Could Supermassive Black Holes be Primordial?

black is the new dark

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Cosmic Controversies
Chicago USA
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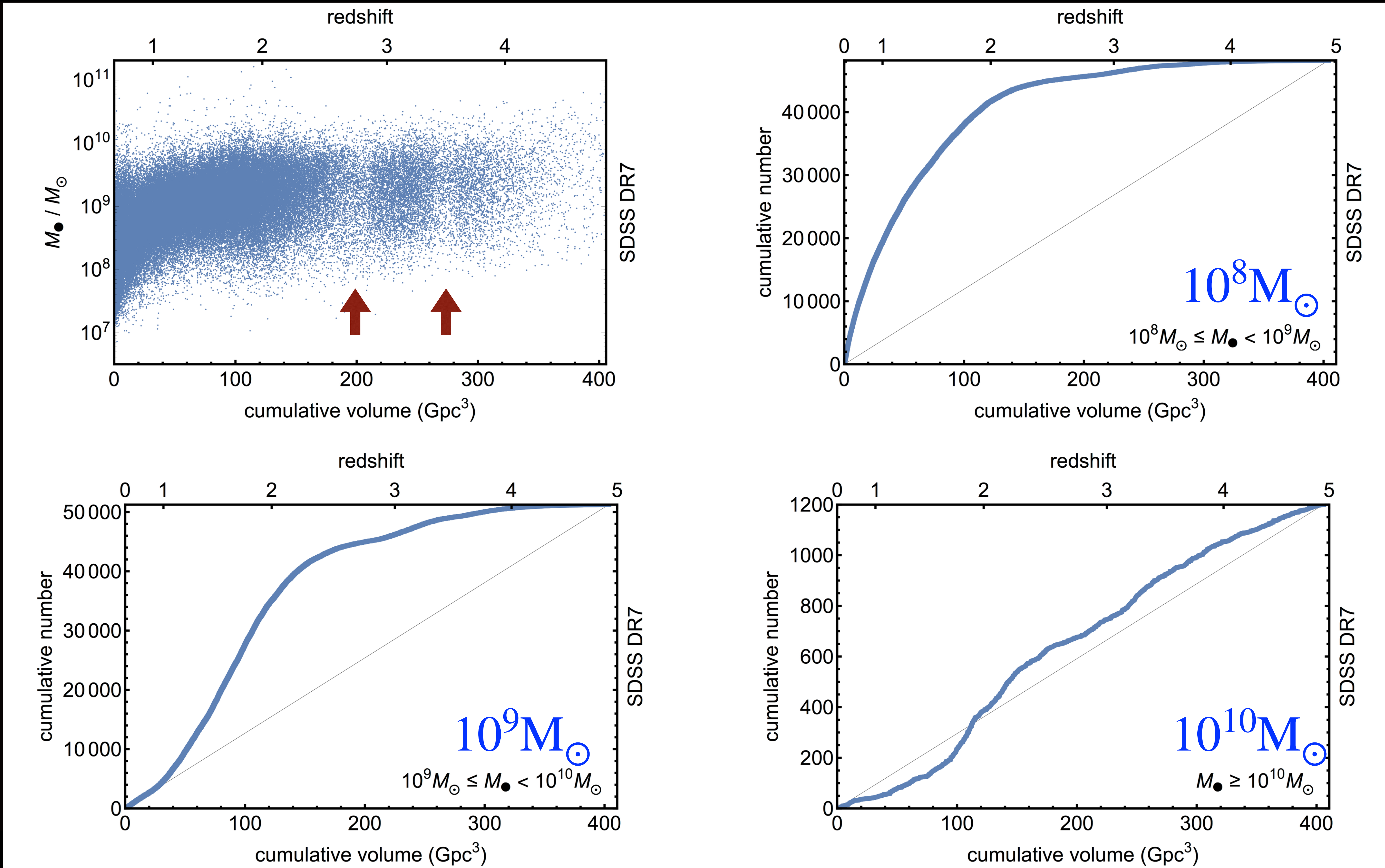
How did the most massive Supermassive Black Holes ($M_\bullet > 10^{10} M_\odot$) seen at high redshifts (z up to 7) come into being?

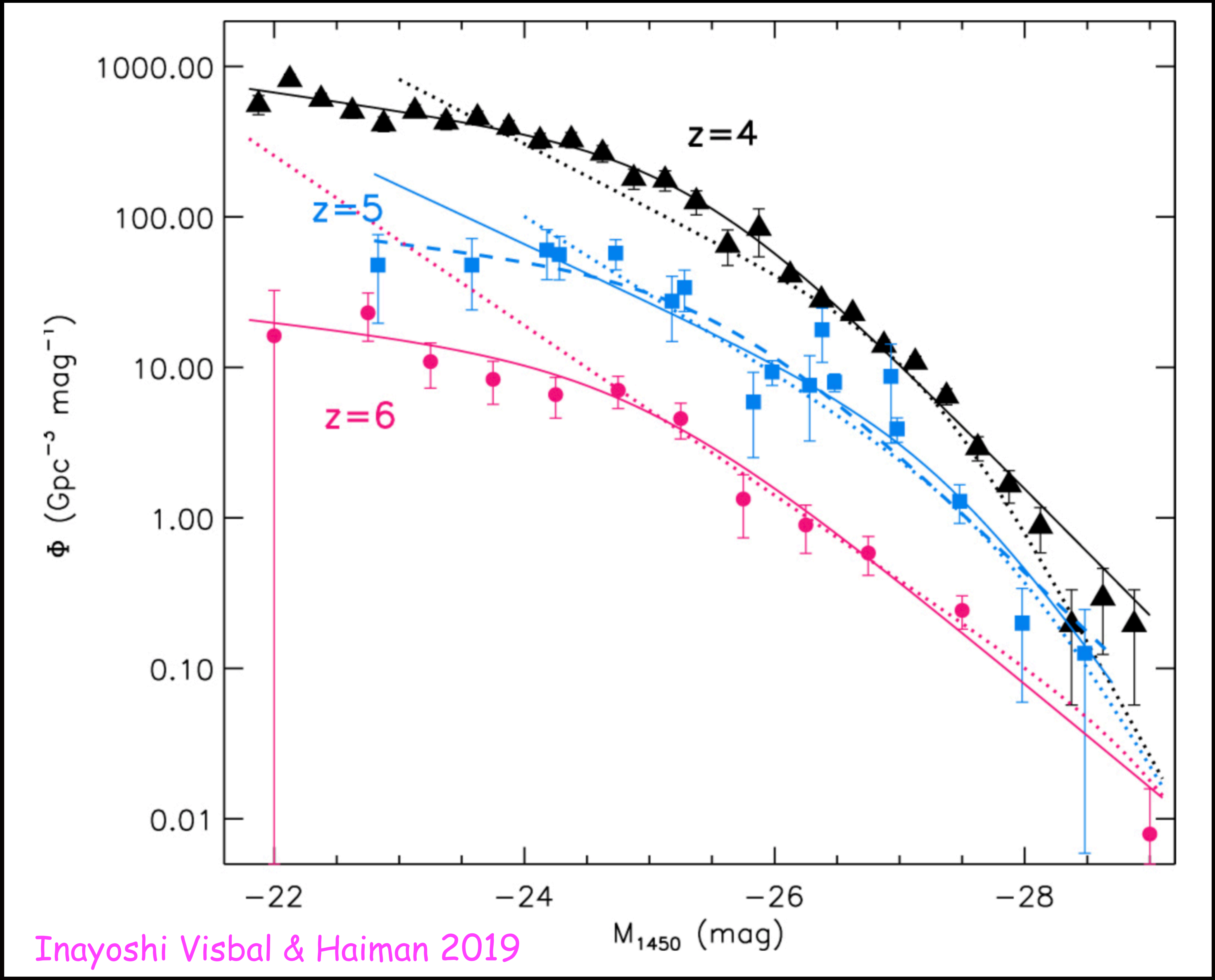
Uncontroversial:

- matter falling onto Super Massive Black Holes (SMBHs) powers emission of quasars (QSOs) and active galactic nuclei (AGN)
- Event Horizon Telescope recently dramatically confirmed this!
- infalling matter accretes into SMBHs causing black hole mass ($M_\bullet$) to grow!

