Primordial Black Holes

and their effect on the cosmic ionization history

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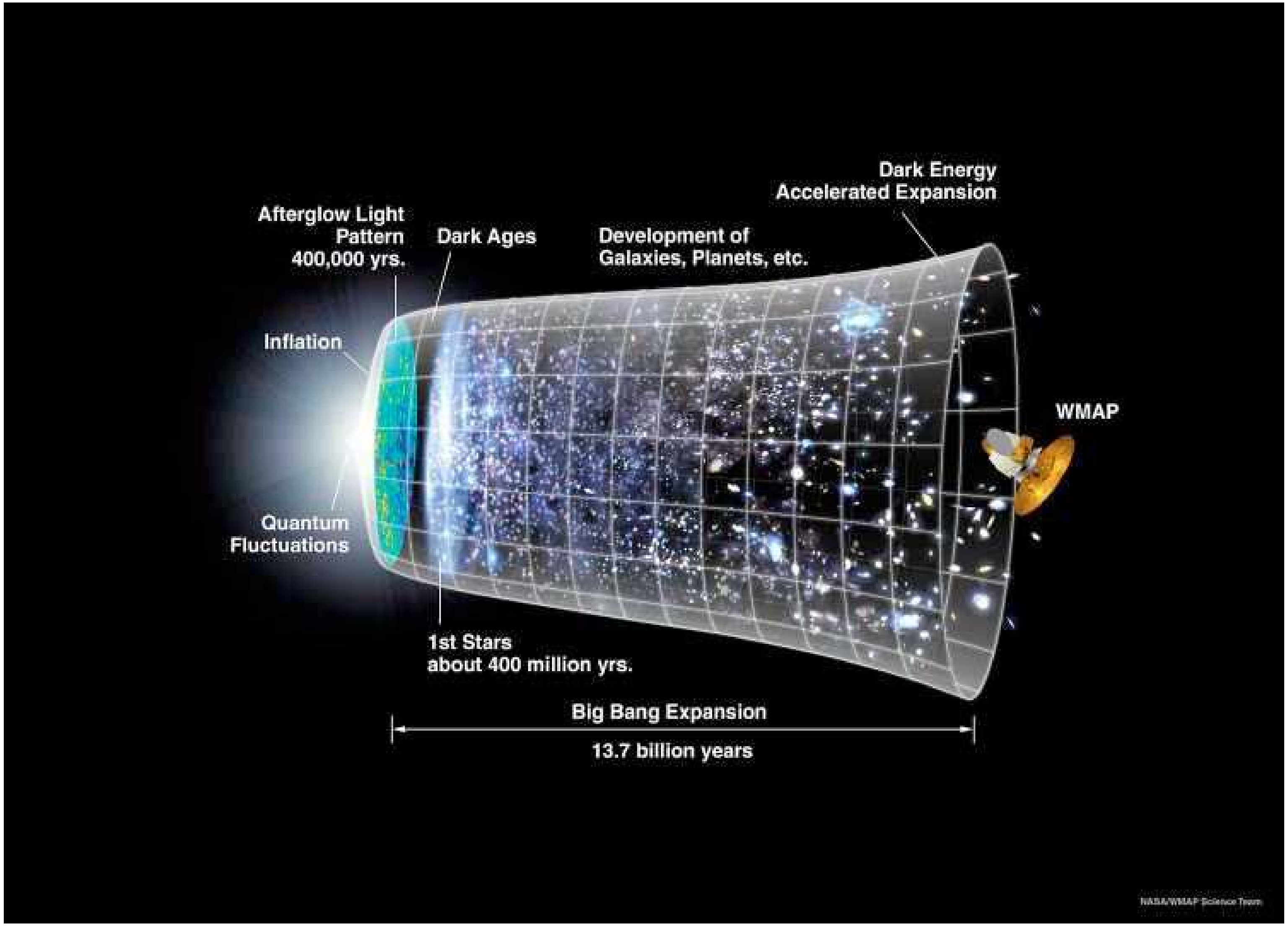
Outline

- What are PBHs and why we do we care?
- Modelling accretion onto PBHs:
  - Growth of DM halos, modified Bondi solutions
  - PBHs motions and feedback processes
- Effect on the ionization history
- Effect on the CMB, new obs. constraints and Implications

Hot Big Bang theory



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1. Collapsed radiation (relativistic matter)
2. Mass comparable to the Horizon mass at formation
3. Form in quasi-linear regime: 50%
4. Tiny collapsed fraction during rad. era may produce all the dark matter!

Newtonian limit easy to understand: During radiation era

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Any linear perturbation $>$ $_{cr}$ 0.1 0.7 collapses into PBH with mass $M_{pbh} = f_{Hor} M_h$ where $f_{Hor} < 1$

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Collapsed fraction depends on the power spectrum of initial density fluctuations and the cosmic equation of state:

- $_{cr}$ w where P = w is the cosmic EOS
- (M, z) exp[($_{cr}$/2 (M, z))^2] (assuming Gaussian fluctuations)

Radiation is redshifted away, PBHs are not:

$$_{pbh} = (1 + z_f)/(1 + z_{eq})$$

$$f_{pbh} = \frac{_{pbh}}{_{dm}} \quad \left(\frac{M_{pbh}}{1\ M}\right)^{1/2} \quad \frac{}{10^{\ \ 9}}$$

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- Example:
  - During QCD phase transition at $t = 10^{\ 5}$ sec
  - $M_{pbh} \quad M_h = 1\ M$
  - if $= 10^{\ 9} \quad f_{pbh} \quad 1$: all the dark matter is made of PBHs

Some models for PBH formation

1. Softening of the EOS during phase transitions: QCD (1 M) or e^+ e annihilation (10^5 M)(Kholopov & Polnarev 80; Jedamzik 97)

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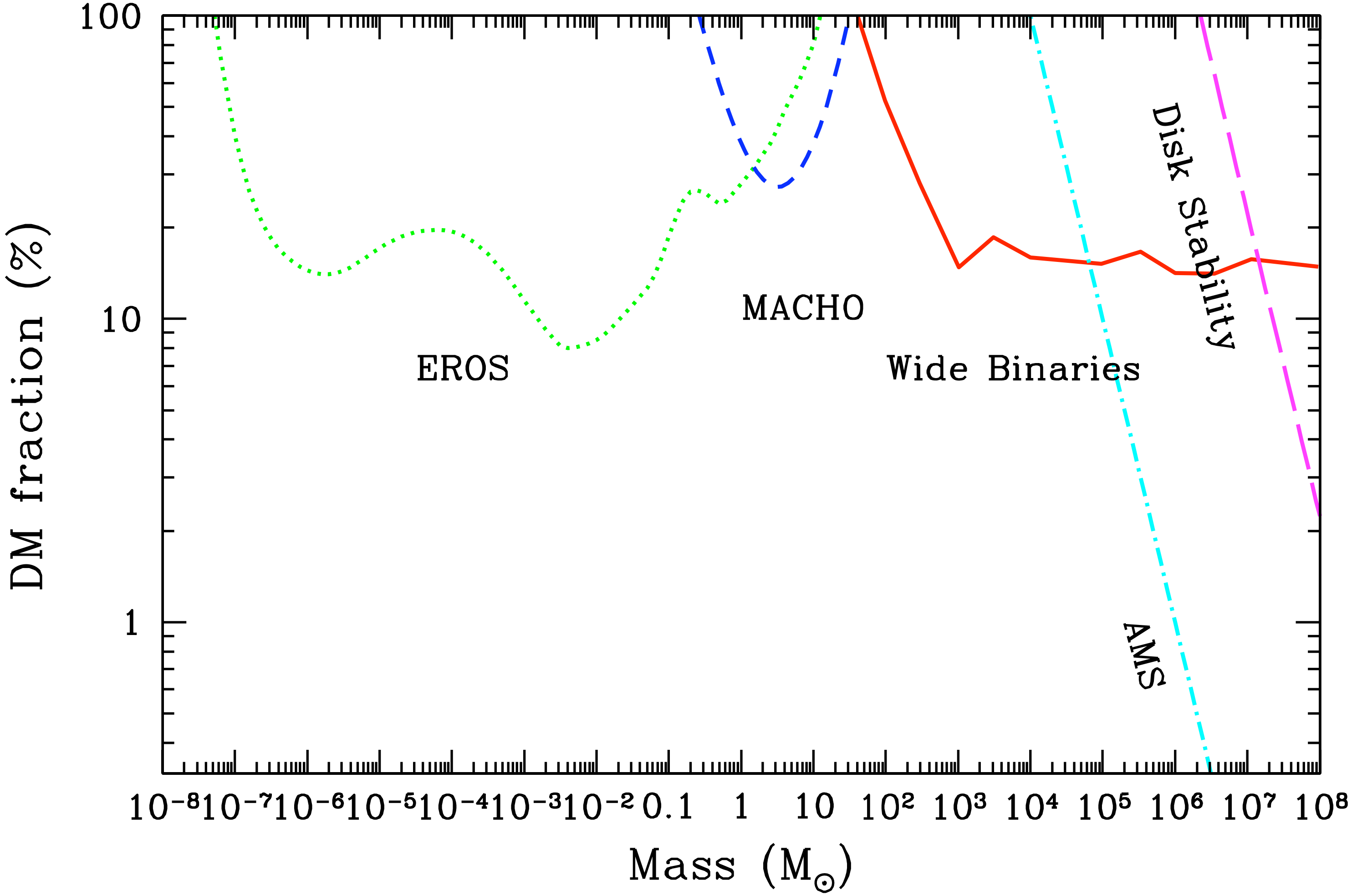
3. Collapse of cosmic string loops (*e.g.*, Polnarev & Zemboricz 88; Hawking 89; Brandenberger & Wichoski 98)
4. Bubble collisions (*e.g.*, Crawford & Schramm 82; La & Steinhardt 89)
5. Collapse of domain walls (Berezin et al 83; Ipser & Sikivie 84; Rubin et al. 00)

Do PBHs exist?

