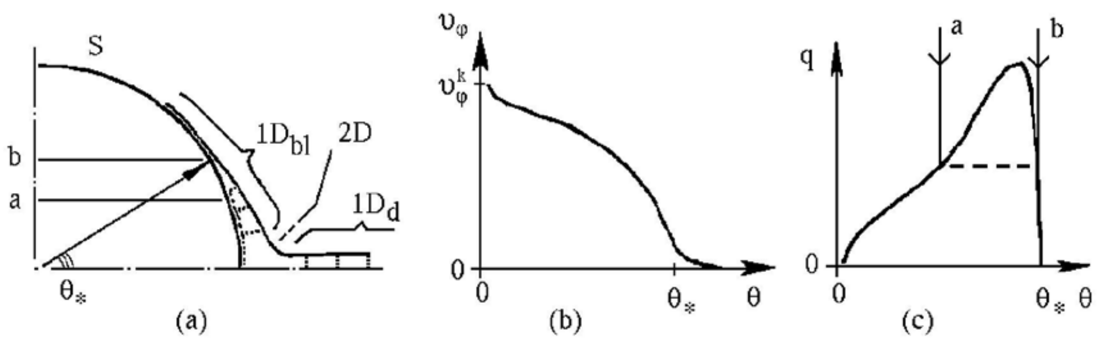
BL spectra are close to Planck spectrum with a color temperature 2.4 ± 0.1 keV

BL as a spreading layer (SL)

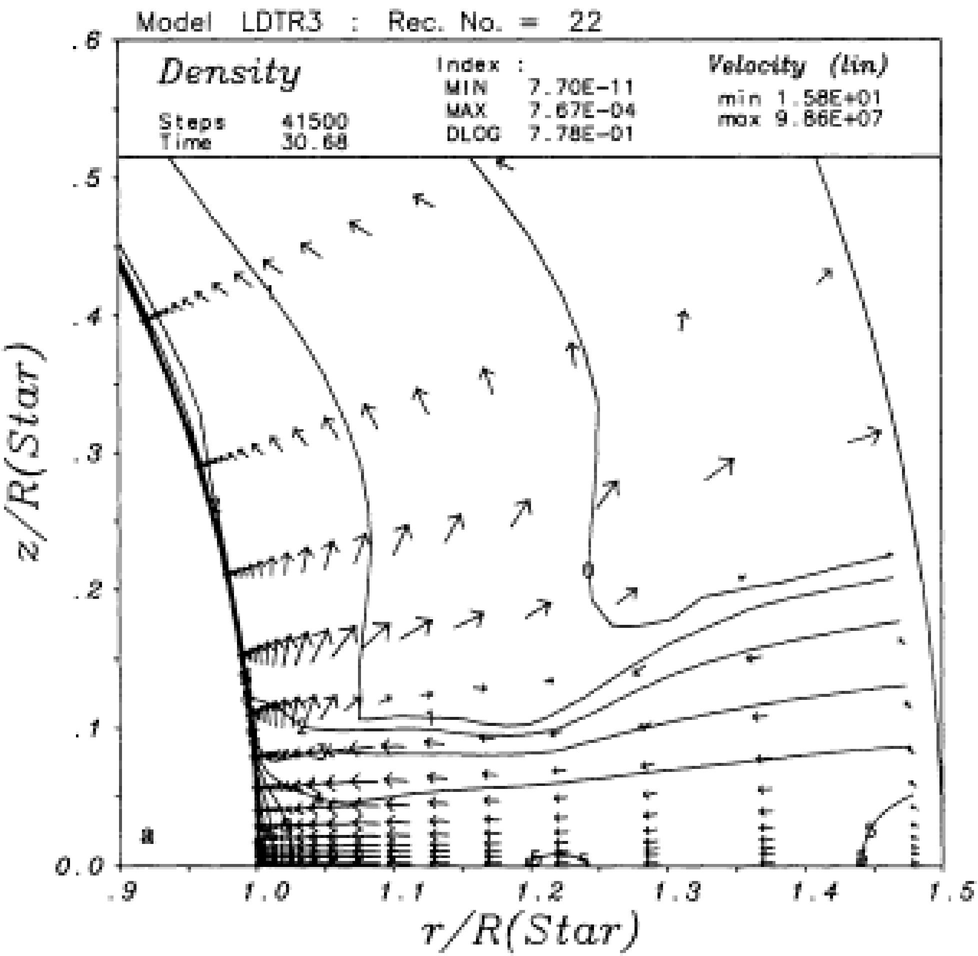


Picture suggested by
Inogamov & Sunyaev (1999), below IS99

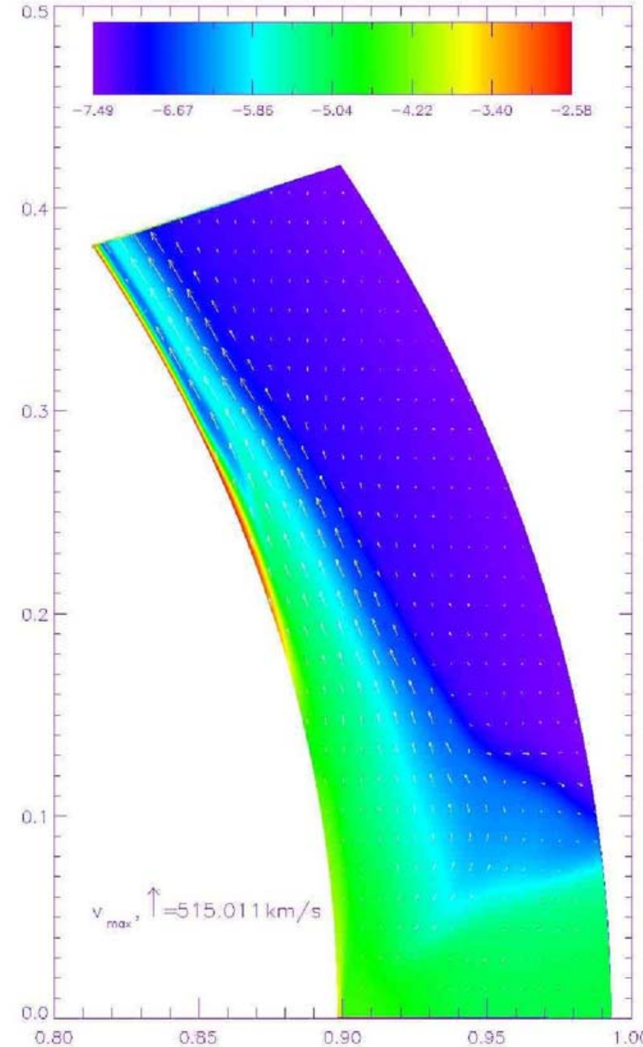
Matter has a significant latitude velocity component, spreading above the neutron star surface and decelerating due to friction at the neutron star surface (wind above the sea).



Figures from Inogamov and Sunyaev (1999)

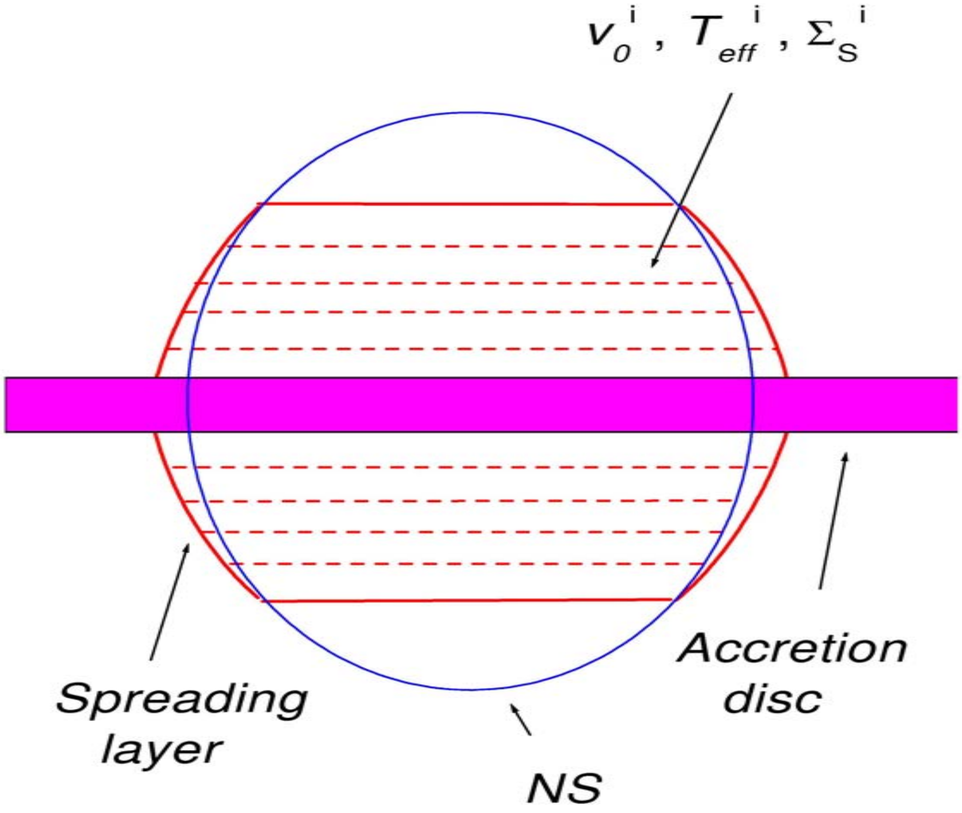


Kley, 1989



Fisker et al. 2005

Numerical simulations confirm this picture



Scheme of the spreading layer spectrum calculation

1. For each ring the model along height and emergent spectrum
2. SL are divided into N rings
   are calculated
3. Spectra of all rings are summed with all relativistic corrections

$$L_E = 4\pi \; R_{NS}^2 \sum_j \; \sum_i \eta^3 \delta_{ij}^{\;3} I_{E'}(\cos\alpha_{ij}{}', \theta_i) \cos\alpha_{ij}{}' \cos\theta_i \; \Delta\theta_i \Delta\varphi_j$$

