

Observational Constraints on the Physical Properties of Neutron Stars

with strong emphasis on X-ray observations

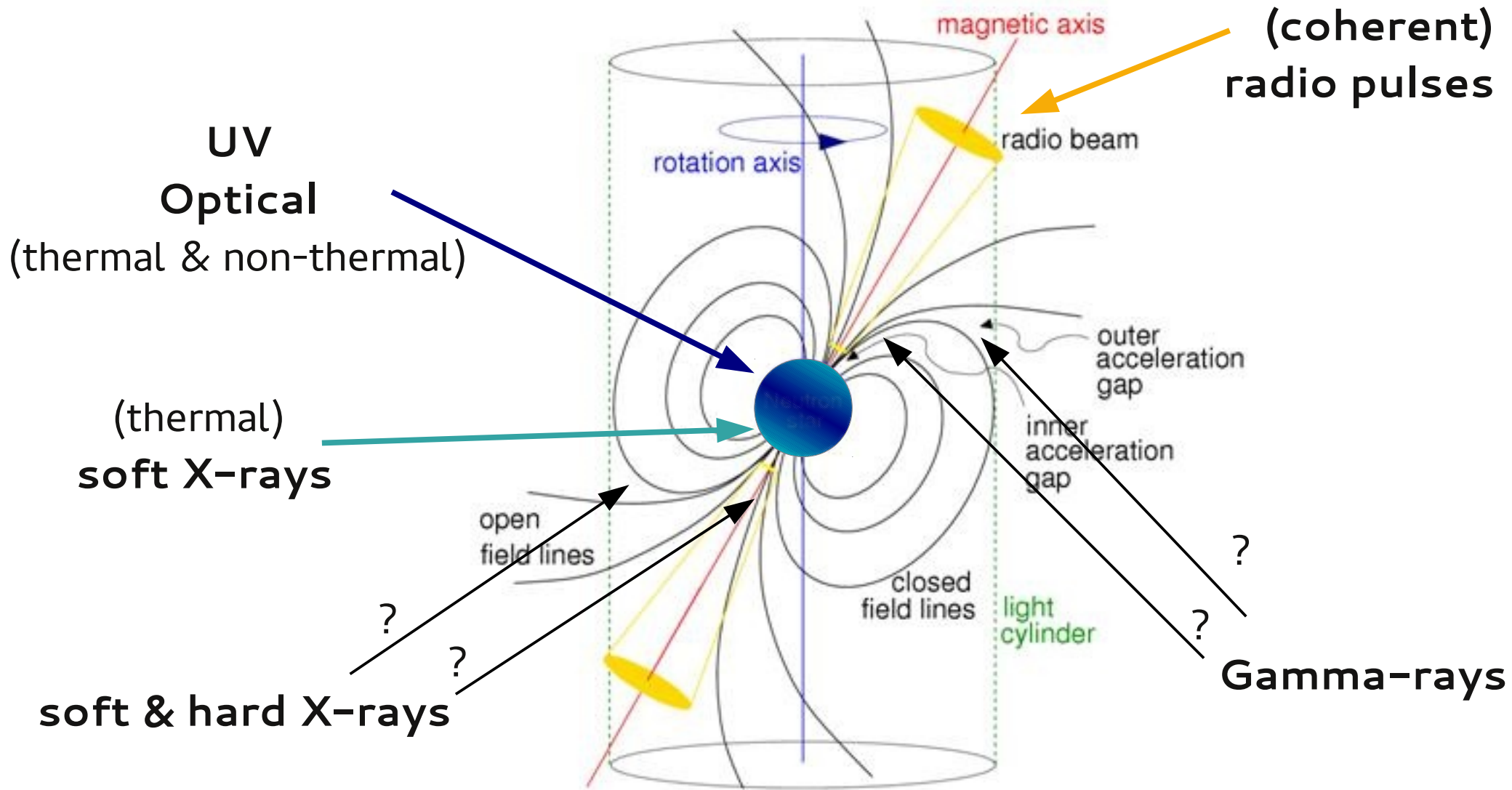
Bettina Posselt
Pennsylvania State University



Outline

- NS emission and physical NS properties
- Constraints from X-ray observations
 - NS surface composition
 - NS temperatures
 - NS radii
 - NS geometry

Emission from an Isolated Neutron Star



Soft X-rays: : 0.1 keV bis 1 keV Hard X-rays : > 1keV (1 eV = 1.602 · 10⁻¹⁹ J)

What do we measure ?

Direct measurements:

- spin-down, pulses, phase lags,
- spectral shapes, phase-resolved spectra
- proper motions, distances, transverse velocities

Indirect measurements:

- temperature (distributions) & surface compositions
- magnetic fields
- mass & radius
- proportions of radiation and particle energy loss
- axis orientations
- distinct properties of non-thermal emission mechanisms
- precession

Constraining Neutron Star Surface Compositions

In order to learn about:

- NS structure
- via radius estimates also EoS
- NS evolution models

Strongly related to observed

- thermal emission properties

Surface Compositions

Is the surface of a NS solid ?

- born with or without an atmosphere?

What type of atmosphere do we expect ?

- hydrogen, helium, carbon after accretion (& bursts) ?
- partly or fully ionized ?
- heavier elements from fallback material ?

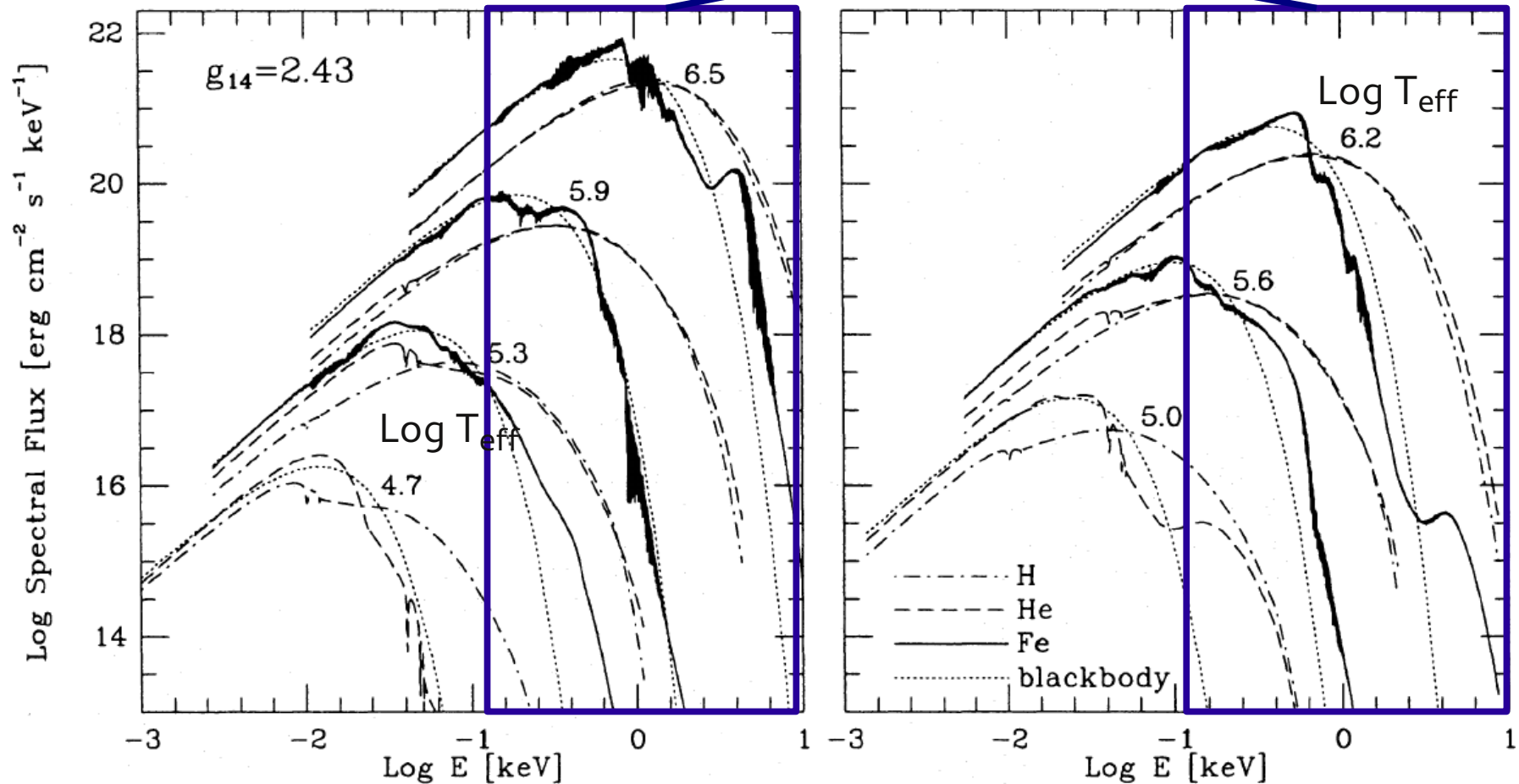
What are the effects of the strong magnetic fields ?

Even if the atmosphere is just \sim cm thick, it influences the observed NS spectra !

Atmosphere models for low magnetic fields

Low magnetic field $B < 10^8 - 10^{10}$ G

Chandra, XMM-Newton X-ray spectral ranges

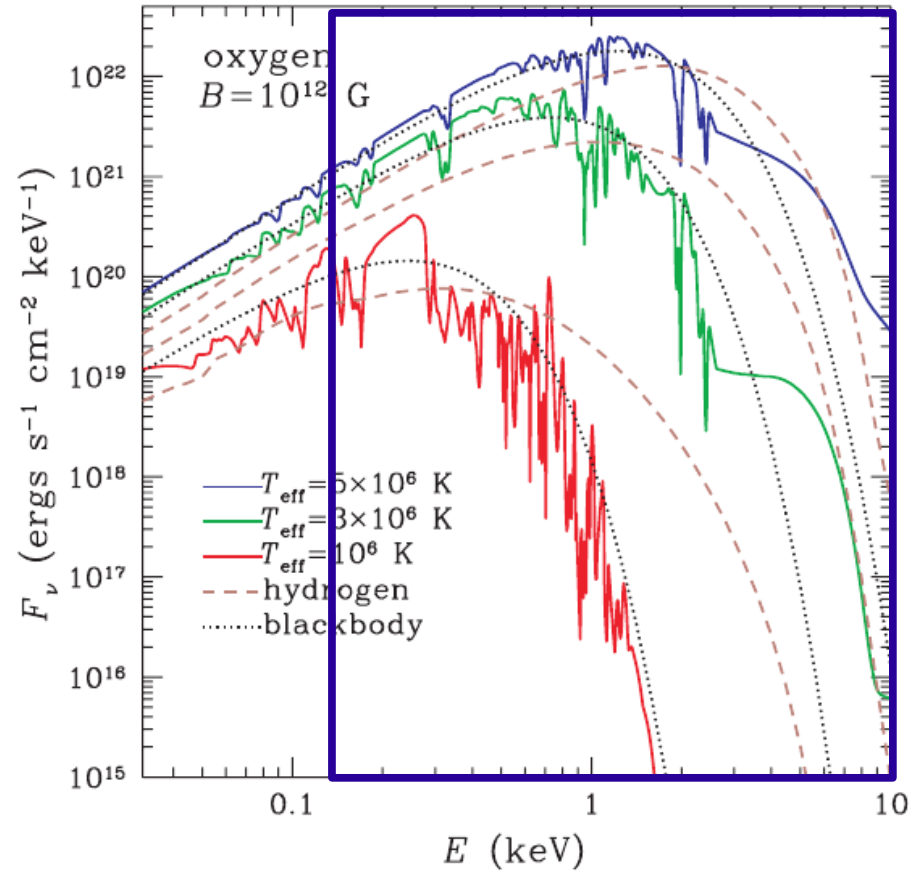
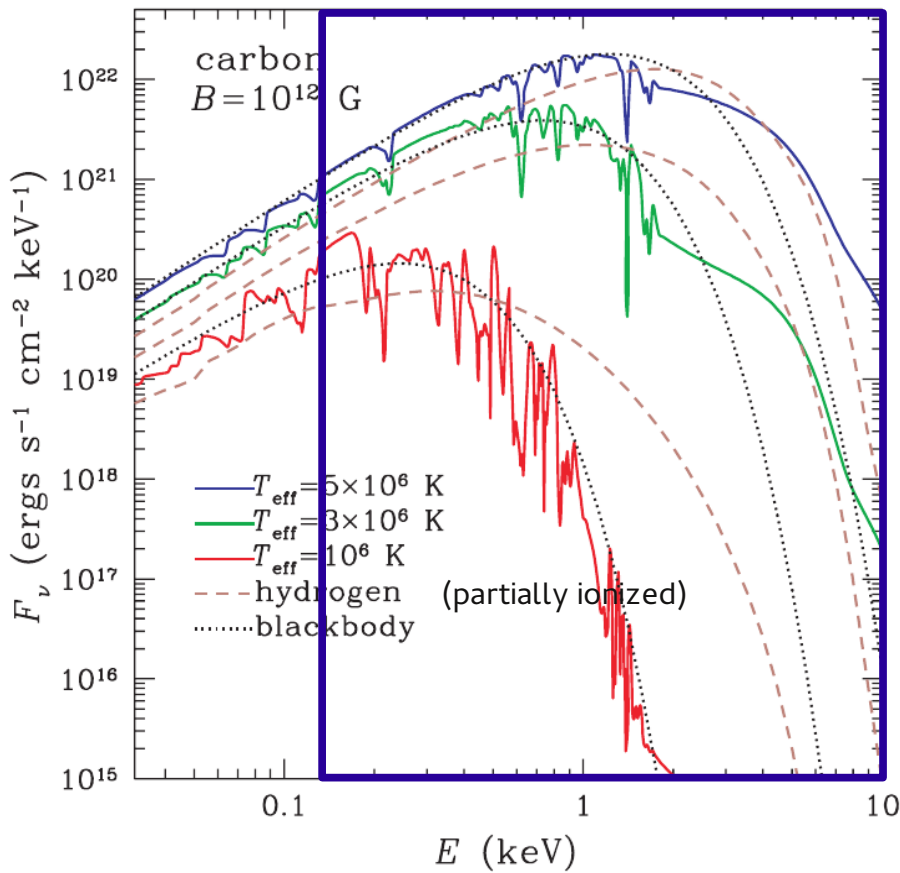


Zavlin et al. 1996

The thermal components of most NS spectra are fit with blackbodies, hydrogen or helium atmospheres.

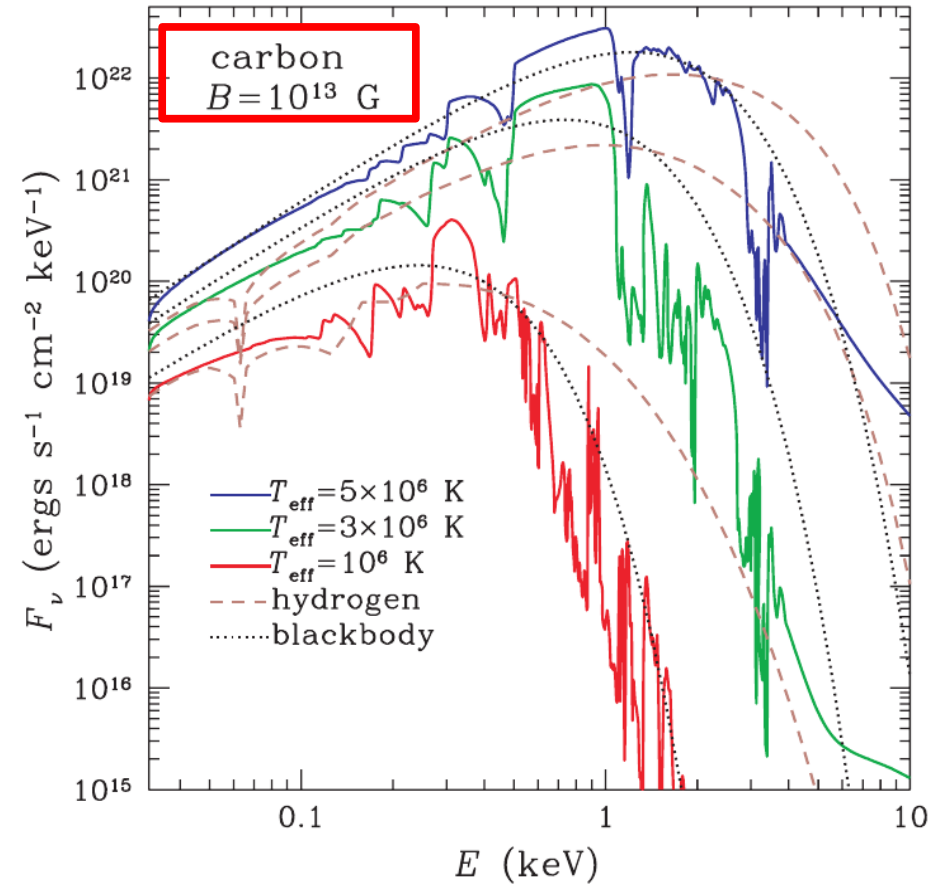
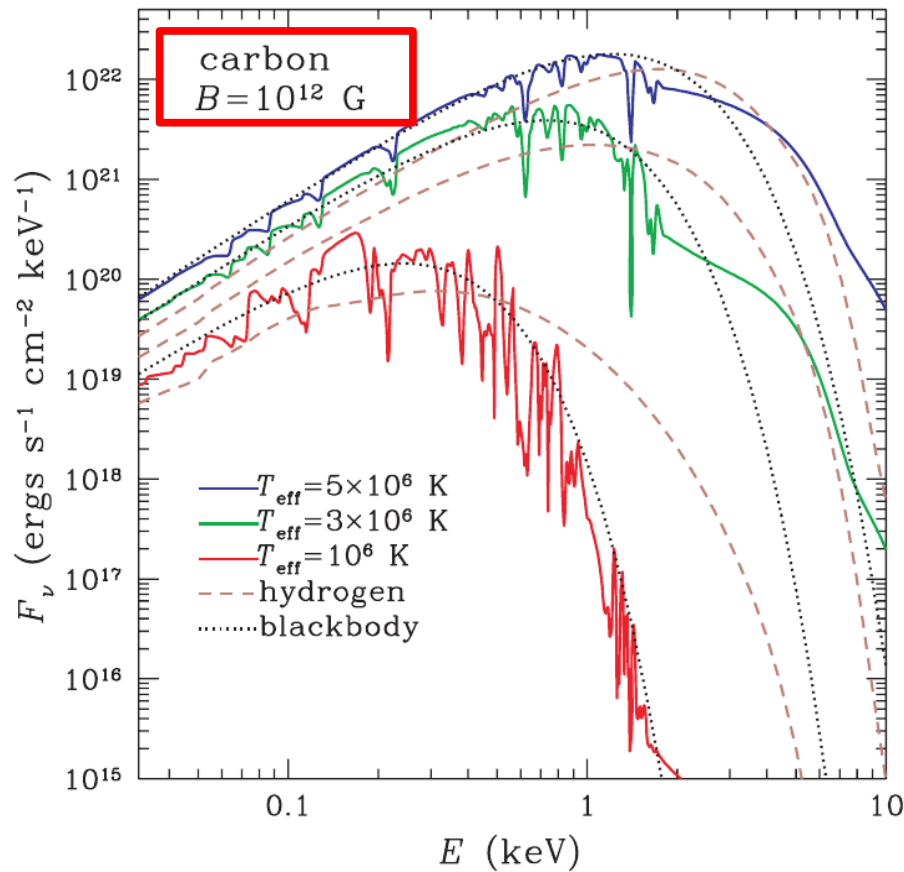
Higher elements introduce many spectral lines

