21cm line signals from minihalos as a probe of primordial fluctuations

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Dark Side of the Universe 2017

IBS-CTPU,12.07.2017

Plan of talk

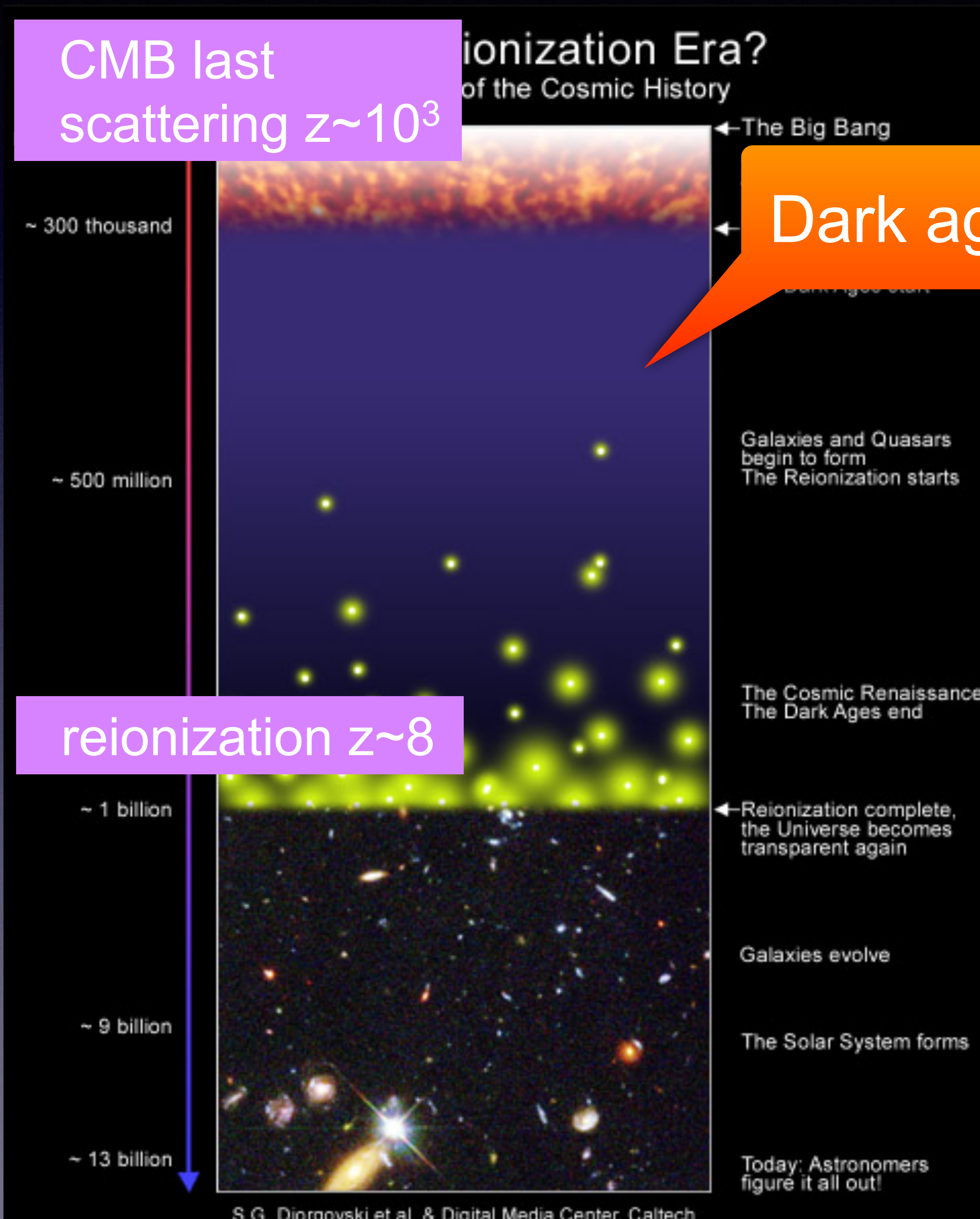
- Introduction: minihalos in dark ages and its redshifted 21 cm line signal
- Application: a probe of primordial fluctuations
  - Spectral runnings of power spectrum
  - Primordial non-Gaussianity
- Summary

Refs:

- H. Tashiro, T. Sekiguchi & J. Silk, N. Sugiyama [arXiv:1311.3295]
- T. Sekiguchi, T. Takahashi, H. Tashiro & S. Yokoyama [arXiv: 1705.00405]
- T. Sekiguchi, T.Takahashi, H. Tashiro & S. Yokoyama [in prep.]

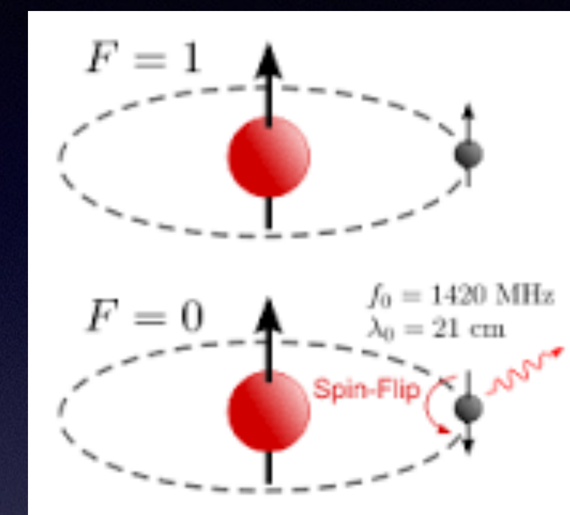
Introduction

CMB last scattering $z\sim10^3$



reionization $z\sim8$

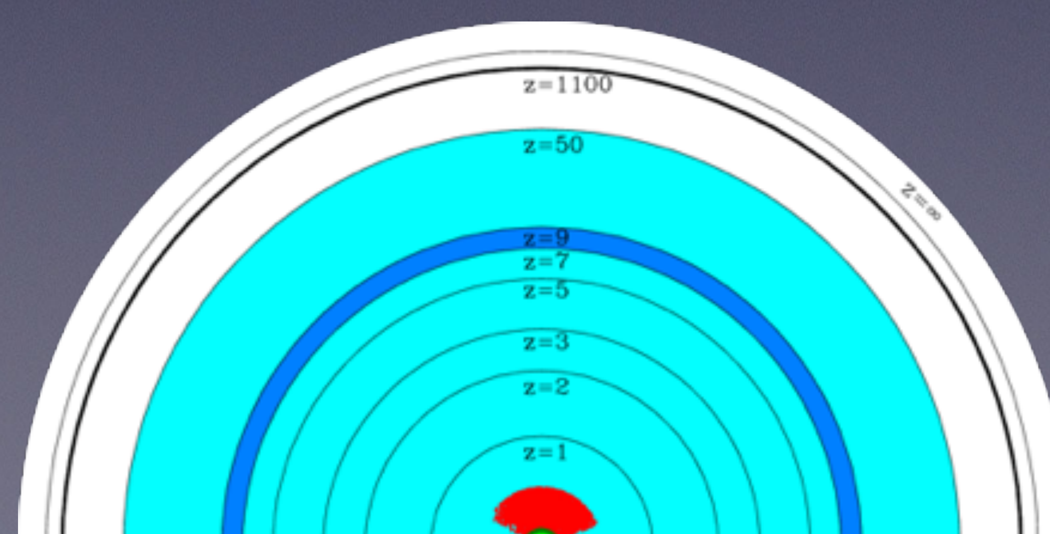
Dark ages (~cosmic dawn)



✓ neutral hydrogen

→ redshifted 21cm line

- tracer of matter fluctuations
- tomography → 3D mapping



Mao+ 2008

Redshifted 21cm line surveys

(c) www.skatelescope.org

On-going:

LOFAR, MWA, PAPER, …

Near future:

- Square Kilometer Array (SKA)

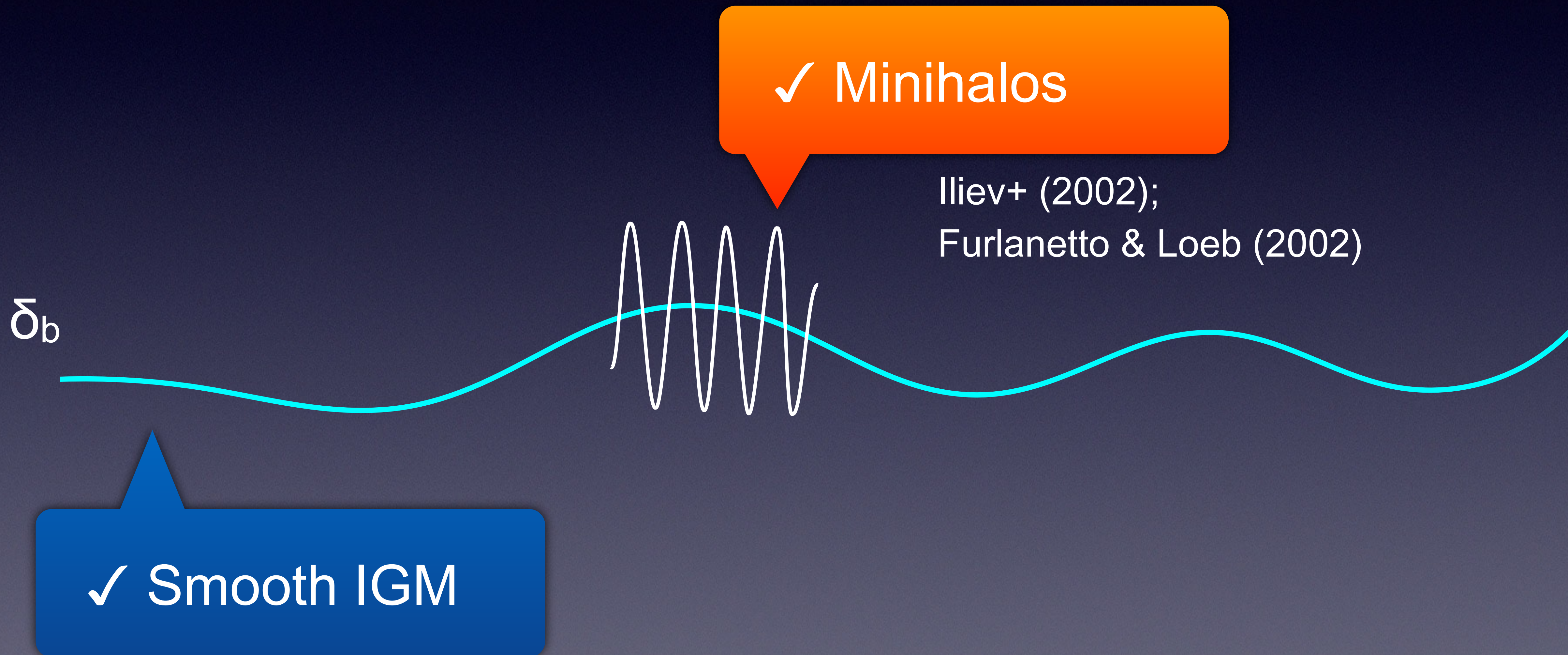
  21cm line from $3<z<27$; SKA1-low will start from 2021

- Hydrogen Epoch Reionization Array (HERA)

  main target: 21cm line from $7<z<12$

➡ Implications for cosmology and particle physics?

Sources of 21cm line



Many many studies…

Minihalos

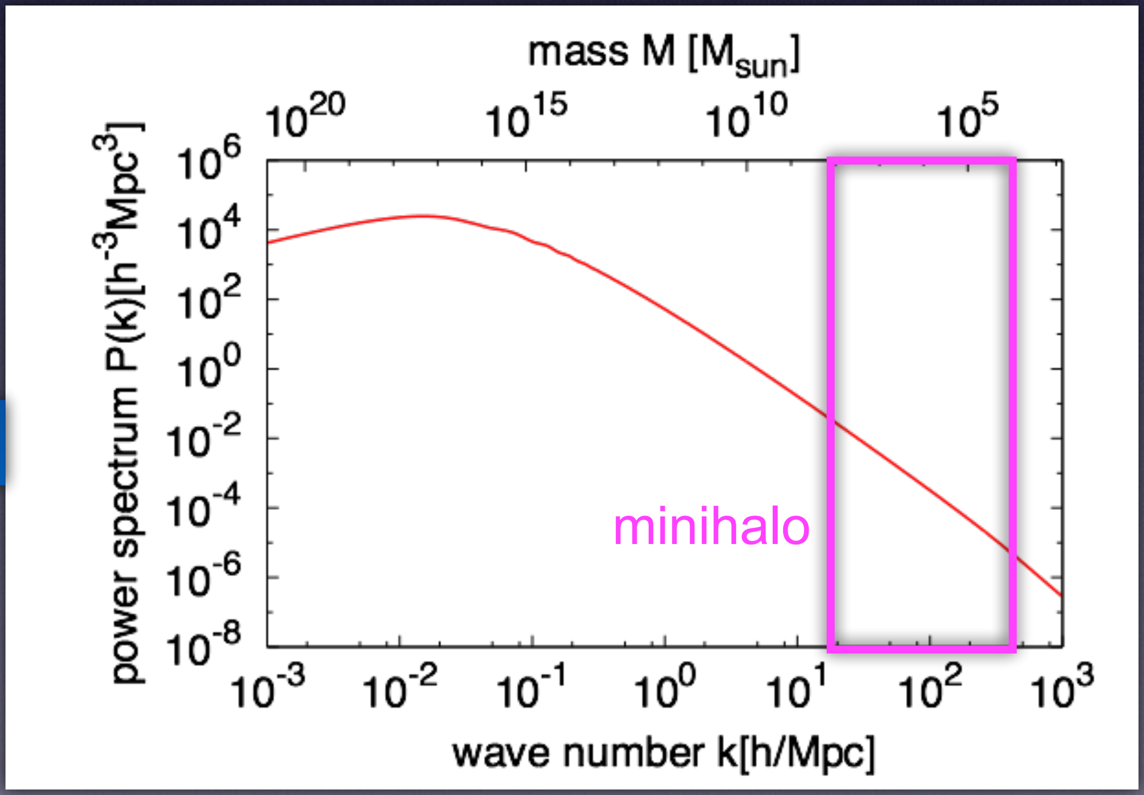
Halos too small to host galaxies

- No star formation: $T_{gas} < 10^4$K (inefficient radiative cooling)

  → dense neutral hydrogen inside; resistant to ionization

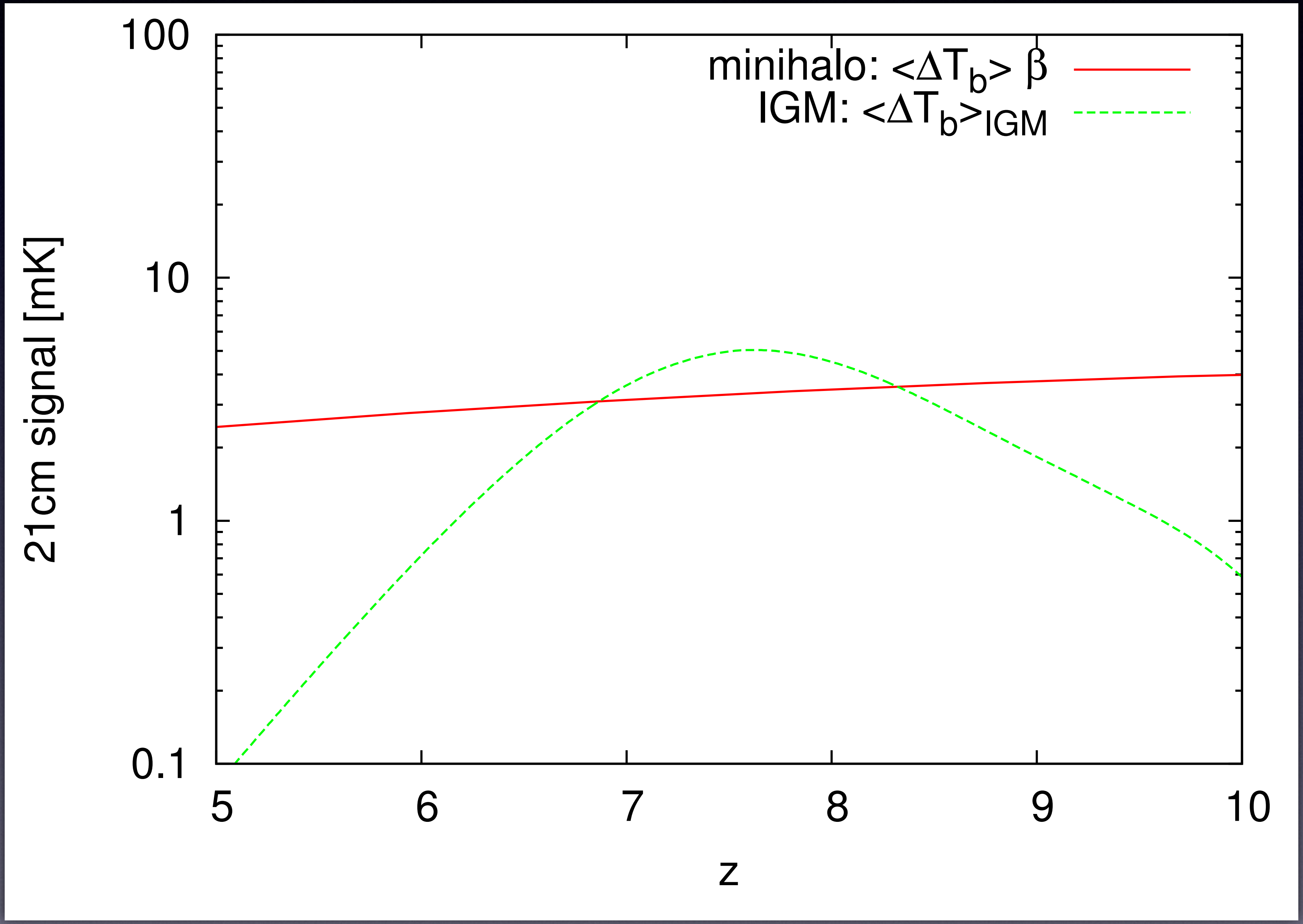
- Mass: $10^4 M_{sun} < M < 10^8 M_{sun}$

