CHASC 2019-jan-29

Intro to High-Energy Astro Data for Statisticians

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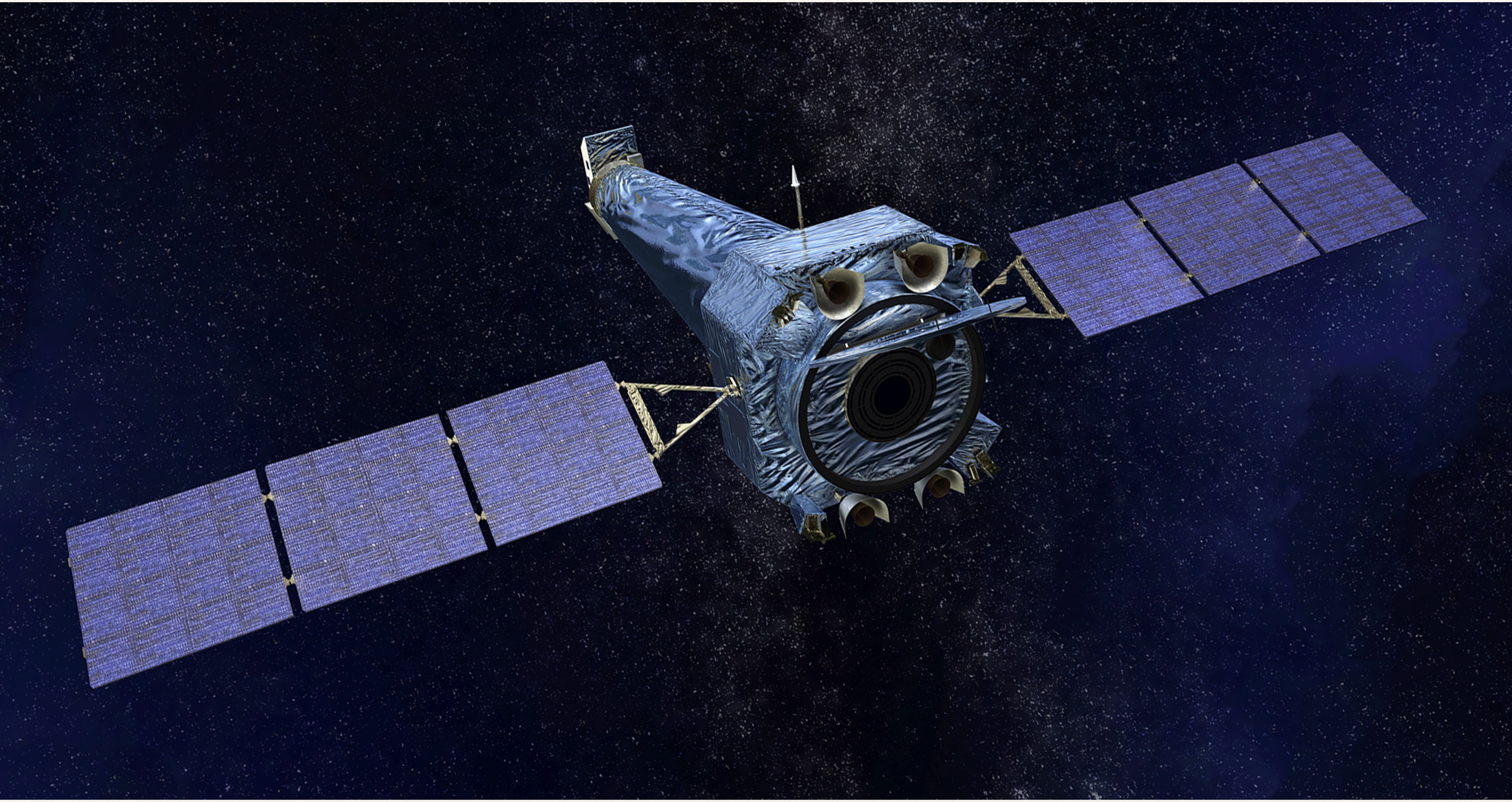
Center for Astrophysics | Harvard & Smithsonian

Outline

1. High-energy Astronomy data, exemplified by *Chandra*
2. A model of the data
3. A chain of BLoCXS: a CHASC review
4. Two current projects:
    1. *Katy McKeough*: LIRA+Ising to isolate extended sources in 2D posterior draws
    2. *Luis Campos*: EBASCS to disambiguate photons in overlapping sources

Chandra X-ray Telescope



One of NASA's Great Observatories along with *Compton*, *Hubble*, and *Spitzer*. Launched 23 July 1999 on Space Shuttle *Columbia* into a highly elliptical high-altitude orbit.

Chandra Instrumentation

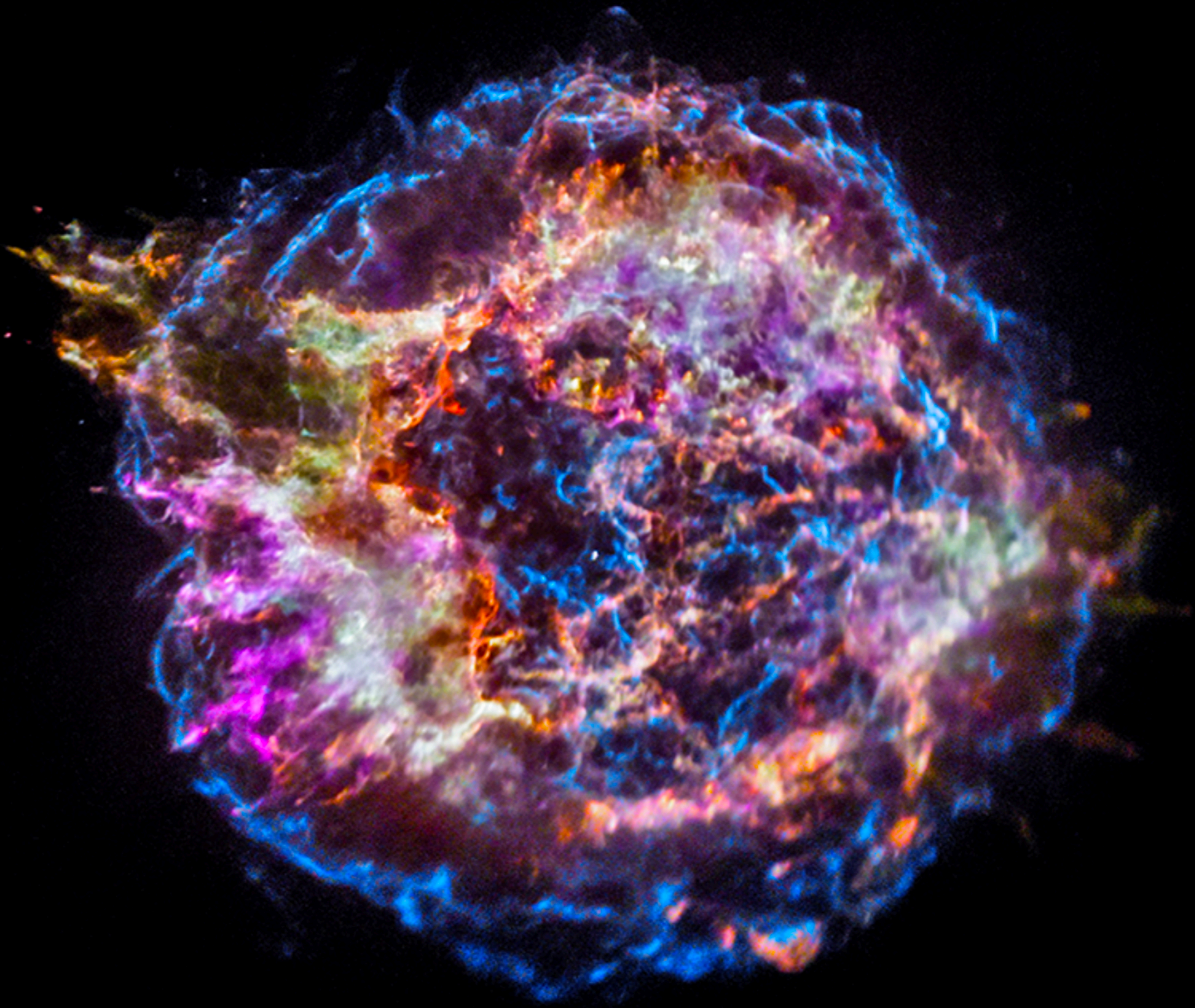
- Four parabolic+hyperbolic mirror shells
- Four photon-counting detectors of two types
  - 4-CCD 16′x16′ imaging array (ACIS-I)
  - 6-CCD 8′x42′ spectroscopic strip (ACIS-S)
  - 1 32′x32′ micro channel plate imager (HRC-I)
  - 3 micro channel plate chips as spectroscopic array (HRC-S)
- Two transmission gratings
  - Low-energy (LETG) for use with HRC-S (2-170 Å) and ACIS-S (1.5-45 Å)
  - High-energy crossed grating (HETG) for use with ACIS-S (and optionally HRC-I) with two arms (MEG 1.5-23 Å and HEG 1.24-18 Å)

What do the data look like?

Keep in mind that we collect a list of photons,
each of which can be assigned
a position in the sky, a time of arrival, and how much energy it deposits

Supernova remnant Cassiopeia A

Silicon (red), Sulphur (yellow), Calcium (green), Iron (purple)



CHANDRA
X-RAY OBSERVATORY

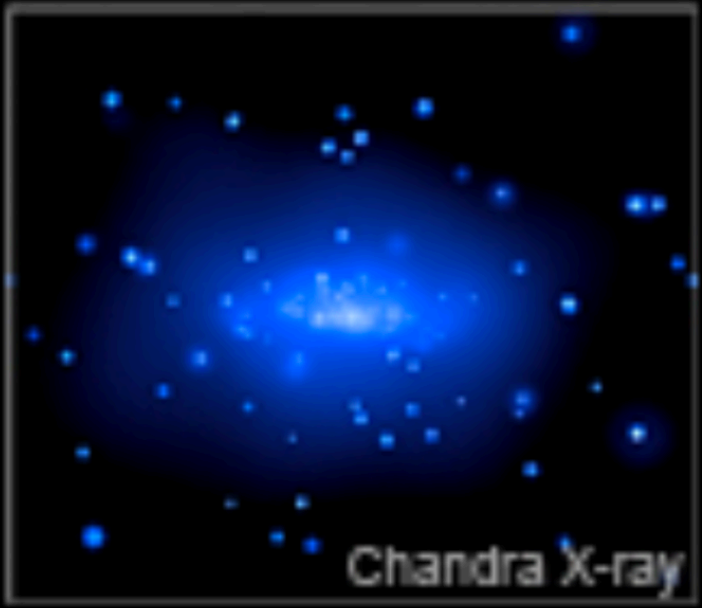
Evidence for Dark Matter in the Bullet Cluster

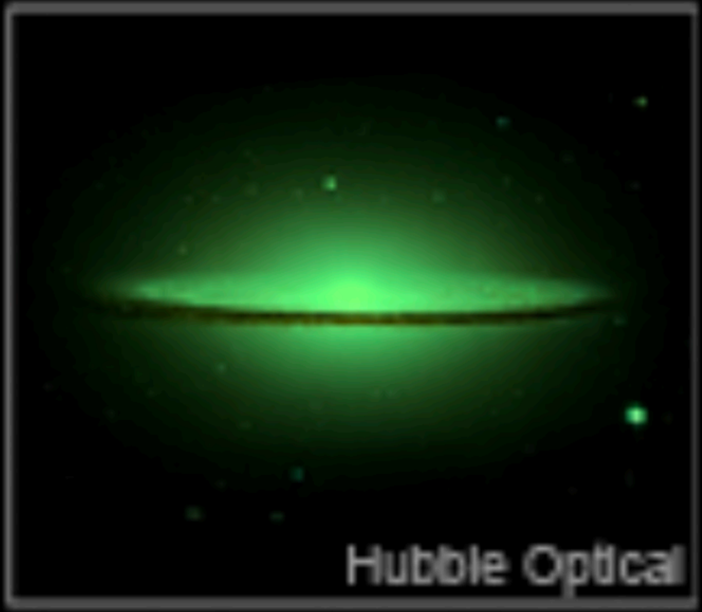
Chandra (pink) + Lensing Mass (blue) + *Hubble* (optical)

Markevitch/Clowe

Sombrero Galaxy

Chandra + Hubble + Spitzer



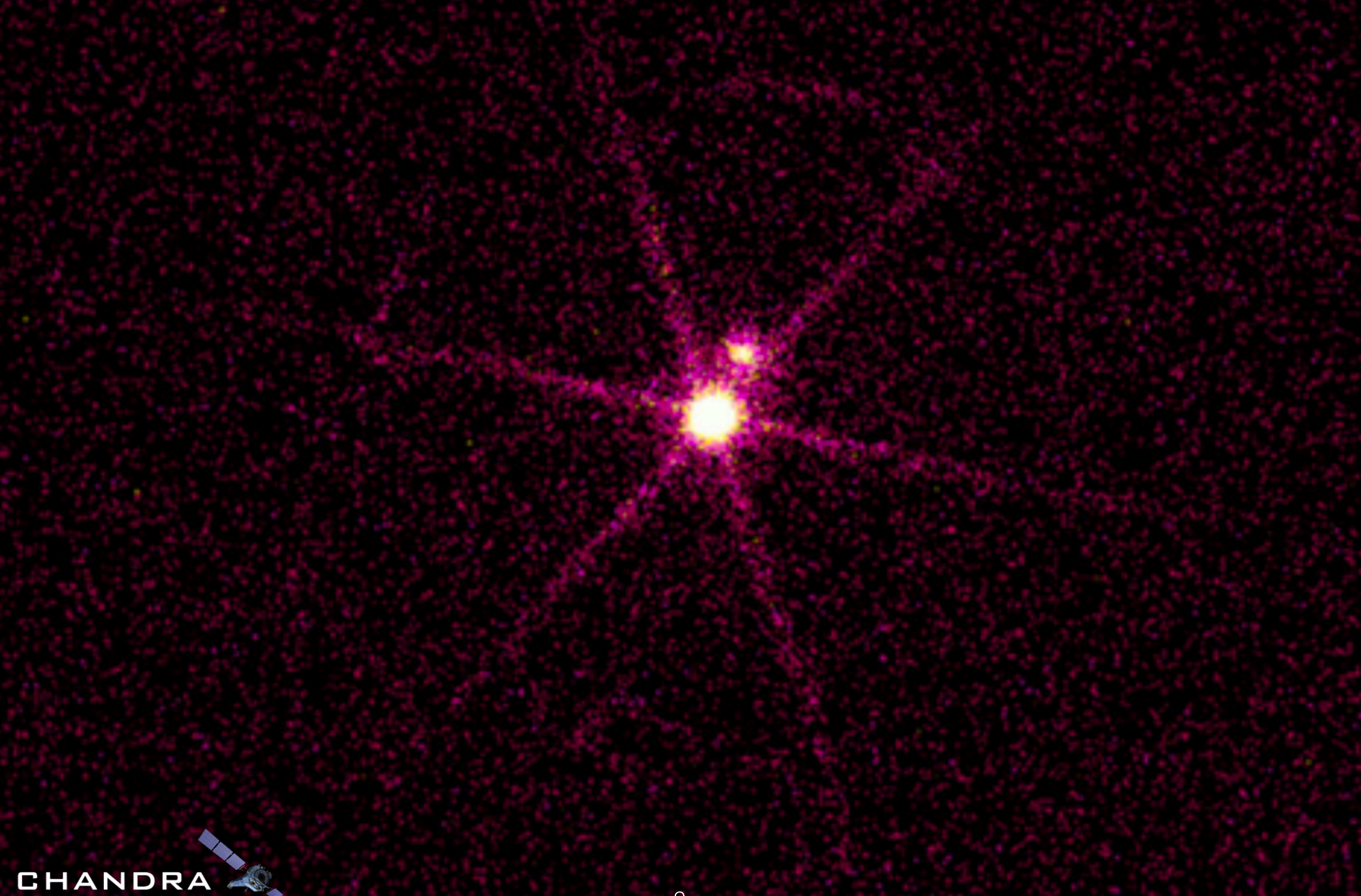


CHANDRA
X-RAY OBSERVATORY

Wang/Hubble Heritage/Kennicutt

White Dwarf Sirius B (and Sirius A)

