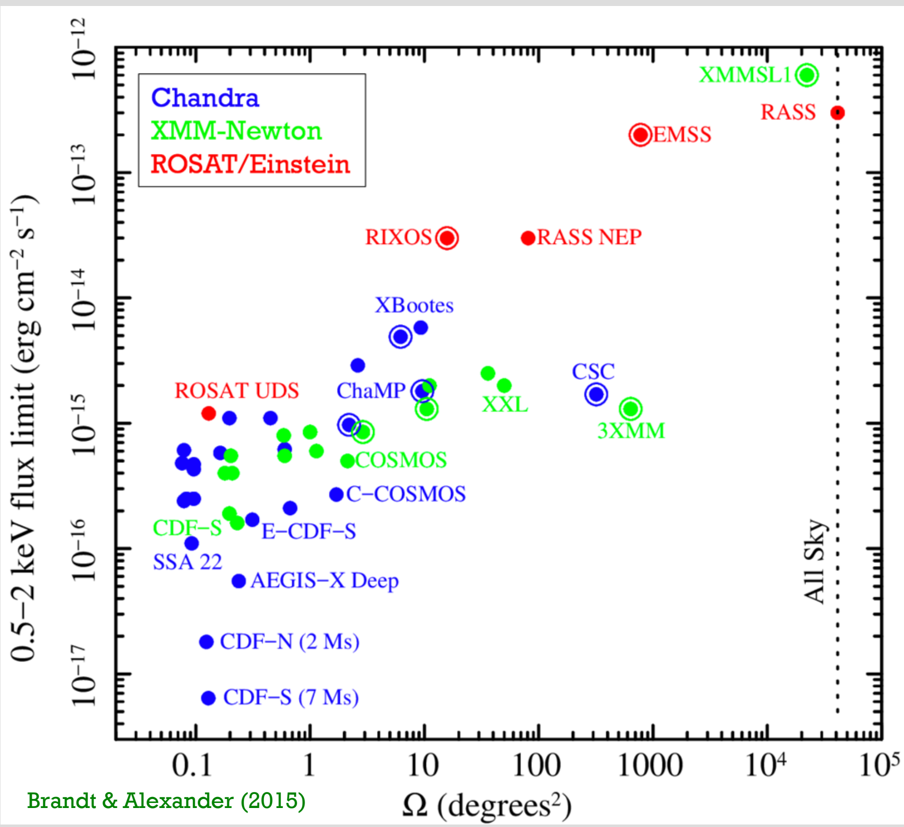
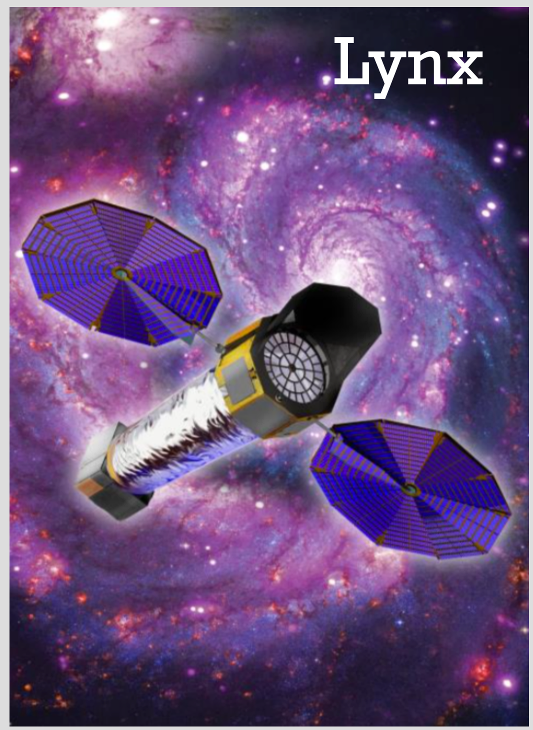
X-raying High-Redshift AGNs and the First Black Holes: From Chandra to Lynx

Niel Brandt, Fabio Vito, the Chandra Deep Fields Team, and the Lynx "First Accretion Light" Working Group

Some Relevant Results from the Deepest X-ray Surveys



Constraining SMBH Seeds with Lynx



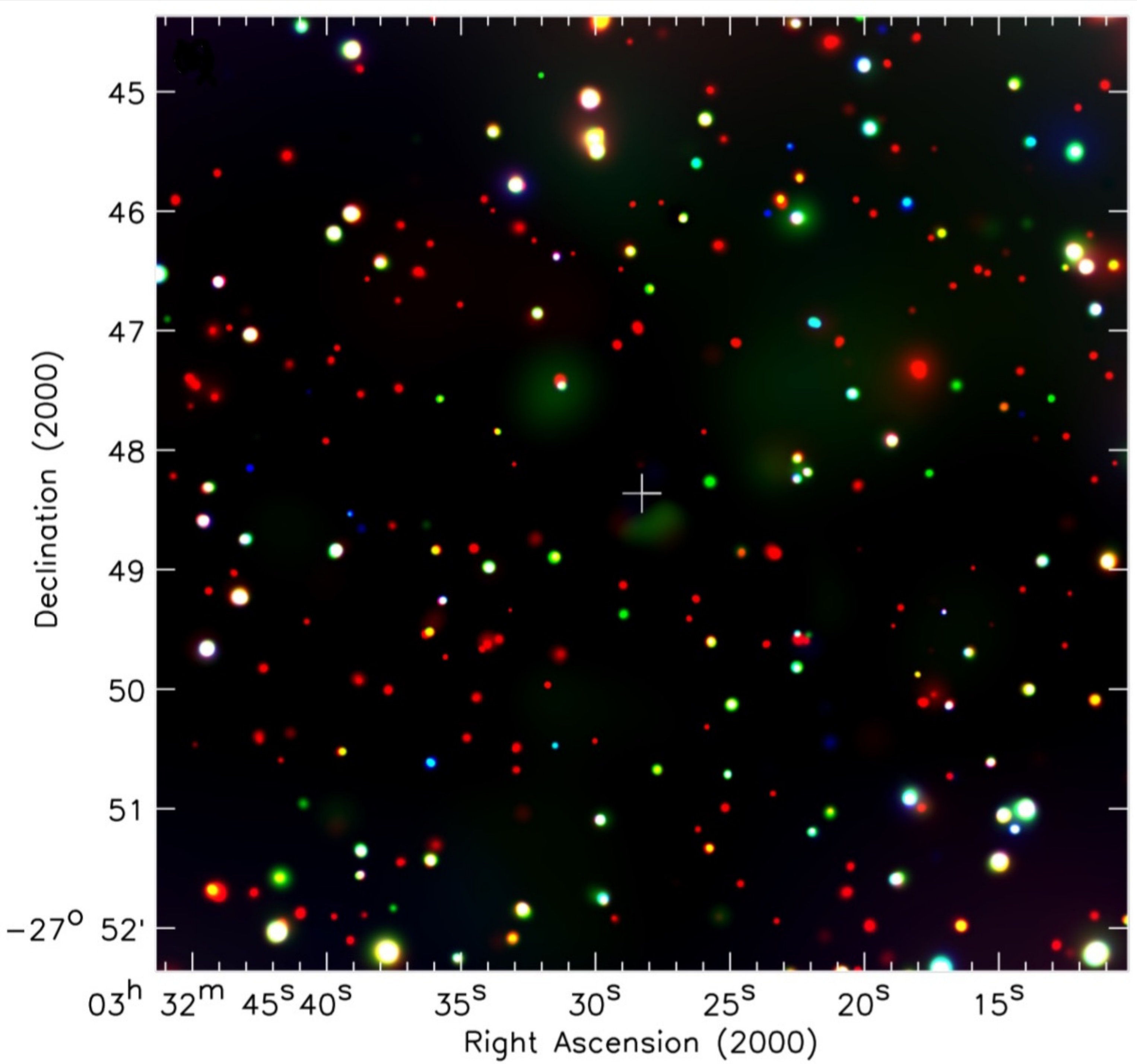
Why X-rays?

Robust and energetically significant component of the overall AGN spectral energy distribution.

Penetrating and not diluted, allowing discovery of obscured and moderate-luminosity AGNs.

Probe accretion / outflow processes in immediate vicinity of the black hole.

Center of the CDF-S



7 Ms exposure

484 arcmin^2

1055 sources

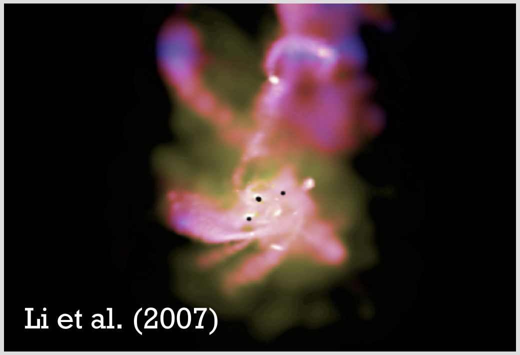
71% AGNs

Faintest sources have 1 count per 10.0 days!

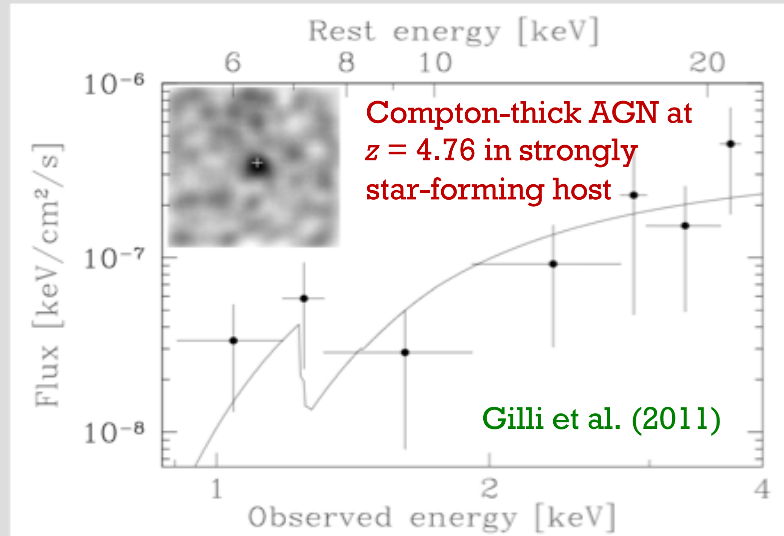
0.5-2 keV
2-4 keV
4-7 keV

Luo et al. (2017)

