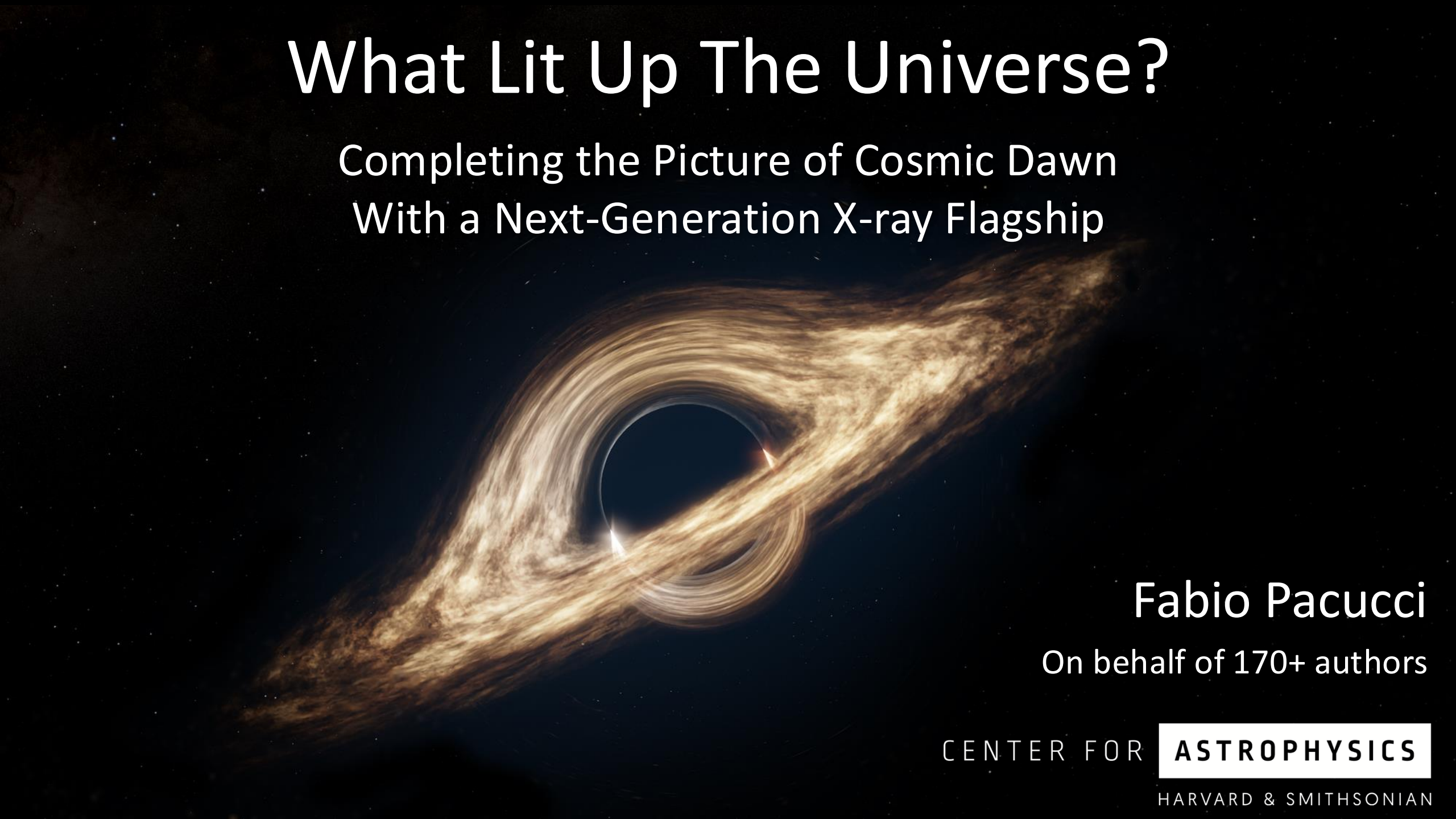
The Universe began in darkness…

What Lit Up The Universe?

