SPECTRAL DISTORTIONS GRAB BAG: Getting the ball rolling

Marc Kamionkowski (Johns Hopkins)

CERN

11 March 2018

Spectral

What are ~~Cognitive~~ Distortions? How do They Fuel Anxiety & Depression?

by Dr Aletta | Aug 18, 2011 | Anxiety, Depression | 5 comments

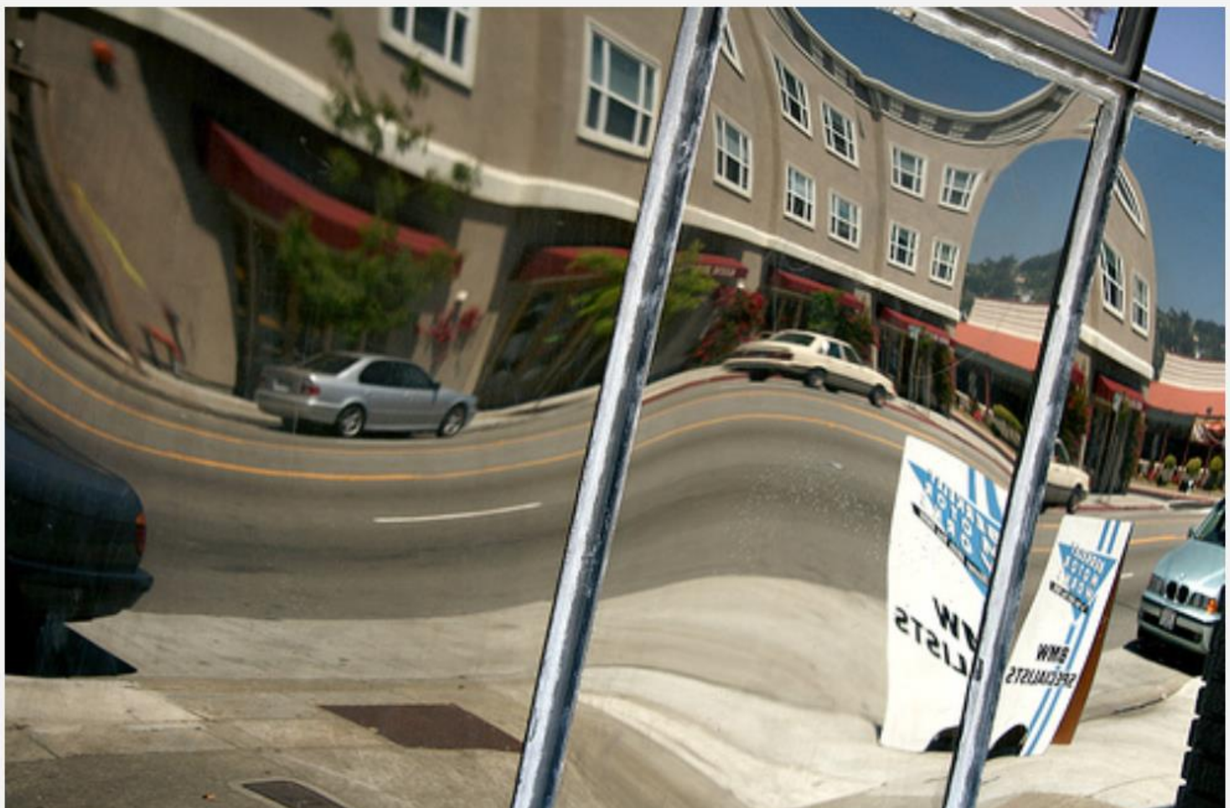


Photo courtesy of Jeremy Brooks

Cosmic Blackbody Constraint to Variable Fine-Structure Constant

Shin'ichiro Ando,[1, 2, *] Marc Kamionkowski,[1] and Robert R. Caldwell[3]

[1] *Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125*
[2] *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125*
[3] *Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755*

(Dated: February 26, 2007)

If the fine-structure constant α varies with time, then it may lead to the growth or decay of electromagnetic waves propagating in a vacuum. The frequency spectrum of the cosmic microwave background (CMB) can thus be used to constrain the variation of α, to be $|\Delta\alpha/\alpha| \lesssim 10^{-4}$, for redshifts $0 < z < 10^3$ through the amplitude of the CMB spectrum. A limit of comparable amplitude can be extended to redshifts $10^3 < z < 10^6$ through the measured limit to the CMB chemical potential.

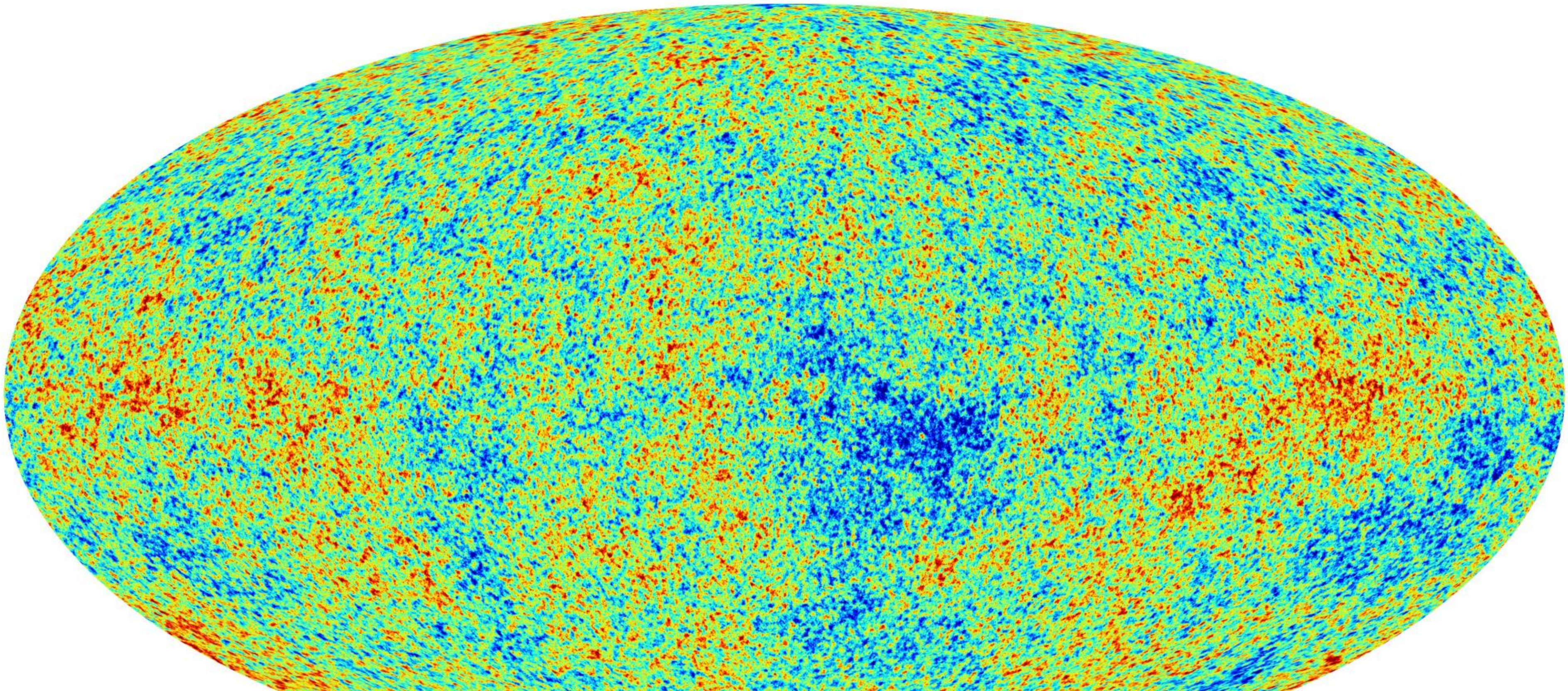
PACS numbers:

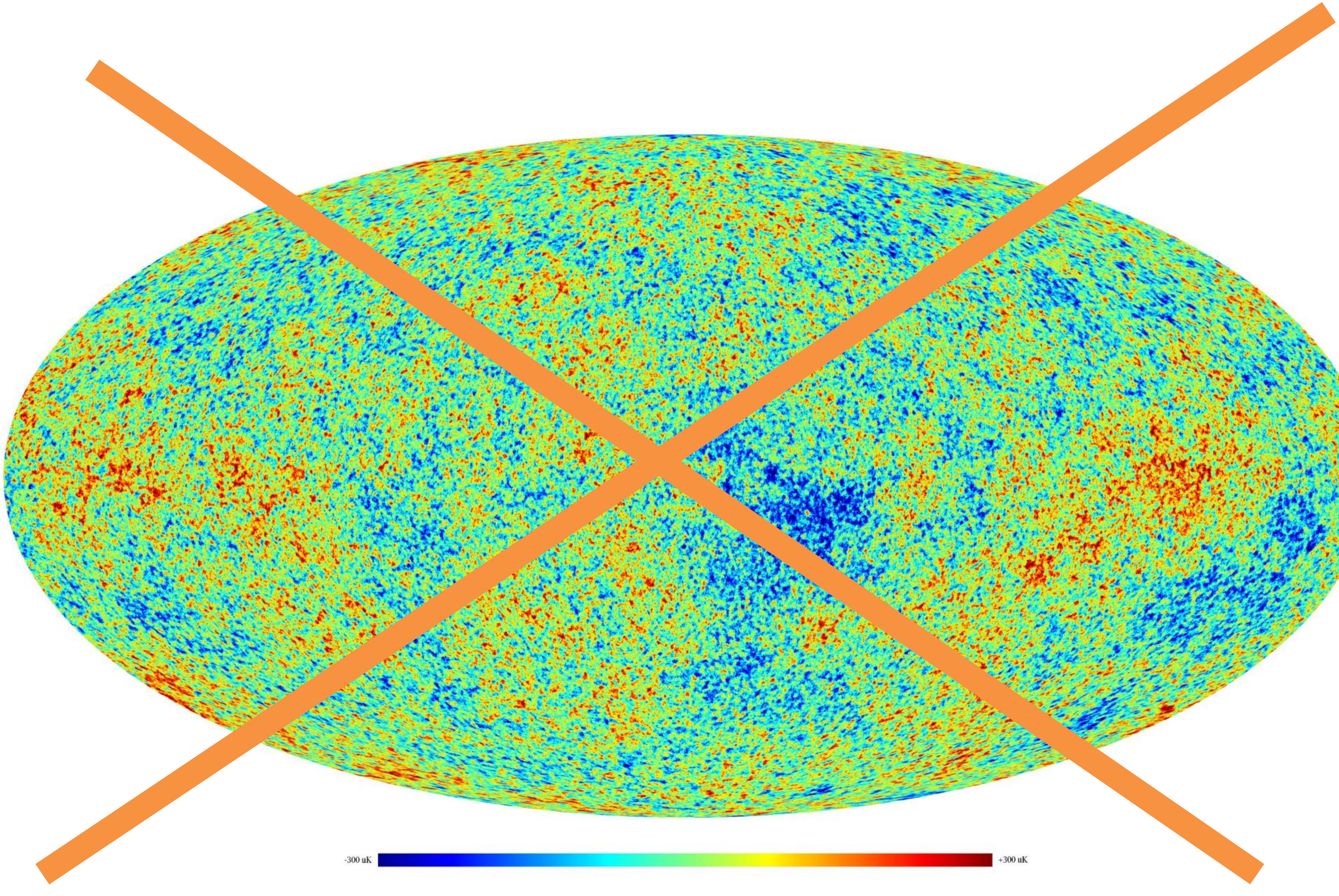
Quasar evidence for a variable fine-structure constant α has spurred a growing body of theoretical work on variable α, a theoretical question that remains interesting, even if the data are not yet conclusive. If taken as upper limits, spectroscopic observations of distant quasars set a constraint to the variation $\Delta\alpha$ of the fine-structure constant to be $|\Delta\alpha/\alpha| \lesssim 10^{-5}$ between redshifts $z = 0.5$–3 and the present [1]. If the effect is real, then it implies a fractional variation $|\Delta\alpha/\alpha| \sim 10^{-5}$ between over this redshift range. Variable α has received perhaps addi-

It is thus apparent that one way to introduce a variable α is to make the coupling e a function of the spacetime variables $x = (t, \vec{x})$: $e = e(x)$. However, since the classical equations of motion depend only on the relative magnitude of the two terms in the Lagrangian, and not on the overall normalization of the Lagrangian, another possibility would be to keep the charge e constant, but introduce a scalar field ϕ that multiplies the electromagnetic term in the Lagrangian:

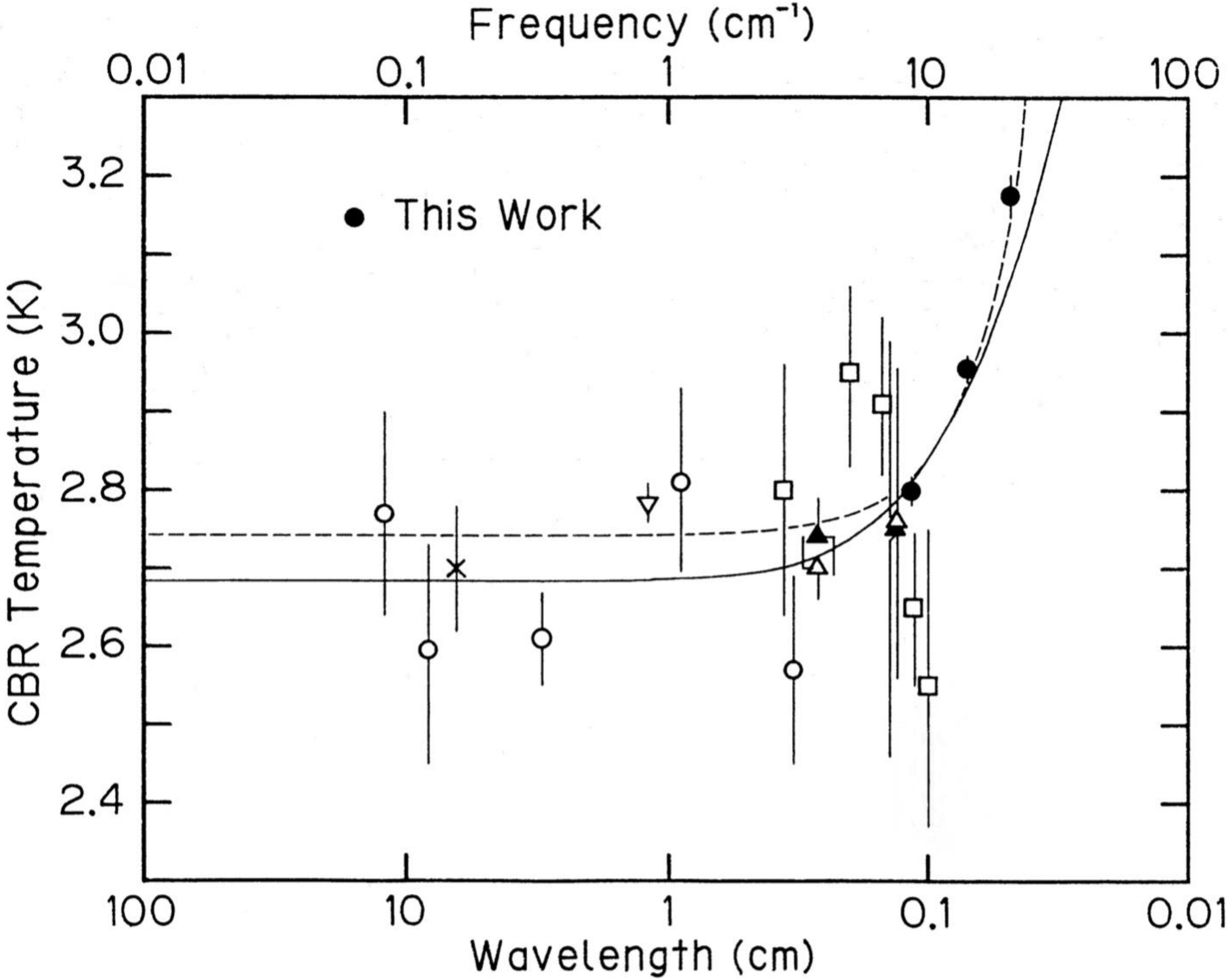
Outline

- Preliminaries
- Dissipation of acoustic modes (“Standard-Model” predictions
  - Tests of inflation
  - Tests of small-scale-suppression mechanisms
  - Non-gaussianity
- Decaying particles / PBHs
- Late-time contributions
- Grab bag
- Shopping list


-300 uK
+300 uK


-300 uK
+300 uK

Discovery of spectral distortions in the cosmic microwave background


Frequency (cm⁻¹)
0.01
0.1
1
10
100
3.2
3.0
2.8
2.6
2.4
CBR Temperature (K)
This Work
100
10
1
0.1
0.01
Wavelength (cm)

Post-Nagoya-Berkeley:

Decaying particles
Left-right symmetric models
Mock gravity
Domain structure of shadow matter
Technibaryons
Superconducting cosmic strings
UHECR cascades
Weird dust

Title:	A cosmic book
Authors:	Peebles, P. J. E.; Silk, Joseph
Affiliation:	AA(Princeton University, NJ), AB(California, University, Berkeley)
Publication:	Nature (ISSN 0028-0836), vol. 335, Oct. 13, 1988, p. 601-606. NSF-NASA-supported research. (Nature Homepage)
Publication Date:	10/1988
Category:	Astrophysics
Origin:	STI
NASA/STI Keywords:	Cosmology, Dark Matter, String Theory, Universe, Astronomical Models, Figure Of Merit, Galaxies, Probability Theory, Stars
DOI:	10.1038/335601a0
Bibliographic Code:	1988Natur.335..601P

Abstract

A system of assigning odds to the basic elements of cosmological theories is proposed in order to evaluate the strengths and weaknesses of the theories. A figure of merit for the theories is obtained by counting and weighing the plausibility of each of the basic elements that is not substantially supported by observation or mature fundamental theory. The magnetized strong model is found to be the most probable. In order of decreasing probability, the ranking for the rest of the models is: (1) the magnetized string model with no exotic matter and the baryon adiabatic model; (2) the hot dark matter model and the model of cosmic string loops; (3) the canonical cold dark matter model, the cosmic string loops model with hot dark matter, and the baryonic isocurvature model; and (4) the cosmic string loops model with no exotic matter.