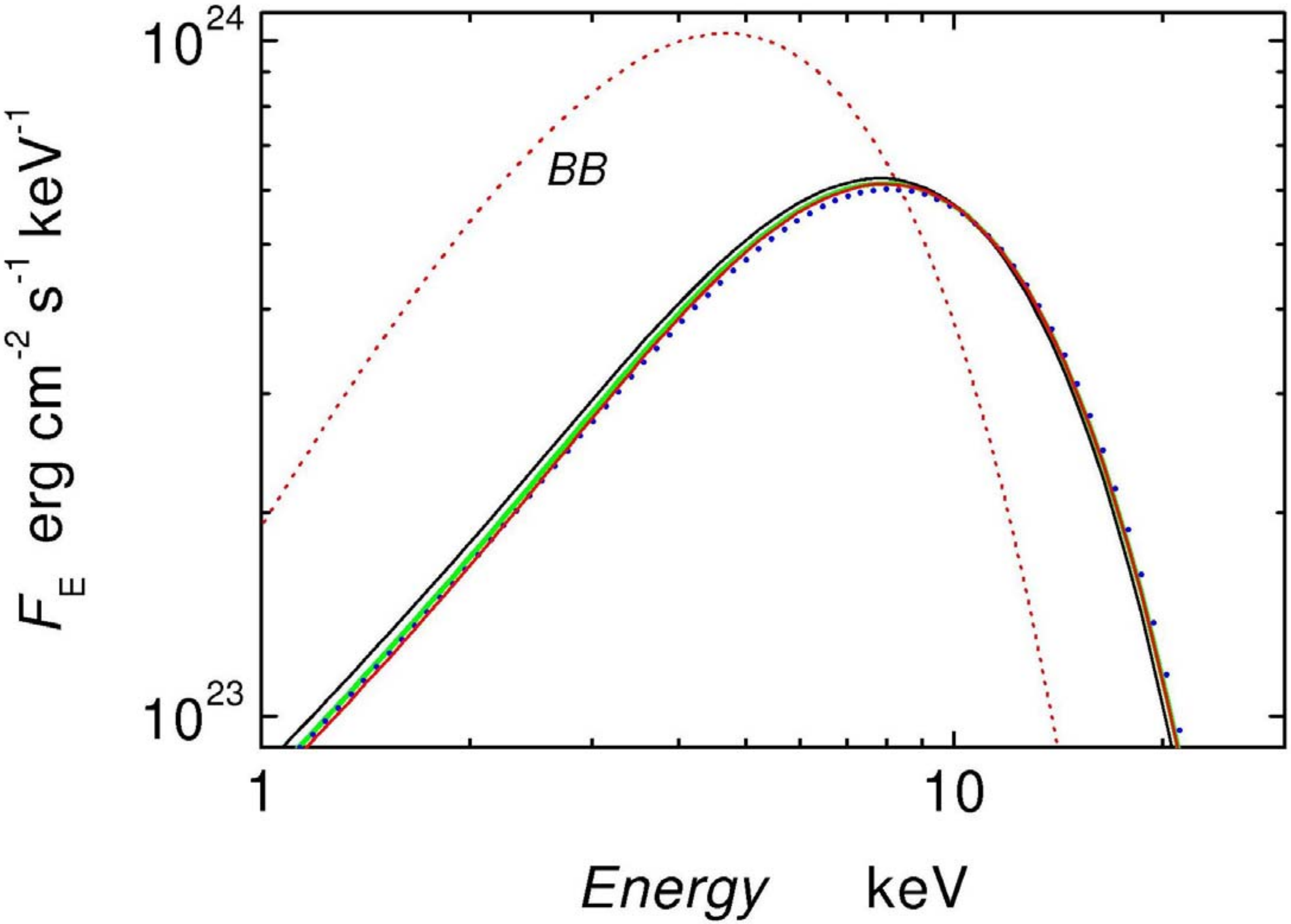
Compton scattering is very important!

If Compton scattering is taken into account, hard photons heat electrons at the surface up to $T>T_{eff}$. This results in an emergent spectrum close to that of a diluted black body.

