Primordial Black Holes

and their effect on the cosmic ionization history

Massimo Ricotti

ricotti@astro.umd.edu

University of Maryland

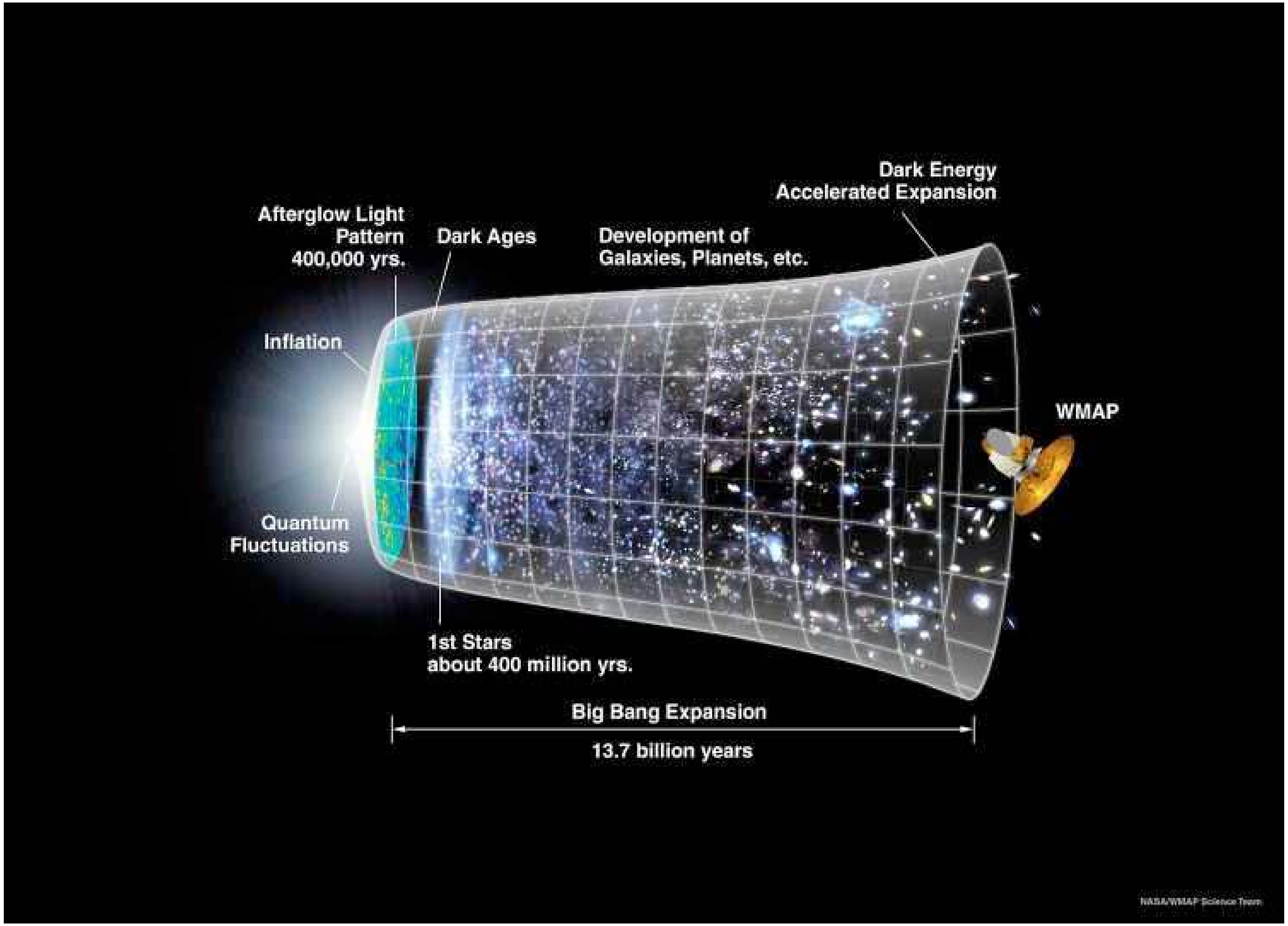
Collaborators:

Jerry Ostriker (Princeton), Katie Mack (Princeton)

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



UNIVERSITY OF MARYLAND

What are Primordial Black Holes?

Can have masses from $10\ ^{5}$ g to 10^{8} M !

What are Primordial Black Holes?

Can have masses from 10 ^{5} g to 10^8 M !

1. Collapsed radiation (relativistic matter)

What are Primordial Black Holes?

Can have masses from $10^{\ 5}$ g to 10^{8} M !

1. Collapsed radiation (relativistic matter)
2. Mass comparable to the Horizon mass at formation

What are Primordial Black Holes?

Can have masses from $10\ ^{5}$ g to 10^{8} M !

1. Collapsed radiation (relativistic matter)
2. Mass comparable to the Horizon mass at formation
3. Form in quasi-linear regime: 50%

UNIVERSITY OF MARYLAND

What are Primordial Black Holes?

Can have masses from $10\ ^{5}$ g to 10^{8} M !

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!

UNIVERSITY OF MARYLAND

Newtonian limit easy to understand: During radiation era

$c_s \quad c/ \quad \overline{3}$ hence $R_J \quad R_{Sch} \quad R_h$

Newtonian limit easy to understand: During radiation era $c_s \quad c/ \quad \overline{3}$ hence $R_J \quad R_{Sch} \quad R_h$

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

Newtonian limit easy to understand: During radiation era $c_s \quad c/\ \overline{3}$ hence $R_J \quad R_{Sch} \quad R_h$

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

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

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

UNIVERSITY OF MARYLAND

Radiation is redshifted away, PBHs are not:

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

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

UNIVERSITY OF MARYLAND

Radiation is redshifted away, PBHs are not:

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

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

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

UNIVERSITY OF MARYLAND

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)

UNIVERSITY OF MARYLAND

Some models for PBH formation

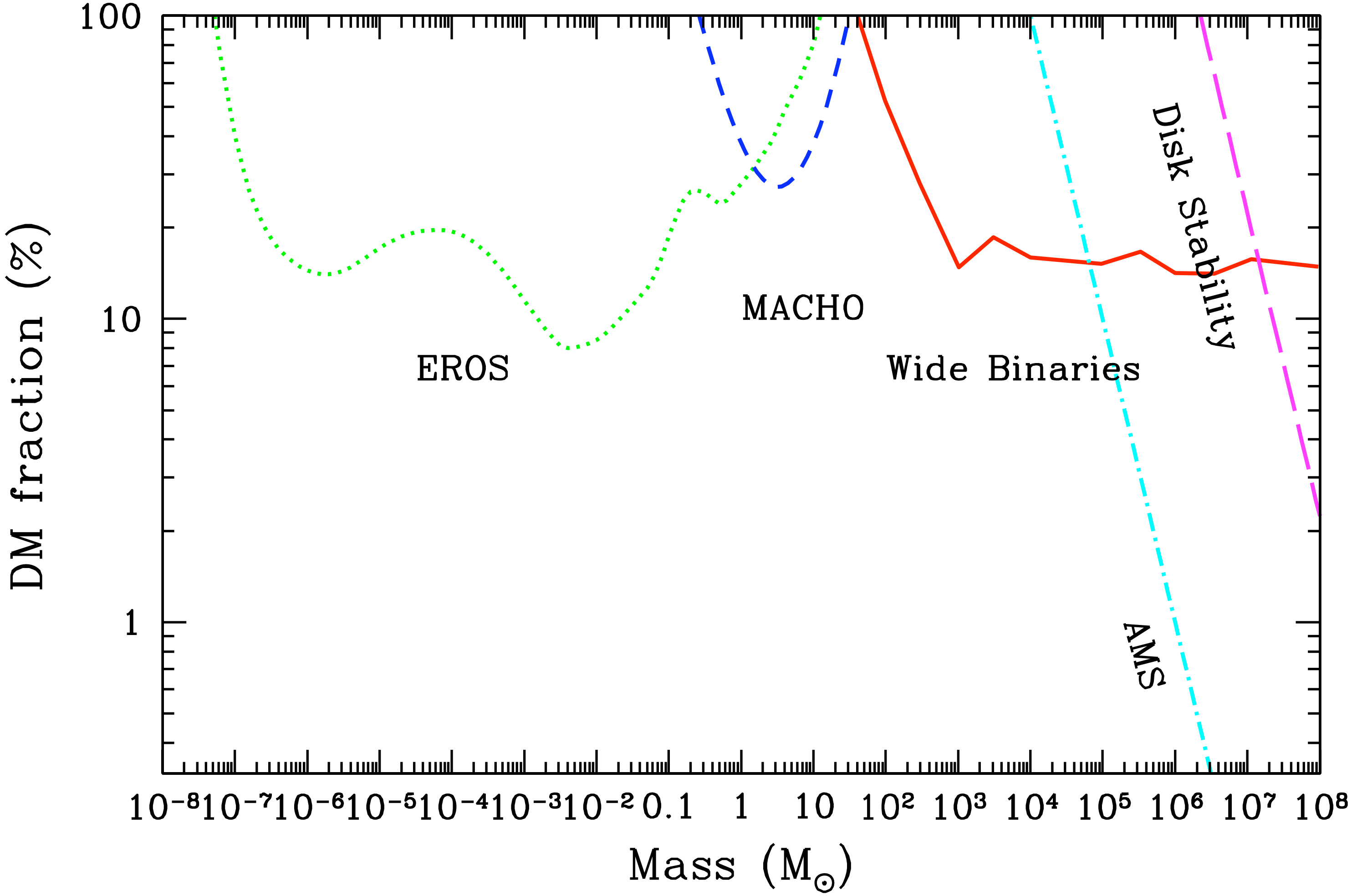
1. Softening of the EOS during phase transitions: QCD (1 M) or e^+ e annihilation (10^5 M)(Kholopov & Polnarev 80; Jedamzik 97)
2. Collapse of rare density peaks: depend on the shape of inflaton potential (*e.g.*, potential as in Kawasaki et al 06 produces 100 M PBHs)

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)
2. Collapse of rare density peaks: depend on the shape of inflaton potential (*e.g.*, potential as in Kawasaki et al 06 produces 100 M PBHs)
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?