Chandra LETGS+HRC-S

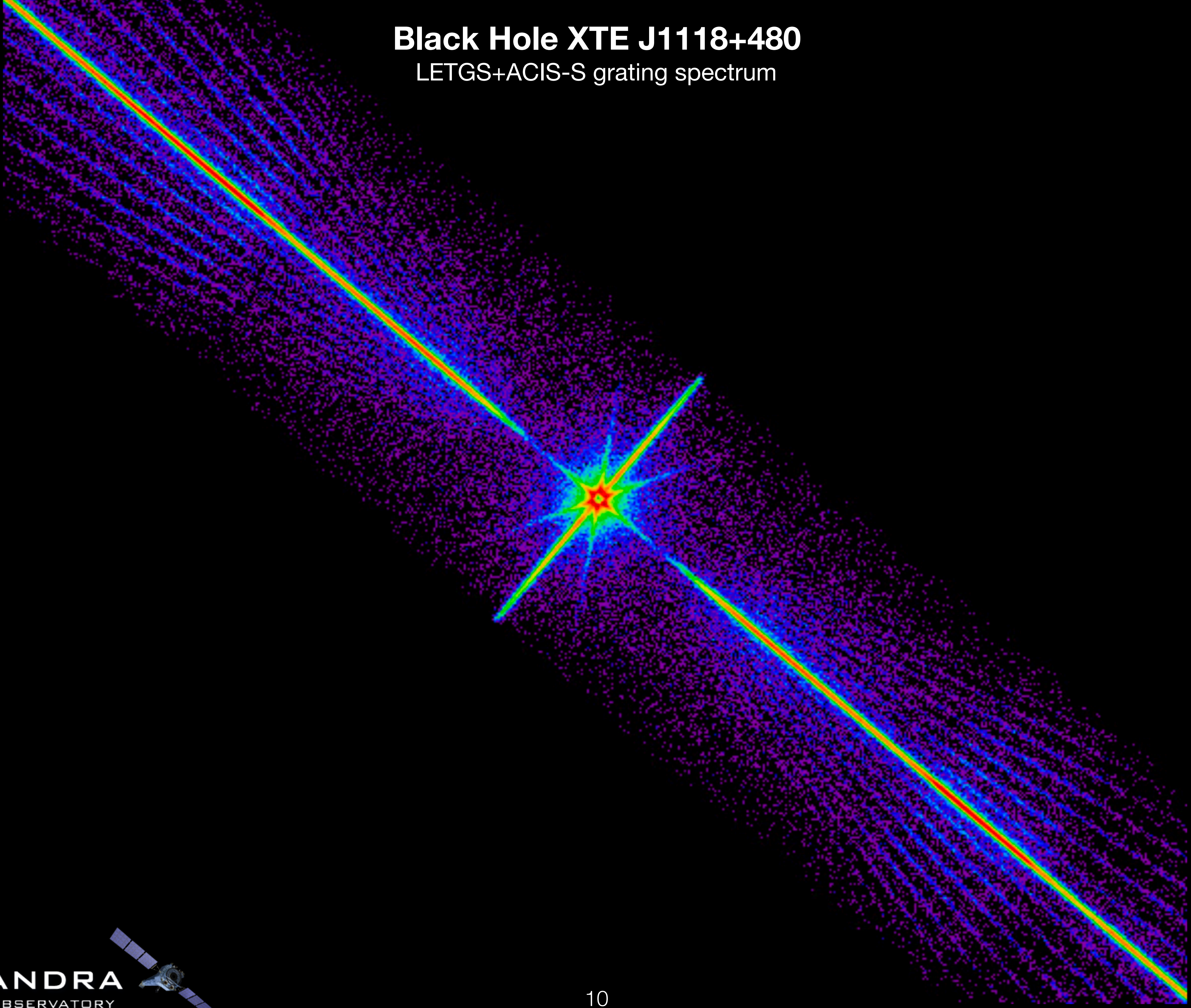


CHANDRA
X-RAY OBSERVATORY

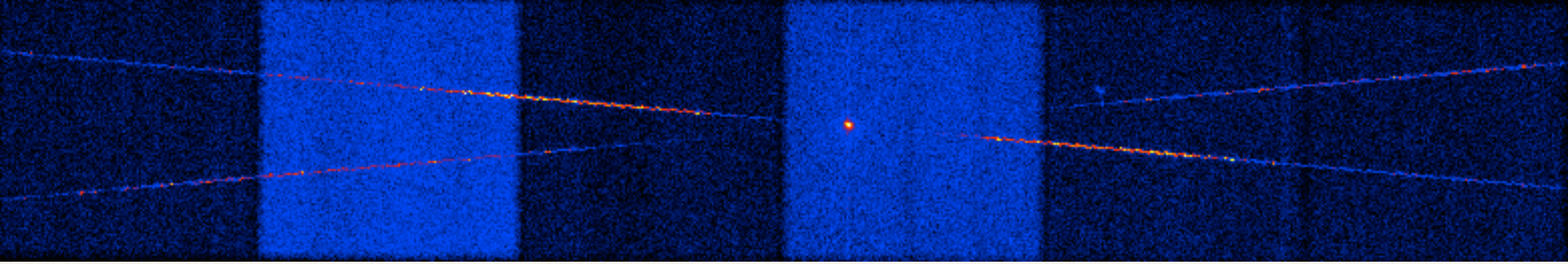
http://chandra.harvard.edu/photo/2000/cygx399/

