EXPLORING GRAVITATIONALLY-LENSED Z $\gtrsim$ 6 X-RAY AGN BEHIND THE RELICS CLUSTERS

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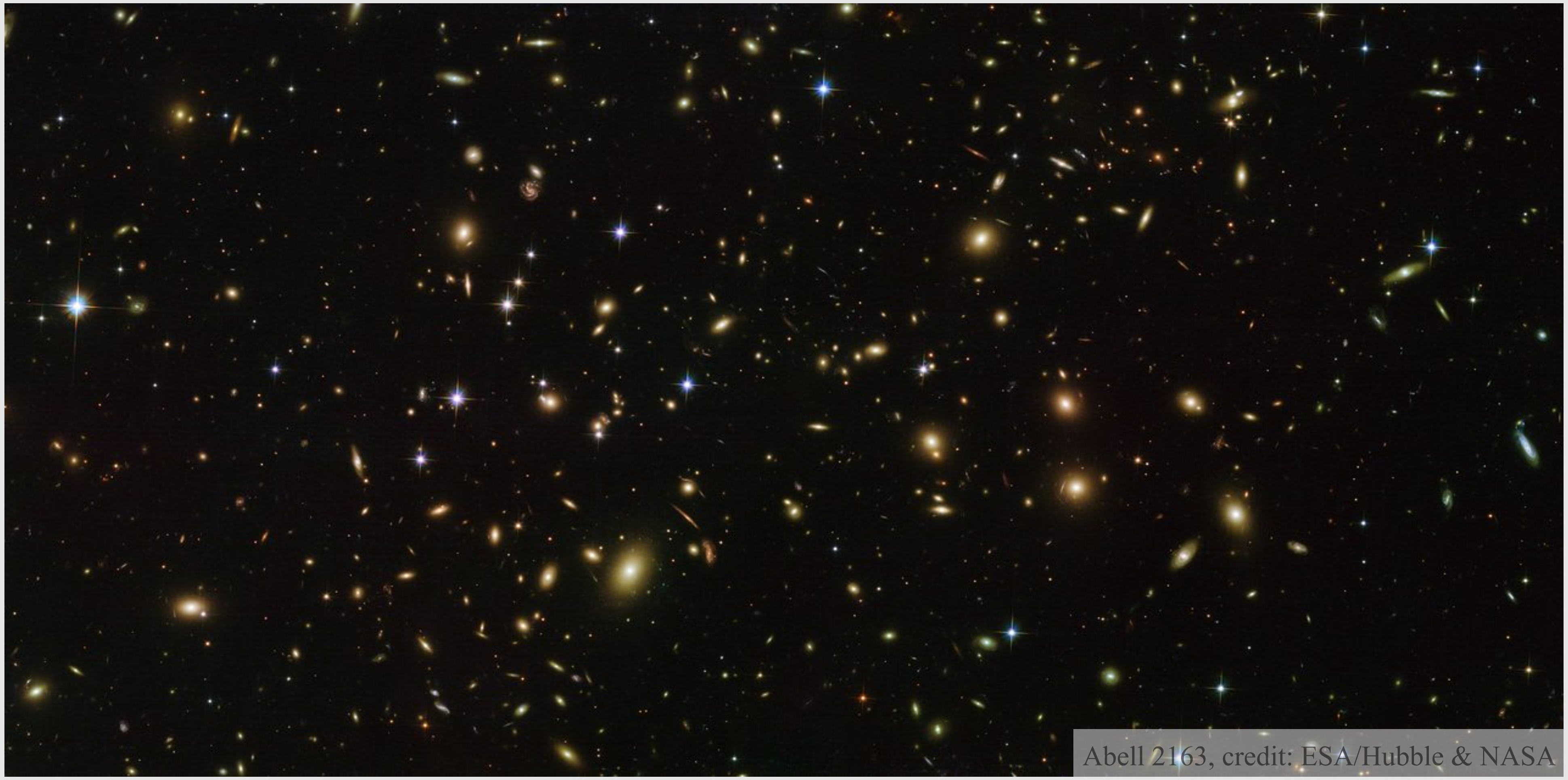
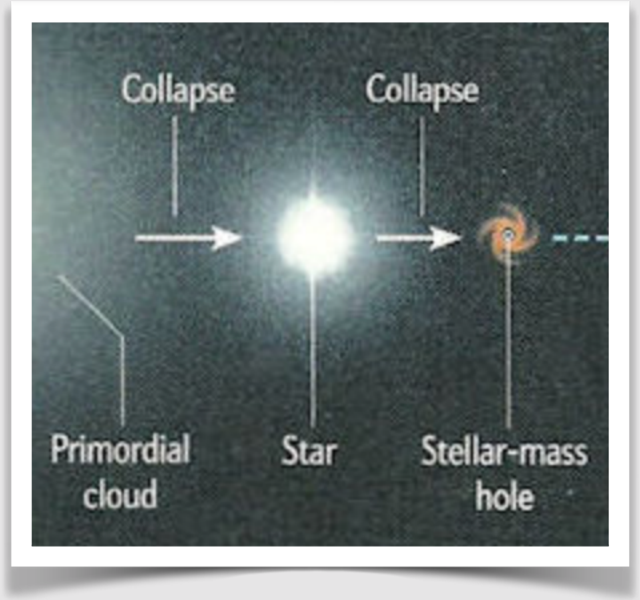
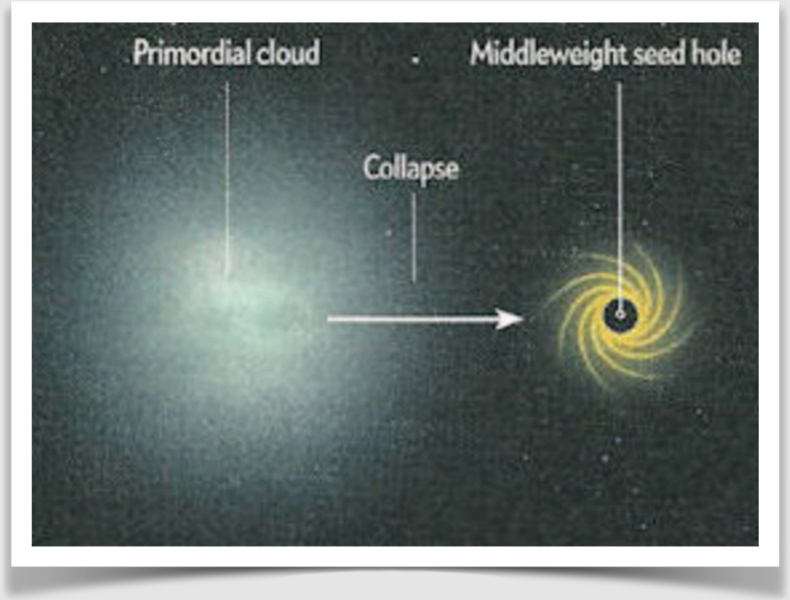