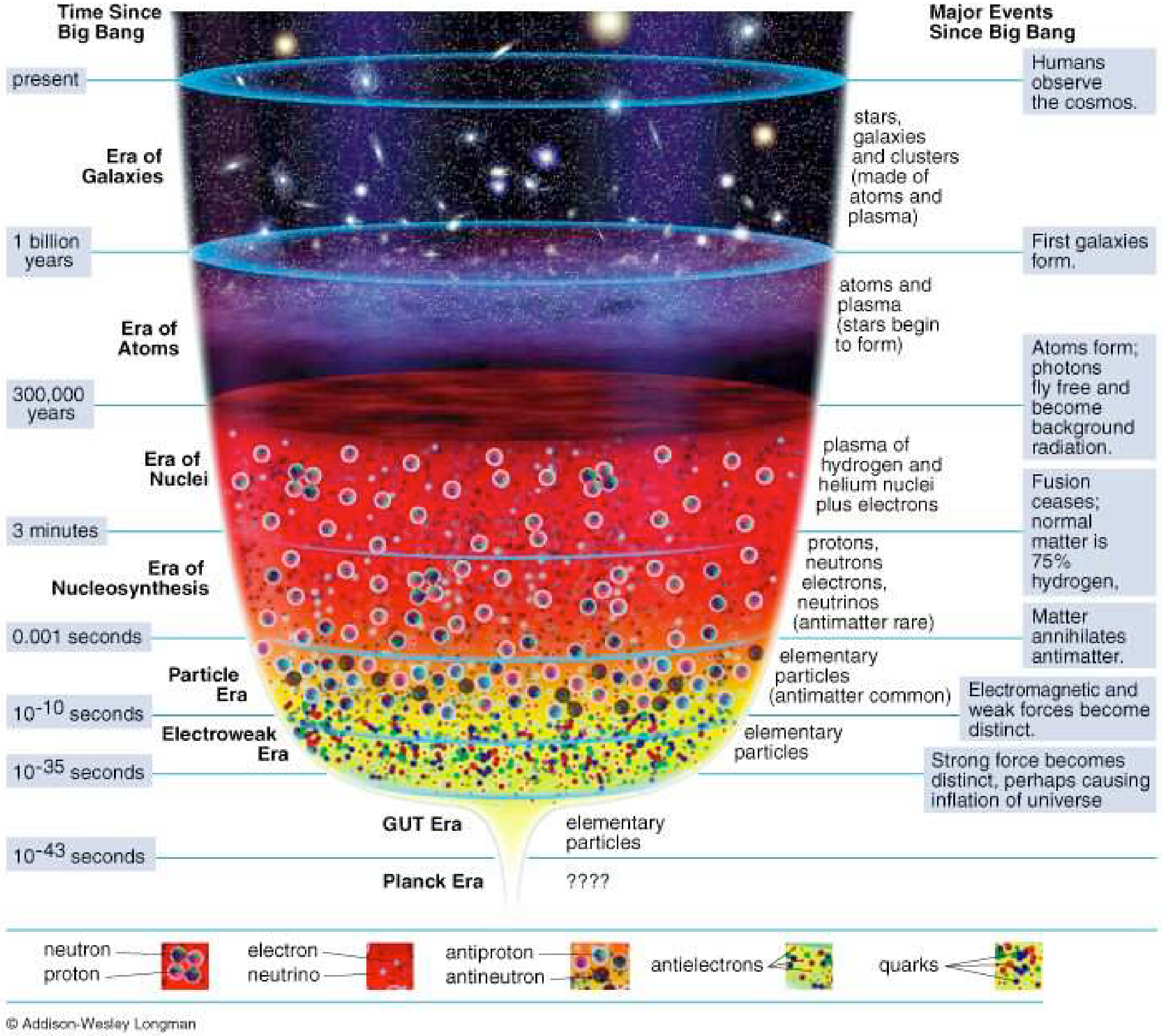
- PBHs with mass $< 10^{15}$ g evaporate in $t < t_H$ (Hawking 1975)
  - Abundance of PBHs with mass $1\text{ g} < M < 10^{15}$ g is $< 10^{\ 20}$ $10^{\ 22}$ (*e.g.*, Carr 2003)
- More massive PBHs are poorly constrained:
  - They may constitute the bulk of the dark matter
  - MACHO collaboration: 20% of Milky-Way halo is in compact objects with M 0.1 1 M (but 2000 result, non confirmed by later data)



Refs: MACHO collaboration [*e.g.*, Alcock et al. (1998, 2000, 2001); Hamadache et al. 2006]; EROS collaboration; Lacey & Ostriker 85; Moore 93; Carr 94; Afshordi, McDonald & Spergel

Why do we care?

1. Physics on scale otherwise unaccessible by observations



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2. The dark matter can be made of PBHs
3. Produce MACHOS, IMBH and ULXs ?
4. Seeds for supermassive Black Holes?

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Physics of PBHs accretion: Outline

Gas accretion onto PBHs produce X-rays and affect the ionization history of the IGM

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2. Gas viscosity: Compton Drag and Hubble flow
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4. Angular momentum of accreted gas and dark matter
5. Feedback processes (global and local radiative feedbacks)

1. Clothing Dark Matter Halo

1. PBHs seed accumulation of dark halo ($f_{pbh} < 1$)
2. The gas accretion rate onto the PBH is increased!

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- growth of order unity during radiation era
- $M_h = 3M_{pbh} \left(\frac{1+z}{1000}\right)^{1}$
- Self-similar secondary infall solution (*e.g.*, Bertschinger 1985)
- Truncated power-law density profile with = 2.25
- Truncation at $r_h = r_{ta}/3$

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2. Bondi type accretion

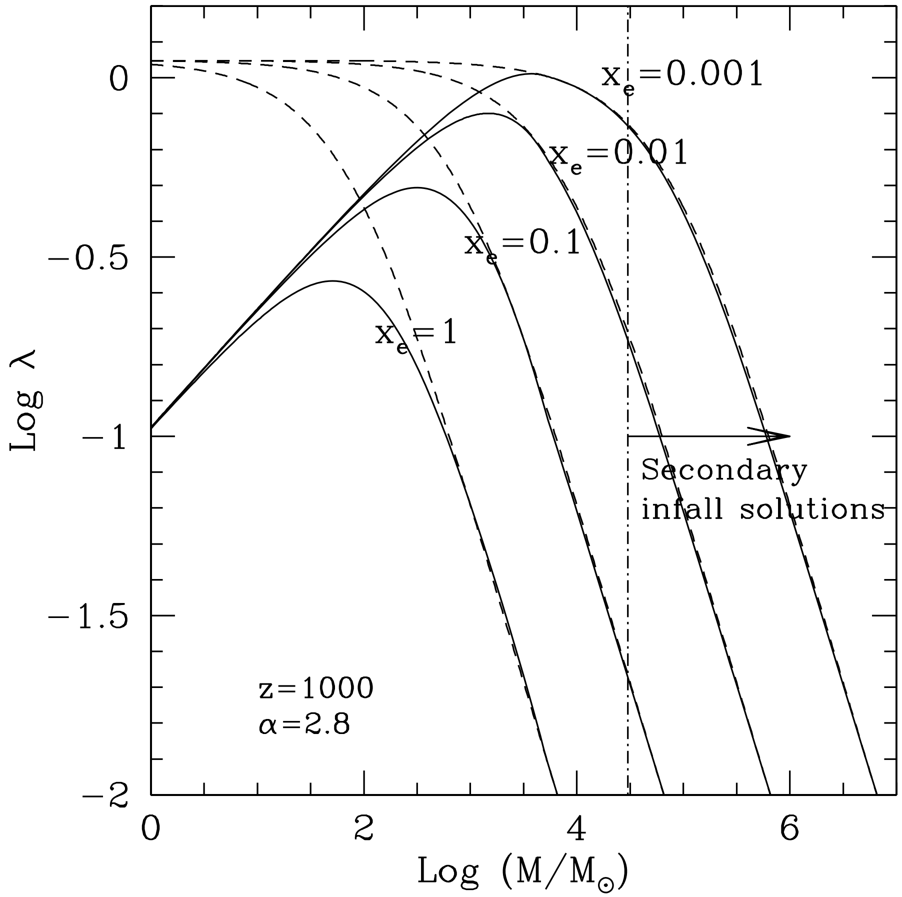
- Spherical accretion ( )
- Steady-state (M < 2 10^4 M ,)
- Viscosity (Compton drag)

$$\frac{dv}{dt} = \quad \frac{4}{3}\frac{x_e \quad {}_T U_{cmb}}{m_p c} v = \quad v$$

- Hubble expansion (M > 2 10^4 M ,)
- Clothing dark halo (power-law density profile,)

Ref: `Ricotti (2007)`

Spherical accretion rate



- point mass potential (dashed curves)
- dark halo potential (solid curves)

3. Relative motion of PBHs and gas

$$\dot{M}_g \quad \frac{M^2}{v_{eff}^3}$$

where $v_{eff} = (v_{rel}^2 + c_s^2)^{1/2}$

1. Linear regime: Silk damping (i =baryons, dark matter)

$$V_i^{\ 2} = \frac{1.2_m H^2}{2\ ^2} \quad {}_0 \quad P_i(k) w_s^2(k, a) w_l^2(k, r_0) dk,$$

$$_i^{\ 2} = \frac{1.2_m H^2}{2\ ^2} \quad {}_0 \quad P_i(k) w_s^2(k, a)[1 \quad w_l^2(k, r_0)] dk.$$

2. Non-linear regime: capture by mini-halos

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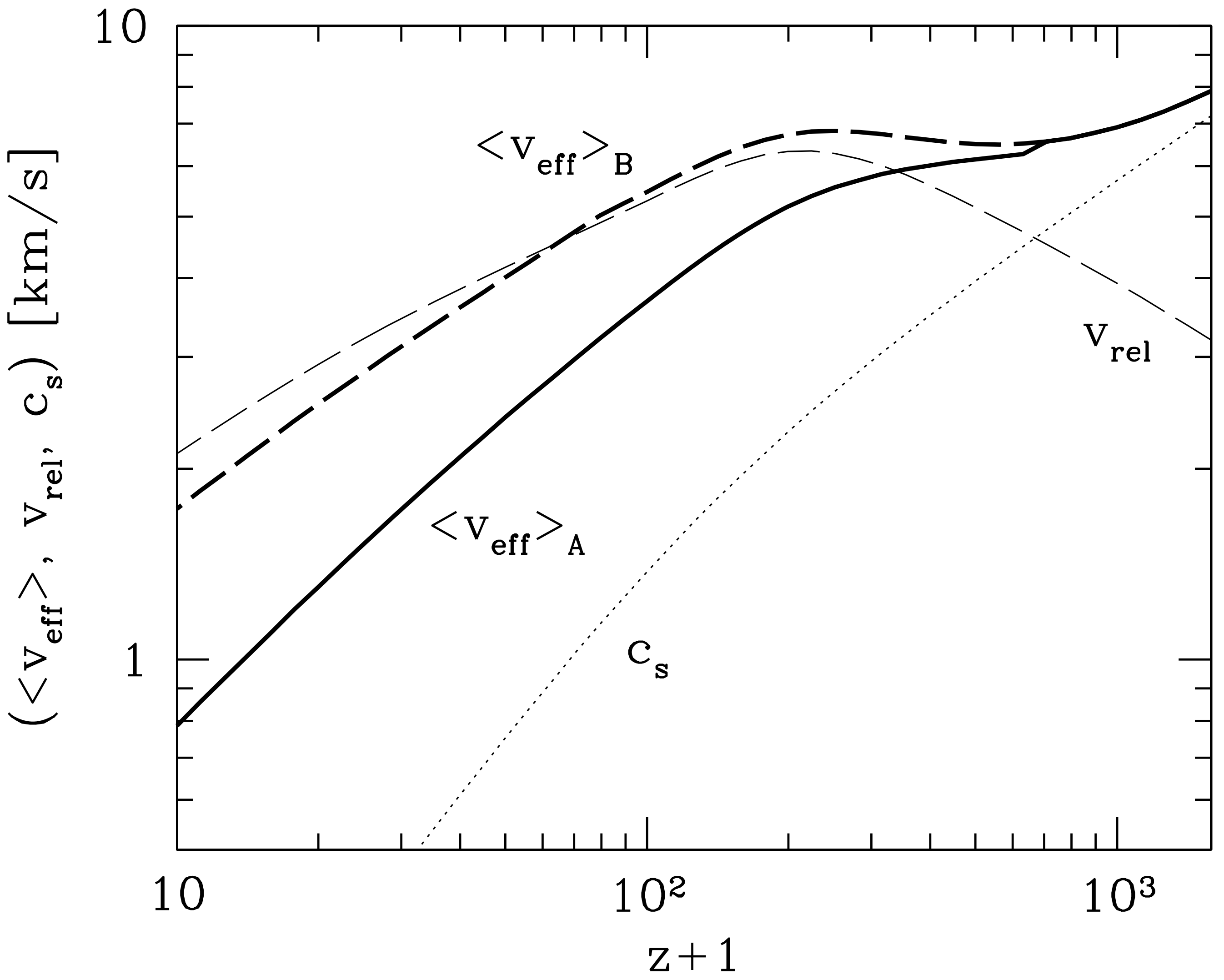

