

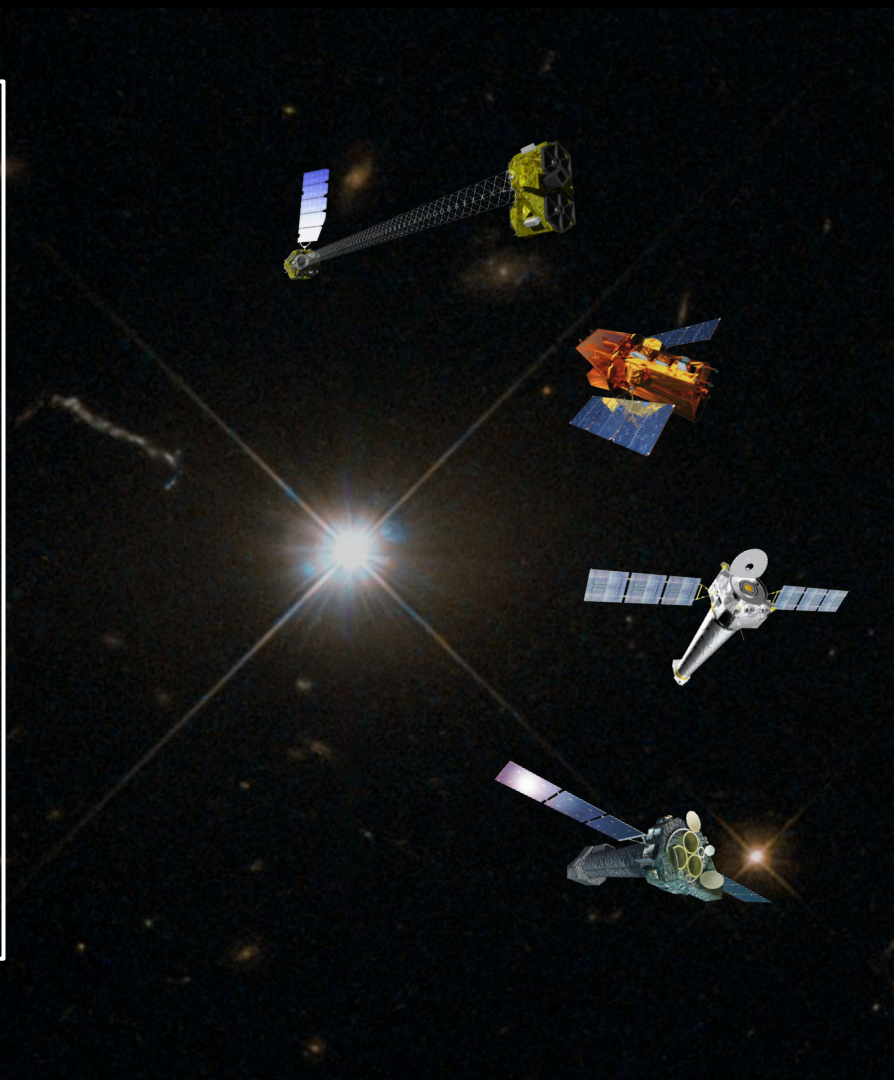
# Cross-Calibrations of X-ray Satellites with Quasar 3C 273

Corin Marasco<sup>1,2</sup> and Dr. Kristin Madsen<sup>1,3</sup>

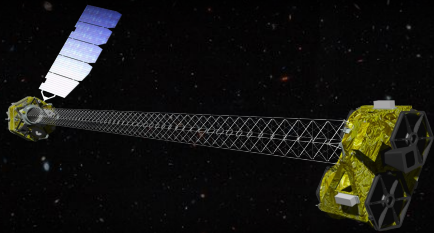
<sup>1</sup> NASA Goddard Space Flight Center, Greenbelt,  
MD

<sup>2</sup> Georgia Institute of Technology, Atlanta, GA

<sup>3</sup> University of Maryland, Baltimore County,  
Baltimore MD



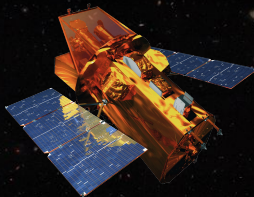
# The Observations



NuSTAR

3–79 keV

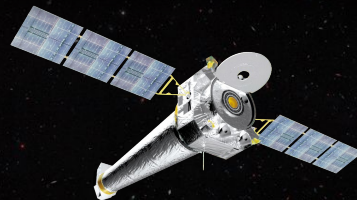
FPMA  
FPMB



Swift

0.2–10 keV

XRT



Chandra

0.08–10 keV

LETGS (0.08-2 keV)  
HETGS (0.8-8 keV)



XMM-Newton

0.15–15 keV

MOS1  
MOS2  
pn

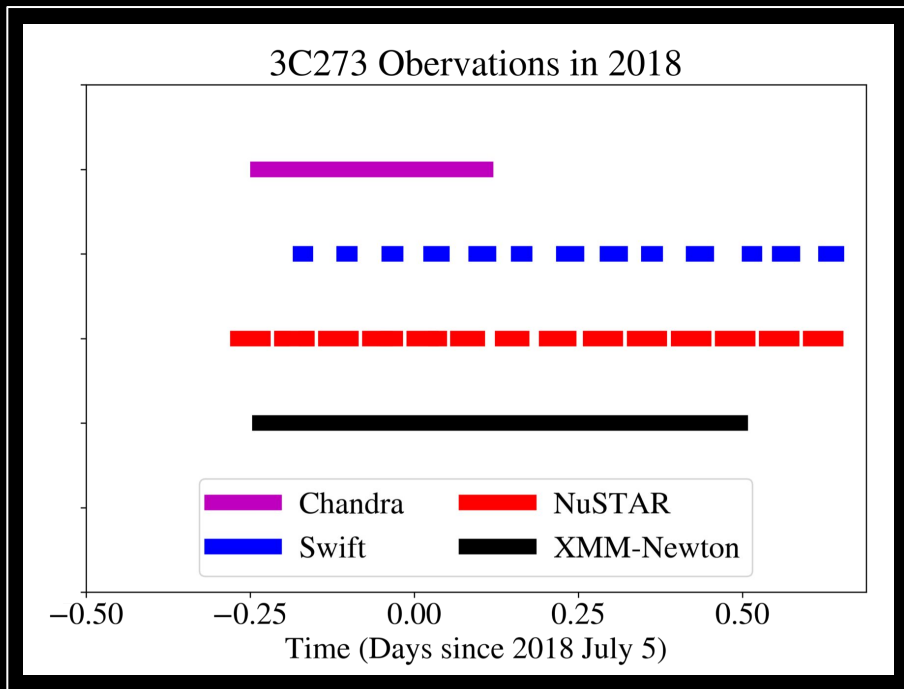
Low Earth orbit

Highly elliptical orbit

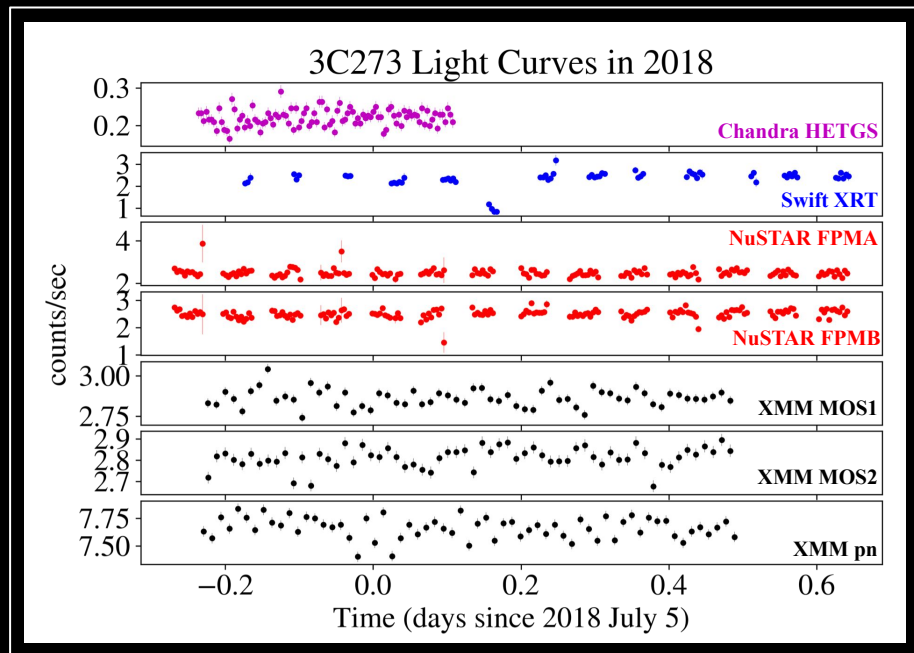
- These satellites observed the bright quasar 3C 273 yearly from **2015–2021**.
- Each observatory has one or more instruments that it uses for X-ray observations.

# Identifying Good Time Intervals (GTIs)

First, we found good time intervals (GTIs) where each pair of observations overlap:

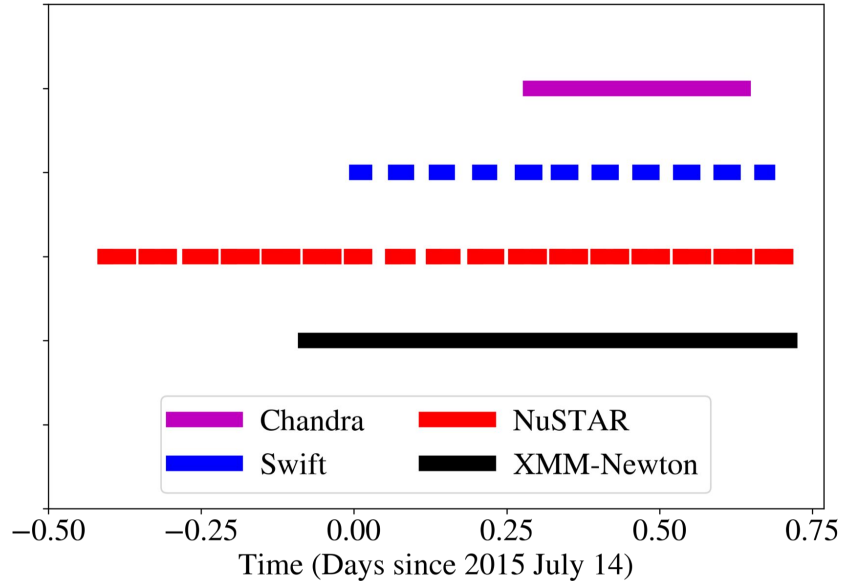


Observatories were analyzed as pairs because cutting away data where all four observations don't line up results in losing most of the data:



# Good Time Intervals - 2015

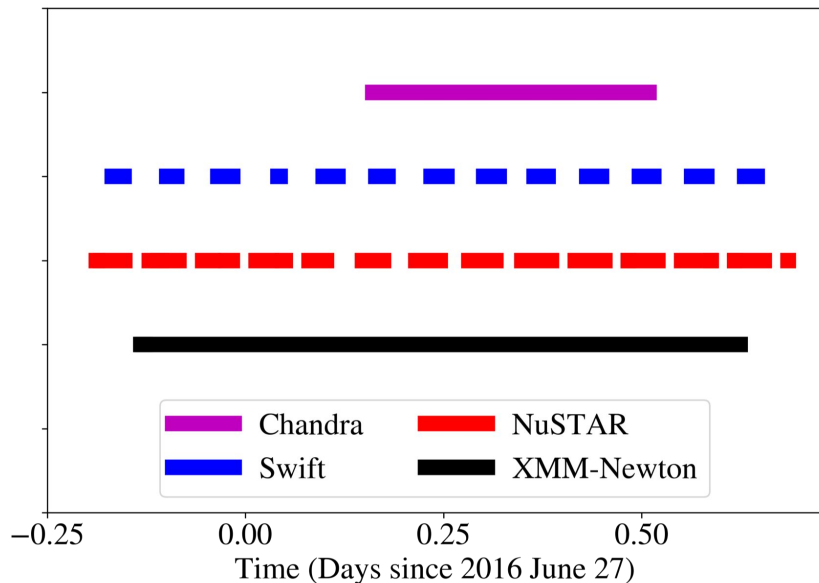
3C273 Observations in 2015



| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 57217.289       | 57217.637      | NuSTAR                   | Chandra              | 16.3/30.0           |
| 57217.004       | 57217.676      | NuSTAR                   | Swift                | 27.6/16.4           |
| 57216.921       | 57217.706      | NuSTAR                   | XMM-Newton           | 31.8/55.5           |
| 57217.289       | 57217.637      | Swift                    | Chandra              | 9.0/30.0            |
| 57217.289       | 57217.637      | XMM-Newton               | Chandra              | 26.6/30.0           |
| 57217.004       | 57217.676      | XMM-Newton               | Swift                | 48.6/16.4           |

# Good Time Intervals - 2016

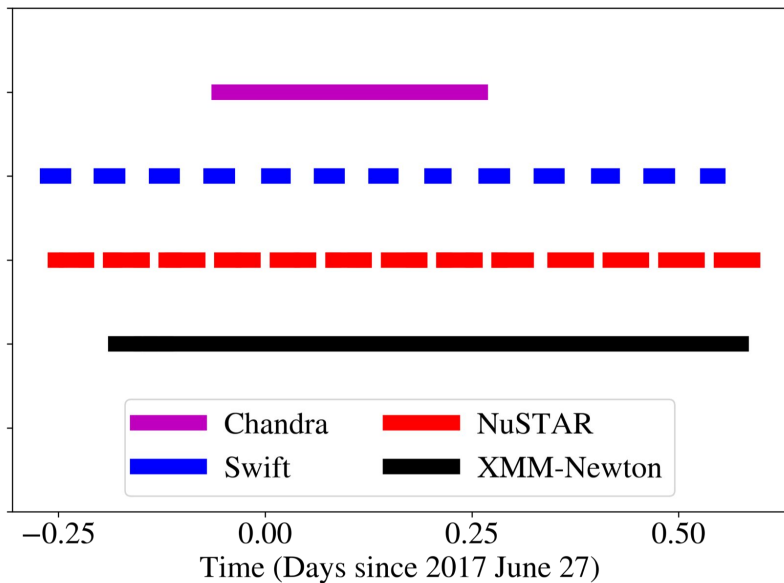
3C273 Observations in 2016



| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 57566.161       | 57566.509      | NuSTAR                   | Chandra              | 14.0/29.9           |
| 57565.832       | 57566.646      | NuSTAR                   | Swift                | 34.7/15.4           |
| 57565.868       | 57566.624      | NuSTAR                   | XMM-Newton           | 30.2/61.3           |
| 57566.161       | 57566.509      | Swift                    | Chandra              | 4.8/24.3            |
| 57566.161       | 57566.509      | XMM-Newton               | Chandra              | 28.8/29.7           |
| 57565.868       | 57566.624      | Swift                    | XMM-Newton           | 11.8/56.1           |

# Good Time Intervals - 2017

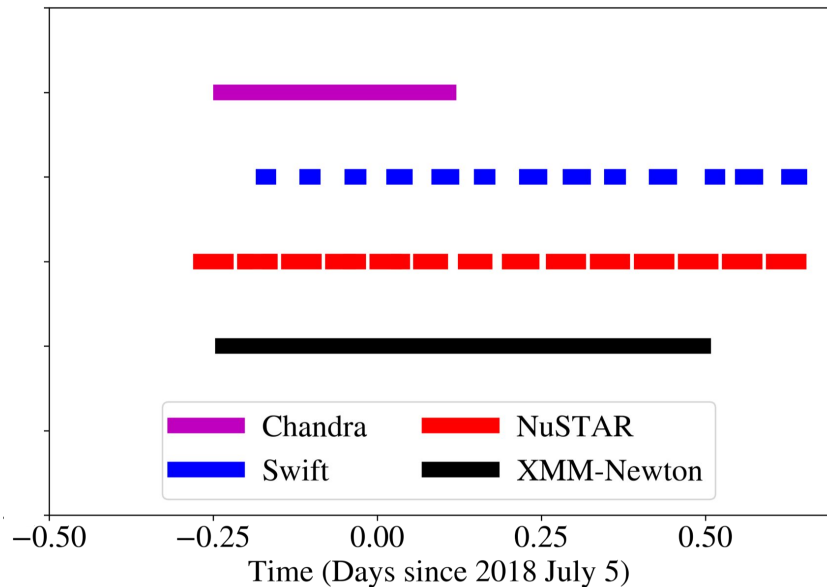
3C273 Observations in 2017



| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 57930.944       | 57931.260      | NuSTAR                   | Chandra              | 12.0/27.3           |
| 57930.746       | 57931.547      | NuSTAR                   | Swift                | 29.4/19.2           |
| 57930.819       | 57931.576      | NuSTAR                   | XMM-Newton           | 29.1/63.0           |
| 57930.944       | 57931.260      | Swift                    | Chandra              | 6.7/27.3            |
| 57930.944       | 57931.260      | XMM-Newton               | Chandra              | 26.5/27.3           |
| 57930.819       | 57931.547      | Swift                    | XMM-Newton           | 16.8/60.7           |

# Good Time Intervals - 2018

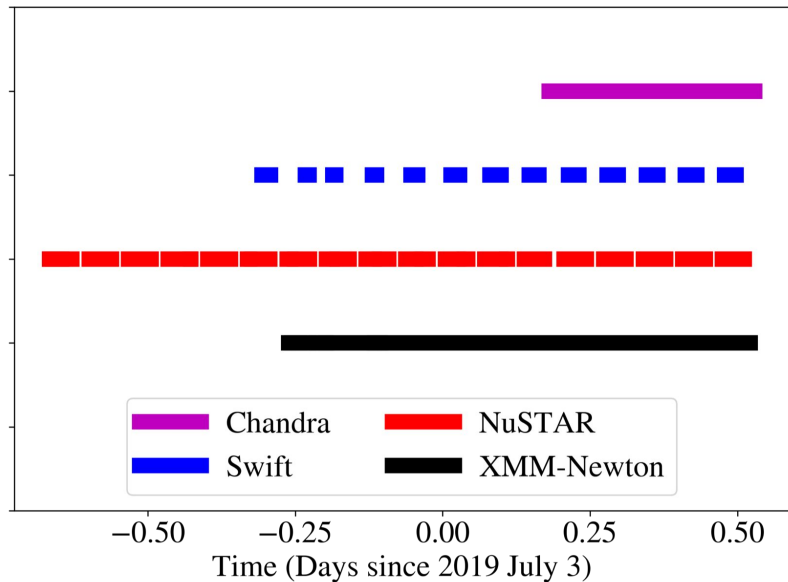
3C273 Observations in 2018



| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 58303.762       | 58304.109      | NuSTAR                   | Chandra              | 14.0/29.9           |
| 58303.827       | 58304.642      | NuSTAR                   | Swift                | 34.7/15.4           |
| 58303.765       | 58304.497      | NuSTAR                   | XMM-Newton           | 30.2/61.3           |
| 58303.827       | 58304.109      | Swift                    | Chandra              | 4.8/24.3            |
| 58303.765       | 58304.109      | XMM-Newton               | Chandra              | 28.8/29.7           |
| 58303.827       | 58304.497      | Swift                    | XMM-Newton           | 11.8/56.1           |

# Good Time Intervals - 2019

3C273 Observations in 2019

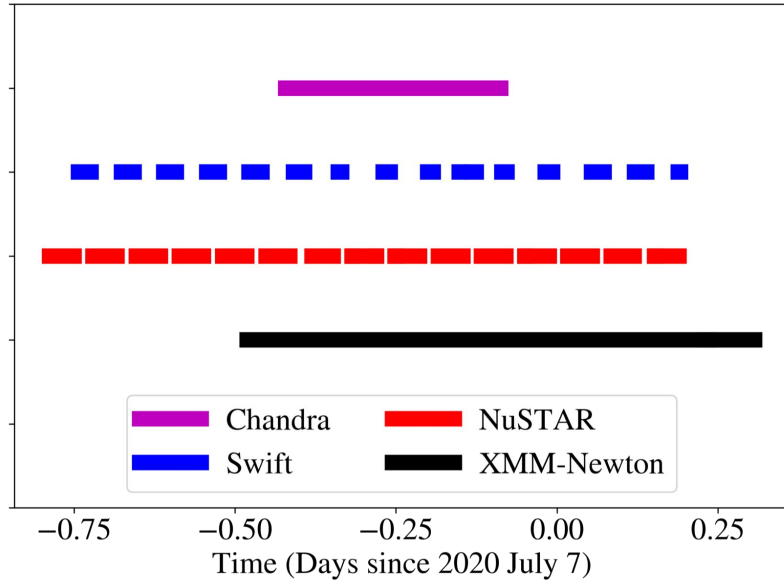


| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 58667.181       | 58667.511      | NuSTAR                   | Chandra              | 15.3/28.5           |
| 58666.693       | 58667.497      | NuSTAR                   | Swift                | 31.0/16.3           |
| 58666.739       | 58667.511      | NuSTAR                   | XMM-Newton           | 30.8/62.6           |
| 58667.181       | 58667.497      | Swift                    | Chandra              | 8.2/27.3            |
| 58667.181       | 58667.521      | XMM-Newton               | Chandra              | 28.5/29.4           |
| 58666.739       | 58667.497      | Swift                    | XMM-Newton           | 15.0/61.4           |