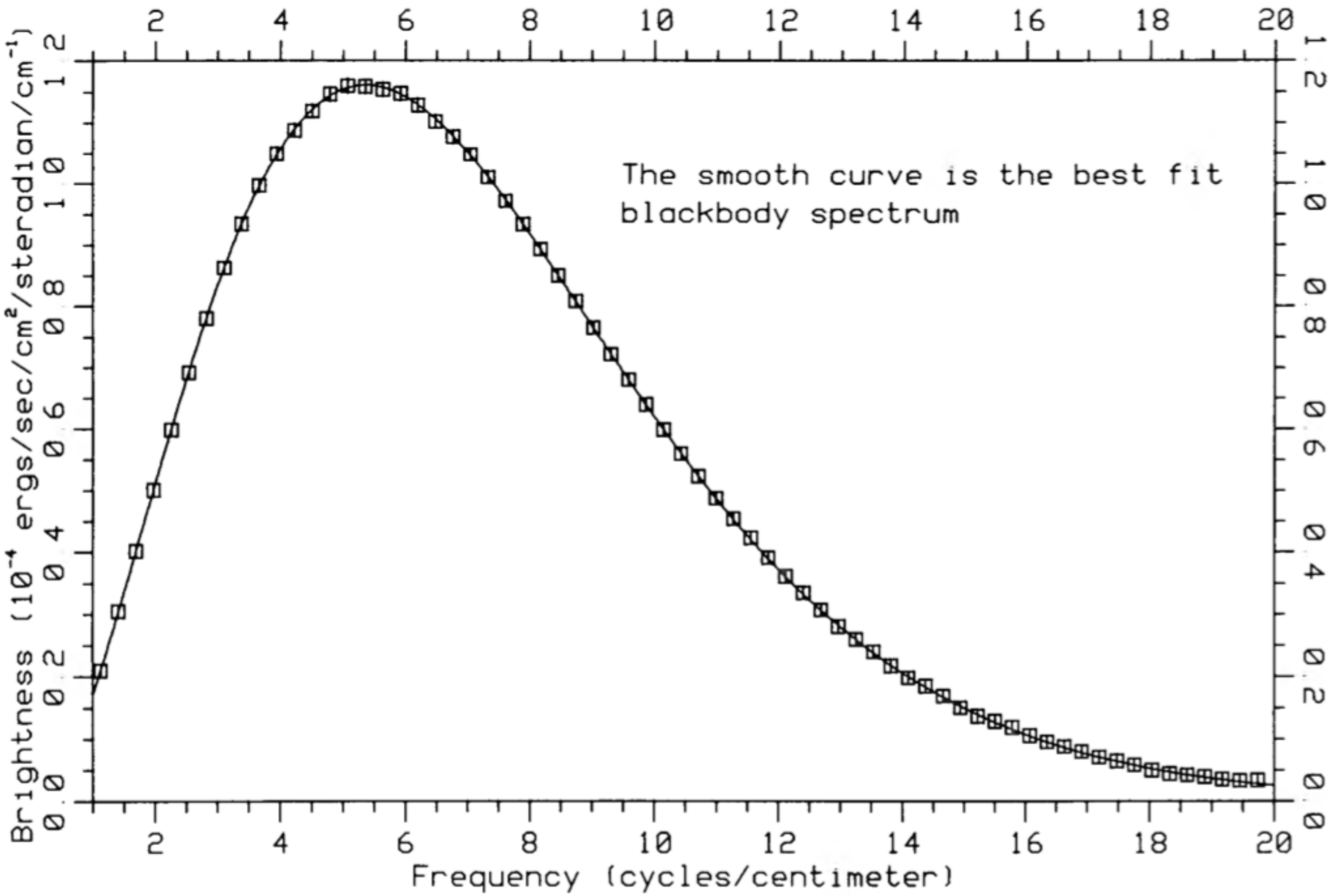


FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

Post-FIRAS

Constraints to post-Nagoya-Berkeley scenarios

Growing interest!!

SPIRES titles with “spectral” and “distortions”

Pre-2010: 22 Post-2010: 64

Citations to 1994 Hu-Silk paper

Pre-2010: 46 Post-2010: 102

Great review article (Chluba, Hamman, Patil 2015)

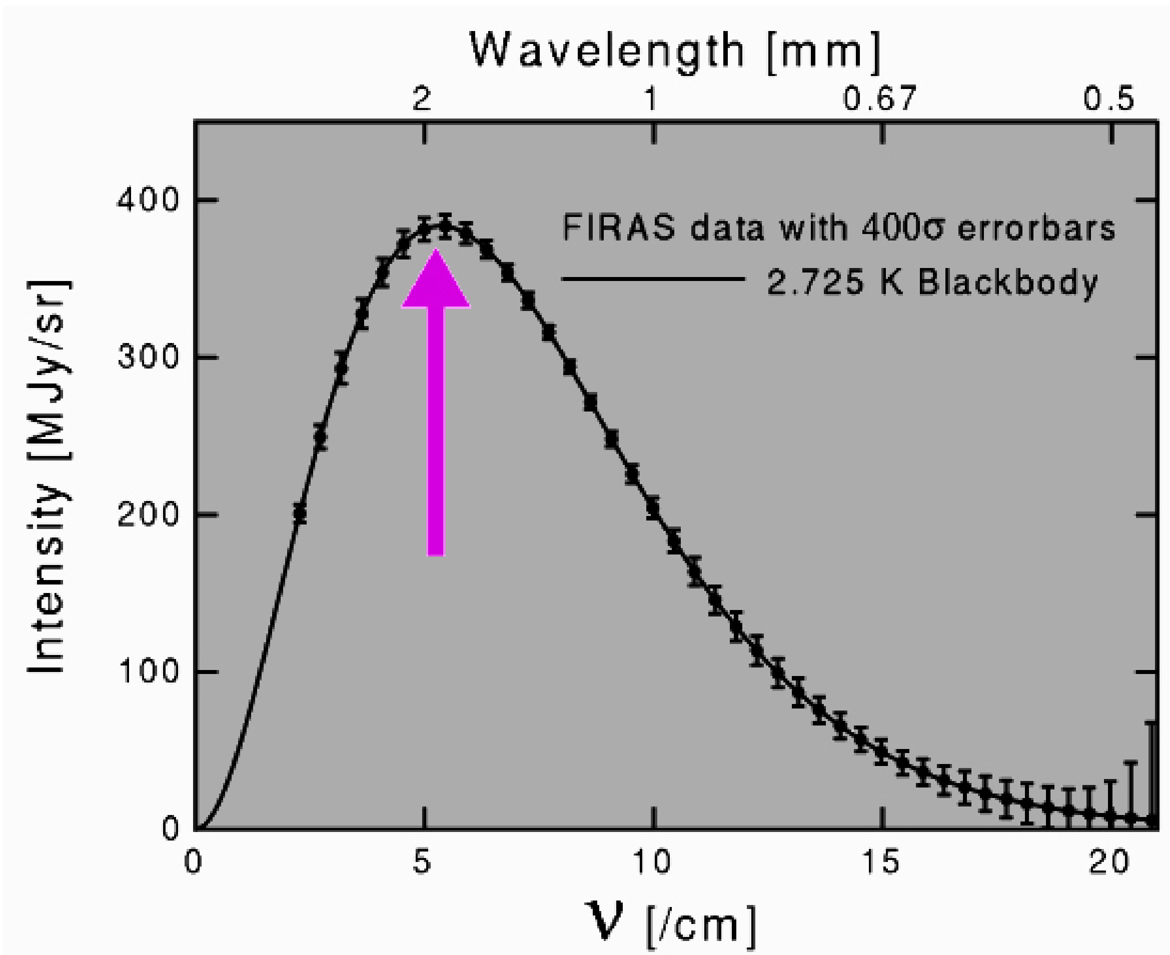
Sources of spectral distortions

1. New source of radiation in late (transparent) Universe

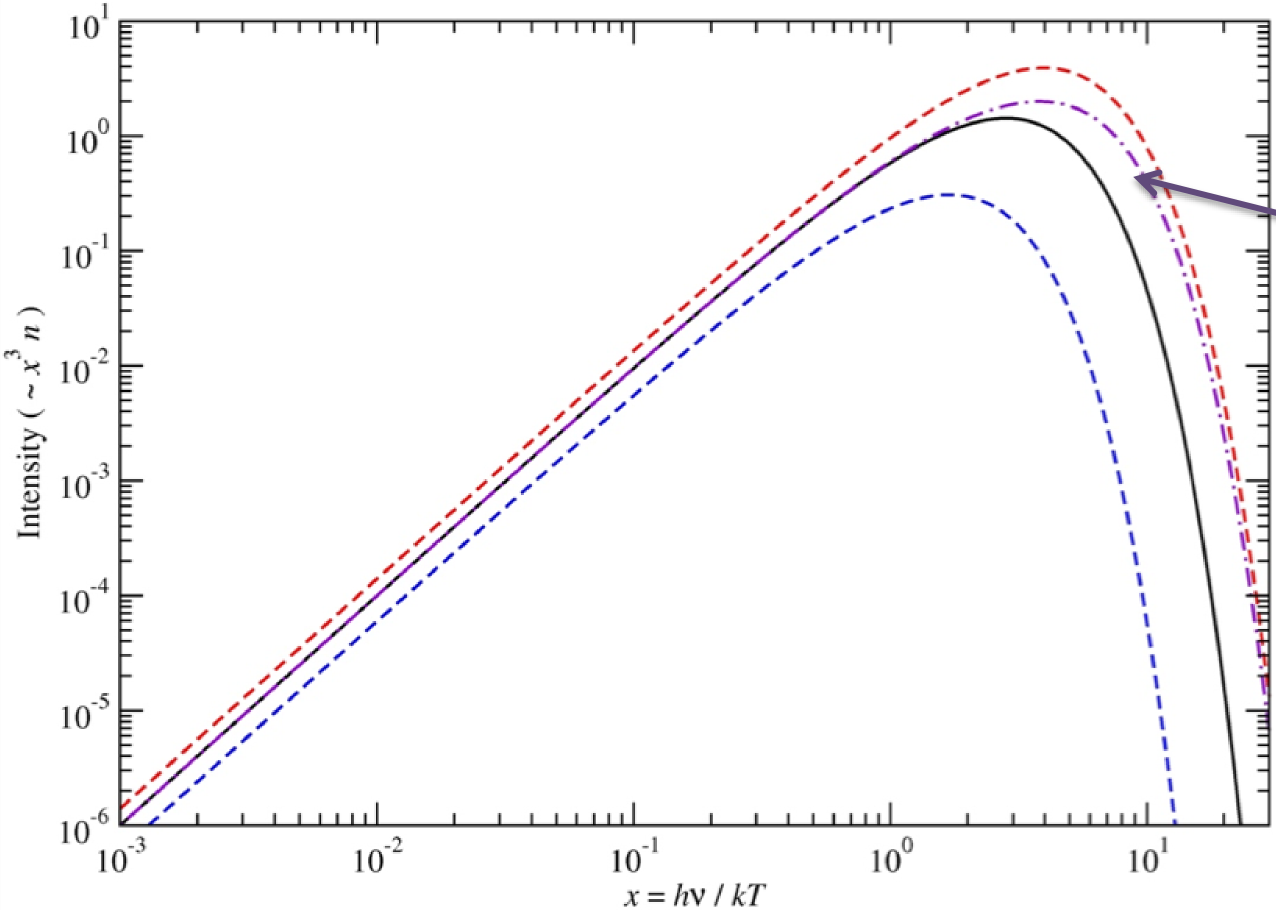
2. Radiative energy injection/augmentation at early times

3. Re-scattering of CMB radiation

If photons can be created/destroyed, will eventually attain complete (kinetic+chemical) equilibrium---a blackbody

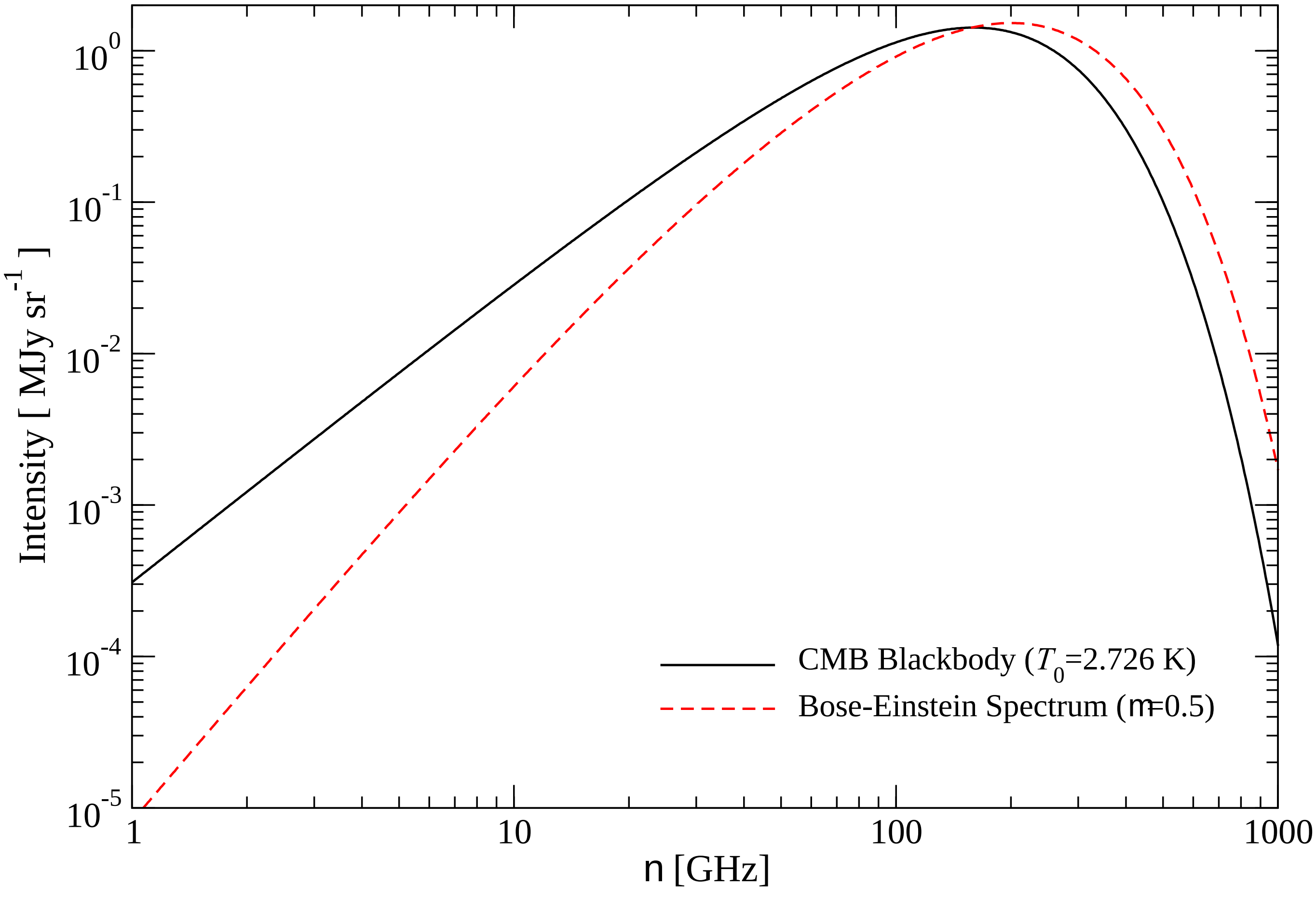


Superposition of two blackbodies of different T has a "Compton-y" distortion with $y \propto (\Delta T)^2$



