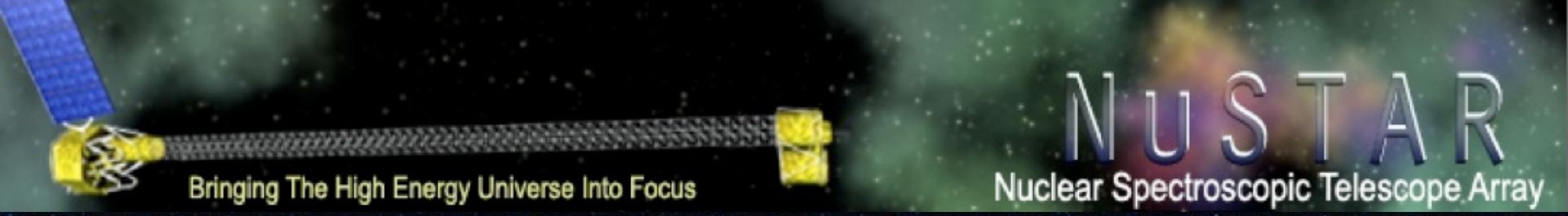


NuSTAR Calibration Status

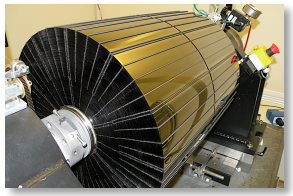
Karl Forster for the NuSTAR team

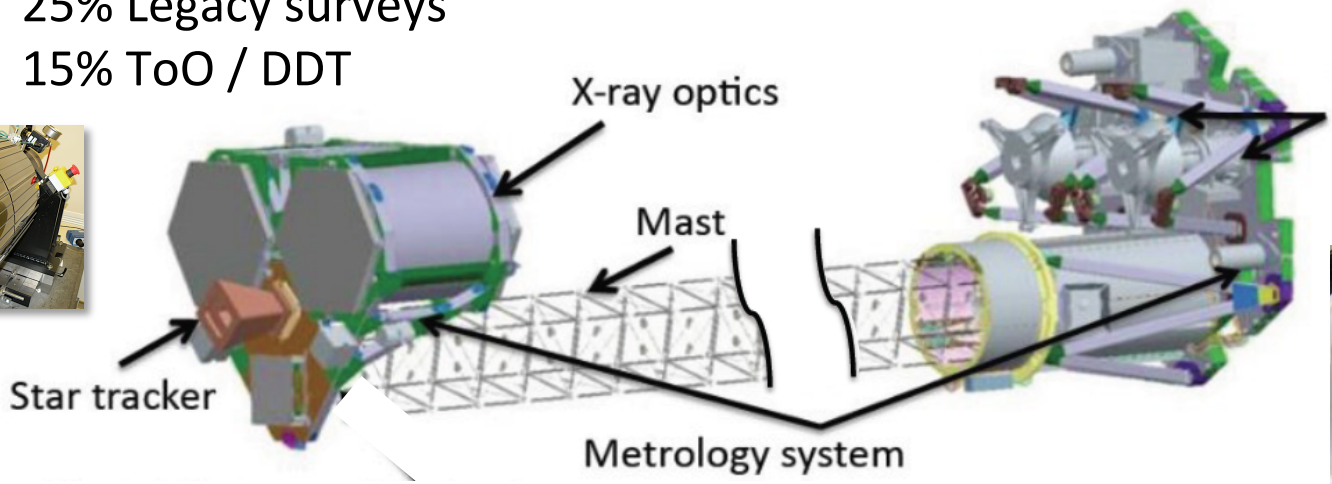
10th IACHAC meeting
Beijing, China

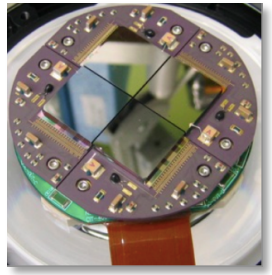
NuSTAR – the basics…

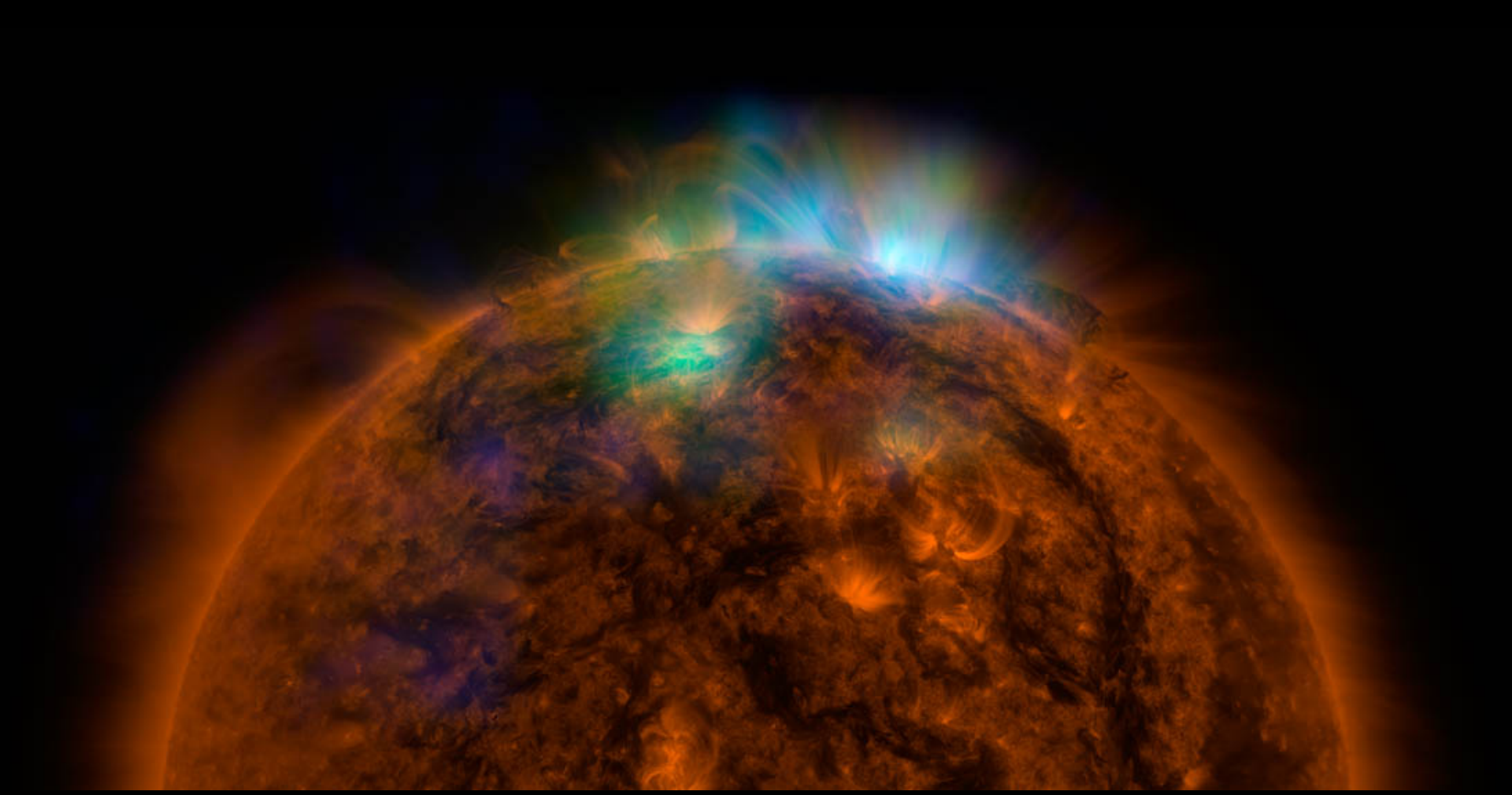
- NASA small explorer class mission
  - PI Fiona Harrison – Caltech
    - Partners: ASI, ASDC, DTK, HEASARC
  - Launched June 2012, 600km 6° orbit
- Completed baseline science mission
- First extended mission
  - 50% Guest Observer Programs
    - Joint XMM, Chandra, Suzaku – Swift
  - 25% Legacy surveys
  - 15% ToO / DDT

- **2 telescopes (FPM)**
- **10.14m focal length**
- **12' x 12' field of view**
- **1 arcmin HPD**
- **2x2 CZT detector array**
- **3-79 keV energy range**
- **0.4 to 1 keV resolution**









NuSTAR and SDO image of the Sun

The NuSTAR data, seen in green and blue, reveal solar high-energy emission (green shows energies between 2 and 3 kiloelectron volts, and blue shows energies between 3 and 5 kiloelectron volts). The high-energy X-rays come from gas heated to above 3 million degrees.

The red channel represents ultraviolet light captured by SDO at wavelengths of 171 angstroms, and shows the presence of lower-temperature material in the solar atmosphere at 1 million degrees.

Mission Status

- Spacecraft and instrument - ***nominal***
  - Detector shield PMT threshold adjusted to return to correct SAA trigger behavior (June 2014)
  - Metrology system laser-1 operating power adjusted in response to trend in laser intensity (December 2014)
- Calibration - ***nominal***
  - Calibration paper submitted to ApJS
    - Madsen et al. 2015 arXiv 1504.01672v1
  - Latest CALDB patch 20150316 addresses time dependent change in detector energy scale (gain)
    - Released 2015-03-20
  - Cross calibration campaign on 3C 273 planned for June 17-19th
    - NuSTAR, Chandra, XMM, Swift, & Suzaku (possibly INTEGRAL)

