Recent results from the NuSTAR satellite and synergy with Astro-H

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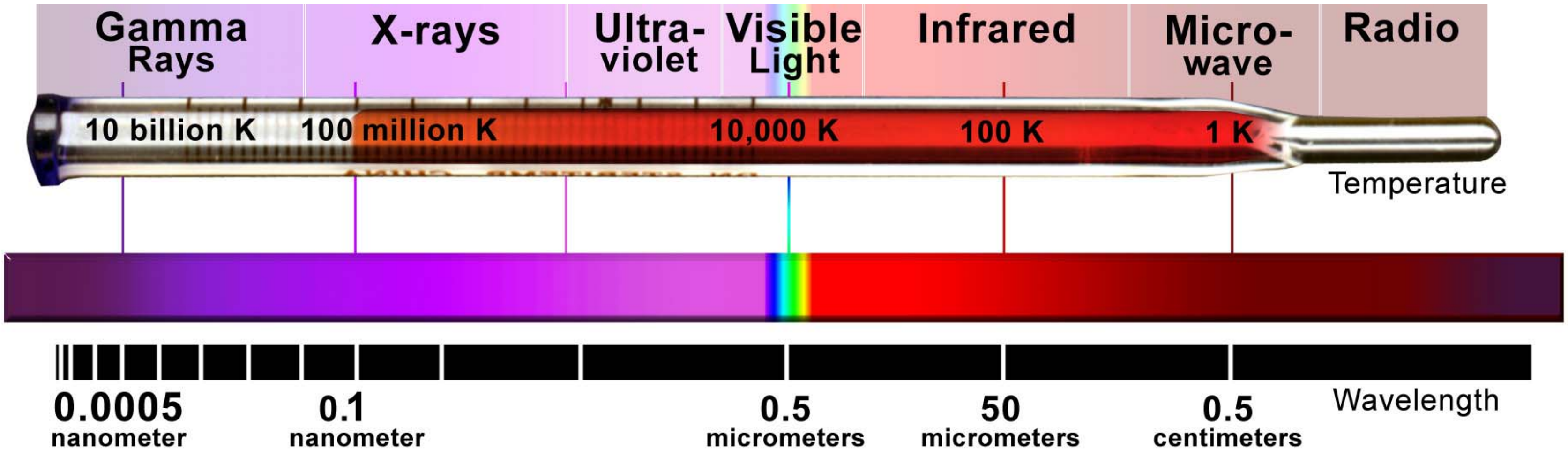
Outline:

- High energy astrophysics as a unique window on the sky
- NuSTAR as a new tools in the sky imaging hard X-ray observatory
- Selected v. recent results from NuSTAR:
    - Supernova remnants and Cas A
    - Active galaxies and their black holes
    - Jet-dominated active galaxies (=blazars)
    - Galaxy clusters
    - Recent supernova in the galaxy M82

X-rays and gamma-rays in perspective

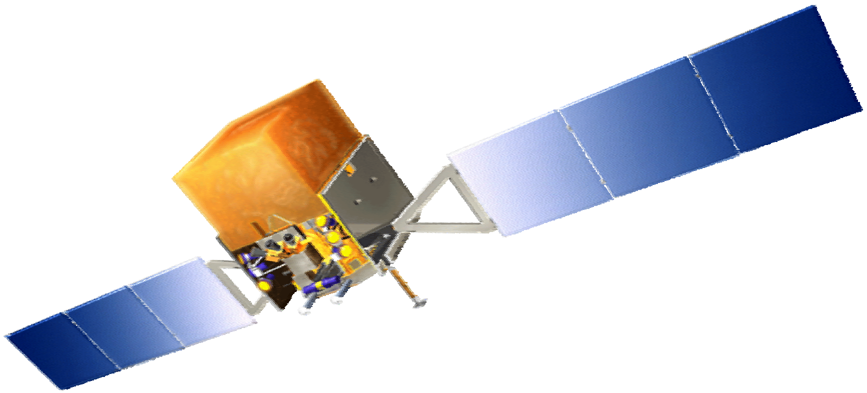


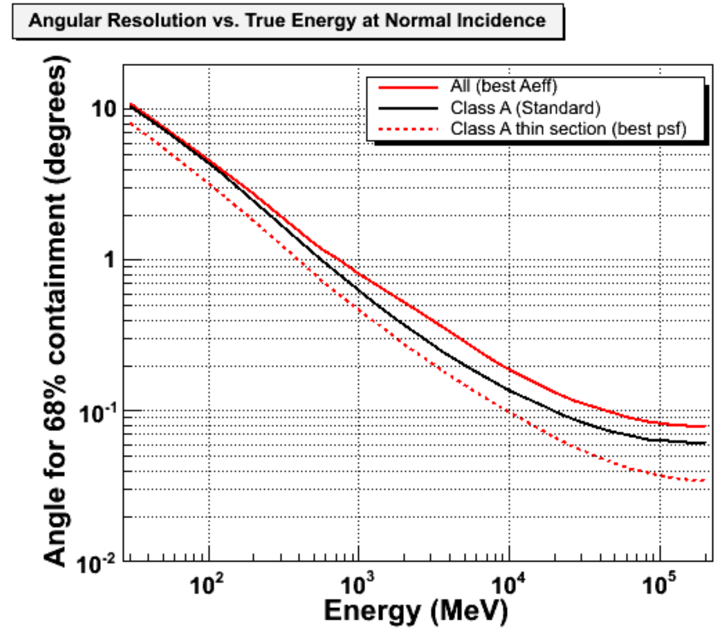
- Hard X-ray and γ-ray data often – but not always – are indicative of non-thermal phenomena

  -> violent, explosive processes

  -> extremely energetic particles

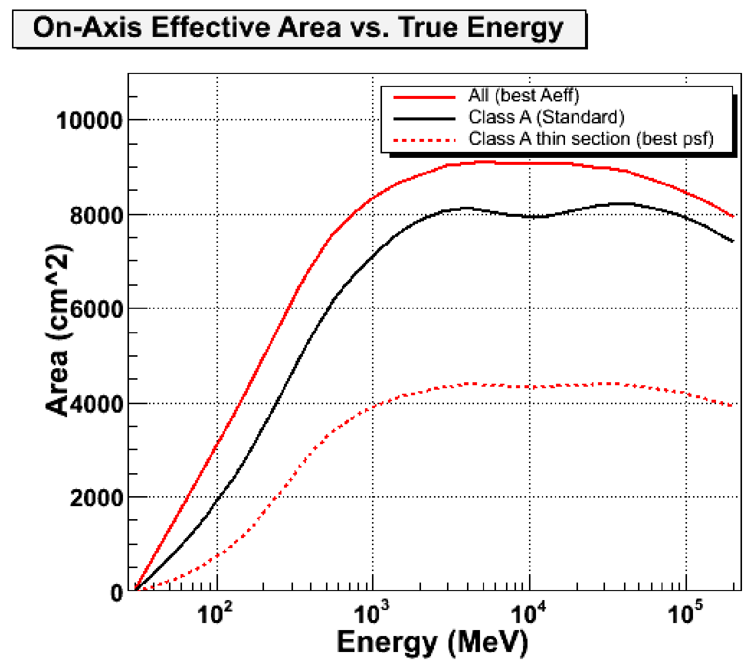
Fermi satellite and γ-rays from the sky



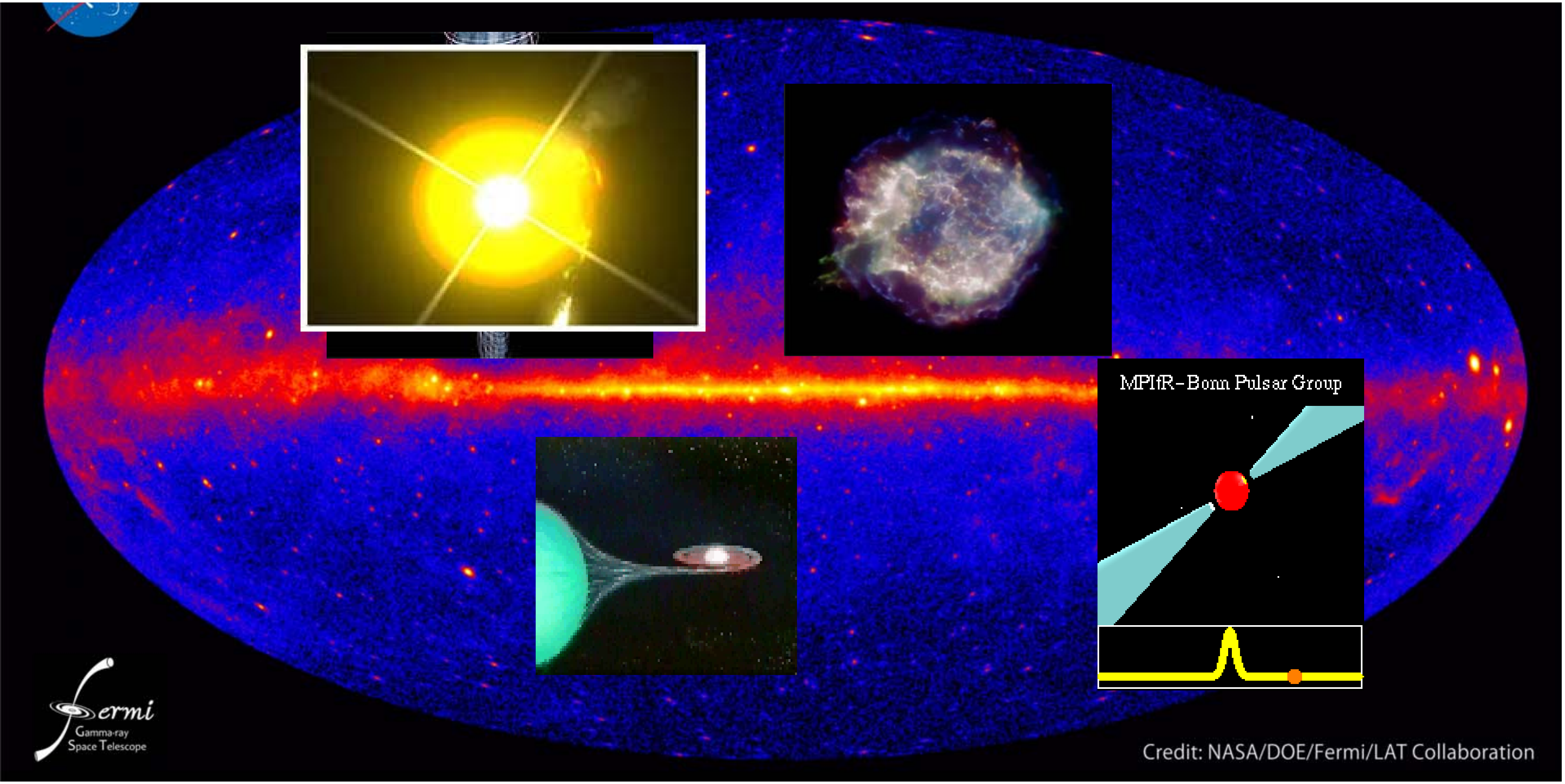


"Take-away" parameters of the Large Area Telescope (LAT)