NOT a blackbody

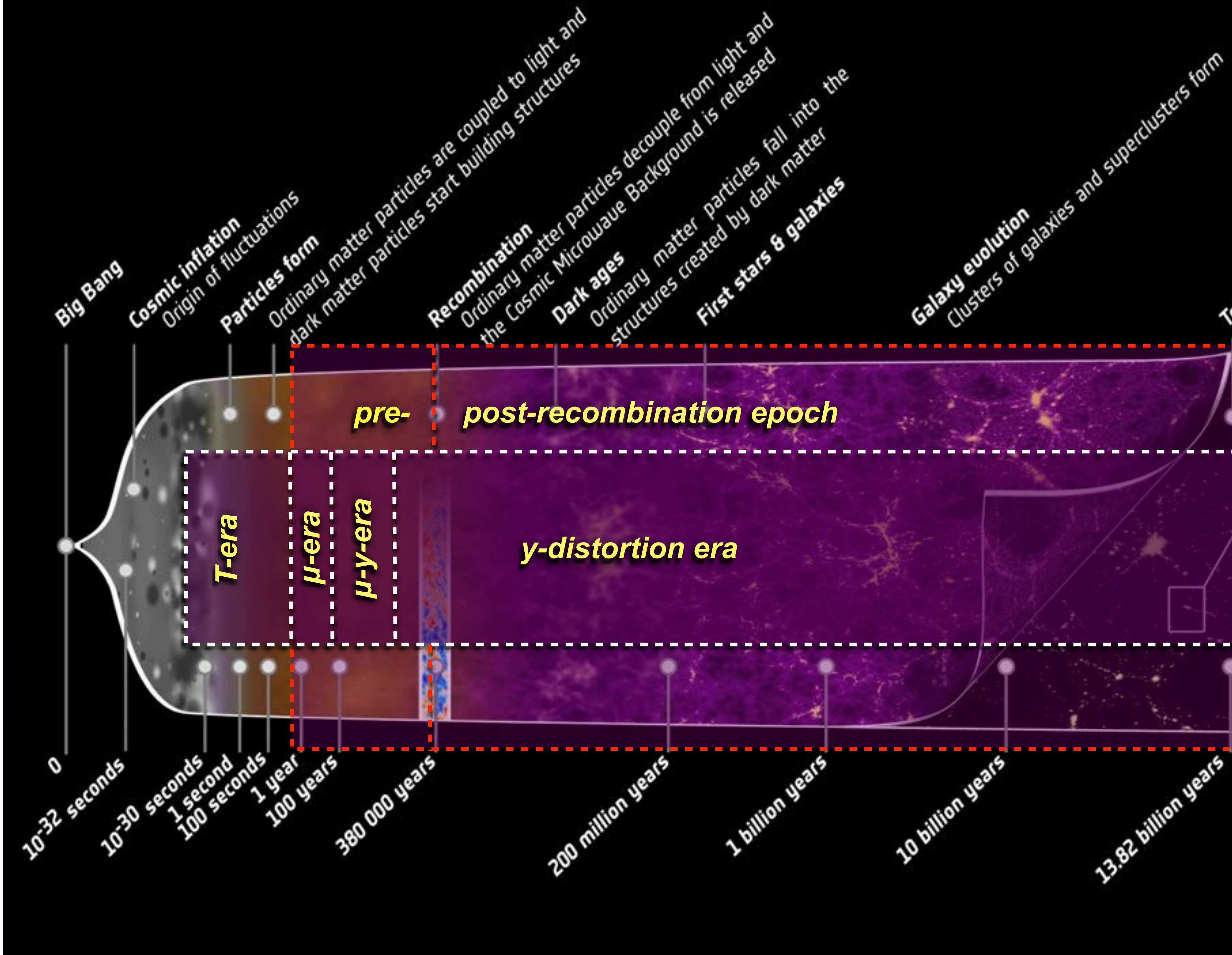
If photons scatter and come to kinetic equilibrium, keeping photon number fixed, spectrum has a Bose-Einstein frequency spectrum with chemical potential μ.



At redshift $z>10^6$, photon-#--changing interactions are rapid compared with expansion rate, so CMB is thermal.

But at $z<10^6$, photon # remains constant.

Thus, any source of heat at $z<10^6$ will induce spectral distortions!



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Benchmarks

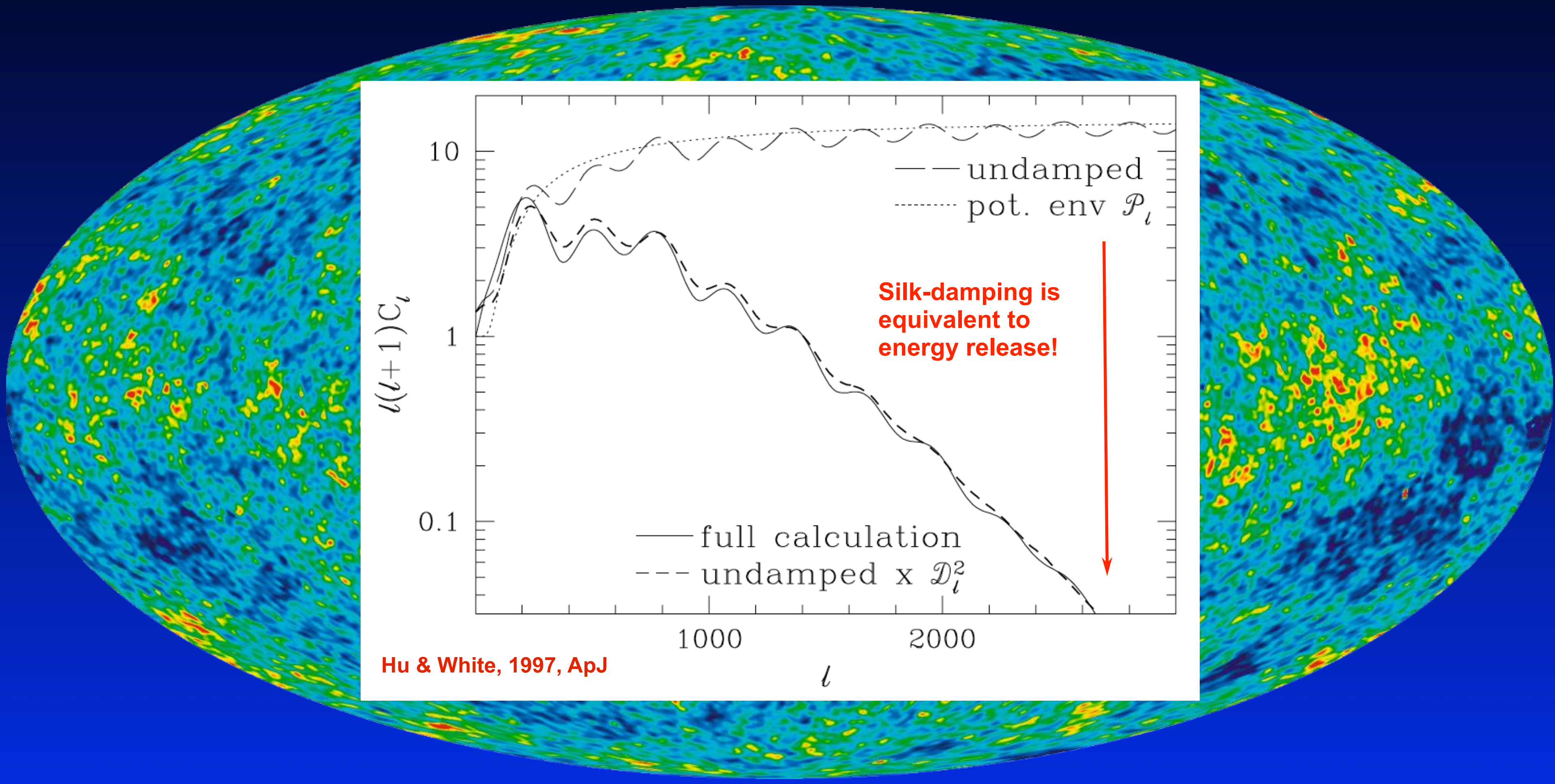
- FIRAS: mu<9x10^{-5} y<2.5x10^{-5}
- Fluctuations: Delta mu < 6.4x10^{-6} (Khatri-Sunyaev 2015)
- PIXIE sensitivity: mu to ~10^{-8}
- PRISM-like: mu to ~10^{-9} y to ~10^{-10}

(fluctuation sensitivity depends on assumed spectrum, cross- vs auto-correlation, etc. ………. more later)

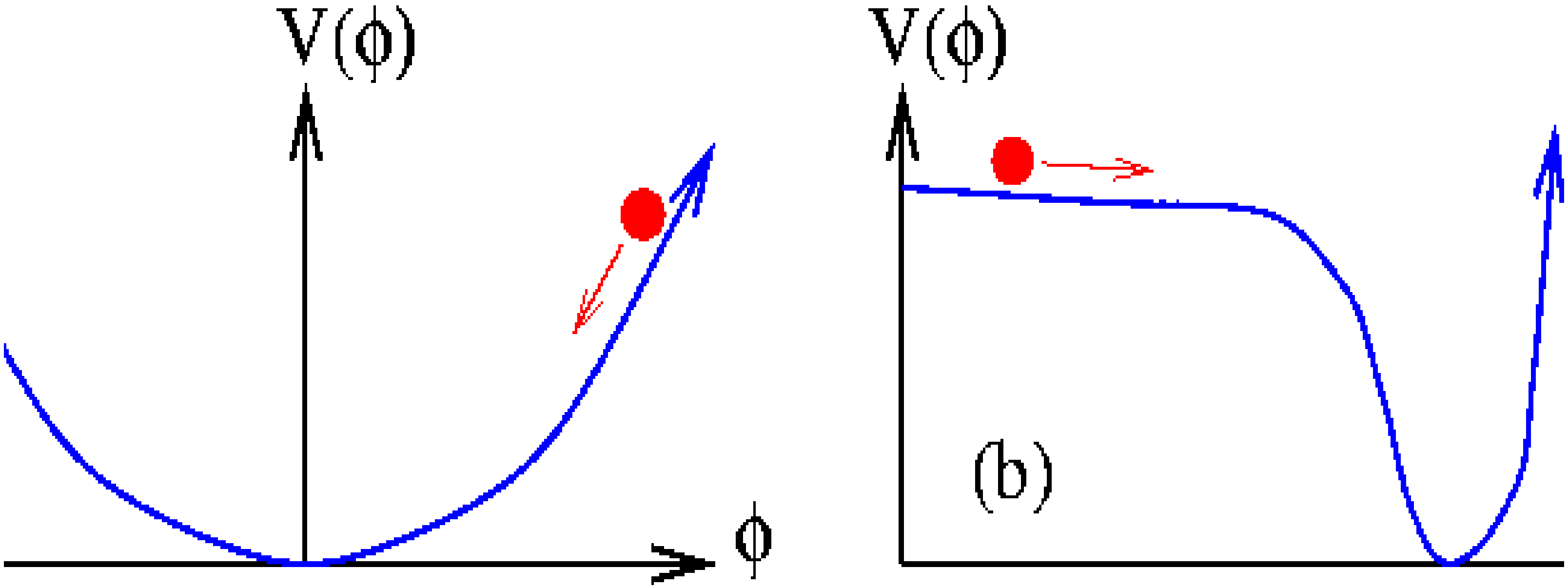
Current FIRAS constraints

- Energy injection into primordial plasma no more than ~10^{-5} of radiation density between $z<\text{few} \times 10^6$ and $z\sim1100$

Dissipation of small-scale acoustic modes



Inflation:



Nearly (but not precisely) scale-invariant primordial perturbations

Inflation predicts power spectrum

$$P(k) \equiv \left\langle \left(\frac{\delta\rho}{\rho} \right)^2_{\vec{k}} \right\rangle \propto k^{n_s}$$