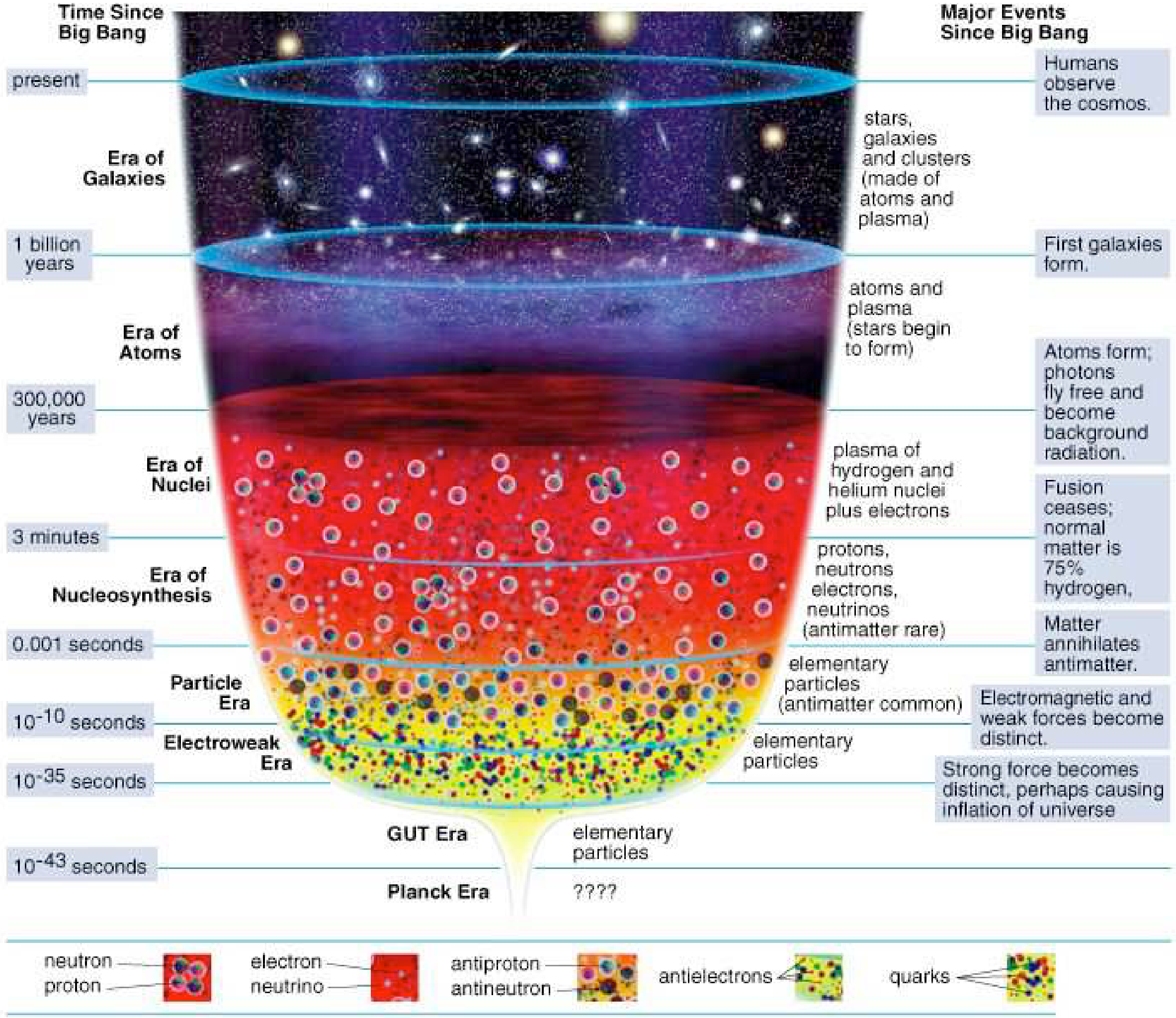
- PBHs with mass $< 10^{15}$ g evaporate in $t < t_H$ (Hawking 1975)
  - Abundance of PBHs with mass 1 g $< M < 10^{15}$ g is $< 10^{20}$ 10^{22} (*e.g.*, Carr 2003)
- More massive PBHs are poorly constrained:
  - They may constitute the bulk of the dark matter
  - MACHO collaboration: 20% of Milky-Way 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



Why do we care?

1. Physics on scale otherwise unaccessible by observations
2. The dark matter can be made of PBHs

Why do we care?

1. Physics on scale otherwise unaccessible by observations
2. The dark matter can be made of PBHs
3. Produce MACHOS, IMBH and ULXs ?

Why do we care?

1. Physics on scale otherwise unaccessible by observations
2. The dark matter can be made of PBHs
3. Produce MACHOS, IMBH and ULXs ?
4. Seeds for supermassive Black Holes?

UNIVERSITY OF MARYLAND

Physics of PBHs accretion: Outline

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

Physics of PBHs accretion: Outline

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

1. Growth of “clothing” dark matter halo (100-1000 times more massive than PBH)

UNIVERSITY OF MARYLAND

Physics of PBHs accretion: Outline

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

1. Growth of “clothing” dark matter halo (100-1000 times more massive than PBH)
2. Gas viscosity: Compton Drag and Hubble flow

Physics of PBHs accretion: Outline

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

1. Growth of “clothing” dark matter halo (100-1000 times more massive than PBH)
2. Gas viscosity: Compton Drag and Hubble flow
3. Proper motion: gas and dark matter are not perfectly coupled (Silk damping)

Physics of PBHs accretion: Outline

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

1. Growth of “clothing” dark matter halo (100-1000 times more massive than PBH)
2. Gas viscosity: Compton Drag and Hubble flow
3. Proper motion: gas and dark matter are not perfectly coupled (Silk damping)
4. Angular momentum of accreted gas and dark matter

Physics of PBHs accretion: Outline

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

1. Growth of “clothing” dark matter halo (100-1000 times more massive than PBH)
2. Gas viscosity: Compton Drag and Hubble flow
3. Proper motion: gas and dark matter are not perfectly coupled (Silk damping)
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!

Ref: `Mack, Ostriker and Ricotti (2007)`

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!

Ref: `Mack, Ostriker and Ricotti (2007)`

- 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 $= \quad 2.25$
- Truncation at $r_h = r_{ta}/3$

UNIVERSITY OF MARYLAND

2. Bondi type accretion

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

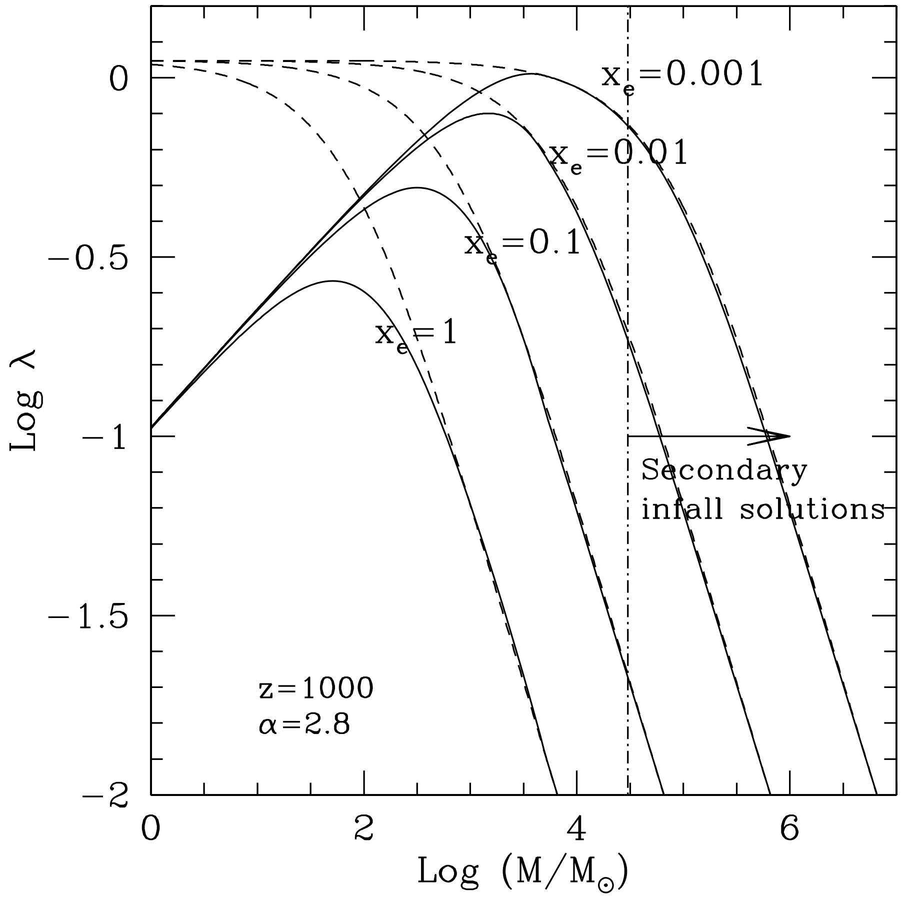
$$\frac{dv}{dt} = \quad \frac{4}{3}\frac{x_e \quad {}_T U_{cmb}}{m_p c} v = \quad v$$

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

Ref: `Ricotti (2007)`

UNIVERSITY OF MARYLAND

Spherical accretion rate



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

3. Relative motion of PBHs and gas

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

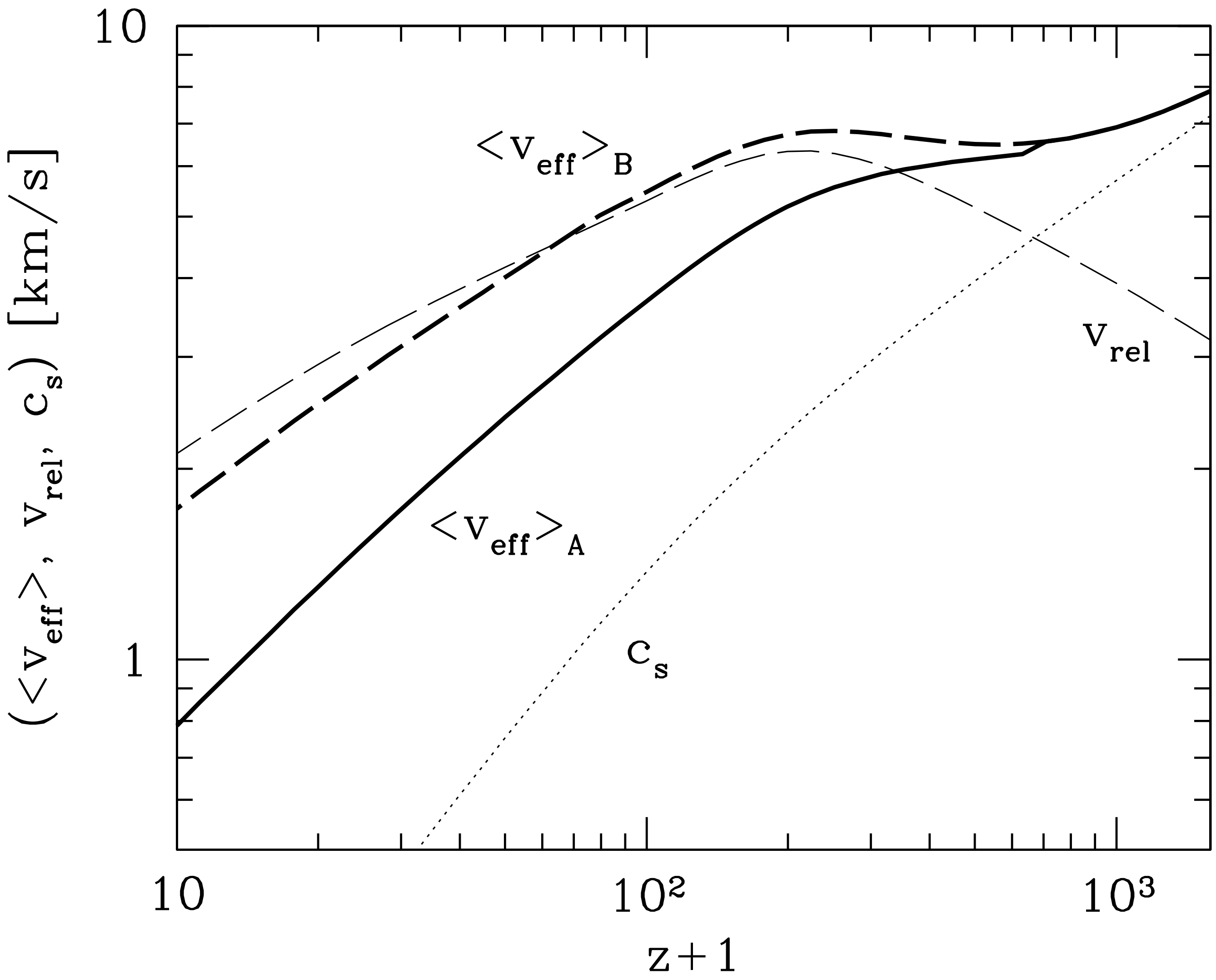
where $v_{eff} = (v_{rel}^2 + c_s^2)^{1/2}$

