Introduction to Astronomy at High Energies

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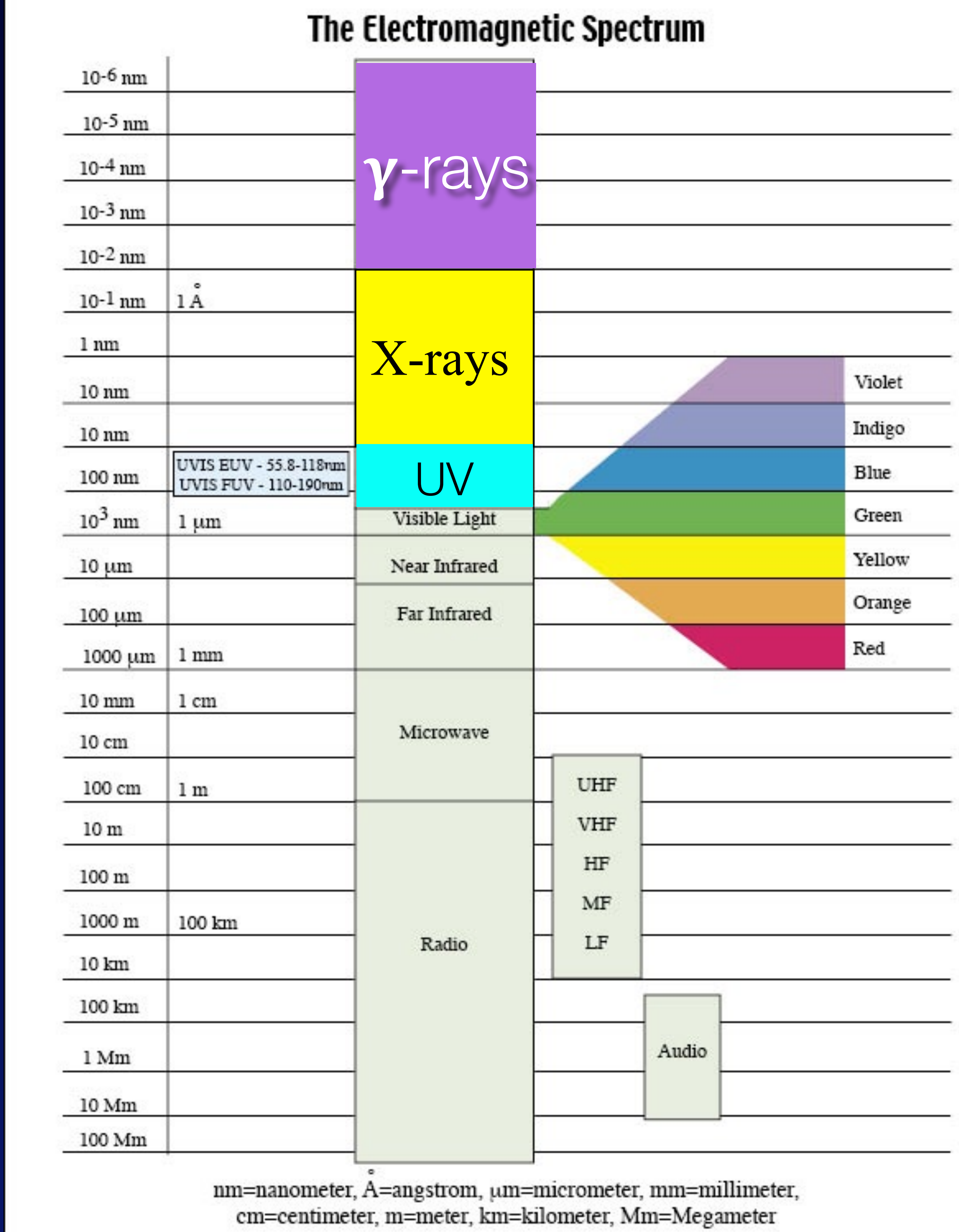
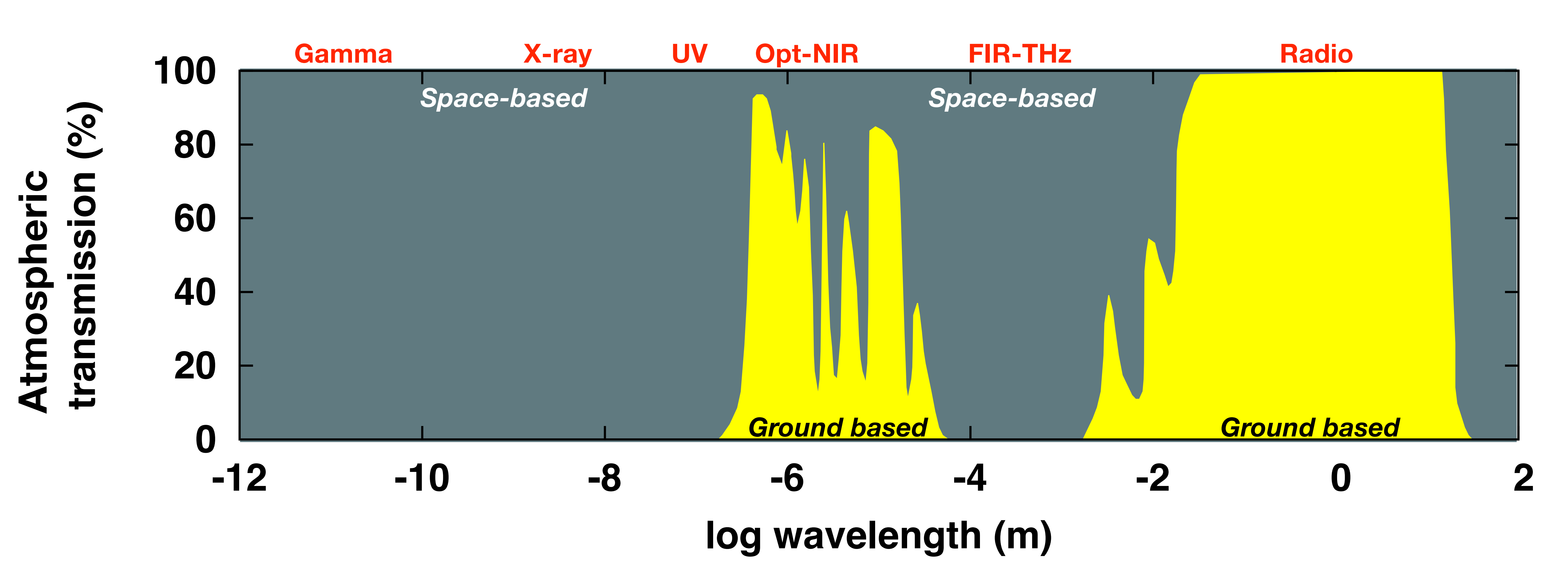
Photon energies in the High Energy regime are large enough to dislodge electrons from atoms.

Typically ~0.1-10 keV band is called “Soft” X-rays, ~10-500 keV band is called “Hard” X-rays and above 500 keV, gamma rays. Between Visible and Soft X-rays lie the Ultraviolet bands (NUV, FUV, EUV)





High Energy photons do not penetrate the Earth's atmosphere
So Astronomy at these energies is done using balloons, rockets and satellites

For very high energy (TeV+) gamma rays the atmosphere itself can be used as a detector - air showers / Cherenkov radiation

This workshop will feature three missions: Chandra, XMM and AstroSat covering UV to hard X-rays

Scope of this lecture will be to introduce astronomy in the X-ray bands

Early Milestones in X-ray Astronomy

First Rocket Flight with X-ray detector

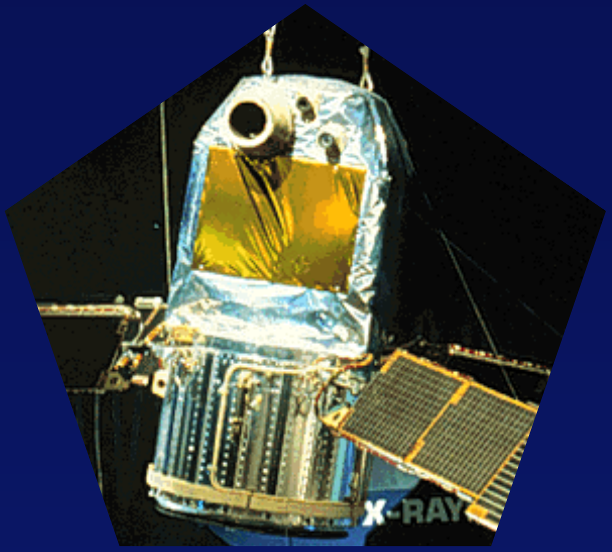
Jan 28, 1949, USA: detected X-ray emission from the Sun

First X-ray detection from outside solar system

June 12, 1962: US sounding rocket detects Sco X-1

First X-ray Astronomy Satellite Mission

Uhuru (NASA) launched 12 Dec 1970 from Kenya. Surveyed the sky in 2-20 keV band. Catalogued 339 sources.

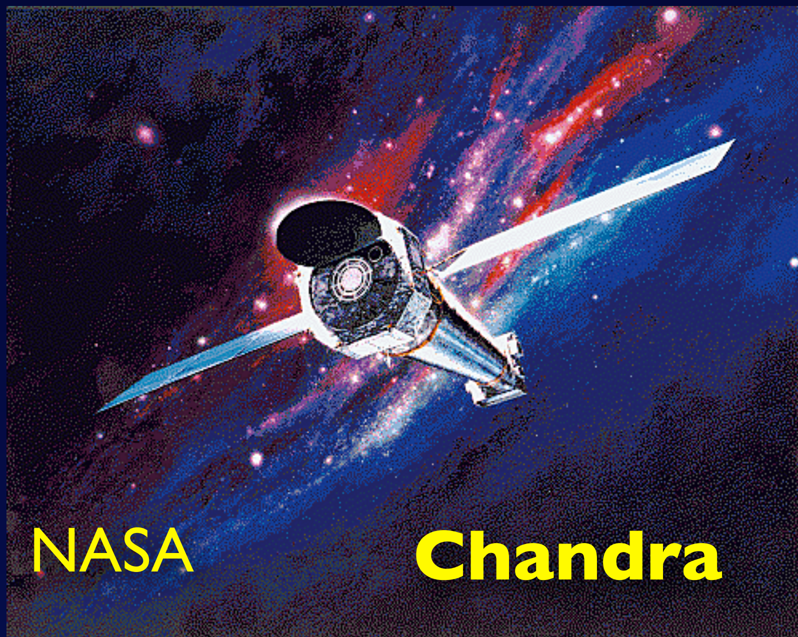


Uhuru replica in US Air and Space Museum

The four dimensions of X-ray Astronomy

- Imaging
- Spectroscopy
- Timing (flux variability)
- Polarimetry

Some operating X-ray Astronomy missions



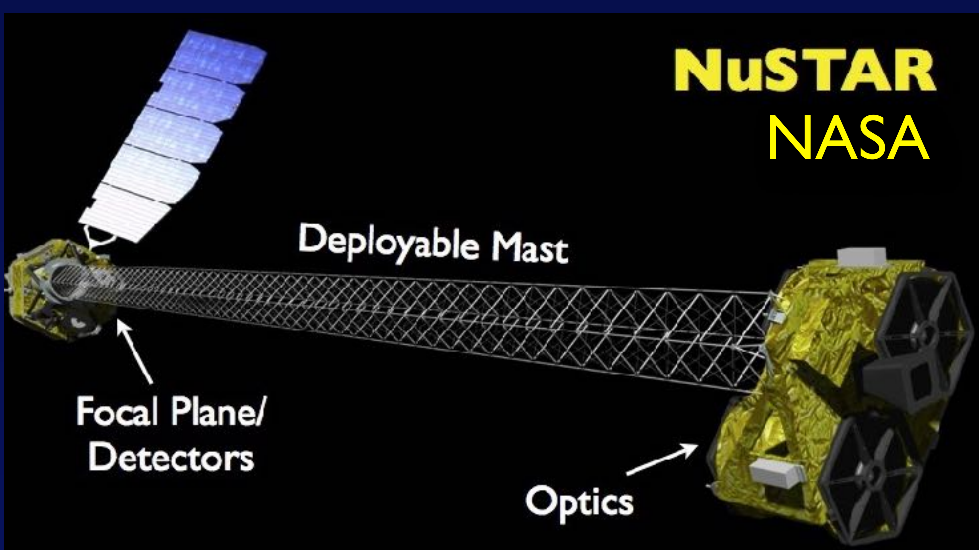
High res imaging,
grating spectroscopy

XMM - Newton

Medium res imaging,
grating spectroscopy

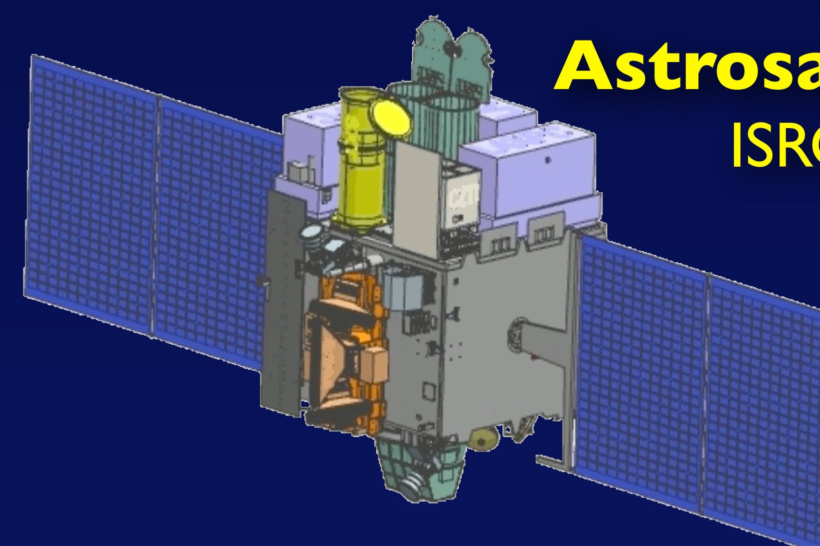
Swift NASA

Med res imaging, low-res spectroscopy, large FOV, quick slew, soft - hard X

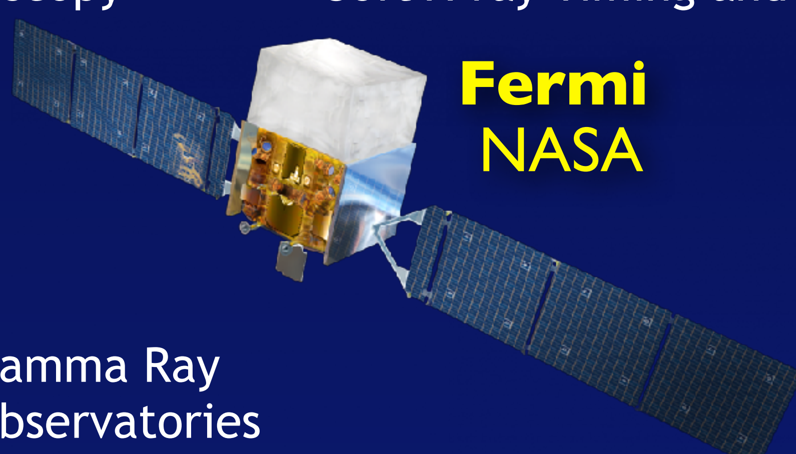


Hard X-ray imaging & spectroscopy

Soft X-ray Timing and Spectroscopy



Simultaneous multi-wavelength
Timing, long-term monitoring
Broad band spectroscopy



Fermi
NASA

Gamma Ray
Observatories

Pictures from NASA, ESA and ISRO

How are X-rays produced ?

Requires highly energetic particles

In the cosmic setting, X-rays are produced by three main processes:

1. From very hot gas (Temperature > 1 million K), thermal bremsstrahlung emission, atomic transitions

2. From relativistic electrons streaming through magnetic fields, synchrotron emission

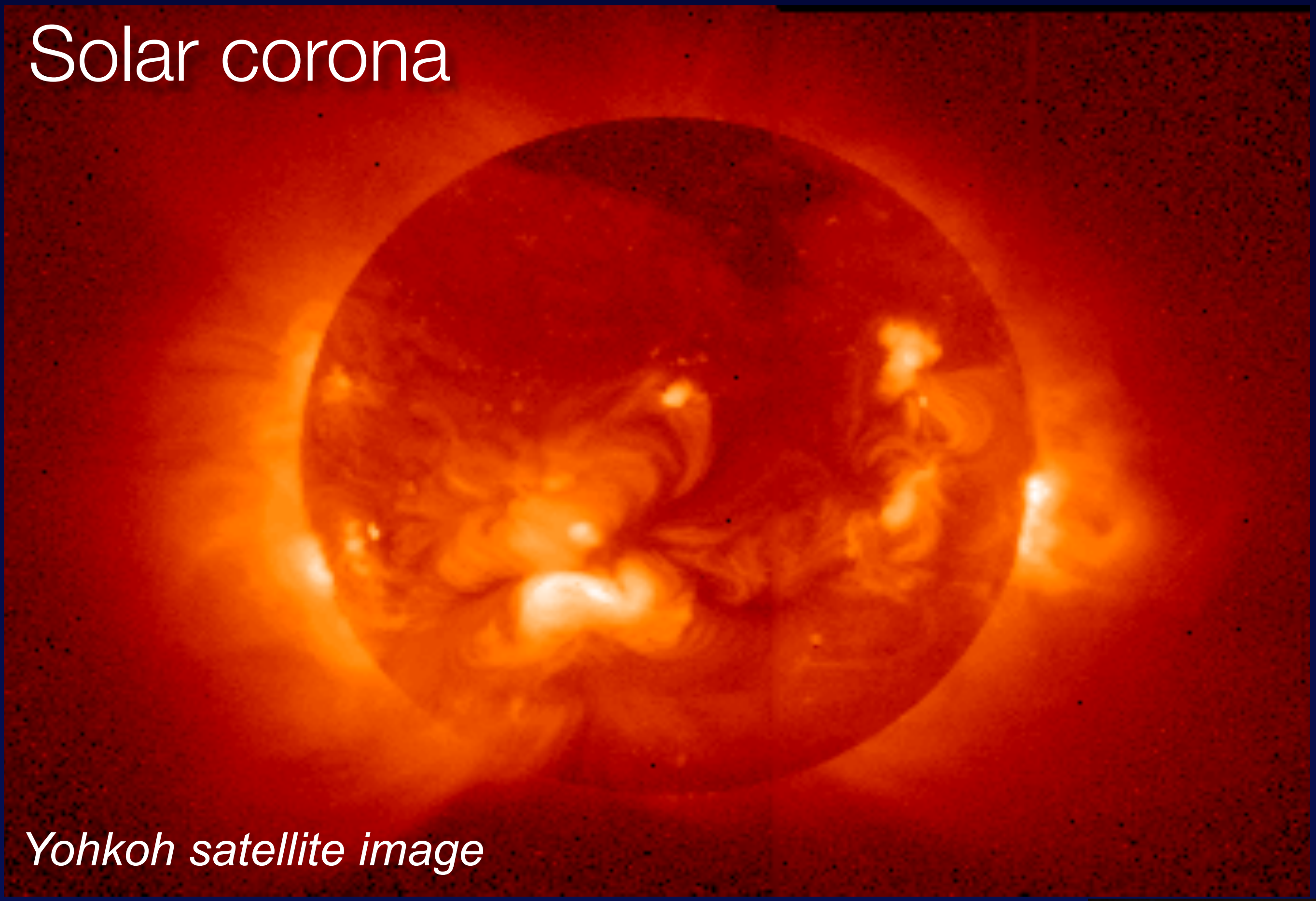
3. Compton Scattering of low-energy radiation field by energetic electrons

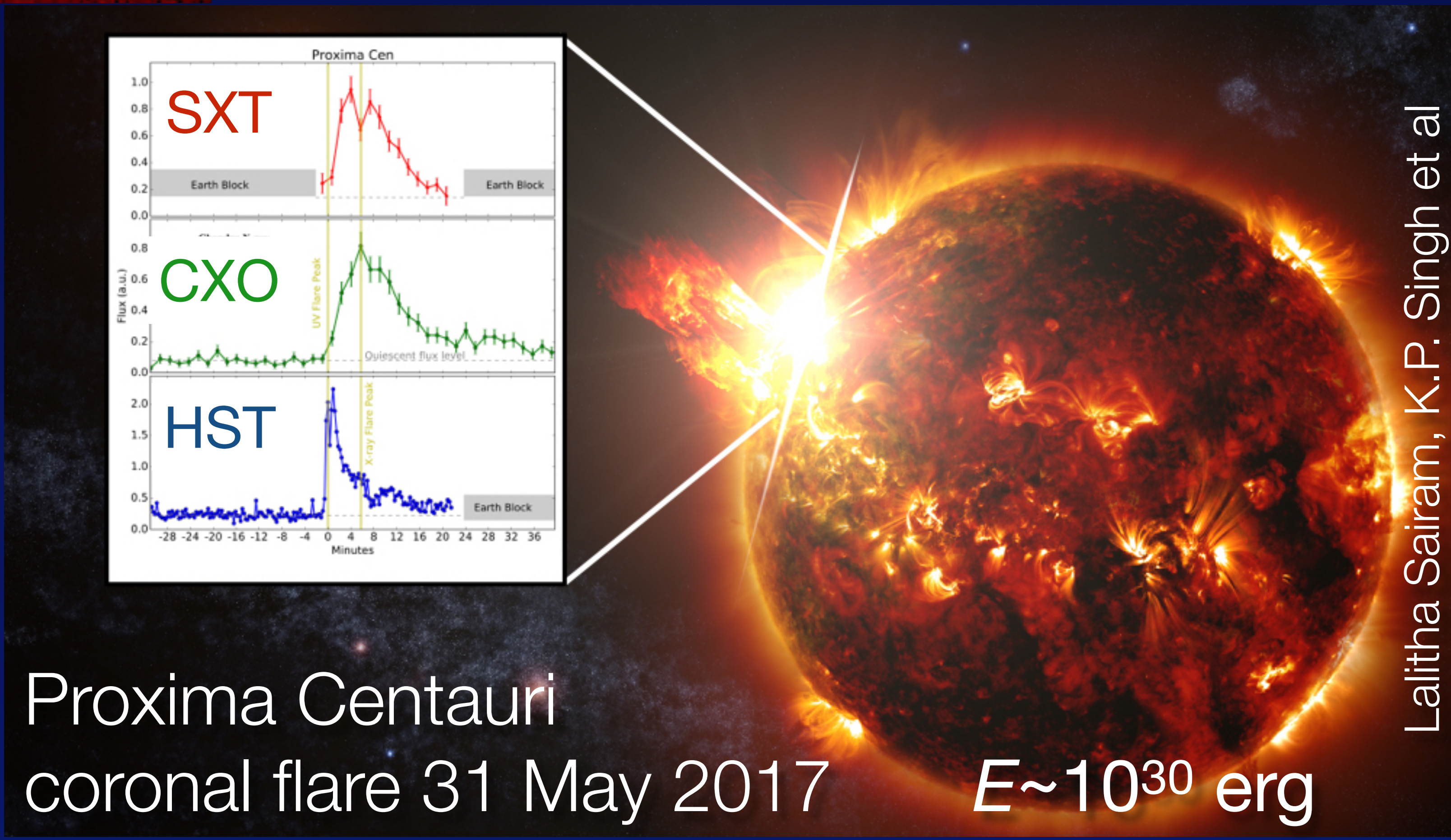
A wide variety of celestial objects produce X-rays