Abell 2163, credit: ESA/Hubble & NASA

BH formation scenarios

- **deep optical surveys**: >200 bright quasars at $z > 6$ →
    - accretion-powered black holes in the center of galaxies (BHs) already exist ~1 billion years after the Big Bang
    - $10^9\,M_\odot$ (this is the high-end tail of BH mass distribution)
    - rapid assembly





- various seeding models explain the origin of BHs
    - **"light seed" scenario** (low-mass BH seeds)
        - collapse of Population III stars → BH seeds with $10 - 100\,M_\odot$
        - rapid growth via accretion /mergers within 1 billion years
    - **"heavy seed" scenario** (massive BH seeds)
        - direct collapse of massive gas clouds → BH seeds with $10^4 - 10^5\,M_\odot$ BH
        - episodic accretion

- **aim of this study: constraining the formation scenarios of BHs**

Constraining formation scenarios

- main (X-ray) observational differences: **luminosity (this work)**, accretion density, number of BH seeds (occupation fraction)

- observations of BHs at the "cosmic dawn" is demanding for present-generation X-ray observatories due to the
    - low luminosity of BHs
    - low sensitivity of telescopes

Previous X-ray studies

- **X-ray follow-up observations** of optically-identified quasars with Chandra
    - $z \sim 6$ AGN from the high-end tail ($\sim 10^9\ M_\odot$) of BH mass distribution
    - these AGN are not representative