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



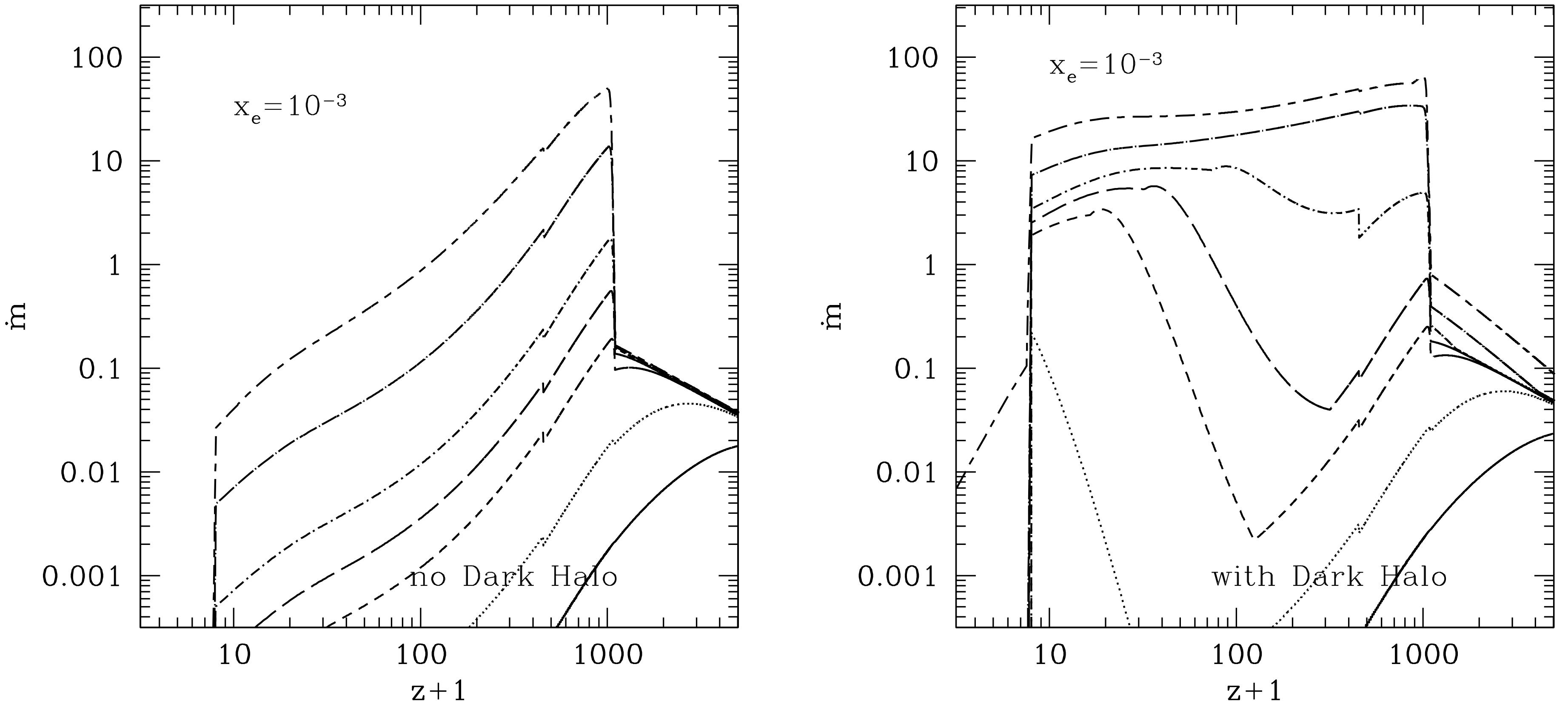
UNIVERSITY OF MARYLAND

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)

UNIVERSITY OF MARYLAND

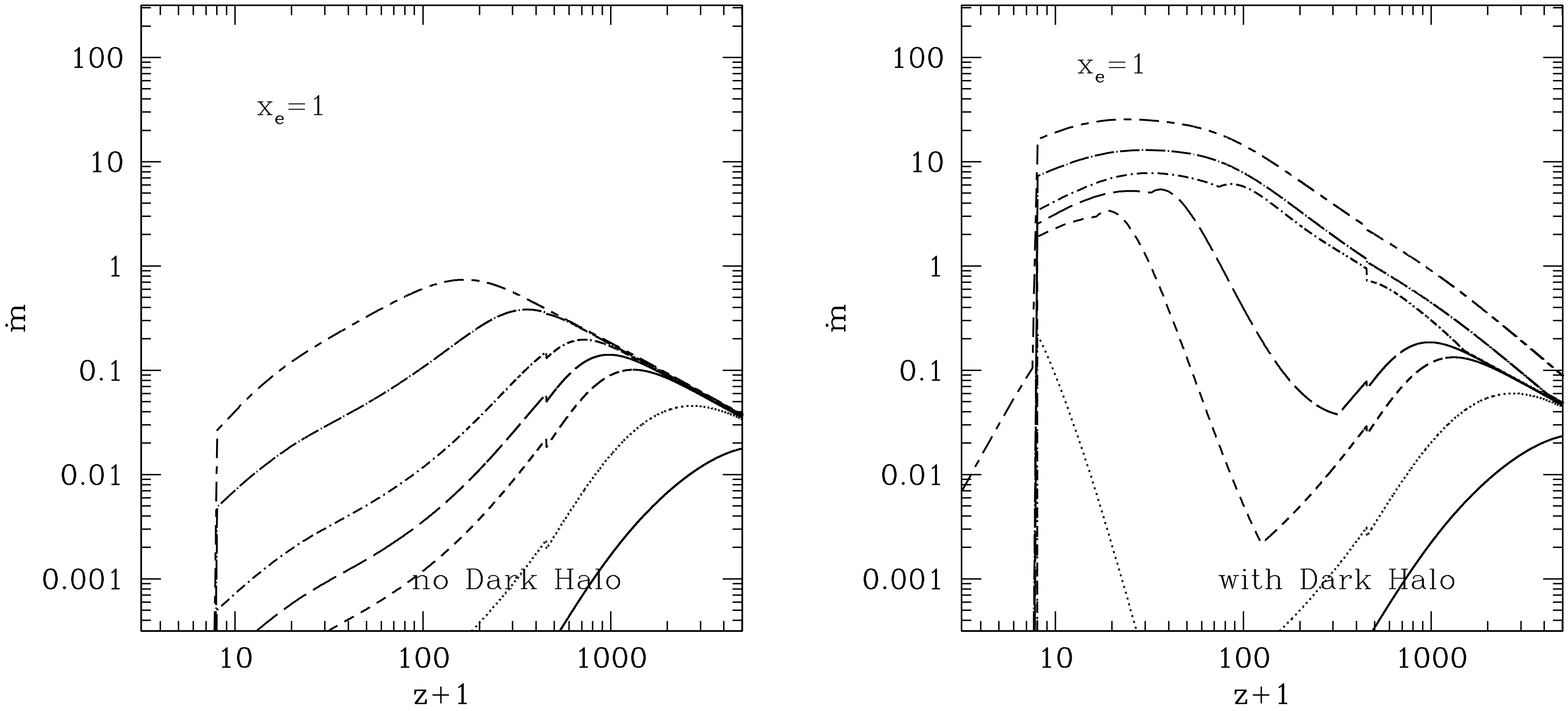
4. Accretion rate neglecting feedback



curves from bottom to top refer to masses of PBHs from

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

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).

UNIVERSITY OF MARYLAND

Accretion Luminosity

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

$l = \quad \dot{m}$, 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)

