Title: Fundamental physics with 21cm observations

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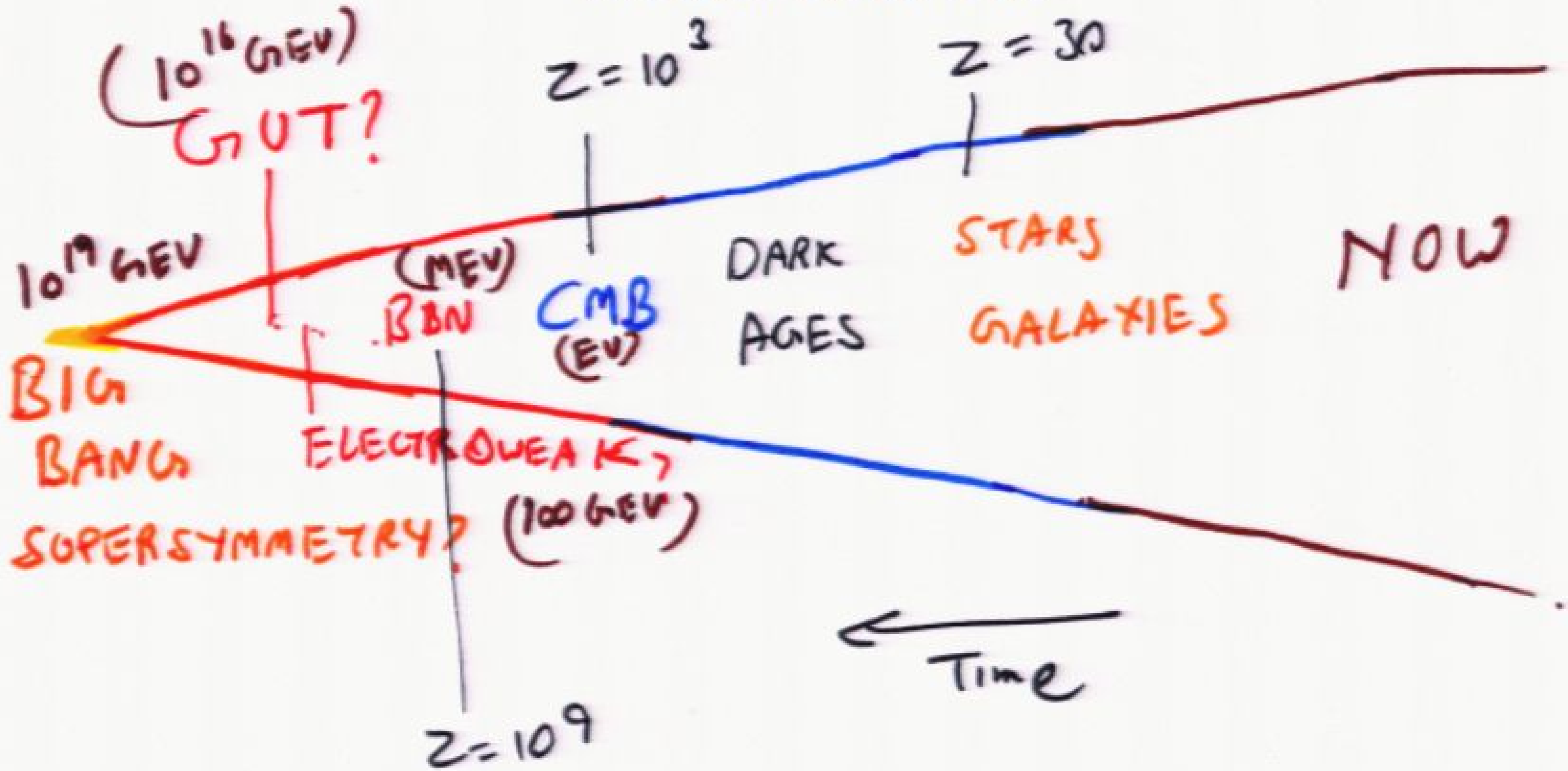
Abstract: TBA

Connecting the early Universe with astronomical 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: $z < 6$, $k \lesssim 1\mathrm{Mpc}^{-1}$

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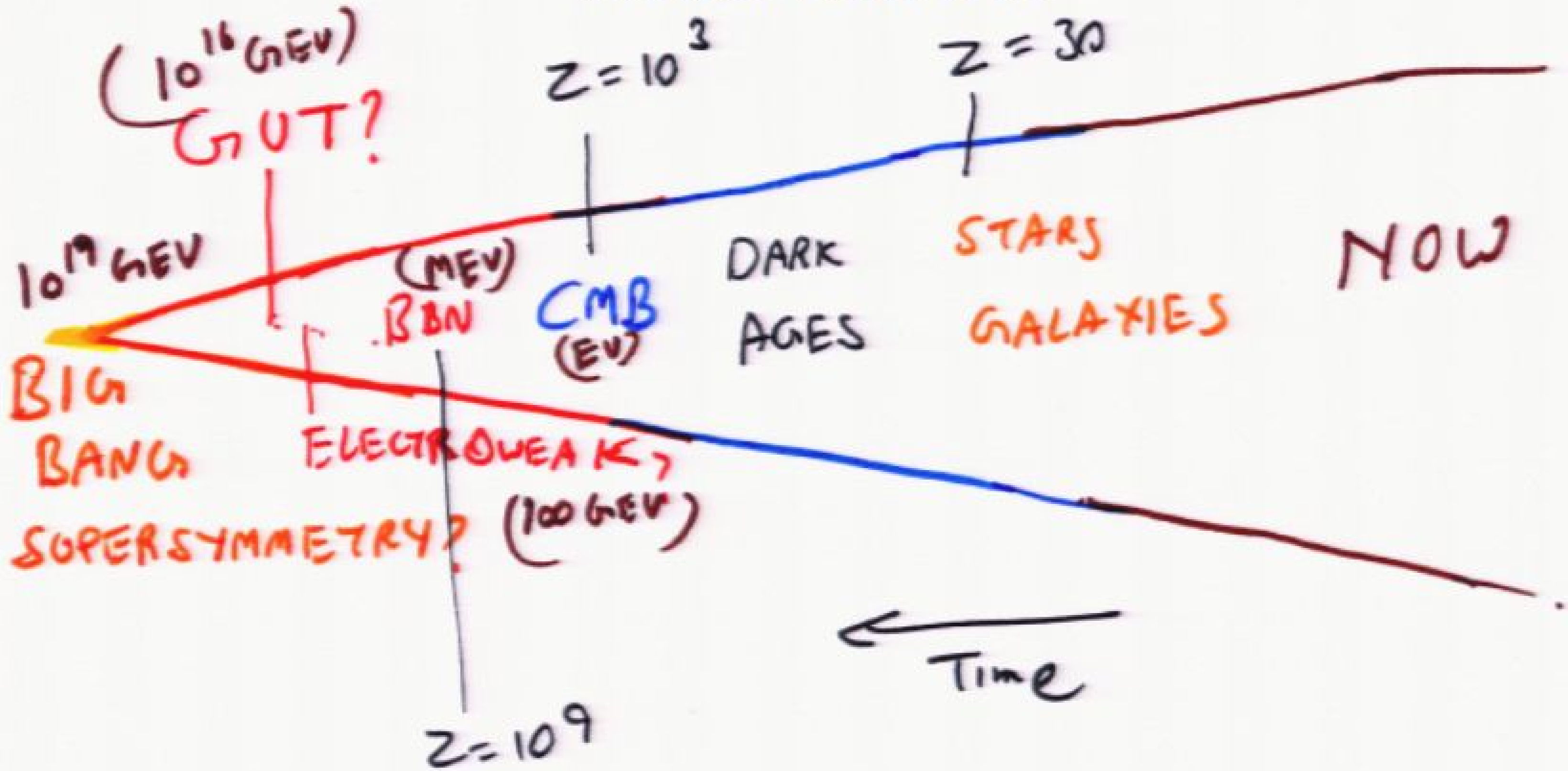

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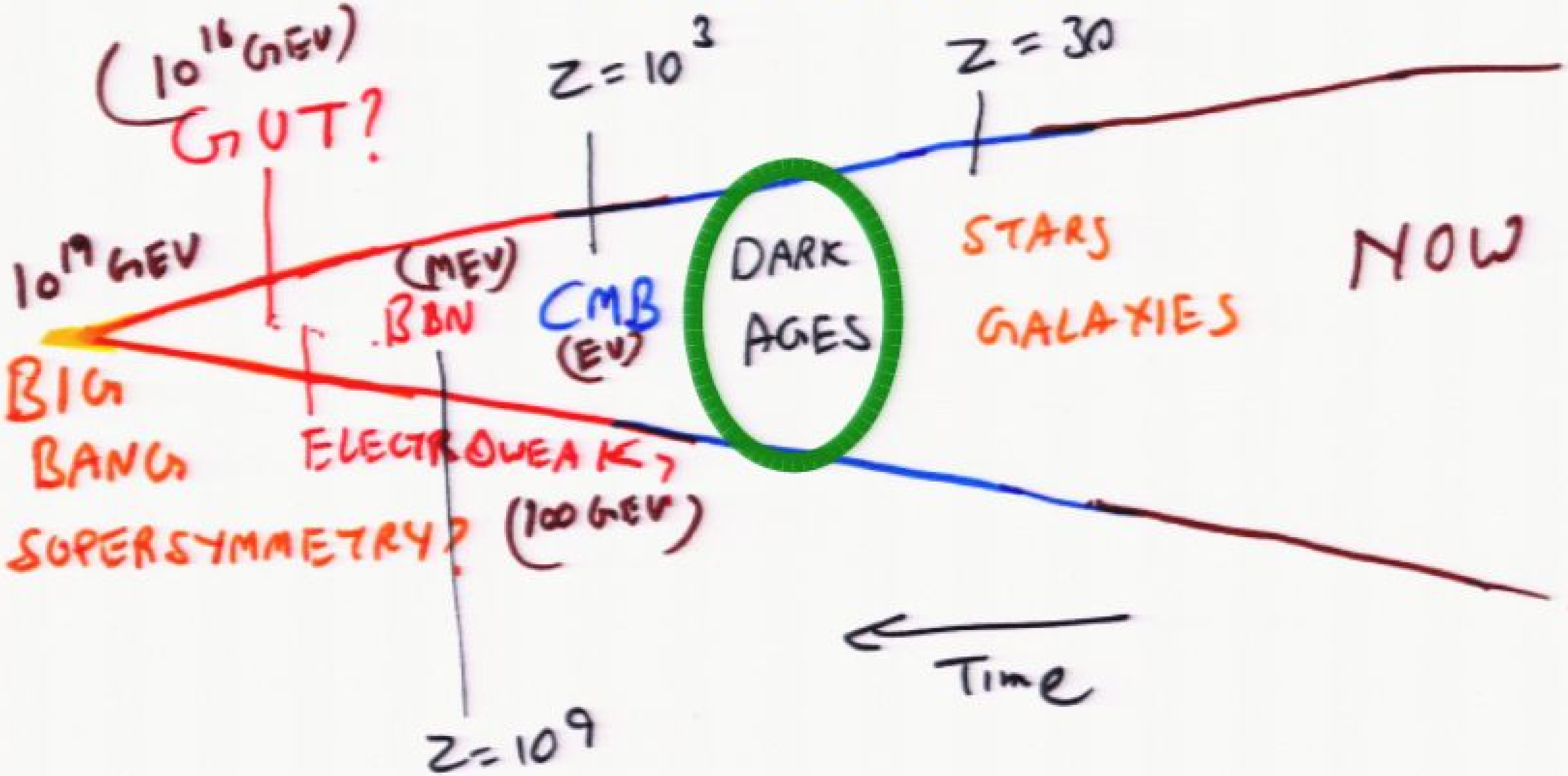

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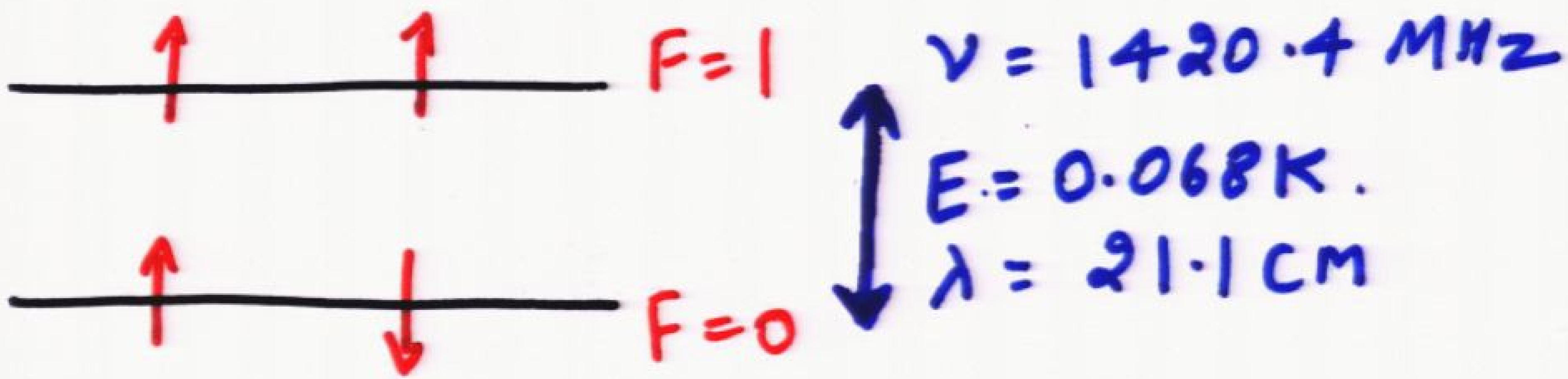
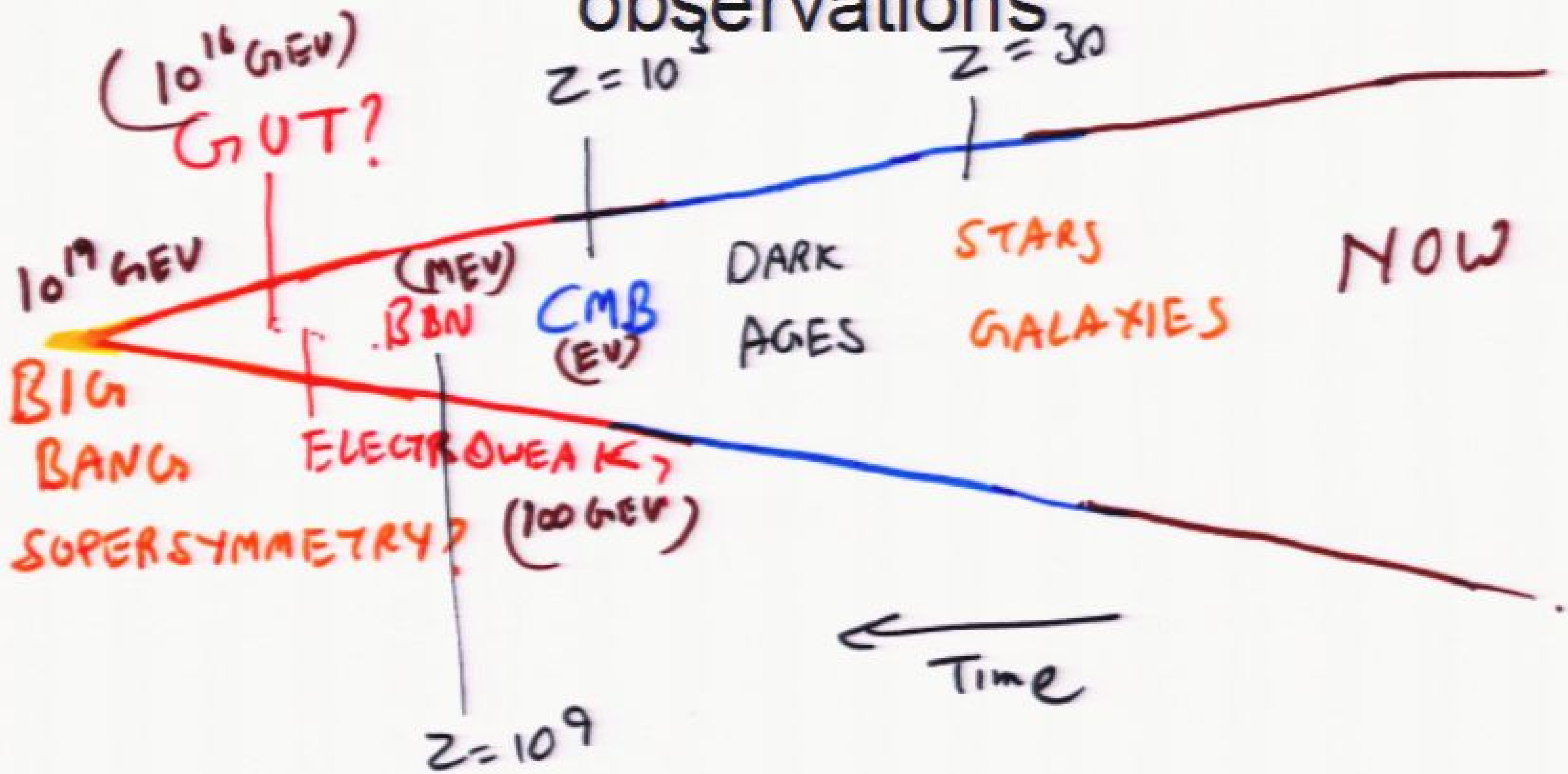
“Lighting up” the dark ages



