Did LIGO Detect Primordial Black Holes?

Constraints from Cosmology

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What are Primordial Black Holes?

Formed from early density perturbations

Have approx horizon mass at formation

$$M_{pbh} \sim \frac{c^3 t}{G}$$

30 solar mass ~ 10^{-4} seconds

Carr, Hawking (1974)

Why Primordial Black Holes?

- LIGO inferred rate (2-50 events per Gpc^3 per year) is very high in this mass range
- We haven't found WIMPS yet
- Super massive black holes (10^9 solar mass) cannot form easily from early collapsed stars

Quick Outline

- Expected Merger Rate of PBH Dark Matter
- Existing Constraints on PBH DM
- PBH Effect on CMB:
    1. Accretion
    2. Ionization
    3. CMB Anisotropy
- Constraints and Questions moving forward

Simple Exercise:

Inspiral Merger Rate per halo assuming:
all PBHs are same mass,
compose all DM,
live in halos of uniform density

$$N \simeq (1/2) V (\rho / M_{\rm pbh})^2 \sigma v$$

Cross section
Geometry

$$\simeq 3.10 \times 10^{-12} \, M_{12} \, \rho_{0.002} \, v_{\rm pbh-200}^{-11/7} \, {\rm yr}^{-1}$$

Bird et al. (2016)

Simple Exercise:

~ 1 for Milky Way

$$\Gamma \simeq 1.1 \times 10^{-4}\, \rho_{0.002}\, v_{\rm pbh-200}^{-11/7}\, {\rm Gpc}^{-3}\, {\rm yr}^{-1}$$

<< 2 detections per Gpc^3 per year

Bird et al. (2016)

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If everything was in dense protohalos…

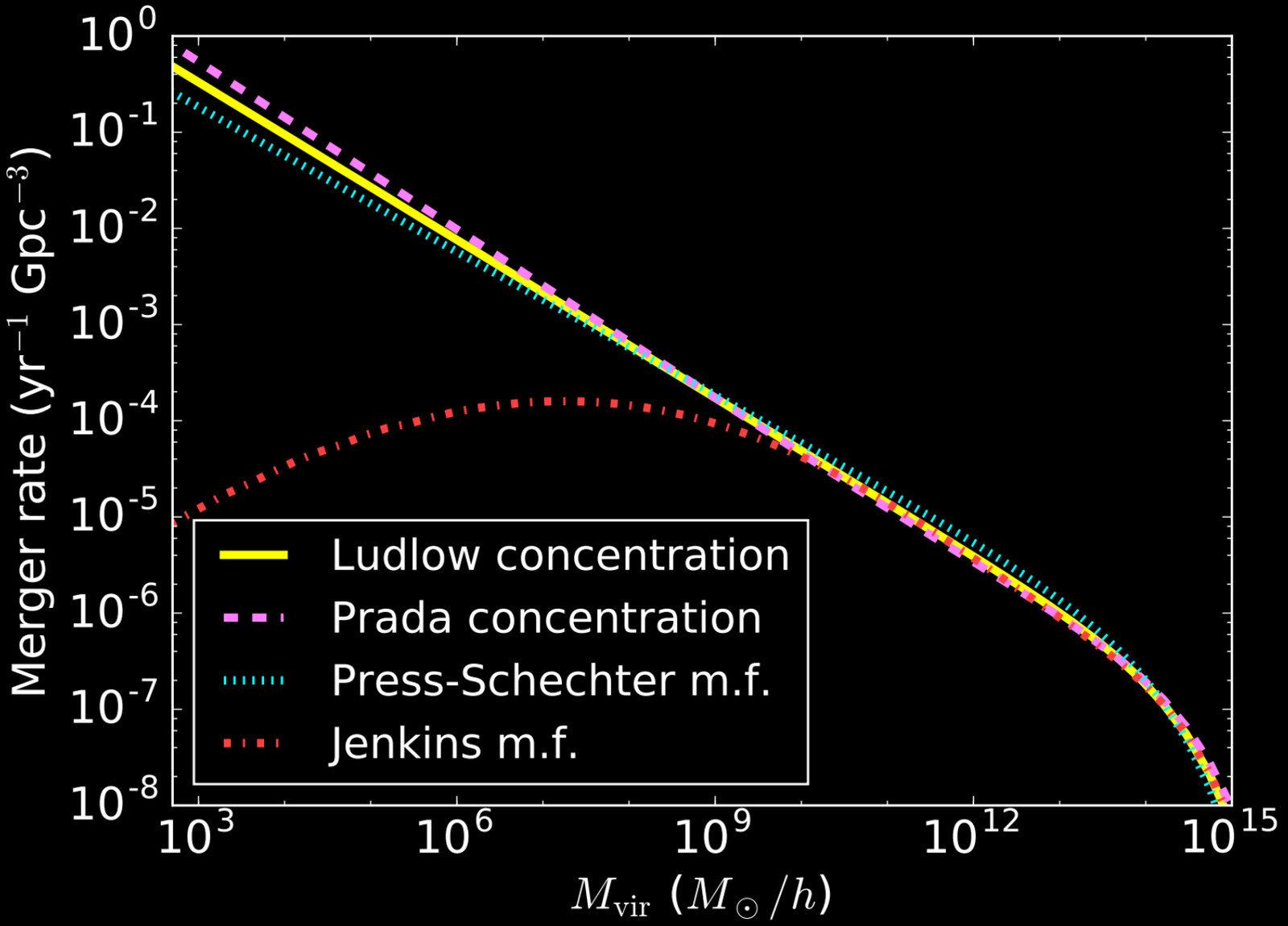
$v \simeq 0.2\ {\rm km\ sec}^{-1}$

$\rho \simeq 0.24\ M_\odot\ {\rm pc}^{-3}$

$$\Gamma \simeq 700\, {\rm Gpc}^{-3}\, {\rm yr}^{-1}$$

Bird et al. (2016)

