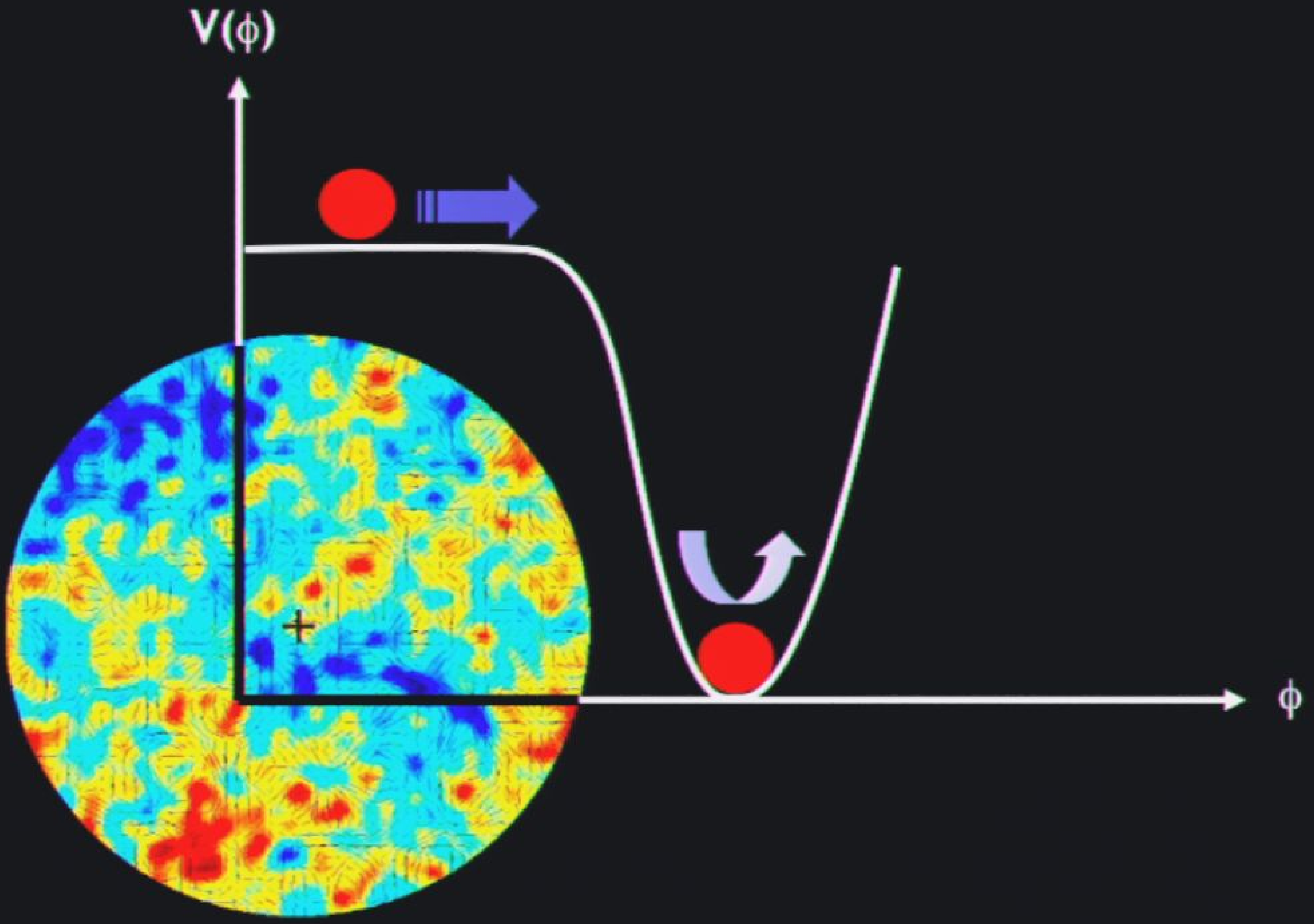
Title: Cosmology - Review (PHYS 621) - Lecture 10

Date: Dec 11, 2009 10:00 AM

URL: http://www.pirsa.org/09120064

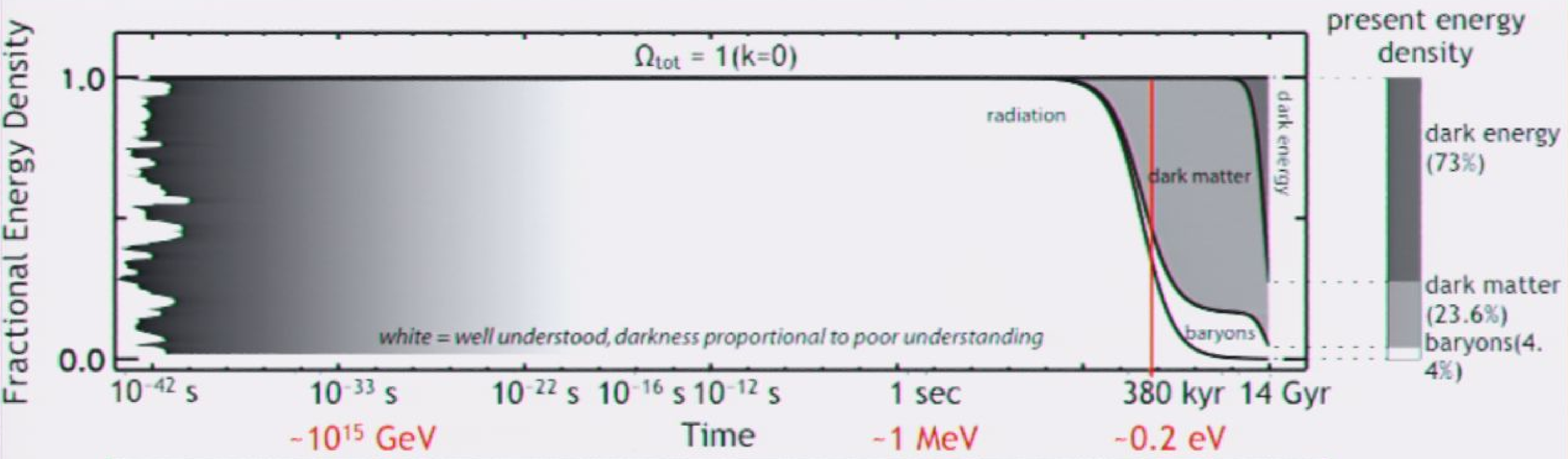
Abstract:

Prospects for CMB observations



Hiranya Peiris

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

non-linear growth of perturbations: signature on CMB through weak gravitational lensing

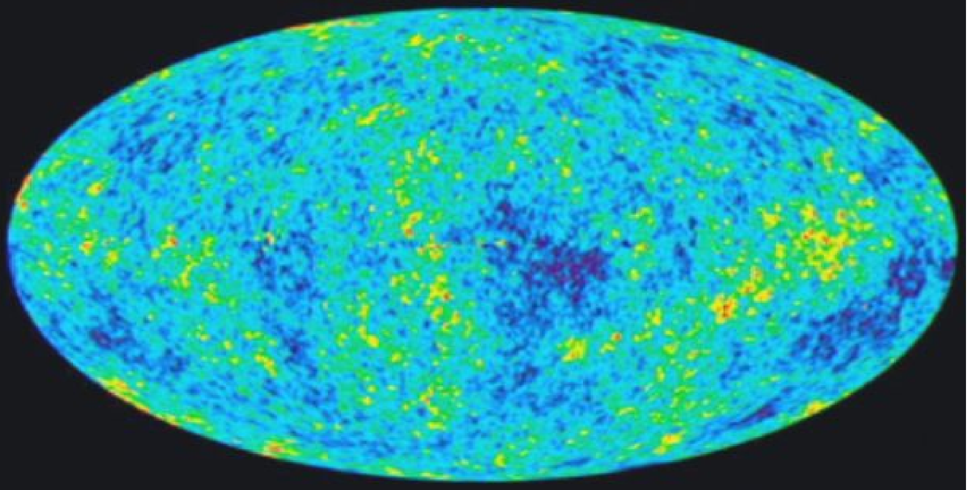
$\Lambda\mathrm{CDM}$: The “Standard Model” of Cosmology

Homogeneous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Perturbations



$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

Λ? CDM?

ORIGIN??

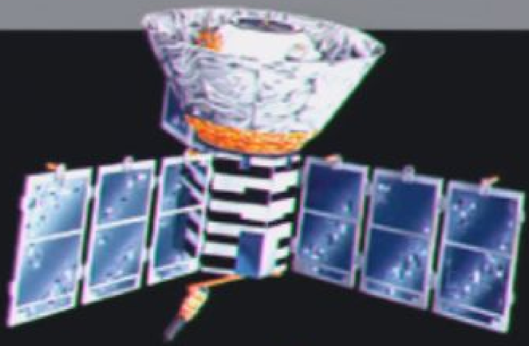
History of CMB temperature measurements

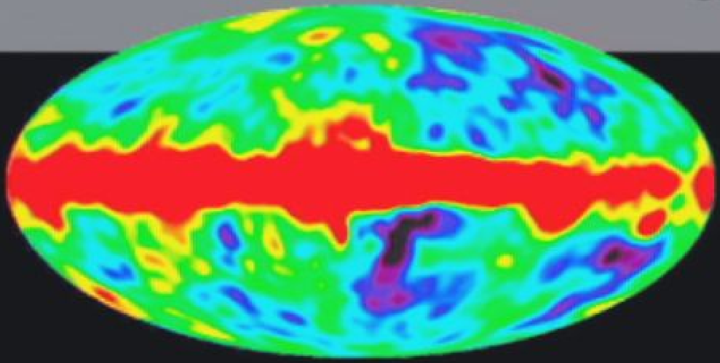
1965

Penzias and
Wilson

1992

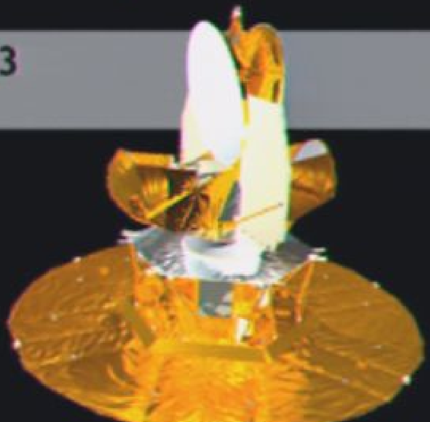
COBE

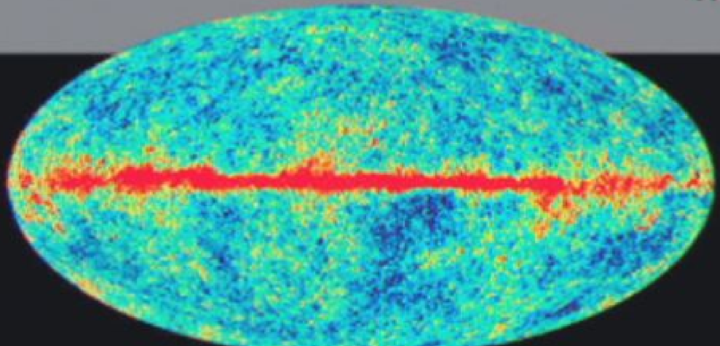




2003

WMAP

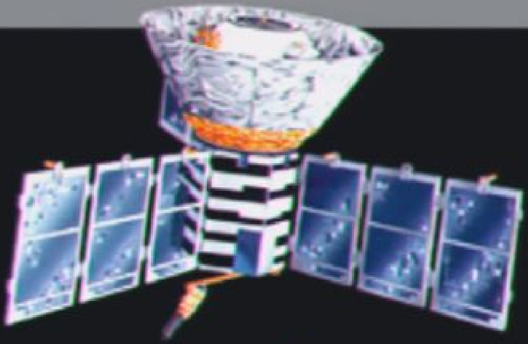


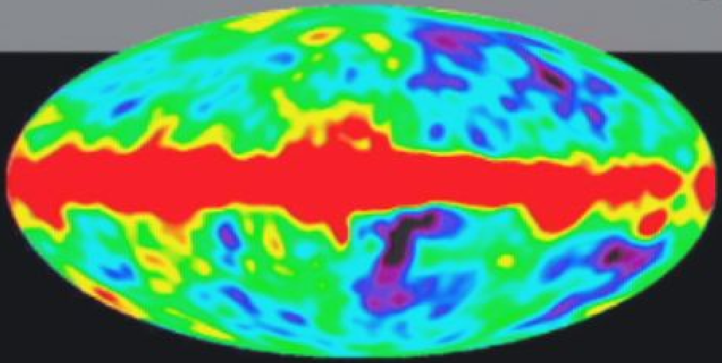


History of CMB temperature measurements

1965 **Penzias and Wilson**

1992 **COBE**





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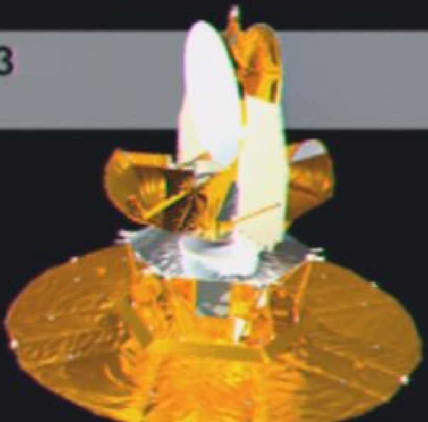
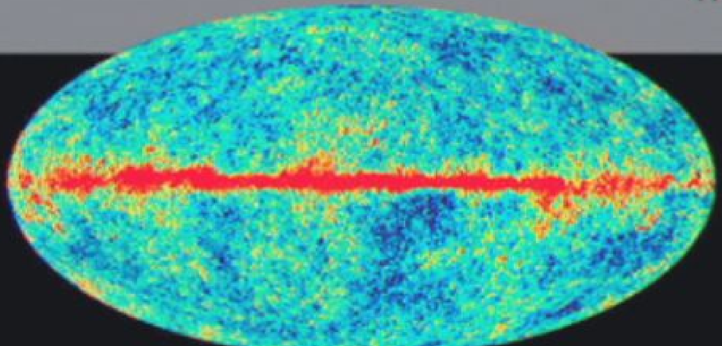




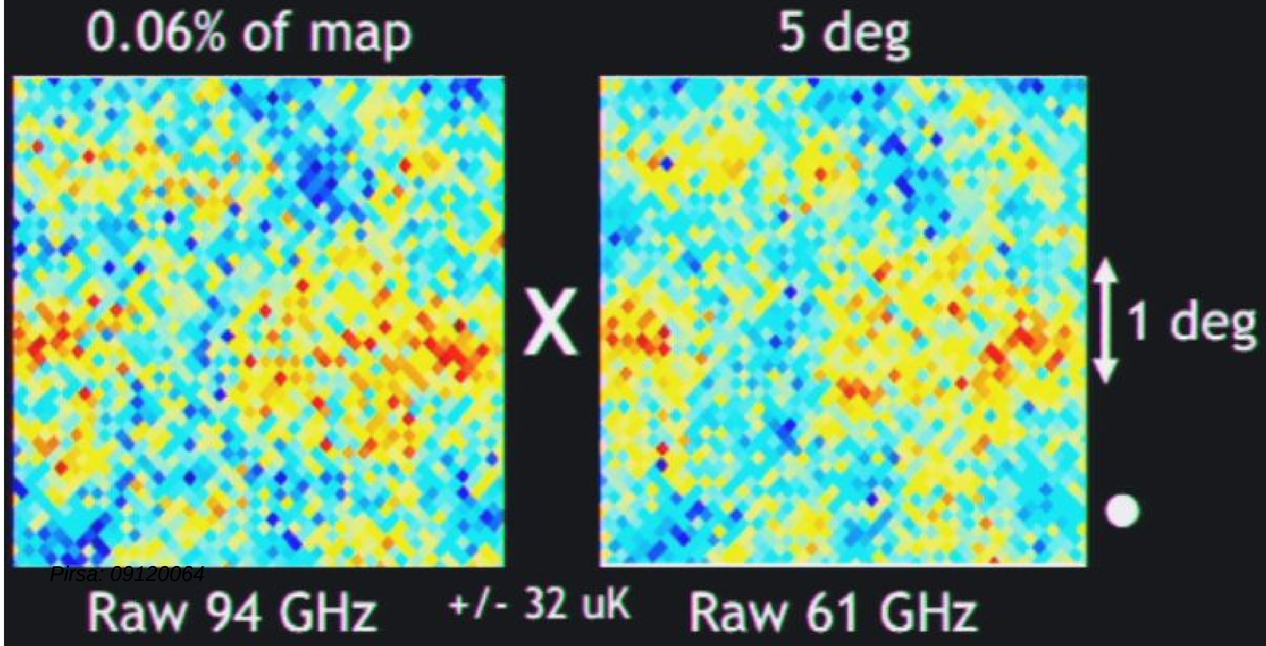
Compress the CMB map to study cosmology

Express sky as: $$\delta T(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

f the anisotropy is a Gaussian random field

real and imaginary parts of each a_{lm} independent normal deviates, not correlated)

ll the statistical information is contained in the angular power spectrum.



$$C_l = \frac{1}{2\ell+1}\sum_m |a_{lm}|^2$$

ANGULAR POWER SPECTRUM

A simplified CMB likelihood function

$$-2\ln\mathcal{L} = \sum_{\ell}(2\ell+1)\left[\ln\left(\frac{\overset{\text{theory}}{C_\ell^{\rm th}} + \overset{\text{noise bias}}{N_\ell}}{\underset{\text{estimator for sky Cls}}{\widehat{C}_\ell}}\right) + \frac{\widehat{C}_\ell}{C_\ell^{\rm th} + N_\ell} - 1\right]$$

- Logarithmic at large scales; more likely to scatter low.
- Approaches Gaussian at small scales.
- Cosmic variance: even ideal experiment can only measure (2l+1) modes.

