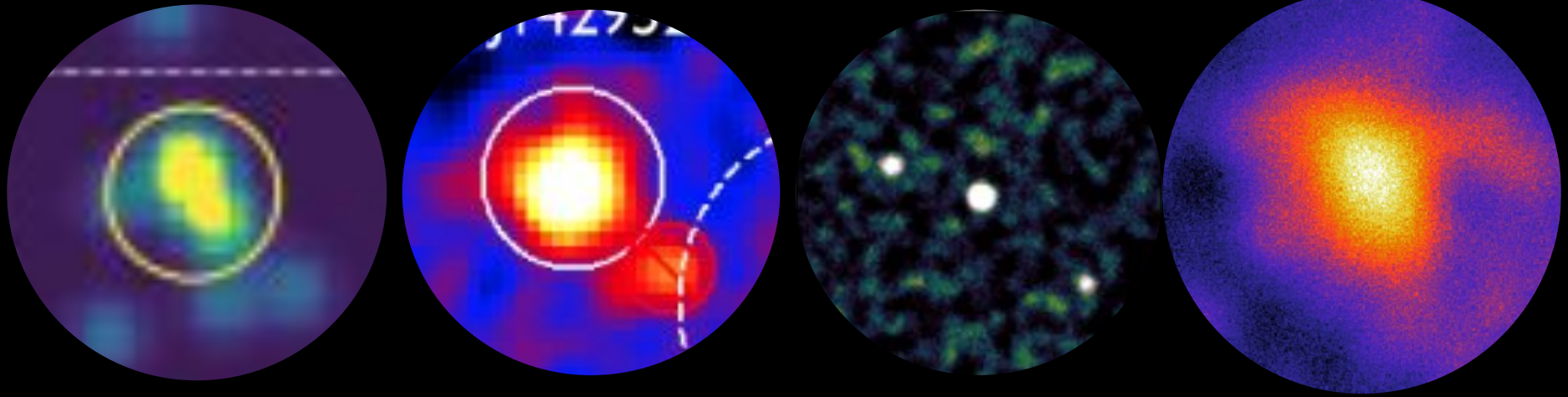


A variable monster at the Epoch of Reionization

Presented by Lea Marcotulli

On behalf of: Thomas Connor, Eduardo Bañados , Peter Boorman , Giulia Migliori, Brian Grefenstette, Emmanuel Momjian , Aneta Siemiginowska, Daniel Stern, Silvia Belladitta , Teddy Cheung , Andy Fabian, Yana Khusanova , Chiara Mazzucchelli , Sofía Rojas-Ruiz , Meg Urry

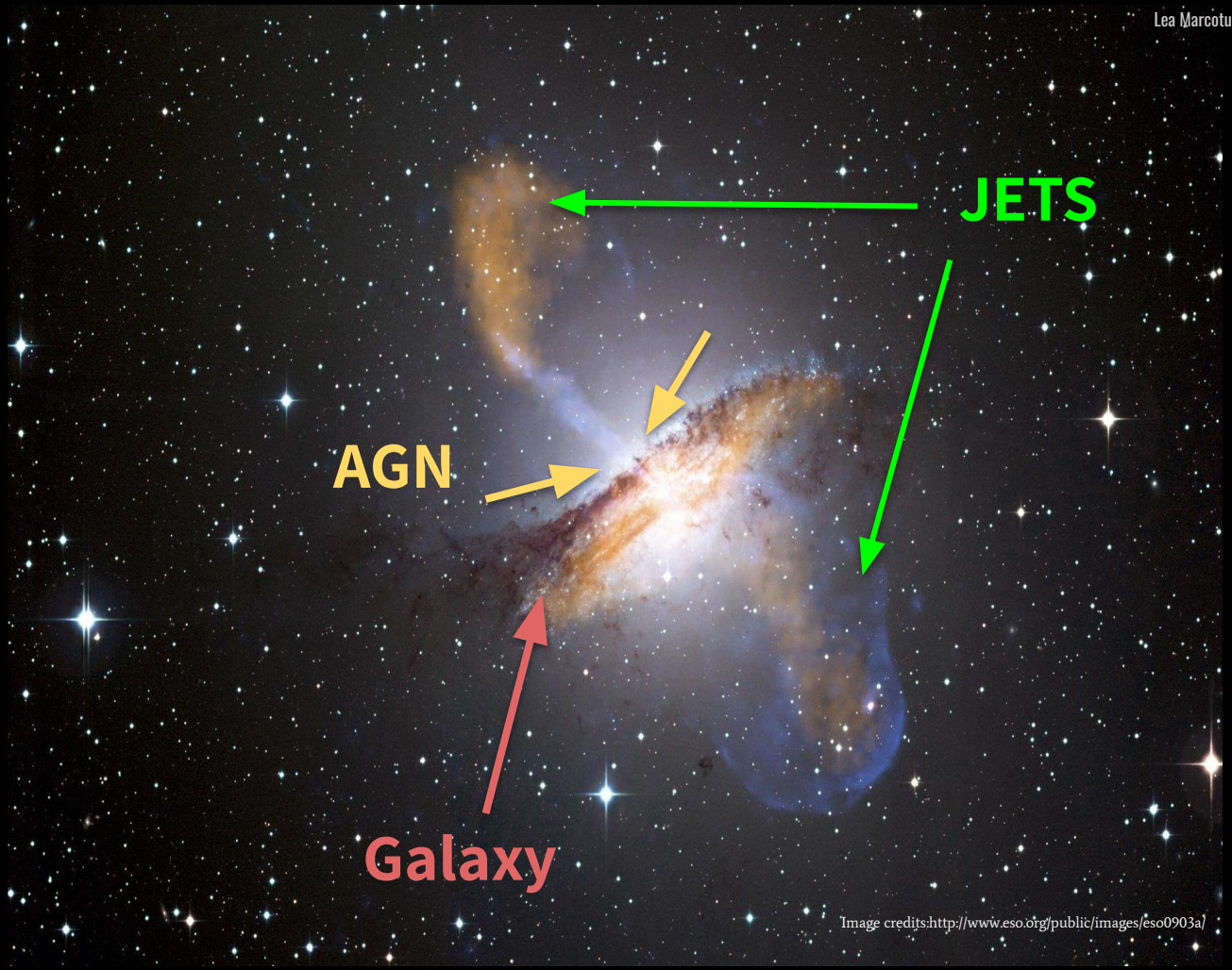
Caltech

25 Years of Science with Chandra, Dec 6th, 2024

Lea Marcotulli | lea.marcotulli@yale.edu

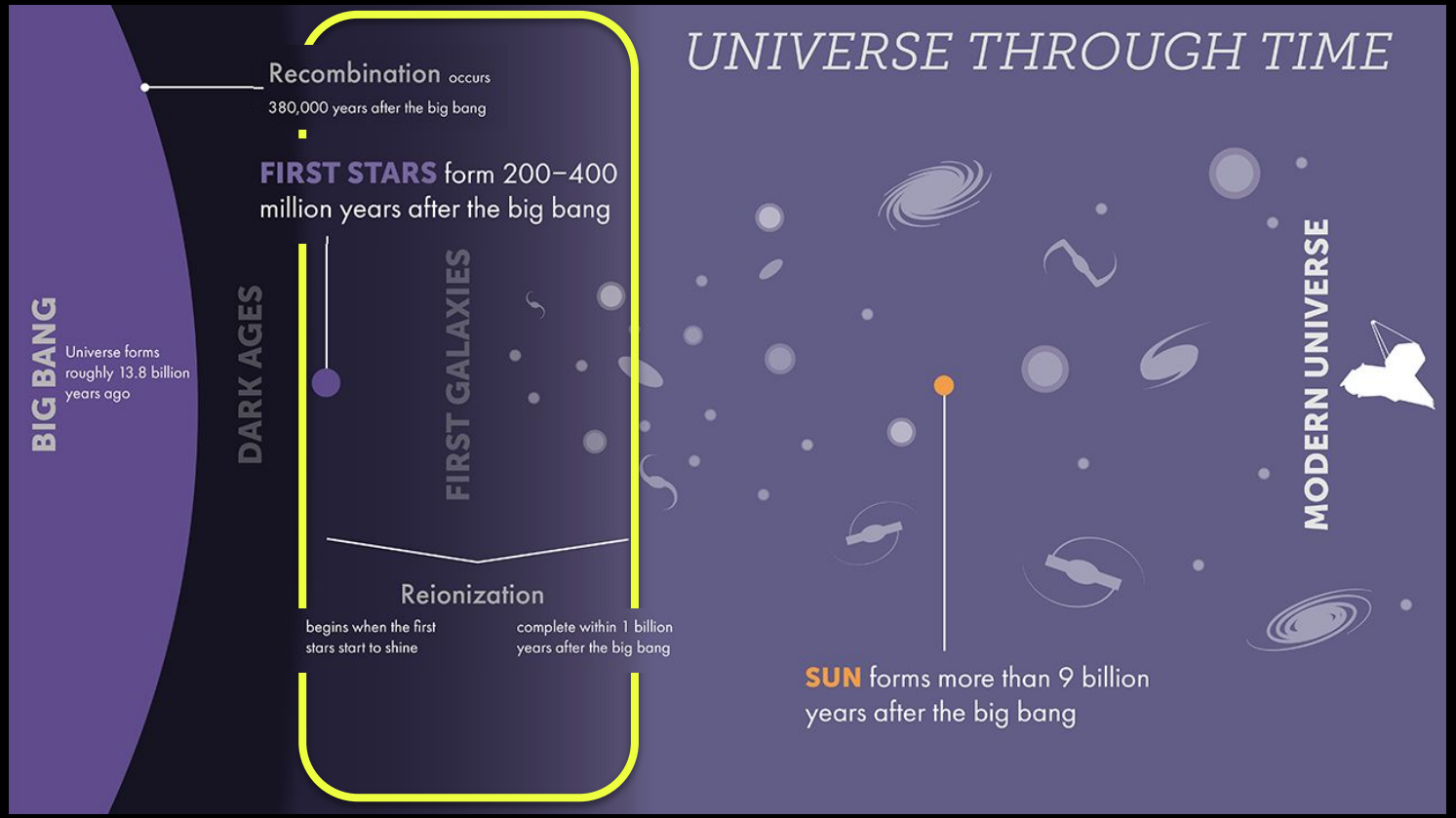
Centaurus A

Active Galactic Nuclei (AGNs)



Lea Marcotulli | lea.marcotulli@yale.edu

Credit: Webb Space Telescope



Epoch of Reionization

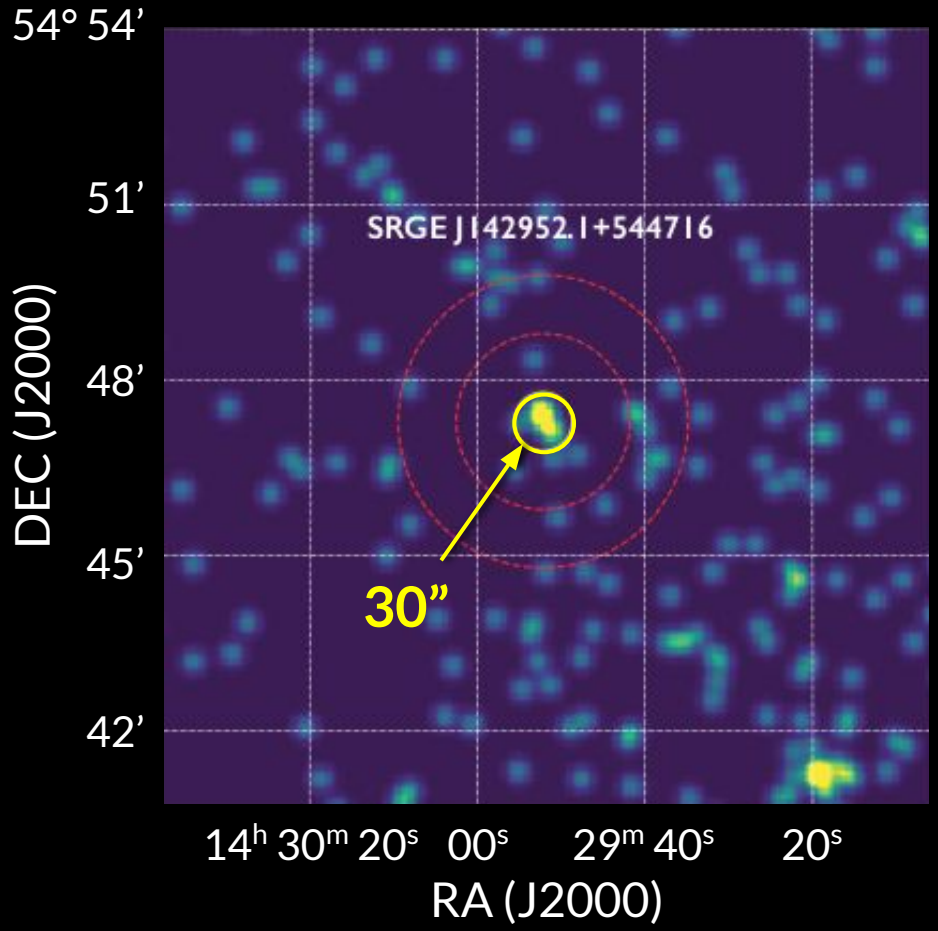
e.g. Bañados+16,+23,+24; Fan+19,+23; Matsuoka+22; Vito+19, Connor+19,+20,+21; Belladitta+20; Ighina+22