Connecting the early Universe with astronomical observations



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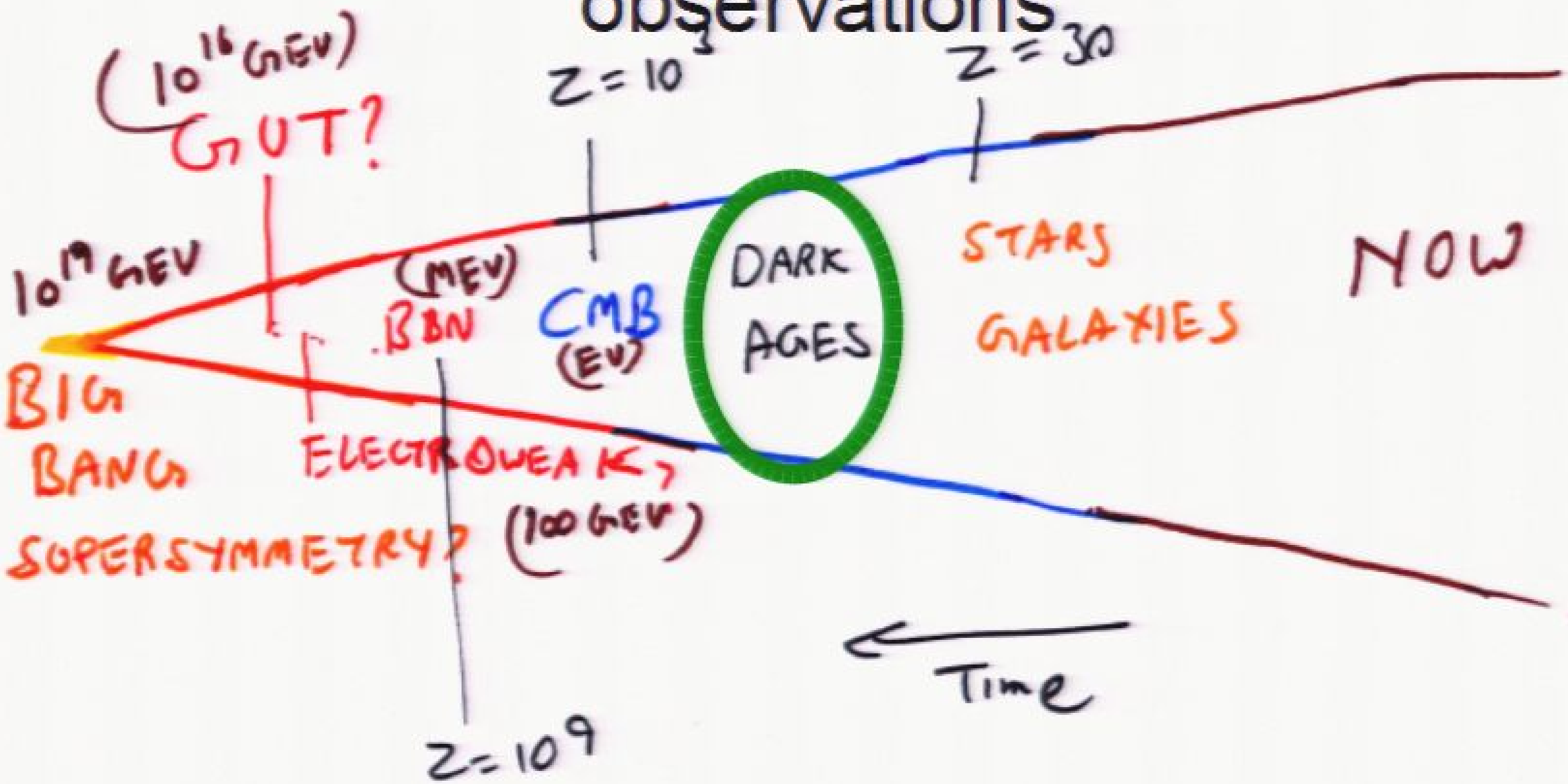
Connecting the early Universe with astronomical observations



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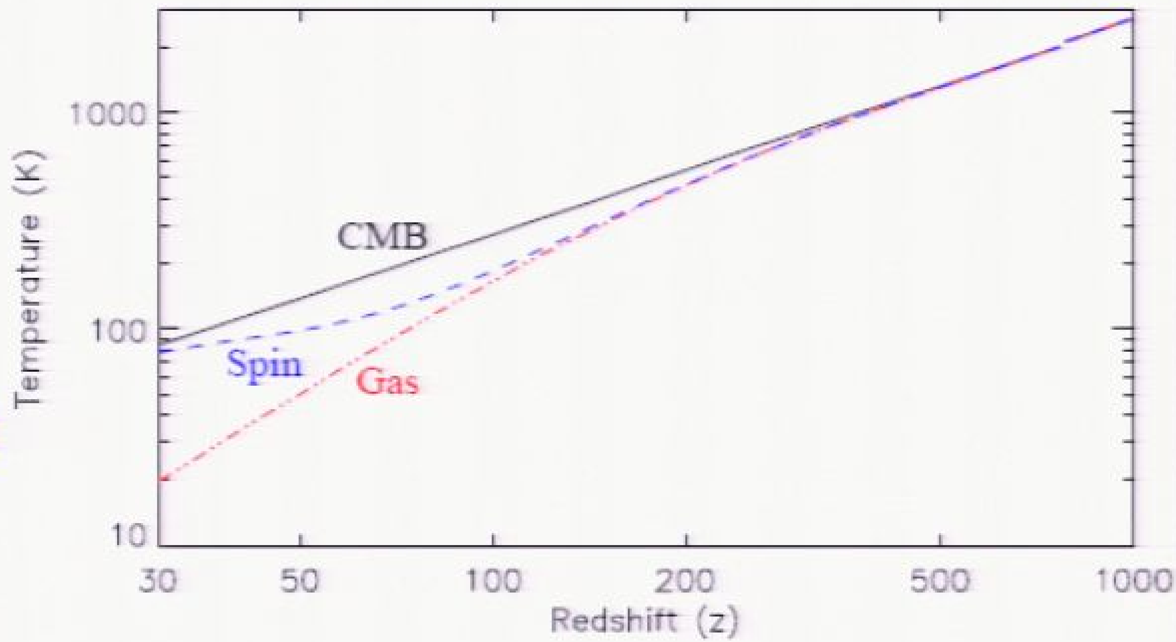
Thermal history of the Universe

- 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



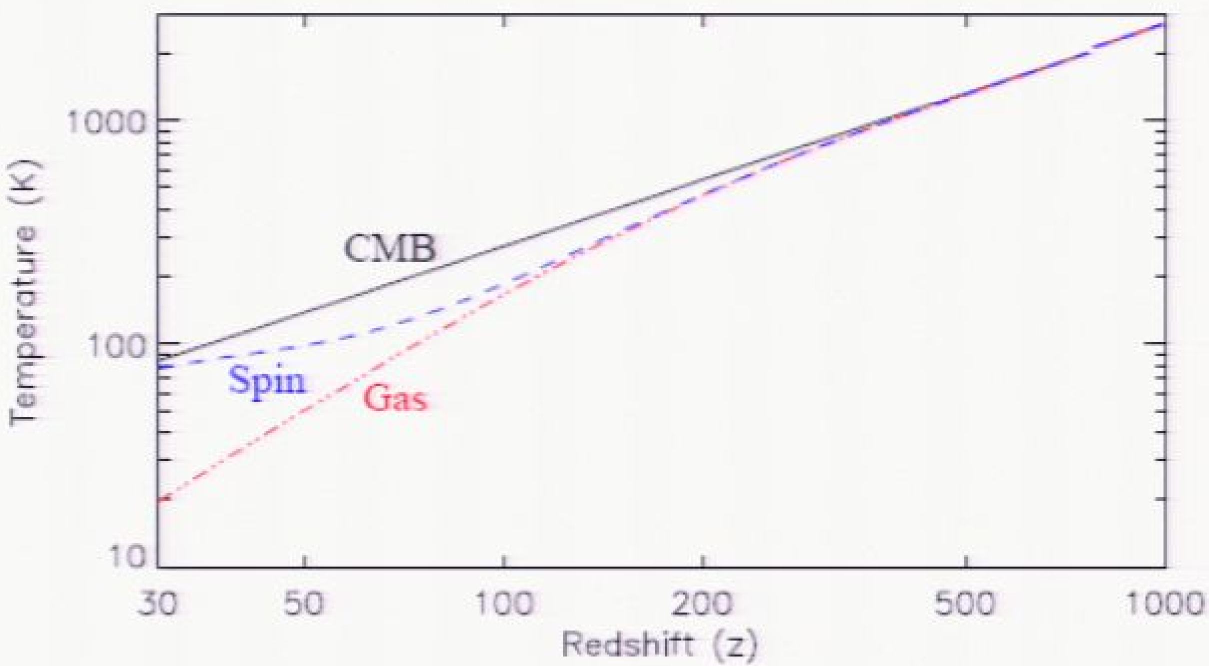
Loeb & Zaldarriaga 2004

The 21cm "brightness temperature"

Brightness temperature = Difference between Observed brightness and CMB

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

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



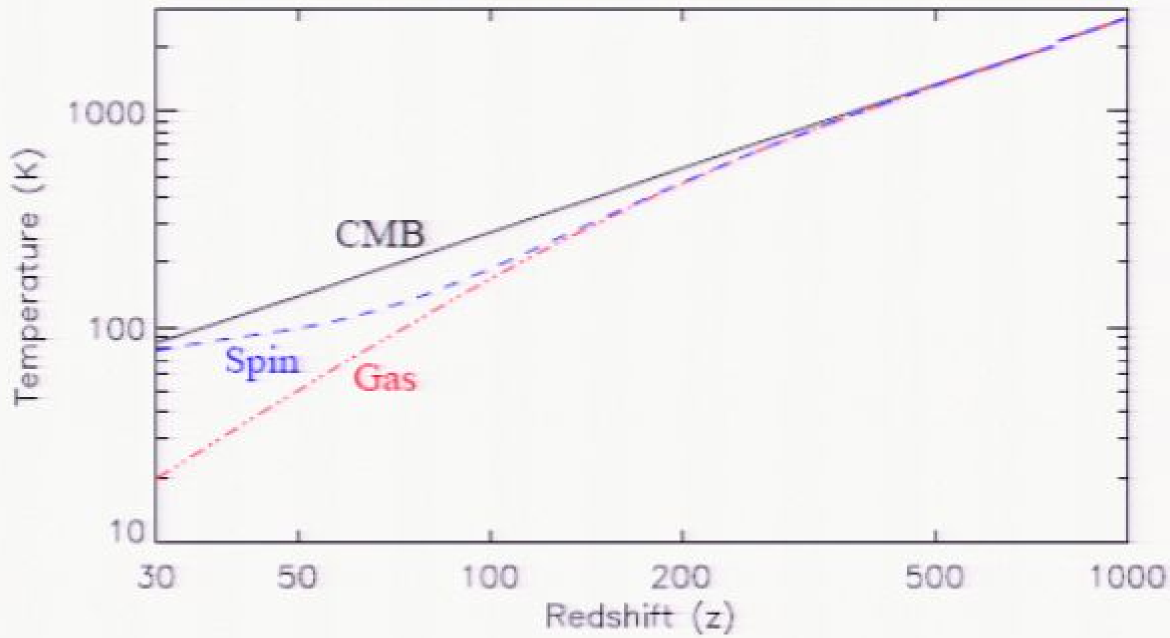
A new observational window

Dark ages:

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

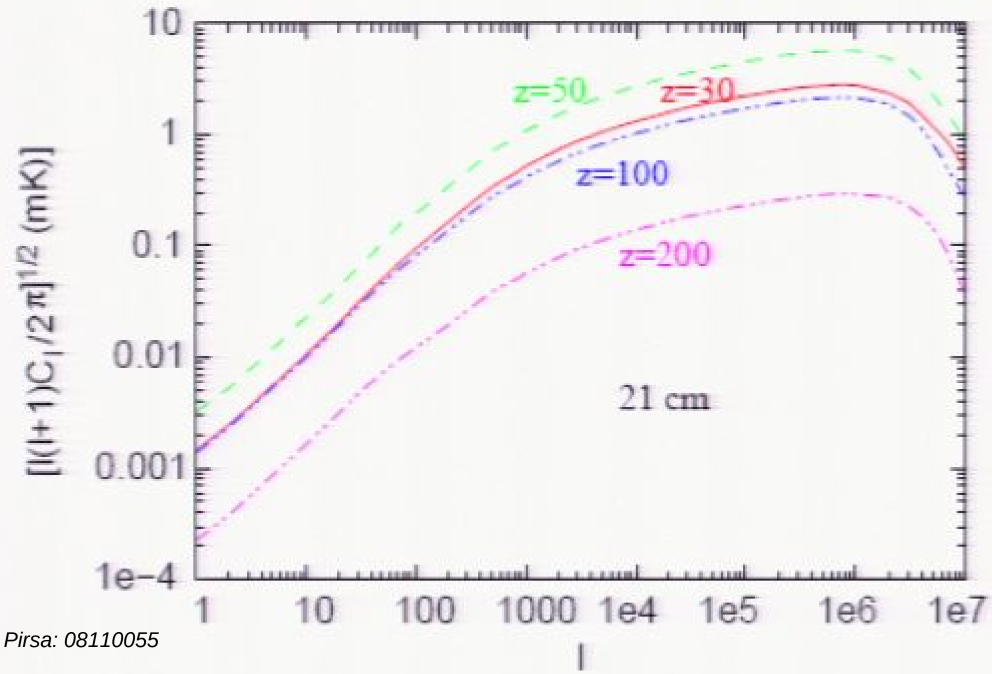
Epoch of reionization:

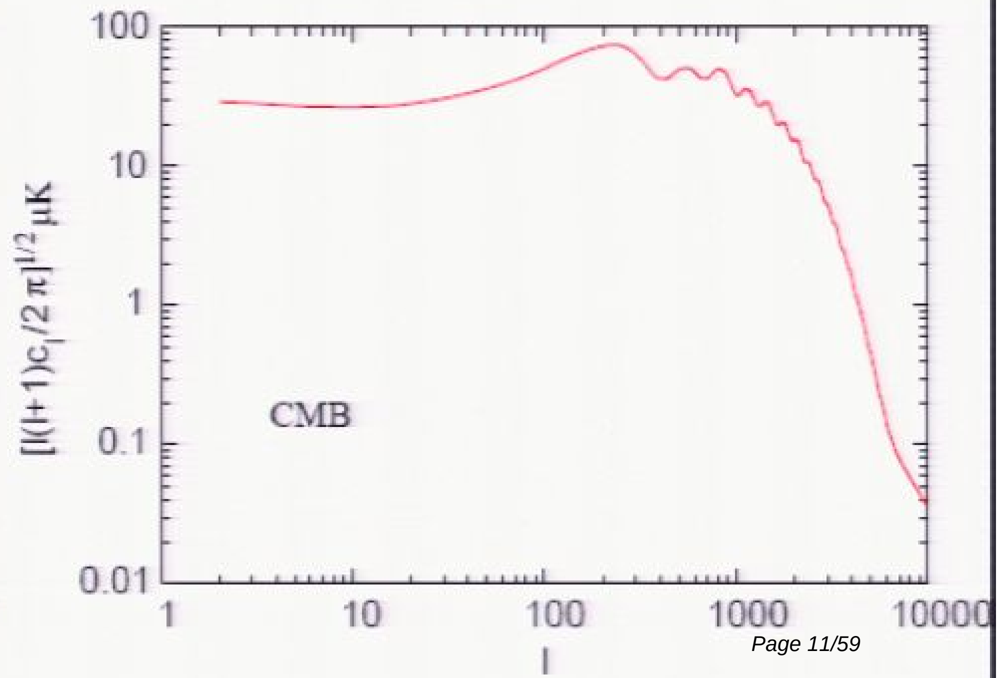
- $30 \geq z \geq 6$
- $46\text{MHz} \lesssim \nu \lesssim 200\text{MHz}$



A information rich observational window

- Smaller scales → 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)

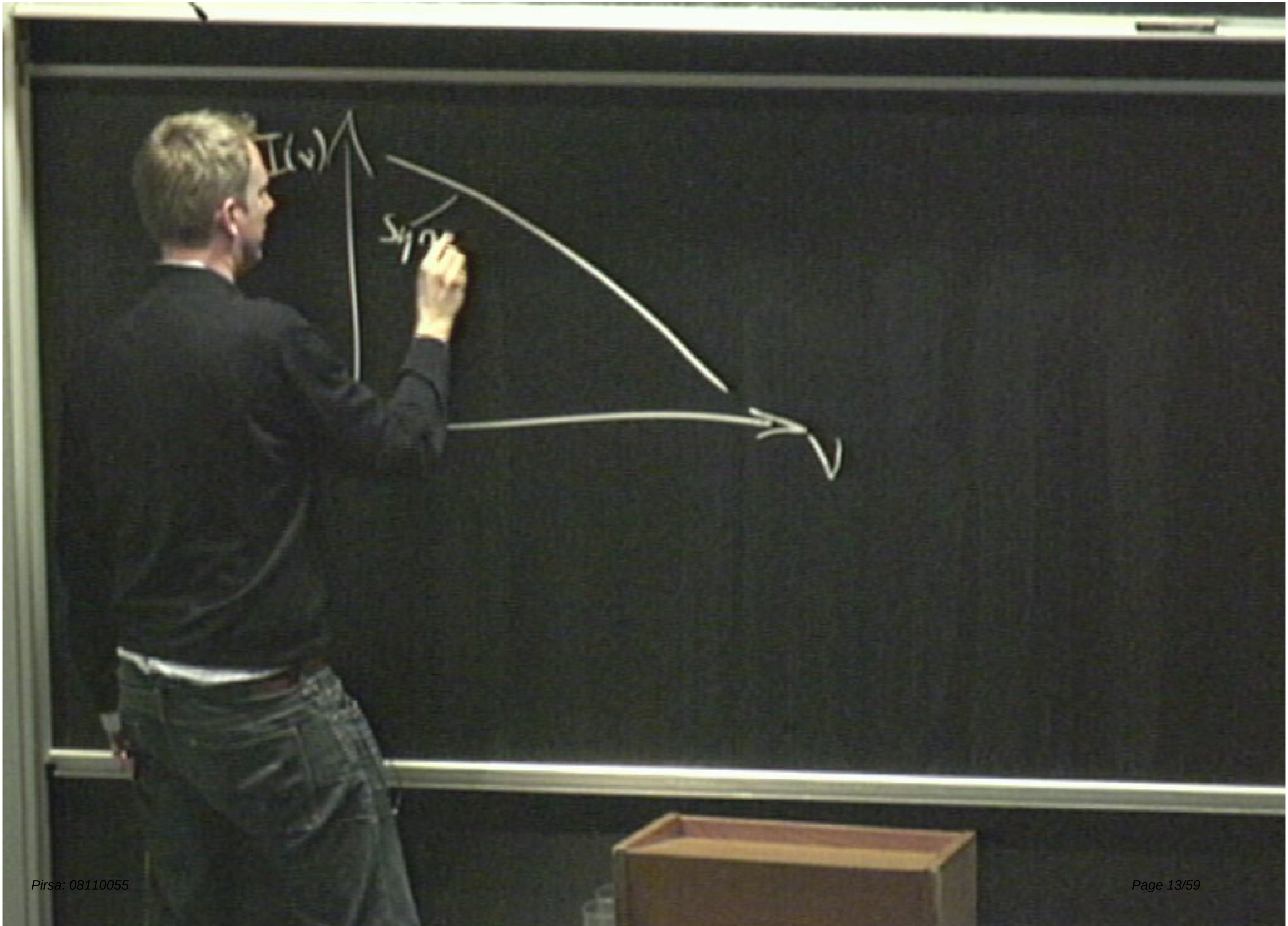


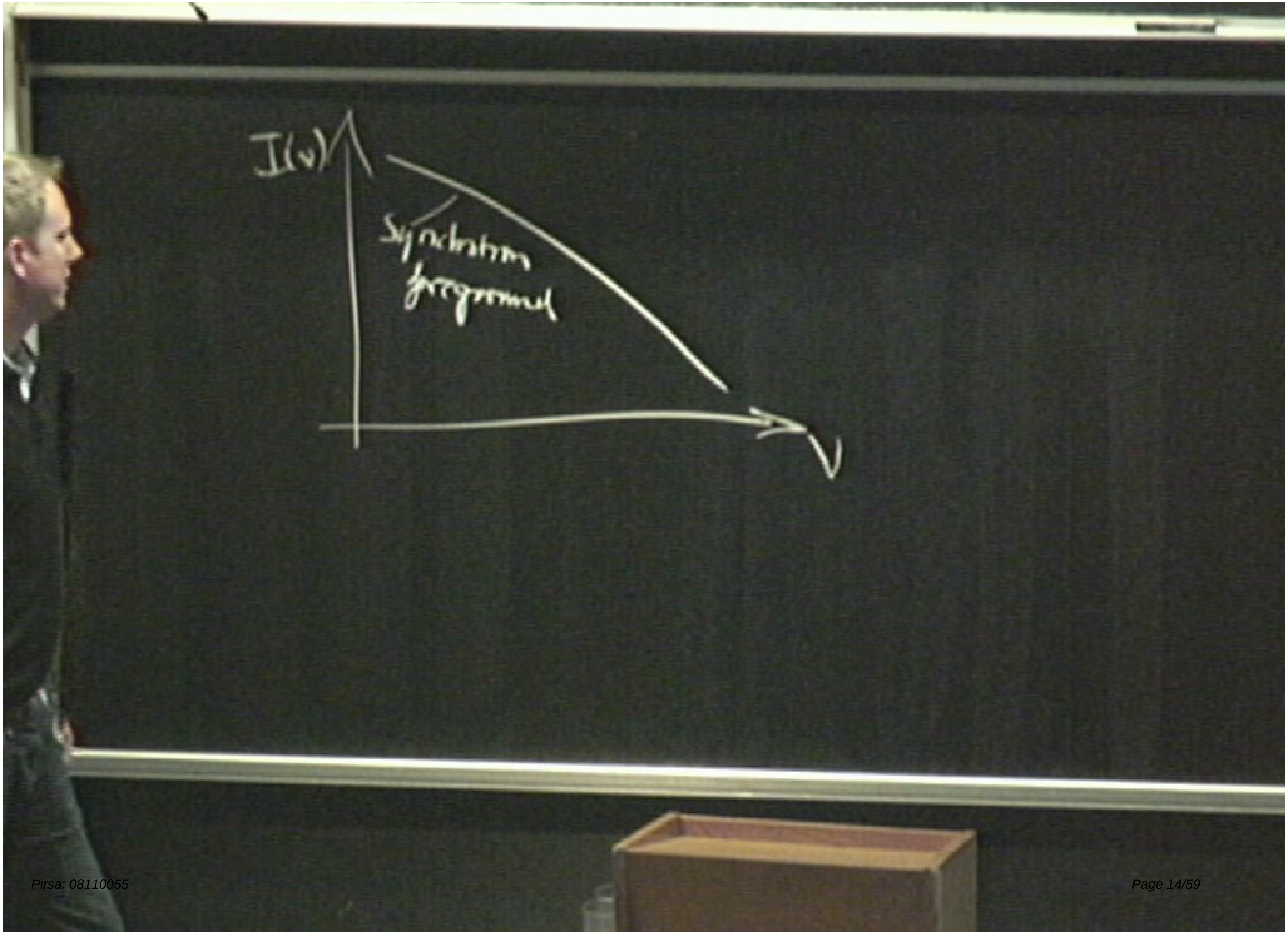


Fundamental Physics from 21cm radiation

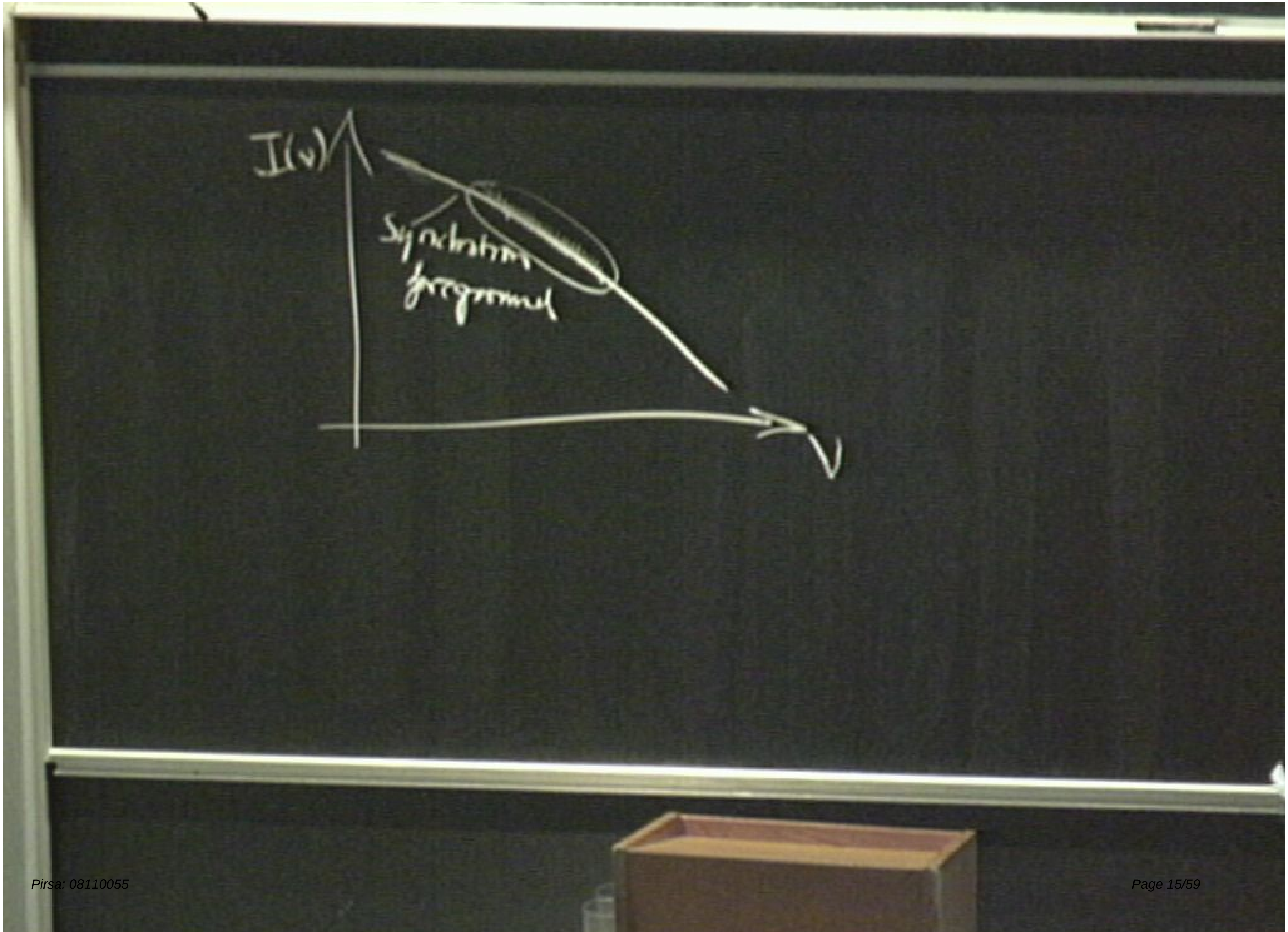
- Variations in the fine structure constant

- Cosmic (super-)strings


I(ν)
ν



I(ν)
ν


I(ν)
Synchrotron
foreground
ν

Why look for variations in the fine structure constant?

