Title: 21 cm radiation: A new probe of fundamental physics

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Abstract: New low frequency radio telescopes currently being built open up the possibility of observing the 21 cm radiation before the Epoch of Reionization in the future, in particular at redshifts 200 â‰¥ z â‰¥ 30, also known as the dark ages. At these high redshifts, Cosmic Microwave Back-ground (CMB) radiation is absorbed by neutral hydrogen at its 21 cm hyperfine transition. This redshifted 21 cm signal thus carries information about the state of the early Universe and can be used to test fundamental physics. We study the constraints these observations can put on the variation of fundamental constants and on fundamental mass scales. We show that the 21 cm radiation is very sensitive to the variations in the fine structure constant and can in principle place constraints comparable to or better than the other astrophysical experiments. Cosmic strings, if they exist, contribute to the anisotropies in the primordial gas leaving an imprint on the 21 cm radiation. They can tell us about the fundamental mass scales involved in the theories beyond the standard model. We show that the 21 cm radiation can potentially probe cosmic strings of tension ~10âˆ’12 asumming intercommutation probability of 1. Making such observations will require radio telescopes of collecting area 10 âˆ’ 106 km2 compared to ~ 1 km2 of current telescopes.

21 cm radiation: A new probe of fundamental physics

Rishi Khatri
Benjamin D. Wandelt

In search of variation of fundamental couplings and mass scales
Perimeter Institute

July 18, 2008

ASTRONOMY
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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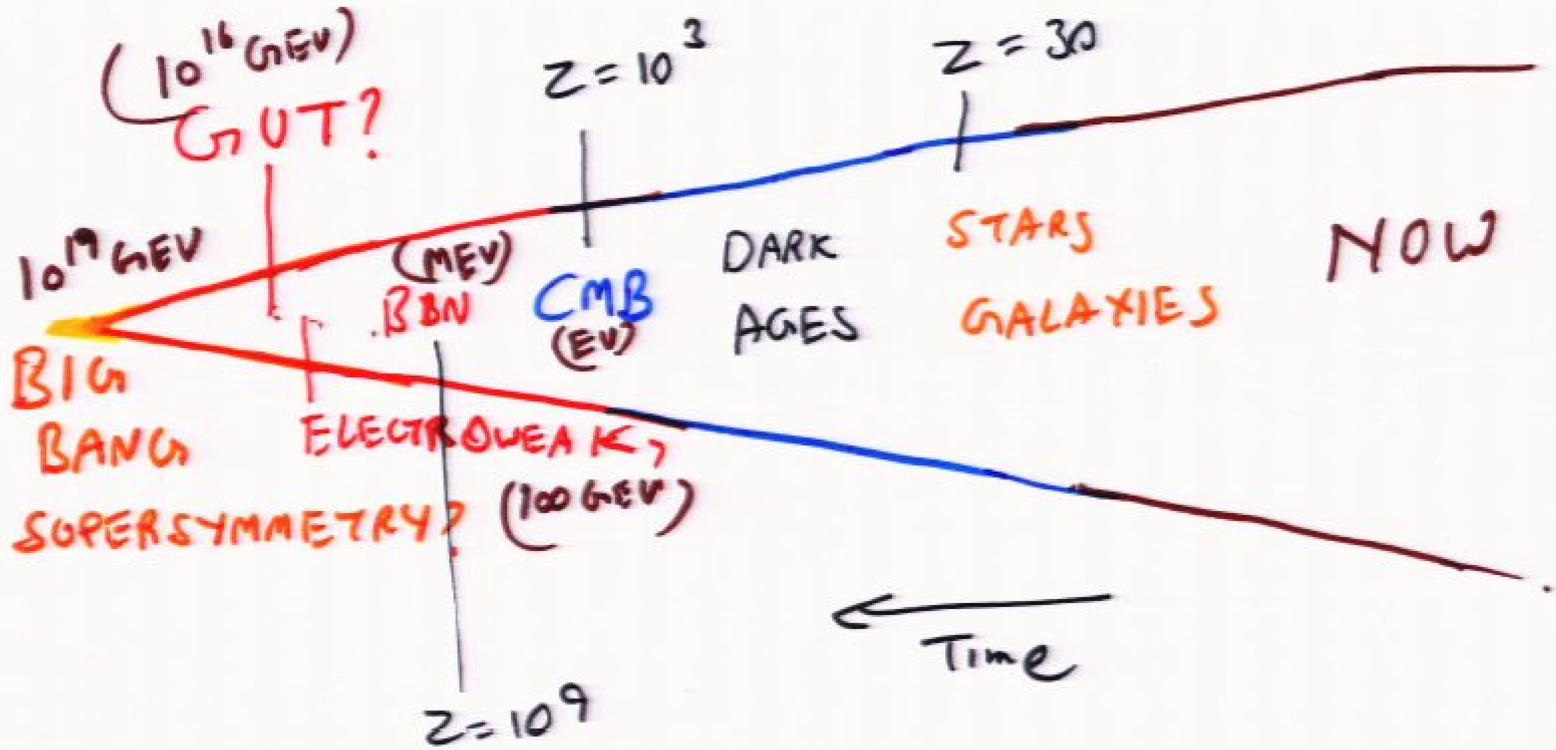
Dark Ages

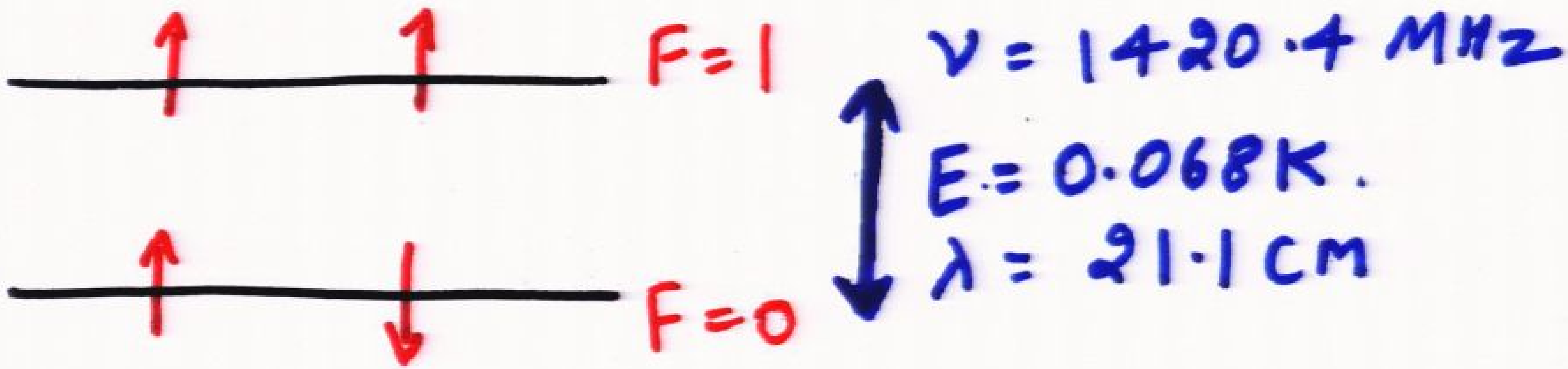
“the last frontier in cosmology”

Cosmological observations

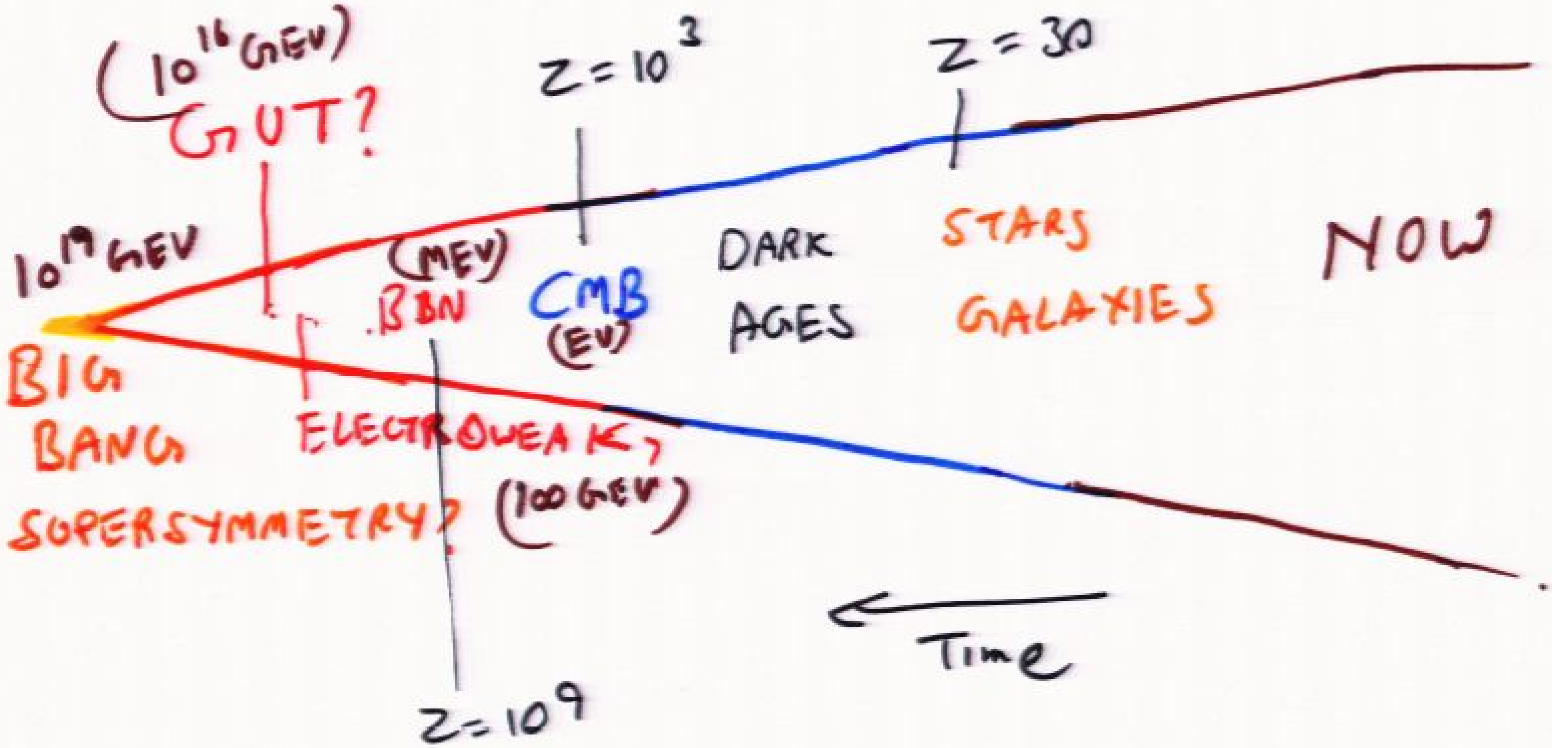


- Big Bang Nucleosynthesis: $z \sim 10^9$, Homogeneous Universe.
- Cosmic microwave background: $z \sim 1100$, $k \lesssim 0.1 \mathrm{Mpc}^{-1}$.
- Large scale structure: $z < 6$, $k \lesssim 0.1 \mathrm{Mpc}^{-1}$.
- Ly-α forest: $z < 6$, $k \lesssim 1 \mathrm{Mpc}^{-1}$.

