Detecting Elusive Black Holes in the JWST Era

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<u>In collaboration with:</u>

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Priyamvada Natarajan
Angelo Ricarte
Meg Urry
Marta Volonteri
and others…

Elusive AGN in the Next Era

George Mason University, Fairfax (VA), 12 June 2017

Outline

INTRODUCTION: THE FIRST BLACK HOLES

THE CODE: GEMS (Growth of Early Massive Seeds)

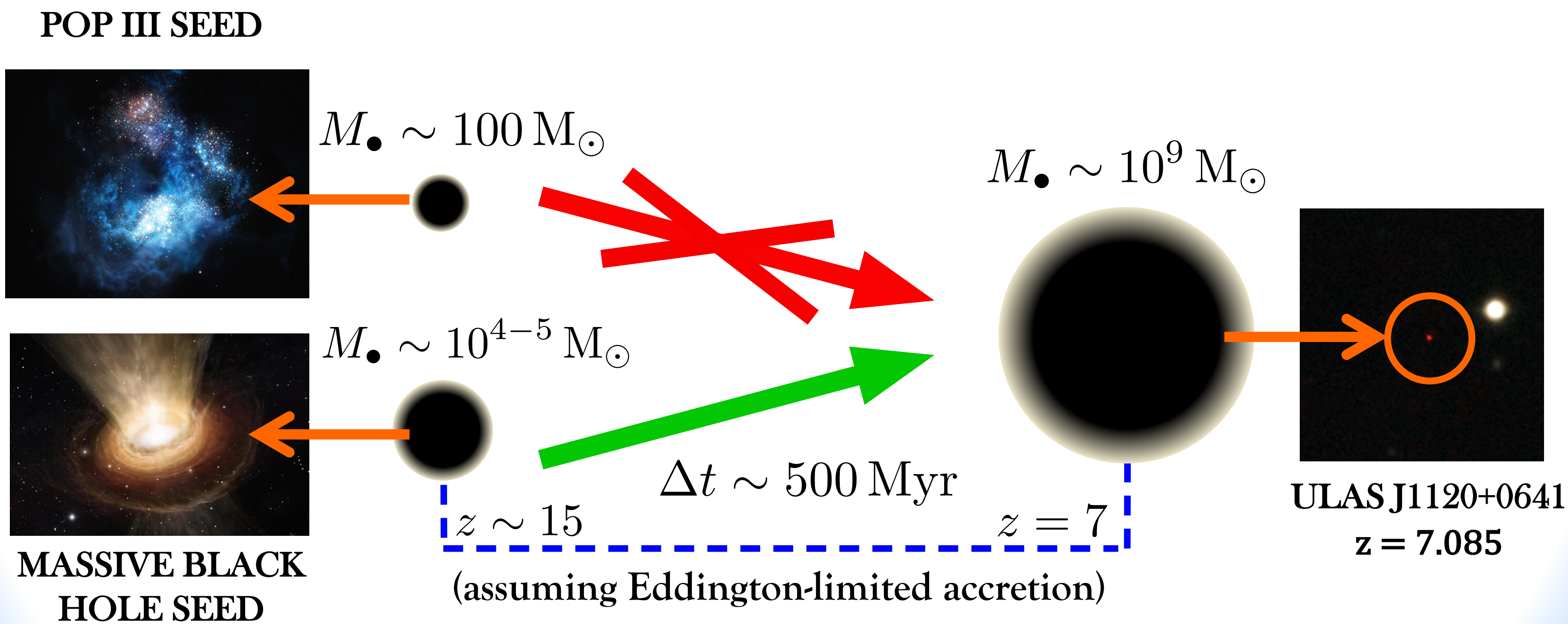
THE SPECTRUM OF THE FIRST BLACK HOLES

THE DETECTION OF THE FIRST BLACK HOLES

The Billion (Dollars) Problem

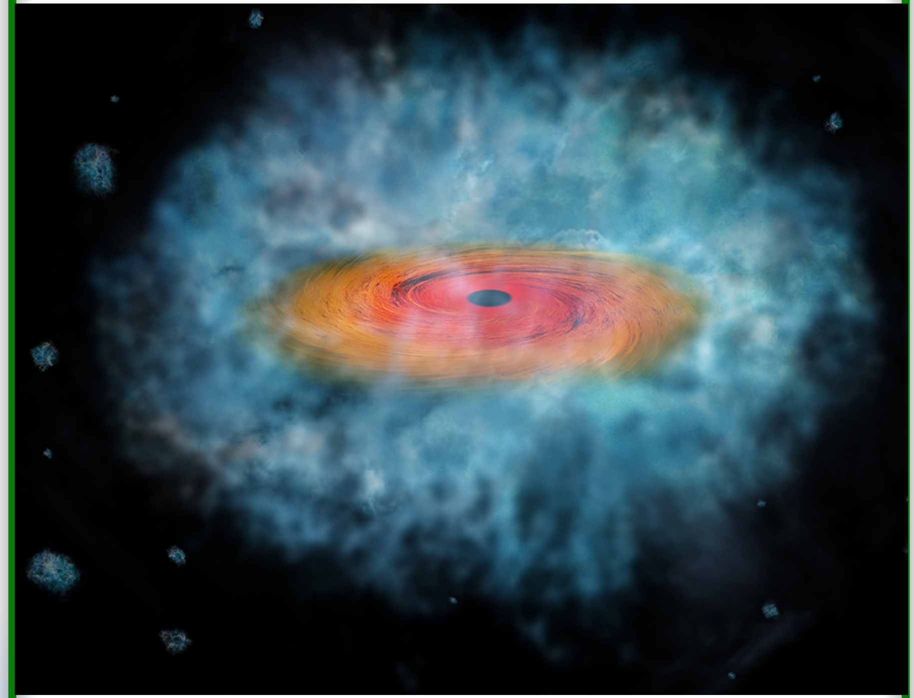
Observations of $10^9\ \mathrm{M}_\odot$ SMBHs < 1 Gyr after the Big Bang

How did they grow up so rapidly?



Making a Massive Seed

Main proposed mechanisms:



Making a DCBH
Host halo & environment:

- Metal-free gas
- Atomic-cooling halo
- Strong Lyman-Werner (11.2 eV – 13.6 eV) flux
- Large inflow rates

Key Questions

THE SPECTRUM OF THE FIRST BLACK HOLES

- What are the emission characteristics of DCBHs?
- Dependence of the DCBH emission on accretion physics.
- How is the spectrum emerging from highly-obscured galaxies?

THE DETECTION OF THE FIRST BLACK HOLES

- Are they observable by current and/or future observatories?
- Survey strategies to find them: the role of HST and JWST

Our Approach:
Analytical + Numerical

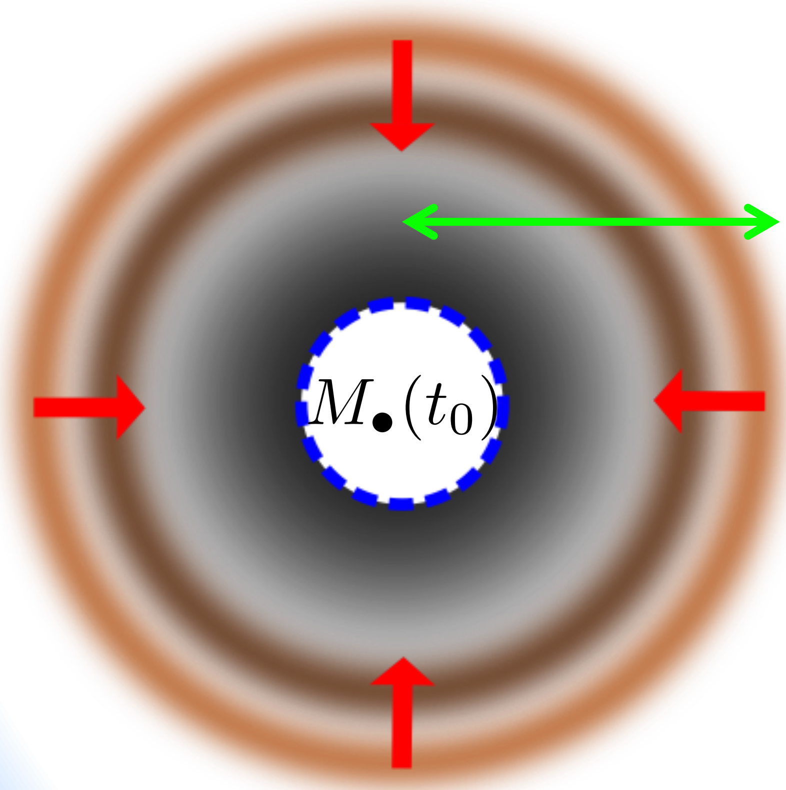
GEMS

CODE

How to Study DCBHs?

Physical Framework:

$T_{\rm vir} \sim 10^4$ K $\quad\quad R \sim R_B$



We do not model the seed formation

Numerical Framework:

GEMS code

(**G**rowth of **E**arly **M**assive **S**eeds):

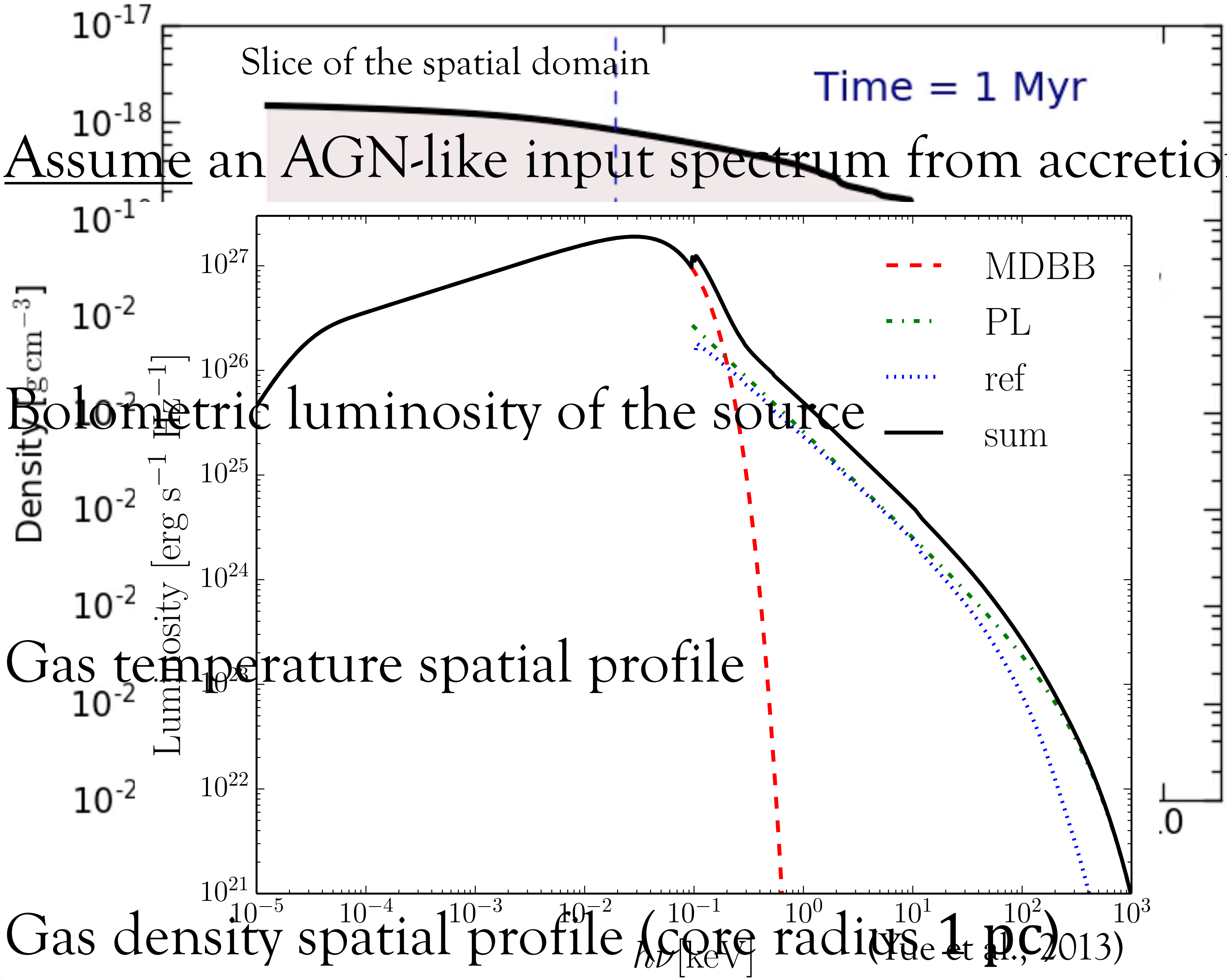
- Spherical symmetry
- Solves Euler's equations
- Solves Radiation Transfer
- Cooling terms: atomic
- Opacity terms: Thomson (main) and electronic transitions

(Pacucci & Ferrara, 2014)

CODE

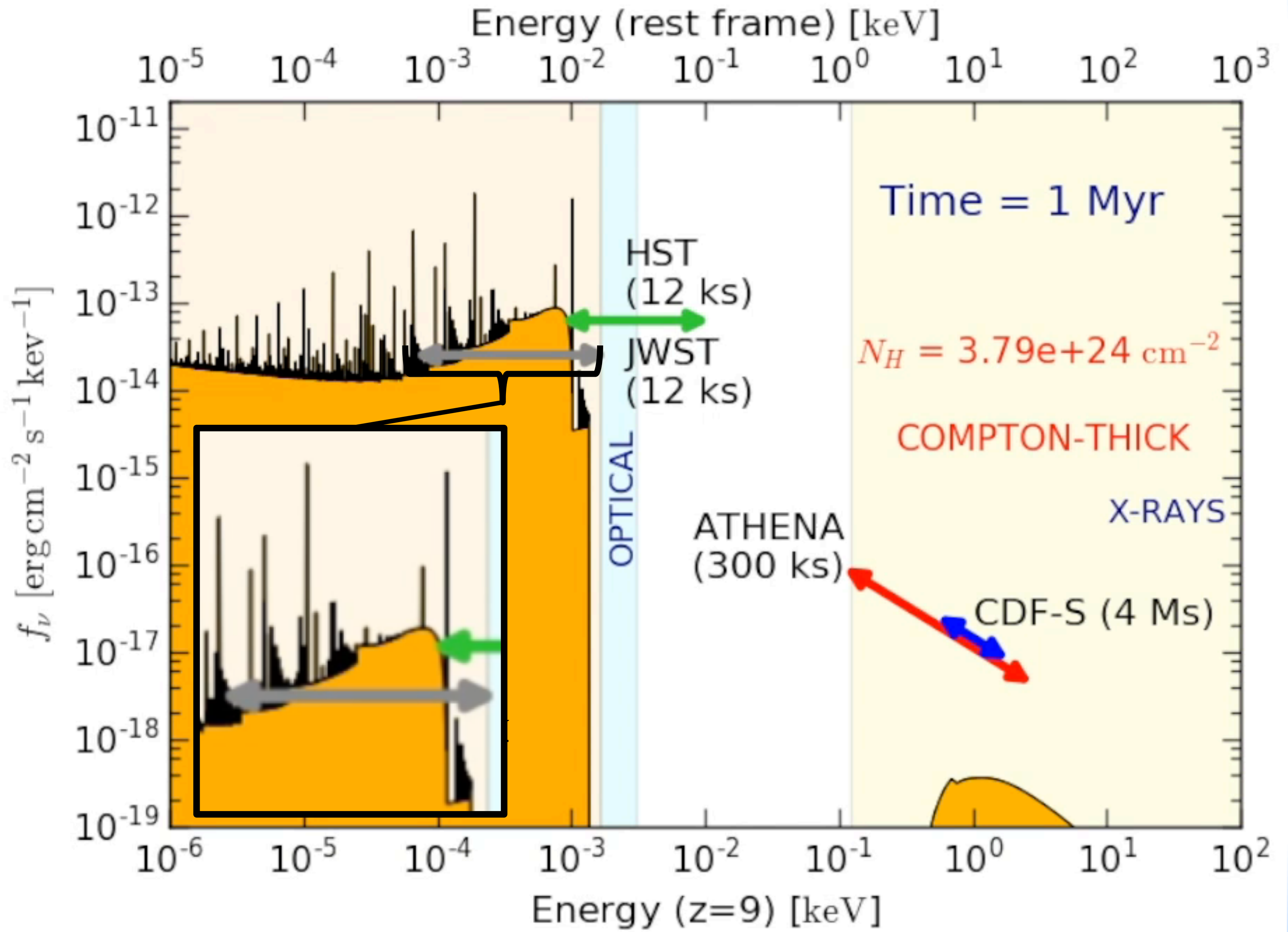
Computing the Spectrum

- Assume an AGN-like input spectrum from accretion
- Bolometric luminosity of the source
- Gas temperature spatial profile
- Gas density spatial profile (core radius 1 pc)

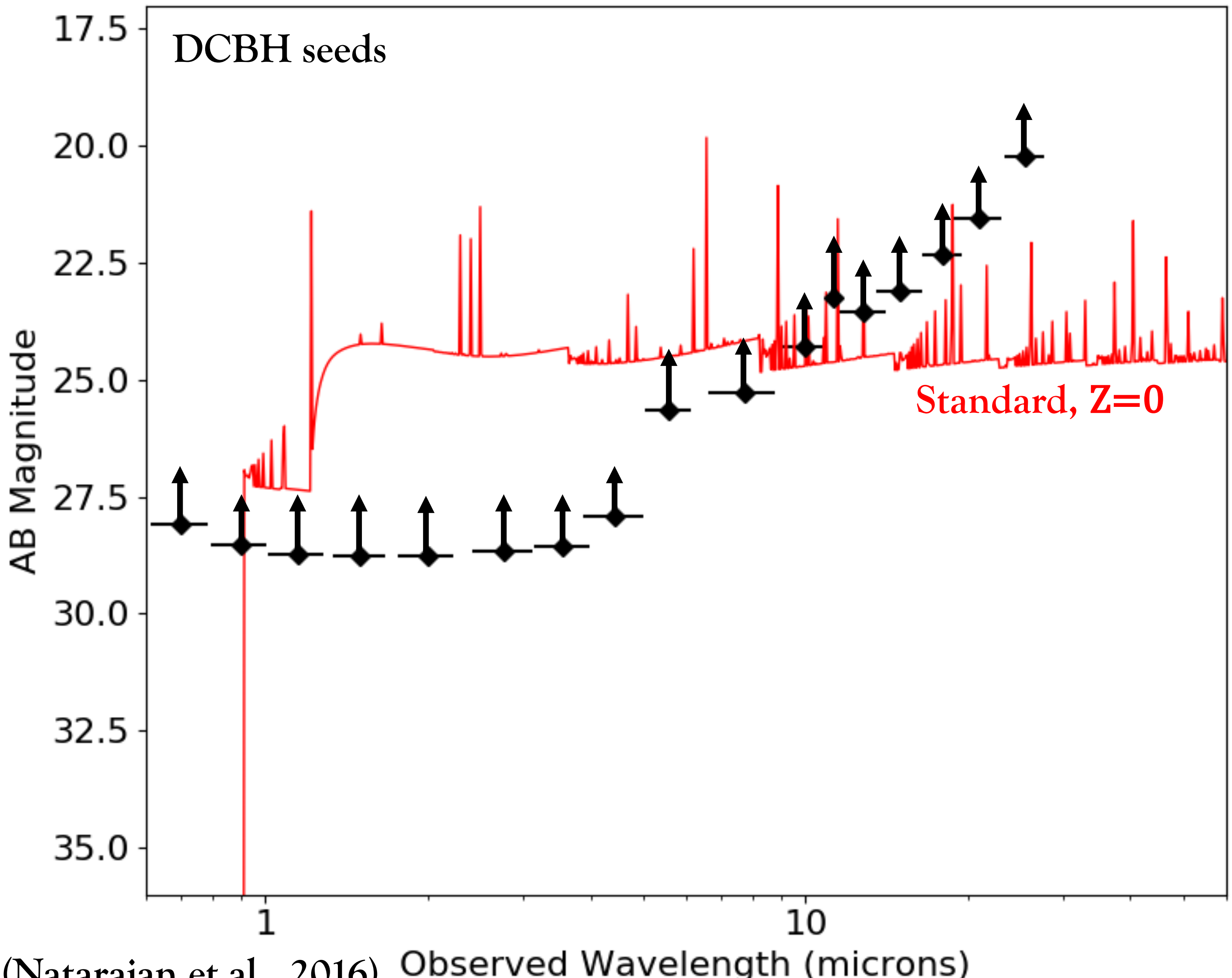


(Yue et al., 2013)