Sensitive to small-scale (<0.1Mpc) fluctuations



- Abundant, even at high-z

Minihalos vs IGM



Model of IGM consistent with the recent Planck constraint
Adam+1605:03507

Minihalo contribution can dominate at a broad range of redshifts

Observable

frequency ↔ redshift ↔ radial distance

$$\nu = \frac{\nu_0}{1+z_\nu} \qquad r_\nu = r(z_\nu)$$

Redshifted 21cm line fluctuations from minihalos

$$\delta[\Delta T_b](\hat{n},\nu) = \left[\int_{M_{\rm min}}^{M_{\rm max}} dM\, \Delta T_b(M,z_\nu)\,\frac{dN(M,z_\nu)}{dM}\, b(M,z)\right] \delta(\vec{x}=r_\nu\hat{n}, z_\nu)$$

- $\Delta T_b(M,z_\nu)$: strength of 21cm line emission/absorption from single minihalo
- $\frac{dN(M,z_\nu)}{dM}$: mass function
- $b(M,z)$: halo bias
- mass function and halo bias: sensitive to small-scale (<Mpc) matter fluctuations
- $\delta(\vec{x}=r_\nu\hat{n}, z_\nu)$: matter fluctuations at large scales (>Mpc)

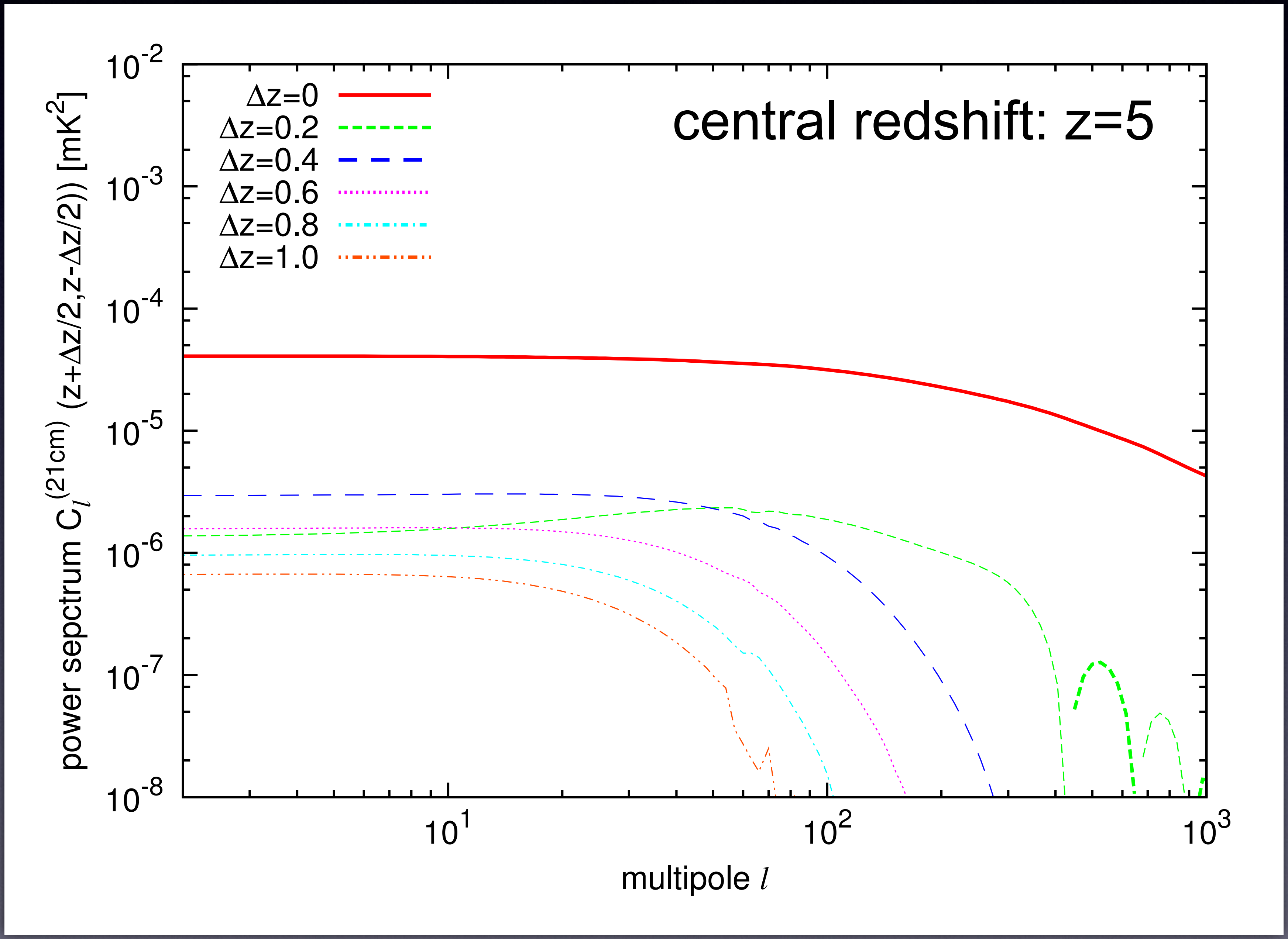
Tomographic angular power spectrum

TS, Takahashi, Tashiro & Yokoyama [arXiv:1705.00405]

$$C_l(z,z') = \frac{1}{2l+1}\sum_m a_{lm}(z)a^*_{lm}(z')$$

with $a_{lm}(z_\nu) = \int d\hat{n}\,\delta[\Delta T_b](\hat{n},\nu)Y^*_{lm}(\hat{n})$

Tomographic angular power spectrum



* Redshift space distortion is included

Application (1): Primordial spectral runnings

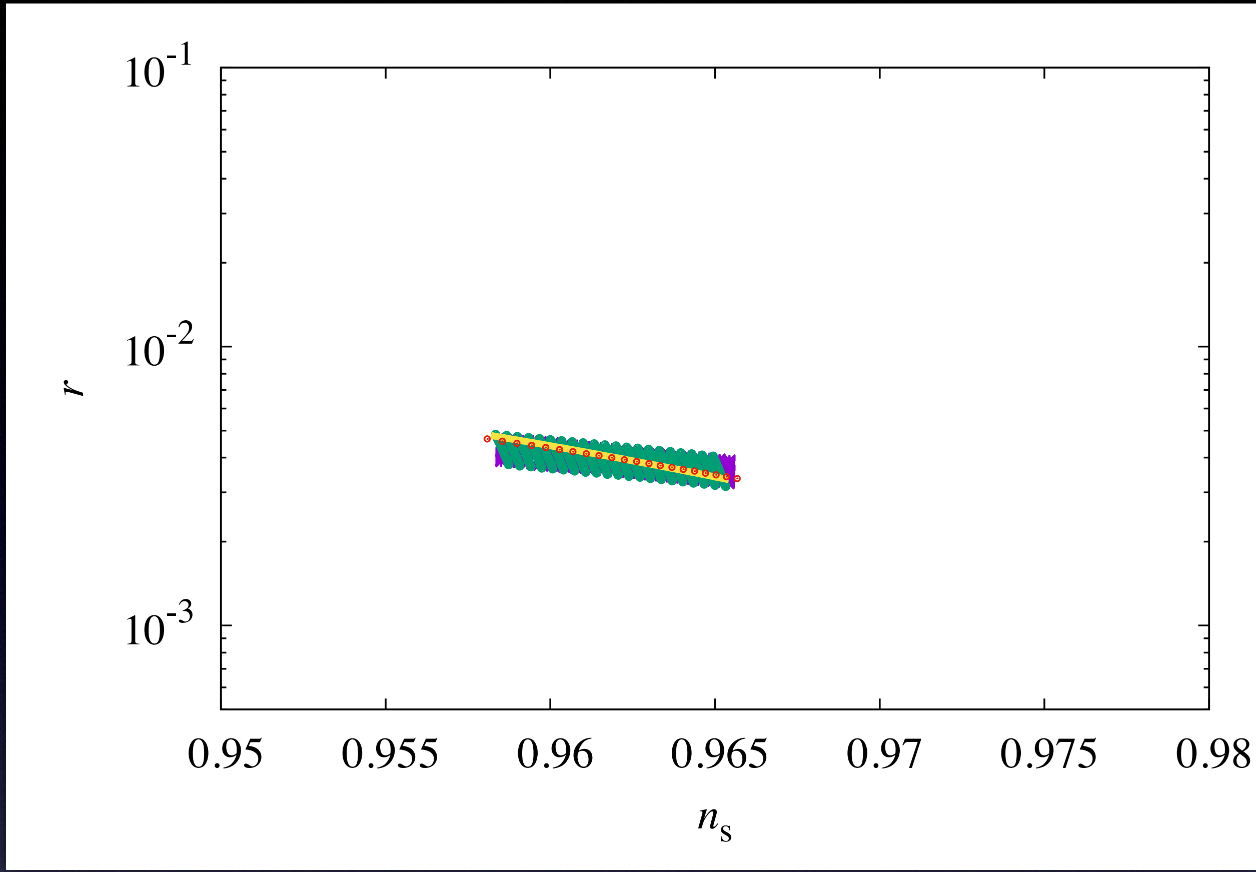
TS, Takahashi, Tashiro & Yokoyama [arXiv:1705.00405]

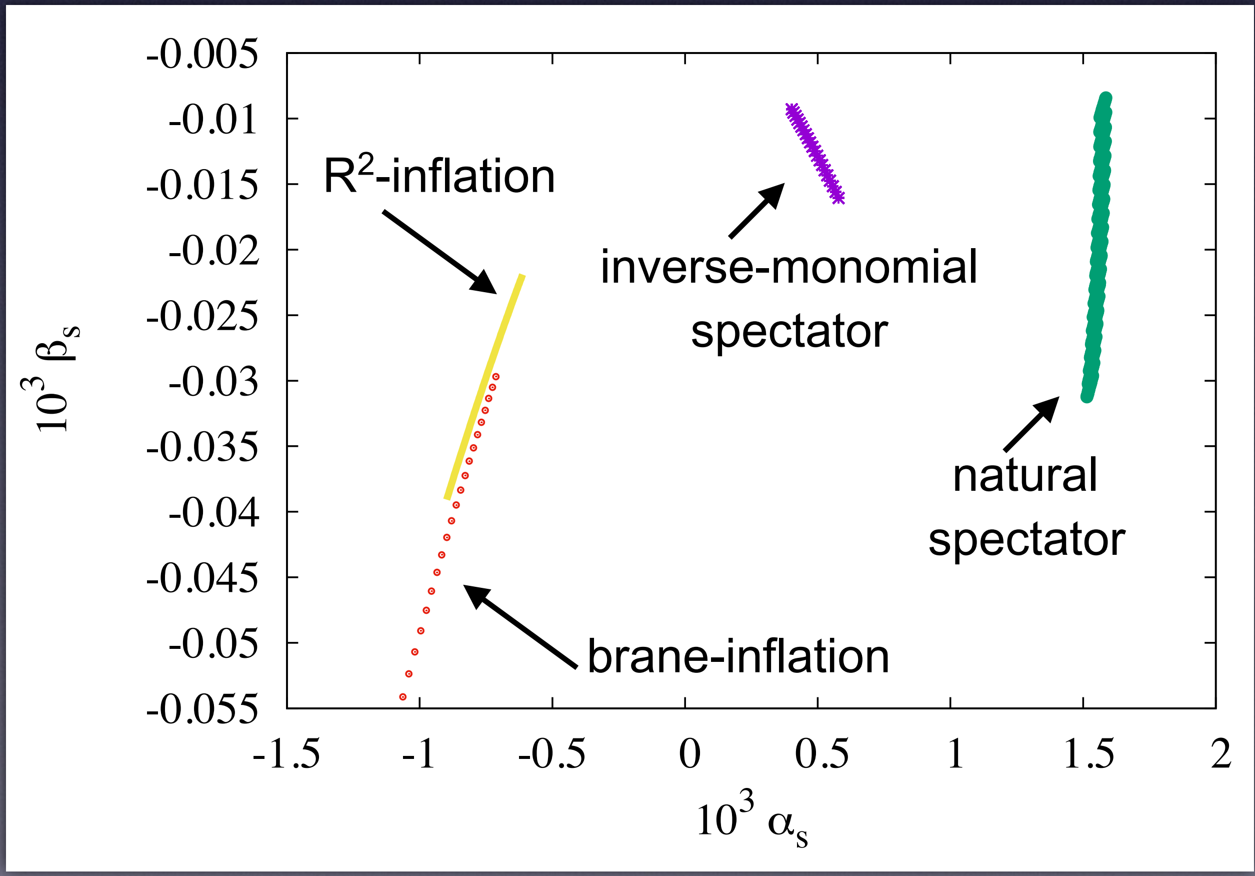
Spectrum of primordial fluctuations

$$\mathcal{P}(k) \propto k^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*) + \frac{1}{6}\beta_s \ln^2(k/k_*) + \ldots}$$

- Many models degenerate in the n_s-r plane
- However, they can be distinguished from the scale dependence of n_s

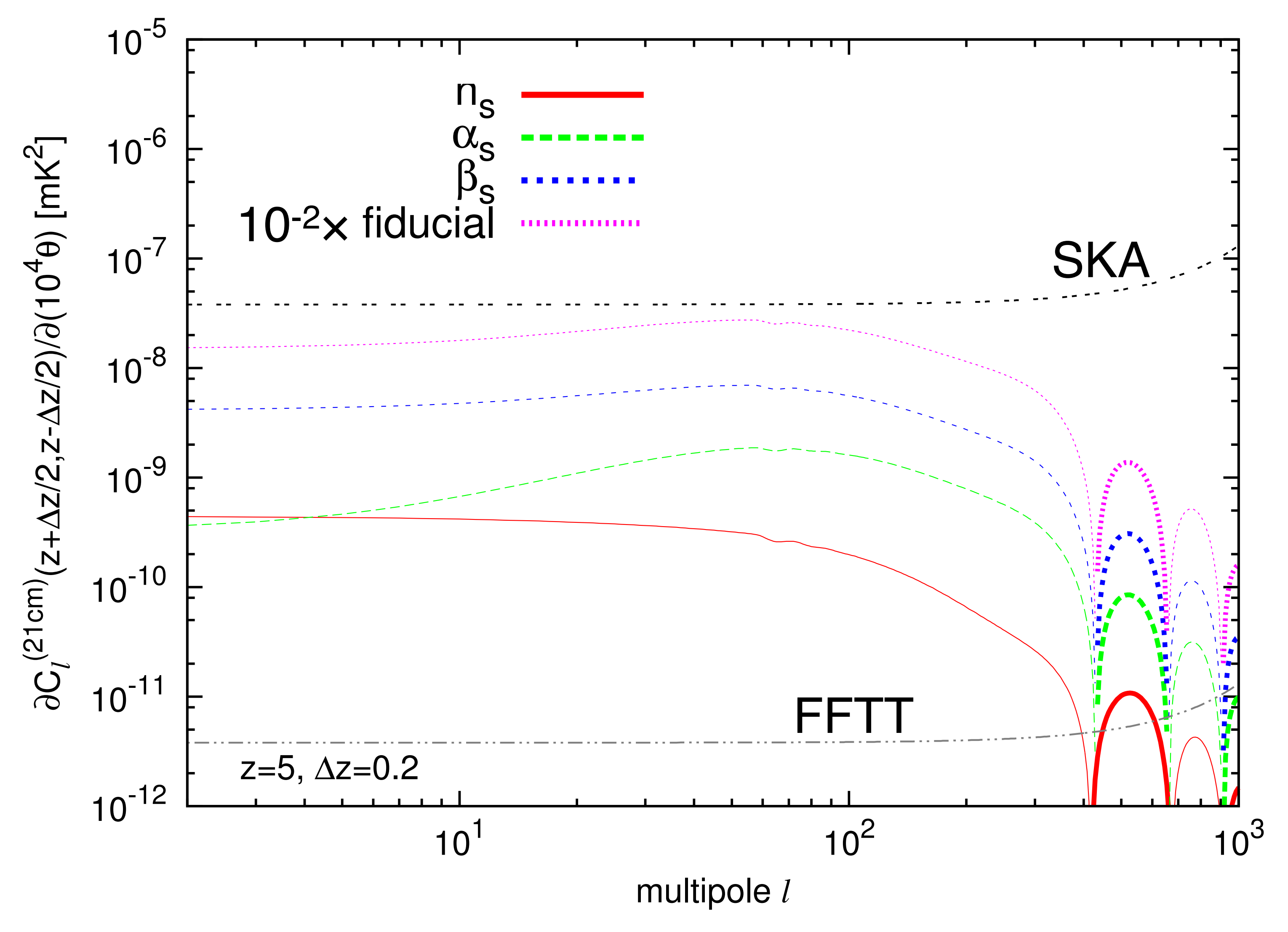
Spectral runnings: a key observable for discriminating inflation models





