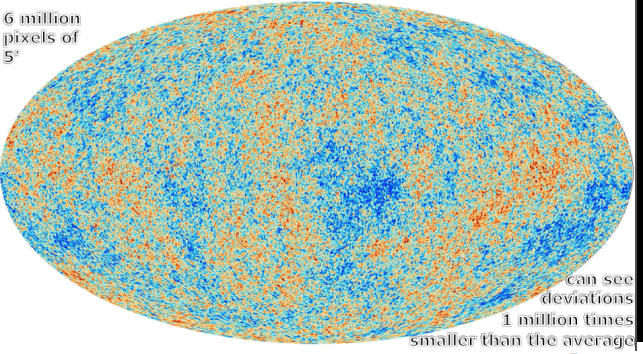
We need a future CMB experiment with spectroscopic capabilities



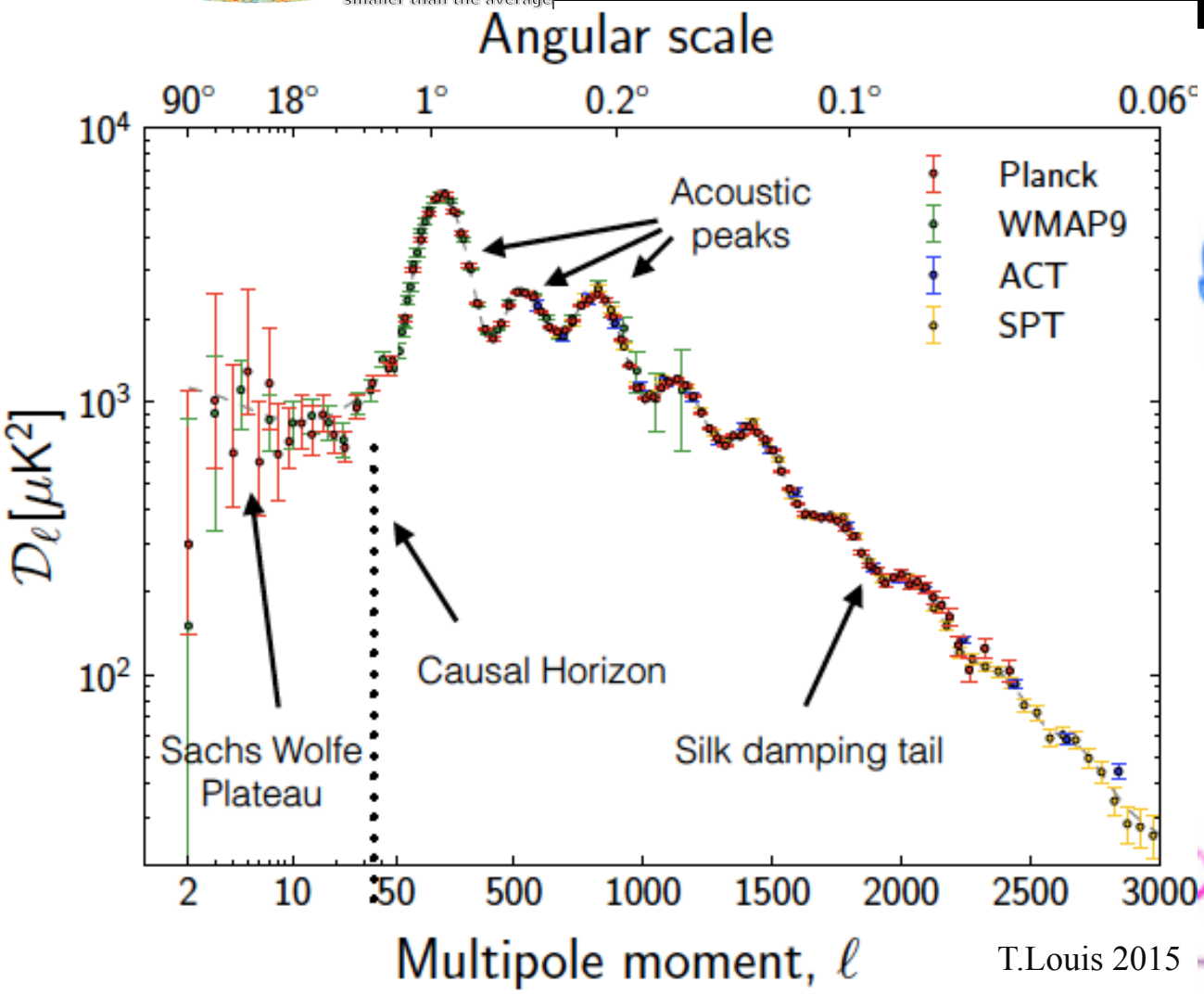
Fourier transform of temperature anisotropies

Multipole moment $\ell \sim \pi/\theta$

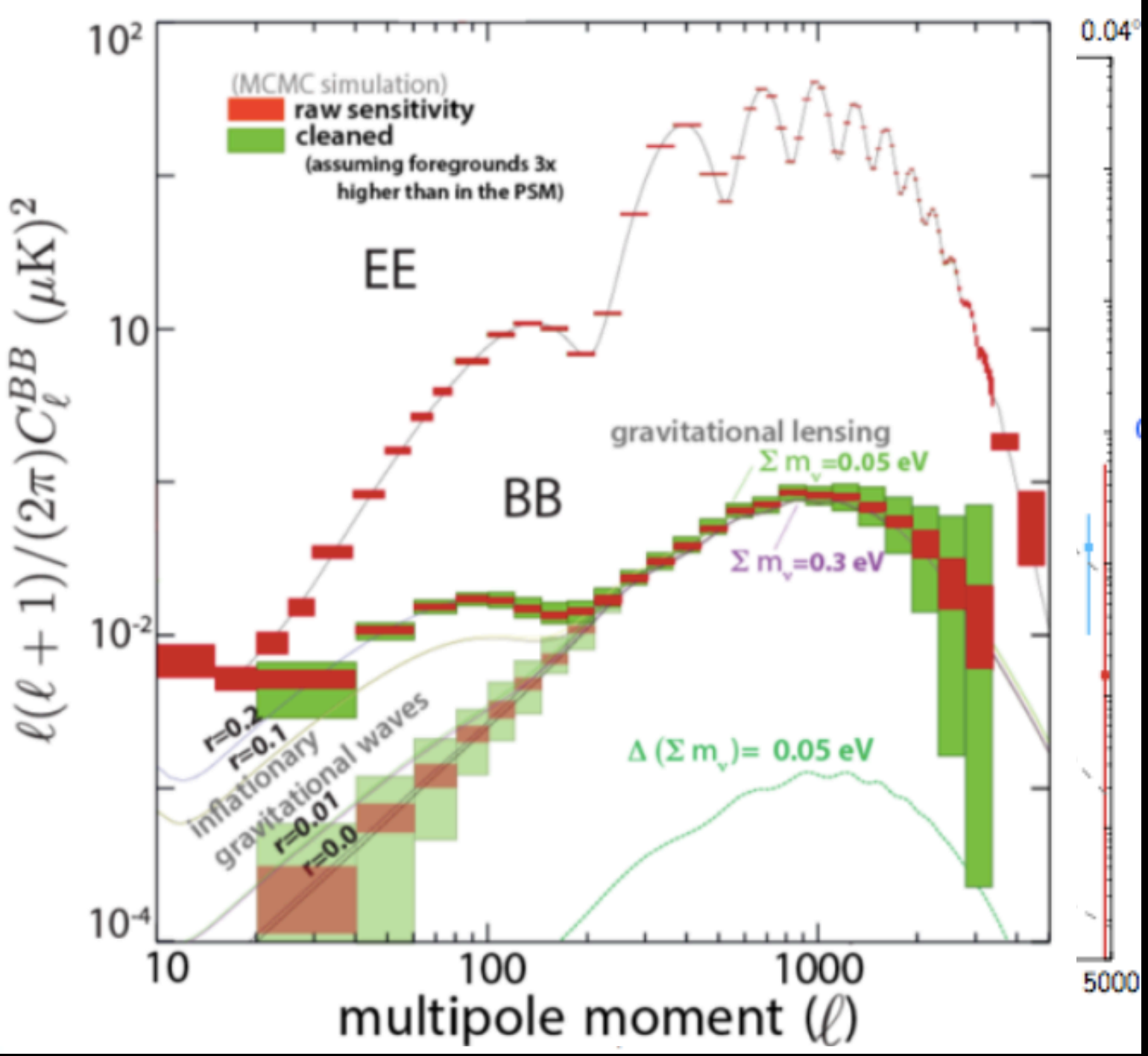
Fluctuations propagate as sound waves until transparency

Peaks are sound wave maxima/mimima at last scattering of photons

Photon mean free path increases as density decreases until fluctuations are damped



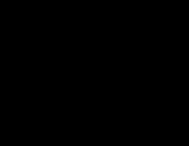
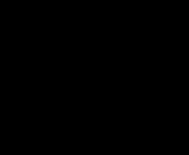
T.Louis 2015



Advanced ACTPOL

~ 2017

FUNDAMENTAL PHYSICS CHALLENGES FOR A FUTURE SPACE CMB EXPERIMENT

- Damping tail and m_ν 
- Primordial B modes 
- Beyond the standard LCDM model 
- Recombination epoch

Thermalization (γ,e-) by double Compton scattering occurs at

$z > z_\mu = 2 \times 10^6 (0.0224/\Omega_B h^2)^{2/5}$ create photons

$e^- + \gamma$ --- $e + \gamma + \gamma$ (also bremsstrahlung: $e^- + X$ --- $e^- + X + \gamma$)

