A Case for Primordial Supermassive Black Holes

Point Defects in the Standard Model of Cosmology
motto: “black is the new dark”

Albert Stebbins
Fermilab

Simplicity II @Fermilab
2016-09-09

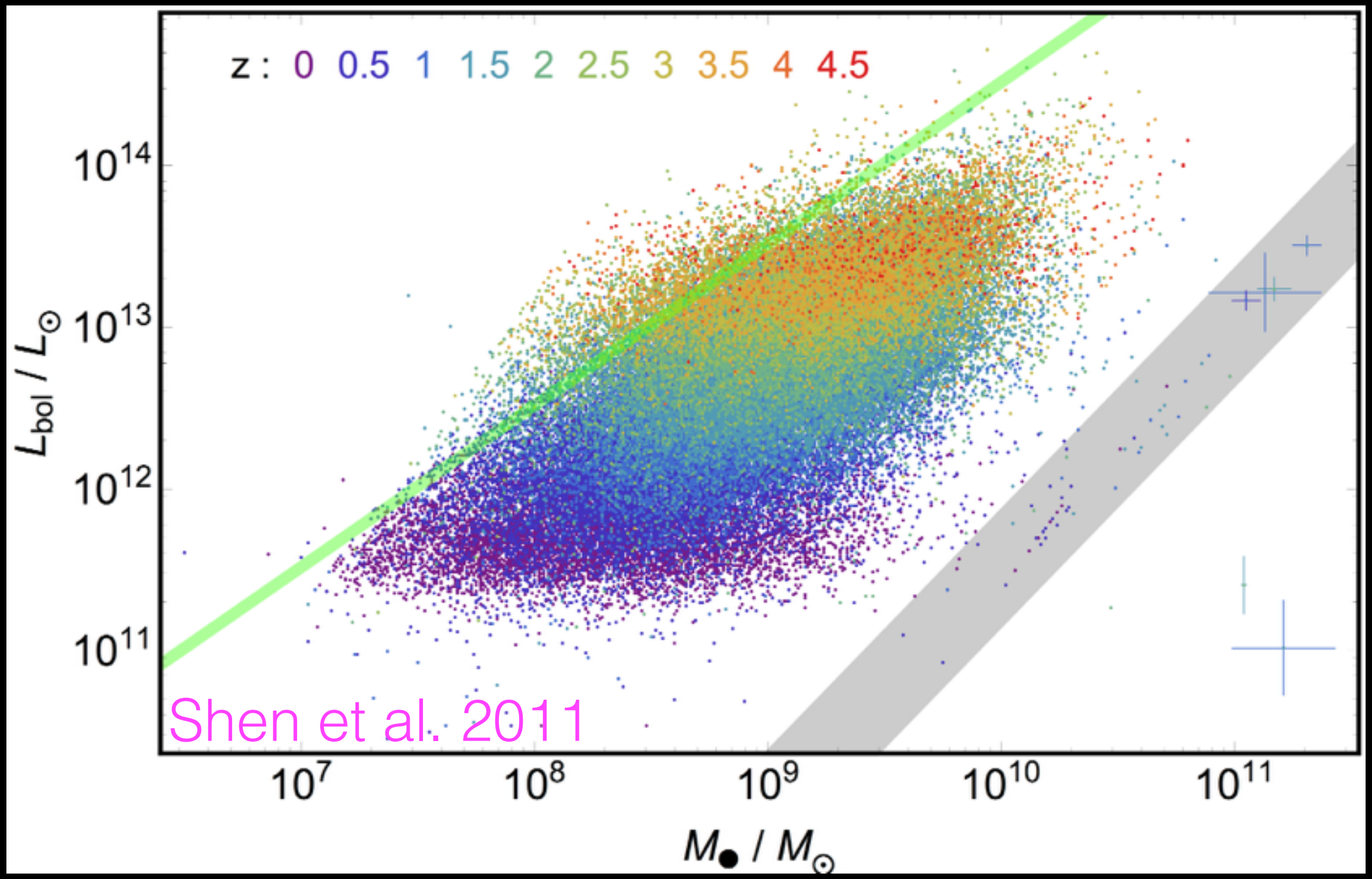
Some Terminology

mass range	name	acronym
1-10	stellar mass BHs	sBH
10	intermediate mass BHs	IMBH
>10	supermassive BH	SMBH

Black Holes, QSOs, AGNs

- The consensus explanation of the most luminous unresolved emitters quasars (QSOs) and active galactic nuclei (AGNs) are the emission of gas falling into supermassive black holes (SMBHs).
- these black holes generally live in the center of galaxies.
- SMBH masses can be measured/estimated
  - reverberation mapping (simple physics based but time consuming)
  - luminosity and line widths (more empirical but can be applied to large surveys)
- estimated masses range from $\sim 10^6 M_\odot$ to $\sim 10^{11} M_\odot$.
  - the credibility of the highest masses are sometimes questioned.
- the redshifts range from 0 to 7.1
- more massive SMBHs are more luminous: $L \propto M$
  - this is theoretically expected for Eddington limited accretion.
  - only the most massive SMBHs are detectable at the highest redshifts.
- for $z<2$ the number density of luminous SMBHs decline
  - they presumably don't disappear but rather become non-luminous
  - they run out of fuel?
  - numerous non-luminous SMBHs have been discovered locally
- locally it is estimated that non-luminous SMBHs are $>10^2$ more numerous than luminous ones.
  - evolution of the total SMBH population can be difficult to determine with large numbers of "dropouts".

SDSS 7 Quasar Survey: A large survey



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

SMBHs: Bottom Up Narrative

- sBHs / IMBHs form from collapse of stars or gas clouds at early times
- these BHs sink by dynamical friction to the center of dark matter haloes (galaxies / proto-galaxies)
- meanwhile gas accretes into the BHs at close to the Eddington limit
  - exponential growth in time with canonical timescale ~45Myr.
- occasionally dark matter haloes merge, central BHs merge soon after
- Certainly everything listed above does happen, but …

The Problem

Can this scenario explain the origin of the most massive SMBHs?

Does this scenario explain the origin of the <u>any</u> SMBHs?

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

The earliest stars <u>may</u> 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! QSO are not Eddington limited!

- Commentary on too many / too massive SMBHs at early times:
  - The recent discovery of the ultraluminous quasar … at z=6.3 has exacerbated the time compression problem implied by the appearance of SMBHs only ~0.9Gyr after the big bang, and only ~0.5Gyr beyond the formation of Pop II/III stars. Aside from heralding the onset of cosmic reionization, these 1st and 2nd generation stars could have reasonably produced the ~5–20 $M_\odot$ seeds that eventually grew into z~6–7 quasars. But this process would have taken ~0.9Gyr, a timeline that appears to be at odds with the predictions of ΛCDM without an anomalously high accretion rate, or some exotic creation of ~$10^5 M_\odot$ seeds. There is no evidence of either of these happening in the local universe. **Melia & McClintock 2015**
  - The highest-redshift (z~7) quasar known already had $M \sim 2\times10^9 M_\odot$ only 0.7Gyr after the Big Bang … this 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**

THE BIG QUESTION

- When and where do original BH "seeds" form?
  - early ($z \gg 10$) with **super growth**
  - later ($z \sim 10$) from baryonic **super seeds**
  - **primordial** ($z \gg 10^3$) super seeds
    - these super seeds need not have grown much
    - formed mostly from photons and neutrinos
    - (new physics)
  - Direct Formation?
    - no intermediate stable star-like configuration
    - $10^9 M_\odot$ @ z=8-10 (Mayer et al. 2015) possible in mergers
    - Is WISE J224507-052635 ELIRG @ z=4.593 (Tsai et al. 2015) a "direct formation" event?

Black Hole Mass Function

$\Psi[M,z]$ comoving # density of BHs per unit mass

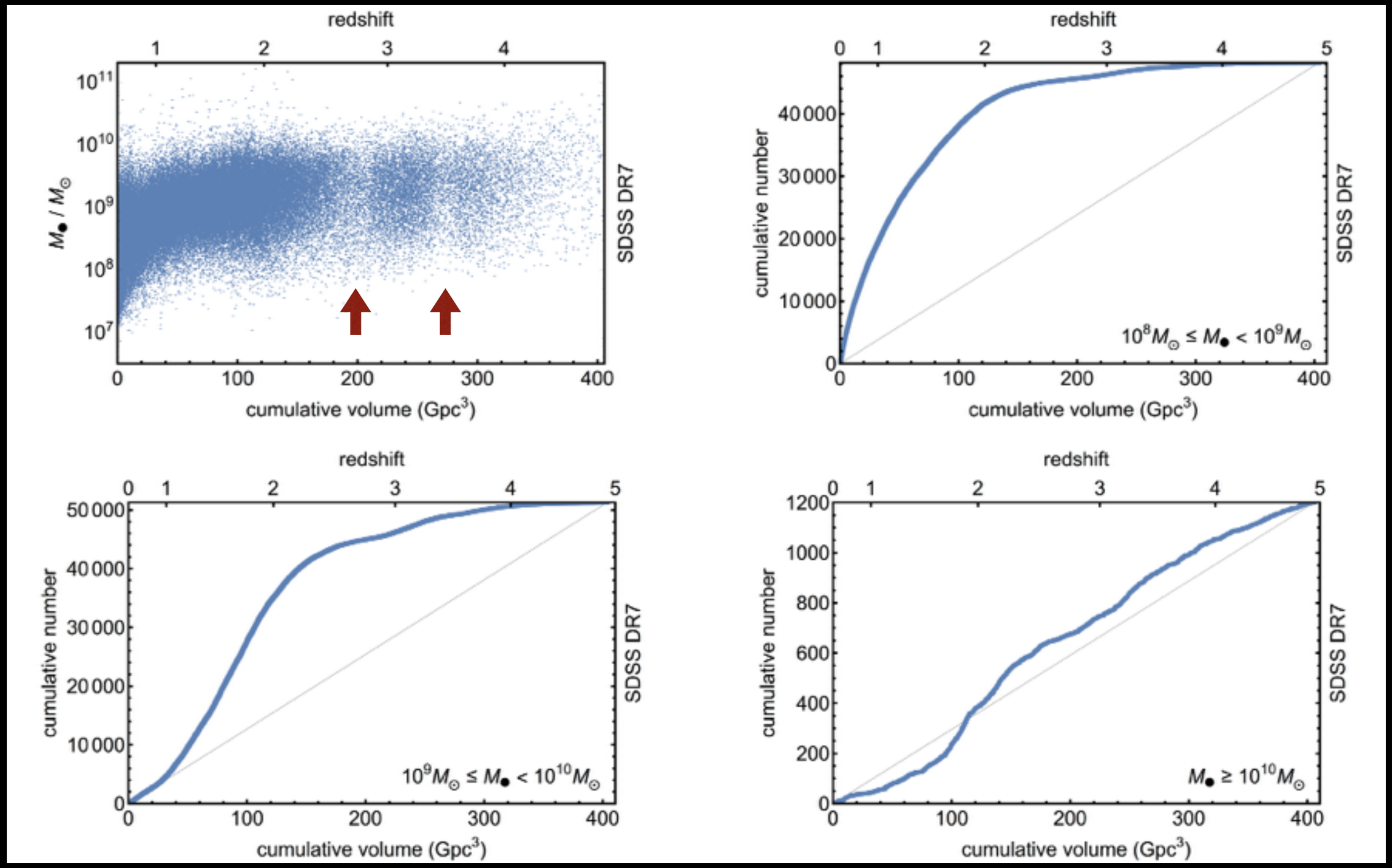
$\Phi[>M,z]$ comoving # density of BHs more massive than **M**