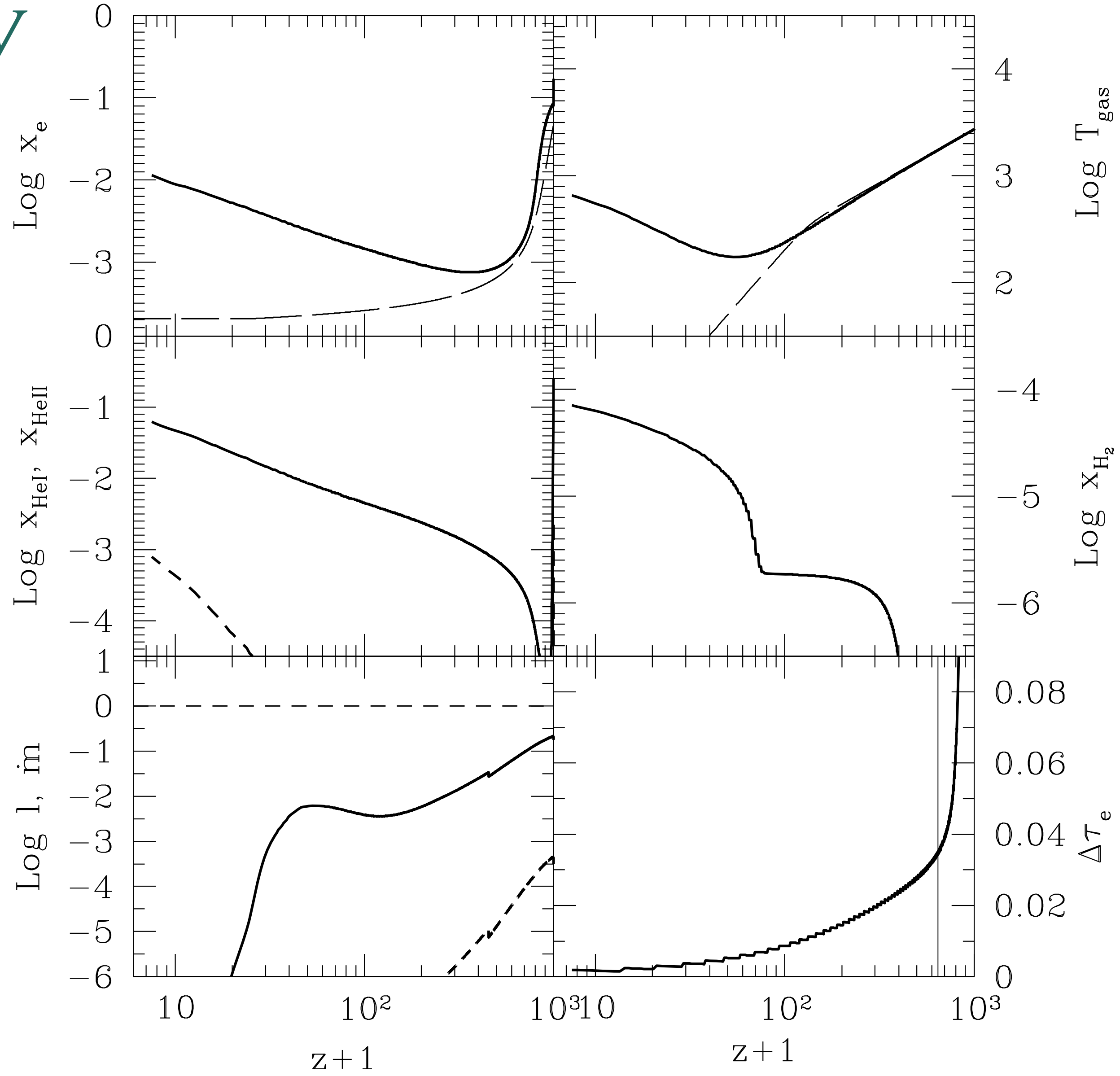
5. Feedback processes

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

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

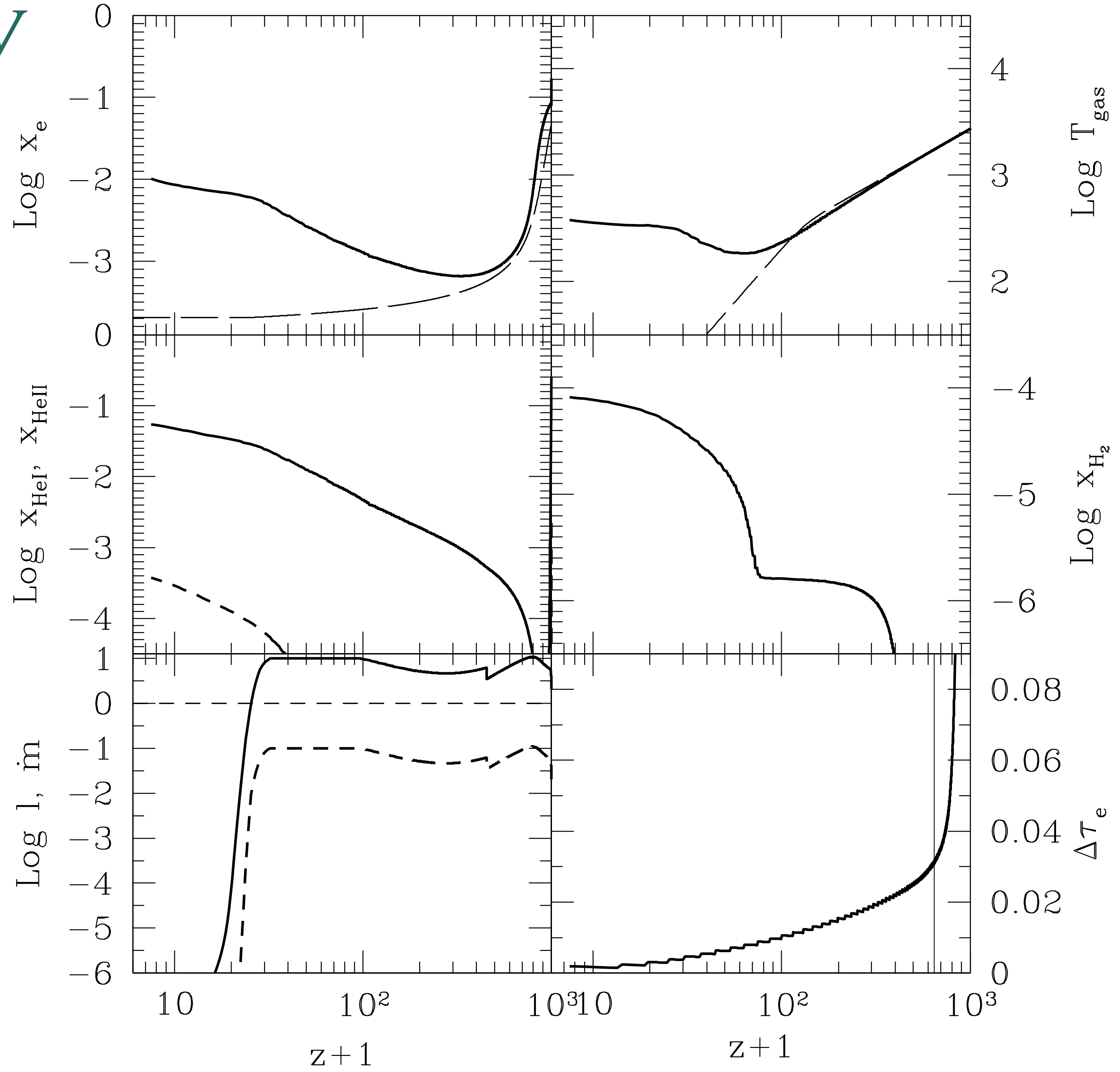
  - Temperature of H II region: $T_{H\,II} \quad T_{cmb}$
- Global feedback (X-ray heating):
  Iterative semi-analytic code (Ricotti & Ostriker 04)

Cosmic ionization, thermal, and chemical history



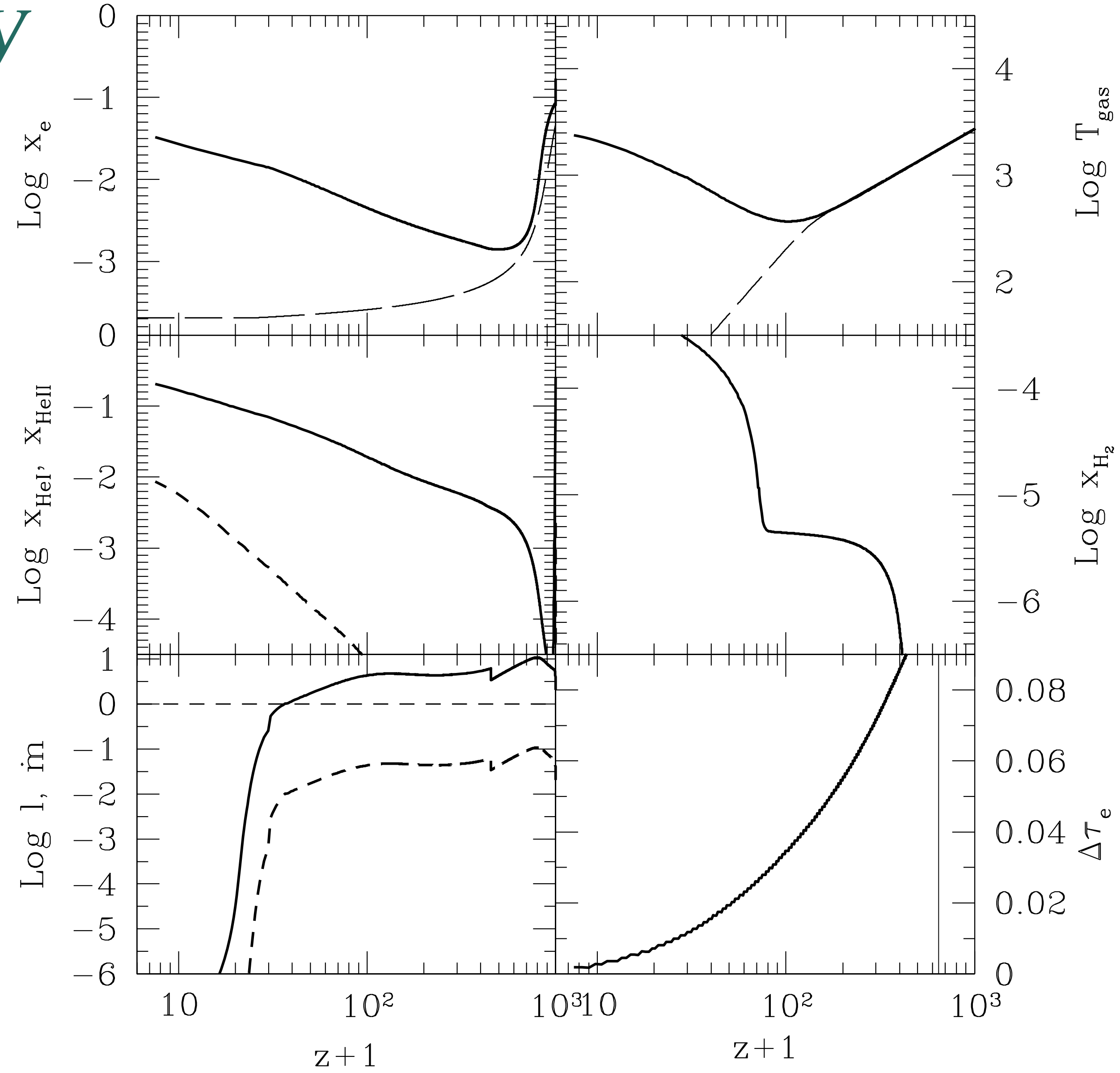
Simulations: $M_{pbh} = 100$, $f_{pbh} = 10^{-4}$