Application (1): Primordial spectral runnings (cont'd)

Parameter response



- Lower order spectral parameters (e.g. n_s or α_s) → spectral shapes
- Higher order parameters (e.g. β_s) → overall amplitudes

→ Solves parameter degeneracy

- Radial scale-dependence also enhances the discrimination

Application (1): Primordial spectral runnings (cont'd)

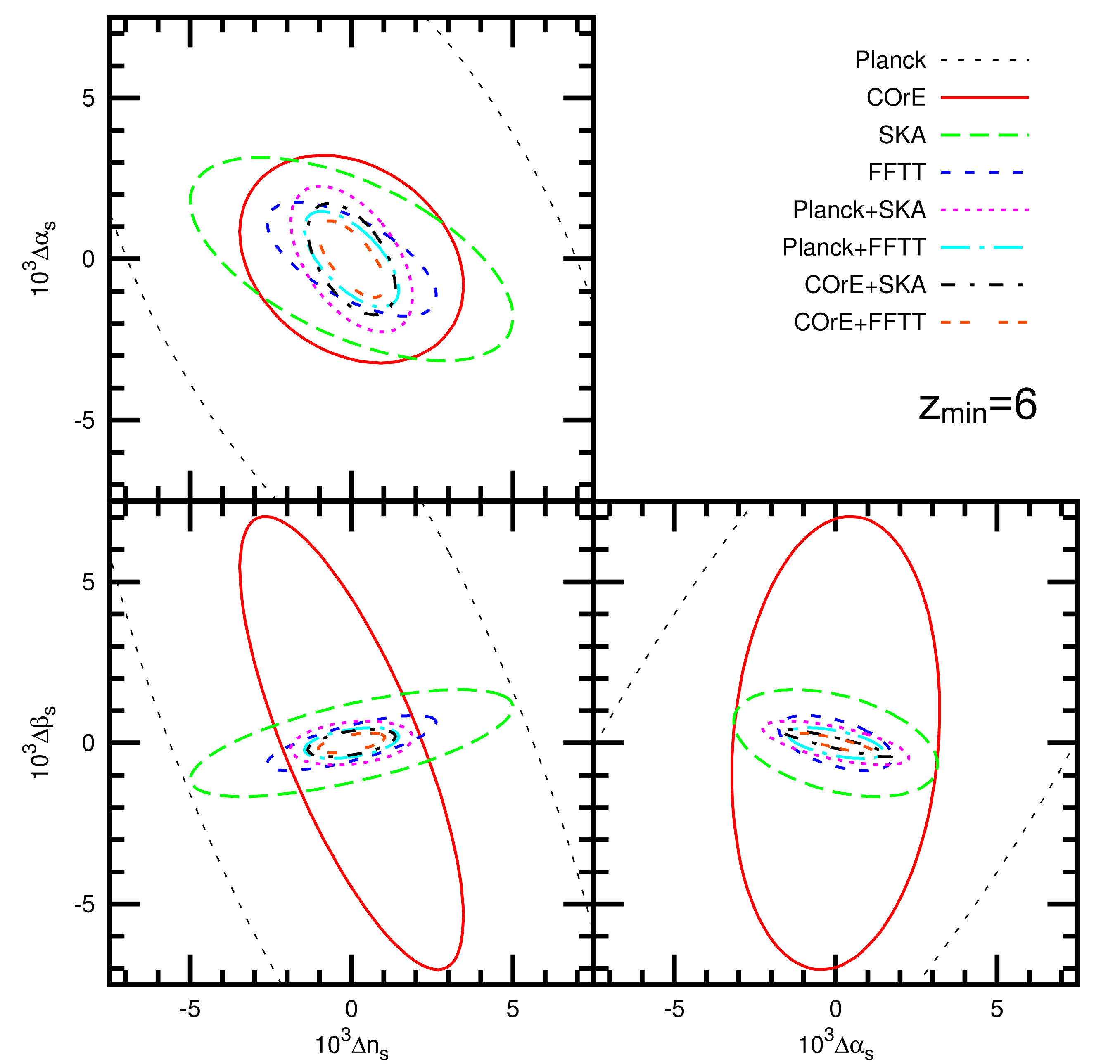
Forecasted constraints

Combination of CMB and 21cm is beneficial due to lever-arm effect.

$\Delta\alpha_s = 10^{-3}$, $\Delta\beta_s = 10^{-4}$

Constraints are dependent on z_{min} only mildly.

	$z_{\rm min}$	$10^{-3}\Delta n_s$	$10^{-3}\Delta\alpha_s$	$10^{-3}\Delta\beta_s$
Planck+SKA	4	1.4	1.4	0.40
	6	1.7	2.0	0.63
	8	2.3	3.0	0.85
	10	3.6	4.7	1.2
COrE+FFTT	4	0.85	0.96	0.24
	6	0.95	1.1	0.28
	8	1.0	1.2	0.31
	10	1.1	1.3	0.33



Application (2):
Primordial non-Gaussianity

TS, Takahashi, Tashiro & Yokoyama, in prep.

Local type non-Gaussianity:

$$\Phi(\vec{x}) = \Phi_{\rm G}(\vec{x}) + f_{\rm NL}(\Phi_{\rm G}(\vec{x})^2 - \langle\Phi_{\rm G}\rangle^2) + g_{\rm NL}\Phi_{\rm G}(\vec{x})^3$$

- Small in single field inflation: f_{NL}~O(0.01), g_{NL}<O(10^{-3})
- Large in multi-field models (e.g. curvaton, modulated reheating, etc.)

Current tightest bound (Planck 2015)

$$f_{\rm NL} = 0.8 \pm 5.0, \quad g_{\rm NL} = (9.0 \pm 7.7) \times 10^4$$

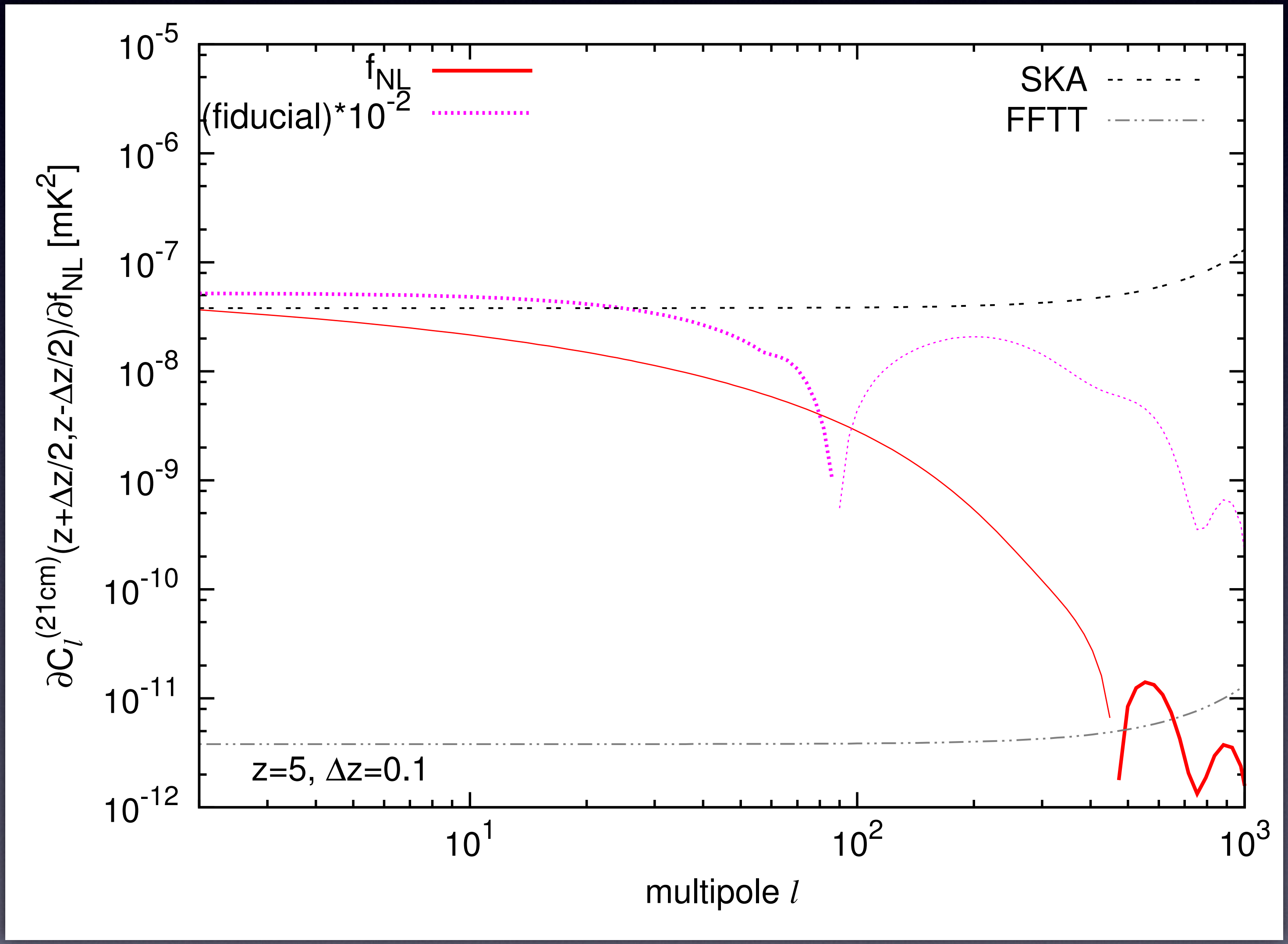
Application (2): Primordial non-Gaussianity (cont'd)

Effects on minihalo spectrum

- Coupling between large and small scale fluctuations
- Abundance of (mini)halos is modulated by large scale fluctuations

→ scale-dependent halo bias

Dalal+(2008); Slosar+(2008)



Application (2): Primordial non-Gaussianity (cont'd)

Forecasted constraints

- SKA

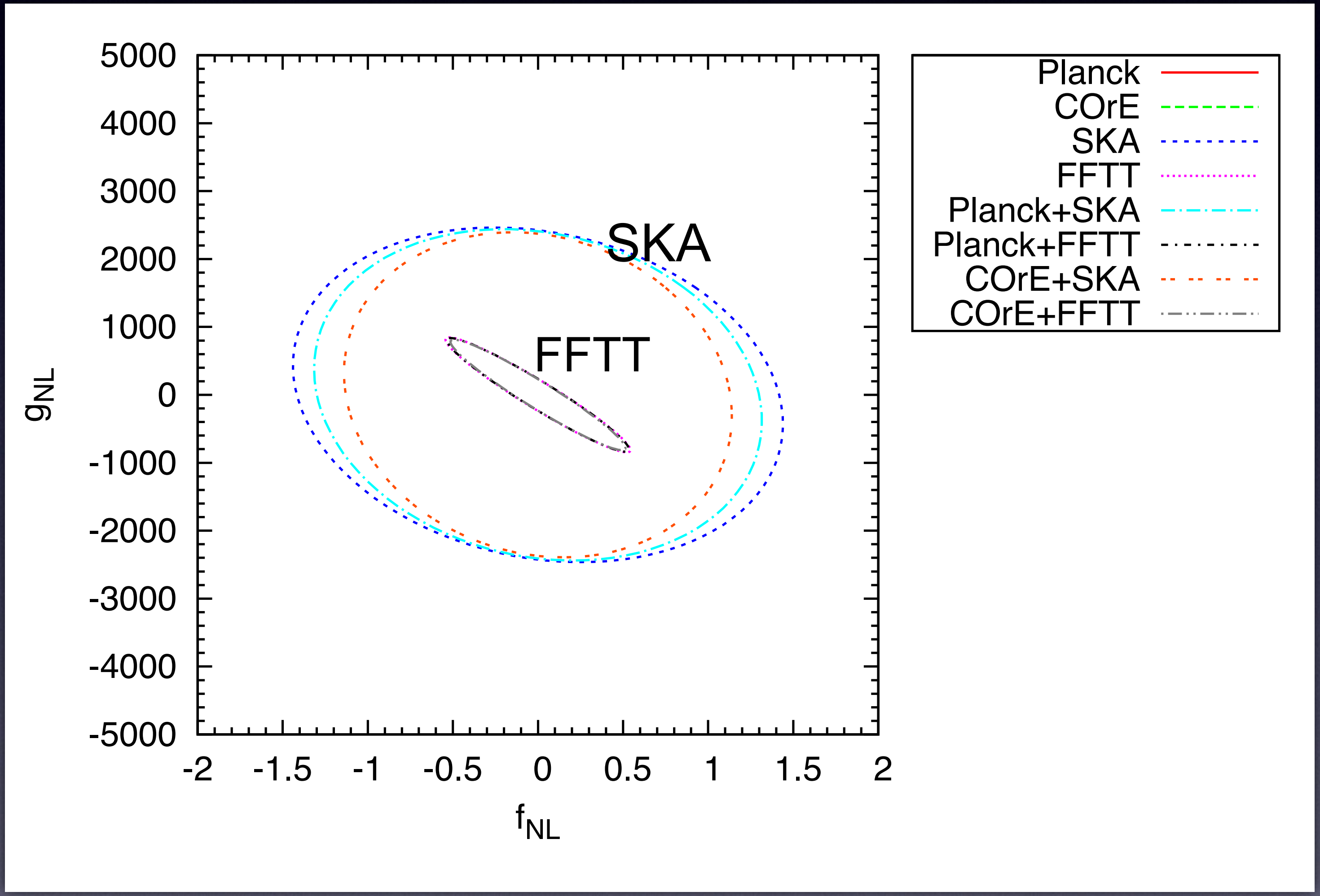
  $\Delta f_{NL}=0.7$, $\Delta g_{NL}=2\text{x}10^3$

- FFTT

  $\Delta f_{NL}=0.1$, $\Delta g_{NL}=7\text{x}10^2$

- cf. Future CMB (COrE)

  $\Delta f_{NL}=2$, $\Delta g_{NL}=2\text{x}10^4$



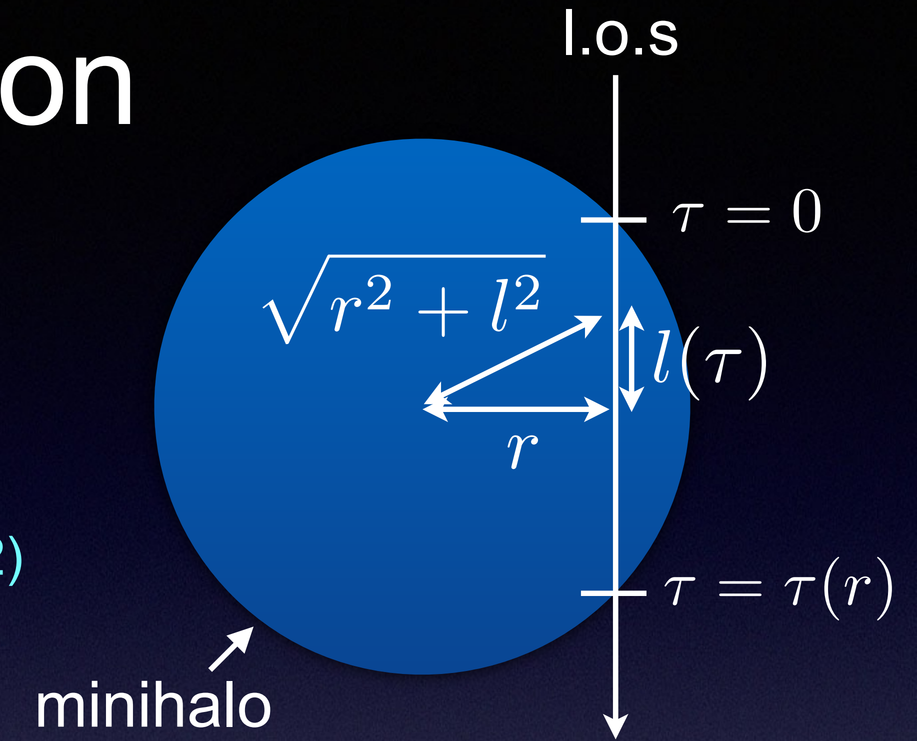
Minihalos potentially improve the (saturated) CMB bound by orders of magnitude