Completing the Picture of Cosmic Dawn With a Next-Generation X-ray Flagship



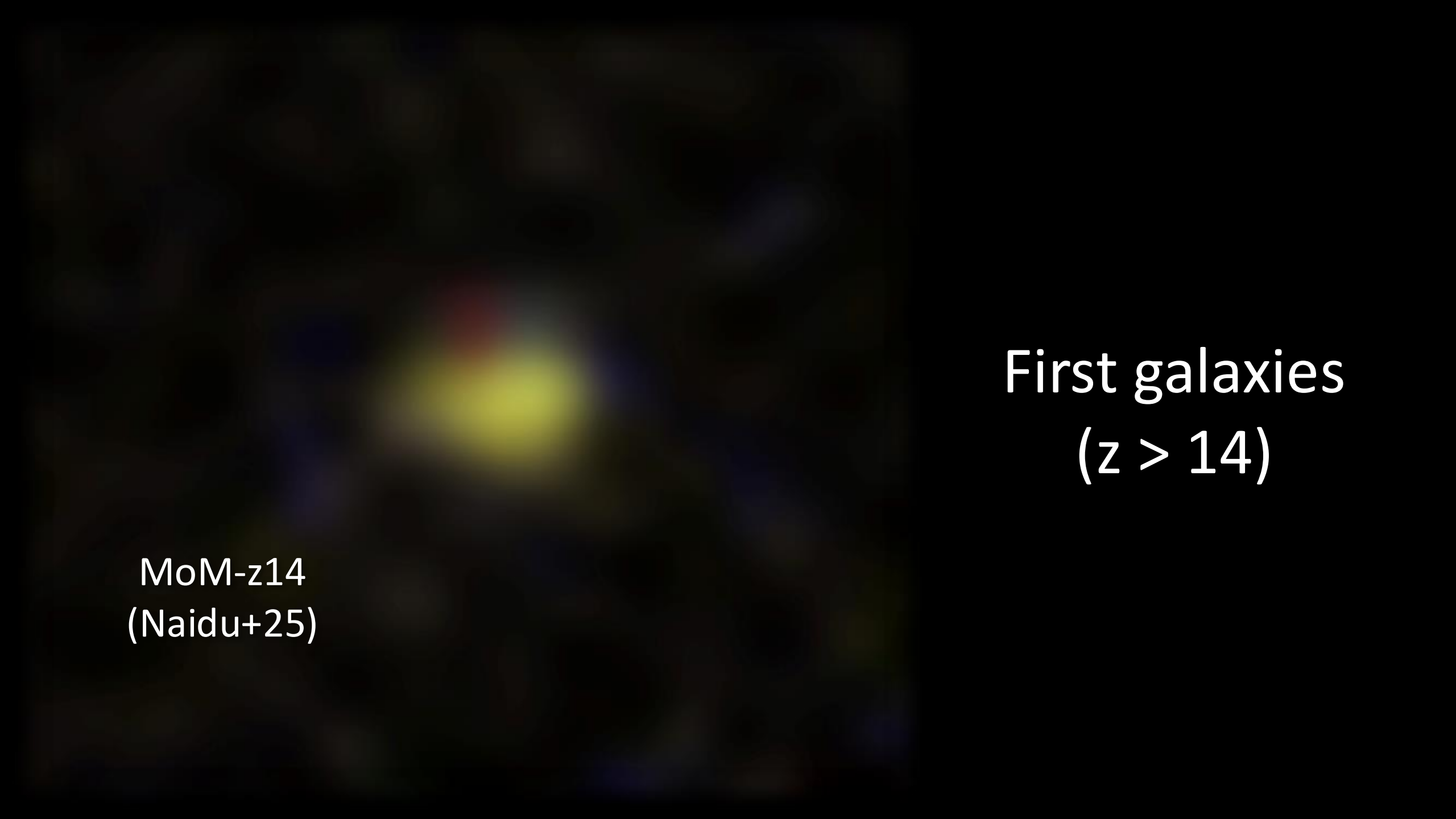
Fabio Pacucci

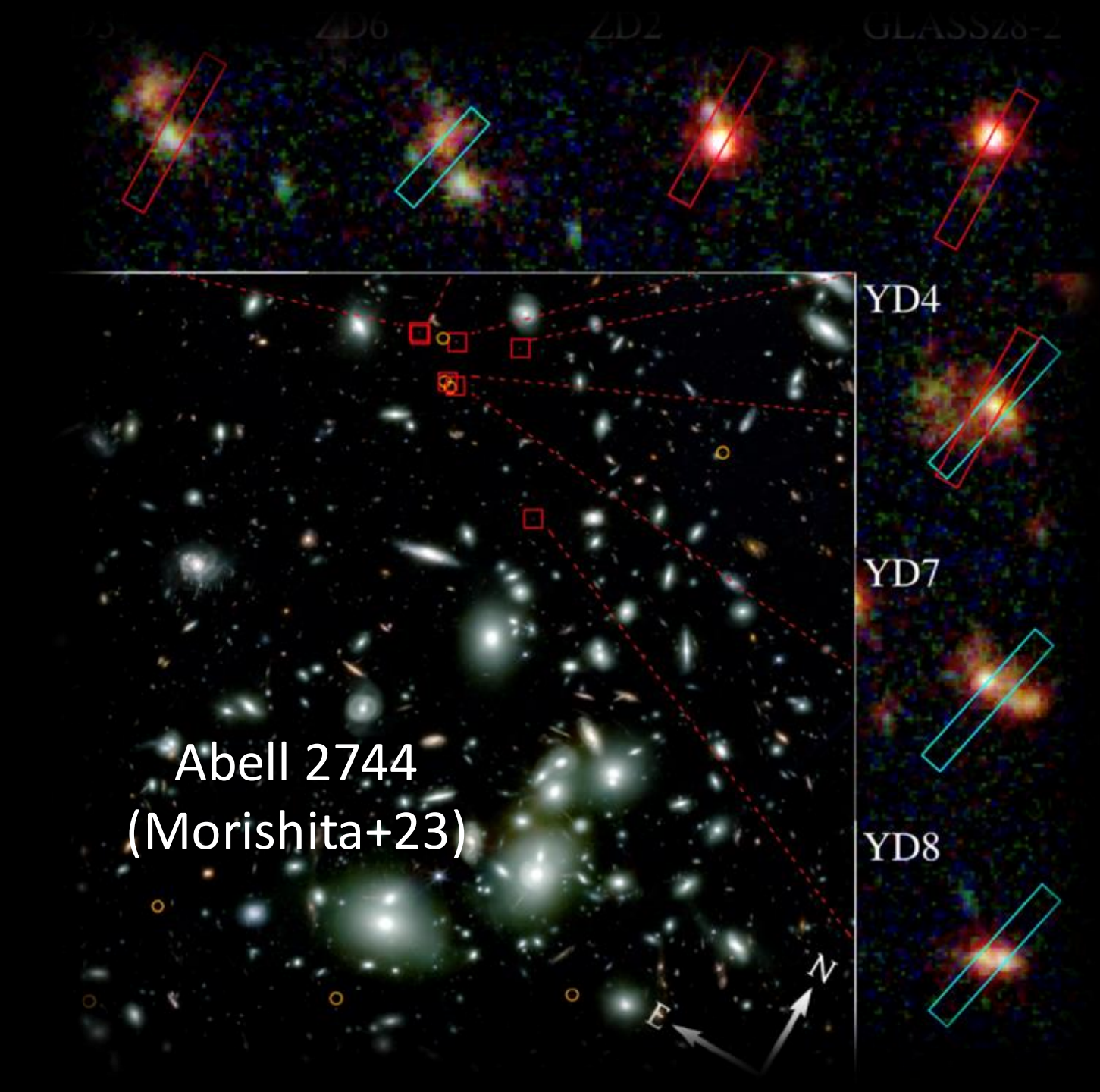
On behalf of 170+ authors

CENTER FOR ASTROPHYSICS

HARVARD & SMITHSONIAN

Black hole seed candidates ($z > 10$)


First galaxies
(z > 14)
MoM-z14
(Naidu+25)



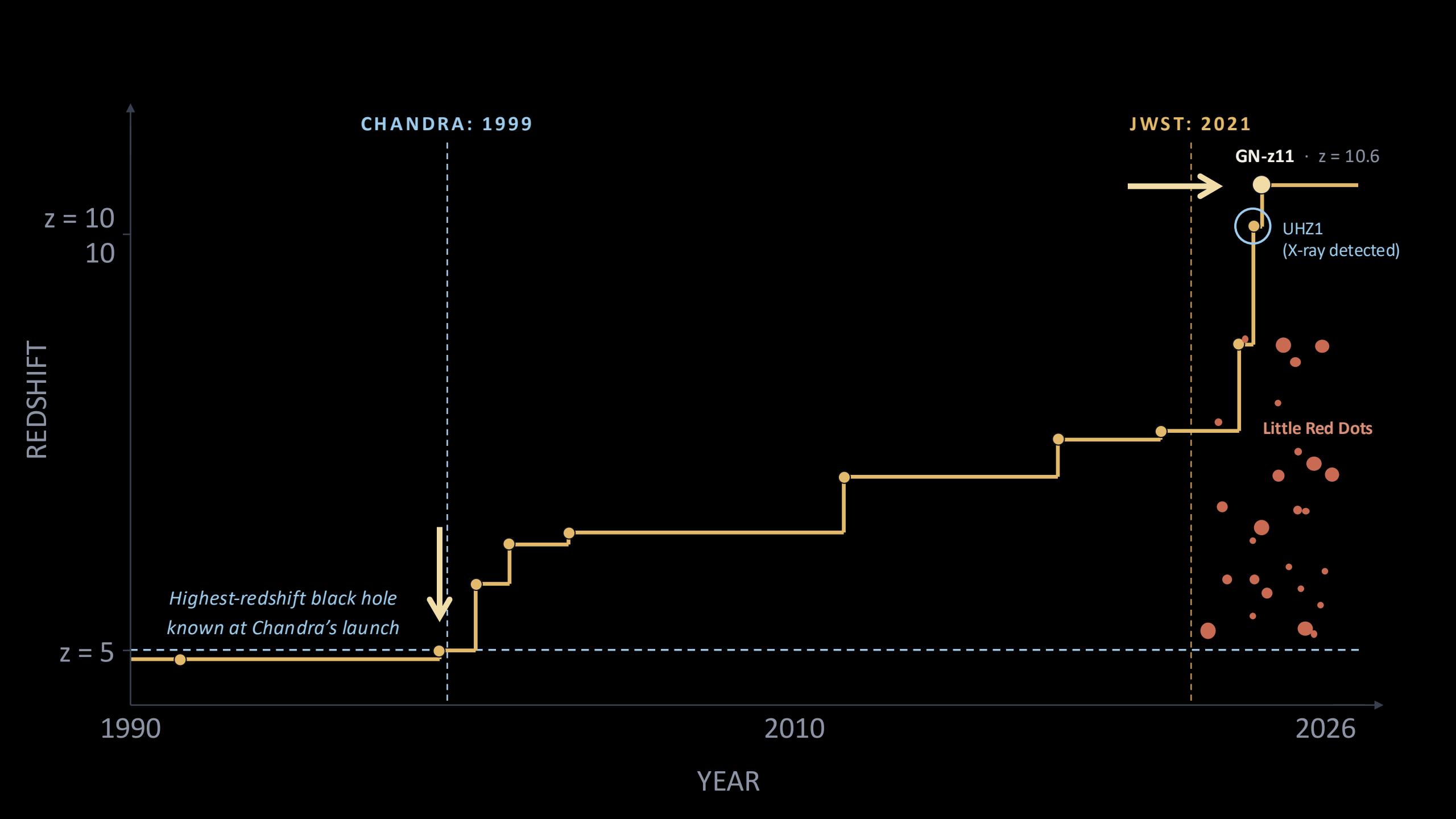
First protoclusters ($z \sim 5$–10)