Cosmic ionization, thermal, and chemical history



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

Cosmic ionization, thermal, and chemical history



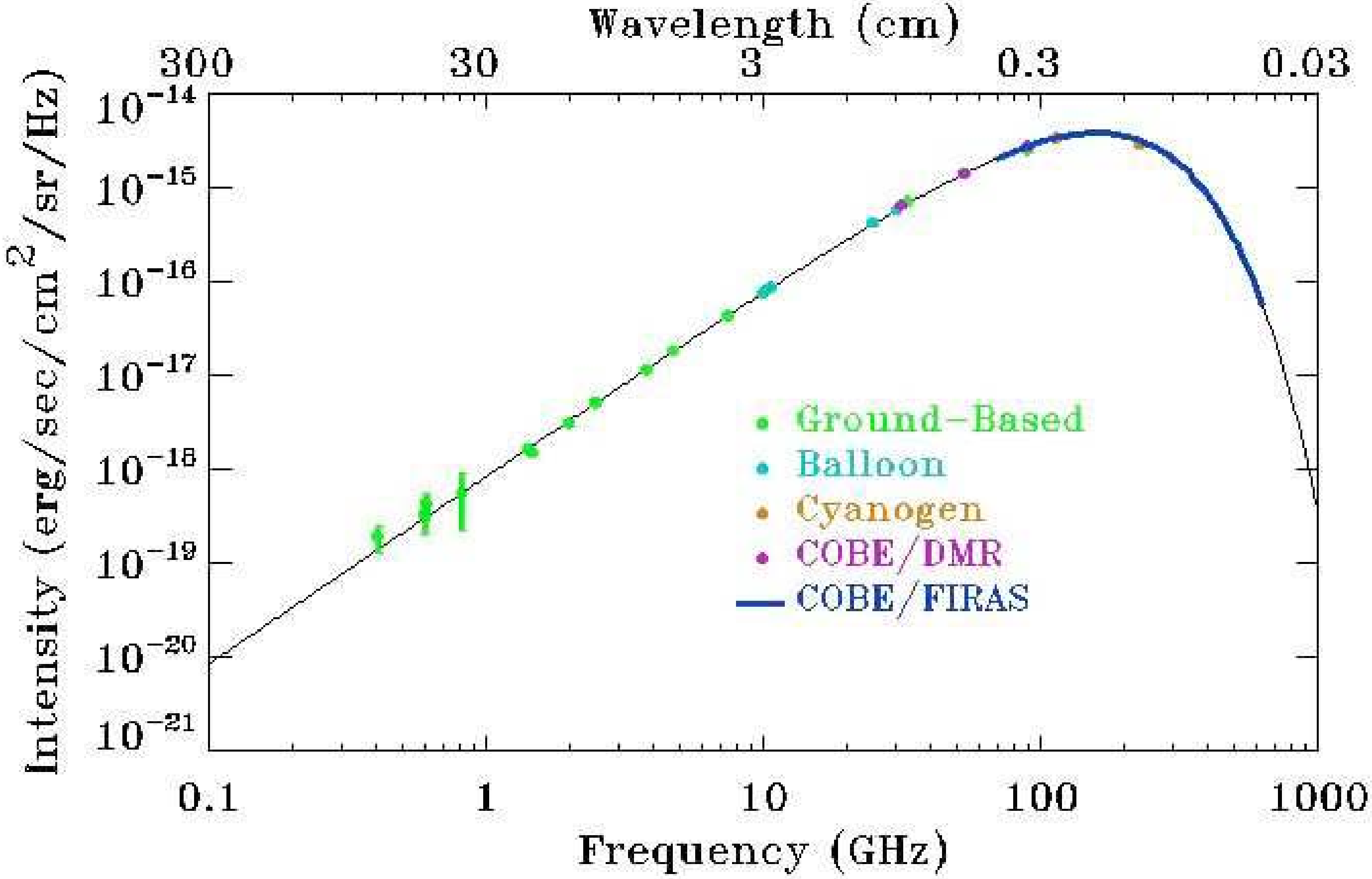
Simulations:

M_{pbh} = 1000,

f_{pbh} = 10 ^{6}

UNIVERSITY OF MARYLAND

Spectrum of the CMB



UNIVERSITY OF MARYLAND

CMB spectral distortions

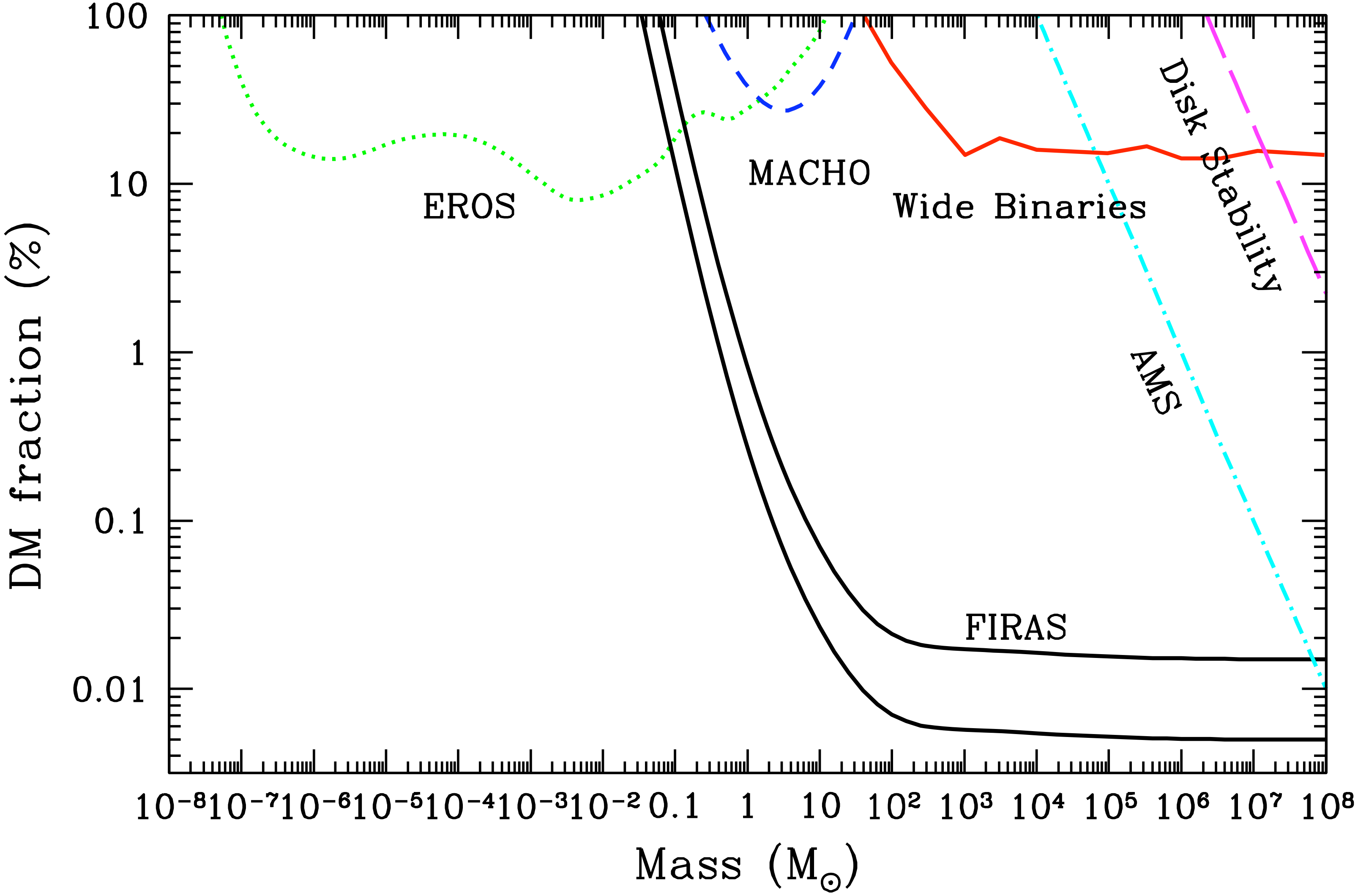
- $M_{pbh} < 10\ M$ weakly affected by Compton drag even before recombination
- FIRAS $y \quad 1.5 \quad 10^{5}$ at at 95% confidence
- 3 phases: $y = y_1 + y_2 + y_3 \quad y_1$
  1. $z_{rec} < z < z_{eq}$: all energy injected absorbed by gas
  2. $z_{dec} < z < z_{rec}$: fraction of energy absorbed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

Constrain on maximum energy injection imposed by:

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

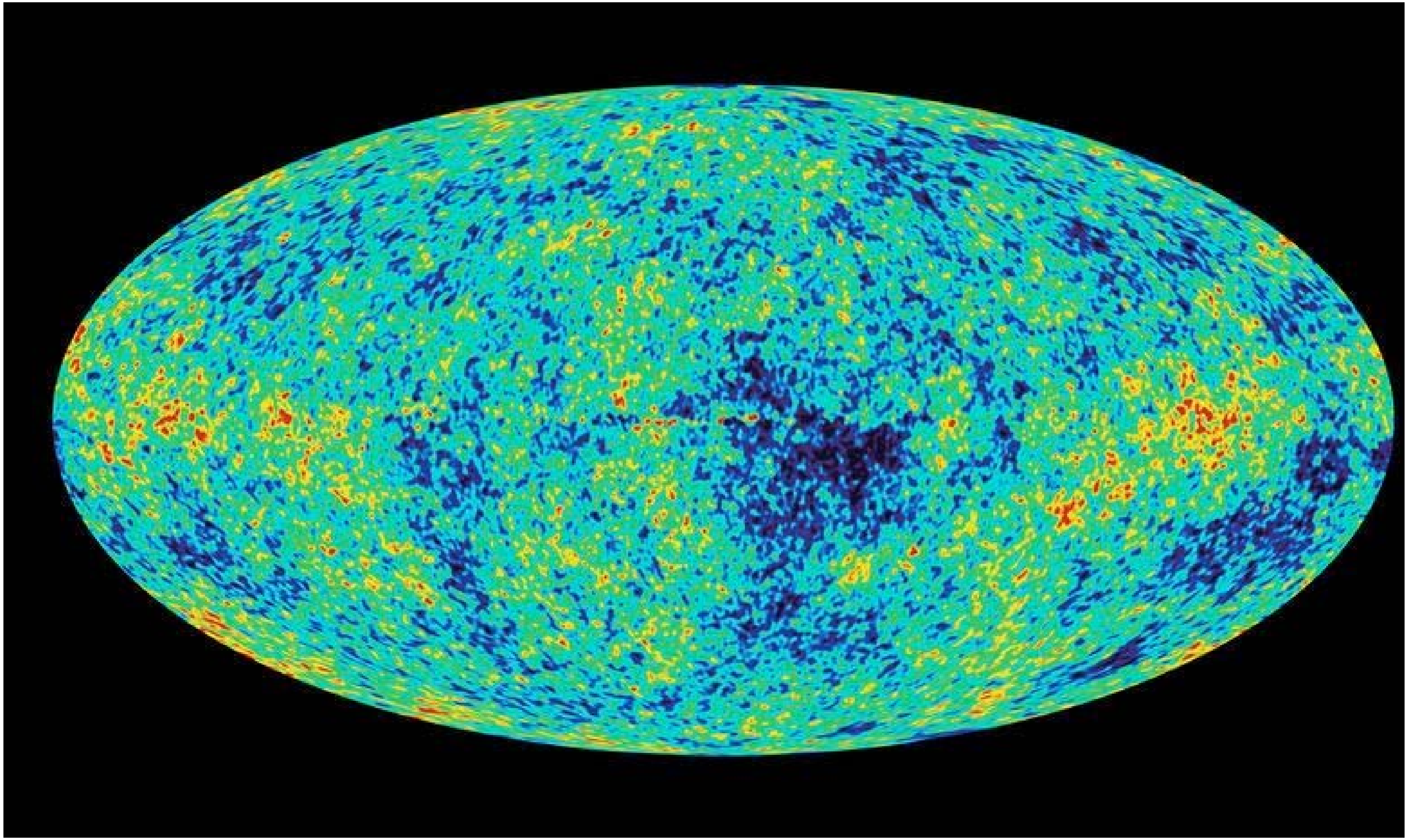
UNIVERSITY OF MARYLAND

Constraints on f_{PBH}



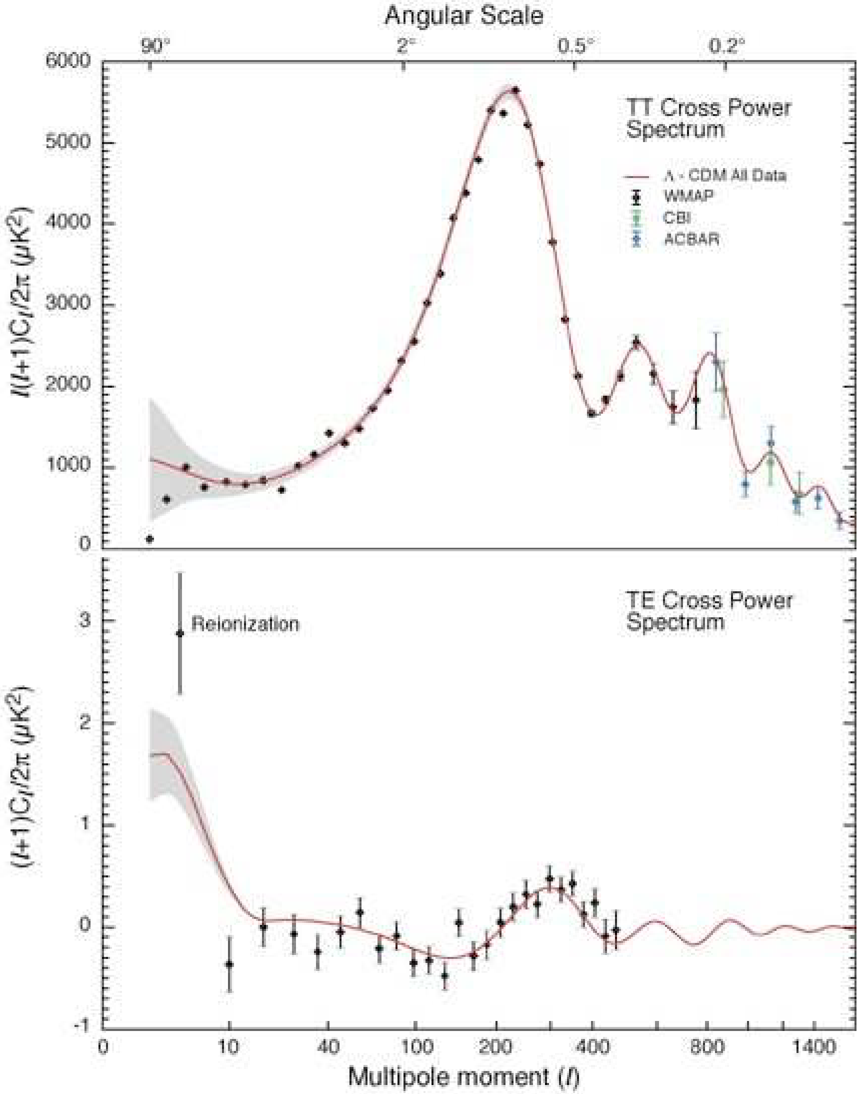
UNIVERSITY OF MARYLAND

CMB anisotropies: WMAP



CMB anisotropies: spectrum

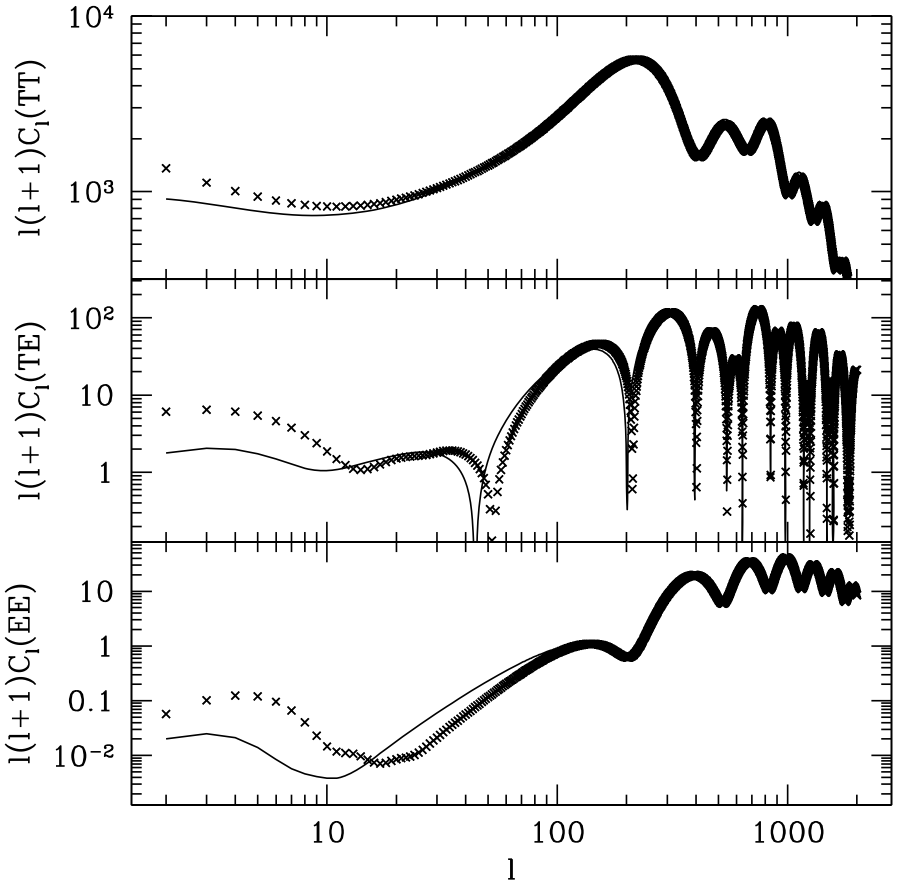
- Cosmological parameters: $_{m}$ = 0.24, = 0.76, h = 0.73
- Initial density perturbations: $_{8}$ = 0.74, n_{s} = 0.95 (little power at small scales!)
- Ionization history: z_{rei} = 12, $_{e}$ = 0.1



