The neutron star in HESS J1731-347 as a nuclear physics laboratory

Valery Suleimanov

Universität Tübingen, Germany
Kazan Federal University, Russia

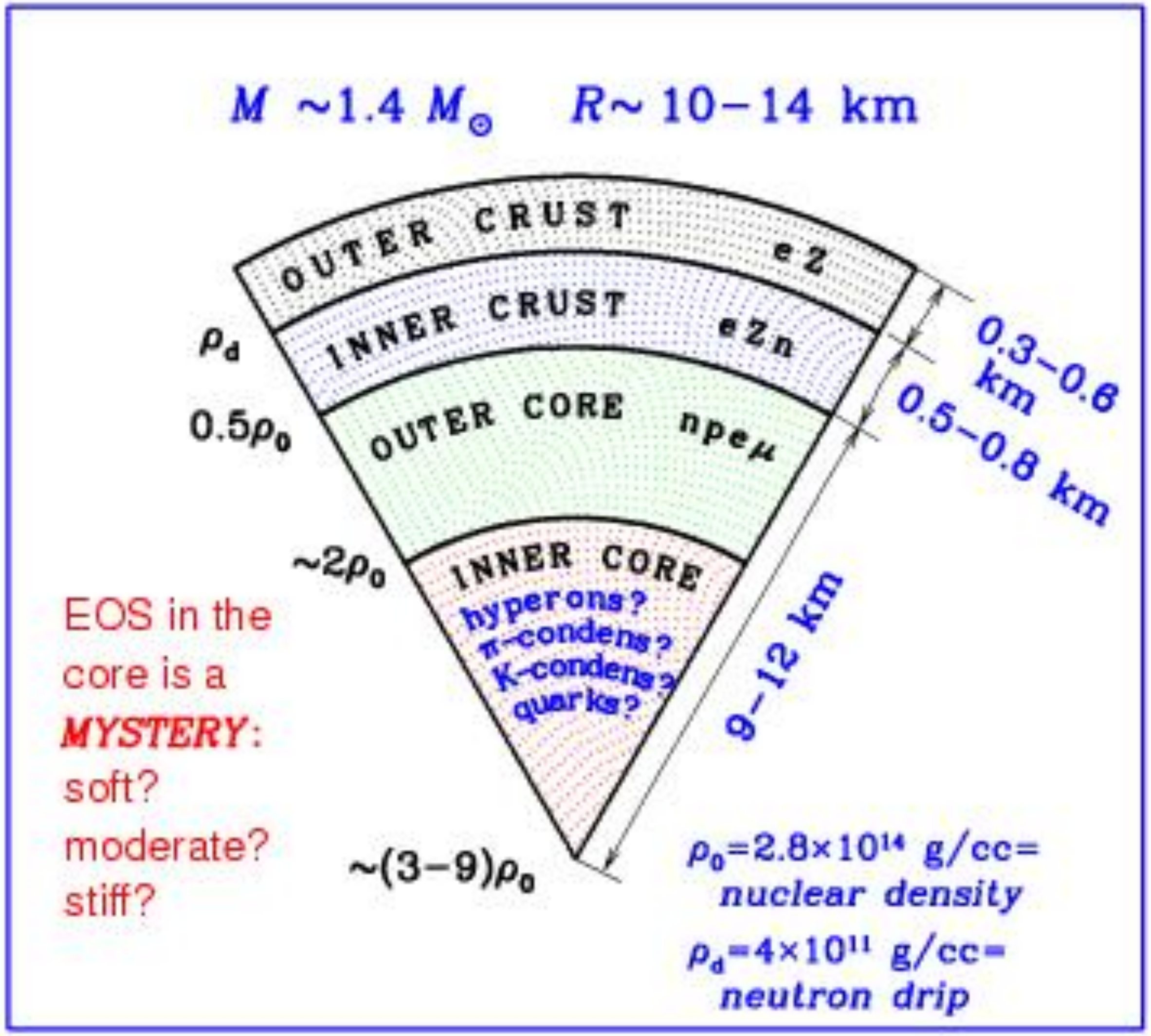
together with

D. Klochkov, G. Pühlhofer, A. Santangelo, K. Werner
Universität Tübingen, Germany

D.G. Yakovlev, D. Ofengeim, A.D. Kaminker
Ioffe Physical-Technical Institute, St. Petersburg, Russia

Workshop “QCD matter: hot and dense”
Januar 19, 2016, Hirschegg, Kleinwalsertal

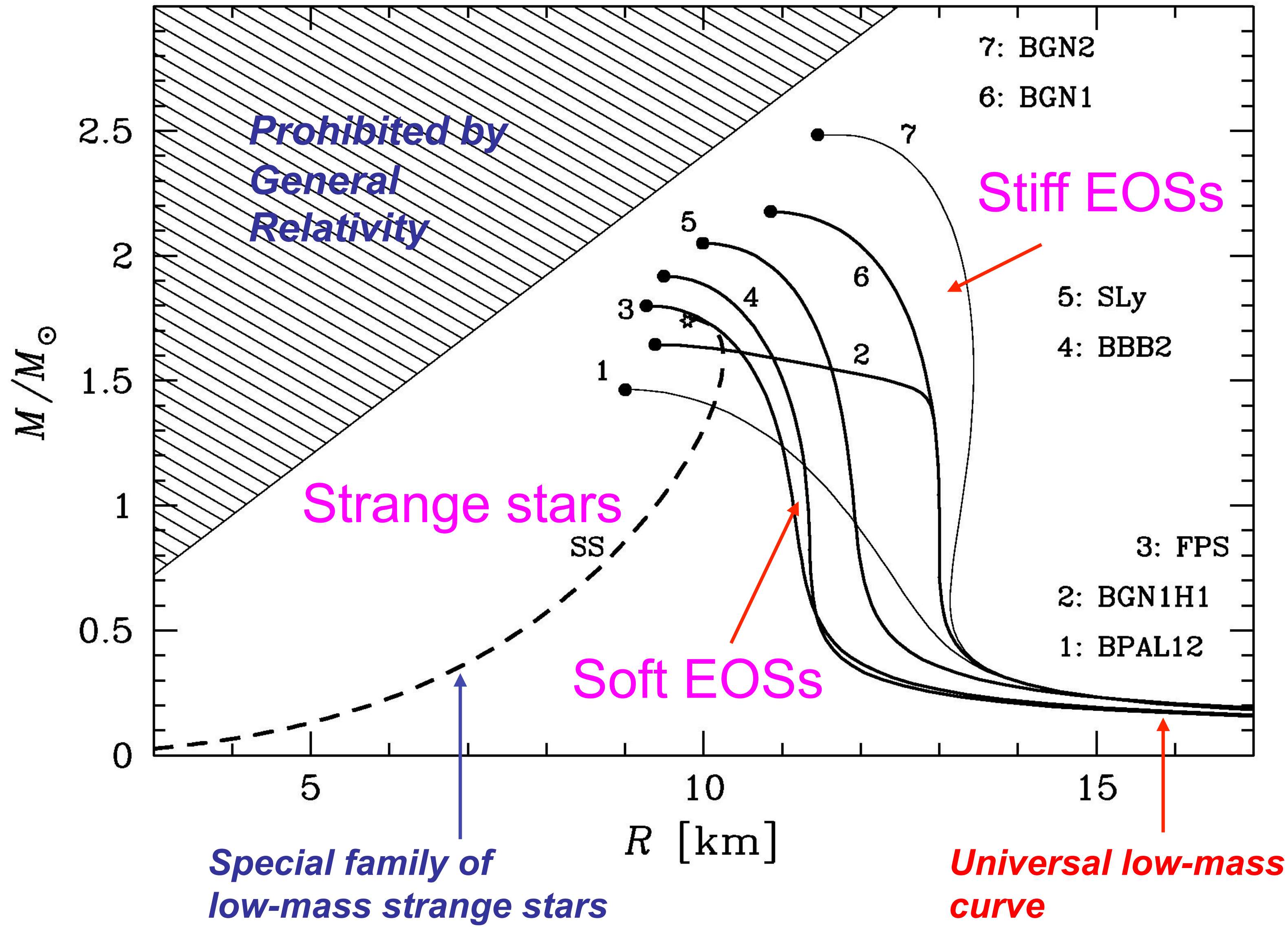
Neutron star structure



Main problem is the dense matter equation of state (EOS) in the inner core.

Important for computation of GW signal from NSs mergers.

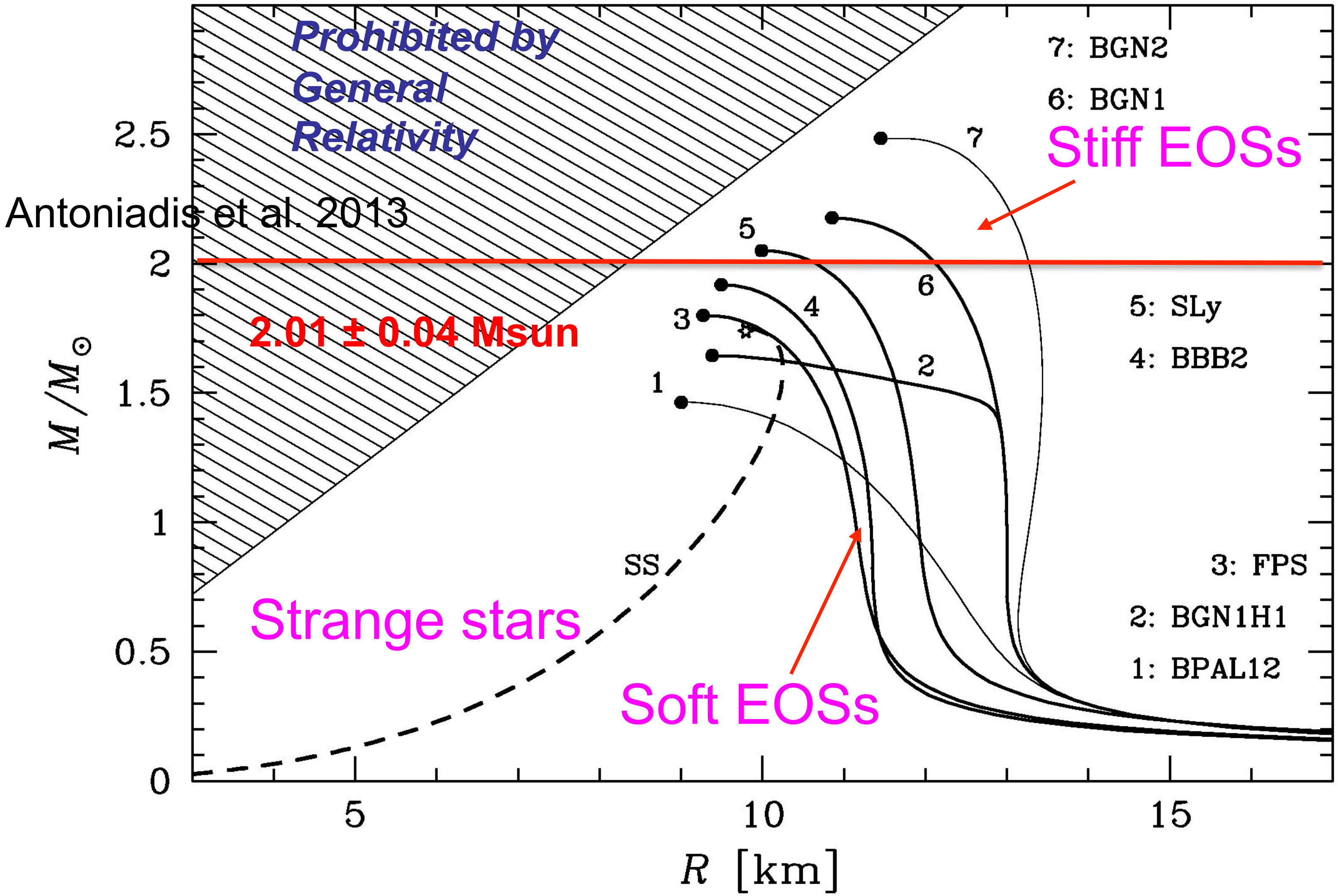
Zoo of EOSs



Prohibited by General Relativity
Strange stars
Stiff EOSs
Soft EOSs
7: BGN2
6: BGN1
5: SLy
4: BBB2
3: FPS
2: BGN1H1
1: BPAL12
SS
7
6
5
4
3
2
1
2.5
2
1.5
1
0.5
0
5
10
15
$M/M_{\odot}$
R [km]
Special family of low-mass strange stars
Universal low-mass curve