A simplified CMB likelihood function

theory

noise bias

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estimator for sky Cls

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Radical data compression

Time-ordered data (e.g. WMAP 5 years 60-100 GB)

↓ mostly experimental characteristics

map (12-50 million pixels)

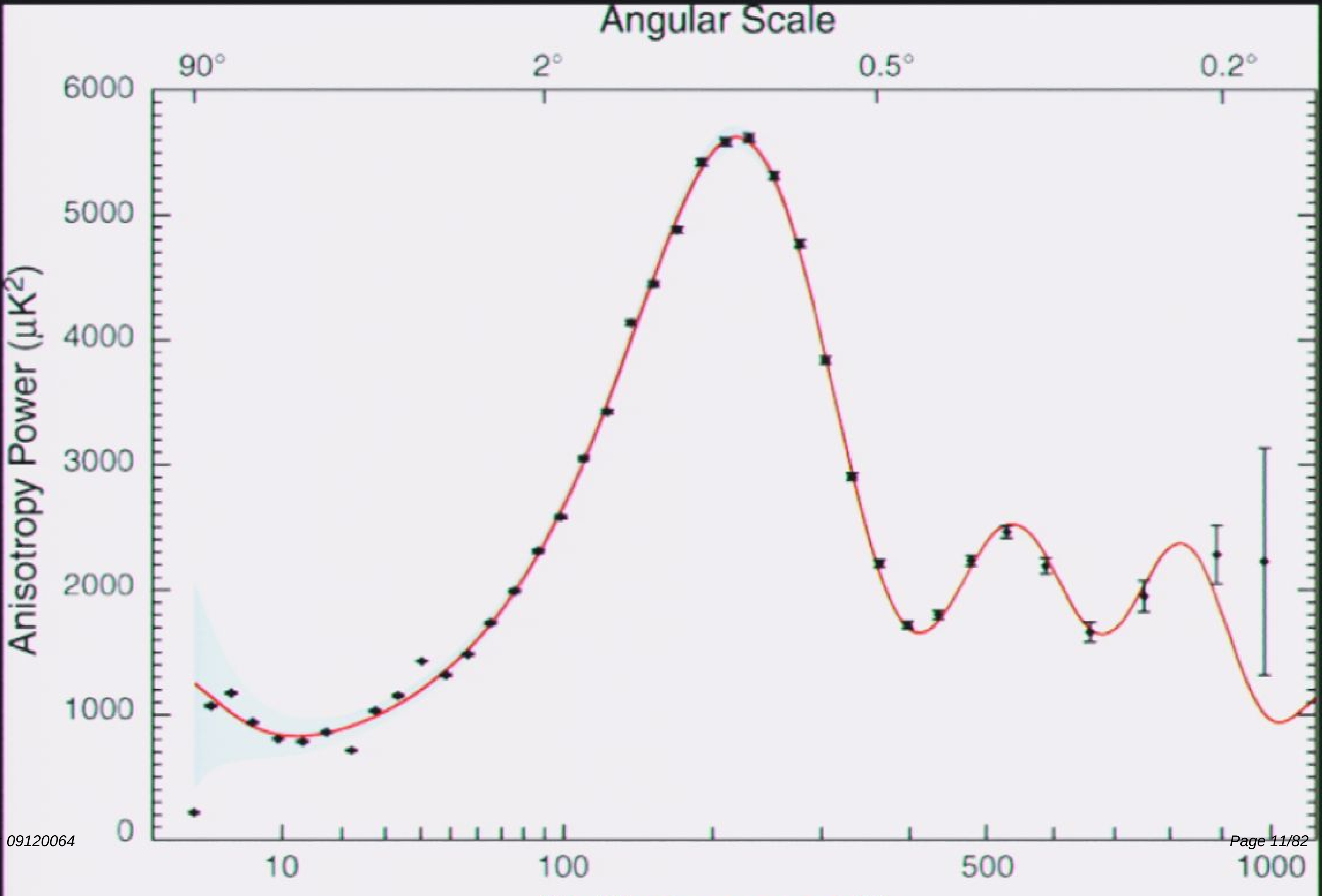
↓ physically motivated statistics

angular power spectrum - O(1000) to O(10000) numbers

↓ experiment, physics, statistics

model - O(10) parameters

WMAP temperature power spectrum



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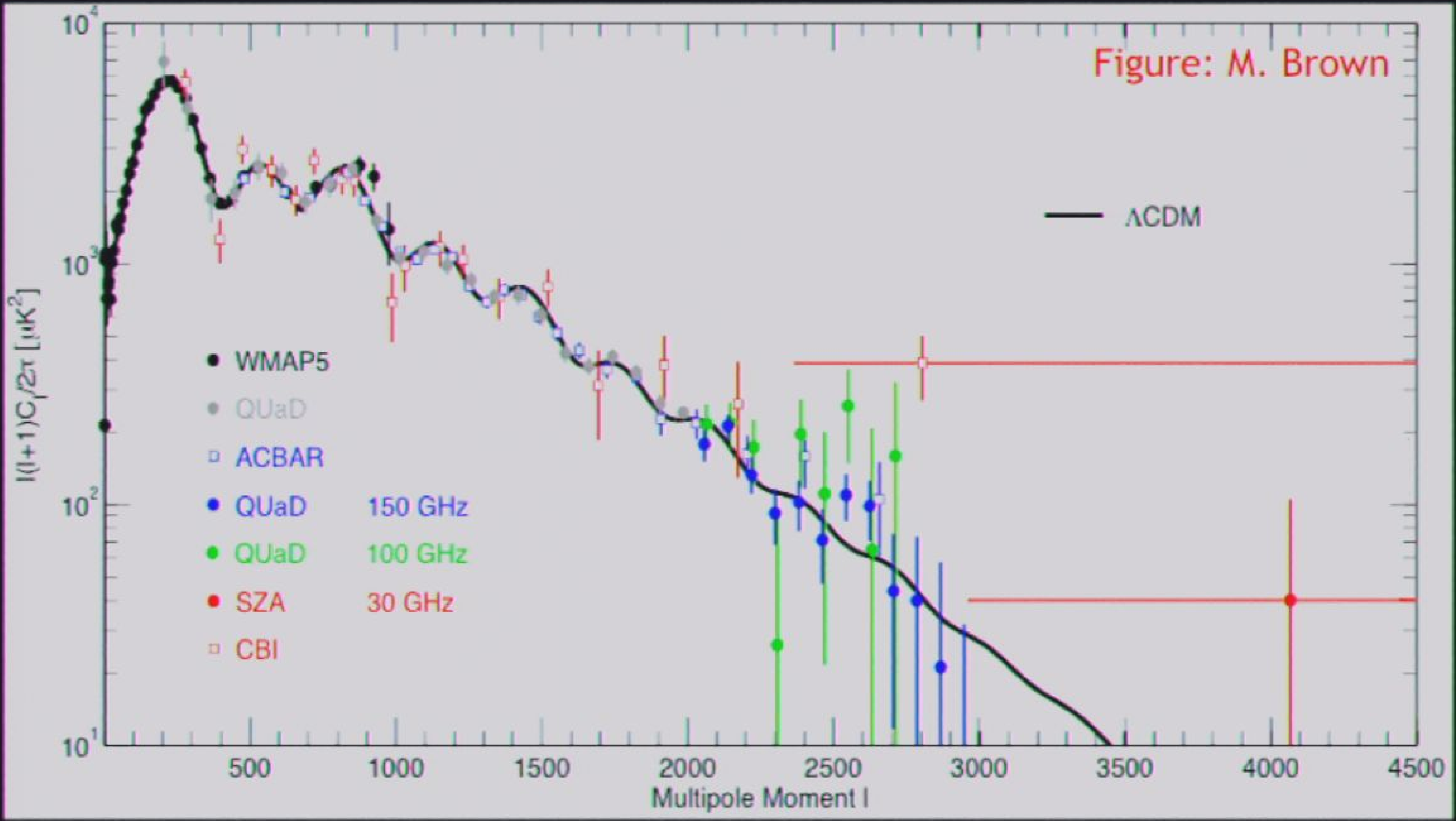
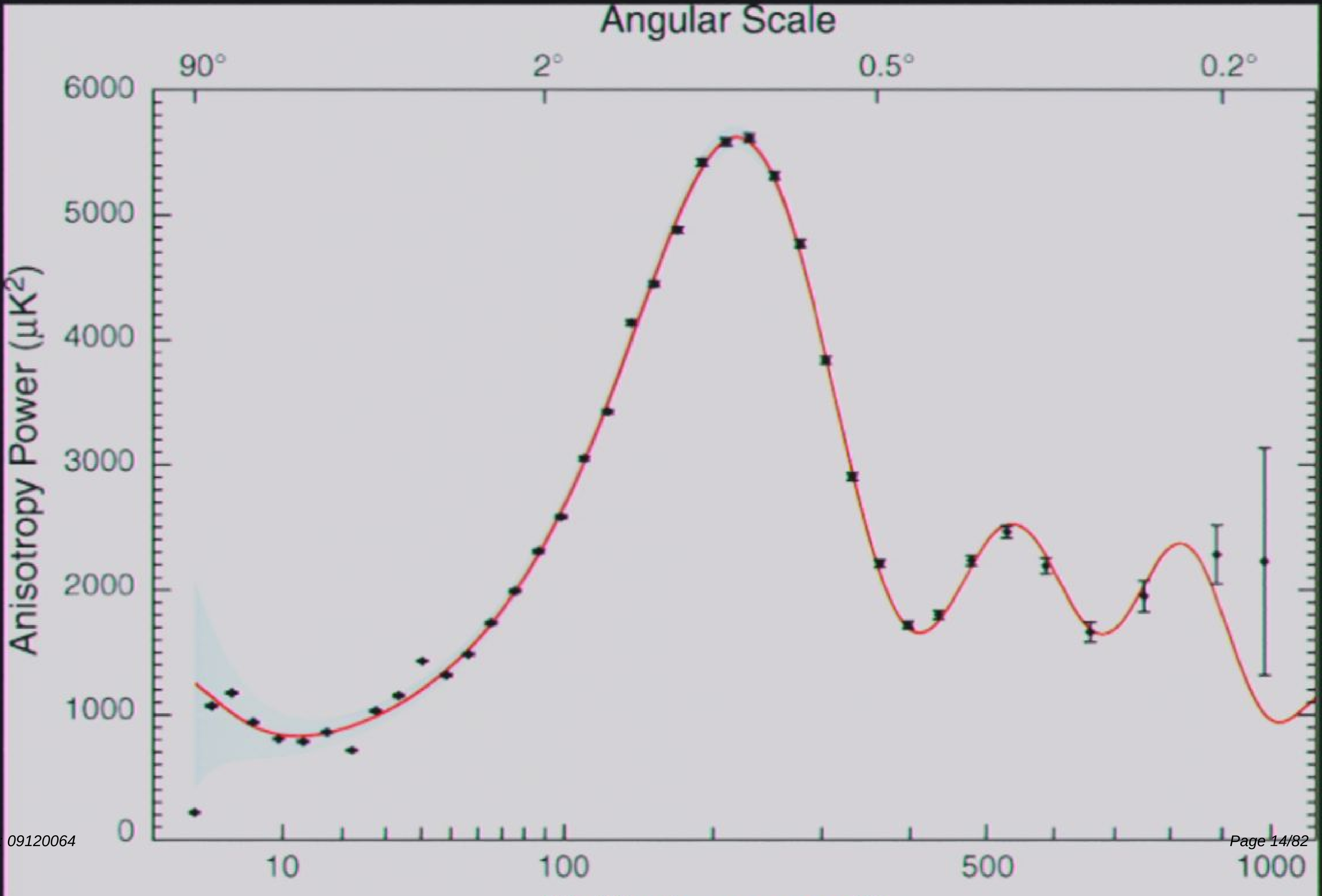


- Sachs-Wolfe plateau and the late time Integrated Sachs-Wolfe effect
- Acoustic peaks at “adiabatic” locations
- Damping tail and photon diffusion

WMAP temperature power spectrum



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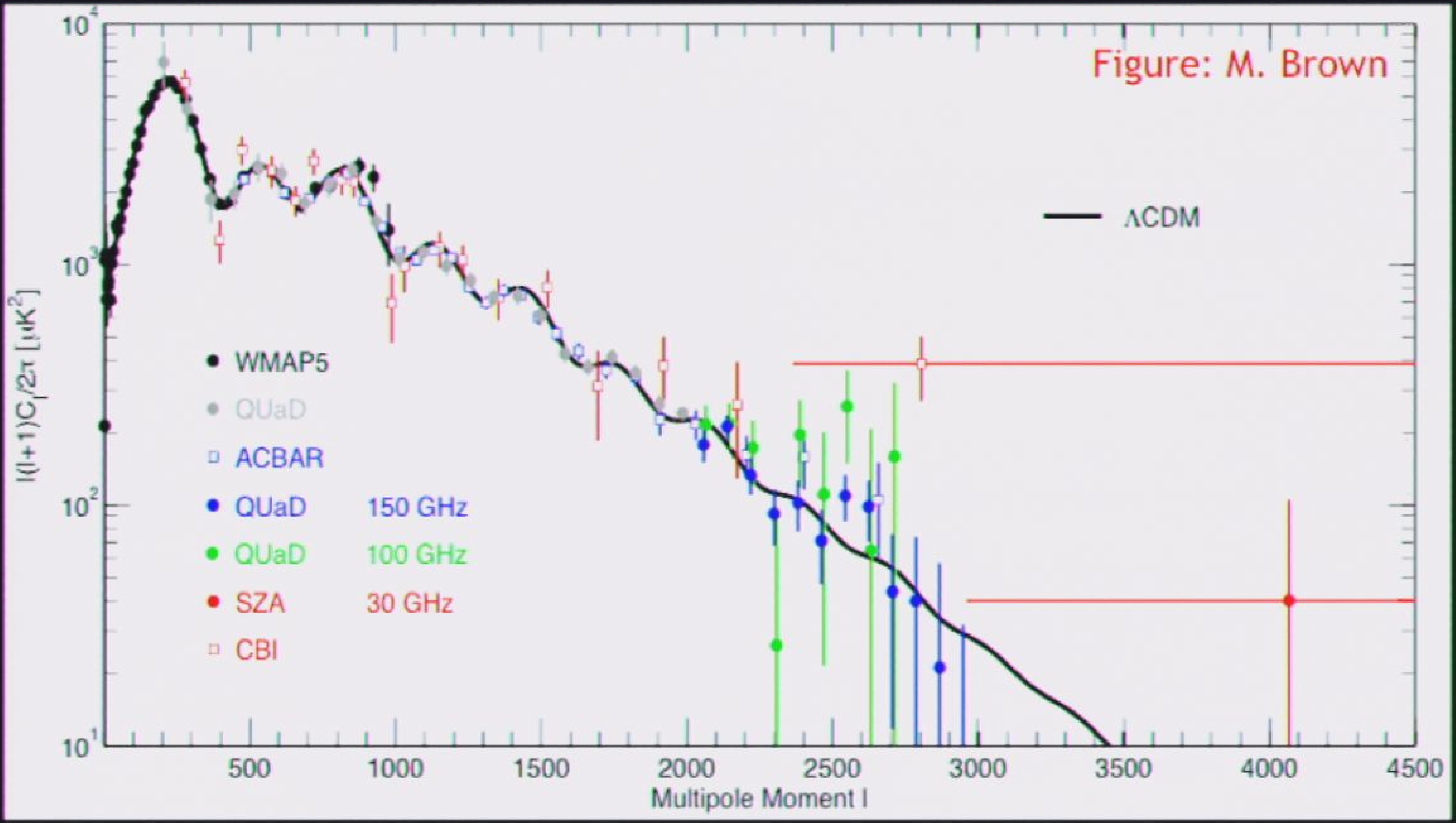

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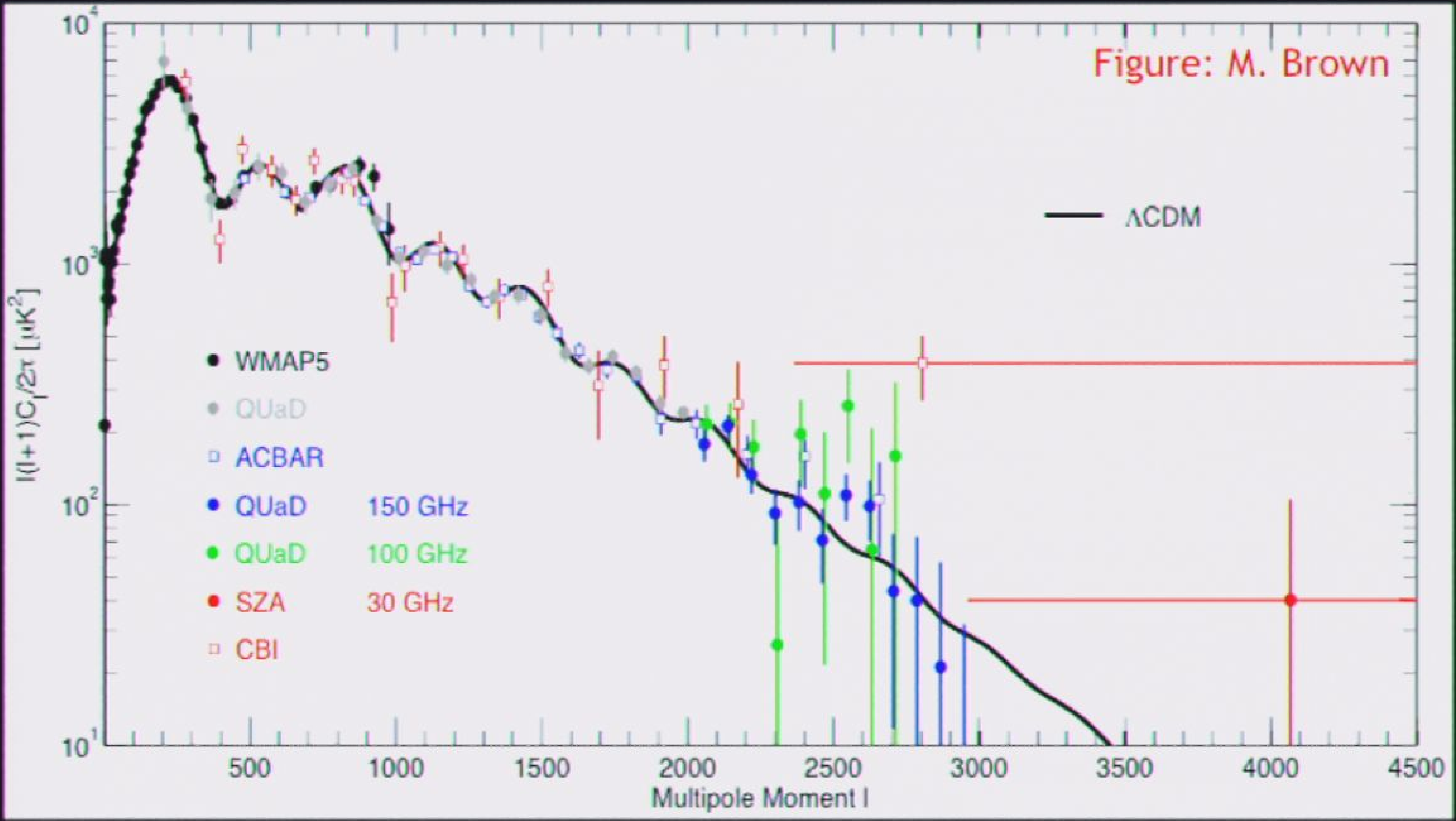