$\beta = \partial_{\ln[M]} \ln[\Psi]$ mass function slope

Naive Qualitative Expectations for Baryonic Models

- only extremely rare objects form the most massive black holes especially early. Expect distributions to fall off rapidly with mass and z.
  - e.g. Gaussian or exponential tail
- expect steepening of mass function with z and M
- rapid evolution of high mass end of mass function

Most Massive SMBHs do not evolve much!



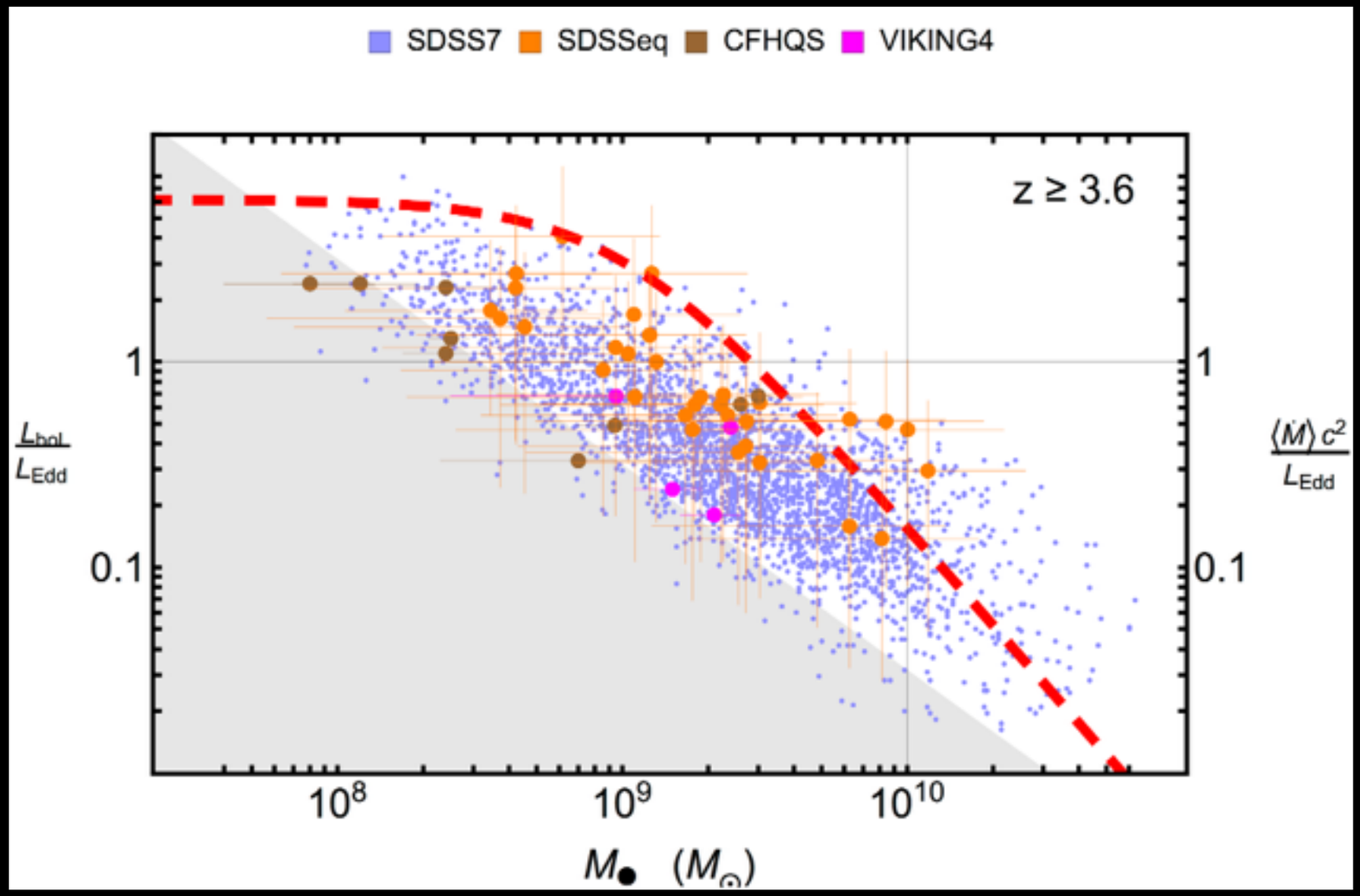
Points to super seeds not super growth!

Population Dynamics

simplify:

- $\langle \partial_t M \rangle = M / \tau[M,z]$ not stochastic (ergodic / advection)
- ignoring mergers and formations continuity equation reads

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

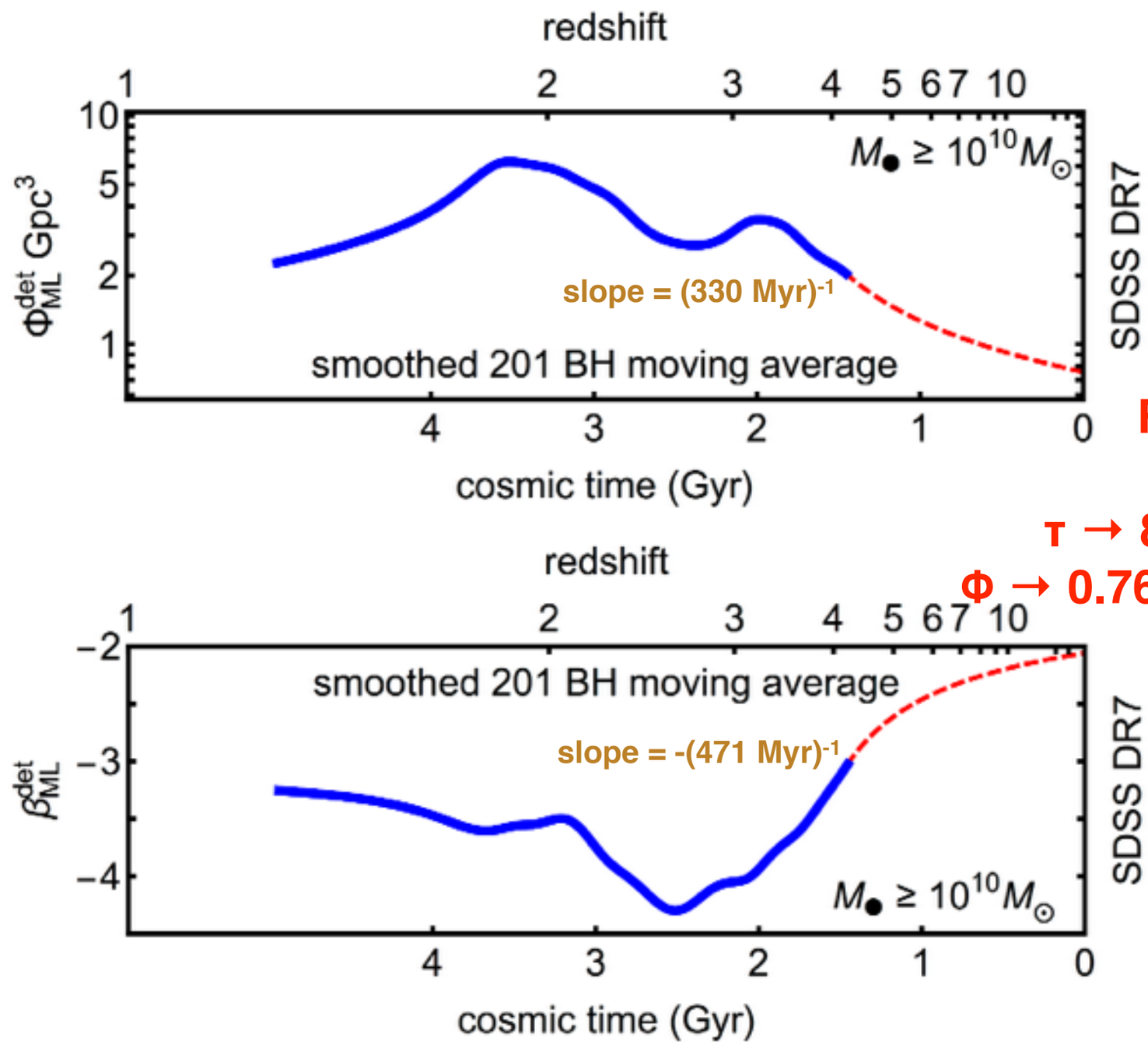


radiative efficiency

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

canonically ≈ 0.1

Extrapolated Evolution of $M>10^{10}\ M_\odot$ SMBHs



FIT :

$\beta \rightarrow -2.05$

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

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

Points to super seeds not super growth!