- **Chandra Deep Field South**
    - average properties of medium-redshift ($z = 2 - 5$) AGN
    - most notable: Vito et al. 2016, stacking → $z \approx 4 - 5$ AGN detection, but no $z \approx 6$ (only upper limit)

- **Gravitational lensing in X-ray**
    - Cluster Lensing And Supernova survey with Hubble (CLASH) clusters
    - individual AGN detections at $z = 2.8 - 5$, but not at $z \approx 6$

CDF-S, credit: ESO La Silla Observatory

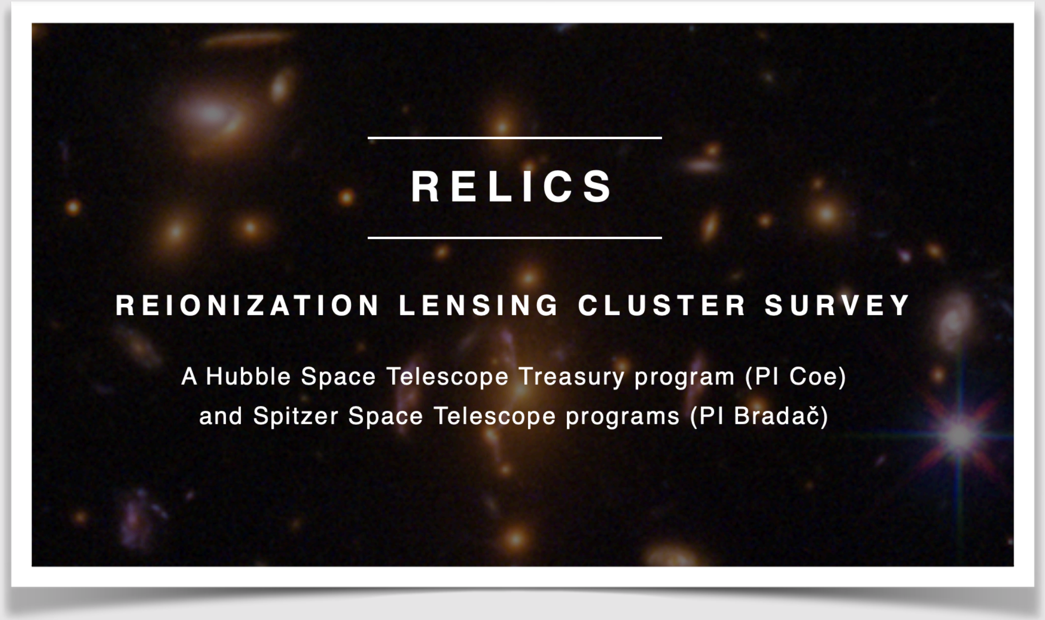
This study

- **gravitational lensing on X-ray data** to magnify fainter AGN
- lensing objects: galaxy clusters
    - magnification of background galaxies
    - no magnifying effect on foreground objects (cluster emission, sky & instrumental background)

- 1st approach: search for individual AGN in background galaxies with amplified signal
- 2nd approach: stacking the amplified signal to further boost signal-to-noise ratios & to probe average characteristics of BHs

- data used in this study:
    - Chandra images
    - HST & Spitzer catalog of lensed galaxies identified in the RELICS survey (from Salmon et al. 2020)