Black Hole XTE J1118+480

LETGS+ACIS-S grating spectrum

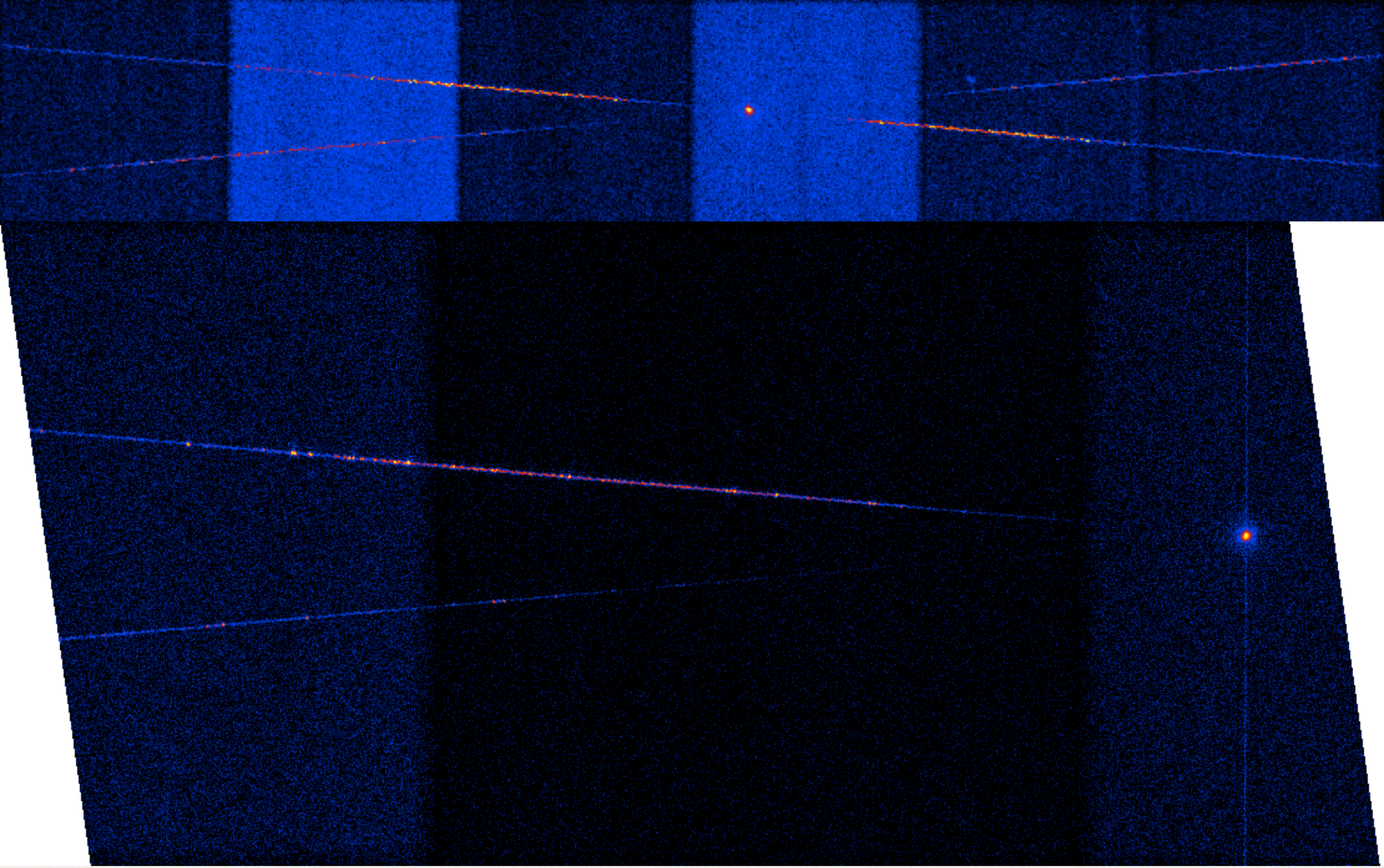


CHANDRA
X-RAY OBSERVATORY



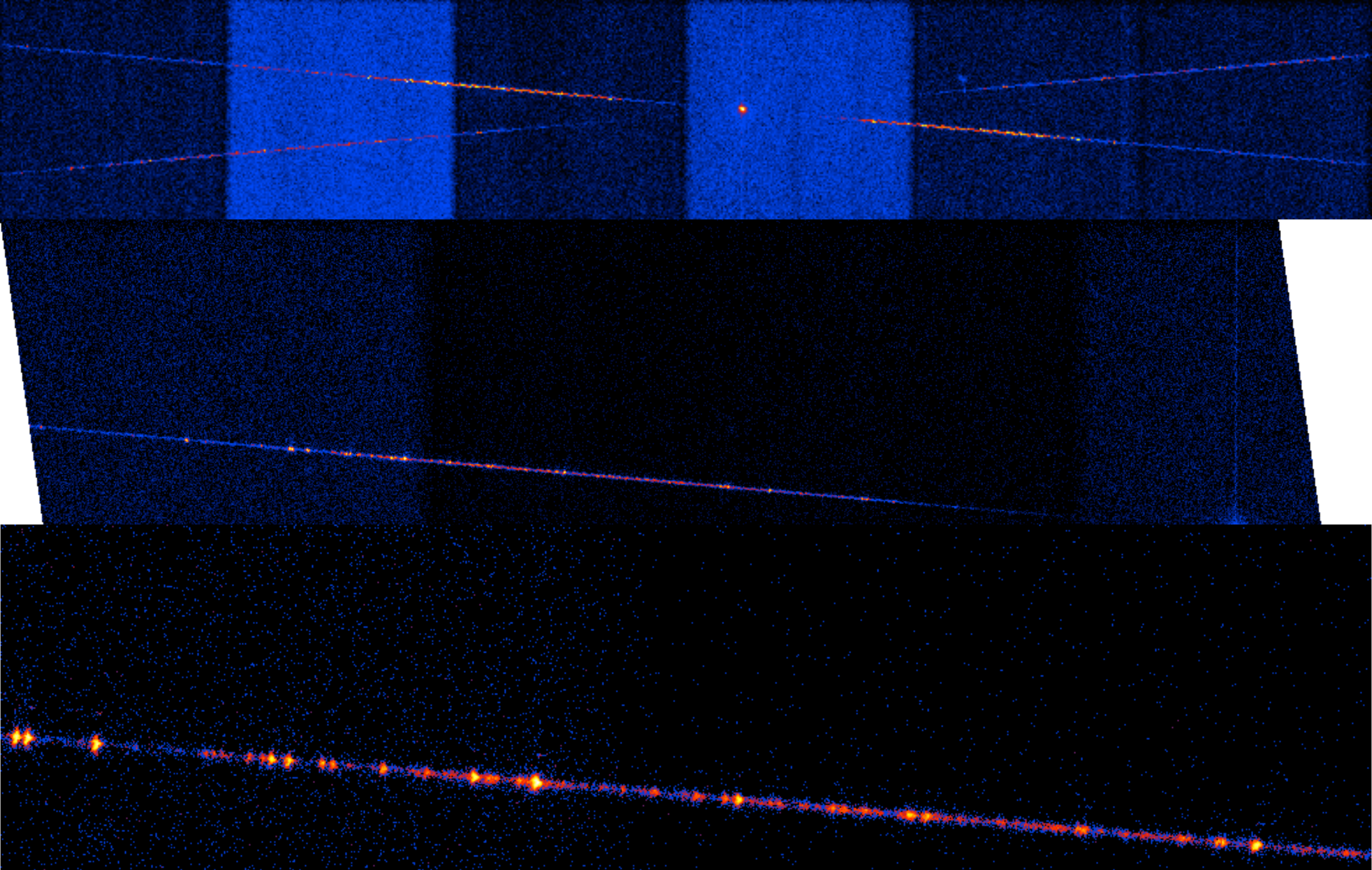
Chandra HETG

Emission Line Source

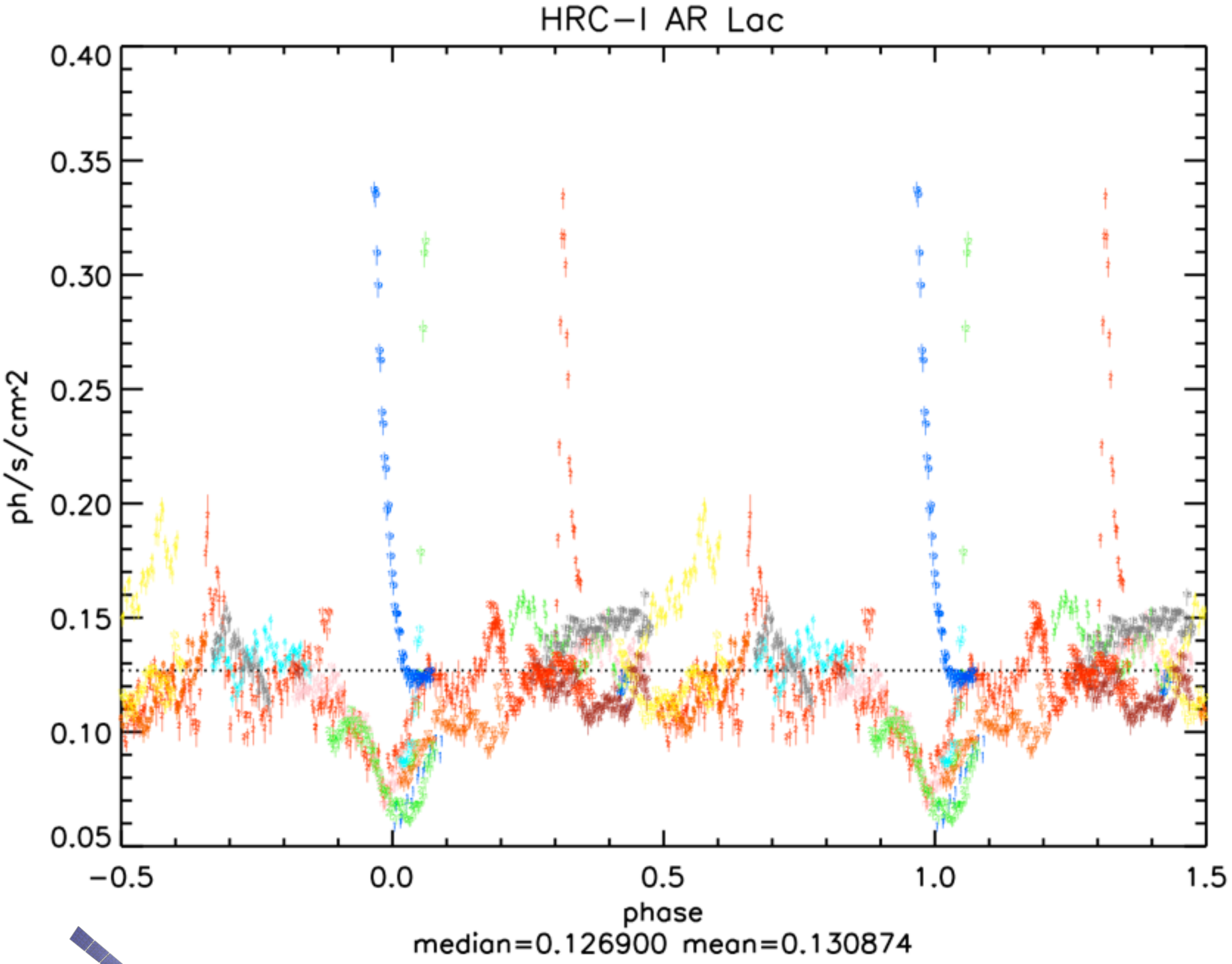


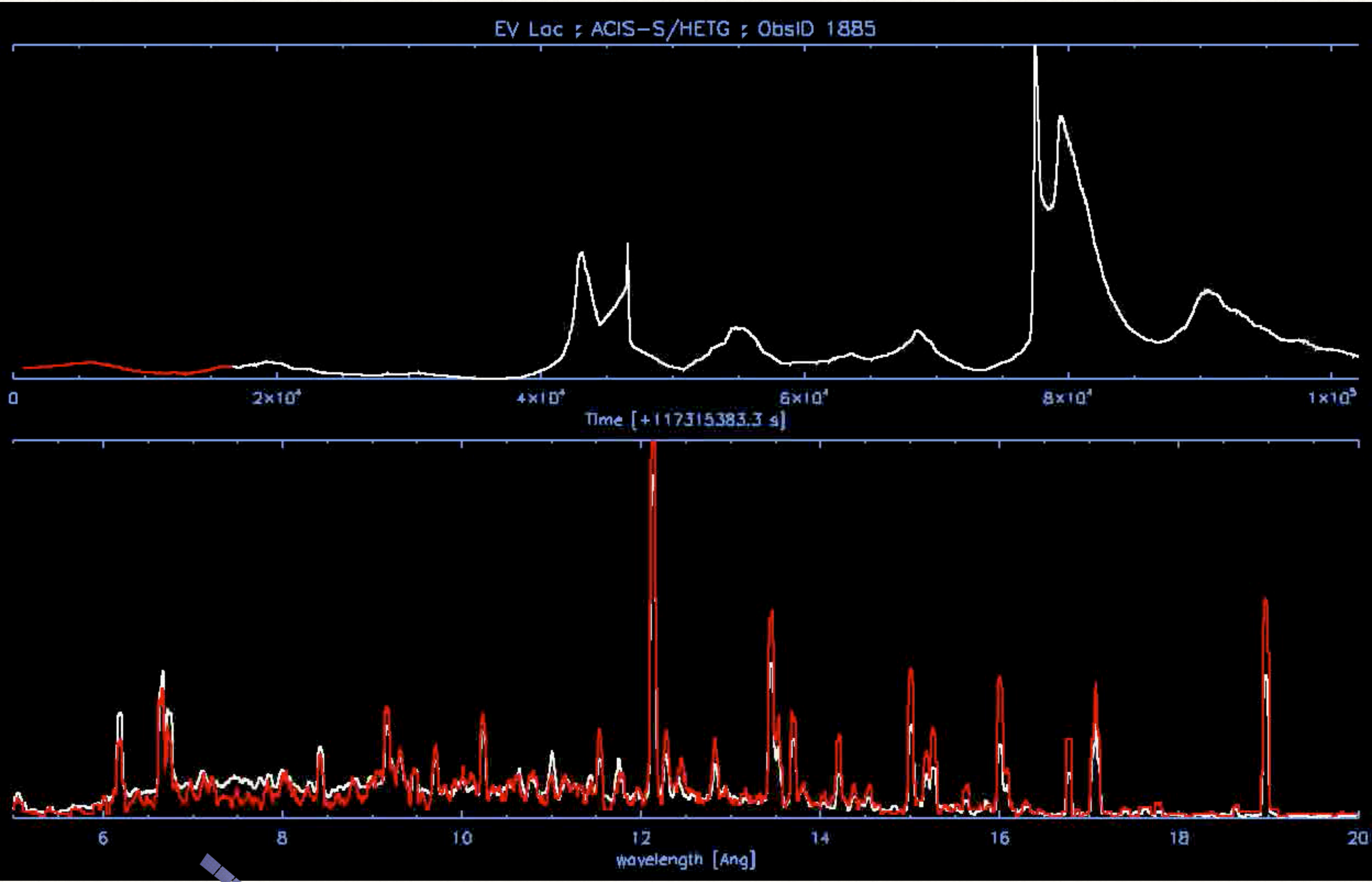
Chandra HETG

Emission Line Source

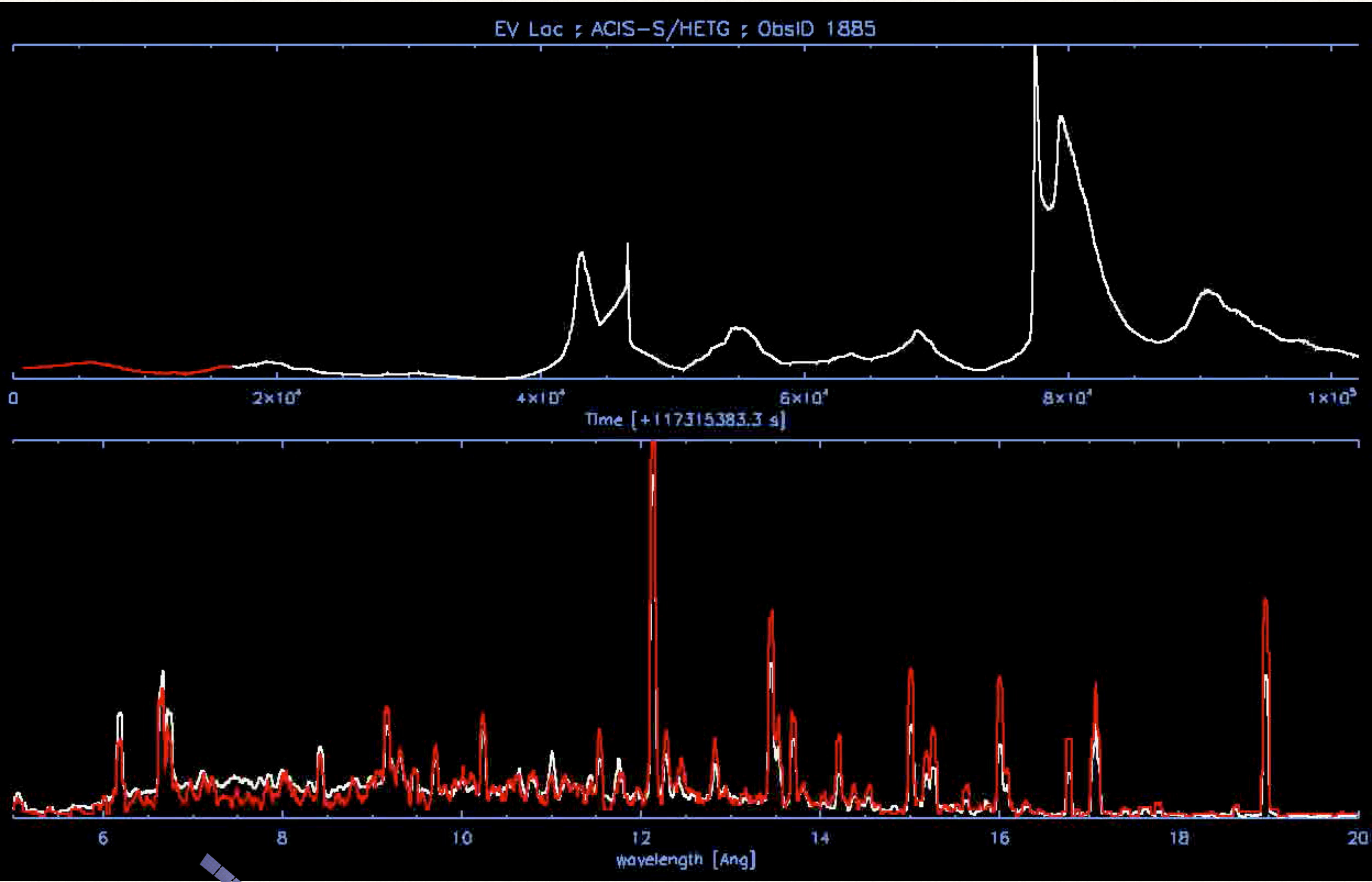


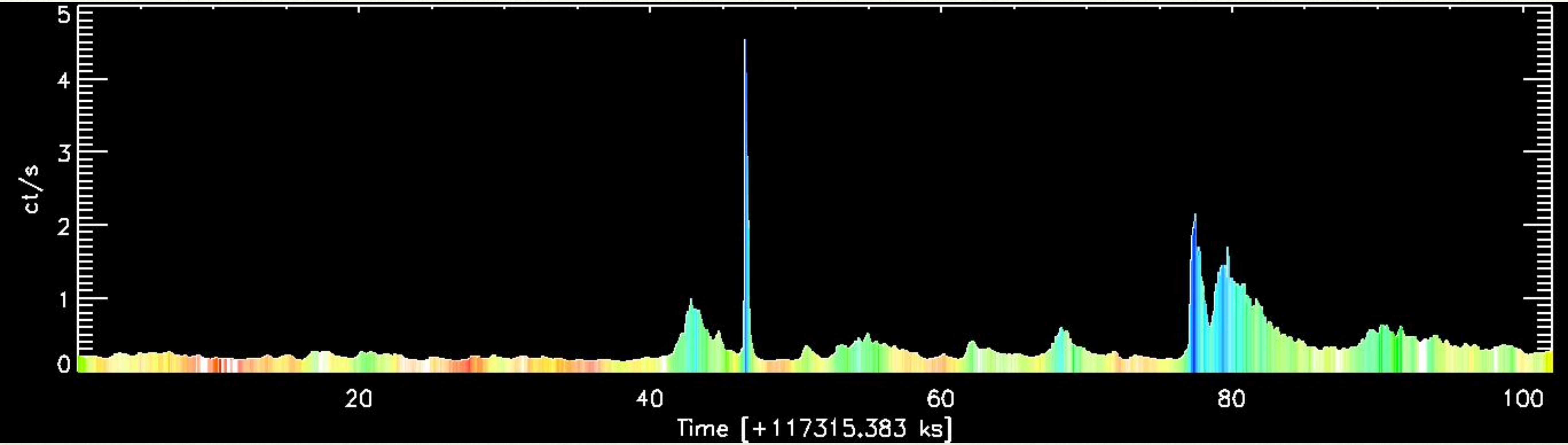
Chandra HETG
Emission Line Source

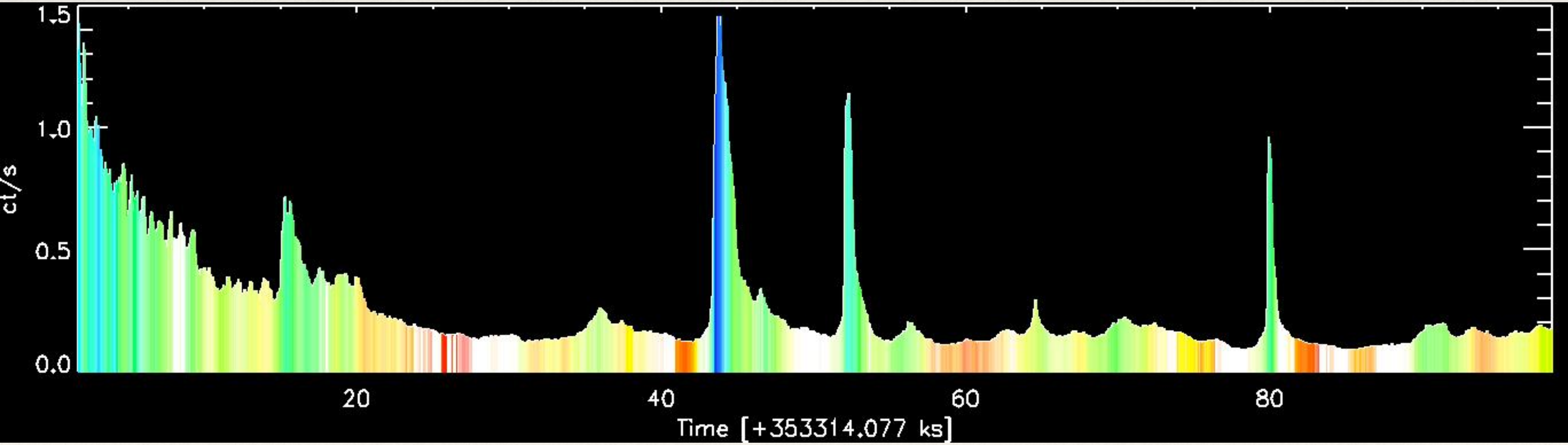

HRC−I AR Lac
ph/s/cm^2
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
−0.5
0.0
0.5
1.0
1.5
phase
median=0.126900 mean=0.130874



CHANDRA
X-RAY OBSERVATORY


EV Lac ; ACIS-S/HETG ; ObsID 1885
0
2×10⁴
4×10⁴
6×10⁴
8×10⁴
1×10⁵
Time [+117315383.3 s]
6
8
10
12
14
16
18
20
wavelength [Ang]





CHANDRA
X-RAY OBSERVATORY

2. The Data Model

The Data Model

the fundamental equation of observational astronomy

$$\begin{aligned}\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta) \\ \times A(E;\mathbf{x}',t,\lambda) \\ \times P(\mathbf{x},\mathbf{x}';E,t,\lambda) \\ \times R(E,E';\mathbf{x}',t,\mathbf{x},\lambda) \\ \times \Delta(t,t';\mathbf{x}',\lambda)\end{aligned}$$

How incoming flux is distorted

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Normal}(\lambda,\sigma_\lambda)$$

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Poisson}(\lambda)$$

observed quantity