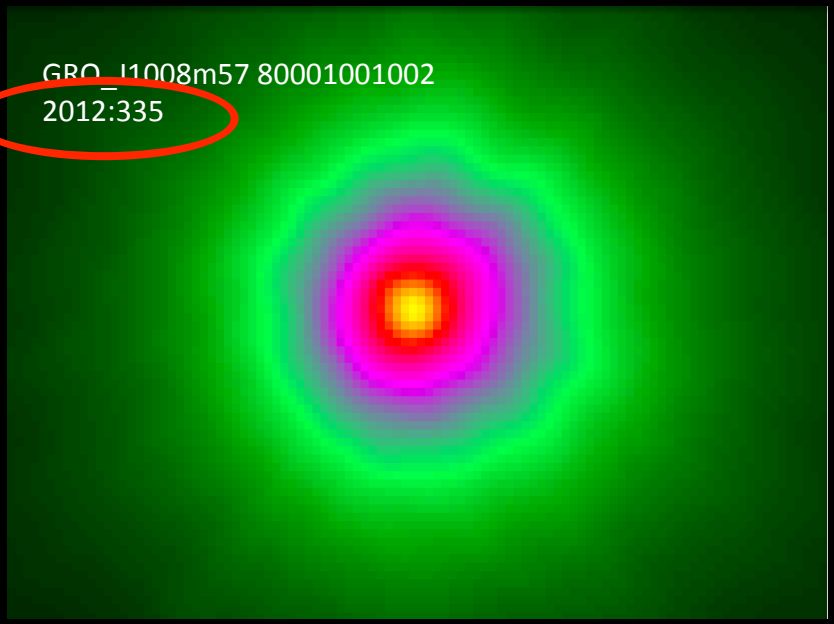
NuSTAR Calibration

- Effective Area
  - Multiple observations of Crab nebula
  - Assume Γ = 2.1 in 3-78 keV range
  - Measure N_H = 2.224 x 10^{21} cm^{-2}
    - normalized using 3C 273 measurement
- Absolute normalization uses cross-calibration observations
  - ***IACHEC organized simultaneous observations of PKS 2255-301 & 3C 273***
  - Simultaneous modeling of data from *NuSTAR* and *Chandra, XMM-Newton, Swift, & Suzaku*
- Vignetting response
  - 39 observations of Crab at multiple off axis angles in 2012 & 2013
    - Uses piece-wise linear spline function to modify ground calibration model
    - Model corrections for energy dependence including ghost-rays (single bounce) and aperture stop
- PSF calibration
  - Multiple observations of bright point sources
    - Cyg X-1, Vela X-1, GRS 1915+105, GS 0834-430, Her X-1
- Detector gain calibration
  - Uses deployable calibration source ^{155}Eu deployed in June 2012 and January 2015
- Timing calibration
  - On-board time reference uses temperature compensated crystal oscillator 24 MHz
  - Routinely correlated with ground time references (referenced to UTC via GPS)
  - Timing performance characterized using observations of pulsars in Crab and B1509-58
  - System performance accuracy of 3 ms
- **See NuSTAR observatory calibration paper (Madsen et al. 2015 arXiv :1504.01672v1)**

PSF stability

(Kristin Madsen)

