Supermassive black hole seeds in cosmological simulations

Elusive AGN
June 12, 2017
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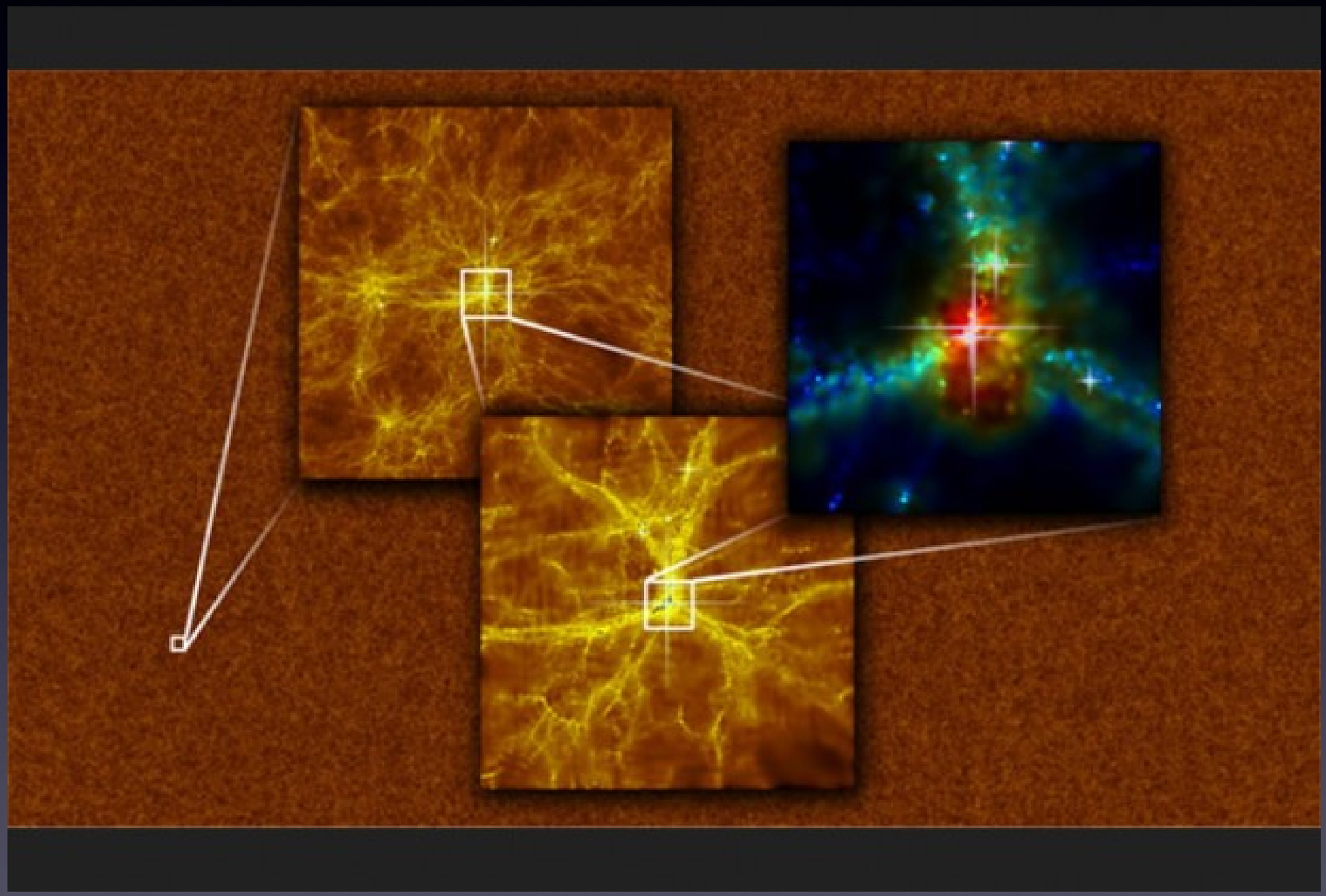
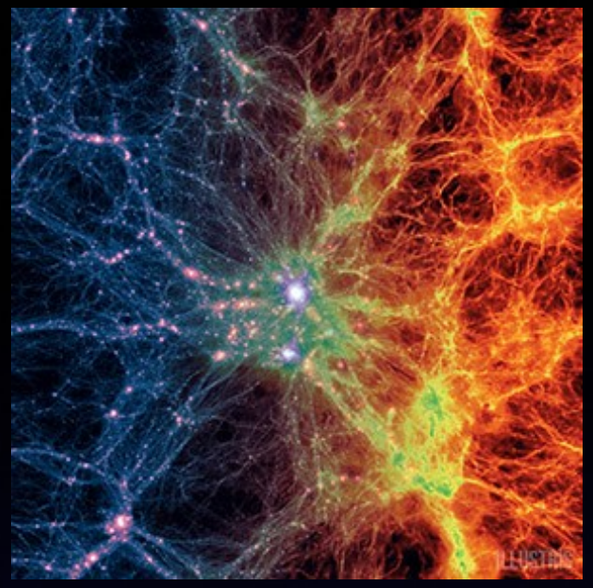
ioa

Outline

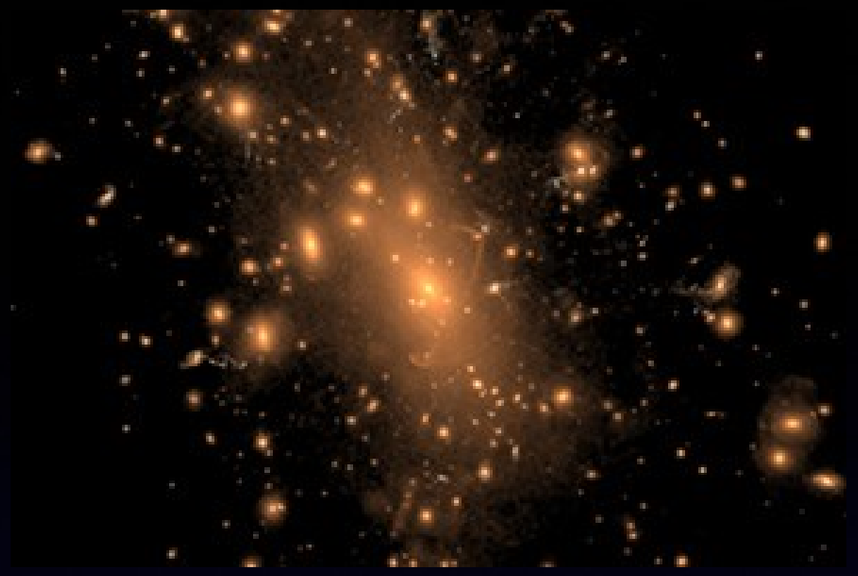
- Simulation overview
- Alternative black hole seeding models
  - Where & when black holes are seeded
  - Implications for BH populations
  - Early BH growth
  - BH mergers

Simulations





Illustris



- Moving mesh code Arepo (Springel 2010)
- Gas Cooling
- Star Formation and Stellar Feedback/Wind

(Springel & Hernquist 2003)

- 75 h^{-1} Mpc box
- Run to z=0
- Data access at illustris-project.org

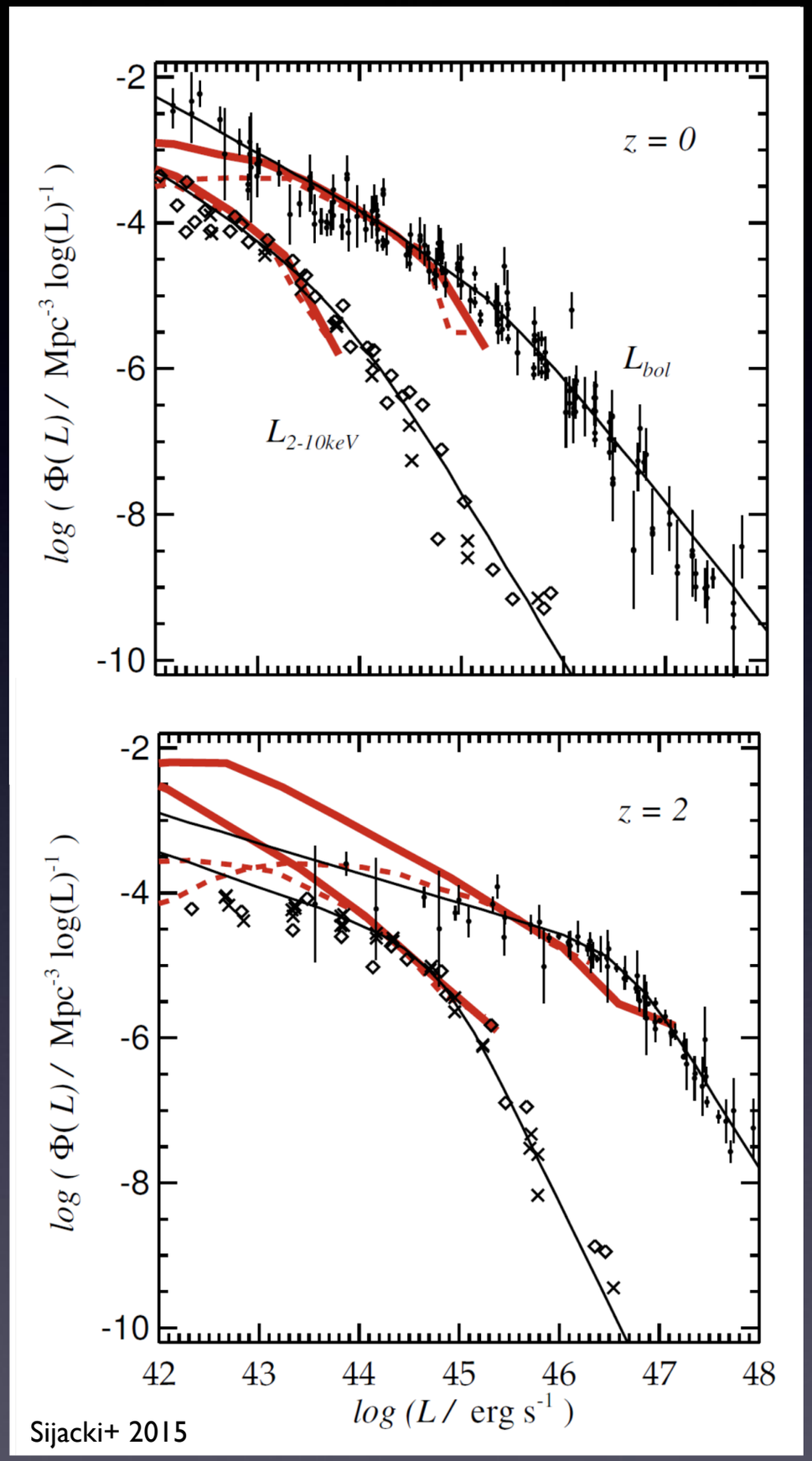
Black Hole Model

- BH growth:

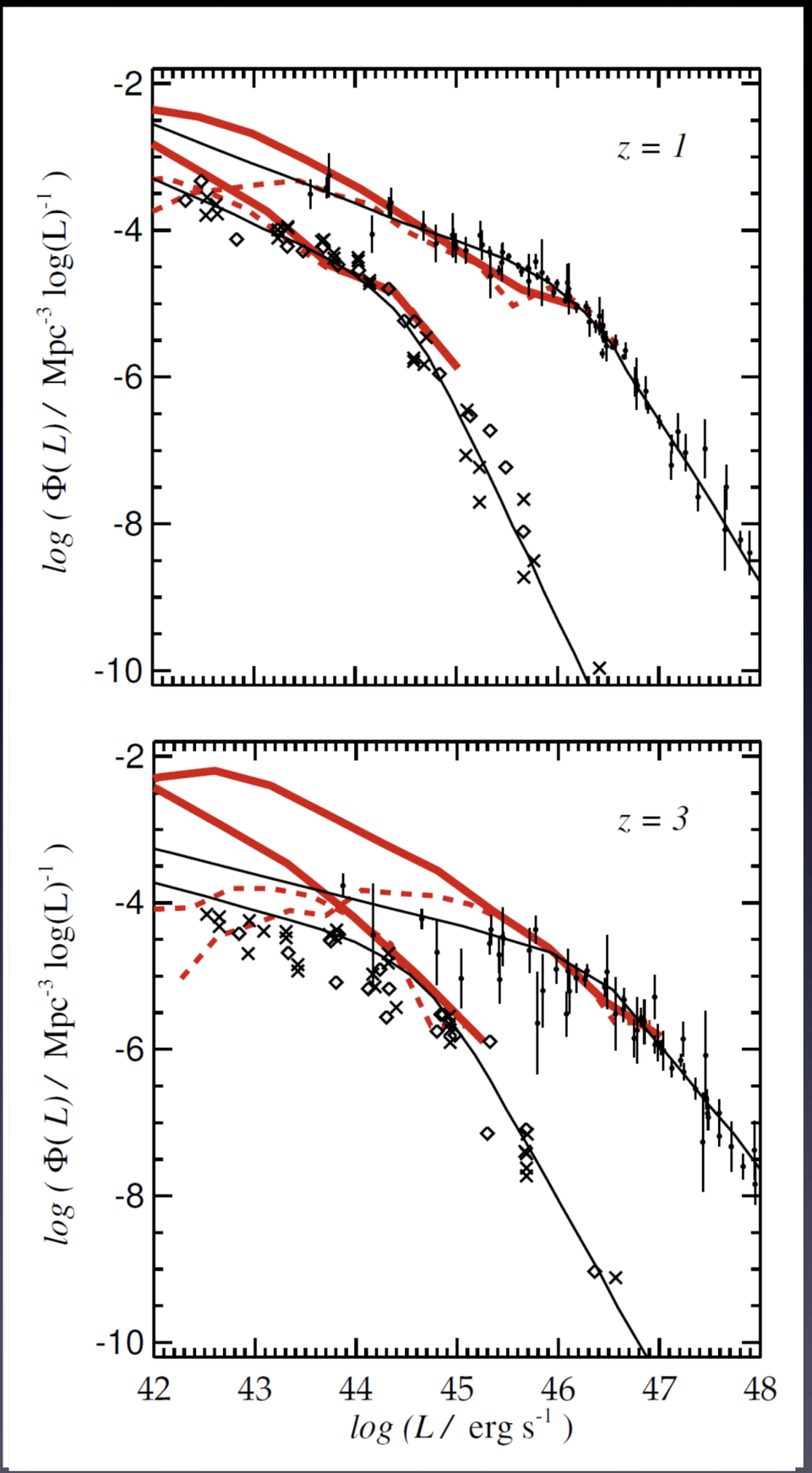
  (with imposed Eddington limit)

$$\dot{M}_{BH} = 4\pi\alpha \frac{\left(G M_{BH}\right)^2}{\left(c_s^2 + v_{rel}^2\right)^{3/2}} \rho$$

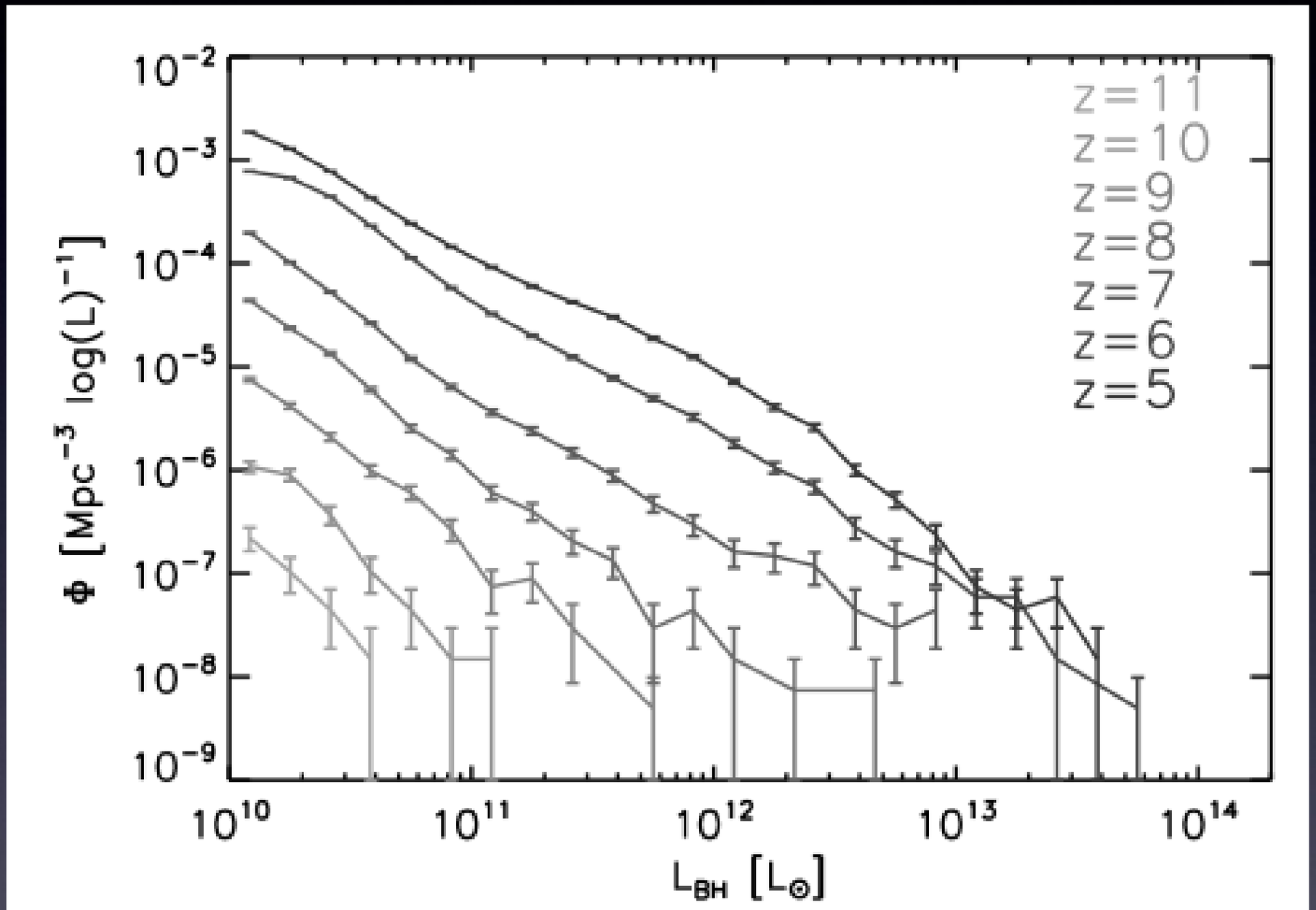
- BH mergers
- BH feedback
  - 3-component feedback:
    - Quasar Mode: Efficient feedback, thermal feedback
    - Radio Mode: Inefficient feedback, energy inserted as radio bubbles
    - Radiative feedback: Modified photo-ionization and photo-heating rates near black hole
- FoF-based seeding: $5 \times 10^5\ h^{-1}\ M_0$ BH seeded into $5 \times 10^{10}\ h^{-1}\ M_0$ halo



Sijacki+ 2015



Black Hole Populations



DeGraf+ 2012

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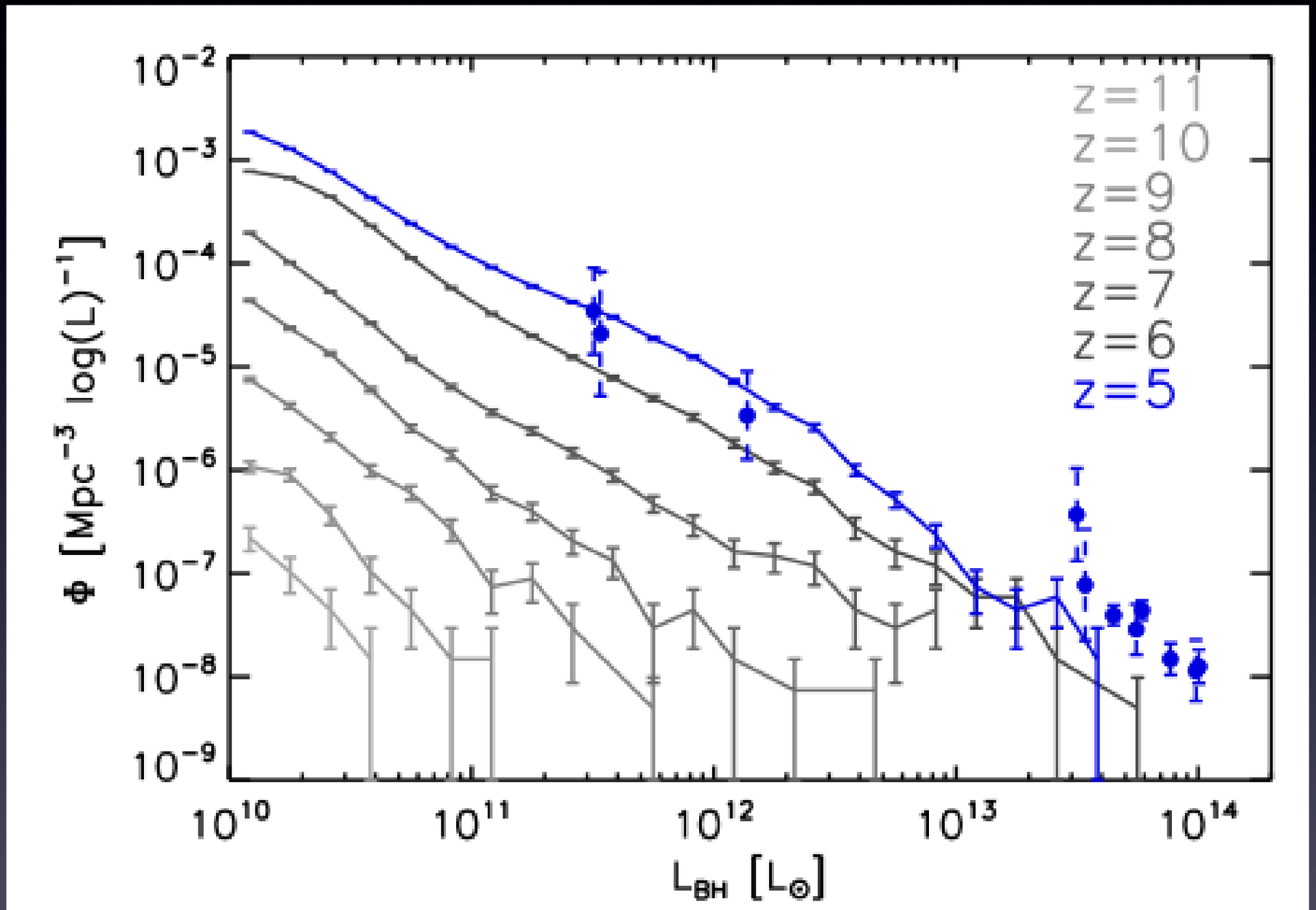

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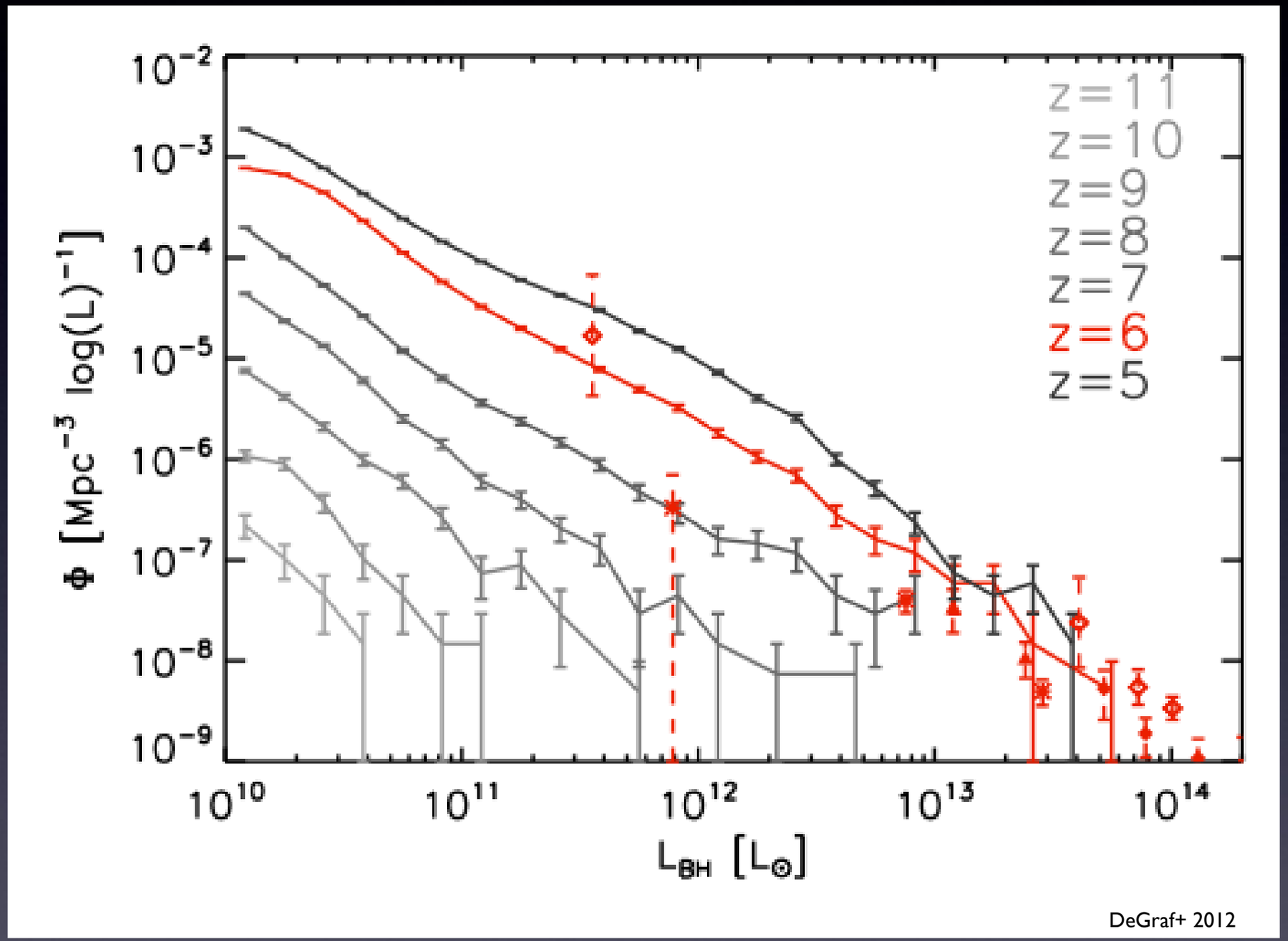
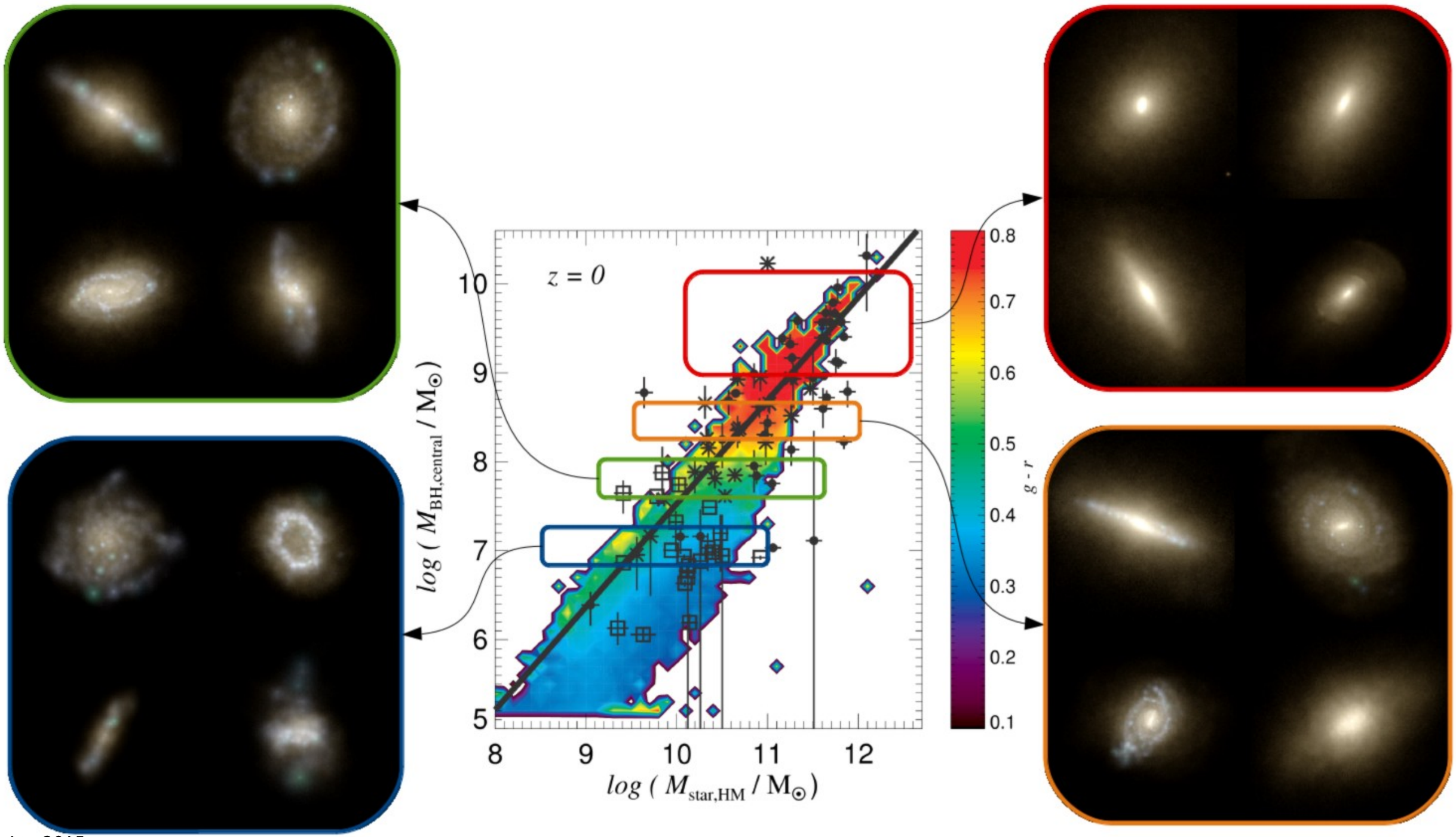
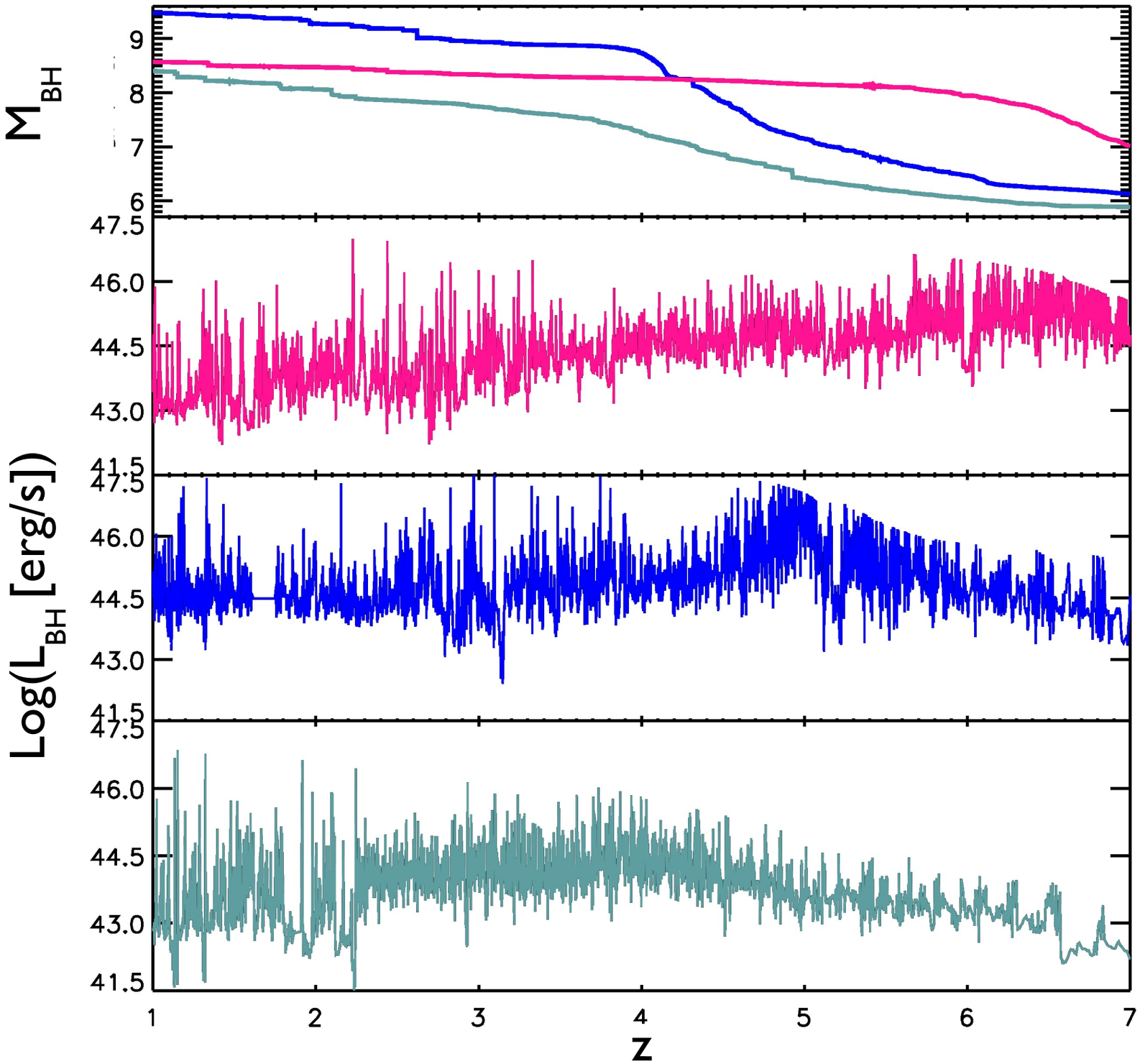


