Looking for True X-ray Modulation through Energy Quantiles

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Spring, 2011

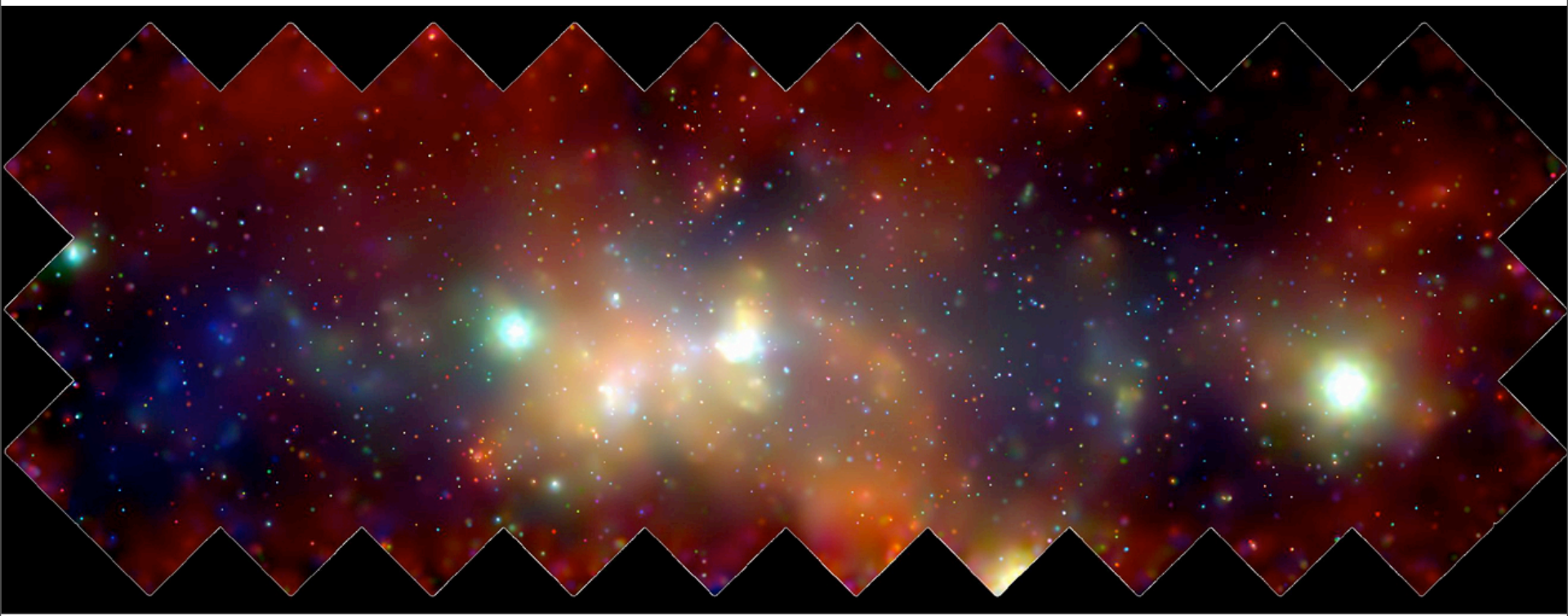
Outline

- The X-ray sources in the Galactic Bulge
- Quantile Analysis
- Periodic Bulge X-ray Sources and Modulating Energy Quantiles

Galactic Center Region (32' x 16')

X-ray (Blue, Purple): NASA/CXC/UMass/D. Wang et al.
Optical/nIR (Yellow) : NASA/ESA/STScI/D. Wang et al.
IR (Red) : NASA/JPL-Caltech/SSC/S. Stolovy

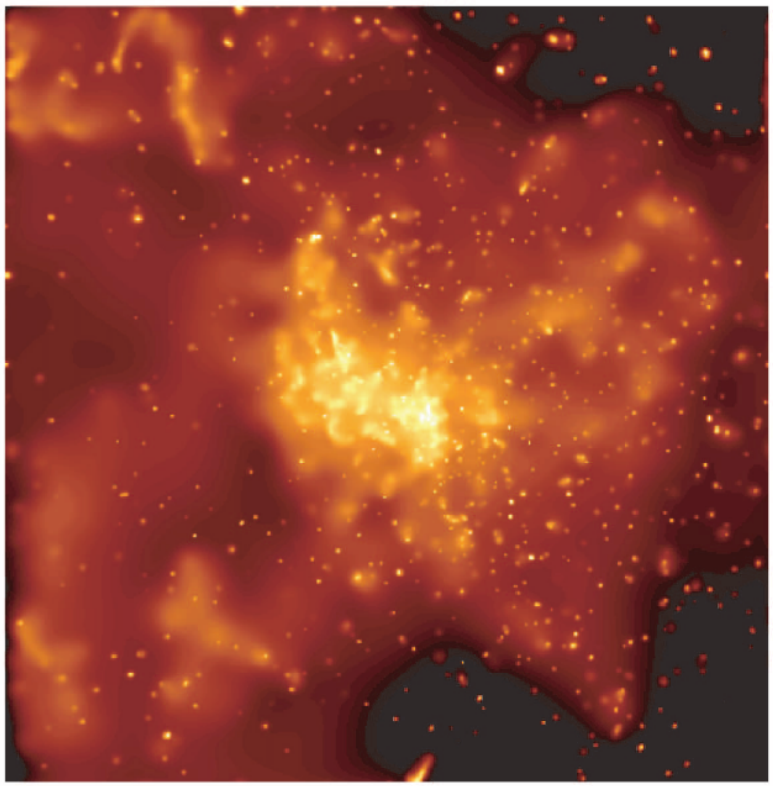
X-ray Sources in the Galactic Center Region



Chandra/ACIS shallow survey of 2 deg x 1 deg around Sgr A*

~1300 discrete X-ray sources (Wang et al. 2002)

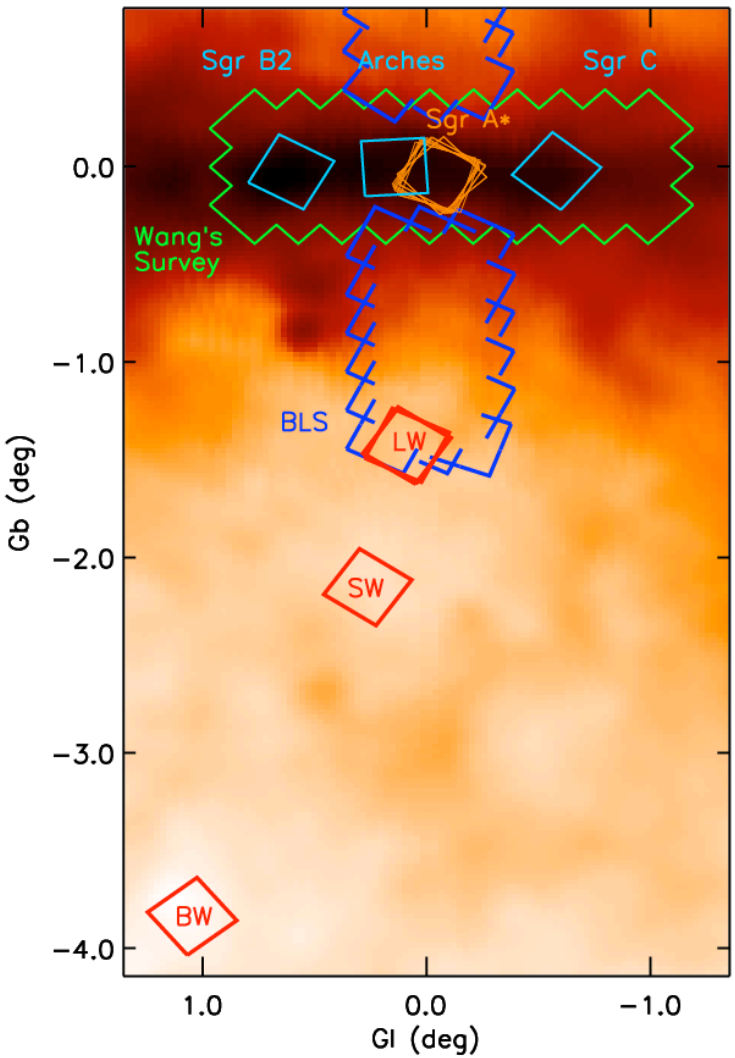
X-ray sources in the Galactic Center (GC)



8.5' x 8.5' Sgr A*
(~500 ks Chandra ACIS)
Muno et al. 2003

- Chandra's superb spatial resolution revealed >3000 low luminosity X-ray sources in the Galactic center region
- Formation and evolutionary history of the inner Galaxy
- Accreting Binary Systems and their evolution
- What are these X-ray sources?

Galactic Bulge Survey



- **Deep Bulge Window Survey**
  (100 ks Chandra, HST & Magellan)

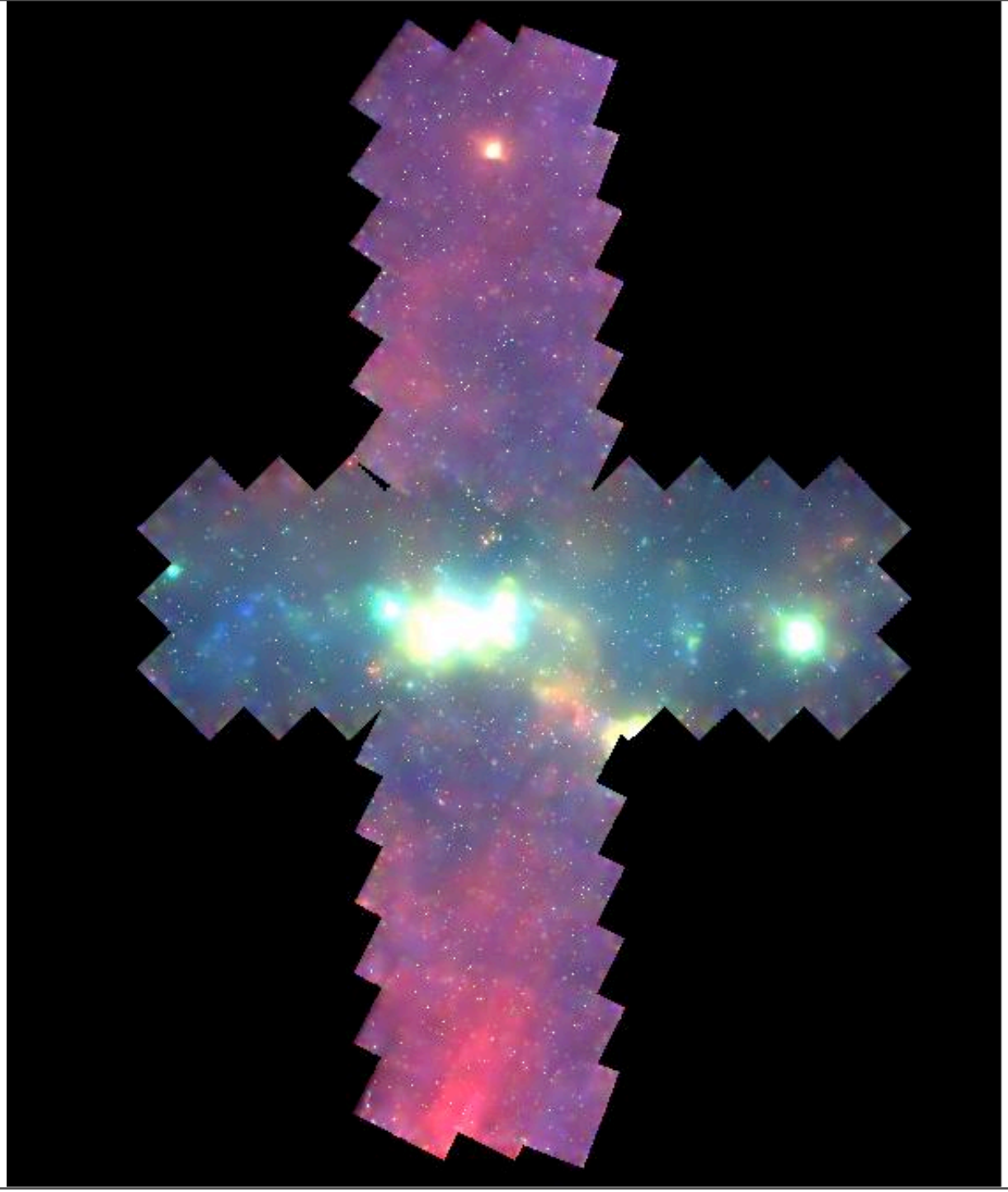
  Baade's Window (BW, Av~1.3)
  Stanek'sWindow (SW, Av~2.0)
  The Limiting Window (LW, Av~4.0)
  vs. Galactic Center (GC, Av~25)

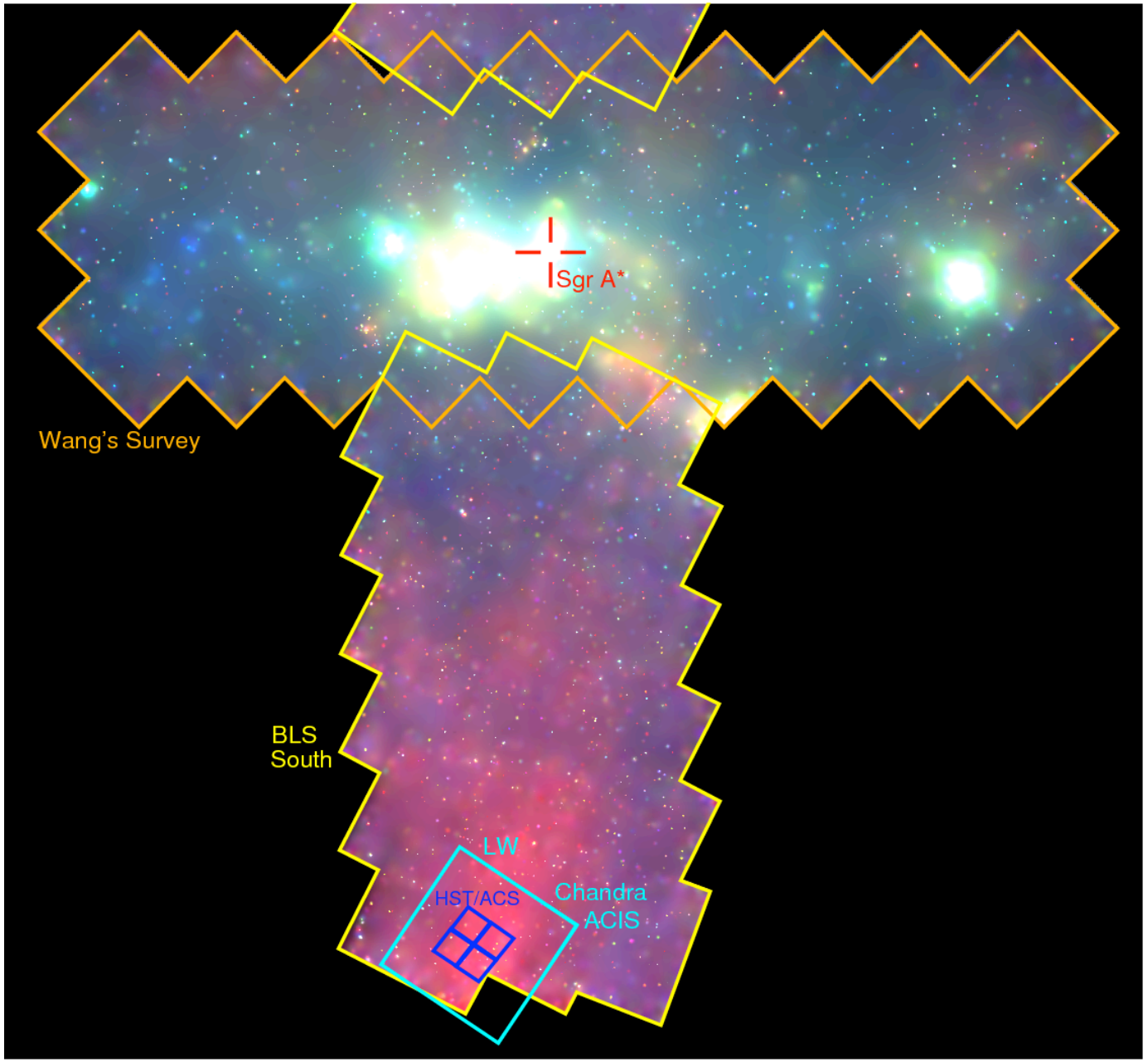
  Hong 2009, van den Berg 2006, 2009

- **Shallow Bulge Latitude Survey**
  (15 ks Chandra & Magellan)

  1 deg x 1.2 deg south and north region of the GC

  Grindlay 2011

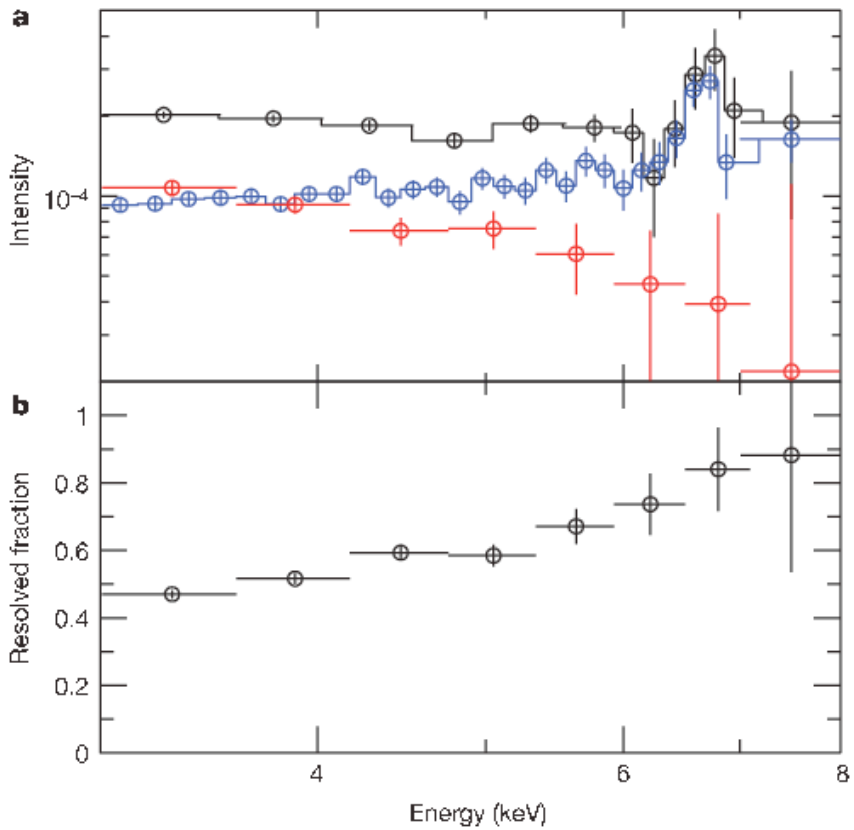



Sgr A*
Wang's Survey
BLS
South
LW
HST/ACS
Chandra
ACIS

The Limiting Window (1.4 deg south of the GC)

