High-redshift Universe

SOC

Jenny Greene
Princeton

Yuexing Li
Penn State

Panelists

Fabio Pacucci
Harvard – CfA

Eli Visbal
Univ. Toledo

Discovery of Supermassive Black Holes at the Cosmic Dawn

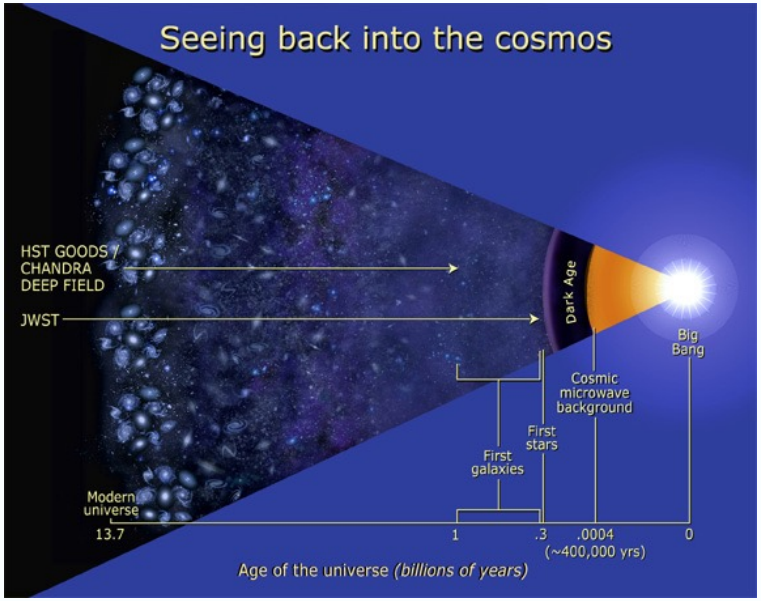
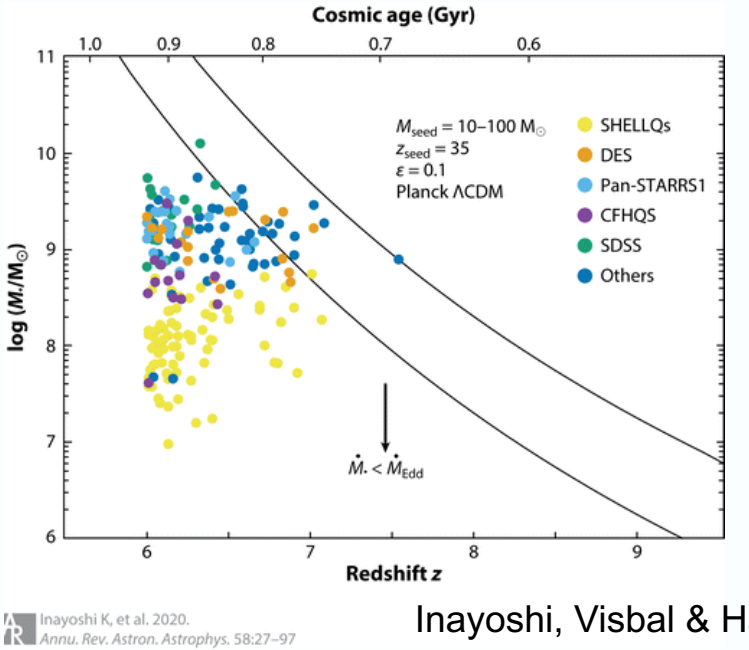
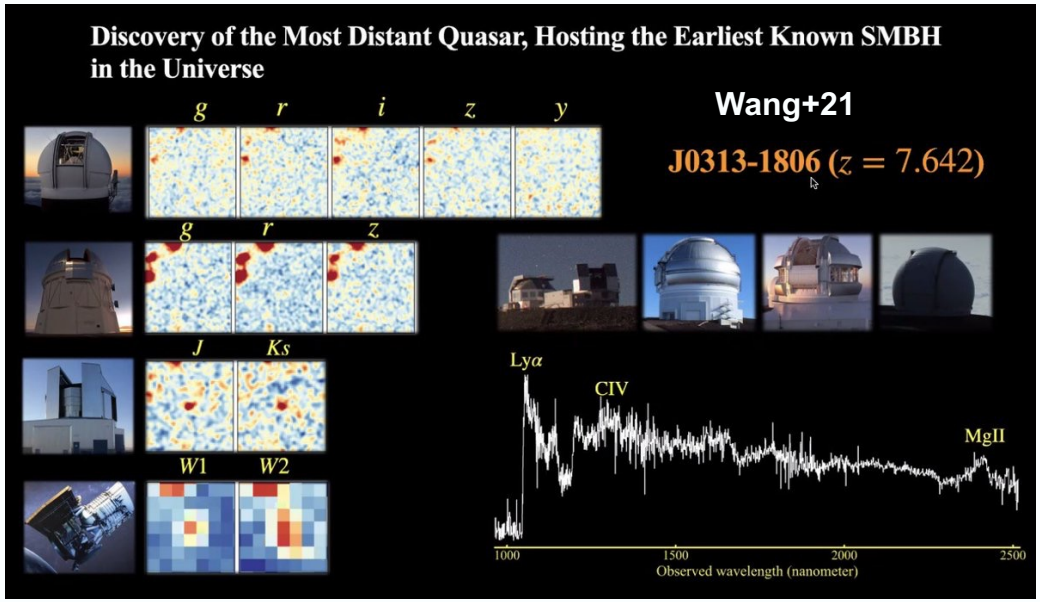


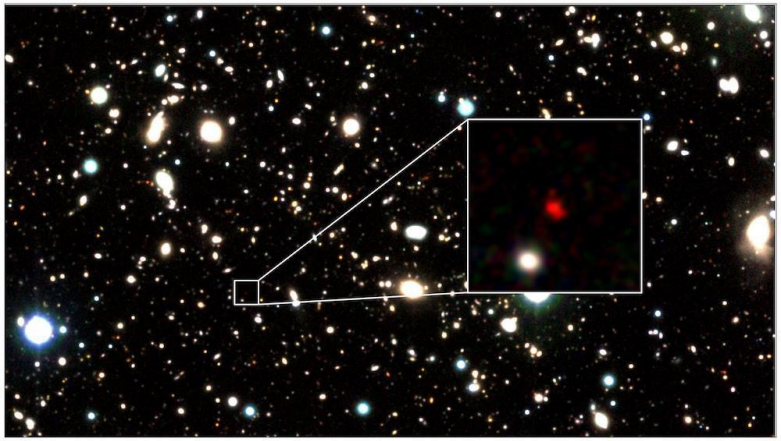
Image credit: NASA and Ann Feild



Inayoshi, Visbal & Haiman 20



Quasar at z~13?



Harikane+22,Pacucci+22

The Big Challenges from the first massive black holes

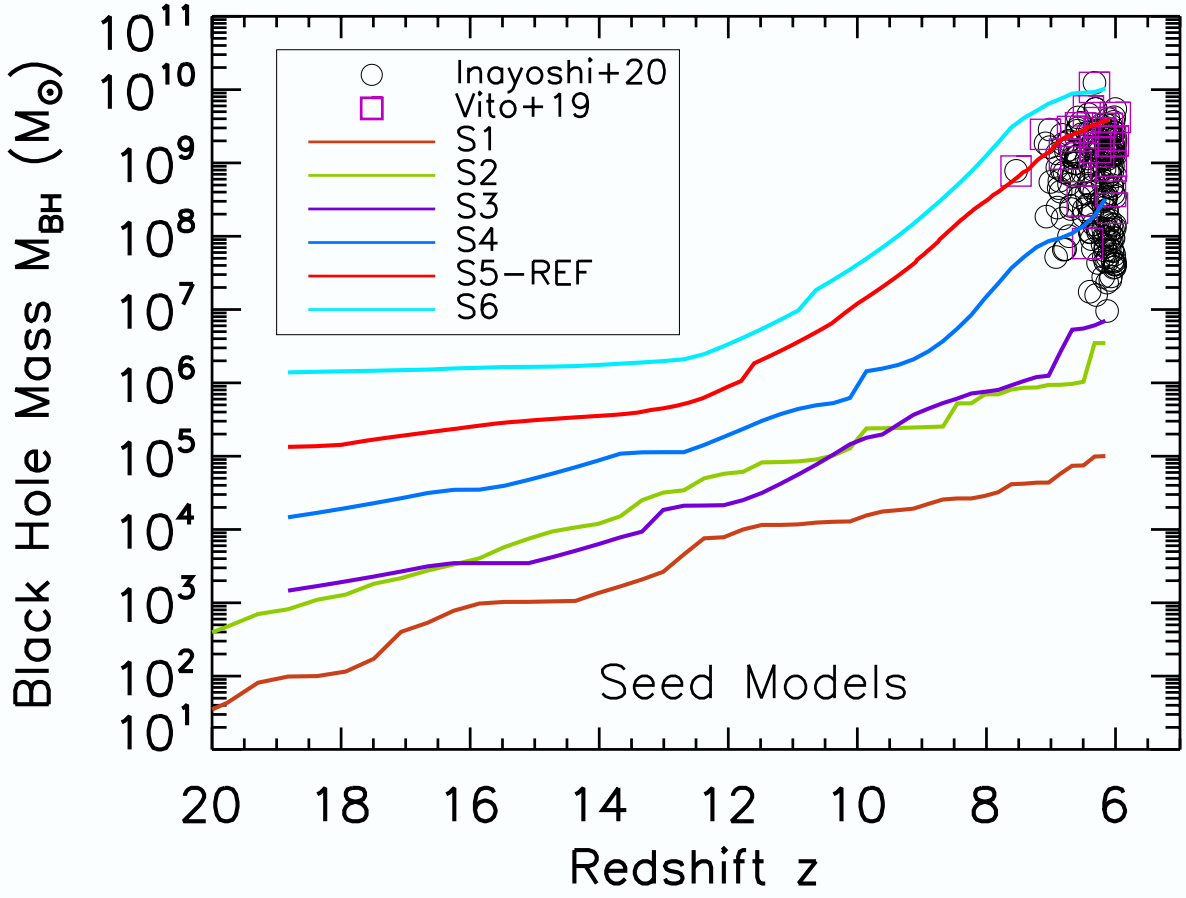
$$t_{\rm grow} \approx \frac{0.45}{f_{\rm duty}} \frac{\epsilon_{\rm r}}{(1-\epsilon_{\rm r})} \ln\left(\frac{M_{\rm BH}}{M_{\rm seed}}\right) \ {\rm Gyr}$$

- **The timescale:**
  - Salpeter time: e-folding time ~45 million yrs
  - The time limit: < 700 million years after Big Bang
- **The seeds:**
  - Did these SMBHs grow from seeds?
  - What were the seeds?
  - Where did the seeds come from?
- **The growth:**
  - How did the black holes grow?
- **The host galaxies:**
  - What are the host galaxies?
  - Did the first BHs co-evolve with their hosts?
- **The detectability:**
  - What are the observational signatures of the first BHs?
  - Can we detect them?
- **The impacts:**
  - How much did the first quasars contribute to the cosmic reionization?
  - How did they affect structure formation and at later times?

The State of the Field

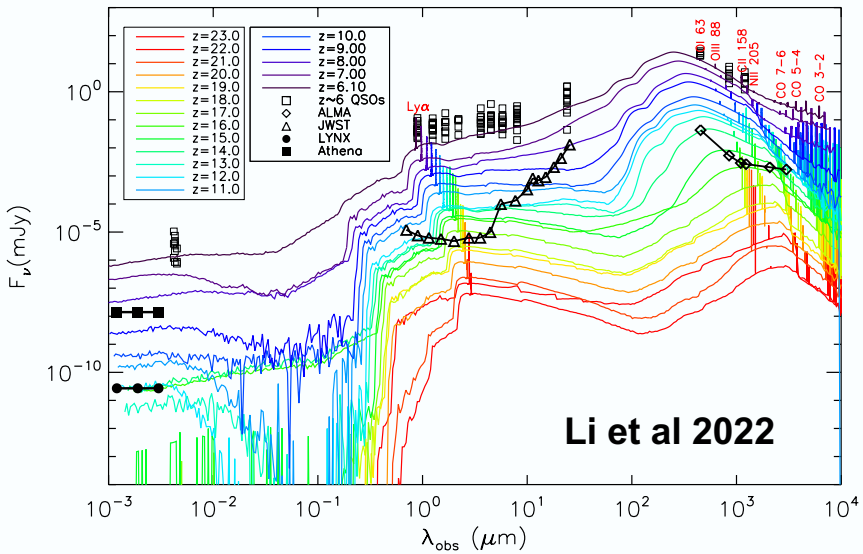
- The seeds
  - Light seeds 10-10 $M_\odot$ from PopIII stars
  - Medium seeds $10^{3\text{-}4}$ $M_\odot$ from supermassive stars and stellar collisions
  - Heavy seeds $10^{5\text{-}6}$ $M_\odot$ from direct collapse of hot, dense gas clumps
  - The question: can all seeds make it?
- The accretion
  - Bondi accretion & chaotic cold accretion
  - Eddington-limited accretion, or super-, hyper-Eddington
  - The question: is super- or hyper-Eddington needed?
- The Feedback
  - Radiative efficient thin-disk accretion with constant radiative efficiency
  - Super-critical slim-disk accretion with varied radiative efficiency
  - The question: thin or slim?
- The host
  - Big halos in highly biased region
  - Small atomic cooling halos
  - The question: big or small?
- The detectability
  - Electromagnetic observatories
  - Gravitational waves instruments
  - The question: can JWST and LISA detect the first BHs?

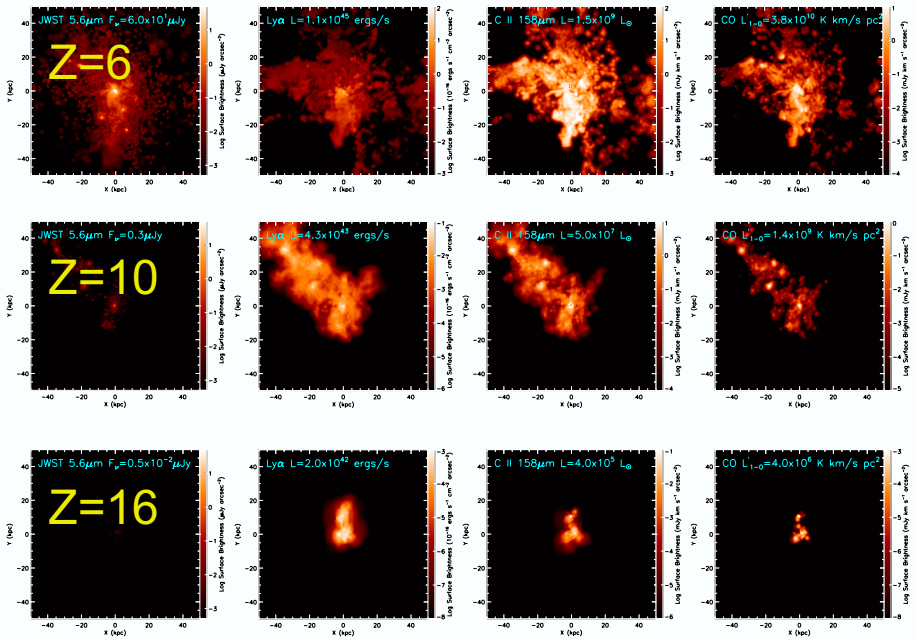
Formation of the first SMBHs & quasars:
What seeds? What accretion model?

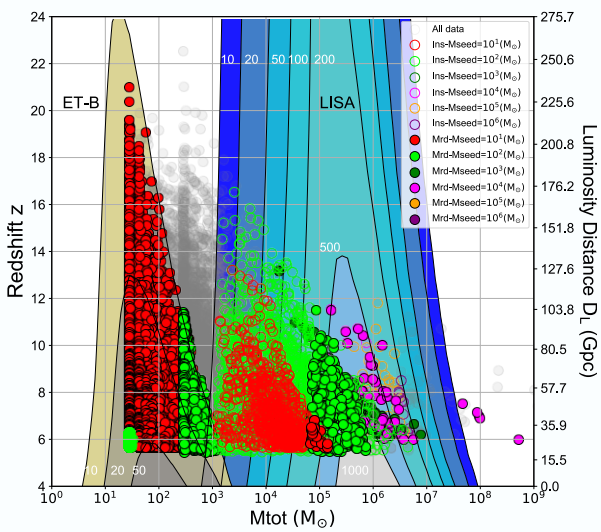


Zhu, Li + 2022

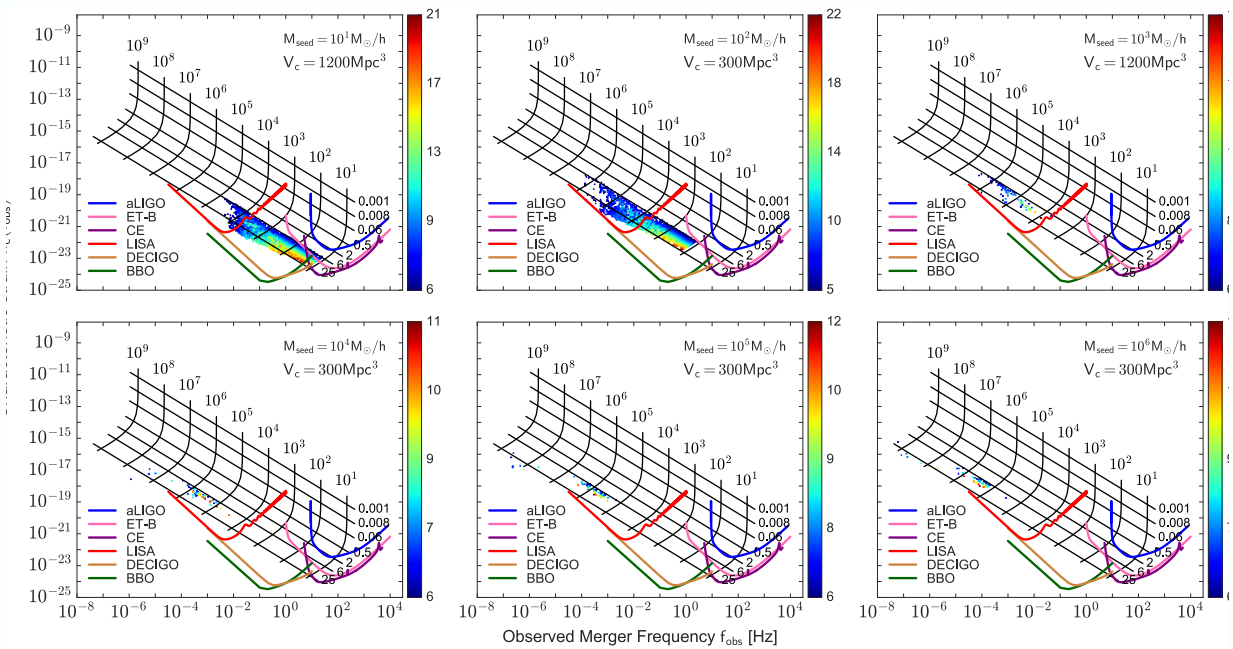
Detecting the first black holes with EM–GW Synergies