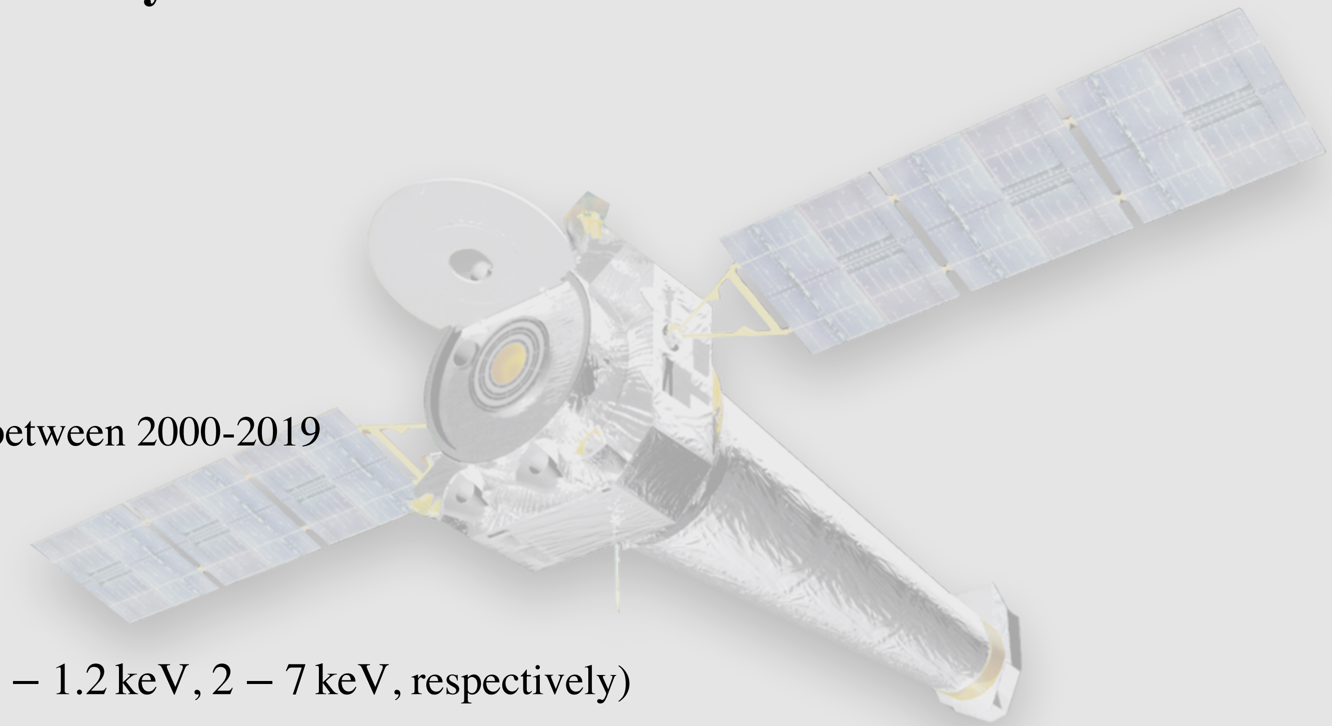
RELICS clusters & background galaxies



- imaging of strongly lensed fields i.e. of 41 galaxy clusters
- cluster redshifts: $z = 0.18 - 0.97$
- science topics: high-redshift galaxies, AGN etc.

- high-resolution Chandra observations of 35 RELICS clusters
- El Gordo (ACT-CLJ0102-49151) cluster excluded from our cluster sample due to its extremely bright ICM
- galaxy sample consists of lensed galaxies behind the remaining 34 galaxy clusters
  - 174 HST&Spitzer–identified galaxies with redshifts of $6 < z < 8$ behind the 34 clusters (Strait et al. 2021)
  - SED fitting of HST & Spitzer fluxes → physical characteristics of the galaxies (photometric redshift, stellar mass, star formation rate etc.) (Strait et al. 2021)
  - based on photometric redshift, 19 low-redshift galaxies were excluded from the sample
  - **final galaxy sample**: 155 $z \approx 6$ galaxies
  - lensing magnification (μ) at the location of the galaxies from cluster lensing magnification maps from Strait et al. 2021
    - $\mu = 1 - 95$

Chandra analysis



- data were obtained from public archive
- 105 high-resolution ACIS-I & ACIS-S imaging observations taken between 2000-2019
- total exposure time is 3.53 Ms
- analysis with standard CIAO tools
- image extraction in the broad, soft, and hard band ($0.5 - 7$ keV, $0.5 - 1.2$ keV, $2 - 7$ keV, respectively)
- images and exposure maps of clusters observed in multiple pointings were merged

