Multi-wavelength (UV/X-ray) Astronomy with AstroSat

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Thanks:

AstroSat teams: K. P. Singh, SXT team (Most observations of AGN)
D. Bhattacharya, A. R. Rao, CZTI team
Shyam Tandon, C. S. Stalin, Joe Postma UVIT team
J. S. Yadav, H. M. Antia, R. Misra, LAXPC team

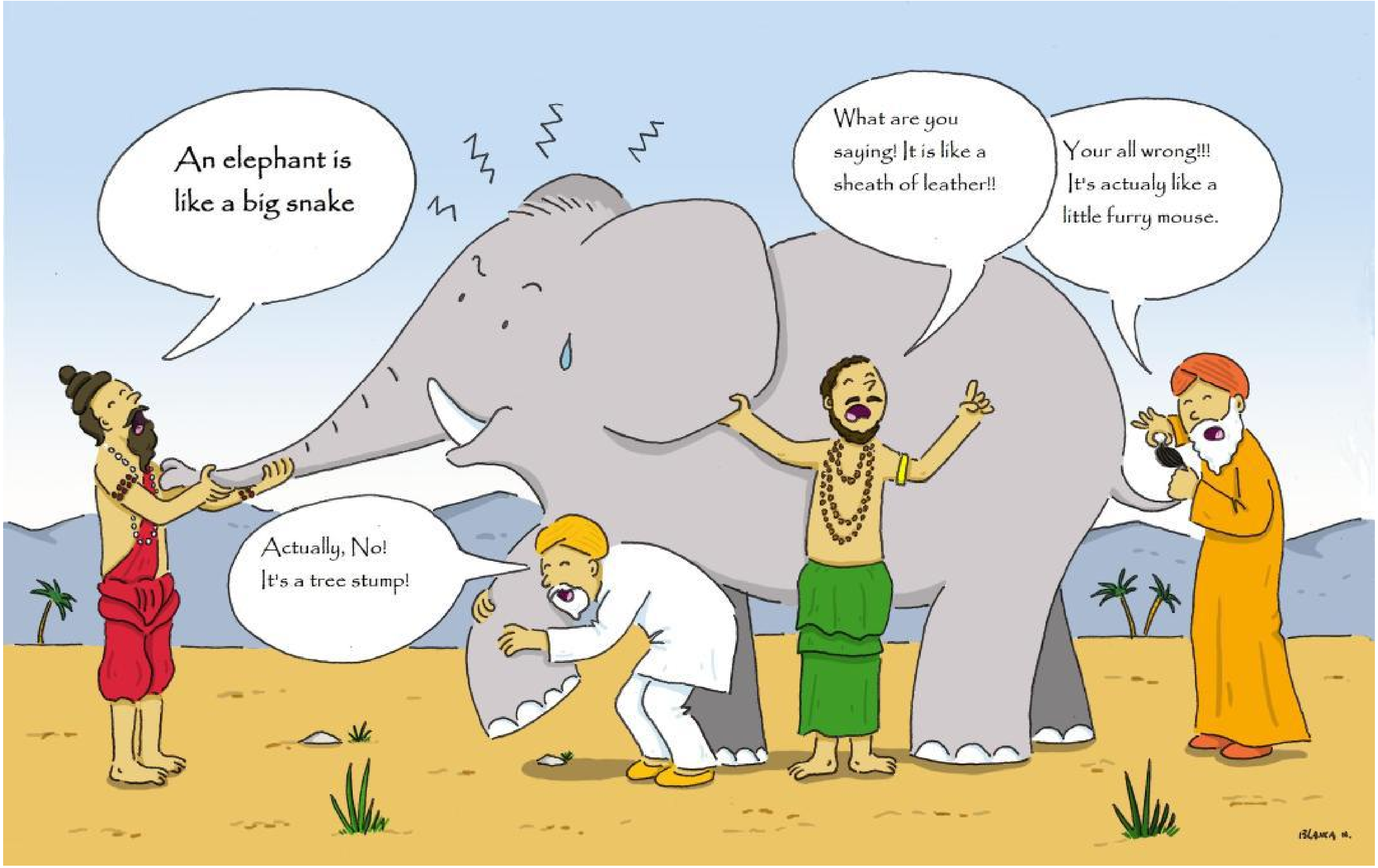
Collaborators: Iossif Papadakis, Ian McHardy, Alex Markowitz, Oluwashina Adegoke

PhD Students: Pranoti Panchbhai, Prakash Tripathi,

Postdocs : Pramod Pawar, Savithri Ezikode

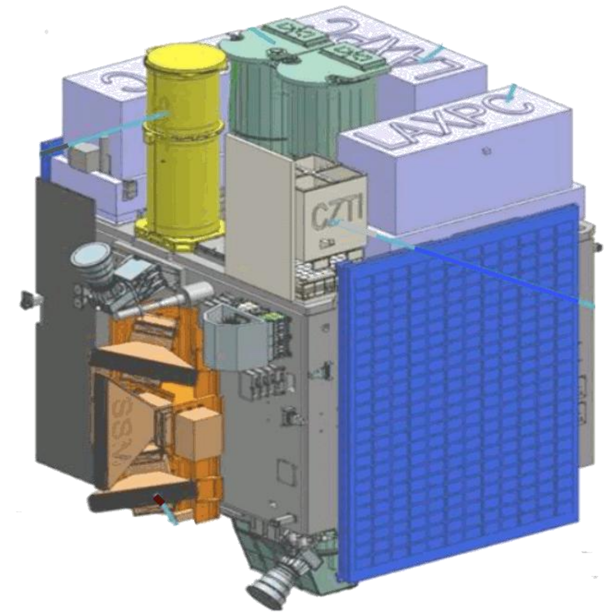
Why MW astronomy?

Tale of the blind men and the elephant



Similarly, it is difficult to find a complete picture of a cosmic source just by studying at a single wave band.

AstroSat Capabilities



UVIT

Imaging (1.2 to 1.5 arcsec PSF) and photometry in 10 UV bands, low resolution spectroscopy with FUV/NUV gratings.

Simultaneous observations in Far UV (130-180nm), Near UV (200-300nm) & Visible (320 - 550nm)

Photon counting mode (FUV/NUV), Fast timing

SXT

Medium resolution soft X-ray Imaging Spectrometer (0.2-8keV), timing (2.4s, 0.278s)

LAXPC

Large Area Timing instrument time resol. : 10 μs)

Broadband (3-80 keV), low resolution (12% @22keV) spectrometer,

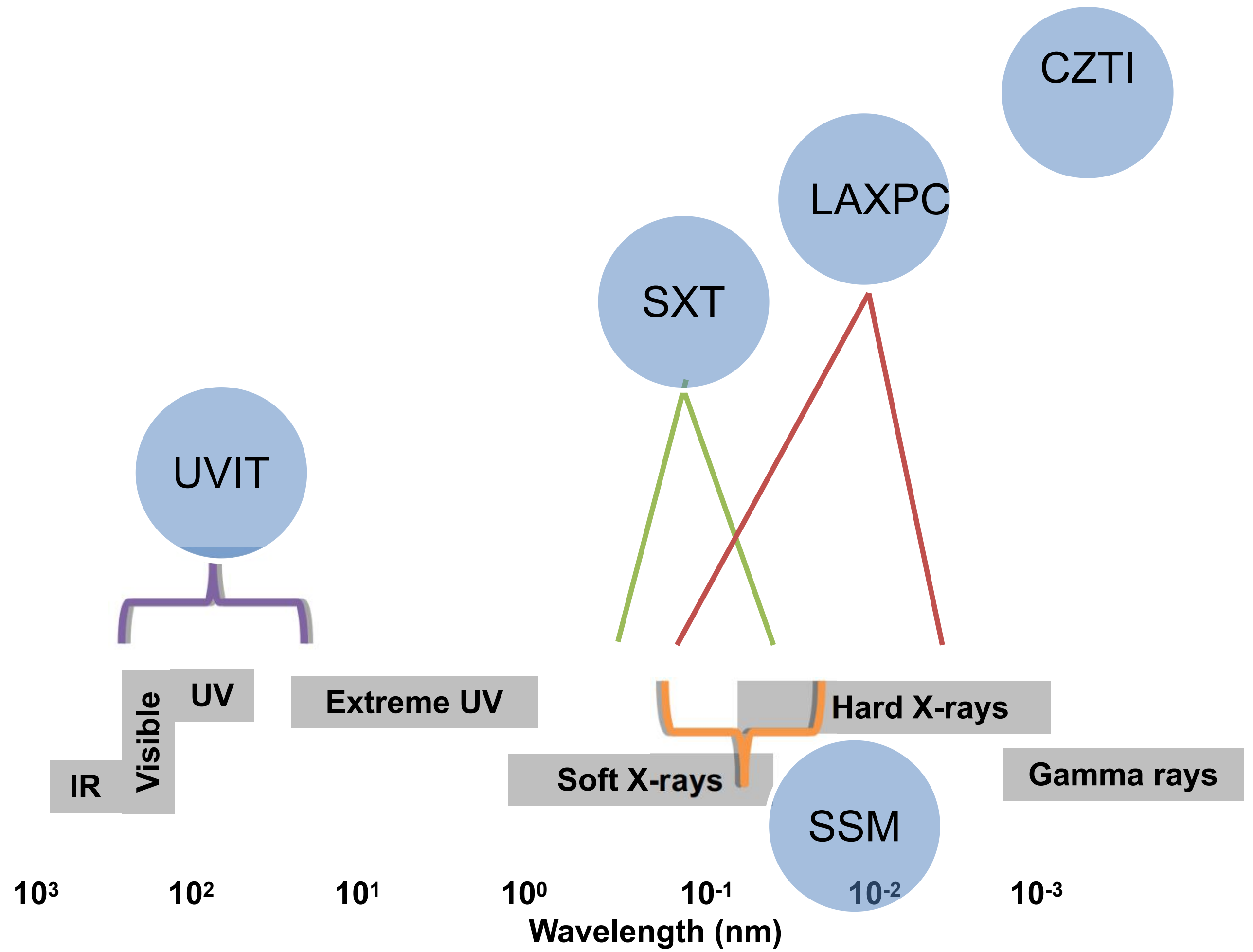
Non-imaging, Coll. FOV: 0.9^{o} X 0.9o (Useful for bright sources)

CZTI

Suitable for sources brighter then 150mCrab
Superior Hard X-ray polarimeter, GRB monitor

Not suitable for faint sources like AGN

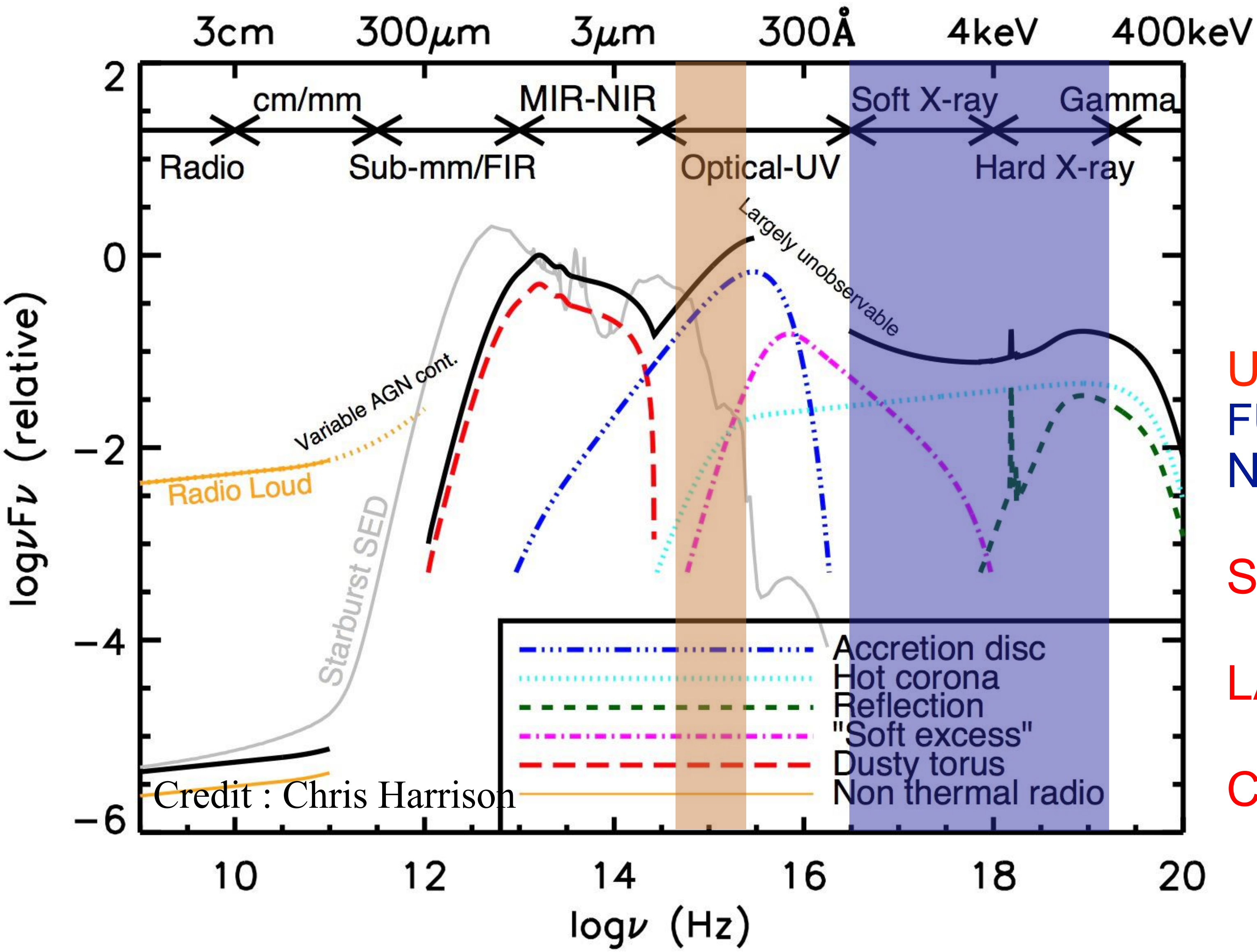
ASTROSAT MW CAPABILITIES

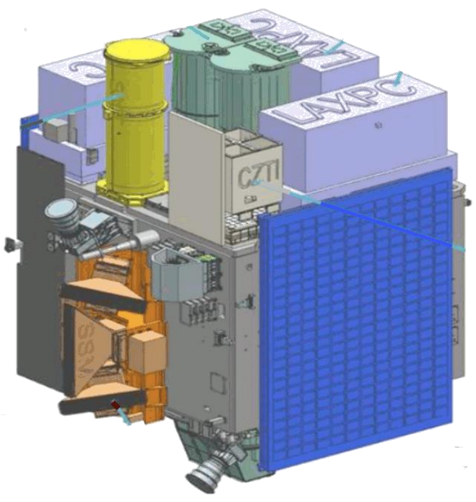


Typical Electromagnetic Spectrum

Active stars, SNRs, CVs, NS and BH X-ray binaries, clusters of galaxies, Seyferts and Blazars.

Astrosat & AGN Science





UVIT : FUV/NUV/VIS
FUV : 5 filters, 2 gratings
NUV: 5 filters, a grating

SXT (0.2-8 keV)

LAXPC (3-80 keV)

CZTI (10-100 keV)

MW Spectroscopy with AstroSat

- UVIT (1300-3000A)
    - 10 broadband filters,
    - two far UV gratings,
    - one near UV grating
- SXT - 0.2-8 keV
- LAXPC - 3-80 keV

Different techniques/instruments => Different types of data and calibration files

Need to cast in the same form to be able to perform MW spectral analysis.

Requires robust (cross-)calibration, analysis tools, etc. for each instrument/detector.

UV/X-ray Spectoscopy with AstroSat

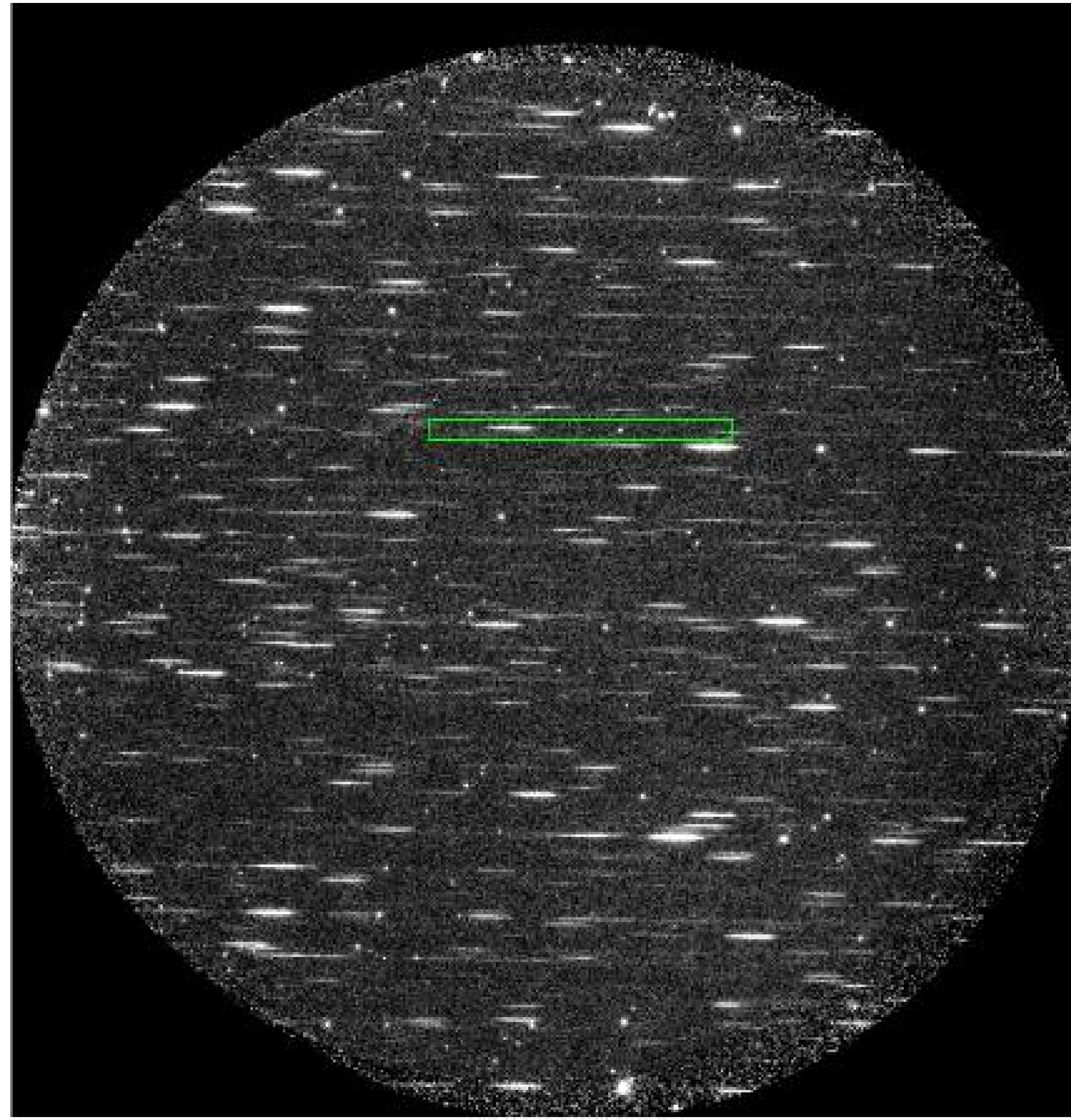
UVIT: MW spectroscopy requires specialized tools/products, calibration of gratings