- Using observations of brightest point sources scattered throughout the mission
  - GRO J1008-57 2012:335
  - GRO J1744-28 2014:047
  - GRS 1739-278 2014:086
  - Cyg X-1 2015:019
- Avoiding detector gaps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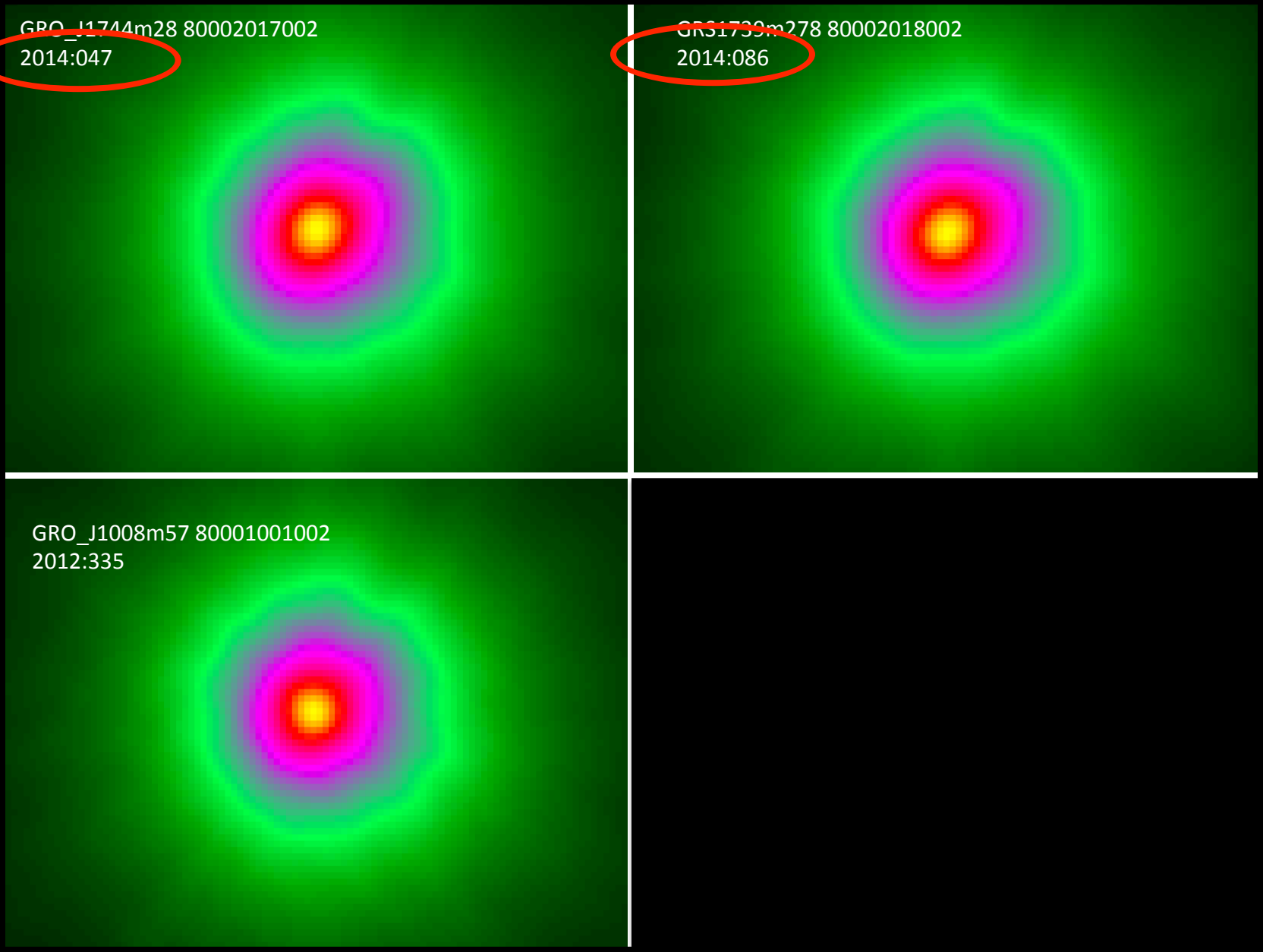
