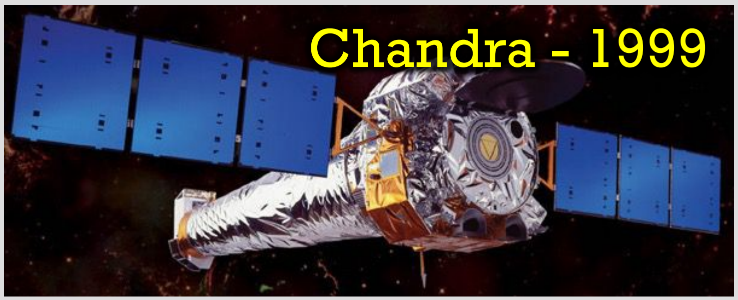
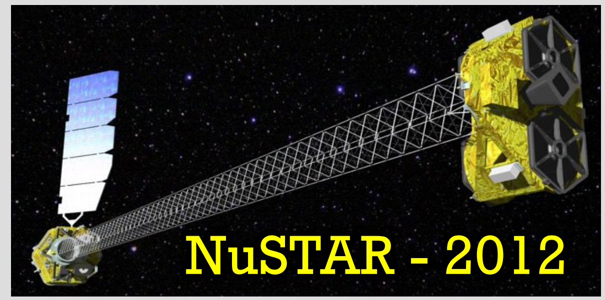
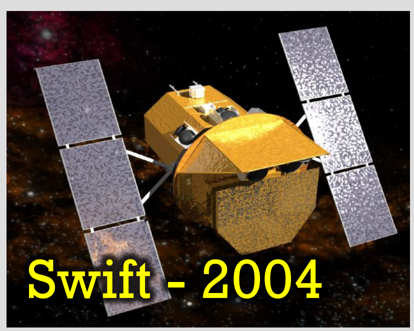
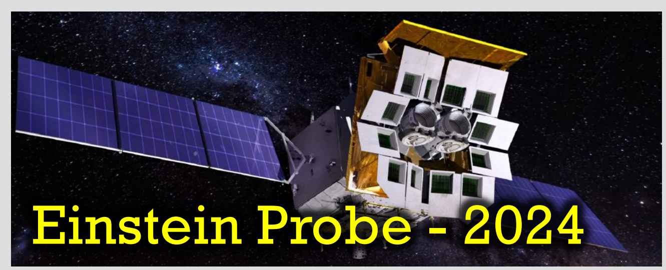
Extragalactic X-ray Surveys from Deep to Wide

W. Niel Brandt (Penn State)









Big 25-Year Survey Successes: AGNs

Contribution of AGNs to the cosmic backgrounds.

Revealed most/much of obscured SMBH growth.

Totally changed understanding of AGN evolution and the "cosmic balance of power".

Much better understanding of high-redshift AGNs and their contribution to reionization.

Clarification of AGN-galaxy and AGN-LSS connections.

Big 25-Year Survey Successes: Galaxies, Clusters, and Transients

Cosmic evolution of X-ray binary populations.

Development of the intracluster and intragroup medium.

Cosmological constraints from large samples of clusters and groups.

New populations of X-ray transients.

Talk Outline

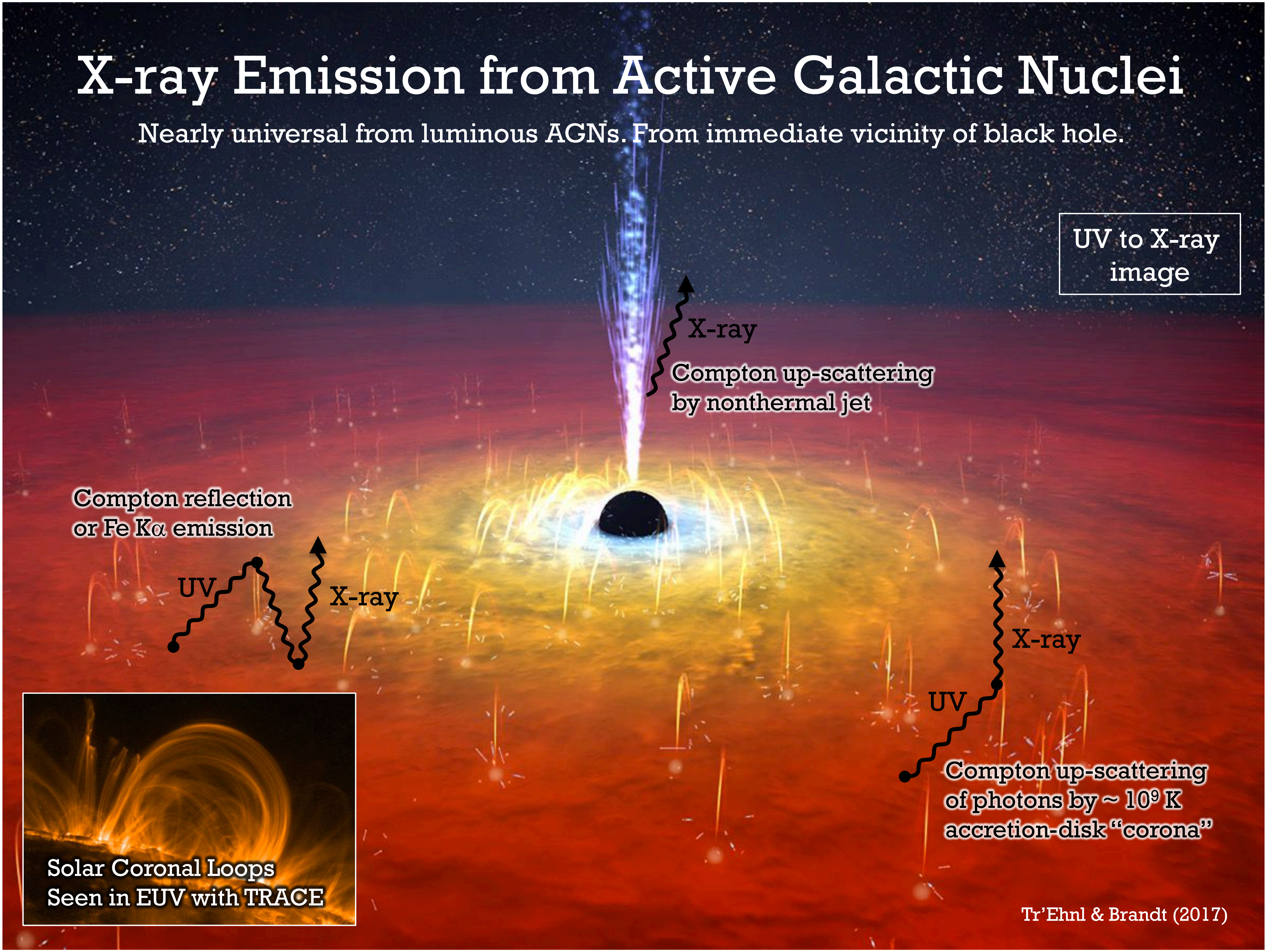
Utility of X-ray Surveys

The Surveys and Their Follow-Up

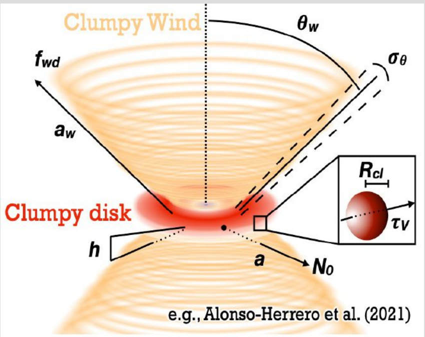
A Few Selected AGN Science Results

The Future: Questions and Prospects

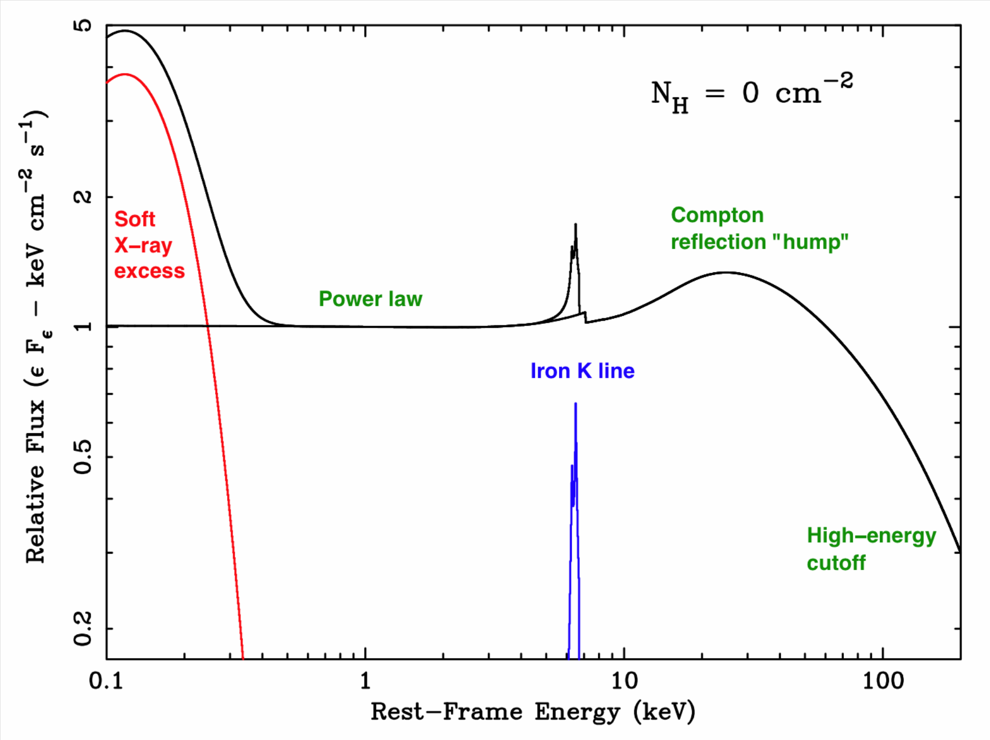
Utility of X-ray Surveys


X-ray Emission from Active Galactic Nuclei
Nearly universal from luminous AGNs. From immediate vicinity of black hole.
UV to X-ray image
X-ray
Compton up-scattering by nonthermal jet
Compton reflection or Fe Kα emission
UV
X-ray
X-ray
UV
Compton up-scattering of photons by ~ 10⁹ K accretion-disk "corona"
Solar Coronal Loops Seen in EUV with TRACE
Tr'Ehnl & Brandt (2017)

X-ray Emission is Penetrating with Reduced Absorption Bias



AGN light usually substantially obscured by both nuclear and galaxy-scale material

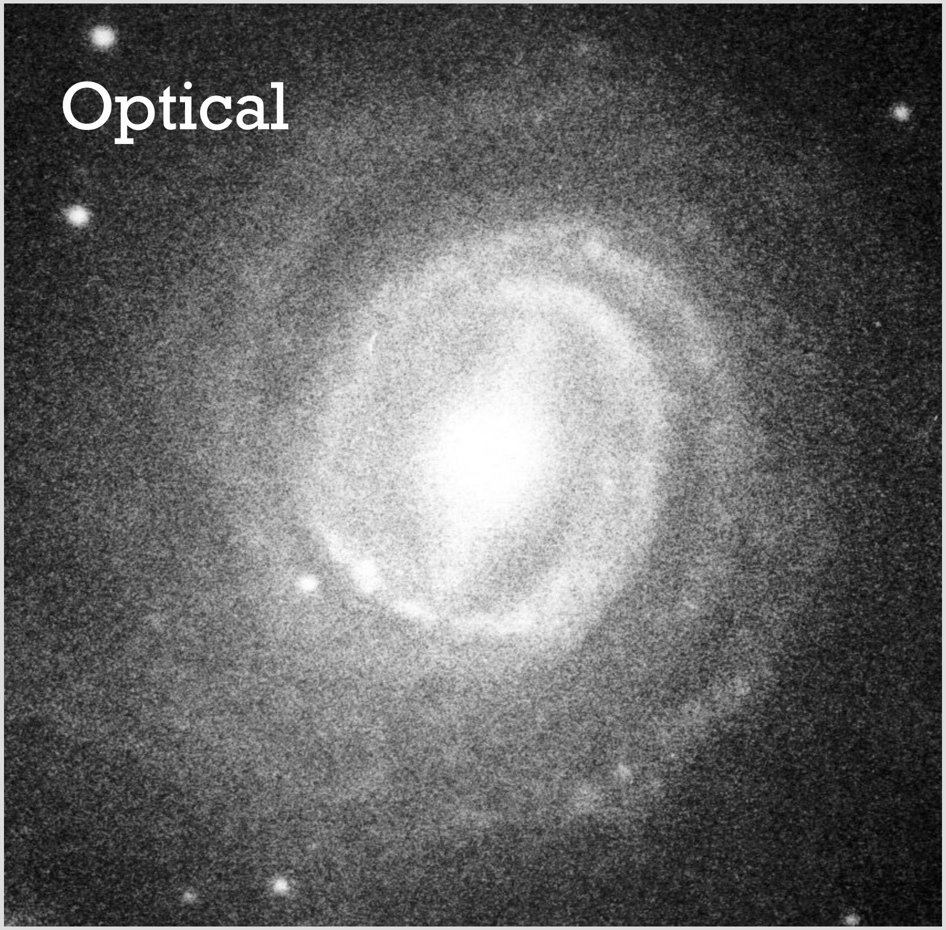


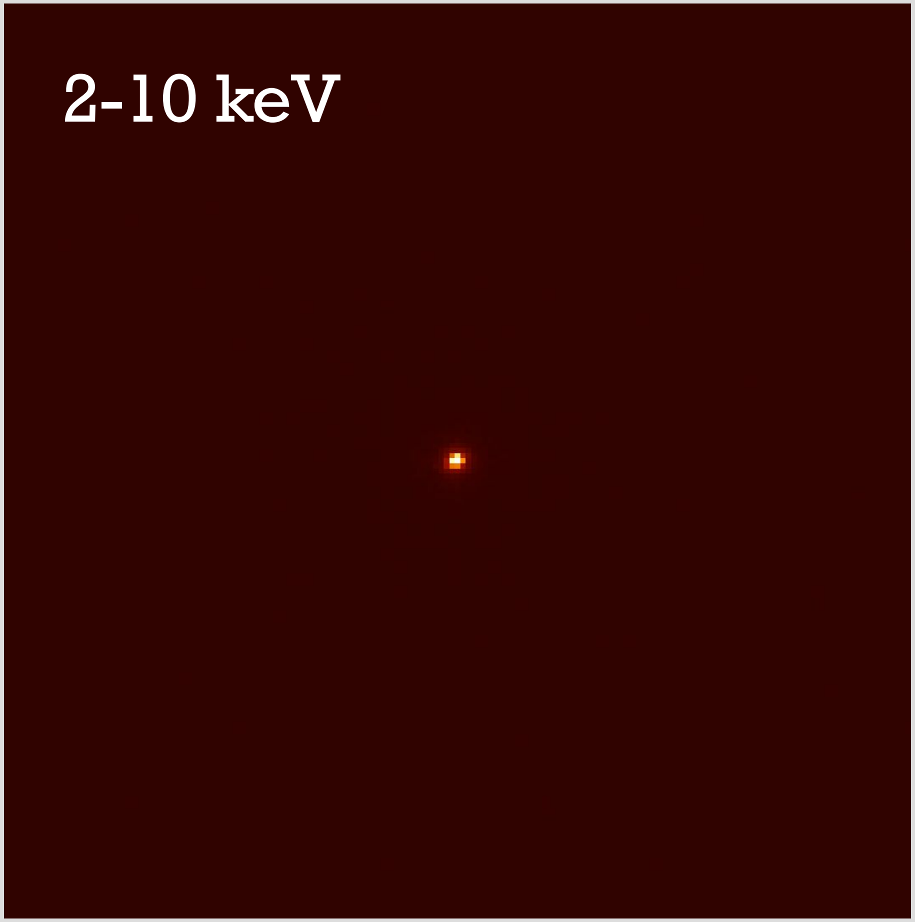
X-ray emission can penetrate *and* measure large column densities. Hand (10^{23} cm^{-2}), chest (10^{24} cm^{-2}).

Absorption bias drops going to high redshift, as gain access to increasingly penetrating rest-frame X-rays.

X-rays Have Low Dilution by Host Starlight

Optical vs. X-ray Emission from a Local AGN (NGC 3783)

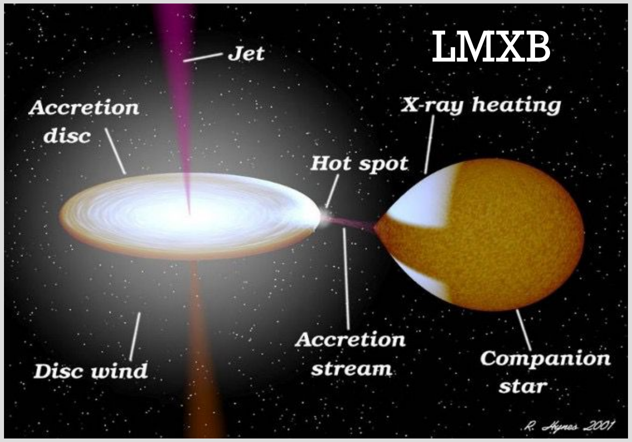


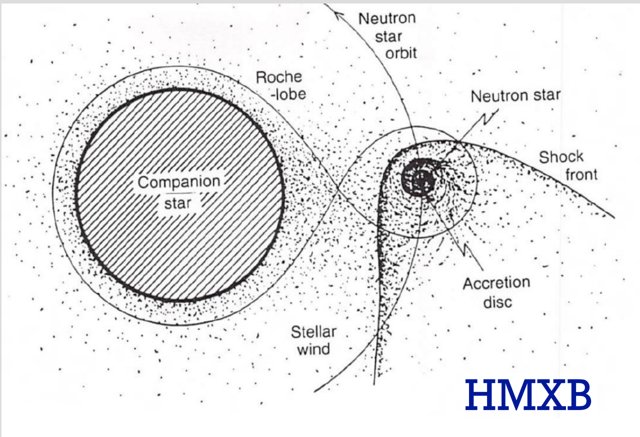


At high redshift cannot spatially resolve AGN light from host starlight.

X-rays maximize contrast for “cleanest” samples.

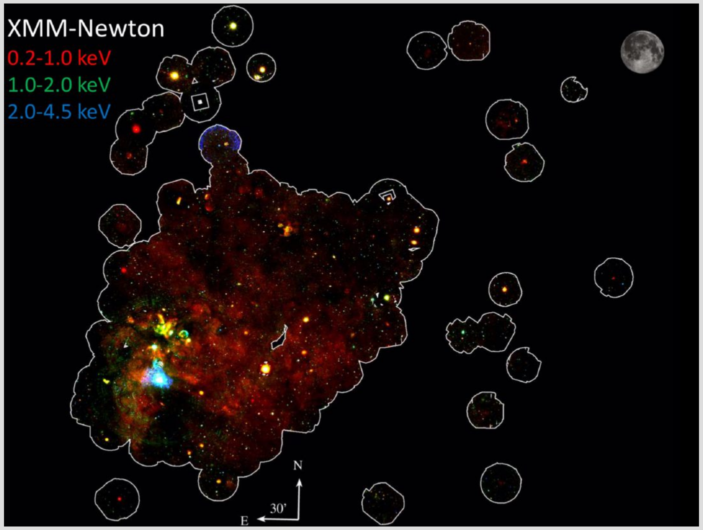
X-ray Binaries, ULXs, and Hot Gas





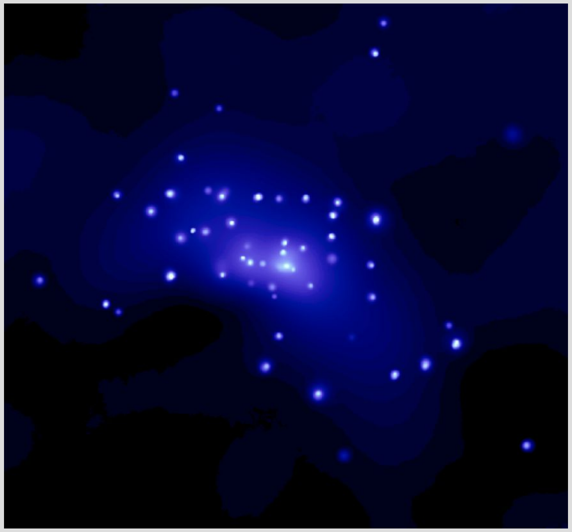
M31 – e.g., Pietsch et al.