UNIVERSITY OF MARYLAND

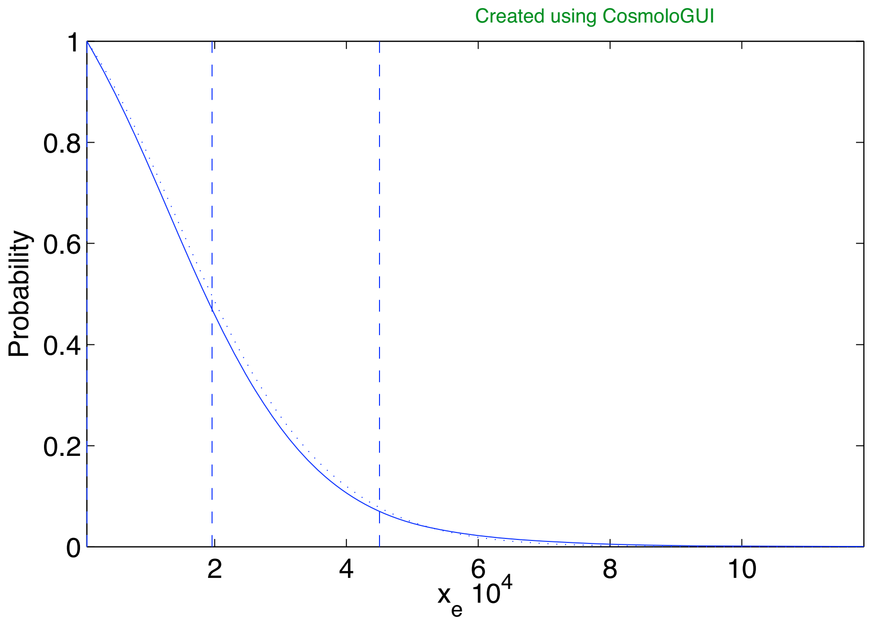
Effects of PBHs on CMB anisotropies

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



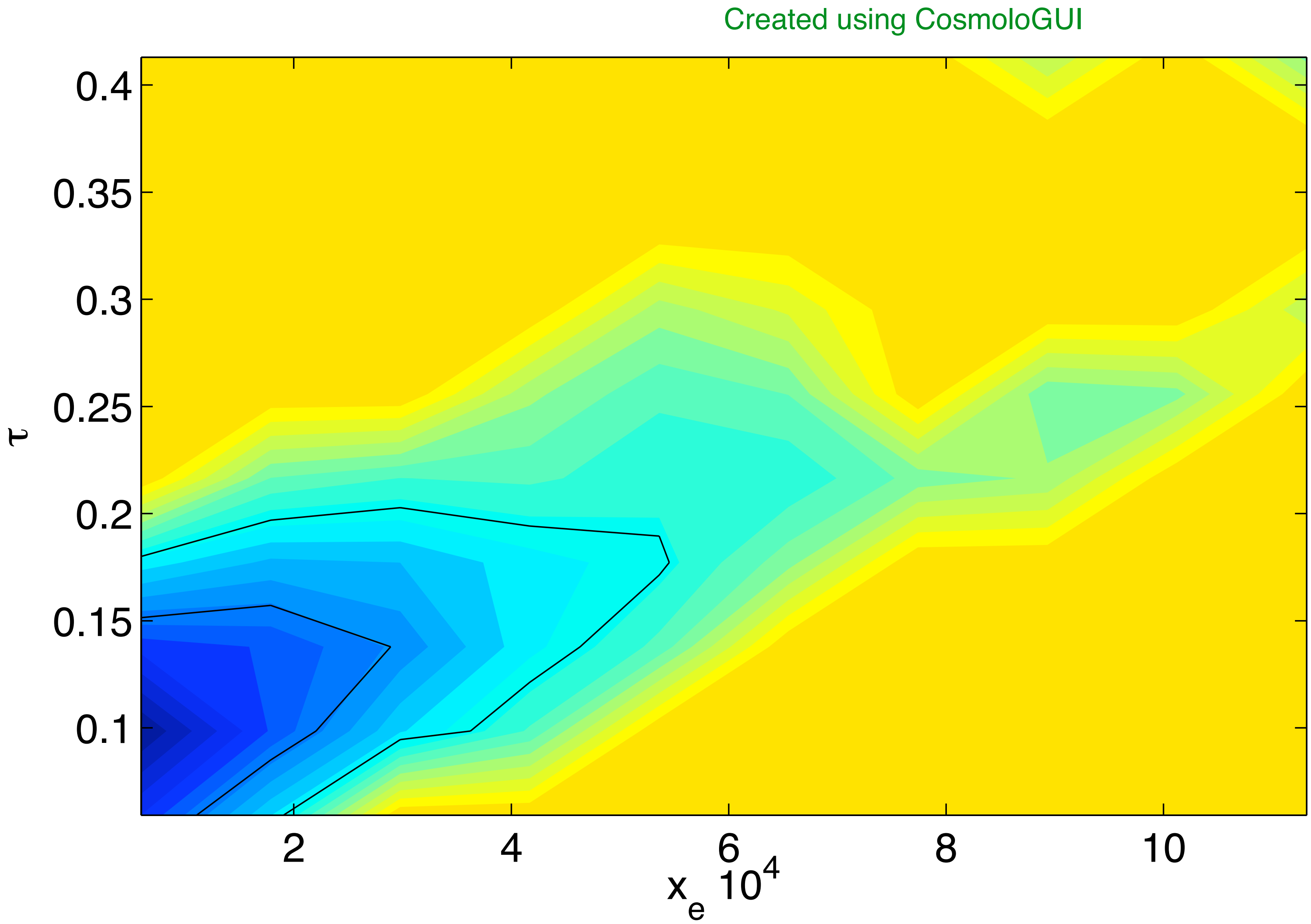
Modified recombination history

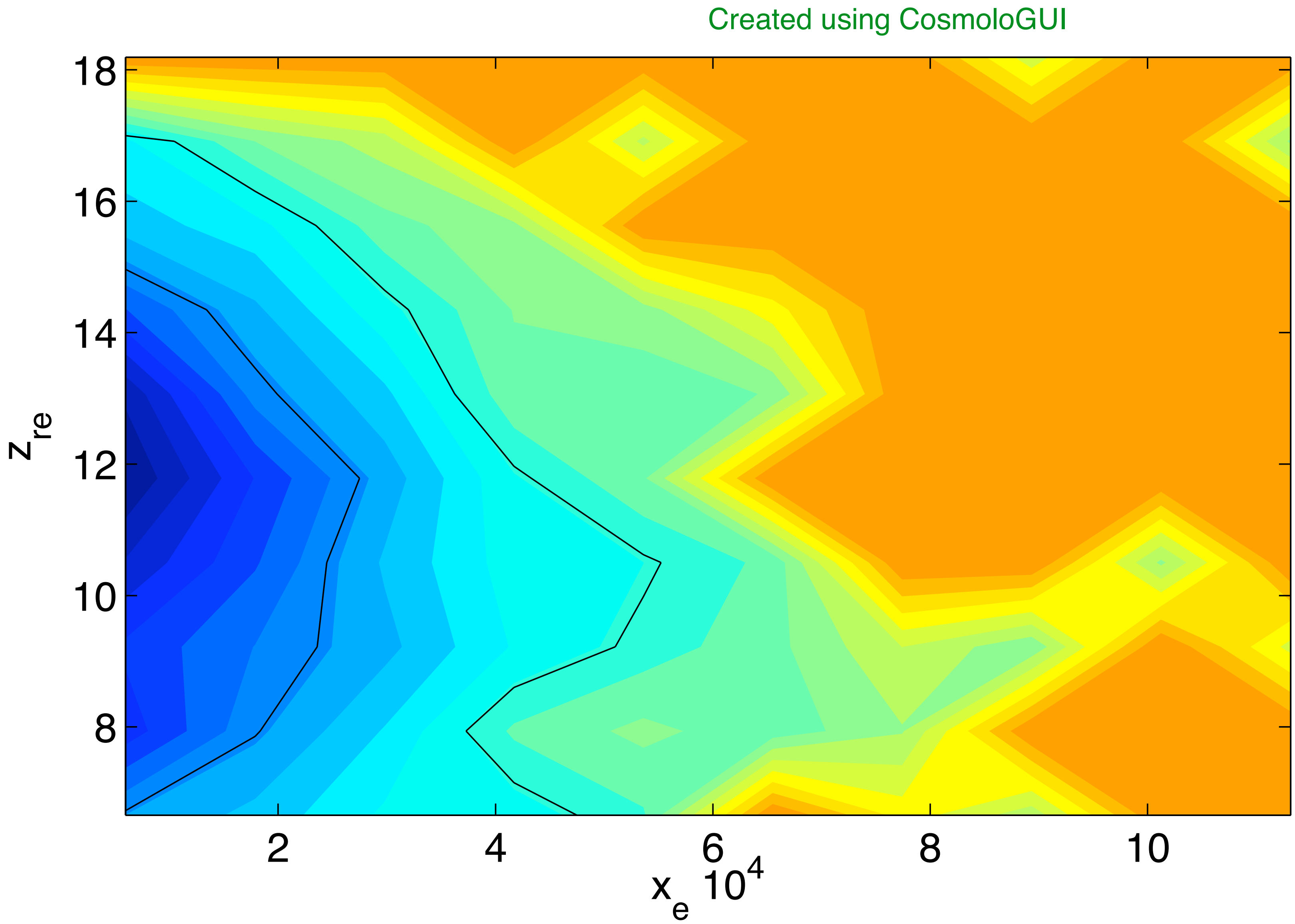
$$x_e(z) = x_{e,rec}(z) + \min\ x_{e0} \ \frac{1+z}{1000}^{1}, 0.1 \ ,$$