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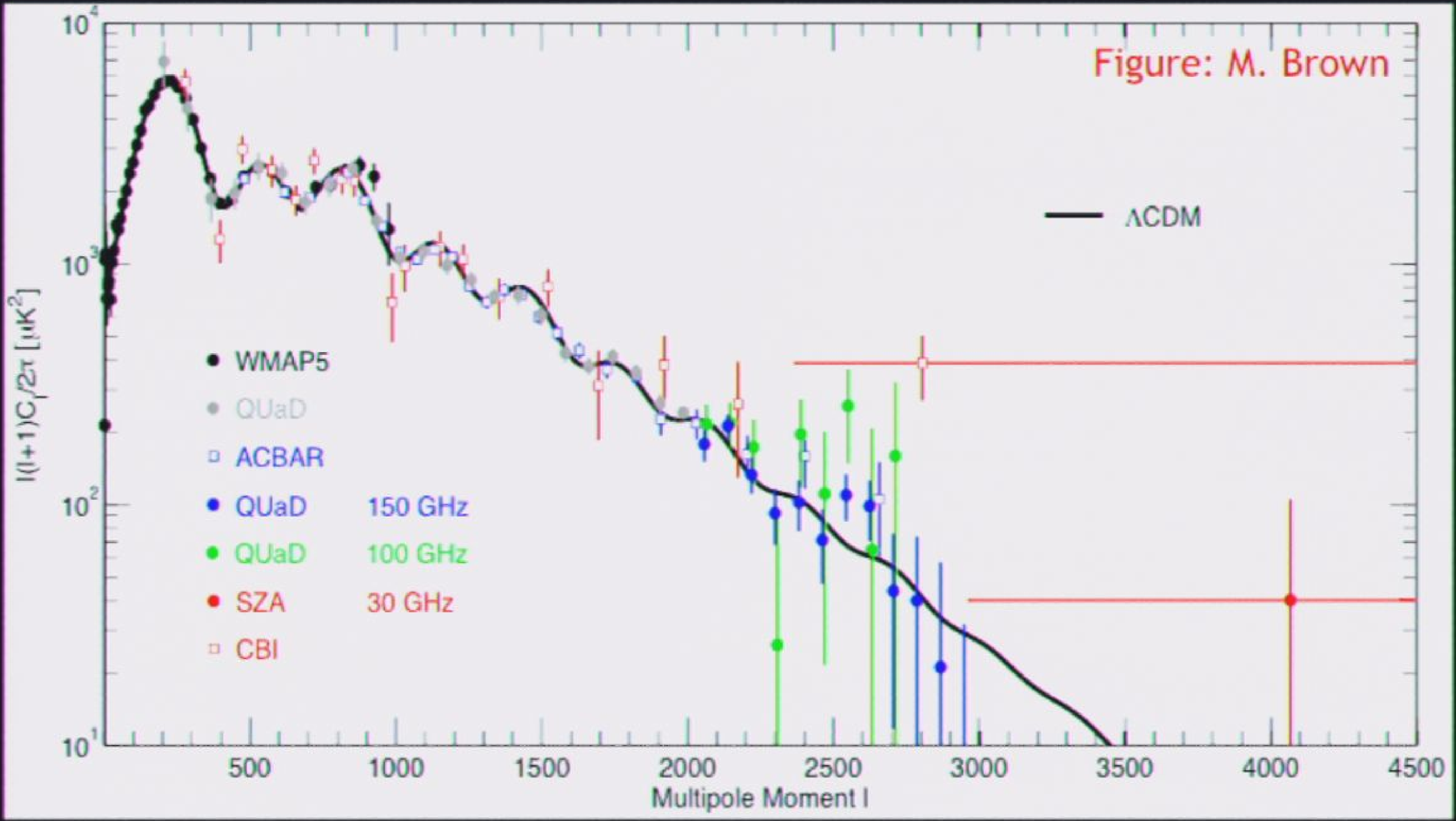

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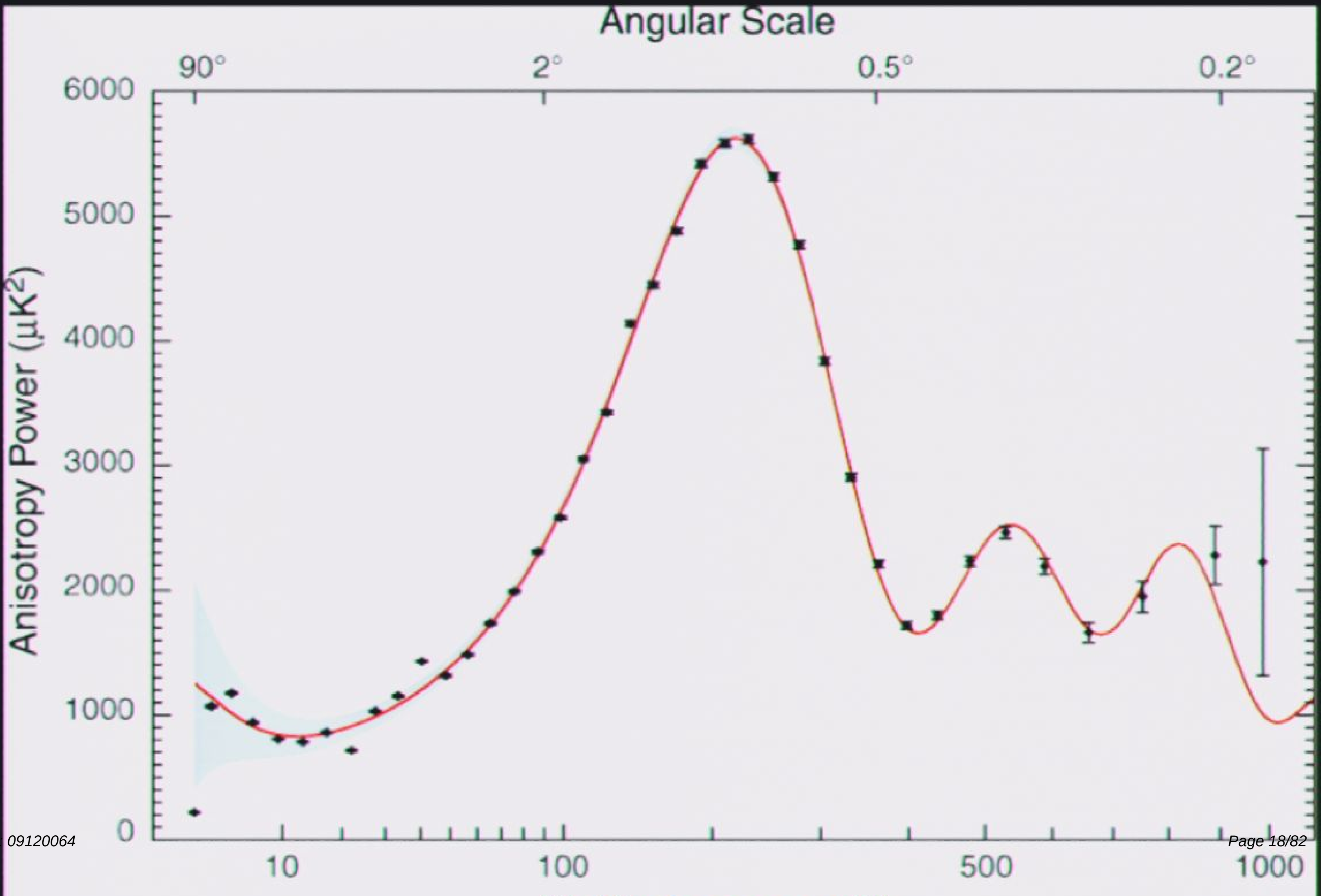

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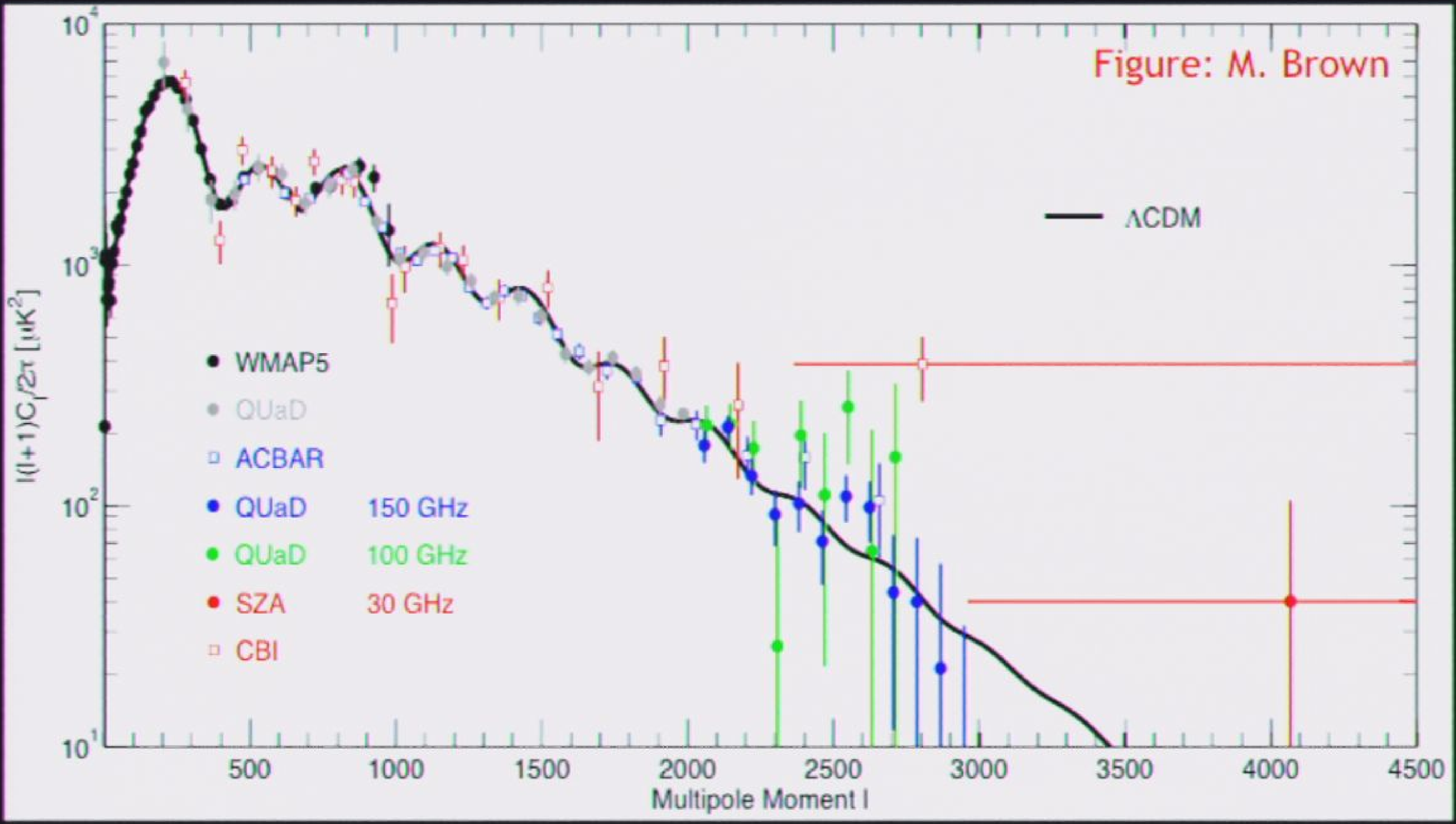

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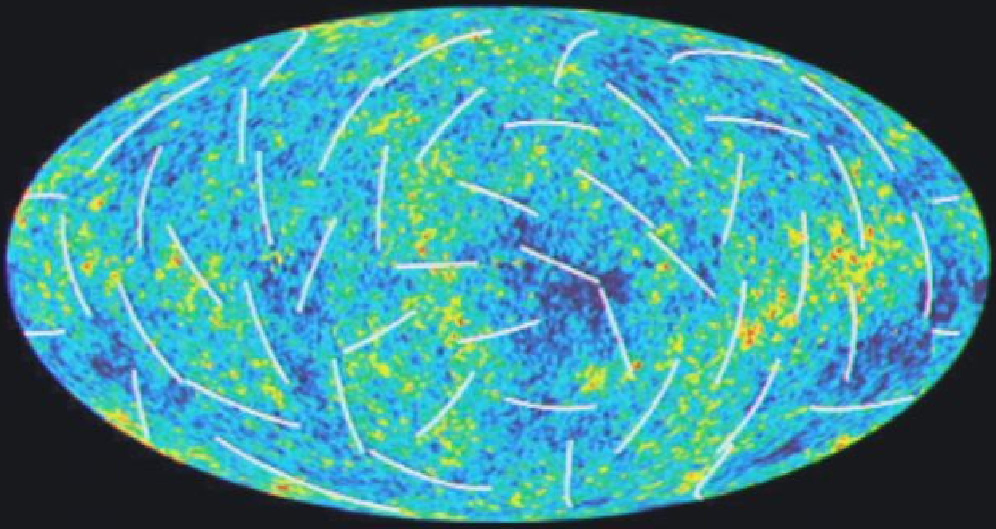
History of CMB polarization measurements



E-mode first detected by DASI in 2002

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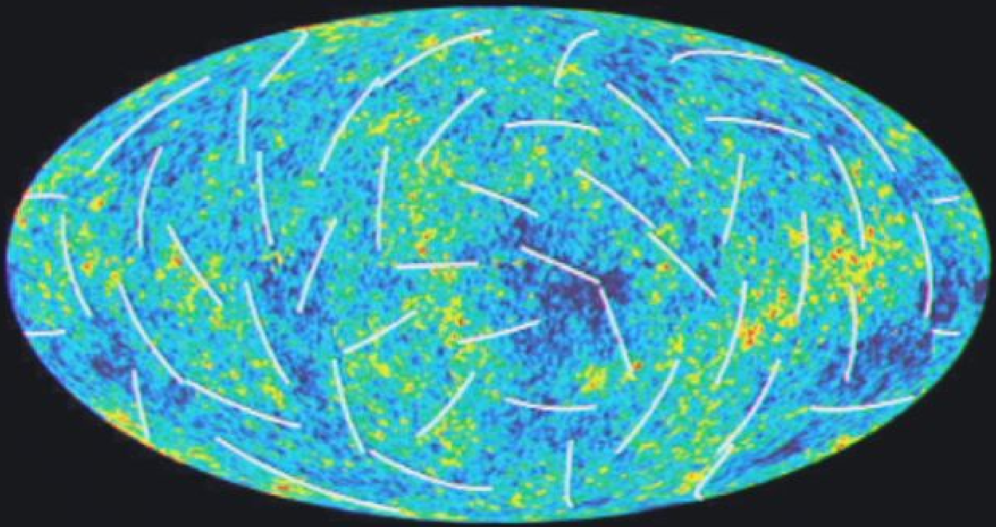

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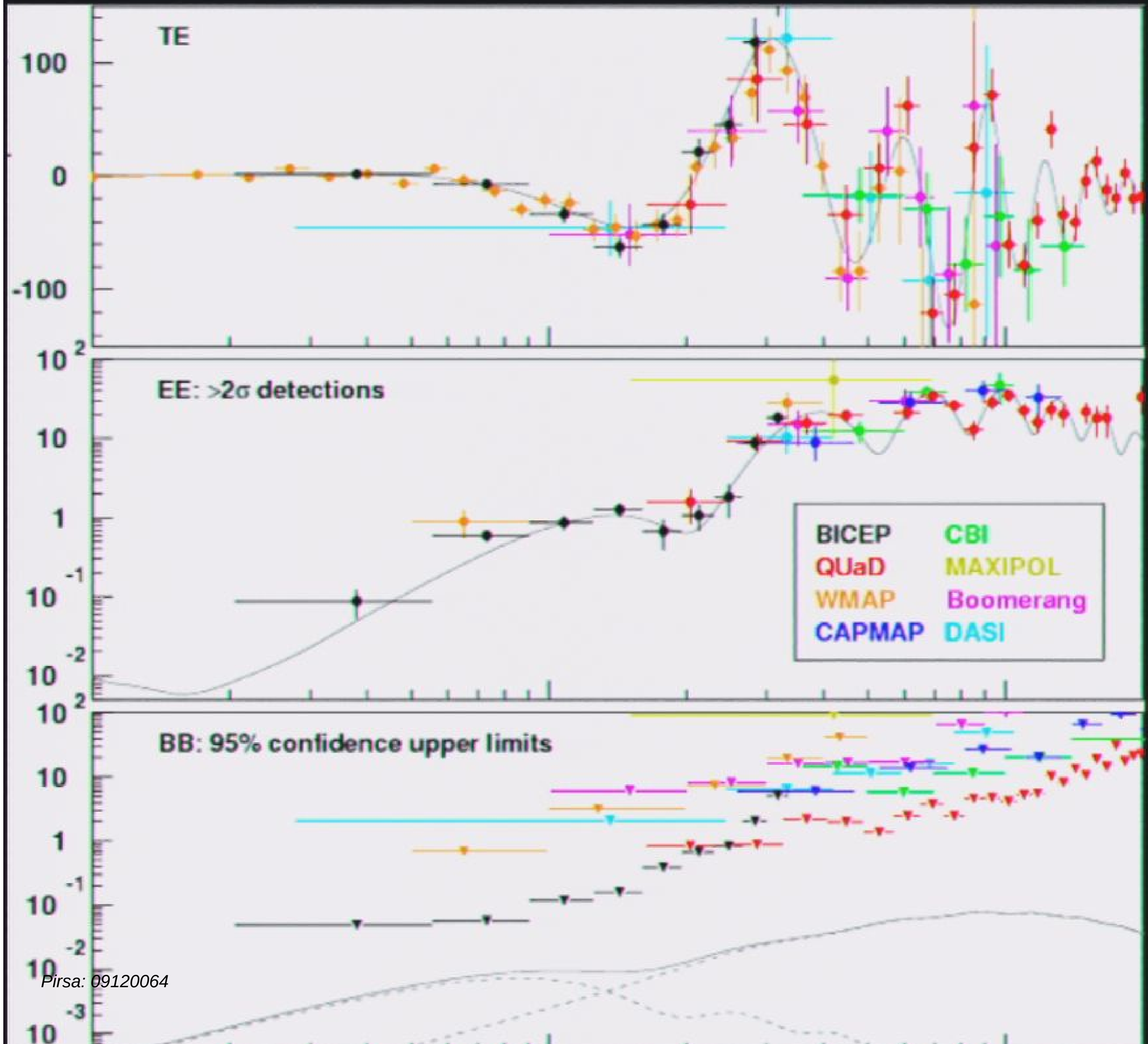

- Acoustic peaks at "adiabatic" locations
- E-mode polarization an cross-correlation with T
- Large angle polarizatio from reionization
- BICEP limit from BB-alone: T/S < 0.73 (95% C