DeGraf+ 2012



Sijacki+ 2015

Sample accretion histories



Di Matteo+ 2008

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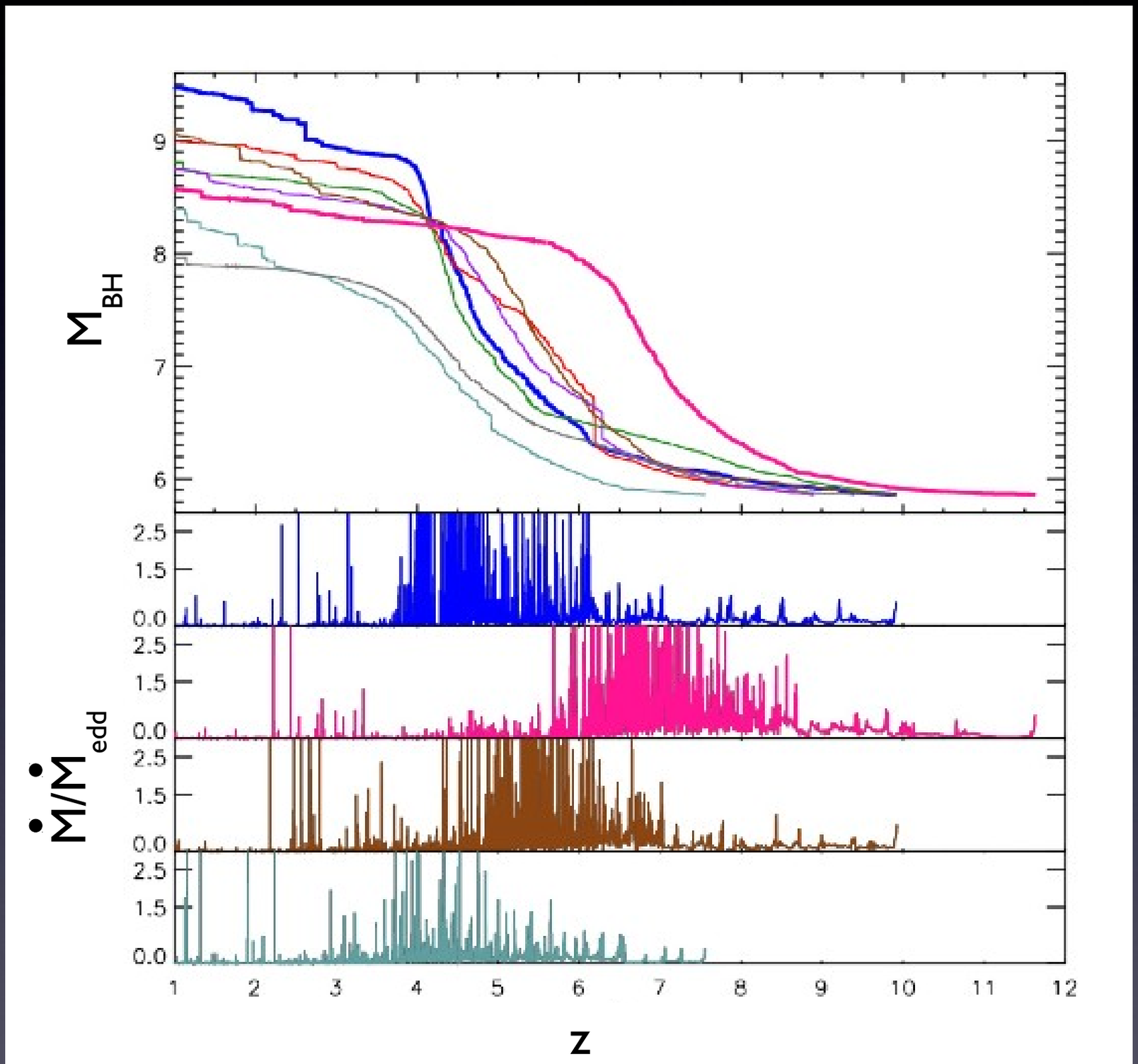
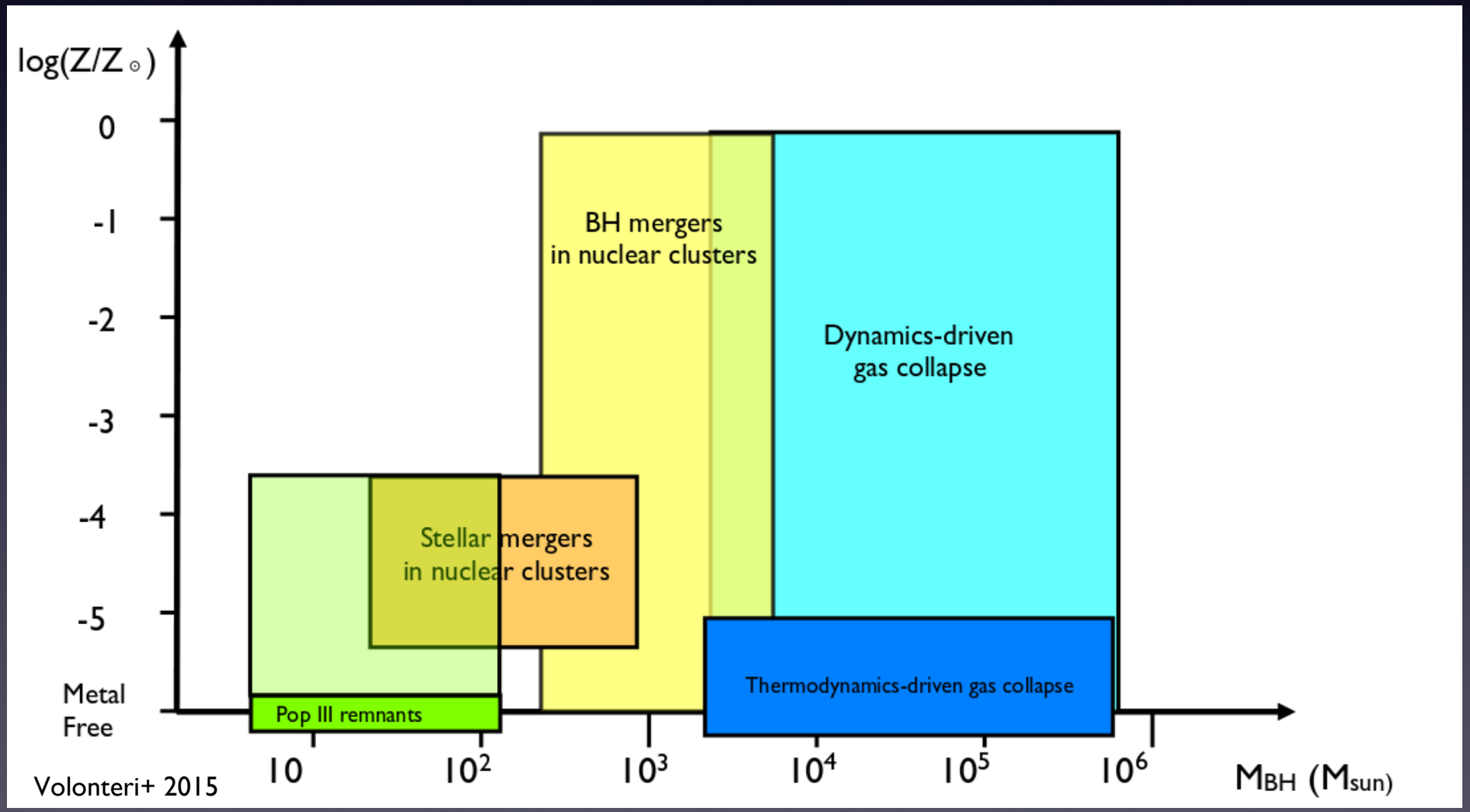


Di Matteo+ 2008

Seeding mechanisms

- Direct collapse seed formation
- PopIII seed formation
- Nuclear star cluster seed formation



Seeding mechanisms

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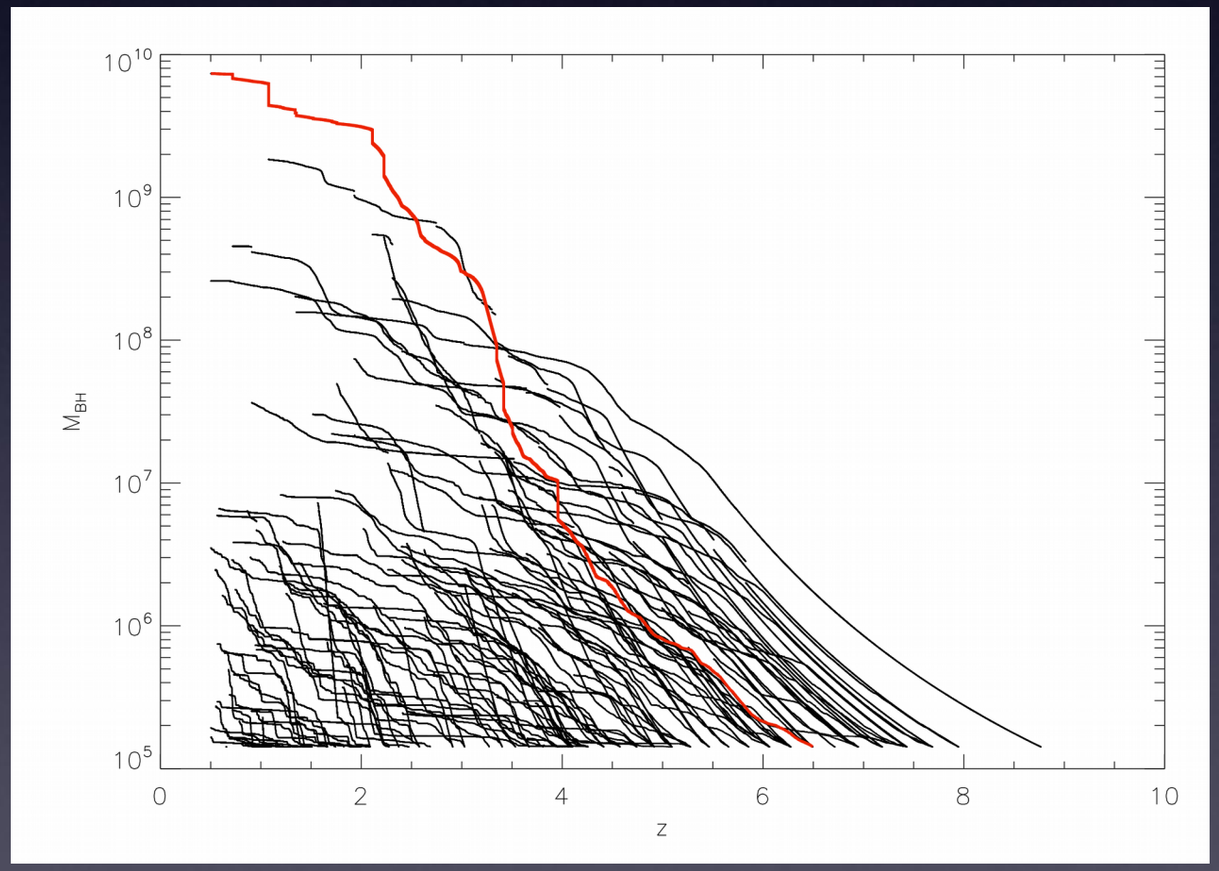
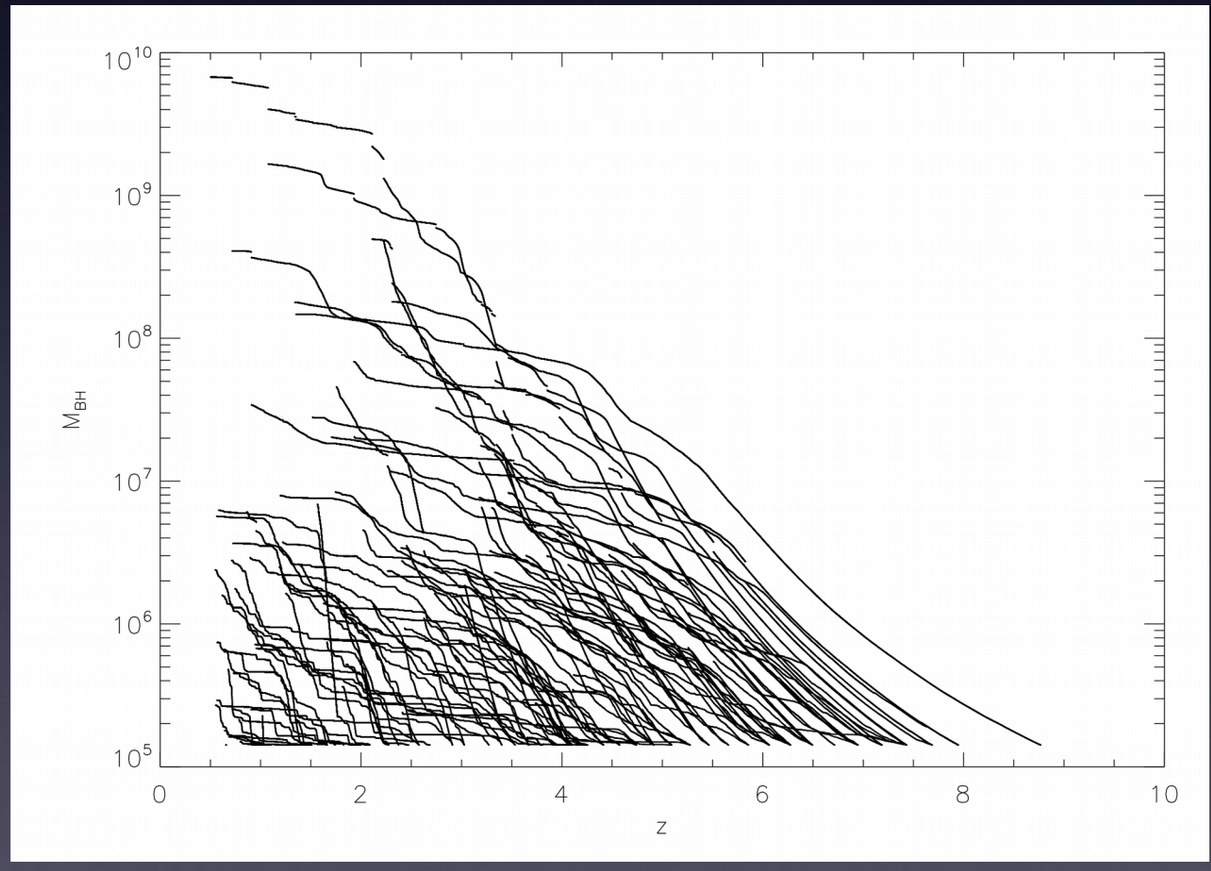


Original Illustris history

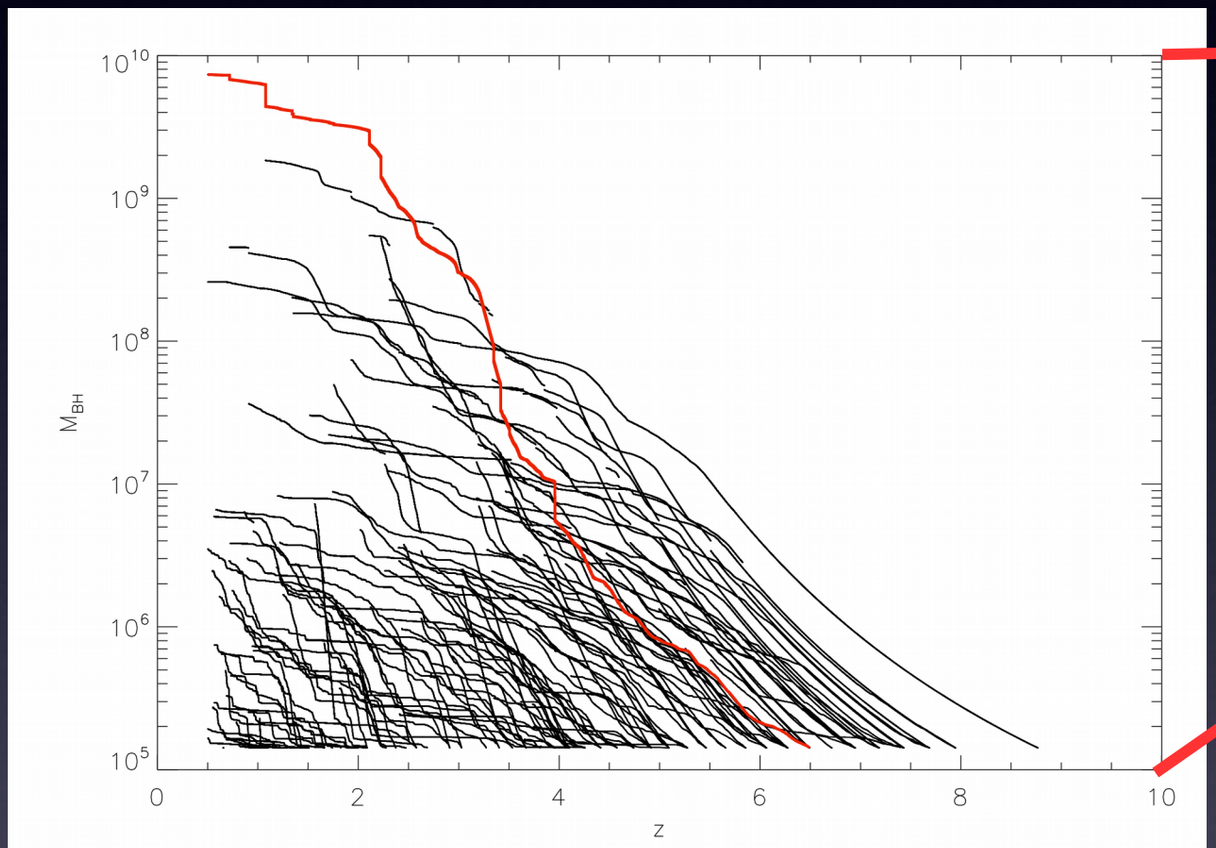


Re-calculated history

Seeding mechanisms

- Post-processing analysis
- Re-calculate accretion rates for black holes
- Vary criteria for seeding
  - M_{seed}, z_{seed}, Host properties, etc.
- Assume minimal change in feedback
  - Saves having to re-run entire simulation!

Sample growth histories



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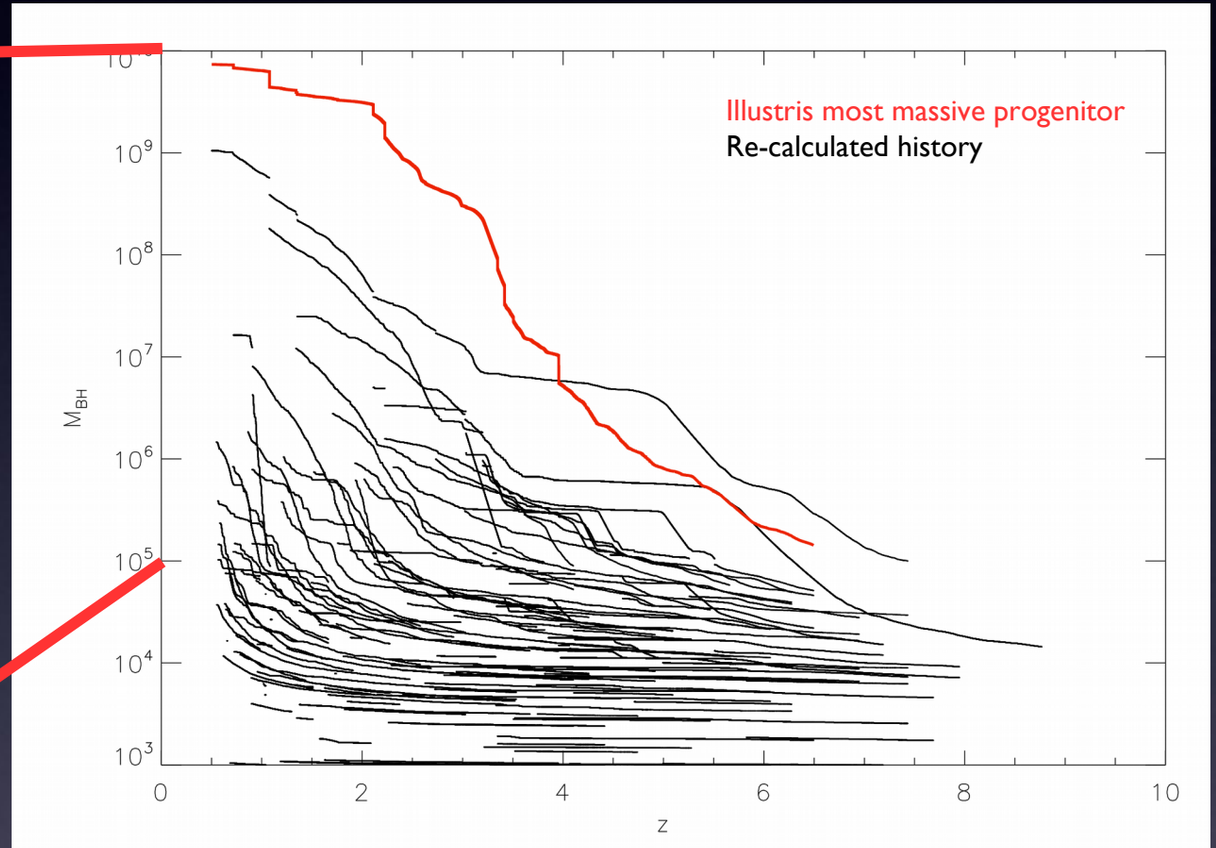
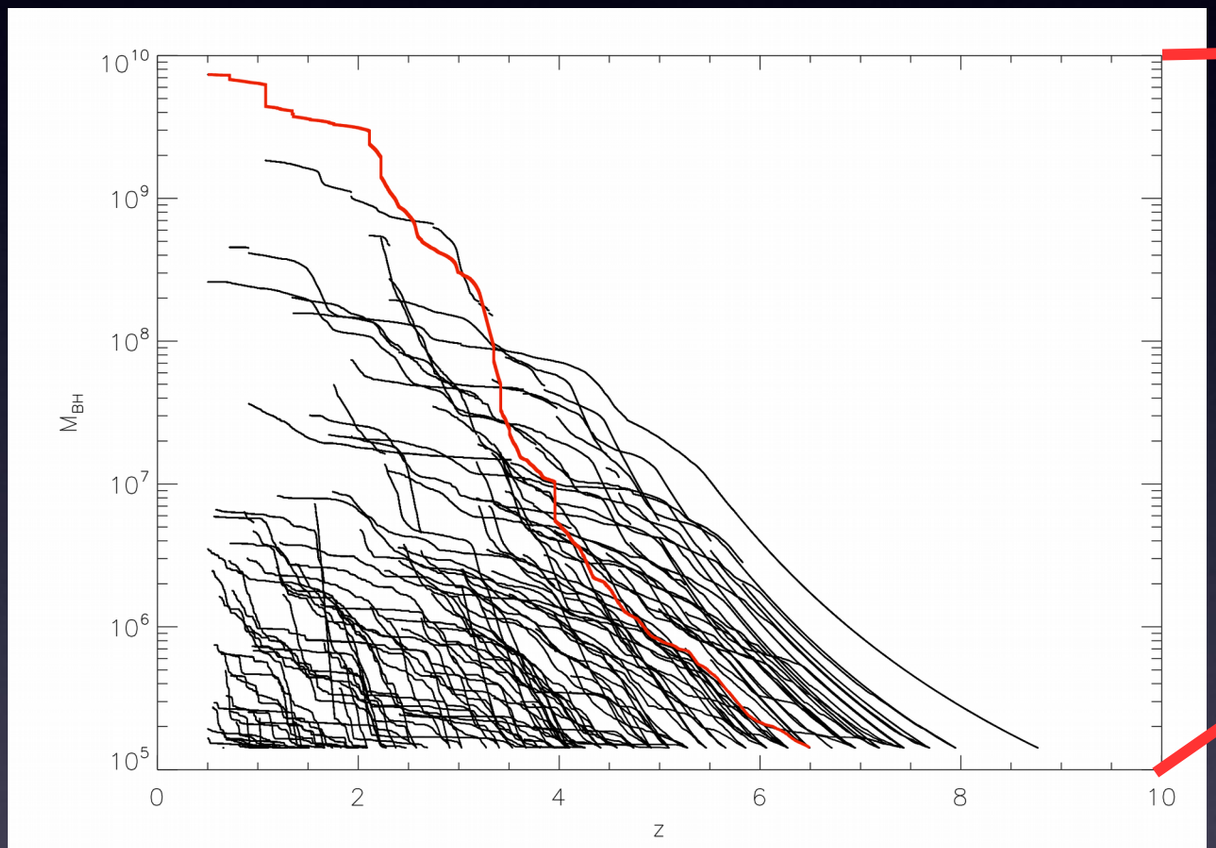