Full Model

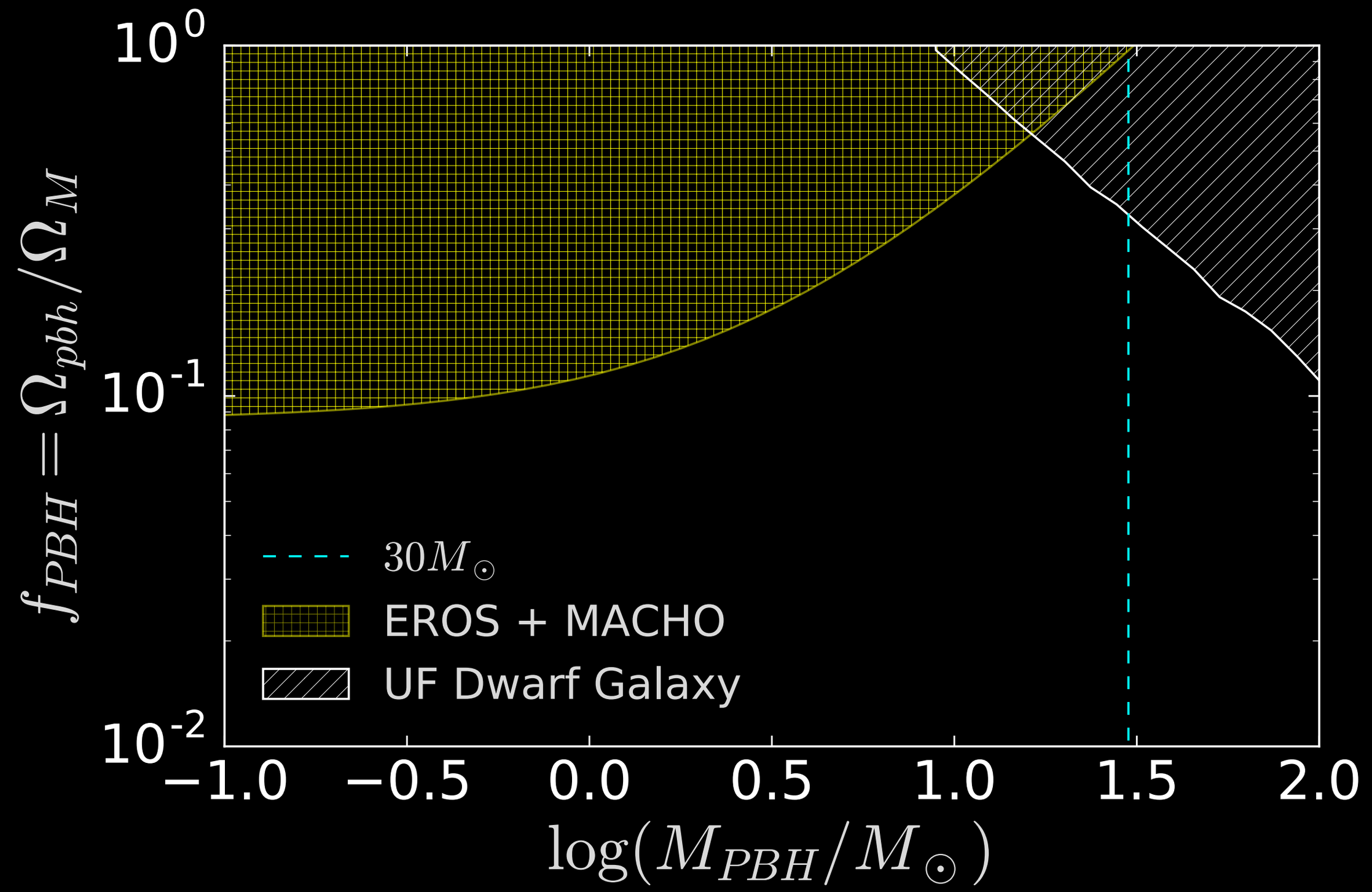


Integrate over halos!

$\sim 3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Bird et al. (2016)

Is this mass range already excluded?