Summary

- Minihalos can probe primordial fluctuations at a wide range of scales, especially those at small scales (<<Mpc), which are difficult to be probed by other observations.
- 21cm signal from can probe primordial fluctuations with increased statistics and enhanced range of scales. Our formulation of tomographic angular spectrum can maximally exploit such advantage in minihalos.
  - Spectral runnings of primordial spectrum
  - Non-Gaussianity
- Lots of other cosmological applications (e.g. WDM [TS & Tashiro arXiv: 1401.5563]) can be considered.

backup slides

Details of calculation



21cm line signals from single minihalo

based on Iliev+(2002)

- minihalo has an inner structure

$\rightarrow$ line of sight integral + average over cross-section

$$\Delta T_b(M, z) = A^{-1} \int dA \int_0^{\tau(r)} d\tau \, [T_S(\sqrt{r^2 + l(\tau)^2}) - T_{\rm CMB}] e^{-\tau}$$

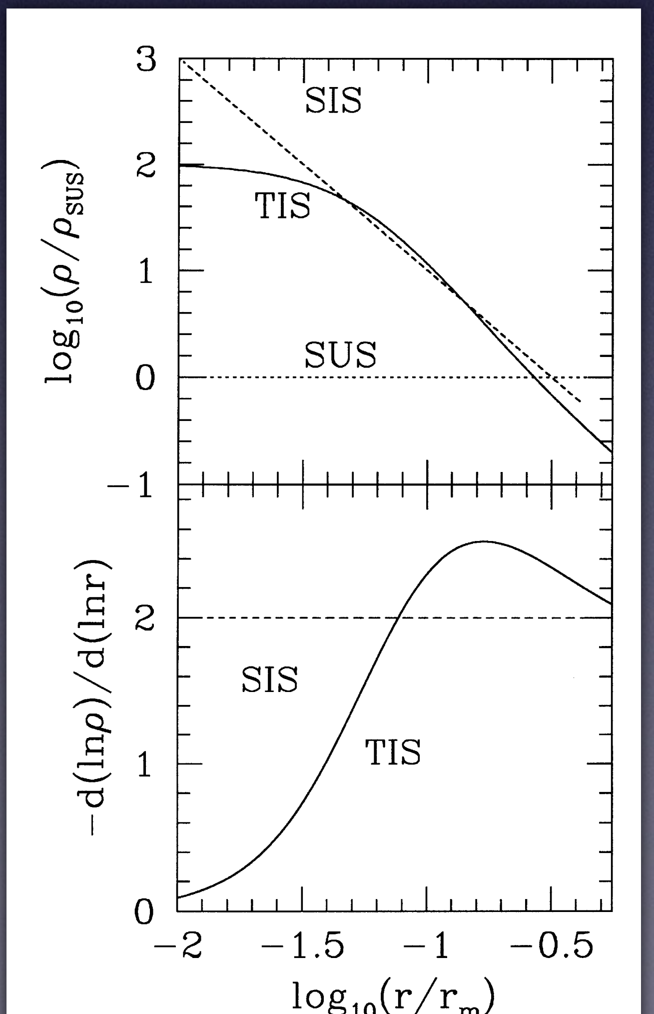
with $A = \pi r_{\rm halo}^2$

- halo profile: truncated isothermal sphere (TIS)

Shapiro, Iliev & Raga (1999)

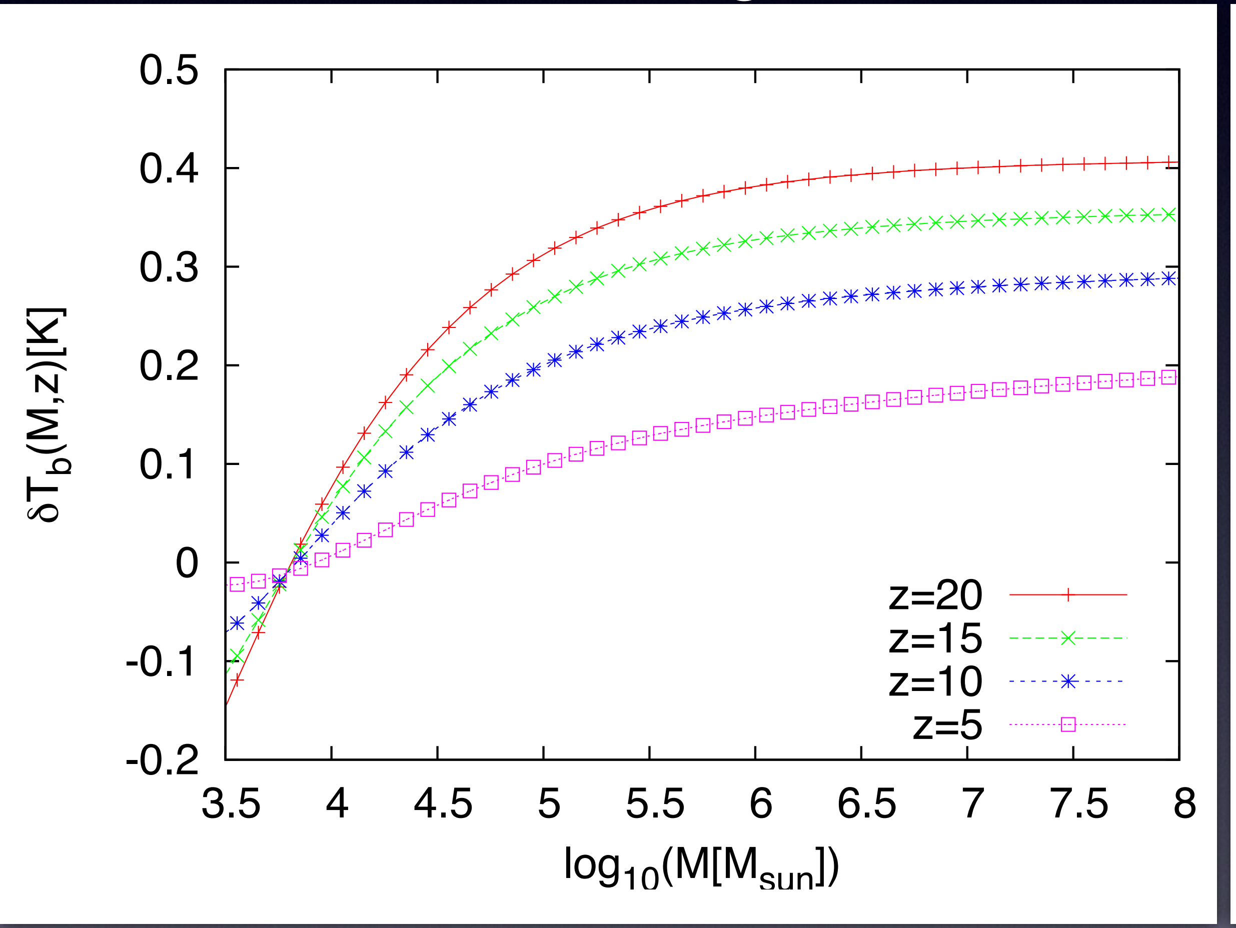
- spin temperature: strongly coupled with gas

$$T_S \approx T_{\rm gas}$$

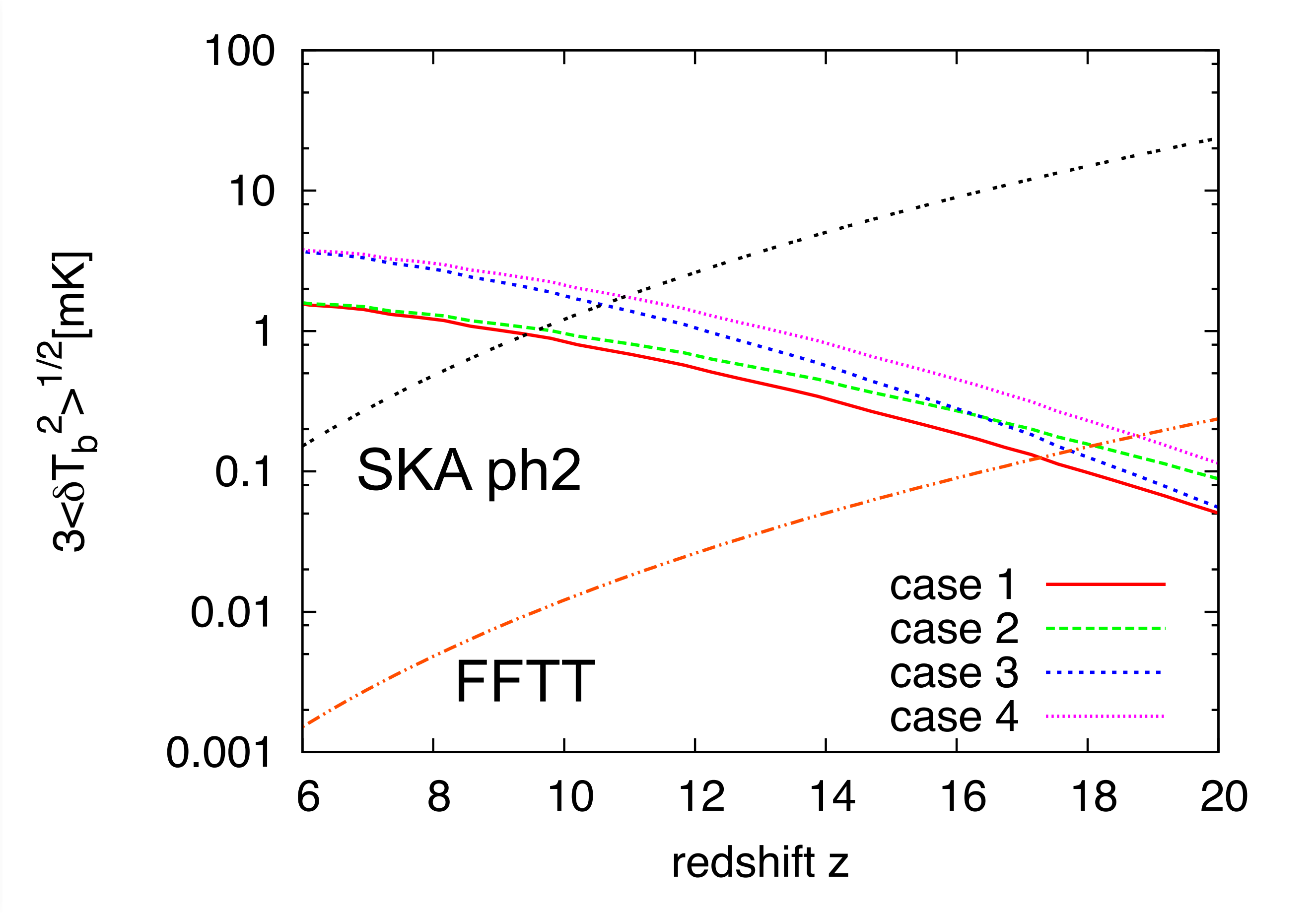


21cm signal

contributions from single halo



rms of 21cm fluctuations (SKA-like survey with Δθ=9', Δν=1MHz)



21cm signal from minihalos can be observed by SKA

case 1: PS & δ_c=1.67

case 2: PS & δ_c=1.52

case 3: ST & δ_c=1.67

case 4: ST & δ_c=1.52

Specification of surveys

	SKA	FFTT
total effective area $A_{\rm tot}$ [m^2]	10^5	10^7
bandwidth $\Delta\nu$ [MHz]	1	
beam width $\Delta\theta$ [arcmin]	9	
integration time t [hour]	1000	

Table 1. Specification of 21 cm surveys.

	Planck			COrE				
band frequency [GHz]	100	147	217	105	135	165	195	225
beam width $\Delta\theta$ [arcmin]	9.9	7.2	4.9	10.0	7.8	6.4	5.4	4.7
Temperature noise Δ_T [μK arcmin]	31.3	20.1	28.5	2.68	2.63	2.67	2.63	2.64
Polarization noise Δ_P [μK arcmin]	44.2	33.3	49.4	4.63	4.55	4.61	4.54	4.57

Table 2. Specification of CMB surveys.

Blue-tilted isocurvature power spectrum

Isocurvature perturbations

Relative perturbations between matter and radiation

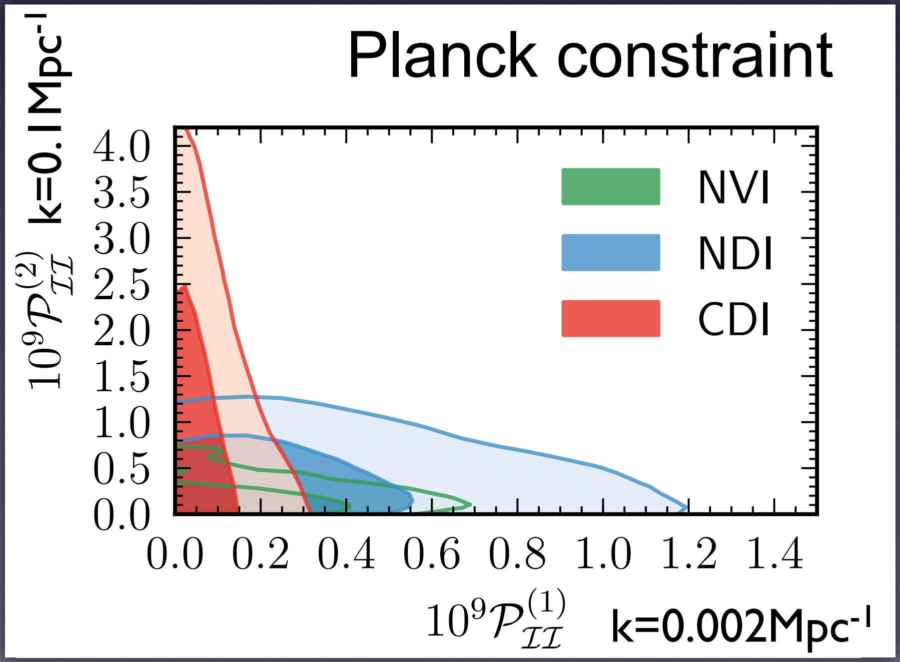
$$S(\vec{x}) = \delta \log\left(\frac{n_{\rm matter}(\vec{x})}{n_{\rm rad}(\vec{x})}\right)$$

Theoretical models: axion (uncorrelated), curvaton (correlated), ...