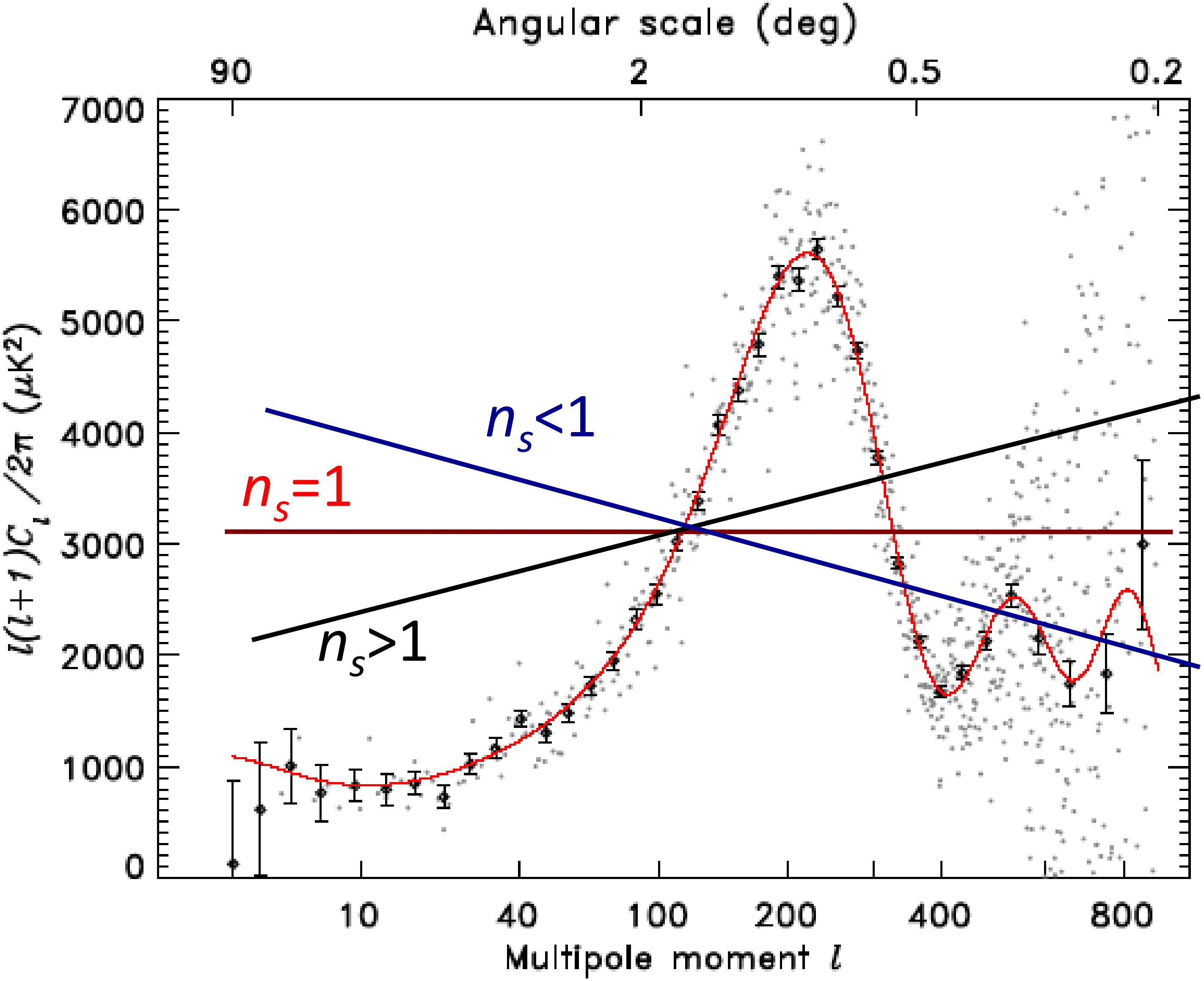
With

$$n_s = 1 - 2\epsilon + 6\eta$$

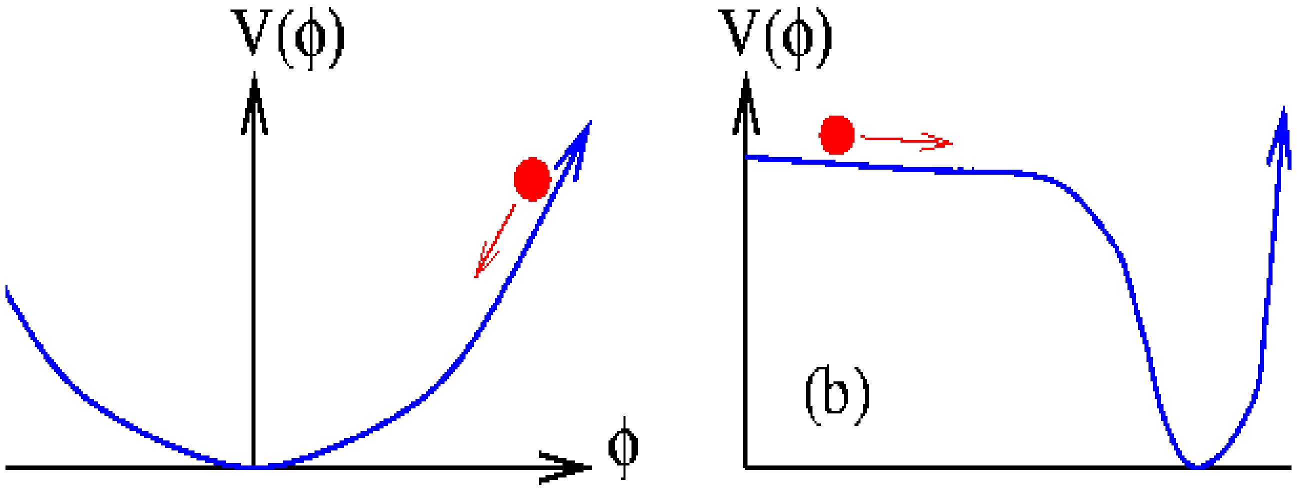
$$\epsilon \propto V' \qquad \eta \propto V''$$

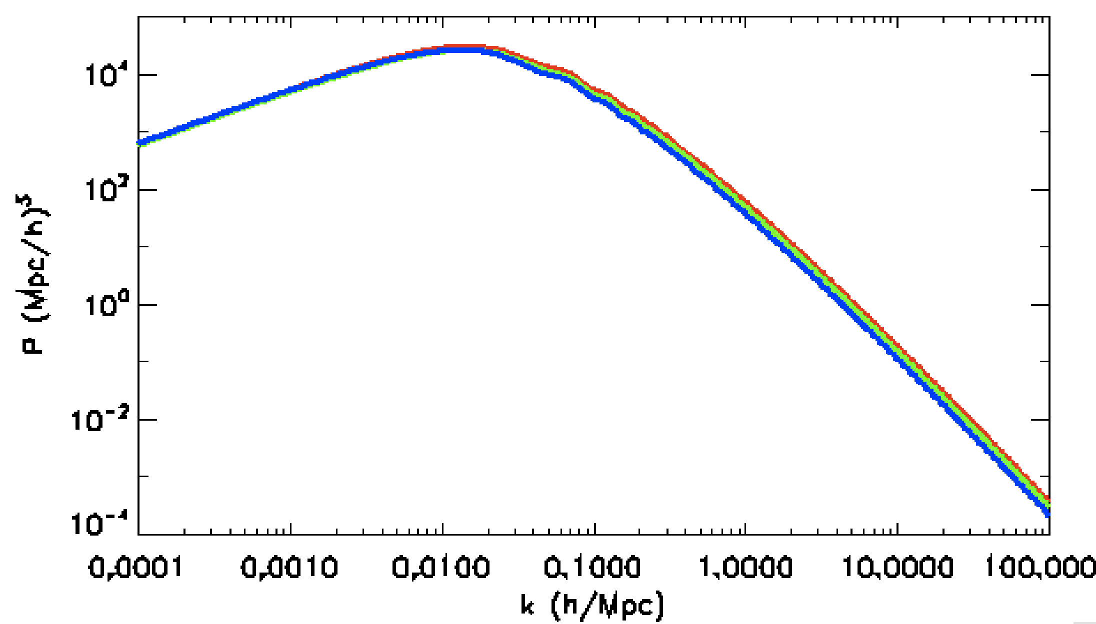
i.e.,

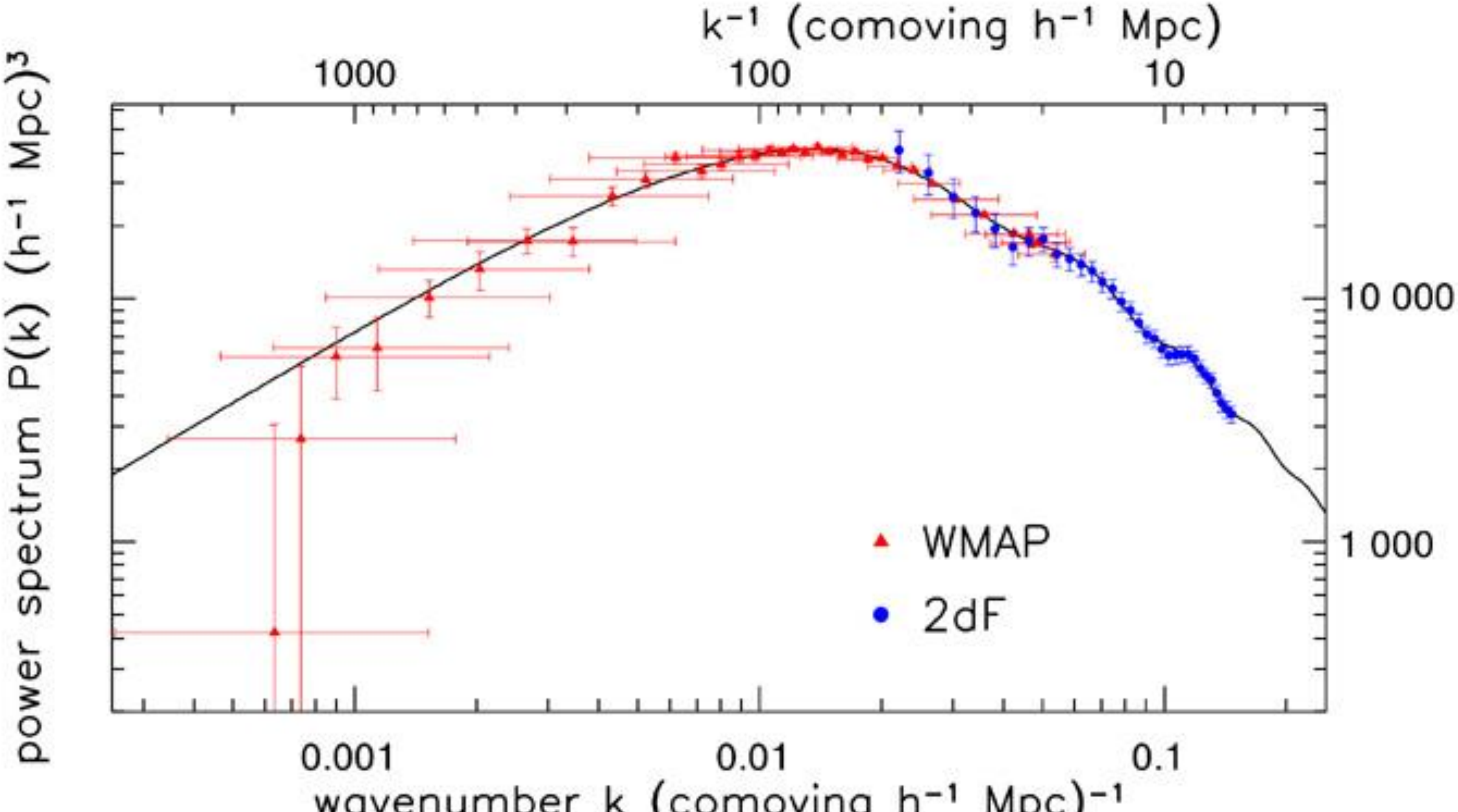
$$V(\phi) \leftrightarrow P(k)$$


Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l\ /2\pi\ (\mu K^2)$
n_s<1
n_s=1
n_s>1
10
40
100
200
400
800
Multipole moment l

WMAP


V(ϕ)
ϕ
V(ϕ)
(b)

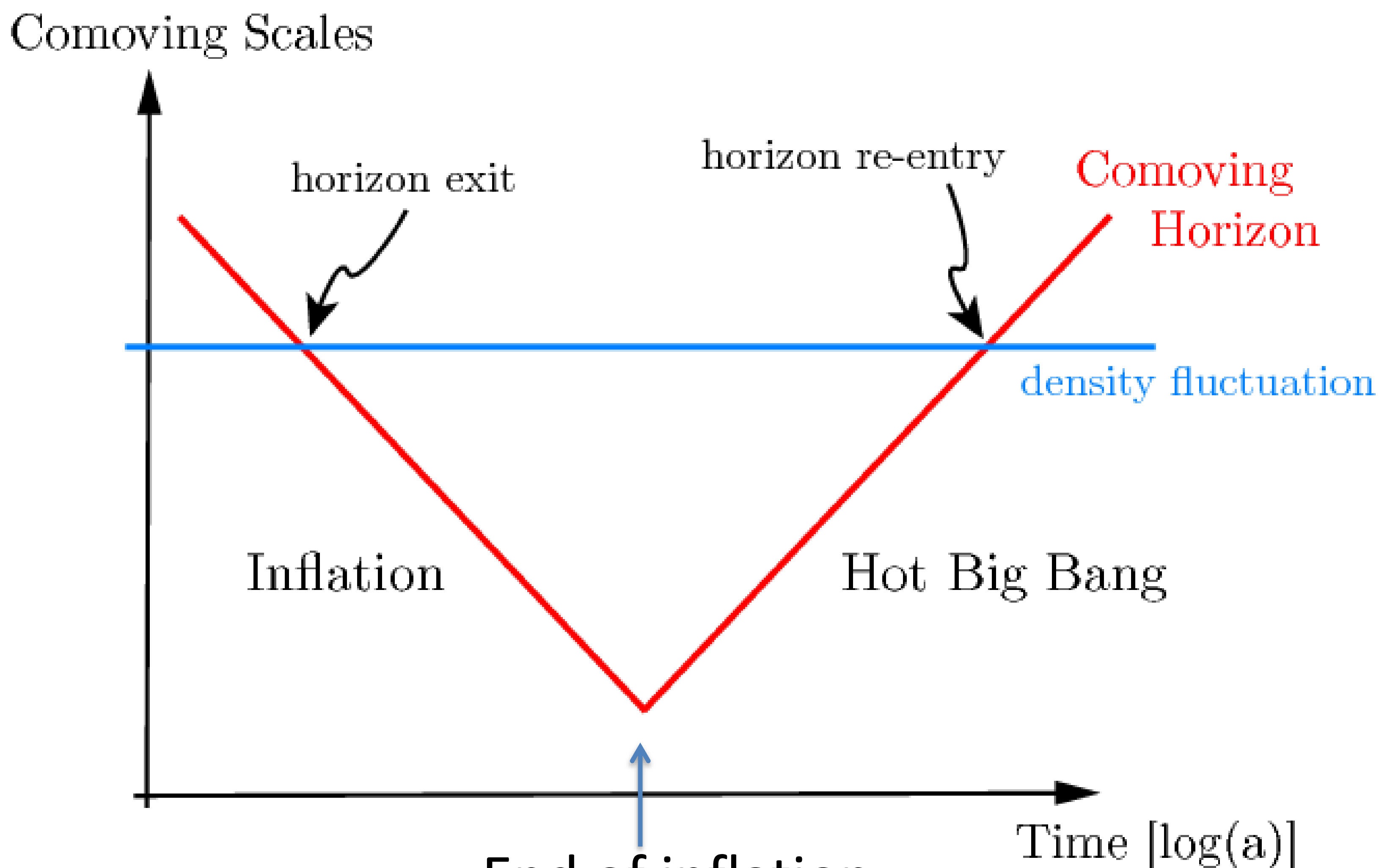

P (Mpc/h)³
k (h/Mpc)
10⁴
10²
10⁰
10⁻²
10⁻⁴
0,0001
0,0010
0,0100
0,1000
1,0000
10,0000
100,000



k⁻¹ (comoving h⁻¹ Mpc)
1000
100
10
power spectrum P(k) (h⁻¹ Mpc)³
10 000
1 000
WMAP
2dF
0.001
0.01
0.1
wavenumber k (comoving h⁻¹ Mpc)⁻¹

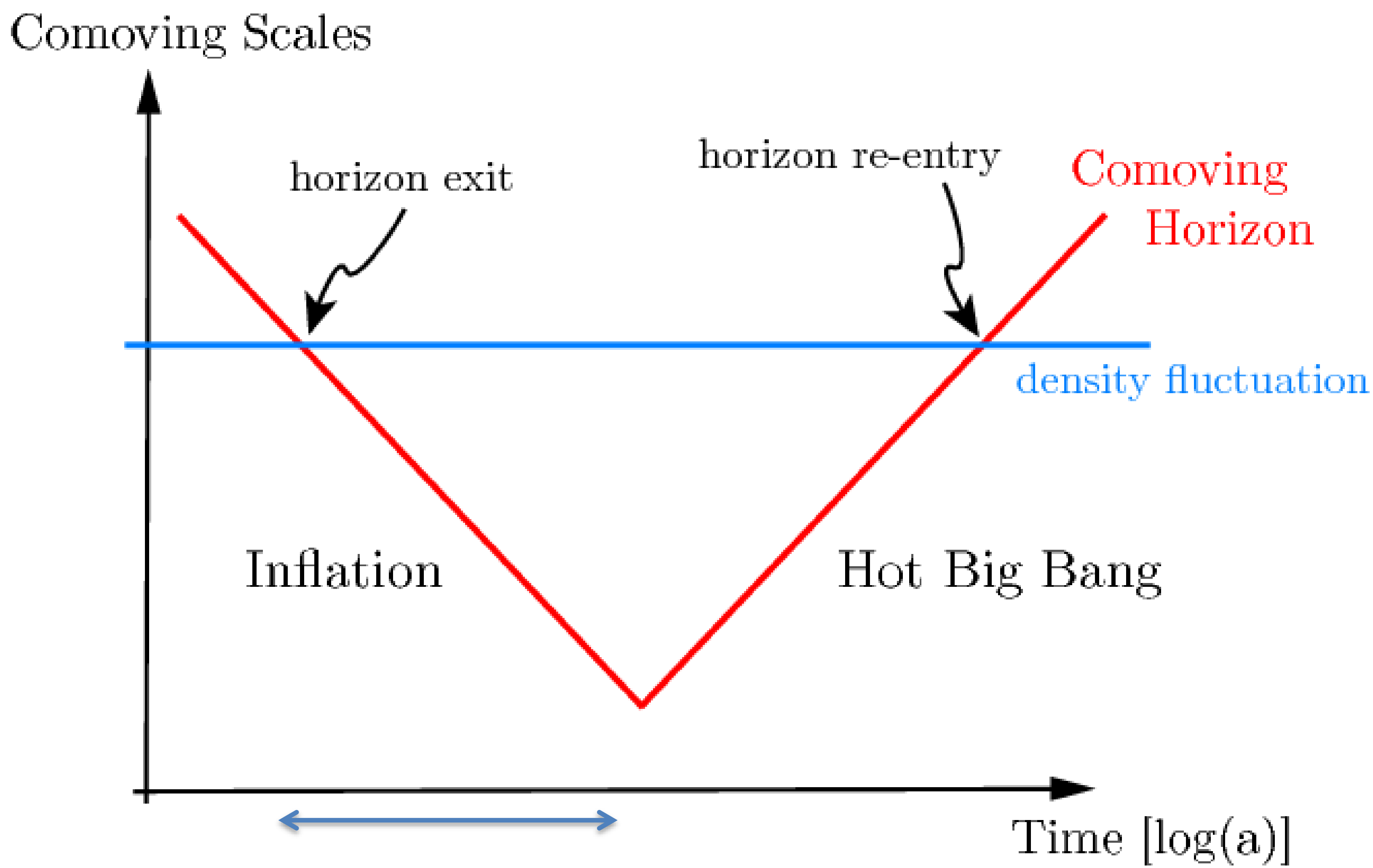
But there is more!