Hyperfine transition of Hydrogen



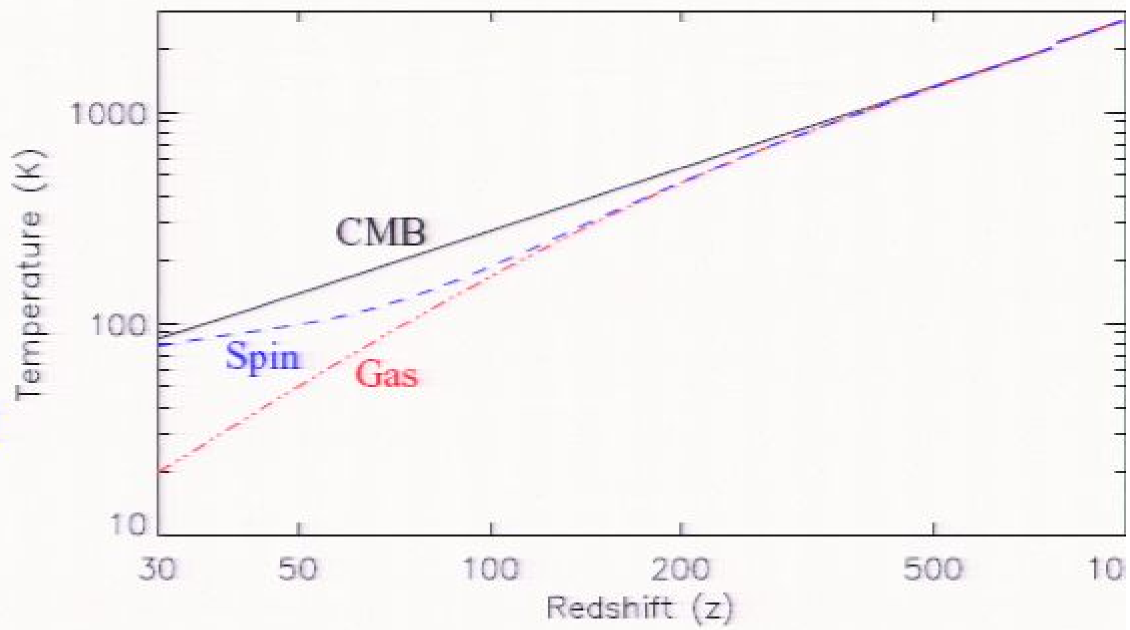
New Observational Window



- 21 cm radiation: $200 > z > 6$, $k \lesssim 1000 Mpc^{-1}$.

Thermal history of the Universe

- Spin temperature:
  $$\frac{n_t}{n_s} = \frac{g_t}{g_s} e^{-T_\star / T_{spin}}$$
- Collisions couple T_{spin} to T_{gas}
  - Dominates at high redshift
- Emission/absorption of CMB couples T_{spin} to T_{CMB}
  - Dominates at low redshift



Loeb & Zaldarriaga 2004

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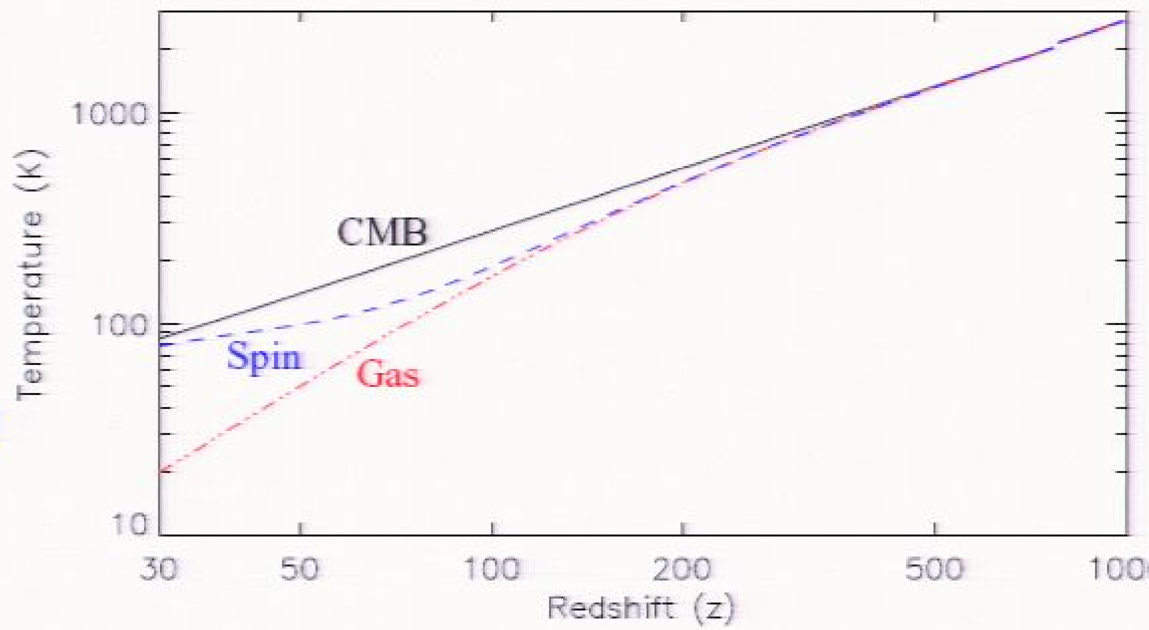

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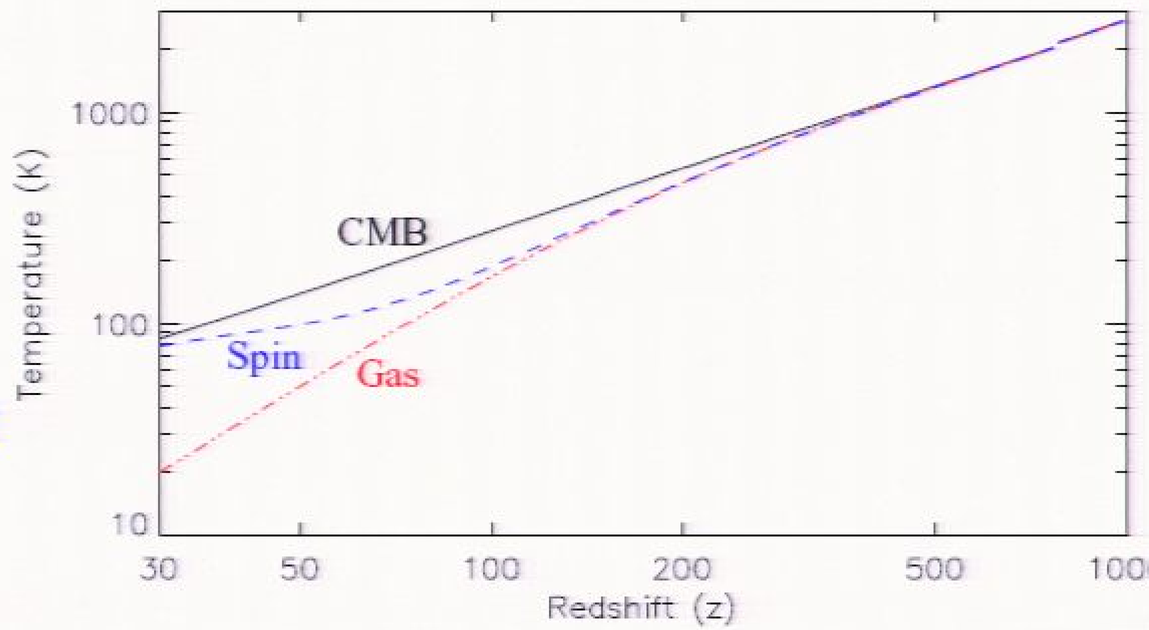


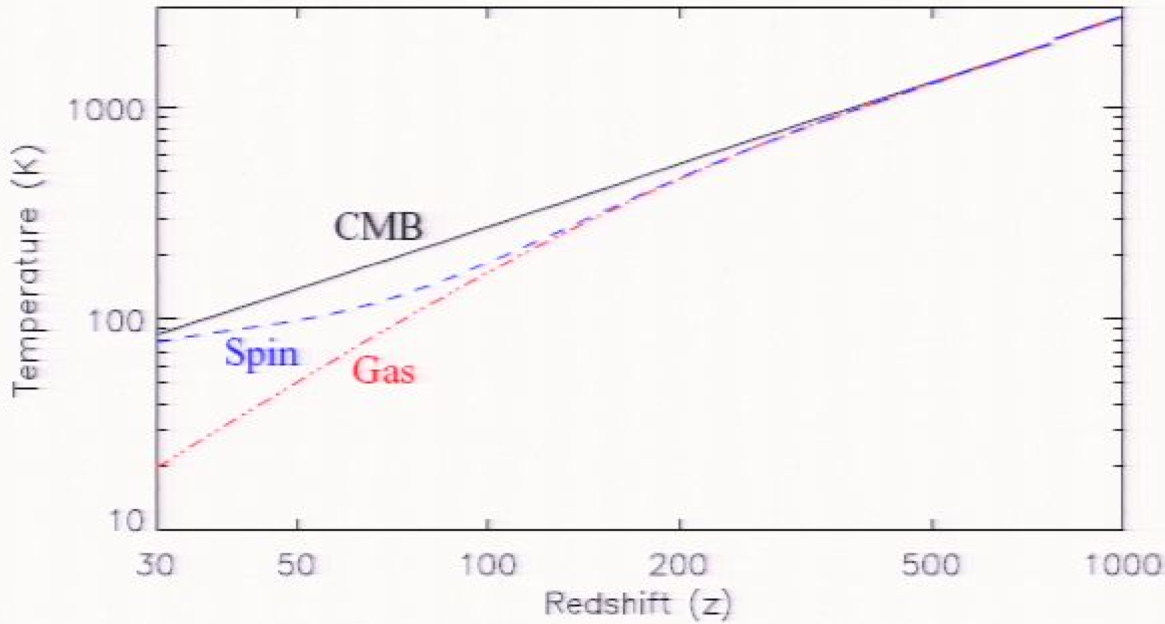
Loeb & Zaldarriaga 2004

21 cm brightness temperature

Brightness temperature = Difference between Observed brightness and CMB
(Rayleigh-Jeans: $T_b = I_\nu c^2/2k_B\nu^2$)

$$T_b = \frac{(T_s - T_{CMB})\tau}{(1+z)}$$

$$\tau = \frac{3c^3\hbar A_{10} n_H}{16 k_B \nu_{21}^2 (H + \frac{dv}{dr}) T_s}$$