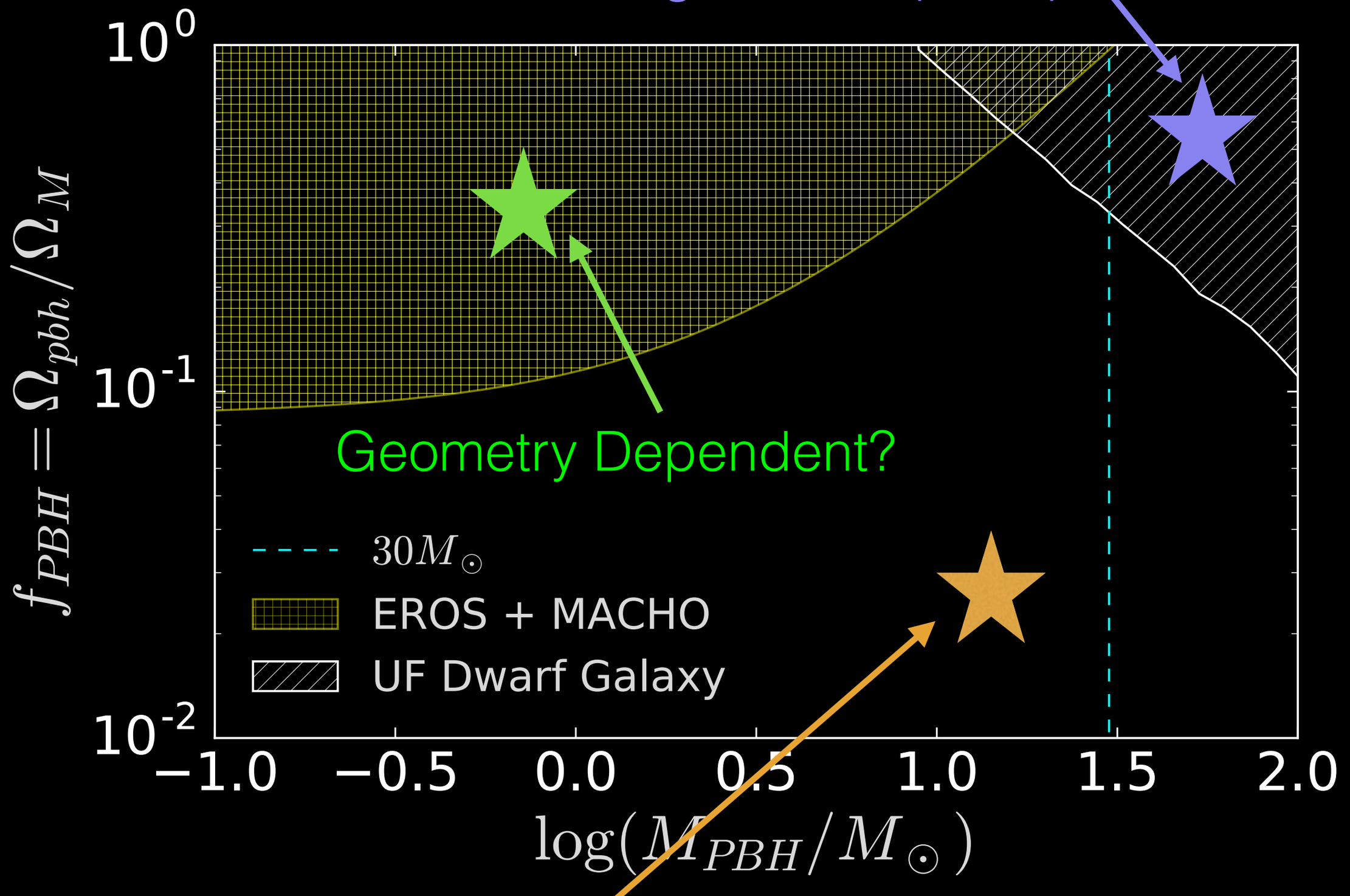


Tisserand et al. (2007)
Brandt (2016)

Horowitz (2017)

Dynamic Friction may be less energetic than predicted

Park, Bogdanović (2017)



Region could still be interesting for SMBH formation

Horowitz (2017)

Additional Constraint…
Cosmic Microwave Background

Two Main Effects:

1) (Partially) ionize universe: Effect CMB power spectra

2) Distort CMB Spectrum

Ricotti et al. (2008)

Additional Constraint…
Cosmic Microwave Background

Two Main Effects:

1) (Partially) ionize universe: Effect CMB power spectra

~~2) Distort CMB Spectrum~~

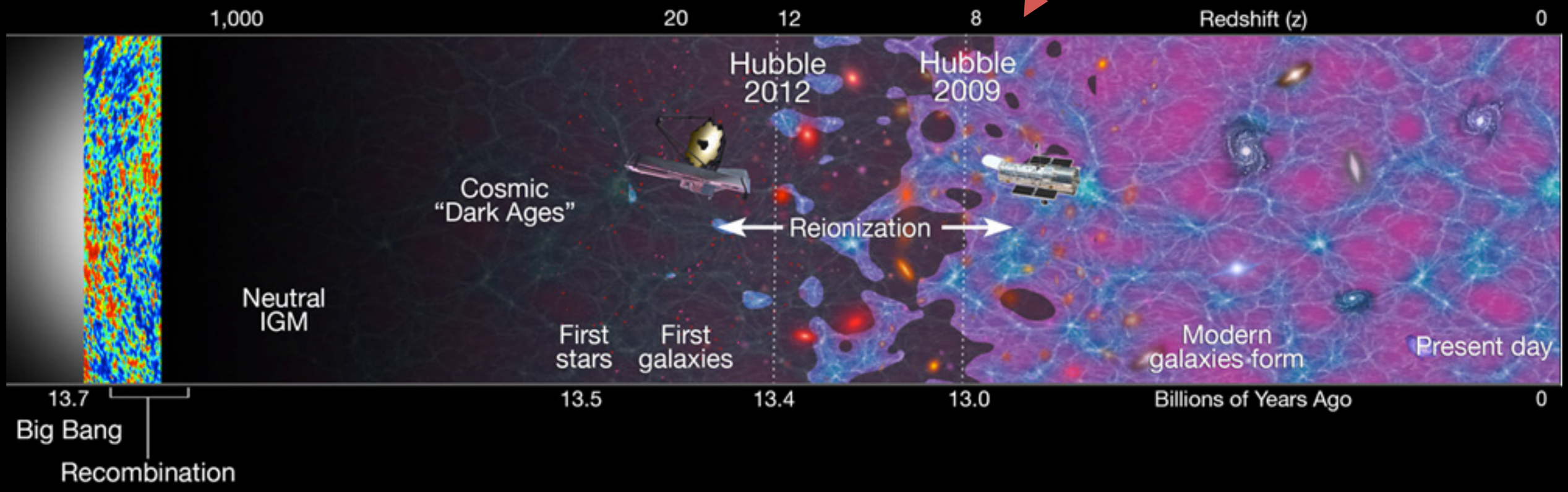
Too subdominant…
Maybe with next generation experiments
(PIXIE/PRISM)

Ricotti et al. (2008)