- Accreting neutron stars and black holes are among the brightest

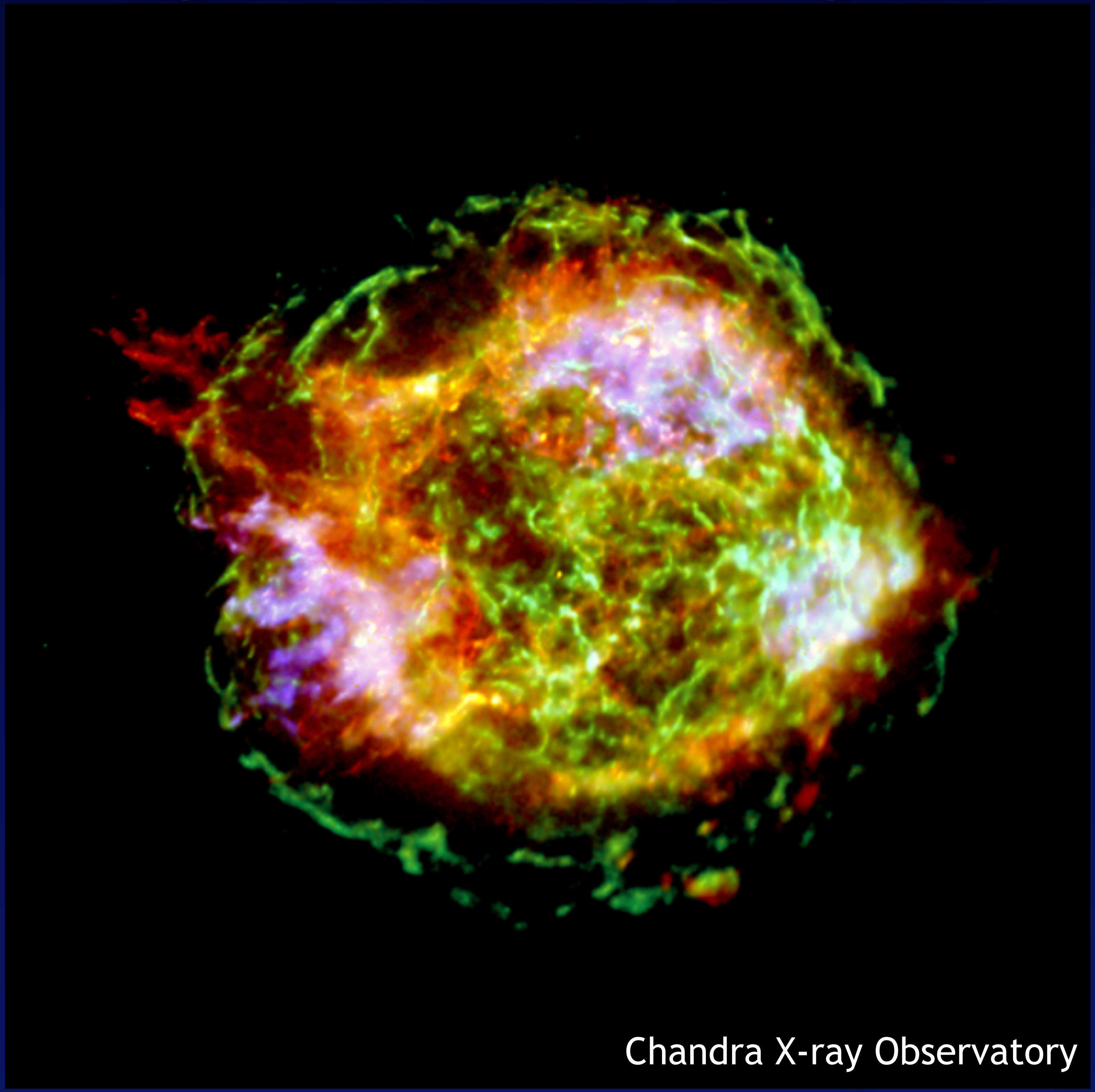
- Solar type stars, remnants of supernovae, diffuse hot gas in galaxies and clusters, gamma ray burst sources are among other prominent sources of X-rays

Coronal X-ray emission in low-mass stars





Supernova Remnant Cassiopeia A



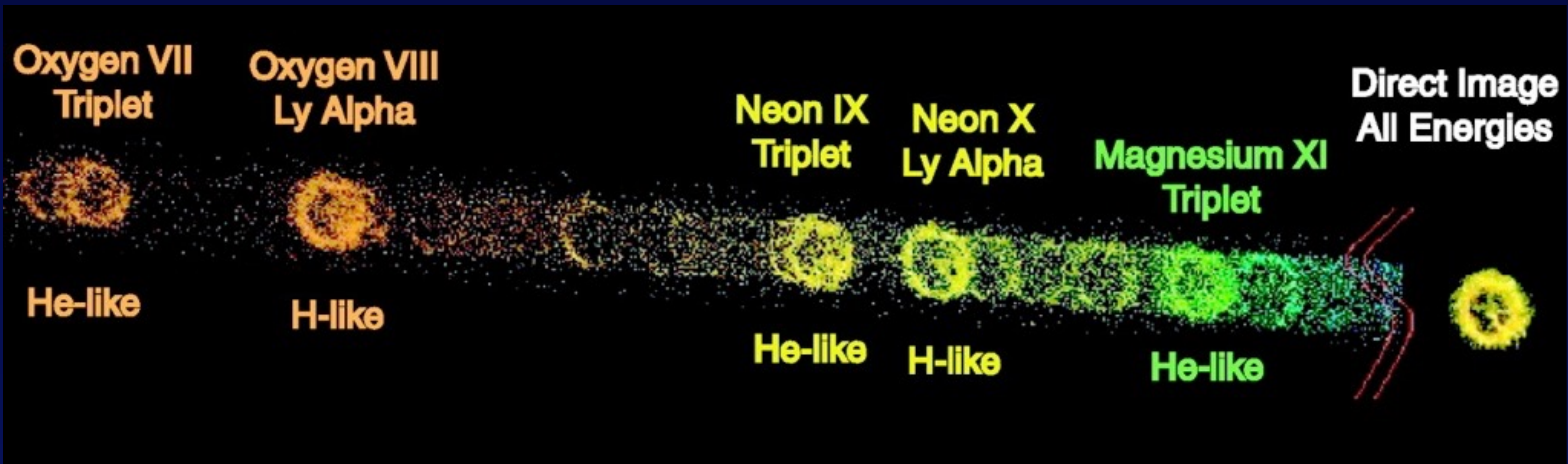
Hwang et al 2004

- Forward Shock
- Reverse Shock

- Thermal continuum
- Synchrotron
- Line emission

SNR map in spectral lines: Grating spectroscopy

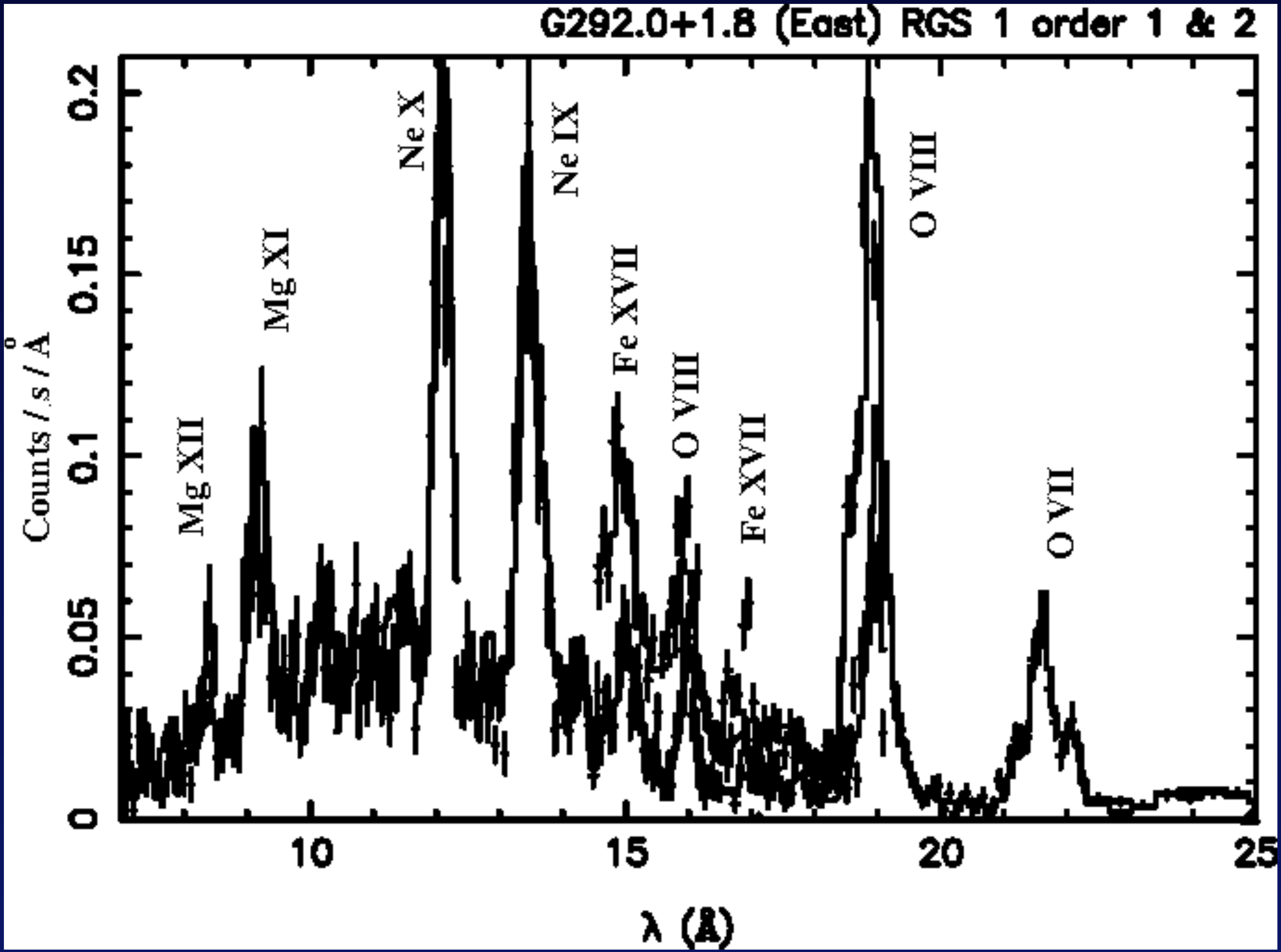
SNR 1E0102.2-7219 Chandra HETG



Flanagan et al 2004

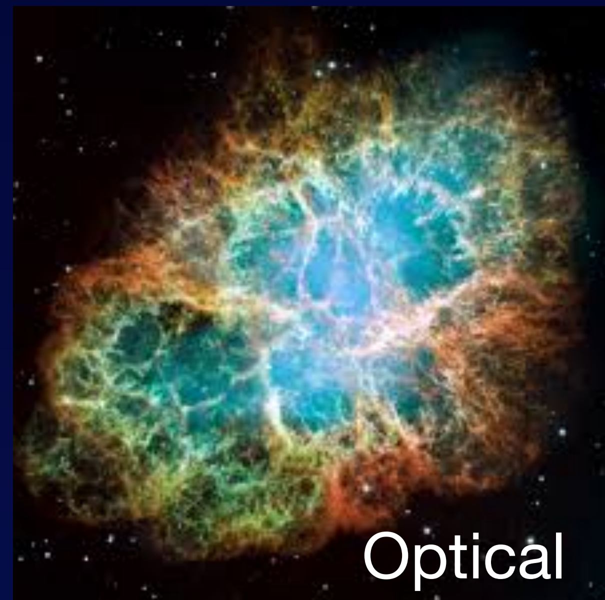
Composition, distribution and thermal state of matter
Nucleosynthesis and gas enrichment

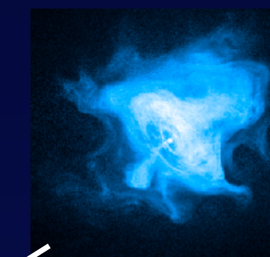
XMM-Newton RGS spectrum

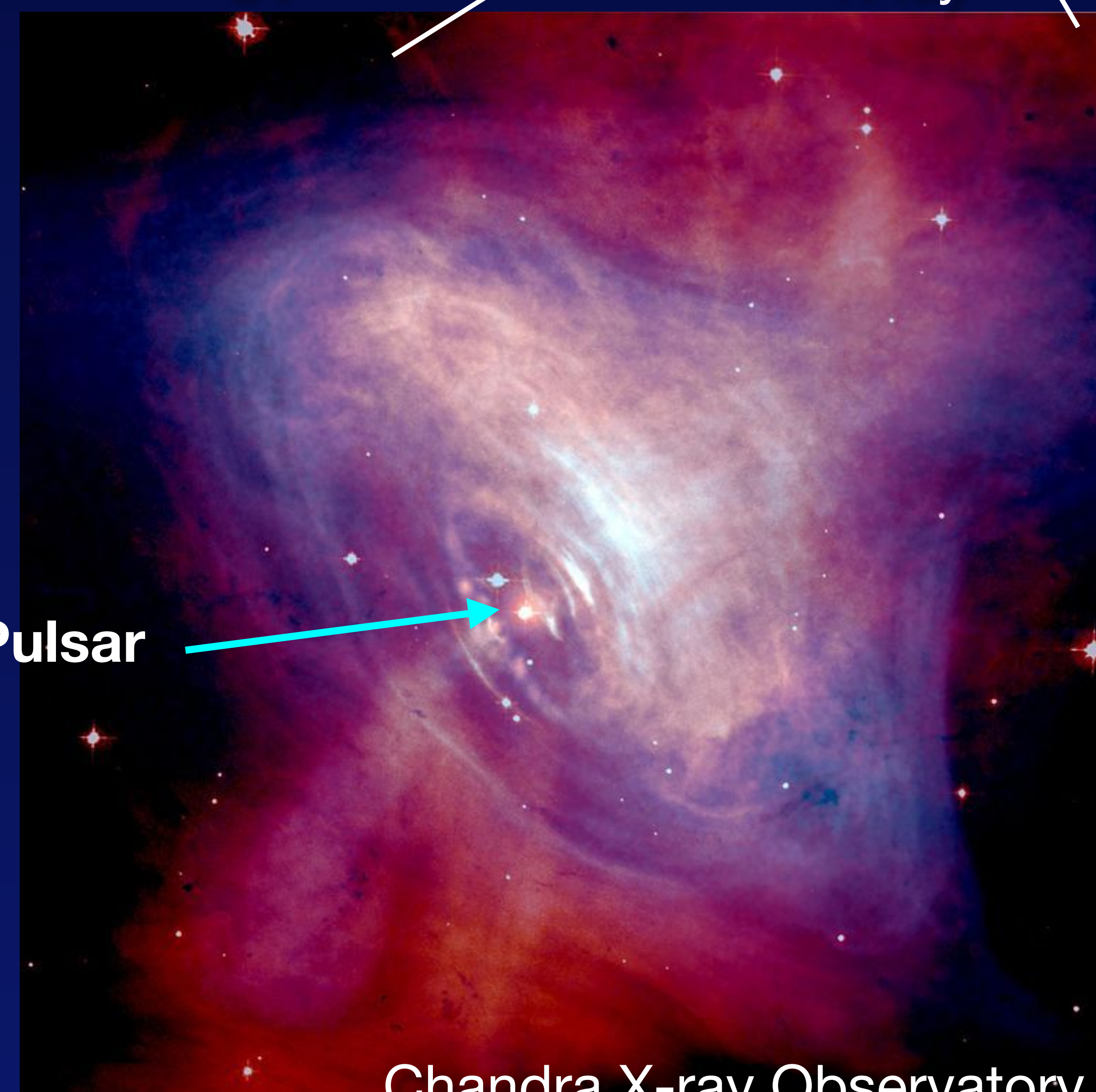


Vink et al 2004

The Crab Nebula



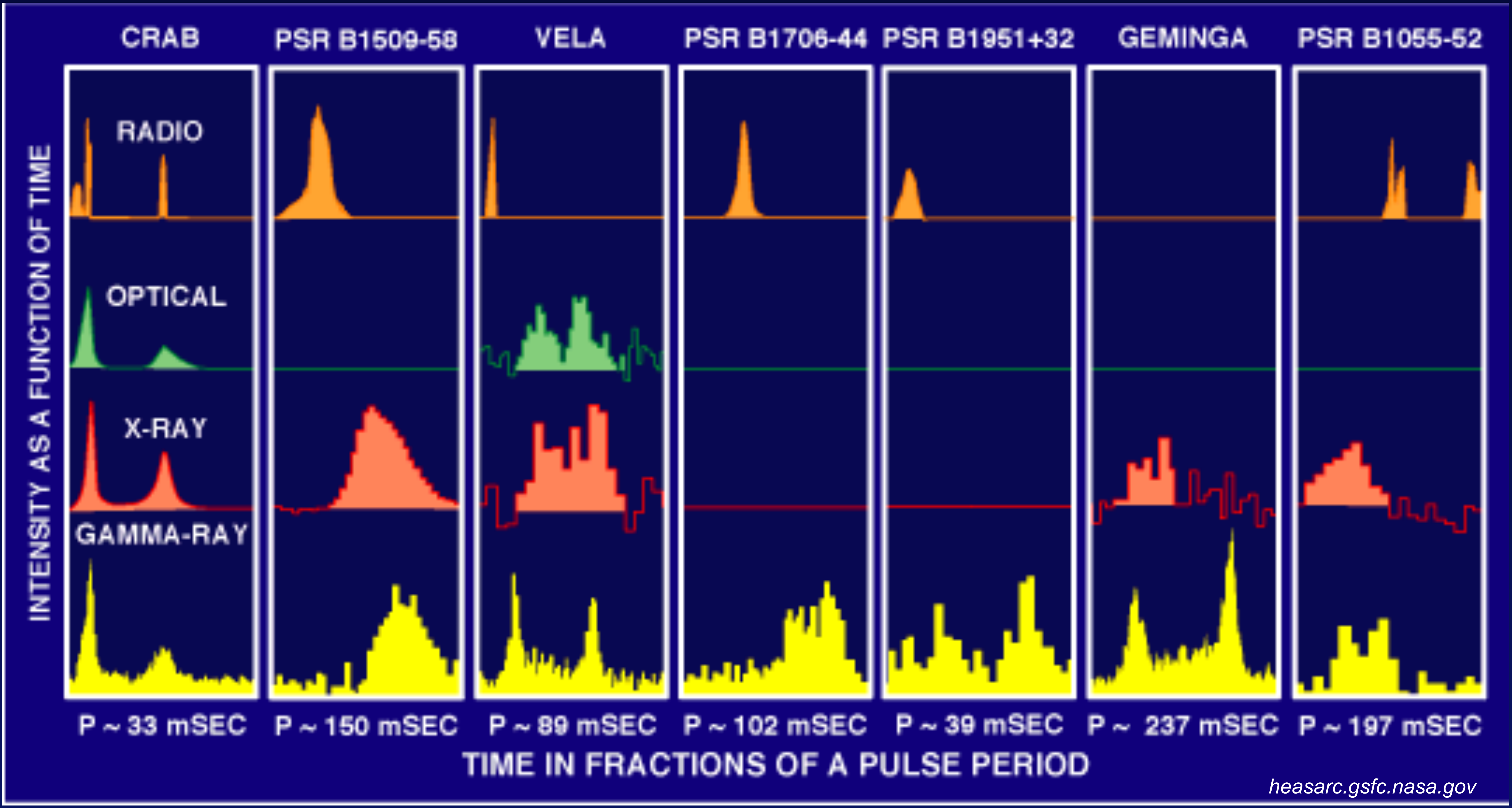


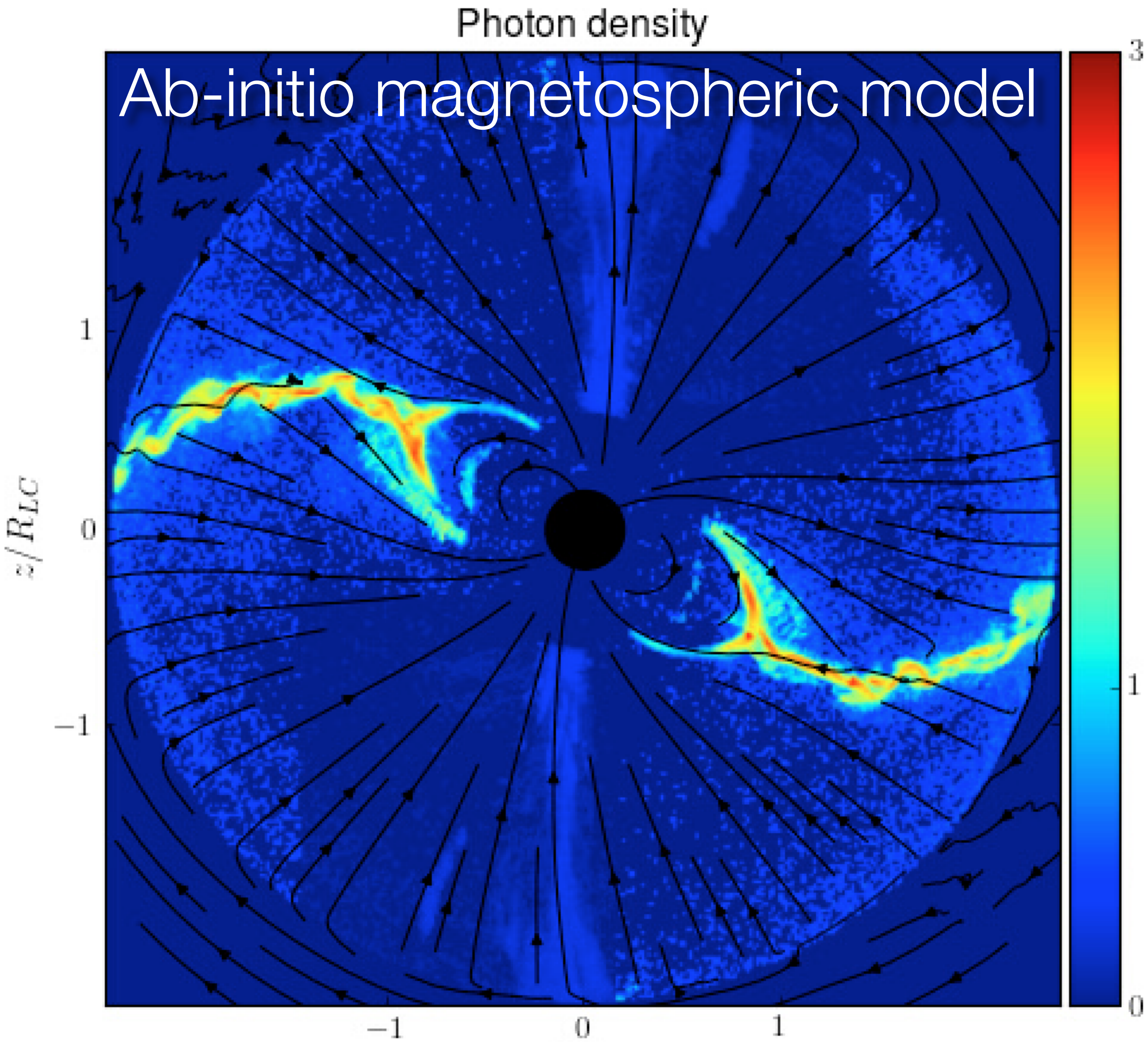


Featureless power-law
X-ray spectrum

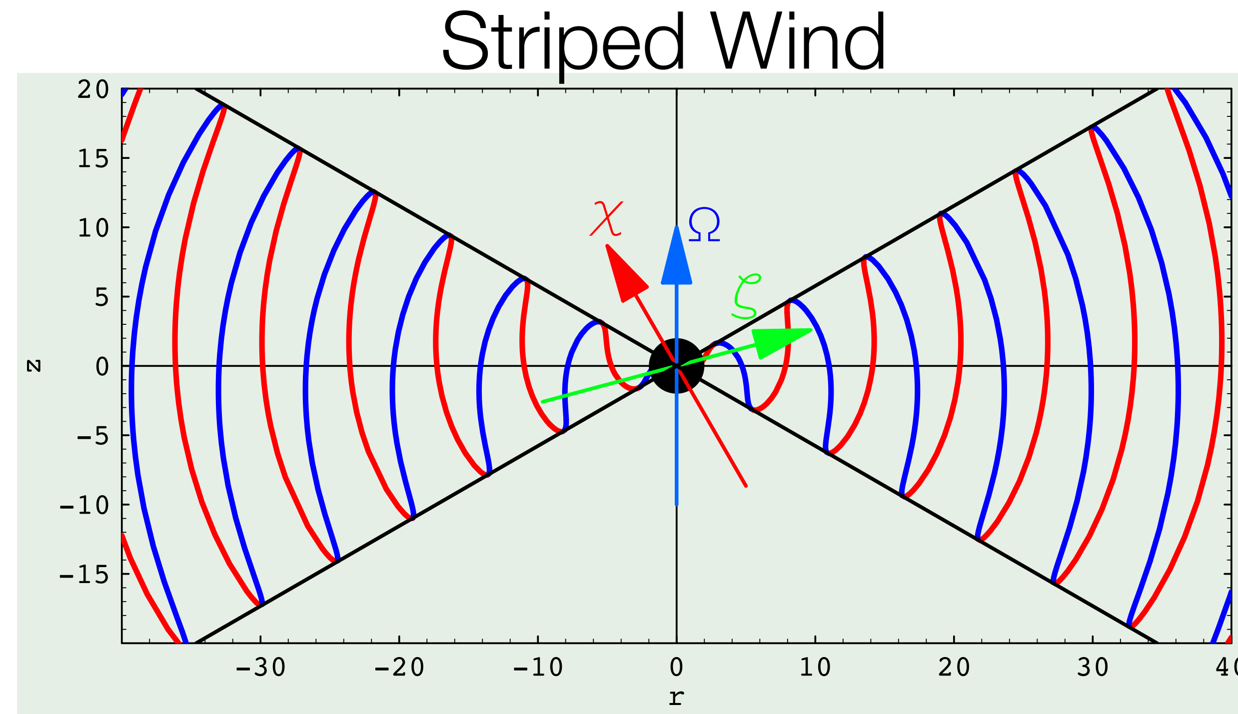
Emission from non-thermal relativistic plasma generated by the pulsar