Number of “e-folds” of inflation



End of inflation

Number of “e-folds” of inflation



How long did this last??

How long did inflation last?

Number of "e-folds" of inflation

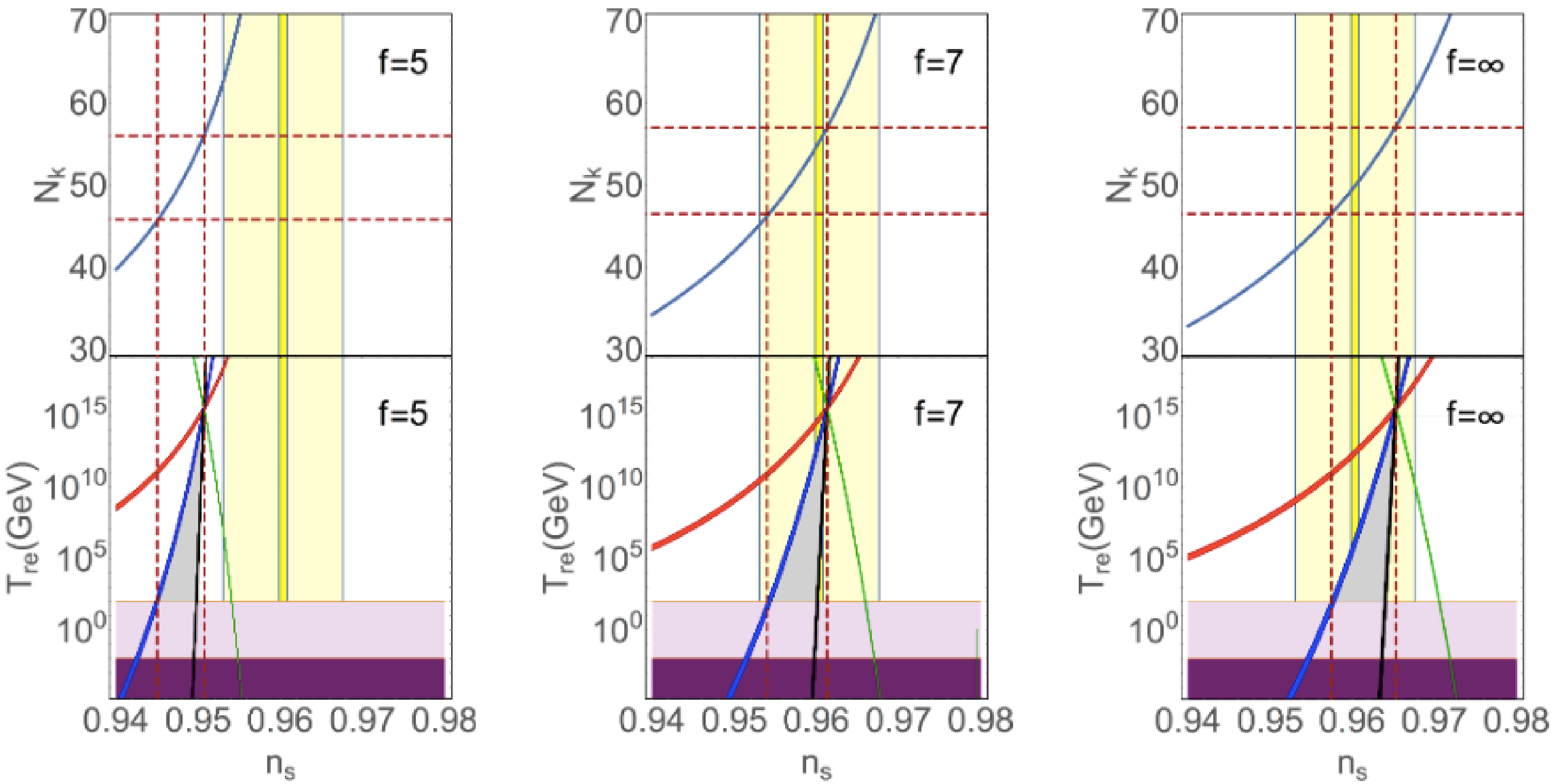
$$N = \log\left(\frac{\text{Hubble distance}}{\text{smallest inflationary distance scale}}\right)$$

$$N \simeq 40 - 60$$

(or ~15-22 decades)

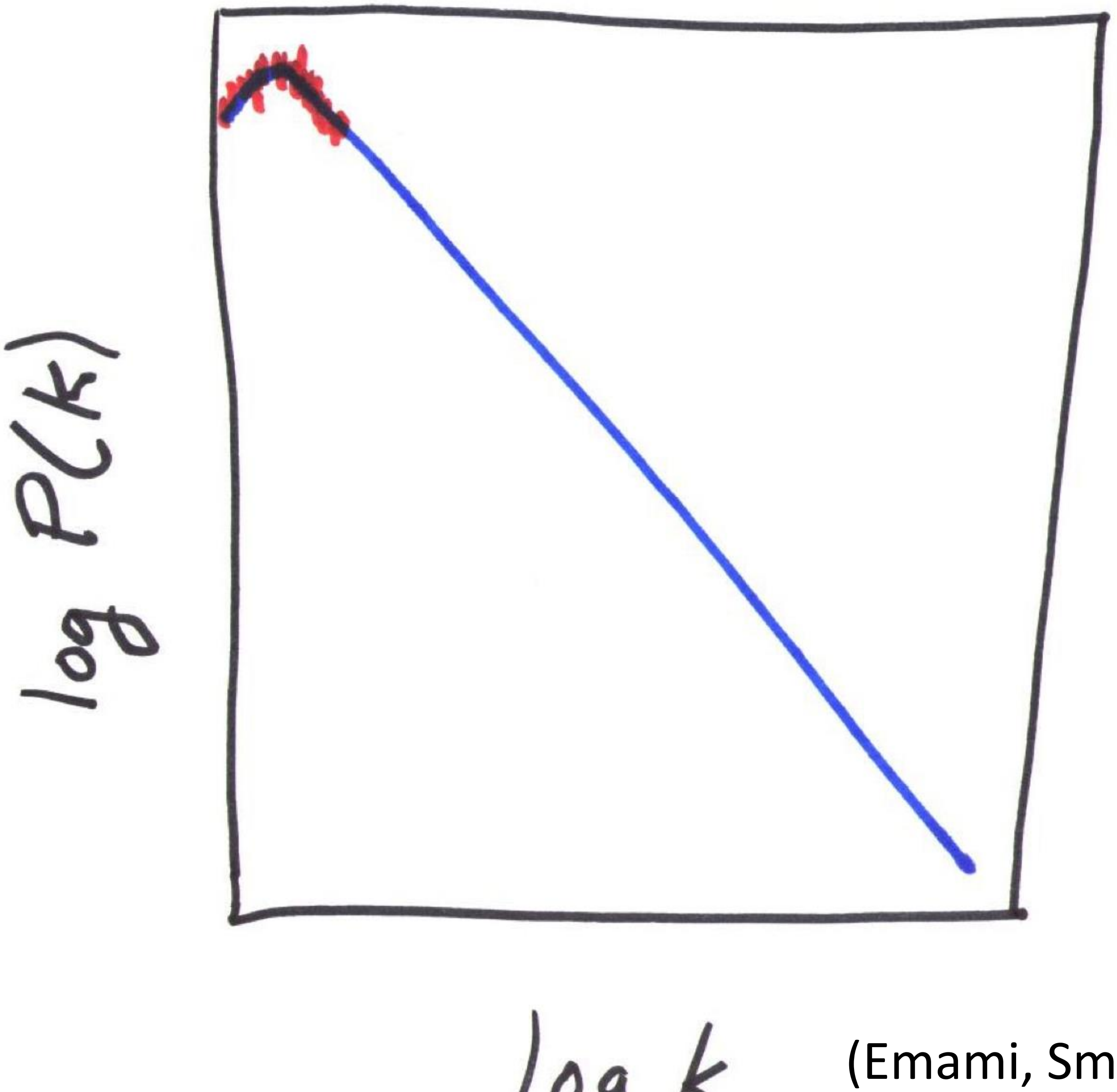
for reheat temperature ~TeV to 10^{16} GeV

Current constraints to n_s narrow N range a bit



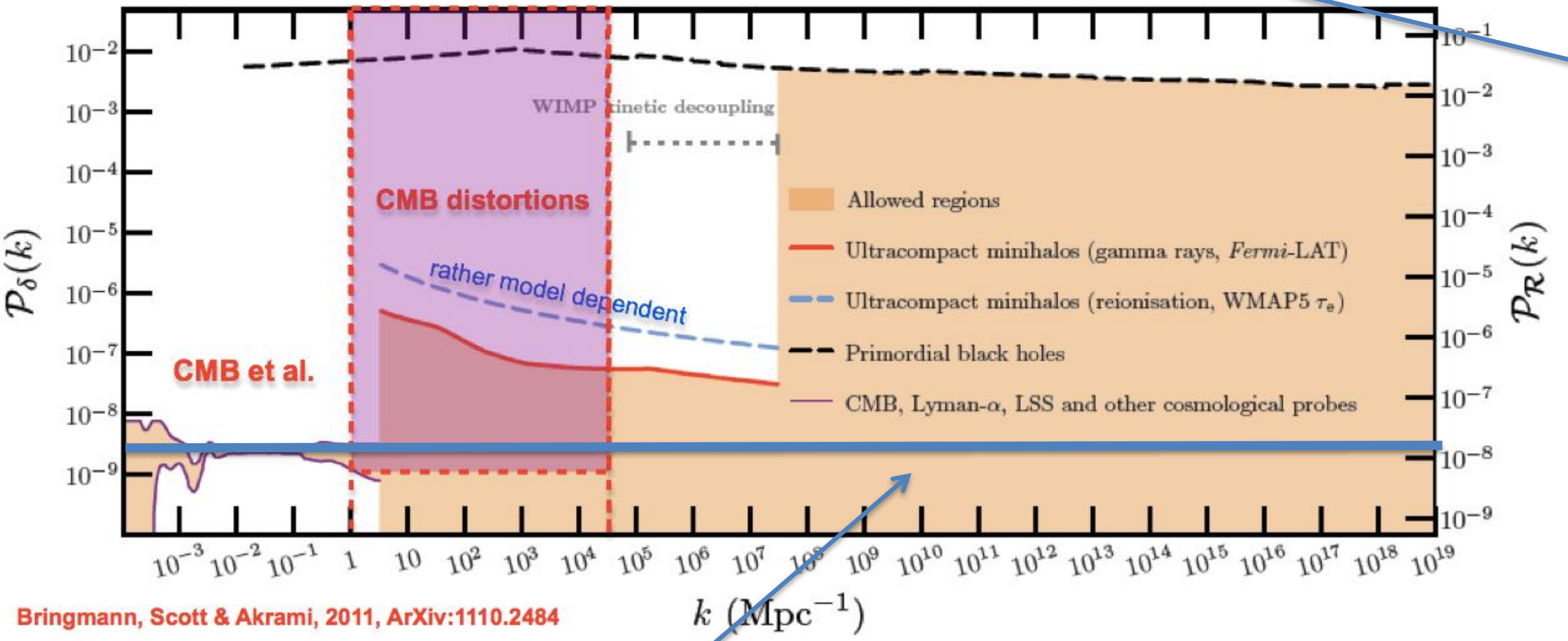
Dai, MK, Wang, PRL 2014; Munoz, MK 2015;
Cook, Dimastrogiovanni, Easson, Krauss, 1502.04673

Inflationary prediction is therefore….



(Emami, Smoot 2018)

TeV inflation GUT inflation

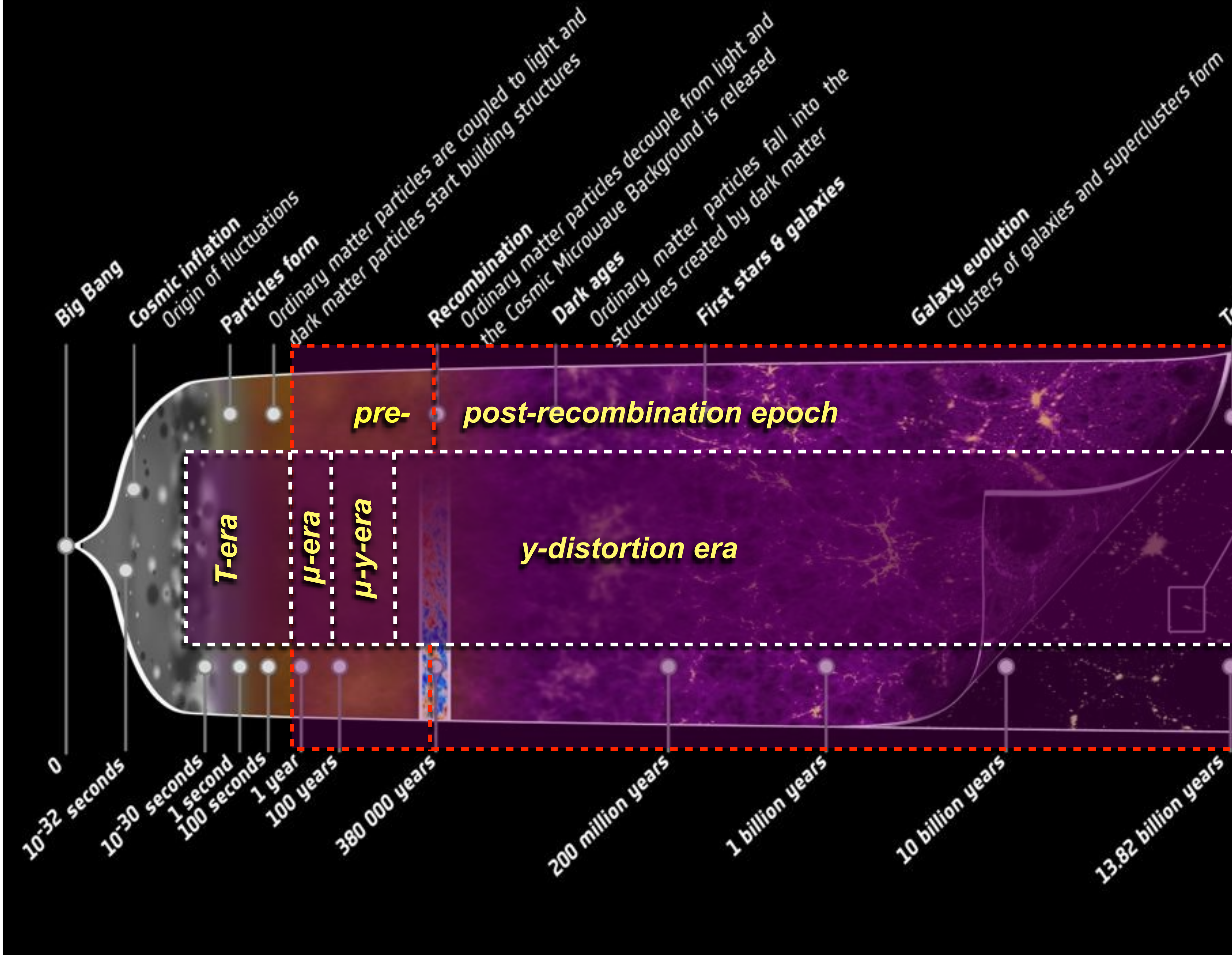


Inflationary prediction!