Re-ionization

Re-ionization changes optical depth to recombination: Tau

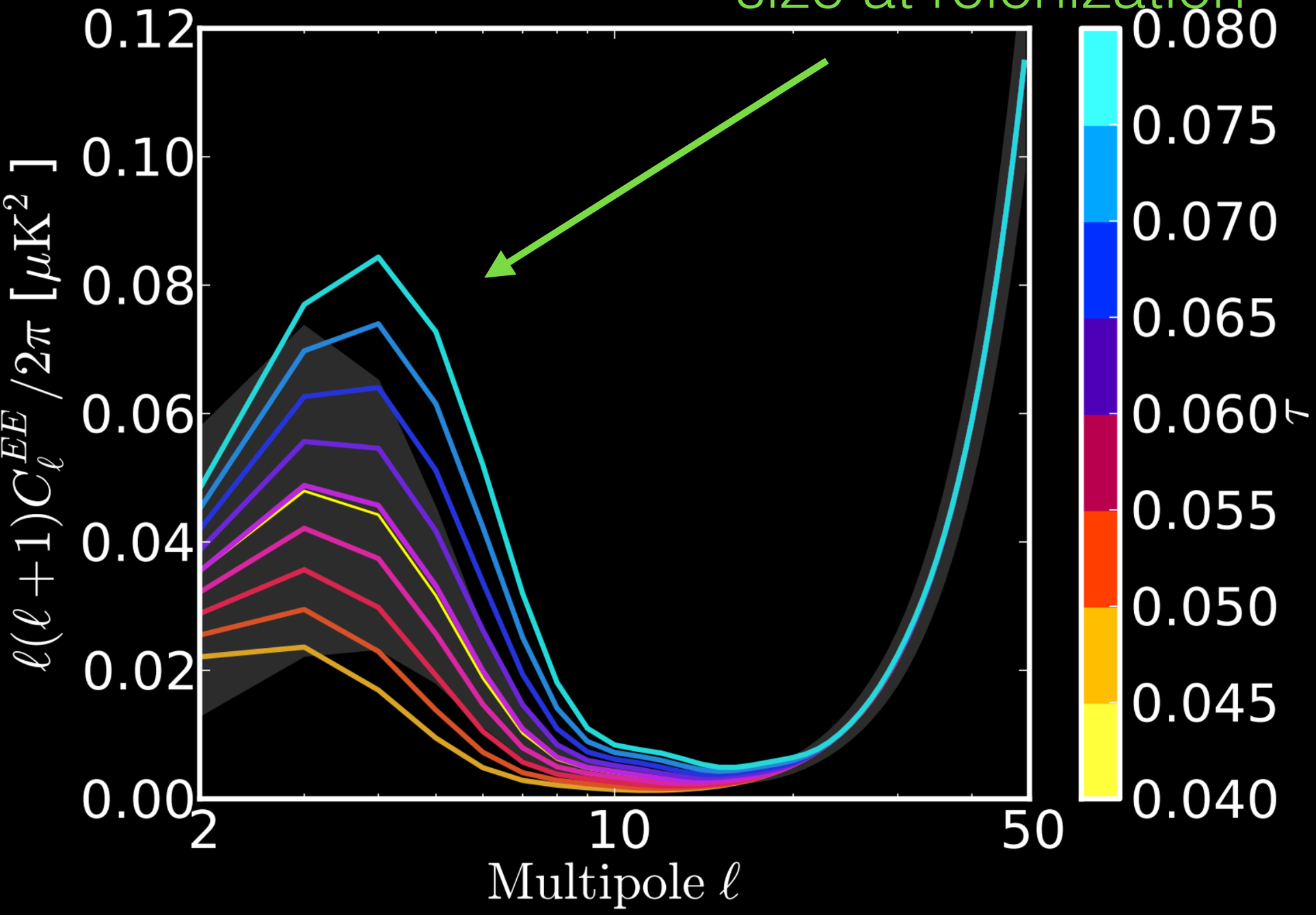
By z=6, fully ionized



Re-scatters light from CMB, suppressing small scale anisotropies

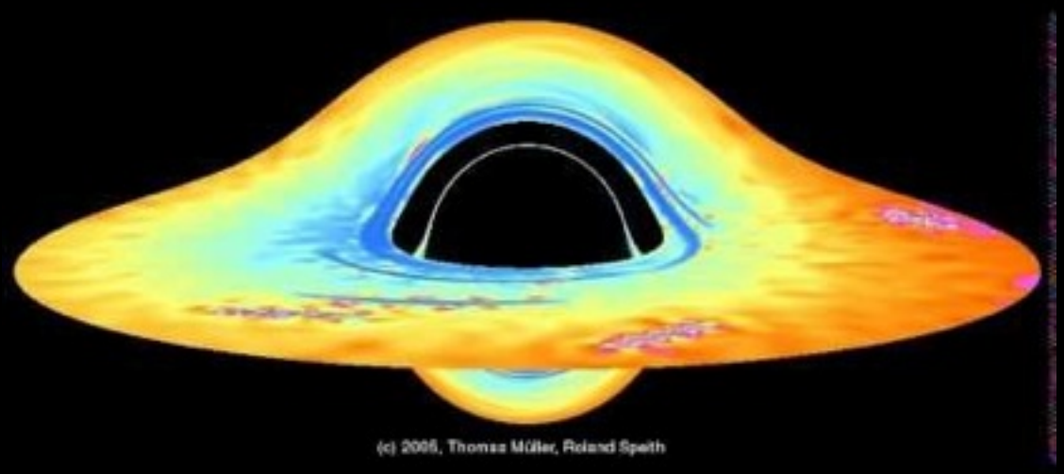
Ionization Bump in CMB

Corresponds to horizon size at reionization



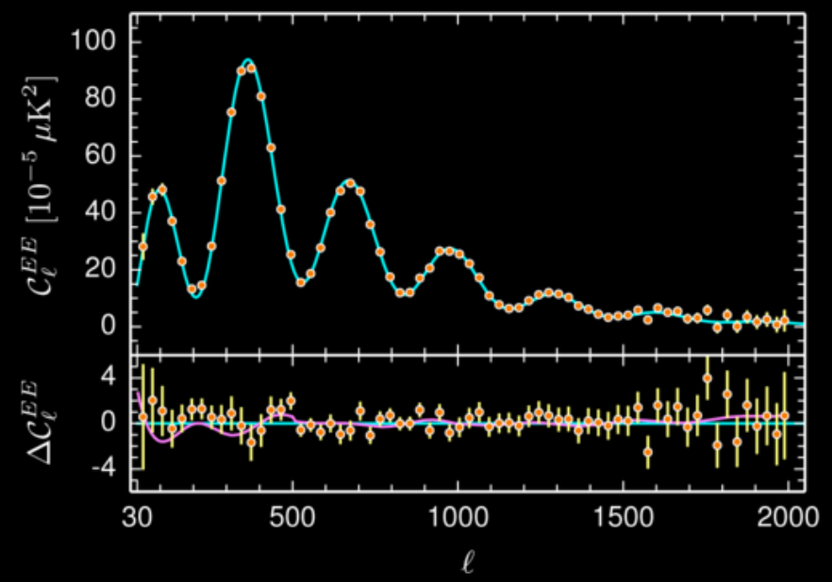
Model

Accretion



Ionization

CMB Effects



Spherical (Bondi) Accretion

mass infall as fraction of Eddington Mass

$$L = 0.011 \dot{m}^2 L_{Ed}$$