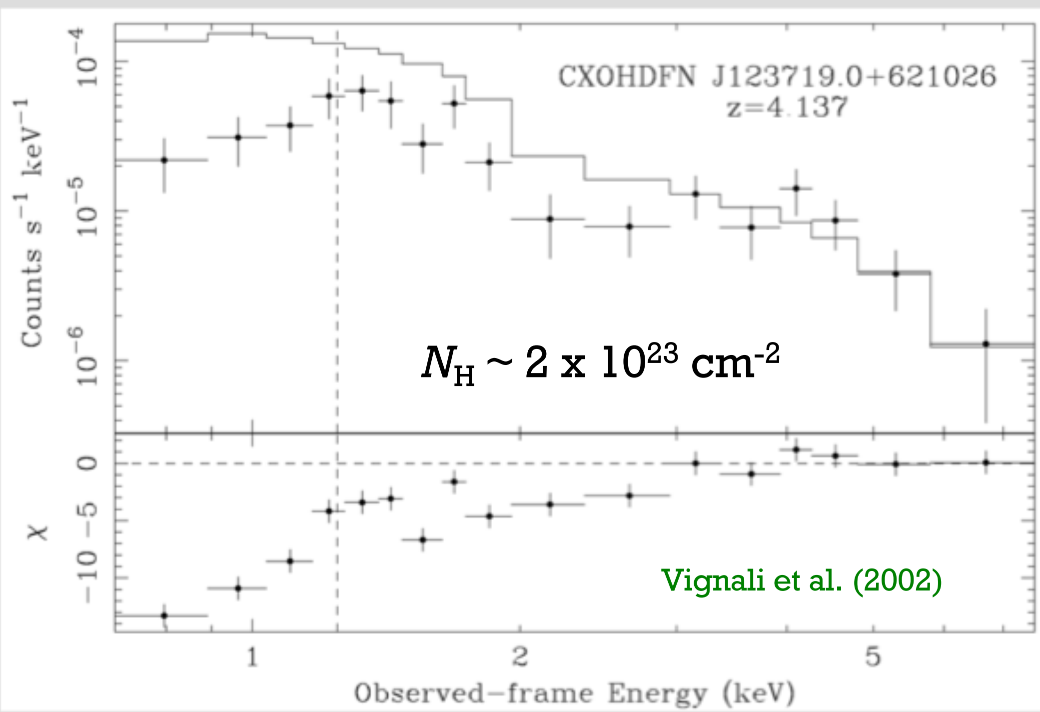
X-ray Obscured Protoquasars of Moderate Luminosity at $z \sim$ 4-5

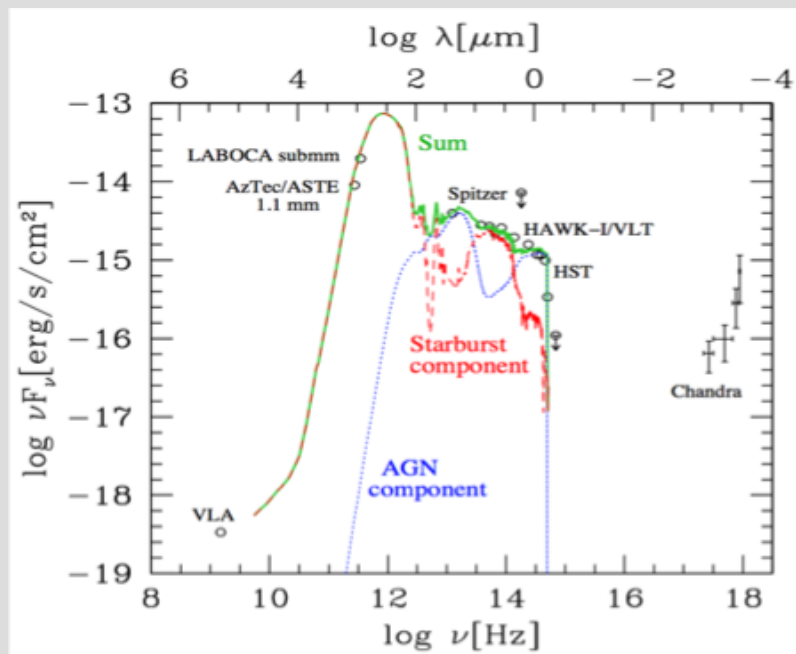


Gas density and temperature for simulated high-redshift protoquasar host



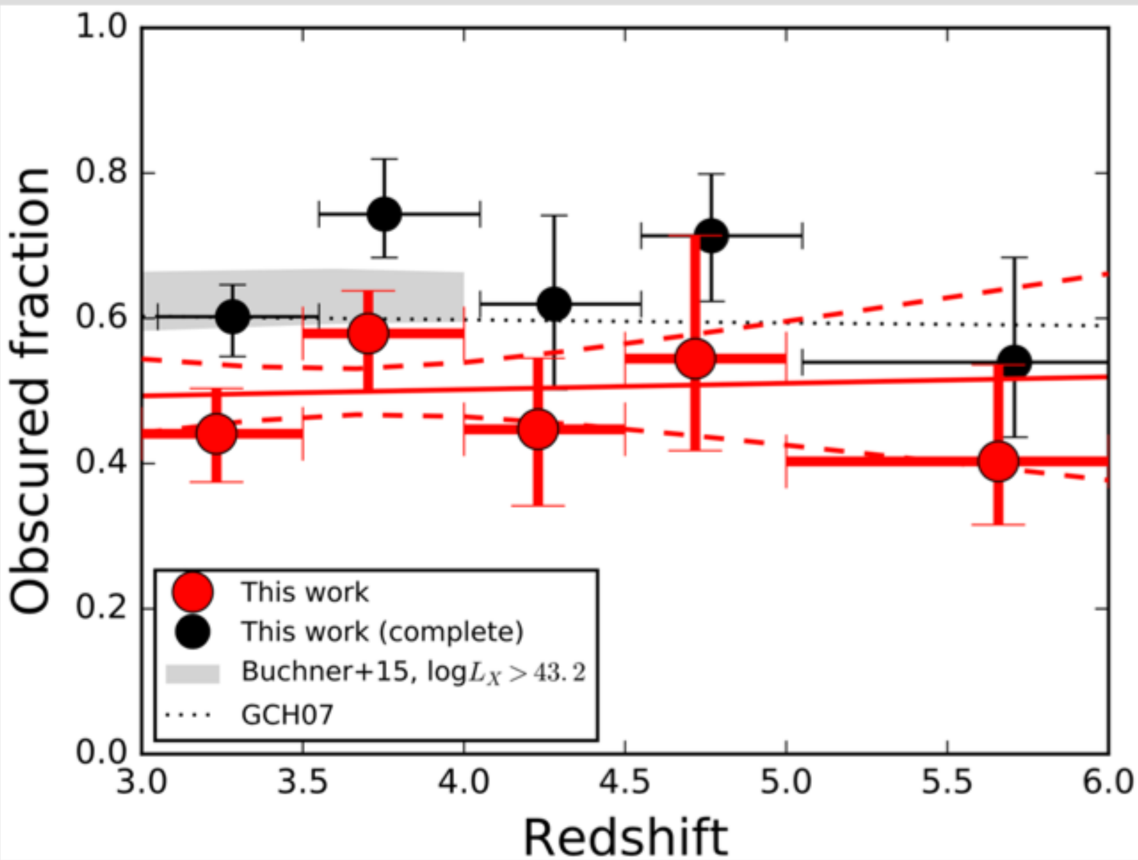
Obscured CDF-N AGN (M_B = -21.4)



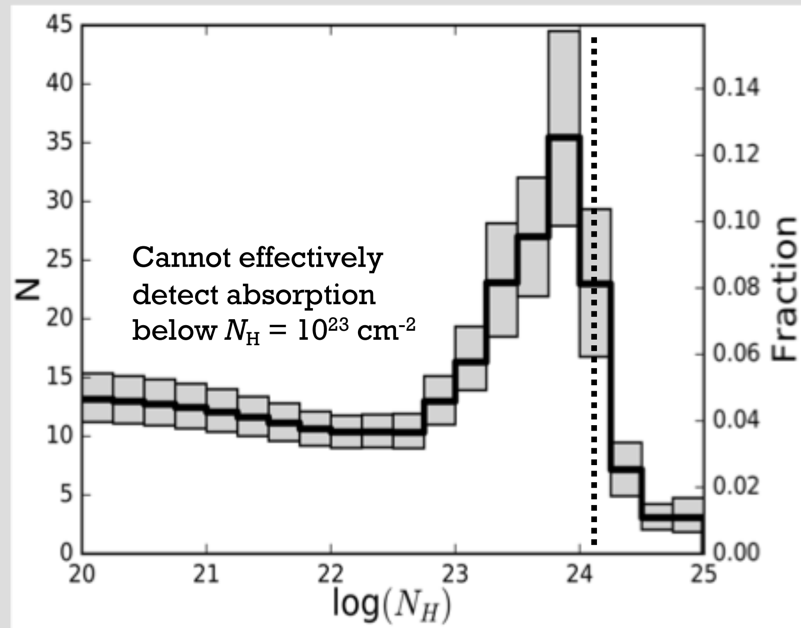


X-ray Obscured Protoquasars of Moderate Luminosity at $z \sim 4$-5

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

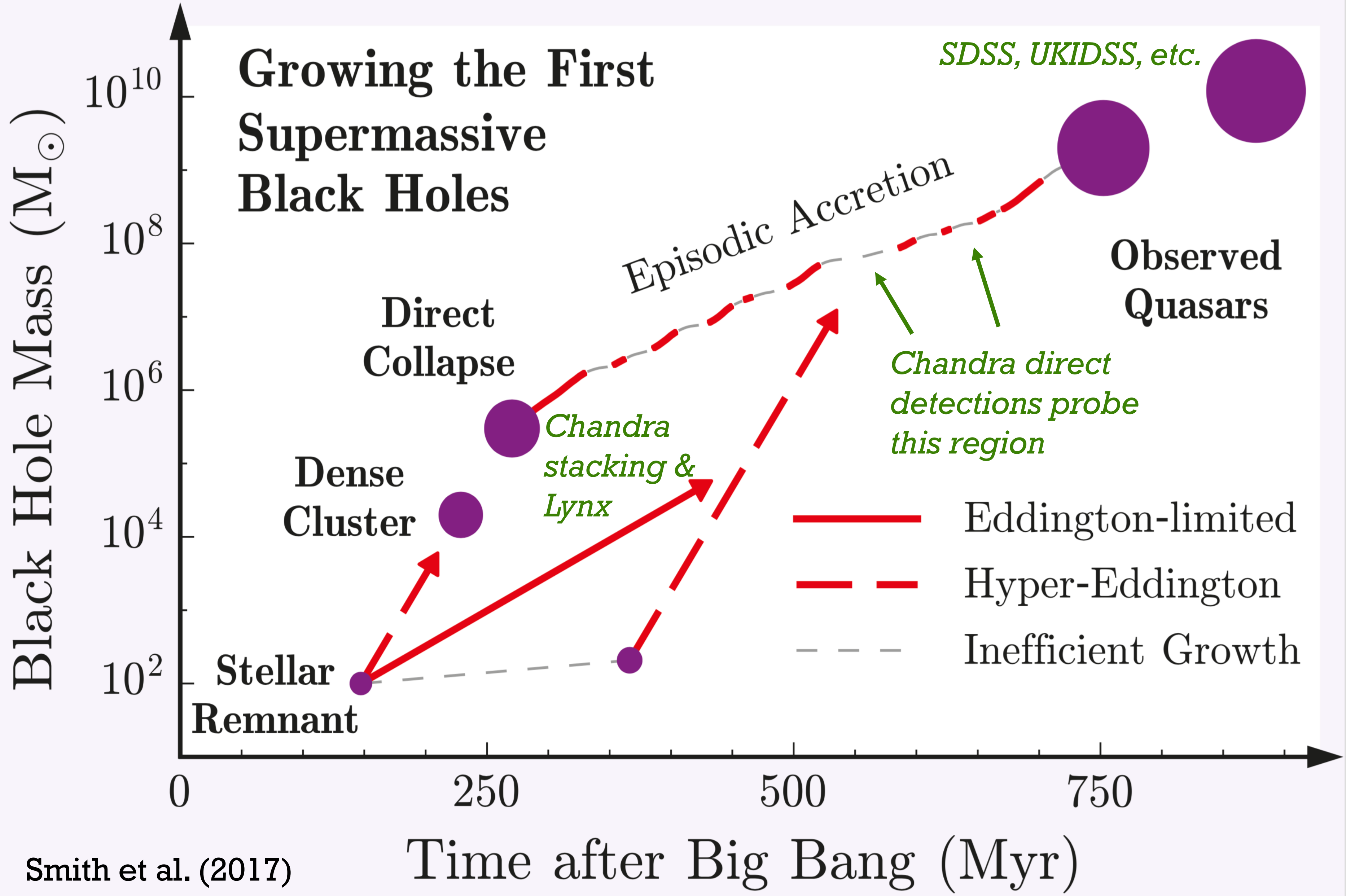


Column Density Distribution of Chandra Deep Fields AGNs



Vito et al. (2018)