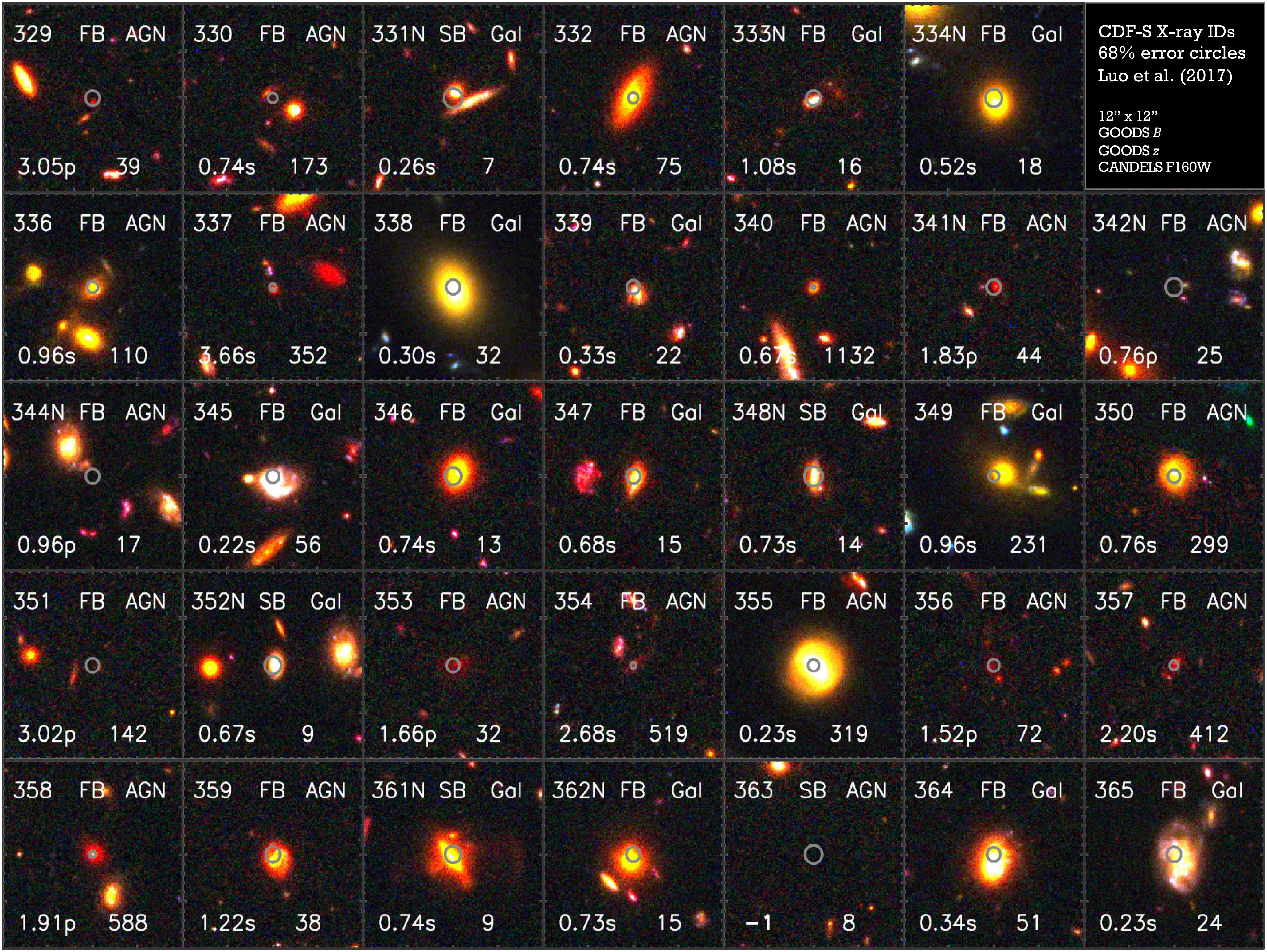
LMC – e.g., Haberl et al.



M82 – e.g., Griffiths et al.

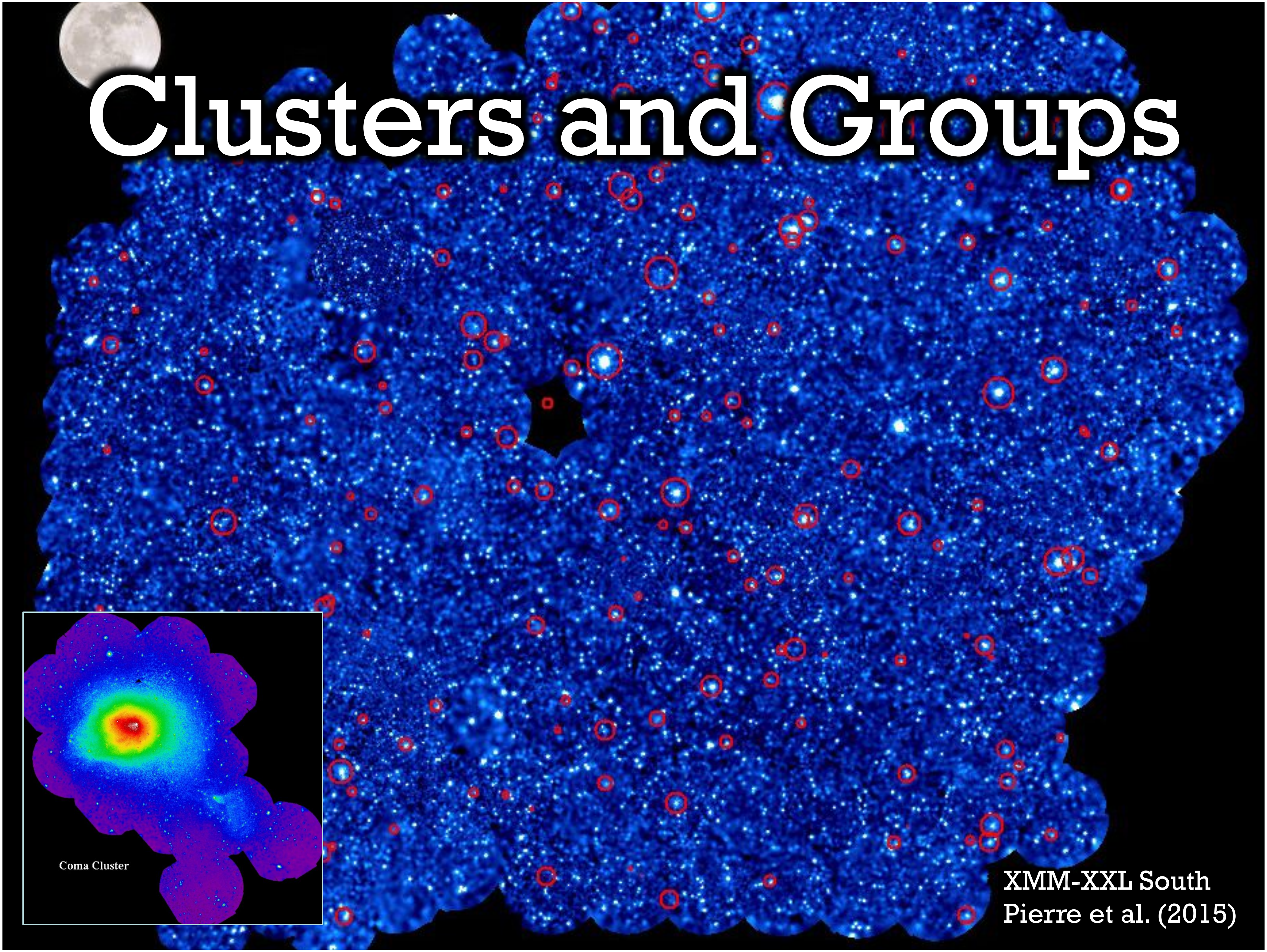
NGC 4697 – e.g., Sarazin et al.





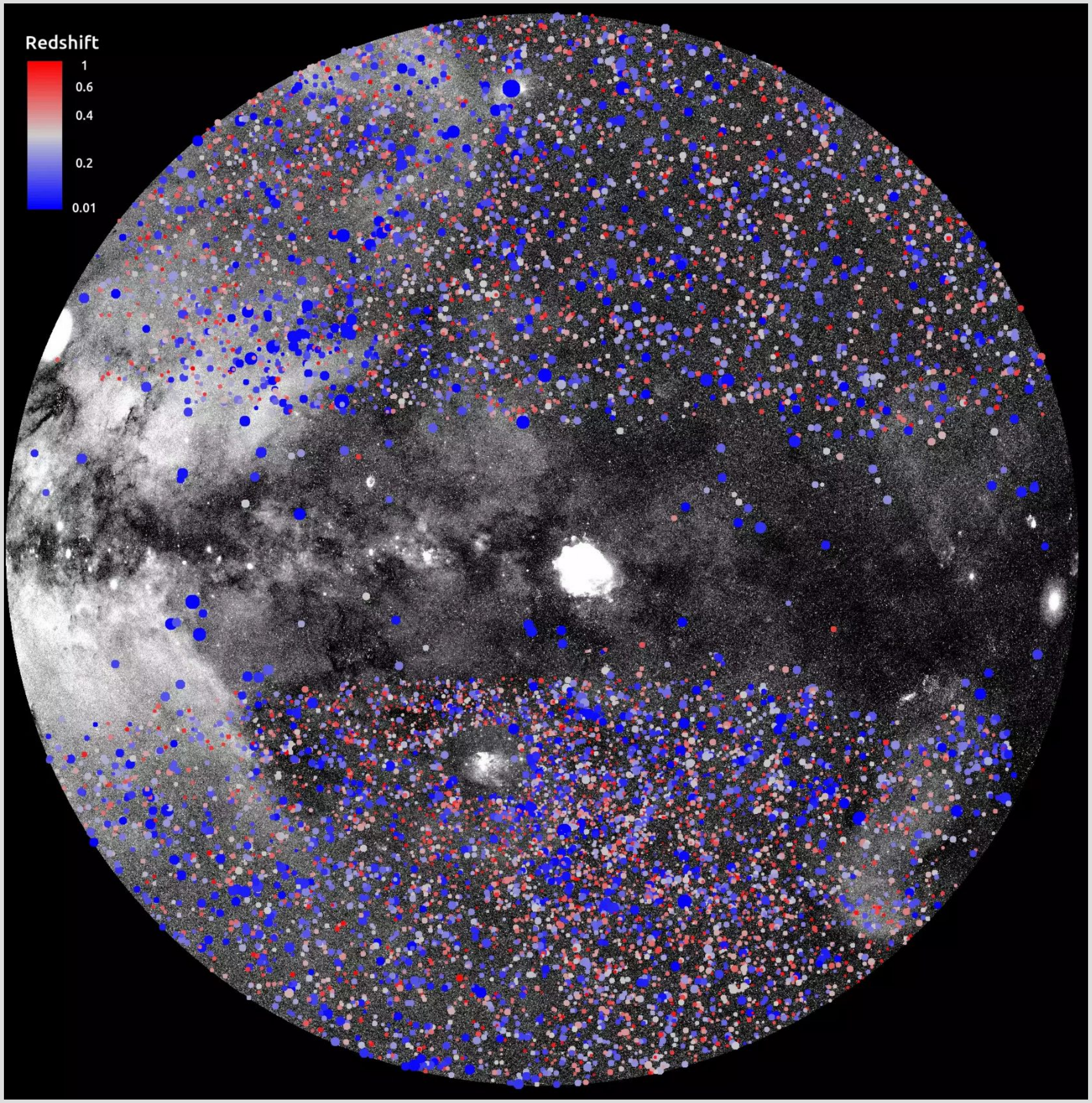
329 FB AGN 3.05p 39
330 FB AGN 0.74s 173
331N SB Gal 0.26s 7
332 FB AGN 0.74s 75
333N FB Gal 1.08s 16
334N FB Gal 0.52s 18
CDF-S X-ray IDs
68% error circles
Luo et al. (2017)
12" x 12"
GOODS *B*
GOODS *z*
CANDELS F160W
336 FB AGN 0.96s 110
337 FB AGN 3.66s 352
338 FB Gal 0.30s 32
339 FB Gal 0.33s 22
340 FB AGN 0.67s 1132
341N FB AGN 1.83p 44
342N FB AGN 0.76p 25
344N FB AGN 0.96p 17
345 FB Gal 0.22s 56
346 FB Gal 0.74s 13
347 FB Gal 0.68s 15
348N SB Gal 0.73s 14
349 FB Gal 0.96s 231
350 FB AGN 0.76s 299
351 FB AGN 3.02p 142
352N SB Gal 0.67s 9
353 FB AGN 1.66p 32
354 FB AGN 2.68s 519
355 FB AGN 0.23s 319
356 FB AGN 1.52p 72
357 FB AGN 2.20s 412
358 FB AGN 1.91p 588
359 FB AGN 1.22s 38
361N SB Gal 0.74s 9
362N FB Gal 0.73s 15
363 SB AGN −1 8
364 FB Gal 0.34s 51
365 FB Gal 0.23s 24

Clusters and Groups

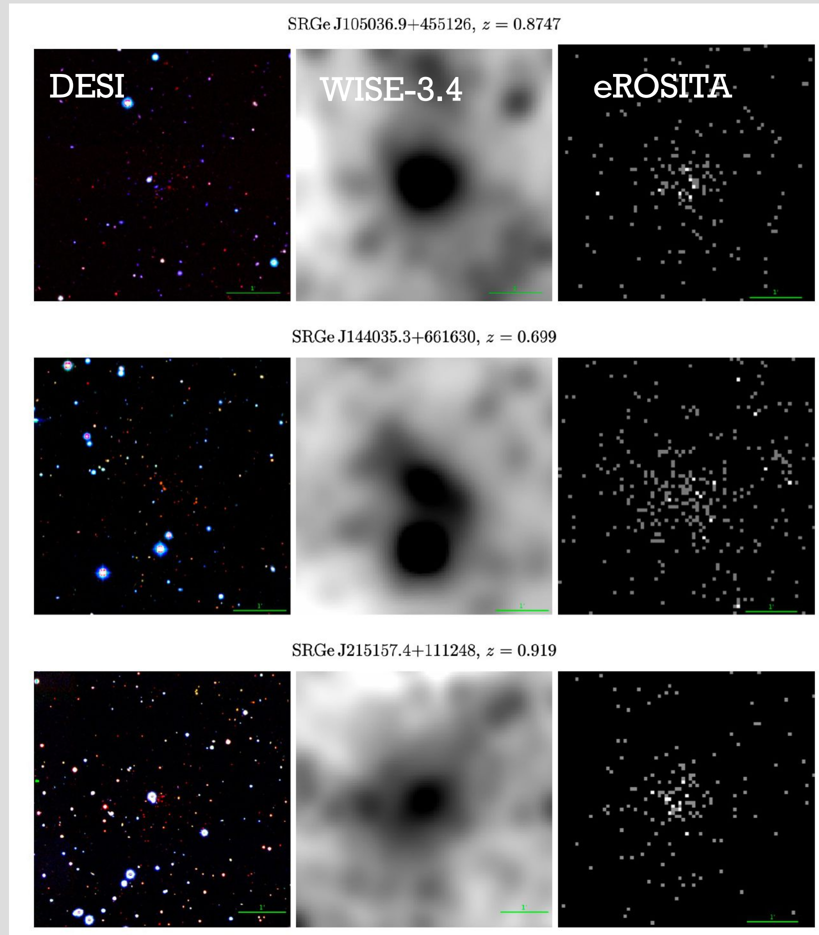


XMM-XXL South
Pierre et al. (2015)

eROSITA Clusters

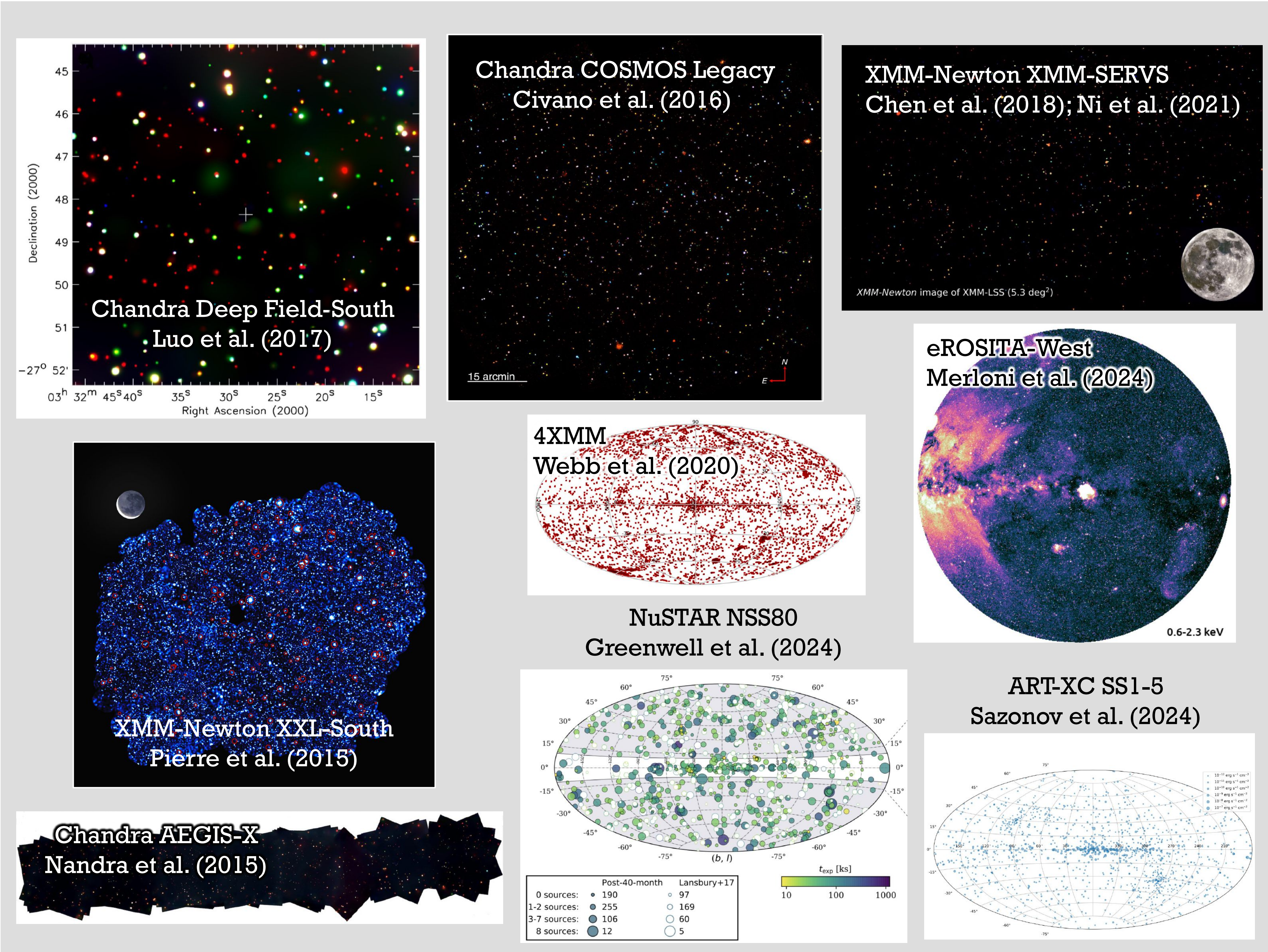


Ghirardini et al. (2024)

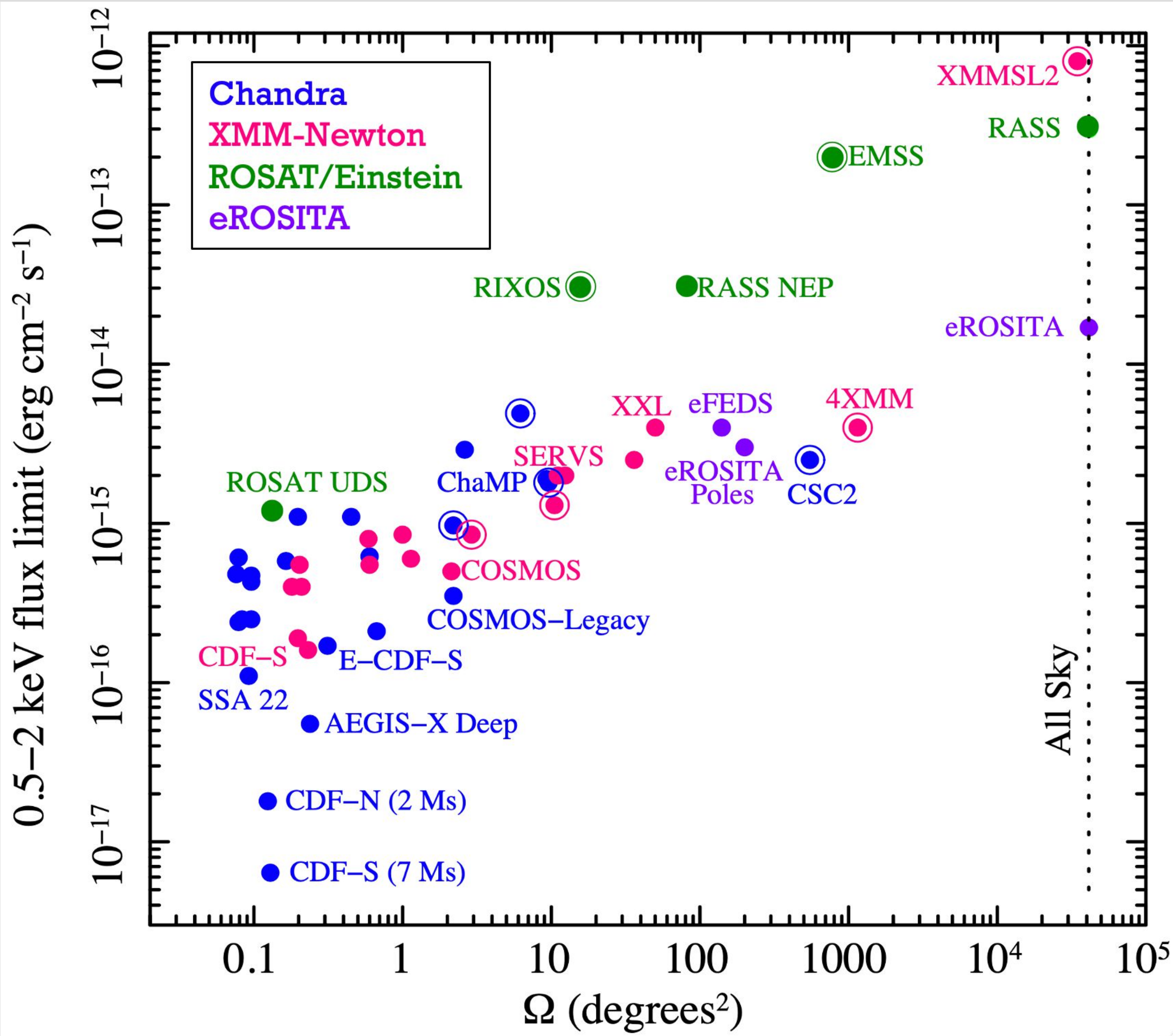


Zaznobin et al. (2024)