depends on gas viscosity

Depends on relative velocity between baryons and DM

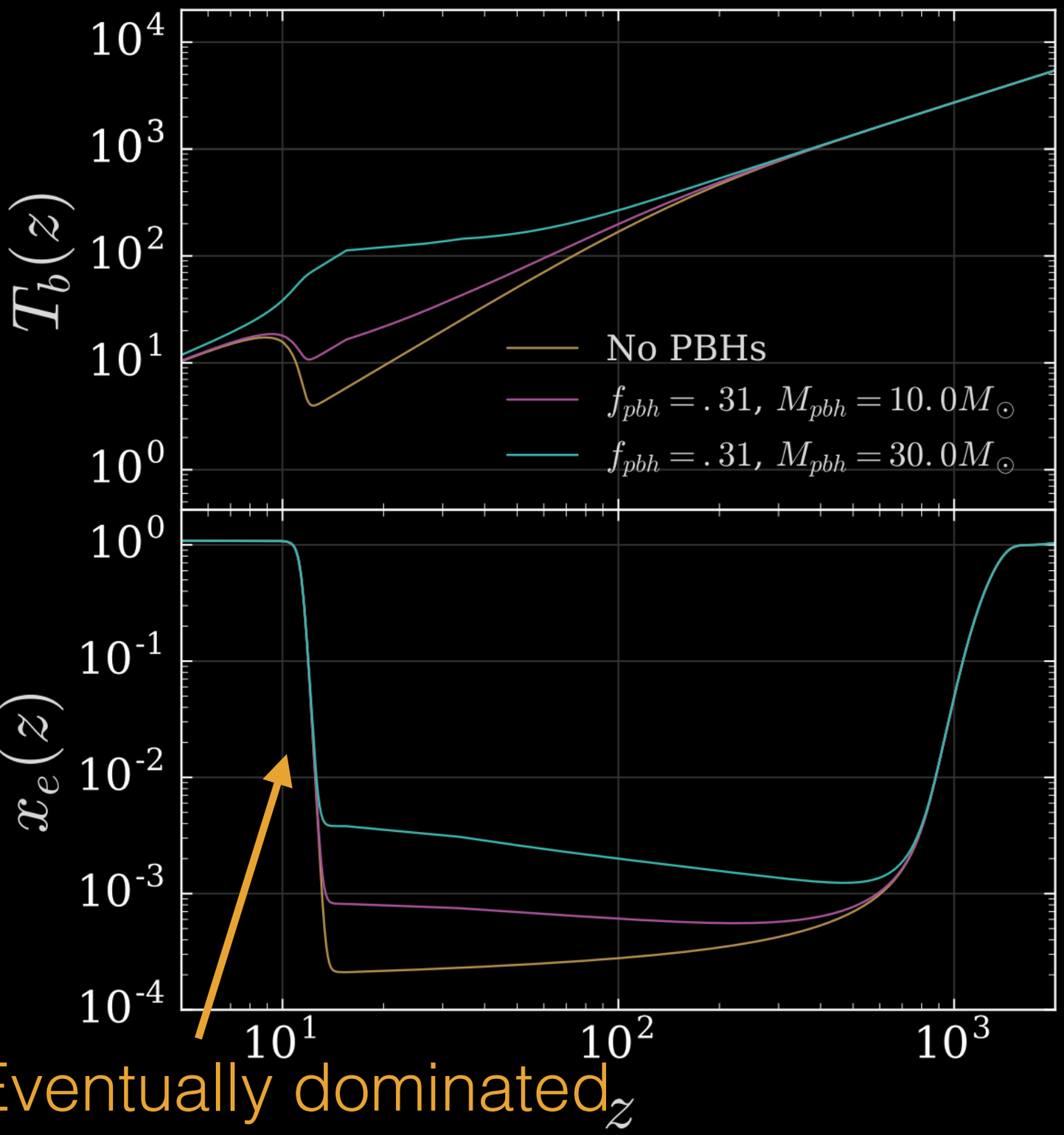
$$\dot{m} = (1.8 \times 10^{-3} \lambda) \left(\frac{1+z}{1000}\right)^3 \left(\frac{M_{pbh}}{1 M_\odot}\right) \left(\frac{v_{eff}}{5.74 \text{ km s}^{-1}}\right)^{-3}$$

Shapiro (1973)
Mack et al (2007)

Eddington Rates (for reference):

$$L_{Ed} \equiv 1.3 \times 10^{38} (\dot{M}_{pbh}/M_\odot) \text{ erg s}^{-1},$$
$$M_{Ed} \equiv L_{Ed}/c^2 = 1.44 \times 10^{17} (M_{pbh}/M_\odot) \text{ g s}^{-1}$$