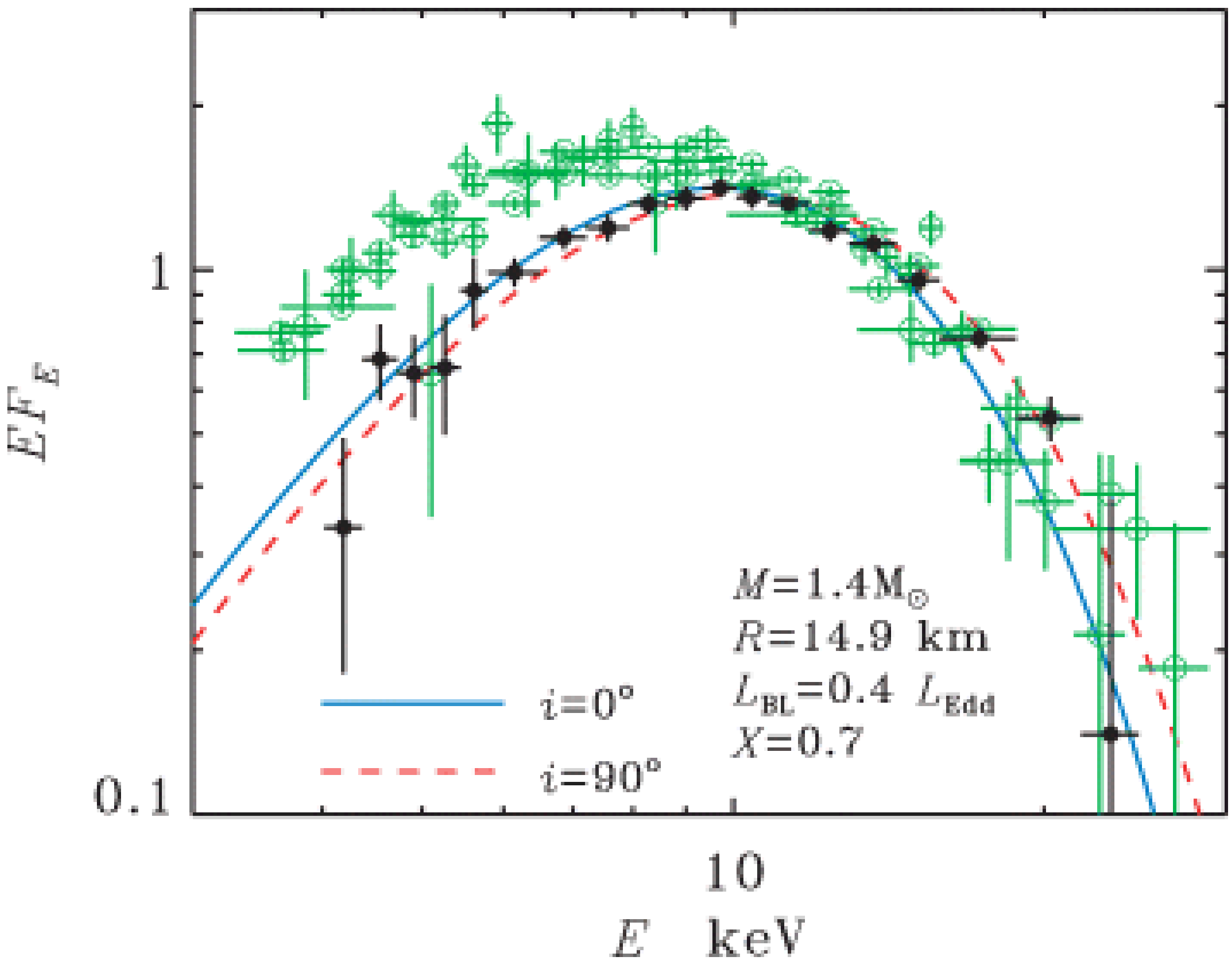
Diluted blackbody spectrum

$$F_\nu = \frac{1}{f_c^4} B_\nu(f_c T_{eff})$$

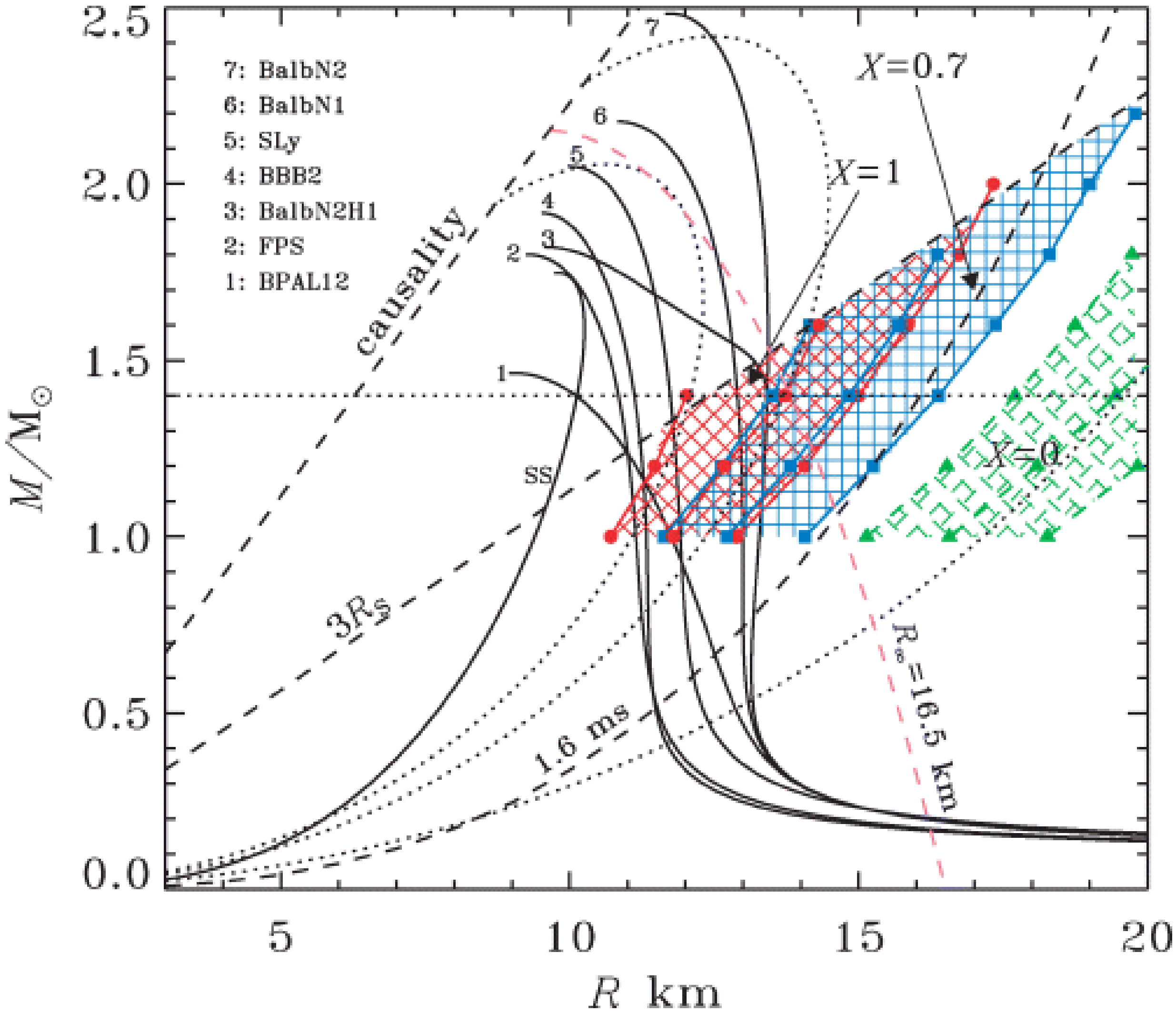
B_ν – Planck function
f_c – color correction (hardness factor)
$T_c = f_c T_{eff}$ - color temperature
f_c ~(1.3 – 1.9) mainly depends on L / L_{Edd}



Spectra of local spreading layer models from previous figure



Comparison of the observed spectra of the BLs and the model spectra of the SL. Black circles – GX 340+0 in the normal branch, green circles – 5 Z and atoll sources in horizontal branch (Suleimanov & Poutanen 2006).



Allowed areas (shaded) for the NS masses and radii, which can have SLs with color temperatures 2.4 +/- 0.1 keV. Various theoretical mass-radius relations for neutron and strange stars are shown for comparison. Red dashed curve corresponds to the NS with apparent radius 16.5 km (Suleimanov & Poutanen 2006).

Conclusions for Observed color temperature of Boundary Layers

- Integral spectra of the high luminosity spreading layers ($L_{SL} > 0.2\, L_{Edd}$) are close to diluted Planck spectra.

- Radiation spectra of the spreading layers on the surface of the neutron stars with stiff equations of state are compatible with the observed spectra of boundary layers in LMXBs.

Observed size of isolated NSs

$$F_{obs} = \sigma T_{obs}^4 \frac{R_{obs}^2}{d^2}$$

or

$$F_{obs}(\nu) = F_{theor}(\nu) \frac{R_{obs}^2}{d^2}$$

Problems: I – distance *d*

a) X-ray transients during quiescence in globular clusters with known distances

b) nearby isolated NSs - distances from astrometry (parallax)

II – theoretical spectra $F_{theor}(\nu)$

model atmospheres (!)

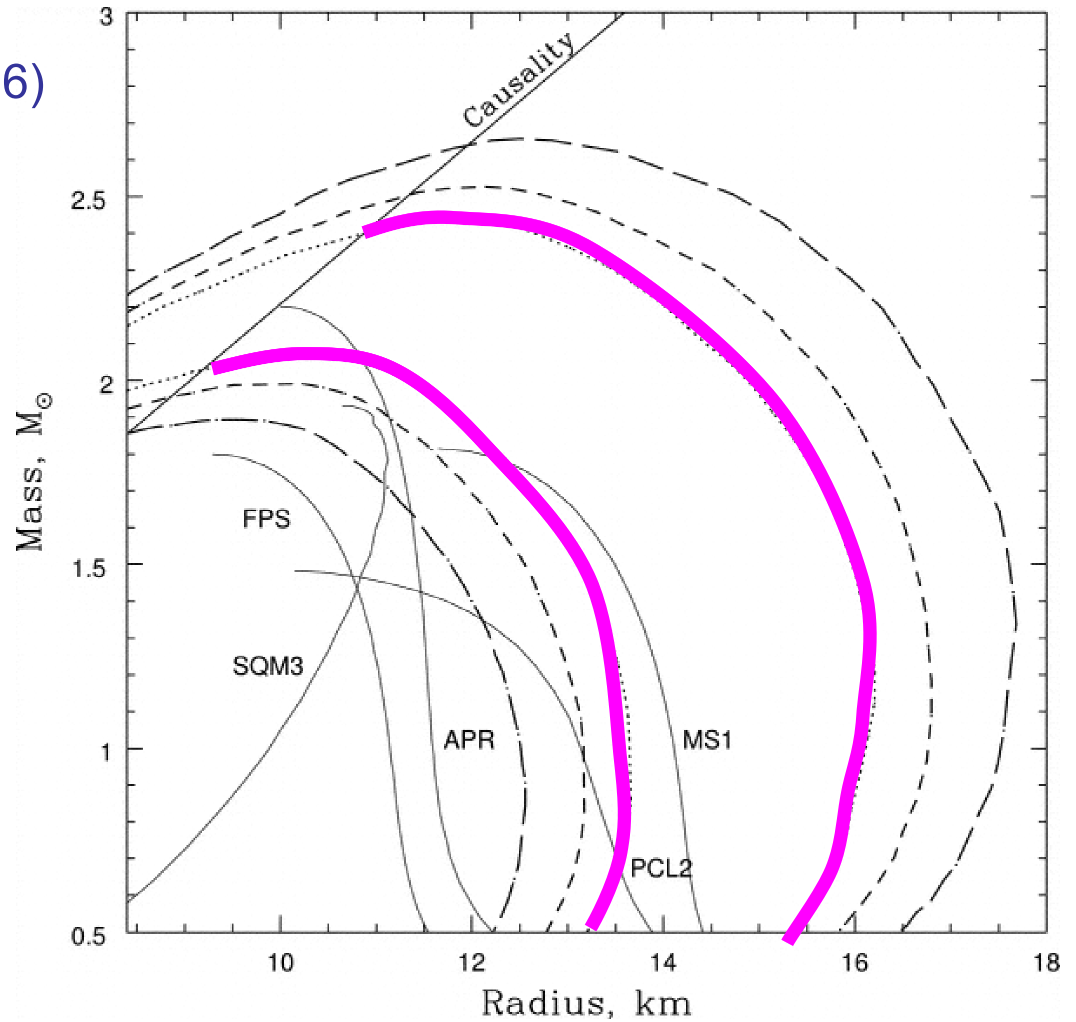
Example

X7 (NS in 47 Tuc, Heinke et al 2006)

They used pure hydrogen
model atmospheres.