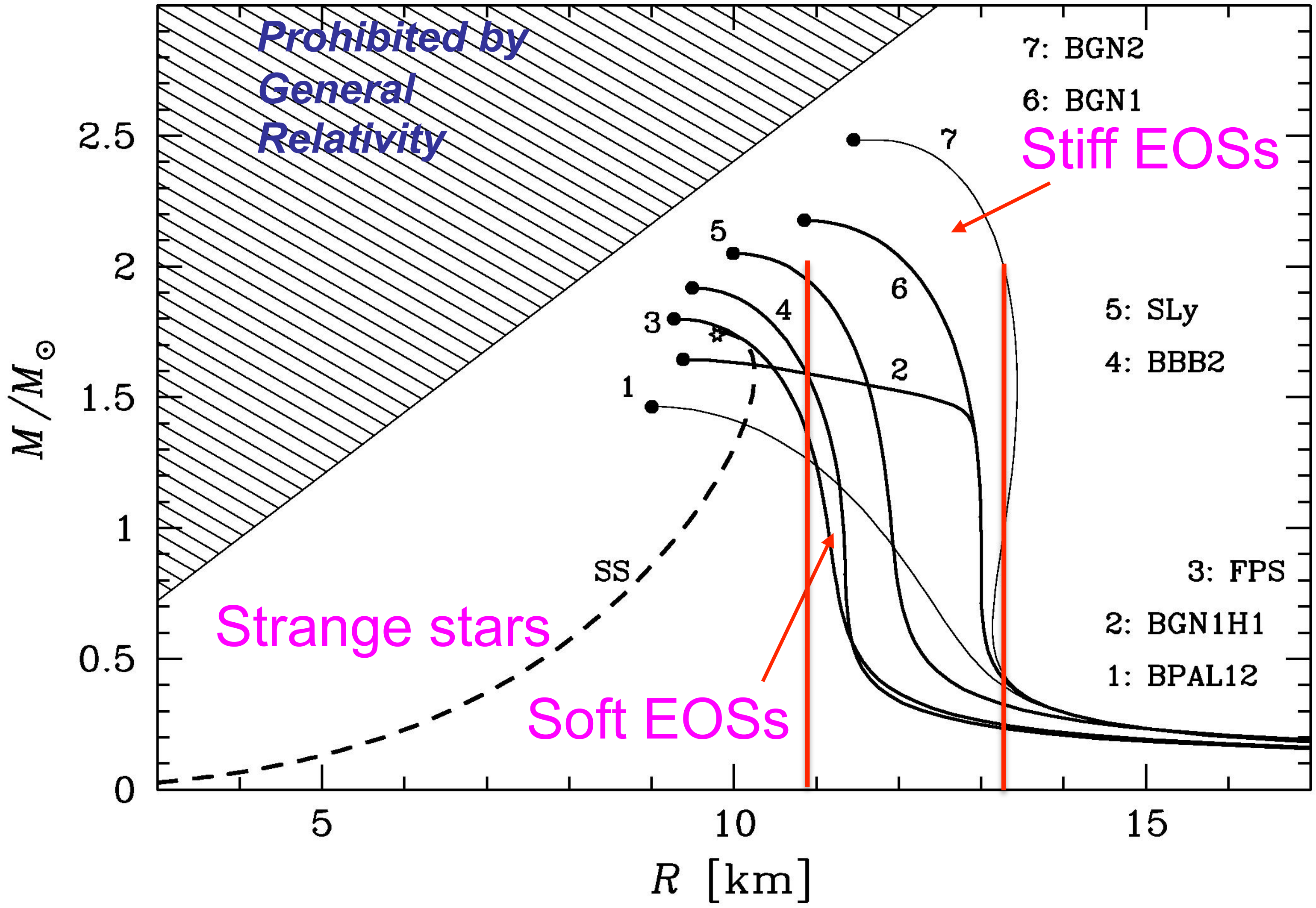
Observational methods of EOS limitation

1. Maximum neutron star mass

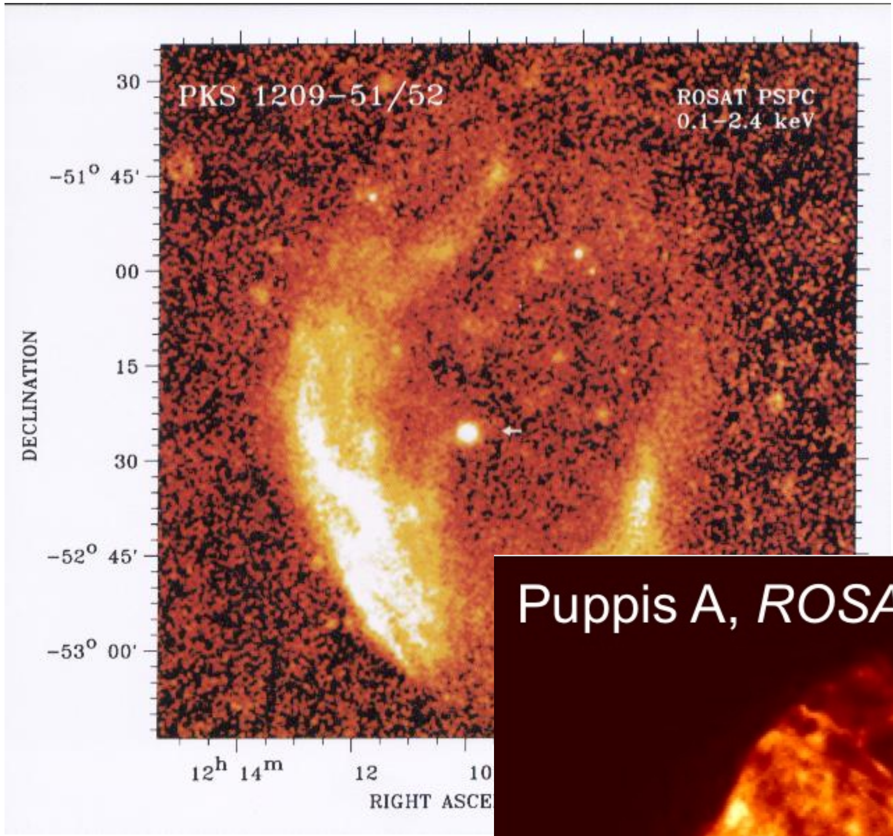


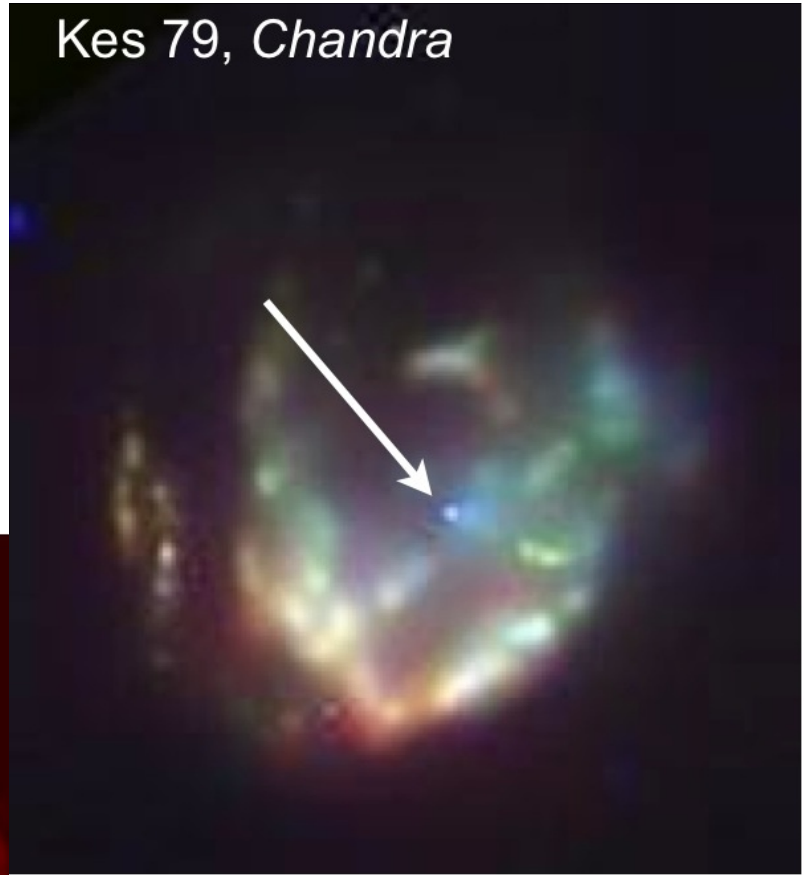
Observational methods of EOS limitation

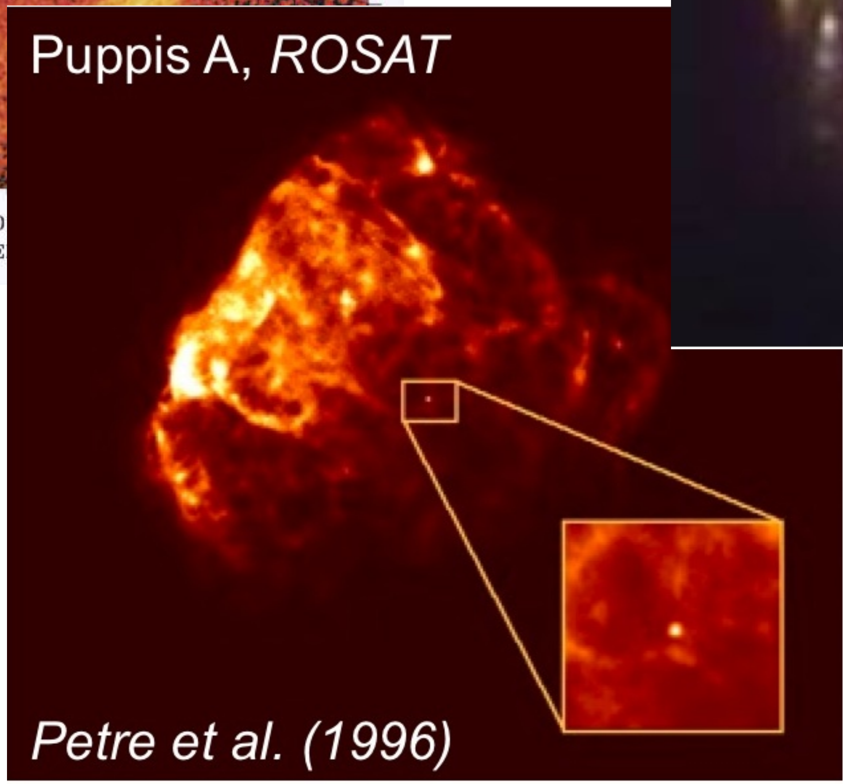
2. Neutron star radii



CCO – central compact objects in Supernova Remnants







Modern X-ray observatories

Chandra

High angular resolution ~0.”5

Small collecting area ~ 340 cm^2

4 nested mirror systems

XMM-Newton

Low angular resoiution ~ 5”

Large collecting area ~4000 cm^2

3×58 nested mirror systems

CCO – central compact objects in Supernova Remnants (SNR)

Properties

- Point X-ray sources ($L_x \sim 10^{33}$ erg/s) in center of SNR
- Young (< 10^4 yr) with thermal spectra (kT ~ 0.1 – 0.5 keV)
- Very stable flux, there is no evidence for accretion
- No optical, radio, and γ- radiation, no pulsar nebula

Table 1
Central Compact Objects in Supernova Remnants

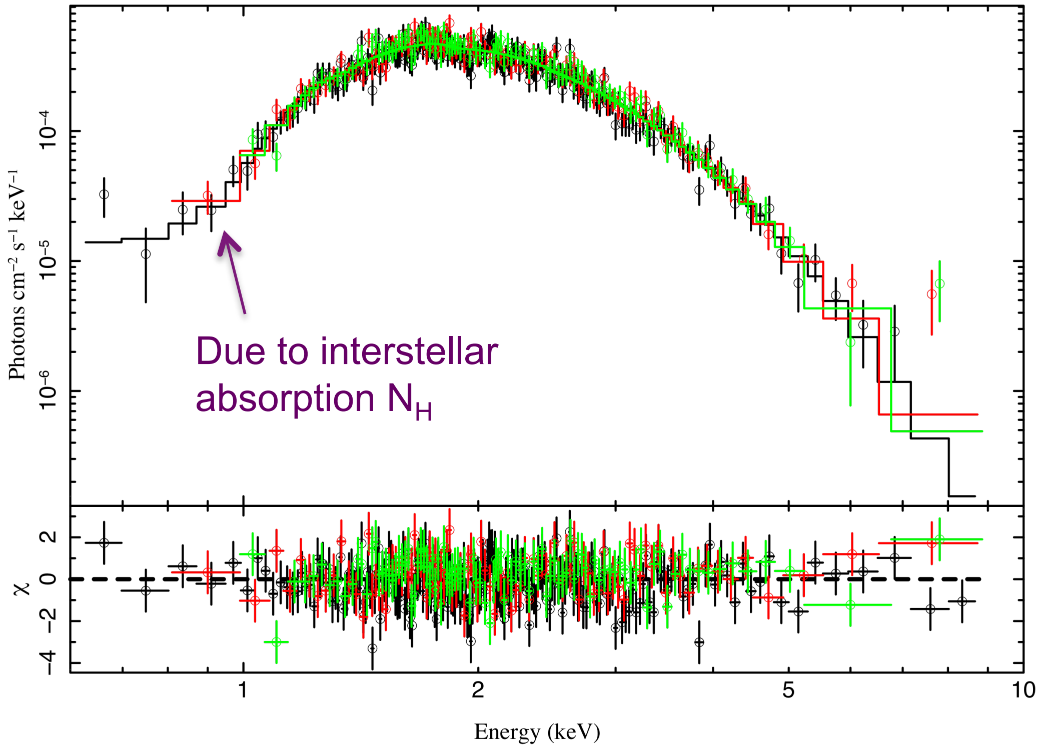
CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p [a] (%)	B_s (10^{10} G)	$L_{x,\rm bol}$ (erg s^{-1})	References
RX J0822.0−4300	Puppis A	4.5	2.2	0.112	11	2.9	5.6×10^{33}	1,2,3,4,5,6
CXOU J085201.4−461753	G266.1−1.2	1	1	···	<7	···	2.5×10^{32}	7,8,9,10,11
1E 1207.4−5209	PKS 1209−51/52	7	2.2	0.424	9	9.8	2.5×10^{33}	6,12,13,14,15,16,17
CXOU J160103.1−513353	G330.2+1.0	$\gtrsim$3	5	···	<40	···	1.5×10^{33}	18,19
1WGA J1713.4−3949	G347.3−0.5	1.6	1.3	···	<7	···	$\sim 1 \times 10^{33}$	11,20,21
XMMU J172054.5−372652	G350.1−0.3	0.9	4.5	···	···	···	3.9×10^{33}	22,23
CXOU J185238.6+004020	Kes 79	7	7	0.105	64	3.1	5.3×10^{33}	24,25,26,27
CXOU J232327.9+584842	Cas A	0.33	3.4	···	<12	···	4.7×10^{33}	27,28,29,30,31,32,33
2XMMi J115836.1−623516	G296.8−0.3	10	9.6	···	···	···	1.1×10^{33}	34
XMMU J173203.3−344518	G353.6−0.7	~27	3.2	···	<9	···	1.3×10^{34}	35,36,37,38
CXOU J181852.0−150213	G15.9+0.2	1–3	(8.5)	···	···	···	$\sim 1 \times 10^{33}$	39

Notes. Above the line are eight well-established CCOs. Below the line are three candidates.
[a] Upper limits on pulsed fraction are for a search down to $P = 12$ ms or smaller.

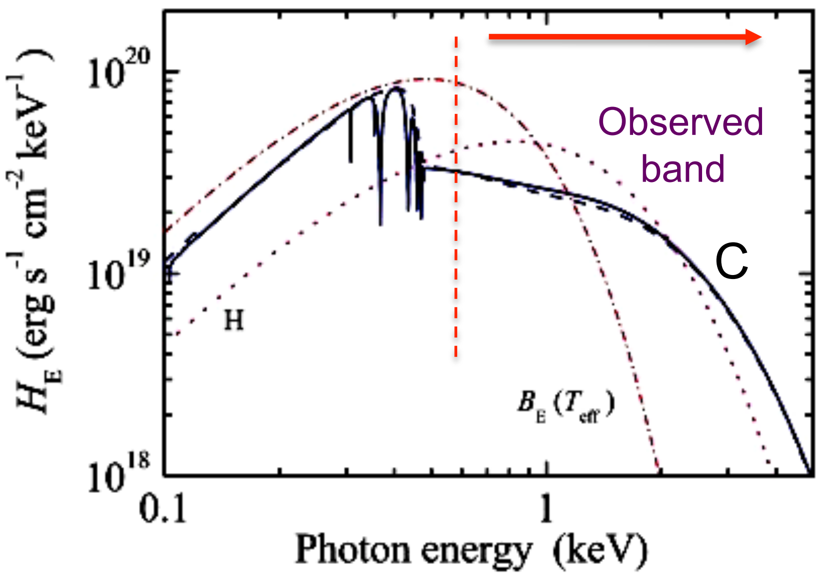
(Gotthelf et al. 2013)

Spectral fitting

Observations



Theory



Model spectrum !

$$f_E = F_E K = F_E \frac{R^2(1+z)^2}{d^2}$$

Redshifted local spectrum

Normalization

Simple approximation

$$F_E \approx w B_E(f_c T_{eff})$$

$$w \approx f_c^{-4}$$

$$R\ (1+z) = R_{BB}\ w^{-1/2} \approx R_{BB} f_c^2$$

Atmosphere

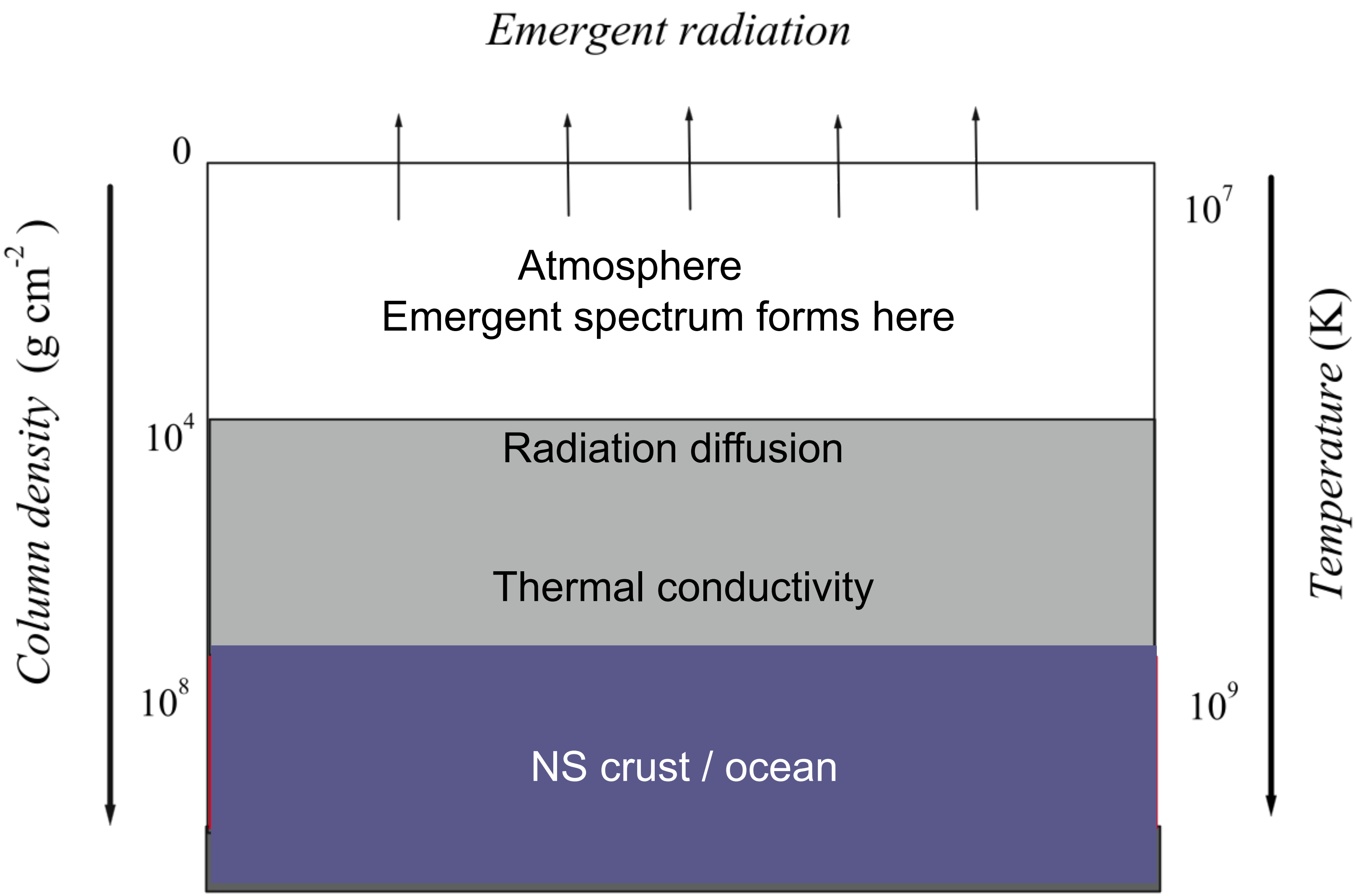
is a thin plasma envelope between a source of energy and the open space. Energy transfers through the envelope and escapes through the open boundary.