Effect on Ionization History



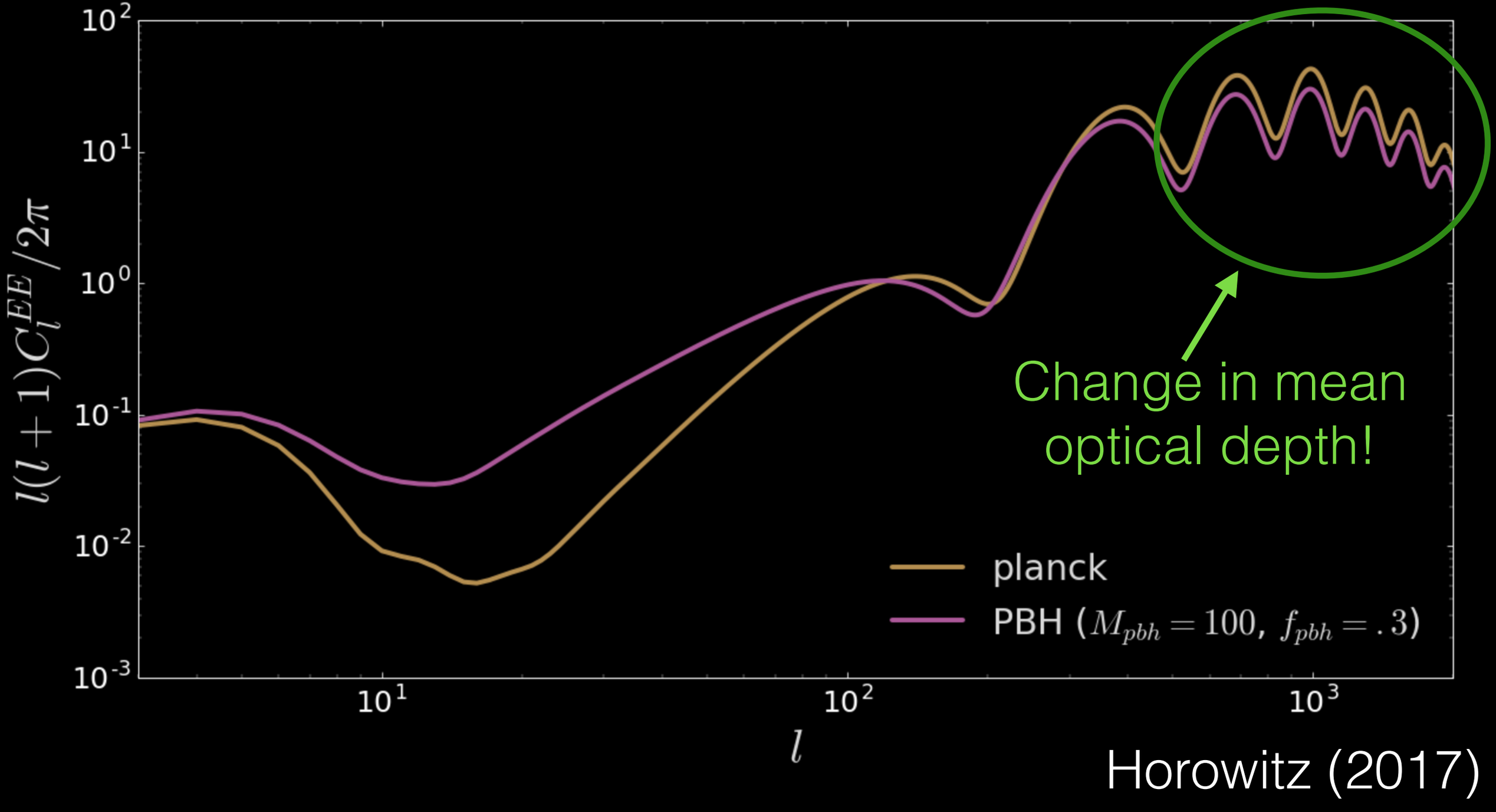
Eventually dominated by stars and AGN

Relative velocity decreases over time, more efficient accretion at late time!

Energy deposition model from Slatyer (2013)

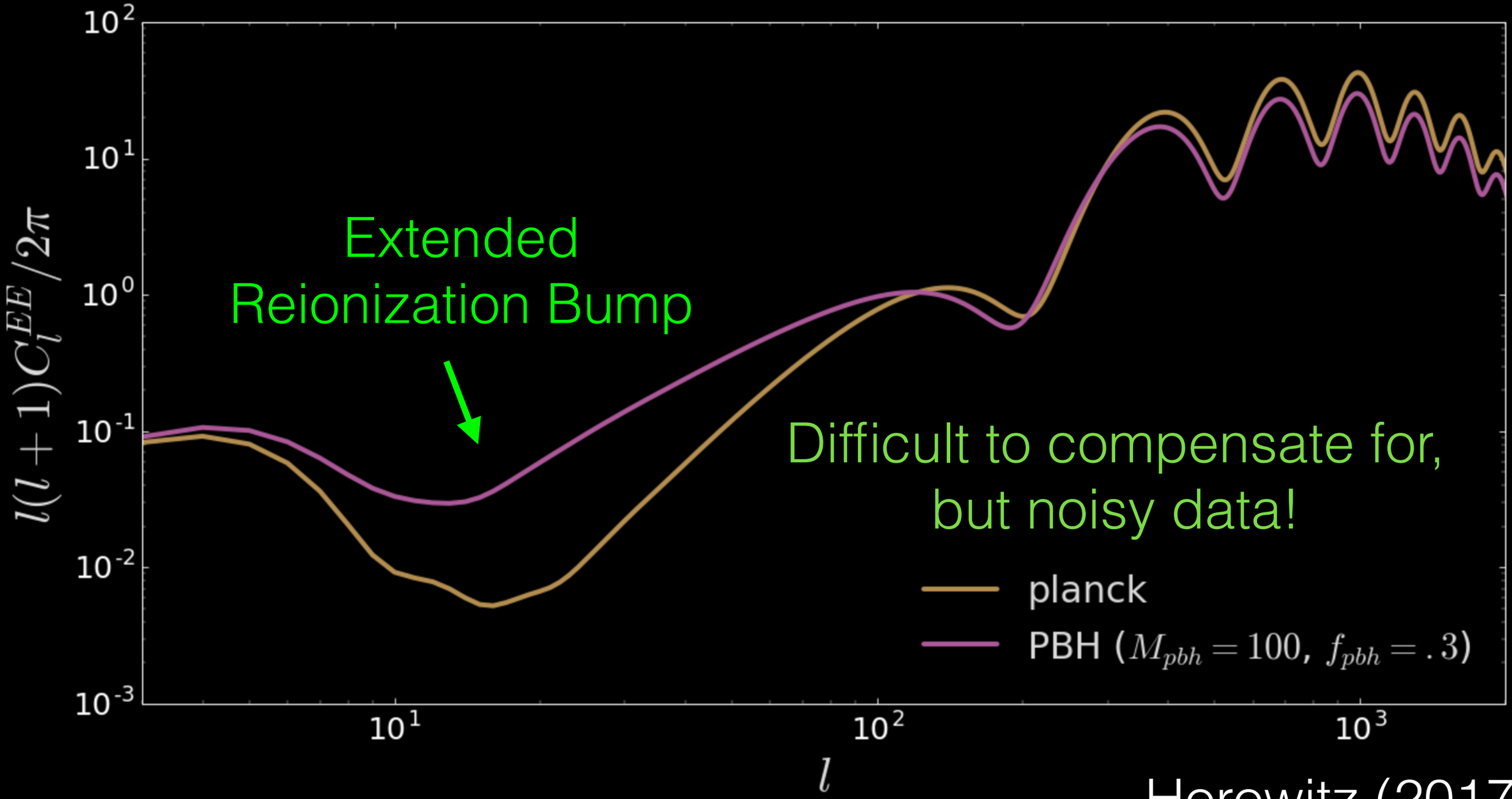
Horowitz (2017)