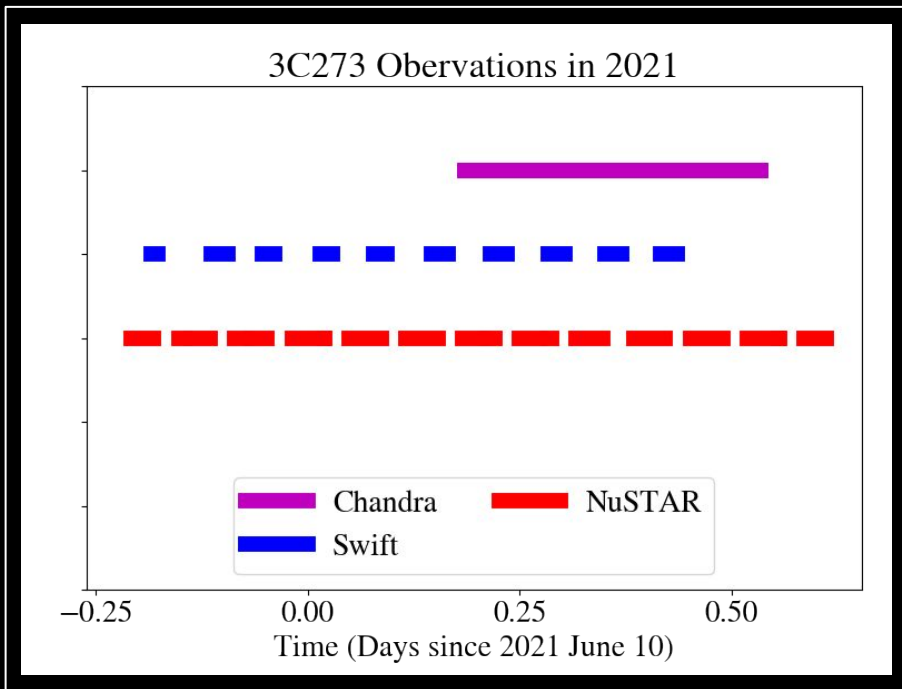
# Good Time Intervals - 2020

3C273 Observations in 2020



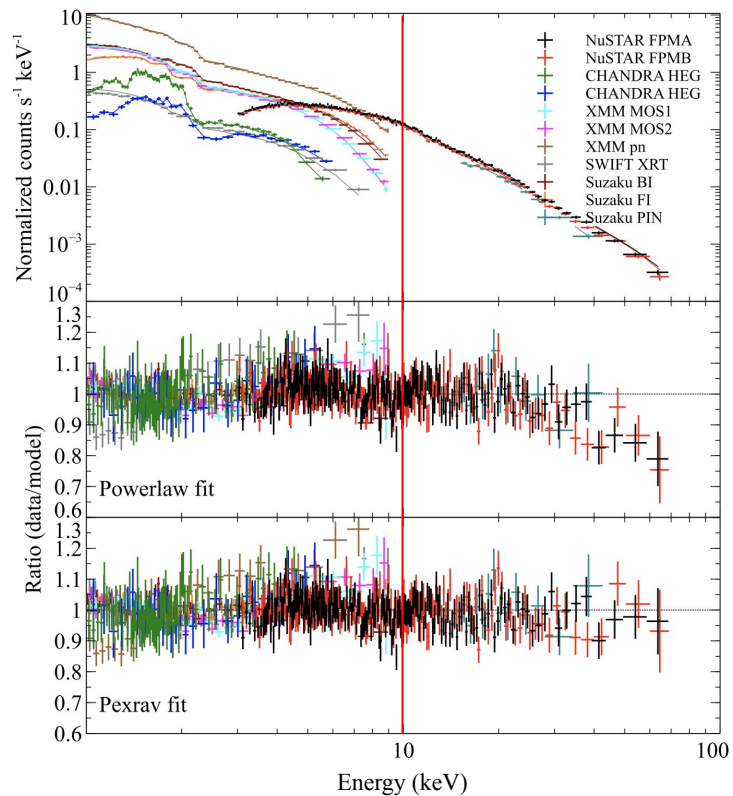
| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 59036.579       | 59036.913      | NuSTAR                   | Chandra              | 13.9/28.9           |
| 59036.257       | 59037.189      | NuSTAR                   | Swift                | 41.0/18.0           |
| 59036.519       | 59037.189      | NuSTAR                   | XMM-Newton           | 28.9/56.2           |
| 59036.579       | 59036.913      | Swift                    | Chandra              | 4.4/28.9            |
| 59036.579       | 59036.913      | XMM-Newton               | Chandra              | 28.0/28.9           |
| 59036.519       | 59037.192      | Swift                    | XMM-Newton           | 11.4/56.4           |

# Good Time Intervals - 2021



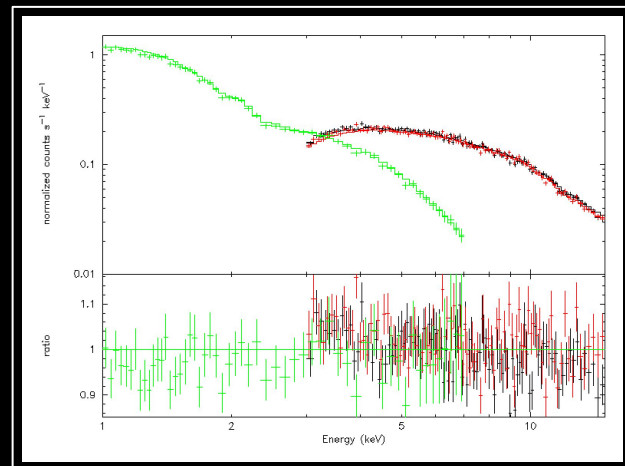
| GTI Start (MJD) | GTI Stop (MJD) | Concatenated observation | Limiting Observation | Total Exposure (ks) |
|-----------------|----------------|--------------------------|----------------------|---------------------|
| 59375.185       | 59375.534      | NuSTAR                   | Chandra              | 14.4/30.1           |
| 59375.015       | 59375.436      | NuSTAR                   | Swift                | 16.7/11.1           |
| 59375.185       | 59375.436      | Swift                    | Chandra              | 6.7/21.7            |

# Fitting 3C 273



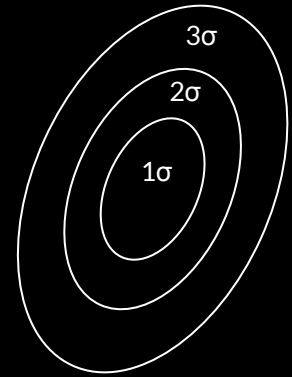
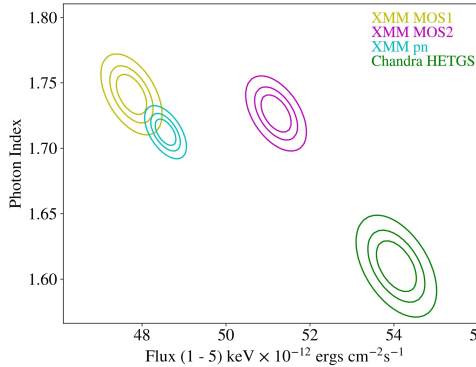
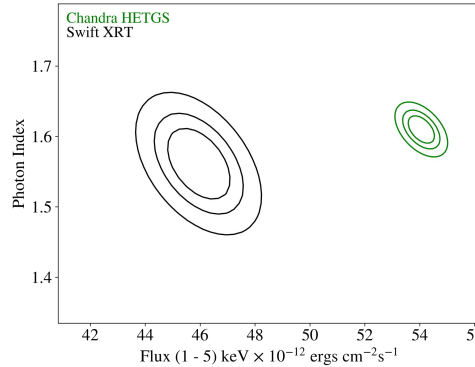
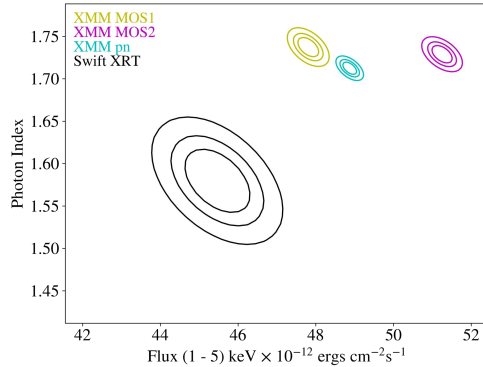
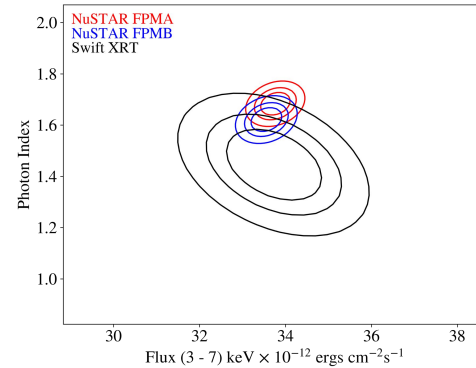
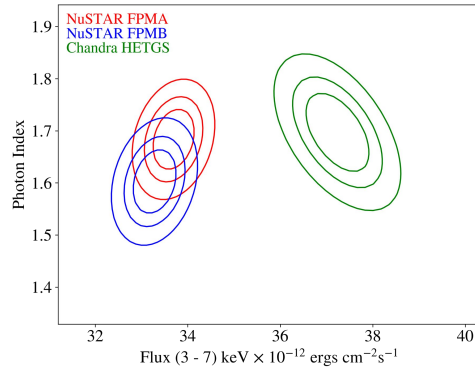
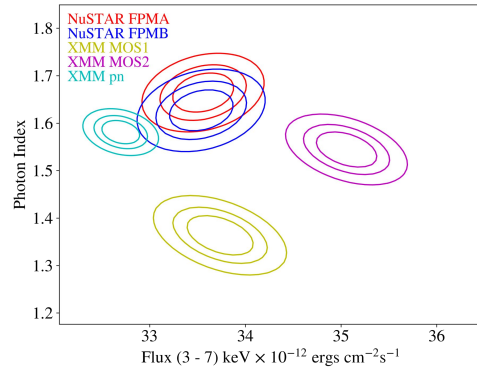
2018 study fitting 3C 273 with a power-law

- Observatories paired with NuSTAR were analyzed in the 3–7 keV band, while the other pairings were analyzed in the 1–5 keV band.
- Fit a power-law model ( $z_{\text{pow}} * \text{cflux} * \text{tbabs}$ ) to the spectral data from each instrument to determine the instrument's flux and photon index when limited by another satellite's GTI.
- Then fit the data from an observatory pair together to get the ratio of the measured flux to the model.



NuSTAR FPMA (black) and FPMB (red) with Swift XRT (green) fitted with XSPEC

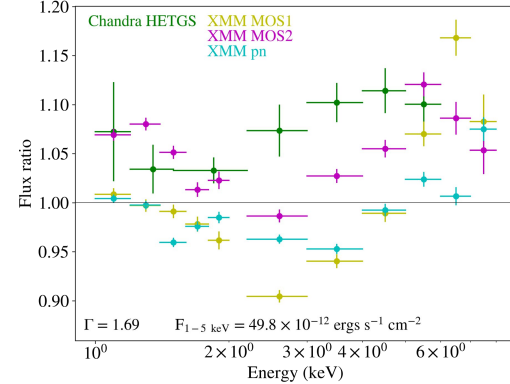
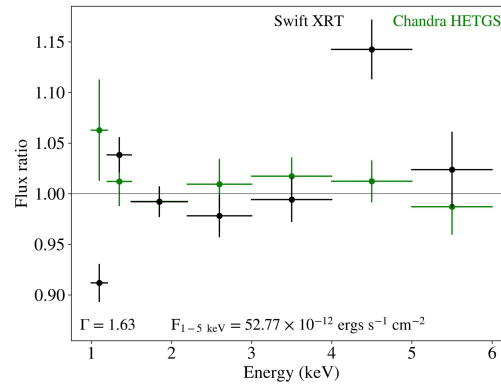
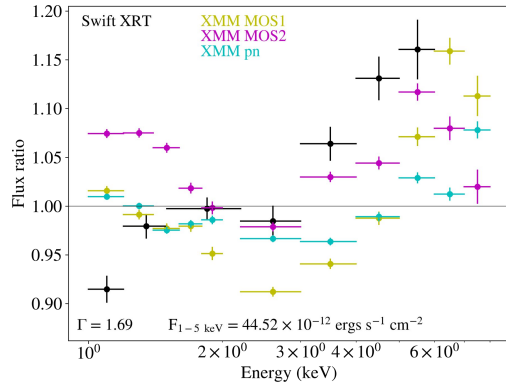
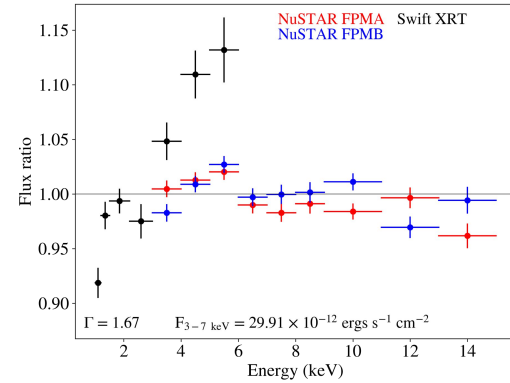
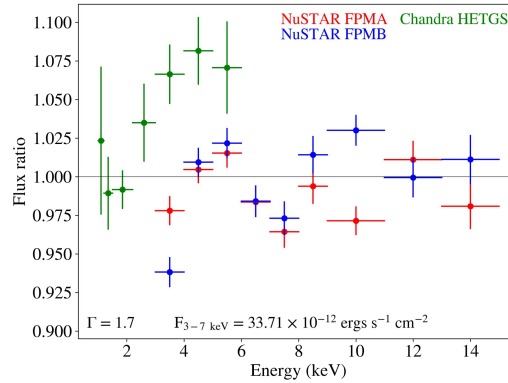
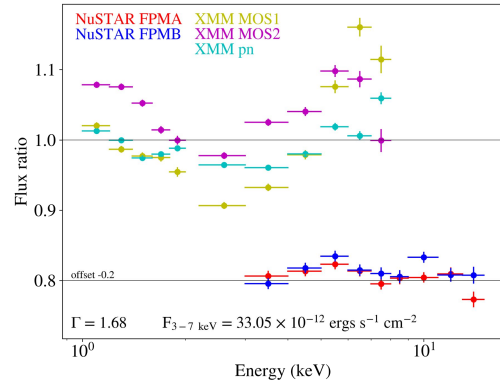
# 2015 - Confidence Contours