The Spectrum of a DCBH

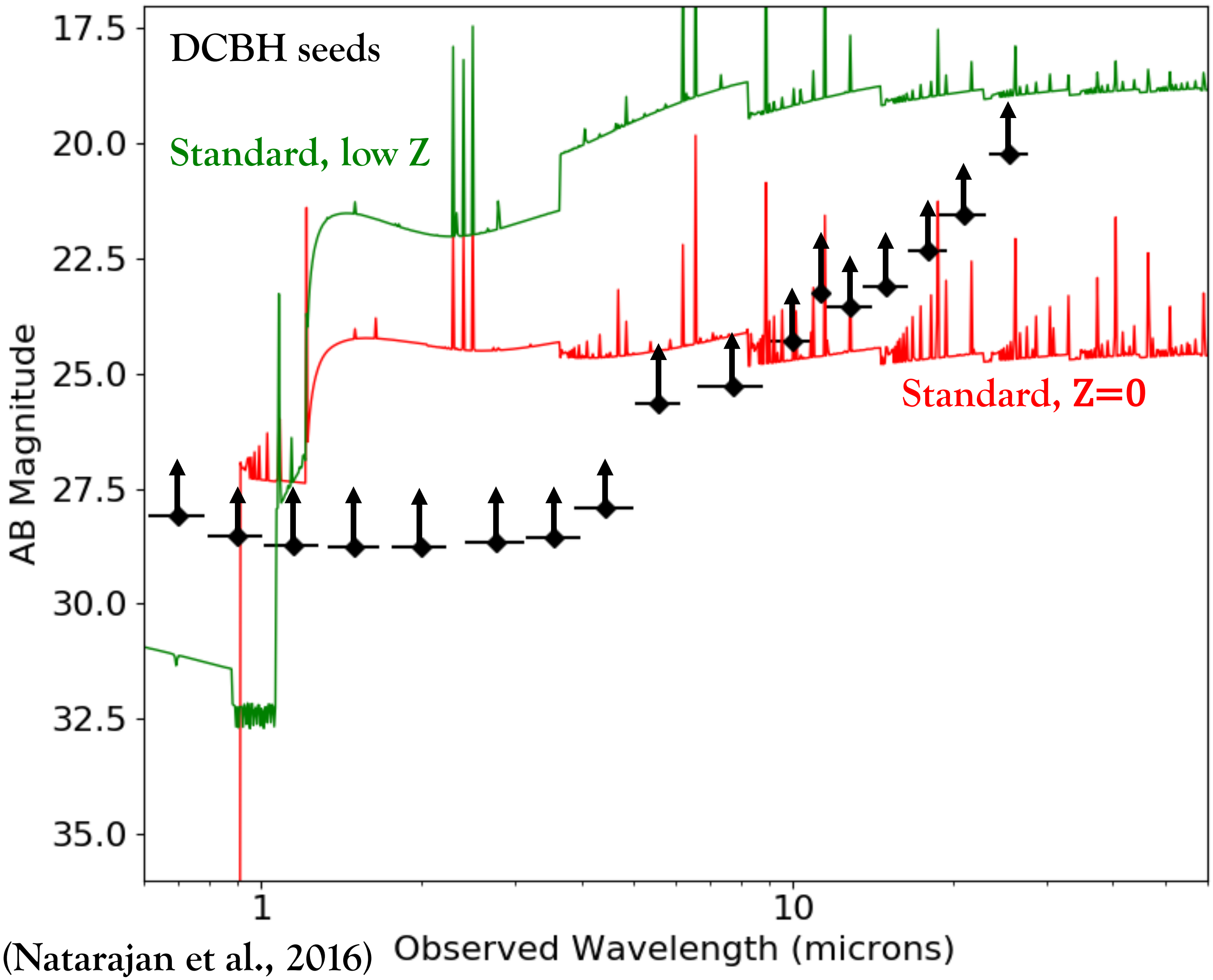


Detecting DCBHs with JWST



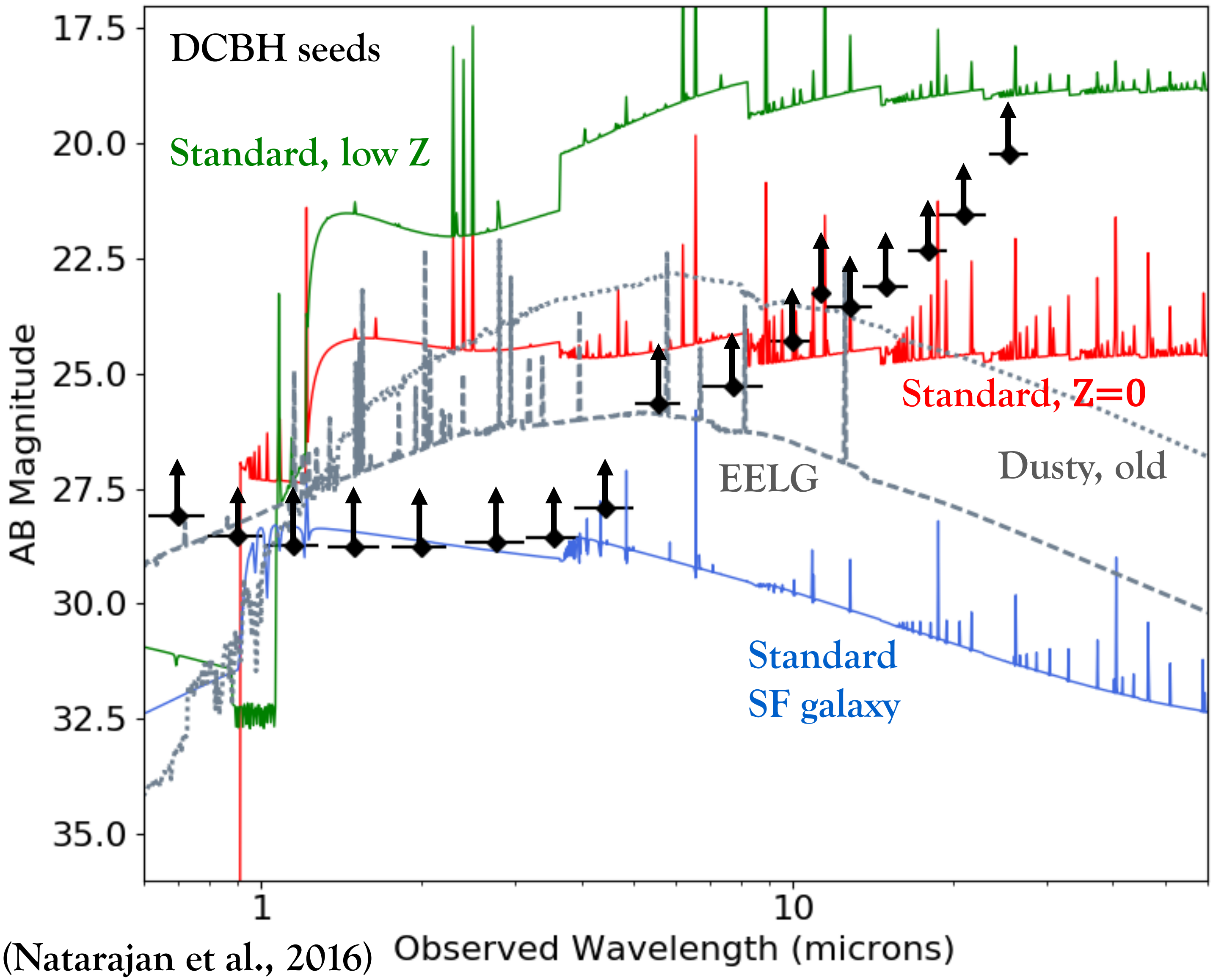
(Natarajan et al., 2016)

Detecting DCBHs with JWST



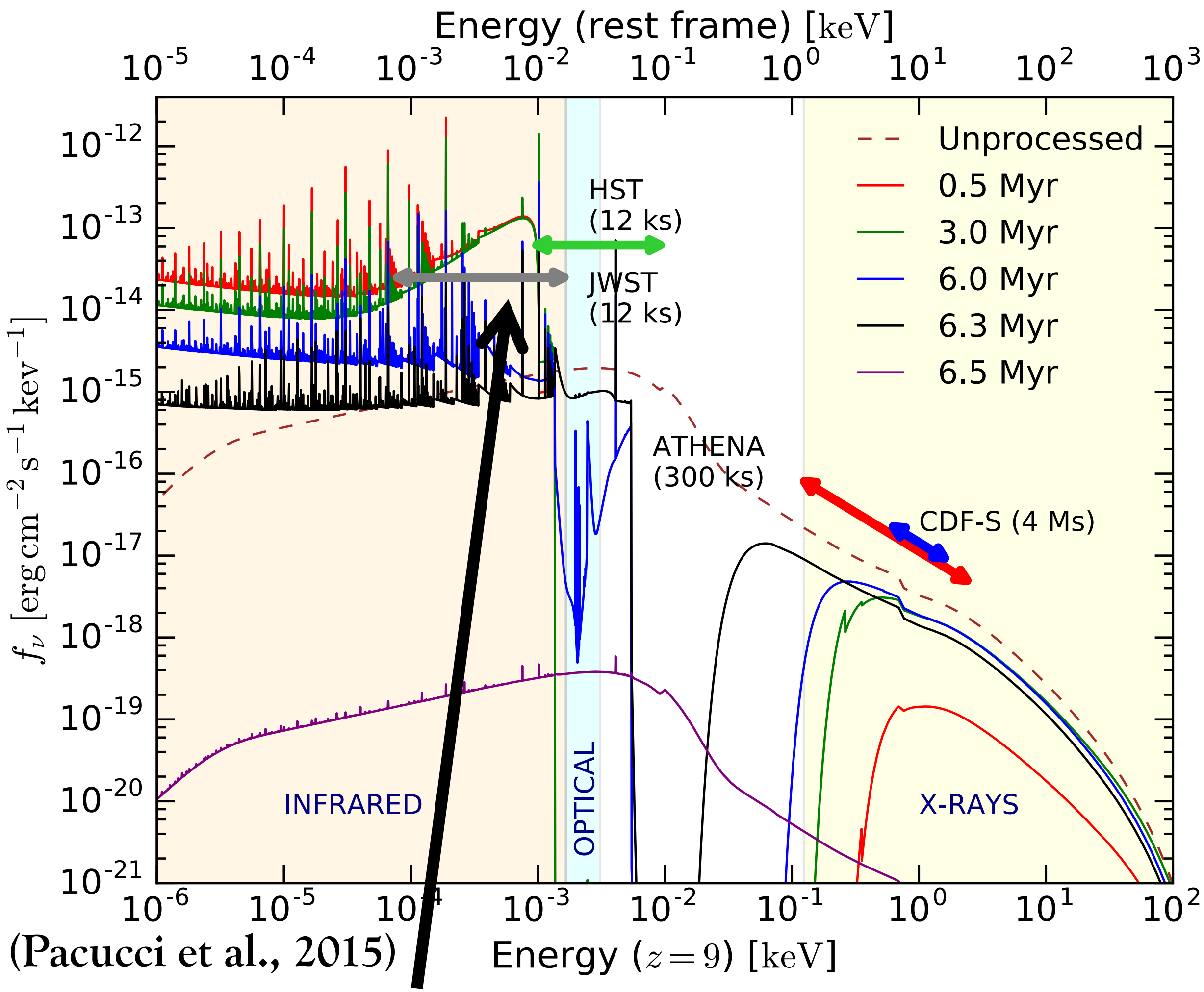
(Natarajan et al., 2016)

Detecting DCBHs with JWST



(Natarajan et al., 2016)

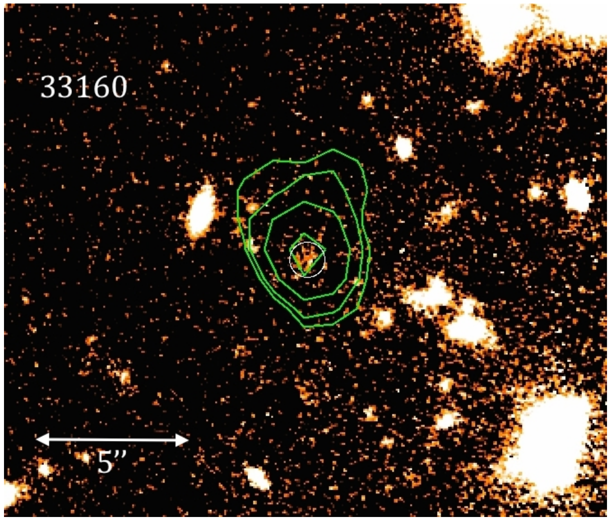
Elusive Black Holes



(Pacucci et al., 2015)

The JWST will be the key observatory to unravel the obscured population of black holes

Status of Black Hole Seeds Searches



DCBH candidate at z = 6.06

SURVEYS

Photometric selection and background fluctuations (IR/X)

Two DCBH candidates in GOODS-S at **z>6**

(Pacucci et al., 2016)

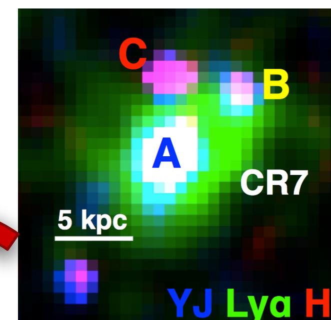
SINGLE SOURCES

The case of CR7 (LAE at z=6.6)

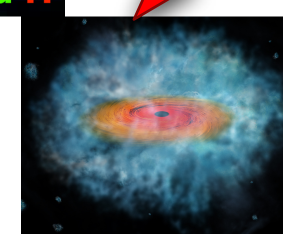
(e.g. Sobral et al., 2015):

- No metal lines
- Strong Lya and He II lines (but see Shibuya et al., 2017)