Effect on CMB (uncompensated)



Horowitz (2017)

Effect on CMB (uncompensated)

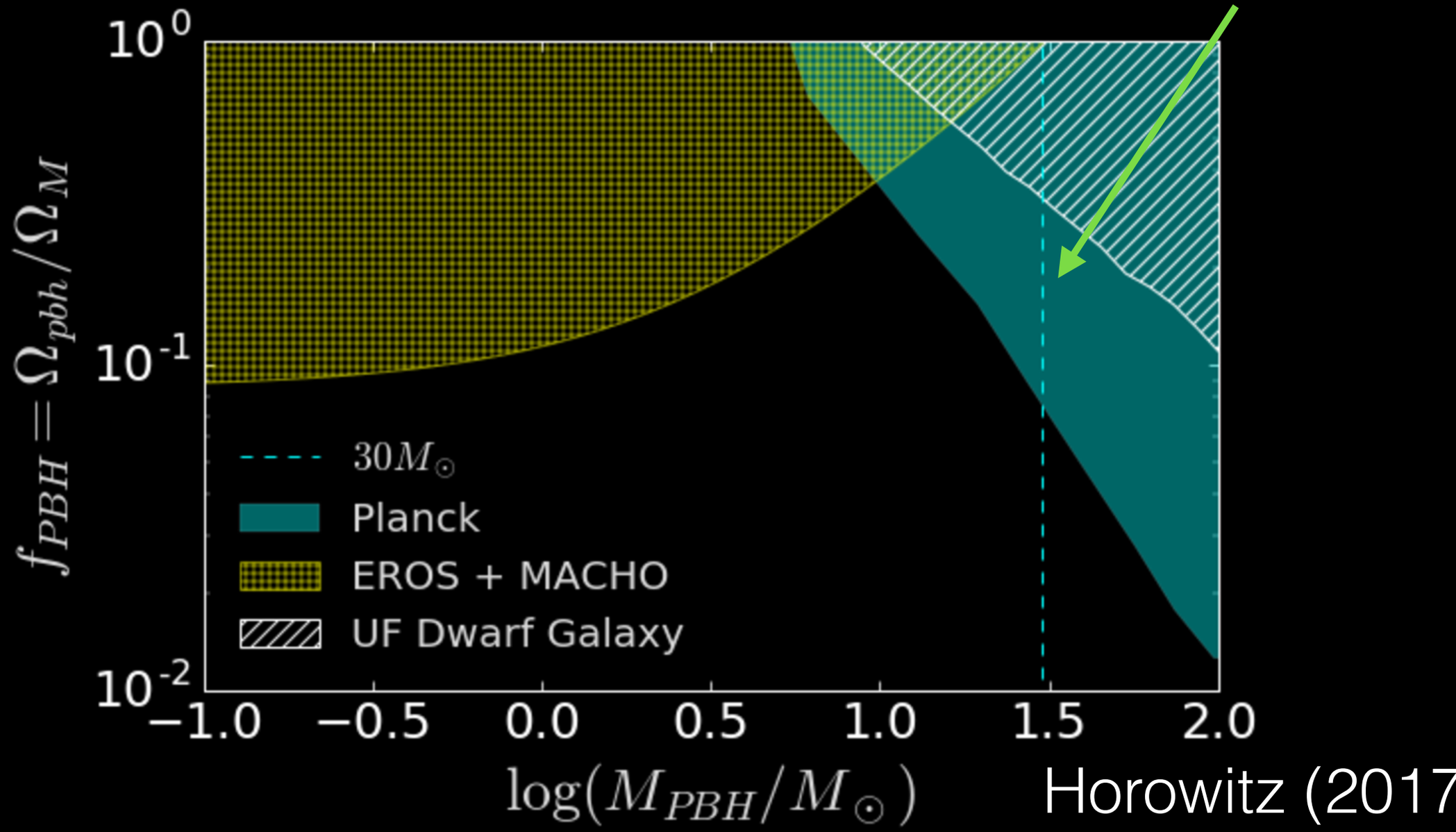


Horowitz (2017)