Possible Seeds of First SMBHs

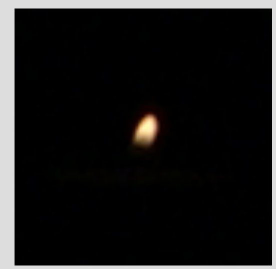


Smith et al. (2017)

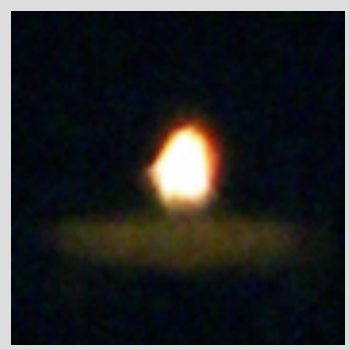
Stacking: A Romantic Example

3 / 100 second exposure

1 / 1000 second exposure



Stacked image →



30 candles with 1/1000 sec exposure = 3/100 sec

Seeds of First SMBHs – 7 Ms Stacking

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

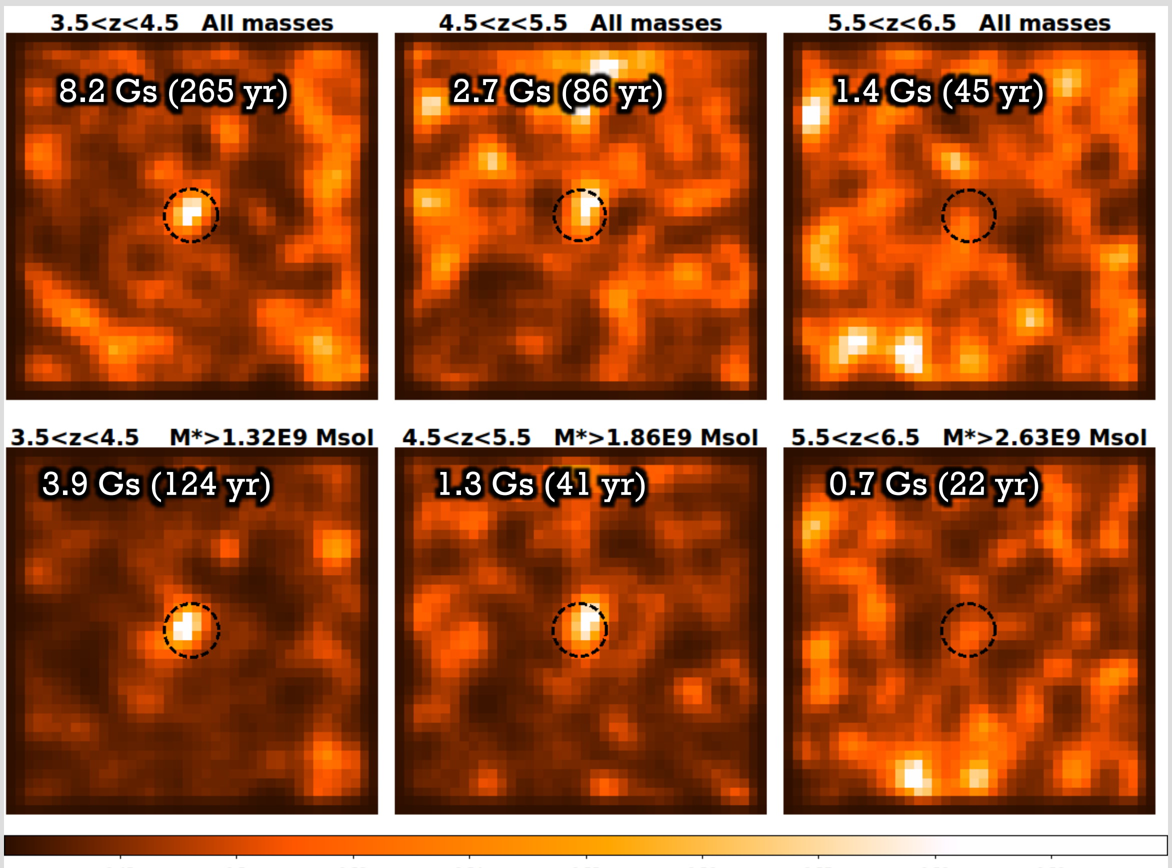
X-ray stacking of individually undetected galaxies (100-1400 per bin) can provide average X-ray detections to z = 4.5-5.5, and useful upper limits at higher redshifts.

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.

All Galaxies in Sample

Most Massive Half of Sample



Note the Gigasecond stacked exposures!

Vito et al. (2016)

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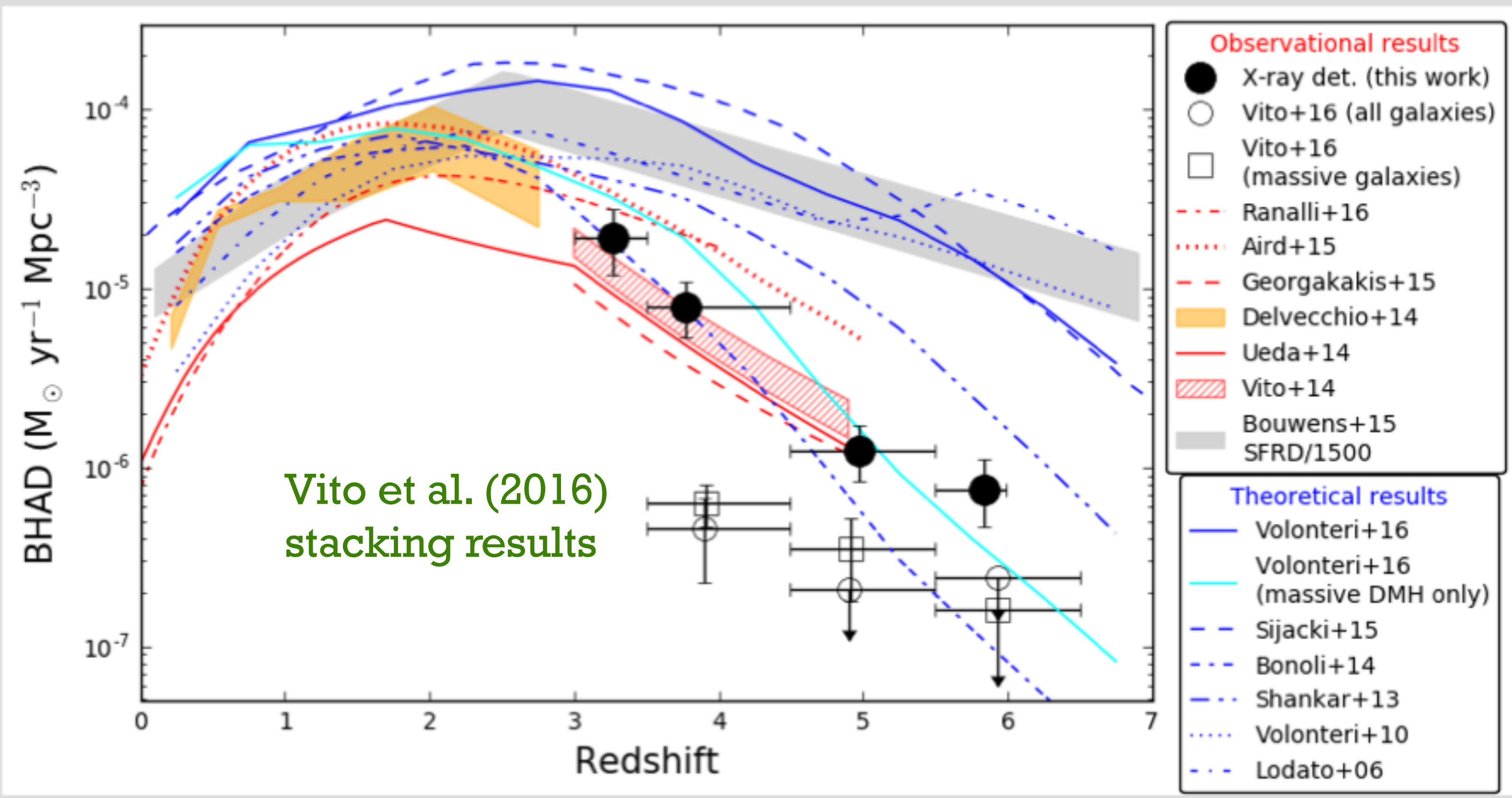
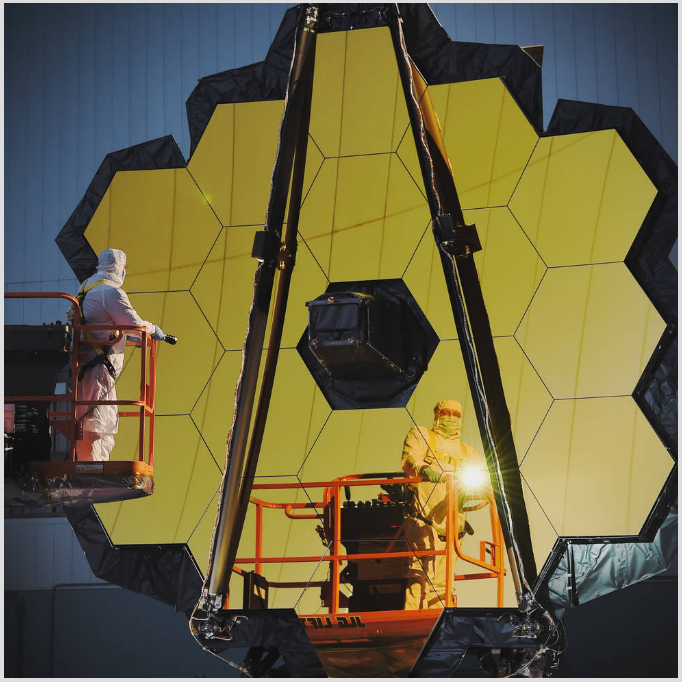


Pushing to the Highest Redshifts with Stacking

Stacking of Lyman Break Galaxy Samples with 7 Ms CDF-S

Vito et al. (2016)

z	N	$\langle H \rangle$ mag	Exp. (10^9 s)	CR^{w}_{TOT} (10^{-5}cts s^{-1})	$F^{w,obs,TOT}_{0.5-2keV}$ (10^{-16}erg cm^{-2} s^{-1})	SNR_{boot} σ
(1)	(2)	(3)	(4)	(5)	(6)	(7)
∼4	2444	26.4	14.33	11.30 ± 5.12	7.06 ± 3.20	2.26
∼5	673	26.7	3.95	< 2.63	< 1.64	0.48
∼6	259	26.8	1.52	< 1.58	< 0.99	−1.89
∼7	107	27.1	0.62	< 1.03	< 0.64	0.60
∼8	36	27.1	0.21	< 0.32	< 0.20	−1.65



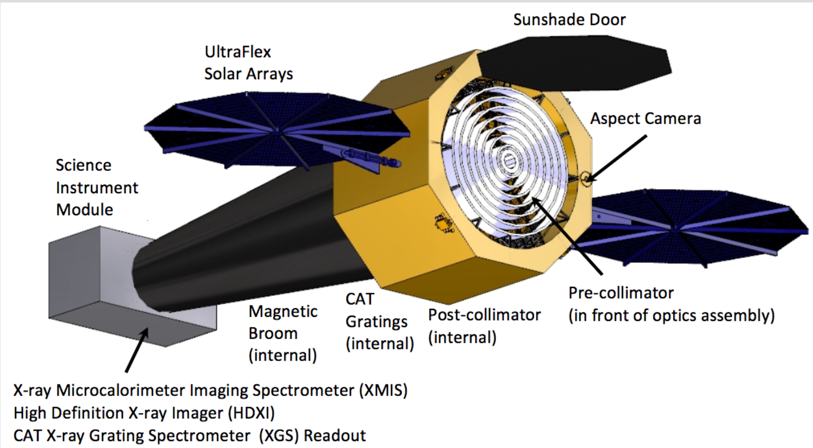
JWST will provide large samples at higher redshifts, better redshift identifications, and better removal of low-redshift interlopers.