UVIT analysis tools for MW science (UVITTools in Julia language)

- Photometry (based on Tandon et al. 2017 calibration)
- PHA spectral and response files for all flters (total 10) for MW analysis
- Grating Spectral calibration for 2 FUV and 1 NUV grating
  - 1d spectral extraction,
  - wavelength calibration
  - flux calibration
  - Effective Area
- Fluxed as well as Grating PHA spectral and response generation for MW analysis

UVIT Grating Data Analysis

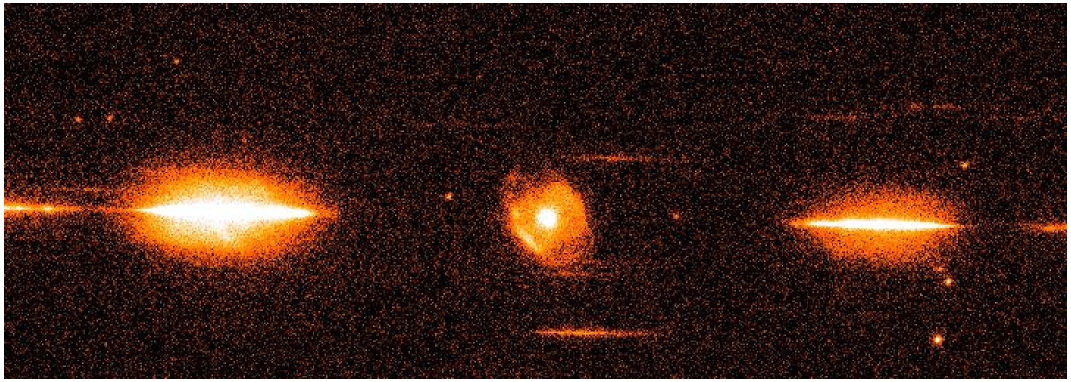
- Merged Level2 image (CCDLAB or your favorite pipeline)
- Identify 0, -1, -2 orders spectra of the target of interest
- Extract 1d spectrum (Dispersion axis slightly tilted wrt to X-axis (NUV-grating, FUV-grating1) or Y-axis (FUV-grating2)
- Counts Vs pixel numbers

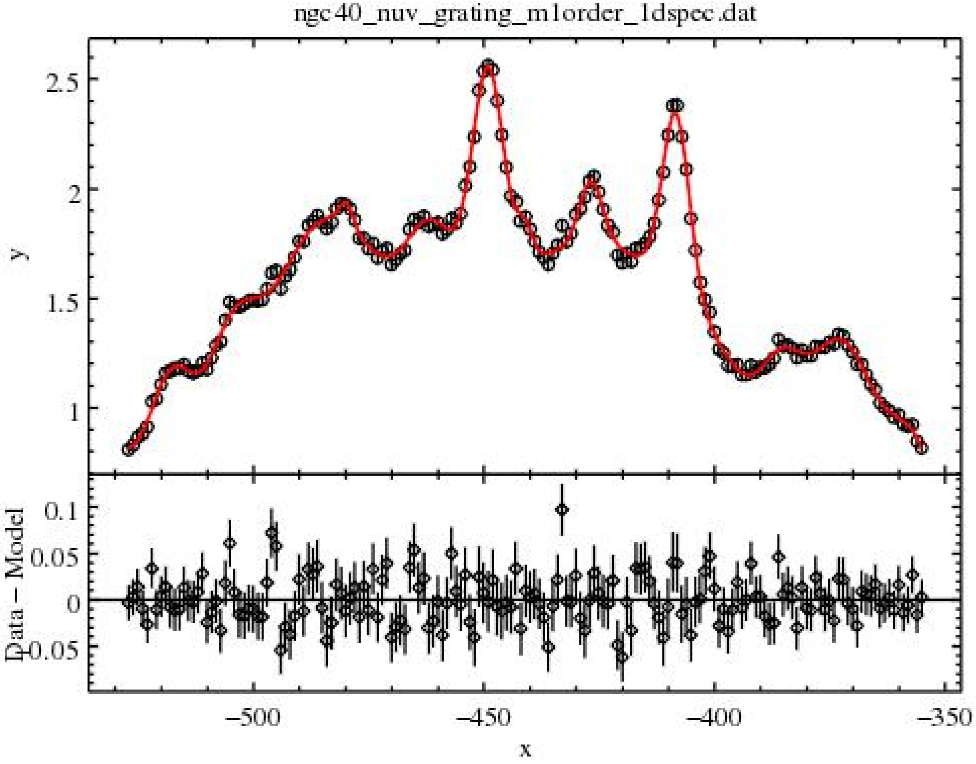


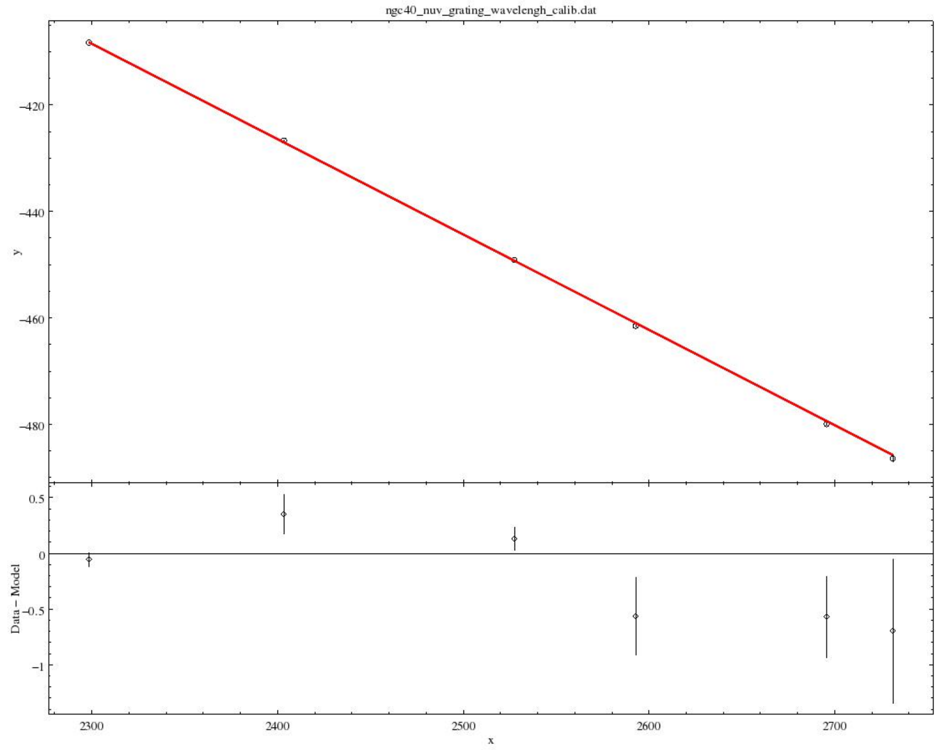
ASASSN-16oh

UVIT Gratings: Wavelength Calibration

Planetary nebula NGC40 with a number of lines







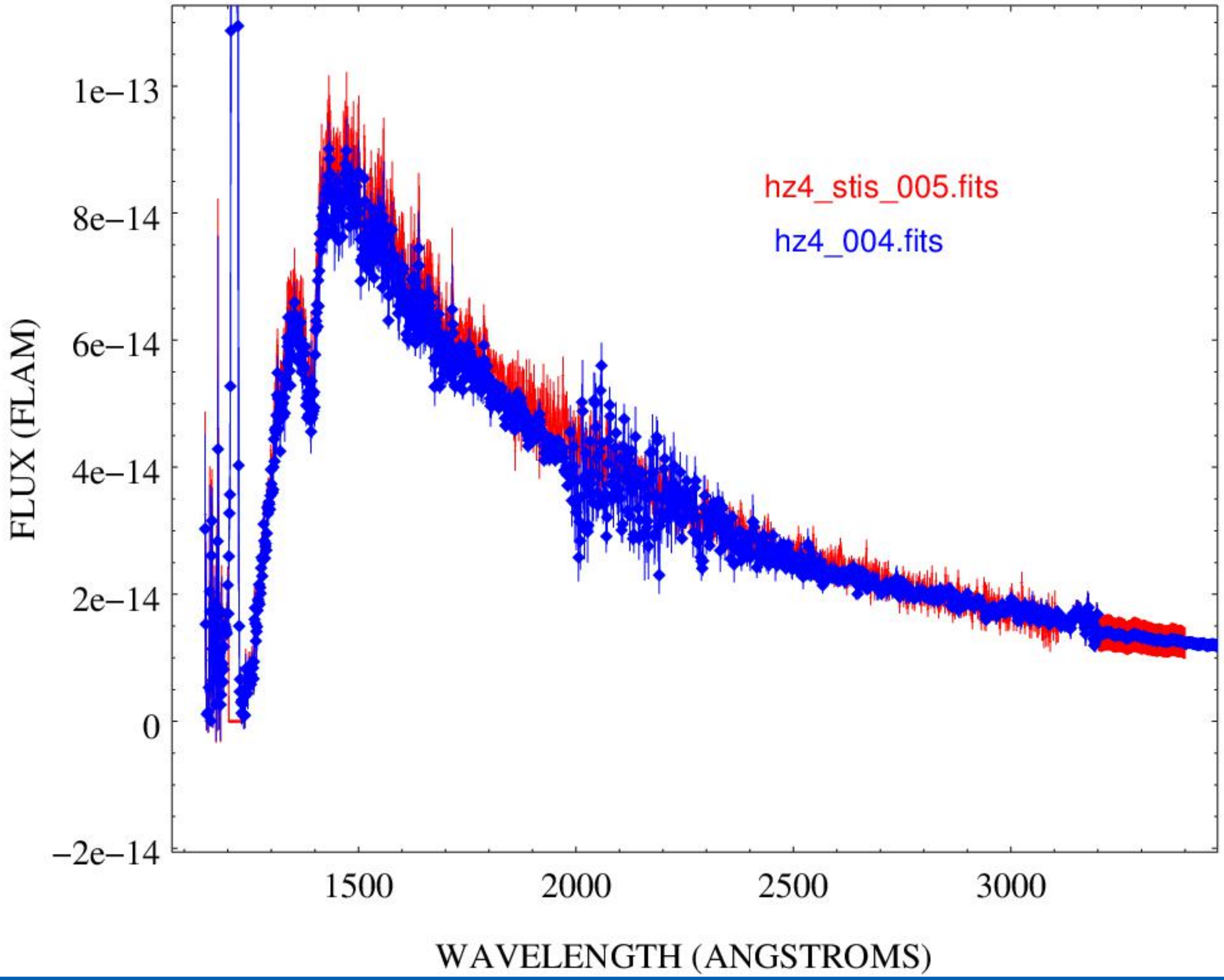
(see also Tandon et al. 2017, Cal paper)

UVIT Grating: Flux Calibration / Effective Area

Spectrophotometric standard

HZ 4 - A white dwarf with well measured spectrum

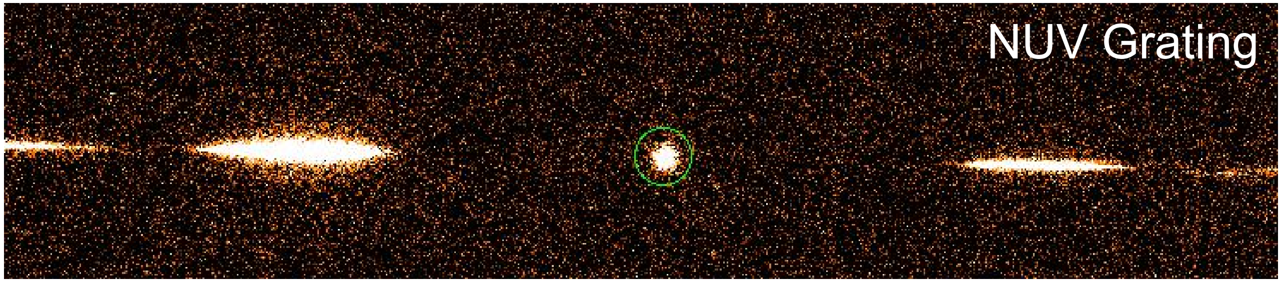
(relatively smooth spectrum)

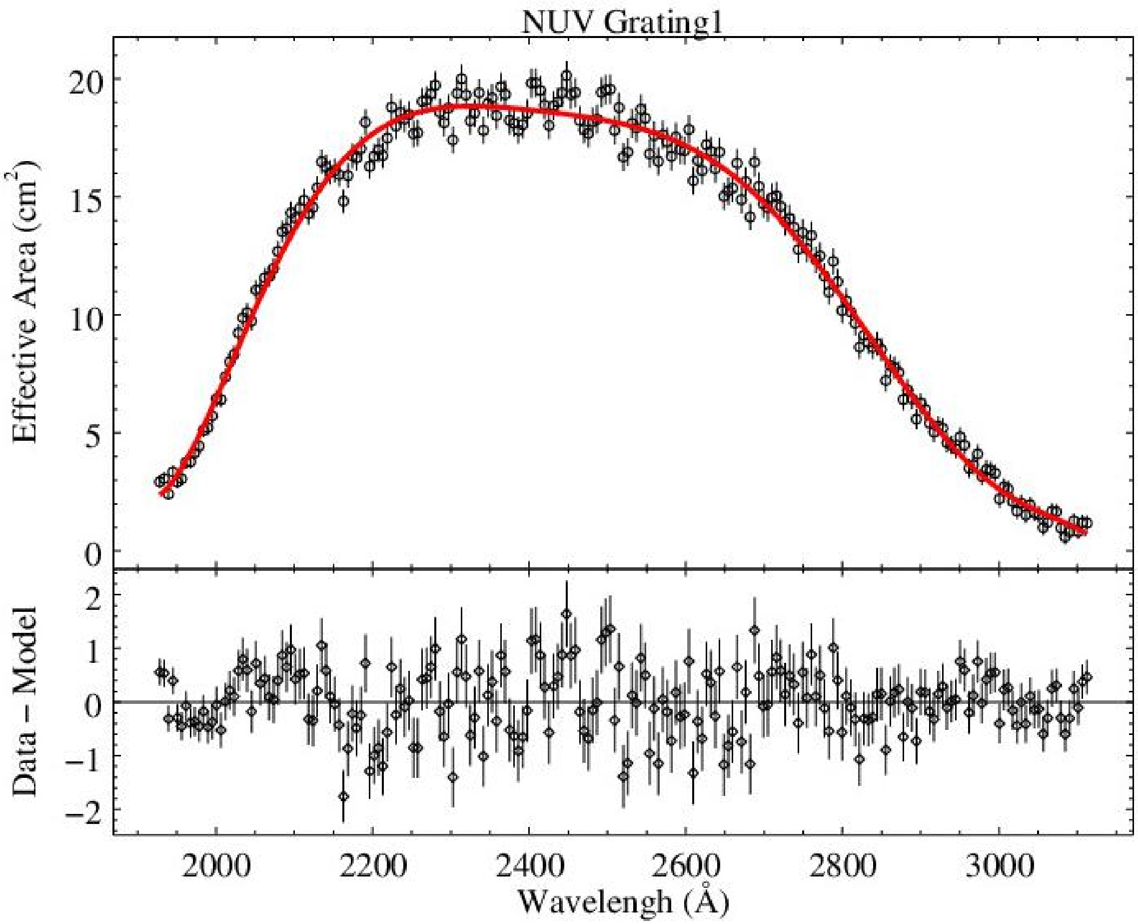


Flux calibration / effective area (NUV)

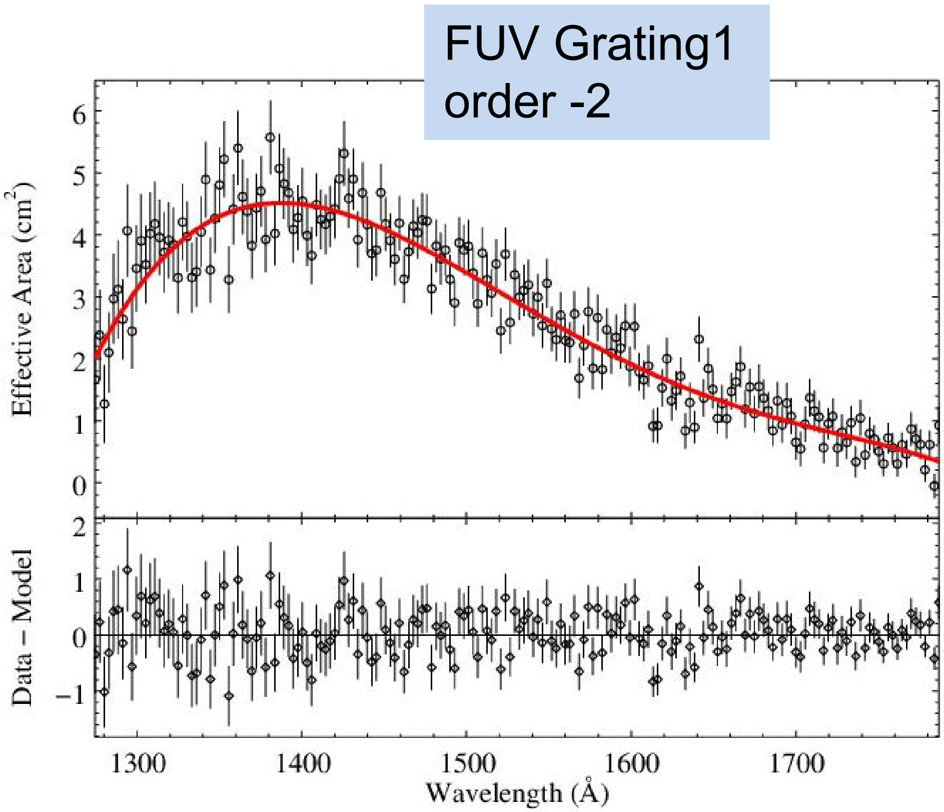
Spectrophotometric standard HZ 4 (a white dwarf)