Li et al in prep

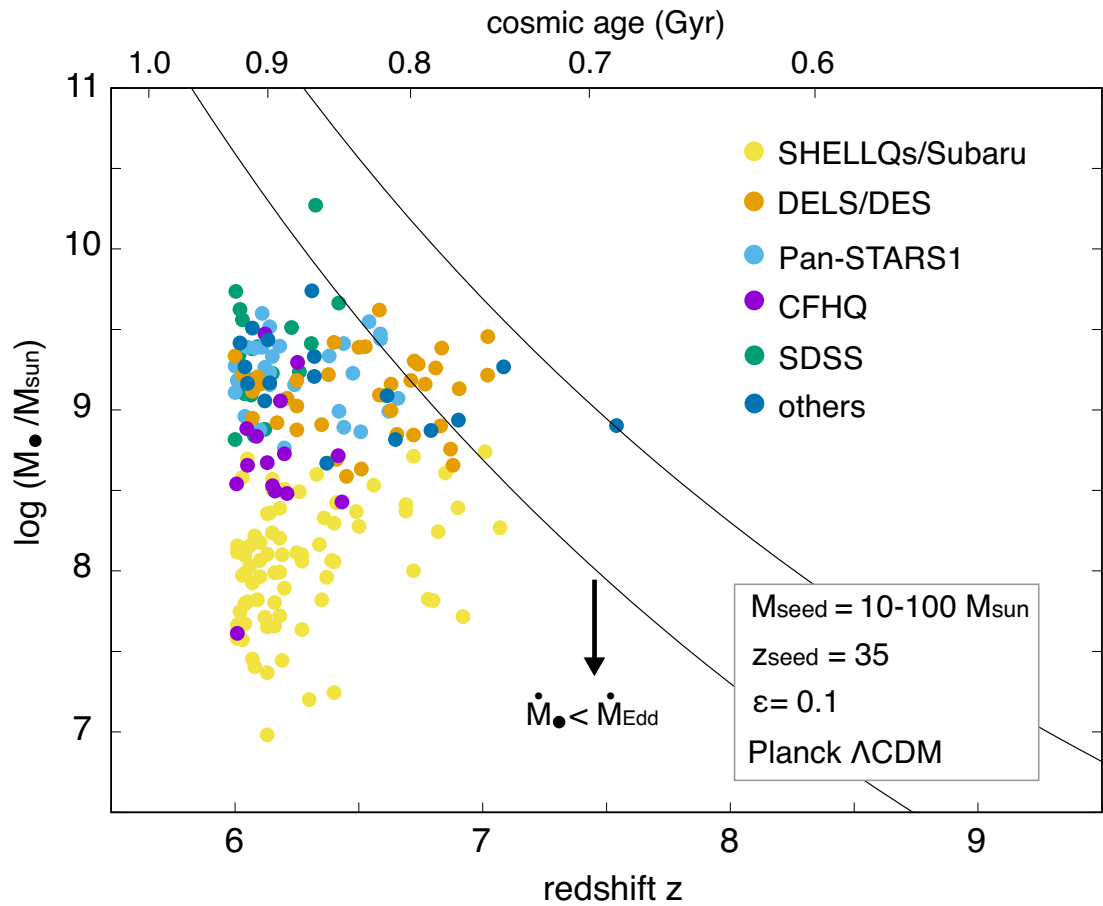


Black Hole Seeding and Growth

Eli Visbal (University of Toledo)

Observational Motivation

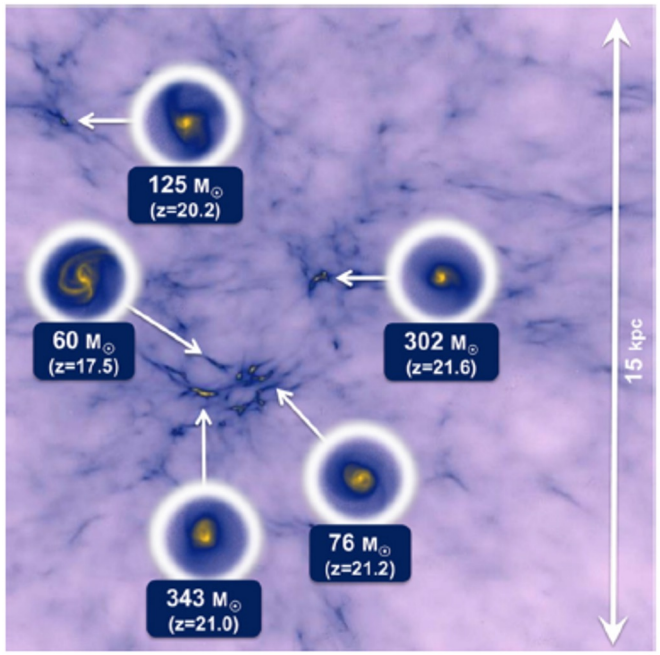
- Billion solar mass black holes by z~6
- How did they get so big so fast?
- Started as black hole "seeds"
  - Gas accretion
  - Mergers



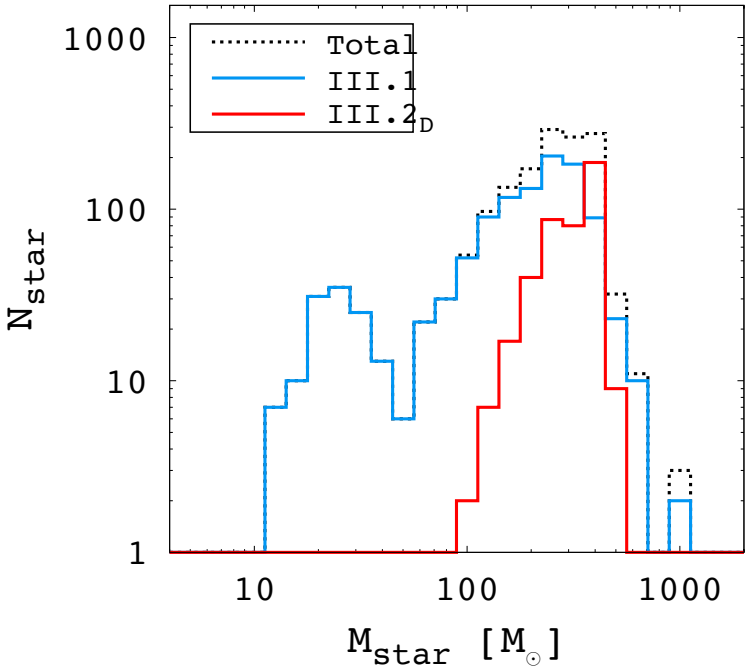
Inayoshi, EV & Haiman (2020)

Population III Stars

- First stars made from primordial (or extremely low-metallicity) gas
- H_2 primary coolant
- Only cools to few hundred K (not as cold as metal enriched gas) → larger stellar masses
- Those with 40-140 $M_\odot$ and >260 $M_\odot$ directly forming BHs
- Simulations show first formed in tiny "minihalos" of ~10^5 $M_\odot$ (e.g., Bromm et al., 1999; Abel et al., 2002; Yoshida et al., 2003; Turk et al., 2009; Stacy et al., 2010; Greif, 2015)

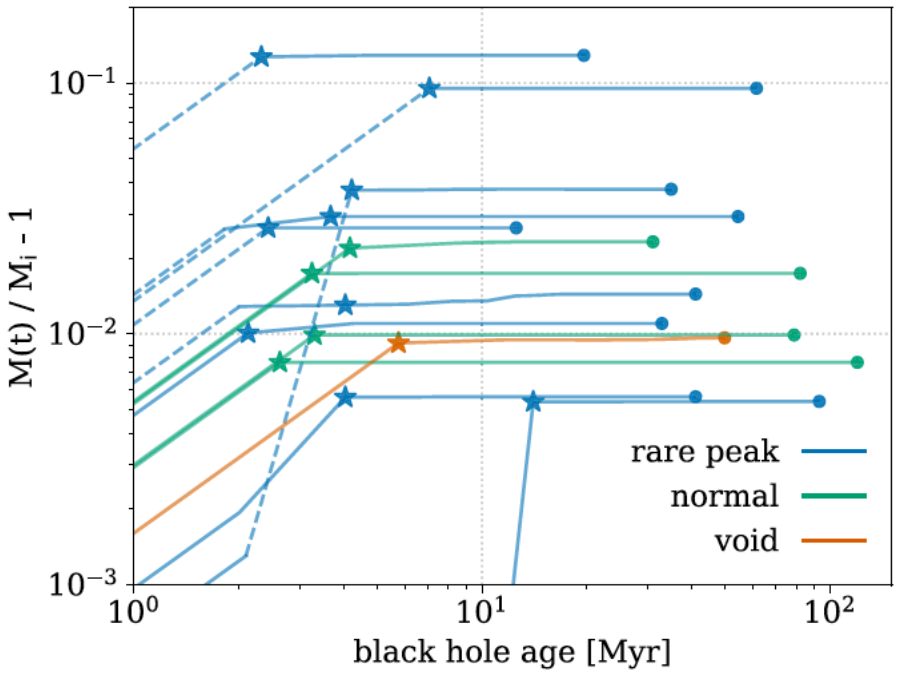


Hirano et al. 2015



Can Pop III grow into early SMBHs?

- ~100 $M_\odot$ Pop III seed produced at z~30 could explain high-z quasar observations w/ constant Eddington-limited accretion
- Feedback seems to make this impossible for most: UV radiation, X-rays, supernovae (e.g., Milosavljevic et al. 2009, Alvarez et al. 2009)
- Maybe some lucky/special Pop III seeds can grow much faster?



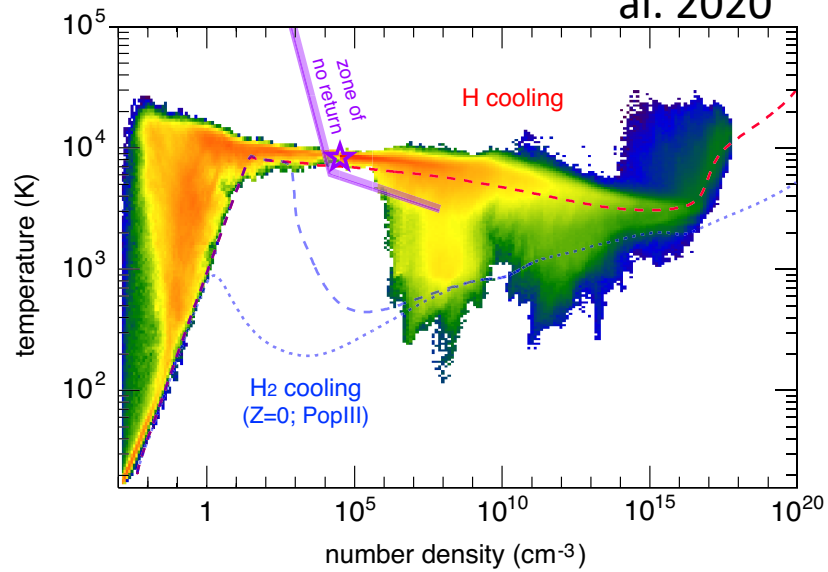
Smith et al. 2018

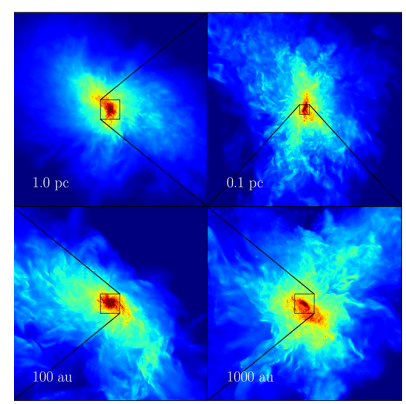
Massive Seeds (often called "Direct Collapse Black Holes", DCBHs)

(see e.g., Eisenstein & Loeb (1995), Oh & Haiman (2002), Bromm & Loeb (2003), Lodato & Natarajan (2006), Dijkstra et al. (2008))

- H_2 cooling → ~200 K gas → fragmentation to 100-1000 $M_\odot$ Pop III stars
- Shut off H_2 cooling → H cooling at ~10^4 K → suppressed fragmentation→ ~10^5 $M_\odot$ star → "DCBH"
- Happens in metal-free "atomic cooling halos"

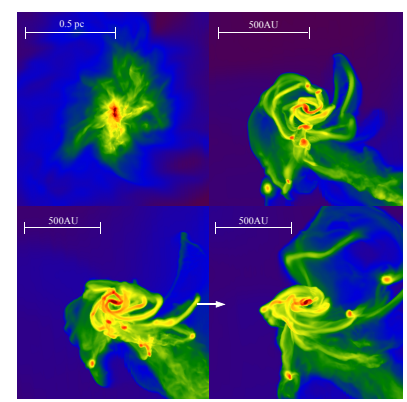
Inayoshi et al. 2020





gravitational collapse

Becerra et al. (2015)

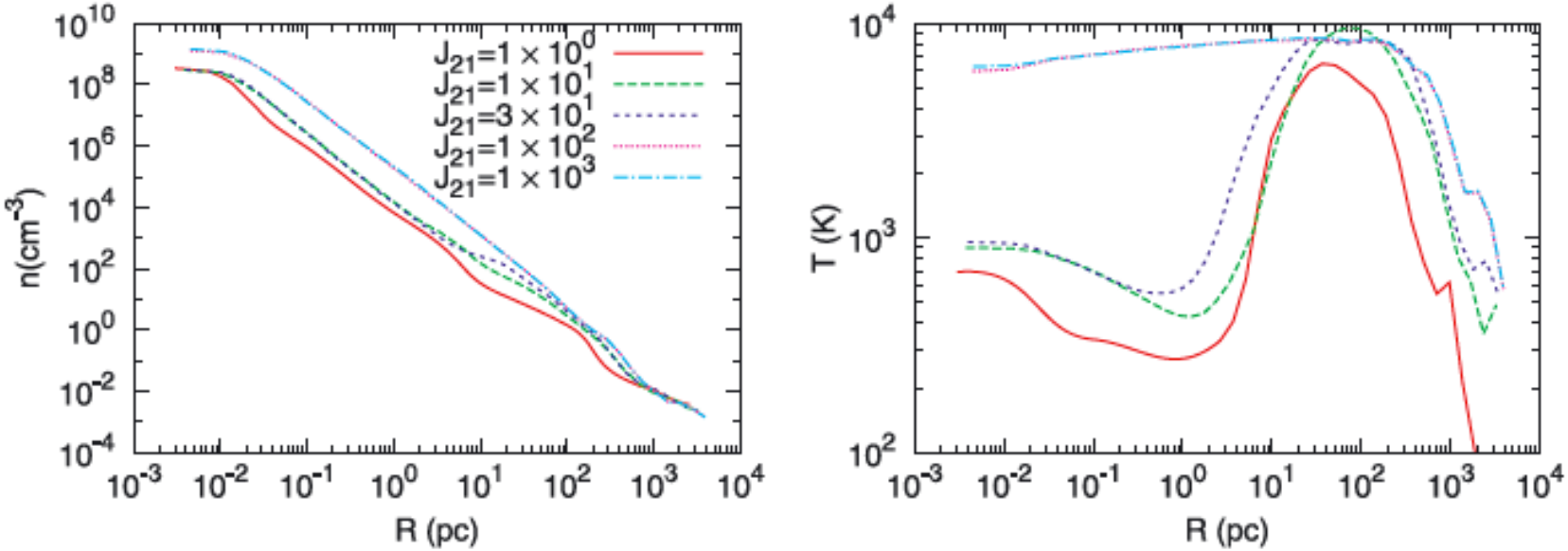


accretion disk

Regan et al. (2014)

Strong Lyman-Werner Radiation

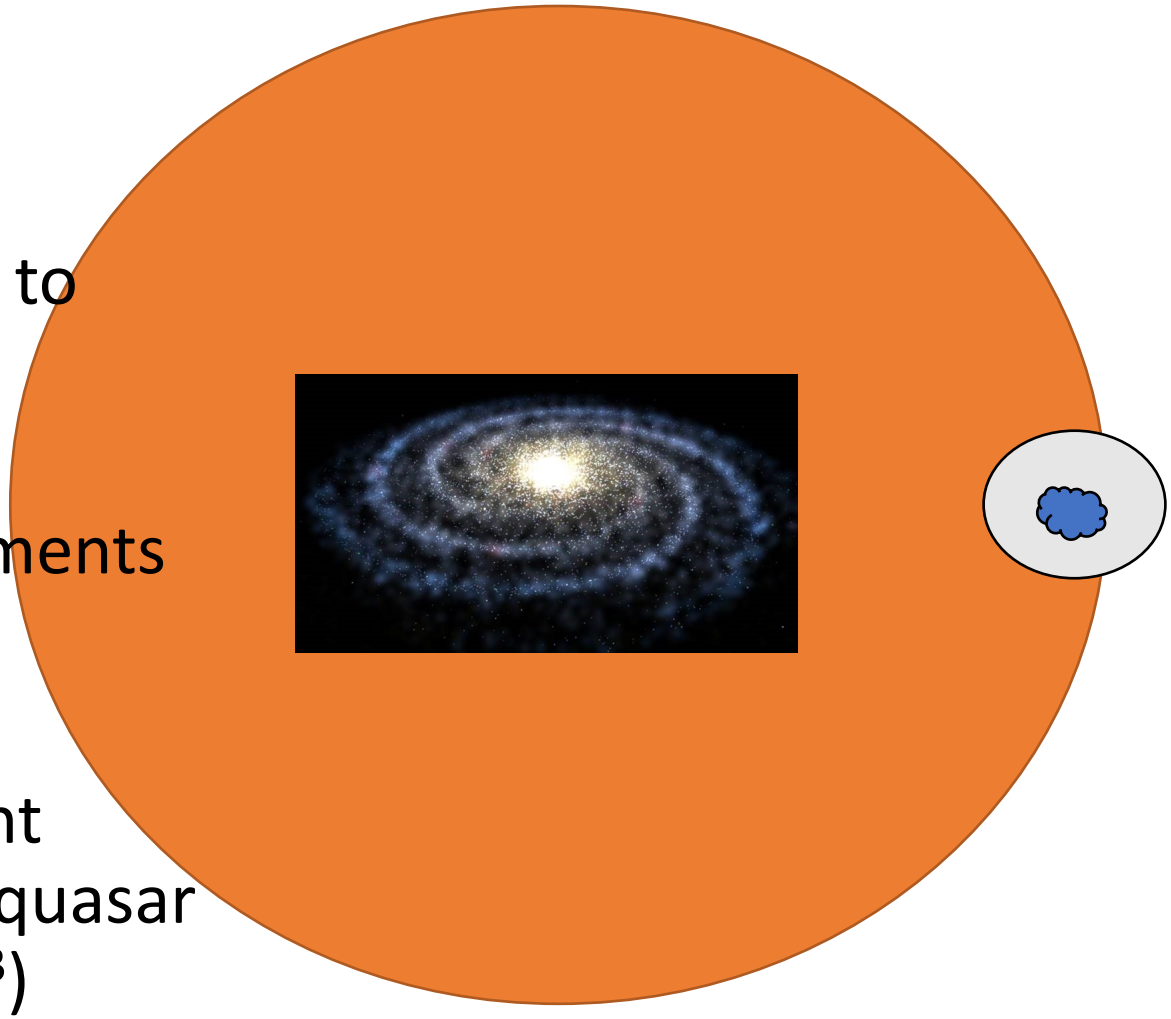
Shang et al. 2010



- Lyman-Werner Flux (11.2-13.6 eV) → photodissociates H_2
- Very high flux needed for DCBH formation (J_{crit})

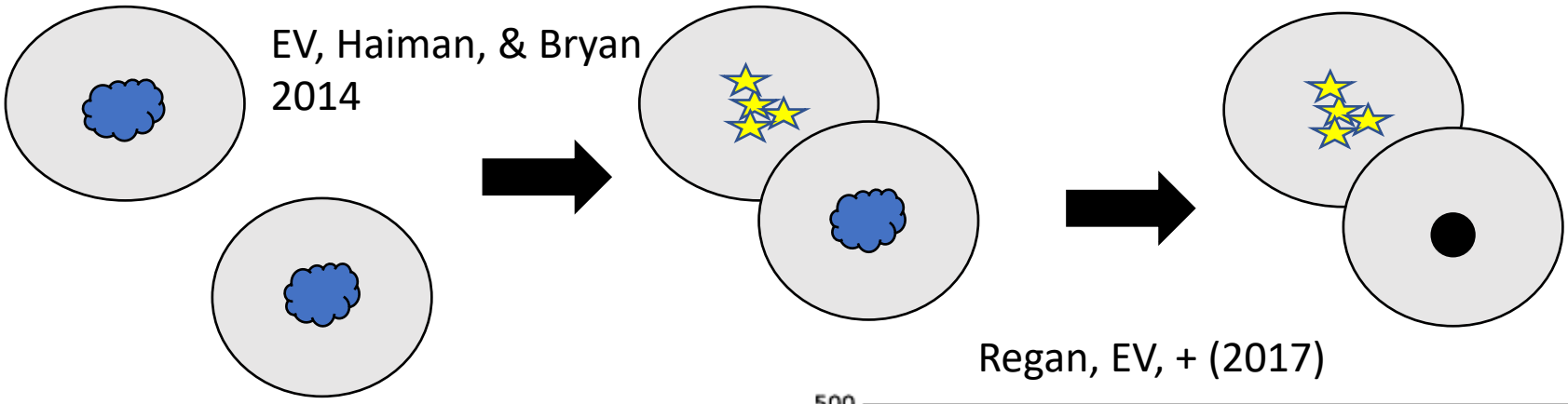
Problem : Very High Flux Required + Supernovae Winds