Model atmosphere

is a result of a self consistent solution of all the equations describing all the basic physical laws:

- mass conservation,
- momentum conservation
- energy conservation
- energy transport
- plasma equation of state

Plane parallel model of the envelope



Input parameters

Surface gravity $$g = \frac{GM}{R^2}(1+z)$$

Bolometric flux $$F = \sigma_{SB} T_{eff}^4$$

Effective temperature T_{eff}

or

Relative luminosity $l = F/F_{Edd}$

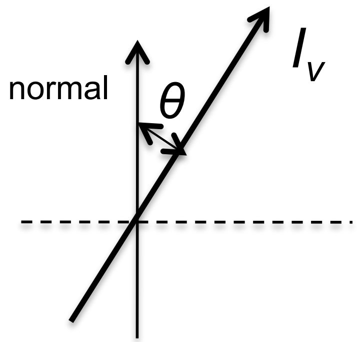
Chemical composition

Accretion – composition of the accreted matter

Low accretion – gravitational separation,
the lightest element domination

Powerful bursts – burning ash ?

Basic equations



Hydrostatic equilibrium
$$\frac{dP}{dm} = g - g_{rad}$$

Radiation transfer
$$\mu \frac{\partial I_\nu}{\partial m} = (k_\nu + \sigma_e)(I_\nu - S_\nu)$$
$$\mu = \cos\theta$$

Radiation equilibrium
$$\int k_\nu (J_\nu - B_\nu) d\nu \boxed{- \sigma_e \int \frac{4kT - h\nu}{m_e c^2} J_\nu \, d\nu} \approx 0$$

Equation of state
$$P = NkT$$

-pressure ionization effects are included
- LTE approximation for number densities

Column density ***m*** – independent variable

$$dm = -\rho \, dz$$

Opacity

Opacity coefficient - inverted column density of the photon free path

$$k = m_{fp}^{-1} \qquad [k] = cm^2 g^{-1} \qquad \tau \approx k\, m$$

Two physically different processes

Electron scattering - photon changes direction only (Thomson, coherent)

$$\sigma_e = \sigma_T \frac{N_e}{\rho} \approx 0.2(1 + X)$$

X is hydrogen mass fraction

Compton scattering – energy and momentum of photon are changed

$$\sigma_e = \sigma_e(\nu, T)$$

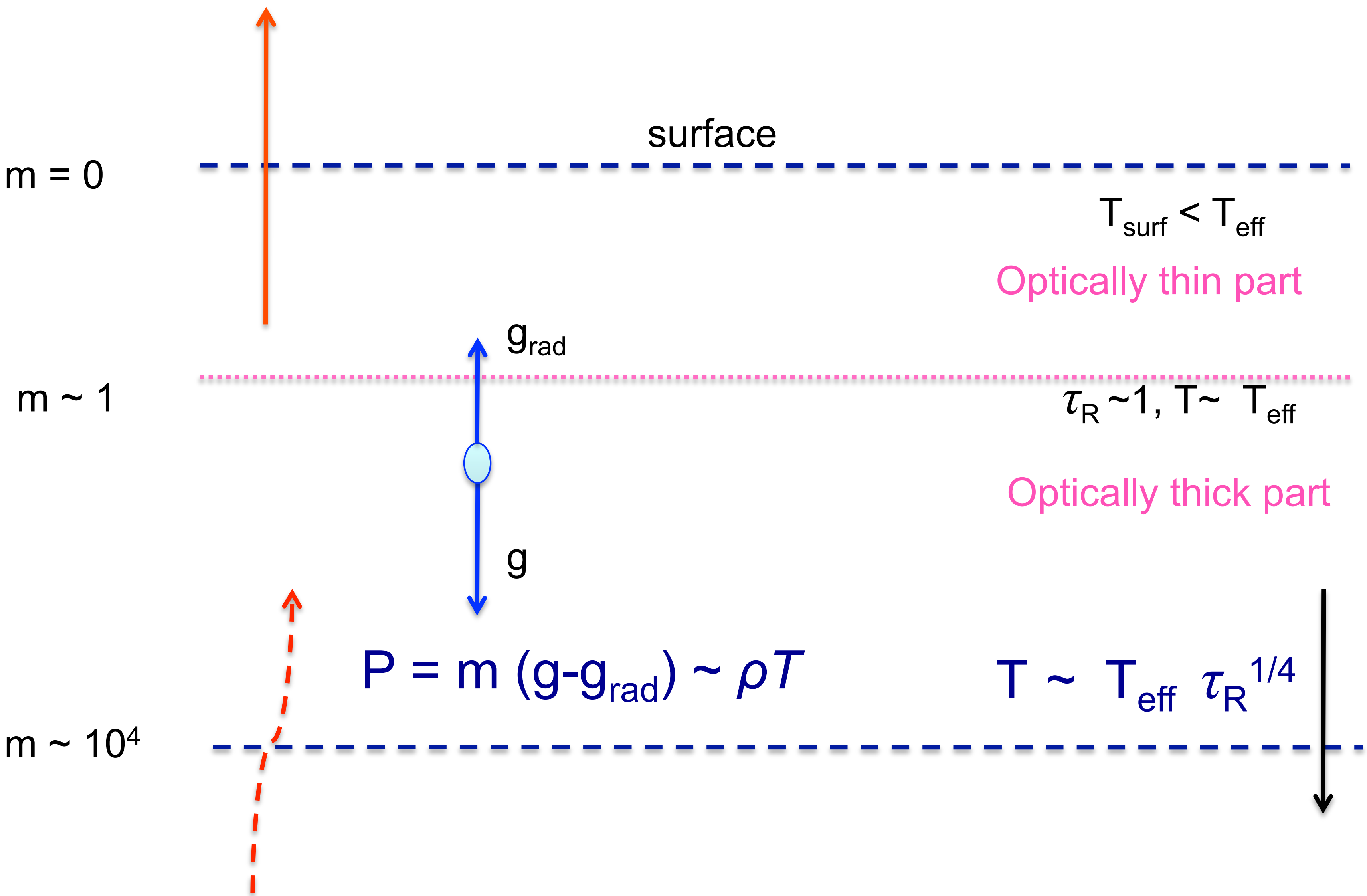
True absorption opacity – interaction with two particles (ion and electron)