$t_\mu = 4.10^6 (\Omega_B h^2/0.0224)^{-1} (2.10^6/z)^{9/2}$ s

Equilibration (γ,e^-) to Bose-Einstein by Compton scattering ($e^- + \gamma$ --- $e + \gamma$) occurs at

$z_\mu < z < z_y = 2.15 \times 10^4 (1/\Omega_B h^2)^{1/2}$ conserve photons

results in μ distortion

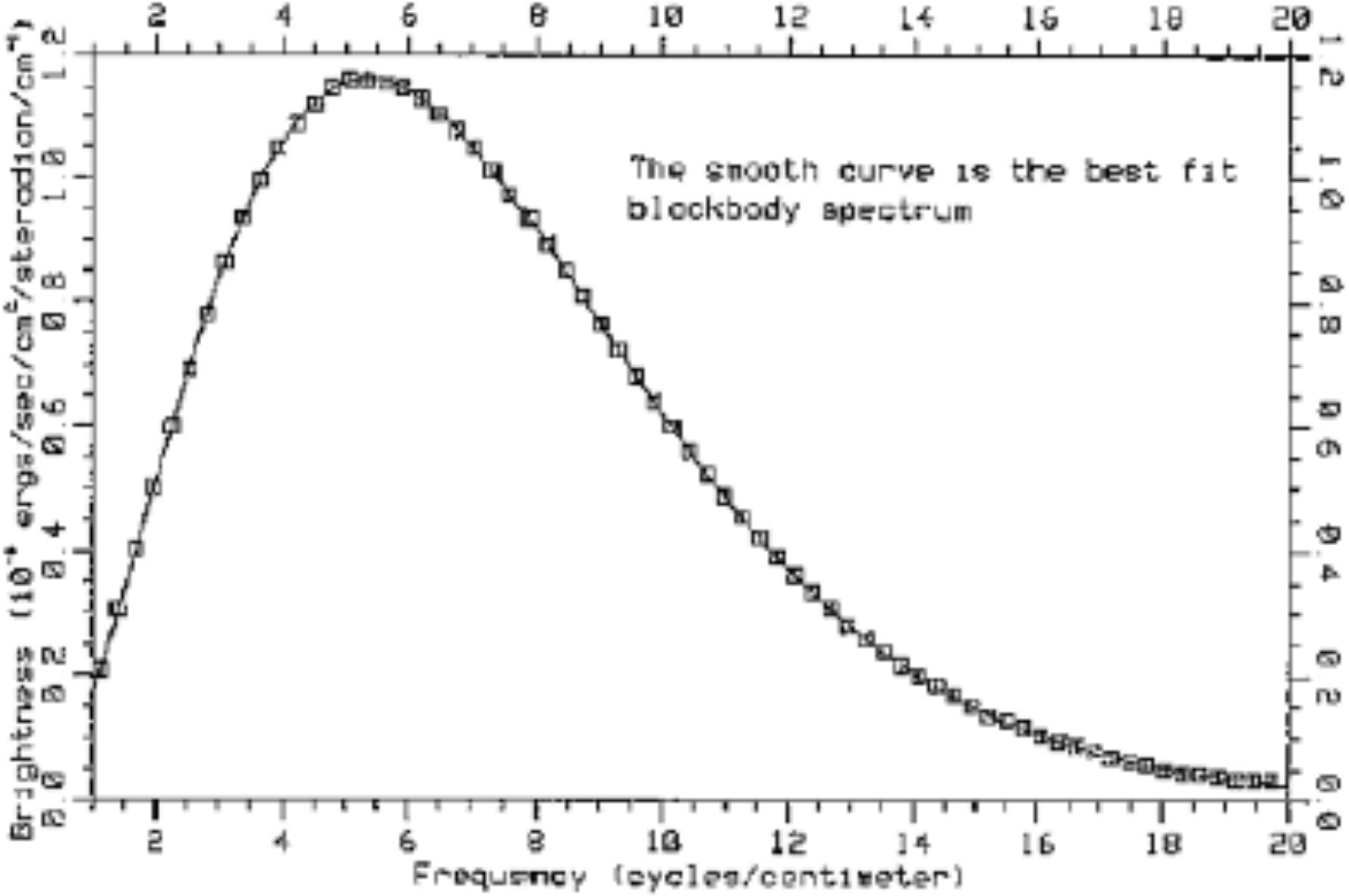
Heating

$z < z_y$: Compton scattering produces y distortion heat photons

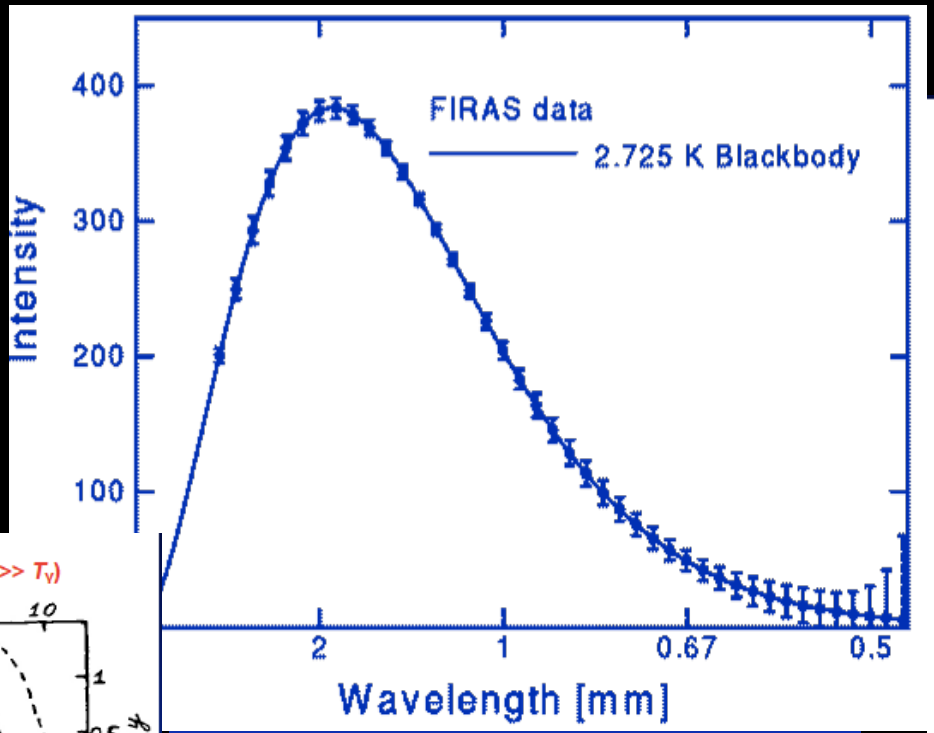
Recombination/transparency at $z_{LSS} = 1060$

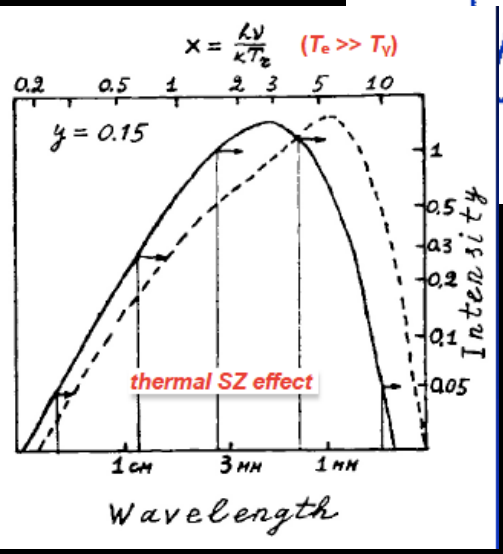
Reionization at z~ 9

1964 1970 1990



WAVELENGTH, cm.