100 ksec Bulge Survey (Hong et al 2009)
+ 900 ksec Ultra-deep Survey (Revnivtsev et al 2009)

Galactic Ridge X-ray Emission



Resolved fraction of X-ray emission
Revnivtsev et al. 2009

- **1 Ms Chandra observations of a low extinction region, the Limiting Window, at 1.4 south of the GC**
- **~ 80% of the X-ray emission was resolved at energies > 6 keV**

Bulge X-ray Sources

At the Galactic Center

- **Low Luminosity: 10^{30-33} erg/s**
- **Relatively Hard X-ray Spectra (Power law Photon Index ~ 0.7)**

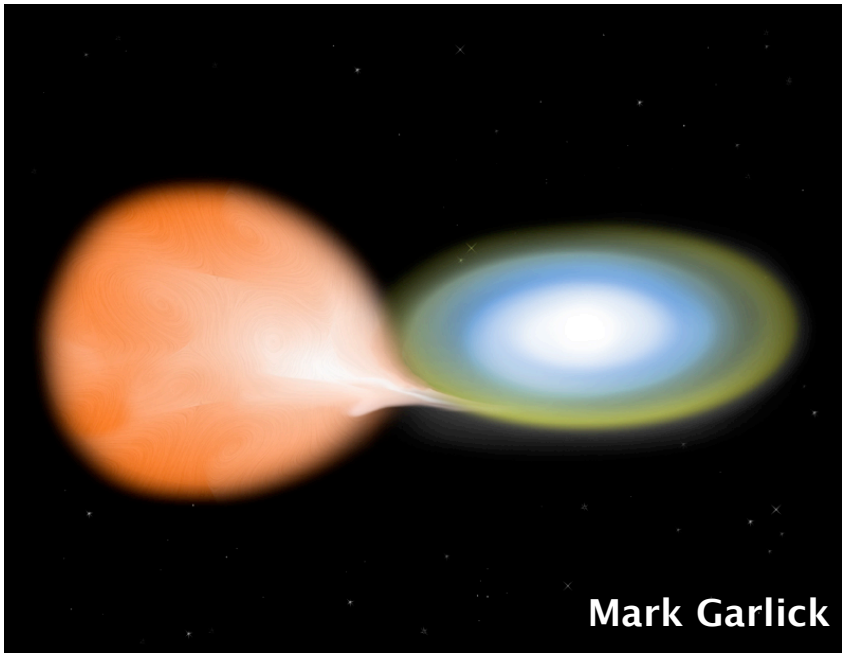
Quiescent High Mass X-ray Binaries (qHMXBs):
<10% (Laycock et al 2005)
Magnetic Cataclysmic Variables (CVs)

In the Window Fields

- **Also see relatively Soft X-ray Sources**

$>10^{30-31}$ erg/s
Quiescent Low Mass X-ray Binaries (qLMXBs)
Non-Magnetic Cataclysmic Variables
$<10^{30-31}$ erg/s
Active Binaries (ABs)

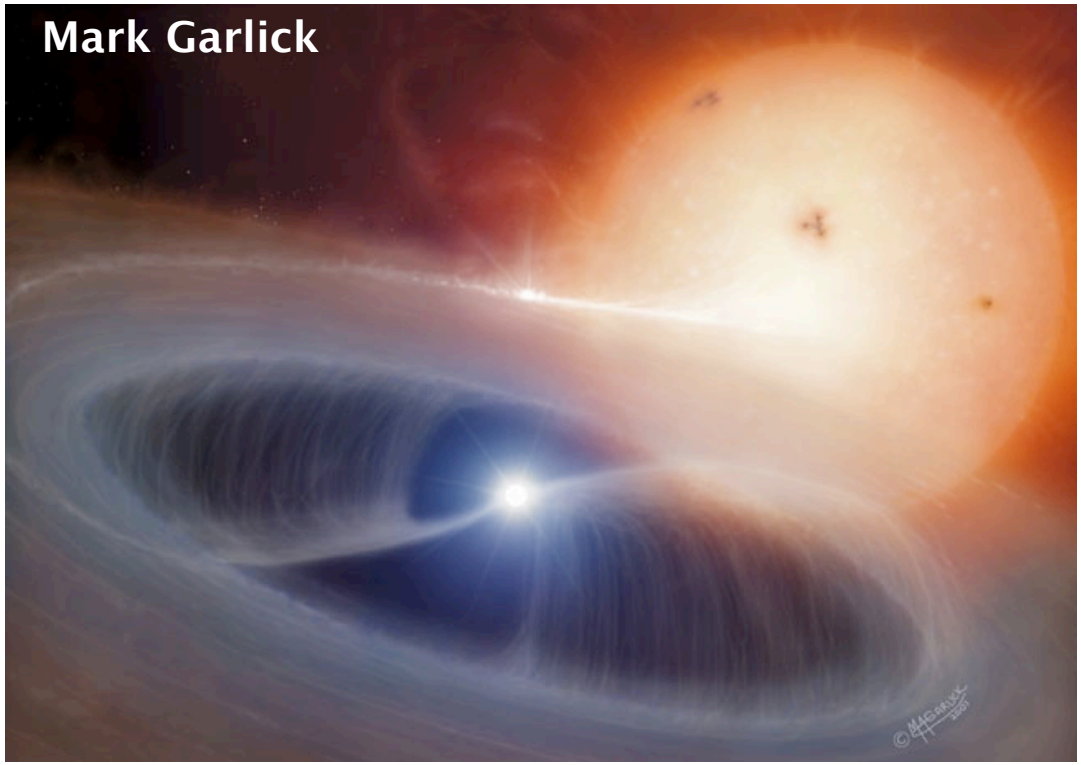
Cataclysmic Variables (CVs): Compact Binaries with white dwarf accreting from late type companion



Non-Magnetic CVs

Polars

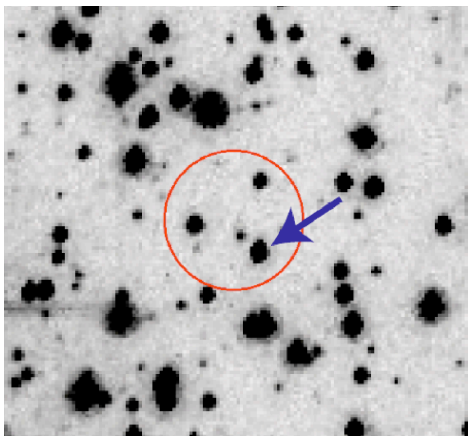
Cataclysmic Variables (CVs):
Compact Binaries with white dwarf accreting from late type companion



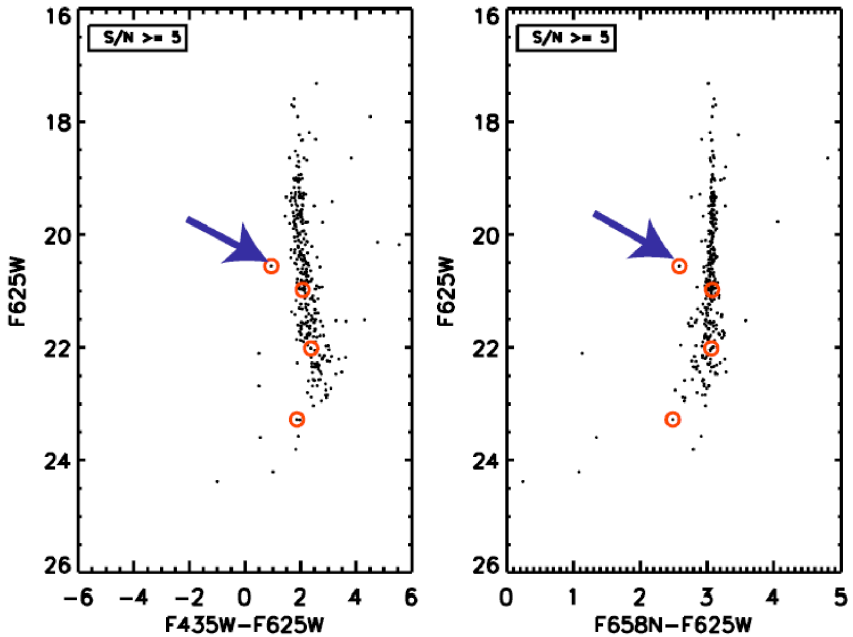
Intermediate Polars

Direct Identification

- At the Galactic Center
  A_V ~ 25, A_K~5
  Confusion limit: K~15 with Magellan/PANIC (6. 5m)
- In the Windows fields (A_V< 4)
  m_V >20-23
  many candidate counterparts, no guarantee



HST ACS/F625W image
with 1" 95 % conf. radius



Source identification in Windows/HST fields

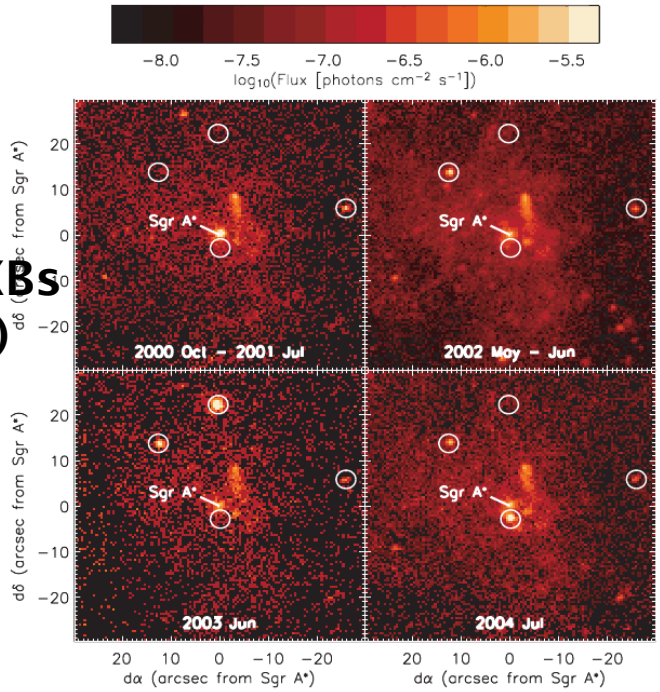
Fields (100 ks)	X-ray sources	X-ray sources In HST/ACS	CV candidates	Predicted
BW	403	162	4 - 9	7
SW	433	139	2 - 10	14
LW	319	100	13 - 25	14

X-ray sources in the Galactic Bulge: More from X-ray data

- **Variable X-ray sources**

  e.g. Scargle's Bayesian Block Searches

  4 Transients within 1pc vs. 7 in 25 pc
  (Muno et al 2005)
  8 Transients in the GCR: quiescent LMXBs
  (Degenaar et al 2009, 2010)

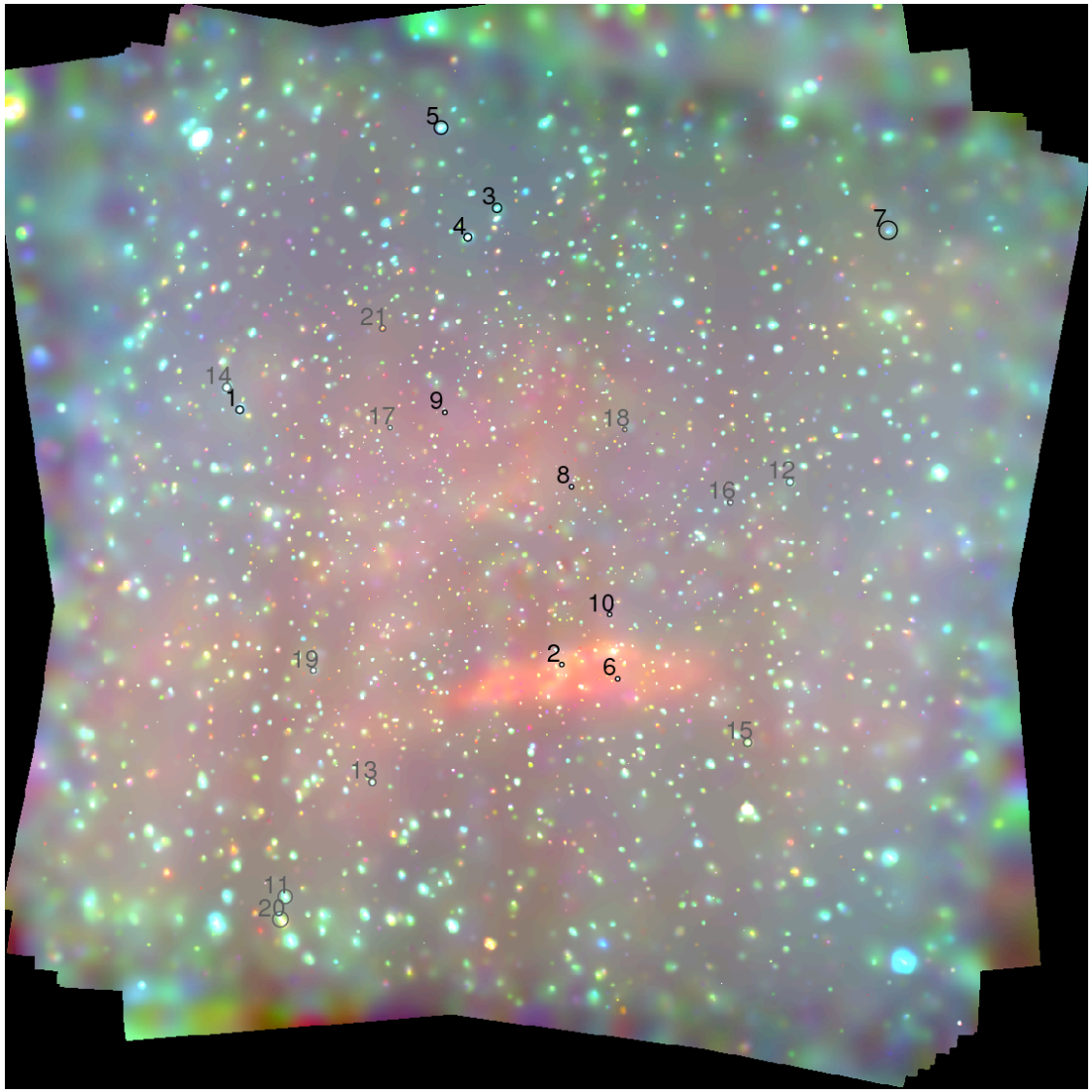


- **Periodic X-ray sources**

  Lomb-Scargle
  Buccheri's z^2 statistics
  Epoch Folding
  .....

