Title: Novel Measurements of Starlight from Cosmic Dawn to the Present

Date: Mar 29, 2016 11:00 AM

URL: http://pirsa.org/16030025

Abstract: <div> </div>

<div>Since the Universe was filled with hydrogen atoms at early times, the
most promising method for observing the epoch of the first stars is to
measure the hyperfine line of hydrogen at a wavelength of 21 cm. Such
an observation of the "cosmic dawn" era was considered speculative
when I helped lay out the theoretical predictions a decade ago, but
there is now an enormous, promising observational effort (in which I
am involved within the Square Kilometre Array). There is also an
important aspect of early cosmic history that can potentially be
probed today. The difference between the early evolution of the
baryons and the dark matter should imprint a specific signature that
can be probed via galaxy surveys. We have recently attempted the first
such measurement; detecting this would provide a novel confirmation of
the standard cosmological model.</div>

NOVEL MEASUREMENTS OF STARLIGHT FROM COSMIC DAWN TO THE PRESENT

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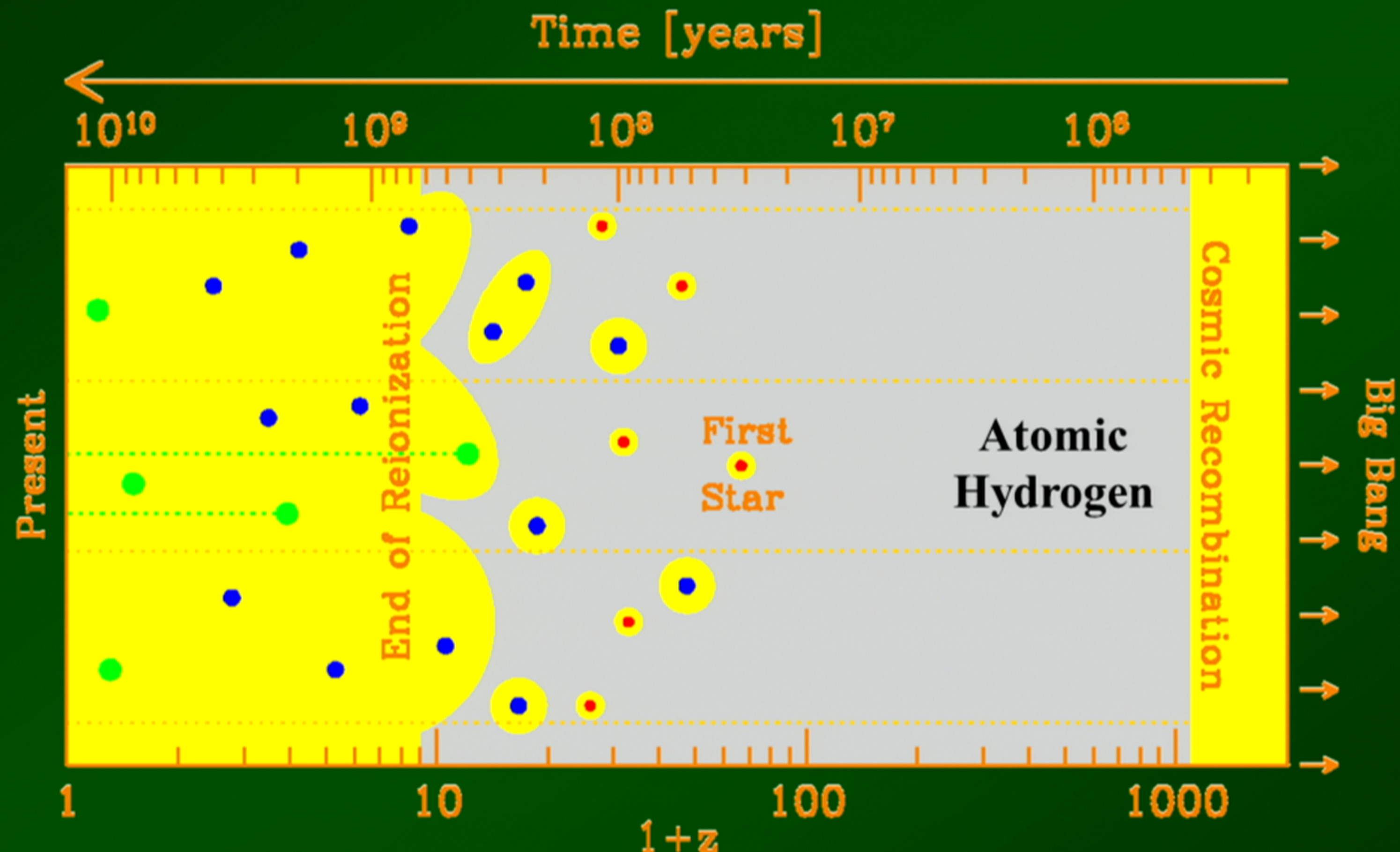
UNIVERSITY OF OXFORD

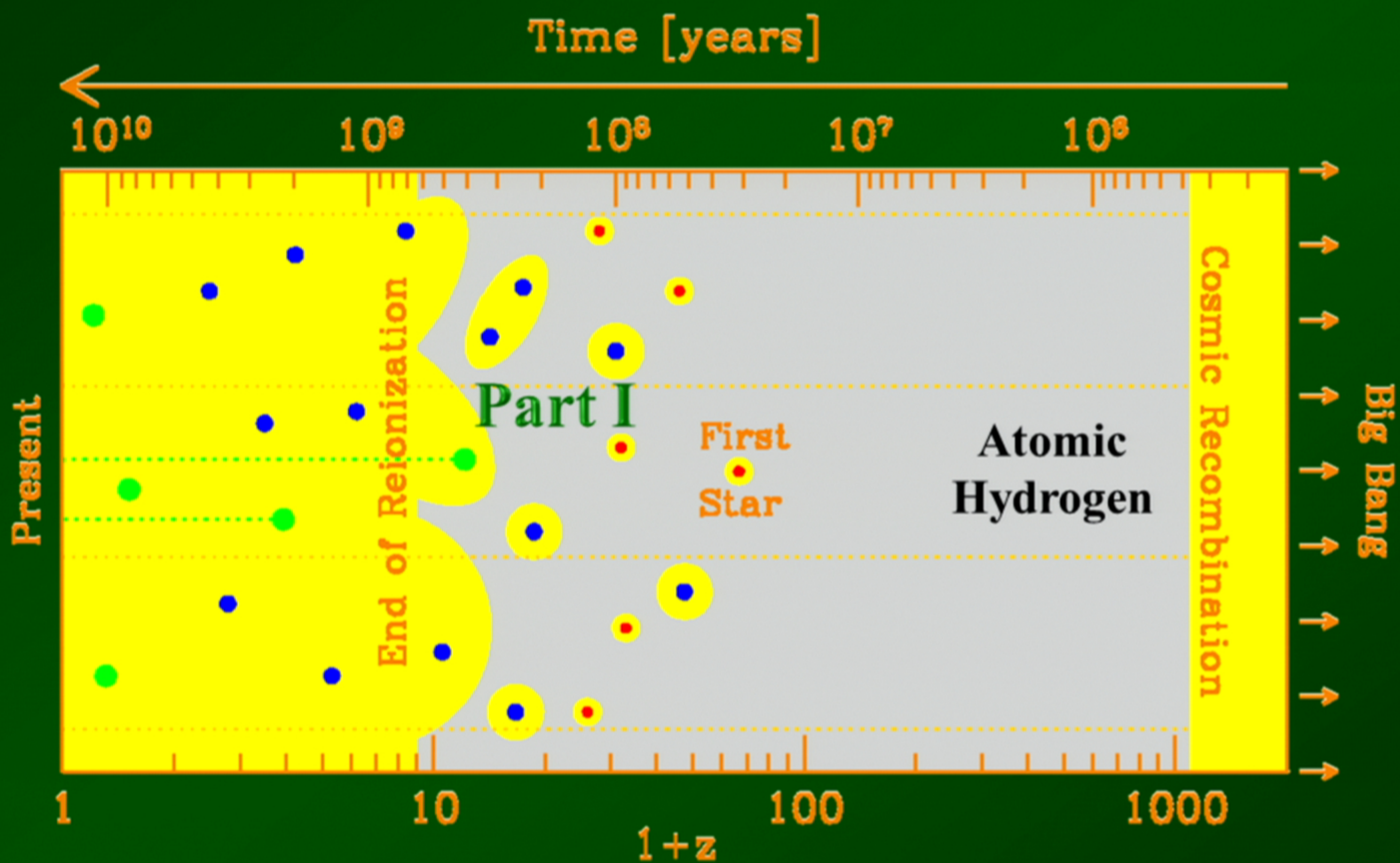
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Cosmic History