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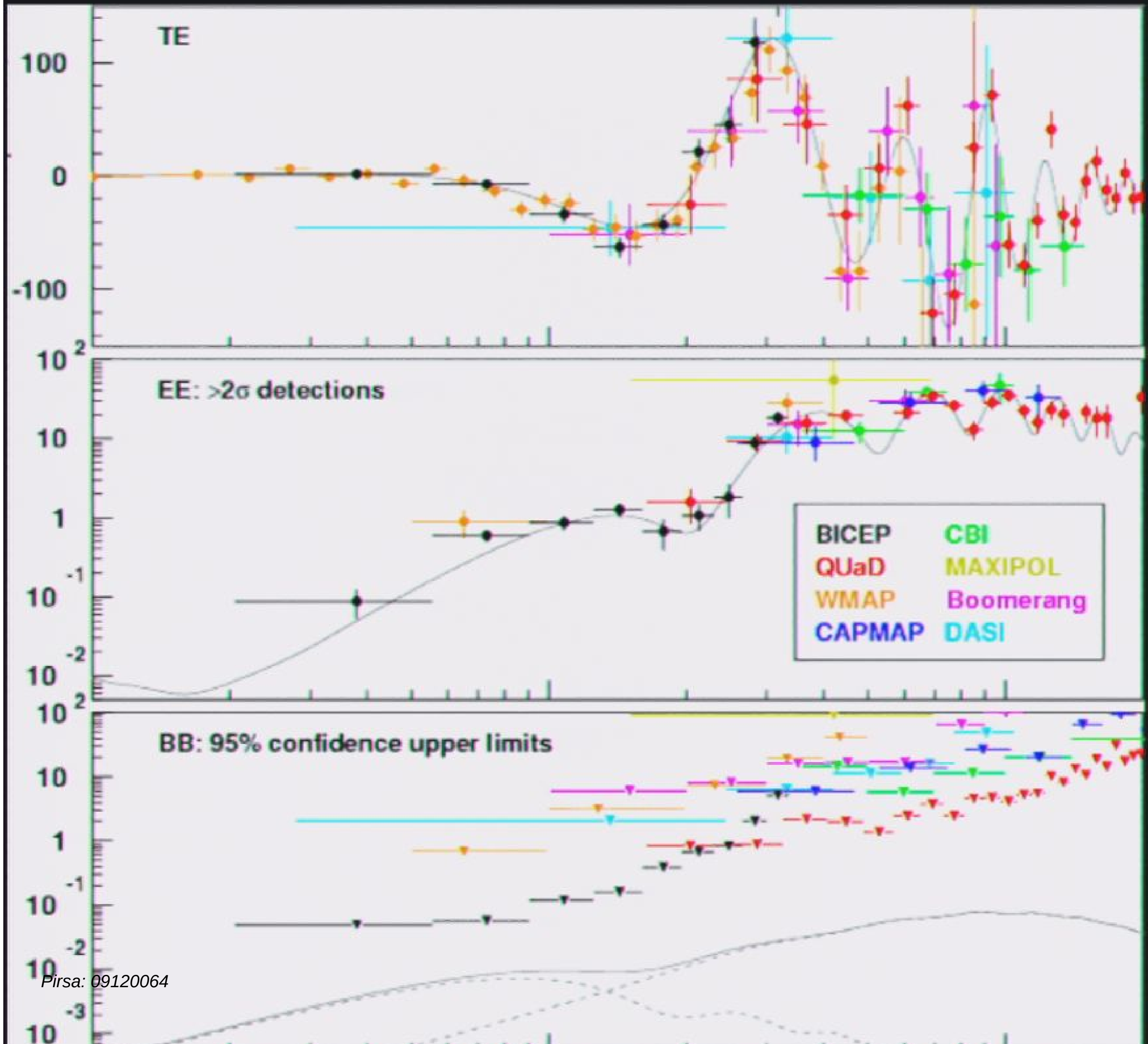

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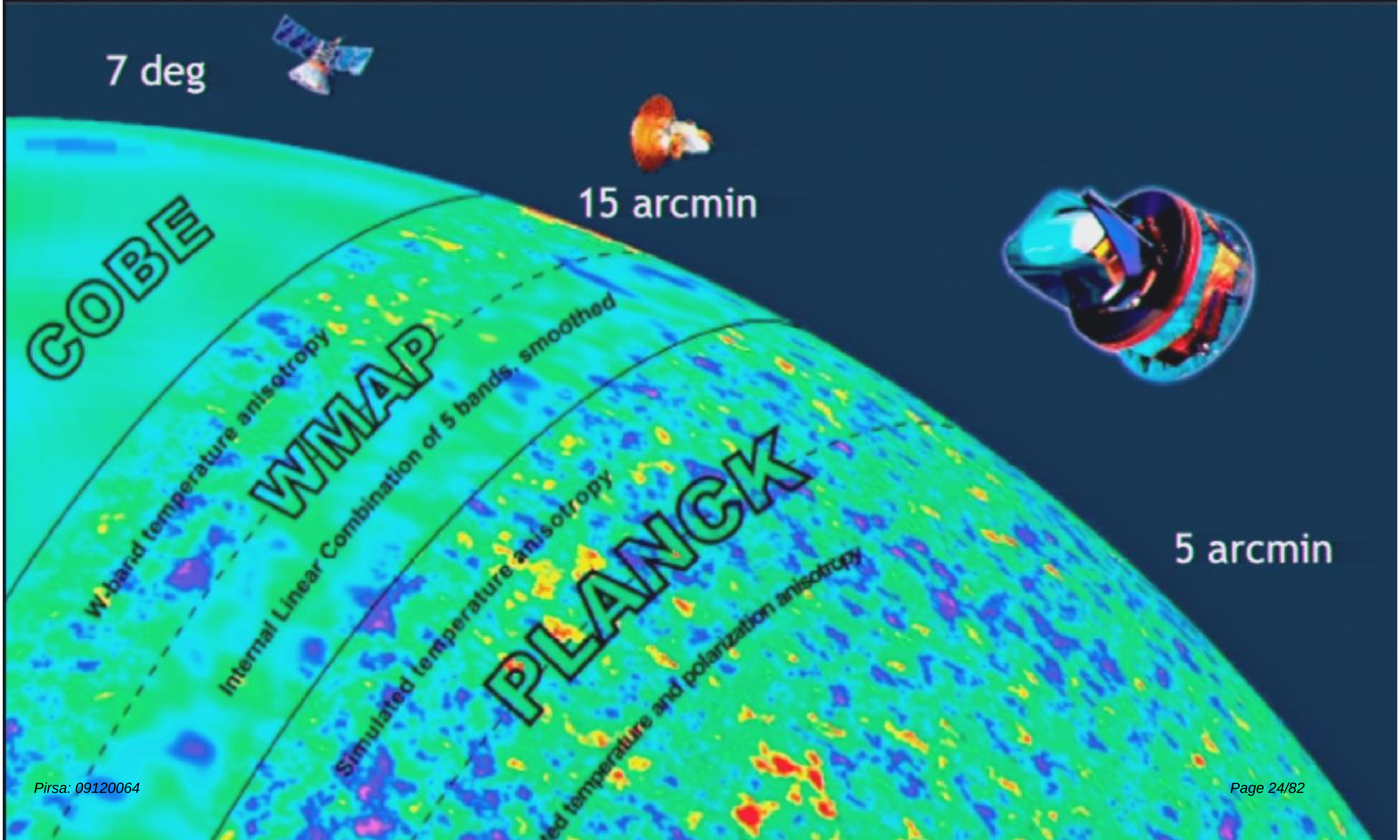
Planck:

THE NEXT GENERATION



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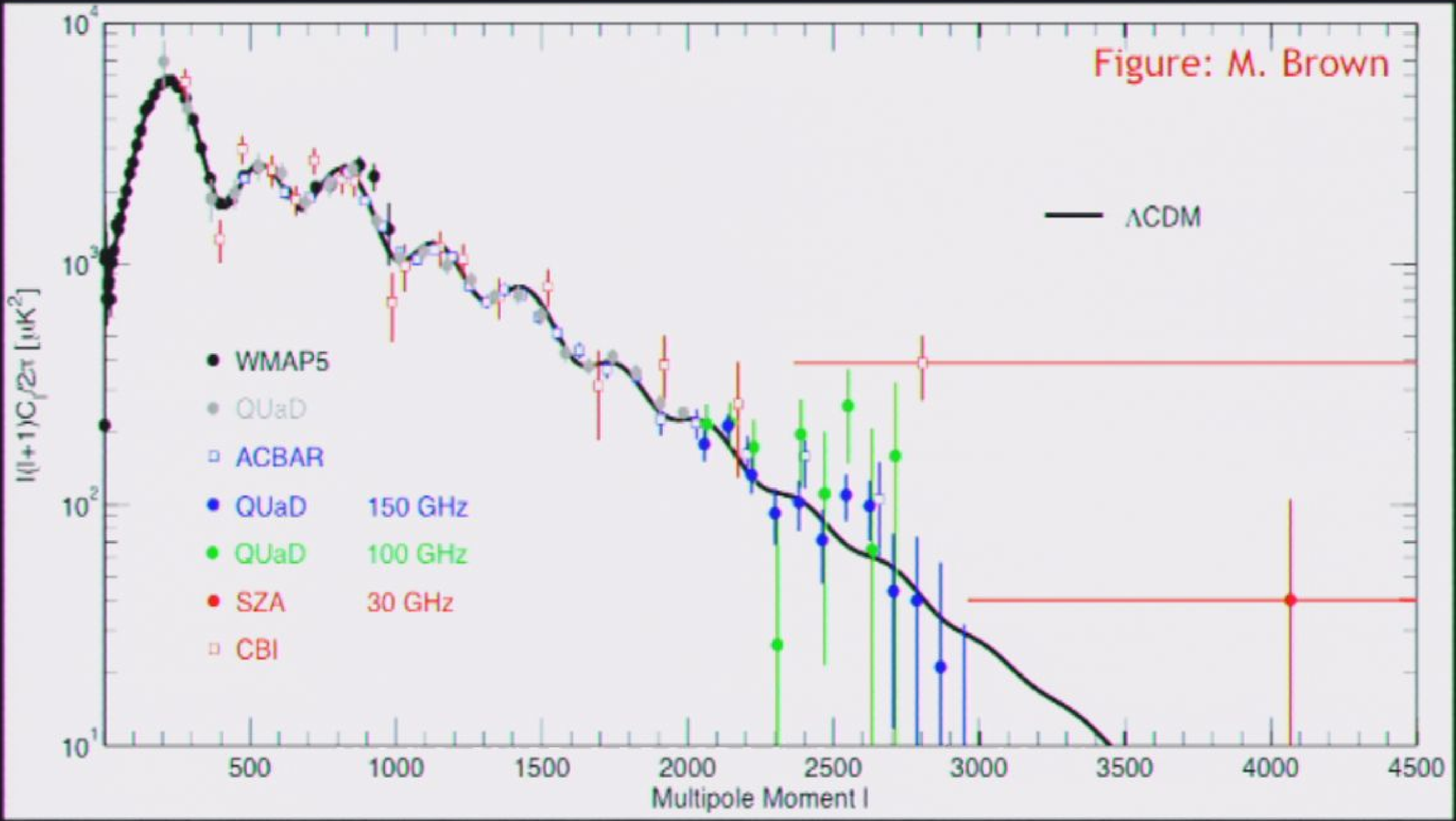

Figure: M. Brown

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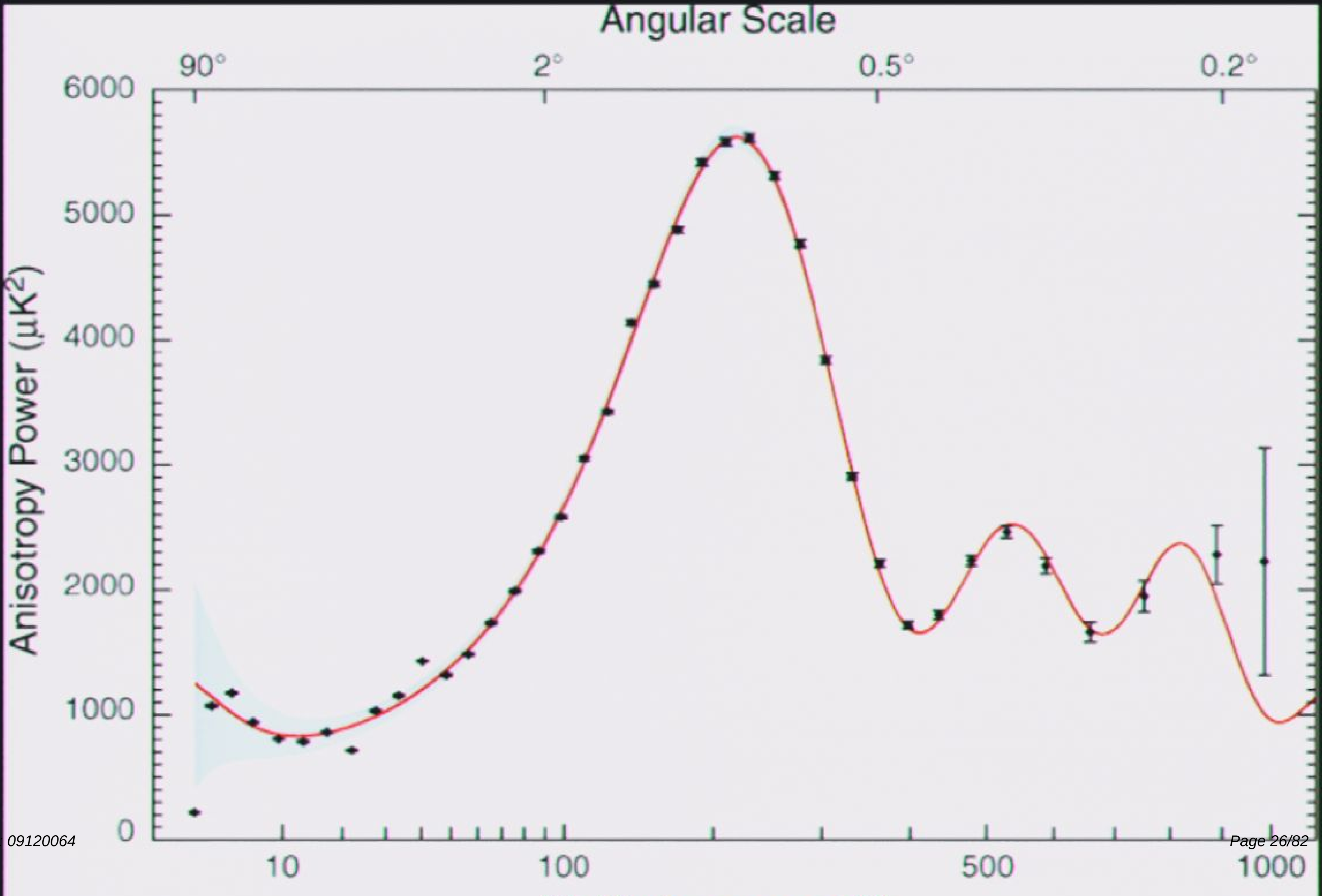

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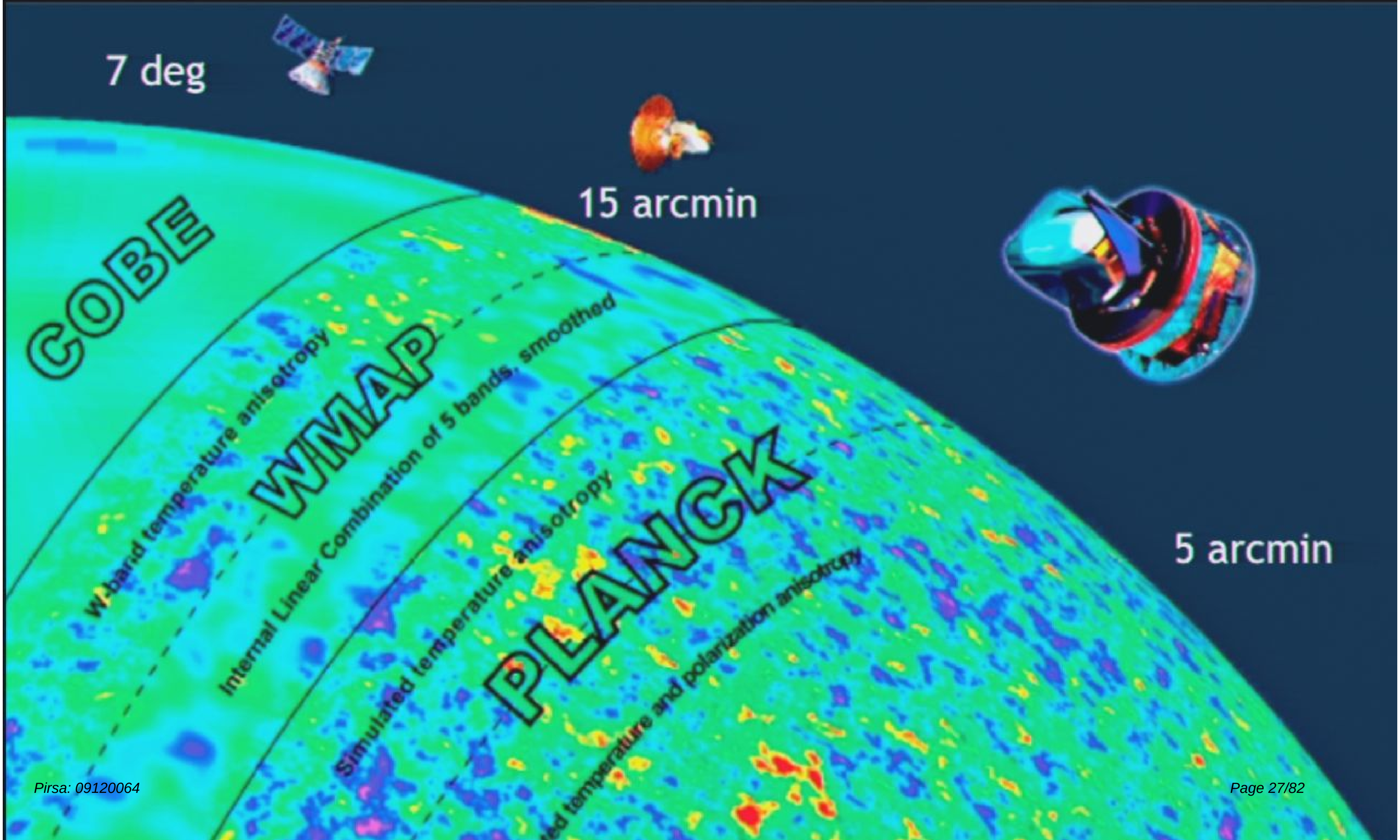

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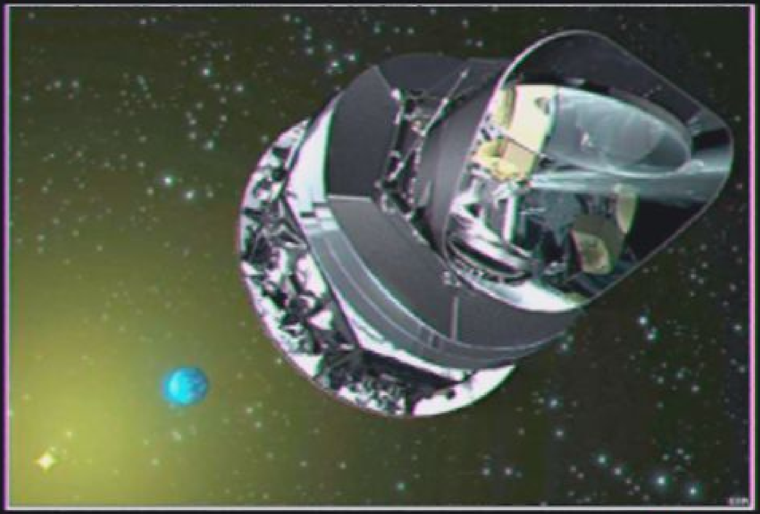
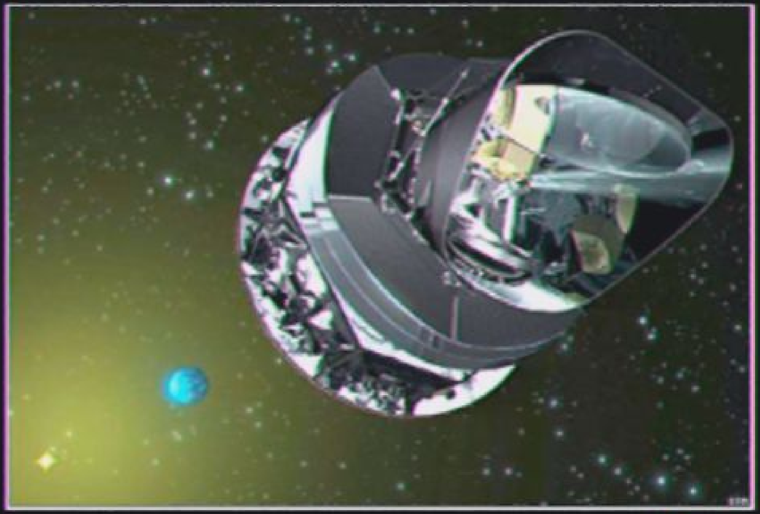


ESA

Extract essentially all information in primary CMB temperature anisotropy; big advance in polarization measurements.