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

PRIMORDIAL SMBHs?

Primordial Black Holes is an old idea!

e.g. Zel'dovich and Novikov 1967, Hawking 1971, Carr & Hawking 1974

Localized large positive amplitude density fluctuations will collapse to a black hole (form closed trapped null surfaces) when enter horizon.

This is not the only possibility.

Not predicted to occur with any observable frequency in standard cosmological model (ΛCDM) - **this is "new physics"!**

Primordial BHs must be small ($<10^5$M) or rare to be consistent with observations.

By normalizing to observed SMBH abundance one satisfies many observational constraints.

Primordial Black Hole Properties

- **Initial mass function (IMF)**
  - **assume power law mass function**
- Spatial distribution
  - assume Poisson where relevant
- Correlation with other density inhomogeneities
  - assume uncompensated adiabatic perturbation where relevant
- Spin
  - assume zero spin where relevant
- Charge, electric or magnetic
  - assume zero charge where relevant
- Boson condensate atmosphere (of spinning black holes)
  - assume none where relevant

Power Law Initial Mass Function

For **simplicity**

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

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 $A_s = 21\times10^{-10} \sim 3.5\, f_{BH}$

Harrison-Zel'dovich Scaling: $\beta_0 = -5/2$

for black holes which enter horizon in radiation era:

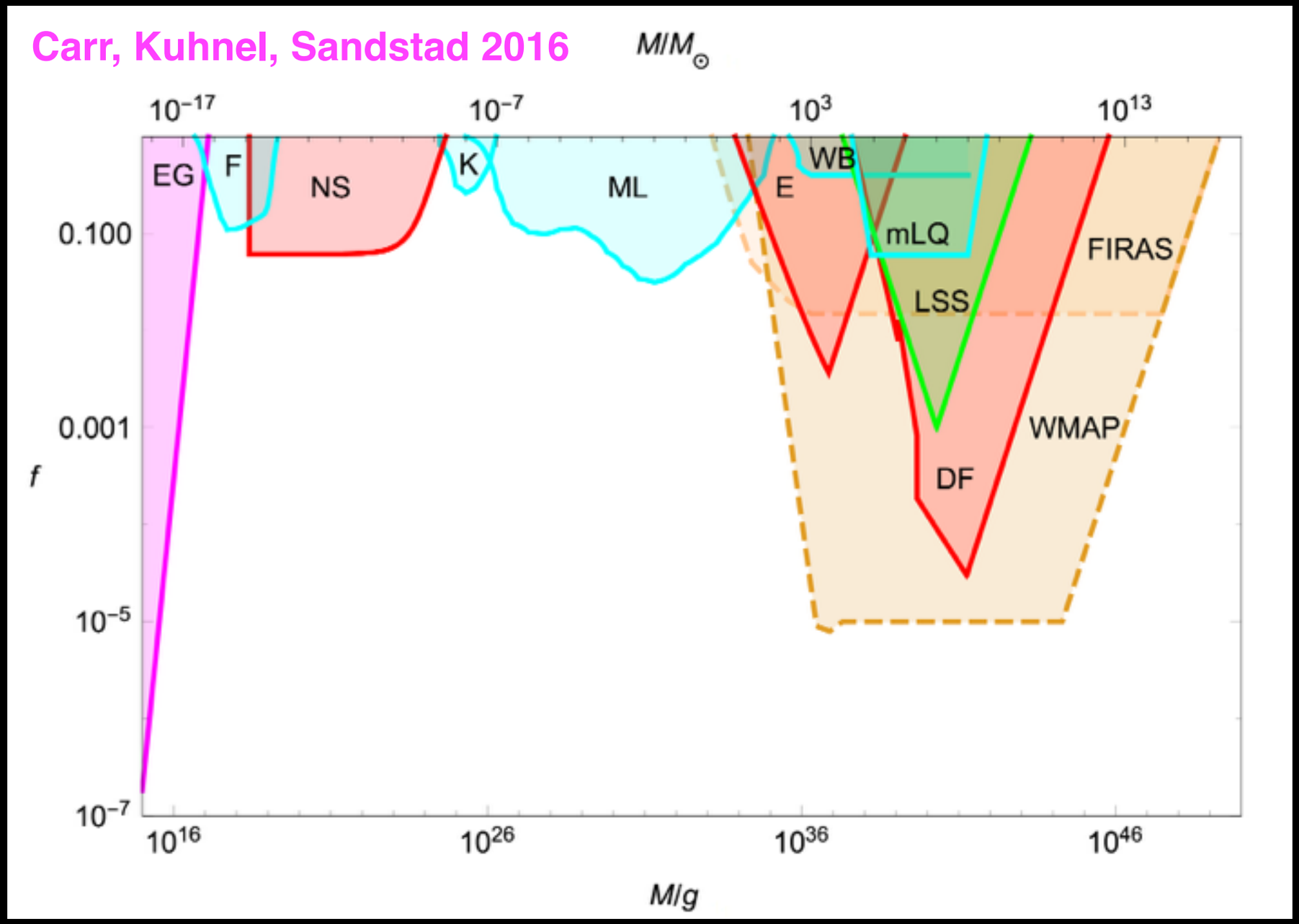
$M \ll M_{eq} \approx 3\times10^{17}\, M_\odot$

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

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

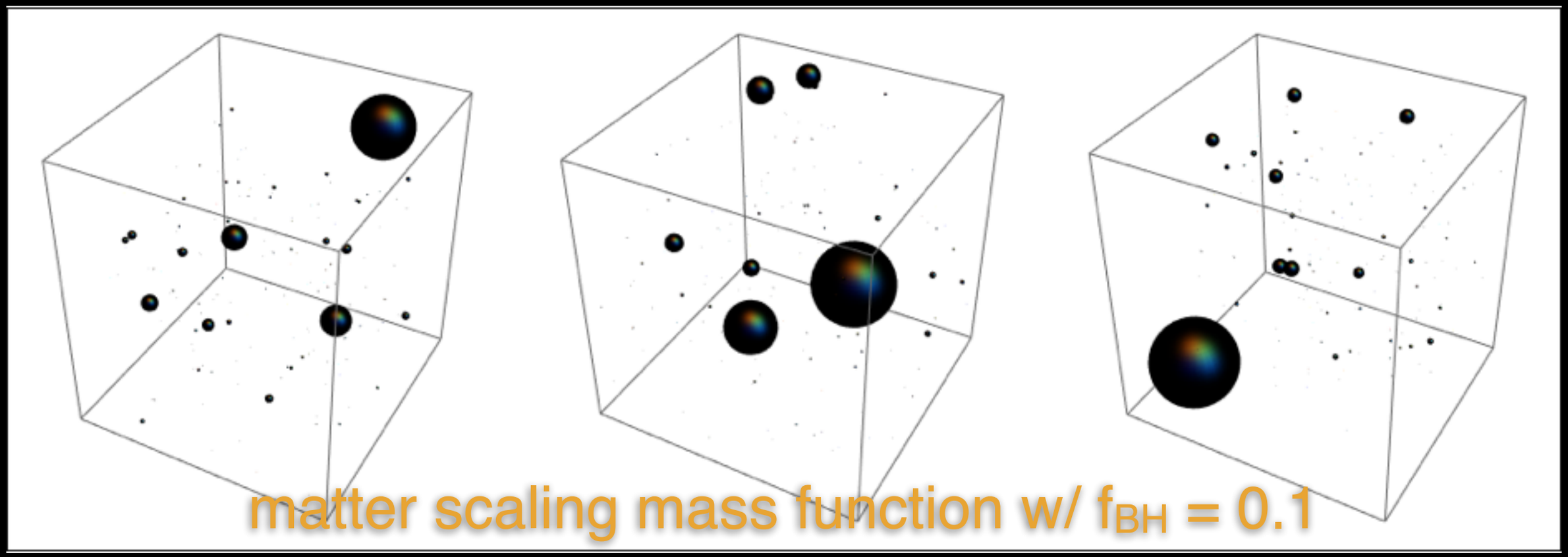
Not Ruled Out (Yet)

- Since normalized to observed GBH mass function for 3.6<z<5 universe it is cannot be ruled out by conventional constraints