- Possible signature of physics beyond the standard model
- Test of the equivalence principle and hence for deviations from GR.
- Nature of dark energy may reveal itself in temporally or spatially changing constants

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Current constraints

Current constraints *(Garcia-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: $\delta\alpha/\alpha = (0.05 \pm 0.24) \times 10^{-5}$, $z = 1.1508$

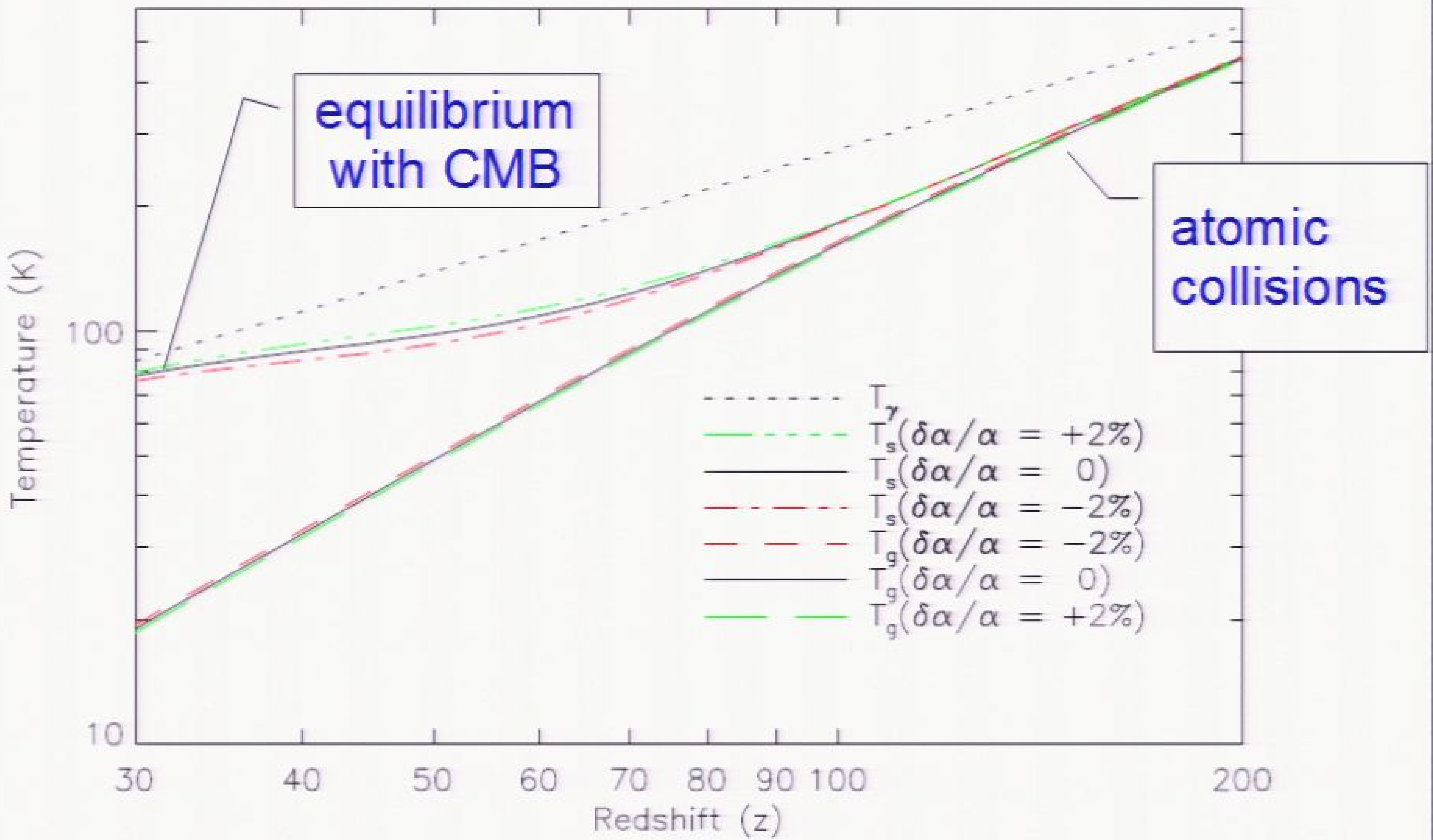
Existing constraints on $\delta\alpha/\alpha$

- Current best constraints are at z~5 from quasar spectra involving fine structure transitions: $\delta\alpha/\alpha<10^{-(4 \text{ or } 5)}$
- CMB limits are of order 3-9% (e.g. Rocha et al. 2004, Ichikawa et al 2006).
- BBN constraints are of order 10% (Cyburt et al 2005).
- No constraints for 10<z<1000, the dark ages.

21cm radiation reveals dark ages

- Thermal decoupling of hydrogen spin temperature from CMB leads to absorption of background CMB.
- The evolution of the spin temperature is set by
  - the Einstein Coefficients and
  - the collision cross section between neutral hydrogen atoms.
- All of these are sensitive to alpha – most of all the Einstein coefficient for spontaneous emission: it scales as α^{13} !

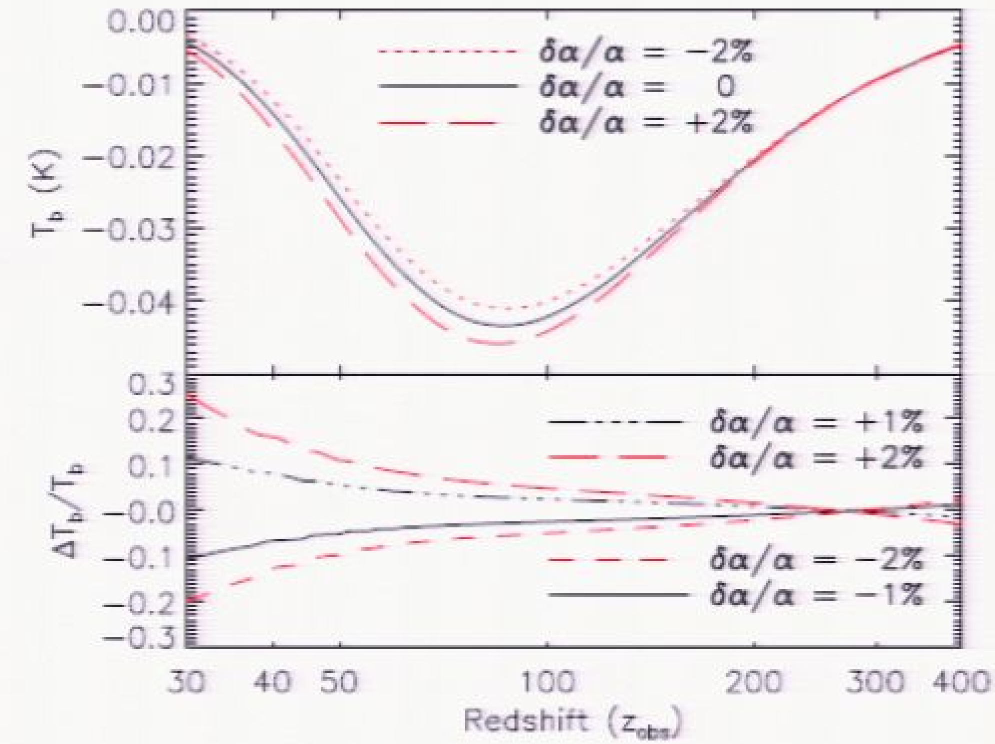
Gas thermal history is sensitive to δα/α

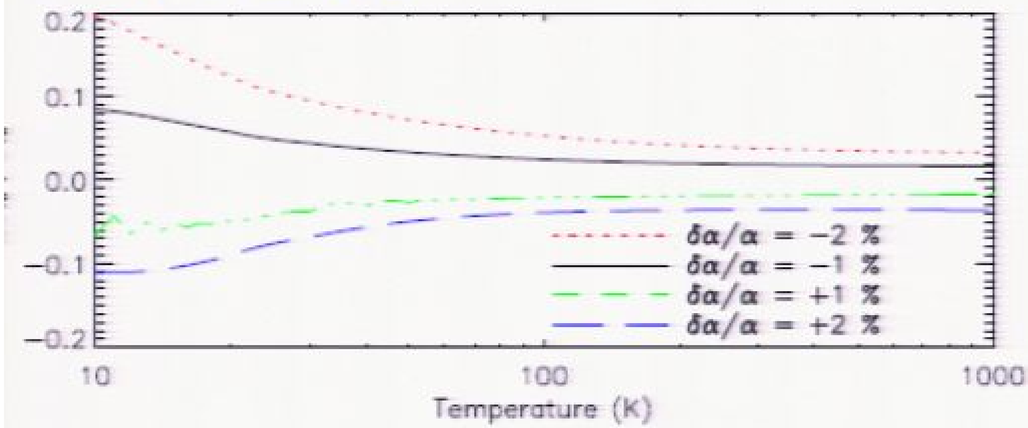


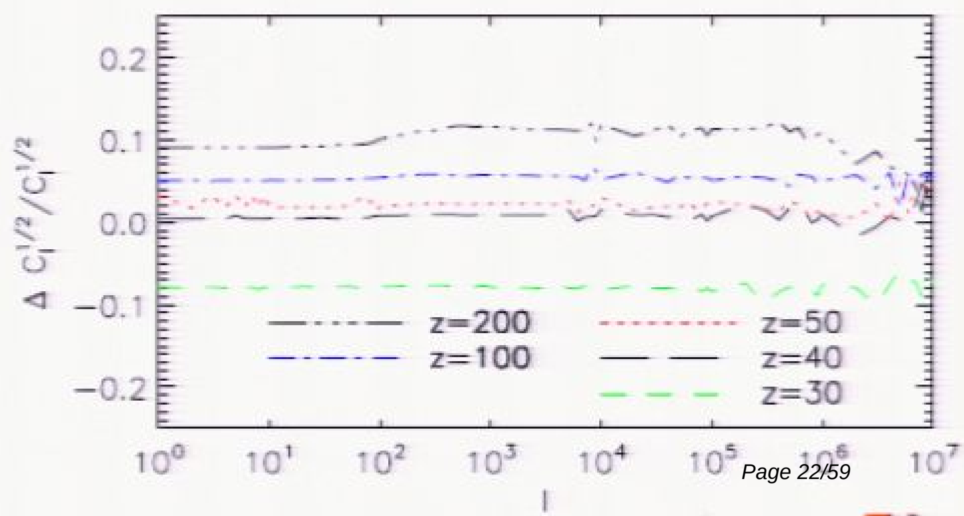
1 cm signal depends strongly on the
ne structure constant.

hatri & Wandelt 2007)

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







Is this measurable?

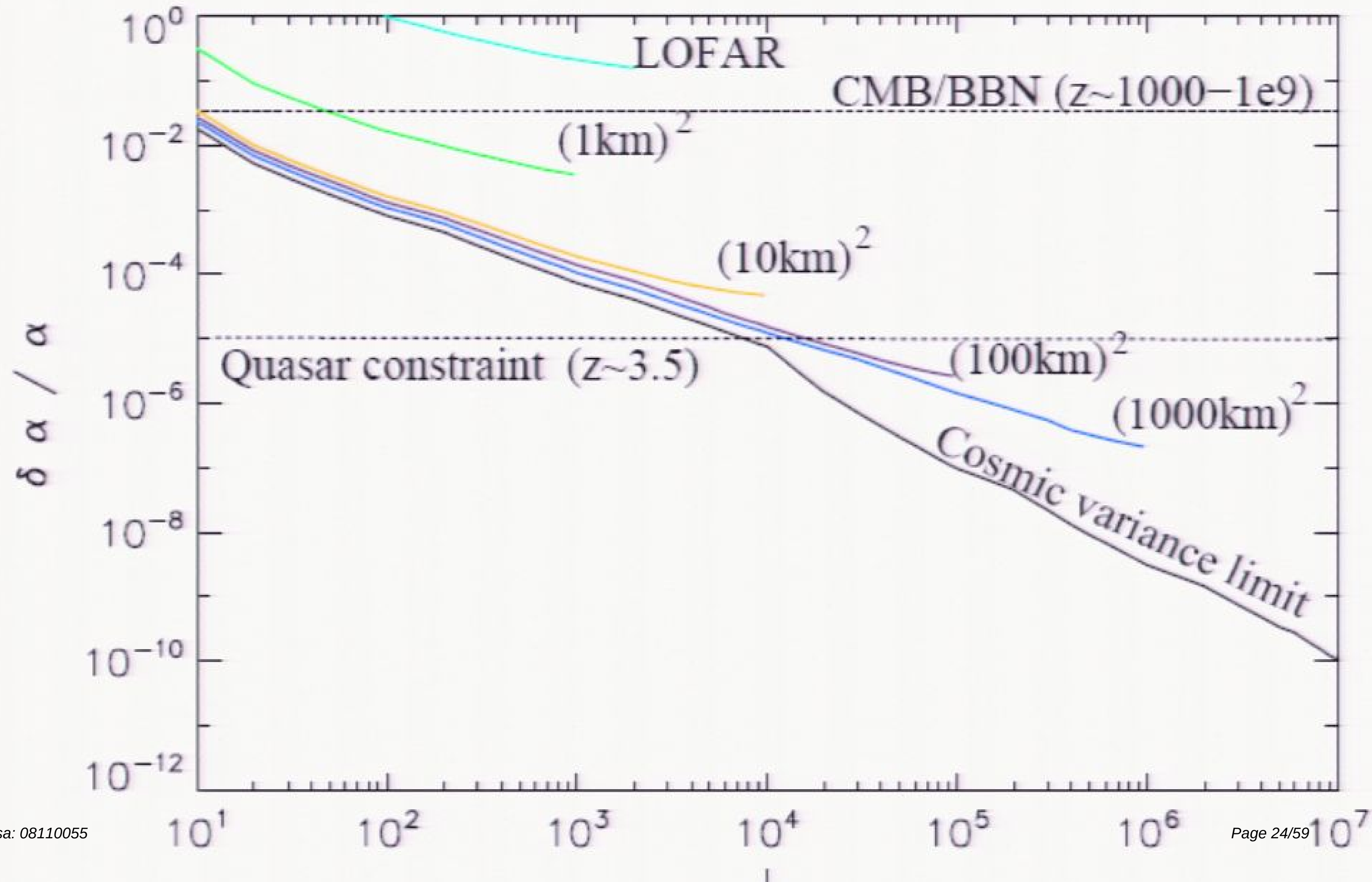
- First consider *sensitivity:*
- For 2000 hours with one station of LWA (starts in 2007!) one can limit

$$\delta\alpha/\alpha<1\%$$

- Within four years the sensitivity could be increased to

$$\delta\alpha/\alpha\sim0.3\%$$

- This is competitive with Planck and probes a new redshift range.