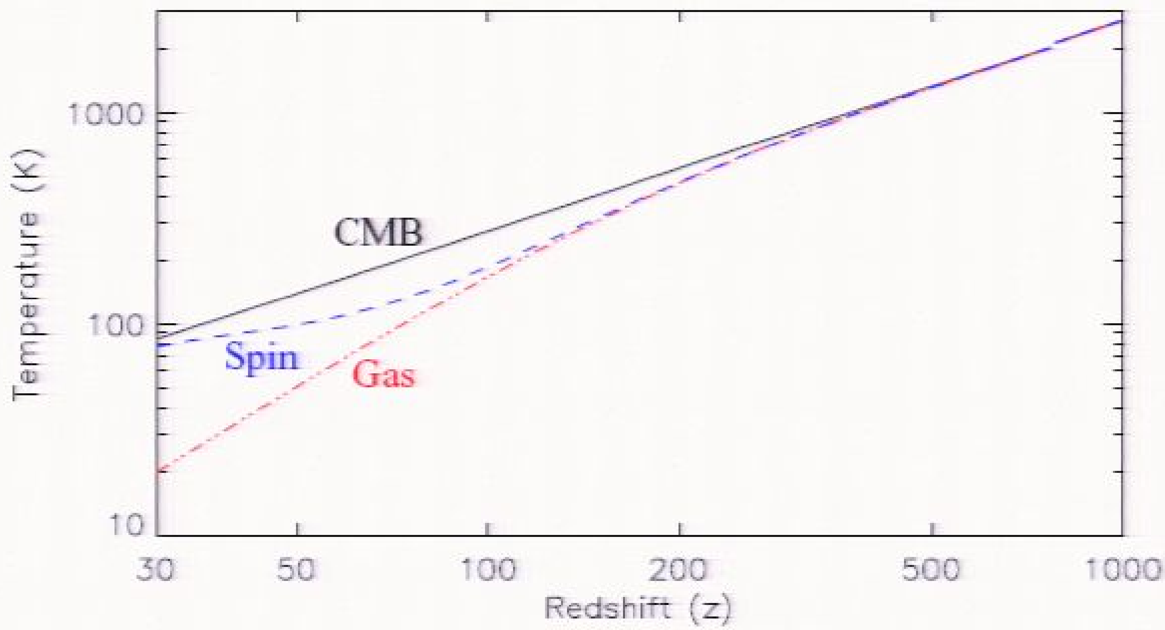
New observational window

Dark ages:

- $200 \geq z \geq 30$
- $7\text{MHz} \lesssim \nu \lesssim 46\text{MHz}$

Epoch of reionization:

- $30 \geq z \geq 6$
- $46\text{MHz} \lesssim \nu \lesssim 200\text{MHz}$



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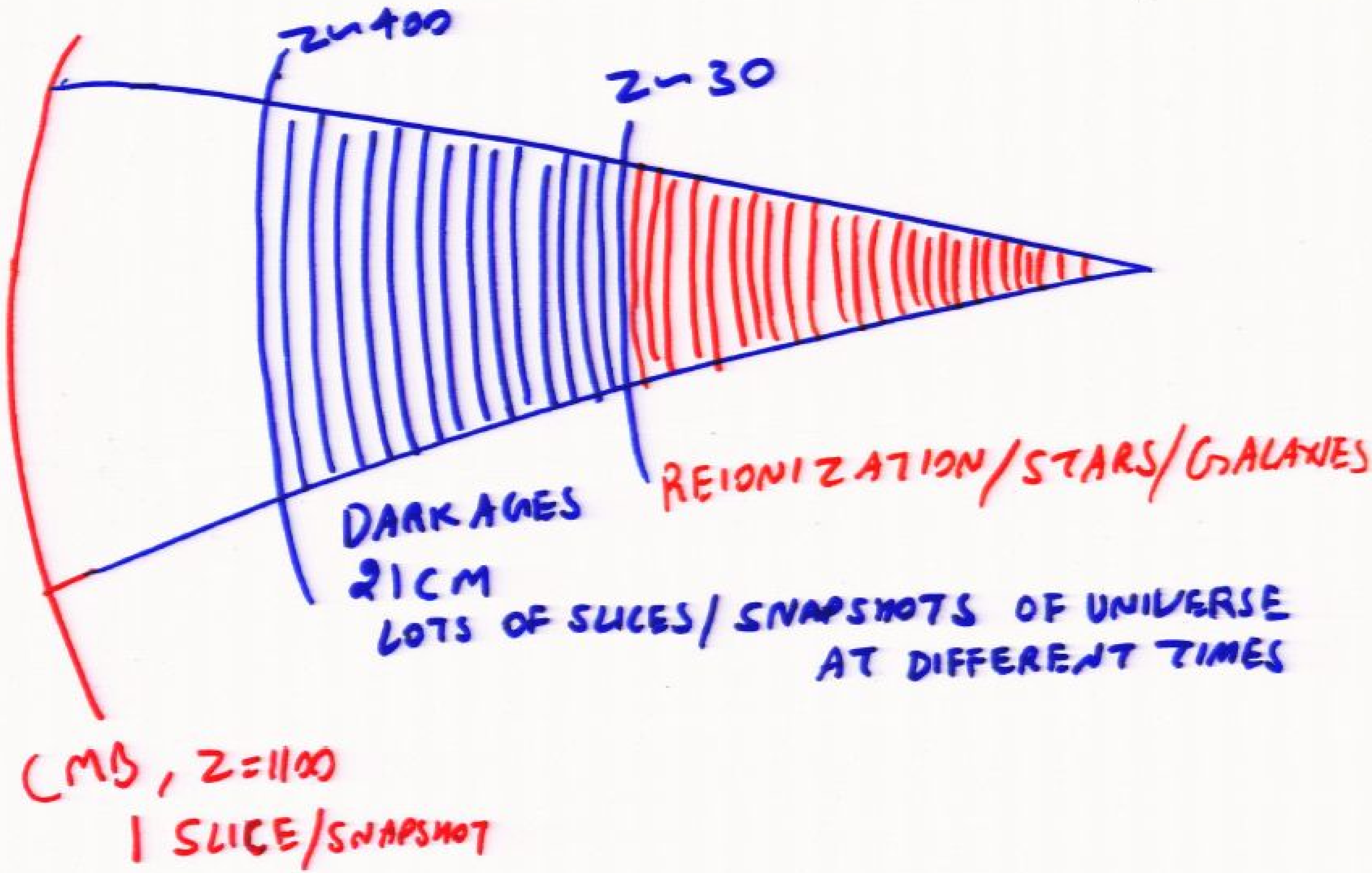
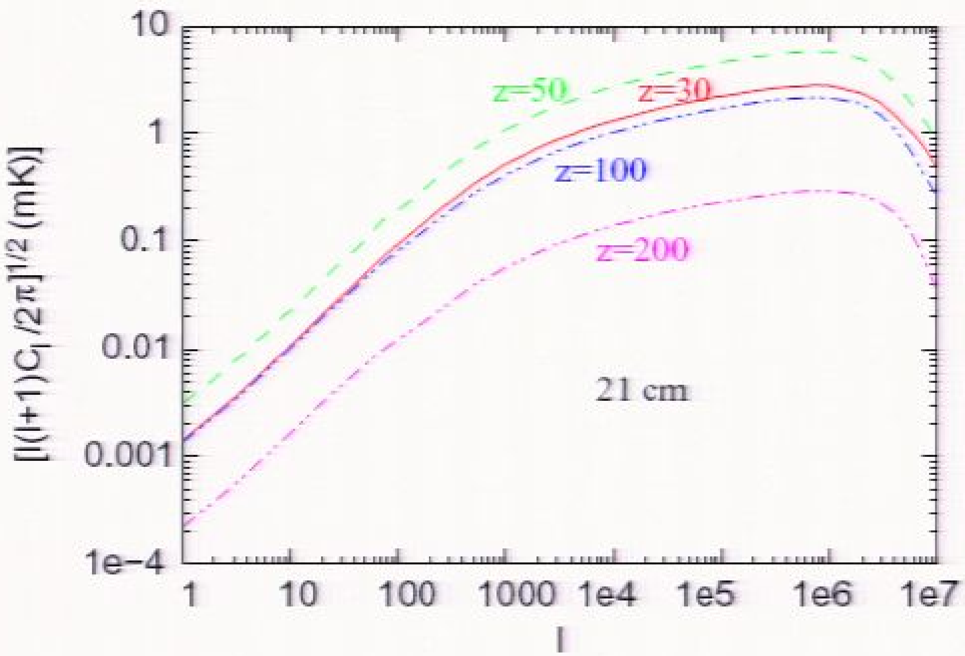
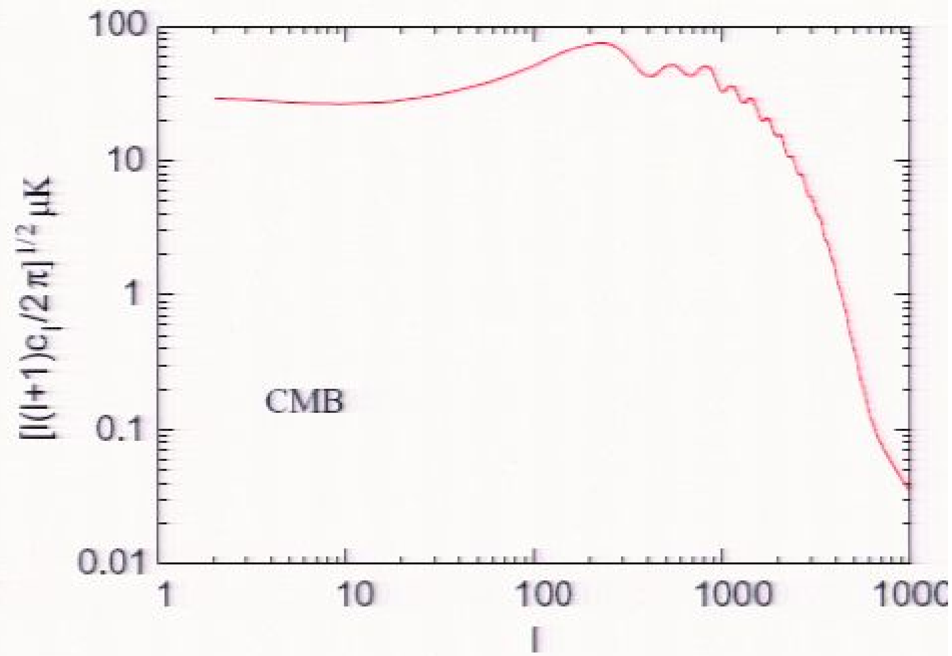