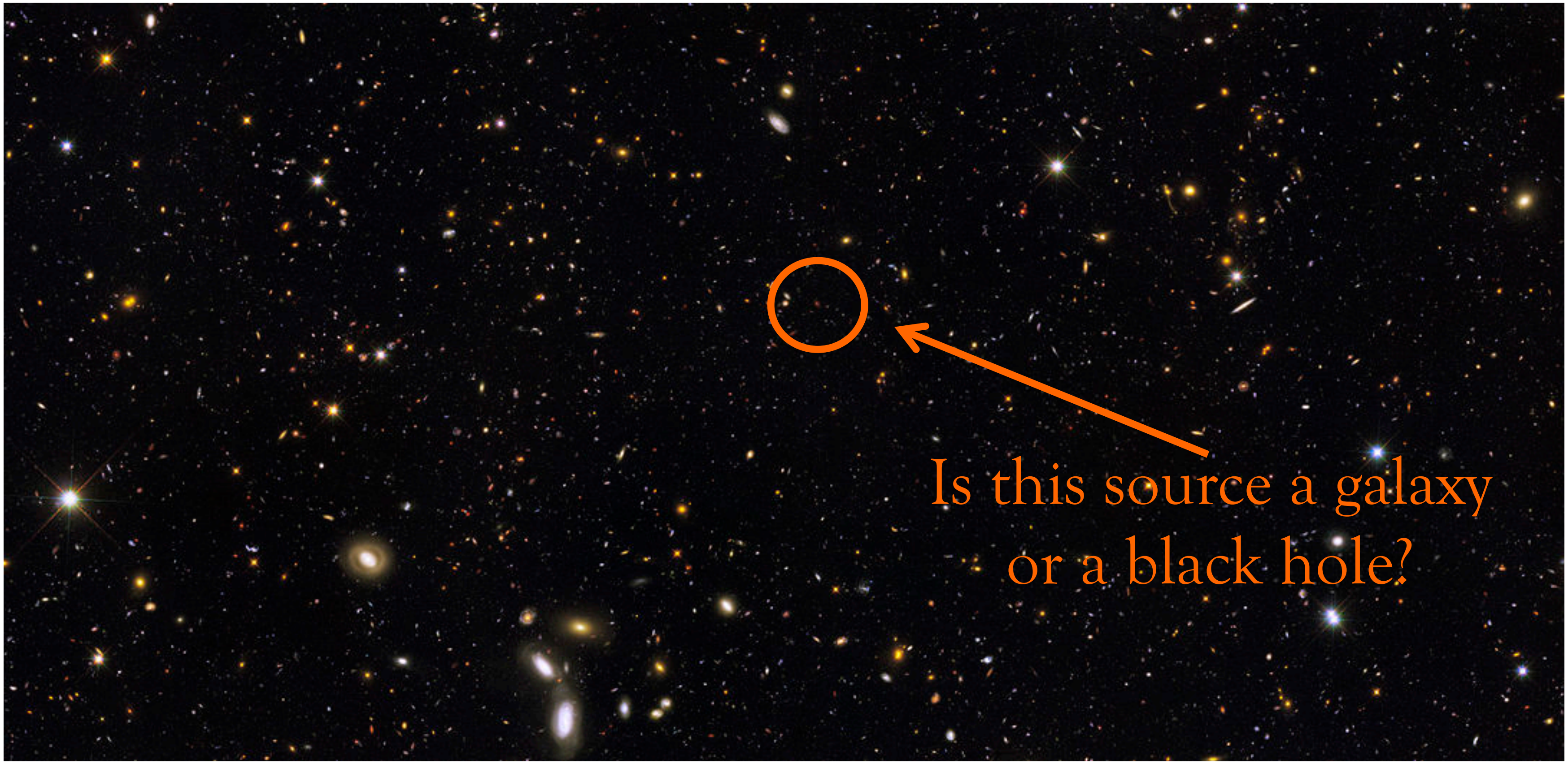
Pop III stars



DCBH

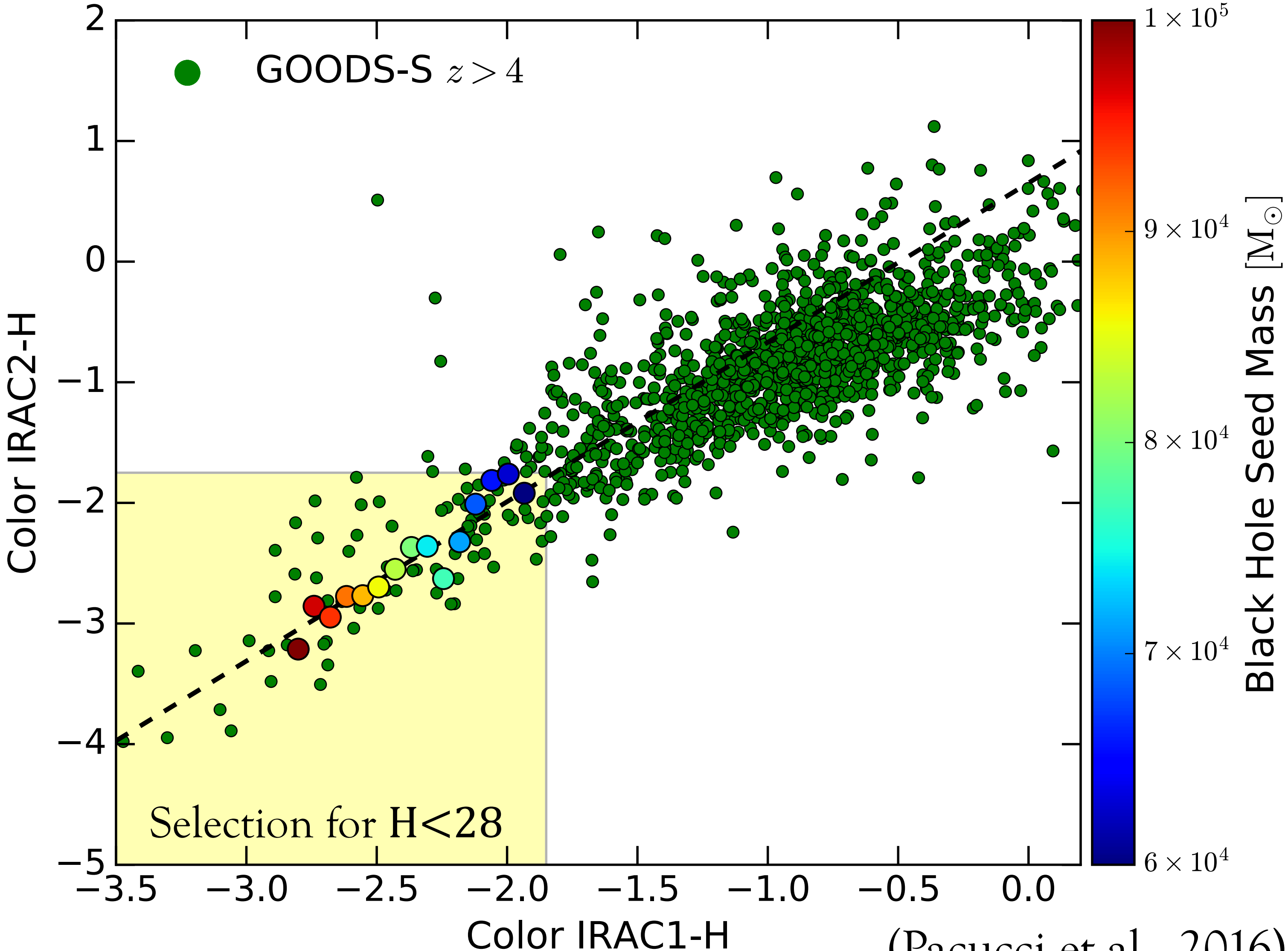


Photometric Searches of the First Black Holes



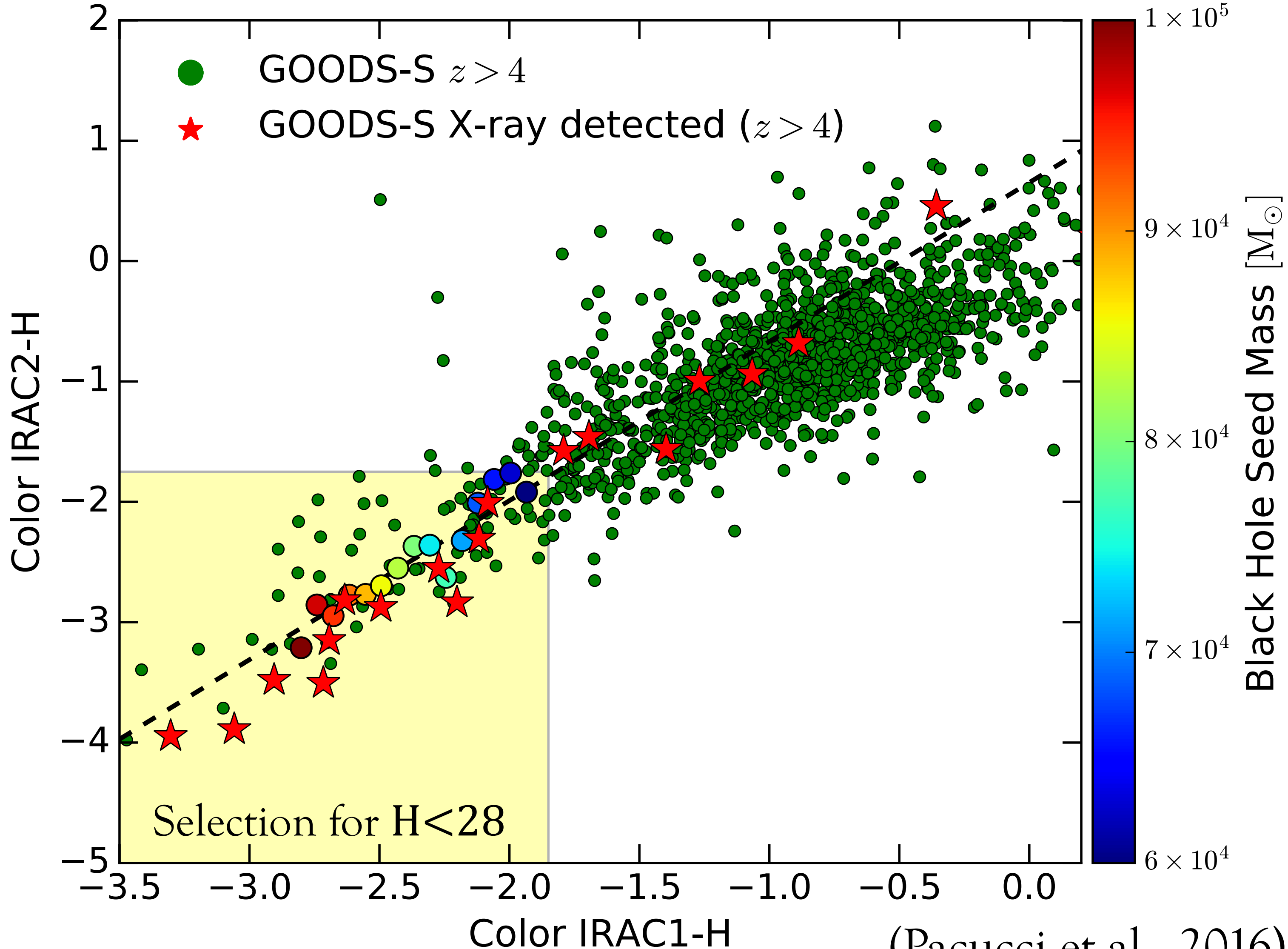
CANDELS GOODS Field

Photometry of DCBHs



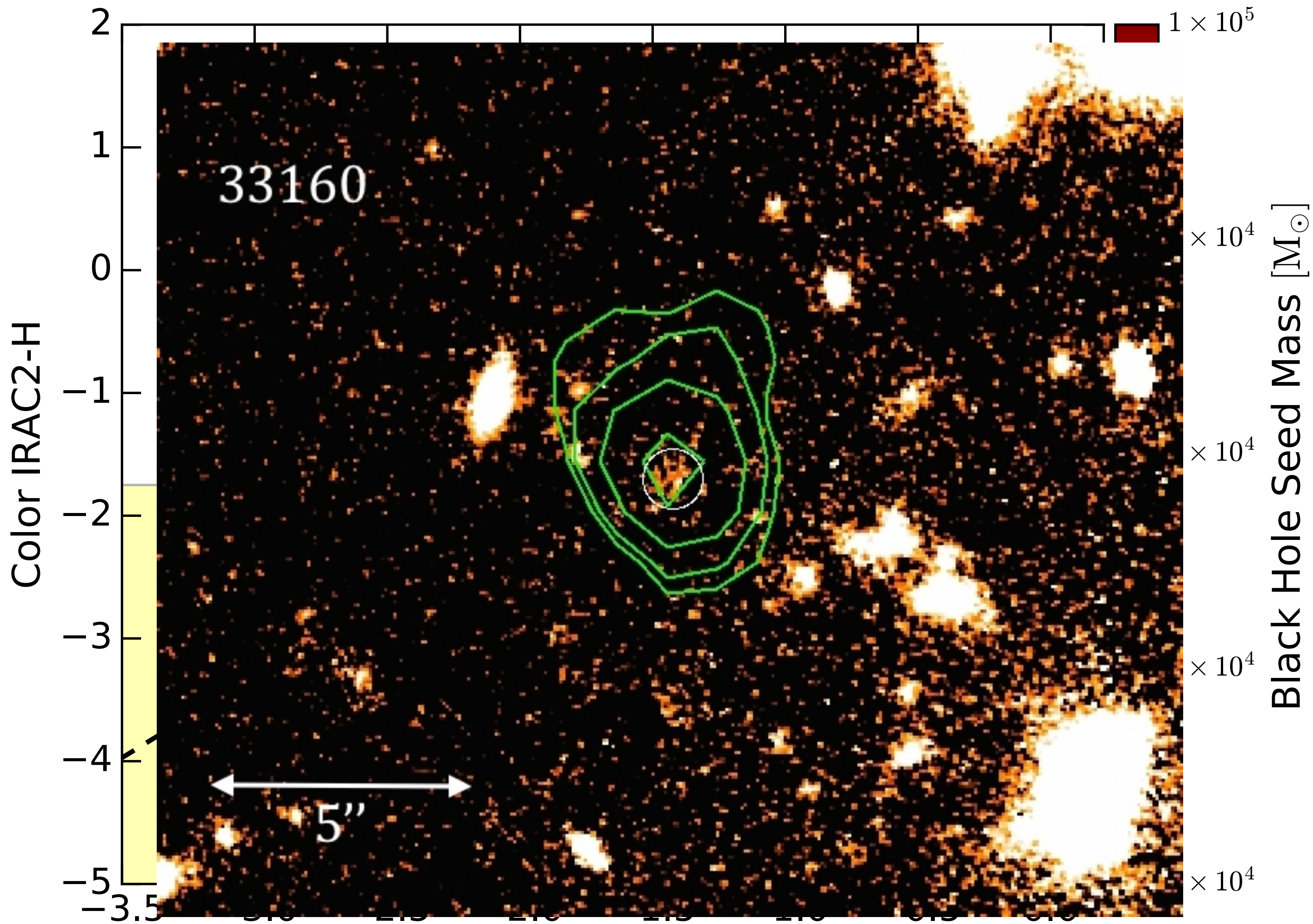
(Pacucci et al., 2016)

X-ray Detected Objects in GOODS-S



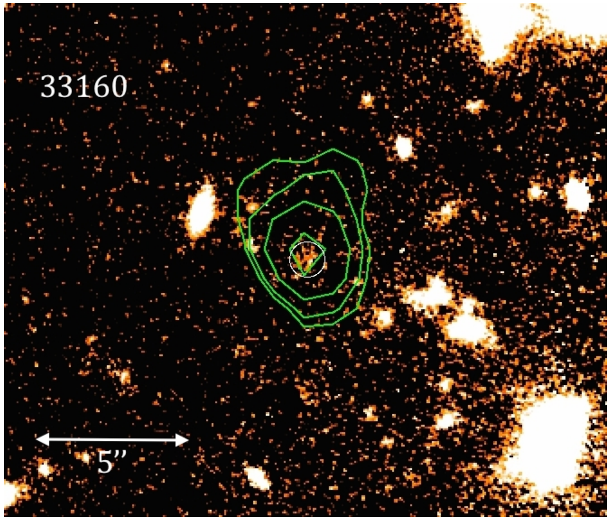
(Pacucci et al., 2016)

DCBH Candidates in GOODS-S



DCBH candidate at **z = 6.06** (Pacucci et al., 2016)

Status of Black Hole Seeds Searches



DCBH candidate at z = 6.06

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Two DCBH candidates in GOODS-S at z>6

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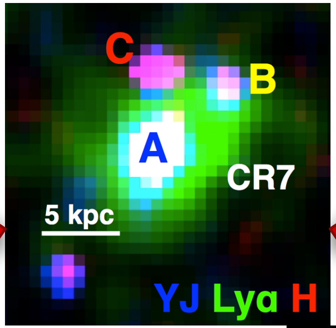
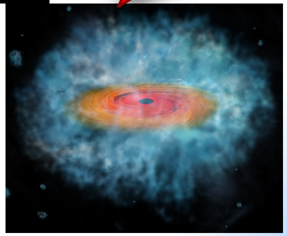


Pop III stars

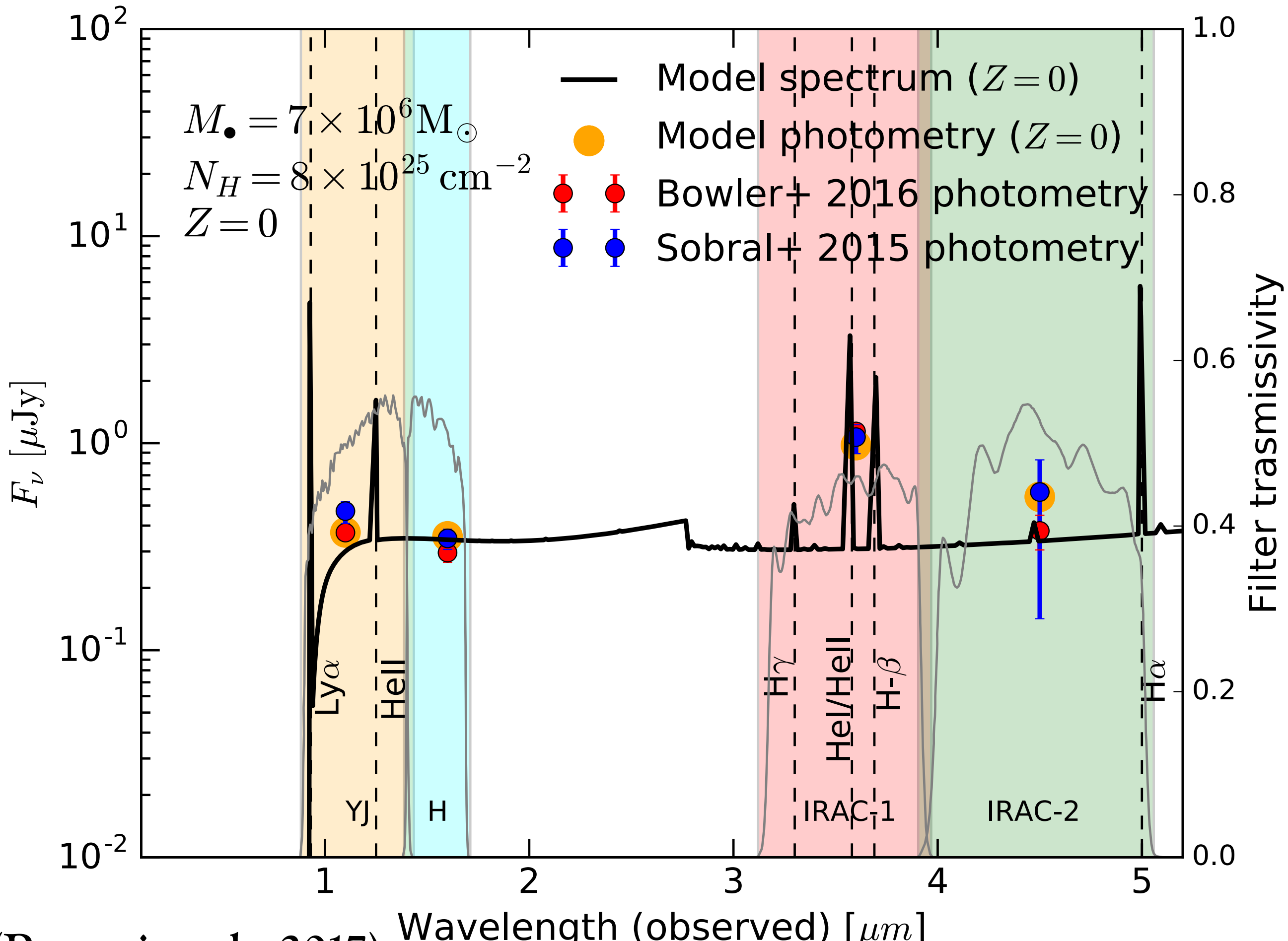
DCBH



The Nature of CR7: a Persisting Puzzle

The photometry of CR7 can be fitted by our DCBH model.

Zero metallicity model

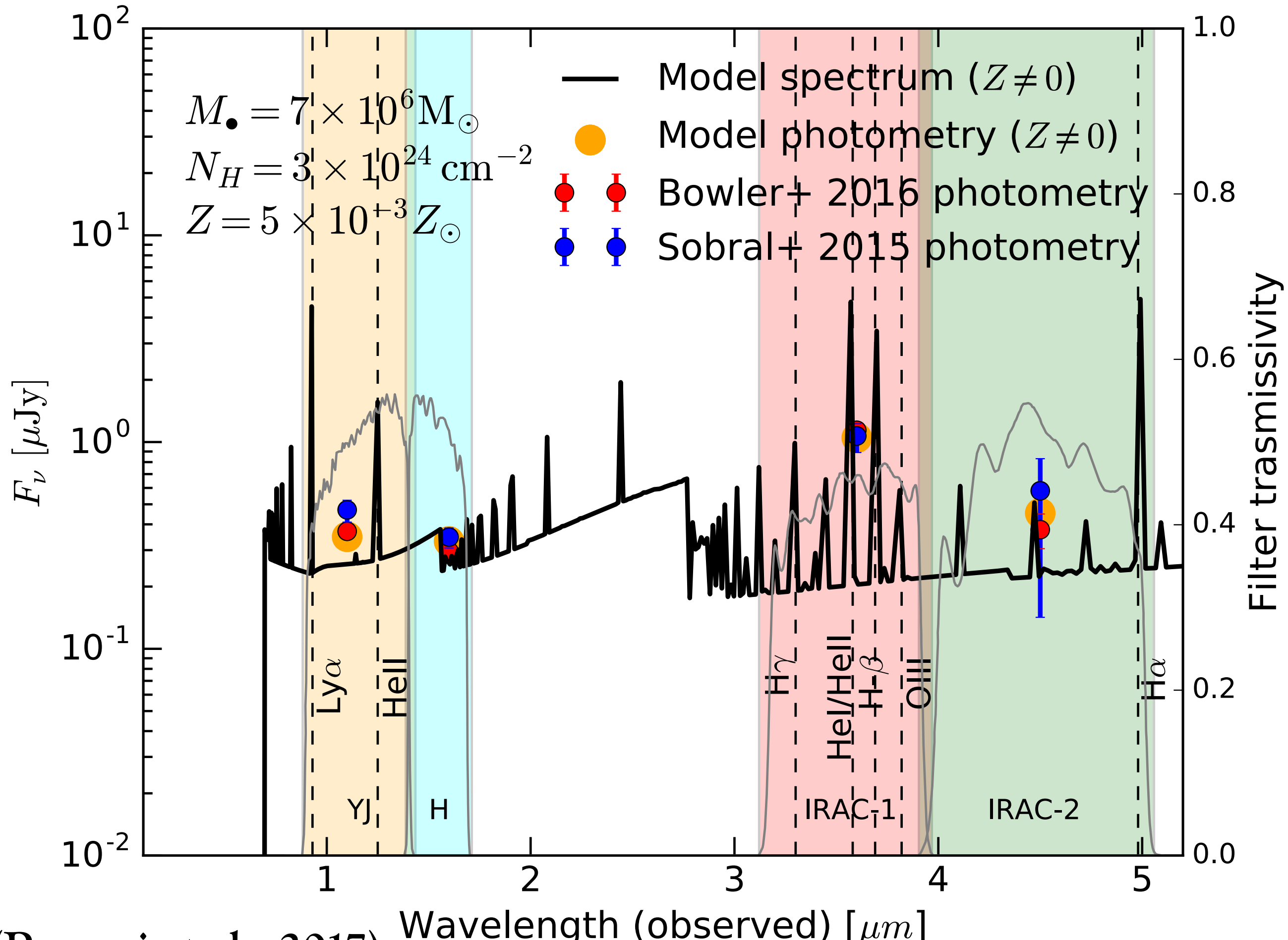


(Pacucci et al., 2017)

The Nature of CR7: a Persisting Puzzle

The photometry of CR7 can be fitted by our DCBH model.

Low metallicity model (see also Agarwal et al., 2017)



(Pacucci et al., 2017)

CR7: a Variability Study with HST

UV variability would **favor** the **black hole** interpretation.

Cycle 24 HST observation
PI: Xiaohui Fan

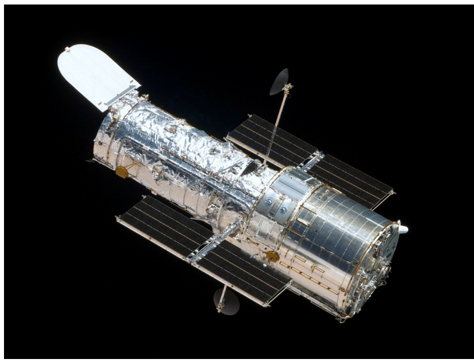
Predictions

- Predicted variability of CR7: **0.15-0.2** mag in rest-frame UV
- Short (one month) and long (one year) term rest-frame variability

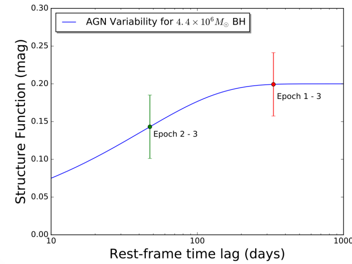
Observations

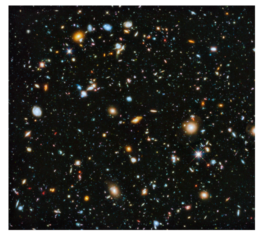
- Deep F110W and F160W exposures of CR7
- Observations separated by 300 days (40 days rest-frame)