LOFAR
CMB/BBN (z~1000−1e9)
(1km)^2
(10km)^2
Quasar constraint (z~3.5)
(100km)^2
(1000km)^2
Cosmic variance limit
$\delta\alpha / \alpha$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^1
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10^3
10^4
10^5
10^6
10^7

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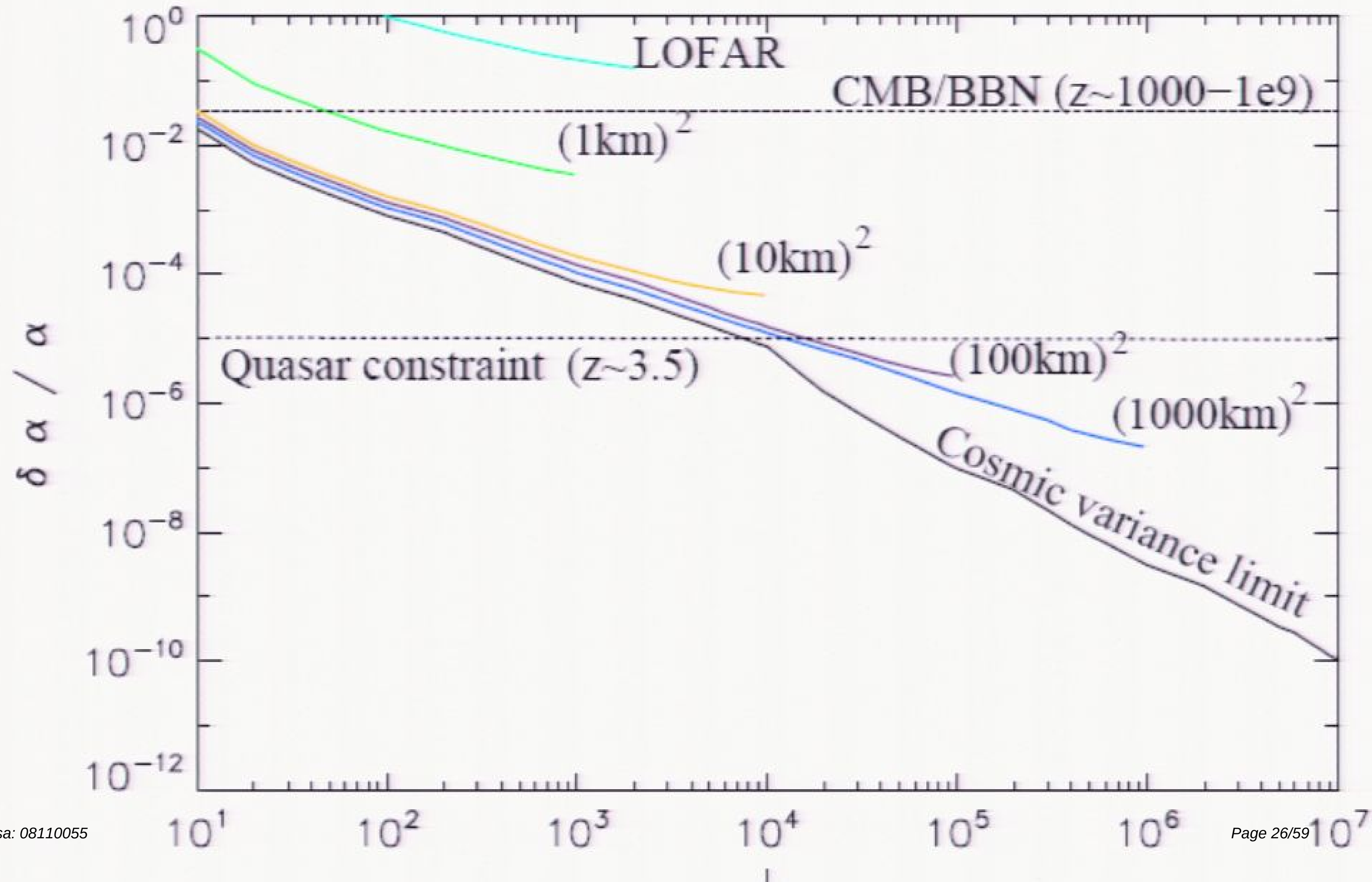

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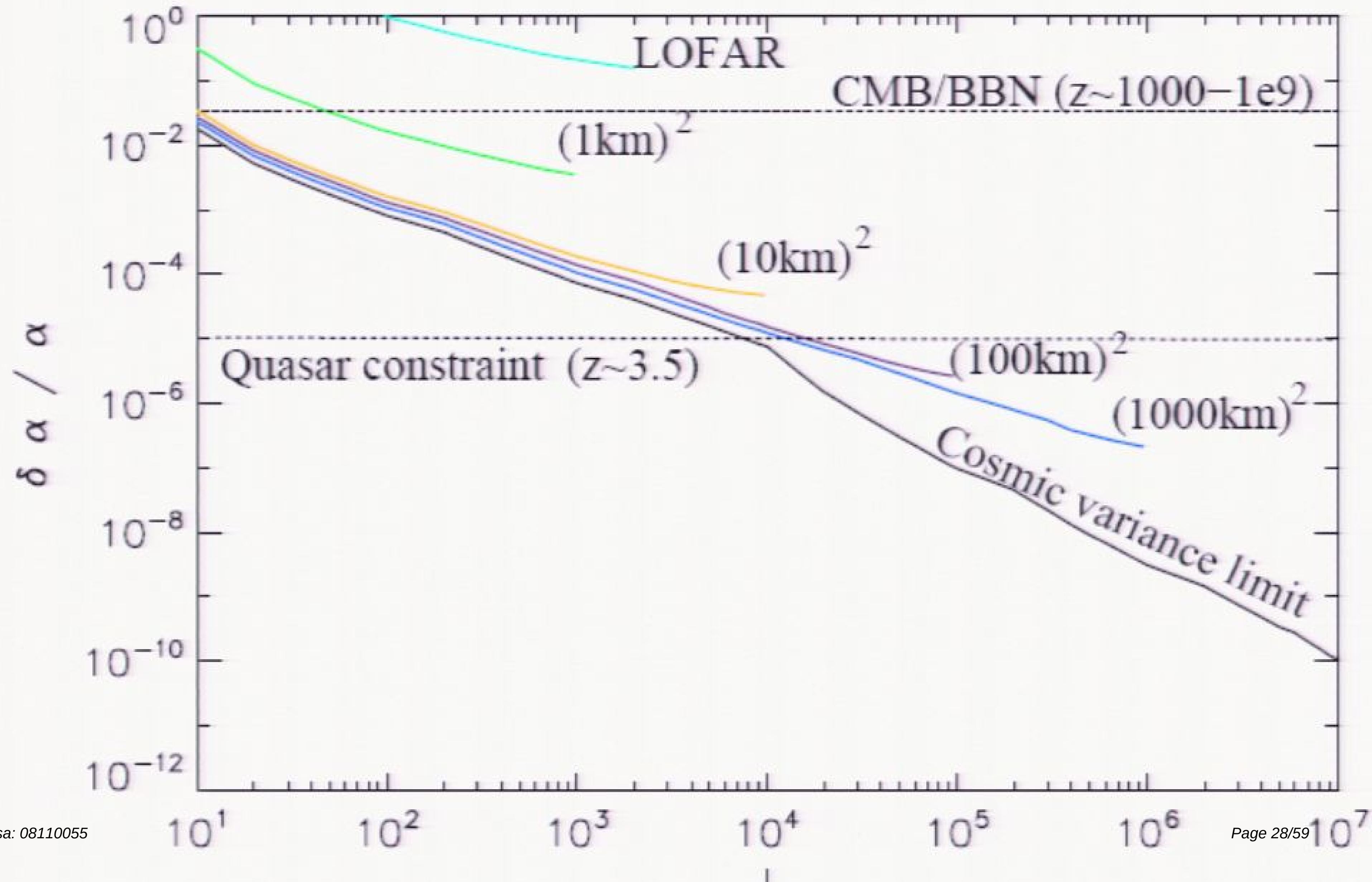

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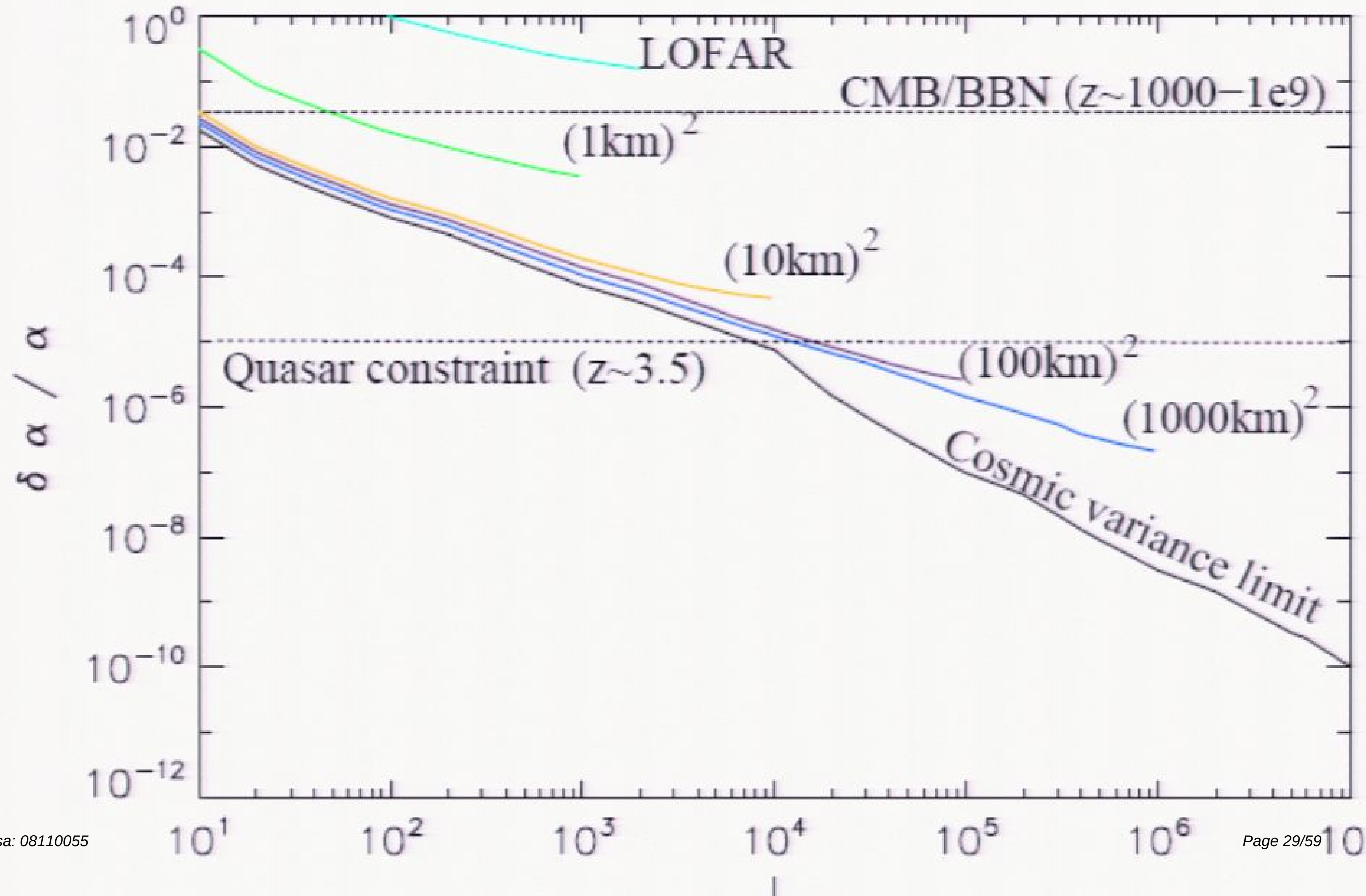

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10^{7}

Caveat

- While the sensitivity estimates include the foreground contribution to the noise temperature, they do not include the error due to foreground subtraction.
- The signal is of order 10mK and foregrounds are of order 10,000K. So we need to be able to model the mean foreground in the observed patch to 1 part in 10^6 over 1 decade in frequency.
- Feasibility depends on how close to a power law the foreground emission is.

Q: Is there any way to get around foregrounds?

$\delta\alpha/\alpha$ also affects amplitude of brightness temperature *fluctuations*

- Fluctuations in the brightness temperature arise from density fluctuations in the gas.
- These fluctuations are on very small scales – this allows them to be distinguished from smoothly varying foregrounds.
- The amplitude of these fluctuations is proportional to the brightness fluctuations.
- Measuring the variance of the fluctuations is then sensitive to $\delta\alpha/\alpha$.
- But the amplitude of this signal is 10 times less, so now sensitivity is more challenging.

Cosmic (super-)string constraints from 21cm radiation

- Why cosmic strings?
- Why cosmic superstrings?
  - Inflation can enlarge fundamental strings (or stringy objects) to superhorizon size.
- Why 21cm radiation?

Why cosmic strings?

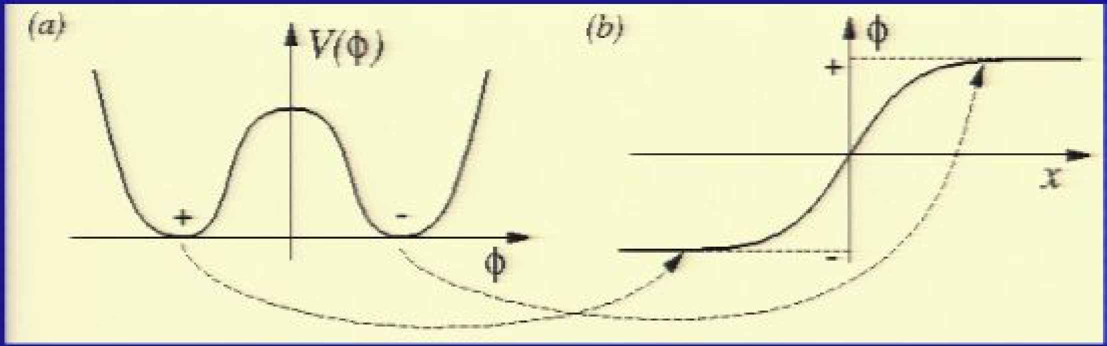
- What are cosmic strings?
- How do they form and why should we not be surprised if they exist?
- Cosmic string dynamics
- Perturbations from cosmic strings

What are cosmic strings?