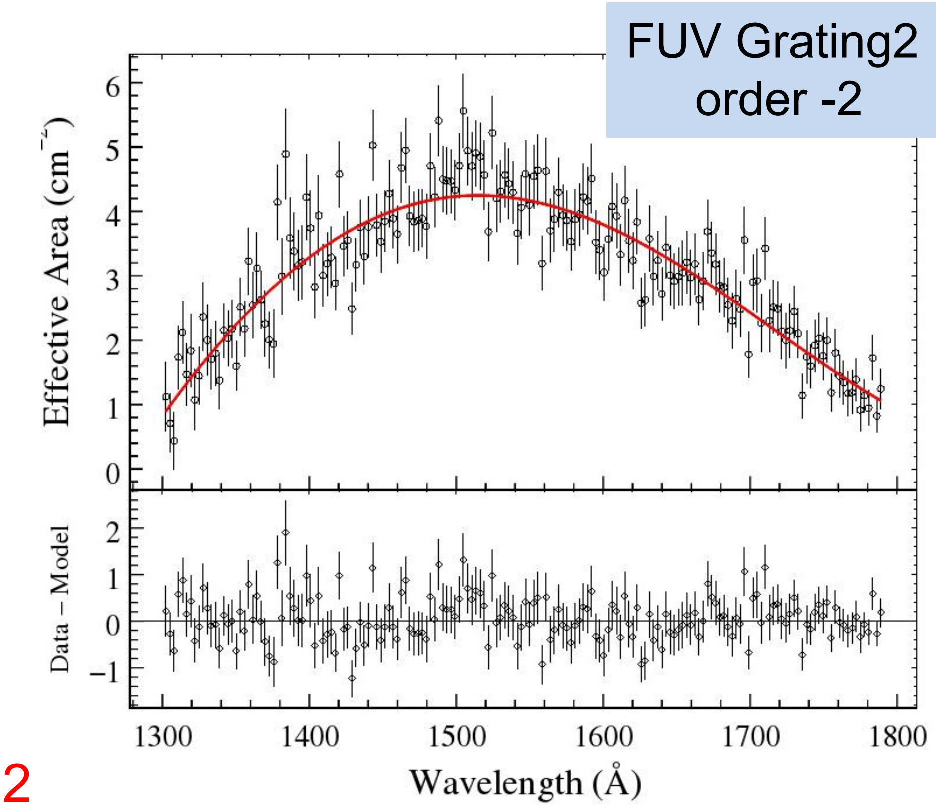
Effective Area : Using standard spectrum of HZ 4 measured with IUE/HST





FUV Grating 1,2 effective area

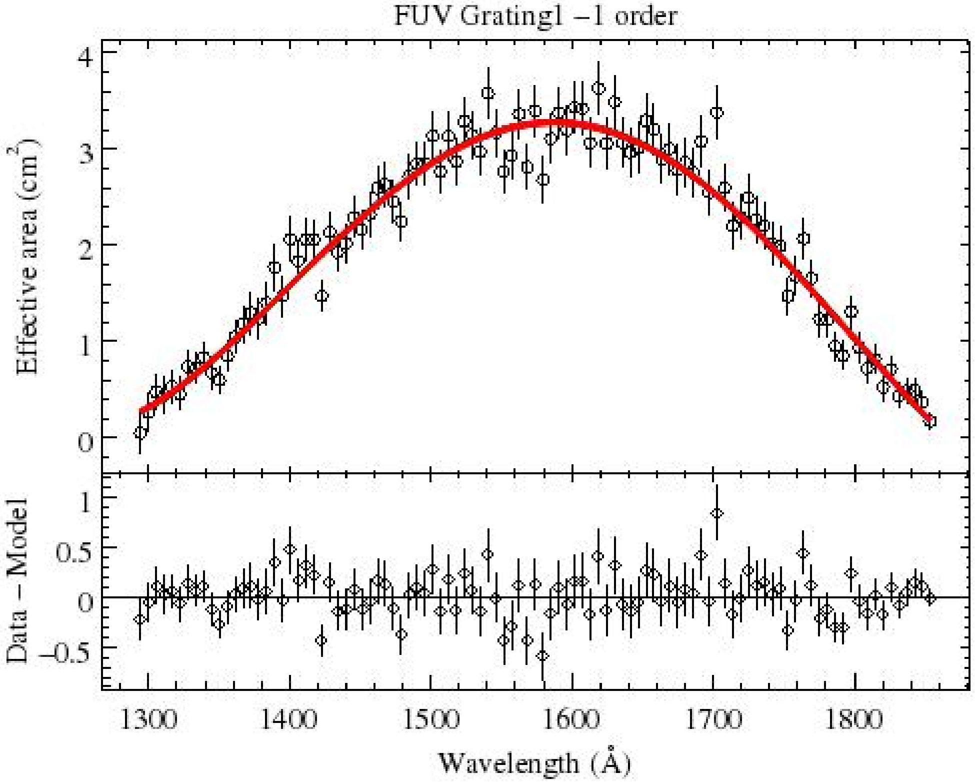


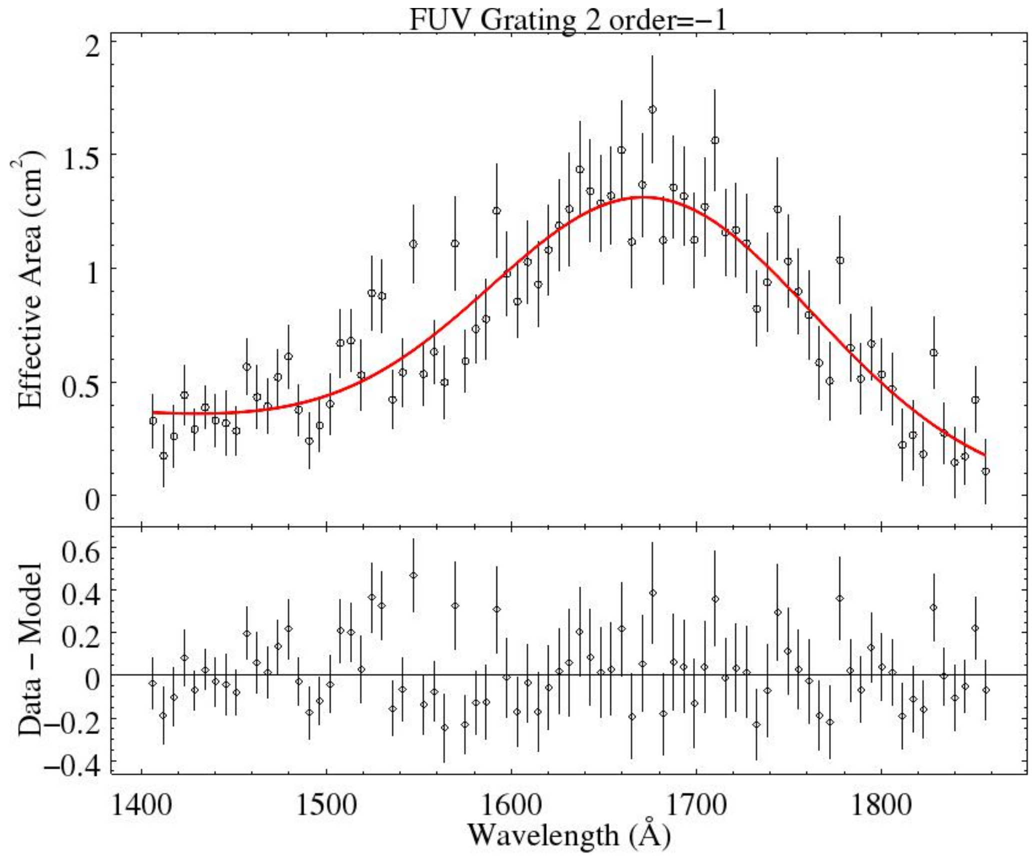


Peak effective area ~ 5 cm^2

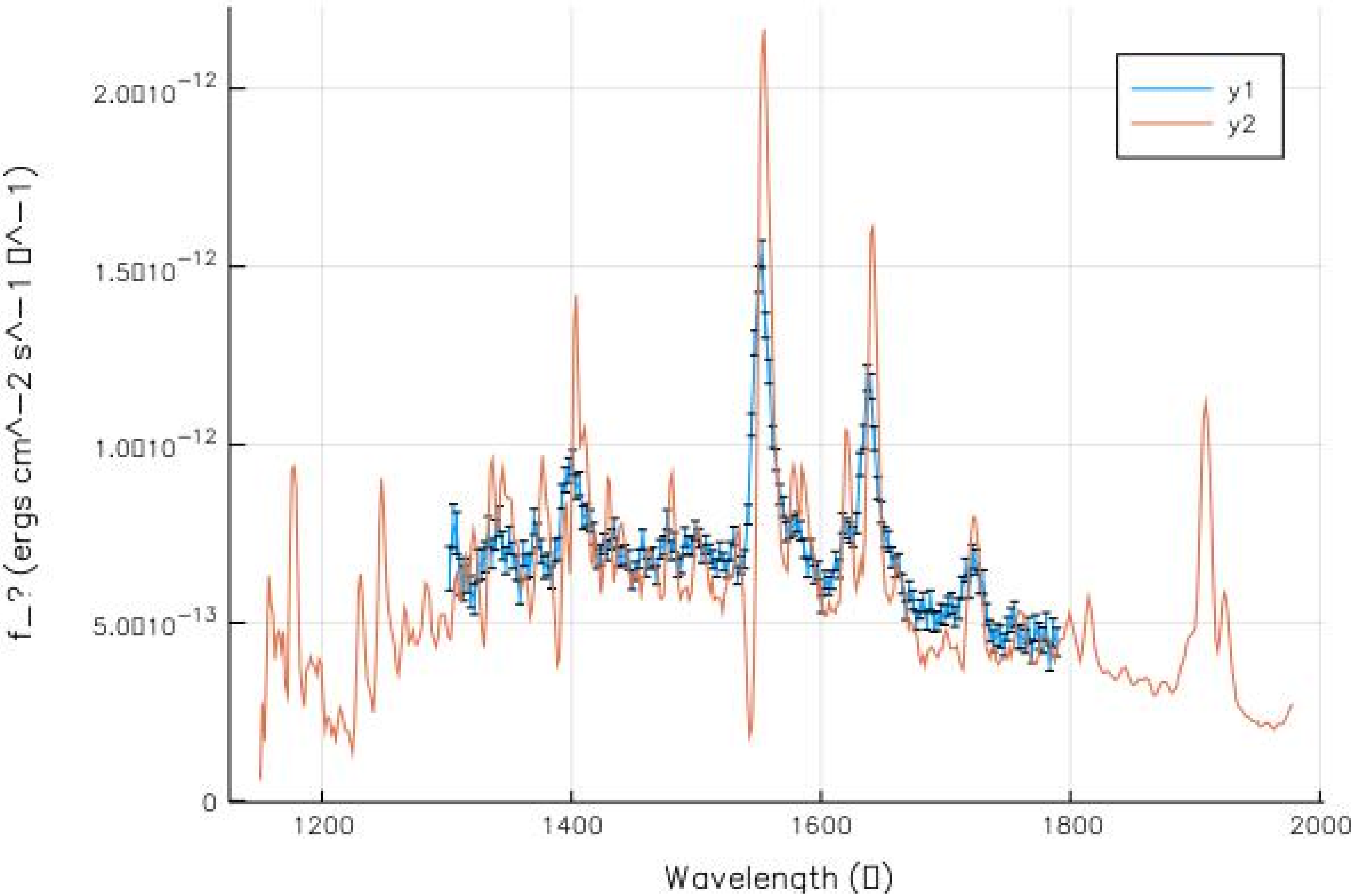
FWHM: 38.4A (NUV-grating), 16A(FUV-grating1), 14A(FUV-grating2)

FUV Gratings -1 order

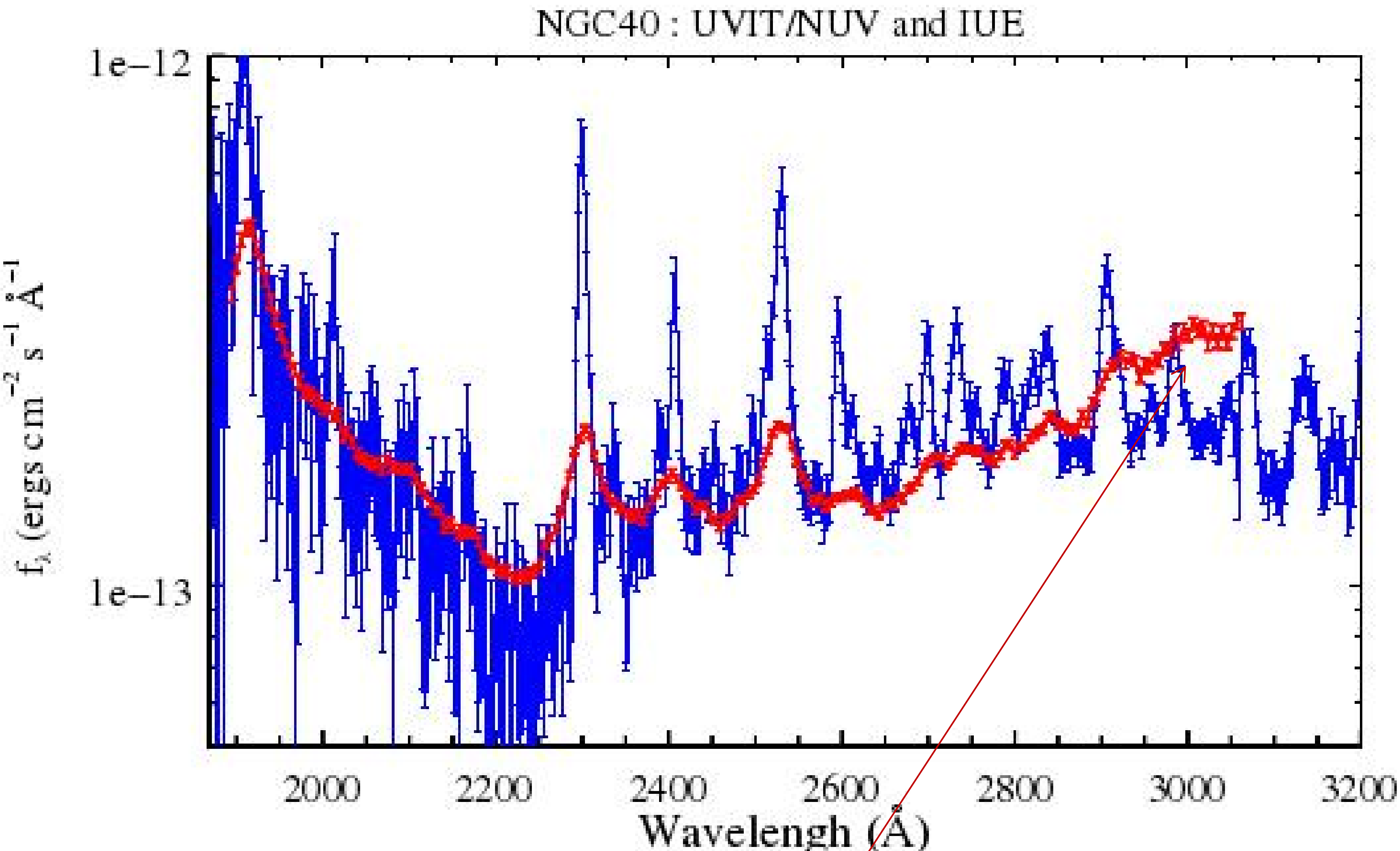




Flux Calibration : NGC40 (FUV-Grating2 & IUE/HST spectrum)

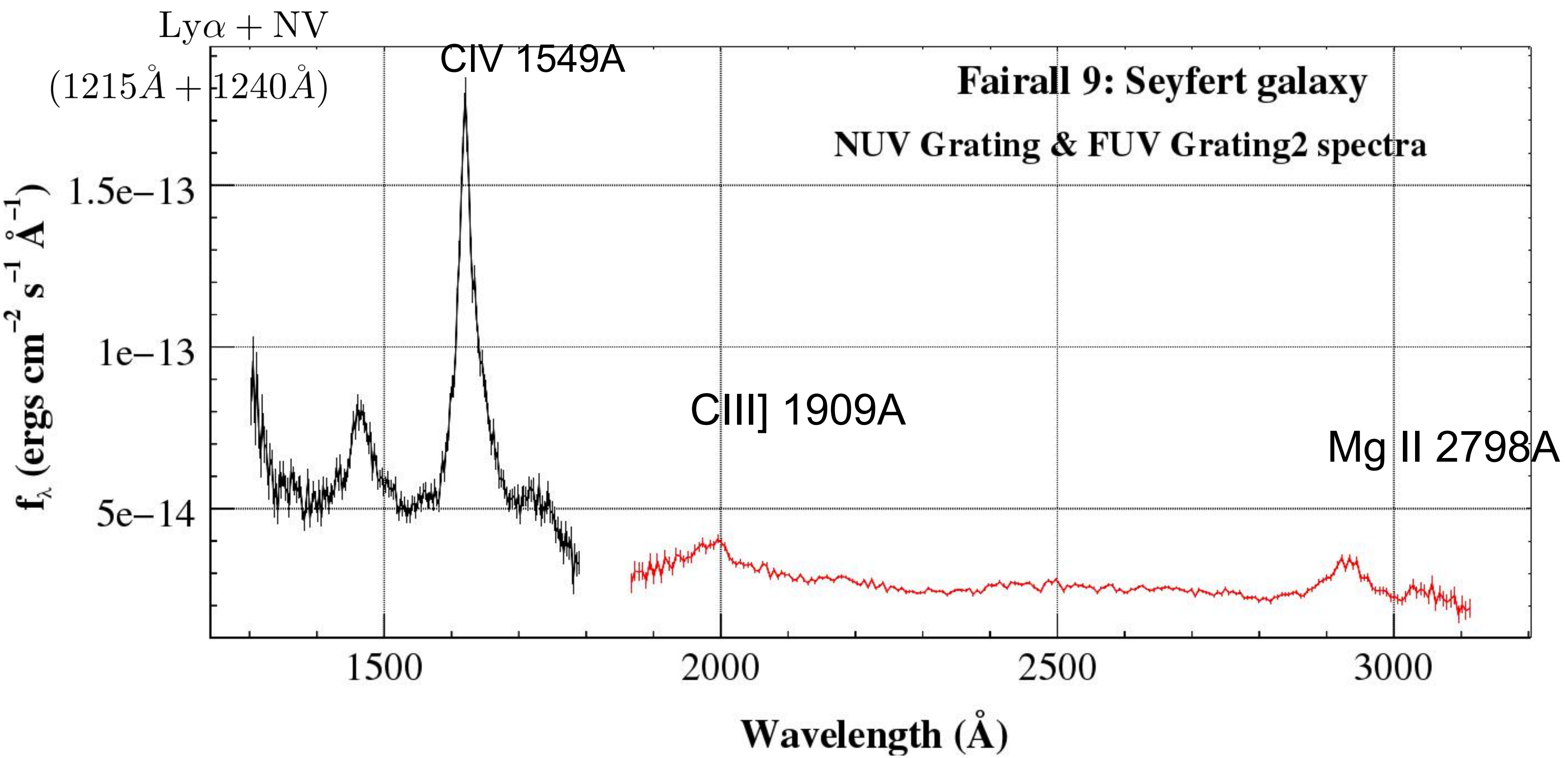


NGC40: UVIT/NUV and IUE



Fairall 9: UVIT Grating Spectra

A Bare Seyfert 1

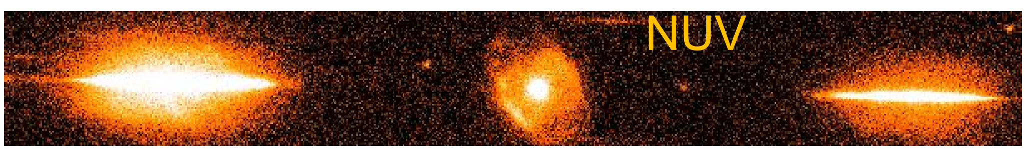


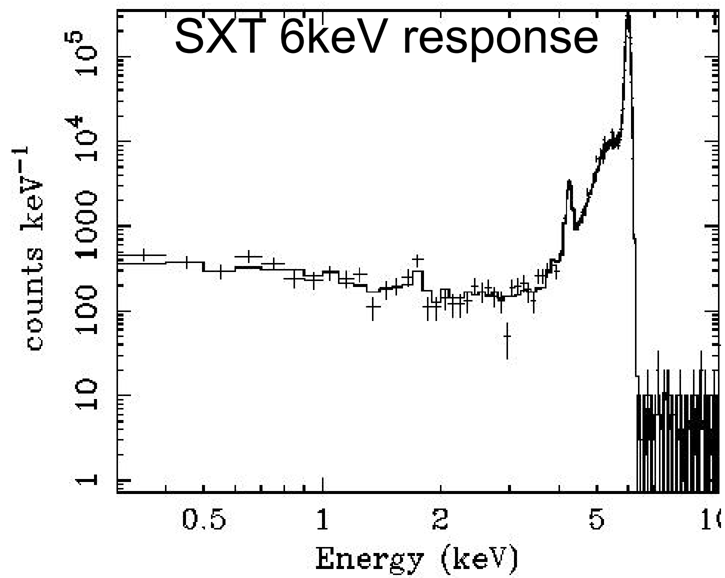
MW spectral analysis

X-ray Spectral Analysis

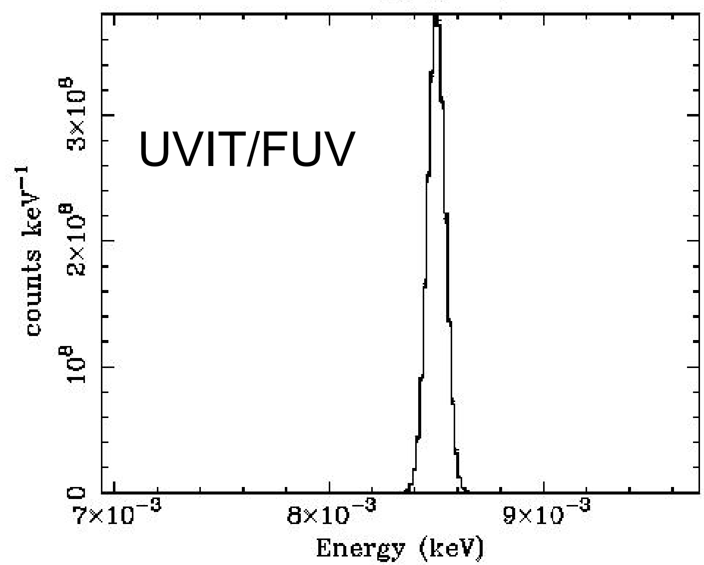
$$D(I) = T \int R(I, E) A(E) f(E) dE + B(I)$$