HST/JWST Synergy

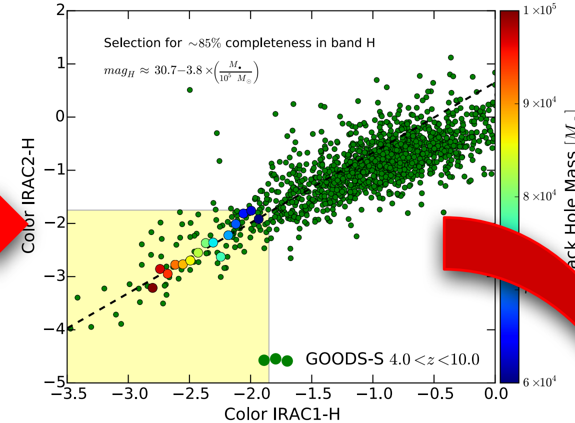


HST

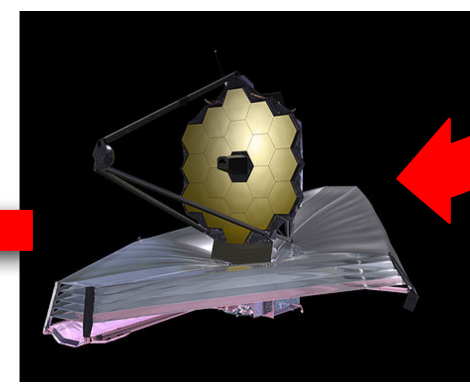




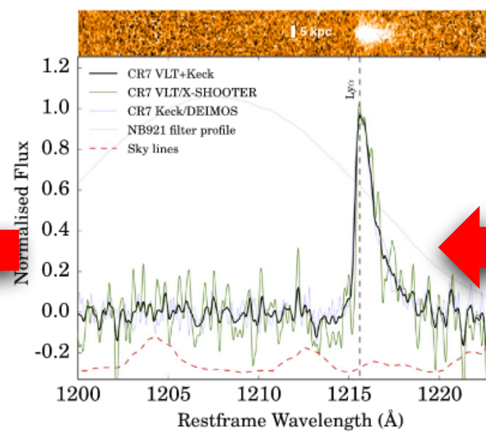
Deep fields/variability



Photometric selection



JWST



Hi-Res spectra

Detection of the first black holes

Conclusions

OBSERVABILITY OF THE FIRST BLACK HOLES

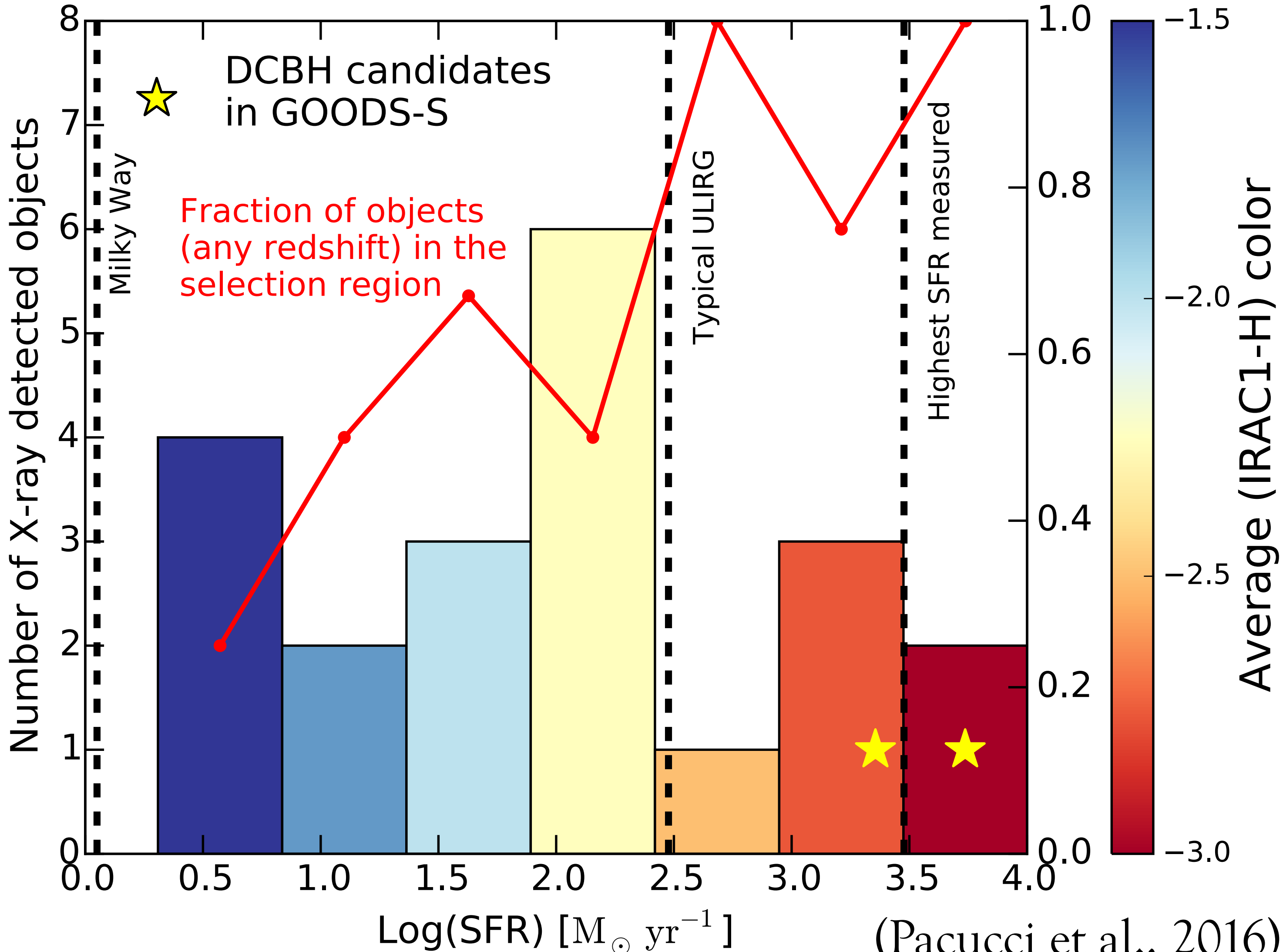
- DCBHs emit in infrared and X-ray
- Elusive black holes only observable in the infrared
- Two DCBH candidates detected in a GOODS-S (HST + Chandra)
- Photometry of CR7 compatible with a DCBH model
- DCBH selection criteria for JWST have been developed
- **JWST: principal observatory to search for the first black holes**

FUTURE PROSPECTS

- Study of the variability of CR7 with HST
- Search for more DCBH candidates in e.g. Stripe 82, GOODS-N
- High-resolution spectra of the first black holes with JWST
- **Strong synergy between HST and JWST in this search**

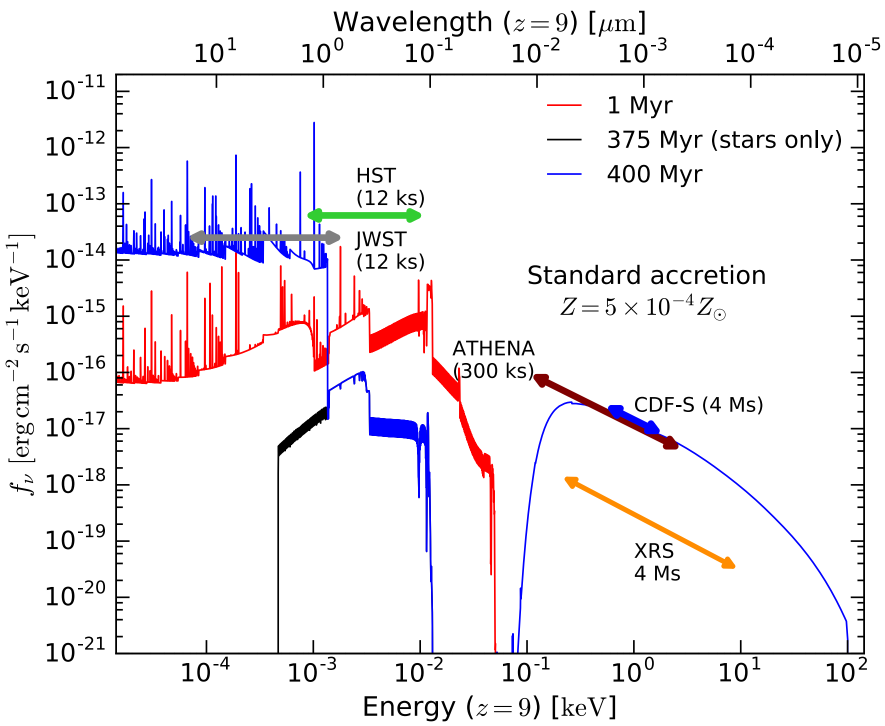
BACKUP SLIDES

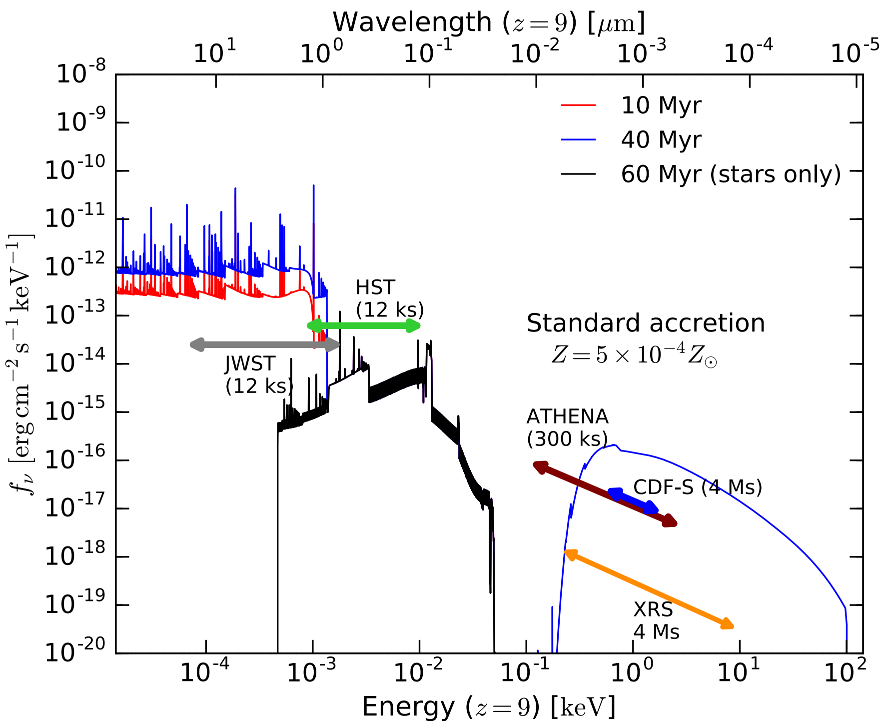
These sources are extremely red!



(Pacucci et al., 2016)

Pop III seed vs. DCBH seed





<u>Pop III seed</u>

Standard accretion model

<u>DCBH seed</u>

Standard accretion model

(Natarajan et al., 2016)

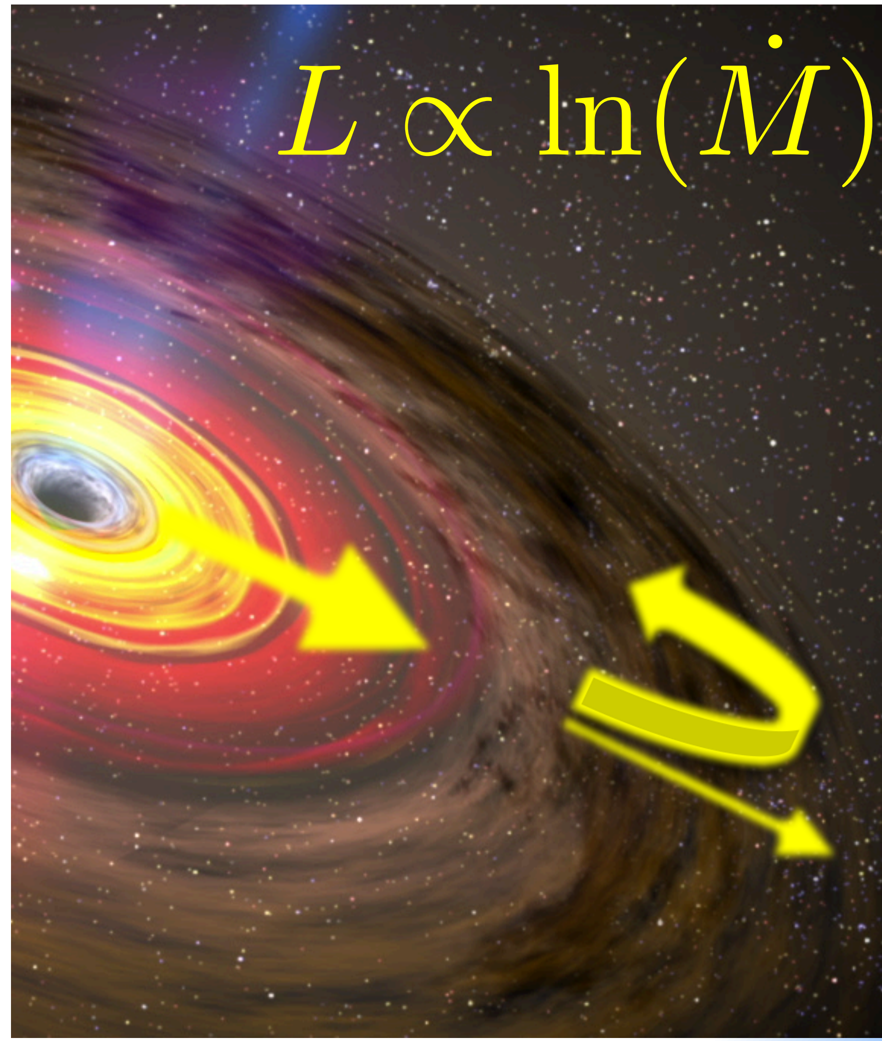
Accretion Models: $L = L(\dot{M})$

Standard Accretion:

$$0.01\dot{M}_{Edd} < \dot{M} < \dot{M}_{Edd}$$

Slim Disk Accretion:

$$\dot{M} > \dot{M}_{Edd}$$



Take-Away Points

SPECTRUM:

- Typical DCBHs detectable by the JWST
- Highly-obscured DCBHs: weaker constraints on high-*z* mass density
- Highly-obscured DCBHs: possibly undetectable in the X-rays but visible in the optical/infrared

DETECTING DCBHs:

- ?

Detecting Direct Collapse Black Holes

Electromagnetic waves

Spectroscopy

Photometry

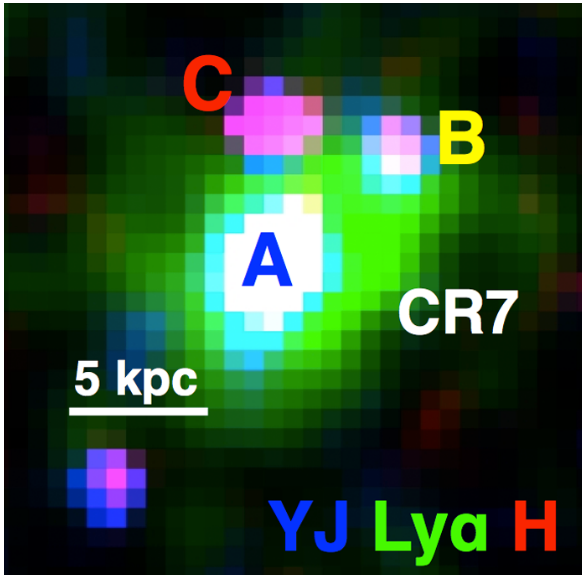
CR7

2 objects in CANDELS/GOODS-S

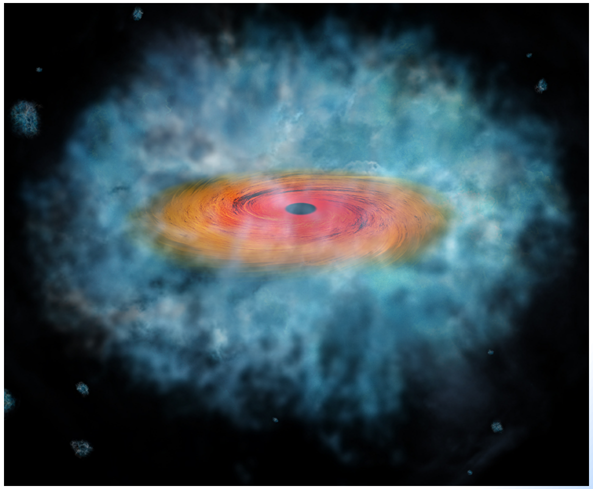
CR7: Black Hole or Early Stars?

Pop III stars

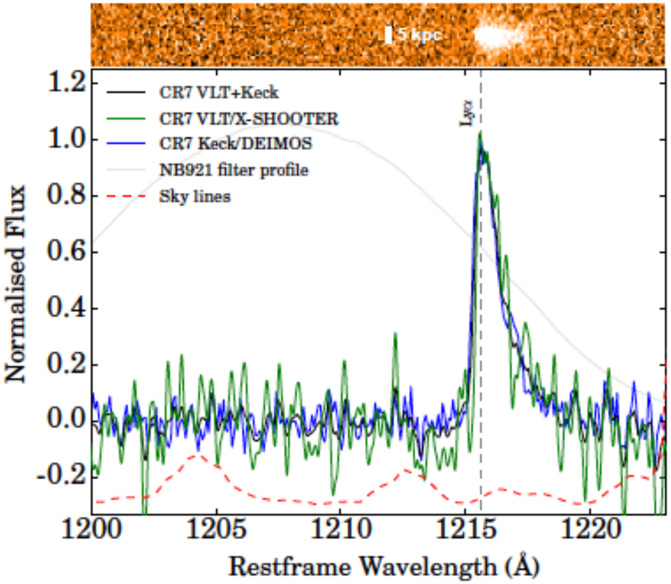
DCBH



(Sobral et al., 2015)

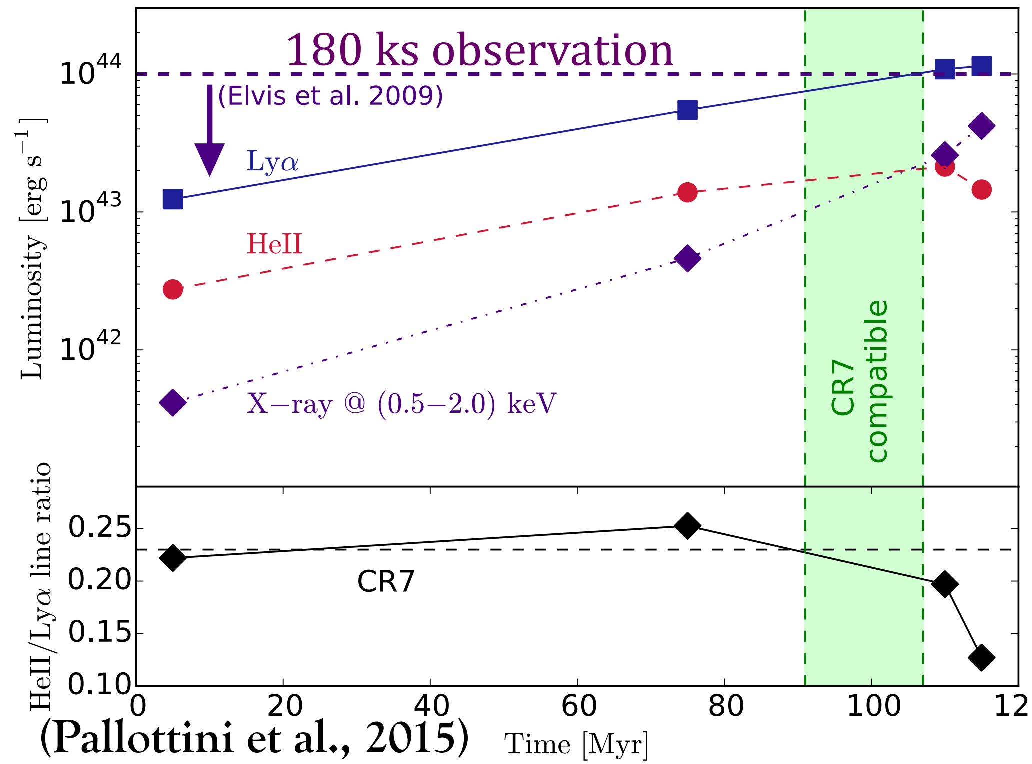


CR7: the DCBH Hypothesis



Main features of CR7 (Sobral et al., 2015):

- z=6.6
- No metal lines
- Strong Lya and He II lines
- Strong Lyman-Werner flux



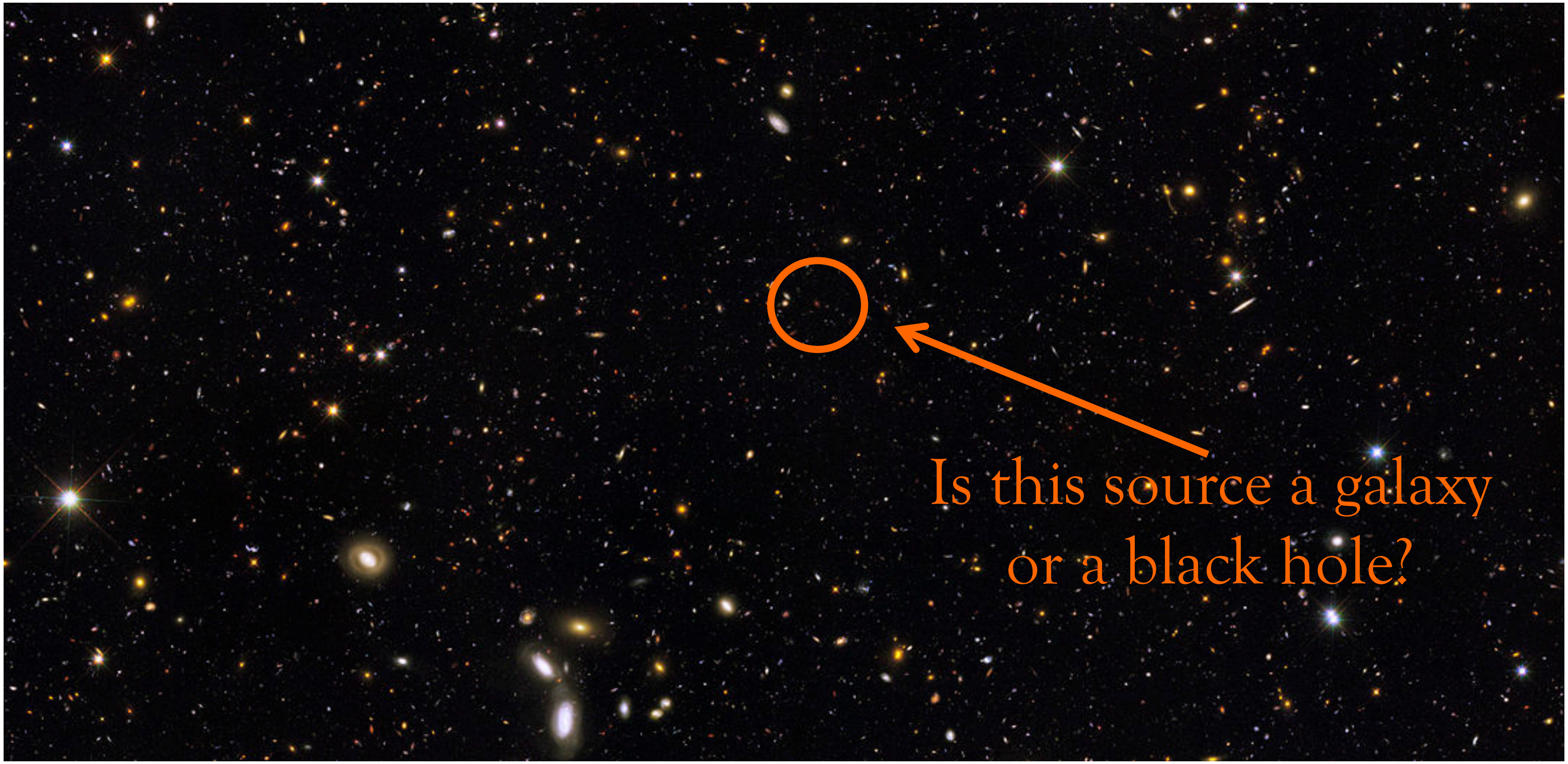
(Pallottini et al., 2015)