Magnetospheric emission from isolated pulsars in multiple wavebands





Philippov & Spitkovsky 2018



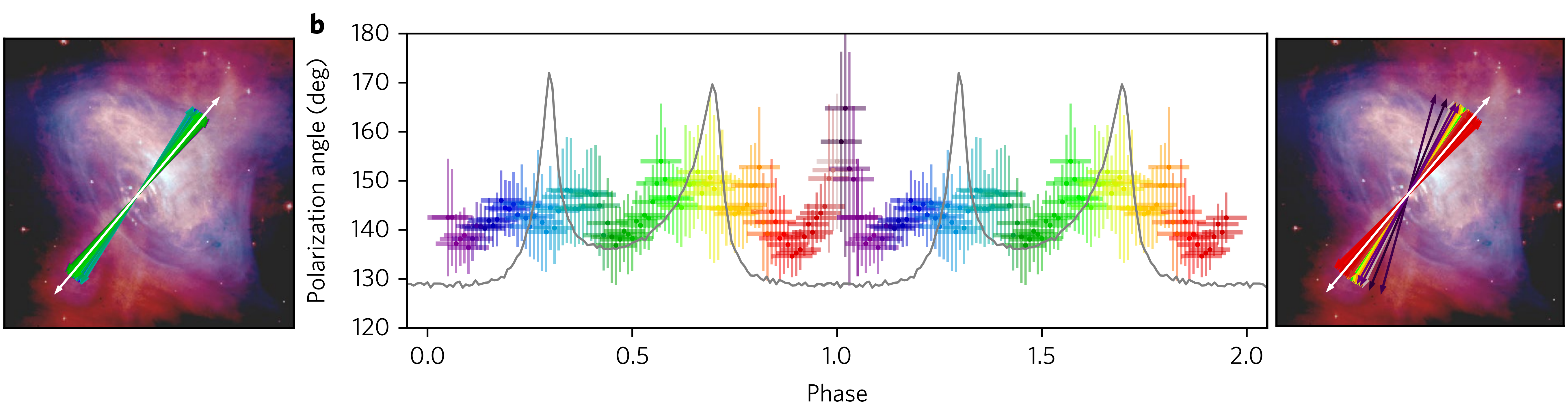
Petri 2013

Clues from polarisation measurements

OSO-8 (Weiskopf et al 1978)

POGO+ (Chauvin et al 2017)

AstroSat CZTI (Vadawale et al 2018)

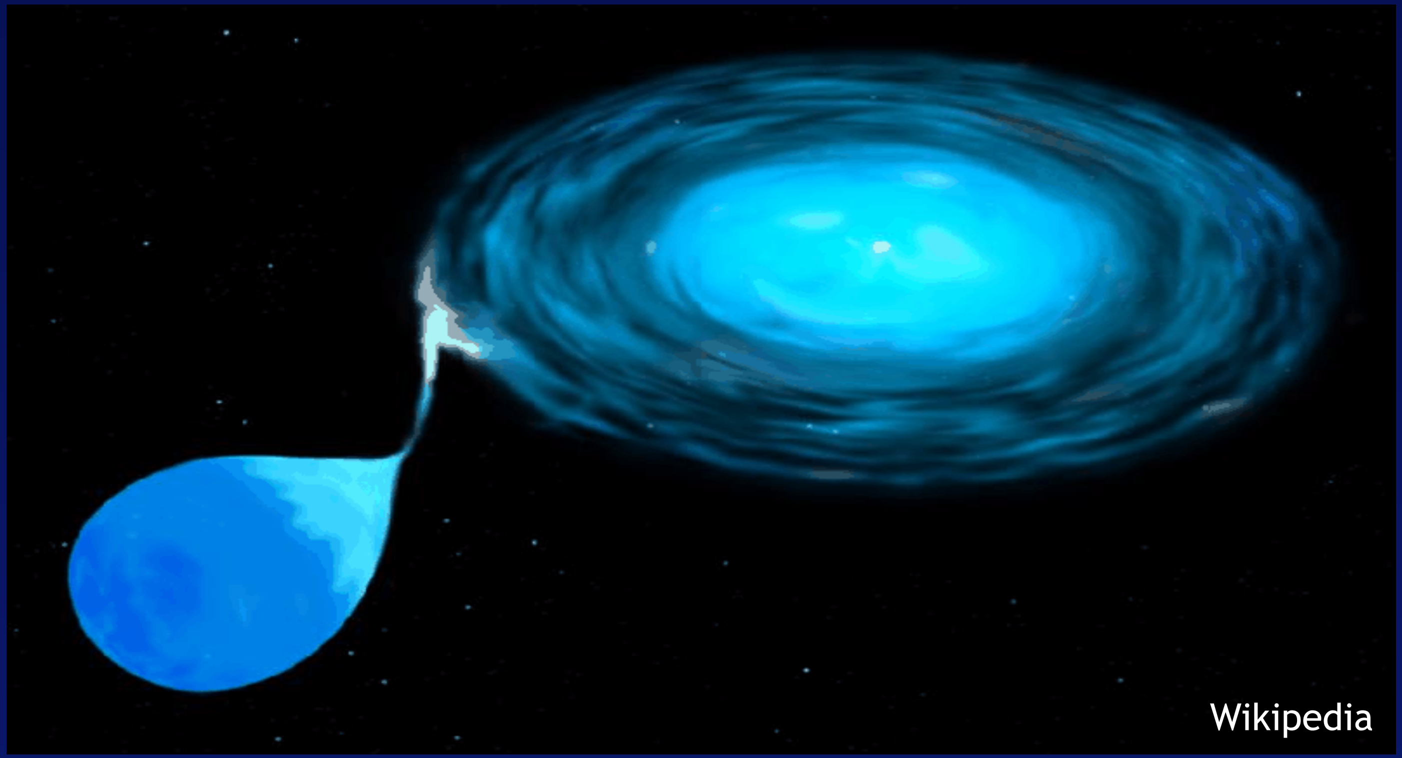


A wide variety of celestial objects produce X-rays

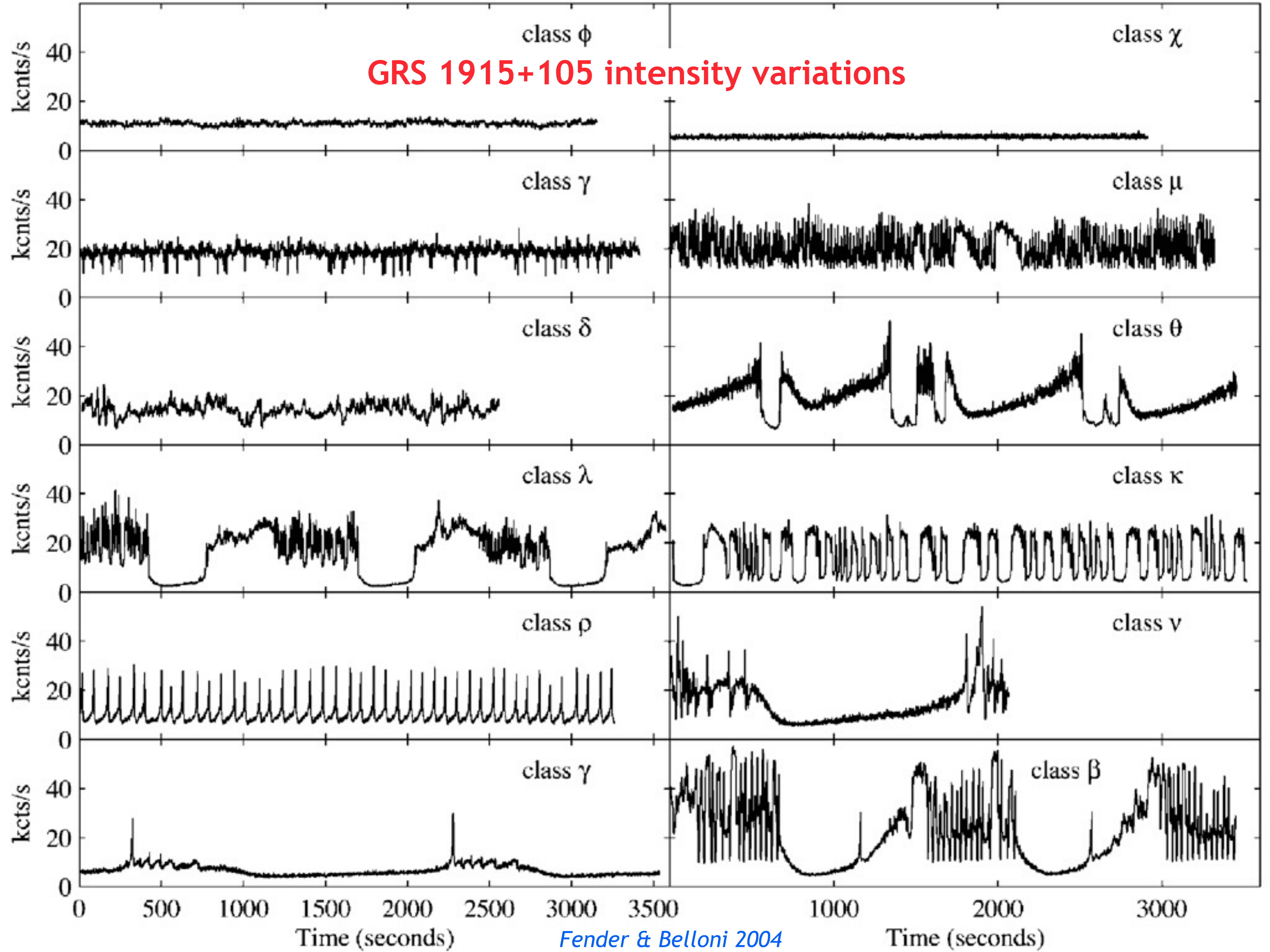
- Accreting neutron stars and black holes are among the brightest

- Solar type stars, remnants of supernovae, diffuse hot gas in galaxies and clusters, gamma ray burst sources are among other prominent sources of X-rays

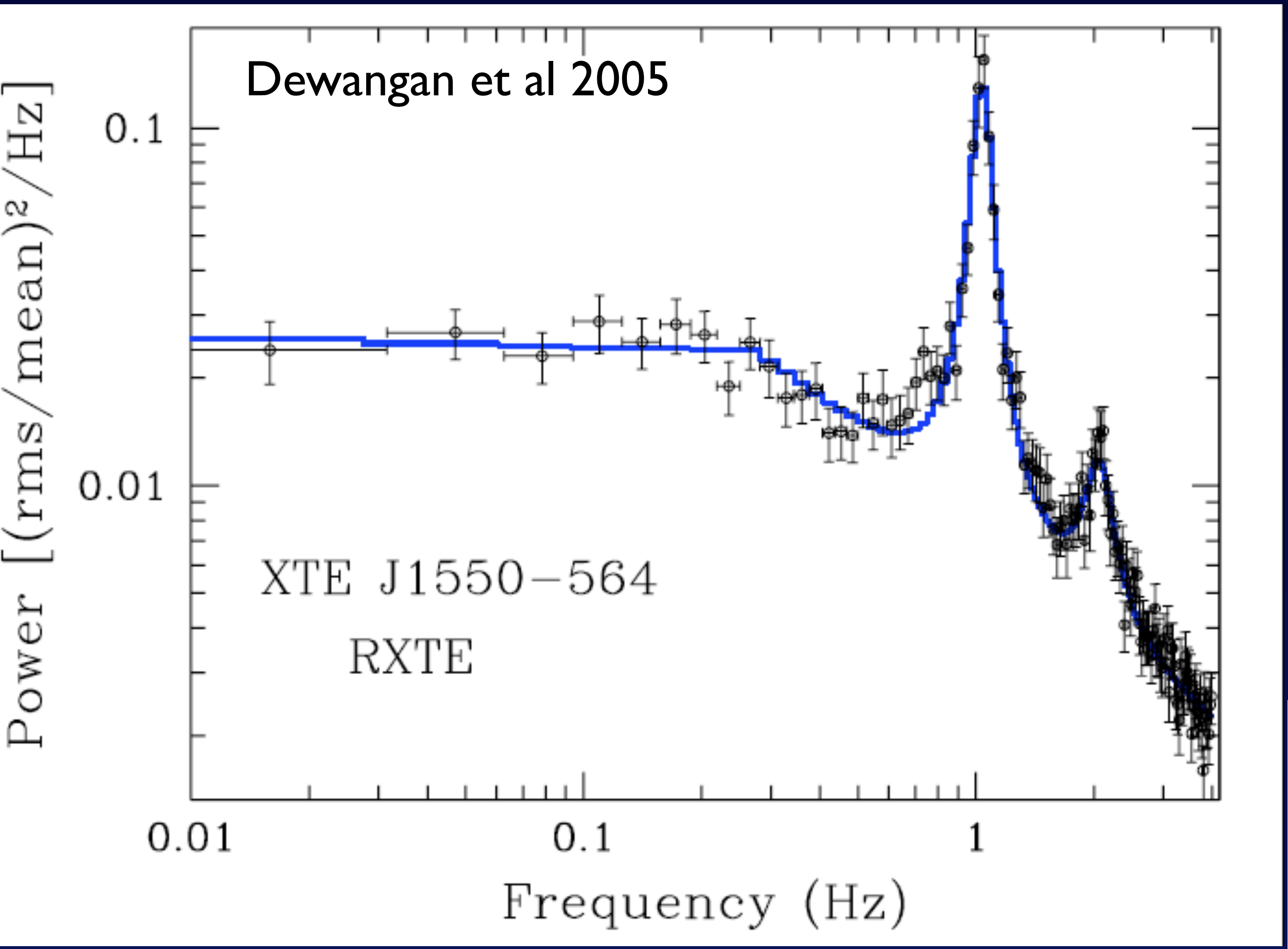
The X-ray sky is extremely variable. Bright sources appear and disappear at short time scales

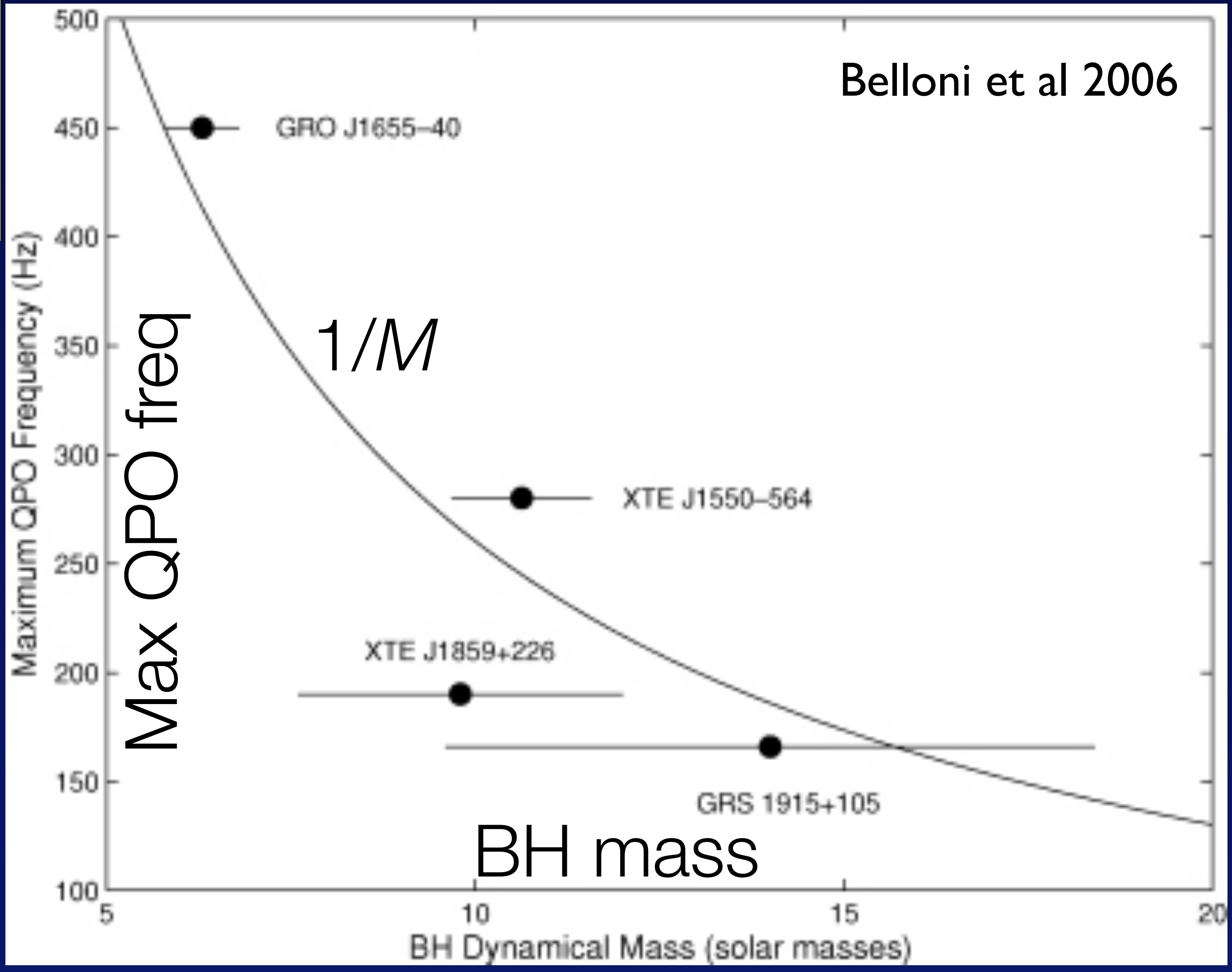


NGC 1637


GRS 1915+105 intensity variations
class φ
class χ
class γ
class μ
class δ
class θ
class λ
class κ
class ρ
class ν
class γ
class β
kcnts/s
kcts/s
Time (seconds)
Time (seconds)
Fender & Belloni 2004