Aim to push Chandra stacking analyses to $z \sim$ 10-15 with the samples of high-redshift galaxies from JWST in the 7 Ms CDF-S (and other fields).

Also could stack 21-cm selected regions, or perform cross-correlation analyses.

Lynx X-ray Surveyor - Parameters

High-Energy Flagship Mission Concept Under Study by NASA for 2020 Decadal Survey



Chandra-like angular resolution

30-50 x effective area of Chandra

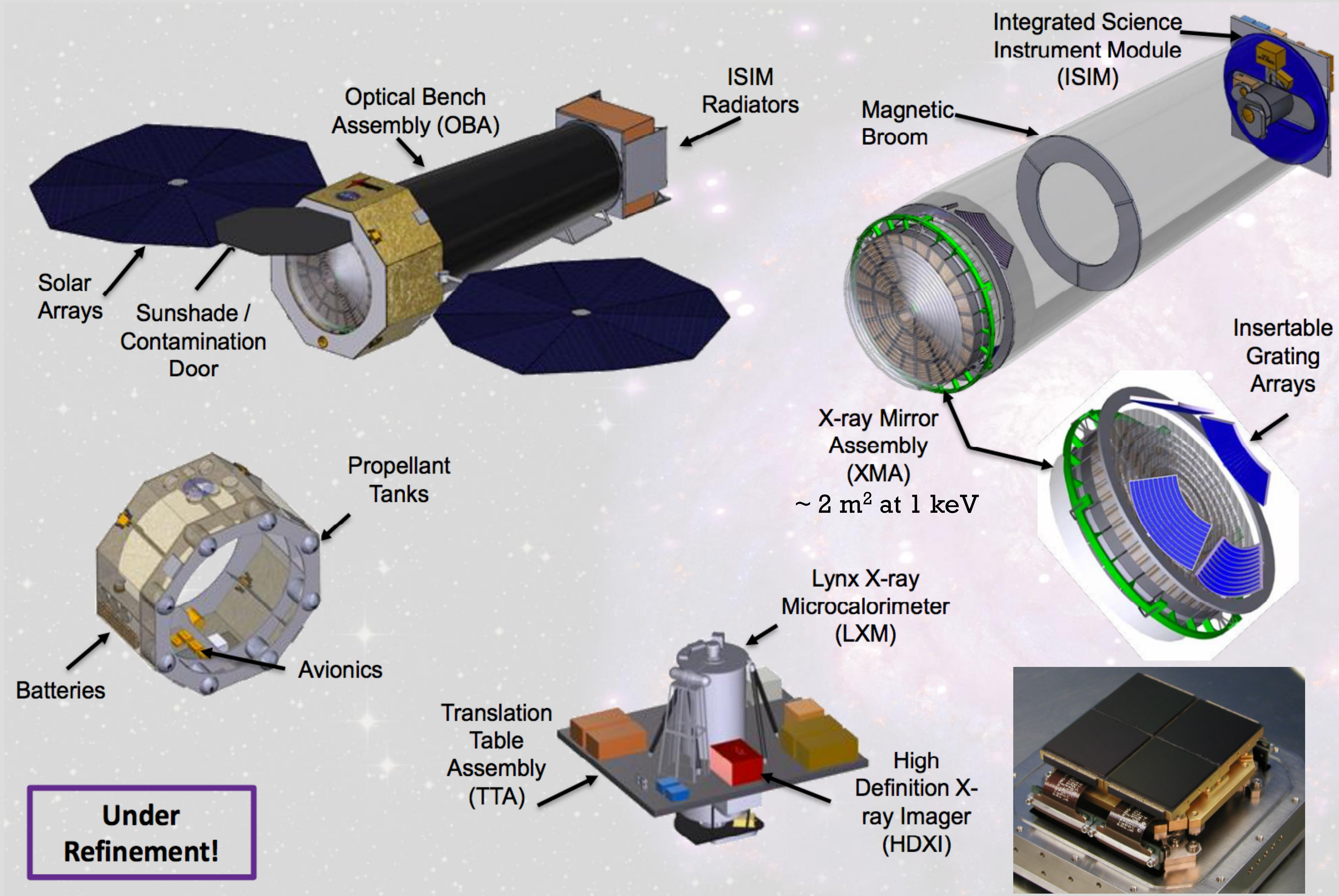
For HPD < 1", 16 x FOV of Chandra

40 x sensitivity of Chandra

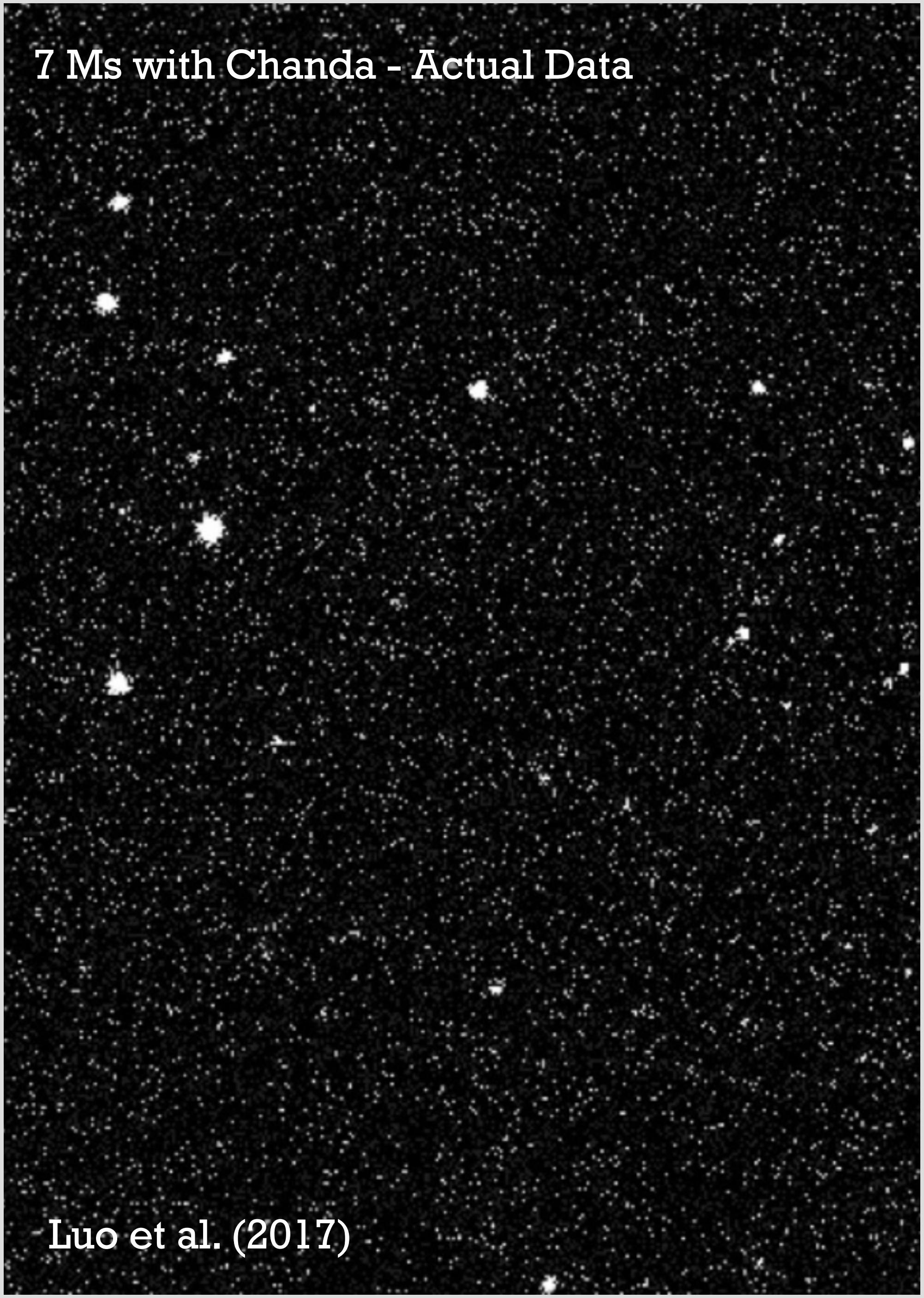
	Chandra	X-Ray Surveyor
Relative effective area (0.5 – 2 keV)	1 (HRMA + ACIS)	50
Angular resolution (50% power diam.)	0.5"	0.5"
4 Ms point source sensitivity (erg/s/cm^2)	5×10^{-18}	3×10^{-19}
Field of View with < 1" HPD (arcmin^2)	20	315
Spectral resolving power, R, for point sources	1000 (1 keV) 160 (6 keV)	5000 (0.2-1.2 keV) 1200 (6 keV)
Spatial scale for R>1000 of extended sources	N/A	1"
Wide FOV Imaging	16' x 16' (ACIS) 30' x 30' (HRC)	22' x 22'