Hypothesis:

CR7 is a DCBH

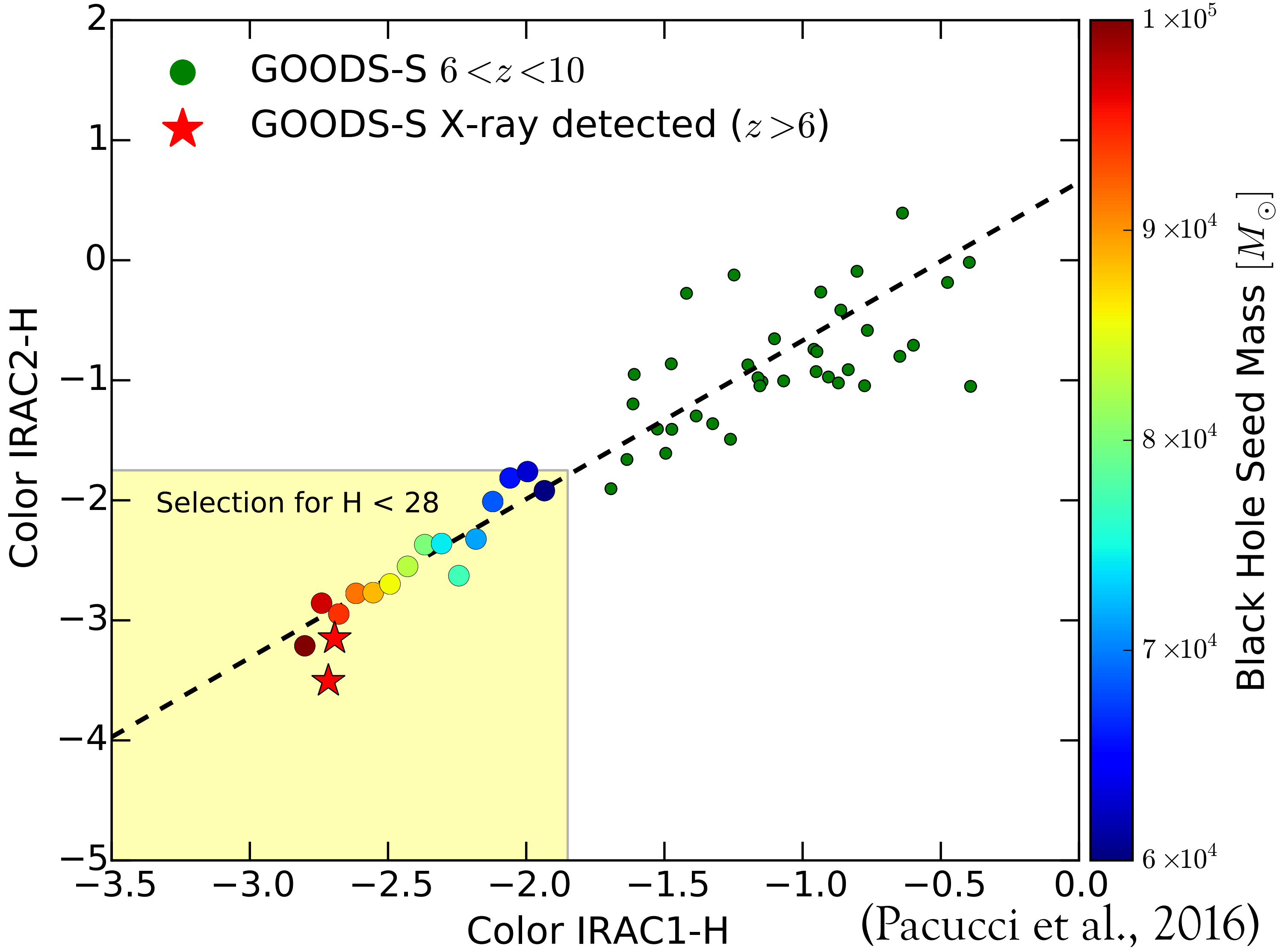
Pallottini, Ferrara, Pacucci et al., 2015:
Agarwal et al., 2015;
Hartwig et al., 2015;
Bowler et al. 2016,
and others

The Quest for Black Hole Seeds



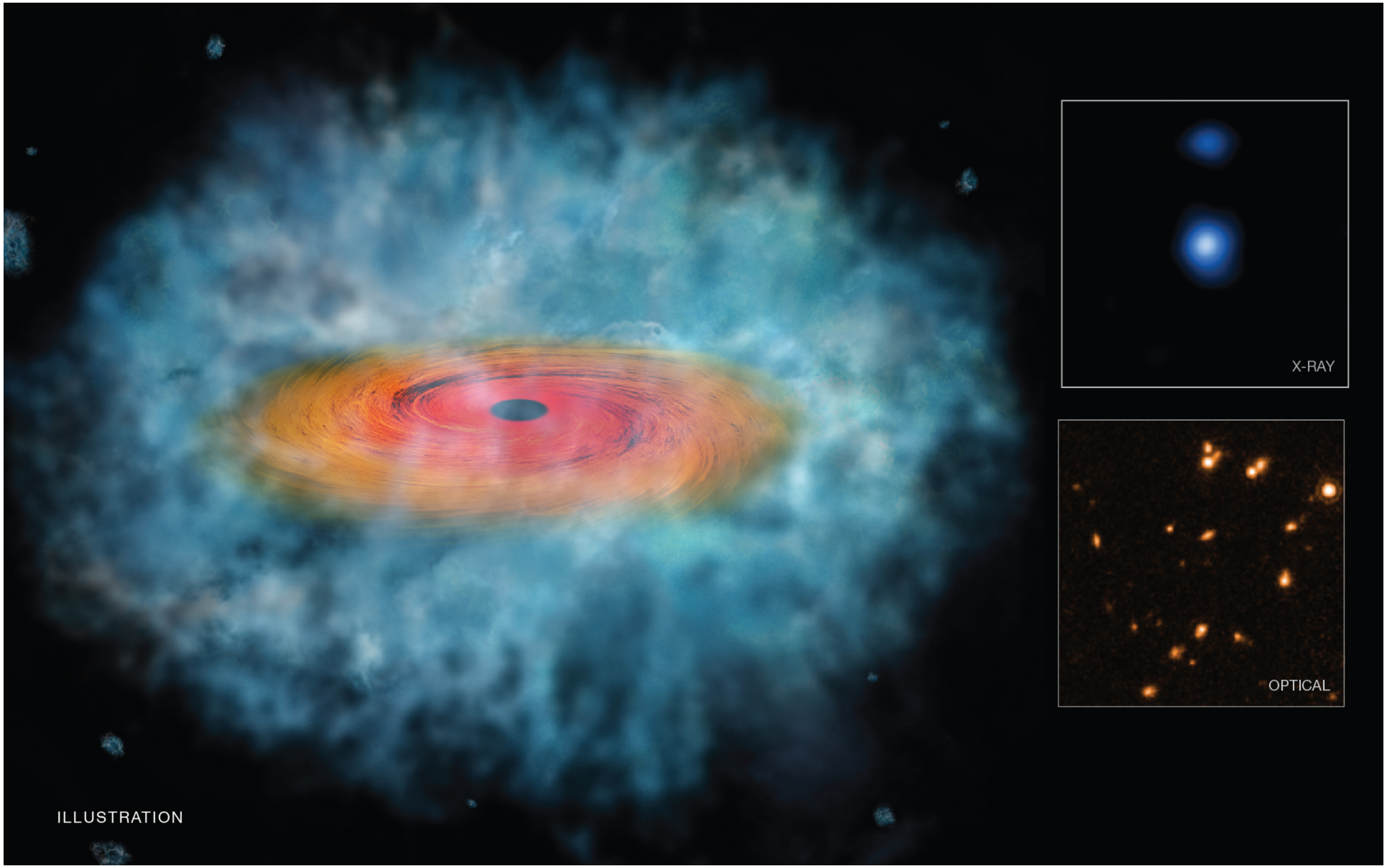
CANDELS GOODS Field

High-z GOODS-S Objects



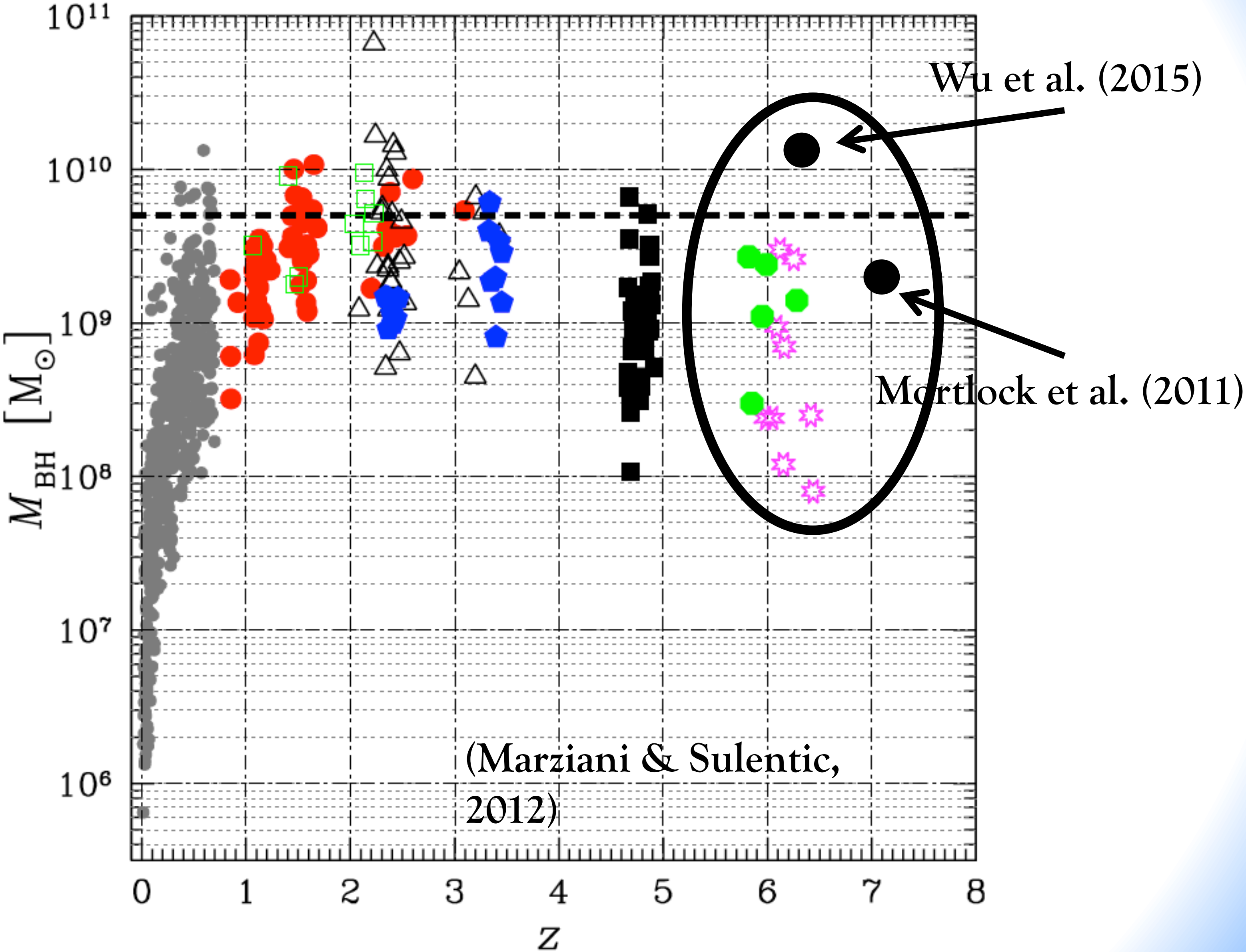
(Pacucci et al., 2016)

The First DCBH Candidates

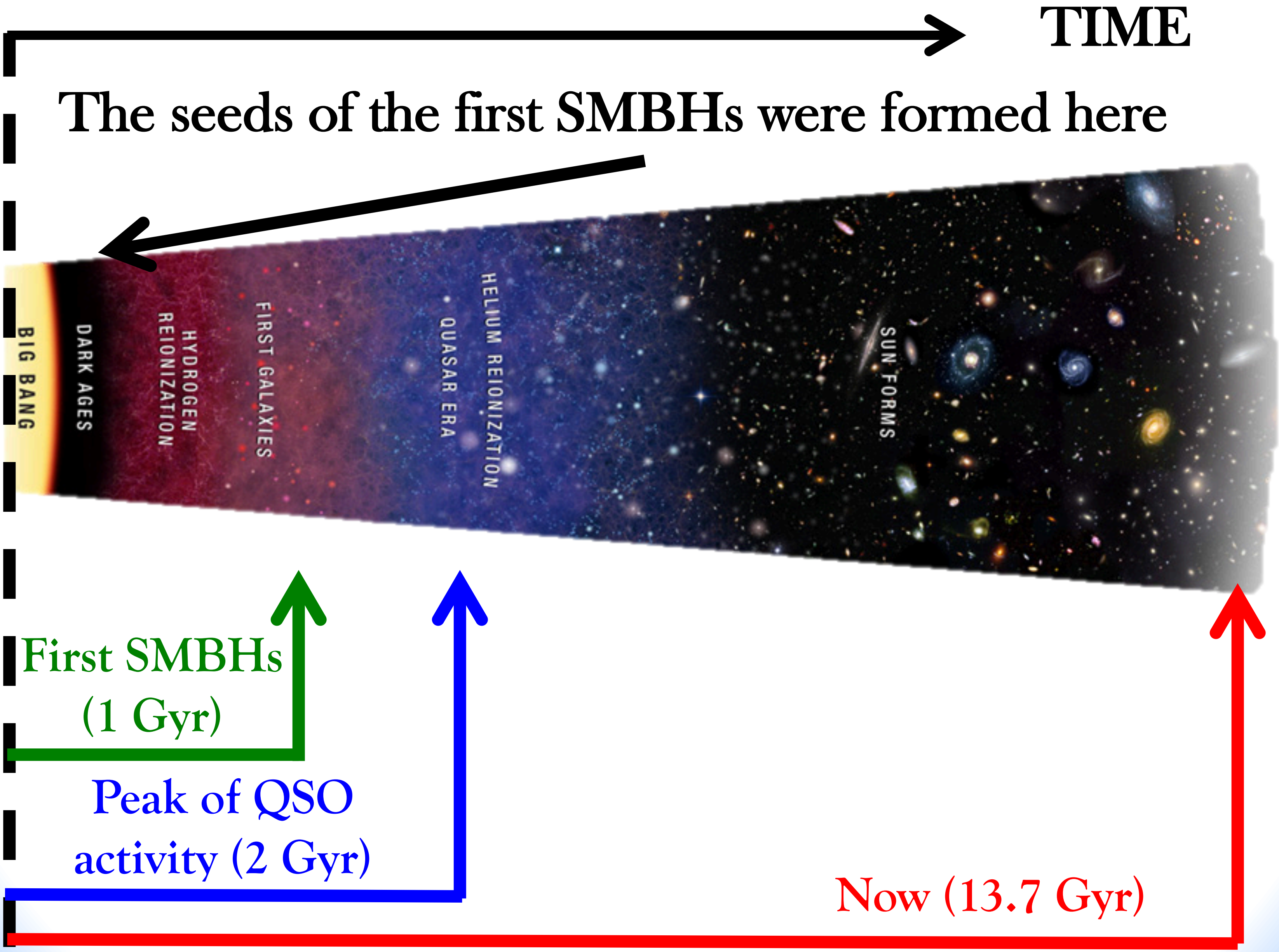


Credit: X-ray: NASA/CXC/Scuola Normale Superiore/Pacucci, F. et al, Optical: NASA/STScI; Illustration: NASA/CXC/M.Weiss

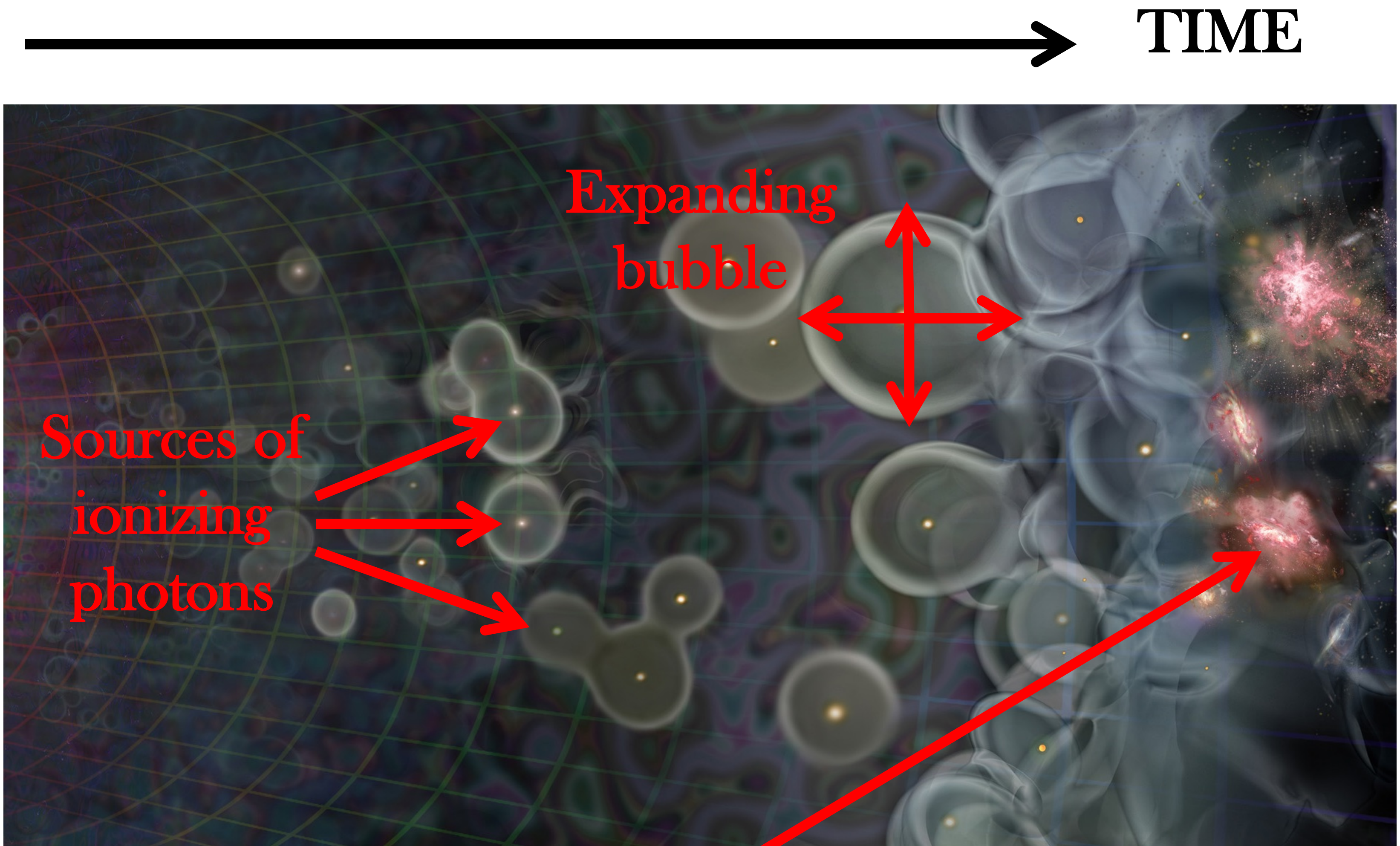
Massive Black Holes Family Portrait



"A Brief History of Time"