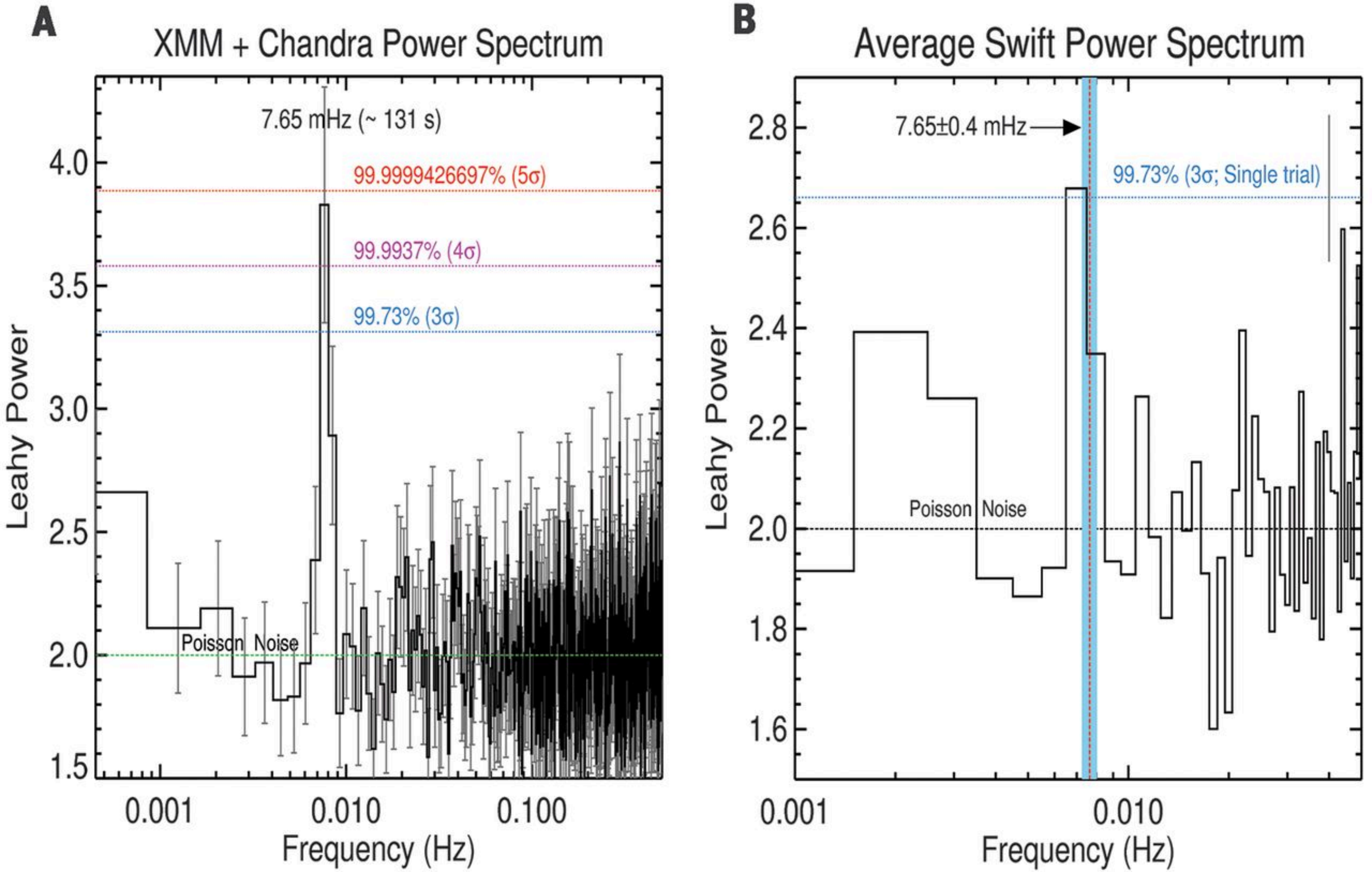
QPO in Black Hole Binary systems





QPO in Tidal Disruption Event

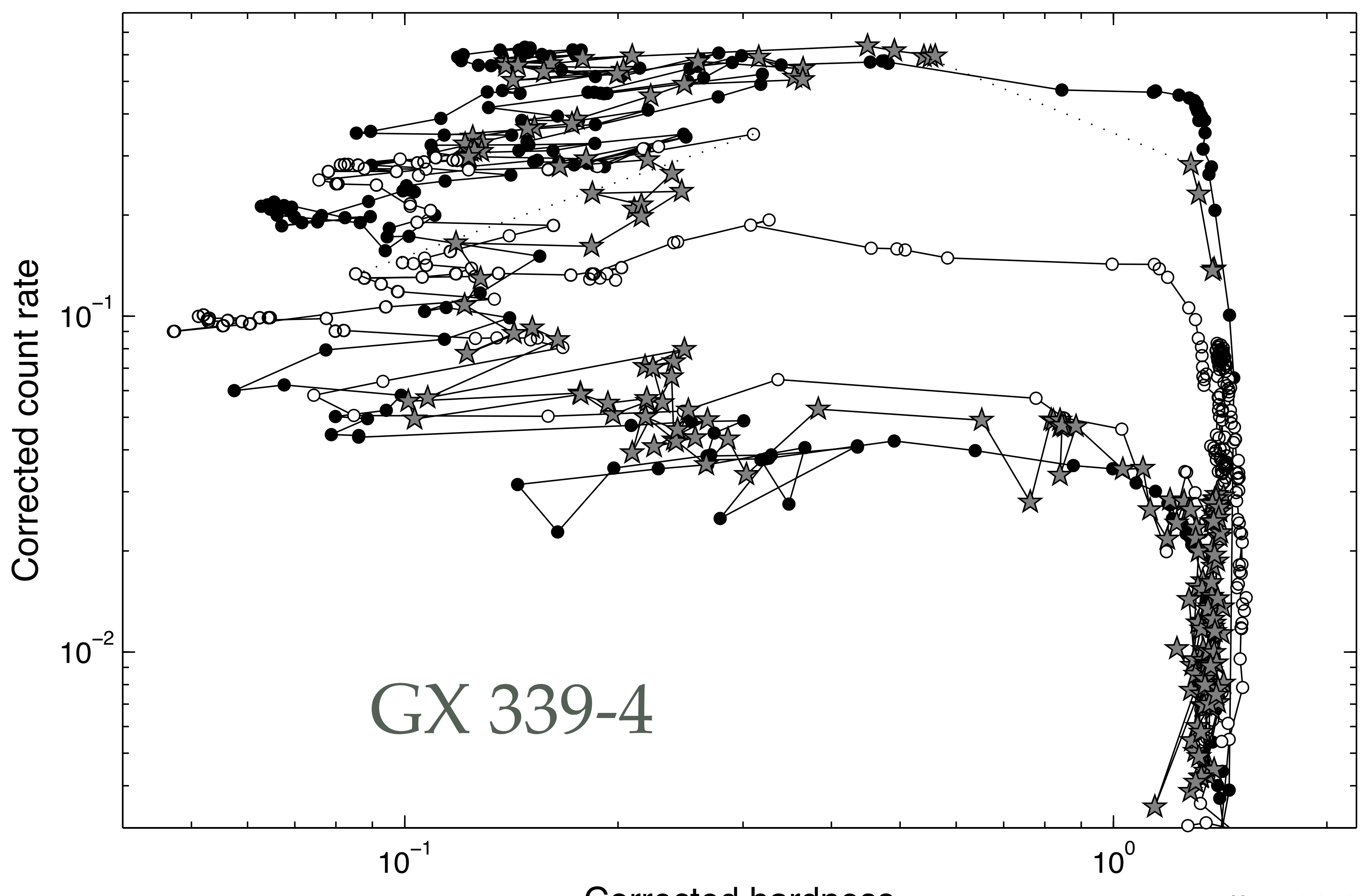
ASASSN 14 li



Indicates fast spin of the BH

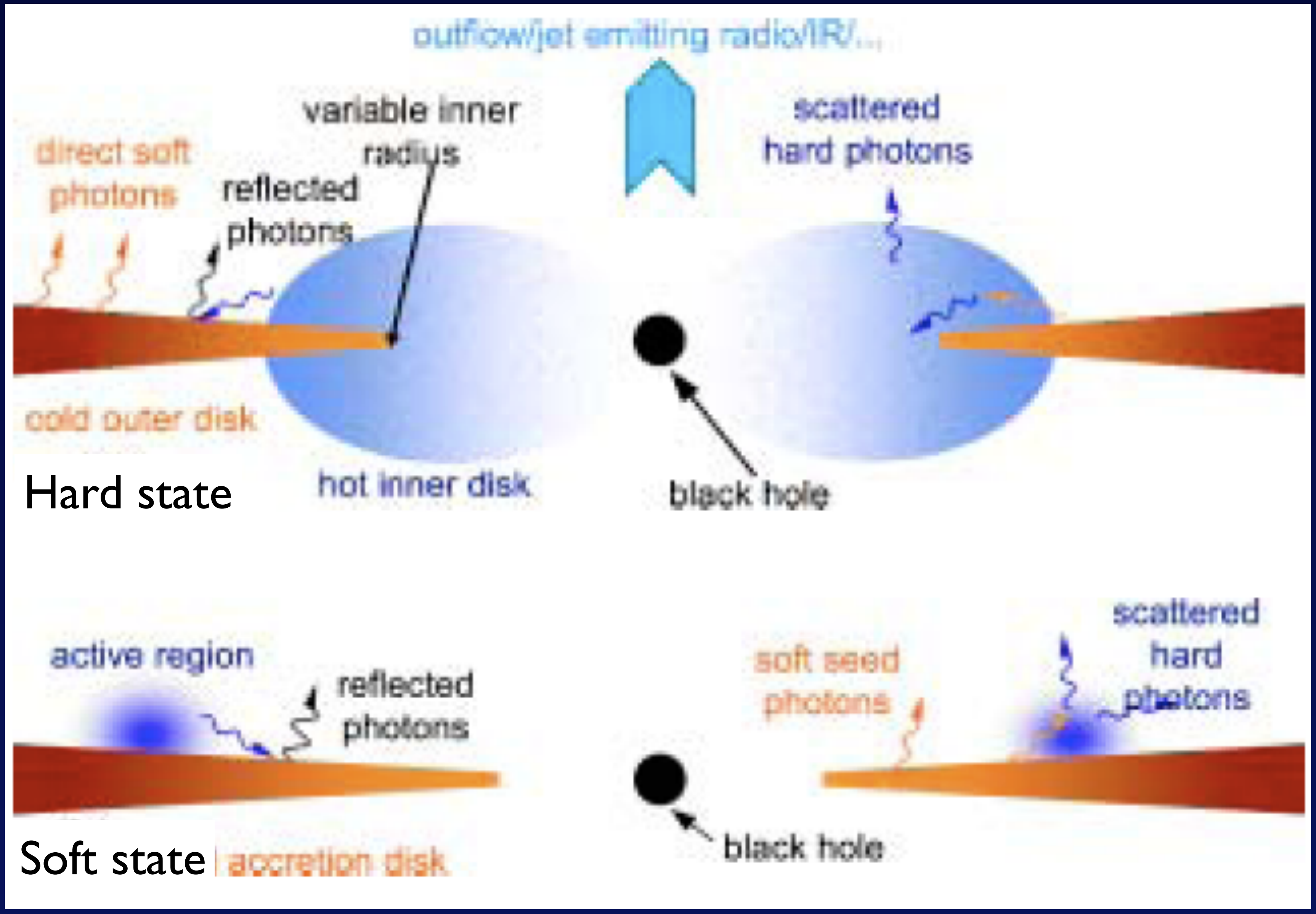
Pasham et al 2019

Black Hole Binary Hardness-Intensity diagram



Belloni 2012

Accreting Black Hole: Radiation Components

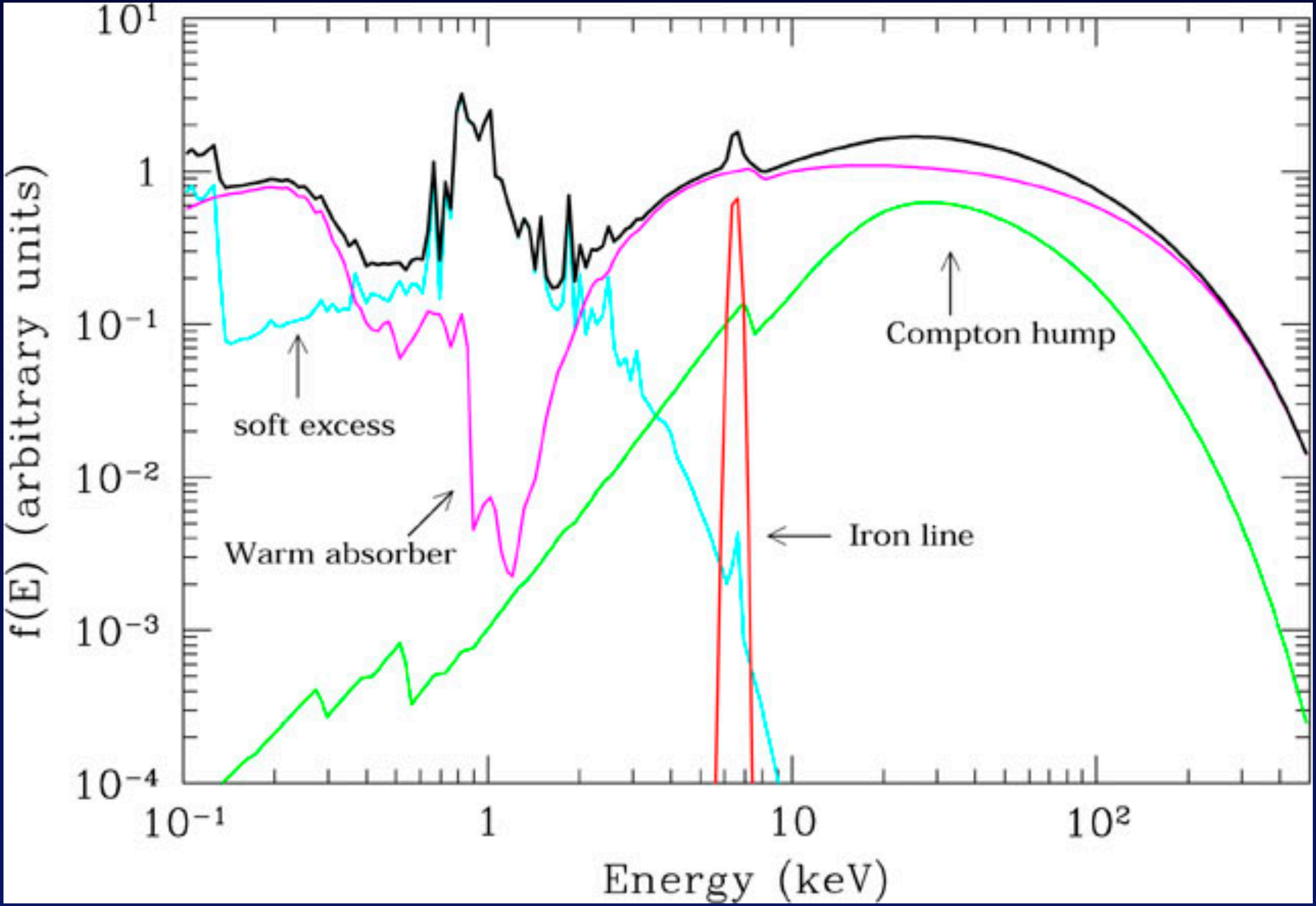


A. Zdziarski

- *Thermal disk radiation (soft) - matter closest to BH hottest : ISCO*
- *Compton upscattered hard photons from hot electrons*
- *"Reflected" hard photons from the accretion disk*
- *Fe K-α line*
- *Jets and outflows, non-thermal synchrotron*

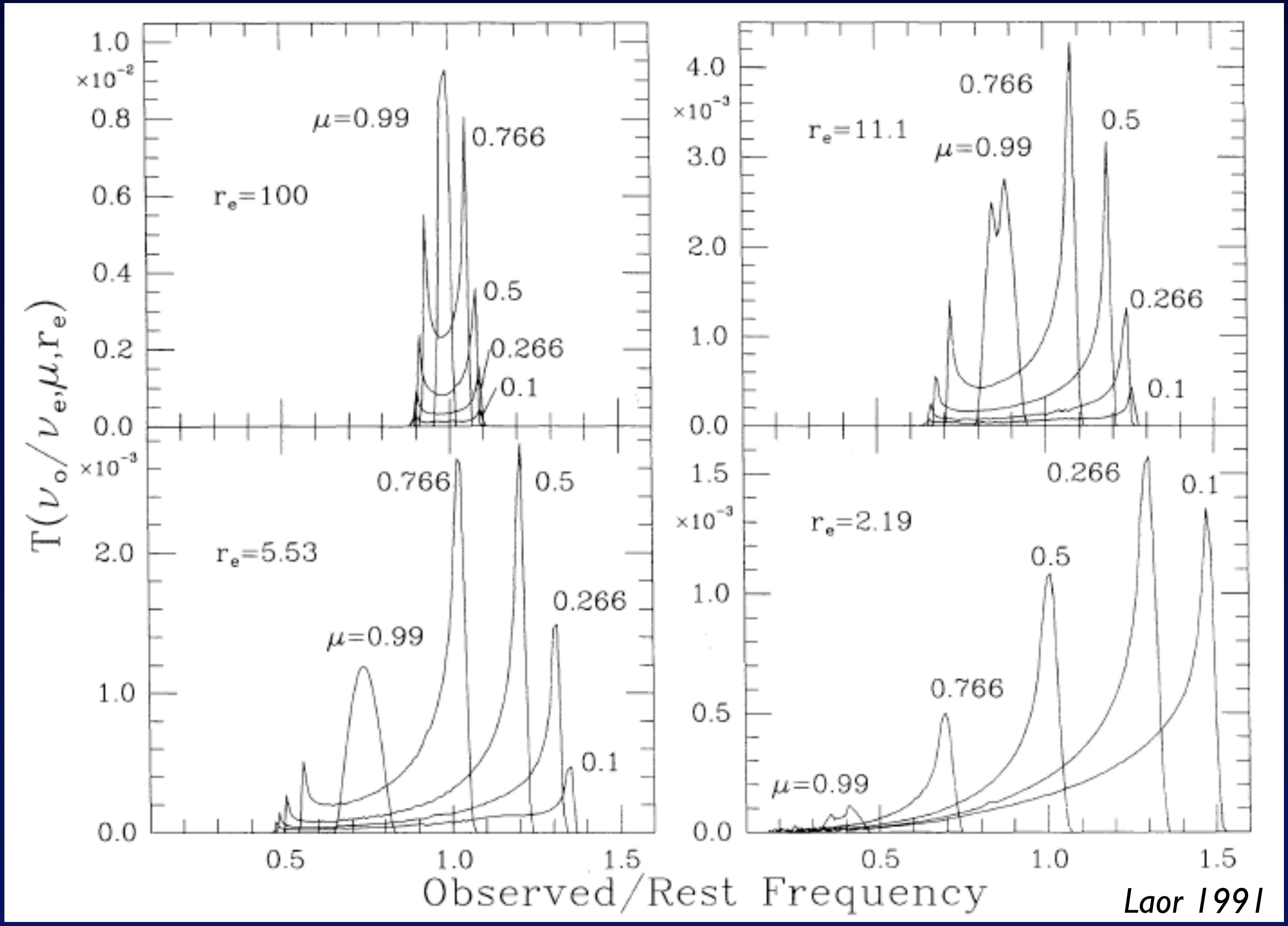
Smaller for
- lower M
- higher J

Active Galactic Nuclei: Supermassive BH



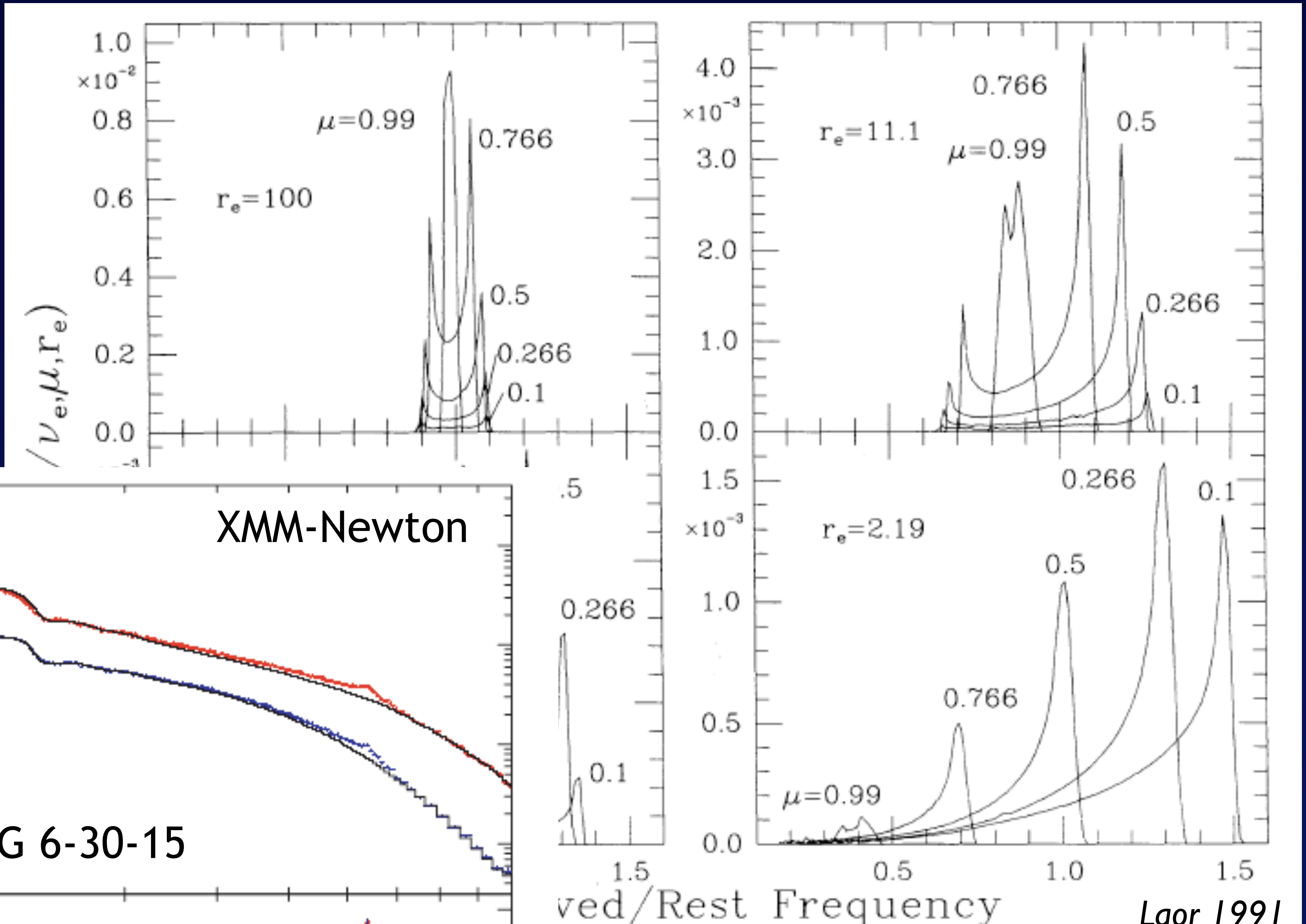
ned.ipac.caltech.edu

Relativistic Fe line: indicator of Black Hole spin

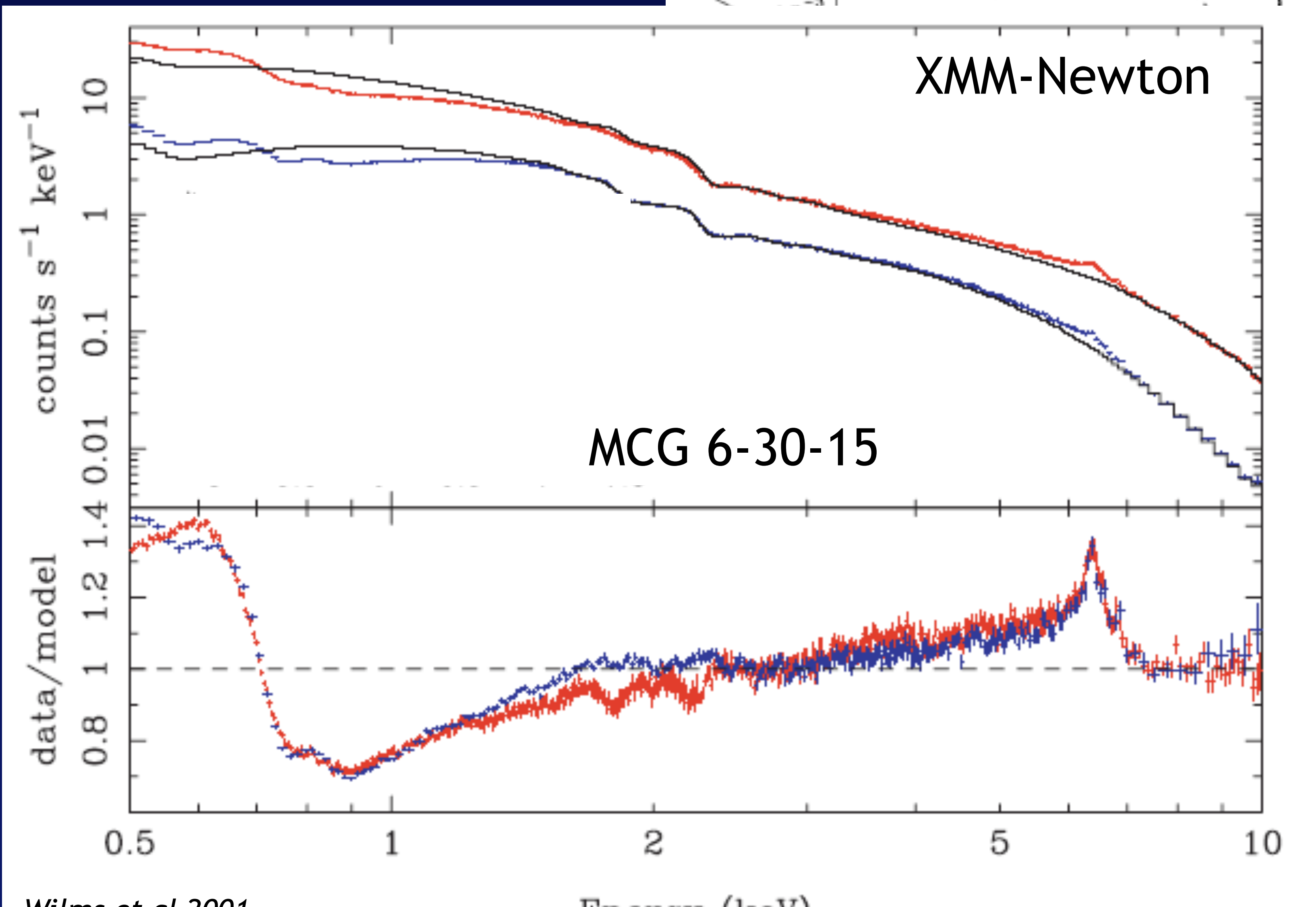


Wilms et al 2001

Relativistic Fe line: indicator of Black Hole spin

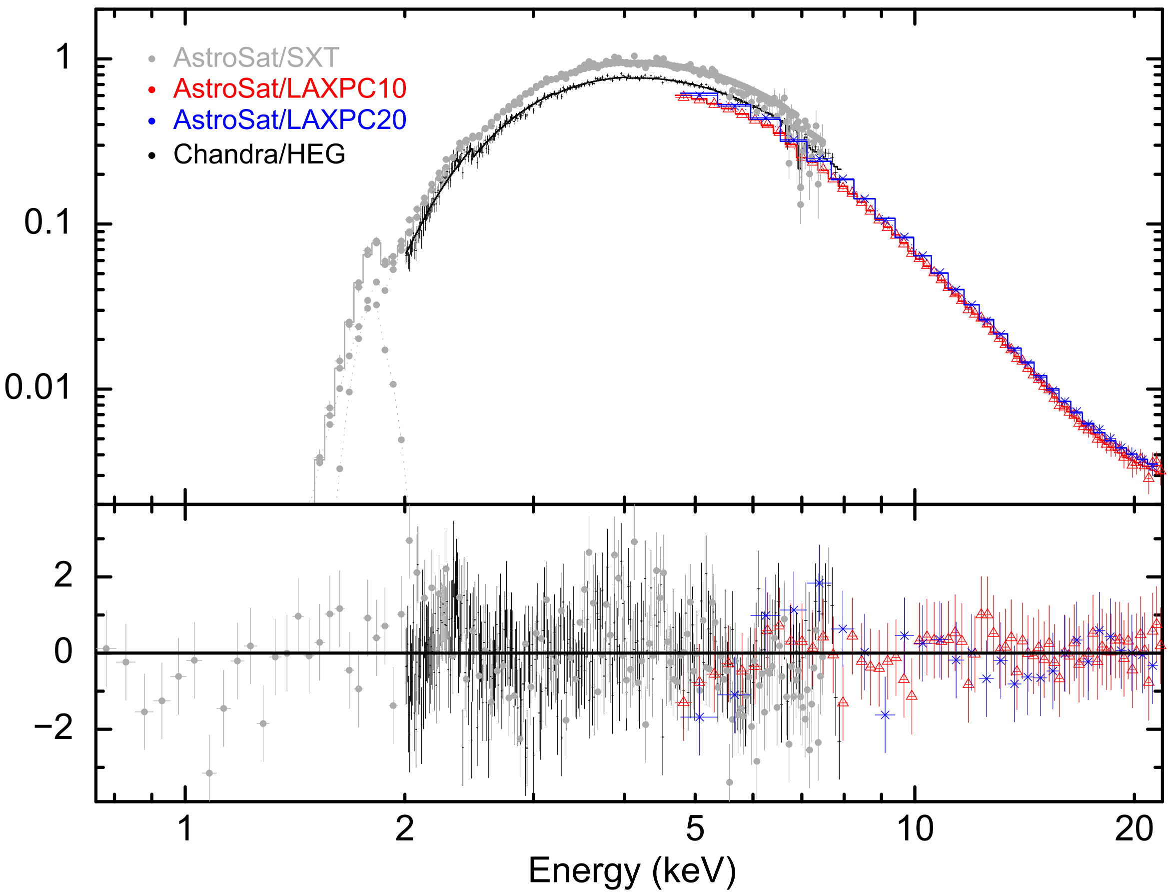


Laor 1991



Wilms et al 2001

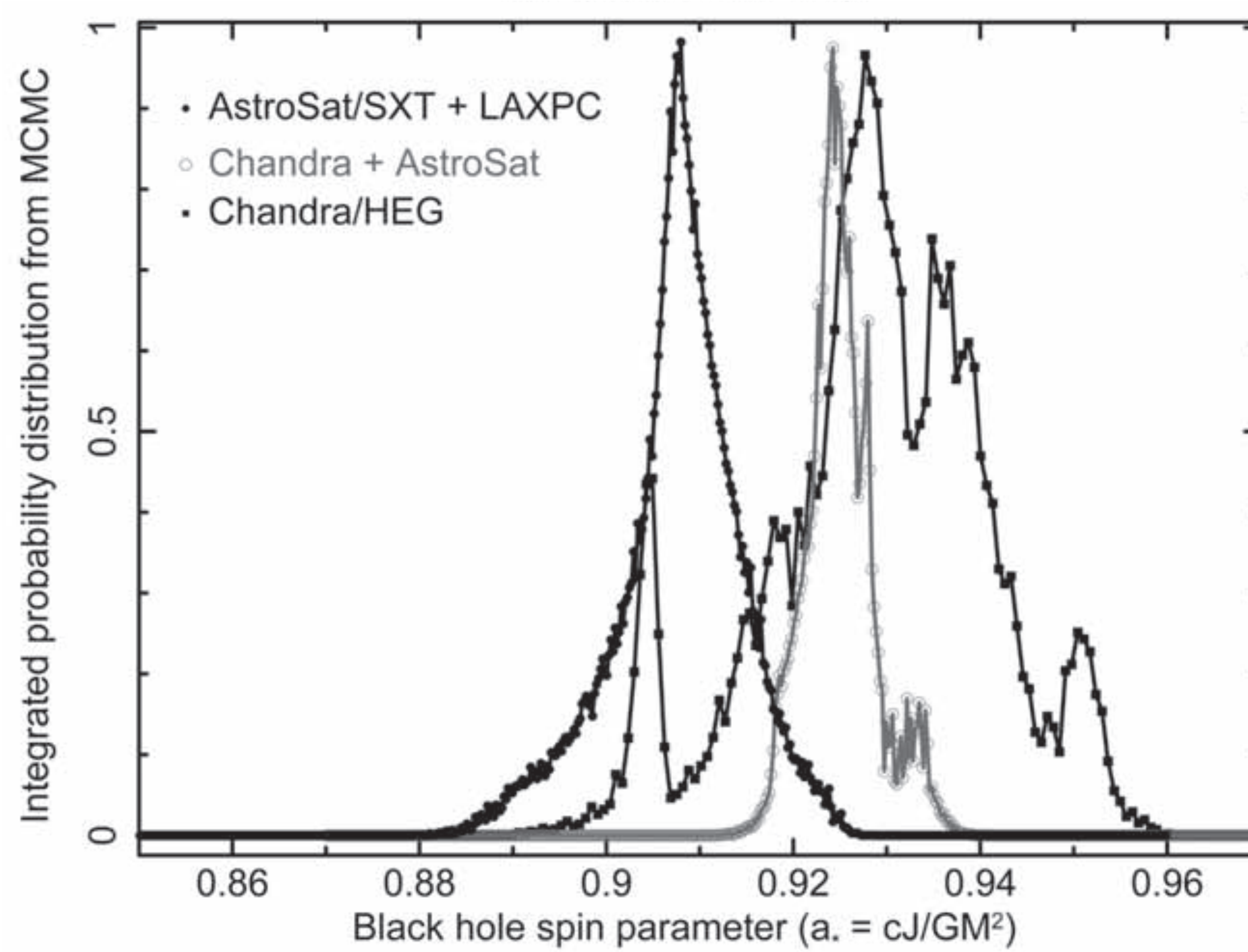
BHXRB 4U 1630-472 Joint Chandra-AstroSat spectroscopy