$$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda)P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

The astrophysical model

$$f(\mathbf{x},E,t;\theta)\ [\mathrm{ph\ s^{-1}\ cm^{-2}}]$$

$$f_{\nu,\lambda}(\mathbf{x},E,t;\theta)\ [\mathrm{ergs\ s^{-1}\ cm^{-2}}]$$

What arrives at the aperture of the telescope, from direction $\mathbf{x}$, with energy E, at time t, and is often modeled with parameters θ.

Watch out for those units!

$$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

Effective Area

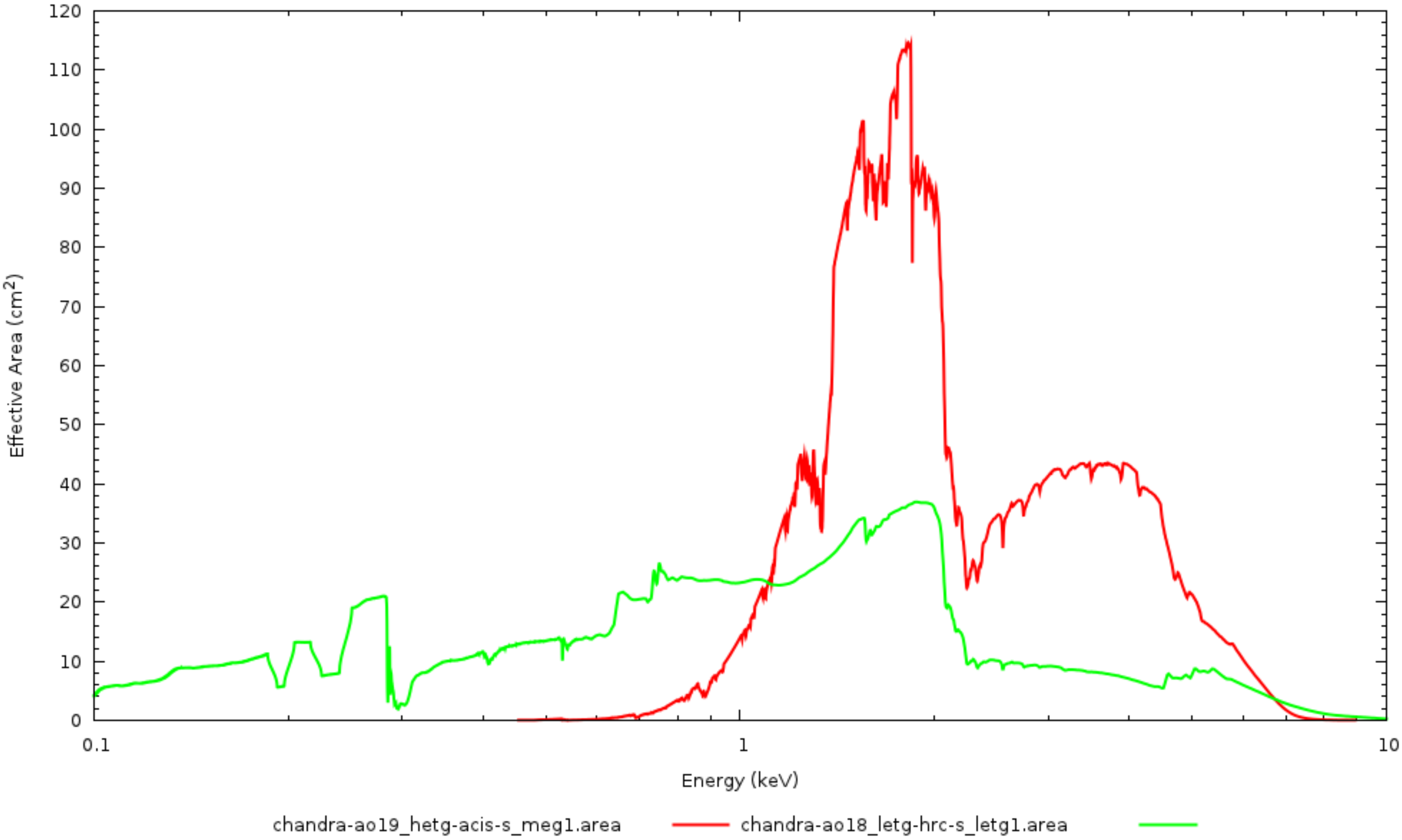
[cm^2]

Describes the efficiency with which incoming photons are detected

Mostly a function of photon energy E, but also depends on where on the detector $\mathbf{x}'$ the photon falls

Can be affected by the brightness of source via Pileup, gain non-linearity, etc.

Chandra effective areas



http://cxc.cfa.harvard.edu/cgi-bin/prop_viewer/build_viewer.cgi?ea

$$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

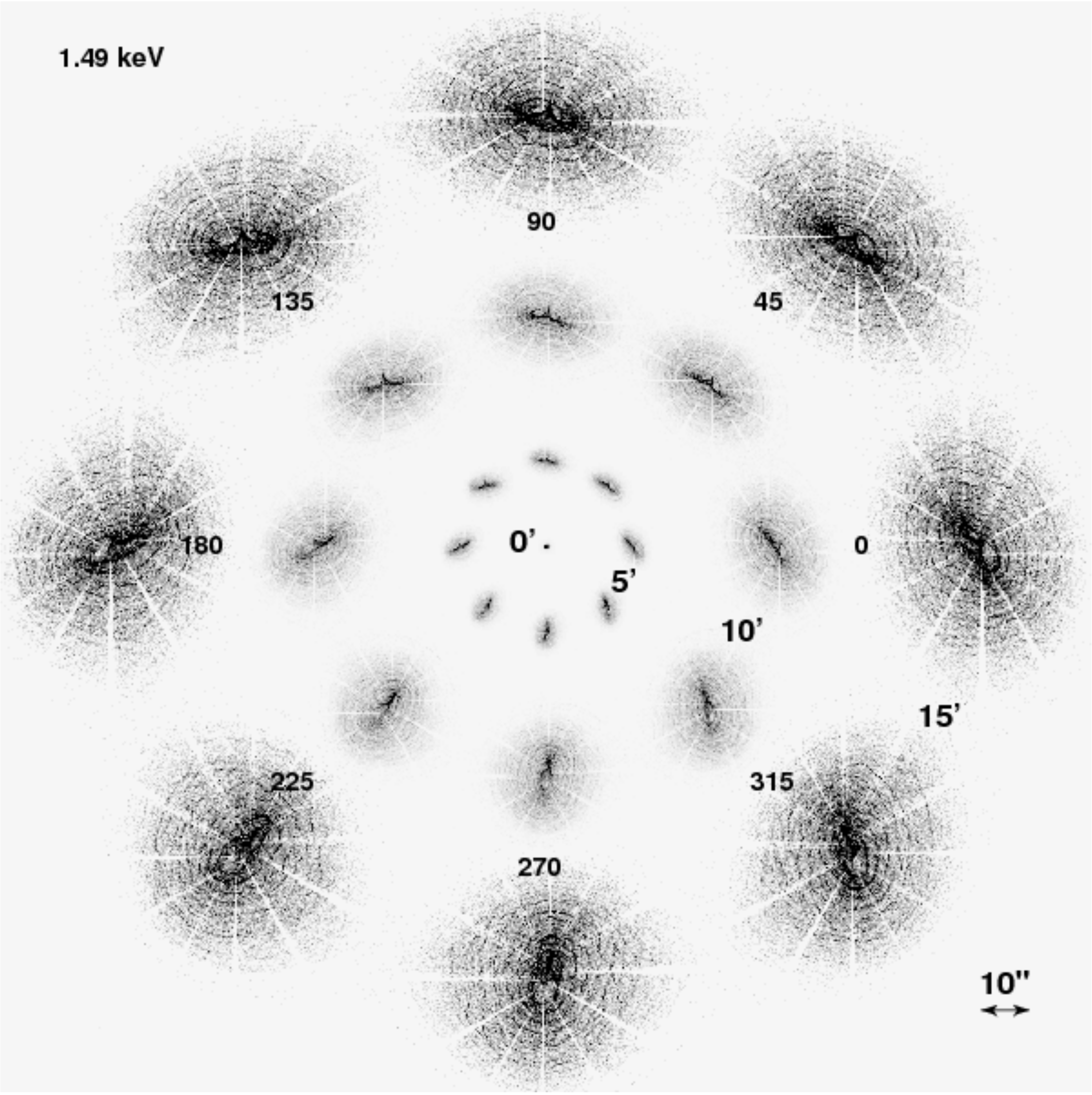
Point Spread Function

Describes the probability that a photon from direction $\mathbf{x}$ lands in detector pixel $\mathbf{x}'$

Energy dependent
Distorted by pileup

aka Modulation Transfer Function (MTF) in Fourier Space

Chandra Point Spread Function



http://cxc.harvard.edu/proposer/POG/html/chap4.html#tth_fIg4.14

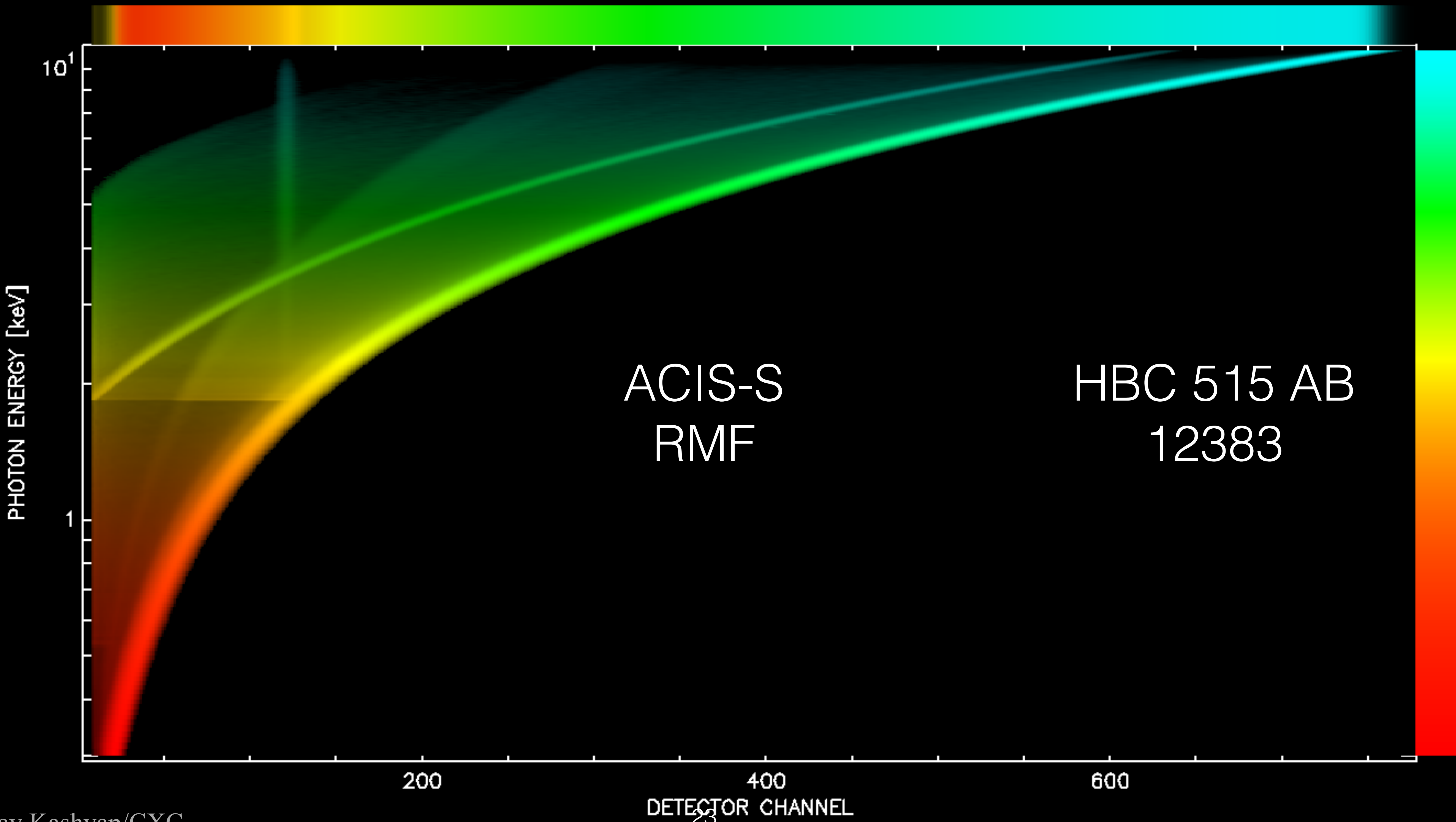
$$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