- H_2 dissociating flux required very high
- Must be very close to massive galaxy
- Supernovae winds carrying heavy elements can prevent DCBH formation
- Initially was thought difficult to explain quasar density (1 per Gpc^3)

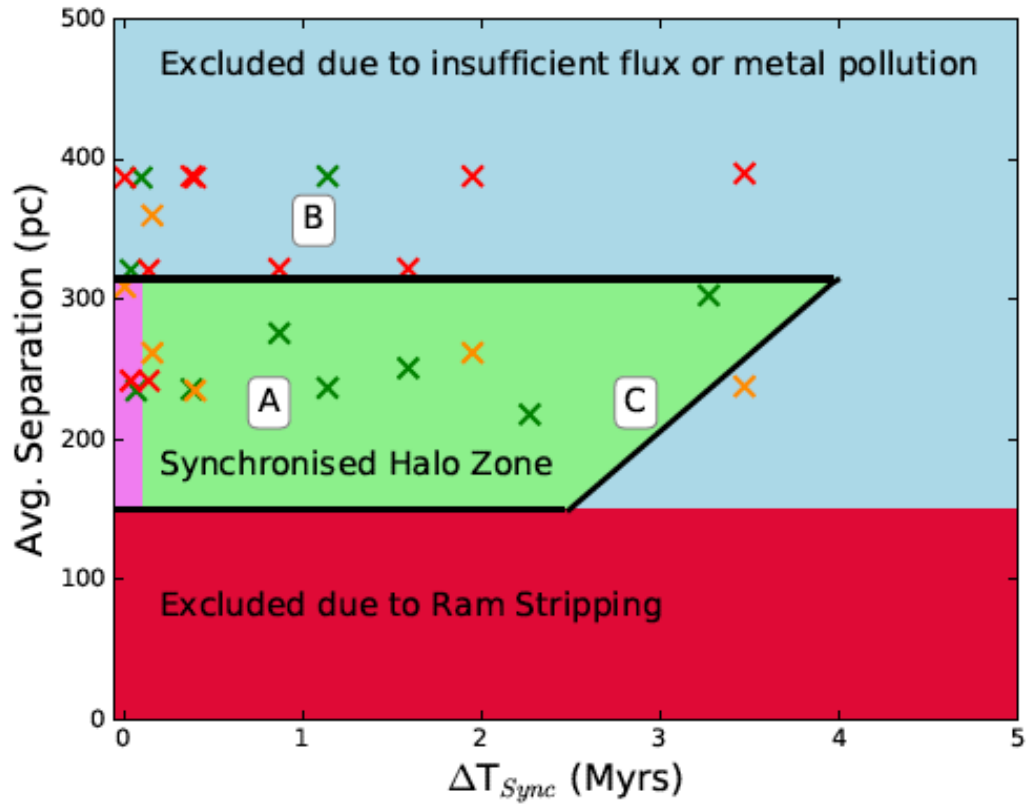


“Synchronized Halo Pairs”

EV, Haiman, & Bryan 2014

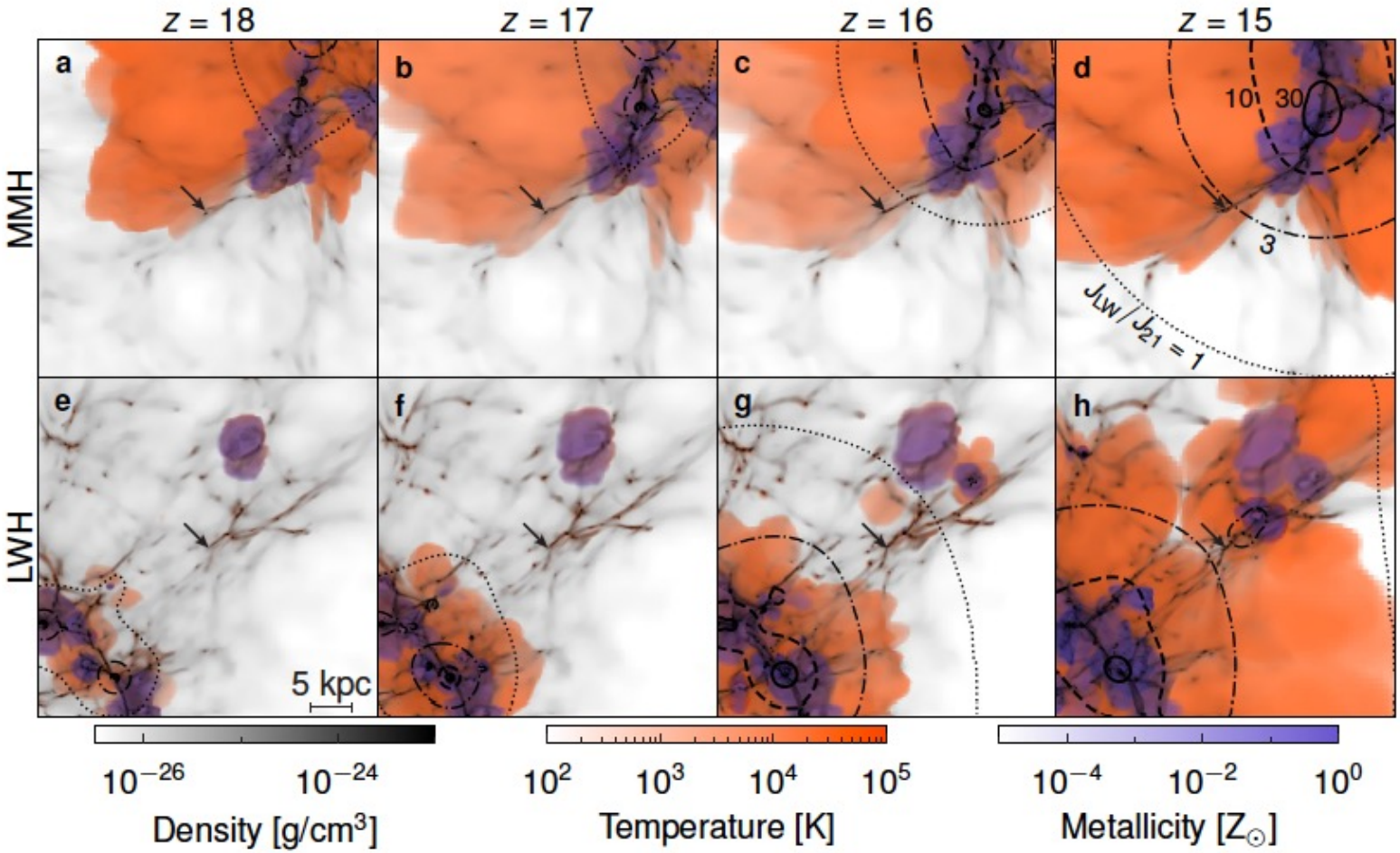


Regan, EV, + (2017)



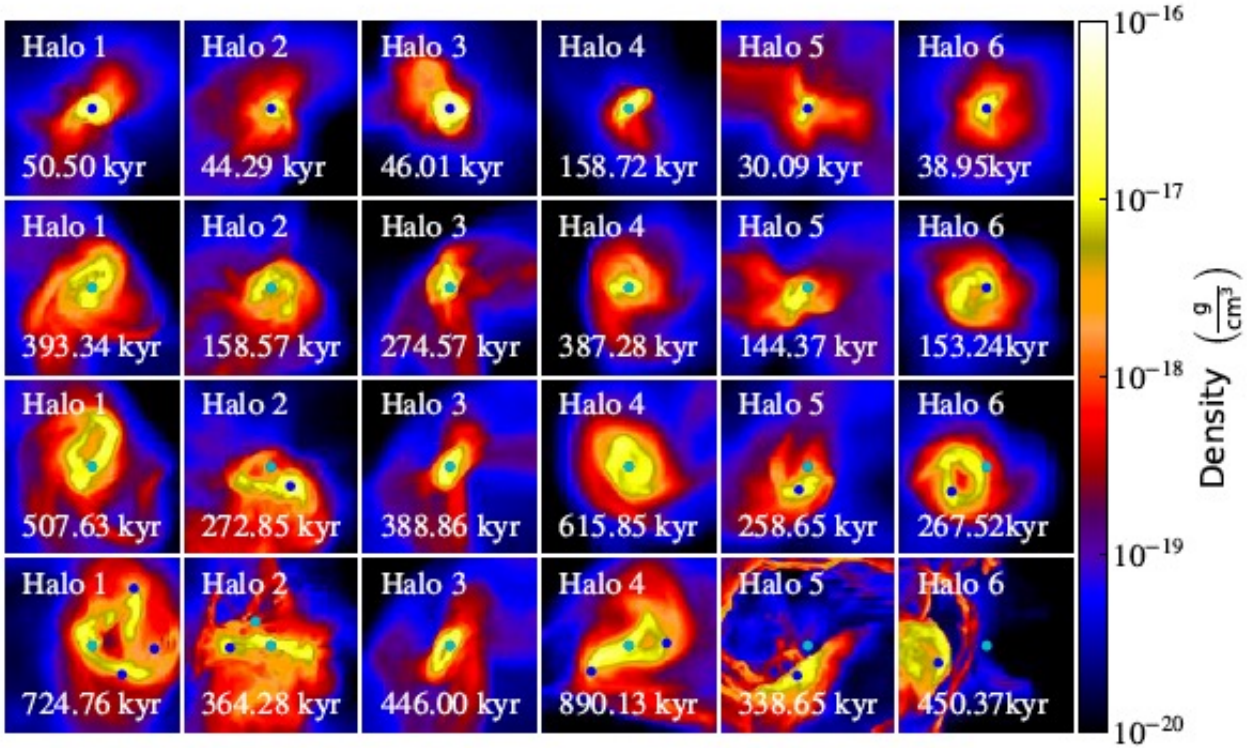
- Pair of pristine atomic cooling halos merge
  - First to cool → stars
  - Second to cool → direct collapse black hole
- High H_2 dissociating flux due to small separation
- Potentially solves supernovae wind problem

Heating Through Rapid Halo Assembly



Wise et al. 2019

“Failed” DCBHs



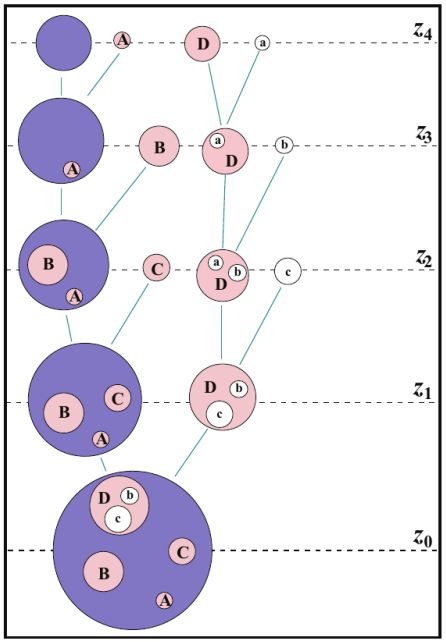
Latif et al. (2021)

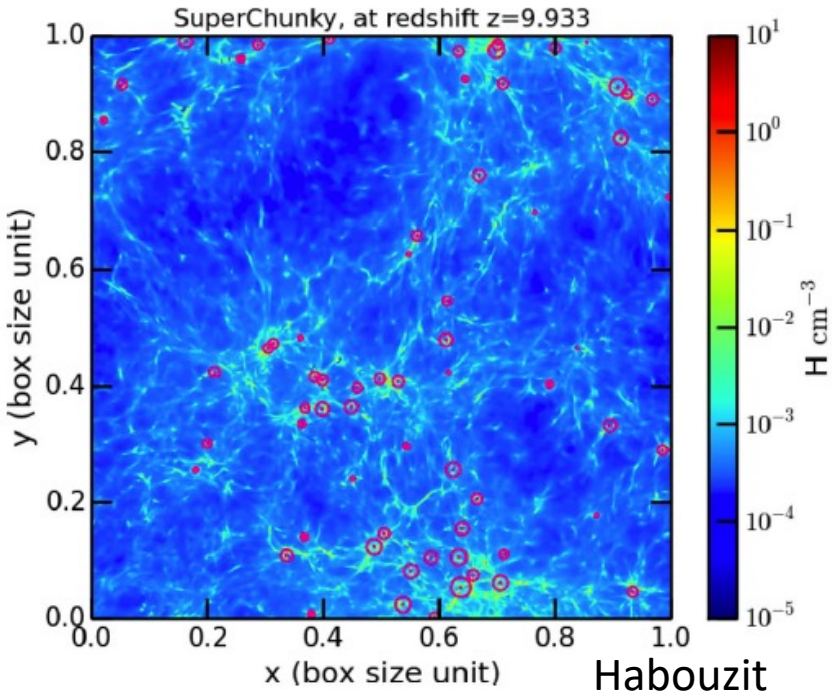
- Moderate Lyman-Werner flux → few thousand solar mass intermediate mass black holes

Comment on Abundances

- $10^9\ M_\odot$ high-z black holes very rare (~10^{-9} Mpc^{-3})
- Some models make enough seeds (though still being worked out fraction that ultimately form SMBHs)
  - Synchronized pairs (~10^{-4} Mpc^{-3})
  - Rapid Accretion (~10^{-6} Mpc^{-3})
- Local SMBH number density (~10^{-2} Mpc^{-3} for BHs above $10^7\ M_\odot$)
  (Shankar et al. 2004)
- <u>Thus, current models of massive seeds cannot explain all nuclear BHs today!</u>

Growth of Seeds – Semi-analytic vs simulations





Habouzit et al. 2016)

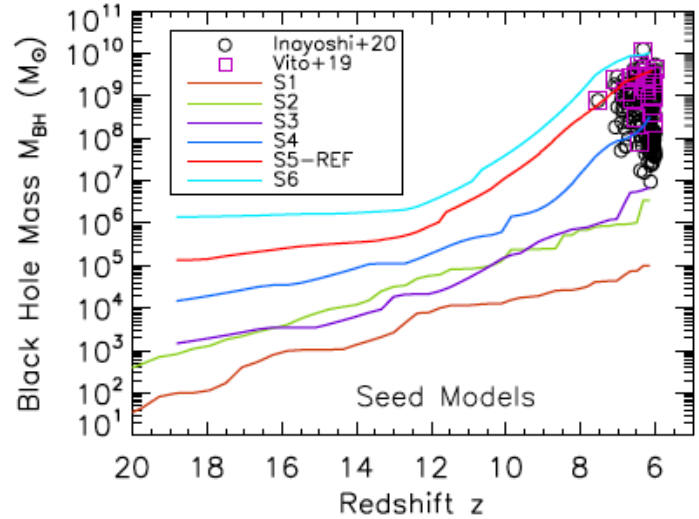
- Semi-analytic
  - Monte Carlo merger trees
  - Fast → can predict observables spanning large volumes
  - Often many free parameters/simplified physics

- Numerical Simulations
  - Expensive
  - Detailed physics
  - Cannot resolve Pop III minihalos over large volumes (subgrid required)

Simulations

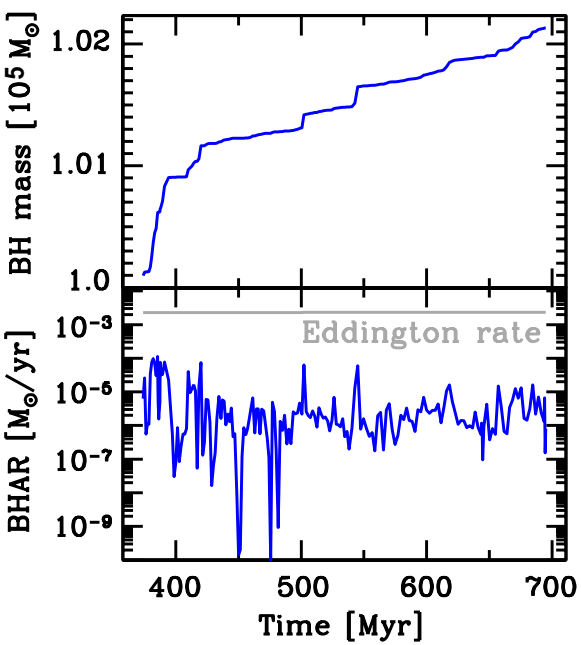
- DCBHs first form in ~$10^{7\text{-}8}\,M_\odot$ "atomic cooling halos" → seems to lead to modest growth
- More massive halos → gas accretion up to observed quasars

Zhu et al. 2022



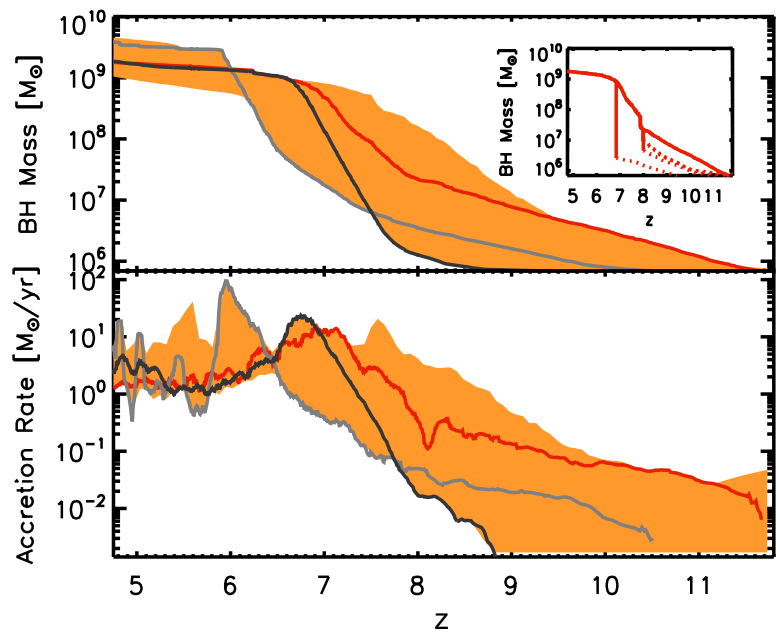
Latif et al. 2018

ordinary ACHs (~2σ)