Changed seed masses

Sample growth histories



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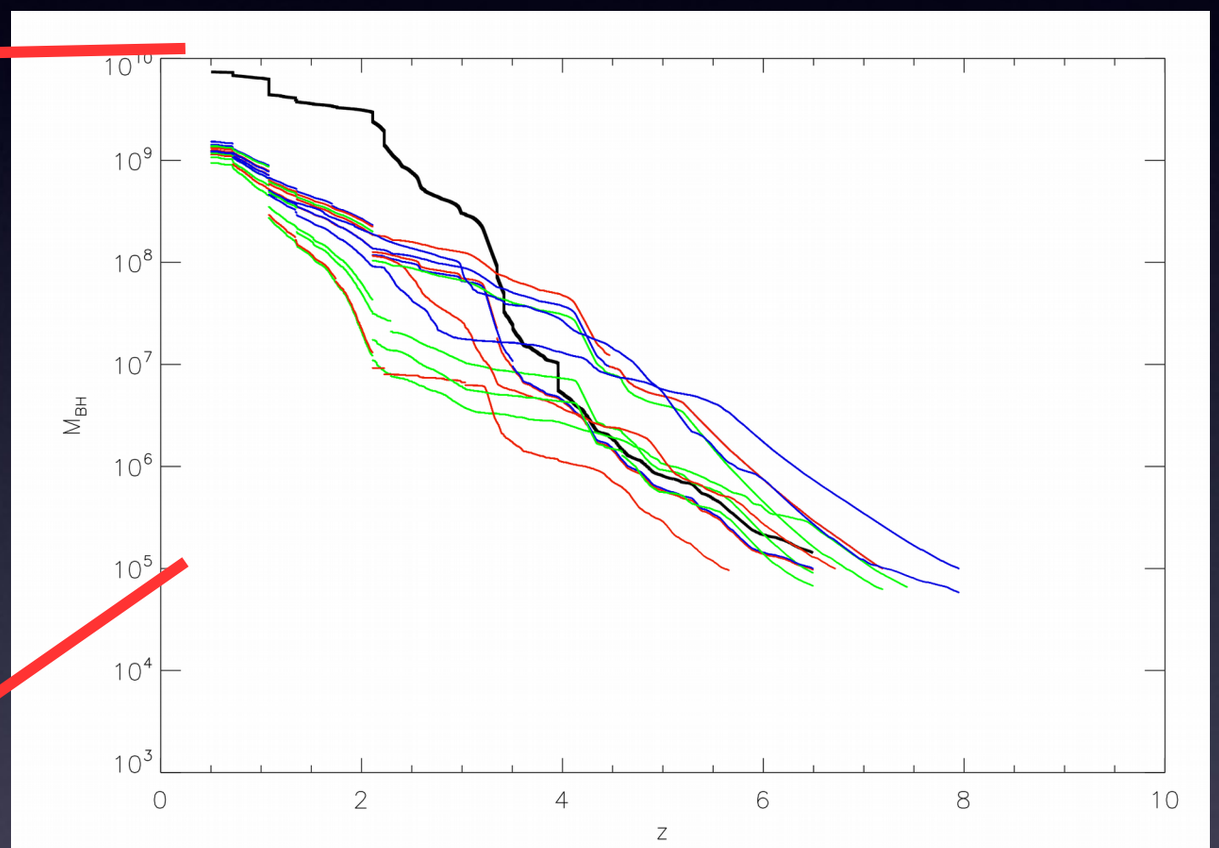

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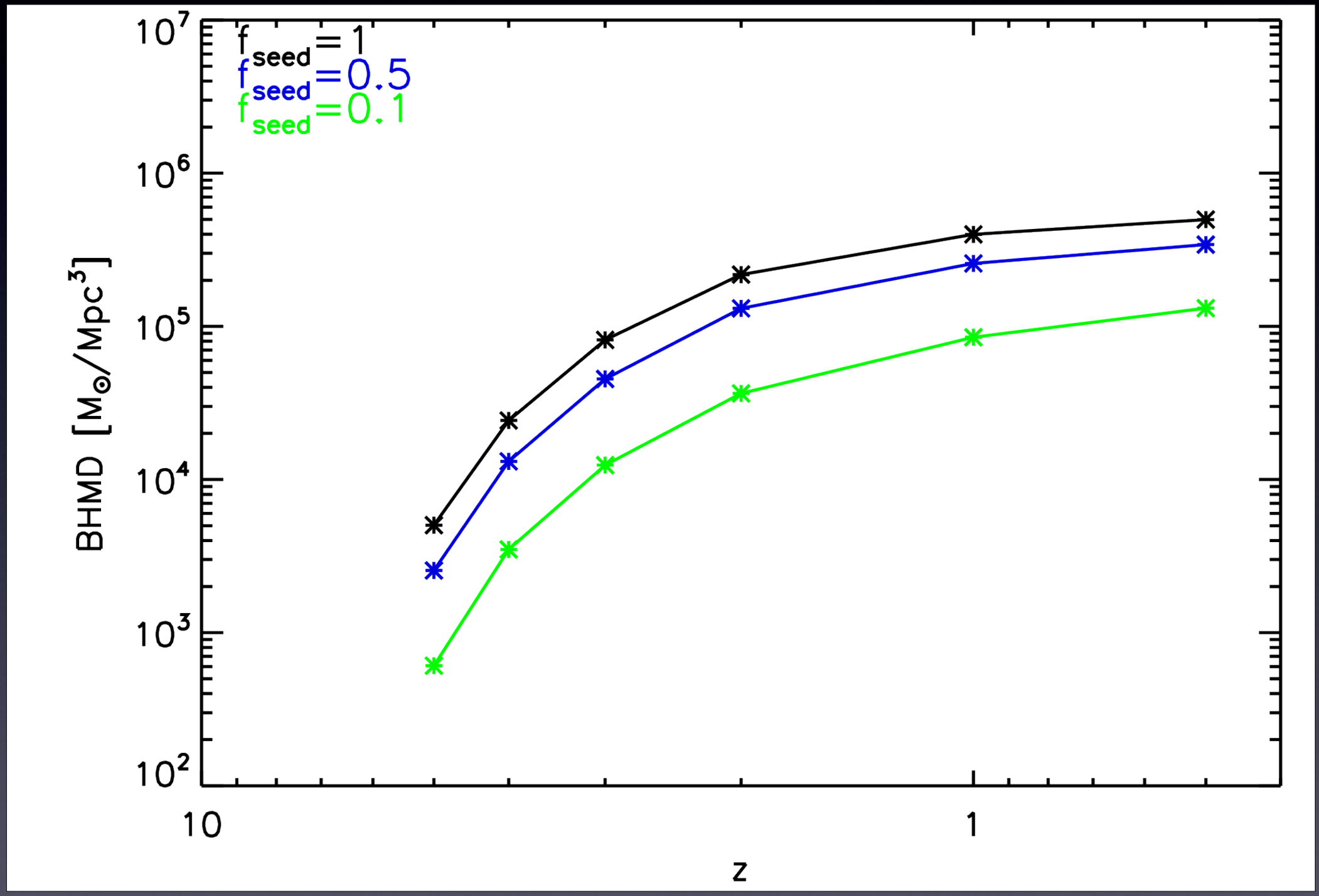
Seeding mechanisms

- Random seeding with fixed probability (f_{seed})

Black Hole Mass Density



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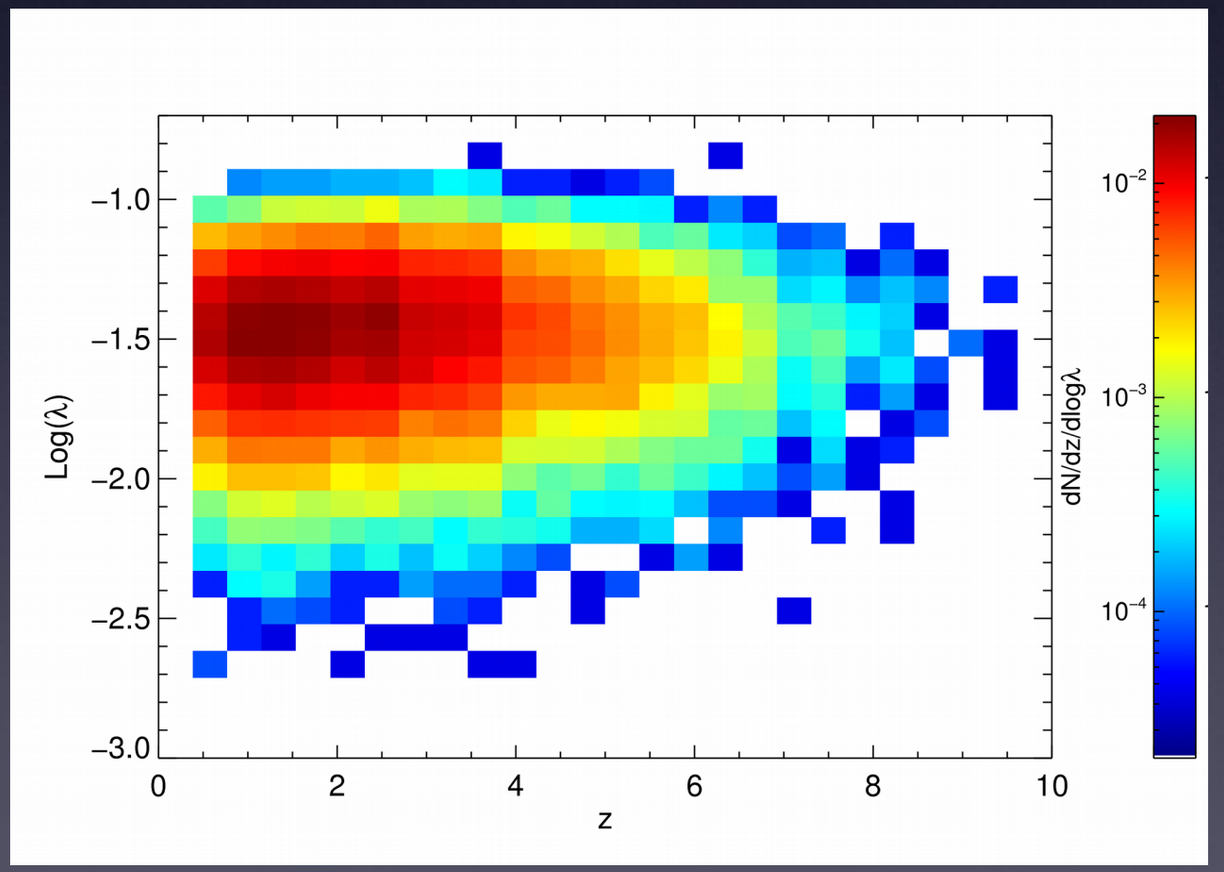

Seeding mechanisms

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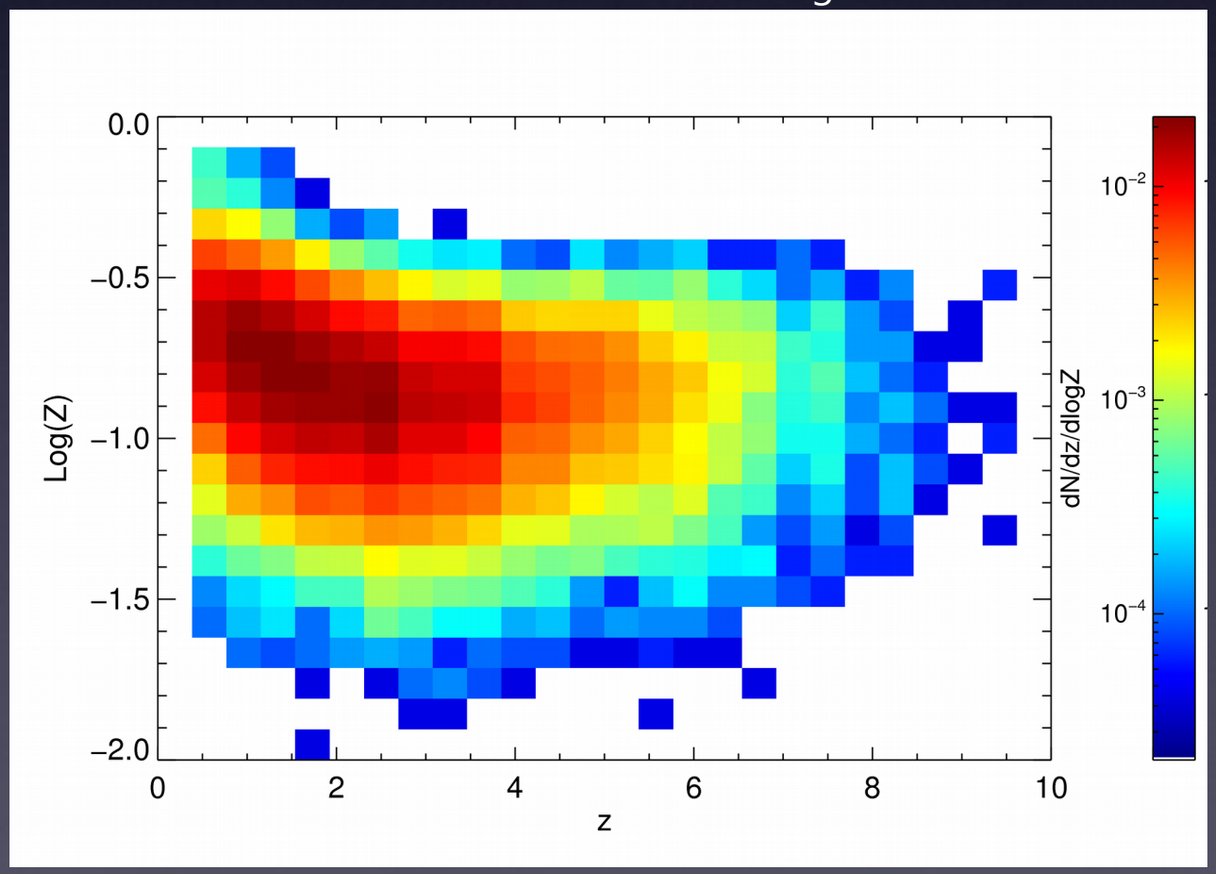
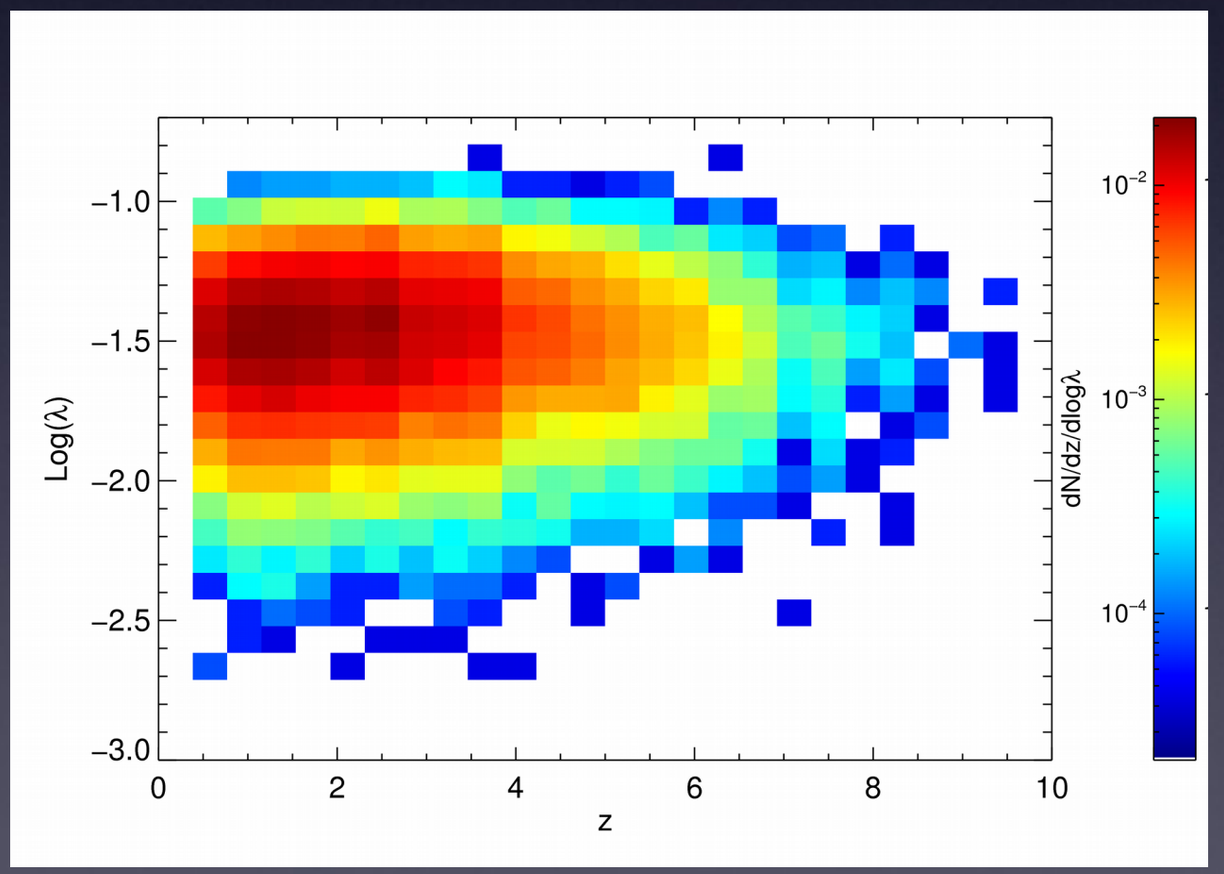
- Seeding according to λ_{gas}
  - According to λ_{gas} and Z





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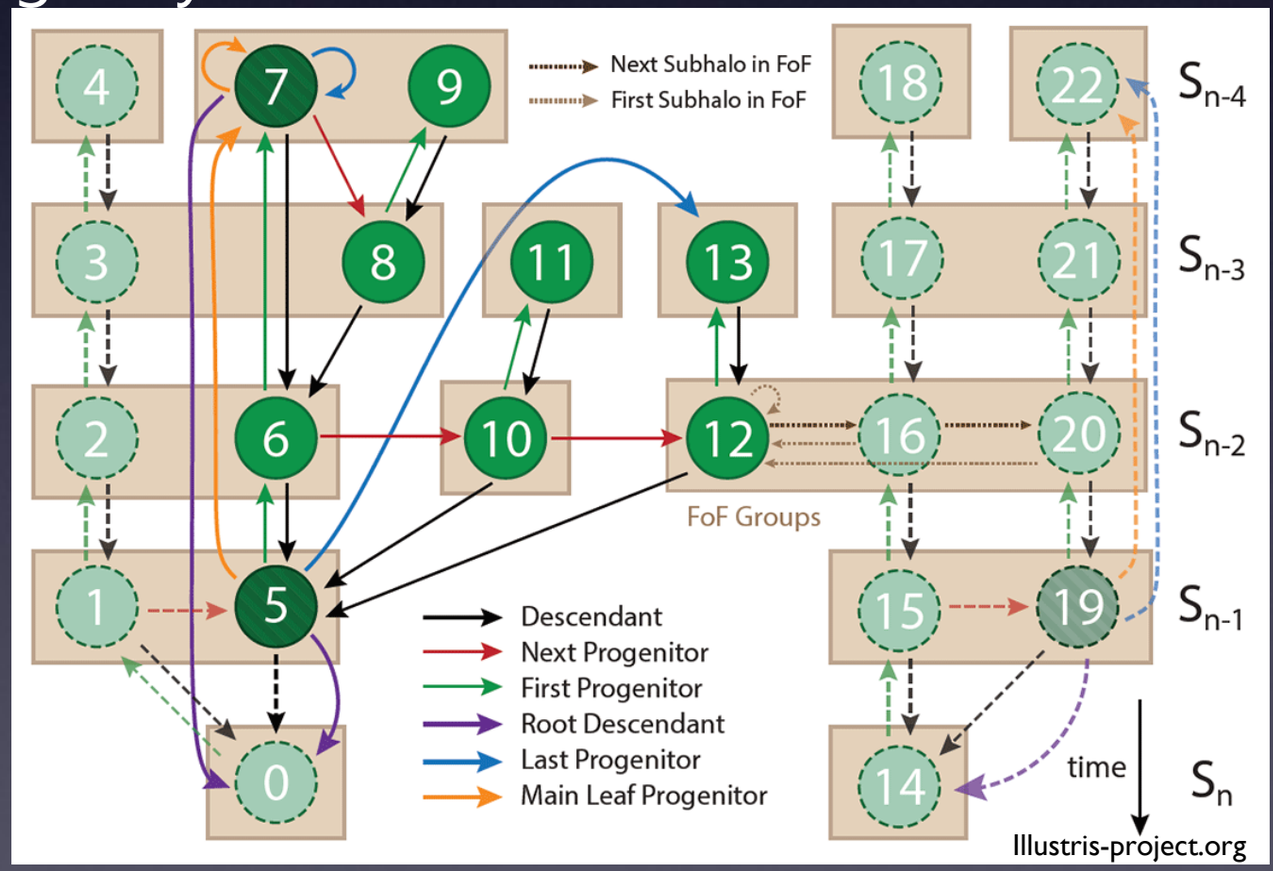

Seeding mechanisms

- Random seeding with fixed probability (f_{seed})
- Seeding according to λ_{gas}
- Seeding according to progenitor galaxy trees
  - $M_{gal} > 3x10^9 M_\odot$
  - $Z < 10^{-5} Z_\odot$
  - $$\lambda_{gas} < \frac{m_d Q_c}{8} \frac{m_d}{j_d} \left(\frac{T_{vir}}{T_{gas}} \right)^{1/2}$$ (Lodato & Natarajan 2006, Natarajan 2011)

m_d = Disk mass fraction of halo (~0.5)

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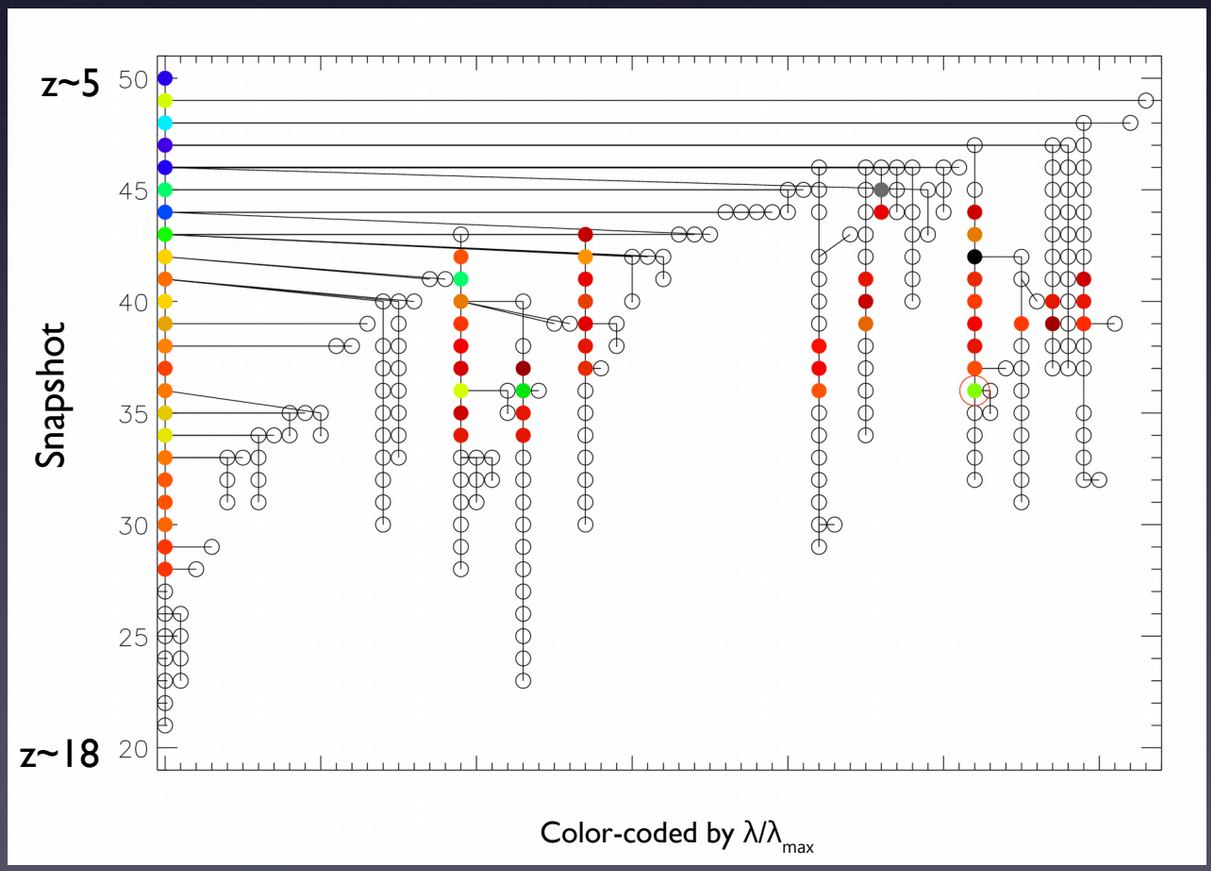