10
1
10
10^2
10^3
z+1
$(\langle v_{eff} \rangle,\ v_{rel},\ c_s)$ [km/s]
$\langle v_{eff} \rangle_B$
$\langle v_{eff} \rangle_A$
v_{rel}
c_s

Angular momentum of accreted material

- Dark matter:
  - Quasi-spherical accretion
  - Ang. momentum sufficiently large to avoid direct accretion of DM into PBH
- Gas:
  - Spherical accretion for $M < 500$ M
  - Compton drag reduces further ang. momentum (Loeb 93; Umemura et al 93)

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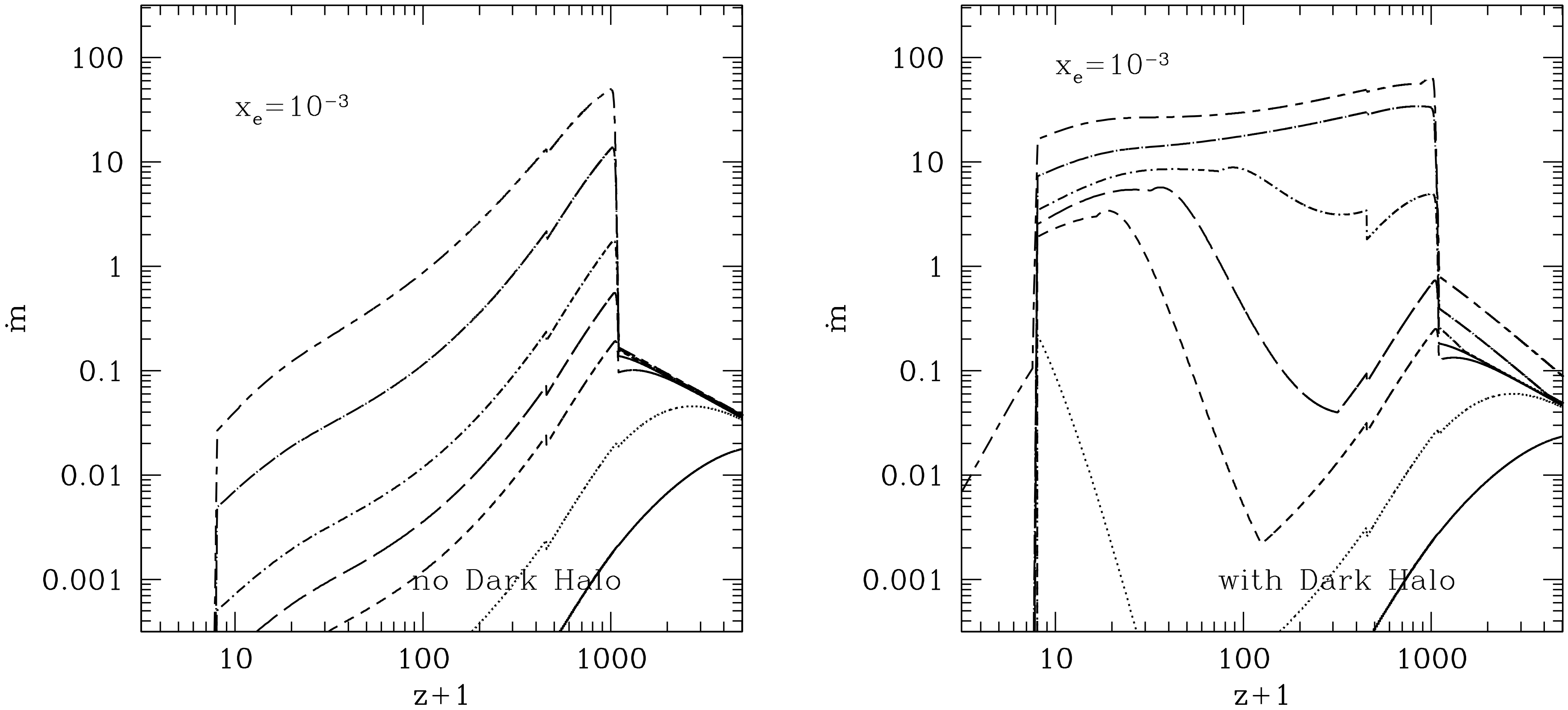
4. Accretion rate neglecting feedback



curves from bottom to top refer to masses of PBHs from

0.1 M to 10^5 M (factor of 10 spacing).

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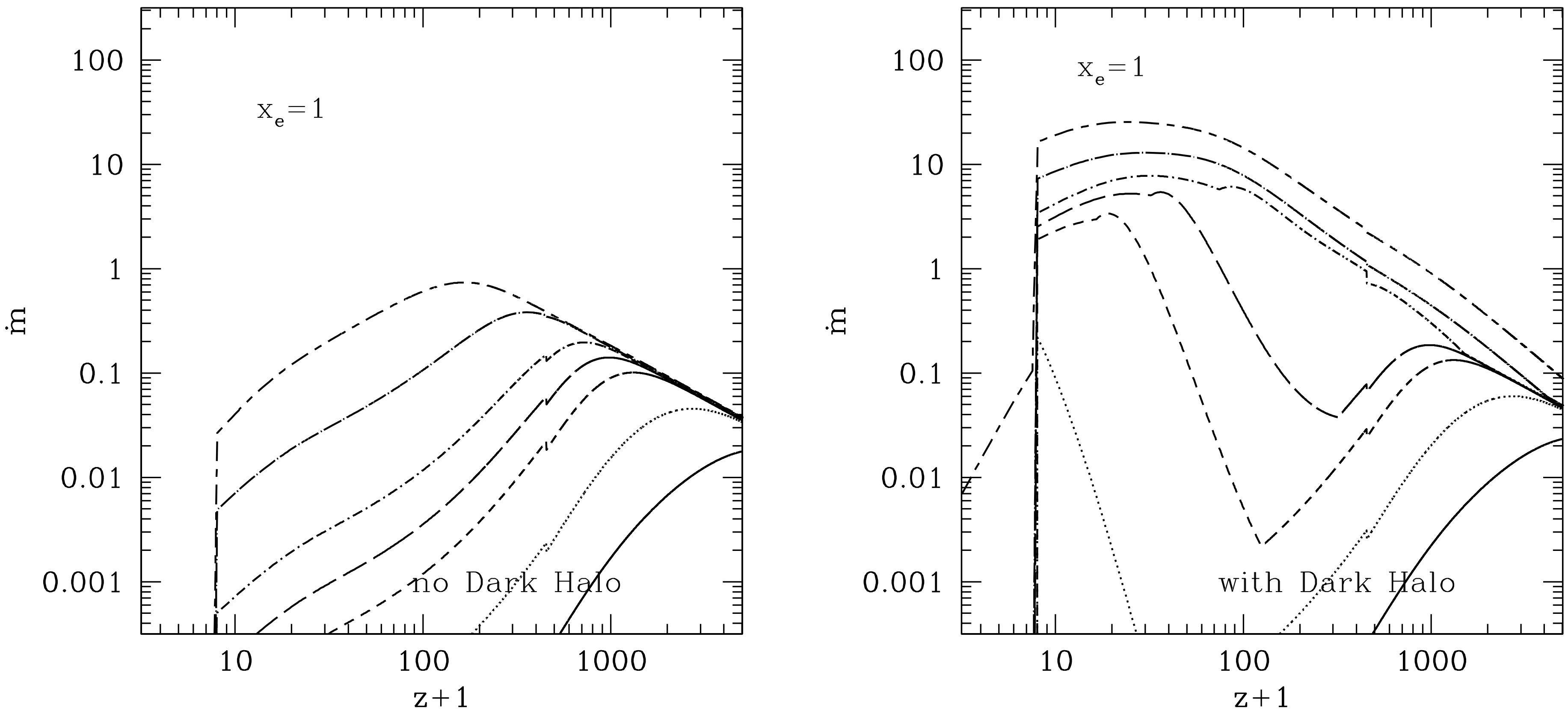


curves from bottom to top refer to masses of PBHs from $0.1\,M_\odot$ to $10^5\,M_\odot$ (factor of 10 spacing).

Accretion Luminosity

Define dimensionless luminosity $l = L/L_{Ed}$ and accretion rate $\dot{m} = \dot{M}/\dot{M}_{Ed}$, then:

$l = \ \dot{m}$, where is the radiative efficiency

We assume:

- $l = 0.01\dot{m}^2$ if $\dot{m} < 1$ (spherical accretion)
- $l = f_{duty}(0.1\dot{m}) < f_{duty}$ if $\dot{m} > 1$ (thin disk)