21 cm power spectrum

- Smaller scales $\rightarrow$ more modes
- 21 cm: No of modes $\propto l^3 \sim 10^{16}$
  (CMB: $\propto l^2 \sim 10^7$)
  (Loeb & Zaldarriaga 2004, Bhardawaj & Ali 2004)





Fundamental Physics From 21 cm Radiation

- Variation of the fine structure constant
- Cosmic (super)strings

Fine structure constant (α) variations

Current constraints *(García-Berro et al 2007)*

- Lab experiments: $\dot{\alpha}/\alpha < 10^{-14}/yr$
- Oklo natural fission reactor: $\delta\alpha/\alpha < 10^{-8}$, 2 billion years ago.
- BBN/CMB: $\delta\alpha/\alpha <$ few percent
- Quasar absorption spectra: $\delta\alpha/\alpha \sim 10^{-5}$ at $z = 3.5$.
  - Webb et al 2001, Murphy et al 2003: $\delta\alpha/\alpha = (-0.543 \pm 0.116) \times 10^{-5}$ at $0.2 < z < 3.7$
  - Chand et al 2006: $\delta\alpha/\alpha = (0.05 \pm 0.24) \times 10^{-5}$, $z = 1.1508$

Fine structure constant (α) variations

Why should the "constants" vary?

- Why should they be constant? *(Dirac 1937)*
- Can vary in GUTs, superstring theories.

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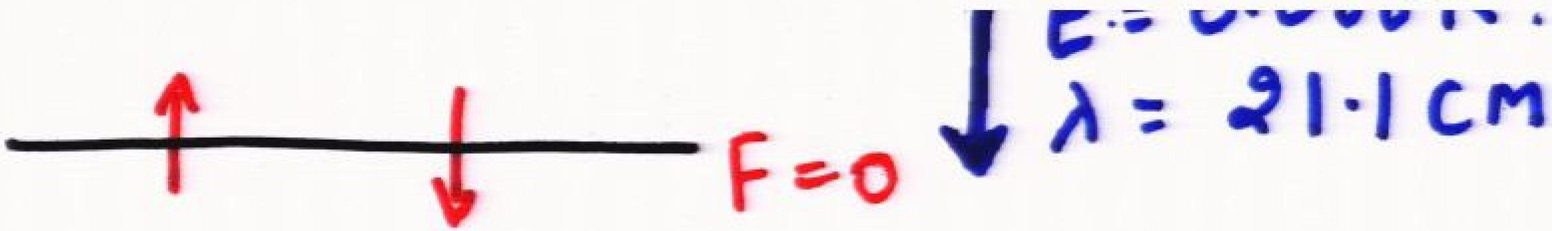

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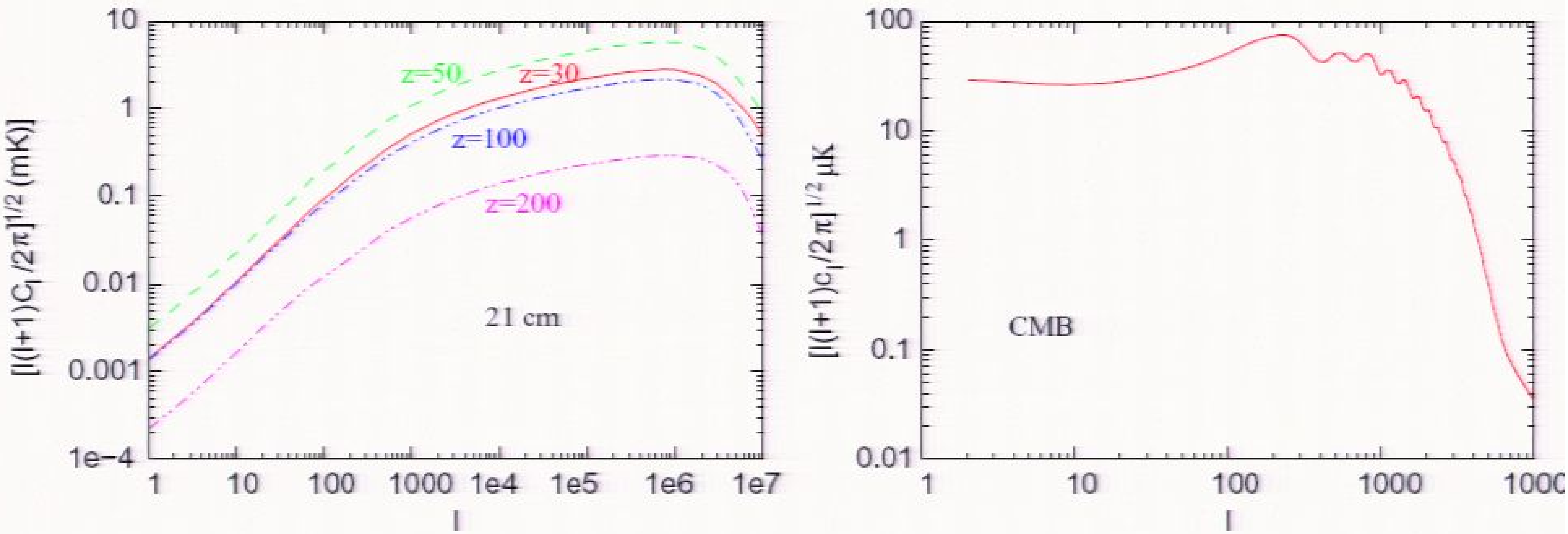

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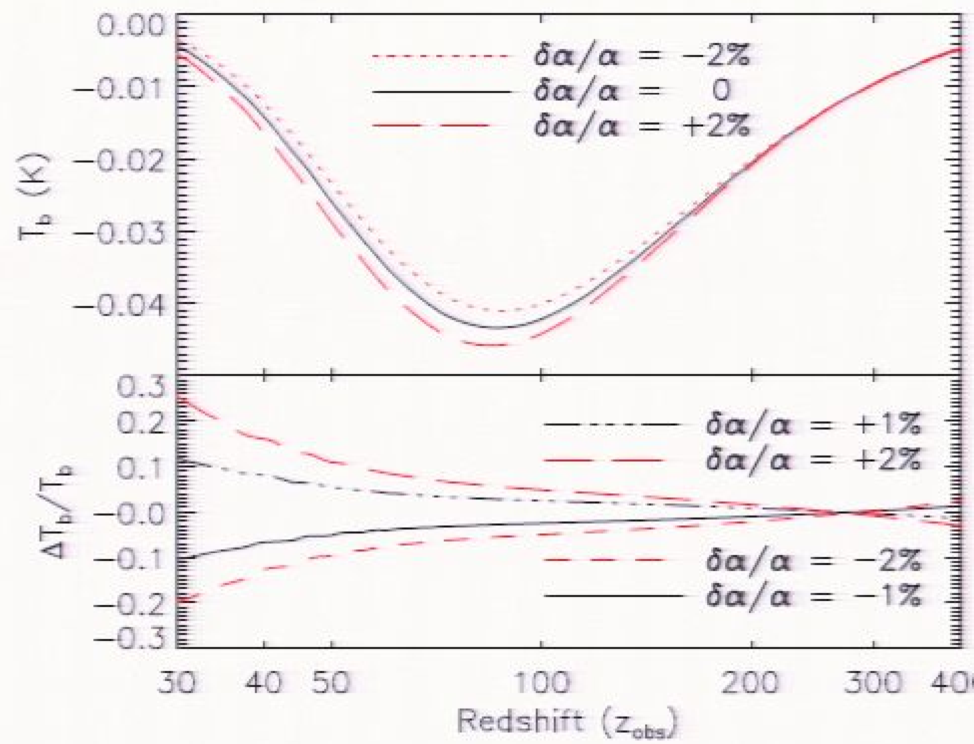
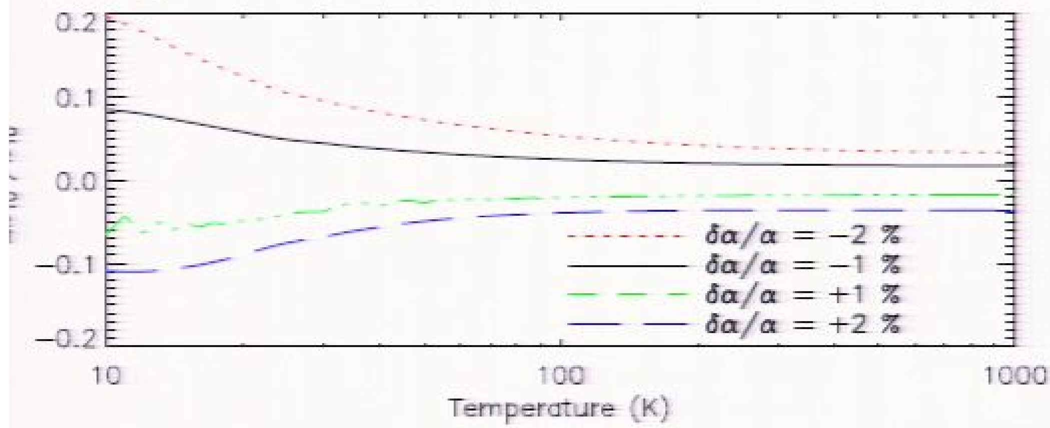
Fine structure constant (α) variations: Results

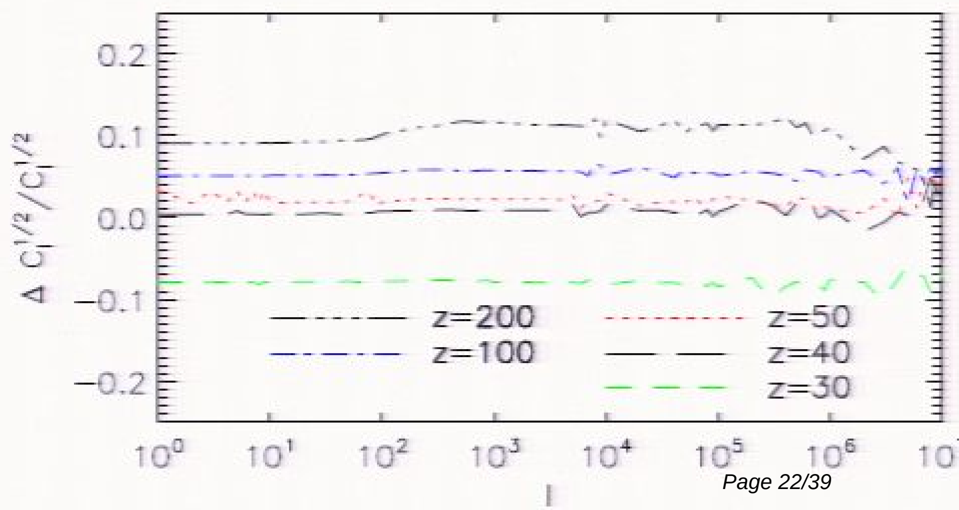
1 cm signal depends strongly on the
ne structure constant.