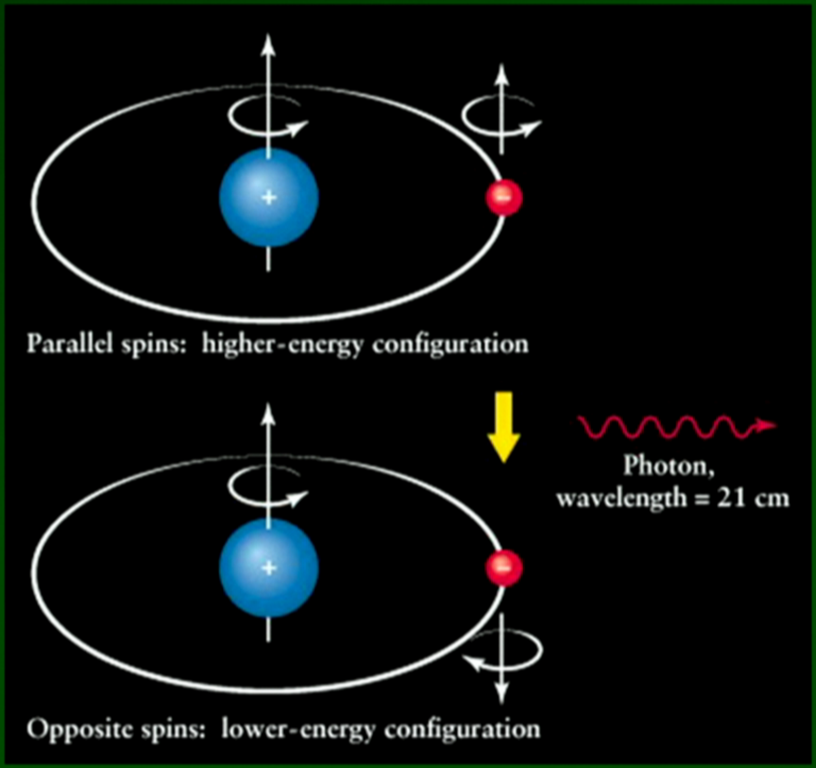
RB 2006, Science

Cosmic History



RB 2006, Science

21-cm Cosmology: The Spin Temperature



$$\lambda = 21\,\mathrm{cm}$$

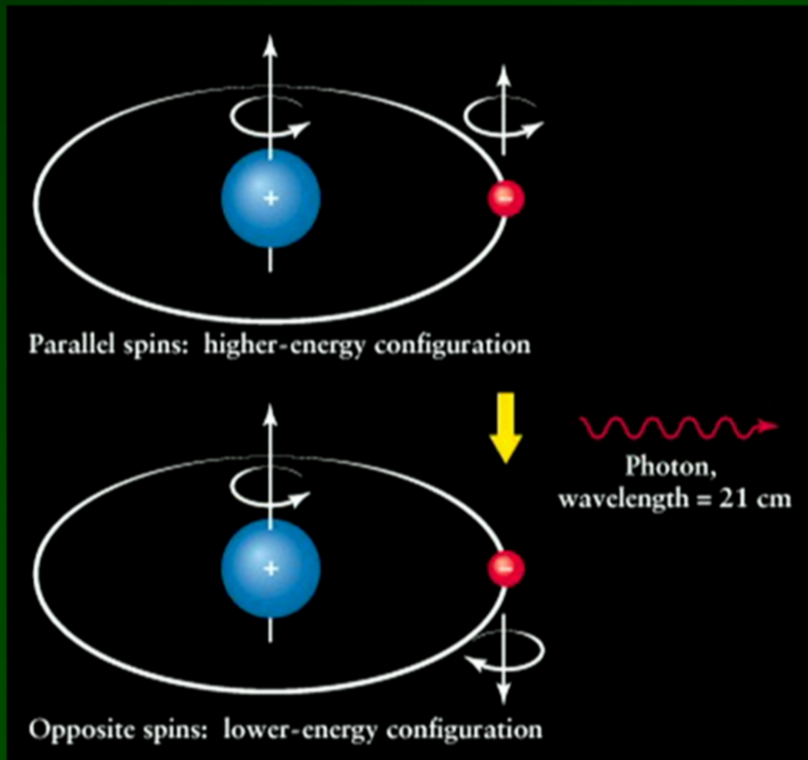
$$\nu = 1420\,\mathrm{MHz}$$

$$E = 5.9 \times 10^{-6}\,\mathrm{eV}$$

$$\frac{E}{k_B} = T_* = 0.068\,\mathrm{K}$$

$$\frac{n_1}{n_0} = 3\exp\left\{-\frac{T_*}{T_S}\right\}$$

21-cm Cosmology: The Spin Temperature



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Ancient History

Reionization:

Gunn & Peterson 1965

……

21-cm Cosmology:

Hogan & Rees 1979: Basic Ideas (ρ, T, T_s)
Scott & Rees 1990: CDM + reionization

Madau, Meiksin & Rees 1997: Pre-reionization

Ancient History

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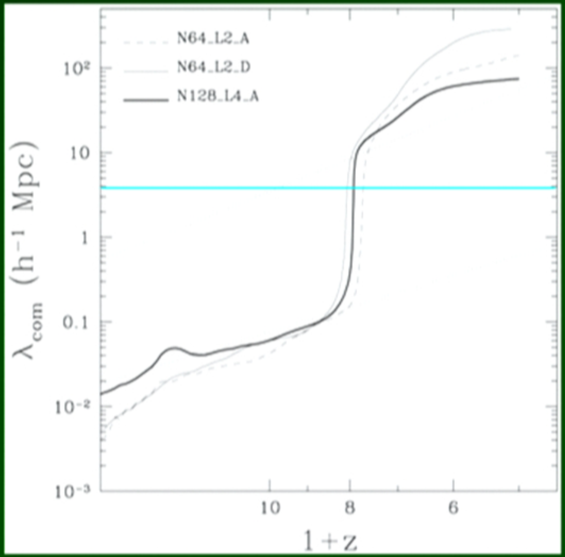
RB & Loeb 2001 In the Beginning: the First Sources of Light and the Reionization of the Universe 3/114

2004

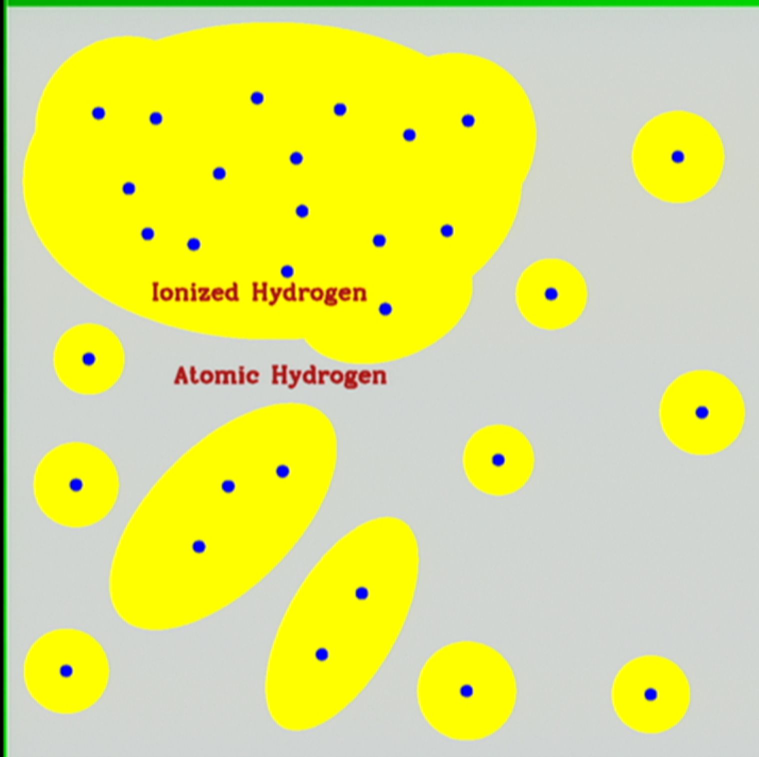
Gnedin 2000
6 Mpc



Santos, Cooray, Haiman, Knox & Ma 2003: CMB & reionization (kSZ)

$R_p \sim 100$ kpc

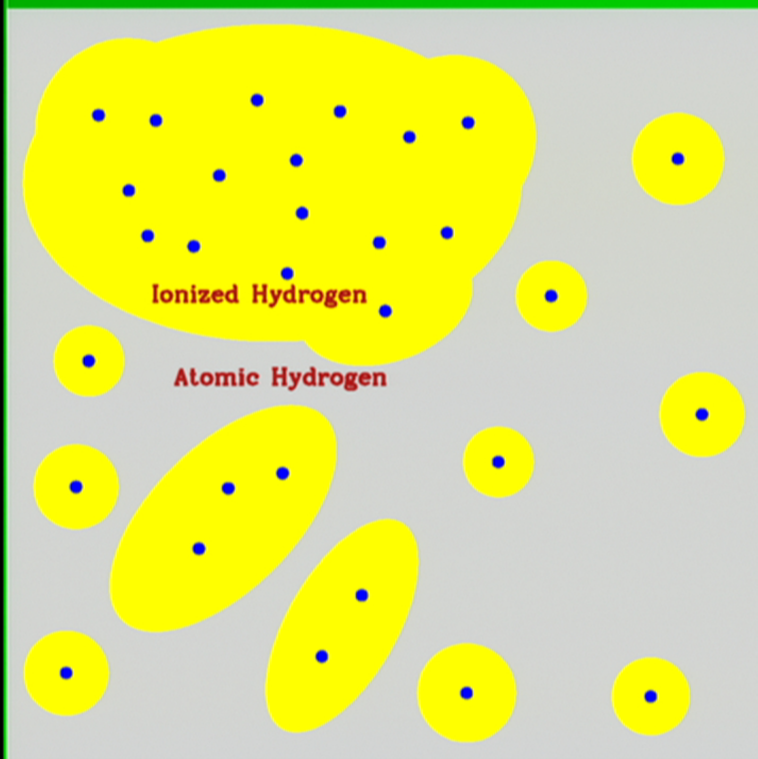
Cosmic Reionization



RB & Loeb 2004

"overdense regions… reionize first"