  9 Periodic sources in the GCR: magnetic CVs
  (Muno et al 2003, 2009)

The Limiting Window (1Ms Chandra/ACIS-I)

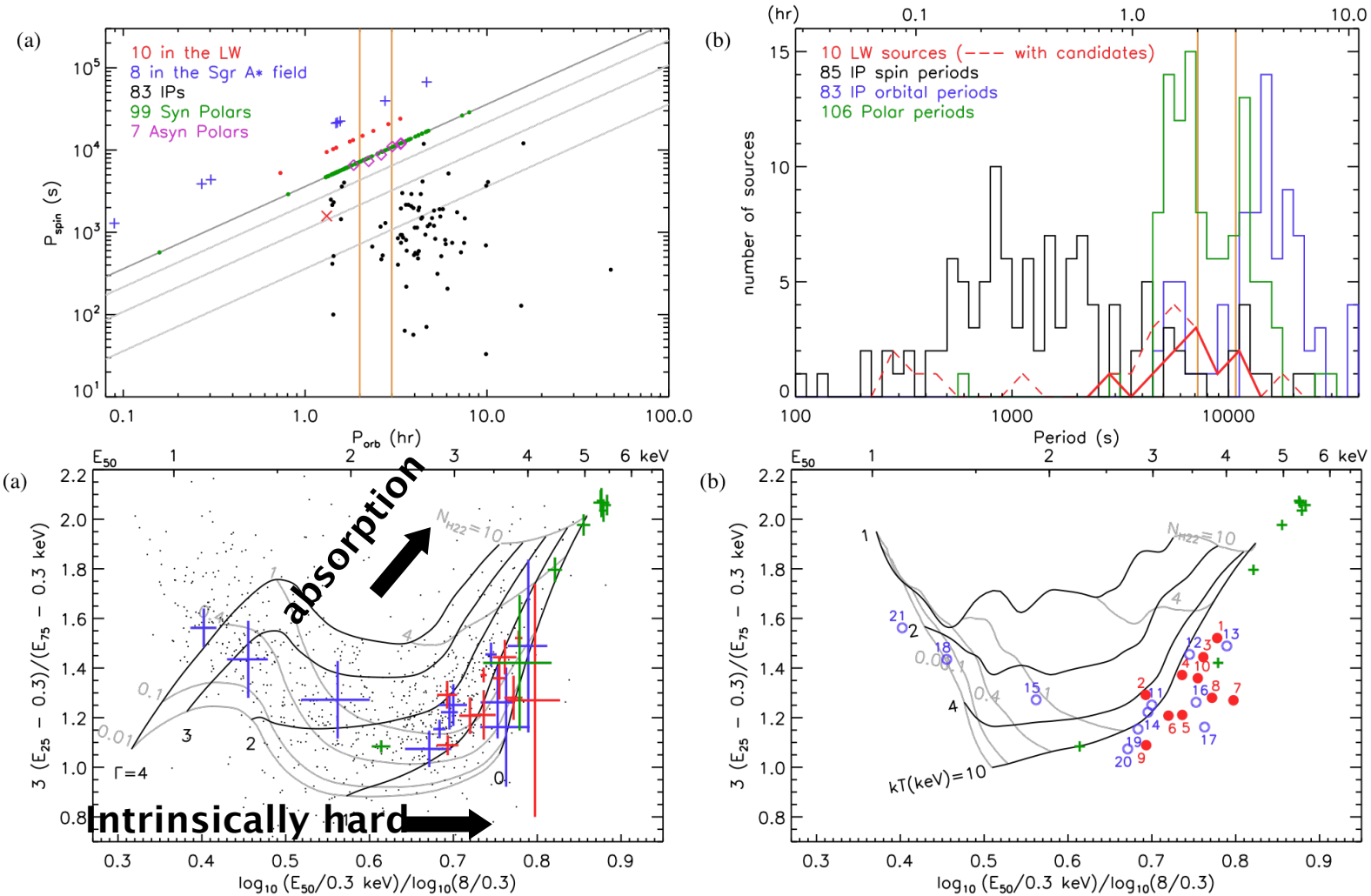


10 periodic sources and 11 candidates
Hong et al 2010, arXiv:1103.2477

Variable X-ray sources in the Bulge Fields (not complete)

Fields	Periodic	Variables
BW (100 ksec)	1	-
SW (100 ksec)	0	-
LW (1 Msec)	10 + 11	~80 (short + long)
GCR (1+1 Msec) (Muno et al)	9	856 (long) + 198 (short)

The Limiting Window (1Ms Chandra/ACIS-I)



- Very hard spectra
- 20-30% of hard X-ray sources can be periodic
  (Hong et al 2010, arXiv:1103.2477)

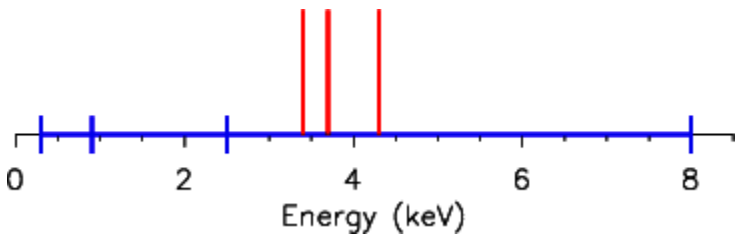
Extracting Spectral Properties or Variations from faint X-ray sources

- **Hardness Ratio**

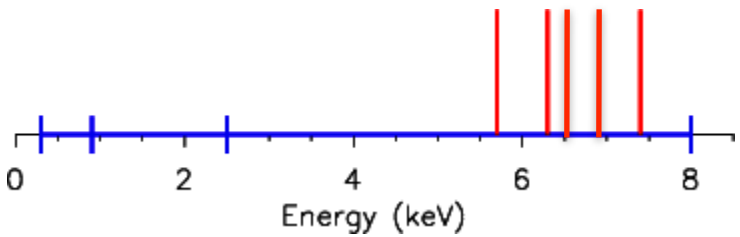
  $HR_1 = (H-S)/(H+S)$ or $HR_2 = \log_{10}(H/S)$

  e.g. S: 0.3–2.5 keV,

  H: 2.5–8.0 keV



$HR_1 = 1$



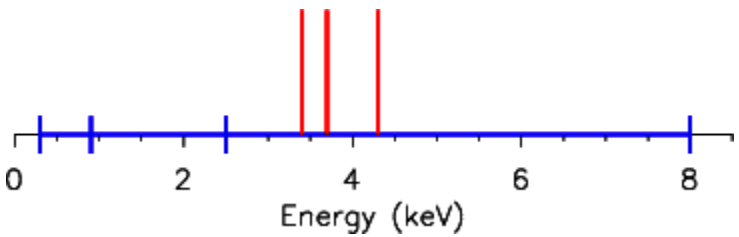
$HR_1 = 1$

- **Bayesian Estimation of Hardness Ratios (BEHR)**
  Park et al, 2006, ApJ

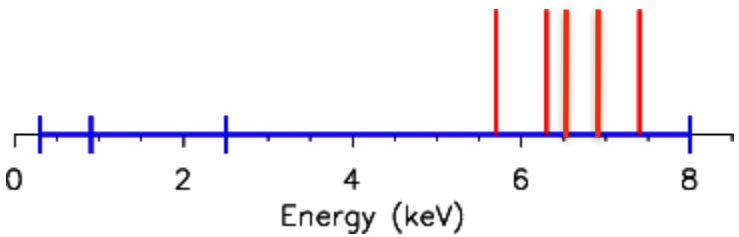
Quantiles

- Low count requirements for quantiles:
  spectral-independent
  2 counts for median
  3 counts for terciles and quartiles

- No energy binning required
- Take advantage of energy resolution
- Optimal use of information



Median (E_{50}) = 3.7 keV



Median (E_{50}) = 6.5 keV

X-ray Spectral Models of Astronomical Objects

Power law (Photon Index: Γ)
Black Body (Temperature: kT)
Thermal Brems. (Plasma Temperature: kT)
MeKaL or APEC (Plasma Temperature: kT, Abundance, …)
….

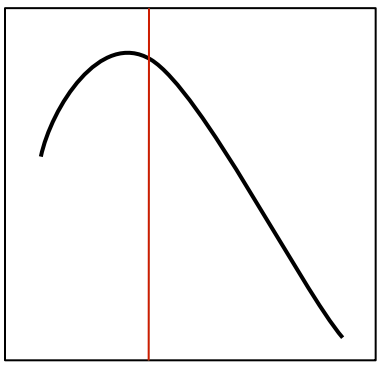
+ Interstellar Absorption (N_H)

Goal: acquire two parameters to describe basic spectral shapes.

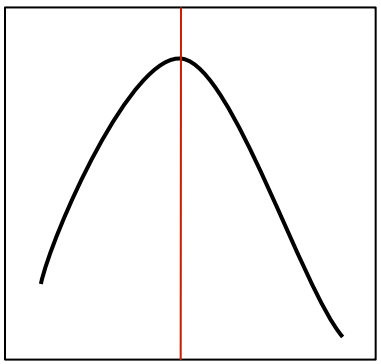
cf. Hardness ratio using three bands:
S, M, H => HR1 = S/M, HR2 = M/H

Two independent parameters from Quantiles

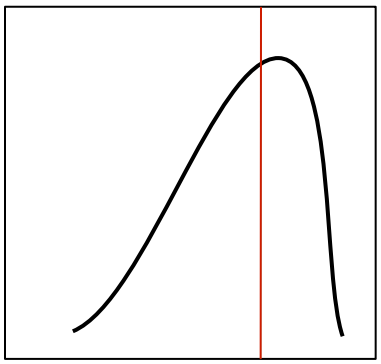
- Median (E_{50})



Energy

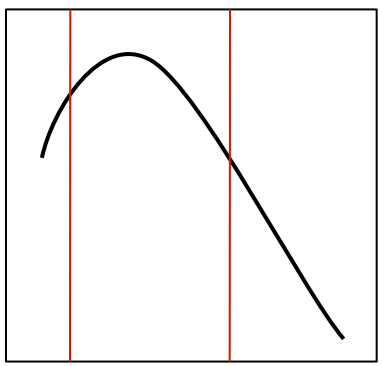


Energy

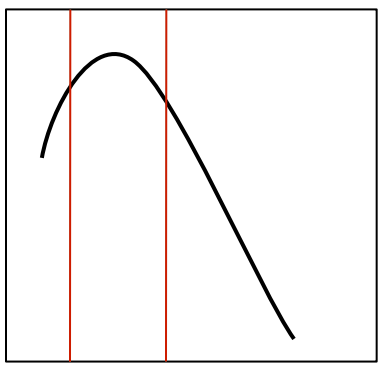


Energy

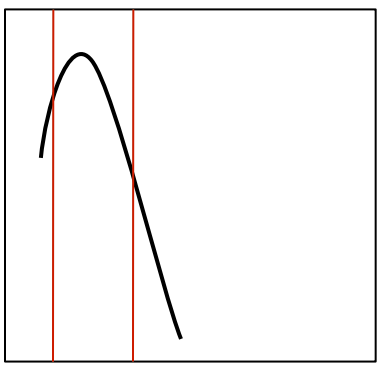
- Quartile Ratio (E_{75}/E_{25})



Energy

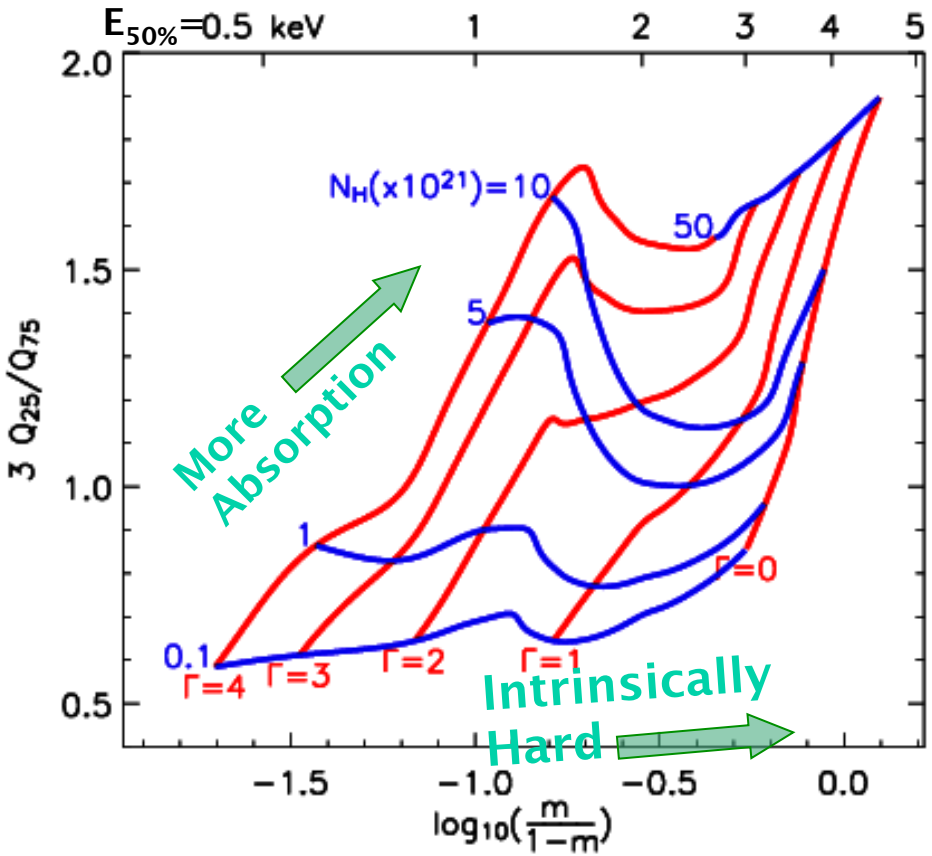


Energy



Energy

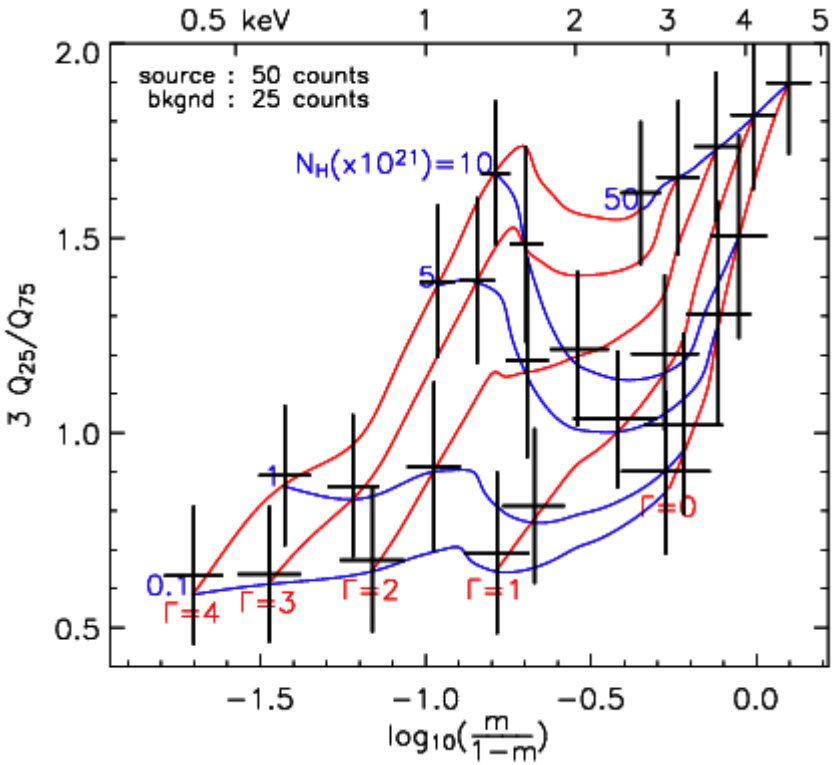
Quantile Diagram



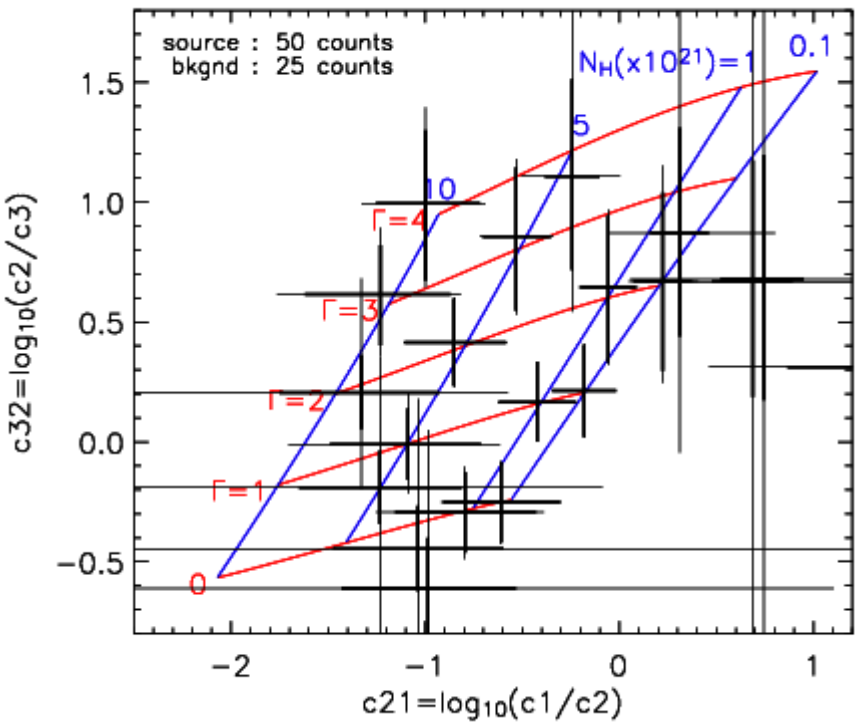
ACIS-S detector
0.3-8.0 keV

- Quantiles are not independent
- $m=Q_{50}$ vs Q_{25}/Q_{75}
- Power-Law : Γ & N_H
- Proper spacing in the diagram