Results, individual detections

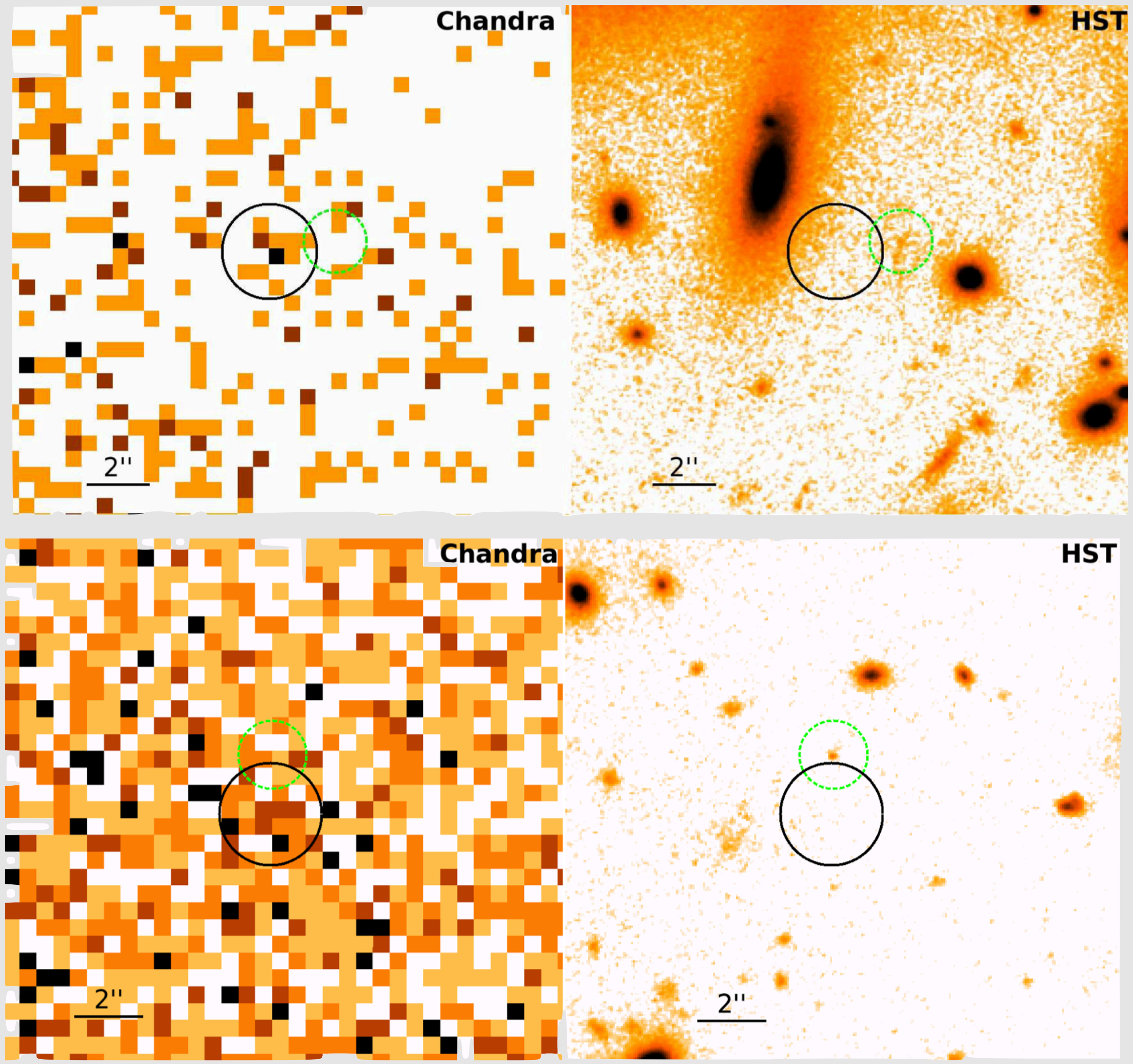
1. source detection with CIAO wavdetect (this detects mainly low-redshift AGN)
2. cross-correlation of the X-ray source list with the HST galaxy positions
    - differences in astrometric accuracy between Chandra and HST (Liu et al. 2021, largest offset $< 0.8''$)
    - broader Chandra point spread function at the edges of the detector
    - search radius: $2.5''$

- **results:** two X-ray point sources in the proximity of lensed galaxies:
- match #1 in cluster MACS0553-33
    - offset: $2.1''$
    - $L_{\rm X}$ assuming the distance of the galaxy ($z = 6.55$): 4.6×10^{43} erg s^{-1}
- match #2 in cluster PLCKG237+32
    - offset: $1.7''$
    - $L_{\rm X}$ assuming the distance of the galaxy ($z = 7.82$): 3.5×10^{44} erg s^{-1}