Uncontroversial SMBH phenomenology



lower mass *active* SMBH #s increase - higher mass **don't**



mass function grows ***more*** steep

uncontroversial statements

- number density ~$10^9\ M_\odot$ SMBHs has increased by orders of magnitude over time
  - w/ timescale ≳100 Myr
- number density >$10^{10}\ M_\odot$ has increased by only a small factor
  - w/ timescale ≳400 Myr
  - small SMBHs growth leads to steepening mass function

commentary

this does not "feel" like a bottom up scenario

the "big ones" have been around "since the beginning"

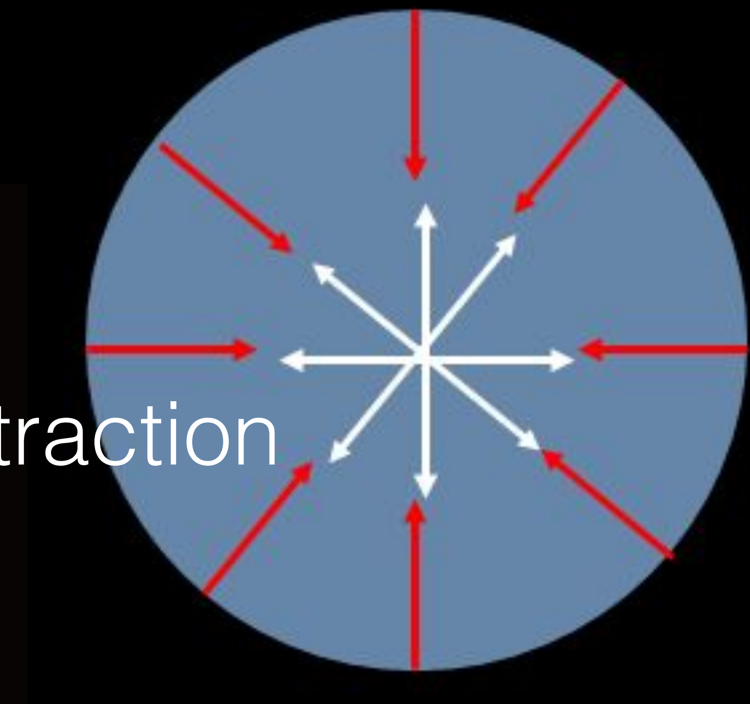
controversy :

- what / when is the beginning ? z~6-7, $z \gg 10^3$

commentary

- *… this (QSO) is only the latest and most extreme of a growing number of known giant BHs at early times whose rapid growth, within the (somewhat squishy) constraint of the Eddington limit, is difficult to understand. …*
- *The point worth making is this: Such objects are so rare that any attempt to find a "natural" explanation is probably wrong.* ***If the suggested process that makes these objects is not extremely unusual, it is probably the wrong process****.* **Kormendy 2013**

Eddington Limit



for accretion radiative repulsion $<$ gravitational attraction

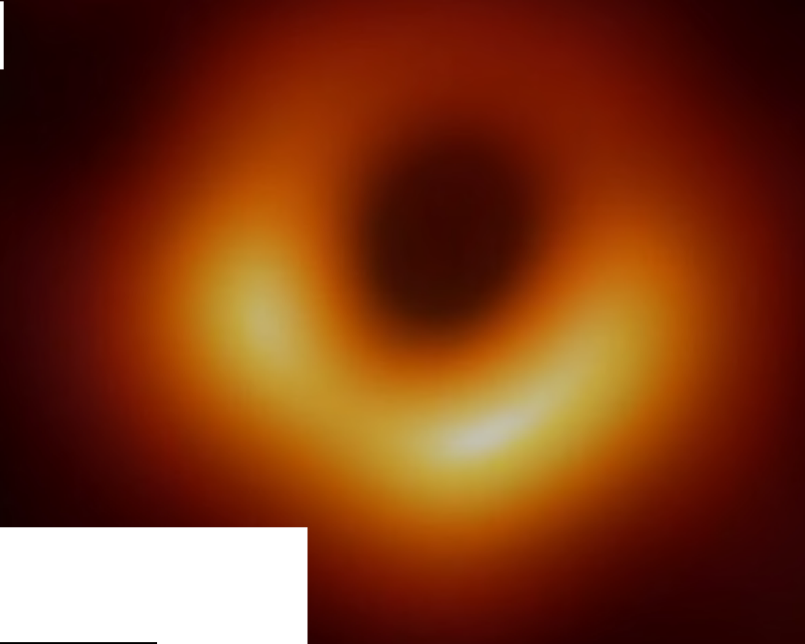
$$\partial_t M < M / \tau_{salpeter}$$

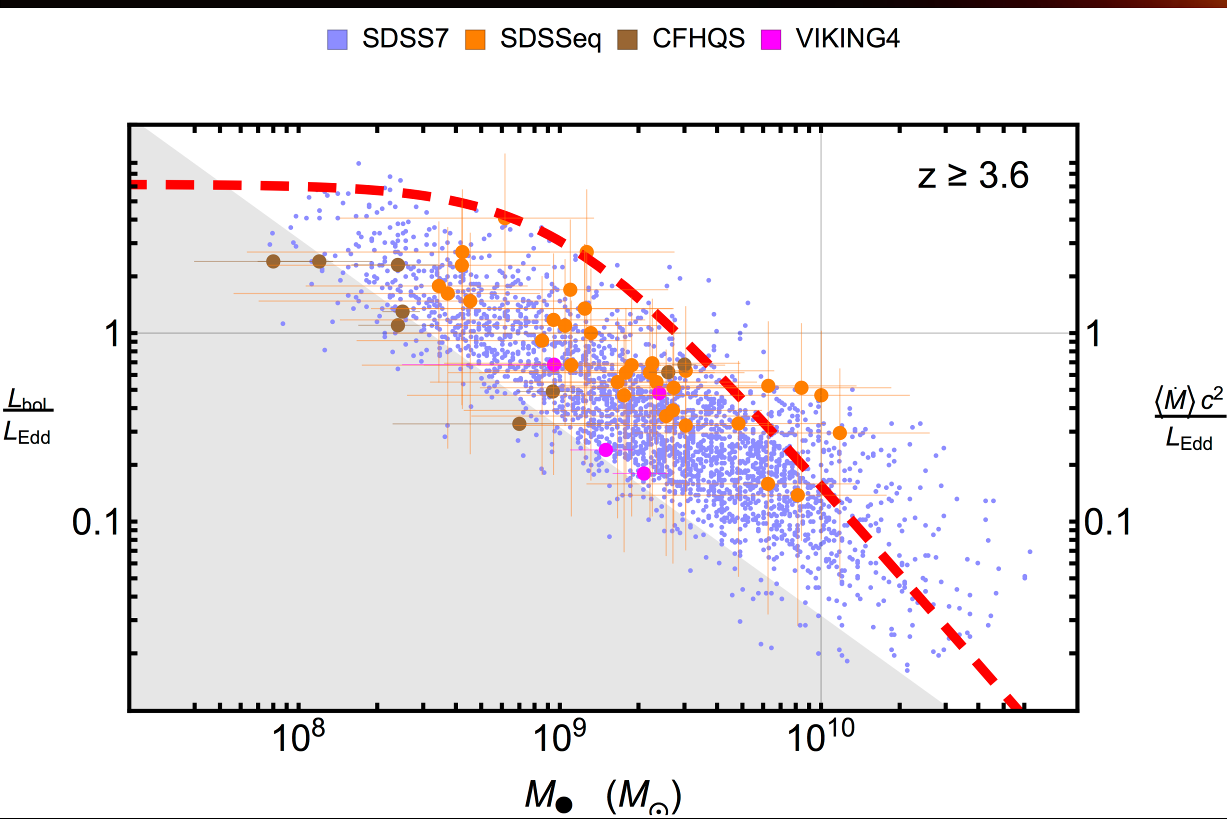
$$\tau_{salpeter} \approx 50\text{Myr}\ \varepsilon/0.1$$