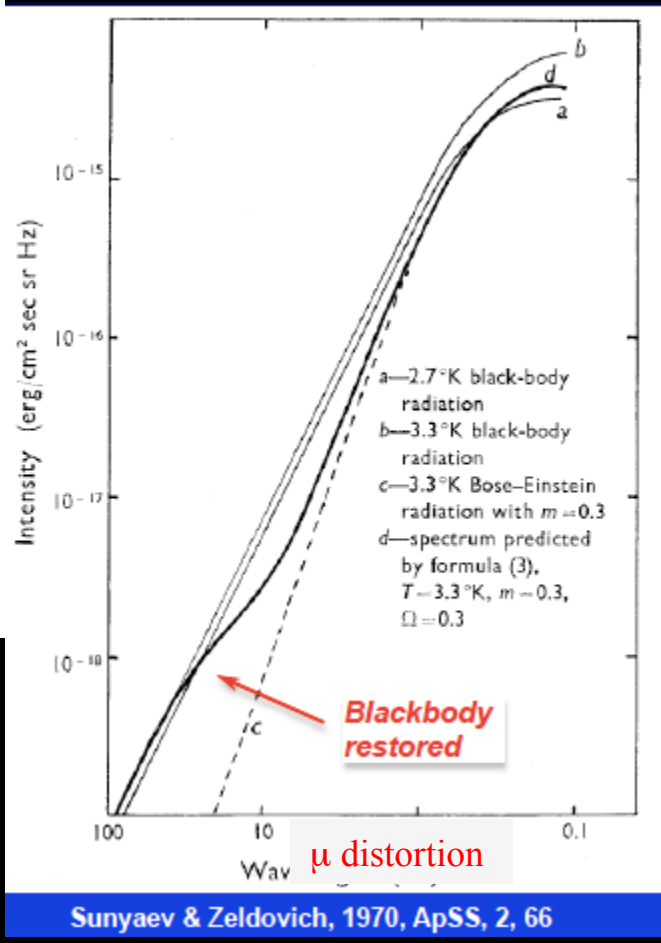




$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \le 1.5\times10^{-5}$$

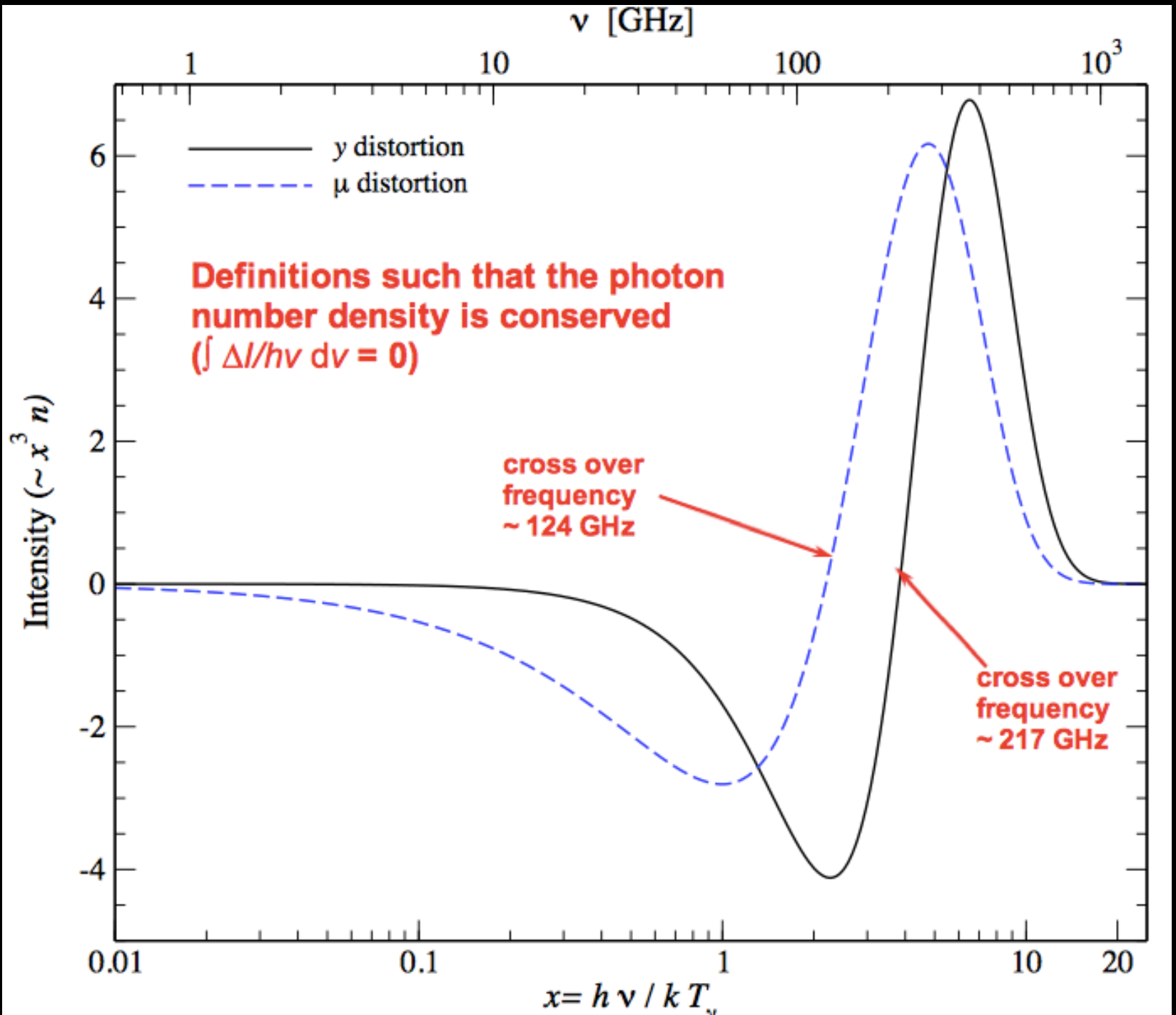
$$|\mu| \le 9\times10^{-5}$$



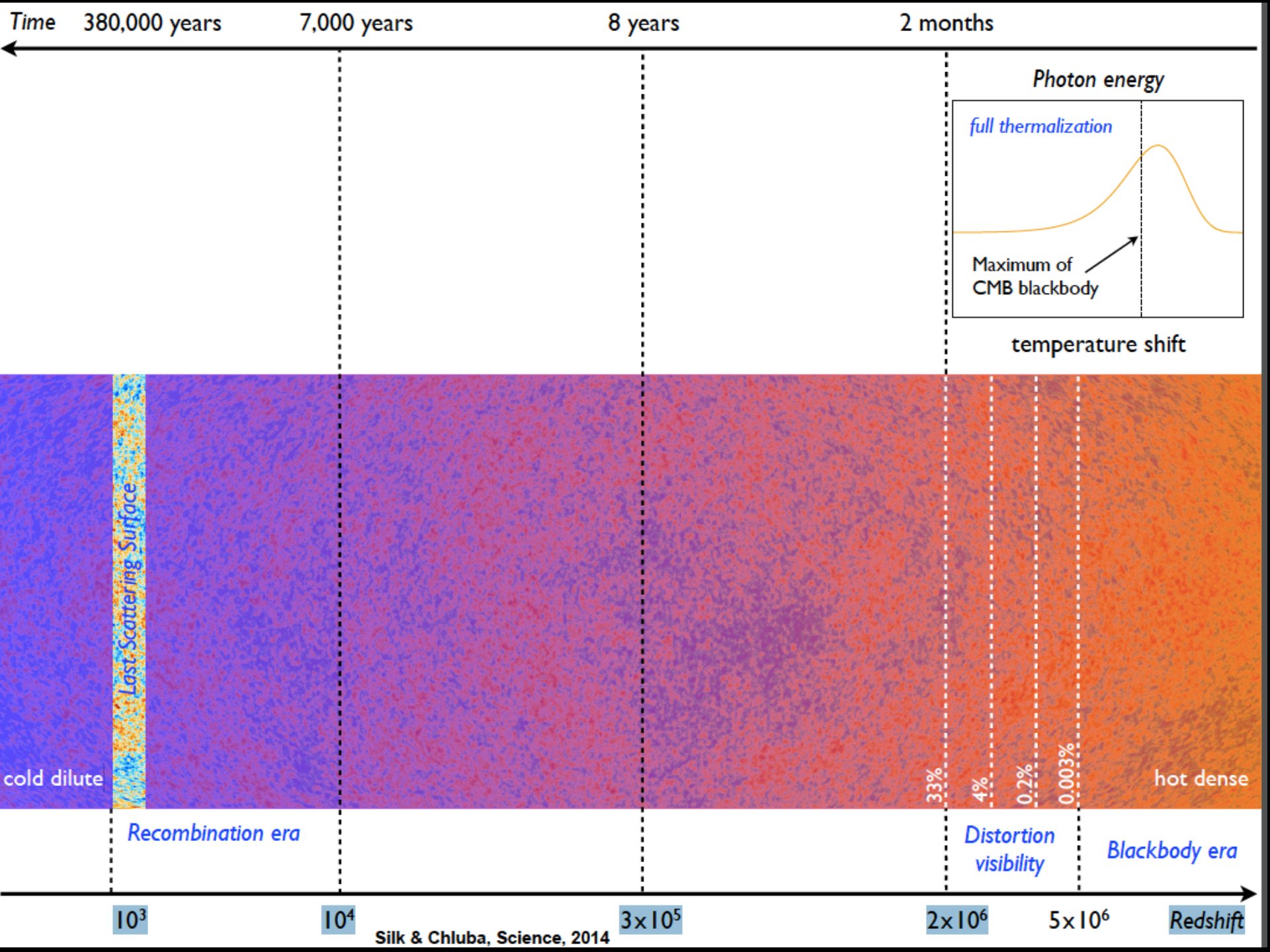
Sunyaev & Zeldovich, 1970, ApSS, 2, 66

Spectral distortions are the next frontier

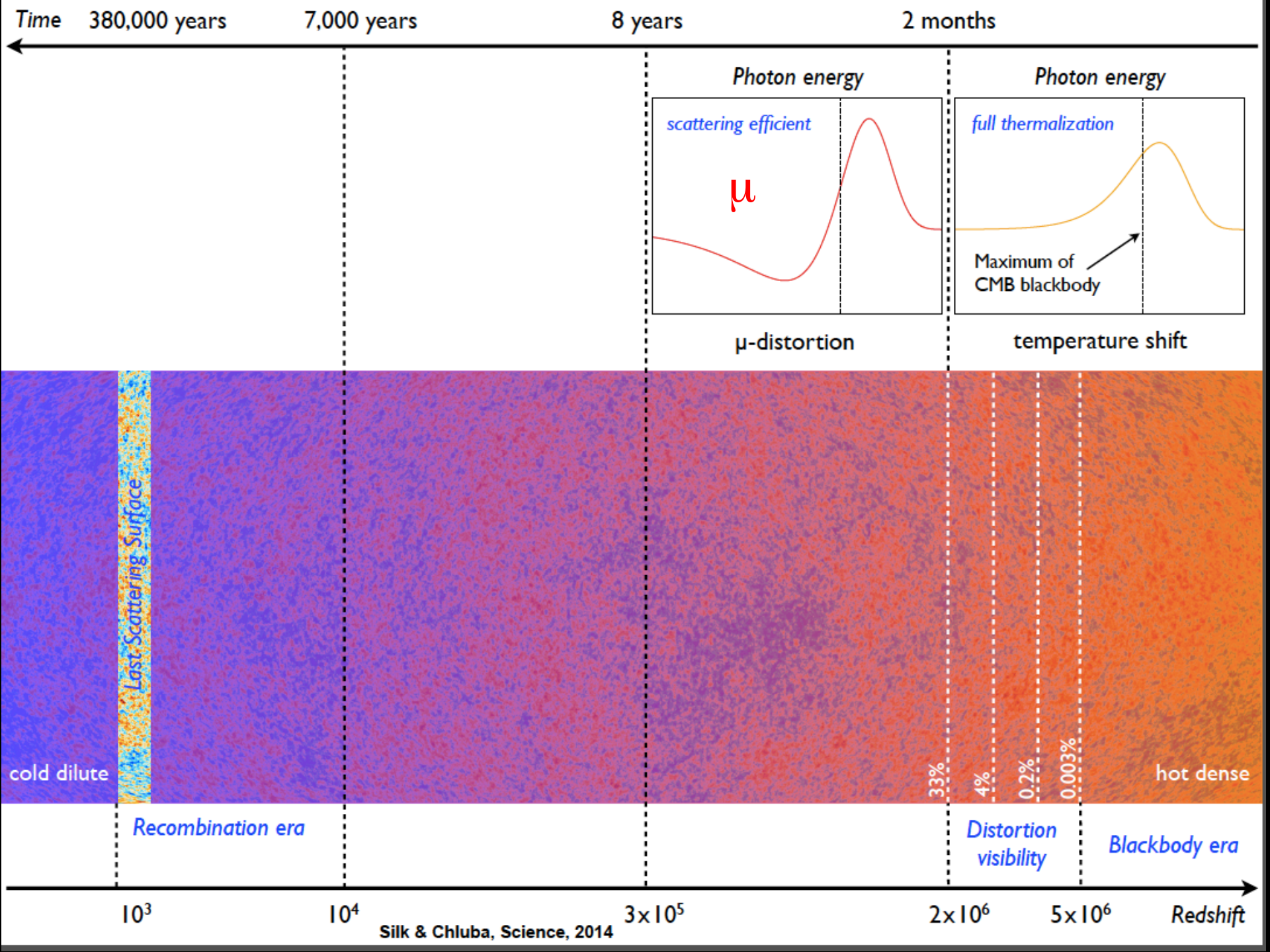
> 3 order of magnitude improvement is feasible!



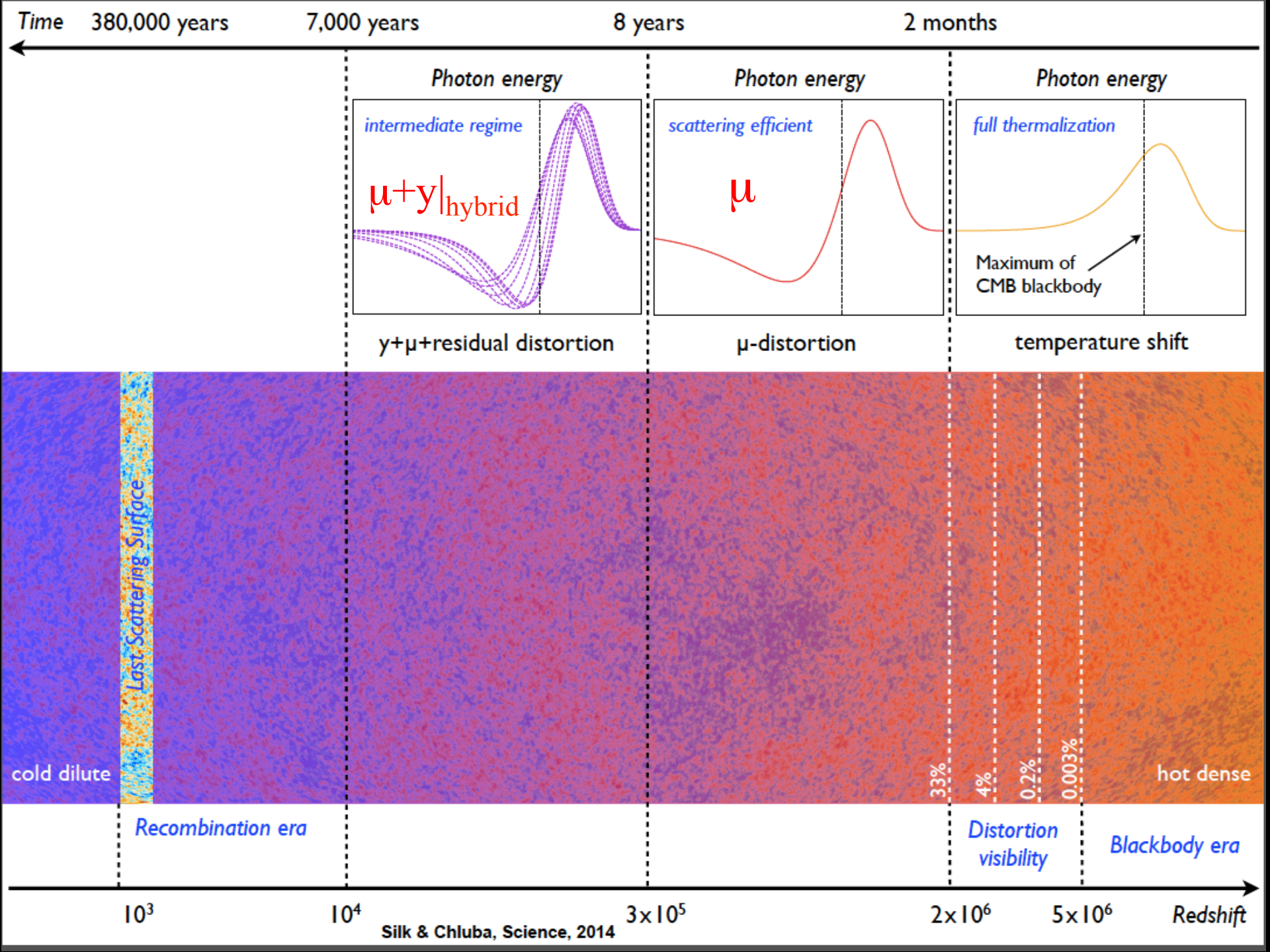
From J. Chluba

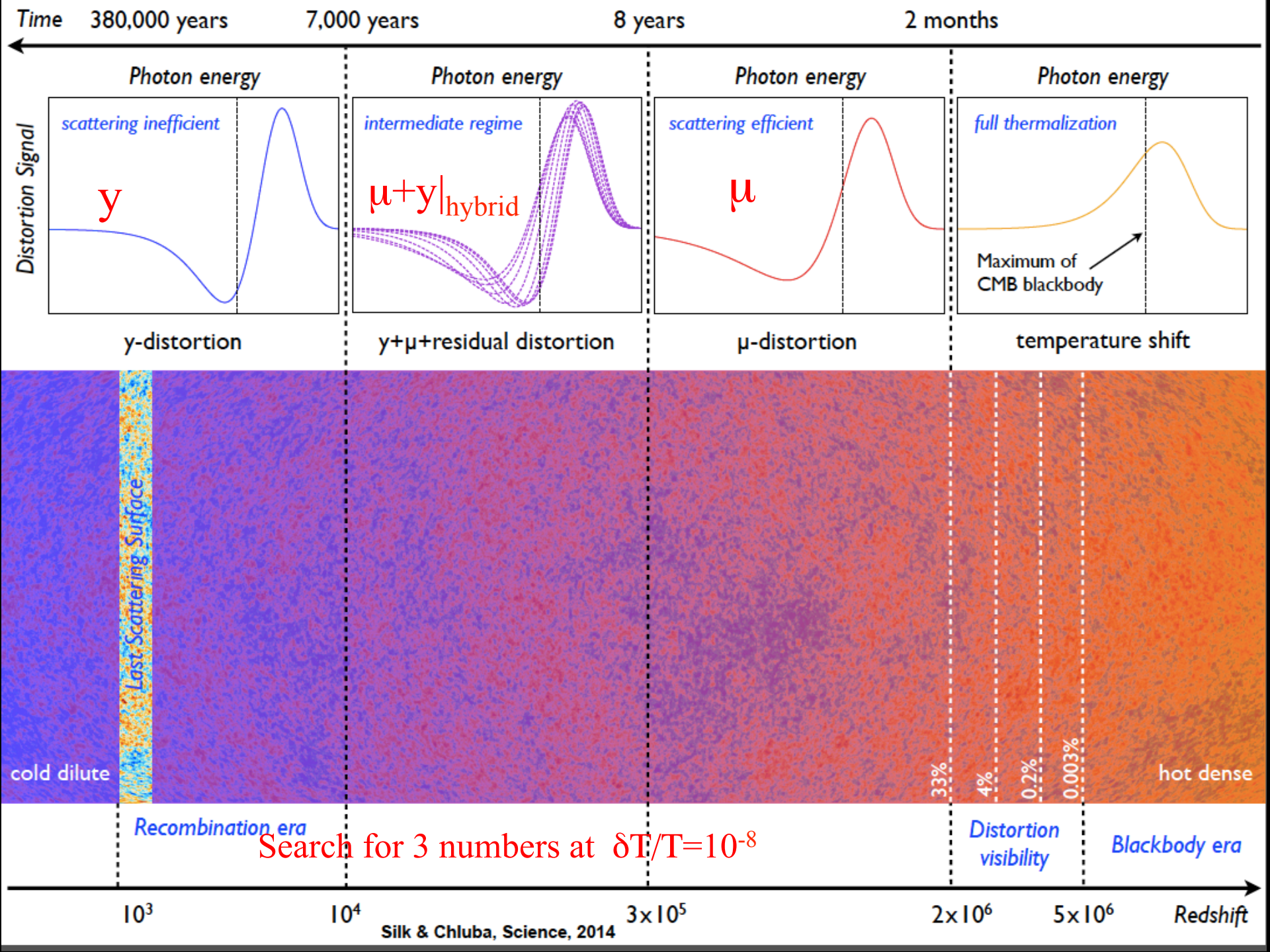


Silk & Chluba, Science, 2014



Silk & Chluba, Science, 2014


Time
380,000 years
7,000 years
8 years
2 months
Photon energy
intermediate regime
$\mu+y|_{hybrid}$
Photon energy
scattering efficient
μ
Photon energy
full thermalization
Maximum of
CMB blackbody
y+μ+residual distortion
μ-distortion
temperature shift
Last Scattering Surface
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
Distortion
visibility
Blackbody era
10^3
10^4
3×10^5
2×10^6
5×10^6
Redshift
Silk & Chluba, Science, 2014


Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
y
intermediate regime
μ+y|hybrid
scattering efficient
μ
full thermalization
Maximum of
CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Last Scattering Surface
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
Distortion
visibility
Blackbody era
Search for 3 numbers at δT/T=10-8
10³
10⁴
3x10⁵
2x10⁶
5x10⁶
Redshift
Silk & Chluba, Science, 2014

Advanced ACTpol, SPT-3G

Sub-orbital by 2017

SPIDER
Polar Bear, Simons Array,
BICEP3/KECK array, CLASS….

Space by 2022

LITEBIRD

low l cosmology ….. cosmic variance limited

What is the choice for a future space mission?
To B or not to B, or ideally spectrum + B

Guaranteed signals (1)

$y \sim 10^{-6}$ tSZ from groups at $z < 1$ $10^{13} M_{sun}$

$dN/dM \sim M^{-2}$ & $T \sim M^{2/3}$, so gain over clusters $\sim M^{4/3} \sim 100$

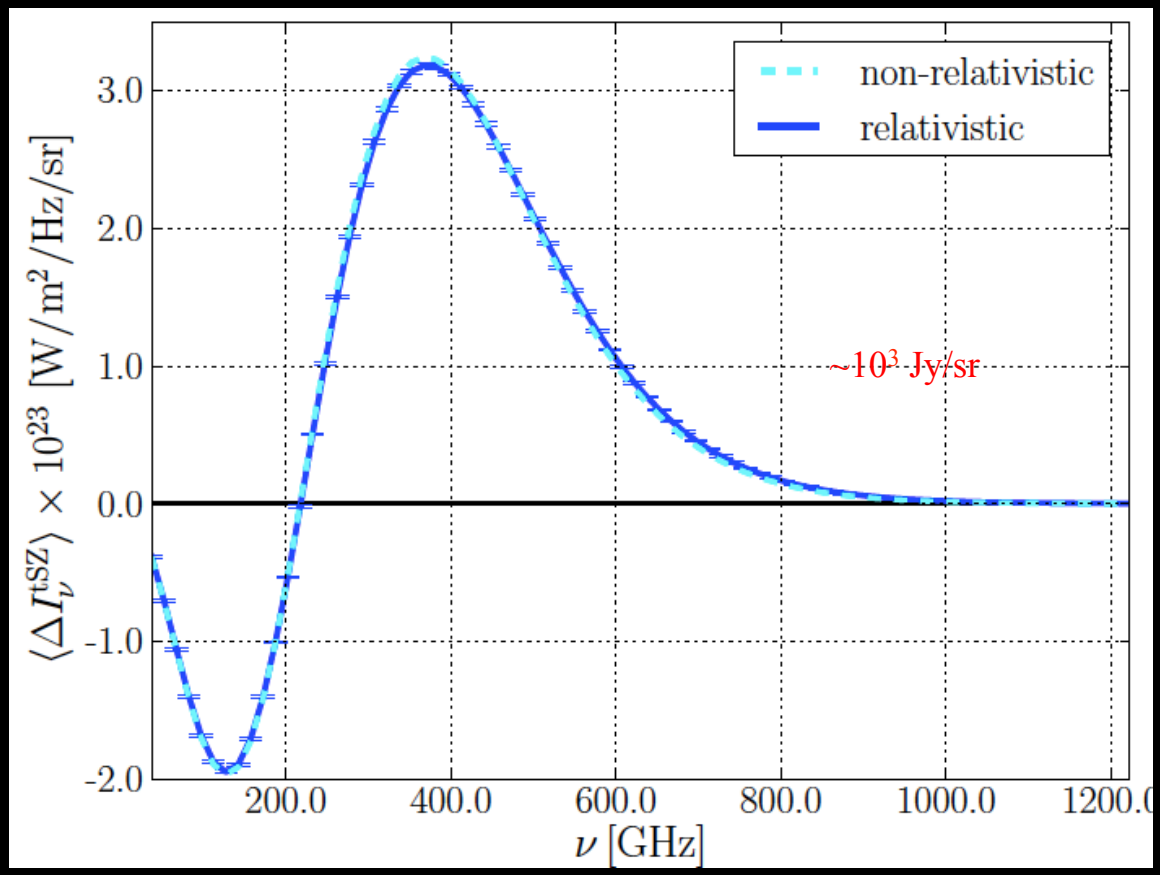
+ T_{groups} from relativistic correction

few per sq deg means $\delta y/y \sim 0.3$

A problem for early universe y?

PIXIE sensitivity is $y \sim 10^{-8}$

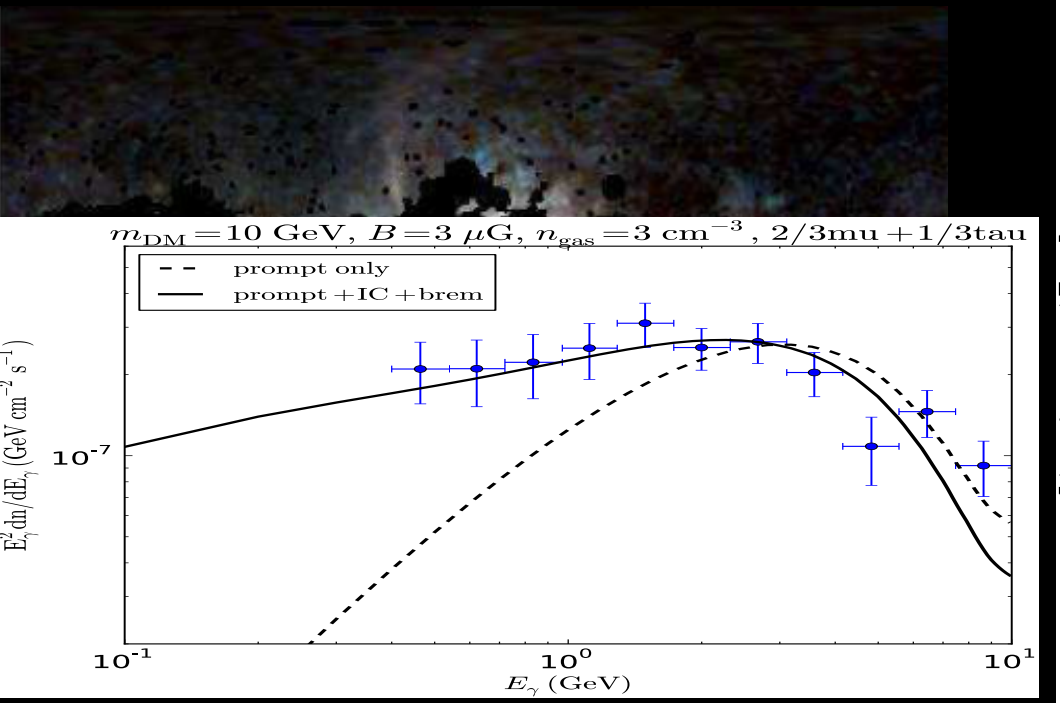
Hill + 2015



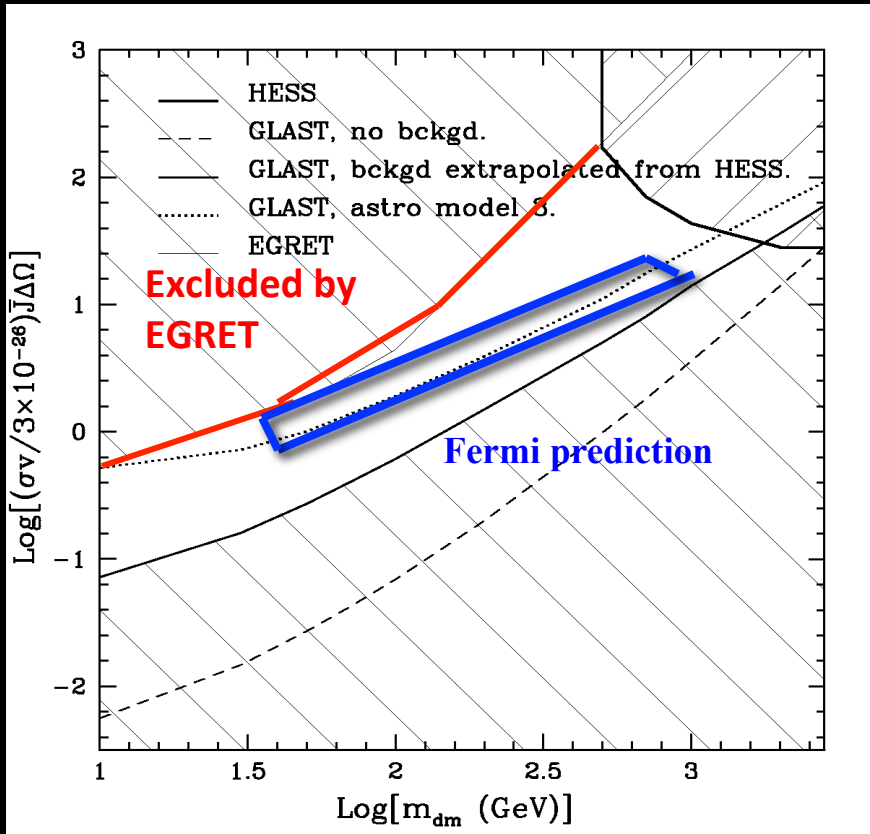
Guaranteed signals (2)