- Cosmic strings are *topological defects.*
- Topological defects are relics of phase transitions in the early Universe, (e.g. the GUT or electroweak phase transition), when the Universe went from a more symmetric to a less symmetric state.
- Defects are places where the Universe cannot relax to the new energy minimum because its efforts are frustrated. TDs are frustrated by topology

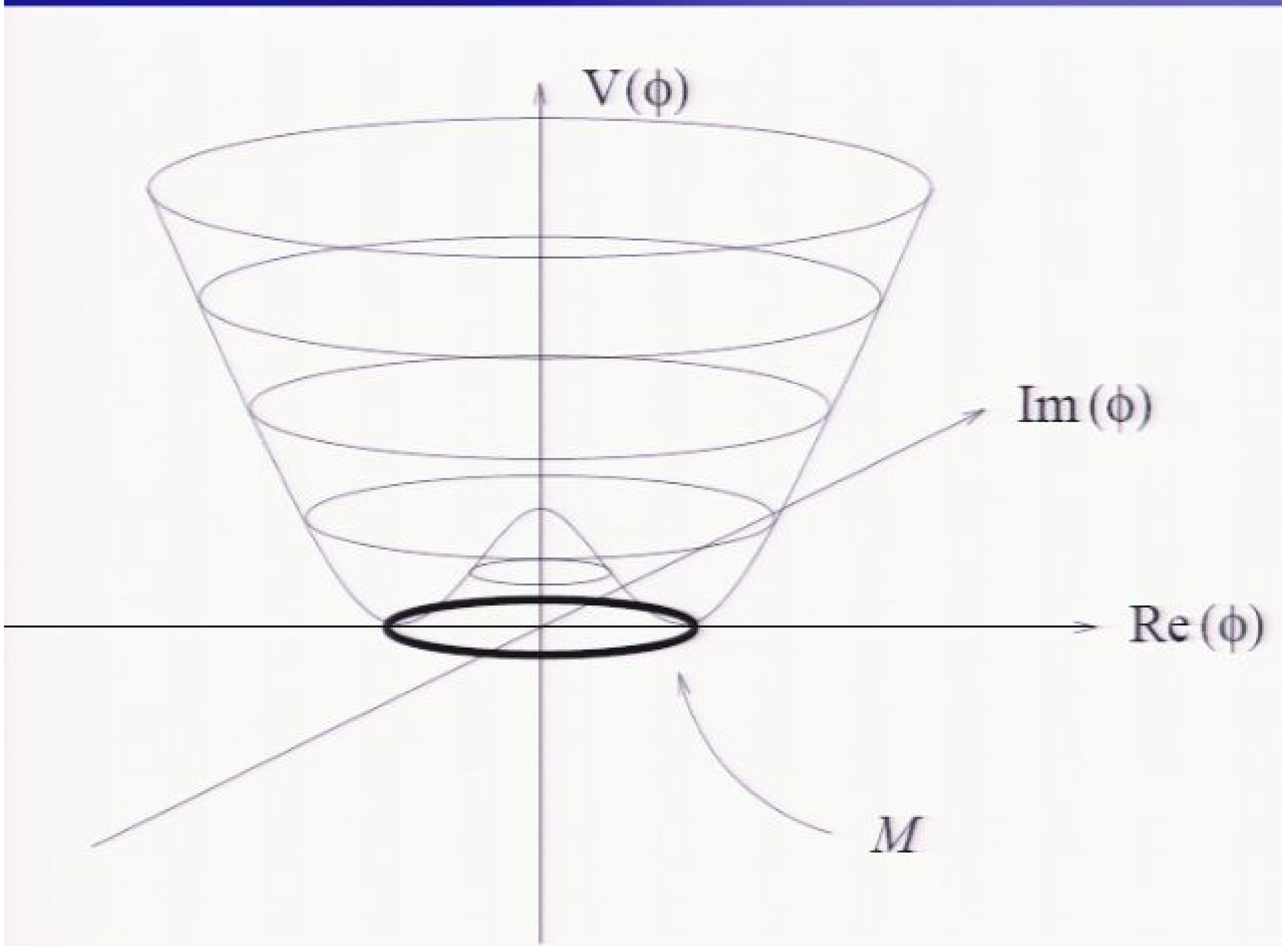
Warmup: Domain Walls

- You already encountered domain walls in Linde's lecture.
- Domain walls occur when a Z_2 symmetry is broken.
- They are sheet-like.



- Bad news: energy density scales as 1/a with expansion

What are Cosmic Strings?



Mexican Hat potential

- Strings are line-like defects.
- They occur when a cylindrical symmetry is broken.

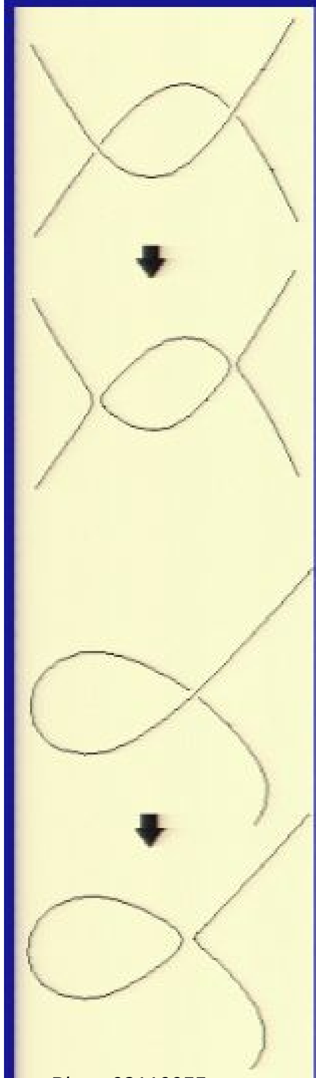
Weird and wonderful properties of Cosmic Strings

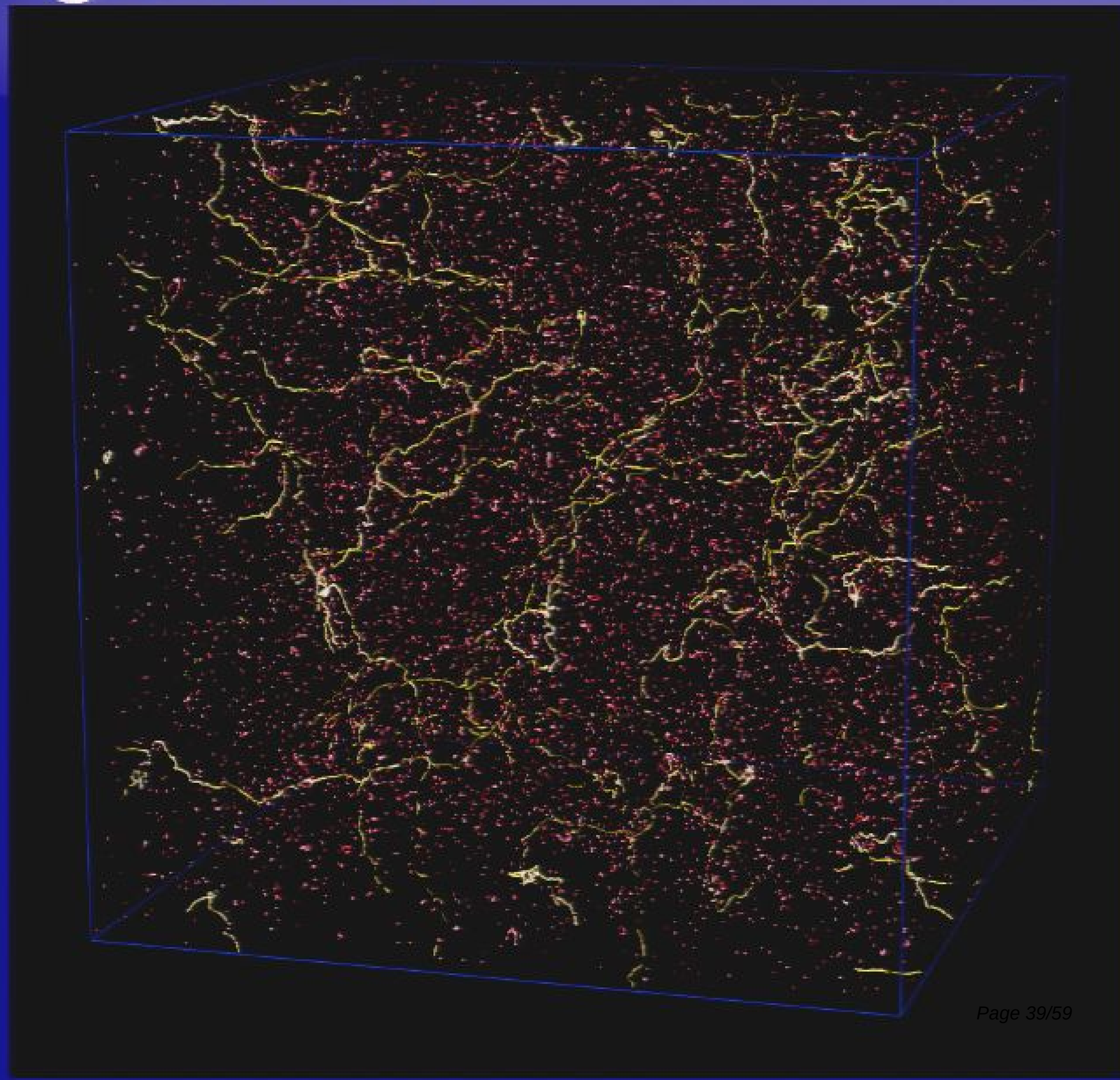
- Cosmic strings have an *angle deficit*
- They act as lenses.
- They couple to gravity and source scalar, vector and tensor perturbations,
- A cuspy string can burst particles.
- Kinky strings and loops will radiate gravitational waves.

Rules of cosmic string dynamics

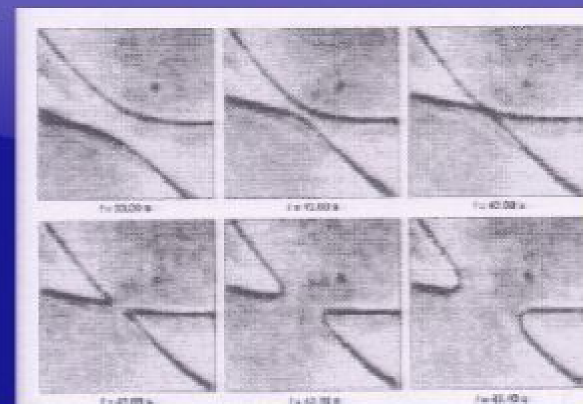
- Strings move such as to minimize the world-sheet area they sweep out.
- They are so massive, that they ignore other matter – the stiff approximation.
- When strings come close to each other, the details of the field theory matter.
  - Strings will intercommute when they intersect
  - Strings with opposite winding numbers will annhiliate.

Cosmic String Movies

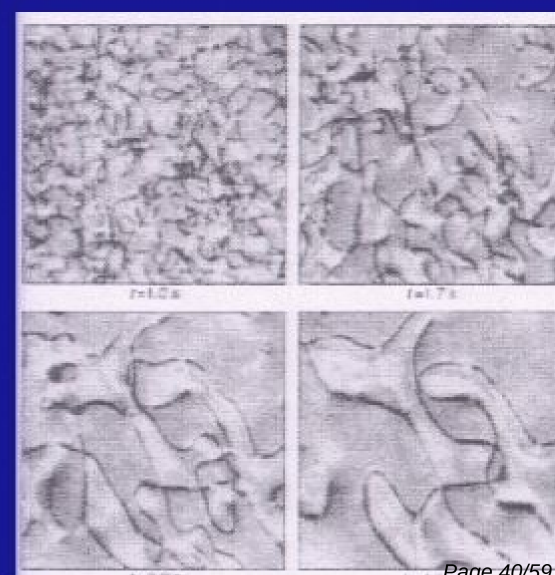




String-like Topological Defects do exist in Nature



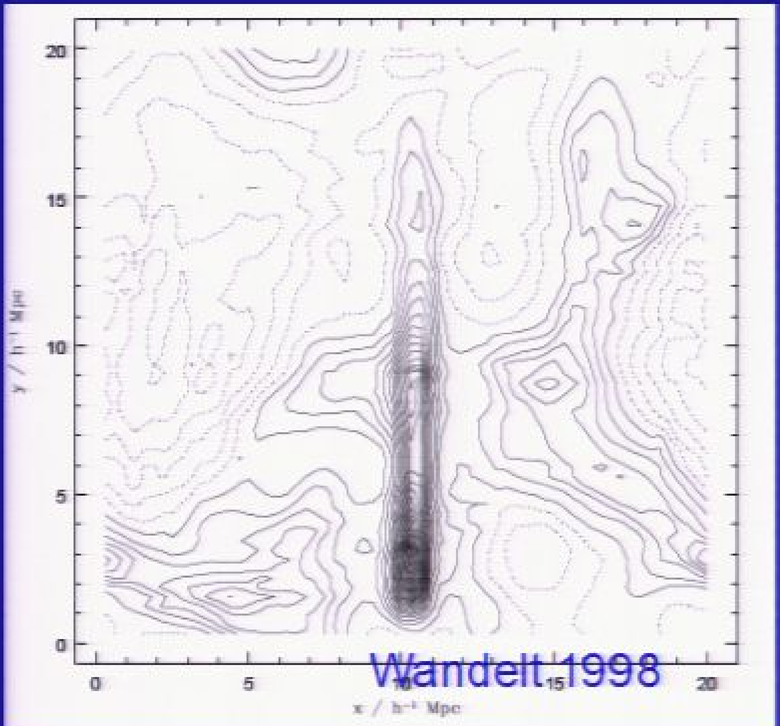
- They really are generic.
- C.S.s occur in phase transition in condensed matter systems
  - Nematic liquid crystals



  - Liquid Helium

String wakes

- Due to their angle deficit, strings kick matter behind them when they move
- This produces a wake.
- The overdensity in this wake *starts out* at 2.



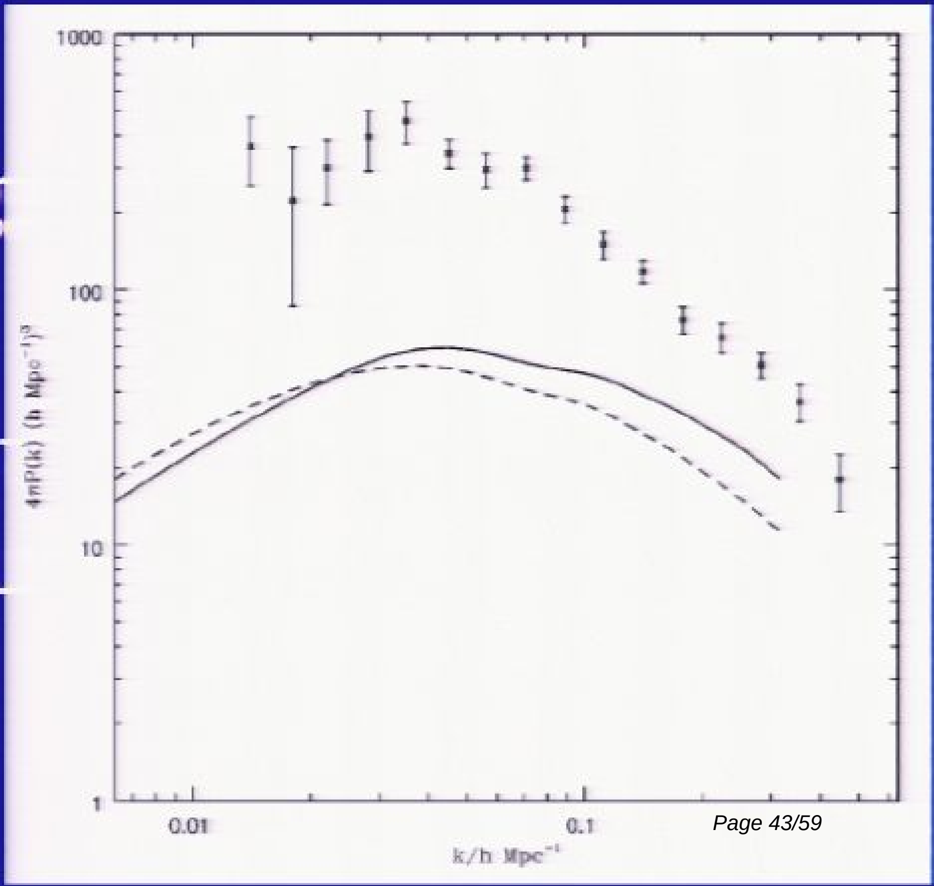
Perturbations from cosmic string: The active perturbation equations

$$\ddot{\delta}_c + \frac{\dot{a}}{a}\dot{\delta}_c - \frac{3}{2}\left(\frac{\dot{a}}{a}\right)^2 (\Omega_c\delta_c + 2\Omega_r\delta_r) = 4\pi(\Theta_{00} + \Theta)$$

$$\ddot{\delta}_r - \frac{1}{3}\nabla^2\delta_r - \frac{4}{3}\ddot{\delta}_c = 0.$$

Observational status of cosmic strings

- Strings overproduce CMB anisotropies for a given amount of large scale structure.
- WMAP limits line density of cosmic strings to $G\mu \sim 10^{-7}$
- This means that at most 10% of the CMB are due to cosmic strings



Vachaspati and Pogosian 1999

Bevis et al 2007

Why cosmic superstrings? (I)

- Polchinksi 2003, 2004: inflation can grow fundamental superstrings (or other stringy objects) to cosmic sizes. (hep-th 0410082)

- These have very similar macroscopic dynamics as cosmic strings so same methods can be revived to study them.