5. Feedback processes

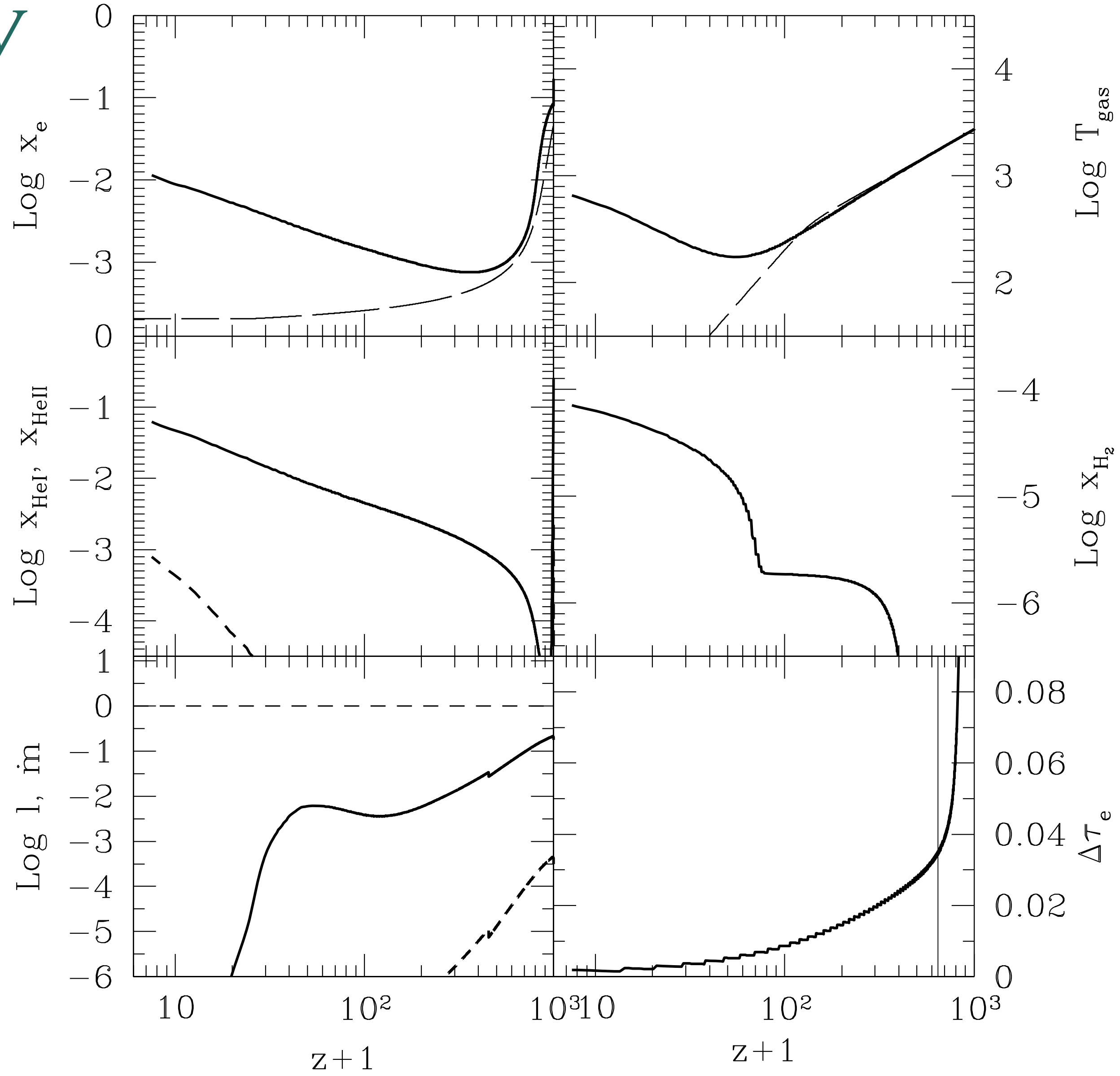
- Local feedbacks (typically negligible)
  - Size of H II region with respect to Bondi radius:
  - In most cases $r_{H\,II}/r_B < 1$
  - If $r_{H\,II}/r_B > 1$

$$I_t = \frac{I}{1 + t_{off}/t_{on}} = \frac{I}{1 + (r_{H\,II}/r_B)^{1/3}} = f_{duty} I$$

  - Temperature of H II region: $T_{H\,II} \quad T_{cmb}$
- Global feedback (X-ray heating):
  Iterative semi-analytic code (Ricotti & Ostriker 04)

Cosmic ionization, thermal, and chemical history

Simulations:
M_{pbh} = 100, f_{pbh} = 10^{-4}



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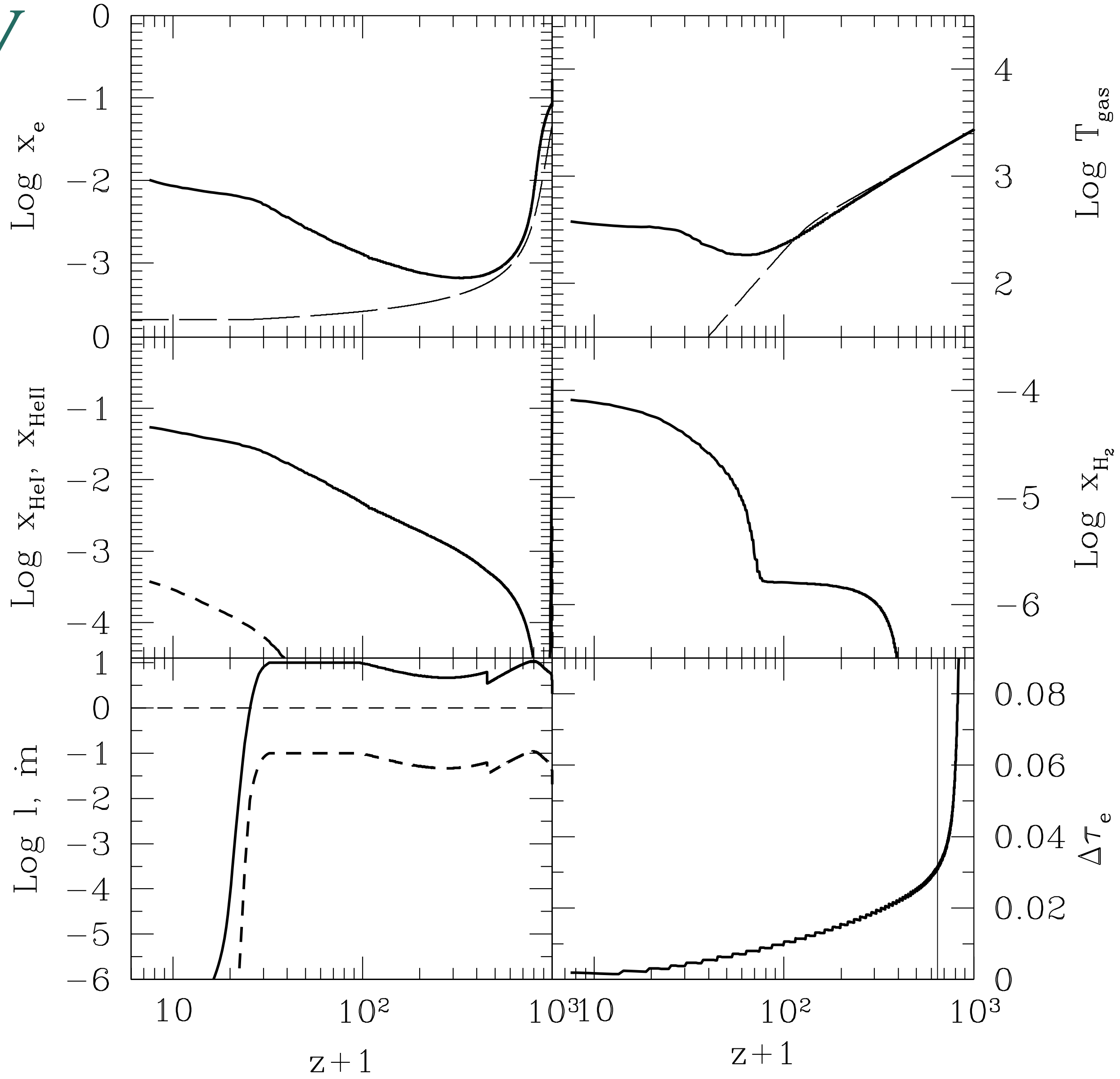

Simulations:
M_{pbh} = 1000,
f_{pbh} = $10^{\ 7}$

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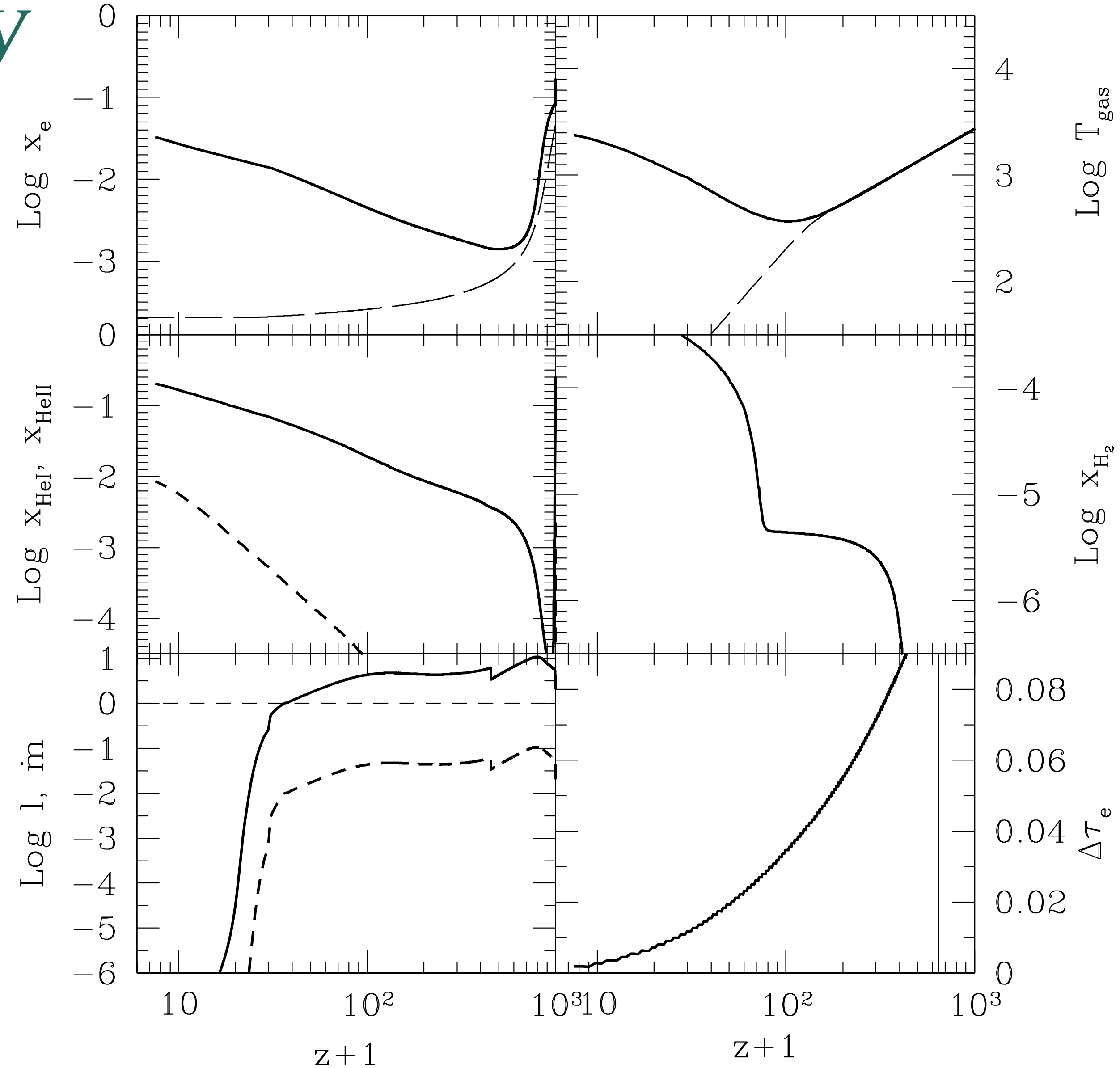