Mori & Ho 2007



Spectra of 2 Central Compact Objects have been fit with low-B C-atmospheres

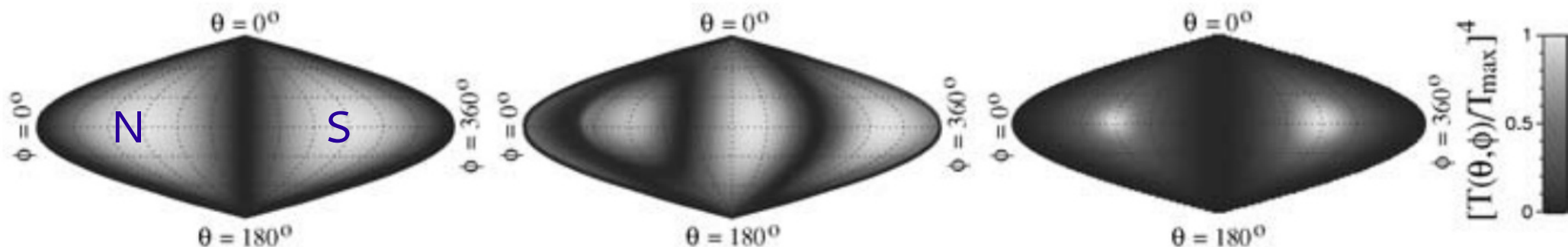
Stronger magnetic fields shift the lines



The magnetic field imposes anisotropies

surface temperature distribution
for different magnetic field configurations

Page et al. 2006, Geppert et al. 2006

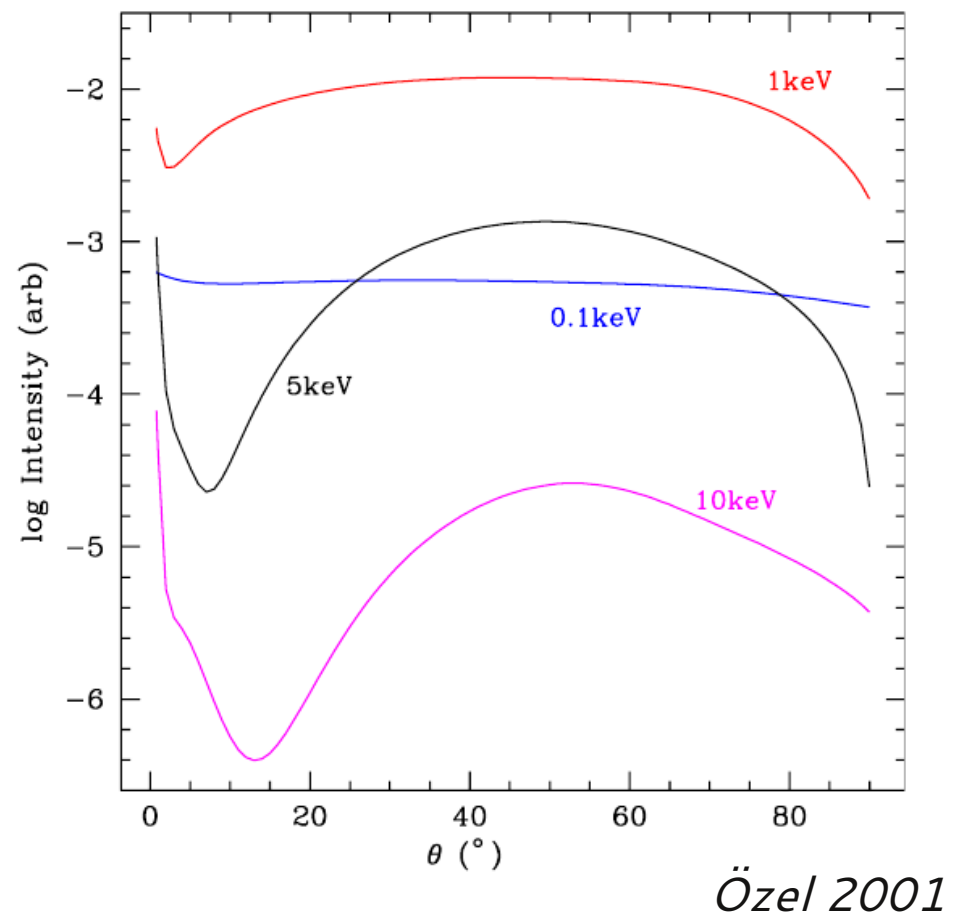
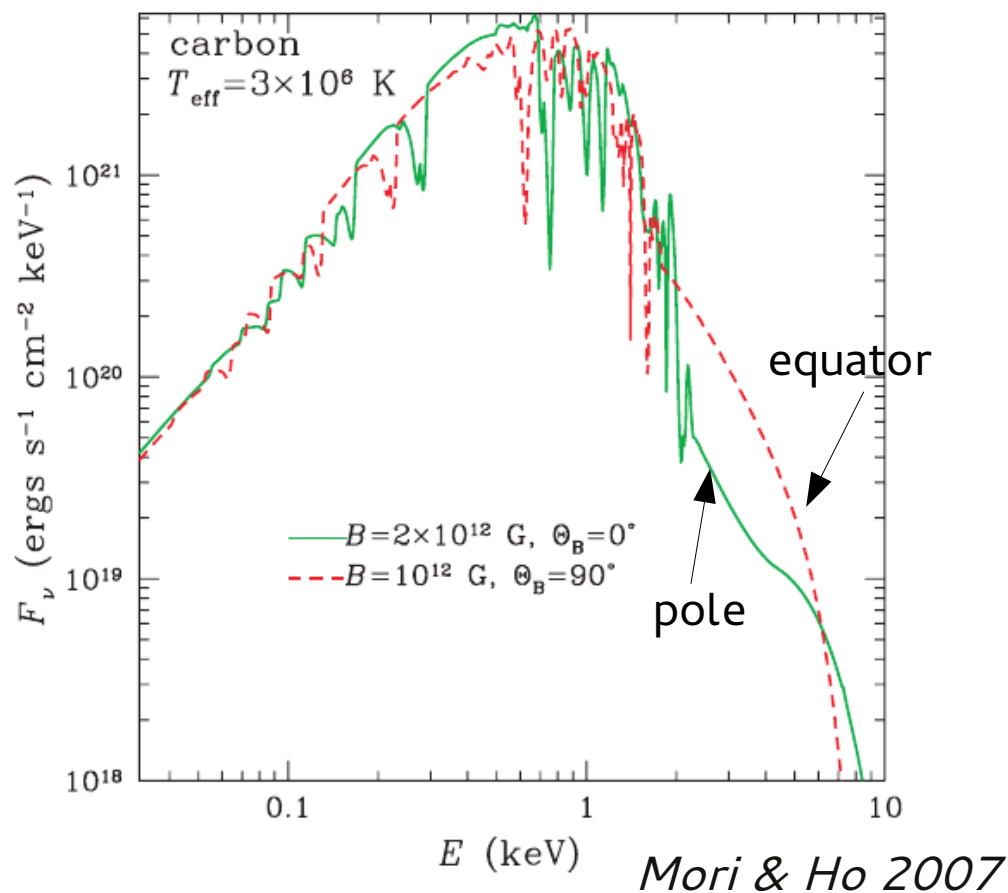


purely polodial field
($B=10^{12}$ G)

polodial dipole field &
polodial quadrupolar component

polodial dipole field &
toroidal component

The magnetic field imposes anisotropies



$B = 10^{12} \text{ G}$

dipole magnetic fields

$B = 10^{14} \text{ G}$

Anisotropies may cause misleading spectral fits

some detected spectral lines in the phase-integrated spectra of X-ray thermal neutron stars (aka' XDINSs or Magnificent Seven) can be interpreted as anisotropic temperature distributions

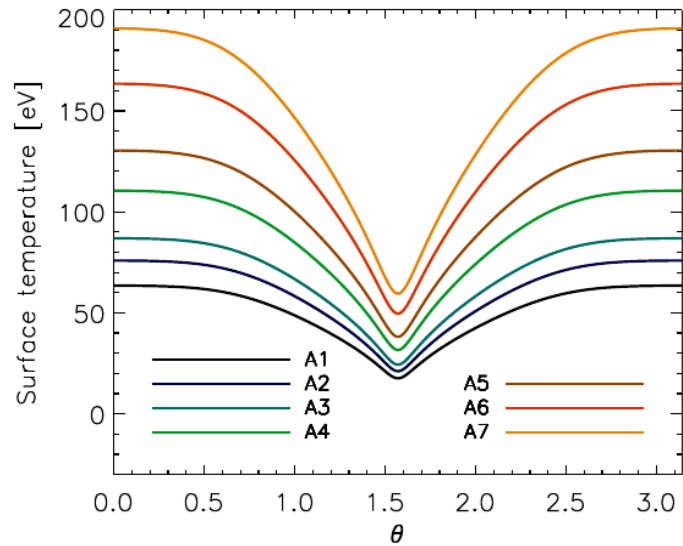
Zane et al. 2006, Turolla & Nobili 2013, Vigano et al. 2014

(→ talk by Silvia Zane)

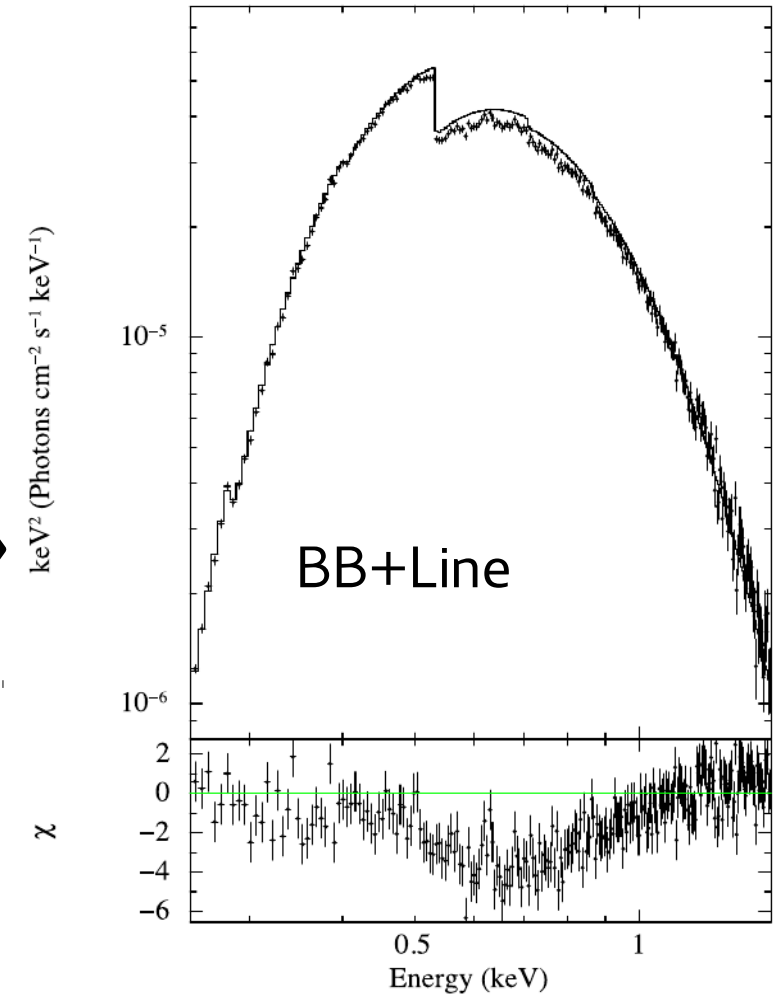
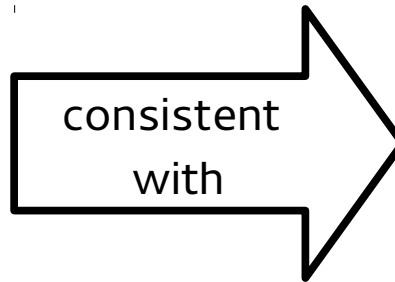
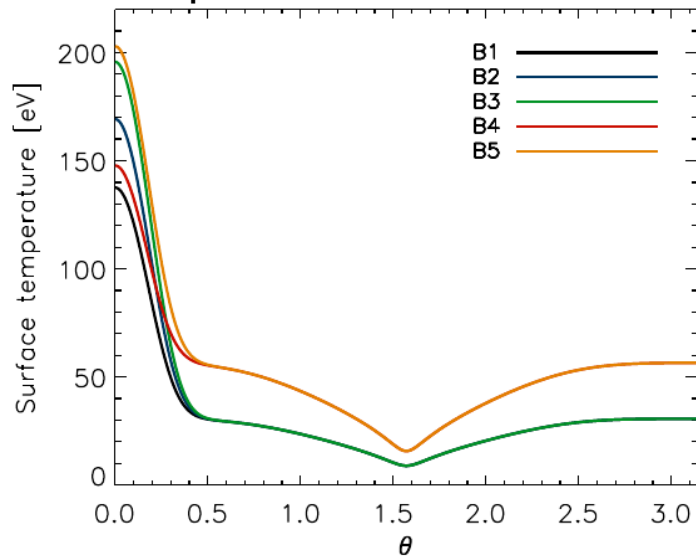
Anisotropies may cause misleading spectral fits

Example: RX J0806.4-4123

Vigano et al. 2014



all these blackbody surface temperature distributions are



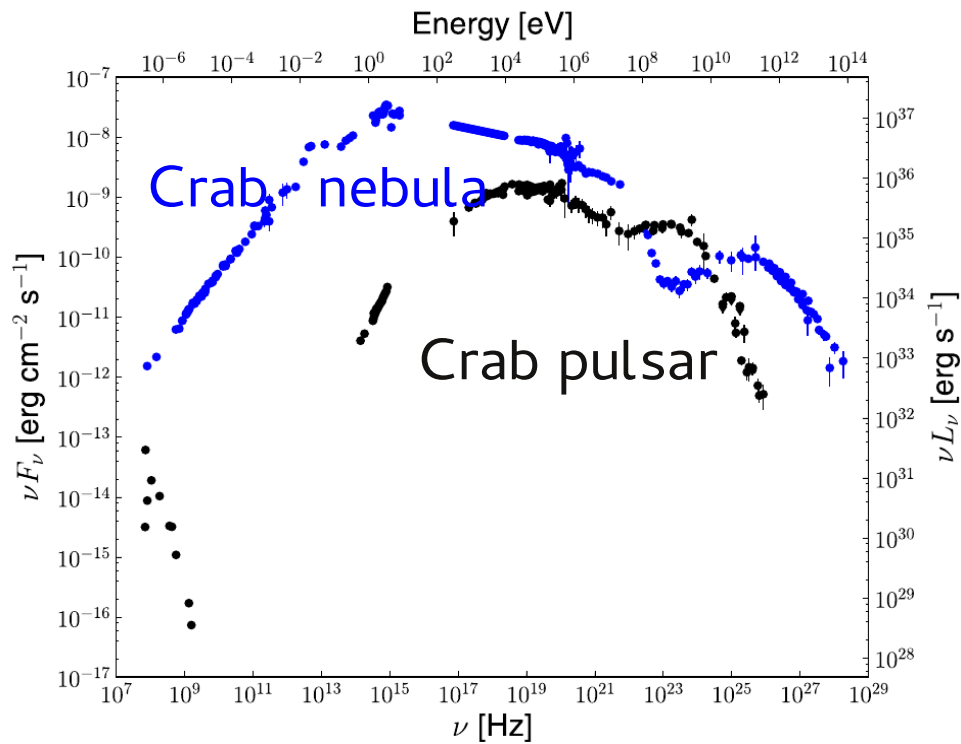
Measuring Neutron Star Temperatures

In order to constrain:

- NS cooling and heating theories
- NS structure / EoS
- NS evolution models

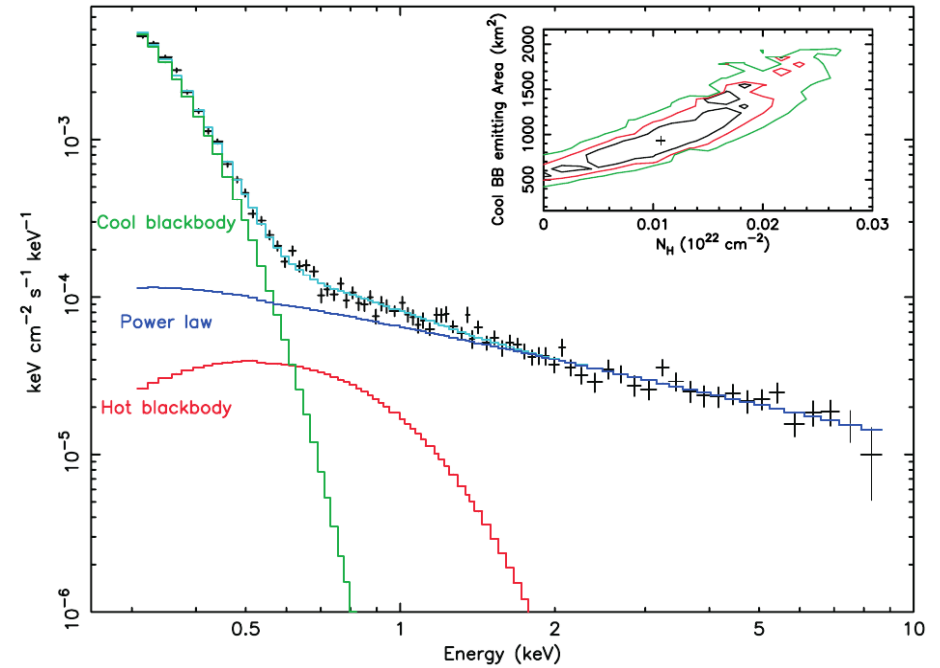
Usually: the NS surface is difficult to see

Bühler & Blandford 2014



thermal emission buried under
magnetospheric emission
(+ pulsar wind nebula)