Planck



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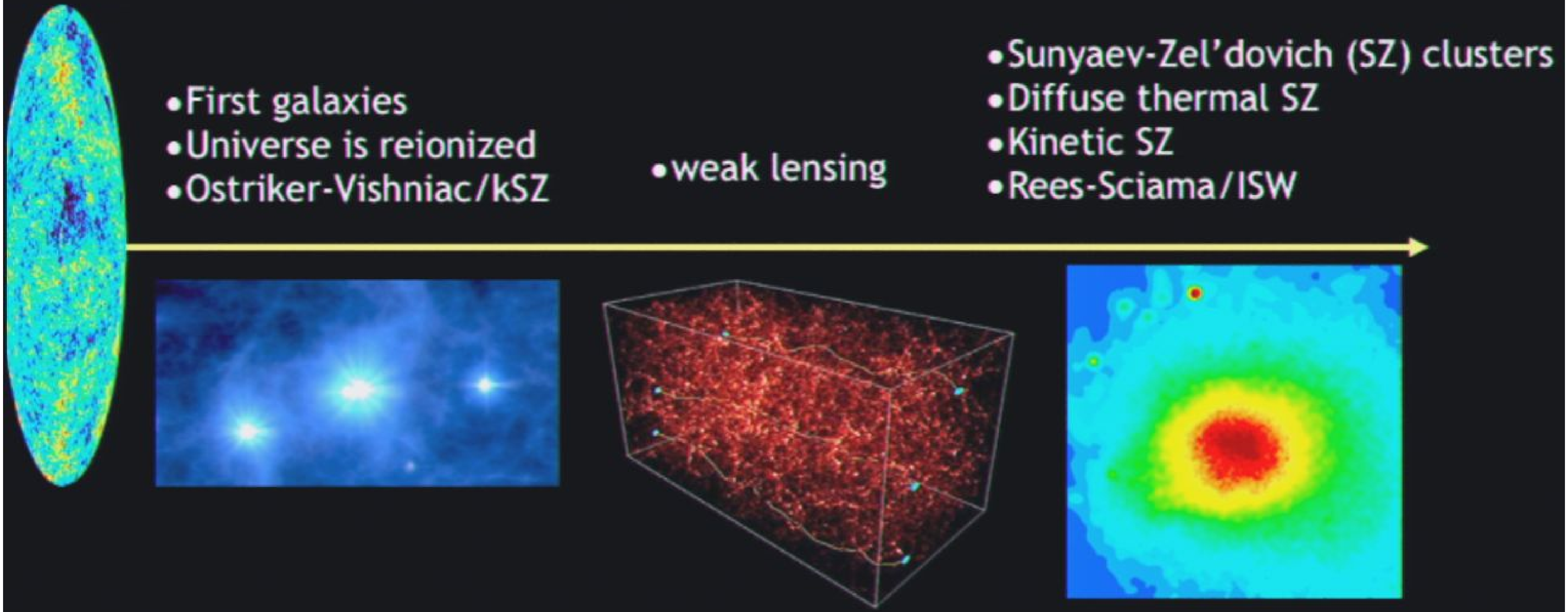
What's next?

Next frontier: secondary anisotropies

Use the CMB as a backlight to illuminate the growth of cosmological structure.



- First galaxies
- Universe is reionized
- Ostriker-Vishniac/kSZ

- weak lensing

- Sunyaev-Zel'dovich (SZ) clusters
- Diffuse thermal SZ
- Kinetic SZ
- Rees-Sciama/ISW

Watch this space because experiments like South Pole Telescope & Atacama Cosmology Telescope are well under way

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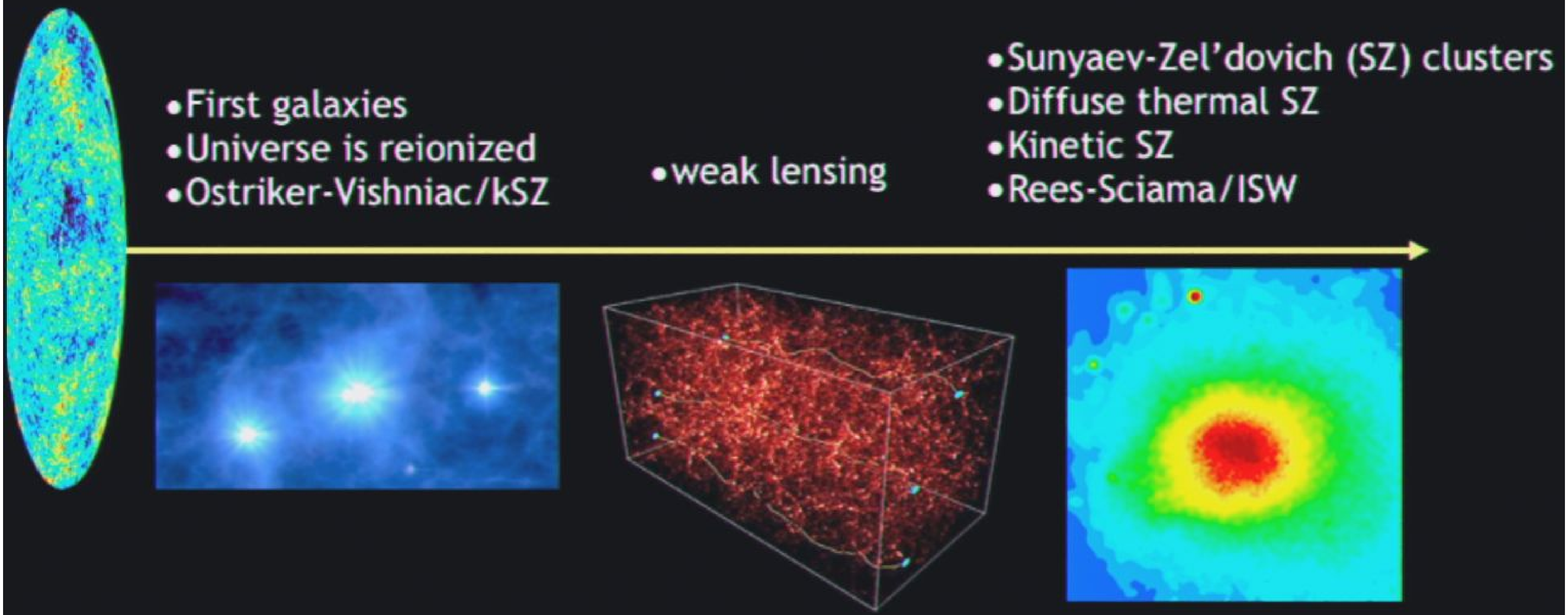

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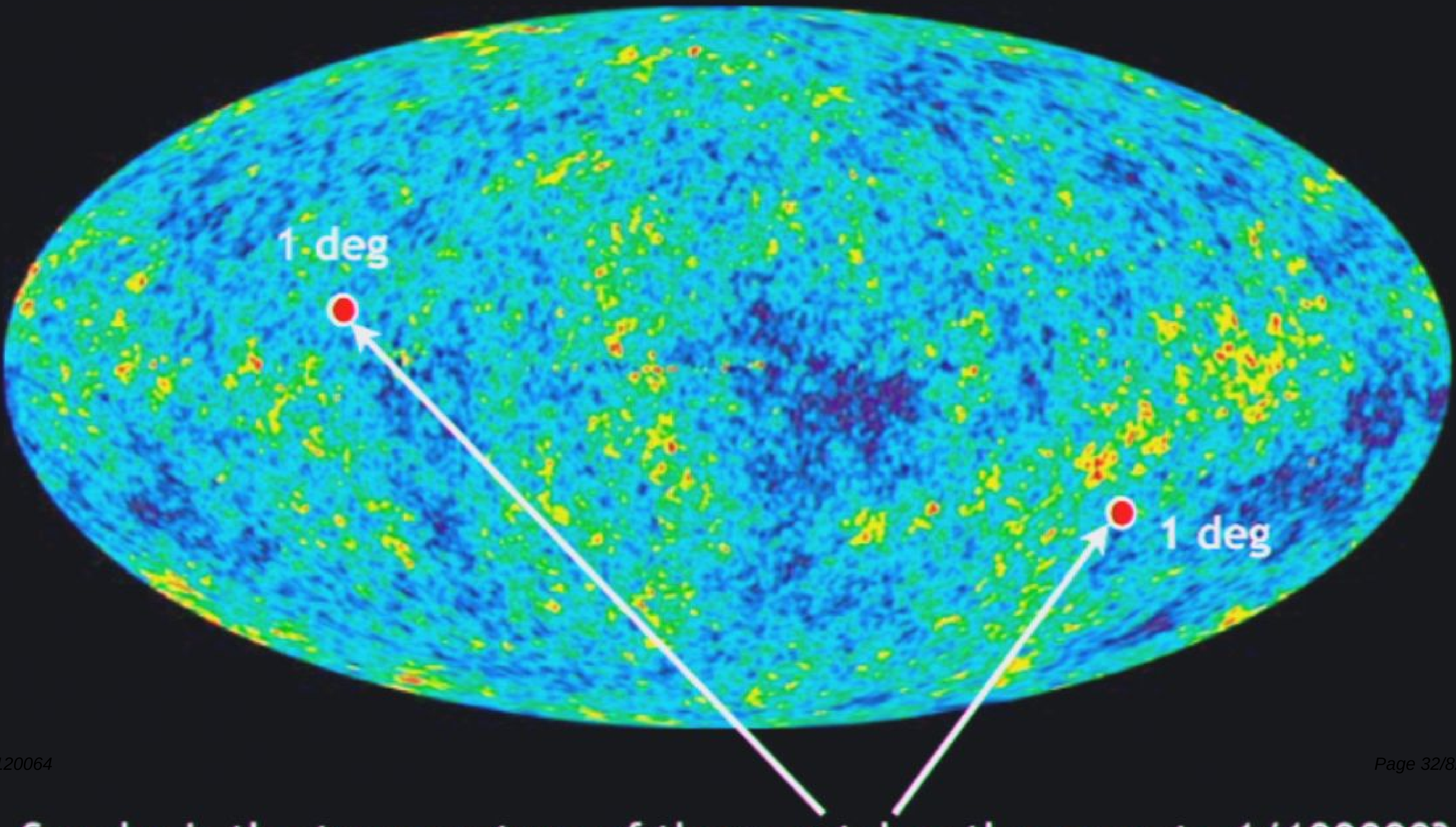
The Horizon Problem

In Standard Big Bang Model, horizon scale at CMB release subtends ~ 1 deg

Regions separated by more than 1 deg could not have interacted previously



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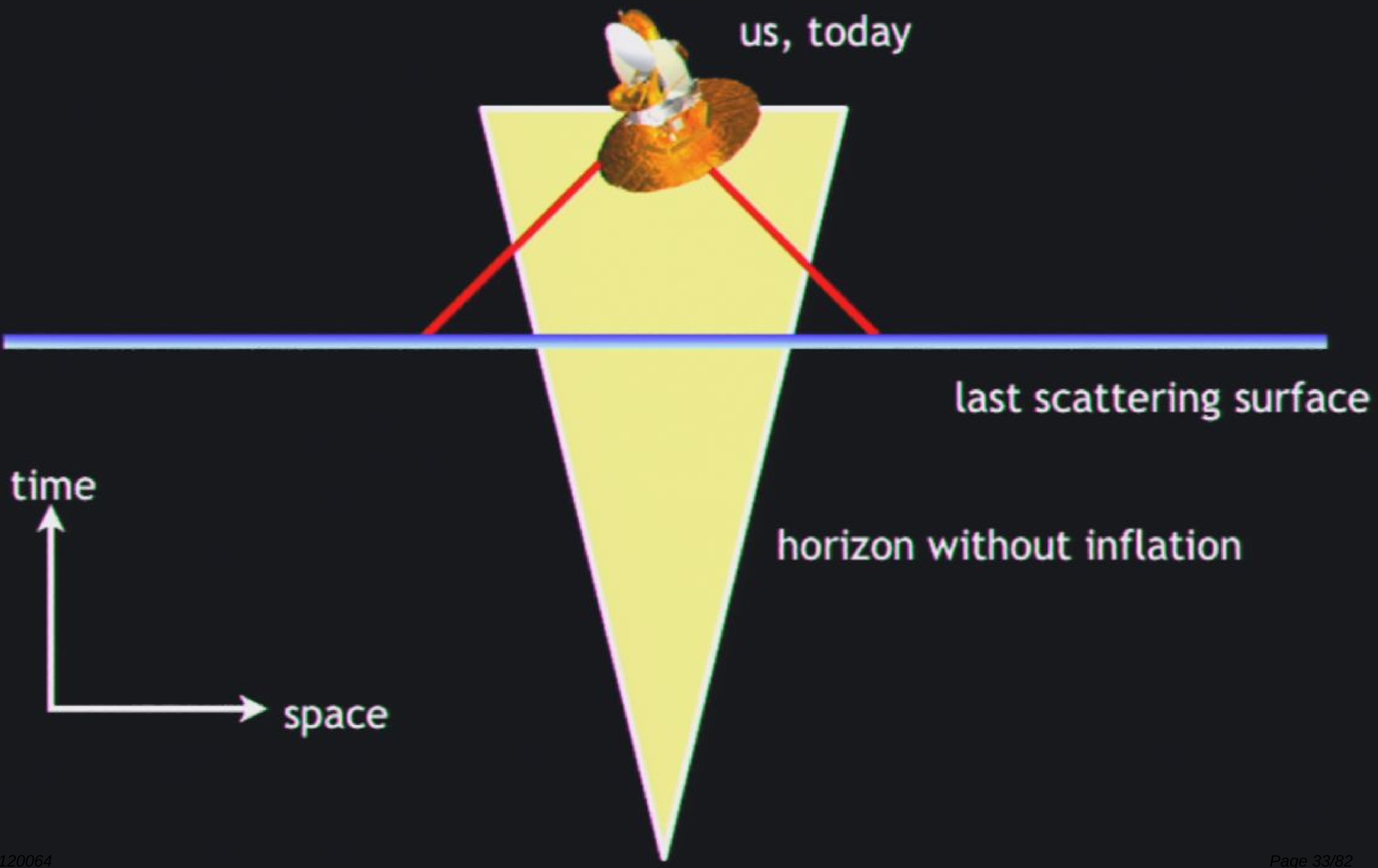
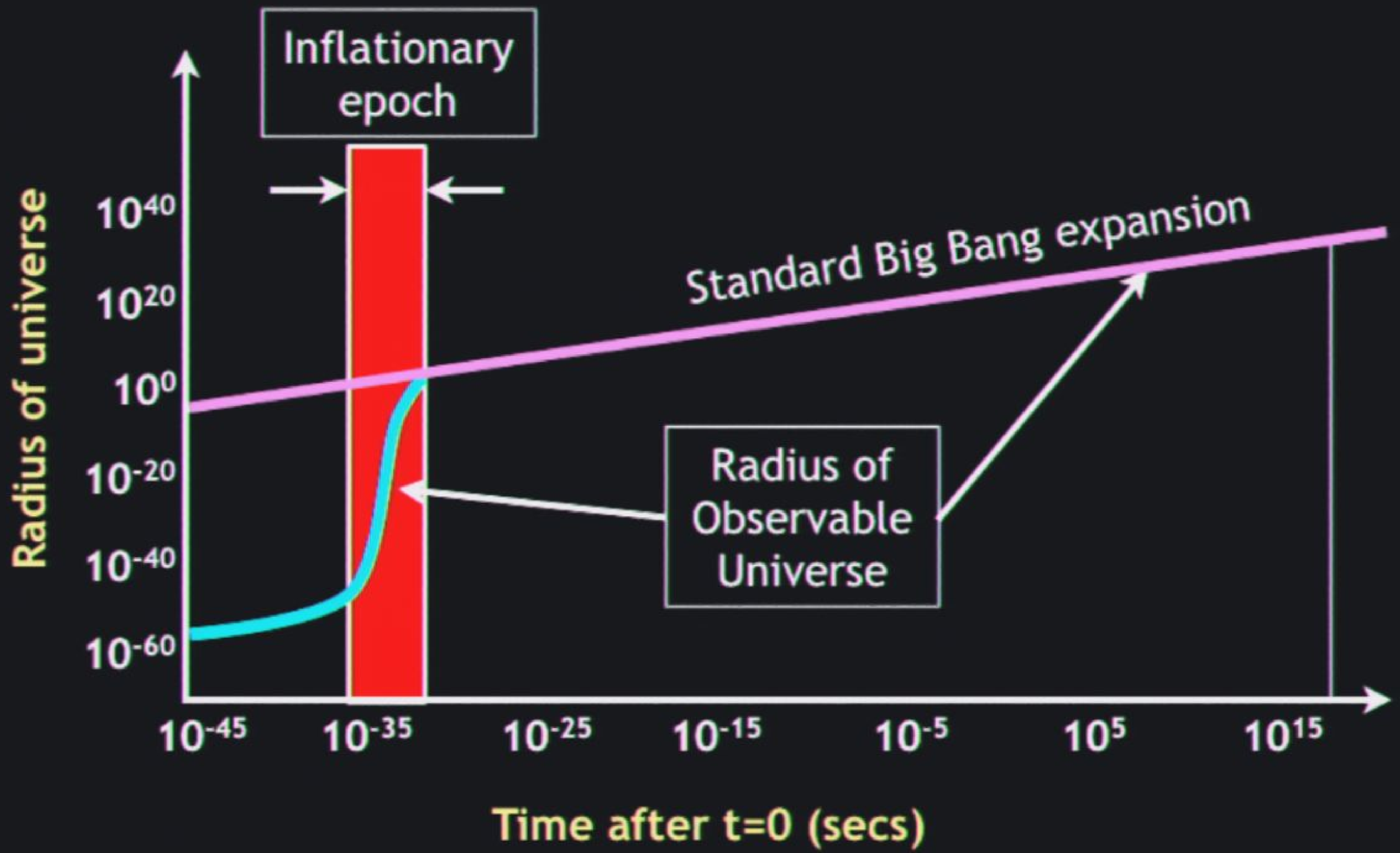
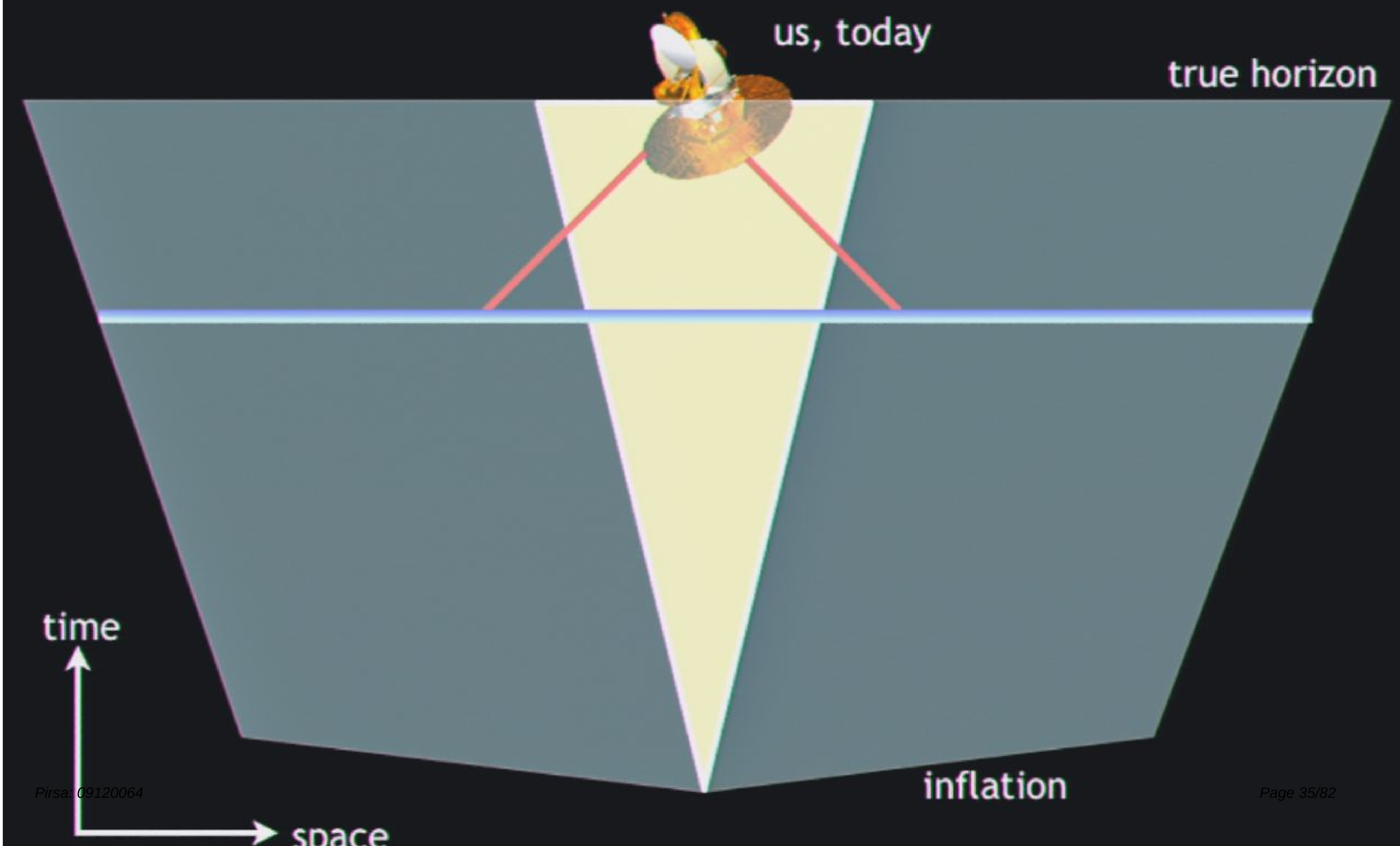