Cosmic Reionization



RB & Loeb 2004

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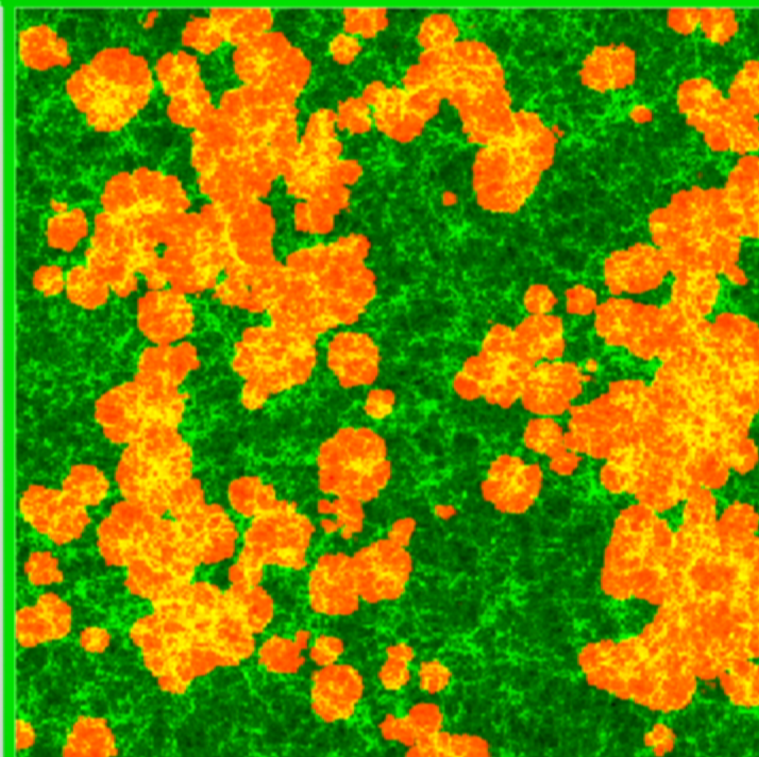
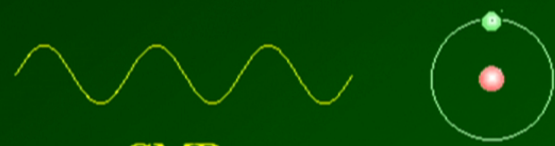


← 100/h Mpc = 0.5° →

Mellema et al. 2006

Furlanetto, Zaldariagga, Hernquist 2004

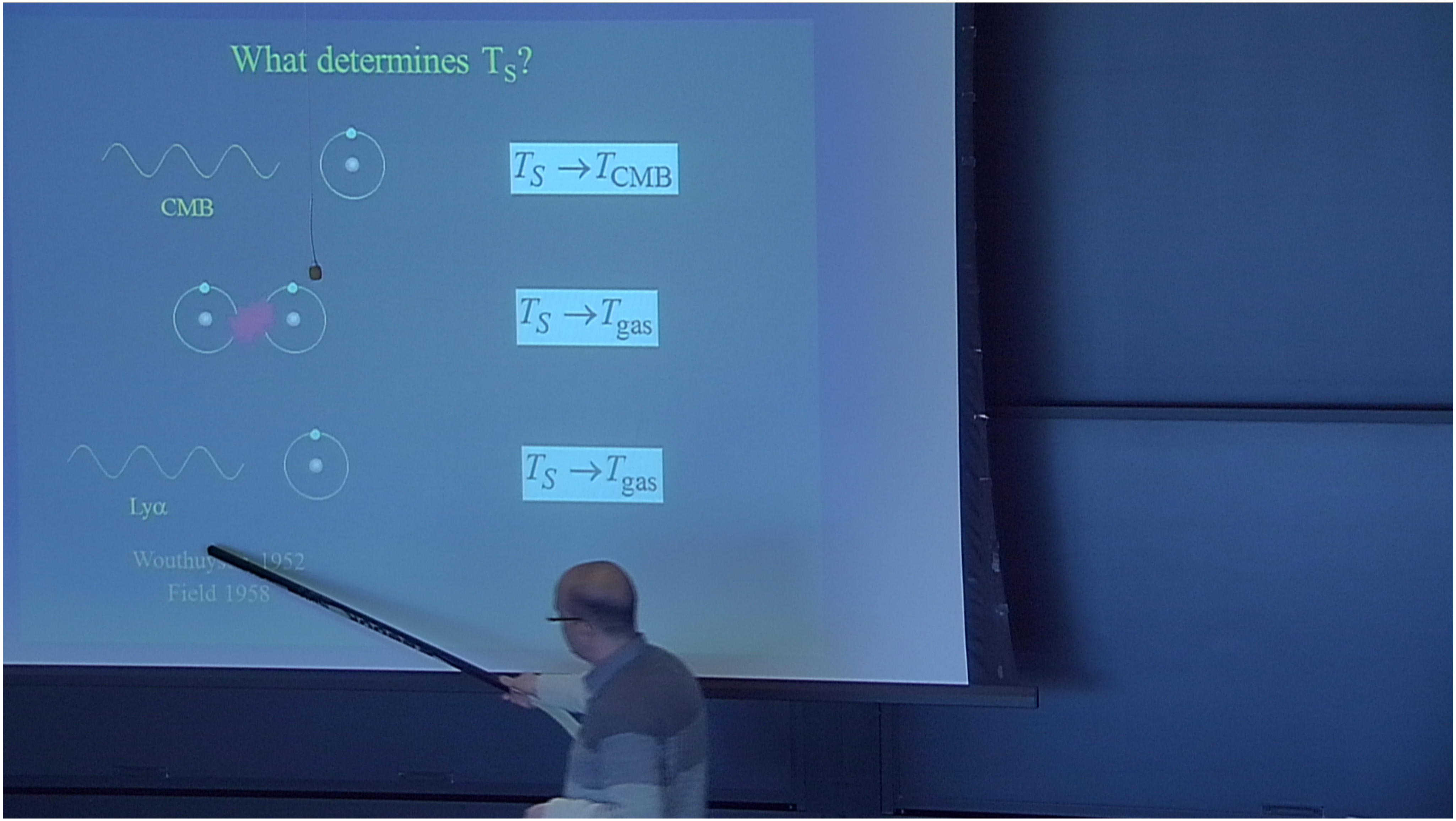
What determines T_S?



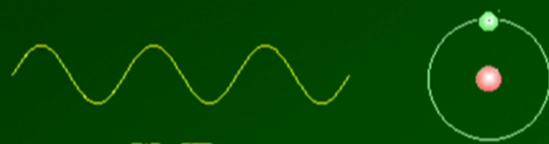
CMB

$$T_S \rightarrow T_{\text{CMB}}$$

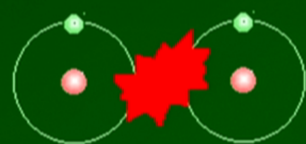
$$T_S \rightarrow T_{\text{gas}}$$


What determines T_S?
CMB
$T_S \rightarrow T_{CMB}$
$T_S \rightarrow T_{gas}$
Lyα
$T_S \rightarrow T_{gas}$
Wouthuys 1952
Field 1958

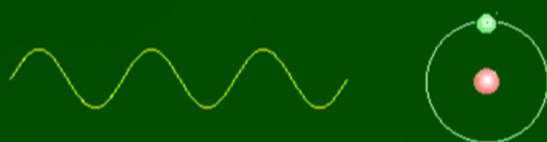
What determines T_S?