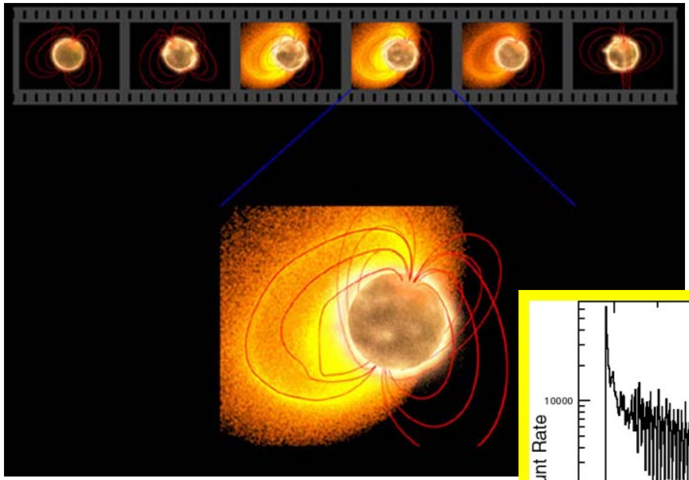
$R_{NS} \approx 14.5 \pm 1.7$ *km*
at $M = 1.4\ M_{Sun}$

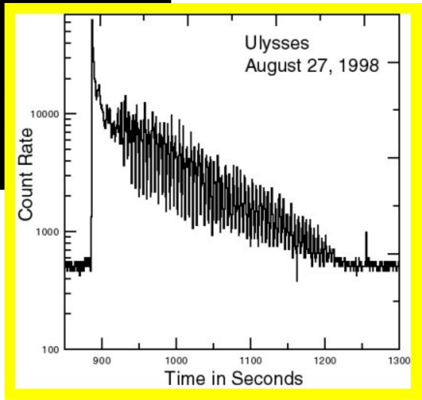
$R_{NS} \approx 14.9 \pm 1.5$ *km*
at $M = 1.4\ M_{Sun}$
(Suleimanov & Poutanen 2006)



Isolated NSs have a strong ($B \geq 10^{12}$ G) magnetic field ?

- Soft Gamma Repeaters (SGR)
- Compact objects in supernova remnants (CCO)
- Dim isolated neutron stars (DINS)
- Anomalous X-ray Pulsars (AXP)





Why strong magnetic field ?

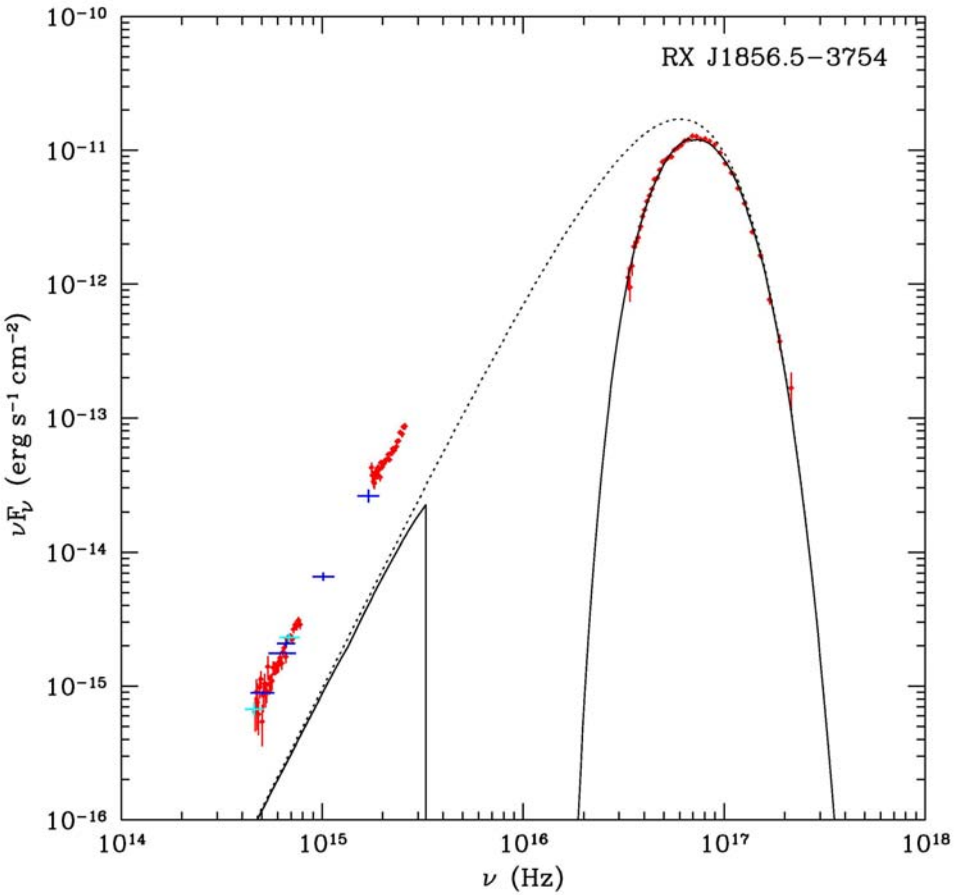
Coherent pulsation of the radiation

Change of period $\dot{P}$ in accordance with magneto-dipole radiation (for isolated NS)

Proton cyclotron line in spectra ($E_{Cp}= 0.63\ (B/10^{14}\ G)$ keV)

Observational properties of dim isolated neutron stars («Magnificent seven» = DINSs)

X-ray and optical flux not explained by a single blackbody spectrum



Two blackbody models - nonuniform temperature distribution ?

Thin plasma layer above solid surface?
Hard radiation is very close to blackbody

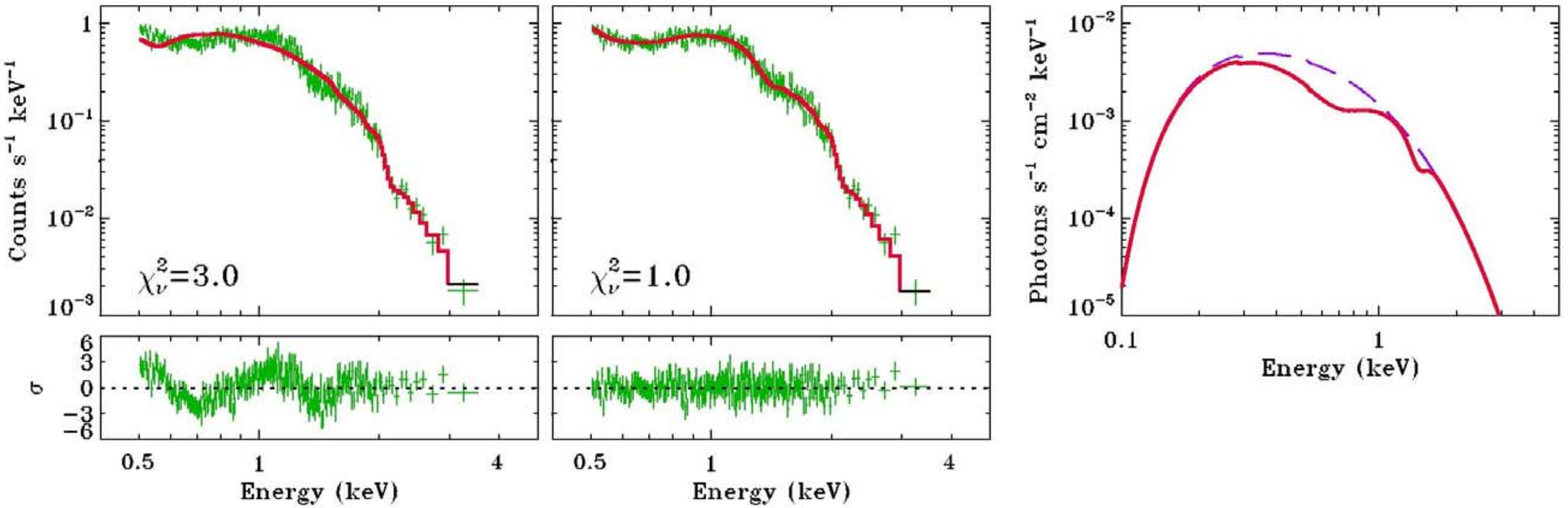
D = 140 +/- 20 pc
R_{obs}> 17 km (Trümper et al. 2005)

RX J1856.5-3754

Excellently fitted by blackbody in X-ray!

Observational properties of dim isolated neutron stars

Absorption features in the spectra – proton cyclotron lines ?



1E 1210-5226 (CCO in the supernova remnant)
0.7 and 1.4 keV

Proton cyclotron line and harmonic ?

B from line doesn't agree to B from Pdot

Blends of the spectral lines of the highly charged ions in the strong magnetic field?

