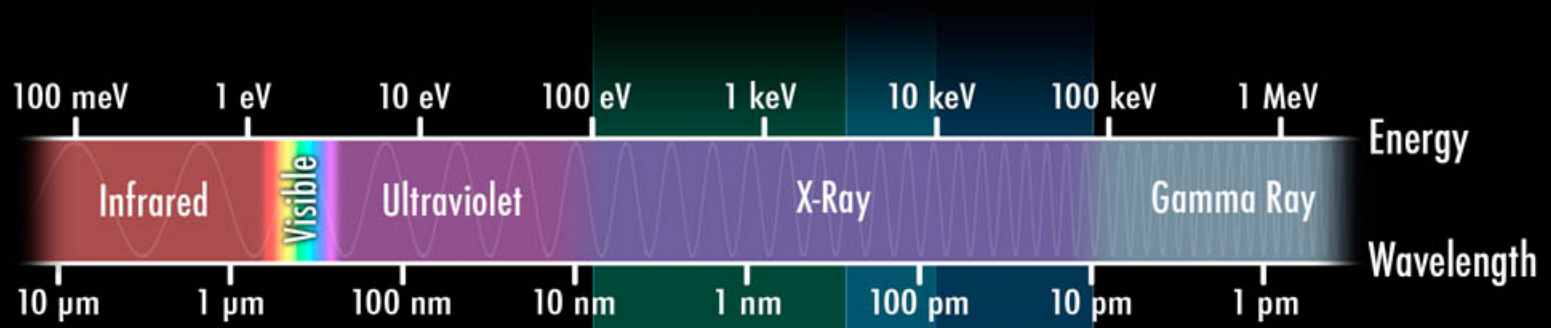
NuSTAR Results: From the Galactic Center to Local Starbursts

Fiona Harrison

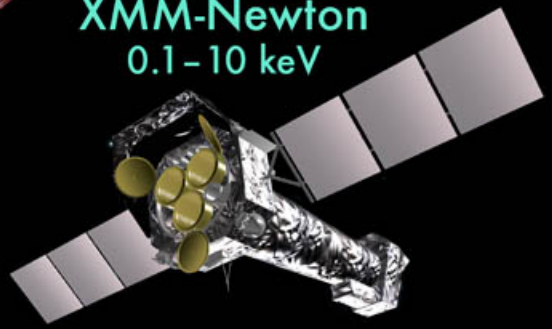
Caltech

On behalf of the *NuSTAR* Team

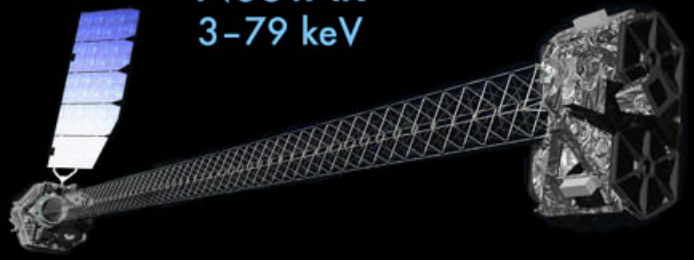
X-Ray Telescopes & the Electromagnetic Spectrum



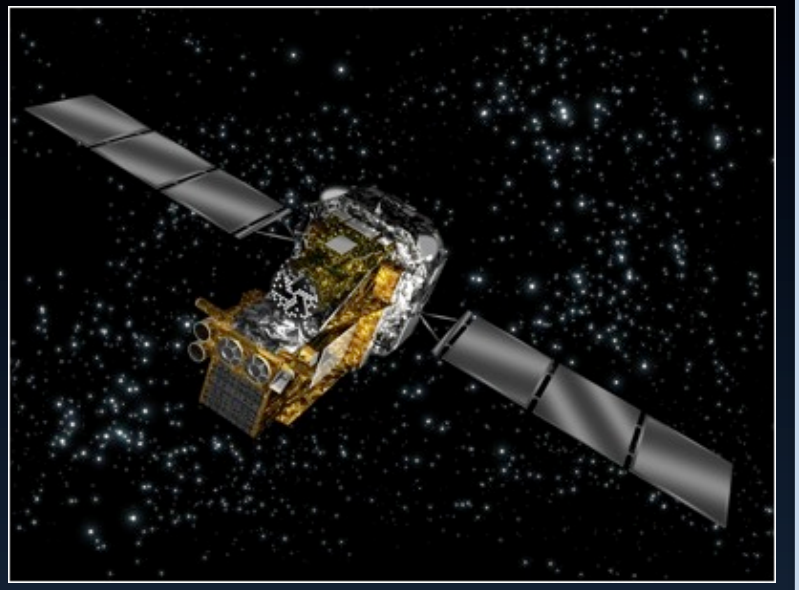
Chandra &
XMM-Newton
0.1–10 keV

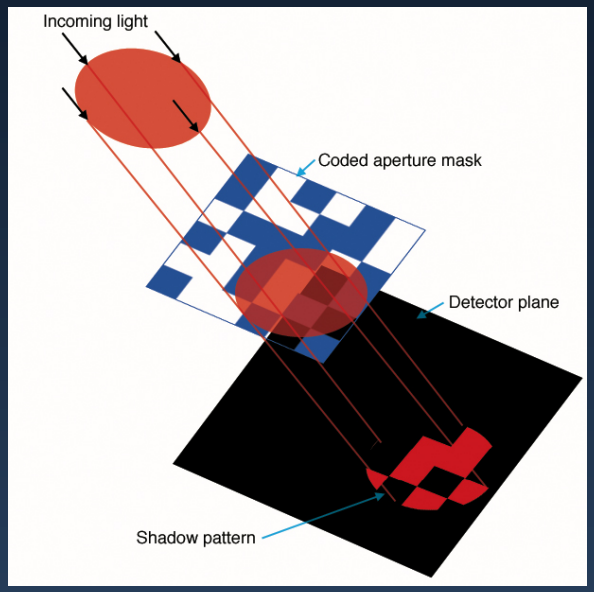


NuSTAR
3–79 keV

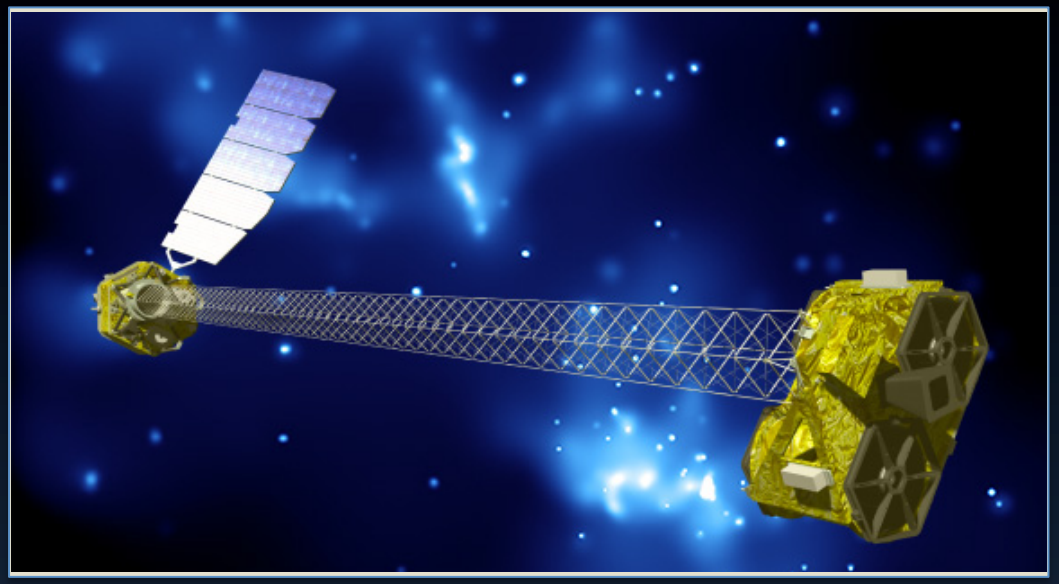


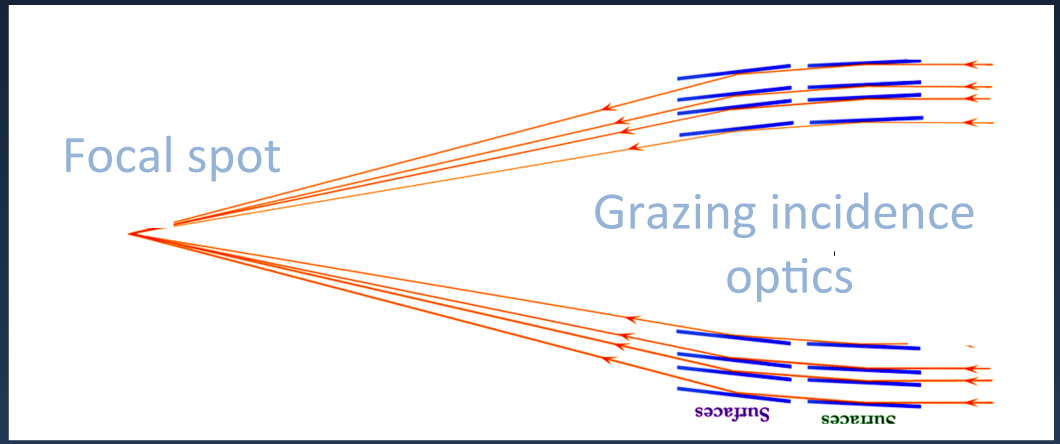
INTEGRAL, Swift BAT



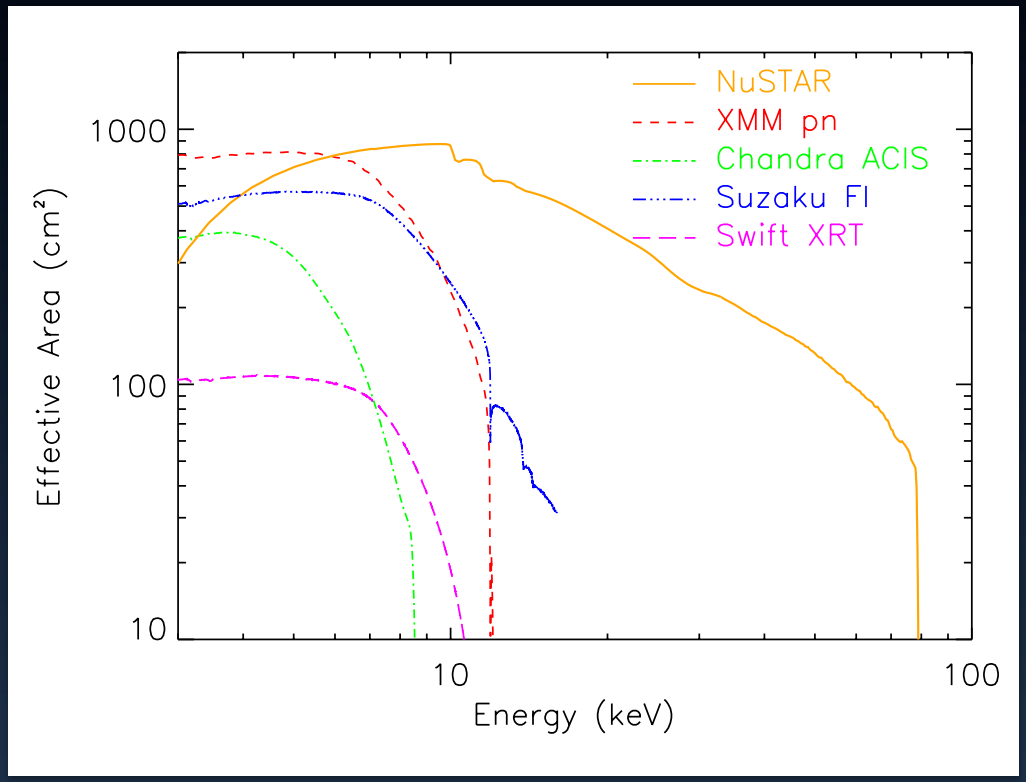


NuSTAR





Sensitivity



NuSTAR two-telescope total collecting area

Satellite (instrument)	Sensitivity
INTEGRAL (ISGRI)	~0.5 mCrab (20-100 keV) with >Ms exposures
Swift (BAT)	~0.8 mCrab (15-150 keV) with >Ms exposures
NuSTAR	1 μCrab (10-40 keV) in 1 Ms

Sensitivity comparison

1 Ms Sensitivity

3.2 x 10^{-15} erg/cm^2/s (6 – 10 keV)

1.4 x 10^{-14} (10 – 30 keV)

Imaging

HPD	58”
FWHM	18”
Localization	2” (1-sigma)

Field of View

FWZI	12.5’ x 12.5’
FWHI	10’ @ 10 keV
	8’ @ 40 keV
	6’ @ 68 keV

Timing

relative	200 microsec
absolute	3 msec

Spectral response

energy range 3-79 keV

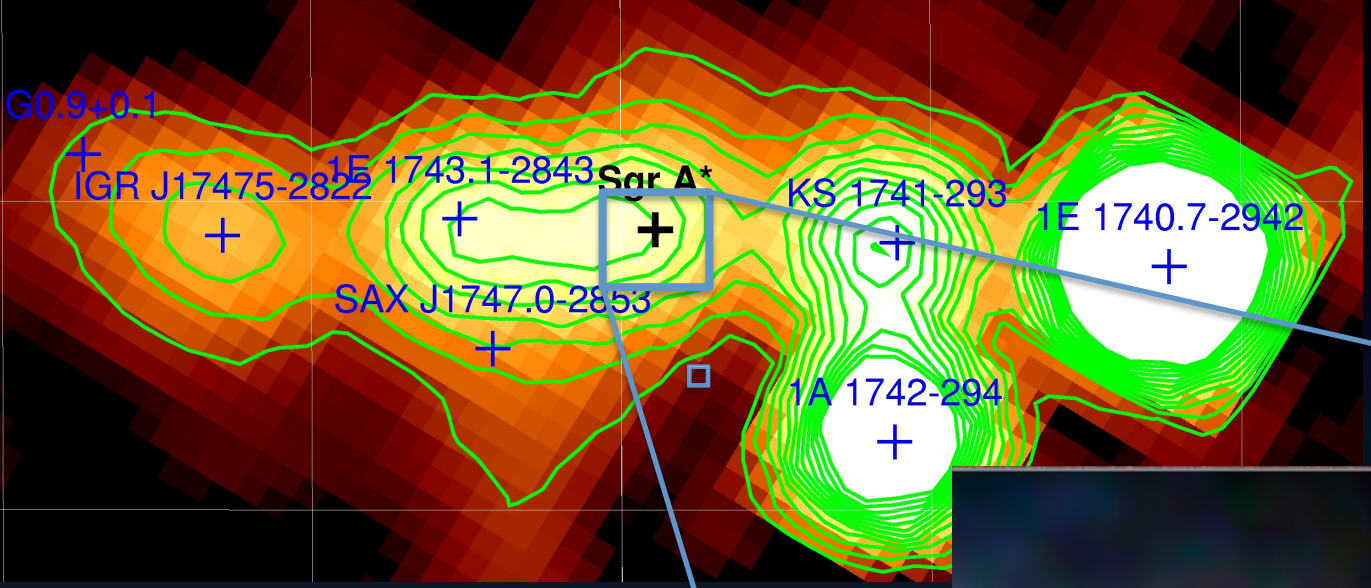
threshold	2.0 keV
ΔE @ 6 keV	0.4 keV FWHM
ΔE @ 60 keV	1.0 keV FWHM