Spectral Response Matrix

Describes the probability that a photon of energy E
is recorded in detector channel E'

Detector position dependent,
in special cases, also dependent on incoming direction

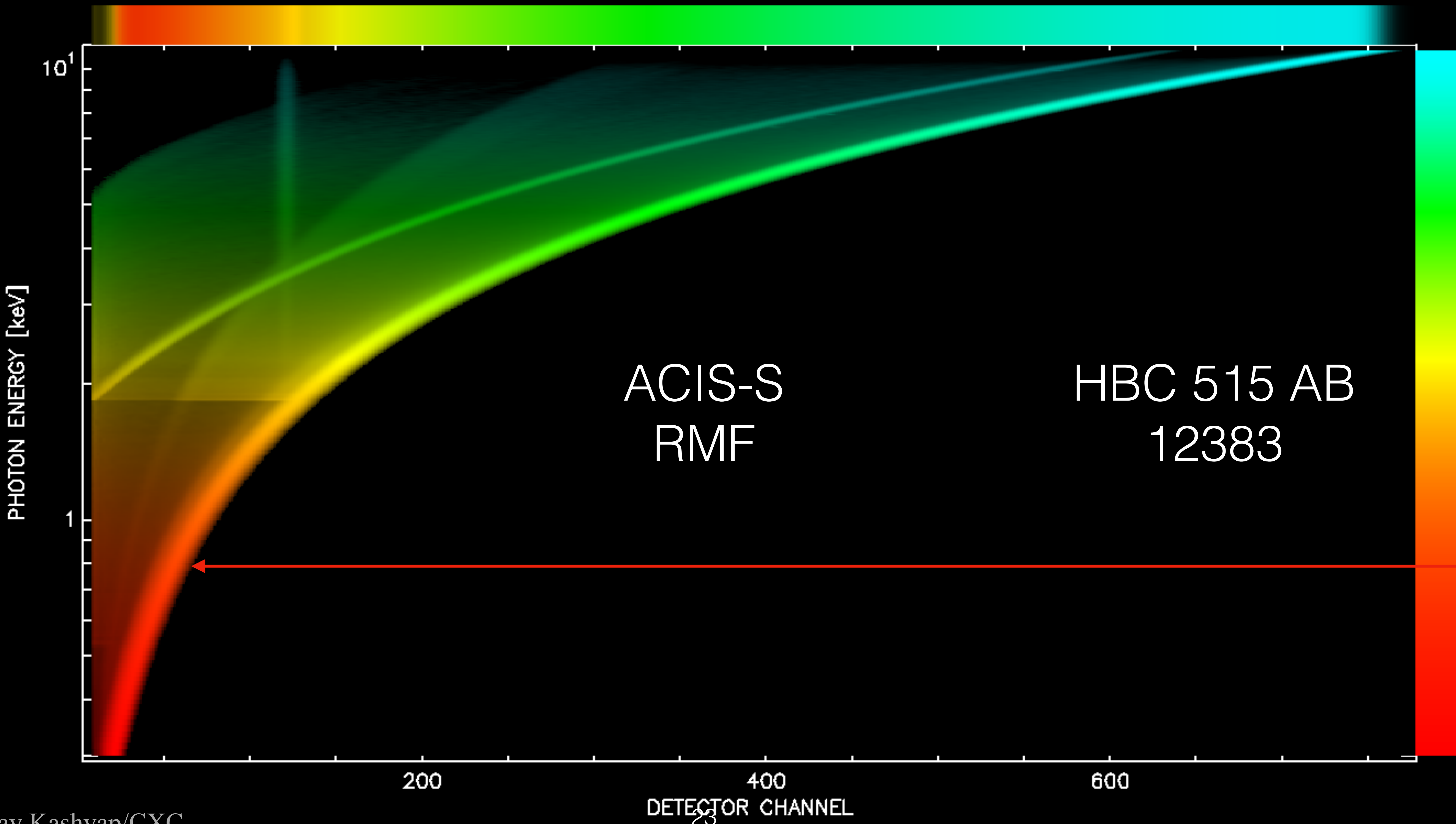
Think as probability; rows of matrix sum to 1.