$$\varepsilon \equiv L_{bol} / (\partial_t M c^2)$$

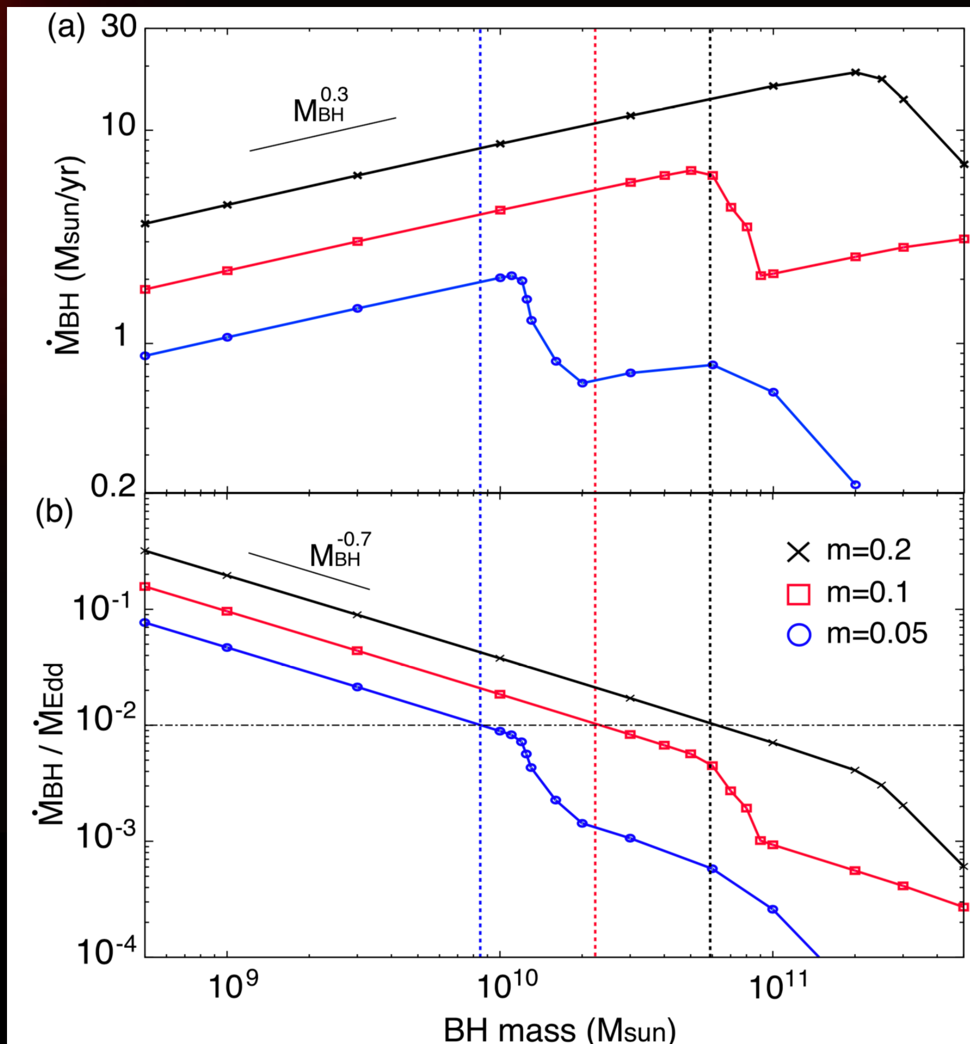
canonically $\varepsilon \approx 0.1$

$$L < L_{eddington} \propto M$$





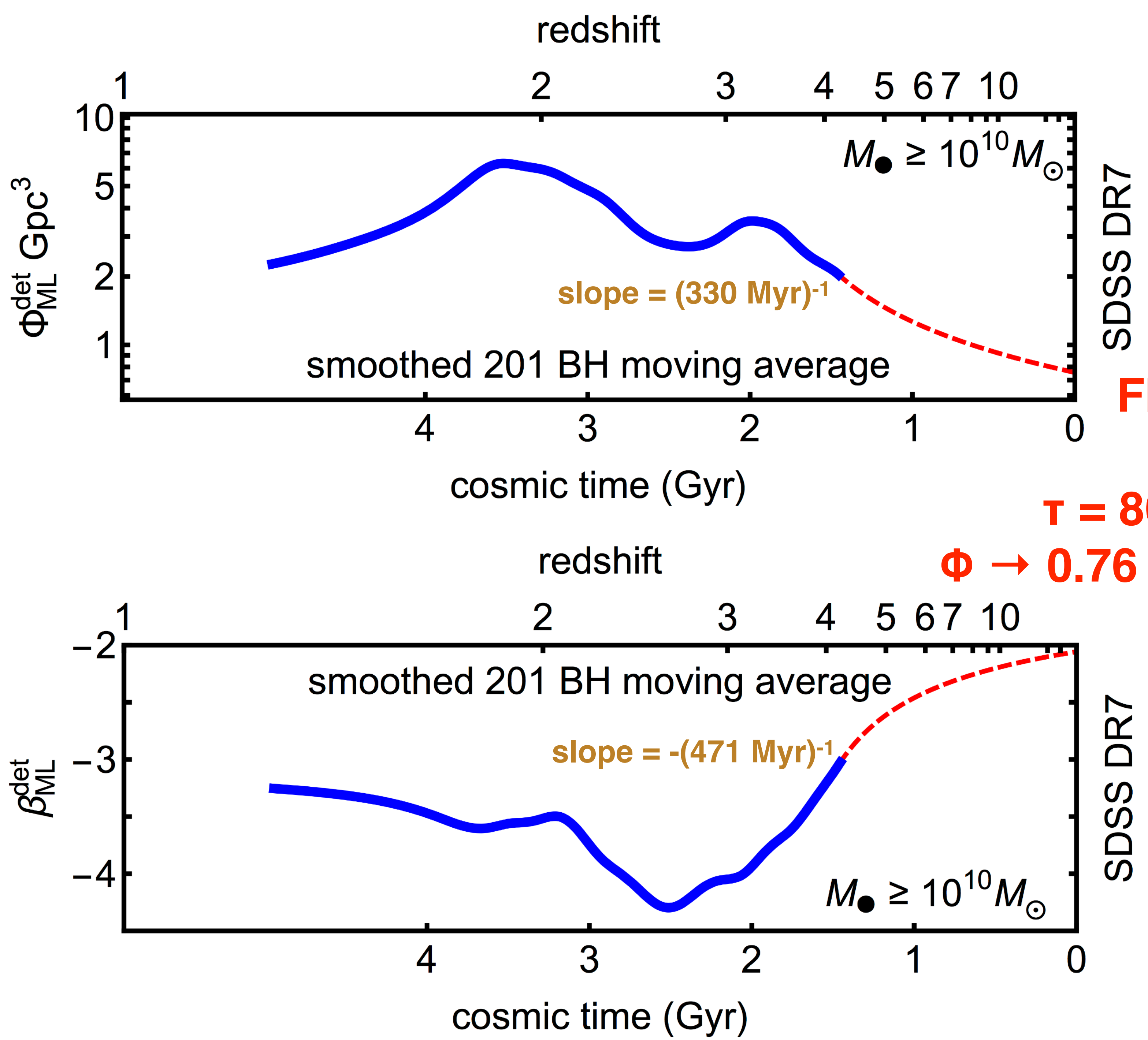
Inayoshi & Haiman 2017



Uniformitarian Population Dynamics

$$\tau\, \partial_t \ln[\Psi] = -\left(1 + \beta - \partial_{\ln[M]} \ln[\tau] \right)$$

$\langle \partial_t M \rangle = M / \tau[M,z]$ $\quad \Psi \equiv \partial_M n[M] \propto M^\beta$ $\quad$ fixed $\tau[M,z] \propto M^\alpha$



FIT :