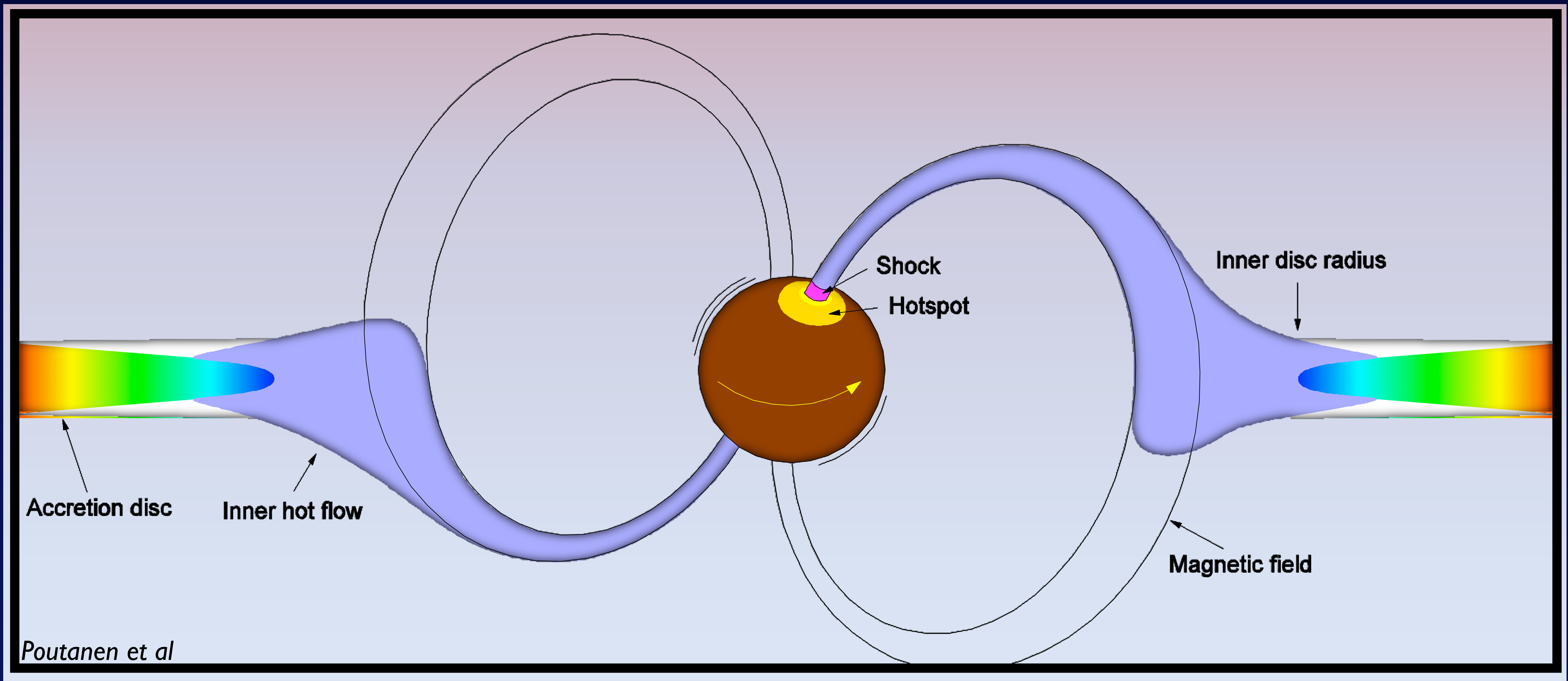
AstroSat SXT, LAXPC+Chandra HEG

Pahari et al 2018

Spectral model (*kerrbb*) indicates that the Black Hole is spinning very rapidly



Accretion on a magnetized neutron star

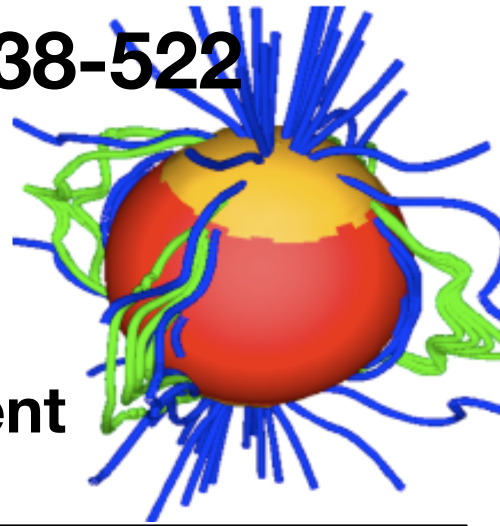


Stellar spin + polar hot spot => pulsar activity (needs B > 10^9 G)
Complex structure in X-ray intensity variations, even for low B
X-ray timing rich source of information

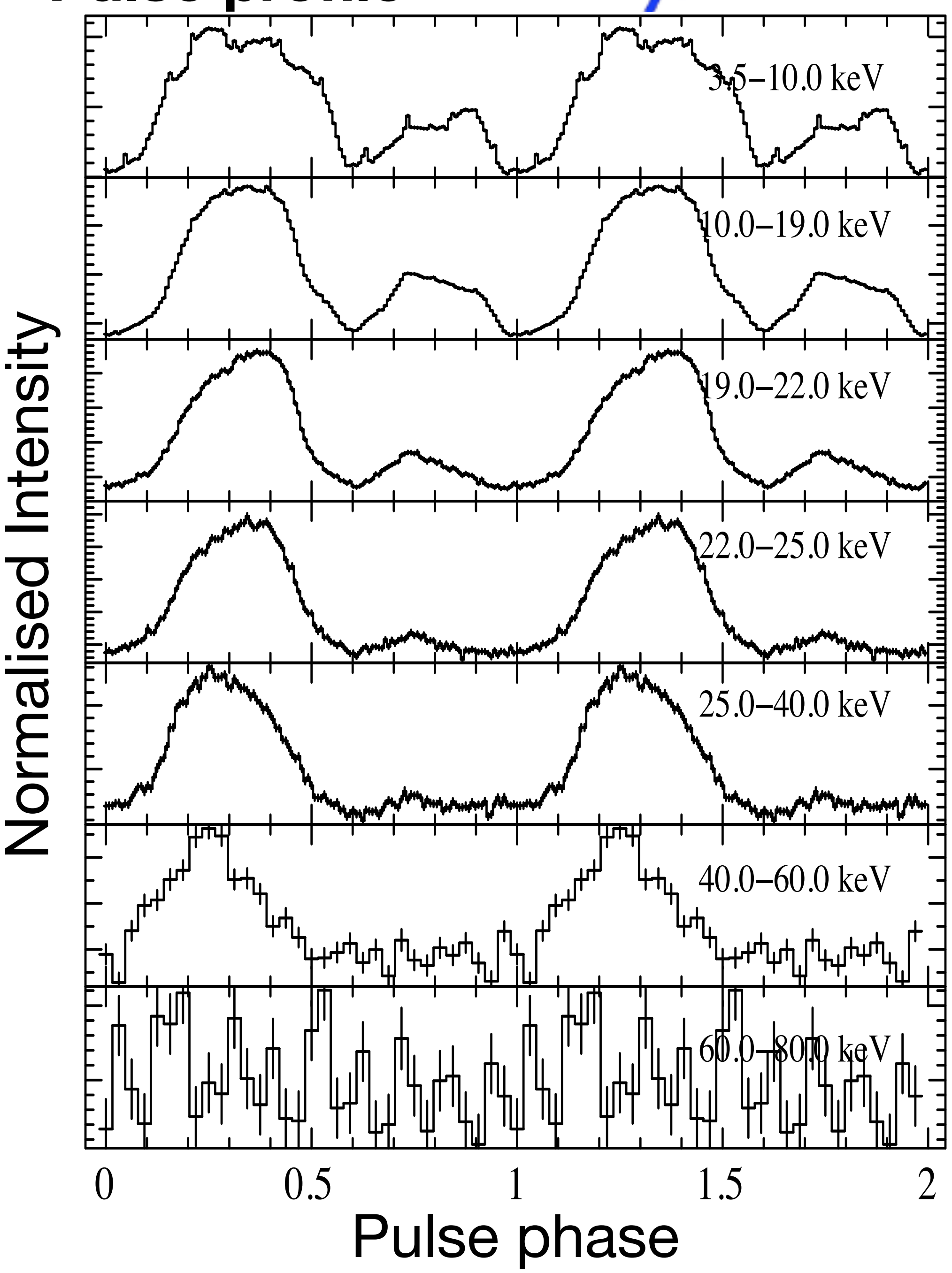
Cyclotron resonance in HMXB: 4U 1538-522