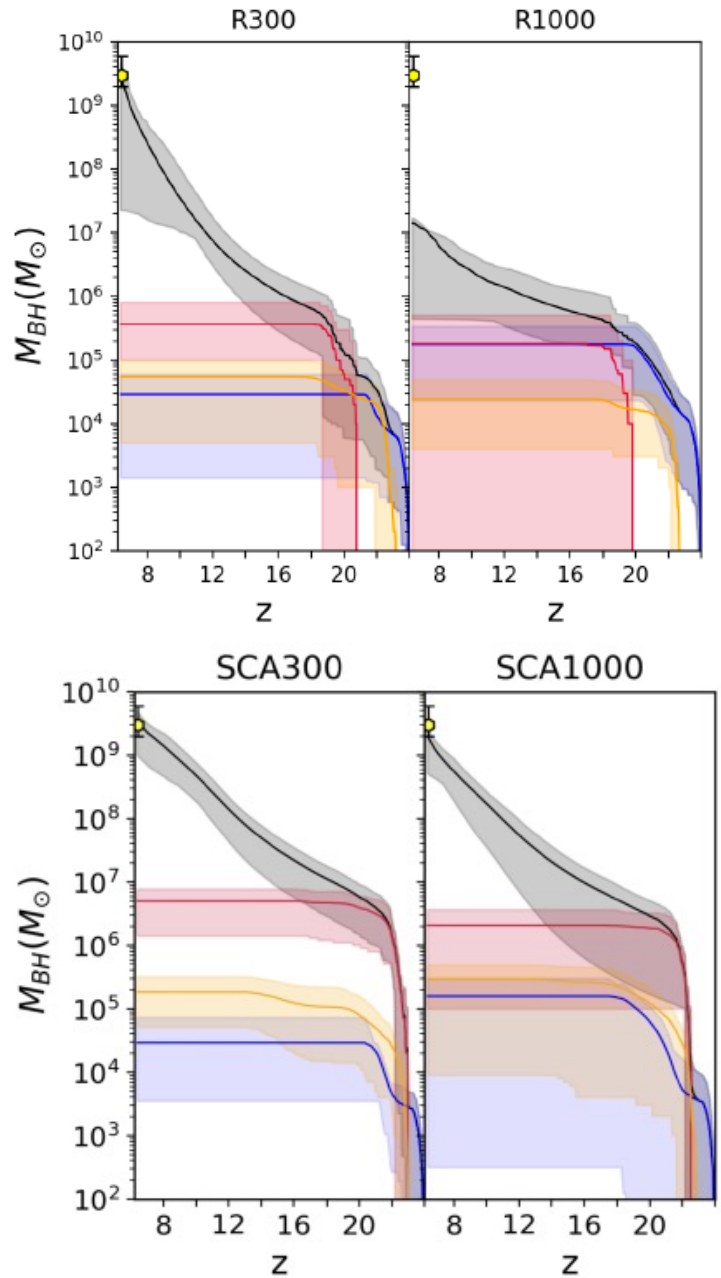
Di Matteo et al. 2012

rare, massive halos (~5σ)



Semi-analytic

- High-z quasars appear possible with massive seeds
- But flexibility of models plus limited observations of low-mass black holes makes strong conclusions difficult



Sassano et al. 2022

Other Seeding Channels

- Intermediate mass BHs via runaway stellar collisions in metal-poor clusters (e.g., Omukai et al. 2008, Devecchi & Volonteri 2009, Katz et al. 2015, Yajima & Khochfar 2016, Sakurai et al. 2017)
- Massive BHs from super-Eddington accretion onto stellar mass seeds (Pacucci et al. 2015b, Inayoshi et al. 2016, Ryu et al. 2016)
- High-velocity collisions of protogalacatic halos (Inayoshi, EV, & Kashiyama 2015)
- Very high baryon-dark matter streaming velocity (Hirano et al. 2017)
- Rare cold flows → supersonic turbulence (Latif 2022)
- Perhaps more speculative: dark stars, self-interacting dark matter…

Conclusions/Open Questions

- We see > $10^9 M_\odot$ SMBHs at z>6
- Simplest Pop III seeds do not appear to work, heavy seeds do seem to
- Lots of modeling efforts for massive seeds, but which (if any) are dominant channels?
- What seeds are important for lower mass/redshift SMBHs? DCBH likely too rare…
- Need to more observations to make definitive claims
  - X-rays → accretion
  - GW → Mergers
  - Local IMBHs
  - JWST
- Most powerful constraints?
- Possible to reduce free parameters/subgrid physics in models?

Observational Signatures of the First Black Holes

Fabio Pacucci

BHI & Clay Fellow
Harvard University
Center for Astrophysics | Harvard & Smithsonian

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

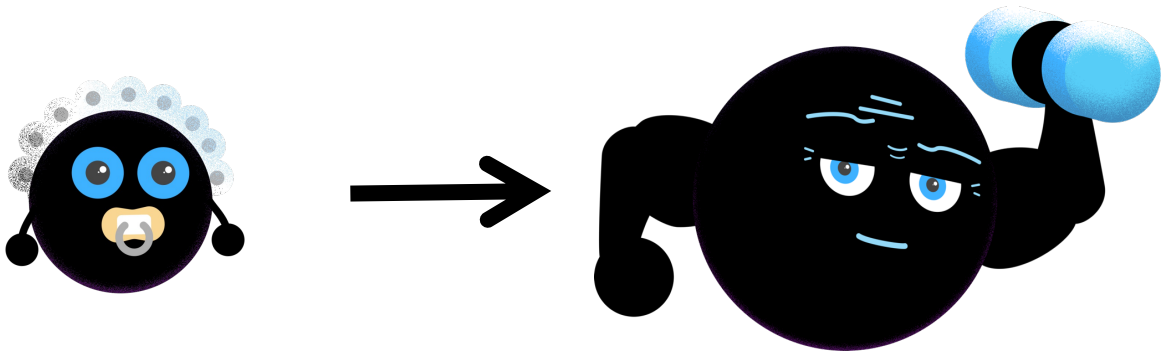
GORDON AND BETTY MOORE FOUNDATION

BLACK HOLE INITIATIVE
HARVARD UNIVERSITY

JOHN TEMPLETON FOUNDATION

PAX 22 Workshop
"High Redshift Universe" — August 2nd, 2022

Observing the First Black Holes



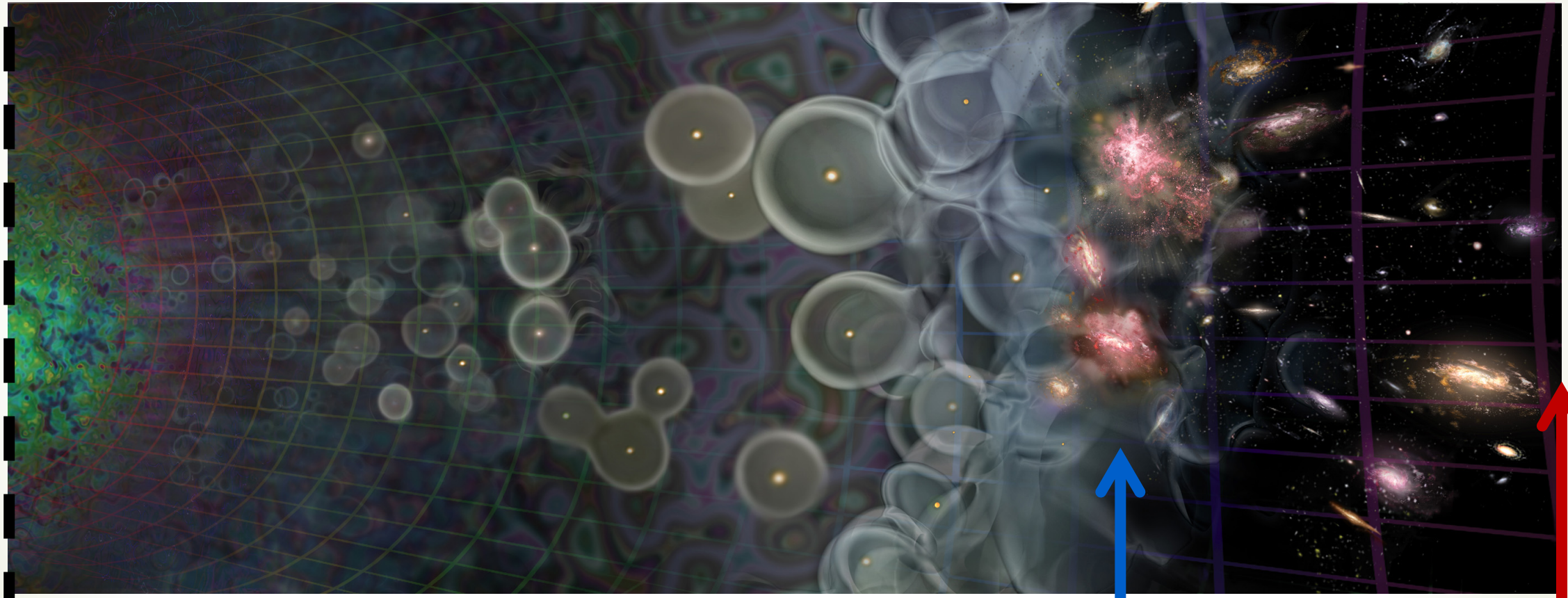
- Electromagnetic signatures (optical, IR, X-rays)
- Gravitational waves signatures
- Some questions/curiosities for later discussion

Image credit: NASA/GSFC

A Brief History of Time

TIME

Black hole seeds were formed 100-200 Myr after the Big Bang (z ~ 20-30)



First detected SMBHs (< 1 Gyr)

Now (13.7 Gyr)

A Brief History of Quasar Discoveries

Published: 16 Marc

3C 273 : A S

M. SCHMIDT

Nature **197**, 1040

6650 Accesses

Quasar®

Industry	Electronics
Founded	1967
Key people	Bob Greenberg CEO Alex Stone CEO F. Jack Pluckhan CEO
Products	Televisions, VCRs, record players, cassette players, air conditioners, Palmcorders, and microwave ovens
Parent	Panasonic Corporation

Red-Shift

Year 1963 — z = 0.158

A Brief History of Quasar Discoveries

LARGE REDSHIFTS OF FIVE QUASI-STELLAR SOURCES

The purpose of this letter is to communicate redshifts of five quasi-stellar radio sources.

TIME

Friday, May. 21, 1965

Astronomy: Toward the Edge of the Universe

plates. One of the spectra of CTA 102 was obtained by Dr. J. L. Greenstein and kindly put at my disposal.

Year 1965 — z = 2.018

A Brief History of Quasar Discoveries

TIME

Monday, Apr. 23, 1973

AMERICAN NOTES: The Edge of Night

“Restlessly computing and quantifying, weighing and rationalizing, man is forever trying to take the measure of the universe. Now Astronomer Allan R. Sandage of the Hale Observatories in Pasadena, Calif., proclaims that he and his colleagues elsewhere in the U.S. may have finally done just that. They have, he said, apparently seen "the edge" of the universe.”

[…]

“Scottish Essayist Thomas Carlyle once noted that man must "always worship something–always see the Infinite shadowed forth in something finite." At the moment, the something worshiped is science, and the something finite is quasar OH471, the blaze marking the edge of the universe.”

Year 1973 — z = 3.408

A Brief History of Quasar Discoveries

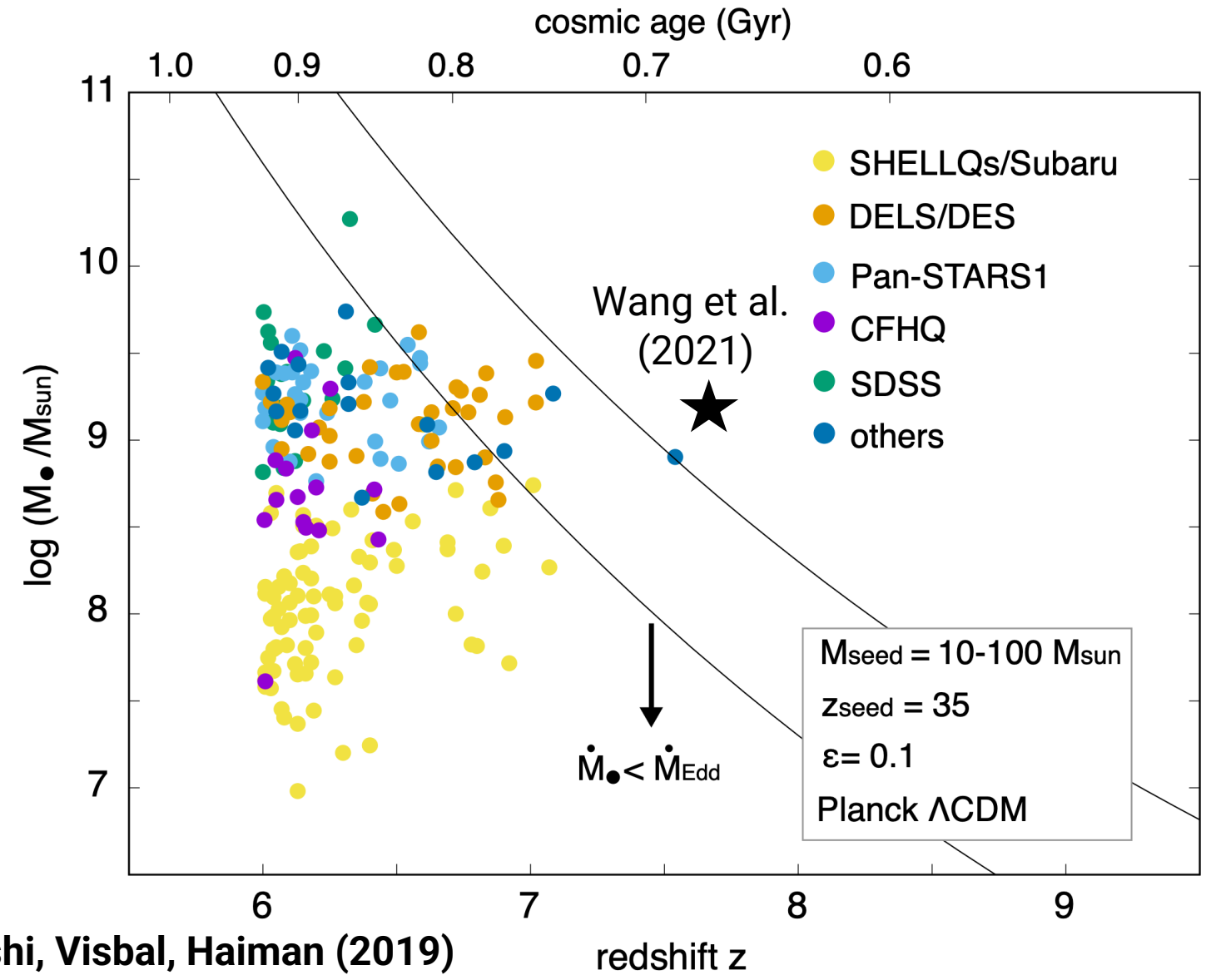
To be published in the Astronomical Journal, Dec 2001

A Survey of $z > 5.8$ Quasars in the Sloan Digital Sky Survey I: Discovery of Three New Quasars and the Spatial Density of Luminous Quasars at $z \sim 6$[1,2]

Xiaohui Fan[3], Vijay K. Narayanan[4], Robert H. Lupton[4], Michael A. Strauss[4], Gillian R. Knapp[4], Robert H. Becker[5,6], Richard L. White[7], Laura Pentericci[8], S. K. Leggett[9], Zoltán Haiman[4,11], James E. Gunn[4], Željko Ivezić[4], Donald P. Schneider[10], Scott F. Anderson[12], J. Brinkmann[13], Neta A. Bahcall[4], Andrew J. Connolly[14], Istvan Csabai[15,16], Mamoru Doi[17], Masataka Fukugita[18], Tom Geballe[19], Eva K. Grebel[8], Daniel Harbeck[8], Gregory Hennessy[20], Don Q. Lamb[21], Gajus Miknaitis[12], Jeffrey A. Munn[22], Robert Nichol[23], Sadanori Okamura[17], Jeffrey R. Pier[22], Francisco Prada[24], Gordon T. Richards[10], Alex Szalay[15], Donald G. York[21]

Year 2001 — z = 6.28

Observation of Quasars at z~7

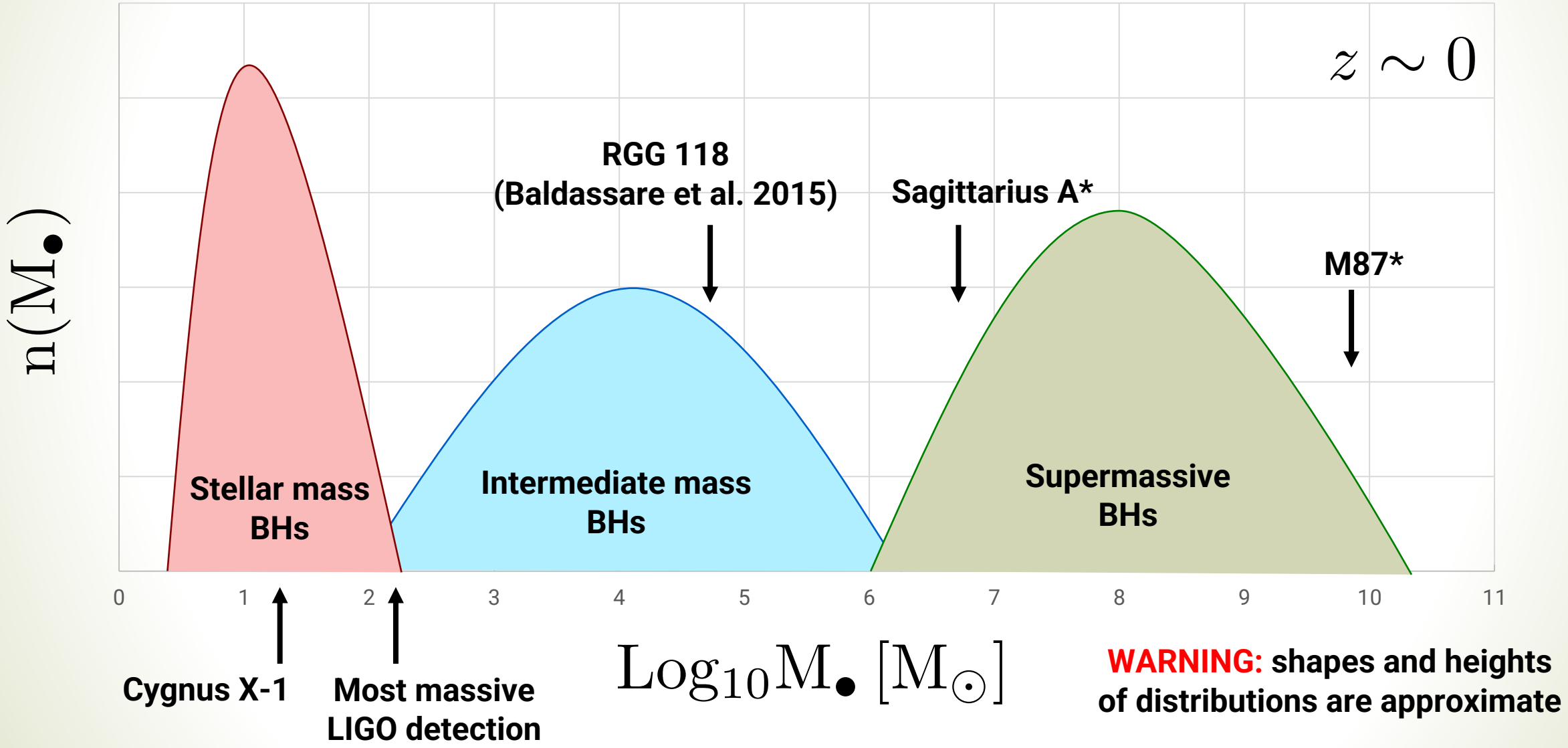


Adapted from Inayoshi, Visbal, Haiman (2019)

Detecting Black Hole Seeds

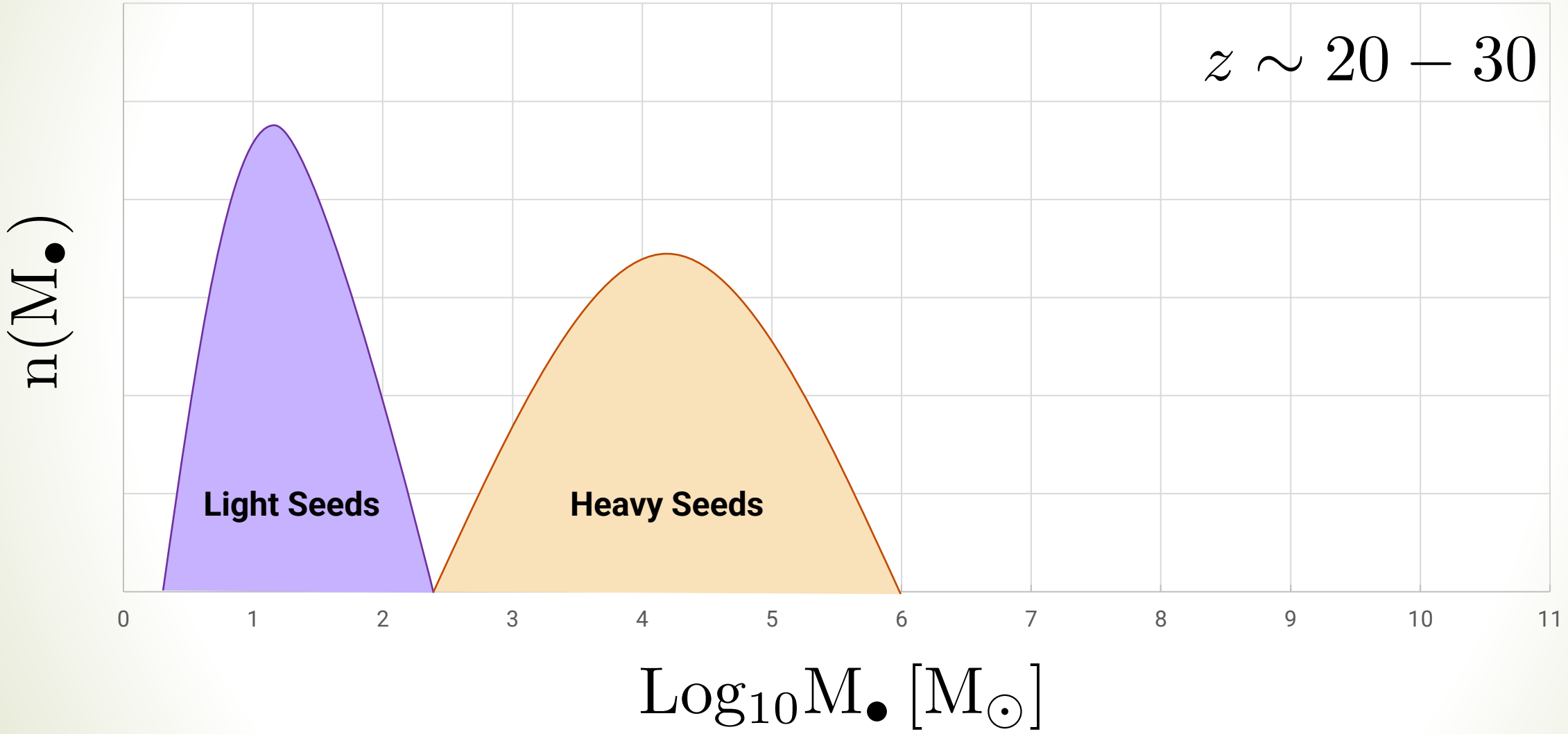
To obtain an unequivocal detection of black hole seeds we need to probe mass scales of ~10^5 solar masses at redshift $z > 15$.