$\beta \to -2.05$

$\tau = 805$ Myr $M_{10}^{1.6}$

$\Phi \to 0.76$ Gpc^{-3} $M_{10}^{-1.05}$

$$\Phi \equiv \int_M^\infty dM\, \Psi$$

Proposed Power Law Initial Mass Function

$$\Psi_0 \propto M^{\beta_0}$$

and β_0 which introduces **no new dimensional parameters**

Matter Scaling: $\beta_0 = -2$

$$\Psi_0 = f_{BH}\, \rho_{m0} / M^2$$

$f_{BH} \sim 10^{-10}$ no BH dark matter

N.B. scalar perturbation amplitude $A_s = 21\times10^{-10} \sim 3.5\, f_{BH}$

Gravitational scaling: $\beta_0 = -5/2$

à la Harrison-Zel'dovich

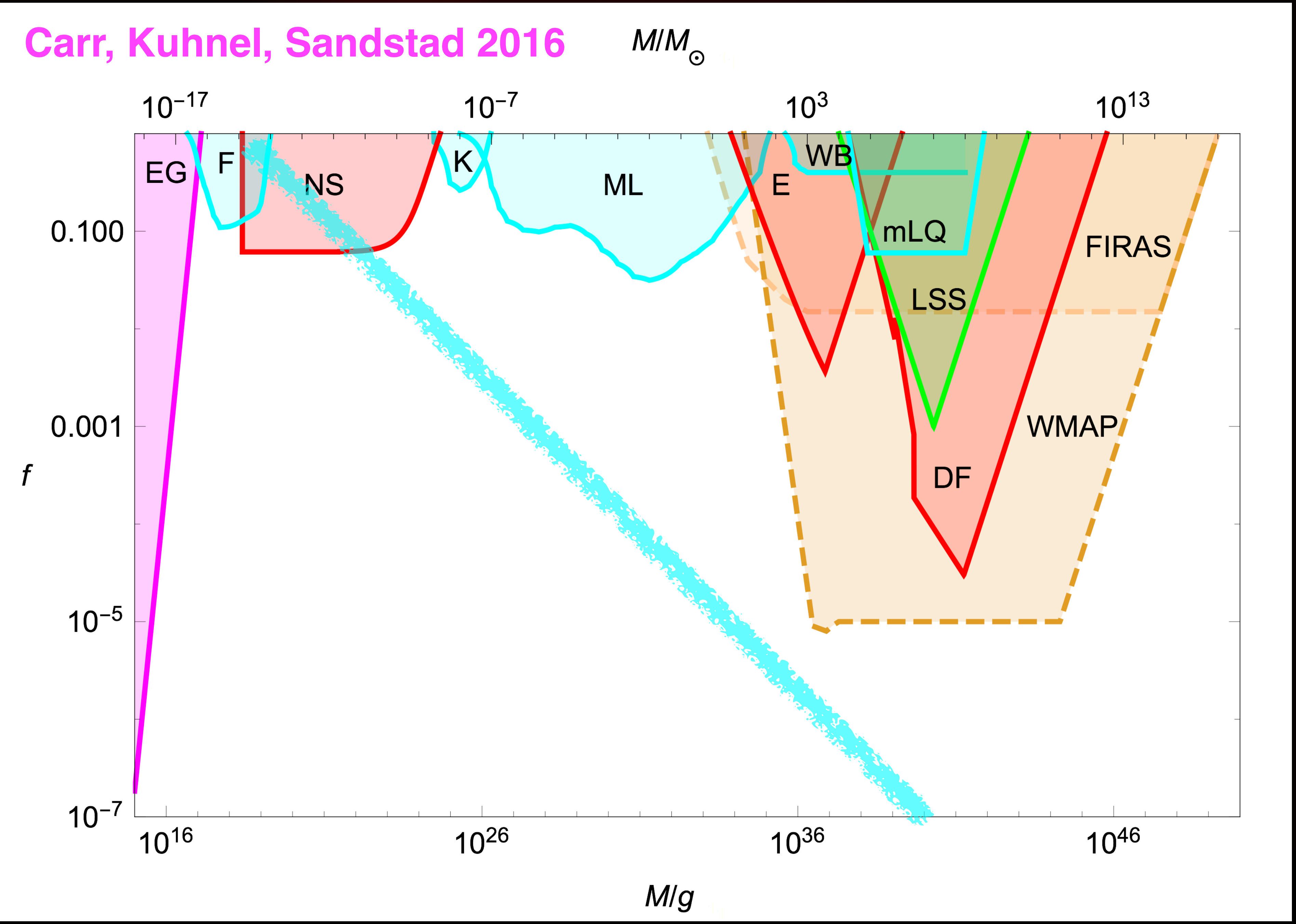
$$\Psi_0 = 2^{5/4}\, \phi_{BH}\, (\Omega_{m0}{}^5/\Omega_{r0}{}^3)(M_{eq}/M)^{5/2}(GH_0{}^4/c^6)$$

(for $M \ll M_{eq} \approx 3\times10^{17}\, M_\odot$)

$\phi_{BH} \sim 10^{-15}$ cutoff / BH dark matter @ $6\times10^{-10}\, M_\odot$

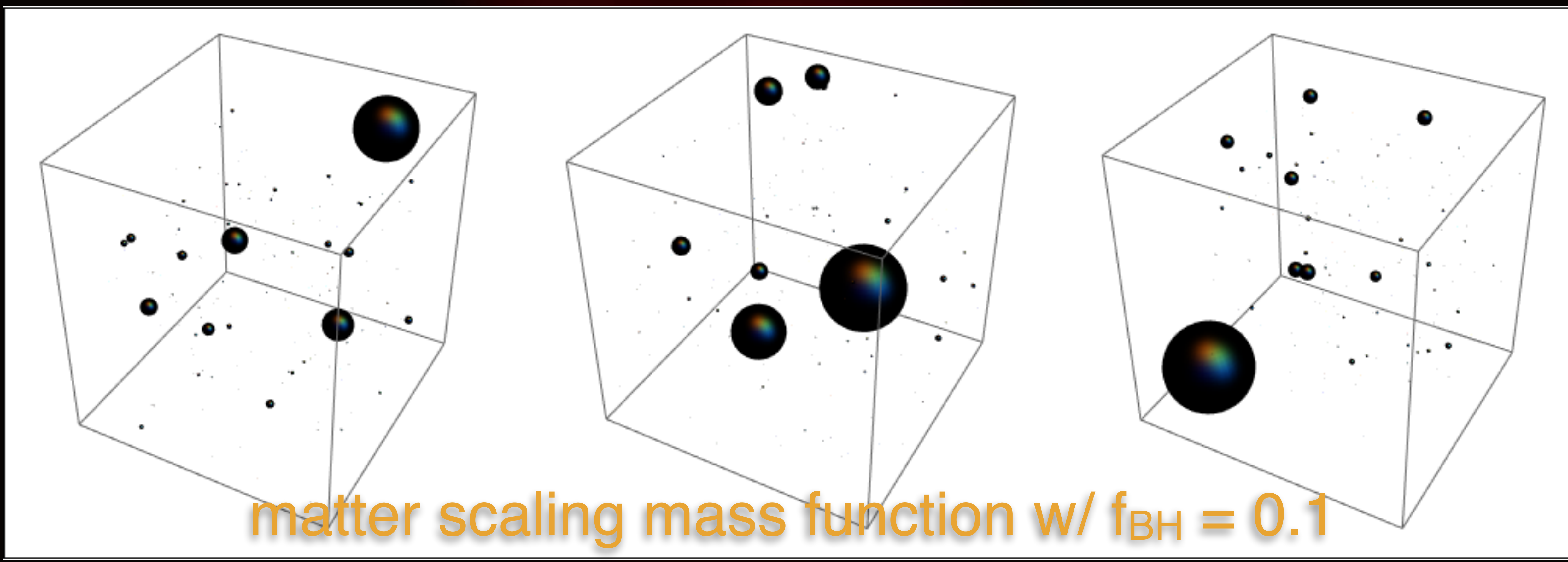
Mostly Unconstrained by usual PBH Arguments

- matter scaling below bottom of this graph
- gravitational scaling must be cutoff



IMF Extremely Red

- Nearly all statistical properties of BH distribution dominated by the most massive BH in the volume.
- All mass moments diverge: but can work with medians.



$$\frac{\left\langle \max_{\text{Hubble volume}}^{\text{max in}}\left[R_{\text{Schwarschild}}\right]\right\rangle_{\text{realization}}^{\text{median}}}{\text{Hubble length}} = \frac{3\,\Omega_m[z]}{4\,\pi \ln[2]}\, f_{BH}$$

Uniformitarian Model

- most massive SMBHs grow slowly due to sub-Eddington accretion and/or low duty cycle
  - super/hyper Eddington accretion not possible unless radiative efficiency very low, we would have seen this
  - growth by major mergers is not possible because large massive SMBHs are observed to be too far apart, >30Mpc.

consequence

- SMBHs existed in the early $z>10$ universe
- they would be extremely rare
- extrapolating to lower mass: an IMBH seed in every galaxy