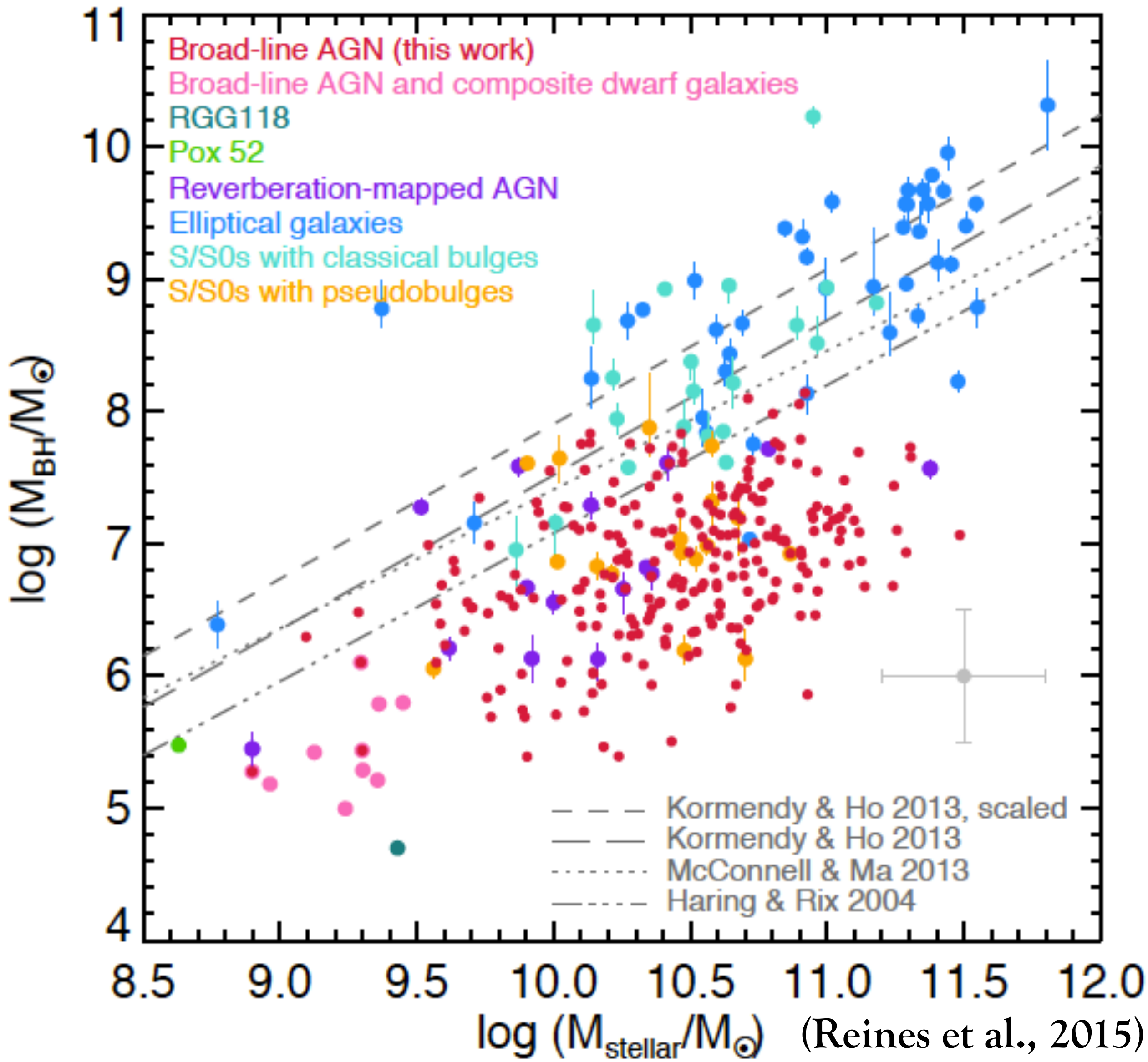
Black Holes and Reionization



Reionization is complete by

$z \sim 6$

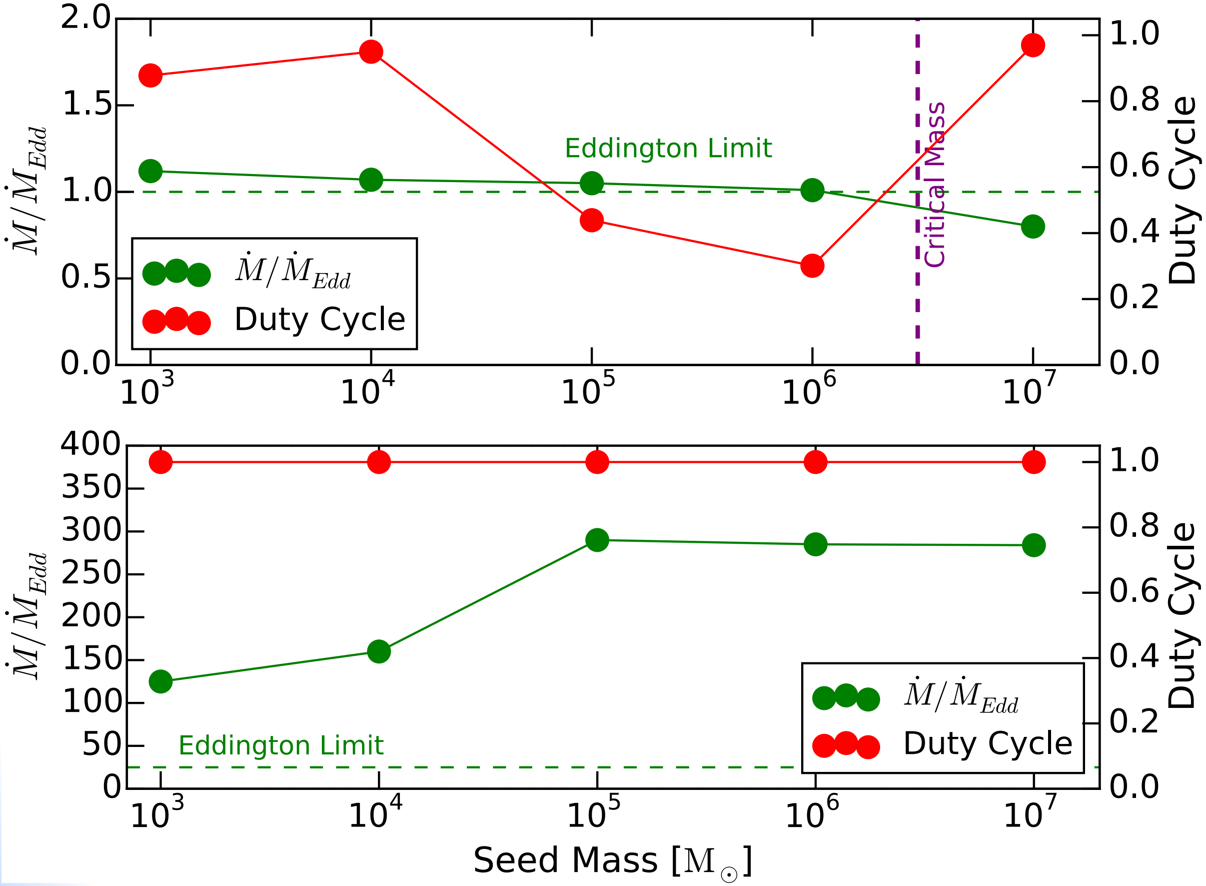
Black Holes and Galaxy Formation



(Reines et al., 2015)

The Growth of the First Black Holes

$$M_\bullet(t) = M_\bullet(0)\exp\left(\mathcal{D}\frac{\dot{M}}{\dot{M}_{\rm Edd}}\frac{t}{t_{\rm Sal}}\right)$$



Standard accretion:

Most of the gas reservoir is ejected

Time scale:

~ 100 Myr

Slim-disk accretion:

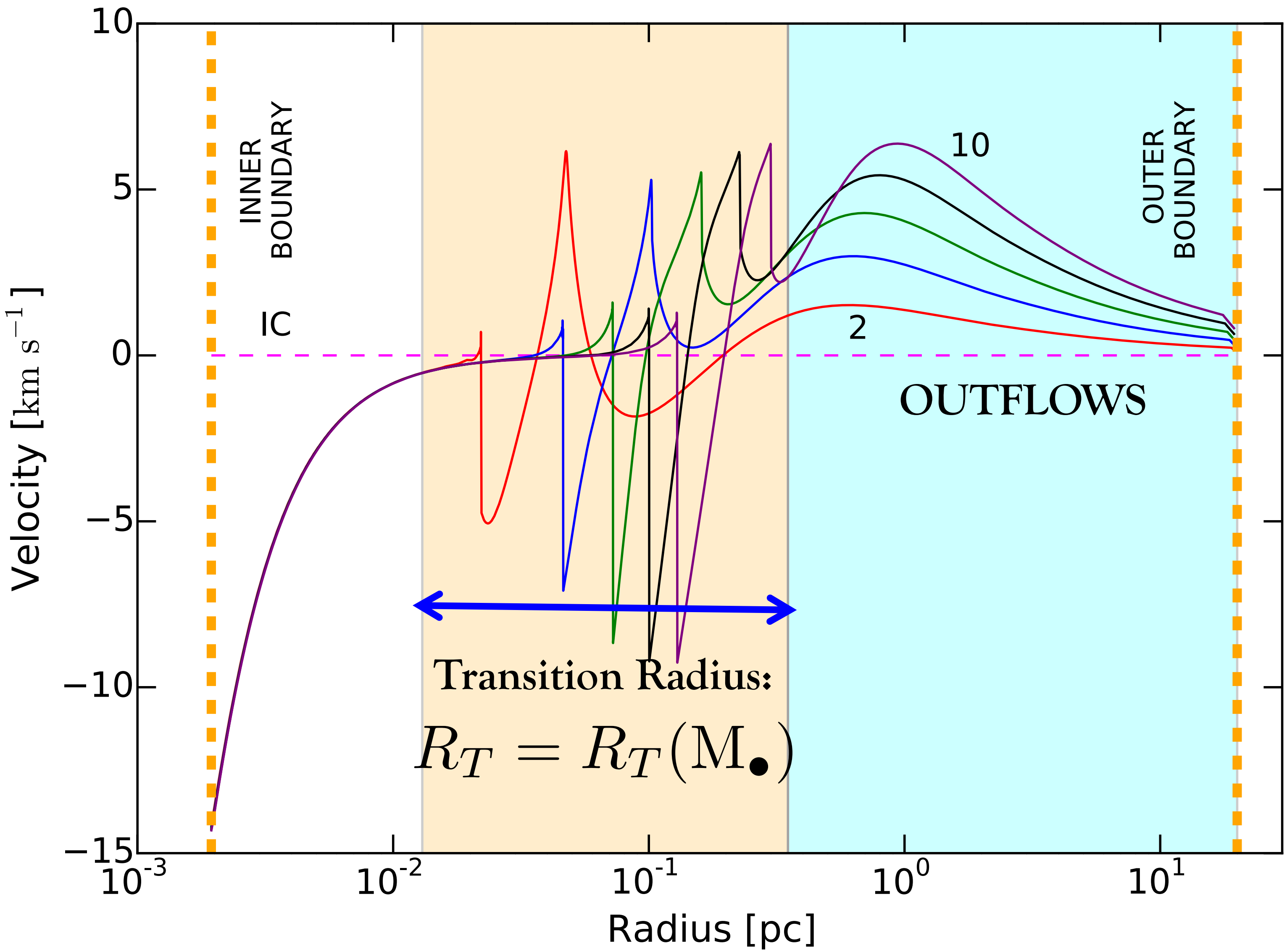
Most of the gas reservoir is accreted

Time scale:

~ 10 Myr

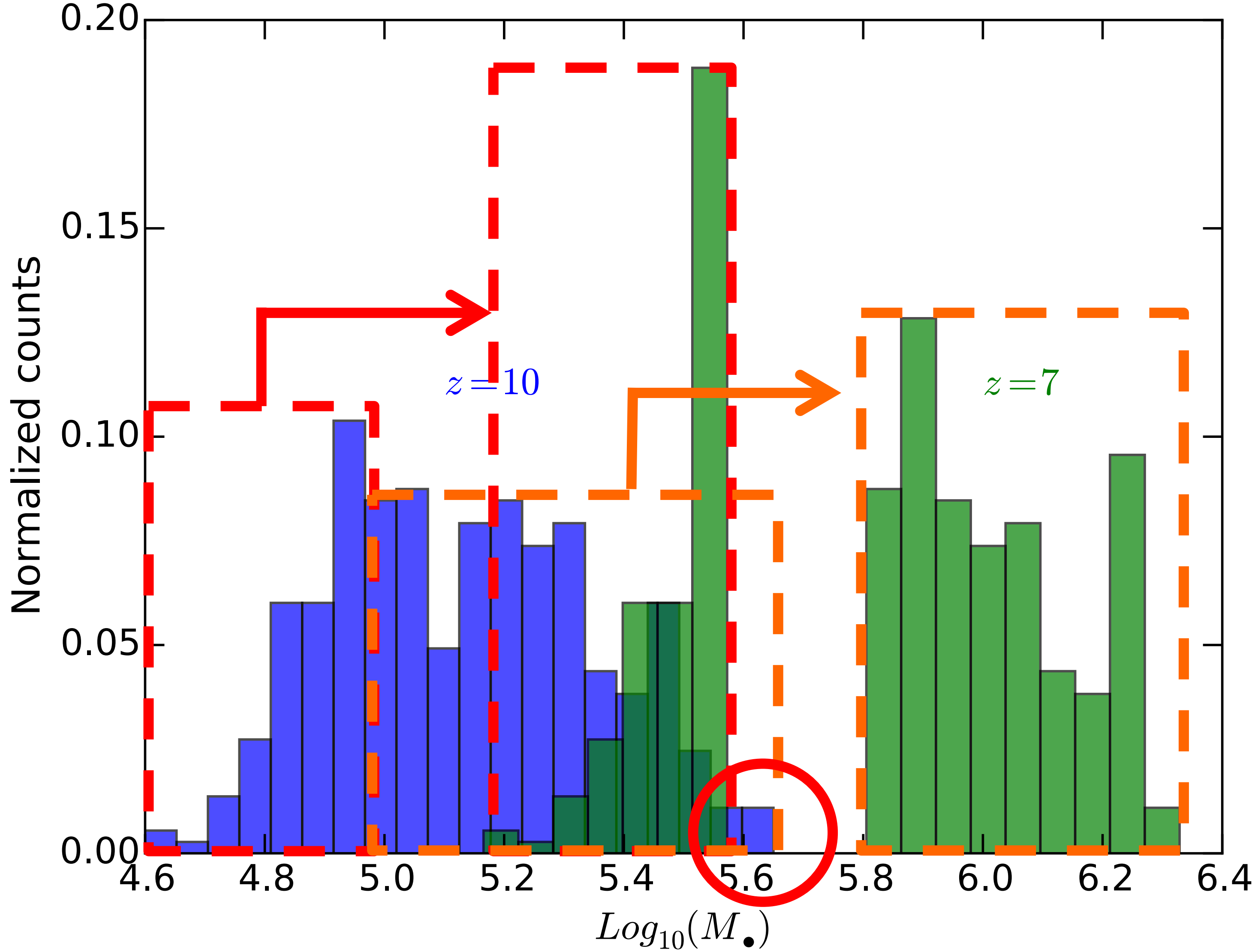
(Pacucci & Ferrara, 2014; Pacucci, Volonteri & Ferrara, 2015)

Structure of the Accretion Flow



(Pacucci, Volonteri & Ferrara, 2015)

Bimodal Evolution of the Black Hole Seeds



(Pacucci, Volonteri & Ferrara, 2015)

Take-Away Points

GROWTH:

- Standard accretion: intermittent, most of gas lost in outflows
- Slim-disk accretion: super-Eddington, continuous, most of gas accreted, short timescales
- Growth is more rapid for larger black hole masses

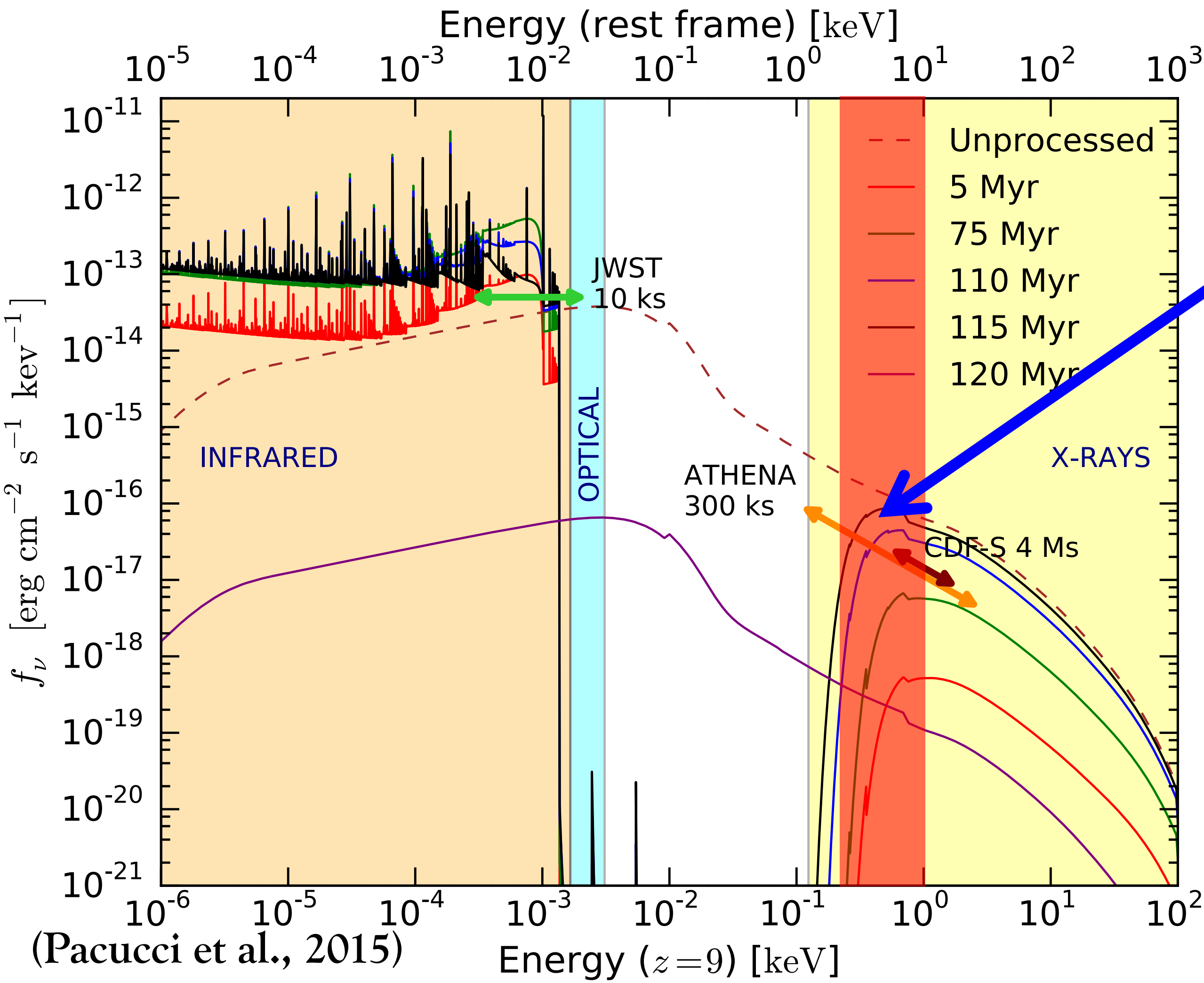
SPECTRUM:

- ?

DETECTING DCBHs:

- ?