Inflation: accelerated super-expansion

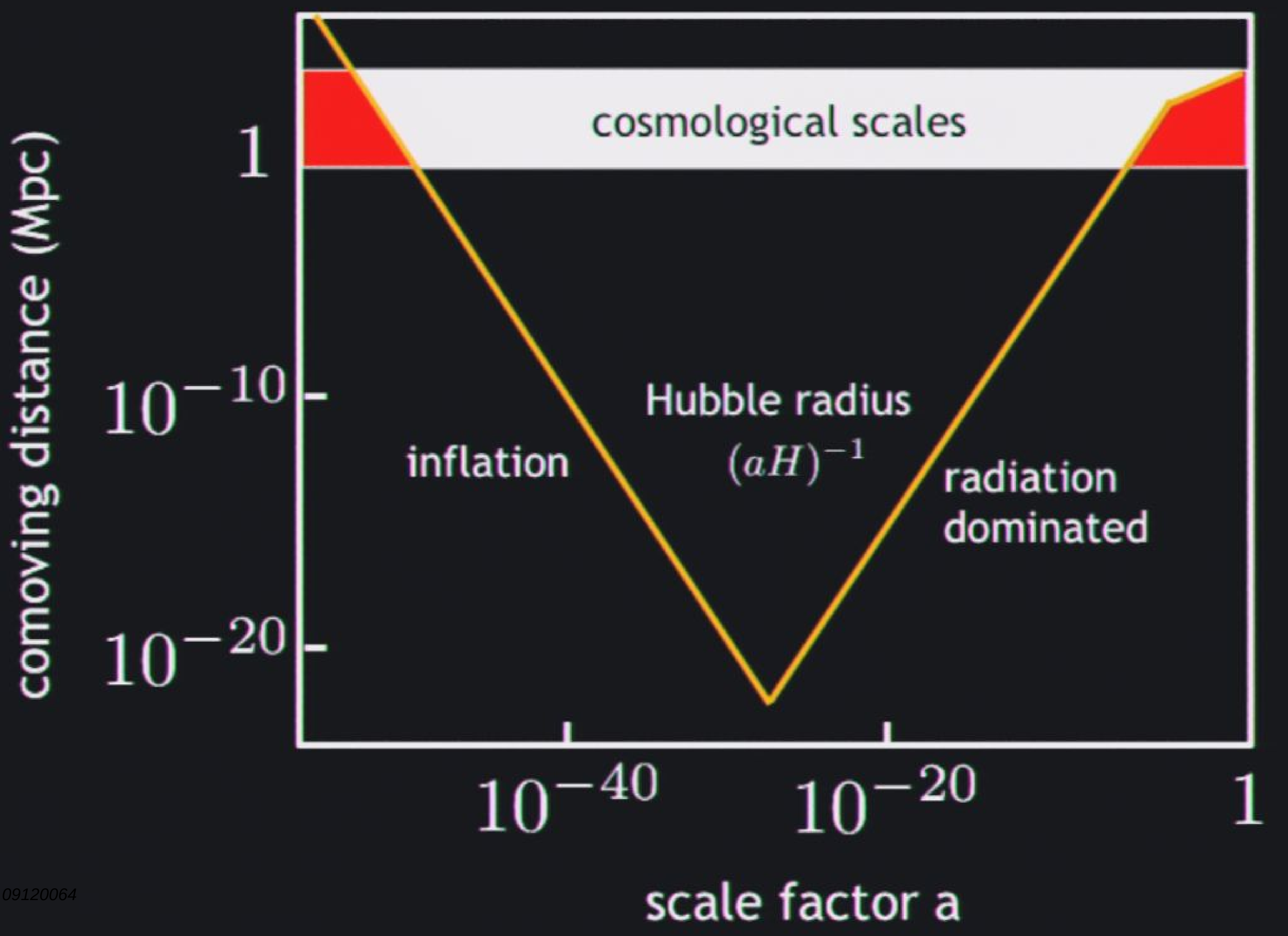


If inflation lasts long enough, CMB patches on opposite sides of the sky

Inflationary resolution of horizon problem



Comoving Hubble radius during inflation



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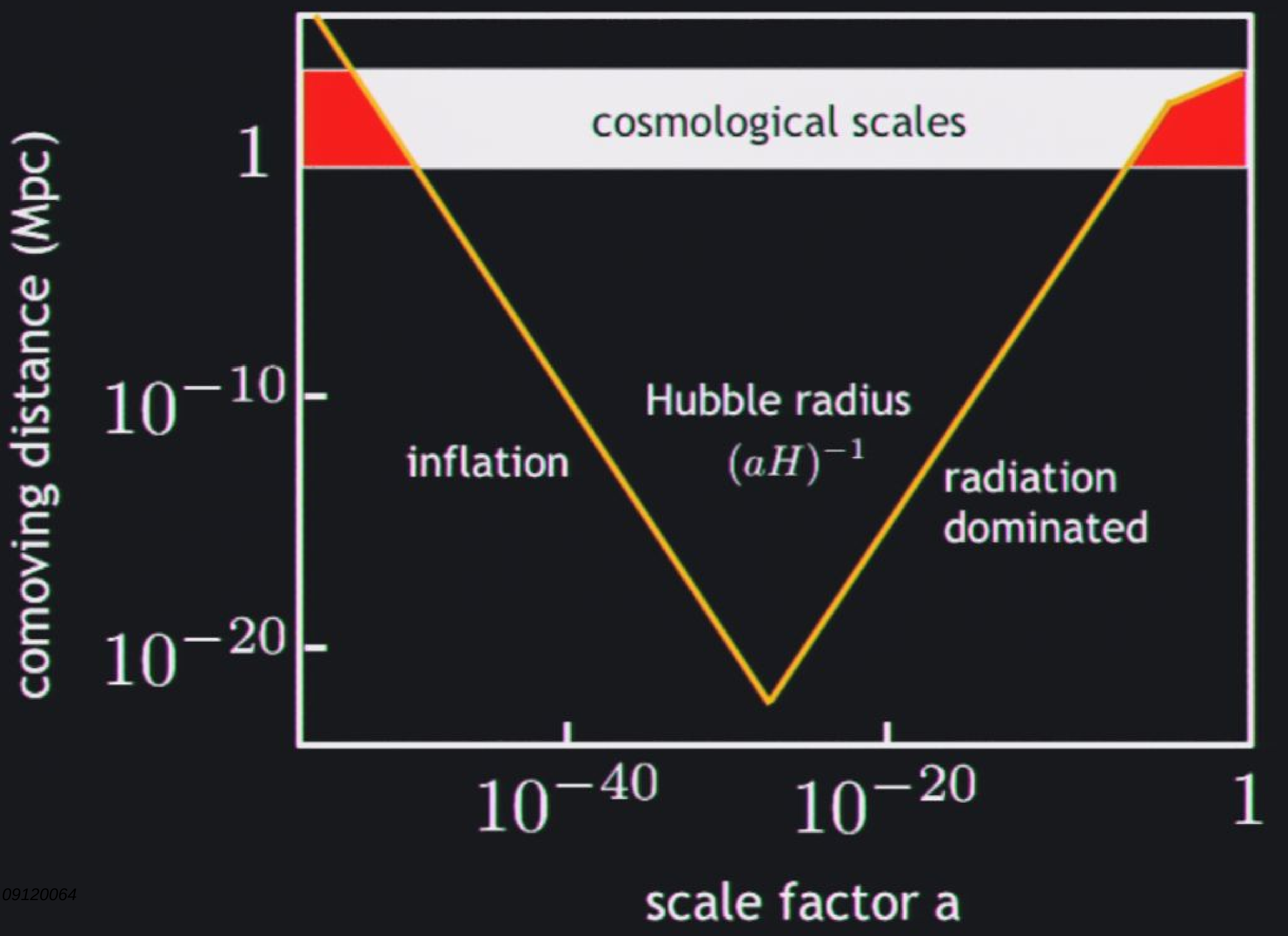


Inflation

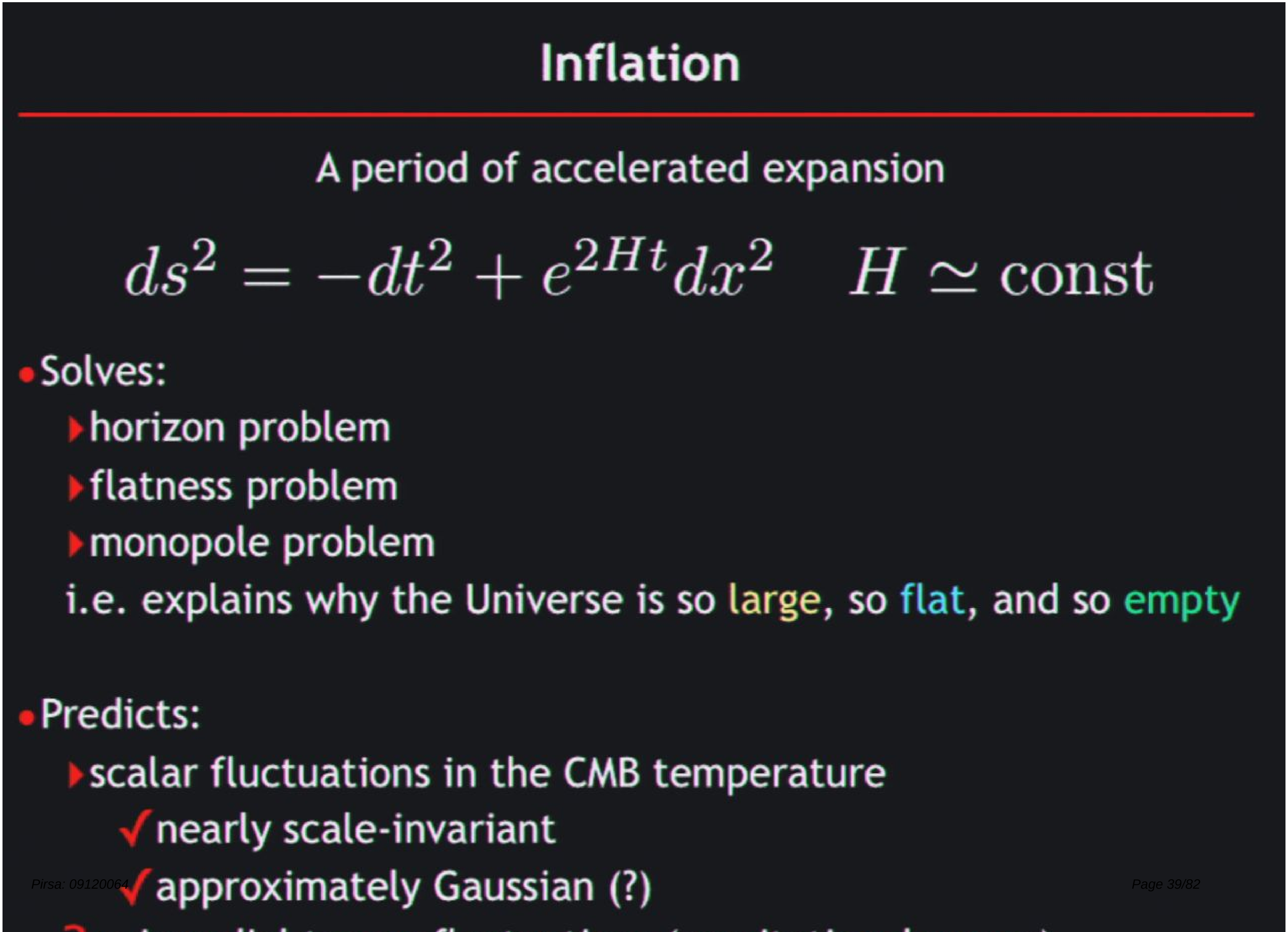
A period of accelerated expansion

$$ds^2 = -dt^2 + e^{2Ht}dx^2 \quad H \simeq \mathrm{const}$$

- Solves:
  - horizon problem
  - flatness problem
  - monopole problem

  i.e. explains why the Universe is so large, so flat, and so empty

- Predicts:
  - scalar fluctuations in the CMB temperature
    - ✓ nearly scale-invariant
    - ✓ approximately Gaussian (?)



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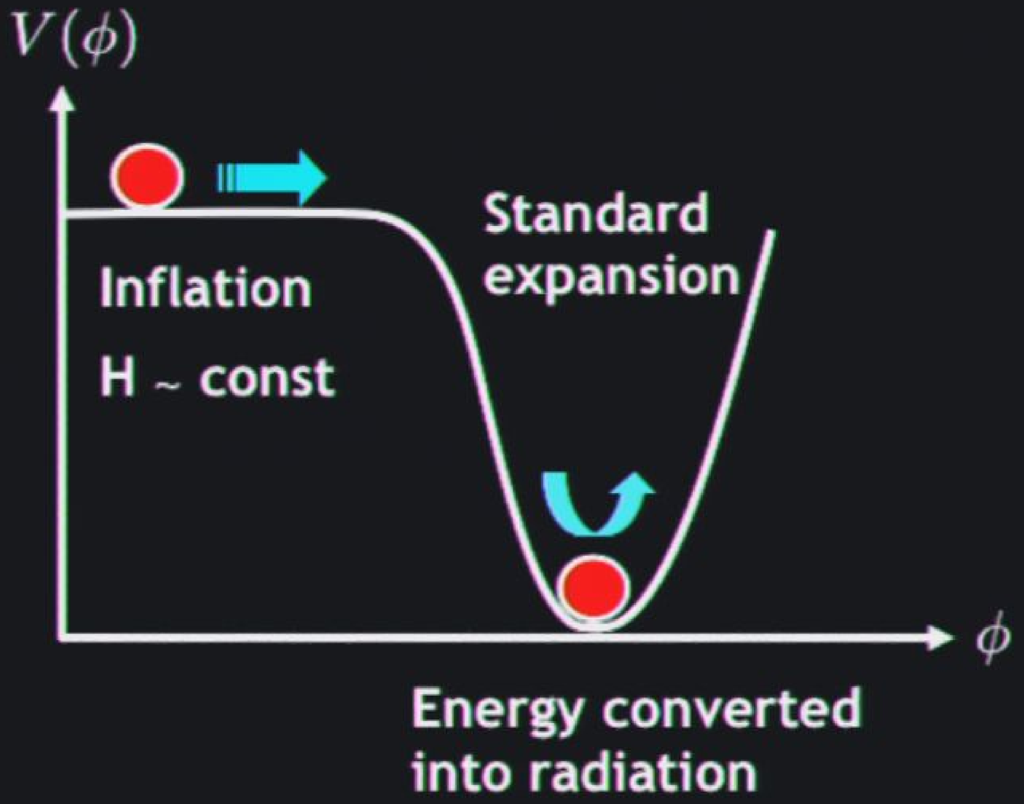
Inflation