Interstellar medium: 1000 x better [CII], N[II] than COBE/FIR

Improved ISM modelling will refine Fermi excess of γ's Galactic Centre region predicted from excess WMAP 'haze' if due to DM annihilations Hooper & Zaharijas 2007

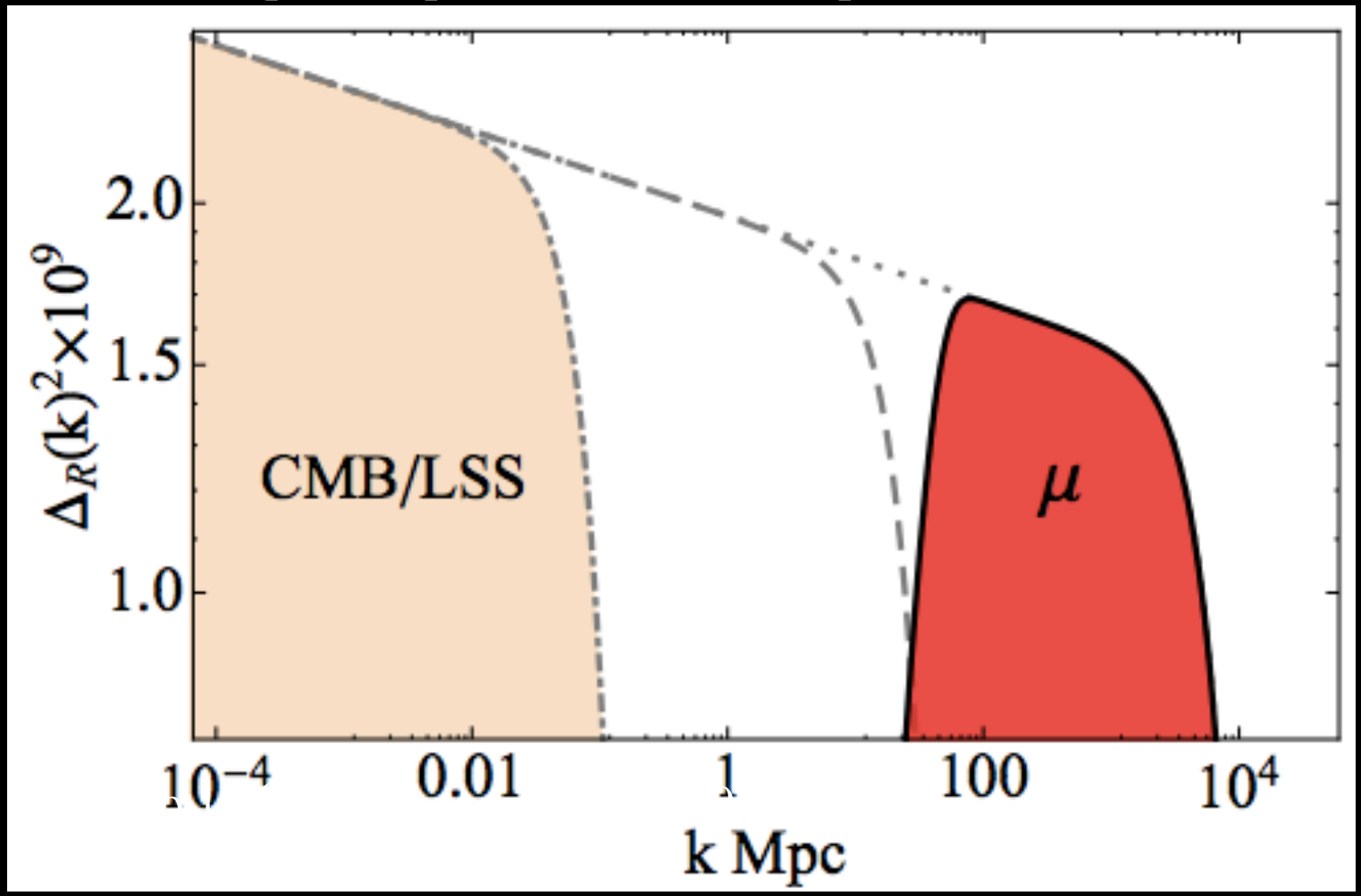


Lacroix, Boehm, JS 2014



Guaranteed signals (3)
Density fluctuation damping gives $\mu=10^{-8}$