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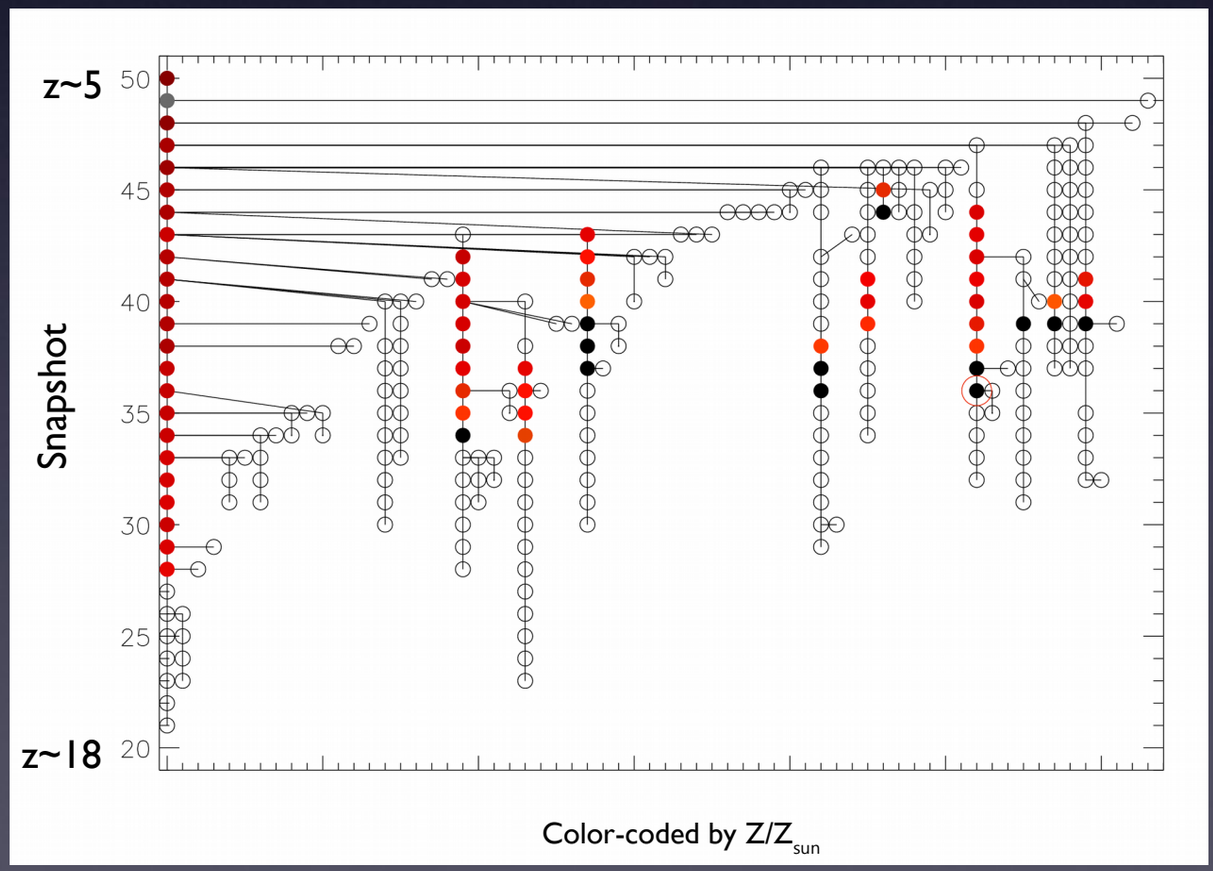
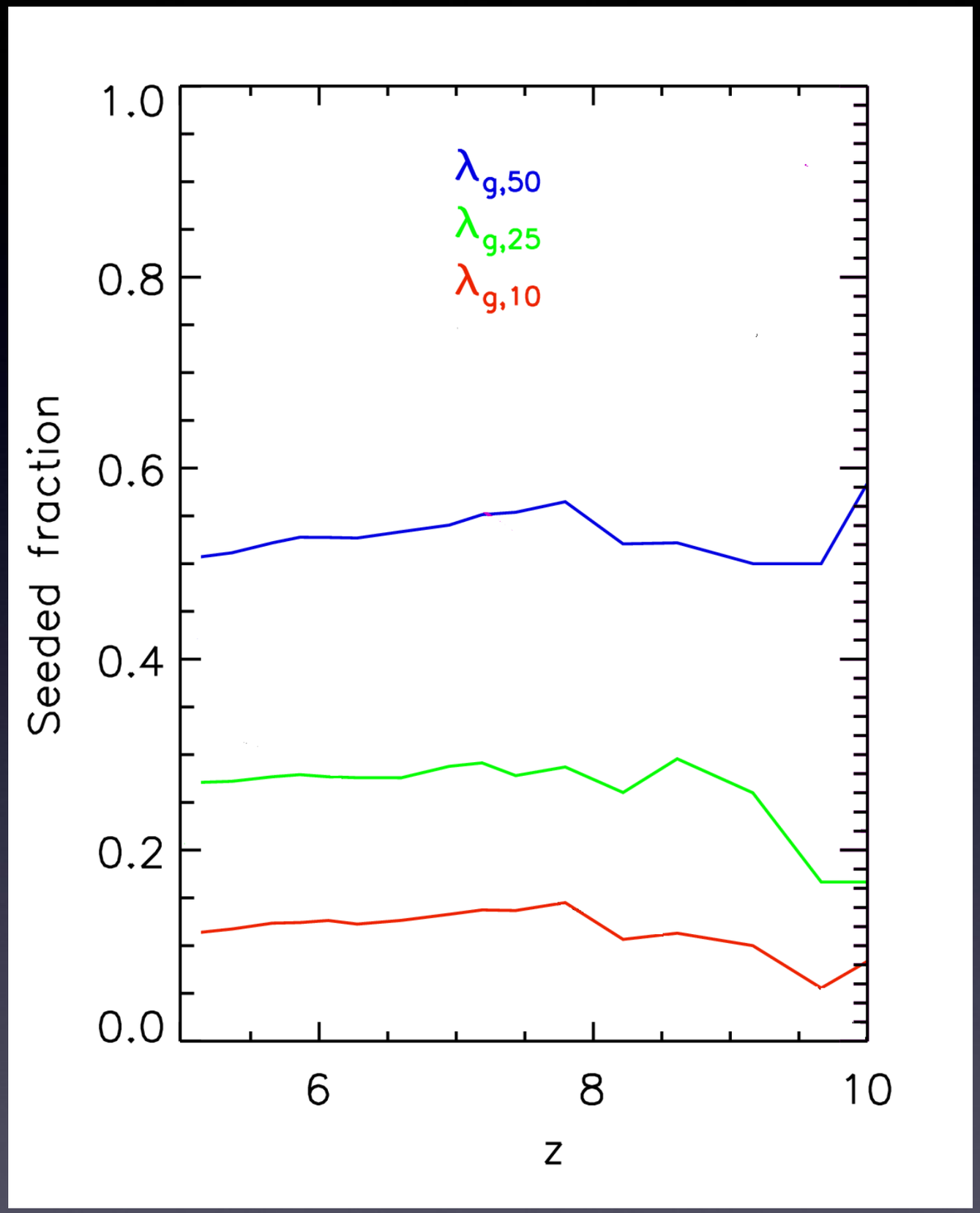
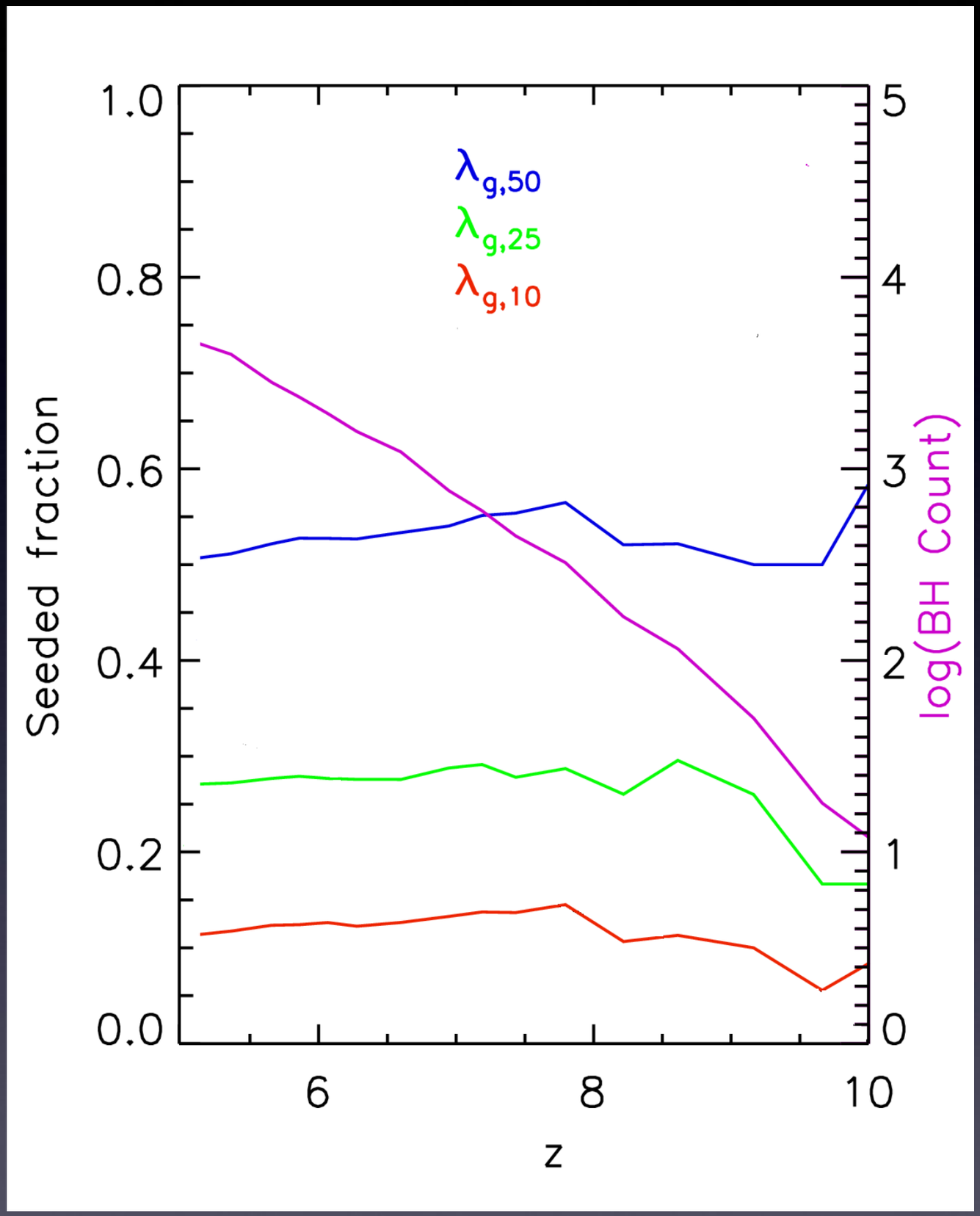




- Fraction of Illustris black holes that should be seeded, using new seeding prescriptions



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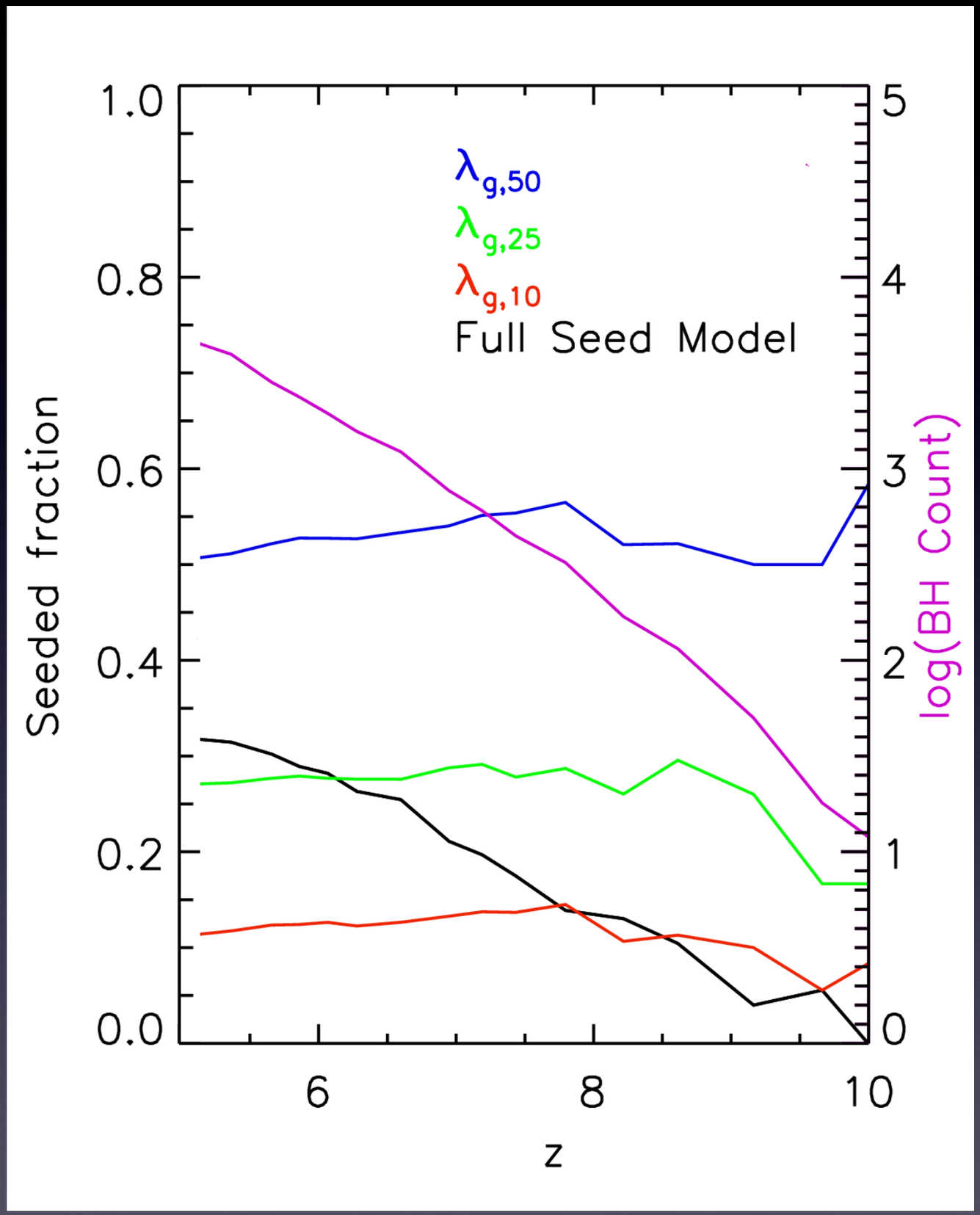

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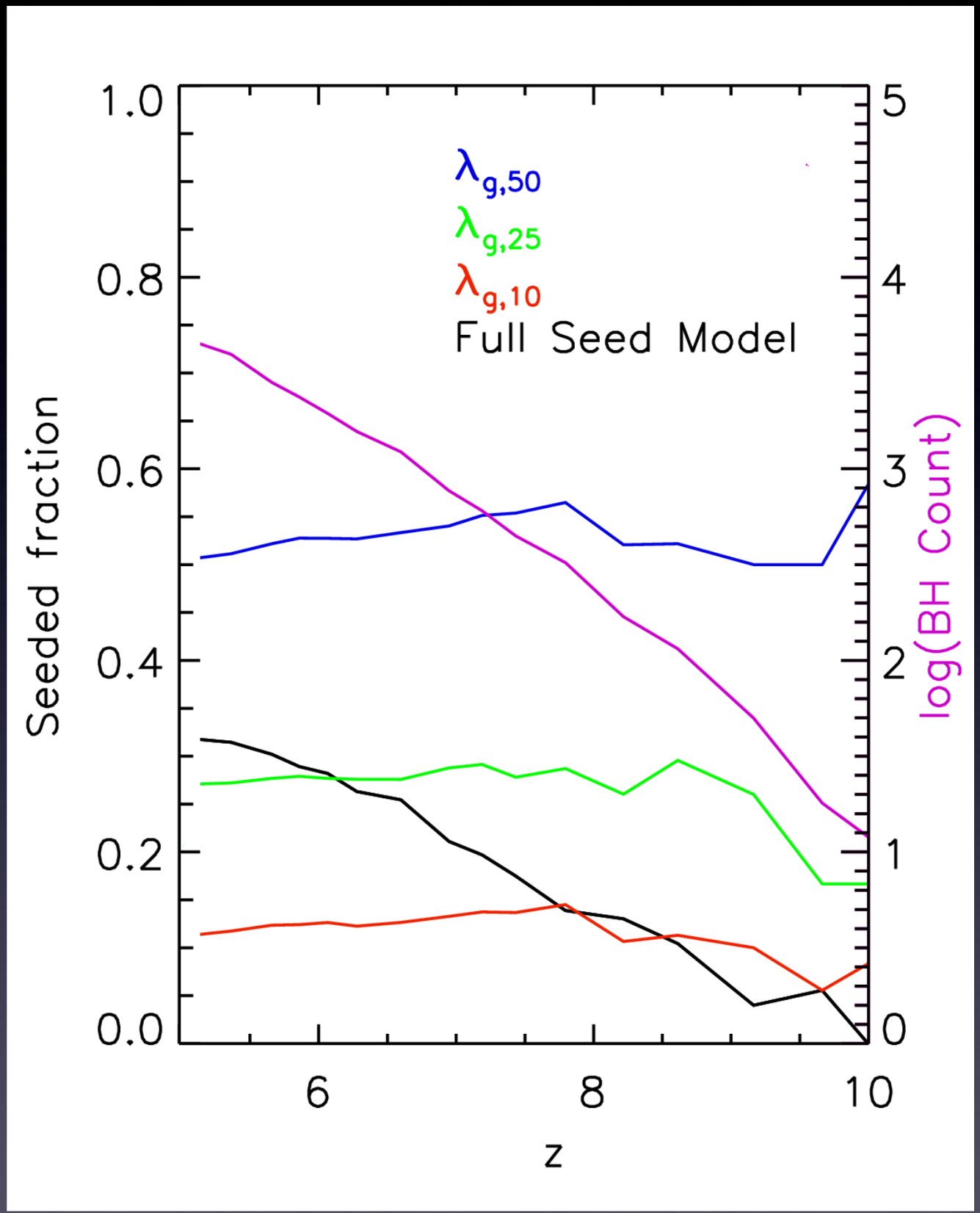
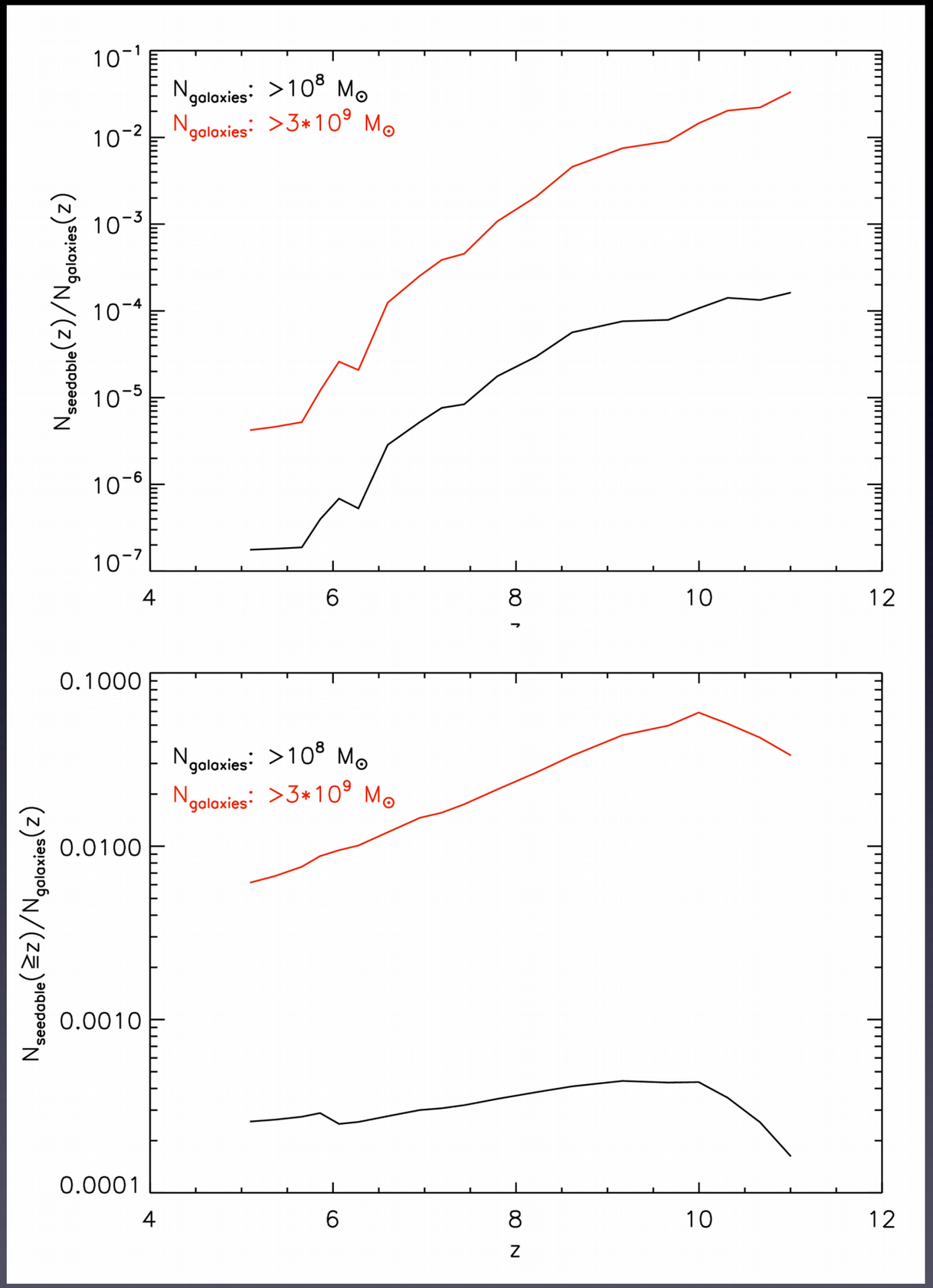
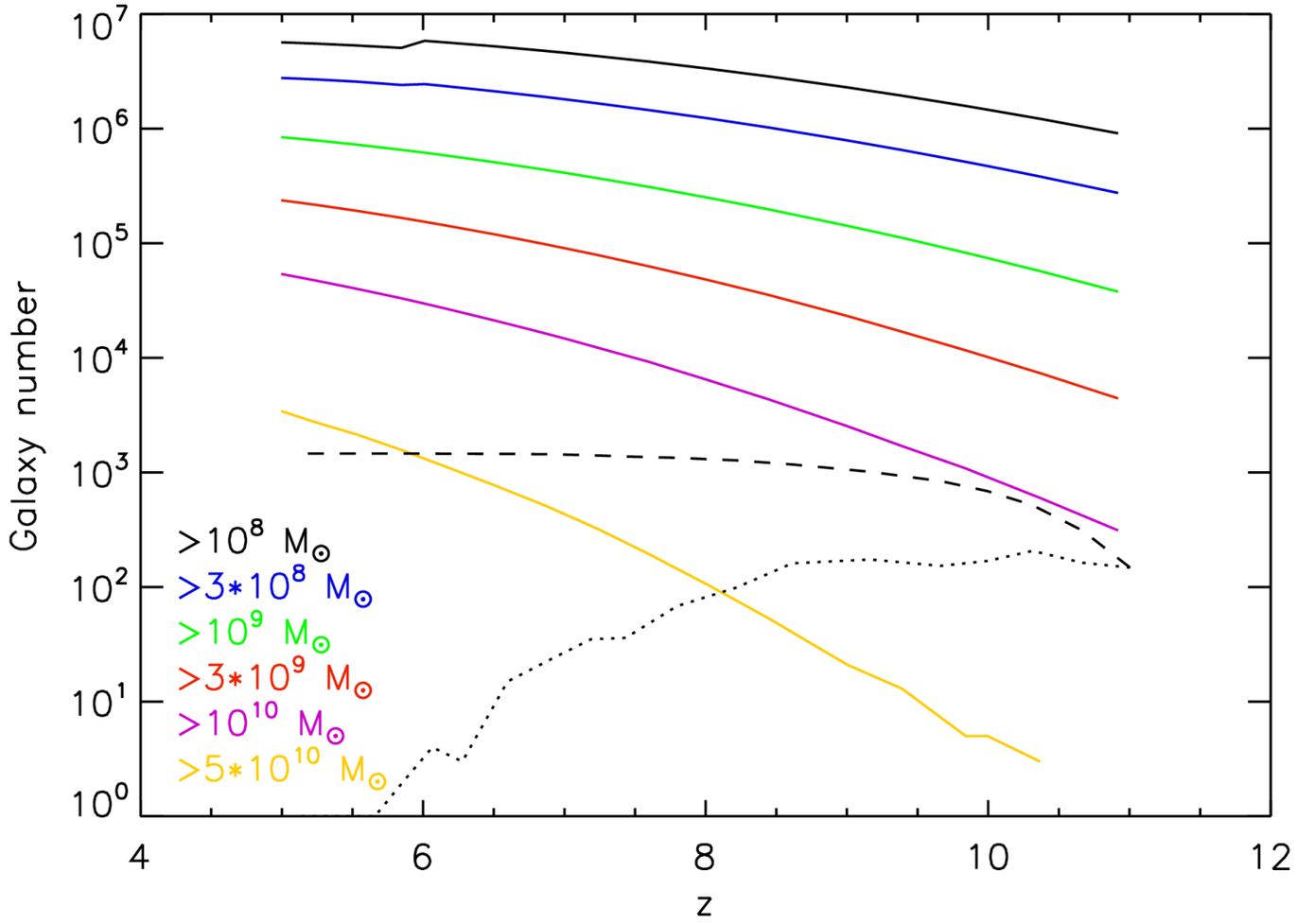


- Fraction of Illustris black holes that should be seeded, using new seeding prescriptions
- Spin-based roughly constant, with total seeded number growing with time
- Progenitor galaxy based seeding grows with time
  - Due to halo mass threshold in Illustris, not when progenitor galaxy satisfies criteria

- Progenitor galaxies tend to form seeds early
- Small fraction of galaxies satisfy conditions

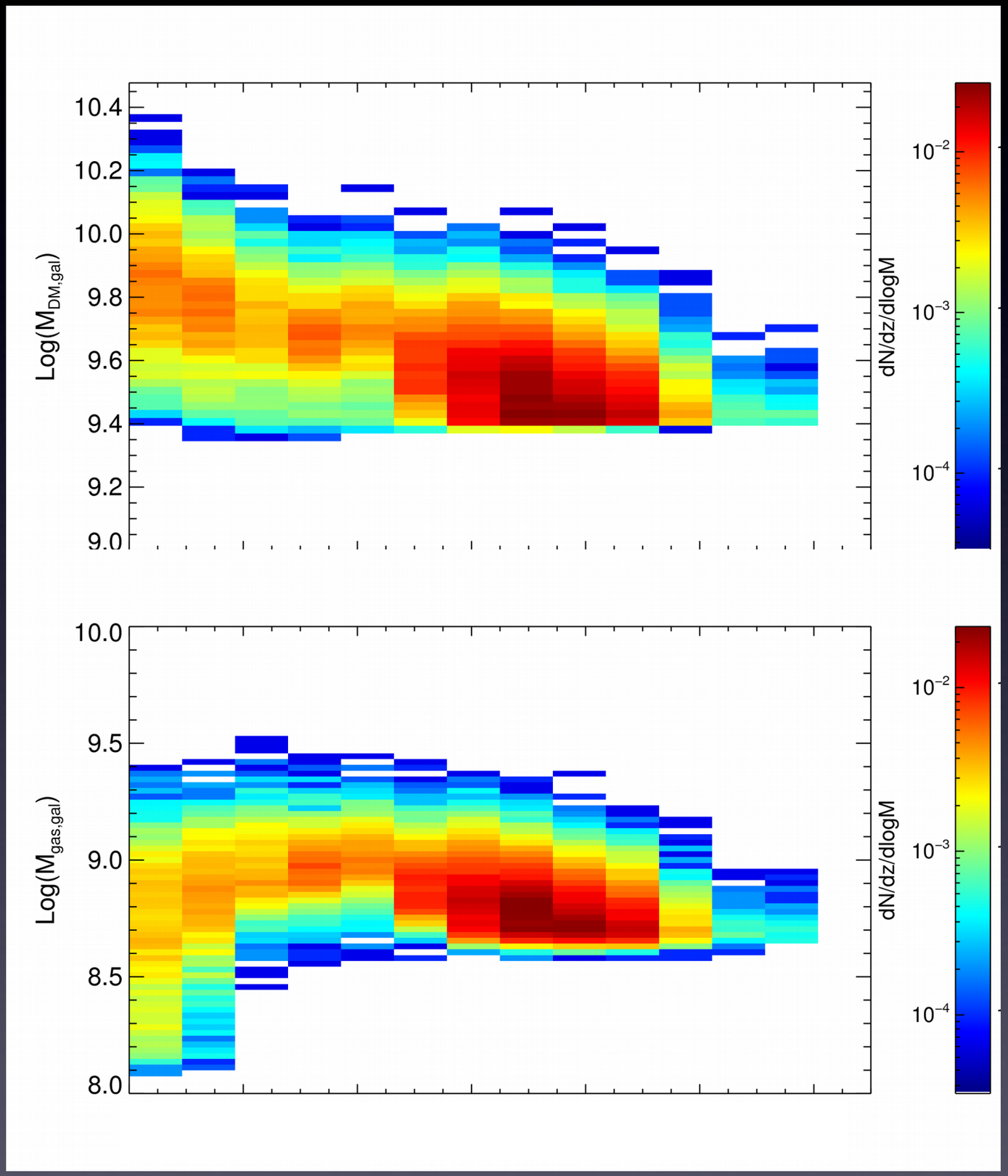


Seeding Numbers



- Galaxy number grows with time
  - Original Illustris seeding rate grows (yellow)
- Progenitor-based seeding decreases with time (dotted)
- Total seeded number