2012:335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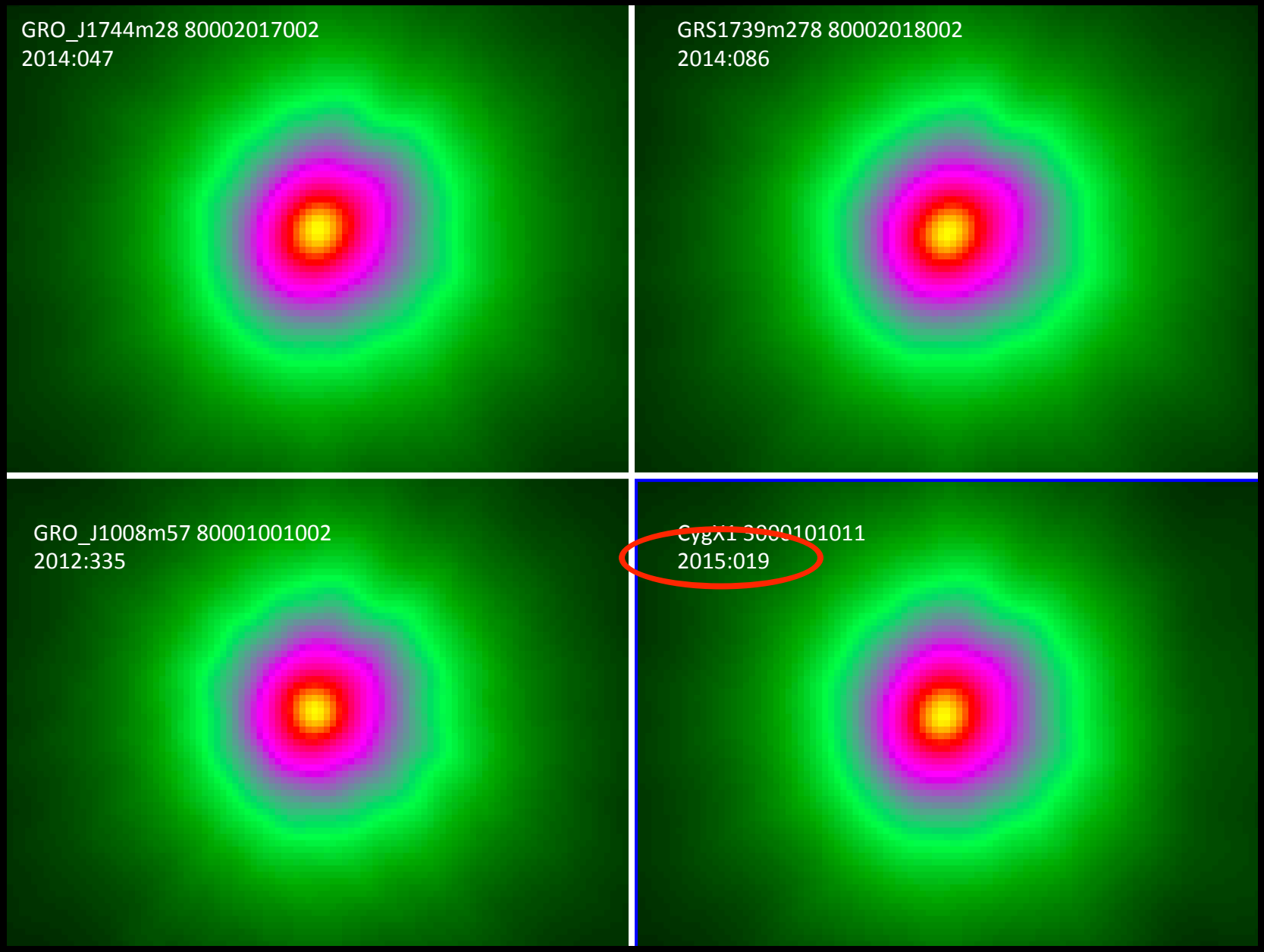
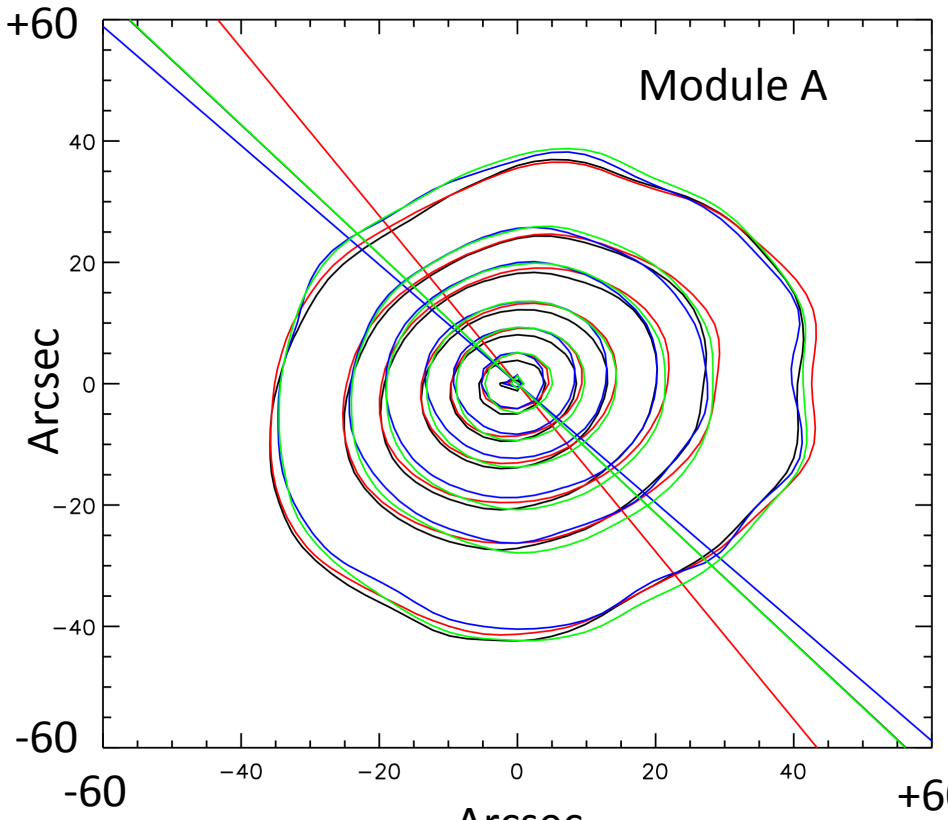
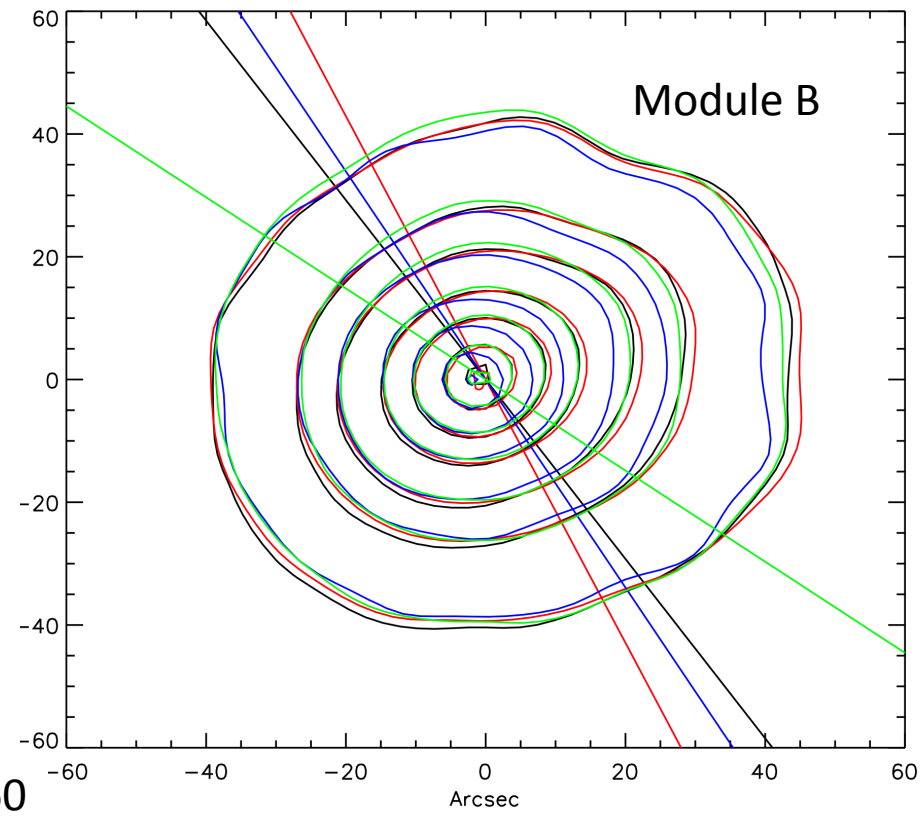
2014:047
GRS1739m278 80002018002
2014:086
GRO_J1008m57 80001001002
2012:335