Photon disappears

$$k_\nu \approx \sigma_\nu \frac{N_e N^+}{\rho} \propto \nu^{-3} \rho T^{-1/2}$$

free-free opacity

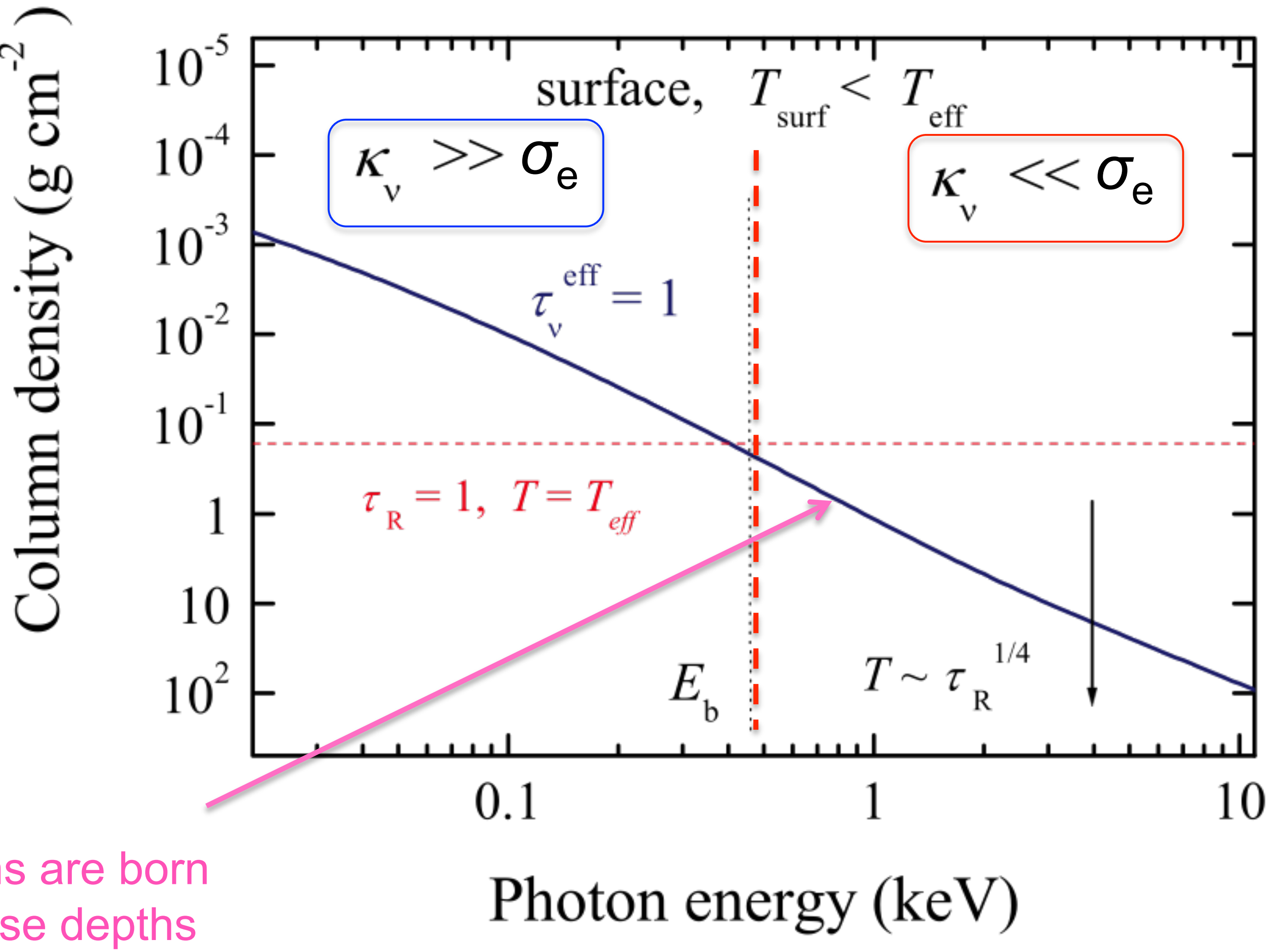
No external radiation / fast particles



Diffusion approximation

Spectrum formation

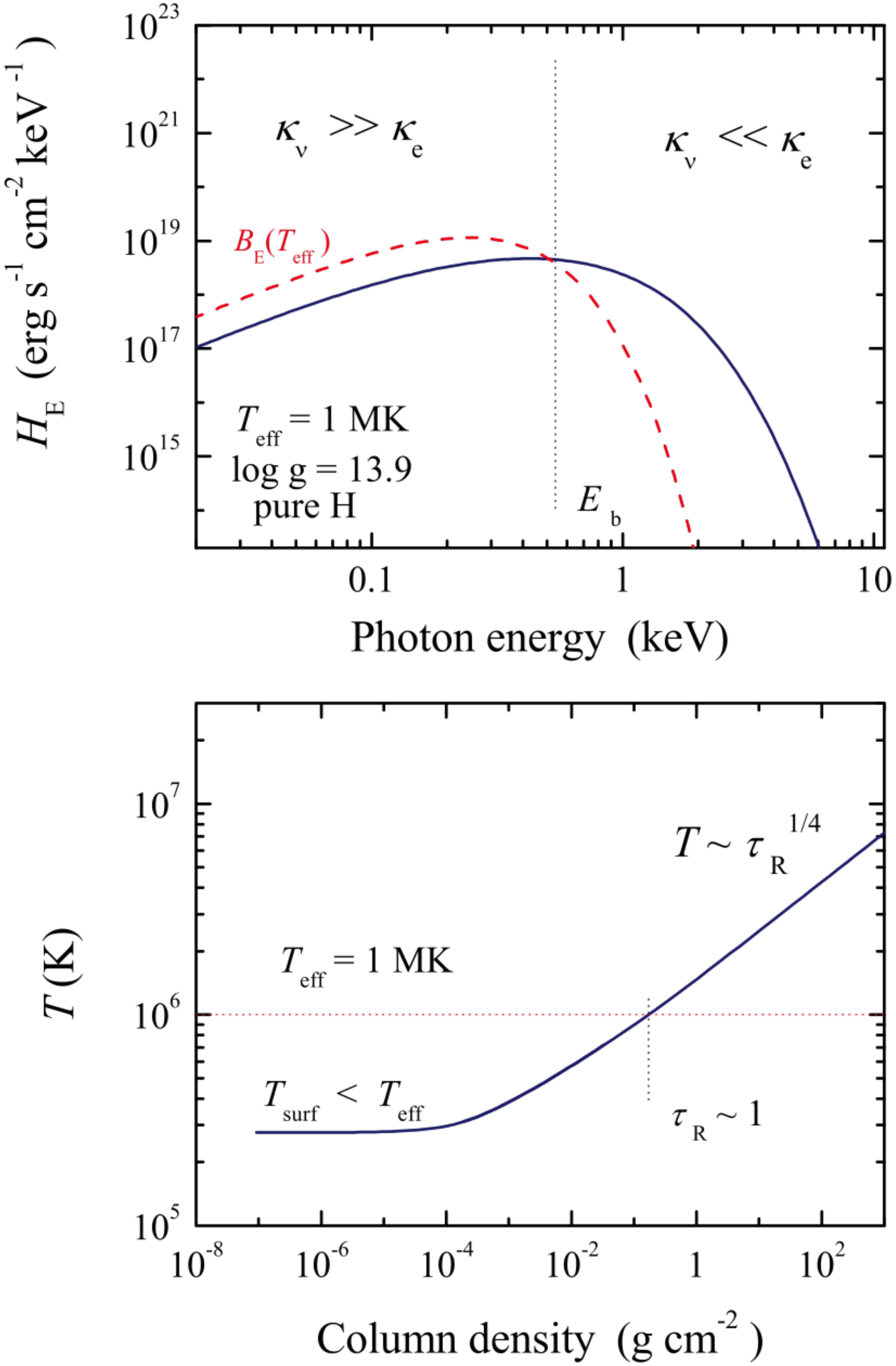
low T_{eff} atmospheres



Photons are born at these depths

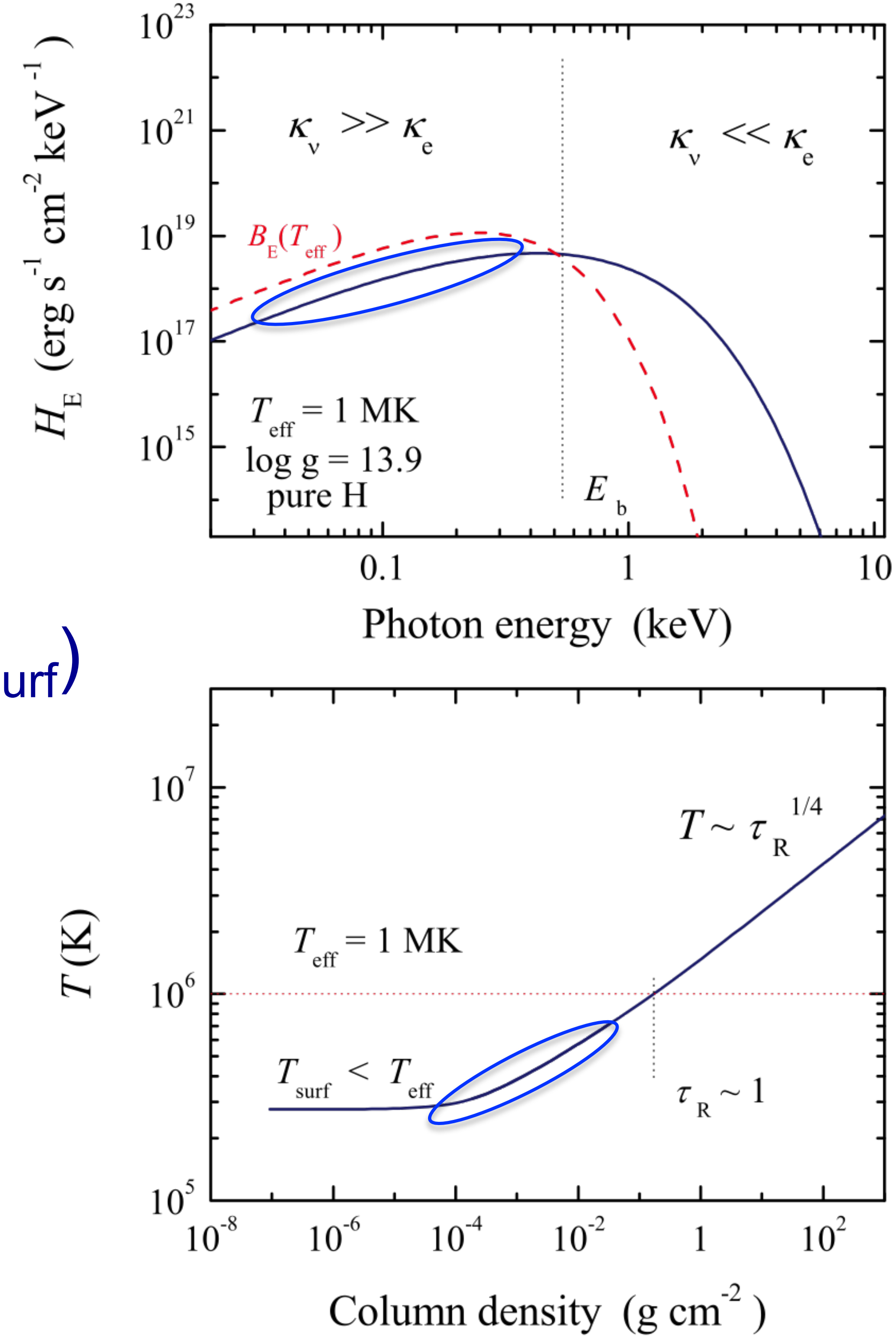
$$\tau_\nu^{eff} \approx \sqrt{k_\nu (k_\nu + \sigma_e)}\; m$$

Two qualitatively different spectral bands

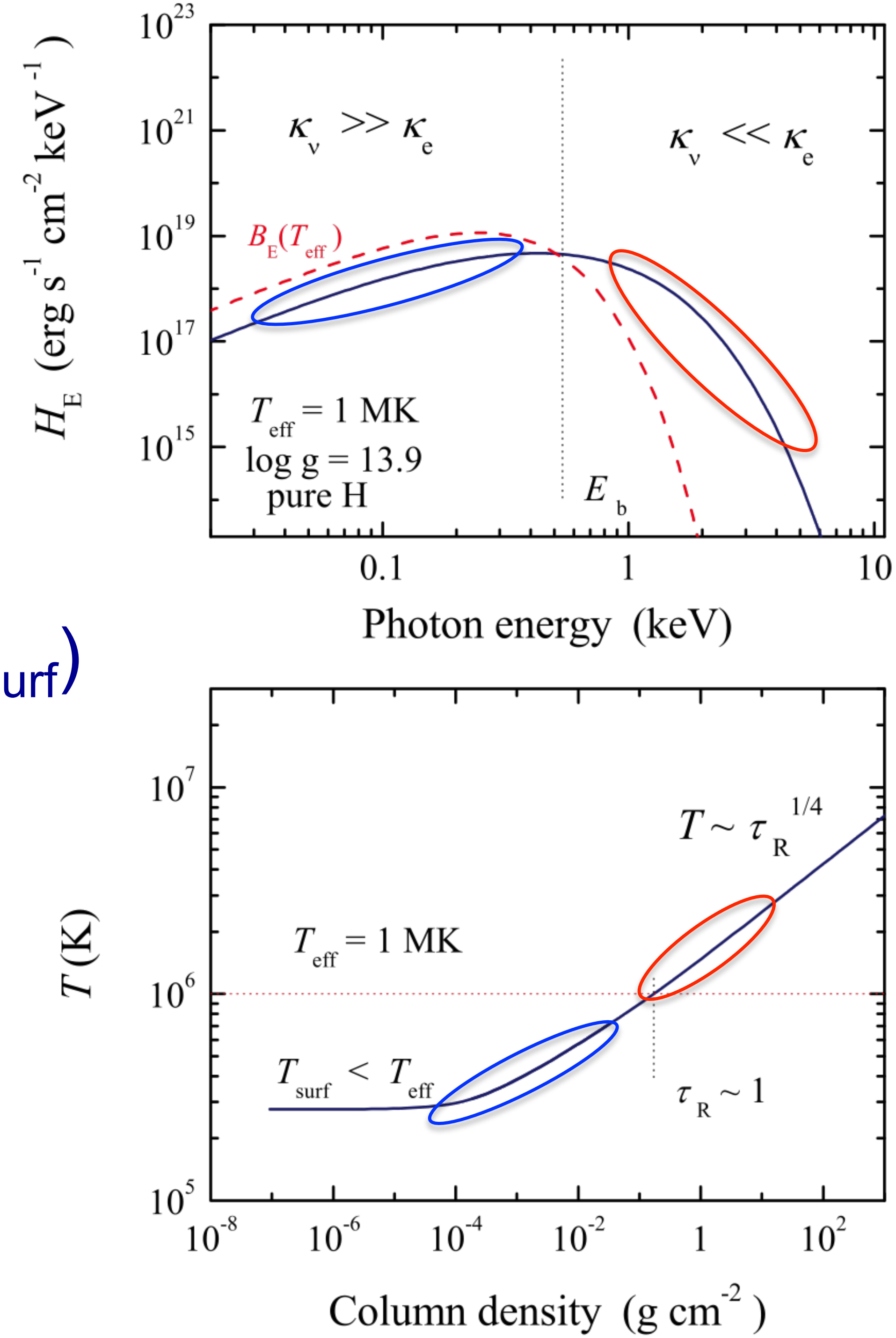


H_E (erg s^{-1} cm^{-2} keV^{-1})
$\kappa_\nu >> \kappa_e$
$\kappa_\nu << \kappa_e$
$B_E(T_{eff})$
T_{eff} = 1 MK
log g = 13.9
pure H
E_b
Photon energy (keV)
T (K)
$T \sim \tau_R^{1/4}$
T_{eff} = 1 MK
$T_{surf} < T_{eff}$
$\tau_R \sim 1$
Column density (g cm^{-2})

$F_{\nu} \approx B_{\nu}(T_{surf})$



$F_\nu \approx B_\nu(\mathrm{T_{surf}})$

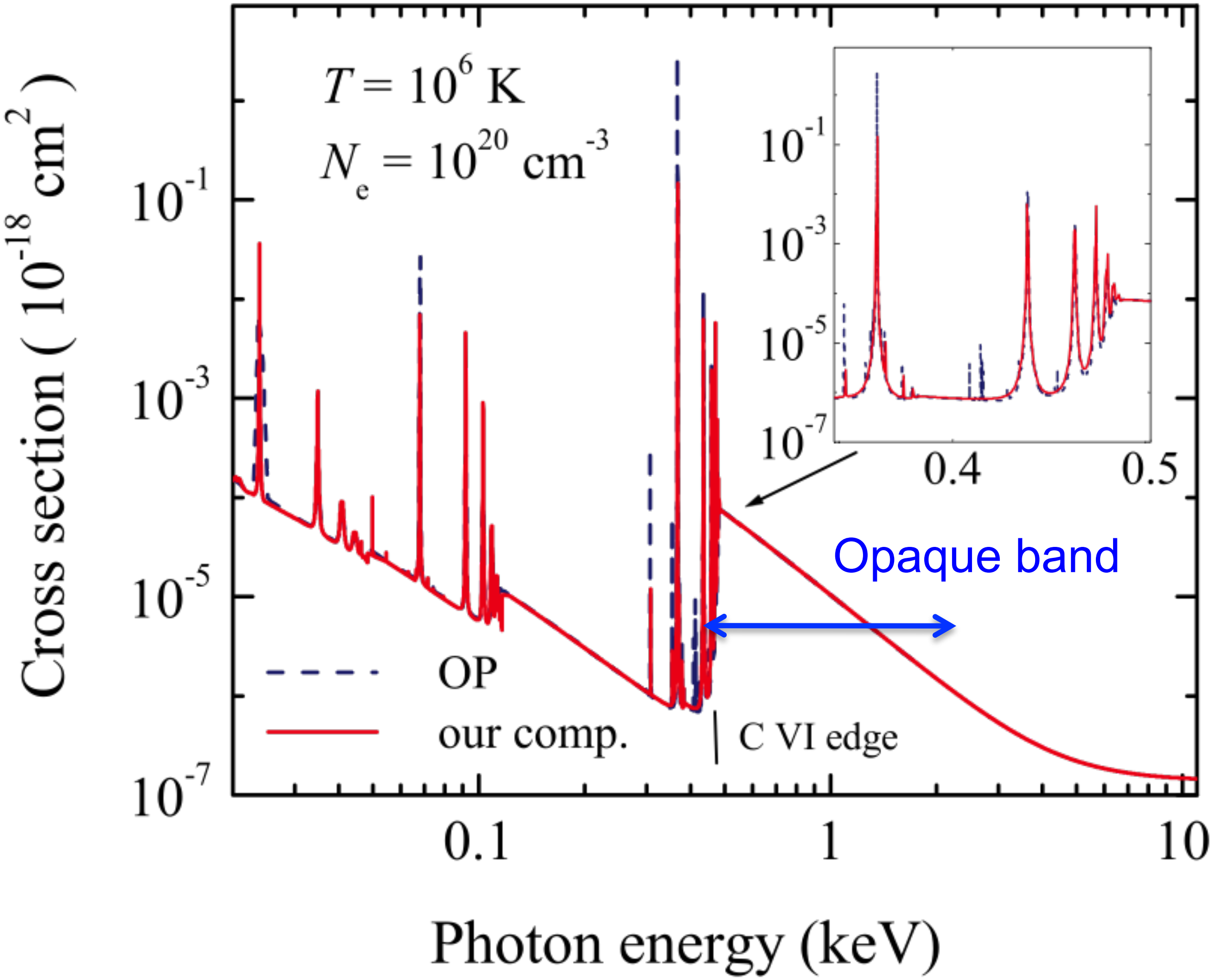


$F_\nu \approx w_\nu B_\nu(\mathrm{T > T_{eff}})$

$$w_\nu \approx \sqrt{\frac{k_\nu}{k_\nu + \sigma_e}}$$

Partially ionized plasma

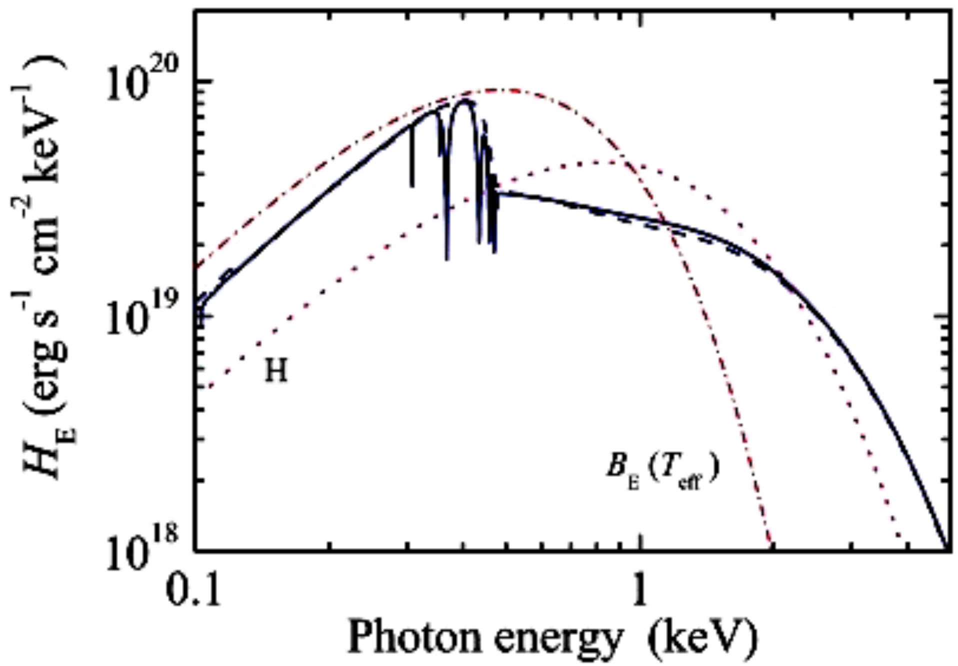
Computed opacities of pure carbon plasma

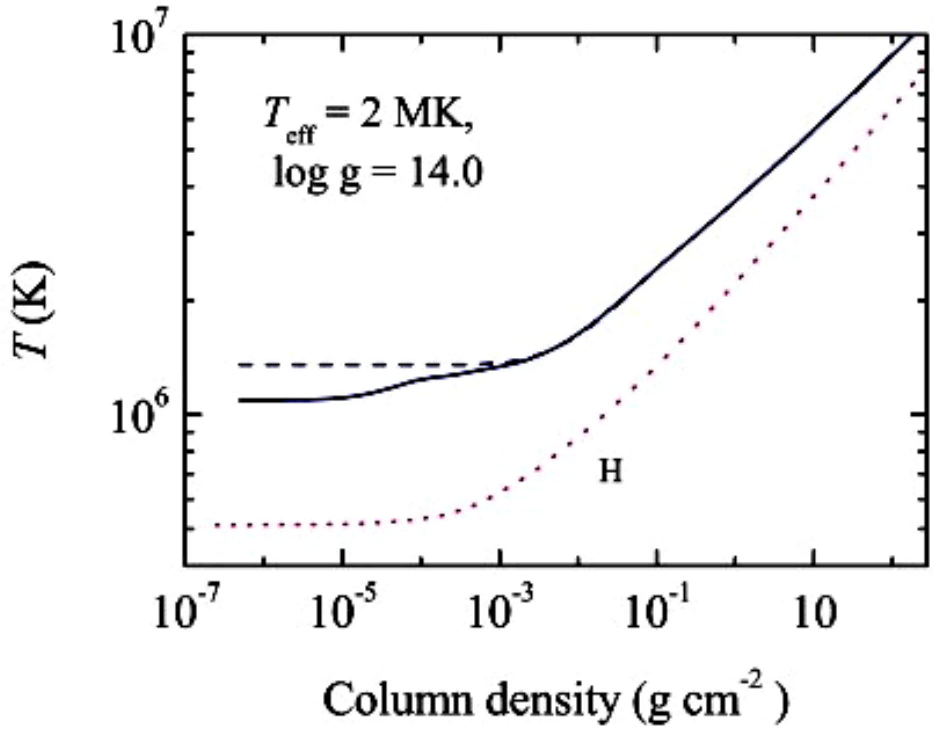


Dashed curve – Opacity Project computation (see Seaton et al. 1994)