The Local Mass Distribution of Black Holes

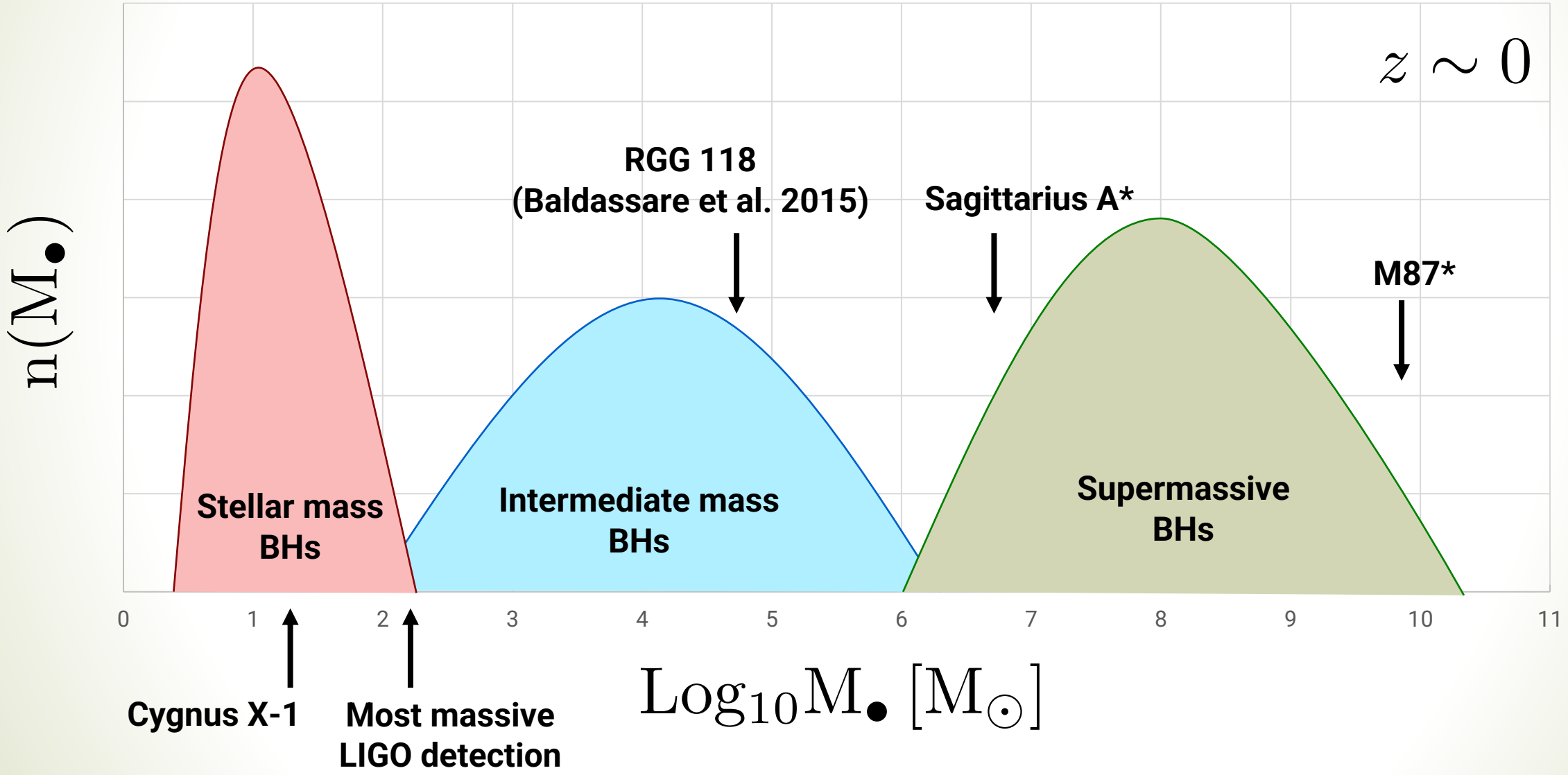


WARNING: shapes and heights of distributions are approximate

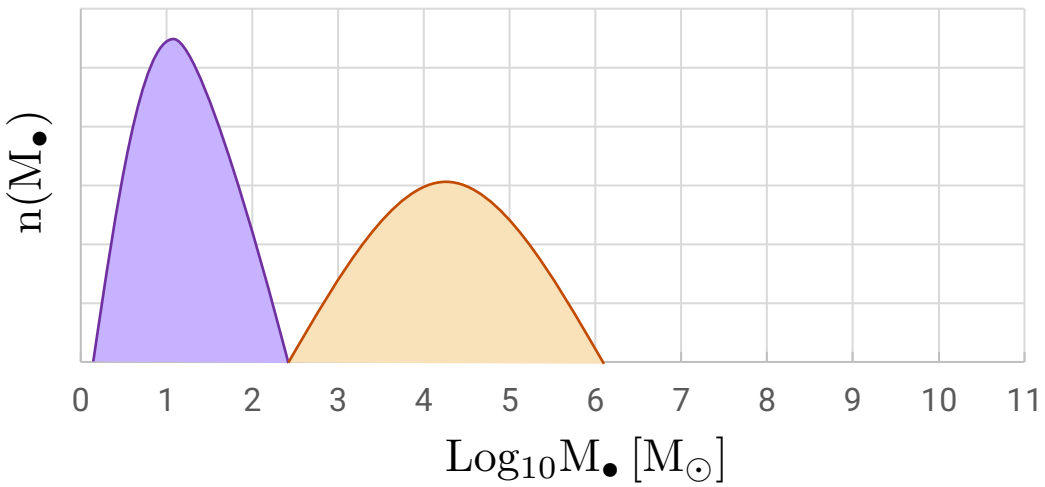
The Mass Distribution of Black Hole Seeds



The Local Mass Distribution of Black Holes



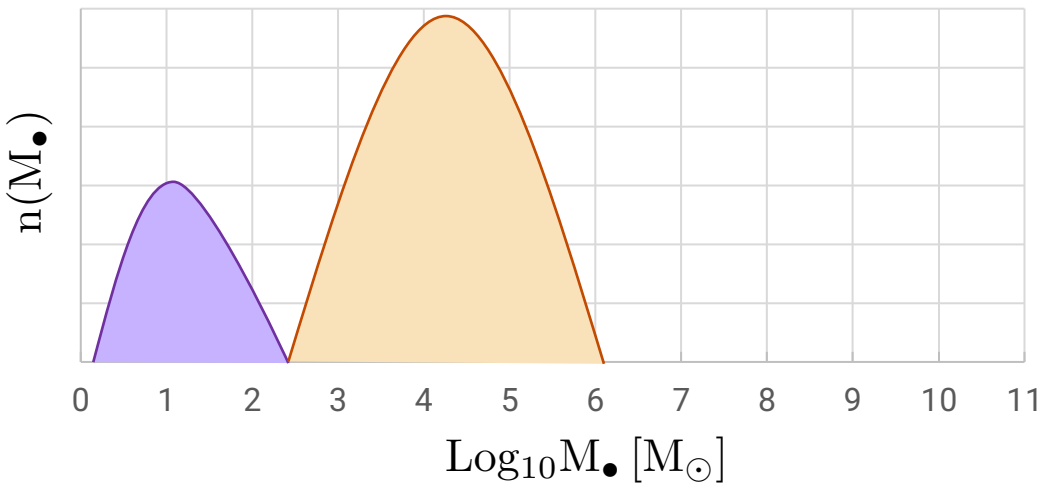
A Degenerate Problem



SOME CONSTRAINTS:

- **Local BH mass distribution**
- **Luminosity functions at various redshift**
- **Future observations of seeds via EM or GW observations**
- **Observation of quasars at z > 7**

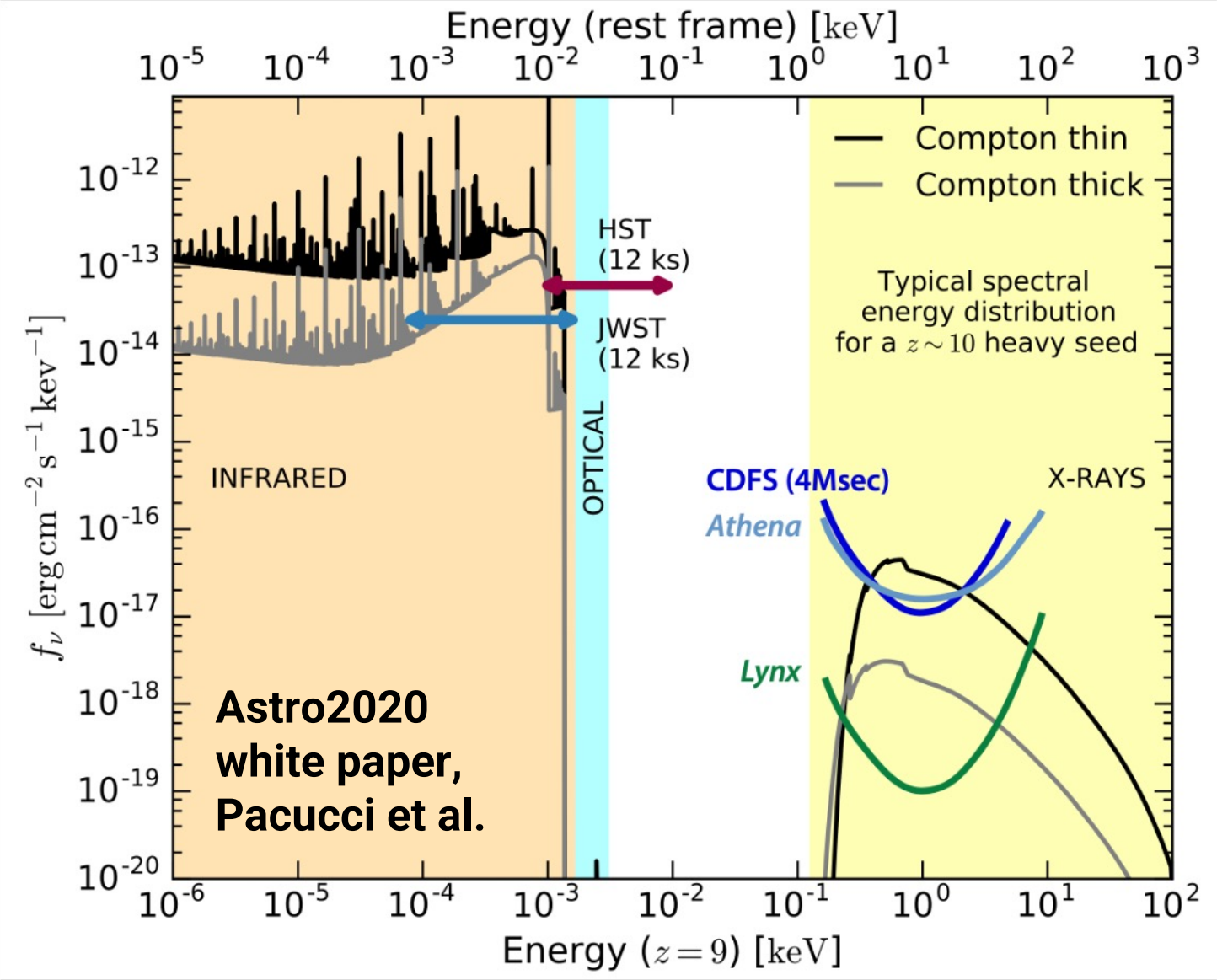
A Degenerate Problem



SOME CONSTRAINTS:

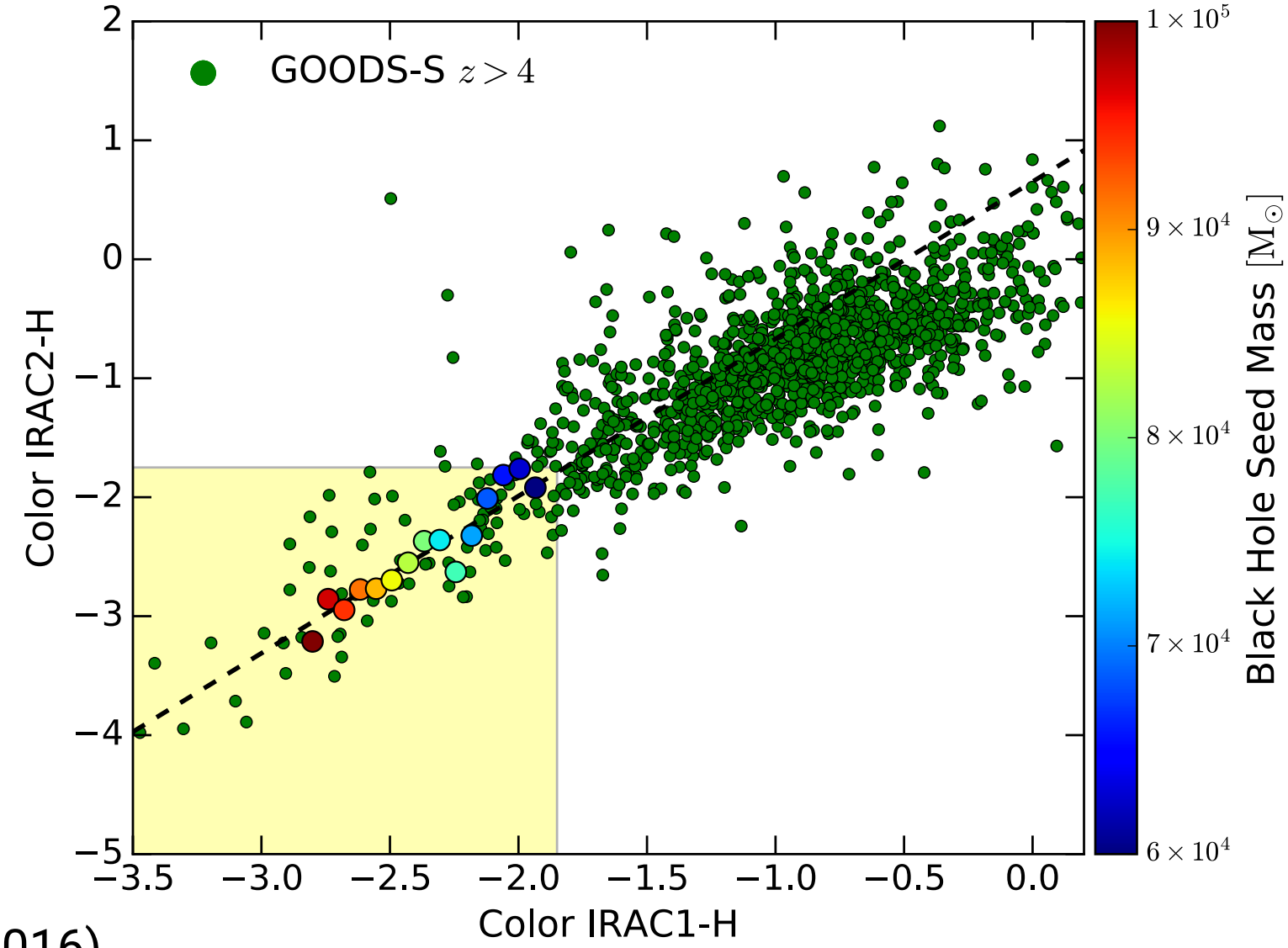
- **Local BH mass distribution**
- **Luminosity functions at various redshift**
- **Future observations of seeds via EM or GW observations**
- **Observation of quasars at z > 7**

Detecting Heavy Seeds



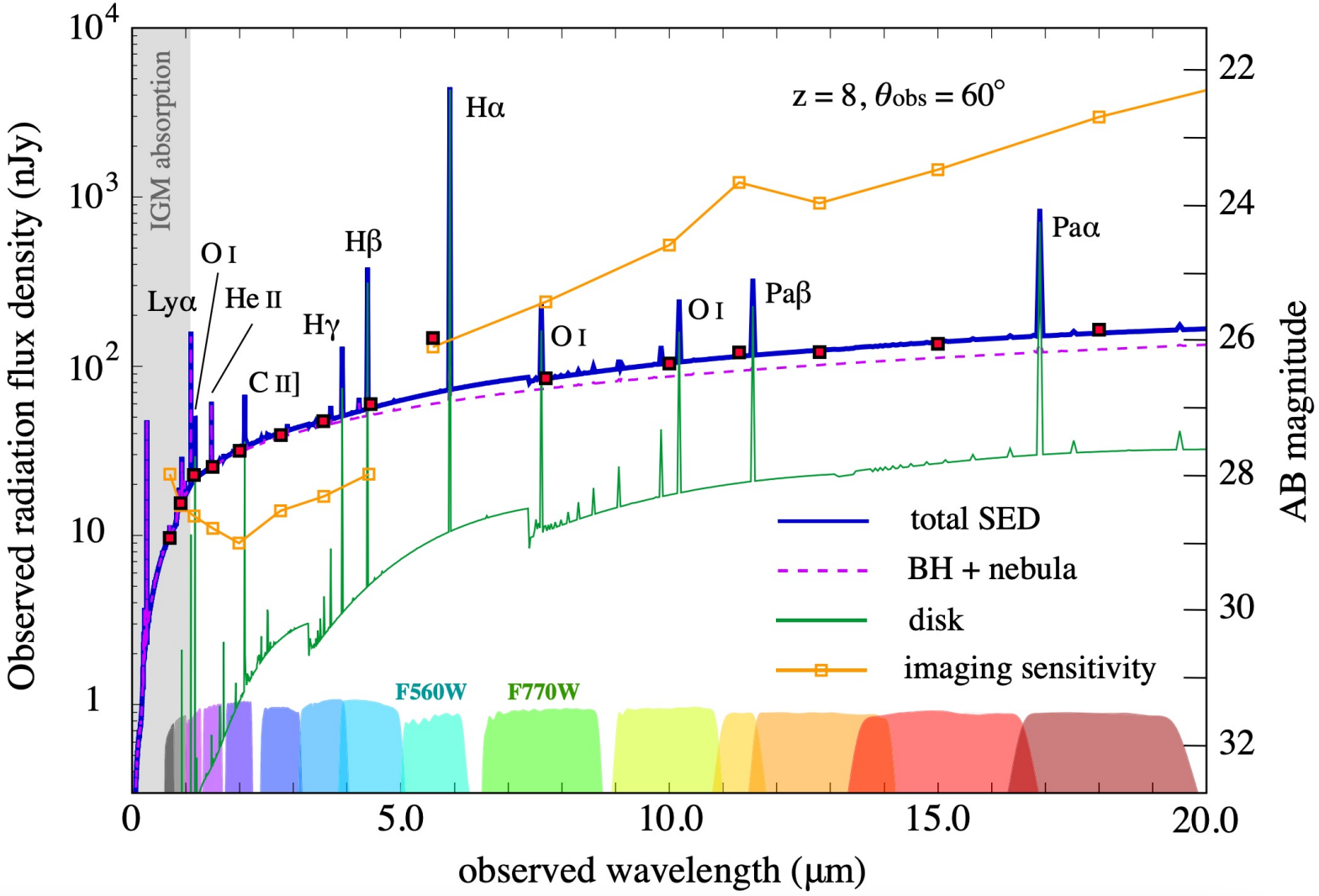
See also studies by Agarwal, Haiman, Natarajan, Pezzulli, Valiante, Visbal, Volonteri