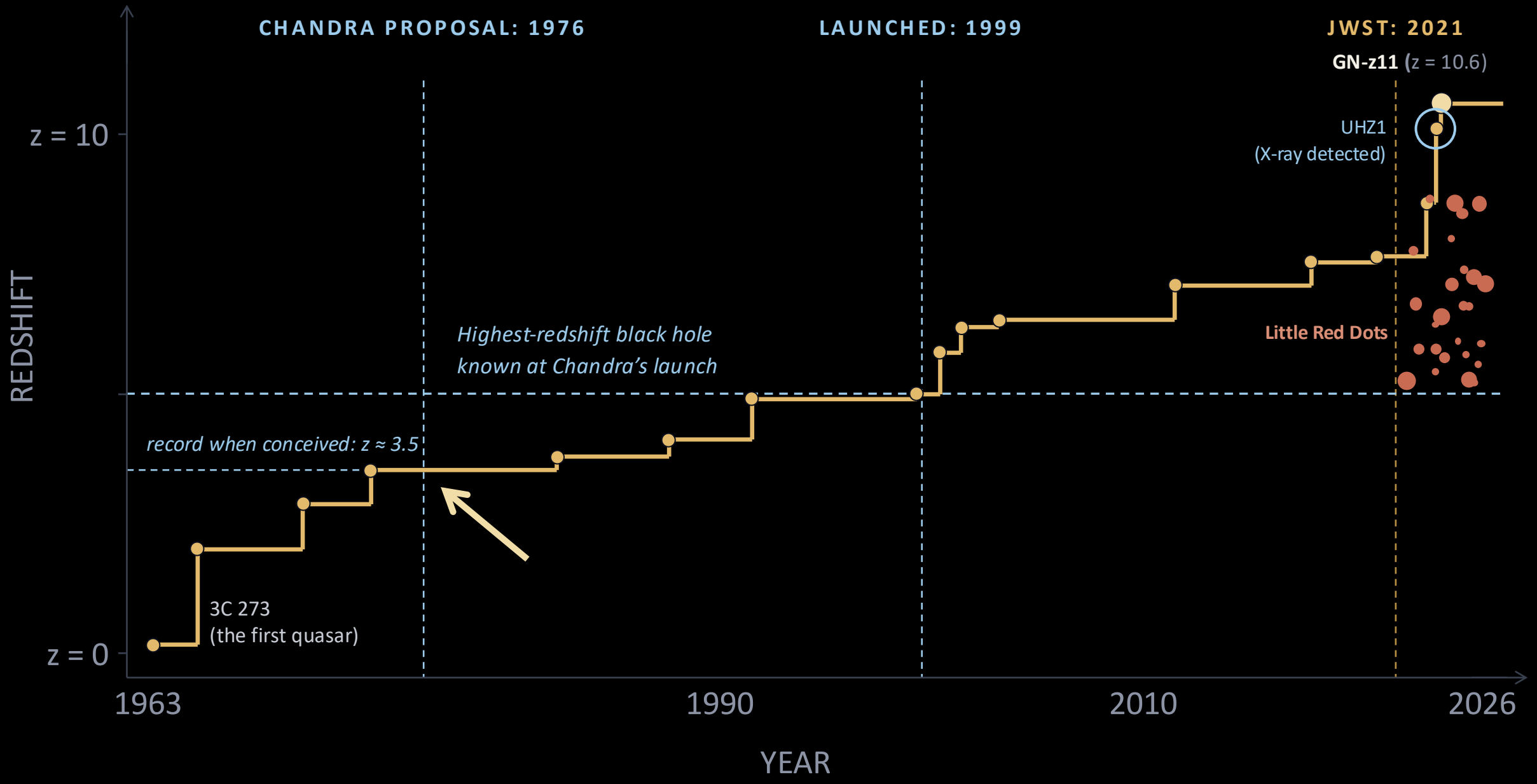
CEERS 14448
(Kocevski+23)

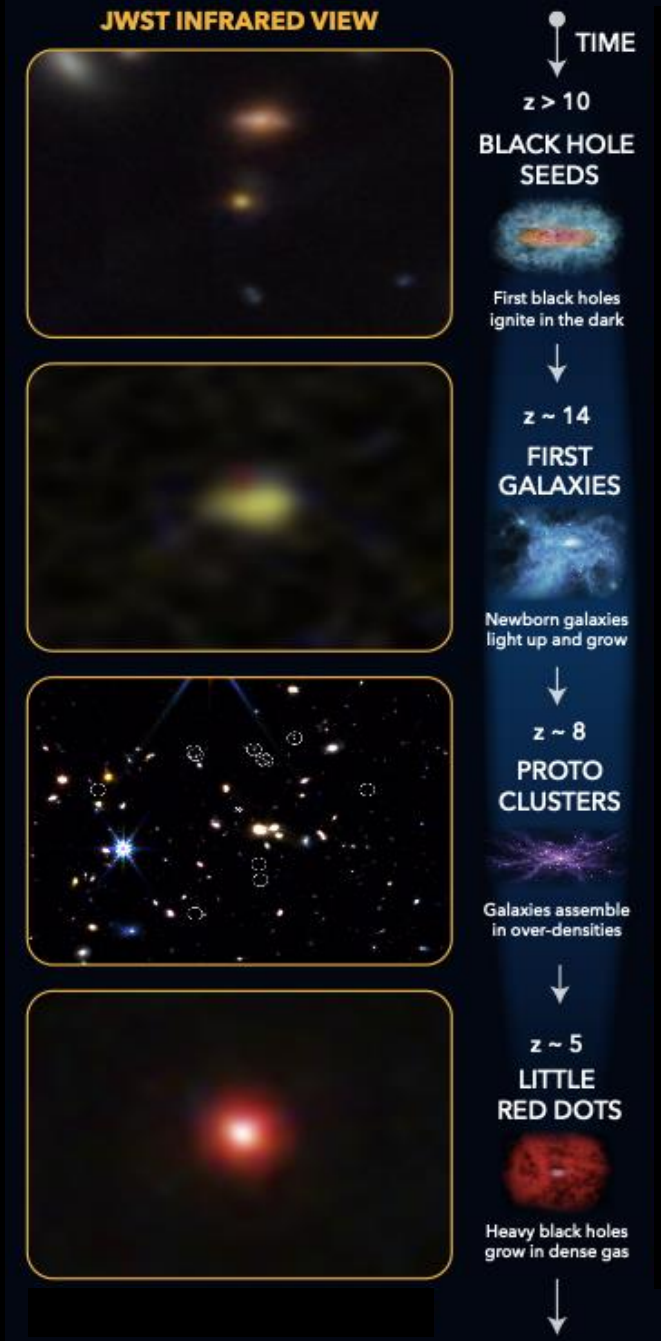
Little Red Dots
(z ~ 4–10)