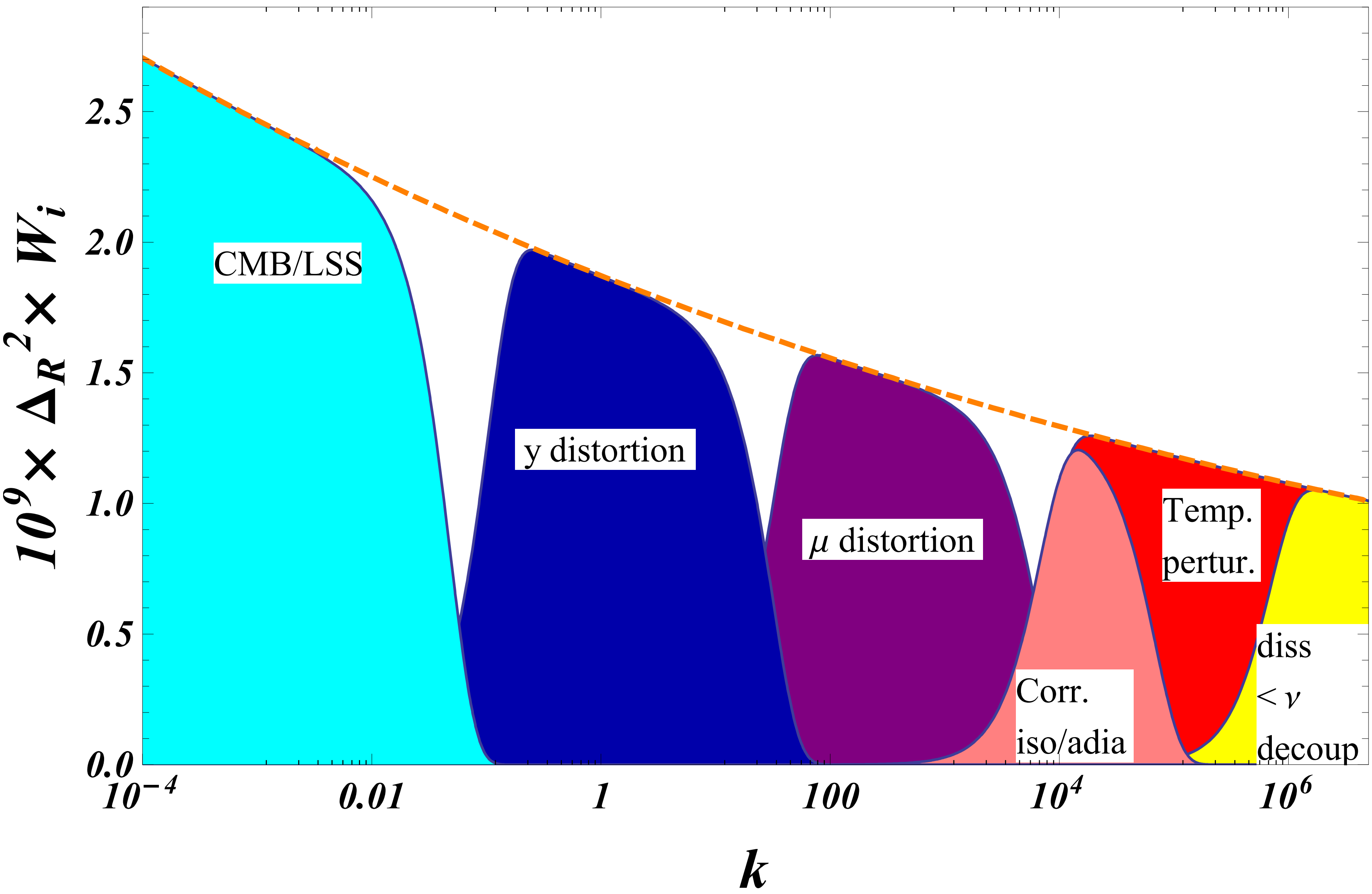
How can we measure, or at least constrain, small-scale primordial power?

How can we measure, or at least constrain, small-scale primordial power?

- **Spectral distortions in the CMB**
- 21-cm fluctuations from the dark ages (Zaldarriaga-Loeb)
- Primordial black holes (Nakama&co;)
- Ultra-compact mini-halos
  – microlensing
  – Annihilation signatures
  – Direct vs indirect detection
- Supernova dispersions



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years



$10^9 \times \Delta_R^2 \times W_i$
2.5
2.0
1.5
1.0
0.5
0.0
10^{-4}
0.01
1
100
10^4
10^6
k
CMB/LSS
y distortion
μ distortion
Corr. iso/adia
Temp. pertur.
diss < ν decoup

Mu distortions or running (Cabass, Melchiorri, Pajer 2016)

Standard LambdaCDM prediction (6-parm):

$$\mu = 1.57^{+1.11}_{-0.13} \times 10^{-8}$$

and including running of n_s:

$$\mu = 1.28^{+0.30}_{-0.52} \times 10^{-8}$$

compared with PIXIE sensitivity to mu~10^{-8}

Implies mu detection with 3xPIXIE, and if not, requires running of spectral index

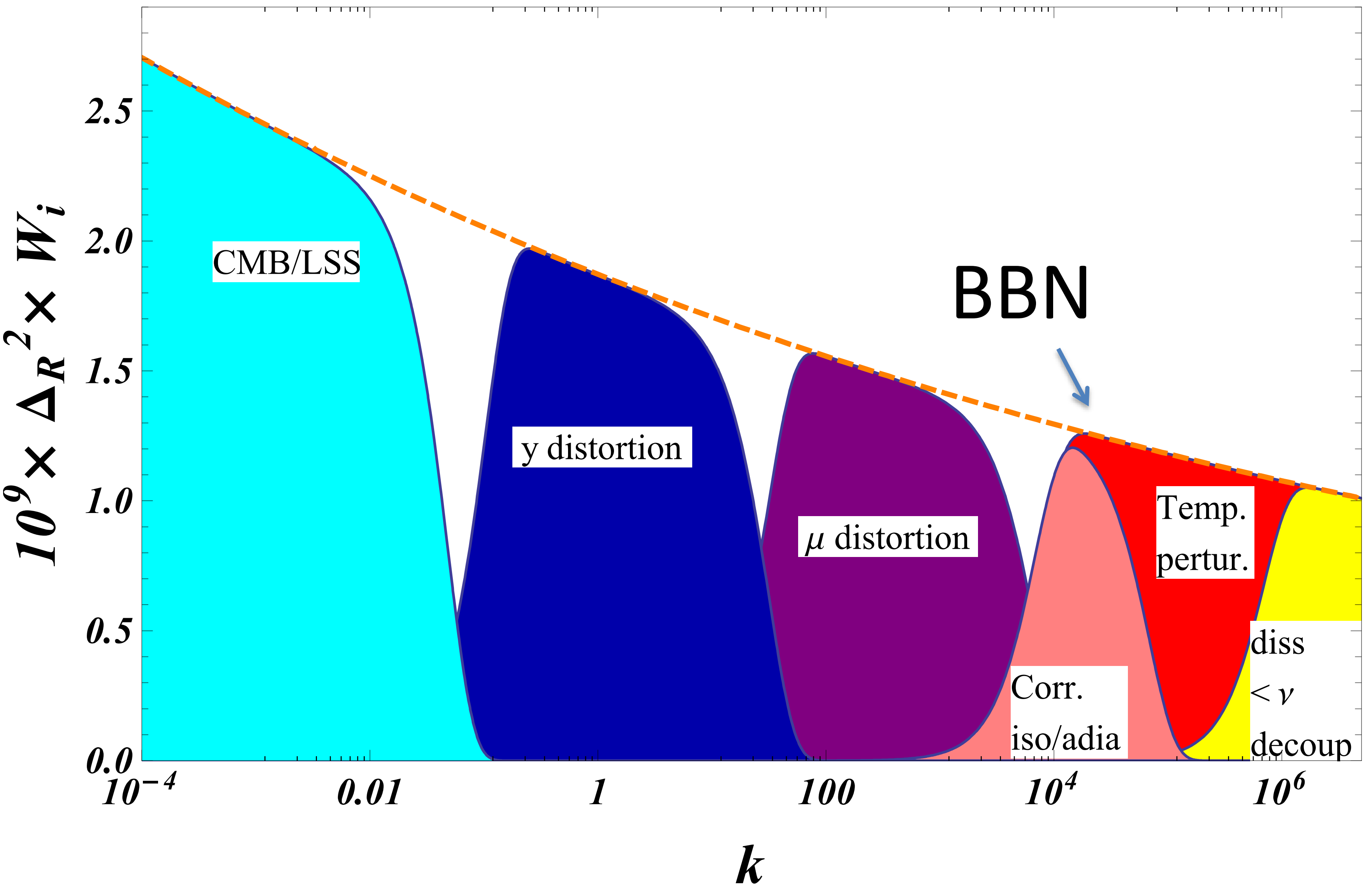
Exotic mechanisms to suppress small-scale power (Nakama, Chluba, MK 2017; also Diacoumis&Wong 2017; Sarkar, Sethi, Das 2017)

- Only mechanisms (e.g., BSI from inflation (e.g., MK-Liddle 2000)) that eliminate *radiation*-density perturbations have effect on mu distortion
- Mechanisms (e.g., DM from charged-particle decay at tau~3.5 yr (e.g., Sigurdson-MK 2004)) that reduce matter fluctuations without smoothing radiation fluctuations do not alter standard mu prediction

Dissipation on smaller scales

(Chluba, Jeong, Pradler, MK, PRL 2014; Nakama, Suyama, Yokoyama 2014)

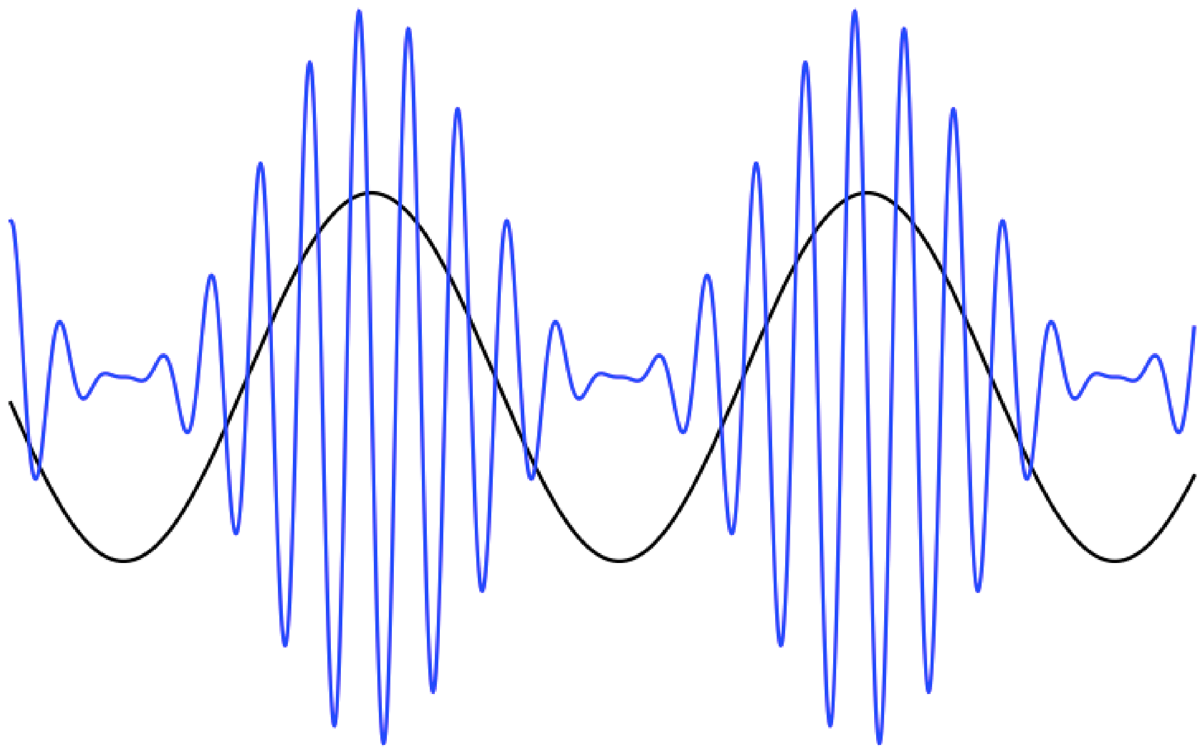
- Silk damping at $z \sim 10^9$ from e^+e^- annihilation
- Heats plasma
  - affects predictions for BBN relative to standard



$10^9 \times \Delta_R^2 \times W_i$
2.5
2.0
1.5
1.0
0.5
0.0
CMB/LSS
y distortion
μ distortion
BBN
Corr.
iso/adia
Temp.
pertur.
diss
< ν
decoup
10^{-4}
0.01
1
100
10^4
10^6
k

Non-gaussianity introduces more possibilities

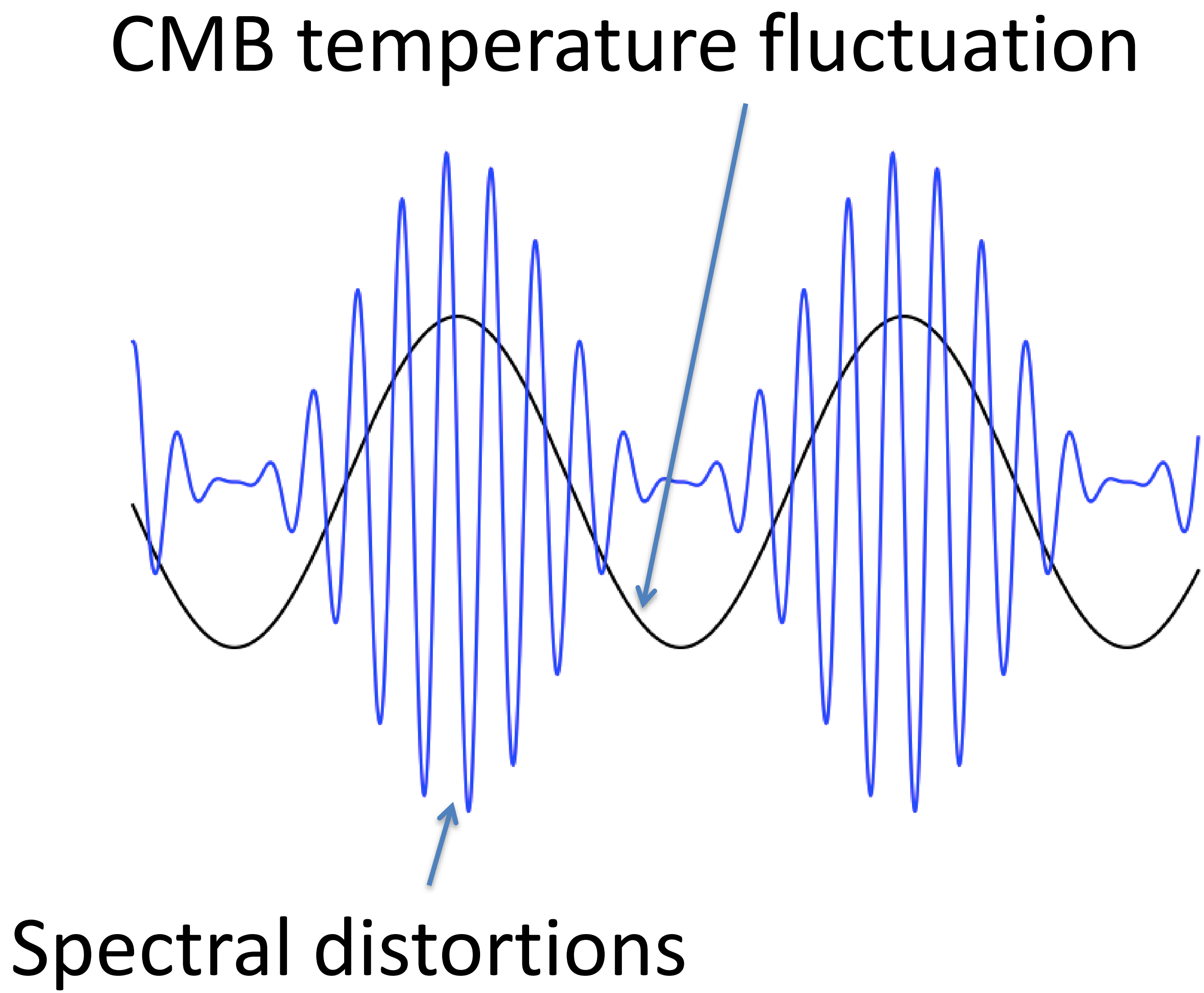
- Inflation → some small (but nonzero) departure from Gaussianity
- Couples small and long-wavelength modes