- chance coincidence?
- Monte Carlo simulations → we expect ≈ 0.23 random matches in our sample → one or even two X-ray sources are associated with a high-redshift galaxy

- **major caveat**: relatively large projected offsets (11.7 kpc & 8.5 kpc at the redshift of corresponding galaxy) > half-light radius of typical galaxies at $z \sim 6$

Results, individual detections



The potential matches between the X-ray sources and high-redshift AGN for MACS0553-33 (top panel) and PLCKG287+32 (bottom panel). The left panels show the $0.5 - 7\,\mathrm{keV}$ band Chandra images and the right panels show the multi-color HST images of the regions around the sources. The images are centered on the X-ra ysources (black solid circle) that are in the vicinity of galaxies at $z = 6.55$ and $z = 7.82$ (dashed green circles). The projected distances between the centroids of the X-ray point sources and the high-redshift galaxies are $2.1''$ and $1.7''$ for the source in MACS0553-33 and PLCKG287+32, respectively. However, due to the relatively large projected distance, the X-ray sources are unlikely to be associated with the high-redshift galaxies.

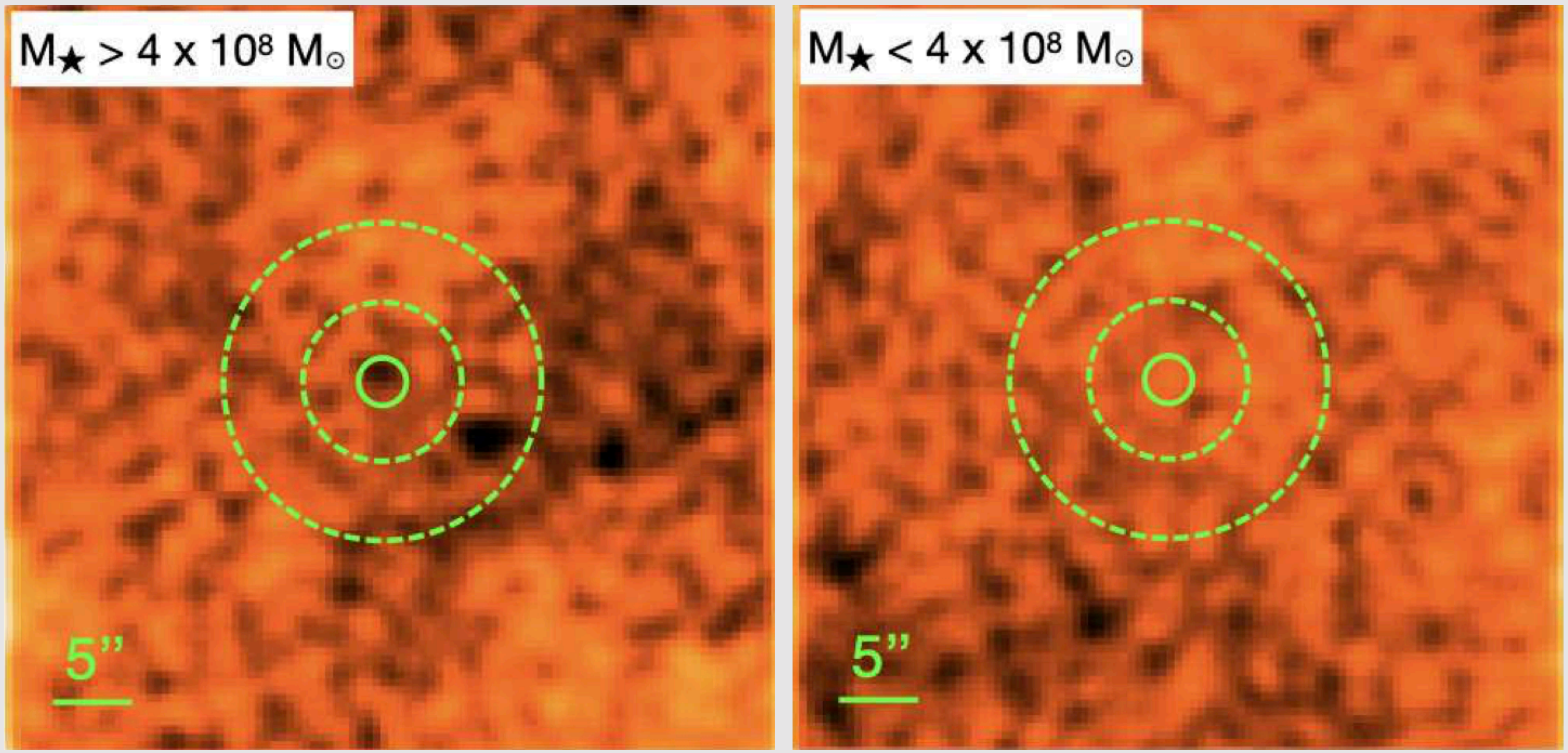
Results, stacking the high-redshift galaxies