- Wide field of view allows monitoring of ~ 2 steradians of the sky
- Fermi-LAT always points away from the Earth (good duty cycle)
- Energy range is ~ 0.03-300 GeV - allows an overlap with TeV observatories
- Peak effective area of ~ 10,000 cm^2
- Energy resolution is about 10%
- In 1 day, it covers the whole sky quite uniformly



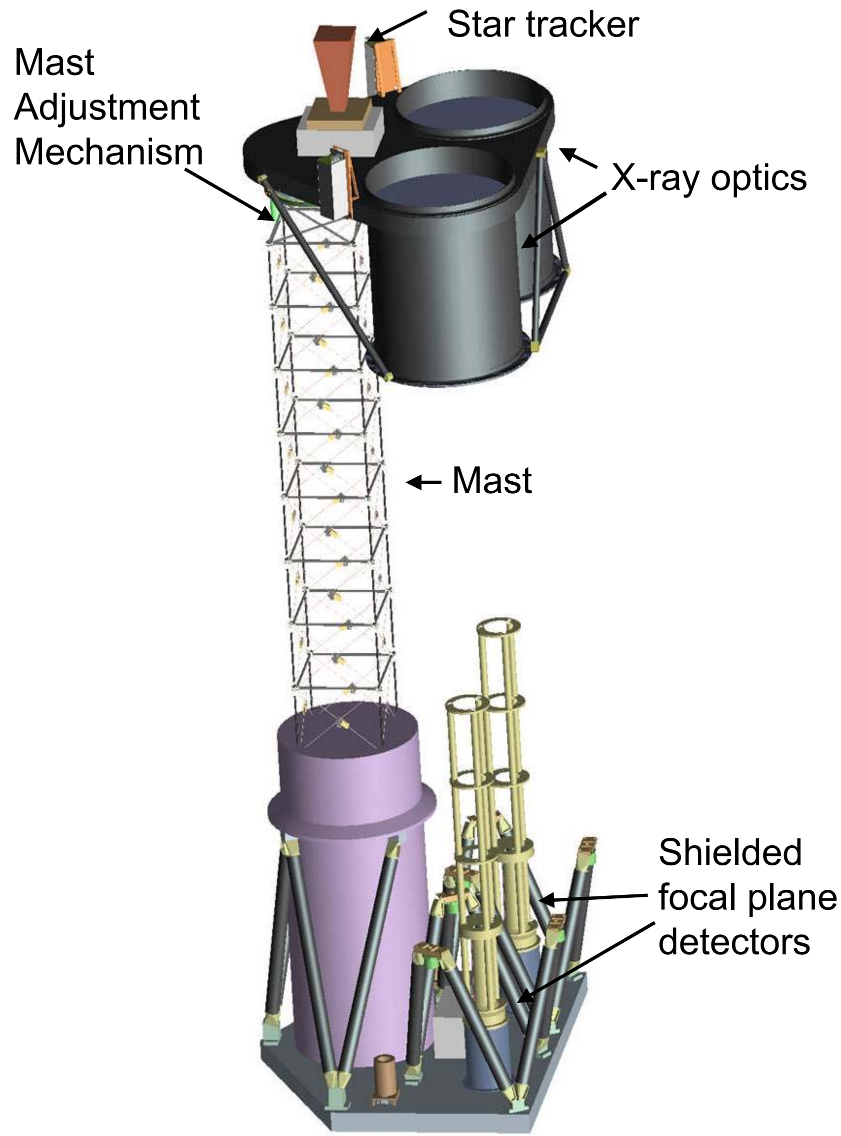
The >1GeV Sky:



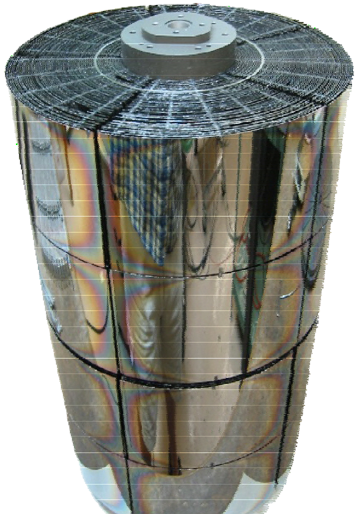
Thousands of celestial gamma-ray sources of all kinds…

Exploring the hard X-ray sky: Basic facts about NuSTAR

- NASA's Small Explorer mission, launched in June 2012
- Two identical coaligned grazing incidence hard X-ray telescopes:
  - Multilayer coated segmented glass optics
  - Actively shielded solid state CdZnTe pixel detectors
- Extendable mast provides 10-m focal length
- Focussing optics reduces background!
- Energy bandpass 6 – 80 keV
- Pegasus rocket / satellite in low-Earth orbit
- Performance as good or better than predicted!



NuSTAR: What is it?



NuSTAR optics

* NuSTAR is the first satellite-based focusing X-ray telescope operating in the hard X-ray band, 5 – 80 keV

* Leading institution is Caltech (Fiona Harrison, PI)

* Launched into a low-Earth, nearly equatorial orbit -> low background

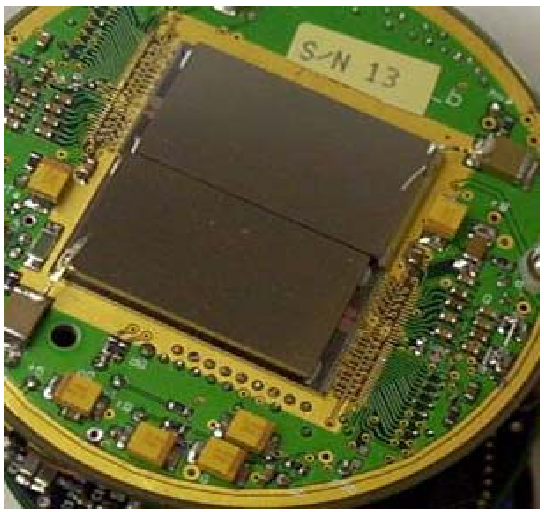
• It is a part of NASA's Small Explorer program

NuSTAR features three key novel technologies:

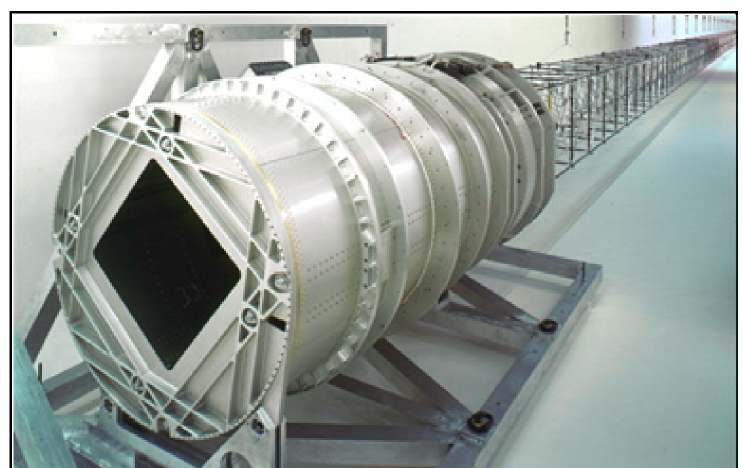
• Co-aligned multi-coated focusing hard X-ray telescopes: excellent angular resolution will allow surveys at unprecedented sensitivity

• Pixellated CdZnTe detectors: broad bandpass well matched to the telescope reflectivity

• Deployable mast, enabling the ~ 10 m focal length
|
|------------------------->

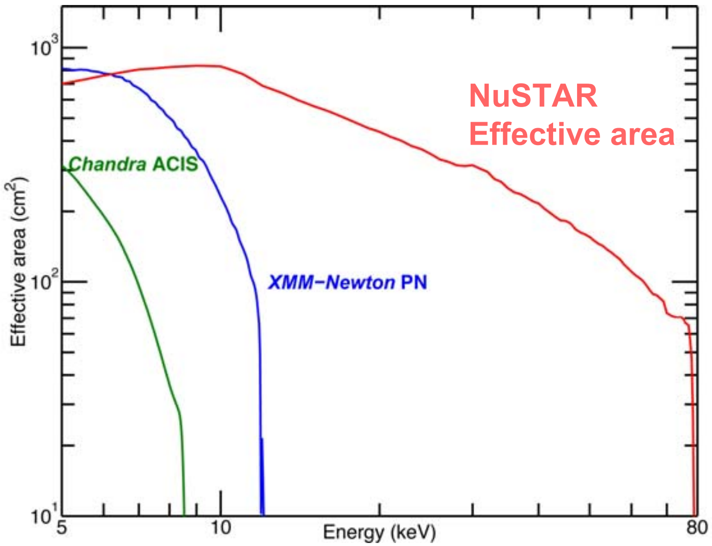


CdZnTe detectors:
pixel size 0.6 mm (~ 12")
Max. count rate: 300 cts/s
HEFT heritage