Power spectrum

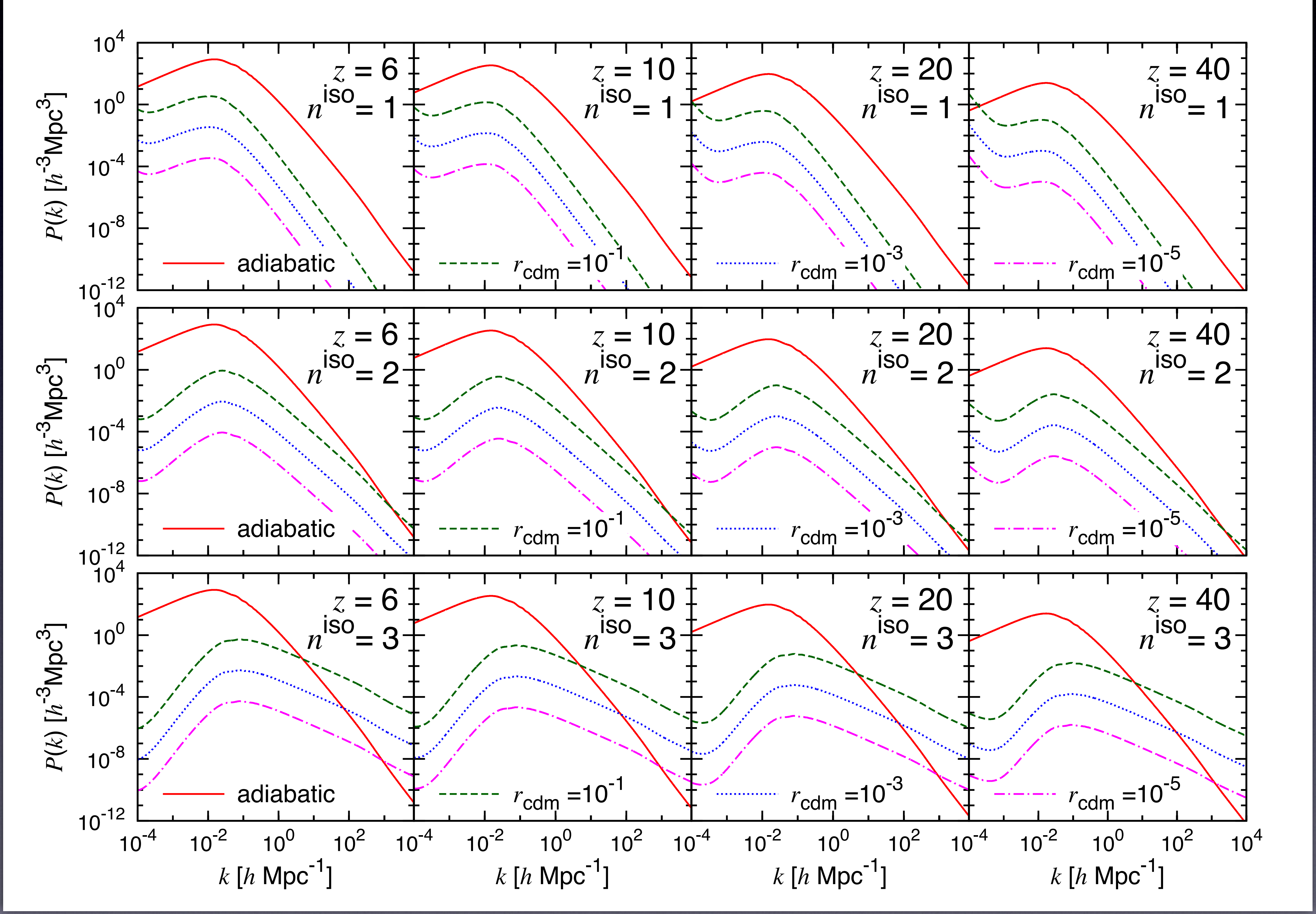
$$P_S(k) \propto \alpha k^{p-1}$$

$$\alpha = P_S(k_0)/P_\zeta(k_0)$$ at k_0=0.002Mpc^{-1}



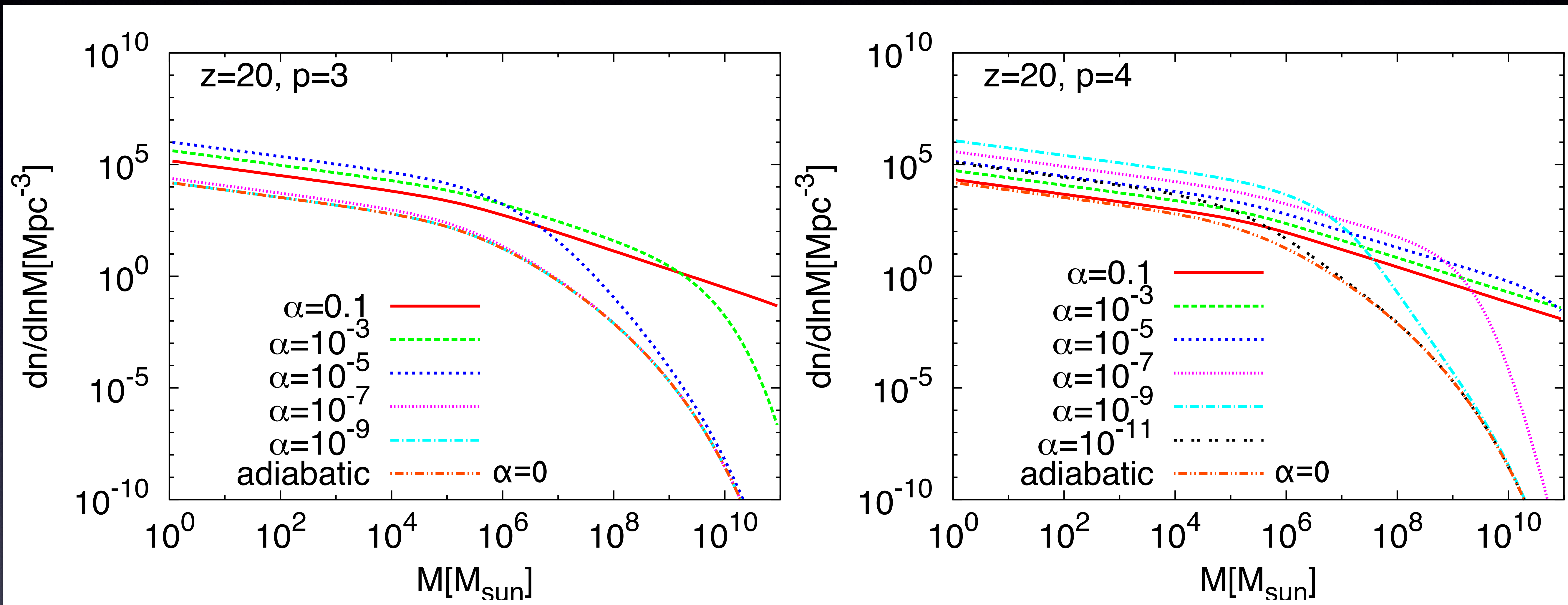
Blue spectrum (e.g, Kasuya & Kawasaki '09) is less constrained from CMB C_l

Matter power spectrum



Takeuchi & Chongchitnan (2013)

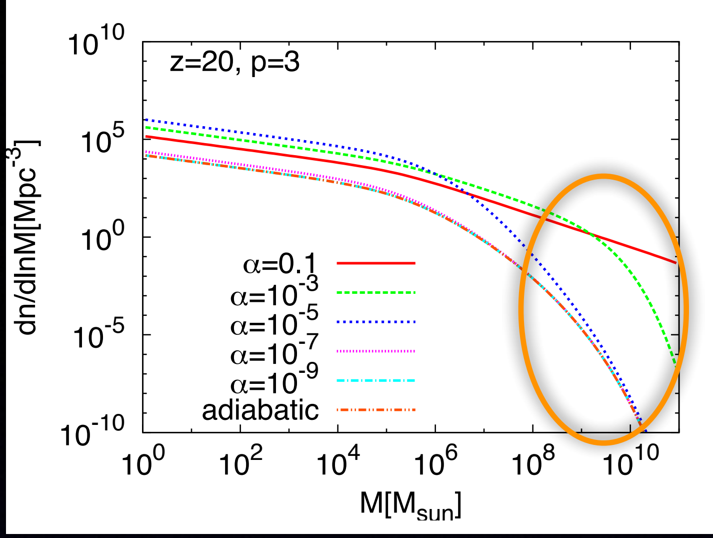
Effects on mass function



Mass function does not change monotonically:

- Small α: abundance of halos increases at all M as α increases
- Large α: abundance of small halos starts to decrease ← incorporation of smaller haloes into larger ones

Constraint from reionization



Isocurvature pert. with blue spectrum can promote reionization

Sugiyama, Zaroubi & Silk (2004)

- Simplified modeling of reionization Tegmark & Silk (1994)

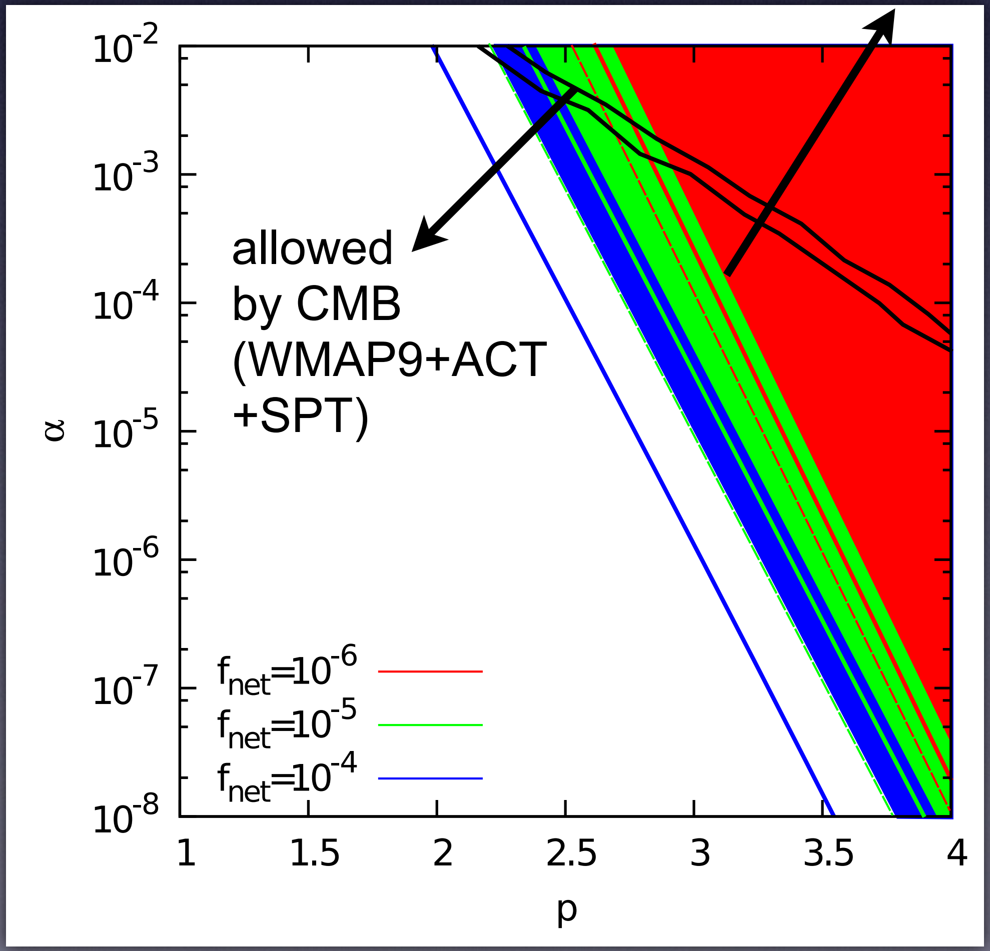
$$x_{\rm reion} = f_{\rm coll} \frac{\Delta m_p c^2}{13.6{\rm eV}} f_{\rm burn} f_{\rm UV} f_{\rm esc} f_{\rm ion}$$

$= f_{net} \sim 10^{-4}$

collapsed baryon fraction in massive halos

for Pop II model
(Sommerville & Lavio 2003)

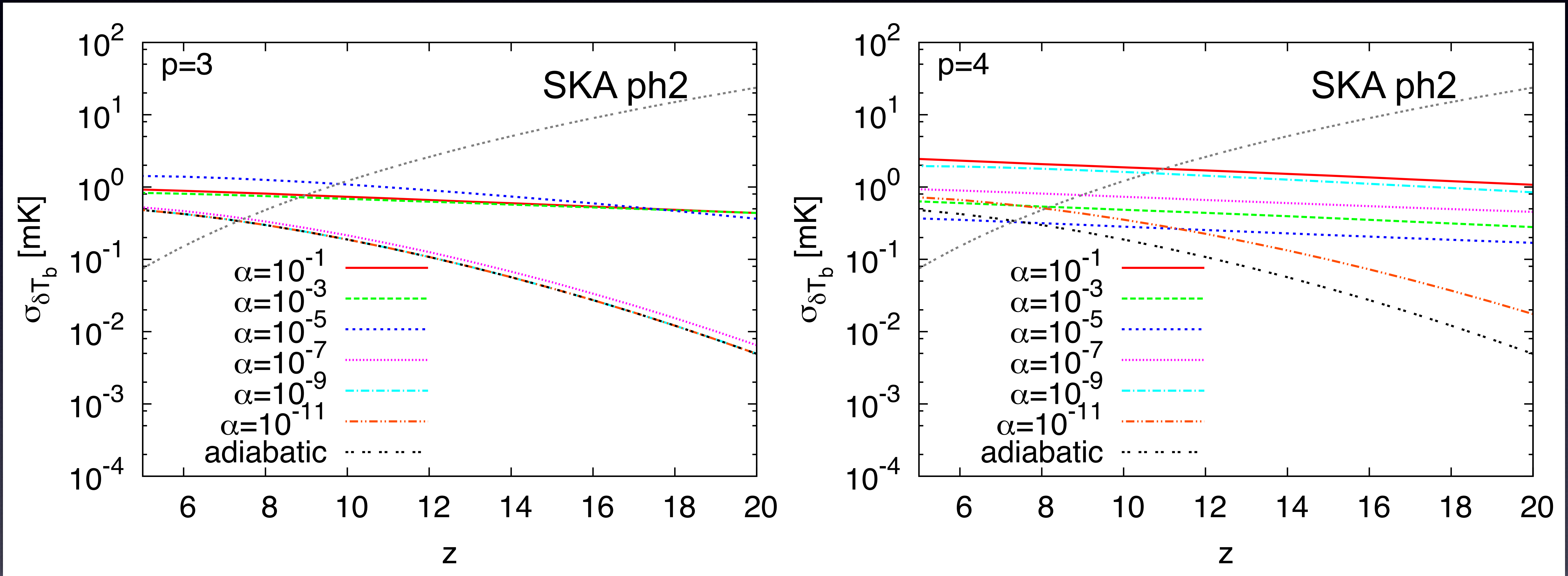
excluded by $\tau_{reion}<0.13$



- Constraints from τ_{reion}

→ Tighter constraints than from C_l^{TT}
(even with the large uncertainty in f_{net})

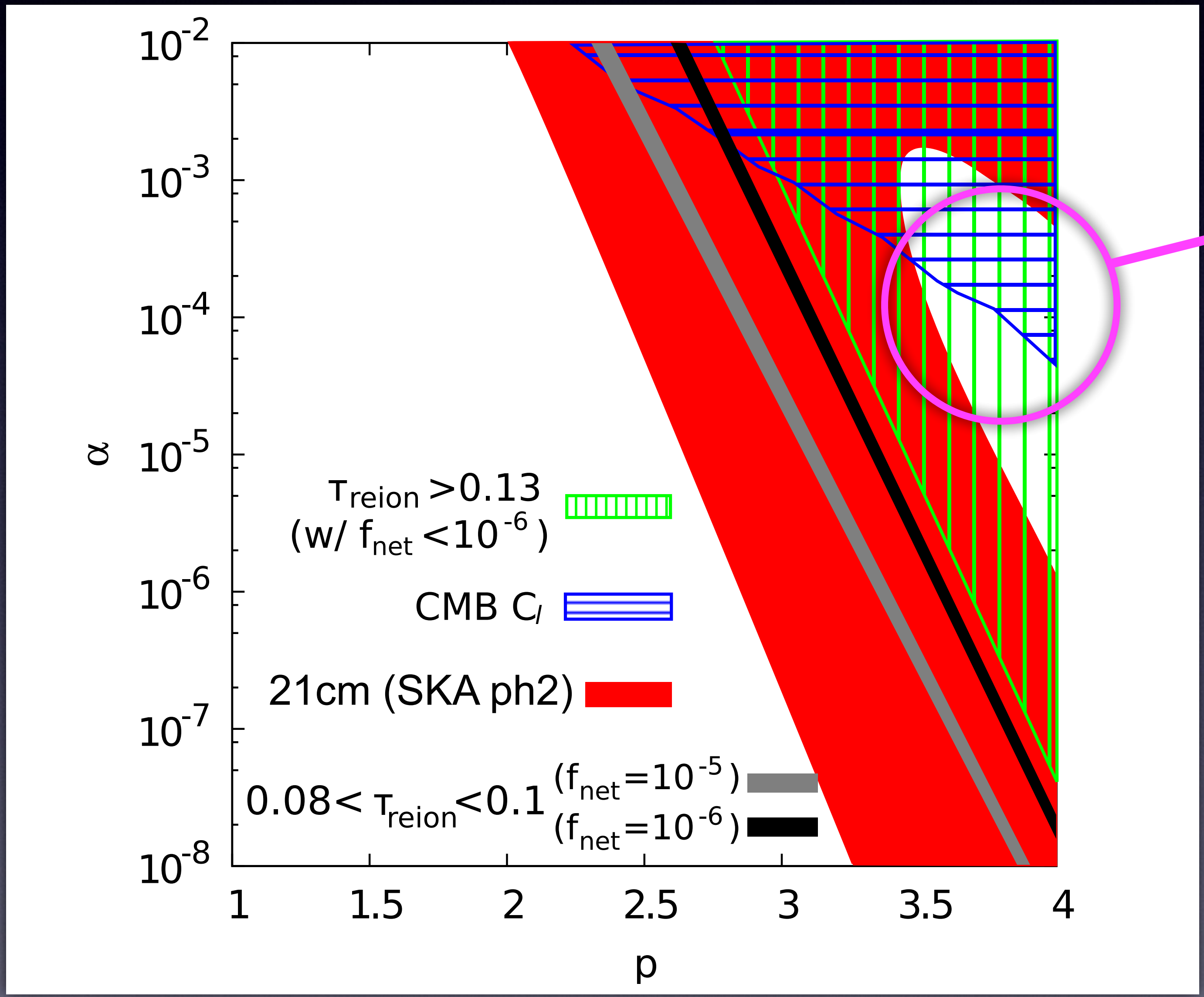
21cm fluctuations from minihalos



Complicated response to α:

- small α → increase in mass function
- intermediate α → decrease in mass function at $M<10^8 M_{sun}$
- large α → increase in matter fluctuations at resolved scales (~Mpc)

(Forecasted) constraint



incorporation of small halos

21cm line fluctuations & reionization optical depth can complementarily constrain isocurvature perturbations

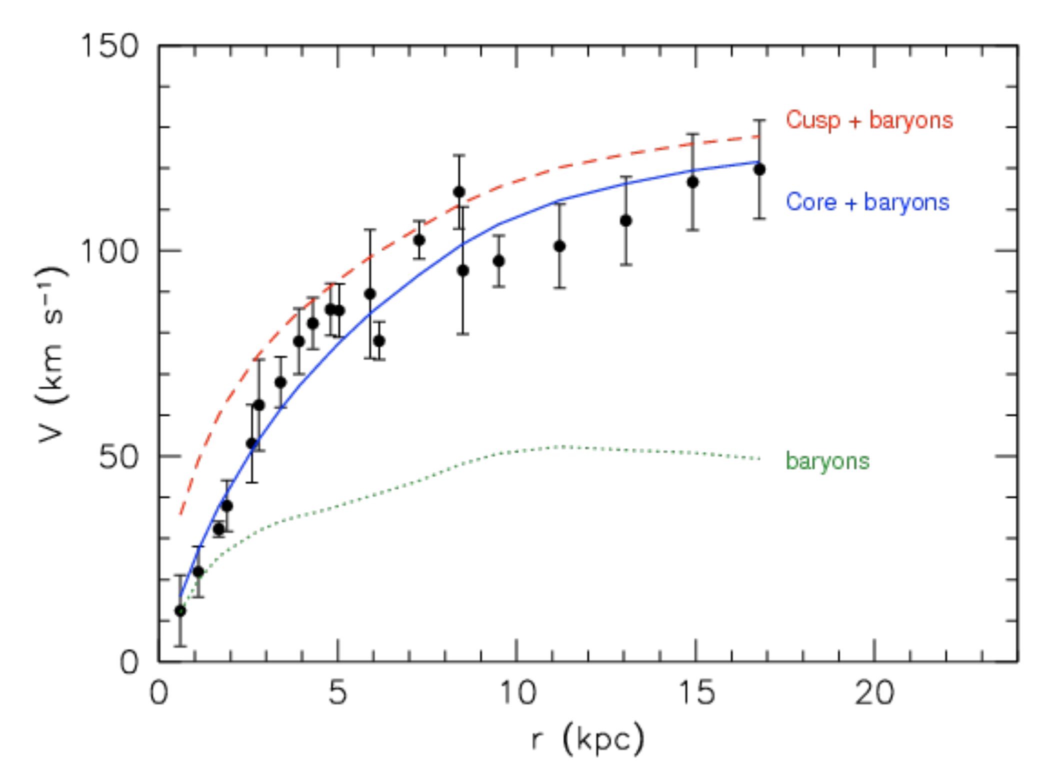
Warm dark matter

Warm dark matter?

Motivation: small-scale problems

- missing satellites
- cusp-core profile

...



D.H.Weinberg+(2013)

Models: thermal/non-thermal relics

ex) sterile neutrino, gravitino, ...

- solution to small scale problems?

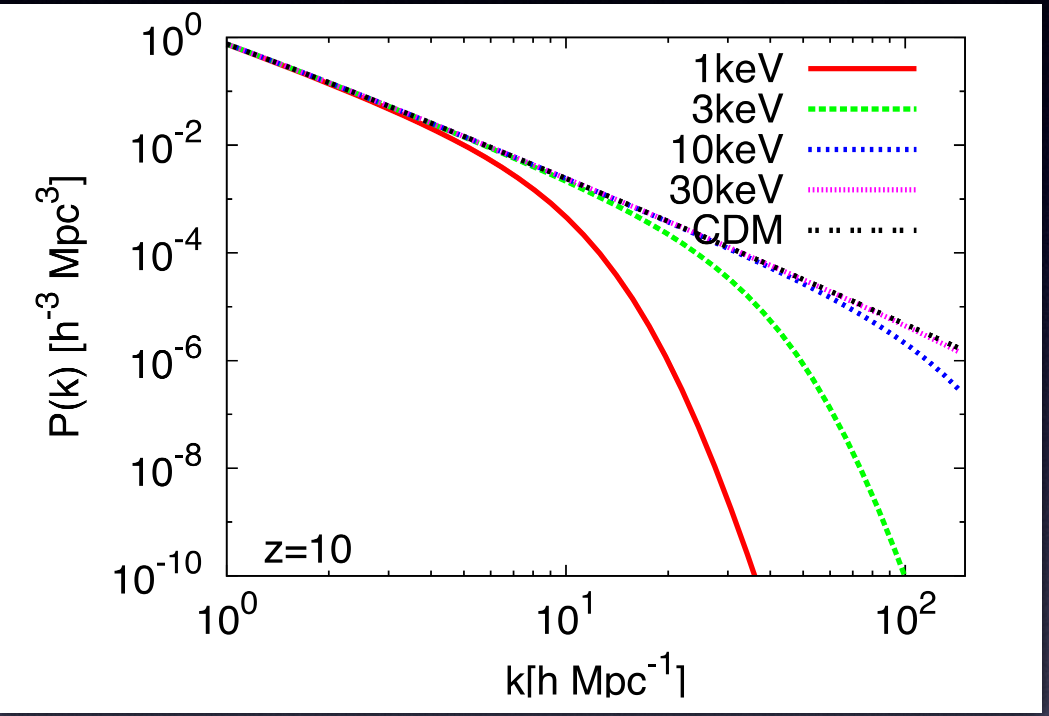
$$m_{\rm WDM} = \mathcal{O}(1){\rm keV}$$

Effects on structure formation

Matter power spectrum

suppressed within free-streaming scale

$$\lambda_{\rm FS} \simeq 0.1 \left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{-4/3} {\rm Mpc}$$



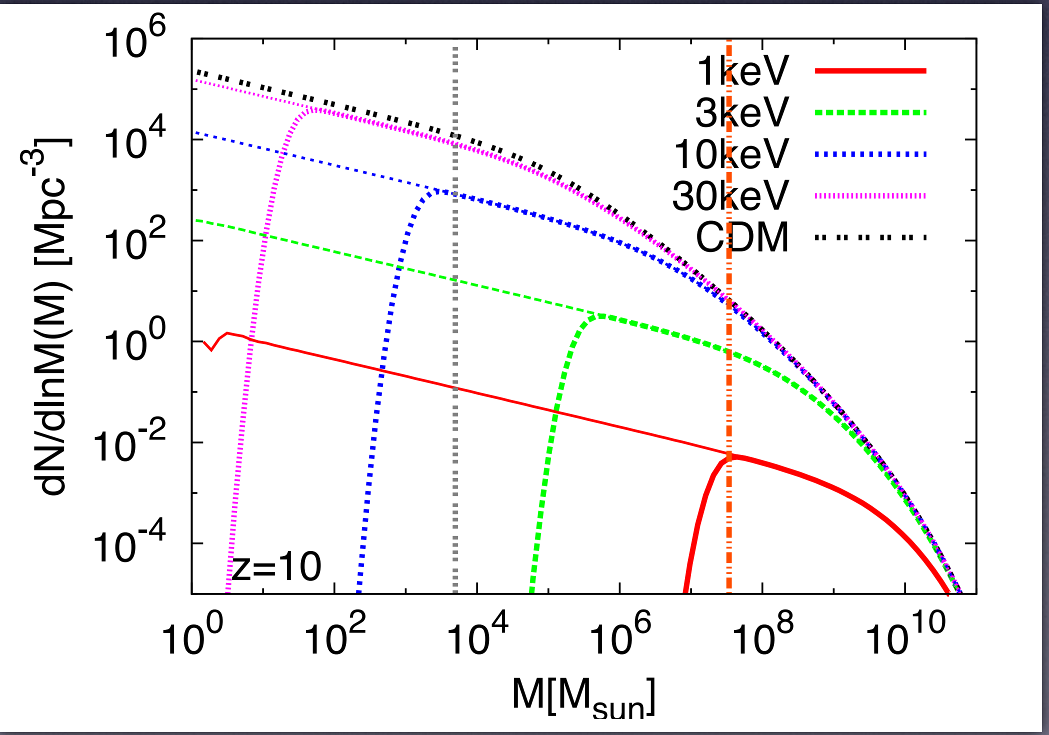
Mass function

- suppressed formation of small halos

- additional cut-off at ~ $M(\lambda_{\rm FS})$?

Zavala+(2009), Polisensky & Ricotti (2011)

← break down of hierarchical formation



Current & Future constraint

Lyman-alpha forest

Narayanan+ (2000), Viel+ (2005), Seljak+ (2006), ...

- recent constraint: O(1) keV

Iršič+ (2013): m_{WDM}>5.3keV (2σ)

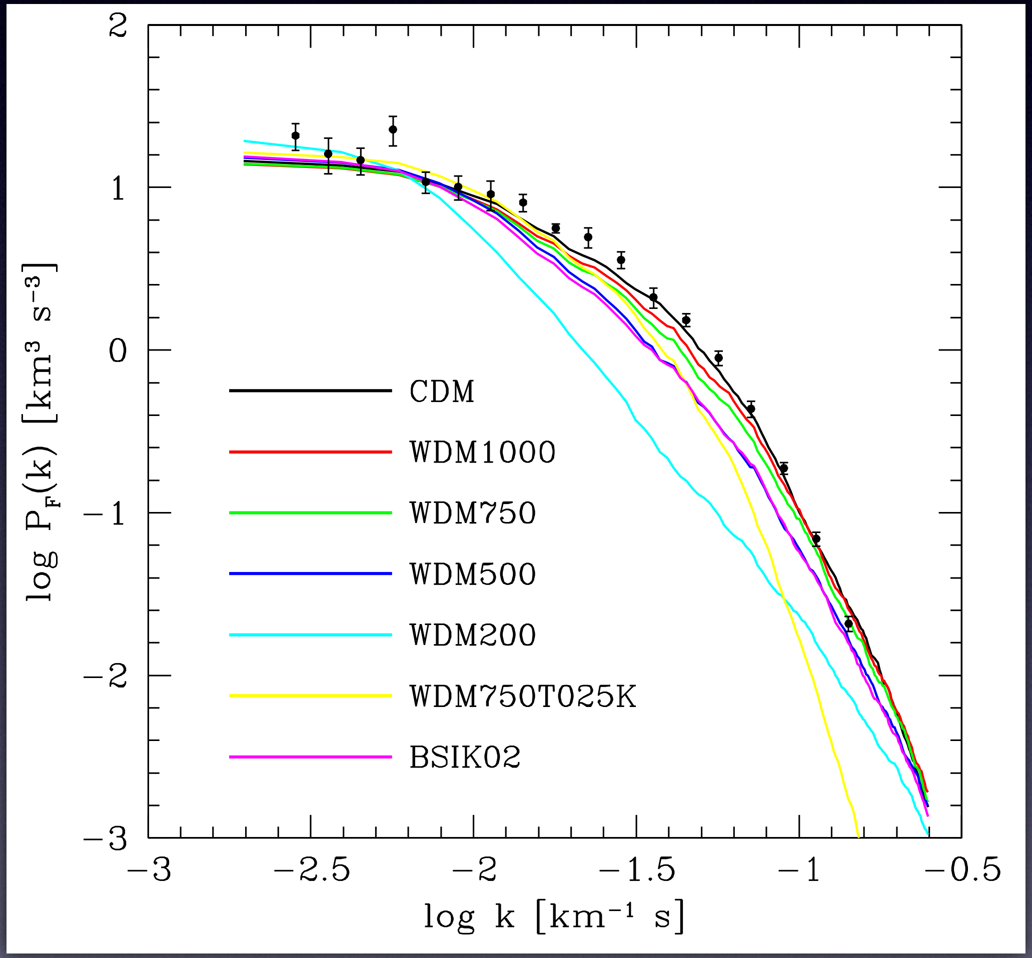
Abundances of GRB

de Souza+ (2013): m_{WDM}>1.6keV (2σ)

Weak lensing

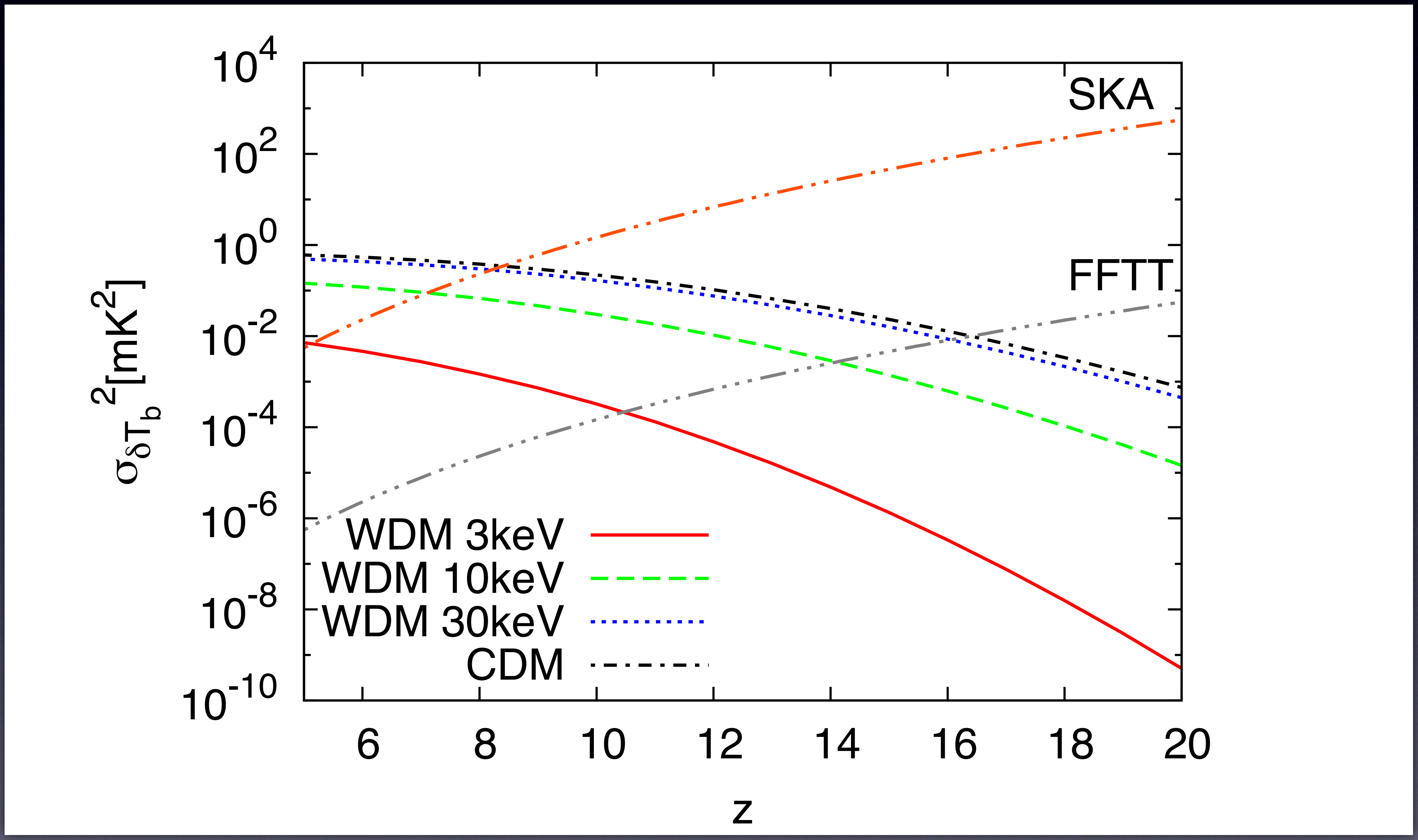
Euclid (forecast): m_{WDM}>2.6keV (2σ)

Smith & Markovic (2011)