1 $\sigma$   $\approx$  68%  
2 $\sigma$   $\approx$  95%  
3 $\sigma$   $\approx$  99.7%

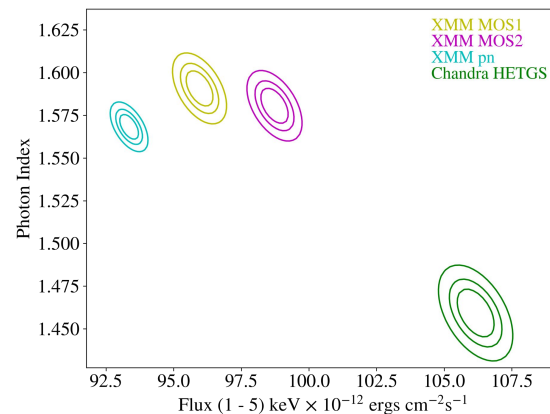
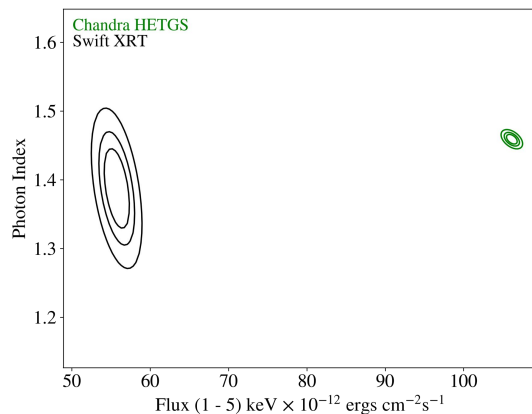
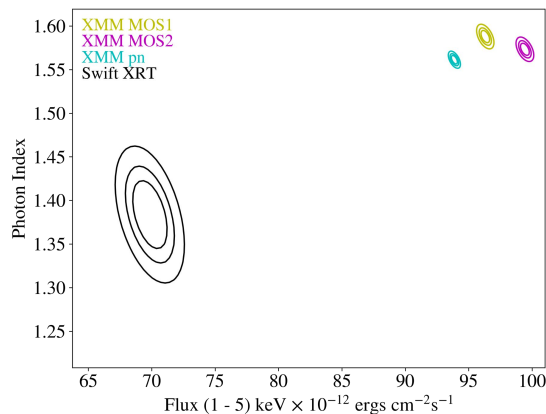
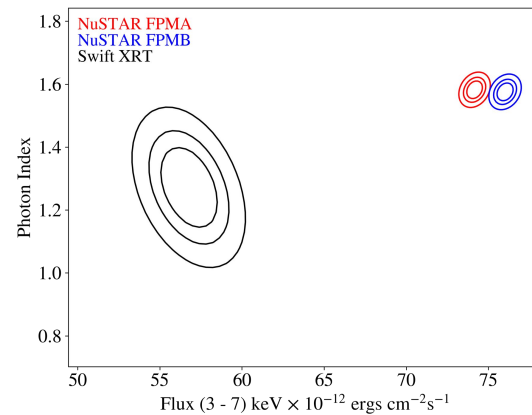
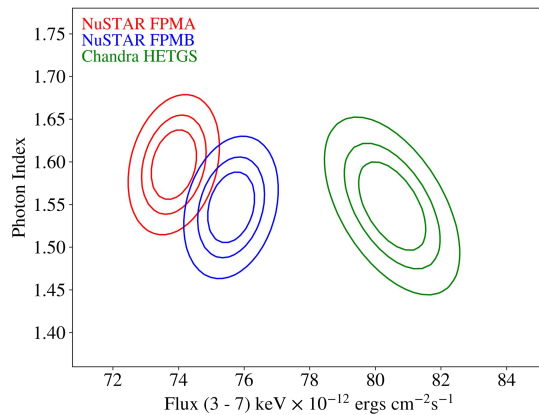
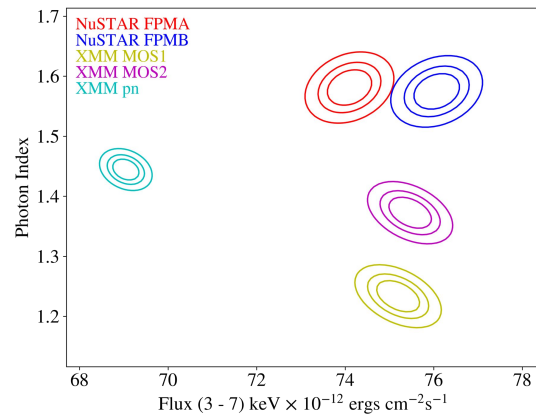
Confidence contour plots for each observatory pair in 2015, showing the photon index and flux estimates for each observation.

# 2015 - Flux Ratios

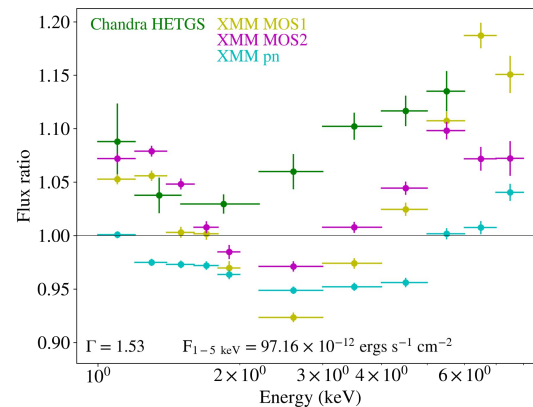
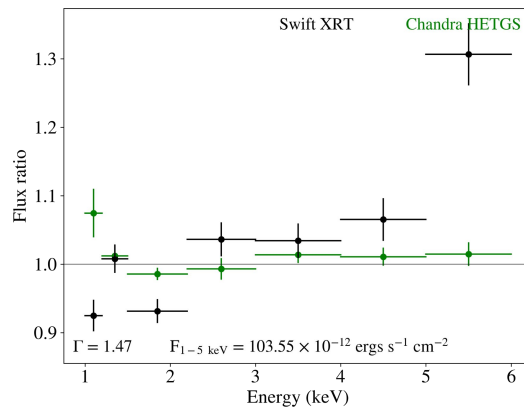
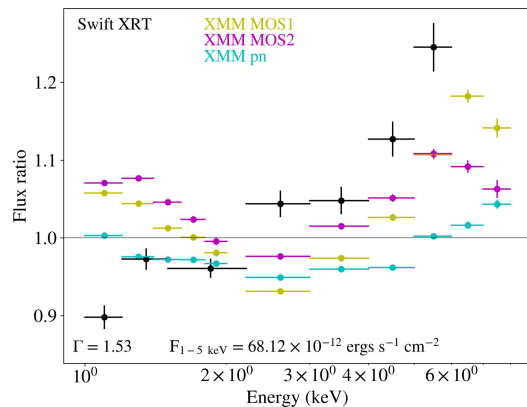
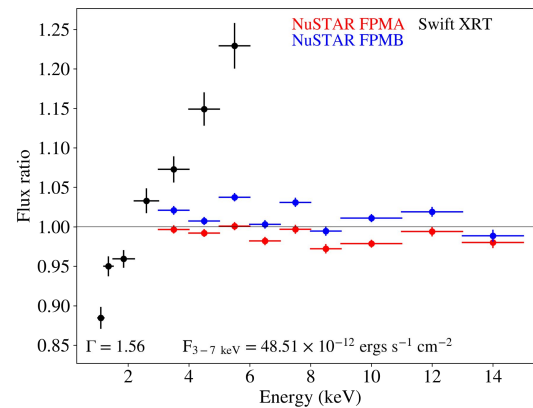
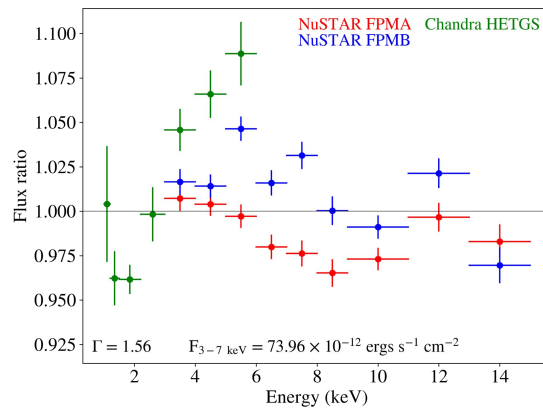
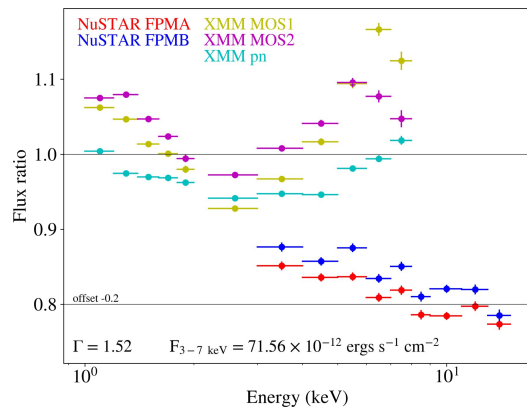


Ratio of the measured flux to the model flux when an observatory pair is fitted together.