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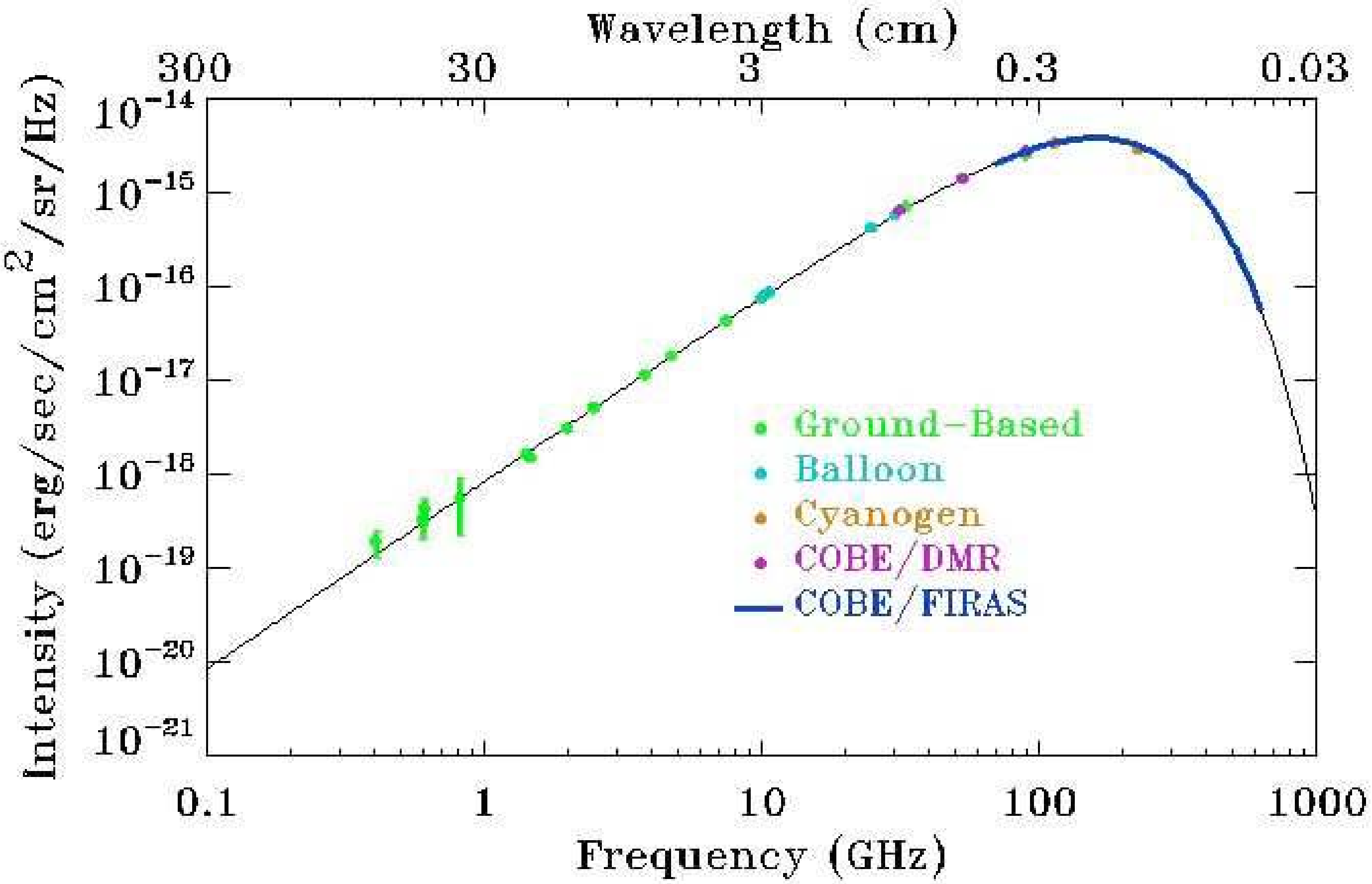
Spectrum of the CMB



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CMB spectral distortions

- $M_{pbh} < 10\ M$ weakly affected by Compton drag even before recombination
- FIRAS $y \quad 1.5 \quad 10^{5}$ at at 95% confidence
- 3 phases: $y = y_1 + y_2 + y_3 \quad y_1$
  1. $z_{rec} < z < z_{eq}$: all energy injected absorbed by gas
  2. $z_{dec} < z < z_{rec}$: fraction of energy absorbed by gas
  3. $z < z_{dec}$: Compton heating becomes negligible

Constrain on maximum energy injection imposed by:

$$y = \frac{1}{4U(z_{eq})} \quad {}_{z_{eq}}^{z_{rec}} \frac{dz}{aH(z)} \frac{d\ \ U(z)}{dt} \quad 1.5 \quad 10^{5}$$

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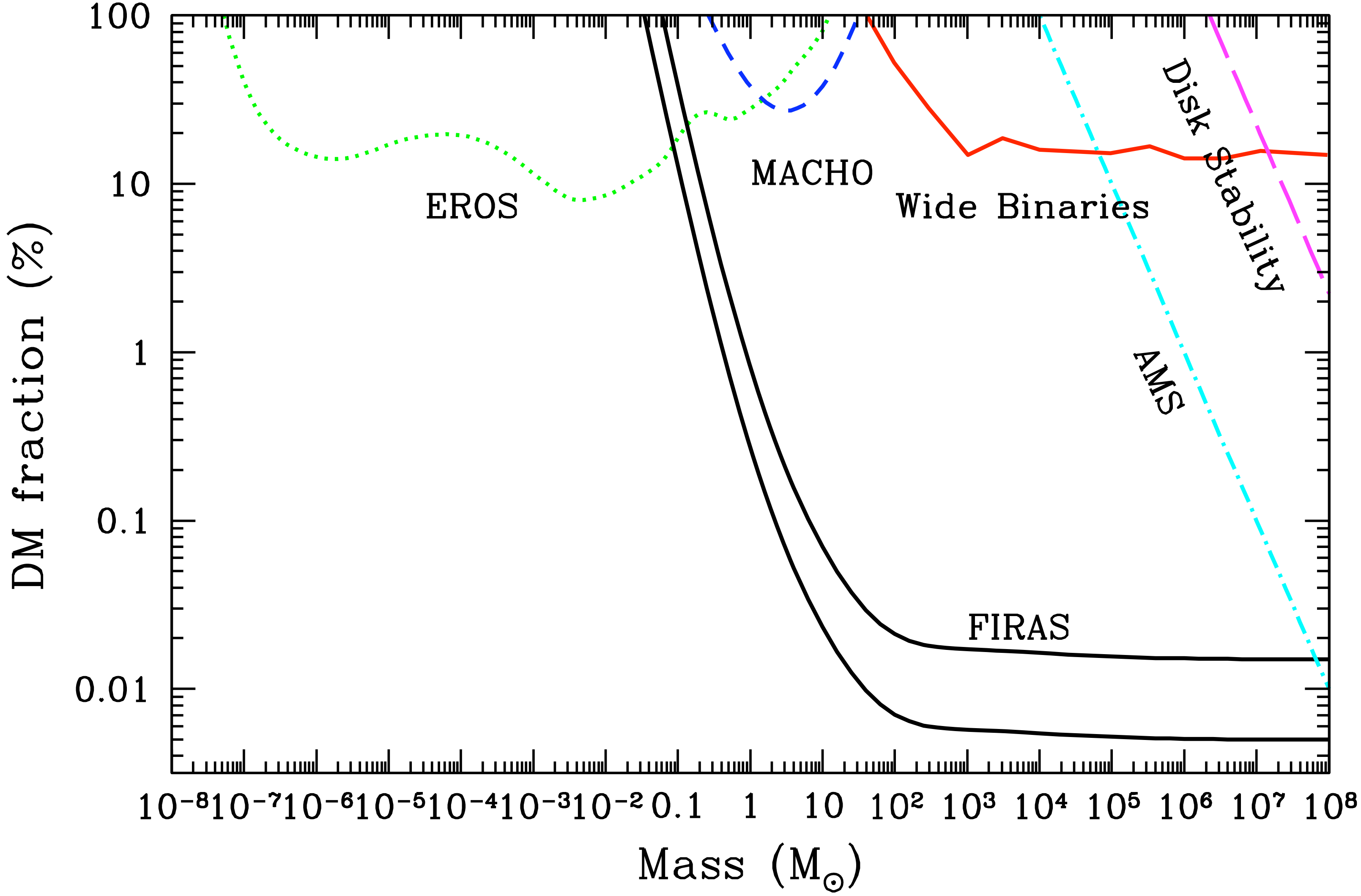
Constraints on f_{PBH}