$$T_S \rightarrow T_{\mathrm{CMB}}$$



$$T_S \rightarrow T_{\mathrm{gas}}$$



$$T_S \rightarrow T_{\mathrm{gas}}$$

Wouthuysen 1952
Field 1958

Beyond Reionization: Cosmic Dawn

Madau, Meiksin &
Rees 1997:
Lyman-α (stars) and
X-ray heating (XRBs)
=>Uniform<=

Beyond Reionization: Cosmic Dawn

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Lyman-α (stars) and
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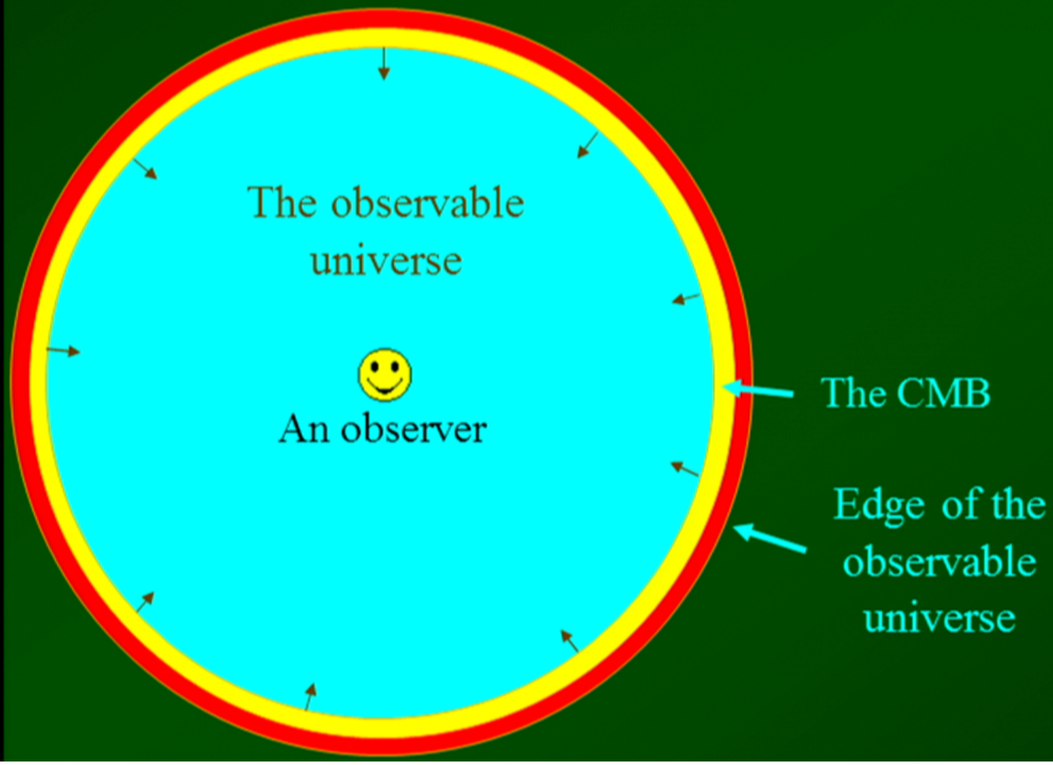
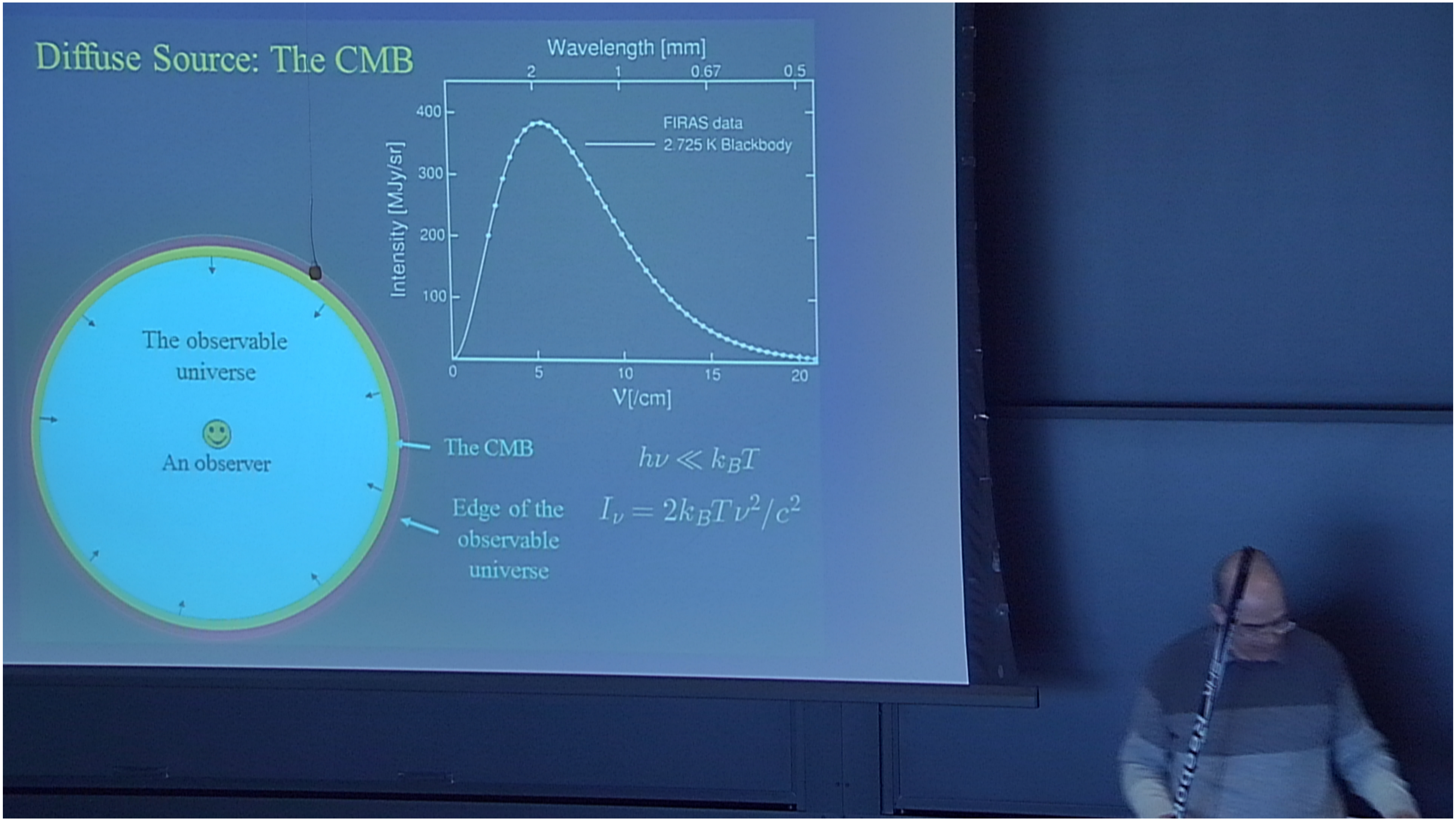
=>Uniform<=

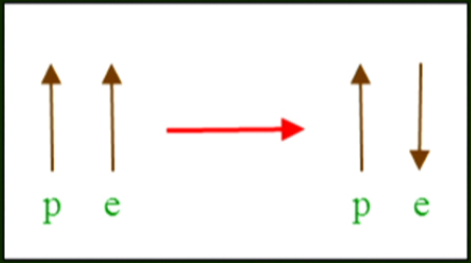
RB & Loeb 2005:
Ly-α fluctuations: z~20-30

Diffuse Source: The CMB

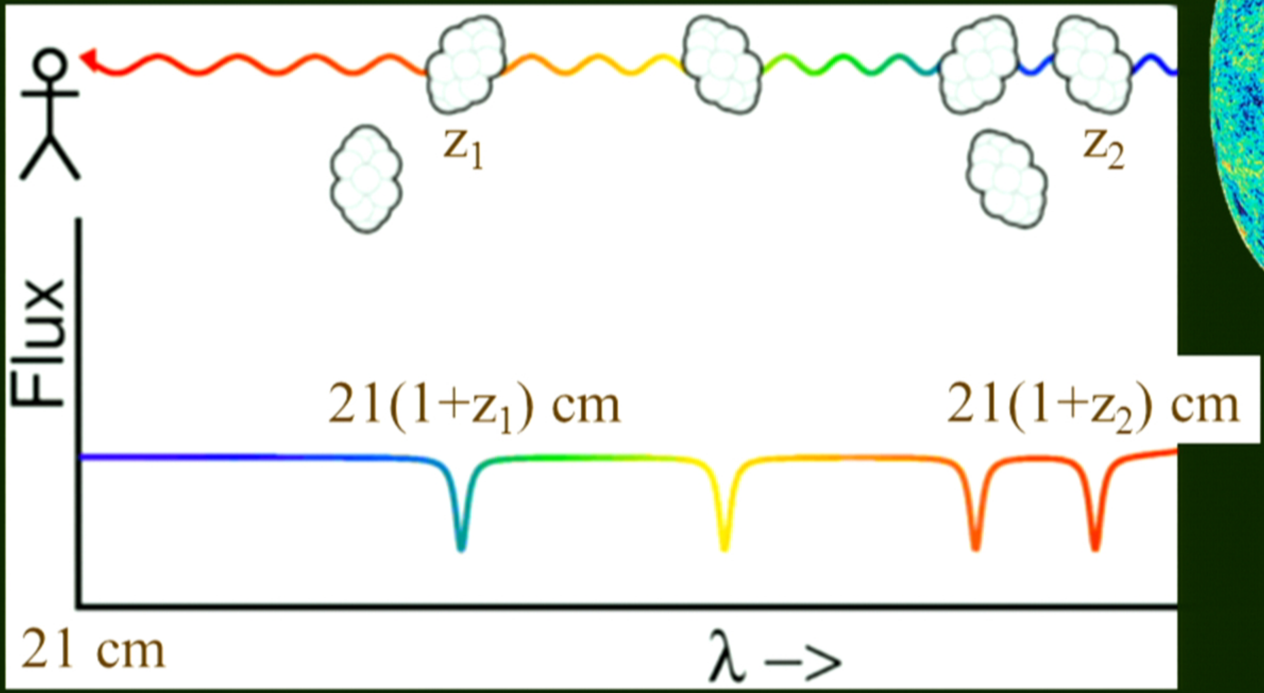


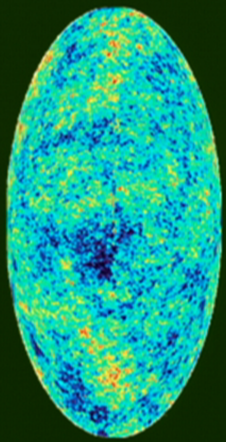

Diffuse Source: The CMB
Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
Intensity [MJy/sr]
FIRAS data
2.725 K Blackbody
0
5
10
15
20
ν[/cm]
The observable universe
An observer
The CMB
Edge of the observable universe
$h\nu \ll k_B T$
$I_\nu = 2k_B T \nu^2/c^2$