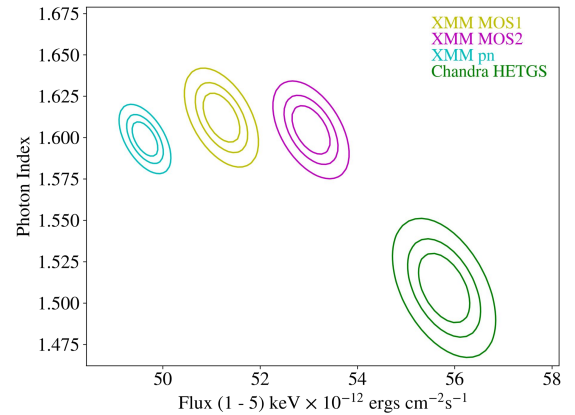
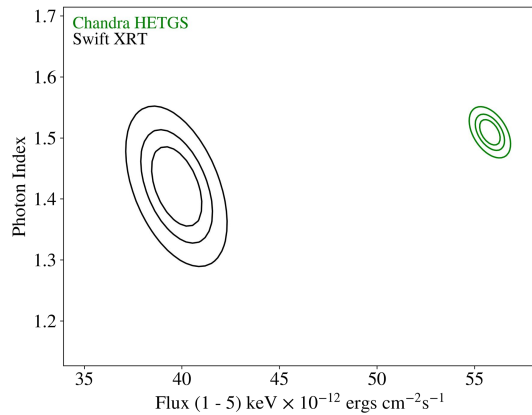
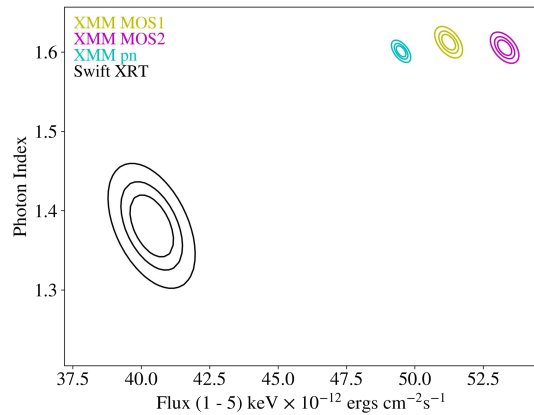
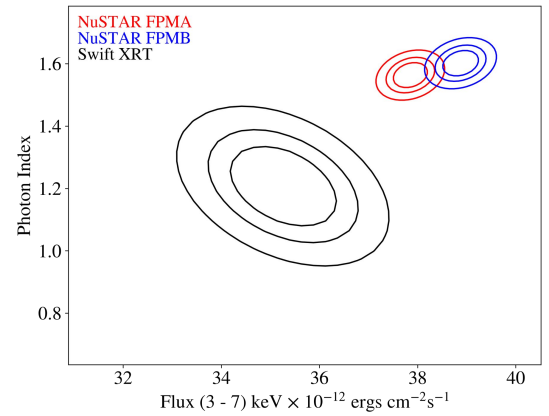
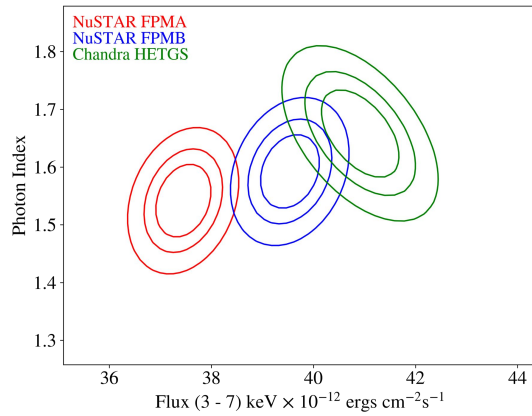
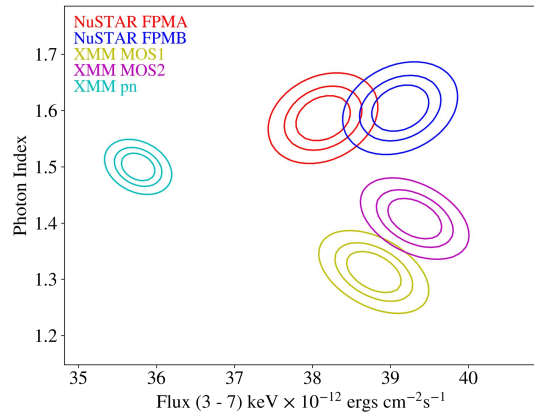
# 2016 - Confidence Contours



# 2016 - Flux Ratios

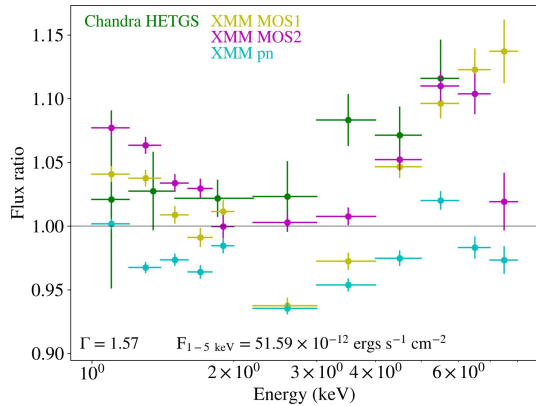
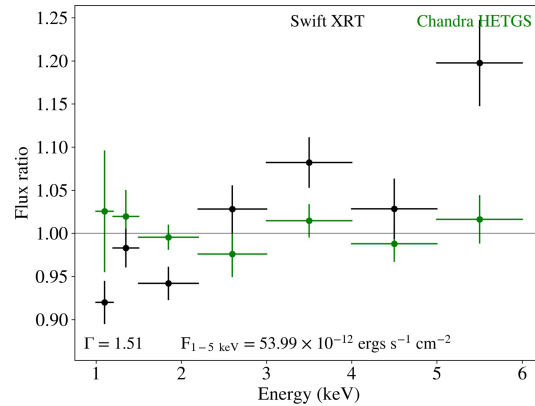
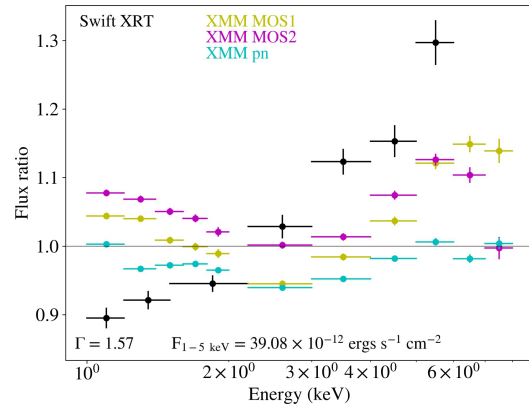
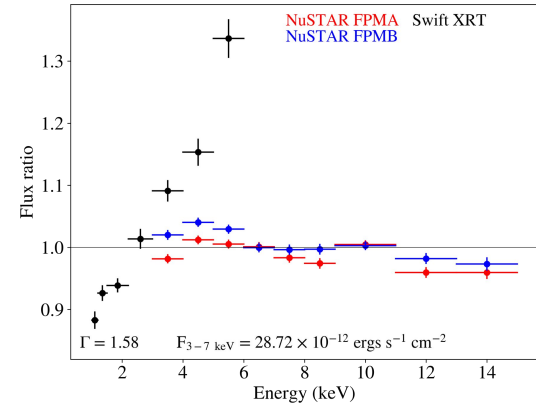
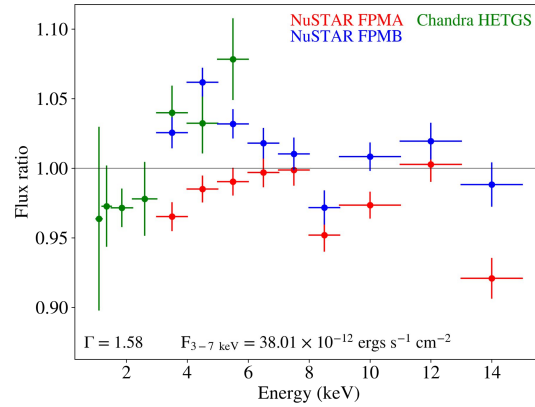
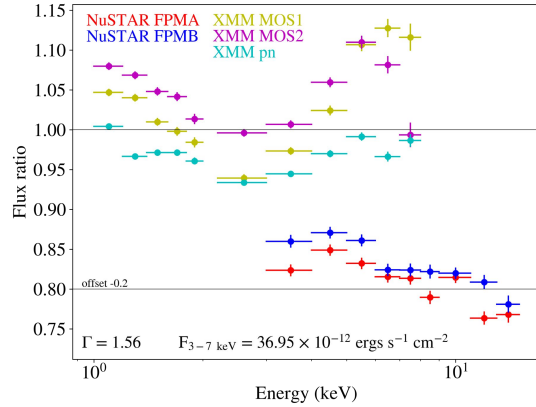


# 2017 - Confidence Contours

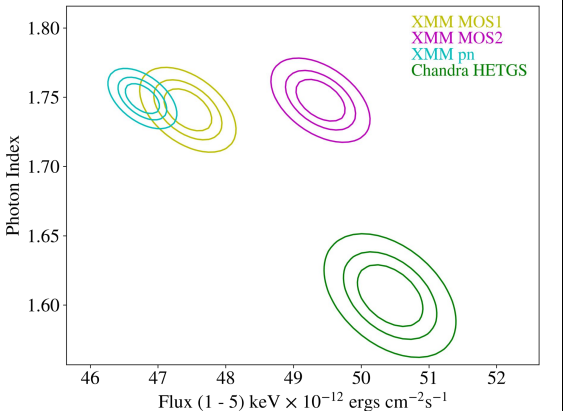
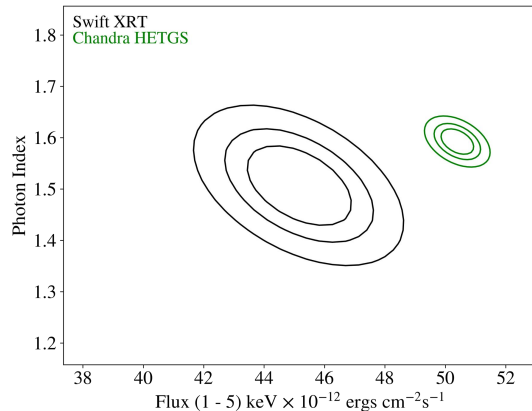
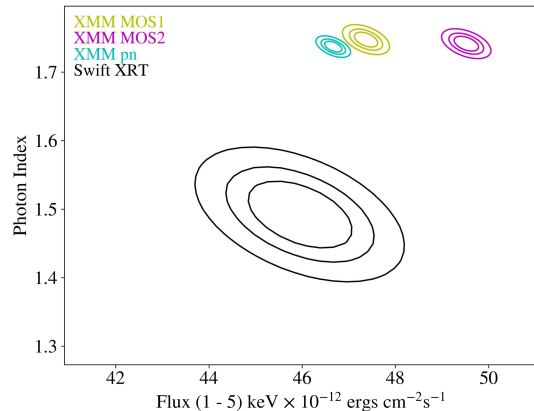
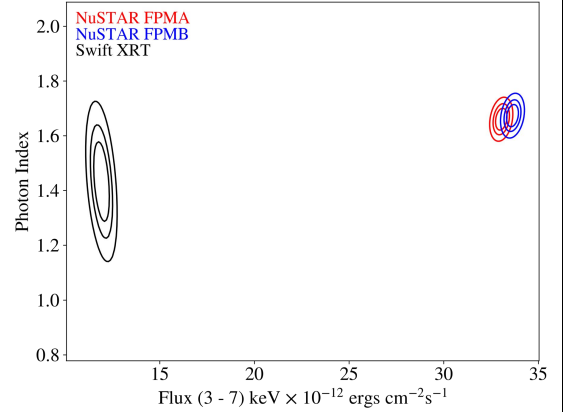
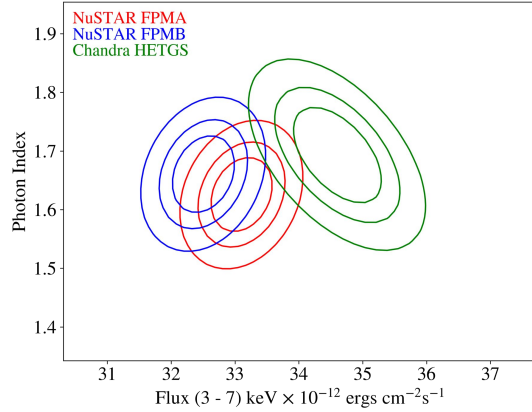
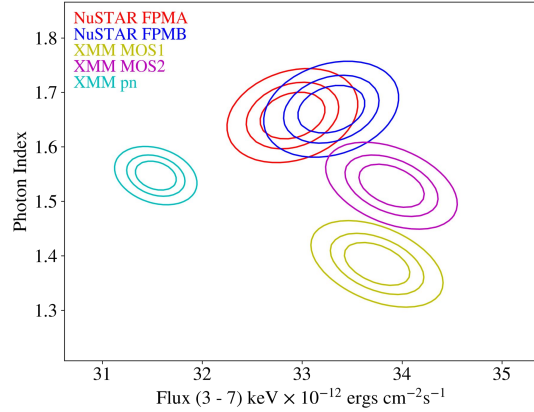