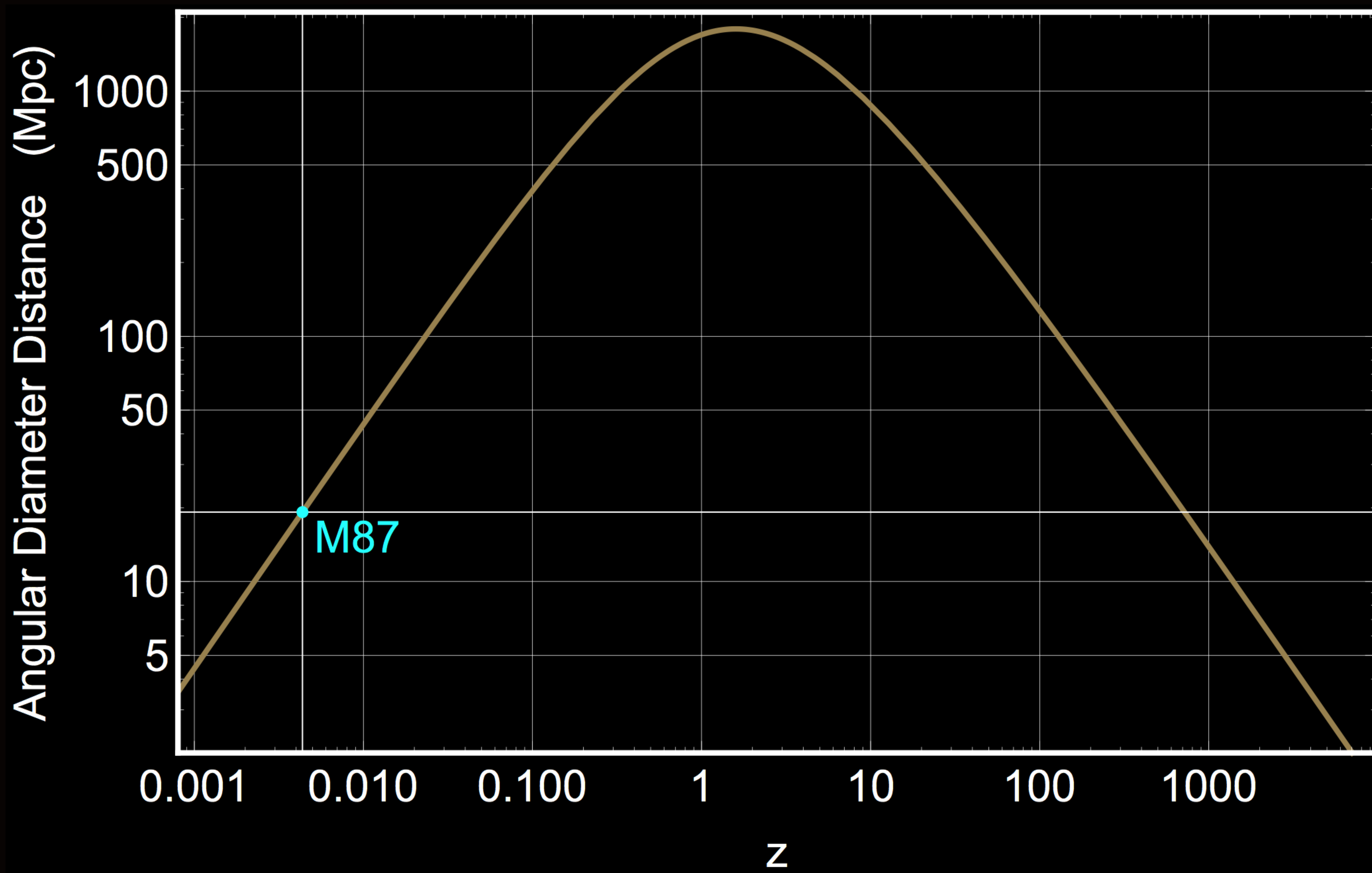
controversy

- massive SMBHs would not form in ΛCDM standard model

Uniformitarianism Issues

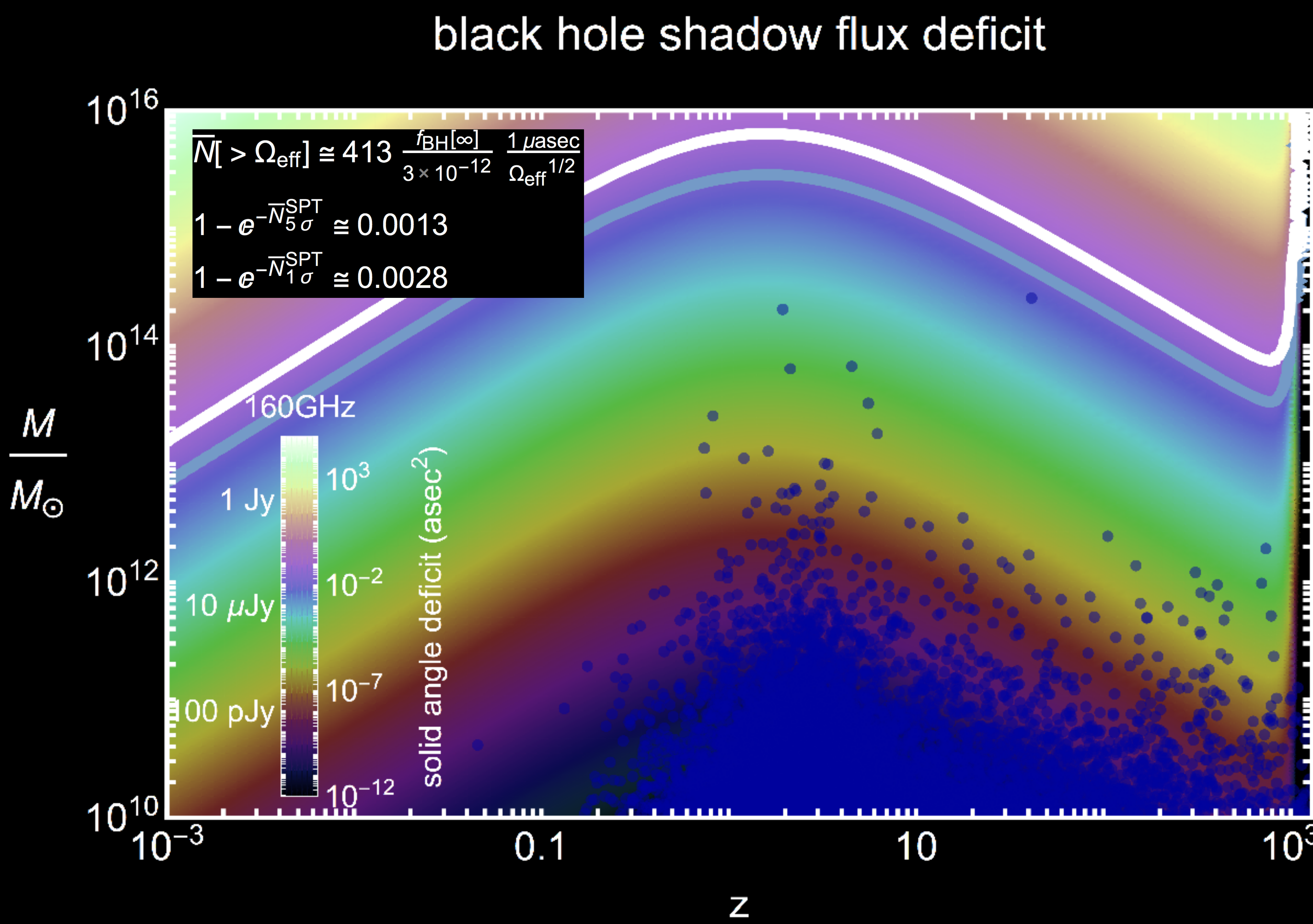
- primordial $10^{10}M_{\odot}$ localized *uncompensated* masses would have accreted halos $>10^{15}M_{\odot}$ which surely would not have gone unnoticed.
- compensated perturbations corresponding to local rearrangements of matter will ameliorate this problem.
- the required modification of ΛCDM is not a different P[k] or f_{nl} but some sort of extreme non-Gaussianity.
- Topological defects such as cosmic textures comes to mind
- what about the CMB?