Geminga pulsar



prominent thermal emission,
but also non-thermal component

De Luca et al. 2005

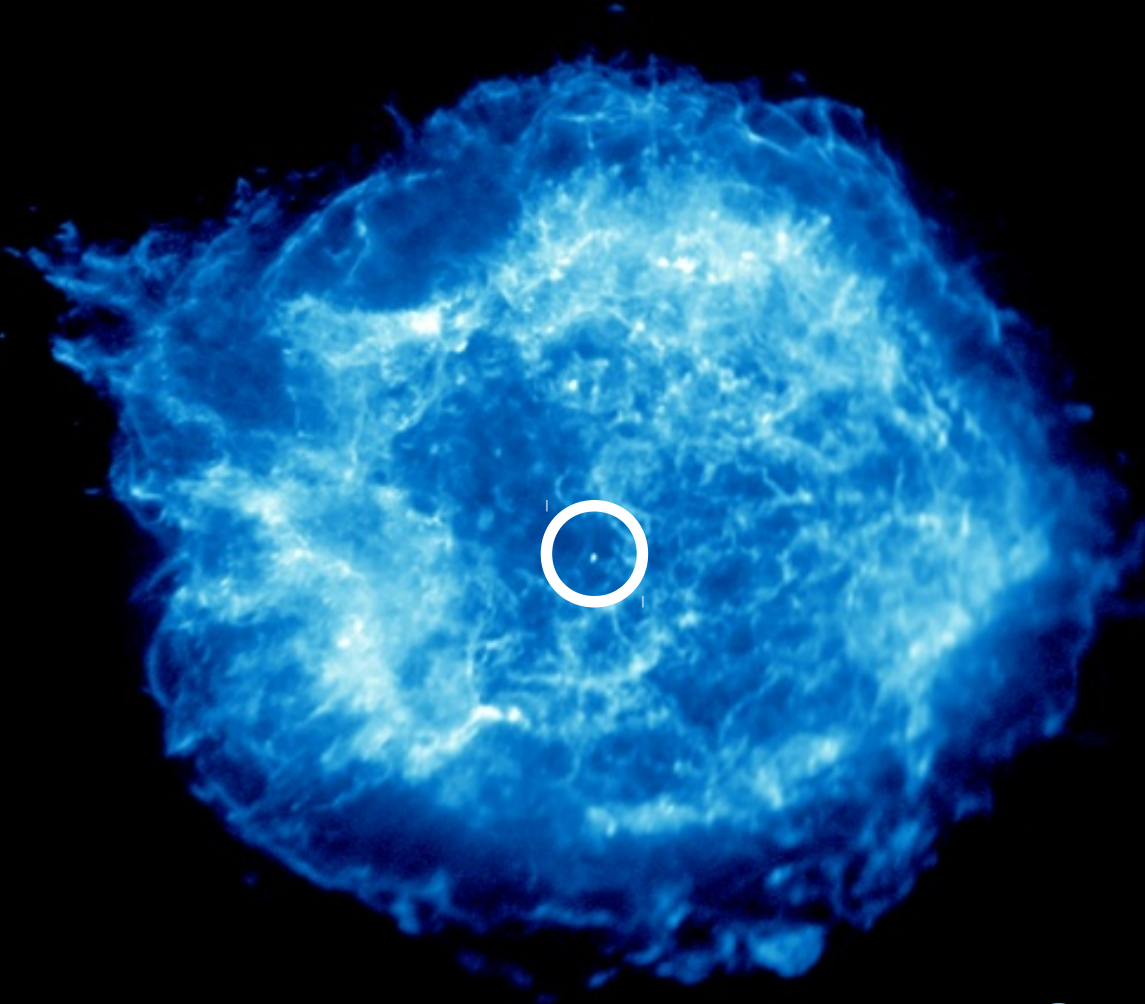
NSs with prominent thermal X-ray components

- Central Compact Objects (CCOs)
- some nearby middle-aged radio pulsars
- X-ray thermal isolated Neutron Stars

(→ talk by Silvia Zane)

- quiescent Low Mass X-ray Binaries (qLMXBs)
- some ms-pulsars

The Cassiopeia A SNR and CCO



SNR

Distance: 3.4 (+0.3/-0.1) kpc

Age: ~ 330 years

CCO

radio-quiet

no X-ray pulsations detected

Pulsed fraction limits:

< ~30% for $P > 0.3$ s

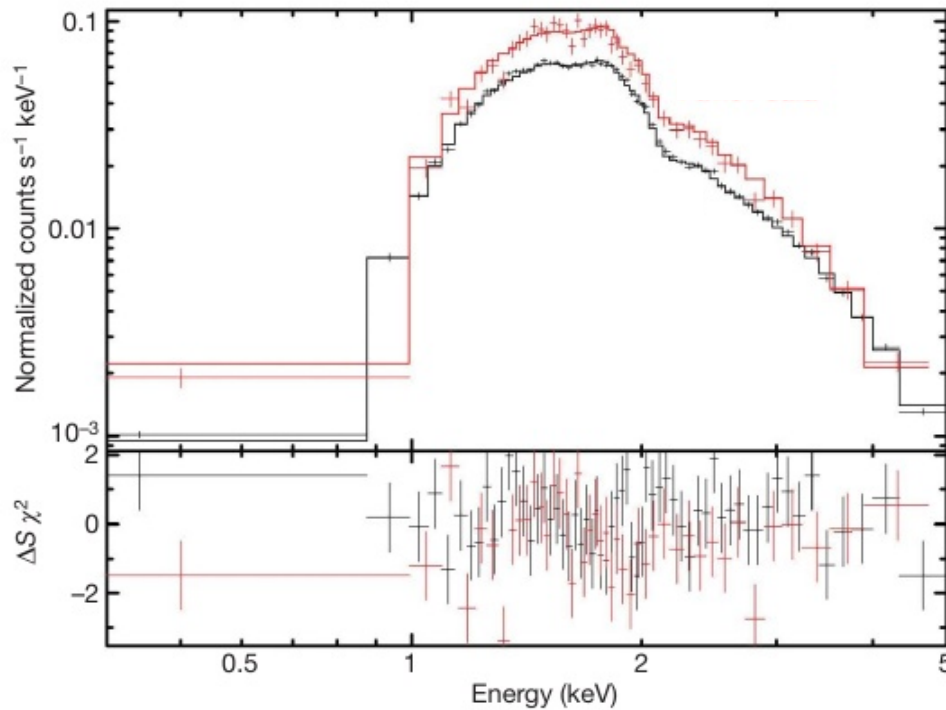
< 16% for $P > 0.68$ s

Spectrum:

dominated by thermal emission

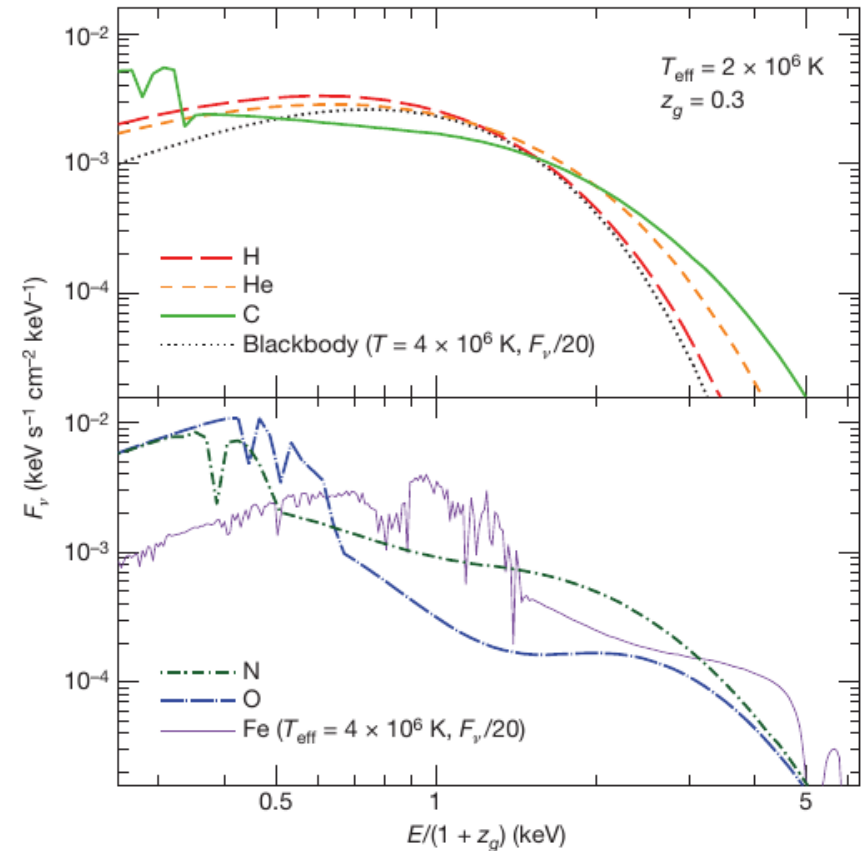
The Cas A CCO – well fit with a C atmosphere

Ho & Heinke 2009



fit of the Chandra X-ray data
with a C-atmosphere

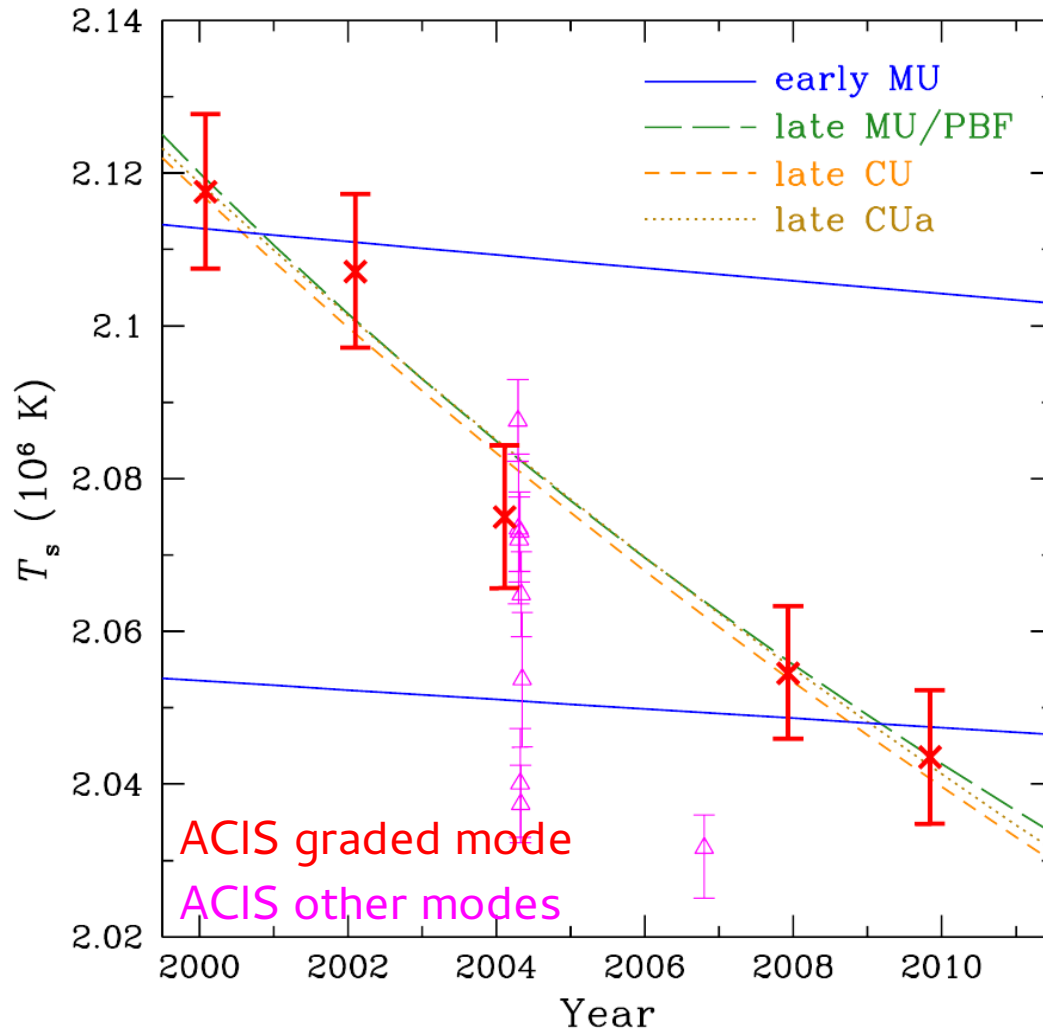
➡ reasonable temperature, radius



considered model spectra

hot spots with hydrogen atmosphere also possible (but pulsations?)

The temperature of the Cas A CCO changed.



⇒ first direct evidence for superfluidity in neutron star core (e.g., Page et al. 2011, Shternin et al. 2011)

↓
 reduces usual neutrino emissivity, but also initiates a pair-breaking-and-formation neutrino emission mechanism
 supports "minimal cooling scenario" (Potekhin, Pons, Page 2015)

Heinke & Ho 2010
 in ~10 years:
 $\Delta T = 4\% (5.4\sigma)$
 $\Delta \text{Flux} = 21\%$

Systematic effects can influence the result

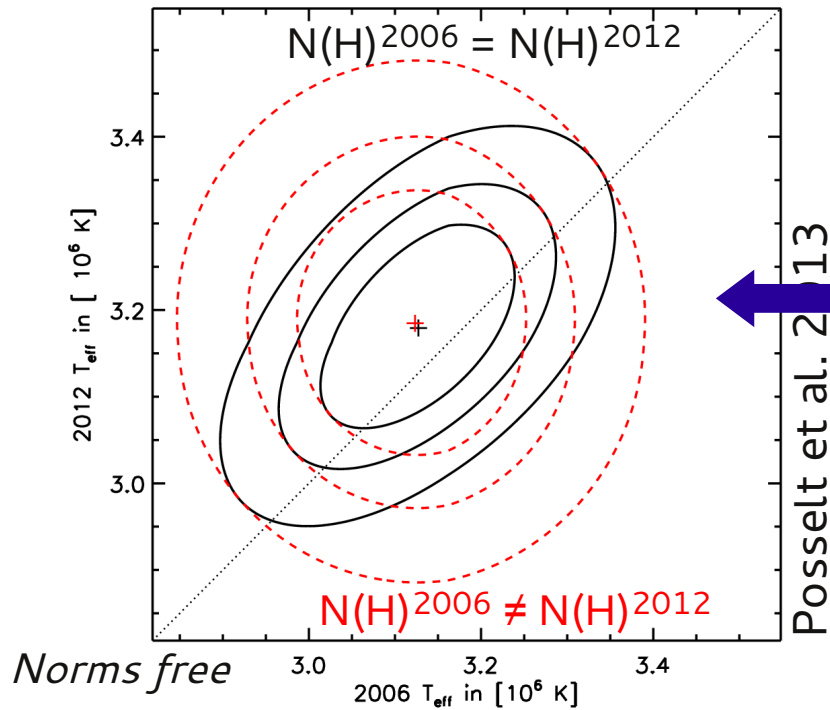
Model assumptions

- chosen neutron star atmosphere model
 - assumption of constant size of the emission area
- assumption of constant NH

Instrument/Calibration effects

- pile-up (reaches ~20% for the CCO)
- ACIS filter contamination
 - position on the ACIS chip

Atmosphere model and NH matter !



Hydrogen atmosphere (NSA, $B < 10^{10} \text{G}$)

(e.g., Pavlov & Luna 2009)

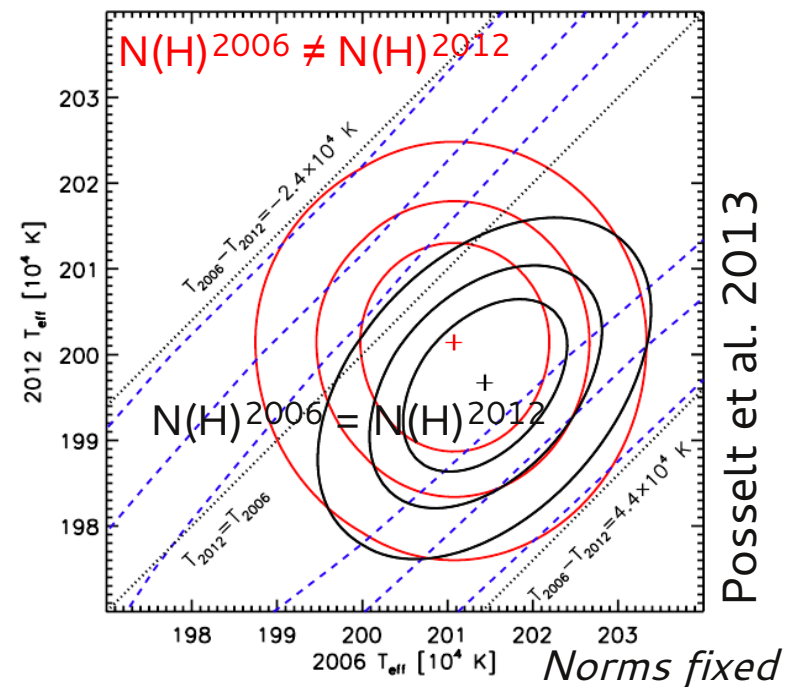
No significant temperature change

Emission Area: $\sim 10\%$ of NS surface

Carbon atmosphere models

(e.g., Ho et al. 2009, Suleimanov et al. 2013)

temperature decrease
if same NH is assumed



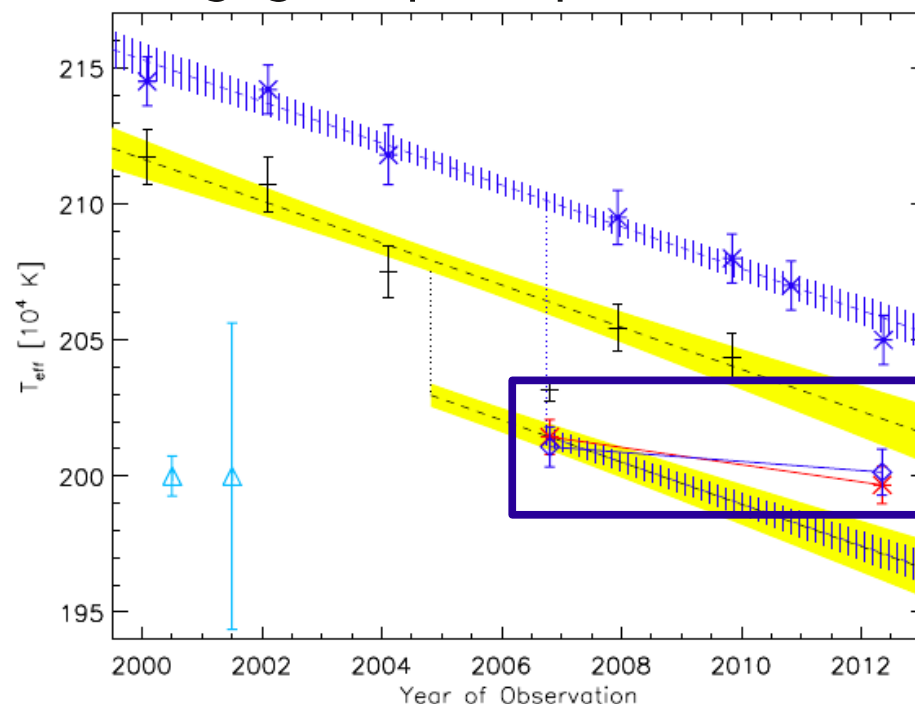
The systematics of the instrument matter !

Posselt, Pavlov, Suleimanov, Kargaltsev 2013

in contrast to previous ACIS graded mode

now: ACIS-S subarray mode – negligible pile-up !