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
X-ray discovery

eROSITA
0.2-8 keV

0.3-2 keV image
Exp.=160 s



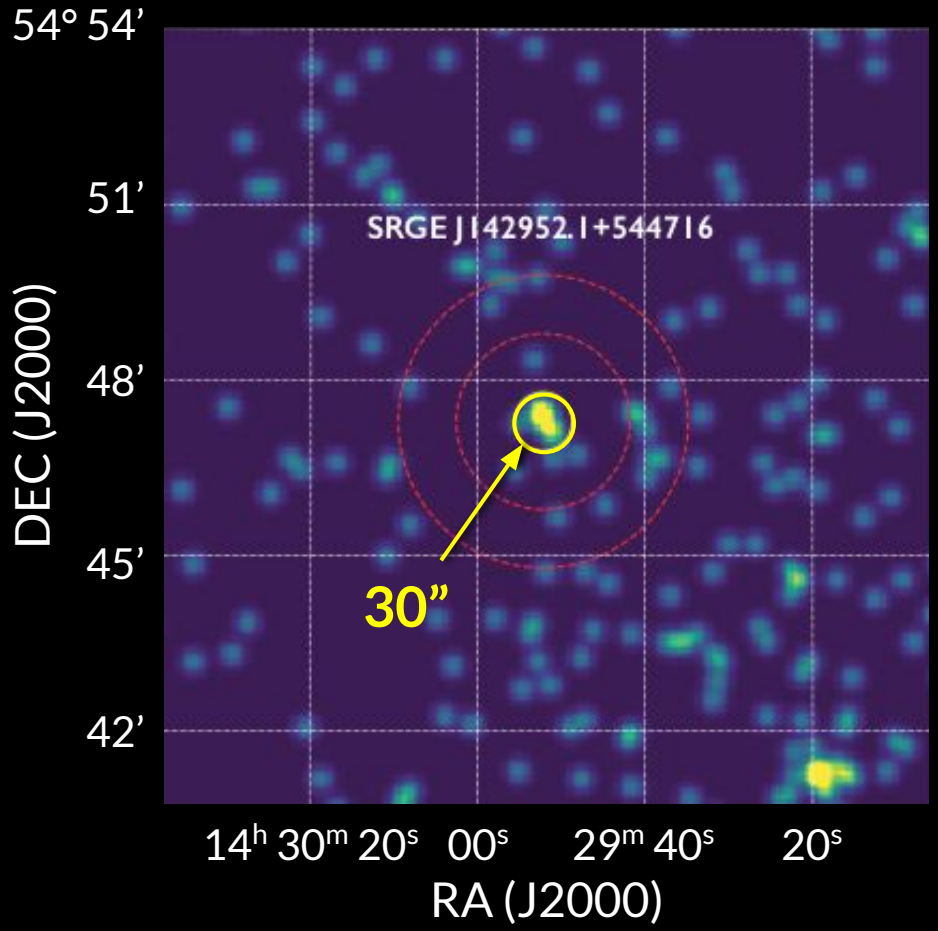
Medvedev+20

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
X-ray discovery

eROSITA
0.2-8 keV

0.3-2 keV image
Exp.=160 s



Medvedev+20

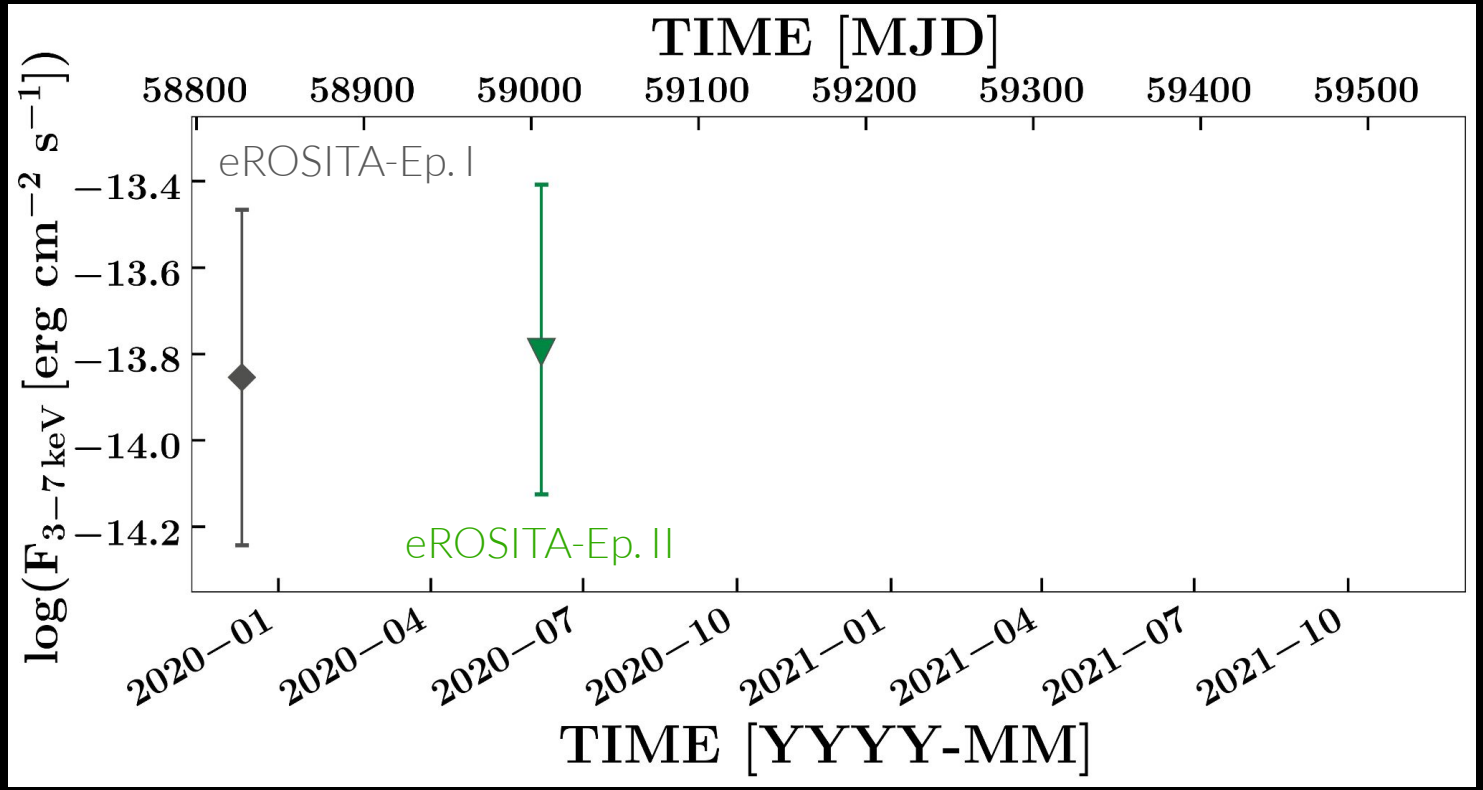
$z=6.19$
[Khusanova+22]

$M_{BH} = 10^{9.26 \pm 0.37} M_{\odot}$ [Shen+19]

Lea Marcotulli | lea.marcotulli@yale.edu

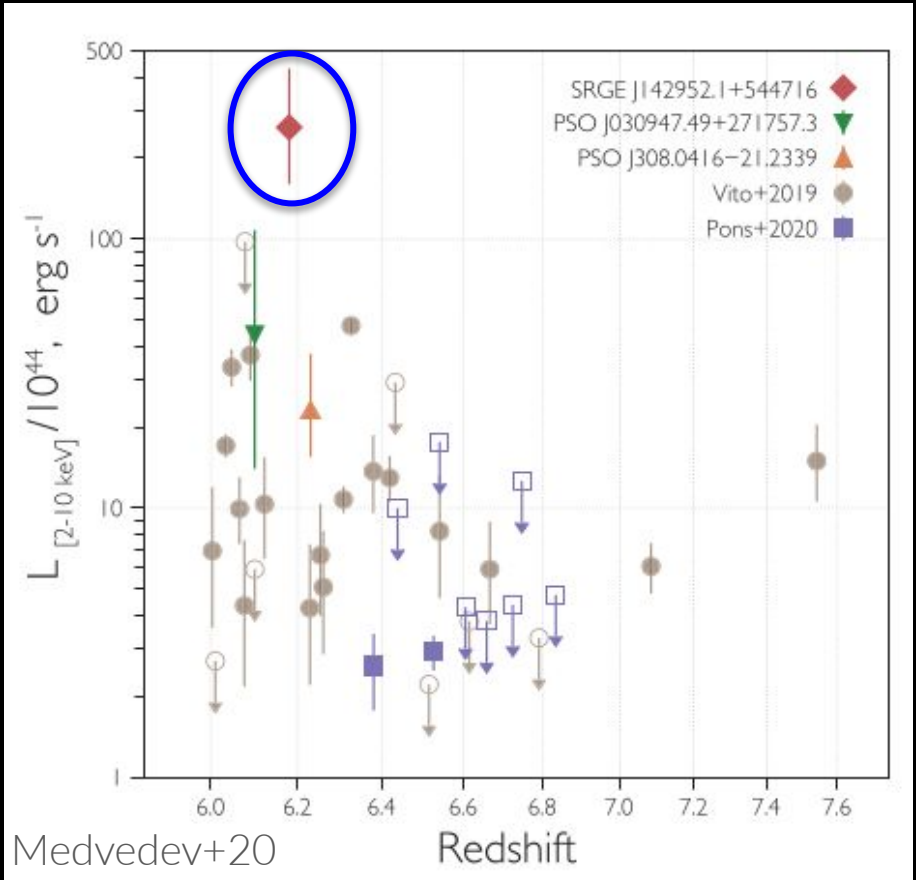
CFHQS J142952+544717
X-ray Lightcurve

Marcotulli, Connor+24,
accepted ApJL



Lea Marcotulli | lea.marcotulli@yale.edu

Multi-wavelength properties



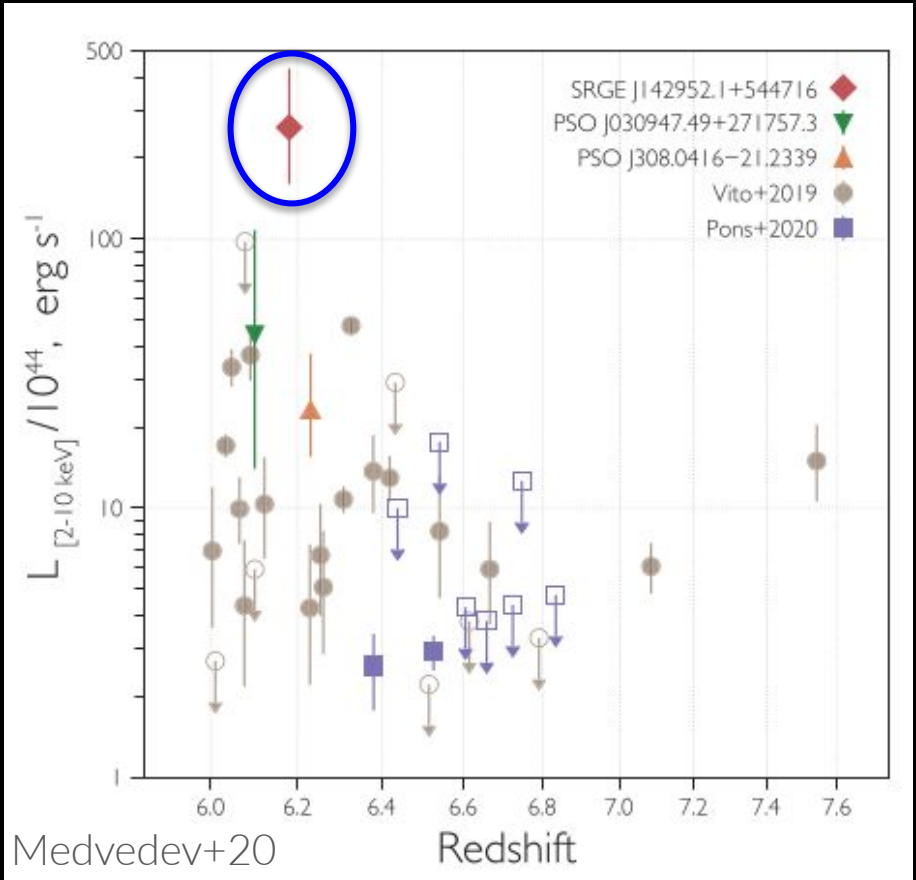
Medvedev+20

X-ray

➔ **Most luminous** X-ray quasar at z>6 to date

Lea Marcotulli | lea.marcotulli@yale.edu

Multi-wavelength properties



Medvedev+20

X-ray

➔ **Most luminous** X-ray quasar at z>6 to date

Radio

➔ **Radio loud** (R~100, usually indicative of strong jets) [Bañados+15]

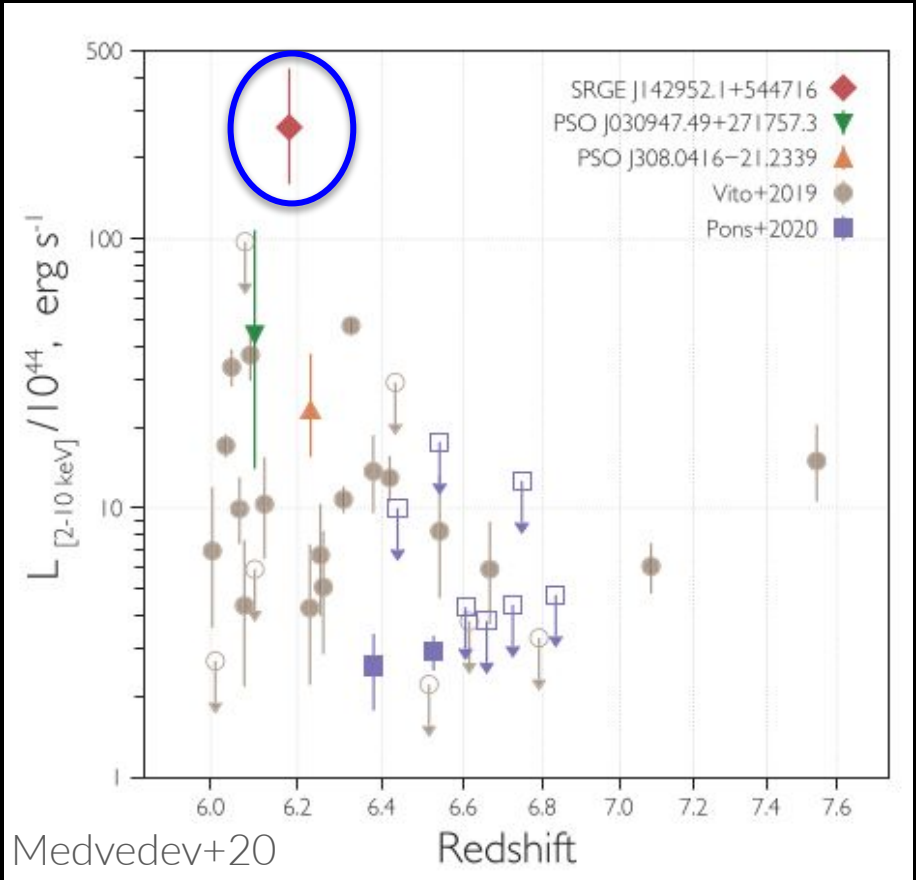
➔ **No** signs of **beaming**, jet resolved to 100pc extension [Frey+11]

➔ **Steep-spectrum** above 1.4 GHz [Coppejans et al. 2017]

➔ **Variable? NO!**

Lea Marcotulli | lea.marcotulli@yale.edu

Multi-wavelength properties



Medvedev+20

X-ray

➔ **Most luminous** X-ray quasar at z>6 to date

Radio

➔ **Radio loud** (R~100, usually indicative of strong jets) [Bañados+15]

➔ **No** signs of **beaming**, jet resolved to 100pc extension [Frey+11]

➔ **Steep-spectrum** above 1.4 GHz [Coppejans et al. 2017]

➔ **Variable? NO!**

Far-Infrared

➔ Sign of **merger** [Omont+13; Khusanova+22]

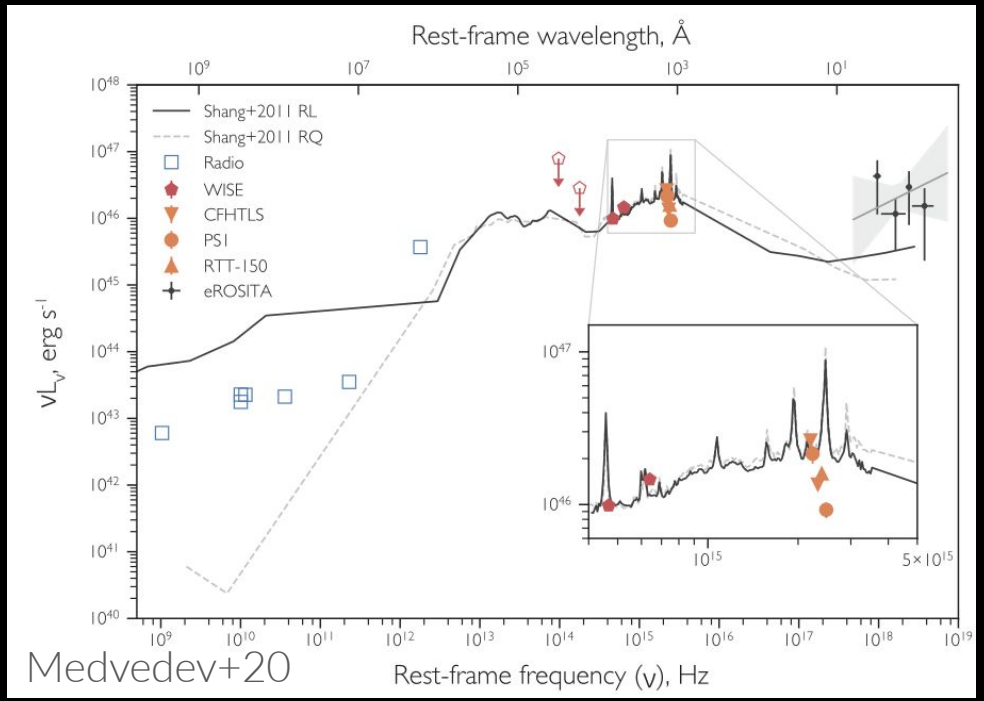
➔ **Star-forming** system (SFR = 520-870 $M_\odot$ yr^{-1}; Kushanova+22)

➔ Hint of **AGN outflow** ionizing the nuclear region [Kushanova+22]

➔ **Variable? NO!**

Lea Marcotulli | lea.marcotulli@yale.edu

Multi-wavelength properties



X-ray

➔ **Most luminous** X-ray quasar at z>6 to date

Radio

➔ **Radio loud** (R~100, usually indicative of strong jets) [Bañados+15]

➔ **No** signs of **beaming**, jet resolved to 100pc extension [Frey+11]

➔ **Steep-spectrum** above 1.4 GHz [Coppejans et al. 2017]

➔ **Variable? NO!**

Far-Infrared

➔ Sign of **merger** [Omont+13; Khusanova+22]