50 source count/ 25 background count

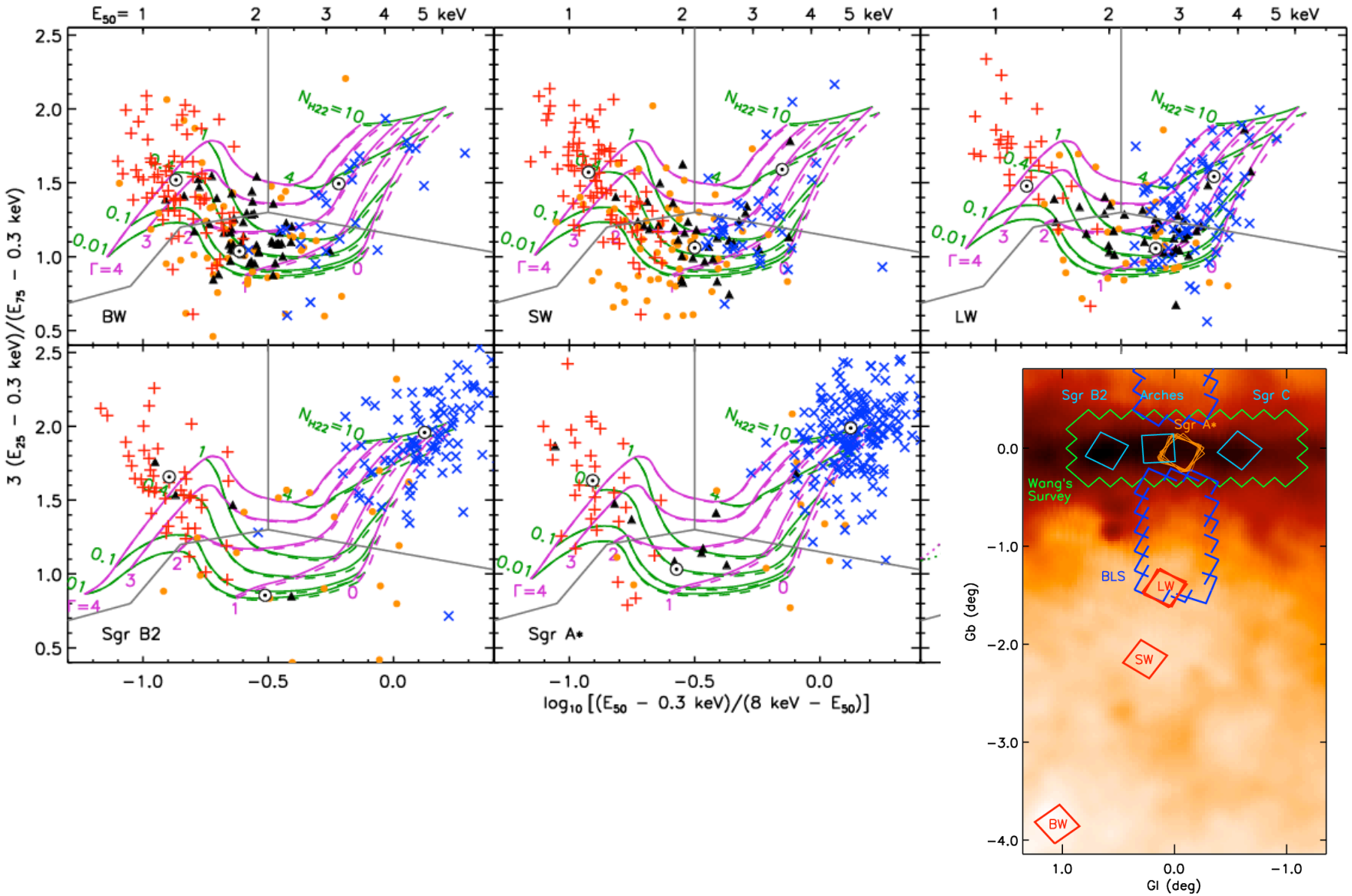


Quantile Diagram
0.3-8.0 keV



Conventional X-ray
Color-Color Diagram
0.3-0.9-2.5-8.0 keV

Quantile Diagrams for Windows and Galactic Center Fields



Future Improvement of Quantile Analysis

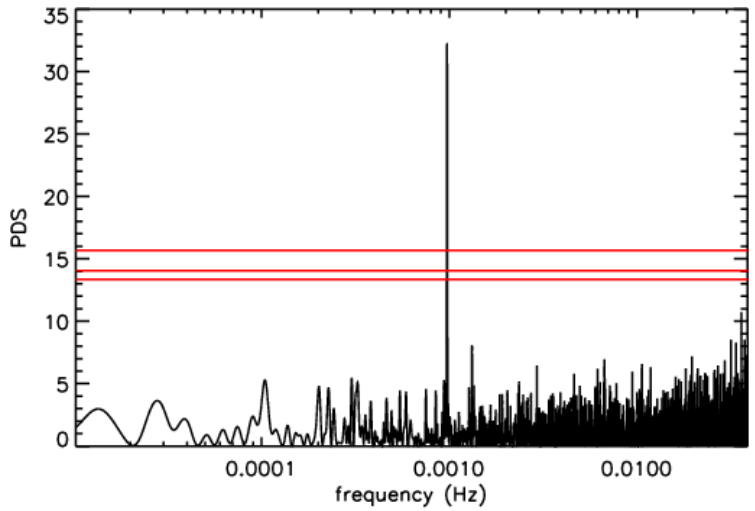
- Logit (Median) => Log (Median)

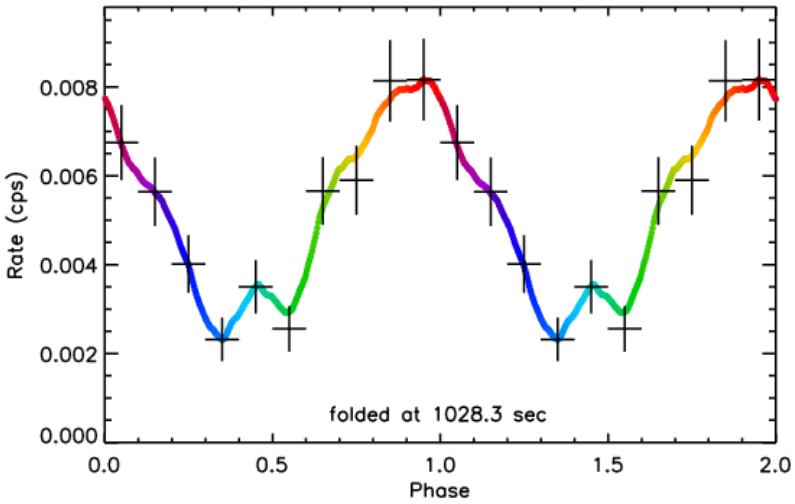
- Quantiles for Photons with Weighting
  e.g. Swift/BAT: each count with weight

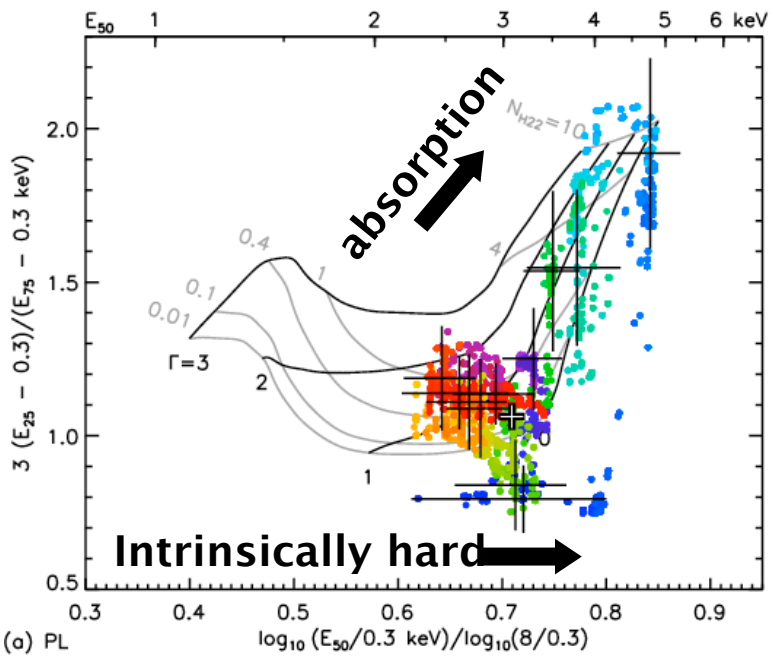
  Allows a unified phase space for a given energy band
  regardless of response function
  => Atlas of X-ray spectral type,
  Physical meaning in Quantiles

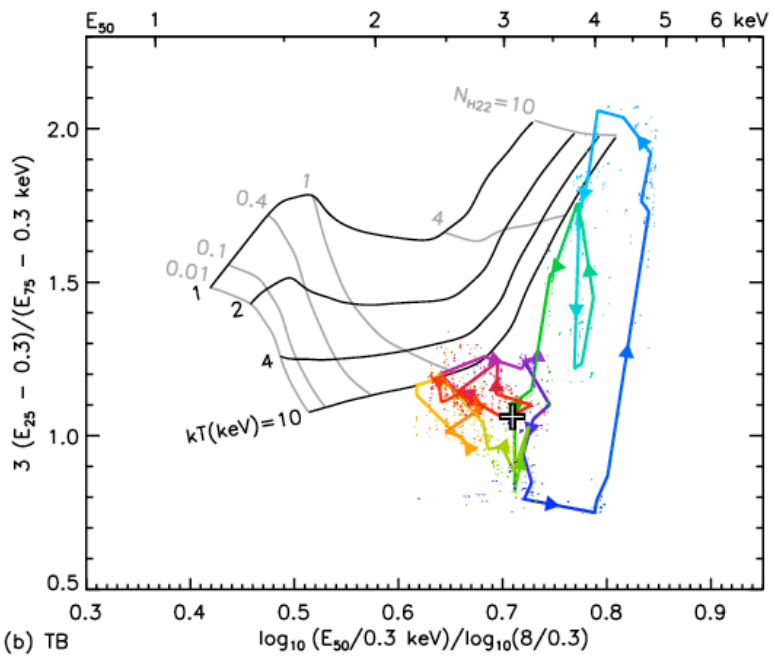
- Improve Error Estimates

Magnetic CV in Baade's Window : CXOPS J180354.3 – 300005 (1028.3 s)

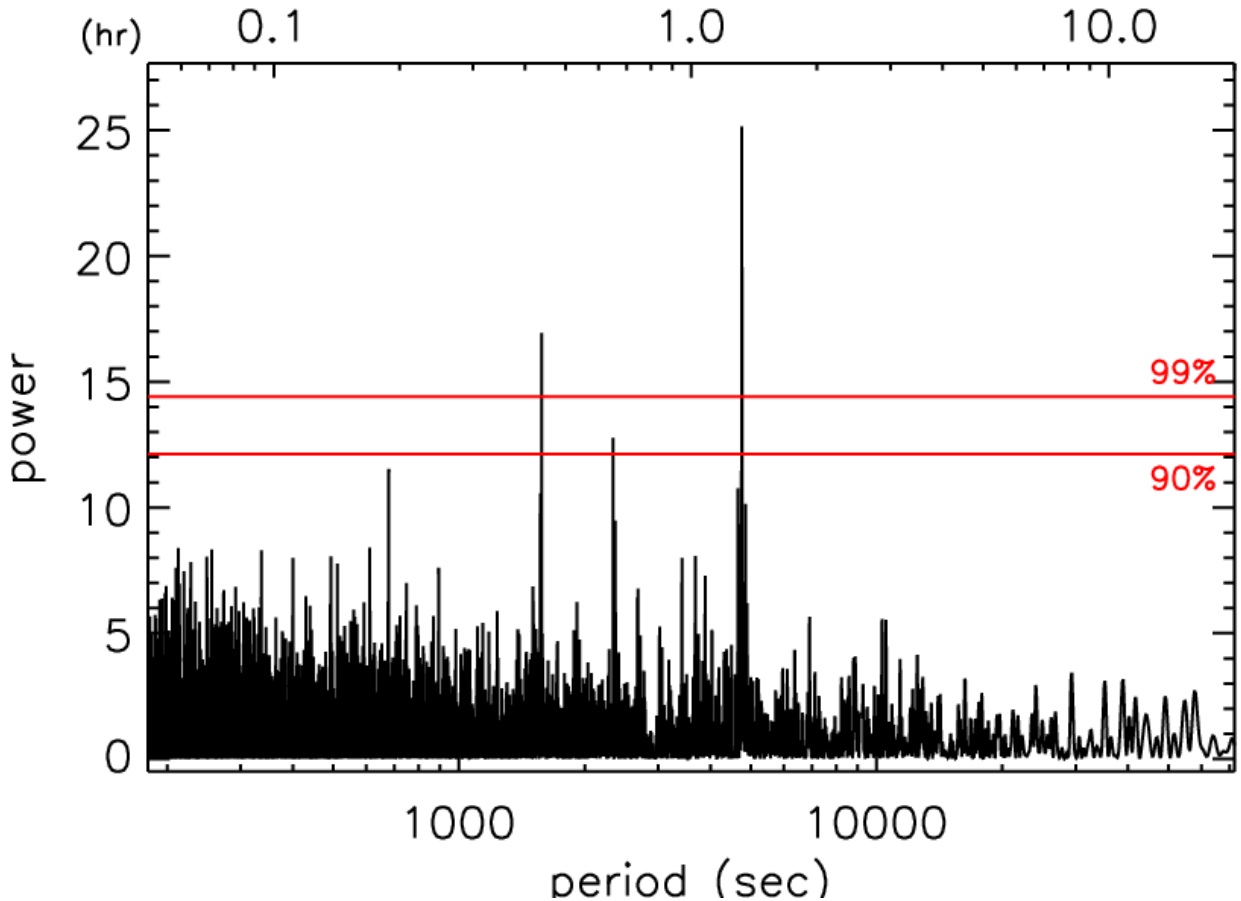


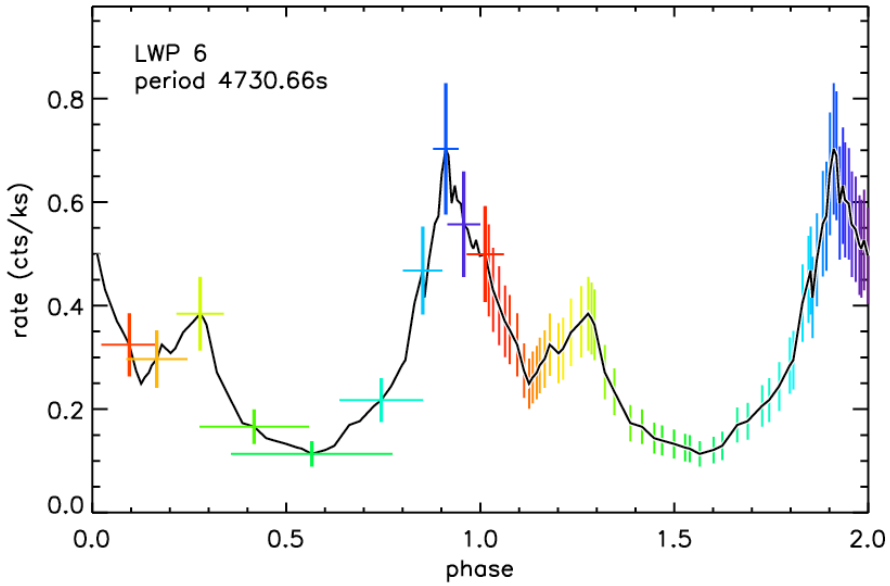


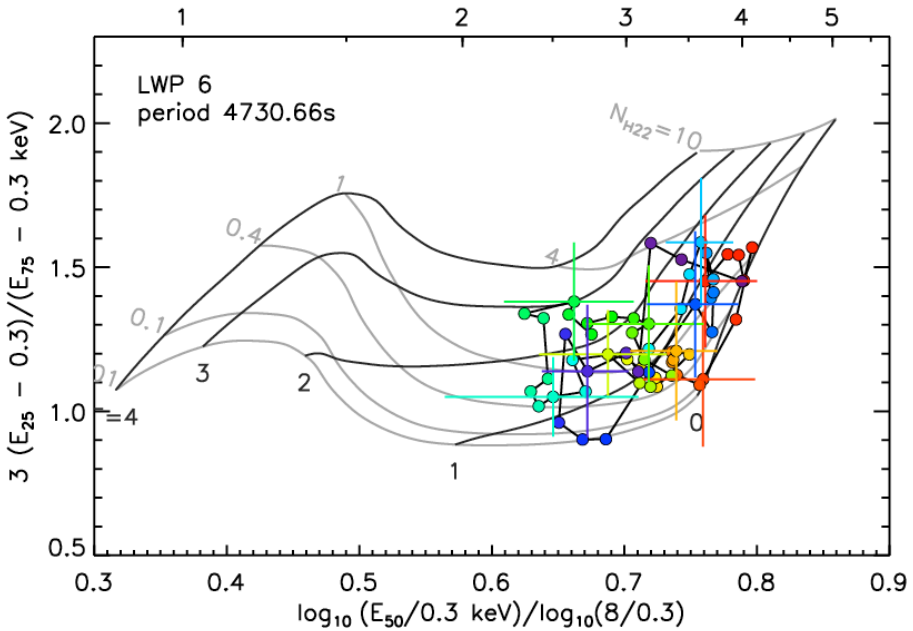


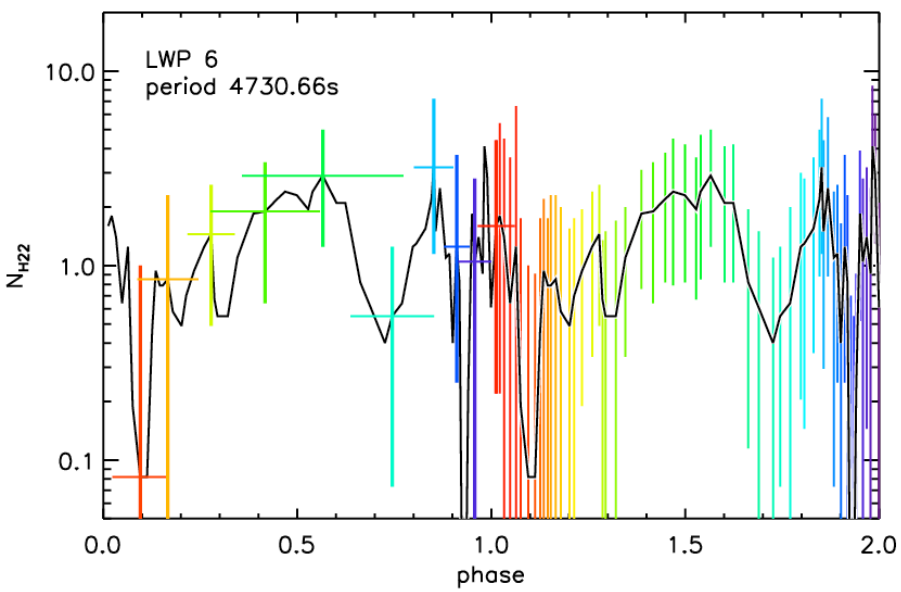


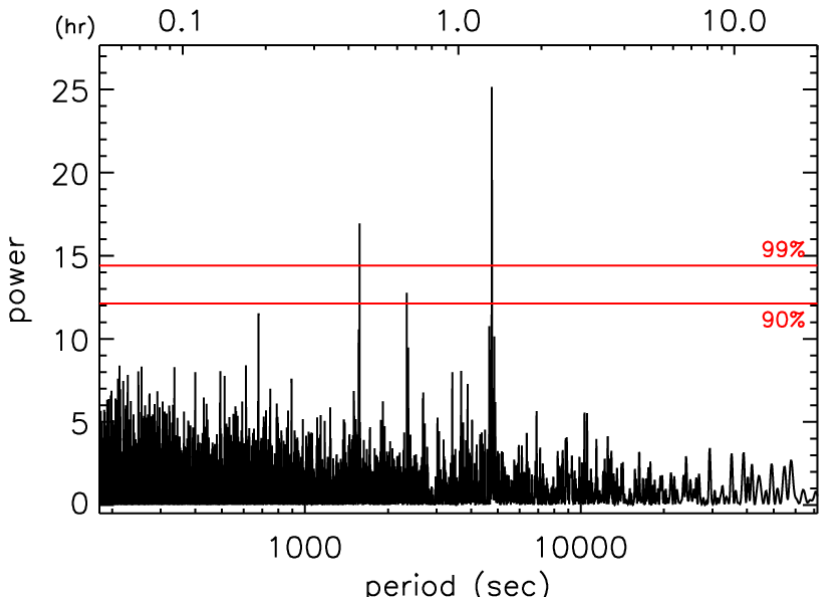
Magnetic CV in LW : CXOPS J175118.7 – 293811 (4731 s)