Launch “on the cheap”

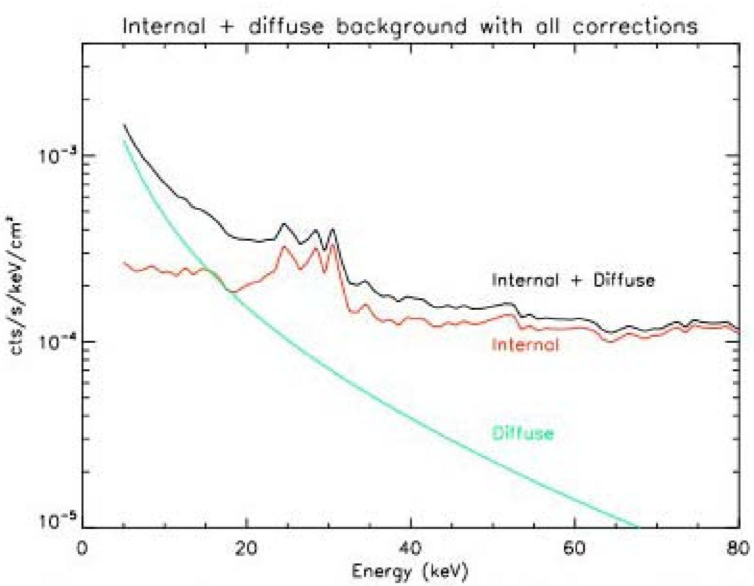
NuSTAR: key parameters



Energy range	**3– 80 keV**
Angular resolution	**50” Half Power Diameter, 7.5” FWHM**
Field of View	**13 arc min x 13 arc min @ 10 keV**
Spectral resolution	**1.2 keV at 68 keV**
Sensitivity (3σ, 10^6 Sec)	**2 x 10^{-15} erg/cm^2/s (6-10 keV) 1 x 10^{-14} erg/cm^2/s (10-30 keV)**
Timing resolution	**0.1 millisecond**
ToO response	**< 48 hour**
Orbit	**6^o inclination, 550 x 600 km**
Mission lifetime	**2 years baseline**
Orbit lifetime	**> 7 years**

FIRST DATA ARE NOW PUBLIC AT HEASARC!

http://www.nustar.caltech.edu/for-astronomers/simulations



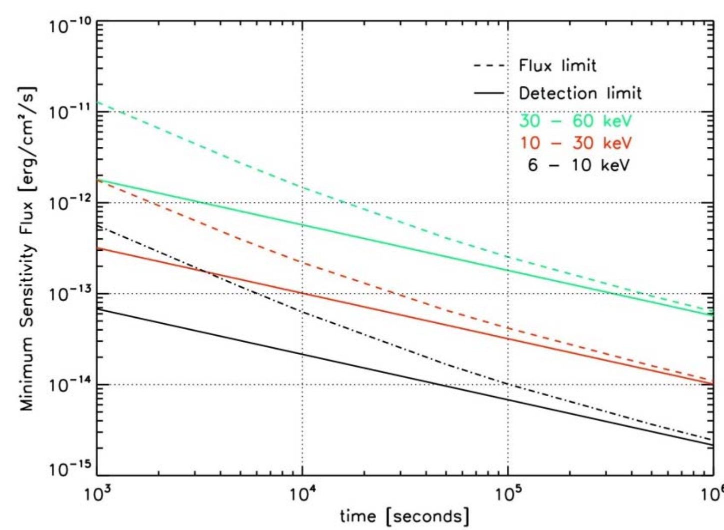
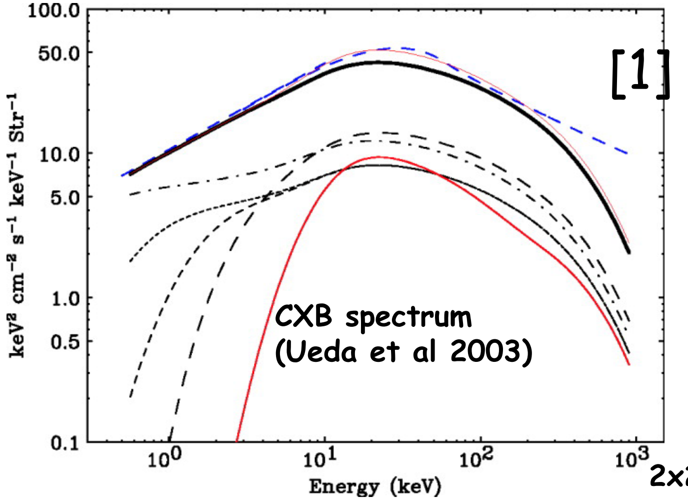


Figure 9. On-axis detection (4-sigma) and flux measurement sensitivity for several energy bands as a function of integration time.

NuSTAR: key science goals



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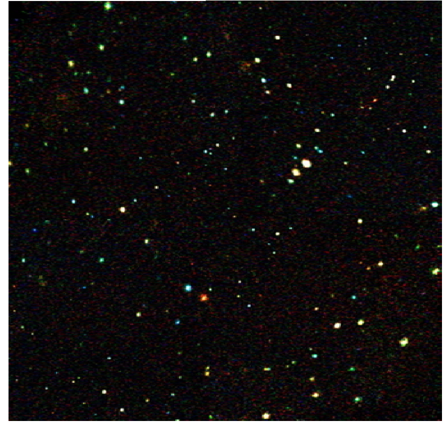
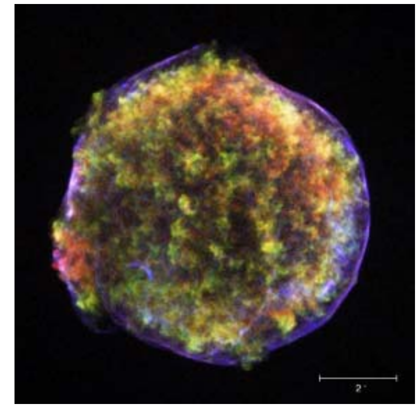


2x2 degrees simulated NuSTAR image

Tycho SNR



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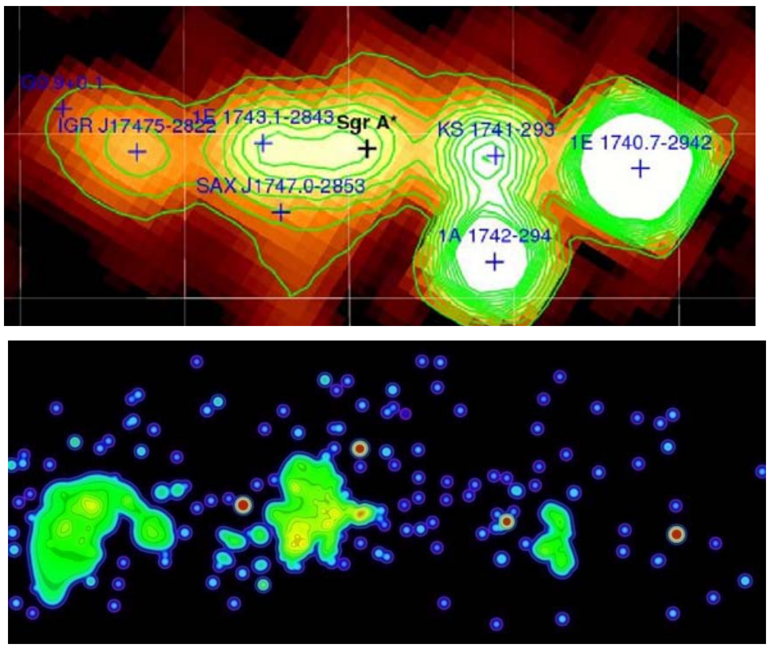


[2]

INTEGRAL observation (top) and
NuSTAR simulation (bottom)
of the Galactic center 2 x 0.8° region