Target of Opportunity

response <24 hr (reqmt)

typical 6-8 hours

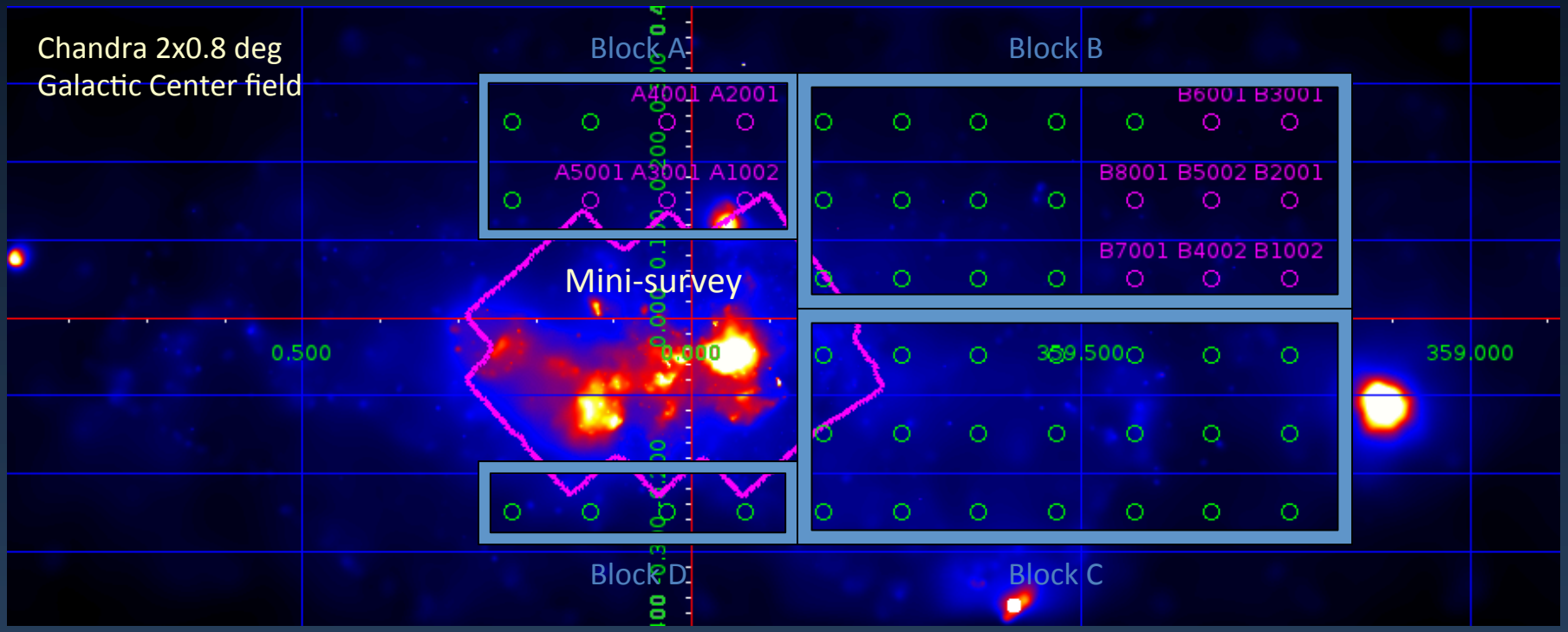
80% sky accessibility



Previous high-energy X-ray view of the heart of the Milky Way

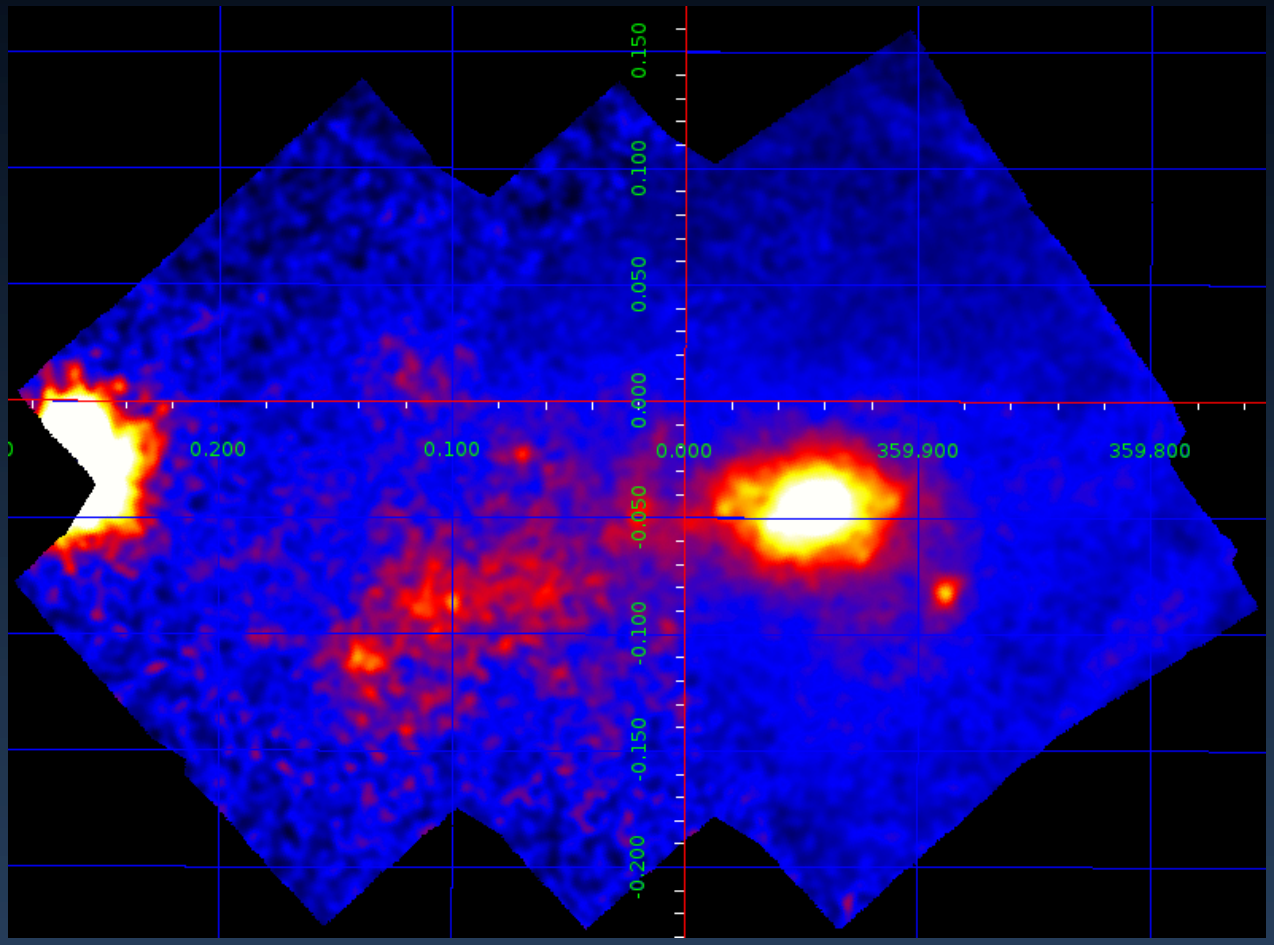
Galactic Center Science Objectives

- Survey Muno field
  - » Point sources
  - » Non-thermal X-ray Filaments
  - » Molecular clouds
  - » SNR/PWN
  - » Hard X-ray emission around Sgr A*
- Sgr A* flares (coordinated with Chandra)
- G2 infall



Galactic Center Survey

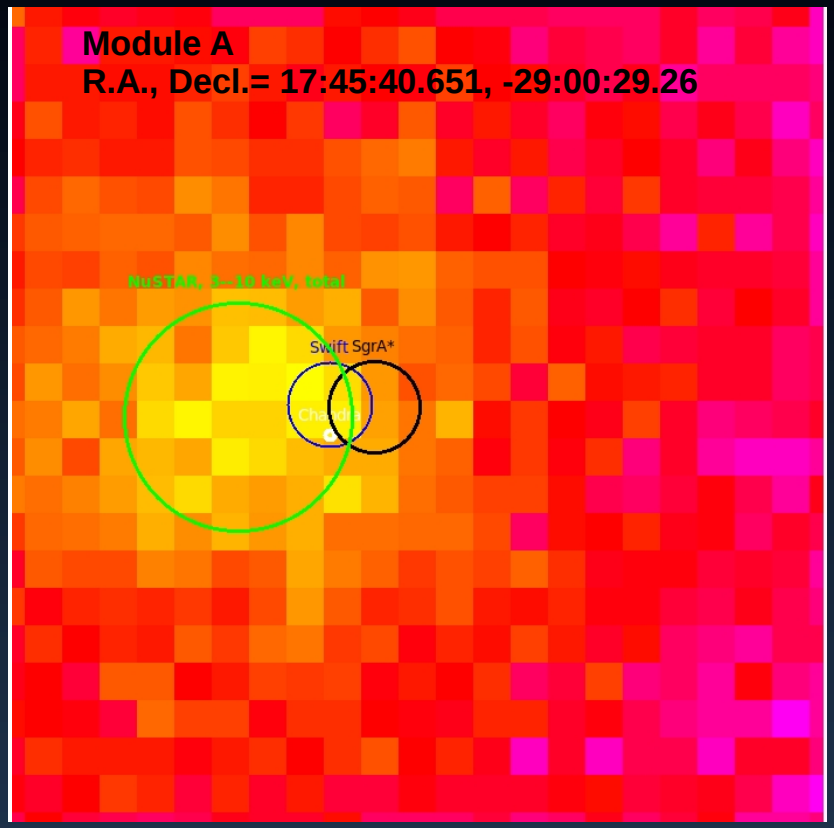
- Talk by C. Hailey (Friday) – diffuse emission, PWNe, Cannonball
- Poster by R. Krivonos (Arches cluster results)

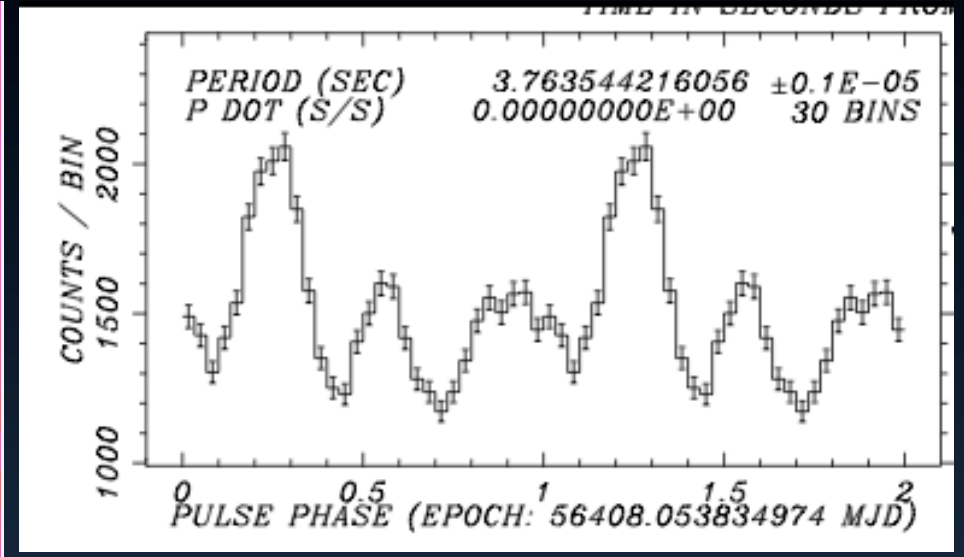


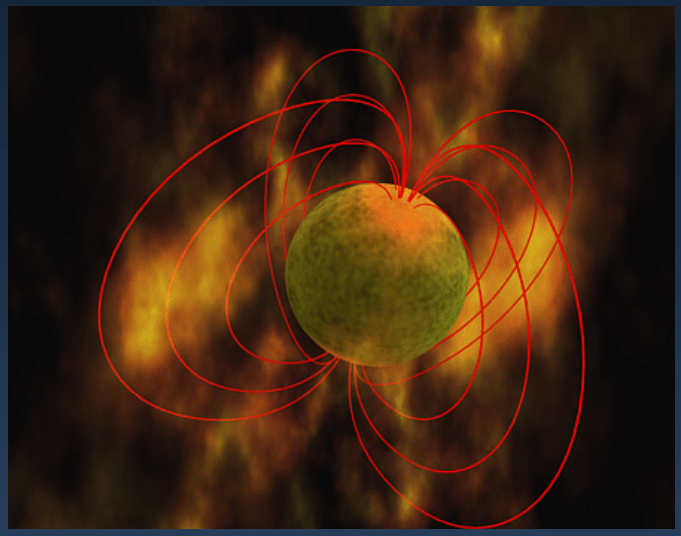
NuSTAR July 21, 2012

Talk by N. Barriere Thursday

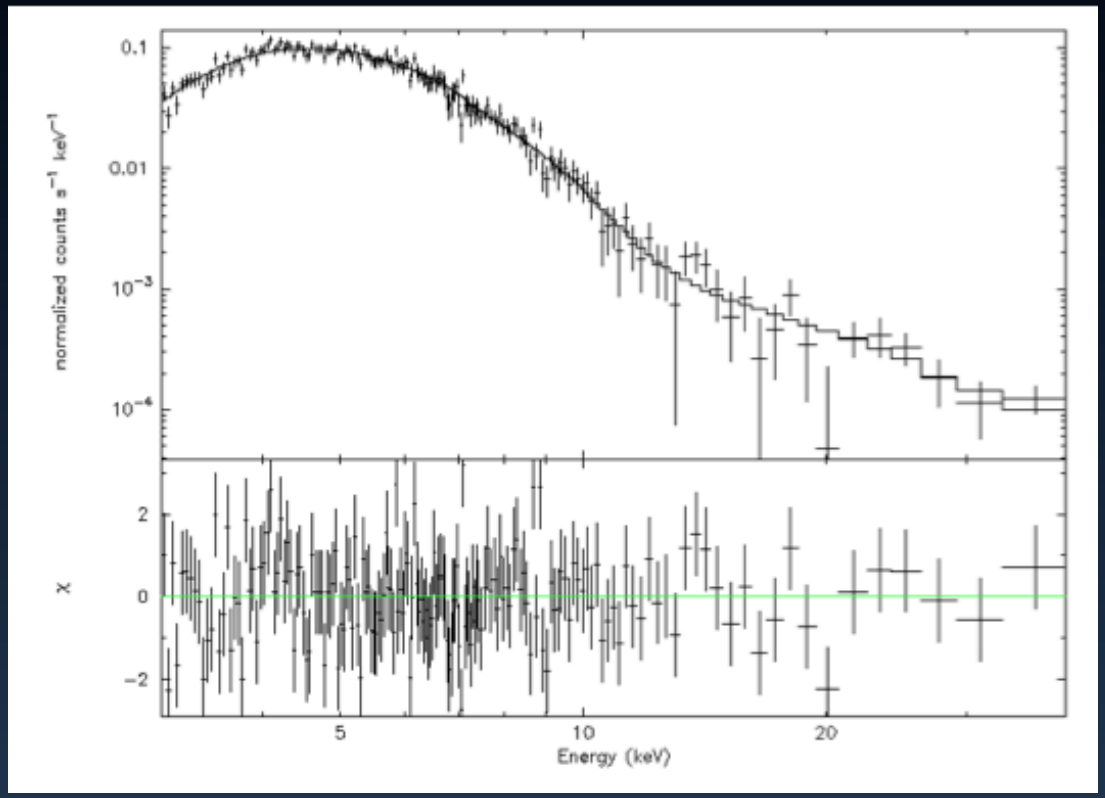
April 25, 2013







A New Magnetar – SGR J1745-29



Mori et al 2013

$N_h = 10^{23}$

Γ=1

kT = 1 keV

$\dot{P} = (6.5 \pm 1.4) \times 10^{-12}$

$\dot{E} = 5 \times 10^{33}$ erg s^{-1}

$B = 1.6 \times 10^{14}$ G

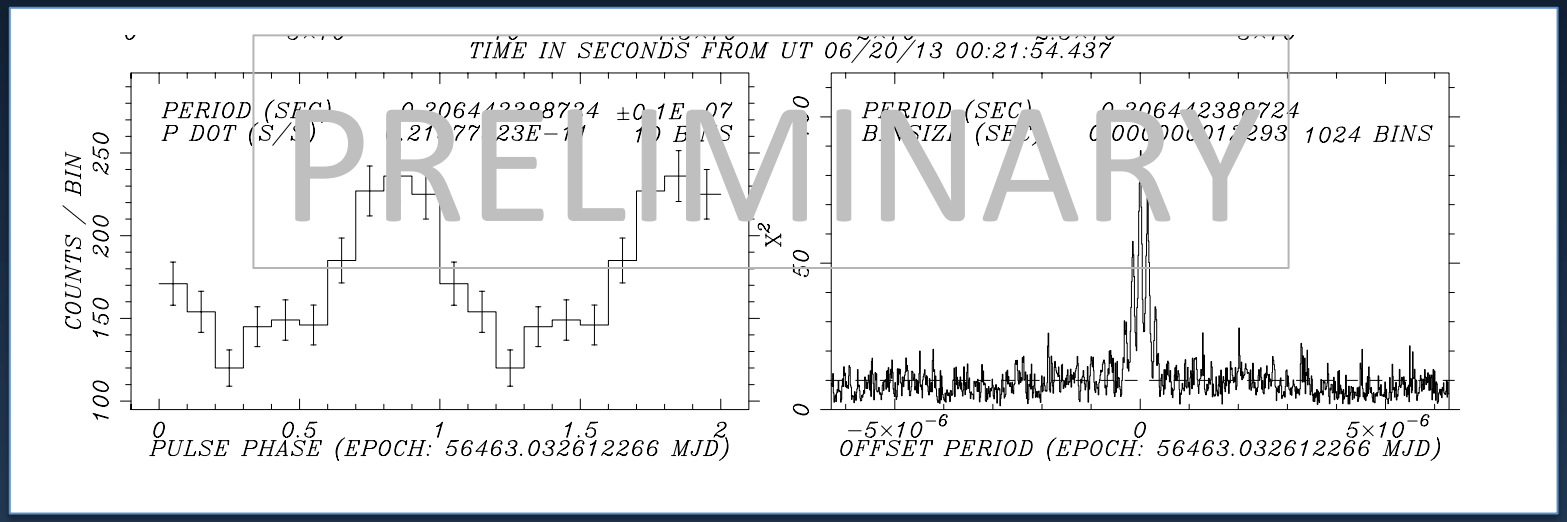
Associated with disk of high-mass stars near Sgr A*?