The Universe is an Excellent Magnifying Glass

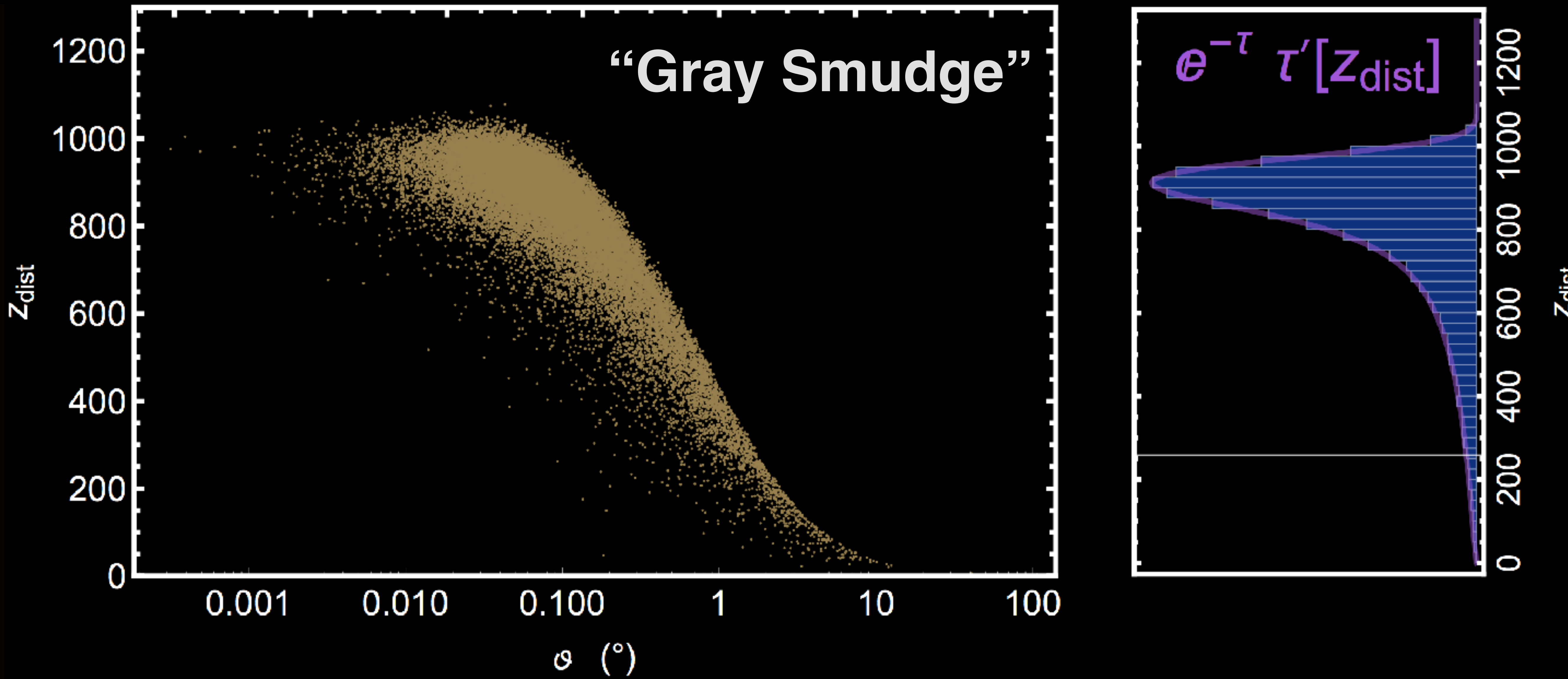


M87 would appear larger (in angle) at z=1000!

Model Distribution of Black Hole Shadows



Black Hole Gray Halos



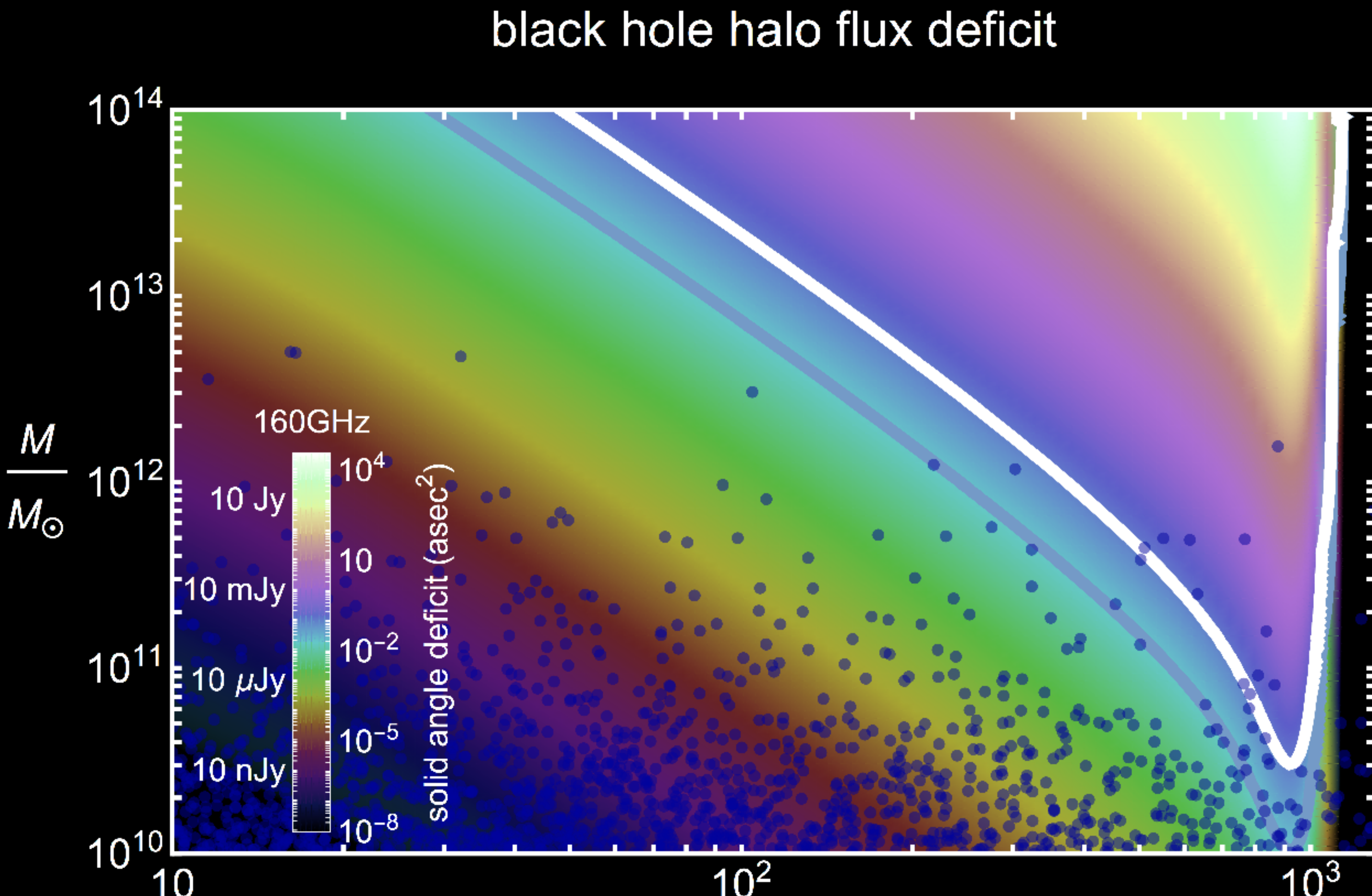
Most photons absorbed near time of BH formation is at very hi-z (rad. era $z_{form} \propto M^{-1/2}$)

- extrapolated shadow past SoLS $\Omega_{eff} \propto M^2 z_{form}^2 \propto M$

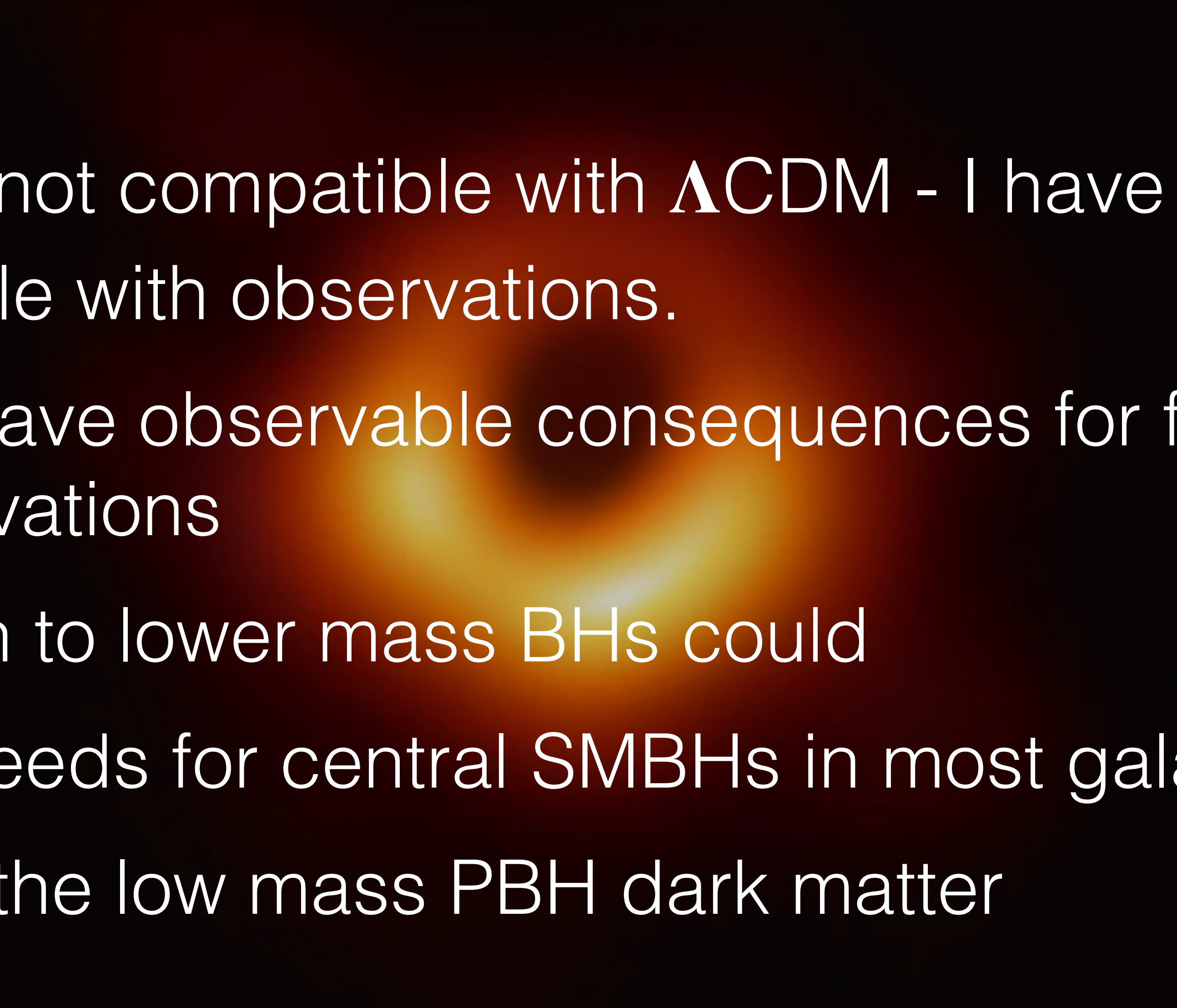
Monte Carlo scattering of "missing photons"