The Effect of DCBHs on Reionization



(Pacucci et al., 2015)

Mean Free Path of X-ray photons:

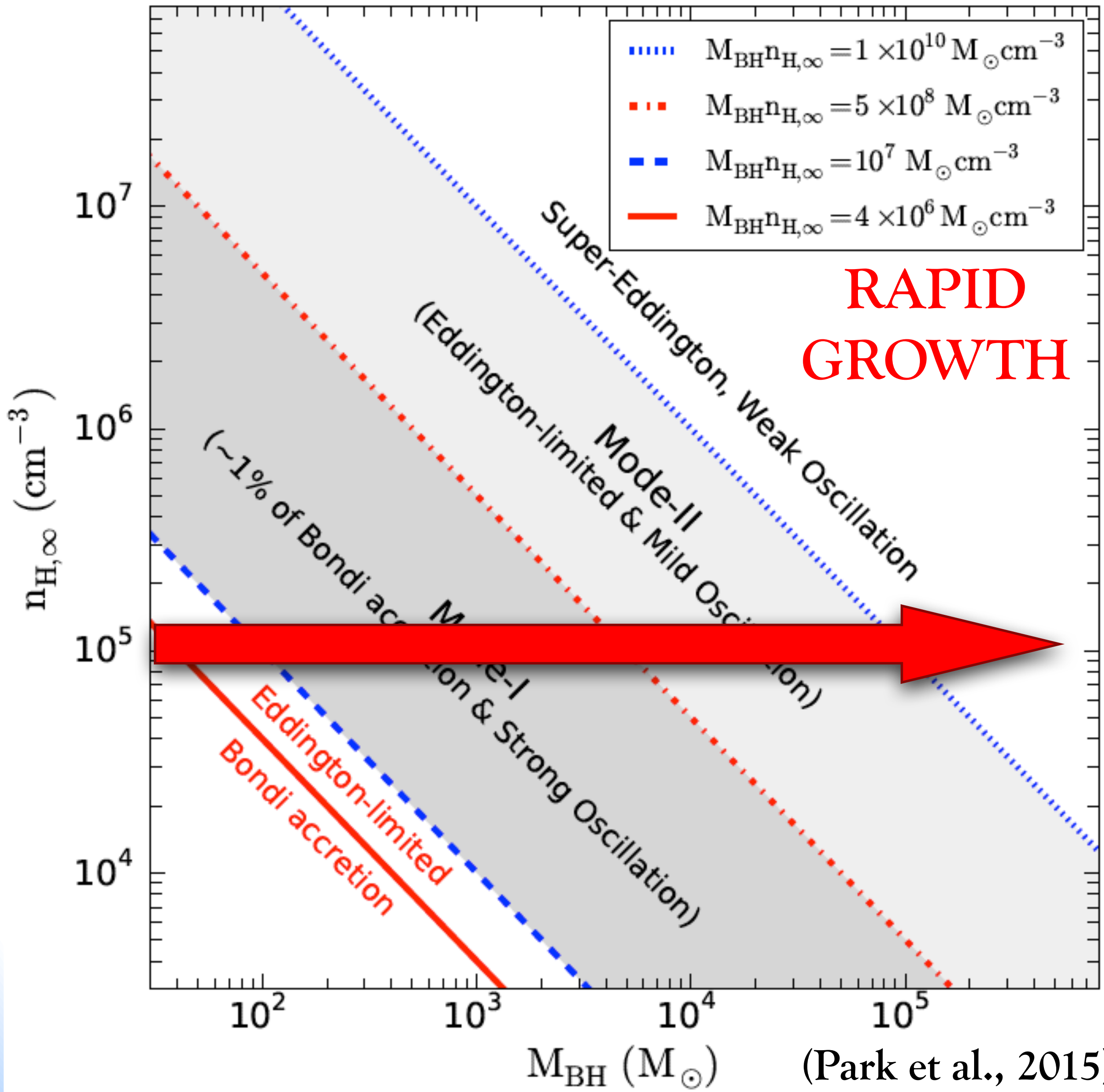
$$\lambda_X \gtrsim 8\,\mathrm{Gpc}$$

Hubble radius at high redshift:

$$R_H^{z=9} \sim 165\,\mathrm{Mpc}$$

Growing DCBH seeds negligibly contribute to reionization

Growth Rapidity and Black Hole Mass



(Park et al., 2015)

Growth is faster for larger black hole masses

Pacucci et al., 2014;
Pacucci et al., 2015;
Inayoshi et al., 2015;
Park et al., 2015

Faint AGN candidates in GOODS-S

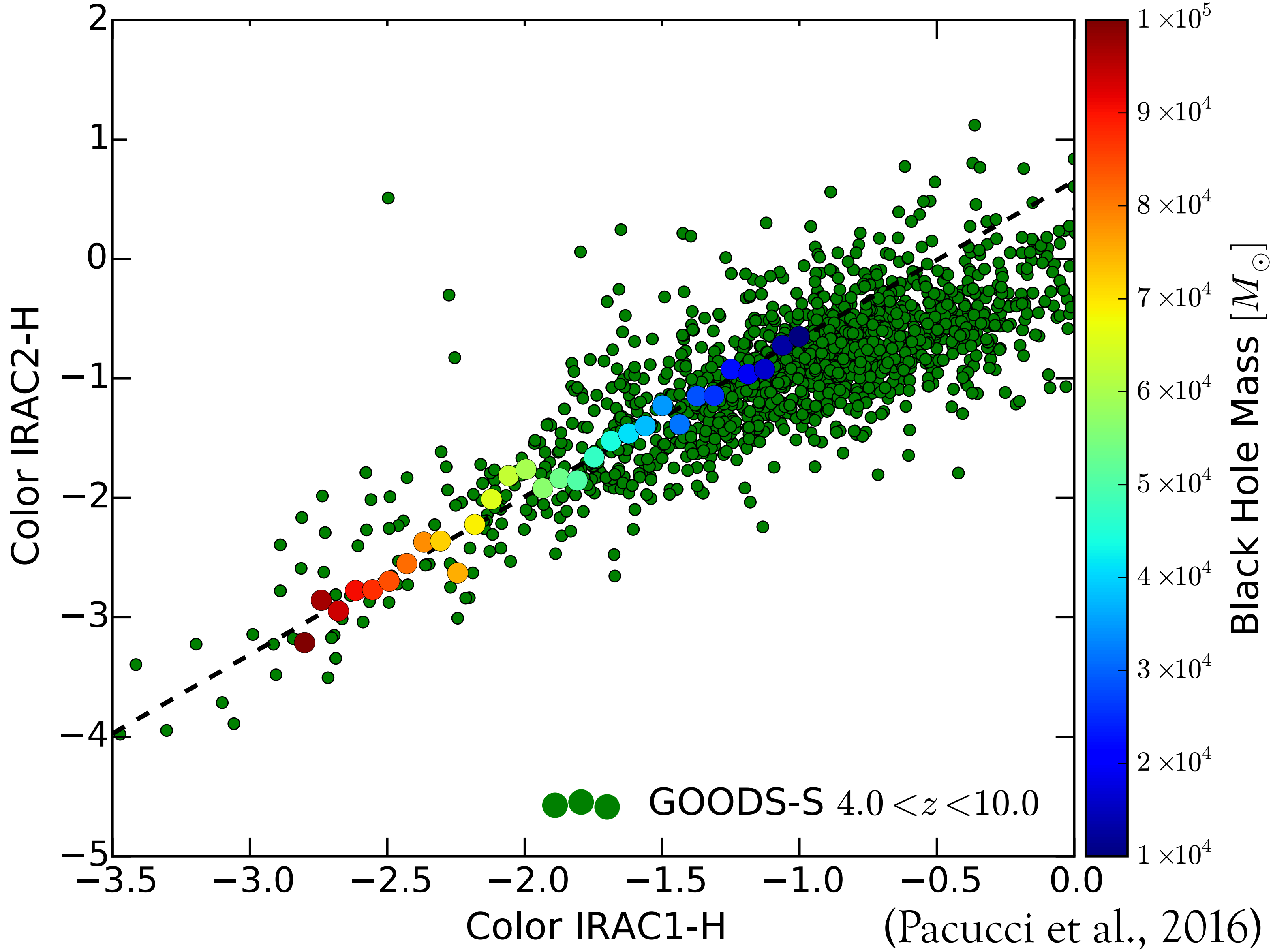
Pre-selection criterium: **mag H < 27**

(corresponding to selecting sources on the basis of their detected rest-frame UV luminosity)

ID	RA	Dec	zphot	zspec	C	H	M_{1450}	$\log F_X$ erg/cm^2/s	$\log L_X$ erg/s	A	Previous Catalogs
273	53.1220463	-27.9387409	4.49	4.762[1]	c	23.96	-21.37	-15.97	43.80	#2	M208,X403
4285	53.1664941	-27.8716803	4.28		cf	25.57	-20.22	-16.46	42.90	#3	–
4356	53.1465968	-27.8709872	4.70		cf	26.36	-18.44	-16.38	43.40	#4	M70437,L306,X485
4952	53.1605007	-27.8649890	4.32		c	25.47	-20.20	-16.50	42.90	#3	–
5375	53.1026292	-27.8606307	4.41		c	25.16	-20.16	-16.66	42.75	#4	X331
5501	53.1280240	-27.8593930	5.39		c	25.71	-20.23	-16.45	43.10	#4	–
8687	53.0868634	-27.8295859	4.23		c	26.90	-19.19	-16.43	42.90	#4	–
8884	53.1970699	-27.8278566	4.52		c	25.74	-19.04	-16.77	42.65	#4	–
9713	53.1715890	-27.8208052	5.86	5.70[2]	c	26.54	-19.87	-16.46	43.15	#4	HUDF322
9945	53.1619508	-27.8190897	4.34	4.497[3]	cd	24.99	-20.93	-16.65	42.75	#4	–
11287	53.0689924	-27.8071692	4.94		c	25.06	-20.48	-16.42	43.10	#4	M8728
12130	53.1514304	-27.7997601	4.43	4.62[4]	c	25.54	-20.60	-16.58	42.85	#5	HUDF3094
14800	53.0211735	-27.7823645	4.92	4.823[5]	c	23.43	-22.51	-16.38	43.10	#3	M10548
16822	53.1115637	-27.7677714	4.52		c	25.67	-18.97	-15.91	43.85	#4	M70168,L245,X371
19713	53.1198898	-27.7430349	4.84		c	25.31	-18.14	-16.48	43.00	#4	E1516,X392
20765	53.1583449	-27.7334854	5.23		f	24.44	-21.06	-16.29	43.25	#3	E2551
23757	53.2036444	-27.7143907	4.13		c	24.56	-20.72	-16.49	42.85	# 1	–
28476	53.0646867	-27.8625539	6.26		f	26.77	-19.03	-16.60	43.10	#4	M70407
29323	53.0409764	-27.8376619	9.73		cf	26.33	-19.50	-15.96	44.00	#3	M70340,L103,X156
31334	53.2131871	-27.7816486	4.73		f	26.41	-19.60	-15.69	43.75	#4	–
33073	53.0547529	-27.7368325	4.98		c	26.89	-19.19	-16.44	43.10	#2	E2199
33160	53.0062504	-27.7340678	6.06		cf	25.90	-19.62	-16.26	43.65	#3	E2498,L57,X85

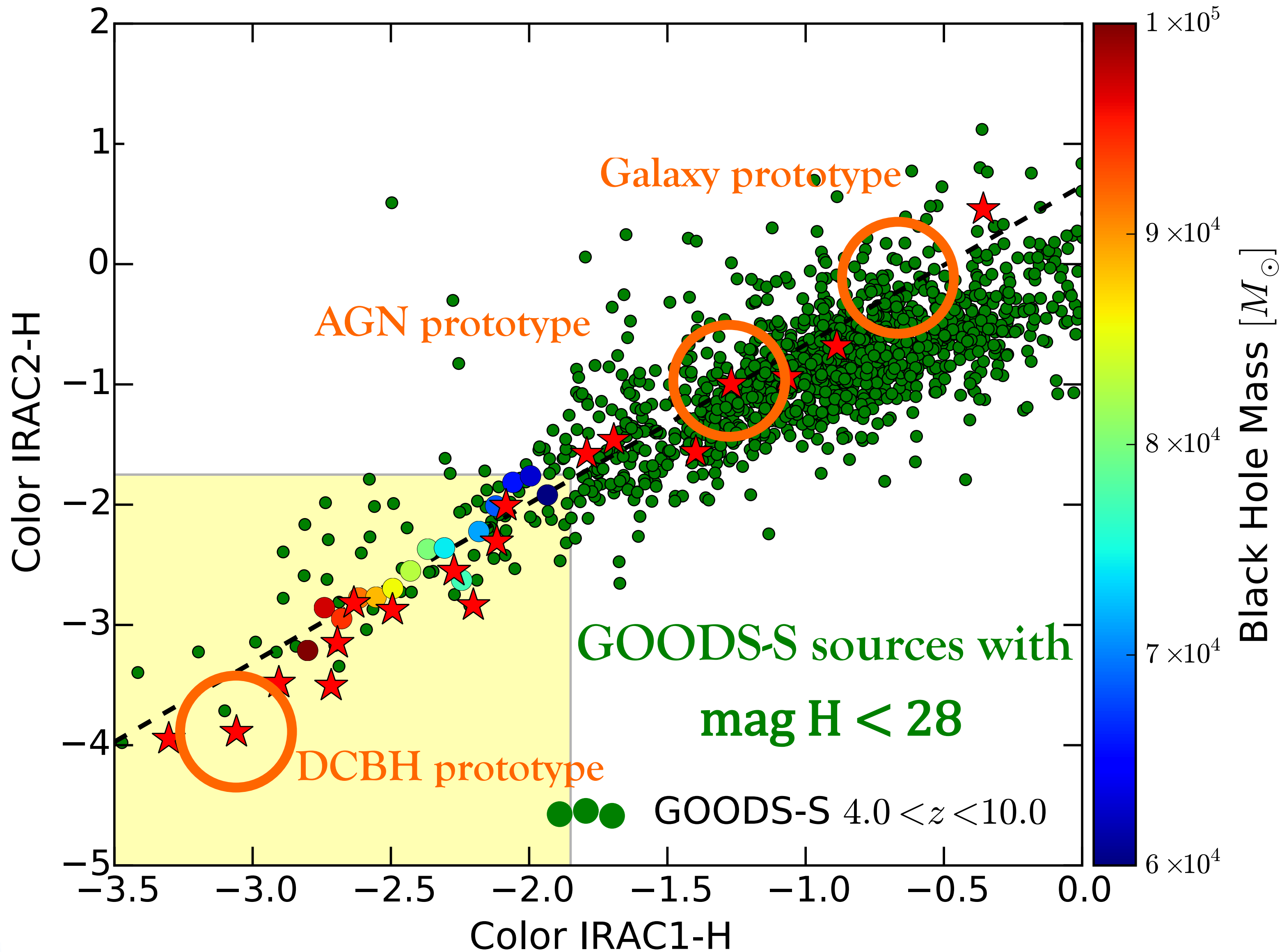
(Giallongo et al. 2015)

Photometry of DCBHs

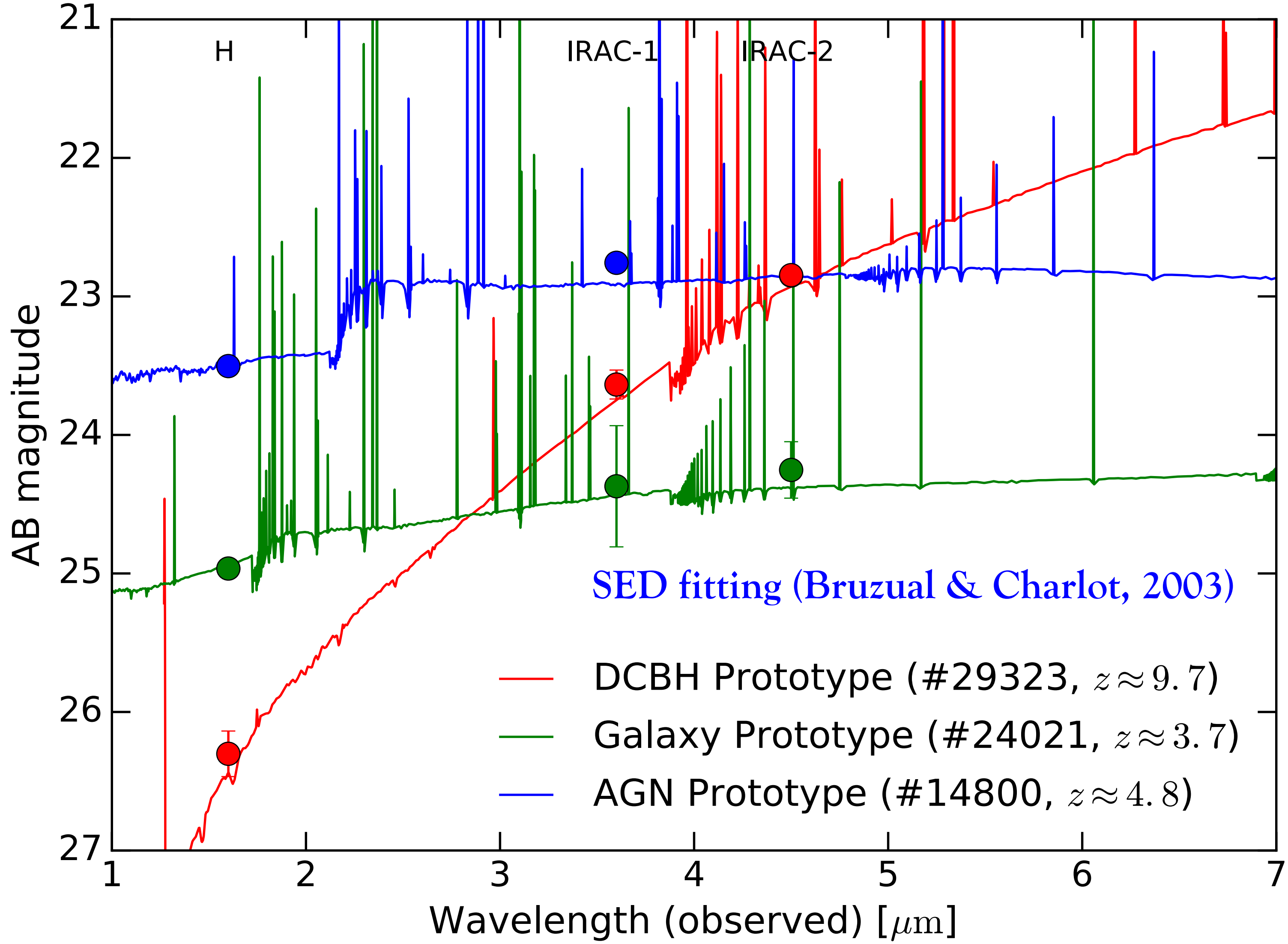


(Pacucci et al., 2016)

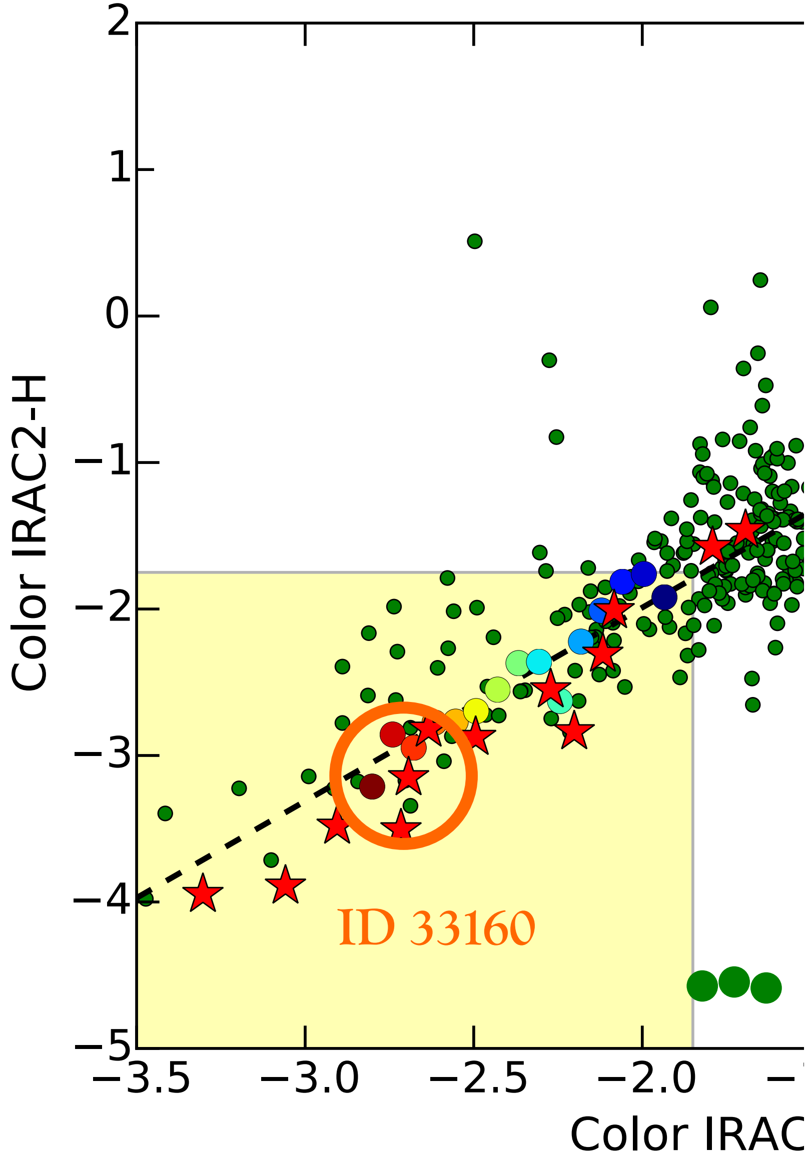
AGNs or DCBHs?