Progenitor ~40 M_{sun}

Sadly – not a stable pulsator

HESS J1640-465

- Detected in survey of Norma region
  - » highly absorbed – very faint for Chandra, XMM
  - » One of most compact HESS sources
  - » Associated with shell-type radio SNR G338.3-0.0?
  - » No direct evidence (until now) for a pulsar

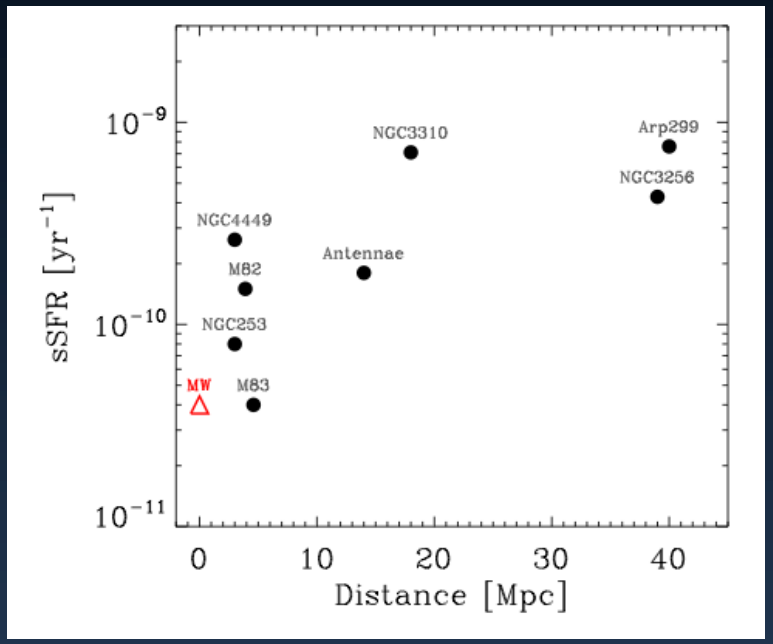


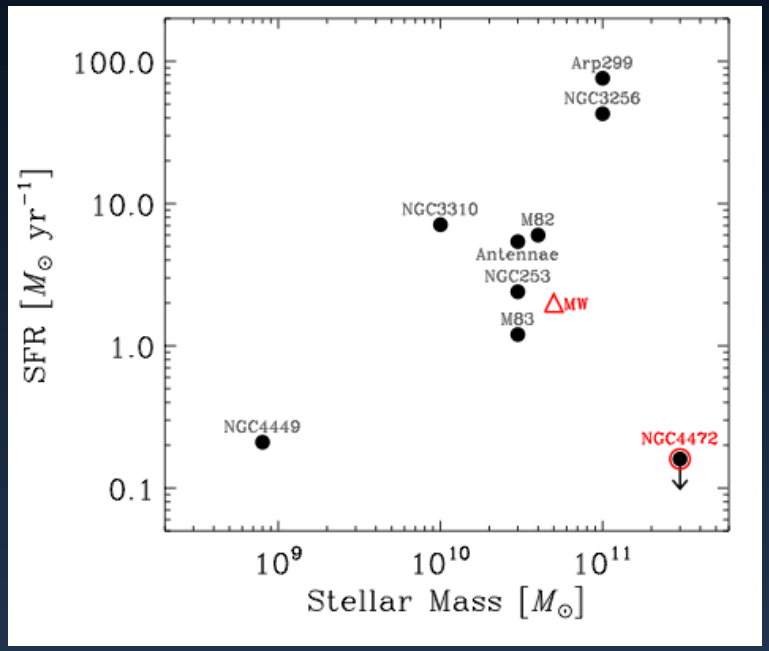
Nearby Starburst Sample

- X-ray binary populations and non-thermal diffuse emission in star-forming environments, constraining:
  - » Compact object populations
  - » Nuclear activity (AGN vs. starburst)
  - » Diffuse emission from hot X-ray gas
  - » Particle acceleration in SF regions
- Many marginally resolved with NuSTAR, but NuSTAR still offers major advantages with respect to sensitivity in the 10-30 keV band
- Lead: Ann Hornschemeier (GSFC)

Survey Sample

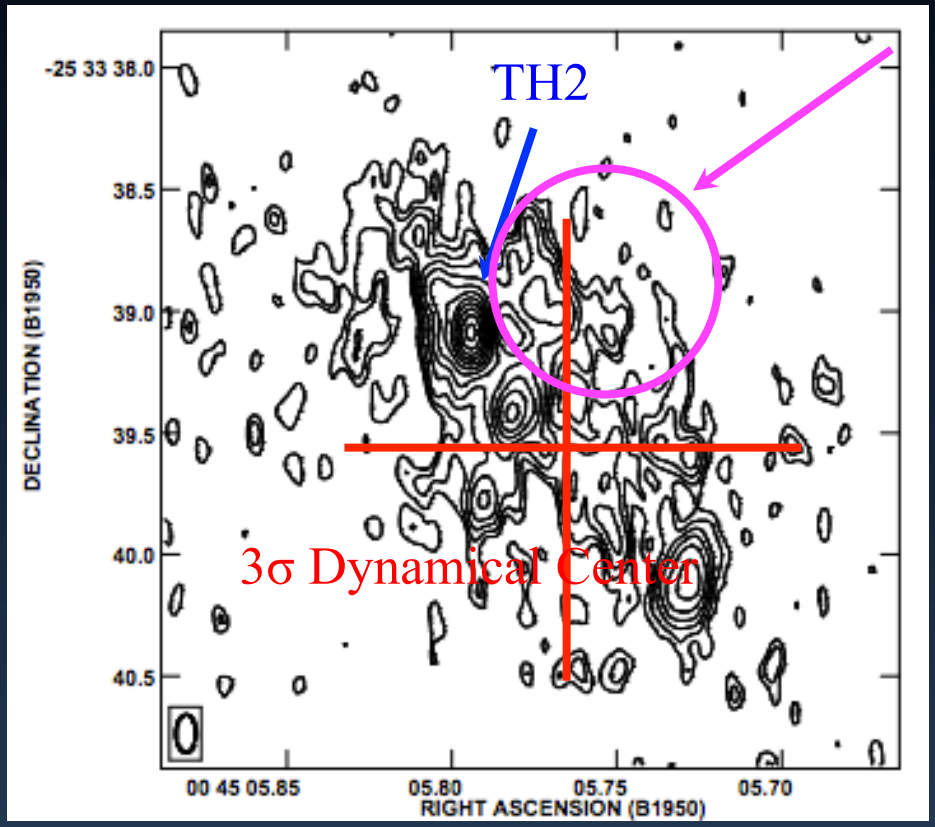
- Sample a range of parameters for starburst galaxies in the local (d < 40 Mpc) Universe





NGC 253

1.3 cm VLA image of central ~60 pc NGC 253



See Lehmer et al 2013

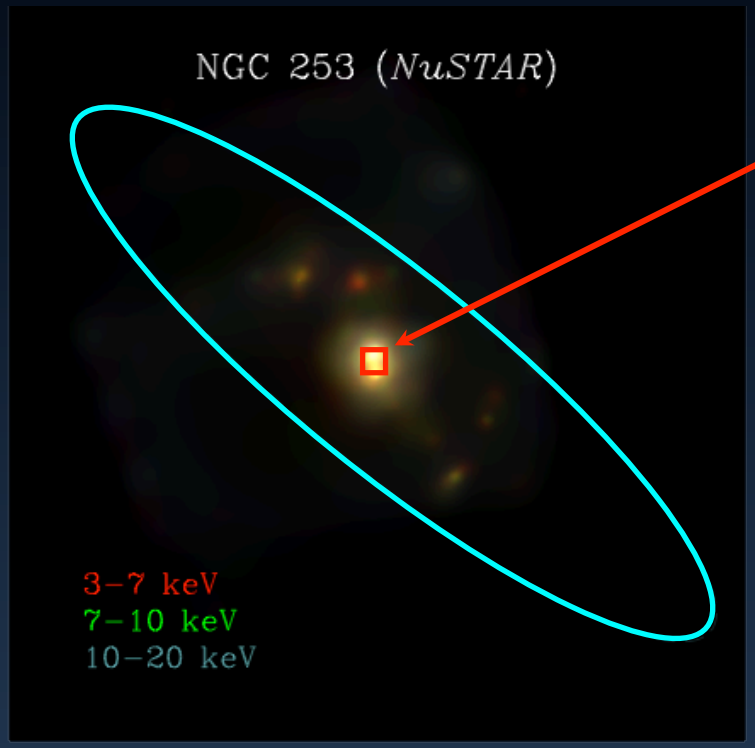
Wik et al in prep

2003 Obscured X-ray source

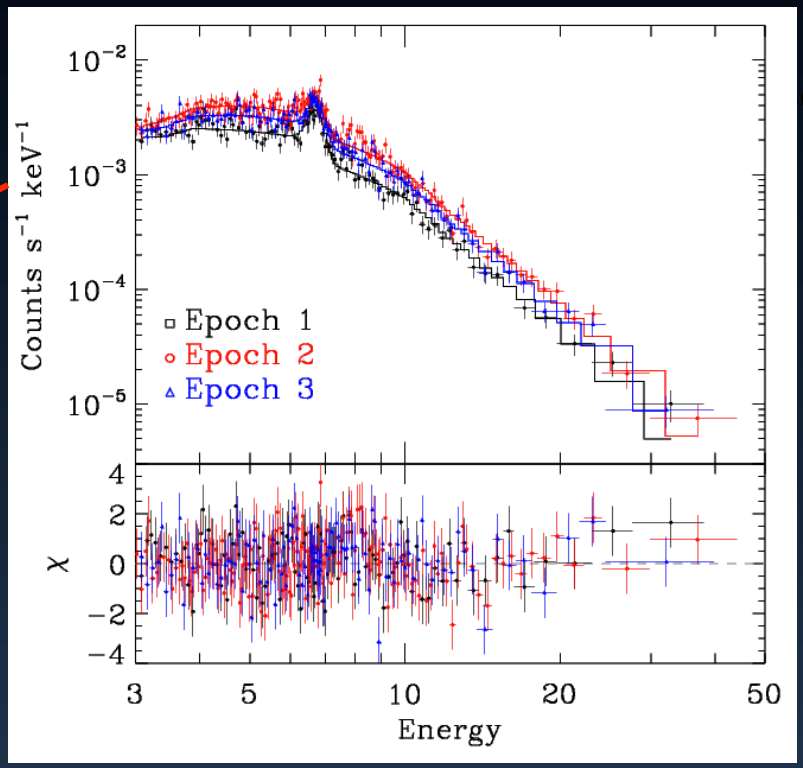
- Inner ~10-15 arcsec (200-300 pc) of NGC 253 -starburst with SFR ~ 2 $M_\odot$ yr^{-}
- Multiple radio sources - SFR, SN remnants, + compact AGN candidate (TH2) near dynamical center
- An obscured ($N_H > 2 \times 10^{23}$ cm^{-2}) X-source found consistent with the dynamical center - a possible AGN

NuSTAR Constraints on Nuclear Spectrum

NuSTAR (3 × 165 ks) 3–50 keV

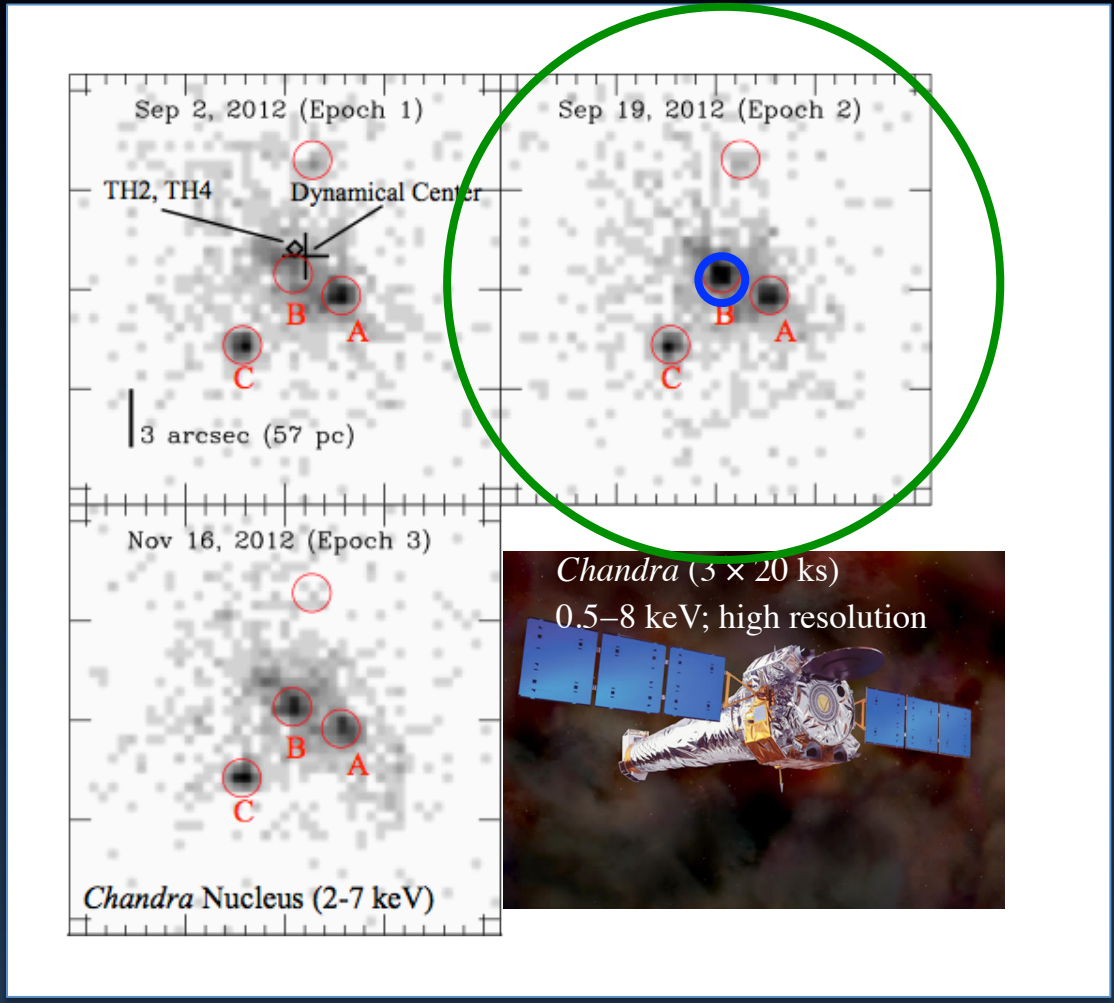


20'' extraction



f(*E*) = hot gas (3.5 keV apec) + abs × power-law --> N_H = 2.5 × 10^{23} cm^{-2}; Γ = 3.0

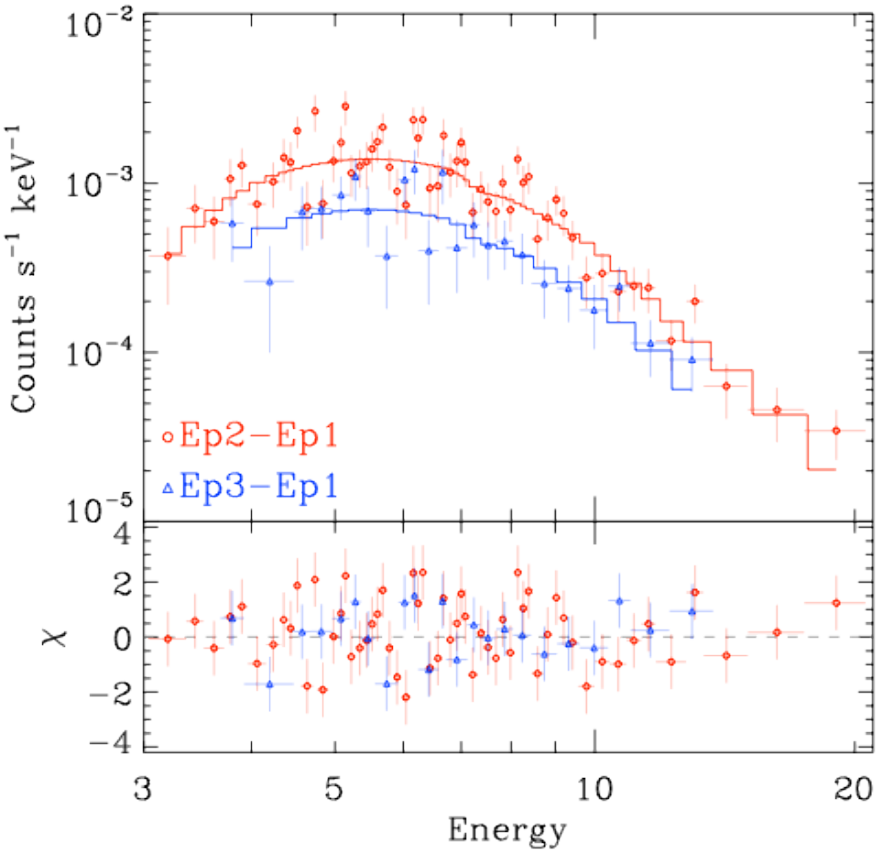
Chandra Imaging Of Nuclear Region Emission



Source B drives the total variability in the inner ~20 arcsec. Can estimate *NuSTAR* spectrum of source B by differencing Epochs 2 and 3 from Epoch 1!