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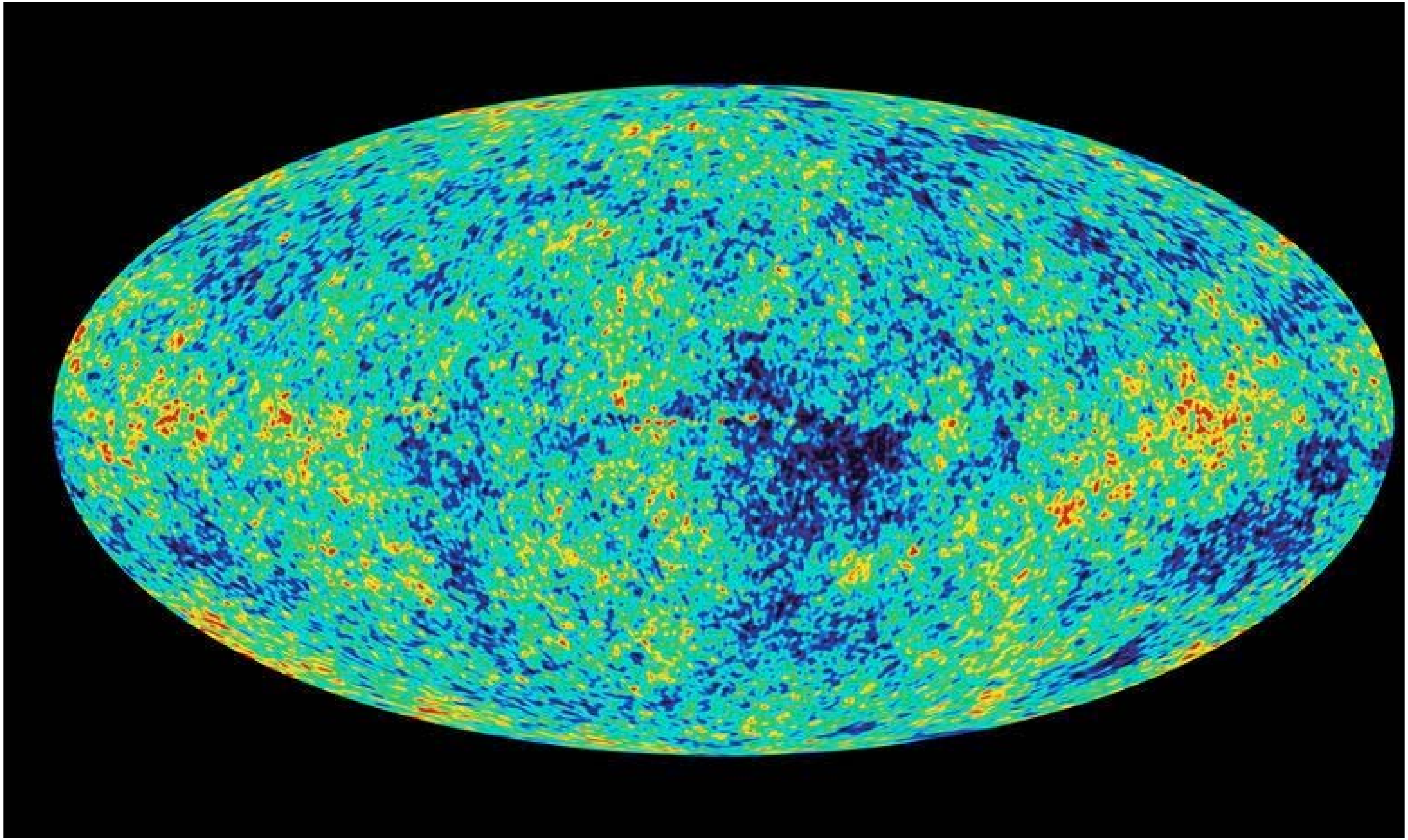
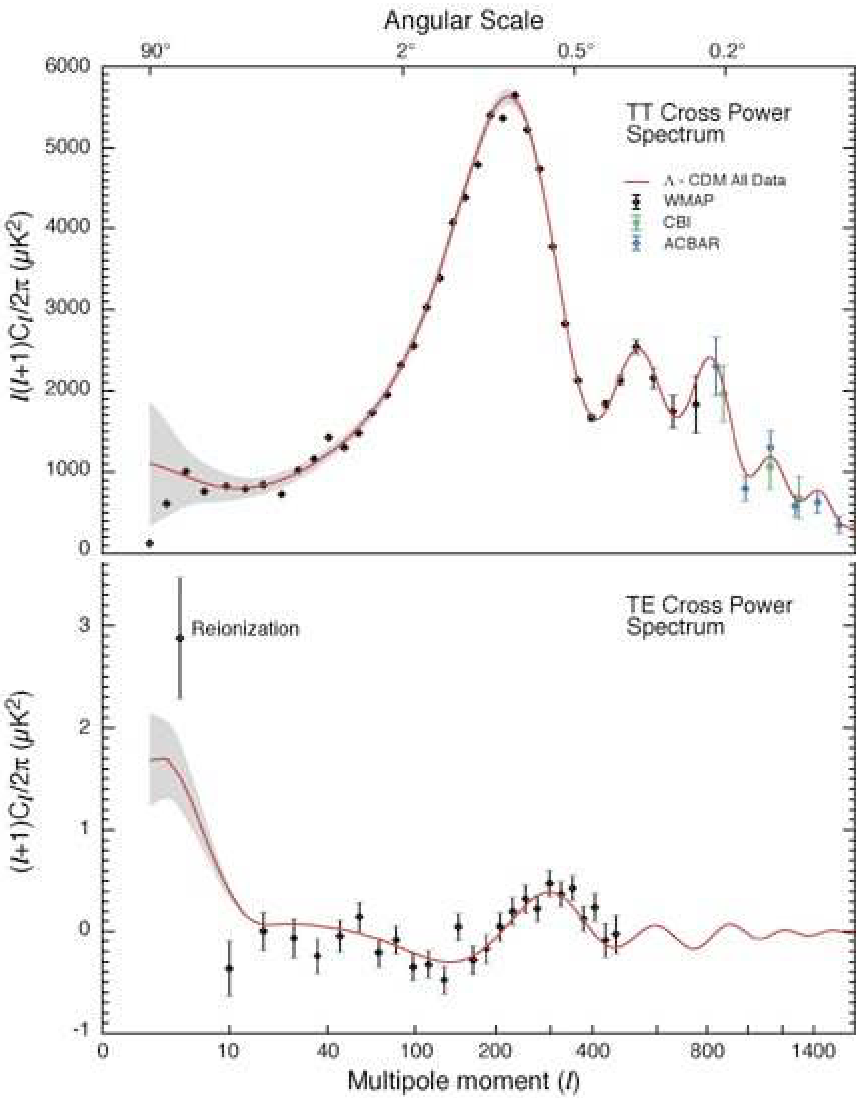
CMB anisotropies: WMAP



CMB anisotropies: spectrum

- Cosmological parameters: $_{m}$ = 0.24, = 0.76, h = 0.73
- Initial density perturbations: $_{8}$ = 0.74, n_{s} = 0.95 (little power at small scales!)
- Ionization history: z_{rei} = 12, $_{e}$ = 0.1



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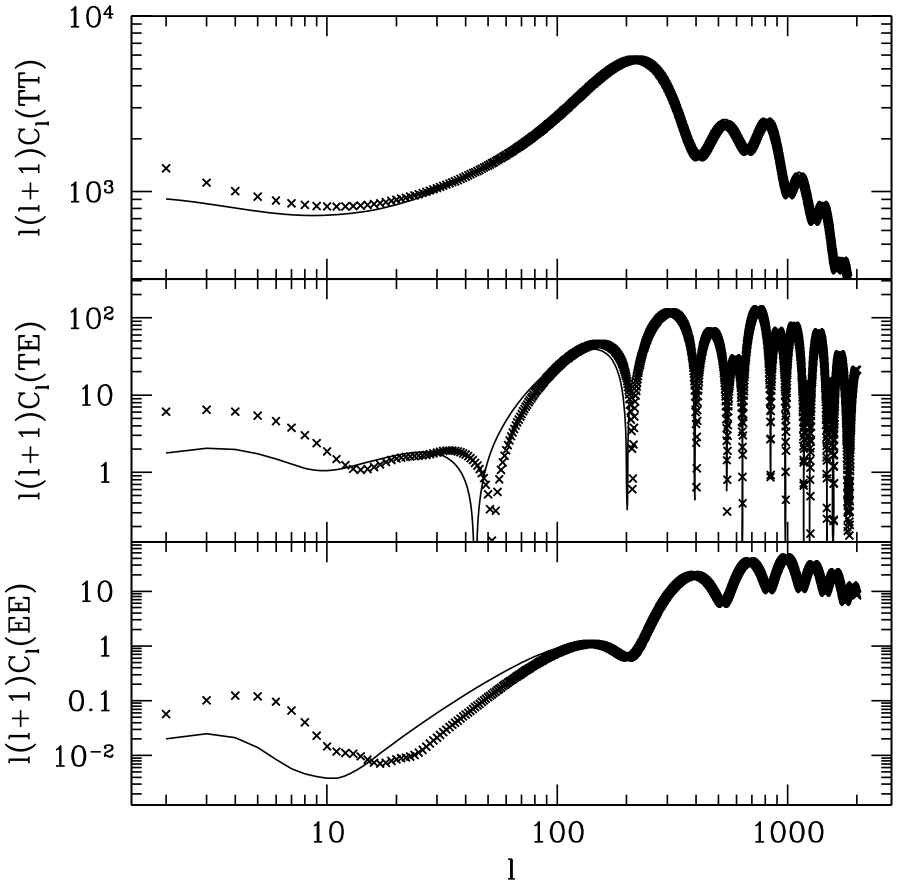
Effects of PBHs on CMB anisotropies

- Affects recombination
- Complementary and uncorrelated to reionization effects
- Affect small angular scales: l>10



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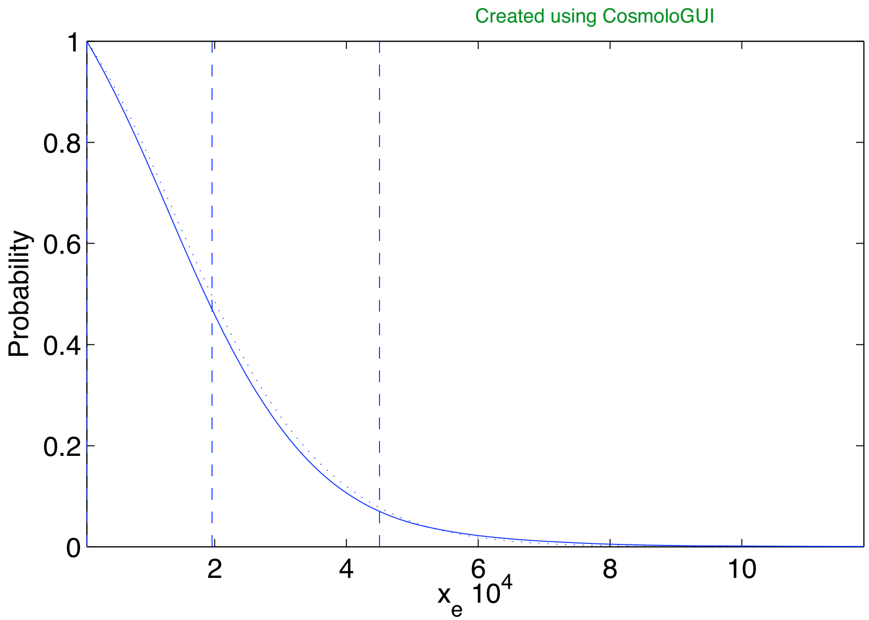
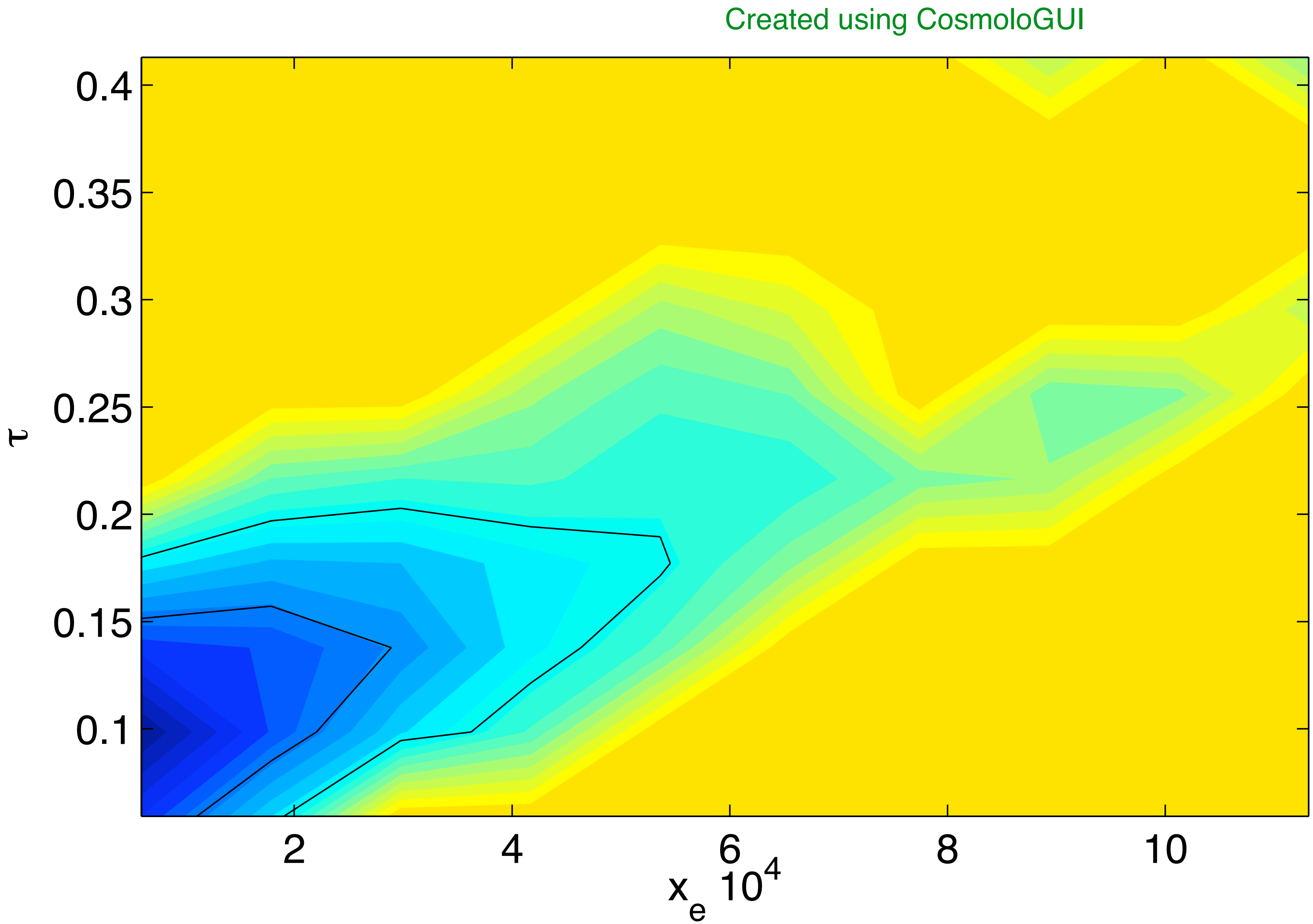
Modified recombination history