GRO_J1744m28 80002017002
2014:047
GRS1739m278 80002018002
2014:086
GRO_J1008m57 80001001002
2012:335
2015:019

PSF stability

Contours





GRO_J1744m28
GRS1739m278
GRO_J1008m57
Cyg_X1

The lines are the direction of the optical axis and the direction along which the PSF compresses

PSF stability

Conclusion

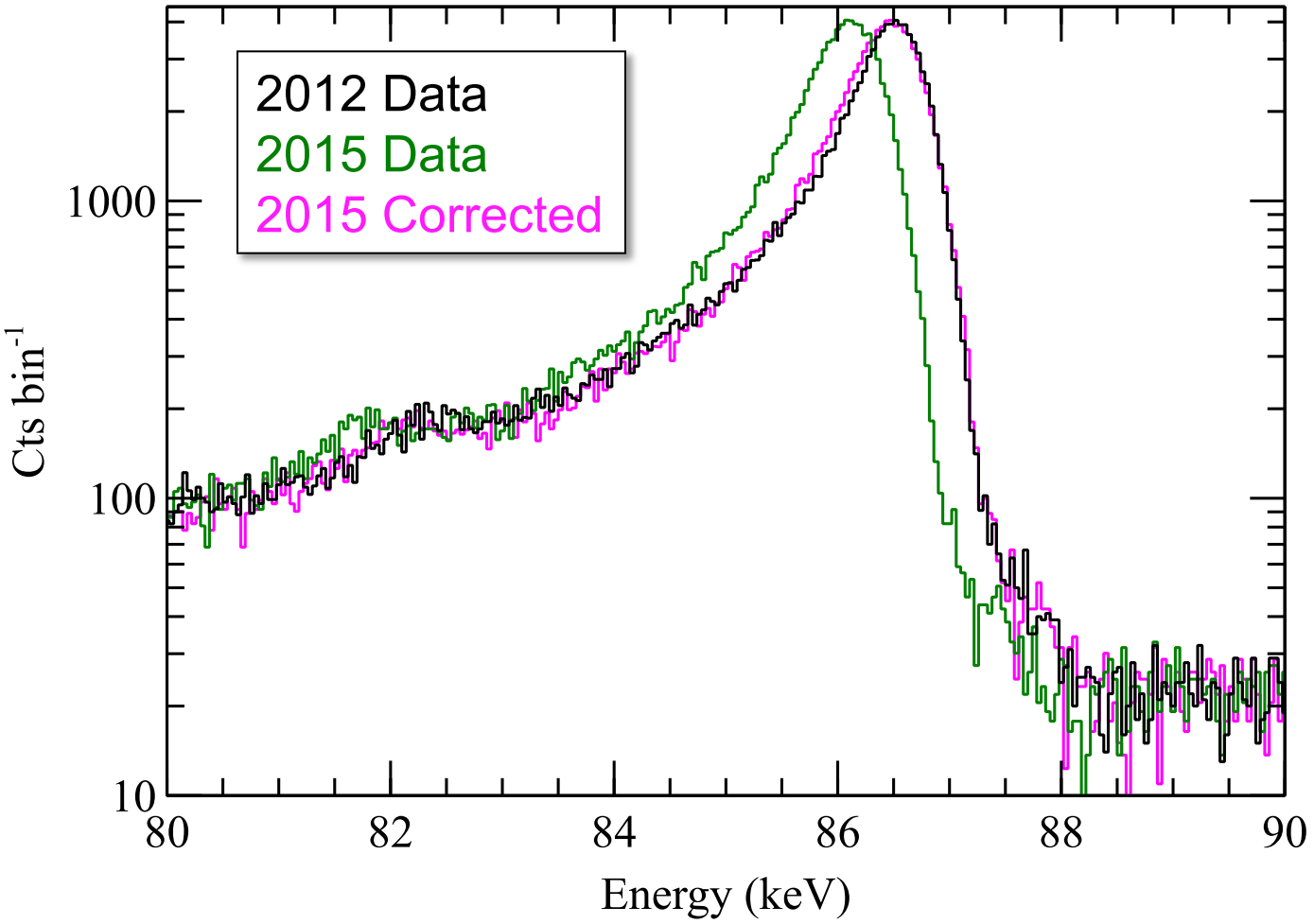
- Both module A and B show remarkable stability over time. The macroscopic figure errors have not changed since launch.
- This means:
  - Internal alignment and aspect reconstruction remains unchanged.
  - No change in figure error and probably no change in microroughness either
  - And therefore no change in the effective area!