Non-gaussianity introduces more possibilities

- Inflation → some small (but nonzero) departure from gaussianity
- Couples small and long-wavelength modes of primordial perturbations

- Correlates spectral distortions to CMB temperature fluctuations (Pajer, Zaldarriaga 2012; Ganc, Komatsu, 2012; Ota et al. 2014,2015)
- Adds long-wavelength entropy perturbation (Naruko, Ota, Yamaguchi 2015) that correlates with adiabatic perturbation (Chluba et al. 2014; Emami et al. 2015)


CMB temperature fluctuation
Spectral distortions

- Mu and y distortions probe different range of k, and so can seek k-dependent non-Gaussianity (Emami, Dimastrogiovanni,Chluba, MK, 2015)
- Confusion with late-time y distortion possibly mitigated by cross-correlation with ISW (Creque-Sarbinowski, Bird, MK 2016) or with polarization (Ota 2016; Ravenni, Liguori, Bartolo, Shiraishi 2017)

- From Planck (Khatri & Sunyaev 2015)

$$\ell(\ell+1)/(2\pi)C_\ell^{\mu\mu}|_{\ell=2-26} < (2.3 \pm 1.0) \times 10^{-12}$$ an

$$\ell(\ell+1)/(2\pi)C_\ell^{\mu T}|_{\ell=2-26} < (2.6 \pm 2.6) \times 10^{-12}\ K.$$

and $f_{NL} < 10^5$

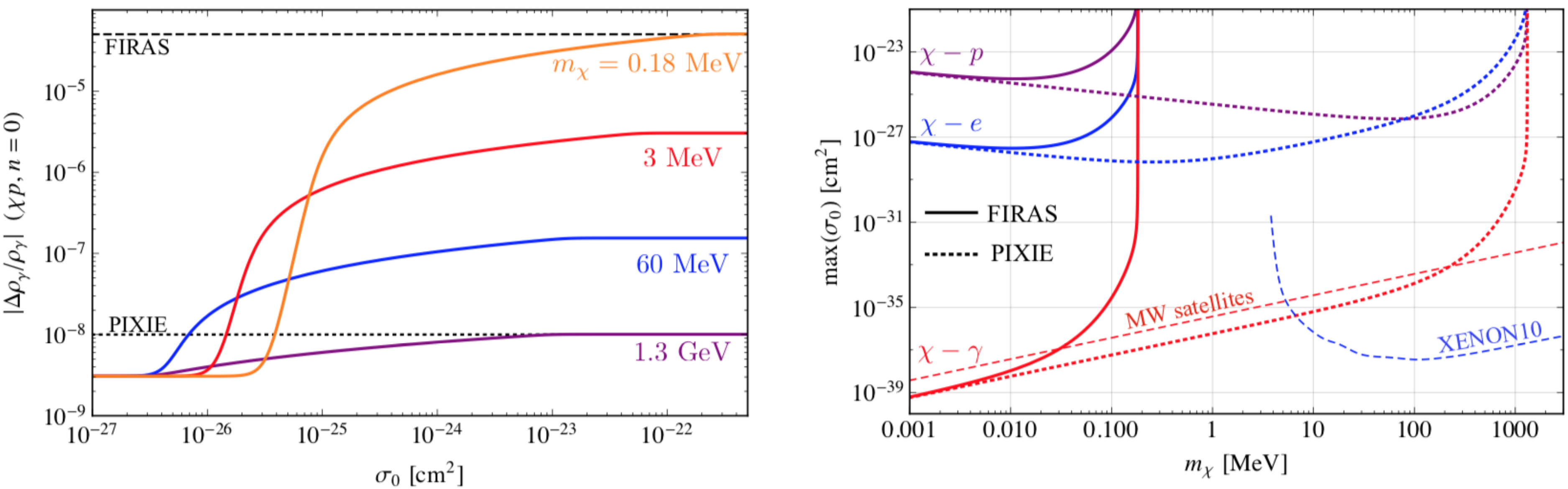
and for future experiments (Emami, Dimastrogiovanni, MK, Chluba2015),

$$f_{\rm nl}^{\mu} \simeq 220 \left(\frac{\mu_{\rm min}}{10^{-9}}\right)\left(\frac{\langle\mu\rangle}{2\times 10^{-8}}\right)^{-1}$$

Another "standard model" prediction: *Cooling* of CMB

(Standard scenario: Chluba, Sunyaev, Khitri; DM-enhanced: Ali-Haimoud, Chluba, MK 2015)

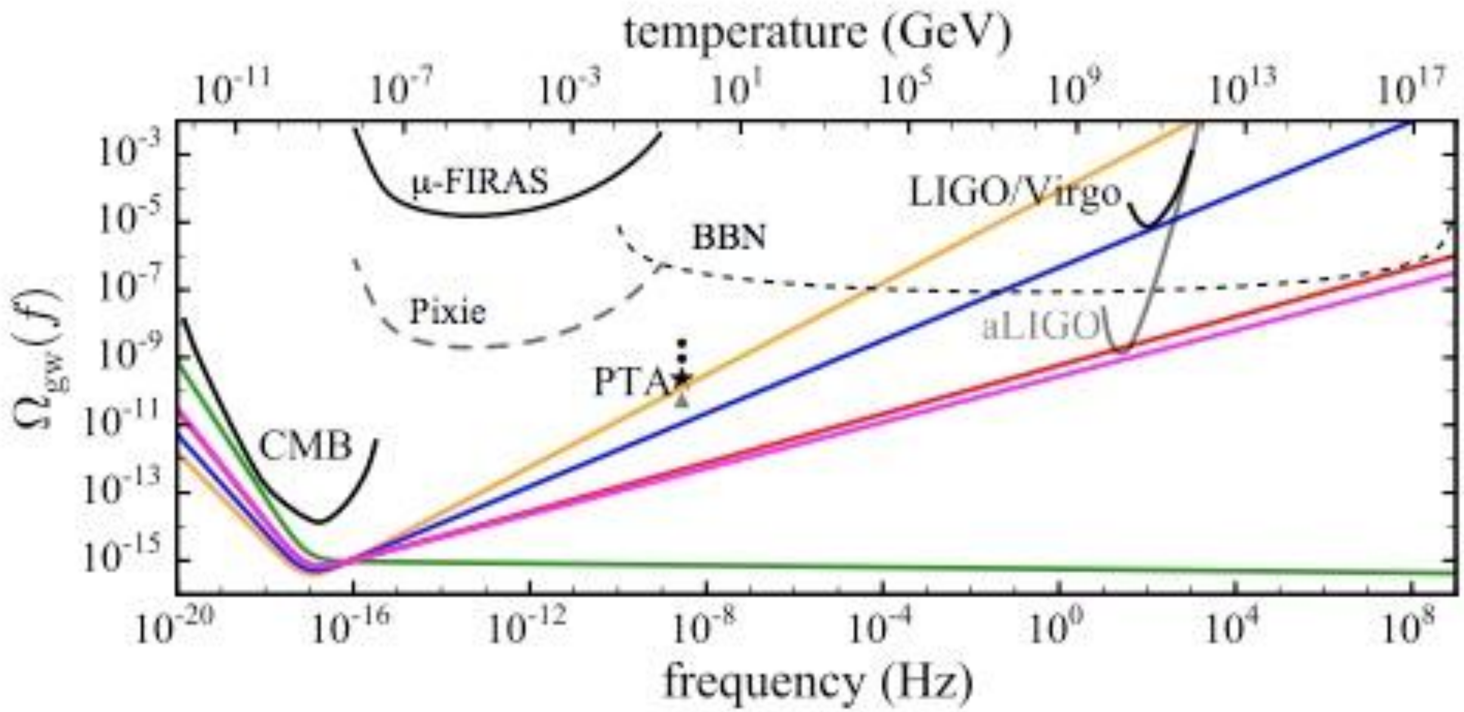
- Radiation: $T \sim a^{-1}$
- Baryons: $T \sim a^{-2}$
- Thomson scattering: heat transferred from radiation to baryons→ *negative* mu distortion (few parts per billion)
- Baryon-SM coupling: cooling enhanced by additional heat absorbed by DM


FIRAS
$m_\chi = 0.18$ MeV
3 MeV
60 MeV
PIXIE
1.3 GeV
$|\Delta\rho_\gamma/\rho_\gamma|$ $(\chi p, n=0)$
σ_0 [cm^2]
$\chi - p$
$\chi - e$
FIRAS
PIXIE
MW satellites
$\chi - \gamma$
XENON10
max(σ_0) [cm^2]
m_χ [MeV]

Early energy injection from exotic sources

- Chluba-Sunyaev thermalization
  - Primordial isocurvature
  - Detailed frequency spectrum (Katri-Sunyaev)
  - DM annihilation
  - DM decays
  - PBHs
  - Magnetic fields
  - Superconducting cosmic strings
  - Axions
  - Damping of tensor perturbations (Chluba, Dai, Grin, Amin, MK 2014)

(From Robert Caldwell….



PBHs

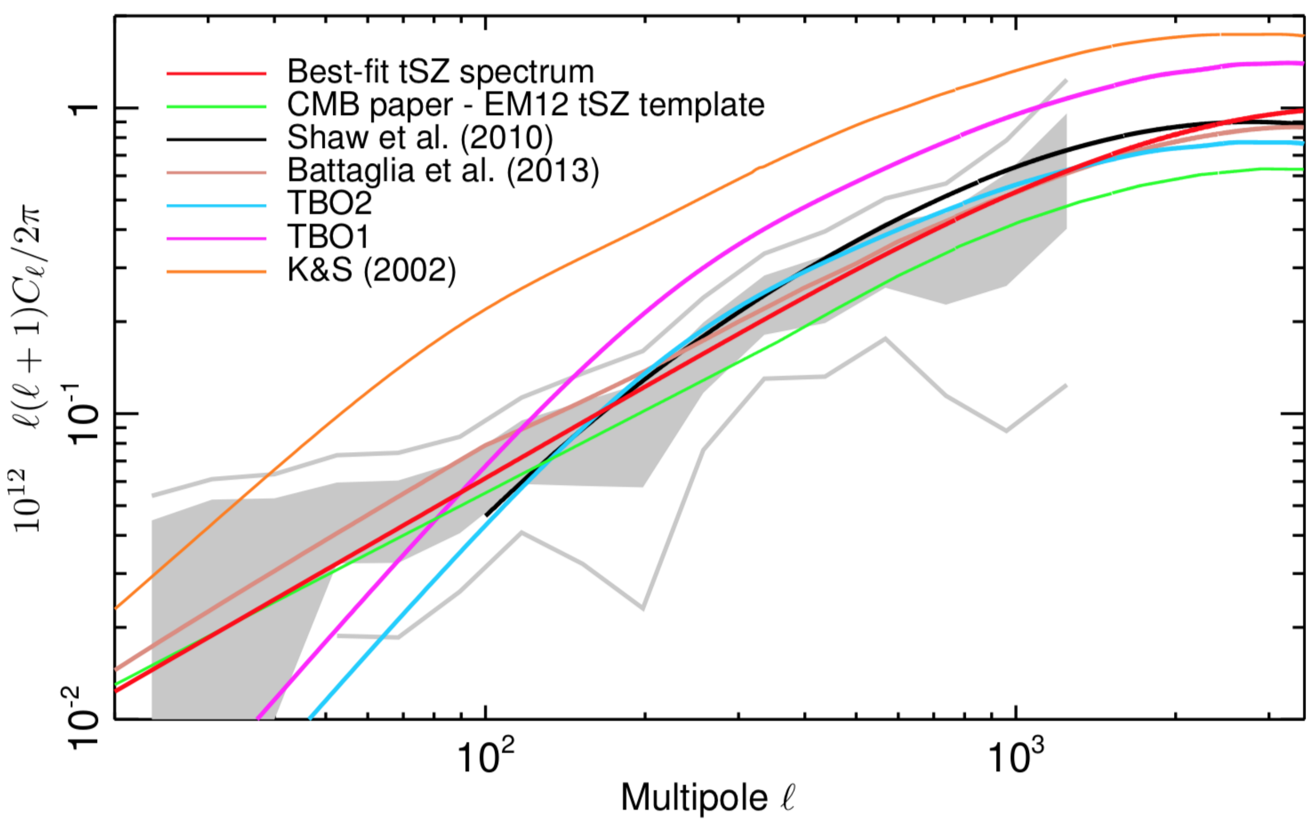
- If 30-Msun BHs make up DM, merger rate in DM halos ~ that observed by LIGO (Bird et al. 2016; Clesse & Garcia-Bellido 2016)
- Since then, numerous interesting astrophysical arguments (dynamics, lensing, diffuse backgrounds) against scenario, though none entirely caveat-free

PBHs

- Ricotti, Ostriker, Mack (2008) infer strong constraints to ~30-Msun PBH DM from FIRAS
- We find distortion detectable with PIXIE only if L~Ledd for accreting PBHs (YAH,MK 2016; also Aloni, Blum, Flauger 2017; Horowitz 2017; Poulin))
- (30-Msun PBH DM scenario faces stiff pressure from early-U binaries; YAH, Kovetz, MK 2017)

SZ fluctuations from late-Universe physics

- Have already seen SZ fluctuations from hot electrons in IGM (mostly clusters)



New-physics connection….

MNRAS **000**, 000–000 (0000) Preprint 5 December 2017 Compiled using MNRAS LaTeX style file v3.0

Dark Energy from the Thermal Sunyaev Zeldovich Power Spectrum

Boris Bolliet,[1,4] Barbara Comis,[1] Eiichiro Komatsu,[2,3] Juan Francisco Macías-Pérez[1]
[1] *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53, avenue des Martyrs, 38026 Grenoble cedex, France*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, 85748 Garching, Germany*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan*
[4] *Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, U.K.*

SZ fluctuations from late-Universe physics (Oh, Cooray, MK 2003)

- But perhaps some contribution from first stars?