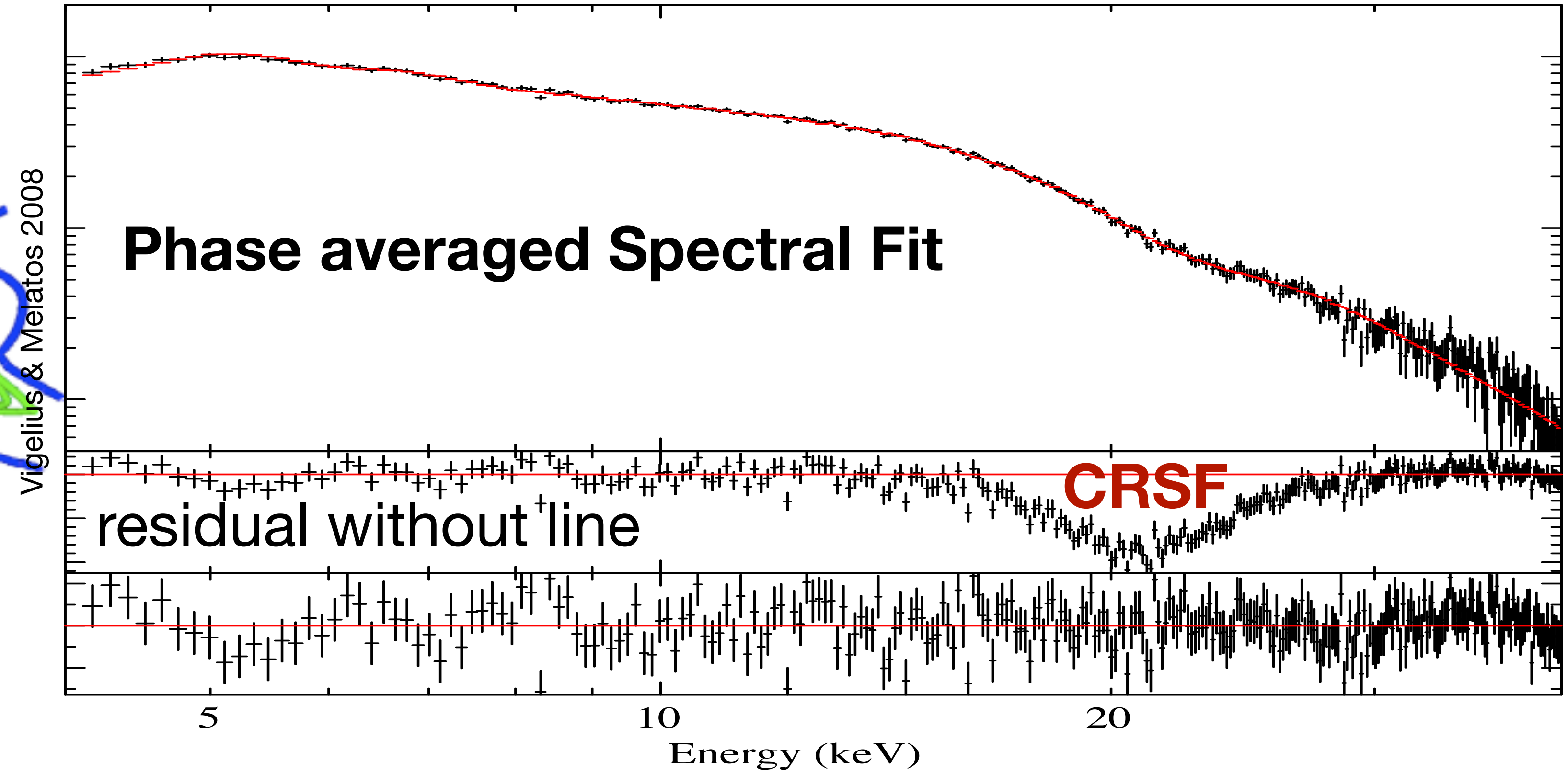
AstroSat LAXPC

Varun et al 2018

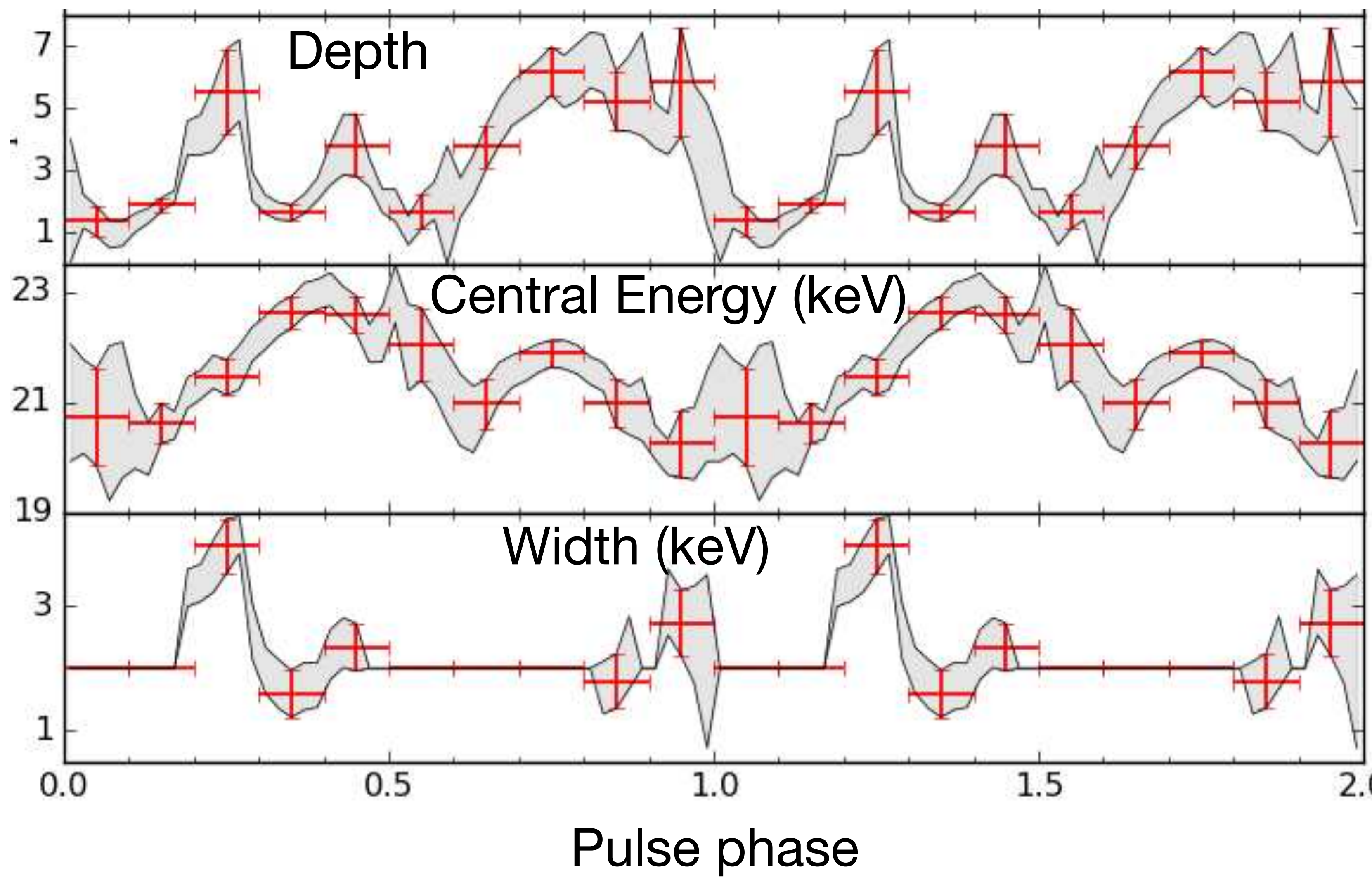


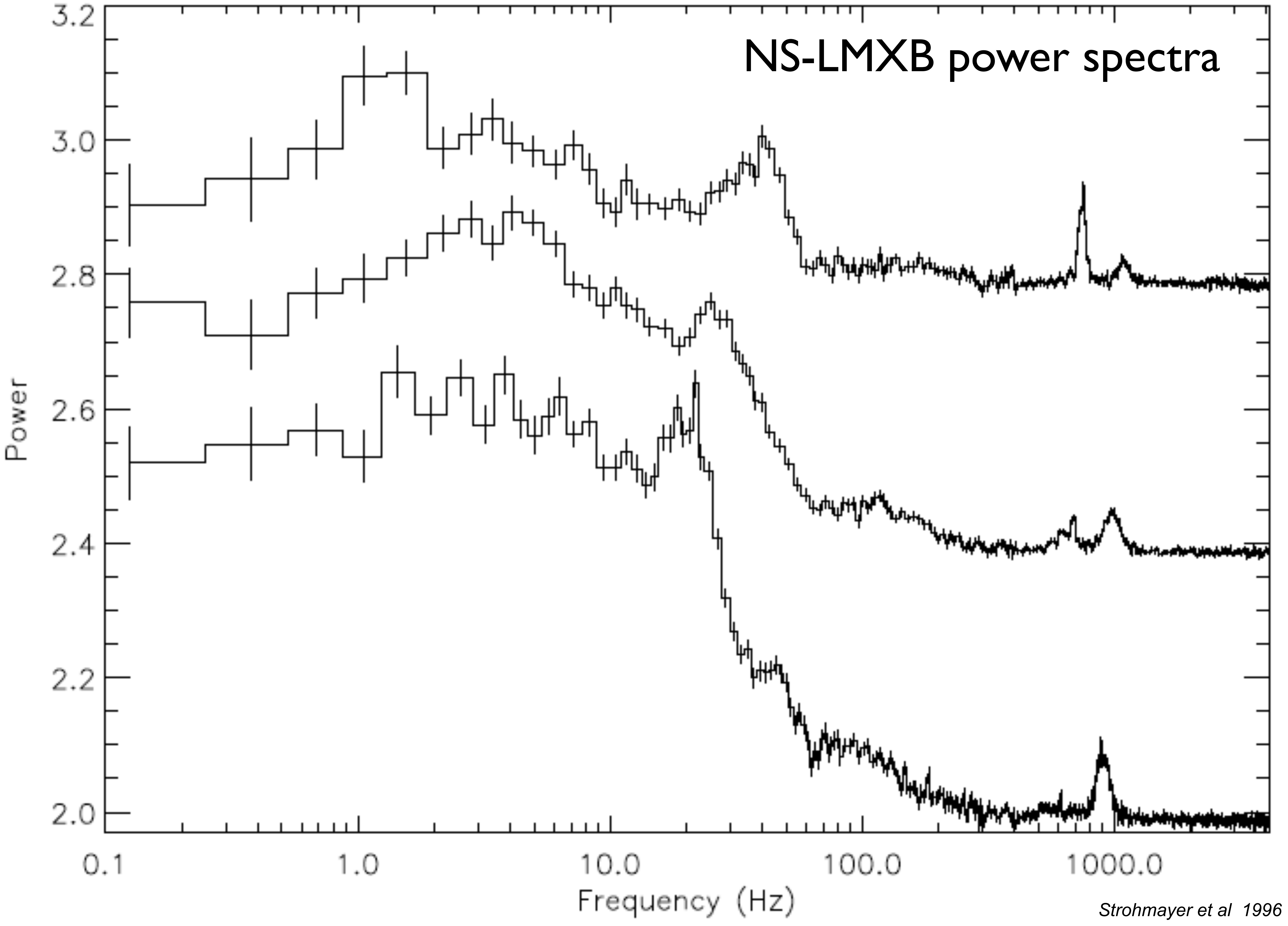
Energy dependent Pulse profile





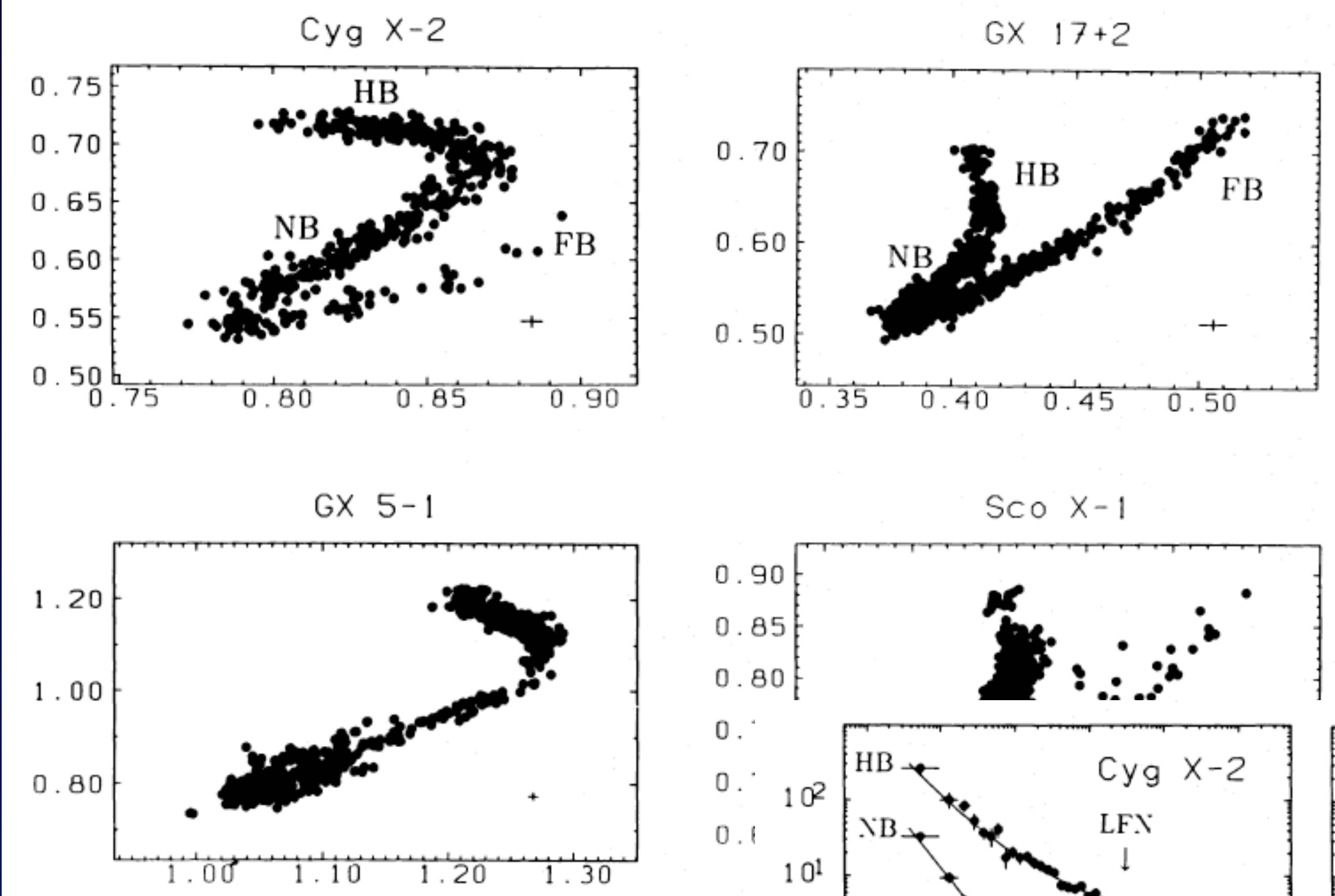
Phase dependence of CRSF

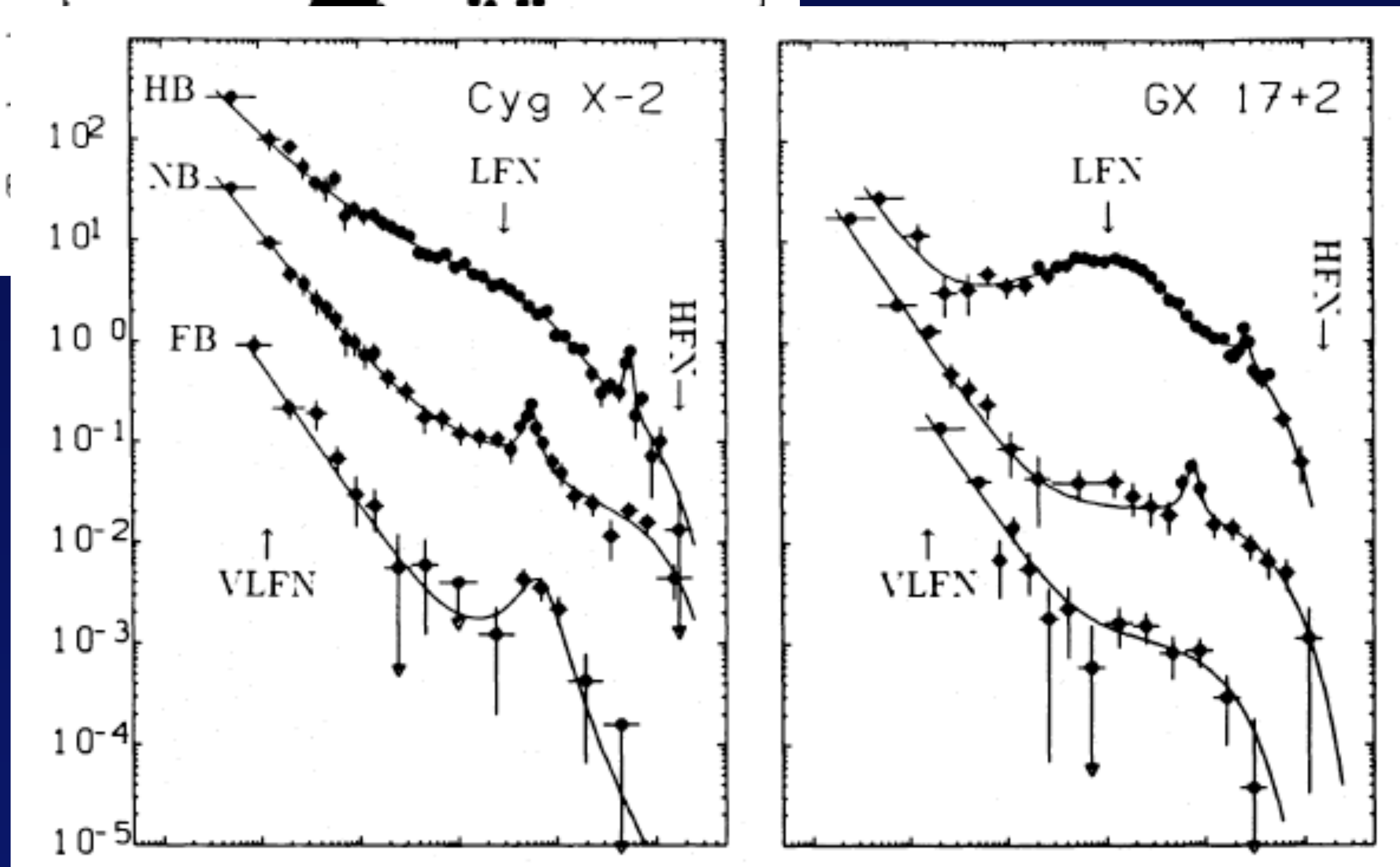



NS-LMXB power spectra
Power
Frequency (Hz)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
0.1
1.0
10.0
100.0
1000.0
Strohmayer et al 1996

Correlated spectral & timing variability

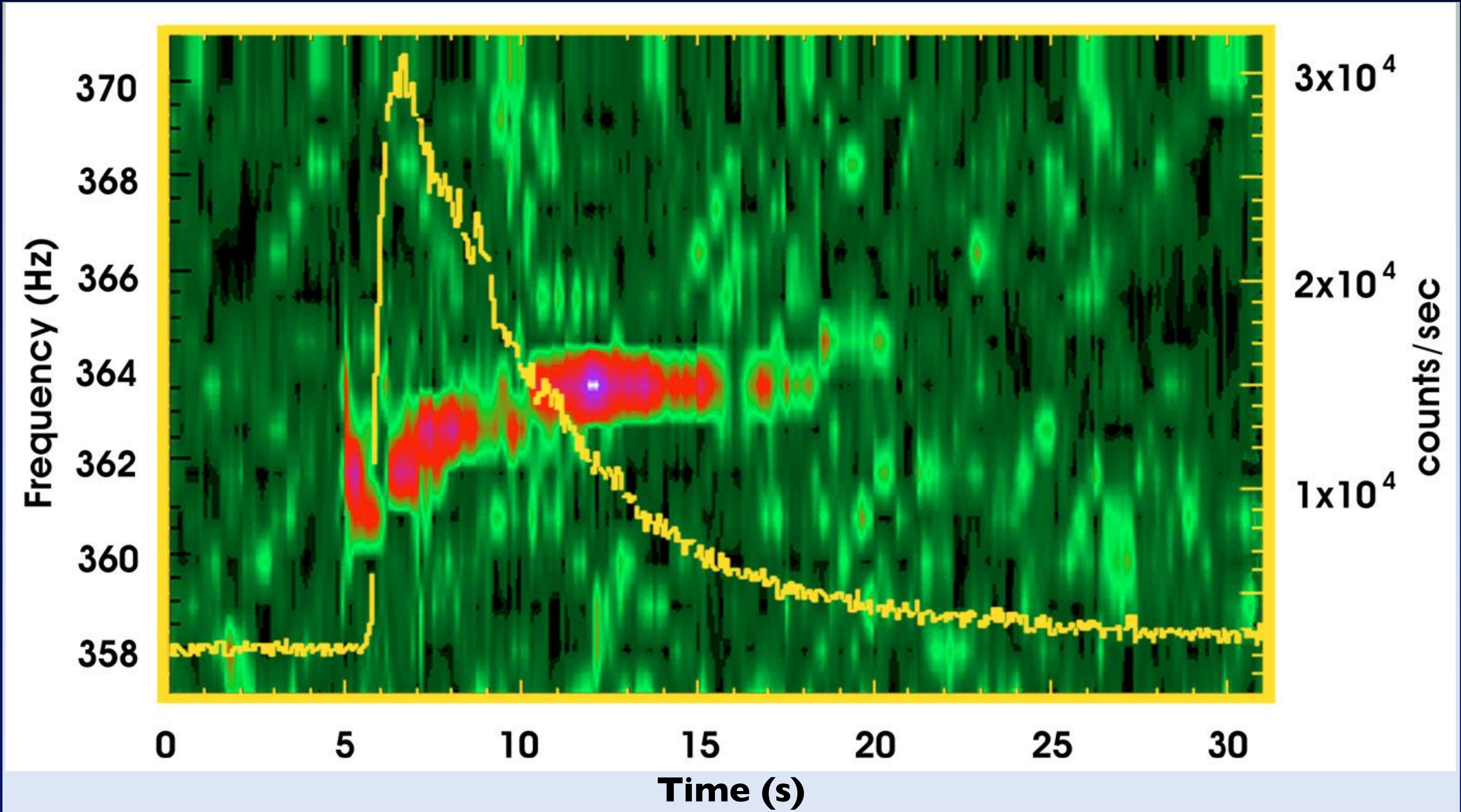
(Hasinger & van der Klis 1989)





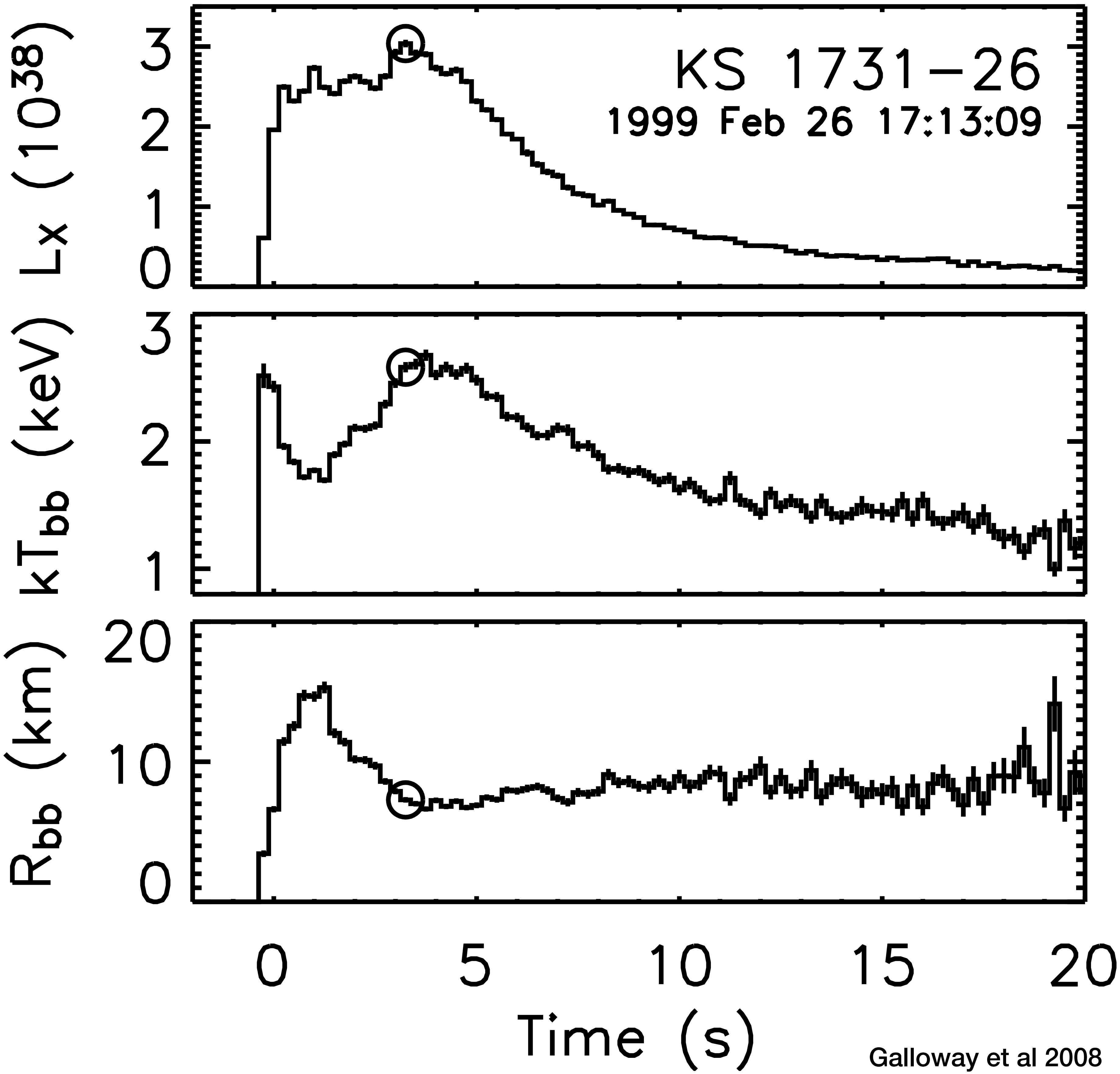
Z sources

Burst Oscillations



T. Strohmayer 1996

Thermonuclear PRE X-ray Bursts

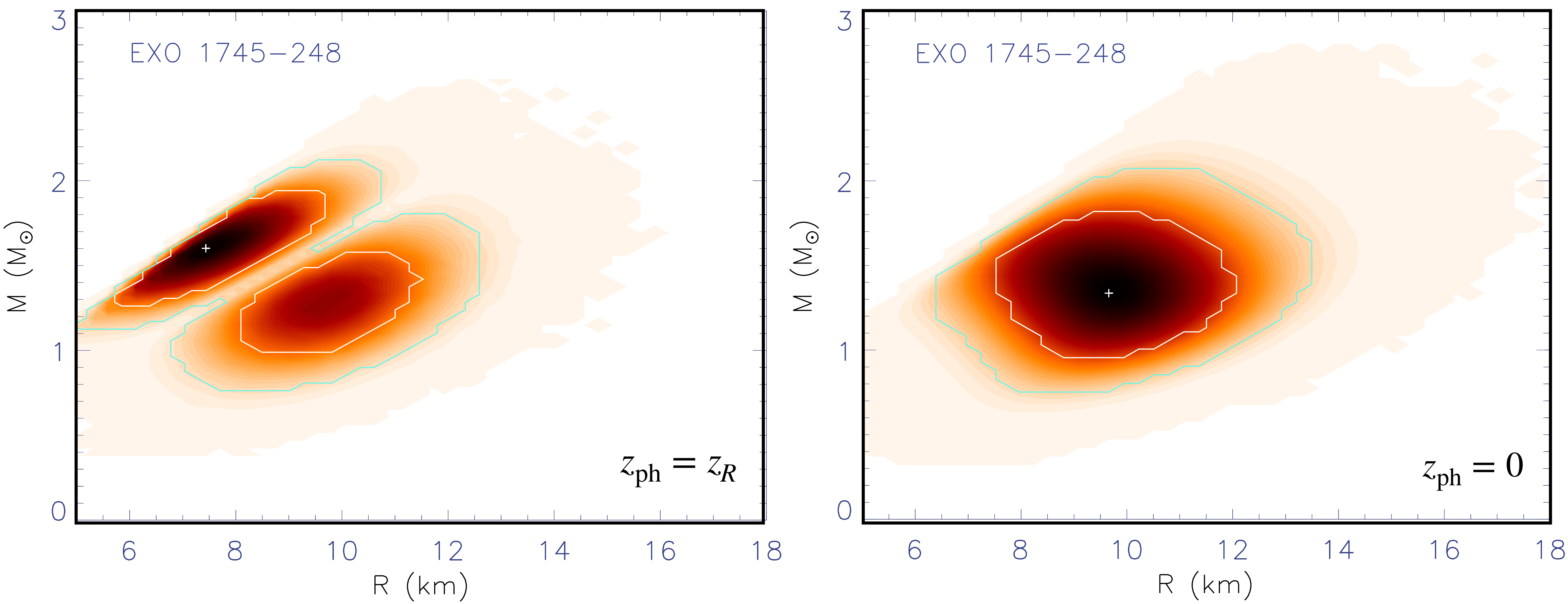


$$\frac{F_X}{\sigma T^4} = \frac{R^2}{d^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

$$F_{\rm Edd} = \frac{GMc}{d^2 \kappa_{\rm es}}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

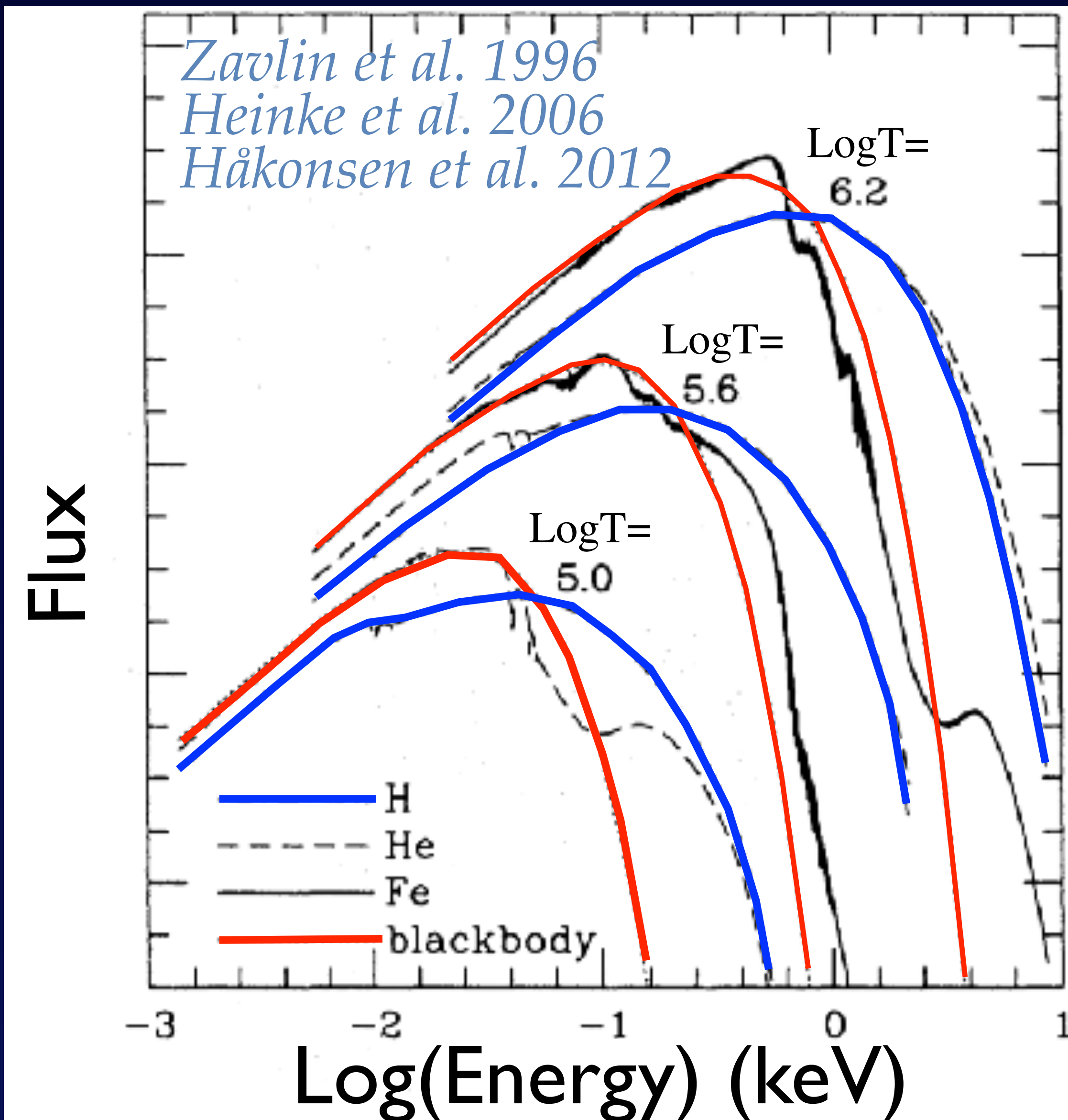
Galloway et al 2008

Mass, Radius constraints from X-ray bursts

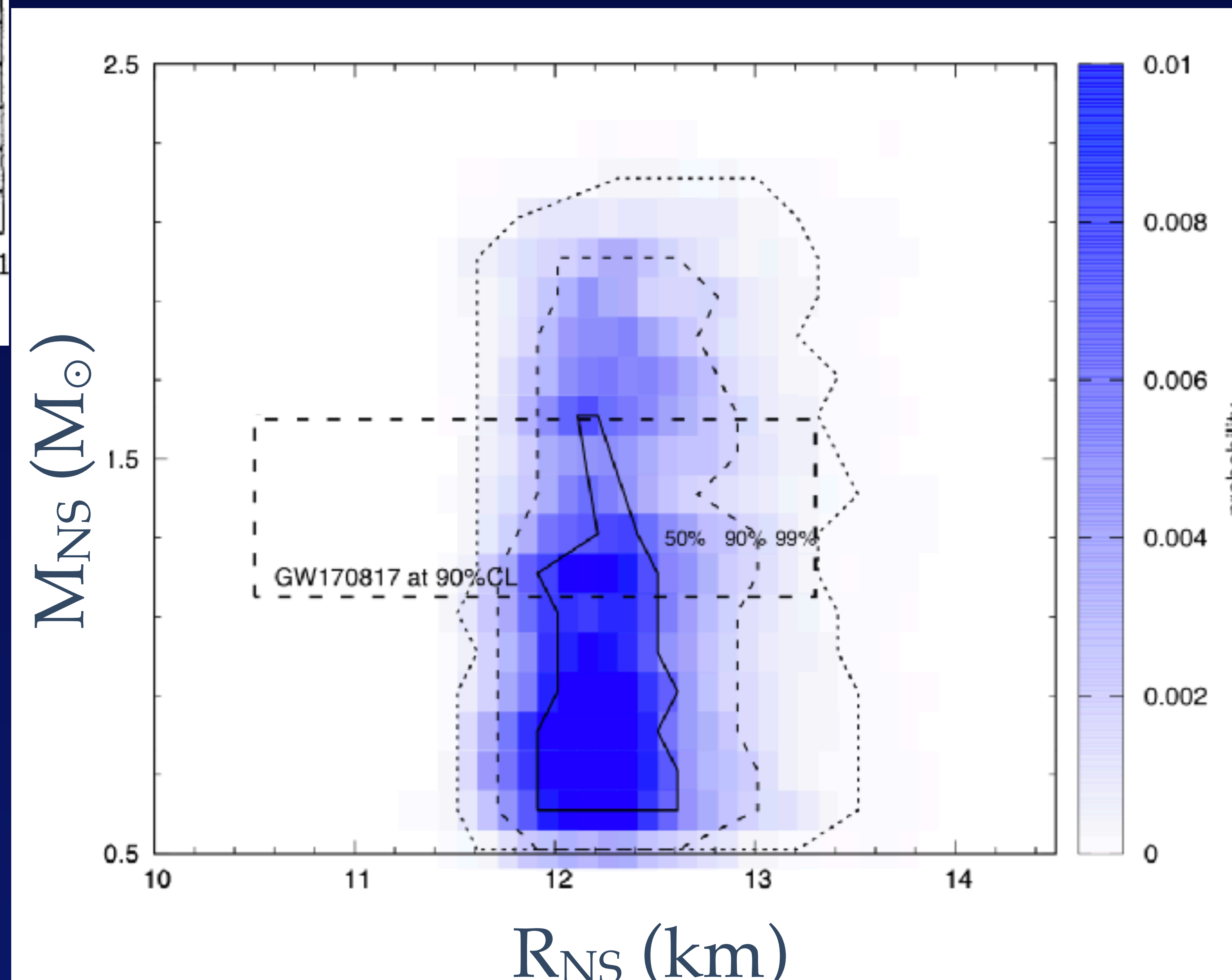


Lattimer & Steiner 2014

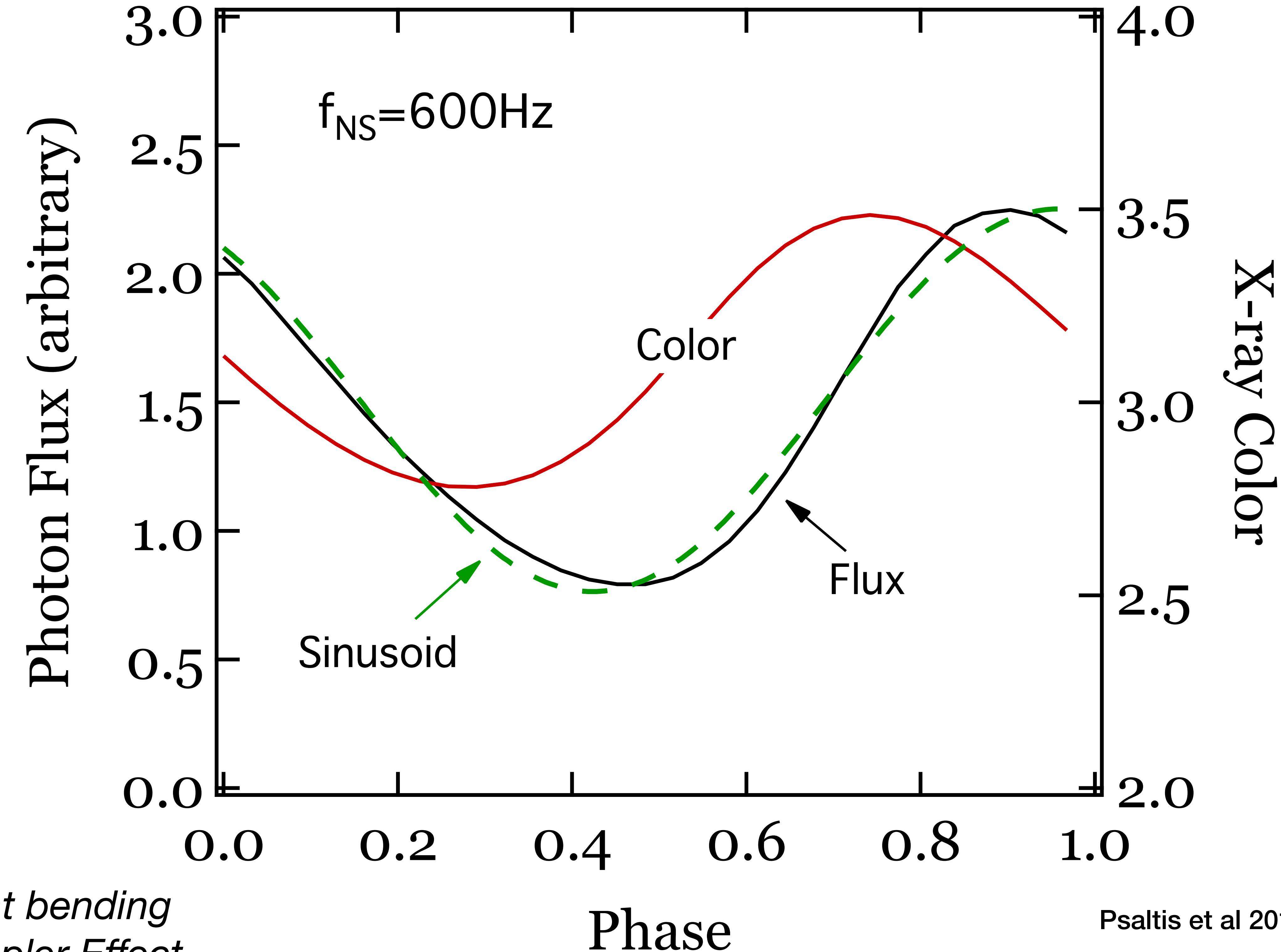
Neutron Star M-R relation from spectra of quiescent LMXBs