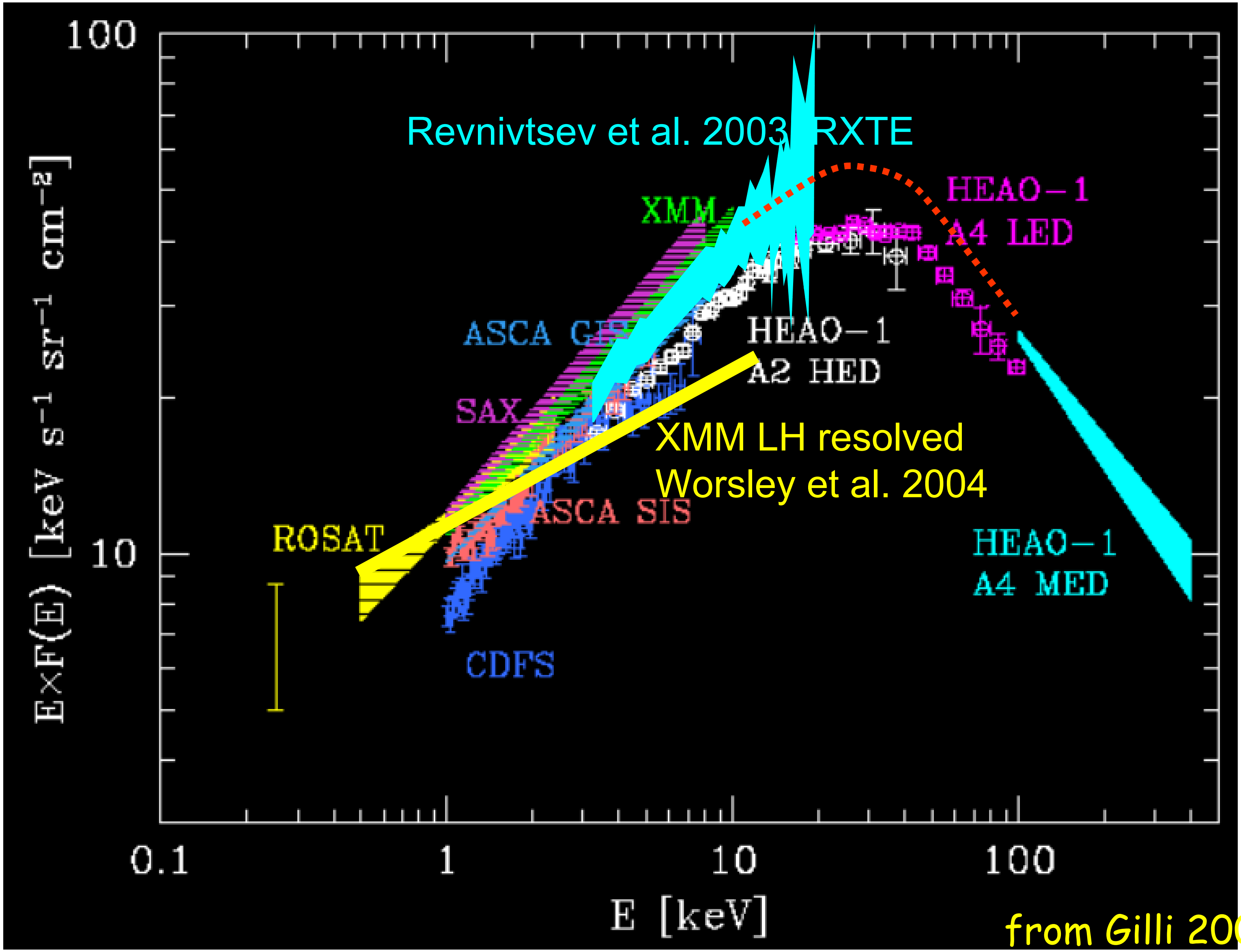
Objective #1: How are black holes distributed through the cosmos, and how do they affect the formation of galaxies?

Objective #2: How are stellar remnants distributed within the Galaxy and near the Galactic center?

Objective #3: How do stars explode and forge the elements that compose the Earth? (Ti 44 lines, 68/78 keV)

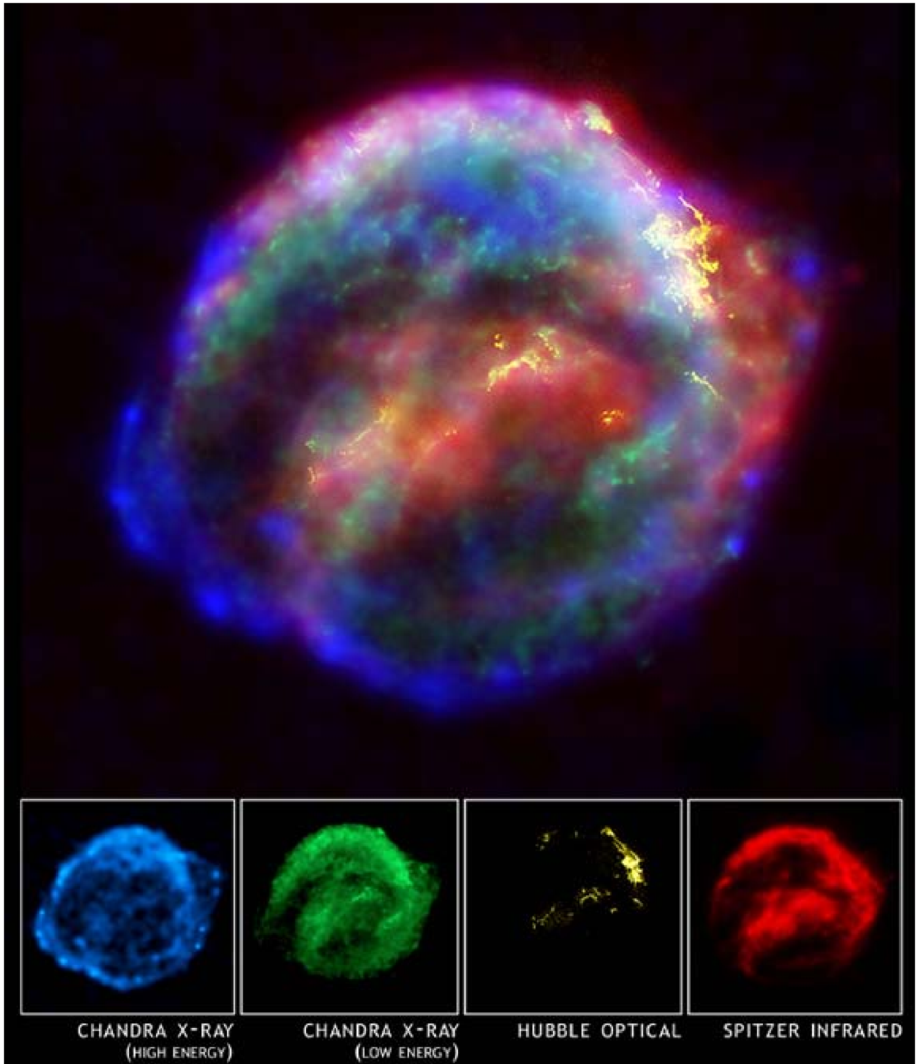
Objective #4: What powers the most extreme, jet-dominated active galactic nuclei?
-> blazar monitoring campaigns

Cosmic X-ray Background Spectrum



from Gilli 2003

Supernovae and their remnants



Composite image of the Kepler's supernova remnant

* Early Universe contained only the lightest elements: hydrogen, helium

* "Heavy" elements were all "cooked" in stars and ejected into the interstellar space via *supernova explosions*

* The velocity of the ejecta, v is roughly 10,000 km/s

* How do we know that v is ~10,000 km/s and not say, 100 or 10^5 km/s?

-> know the age t (typically ~ 1000 years) also know the angular size θ, distance D –> linear size ~ $D^*\theta$ and thus $v = D^*\theta/t$

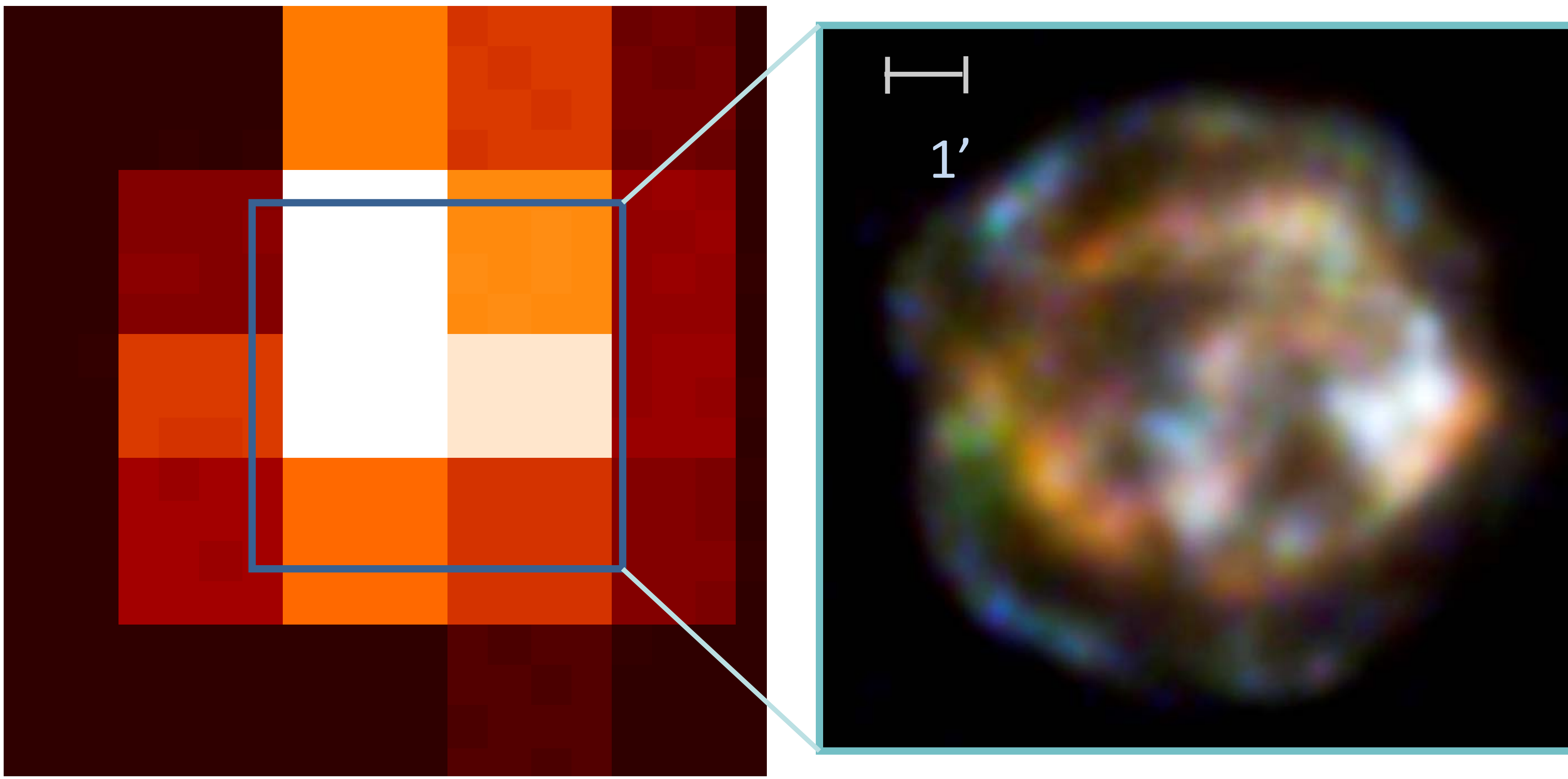
* Multiple observations of SNR separated by ~ years also clearly show the expansion