The Surveys and Their Follow-Up



Chandra Deep Field-South
Luo et al. (2017)
Declination (2000)
Right Ascension (2000)
Chandra COSMOS Legacy
Civano et al. (2016)
15 arcmin
XMM-Newton XMM-SERVS
Chen et al. (2018); Ni et al. (2021)
XMM-Newton image of XMM-LSS (5.3 deg²)
eROSITA-West
Merloni et al. (2024)
0.6-2.3 keV
4XMM
Webb et al. (2020)
NuSTAR NSS80
Greenwell et al. (2024)
Post-40-month
Lansbury+17
0 sources: 190 97
1-2 sources: 255 169
3-7 sources: 106 60
8 sources: 12 5
t_exp [ks]
XMM-Newton XXL-South
Pierre et al. (2015)
ART-XC SS1-5
Sazonov et al. (2024)
Chandra AEGIS-X
Nandra et al. (2015)

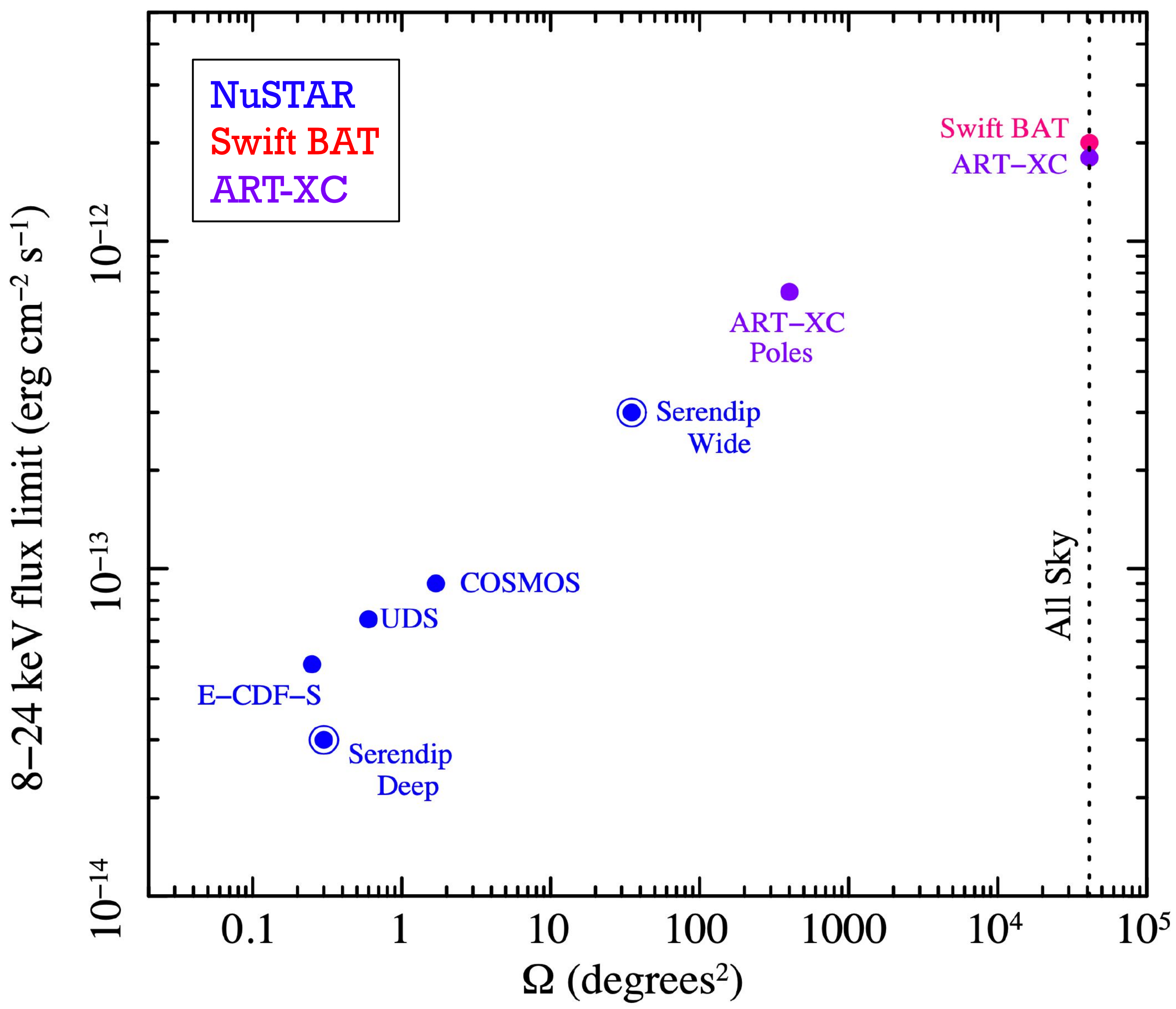


Brandt & Yang (2022)

Have now filled much of the F_X-Ω "discovery space" in the standard "wedding cake" design.

Very ambitious projects or new missions would be needed for further large advances.

A lot more work is needed on federated survey analyses.



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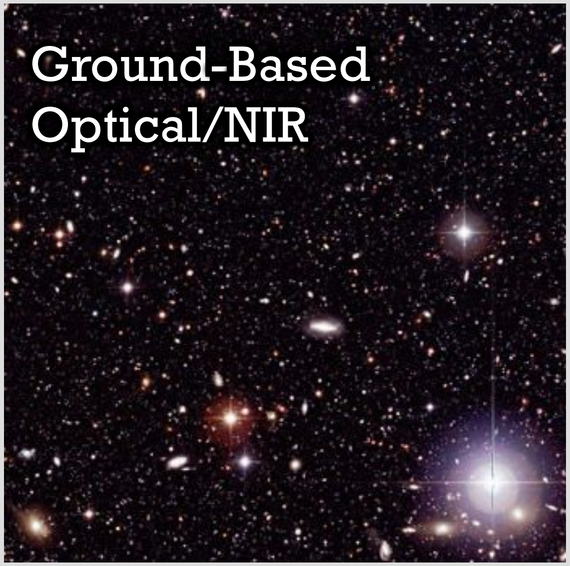
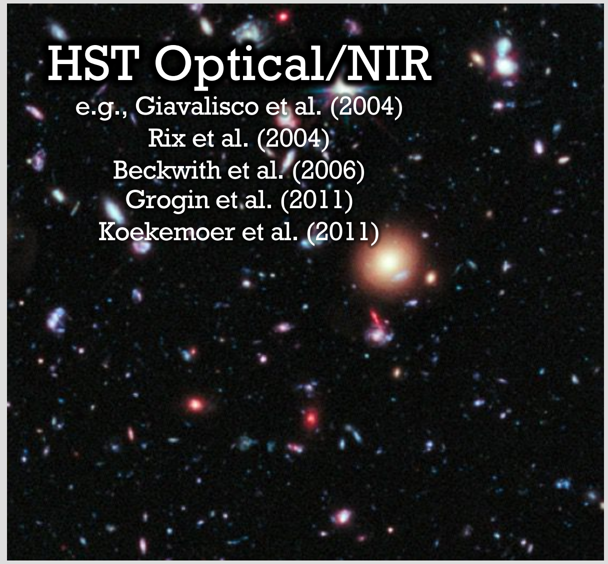
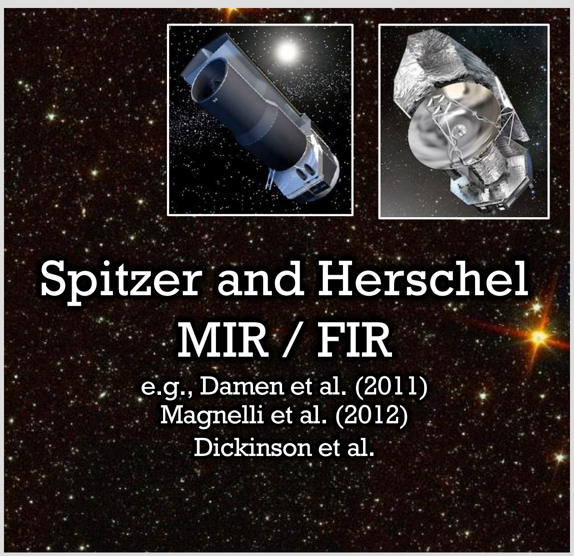
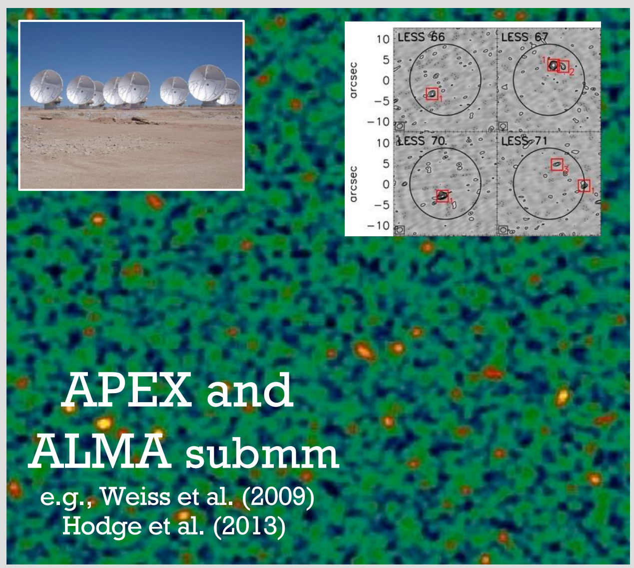
Brandt & Yang (2022)

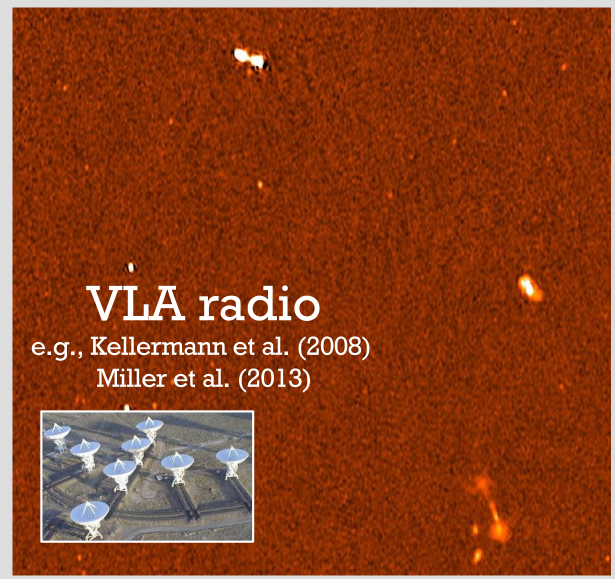
Ultradeep Multiwavelength Coverage (CDF-S Examples)





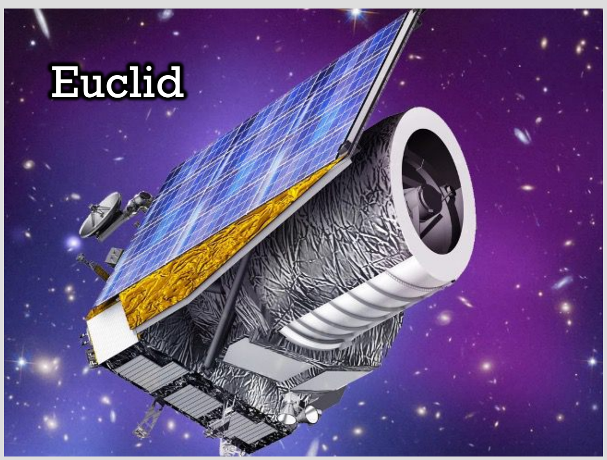


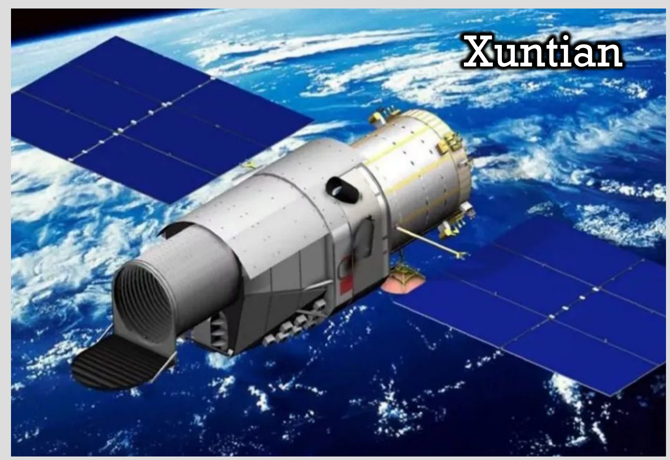




Continues to improve rapidly, keeping the science exciting.

Very Wide-Field Multiwavelength Coverage

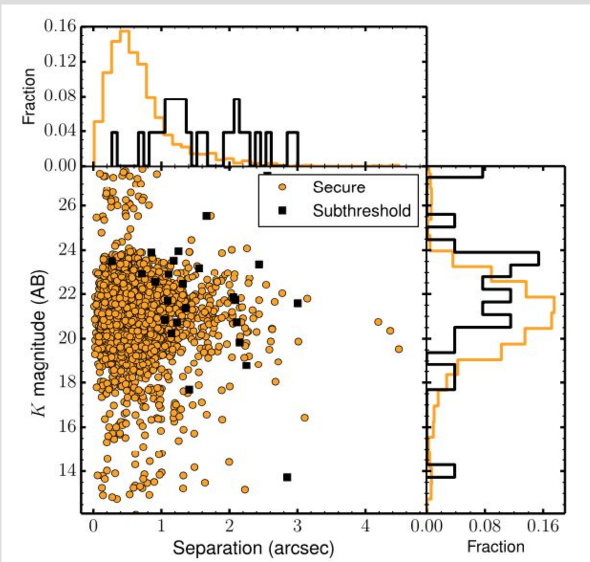




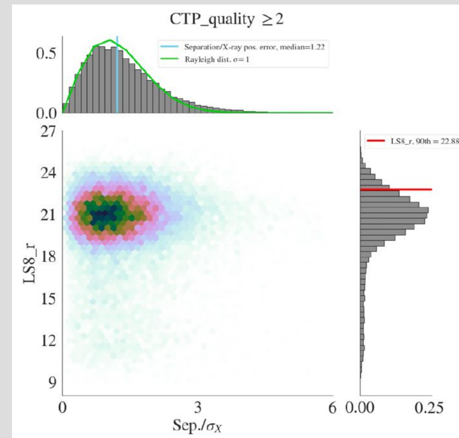
Also, powerful wide-field spectrographs – e.g., SuMIRe PFS, 4MOST, SPHEREx.

Source Identification

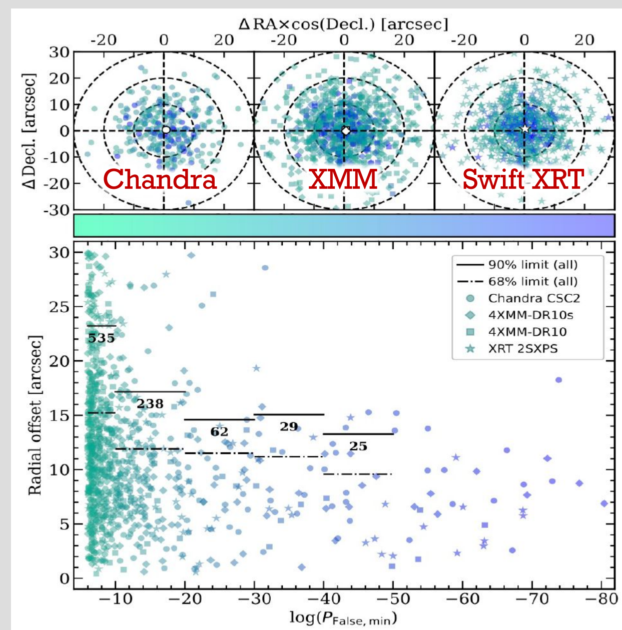
COSMOS Legacy IDs - Marchesi et al. (2016)



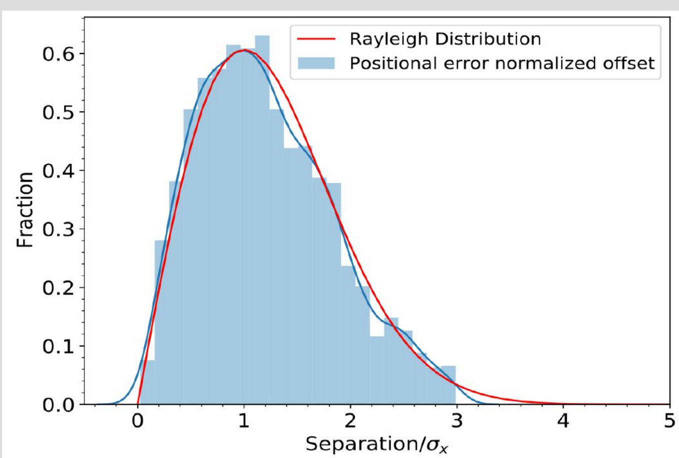
eROSITA EFEDS - Salvato et al. (2022)



Serendipitous NuSTAR IDs - Greenwell et al. (2024)



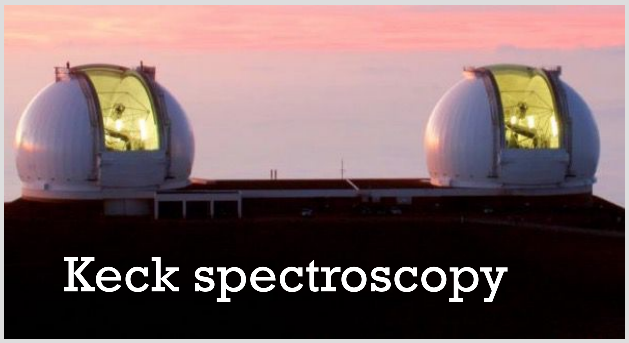
W-CDF-S IDs - Ni et al. (2021)

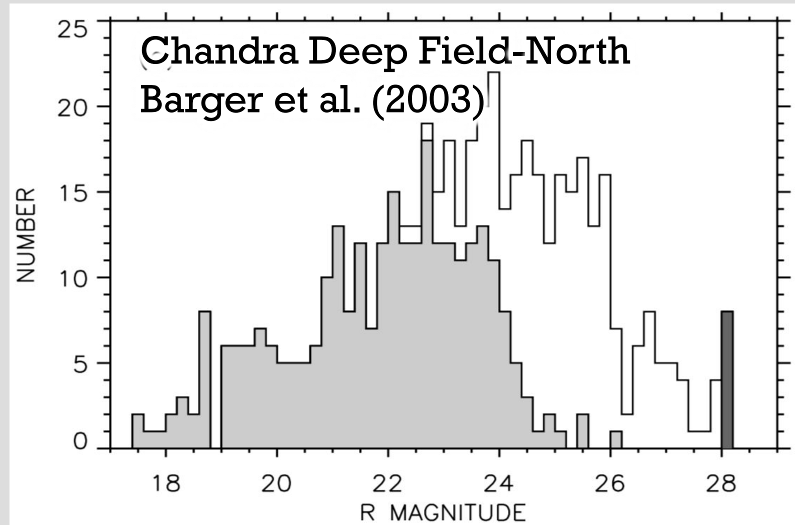


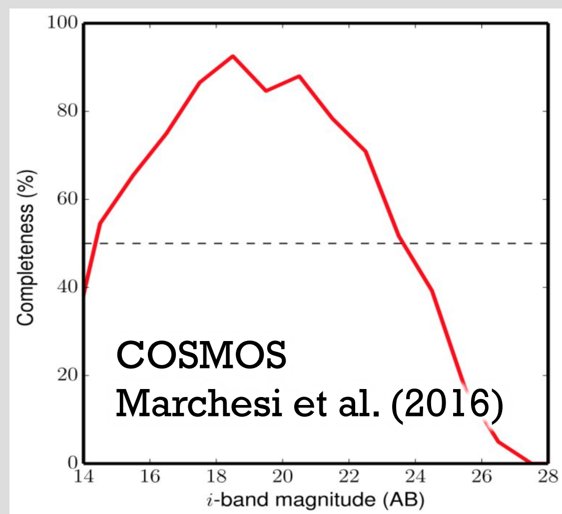
Spectroscopic Redshifts

A large enterprise and rate-limiting step for ~ 25 years.