NuSTAR Spectral Constraints on Variable Source B

NuSTAR Spectrum of Source B



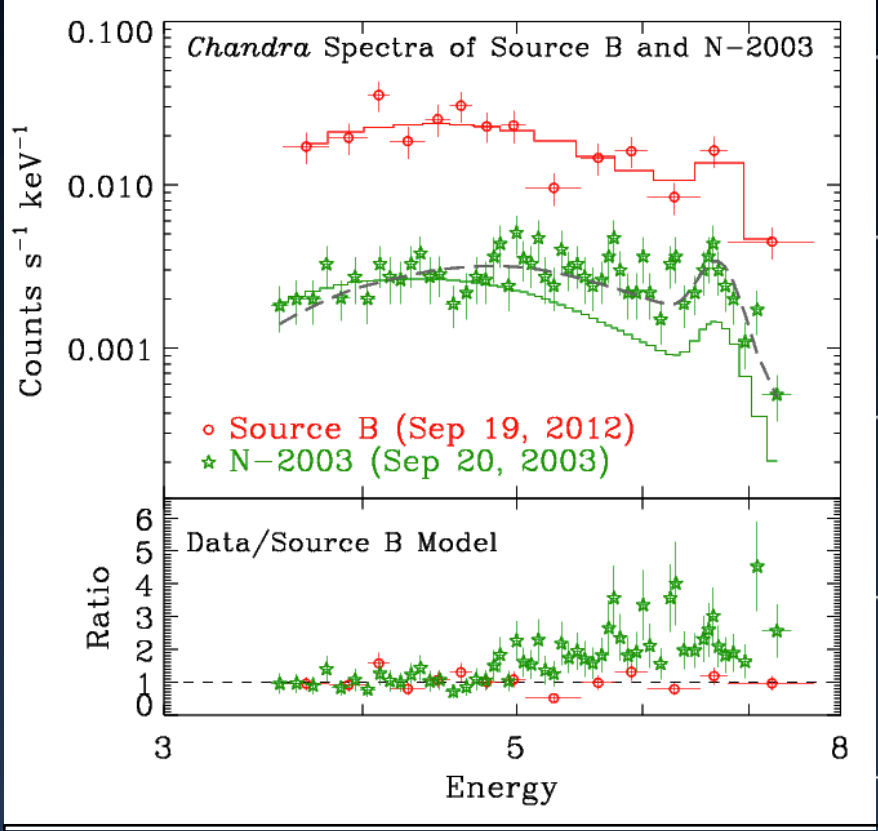
Luminosity/spectrum consistent with ULX

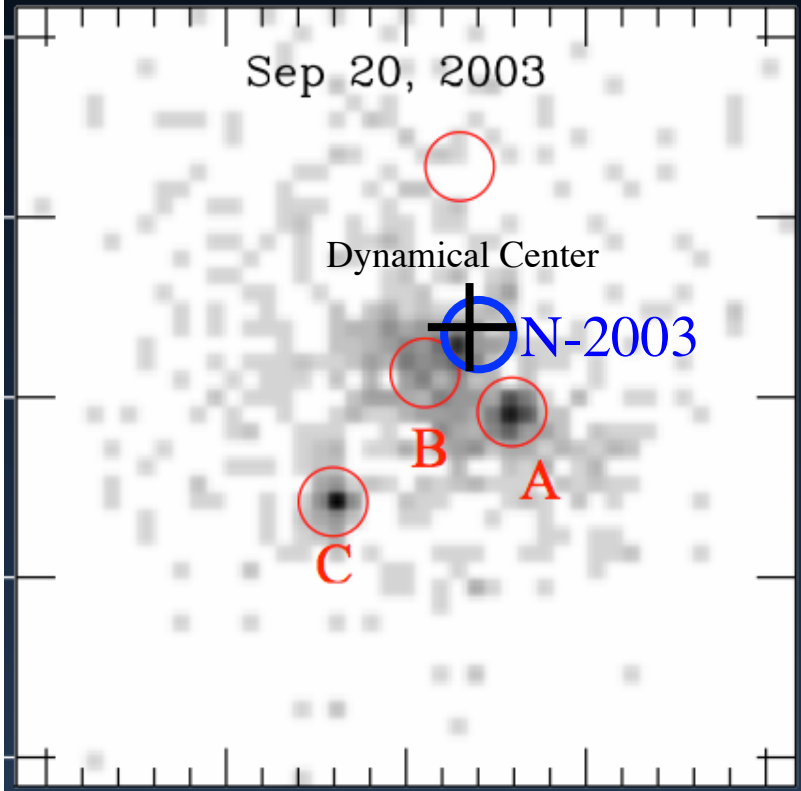
Source – is ULX implying that the supermassive black hole was not growing in 2012.

Was it active in the past?

Comparison with 2003 Deep *Chandra* Observations

- Deep 80 ks Chandra observation in 2003 - three clear X-ray detected point sources; central source is different...





2012 observation when the best AGN candidate N-2003 was off!

NGC 253 Summary

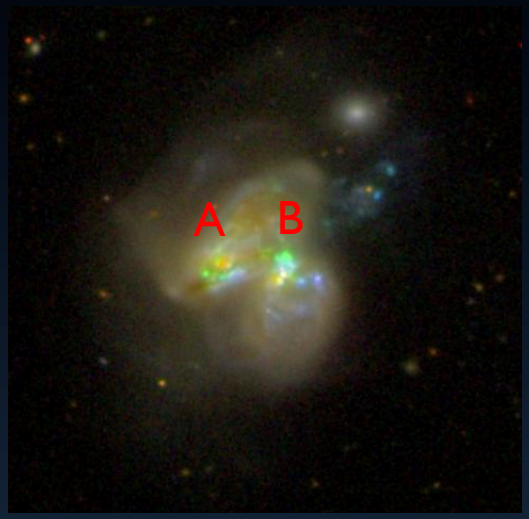
- Eliminate multiple candidates as source of nuclear emission
- Nucleus is variable and turns off on few decade timescales
- Nuclear emission may be overestimated due to contributions from ULXs
- Upcoming work – constraining diffuse Inverse Compton emission

Arp 299

D ~ 40 Mpc

Most luminous IR galaxy in the local universe

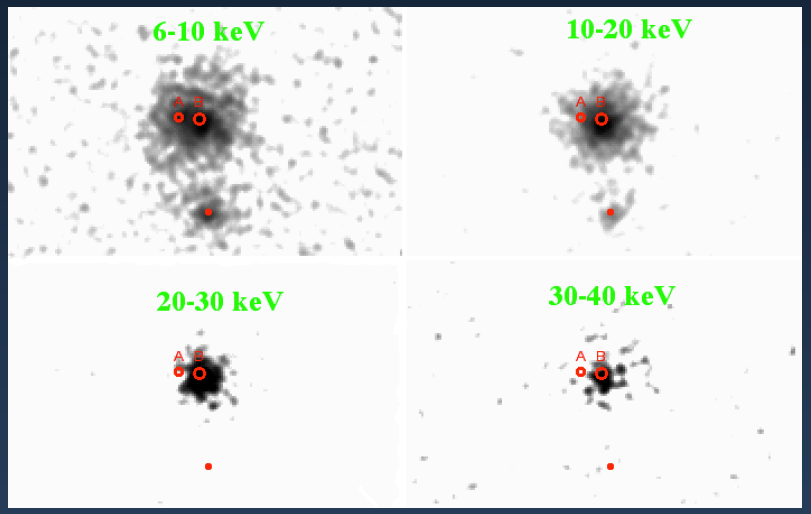
Merger: two nuclei separated by 21” (> FWHM of NuSTAR PSF) – dual AGN?



SDSS Image of Arp 299

First detection above 10 keV
First definitive detection of marginally Compton-thick AGN in Arp 299-B; N_H=1.5 x 10^{24}

NuSTAR also rules out a luminous obscured AGN in Arp 299-A



Baseline Mission Science

Science Group	Working Group Chair
Galactic Surveys, Galactic Center	Chuck Hailey
Supernovae and ToOs	Steve Boggs
Supernova remnants and Pulsar Wind Nebulae	Fiona Harrison
Magnetars and Rotation Powered Pulsars	Vicky Kaspi
Galactic Binaries	John Tomsick
Ultraluminous X-ray Sources	Fiona Harrison
Extragalactic Surveys	Daniel Stern
Blazars and Radio Galaxies	Greg Madejski
Obscured AGN	Daniel Stern
AGN Physics	Giorgio Matt
Galaxy Clusters	Allan Hornstrup, Silvano Molendi
Starburst Galaxies	Ann Hornschemeier
Solar Physics	David Smith

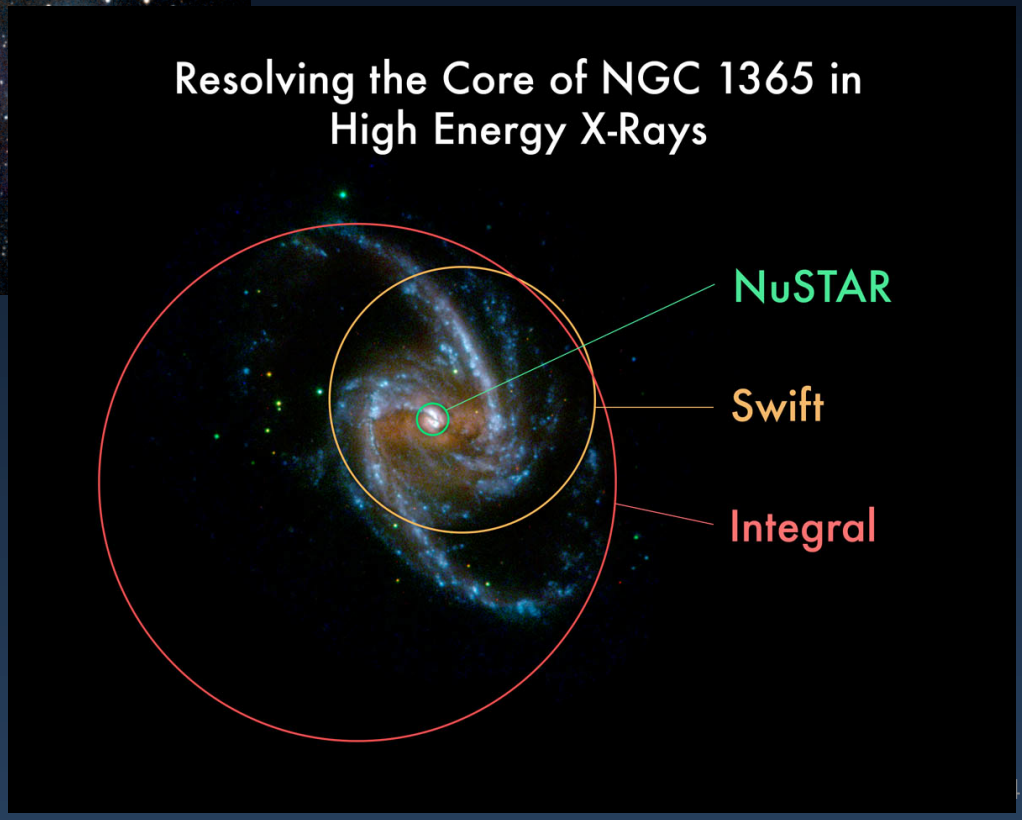
http://www.nustar.caltech.edu (look under 'for astronomers')

Summary

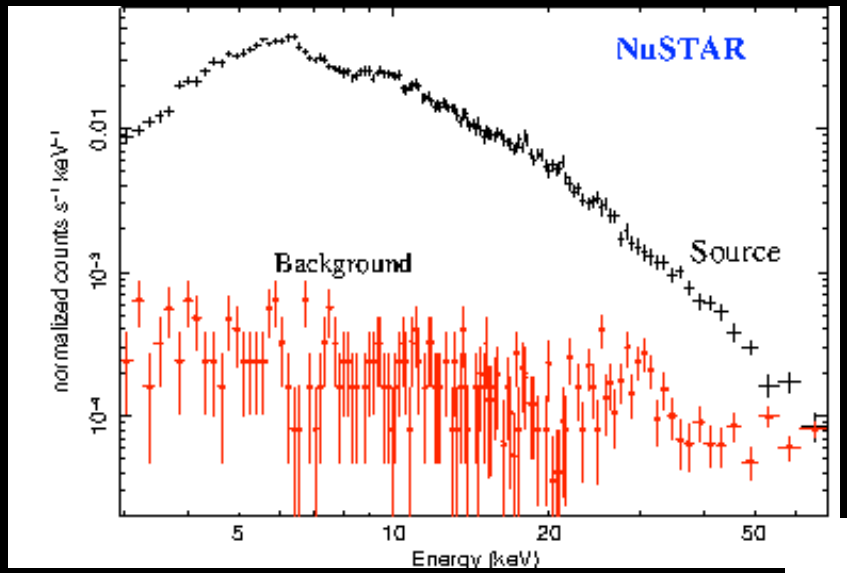
- First results from NuSTAR's Galactic center program coming out
  - » Talks by Barriere, Hailey, poster by Krivonos
- Combination of Chandra and NuSTAR proving powerful for studying nuclei of nearby star forming galaxies
- Baseline mission ends 8/2014 – proposing mission extension to allow GO program

Imaging - Nearby Galaxies

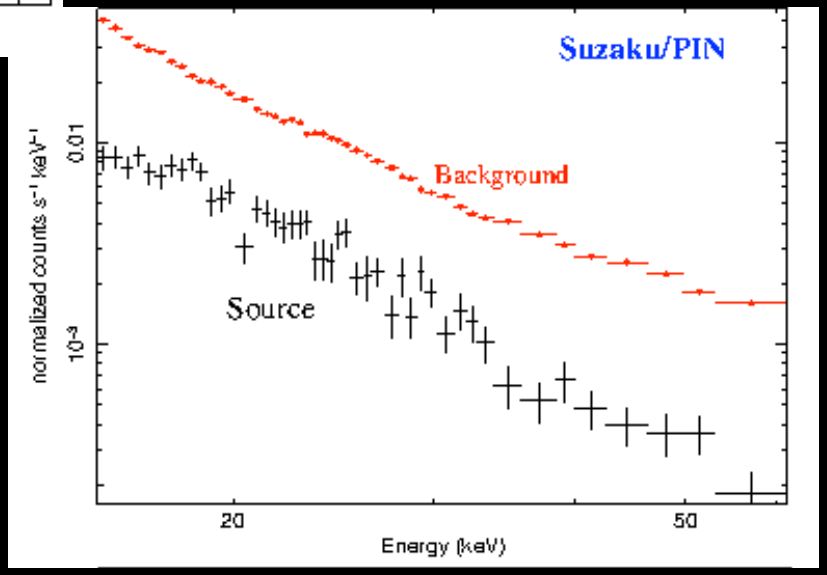
The galaxy IC 342, resolved for the first time in high energy X-rays