Properties of carbon model atmospheres

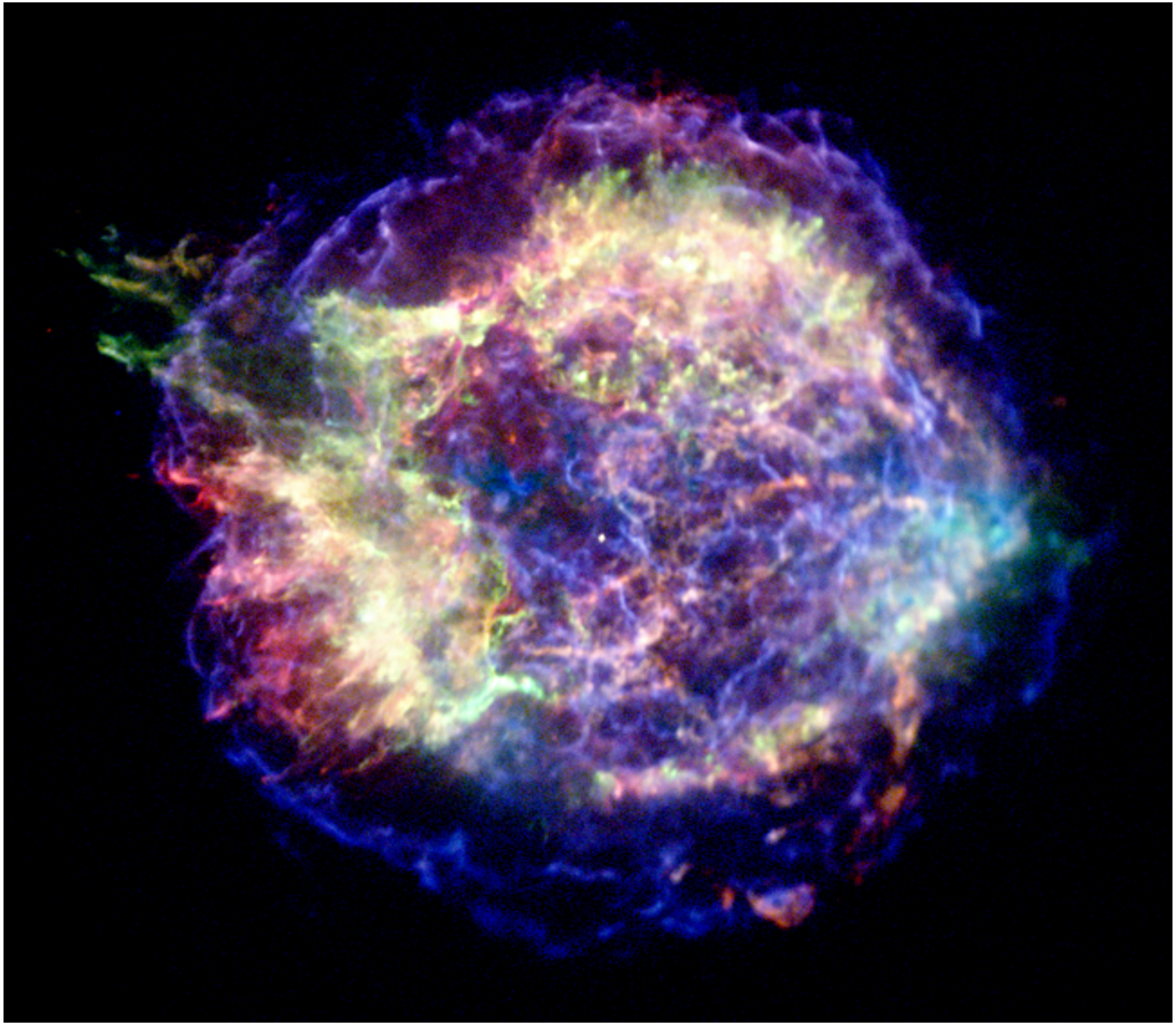
Spectra and temperature structures





Carbon model atmosphere spectra are harder and more diluted in comparison with hydrogen/helium models

Chandra image of Cas A



Problem: size of CCO in Cas A

THE COMPACT CENTRAL OBJECT IN CASSIOPEIA A: A NEUTRON STAR WITH HOT POLAR CAPS OR A BLACK HOLE?

ApJ, 2000, 531,L53

G. G. PAVLOV,[1] V. E. ZAVLIN,[2] B. ASCHENBACH,[2] J. TRÜMPER,[2] AND D. SANWAL[1]

Received 1999 November 19; accepted 2000 January 7; published 2000 February 4

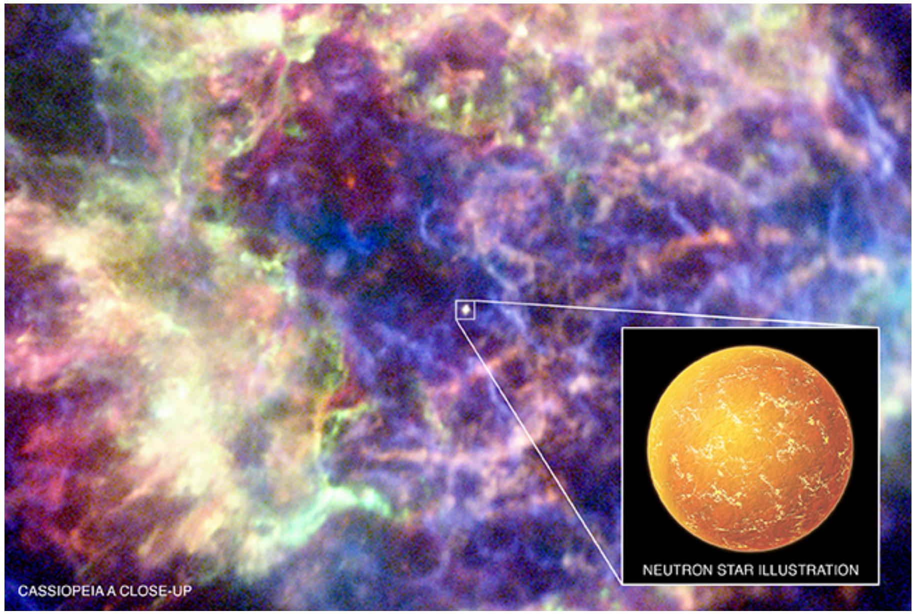
Blackbody: $T = 6\text{–}8$ MK, $R = 0.2\text{–}0.5$ km, and $L_{\rm bol} = (1.4\text{–}1.9) \times 10^{33}$ ergs s^{-1}.

Two component model atmospheres:

Hydrogen polar caps: $T_{\rm pc}^{\infty} = 2.8\ \mathrm{MK},\ R_{\rm pc} = 1\ \mathrm{km}$

Cooler iron surface : $T_s^{\infty} = 1.7\ \mathrm{MK},\ R = 10\ \mathrm{km}$

NO PULSATION FOUND



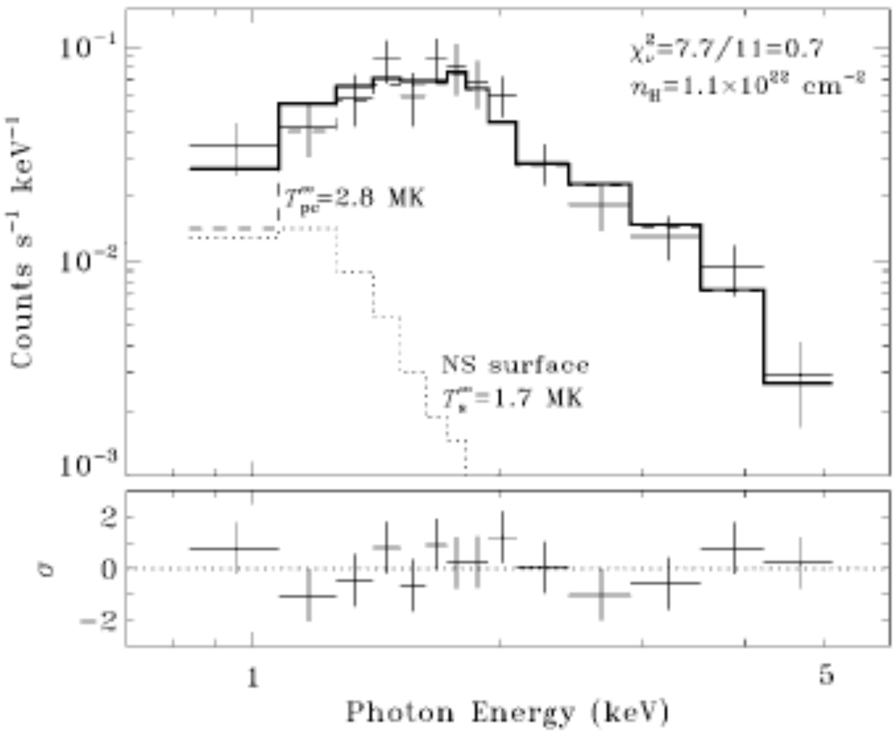


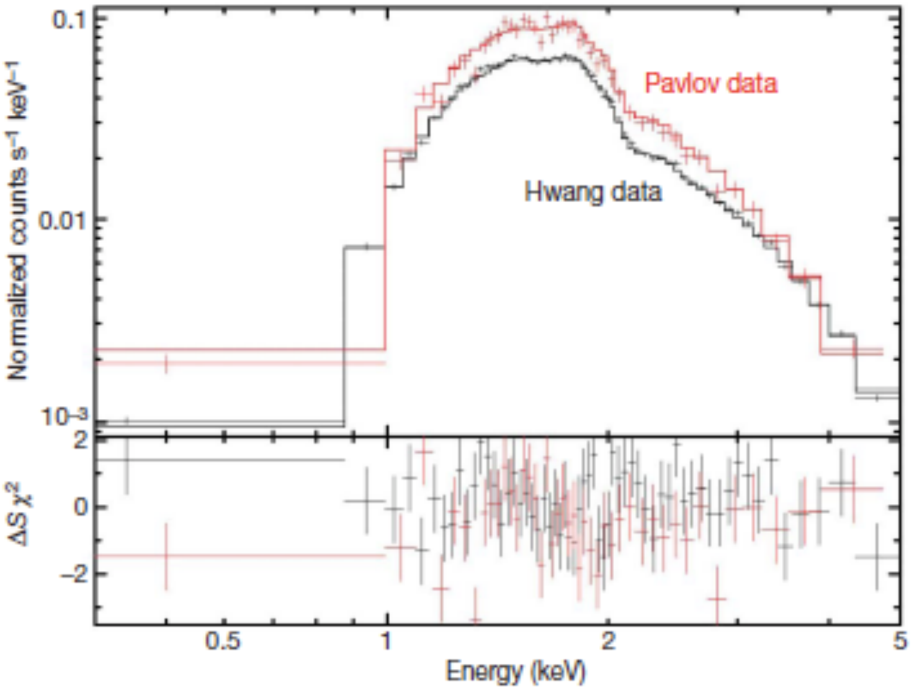
FIG. 1.—*Chandra* ACIS-S3 count rate spectrum from the compact central

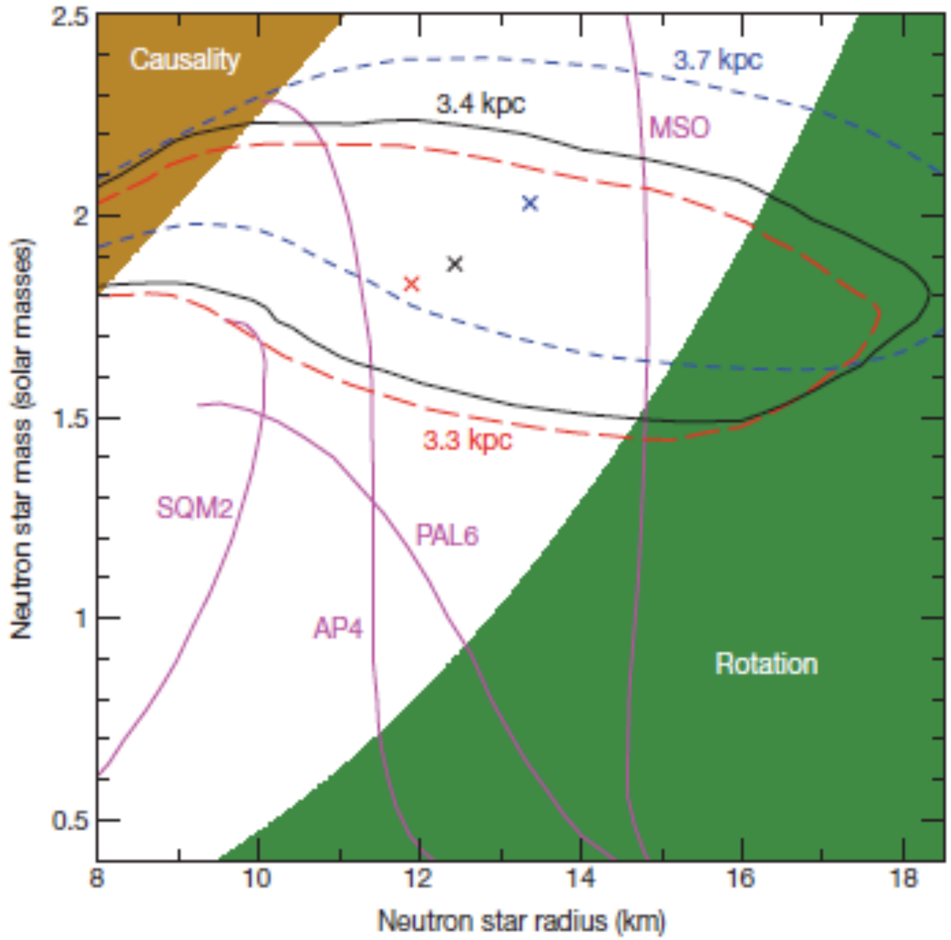
Possible solution: size of CCO in Cas A

A neutron star with a carbon atmosphere in the Cassiopeia A supernova remnant

Wynn C. G. Ho[1] & Craig O. Heinke[2]