Typical Hosts



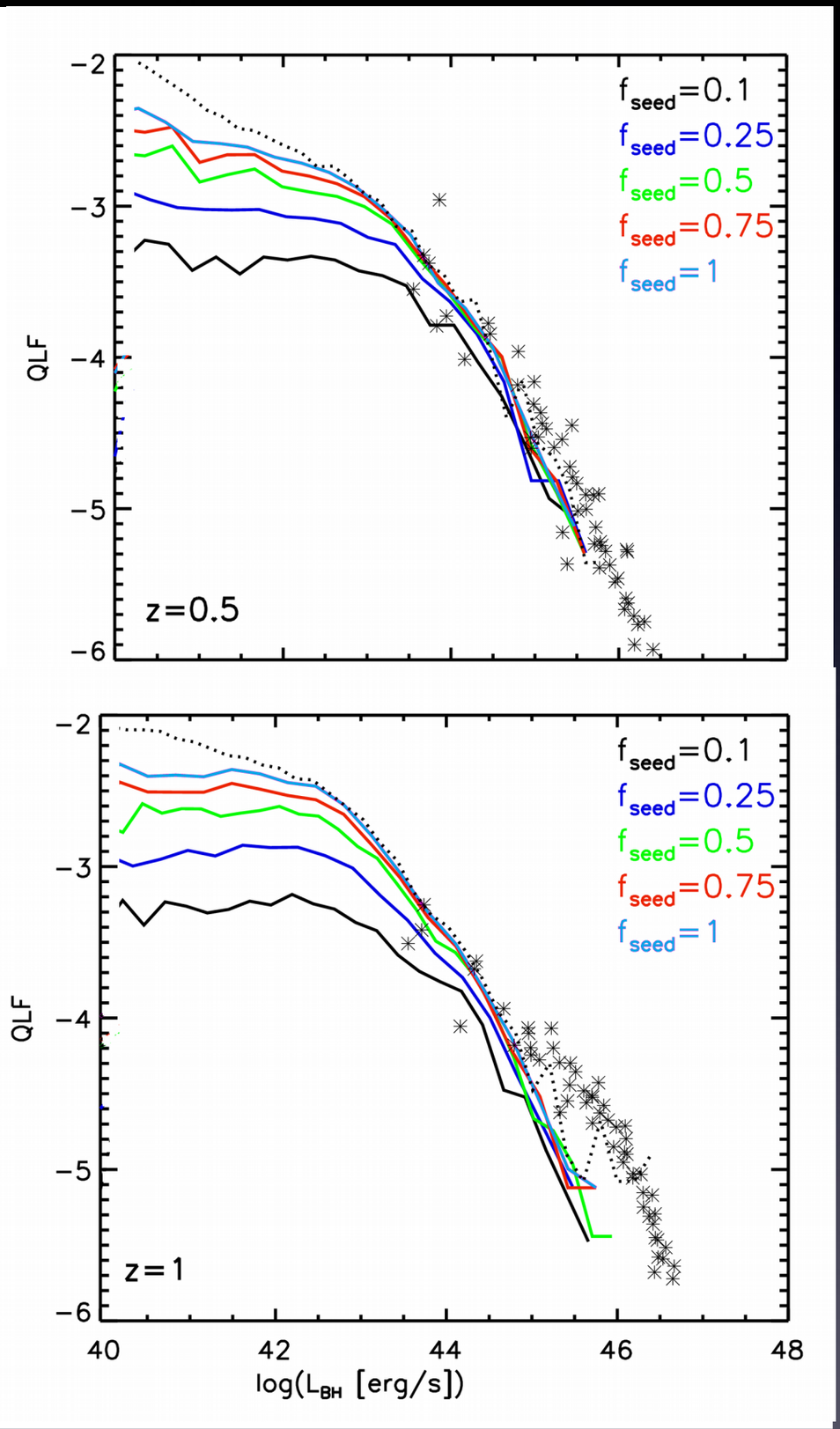
- Full seeding model:
  - $z > 5$:

    Roughly constant galaxy masses
  - $z < 5$:

    Increasing M_{DM}

    Decreasing M_{gas}

Quasar Luminosity Function



- Bright-end largely unaffected by seeding criteria
- Faint end shows normalization shift with changing f_{seed}

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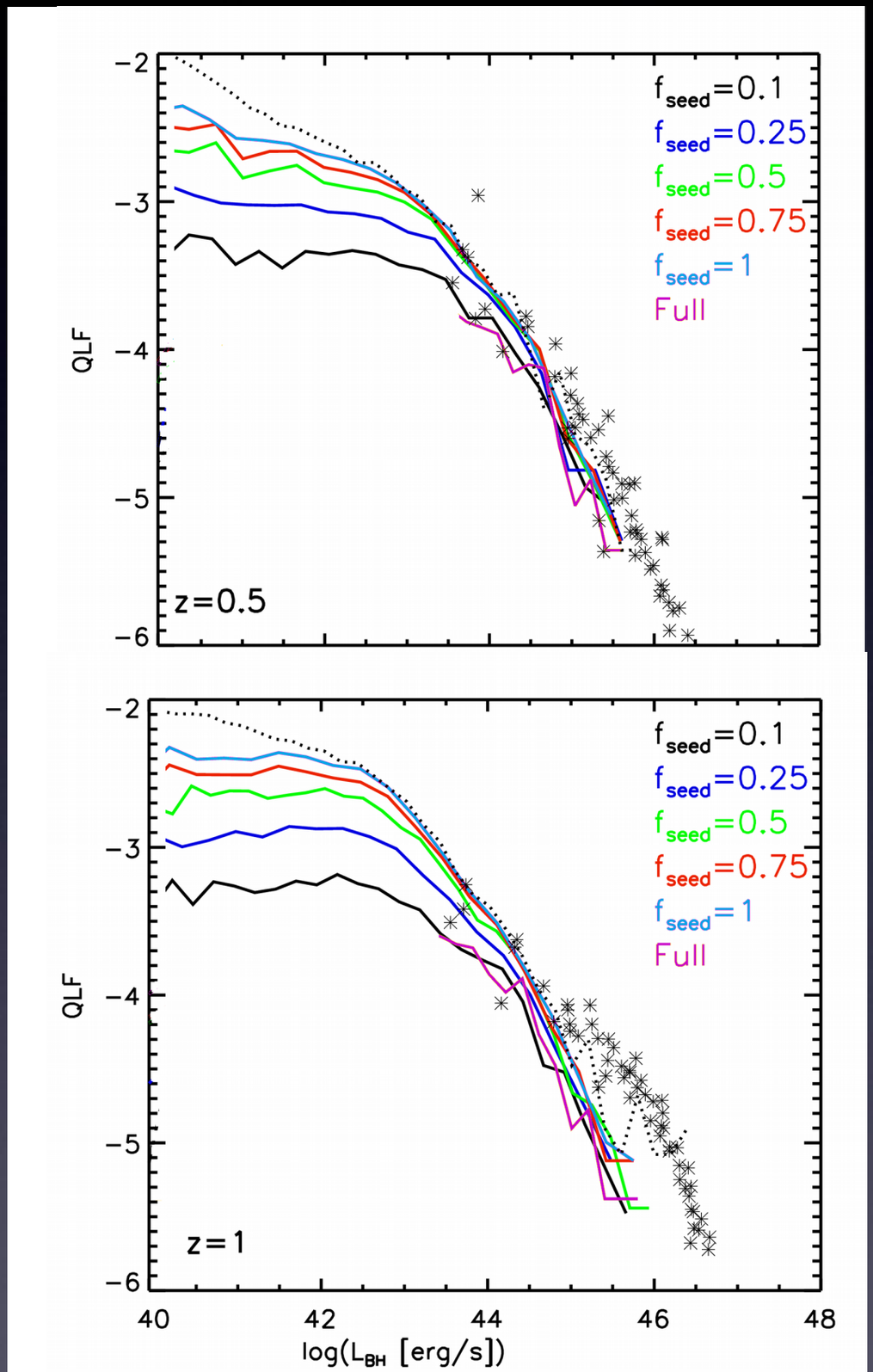

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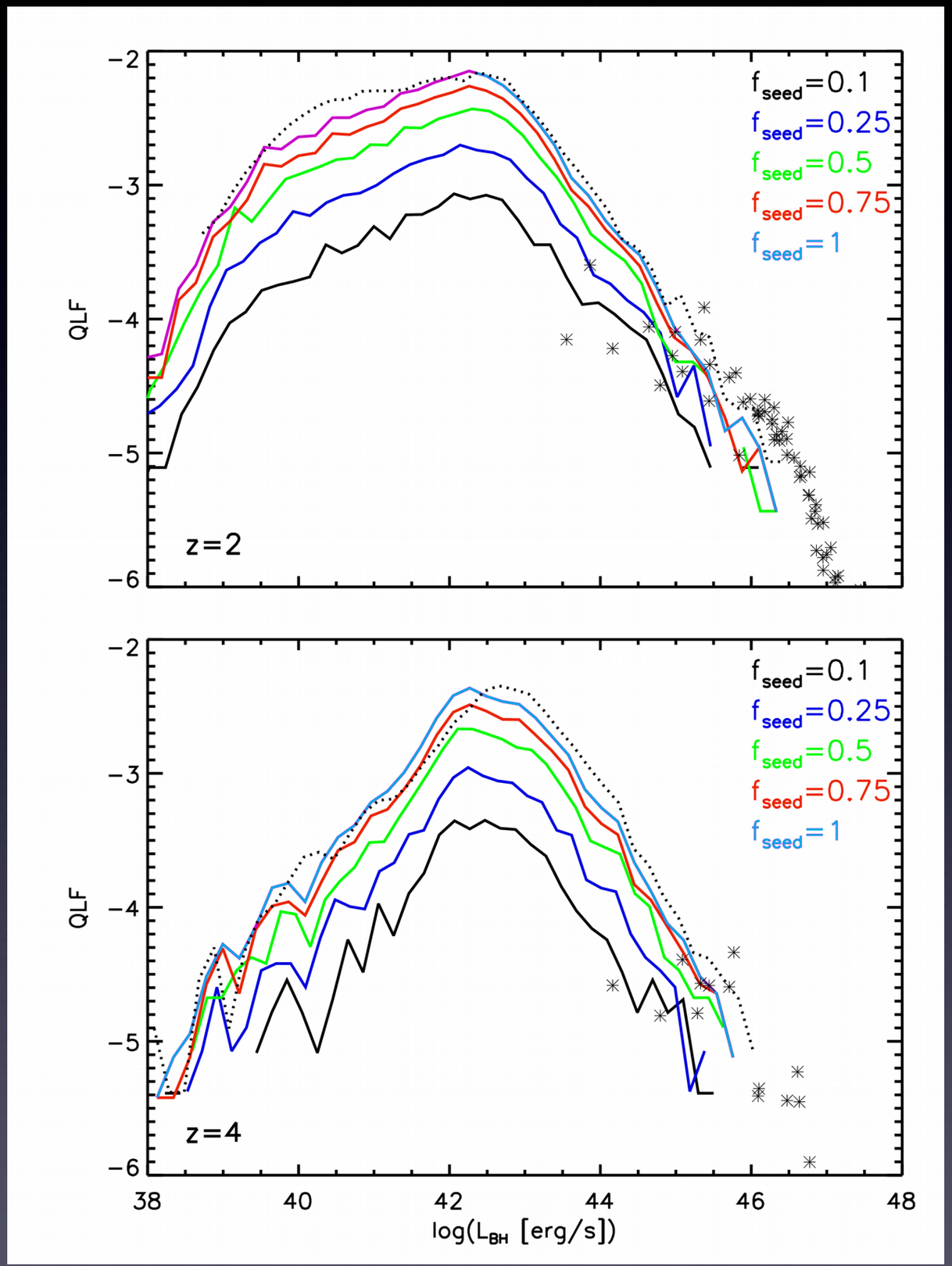

- Some bright-end dependence at high-z
- Very difficult to constrain observationally

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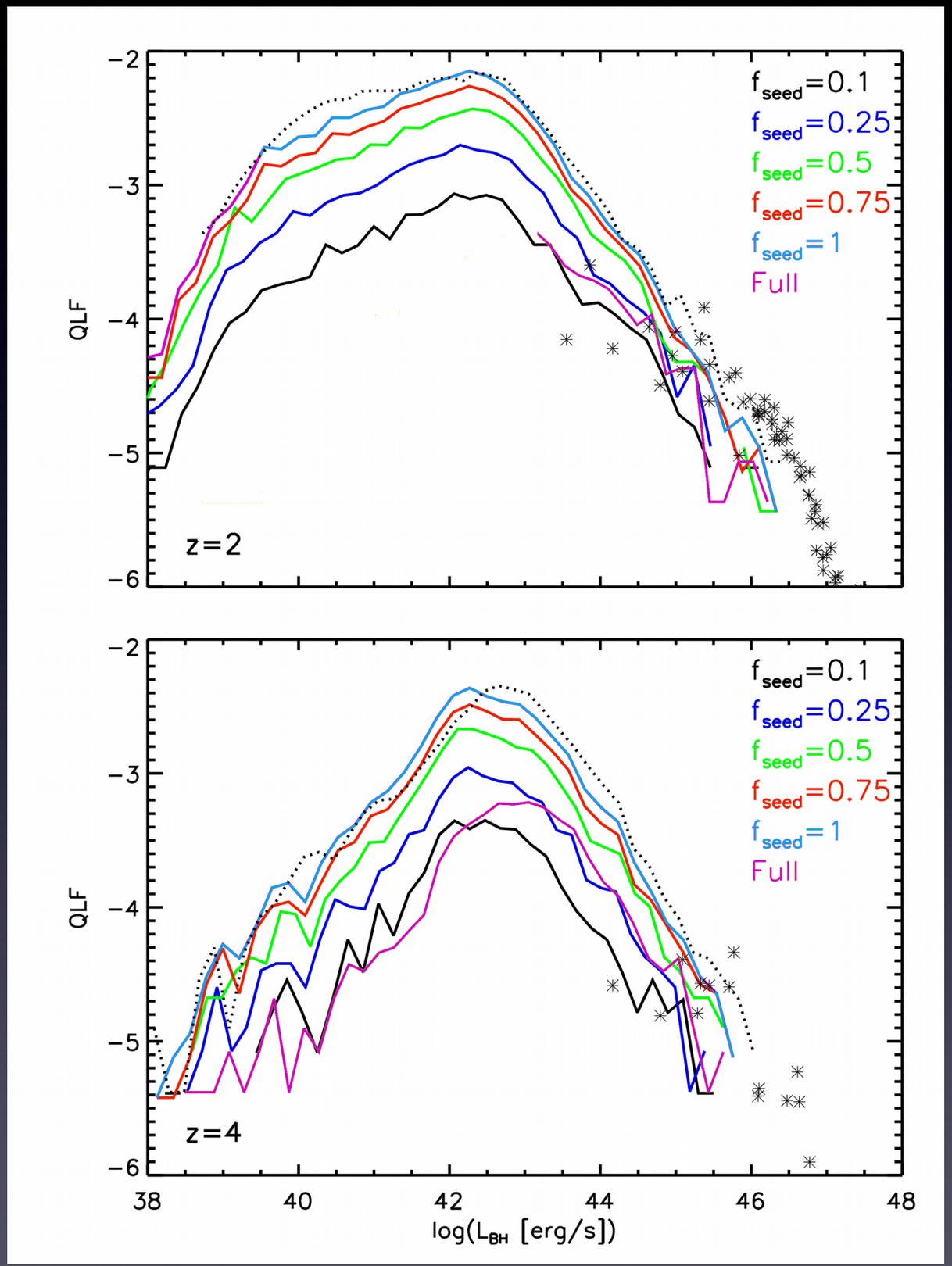

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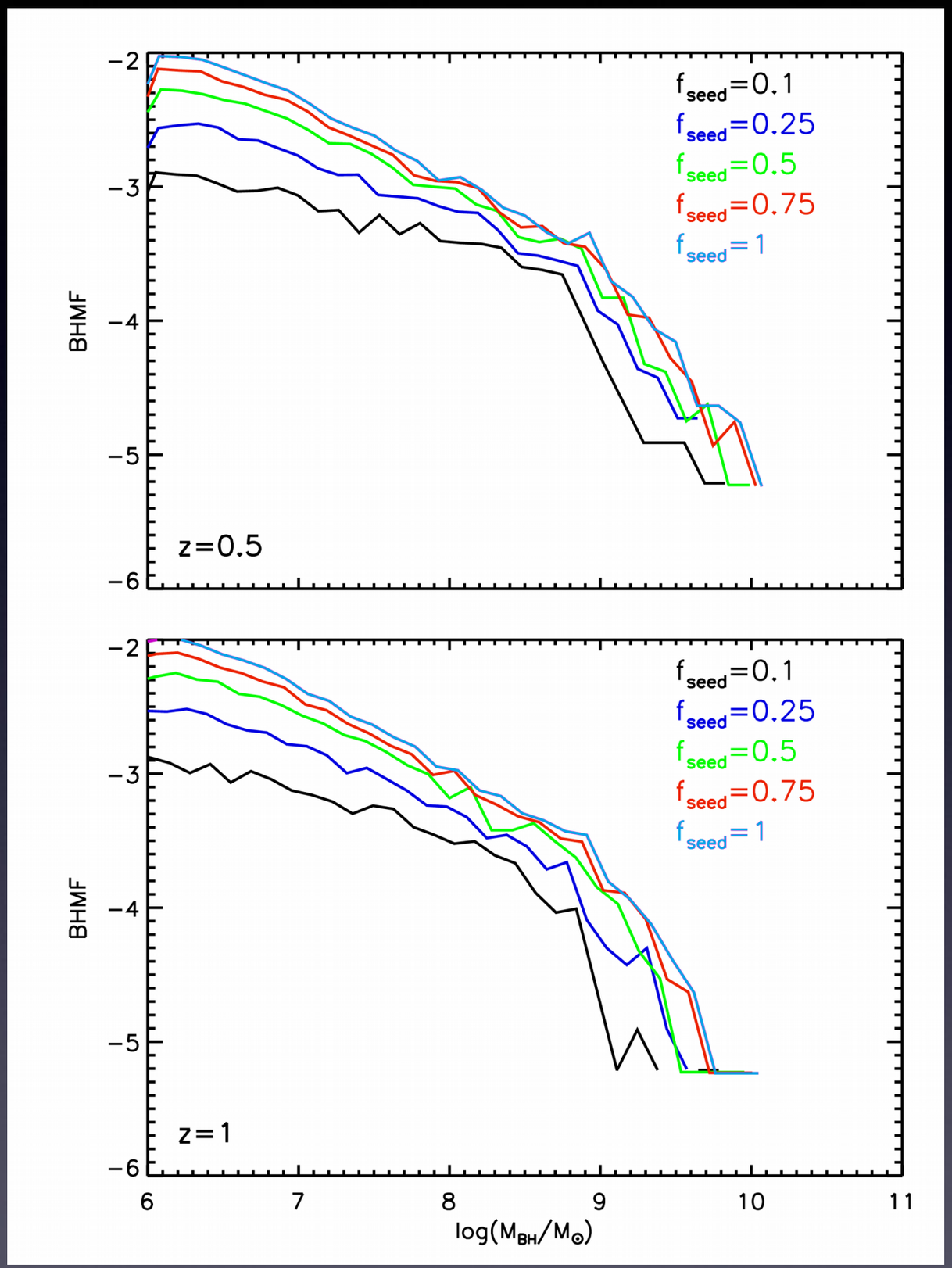
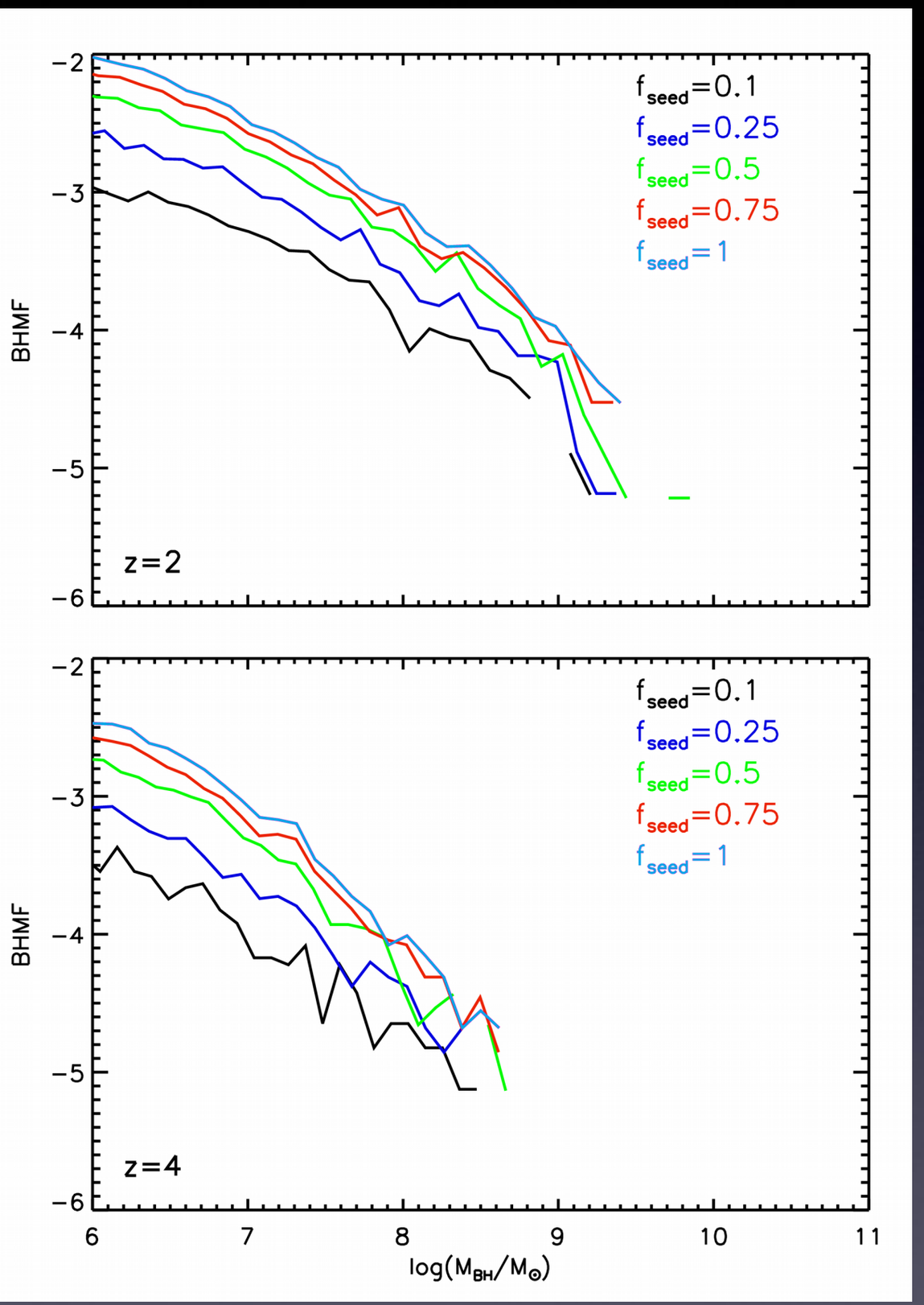
Black Hole Mass Function