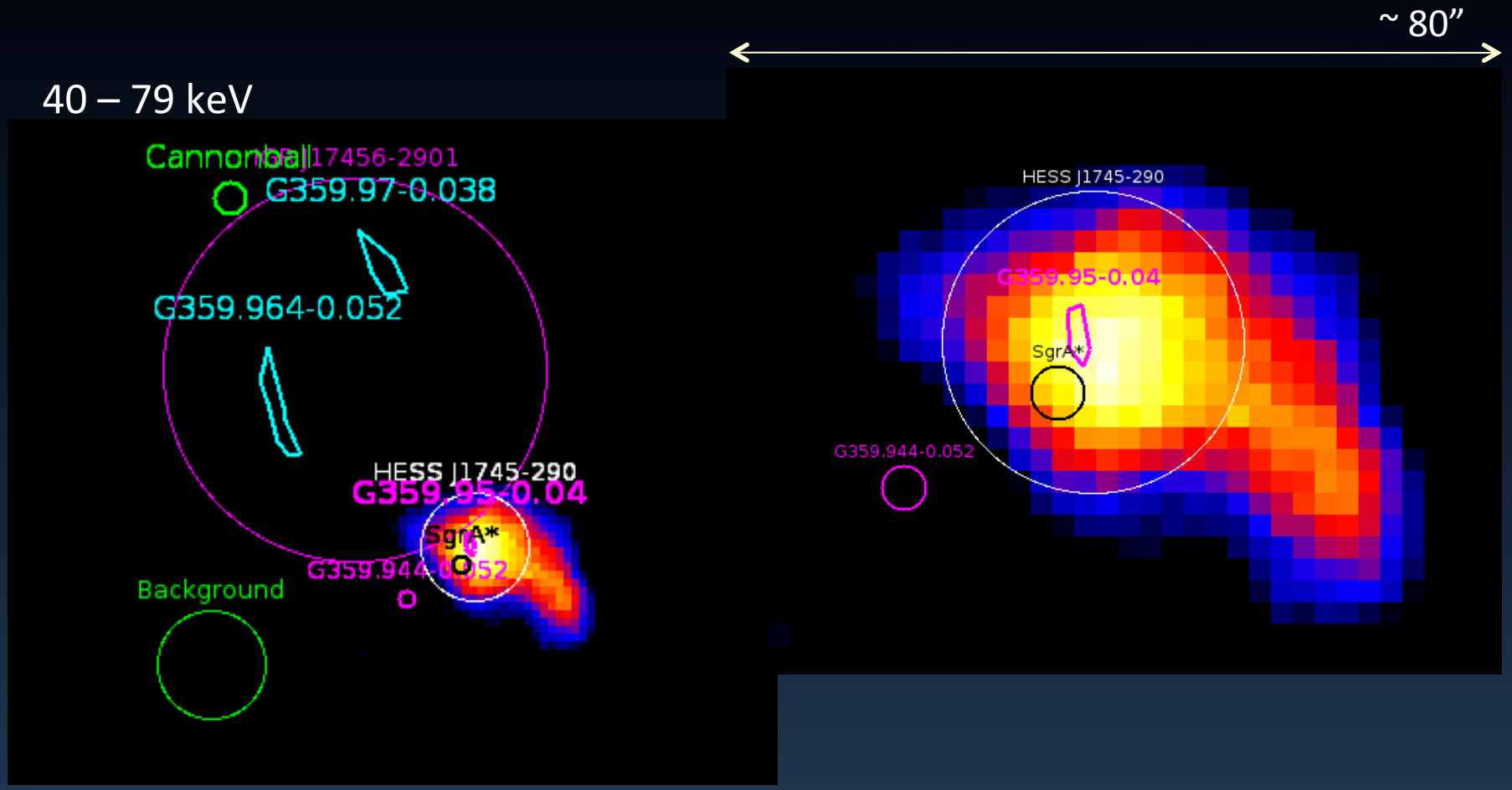
Measurement of Black Hole Spin in NGC 1365



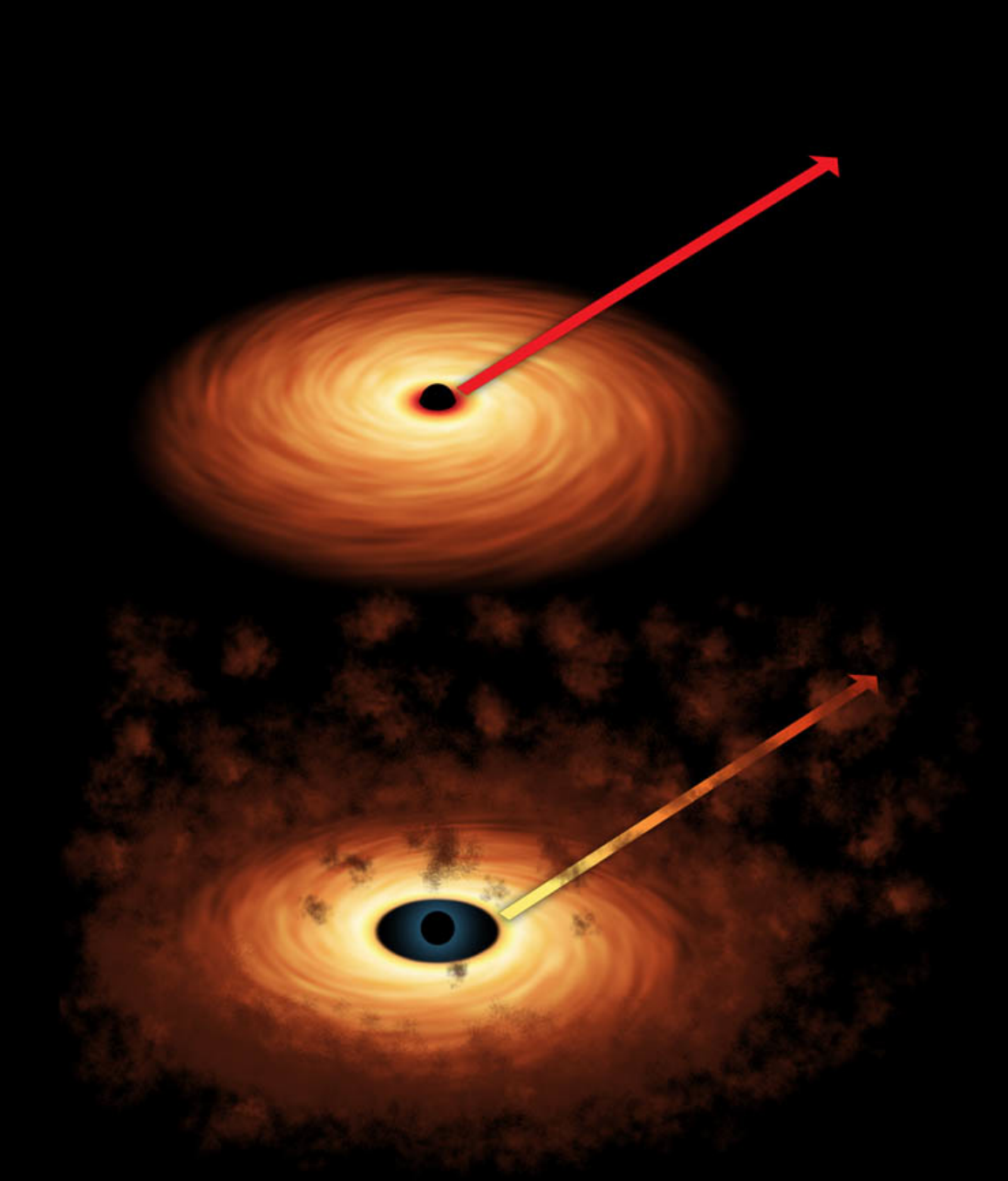
Risaliti, FH et al. Nature 2013



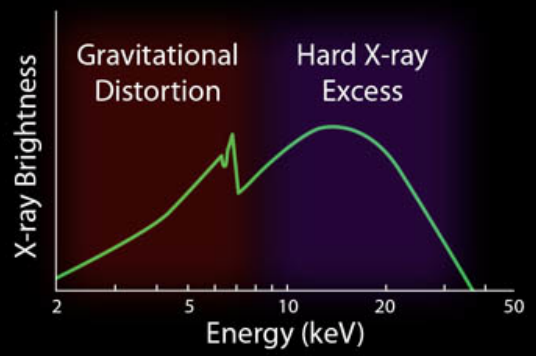
Hard X-ray Emission from Sgr A* Region



Sgr A* region: 40 – 79 keV – hard emission is from PWN G359.95-0.04
consistent with Chandra spectral extrapolation
SED consistent with HESS source being PWN G359.95-0.04