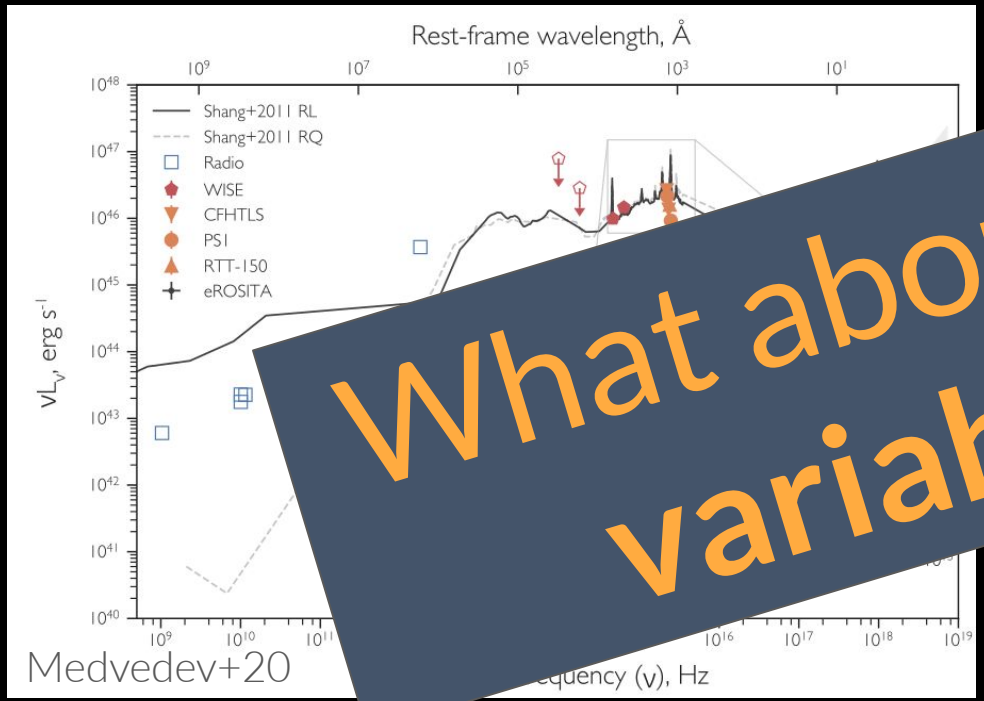
➔ **Star-forming** system (SFR = 520-870 $M_\odot$ yr^{-1}; Kushanova+22)

➔ Hint of **AGN outflow** ionizing the nuclear region [Kushanova+22]

➔ **Variable? NO!**

Lea Marcotulli | lea.marcotulli@yale.edu

Multi-wavelength properties



X-ray

➔ **Most luminous** X-ray quasar at z>6 to date

➔ **Radi** indicative of

lved to 100pc

Hz [Coppejans

Far-Infrared

➔ Sign of **merger** [Omont+13; Khusanova+22]

➔ **Star-forming** system (SFR = 520-870 $M_\odot$ yr^{-1}; Kushanova+22)

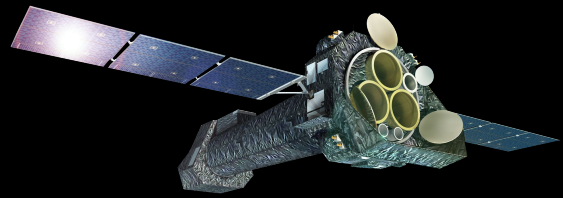
➔ Hint of **AGN outflow** ionizing the nuclear region [Kushanova+22]

➔ **Variable? NO!**

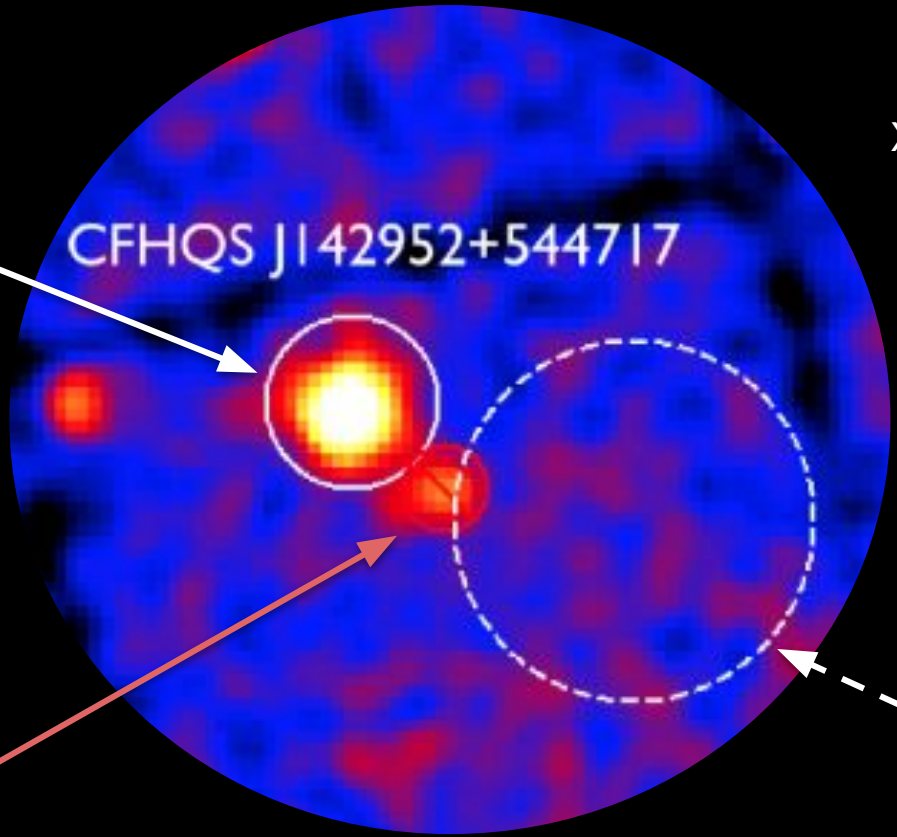
What about X-ray variability?

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
XMM
Follow-up



XMM-Newton: 0.2-10 keV



There is a SECOND source ~45” away (I-SW)

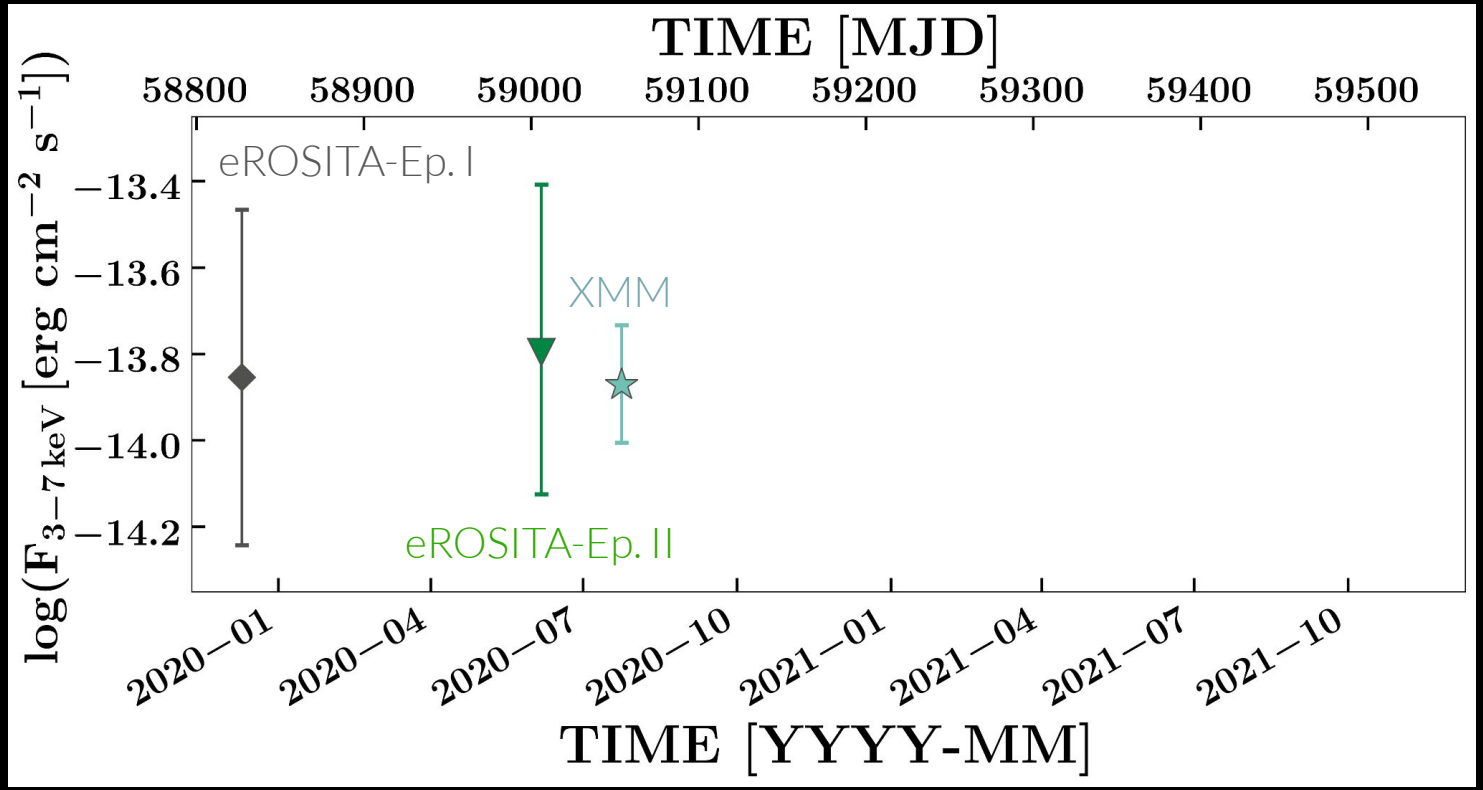
XMM background region

Medvedev+21

Lea Marcotulli | lea.marcotulli@yale.edu

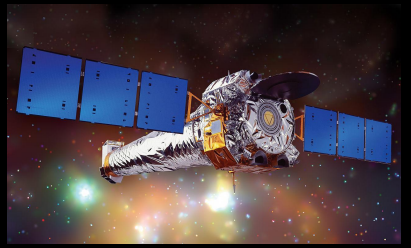
CFHQS J142952+544717
X-ray Lightcurve

Marcotulli, Connor+24,
accepted ApJL

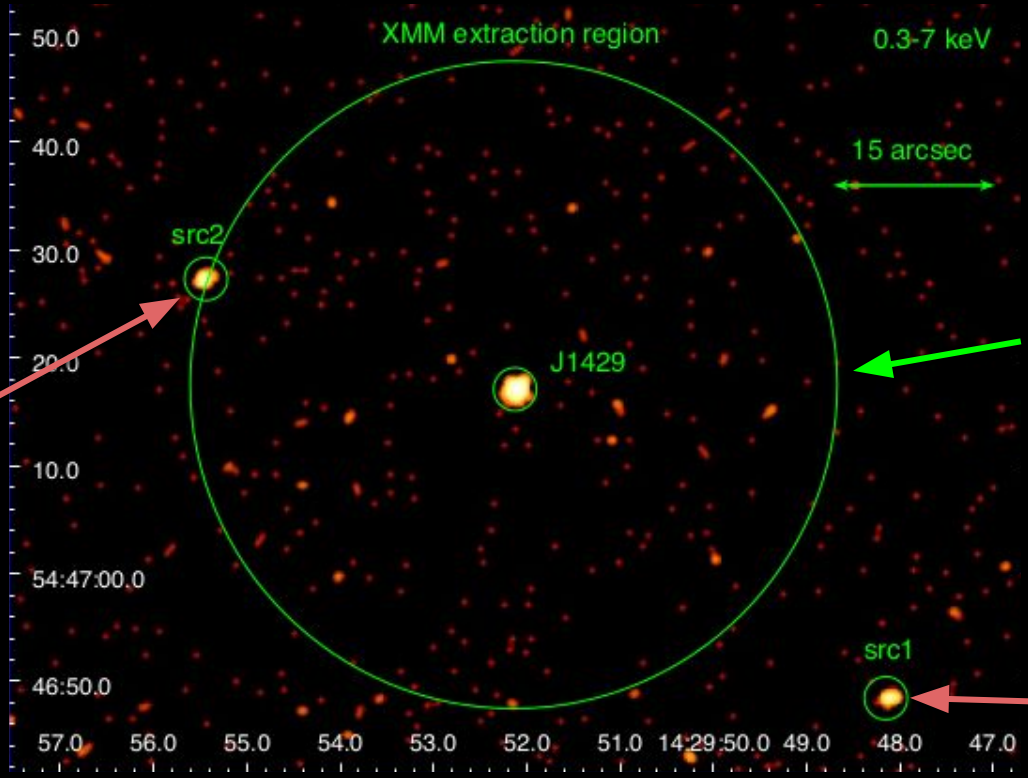


Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
Chandra Follow-up



Chandra: 0.5-7 keV



There is a THIRD source ~30” away! (I-NE)

30”