Comparing SEDs



Predicting Observables



ID 33160 (z=6.06)

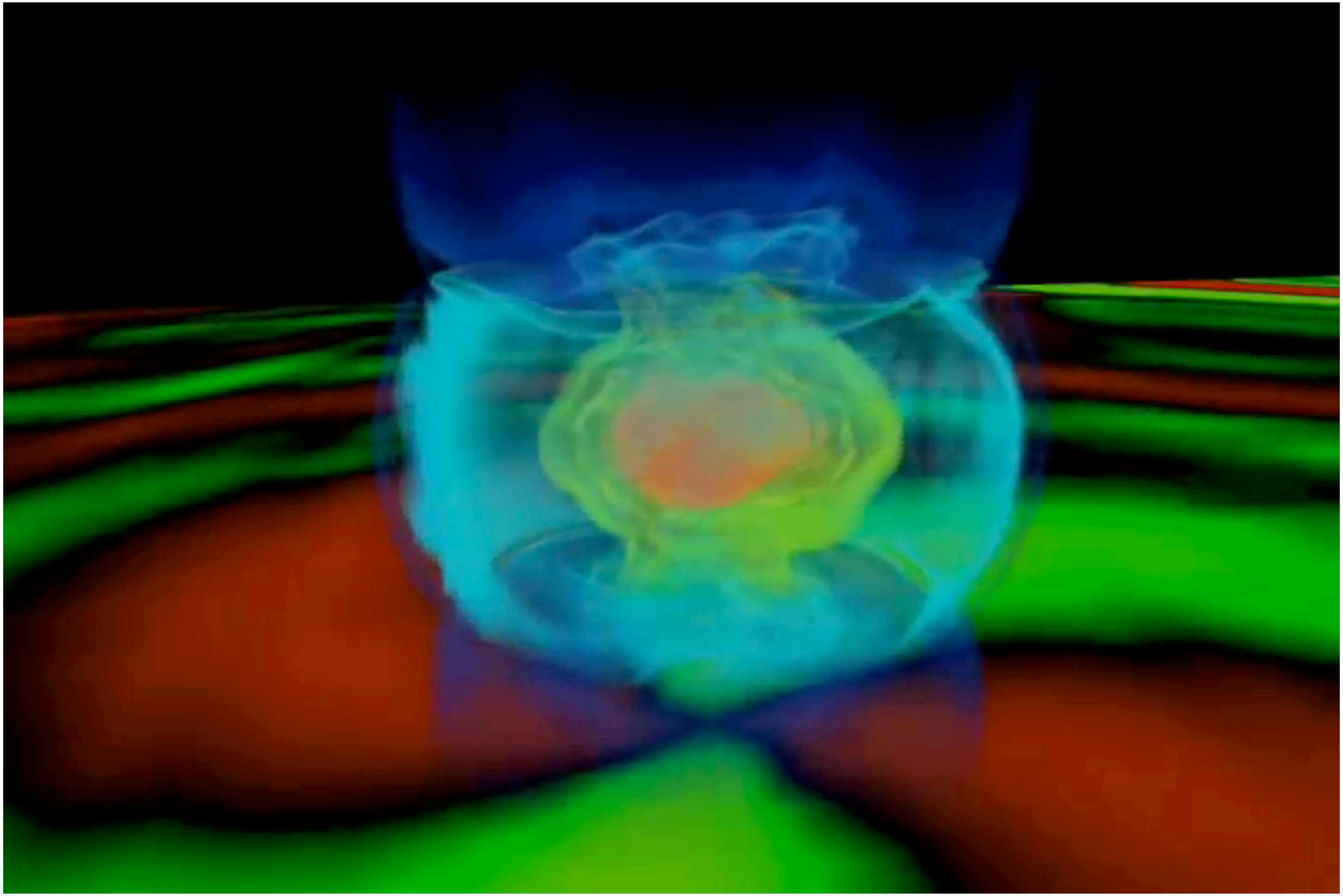
Observations:

- mag H = 25.9(2) +/- 0.2
- Log(L_x) = 43.65 +/- 0.12
- z = 6.06

Our current prediction:

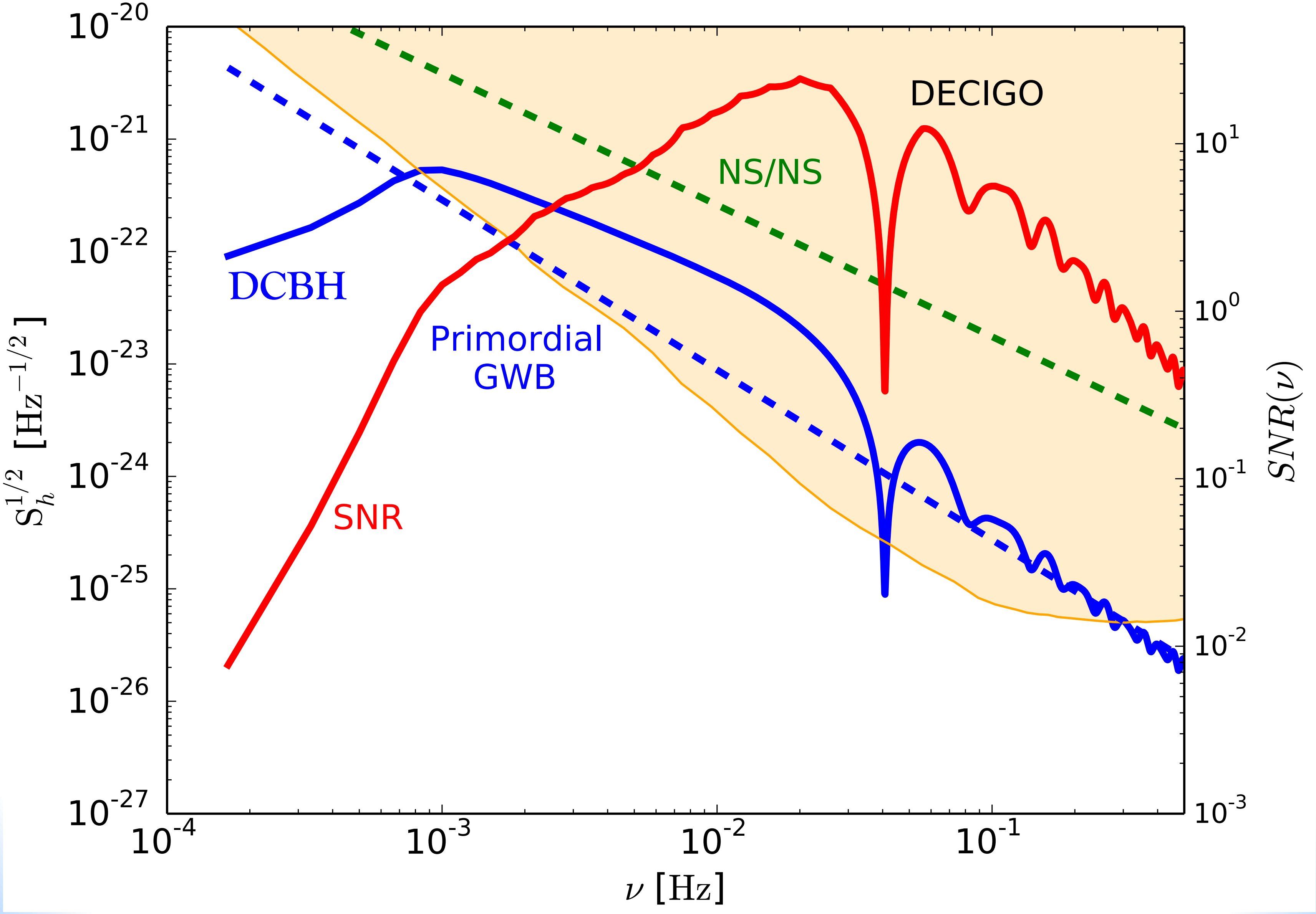
- mag H = 25.9(4)
- Log(L_x) = 43.49
- DCBH mass: $4 \times 10^6 \, M_\odot$

Gravitational Waves from DCBHs

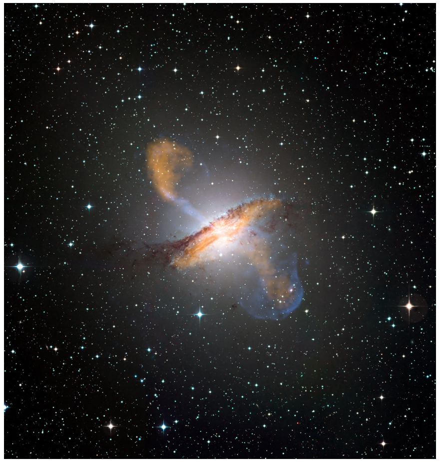


Simulation of GW emission from a collapsing and rotating SMS

Gravitational Waves from DCBHs



Classes of objects at high-z (z>6)



Galaxies:

- Stellar emission

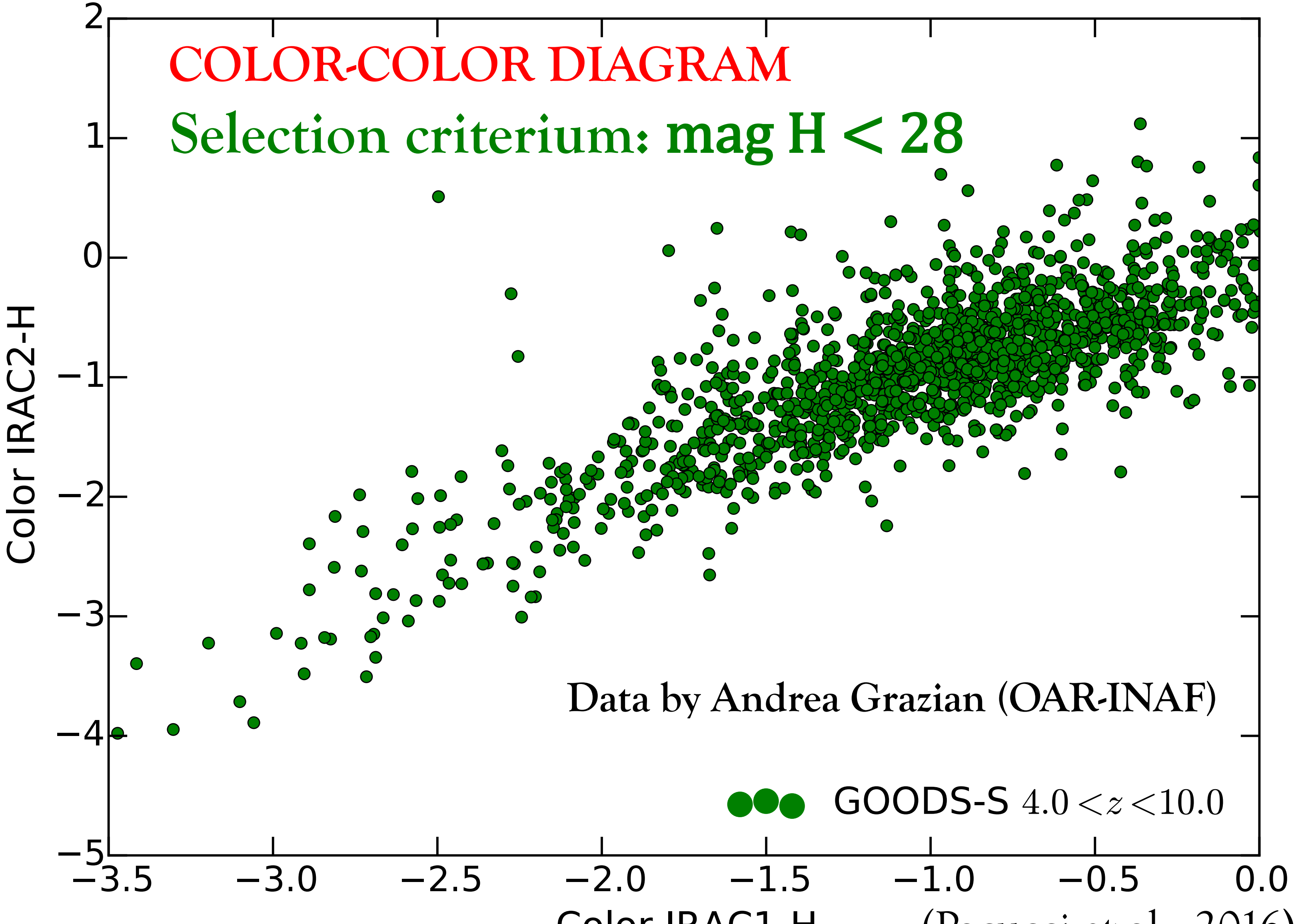
First black holes (DCBHs):

- BH-only emission
- No stellar emission
- No metals

Early AGNs:

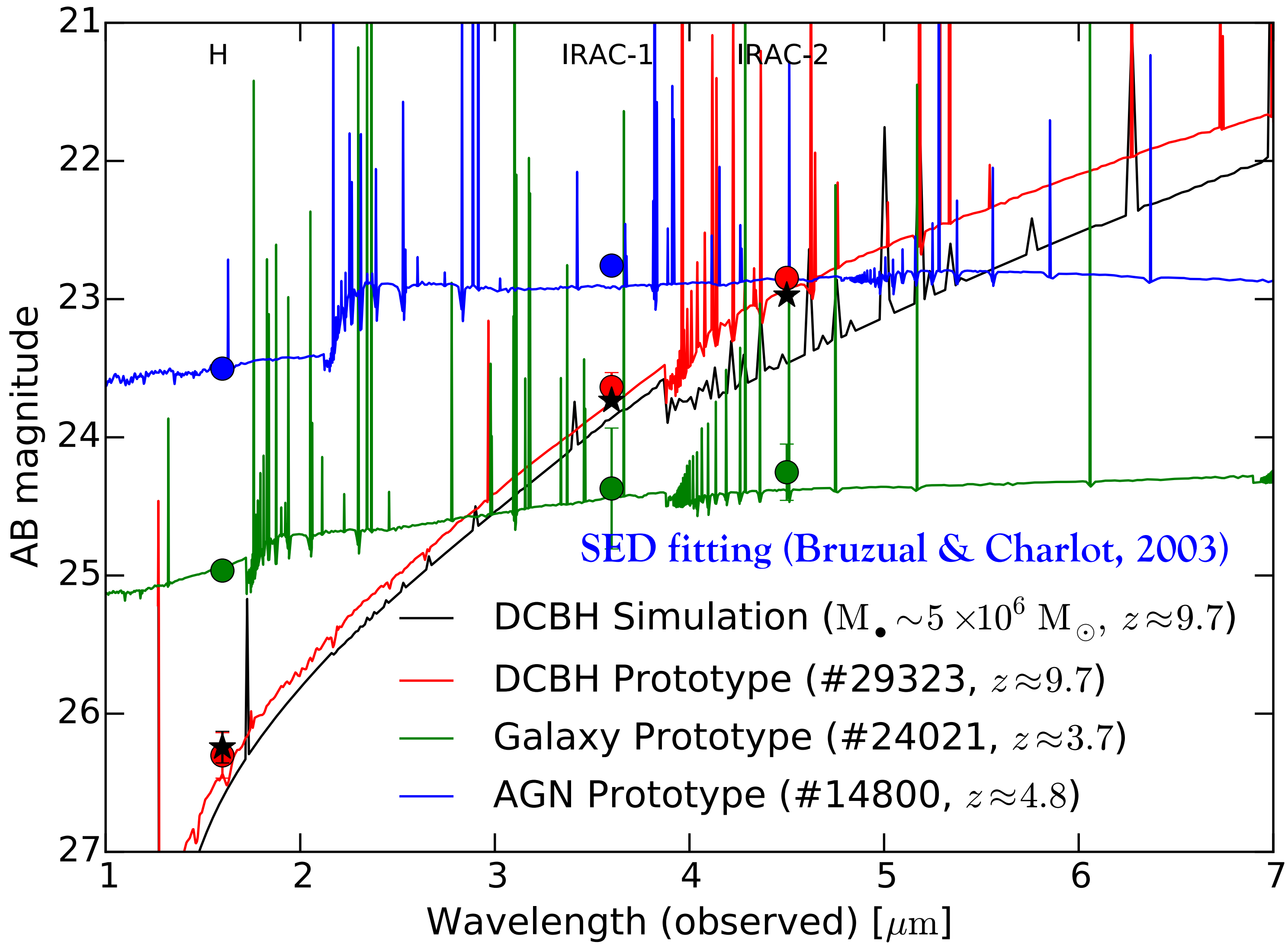
- BH emission
- Stellar emission

GOODS-S Infrared Colors

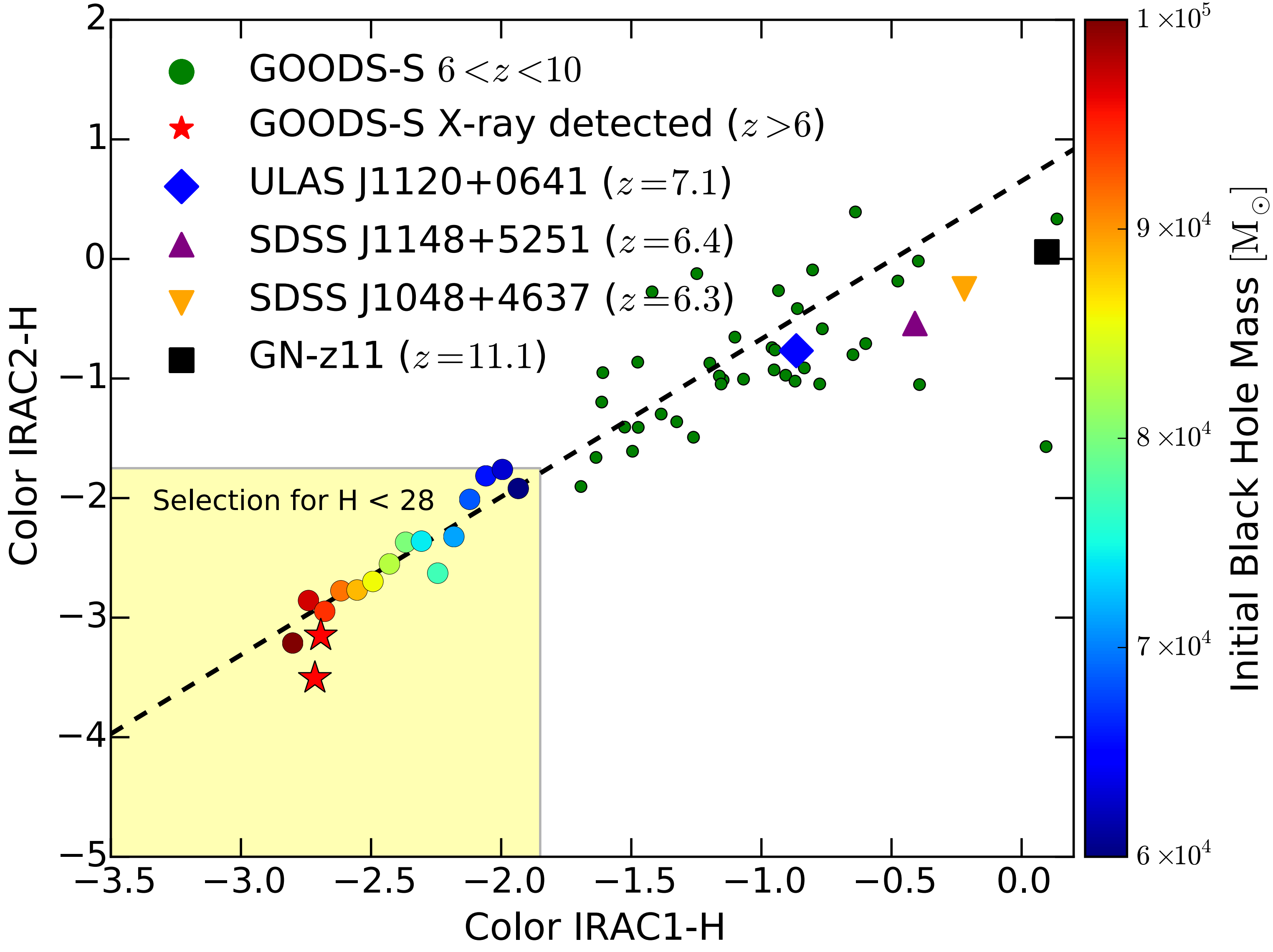


(Pacucci et al., 2016)

The SED of a DCBH



Colors of Other z>6 Objects



The High-z Criterion - Interpretation

High Redshift ($z>6$)

In this period DCBHs are formed.

- No stellar emission: pure DCBH radiation.
- Optical depths in host halos are large.

Low Redshift ($z<6$)

Evolution acts via star formation and feedback.

- Stars are formed: DCBH spectrum approaches the spectrum of galaxies.
- Feedback reduces the optical depth: DCBH spectrum approaches the spectrum of AGNs.

Hypothesis: Evolution of Colors