$$x_e(z) = x_{e,rec}(z) + \min\left(x_{e0}\left(\frac{1+z}{1000}\right)^{1}, 0.1\right),$$



RECFAST: Seager, Sasselov & Scott 99;
COSMOMC: Lewis & Bridle 02



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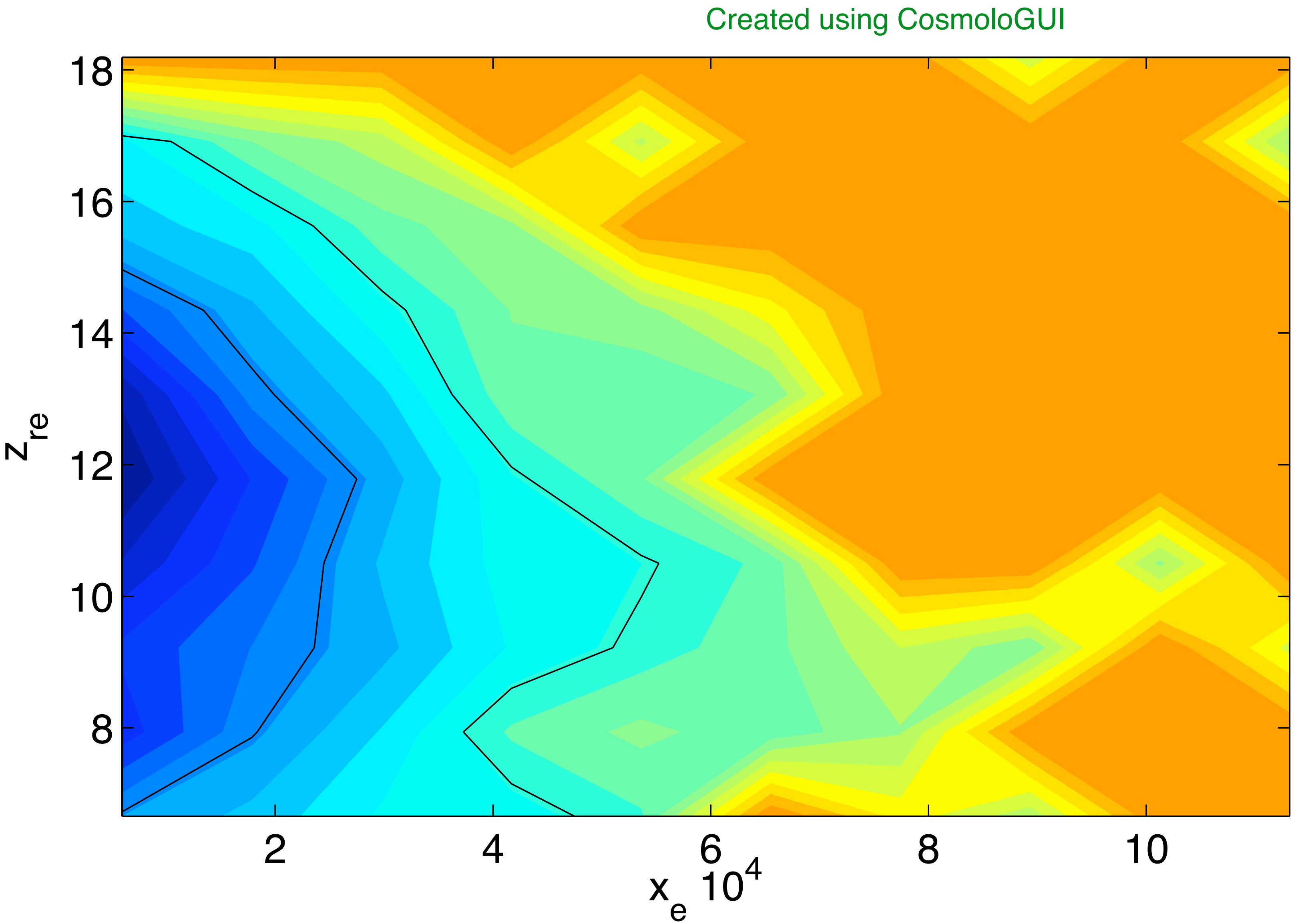
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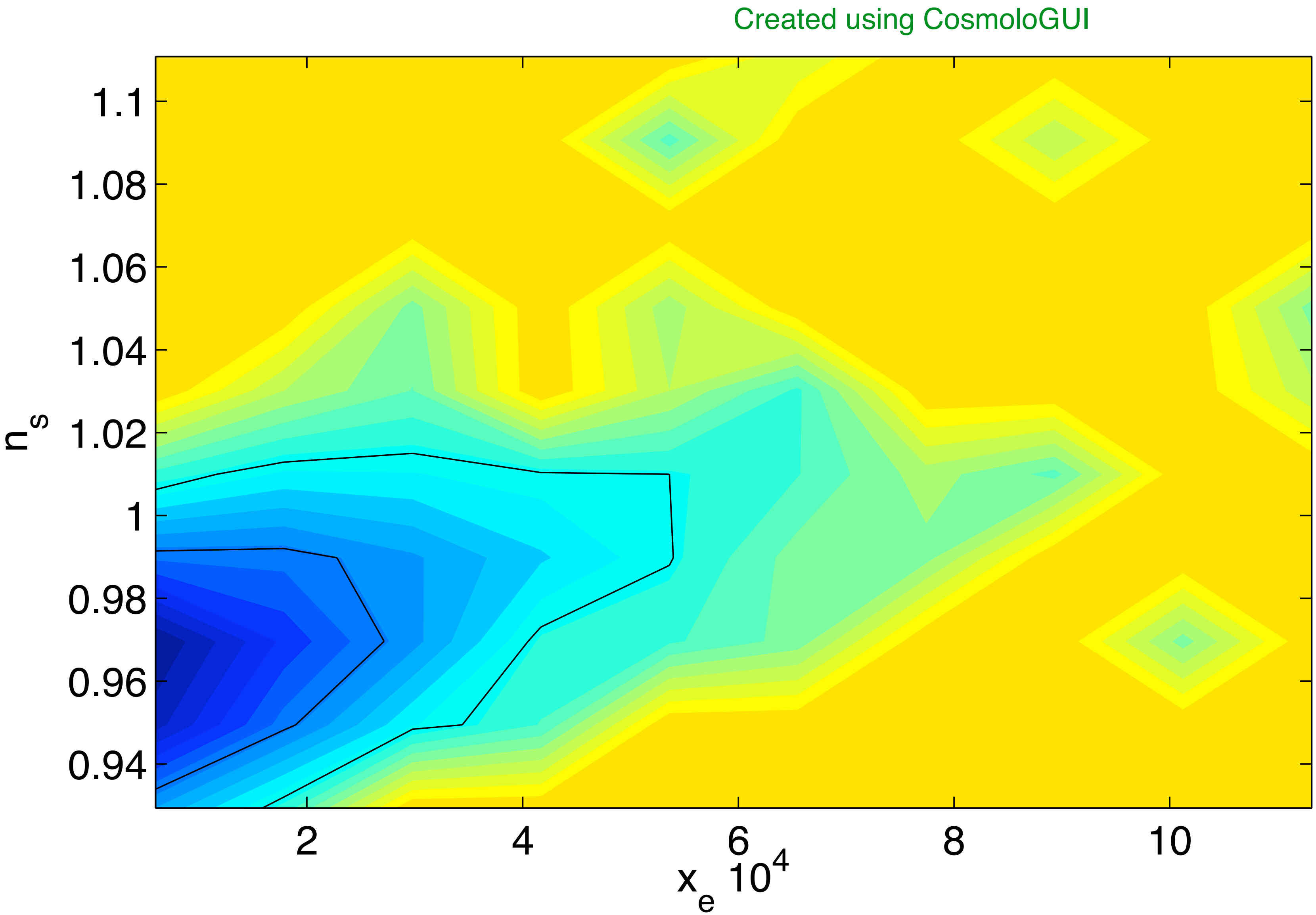
18
16
14
12
10
8
z_{re}
2
4
6
8
10
$x_e\ 10^4$