T : Exposure time
f(E): Source spectrum (in photons/cm2/s/keV)
B(I) : Background spectrum
R(I,E) : Probability that a photon of energy E will be detected in channel I.
A(E) : energy-dependent effective area of the telesco
and detector system (in cm2),

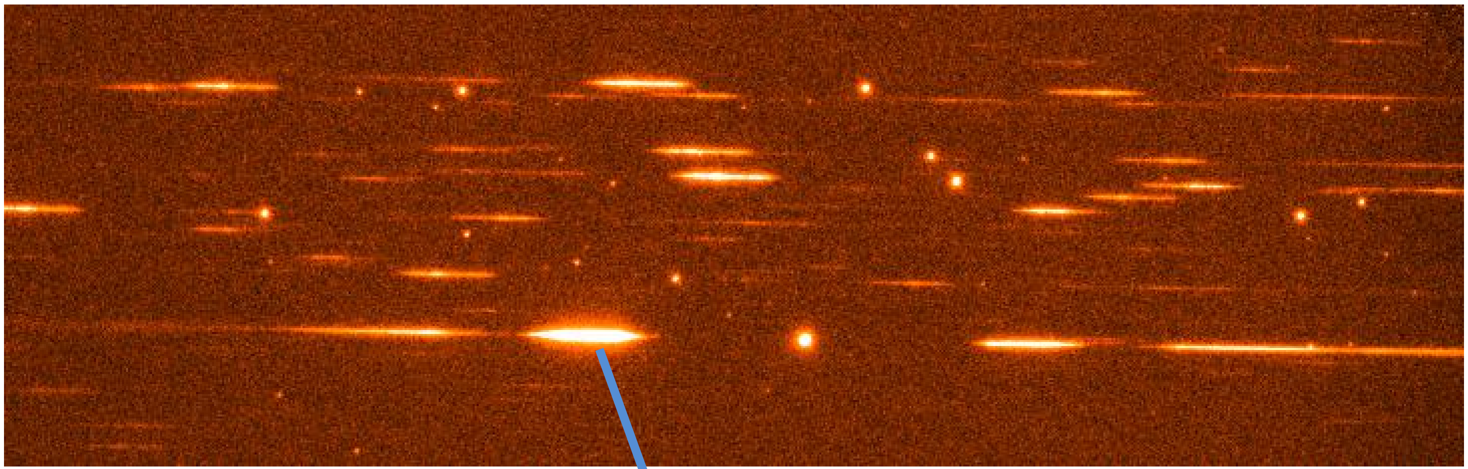


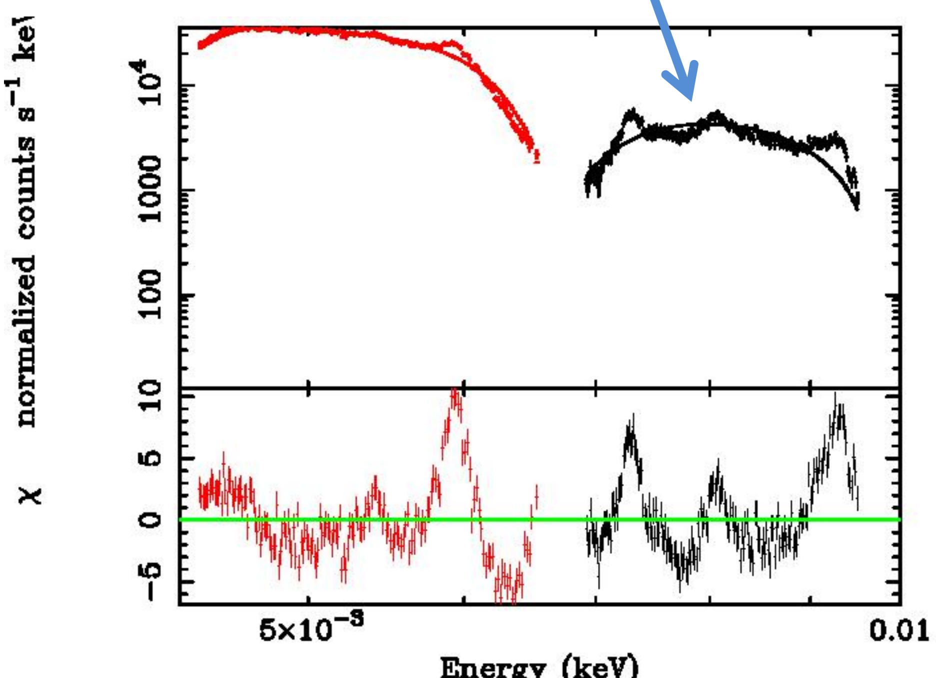


UVIT Grating response R(I,E)
(pixel no. along the dispersion direction => channel I)
UVIT gratings - Gaussian response to delta function
FWHM: 38.4A (NUV-grating), 16A(FUV-grating1), 14A(FUV-grating2)
A(E) : Effective area curves derived for the gratings



PG0804+761 : UVIT Grating spectra





NUV Grating
Exposure : 4ks

FUV Grating: 4ks

Broadband filter response

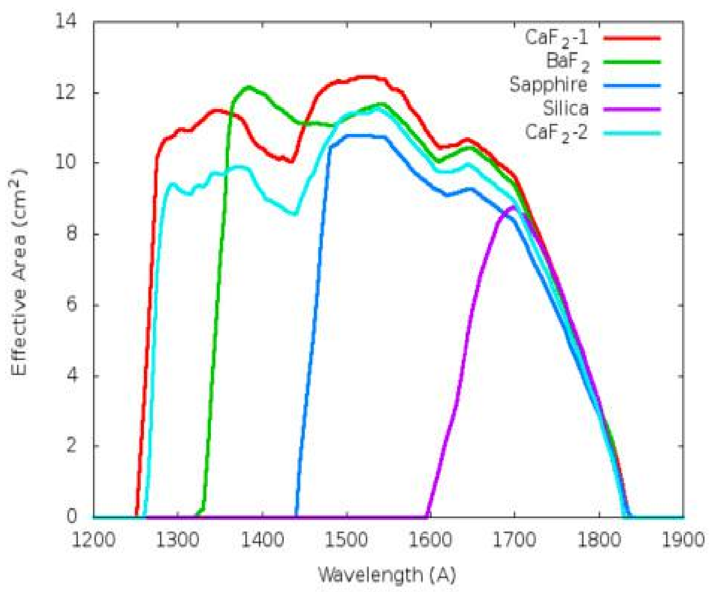
$$D(I) = T \int R(I, E)A(E)f(E)dE + B(I)$$

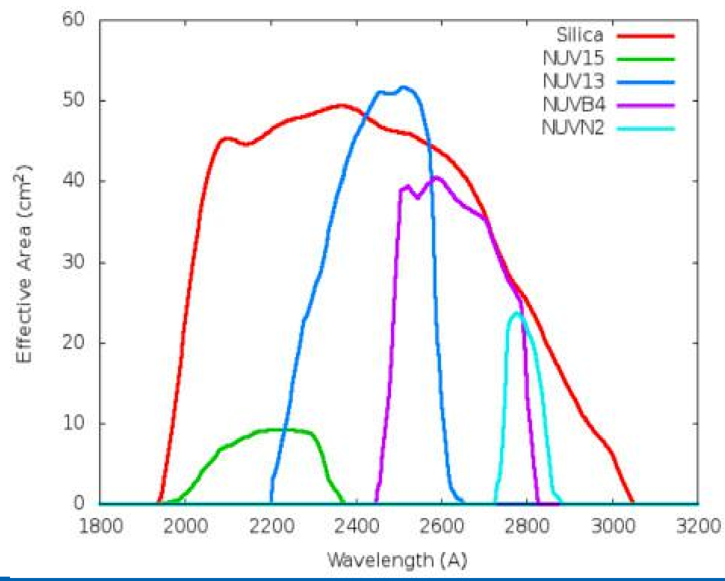
R(I,E) : Probability that a photon of energy E will be detected in the filter i.e. single channel.

A(E) : Effective area curves for broadband filters, adjusted to produce the same flux density as provided by the photometric calibration of Tandon et al.

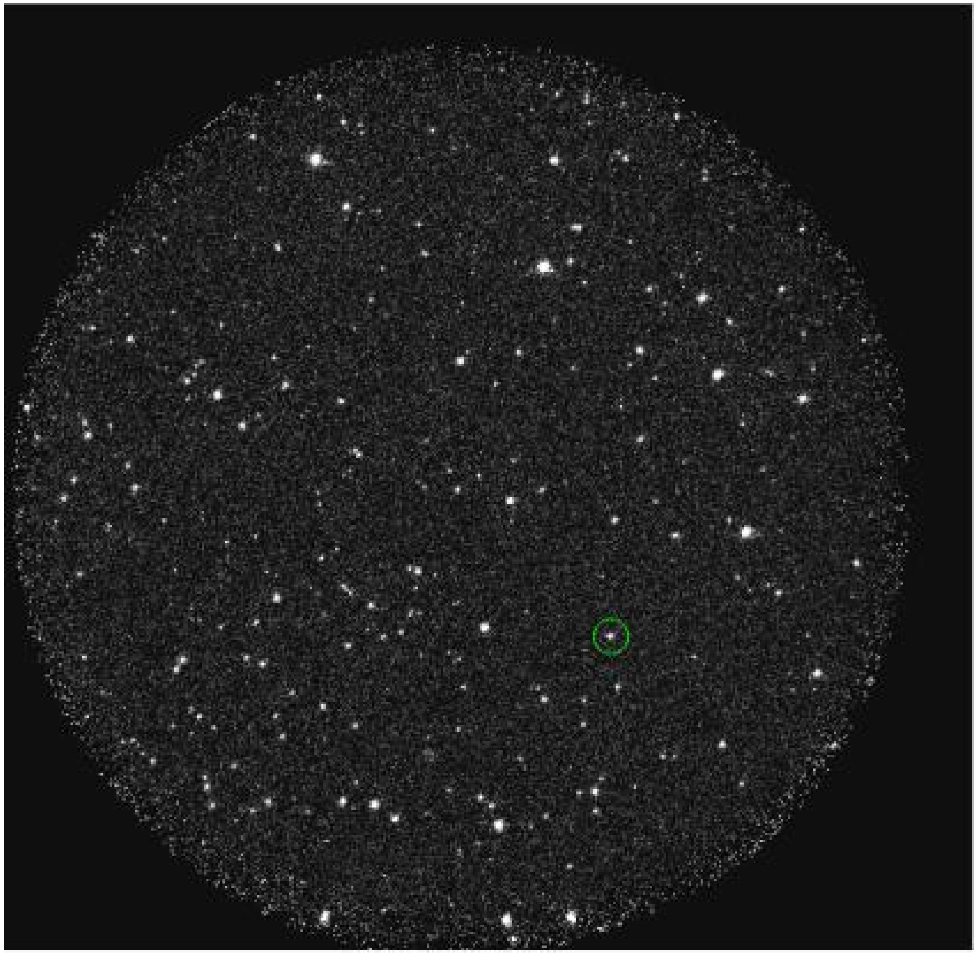
Counts in the filter require saturation correction.

C(I) = D(I) - B(I) i.e. net counts in filter I.

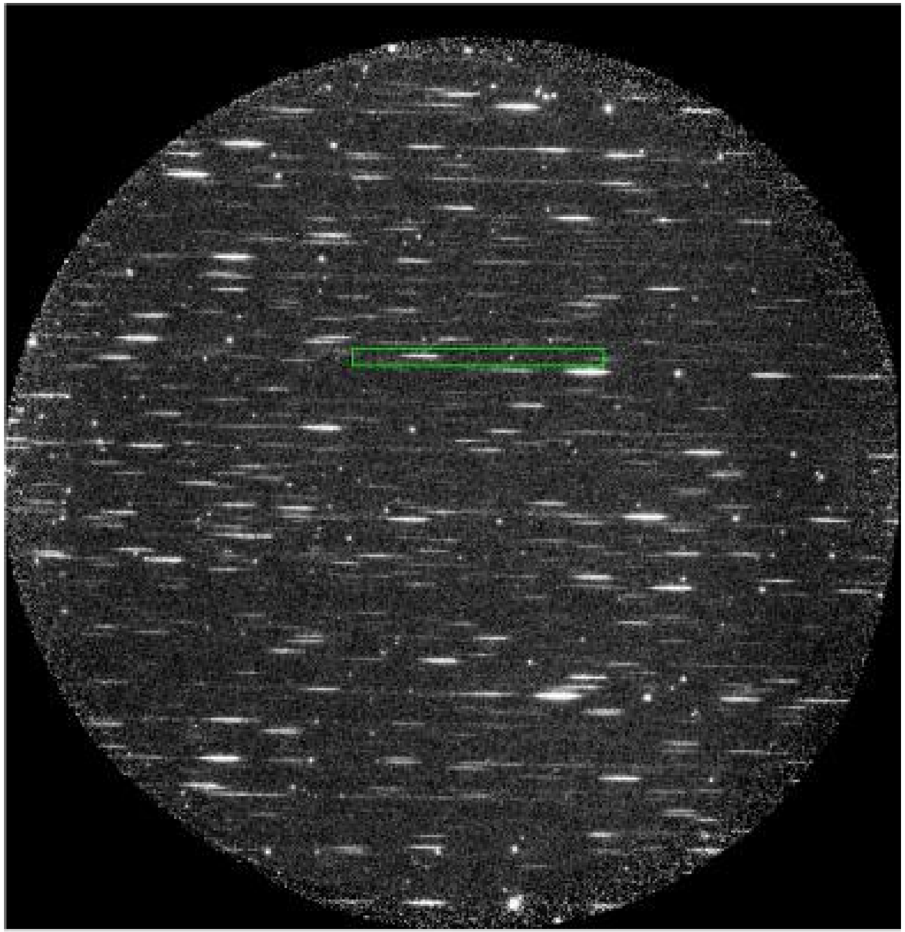




ASASSN-oh SupersSoft X-ray source : AstroSat/ ToO



FUV BaF2

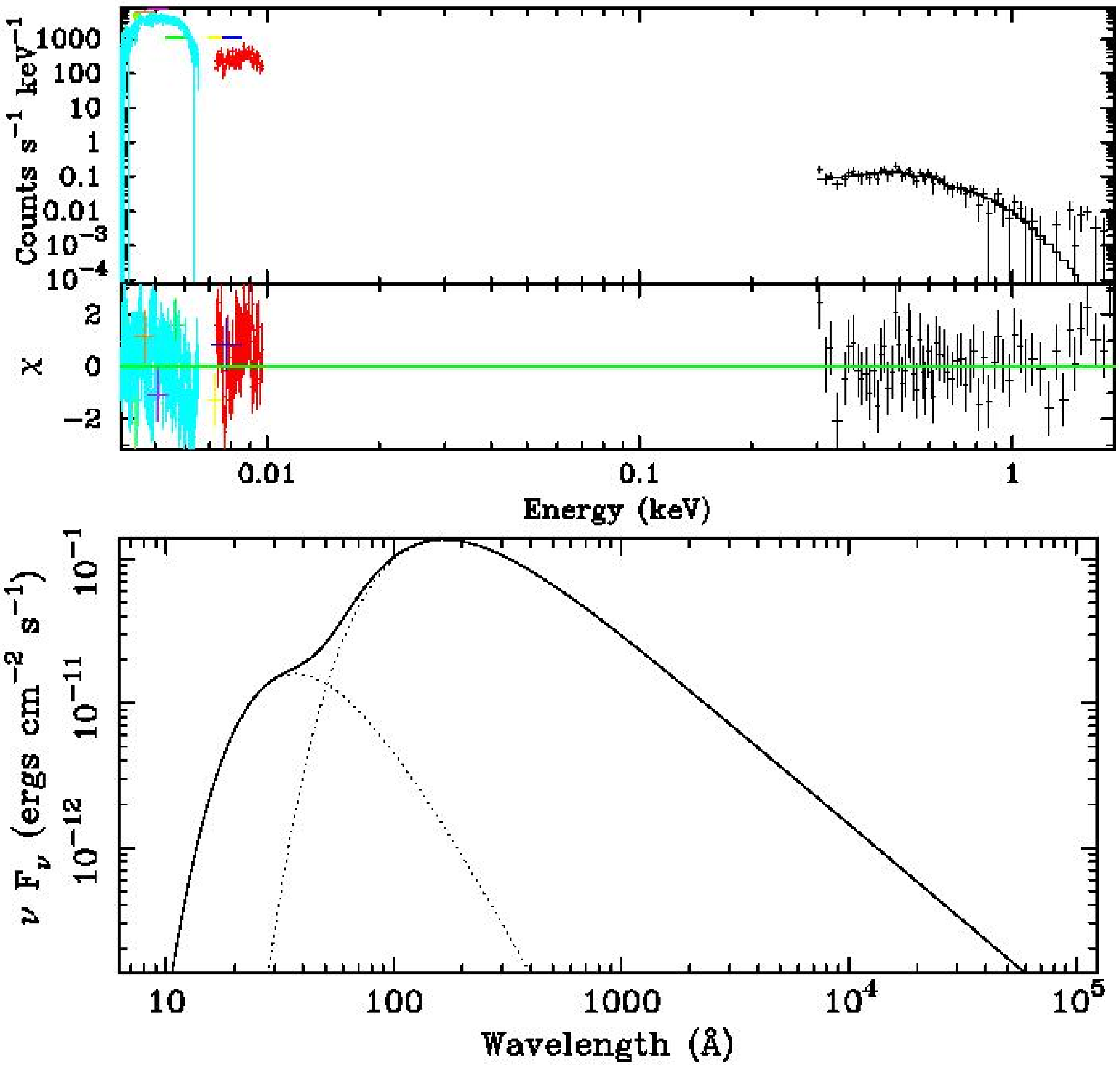


NUV grating

Accurate astrometry and/or comparison of the field with other observations important!