NuSTAR images of Cas A

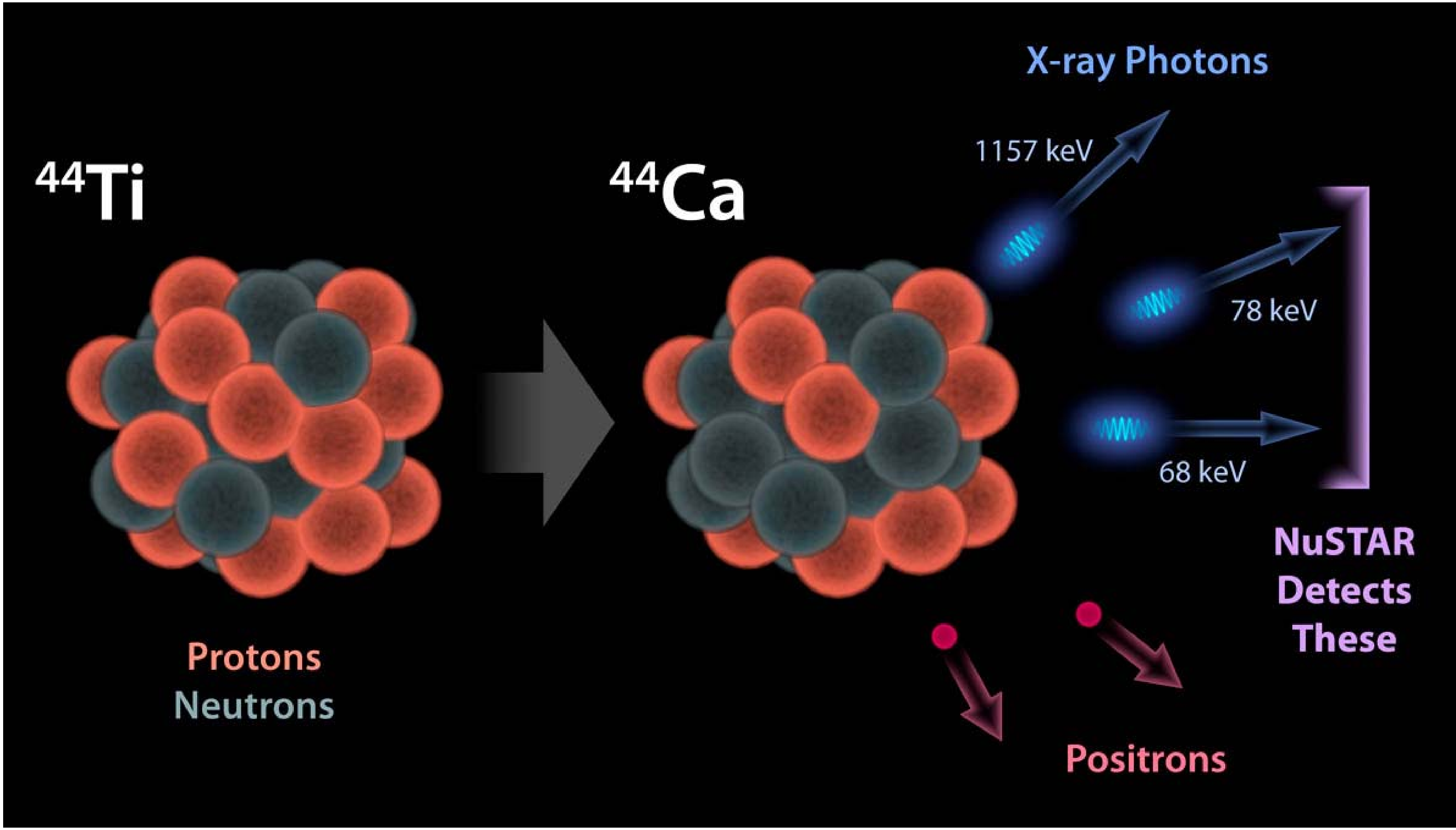
Cas A supernova remnant

INTEGRAL ISGRI
E>15 keV

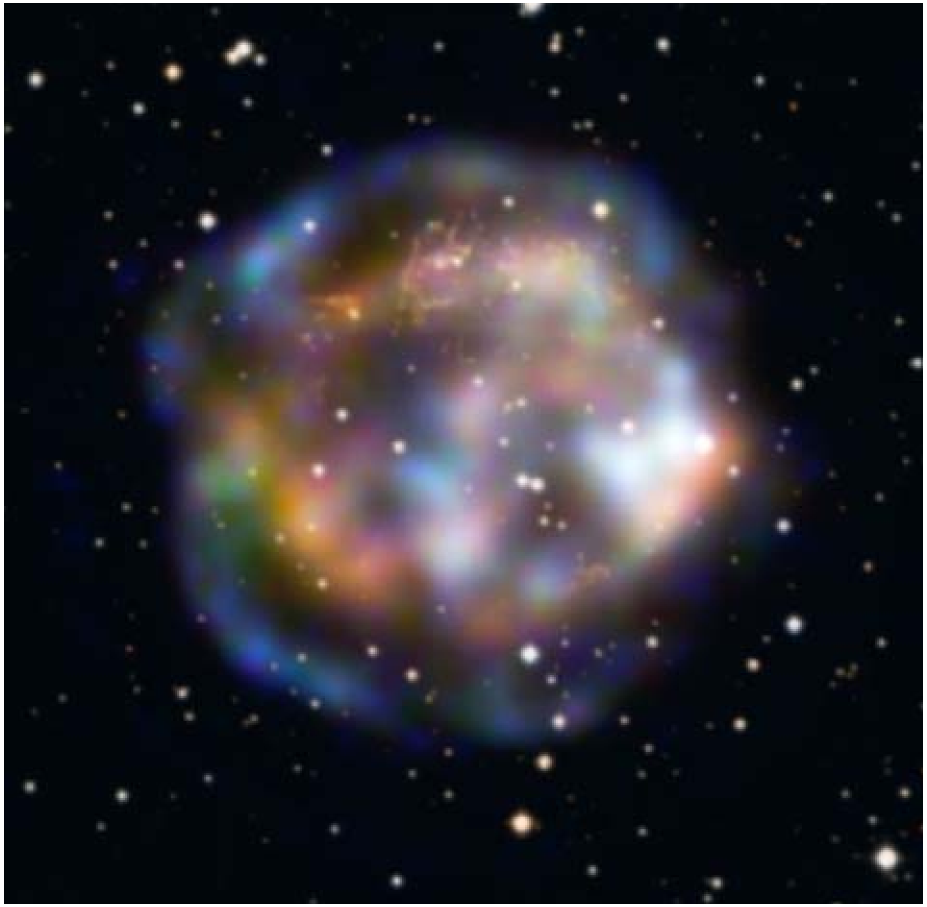
NuSTAR Image
Red : 4.5 – 5.5 keV
Green: 8 – 10 keV
Blue: 10 – 25 keV



Radioactive Titanium



Cassiopeia A:
A 2+ Ms Hard X-ray Study



First images used the ~500 ks of NuSTAR exposure

The total NuSTAR exposure is in excess of 2.5 Ms

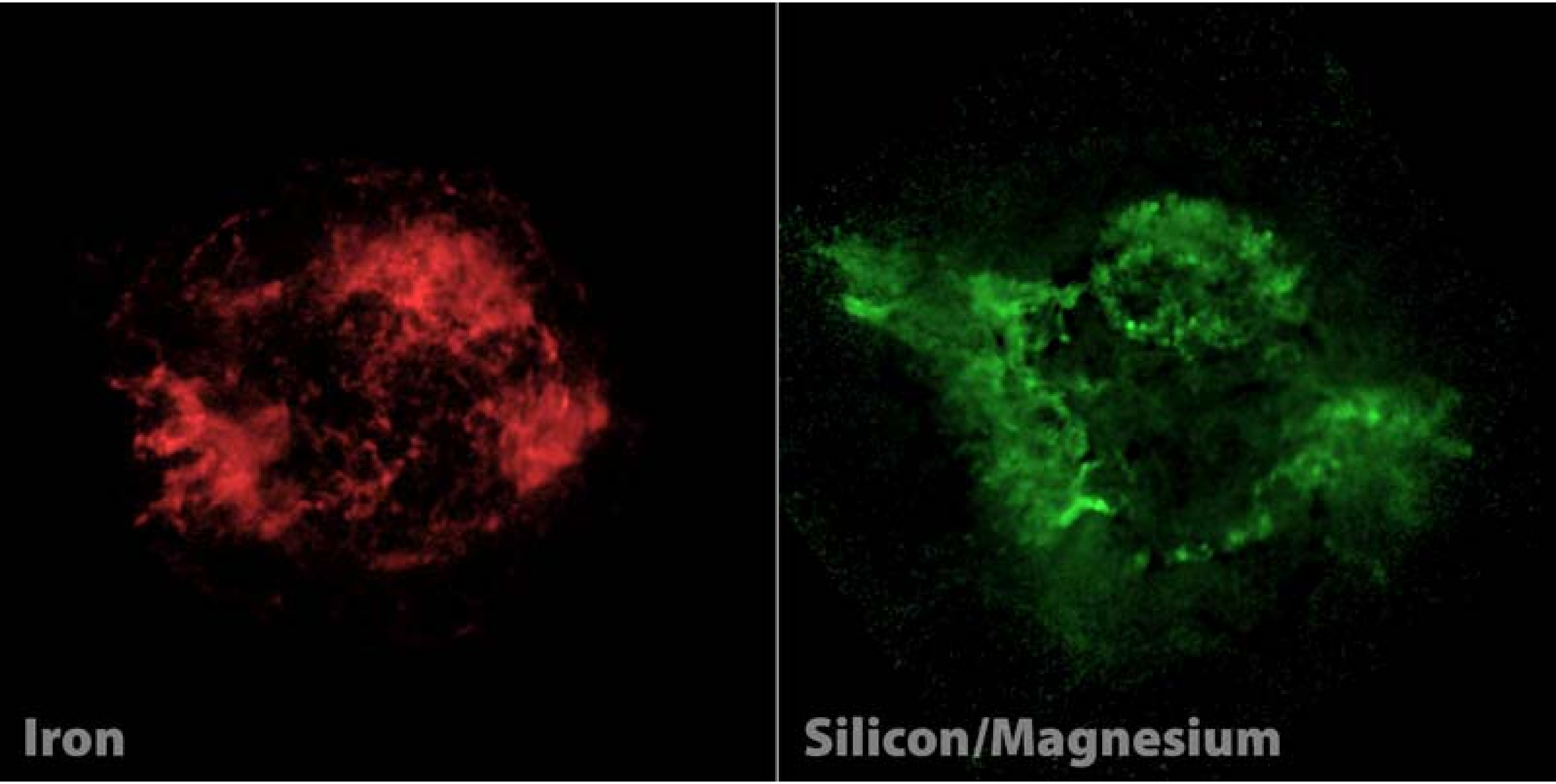
Final observations to be taken Spring 2014