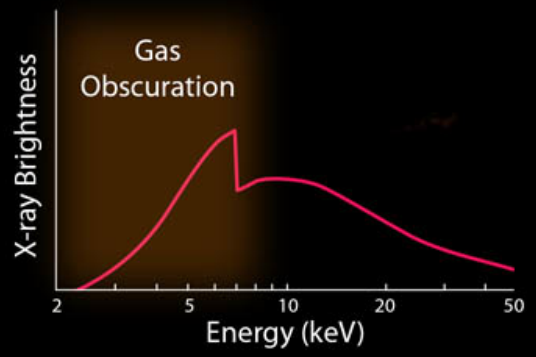


Prograde Rotation Model

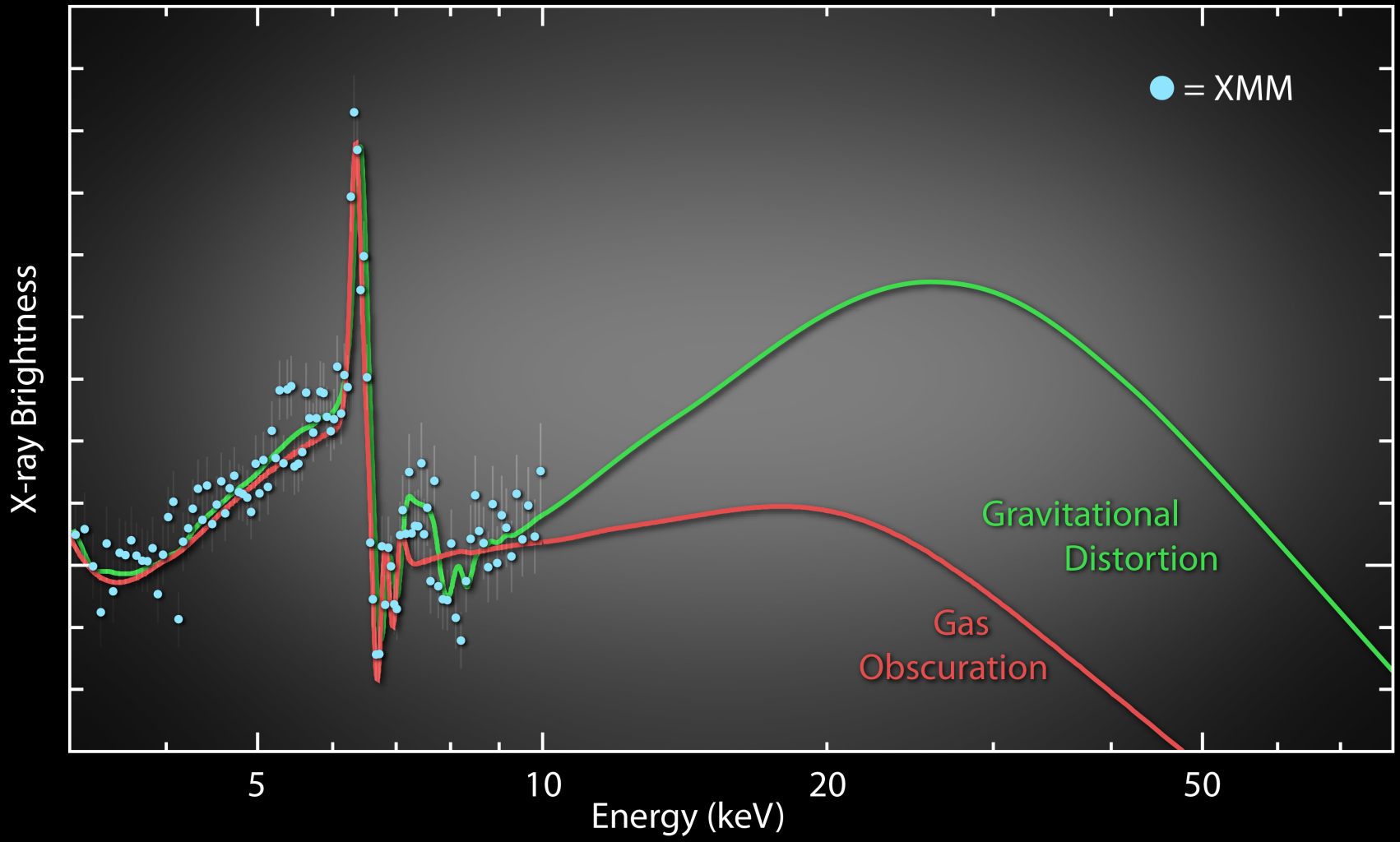


For N_H~10 $^{22\text{-}23}$ cm-2
E>10 keV continuum not affected

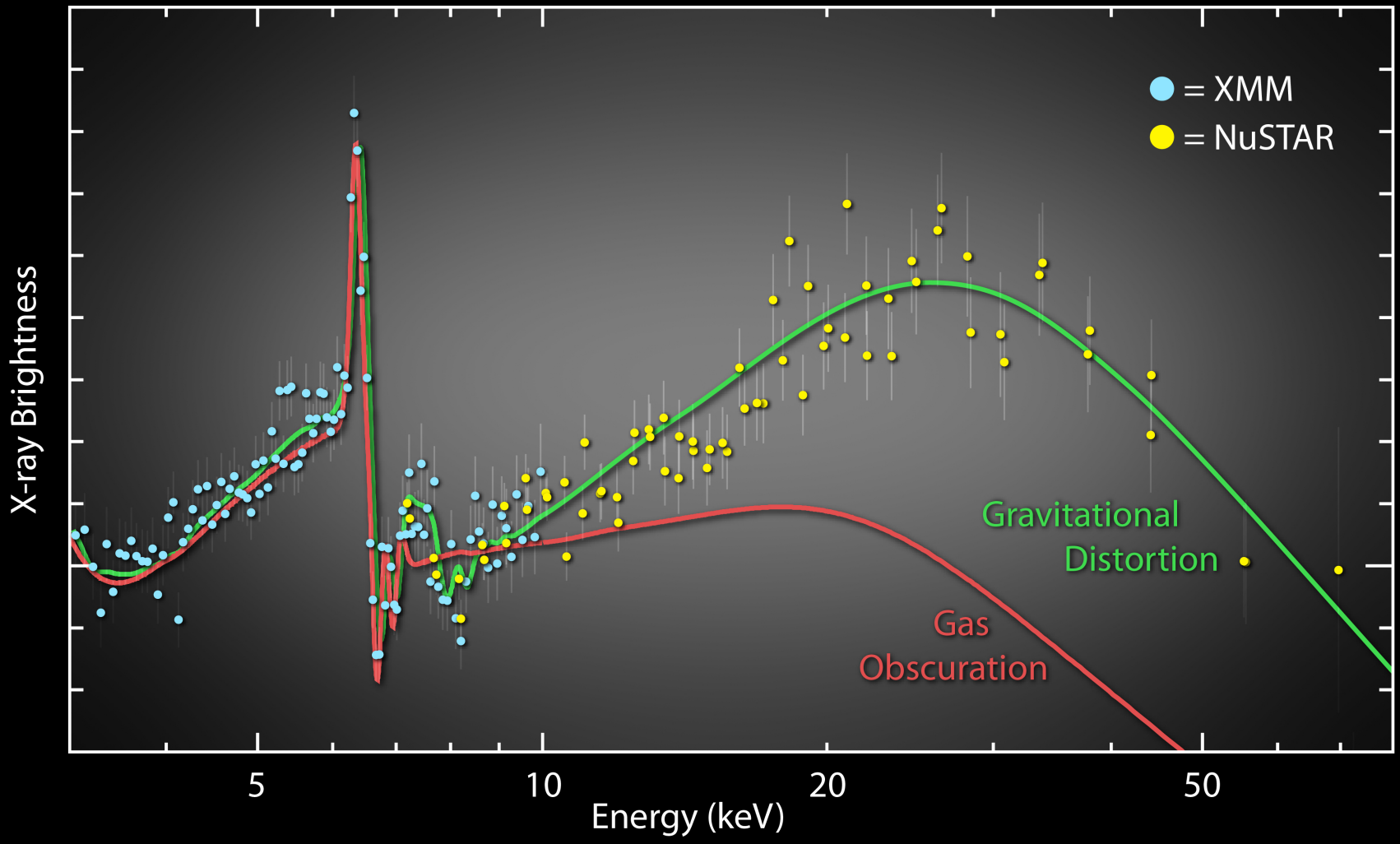
Foreground Obscuration Model



Fit to XMM data alone

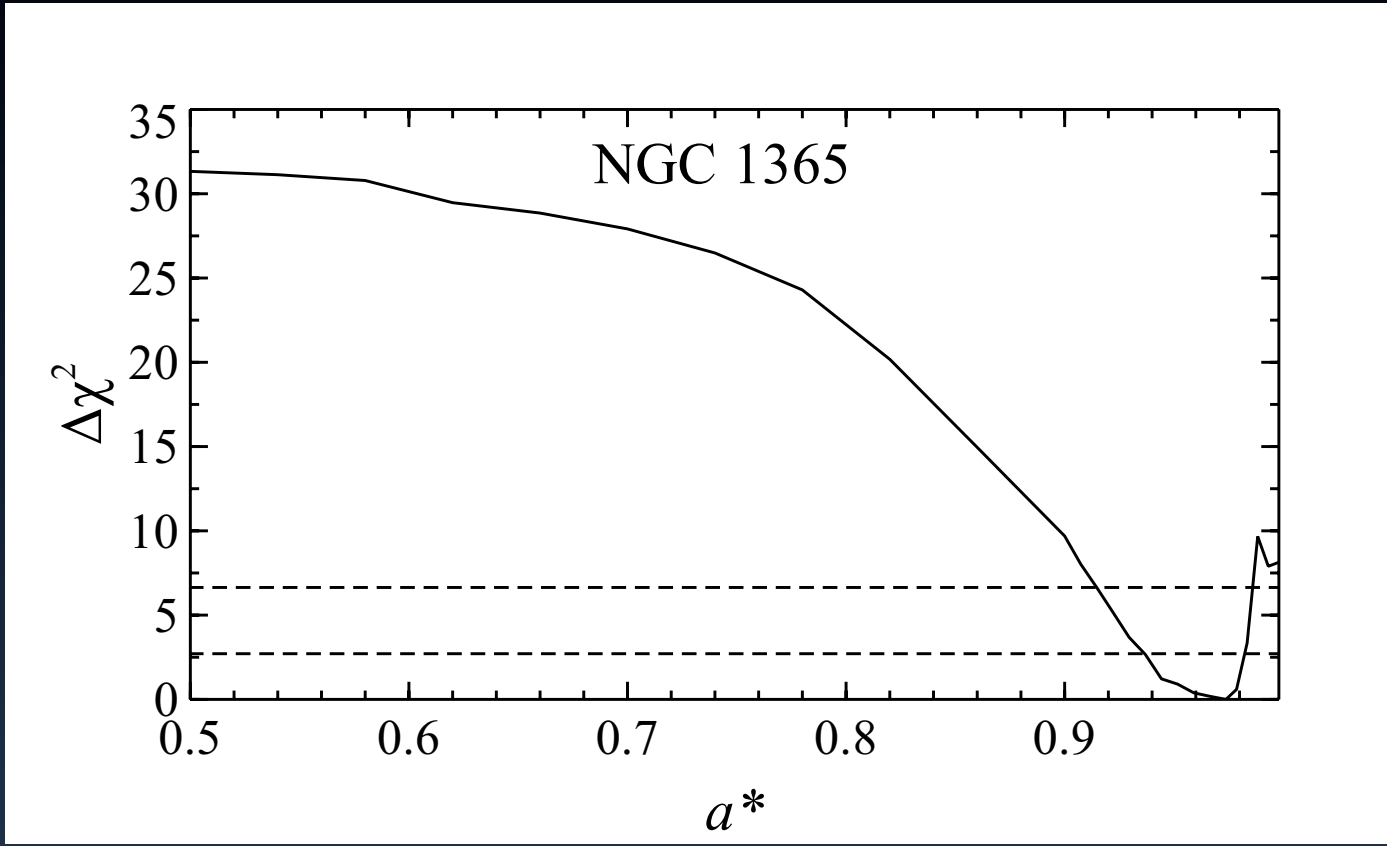


Fit adding NuSTAR data



Obscuration model requires τ_c >5 – unphysical consequences

Spin Constraint

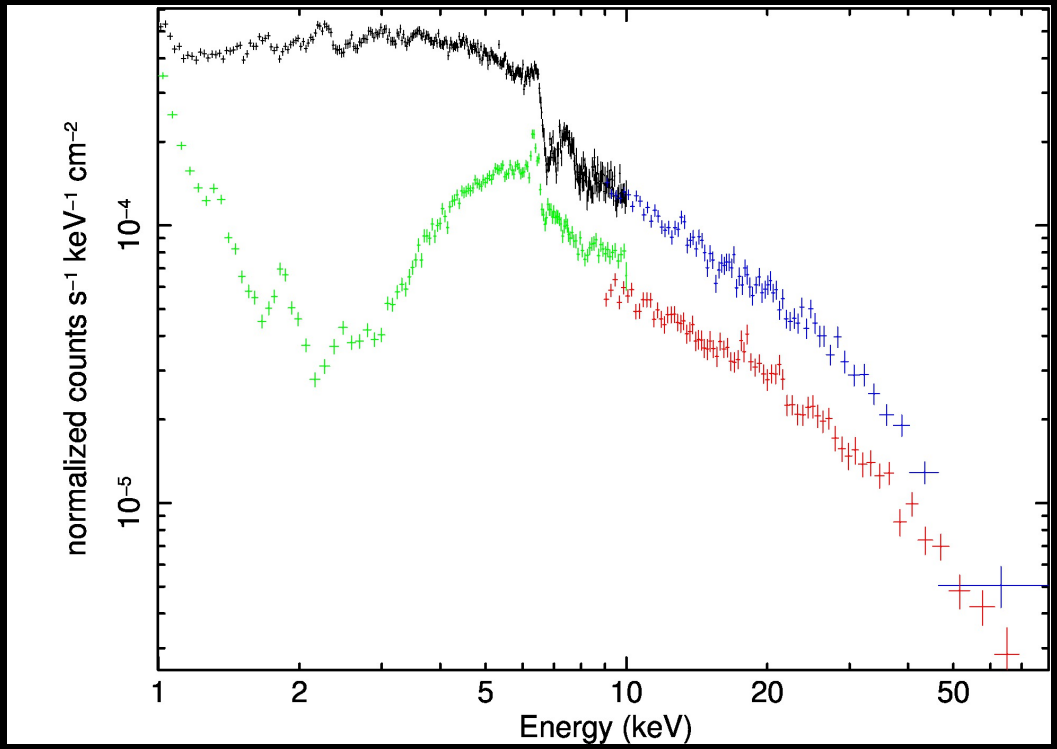


a (Jc/GM^2) > 0.84 (90% confidence)

Spin, disk inclination, ionization, emissivity profile allowed to vary

NGC 1365 Later Epochs (4 total)

NuSTAR+XMM: Second Observation



Different absorption, different flux, different reflection/ power law ratio, but same disk and BH parameters!

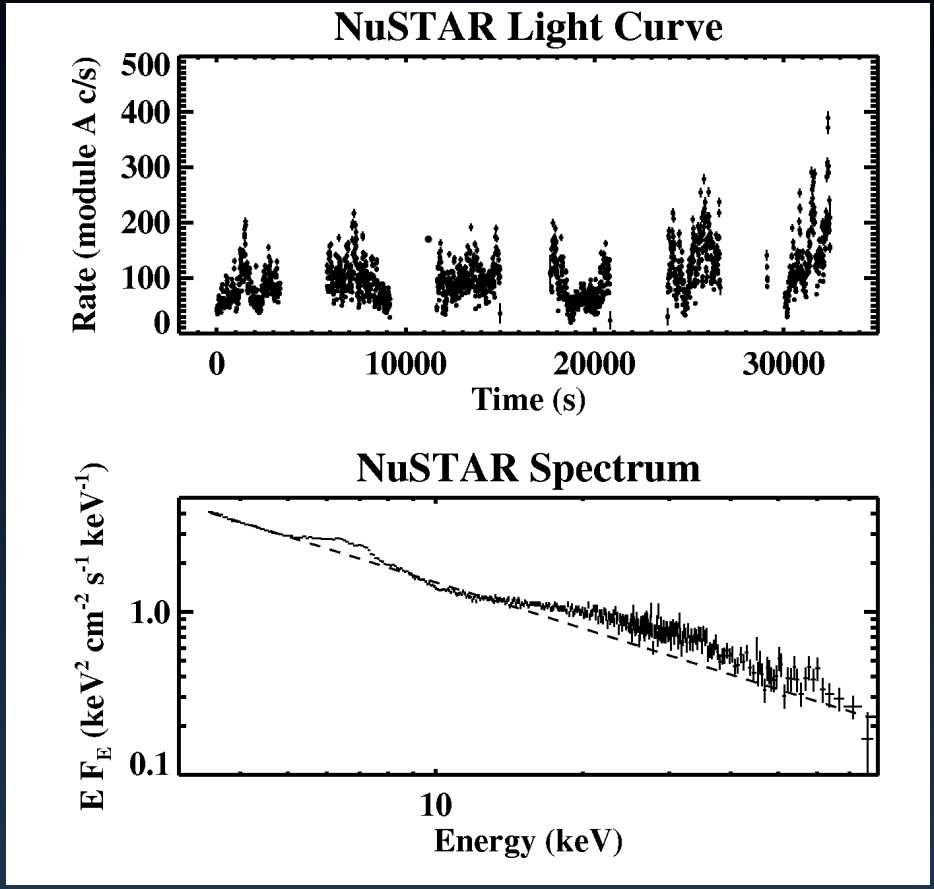
Other Spin (and AGN Physics) Targets

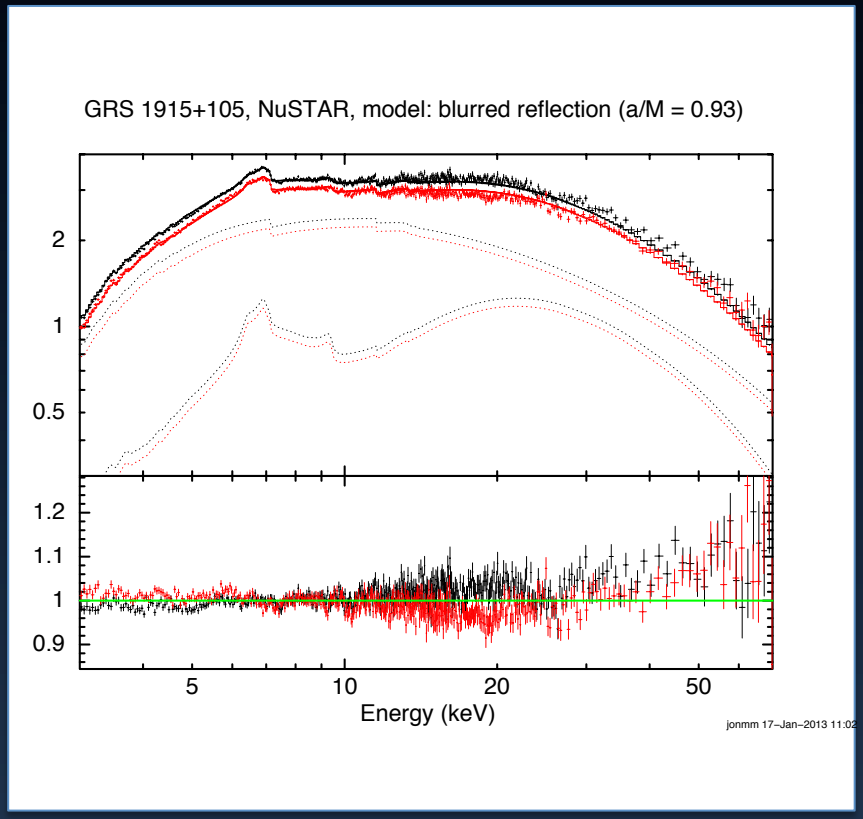
Between AGN and ULX observations, XMM allocated 10% of observing time to joint programs with NuSTAR

AGN Targets joint with XMM or Suzaku

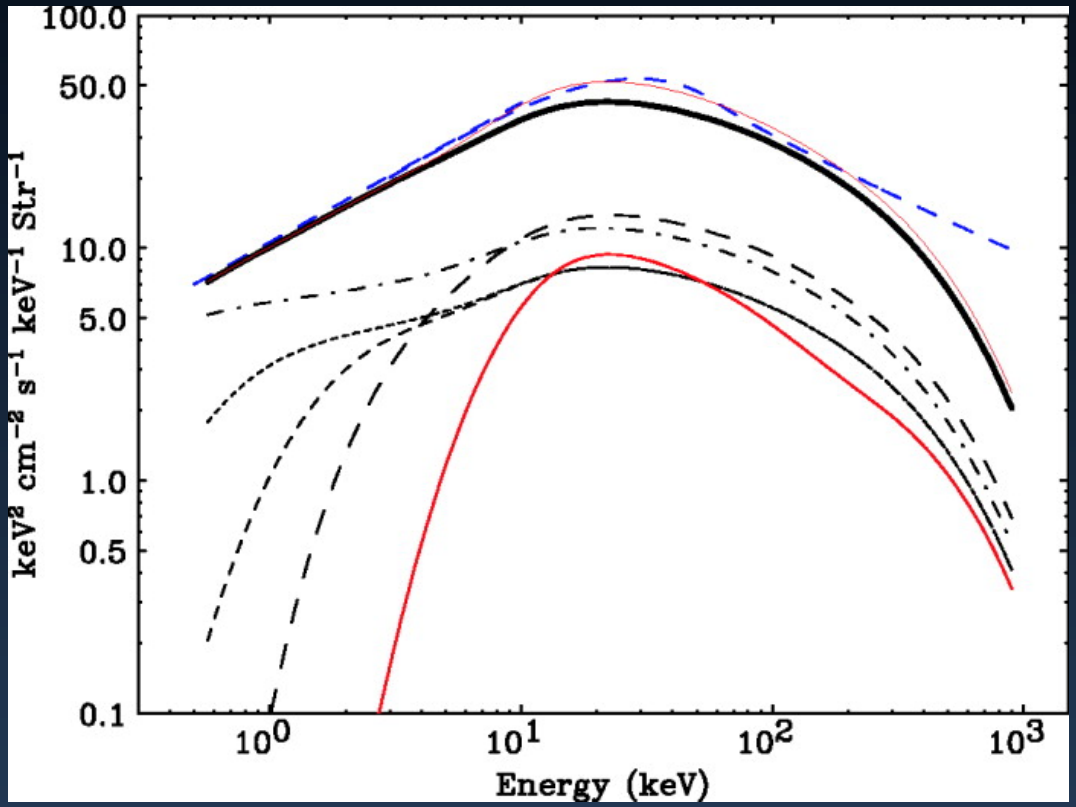
•Ark 120	90 ks
• MCG—6-30-15	180 ks
• 3C 120	180 ks
• Swift J2127.4+5654	180 ks
• NGC 4151	150 ks
•IC 4329A	120 ks
•NGC 3783	300 ks
•MCG—5-23-16	300 ks
•NGC 1365*	4 x 120 ks

Galactic Binaries





Extragalactic Surveys

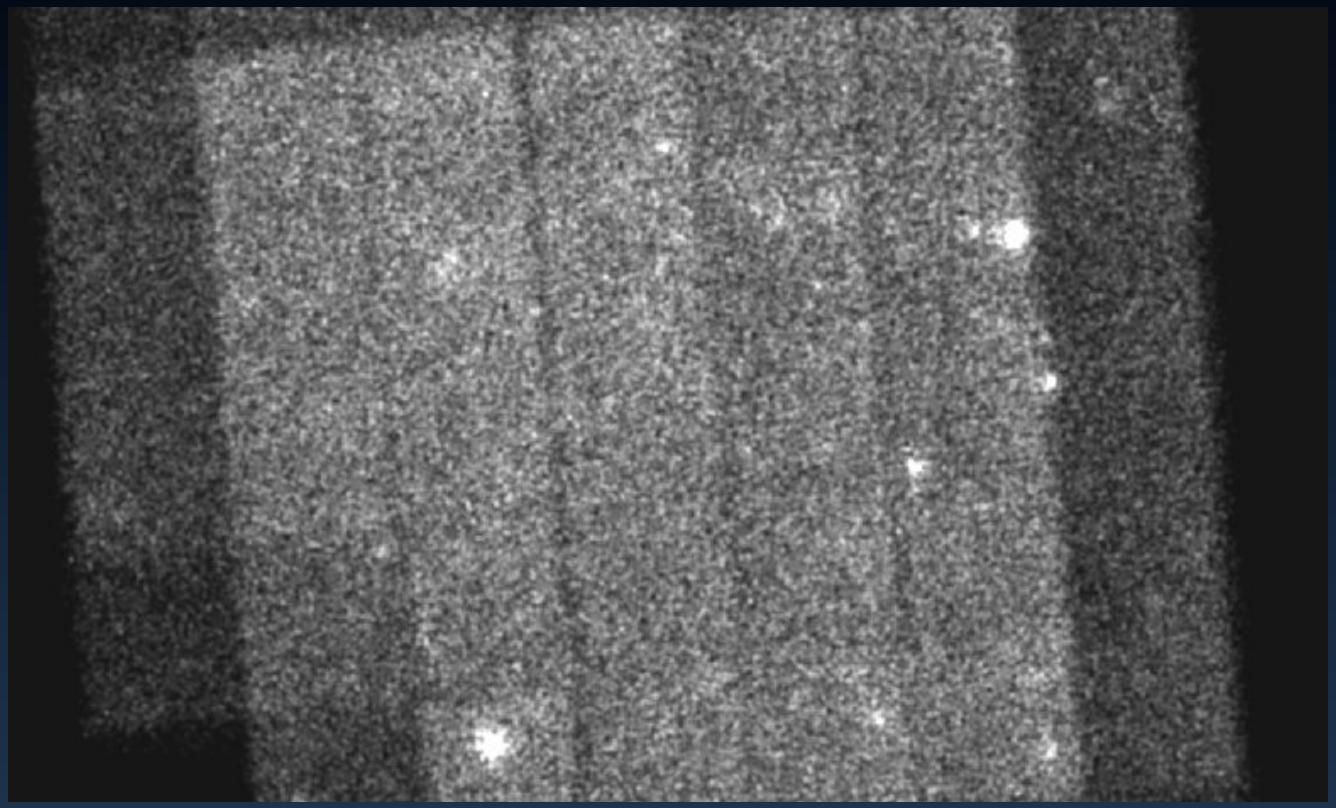


- peaks at ~30 keV
- constrains the accretion history of the universe, e.g., the formation history of supermassive black holes
- requires a population of heavily obscured AGN