ASASSN-16oh : A transient supersoft X-ray source

AstroSat ToO observations



UVIT FUV/NUV gratings, filters + SXT data

Blackbody from from WD (kT~90eV),

accretion disk emission with kT_in ~30eV

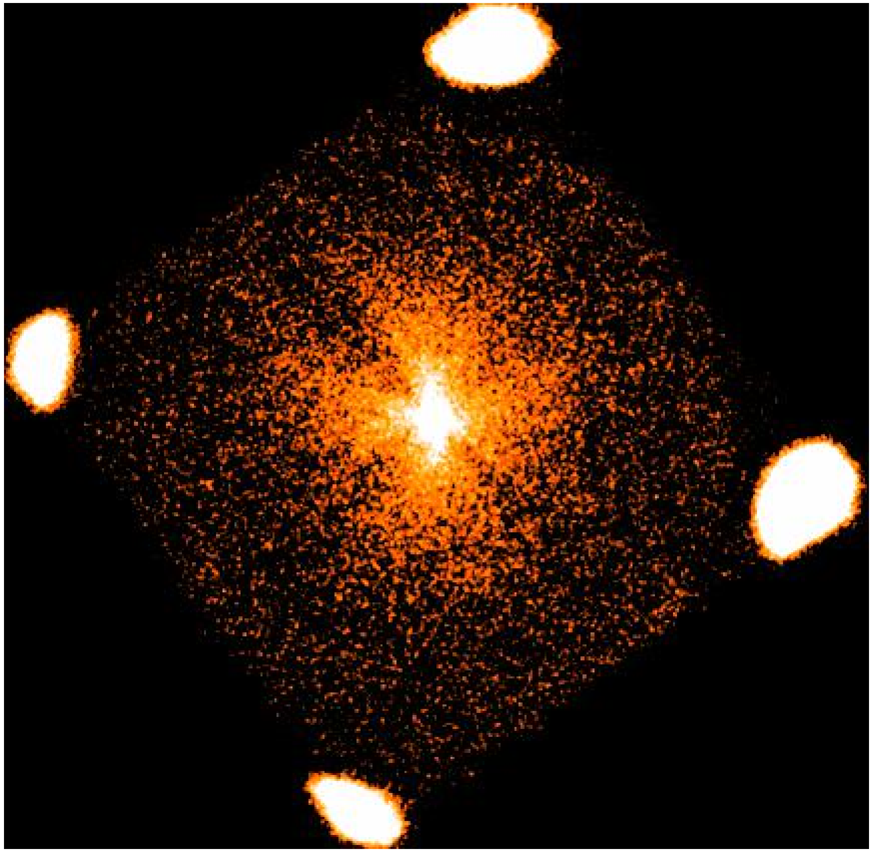
Possible discovery of an accretion disk in a supersoft X-ray source?

SXT Data

Issues with SXT data :

1. GTI related to currupted data packates (**solved**, **sxtpipeline 1.4b**)
2. Merging of events from different orbits/download streams (**solved**, **new Julia Tool**)
3. Bias/CTI characterization as a function of time (ongoing)
4. Low energy calibration (ongoing)
5. Current Instrument response acceptable with ~2% systematic error.

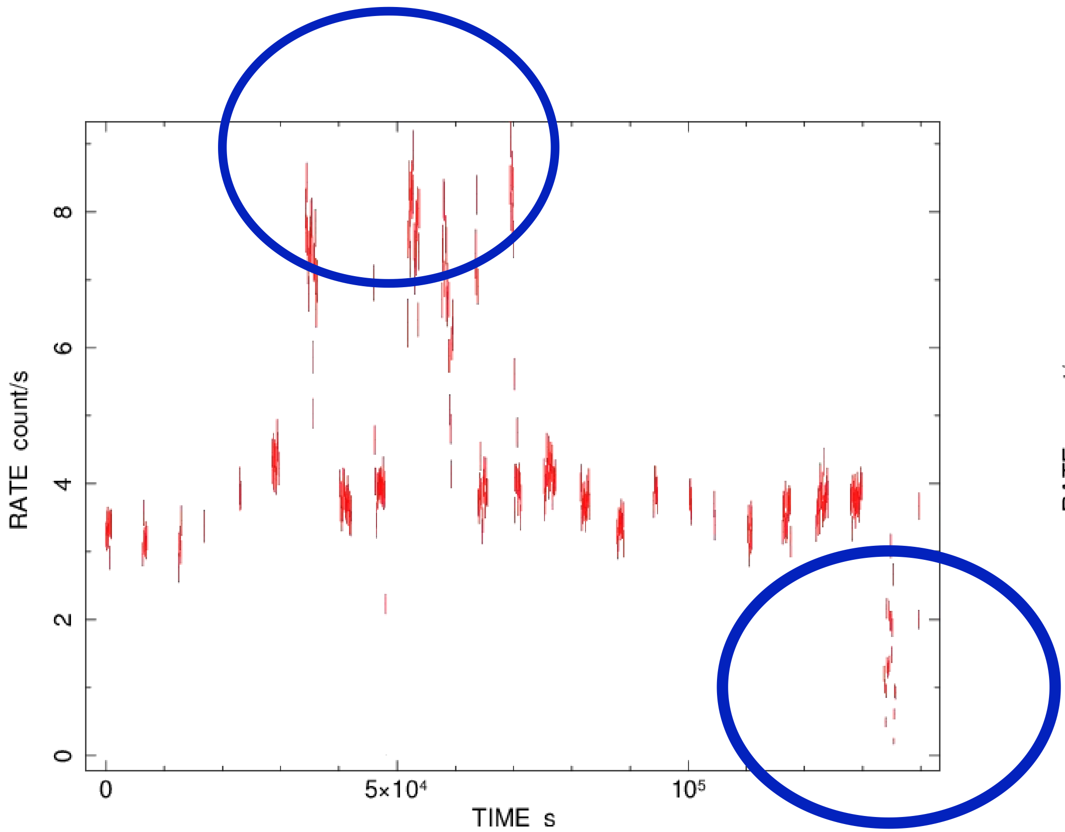
NGC4051 : SXT Image

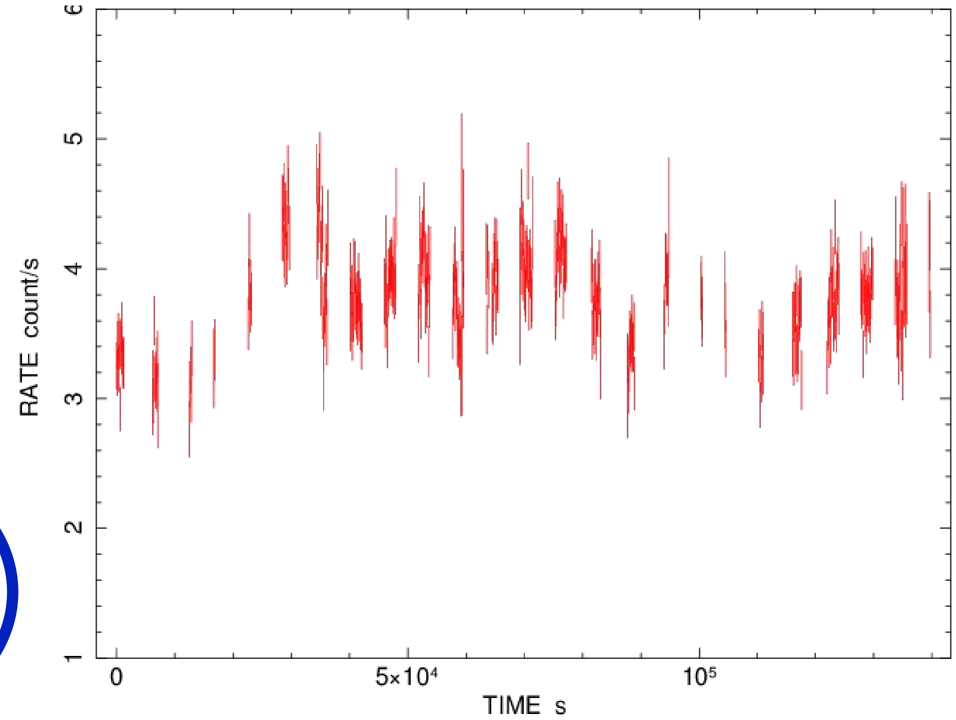


Use calibration source data to check the quality of SXT data.

SXT : Suitable for bright sources

Data Issues & Calibration





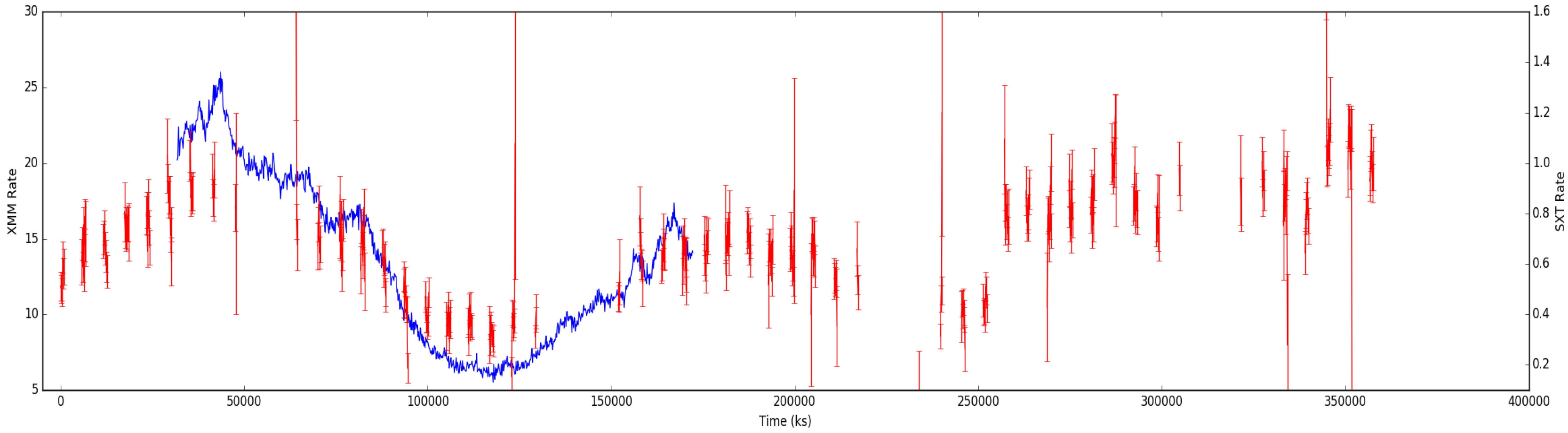
Double counting of events

(A new merger tool developed, **sxt_l2evtlist_merge.jl**)

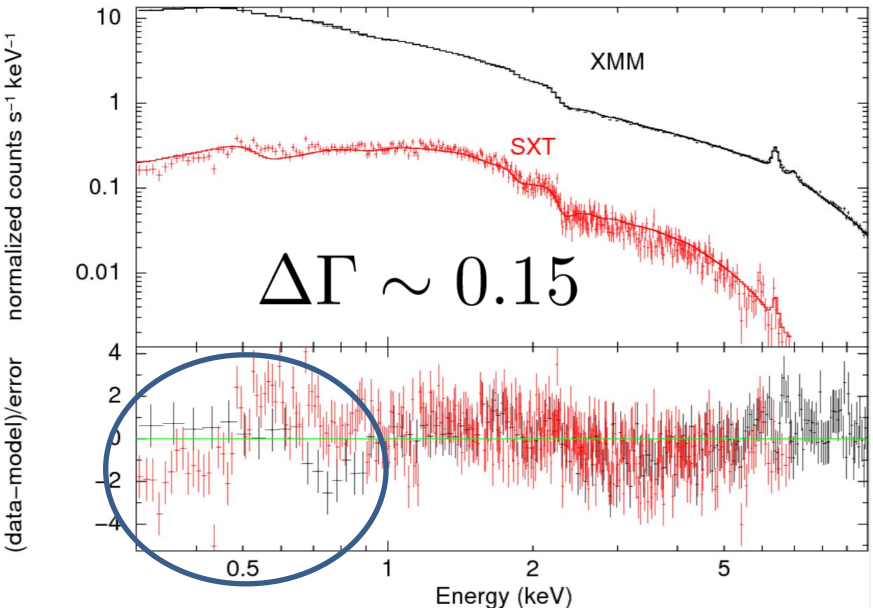
Noisy data packets (a new algorithm implemented, **sxtpipeline 1.4b**).

NGC4593 : XMM-Newton and AstroSat SXT

- Simultaneously observed on 2016-07-14 by SXT (446.7 ks) and XMM-Newton EPIC-pn (140.5 ks).



Refinement in spectral response required (ongoing).



Credit: Pranoti / GCD / Pramod

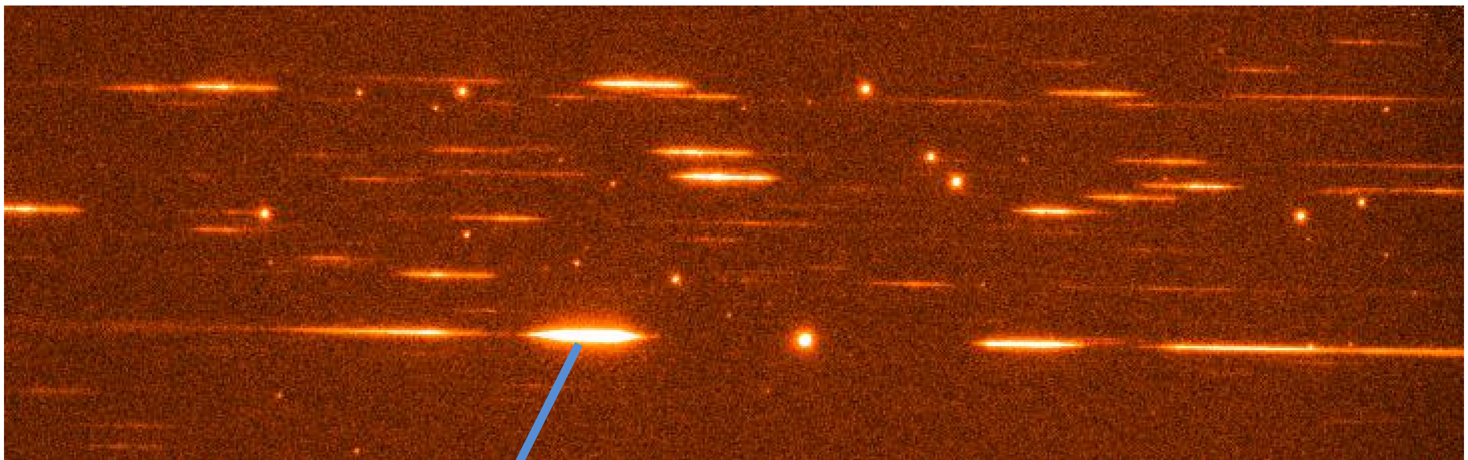
(RQ)AGN Science with AstroSat

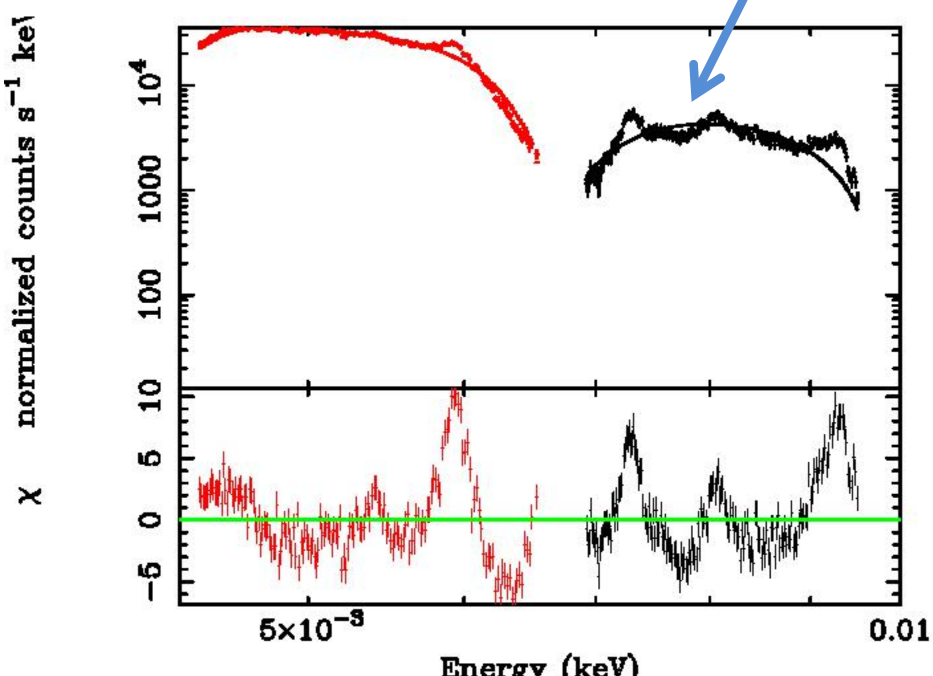
- UV-X-ray Spectral Energy Distribution, measure L_{bol} / L_{Edd}
- Test Optically thick thermal Comptonisation model, and deficit of UV emission
- Test standard accretion disk model of SS.
- Origin of UV/Optical variability - Intrinsic Vs X-ray reprocessing?
- Seed photons for thermal Comptonisation? Testing thermal Comptonsation model - cooling of hot corona by seed UV/optical UV photons?
- Disk/Corona geometry? Disk truncation in low luminosity AGN ? inner disk emission from massive, high redshift AGN - BH spin measurement?
- Absorption-induced X-ray variability ?