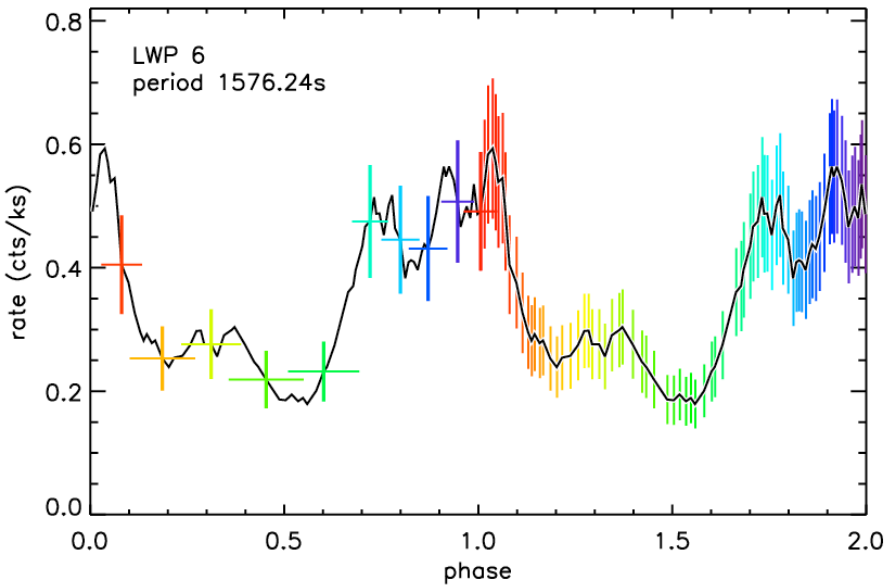


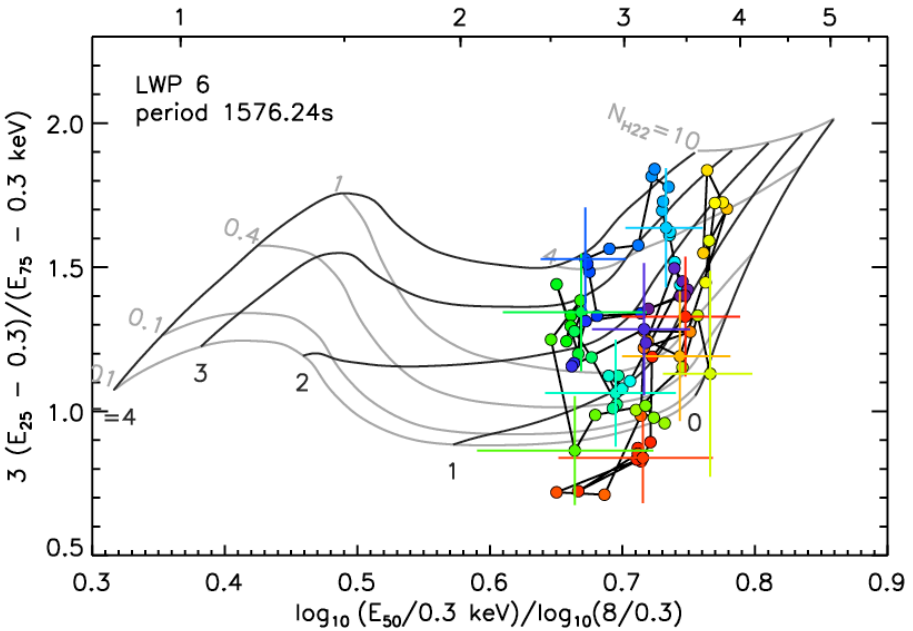

LWP 6
period 4730.66s
rate (cts/ks)
phase

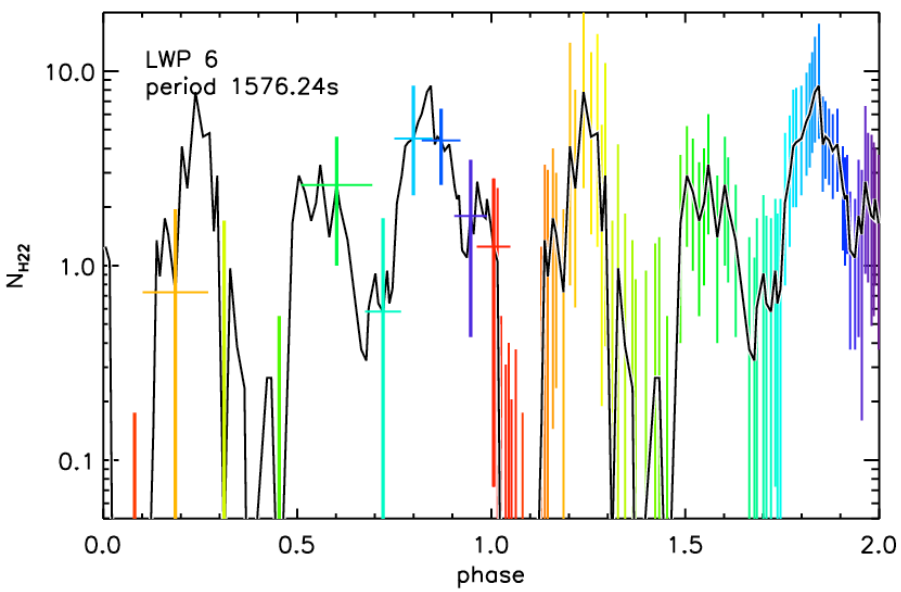

LWP 6
period 4730.66s
$N_{H22}=10$
1
0.4
0.1
0.01
=4
4
3
2
1
0
$3\ (E_{25}-0.3)/(E_{75}-0.3\ keV)$
$\log_{10}(E_{50}/0.3\ keV)/\log_{10}(8/0.3)$

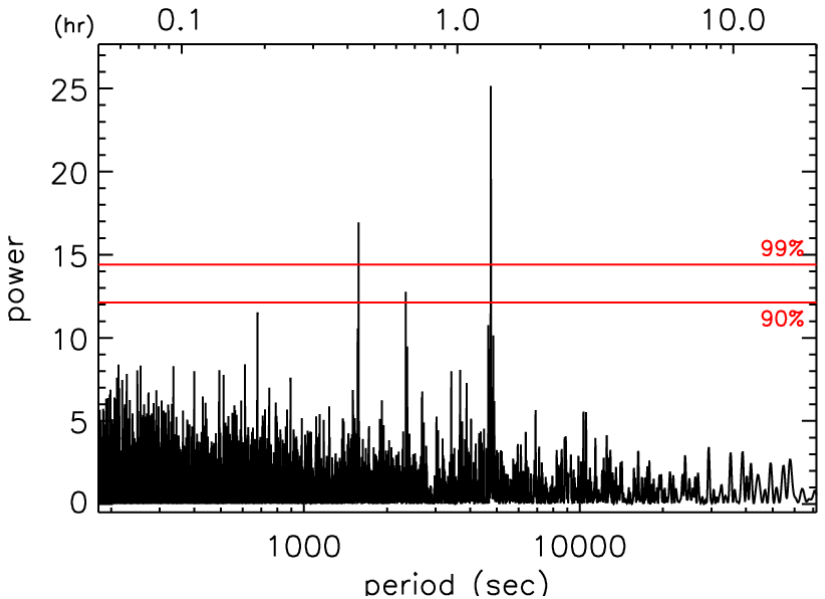

LWP 6
period 4730.66s
N_{H22}
phase

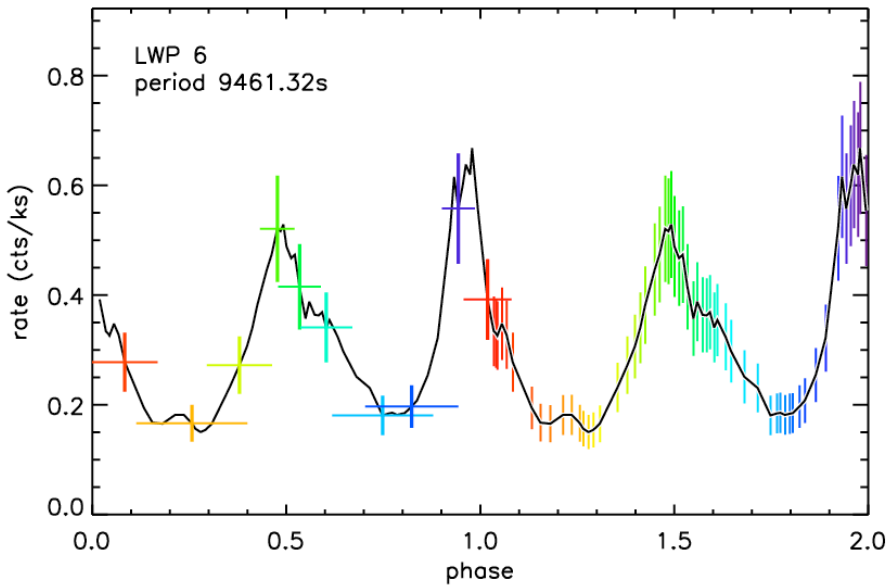

(hr)
0.1
1.0
10.0
power
99%
90%
period (sec)

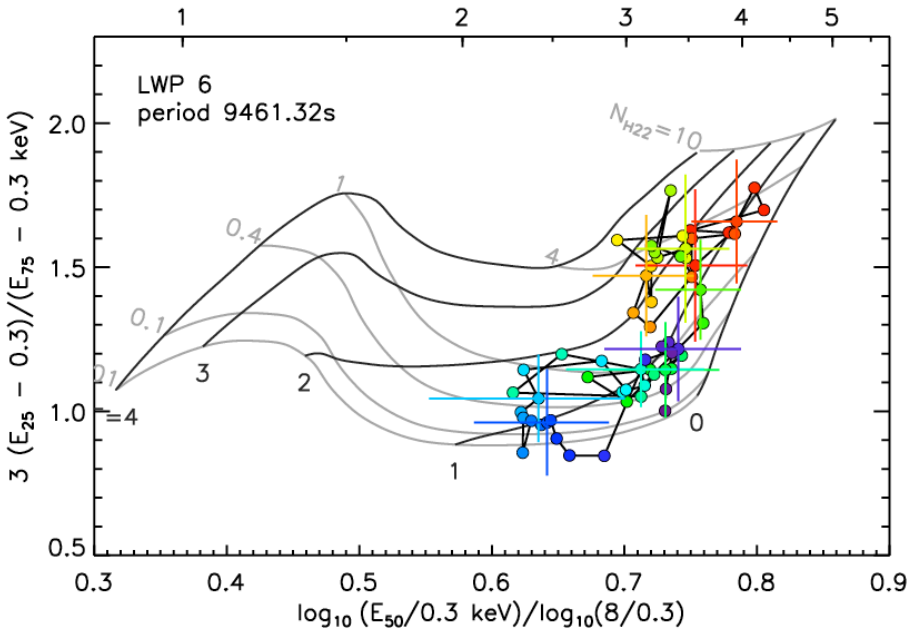

LWP 6
period 1576.24s
rate (cts/ks)
phase

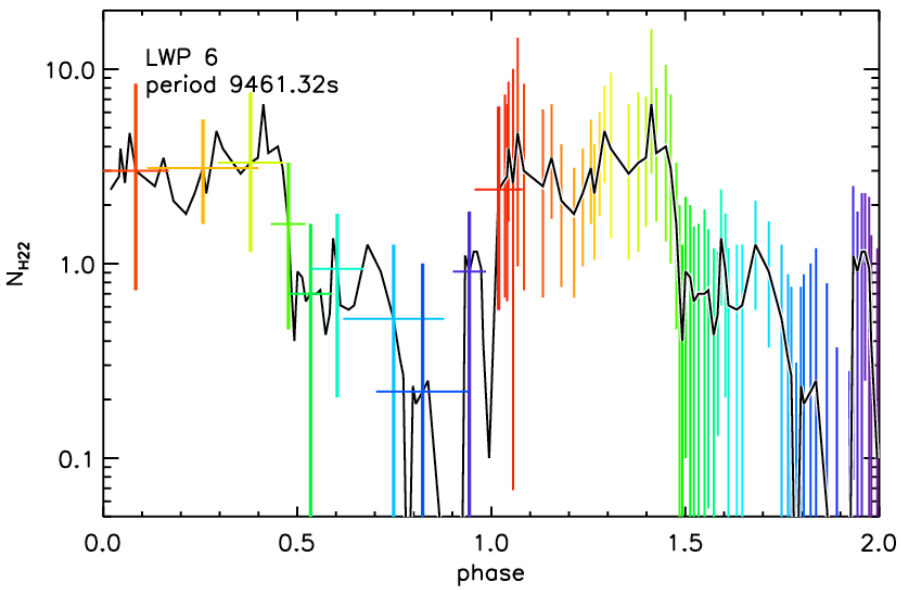

LWP 6
period 1576.24s
3 (E25 − 0.3)/(E75 − 0.3 keV)
log10 (E50/0.3 keV)/log10(8/0.3)
NH22=10
1
0.4
0.1
0.01
=4
4
3
2
1
0

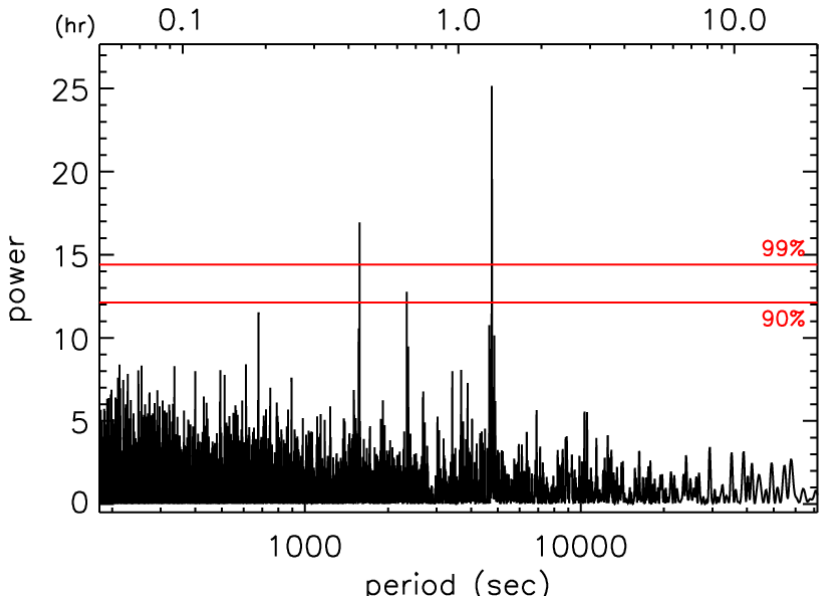

LWP 6
period 1576.24s
NH22
phase


(hr)
power
99%
90%
period (sec)

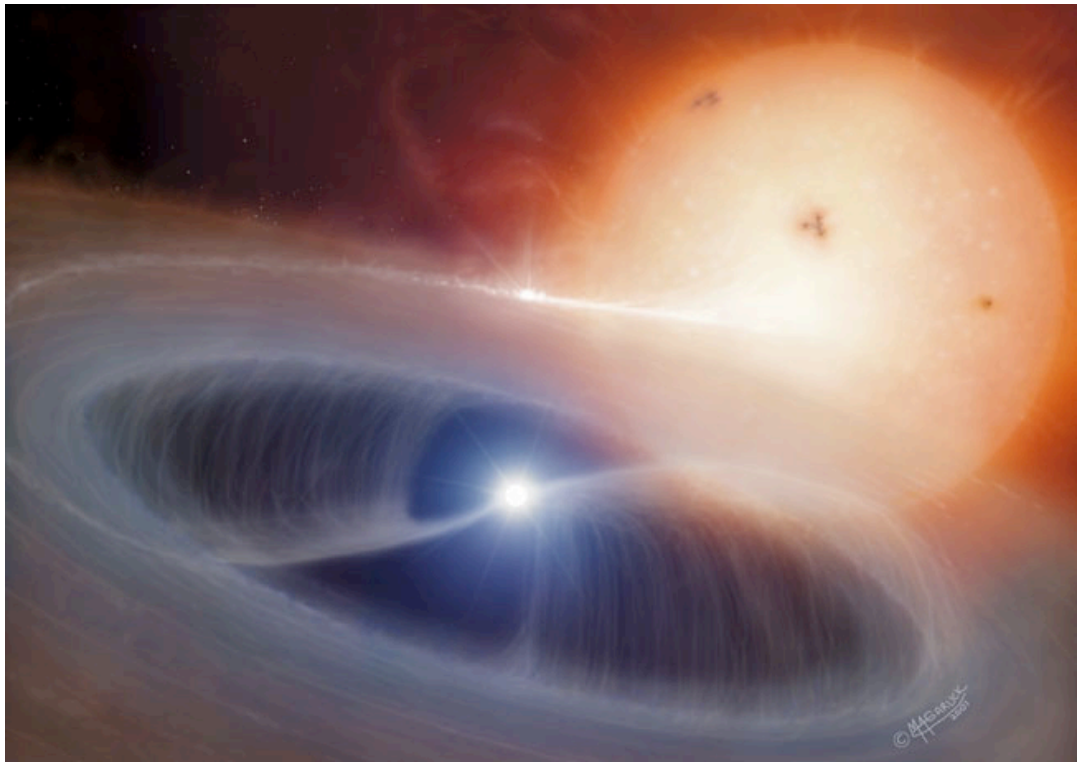

LWP 6
period 9461.32s
rate (cts/ks)
phase


LWP 6
period 9461.32s
$N_{H22}=10$
1
0.4
0.1
0.01
4
3
2
1
0
$3\ (E_{25}-0.3)/(E_{75}-0.3\ keV)$
$\log_{10}(E_{50}/0.3\ keV)/\log_{10}(8/0.3)$