JWST INFRARED VIEW
TIME
z > 10
BLACK HOLE SEEDS
First black holes ignite in the dark
z ~ 14
FIRST GALAXIES
Newborn galaxies light up and grow
z ~ 8
PROTO CLUSTERS
Galaxies assemble in over-densities
z ~ 5
LITTLE RED DOTS
Heavy black holes grow in dense gas

?


CHANDRA: 1999
JWST: 2021
GN-z11 · z = 10.6
UHZ1
(X-ray detected)
Little Red Dots
Highest-redshift black hole
known at Chandra's launch
z = 10
10
z = 5
REDSHIFT
1990
2010
2026
YEAR


CHANDRA PROPOSAL: 1976
LAUNCHED: 1999
JWST: 2021
GN-z11 (z = 10.6)
UHZ1
(X-ray detected)
Little Red Dots
Highest-redshift black hole
known at Chandra's launch
record when conceived: z ≈ 3.5
3C 273
(the first quasar)
z = 10
z = 0
REDSHIFT
1963
1990
2010
2026
YEAR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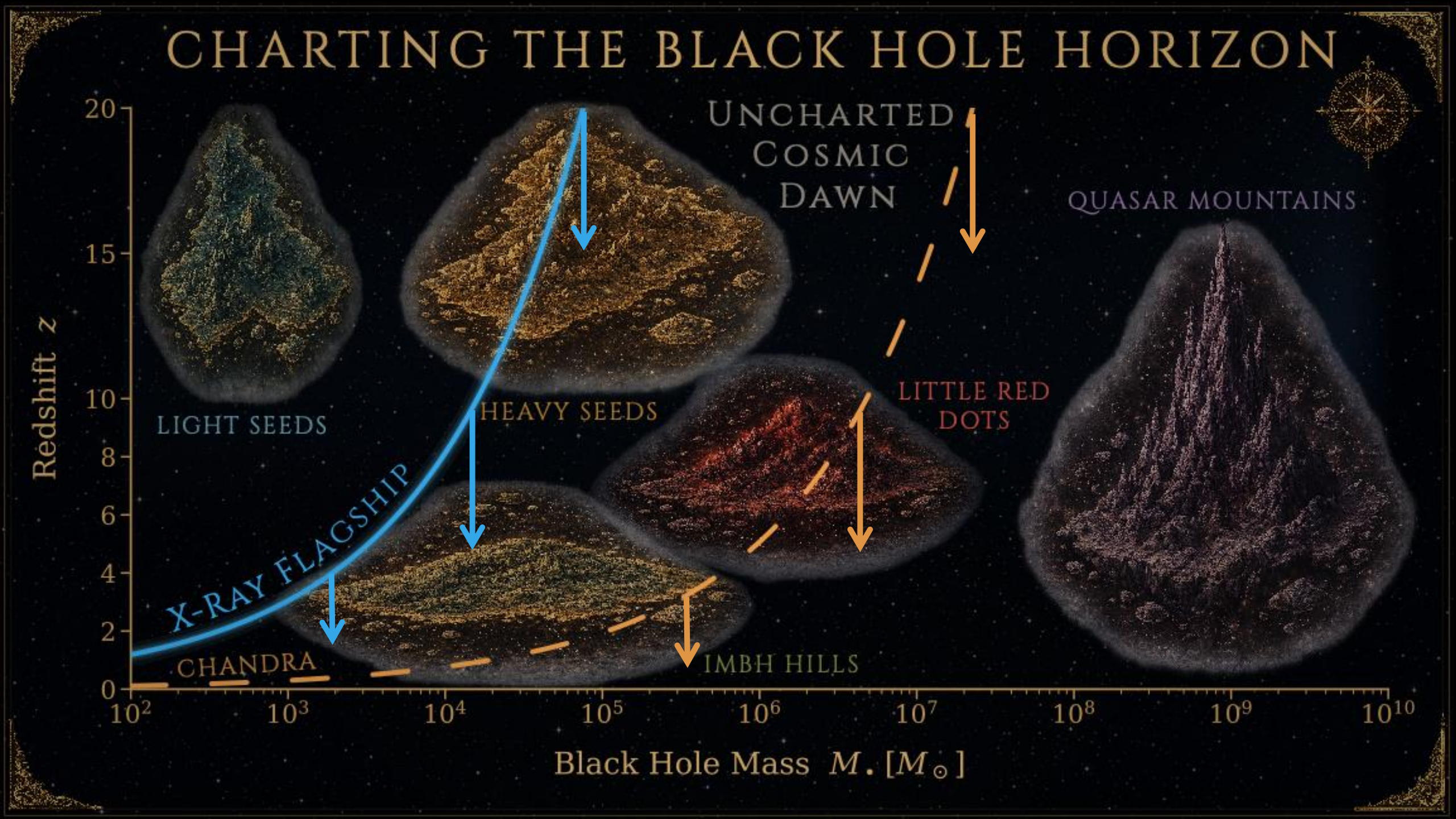
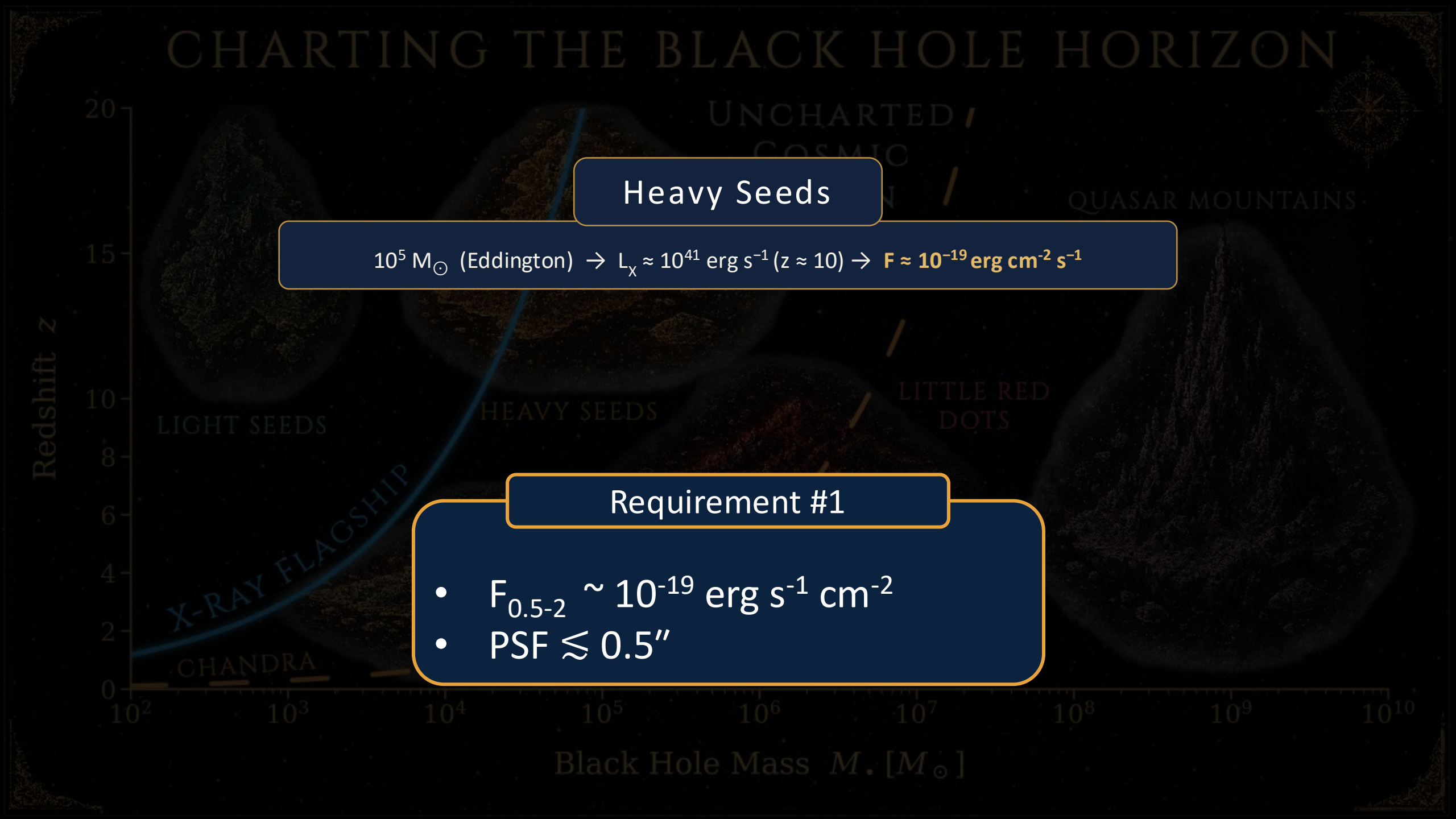