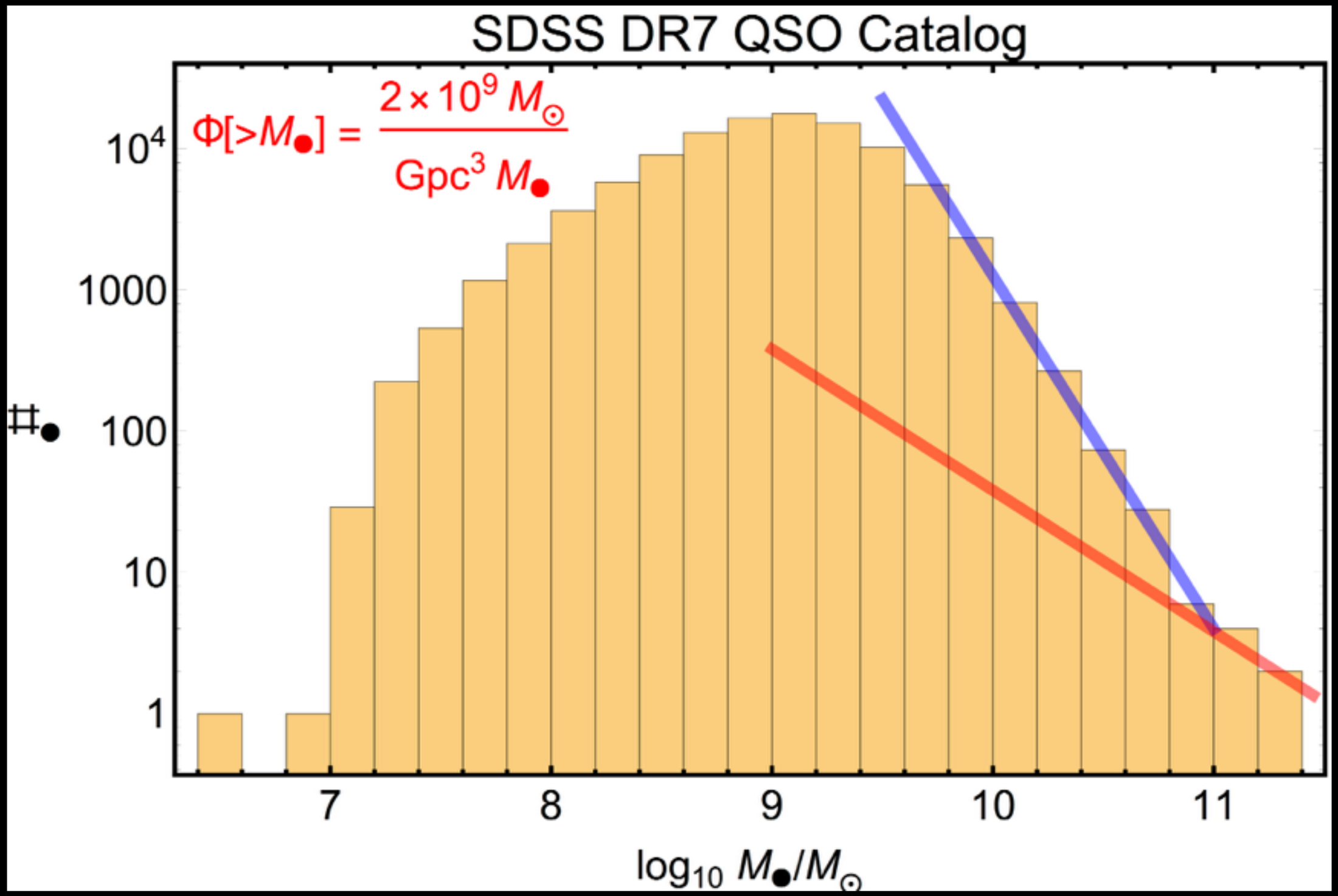
IMF Extremely Red

- 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.
- **key prediction:** more massive BHs than have been observed exist in our universe



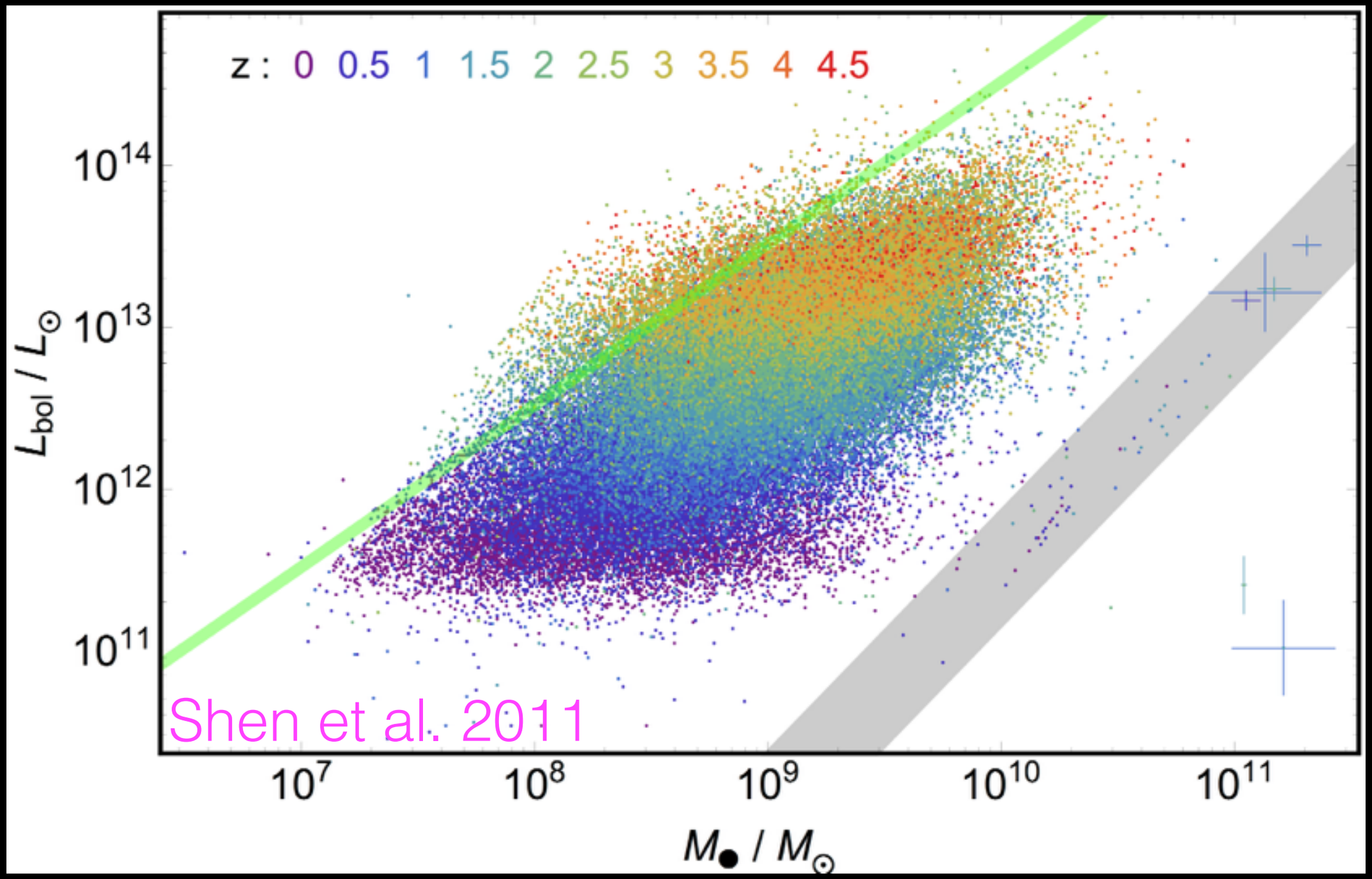
$$\frac{\langle {}^{\text{max in}}_{\text{Hubble volume}}[R_{\text{Schwarschild}}]\rangle^{\text{median}}_{\text{realization}}}{\text{Hubble length}} = \frac{3\,\Omega_m[z]}{4\,\pi\,\ln[2]}\,f_{BH}$$

Are They There?



Have we detected the pristine population?