complements CMB power spectrum of acoustic peaks

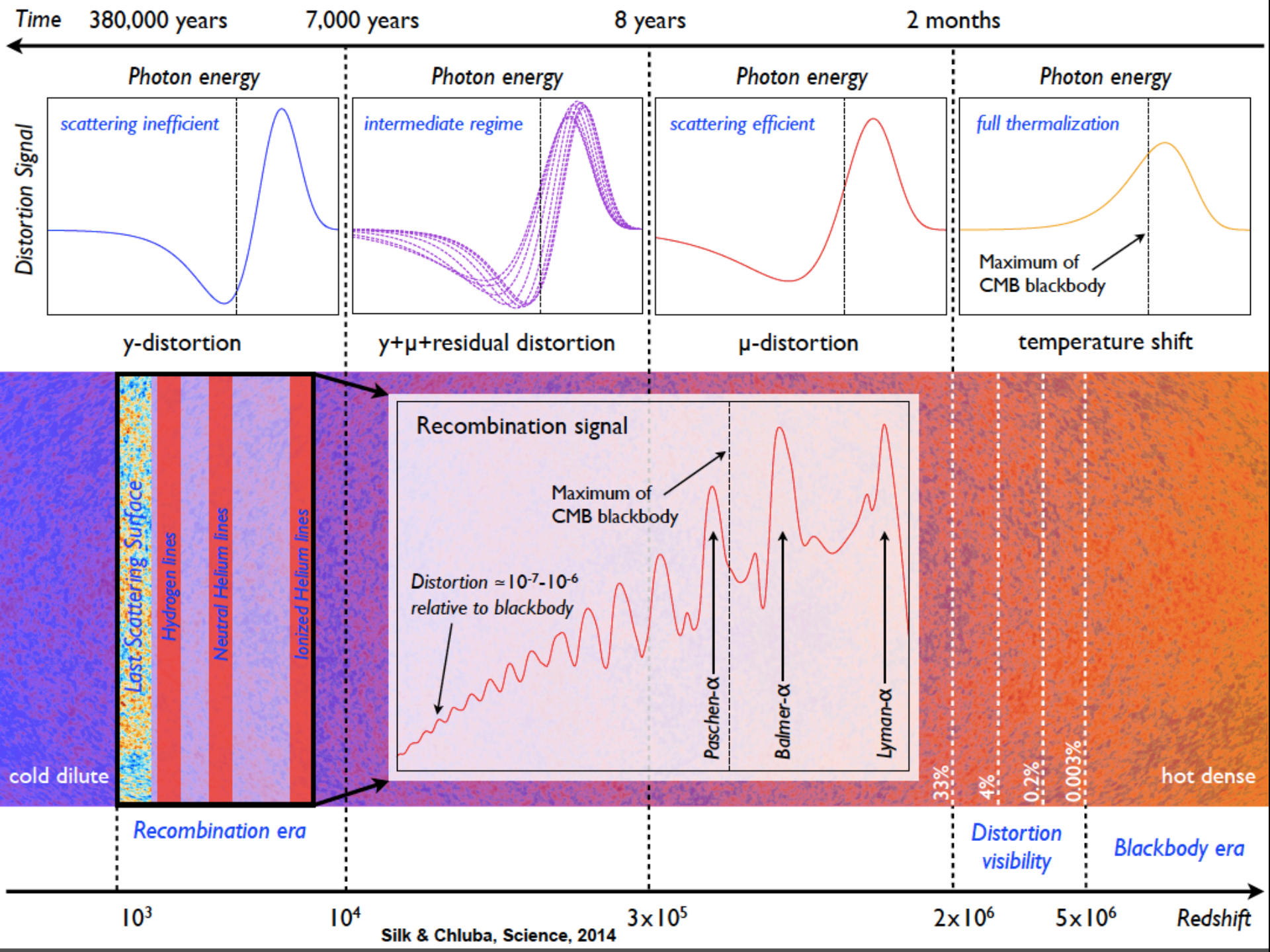


the most massive galaxy clusters | The first star-forming dwarfs | CDM subhalos

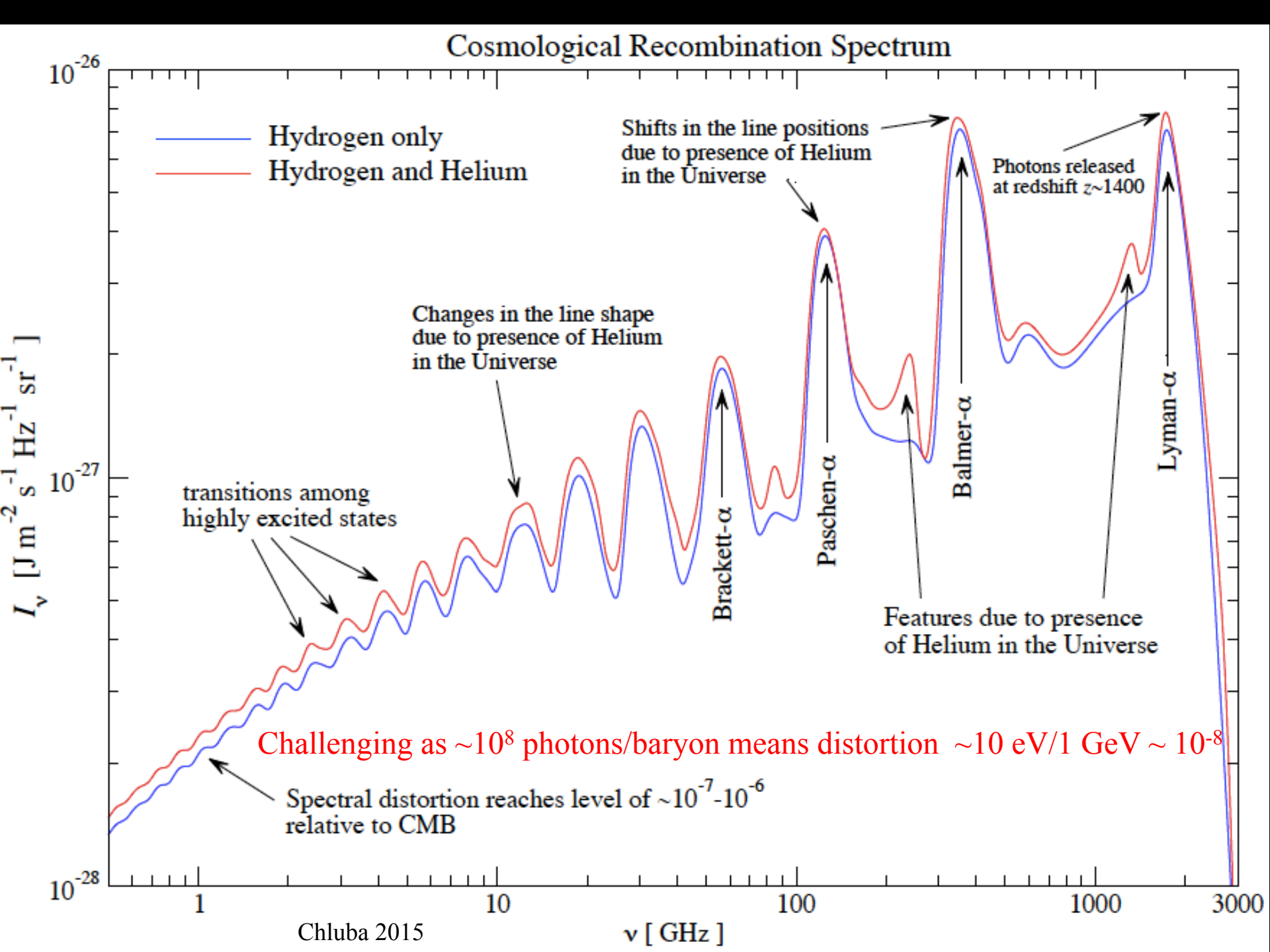
Pajer & Zaldarriaga 2013

These numbers are integrated over z

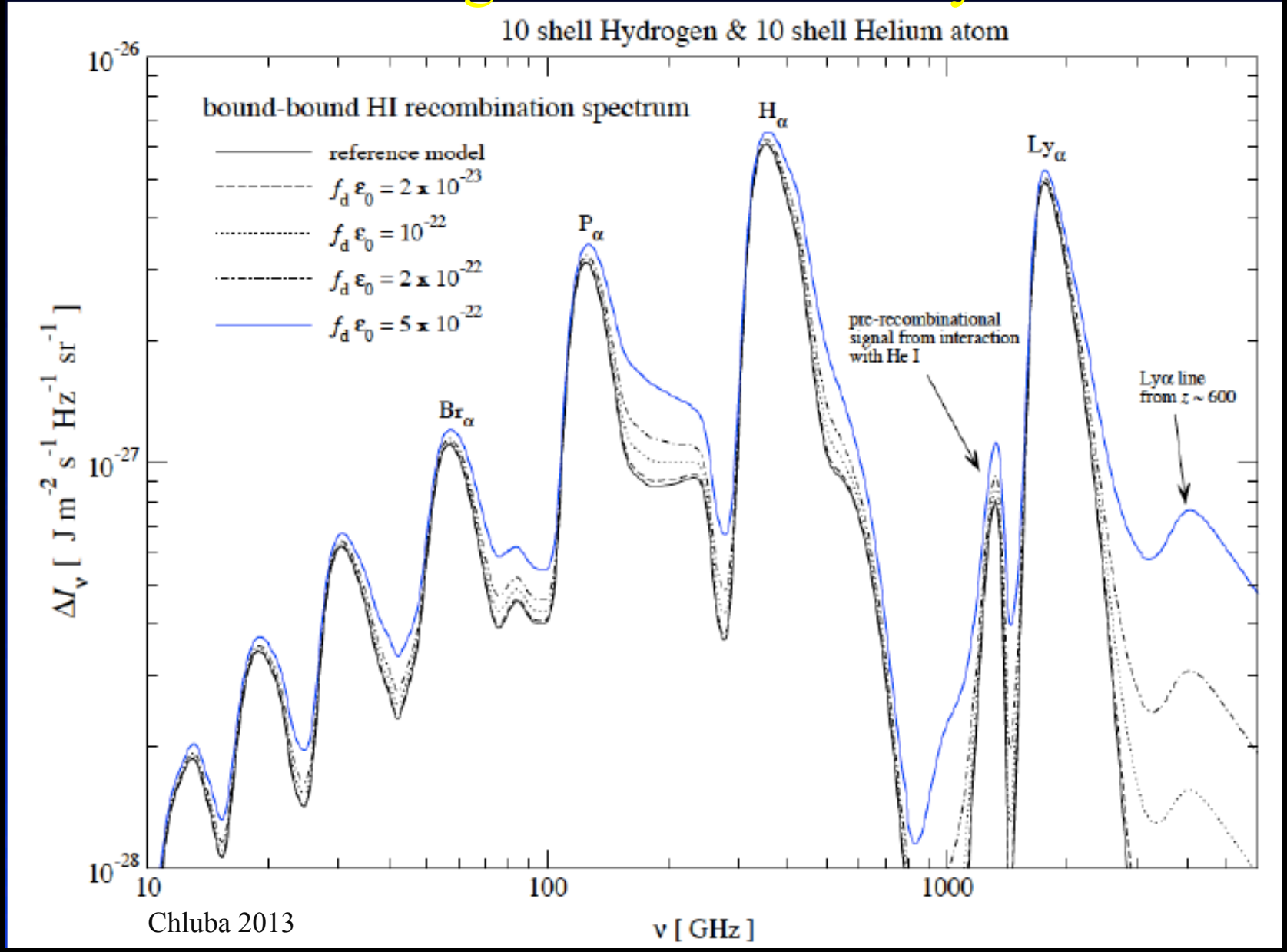
Can we do better?