Nature, 2009, 462, 71



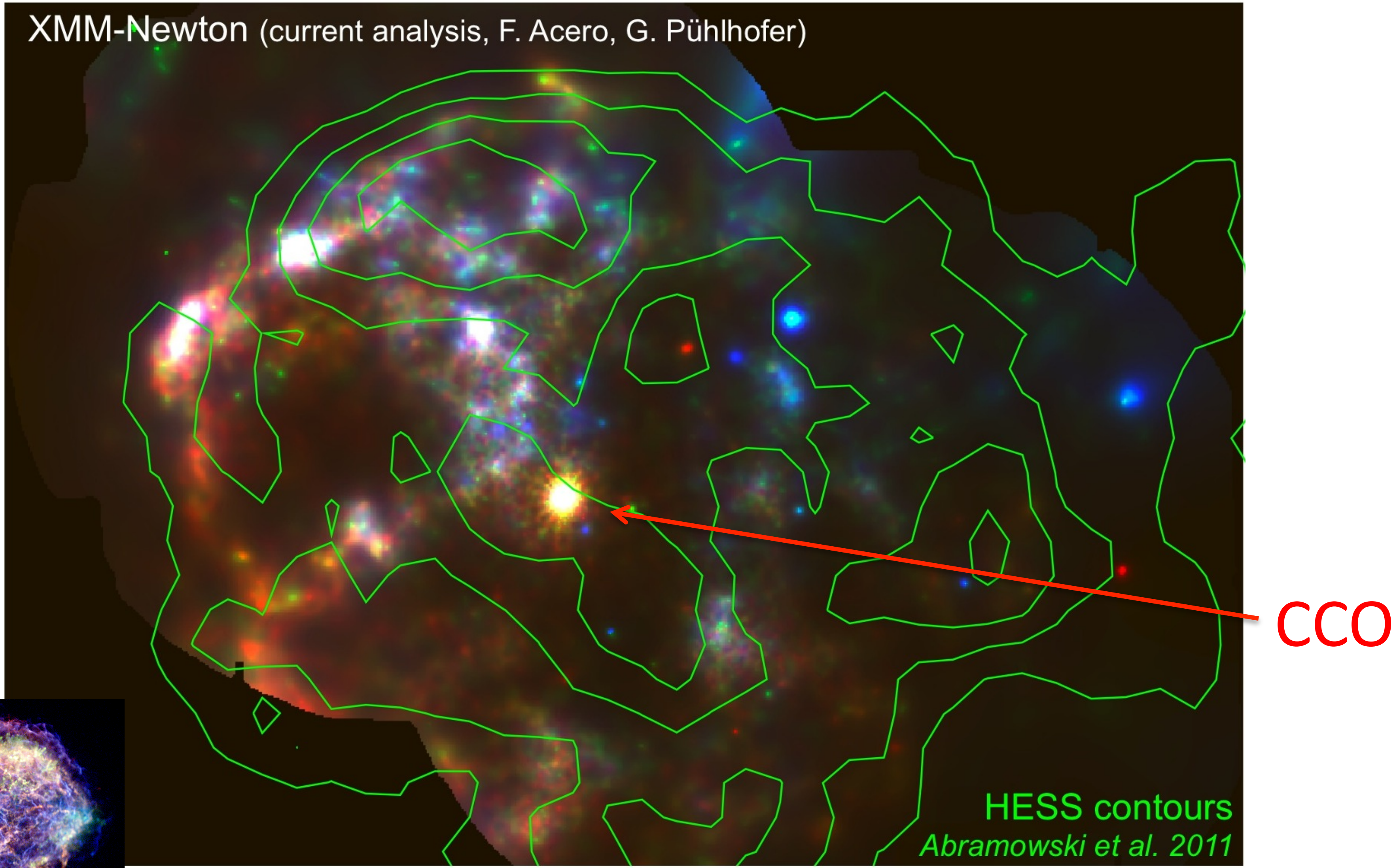


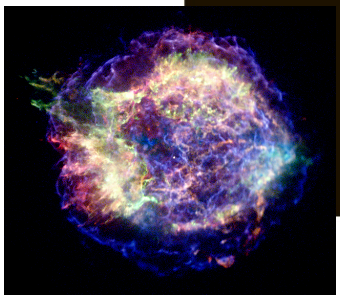
CCO in HESS J1731-347

A&A, 2011, 531, A81

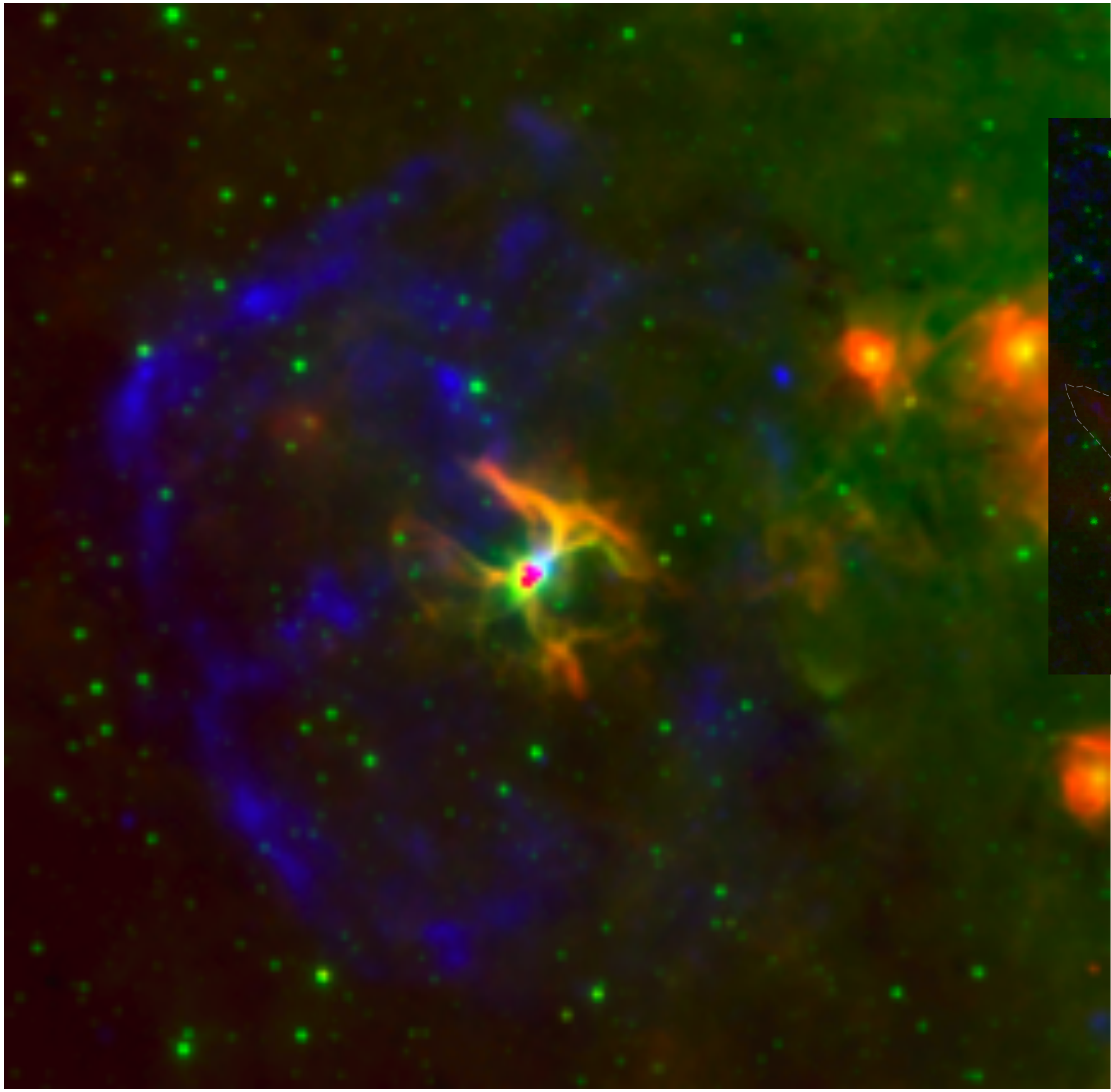
A new SNR with TeV shell-type morphology: HESS J1731-347

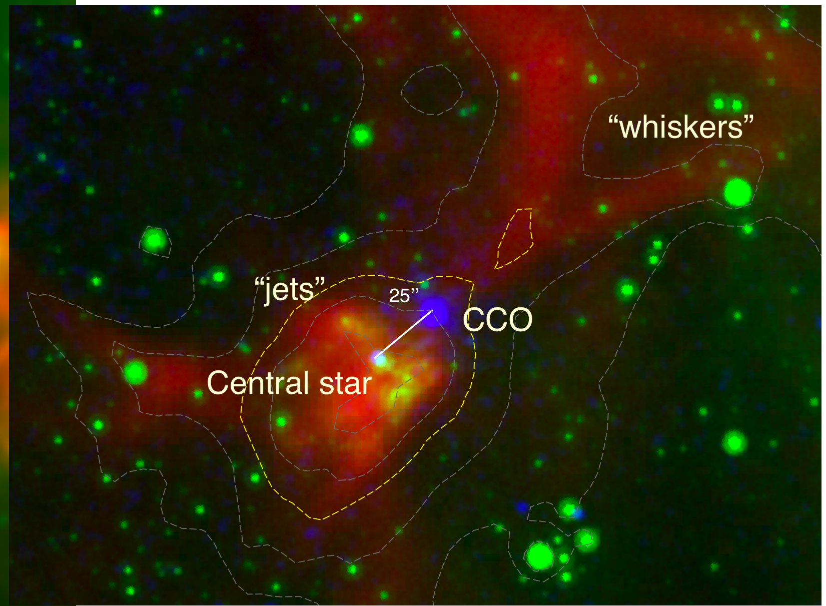
HESS Collaboration, A. Abramowski[1], F. Acero[2], F. Aharonian[3,4,5], A. G. Akhperjanian[6,5], G. Anton[7], A. Balzer[7],





CCO in HESS J1731-347





Green - 8 µm, Spitzer

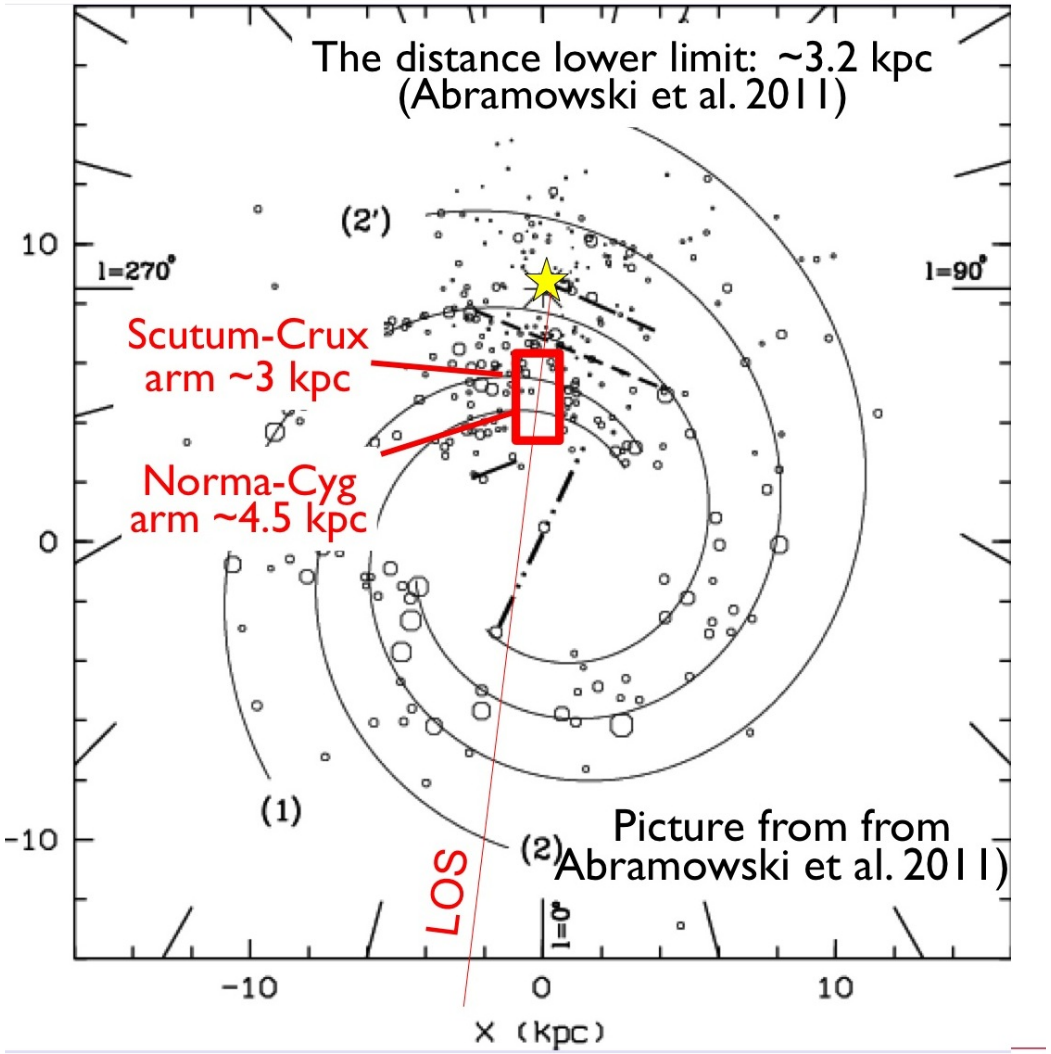
Figures from
Doroshenko V. + 2015

Blue: XMM-Newton contours (0.2-10 keV), Red –70 µm, Green - 24 µm, Spitzer

CCO in HESS J1731-347 – twin of CCO in Cas A

A new SNR with TeV shell-type morphology: HESS J1731-347

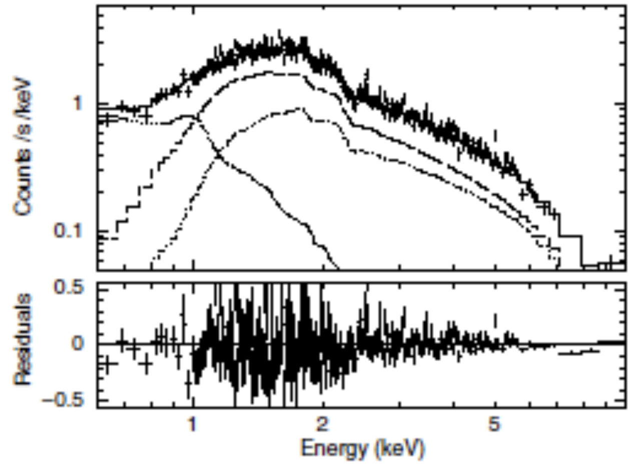
HESS Collaboration, A. Abramowski[1], F. Acero[2], F. Aharonian[3,4,5], A. G. Akhperjanian[6,5], G. Anton[7], A. Balzer[7],



NO PULSATION FOUND

PF < 8.3% up to P > 0.2ms

CCO spectrum (XMM-Newton)



Blackbody fit:

kT ≈ 0.5 keV (T ≈ 6 MK),

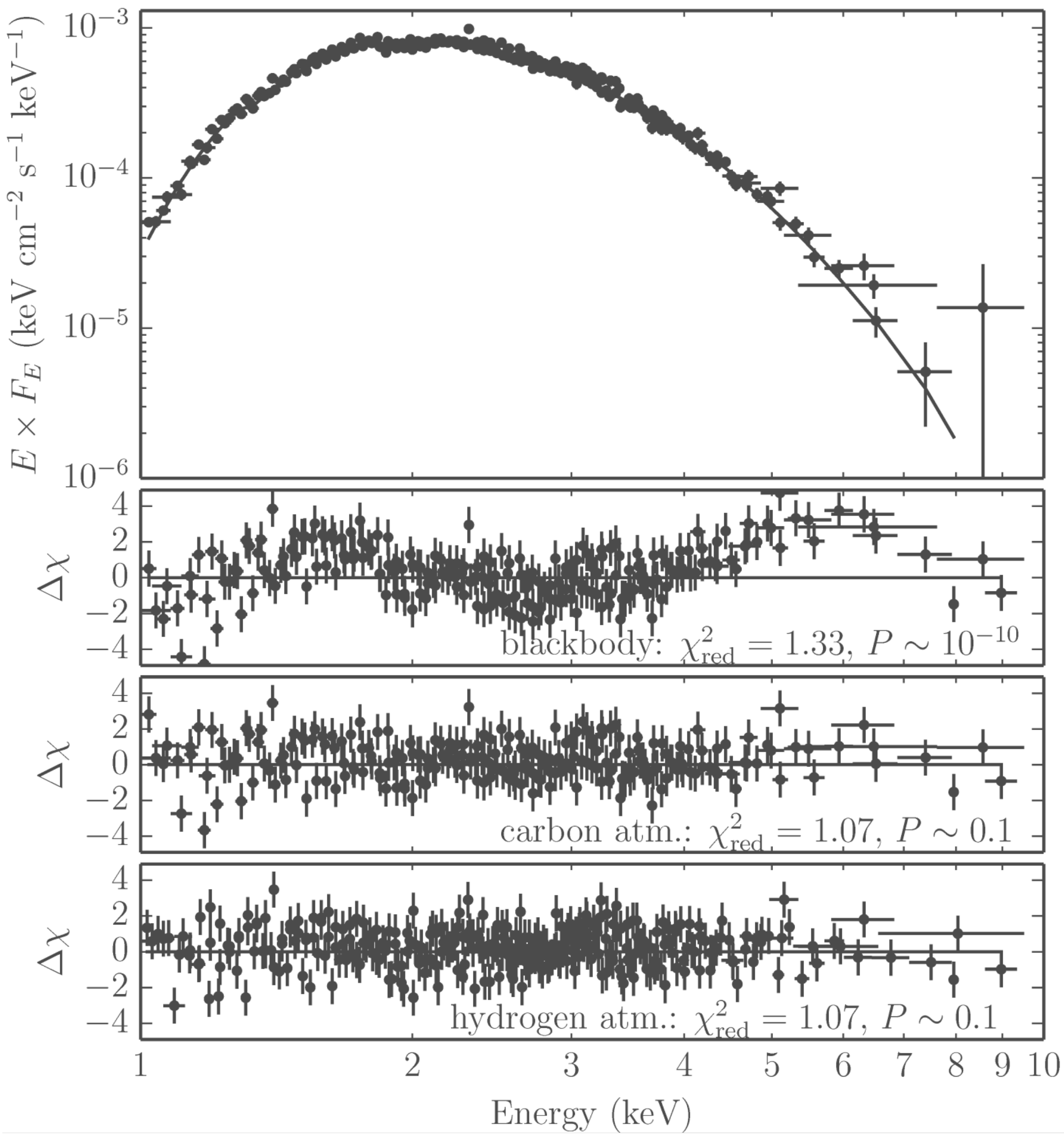
R ≈ 1 km at D=3.2 kpc

D(R=10km) = 30 kpc !!!