Many telescopes used, including the best on Earth and in space.







Spectroscopic completeness typically drops beyond ~ 24^{th} mag.

Quality X-ray redshifts still rare.

Faint X-ray source spectroscopy remains challenging - driver for ELTs!

Photometric Redshifts

Need Many Bands Spanning Optical-NIR Range and AGN Templates

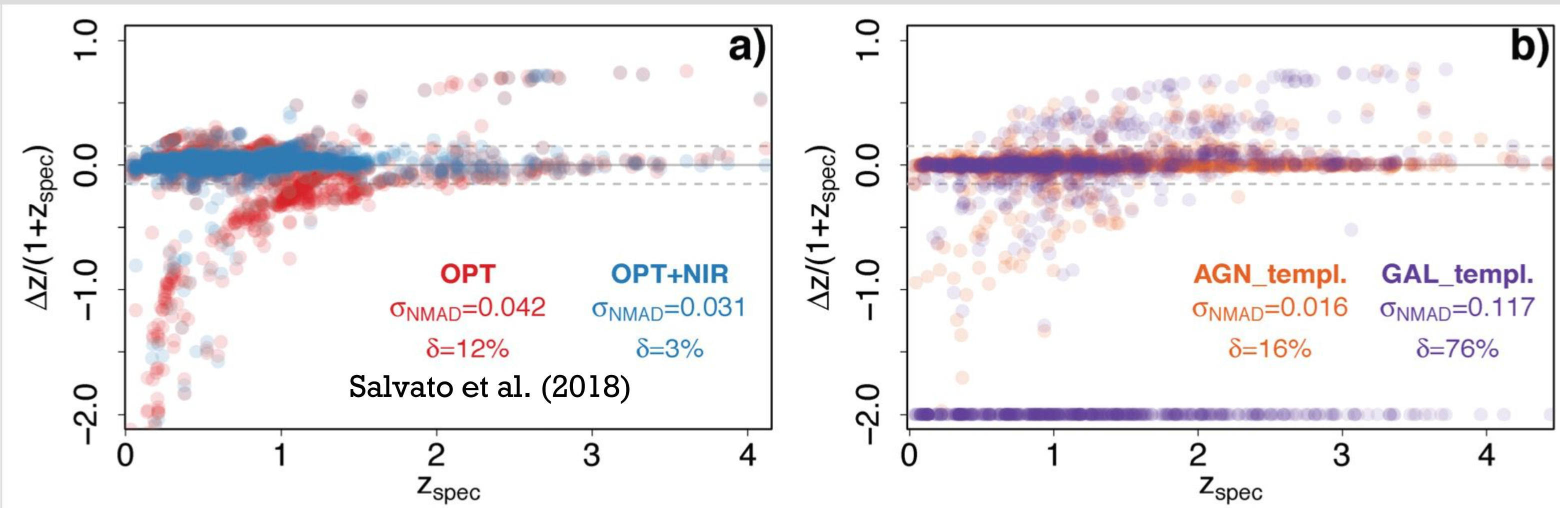


Photo-*z* - CDF-S AGNs

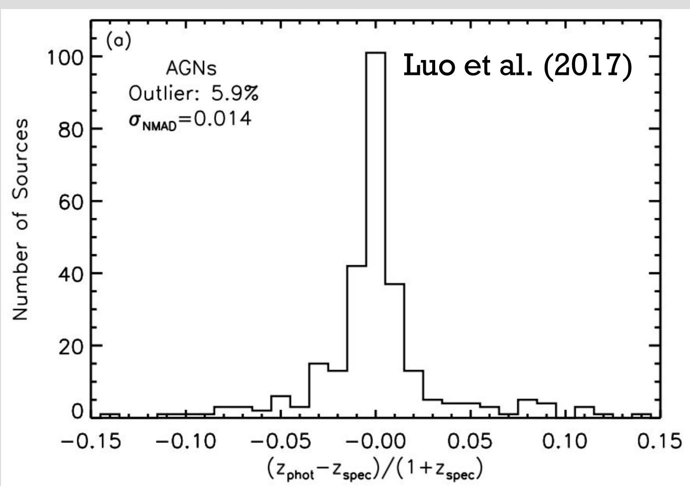


Photo-*z* - COSMOS AGNs

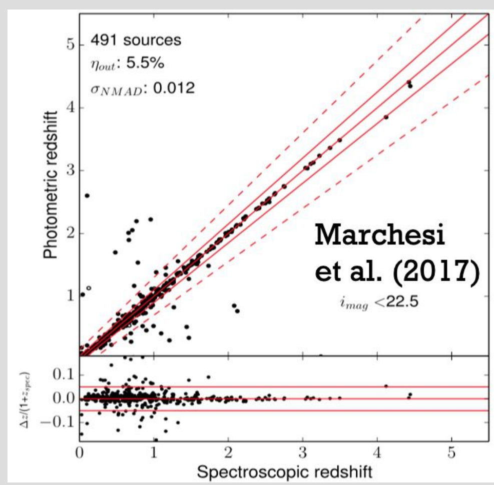
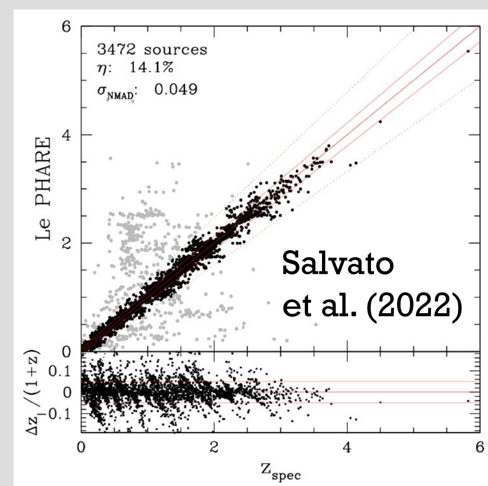


Photo-*z* – eROSITA EFEDS



In total, large samples generated from $z \sim 0$ to $z \sim$ 3-4. Some sources at even higher redshifts.

X-ray Source Classification

X-ray luminosity, spectral shape, variability, and morphology

X-ray-to-optical/infrared flux ratio

Broad-band SED fitting

Optical/infrared emission-line and continuum properties

Radio morphology and core surface brightness

Usually, several independent approaches
are used to cross-check classifications

Extragalactic X-ray Source Types

Active Galactic Nuclei (AGNs): $z \approx 0\text{-}5$

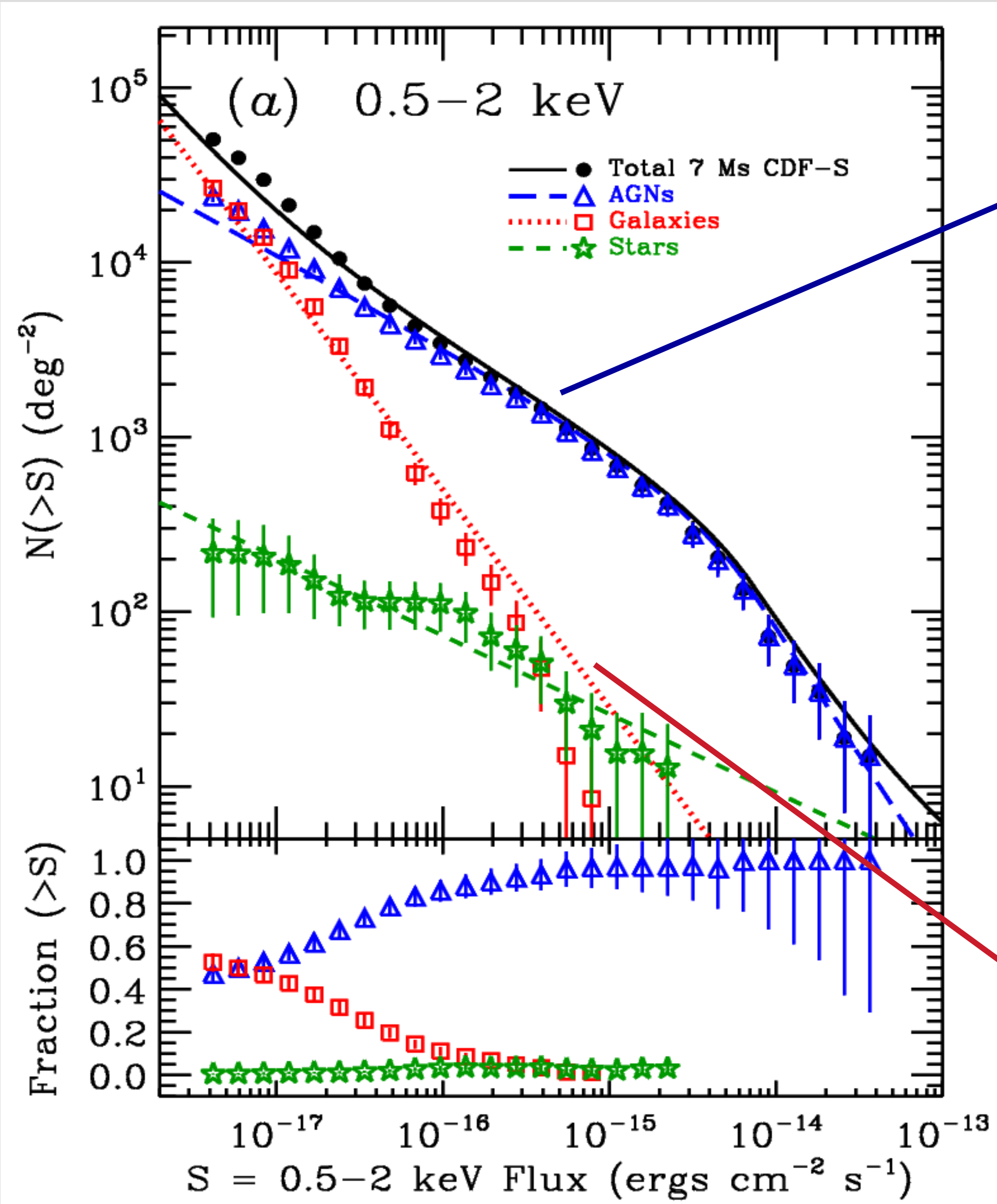
Galaxies: $z \approx 0\text{-}1.5$

Clusters and groups: $z \approx 0\text{-}2$

Transients: e.g., FXTs, TDEs, QPEs

AGNs are energetically and usually numerically dominant

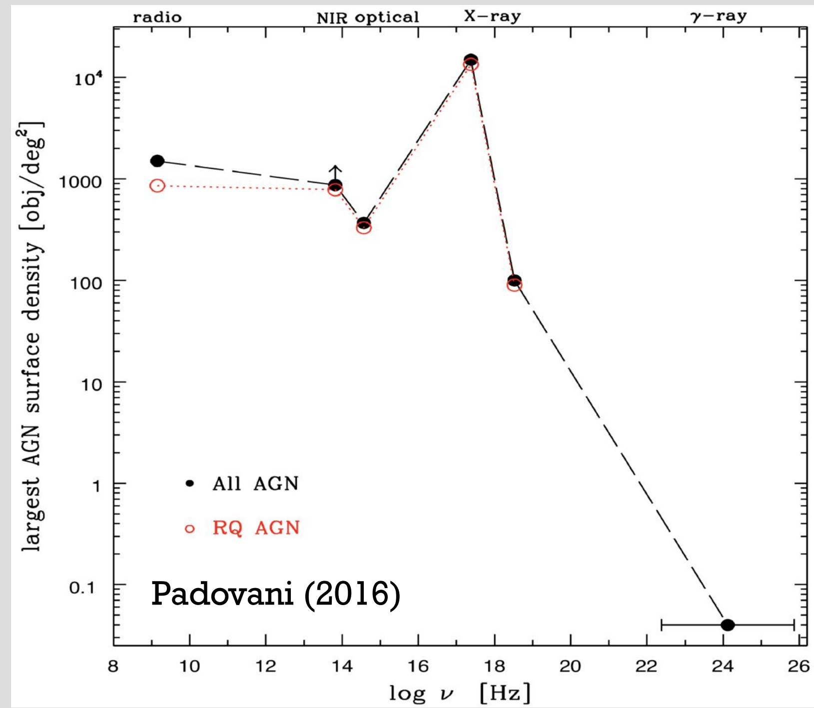
Detected Source Number Counts



Luo et al. (2017)

In deepest surveys, AGN number counts now reach 10,000-24,000 deg^{-2}.

1.0 billion across entire sky!



Large population of cosmologically distant normal and starburst galaxies - X-ray binaries.

A Few Selected AGN Science Results

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Contribution of AGNs to the cosmic backgrounds.

Revealed most/much of obscured SMBH growth.

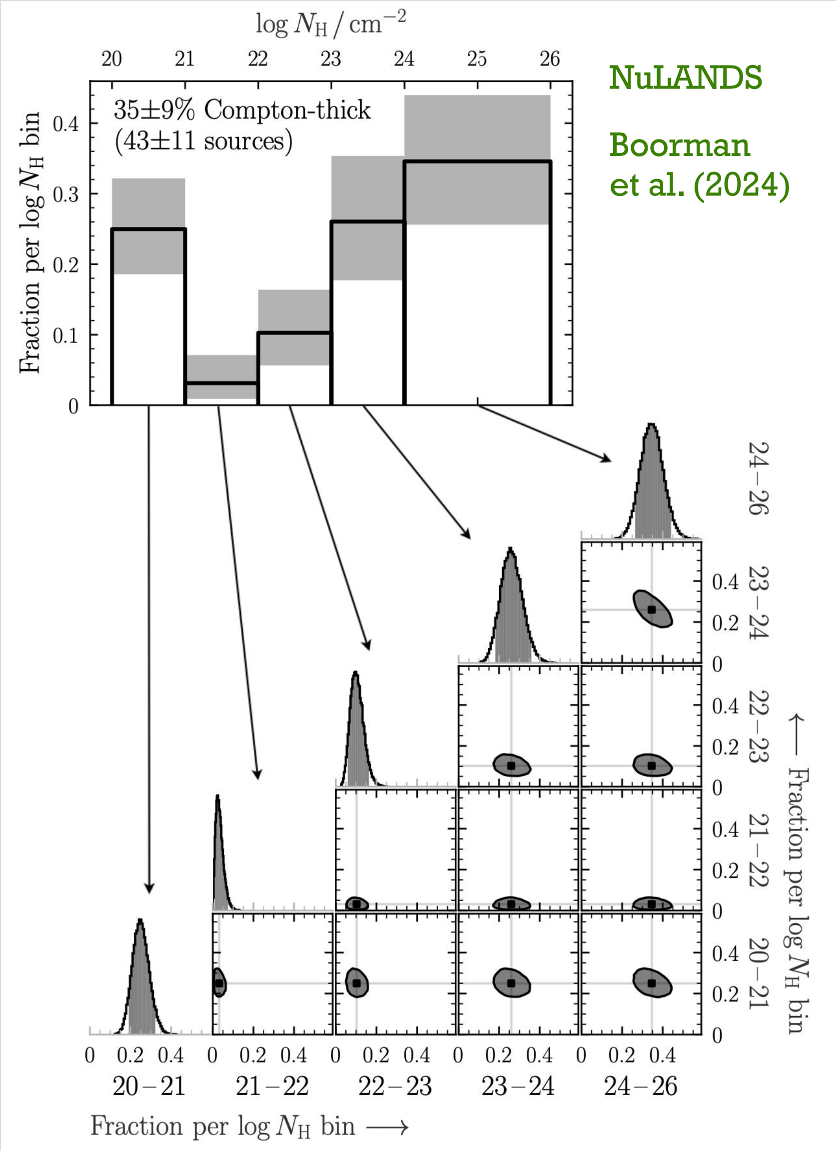
Totally changed understanding of AGN evolution and the "cosmic balance of power".

Much better understanding of high-redshift AGNs and their contribution to reionization.

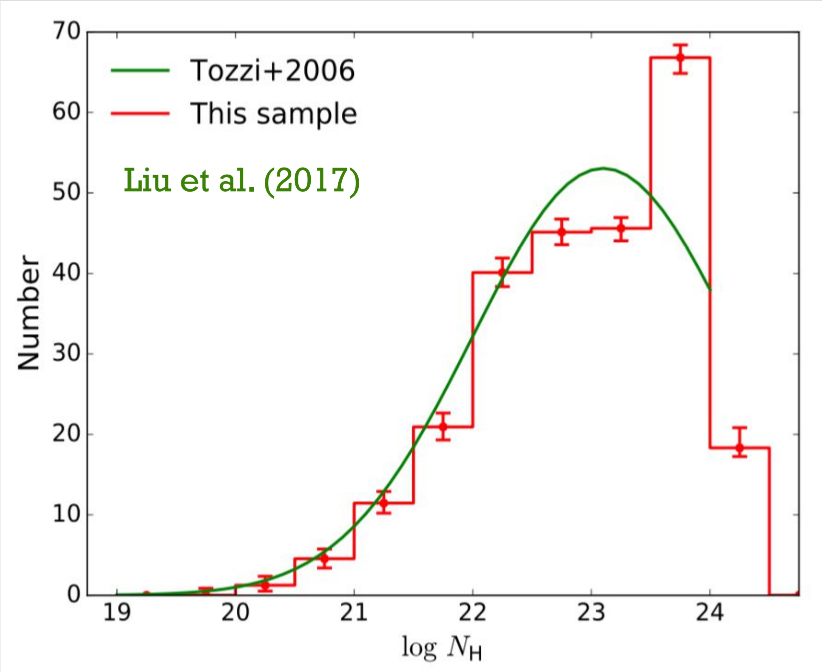
Clarification of AGN-galaxy and AGN-LSS connections.