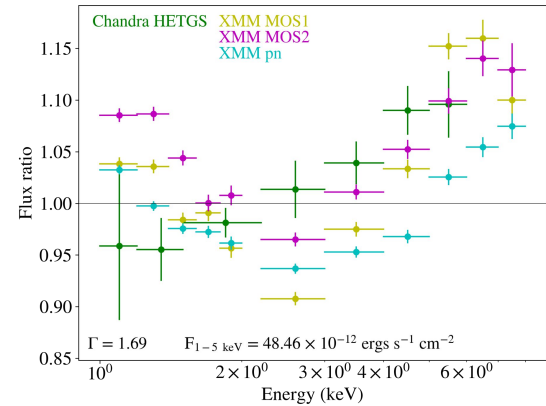
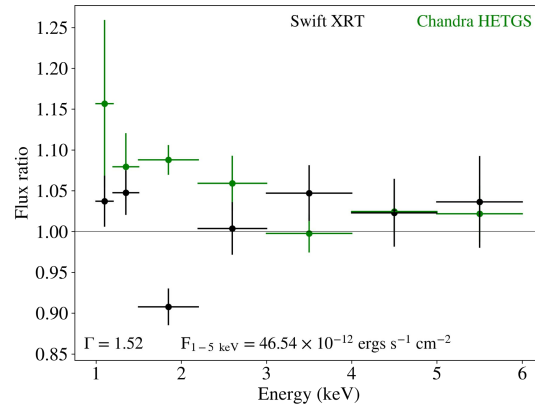
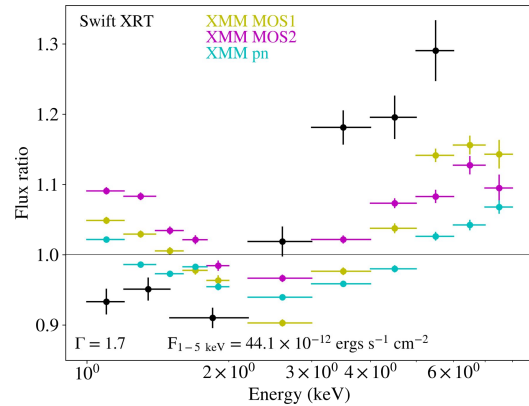
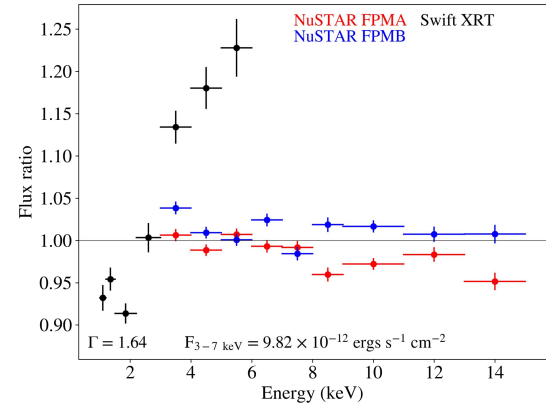
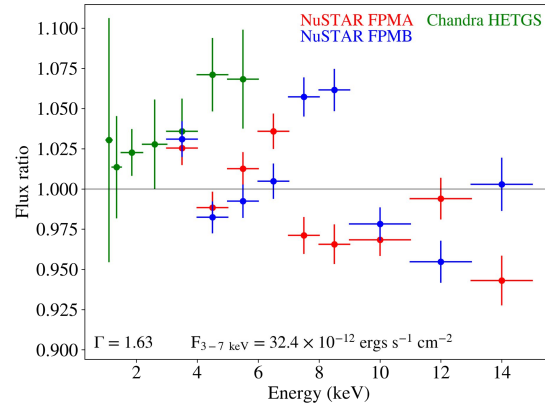
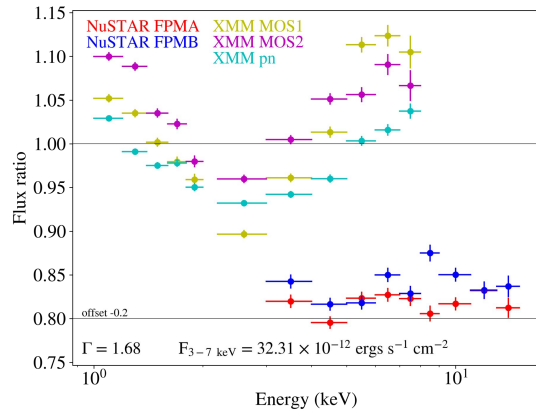
# 2017 - Flux Ratios



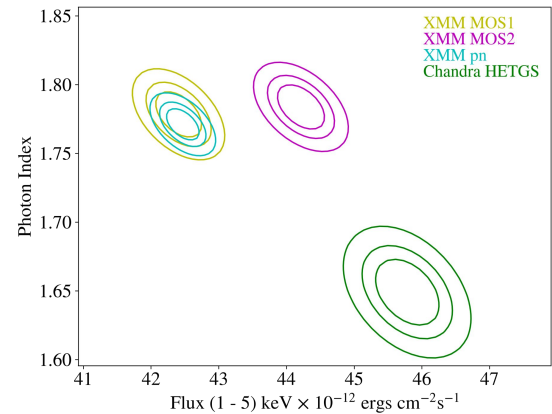
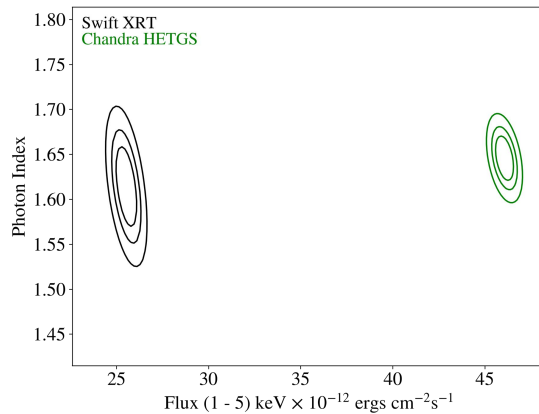
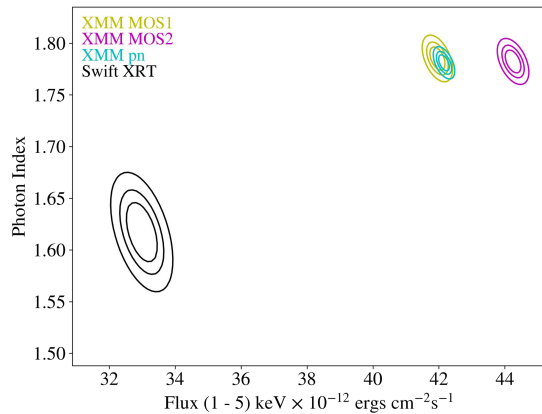
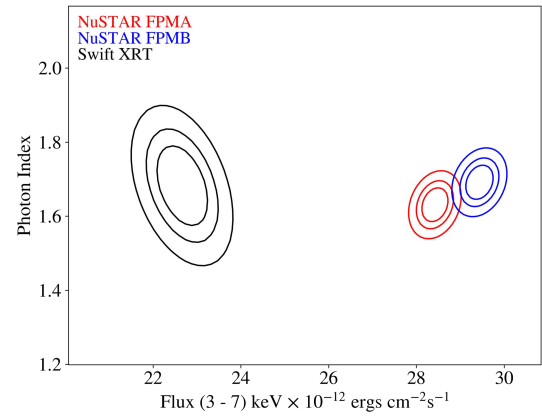
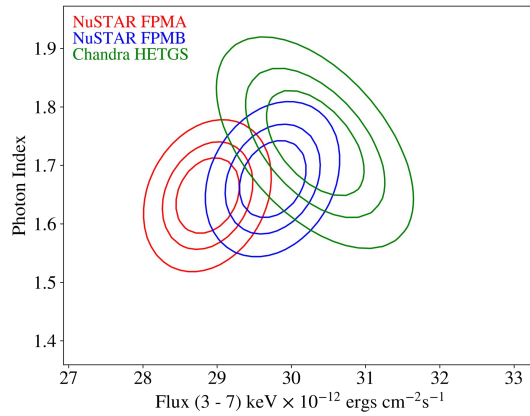
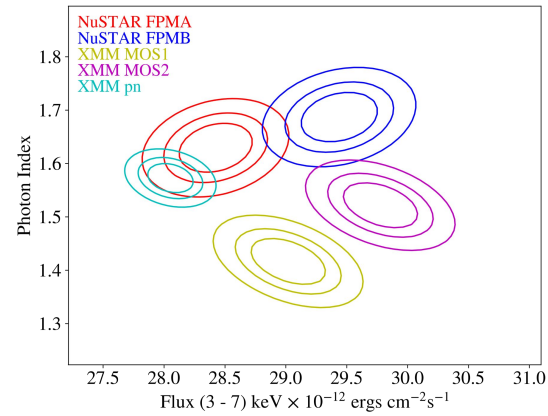
# 2018 - Confidence Contours