Detector Calibration

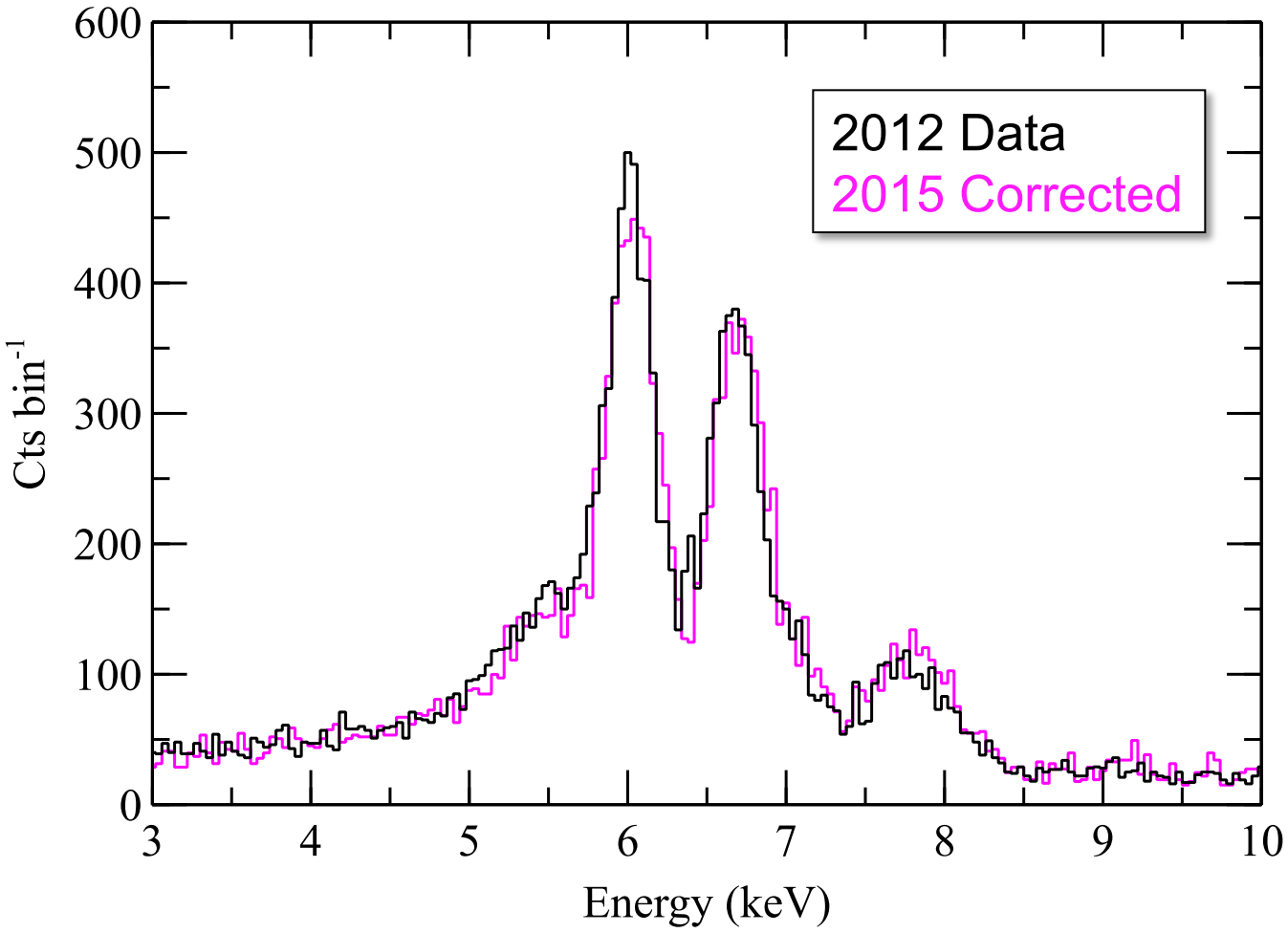
(Brian Grefenstette)

- Hints based on background lines of a slow decrease in apparent line energy. (Takao Kitaguchi and Andreas Zoglauer)
  - Need to integrate ~6 months of background data to get enough statistics to measure this.
- ^{155}Eu Calibration source deployed in January 2015 to measure any potential gain shift since June 2012.
  - Emission lines complexes at 6, 45, & 85 keV
  - Led to recalculation of all gain parameters.