Obscured SMBH Growth

Local Universe - Intrinsic Absorption



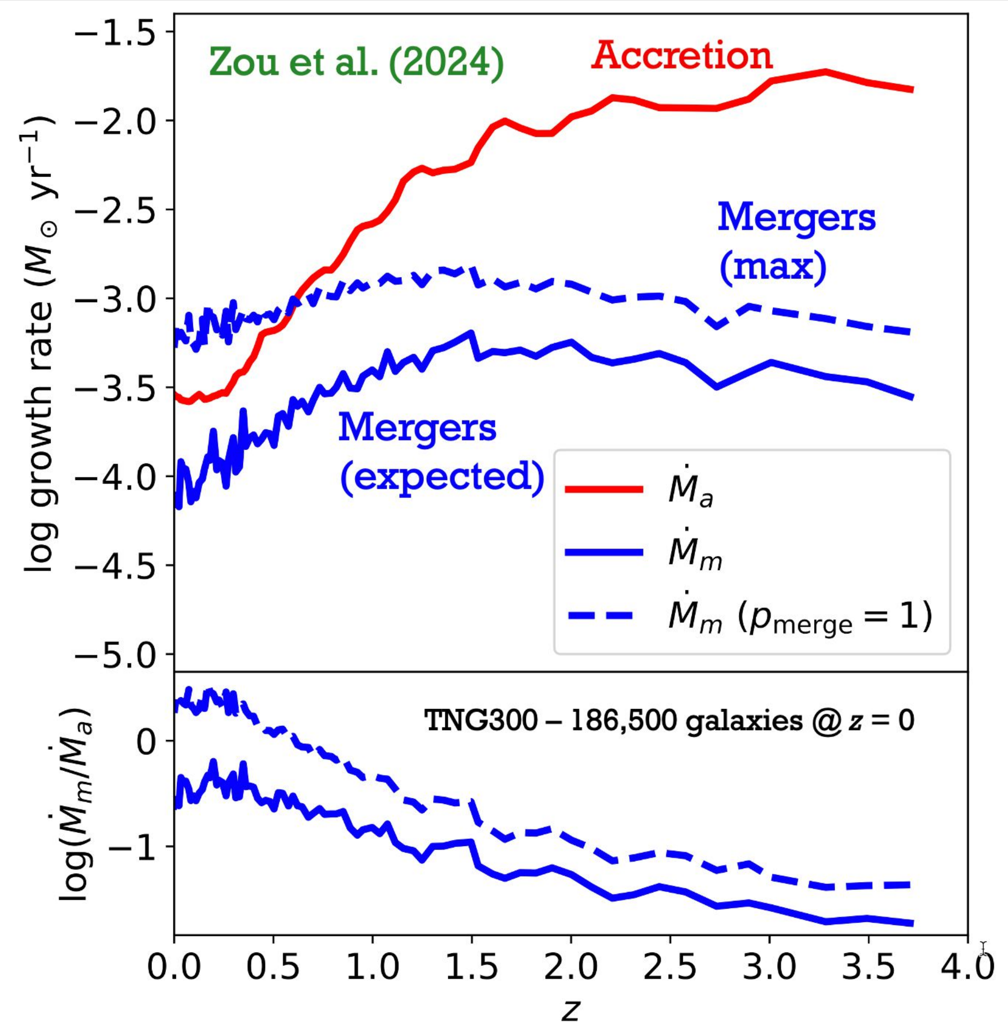
CDF-S - Intrinsic Absorption



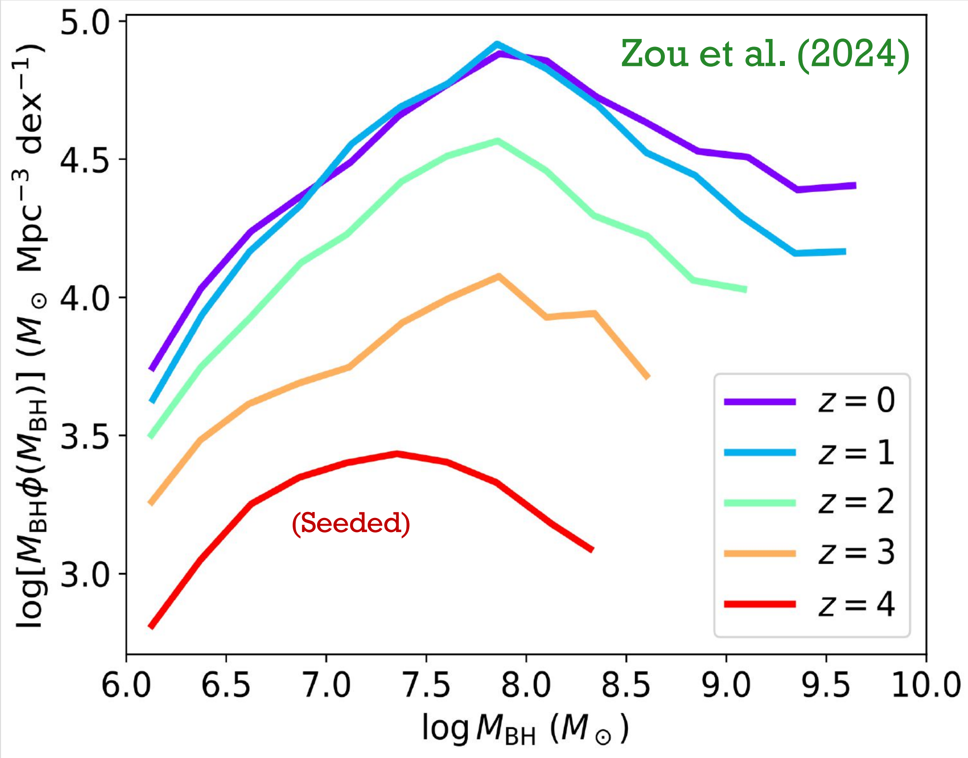
- f_{obs} rises with redshift
- f_{obs} declines with luminosity
- f_{obs} declines with λ_{Edd}
- X-ray and optical/IR obscuration generally linked, with exceptions

SMBH Growth Constraints

Most SMBH Growth Driven by Accretion



Mass Function Build-Up Action is at z ~ 1-4



Integrating observed SMBH growth can plausibly explain the local mass density of SMBHs (Soltan argument).

No exotic growth mechanisms required.

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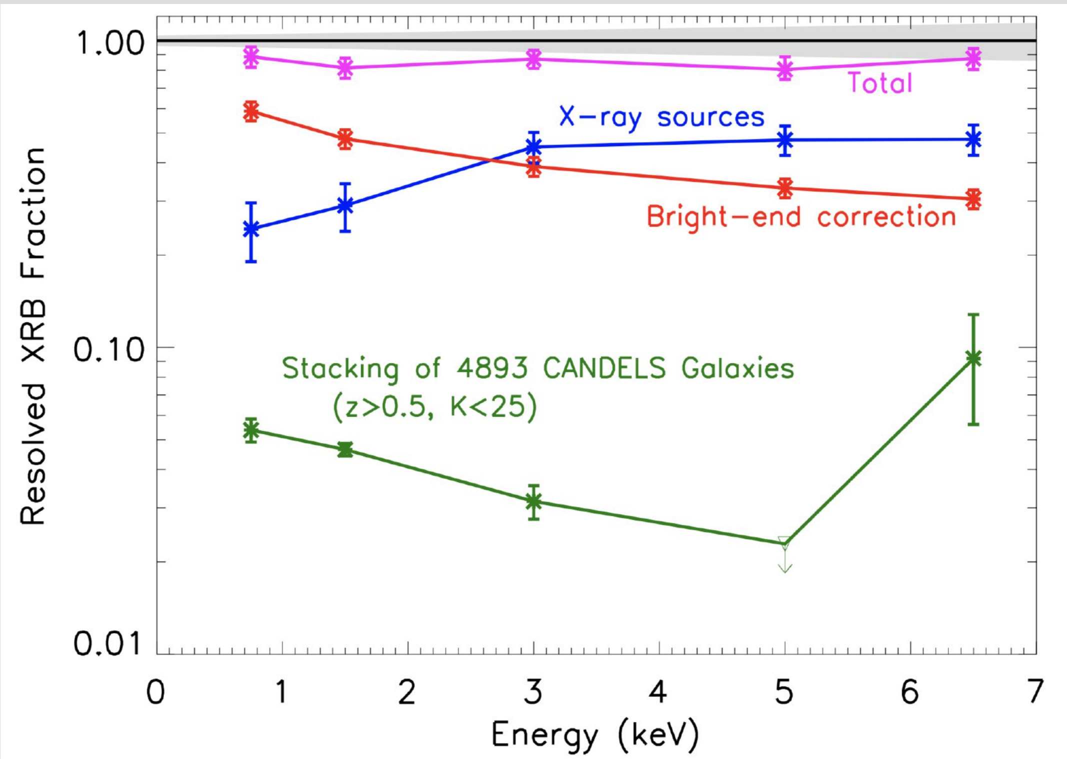
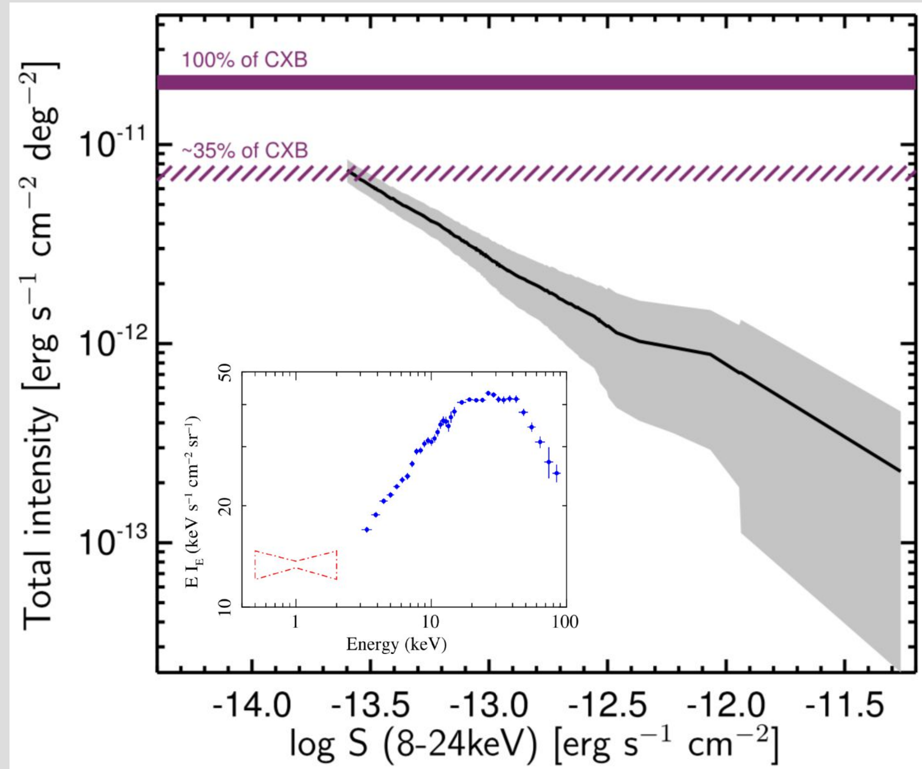
Resolving the CXRB

Resolved Fraction in 7 Ms CDF-S vs. Energy



Luo et al.

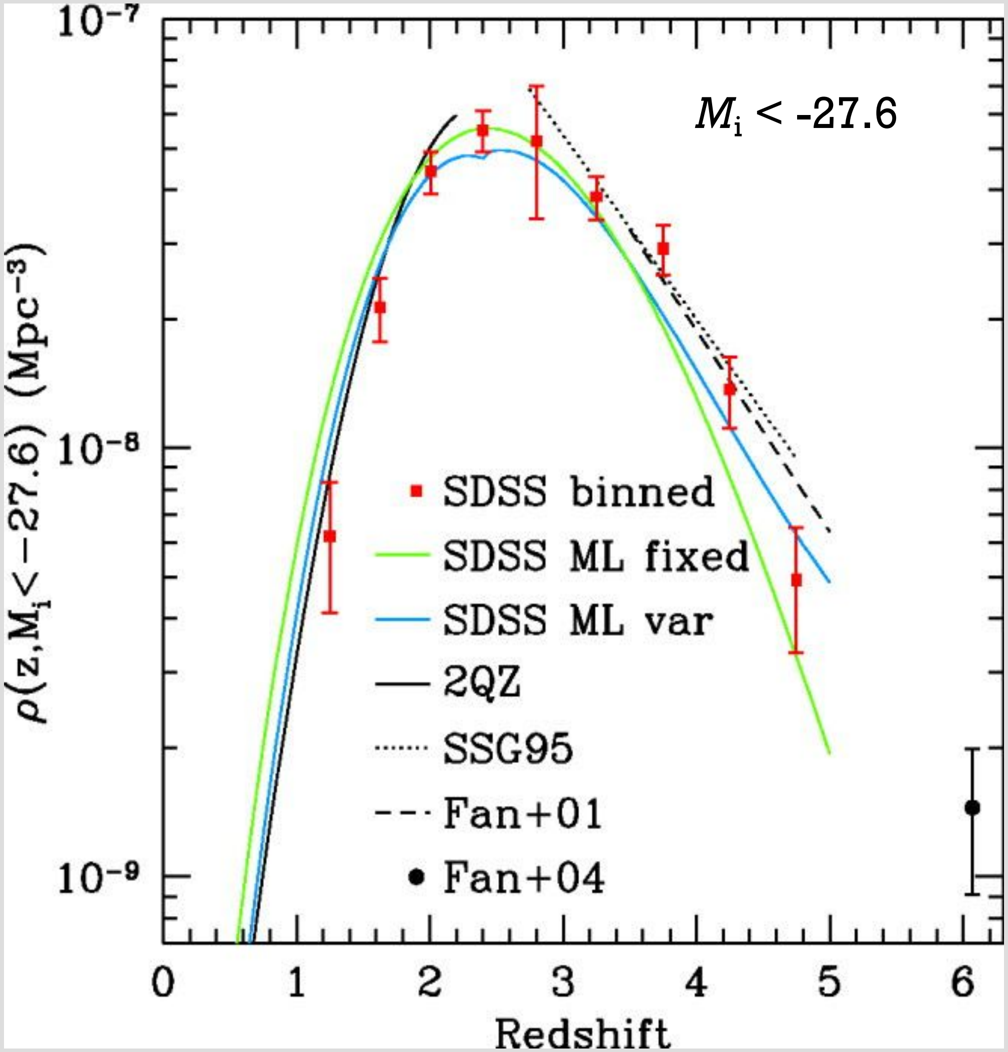
Total Intensity vs. 8-24 keV
Flux for NuSTAR Surveys



Harrison et al. (2016)

Still need better resolution of the CXRB peak and beyond

Luminous Quasar Evolution



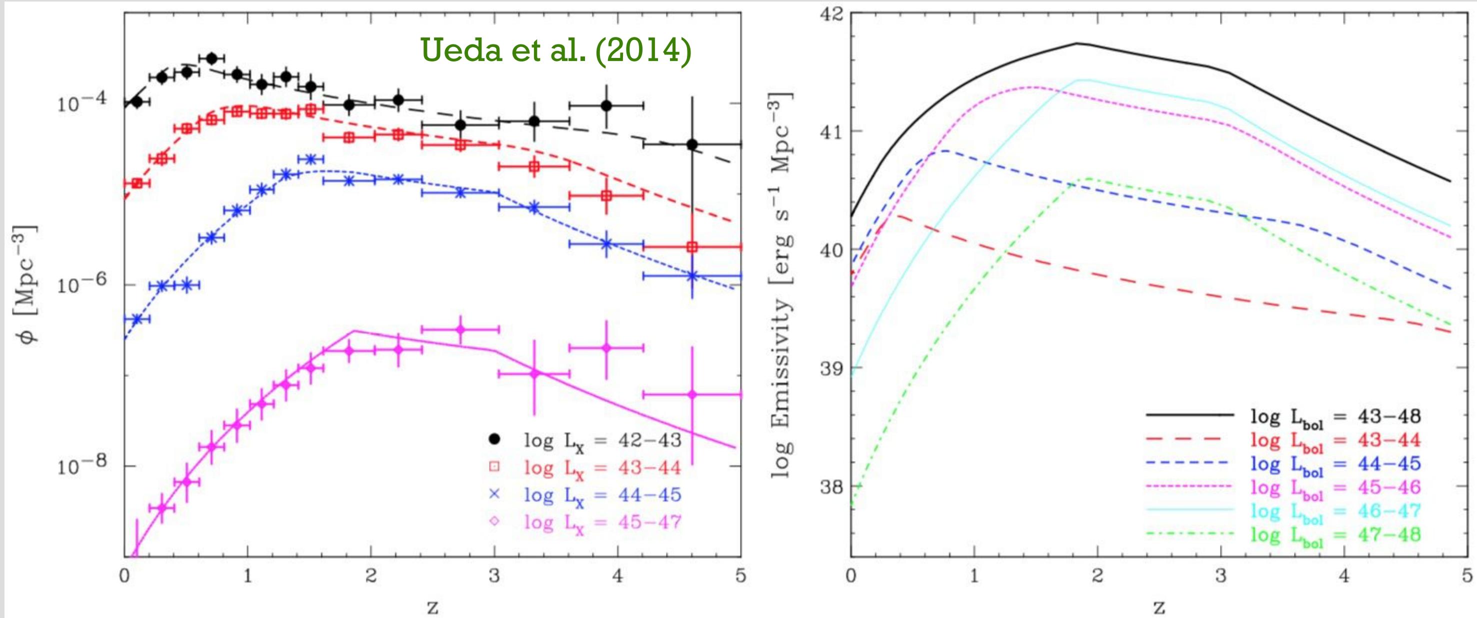
e.g., Richards et al.

How will more typical AGNs evolve?

AGN Evolution Revised

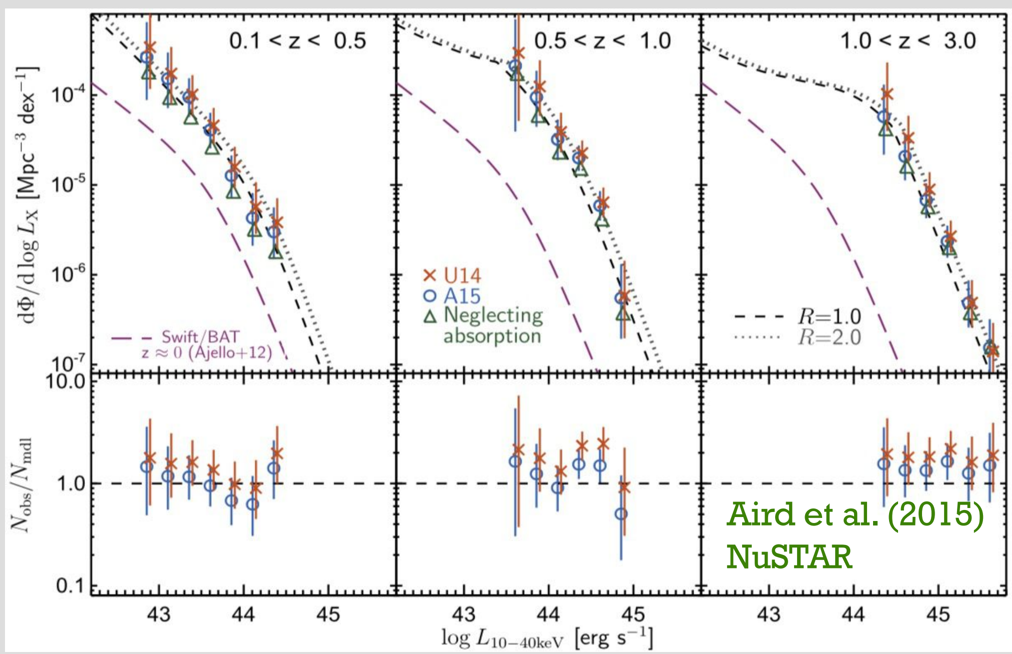
Basic idea of AGN "cosmic downsizing" from 2003 seems well established.

Some details still under debate.



Hard X-ray results do not greatly alter the strong XLF evolution seen at lower energies.

Key absorption vs. reflection constraints.

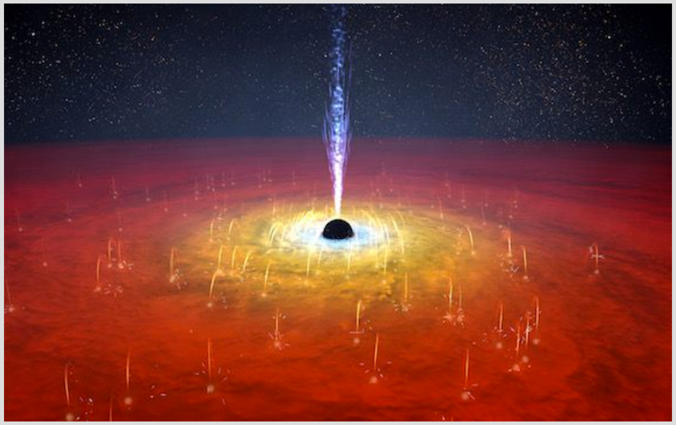


Likely driven by cold-gas content of galaxies with different M_*.

Detailed causes still need clarification.

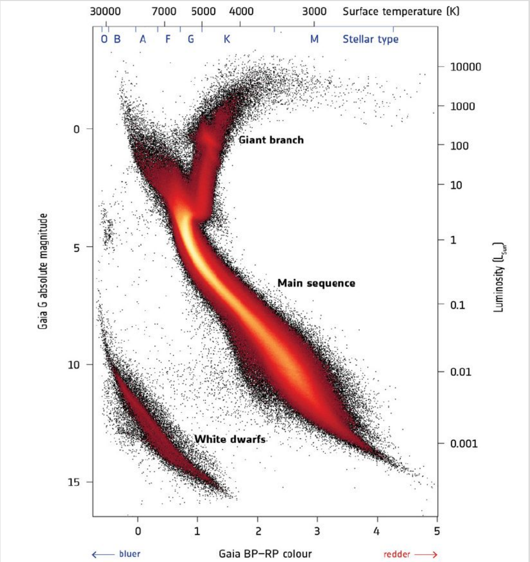
Cosmic Balance of Power

SMBH Accretion



vs.