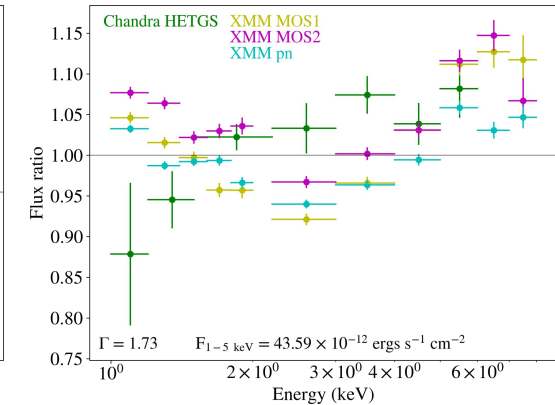
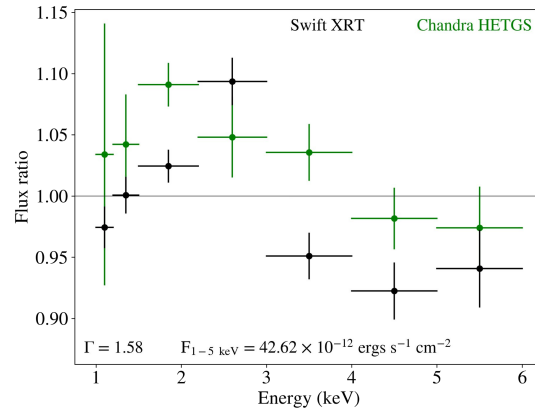
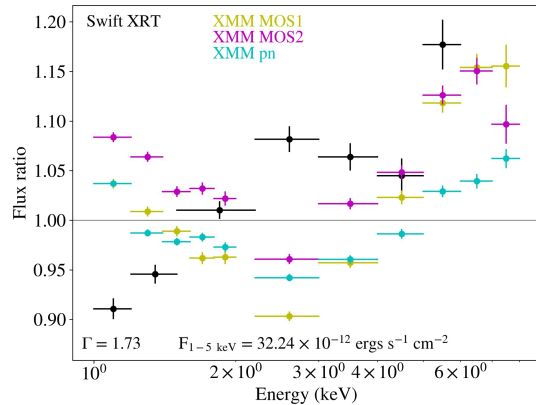
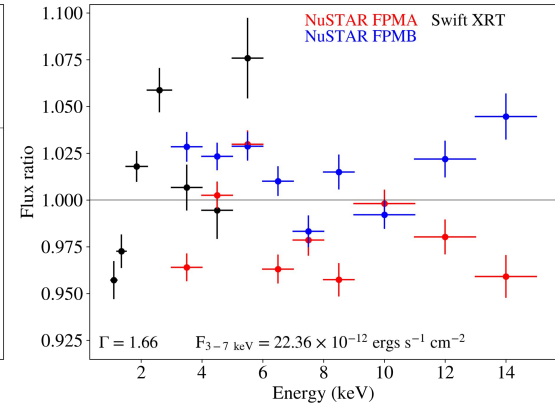
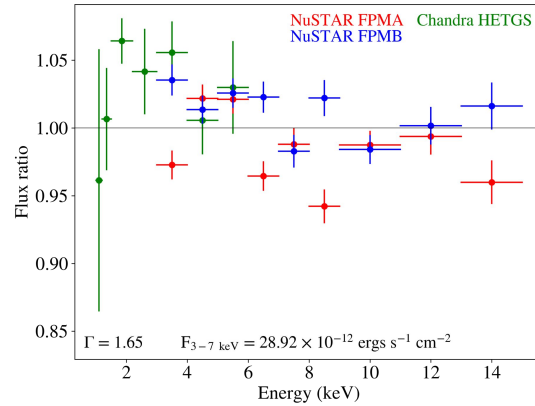
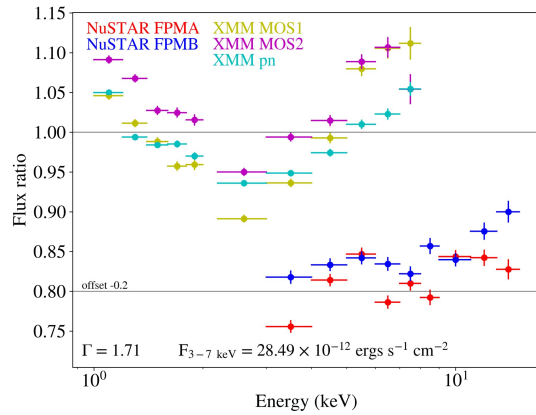
# 2018 - Flux Ratios



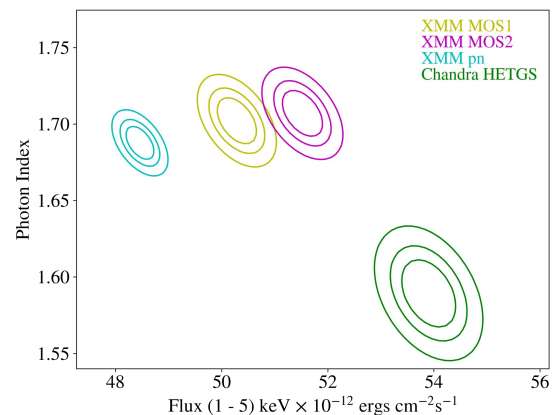
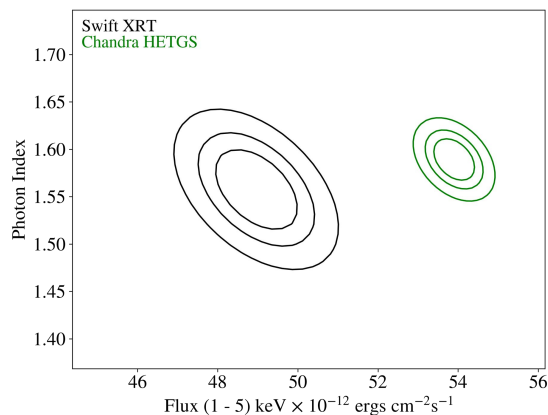
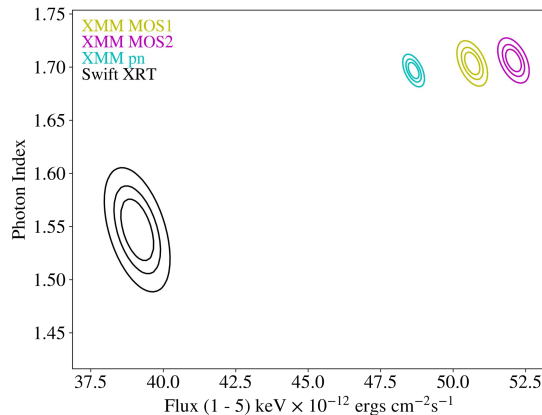
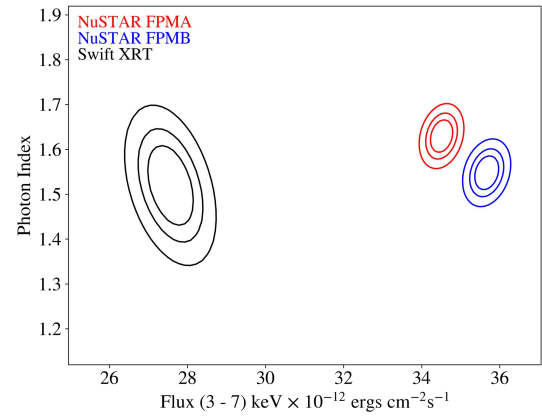
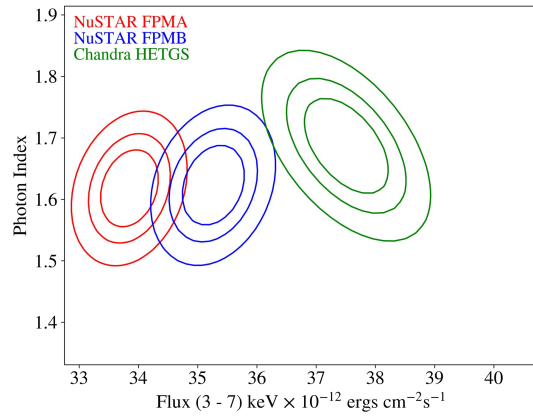
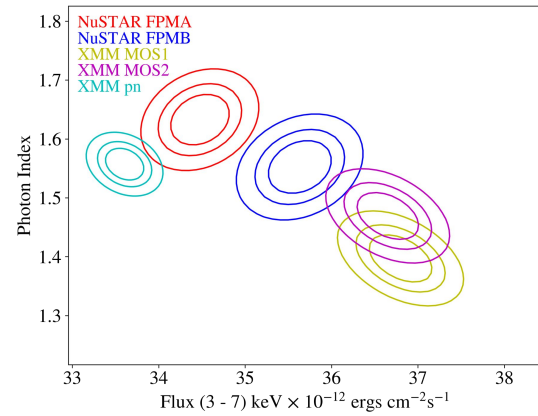
# 2019 - Confidence Contours



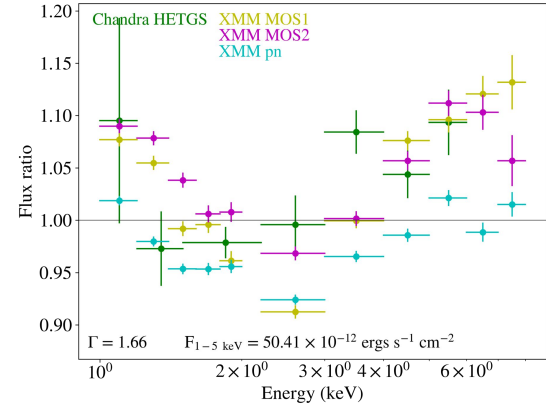
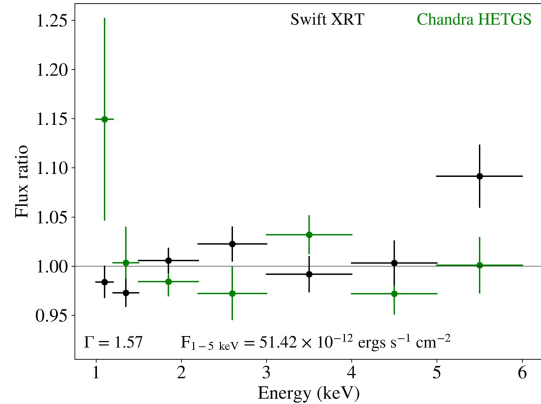
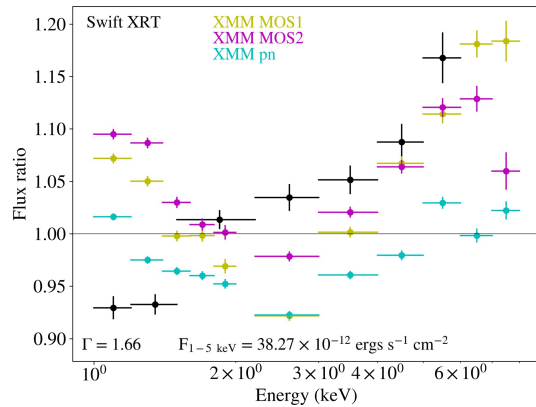
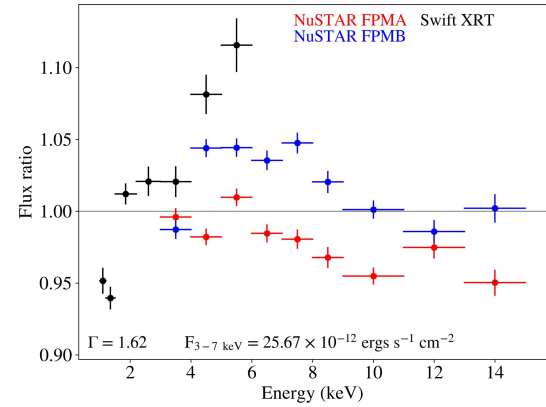
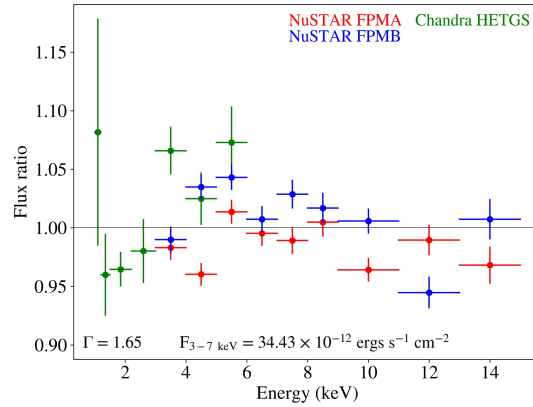
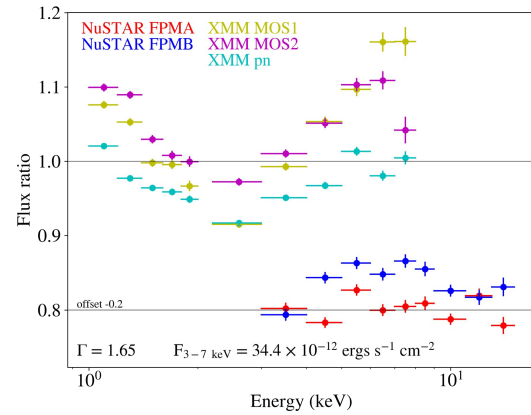
# 2019 - Flux Ratios