Final Constraint

Marginalize over cosmology

$(\Omega_b, \Omega_{cdm}, h, \tau, A_s, n_s) + (M_{pbh}, f_{pbh})$

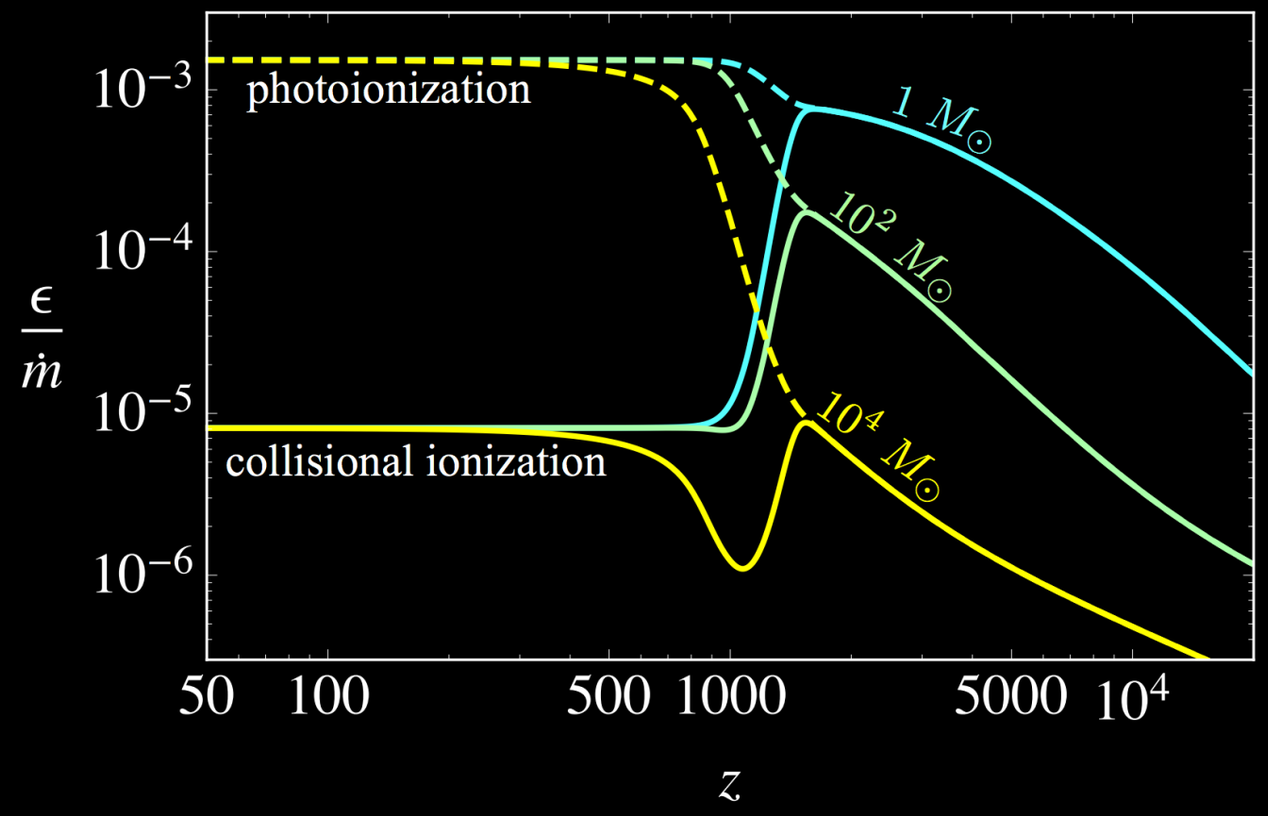


Horowitz (2017)

New Accretion Model that might be less efficient?

$$L = 0.011 \dot{m}^2 L_{Ed}$$

Not constant!
Depends on ionization fraction of the accretion zone!?



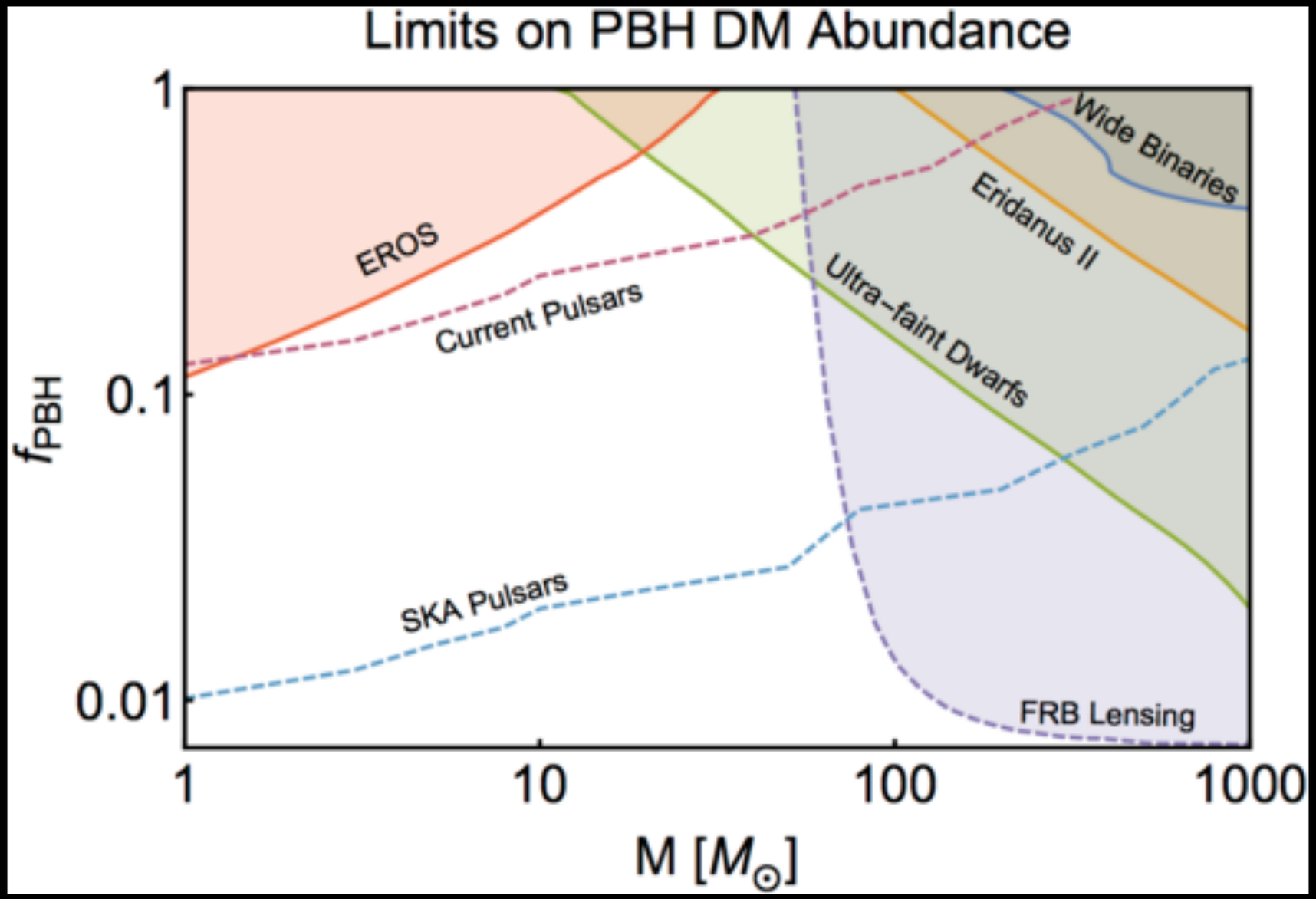
Ali-Haïmoud, Kamionkowski (2016)

Questions going forward…

- Accretion model is fairly rudimentary and conservative; how would a more realistic accretion model improve the constraint bounds?
- What are the interesting bounds from the standpoint of seeding SMBHs?
- Are there other ways to distinguish between astrophysical black holes and PBHs from their GW signal? Eccentricity of orbits? (Cholis et al. (2016))
- New CMB data might significantly increase this constraint!

THANKS!

Other Constraints on PBHs



Schutz, Liu (2016)

Extended Function (Log-Normal)