CHARTING THE BLACK HOLE HORIZON
UNCHARTED COSMIC DAWN
QUASAR MOUNTAINS
LIGHT SEEDS
HEAVY SEEDS
LITTLE RED DOTS
X-RAY FLAGSHIP
CHANDRA
IMBH HILLS
Redshift z
Black Hole Mass $M_\bullet$ [$M_\odot$]
0
2
4
6
8
10
15
20
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}



Heavy Seeds

$10^5\ M_\odot$ (Eddington) → $L_X \approx 10^{41}$ erg s^{-1} ($z \approx 10$) → **$F \approx 10^{-19}$ erg cm^{-2} s^{-1}**

Requirement #1

- $F_{0.5\text{-}2} \sim 10^{-19}$ erg s^{-1} cm^{-2}
- PSF $\lesssim 0.5''$

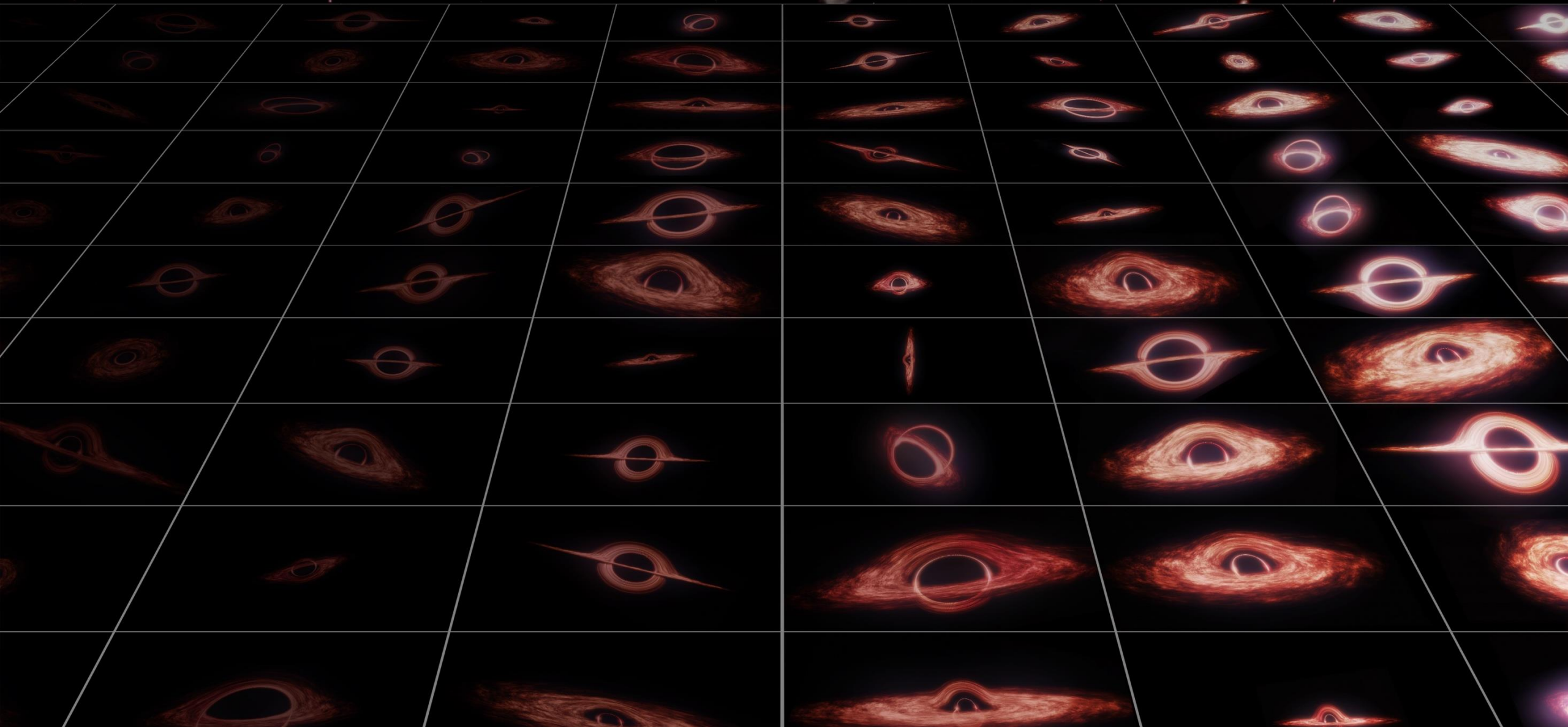
The X-Ray Fossil Record of Black Hole Seeds