(Khatri & Wandelt 2007)

- $\nu \propto \alpha^4, A_{10} \propto \alpha^{13}, \kappa_{10} \propto \alpha^{2-8}$
- $\sigma_T \propto \alpha^2, x_e$







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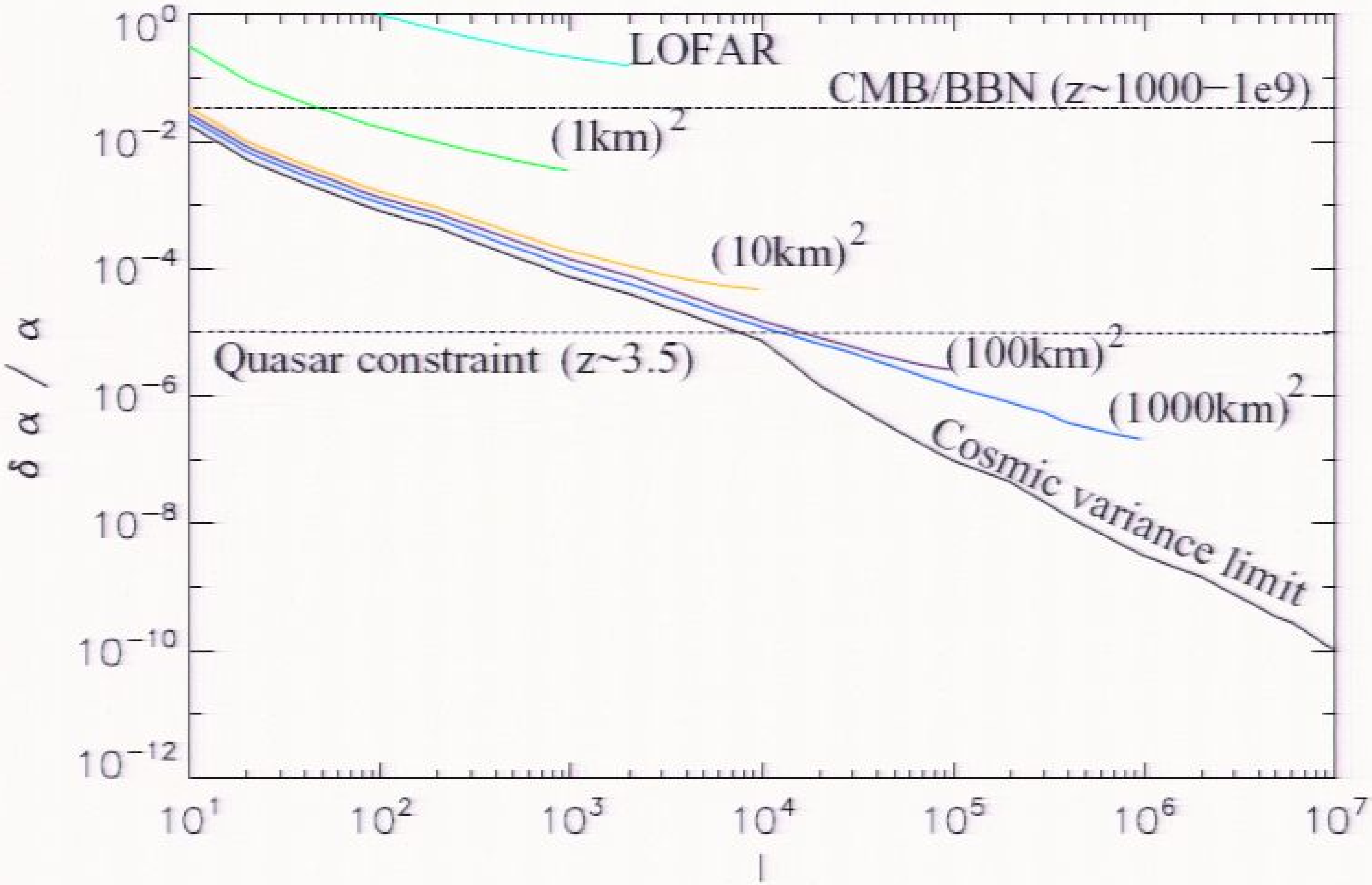
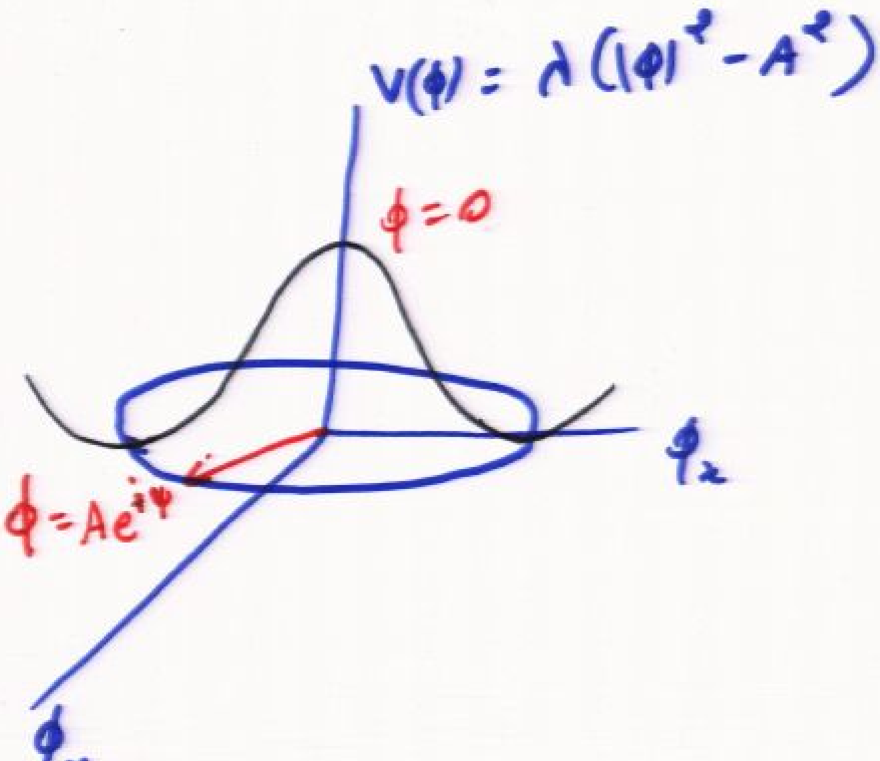
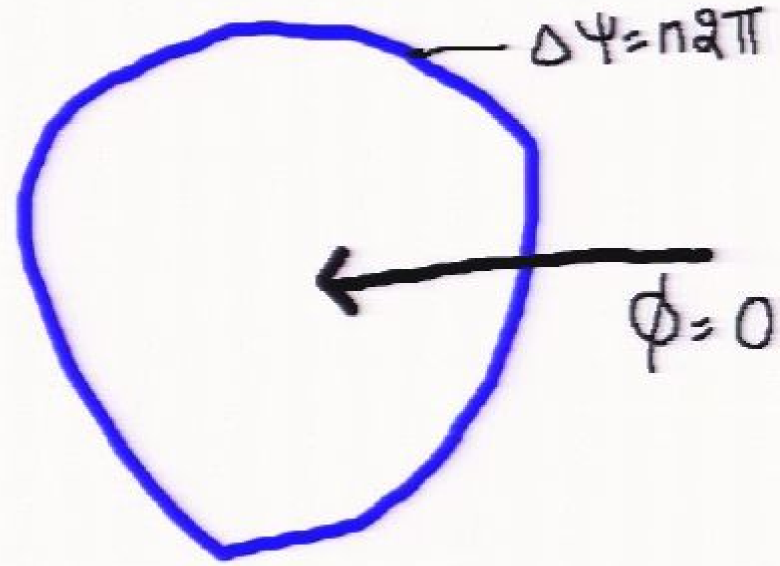


Cosmic (super)strings

Line like topological defects of cosmic lengths: Alternative to inflation for seeding perturbations in primordial gas (before WMAP)

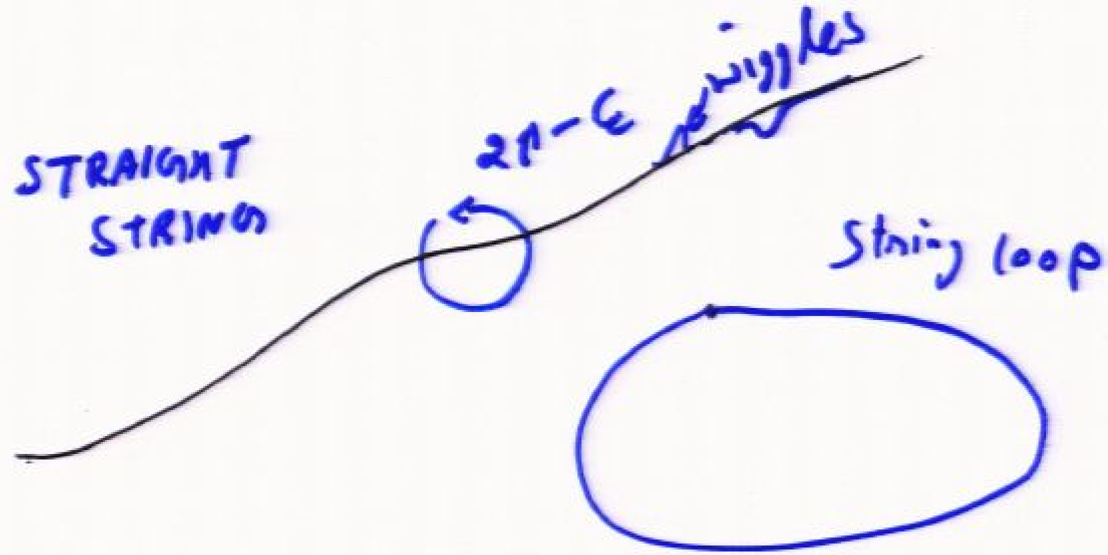
- Breaking of circular symmetry *(Polchinski 2007)*
- Characterized by the dimensionless string tension $G\mu$ (speed of light = 1)





Cosmic (super)strings

- Perturb the matter through which they move at relativistic speeds.