- Important additional parameter: p, the intercommutation probability

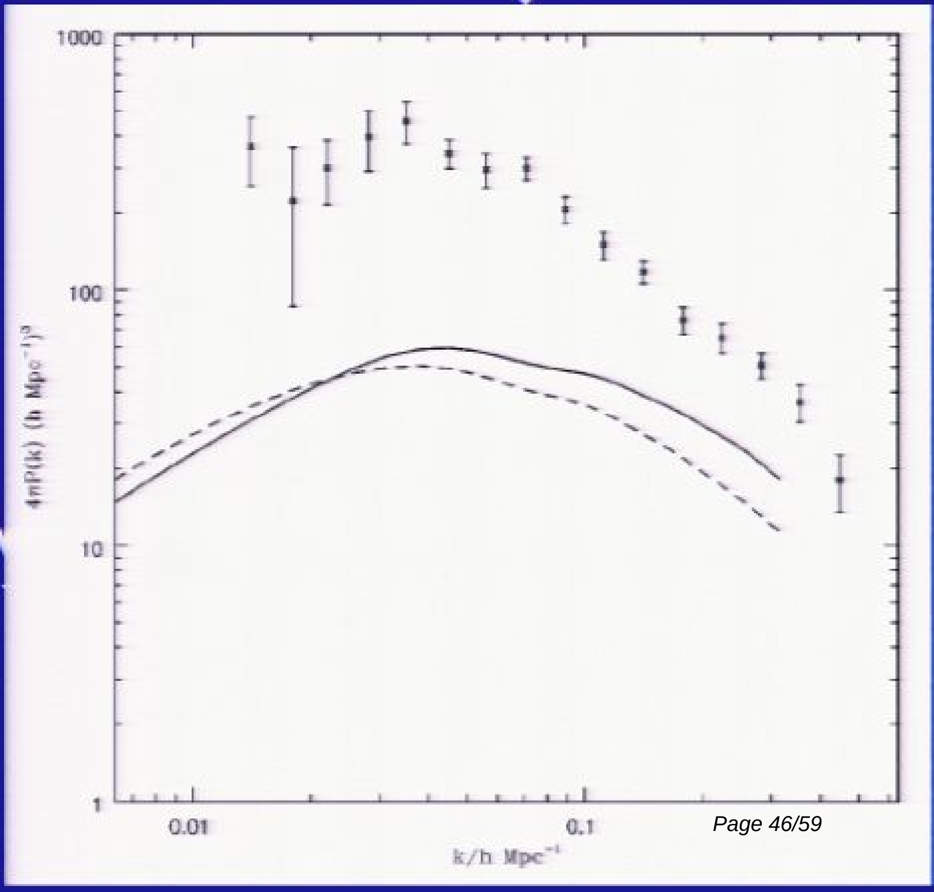
Why cosmic superstrings? (II)

- Cosmic superstrings will have the same line density as when they started out
- So constraining the line density of cosmic superstring constrains E_{string}, the fundamental parameter in string theory.
- Theoretical estimate based on supersymmetry and grand unification: $E_{string} \sim E_{Planck}/1000 \sim 10^{16}$GeV

Why 21cm radiation?

- Looking at the P(k) from cosmic string we noticed that string produce relatively more small scale power than inflation.

- This is in addition to immediate non-linearity of wakes.

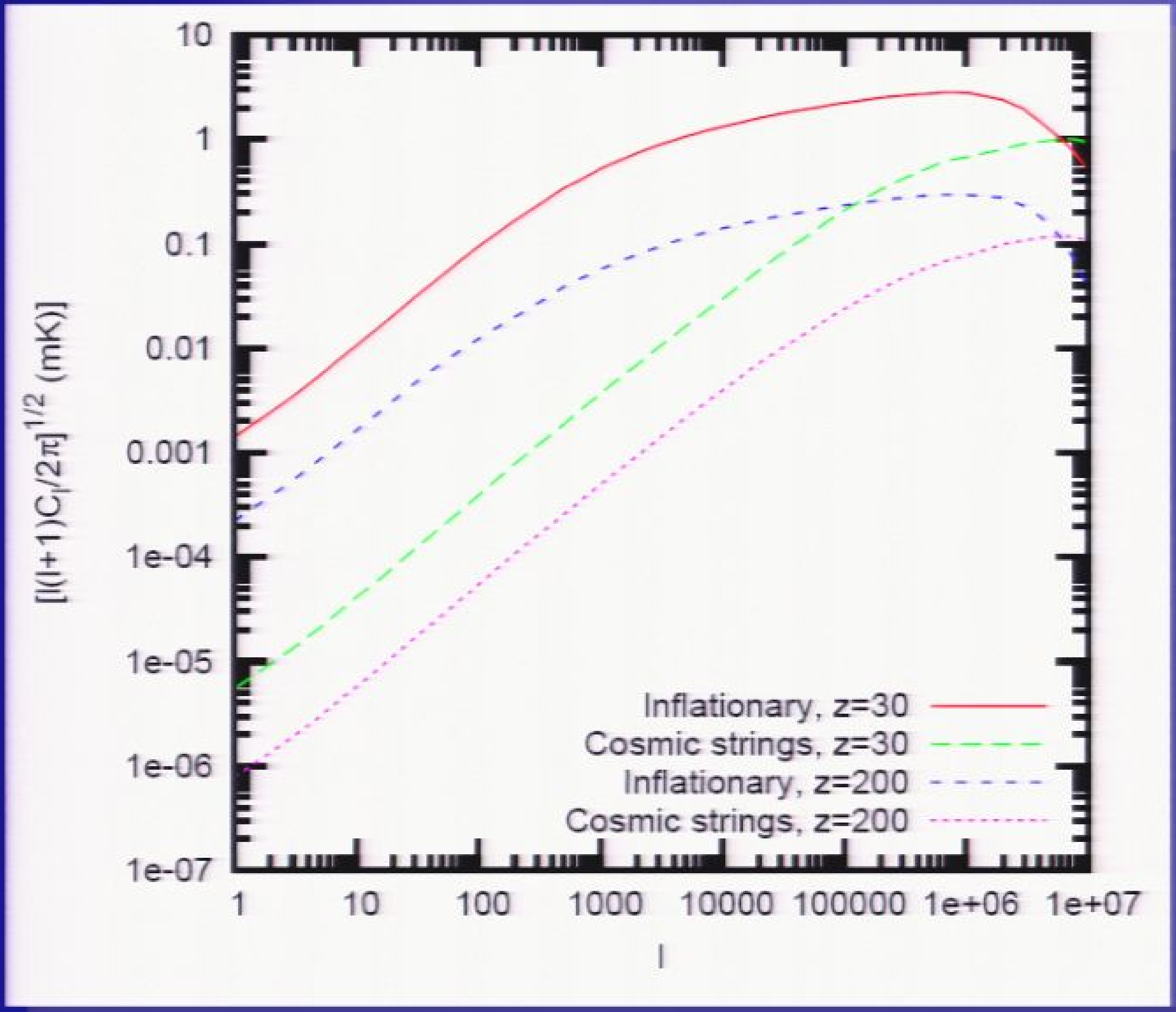


The promise of 21cm absorption

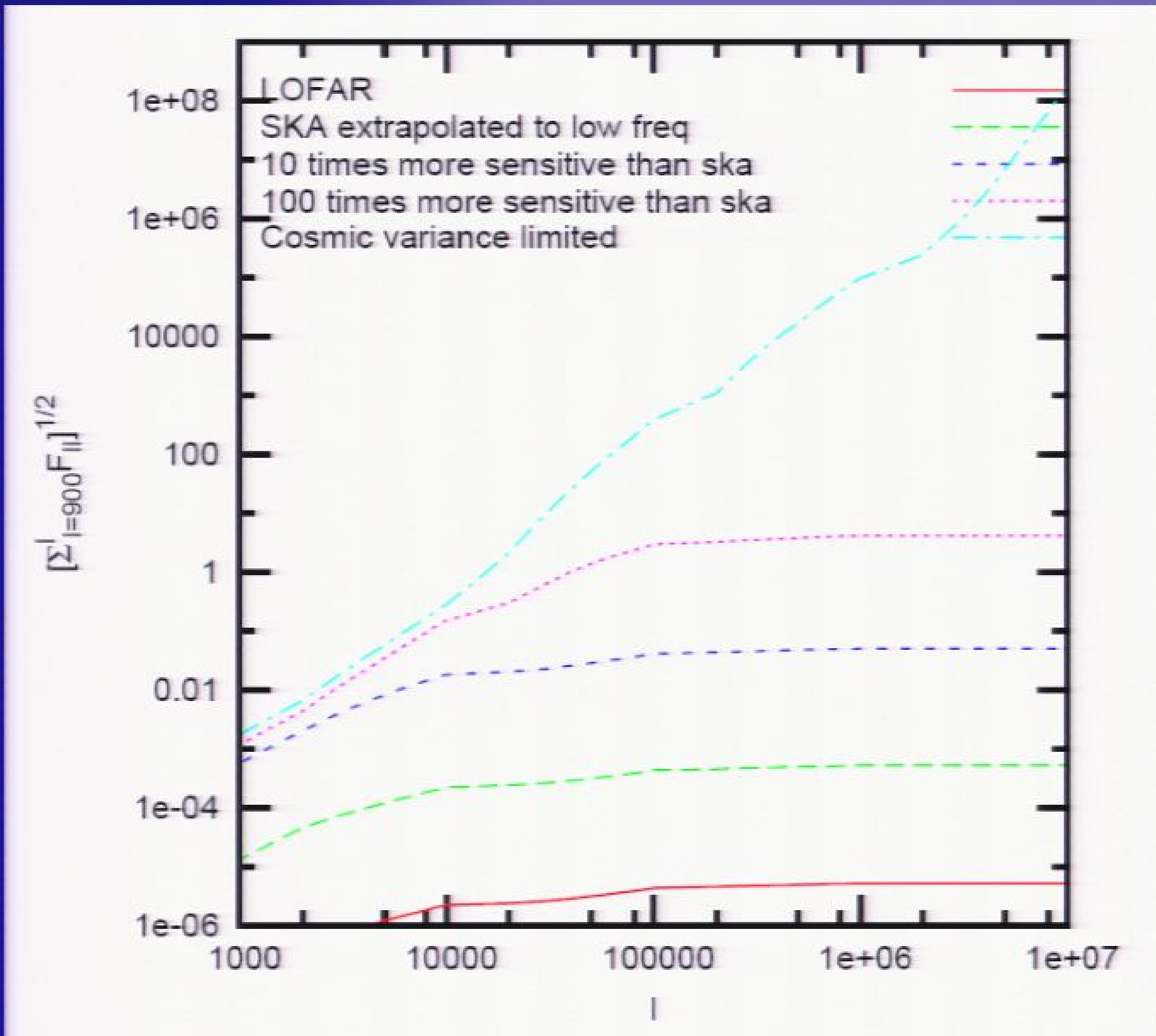
- Absorption of 21cm radiation in the primordial hydrogen probes the small structure of the primordial hydrogen.

- We computed the line of sight integral for 21cm perturbations, by adapting CMBACT, a version of CMBFAST that solves the active perturbation equations.

Small scale power from cosmic string



A treasure trove of information



21cm: Information content

- If we can access the information contained in 21cm absorption, we can limit $E_{string} < 10^{11}$ GeV $\sim E_{planck}/10^8$

- This will be a unique (and rare!) constraint on string theory

p=1 gives a conservative estimate

- Unit intercommutation probability gives the least amount of string per unit volume