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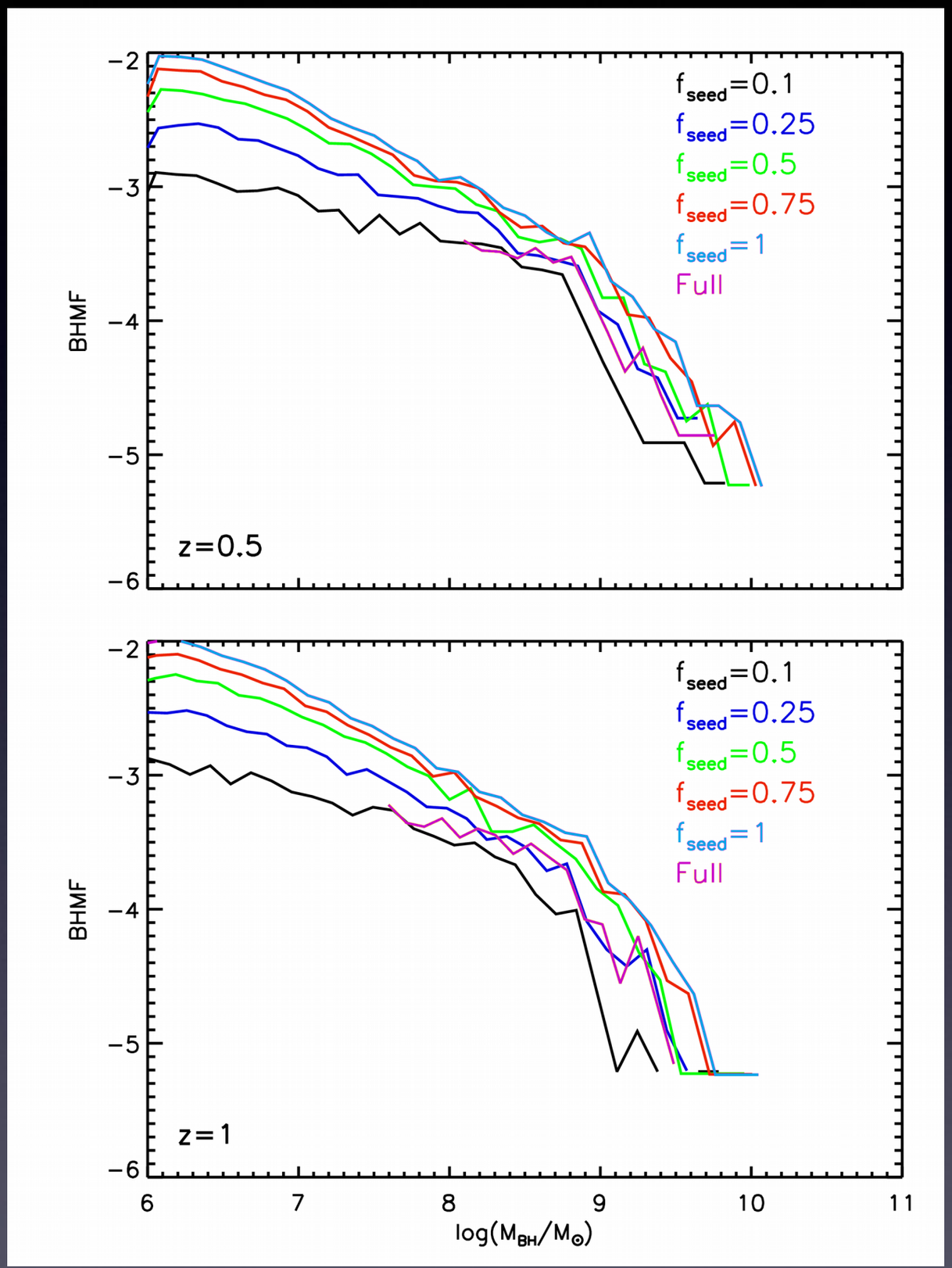
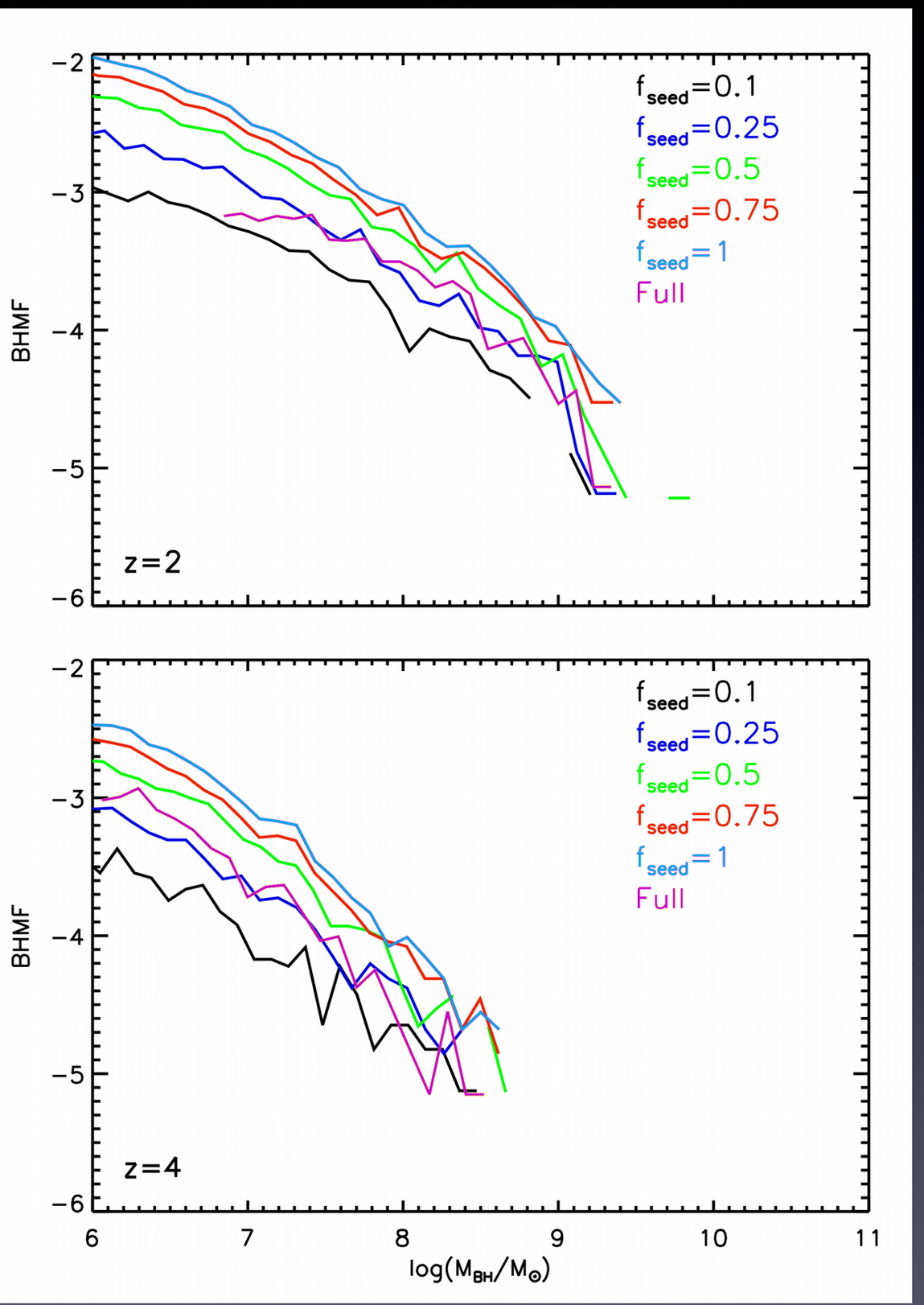
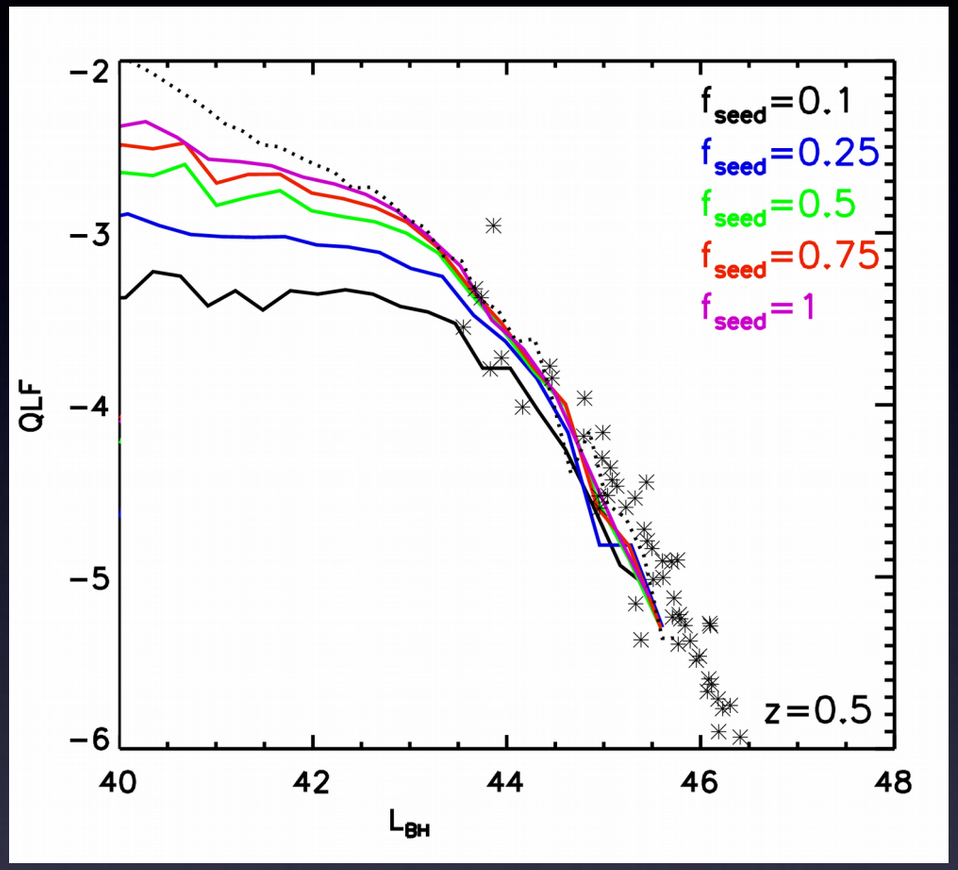
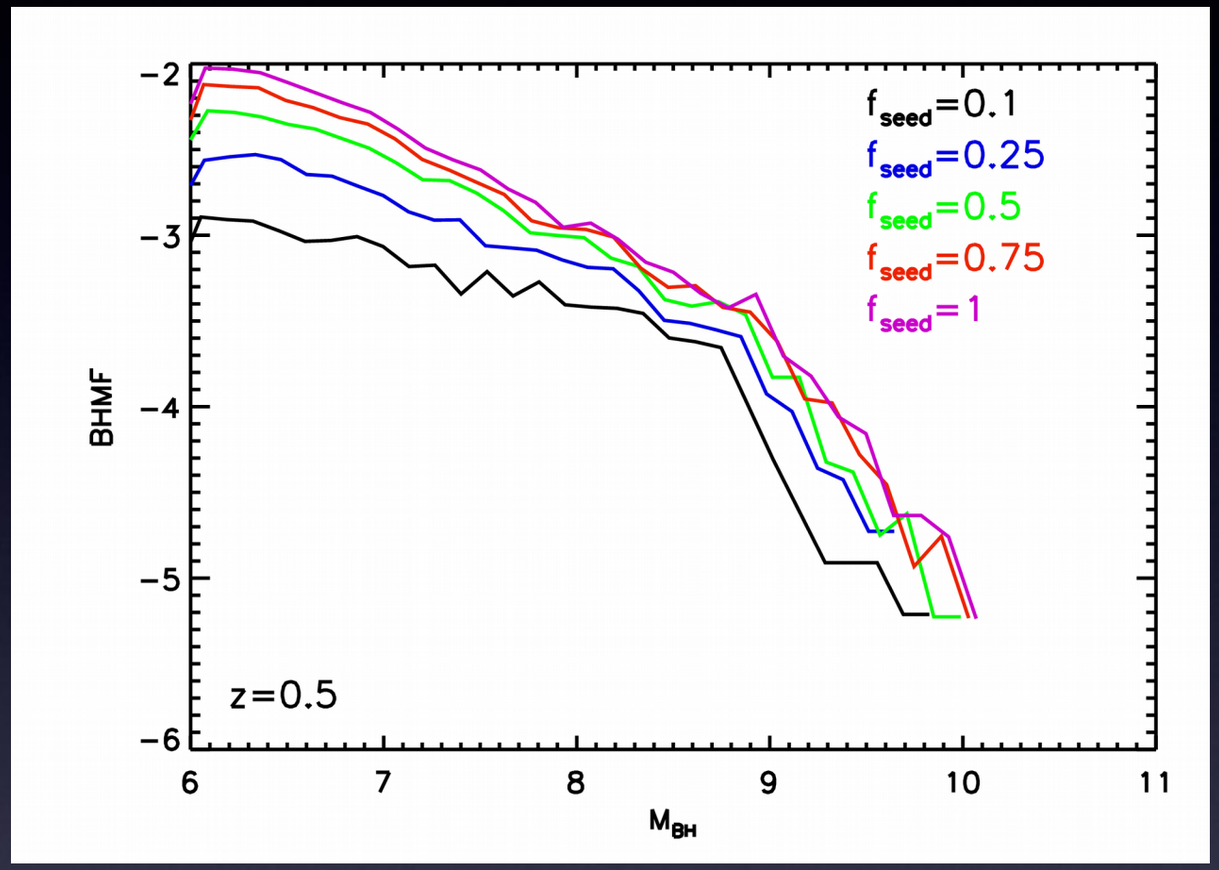




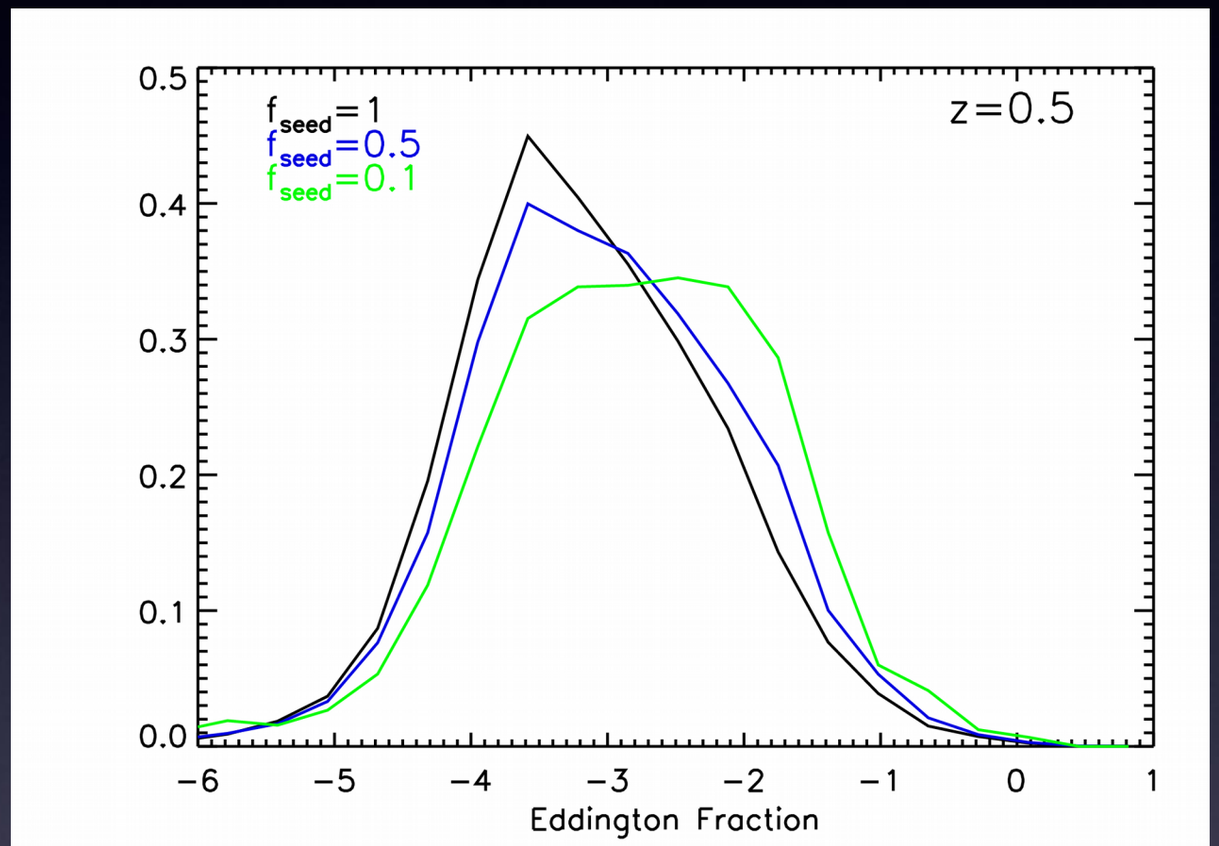
Luminosity vs Mass Functions

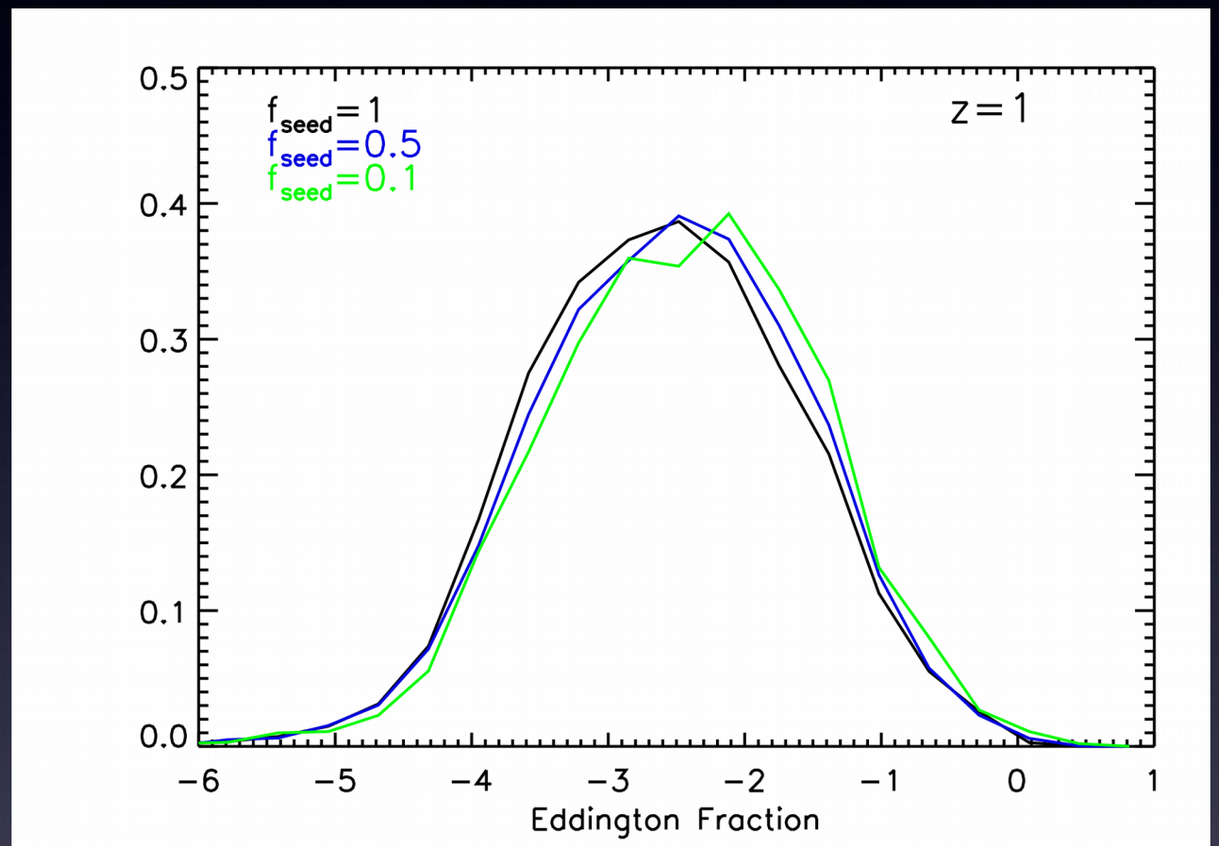




- Unlike Luminosity Function, high-end of Mass Function does depend on f_{seed}
- Lower f_{seed} → lower M_{BH} but comparable L_{BH}
  - Implies higher f_{edd}

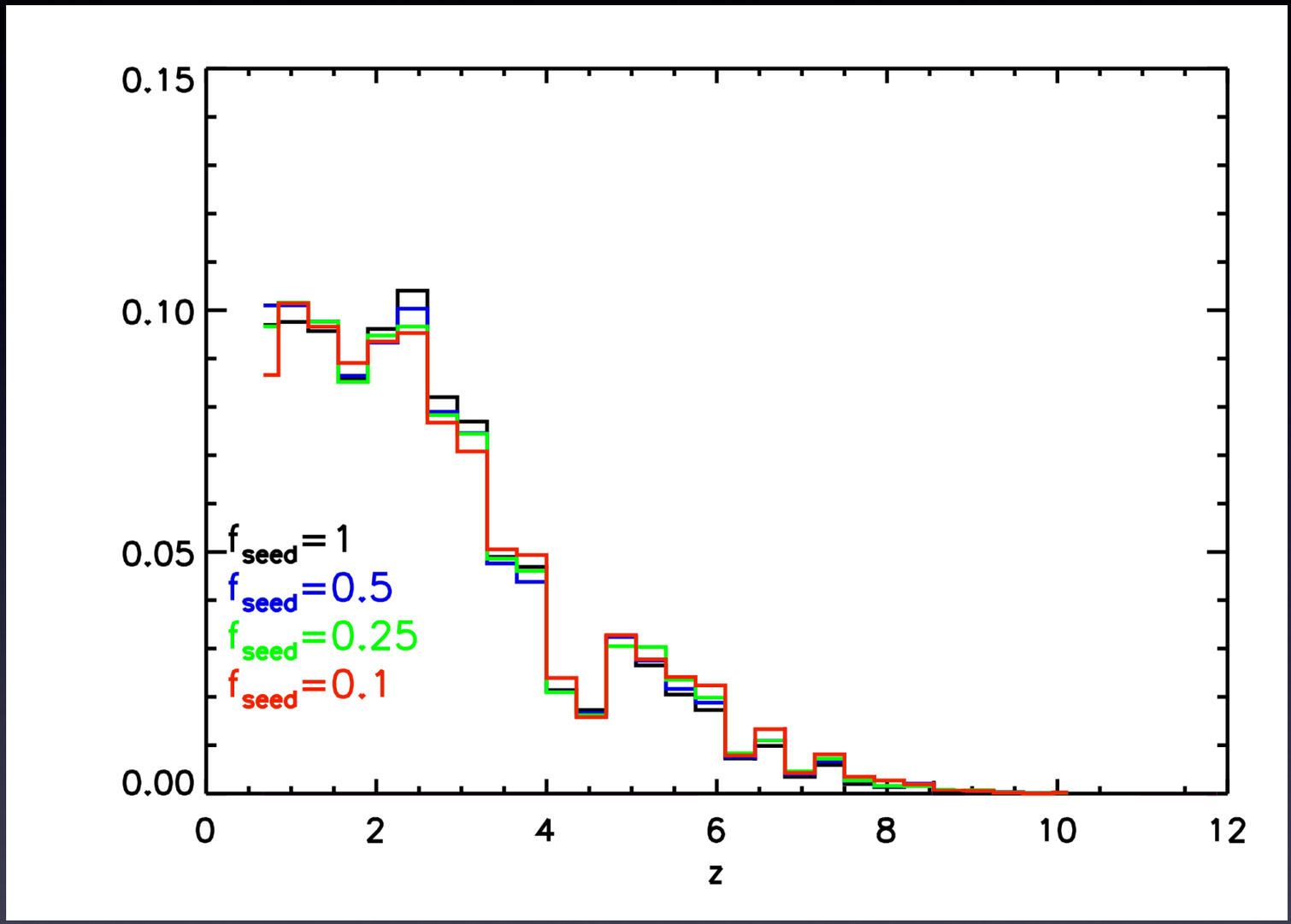
Eddington Fractions





- Lower f_{seed} → lower M_{BH} but comparable L_{BH} → higher f_{edd}
- Higher f_{seed} → reaches self-regulated regime earlier

‘Pre-seeding’ growth



- Standard seed model: Most seeds at low-z

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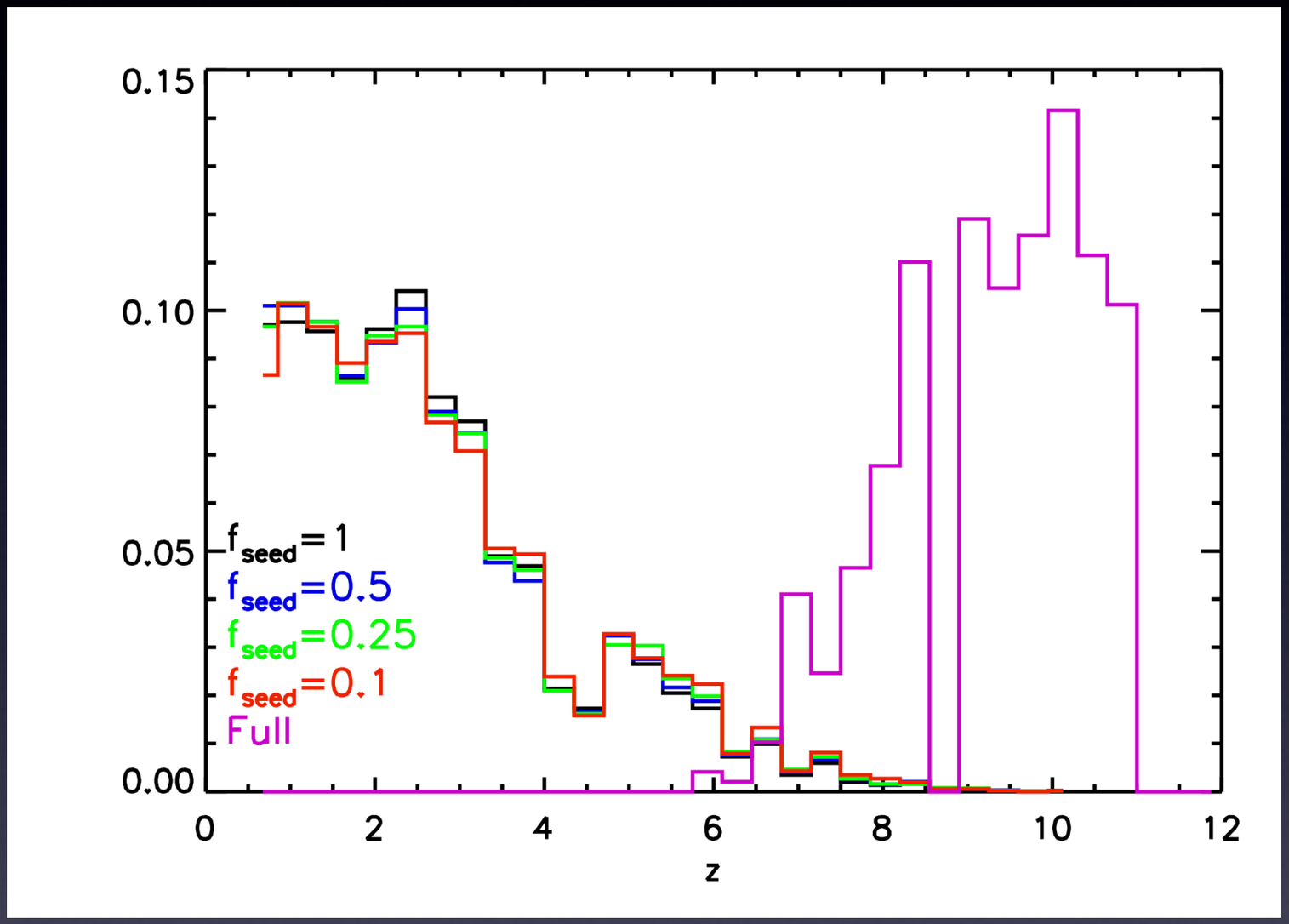
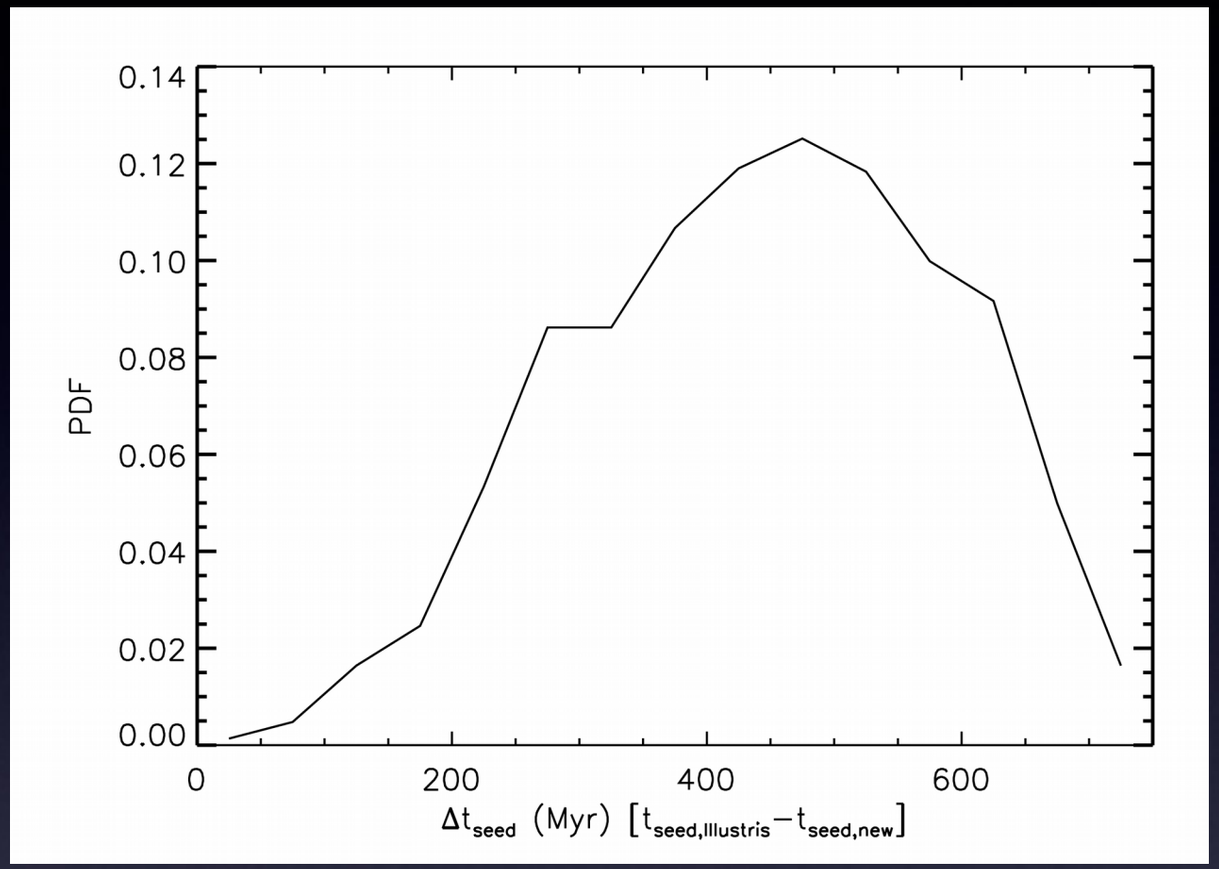


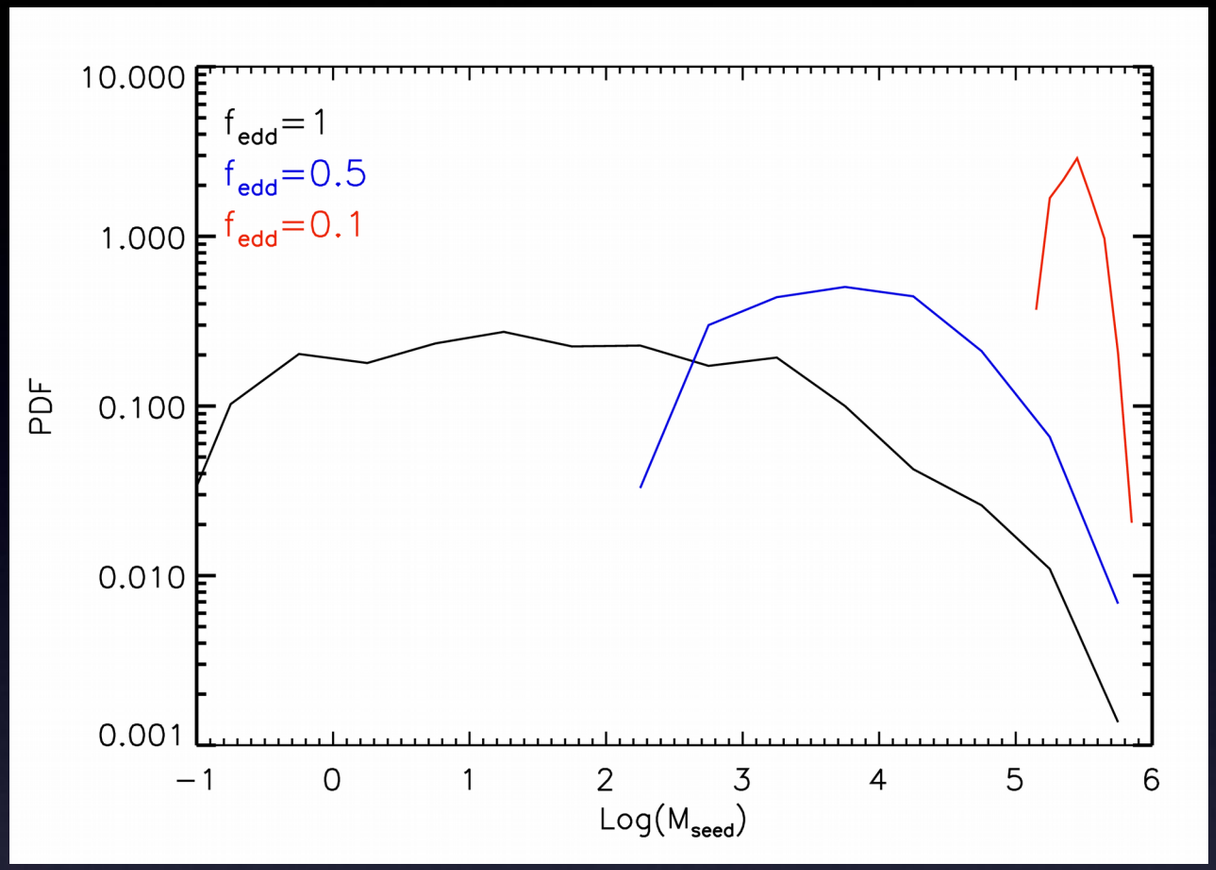
- Standard seed model: Most seeds at low-z
- Galaxy progenitor model: Most seeding occurs at high-z