- Ubiquitous in GUTs, brane inflation.
- Observed in lab experiments!
  - superfluids
  - superconductors
  - nematic crystals

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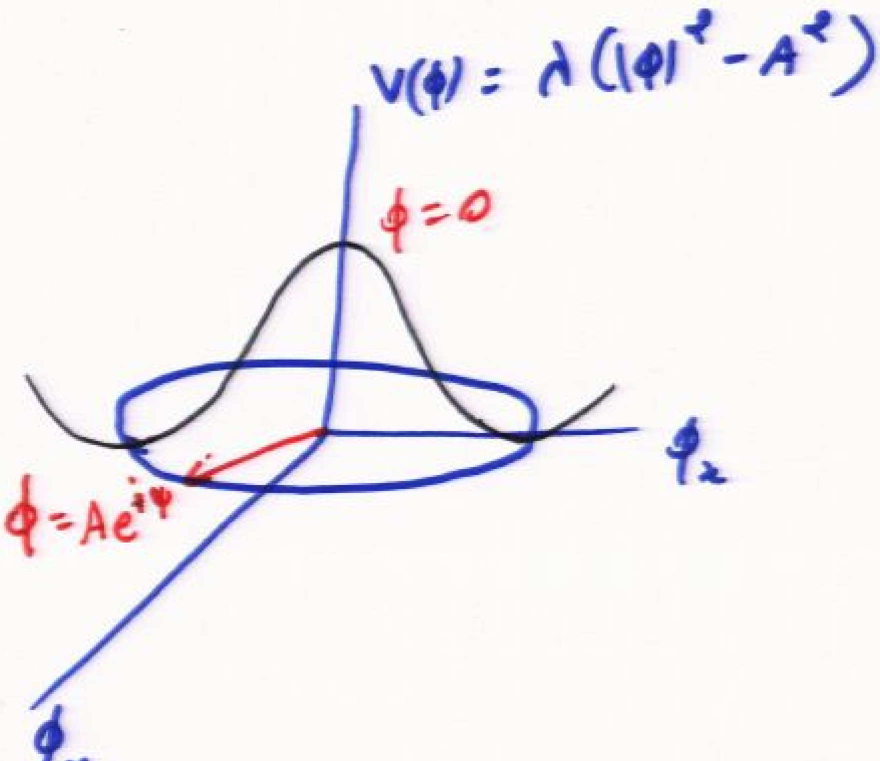

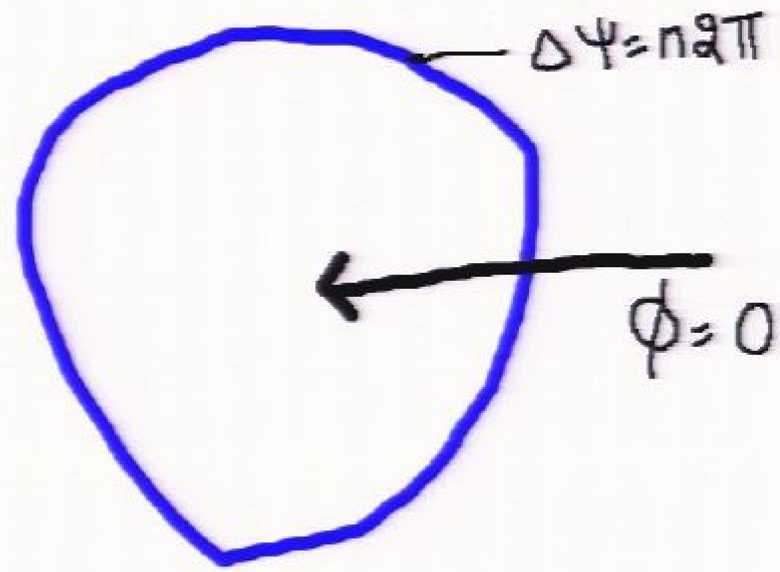

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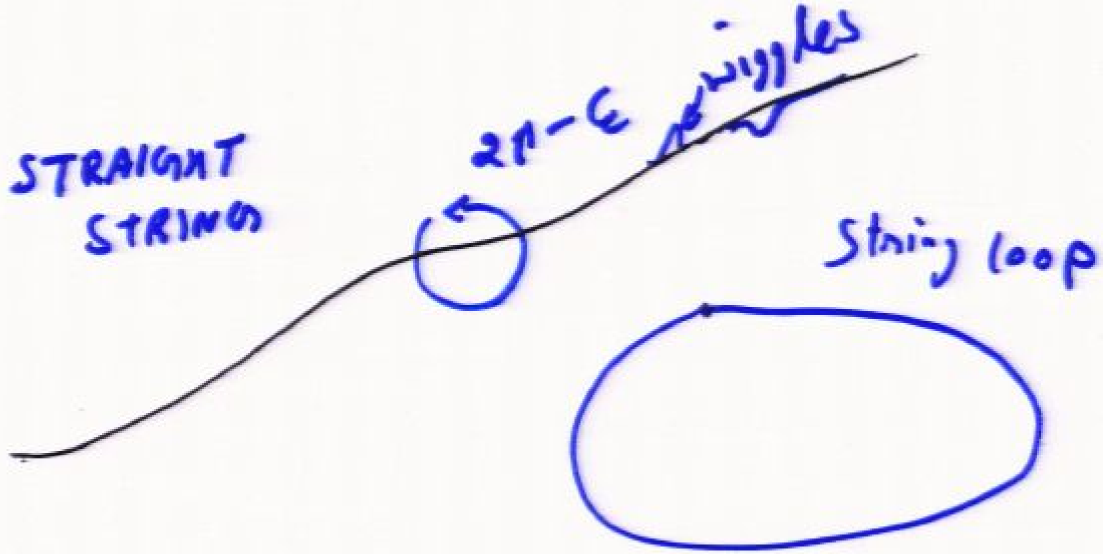

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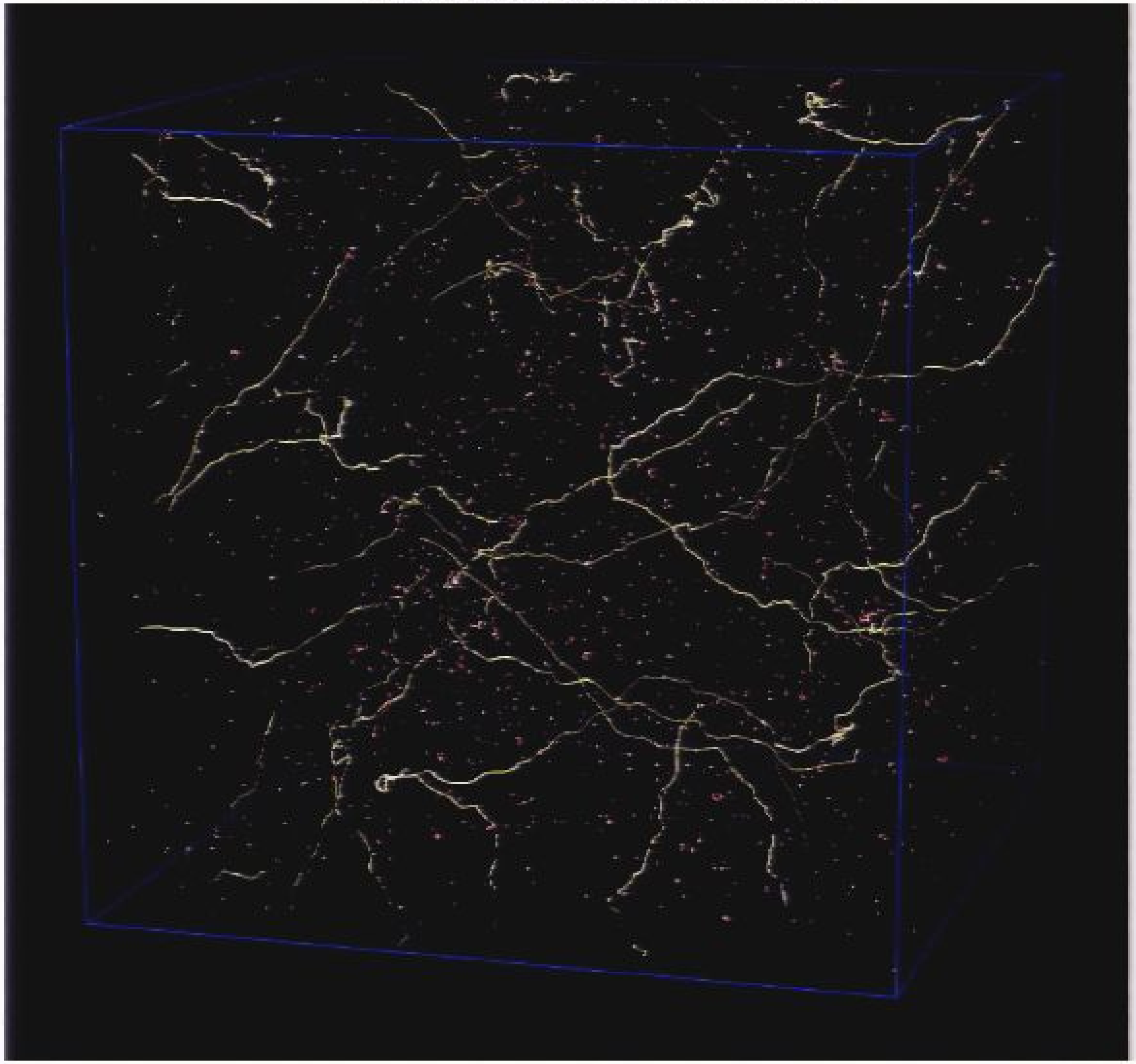
Cosmic (super)strings

Cosmic string network simulation. Box size is 2× Hubble length.