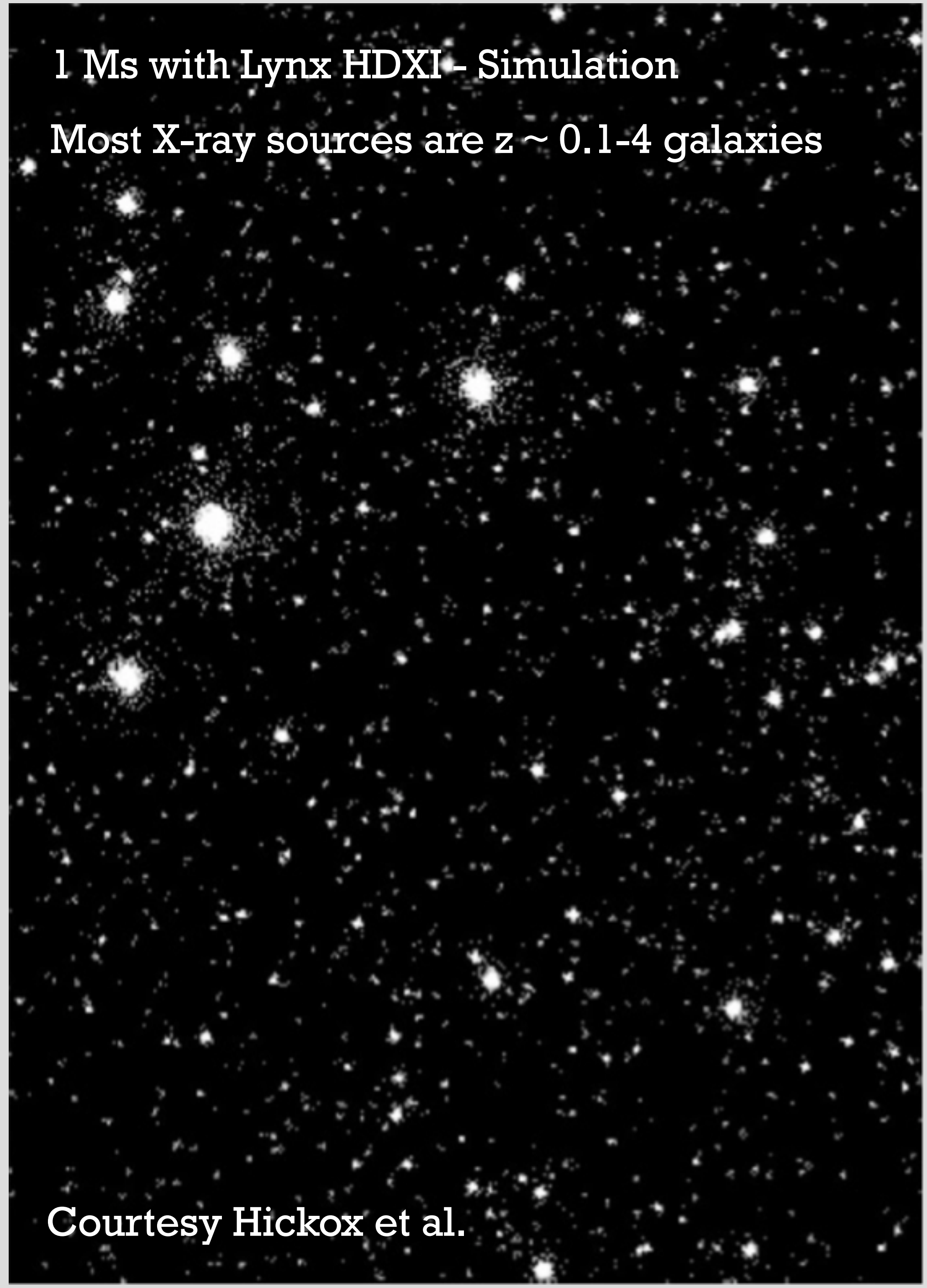
	3x10
Detection threshold @ 4Msec (0.5-2 keV) (for known locations)	→ 3.0×10^{-19} erg/s/cm^2 (1.1×10^{-19})
2–10 keV luminosity at z=10 assuming Γ=1.7	3.7×10^{41} erg/s (1.35×10^{41})
Bolometric luminosity at z=10, assuming 10% correction	3.7×10^{42} erg/s (1.35×10^{42})
Black Hole Mass assuming Eddington rate	→ 29,000 Msun (11,000 Msun)
For X-rays from star forming galaxies, assuming x10 higher Lx/SFR ratio at z=10 relative to local normalization	SFR=7.4 Msun/yr (2.7 Msun/yr)

Lynx X-ray Surveyor - Schematic



Chandra Deep Field-South



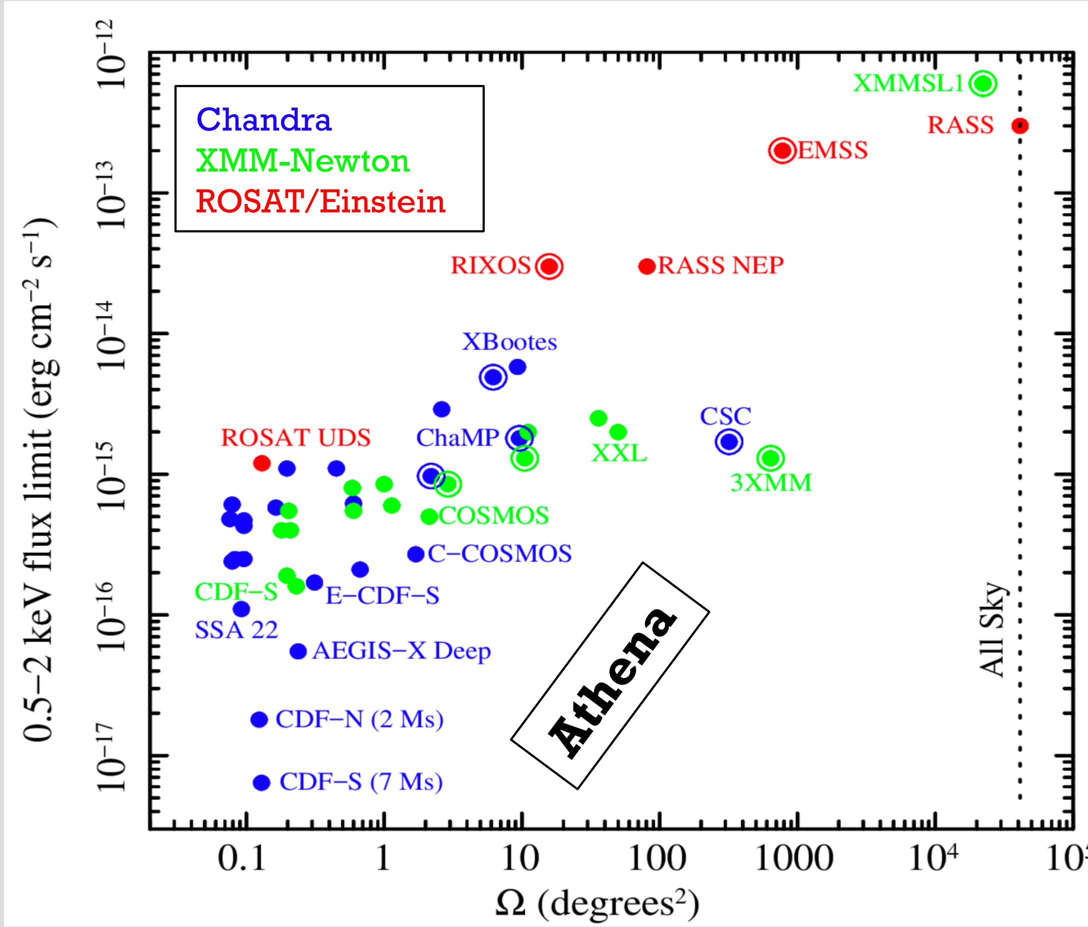


Relevance of Athena

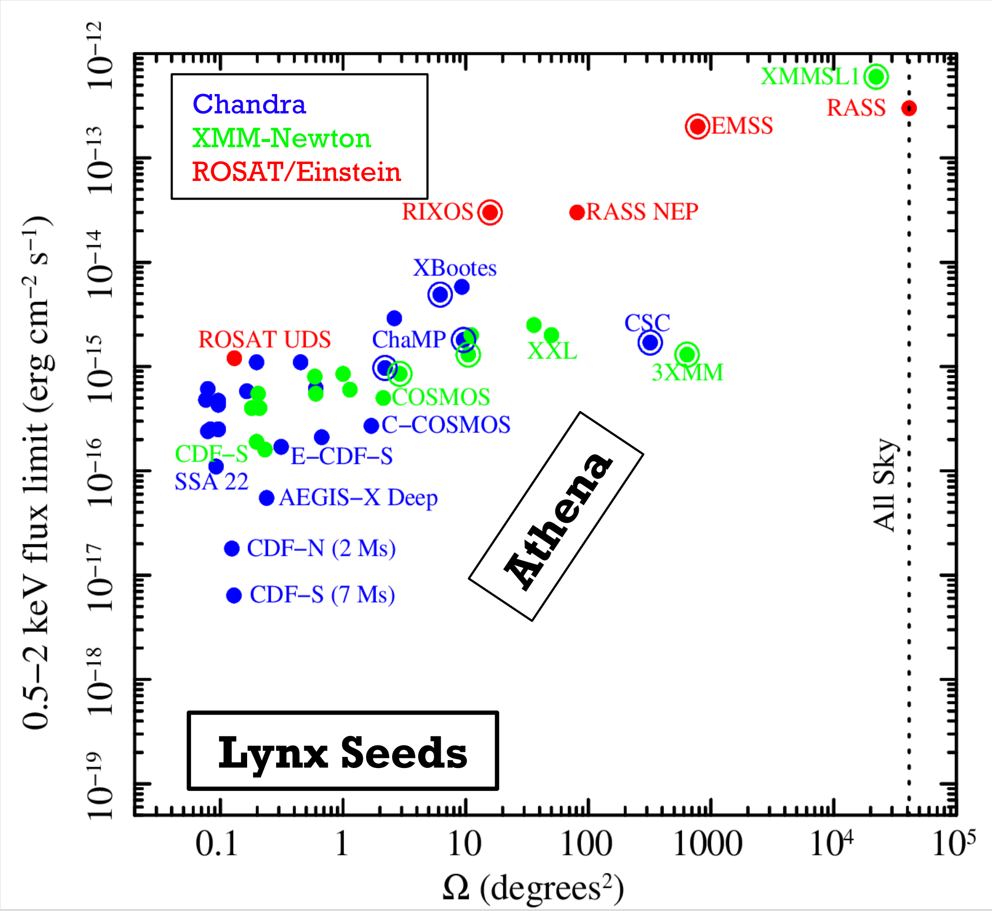
Athena will do a great job at generating many fields almost as deep as the Chandra Deep Fields.

But, mainly due its limited PSF, it *cannot* reach the very low X-ray fluxes needed to study the seeds of the first SMBH.

Hits source confusion at X-ray fluxes ~ 100 times higher than those of the seeds.



Lynx Survey of SMBH Seeds



Details given in Brandt, Haiman, & Vito report on behalf of the Lynx "First Accretion Light" working group.

A Lynx survey of 1 deg^2 to 0.5-2 keV fluxes of 1.1 x 10^{-19} cgs can plausibly detect ~ 1000 SMBH seeds at z ~ 8-10 to ~ 3 x 10^4 $M_\odot$.

Sampling hard 5-20 keV rest-frame X-rays to overcome obscuration effects.