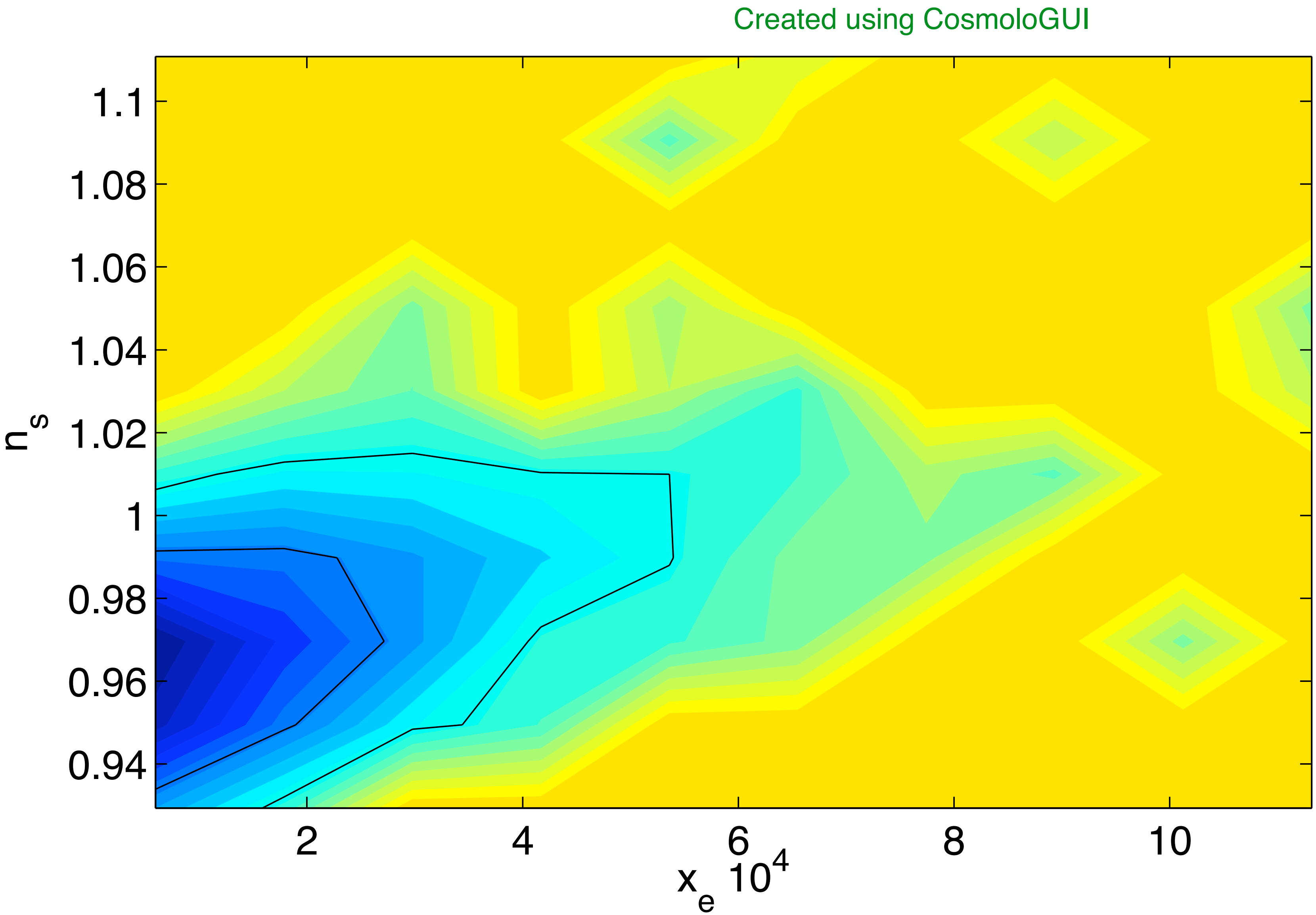


RECFAST: Seager, Sasselov & Scott 99;
COSMOMC: Lewis & Bridle 02

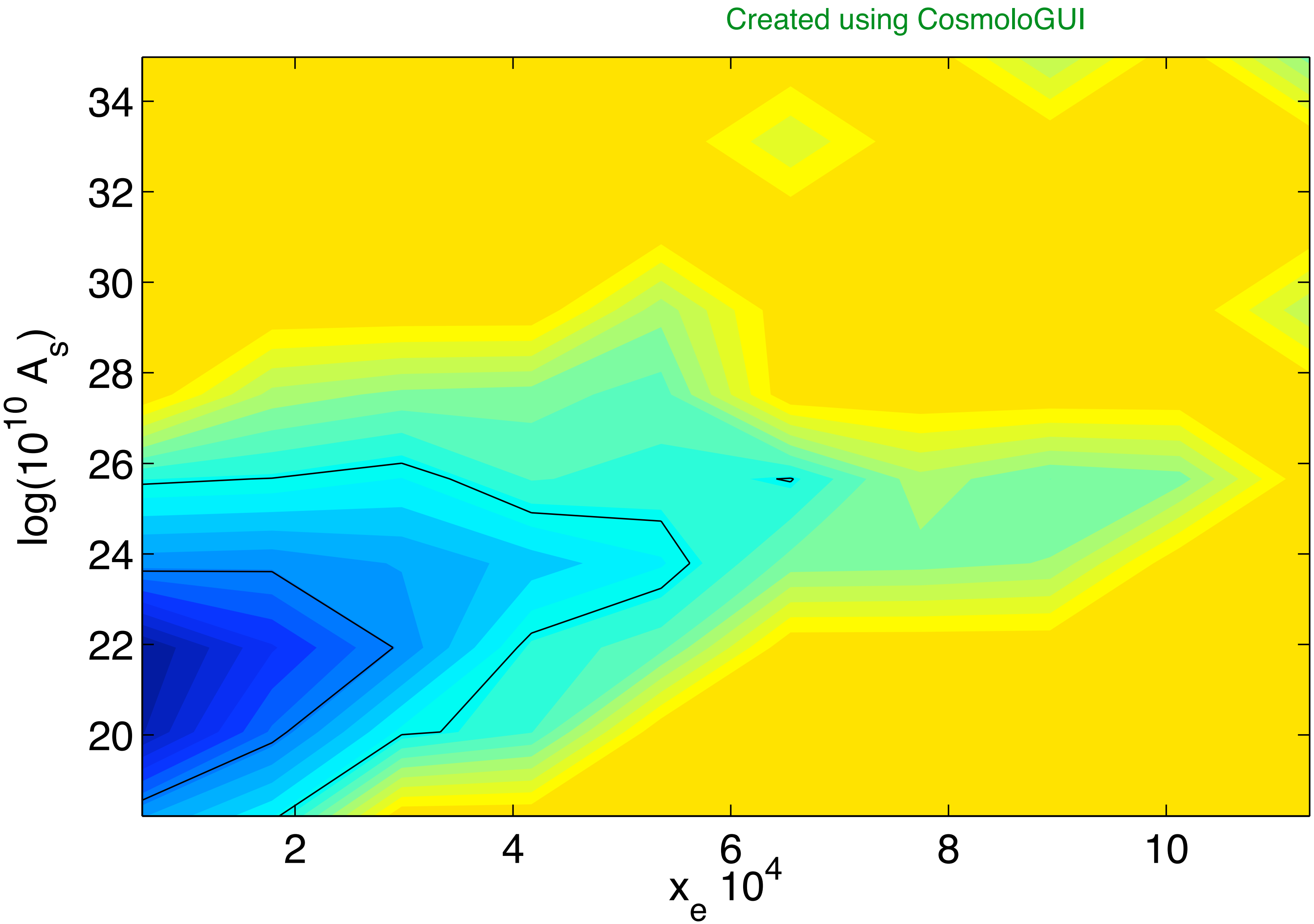
UNIVERSITY OF MARYLAND


Created using CosmoloGUI
0.4
0.35
0.3
0.25
0.2
0.15
0.1
τ
2
4
6
8
10
$x_e\ 10^4$


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

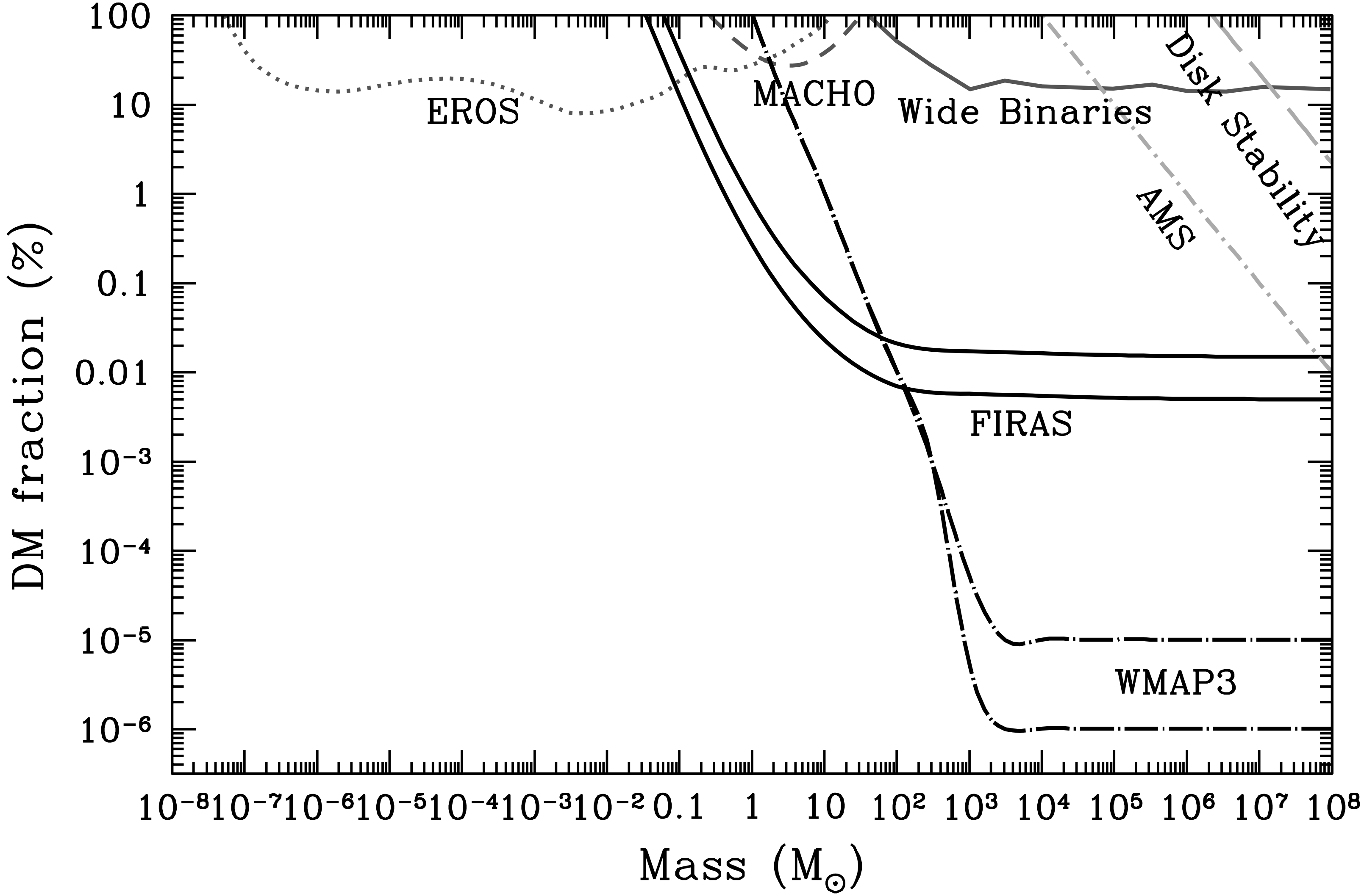


UNIVERSITY OF MARYLAND



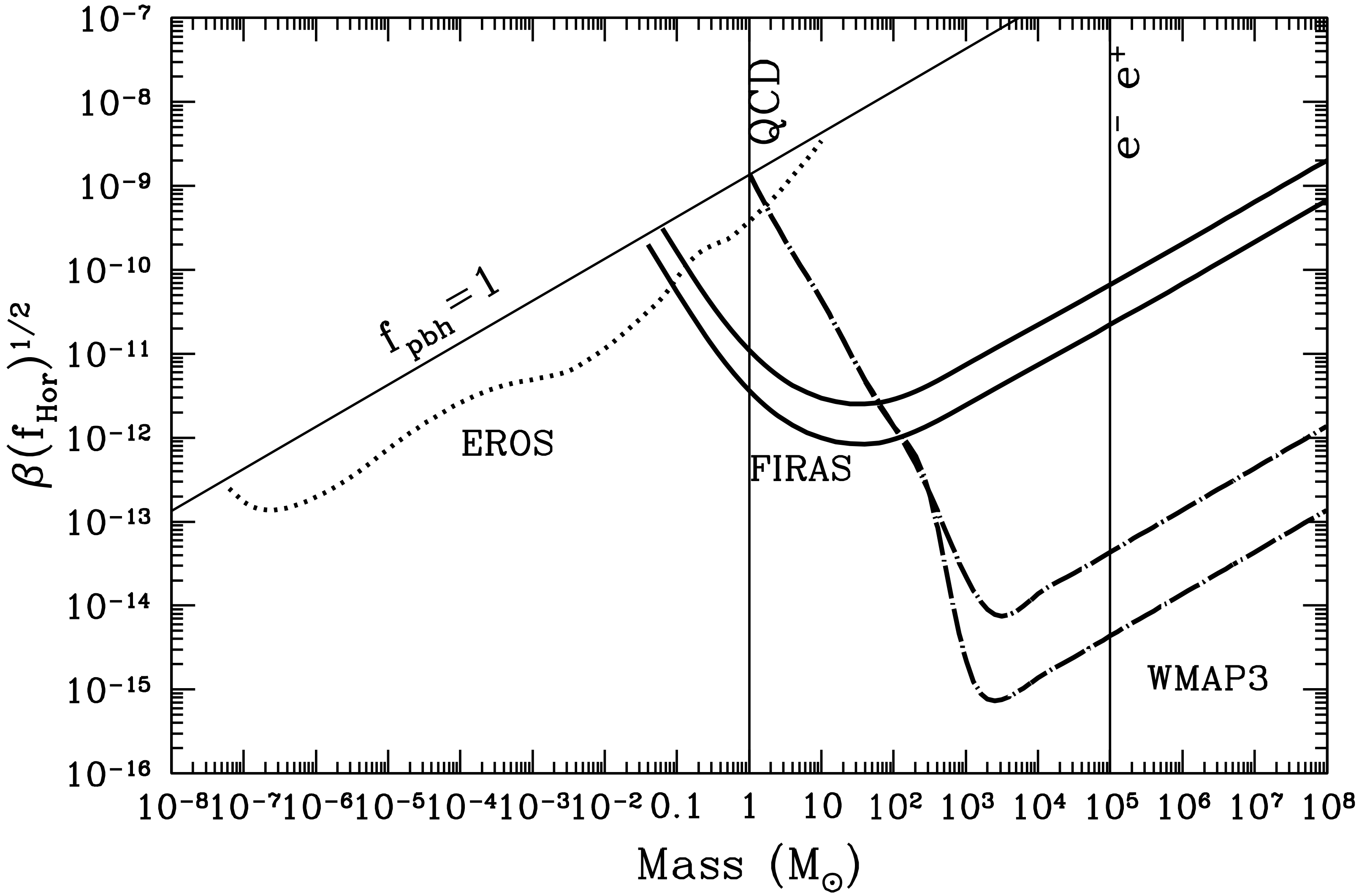
UNIVERSITY OF MARYLAND

New constraints on f_{PBH} *and*



UNIVERSITY OF MARYLAND

New constraints on f_{PBH} *and*



UNIVERSITY OF MARYLAND

Summary

PBHs probe high-energy physics, dark matter candidate?

Summary

PBHs probe high-energy physics, dark matter candidate?

- PBHs produce spectral distortions and modify recombination:
  - standard CMB perturbations analysis may underestimate $_8$ and n_s if relativelly massive PBHs exist (but result is more general)

Summary

PBHs probe high-energy physics, dark matter candidate?

- PBHs produce spectral distortions and modify recombination:
  - standard CMB perturbations analysis may underestimate $_8$ and n_s if relativelly massive PBHs exist (but result is more general)
- Upper limits on f_{pbh} improved by a lot:
  - PBHs more massive than the moon (10^{26} grams) cannot be the dark matter
  - PBHs may explain origin of ULXs and SMBHs

UNIVERSITY OF MARYLAND

Summary

PBHs probe high-energy physics, dark matter candidate?

- PBHs produce spectral distortions and modify recombination:
  - standard CMB perturbations analysis may underestimate $_{8}$ and n_s if relativelly massive PBHs exist (but result is more general)
- Upper limits on f_{pbh} improved by a lot:
  - PBHs more massive than the moon (10^{26} grams) cannot be the dark matter
  - PBHs may explain origin of ULXs and SMBHs
- PBHs promote formation of primordial H_2 and first stars