NuSTAR Cas A Composite Image
- Deconvolved with instrument PSF
- Overlaid on DSS image

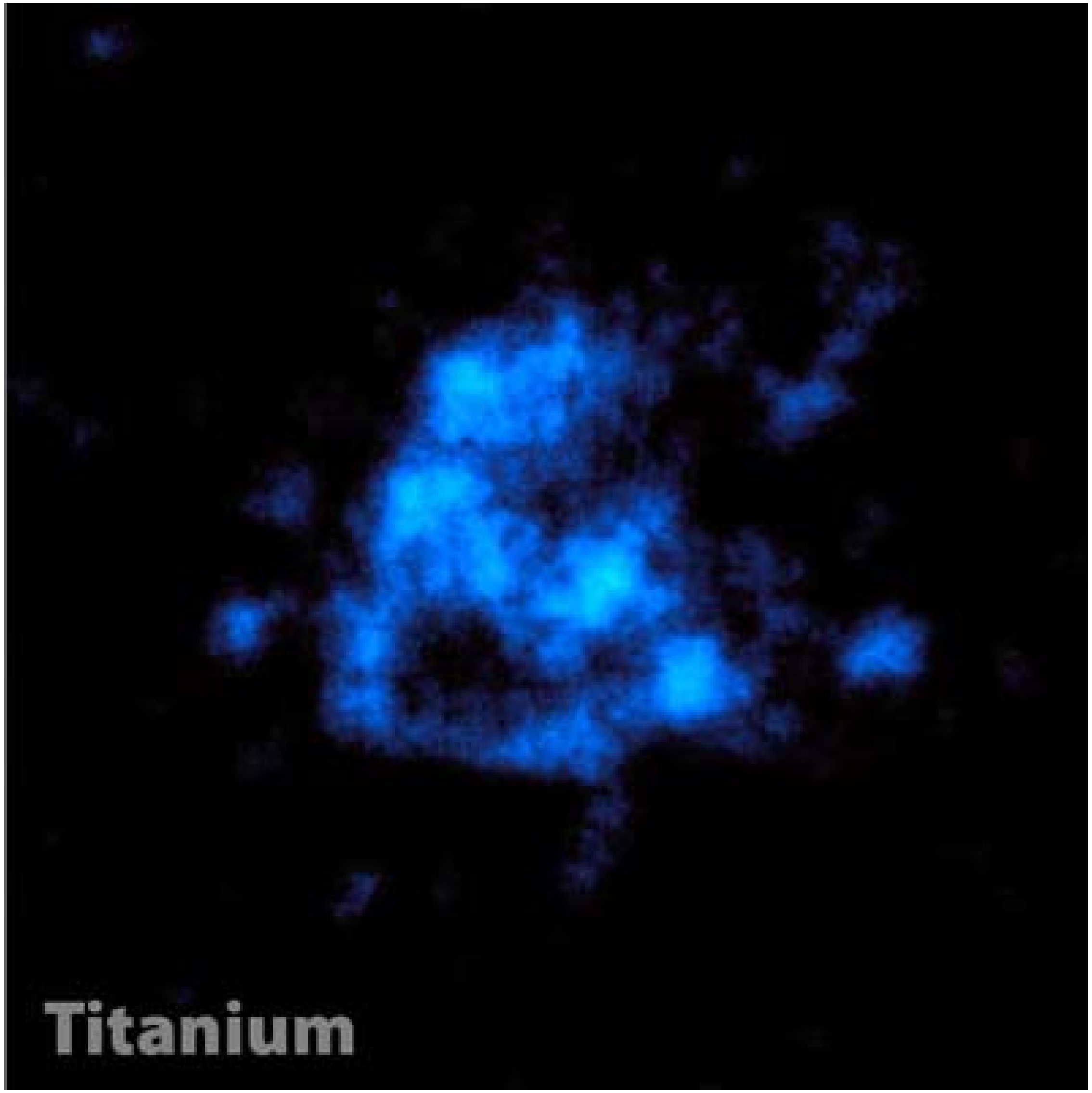
3-6 keV
8-10 keV
15-20 keV

Brian Grefenstette et al 2014, submitted

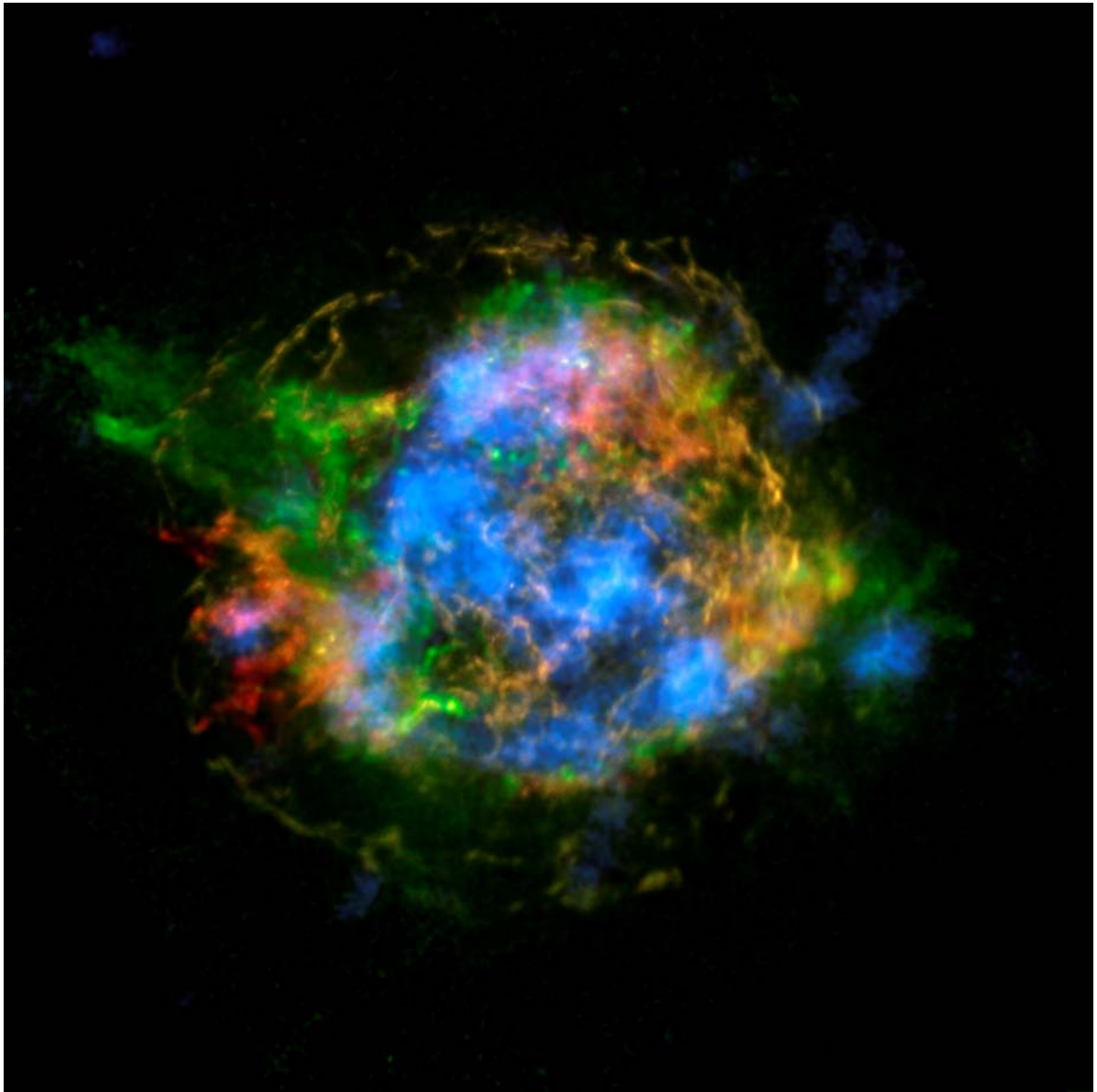
Cassiopeia A: Expectations



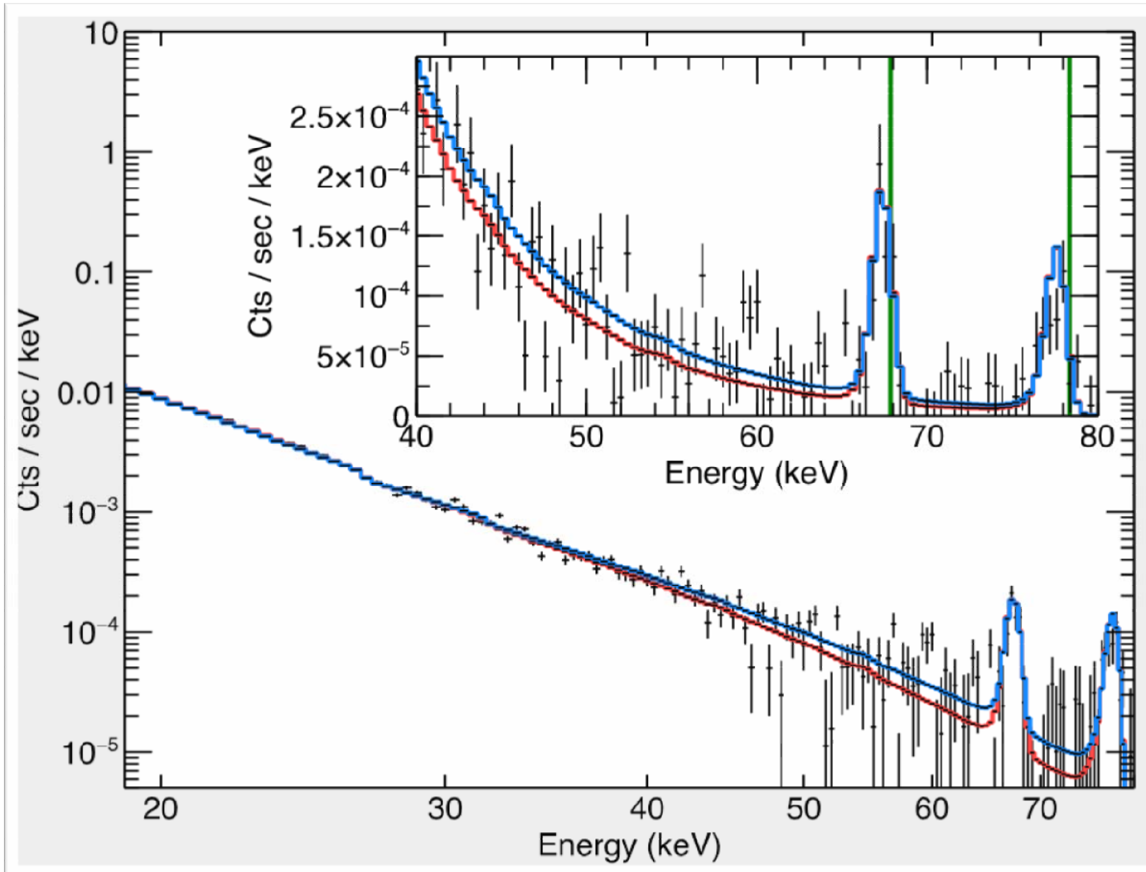
^{44}Ti Morphology



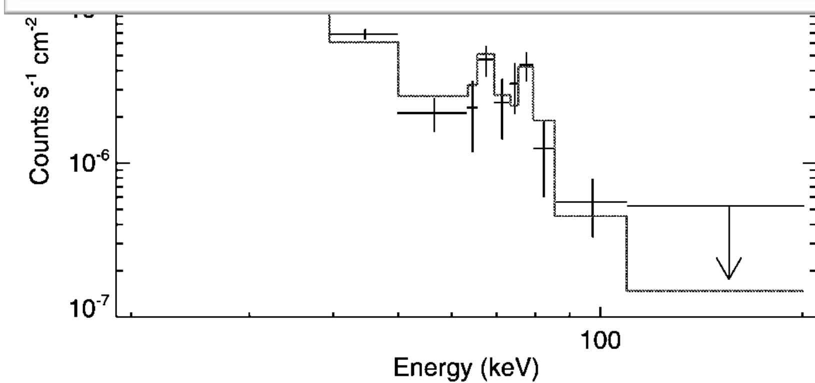
^{44}Ti Morphology



Previous Titanium Evidence



s, non-imaging
s detected but did
lve the lines.



AL has the best
5-sigma with no
on about the lines

Cas-A in numbers:

- **Numbers**:
  - Detection at ~13-sigma* (previous ~4.5-sigma or worse)
  - (in 10^{-4} M_{sun}) 1.25 +/- 0.3 of ^{44}Ti (previously $1.6^{+0.6}_{-0.3}$)

- **Radoactive Titanium is…**
  - …in the un-shocked interior (in 3-D).
  - …non-uniformly distributed in clumpy ejecta.
  - …redshifted from the rest-frame and Doppler-broadened.
  - …does not trace the Fe

Active galaxies: the "working picture"

- Presumably all AGN have the same basic ingredients: a black hole accreting via disk-like structure

- Some of those active galaxies possess a relativistically boosted jet, so bright that its emission masks the isotropically emitting "central engine"