Problem:

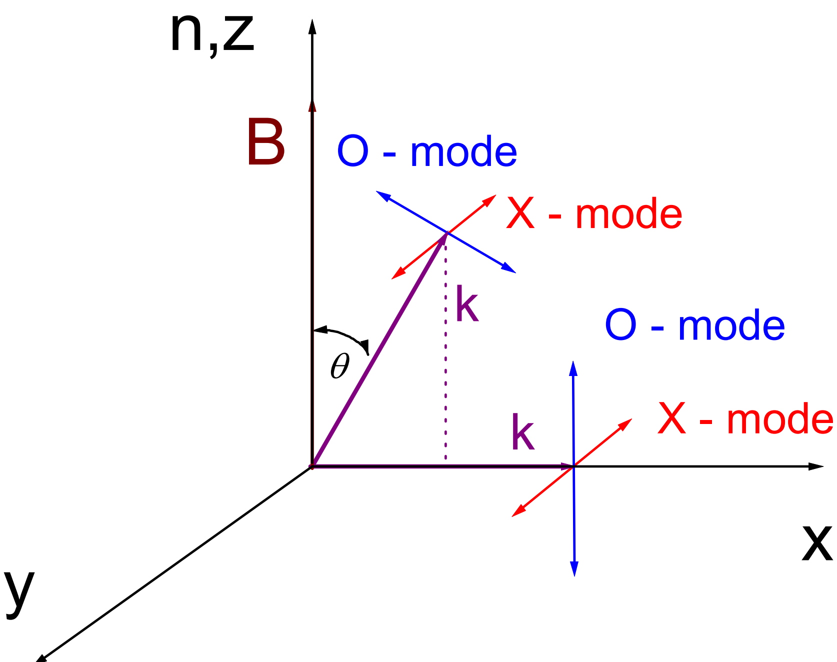
Modeling the magnetized neutron star atmospheres

Radiation transfer in a plasma with a strong magnetic field

Plasma in a strong magnetic field acts like quartz crystal: **birefringence!**

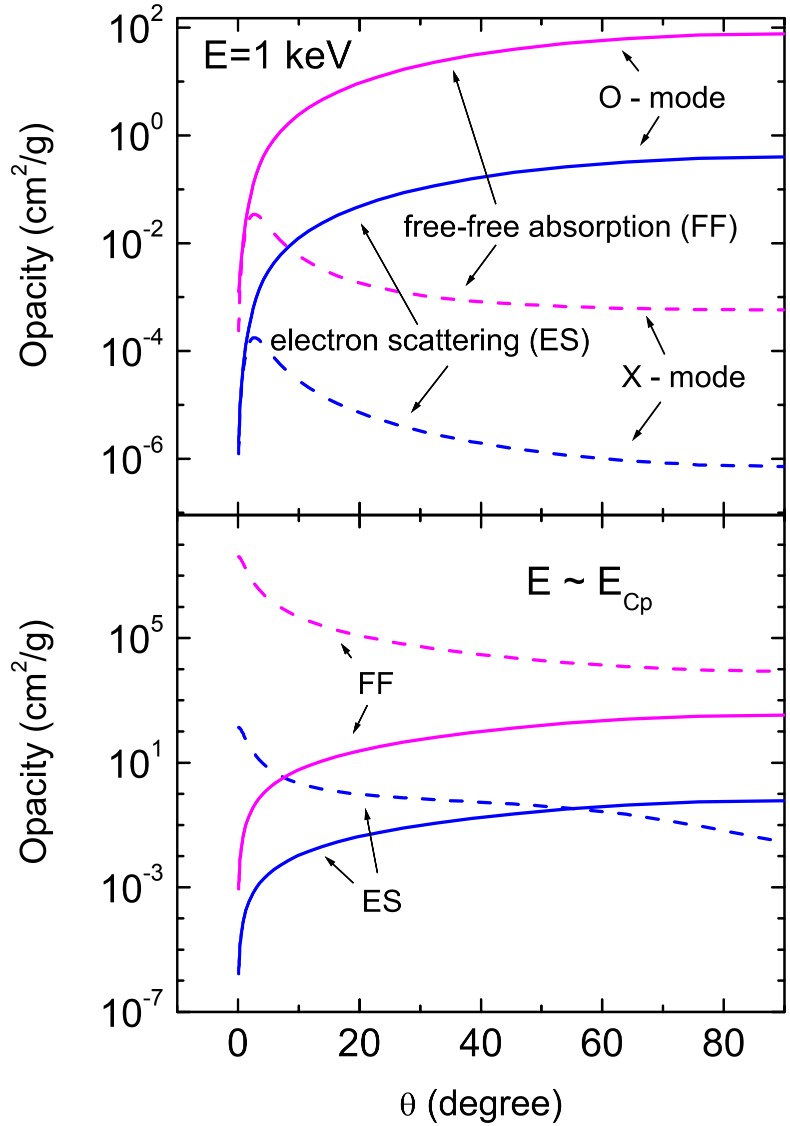
It is necessary to consider

TWO modes of radiation



$$\sigma_X \propto \sigma_e \frac{E^2}{(E - E_{Ce})^2}, \quad \sigma_O \propto \sigma_e$$

Opacity: Strong angular dependence



Radiation transfer in a plasma with a strong magnetic field

Opacity

Proton cyclotron line

$$\sigma_X \propto \frac{E^2}{(E_{Ce})^2} + \frac{E^2}{(E - E_{Cp})^2}\left(\frac{m_e}{m_p}\right)^2$$

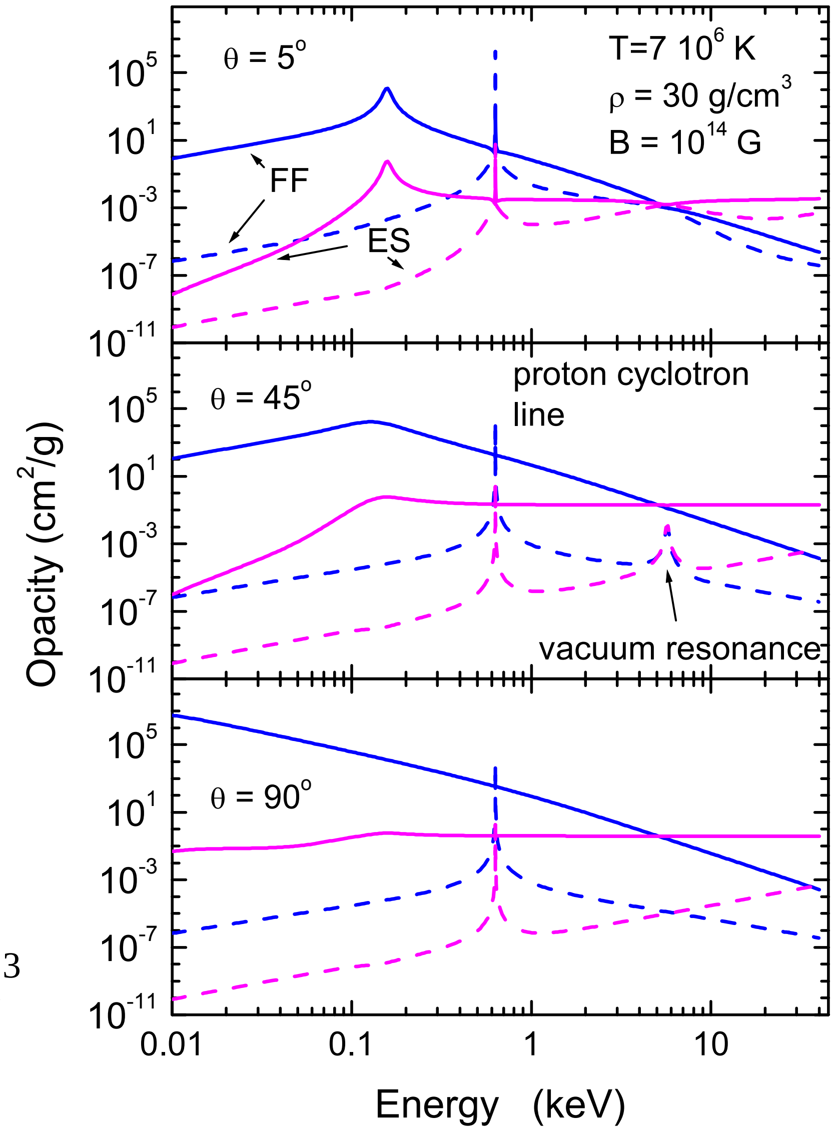
$$k_{ff,X} \propto \frac{E^2}{(E_{Ce})^2 (E - E_{Cp})^2}, \quad E << E_{Ce}$$