SDSS 7 Quasar Survey: A large survey

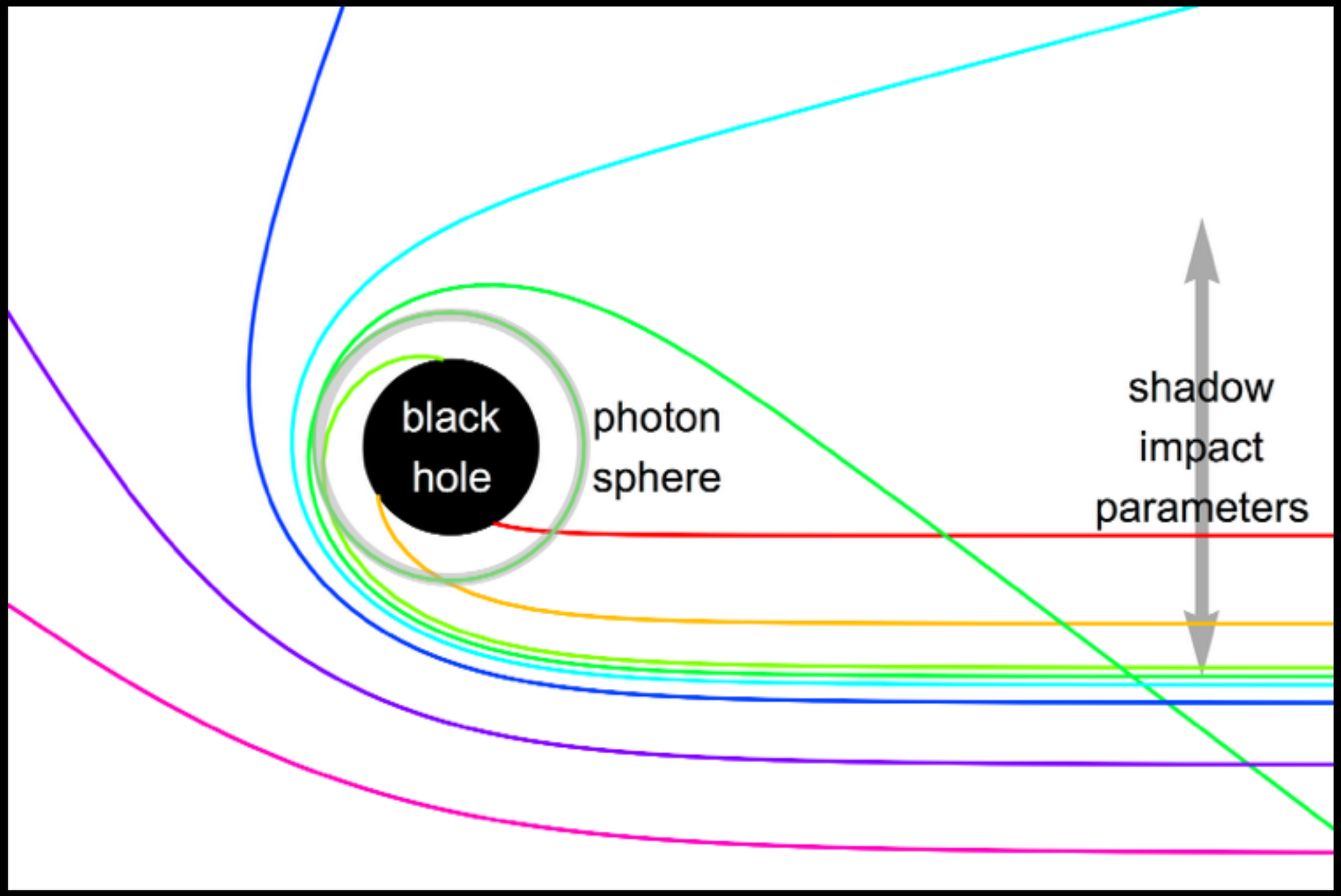


$0<z<5$ $f_{sky}=0.194$ 410 Gpc^3 104,746 SMBHs

Detection Using CMB Backlighting

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

Black Hole Shadow



$R_{Schwarzschild} = 2 \; GM/c^2 = 20 \text{ AU} \; (M / 10^9 \, M_\odot)$

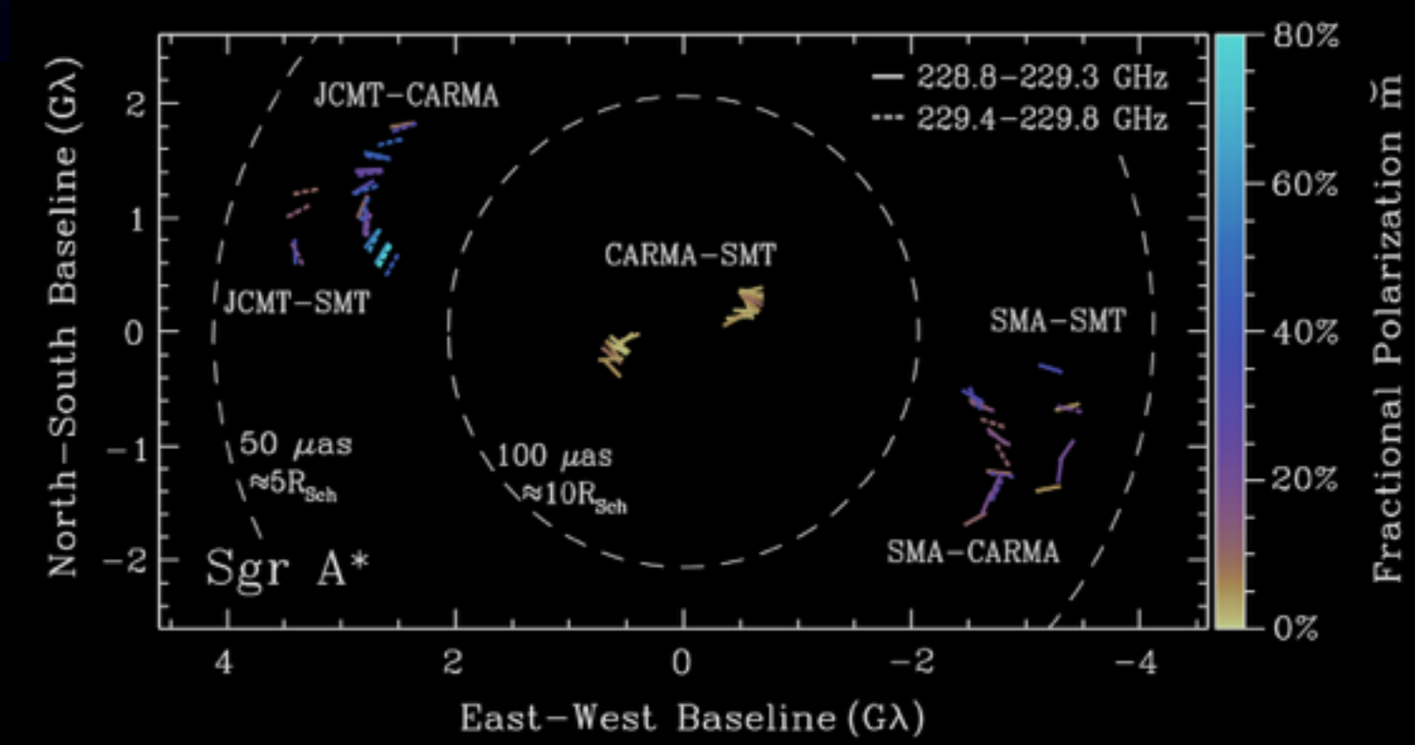
$R_{photon} = 3 \; GM/c^2 = 30 \text{ AU} \; (M / 10^9 \, M_\odot)$

$R_{shadow} = 3\sqrt{3} \; GM/c^2 = 51 \text{ AU} \; (M / 10^9 \, M_\odot)$

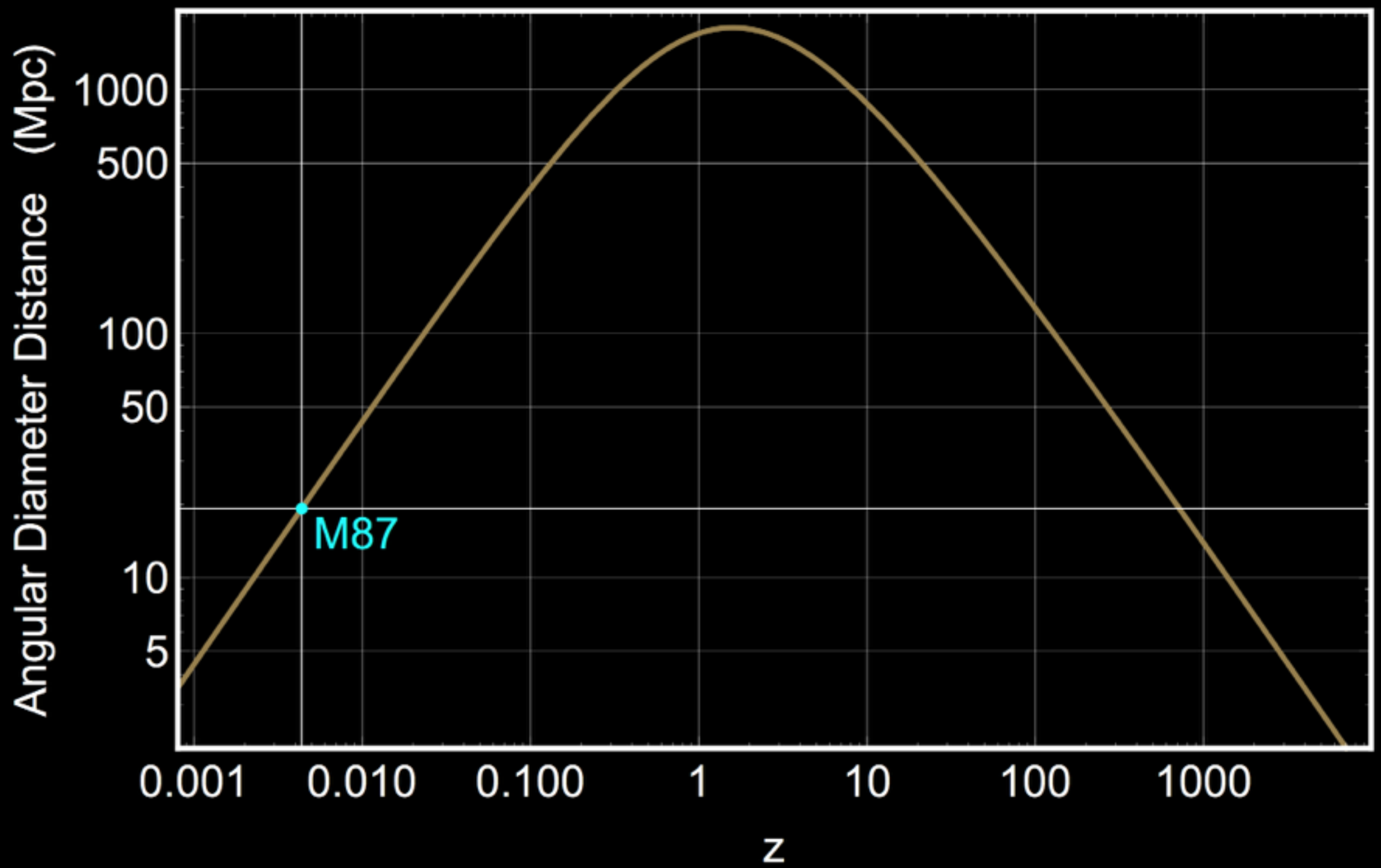
EventHorizonTelescope

BH targets	M/M	distance
Sgr A*	4 10	8 kpc
M87	3.5 10	16 Mpc

Johnson *et al.* 2015



The Universe is an Excellent Magnifying Glass



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

Should EHT Be Looking for SMBH Shadows at $z \sim 10^3$?