- tested different model assumptions
- checked influence of contamination

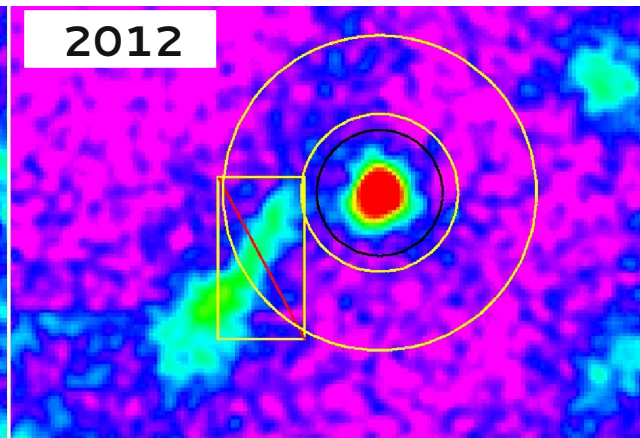
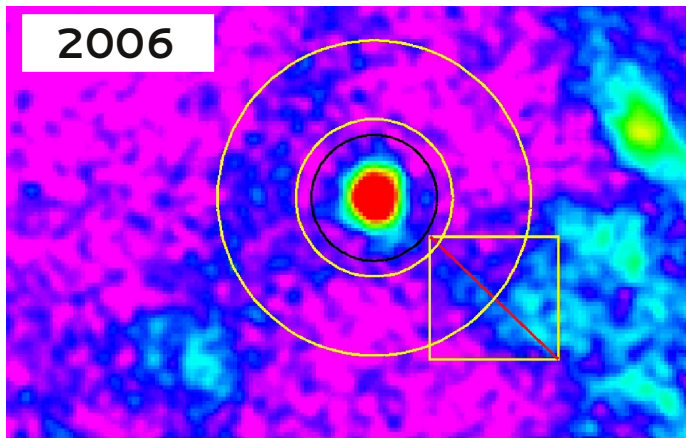


no statistically significant temperature drop,
but the uncertainties are too large to firmly
exclude the previously reported fast cooling.

Most recent Cas A CCO observations

black circle radii:
4 ACIS pixel
(or 1.97 arcsec)

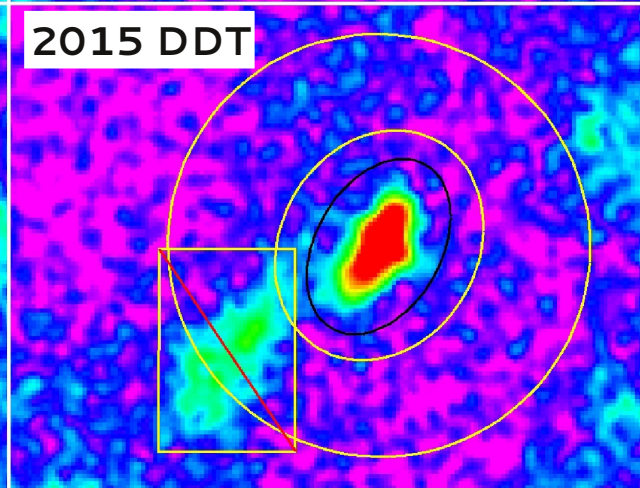
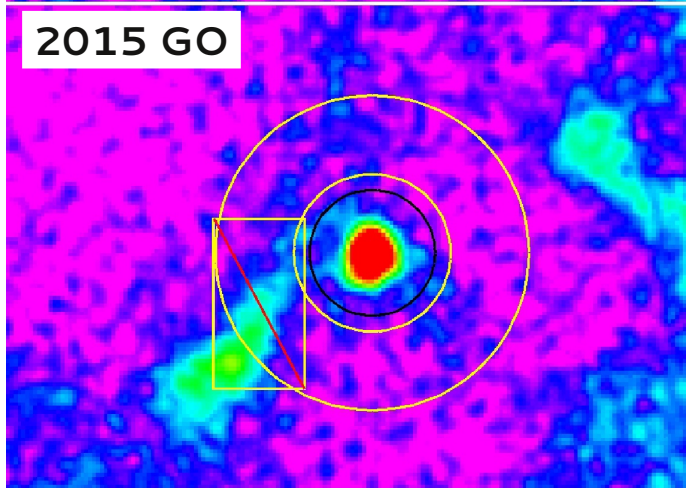
edge of chip



edge of chip



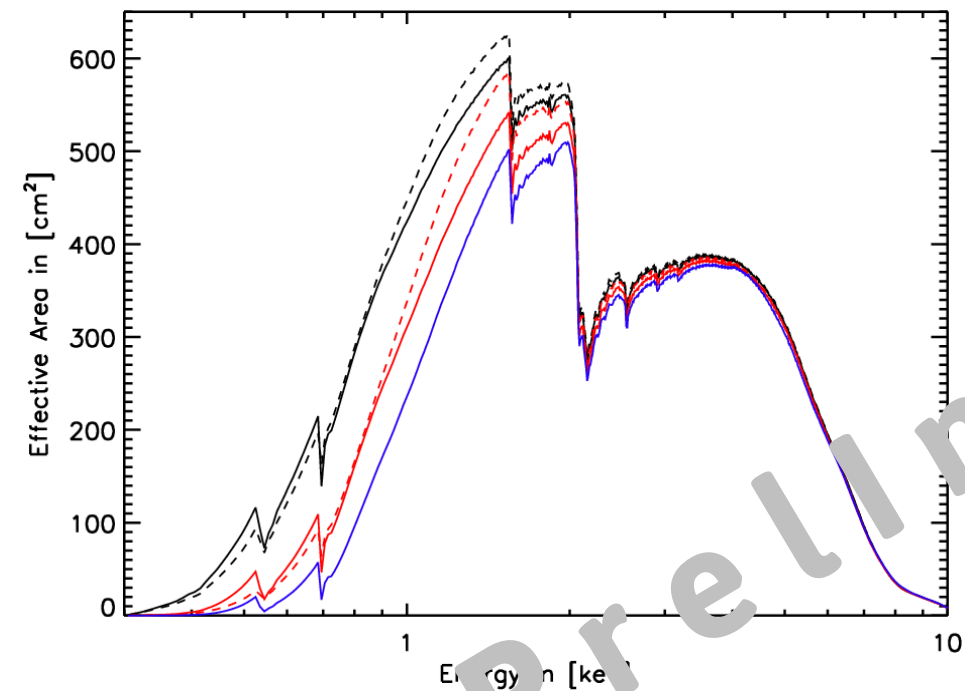
edge of chip



center of chip
off-axis

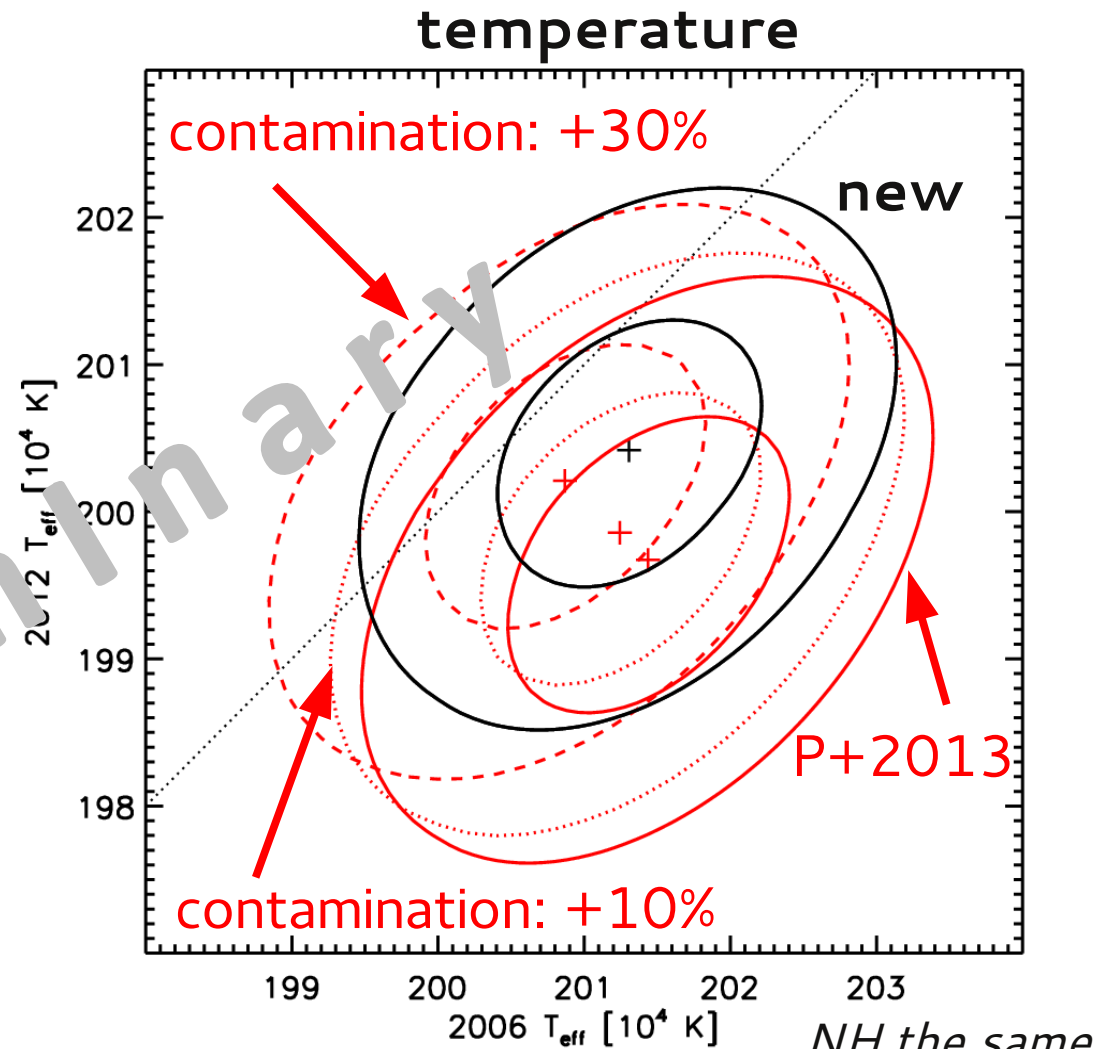
	ObsID	MJD days	T_{exp} ks	Counts	S3 _X pix	S3 _Y pix	θ_{offaxis} arcsec
2015 GO	6690	54027	61.6	7340	211.21	49.41	7.8
	13783	56052	63.4	6720	215.52	51.48	7.3
	16946	57140	68.1	6277	229.57	55.18	23.0
2015 DDT	17639	57143	42.7		574.84	509.03	190.4

The changing calibration has an effect !



P+2013: CALDB 4.5.5.1 (dashed)

New: CALDB 4.6.8



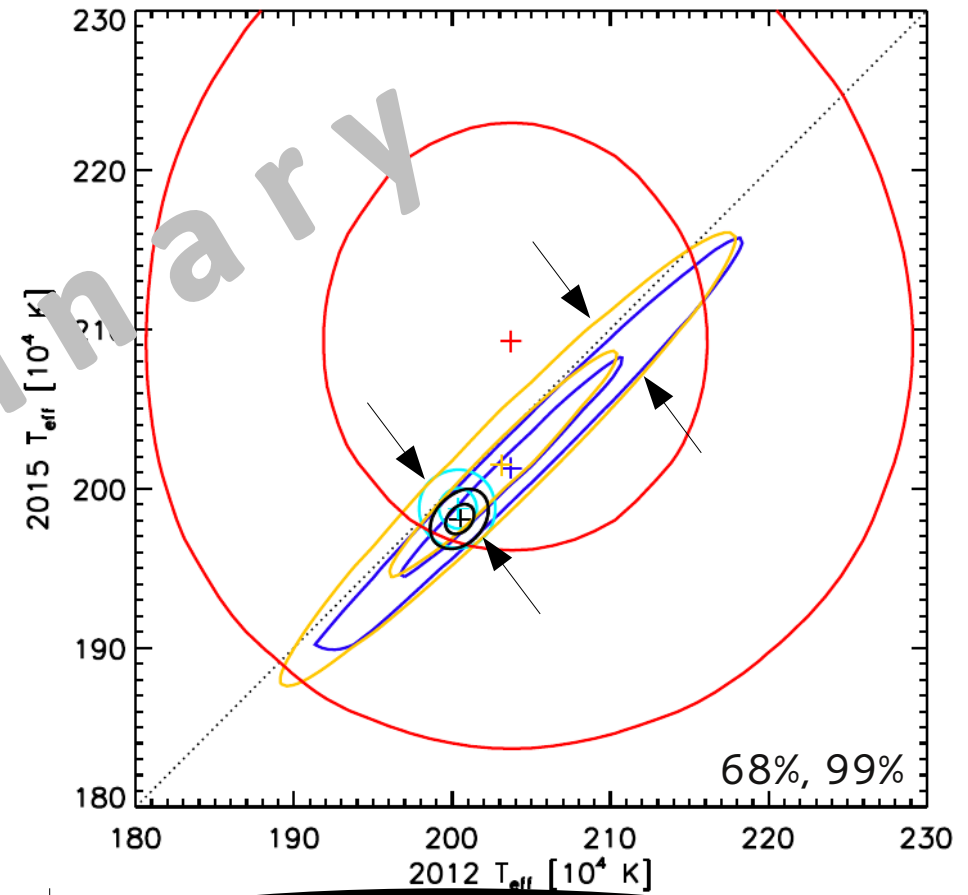
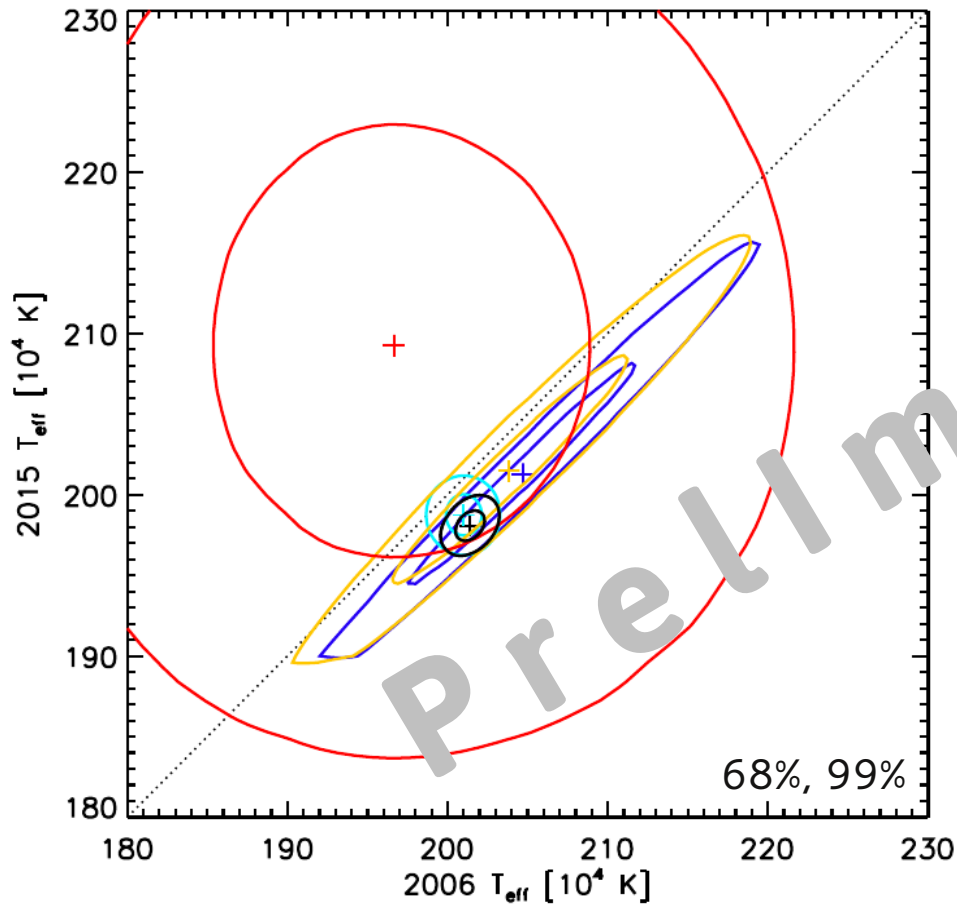
Less severe if NH different

**Temperature/Flux changes between 2006 and 2012
even less than in P+2013!**

2006 – 2012 – 2015

2006 – 2012 – 2015

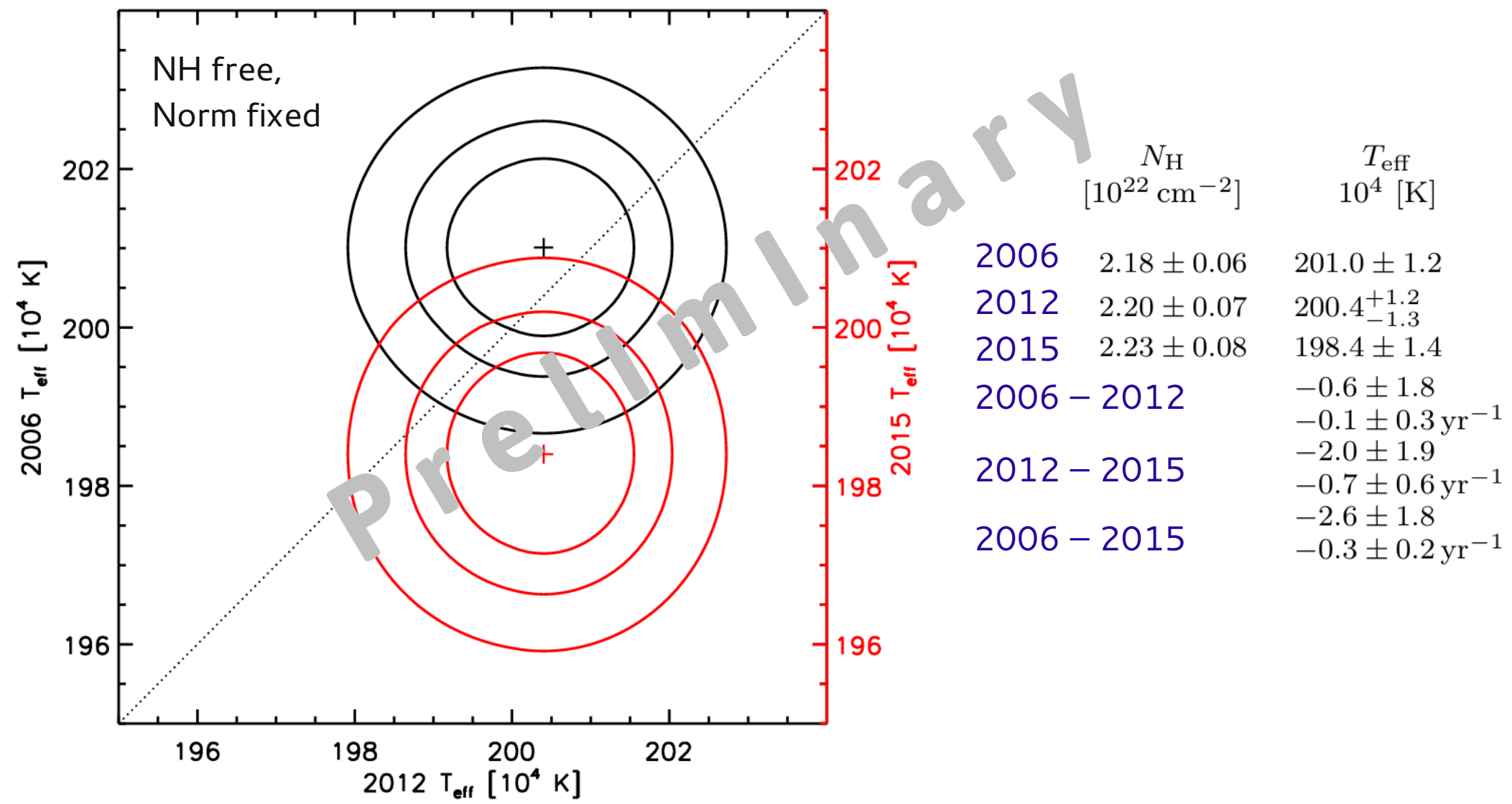
Temperature



- NH the same, Norm fixed (black); **NH free, Norm fixed (cyan)**
- NH the same, Norm tied (blue); **NH free, Norm tied (yellow)**
- NH free, Norm free (red)