BOTH PATHWAYS PRODUCE SIMILAR AGN
BUT NOT IN THE SAME NUMBERS

LIGHT SEEDS
Pop III
Remnants

HEAVY SEEDS
Direct Collapse
Black Holes

A Black Hole Luminarium



A Black Hole Luminarium

Seed Demographics

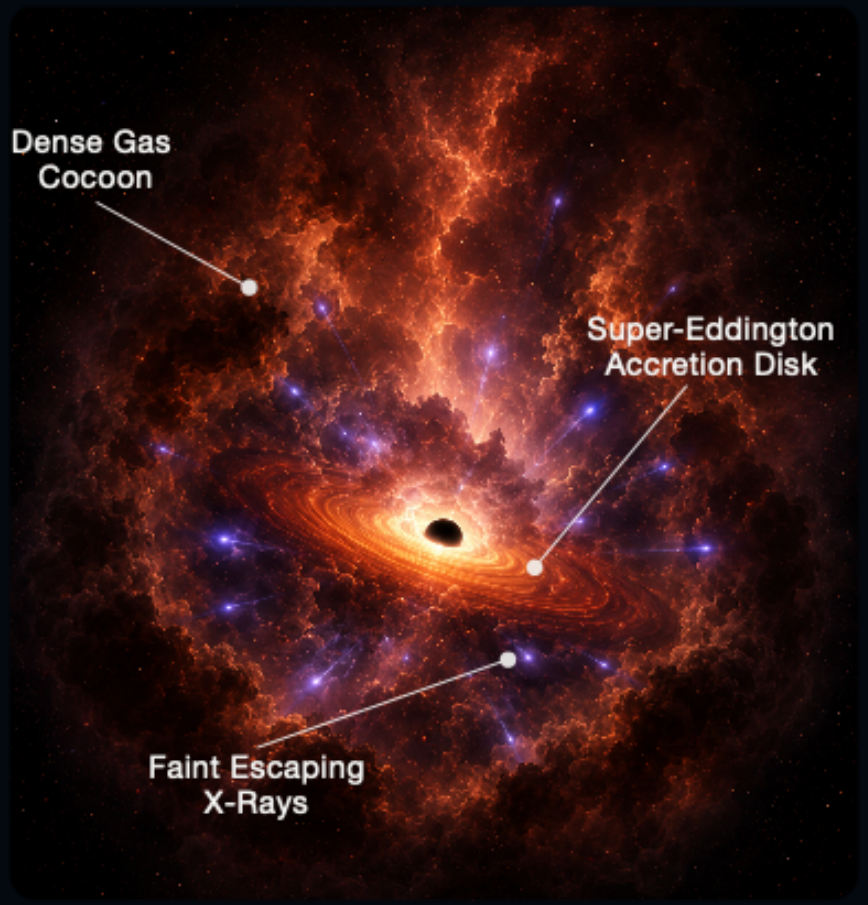
$z = 12$: light ~1 deg^{-2} vs heavy ~1000 deg^{-2} → statistically significant split → **$\Omega \gtrsim 1\ deg^2$**

Requirement #2

- $F_{0.5\text{-}2} \sim 10^{-19}$ erg s^{-1} cm^{-2}
- Area $\gtrsim 1\ deg^2$

LITTLE RED DOTS: WHERE ARE THE X-RAYS?

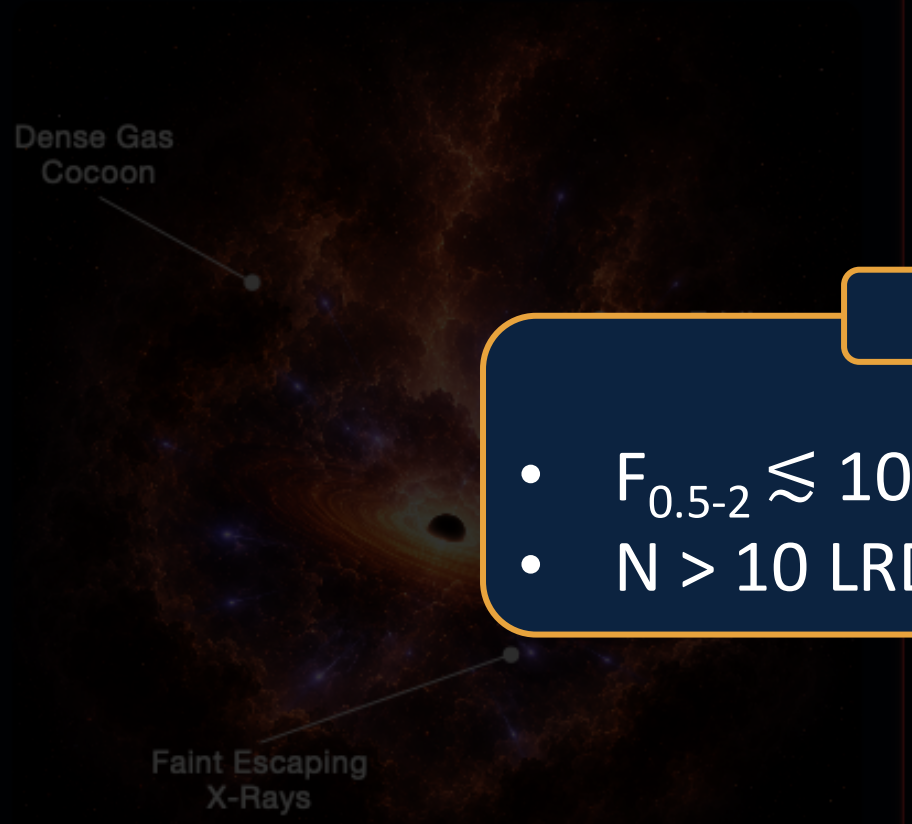
THE HIDDEN ACCRETING ENGINE



LRDs are enshrouded in extremely dense gas.
Only a faint X-ray component escapes.

LITTLE RED DOTS: WHERE ARE THE X-RAYS?