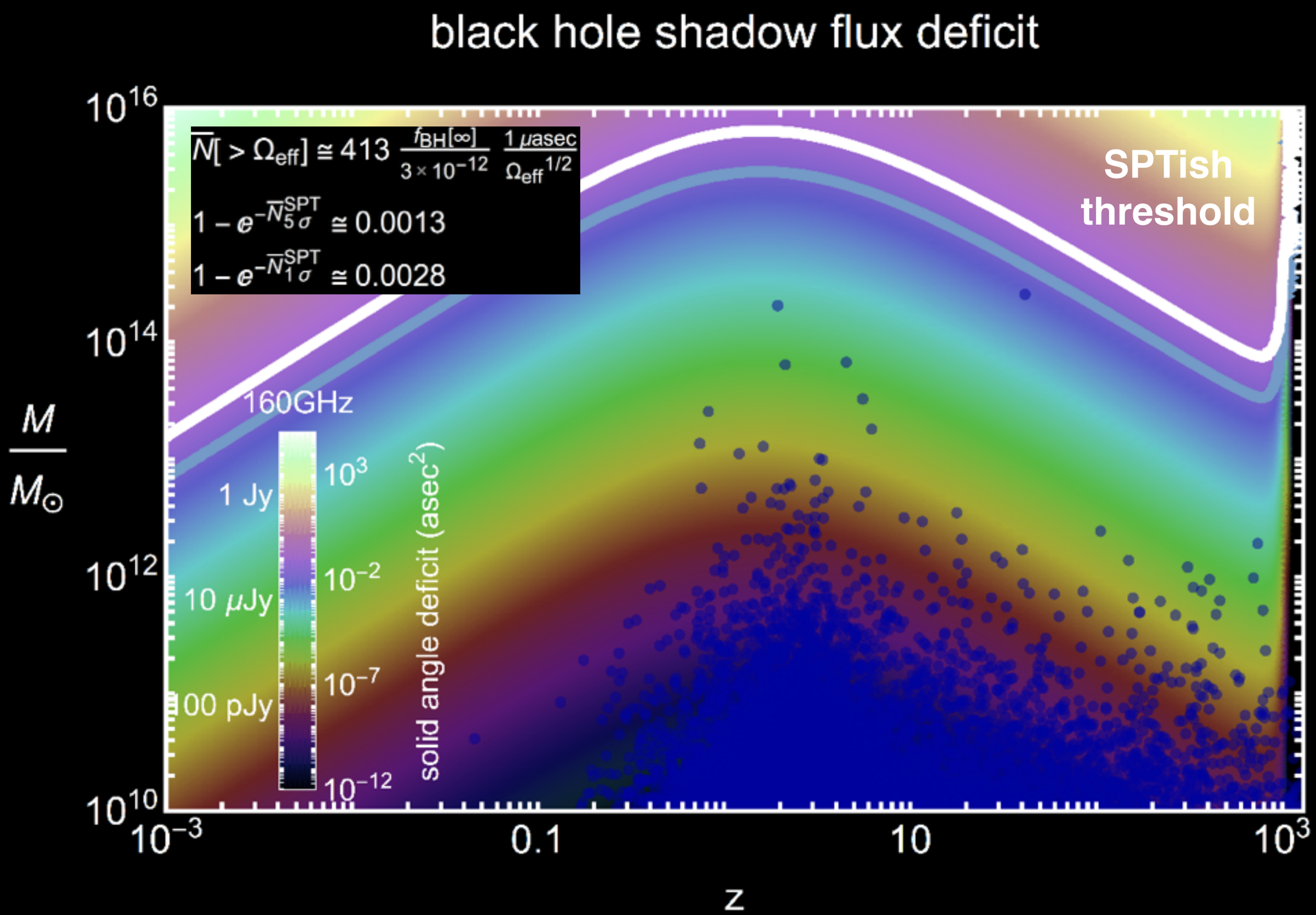
Pros

- There is much more volume “closer” at hi-z than lo-z

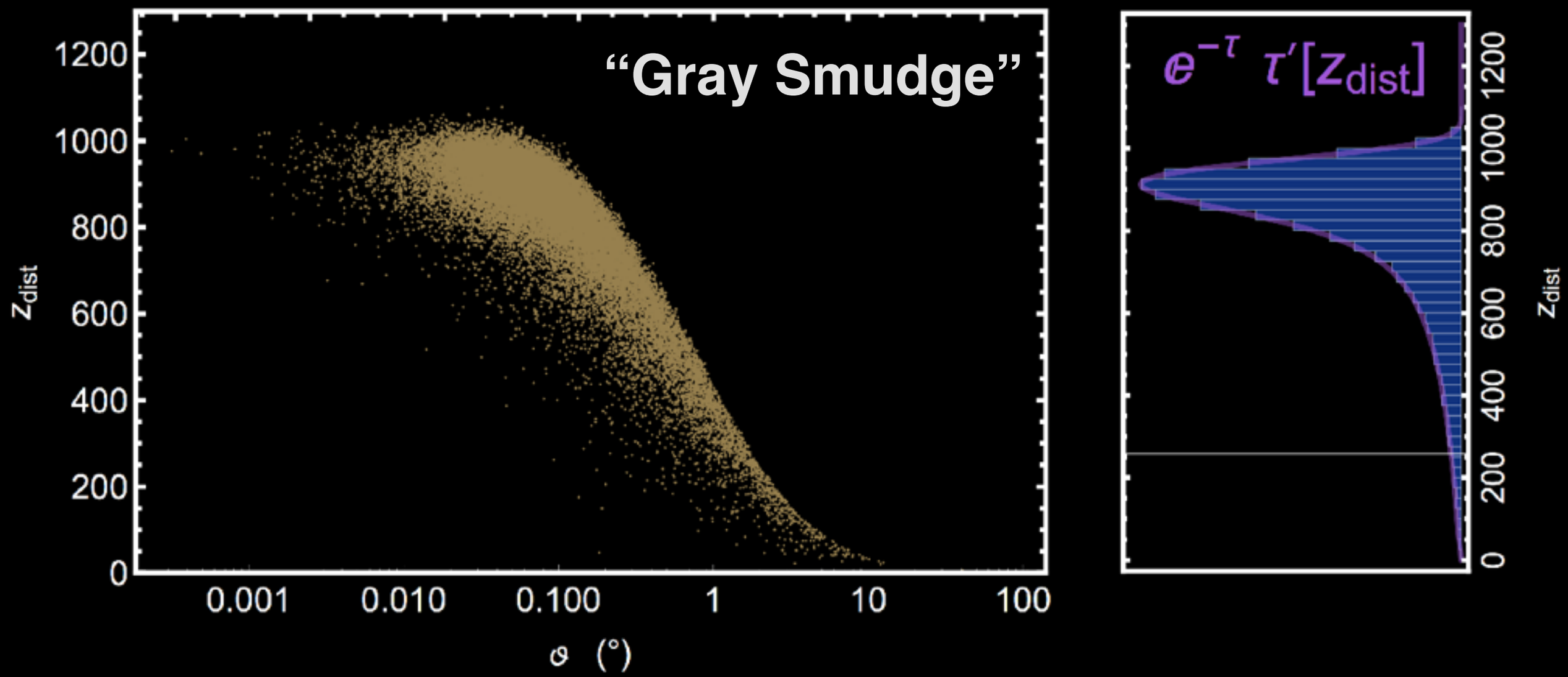
Cons

- The canonical wisdom is there are none.
- Even if there were they wouldn’t know where (to point)
- EHT can only see shadows in contrast with a bright (accreting) background. CMBR is relatively dim.

Model Distribution of Black Hole Shadows



Black Hole Gray Halos



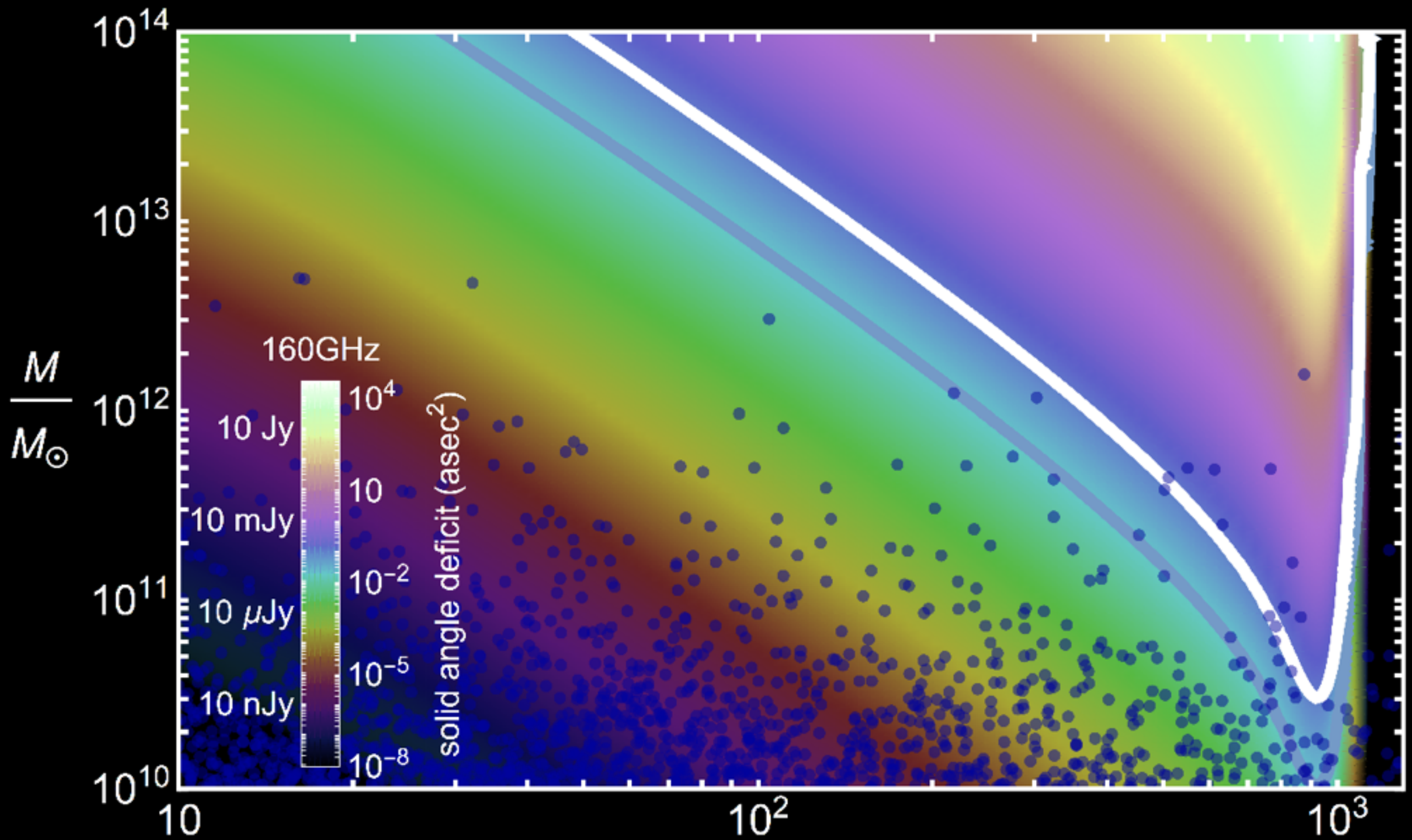
Most photons absorbed near time of BH formation is at very hi-z (rad. era $z_{form} \propto M^{-1/2}$)