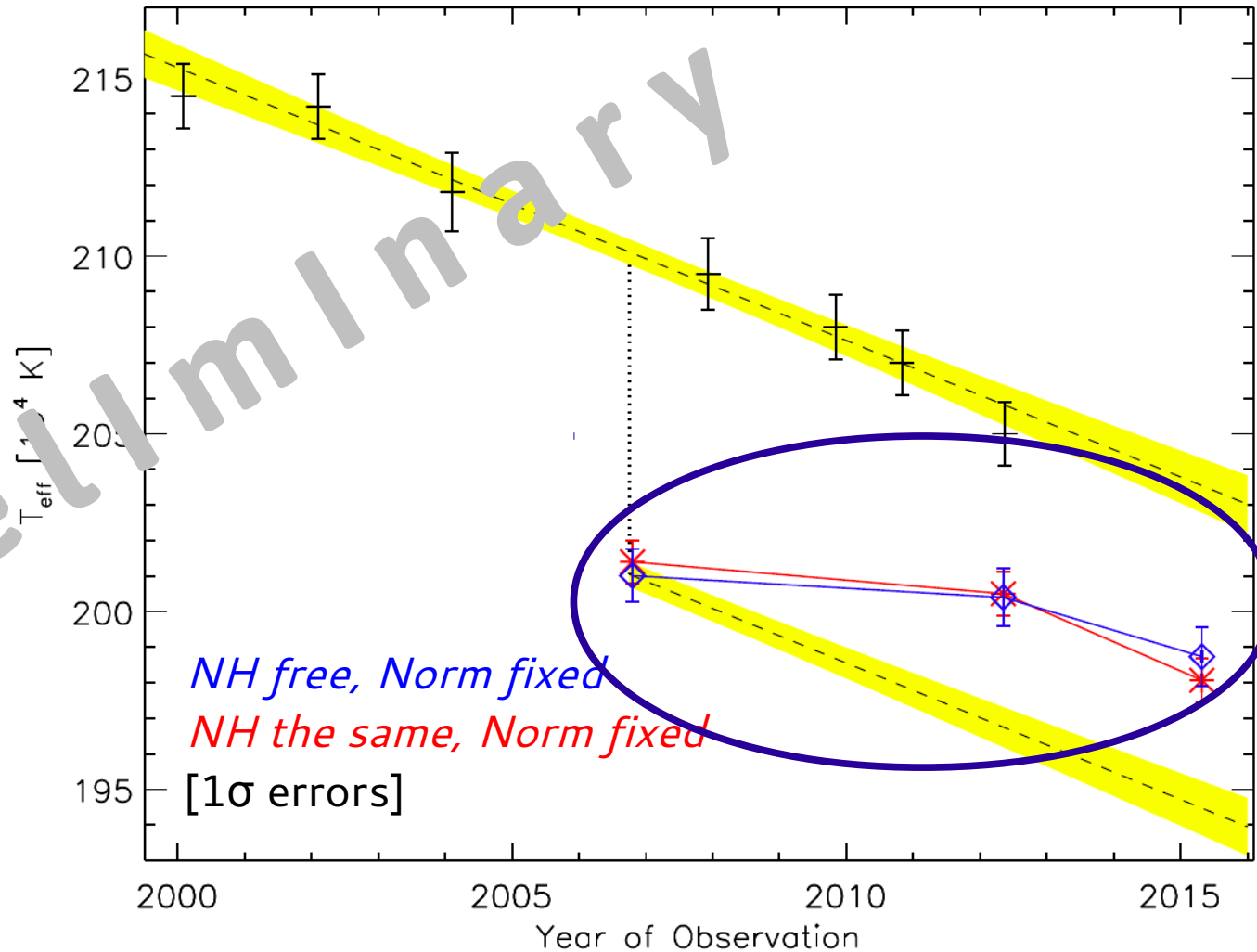
2006 – 2012 – 2015

Temperature



2006 – 2012 – 2015

Temperature



stay tuned

Instead of just one CCO, use many NSs

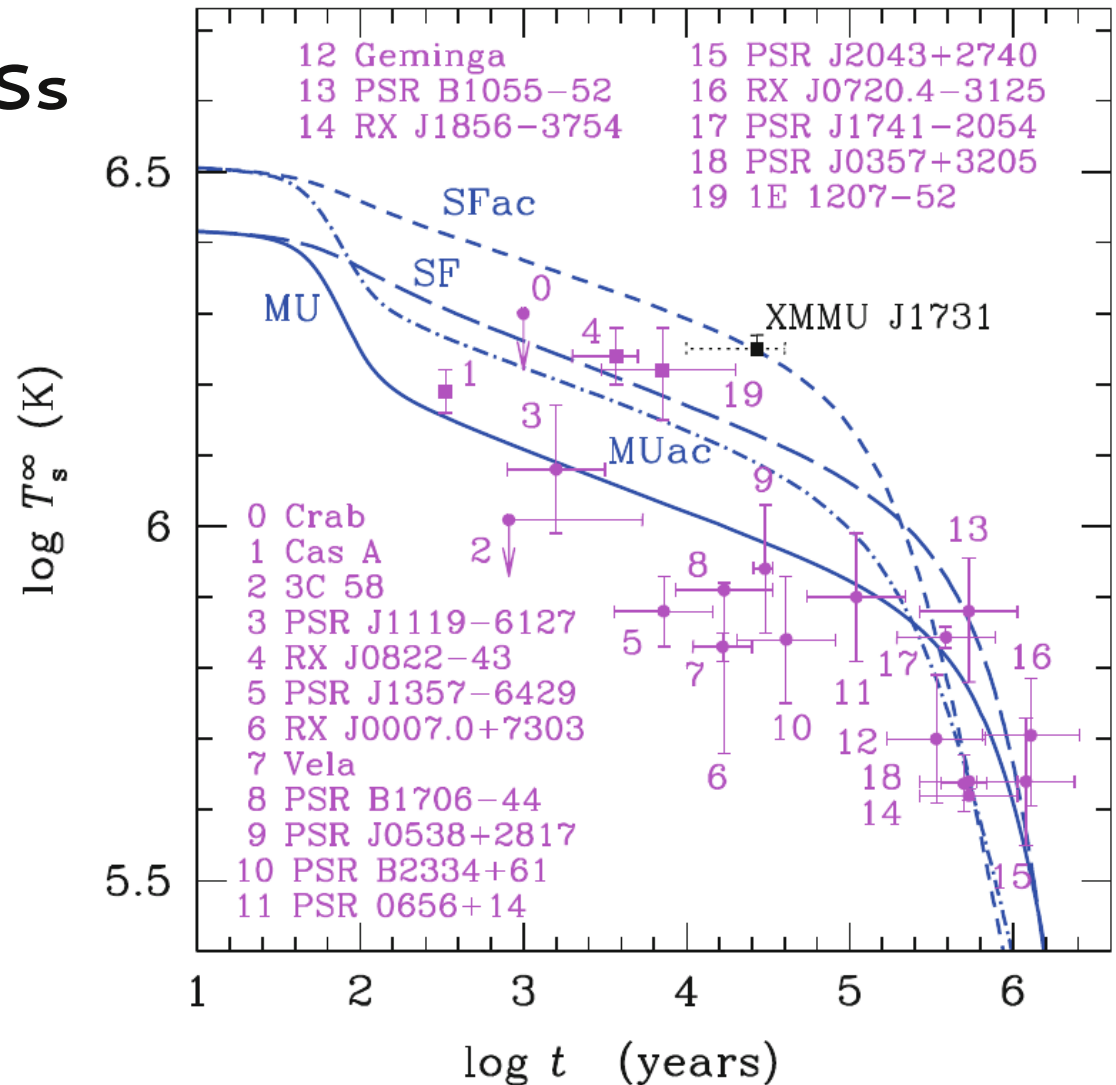
ensemble of many neutron stars at different ages

Thermal evolution of NSs

can – in principle –
constrain

- physics in core
- composition of heat blanketing envelope

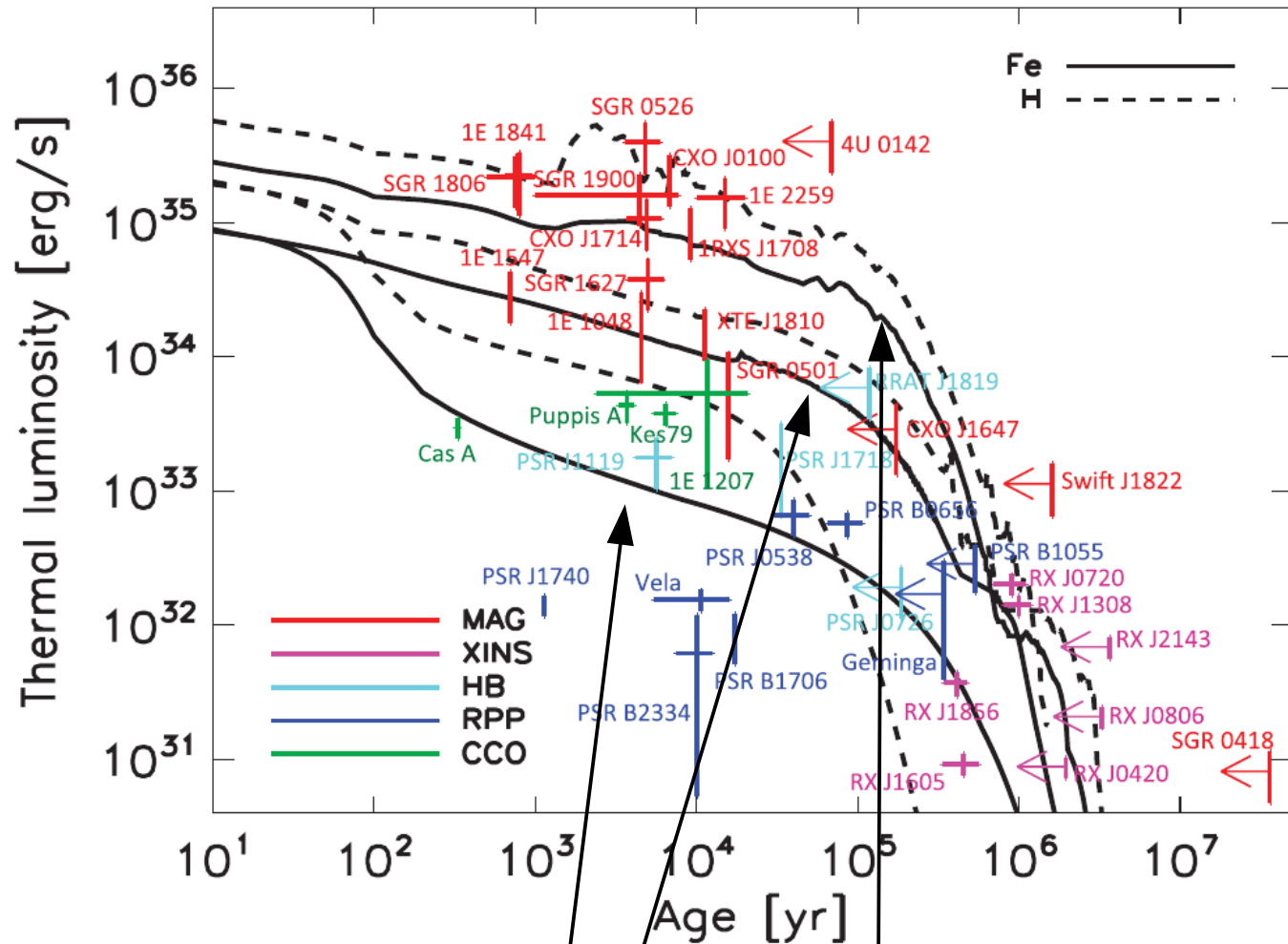
MU: non-superfluid star; Fe envelope
SF: strong proton superfluidity, Fe envelope
MUc and SFc instead: carbon envelope



Klochov et al. 2015

Instead of just one CCO, use many NSs

magnetic fields also influence surface temperatures



Vigano et al. 2013

Models with $B_0 = 0, 3 \times 10^{14}, 3 \times 10^{15}$ G are shown for Fe envelopes (solid) and light-element envelopes (dashed).

Measuring Neutron Star Radii

In order to constrain:

- NS EoS / structure

Measuring Neutron Star Radii in X-rays

in isolated neutron stars

- surface emission
- if pulsating – pulse profile (waveform) analysis

in neutron star binaries

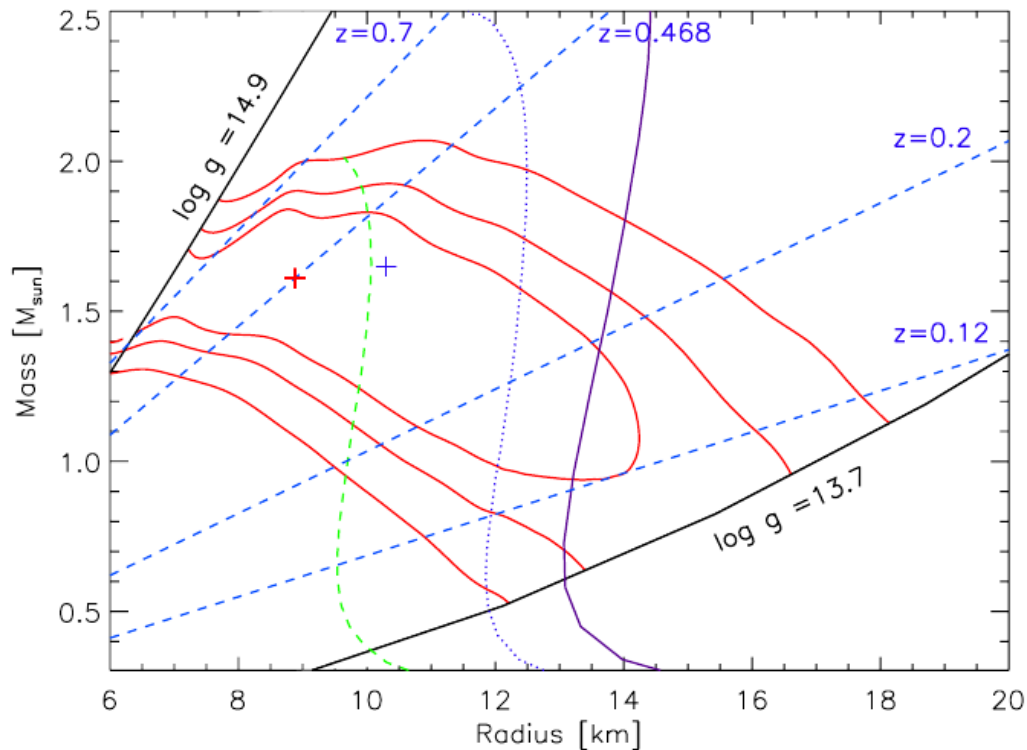
- quiescent low-mass X-ray binaries (qLMXBs)
- thermonuclear bursts I
 - (1) properties at time of maximal (Eddington) flux
 - (2) cooling tail method
 - (3) burst oscillations
- waveform analysis of ms-pulsar hot spots

(→ talk by Tolga Güver)

Neutron Star Radii from CCO's surface emission

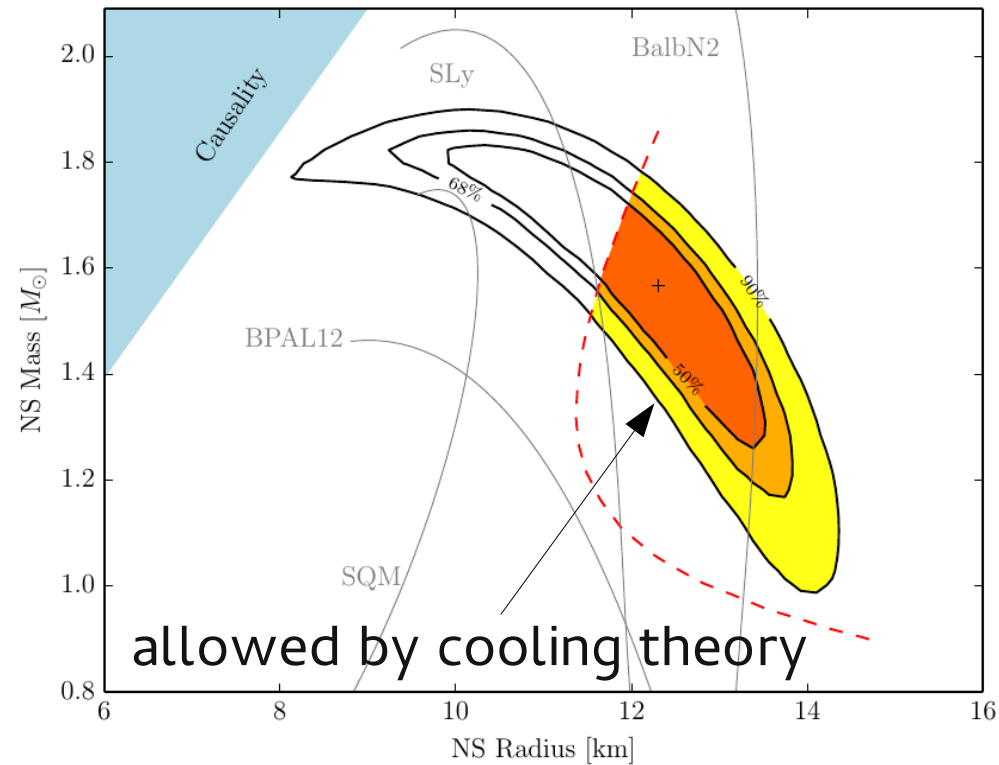
Both: no measured pulsations, carbon atmospheres

Cas A



Posselt et al. 2013

XMMU J173203.3-344518



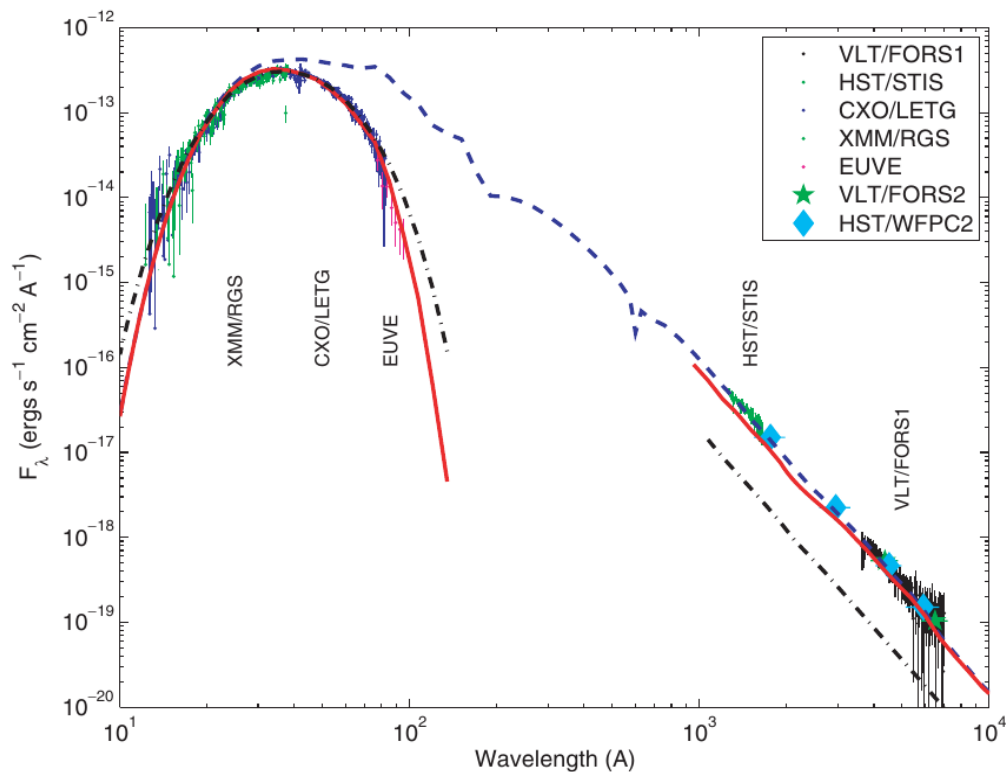
Klochkov et al. 2015

Problems: distances, right atmosphere model?