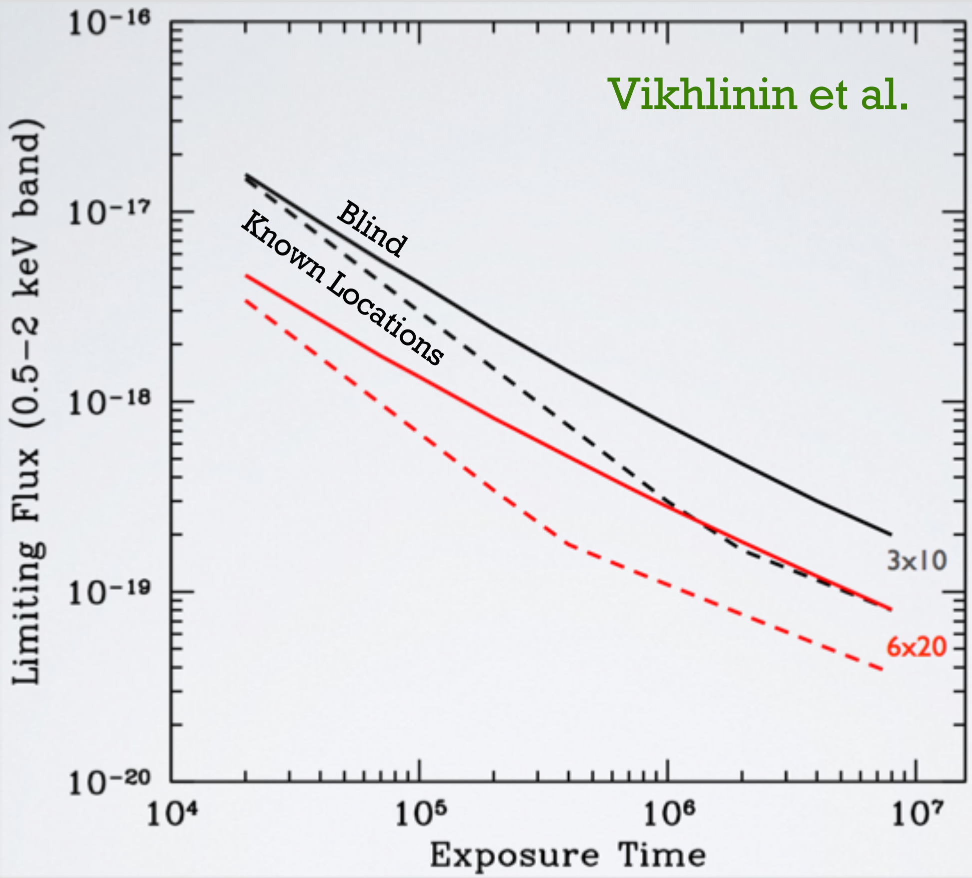
Precise yield is uncertain by factors of at least several (e.g., Volonteri, Habouzit, et al.).

Need ~ 1000 such seeds to derive an X-ray luminosity function (XLF) for them.

Survey needs 8.2 Lynx fields of ~ 4 Ms each.

Even if instrumentation allowed, difficult to push deeper owing to expected confusion with X-ray binary populations.

Lynx Survey of SMBH Seeds



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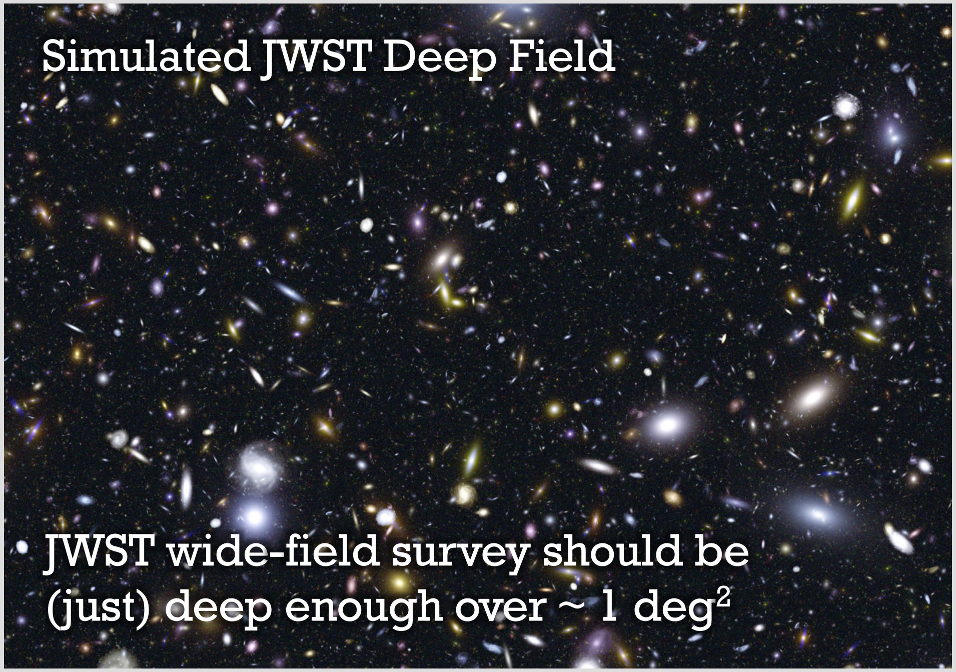
Sites for the Lynx Survey

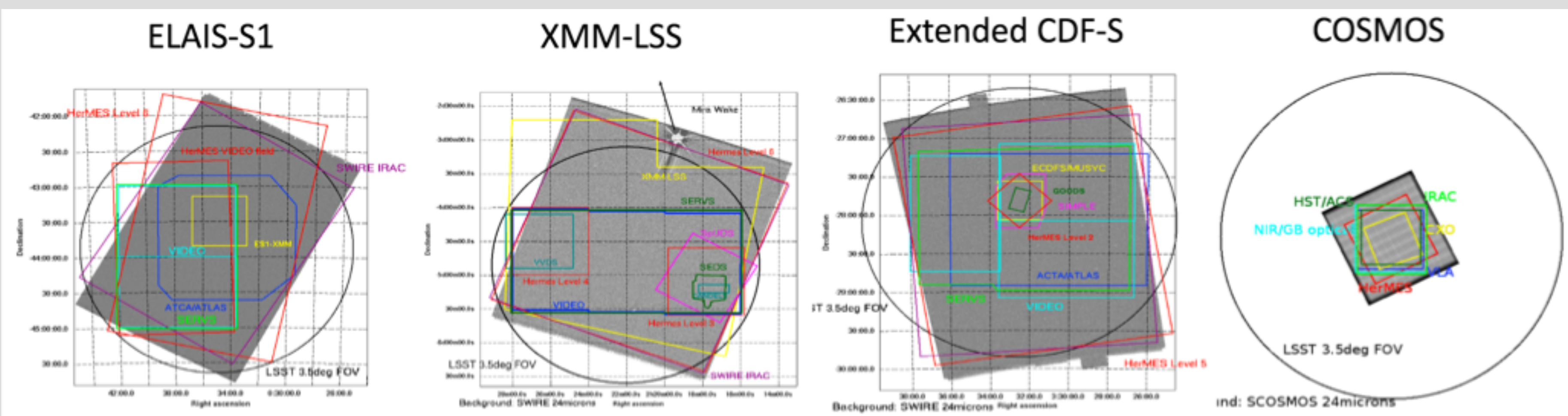


This survey must be sited in regions with ultradeep MIR/NIR/optical data from JWST, WFIRST, LSST, GSMTs, 21 cm, etc.

Needed to
- Aid the X-ray source searching
- Identify $z \sim 7$-15 counterparts reliably
- Measure host stellar masses

Likely would target 3-5 fields to minimize cosmic variance effects.

Some Good Potential Sites: The Central LSST Deep Drilling Fields



XLF for Light Seeds and Heavy Seeds

The behavior of the high-redshift X-ray luminosity function (XLF) at the very faint end will be key for insights into seed-growth models:

Light Seeds:

Growth should lead to a large number of faint high-redshift AGN fueled by accretion onto low-mass BH – steep XLF.

Heavy Seeds:

AGNs can more easily reach luminosities close to L_*, producing a flatter faint end of XLF.

But seed mass, Eddington-ratio distribution, and occupation fraction can be traded-off against each other to give similar XLFs (e.g., Volonteri et al. 2017).

Using XLF + Hosts to Study Seeds

The Lynx XLF alone cannot not determine seed masses - utilize additional information such as their host stellar masses.

Light seeds:

The ~ 3 x 10^4 $M_\odot$ black hole was assembled from many stellar-mass black holes, and a larger stellar cluster (M_* ~ 2 x 10^7 $M_\odot$) is needed to make them (cf. gas blow out, black-hole ejections, etc.).

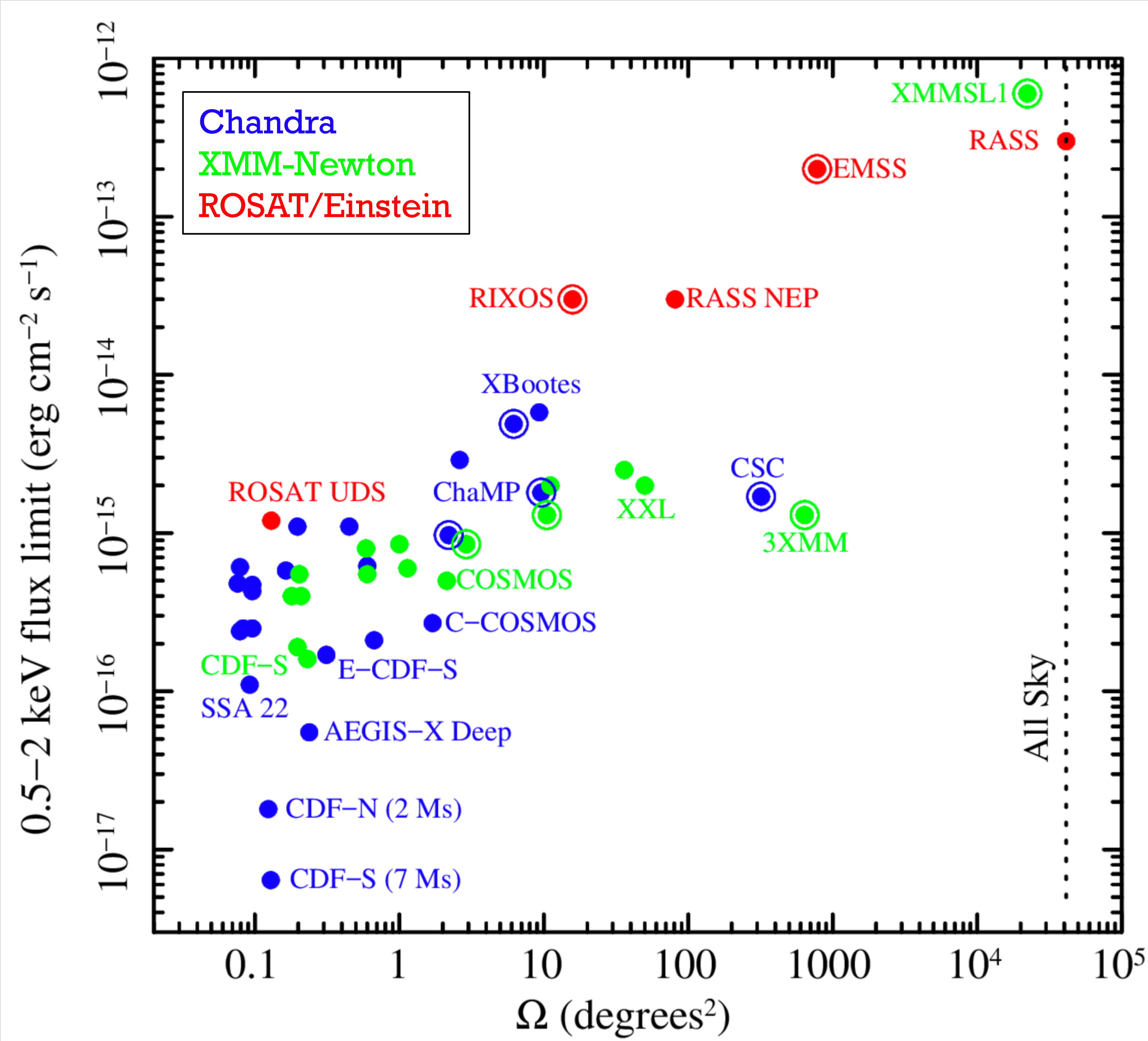
Heavy seeds:

The black hole can consume most of the gas in its halo, so it will have only a small stellar cluster around it ($M_* < 10^6$ $M_\odot$). This cluster's light will be subdominant compared to black-hole emission.