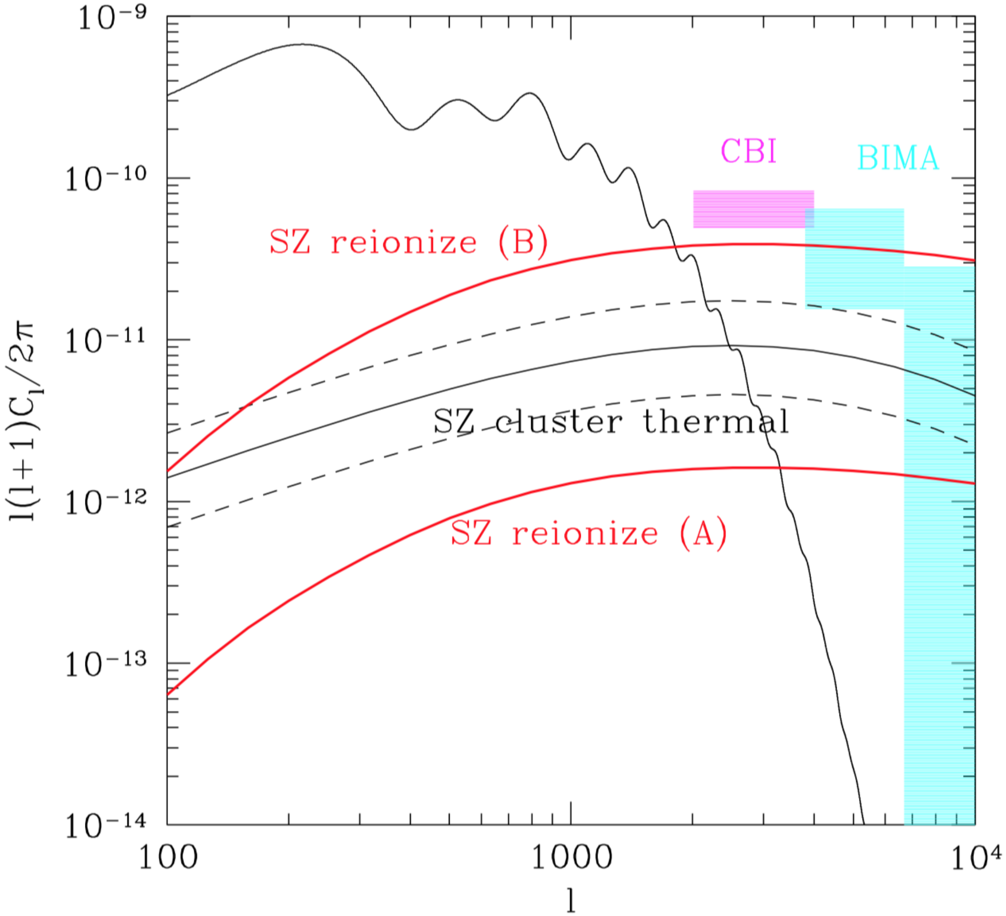
$$\rho_\gamma \propto (1+z)^4$$

SN-driven winds cool via Compton cooling at $z \gtrsim 10$

ionizing flux → Star formation → supernovae → SN-driven winds → Compton cooling → Compton-y distortion (e.g., Kamionkowski, Spergel, Sugiyama 1994)

Ionizing sources are rare → Come from highest-density peaks in primordial density field → are therefore very highly biased

→ SZ signal from first stars strongly clustered



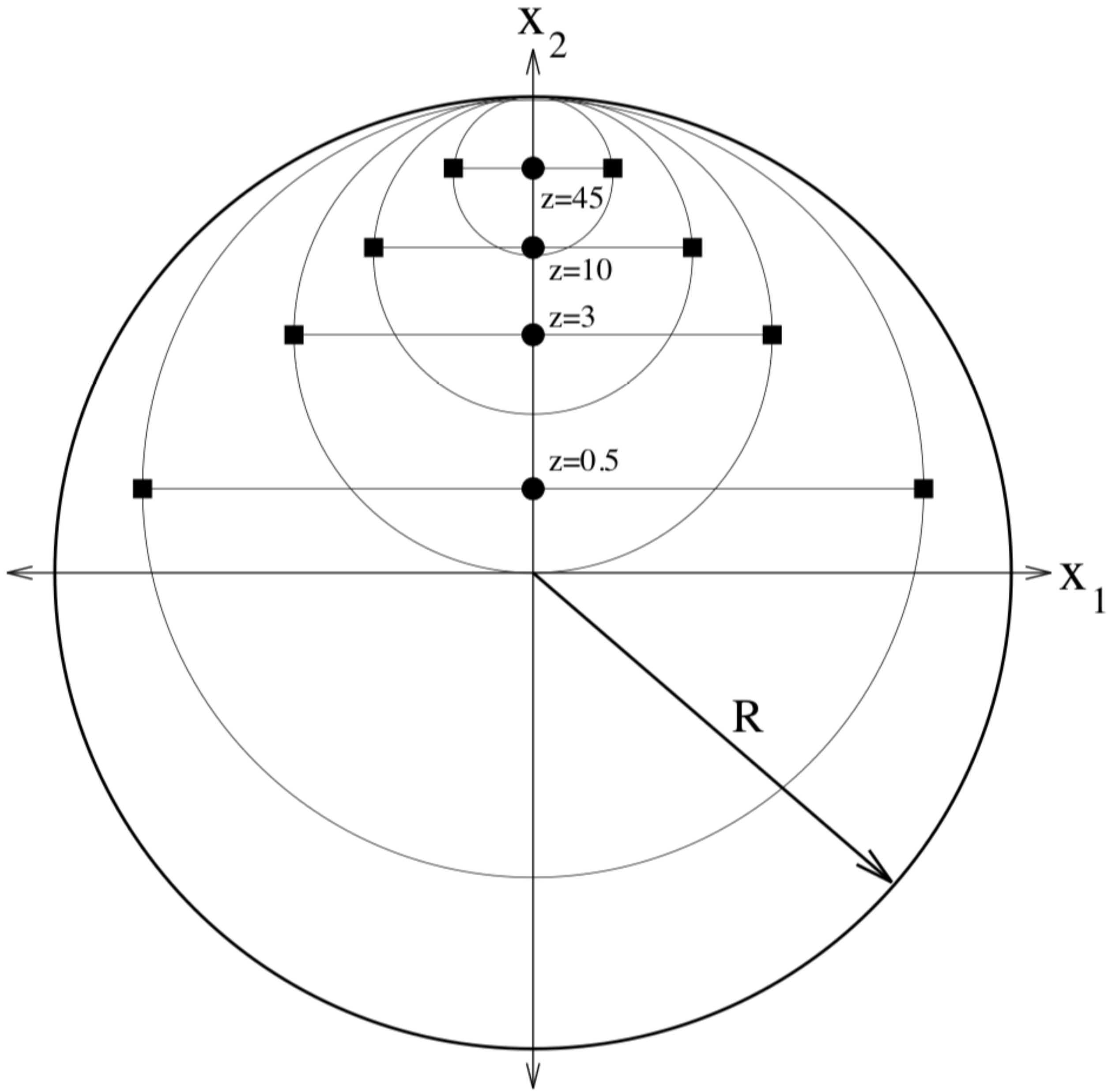
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$l(l+1)C_l/2\pi$
CBI
BIMA
SZ reionize (B)
SZ cluster thermal
SZ reionize (A)
100
1000
10^4
l

Global SZ Signal (Hill et al. 2015)

- Global SZ distortion ~ one OoM below FIRAS sensitivity and ~1000-sigma with PIXIE
- Relativistic corrections (at ~30-sigma with PIXIE) break degeneracy in Compton-y between electron temperature and density---measure T for the Universe!

Polarization and Spectral Distortions?

- Re-scattered SZ photons may have several sources of polarization (Sunyaev-Zeldovich 1980)
- E.g., by re-scattering of CMB quadrupole; allows primordial density field at z=110 to be probed over volume (rather than just surface) of Universe (Kamionkowski-Loeb 1996; Deutsch, Johnson, Munchmeyer, Terrana 2017)


x2
z=45
z=10
z=3
z=0.5
x1
R

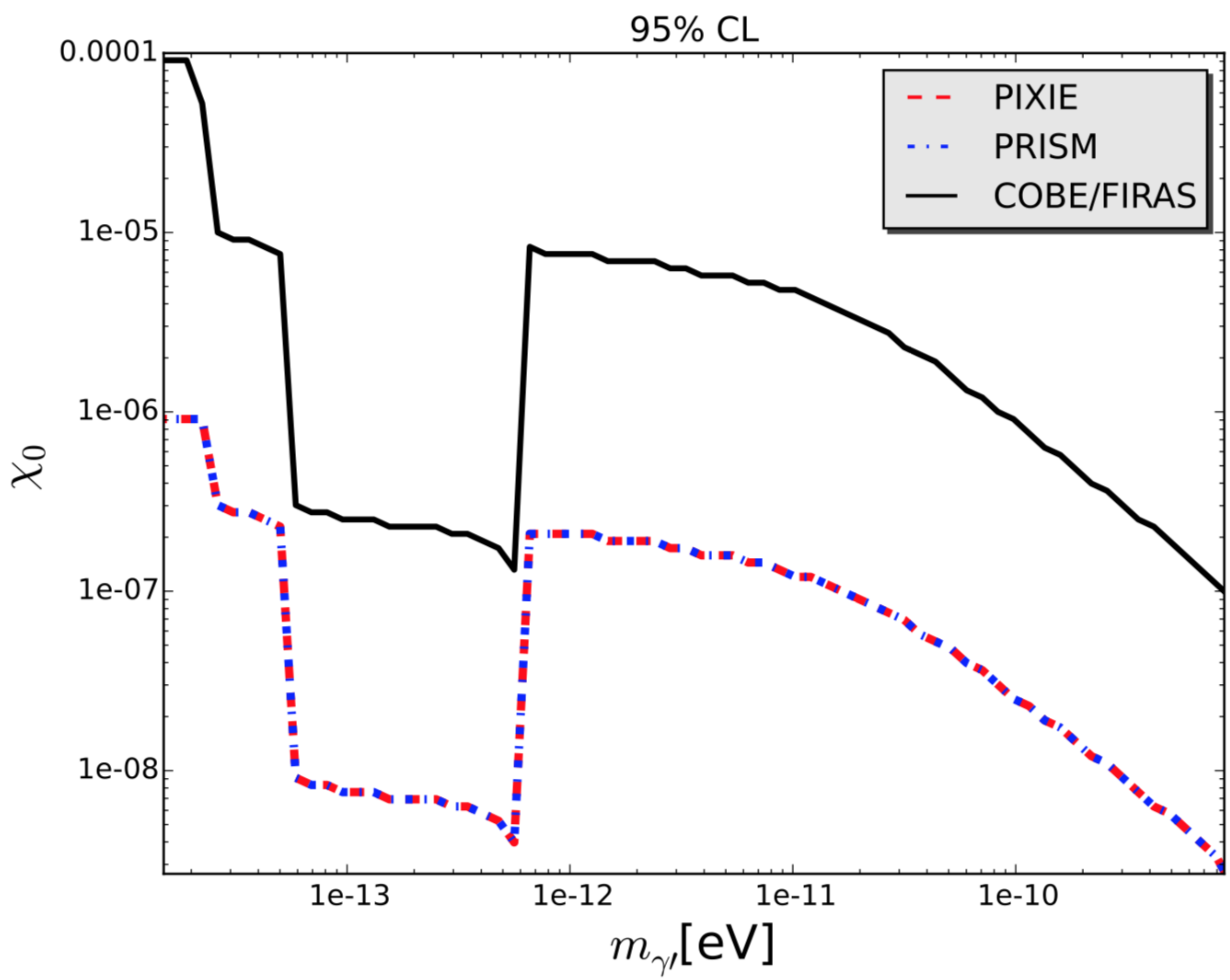
Another probe of different surfaces of last scatter

- CMB photons scattered in atomic/molecular resonances will have different angular power spectra
- E.g., by OI, OII, OIII, NII, NIII, CI, CII (e.g., Hernandez-Monteagudo, Verde & Jimenez 2006; Hernandez-Monteagudo, Rubino-Martin & Sunyaev 2007); or at higher redshift by hydrogen lines
- And Rayleigh scattering by neutral hydrogen (Lewis 2013; Yu, Spergel, Ostriker 2001)

Spectral features

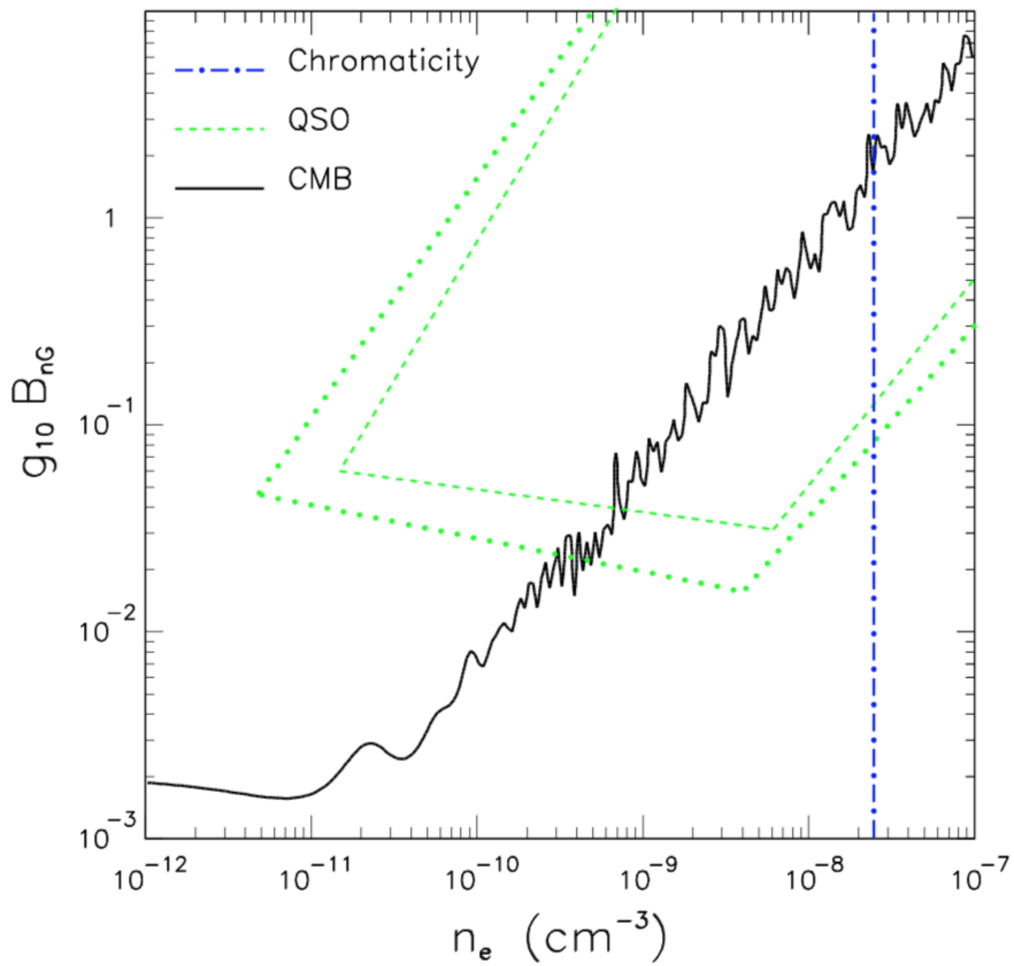
- From hydrogen/helium recombination lines before last scattering (e.g., Wong, Seager, Scott 2005; Chluba-Sunyaev 2006)
- May be possible to seek/constrain primordial metals (Ali-Haimoud, Hirata, MK 2011)?

Spectral distortions from mixing with hidden photons? (Kunze and Vazquez-Mozo



Constraints to photon-axion mixing

(Mirizzi, Raffelt, Serpico 2008)



Shopping List / To Do

- Foregrounds (e.g., Abitbol, Chluba, Hill, Johnson 2017; Remazeilles&Chluba 2018; Remazeilles, Delabrouille, Cardoso 2010; Sathyanarayana Rao, Subrahmanyan,Udaya Shankar, Chluba 2017)?
- More sophisticated frequency-space characterization (beyond mu and y) ? (Chluba & Jeong 2014; Mukherjee, Silk, Wandelt 2018)
- Complementarity with fluctuations? (e.g., Poulin, Lesgourgues, Serpico 2017)
- Build the science case
  - What *essential* science results?
  - What is the elevator pitch?