THE HIDDEN ACCRETING ENGINE



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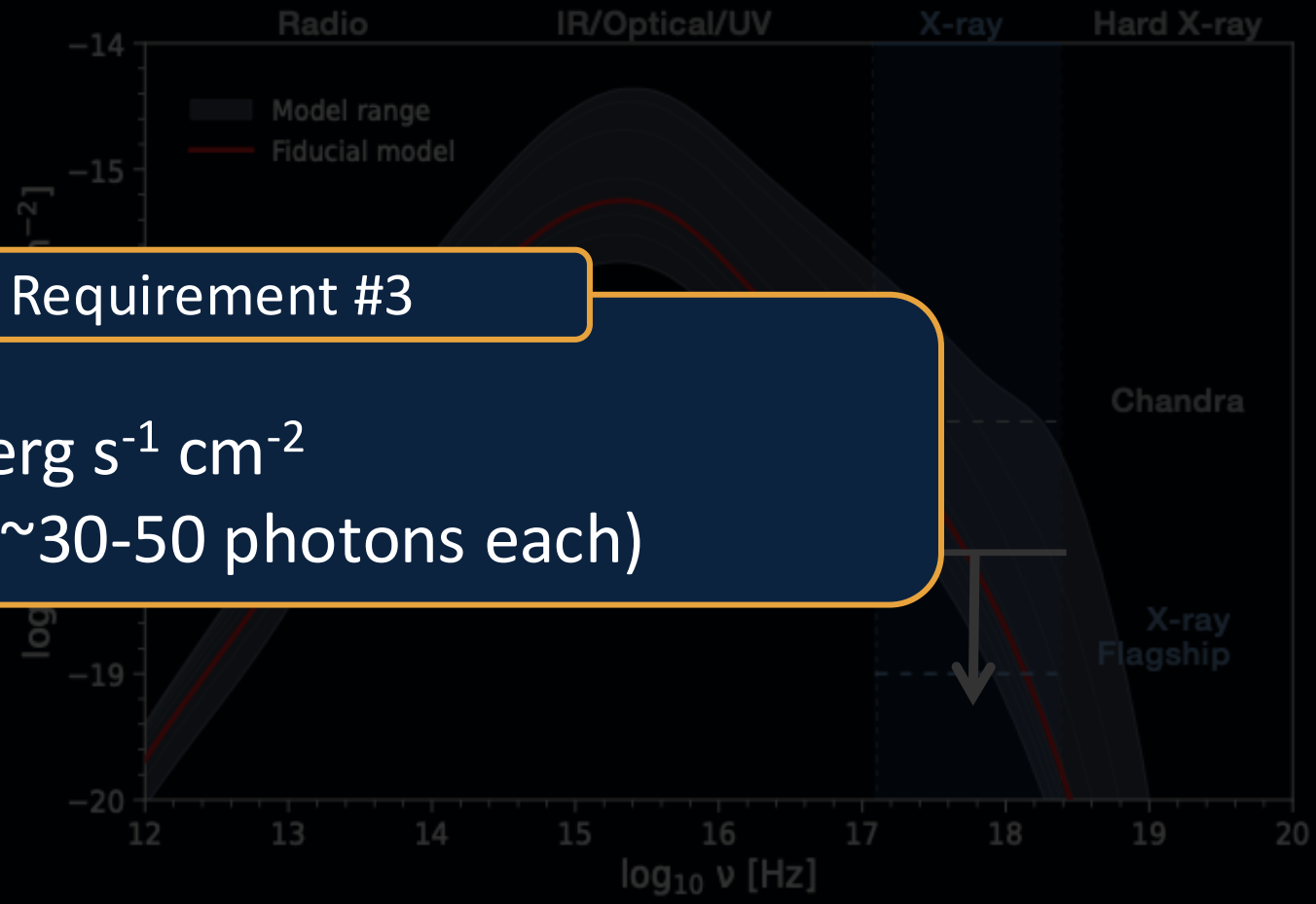
MODEL SPECTRAL ENERGY DISTRIBUTIONS FOR LRDs (z ~ 6)



Model X-ray fluxes lie below current limits.
A next-generation X-ray flagship reaches the bulk LRD population.

Requirement #3

- $F_{0.5\text{-}2} \lesssim 10^{-18}$ erg s^{-1} cm^{-2}
- N > 10 LRDs (~30-50 photons each)

First Galaxies

First Galaxies

First Galaxies

$L_X \approx 3\times10^{39} \cdot SFR \cdot (1+z) \rightarrow SFR = 100\ M_\odot\ yr^{-1}\ (z = 8) \rightarrow$ **$F \approx 10^{-18}$ erg cm^{-2} s^{-1}**

Requirement #4

- $F_{0.5\text{-}2} \lesssim 10^{-18}$ erg s^{-1} cm^{-2} (for individual detections)