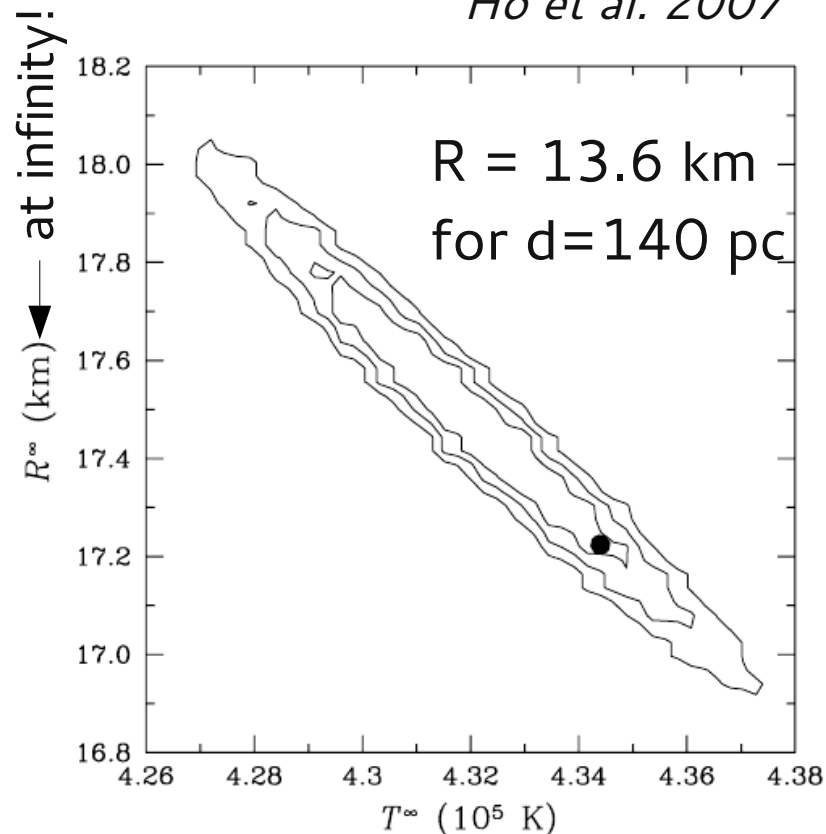
Neutron Star Radii from an X-ray thermal NS

pulsed fraction: 1.2%

RX J1856.5-3754



Ho et al. 2007



very thin H atmosphere, assumed $B = 4 \cdot 10^{12}$ G

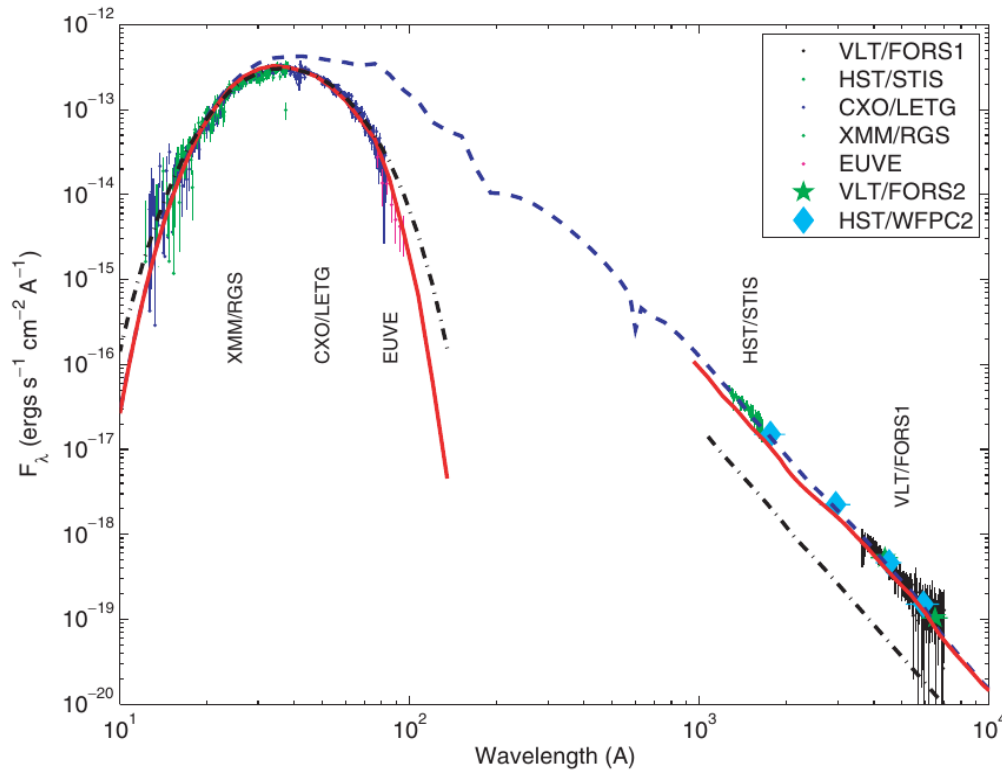
B more likely $1.3 \cdot 10^{13}$ G (van Kerkwijk & Kaplan 2008), not big effect expected

Neutron Star Radii from an X-ray thermal NS

pulsed fraction: 1.2%

RX J1856.5-3754

Ho et al. 2007



R = 12.1 (+1.3/-1.6) km
for **d=123 (+11/-15) pc**

M = 1.5 +/- 0.2 M_{sun}

Pothekin 2014, Walter et al. 2010

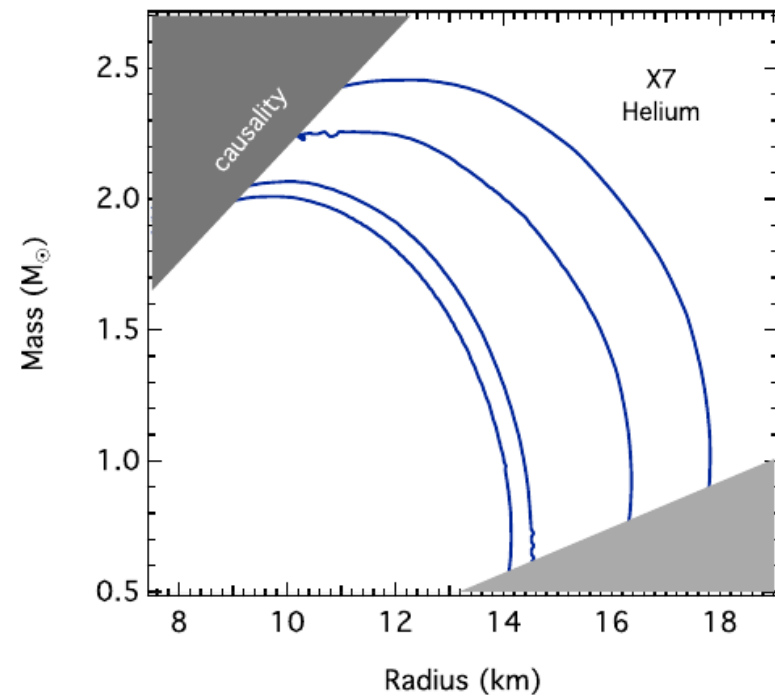
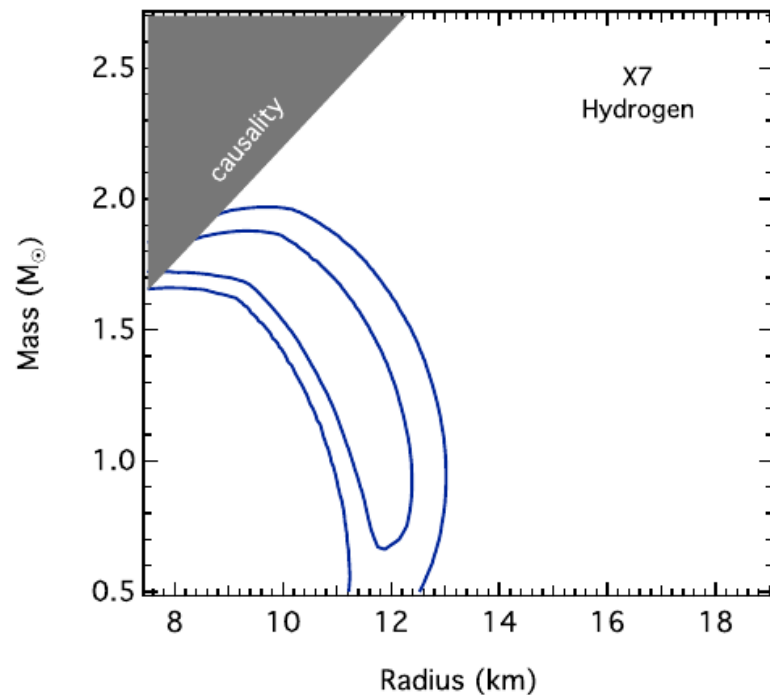
very thin H atmosphere, assumed $B = 4 \cdot 10^{12}$ G

B more likely $1.3 \cdot 10^{13}$ G (*van Kerkwijk & Kaplan 2008*), not big effect expected

Neutron Star Radii from quiescent LMXBs

(→ talk by Tolga Güver)

Influence of atmosphere model



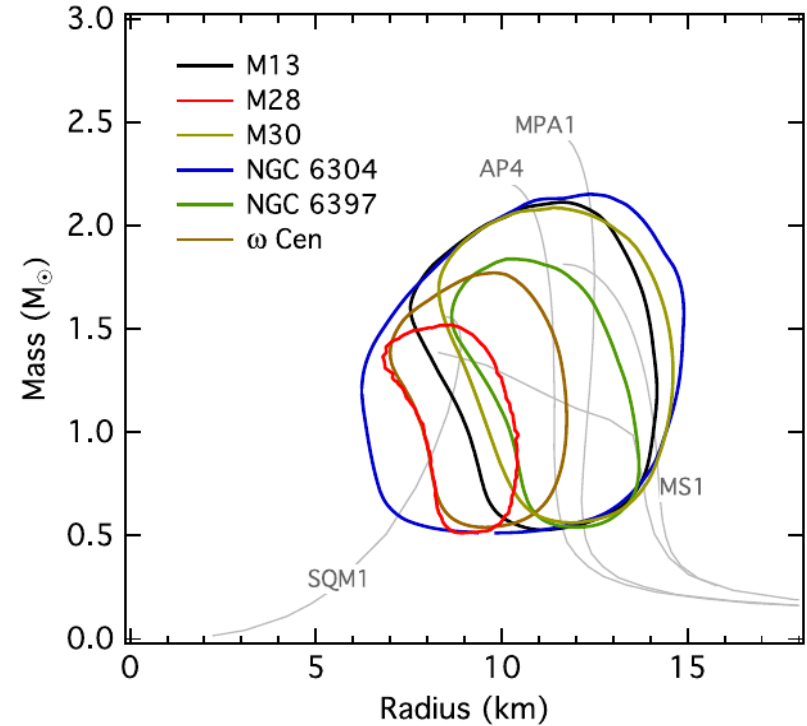
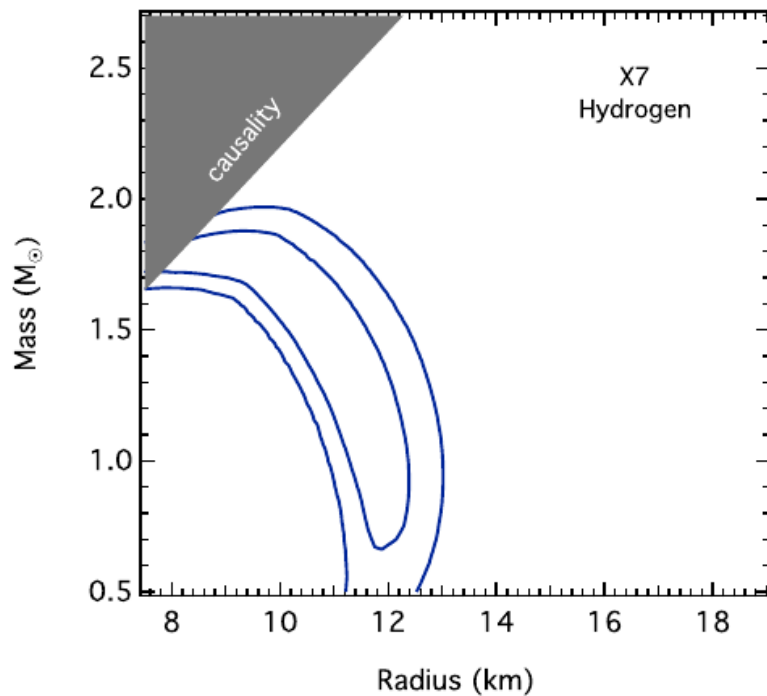
Bogdanov et al. 2016

Bogdanov et al. favor a hydrogen atmosphere since a helium atmosphere would require a high mass ($>1.7M_{\text{sun}}$) neutron star
→ at odds with cooling processes of other qLMXBs

Neutron Star Radii from quiescent LMXBs

(→ talk by Tolga Güver)

Bogdanov et al. 2016

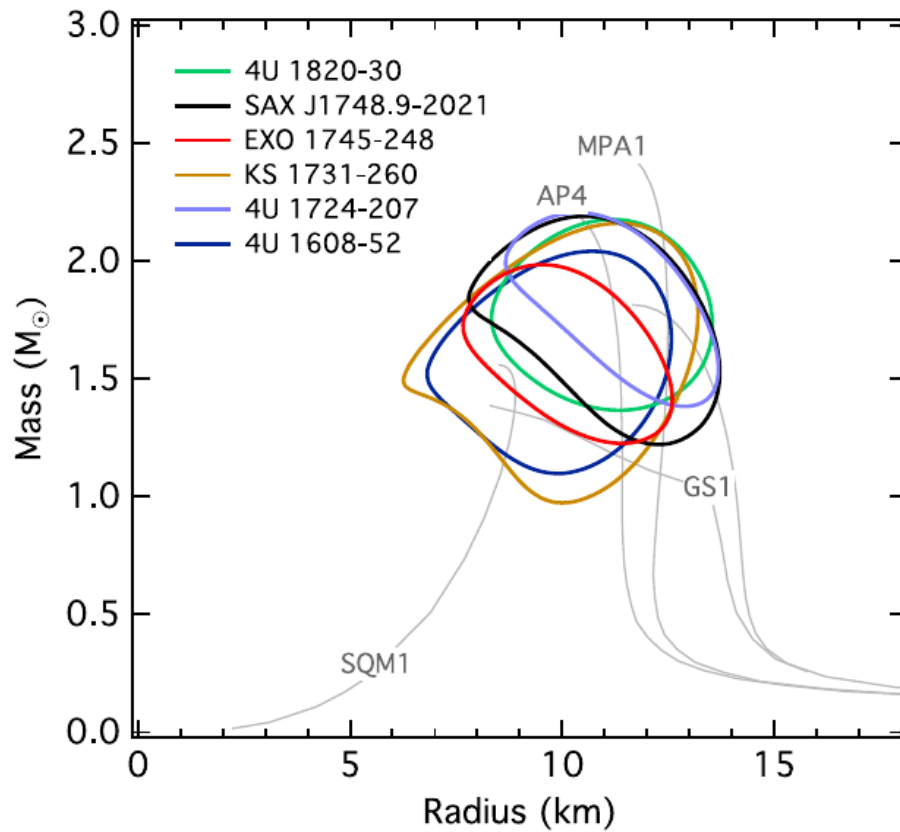


Özel et al. 2016

hydrogen atmosphere models

Neutron Star Radii from PRE bursts (1)