Photometric Selection Criteria



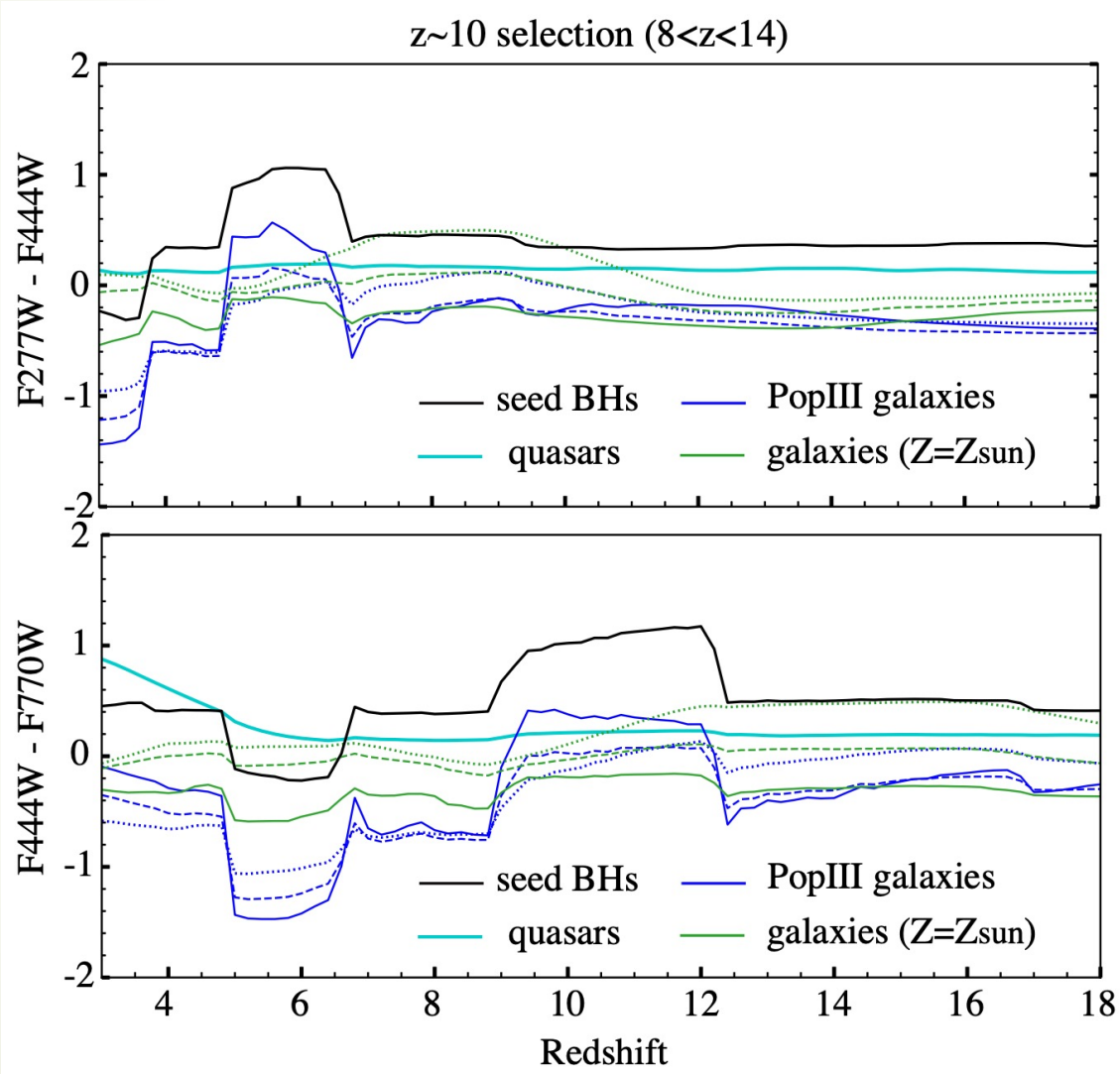
Pacucci et al. (2016)

(Improved) Photometric Selection Criteria

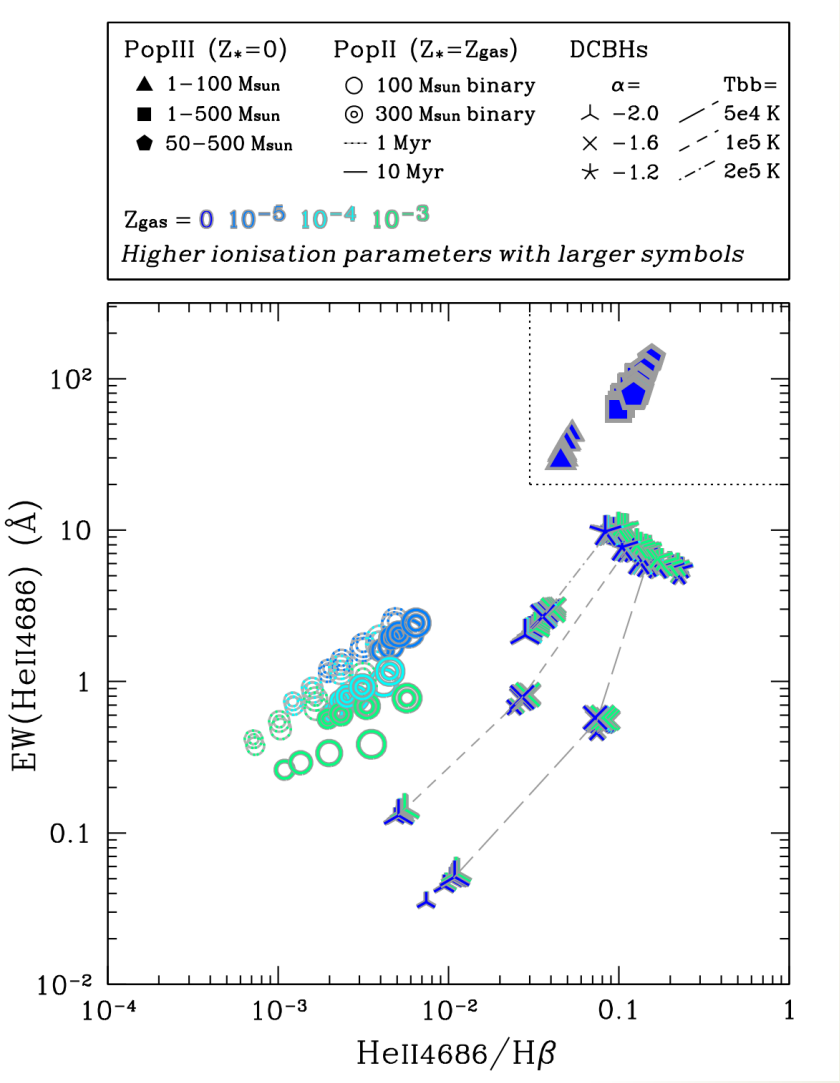


Inayoshi et al. (2022)

(Improved) Photometric Selection Criteria



Inayoshi et al. (2022)



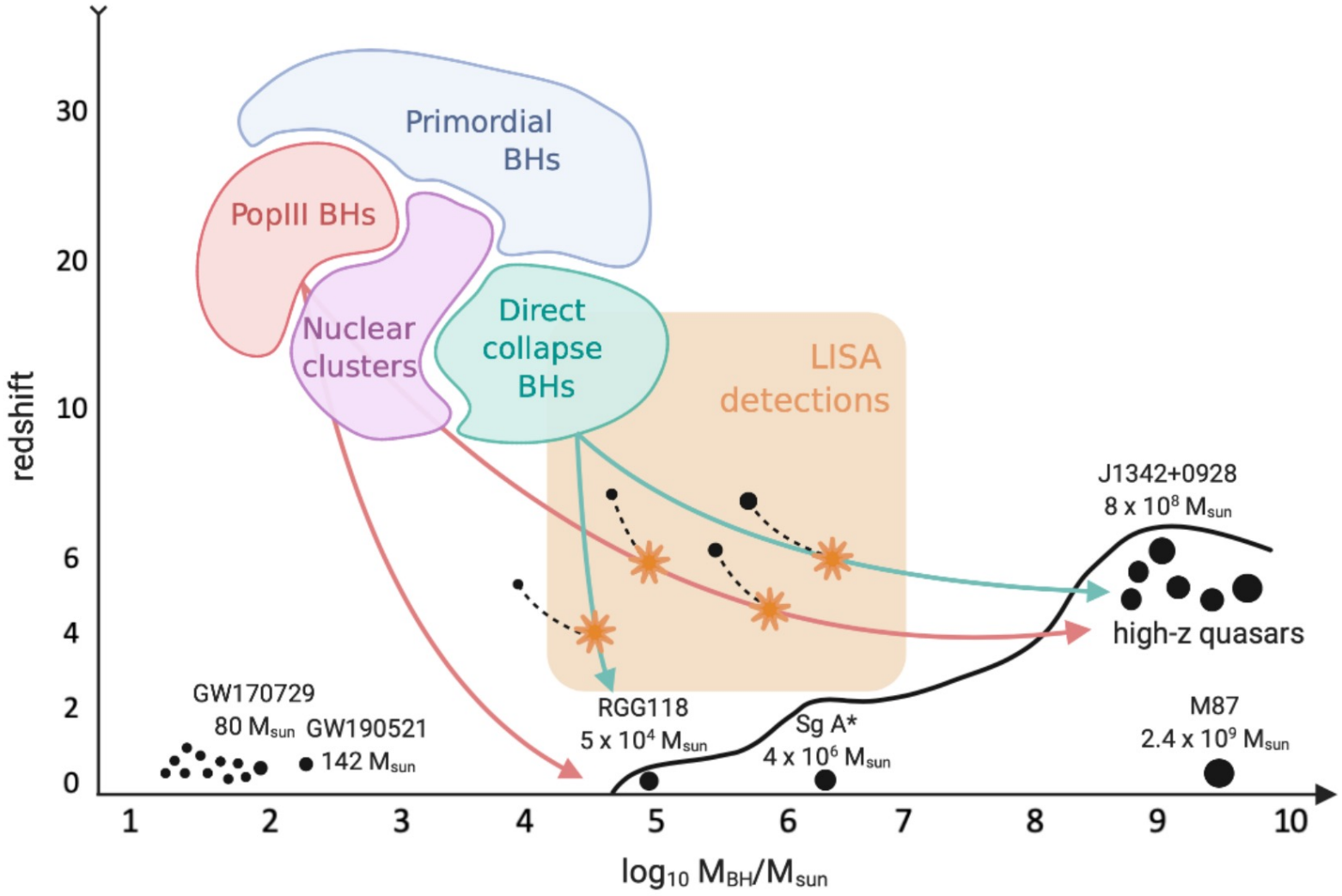
Nakajima & Maiolino (2022)

Expectations for Heavy Seeds (IR/X)

	REQUIREMENTS	EXPECTATIONS
INFRARED	$f \gtrsim 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$	**JWST:** $0.1 - 10\,\mathrm{deg}^{-2}$
X-RAYS	$f_{\mathrm{thin}} \gtrsim 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ $f_{\mathrm{thick}} \gtrsim 10^{-18}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$	**Deep Survey:** $0.5 - 50\,\mathrm{deg}^{-2}$

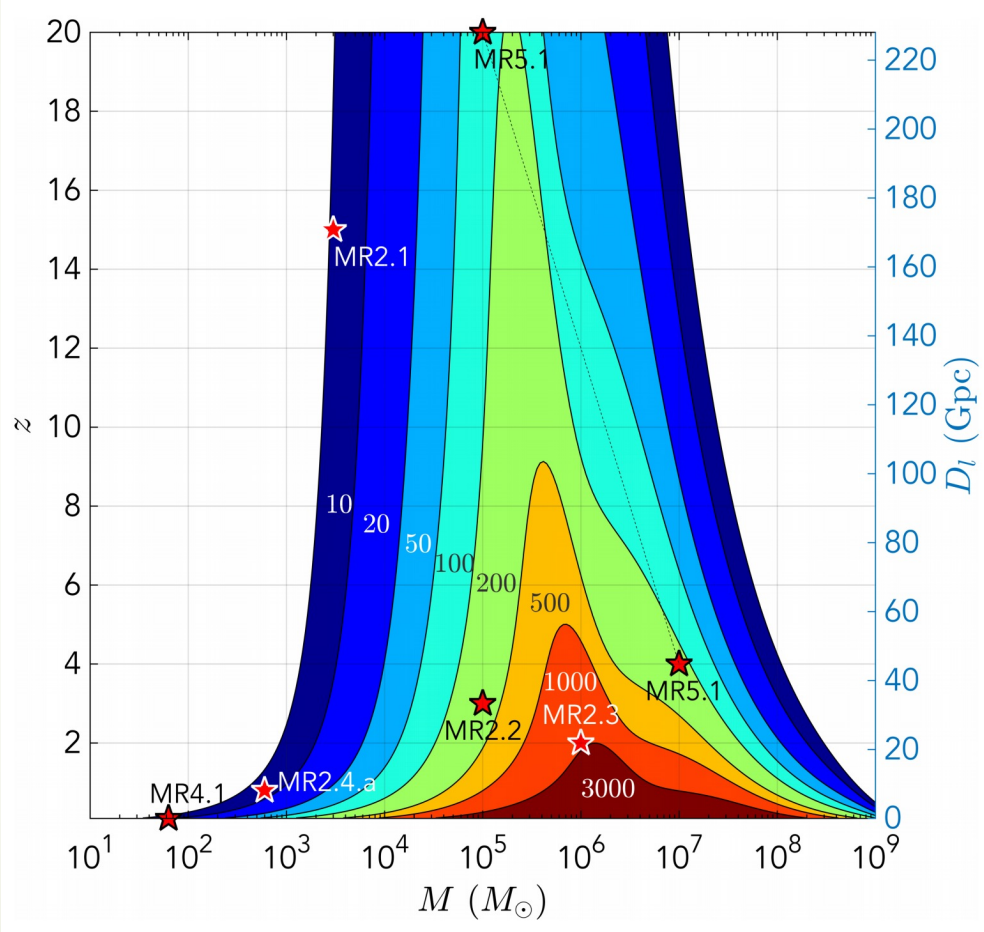
(Adapted from Astro2020 white papers)

The Role of Gravitational Waves

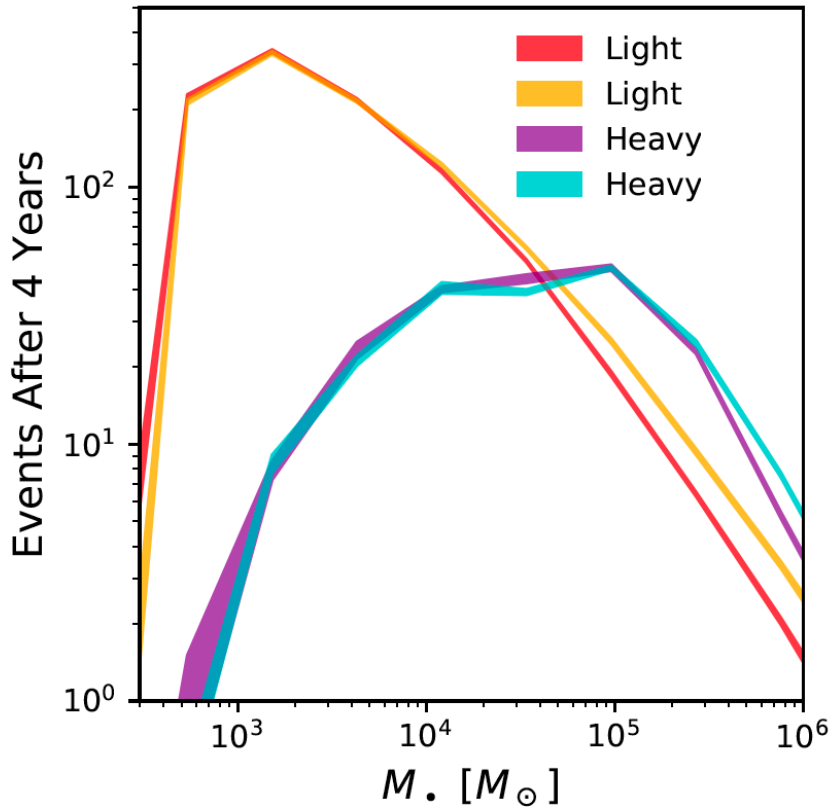


(Astrophysics with the Laser Interferometer Space Antenna, review 2022)