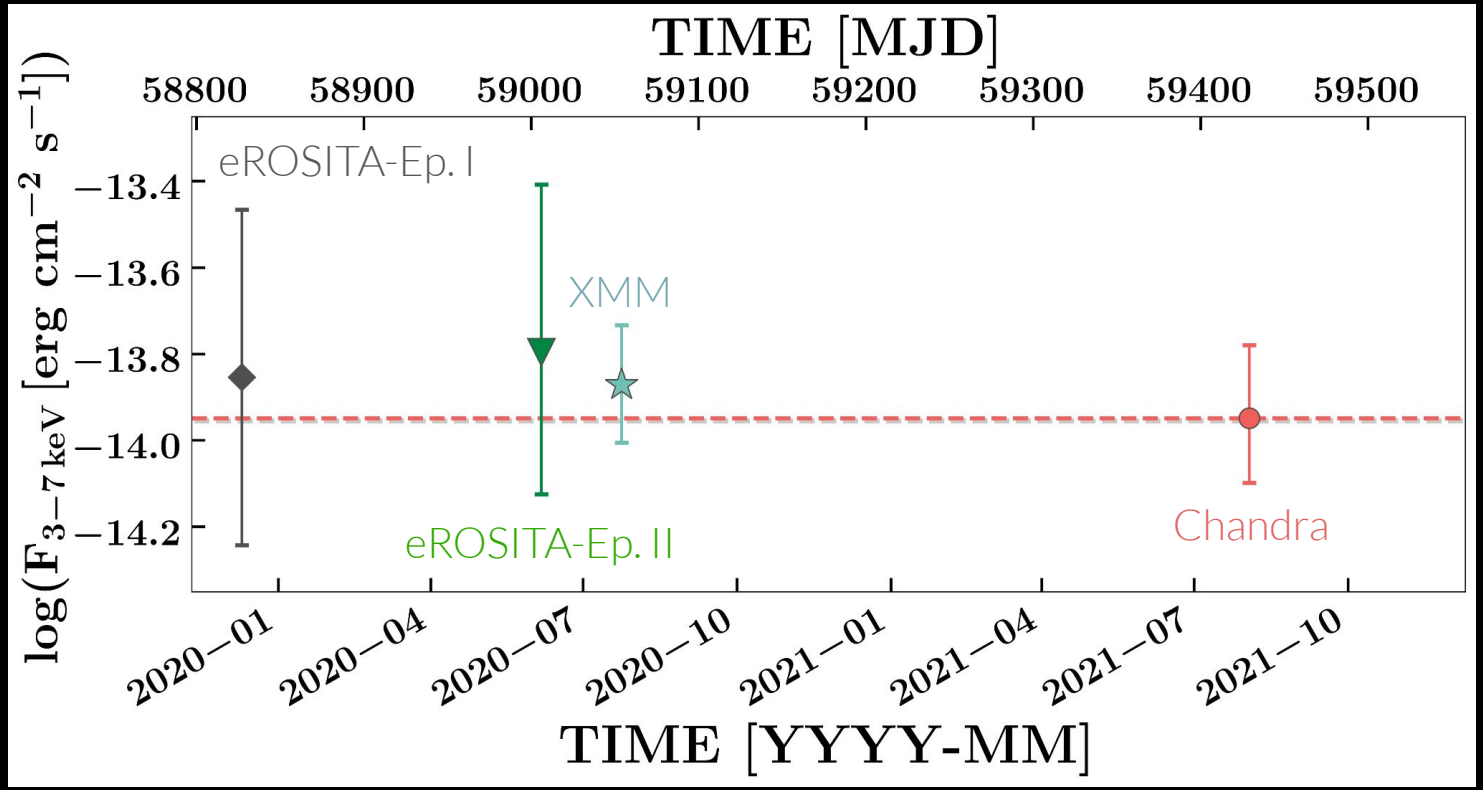
I-SW

Migliori+23

Lea Marcotulli | lea.marcotulli@yale.edu

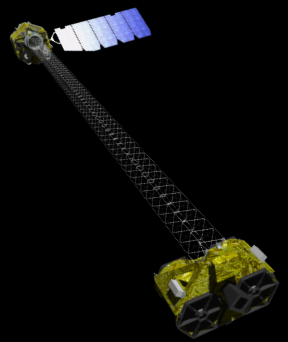
CFHQS J142952+544717
X-ray Lightcurve

Marcotulli, Connor+24,
accepted ApJL

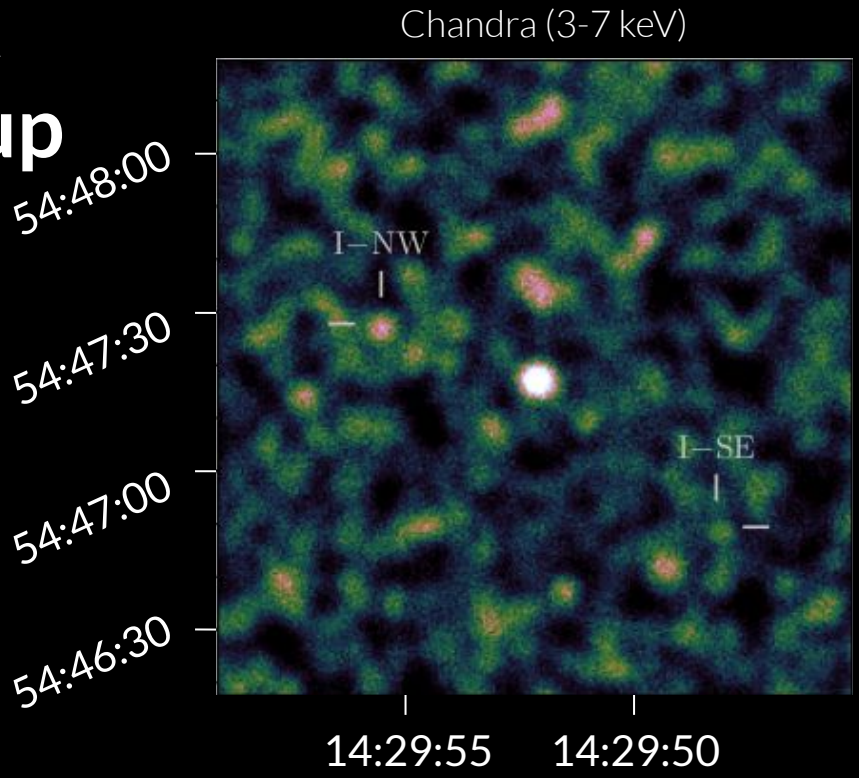


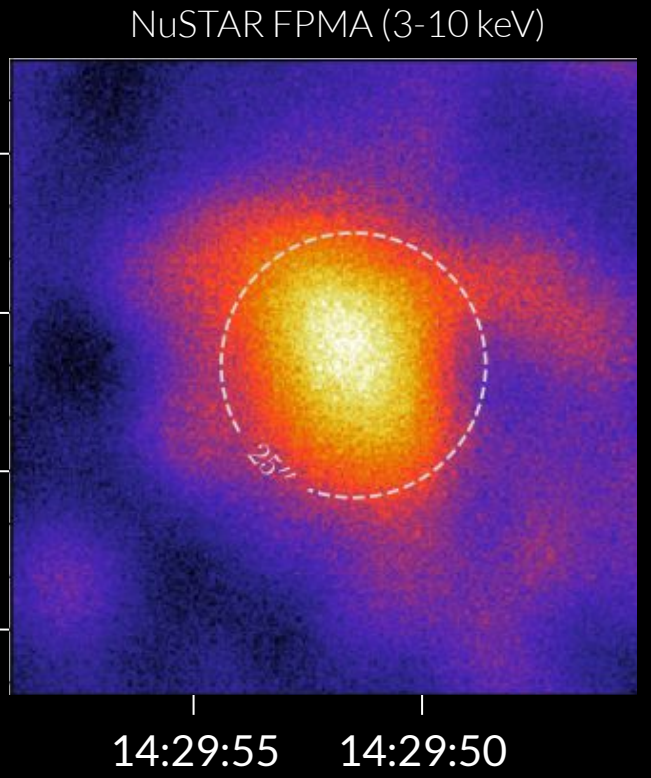
Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
NuSTAR Follow-up



NuSTAR: 3-78 keV

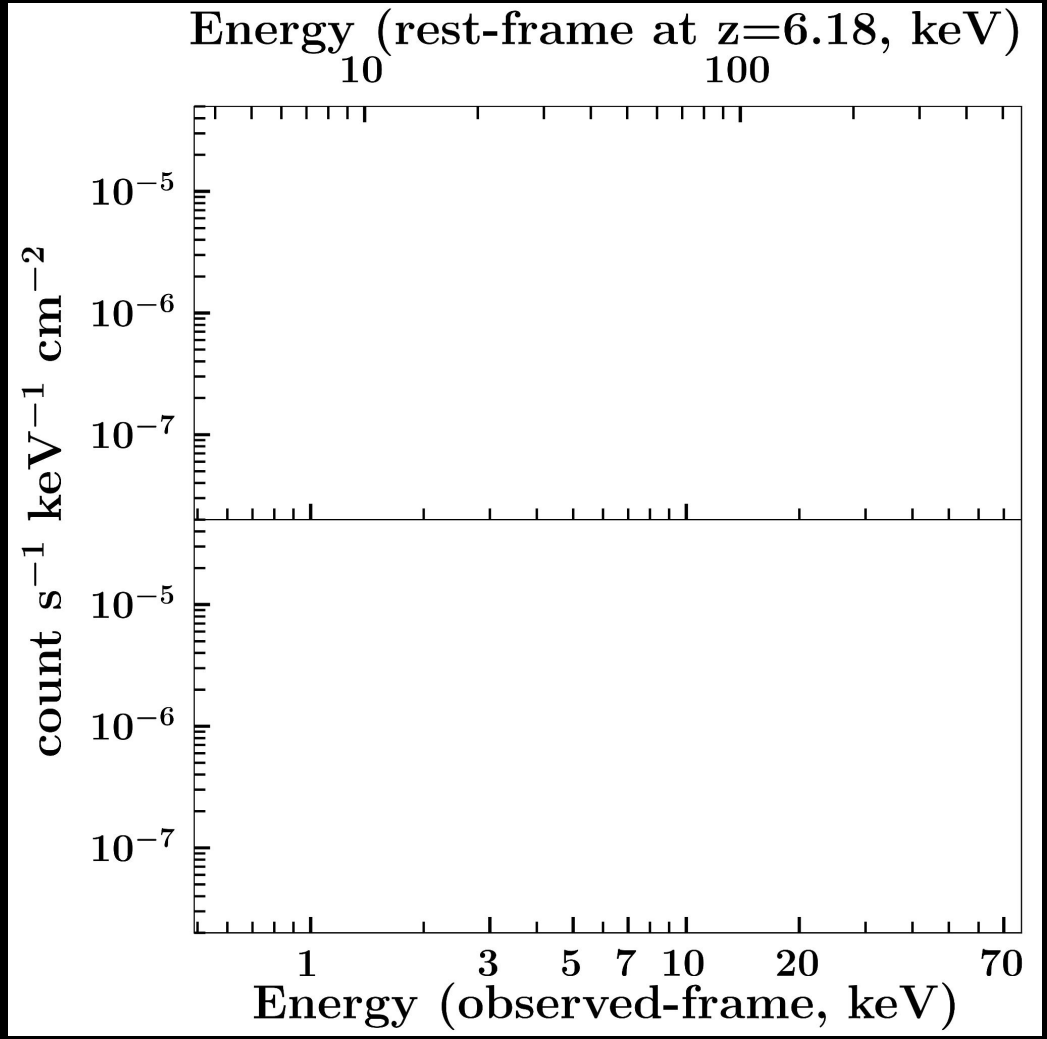




Marcotulli, Connor+24, accepted ApJL

X-ray Spectral Fit

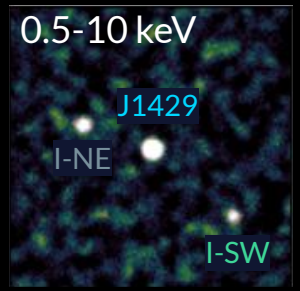
Lea Marcotulli | lea.marcotulli@yale.edu