The hope is that both XLF + host information *together* can discriminate light seeds vs. heavy seeds.

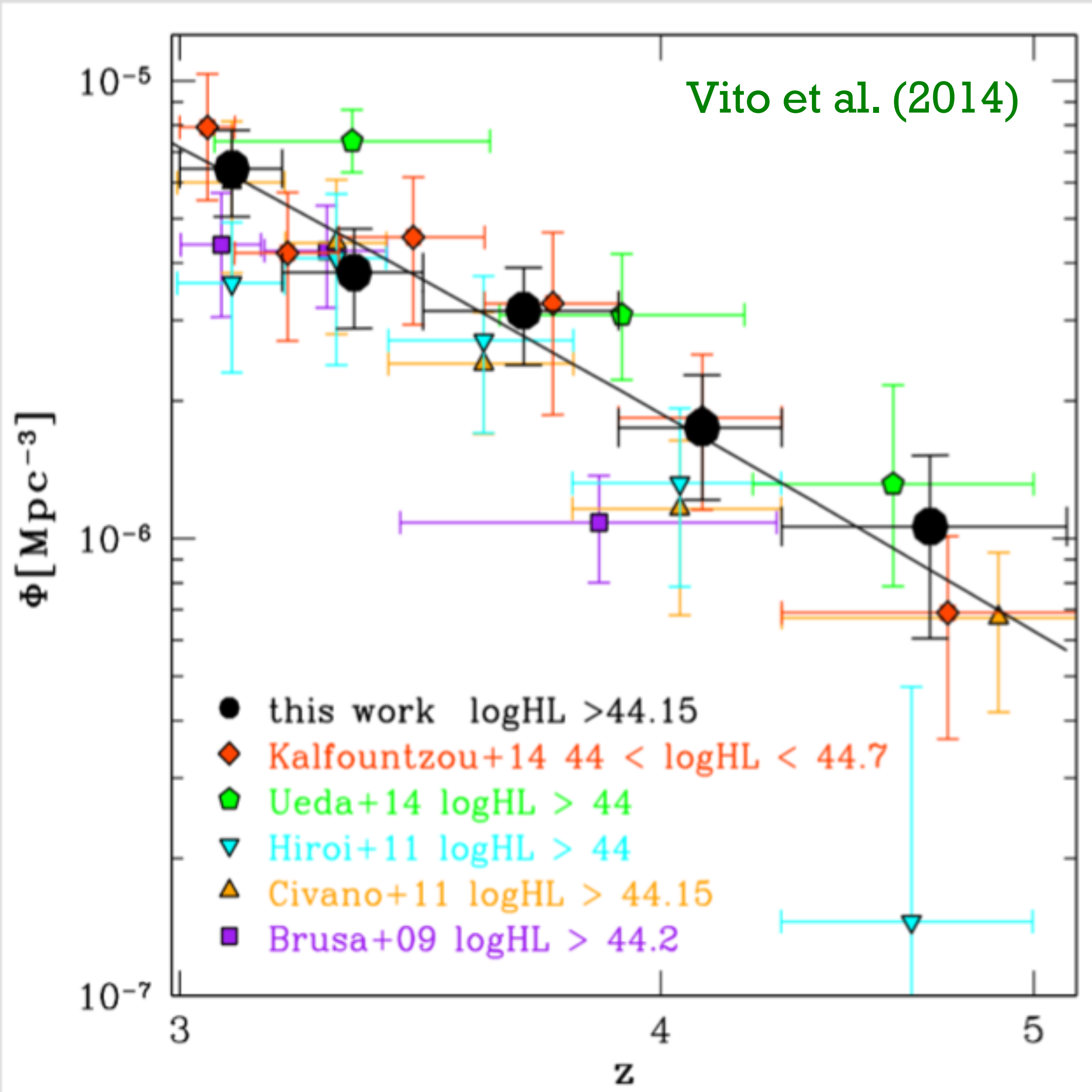
The End

Extra Slides



Brandt & Alexander (2015)

Space Density Declines for High-Luminosity X-ray AGNs



In contrast to early suggestions from ROSAT, clearly see ~ exponential decline for luminous X-ray selected AGNs at $z > 3$.

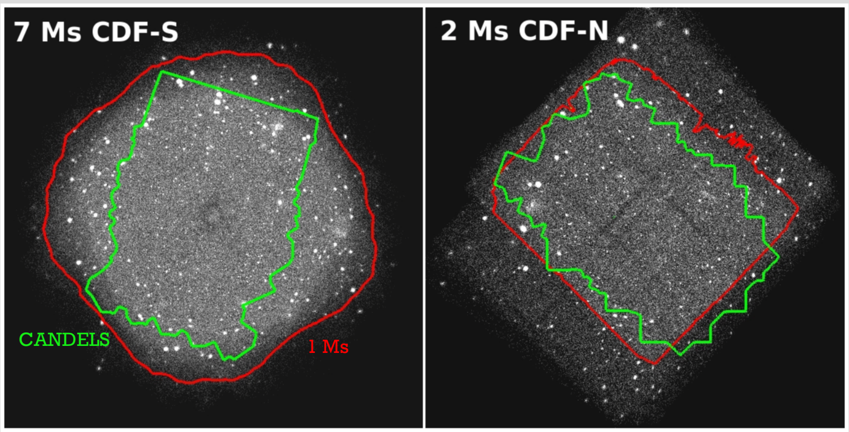
$\Phi \propto (1 + z)^p$ with p = -6.0 +/- 0.8

Space-density comparisons with optically selected quasars indicate agreement to within factors ~ 2-3.

Decline is similar to that of massive galaxies - driven by evolution of galaxy number density?

Space Density at z ~ 3-5 for Moderate-Luminosity X-ray AGNs

Utilized Regions of CDFs



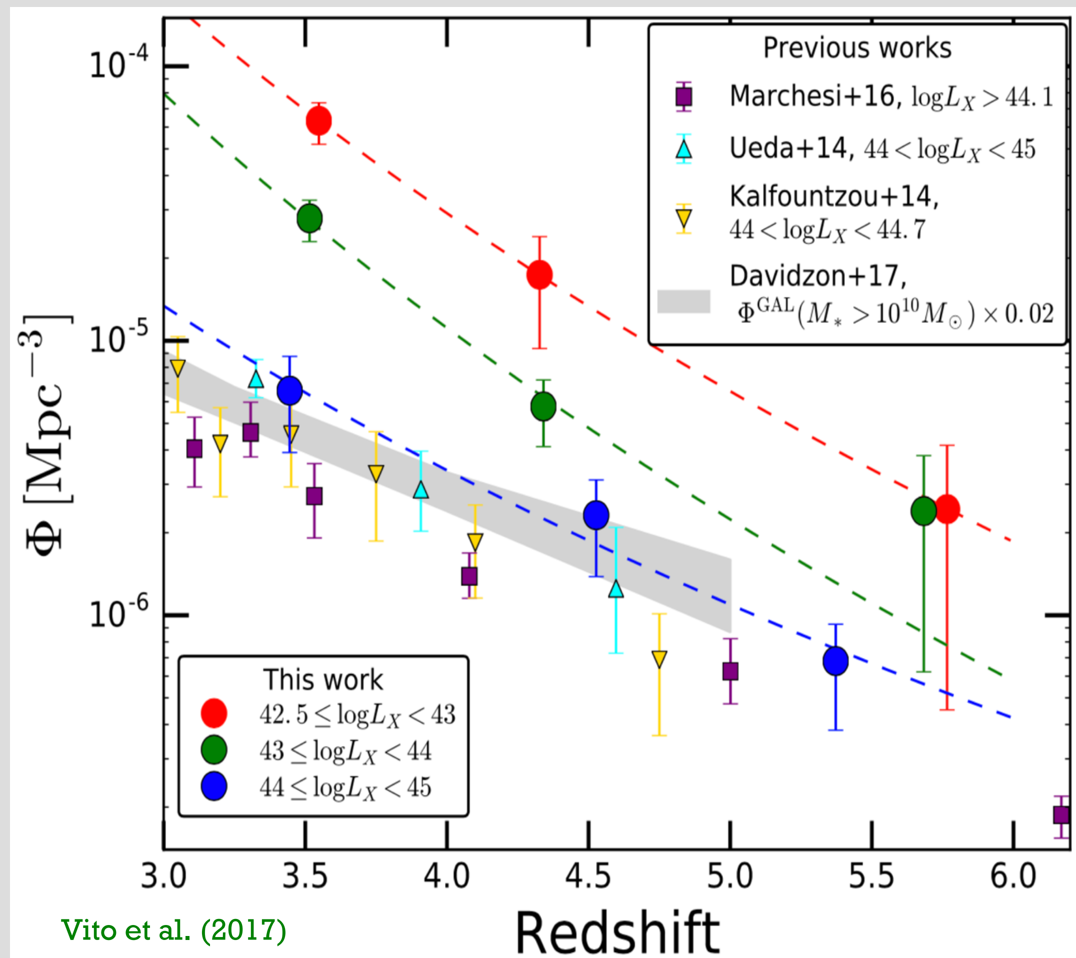
Tough work – small samples, follow-up hard, incompleteness corrections.

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

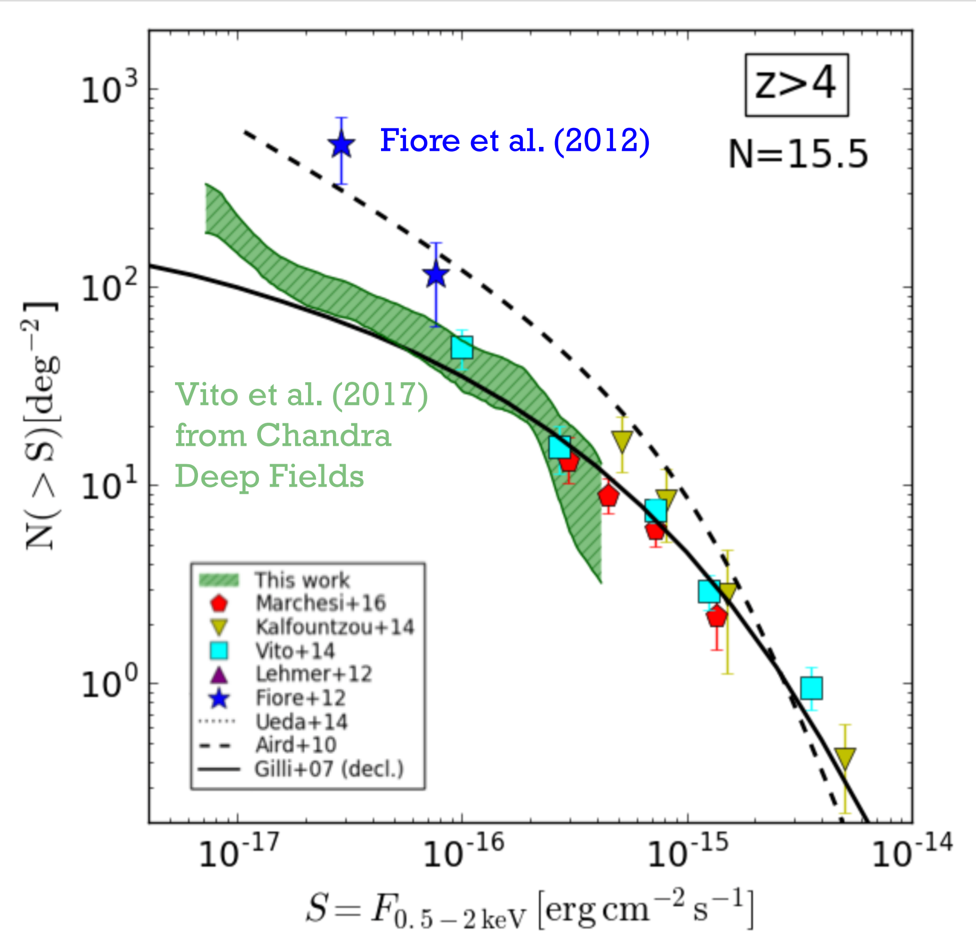
Similar to but weaker than trend in Georgakakis et al. (2015).