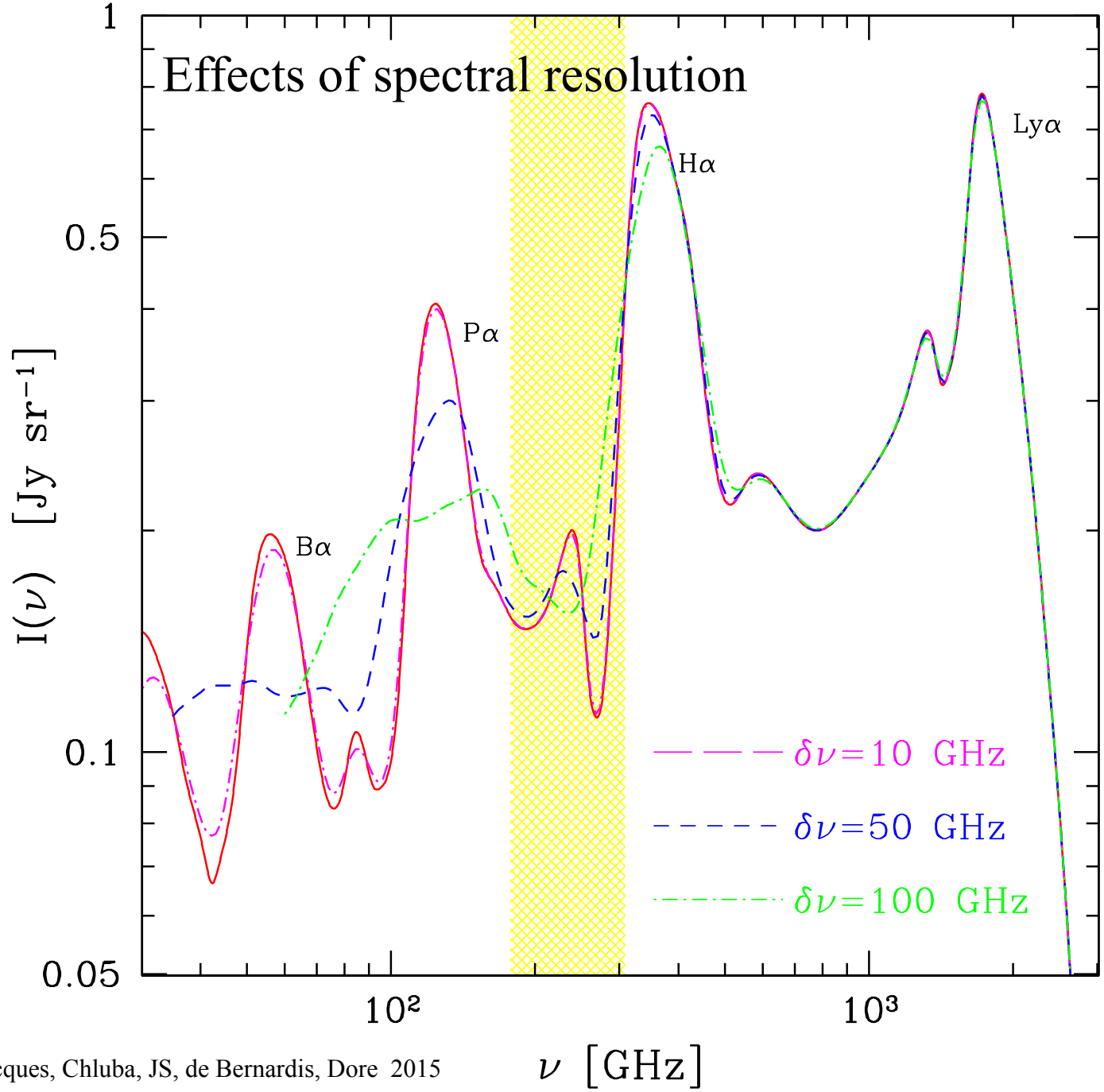
Silk & Chluba, Science, 2014


Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Challenging as ~10^8 photons/baryon means distortion ~10 eV/1 GeV ~ 10^-8
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
10^-26
10^-27
10^-28
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
1
10
100
1000
3000
ν [GHz]
Chluba 2015

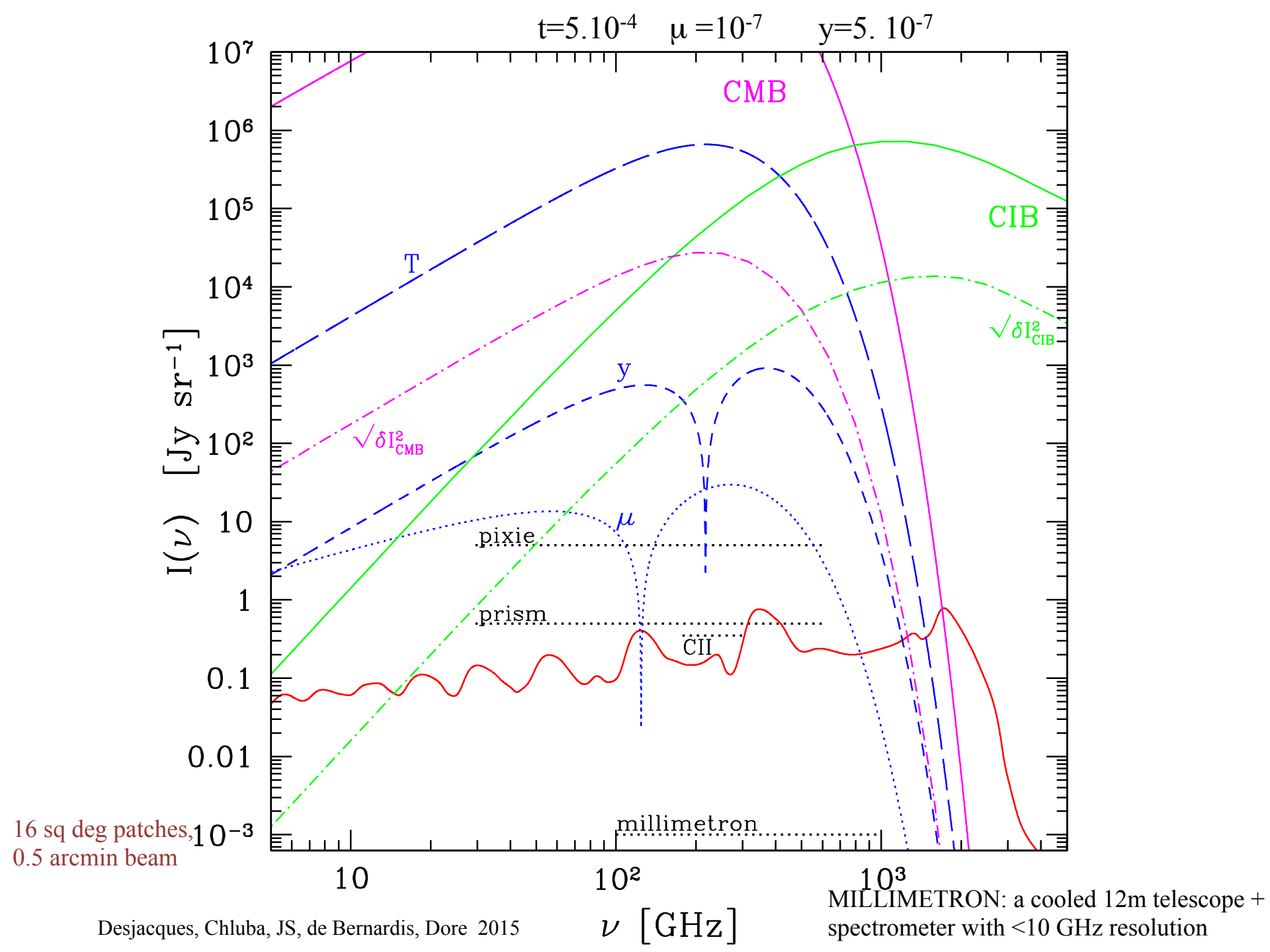
Detecting dark matter decays



Chluba 2013



Desjacques, Chluba, JS, de Bernardis, Dore 2015



16 sq deg patches,
0.5 arcmin beam

Desjacques, Chluba, JS, de Bernardis, Dore 2015

MILLIMETRON: a cooled 12m telescope + spectrometer with <10 GHz resolution

CMB spectral distortions open a new window into the early universe
Unexploited for 25 years…ripe for improvement by 3 or 4 factors of 10

EARLY ENERGY RELEASE IS A PREDICTION OF THE STANDARD MODEL
This gives integrated information that will be complementary & independent,
eg for damping already measured at z~1000, to $z=2.10^6$

+ SOMETHING NEW: exploration of exotic physics
Eg annihilating/decaying dark matter, bubble universe collisions, decaying cosmic strings….

+ EXPLORE DECOUPLING OF PRIMEVAL PLASMA AT EPOCH OF 380000 YR
Potentially revelatory, eg for directly measuring recombination & for primordial He

QUESTIONS: Is it feasible? Need 10 x PIXIE sensitivity!

Is a space experiment required?

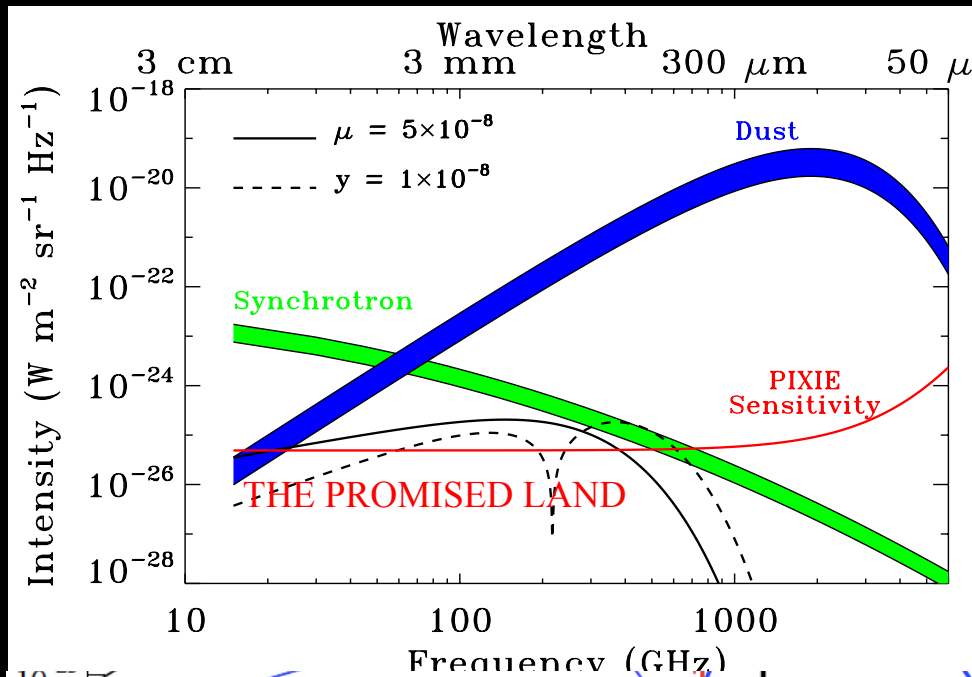
FUTURE SPACE MISSIONS WITH SPECTRAL CAPABILITY

PIXIE (for 2022 launch?)
T/S ~2.10^{-4} at 1 σ
+ marginal detection of
μ at z~10^6 and y at z~10^3 (~0.01 late y)

cf: LiteBIRD's design goal is ~10^{-3} for 2022 launch

PIXIE+
With a modest increase x3 in sensitivity,
a significant detection of canonical μ
is guaranteed

HYPERPIXIE
Theorist's dream:
EXPLORE DECOUPLING at z = 1080
Potentially revelatory for directly measuring
recombination & for primordial He
BUT need 30x PIXIE sensitivity!



cam on!