Implemented as a slowly-rolling scalar field evolving in a potential:



$$H^2 = \left(\frac{\dot a}{a}\right)^2$$

expansion rate

$$= \frac{8\pi G}{3}\left[\frac{1}{2}\dot\phi^2 + V(\phi)\right]$$

density

$$\ddot\phi + 3H\dot\phi + V' = 0$$

friction

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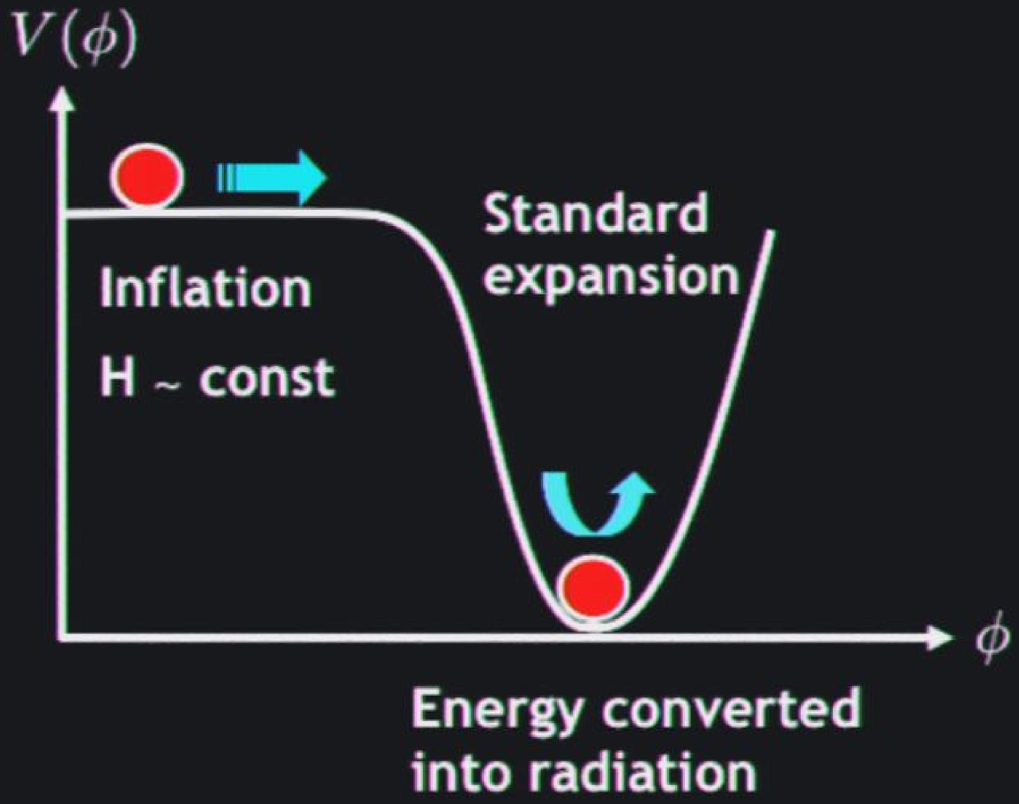

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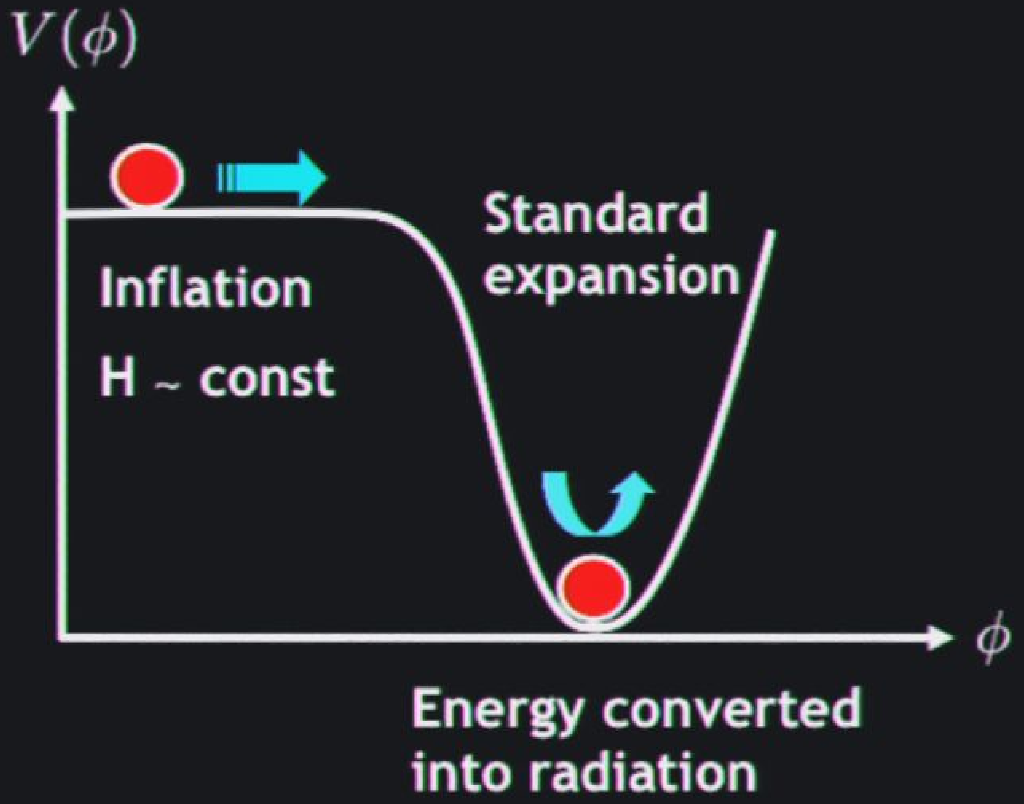

$$
\begin{aligned}
H^2 &= \left(\frac{\dot{a}}{a}\right)^2 \\
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\end{aligned}
$$

expansion rate

density

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friction

Perturbations from inflation

Cosmological perturbations arise from quantum fluctuations, evolve classically.

Perturbations from inflation

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Inflation

- Solves the flatness/horizon problems if the early universe inflates by factor ~10^{30}.
- Cosmological perturbations arise from quantum fluctuations, evolve classically.

$$\begin{tikzcd}
 & P_{\mathcal{R}} \simeq \frac{\hbar}{4\pi^2}\left(\frac{H^4}{\dot{\phi}^2}\right)^2_{k=aH} \\
P_\phi(k) \simeq \hbar\left(\frac{H}{2\pi}\right)^2 \arrow[ur] \arrow[dr] & \\
 & P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_{\rm Pl}}\right)^2_{k=aH}
\end{tikzcd}$$

scalar

tensor

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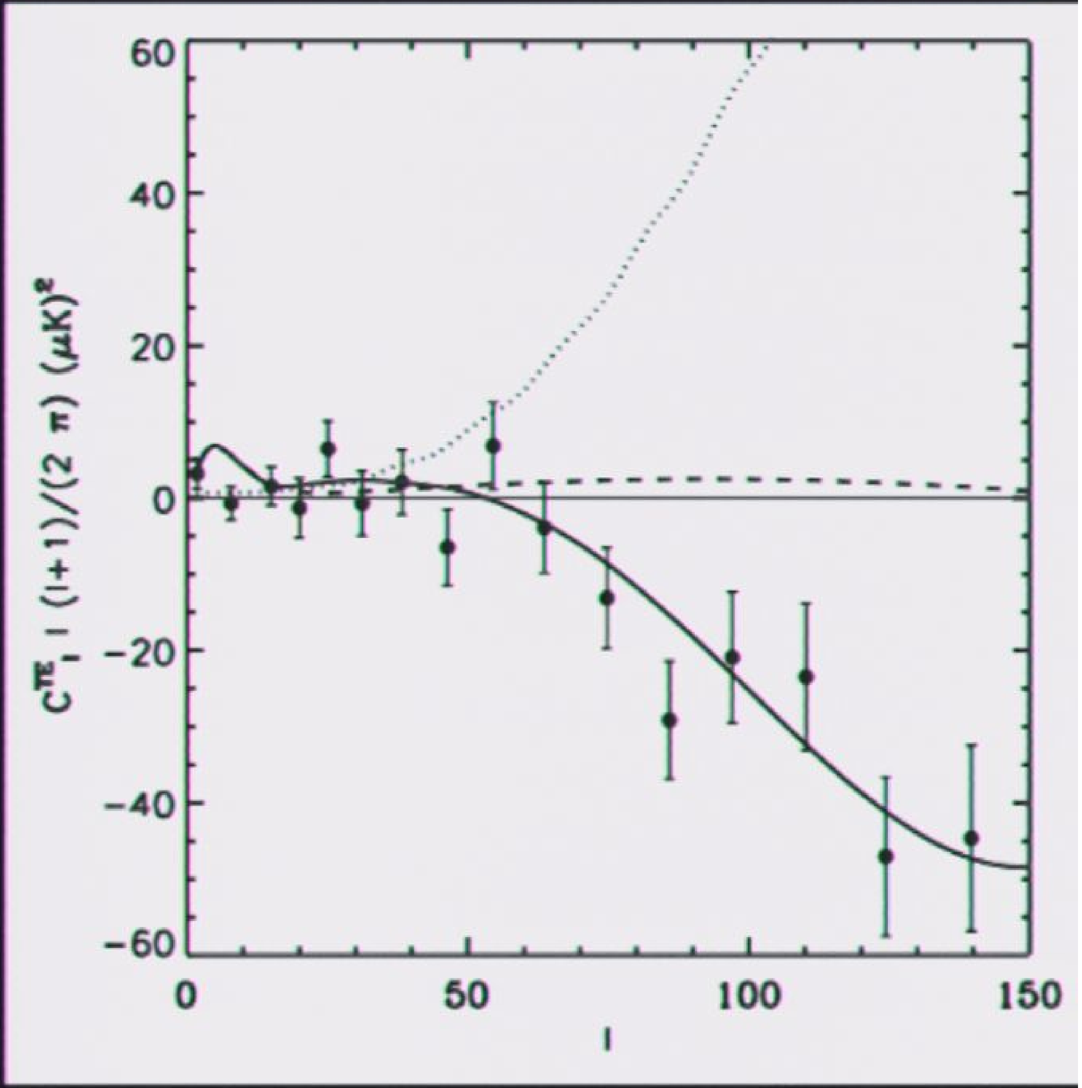
 & P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_{\rm Pl}}\right)^2_{k=aH} & \text{tensor}
\end{tikzcd}$$

- Don't know the dynamics of inflation: parameterize weakly scale-dependent functions with a few numbers to pin down observationally.

$$P_\mathcal{R}(k) \simeq A_s\left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_h(k) \simeq A_t\left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_\mathcal{R}(k_0)}$$

Slow roll inflation consistent with WMAP+

- Superhorizon, adiabatic fluctuations
  - T and E anticorrelated at superhorizon scales
- Flatness tested to 1%.
- Gaussianity tested to 0.1%.
- nearly scale-invariant fluctuations
  - red tilt indicated at ~2.5 σ



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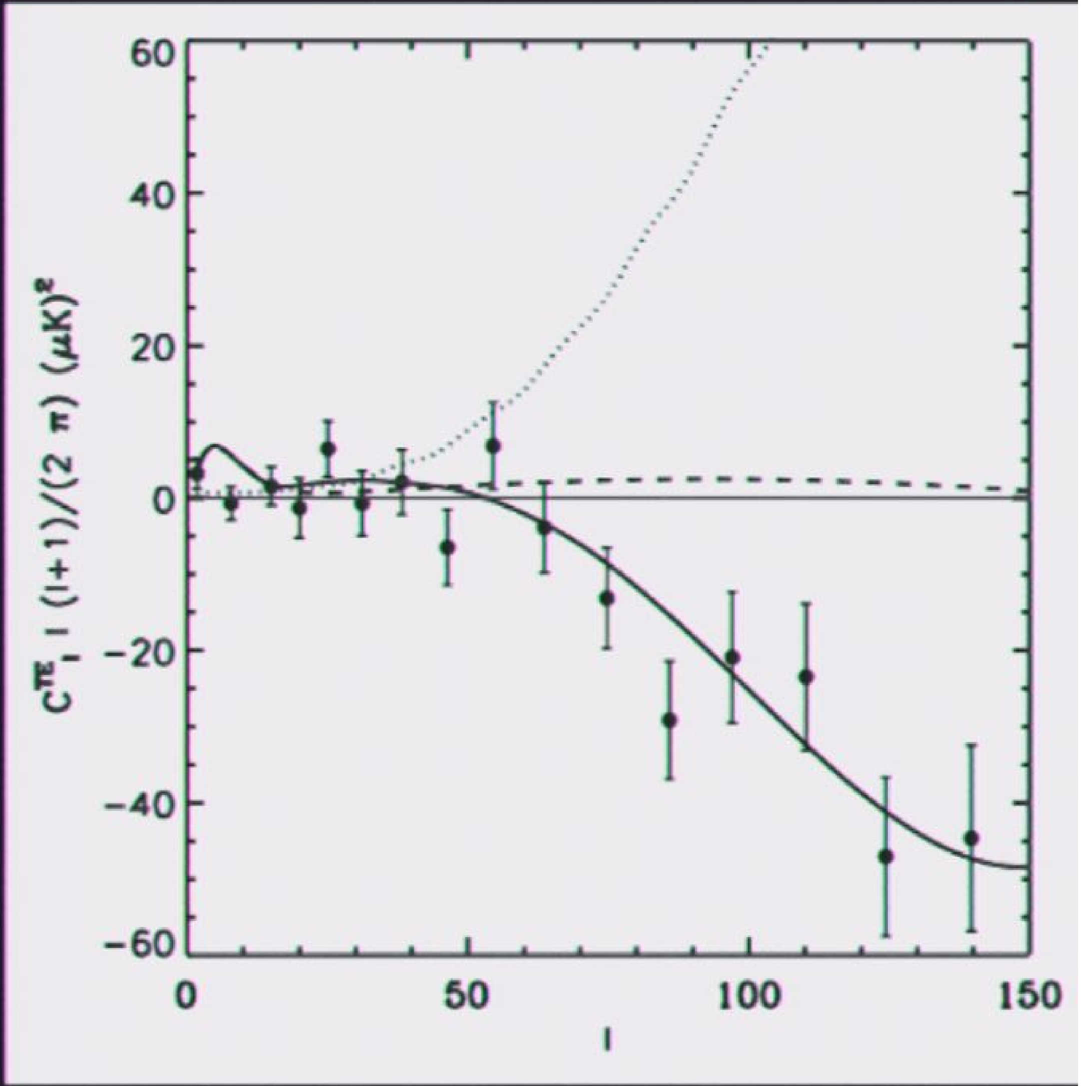
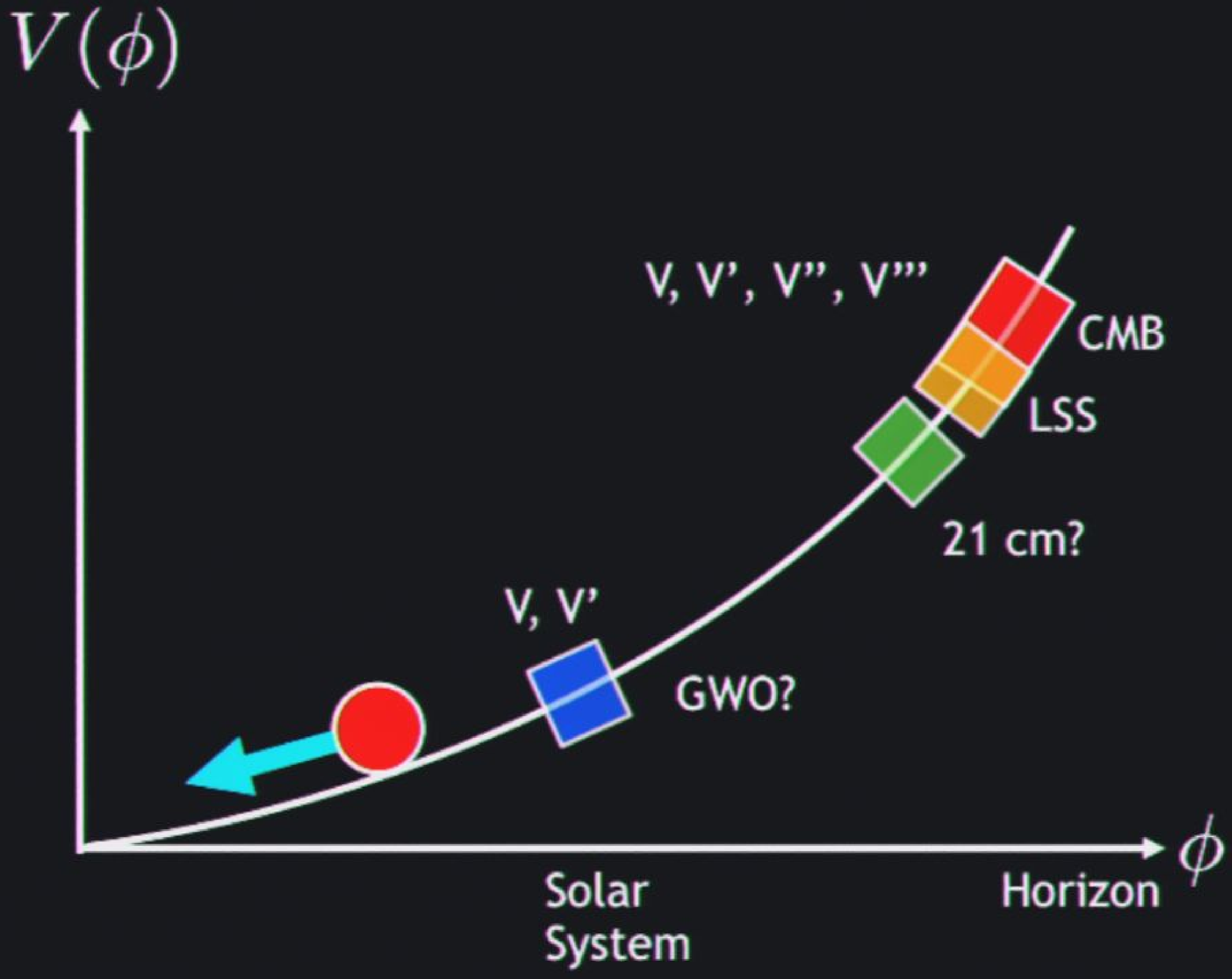


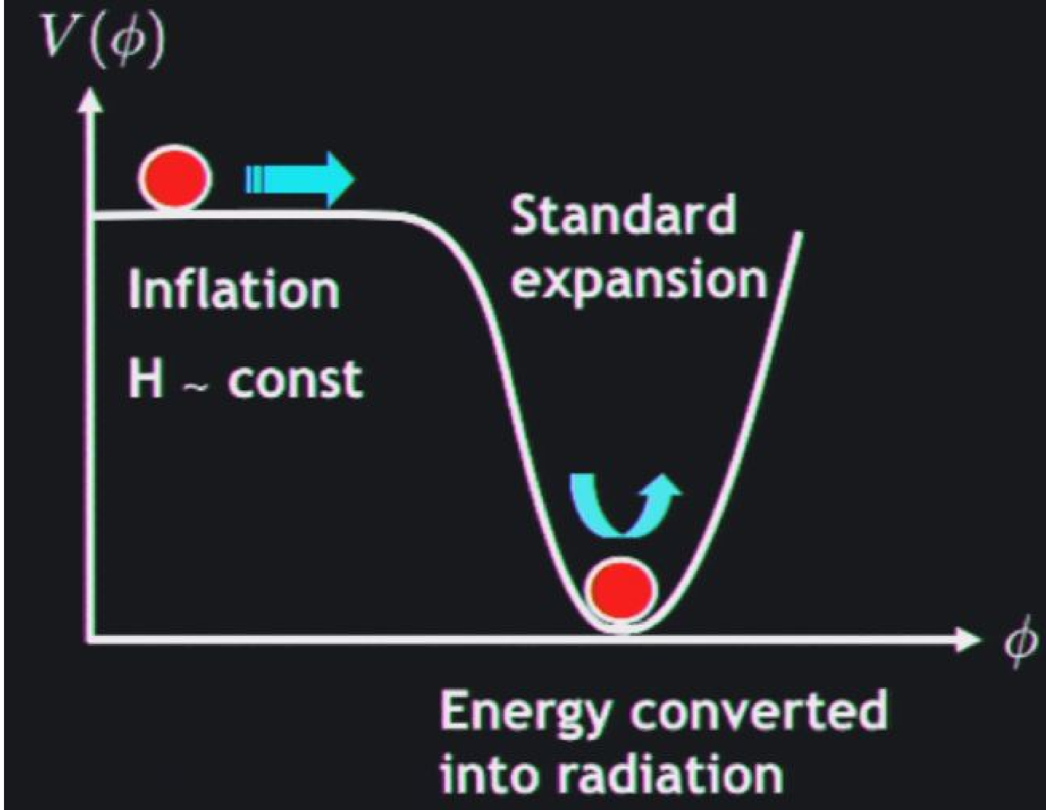
Still testing basic aspects of inflationary mechanism rather than specific implementation.