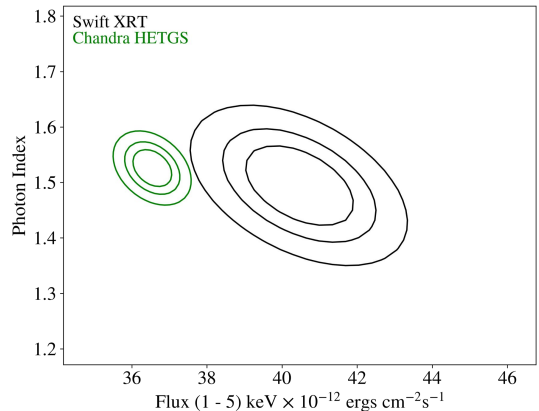
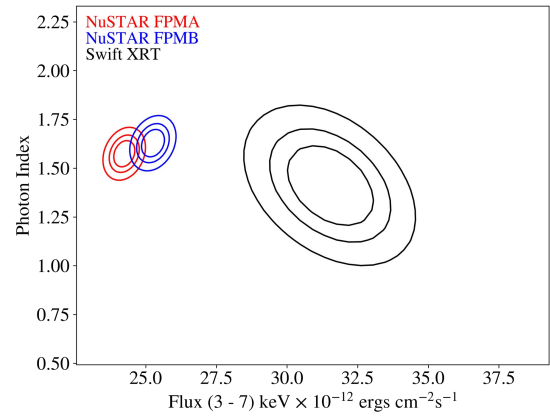
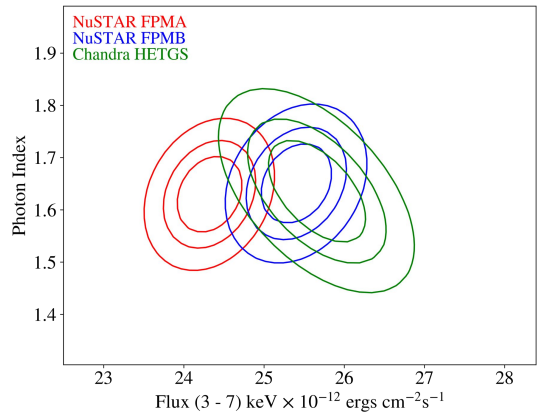
# 2020 - Confidence Contours



# 2020 - Flux Ratios

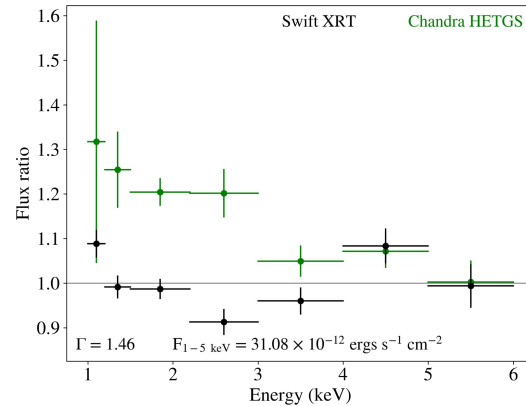
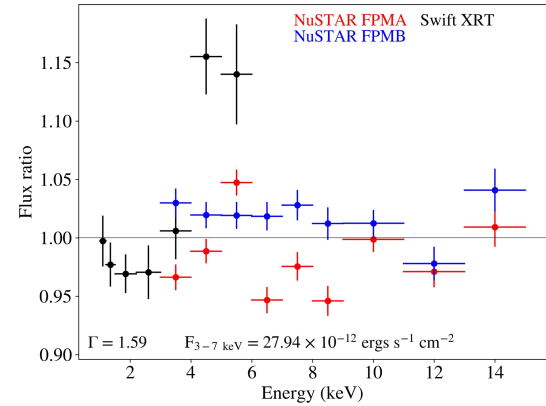
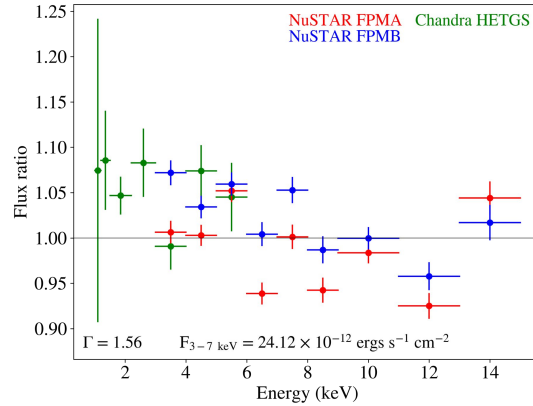


# 2021 - Confidence Contours





# 2021 - Flux Ratios



# Cross-Normalization Constants (1–5 keV)

| 2015          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 1.13          | 1.04     | 1.11     | 1.06   |
| Chandra HETGS | 0.88      | 1             | 0.91     | 0.97     | 0.92   |
| XMM MOS1      | 0.96      | 1.10          | 1        | 1.07     | 1.02   |
| XMM MOS2      | 0.90      | 1.03          | 0.93     | 1        | 0.95   |
| XMM pn        | 0.95      | 1.09          | 0.98     | 1.05     | 1      |

| 2016          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 2.10          | 1.64     | 1.69     | 1.59   |
| Chandra HETGS | 0.48      | 1             | 0.93     | 0.96     | 0.90   |
| XMM MOS1      | 0.61      | 1.07          | 1        | 1.03     | 0.97   |
| XMM MOS2      | 0.59      | 1.05          | 0.97     | 1        | 0.94   |
| XMM pn        | 0.63      | 1.11          | 1.03     | 1.06     | 1      |

| 2017          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 1.43          | 1.15     | 1.19     | 1.11   |
| Chandra HETGS | 0.70      | 1             | 0.94     | 0.97     | 0.91   |
| XMM MOS1      | 0.87      | 1.07          | 1        | 1.04     | 0.96   |
| XMM MOS2      | 0.84      | 1.03          | 0.96     | 1        | 0.93   |
| XMM pn        | 0.90      | 1.10          | 1.04     | 1.08     | 1      |

# Cross-Normalization Constants (1–5 keV)

| 2018          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 1.13          | 1.09     | 1.14     | 1.07   |
| Chandra HETGS | 0.89      | 1             | 0.96     | 1.01     | 0.95   |
| XMM MOS1      | 0.92      | 1.04          | 1        | 1.04     | 0.98   |
| XMM MOS2      | 0.88      | 0.99          | 0.96     | 1        | 0.94   |
| XMM pn        | 0.93      | 1.05          | 1.02     | 1.06     | 1      |

| 2019          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 1.87          | 1.34     | 1.41     | 1.35   |
| Chandra HETGS | 0.53      | 1             | 0.95     | 0.99     | 0.95   |
| XMM MOS1      | 0.75      | 1.05          | 1        | 1.05     | 1.00   |
| XMM MOS2      | 0.71      | 1.01          | 0.95     | 1        | 0.95   |
| XMM pn        | 0.74      | 1.05          | 1.00     | 1.05     | 1      |

| 2020          |           |               |          |          |        |
|---------------|-----------|---------------|----------|----------|--------|
|               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT     | 1         | 1.13          | 1.30     | 1.34     | 1.25   |
| Chandra HETGS | 0.89      | 1             | 0.95     | 0.98     | 0.91   |
| XMM MOS1      | 0.77      | 1.05          | 1        | 1.03     | 0.96   |
| XMM MOS2      | 0.75      | 1.03          | 0.97     | 1        | 0.93   |
| XMM pn        | 0.80      | 1.09          | 1.04     | 1.07     | 1      |

| 2021          |           |               |
|---------------|-----------|---------------|
|               | Swift XRT | Chandra HETGS |
| Swift XRT     | 1         | 1.20          |
| Chandra HETGS | 0.83      | 1             |

# Cross-Normalization Constants (3-7 keV)

| 2015        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.00        | 0.96      | 1.11          | 0.99     | 1.05     | 0.98   |
| NuSTAR FPMB | 1.00        | 1           | 0.97      | 1.12          | 0.99     | 1.05     | 0.98   |

| 2016        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.03        | 0.59      | 1.09          | 1.00     | 1.02     | 0.94   |
| NuSTAR FPMB | 0.98        | 1           | 0.58      | 1.06          | 0.98     | 0.99     | 0.92   |

| 2017        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.02        | 0.88      | 1.10          | 1.01     | 1.03     | 0.95   |
| NuSTAR FPMB | 0.98        | 1           | 0.86      | 1.04          | 0.98     | 1.00     | 0.92   |

| 2018        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.02        | 0.96      | 1.05          | 1.01     | 1.03     | 0.96   |
| NuSTAR FPMB | 0.98        | 1           | 0.94      | 1.07          | 1.00     | 1.02     | 0.95   |

# Cross-Normalization Constants (3-7 keV)

| 2019        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.03        | 0.75      | 1.05          | 1.01     | 1.05     | 0.99   |
| NuSTAR FPMB | 0.97        | 1           | 0.73      | 1.02          | 0.98     | 1.01     | 0.96   |

| 2020        |             |             |           |               |          |          |        |
|-------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA | 1           | 1.04        | 0.73      | 1.11          | 1.06     | 1.06     | 0.98   |
| NuSTAR FPMB | 0.96        | 1           | 0.70      | 1.07          | 1.02     | 1.02     | 0.95   |

| 2021        |             |             |           |               |
|-------------|-------------|-------------|-----------|---------------|
|             | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS |
| NuSTAR FPMA | 1           | 1.04        | 0.92      | 1.05          |
| NuSTAR FPMB | 0.96        | 1           | 0.88      | 1.01          |

# Average Cross-Normalization Constants

| Averages (1-5 keV) |           |               |          |          |        |
|--------------------|-----------|---------------|----------|----------|--------|
|                    | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT          | 1         | 1.43          | 1.26     | 1.31     | 1.24   |
| Chandra HETGS      | 0.74      | 1             | 0.94     | 0.98     | 0.92   |
| XMM MOS1           | 0.81      | 1.06          | 1        | 1.04     | 0.98   |
| XMM MOS2           | 0.78      | 1.02          | 0.96     | 1        | 0.94   |
| XMM pn             | 0.83      | 1.08          | 1.02     | 1.06     | 1      |

| Standard Deviations (1-5 keV) |           |               |          |          |        |
|-------------------------------|-----------|---------------|----------|----------|--------|
|                               | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| Swift XRT                     | 0         | 0.40          | 0.22     | 0.22     | 0.21   |
| Chandra HETGS                 | 0.18      | 0             | 0.02     | 0.02     | 0.02   |
| XMM MOS1                      | 0.13      | 0.02          | 0        | 0.02     | 0.02   |
| XMM MOS2                      | 0.12      | 0.02          | 0.02     | 0        | 0.01   |
| XMM pn                        | 0.13      | 0.03          | 0.02     | 0.01     | 0      |

| Averages (3-7 keV) |             |             |           |               |          |          |        |
|--------------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|                    | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA        | 1           | 1.03        | 0.83      | 1.08          | 1.01     | 1.04     | 0.97   |
| NuSTAR FPMB        | 0.98        | 1           | 0.81      | 1.06          | 0.99     | 1.02     | 0.95   |

| Standard Deviations (3-7 keV) |             |             |           |               |          |          |        |
|-------------------------------|-------------|-------------|-----------|---------------|----------|----------|--------|
|                               | NuSTAR FPMA | NuSTAR FPMB | Swift XRT | Chandra HETGS | XMM MOS1 | XMM MOS2 | XMM pn |
| NuSTAR FPMA                   | 0           | 0.01        | 0.14      | 0.03          | 0.02     | 0.02     | 0.02   |
| NuSTAR FPMB                   | 0.01        | 0           | 0.14      | 0.04          | 0.02     | 0.02     | 0.02   |

# Future Work

- Double check our spectral data for Swift and Chandra.
- Wait for the XMM-Newton 2021 data.
- Write a paper with these results.

Cross-calibrations of satellites are essential to ensuring accurate results obtained from these observatories. This work may serve as a reference for those using data collected from multiple satellites at different times.