Stellar Fusion



Press release from 1999…

Black Holes May Supply Up to Half the Universe's Energy Output

Contact:
Christopher Wanjek
wanjek@gsfc.nasa.gov
301-286-4453

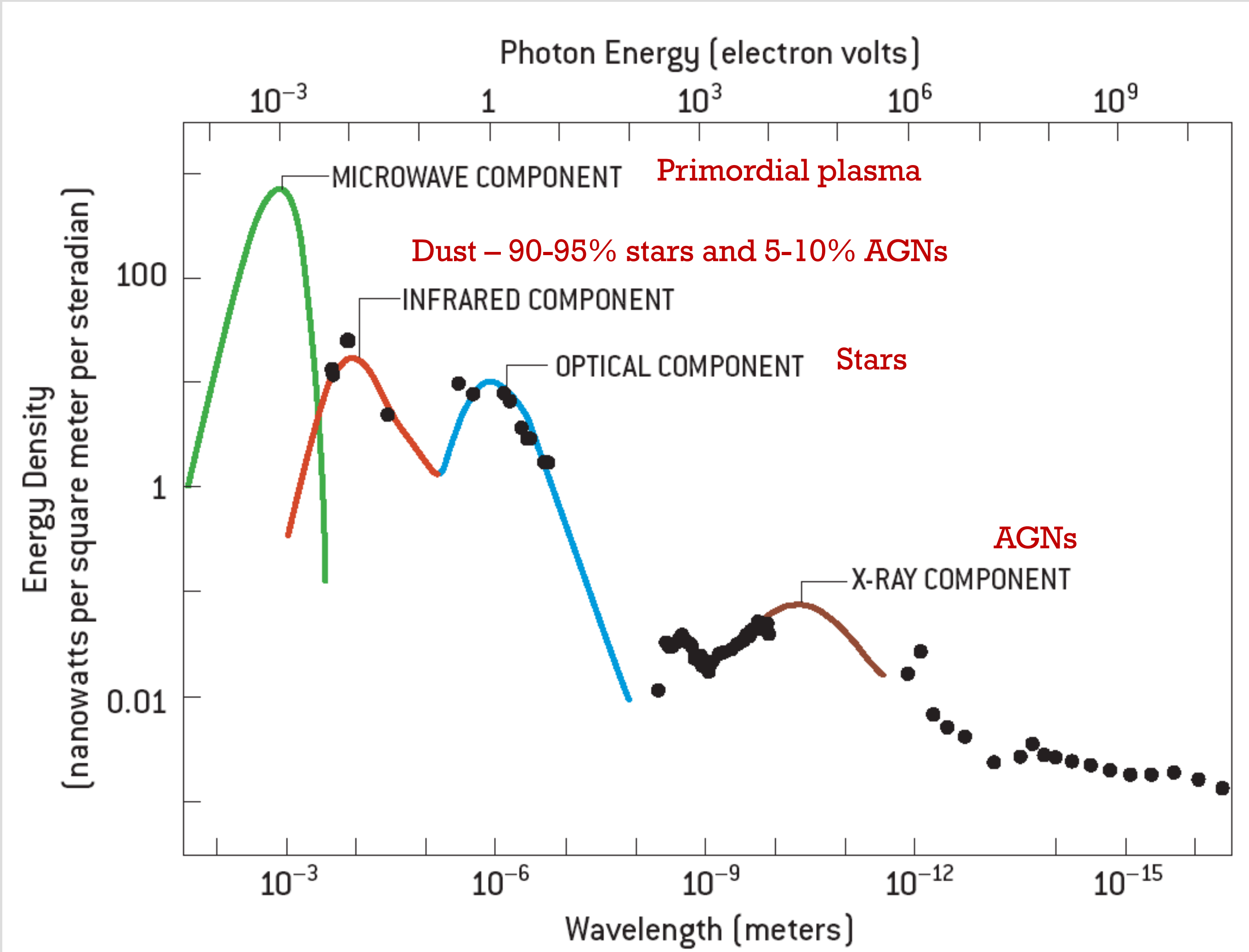
September 10, 1999

Greenbelt, Md. -- Massive black holes, long-thought to produce only a mere fraction of the universe's total energy output, may actually be the force behind half of the universe's radiation produced after the Big Bang, chipping away the coveted power monopoly believed to be held by ordinary stars.

Details of this energy theory, based on measurements of background X-ray radiation and the gas-obscured growth of massive black holes, are presented today by the University of Cambridge Institute of Astronomy theorist Dr. Andrew Fabian at the X-ray Astronomy 1999 meeting in Bologna, Italy. The meeting is being chaired by Dr. Nicholas White, head of NASA Goddard Space Flight Center's (Greenbelt, Md.) X-ray Astrophysics Branch in the Laboratory for High Energy Astrophysics.

What has dominated cosmic radiated power since the formation of galaxies?

Cosmic Balance of Power



Hasinger & Gilli (2009)

SMBHs have made 5-10% of cosmic power since the formation of galaxies, and stars made 90-95% – see Section 5 of Brandt & Alexander (2015) for details.

Big 25-Year Survey Successes: AGNs

Contribution of AGNs to the cosmic backgrounds.

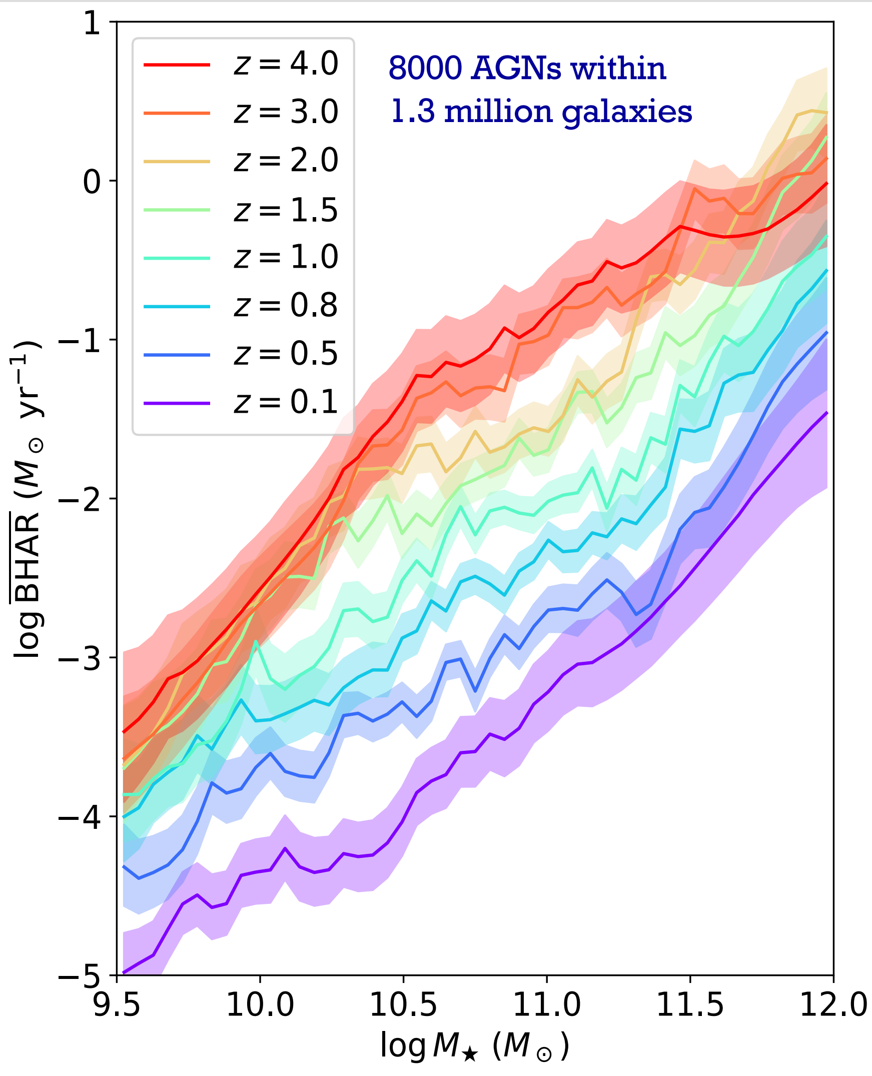
Revealed most/much of obscured SMBH growth.

Totally changed understanding of AGN evolution and the “cosmic balance of power”.

Much better understanding of high-redshift AGNs and their contribution to reionization.

Clarification of AGN-galaxy and AGN-LSS connections.

Stellar Mass



For the general galaxy population at z = 0.1-4, long-term SMBH growth correlates most strongly with M_*

Effect spans ~ 3 orders of magnitude

Implications for the high-redshift decline of quasars

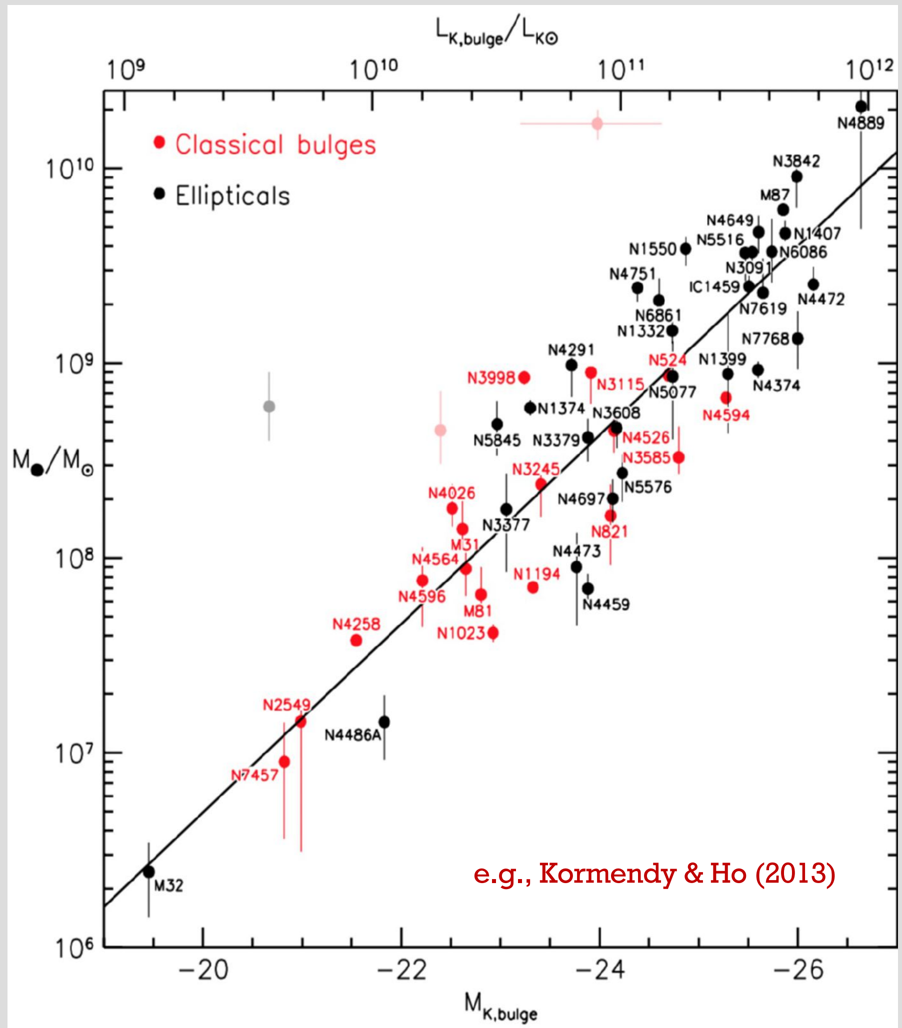
Also have fairly precise $p(\lambda | M_*, z)$ constraints, encoding rich information about SMBH growth ($\lambda = L_X/M_*$)

e.g. Zou et al. (2024); Yang et al. (2018)

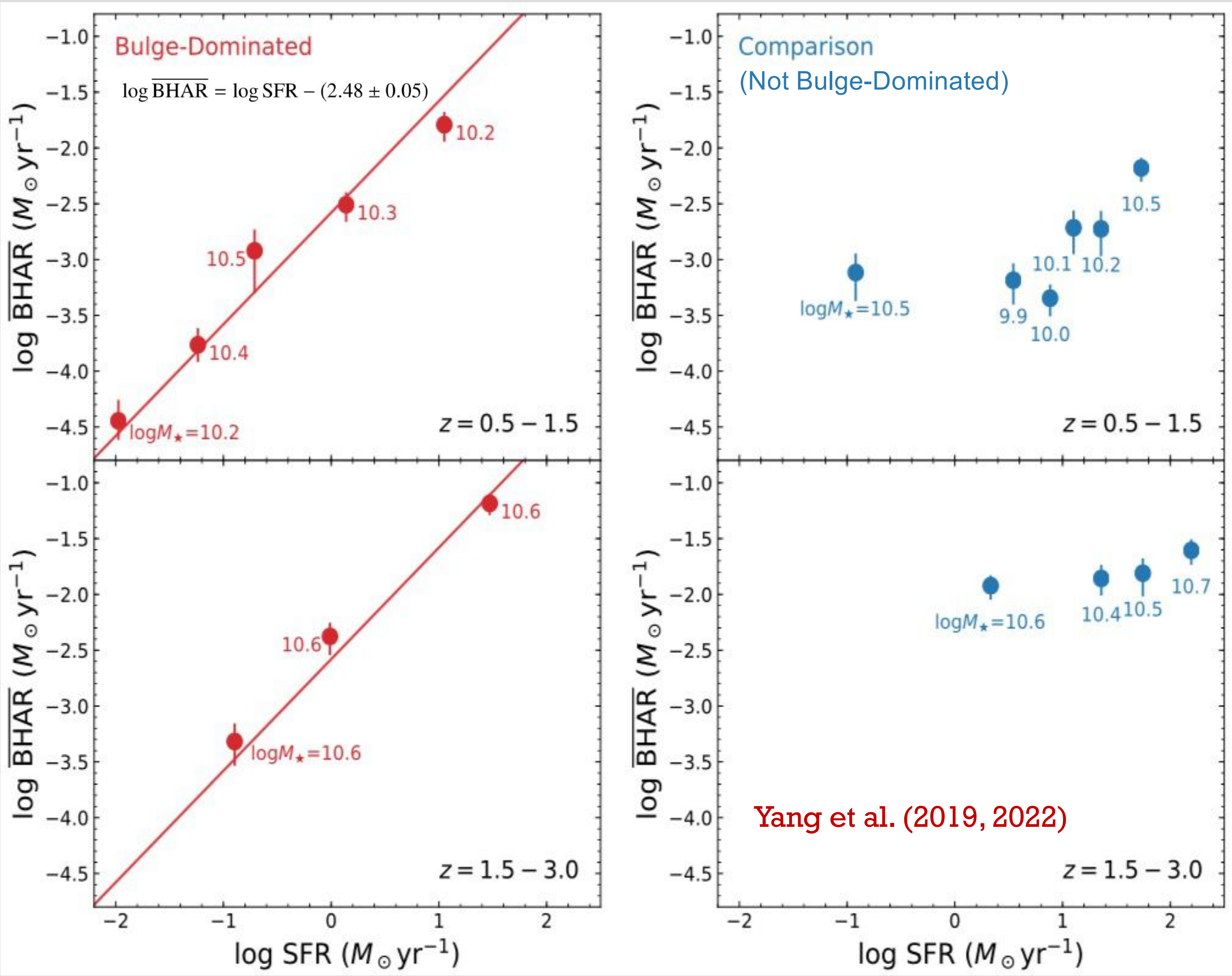
SMBH – Bulge Relations

$M_\bullet$ tightly related to bulge M_* – but *not* tightly related to total M_* or disk M_*

$$\frac{d}{dt}$$



SFR for Bulge-Dominated Galaxies



Results cover z = 0.5-3.0, reaching into the peak era of SMBH growth.

BHAR/SFR for bulge-dominated galaxies (~ 1/302) similar to typical M_{BH}/M_{Bulge} locally.

Evidence for true co-evolution - since we observe apparent lockstep growth of SMBHs and bulges, at least at z = 0.5-3.0.

See Yang et al. (2022) for assessment of creation vs. maintenance.

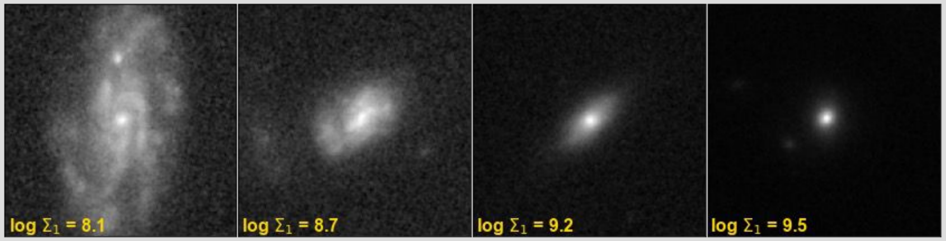
Compactness

Compactness is a measure of the mass/size ratio of galaxies

$$\Sigma_1 = \frac{M_*(< 1\ \mathrm{kpc})}{\pi\ (1\ \mathrm{kpc})^2}$$

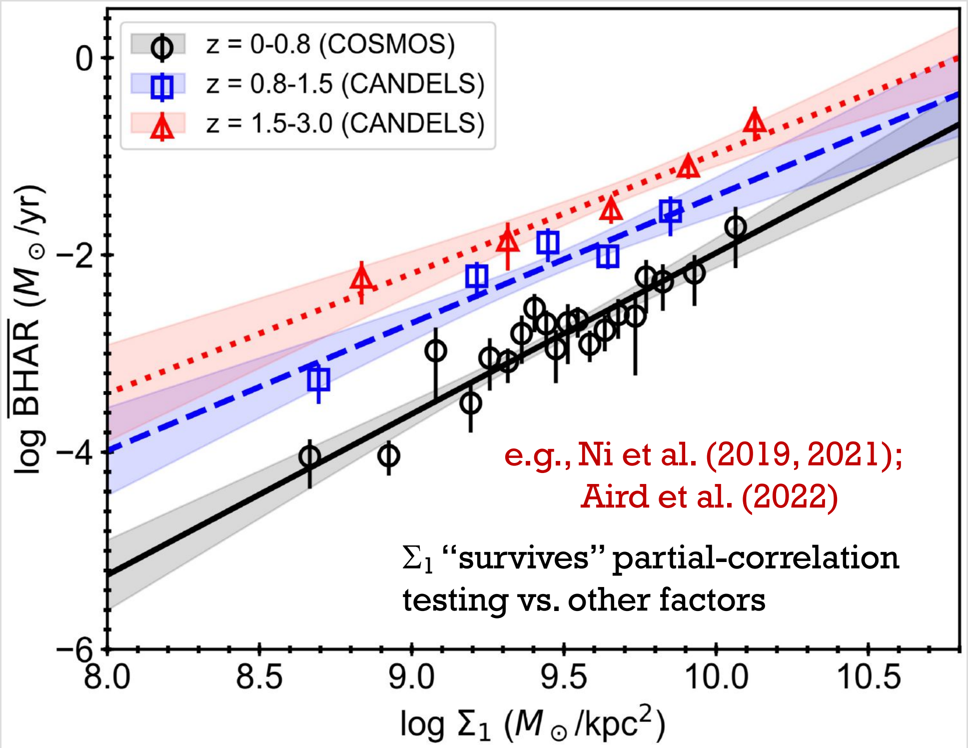
At least for gas-rich, star-forming galaxies, Σ_1 may also serve as a tracer of central-gas density on a kpc-scale.

Compactness Examples for log M_* ~ 10.3



z = 0.3-0.5 COSMOS *I*-band

BHAR vs. Compactness for Star-Forming Galaxies



Not seen for quiescent galaxies, suggesting the role of gas density.

Redshift dependence can also be understood via gas evolution.

STAY TUNED...

for the great in-depth talks coming up!

Astron Astrophys Rev (2015) 23:1
DOI 10.1007/s00159-014-0081-z

REVIEW PAPER

Cosmic X-ray surveys of distant active galaxies

The demographics, physics, and ecology of growing supermassive black holes

W. N. Brandt · D. M. Alexander

arXiv:1501.01982

Abstract We review results from cosmic X-ray surveys of active galactic nuclei (AGNs) over the past ≈ 15 years that have dramatically improved our understanding of growing supermassive black holes in the distant universe. First, we discuss the utility of such surveys for AGN investigations and the capabilities of the missions making these surveys, emphasizing *Chandra*, *XMM-Newton*, and *NuSTAR*. Second, we briefly describe the main cosmic X-ray surveys, the essential roles of complementary multi-wavelength data, and how AGNs are selected from these surveys. We then review key results from these surveys on the AGN population and its evolution ("demographics"), the physical processes operating in AGNs ("physics"), and the interactions between AGNs and their environments ("ecology"). We conclude by describing some significant unresolved questions and prospects for advancing the field.

Keywords Surveys · Cosmology: observations · Galaxies: active · Galaxies: nuclei · Galaxies: Seyfert · Galaxies: quasars · Galaxies: evolution · Black hole physics

Surveys of the Cosmic X-ray Background

W.N. Brandt* and G. Yang

arXiv:2111.01156

Abstract We provide a highly concise overview of what X-ray surveys and their multiwavelength follow-up have revealed about the nature of the cosmic X-ray background (CXRB) and its constituent sources. We first describe early global studies of the CXRB, the development of imaging CXRB surveys, and the resolved CXRB fraction. Second, we detail the sources detected in CXRB surveys describing their identification, classification, and basic nature. Third, since active galactic nuclei (AGNs) are the main contributors to the CXRB, we discuss some key insights about their demographics, physics, and ecology that have come from CXRB surveys. Finally, we highlight future prospects for the field.

Keywords Surveys; Cosmic X-ray background; Cosmology: observations; Galaxies: active; Galaxies; Galaxies: evolution; Galaxies: clusters; Galaxies: groups; X-ray astronomy

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The Future:
Questions and Prospects

A Few Big Questions for X-ray Surveys

Growth and feedback of highly obscured SMBHs through the $z \sim$ 1-4 galaxy formation era.

SMBH growth in the first galaxies at $z \sim$ 5-15.

Host-galaxy properties driving SMBH growth.

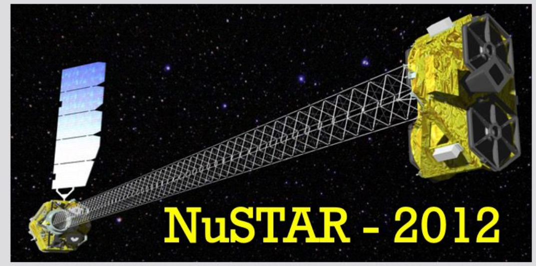
Drivers of X-ray binary population evolution.