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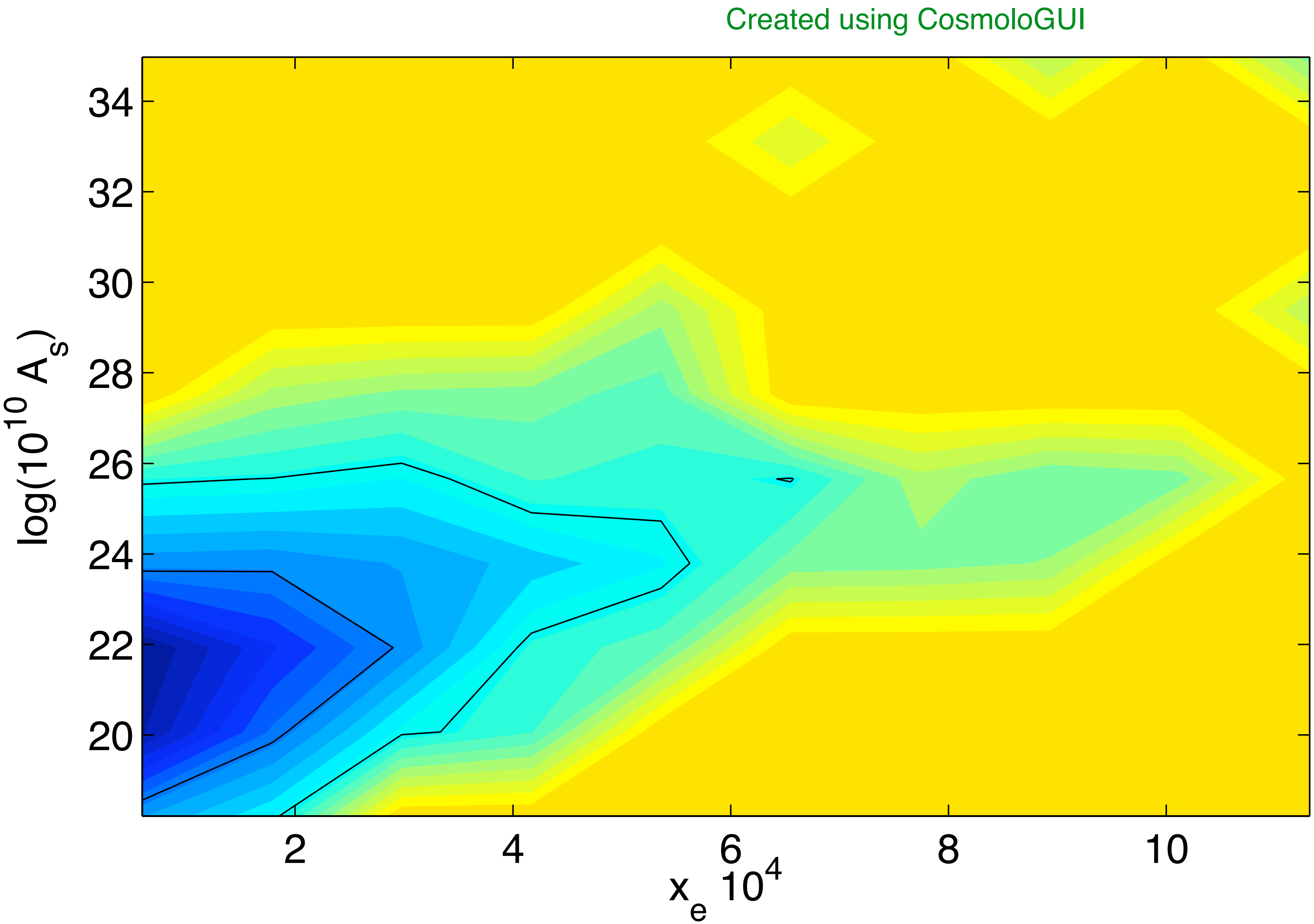

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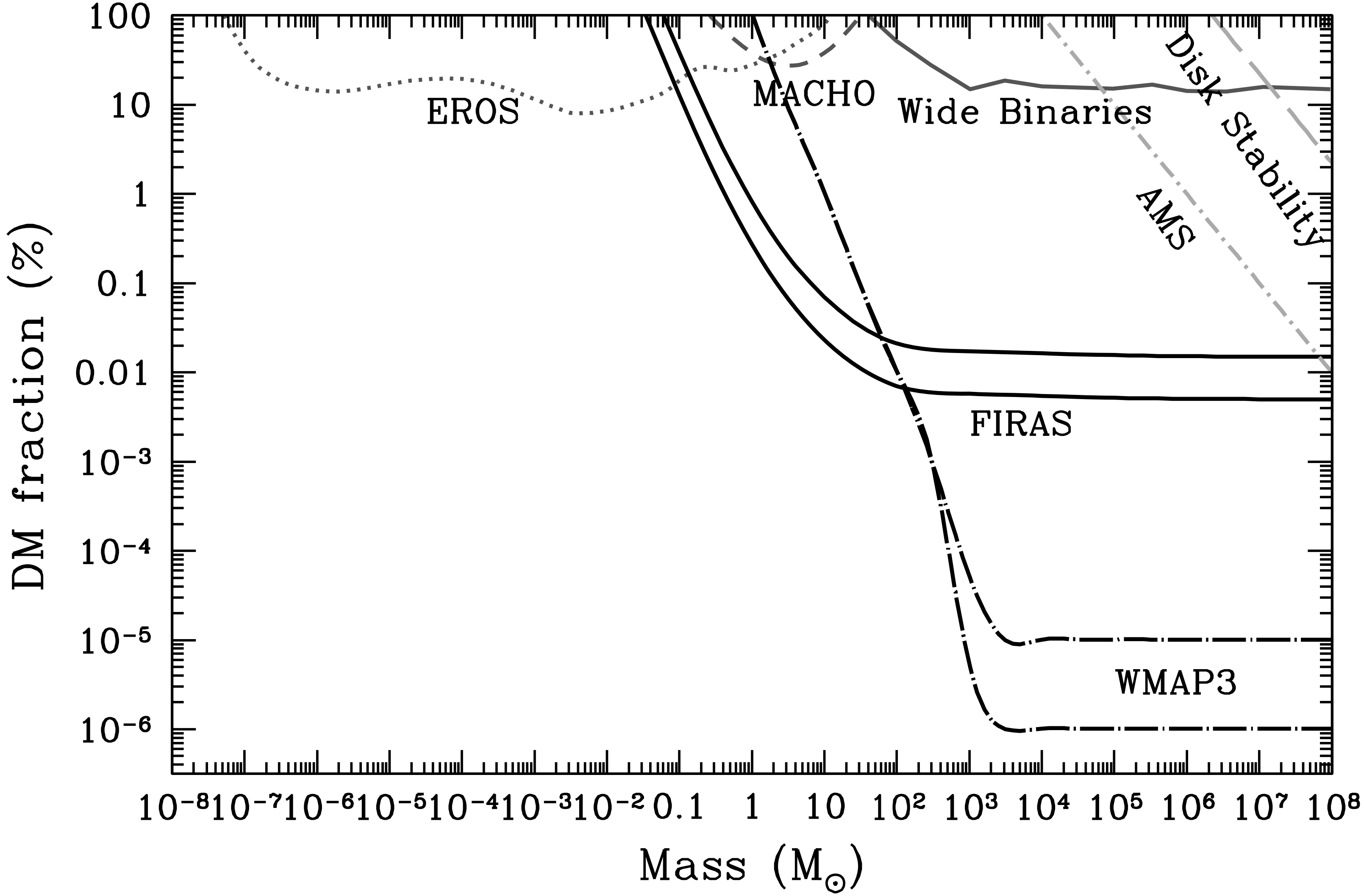
New constraints on f_{PBH} *and*



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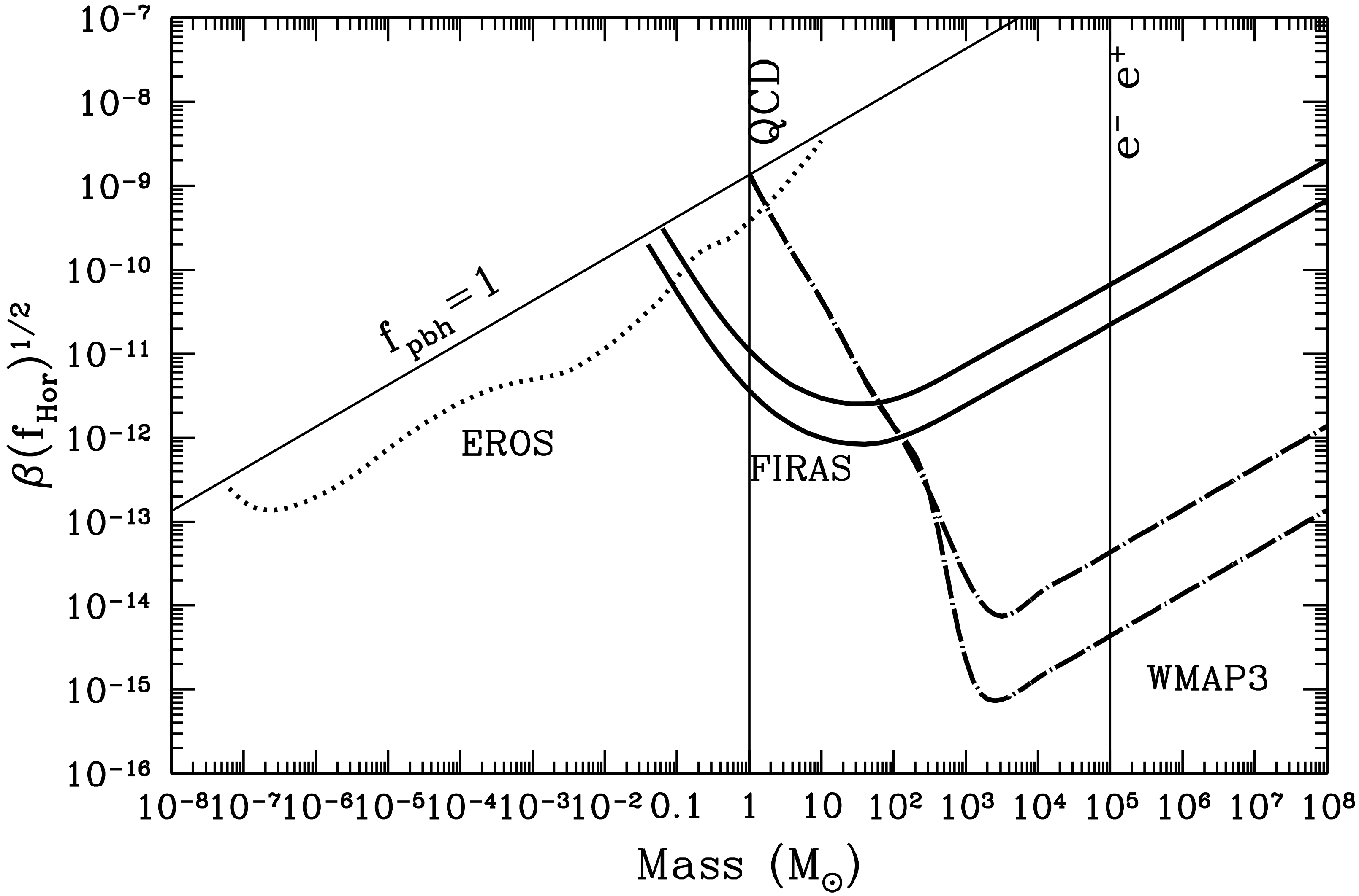

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- PBHs promote formation of primordial H_2 and first stars