2012 vs. 2015


2012 Data
2015 Data
2015 Corrected
1000
100
10
Cts bin-1
80
82
84
86
88
90
Energy (keV)

2012 vs. 2015


2012 Data
2015 Corrected
Cts bin^{-1}
Energy (keV)
0
100
200
300
400
500
600
3
4
5
6
7
8
9
10

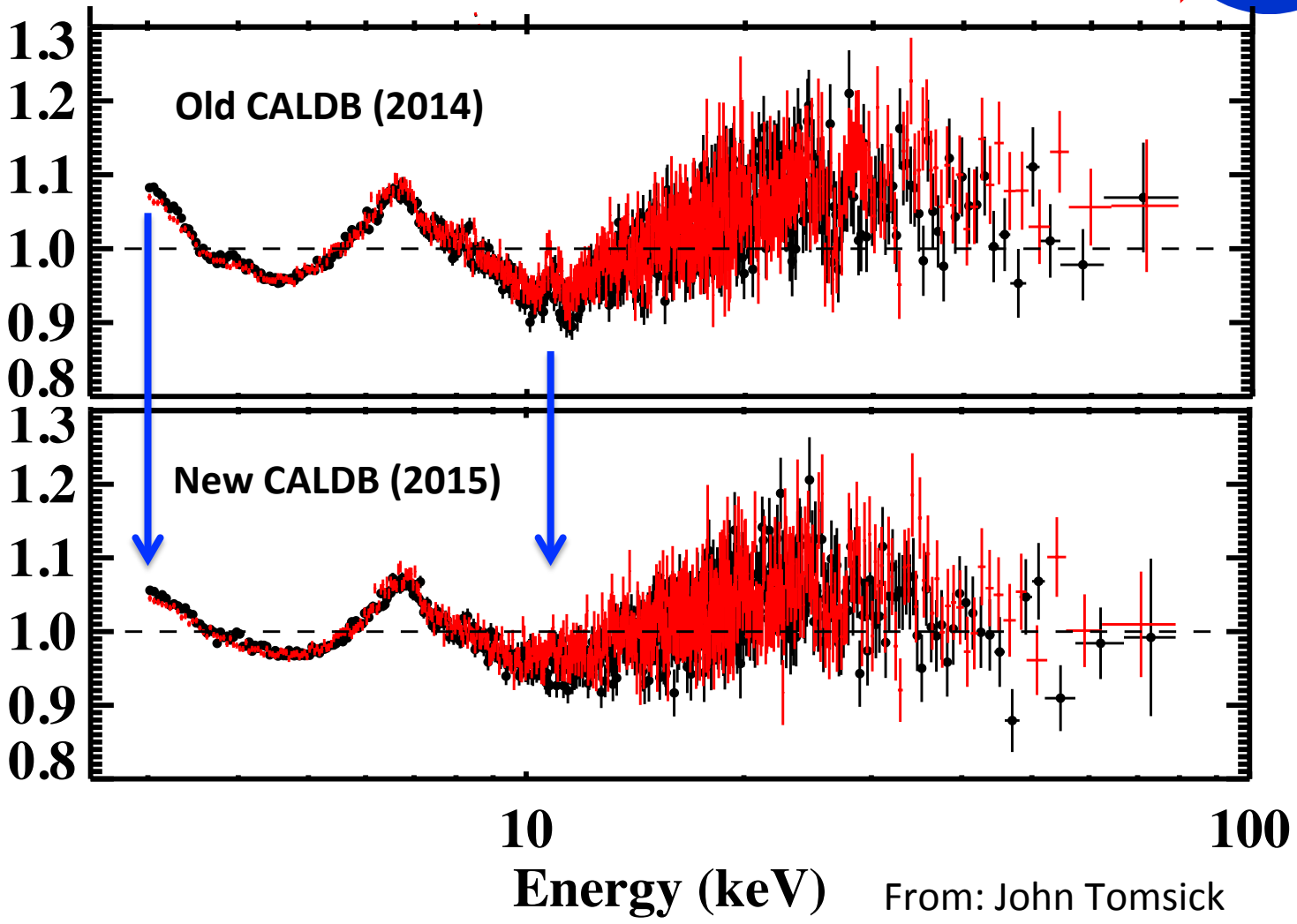
Detector Calibration

(Brian Grefenstette)

- Hints based on background lines of a slow decrease in apparent line energy. (Takao Kitaguchi and Andreas Zoglauer)
  - Need to integrate ~6 months of background data to get enough statistics to measure this.
- ^{155}Eu Calibration source deployed in January 2015 to measure any potential gain shift since June 2012.
  - Emission lines complexes at 6, 45, & 85 keV
  - Led to recalculation of all gain parameters.
- Absolute gain shift for DET0 FPMA/B over ~2.6 years:
  - **A: 0.55% B: 0.26%**
  - So… roughly 0.15 to 0.25% per year *(assumed linear)*
- Recommend quoting a systematic error of **~40 eV** near the Fe K-lines rising to a systematic error of **~60 eV** near 68 keV ^{44}Ti lines.
  - Reprocess data taken after mid-2013

Example: GX 339

No more residual features



From: John Tomsick

Summary of NuSTAR calibration status

- ARF - *completed*
  - ARF revisions:
  - 2013-08-04 CALDB version 20130509
    - Based on 1st Crab calibration
  - 2013-11-25 CALDB version 20131007
    - Absolute normalization adjustment (+15% area, -15% flux) based on IACHEC cross calibration observations
  - 2014-01-17 CALDB version 20131223
    - Revised Crab high energy calibration
- PSF – *completed*
- Detectors – *completed*
  - Gain/CLC revisions:
  - CALDB version 20140414: Corrections for some high-grade events
  - CALDB version 20150316: Time dependent gain calibration
- Background – *Understood and managed*
  - QA & NuSTARDAS screening