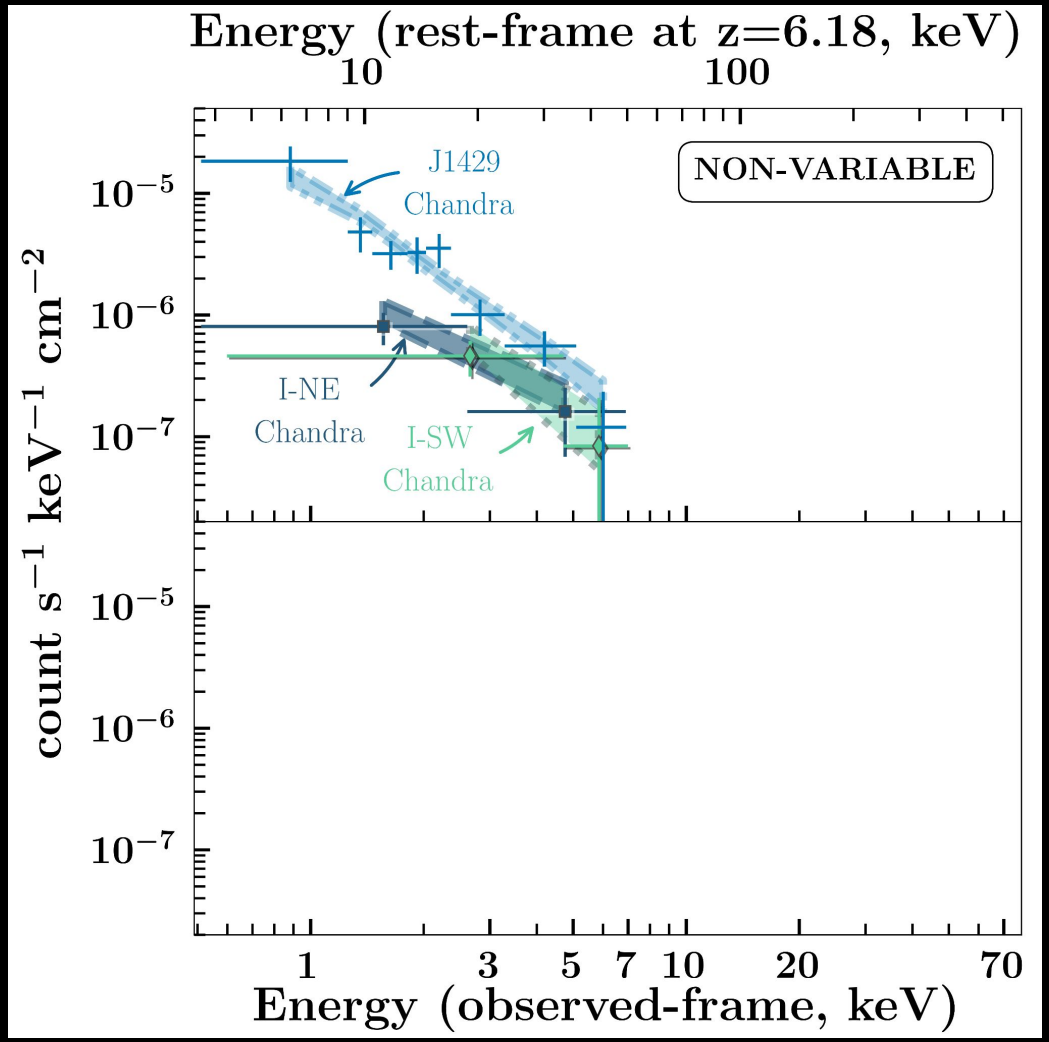


Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

X-ray Spectral Fit

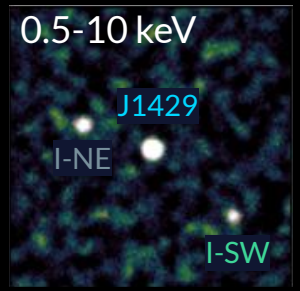


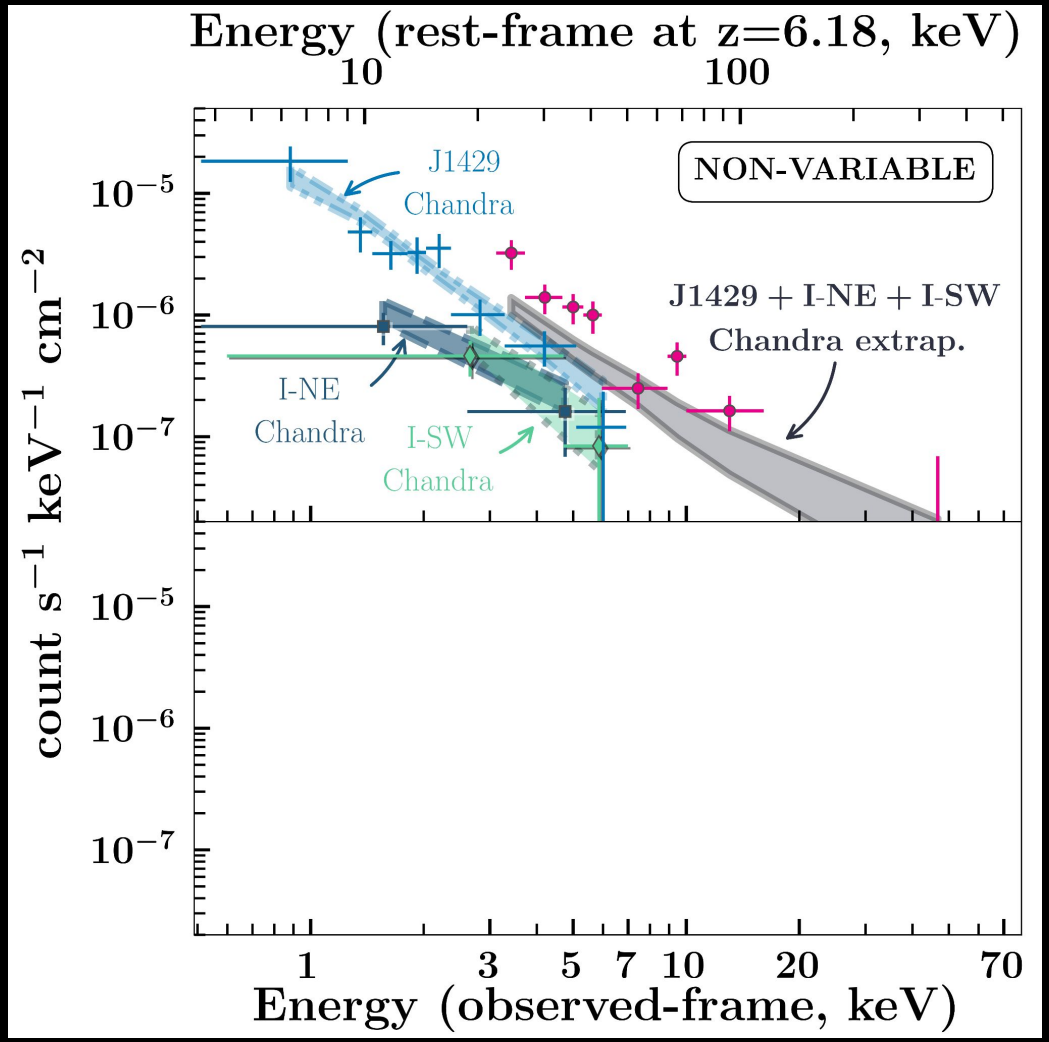


Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

X-ray Spectral Fit

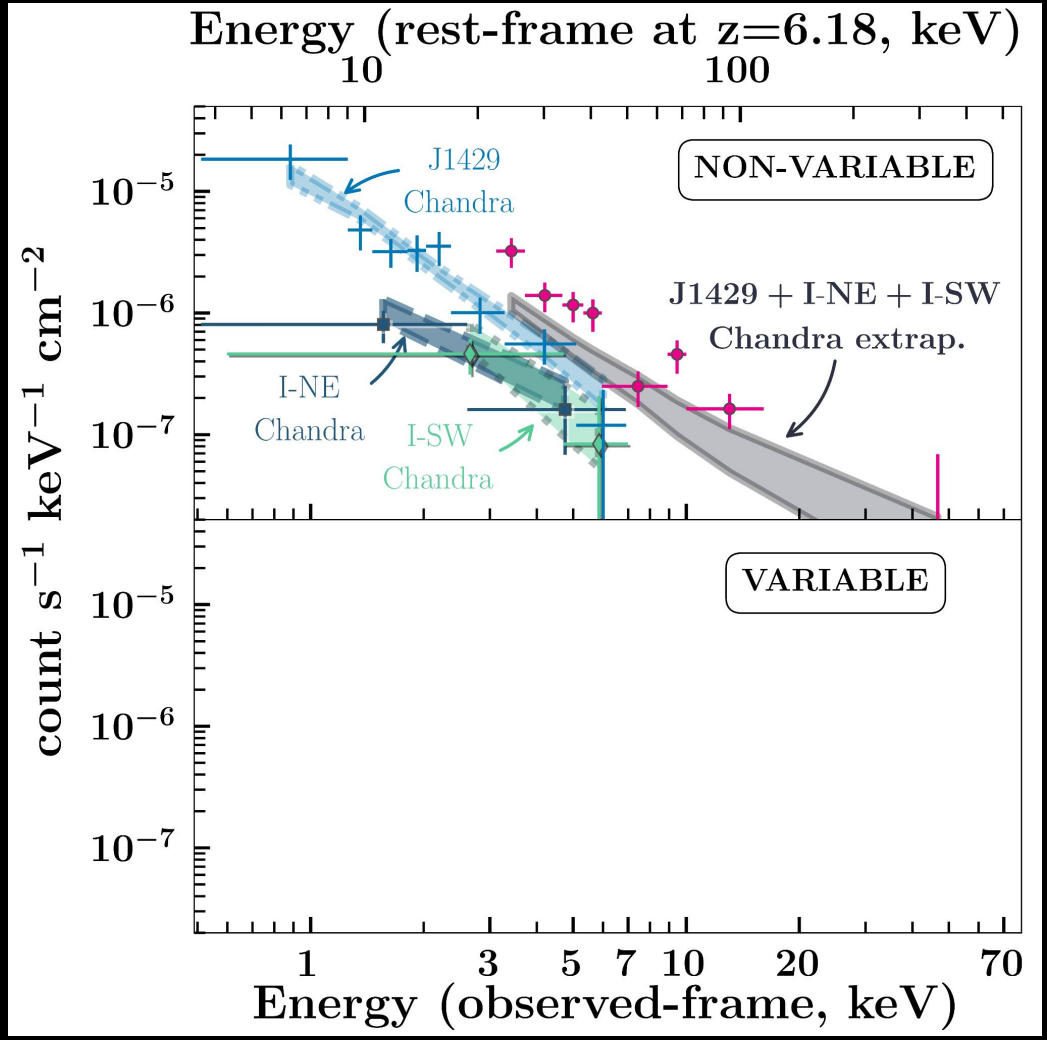




Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

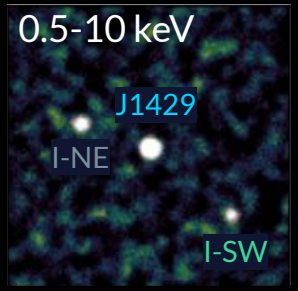
X-ray Spectral Fit



Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

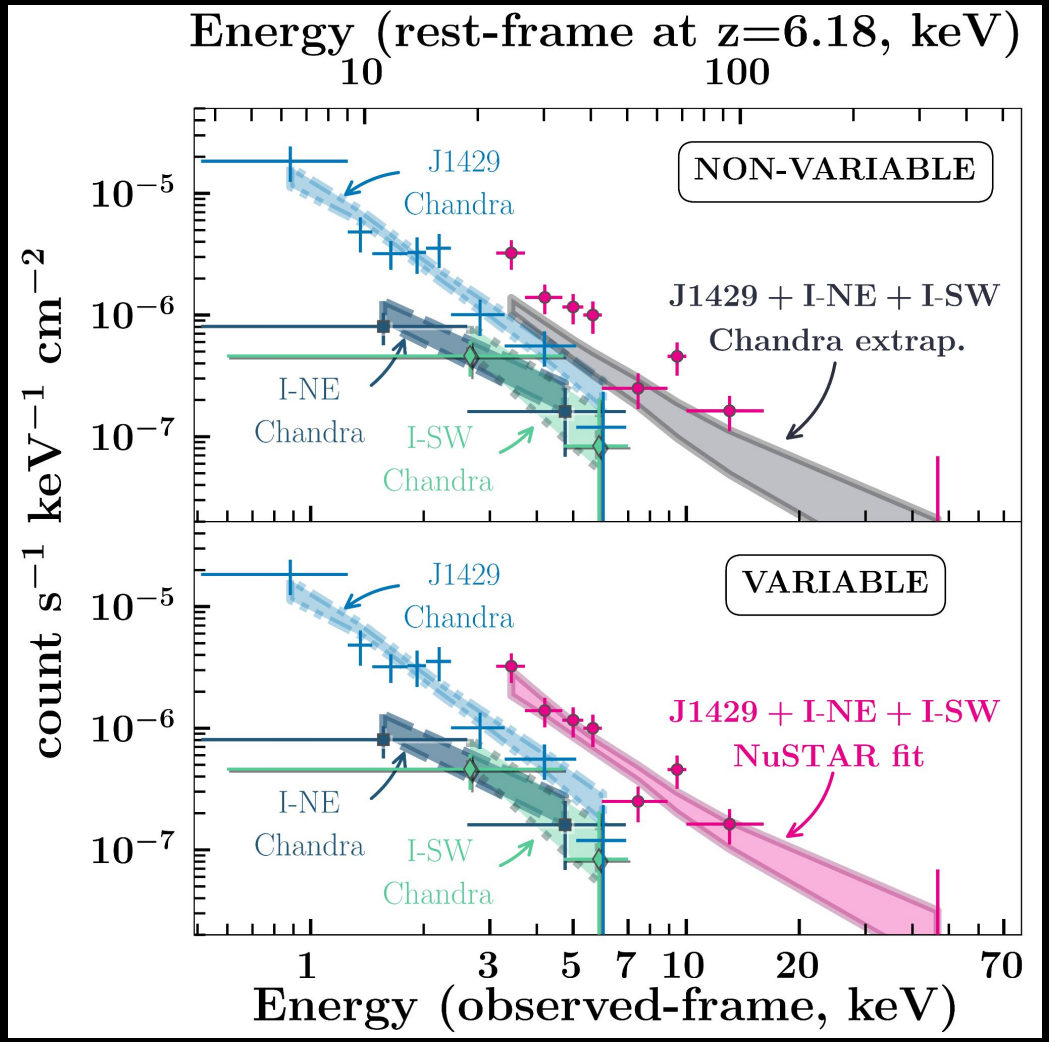
X-ray Spectral Fit

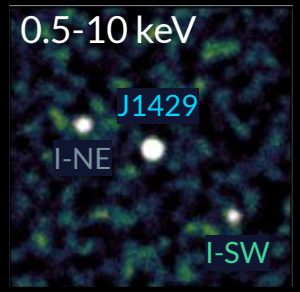


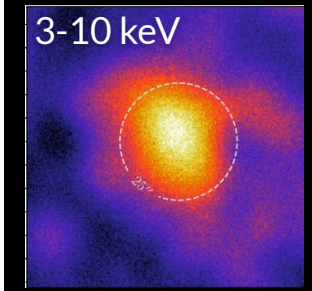
Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

X-ray Spectral Fit





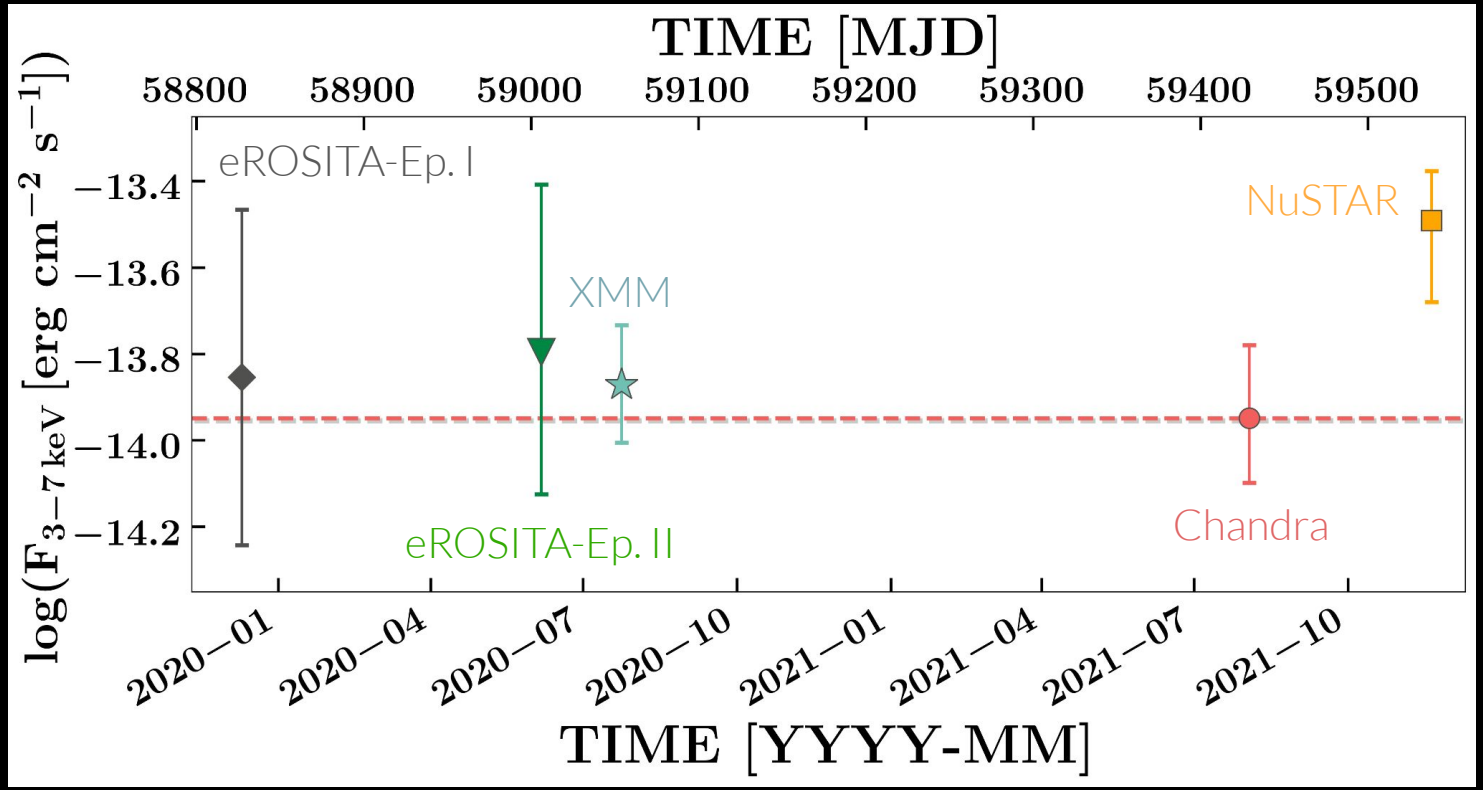


Marcotulli, Connor+24, accepted ApJL

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
X-ray Lightcurve

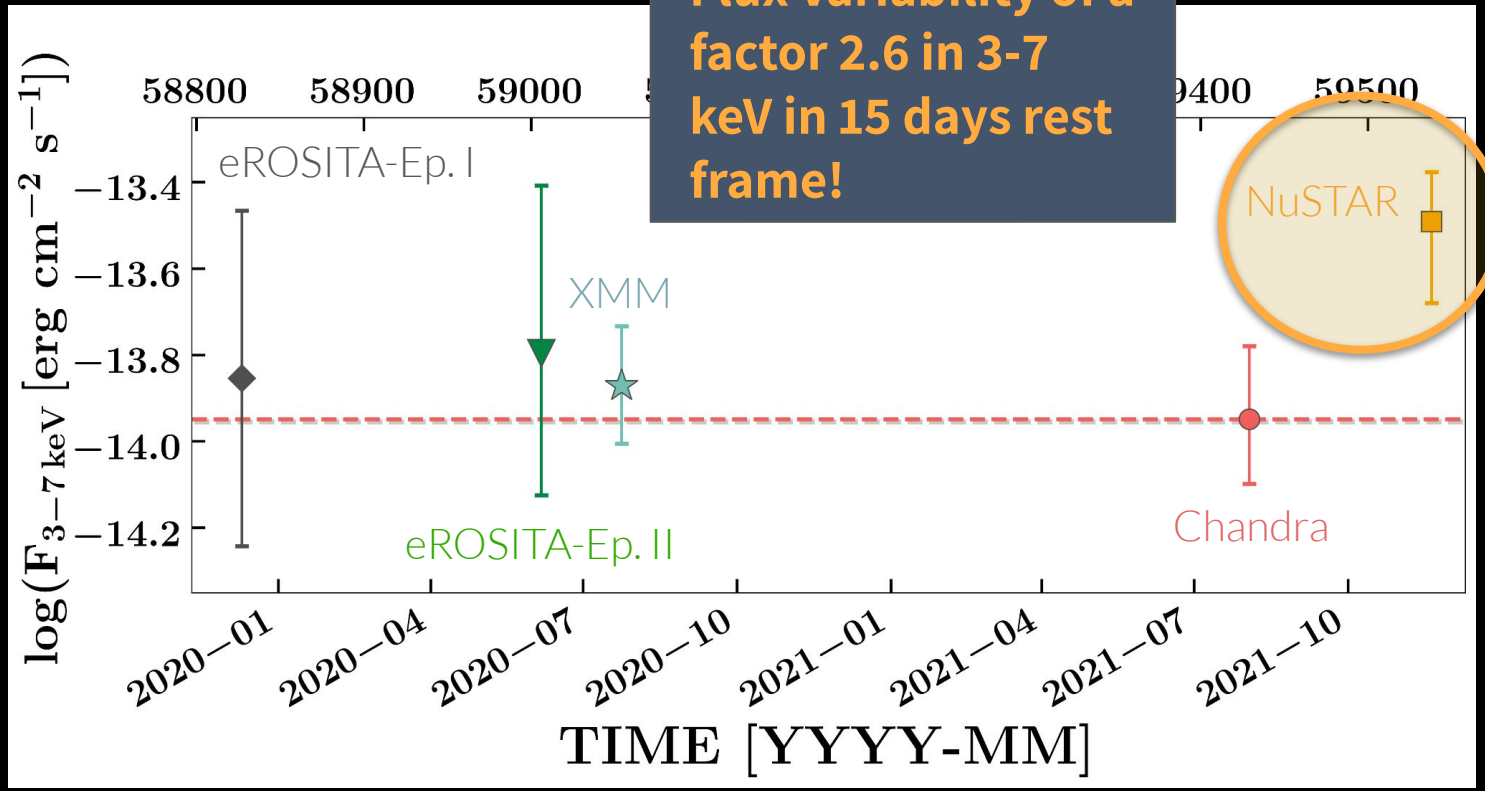
Marcotulli, Connor+24,
accepted ApJL



Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717
X-ray Lightcurve

Marcotulli, Connor+24, accepted ApJL



Possible Origins of the X-ray variability

More likely interpretations

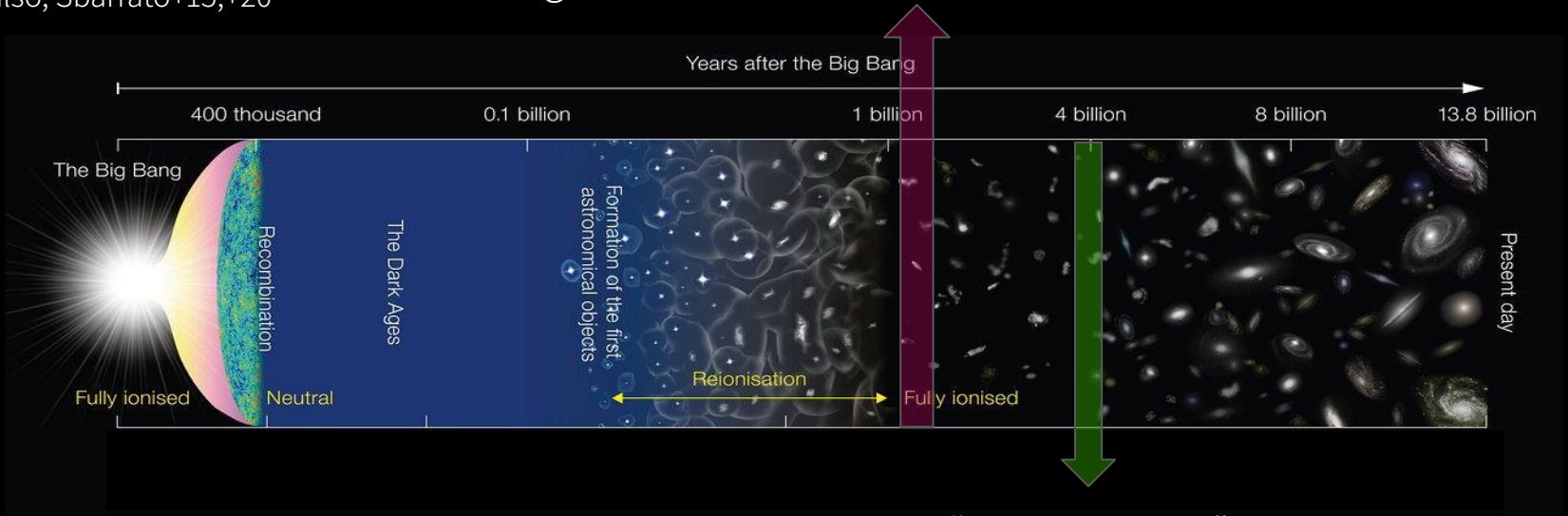
AGN corona variability or obscuration origin
[e.g. Vito+22;Tortosa+23; Serafinelli+24, Georgakakis+24]