ACIS-S
RMF

HBC 515 AB
12383

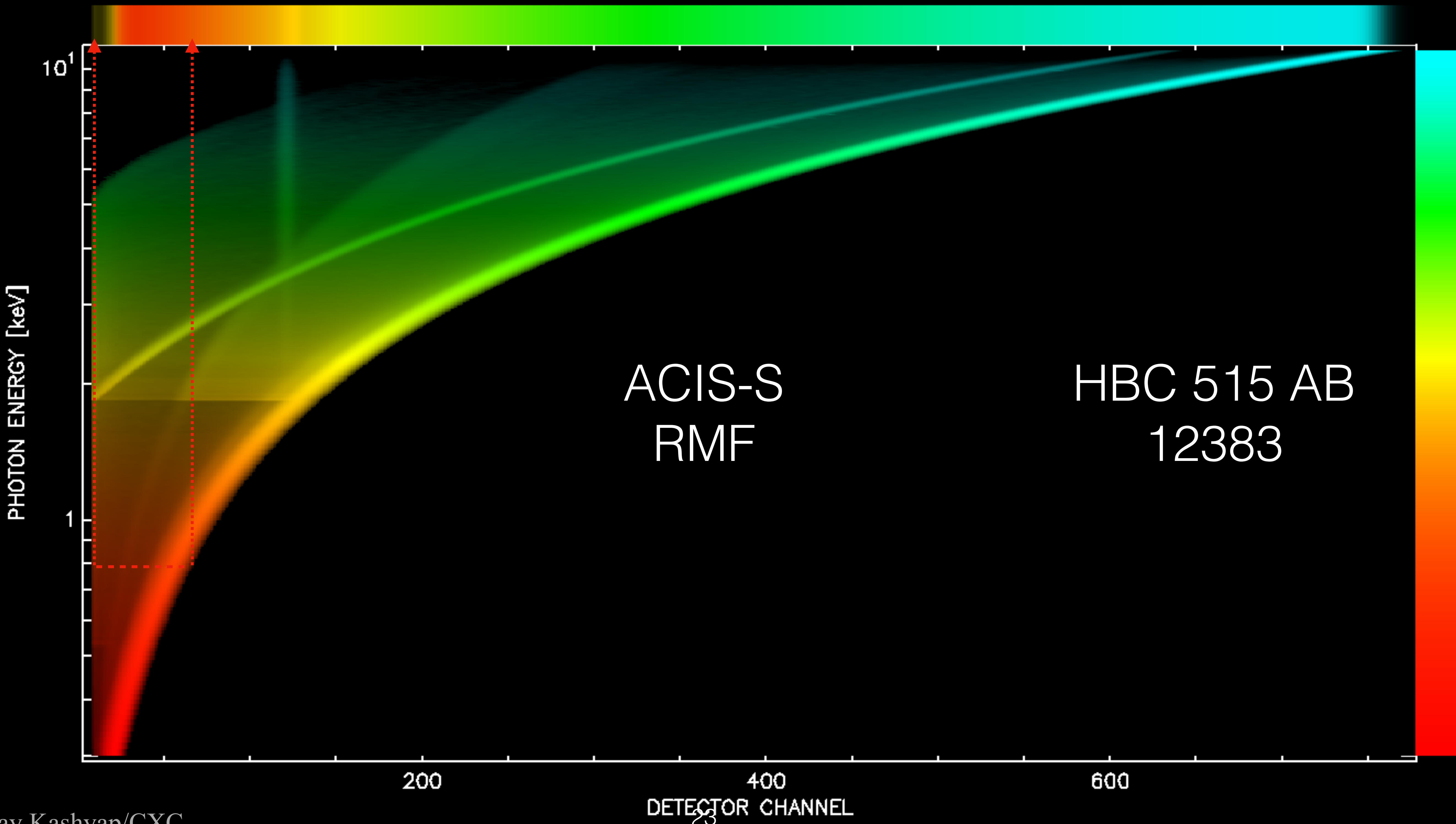
Vinay Kashyap/CXC



ACIS-S
RMF

HBC 515 AB
12383

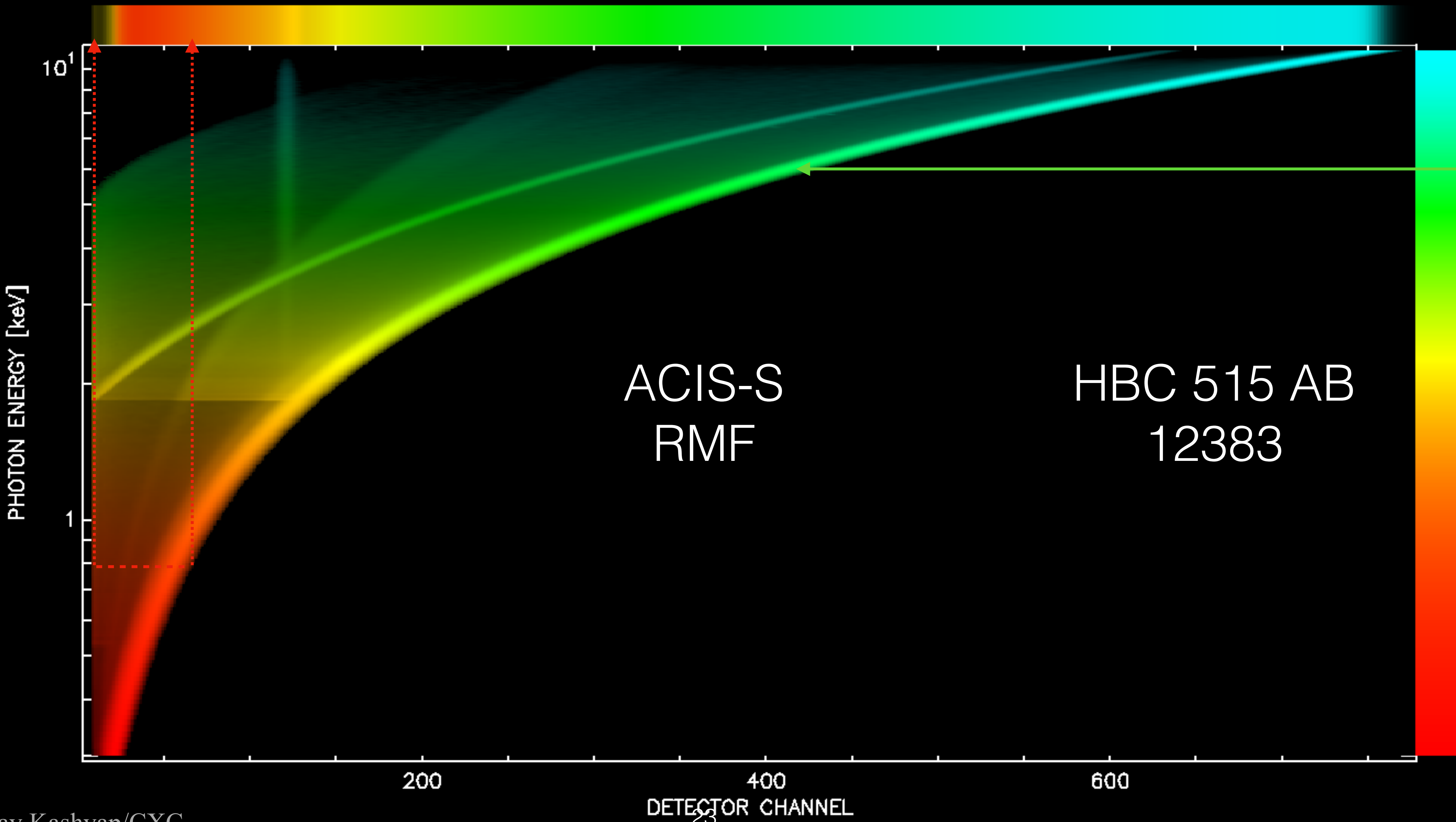
Vinay Kashyap/CXC



ACIS-S
RMF

HBC 515 AB
12383

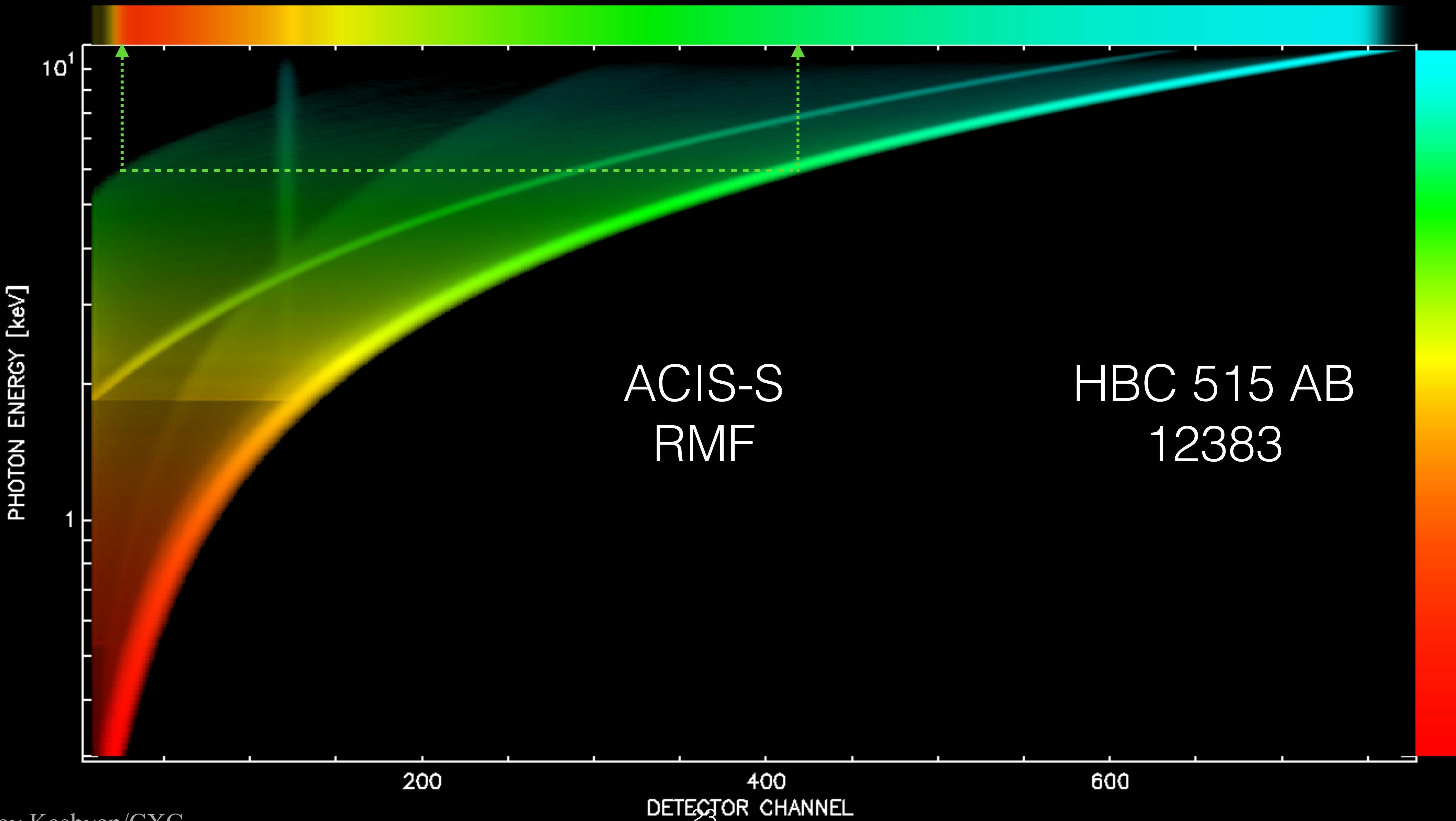
Vinay Kashyap/CXC



ACIS-S
RMF

HBC 515 AB
12383

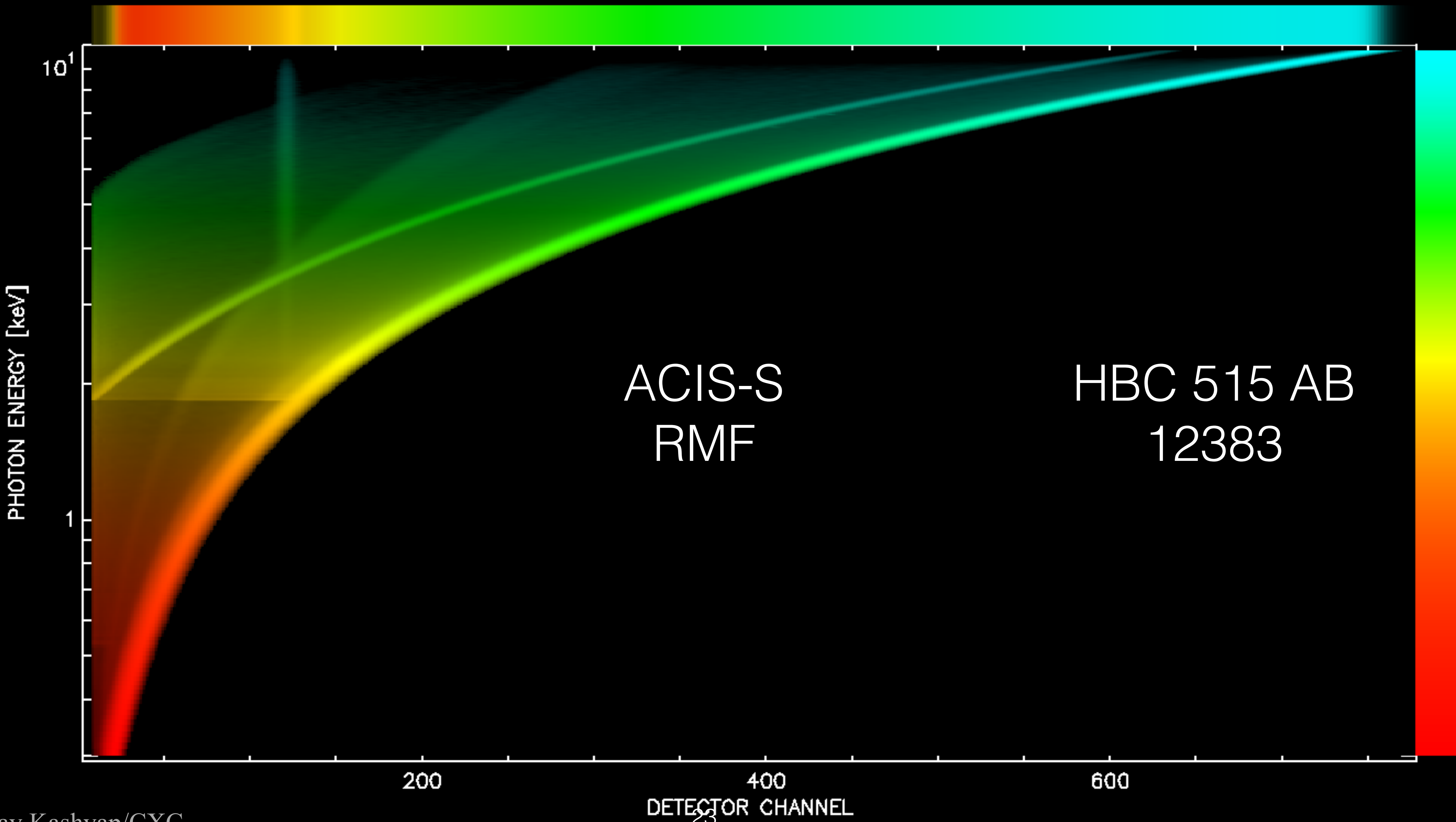
Vinay Kashyap/CXC



ACIS-S
RMF

HBC 515 AB
12383

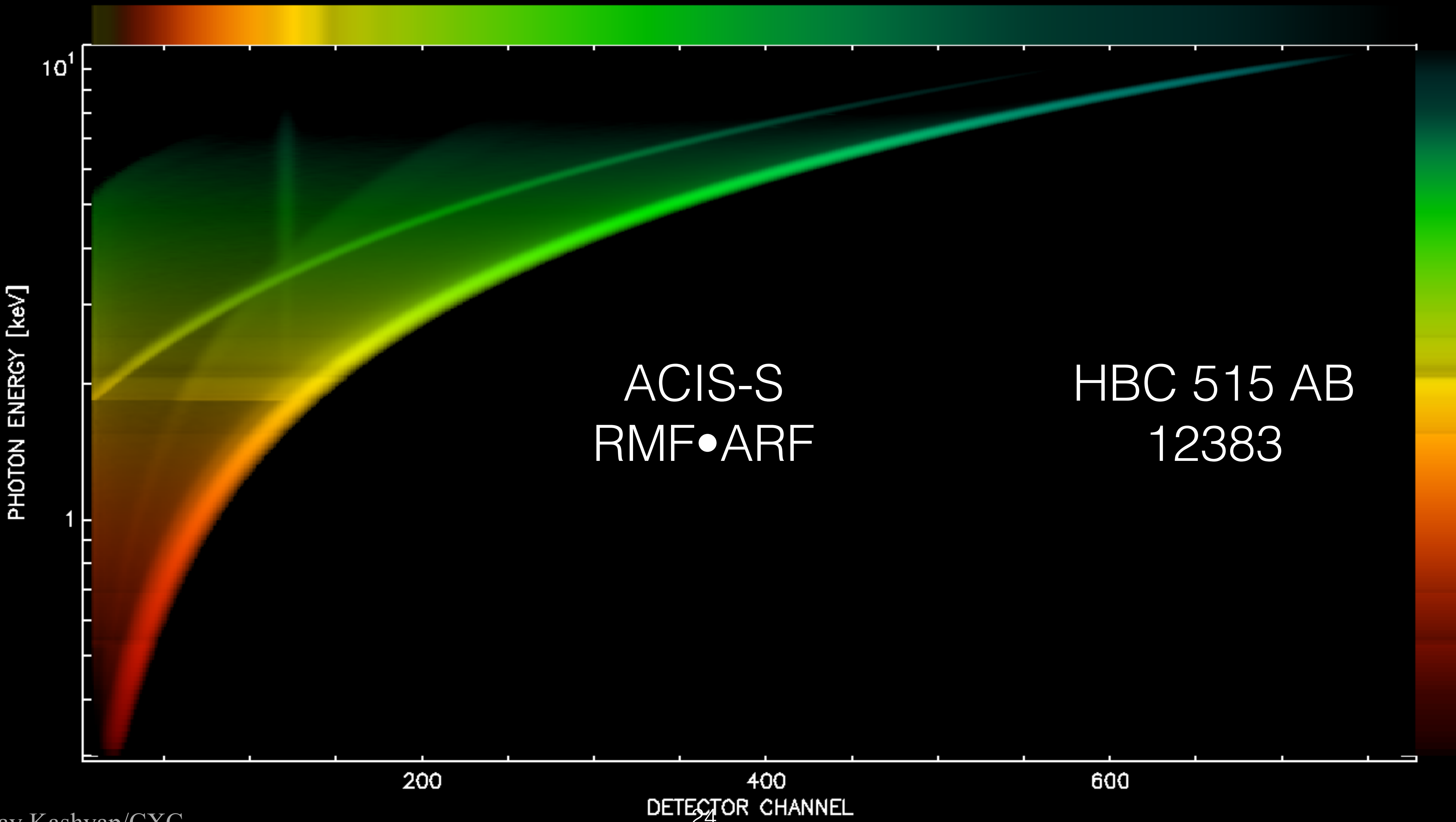
Vinay Kashyap/CXC



ACIS-S
RMF

HBC 515 AB
12383

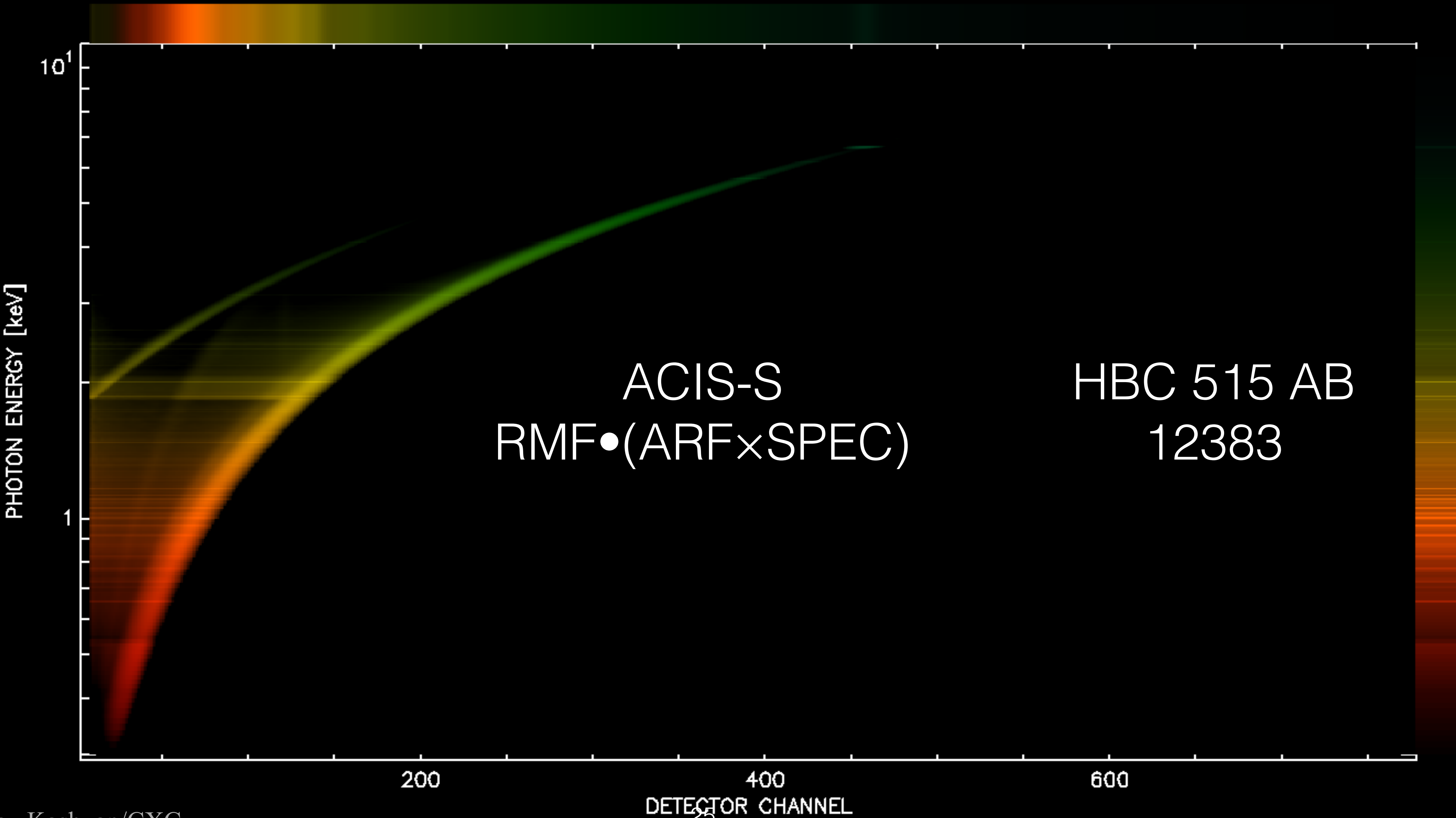
Vinay Kashyap/CXC



ACIS-S
RMF•ARF

HBC 515 AB
12383

Vinay Kashyap/CXC



ACIS-S
RMF•(ARF×SPEC)