- analysis steps:
    1. source exclusion
    2. cutout images and exposure maps around each galaxy
    3. stacking the cutout images and exposure maps → increased signal-to-noise ratios & detection likelihood
    4. magnification correction on net count rates

- multiple approaches of stacking:
    1. stacking **all** 155 galaxies together
    2. stacking the subsample of low- ($< 4\,\mathrm{M_\odot\,yr^{-1}}$) and high-**SFR** ($> 4\,\mathrm{M_\odot\,yr^{-1}}$) galaxies separately
    3. low- ($\log\mu < 0.5$) and high-**lensing-magnification** ($\log\mu > 0.5$) galaxies
    4. low- ($M_\star < 4 \times 10^8\,\mathrm{M_\odot}$) and high-**stellar-mass** ($M_\star > 4 \times 10^8\,\mathrm{M_\odot}$) galaxies

- **result:** weak (2.2σ) detection only in the high-mass sample
- Jackknife resampling confirms the detection → only $\sim\ 0.3\,\%$ of the random resampling simulations show $\geq 2.2\,\sigma$ detections.

Results, stacking the high-redshift galaxies



Stacked $0.5 - 7$ keV band Chandra images of lensed high-redshift galaxies using stellar mass as binning criteria. We obtained a weak, 2.2σ detection for the high-mass sub-sample, while other sub-samples remained undetected.

Constraining the properties of z $\sim$ 6 BHs

- constraints from the stack of all 155 galaxies:

- estimating the BH mass using two approaches:

  1. luminosity upper limit $L_{0.5-7\,\mathrm{keV}} \lesssim 8.4 \times 10^{41} \mathrm{ergs}^{-1}$ $\rightarrow$ in case of accretion at Eddington rate the mean BH mass of the sample is $< 6.7 \times 10^4\,\mathrm{M}_\odot$
  2. mean stellar mass of the galaxy sample is $1.3 \times 10^9\,\mathrm{M}_\odot$ $\rightarrow$ BH mass–stellar bulge mass scaling relation (Schutte et al. 2019) $\rightarrow$ $2.6 \times 10^6\,\mathrm{M}_\odot$ for the mean BH mass $\rightarrow$ 40 times larger

- possible explanations:

  - the scaling relation only valid locally, and high-redshift BHs are much less massive

    - this explanation is incompatible with some observational studies, e.g.

      - Merloni et al 2010: high-redshift BHs may be over-massive relative to their host galaxies