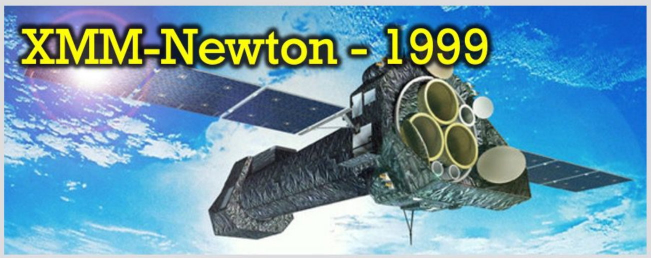
ICM formation and SMBHs in protoclusters.

Distant X-ray transient populations.

Multi-messenger connections.

A Toast to Good Health!



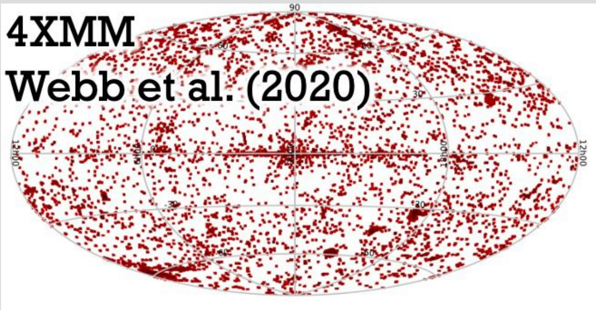


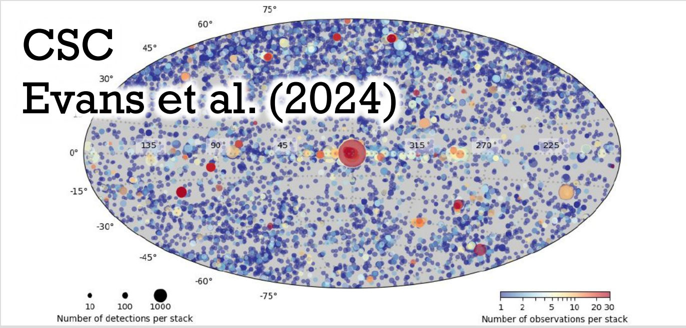
Good to build missions to last!

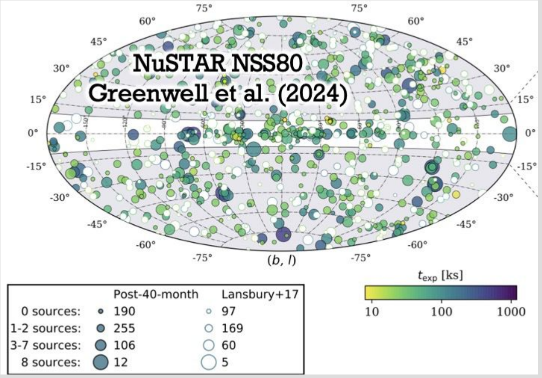
Just from these missions, hope for another great decade of X-ray surveys.

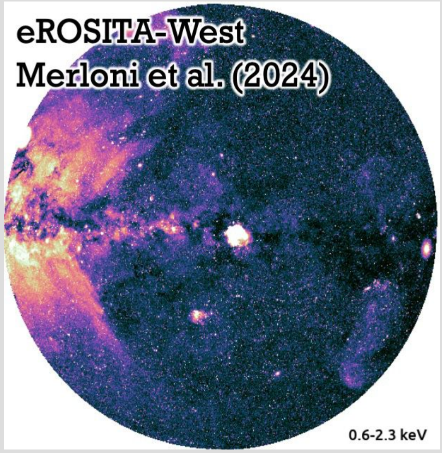
Aggressive projects needed to make big advances on the key questions.

Massive Archive Exploitation









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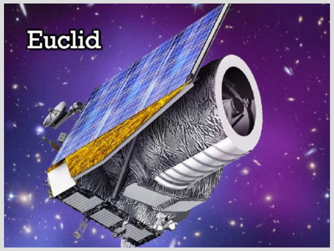
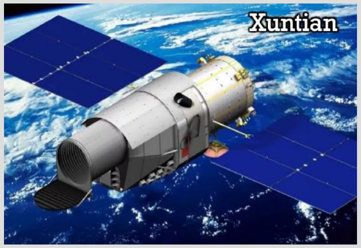
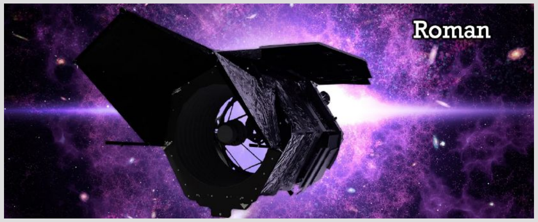
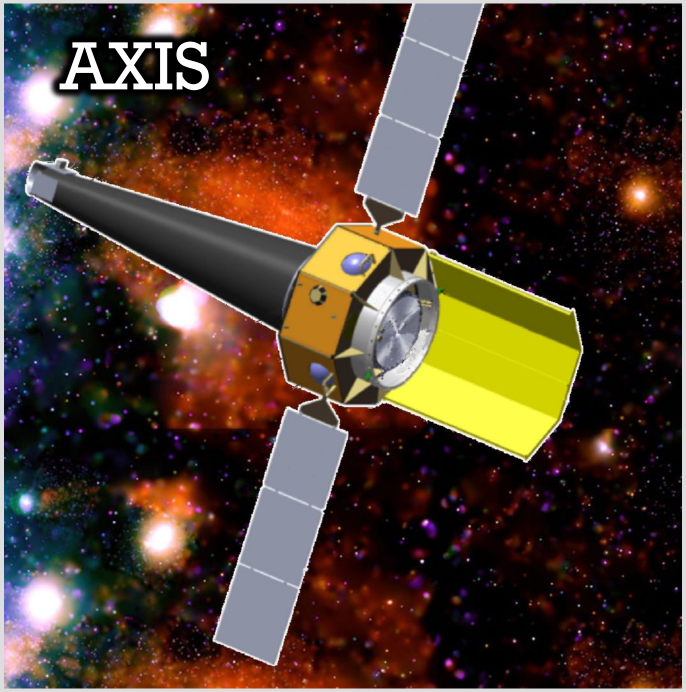


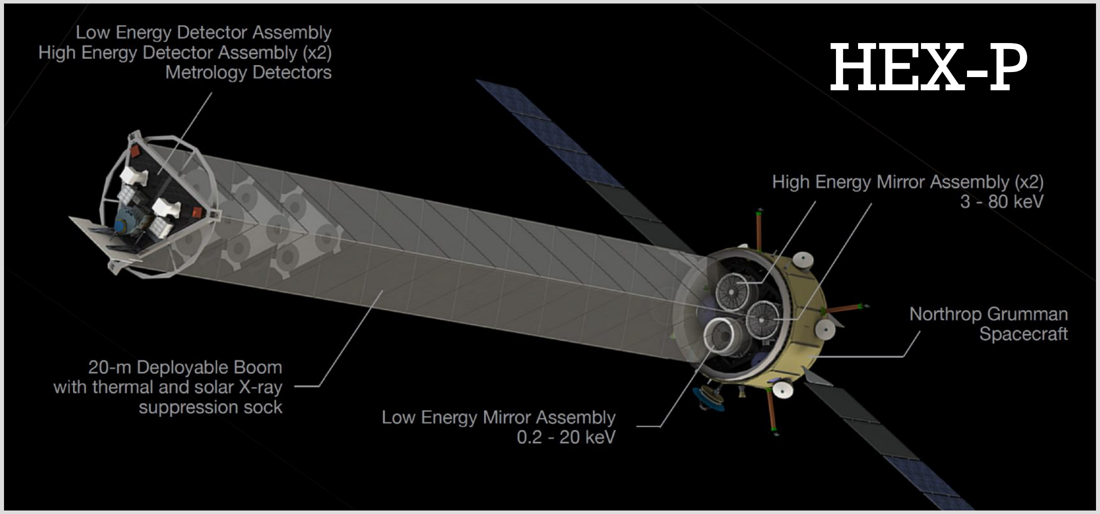


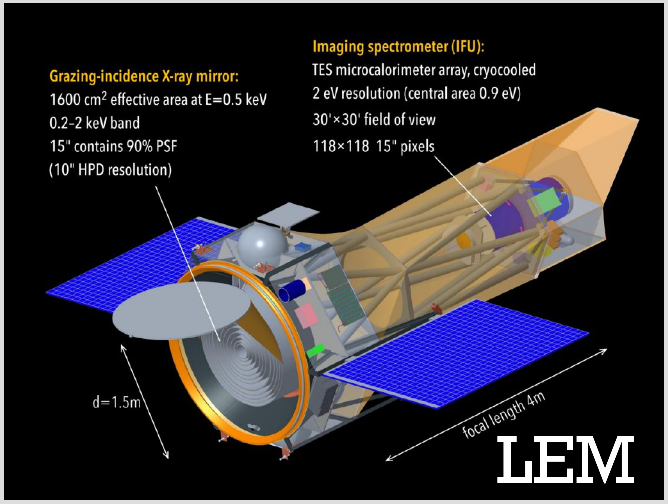


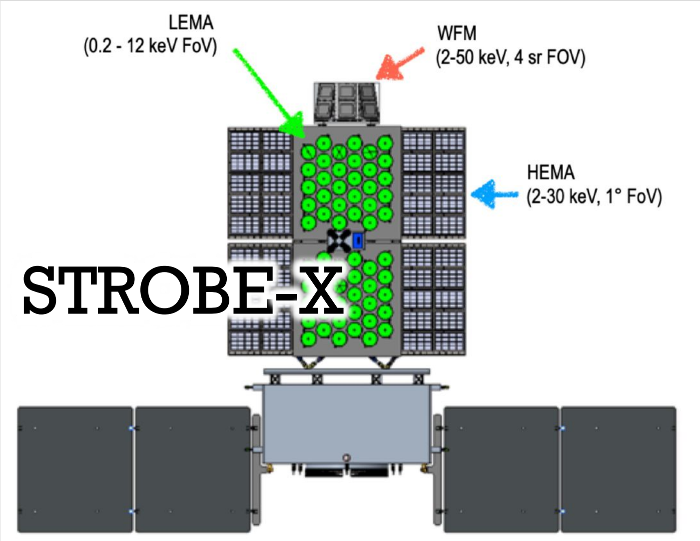
And wide-field spectrographs

Surveys with NASA X-ray Probes



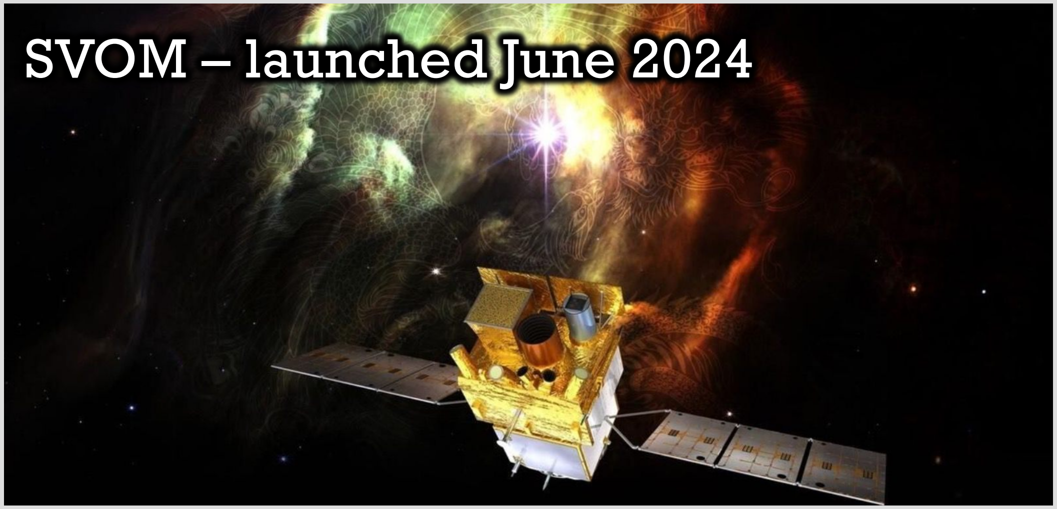


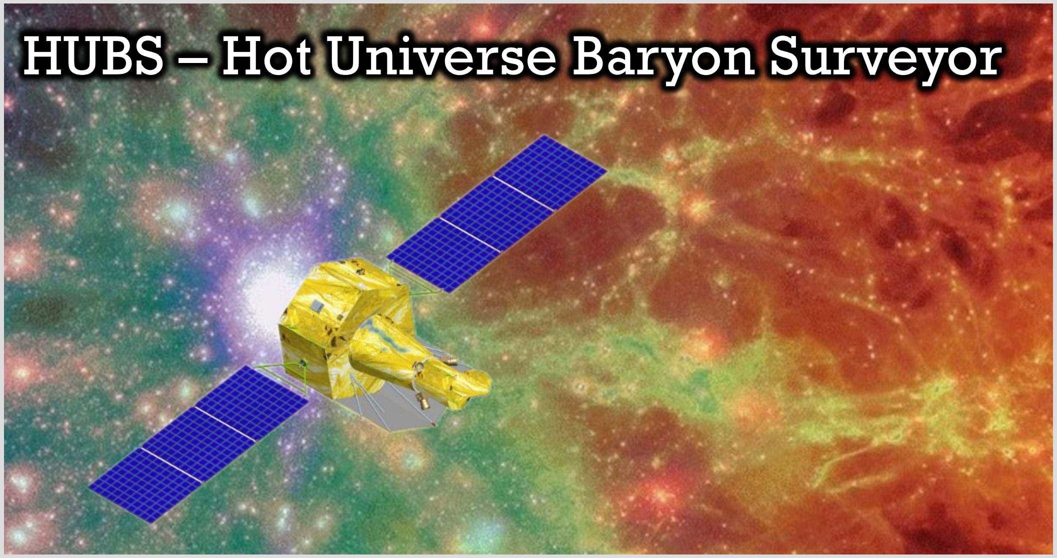




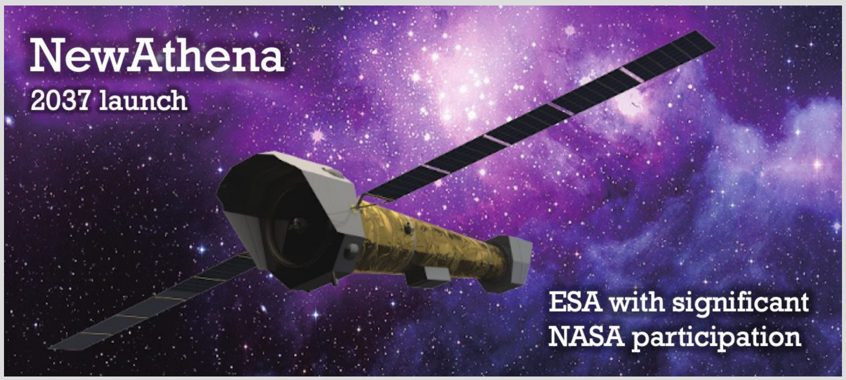
See Civano talk

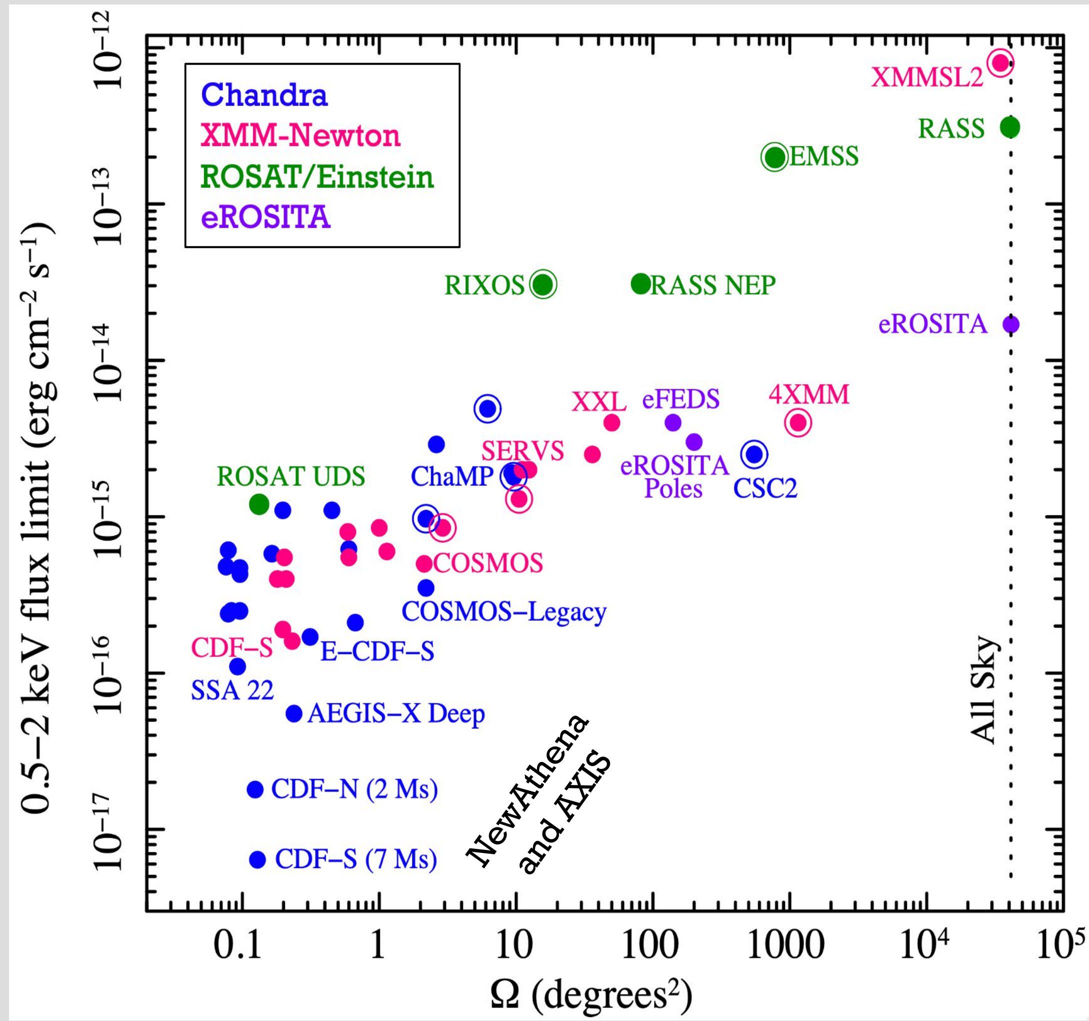
Surveys with International Missions





NewAthena Surveys



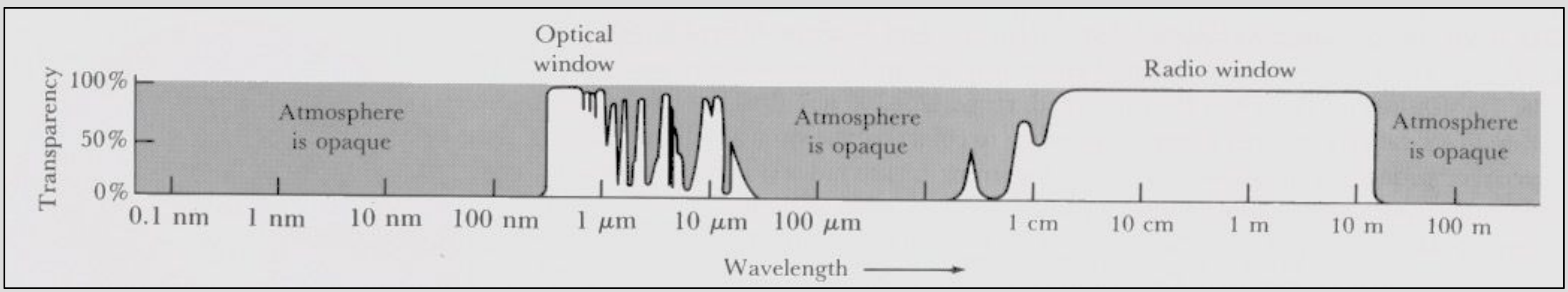


X-ray Missions Still Need Progress in Very Wide-Field Surveys

X-ray: $F_{\mathrm{eROSITA}} / F_{\mathrm{CDF\text{-}S}} \sim 2000$

Optical: $F_{\mathrm{DES}} / F_{\mathrm{HST\text{-}UDF}} \sim 100$

(with LSST ratio will be ~ 10)



Ground-based optical rapidly benefits from relentless growth of information technology (wide-field detectors, large-volume data storage and transmission). And X-ray mirrors tough!