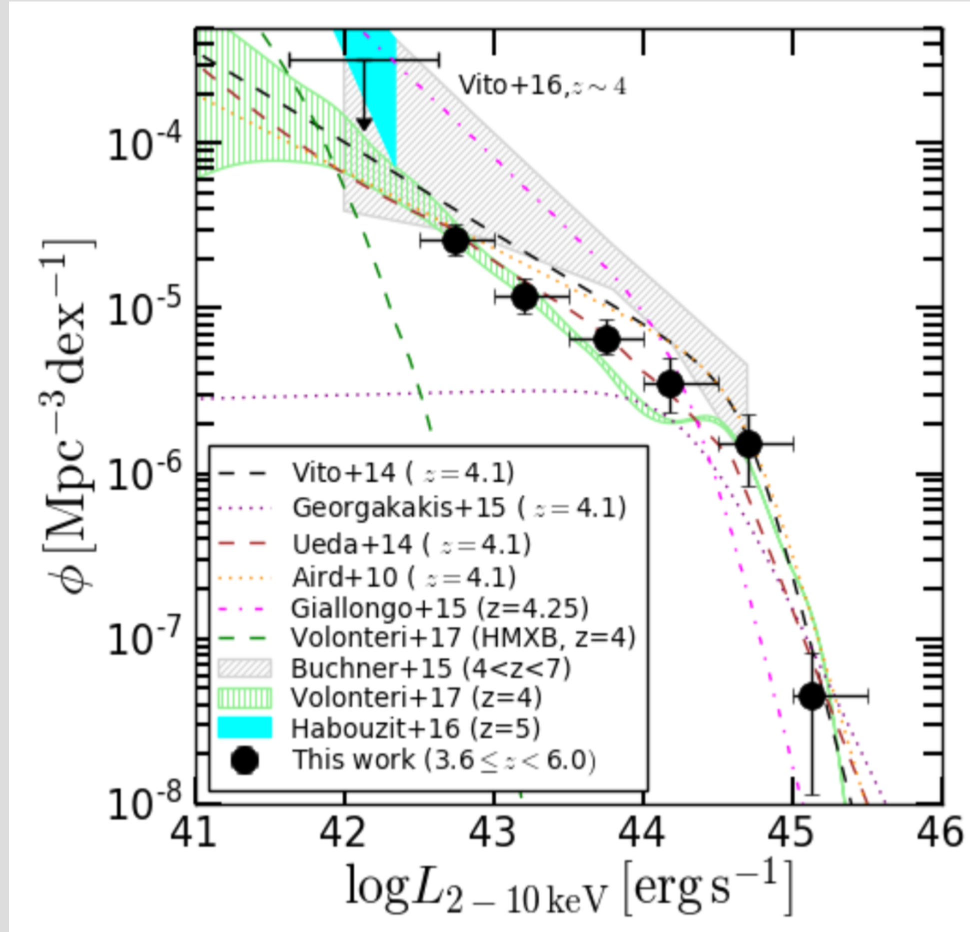
Decline at moderate L_X also steeper than for massive galaxies at high redshifts.

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



log*N* – log*S* and X-ray Luminosity Function



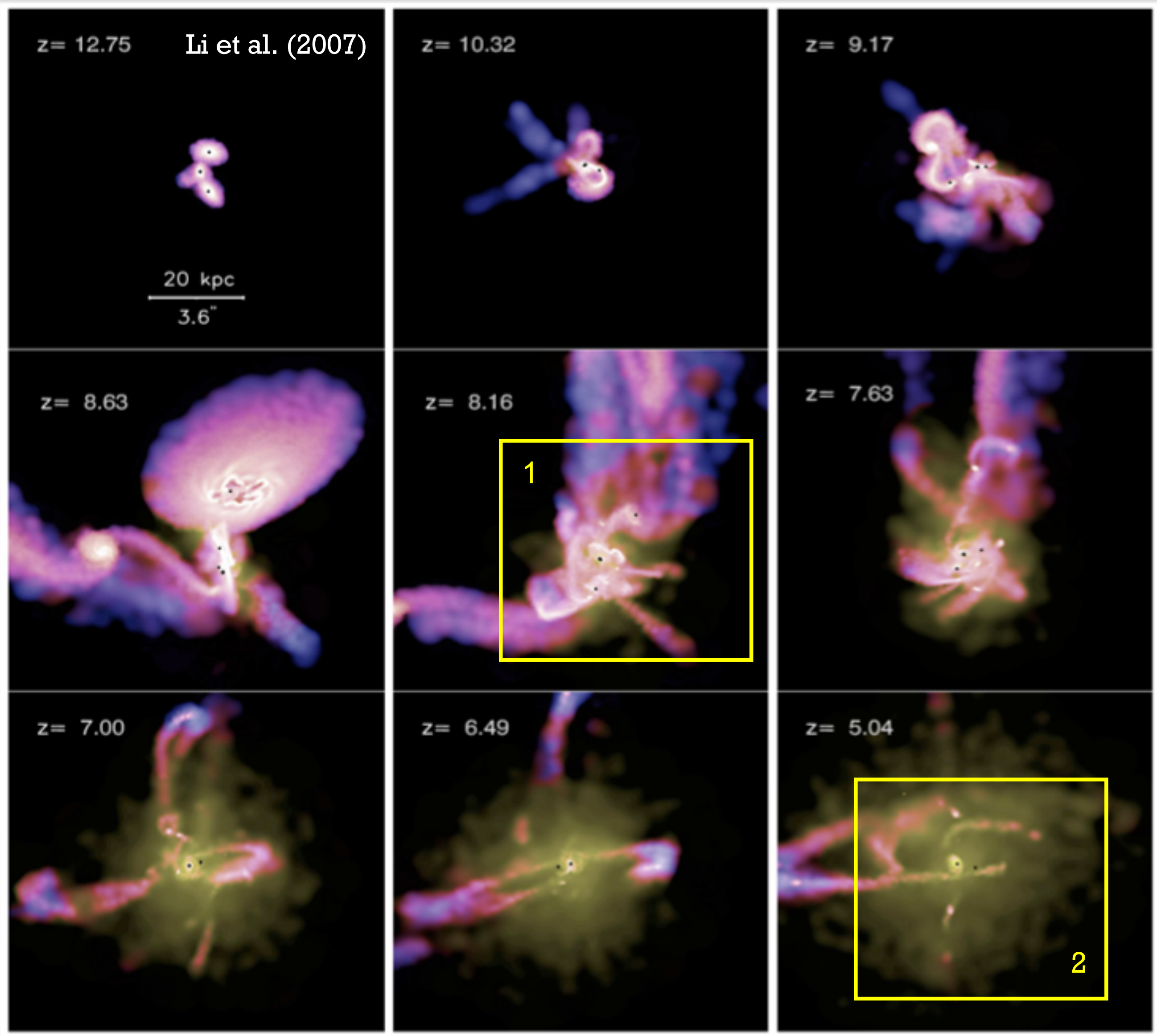


Agree with earlier work at the bright end, and lower than some past claims at the faint end.

Space density is lower than many theoretical model predictions from 2010-2015.

AGNs are unlikely to drive *z* ~ 6 cosmic reionization.

Simulation of the Formation of a $z \sim 6$ Quasar from Hierarchical Galaxy Mergers



Gas density and temperature for high-redshift quasar host

Albeit at somewhat lower redshifts, we observe similar phenomena at $z \sim 4$-5 via X-ray spectroscopy:

(1) X-ray obscured protoquasars of moderate luminosity.

(2) powerful winds from luminous quasars, likely capable of host feedback.

Possible Seeds of First SMBHs

Possible Black Hole "Seeds"
Formed in a Protogalaxy

Early AGN

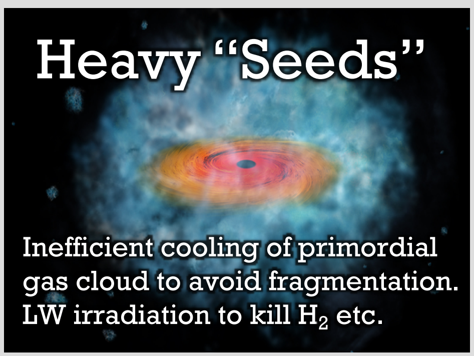
Early Pop III Remnants - Isolated and Binaries

Eddington-Limited or Super-Eddington Growth (Sustainable?)

→

Likely obscured

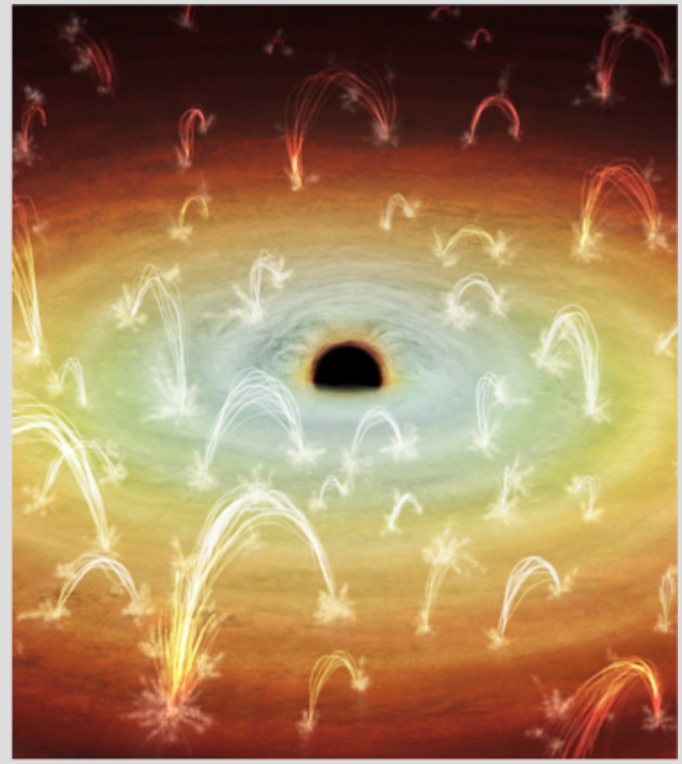
Direct Collapse Black Holes (10^4-10^5 $M_\odot$)



Episodic Growth

→

Likely obscured



What is the nature of the seeds? Light or heavy?

Extremely sensitive X-ray measurements needed.