21-cm Spectra

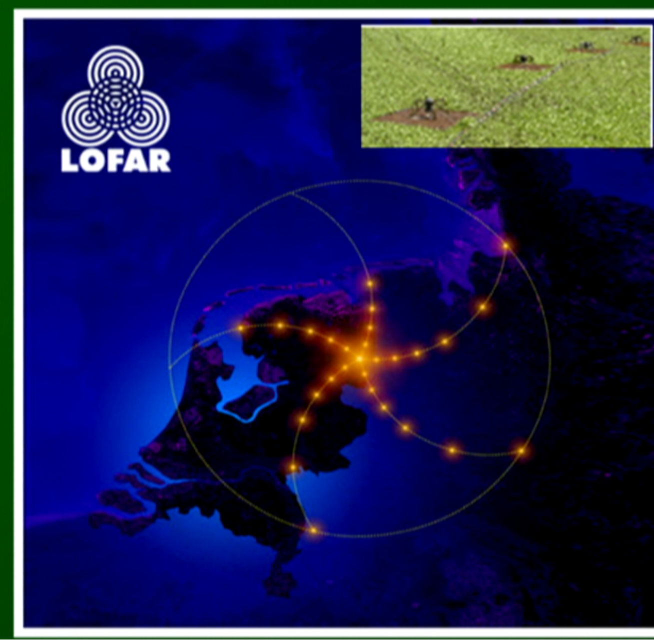


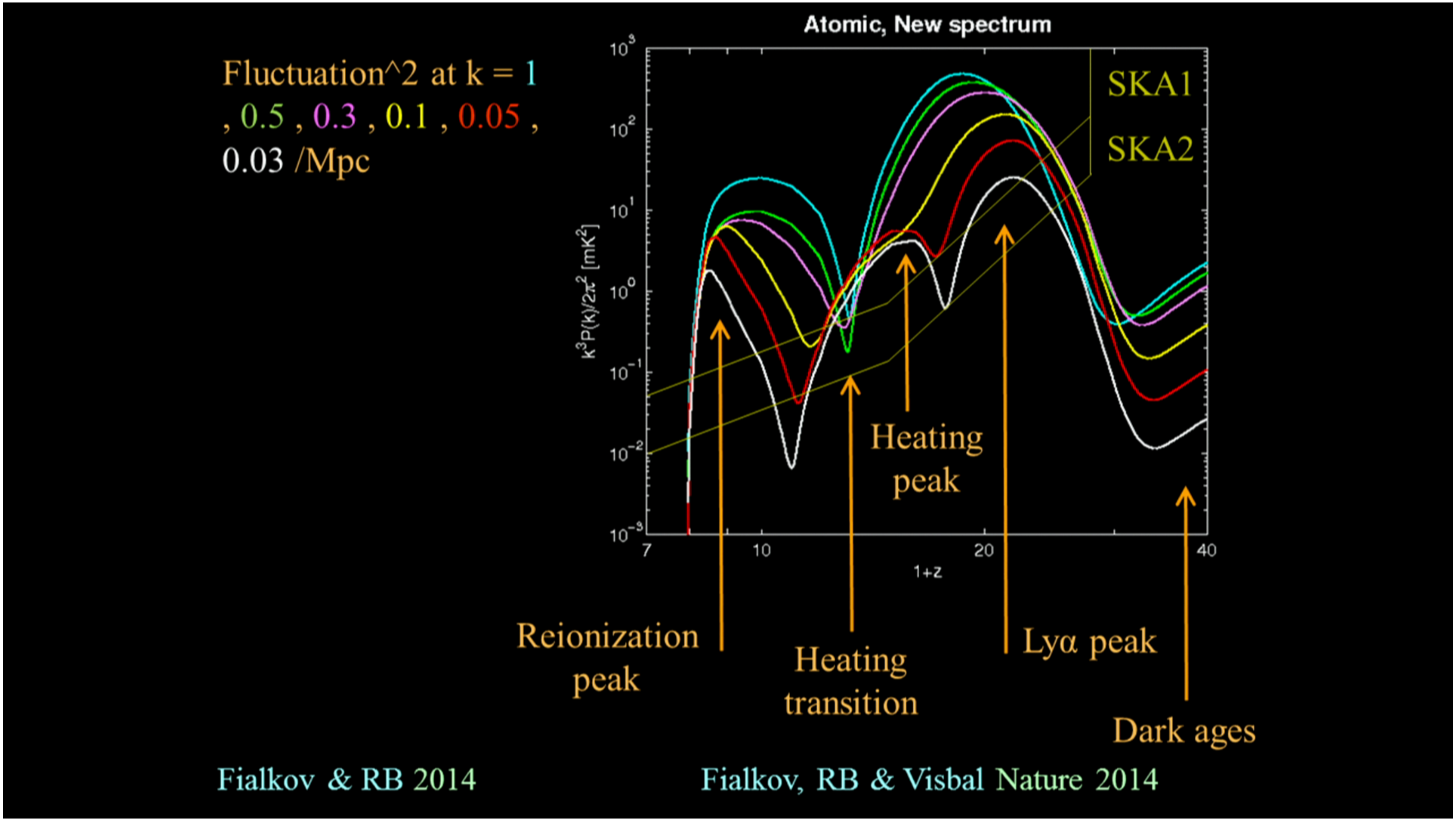
Resonance Line +
Cosmological Redshift



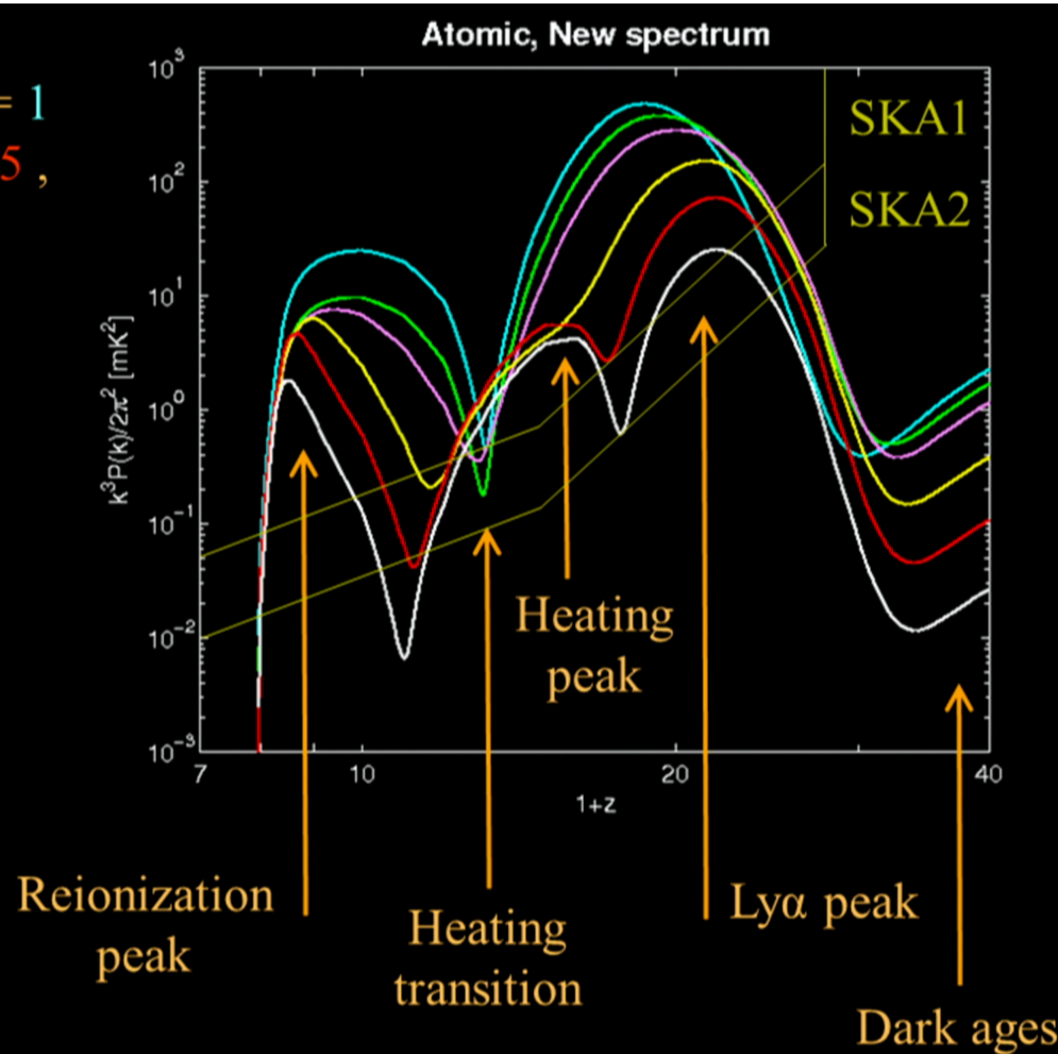


Experiments




Fluctuation^2 at k = 1
, 0.5 , 0.3 , 0.1 , 0.05 ,
0.03 /Mpc
Atomic, New spectrum
SKA1
SKA2
k^3P(k)/2π^2 [mK^2]
1+z
Heating peak
Reionization peak
Heating transition
Lyα peak
Dark ages
Fialkov & RB 2014
Fialkov, RB & Visbal Nature 2014

Fluctuation^2 at k = 1 , 0.5 , 0.3 , 0.1 , 0.05 , 0.03 /Mpc



Fialkov & RB 2014

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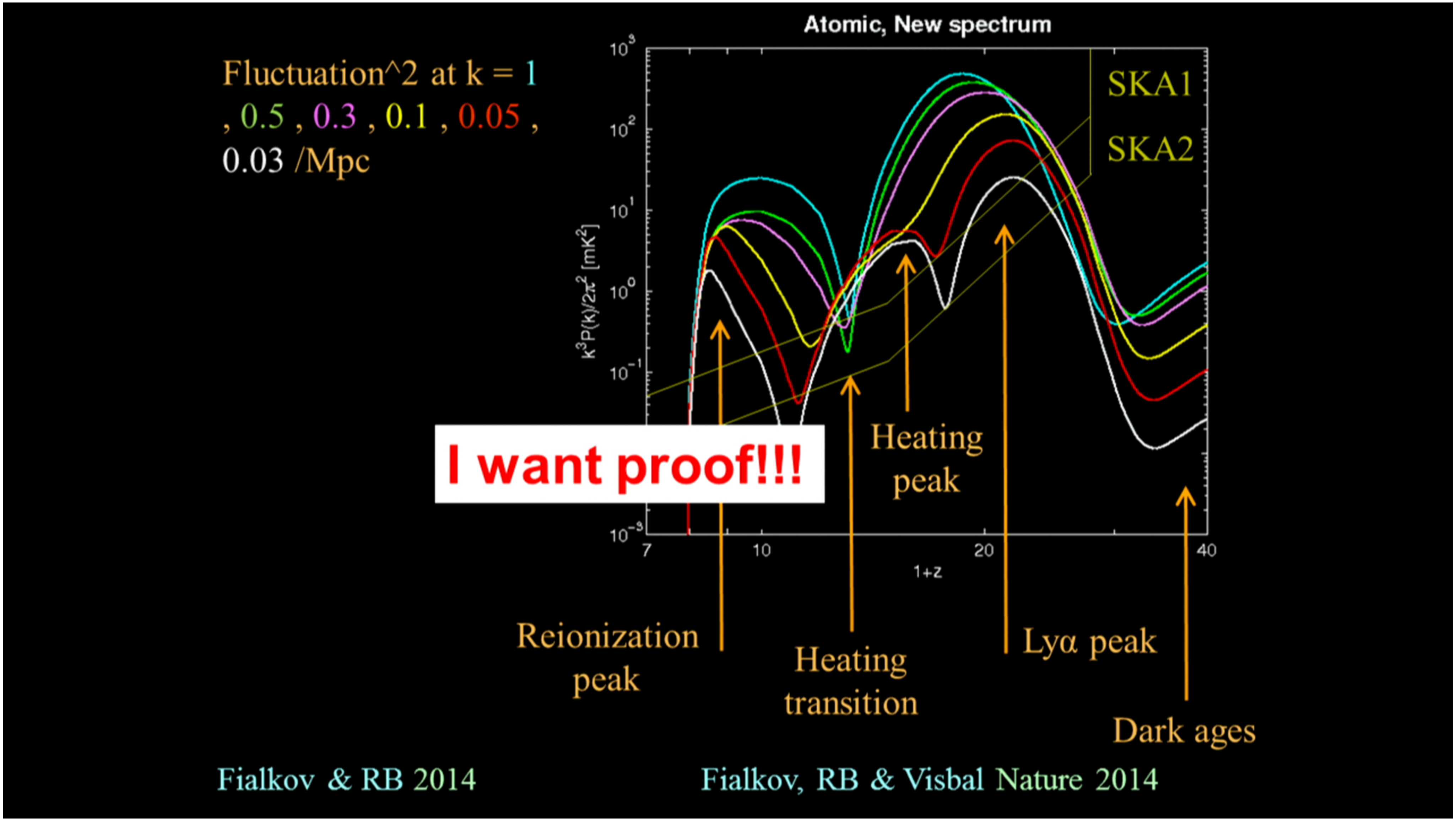
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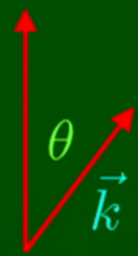
I want proof!!!
Fialkov & RB 2014
Fialkov, RB & Visbal Nature 2014