- scattered missing photons form a "gray halo"
- proper Boltzmann analysis more accurate
- polarized scattering yields highly polarized halo

Halos are Much More Easily Seen



Summary



- A simple extrapolation of observed QSO/SMBH mass evolution suggest $M > 10^{10} M_{\odot}$ existed early in the universe.
- While this is not compatible with ΛCDM - I have argued it is compatible with observations.
- This would have observable consequences for future CMB observations
- Extrapolation to lower mass BHs could
  - provide seeds for central SMBHs in most galaxies
  - might be the low mass PBH dark matter

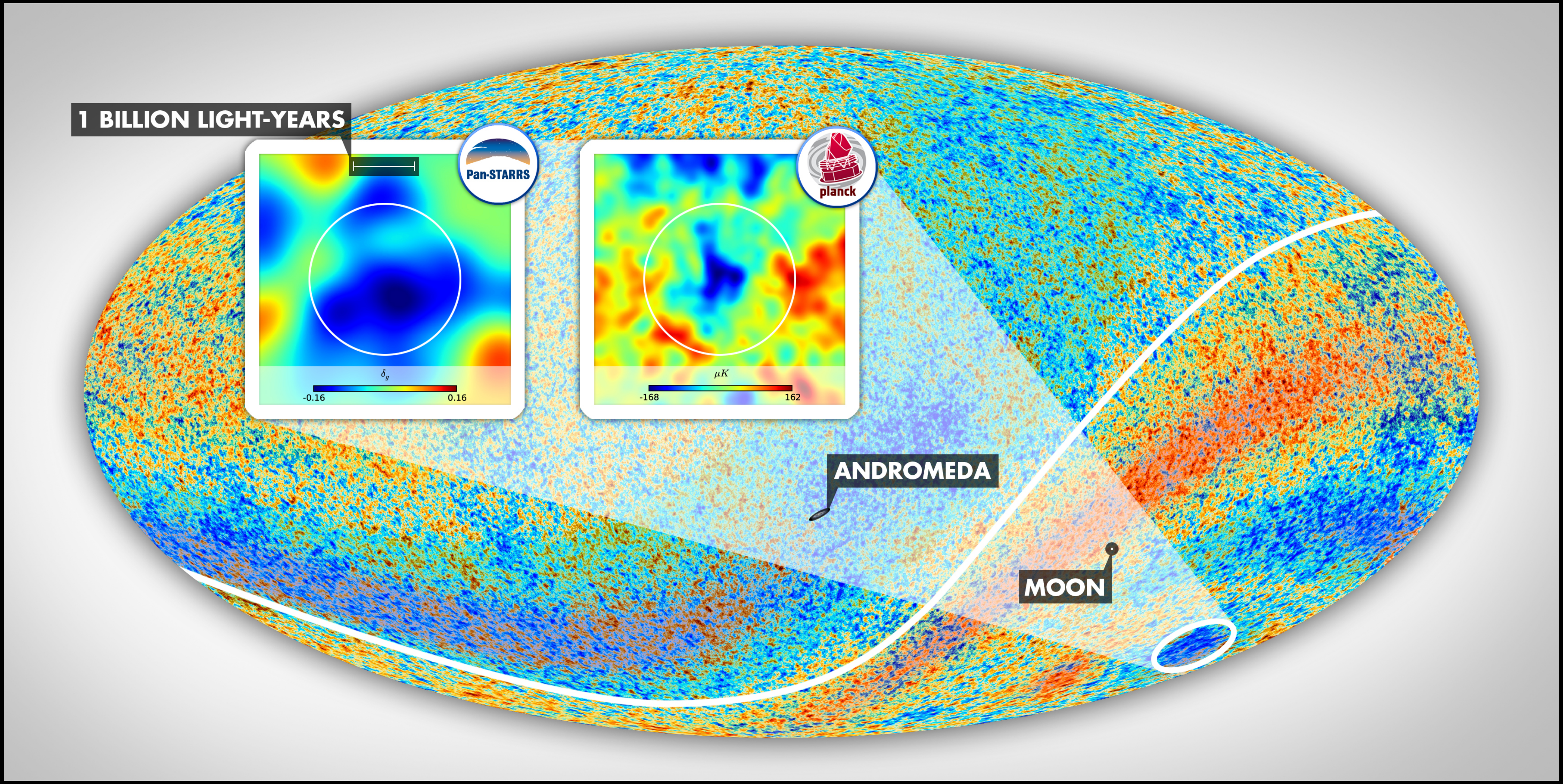
What's this Cheshire Cat smiling about?

Additional Slides

Is WMAP cold spot a SMBH?

Sachs Wolfe (⅓Φ) effect from 10^{14} $M_\odot$ SMBH ~200 Mpc (comoving) in front or back of surface of last scattering.

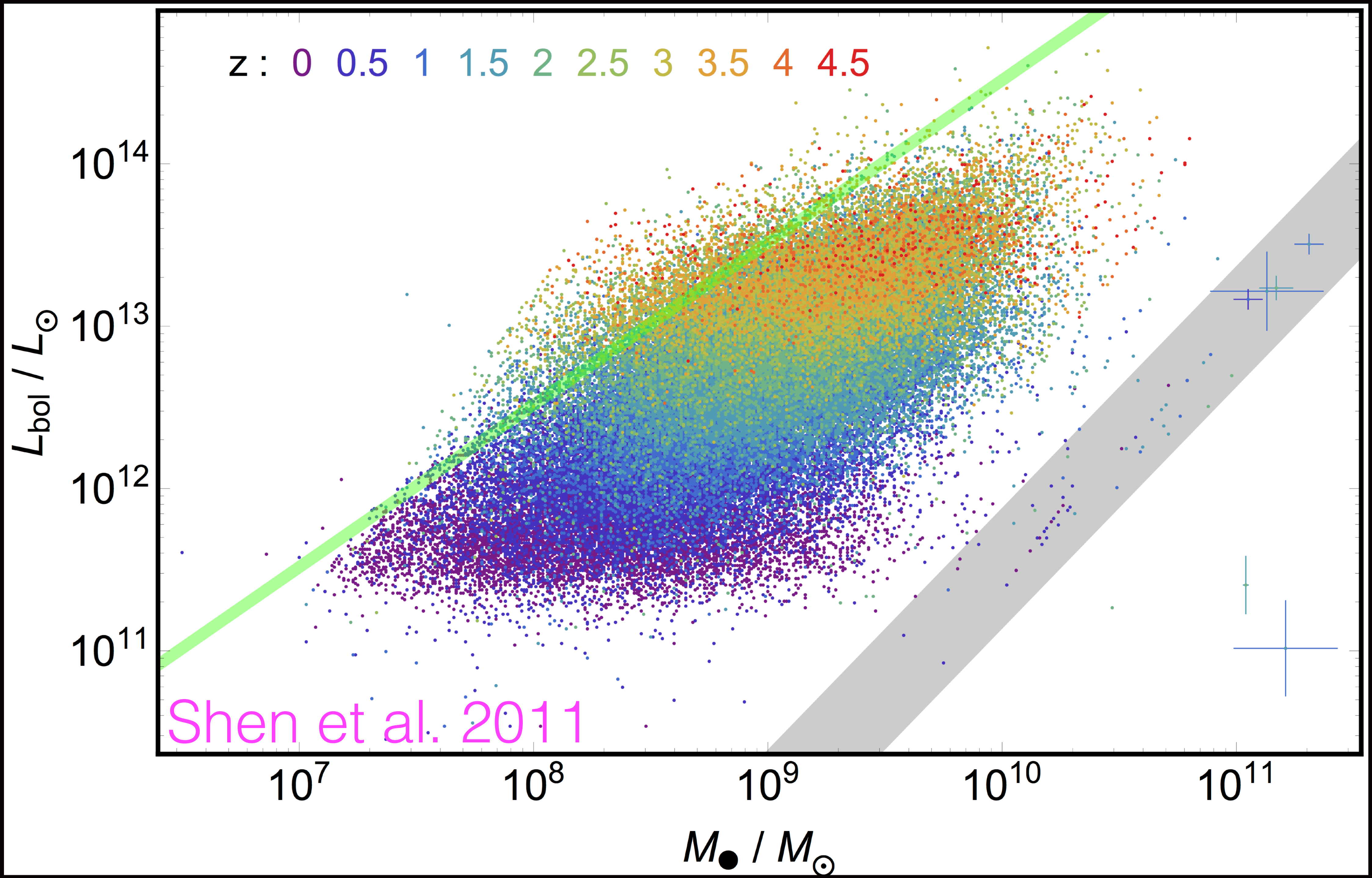
~ most massive SMBH expected in observable universe