- 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

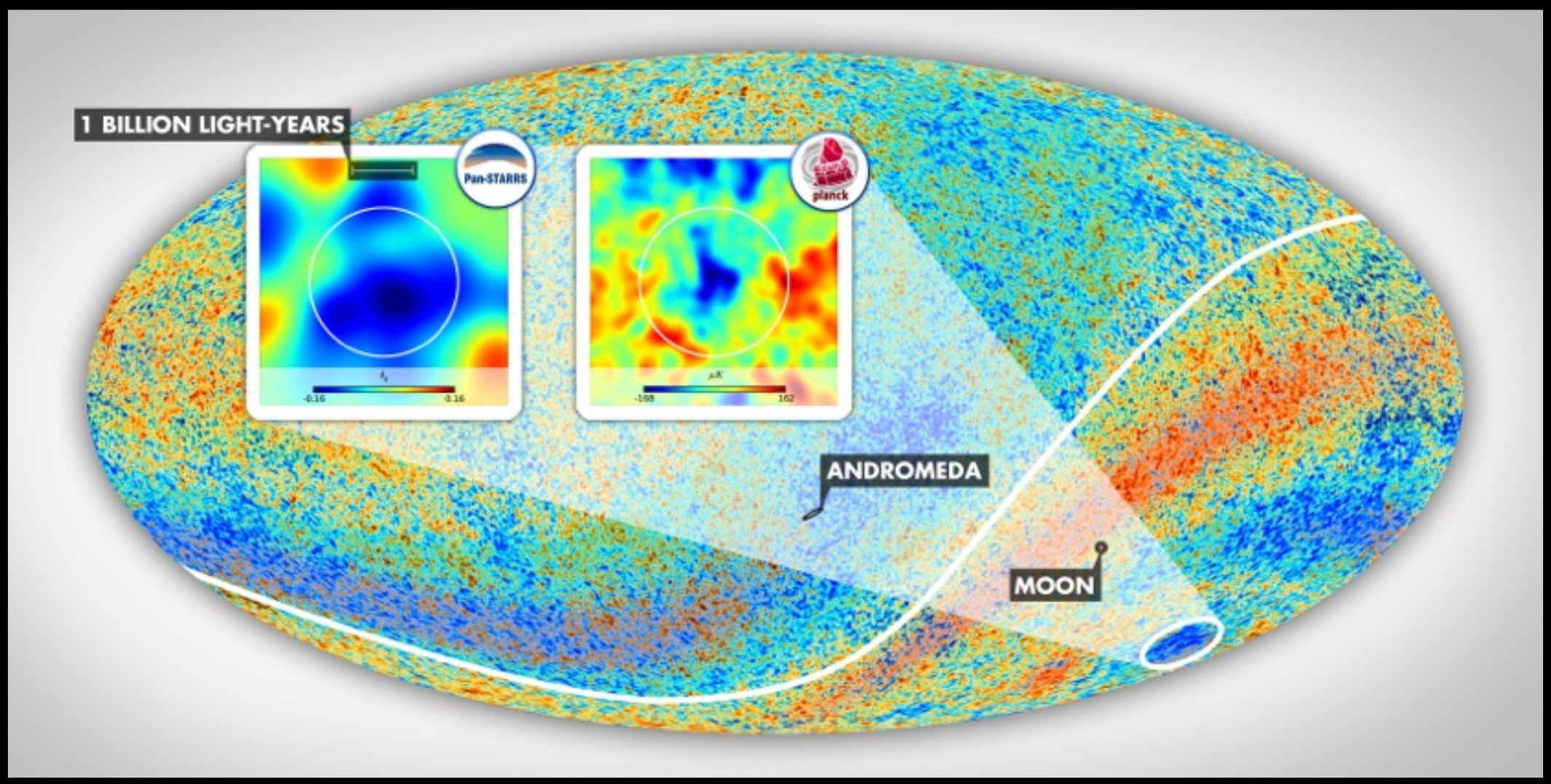
Halos are Much More Easily Seen



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



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.

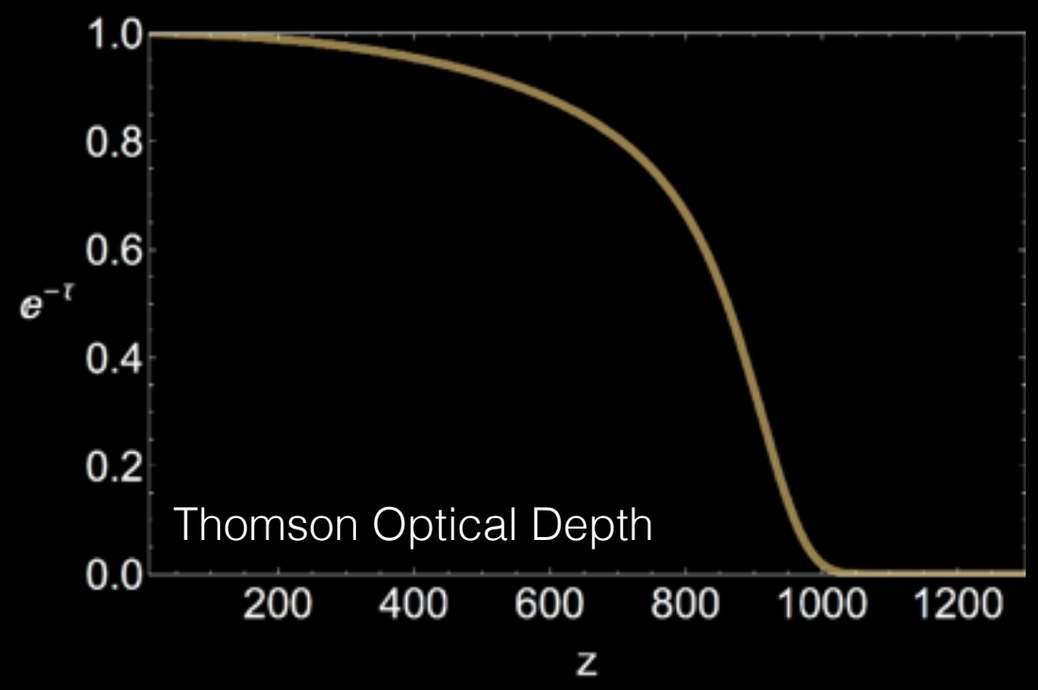
QSO outliers and CMB anomalies may be the key for detection.

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

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

BACKUP SLIDES

What Mass Range Is Interesting?



Comment on DES motto
"**Mapping the Universe 1 Gpc^3 at a time**"
It would still take quite a few times to map the entire observable universe!

for mass function extrapolation

- $\lesssim 3\times10^{13}$ M⊙ SoLS interior
- $\lesssim 10^{12}$ M⊙ SoLS embedded

or conservatively

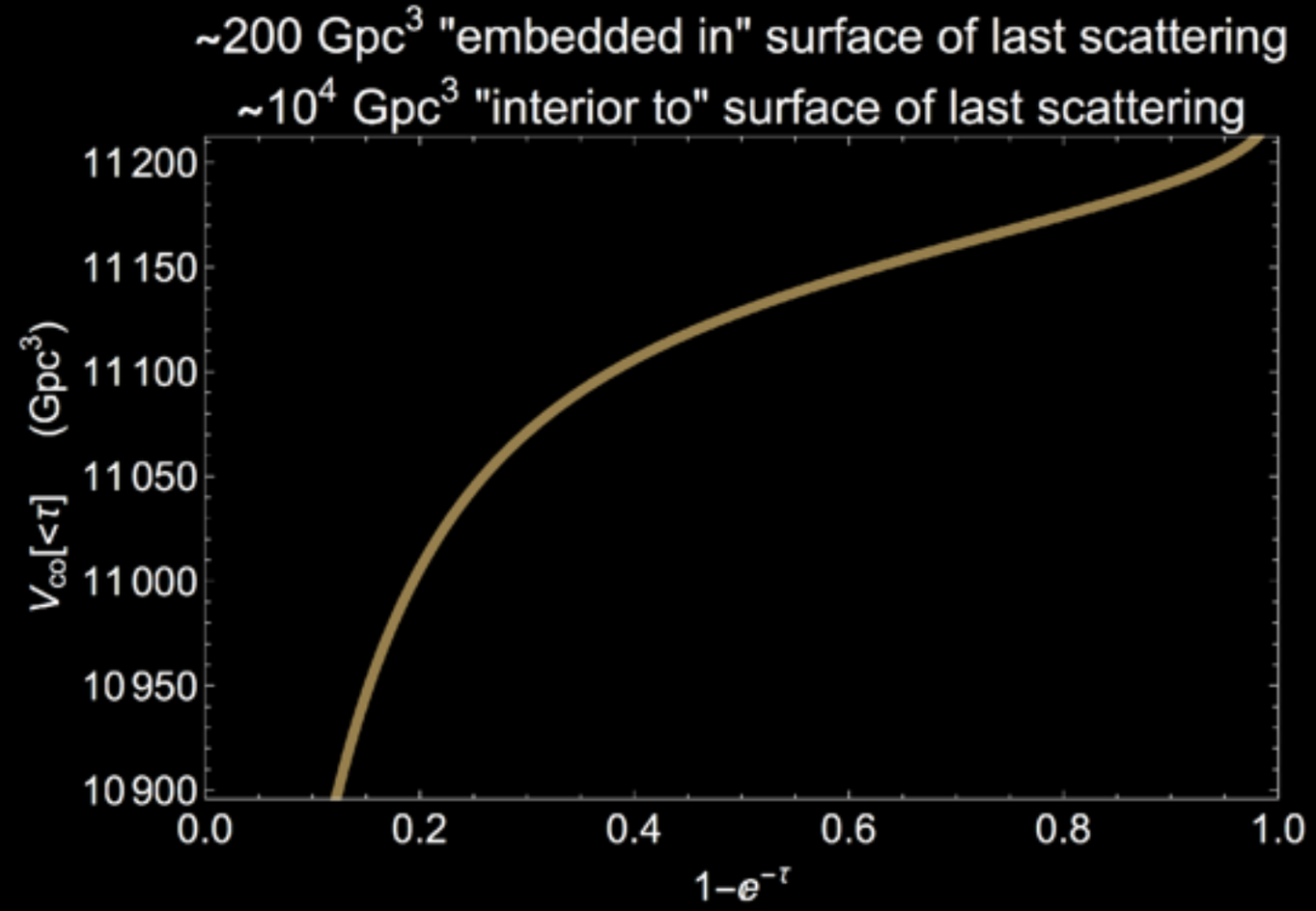
- $\lesssim 10^{10}$ M⊙ (observed)