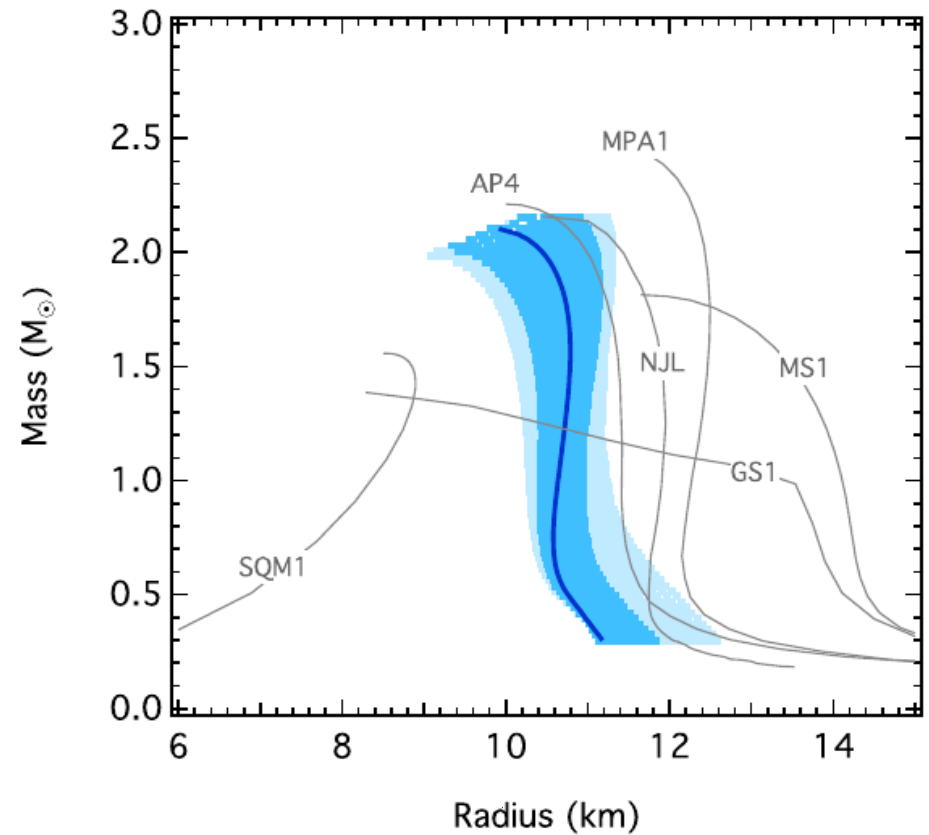
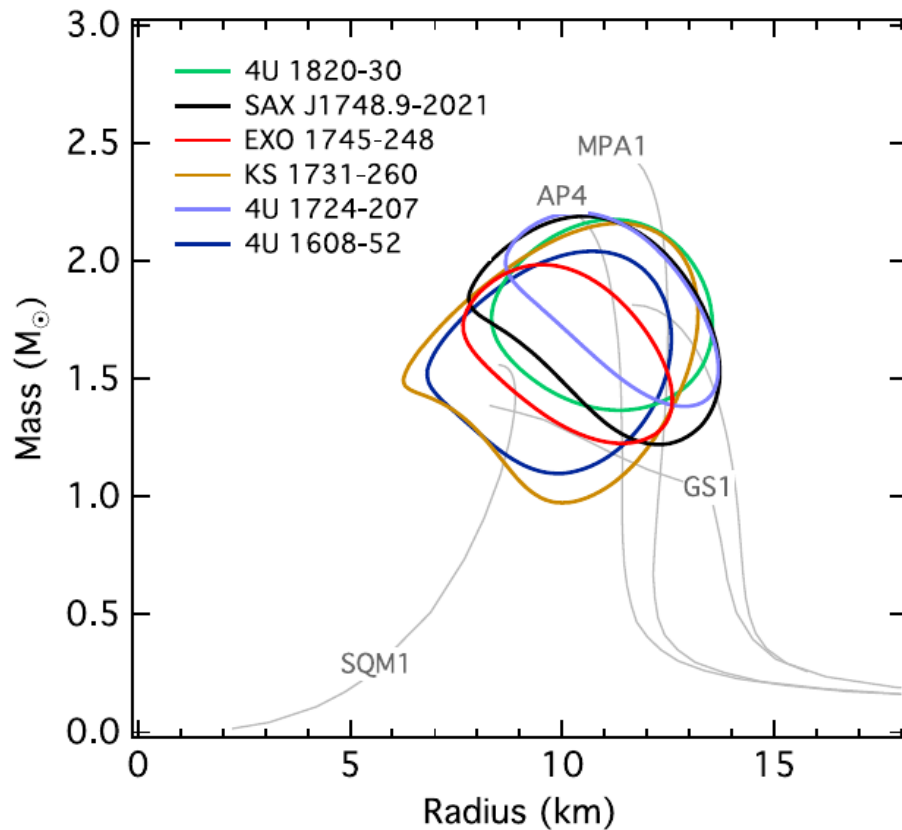
(→ talk by Tolga Güver)



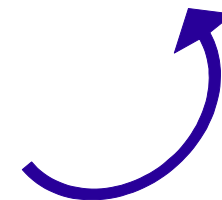
Özel et al. 2016

Neutron Star Radii from PRE bursts (1)

(→ talk by Tolga Güver)



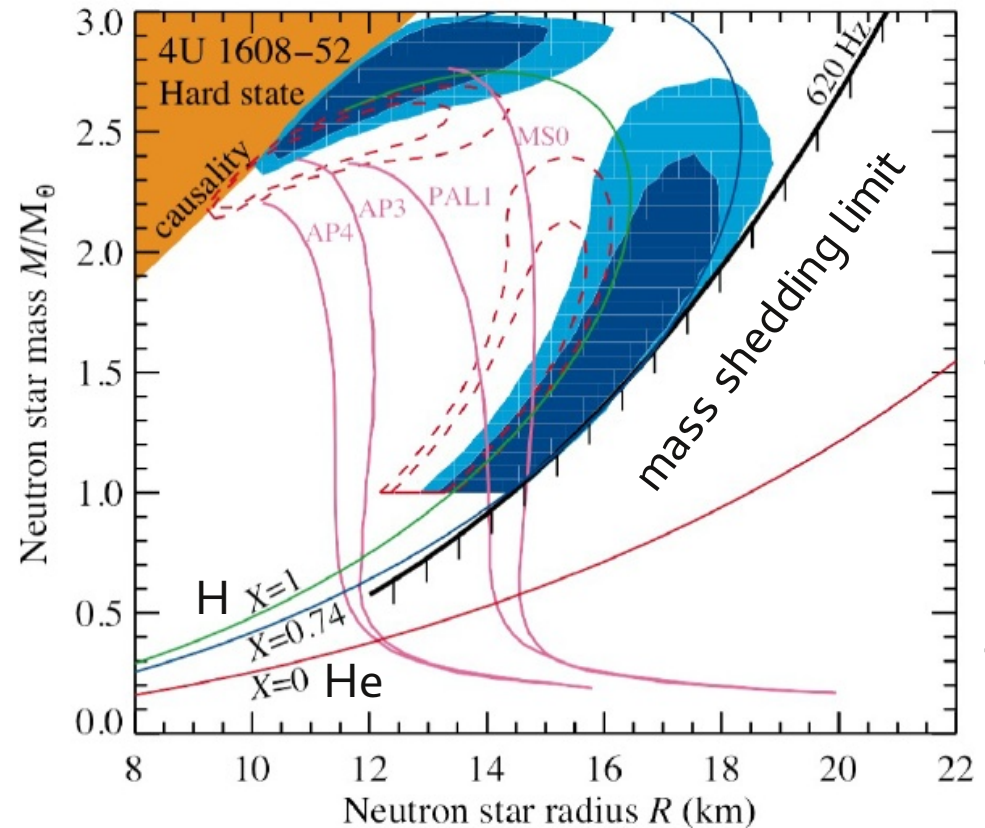
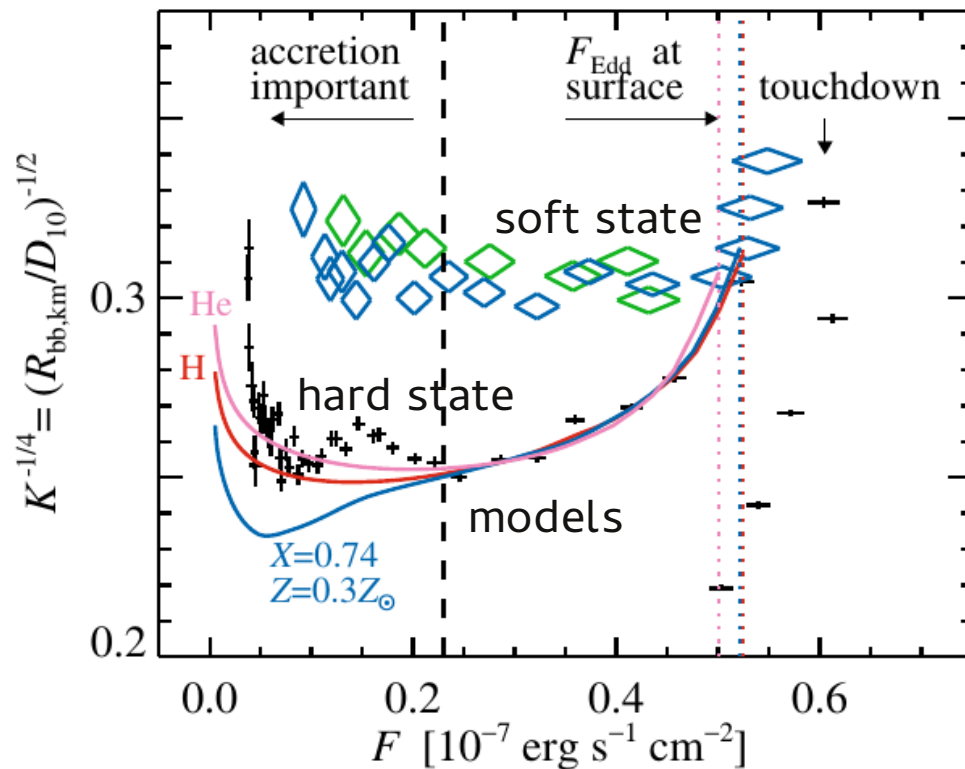
+ qLMXB results



Neutron Star Radii from PRE bursts (2)

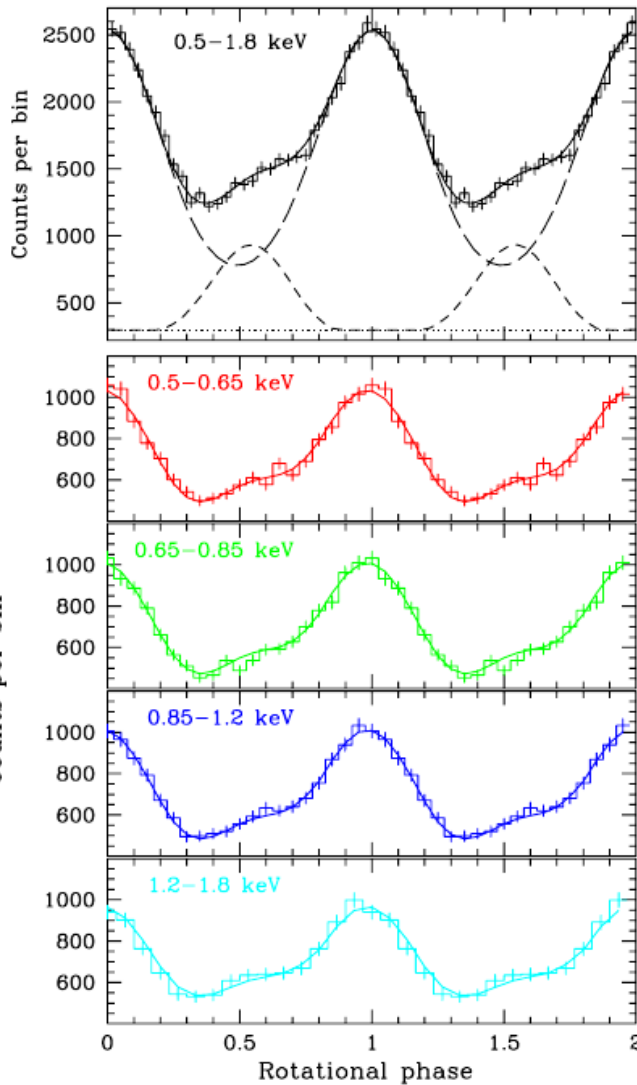
cooling tail method

- NS burst atmosphere models → evolution of color correction factor K
- only bursts in hard persistent state follow predictions,
- don't need touchdown flux



Suleimanov et al. 2016

Neutron Star Radii from Pulse Profile Modeling



Best example: recycled ms-pulsar J0437-4715

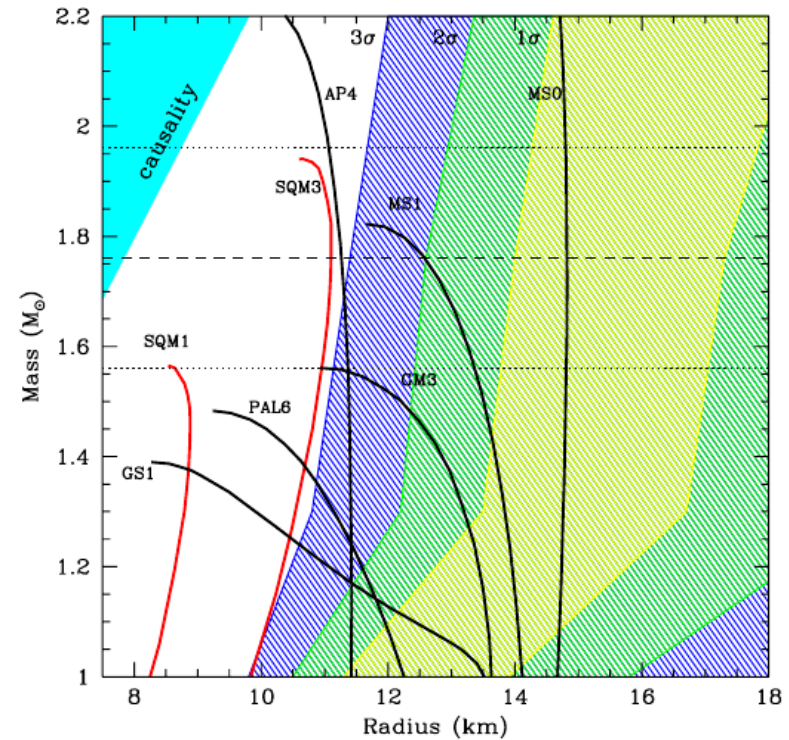
known:

$$d = 156.3 \pm 1.3 \text{ pc}$$

$$M = 1.76 \pm 0.2 M_{\text{sun}}$$

$$R > 11.1 \text{ km}$$

- 2 hot spots surrounded by a cooler annular region
- non-magnetic, optically thick H atmosphere
- includes reasonable approximation of relativistic effects



Bogdanov 2013, Bogdanov et al. 2007

accuracy mainly limited by current low count numbers ➡ ideal NICER target

Neutron Star Radii from Pulse Profile Modeling

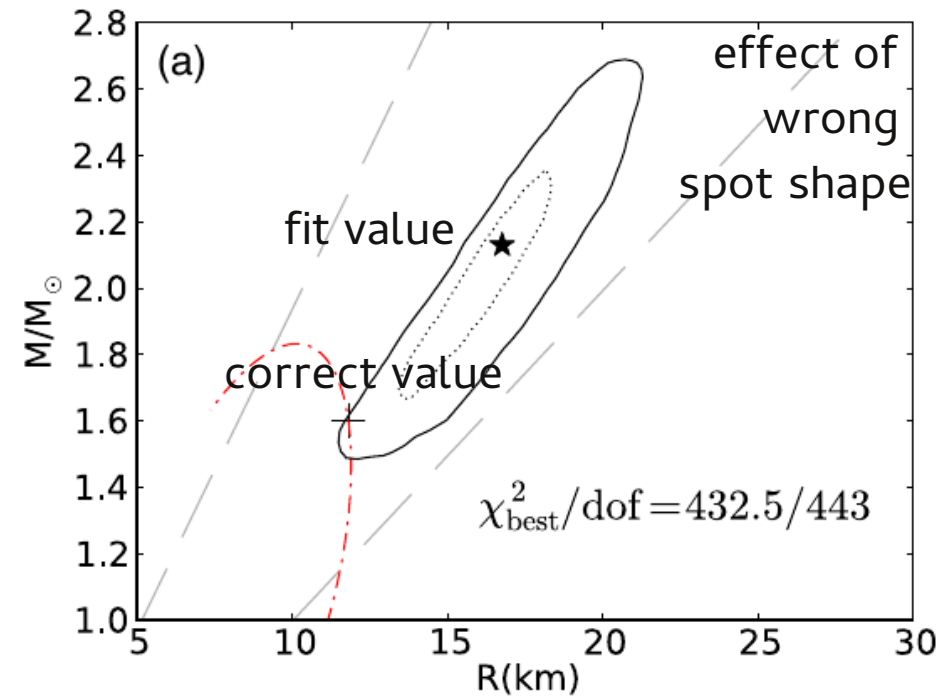
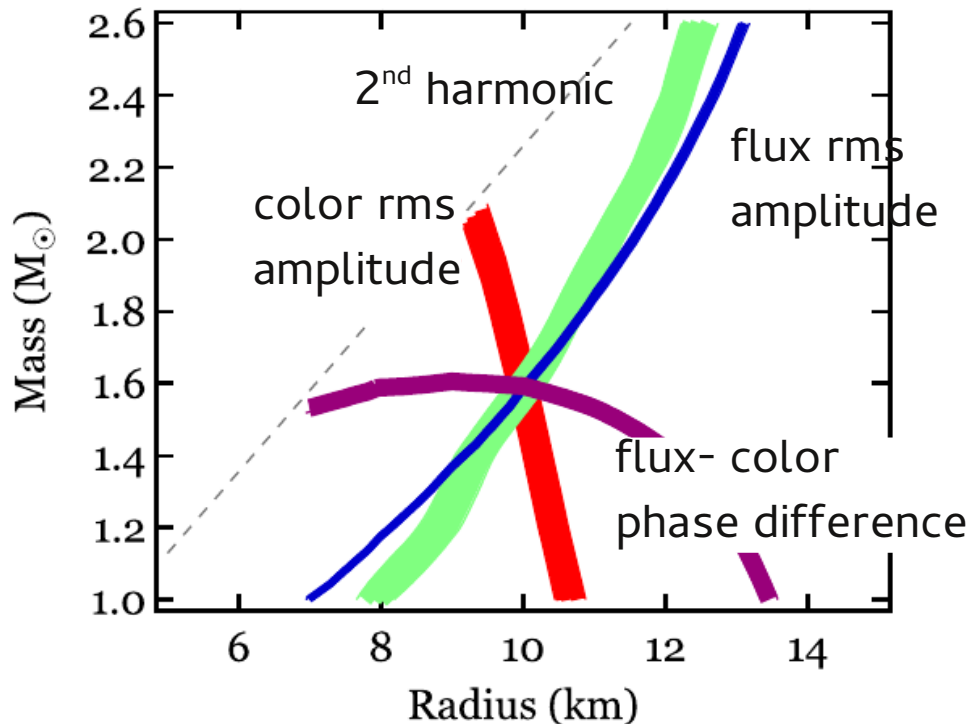
for fast ($\sim 300\text{--}800$ Hz)

can disentangle degeneracies using

- different energy bands
- higher harmonics

insensitive to several systematics (distance, background, inclination), but not all

Psaltis et al. 2014



Lo et al. 2013

could be also used for rotating hot spots created by burst (during rise)