The Role of Gravitational Waves

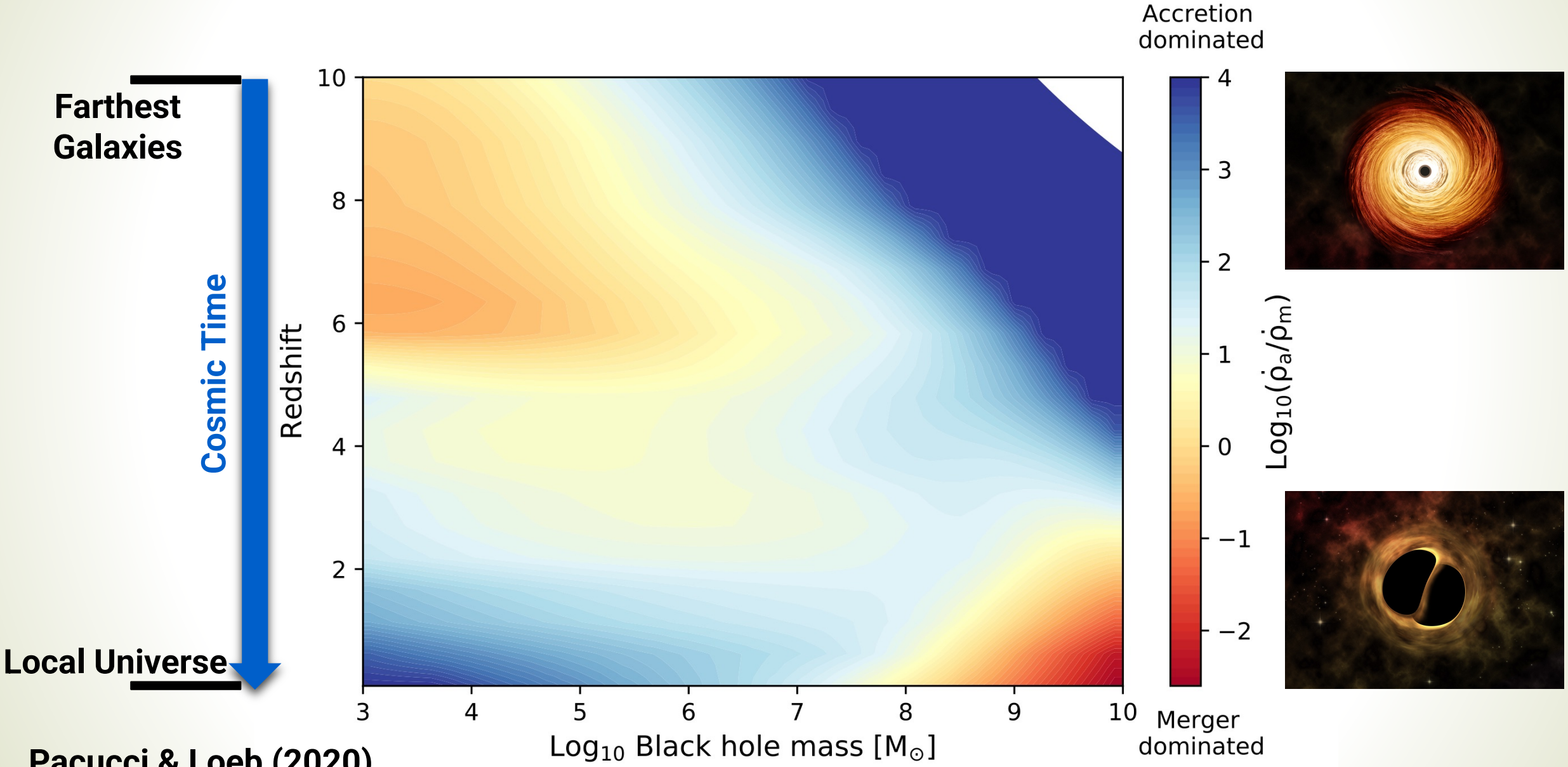


Amaro-Seoane et al. (2017)



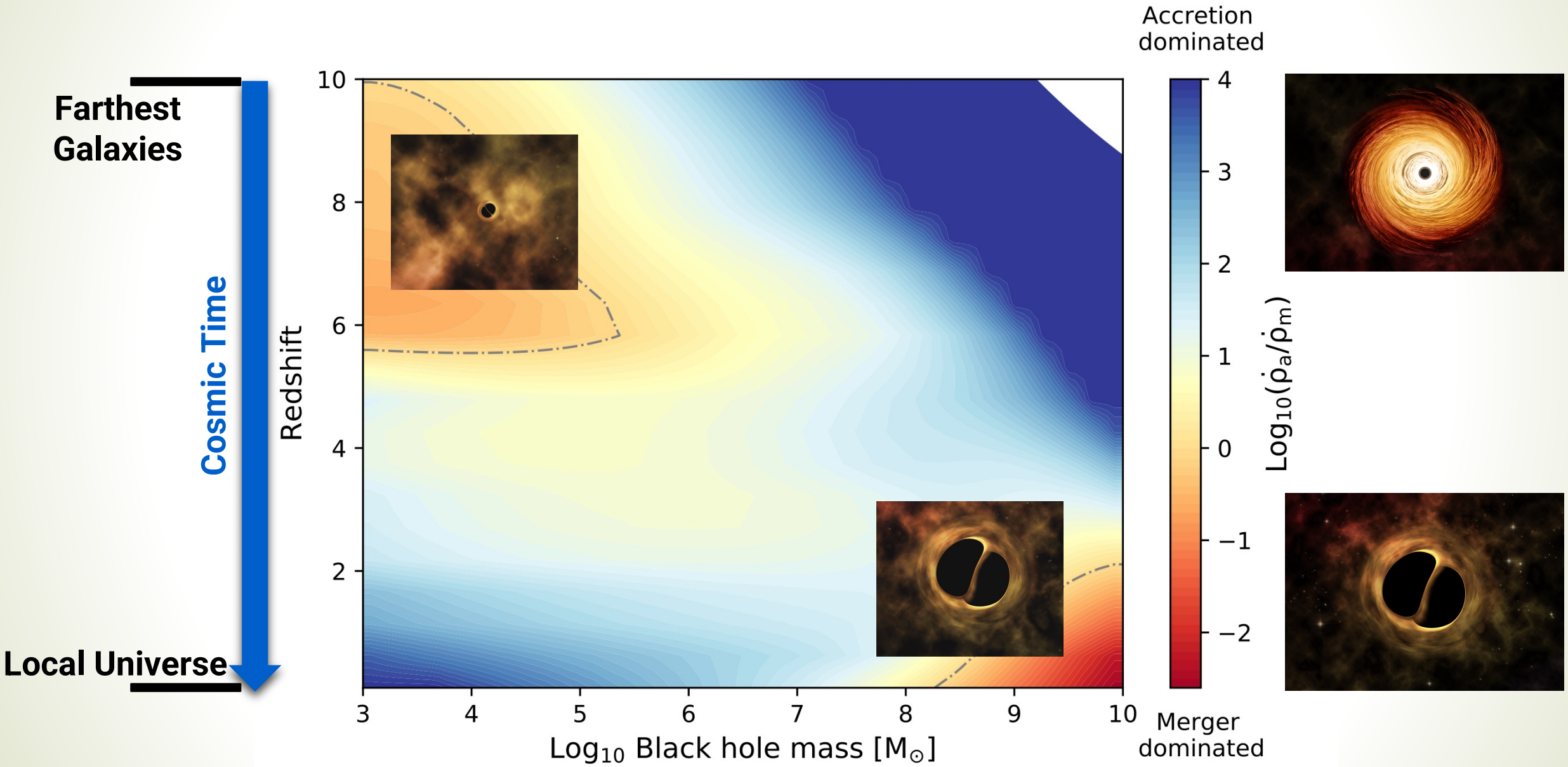
Ricarte & Natarajan (2018)

Accretion vs. Mergers Across Cosmic Time

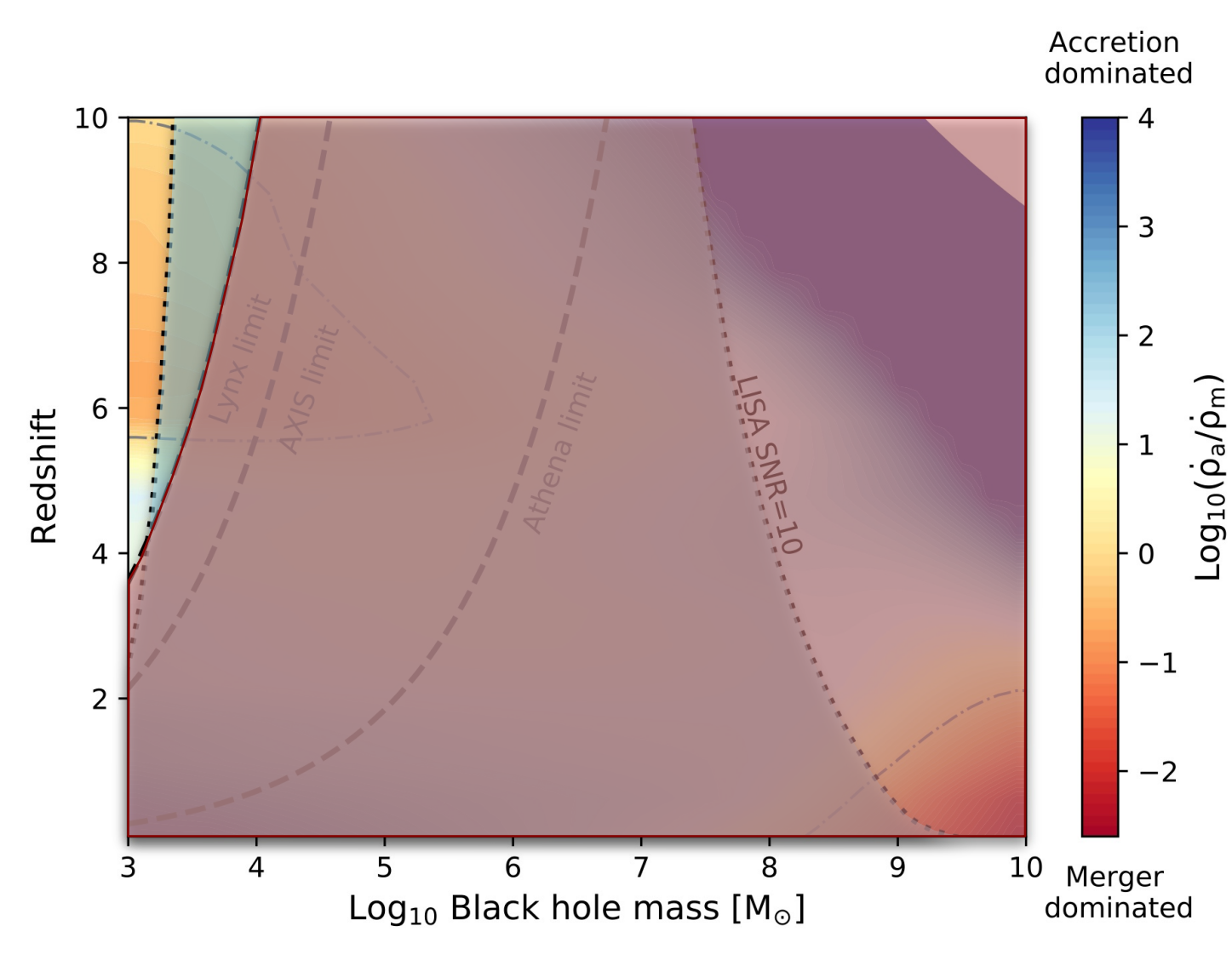


Pacucci & Loeb (2020)