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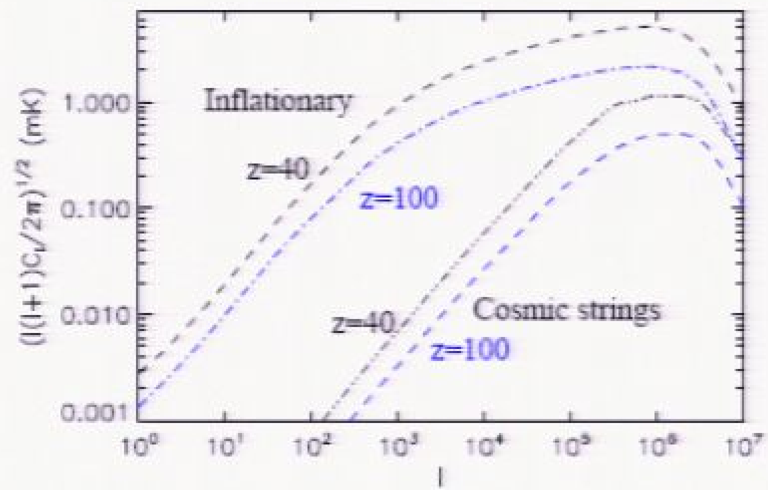
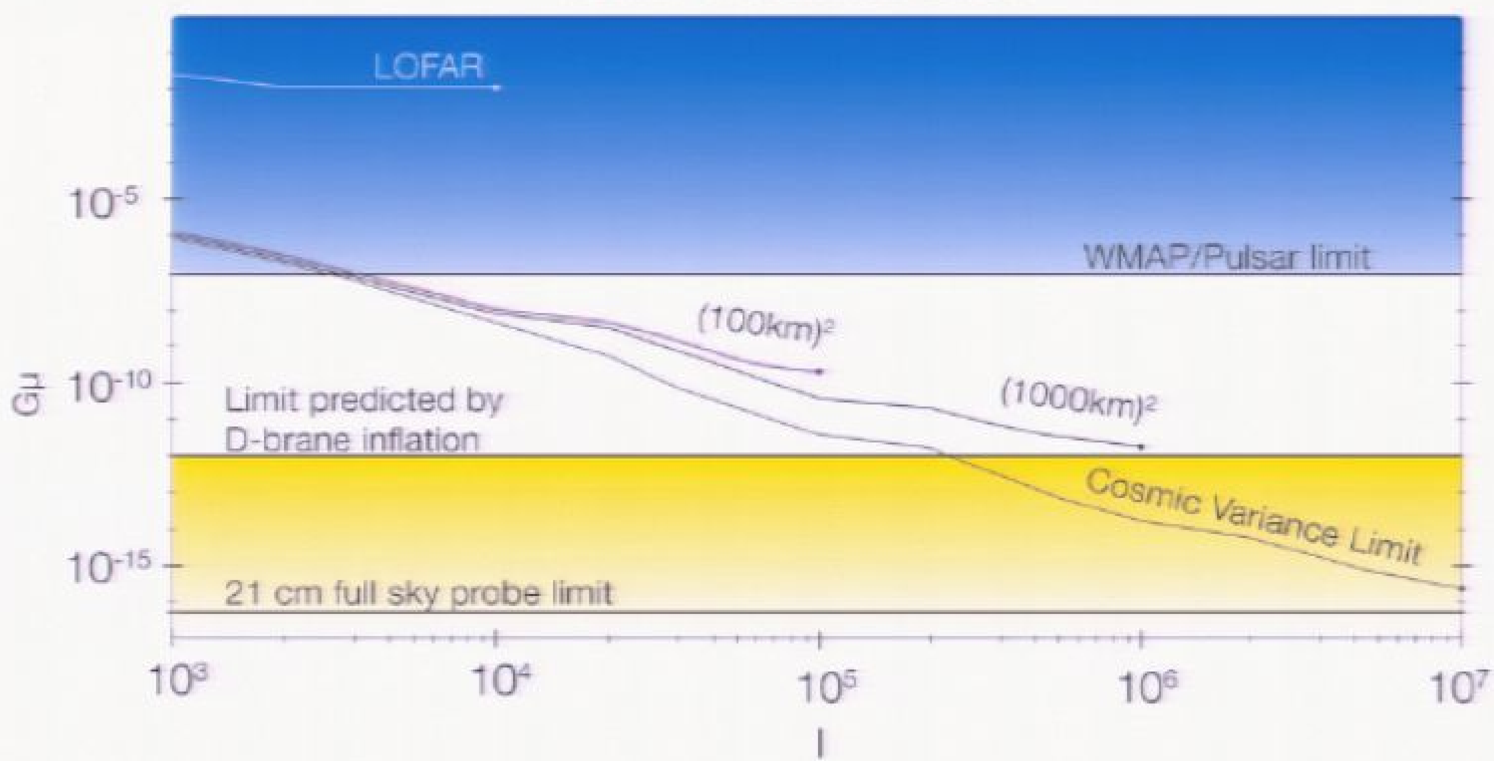
Cosmic string induced perturbations
from CMBACT *Pogosian and Vachaspati 1999*

$\mu \sim M_s^2, M_{GUT}^2$

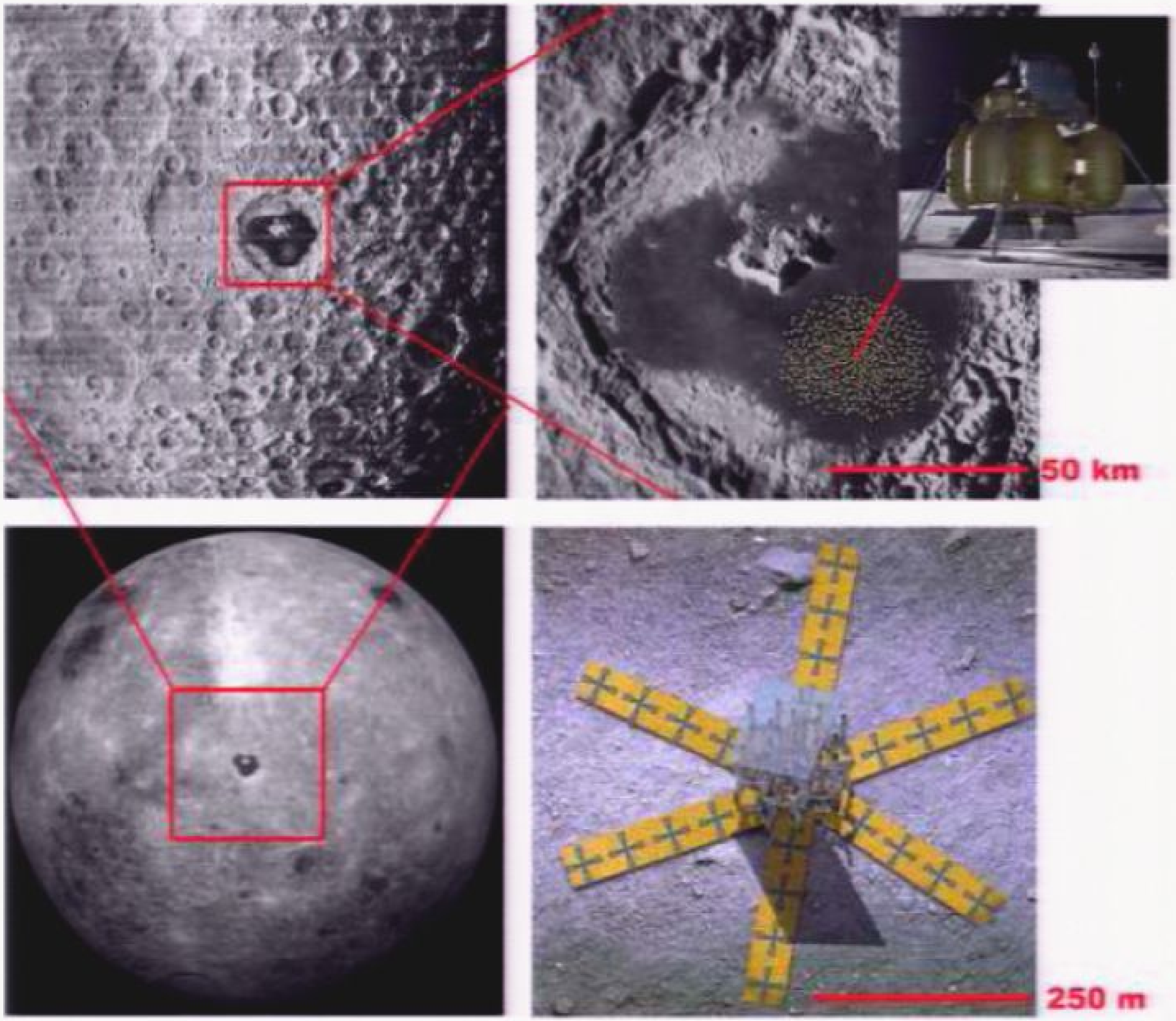
$G\mu = 10^{-12} \Rightarrow M_s, M_{GUT} \sim 10^{13}\mathrm{GeV}.$



Khatri & Wandelt 2008

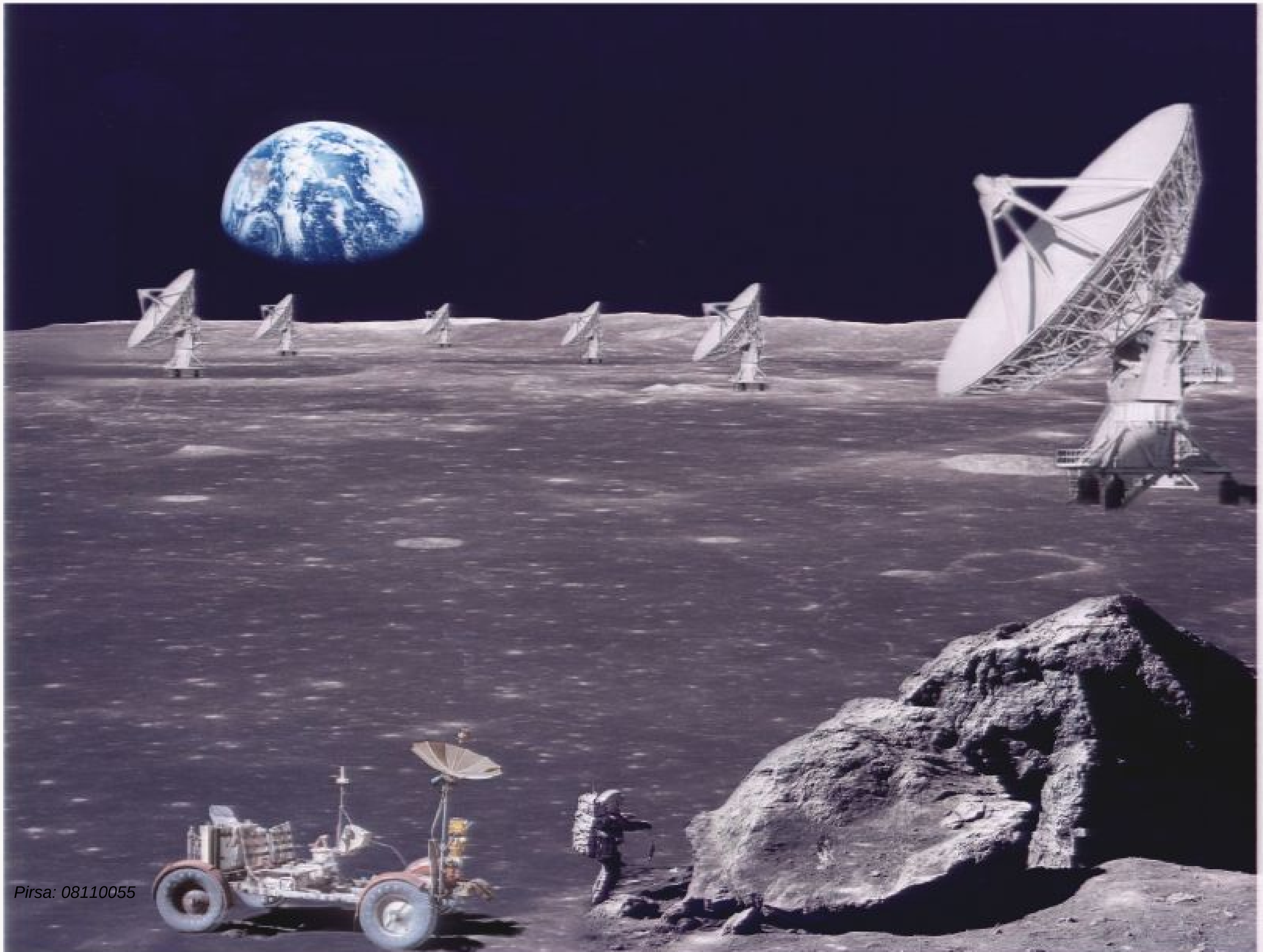


Dark Ages Lunar Interferometer

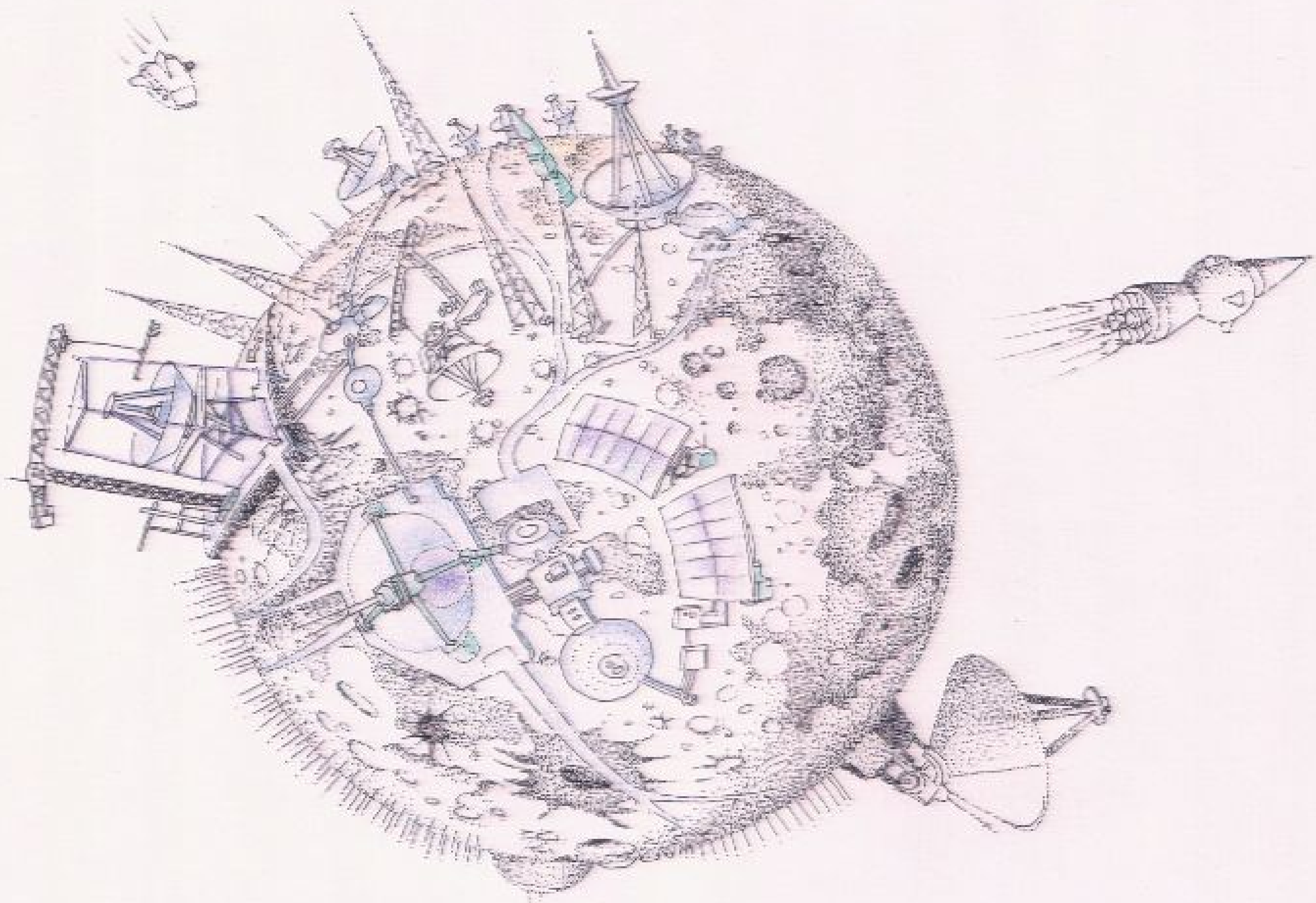


Source: Naval Research Lab

21cm observations from the Moon?



A scientific future for the Moon?



Conclusions

- Observations of $\delta\alpha/\alpha$ open a new window on physics beyond the standard model and modifications of gravity.
- Observations of 21cm absorption allow constraining $\delta\alpha/\alpha$ to subpercent precision for $20<z<150$
- Observations will reach the required sensitivity within 2 years
- Precision of foreground subtraction will limit the detection of the mean temperature perturbation
- Spatial fluctuations in brightness temperature decouple observationally from foregrounds – but require 10x higher sensitivity.

A scientific future for the Moon?