In the future – e.g., using a LOFT-like telescope

Measuring Neutron Star Geometries

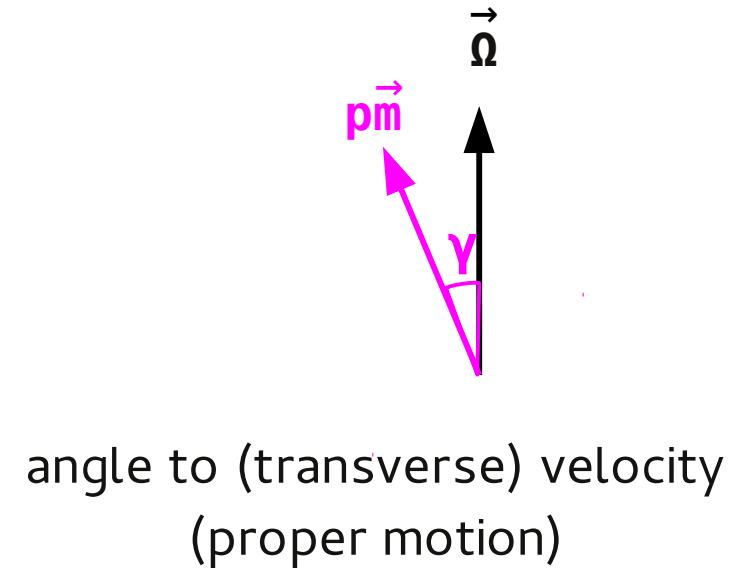
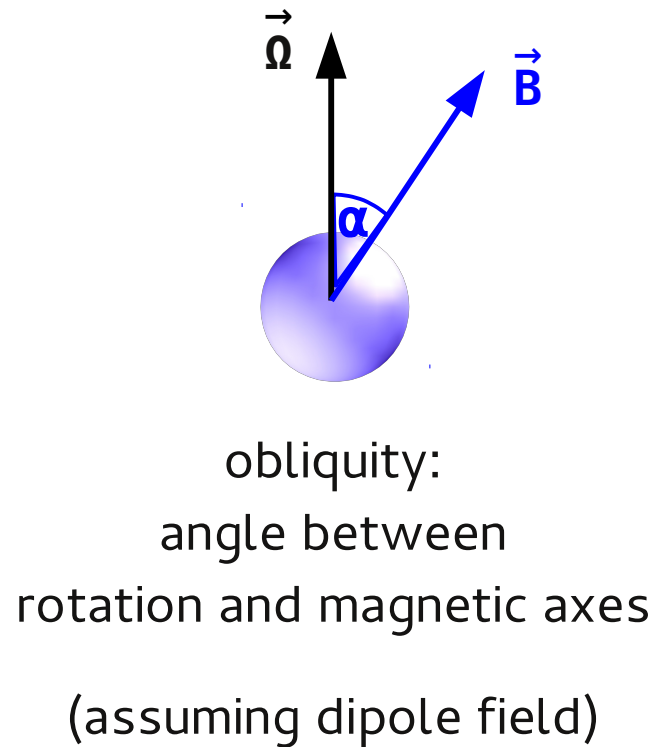
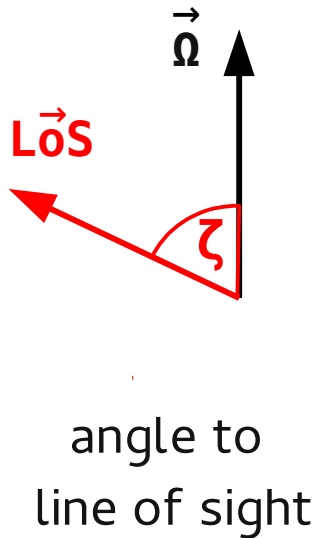
In order to constrain:

- NS kick / birth properties – SN explosion
- NS evolution (alignment of axes)

Strongly related to observed

- thermal and non-thermal emission properties
- pulsar wind properties

Angles in Neutron Star Geometry



Observational constraints come from:

- radio pulse polarization measurements
- pulse profile analysis
- proper motion measurements
- pulsar wind nebula properties

Neutron Star Geometry from Pulse Shape Fits

fit coherent radio and non-thermal gamma-ray pulse profiles:

- emission models work only partly, in particular if fit together

fit X-ray thermal pulse profiles:

- can be reasonable done for low ($<10^{10}$ G) magnetic fields
- depends on atmosphere model
- difficult for medium/high magnetic fields
(models only for few selected angle combinations available)

often:
superposition
of both

fit X-ray non-thermal pulse profiles:

- there are no applicable sophisticated models!

Neutron Star Geometry from Pulse Shape Fits

fit radio and gamma-ray together *Pierbattista et al. 2014*

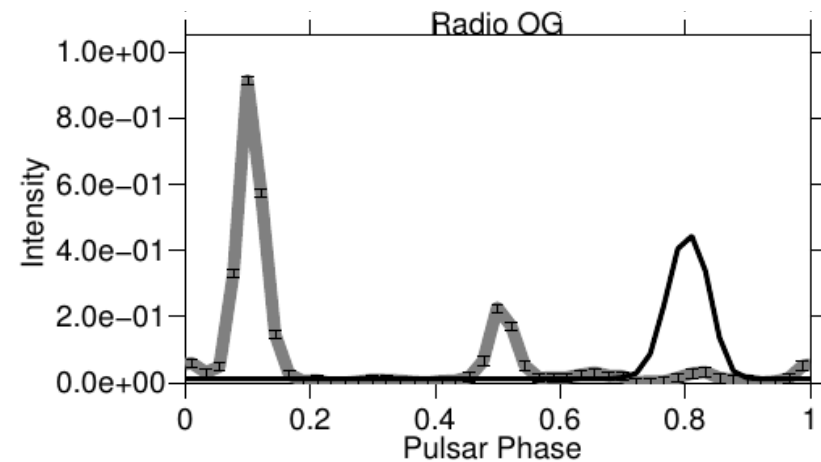
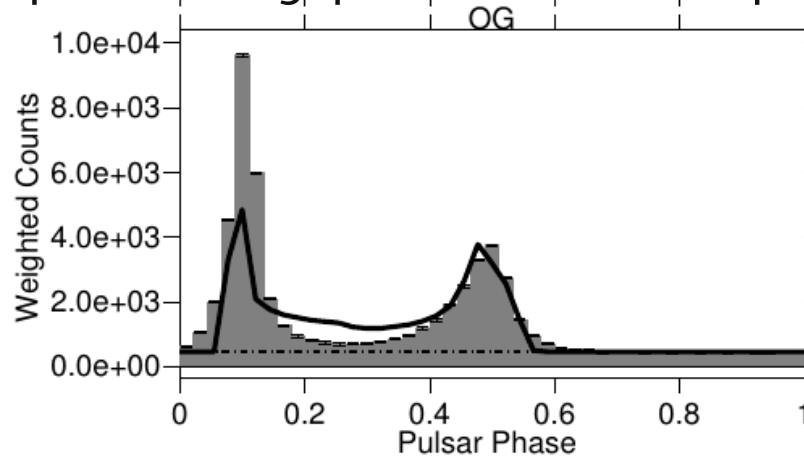
radio emission from rotating cone, gamma-ray emission model:

PC: polar cap model, SG: slot gap model, OG: outer gap model; OPC: one pole caustic model

	α_{PC}	α_{SG}	α_{OG}	α_{OPC}
	◦	◦	◦	◦
Crab	12_2^2	53_2^2	50_2^2	50_2^2
Vela	3_3^2	45_2^2	71_2^2	56_2^2

	ζ_{PC}	ζ_{SG}	ζ_{OG}	ζ_{OPC}
	◦	◦	◦	◦
Crab	14_2^2	74_2^2	74_2^2	73_2^2
Vela	4_2^2	69_2^2	83_2^2	77_2^2

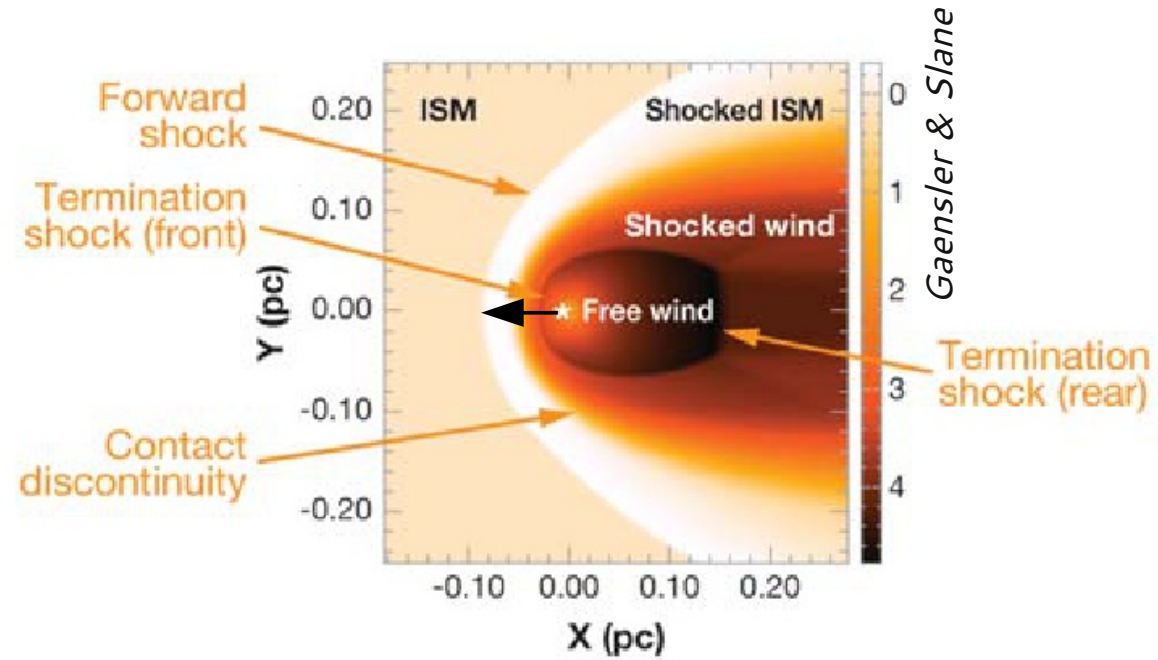
Example: outer gap model for Crab pulsar



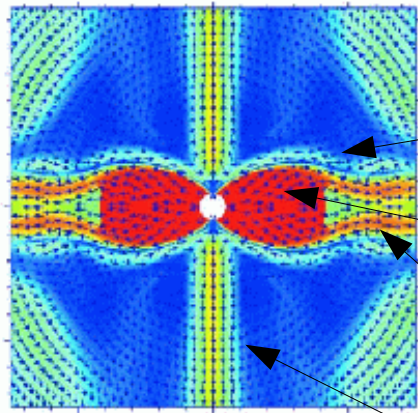
So far, magnetospheric emission models work only for some pulsars !

Axis Orientations from Pulsar Wind Nebulae

isotropic wind
 + the pulsar moves supersonically through the Interstellar Medium
 → a **bow shock** can form



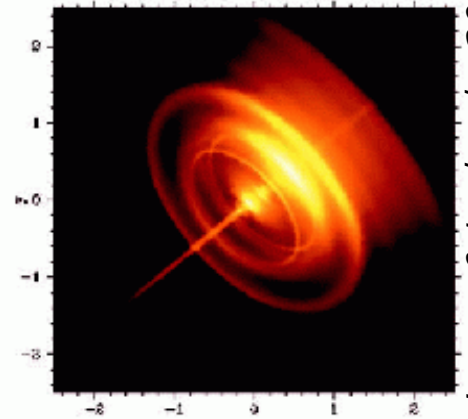
Komissarov & Lyubarsky 2003



velocity field

backflow
 unshocked wind
 shocked equatorial outflow
 jet

rotation & magnetic field
 anisotropic outflows
 → **jets & tori**



synchrotron radiation

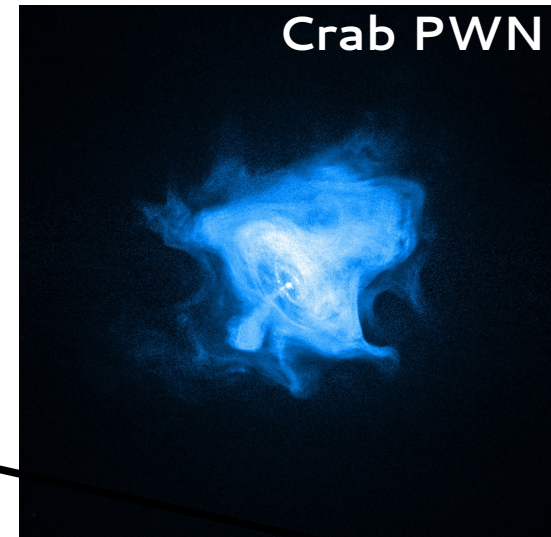
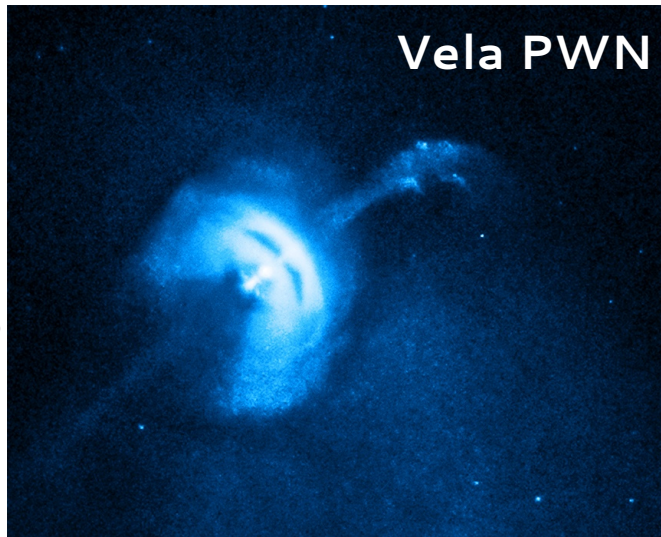
Komissarov & Lyubarsky 2003

Axis Orientations from Pulsar Wind Nebulae

PC: polar cap model, SG: slot gap model, OG: outer gap model; OPC: one pole caustic model

α_{PC}	α_{SG}	α_{OG}	α_{OPC}	α_{others}	ζ_{PC}	ζ_{SG}	ζ_{OG}	ζ_{OPC}	ζ_{others}
o	o	o	o	o	o	o	o	o	o
Crab	12_2^2	53_2^2	50_2^2	50_2^2	14_2^2	74_2^2	74_2^2	73_2^2	$60.1 - 64.35^{(2)}$

Pavlov, Kargaltsev et al. / CXO

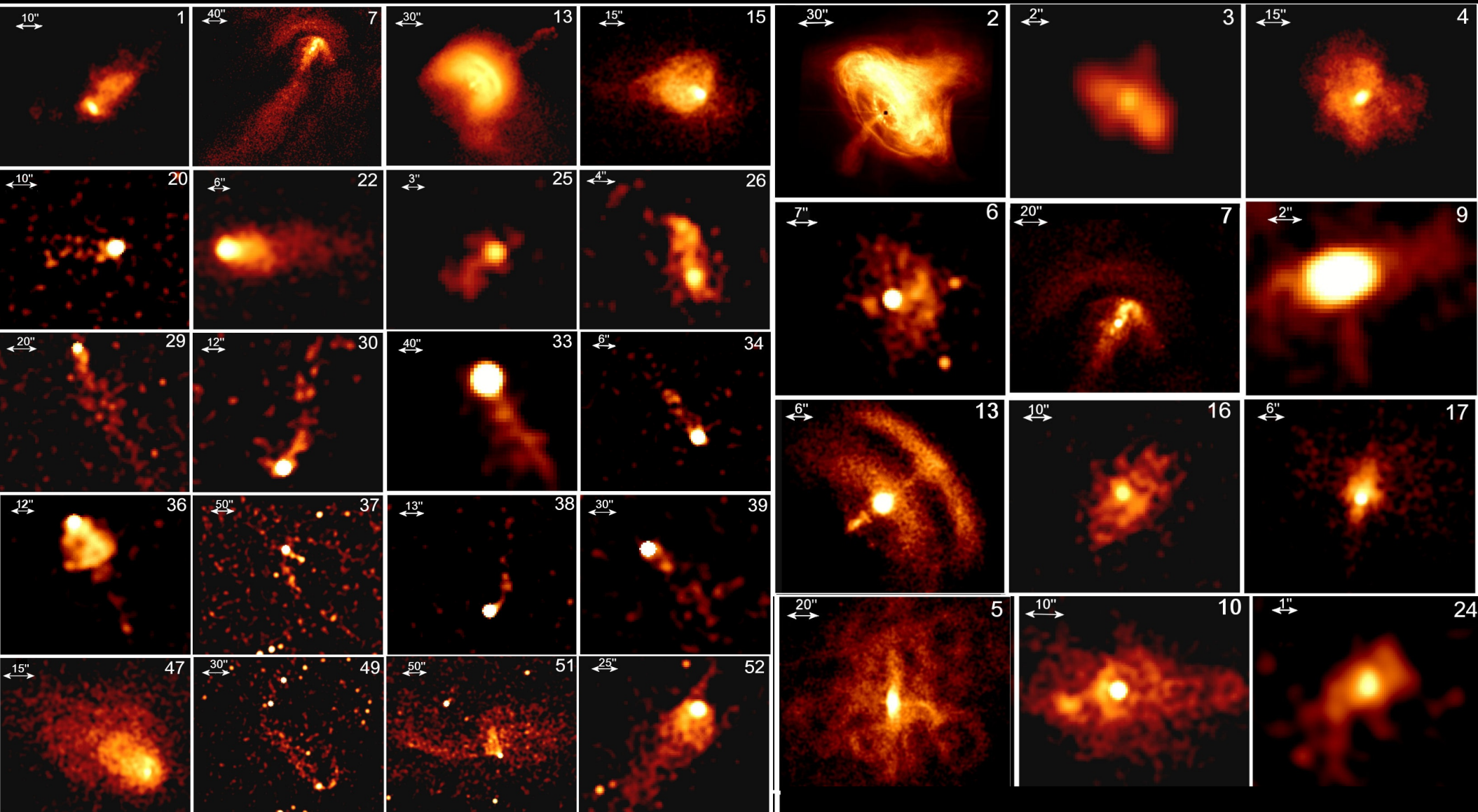


Weiskopf et al. / CXO

Vela	3_3^2	45_2^2	71_2^2	56_2^2	$43^{(1)}/70^{(3)}$	4_2^2	69_2^2	83_2^2	77_2^2	$62.95 - 64.27^{(2)}$
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PWNe are very diverse and not fully understood

One problem: environment (density, magnetic field, ionization) often unknown



Summary

lots of progress in constraints from observations in the last decade;
can now probe small structures on NS surface and in NS magnetosphere

Problems:

- calibration of instruments, in particular cross-calibration
- count statistics (X-rays, gamma-rays)
- few UV/optical constraints
- adequate models for connecting NS interior physics to small-scale phenomenology of surface/magnetosphere
(→ e.g. talk by Taner Akgün)