LWP 6
period 9461.32s
N_{H22}
phase

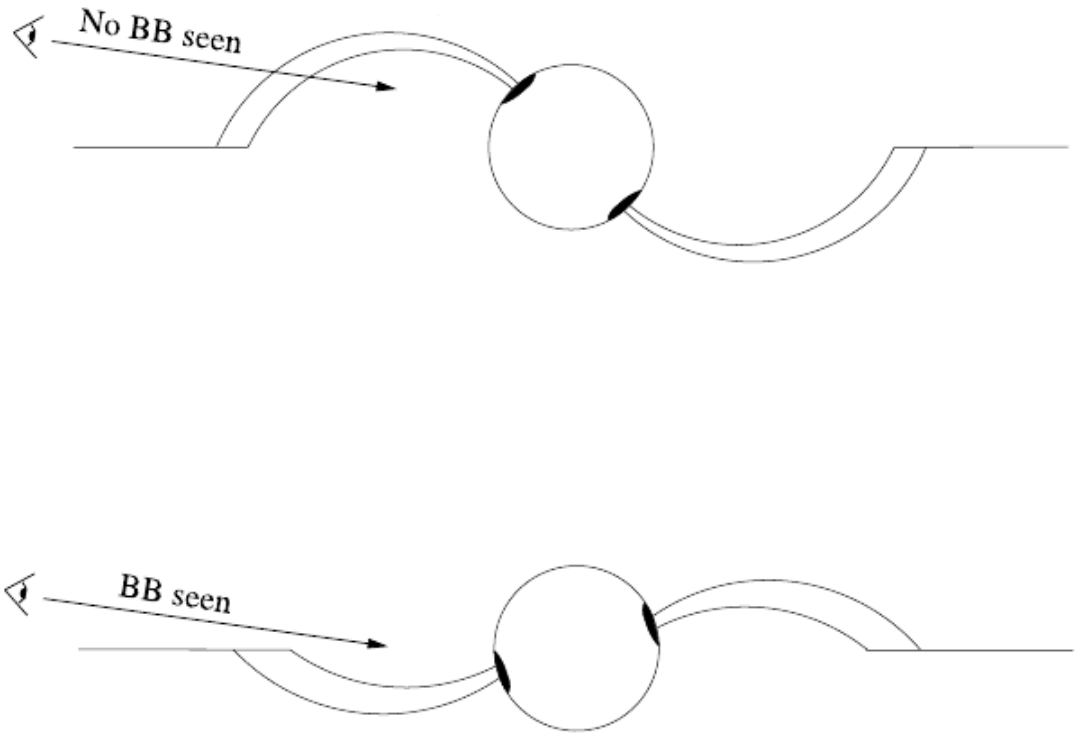

(hr)
power
99%
90%
period (sec)

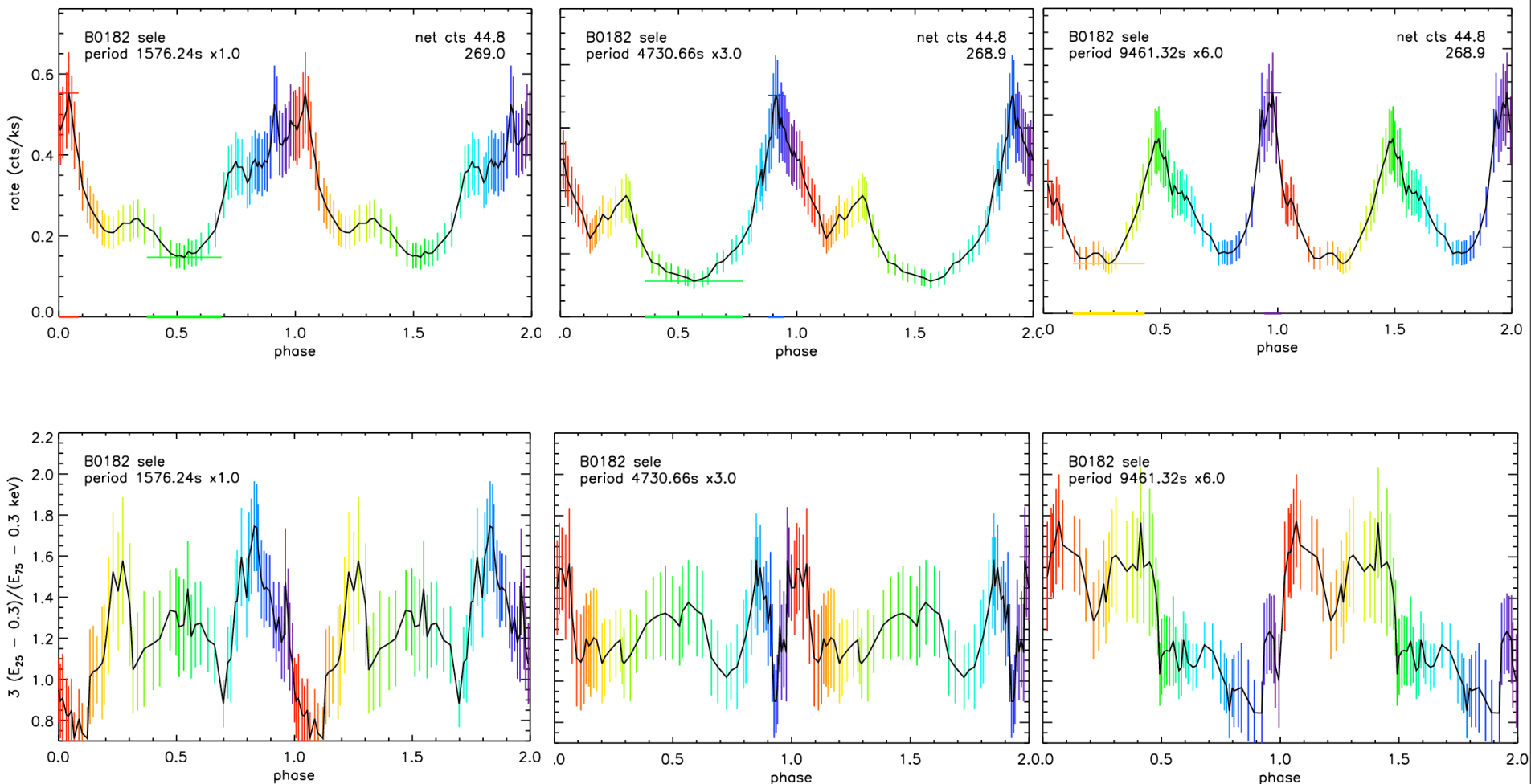
Cataclysmic Variables (CVs): white dwarf with late type companion



Intermediate Polars

Evans & Hellier
2007

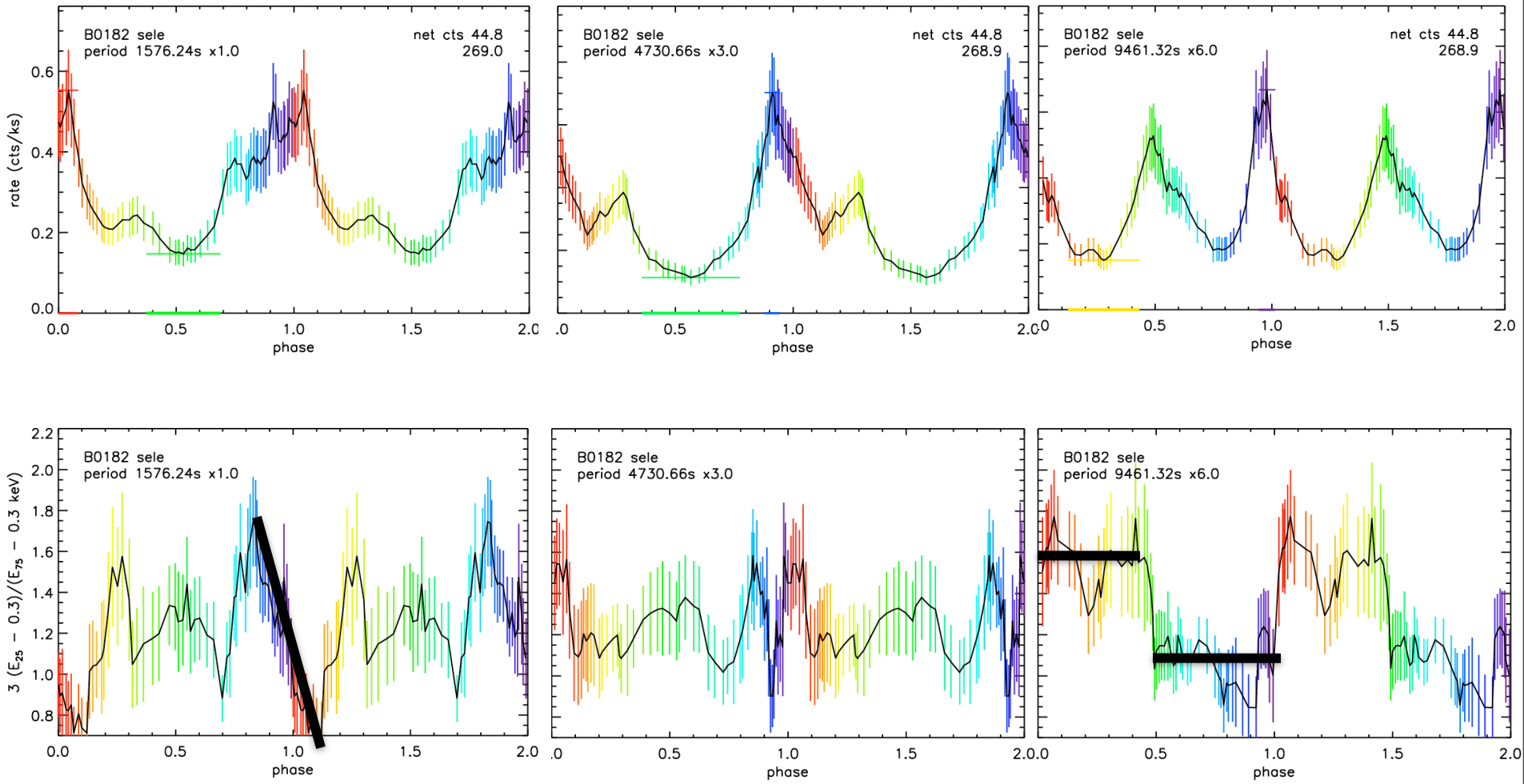



1576 s
4730 s
9461 s
B0182 sele
period 1576.24s x1.0
net cts 44.8
269.0
B0182 sele
period 4730.66s x3.0
net cts 44.8
268.9
B0182 sele
period 9461.32s x6.0
net cts 44.8
268.9
rate (cts/ks)
phase
3 (E25 − 0.3)/(E75 − 0.3 keV)