Therefore, we need carbon model atmospheres!

Observed CCO spectrum with the best fitting model spectra

Observation: XMM-Newton, 2007,2013 ~ 100 ks, PI: Gerd Pühlhofer



$$\chi^2_{d.o.f.} = 1.07$$

$$M = 1.55^{+0.28}_{-0.24}\ M_\odot$$

$$R = 12.4^{+0.9}_{-2.2}\ km$$

$$T_\infty = 1.78^{+0.04}_{-0.02}\ MK$$

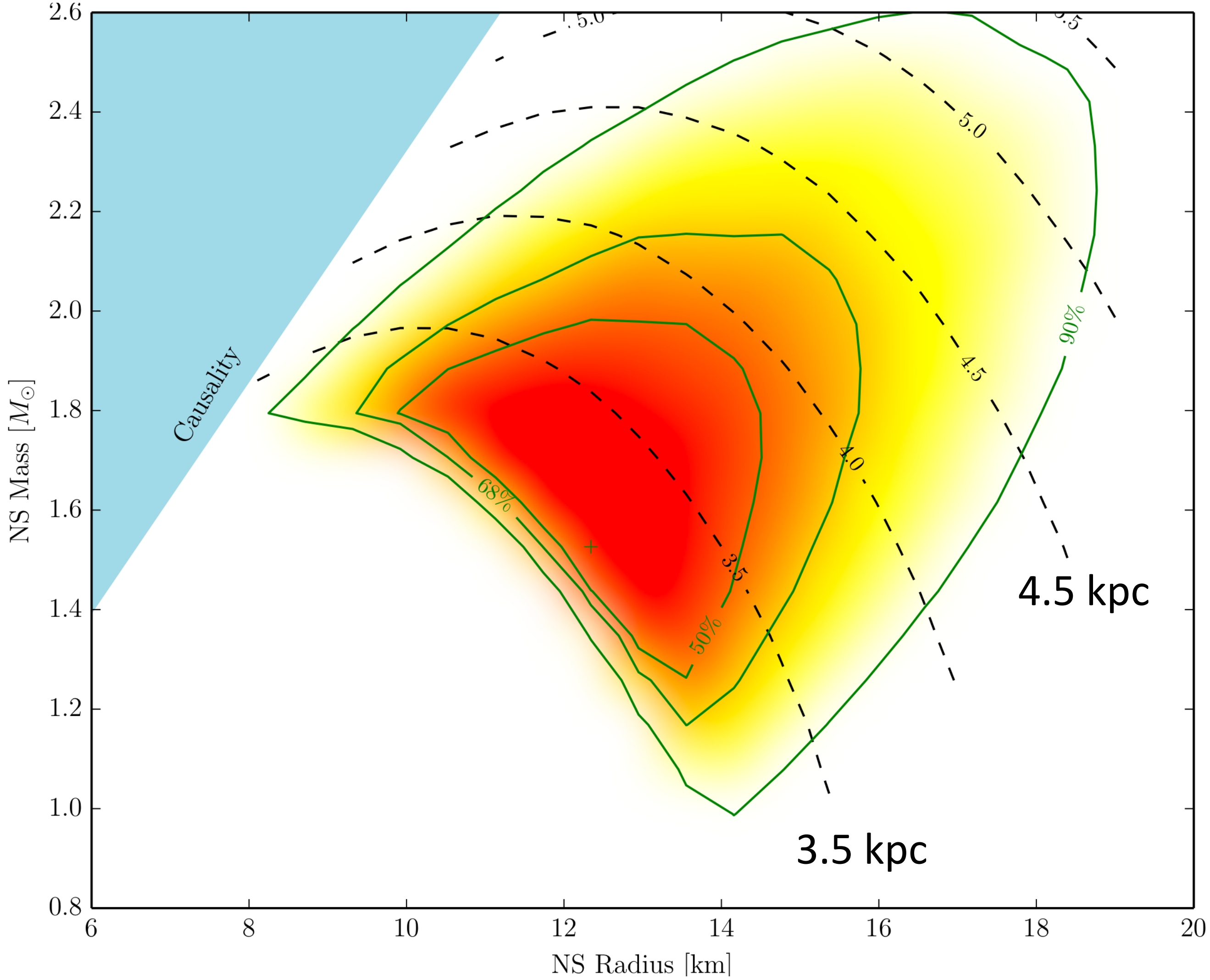
$$n_H = 2 \pm 0.03\ 10^{22}\ cm^{-2}$$

at d = 3.2 kpc

From Klochkov, SV,+ 2015

Best fit and contours in *M*-*R* plane

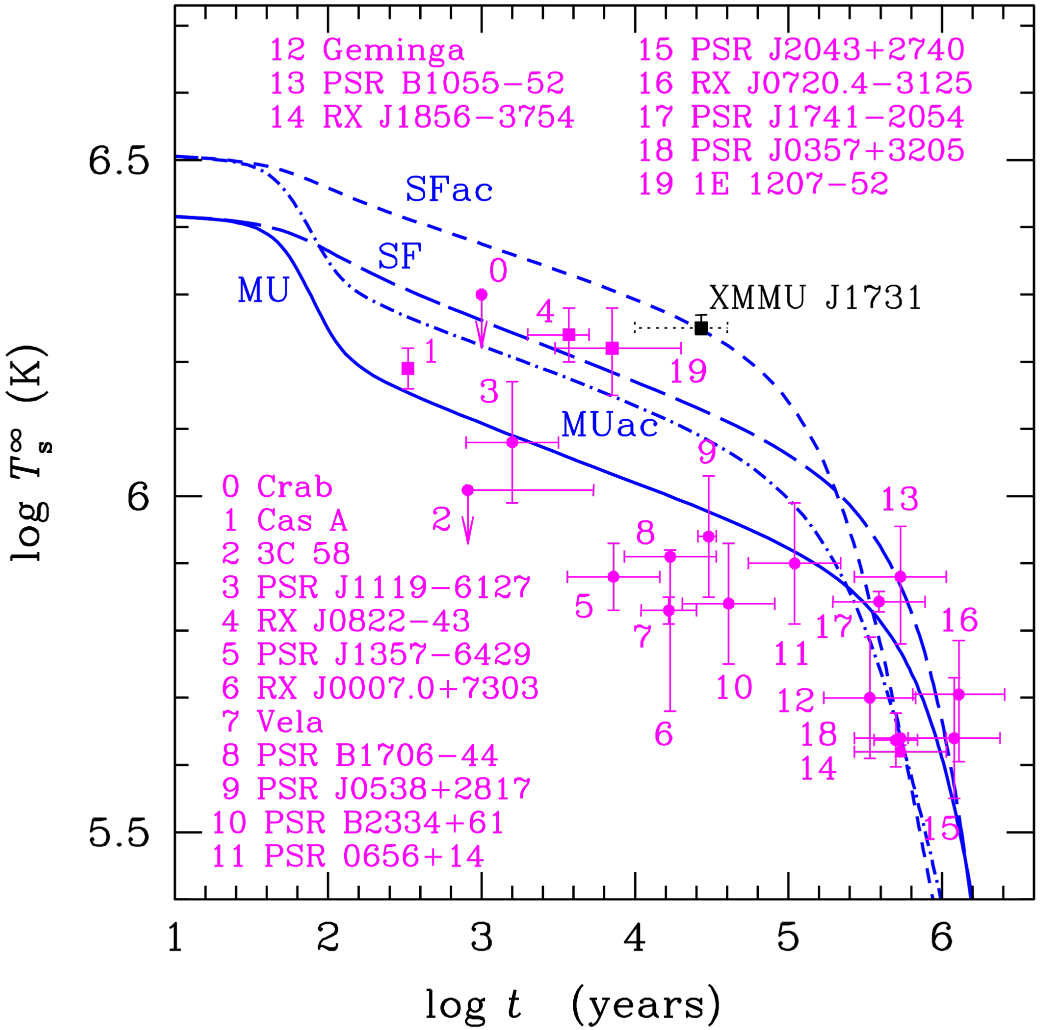
Contours correspond to 50%, 68%, and 90% probability



From Klochkov, SV,+ 2015

Cooling of neutron stars

Due to neutrino emission from the core (DUrca & MUrca)
Superfluidity (both, *p* or *n*) suppress cooling rate



MU – without superfluidity,
iron envelope,
modified URCA

MUac – without superfluidity,
carbon envelope $\Delta M = 10^{-8}\ M_\odot$,
modified URCA

SF – strong proton superfluidity,
iron envelope,
neutron-neutron collisions

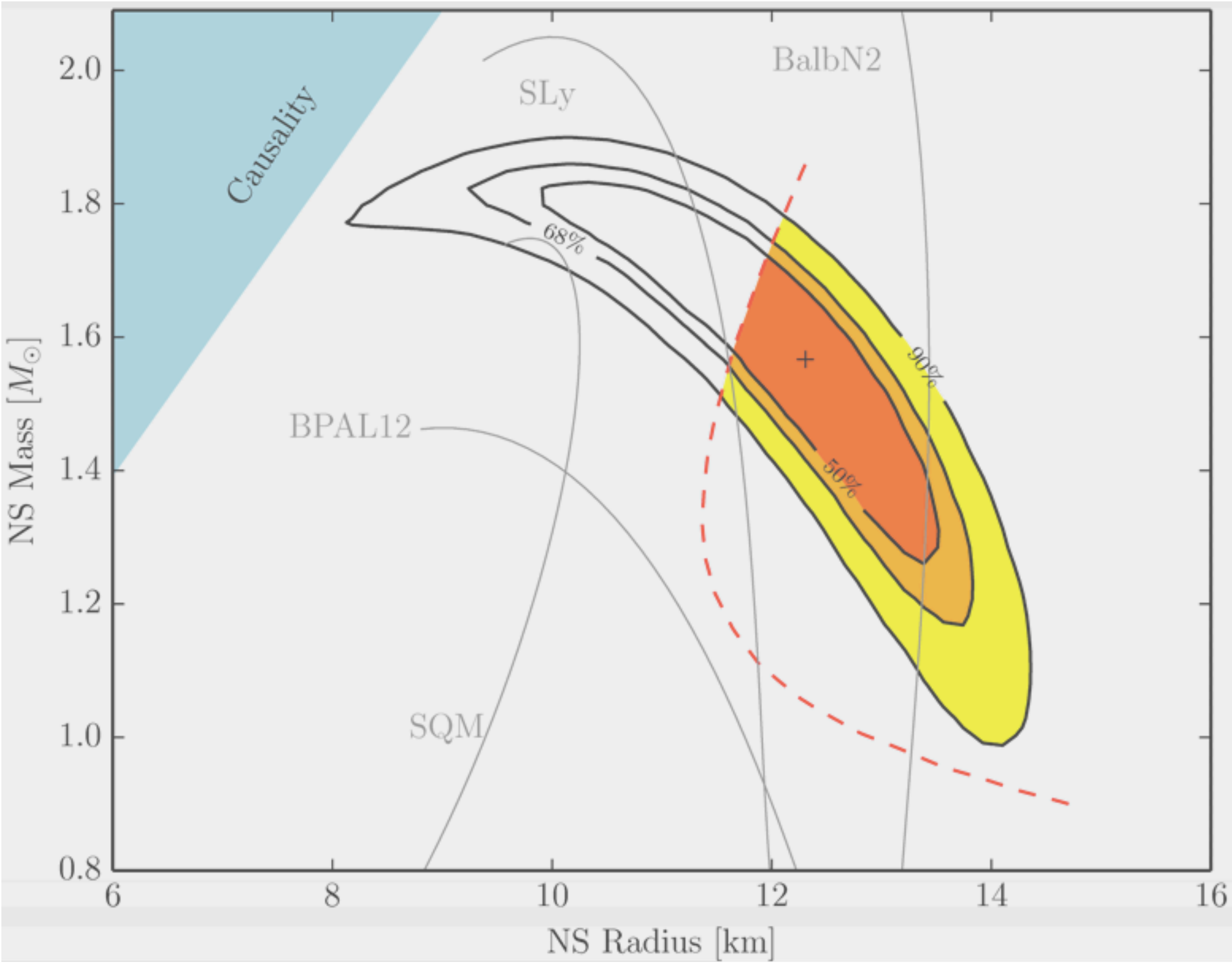
SFac – strong proton superfluidity,
carbon envelope $\Delta M = 10^{-8}\ M_\odot$,
neutron-neutron collisions