Blazar X-ray jet
[e.g. Sbarrato+15,+22; Cao+17; Caccianiga+19; Ighina+19; An & Romani 20; Marcotulli+22]

Timeline of the universe

Marcotulli+20,
Marcotulli+22
see also, Sbarrato+15,+20

Point in time when we find the majority of blazars jets tracing the most massive black holes in the universe

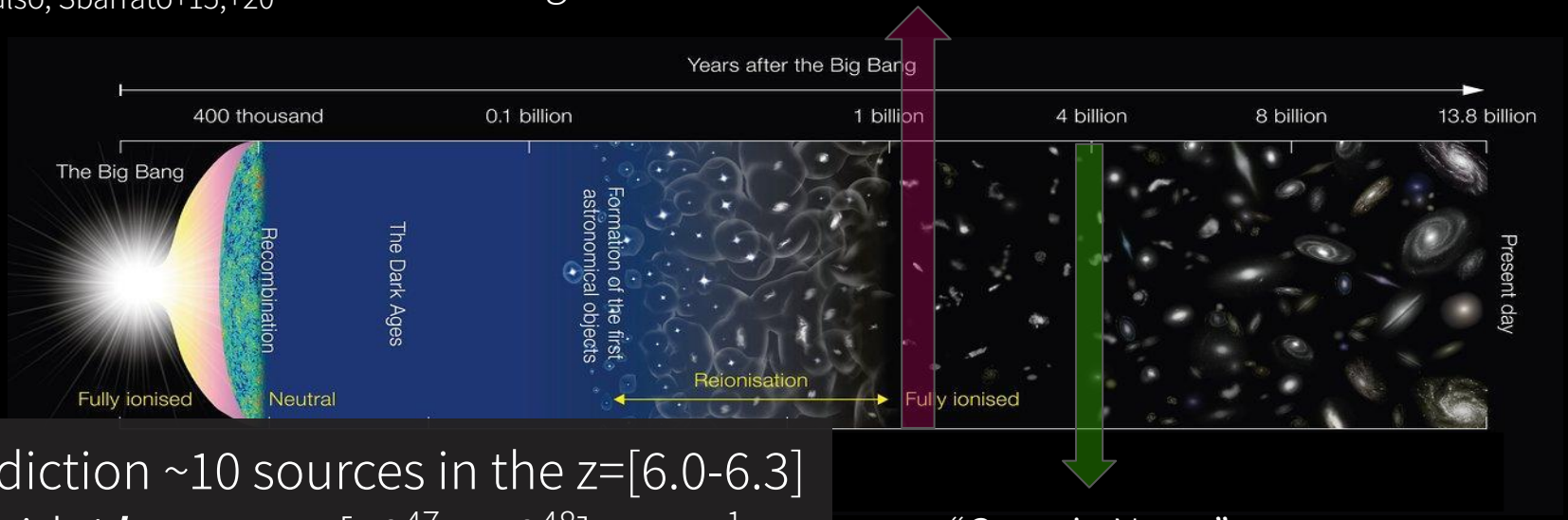


"Cosmic Noon"
Point in time when we find the majority of stars & galaxies

Timeline of the universe

Marcotulli+20,
Marcotulli+22
see also, Sbarrato+15,+20

Point in time when we find the majority of blazars jets tracing the most massive black holes in the universe



Prediction ~10 sources in the z=[6.0-6.3] with $L'_{14-195\ keV} = [10^{47} - 10^{48}]$ erg s^{-1}

"Cosmic Noon"
Point in time when we find the majority of stars & galaxies

Possible Origins of the X-ray variability

More likely interpretations

AGN corona variability or obscuration origin
[e.g. Vito+22;Tortosa+23; Serafinelli+24, Georgakakis+24]

Blazar X-ray jet
[e.g. Sbarrato+15,+22; Cao+17; Caccianiga+19; Ighina+19; An & Romani 20; Marcotulli+22]

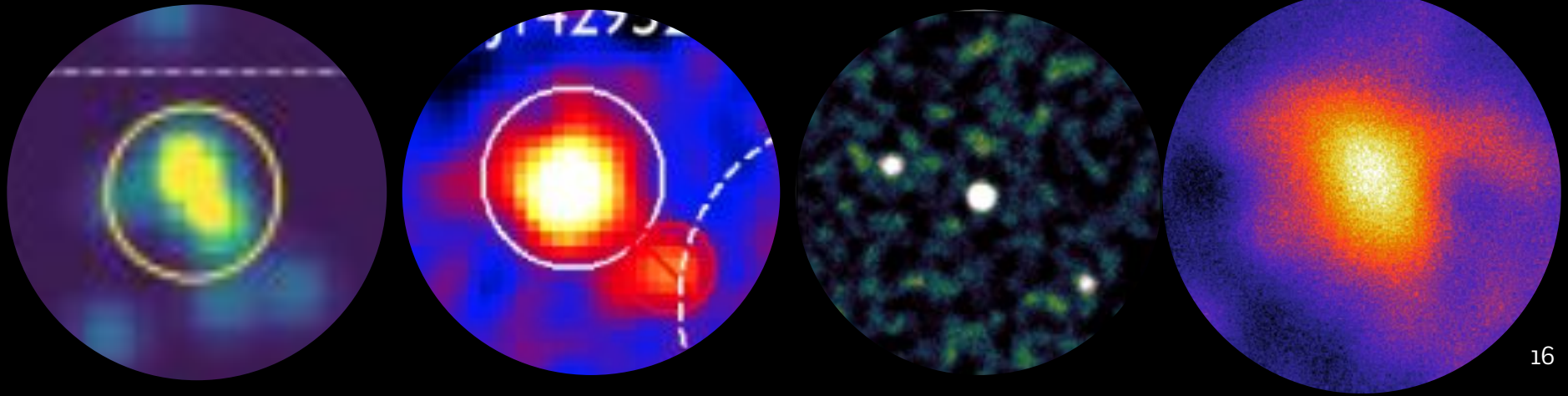
Less likely interpretations

IC/CMB
Too fast variability
[e.g. Ghisellini+2014; Connor+21; Ighina+22; Migliori+23]

Interlopers variability?
Too large variability + follow-up Chandra show sources are not variable
[PRELIMINARY, Connor et al. in prep.]

Take home points

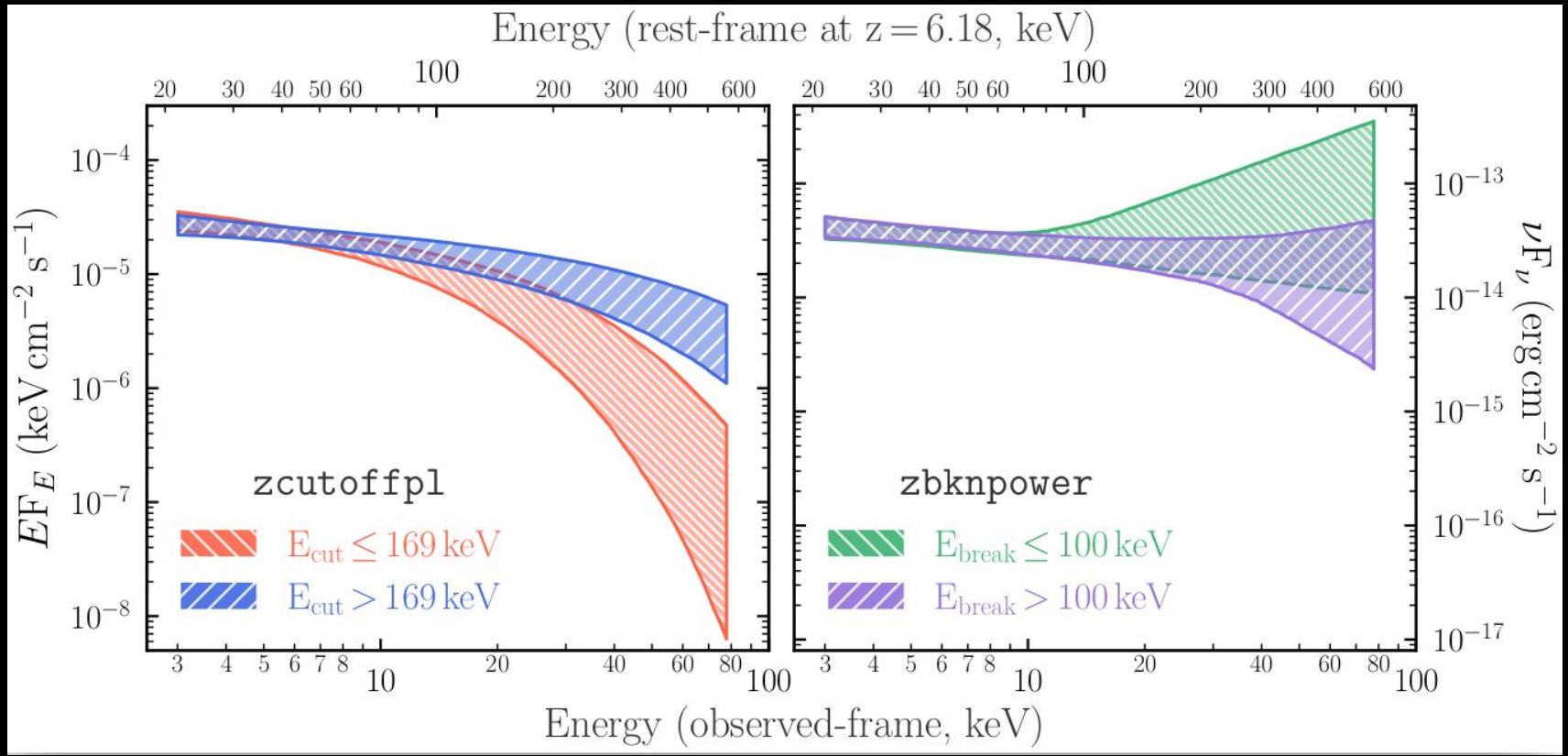
- **J1429 (z=6.18)** is the **most luminous X-ray quasar** at the epoch of reionization
- **Farthest** source detected by **NuSTAR**
- We detected the **first evidence of X-ray variability** at a factor of **~2.6 in 15 days (rest-frame)!**
- This variability may hint to the **presence of beaming**
- Follow-up necessary (Connor et al. in prep)



EXTRA

Lea Marcotulli | lea.marcotulli@yale.edu

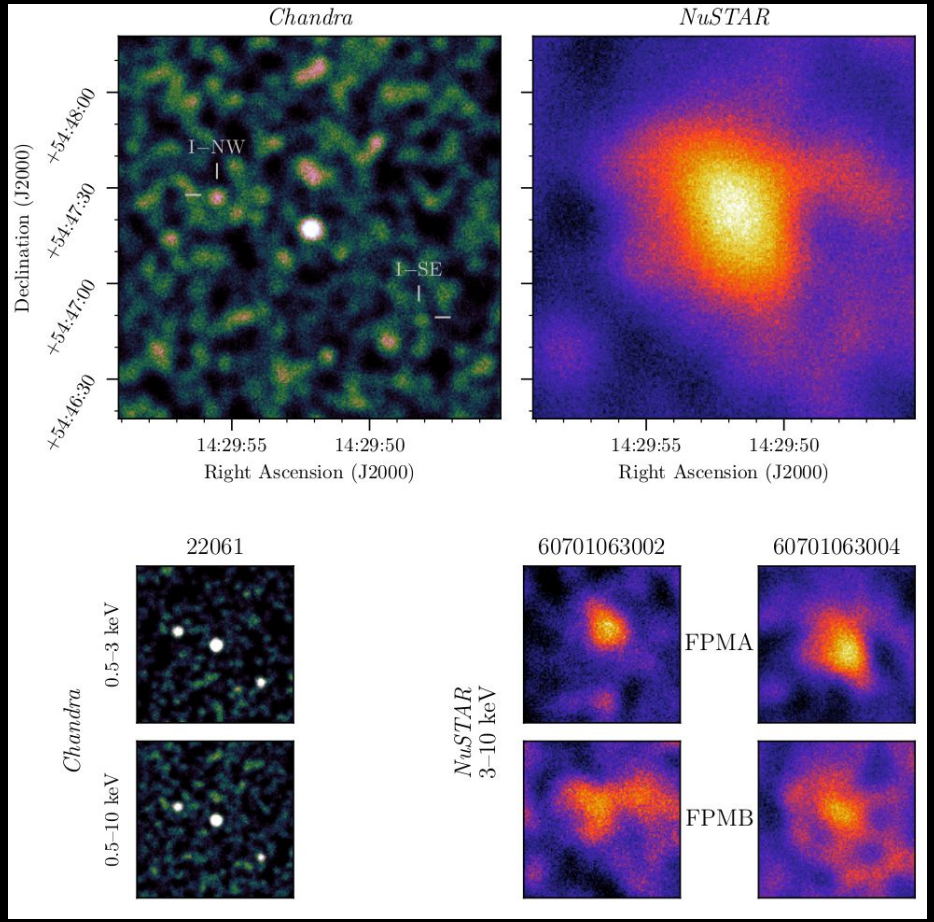
CFHQS J142952+544717 - NuSTAR follow-up (Marcotulli+24, ApJL accepted)



Testing more complex models

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717 - NuSTAR follow-up (Marcotulli+24, ApJL accepted)