Model-independent signatures: Redshift-space distortions

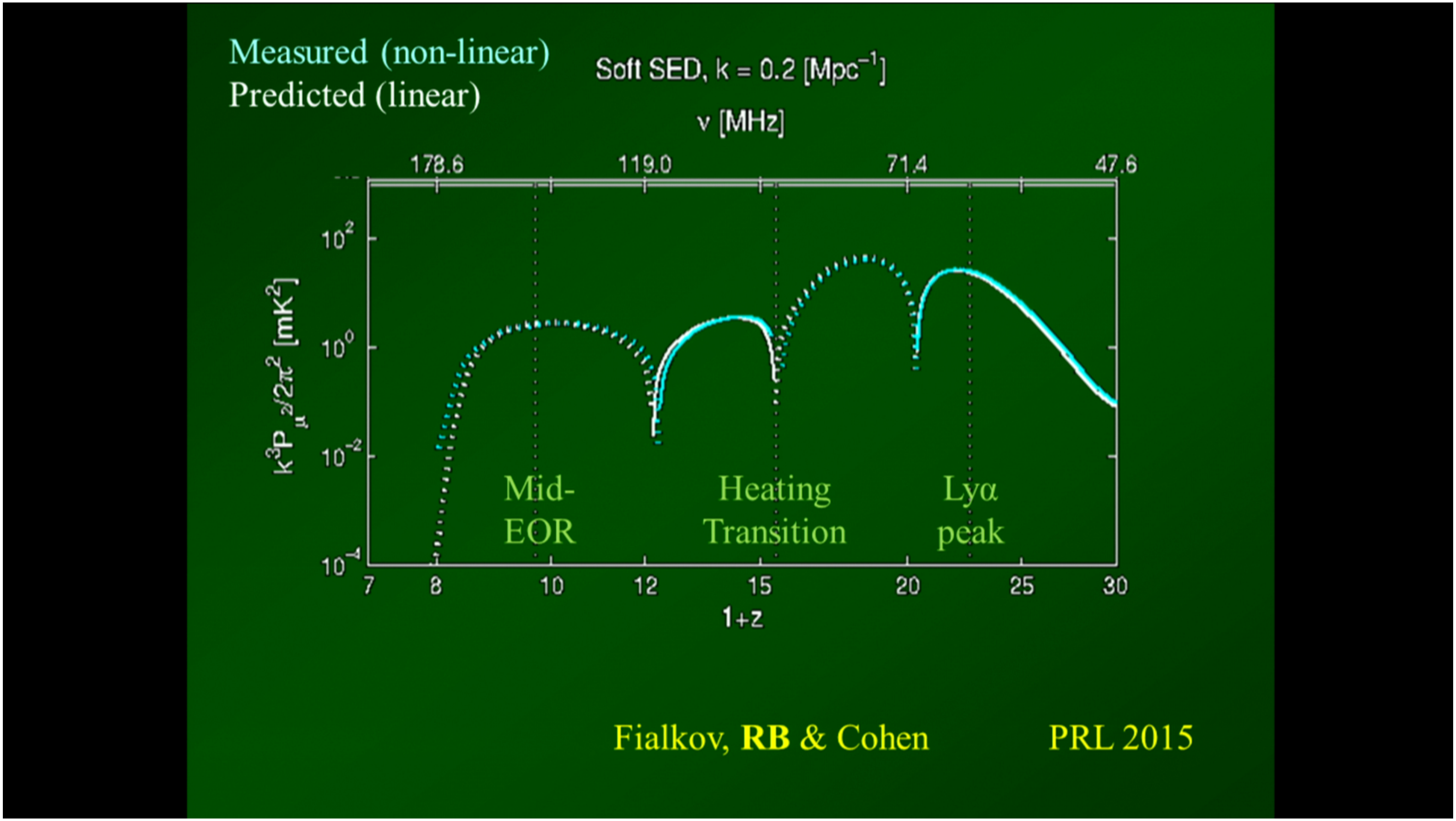
Sobolev 1960
Kaiser 1987
Bharadwaj & Ali 2004

Anisotropy: $\mu=\cos(\theta)$



$$P_{\rm iso}(k) \;\; => \;\; \mu^4 P_\delta(k) + 2\mu^2 P_{\delta-{\rm iso}}(k) + P_{\rm iso}(k)$$

RB & Loeb 2005


Measured (non-linear)
Predicted (linear)
Soft SED, k = 0.2 [Mpc^-1]
ν [MHz]
178.6
119.0
71.4
47.6
$k^3 P_{\mu^2}/2\pi^2$ [mK²]
10^2
10^0
10^-2
10^-4
Mid-
EOR
Heating
Transition
Lyα
peak
7
8
10
12
15
20
25
30
1+z
Fialkov, RB & Cohen
PRL 2015

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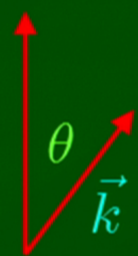

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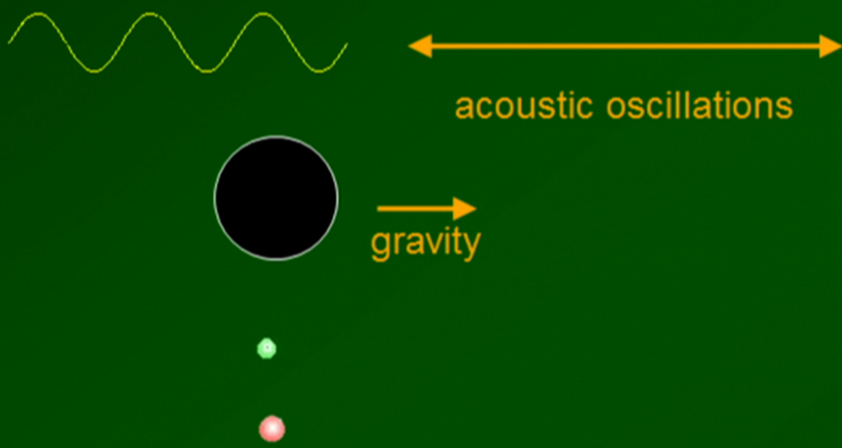
RB & Loeb 2005

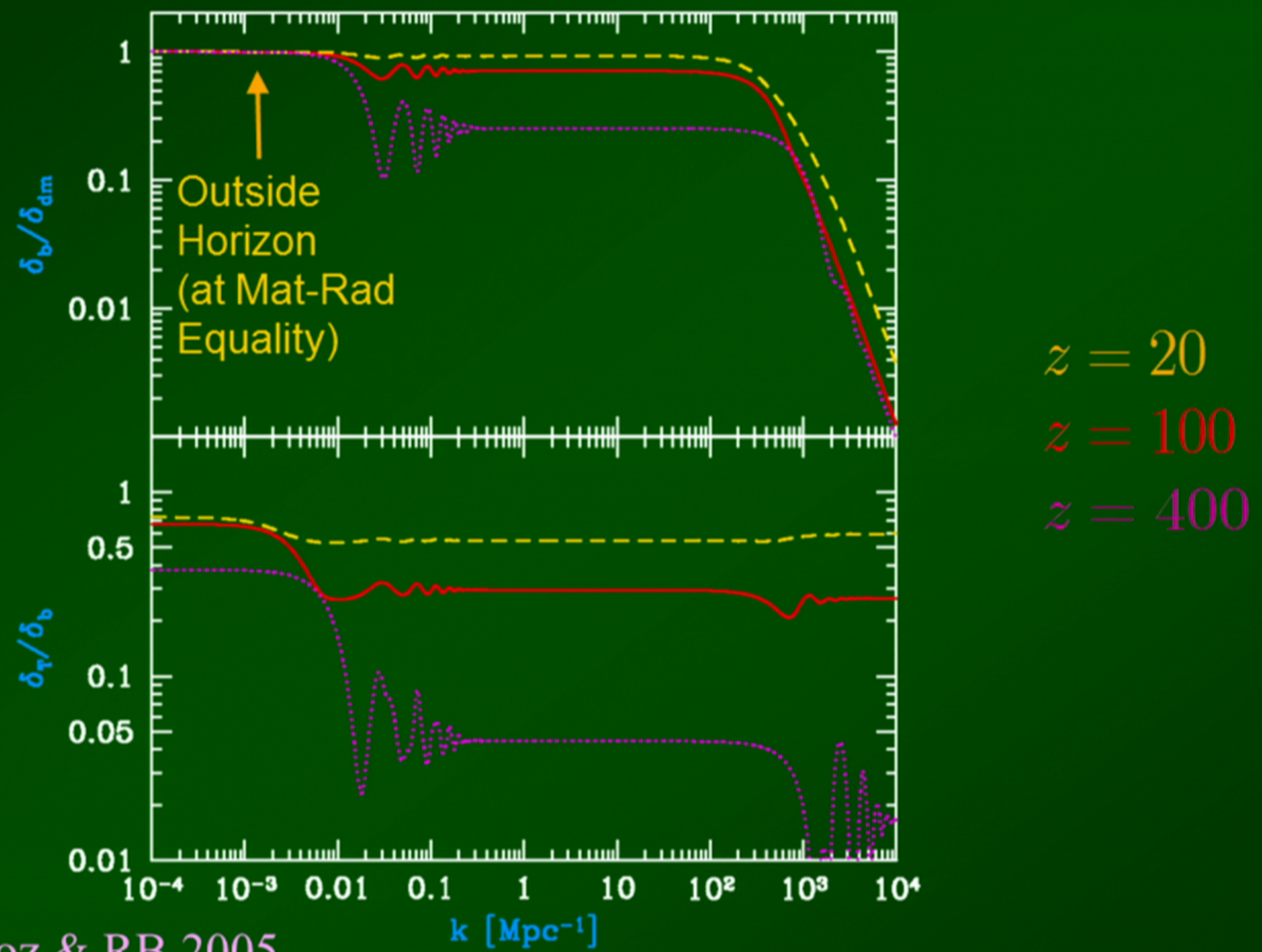
Do Baryons Follow Dark Matter?