Narayanan+(2000)

21cm fluctuations



- As WDM deviates from CDM ($m_{WDM} \rightarrow 0$), 21cm line fluctuations are suppressed
- Sensitive to m_{WDM}>10keV

Forecast constraint

2σ lower bounds (z_{min}=5)

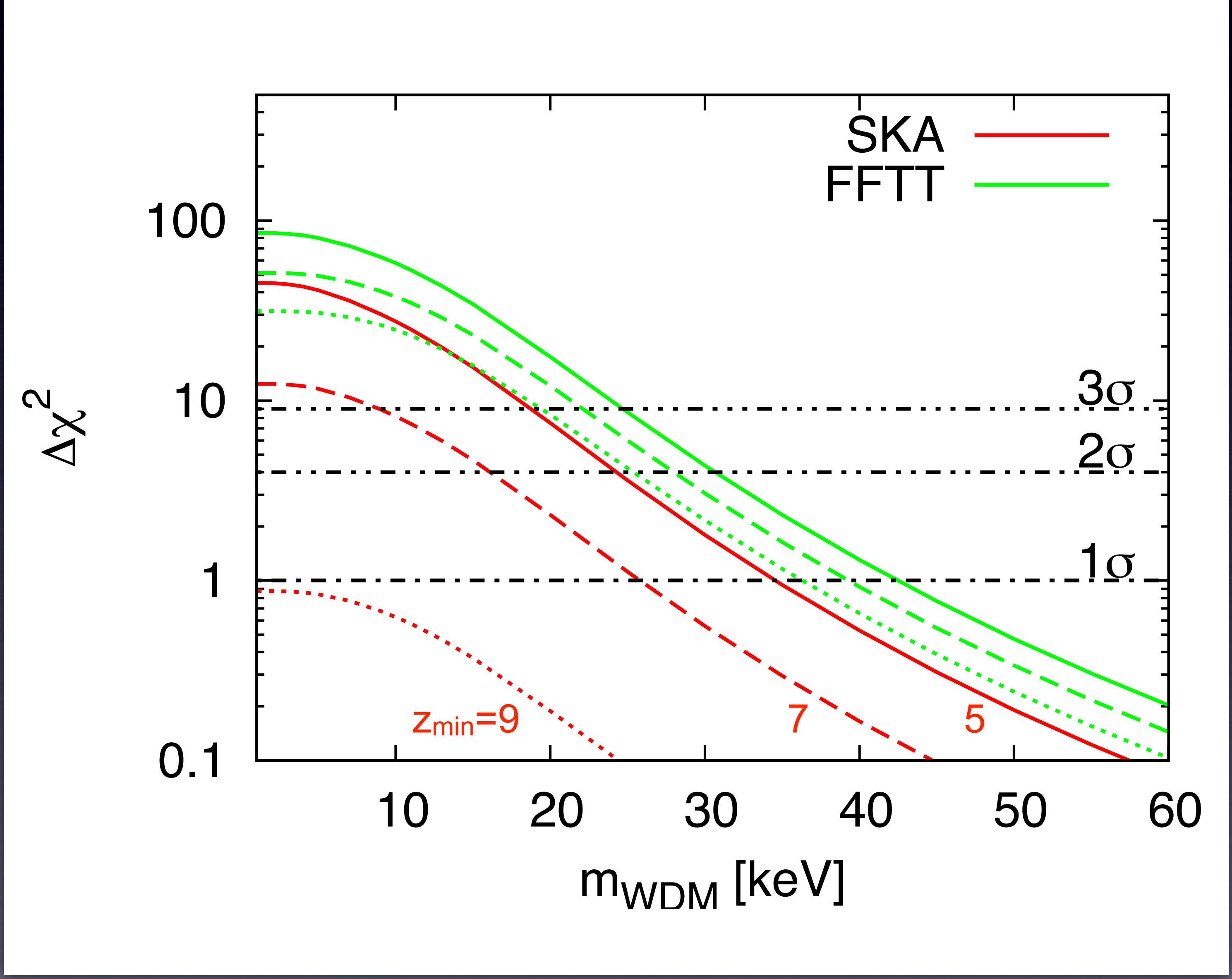
- SKA-low

$$m_{\rm WDM} > 22{\rm keV}$$

- FFTT

$$m_{\rm WDM} > 30{\rm keV}$$

cf. current constraint
m_{WDM}>3keV (Lyα forest)



→ WDM of O(10)keV may be probed and precluded from the solution of small-scale crisis

Further suppression effects?

Modification of halo profile

– Formation of small halos delays

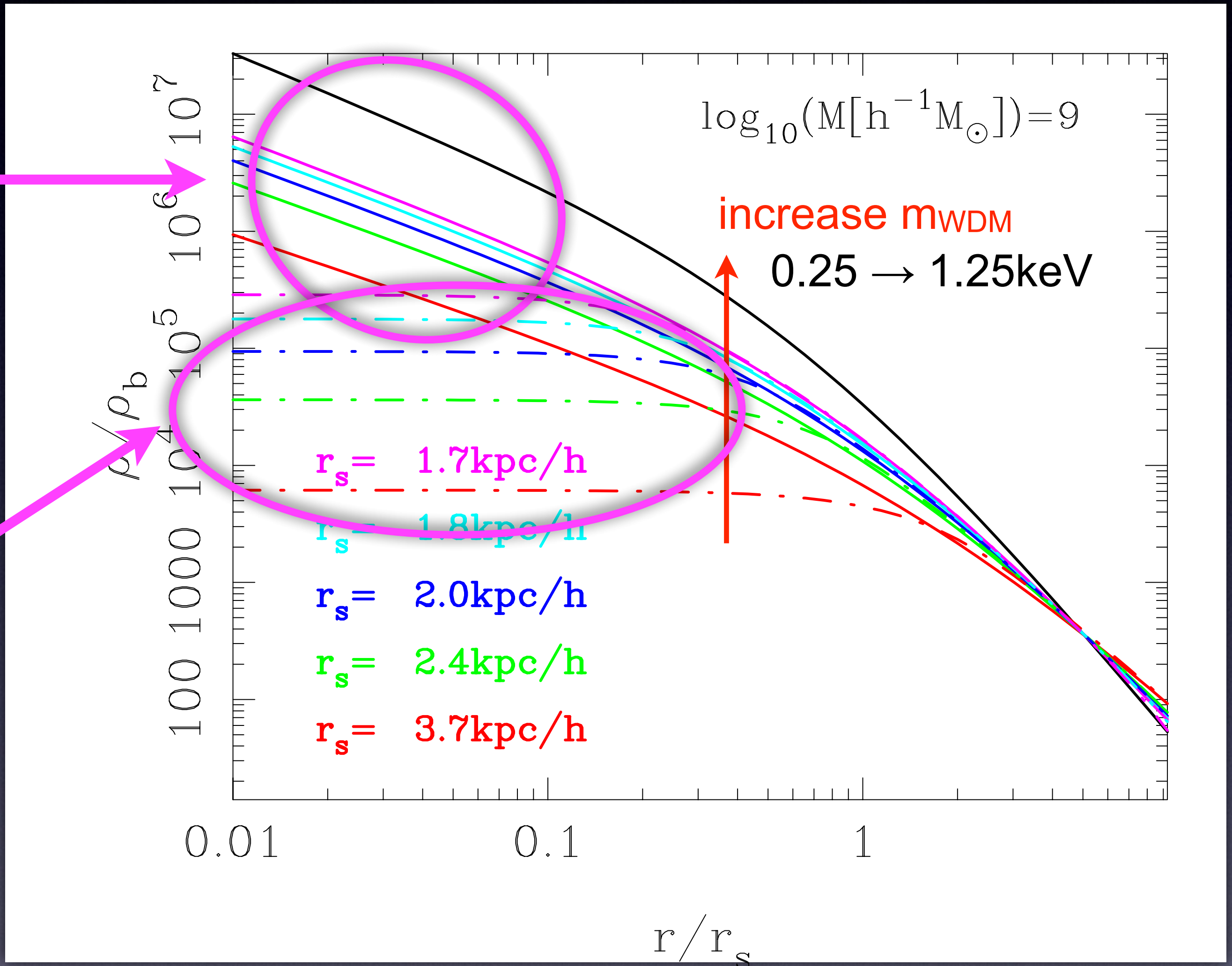
$$\langle 1 + z_{\rm coll}\rangle(M) = \sigma_M/\delta_c$$

$\rightarrow$ less concentration

– Thermal velocity

$$vt \sim 0.5(1+z)^{-1/2}\left(\frac{m_{\rm WDM}}{1{\rm keV}}\right)^{-4/3}{\rm kpc}$$

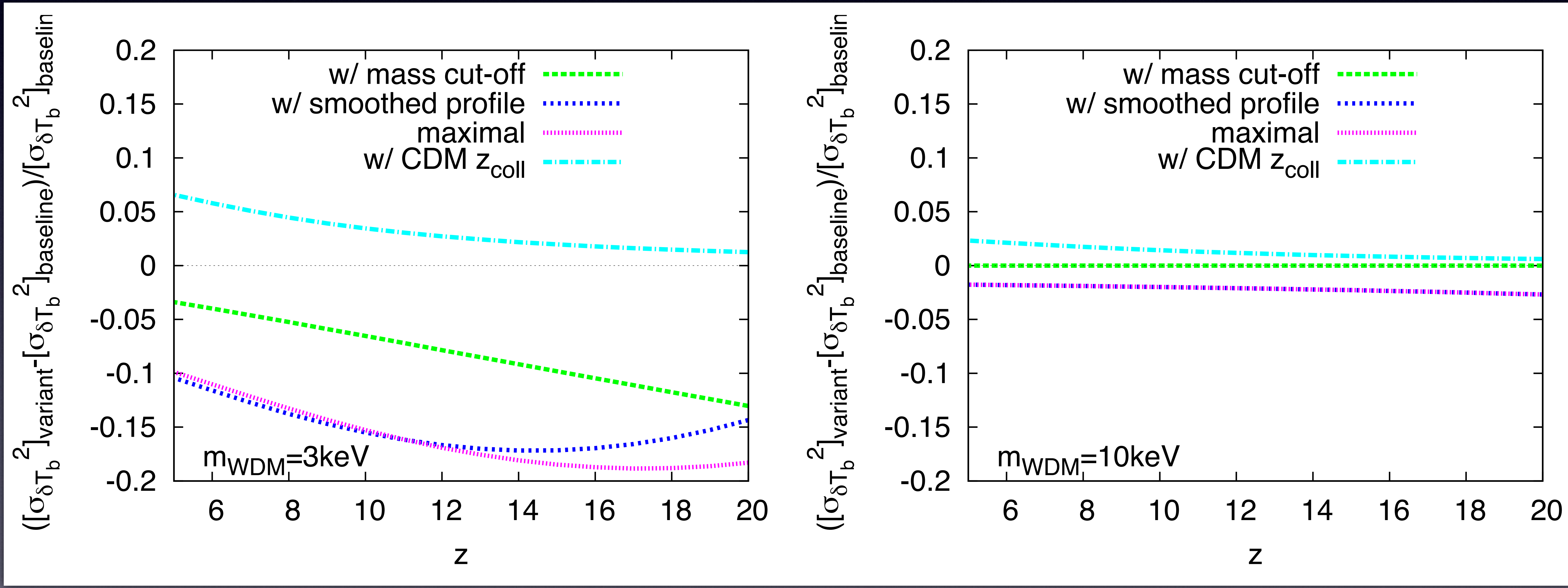
$\rightarrow$ cored profile



Smith & Markovic (2011)

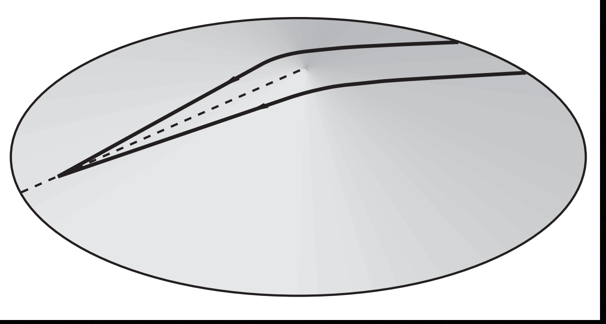
Further suppression effects? (cont'd)

Relative difference from the baseline case



Additional effects unique to WDM are important only for m_{WDM} < a few keV and negligible for m_{WDM}>10keV

String wakes



(c) Vilenkin & Shellard

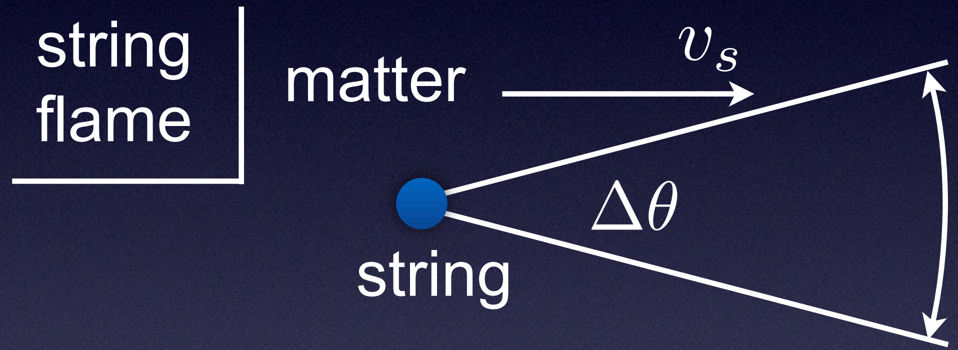
String wakes: overview

- Conical spacetime around a string
  - deficit angle: $\Delta\theta = 8\pi G\mu$

    μ: string tension

  → Matter gets velocity kick

  $v_{\rm kick} = 4\pi G\mu v_s \gamma_s$



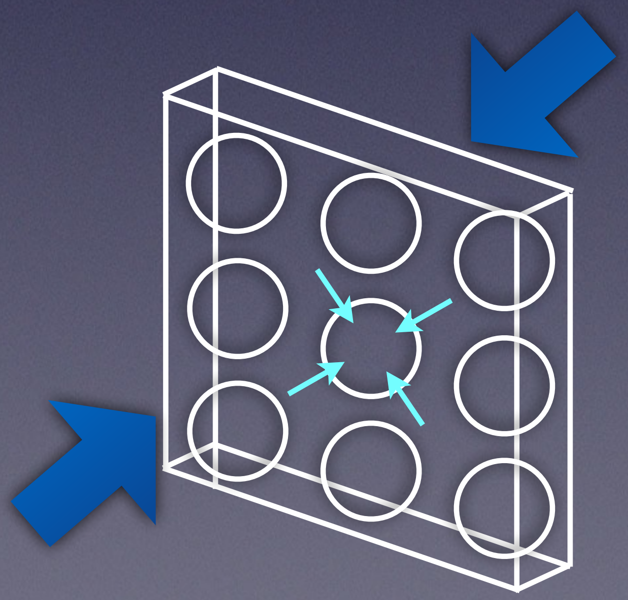
- Formation of string wakes and minihalos
  - Matter accretes around trace of strings

    → sheet-like structure=*wake*

  - Shock front on wake surface → thermalization

  - Instability of planar structure

    → fragmentation into minihalos (size ~ wake thickness)



Formation wakes

based on Duplessis & Brandenberger (2013)

- Zel'dovich approximation (in MD)

  physical distance from wake $r_{\rm phys}(x_{\rm ini}, t) = a(t)(x_{\rm ini} + \psi(x_{\rm ini}, t))$

$$\frac{d^2\psi}{dt^2} + \frac{3}{4t}\frac{d\psi}{dt} - \frac{2}{3t^2}\psi = 0 \quad \rightarrow \quad \psi \simeq -\frac{5}{3} v_{\rm kick} t_{\rm ini} \left(\frac{t}{t_{\rm ini}}\right)^{3/2}$$

- Decoupling from global expansion → virialization

  physical wake size ~ 1/2 turn around scale ($\dot{r}_{\rm phys} = 0$)

$$w(t) = \frac{5}{3} v_{\rm kick} t_{\rm ini} \left(\frac{t}{t_{\rm ini}}\right)^{4/3} \propto a(t)^2$$

  Baryon is thermalized at shock on wake surface

$$\frac{3}{2} k_B T = \frac{m_p}{2} v_{\rm surface}^2 \rightarrow T = 10\,{\rm K} \left(\frac{G\mu}{10^{-6}}\right)^2 (v_s \gamma_s)^2 \frac{z_{\rm ini}+1}{z+1}$$