UV-X-ray SED and L_{bol}/L_{Edd}

PG0804+761 : AstroSat view (GT)

A bright RQ quasar (V=14.7 mag) at z=0.1, $M_{BH} = 5.4 \times 10^8 M_\odot$





NUV Grating
Exposure : 4ks

FUV Grating: 4ks

SXT : 15ks

LAXPC: 25ks

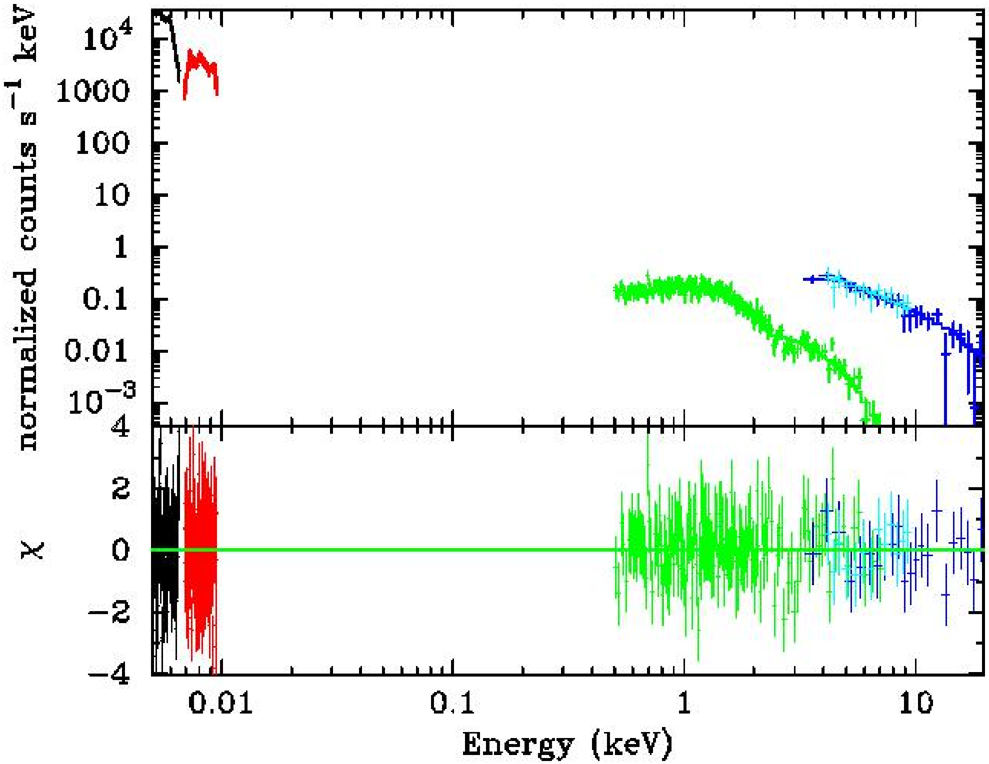
PG0804+761: UV-X-ray SED and L_{bol} / L_{Edd}

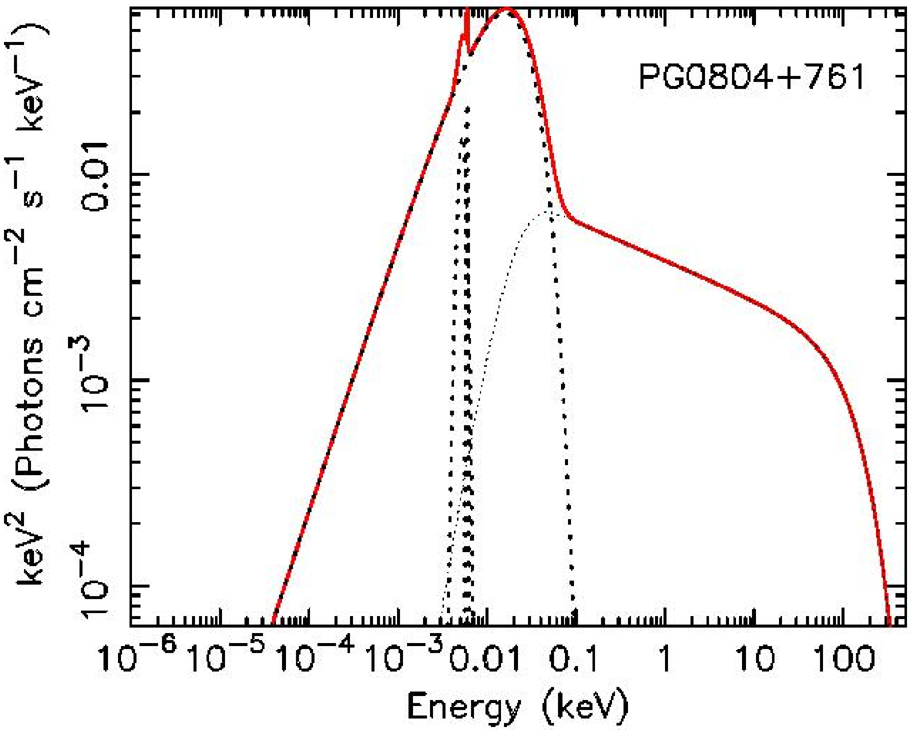
Model : accretion disk + Thermal Comptonization + UV emission lines modified by UV reddening and X-ray absorption in our Galaxy

$$kT_{in} \sim 6eV, \Gamma \sim 2.2, kT_e = 100keV(fixed)$$

$$f(1\mu m - 100keV) \sim 2.6 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}$$

Pranoti/GCD+, in prep



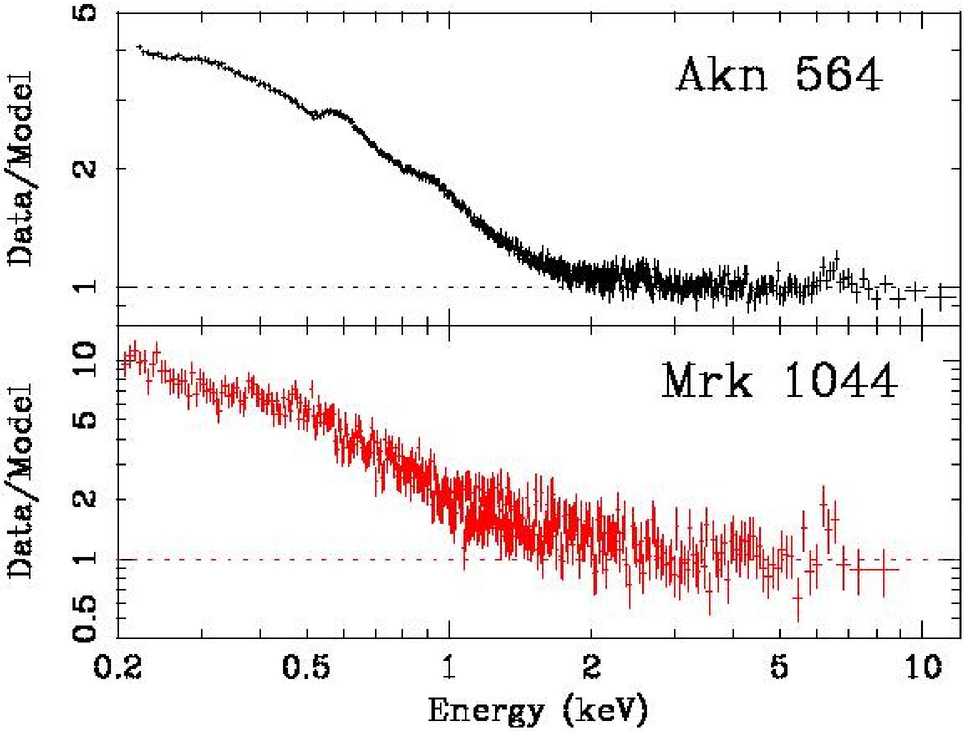


$L_{bol} \sim 6.2 \times 10^{45}$ ergs s^{-1} $\quad M_{BH} = 5.4 \times 10^8 M_\odot \quad \frac{L_{bol}}{L_{Edd}} \sim 0.1$

Soft X-ray Excess Emission

- Soft X-ray excess emission (discovered by Singh et al. 1985 & Arnaud et al. 1985)
- Single or multiple BB kT~100-300eV
- Optically thick emission from an accretion disk – NO
- Different Spectral models degenerate.
- Optically thick Th. Comptonization (Magdziarz et al. 1998, Gierlin´ski & Done (2004), Dewangan et al. 2007)
- Blurred reflection model (e.g., Fabian et al. 2002)

Dewangan et al. (2007)
XMM-Newton

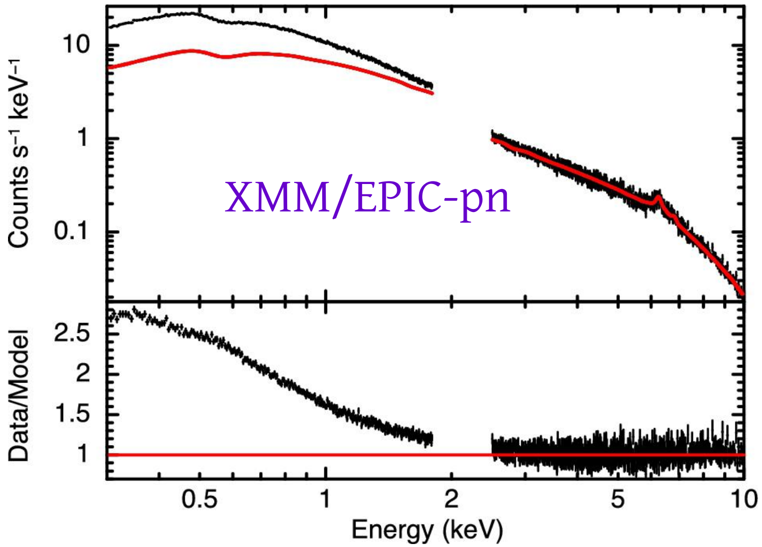


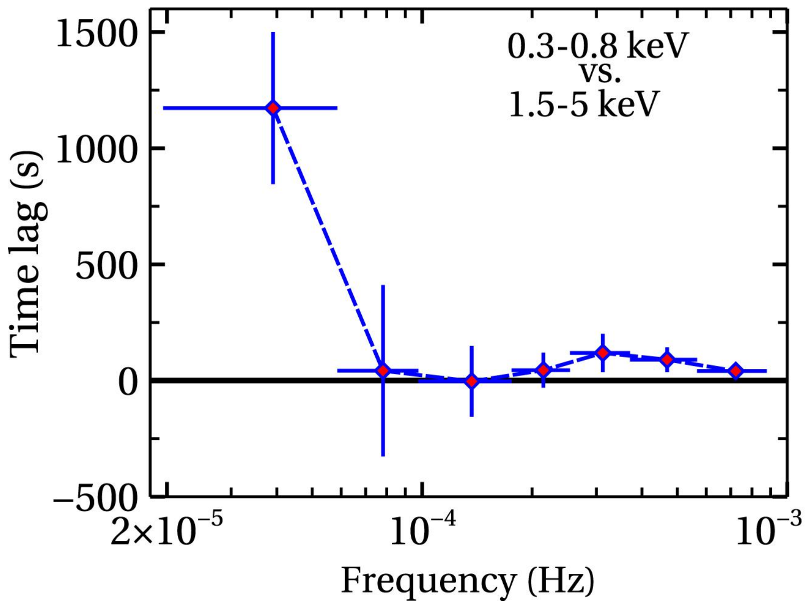
Origin of the Soft X-ray Excess

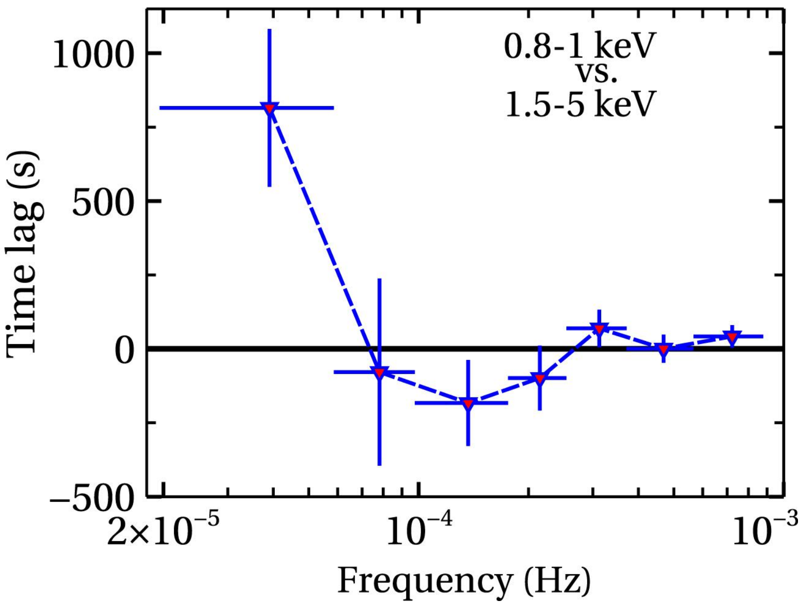
- Strong soft excess without strong broad iron line
- .Soft band leading hard X-ray bands in many AGN

=> unlilkely to be blurred reflection

Mallick, GCD+2017



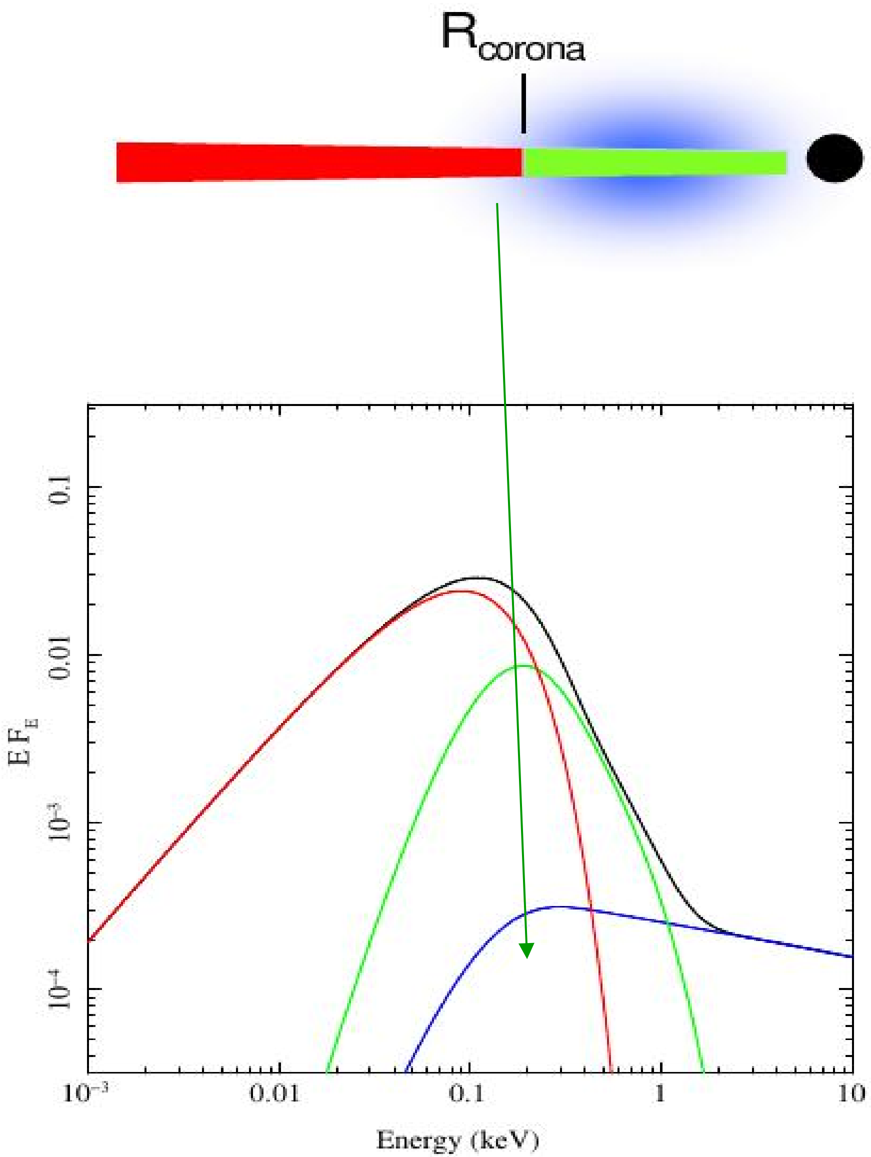




Soft X-ray Excess

Intrinsic Comptonized disk model

Done et al. (2012)



Standard disk emission only down to R_{corona}

Soft X-ray excess
Optically-thick, warm (kT_e ~ 0.1-1keV) corona in the inner regions below R_{corona}

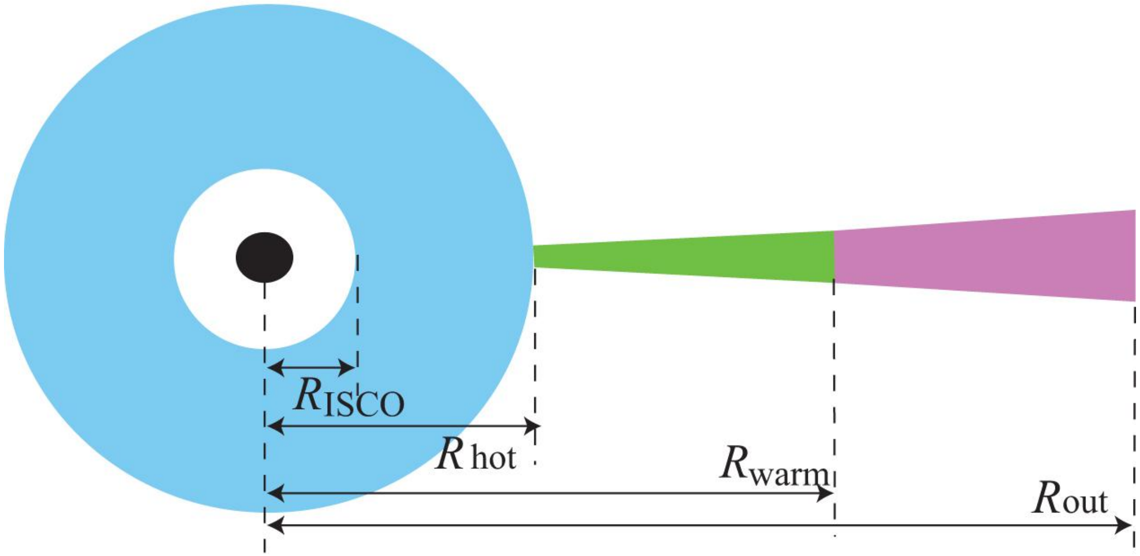
High energy X-ray powerlaw
Optically thin, hot (kT_e ~ 100keV) corona

Origin of both warm and hot corona not well understood.

Soft X-ray Excess & UV emission

Kubota & Done (2018) model

(a)The geometry for three emission regeons



Improved version of Comptonized disk model of Done et al. 2012

Completely radially stratified flow.