Vacuum polarization

$$\varepsilon_{ij} = \varepsilon_{ij}{}^{pl} + \varepsilon_{ij}{}^{vac}$$

Vacuum resonance

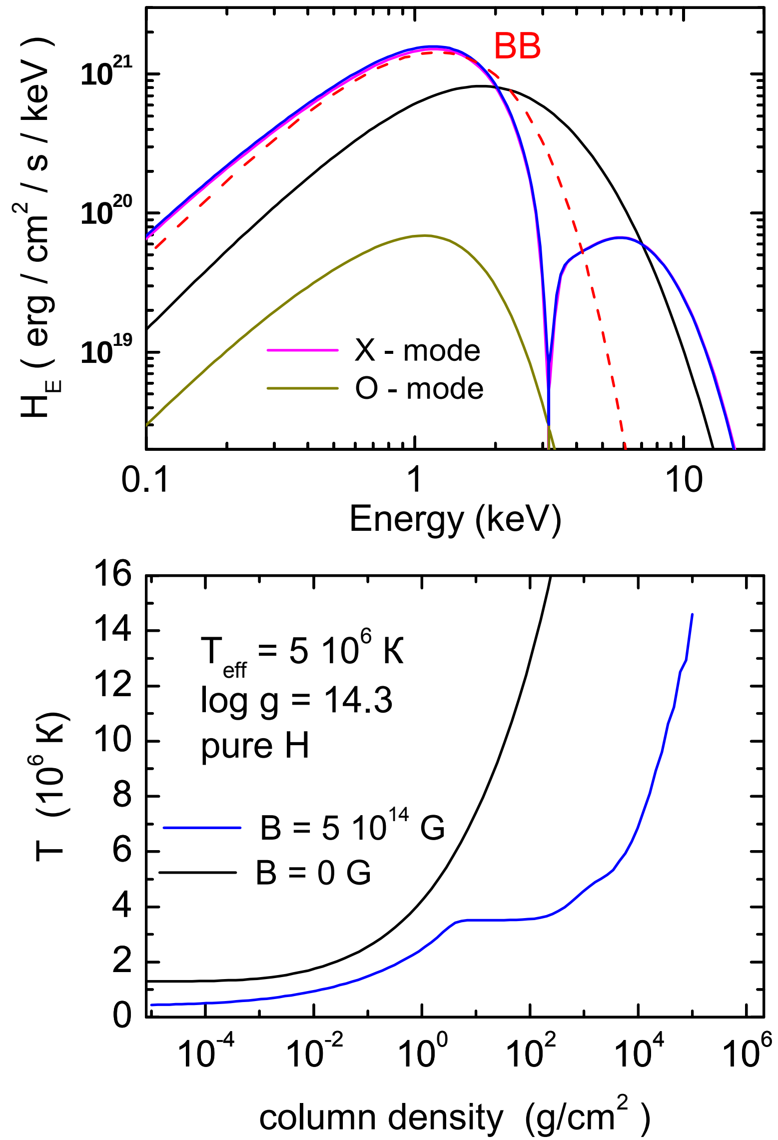
$$\rho_V = 0.96\left(\frac{E}{1\,keV}\right)^2 \left(\frac{B}{10^{14}G}\right)^2 f_B^{-2} \quad g/cm^3$$



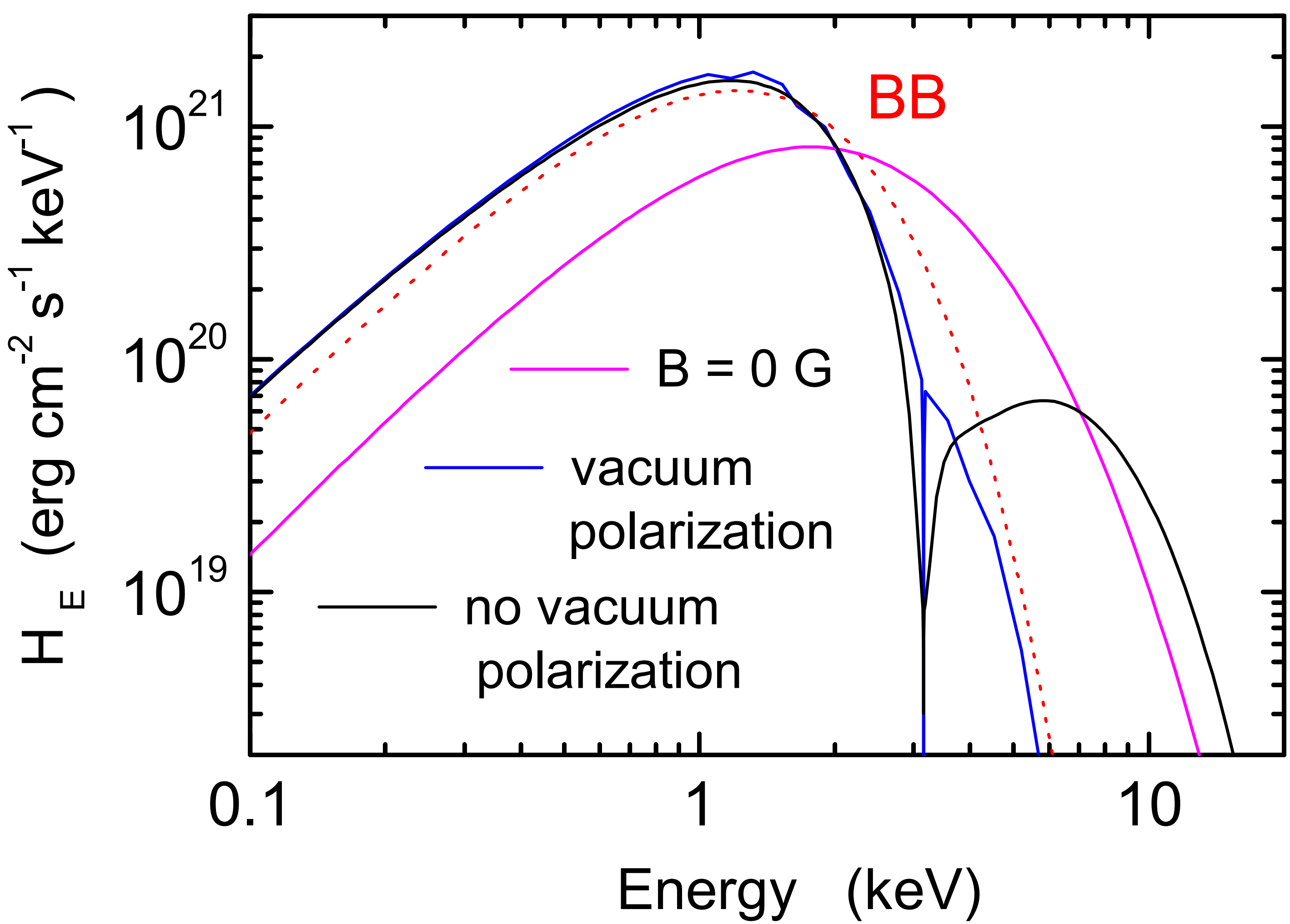
Models of magnetized NS atmospheres

Magnetized model atmospheres:

- have two photospheres corresponding to fluxes in two modes
- radiation is formed in deeper layers in comparison with atmosphere without magnetic field
- flux in the X-mode is dominating
- radiation is strongly polarized



Models of magnetized NS atmospheres

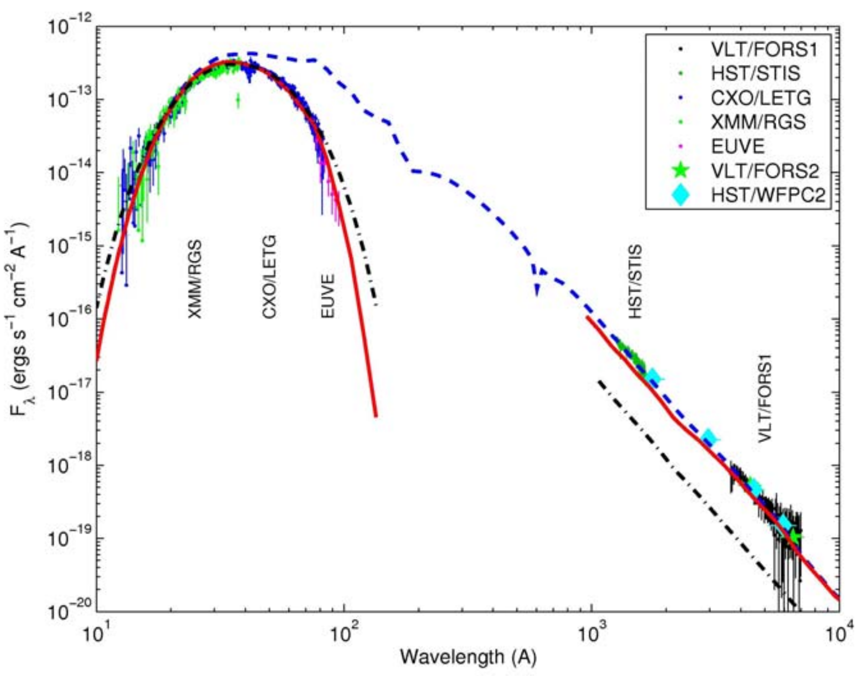


Vacuum polarization suppresses the proton cyclotron line, if the resonance layers are close to X-mode photosphere ($B > 10^{14}$ G)