HBC 515 AB
12383

Vinay Kashyap/CXC

$$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)\, A(E;\mathbf{x}',t,\lambda) P(\mathbf{x},\mathbf{x}';E,t,\lambda)\, R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)\, \Delta(t,t';\mathbf{x}',\lambda)$$

Timing corrections

Types of corrections:

frame time / integration time
dead time
Barycentric

The Data Model

the fundamental equation of observational astronomy

$\lambda(\mathbf{x}',E',t';\theta) = \int\int\int dt\, dE\, d\mathbf{x}\, f(\mathbf{x},E,t;\theta)$ incoming flux

Expected counts

$\times\ A(E;\mathbf{x}',t,\lambda)$ Effective area

$\times\ P(\mathbf{x},\mathbf{x}';E,t,\lambda)$ Point Spread Function

$\times\ R(E,E';\mathbf{x}',t,\mathbf{x},\lambda)$ Spectral Response matrix

$\times\ \Delta(t,t';\mathbf{x}',\lambda)$ timing corrections

observed counts

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Normal}(\lambda,\sigma_\lambda)$$

$$Y(\mathbf{x}',E',t';\theta) \sim \mathrm{Poisson}(\lambda)$$

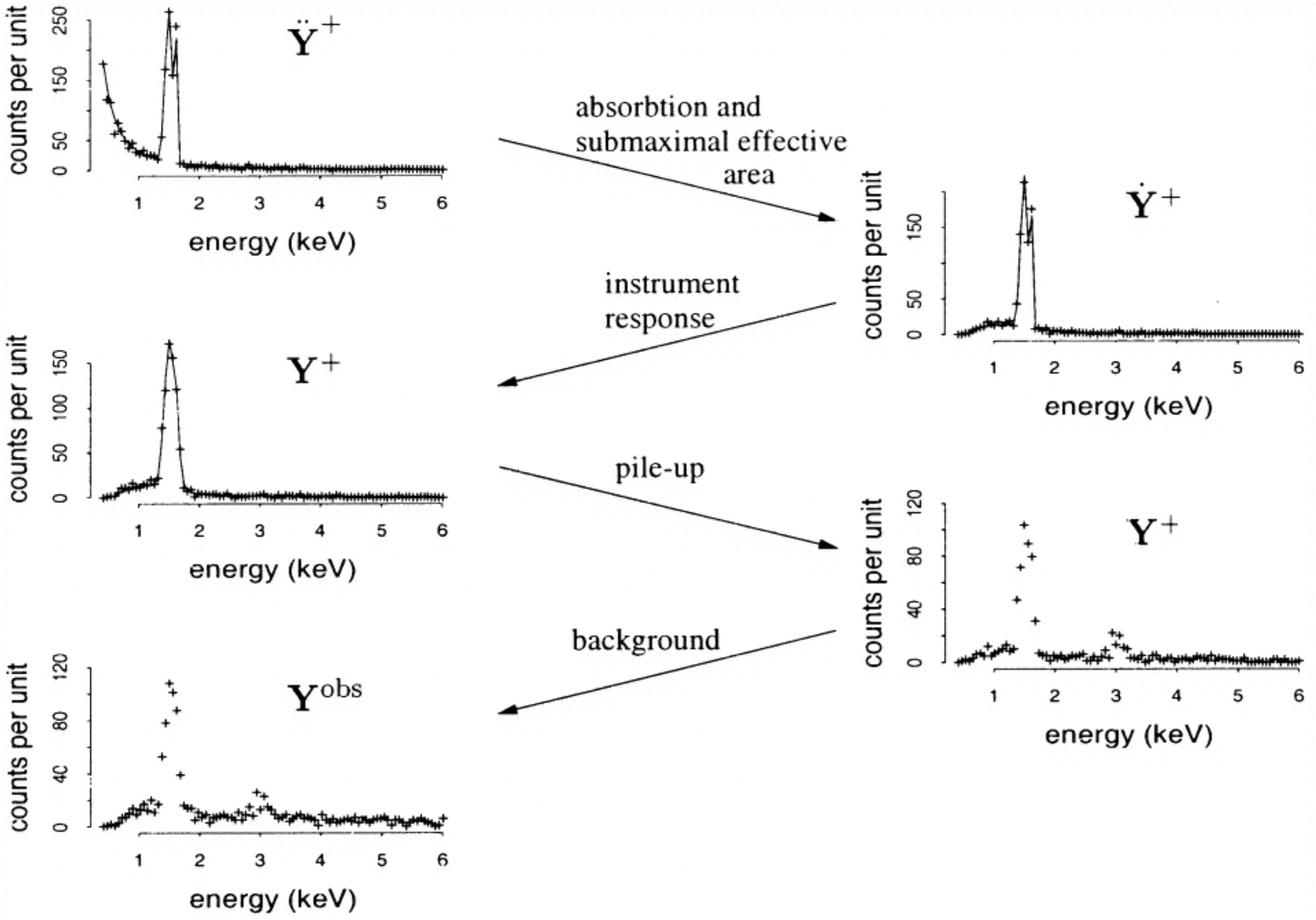
3. A CHASC of BLoCXS
Or, what have been doing about it

CHASC AstroStatistics Collaboration

- Started 1997
- http://hea-www.harvard.edu/AstroStat/

BLoCXS

CJ Shen / Chris Hans / Rostislav Protassov / Yaming Yu / Taeyoung Park / Hyunsook Lee / Jin Xu / Shandong Min



van Dyk, D. A., Connors, A., Kashyap, V. L., Siemiginowska, A. (2001)
Analysis of Energy Spectra with Low Photon Counts via Bayesian Posterior Simulation.
The Astrophysical Journal , 548, 224-243.

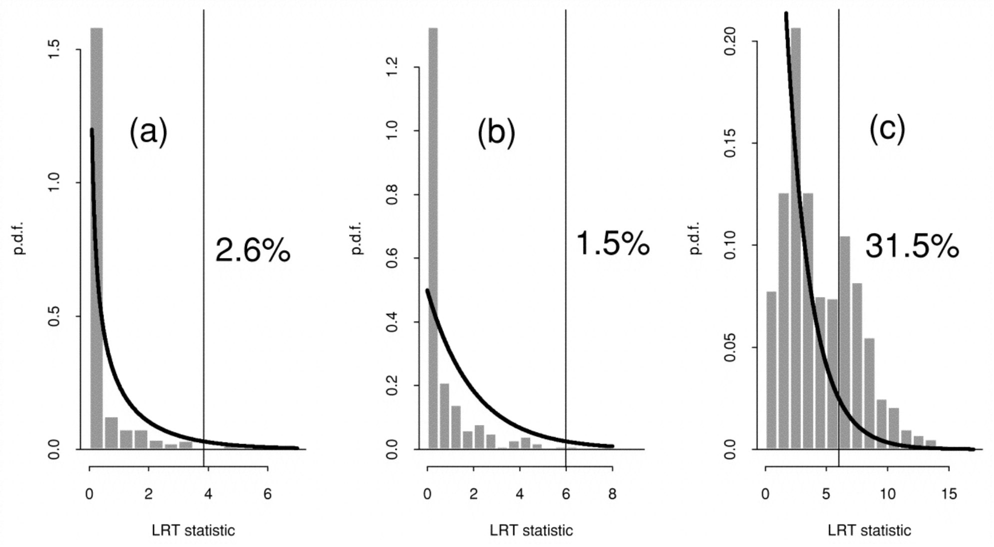
(David van Dyk/Aneta Siemiginowska)

BLoCXS / ppp

Rostislav Protassov / Yaming Yu / Taeyoung Park

Protassov LRT

- plot of LRT distributions
line detection



F-test was being commonly misused in astro analyses
because of a lack of appreciation
of the asymptotic conditions under which it was valid.

posterior predictive p-values for LRTs

Protassov+ 2002, became our most famous paper
has been cited 400+ times

Protassov, R., van Dyk, D. A., Connors, A., Kashyap, V. L. and Siemiginowska, A. (2002). *Statistics: Handle with Care, Detecting Multiple Model Components with the Likelihood Ratio Test.* ApJ, 571, 545-559.

Park, T. van Dyk, Siemiginowska, A. (2008) -*Searching for Narrow Emission Lines in X-ray Spectra: Computation and Methods,* ApJ. 688, 807

(Aneta Siemiginowska)

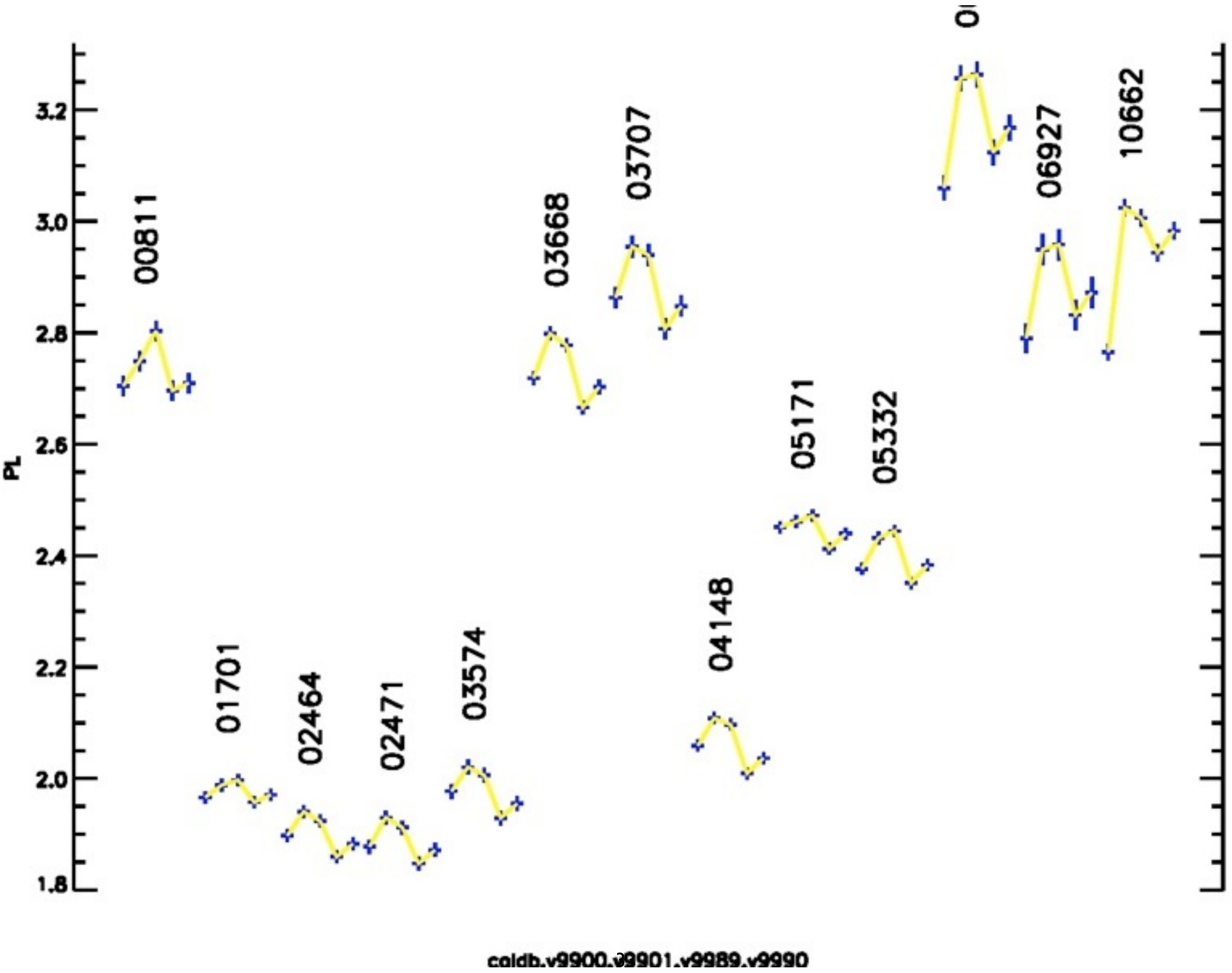
pyBLoCXS / Calibration

Yaming Yu / Taeyoung Park / Hyunsook Lee / Jin Xu / David Stenning / Nathan Stein / Xixi Yu

Foundations of Astronomical inference:
Measurement
Significance
Calibration

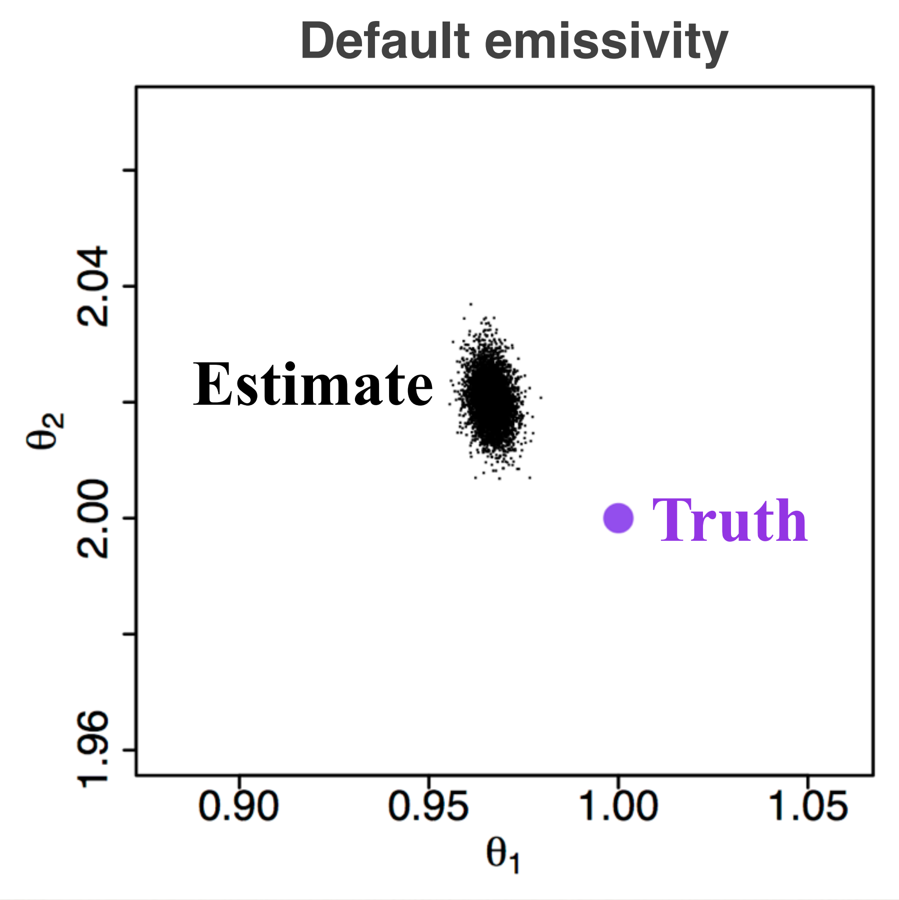
Calibration is not perfect, it has known statistical and systematic errors, and unknown errors that are only guessed at.