‘Pre-seeding’ growth

- Typical time between conditions for Direct Collapse and seeding within Illustris

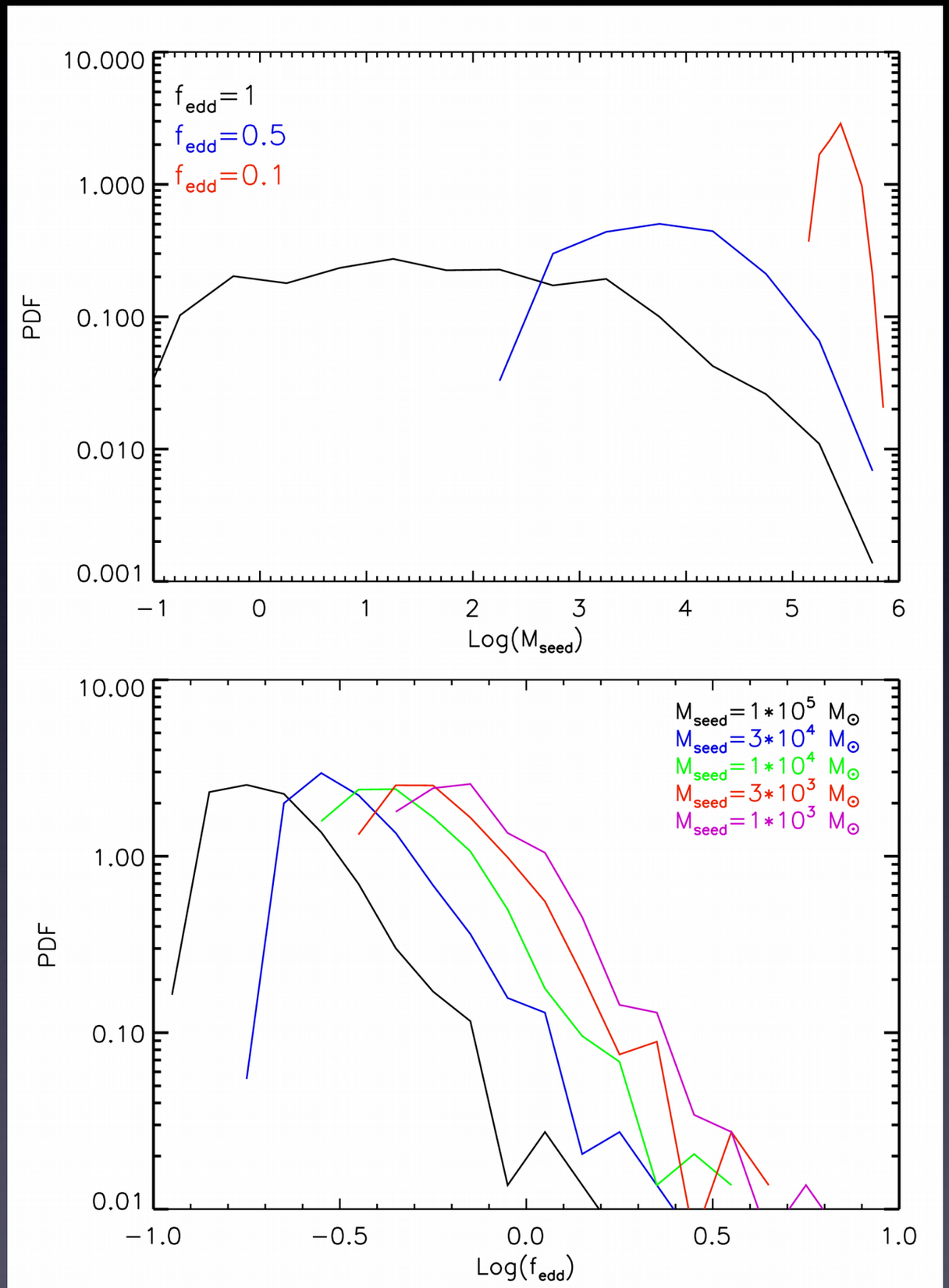


‘Pre-seeding’ growth



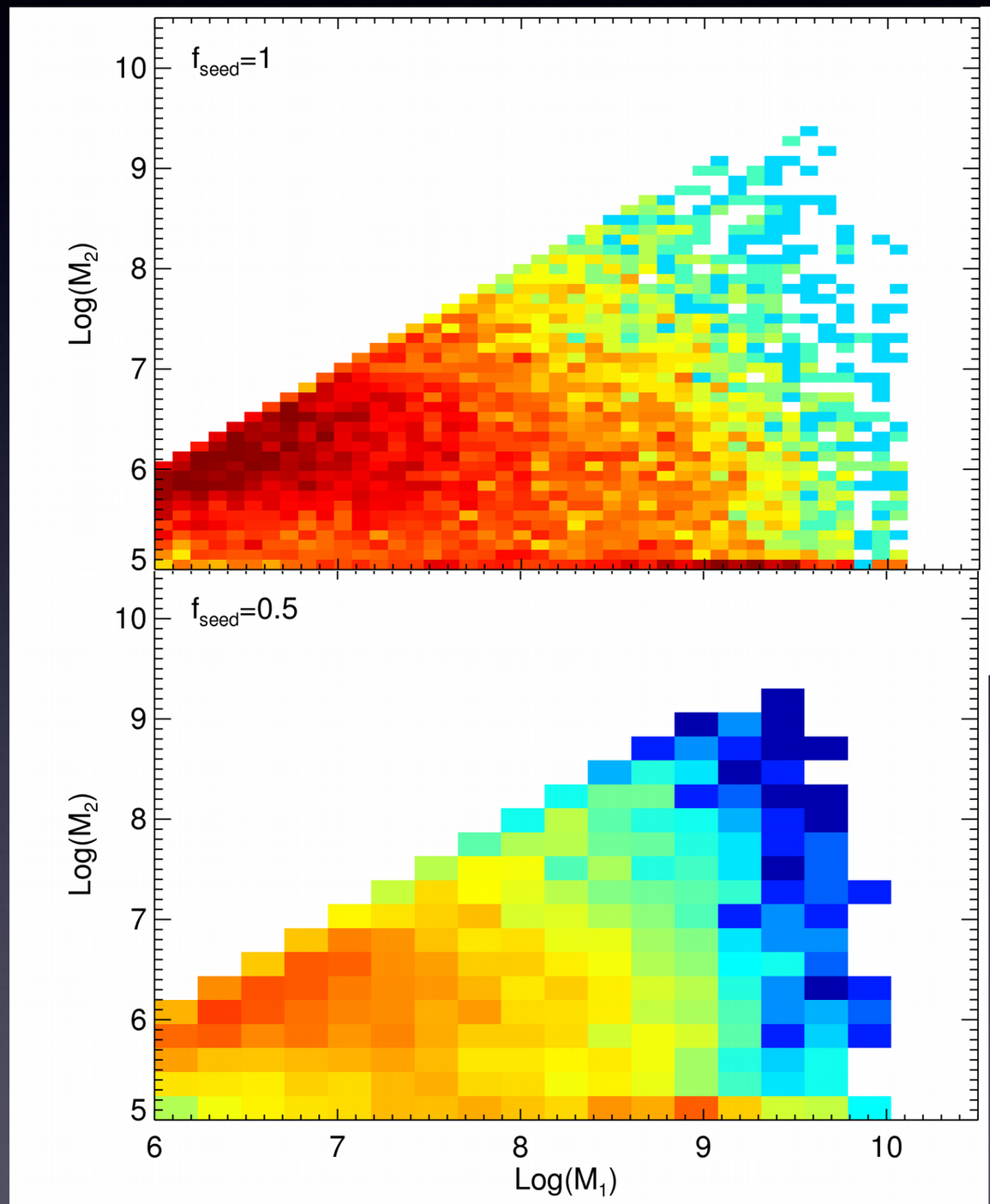
- Assume accretion at fixed Eddington fraction
- Wide range of possible M_{seed} and/or f_{edd}

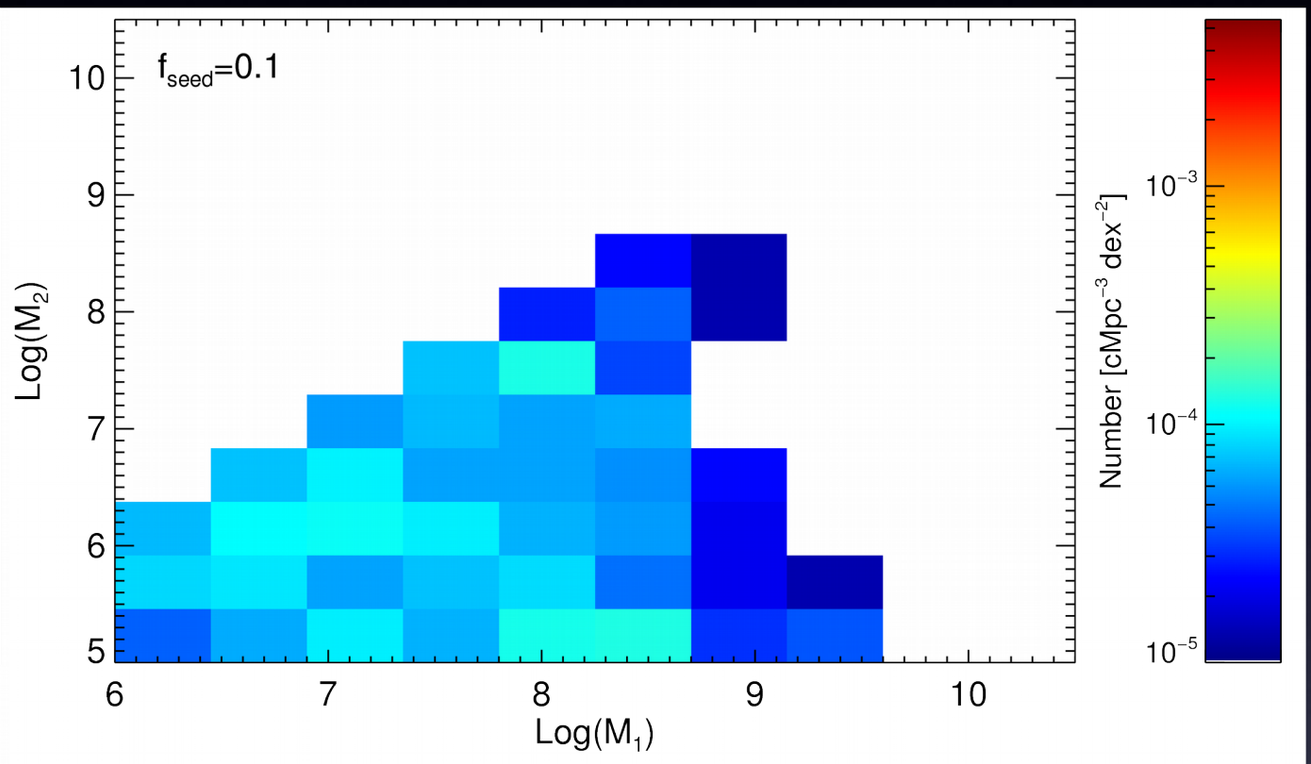
‘Pre-seeding’ growth



- Assume accretion at fixed Eddington fraction
- Wide range of possible M_{seed} and/or f_{edd}

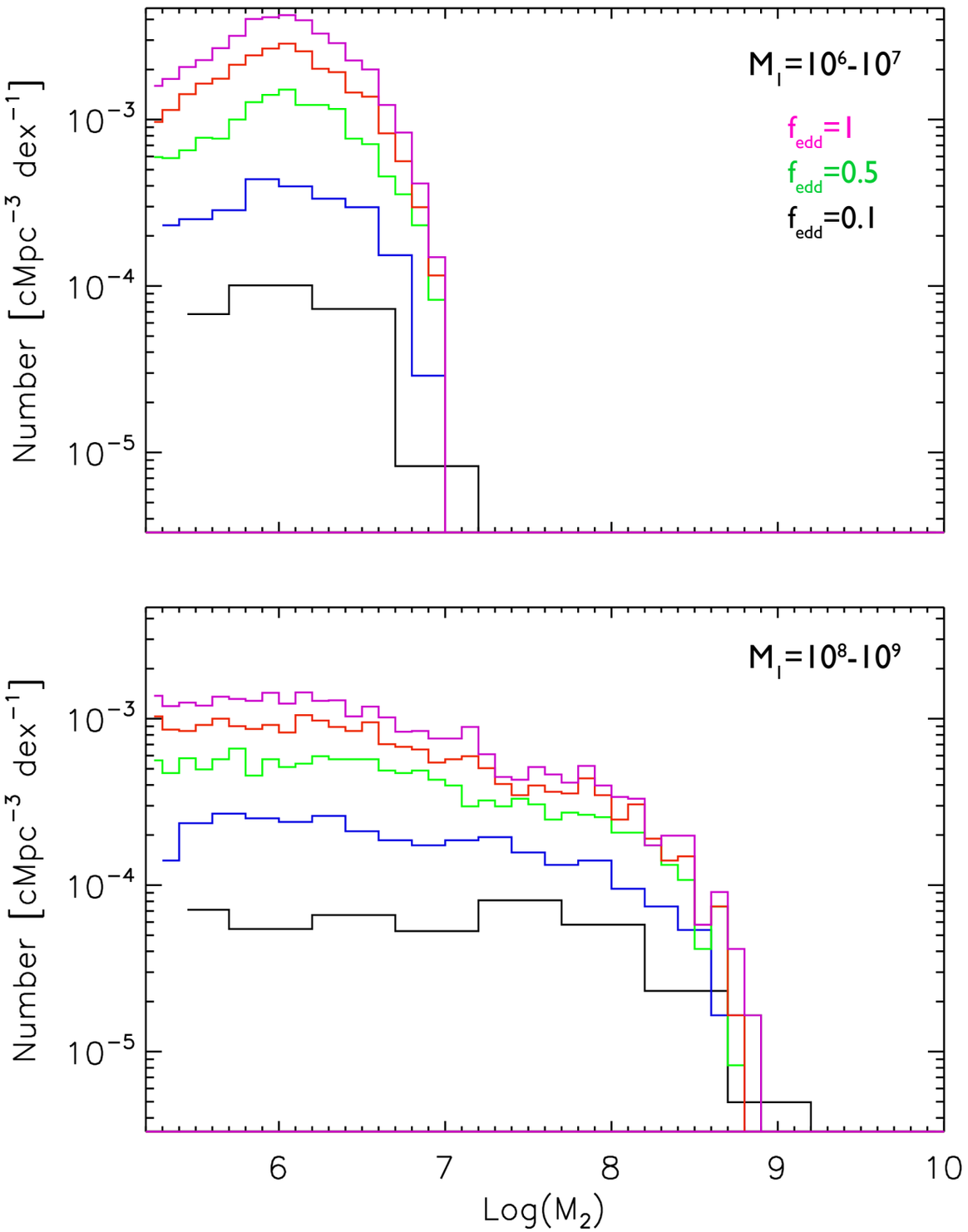
Black Hole Merger Rates





- Merger distribution peaks at ~2-3x10^6 M_o with ~10^6 M_o
- Peak independent of f_{seed}

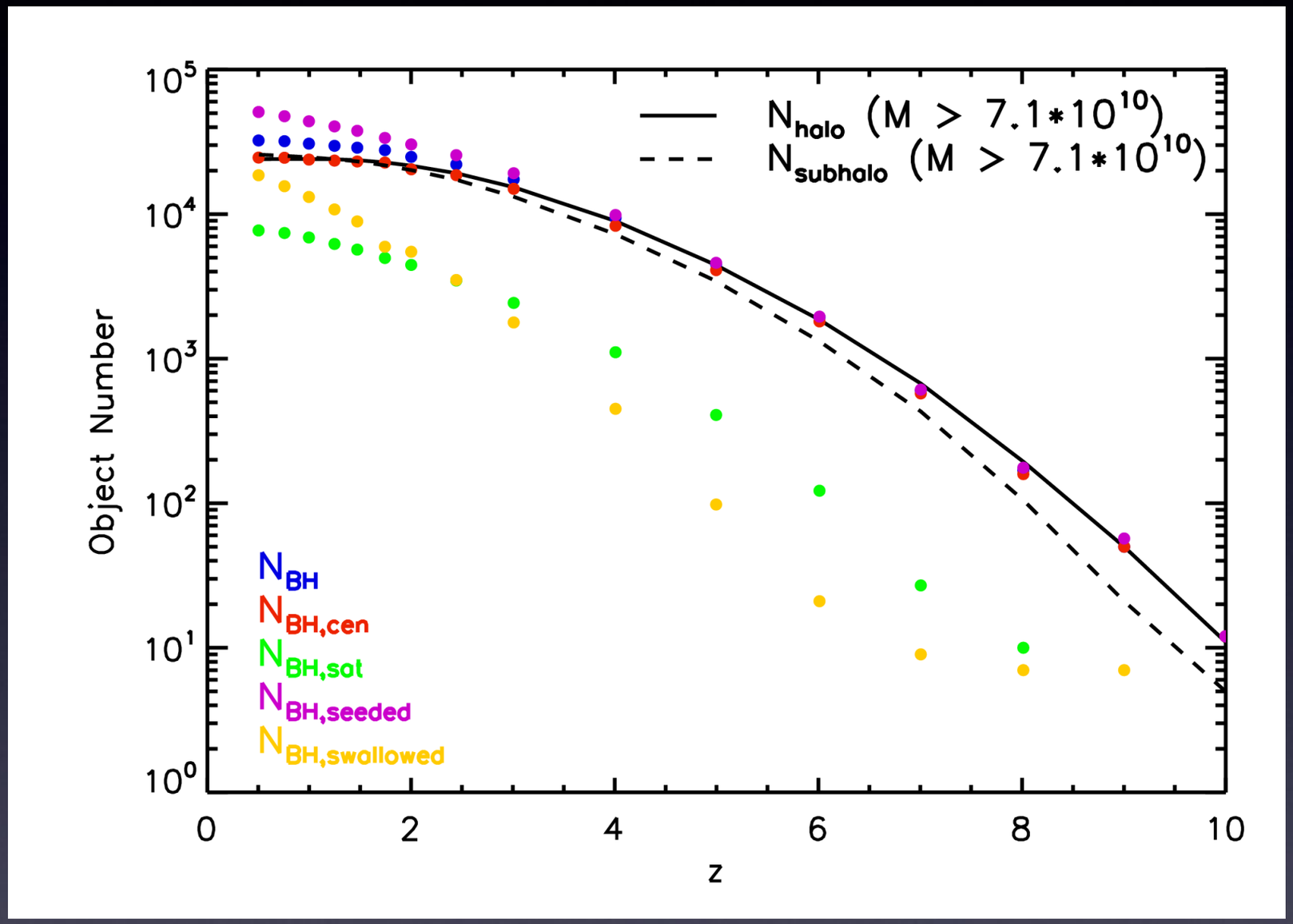
Black Hole Merger Rates

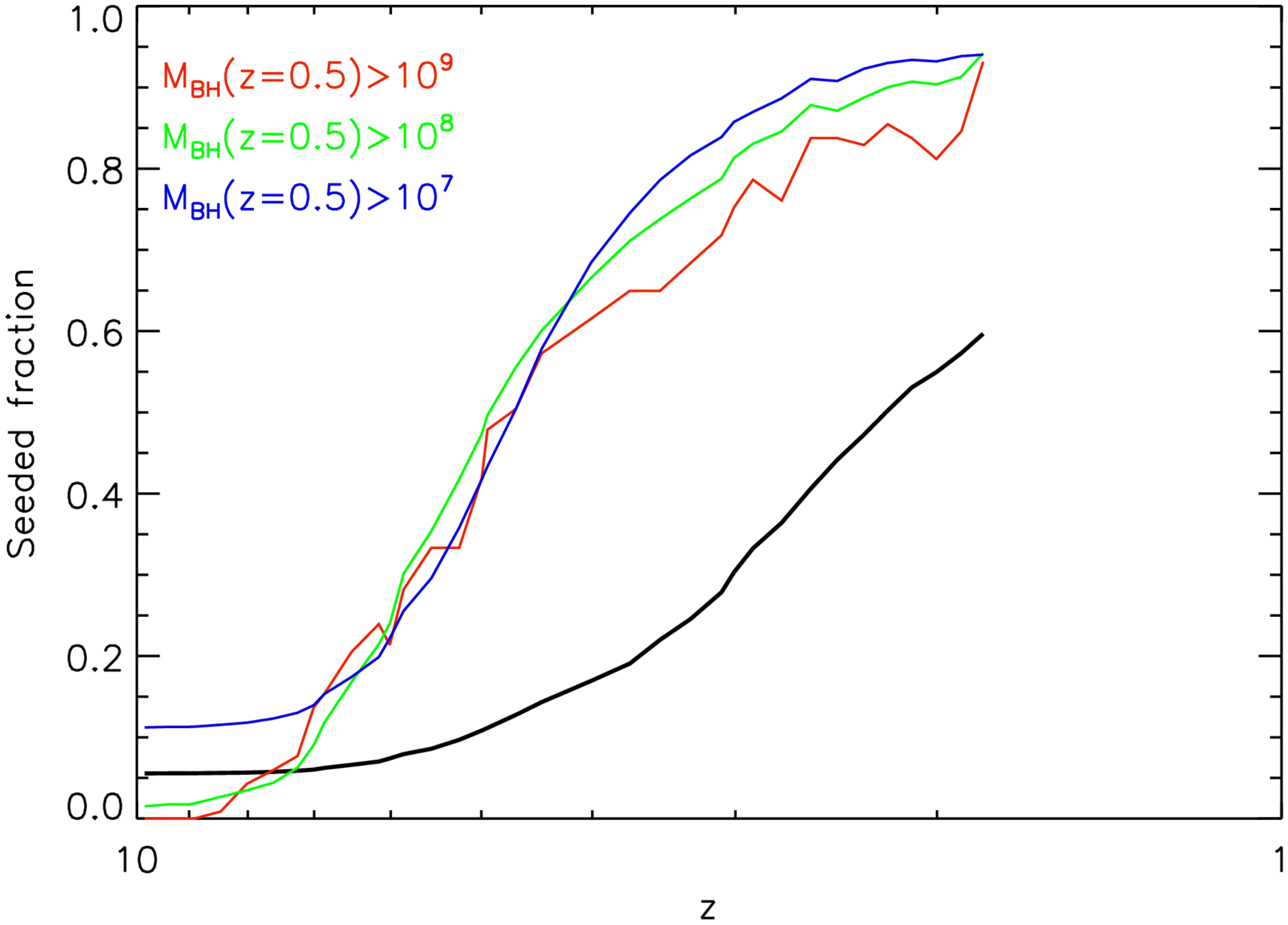


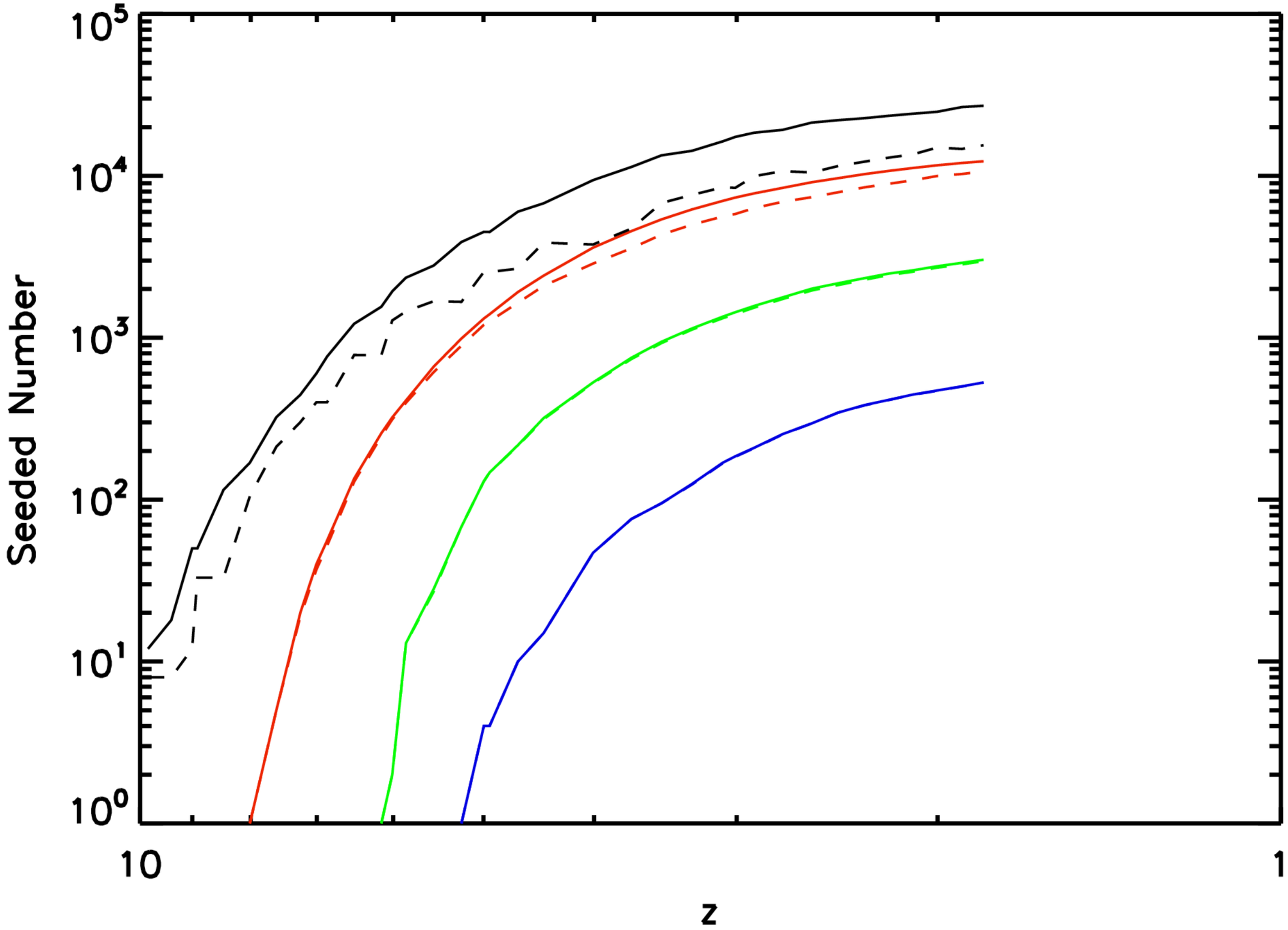
- Decreased f_{edd} → significantly fewer BH mergers
- Normalized distribution broadly insensitive to f_{edd}
  → Challenging to constrain observationally