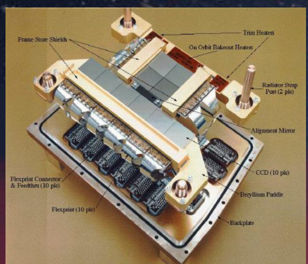

The End
NASA
NSF
PennState
Eberly College
of Science

Extra Slides

X-ray Emission from Active Galactic Nuclei

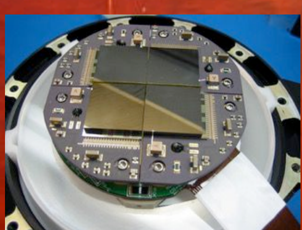
Typical AGN X-ray Spectral Energy Distribution

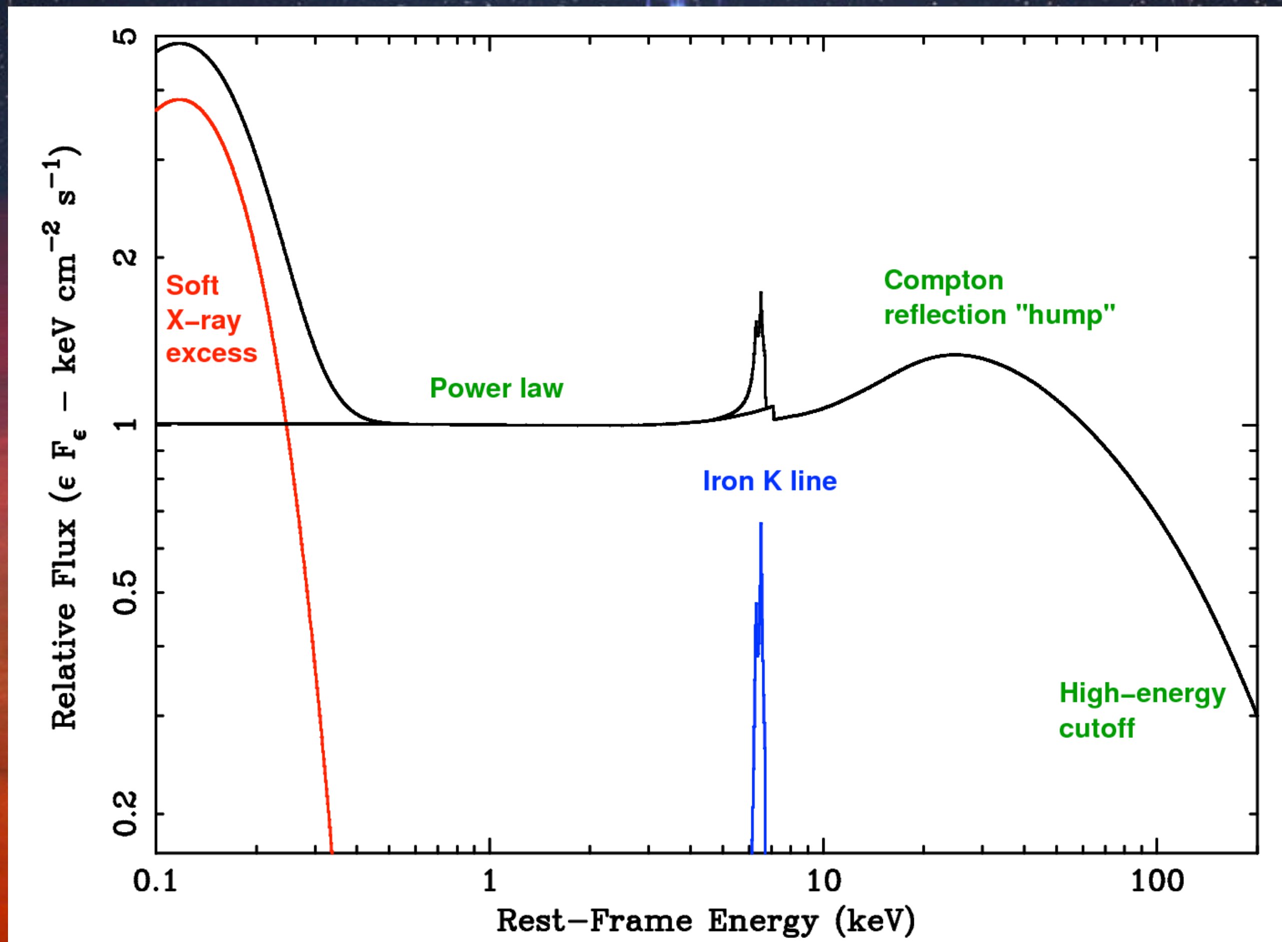
Chandra ACIS



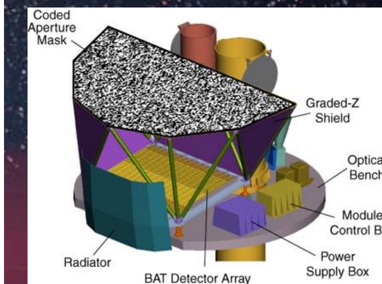
XMM-Newton EPIC

NuSTAR FPM

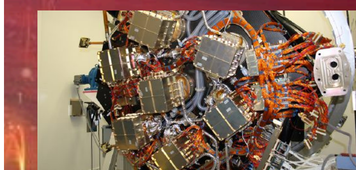




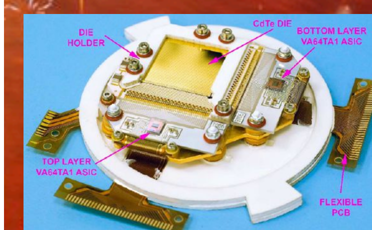
Swift BAT



SRG eROSITA



SRG ART-XC

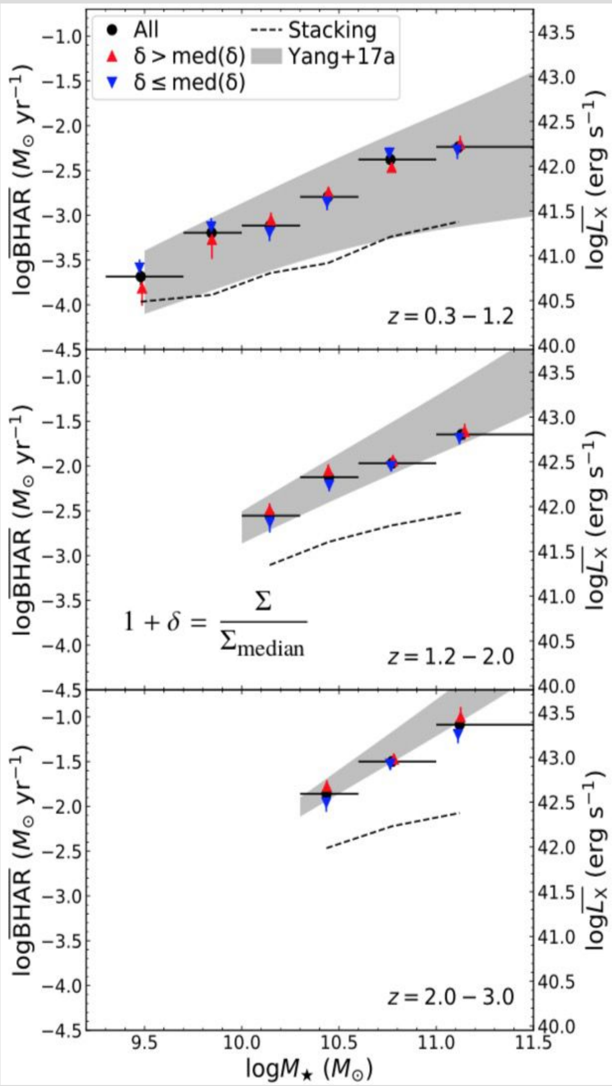


X-ray detectors provide broad-band spectra and variability for all sources.

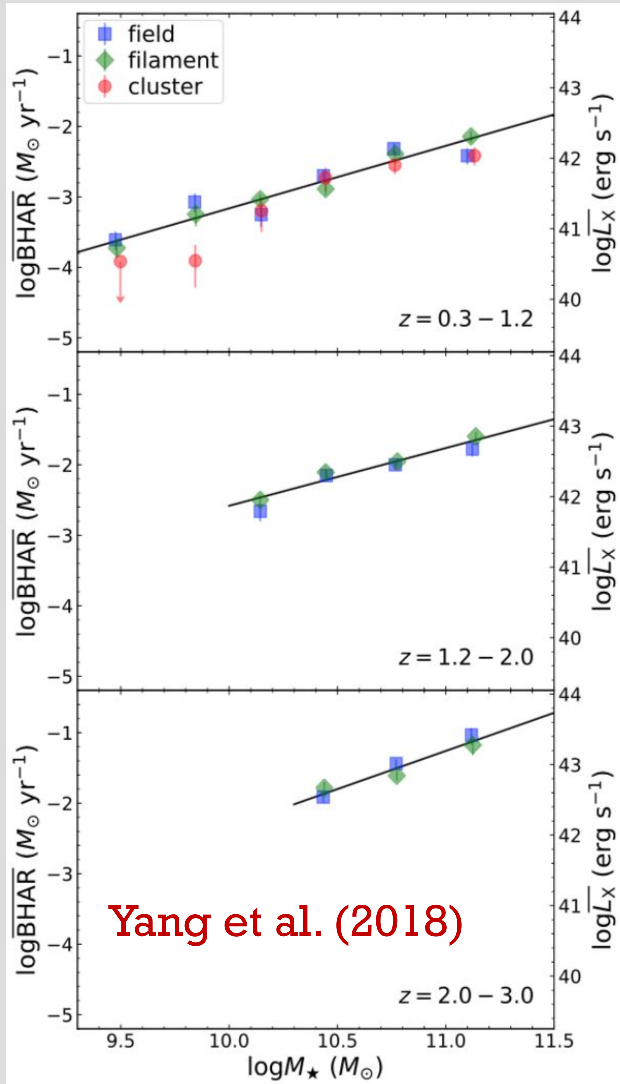
Primary survey bands: Chandra (0.5-8 keV), XMM-Newton (0.3-10 keV), NuSTAR (3-24 keV), Swift BAT (14-195 keV), INTEGRAL (17-60 keV), eROSITA (0.2-5 keV), ART-XC (4-30 keV)

Cosmic Environment

0.1-1 Mpc Scales



1-10 Mpc Scales



Using COSMOS UltraVISTA

Probe environments from field to $M_{\rm Halo} \sim 10^{14}\ M_\odot$ clusters

M_* is linked with environment

Partial-correlation testing shows M_* easily beats environment

Any environmental enhancement arises because massive galaxies tend to live in rich environments

Must push above $M_{\rm Halo} \sim 10^{14}\ M_\odot$ with LSST DDFs and MOONS – to connect to targeted protoclusters

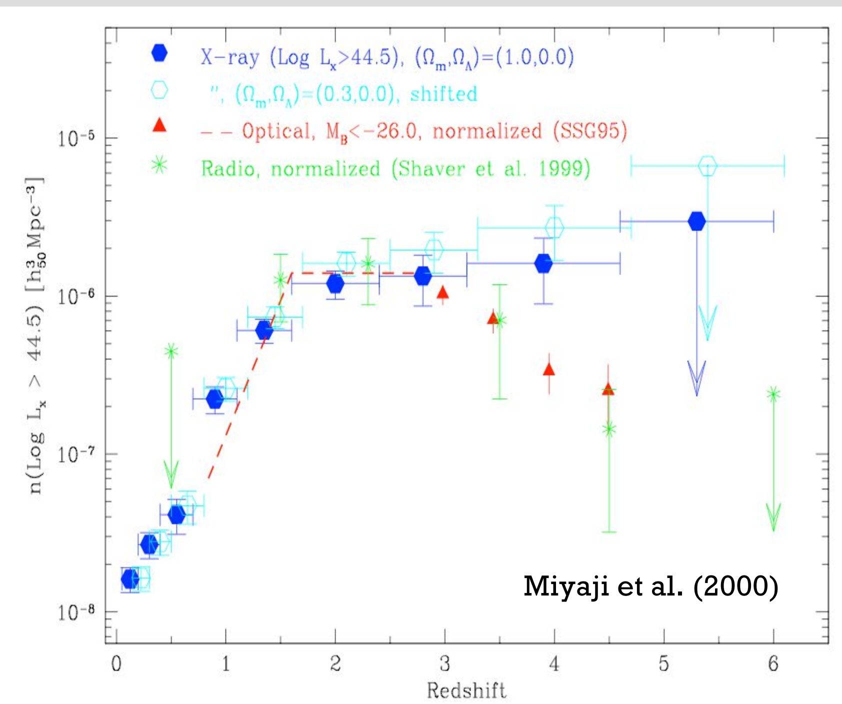
High-Redshift Demography in 1999

Constraints on high-redshift ($z > 3.5$) demography *highly* uncertain.

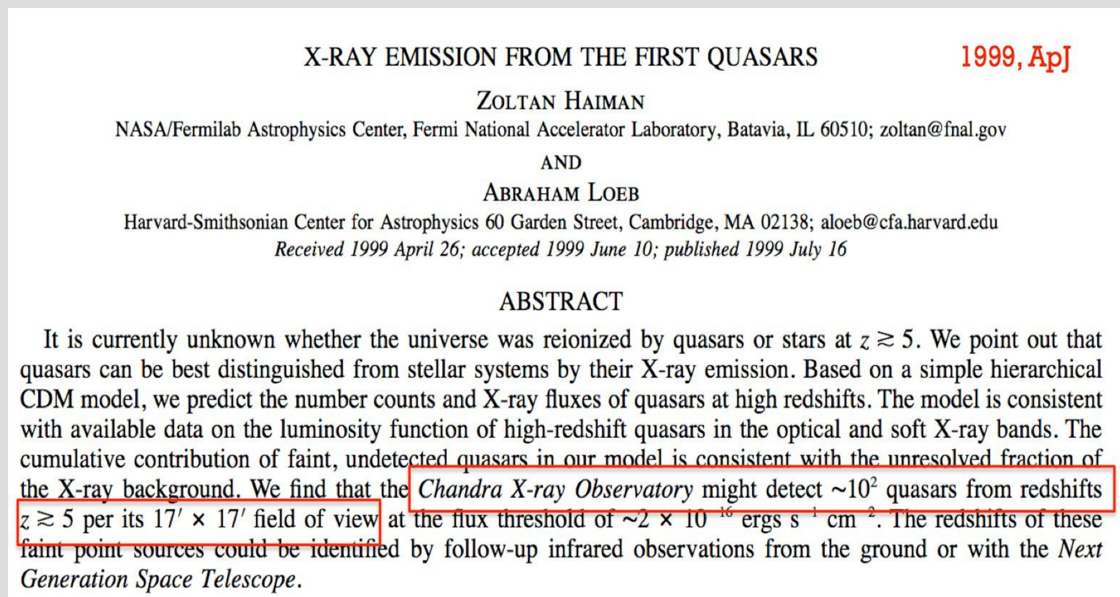
Hints of no decline in the X-ray quasar number density at high redshift.

AGNs plausibly dominated reionization.

No Decline of X-ray Quasars at High Redshift?



One prediction for Chandra…



X-RAY EMISSION FROM THE FIRST QUASARS

1999, ApJ

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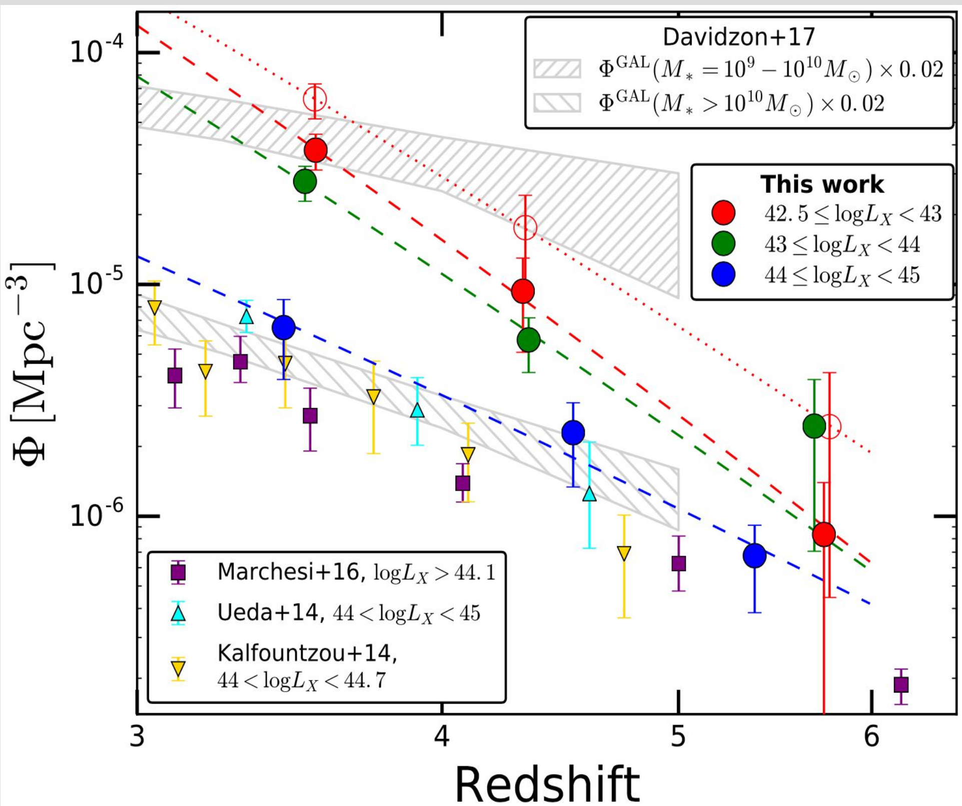
Received 1999 April 26; accepted 1999 June 10; published 1999 July 16

ABSTRACT

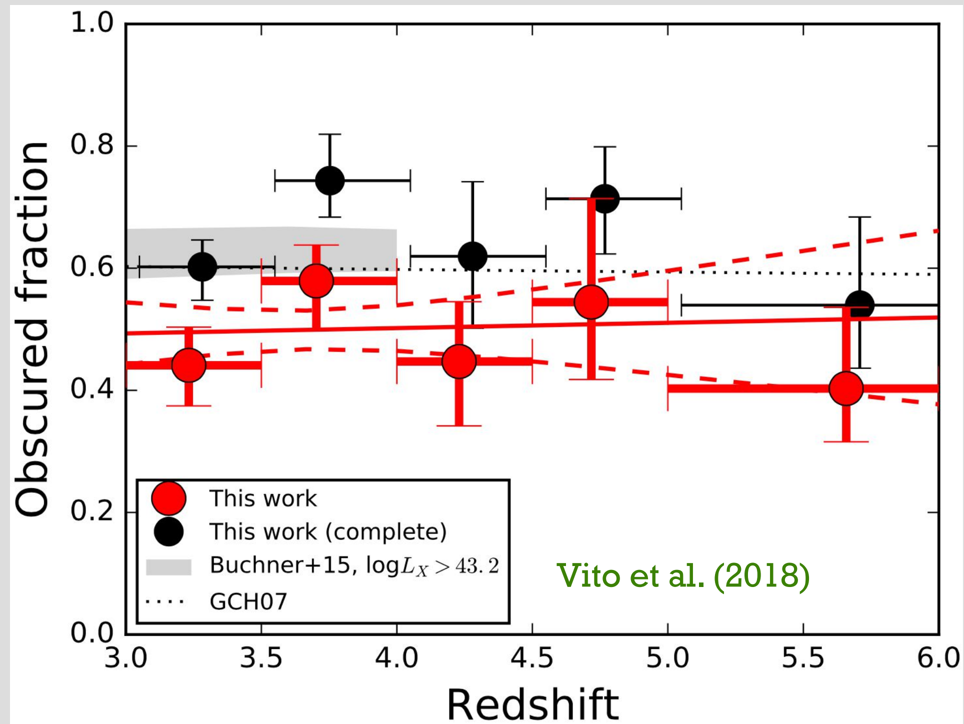
It is currently unknown whether the universe was reionized by quasars or stars at $z \gtrsim 5$. We point out that quasars can be best distinguished from stellar systems by their X-ray emission. Based on a simple hierarchical CDM model, we predict the number counts and X-ray fluxes of quasars at high redshifts. The model is consistent with available data on the luminosity function of high-redshift quasars in the optical and soft X-ray bands. The cumulative contribution of faint, undetected quasars in our model is consistent with the unresolved fraction of the X-ray background. We find that the *Chandra X-ray Observatory* might detect $\sim 10^2$ quasars from redshifts $z \gtrsim 5$ per its $17' \times 17'$ field of view at the flux threshold of $\sim 2 \times 10^{-16}$ ergs s^{-1} cm^{-2}. The redshifts of these faint point sources could be identified by follow-up infrared observations from the ground or with the *Next Generation Space Telescope*.

Space Density and Obscured Fraction at $z \sim$ 3-5 for High-to-Moderate L_X AGNs

High-Redshift Decline at Low, Moderate, and High Luminosities



High Obscured Fraction ($N_H > 10^{23}$ cm^{-2}) of Chandra Deep Fields AGNs



Decline at low-to-moderate L_X slightly steeper than at high luminosities.

High-L_X decline has similar form to decline of massive galaxies, but not moderate-L_X decline.

7 Ms Stacking - Seeds of First SMBHs

Pushing as faint as possible to constrain first SMBH seeds with Chandra.

X-ray stacking of individually undetected galaxies (100-1400 per bin) can provide average X-ray detections to z = 4.5-5.5, and useful upper limits at higher redshifts.

Signal appears to be mostly from high-mass X-ray binaries in massive galaxies.

Most high-redshift SMBH accretion occurs in short AGN phase – continuous low-rate accretion contribution appears small.

AGNs unlikely to dominate cosmic reionization, but will have secondary effects.