Accretion vs. Mergers Across Cosmic Time



Growth Channel → Observation



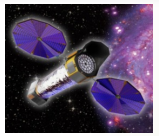
Future Space Observatories

GRAVITATIONAL WAVES to probe MERGERS

- **LISA**

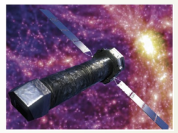
X-RAYs to probe ACCRETION

- **Lynx**

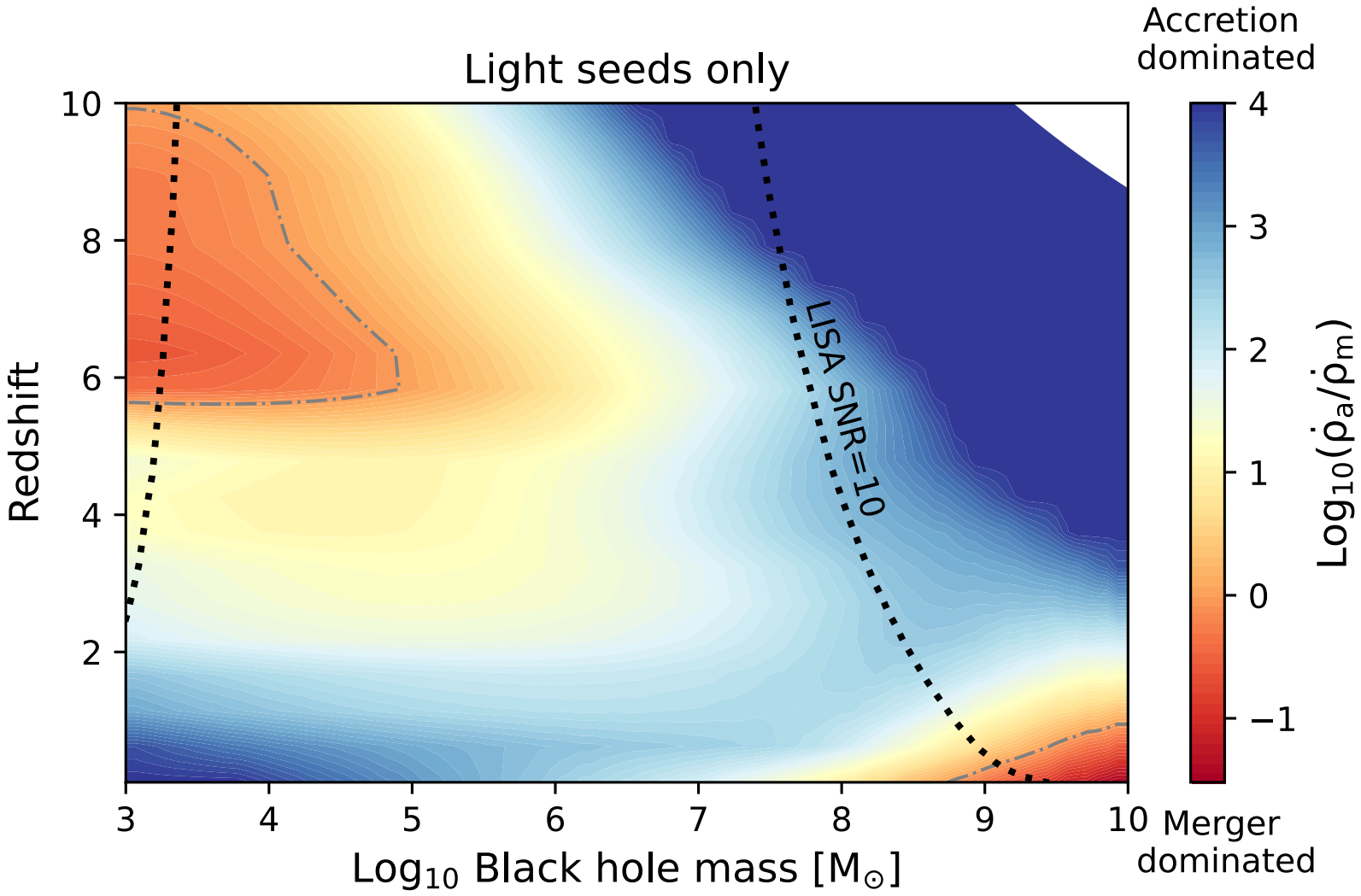


- **AXIS**

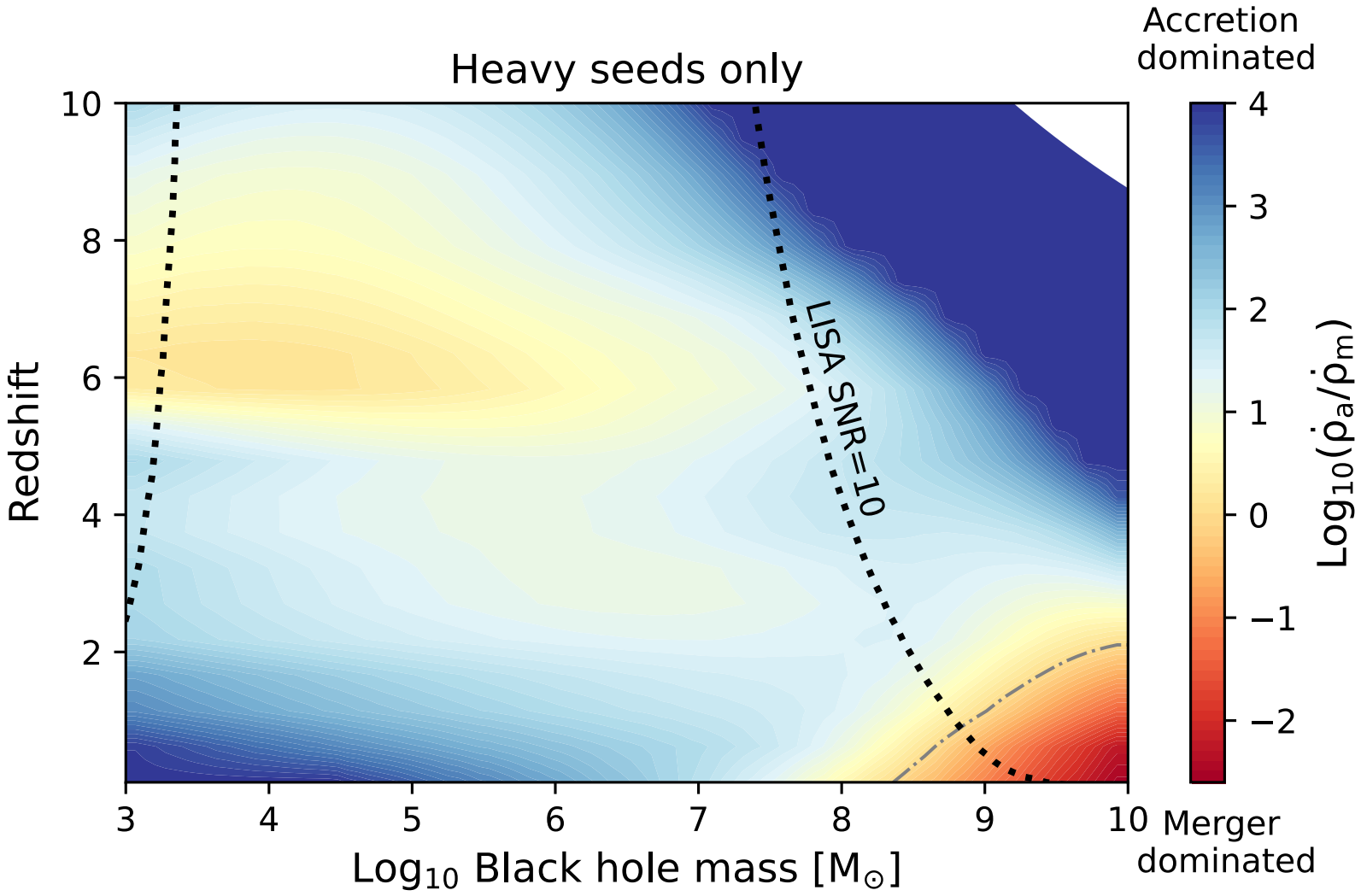
- **Athena**



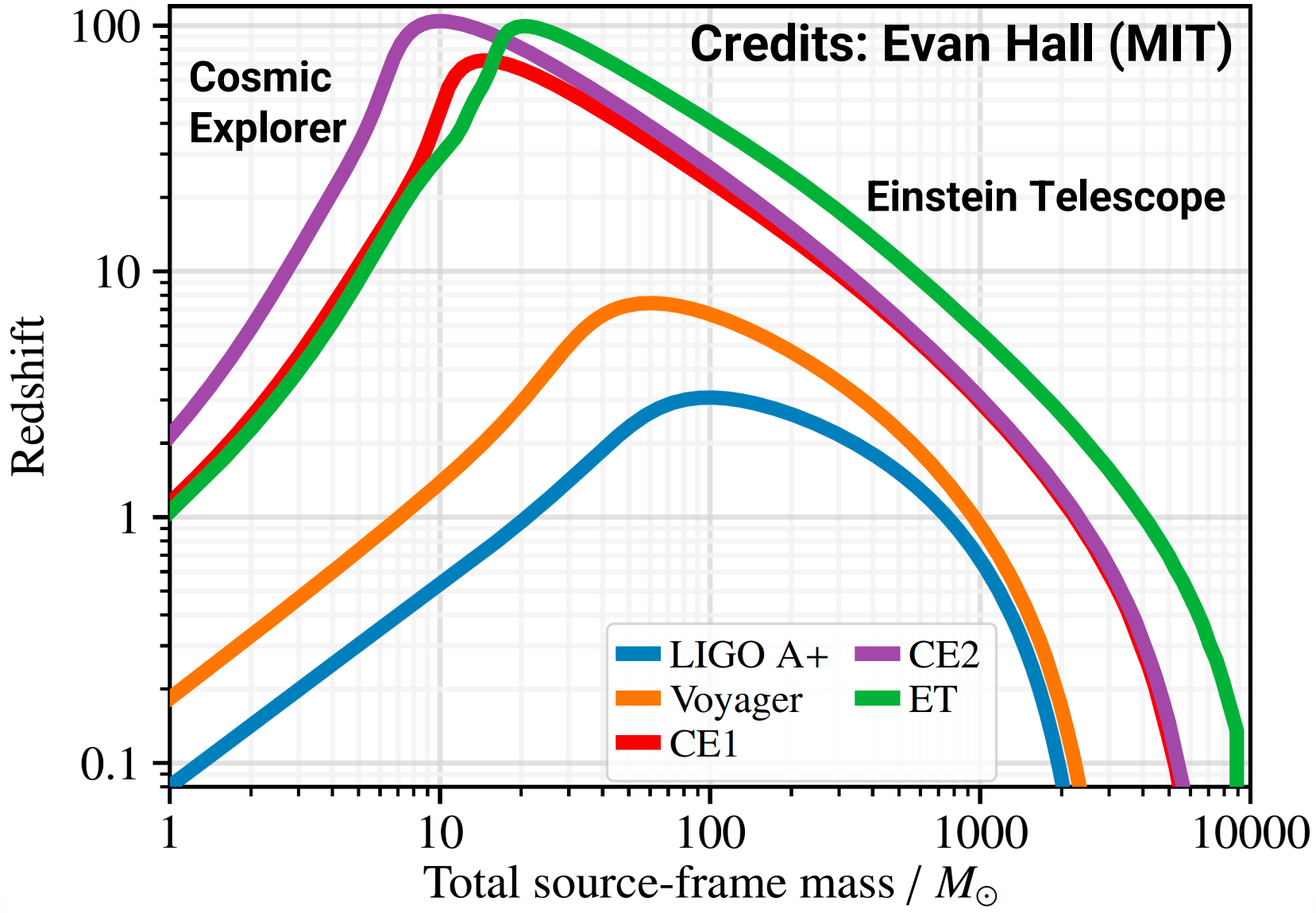
The Role of Gravitational Waves



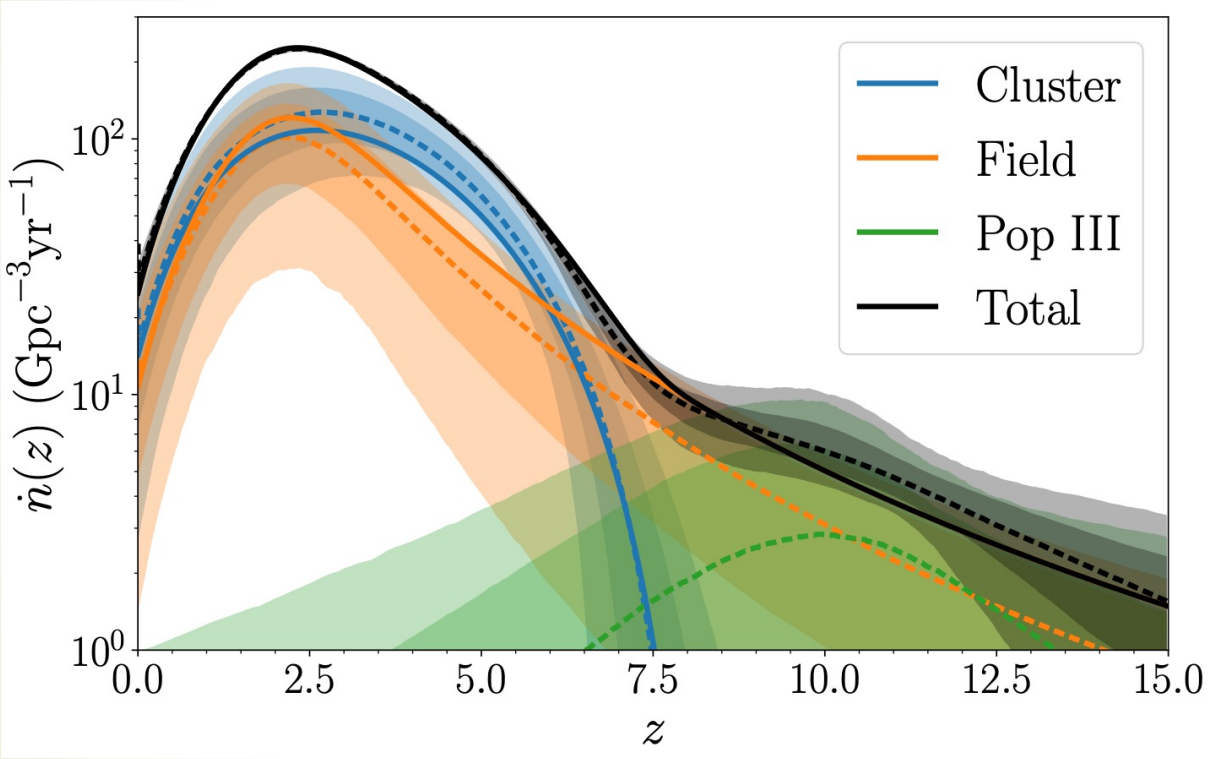
The Role of Gravitational Waves

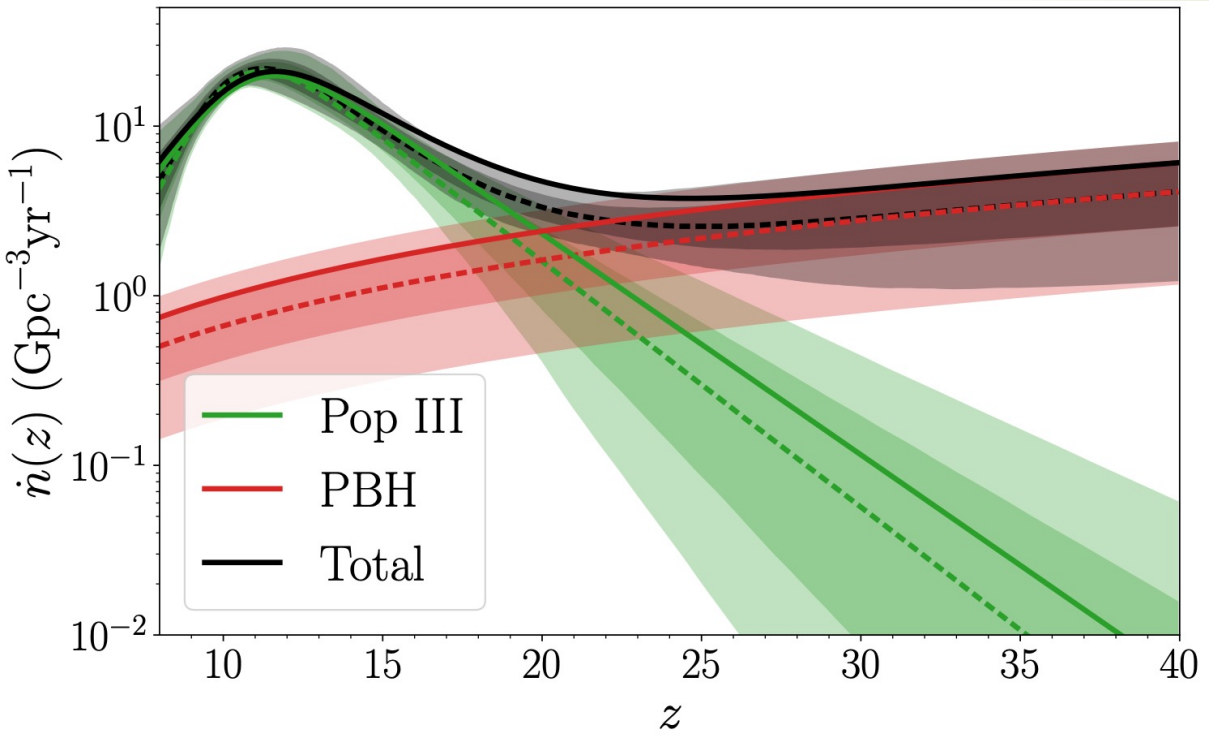


Third-Generation GW observatories



3G for PBHs and Pop III Remnants

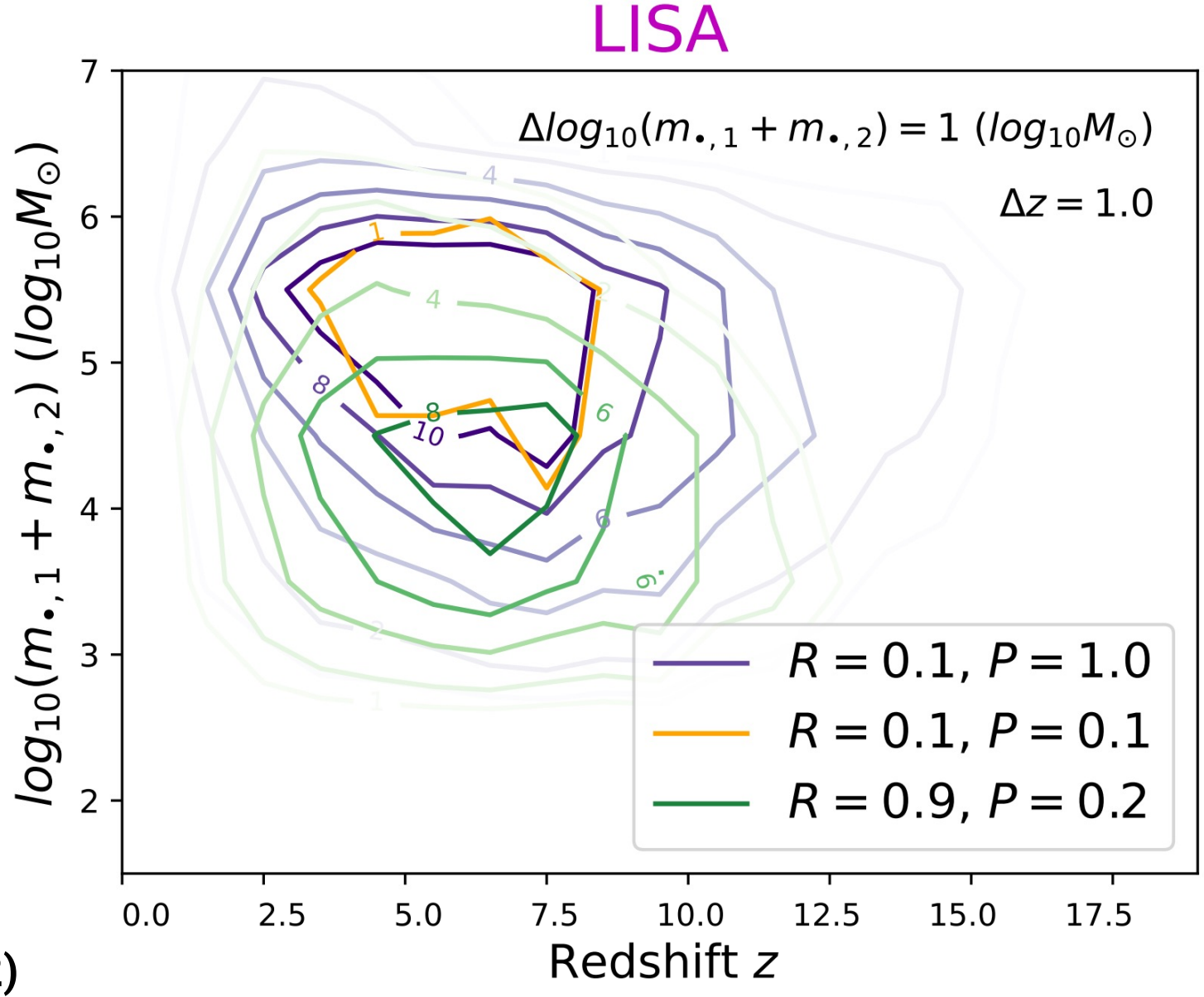




Ng, Vitale, Farr, Rodriguez (2022)

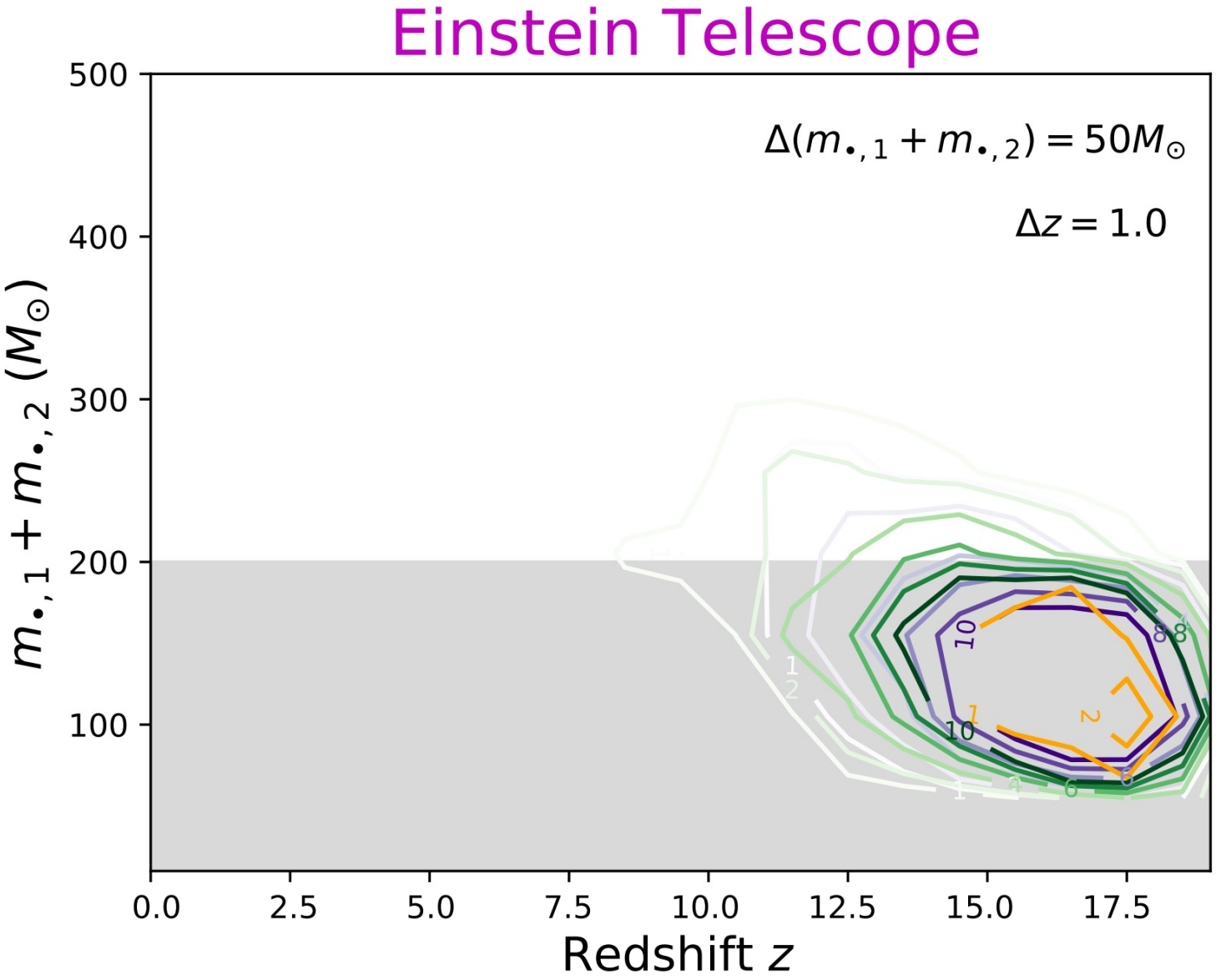
Ng et al. (2022)

Multiband GW Observations

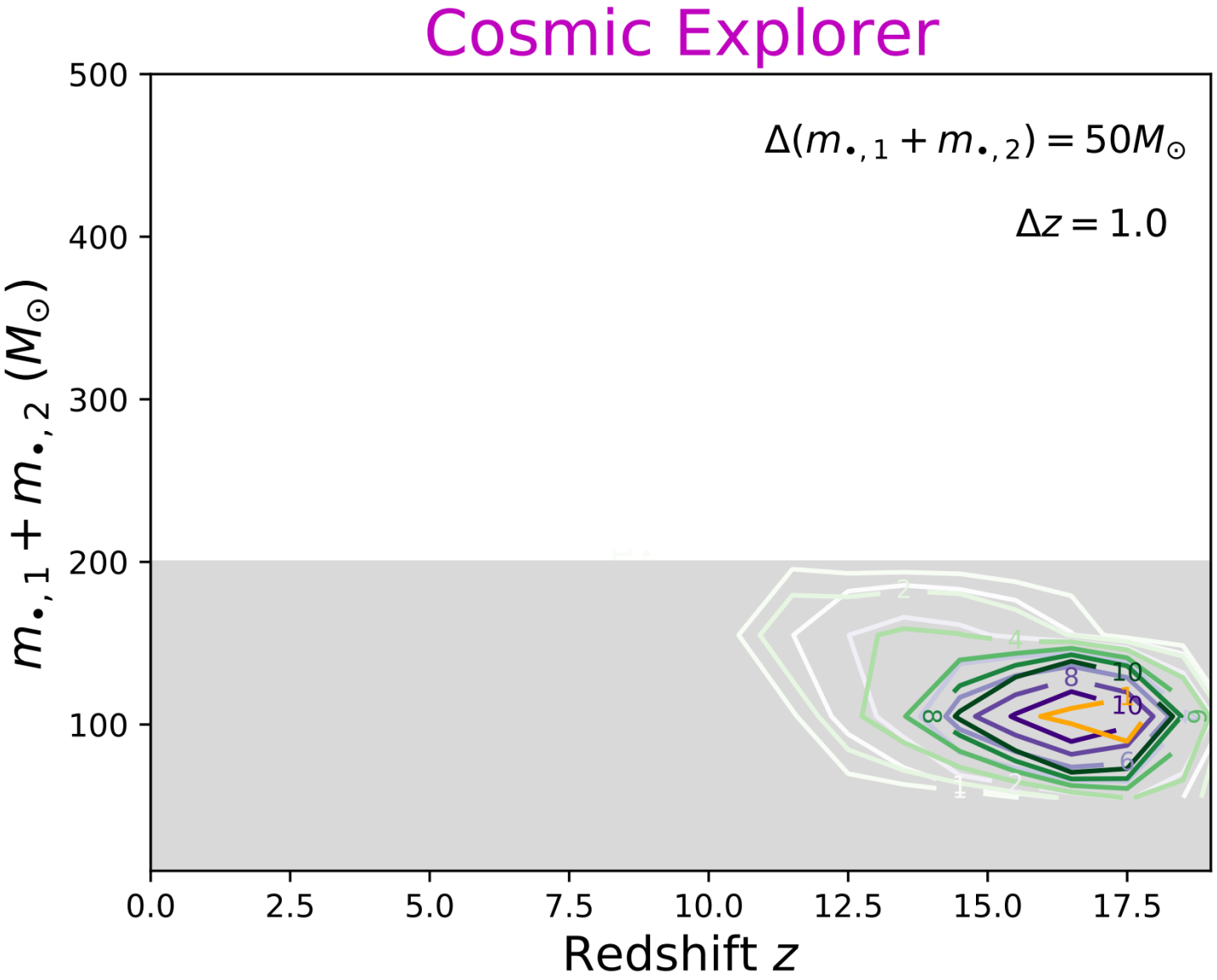


Chen et al. (2022)

Multiband GW Observations



Multiband GW Observations



The Search in the Next Decade

Detecting the Dawn of Black Holes

Observatory	Importance for Seeds
JWST	• Detect peak emission of typical seeds • Detect heavily obscured seeds
Athena (planned: 2035)	• Larger field of view for surveys • Detect Compton-thin sources
Lynx and/or AXIS	• Higher angular resolution • Detect heavily Compton-thick sources
LISA (planned: 2037)	• Detecting lighter seeds • Constraining main formation channel

(Adapted from Astro2020 white papers)

Open Questions / Curiosities

Assume JWST detects a SMBH so massive and far to require a heavy seed. How do we discriminate between DCBH-like formation or later hyper-Eddington accretion?

Which category of observations can unequivocally constrain the mixture of light vs. heavy seeds at z>15?

How much the unknown merger probability function affects our chances of constraining the mixture of light vs. heavy seeds?

More “philosophical”: how do we DEFINE a black hole seed detection in the EM regime?