Guillot 2018
Baillot d'Etivaux et al 2019



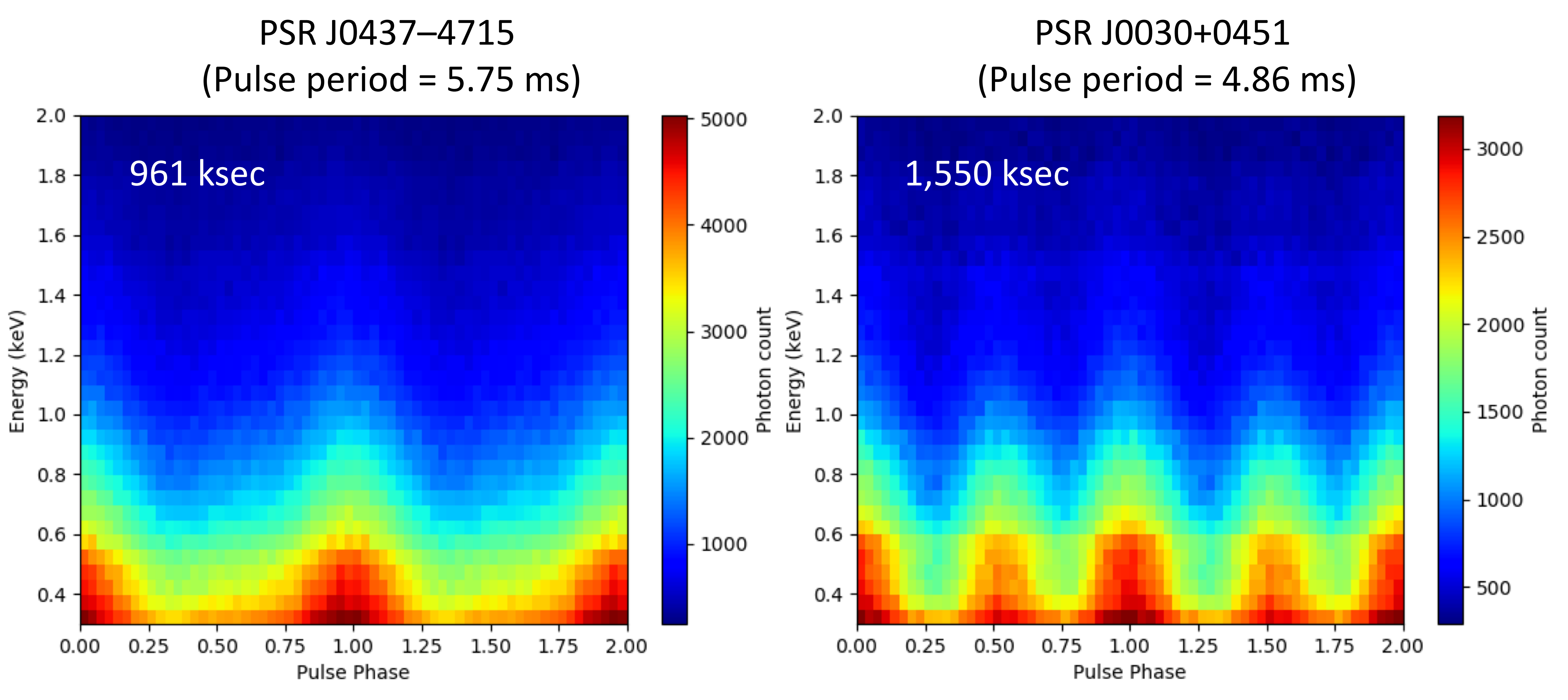
Pulse profile of a small hotspot on a NS surface



Light bending
Doppler Effect
Propagation Delays

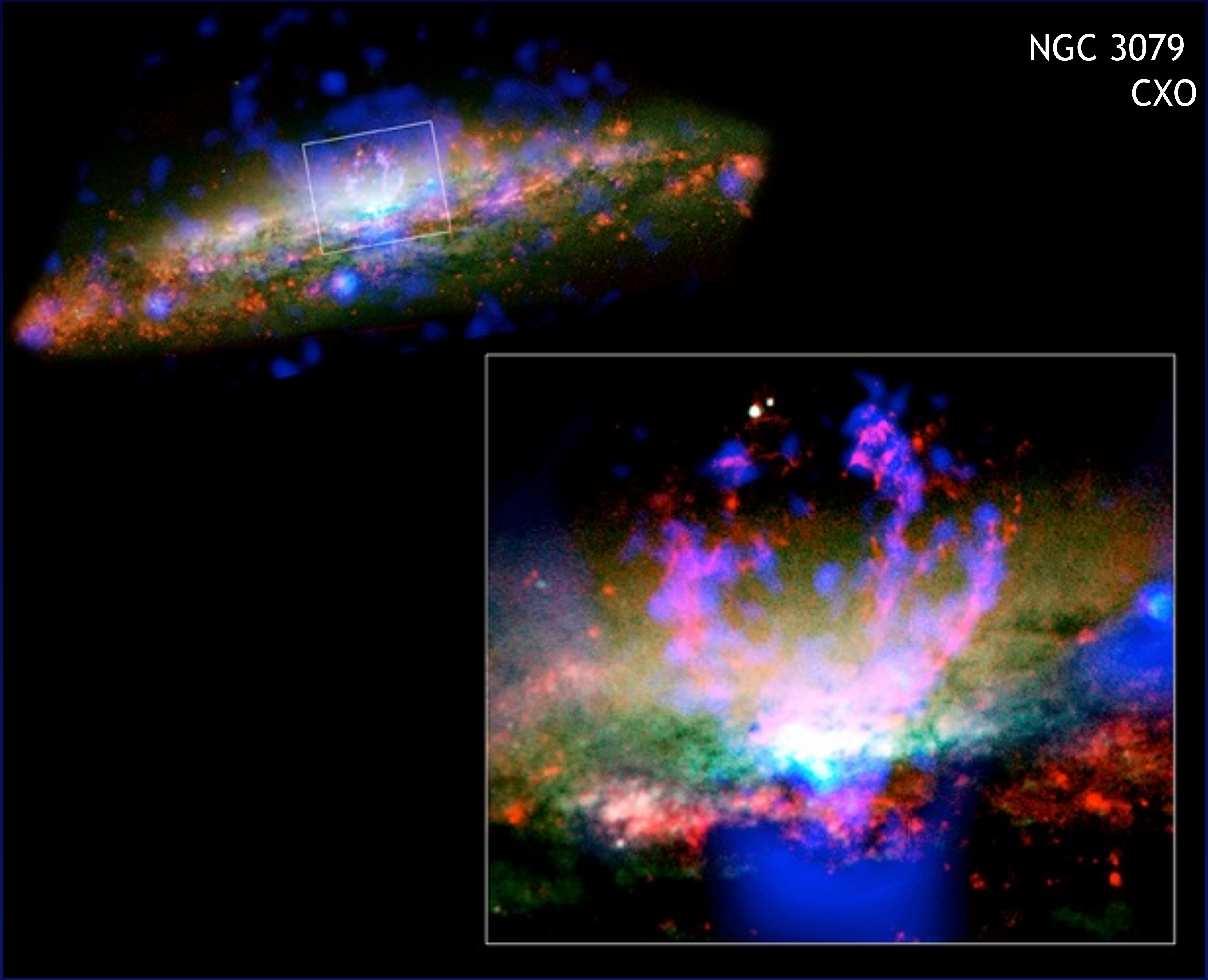
Psaltis et al 2014

Energy dependent pulse profiles of isolated millisecond pulsars



NICER mission results : heasarc.gsfc.nasa.gov

Hot Gas in Galaxies

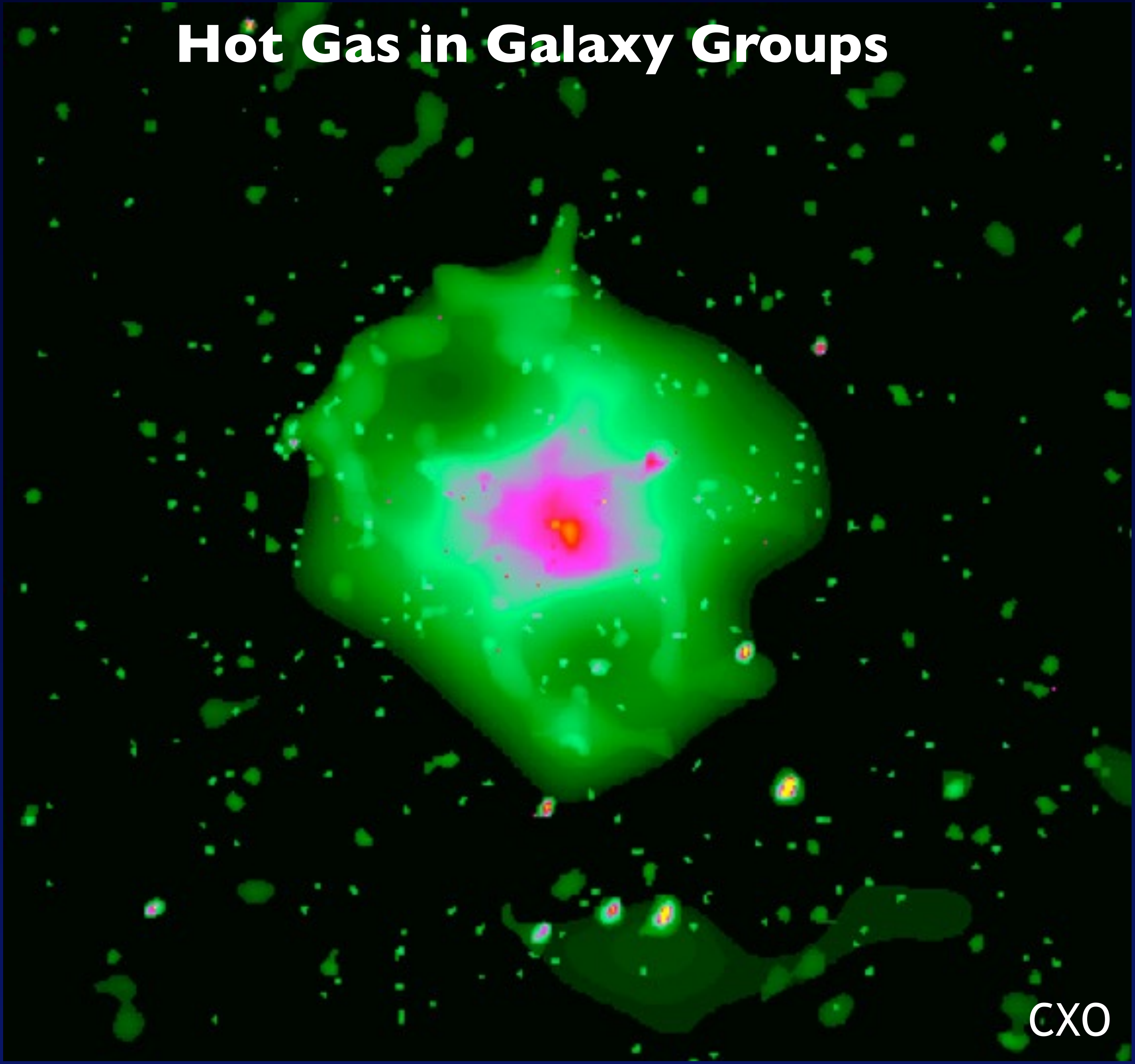


Hot Gas in Galaxy Groups

Hickson
Compact
Group
of
Galaxies

62

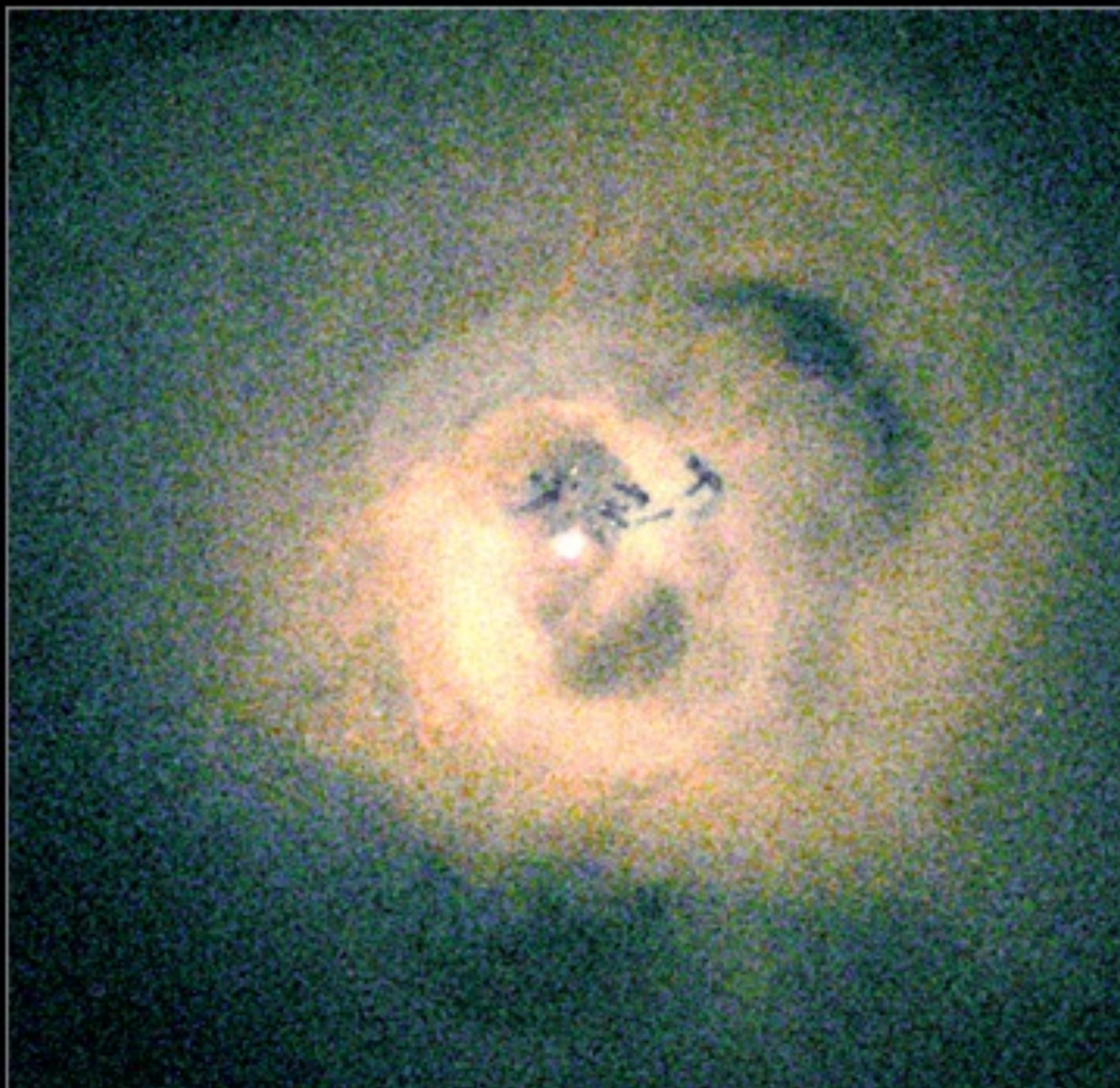
Gas
heated by
gravity of
dark matter



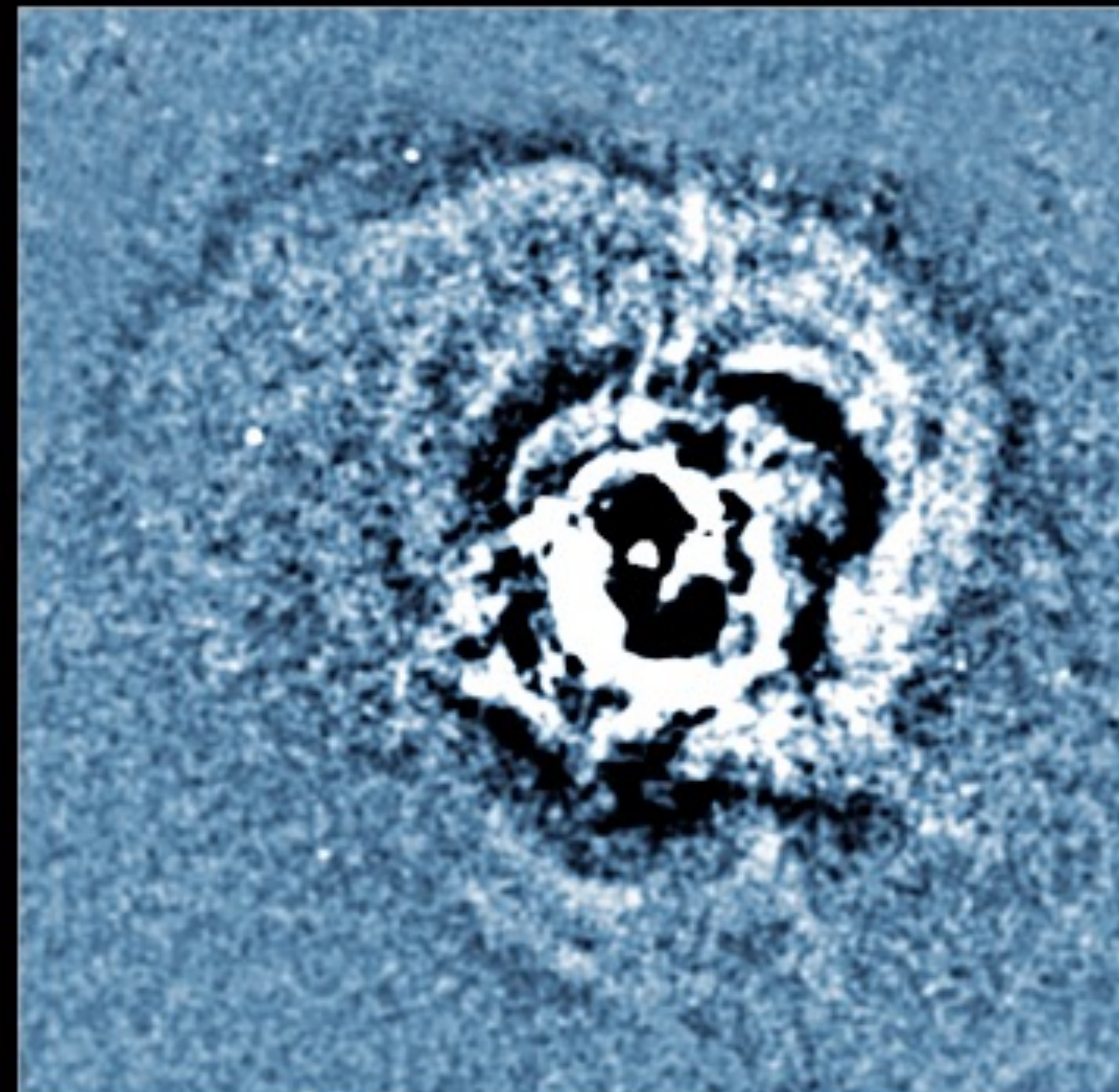
Hot Gas in Galaxy Clusters

Red: Hot X-ray emitting gas; **Blue**: Dark matter mapped through gravitational lensing

X-rays from the Perseus Cluster



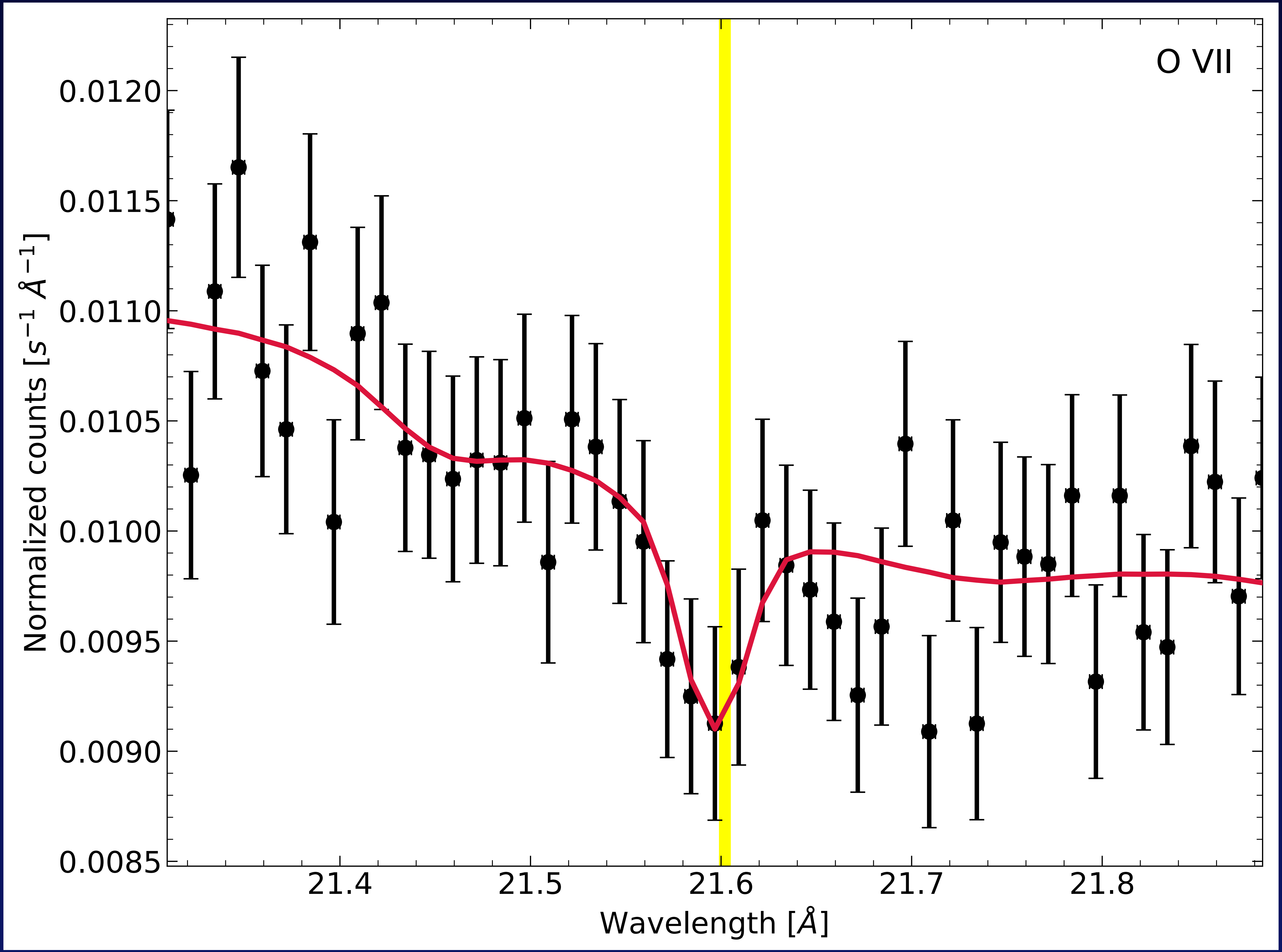
CHANDRA X-RAY [3-COLOR]



CHANDRA X-RAY [SOUND WAVES]