$M_{NS} = 1.5\ M_\odot$, R = 12 km, APR EOS

From Klochkov, SV,+ 2015

Best fit and contours in *M*-*R* plane

Contours correspond to 50%, 68%, and 90% probability

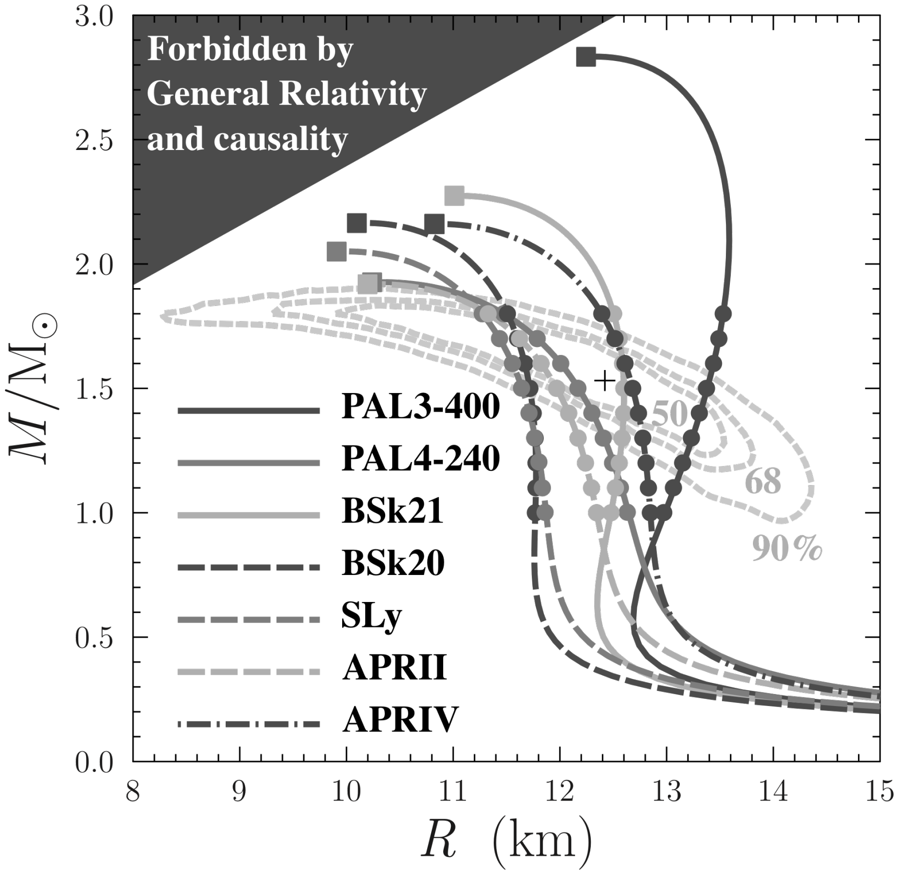


For fixed d = 3.2 kpc

From Klochkov, SV,+ 2015

Cooling of neutron stars

Approximations



$$\frac{dT}{dt} = -l(T) = -\frac{L_\nu(T)}{C(T)} = -qT_9^7$$

$$T_9 = \left(\frac{6qt}{10^9 K}\right)^{-1/6}$$

$T_9 = T / 10^9$ K – is redshifted core temperature

$$q(M,R) = f_{lp} q_{MU}(M,R) + q_{SF}(M,R)$$

$$q_{SF} \approx (0.01 - 0.02)\, q_{MU}$$

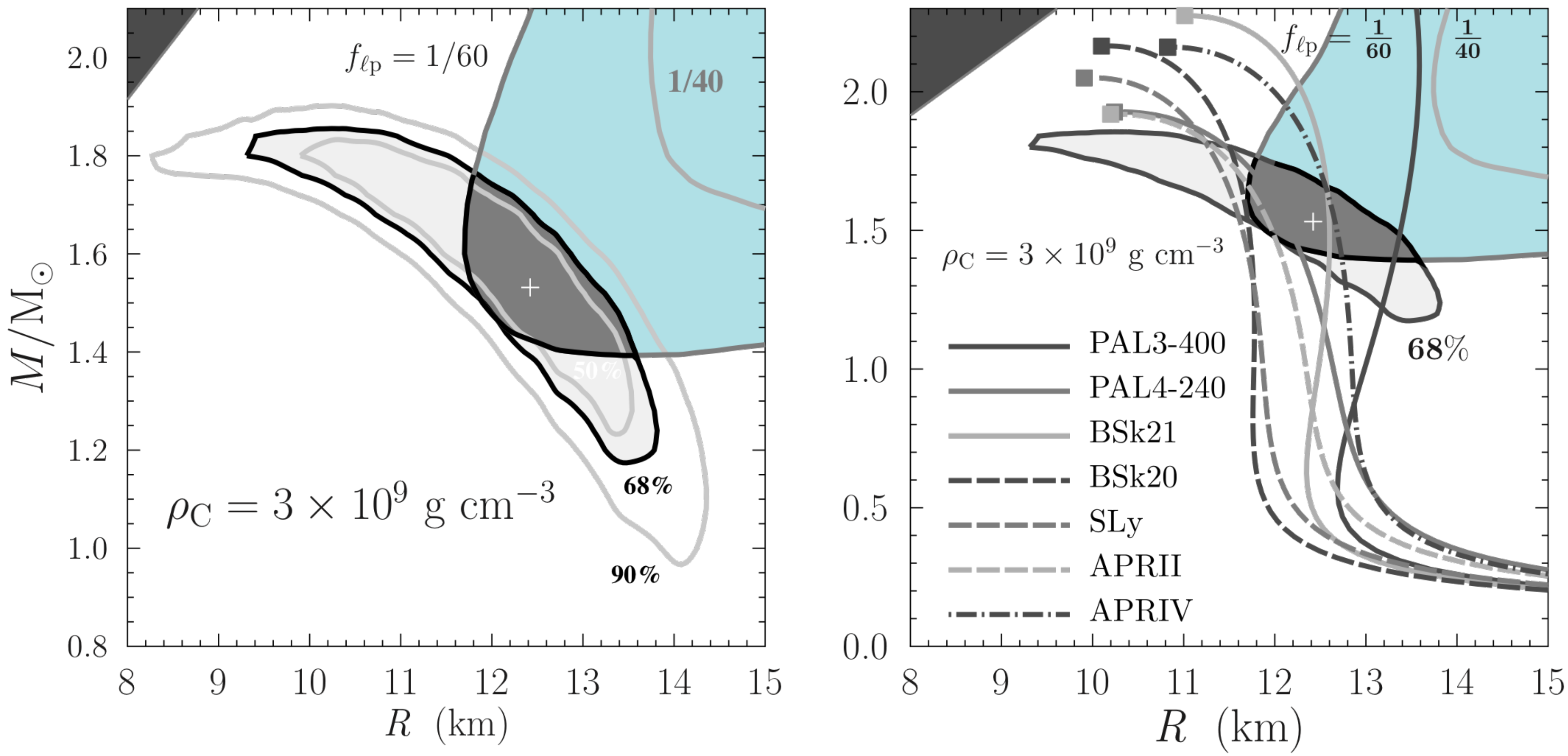
q_{MU} and q_{SF} were computed for some NS models and analytical approximations were derived

Core temperature – surface temperature connection $T_9 - T_{surf}$ depends on envelope thickness and its chemical composition (taken from Yakovlev + 2011)

Additional limitation from cooling

Fixed distance (3.2 kpc) and age (27 kyr)

Fixed carbon density ρ_C at the bottom of envelope instead of total envelope mass



$$l(T) = \frac{L_\nu(T)}{C(T)} \approx (f_{lp} q_{MU} + q_{SF}) T_9^7$$

- neutrino cooling function, MUrca is not completely suppressed ($f_{lp} > 0$)

From Ofengeim, Kaminker, Klochkov, SV, Yakovlev 2015

Conclusions

The method of model atmospheres is a very powerful tool.

CCO in SNR HESS J1731-347 is a twin of Cas A CCO; their spectra can be interpreted as emitted from carbon neutron star atmospheres.

CCO in SNR HESS J1731-347 is too hot for its age. This fact can be explained with a significant proton superfluidity in the core and a thick carbon envelope above the crust.

-

Back to CCO in Cas A

NEW CONSTRAINTS ON THE COOLING OF THE CENTRAL COMPACT OBJECT IN CAS A

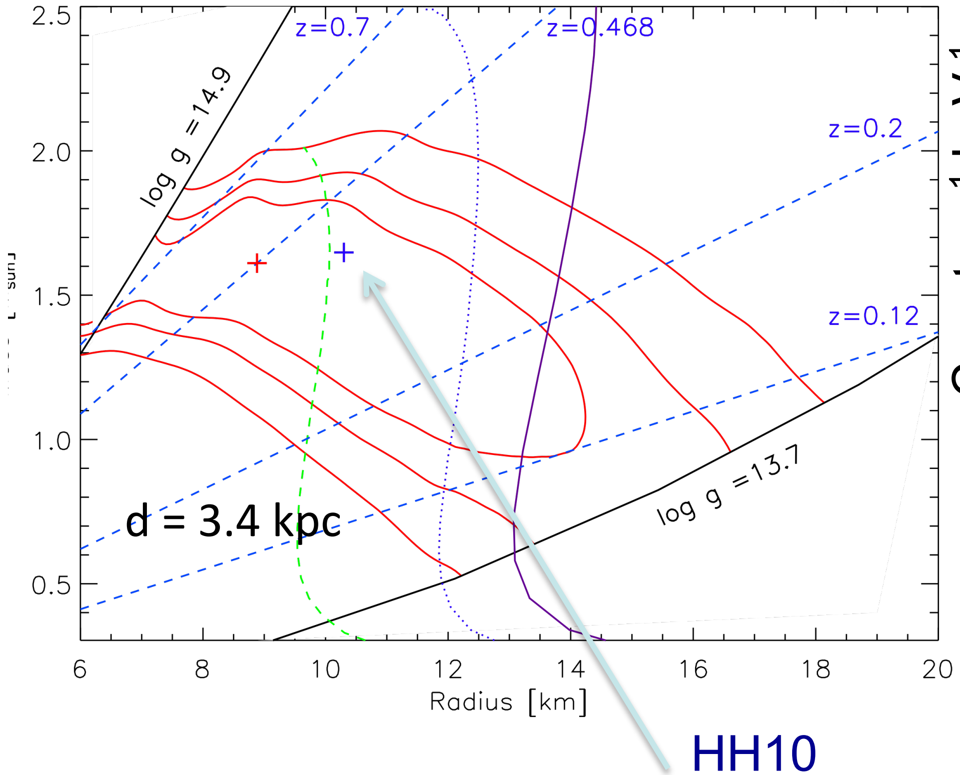
B. Posselt
Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Lab,University Park, PA 16802, USA

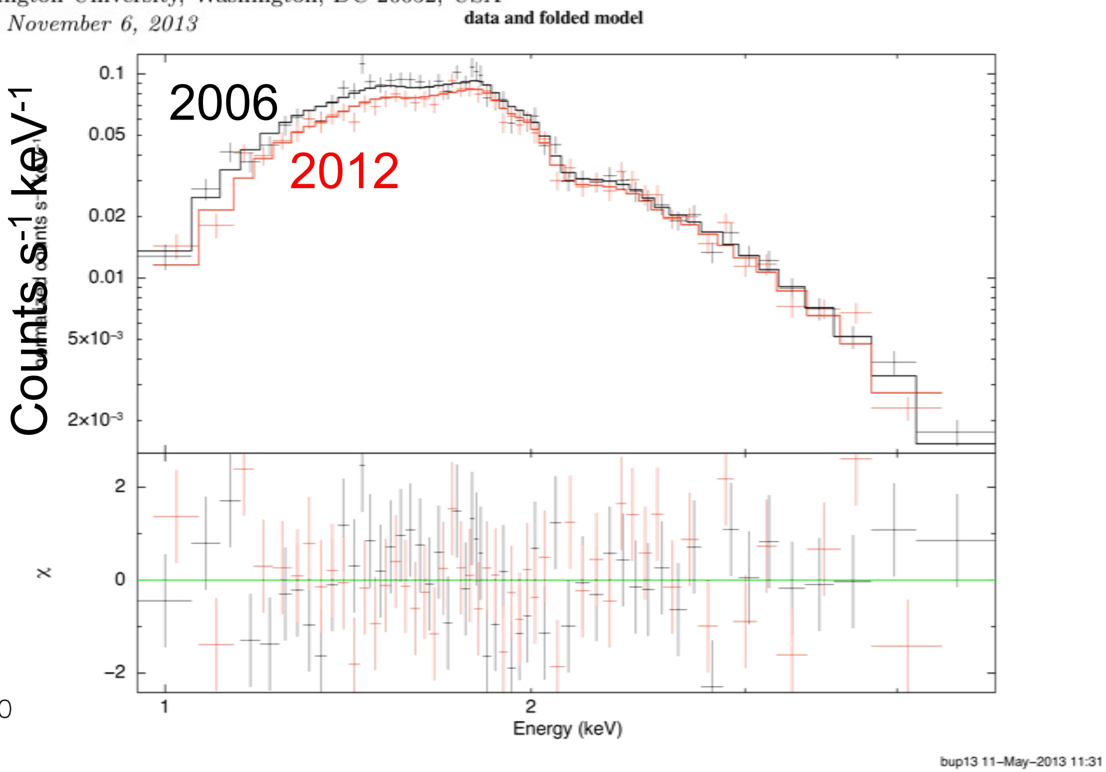
G. G. Pavlov
Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Lab,University Park, PA 16802, USA

V. Suleimanov[1]
Institut für Astronomie und Astrophysik Tübingen, Sand 1, 72076 Tübingen, Germany

O. Kargaltsev
Department of Physics, The George Washington University, Washington, DC 20052, USA

Draft version November 6, 2013



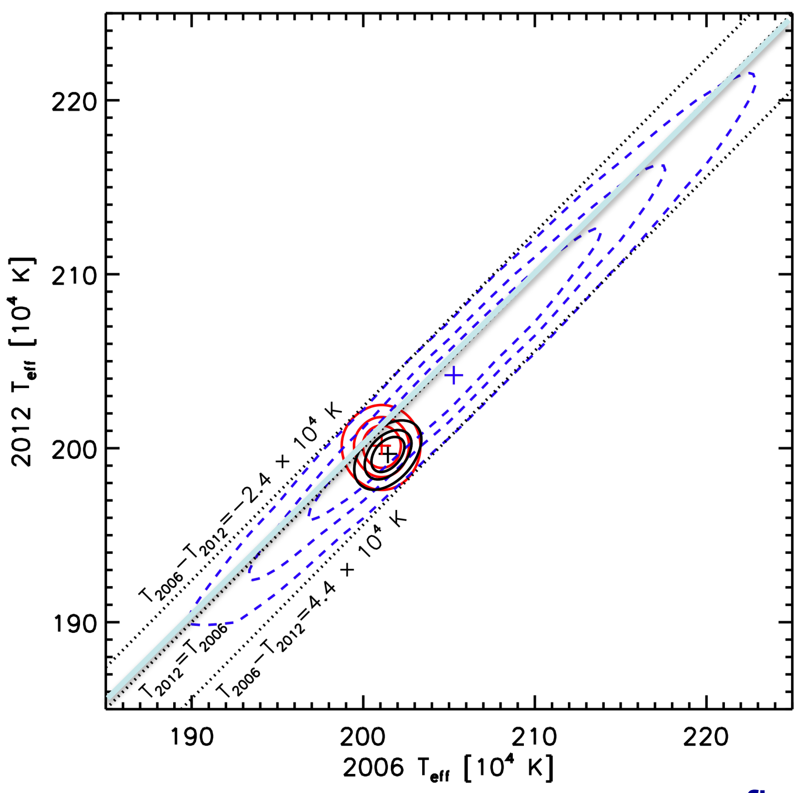


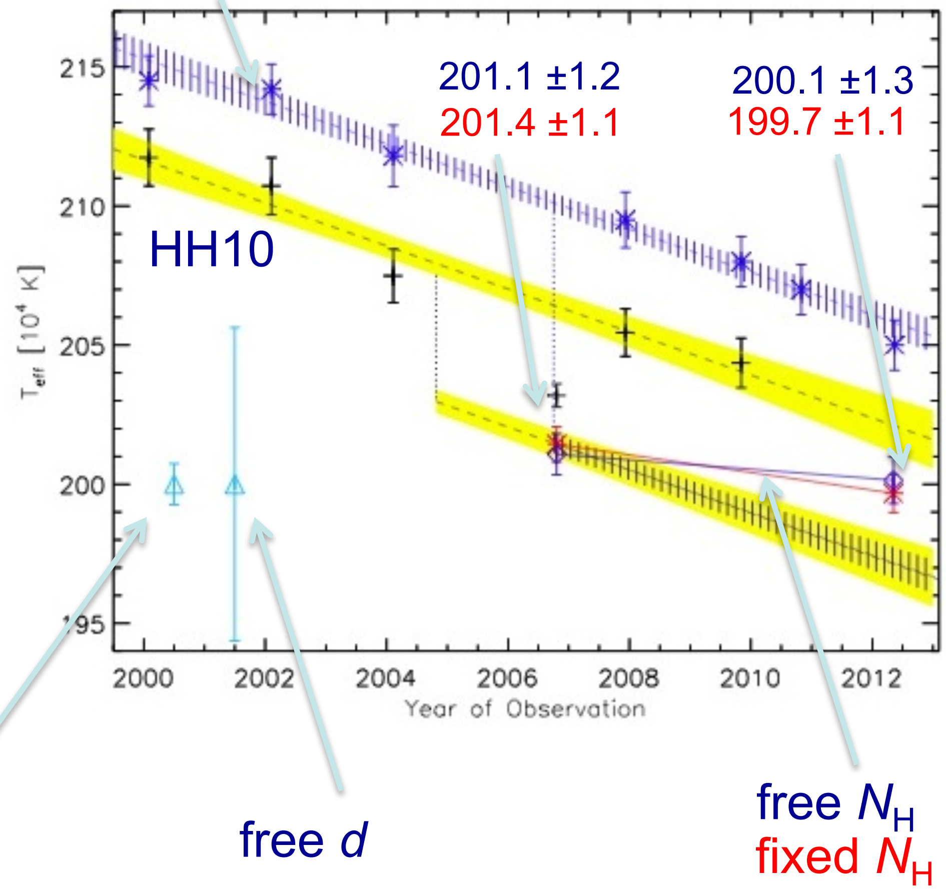
Difference mainly due to detector degradation

Contours correspond to 68%, 90%, and 99% probability

Back to CCO in Cas A

CCO in Cas A is cooling much slower than Heinke & Ho (2010) (and Elshamouty et al. 2013) found. The time dependence of temperature is compatible with a constant temperature.





Grid of pure C model atmospheres

T_{eff} from 1 to 4 MK with the step 0.05 MK (61 values)
log g from 13.7 to 14.9 with the step 0.15 (9 values)
alltogether 549 models