or for kBH seeds

- $\lesssim 10^{6}$ M⊙

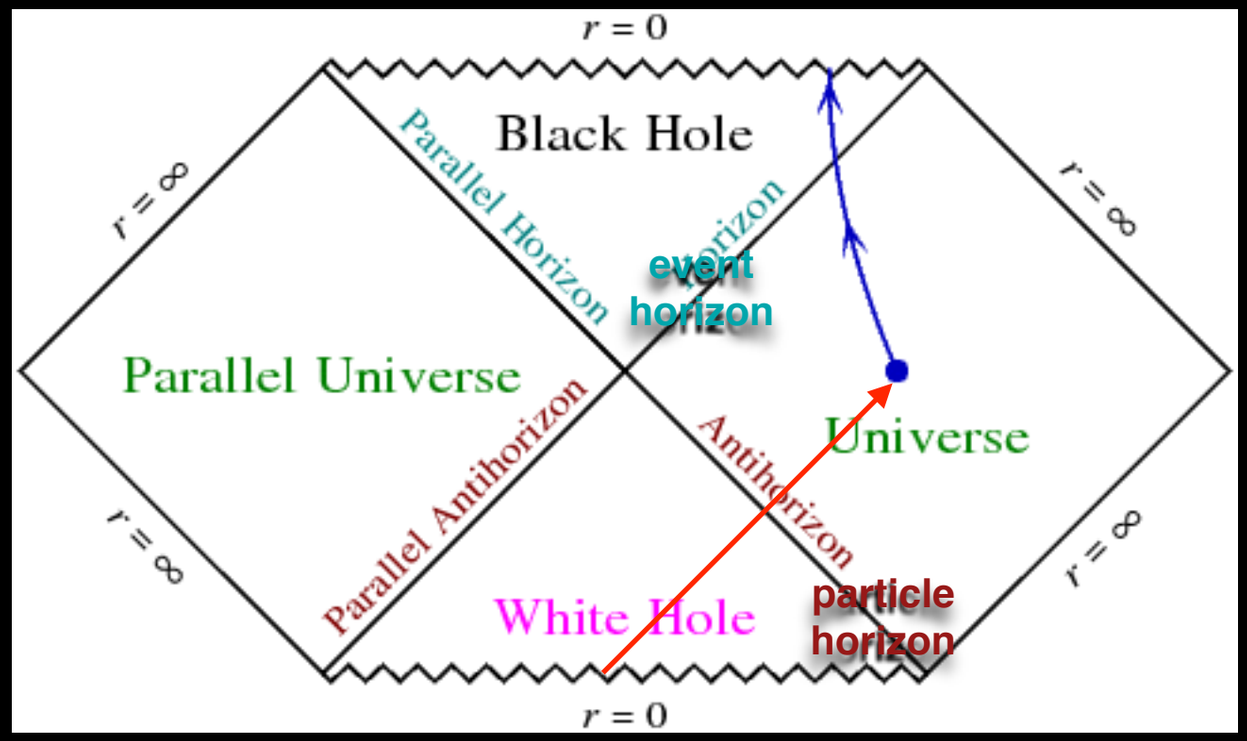
or for "aLIGO dark matter"

- ~30 M⊙



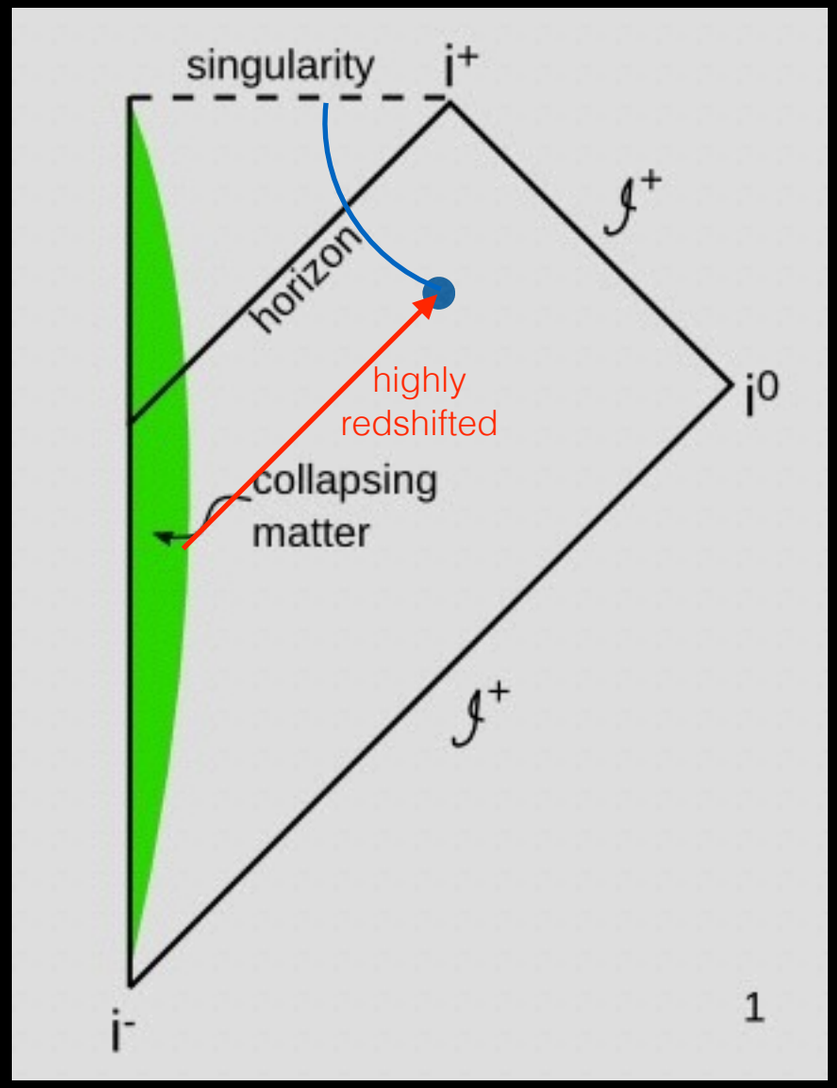
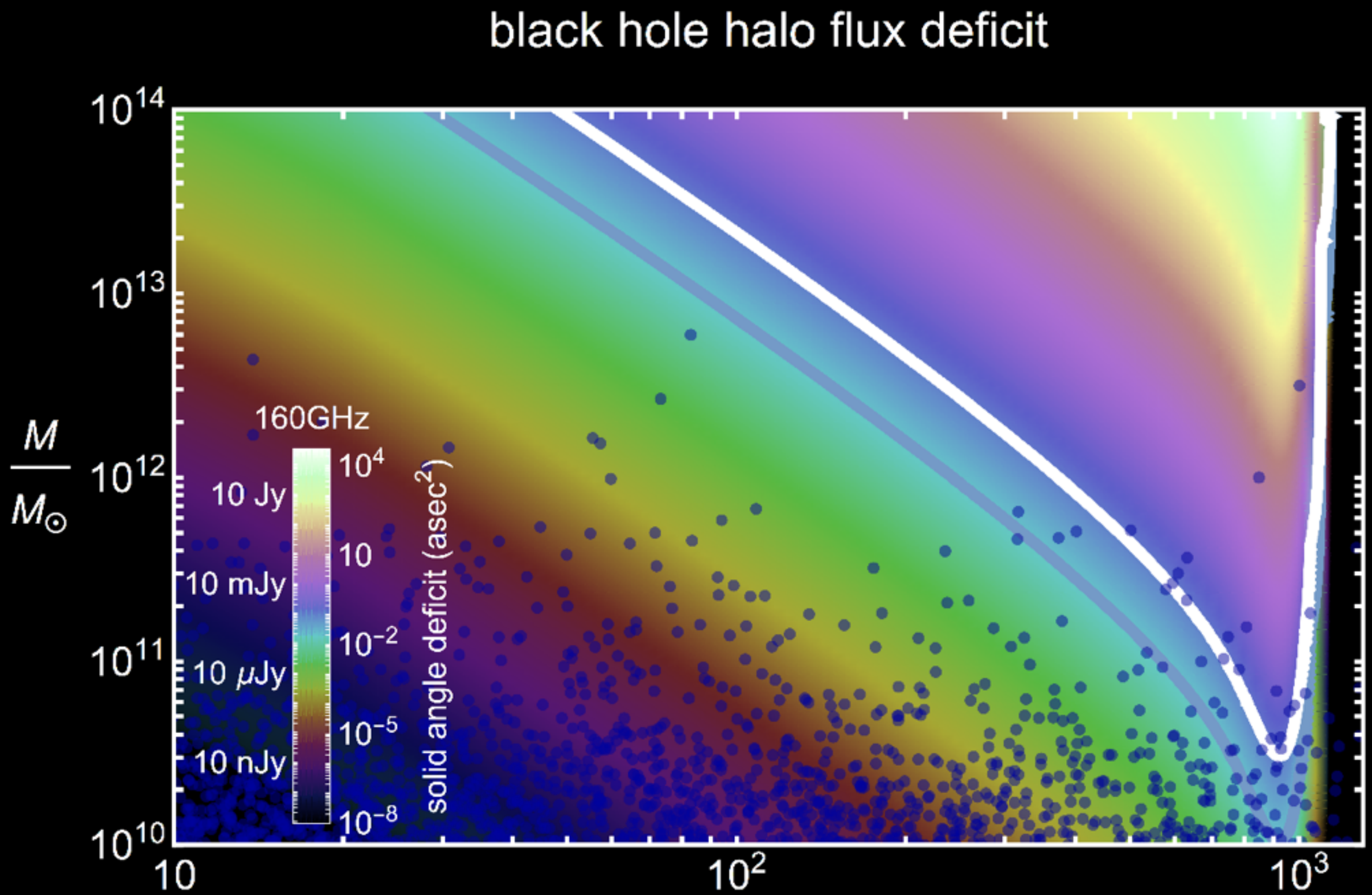
Black?

Eternal Non-Rotating Black Hole



- no light comes out of event horizon,
- eternal BH: light can exit particle horizon
- collapsed BH: highly redshifted light from formation
- Hawking Radiation from near horizon:
  - unmeasureably dim for macroscopic black holes
- Accreting (infalling) matter can shine brightly: QSOs

Black Hole Formed by Collapse



Halos are Much More Easily Seen