- Accretion process and jet properties can be studied separately

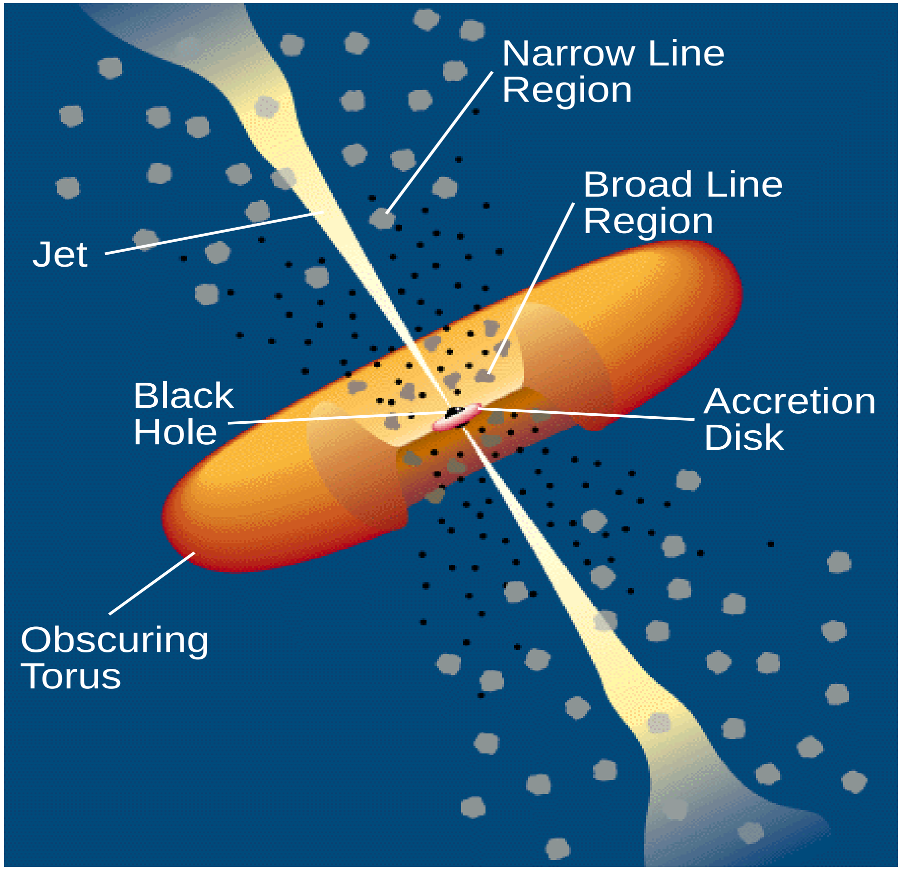
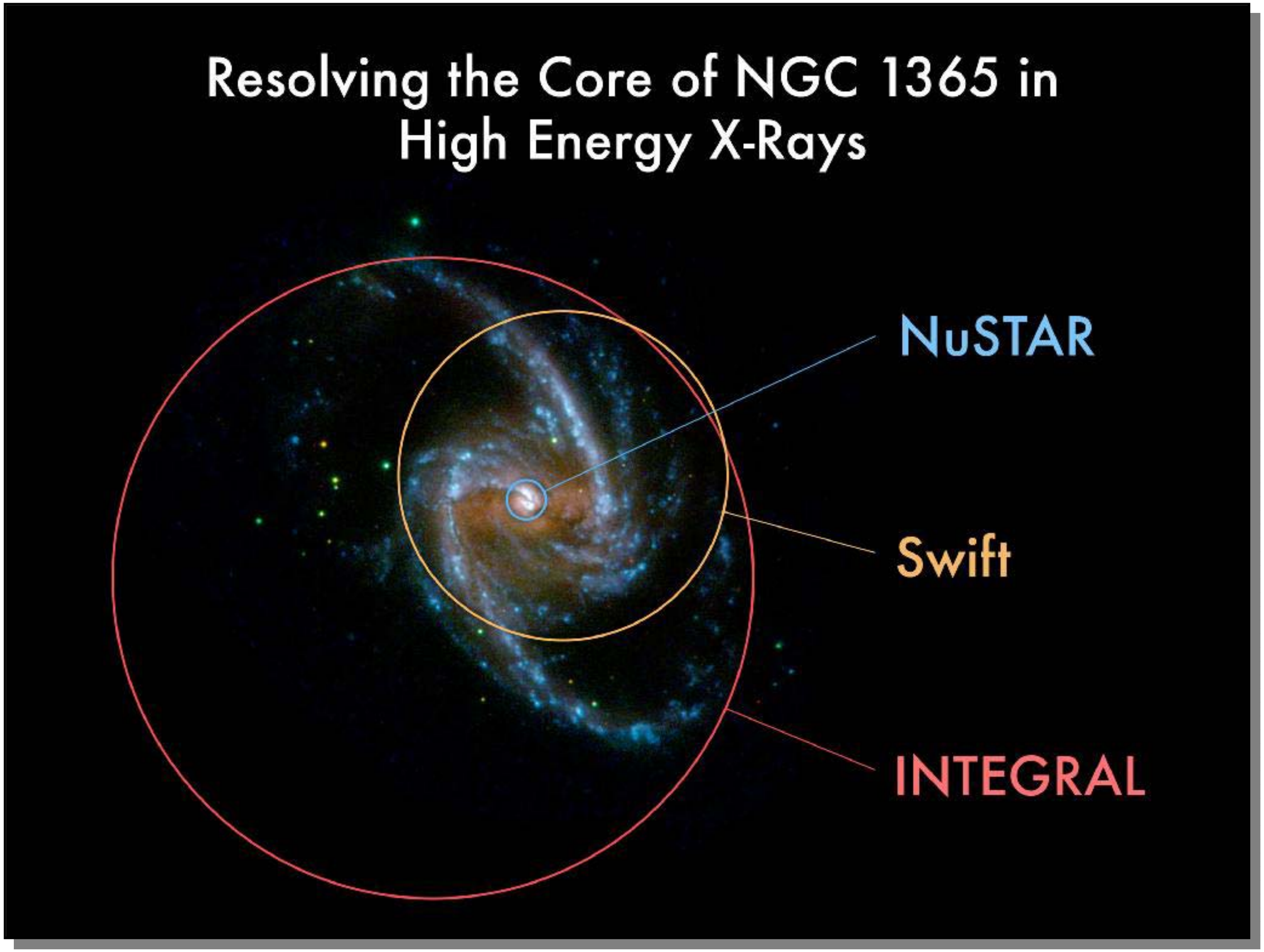
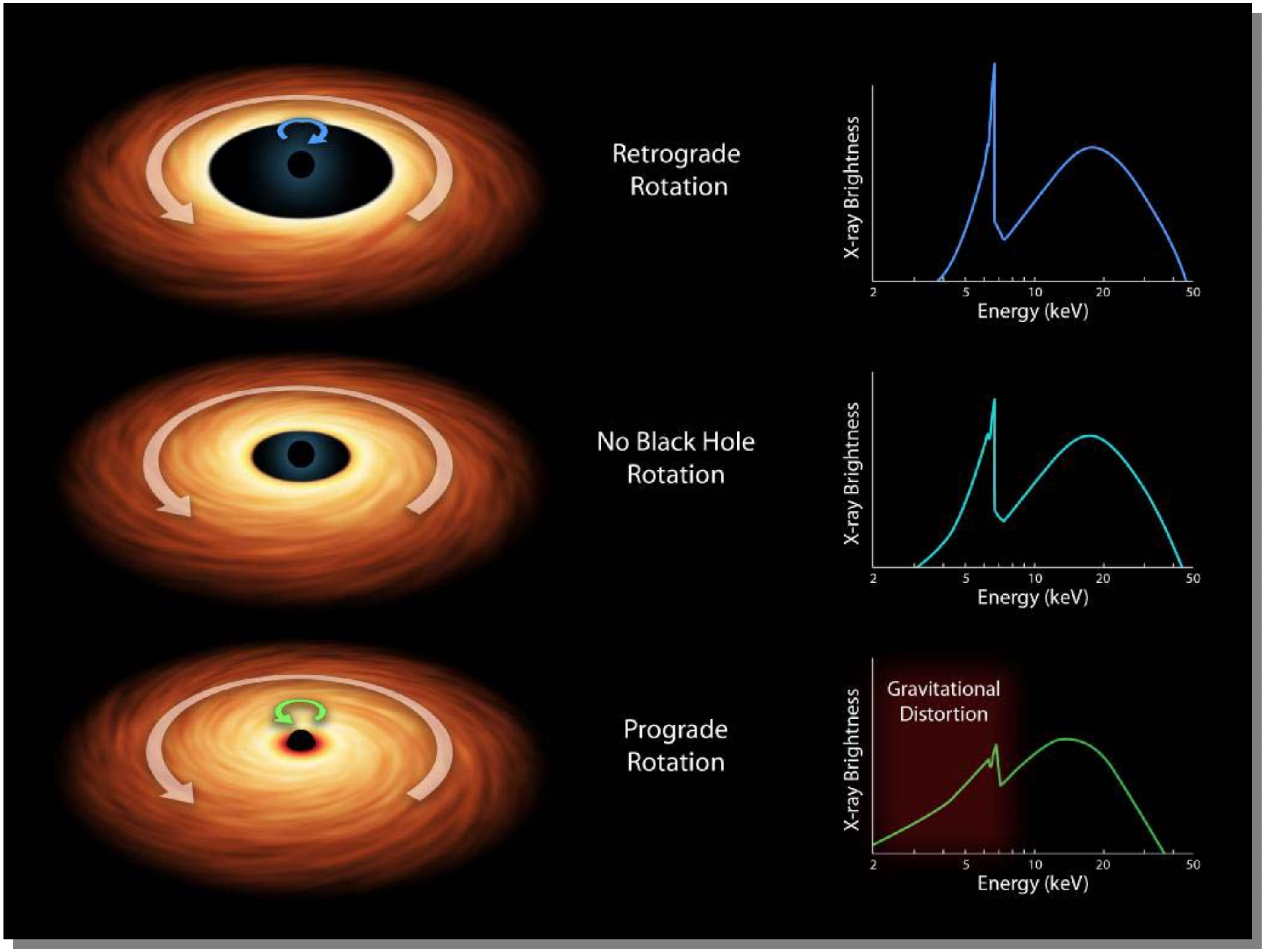


Diagram from Padovani and Urry