Extragalactic Surveys

Target	Exp. Time	Goals	Status
ECDFS	3.7 Ms	**Deep extragalactic survey** Four epochs of 50 ks depth, covering 0.25 deg^2. Epochs separated by ~6 months; total depth = 200 ks	First pass pass completed Sep-Dec 2012
COSMOS	3.7 Ms	**Moderate-depth extragalactic survey** Baseline plan 1 deg^2 to 50 ks depth - strategy maintains flexibility to change to 2 deg^2 at 25 ks	25 ks depth of 1 deg^2 being completed this week
Swift-BAT Survey	100 x 15 ks	**Shallow extragalactic survey** (had also considered a single wide-area, shallow survey, but number count predictions were low; targeted snapshot survey easier for scheduling and guarantees science)	~35/100 observed thus far

COSMOS

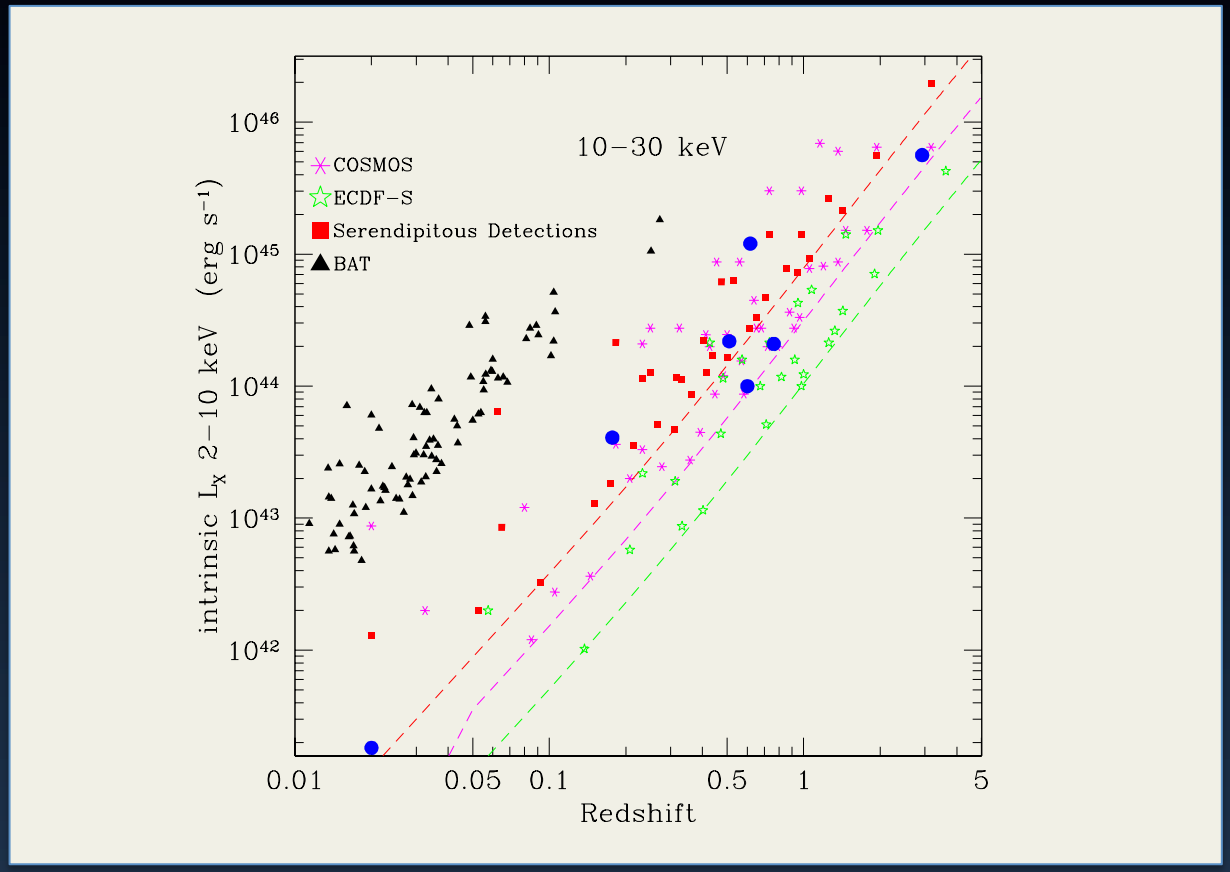


3 Ms planned
on 1 deg^2

34 fields observed
Area: 0.6deg^2
~35 detected sources

NuSTAR COSMOS Mosaic

Extragalactic Surveys



Summary

- NuSTAR is working well on orbit
  - » Several 100-fold improvement in sensitivity over previous hard X-ray missions
- 10-year orbit lifetime
- Lots more to come!

Baseline Mission Science

Science Group	Working Group Chair
Galactic Surveys, Galactic Center	Chuck Hailey
Supernovae and ToOs	Steve Boggs
Supernova remnants and Pulsar Wind Nebulae	Fiona Harrison
Magnetars and Rotation Powered Pulsars	Vicky Kaspi
Galactic Binaries	John Tomsick
Ultraluminous X-ray Sources	Fiona Harrison
Extragalactic Surveys	Daniel Stern
Blazars and Radio Galaxies	Greg Madejski, Paolo Giommi
Obscured AGN	Daniel Stern
AGN Physics	Giorgio Matt
Galaxy Clusters	Allan Hornstrup, Silvano Molendi
Starburst Galaxies	Ann Hornschemeier
Solar Physics	David Smith

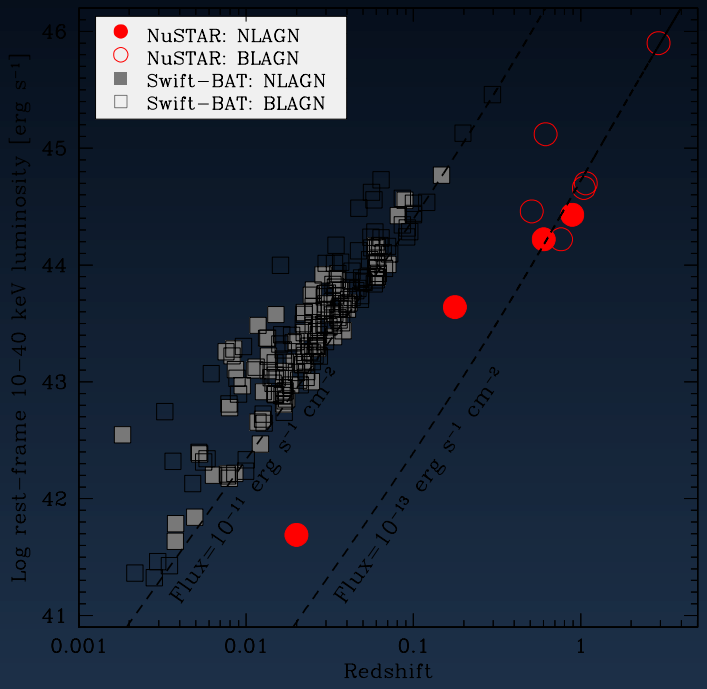
http://www.nustar.caltech.edu (look under 'for astronomers')

Black Holes

Appearance
- Mass (3 – 10^{10} M_{sun})
- Spin
- Accretion rate (L/L_{Edd})
- (environment)

NGC 1365 – measuring BH spin
- $M \sim 2 \times 10^6$ M_{sun}
- $L \sim 0.1$ L_{Edd}

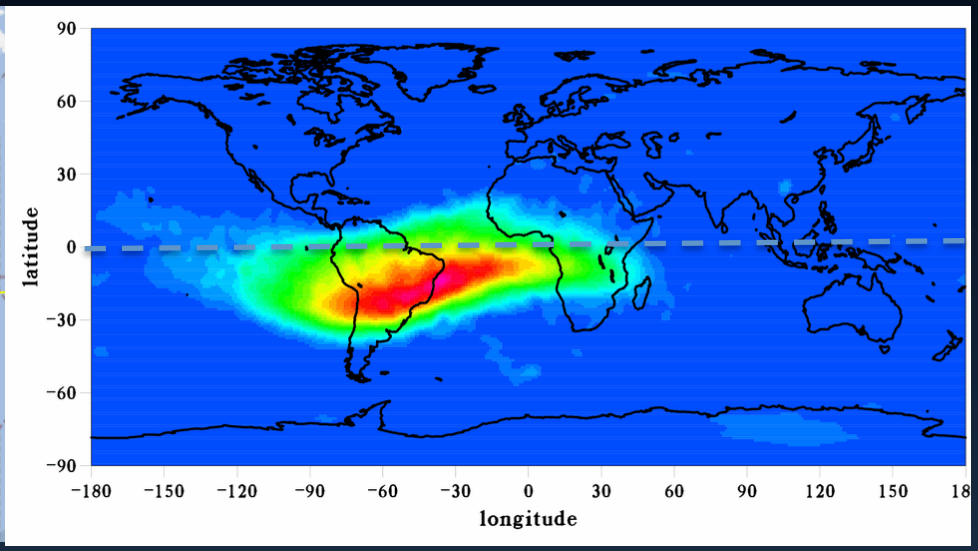
Sgr A* - flares at high energy
- $M = 4 \times 10^6$ M_{sun}
- $L = 10^{-9}$ L_{Edd}


NuSTAR: NLAGN
NuSTAR: BLAGN
Swift−BAT: NLAGN
Swift−BAT: BLAGN
Log rest−frame 10−40 keV luminosity [erg s⁻¹]
Redshift
Flux=10⁻¹¹ erg s⁻¹ cm⁻²
Flux=10⁻¹³ erg s⁻¹ cm⁻²
46
45
44
43
42
41
0.001
0.01
0.1
1

Orbit

NuSTAR orbit

South Atlantic anomaly



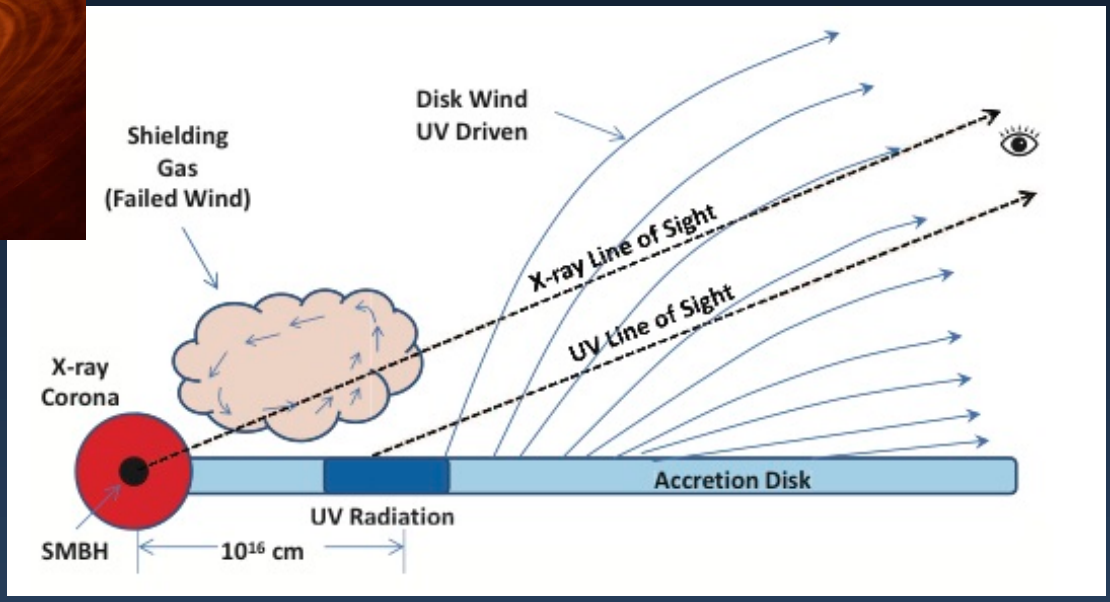
637 x 623, 6.0 deg inclination
Lifetime ~ 10 years
Saa passages: not quite every orbit, never through highest intensity

X-ray Weak Quasars: Intrinsic or Obscuration?

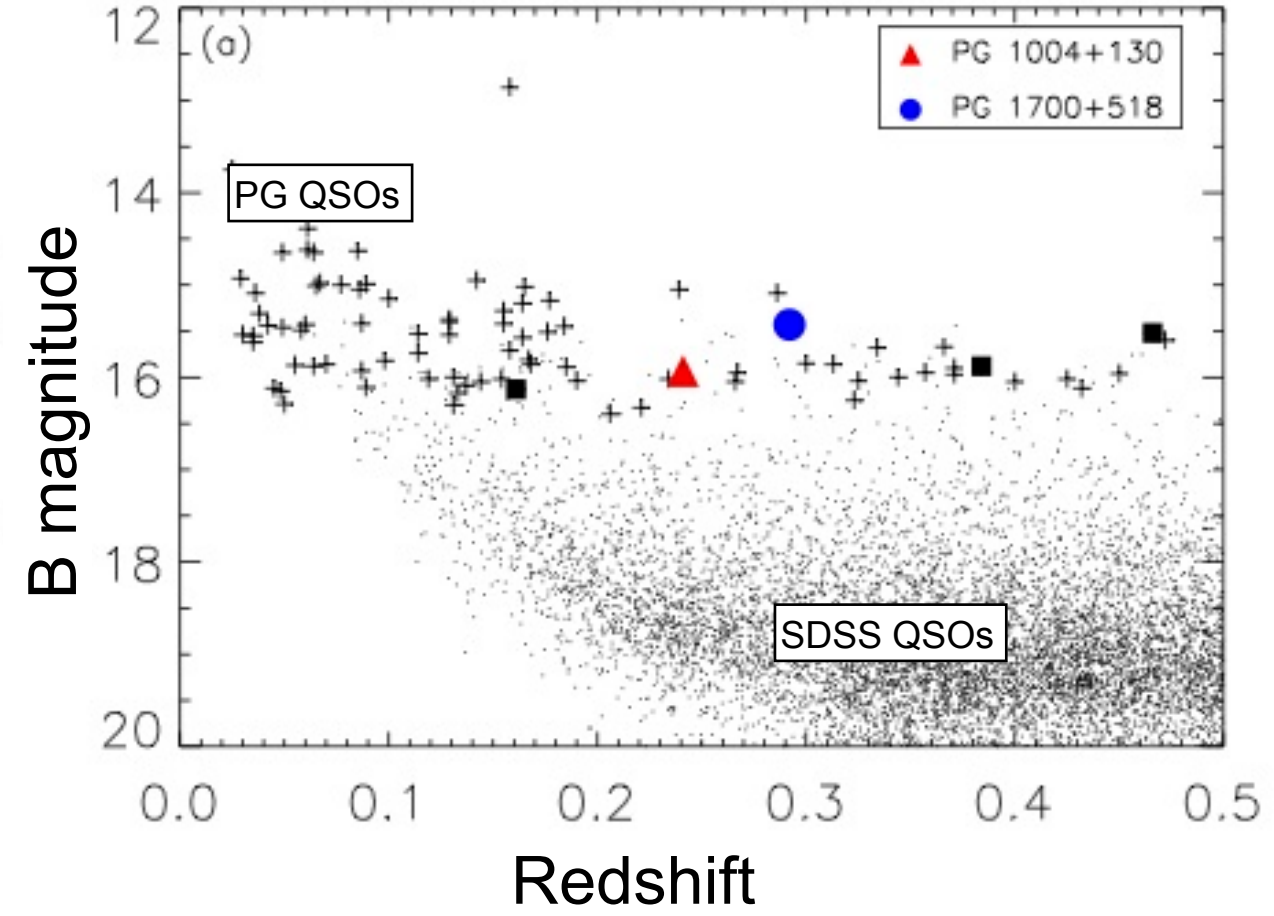
What fraction of quasars are X-ray obscured?