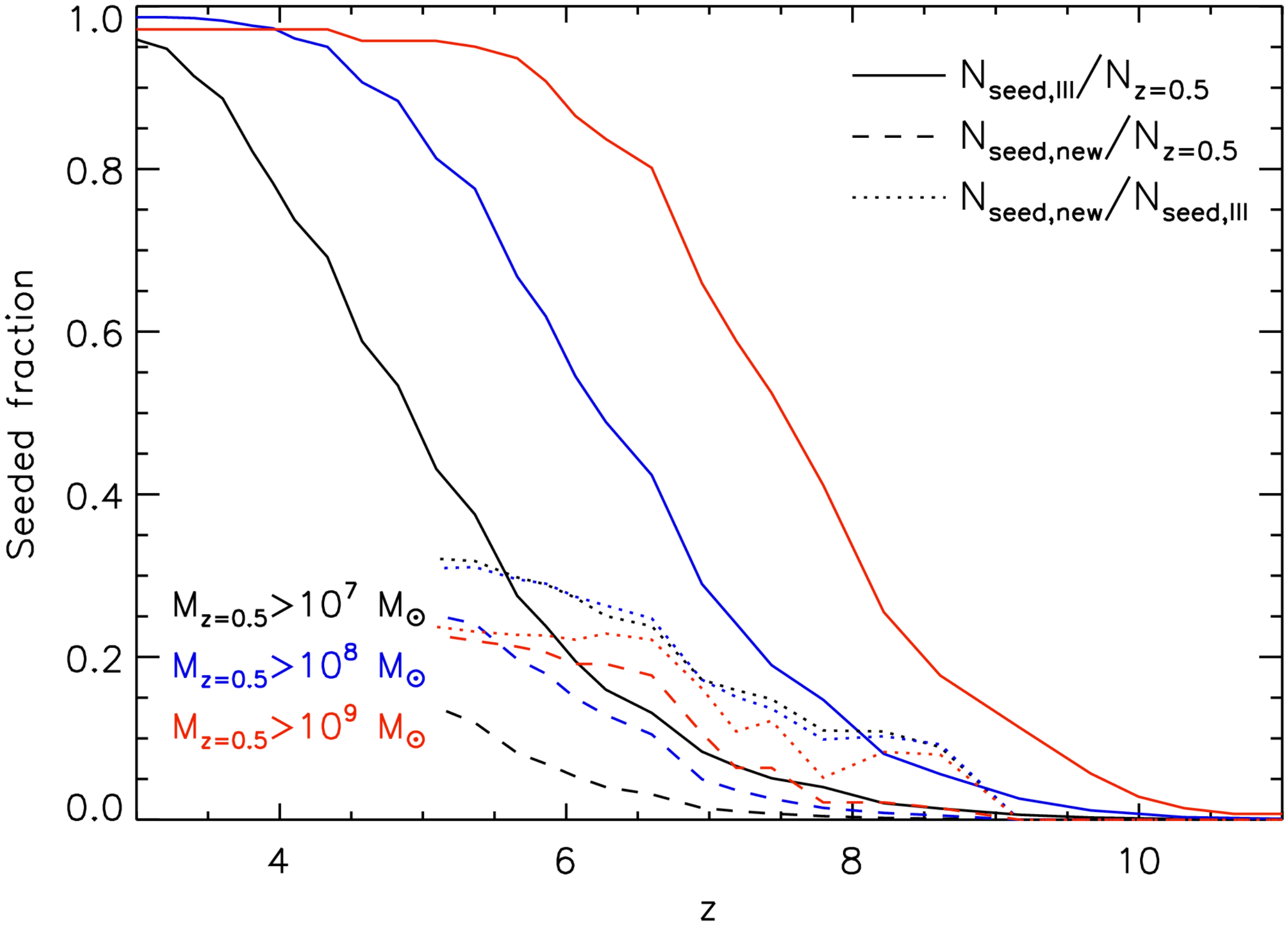
Conclusions

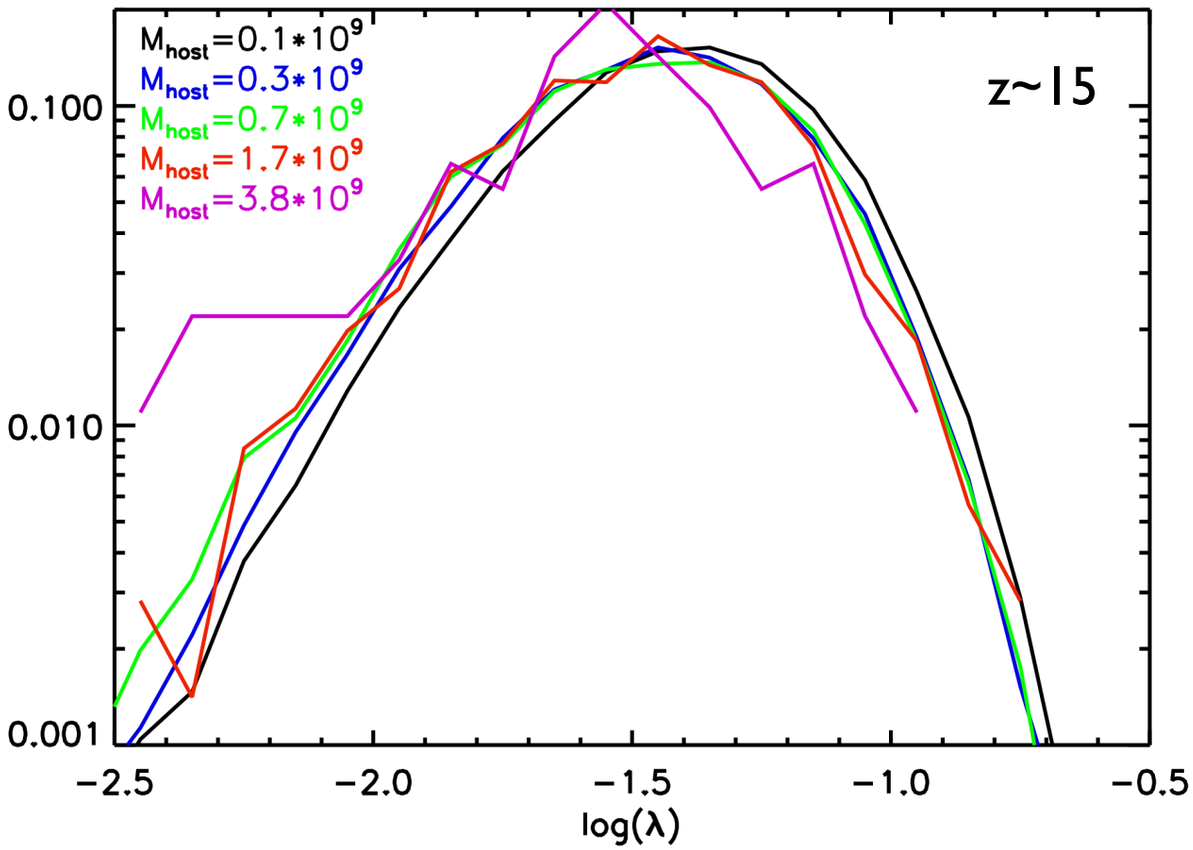
- Early-time evolution affected by seed model
  - High-z and low-M_{BH}
- Main BH populations largely unchanged by altered seeding model
  - Still match QLF, Scaling relations, etc.
- Decreased seed probability → later onset of self-regulation
- Significantly decreased merger frequency
- Still to do:
  - Additional requirements for seeding (e.g. Lyman-Werner radiation)
  - Seed mechanism -> initial growth behavior
  - Seed formation from nuclear star clusters/PopIII stars
  - Direct simulations including each seed mechanism

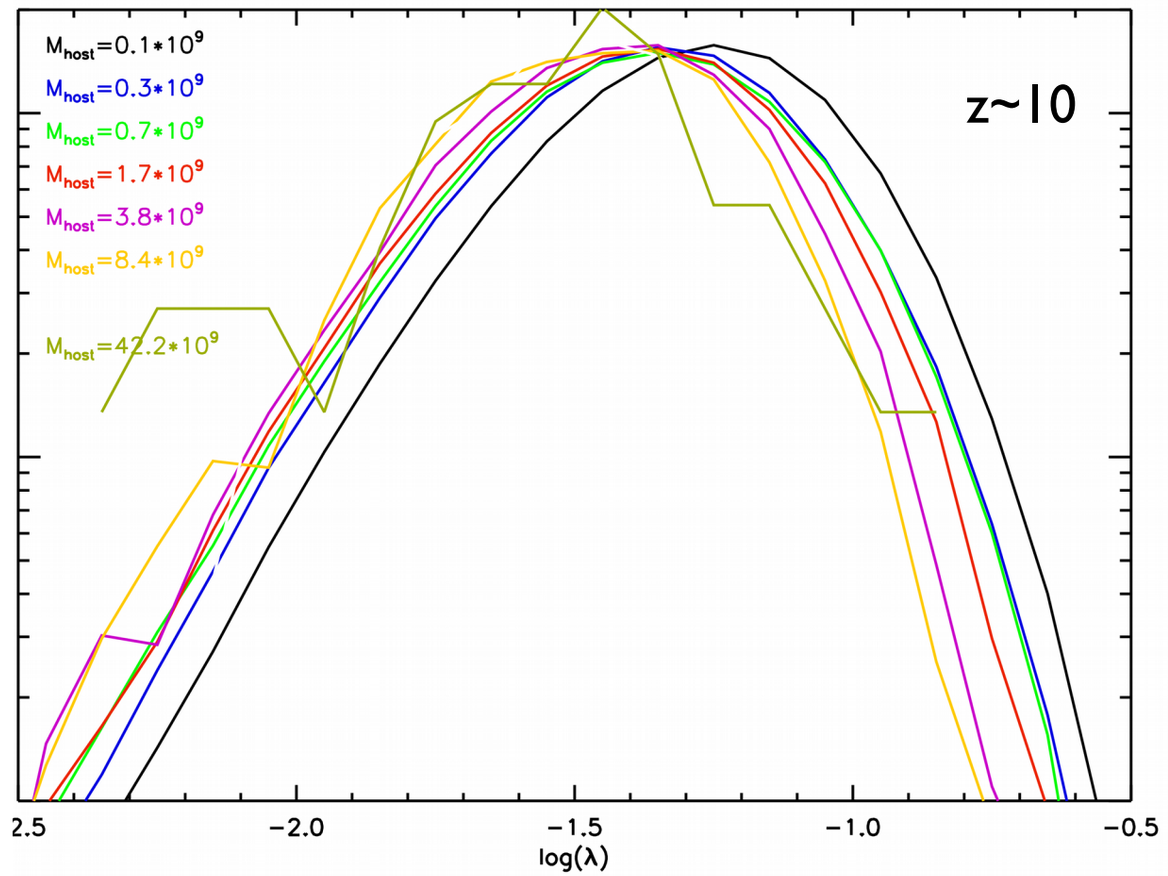

10^5
10^4
10^3
10^2
10^1
10^0
Object Number
0
2
4
6
8
10
z
N_{halo} (M > 7.1*10^{10})
$N_{subhalo}$ (M > 7.1*10^{10})
N_{BH}
$N_{BH,cen}$
$N_{BH,sat}$
$N_{BH,seeded}$
$N_{BH,swallowed}$

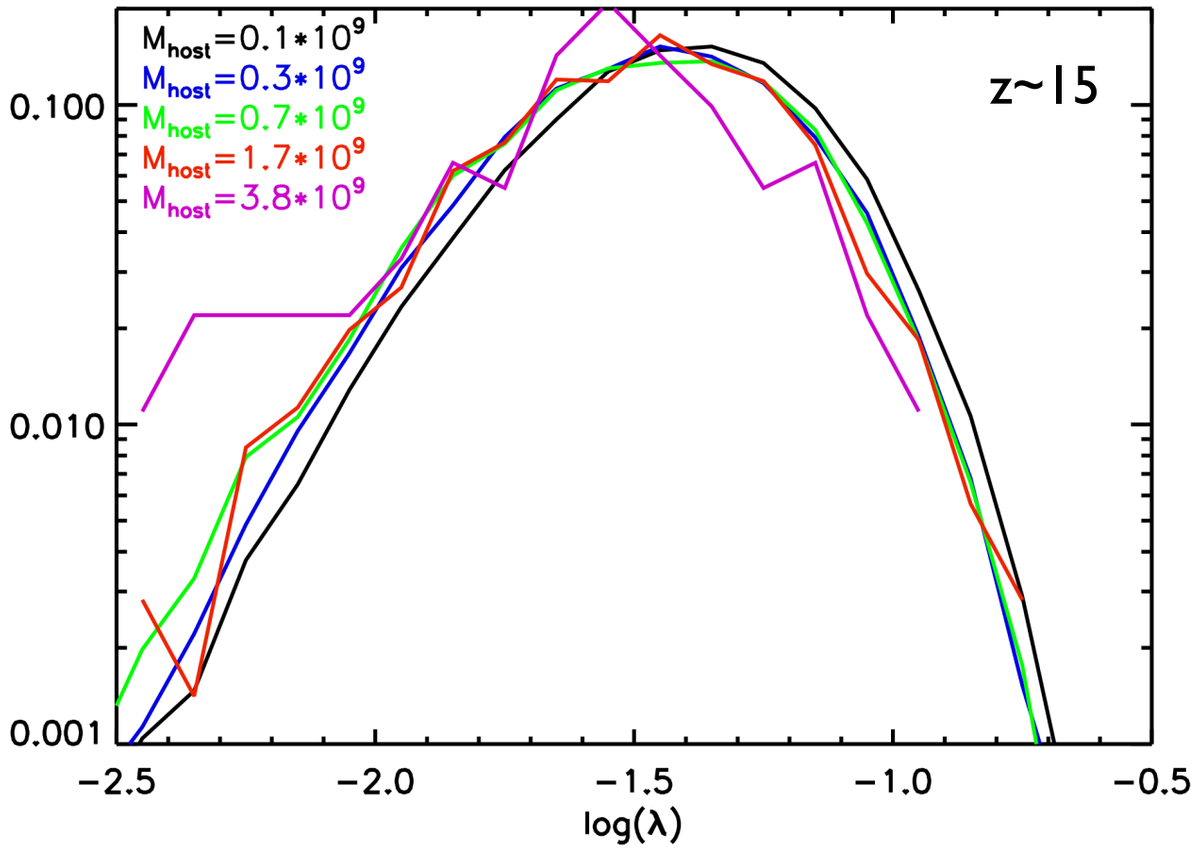

1.0
0.8
0.6
0.4
0.2
0.0
Seeded fraction
M_BH(z=0.5)>10^9
M_BH(z=0.5)>10^8
M_BH(z=0.5)>10^7
10
1
z

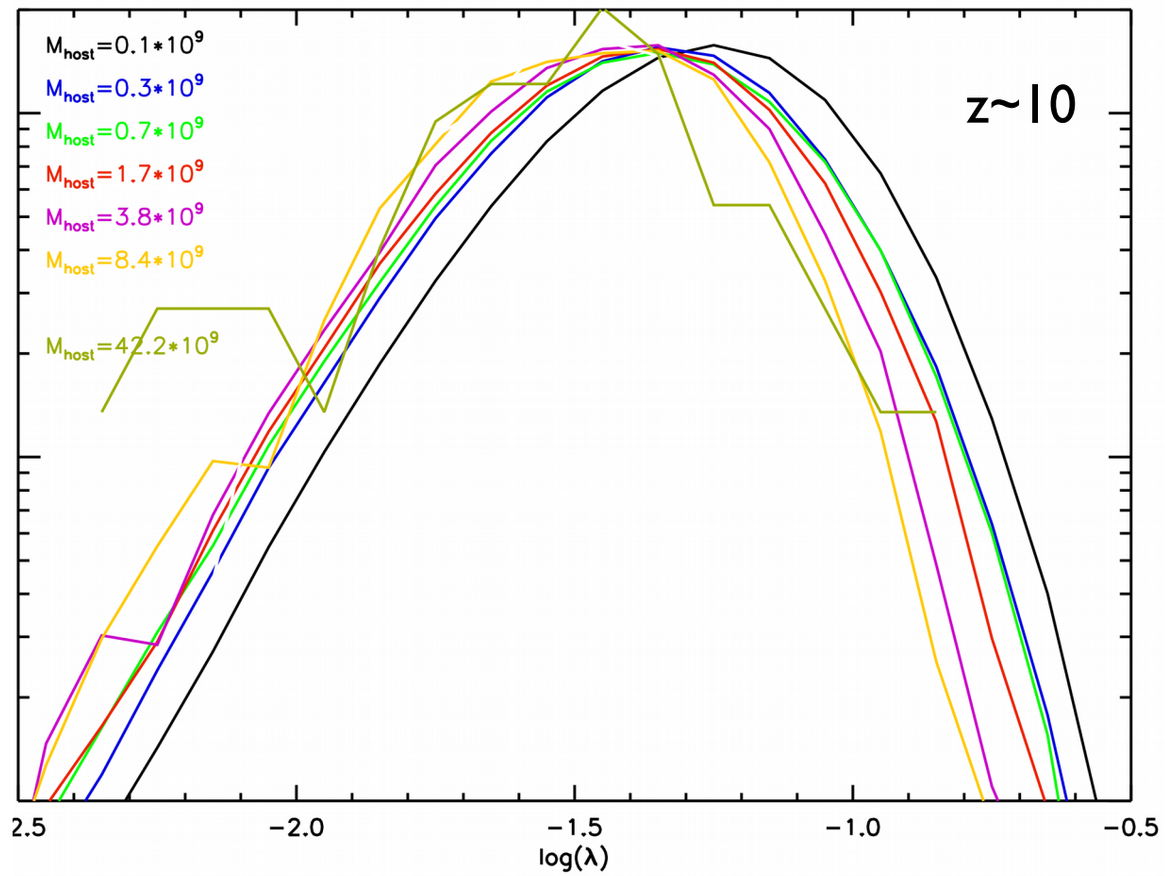

10^5
10^4
10^3
10^2
10^1
10^0
Seeded Number
10
1
z

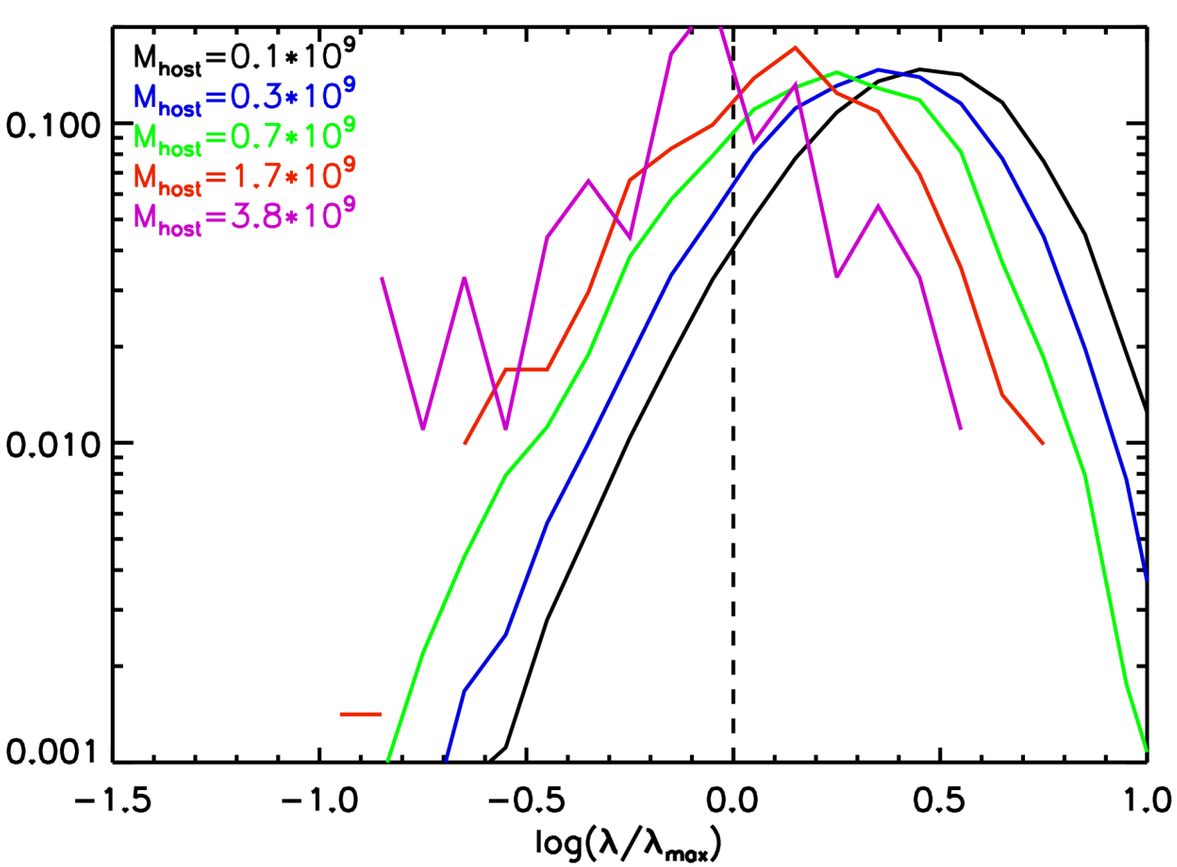

1.0
0.8
0.6
0.4
0.2
0.0
Seeded fraction
4
6
8
10
z
$N_{seed,III}/N_{z=0.5}$
$N_{seed,new}/N_{z=0.5}$
$N_{seed,new}/N_{seed,III}$
$M_{z=0.5}>10^7\ M_\odot$
$M_{z=0.5}>10^8\ M_\odot$
$M_{z=0.5}>10^9\ M_\odot$

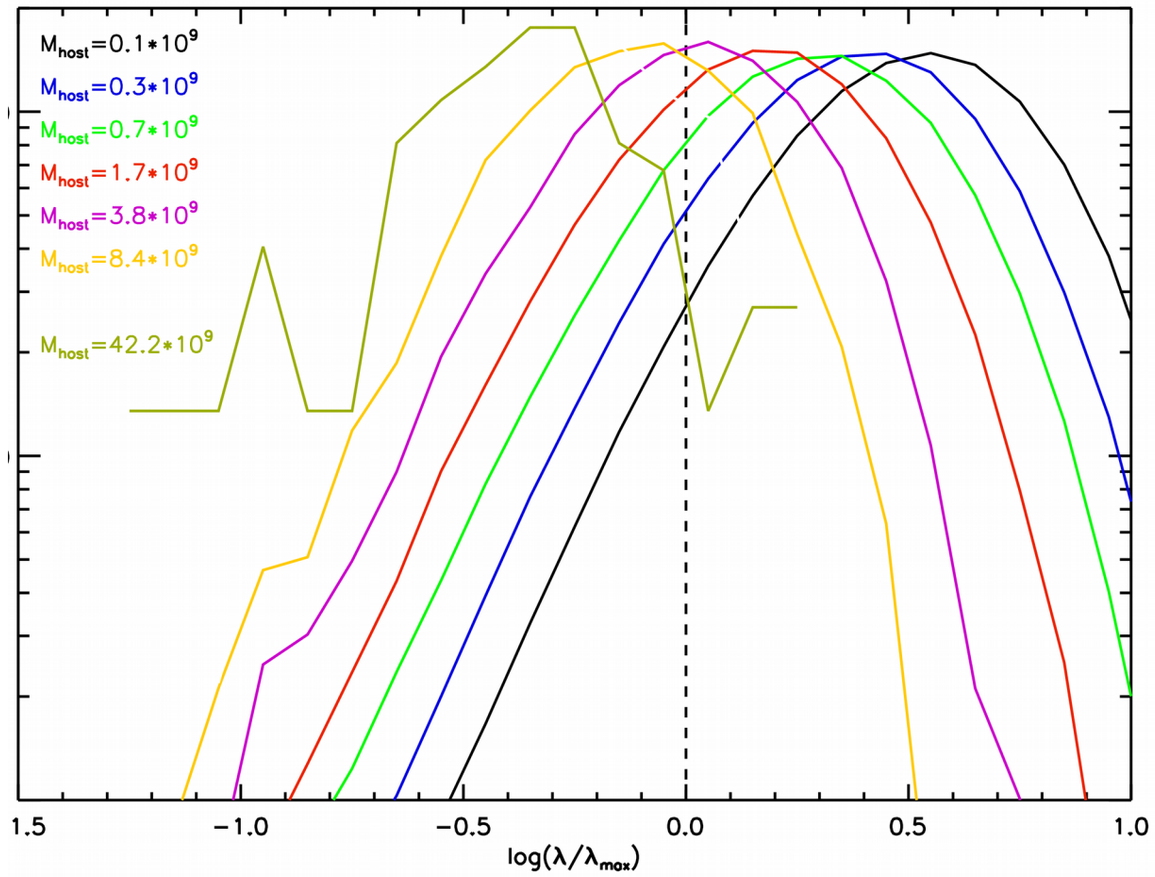

M_host=0.1*10^9
M_host=0.3*10^9
M_host=0.7*10^9
M_host=1.7*10^9
M_host=3.8*10^9
z~15
0.100
0.010
0.001
−2.5
−2.0
−1.5
−1.0
−0.5
log(λ)


M_host=0.1*10^9
M_host=0.3*10^9
M_host=0.7*10^9
M_host=1.7*10^9
M_host=3.8*10^9
M_host=8.4*10^9
M_host=42.2*10^9
z~10
2.5
−2.0
−1.5
−1.0
−0.5
log(λ)

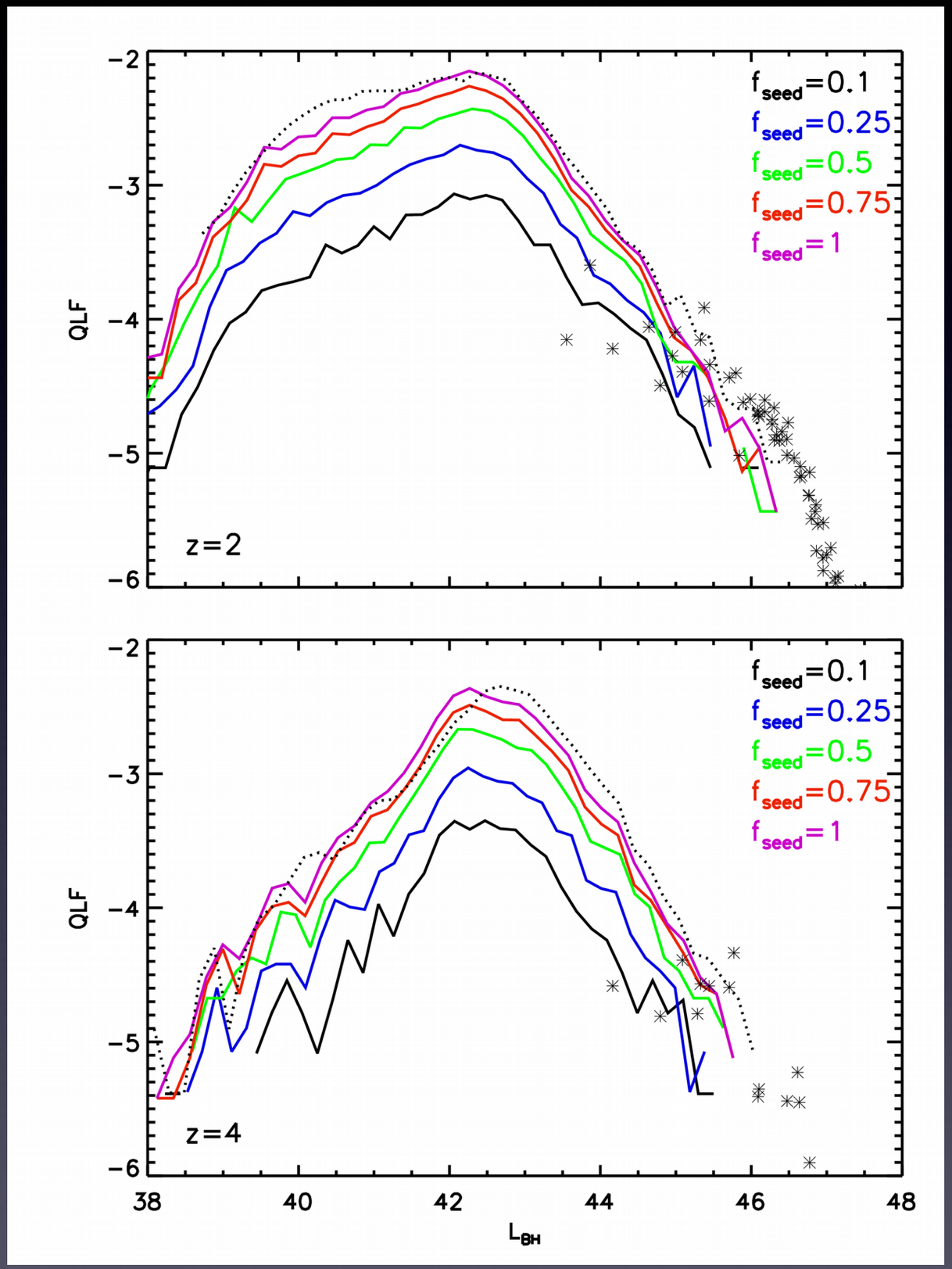

$M_{host}=0.1*10^9$
$M_{host}=0.3*10^9$
$M_{host}=0.7*10^9$
$M_{host}=1.7*10^9$
$M_{host}=3.8*10^9$
z~15
0.100
0.010
0.001
−2.5
−2.0
−1.5
−1.0
−0.5
log(λ)


$M_{host}=0.1*10^9$
$M_{host}=0.3*10^9$
$M_{host}=0.7*10^9$
$M_{host}=1.7*10^9$
$M_{host}=3.8*10^9$
$M_{host}=8.4*10^9$
$M_{host}=42.2*10^9$
z~10
2.5
−2.0
−1.5
−1.0
−0.5
log(λ)


$M_{host}=0.1*10^9$
$M_{host}=0.3*10^9$
$M_{host}=0.7*10^9$
$M_{host}=1.7*10^9$
$M_{host}=3.8*10^9$
0.100
0.010
0.001
−1.5
−1.0
−0.5
0.0
0.5
1.0
$\log(\lambda/\lambda_{max})$


$M_{host}=0.1*10^9$
$M_{host}=0.3*10^9$
$M_{host}=0.7*10^9$
$M_{host}=1.7*10^9$
$M_{host}=3.8*10^9$
$M_{host}=8.4*10^9$
$M_{host}=42.2*10^9$
1.5
−1.0
−0.5
0.0
0.5
1.0
$\log(\lambda/\lambda_{max})$

Quasar Luminosity Function



- Some bright-end dependence at high-z
- Very difficult to constrain observationally