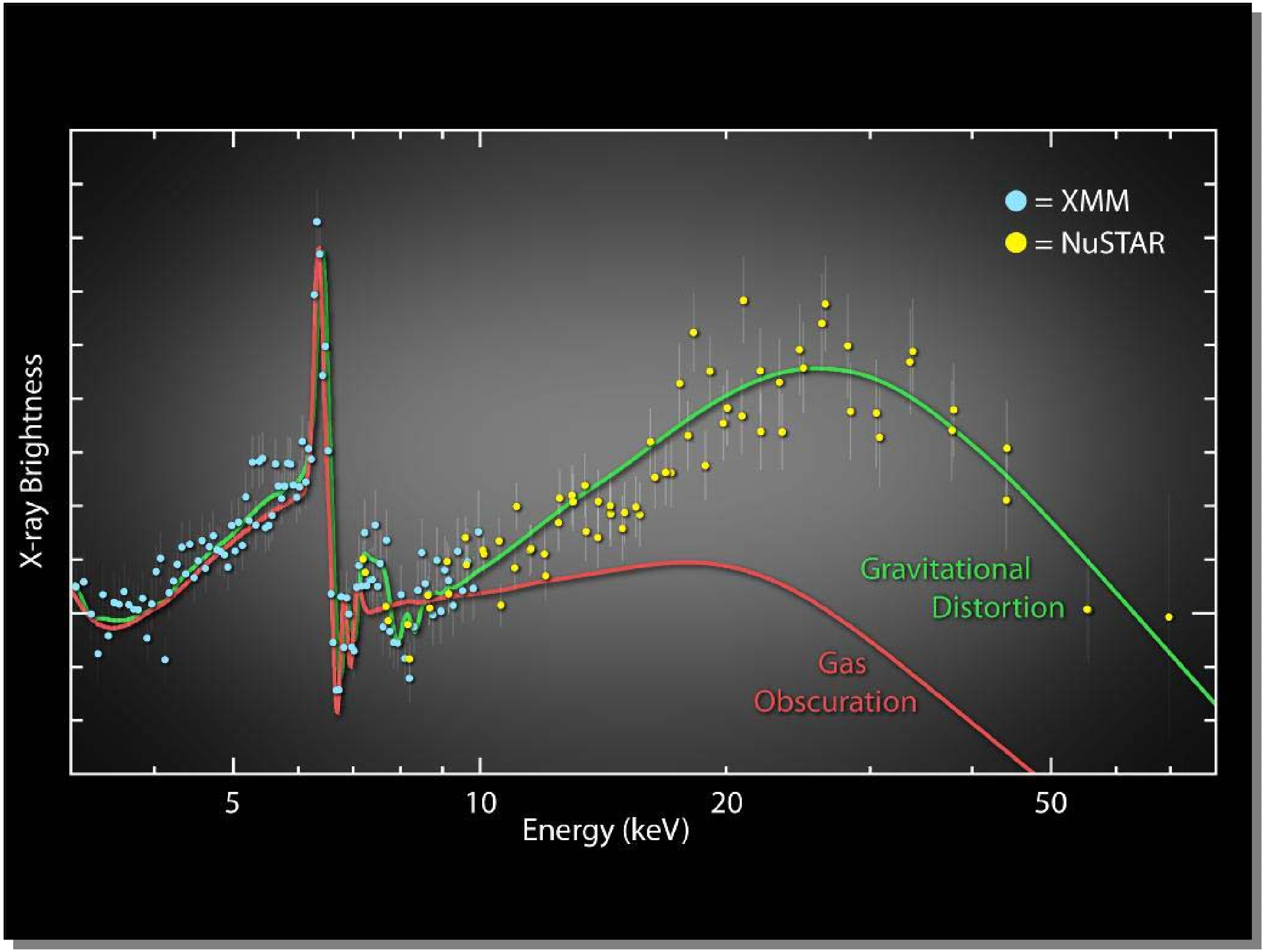
Active galaxies with NuSTAR



Active galaxies as tools to study strong gravity



Spinning black hole in NGC 1365



IC 4329a Suzaku + NuSTAR spectrum: Best-Fitting Model (Comptonization)