Dual AGN

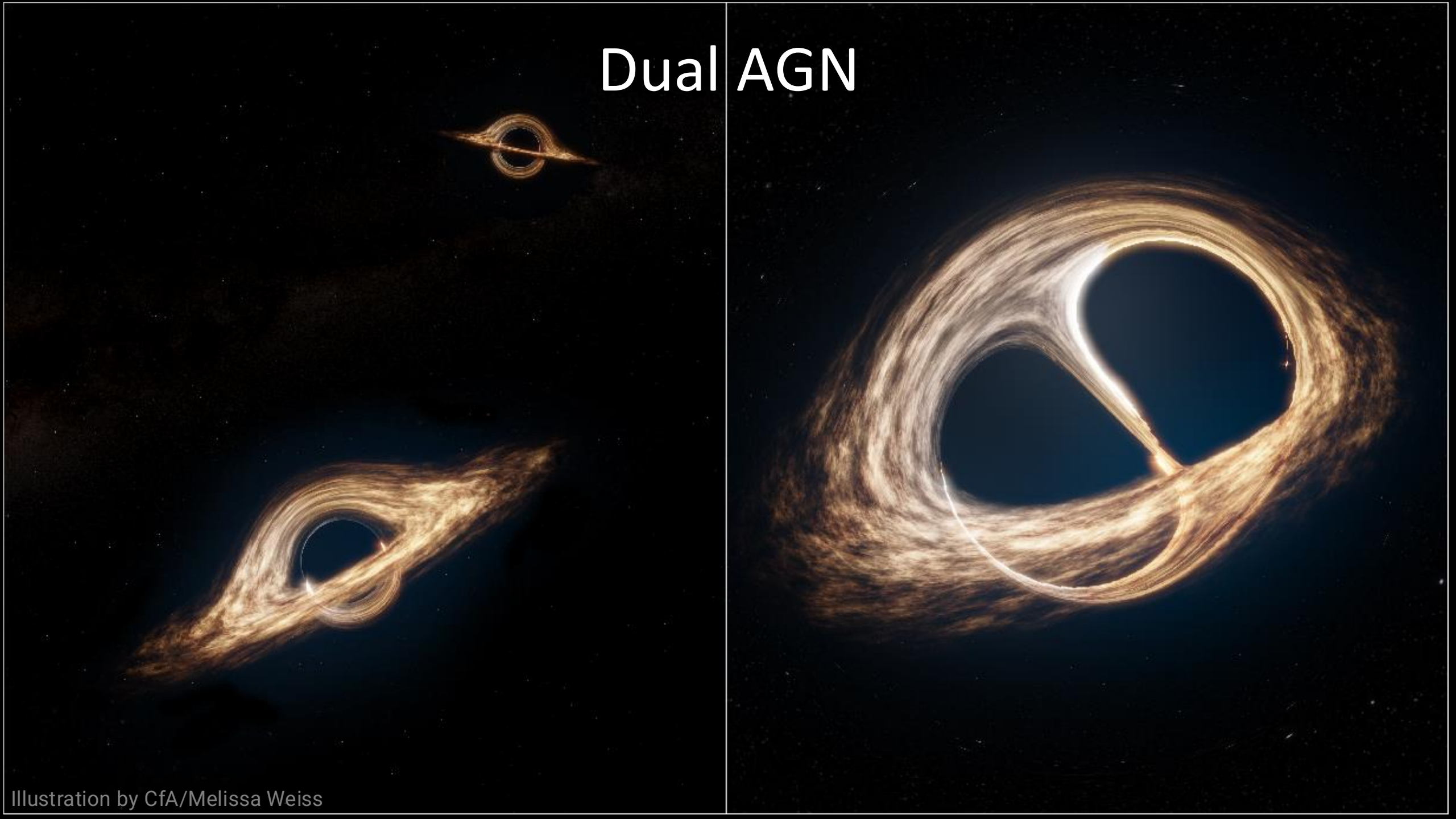


Illustration by CfA/Melissa Weiss

Dual AGN

Dual AGN

1 arcsec @ z ~ 6: 4 kpc → **0.5 arcsec resolves ~kpc pairs**

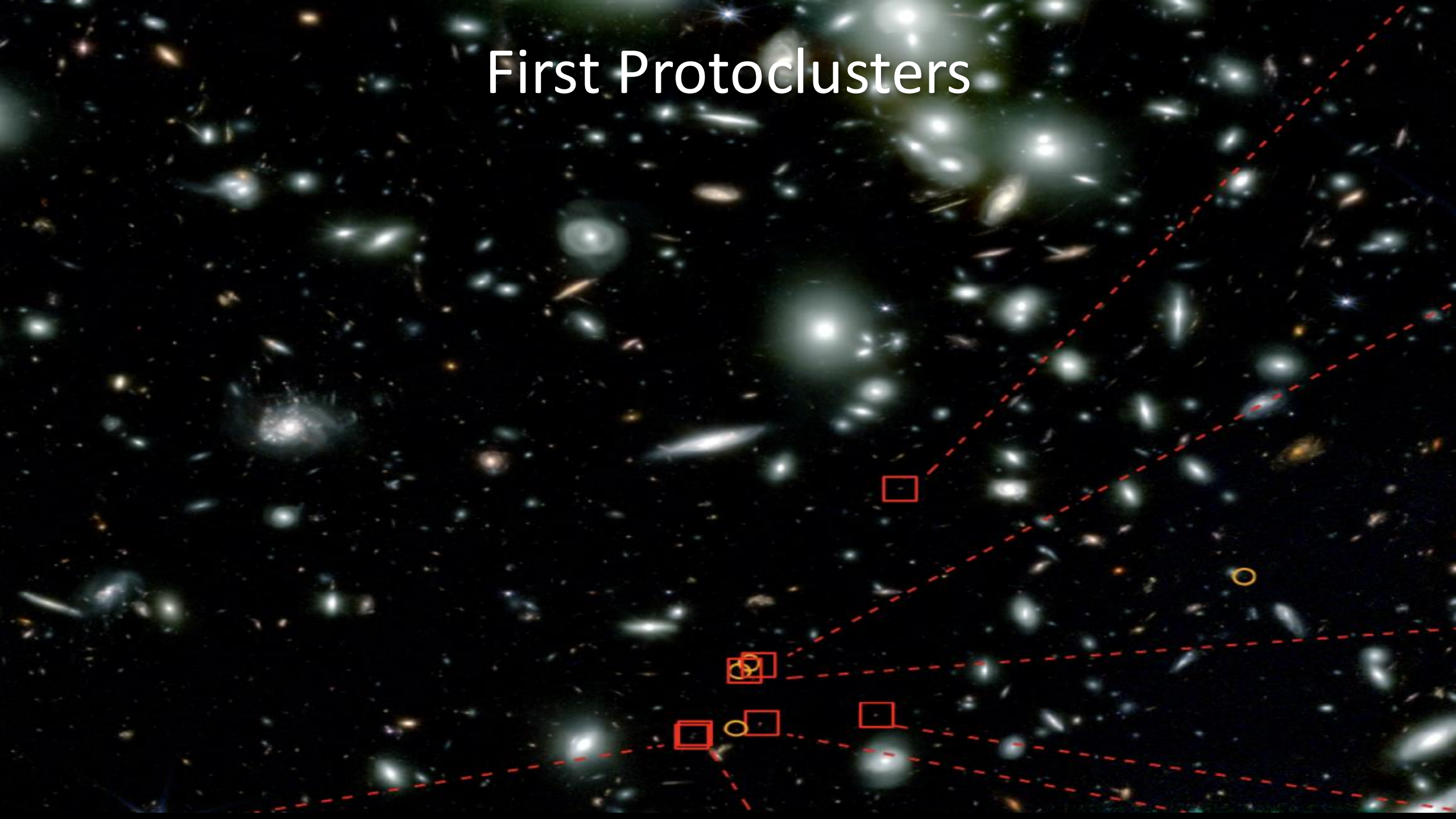
Requirement #5

For ~ 1 kpc pairs at z ~ 6:

- $F_{0.5\text{-}2} \lesssim 10^{-18}$ erg s^{-1} cm^{-2}
- PSF $\lesssim$ 0.5″

Illustration by CfA/Melissa Weiss

First Protoclusters



First Protoclusters

Proto-cluster Hot Gas

$F \approx 10^{-18}$ erg cm^{-2} s^{-1} over ~50 arcsec^2 → **$S \approx 2\times10^{-20}$ erg cm^{-2} s^{-1} arcsec^{-2}**

Requirement #6

- $S \lesssim 10^{-20}$ erg s^{-1} cm^{-2} arcsec^{-2}

Summary of Requirements

	FLUX THRESHOLD 0.5–2.0 keV [erg/s/cm²]	PSF half-power radius	SURVEY AREA	ENERGY RESOLUTION
1 Black hole seeds · $z \gtrsim 6$	10^{-19}	$\lesssim$ 0.5 arcsec		
2 Seed demographics · $z \gtrsim 8$	10^{-19}		$\gtrsim$ 1 deg²	
3 Little Red Dots · $z \sim 4$–10	10^{-18}			
4 First galaxies · $z \gtrsim 8$	10^{-18}			
5 Dual AGN · $z \gtrsim 6$	10^{-18}	$\lesssim$ 0.5 arcsec		
6 Proto-cluster hot gas · $z \gtrsim 5$	10^{-18} diffuse 2×10^{-20} arcsec^{-2}			few eV (Fe-K)

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COMBINED REQUIREMENTS	$\sim 10^{-19}$	$\lesssim$ 0.5 arcsec	$\gtrsim$ 1 deg²	few eV

What Lit Up the Universe?

Revealing the Hidden Engines of Cosmic Dawn with a Next-Generation X-ray Observatory

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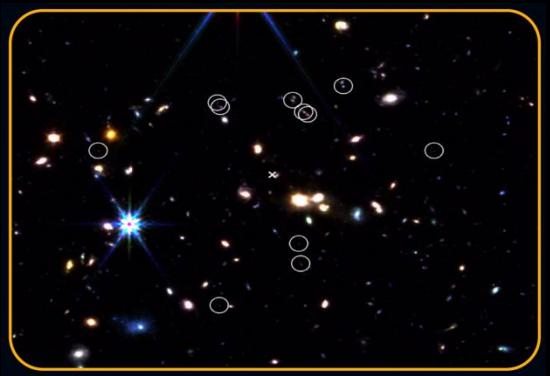

JWST Revealed the Sources

X-Rays Will Reveal the Engines