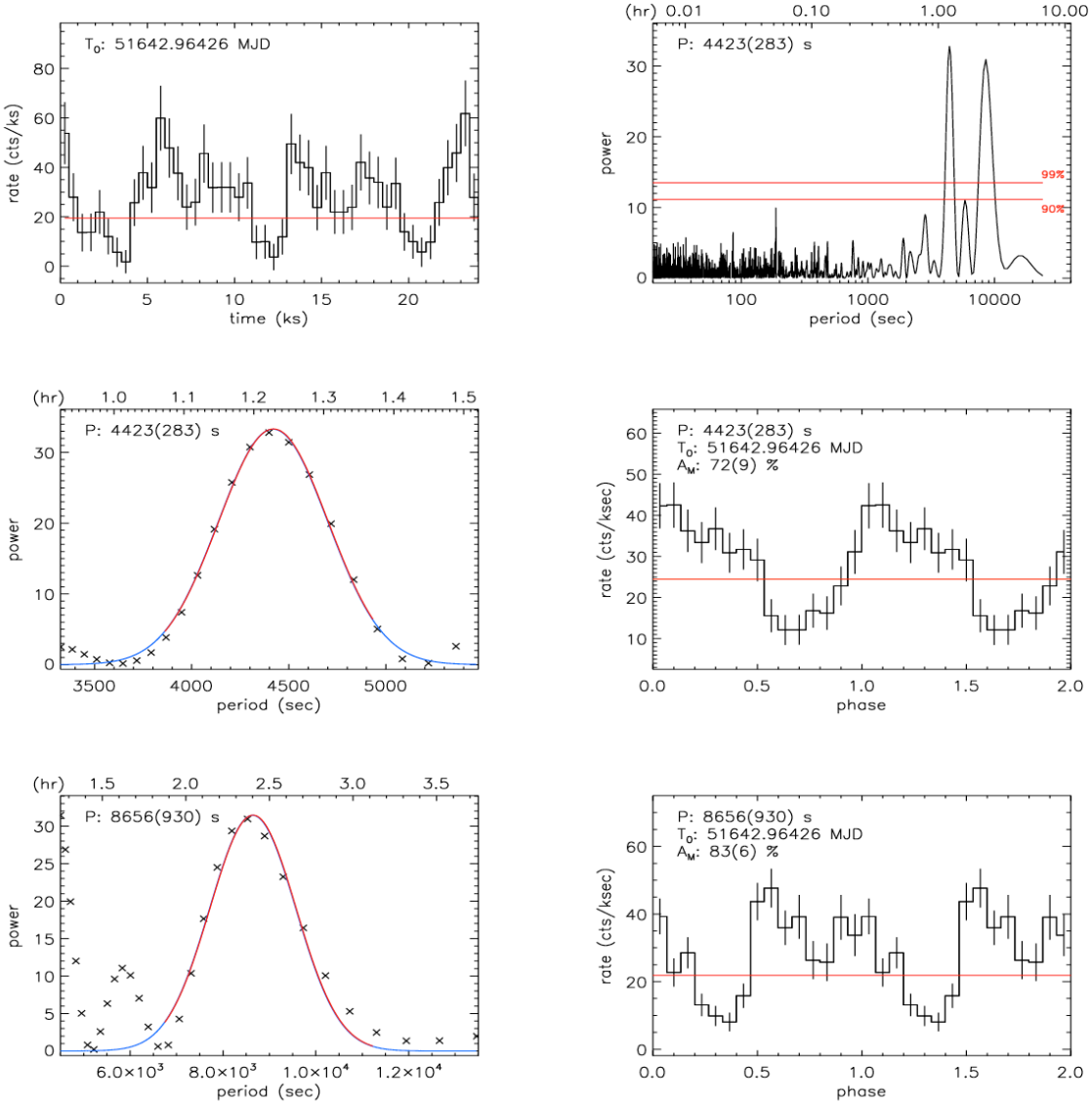
1576 s

4730 s

9461 s

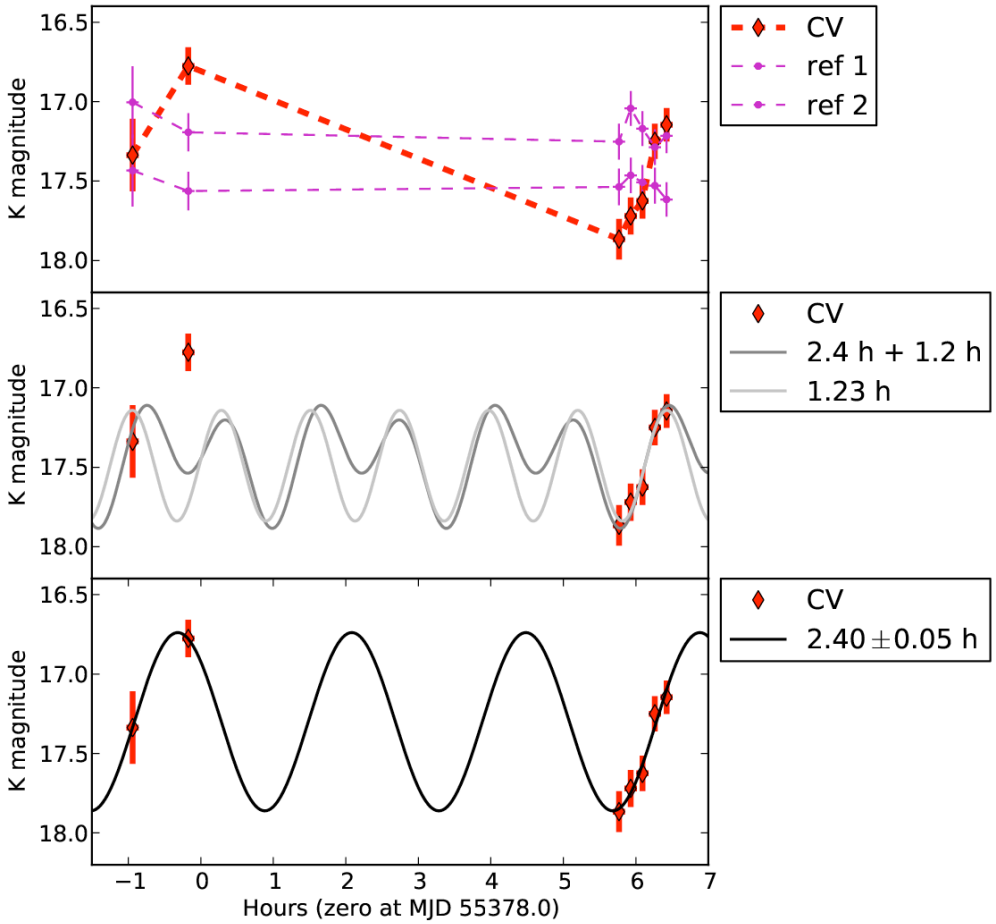


Bright X-ray source in ChaMPLane



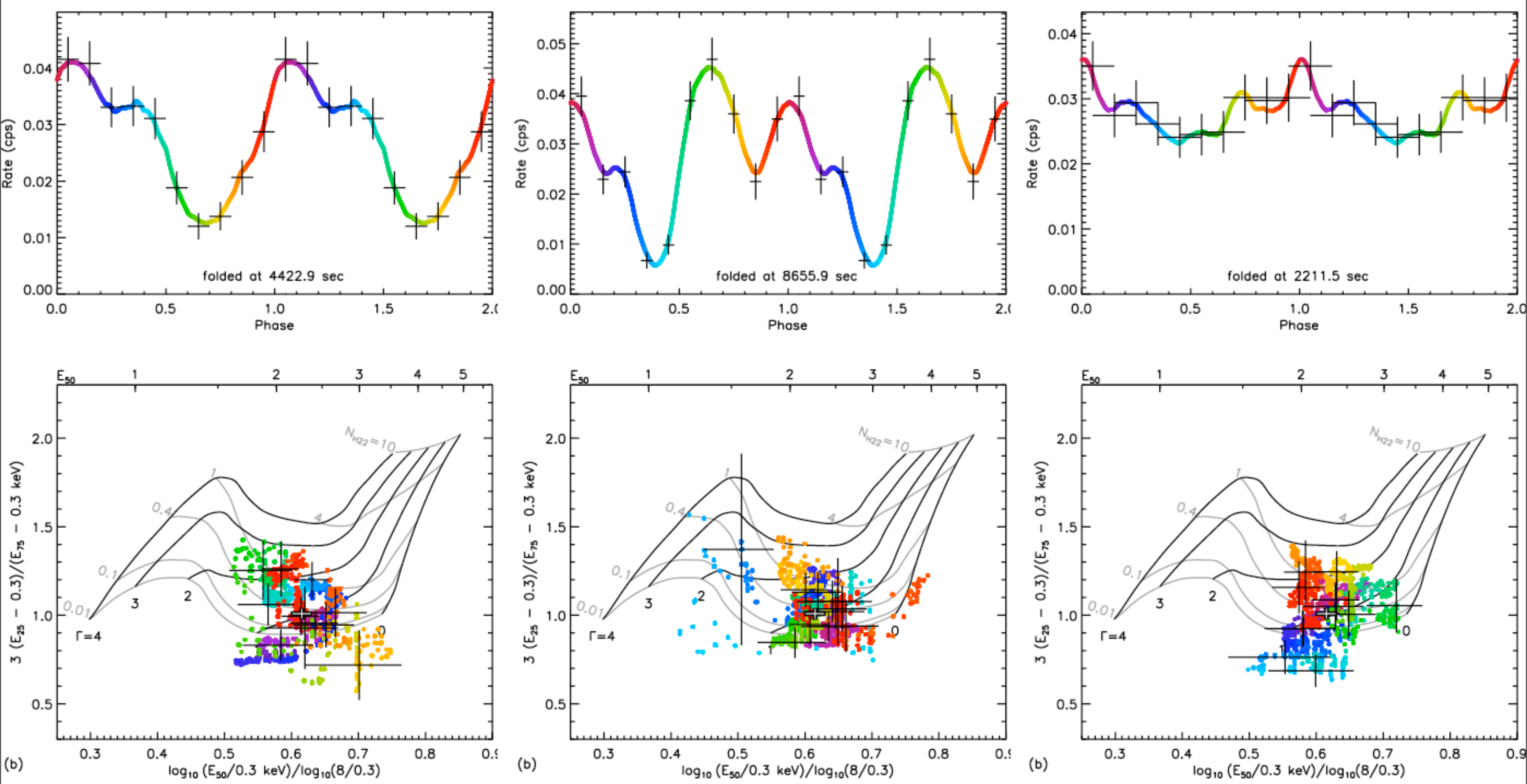
(van den Berg et al 2011)

Bright X-ray source in ChaMPLane



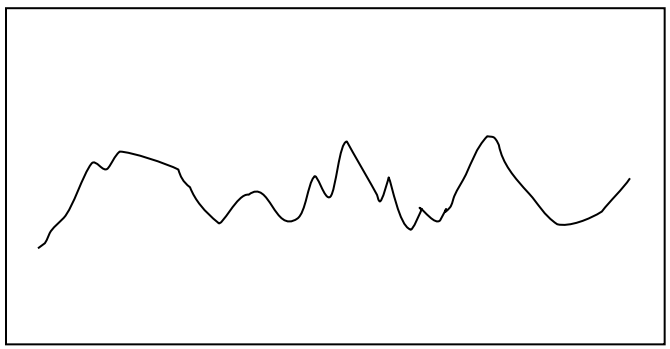
(Servillat et al 2011)

Bright X-ray source in ChaMPLane

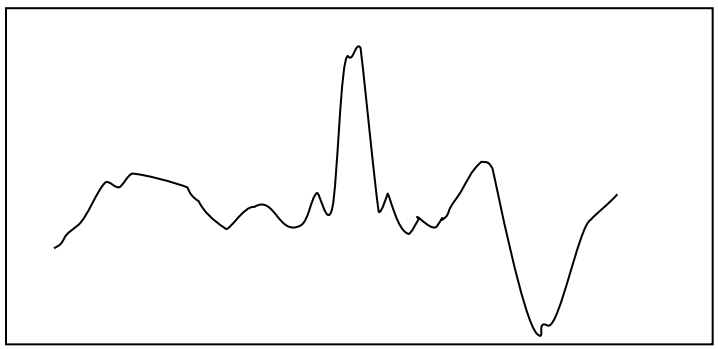


Modulation associated with peculiar spectral state

Observables



vs.



Phase folded at P

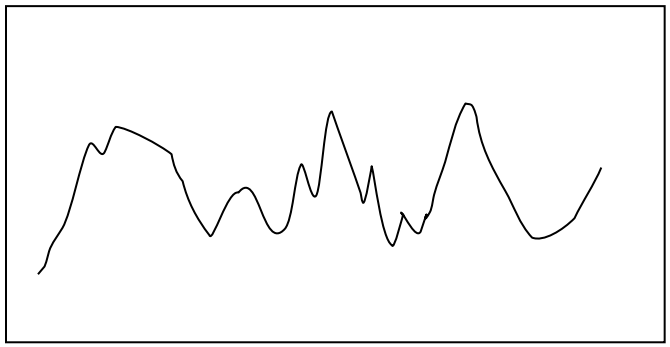
Not much variations

Phase folded at P'

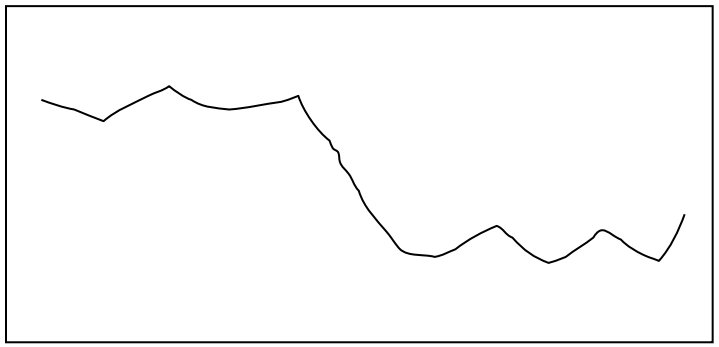
Noticeable variations

Pattern or order of values gives a clue?

Observables



vs.



Phase folded at P

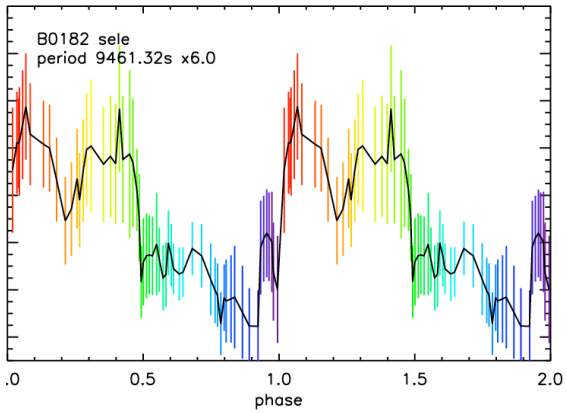
Chaotic

Phase folded at P'

Orderly

e.g. DisCan for quantum gravity photon disperson:

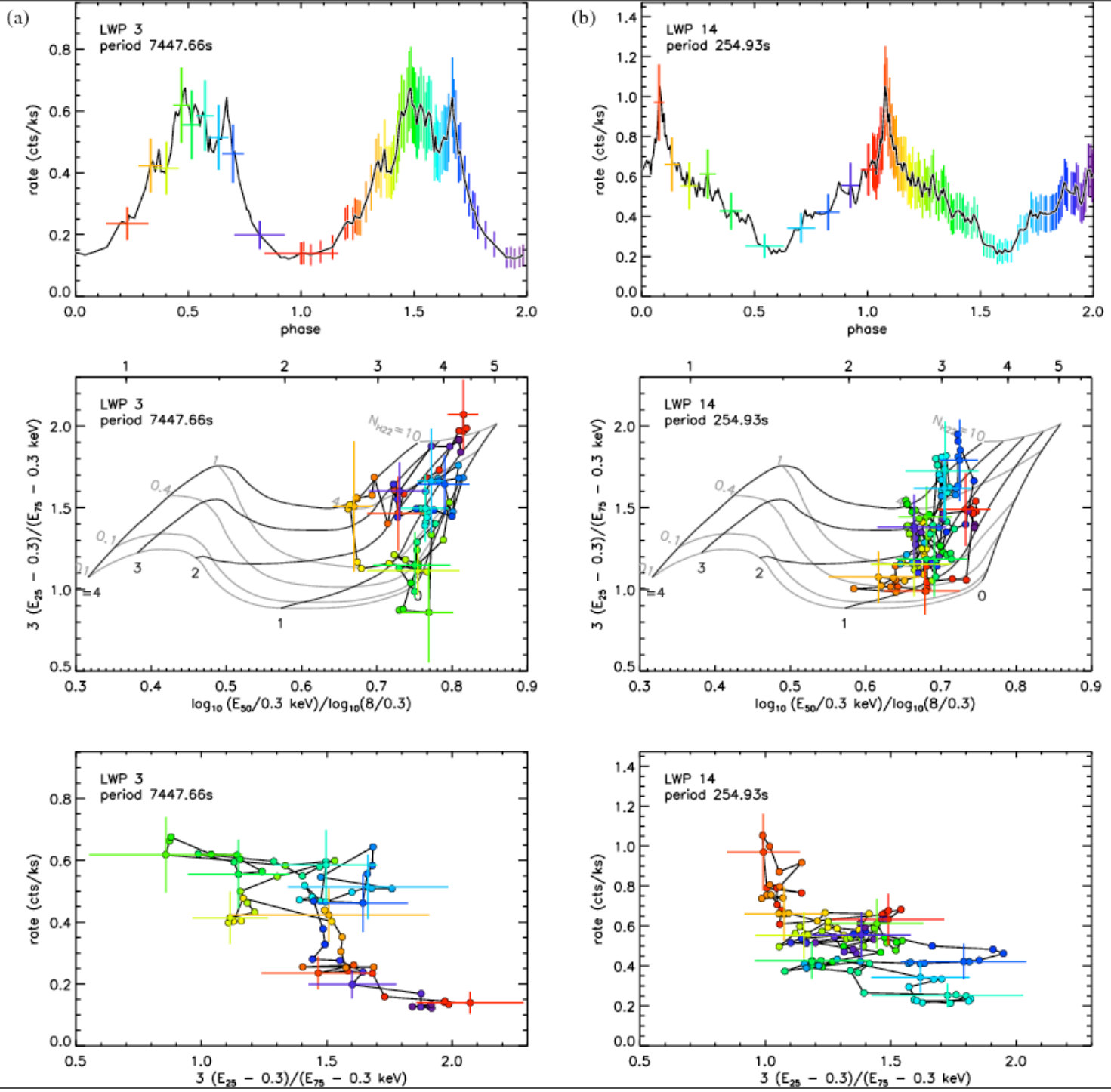
Scargle, Norris, Bonnel, 2008
Sharpness : Shannon, Reny,
Fisher information, variance



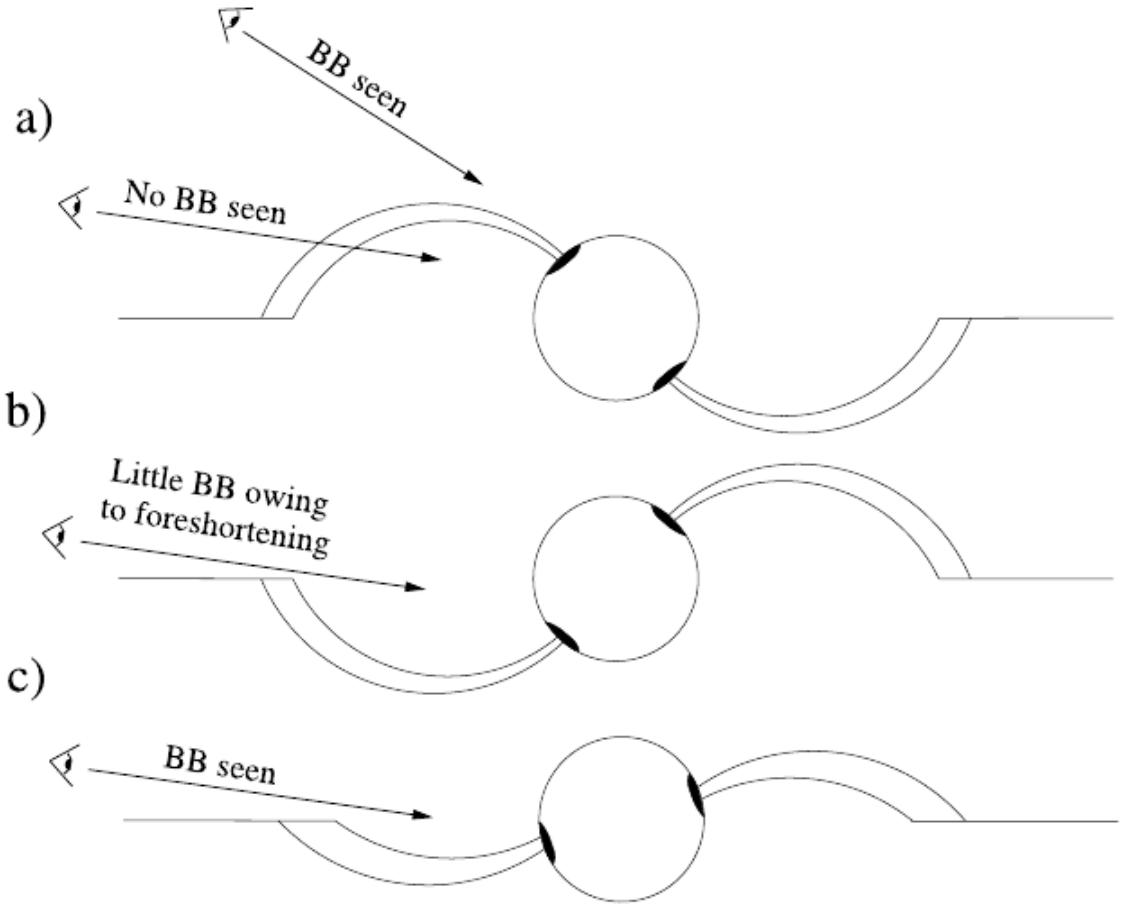
Summary

- The sheer number of Bulge X-ray sources indicate their importance in understanding the evolutionary history of accreting binaries and the inner Galaxy. But the large number of them are not identified.
- High obscuration, faint optical flux and source crowding limit direct spectroscopic identification.
- X-ray variability provides another clue. Sometimes multiple periodicities are observed: not all of them are independent.
- Energy quantiles (or equivalent quantities) might help revealing the true periodicity. Further study is needed to assign credible statistical significance.