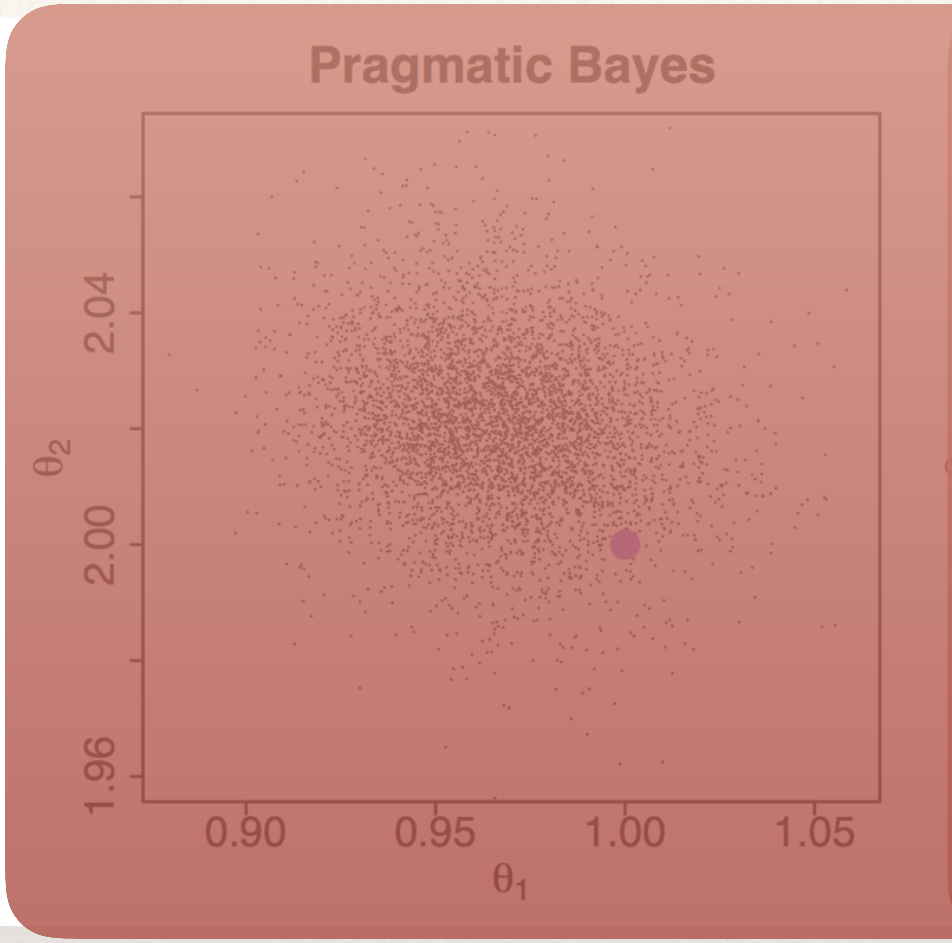
Drake, J.J., et al. 2006, *"Monte Carlo processes for including Chandra instrument response uncertainties in parameter estimation studies"*, SPIE Proc. 6270, 49
Kashyap, V.L., et al. 2008, *"How to handle calibration uncertainties in high-energy astrophysics"*, SPIE Proc. 7016, 21
Lee, H., et al. 2011, *"Accounting for Calibration Uncertainties in X-ray Analysis: Effective Areas in Spectral Fitting"*, ApJ, 731, 126
Xu, J., et al. 2014, *"A Fully Bayesian Method for Jointly Fitting Instrumental Calibration and X-ray Spectral Models"*, ApJ, in press


PL
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
00811
01701
02464
02471
03574
03668
03707
04148
05171
05332
0
06927
10662
caldb.v9900.v9901.v9989.v9990

Lee et al. 2011, ApJ 731, 126 § Xu et al. 2014, ApJ 794 97 § Yu et al. 2018, ApJ 866 146

Standard → Prag Bayes → Full Bayes

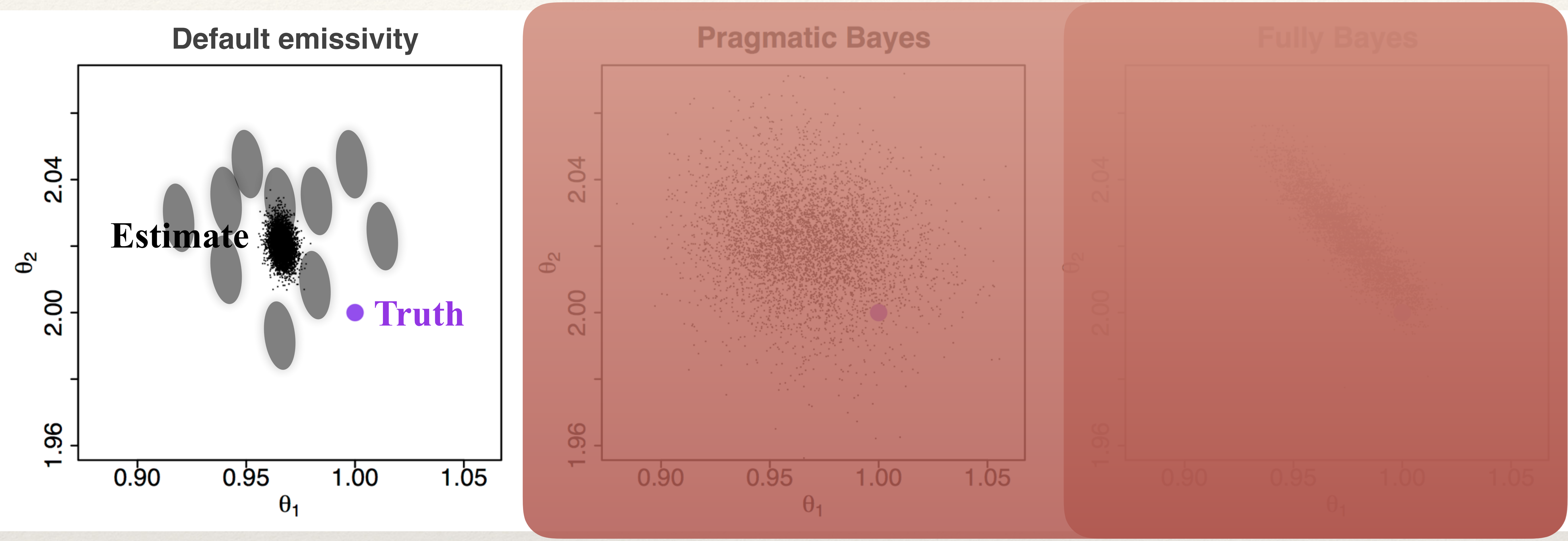




$p(\theta|D,\varepsilon^{(def)})$

Lee et al. 2011, ApJ 731, 126 § Xu et al. 2014, ApJ 794 97 § Yu et al. 2018, ApJ 866 146

Standard → Prag Bayes → Full Bayes

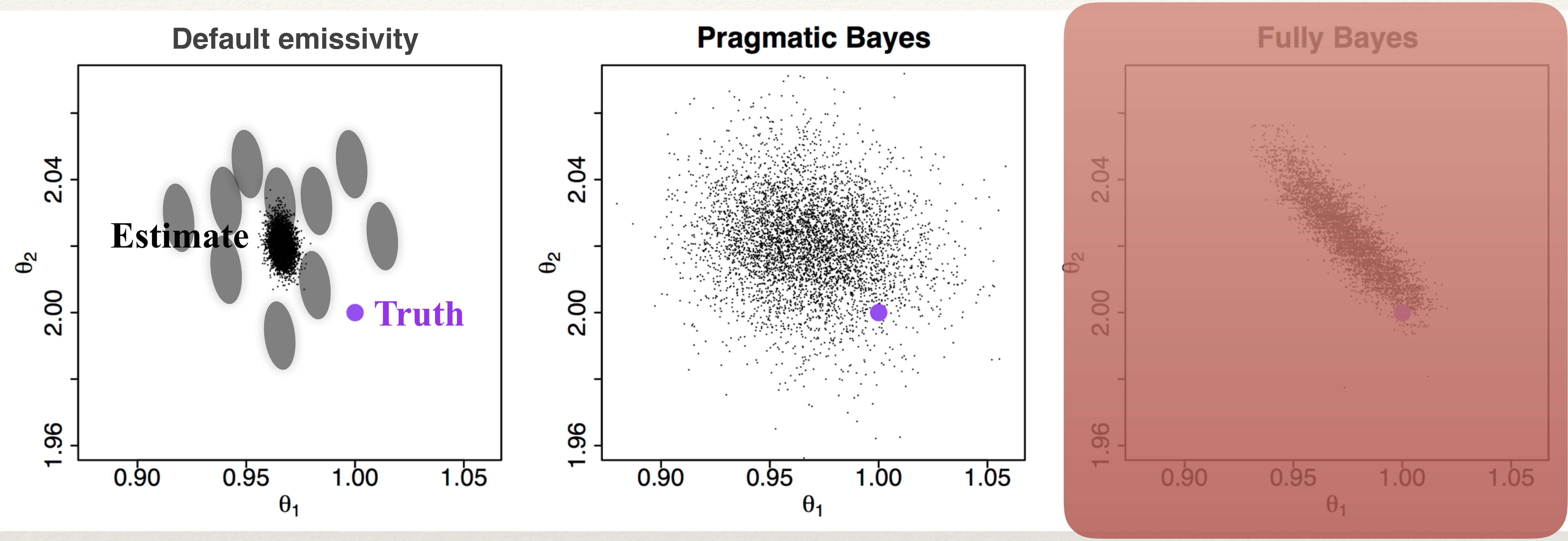


$p(\theta|D,\varepsilon^{(m)})$

$p(\theta|D,\varepsilon^{(def)})$

Lee et al. 2011, ApJ 731, 126 § Xu et al. 2014, ApJ 794 97 § Yu et al. 2018, ApJ 866 146

Standard → Prag Bayes → Full Bayes

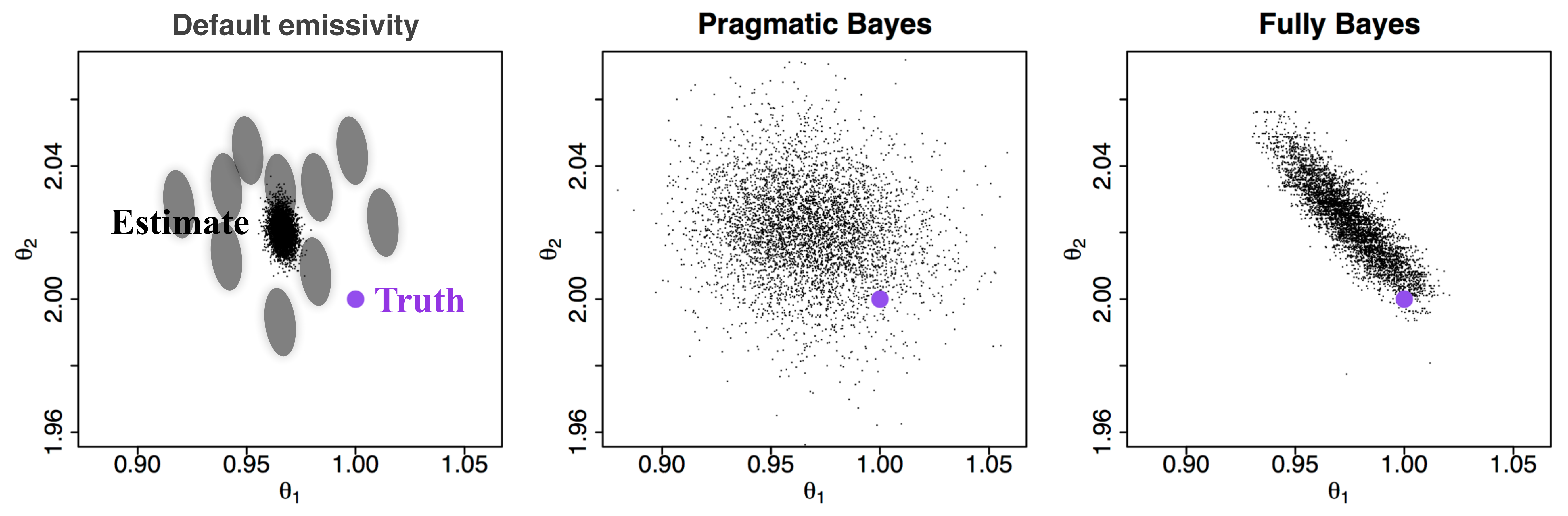


$p(\theta|D,\varepsilon^{(m)})$ $p(\varepsilon,\theta|D)$

$p(\theta|D,\varepsilon^{(def)})$ $\rightarrow p(\theta|D,\varepsilon) \cdot p(\varepsilon)$

Lee et al. 2011, ApJ 731, 126 § Xu et al. 2014, ApJ 794 97 § Yu et al. 2018, ApJ 866 146

Standard → Prag Bayes → Full Bayes



$p(\theta|D,\varepsilon^{(m)})$ $p(\varepsilon,\theta|D)$ $p(\varepsilon,\theta|D)$

$p(\theta|D,\varepsilon^{(def)})$ $\rightarrow p(\theta|D,\varepsilon) \cdot p(\varepsilon)$ $\rightarrow p(\theta|D,\varepsilon) \cdot p(\varepsilon|D)$

4. Next

LIRA+Ising

EBASCS