Soft X-ray excess - thermal Comptonisation of mid plane disk photons in the inner accretion disk

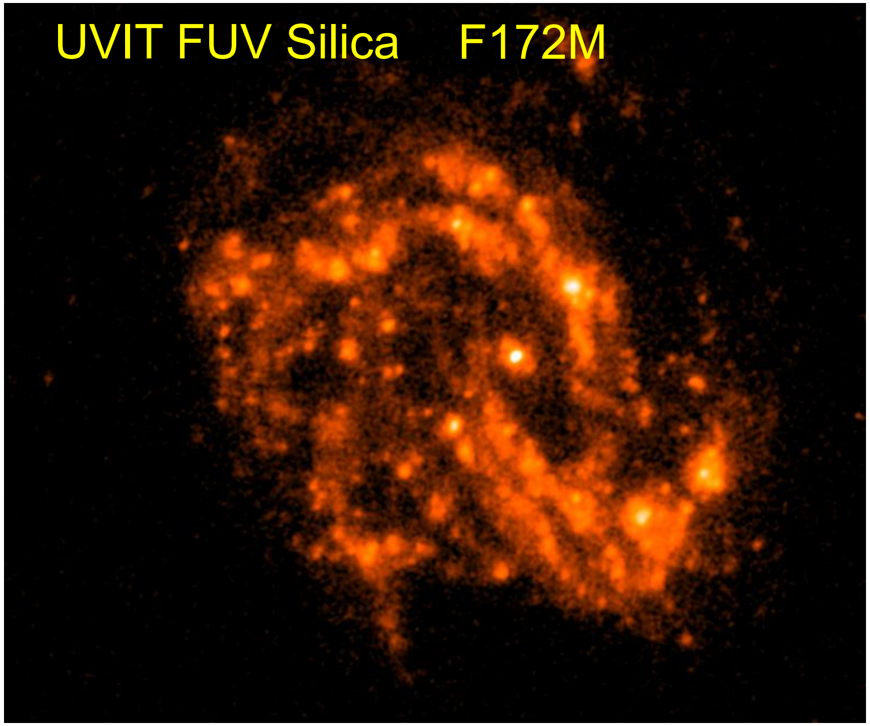
Deficit of UV emission below ~2000A from the disk

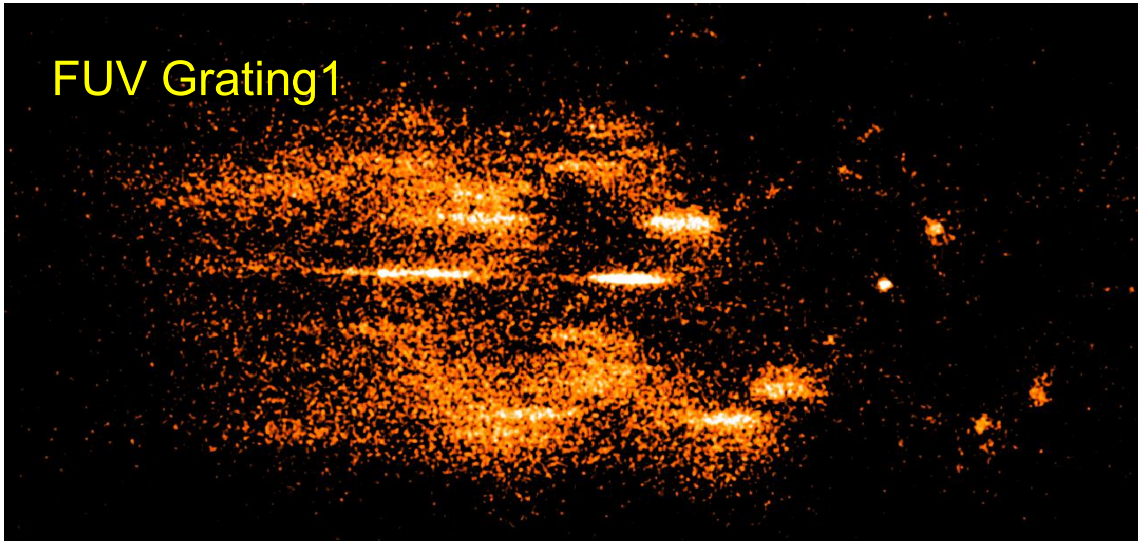
Use UVIT grating and SXT data

AstroSat observations of NGC4051

A nearby narrow-line Seyfert 1 galaxy

$$M_{BH} = 1.34 \times 10^6 M_\odot$$

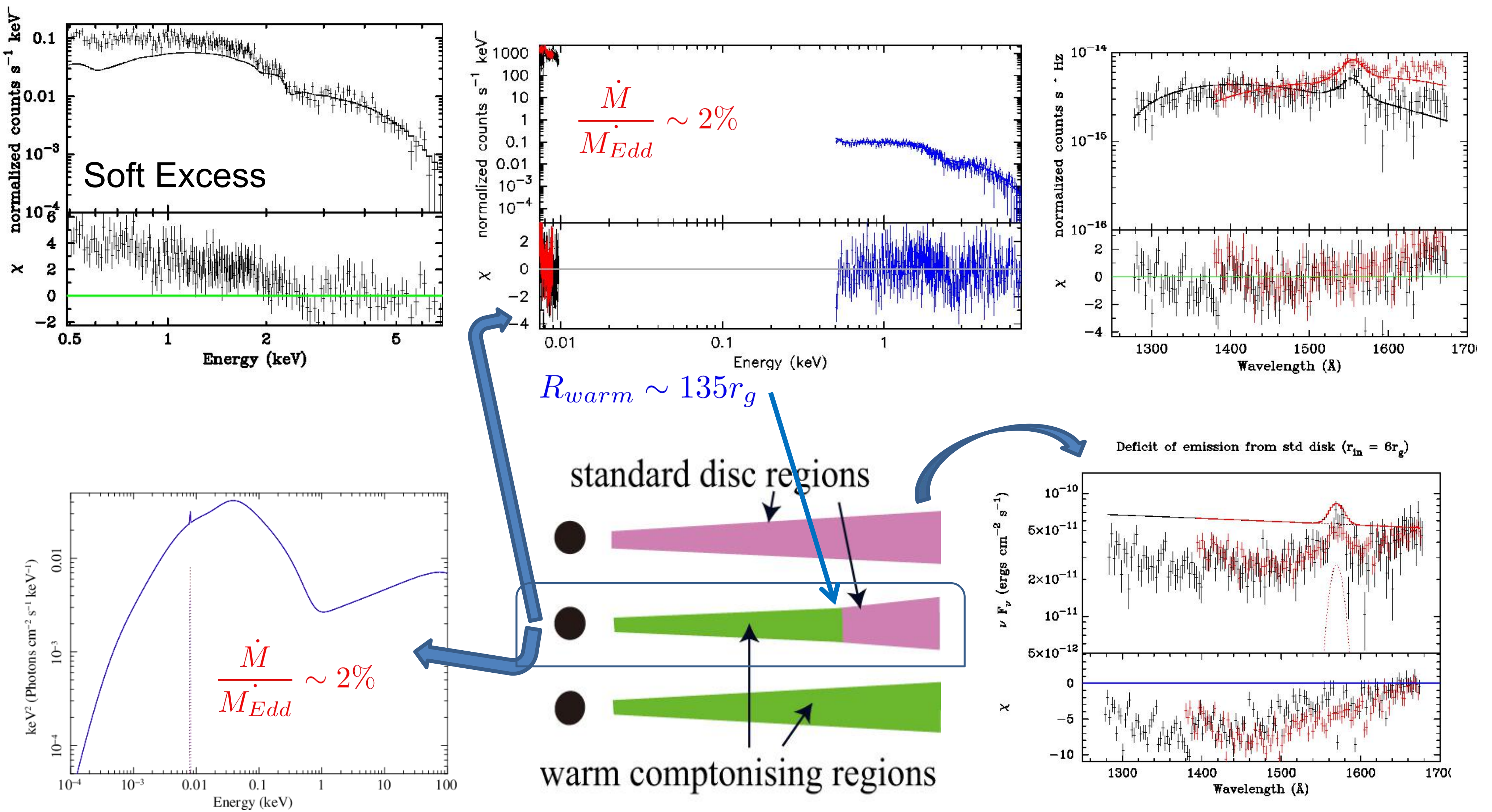




$$d = 13.84\mathrm{Mpc}$$

$$N_H = 1.15 \times 10^{20}\mathrm{cm}^{-2}$$

NGC4051: Soft X-ray Excess & UV emission



Deficit of UV emission compared to SS disk

Departure from Standard SS accretion disk

MW Astronomy with AstroSat

UV/X-ray Timing

UVIT : FUV/NUV channels operate in Photon counting mode (time resolution: ~2ms)

SXT : Photon counting mode (time resolution: 2.4s full frame), Window mode (0.278s)

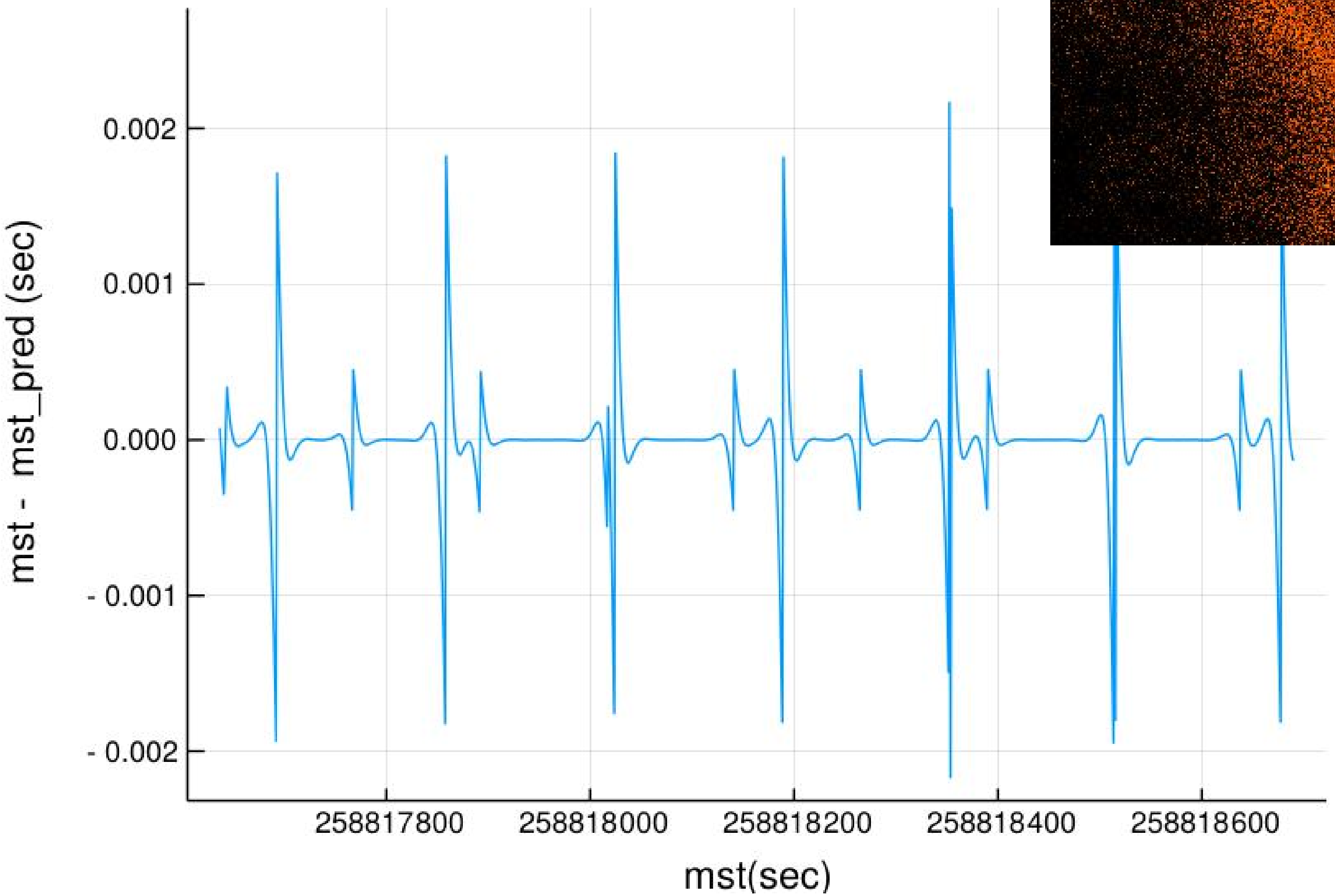
LAXPC : Event mode (time resolution: 10 micro-sec)

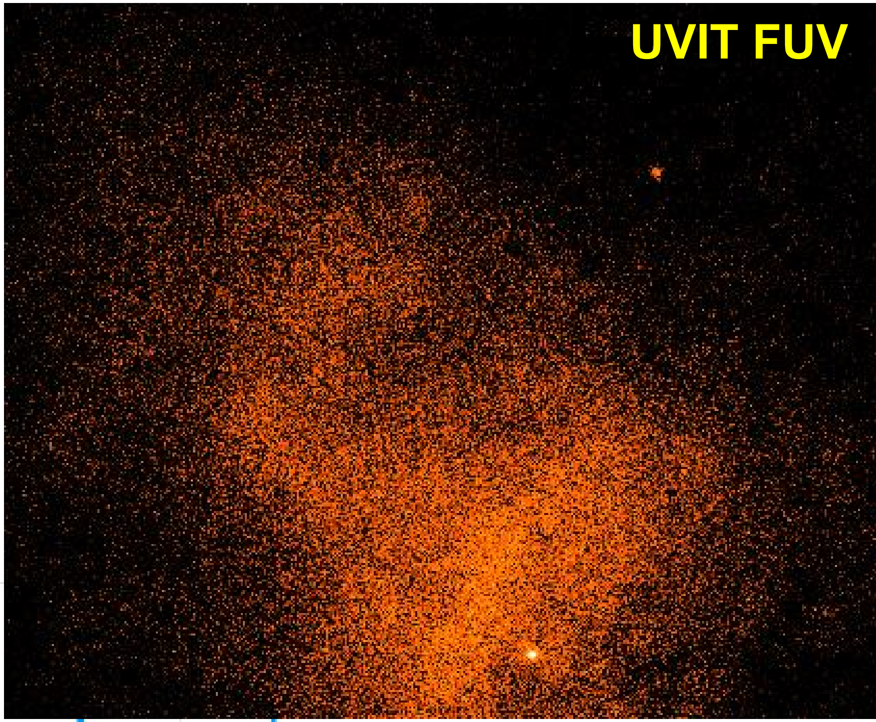
CZTI : Event mode (time resolution: 20 micro-sec_

LAXPC, CZTI and SXT timing well calibrated as well as cross-calibrated.

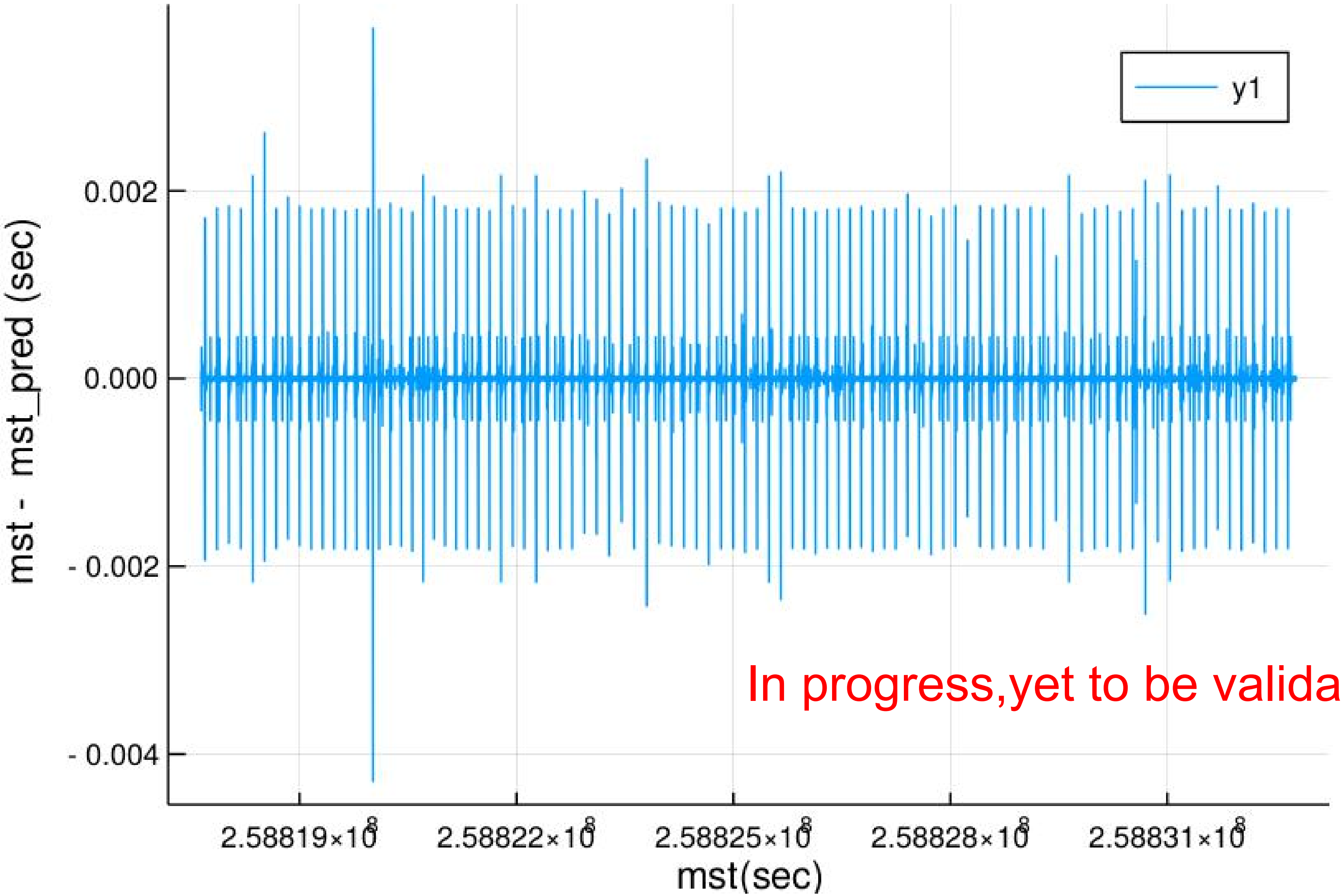
UVIT fast timing calibration has been in progress!
Fine for slower timing studies down to 10s or so.

UVIT Fast time calibration: Crab data





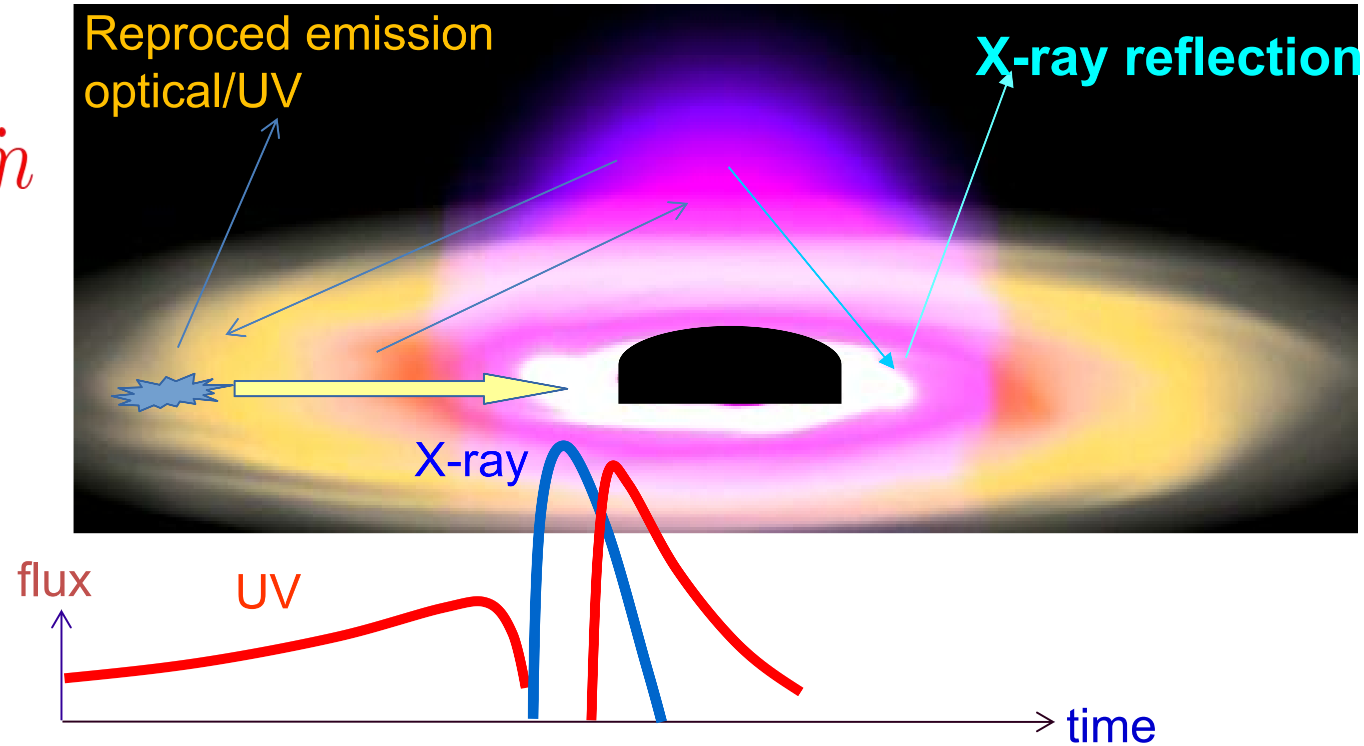
UVIT Time calibration : Crab one orbit data



In progress,yet to be validated.