2’x2’ fields

~245 ks NuSTAR time

Lea Marcotulli | lea.marcotulli@yale.edu

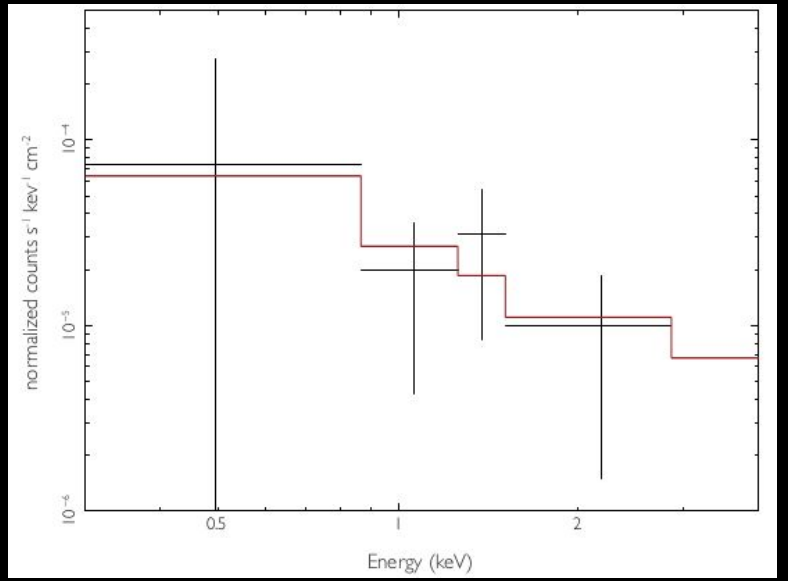
CFHQS J142952+544717
e-ROSITA spectrum

Best-fit spectrum: power-law

$\Gamma = 1.4 +-0.9$

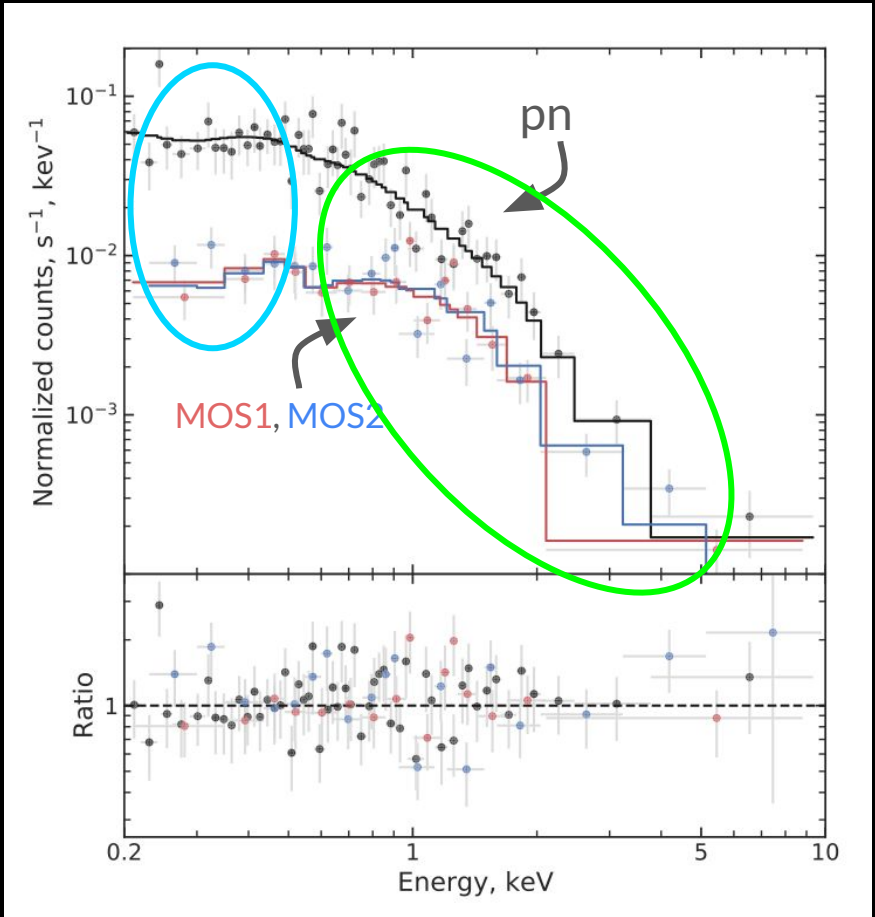
$F_{2\text{-}4\ keV} = 6.2^{+8.9}_{-3.9}\ 10^{-14}\ erg\ cm^{-2}\ s^{-1}$

$Flux \propto E^{-\Gamma}$



Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717 - XMM spectrum (Medvedev+21)



Best-fit: absorbed power-law spectrum

$N_H = 3(+-2)\ 10^{22}\ cm^{-2}$

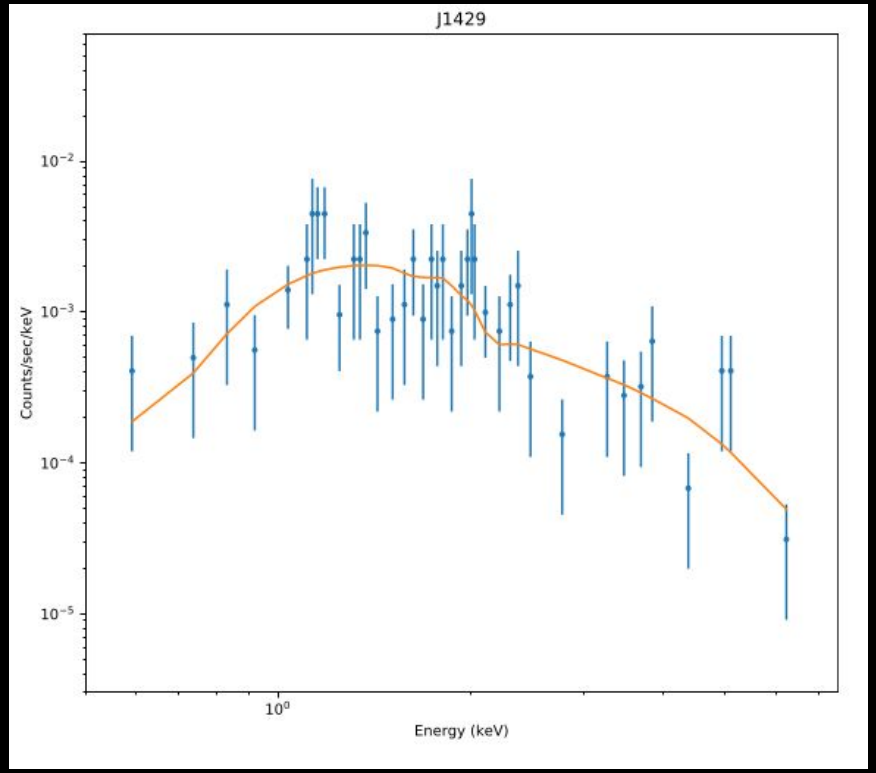
$\Gamma = 2.5 \pm 0.2$

$F_{0.2\text{-}10\ keV} = 1.2\ (+-0.1) \times 10^{-13}\ erg\ cm^{-2}\ s^{-1}$

$Flux \propto absorber \times E^{-\Gamma}$

Lea Marcotulli | lea.marcotulli@yale.edu

CFHQS J142952+544717 - Chandra spectrum (Migliori+23)



Best-fit: power-law spectrum

$\Gamma = 2.0 \pm 0.2$

$F_{0.5\text{-}10\,keV} = 5.4\ (+\text{-}1.4) \times 10^{-14}$ erg cm^{-2} s^{-1}

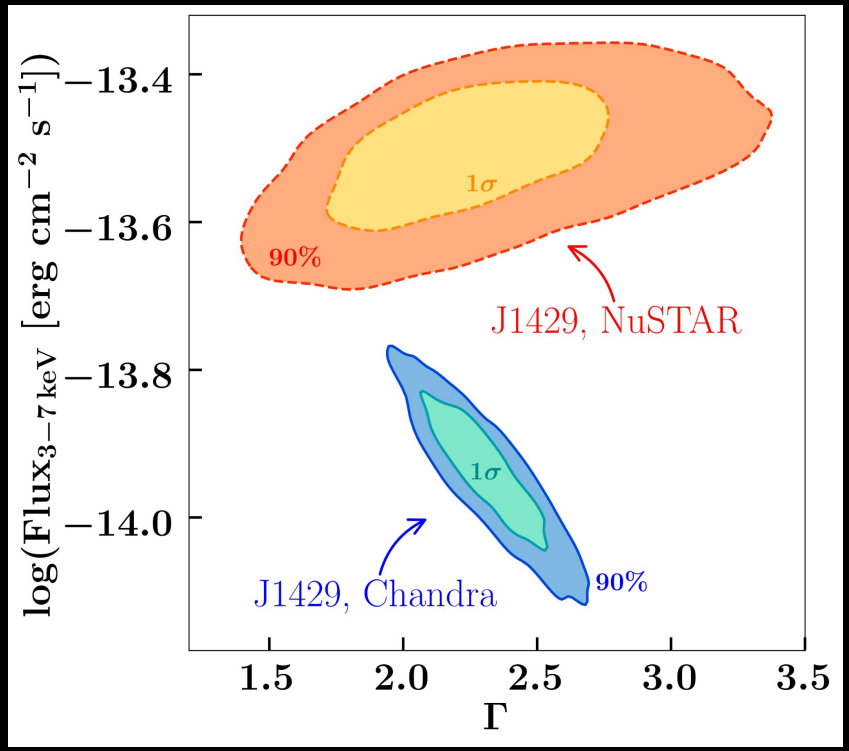
Extra absorption & higher XMM flux attributed to interloper sources

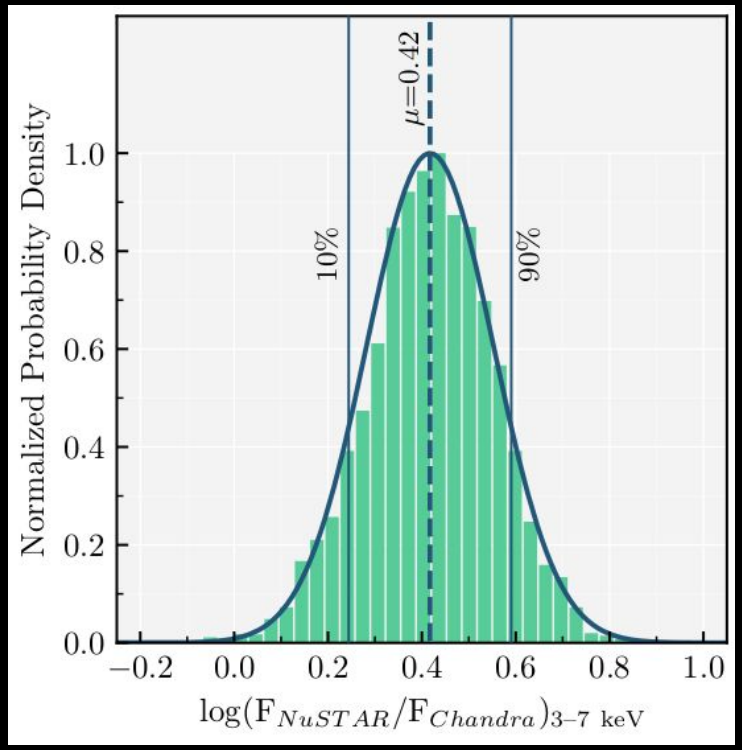
$$\text{Flux} \propto E^{-\Gamma}$$

Lea Marcotulli | lea.marcotulli@yale.edu

X-ray Variability (Marcotulli+24, ApJL accepted)

Flux variability of ~2.6 in 3-7 keV in 15 days rest frame!

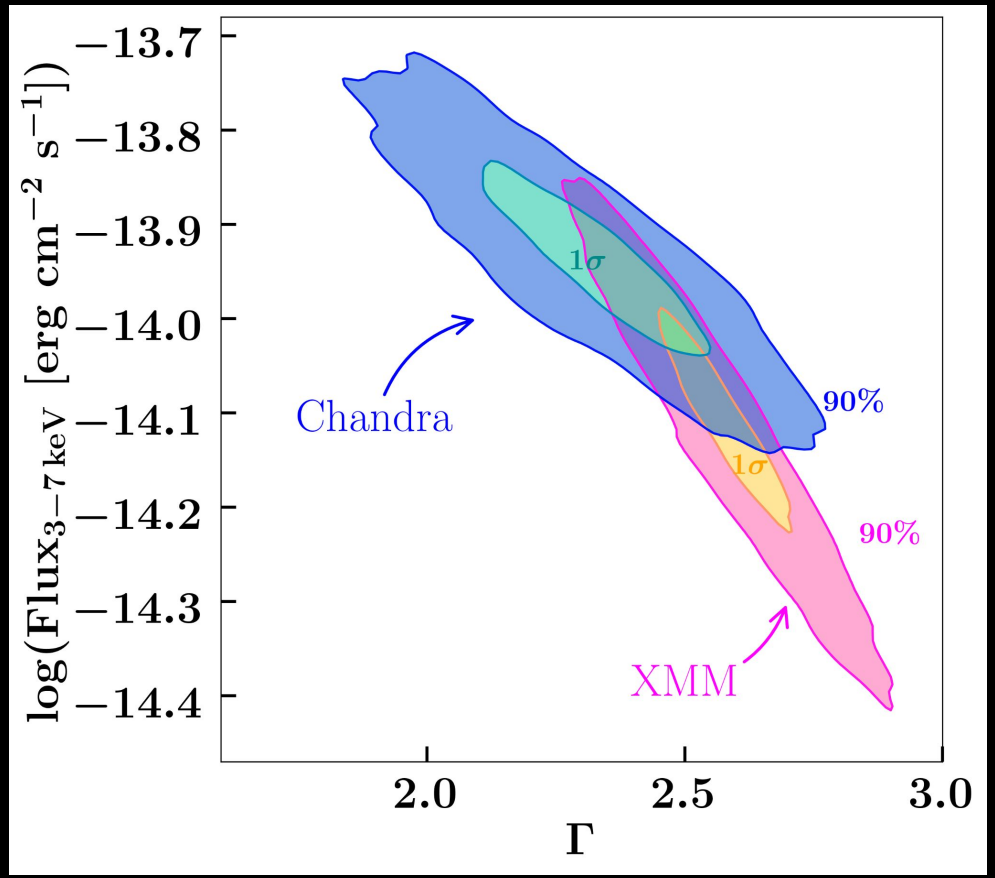




Lea Marcotulli | lea.marcotulli@yale.edu

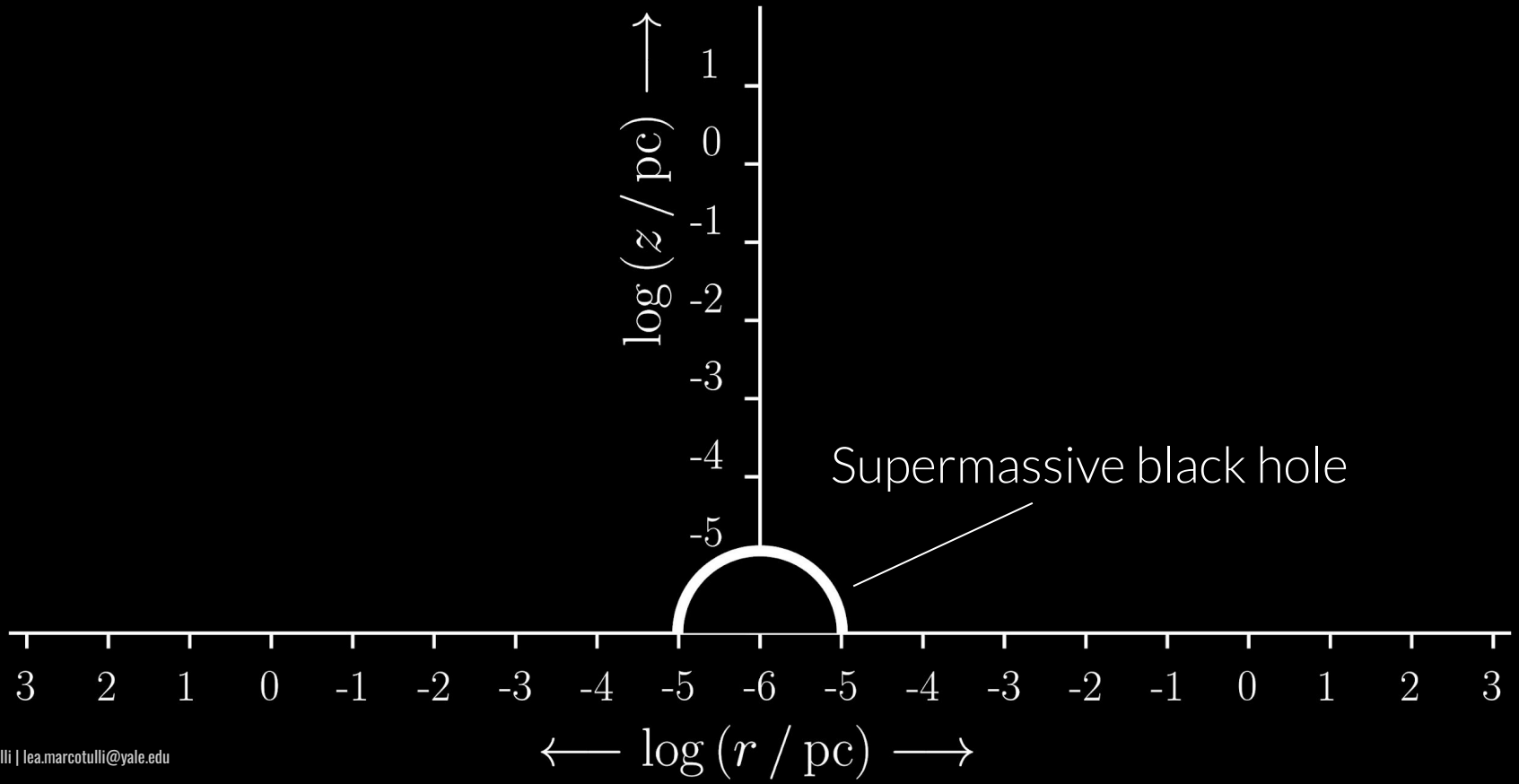
X-ray Variability (Marcotulli+24, ApJL accepted)