No

Cosmic Recombination



Perturbation Ratios



Naoz & RB 2005

Varying gas fraction in galaxies

Mon. Not. R. Astron. Soc. **415,** 3113–3118 (2011) doi:10.1111/j.1365-2966.2011.18922.x

Scale-dependent bias of galaxies from baryonic acoustic oscillations

Rennan Barkana[1★] and Abraham Loeb[2★]

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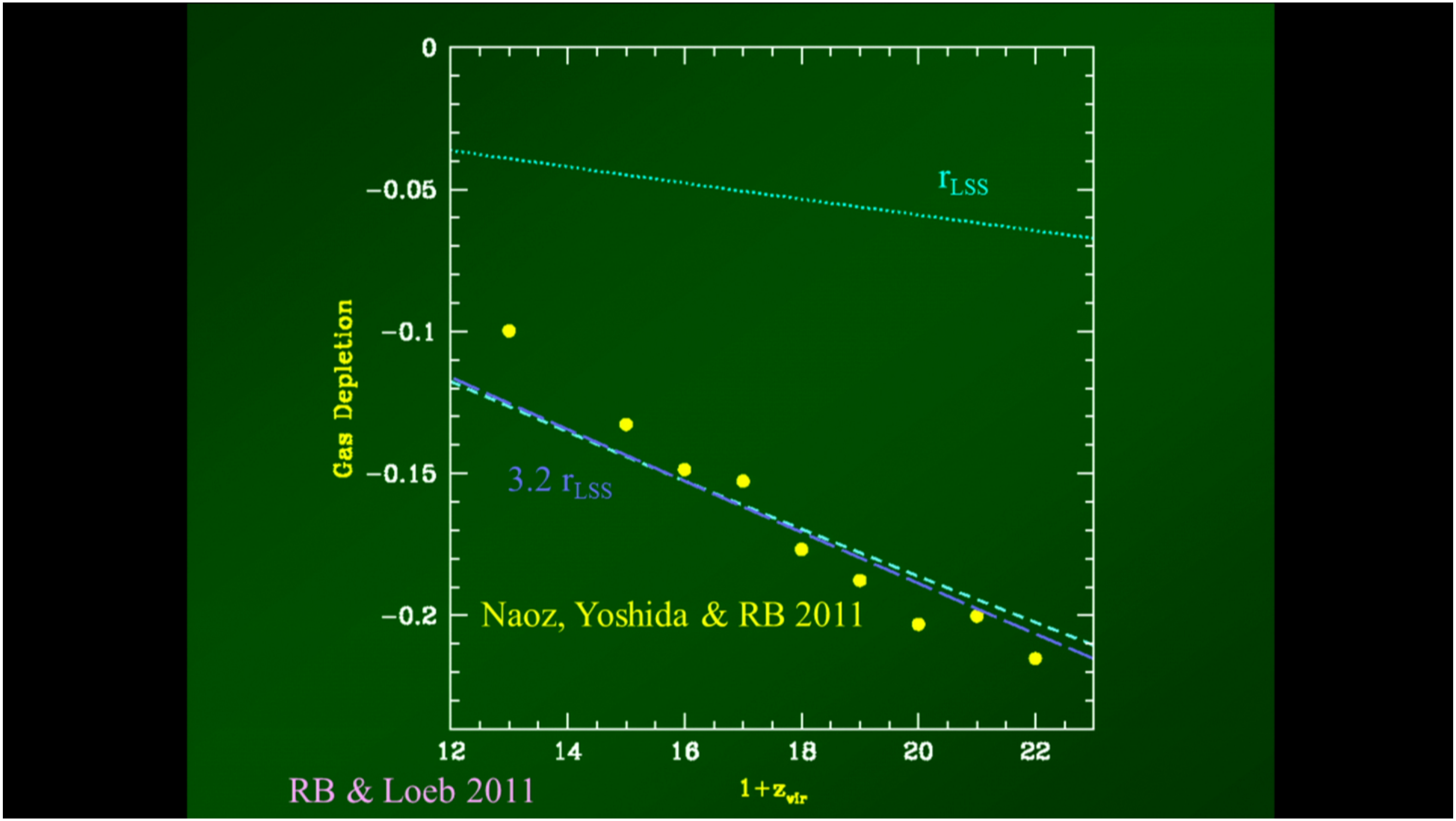
Scale-dependent bias of galaxies from baryonic acoustic oscillations

Rennan Barkana[1★] and Abraham Loeb[2★]

Gas/DM ratio varies.
More gas in a region =>
More gas in its galactic halos =>
More stars =>
Lower M/L ratio



0
−0.05
−0.1
−0.15
−0.2
Gas Depletion
r_{LSS}
3.2 r_{LSS}
Naoz, Yoshida & RB 2011
12
14
16
18
20
22
$1+z_{vir}$
RB & Loeb 2011

Basically:

$$\delta_n = b_n \, \delta_{tot}$$
$$\delta_L = b_L \, \delta_{tot} + b_{L,\Delta}[r(k) - r_{LSS}] \, \delta_{tot}$$

RB & Loeb 2011

Large scale distribution of total mass versus luminous matter from Baryon Acoustic Oscillations:
First search in the SDSS-III BOSS Data Release 10

M.T. Soumagnac,[1] R. Barkana,[2,3,4] C. G. Sabiu,[5] A. Loeb,[6] A. J. Ross,[7] F. B. Abdalla,[8,9] S. T. Balan,[8] and O. Lahav[8]

PRL 2016

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PRL 2016

Importance:

1) Measure $b_{L,\Delta}$, a novel aspect of galaxy formation

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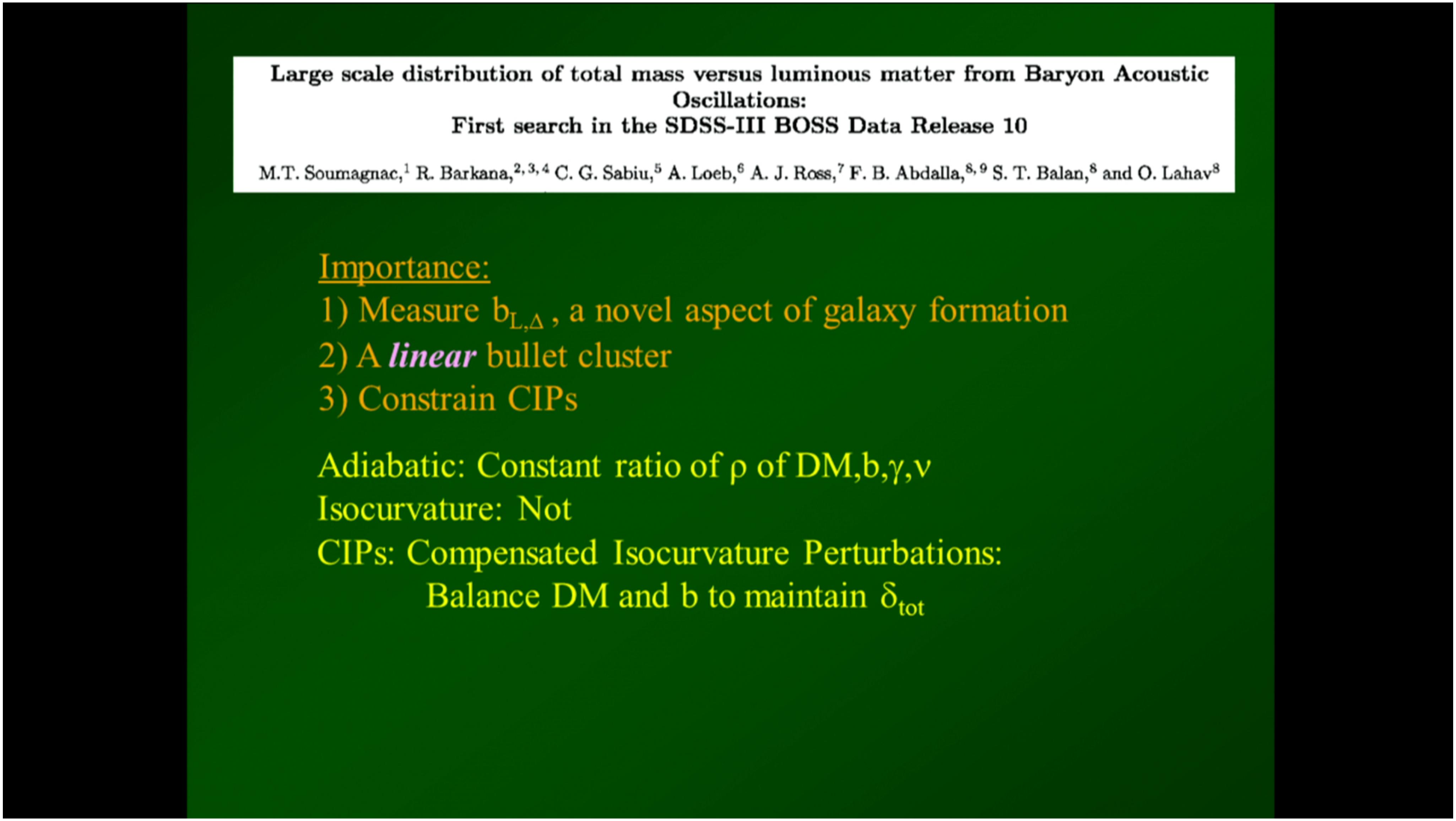
Importance:

1) Measure $b_{L,\Delta}$, a novel aspect of galaxy formation

2) A ***linear*** bullet cluster

3) Constrain CIPs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Importance:
1) Measure $b_{L,\Delta}$, a novel aspect of galaxy formation
2) A *linear* bullet cluster
3) Constrain CIPs
Adiabatic: Constant ratio of ρ of DM,b,γ,ν
Isocurvature: Not
CIPs: Compensated Isocurvature Perturbations:
Balance DM and b to maintain δ_{tot}

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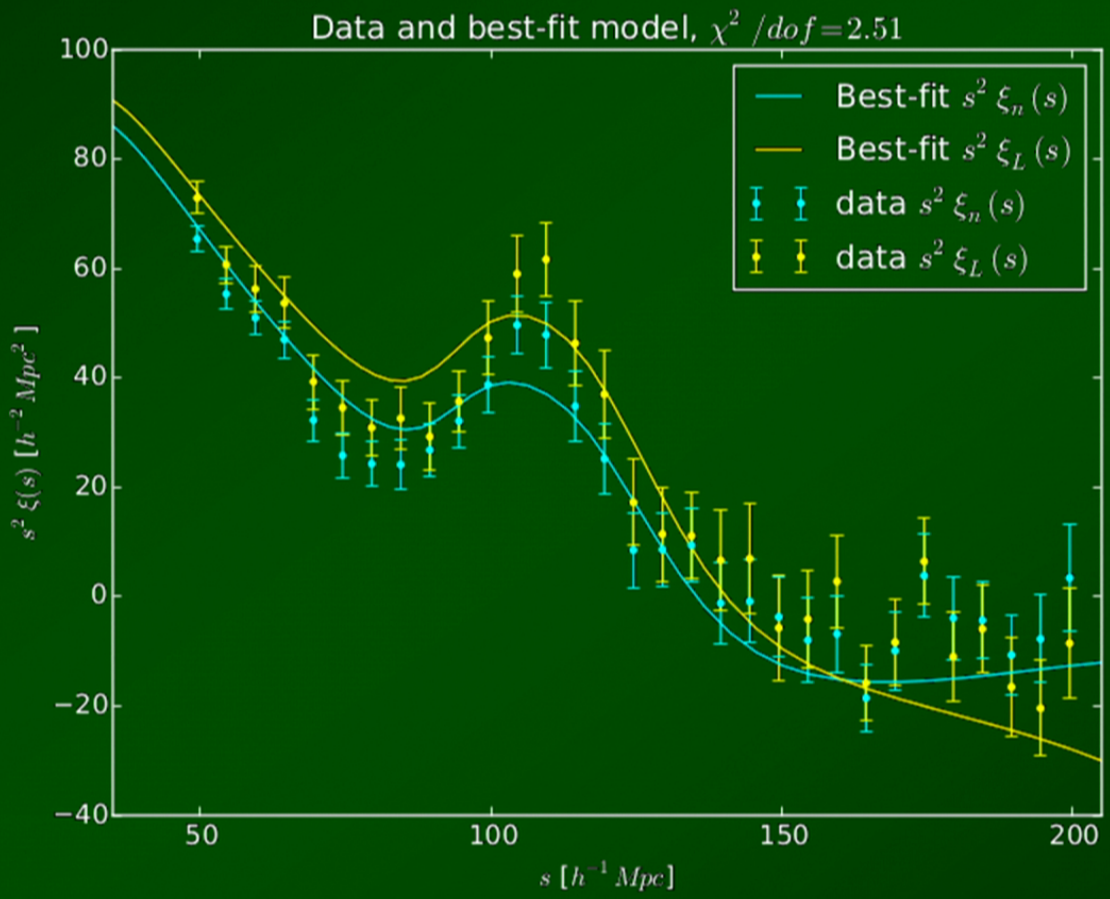
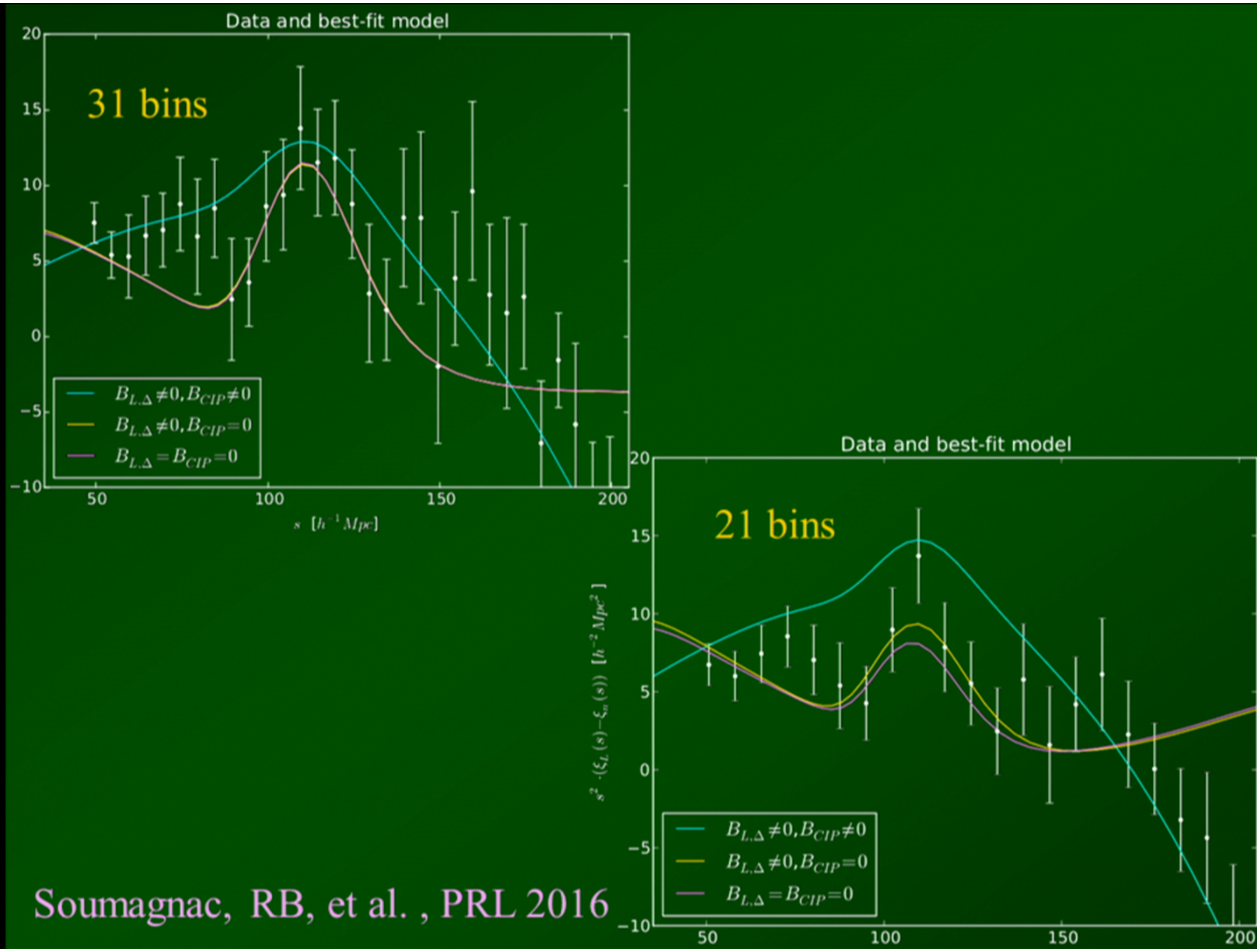
CIPs: σ_b<8% [Cluster baryon fraction] — Holder, Nollett & van Engelen 2010
σ_b<11% [CMB trispectrum] — Grin, Hanson, Holder, Dore & Kamionkowski 2014



Soumagnac, RB, et al. , PRL 2016



Data and best-fit model
31 bins
$B_{L,\Delta}\neq0, B_{CIP}\neq0$
$B_{L,\Delta}\neq0, B_{CIP}=0$
$B_{L,\Delta}=B_{CIP}=0$
$s\ [h^{-1}Mpc]$
Data and best-fit model
21 bins
$s^2\cdot(\xi_L(s)-\xi_n(s))\ [h^{-2}Mpc^2]$
$B_{L,\Delta}\neq0, B_{CIP}\neq0$
$B_{L,\Delta}\neq0, B_{CIP}=0$
$B_{L,\Delta}=B_{CIP}=0$
Soumagnac, RB, et al. , PRL 2016

Summary

Cosmic Dawn: 21-cm Cosmology

- RB & Loeb 2004 Fluctuations: galaxies, reionization
- RB & Loeb 2005a Ly-α fluctuations
- RB & Loeb 2005b Power spectrum anisotropy

21-cm power spectrum

- Fialkov, **RB** & Visbal XRBs: hard X-rays Nature 2014

Model-independent signatures

- Fialkov, **RB** & Cohen PS anisotropy PRL 2015

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21-cm power spectrum

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Do Baryons follow the DM?

- RB & Loeb 2011 Galaxy clustering: luminosity/number

Current data close to detection:

- Soumagnac, **RB** et al. PRL 2016

  Confirm standard cosmological model

  3.2σ evidence but NOT robust