UV/X-ray connection in Seyferts

- Propagation of $\dot{m}$ fluctuations



- Reprocessing of X-rays into optical/UV

Optical/UV lag behind X-rays with light crossing time

Time lag Vs wavelengh => Test standard disk model

- Compton upscattering of optical/UV photons into X-rays

Optical/UV lead X-rays

Seed photons for thermal Comptonisation

Accretion disk: UV/Opt lag spectrum

Energy balance in an annulus of acc. disk

$$4\pi R\, dR\sigma T^4 = \left(\frac{GM}{R} - \frac{GM}{R+dR}\right)\dot{m} \qquad => R^3 = \frac{GM\dot{m}}{4\pi\sigma T^4}$$

with

$$\dot{m}_E = \frac{L_{bol}}{L_{Edd}}, L_{bol} = \eta\dot{m}c^2, L_{Edd} = \frac{4\pi GMm_pc}{\sigma_T}, kT = hc/\lambda$$

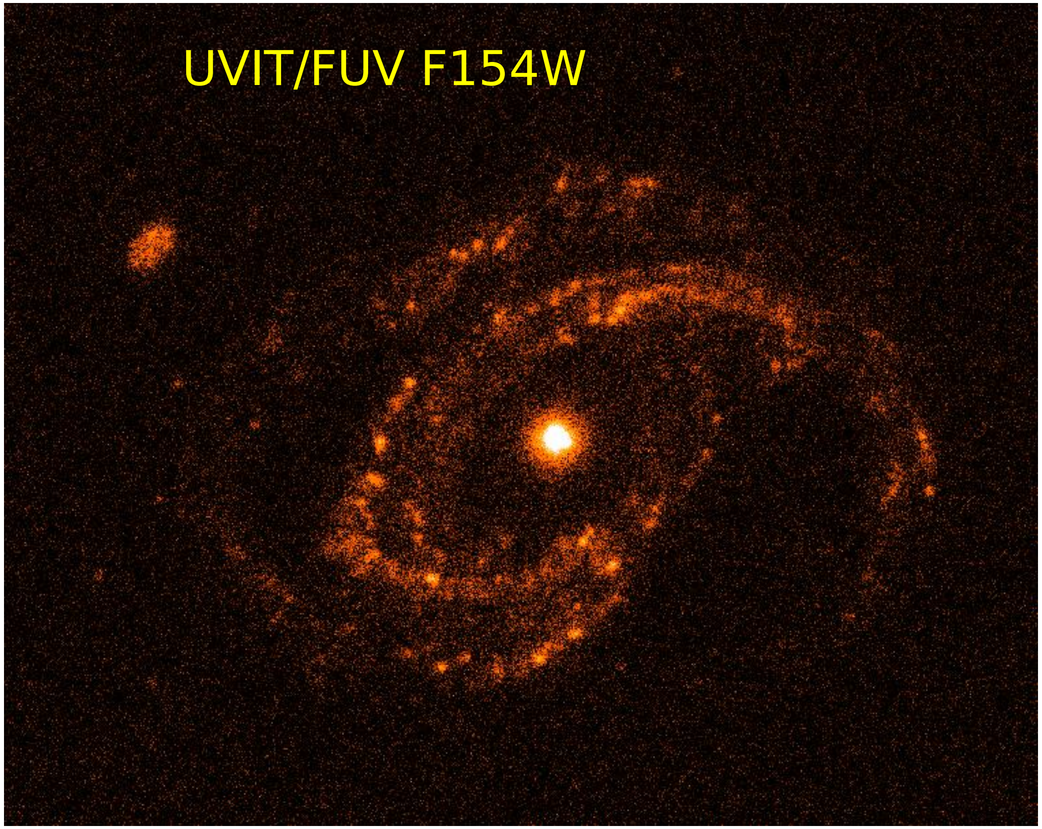
Time lag - wavelengh relation

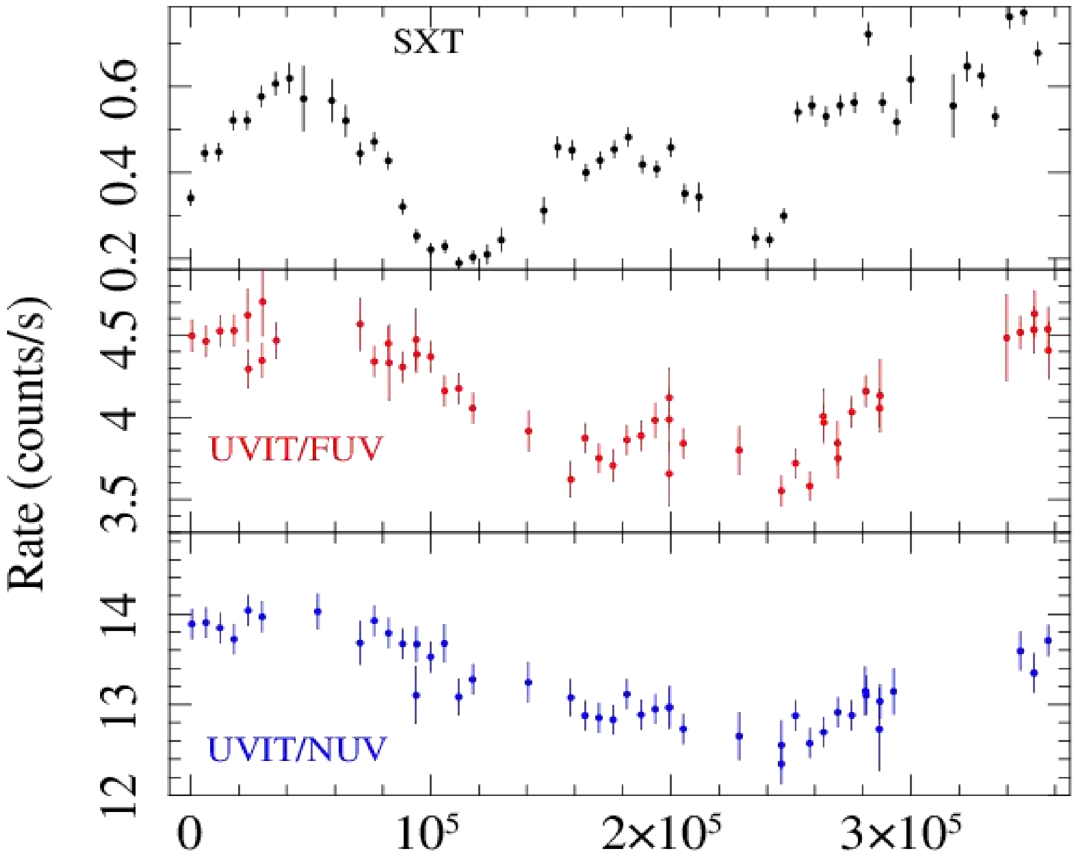
$$\tau = R/c = \left(\frac{G^2 m_p k^4}{\sigma_T \sigma c^2 h^4}\right)^{1/3} \eta^{-1/3} M^{2/3} \dot{m}_E{}^{1/3} \lambda^{4/3}$$

(Cackett et al. 2007, McHardy et al. 2015)

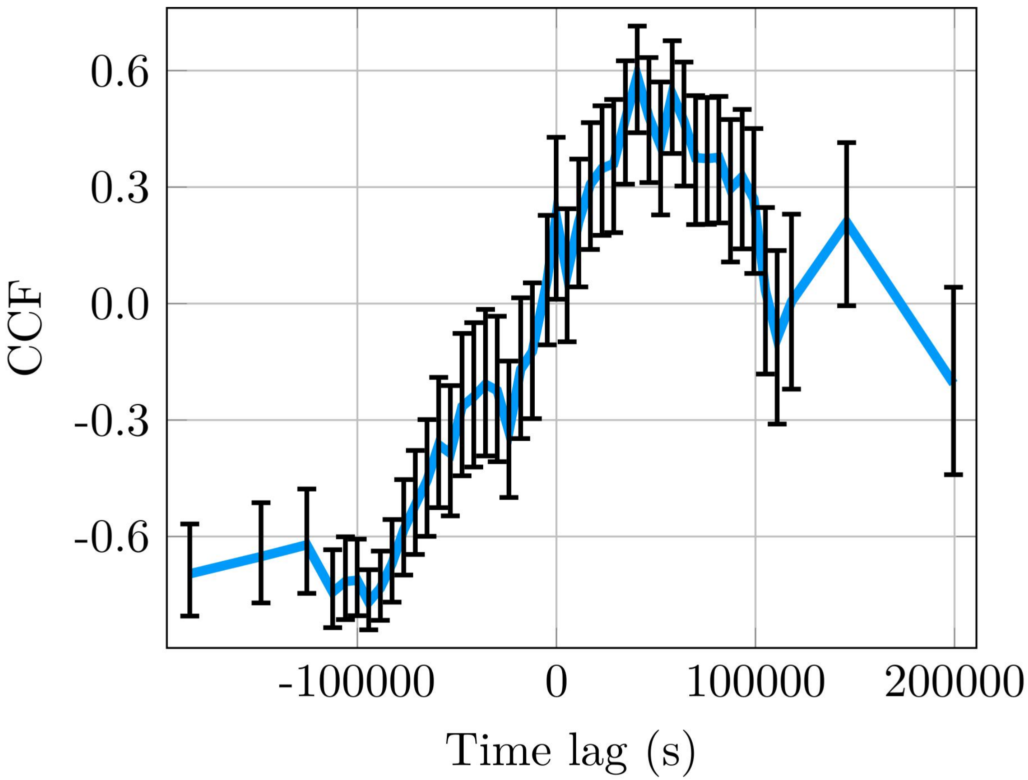
NGC4593 : A Seyfert 1 galaxy

4 day long AstroSat observation (CZTI GT)



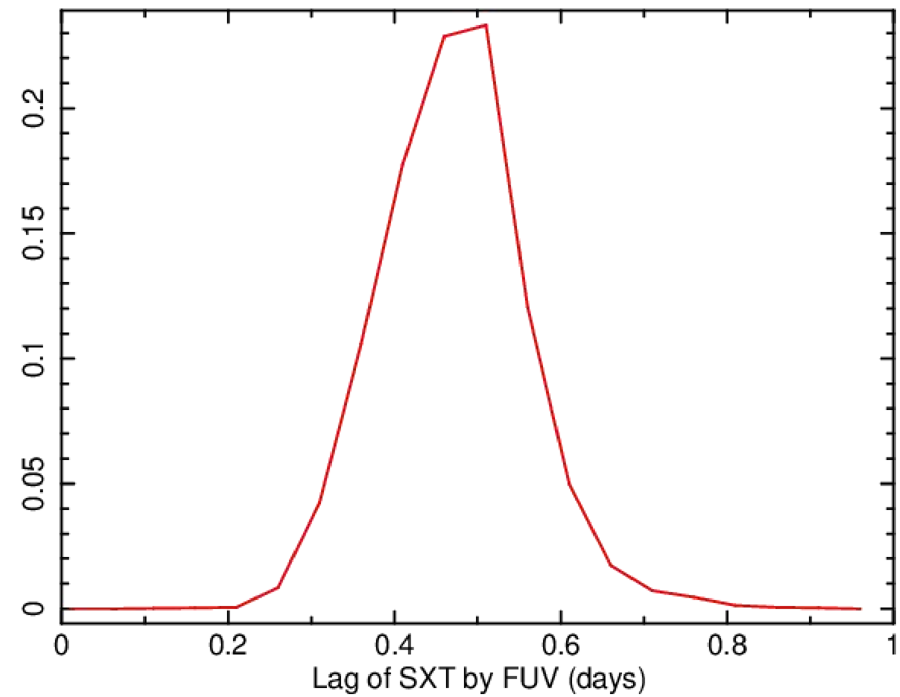


NGC4593: UV/X-ray variability



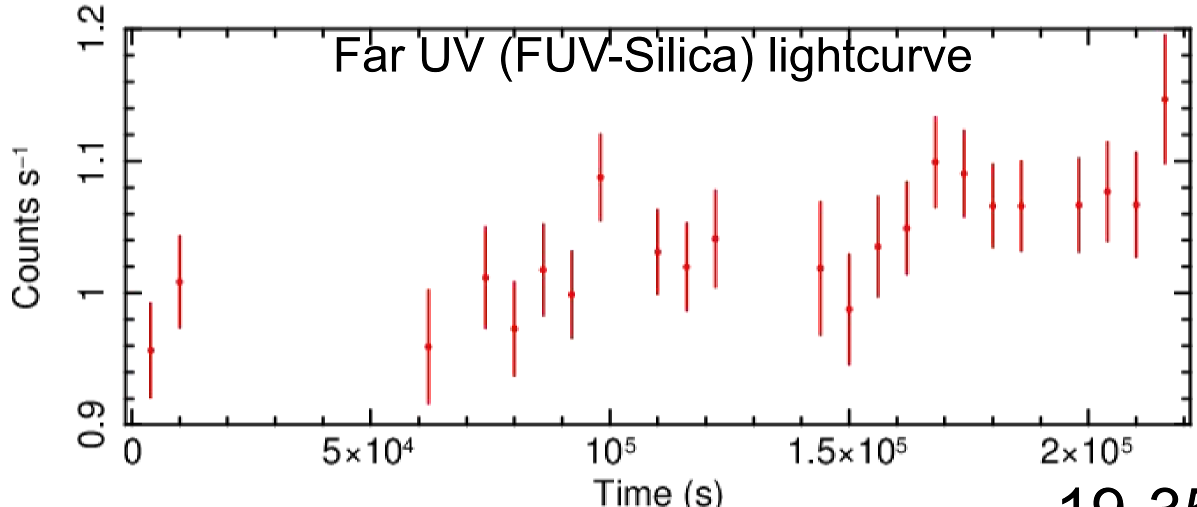
$$\tau = 0.475 \pm 0.086 \text{ days}$$

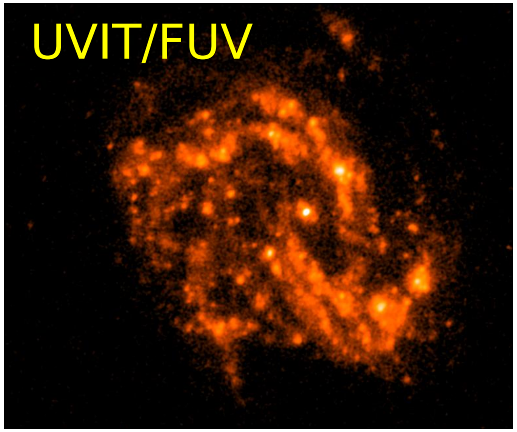
Time lag Distributions
(FR/RSS technique)



Evidence for X-ray processing in accretion disk into UV

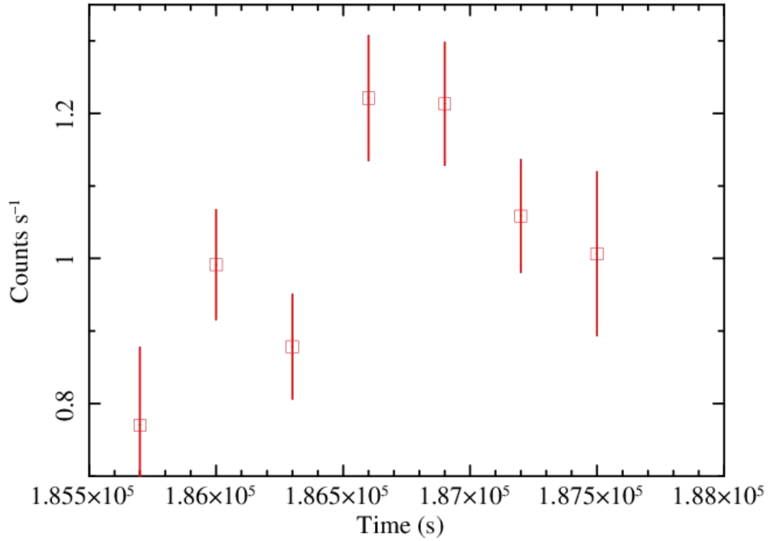
Rapid UV variability in NGC4051

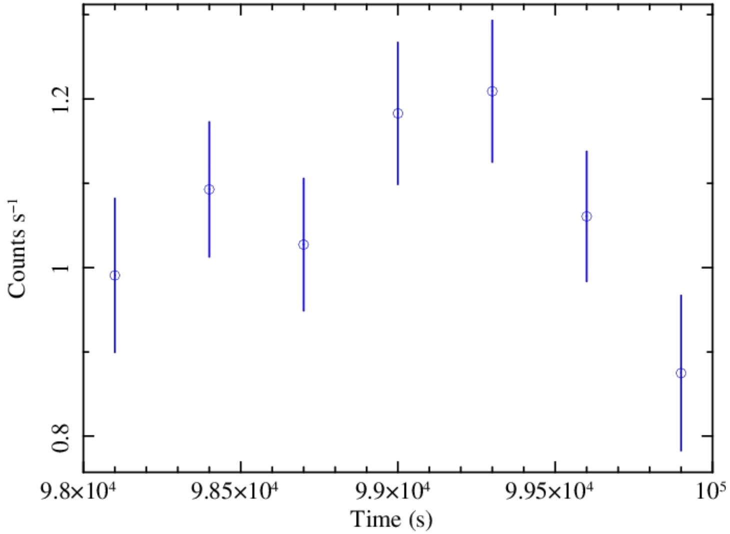




15-30% increase in 900s

19-35% decline in 600s





→ Fastest UV variability observed in any RQ AGN!

Summary

- After many hurdles, we are reaching to a position to be able to do UV/X-ray MW science with AstroSat.
- AstroSat can measure Eddington efficiency of AGN
- Simultaneous UV/X-ray spectral observations with AstroSat can probe the Comptonised disk model.
- AstroSat UV/X-ray observations will play significant role in understanding the disk/corona connection in AGN both via broadband sectroscopy and UV/X-ray timing.
- Refinement & monitoring of instrumental cross-calibration are required..

Thank You