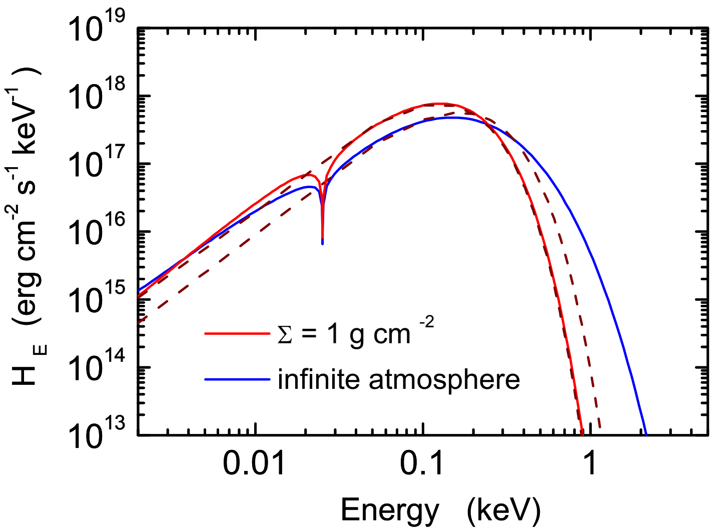
Models of magnetized NS atmospheres

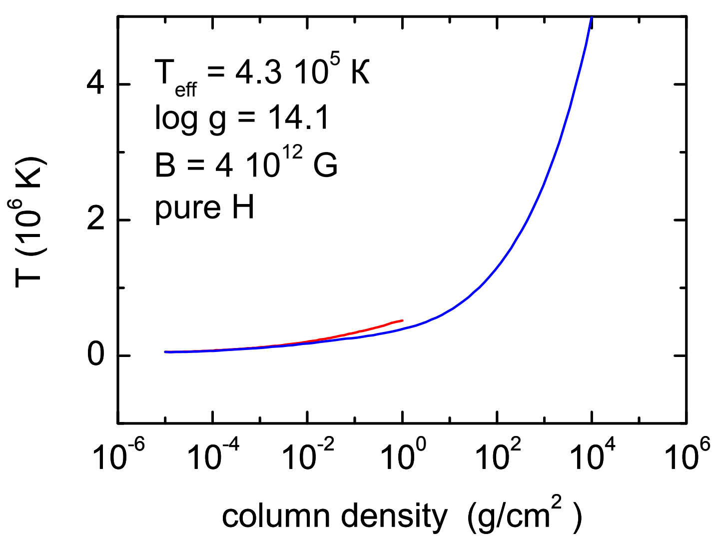
Thin atmosphere above solid surface

Used to explain the relation between optical and X-ray fluxes



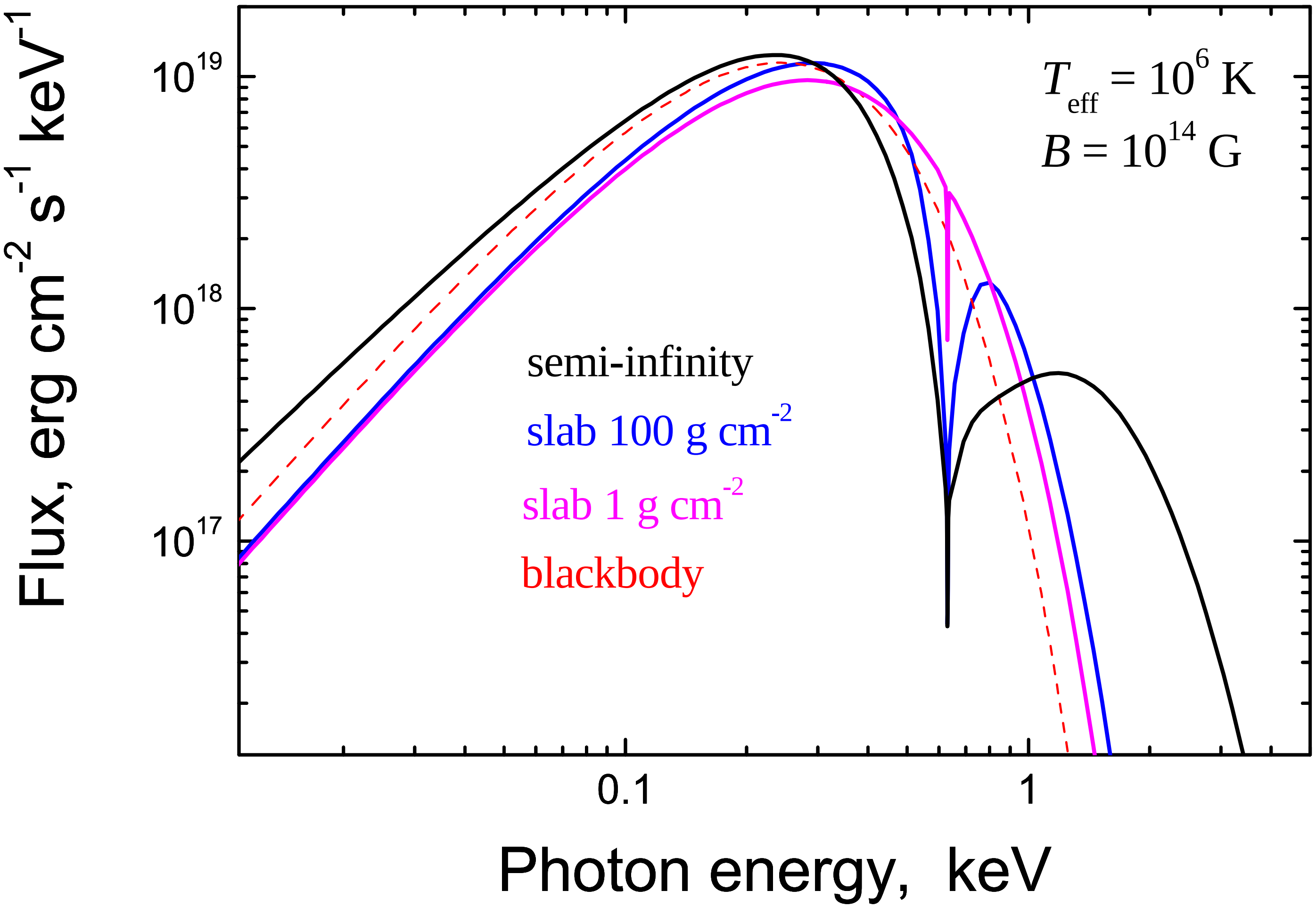
From Ho et al. 2007





Models of magnetized NS atmospheres

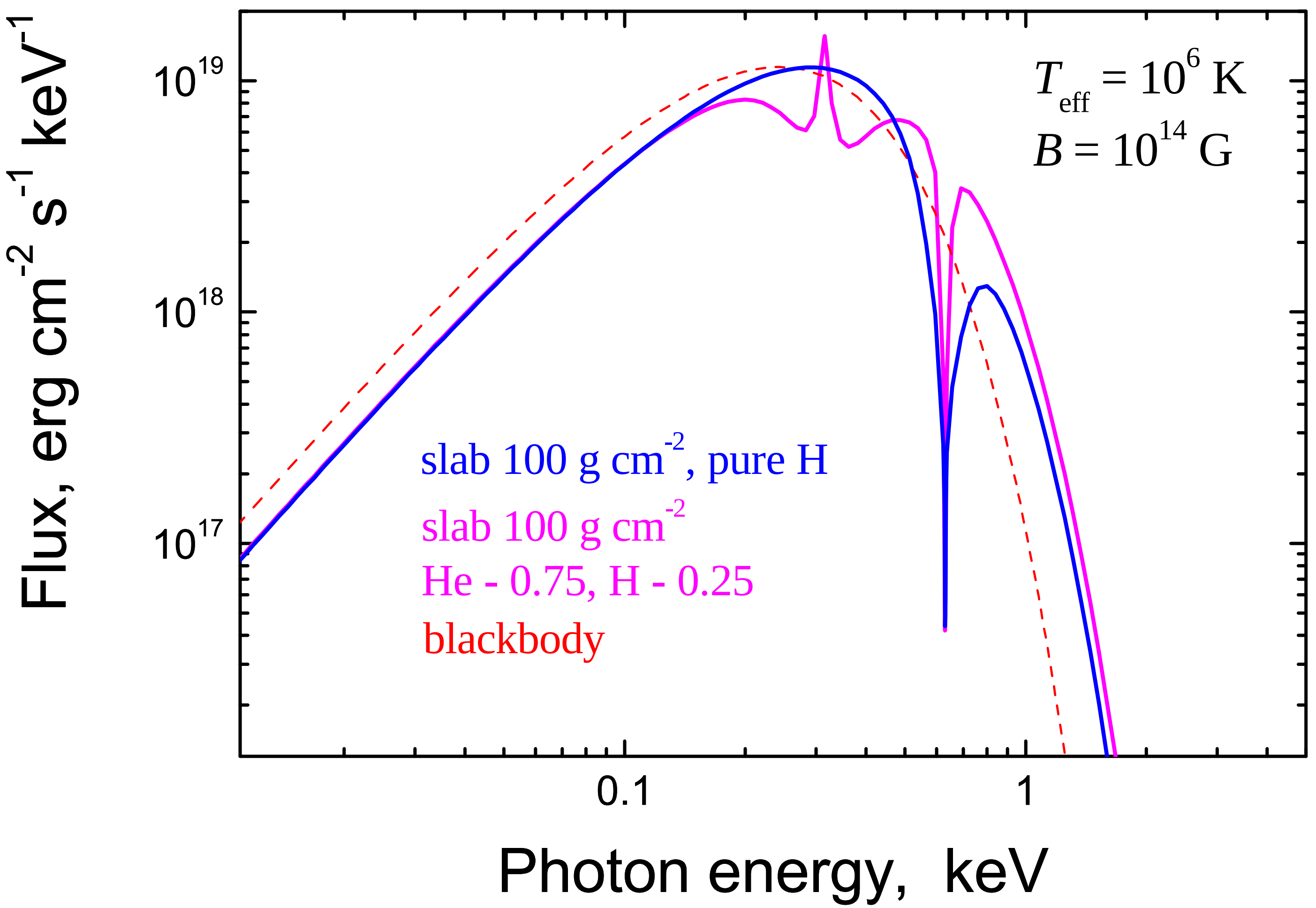
Thin atmosphere above solid surface



Proton cyclotron line can be depressed if the atmosphere is thin

Models of magnetized NS atmospheres

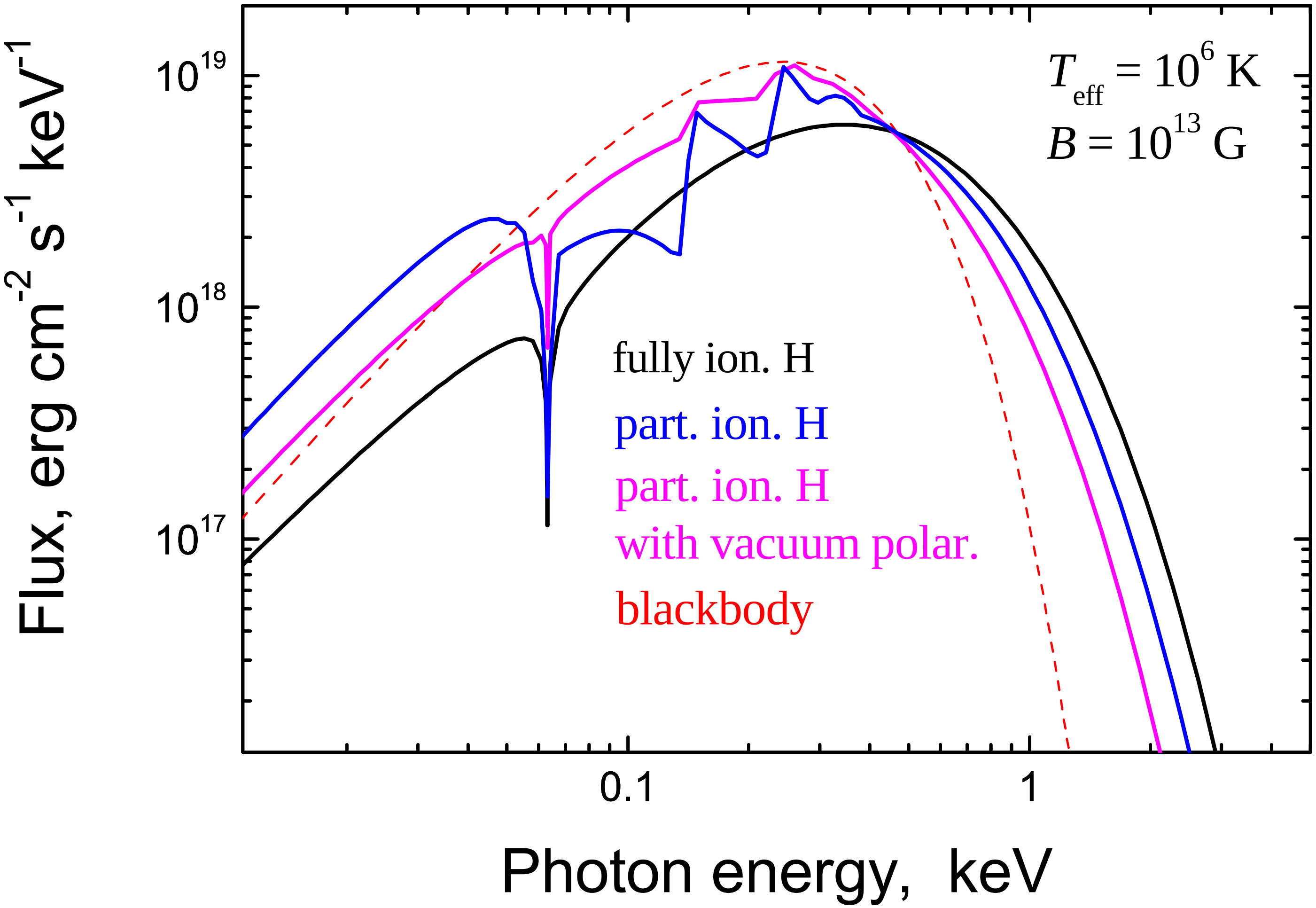
Thin atmosphere above solid surface



Hydrogen slab above helium slab can explain two absorption features

Unresolved problems

Partially ionized atmospheres (especially with heavy elements)



Problem resolved for partially ionized hydrogen atmosphere only

Conclusion for observed size of isolated NSs