- A fraction of quasars (mostly BALQSOs) are much fainter at (soft) X-ray energies than expected from optical

- Intrinsically weak? Or heavily obscured?

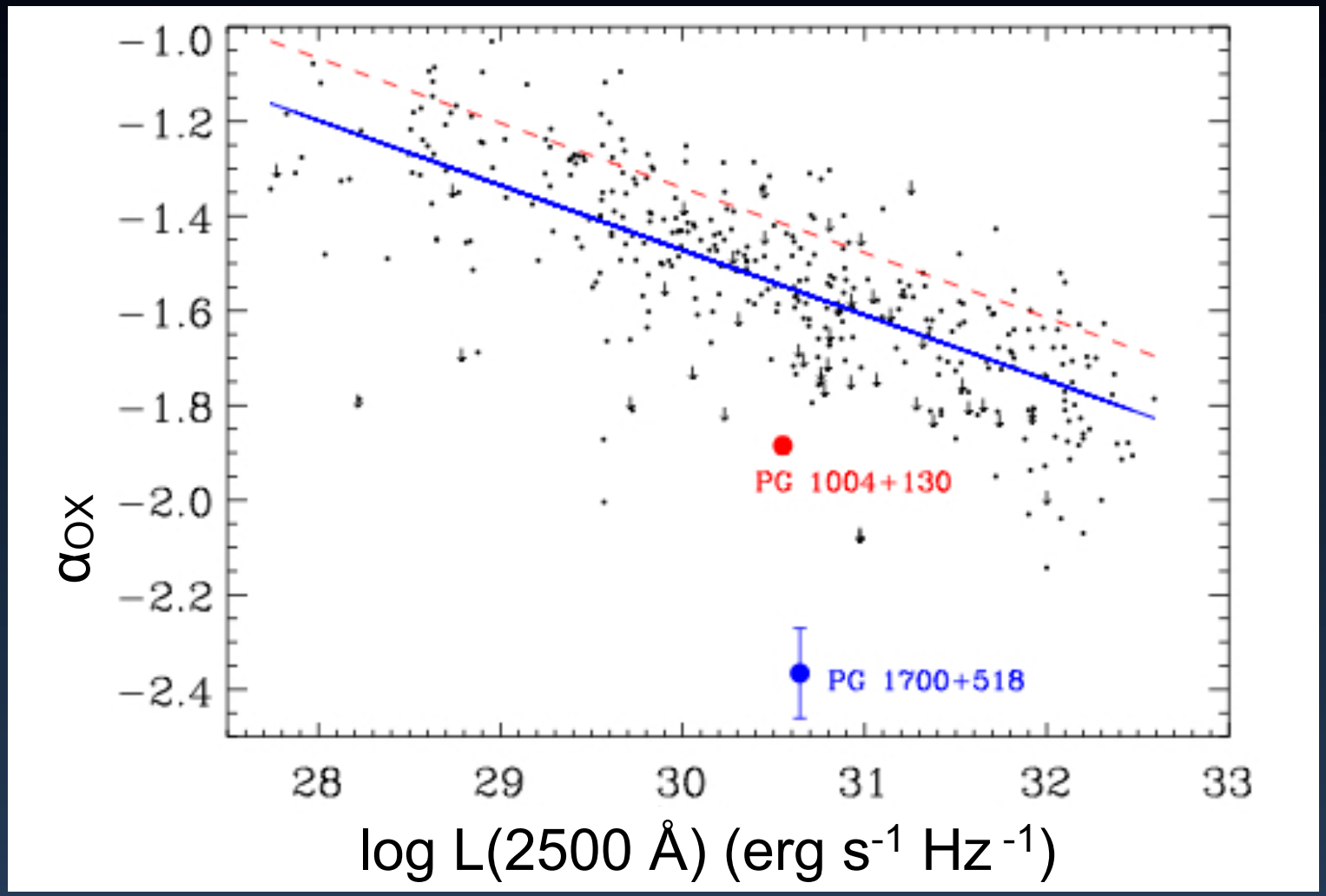


-Ray Weak Quasars: Intrinsic or Obscuration?



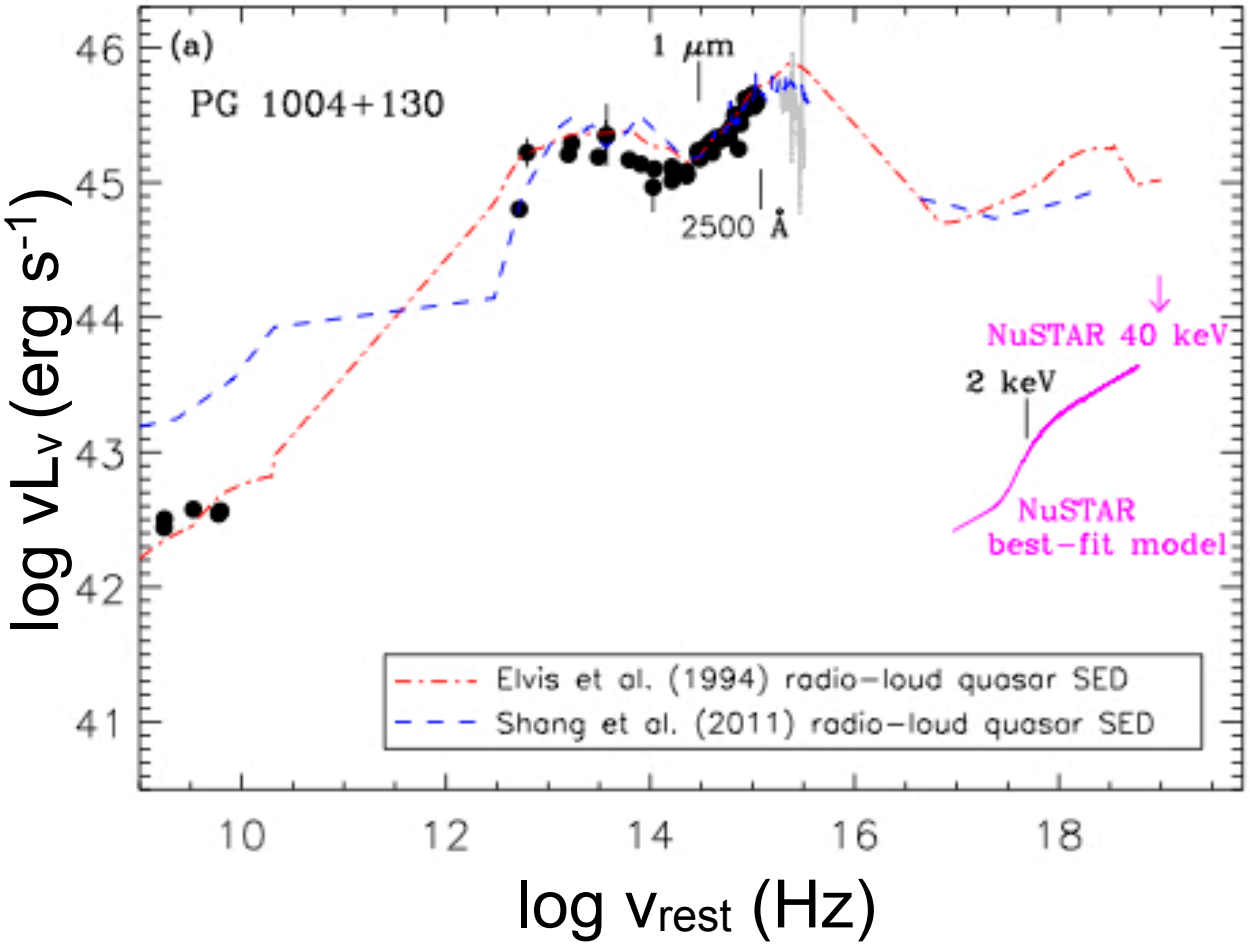
Luo et al., *ApJ*, submitted

X-Ray Weak Quasars: Intrinsic or Obscuration?



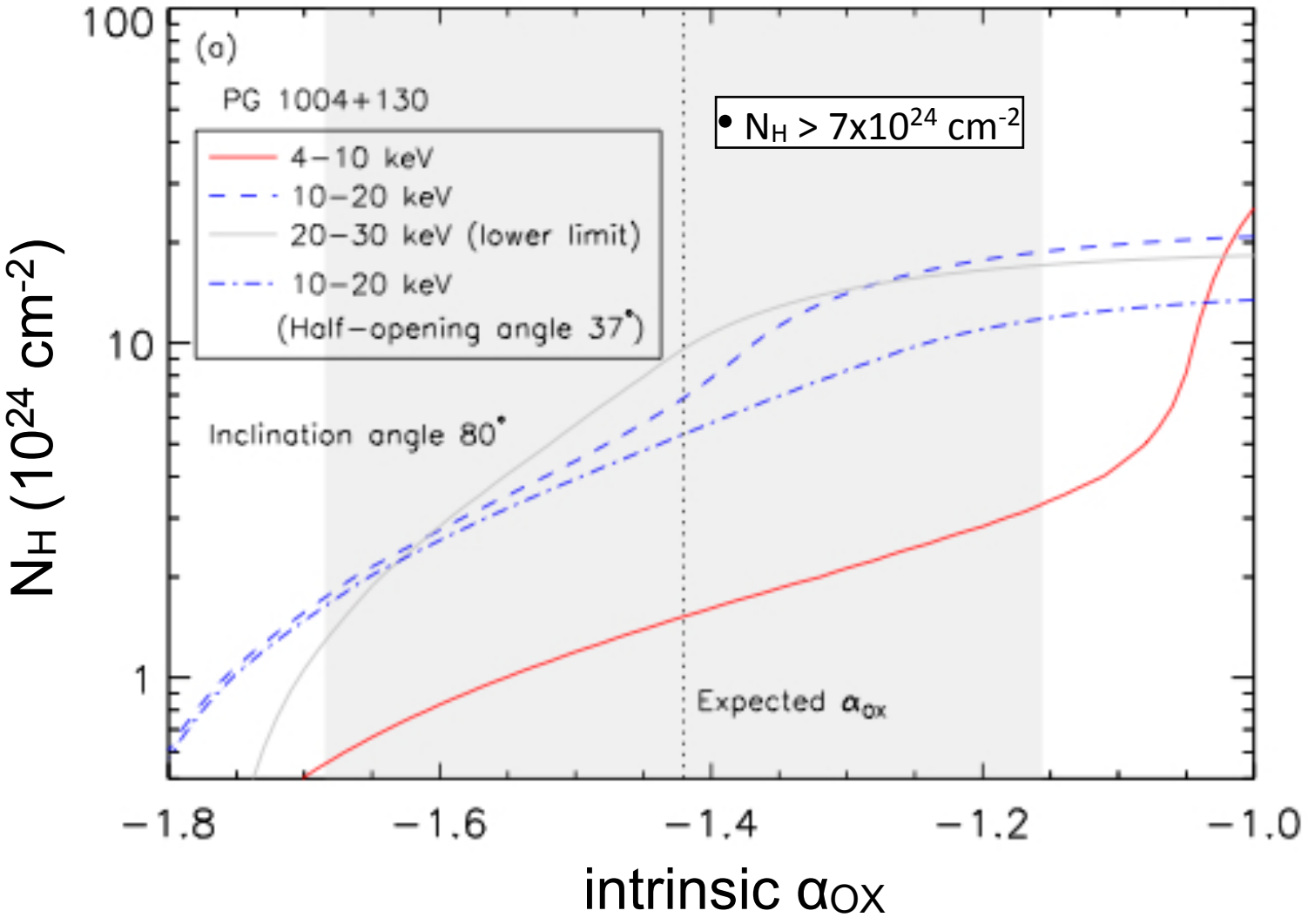
Luo et al., *ApJ*, submitted

X-ray Weak Quasars: Intrinsic or Obscuration?



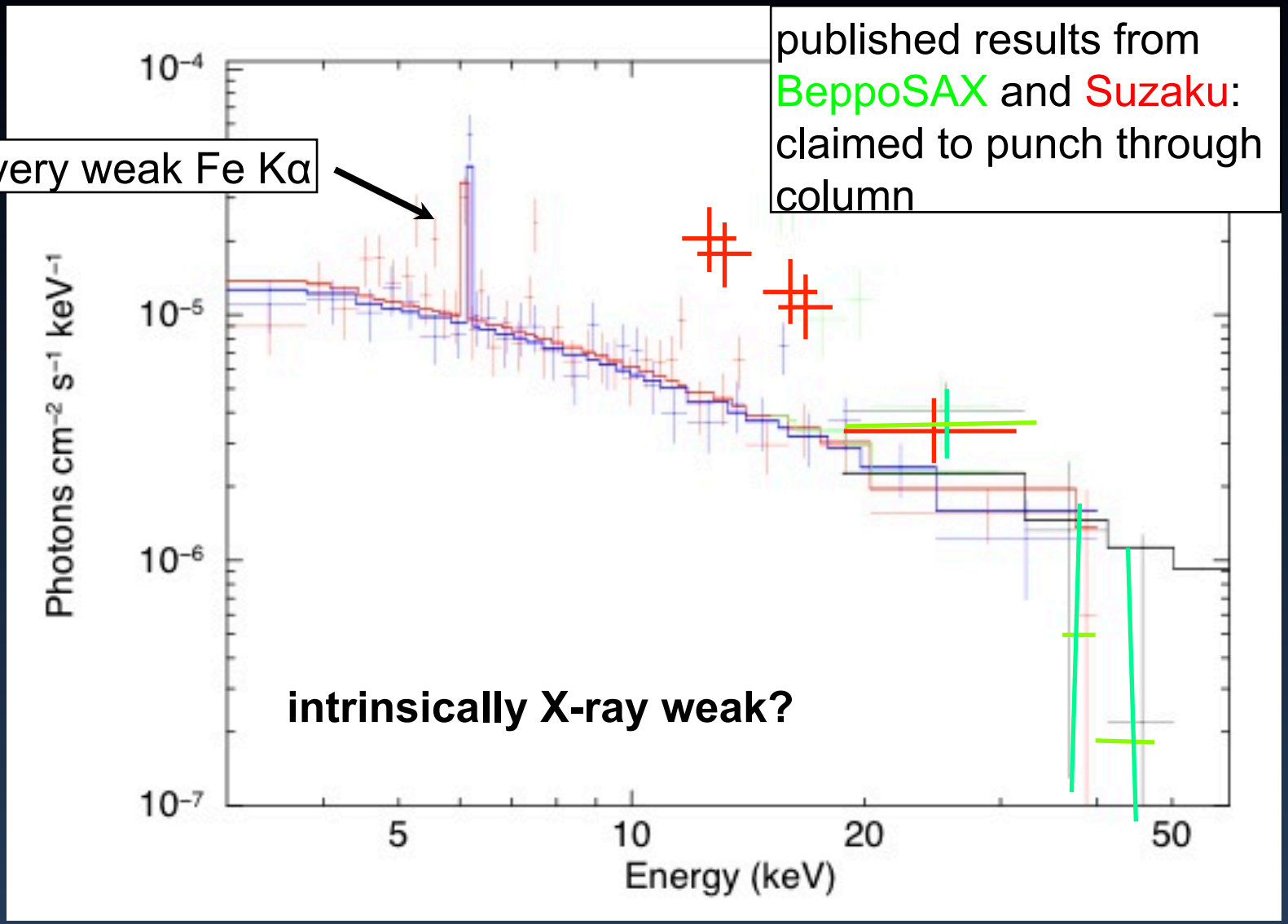
Luo et al., *ApJ*, submitted

Ray Weak Quasars: Intrinsic or Obscuration?



Luo et al., *ApJ*, submitted

X-Ray Weak Quasars: Mrk 231



Teng et al., in prep.


X-RAY
VISION


NET WEIGHT 3 LBS.
CLEANS EVERYTHING
HURTS NOTHING
X-RAY
THAT
WONDERFUL
SOAP
BEST SOAP
MADE FOR
AUTOMOBILES
X-RAY PRODUCTS CO.
PORT HURON, MICH.