Detection Using CMB Backlighting

effect	where operative	volume	spectrum
shadow $\propto z^2$	$z<10^3$	10^4 Gpc^3	black
halo scattered shadow	$z\sim10^3$	200 Gpc^3	~gray
doppler	$z\sim10^3$	200 Gpc^3	ΔT
Sachs-Wolfe	$z\sim10^3$	10^3 Gpc^3	ΔT
nonlinear ISW	$z<10^3$	10^4 Gpc^3	ΔT
linear ISW	$z<0.5$	10 Gpc^3	ΔT

SDSS 7 Quasar Survey: A large survey



0<z<5 f_{sky}=0.194 410 Gpc^3 104,746 SMBHs

The Problem

Can supergrouth explain the origin of the most massive SMBHs?

Does supergrowth scenario explain the origin of the any SMBHs?

We only know of formation of stellar mass BHs which may not sink by dynamical friction or accrete much.

The earliest stars may be more massive but are they massive enough?

Illustration: ULAS J1120+640

$M = 2^{+1.5}_{-0.7} \times 10^{9} M_{\odot}$ @ $z=7.085$

assuming canonical Eddington limited accretion $\varepsilon=0.1$ $\tau_{Salpeter}=45$Myr.

$M = 4.2^{+3.1}_{-1.5} \times 10^{6} M_{\odot}$ @ $z=10$

$M = 168^{+126}_{-59} M_{\odot}$ @ $z=100$

Is it plausible to produce required seed BHs?

N.B. this only needs to happen rarely.

There is no evidence that BH masses evolve at anything as short as a 45Myr timescale! Most massive QSOs are not Eddington limited!

Worse Problem

At large **M** and **z** observations indicate

- Flattening not steepening of mass function.
- Slow not fast growth of **Ψ** and therefore **M**.

Can super growth or direct formation explain this?

Illustration: ULAS J1120+640

$M = 2^{+1.5}_{-0.7} \times 10^9 M_\odot$ @ z=7.085

assuming canonical $\tau_{Salpeter}$=45Myr versus empirical τ_{growth}=805 Myr

$M = 4.2^{+3.1}_{-1.5} \times 10^6 M_\odot$ versus $M = 1.4^{+1.1}_{-0.5} \times 10^9 M_\odot$ @ z=10

$M = 168^{+126}_{-59} M_\odot$ versus $M = 8.0^{+6.0}_{-2.1} \times 10^8 M_\odot$ @ z=100

Summary

The observed existence of large mass large redshift SMBHs is difficult to understand.

The flat mass function and slow evolution does not match expectations for baryonic formation.

Simple extrapolation suggests formed very early at nearly the observed mass.

Primordial SMBHs is an option for their origin.

A variety observational tests could validate this hypothesis.

- QSO outliers and CMB anomalies may be the key for detection.

If confirmed this would change our understanding of the early universe.

Could the same mechanism produce negative density "point defects" resulting in super voids?

Black Hole Dominated Ellipticals?

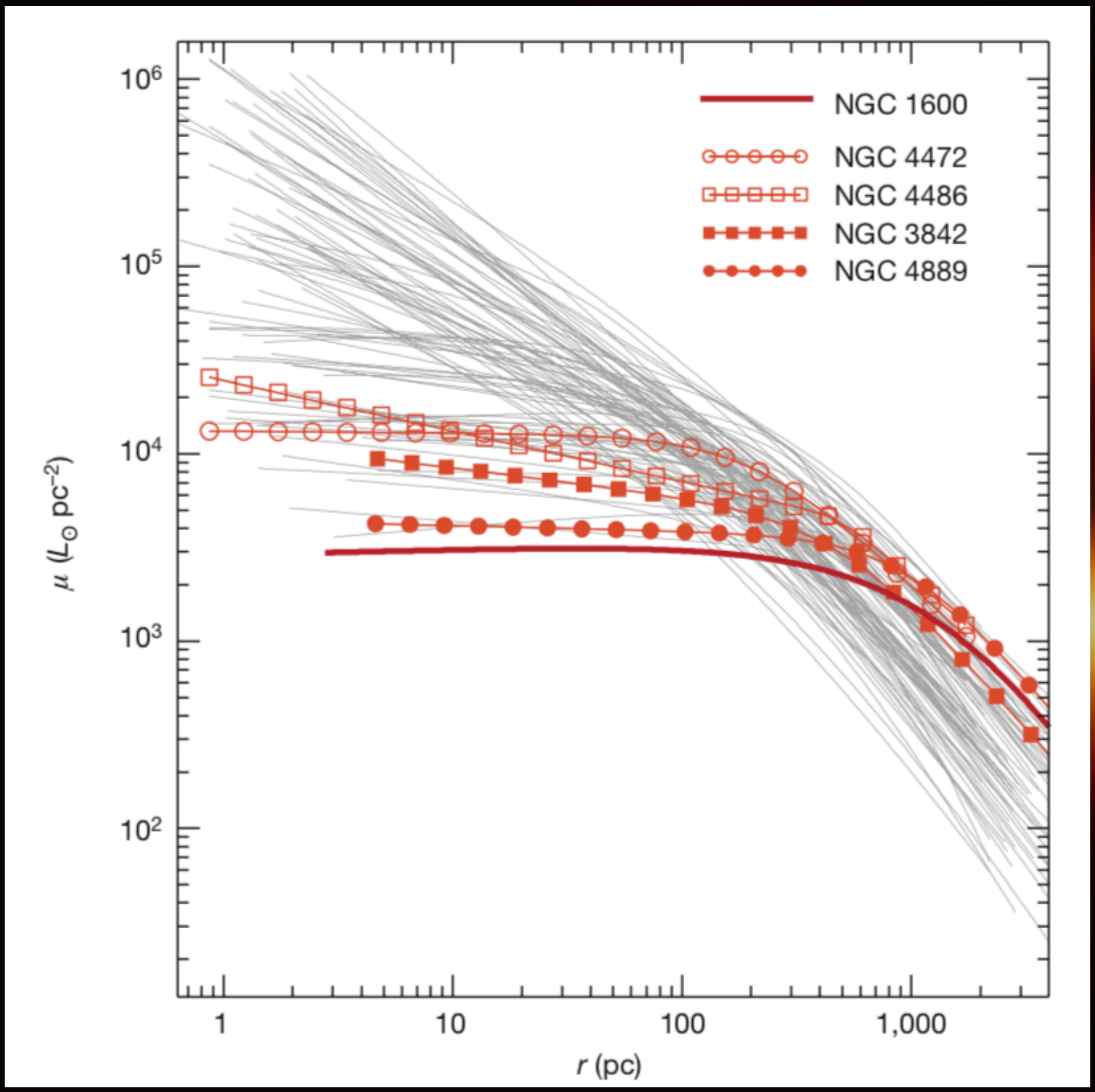


Figure 2 | Central stellar light profiles for NGC 1600 and for a sample of other core and coreless elliptical galaxies. Surface brightness profiles (in the V-band) are shown for a sample of galaxies, on the basis of HST observations[13] up to a distance of 100 Mpc from Earth. NGC 4889, at 102 Mpc, is included because its black-hole mass has been measured[2]. μ is the surface brightness and r is the galactic radius at which the brightness was measured. Lower-luminosity elliptical galaxies typically have rising light profiles towards the galactic centres (steep grey curves), whereas NGC 1600 and other very massive elliptical galaxies often exhibit a marked deficit of stars in the central region (red curves). Highlighted are the brightest galaxies in the Leo Cluster (NGC 3842) and the Coma Cluster (NGC 4889), and the brightest (NGC 4472) and central (NGC 4486 or M87) galaxies of the Virgo Cluster. The stellar core in NGC 1600 (dark red curve) is the faintest known among all galaxies for which dynamical M_{BH} measurements are available.

Thomas Ma McConnell Greene Blakeslee Janish **Nature (2016)**

NGC 1600 M● =1.7×10^{10} $M_\odot$ @ 64 Mpc from Earth