Testing XMM variability



Slide credit: Peter Boorman

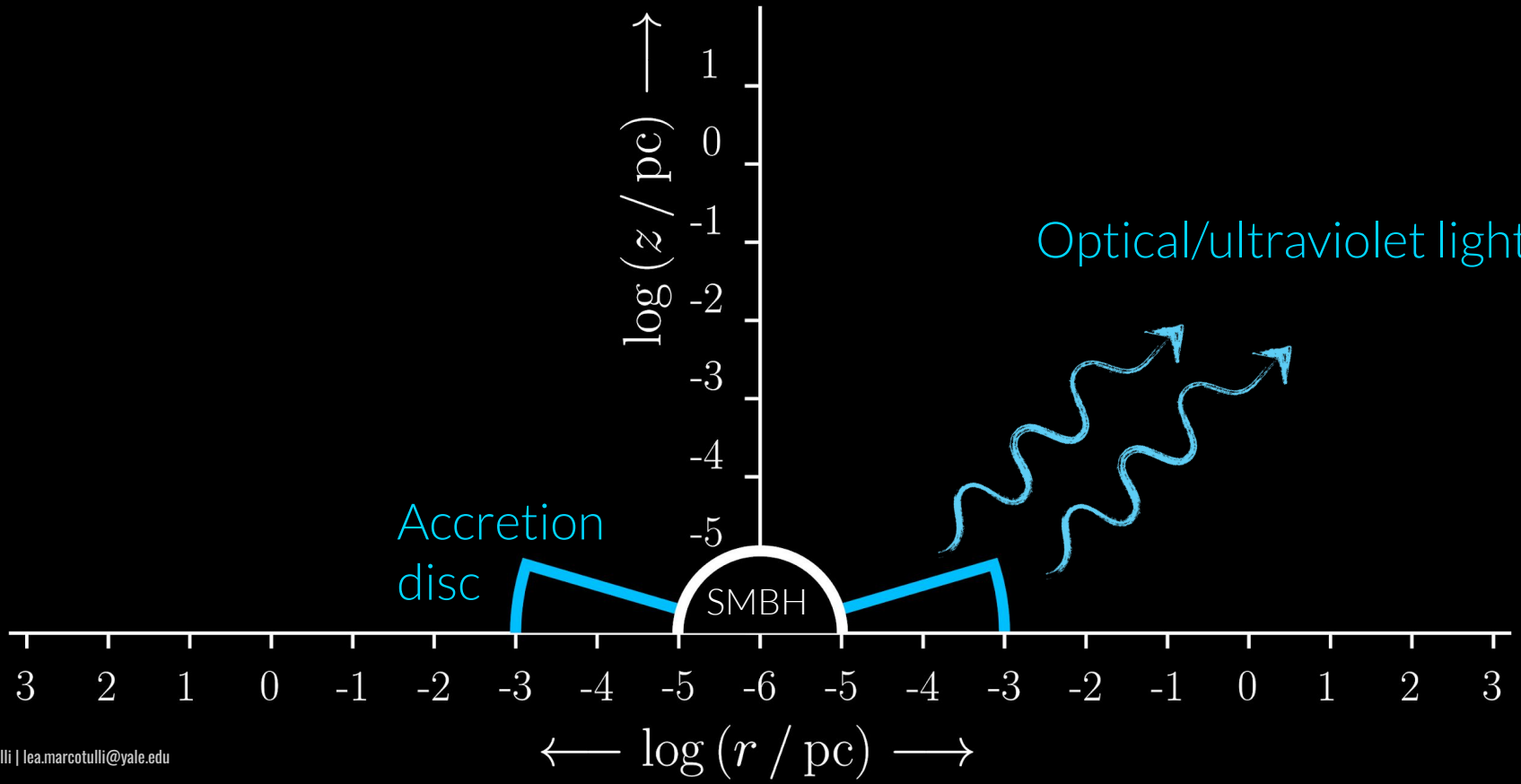
A single supermassive black hole



Lea Marcotulli | lea.marcotulli@yale.edu

Slide credit: Peter Boorman

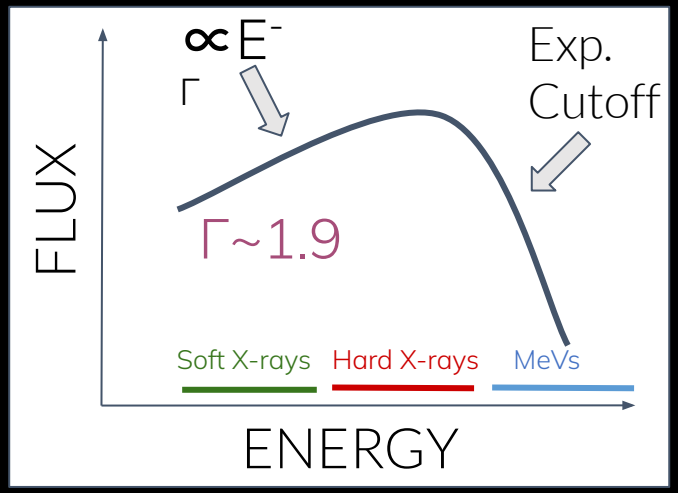
Accretion disc – optical/ultraviolet light



Lea Marcotulli | lea.marcotulli@yale.edu

Slide credit: Peter Boorman

Hot gas of electrons (corona) – X-rays



Accretion disc photons Compton up-scattered to X-rays and MeV γ-ray

Corona

Accretion disc

SMBH

$\log(z\ /\ \mathrm{pc}) \longrightarrow$

1 0 -1 -2 -3 -4 -5

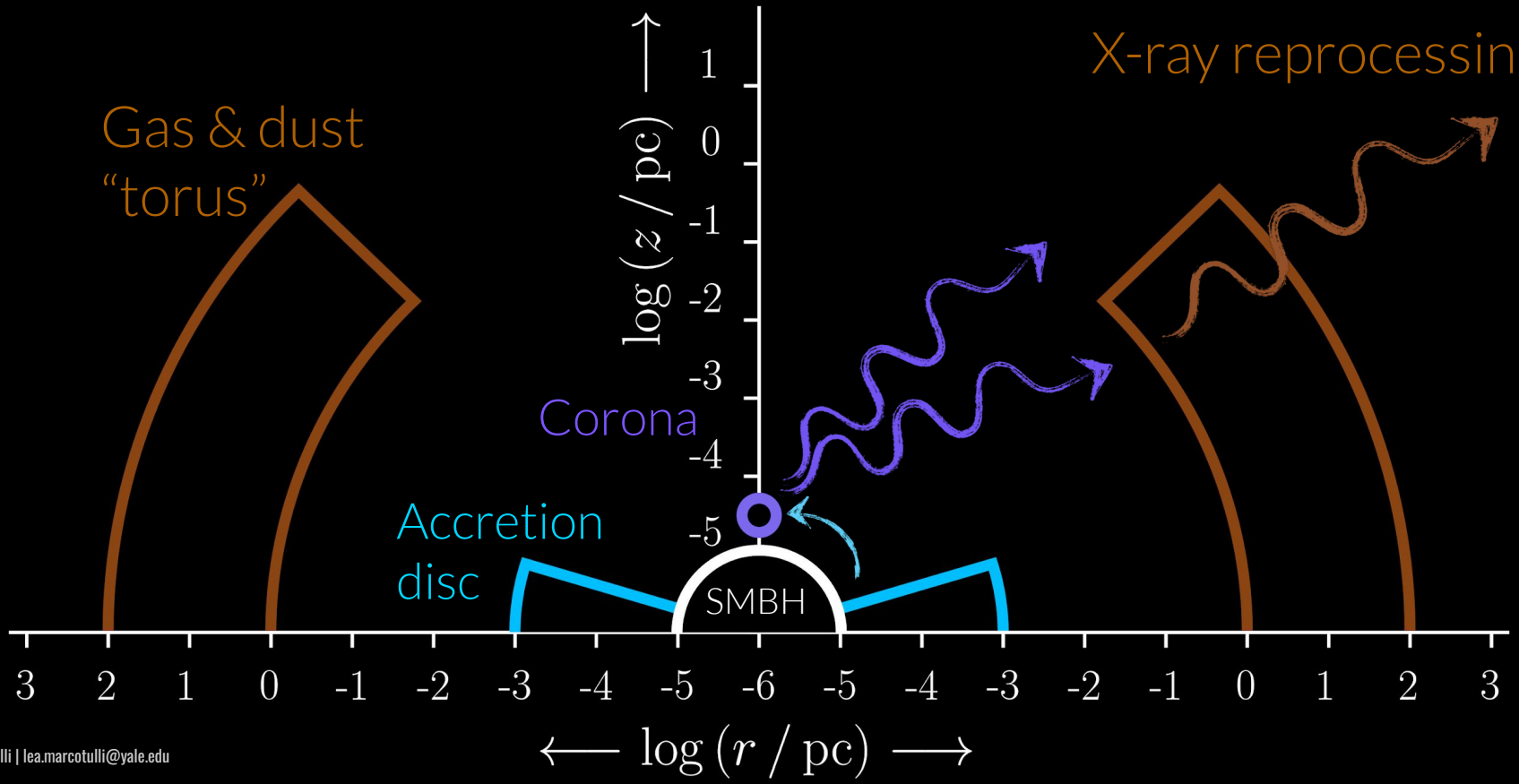
3 2 1 0 -1 -2 -3 -4 -5 -6 -5 -4 -3 -2 -1 0 1 2 3

$\longleftarrow \log(r\ /\ \mathrm{pc}) \longrightarrow$

Lea Marcotulli | lea.marcotulli@yale.edu

Slide credit: Peter Boorman

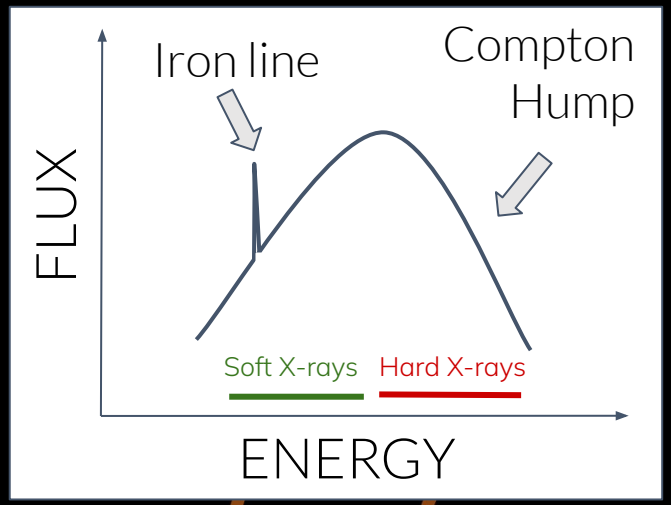
Obscuring distant gas and dust



Lea Marcotulli | lea.marcotulli@yale.edu

Slide credit: Peter Boorman

Obscuring distant gas and dust



X-ray reprocessing

Corona

Accretion disc

SMBH

$\log(z\,/\,\mathrm{pc}) \longrightarrow$

1 0 -1 -2 -3 -4 -5

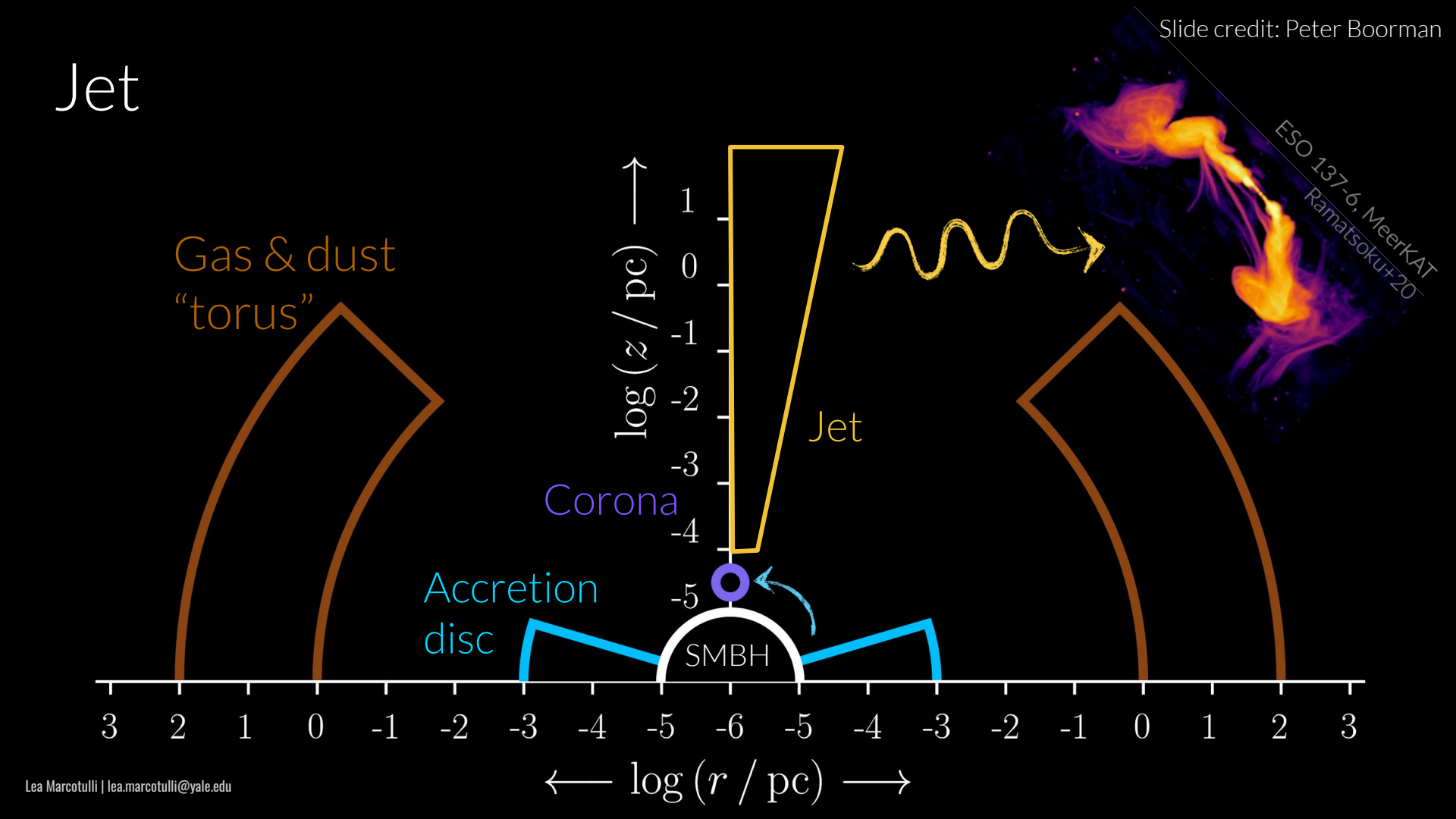
3 2 1 0 -1 -2 -3 -4 -5 -6 -5 -4 -3 -2 -1 0 1 2 3

$\longleftarrow \log(r\,/\,\mathrm{pc}) \longrightarrow$

Lea Marcotulli | lea.marcotulli@yale.edu

Jet

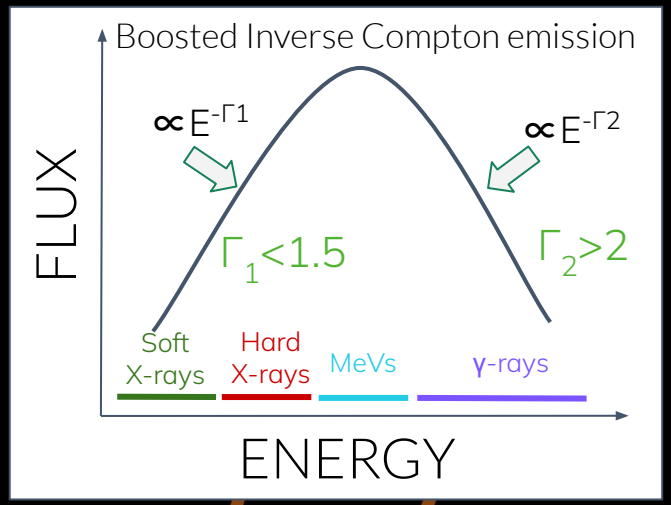
Slide credit: Peter Boorman



Lea Marcotulli | lea.marcotulli@yale.edu

Jet

Slide credit: Peter Boorman



X-ray & γ-ray

Jet

Corona

Accretion disc

SMBH

log (z / pc)

log (r / pc)

Lea Marcotulli | lea.marcotulli@yale.edu