Formation of minihalos

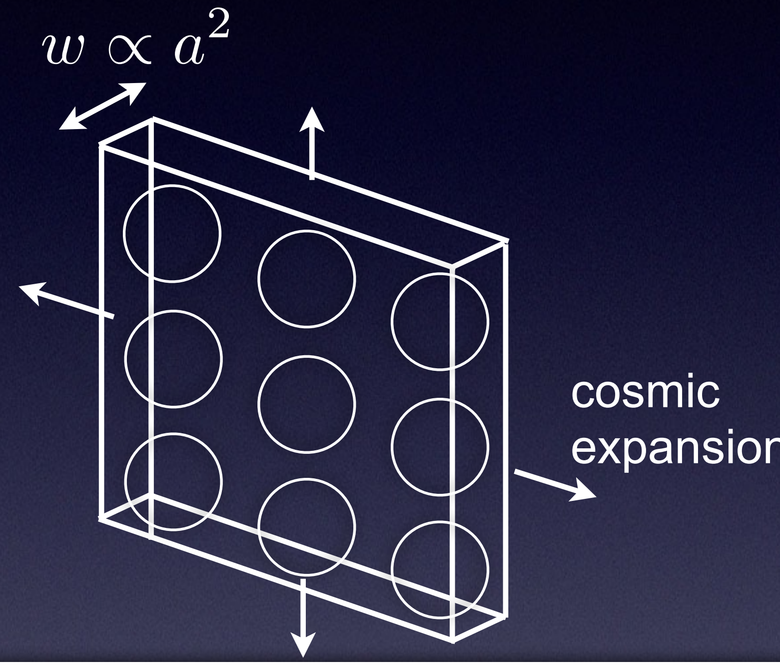
based on Duplessis & Brandenberger (2013)

- Wake volume in horizon

fractional volume of wakes generated in Δt_i at t_i

$$\Delta f_i(t) = \frac{\gamma t_i \times v_s \gamma_s \Delta t_i \times w_i(t) a(t)^2 / a_i^2}{t_i^3 a(t)^3 / a_i^3}$$

scaling solution: # of strings in horizon $= \gamma \sim \mathcal{O}(1)$



- Fragmentation into minihalo

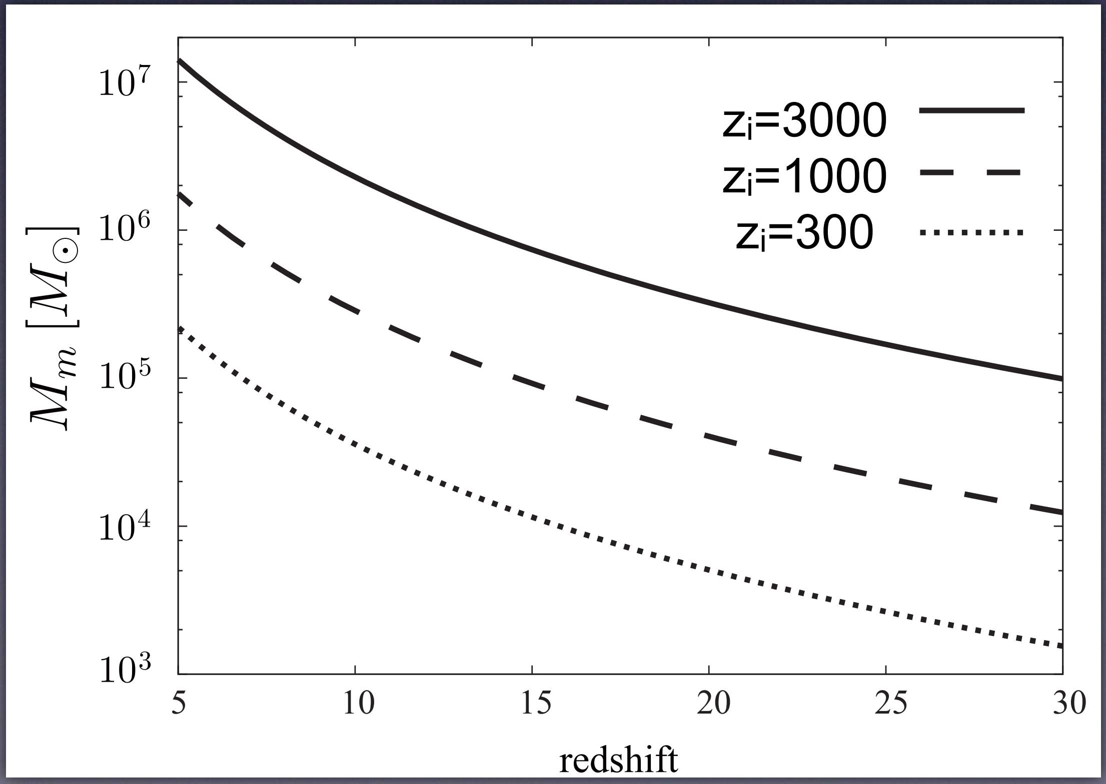
time scale ~ $w_i(t)$ (Zel'dovich pancakes)

$$\rightarrow V_i(t) = \frac{4\pi}{3} w_i(t)^3$$

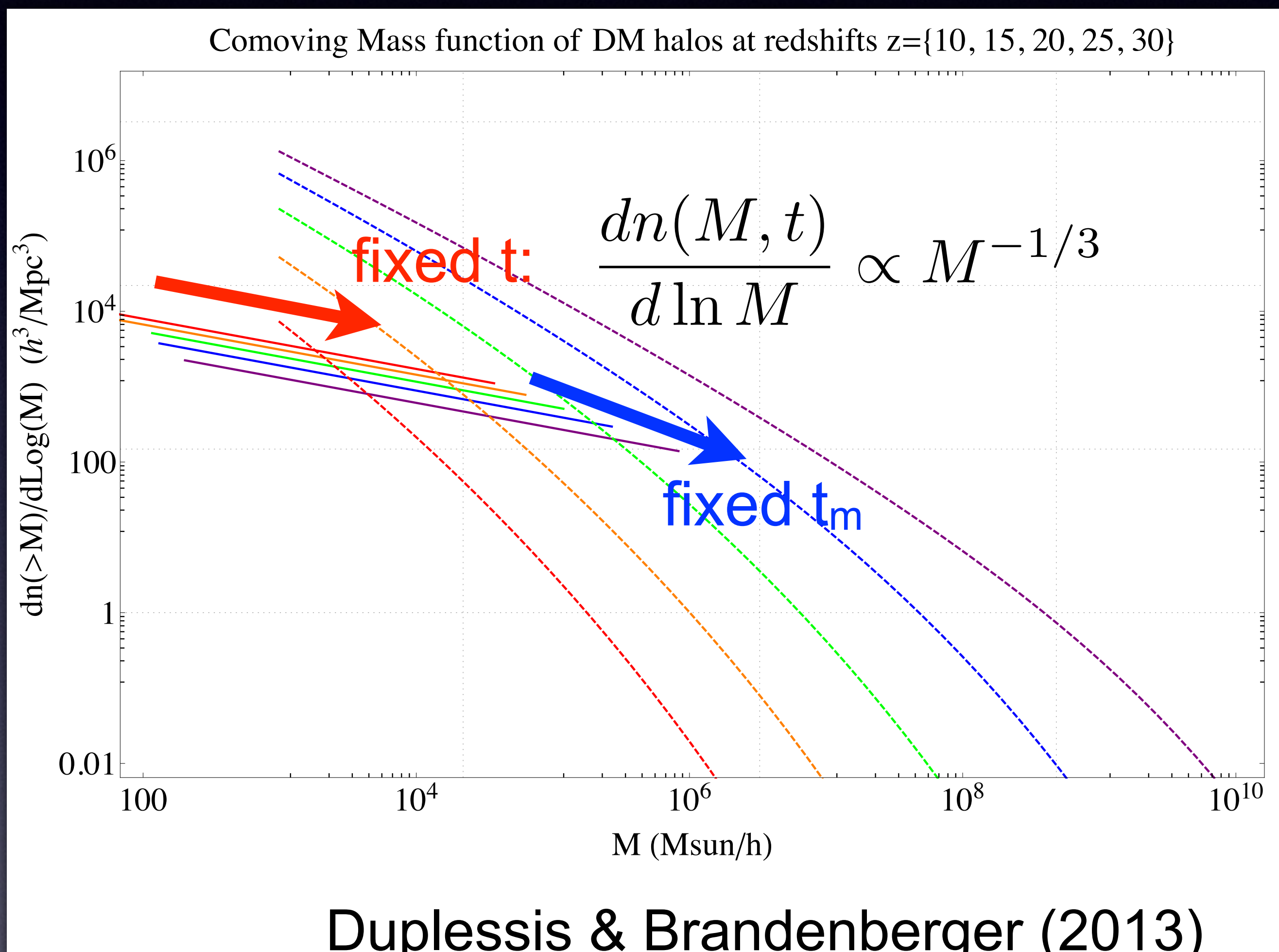
$$M_i(t) = 4\bar{\rho}(t) V_i(t)$$

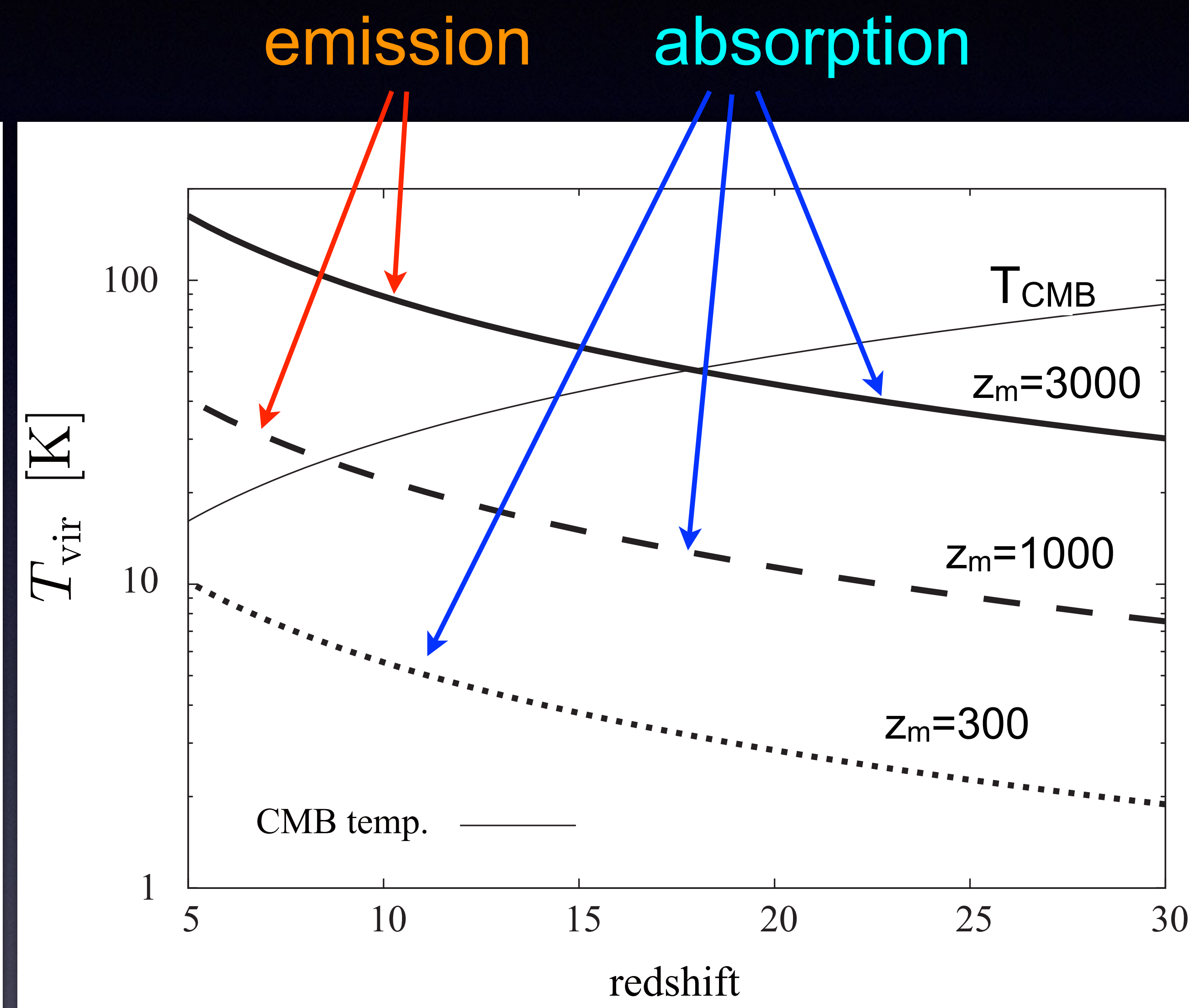
- Mass function

$$\frac{dn(M,t)}{dM} = \frac{a(t)^3}{V_i(t)} \frac{df_i(t)/dt_i}{dM_i(t)/dt_i}$$



mass function & gas temperature





- Mass of minihalos increases: absorption → emission in 21cm line
- Atomic cooling is ineffective

→ can be observed by 21cm line fluctuations

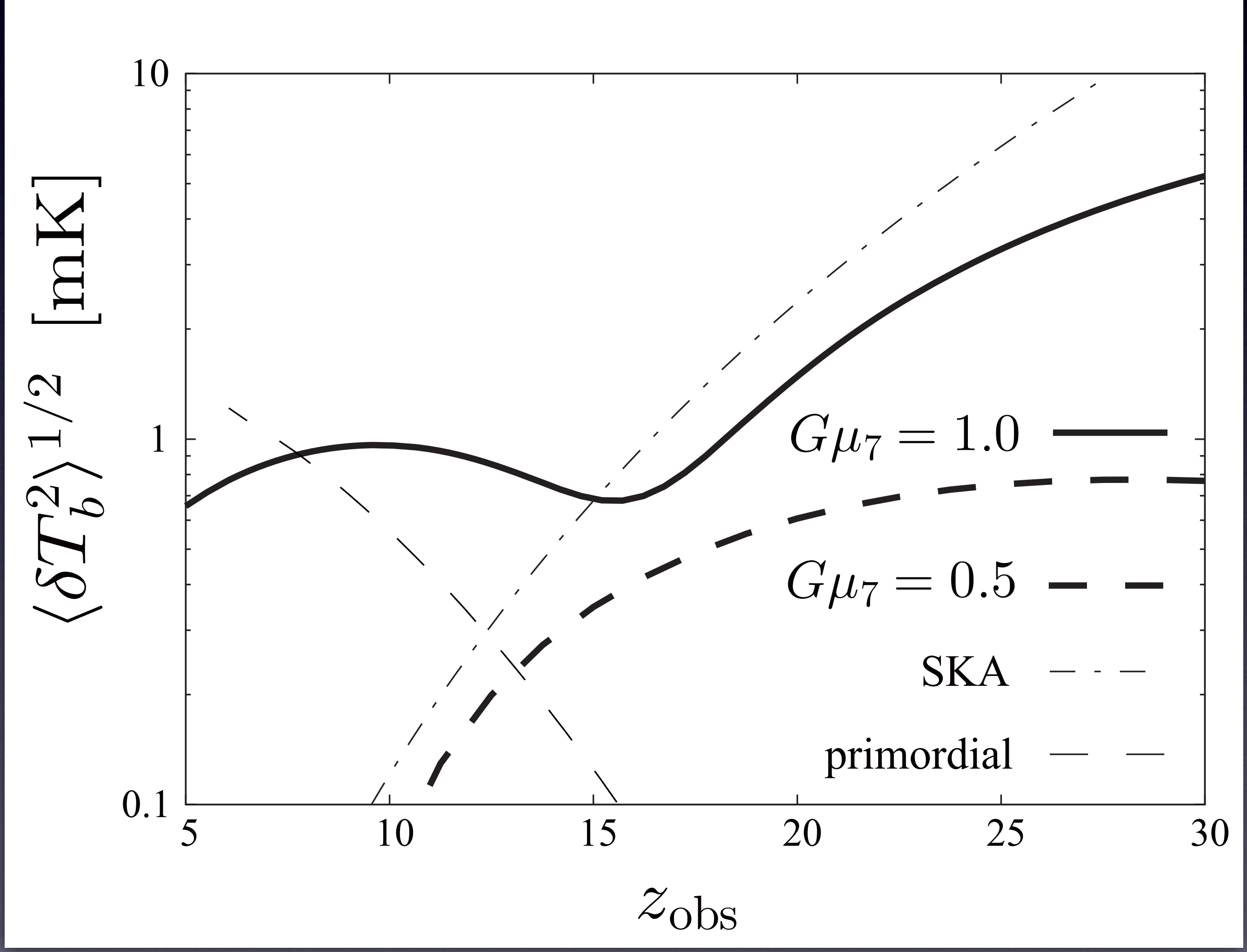
21cm fluctuations

- string distributions

  → 21cm line fluctuations

- Upper bound on string tension

  SKA: Gμ< 4x10^{-8} (2sigma)



➡ Strings with Gμ=10^{-7} (Planck upper bound) can be observed with SKA