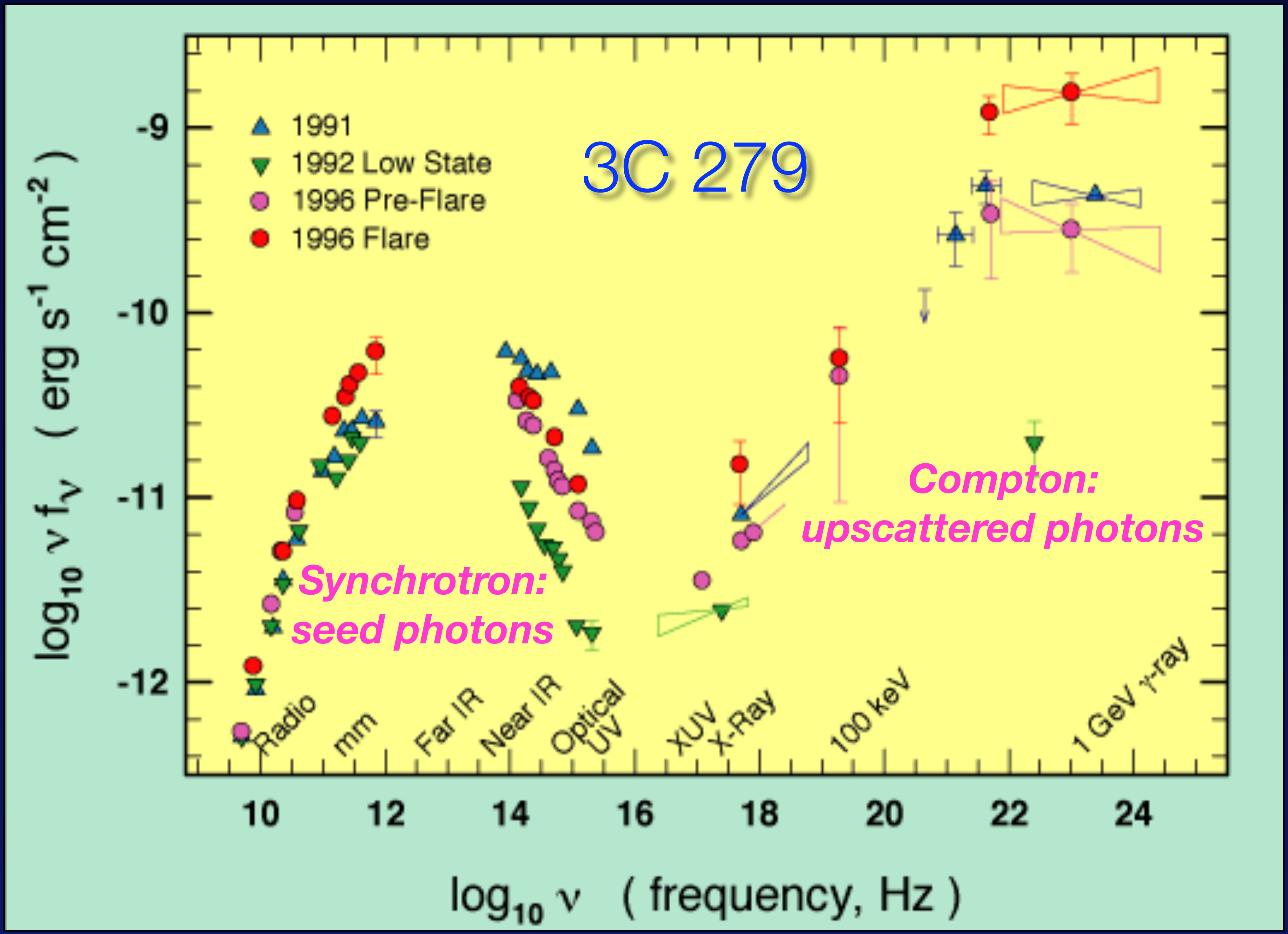
Fabian et al *http://apod.nasa.gov/apod/ap030912.html*

WHIM in the line of sight to QSO H1821+643



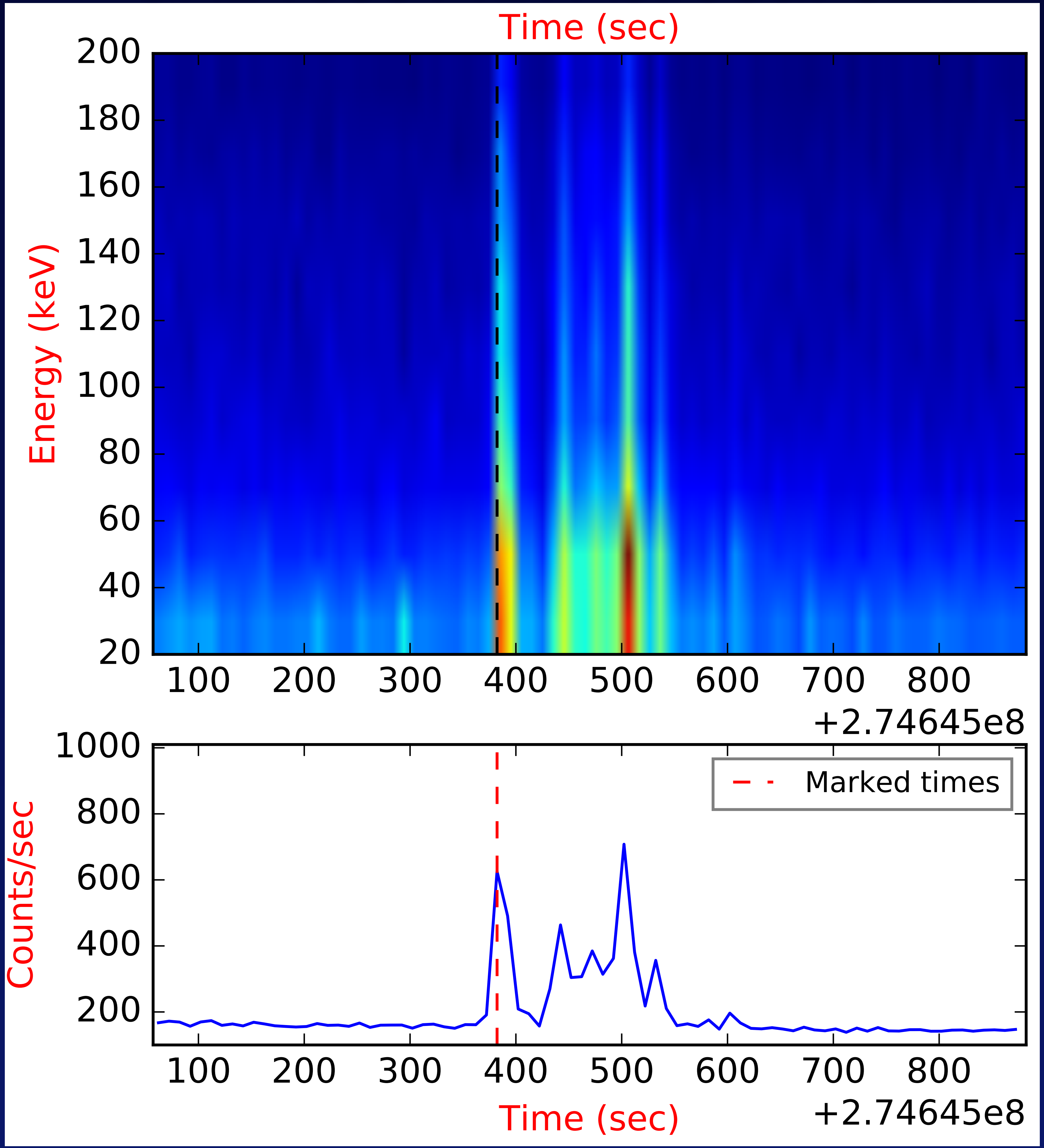
Kovacs et al 2019

Non-thermal emission from relativistic jets: Blazars

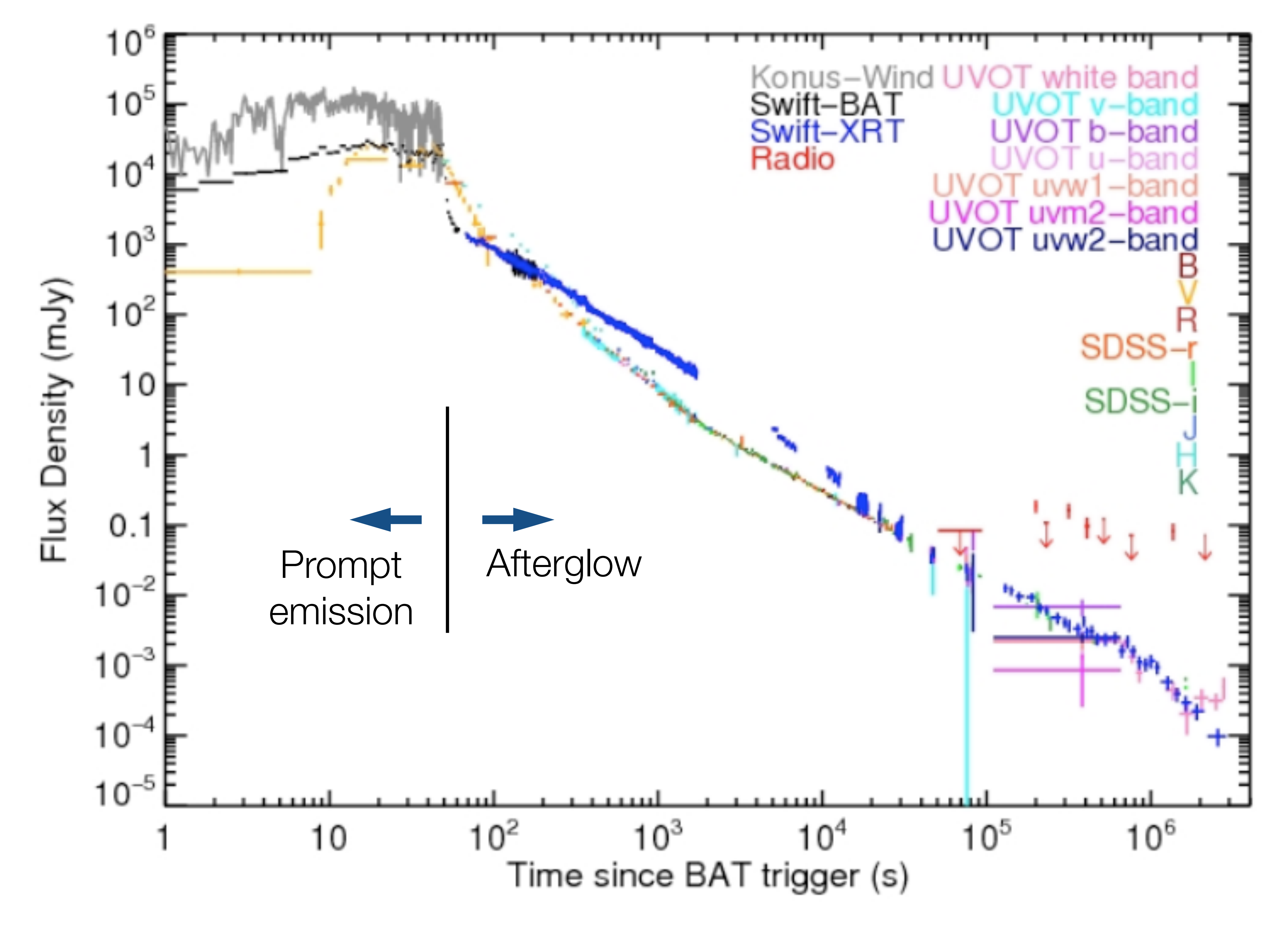


http://heasarc.gsfc.nasa.gov

GRB180914B: AstroSat CZTI



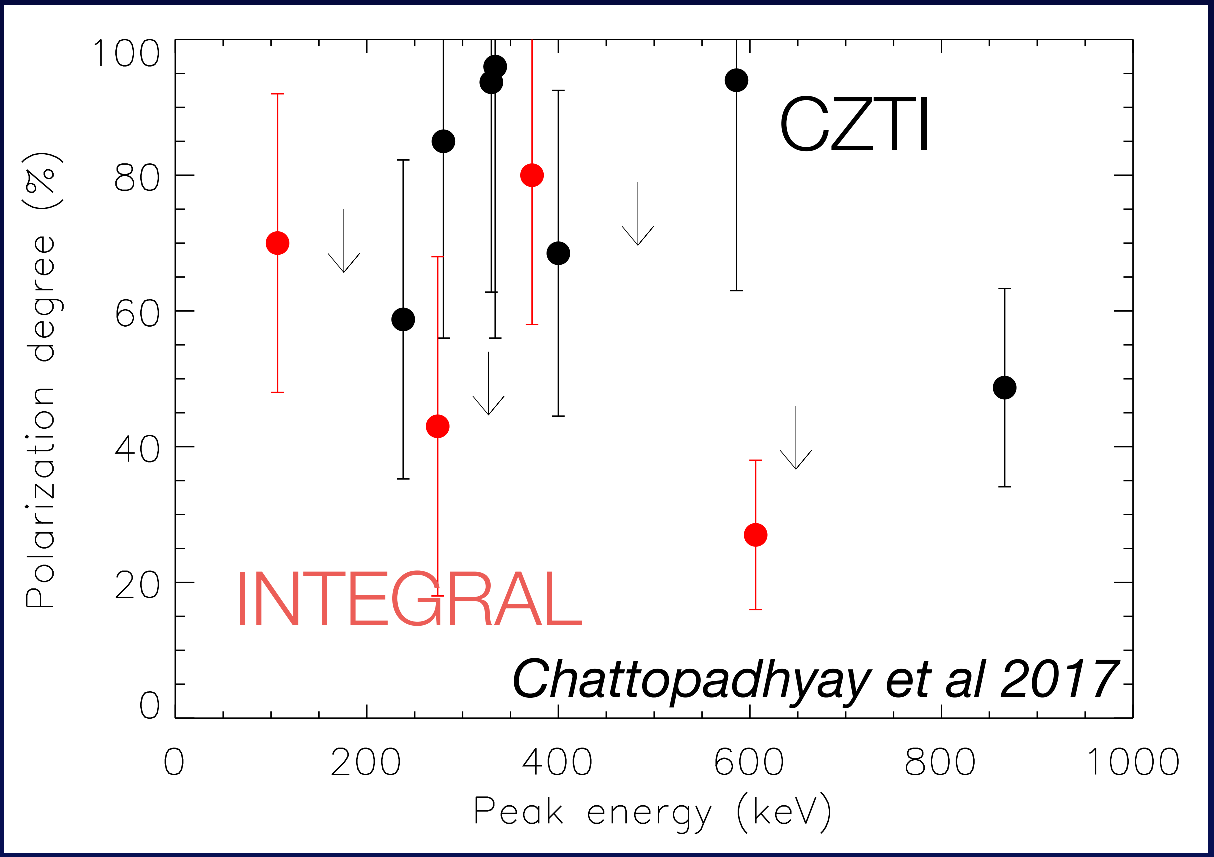
GRB 080319B

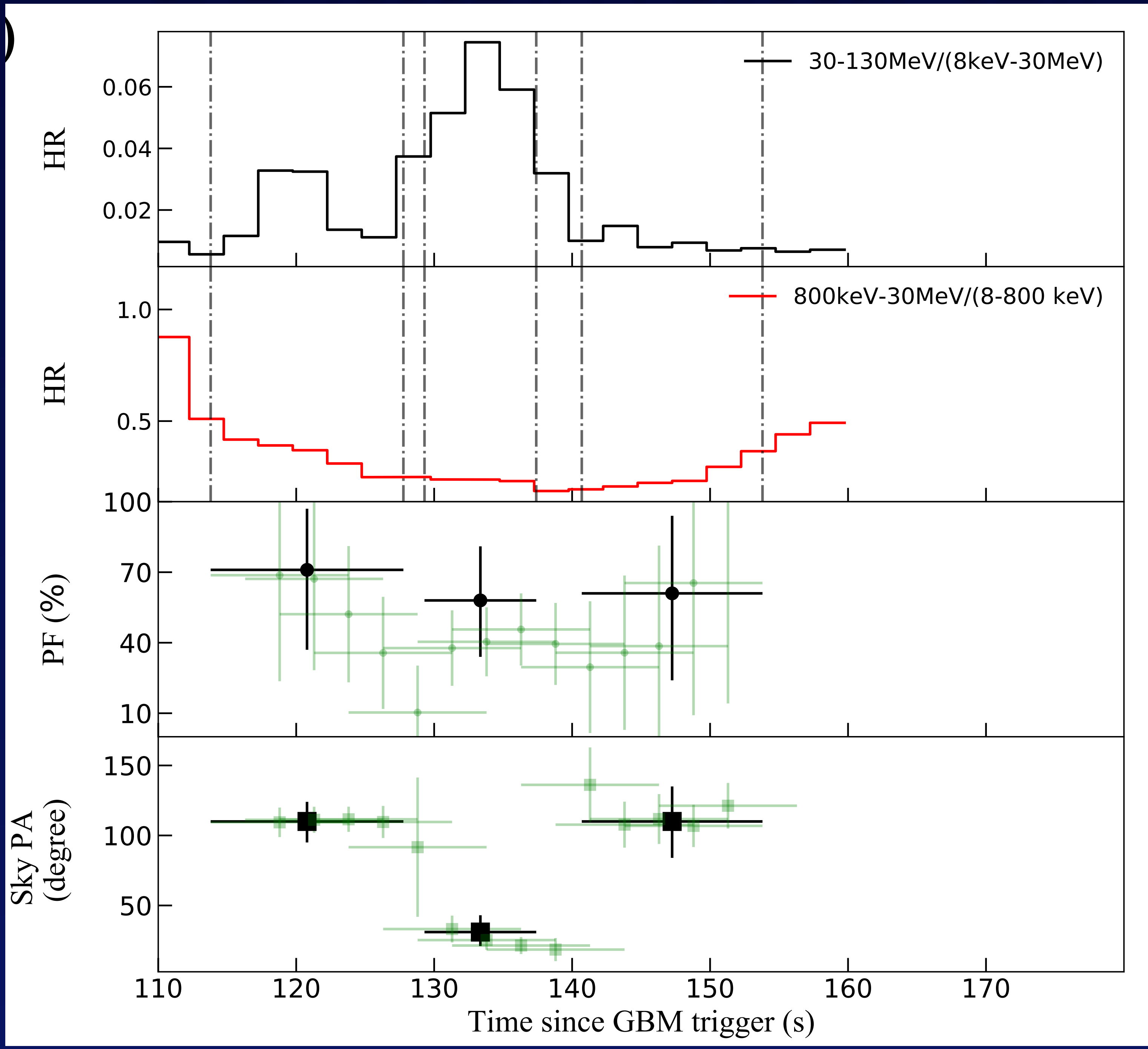


Racusin et al 2008

Polarimetry of GRB prompt emission

GRB 160821A AstroSat CZTI





POLAR

5 GRBs, PD 4-40%

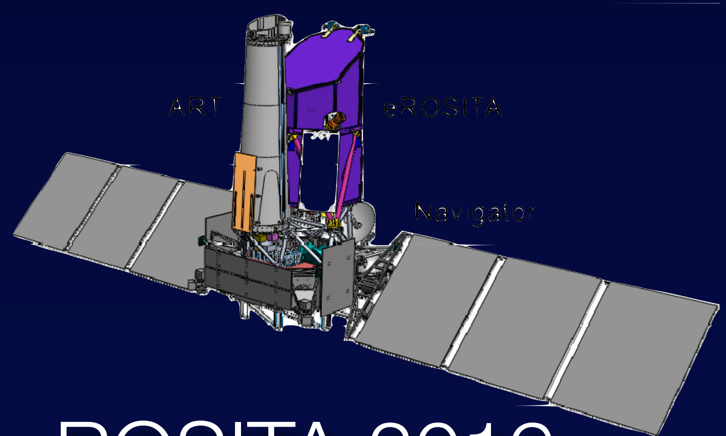
Possible evidence of temporal variability of polarisation

Zhang et al 2019

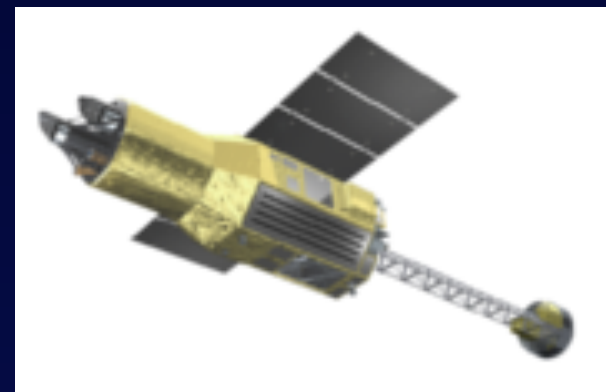
Sharma et al 2019

Magnetic order, view geometry, radiation mechanism, nature of central engine

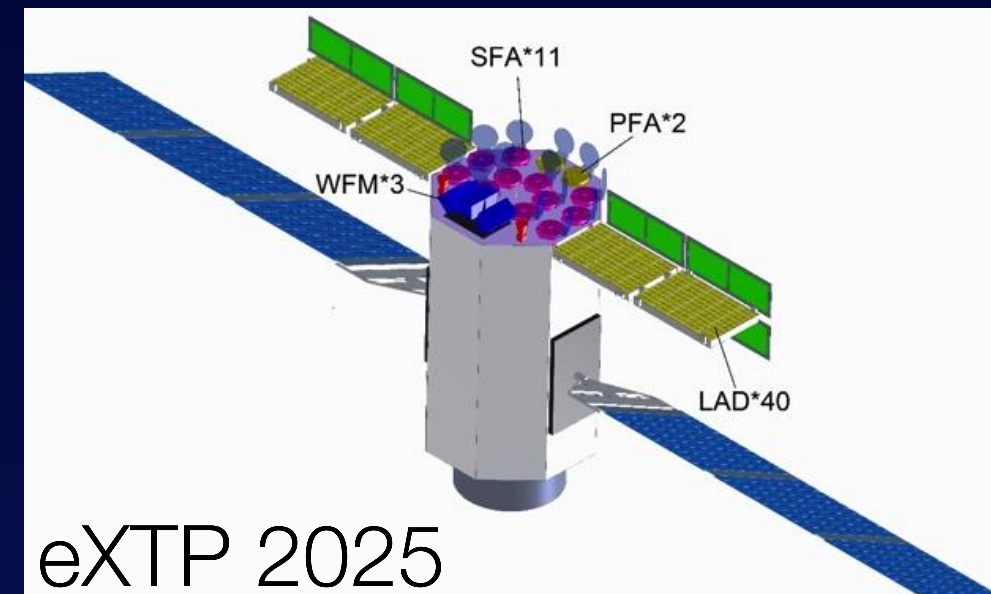
The near future of X-ray Astronomy



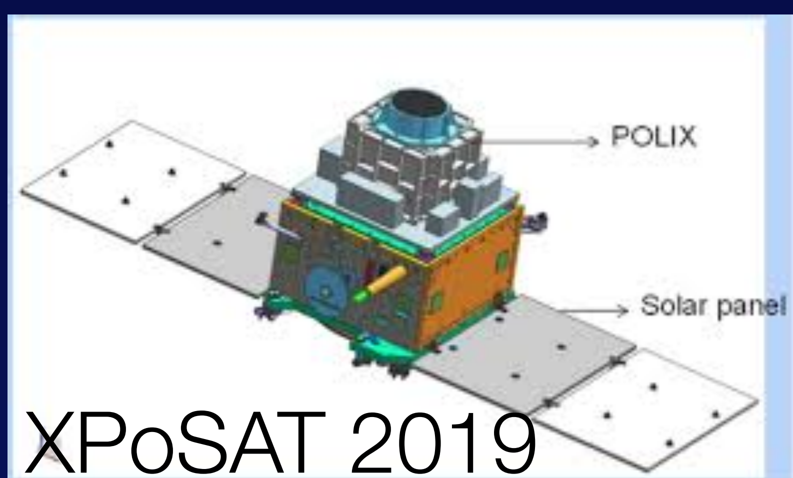
eROSITA 2019
Soft X-ray all-sky survey



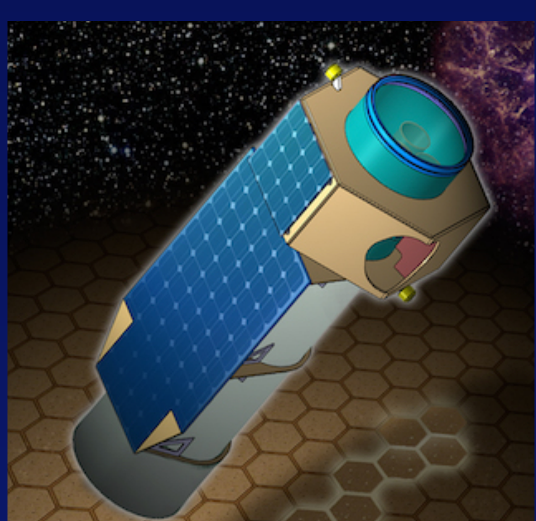
XARM 2021
Very high resolution spectroscopy



eXTP 2025
Soft X-ray Timing and Polarimetry



XPoSAT 2019
Medium-energy X-ray polarimetry



IXPE 2020
Soft X-ray polarimetry

Athena 2028
Soft X-ray high resolution spectroscopy & imaging

Summary

- X-ray astronomy is a very active discipline covering an impressive range of scales - from the most compact stars to clusters of galaxies
- Tracer of hot gas in the universe - baryon census, galactic outflows, feedback, mergers, structure formation history
- SNR spectroscopy - origin of heavy elements
- Vital probe of regions of strong gravity
  - Tests of GR
  - Equation of State of dense matter
  - Mass, spin and evolutionary history of Black Holes
- High energy non-thermal processes - magnetospheres, relativistic jets - can be studied in detail.
- Several missions, including polarimeters, planned for launch - exciting prospects ahead