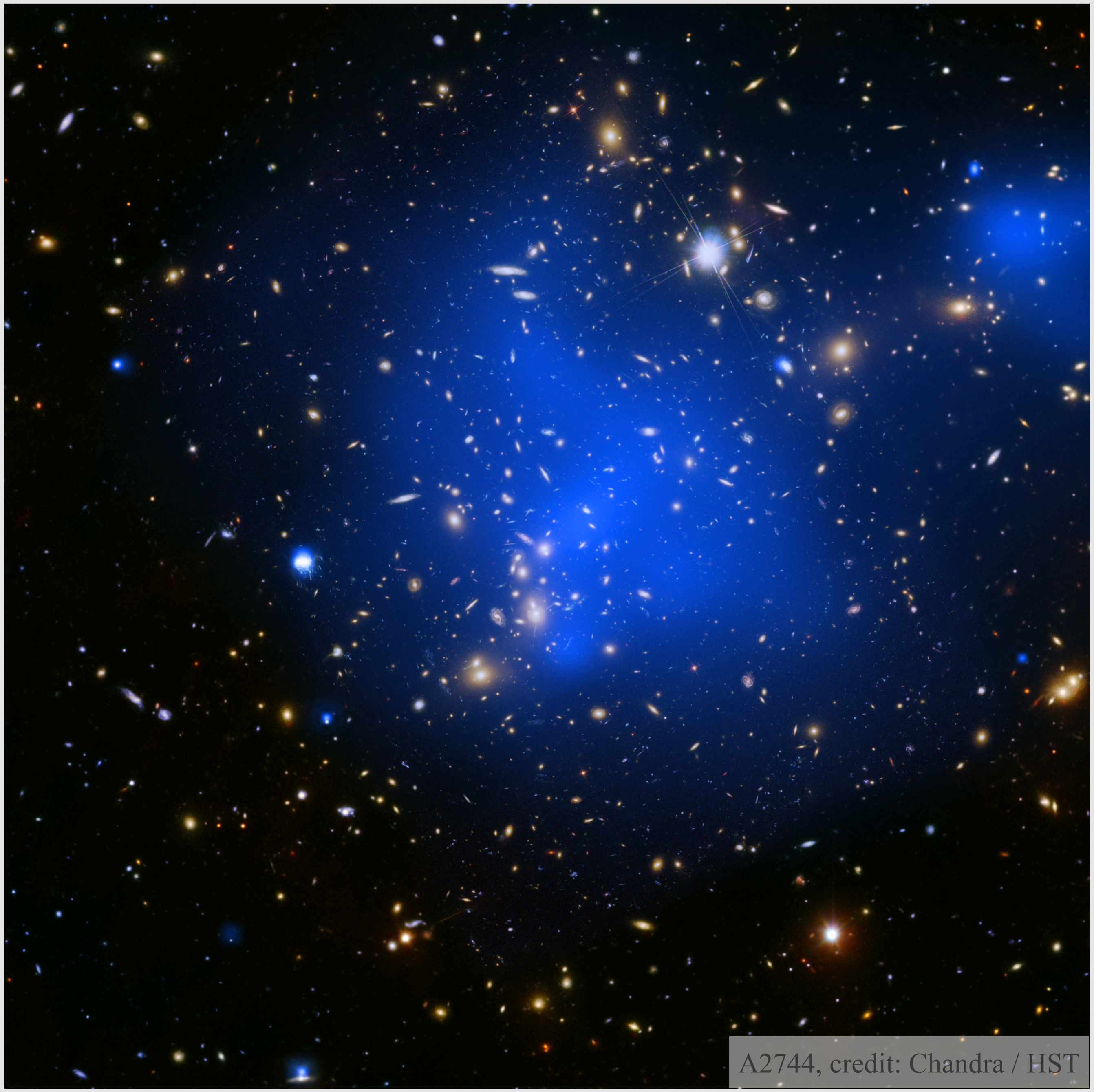
      - Bogdán et al. 2012: some high-redshift BHs may grow faster than their host galaxies

  - BHs accrete at a few per cent of their Eddington rate $\rightarrow$

    - **low mean accretion rate supports the "heavy seed" scenario:** BHs may experience episodic periods with high accretion rates, while most times they accrete at low Eddington rates

Summary

- Chandra analysis of 155 high-redshift ($z \approx 6$) gravitationally-lensed galaxies identified by Hubble behind 34 RELICS clusters
- probing the X-ray emission both individually and in stacks
- search for individual high-redshift AGN revealed two X-ray source–high-redshift galaxy pairs, but due to their large offset, X-ray sources are not likely associated with a high-redshift galaxy
- stack of 155 high-redshift galaxies resulted in non-detection → upper limit on luminosity and BH mass
- the upper limit on the luminosity implies that typical high-redshift BHs accrete at a few per cent of their Eddington rate
- splitting the sample based on stellar mass, SFR, and lensing magnification
- stack of massive galaxies resulted in a 2.2 σ detection, other subsamples remained undetected



Future studies

- high-redshift galaxies behind Hubble Frontier Field clusters
- high-redshift galaxies behind Abell 2744, which is a JWST target in its early release science program + **2.1 Ms Chandra VLP project** (PI: Ákos Bogdán, me: Co-I)