Necessary to perform a lot of theoretical work with magnetized NS atmospheres before the confidence results will be obtained

Common Conclusion

It seems that NS inner core has a stiff EoS

X7

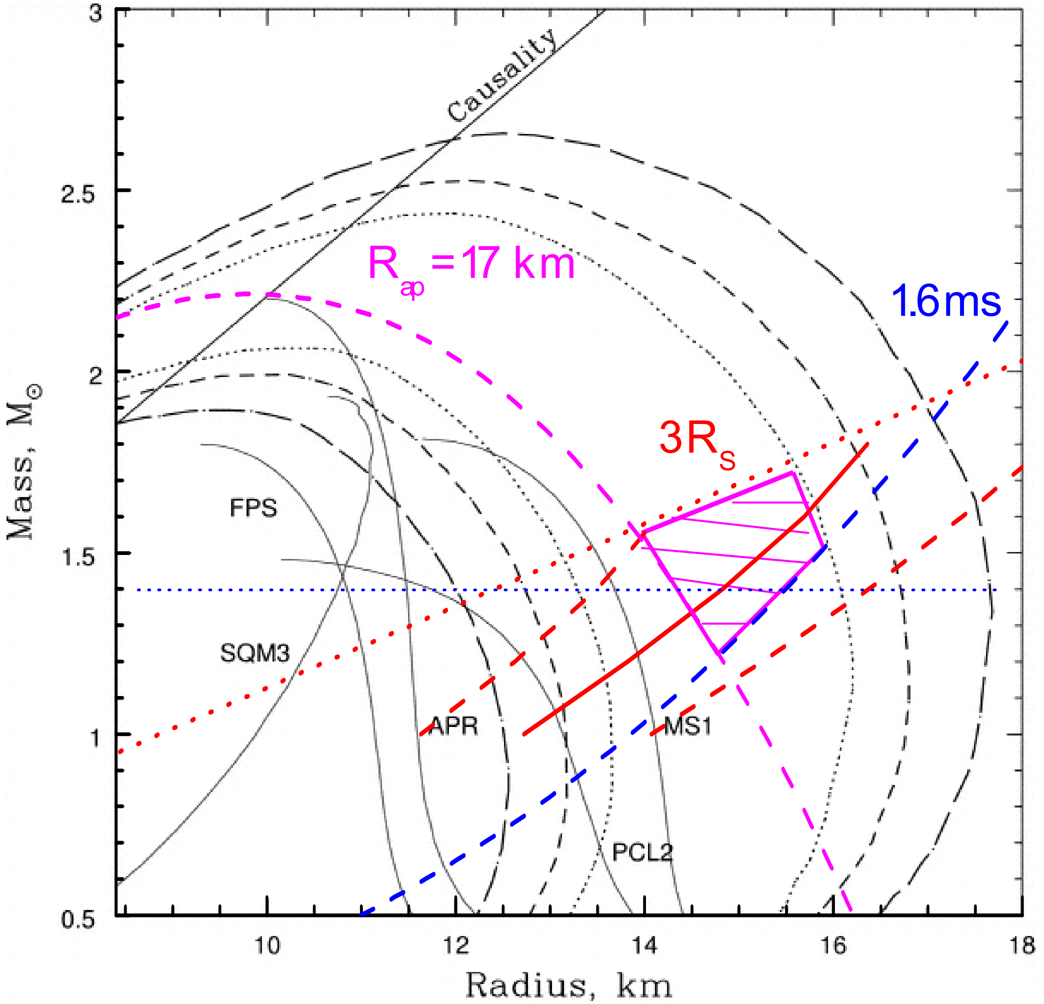
R=14.5 +/- 1.7 km

(1.4 M_sun)

Our Result

R=14.9 +/- 1.5 km

(1.4 M_sun)



Contours at 68% (dotted curves), 90% (dashed curves), and 99% (long-dashed curves) confidence in the mass-radius plane derived for X7 (NS in 47 Tuc) by spectral fitting (Heinke et al. 06). Allowed area from our model and limitations from the apparent radius of RX J1856 and from the rotation period of B1937 are added.

Absorption in spectral lines

$k_{line} \sim N_{Low}\, gf_{line}$, $N_{Low} \approx N_{Ion} \exp(-E_{Low}/kT)$

$N_{FeXXV} > N_{FeXXIV}$ BUT:

for FeXXV 10.5 A $E_{Low} \sim 7\ keV$

for FeXXIV 10.6-11.2 A $E_{Low} \sim 0\ keV$

$kT \sim 1\ keV$ → $N_{Low}(FeXXV) << N_{Low}(FeXXIV)$