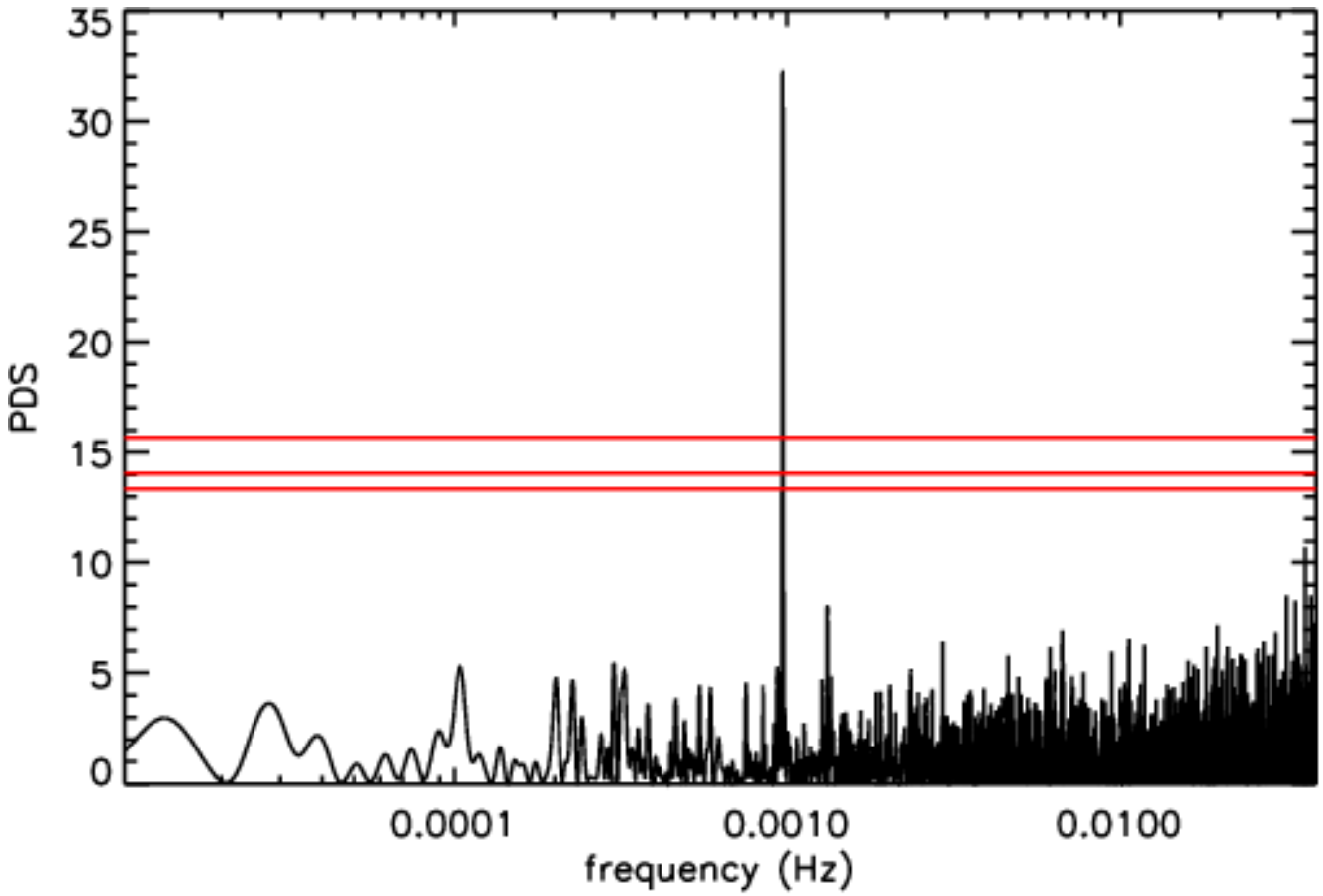
Magnetic CVs in LW



Evans &Hellier 2007

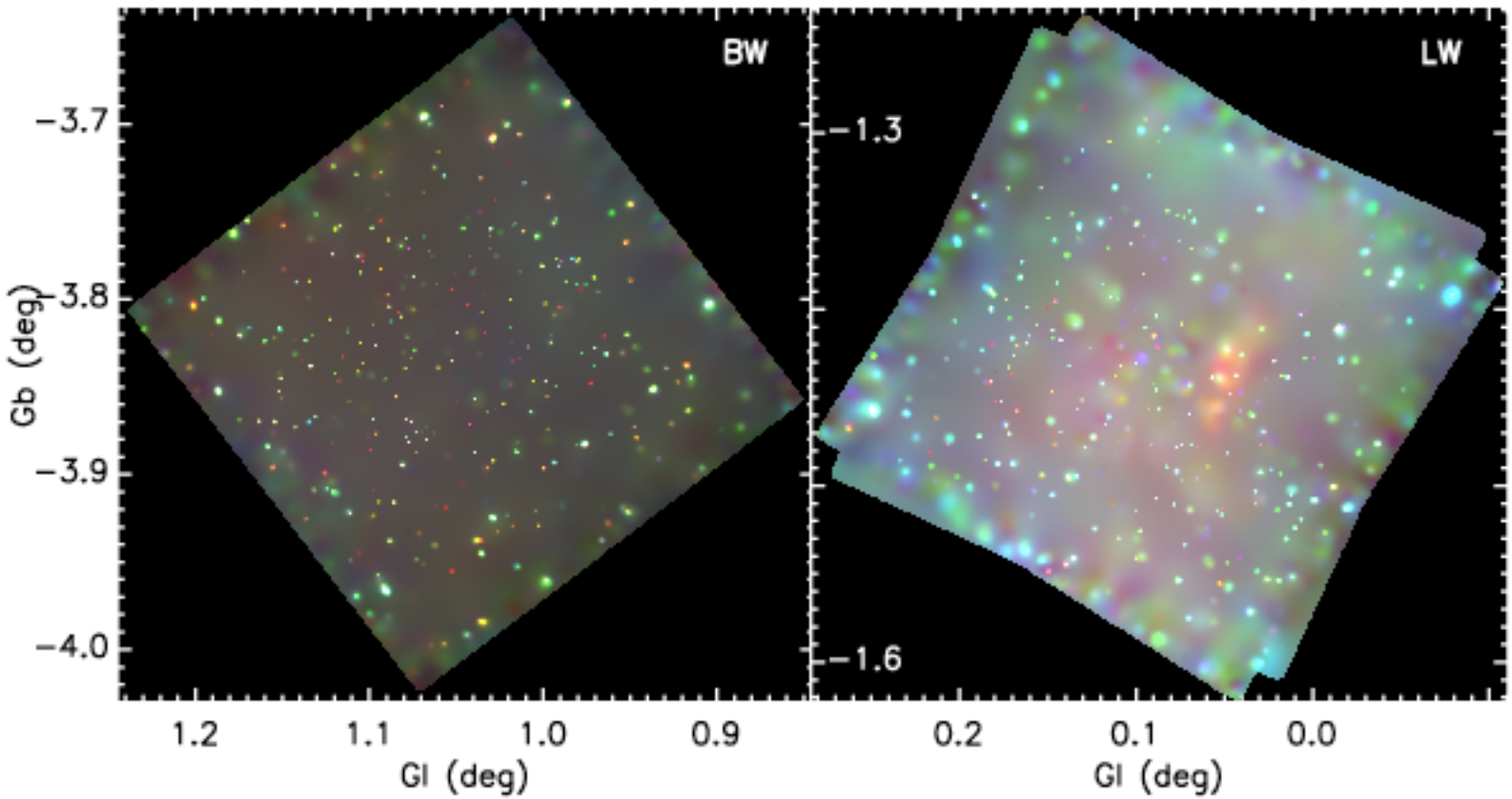


Identifying X-ray Sources by Periodicity (Lomb-Scargle Method)



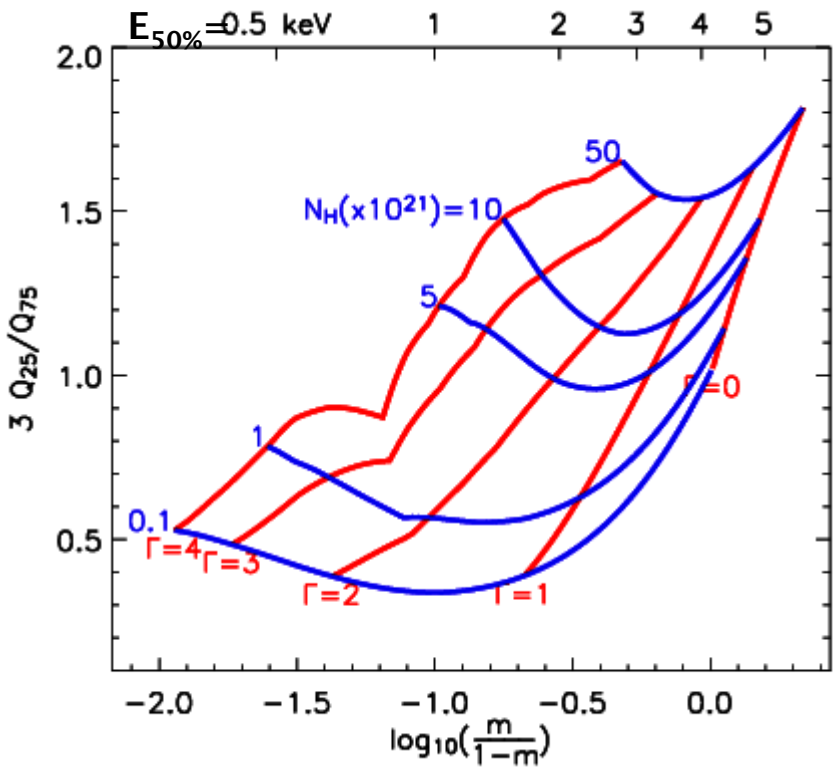
A Magnetic CV in Baade's Window (100 ks) :
CXOPS J180354.3 – 300005 (1028.3 s)
Hong et al, ApJ, 2009

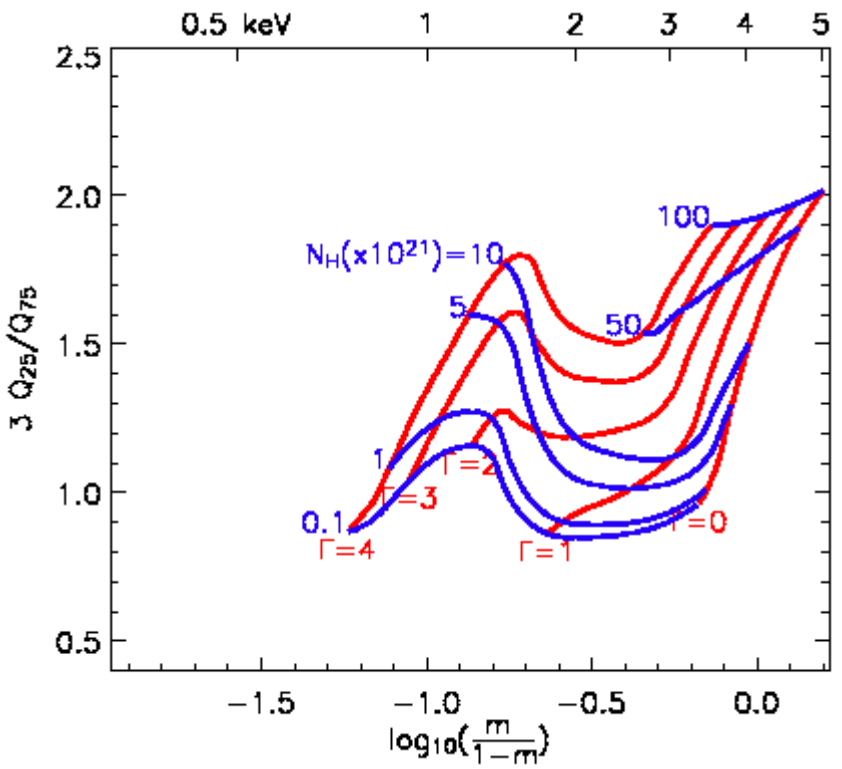
Chandra ACIS Image of BW and the LW



~320 – 400 X-ray sources with 100 ks

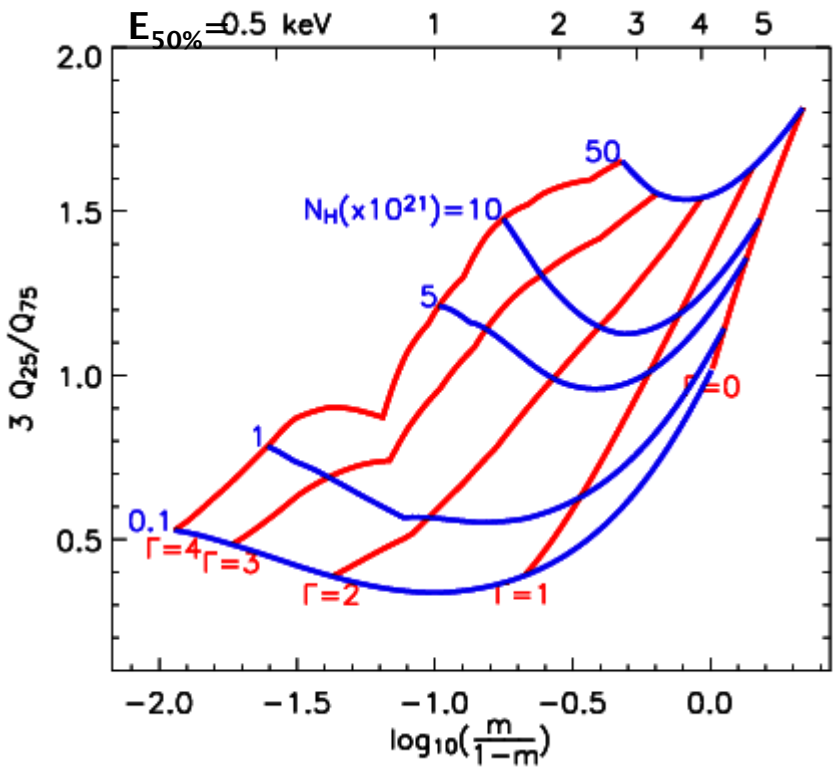
Realistic Cases

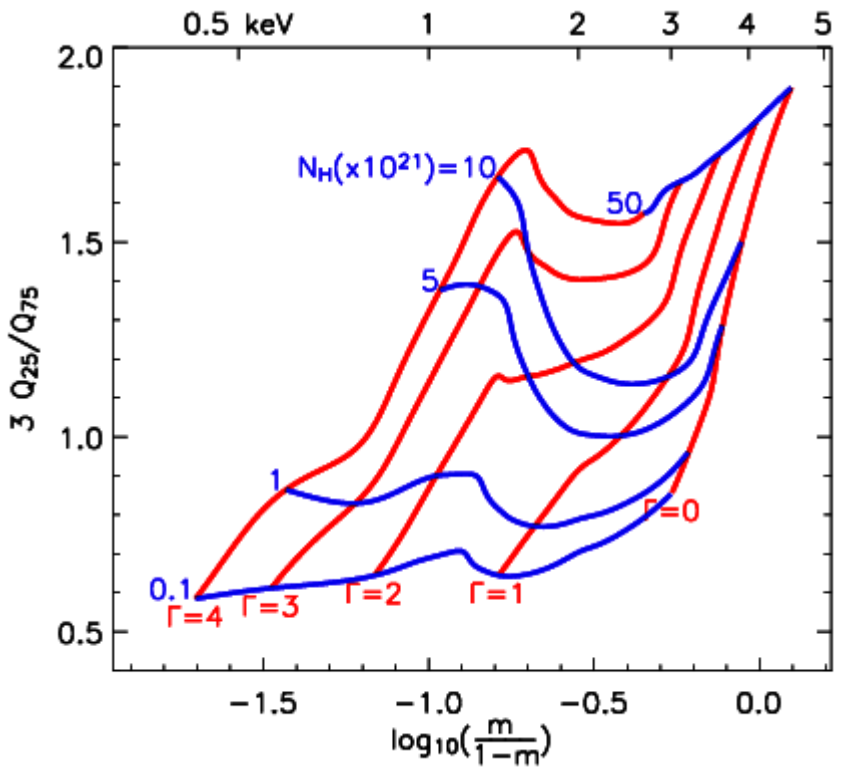




An ideal detector → **ACIS-I response**

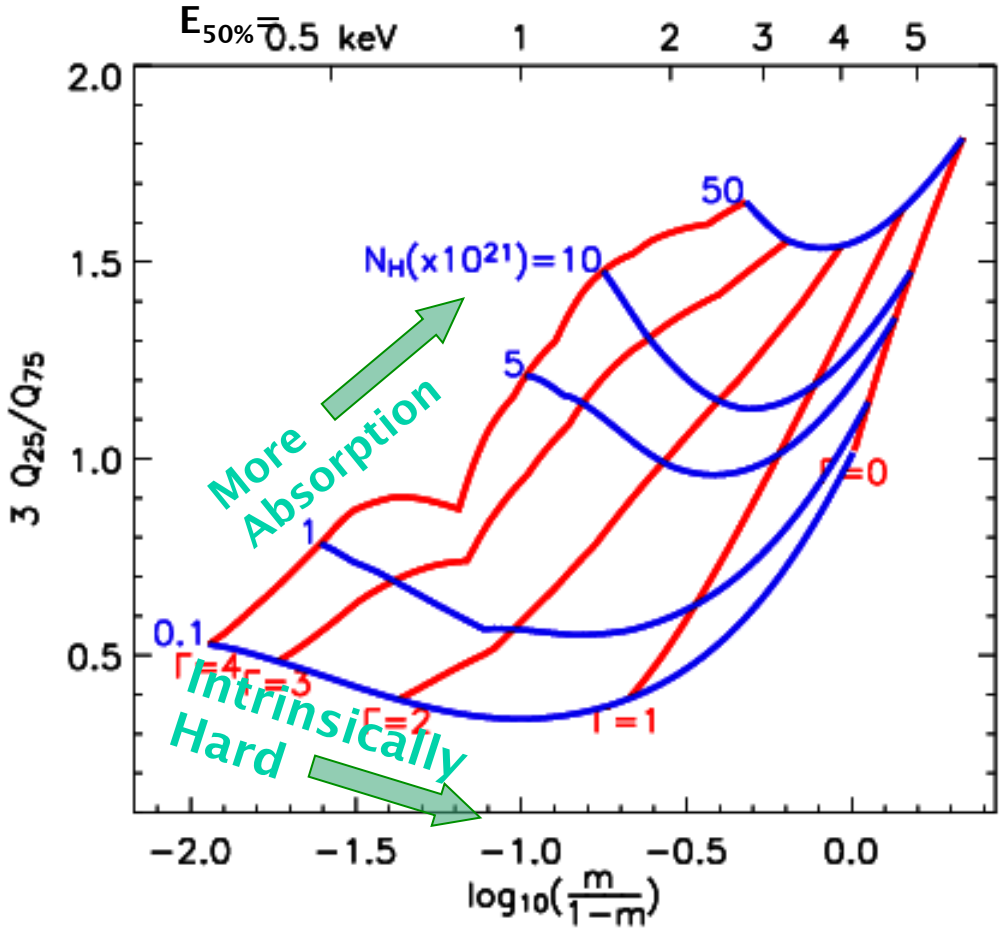
Realistic Cases





An ideal detector → **ACIS-S response**

Quantile Diagram



- Quantiles are not independent
- $m=Q_{50}$ vs Q_{25}/Q_{75}
- Power-Law : Γ & N_H
- Proper spacing in the diagram

An ideal detector
03-8.0 keV