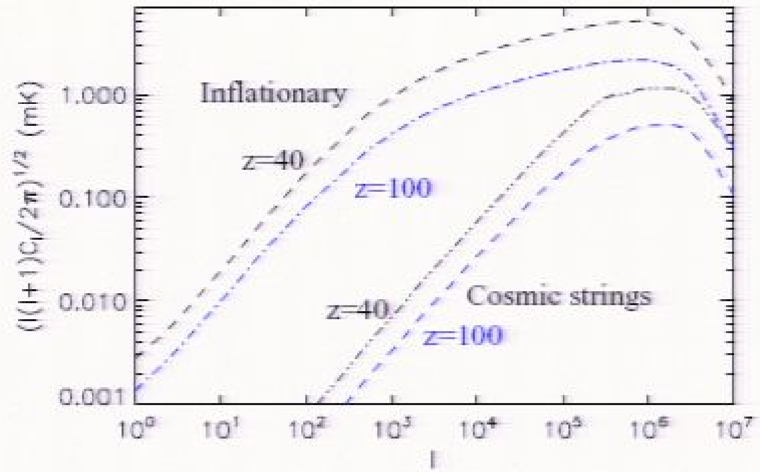
Allen and Shellard 1990



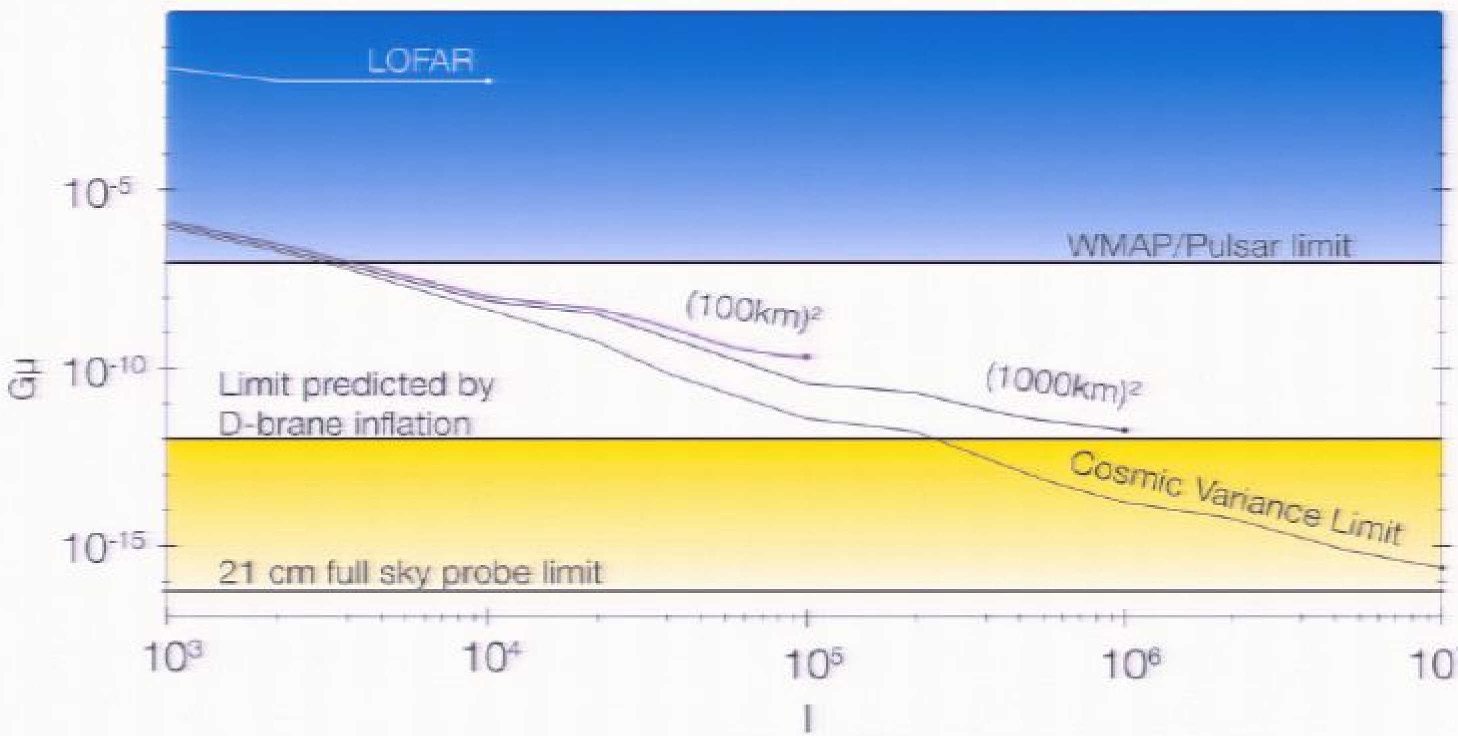
Cosmic (super)strings

Cosmic string induced perturbations from CMBACT *Pogosian and Vachaspati 1999*
$\mu \sim M_s^2, M_{GUT}^2$

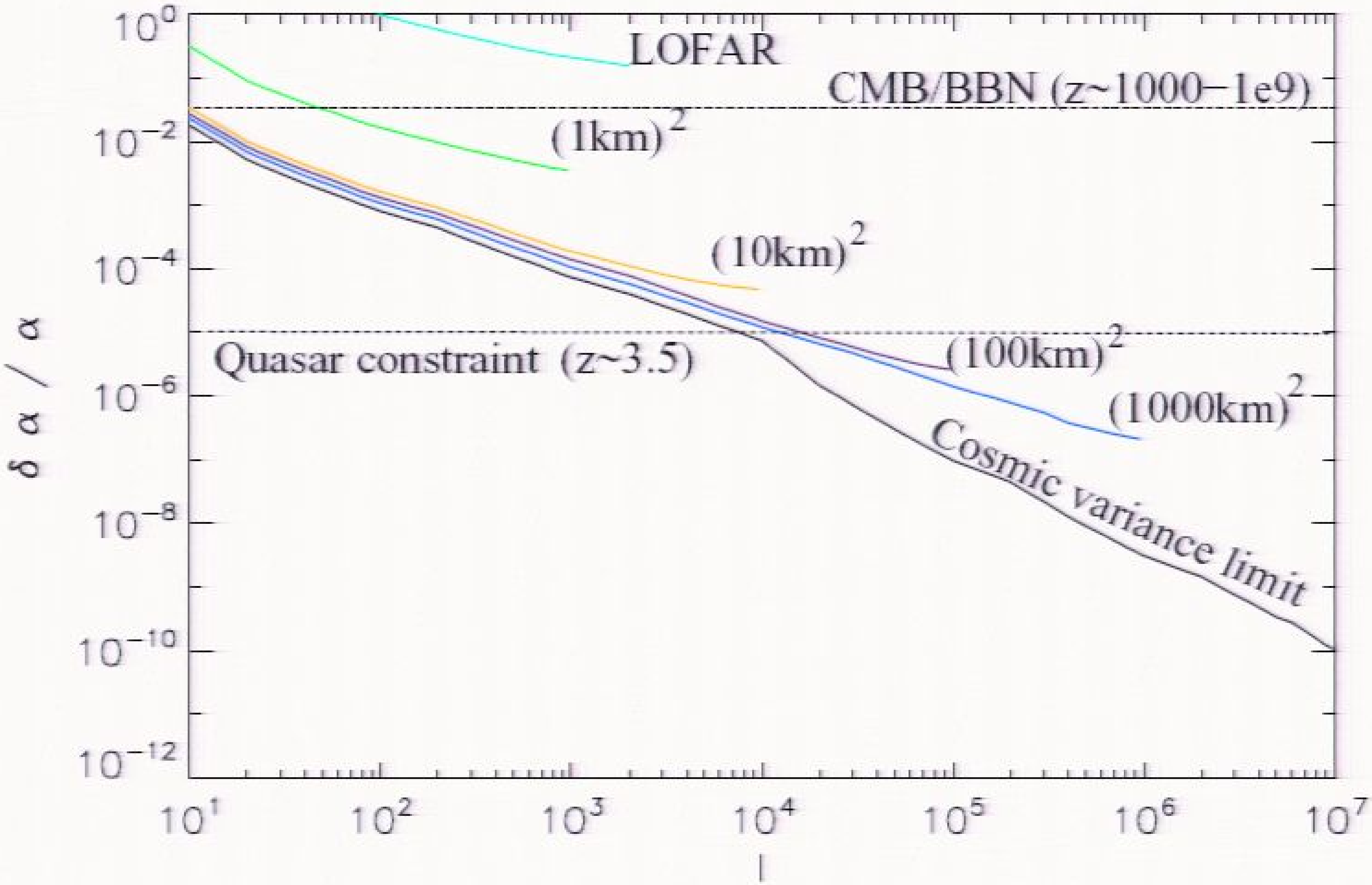
$G\mu = 10^{-12} \Rightarrow M_s, M_{GUT} \sim 10^{13}\text{GeV}.$



Khatri & Wandelt 2008



Fine structure constant (α) variations: Results

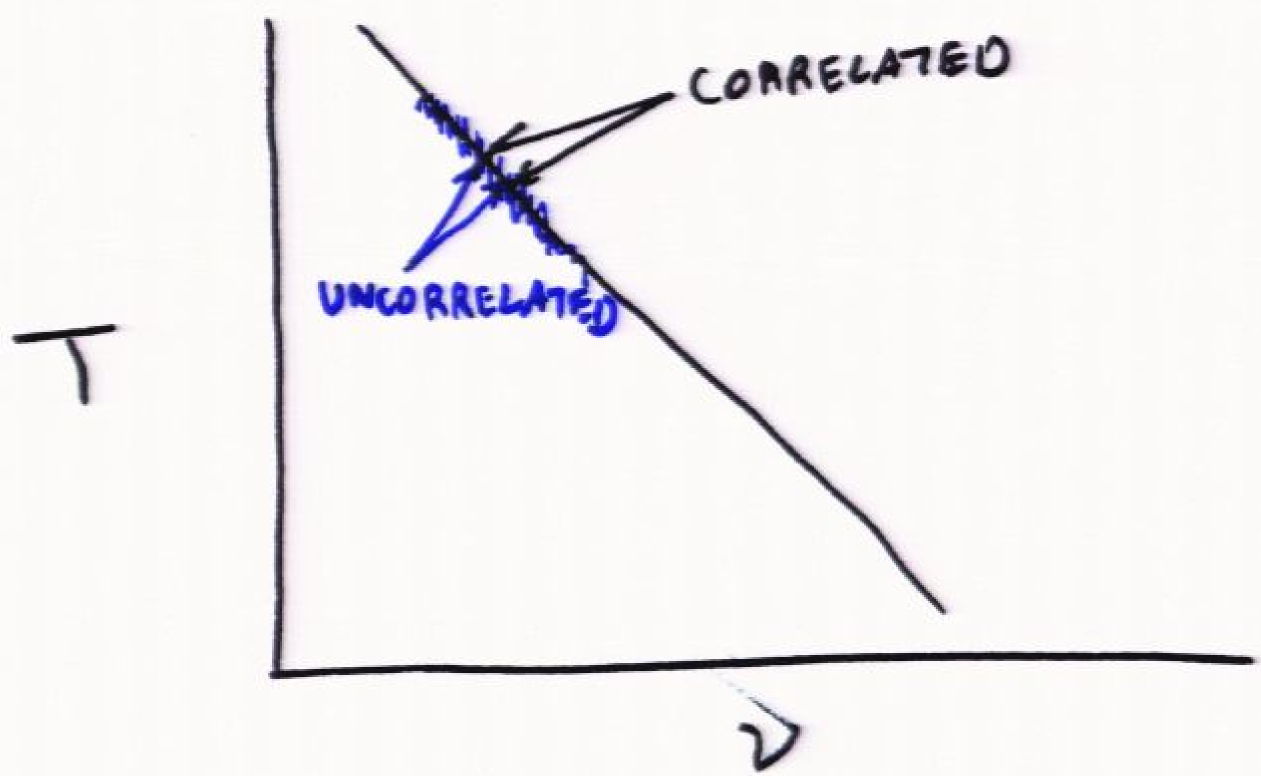


Challenges

Galactic and extra galactic foregrounds:

- Mostly synchrotron, $T_{Sky} \sim 19000K \left(\frac{22\mathrm{MHz}}{\nu}\right)^{2.5}$ (*Roger et al. 1999*)

Foreground Removal (*Zaldarriaga et al. 2004*)



Challenges

- Interstellar scattering, $\theta_{scatter} \propto \lambda^2$
  $\sim$ 1 arc-second at 30 MHz
  $l = 2\pi/\theta \sim 10^6$
  (*Cohen & Croyen 1964*)
- Terrestrial interferance (FM,TV)

Far side of the Moon

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FEATURE

181 Things To Do On The Moon

02.02.2

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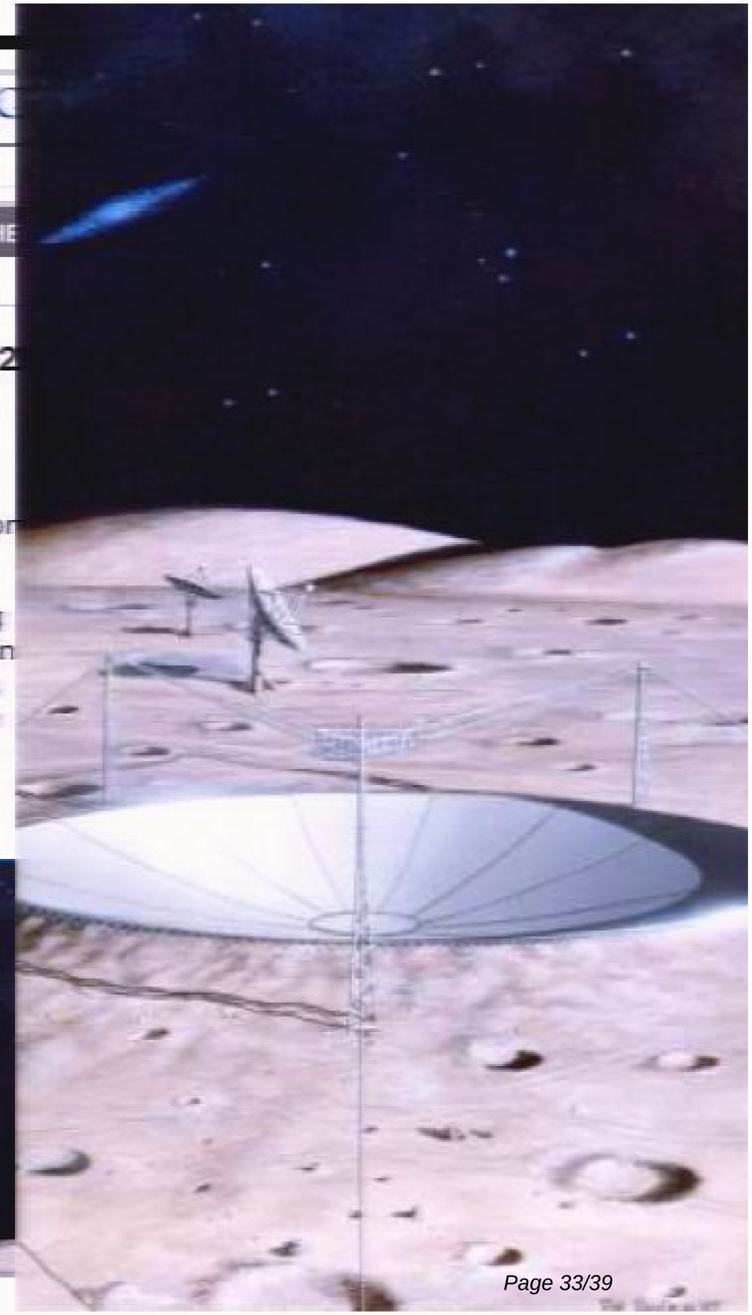
February 2, 2007: If you woke up tomorrow morning and found yourself on the moon what would you do? NASA has just released a list of 181 good ideas.

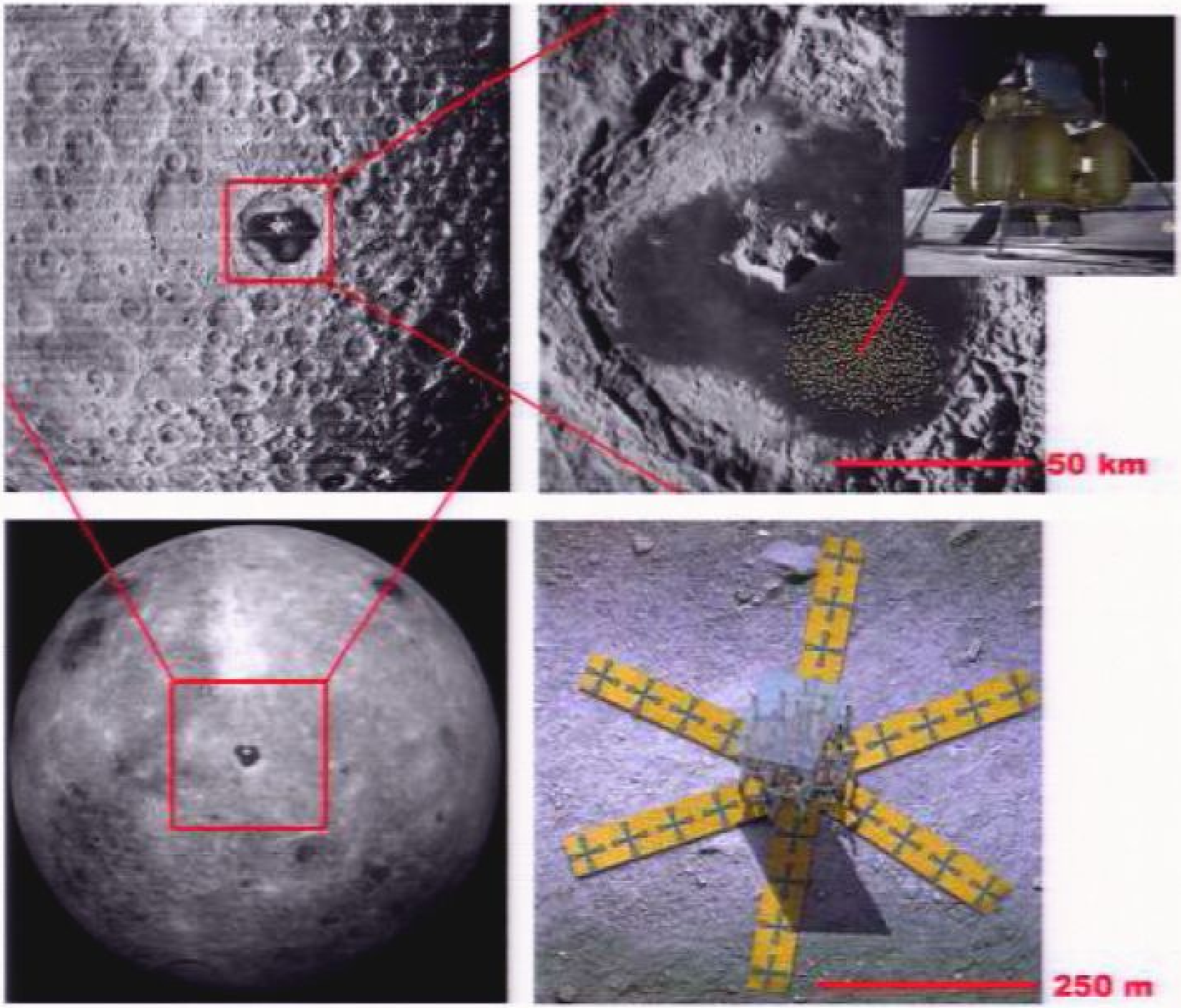
Ever since the end of the Apollo program, "folks around the world have been thinking about returning to the moon, and what they would like to do there," says Jeff Volosin strategy development lead for NASA's Exploration Systems Mission Directorate. Now, NASA *is* going back; the agency plans to send astronauts to the Moon no later than 2020. "So we consulted more than 1,000 people from businesses, academia and 13 international space agencies to come up with a master list of 181 potential lunar objectives."

For example, the moon could be a good location for radio astronomy. A radio telescope on the far side of the Moon would be shielded from Earth's copious radio noise, and would be able to observe low radio frequencies blocked by Earth's atmosphere. Observations at these frequencies have never been made before and opening up a window into this low frequency universe will likely lead to many exciting new discoveries.

Right: A radio telescope on the moon uses a crater to support its giant primary dish. Artist's concept by Pat Rawlings. [More]



Dark Ages Lunar Interferometer



Source: Naval Research Lab

The Dark Ages Lunar Interferometer (DALI)

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International Union of Radio Science (URSI) General Assembly,
Chicago, IL; 2008 August 10–16

Abstract

The Dark Ages represent the last frontier in cosmology, the era between the genesis of the cosmic microwave background (CMB) at recombination and the formation of the first stars. During the Dark

Dark Ages Lunar Interferometer

the only site in the solar system shielded from human-generated interference and, at night, from solar radio emissions. The DALI array will observe at 3–30 m wavelengths (10–100 MHz; redshifts $15 < z \leq 150$), and the DALI baseline concept builds on ground-based telescopes operating at similar wavelengths, e.g., the Long Wavelength Array (LWA) and Murchison Widefield Array (MWA). Specifically, the fundamental collecting element will be dipoles. The dipoles will be grouped into "stations," deployed via rovers over an area of approximately 50 km in diameter to obtain the requisite angular resolution. The desired three-dimensional imaging requires approximately 1000 stations, each containing 100 dipoles (i.e., $\sim 10^5$ dipoles); alternate processing approaches may produce useful results with significantly fewer dipoles (factor $\sim$ 3–10). Each station would be deployed by one rover, which would also serve as a "transmission hub" for sending the signals for correlation to a central processing facility. After sending the correlator output to Earth, analysis would then proceed via standard methods being developed for ground-based arrays.

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Edwin Hubble

THUS the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.

Edwin Hubble, The Realm of the Nebulae, 1936.