Fingerprints of the early universe



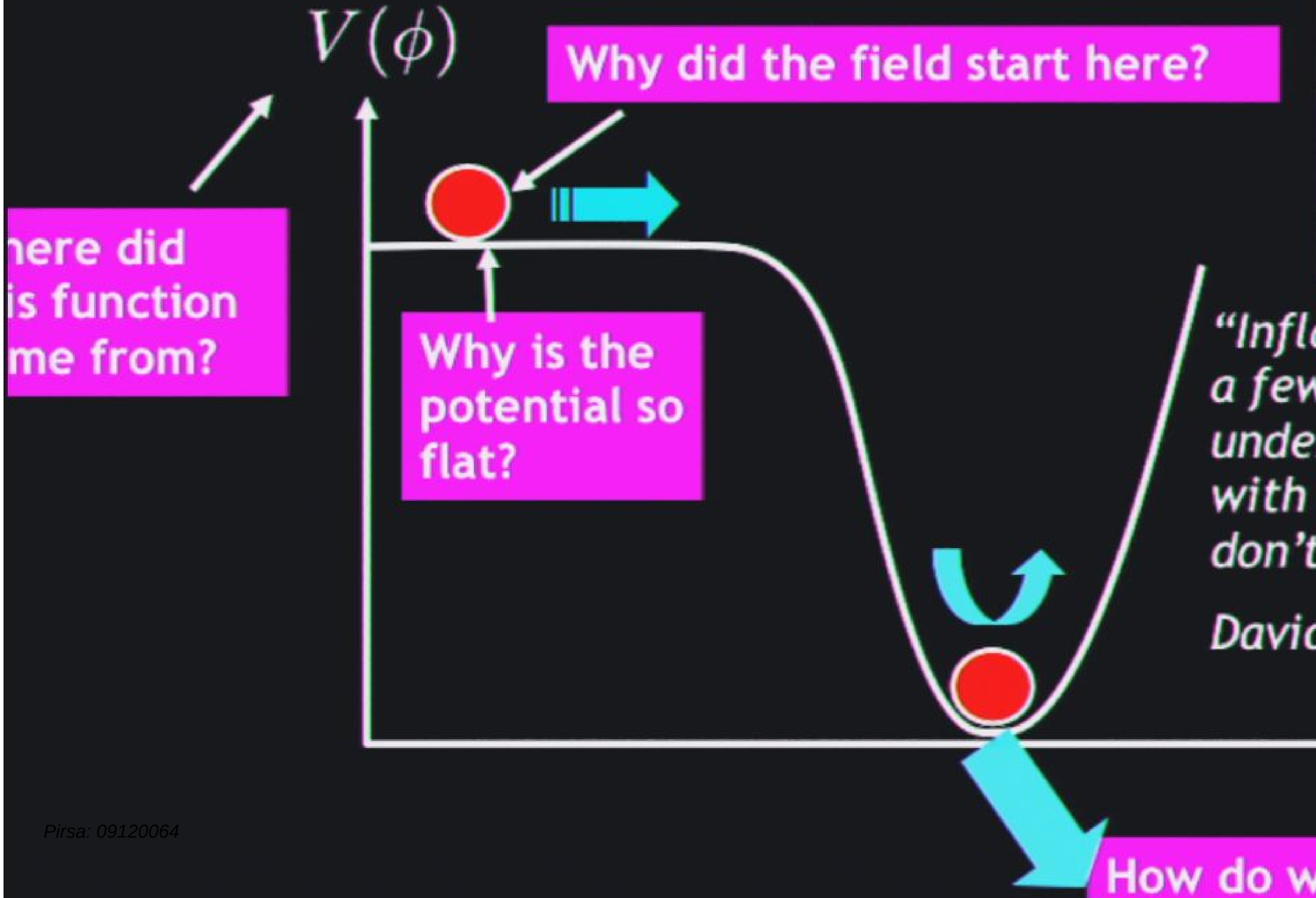
Inflation

Modelled as a scalar field (inflaton) evolving in a potential



Many potentials from different physical motivations are consistent with the data

What is the physics of inflation?



Why did the field start here?

here did
is function
me from?

Why is the
potential so
flat?

How do we convert the

"Inflation consists of takin
a few numbers that we do
understand and replacing i
with a function that we
don't understand"

David Schramm 1945 - 199

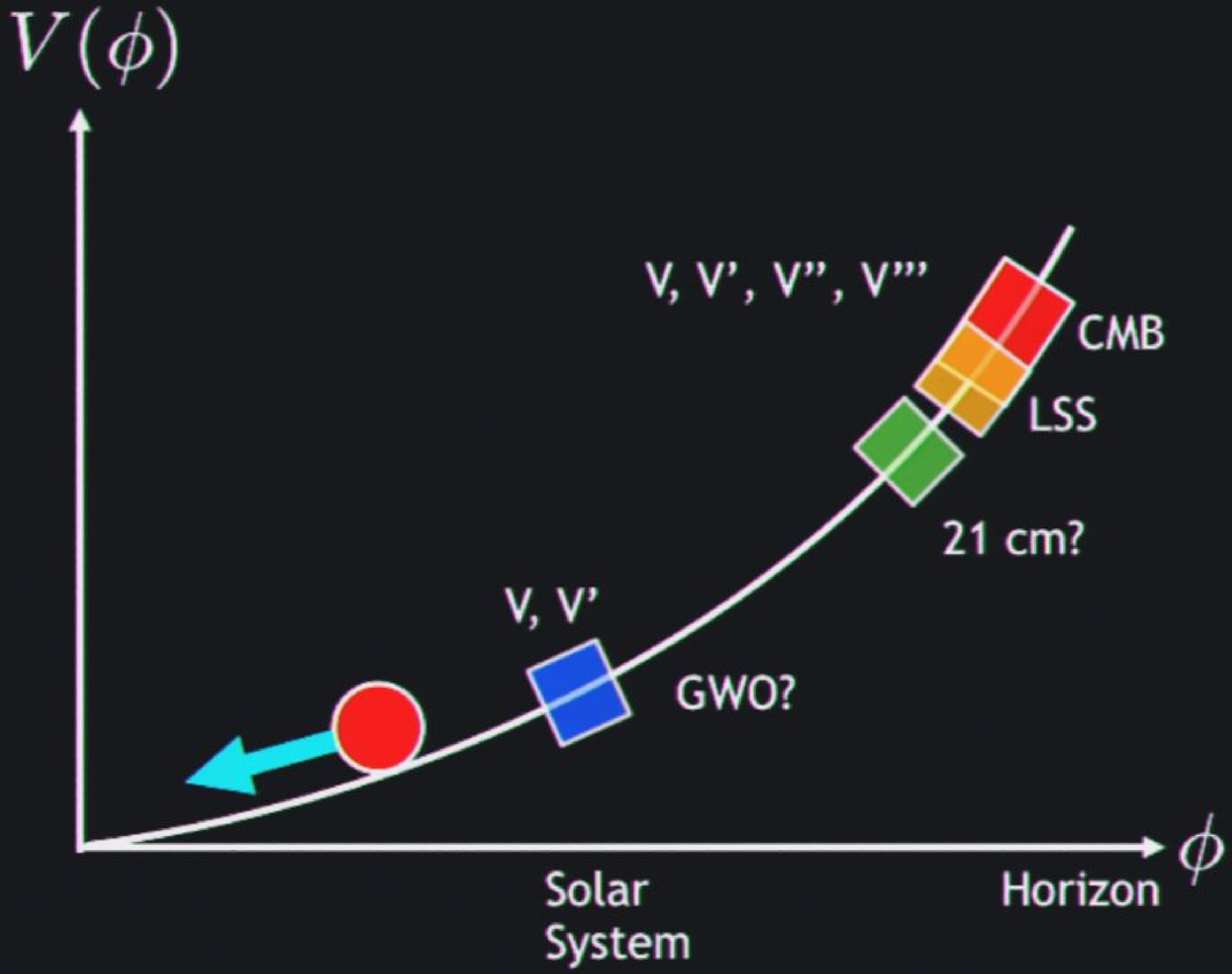
Primordial gravitational waves: a smoking gun

- Temperature only sensitive to scalars. Polarization can differentiate between scalars (density) and tensors (gravitational waves).

- Current limit $r_{\mathrm{CMB}} < 0.2$. "Realistically" observable: $r_{\mathrm{CMB}} \geq 0.01$

- Measurement gives two critical pieces of info:
  - -energy scale of inflation: $V^{1/4} \sim \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4} 10^{16}\ \mathrm{GeV}$
  - -super-Planckian field variation: $\frac{\Delta\phi}{M_{\mathrm{Pl}}} > \mathcal{O}(1) \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/2}$

Fingerprints of the early universe



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Lyth Bound

In a de Sitter spacetime,

tensors: $P_h \propto \frac{H^2}{M_{\rm Pl}^2}$ scalars: $P_s \propto H^2 \left(\frac{H}{\dot{\phi}}\right)^2$

tensor to scalar ratio: $r \equiv \frac{P_h}{P_s} = 8 \left(\frac{1}{M_{\rm Pl}} \frac{d\phi}{dN_e}\right)^2$

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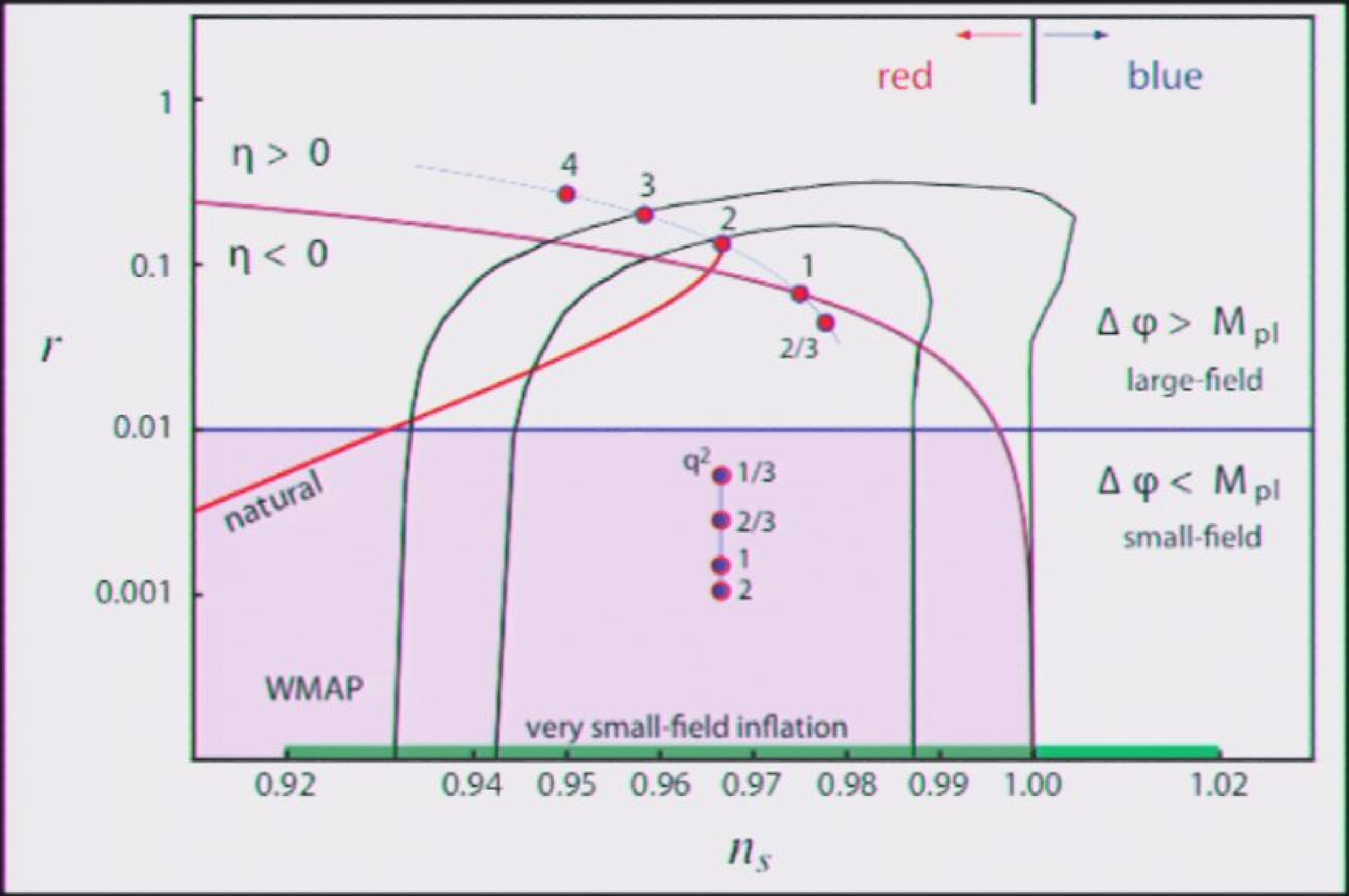
Primordial gravitational waves: the challenges

Gravity's waves are
Traceless; which does not mean they
Can never be found.

Haiku by Peter Coles

Challenge I: what is the amplitude?



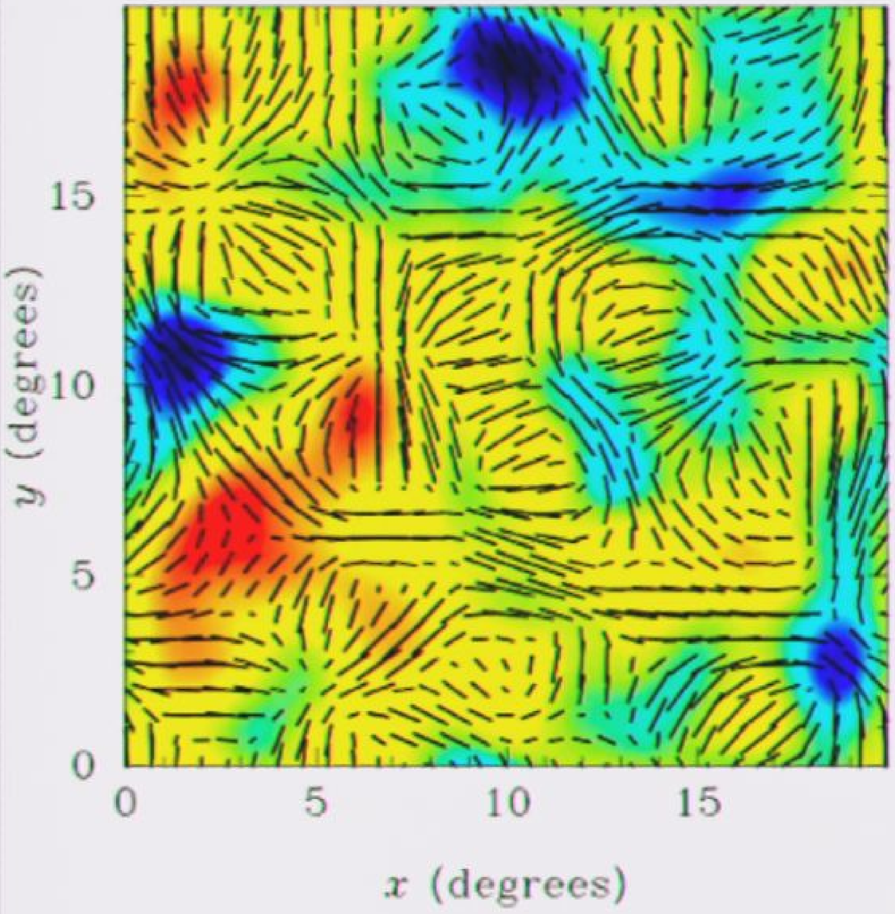
- r determines whether model is large or small field.

- n_s determines whether spectrum is red or blue.

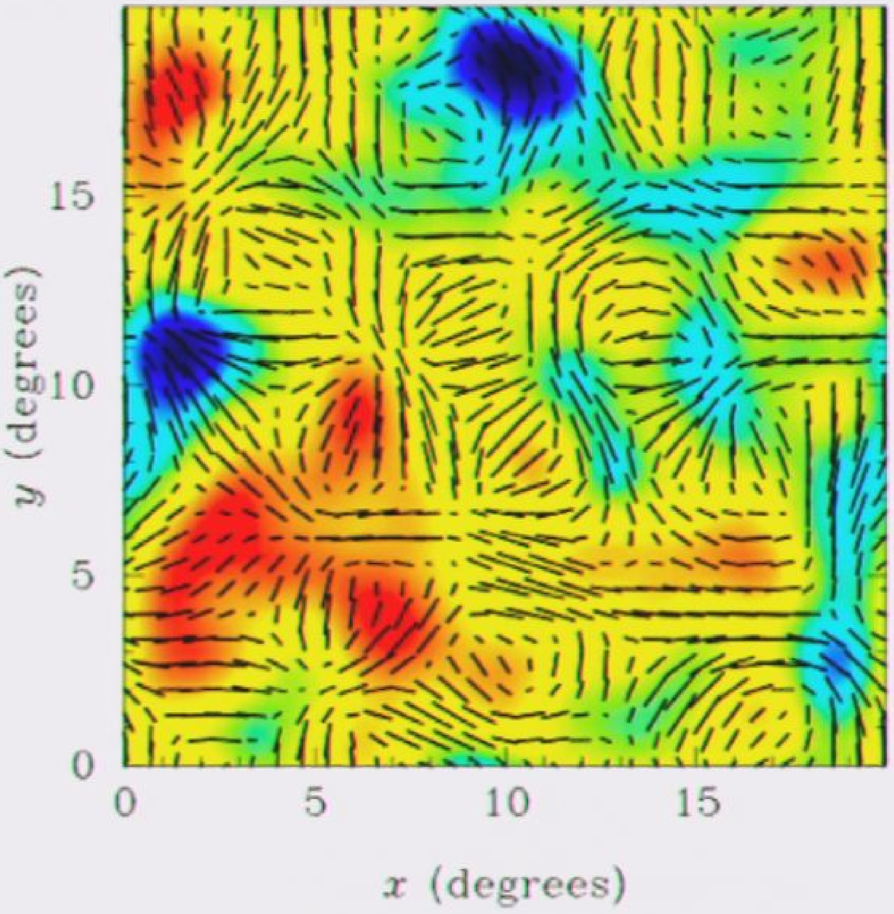
- a combination of n_s and r determines the curvature of the potential η.

Tensors: B-mode contribution is small!

- R.m.s. B-mode signal from gravity waves $< 200\,\text{nK}$



$r = 0.28$



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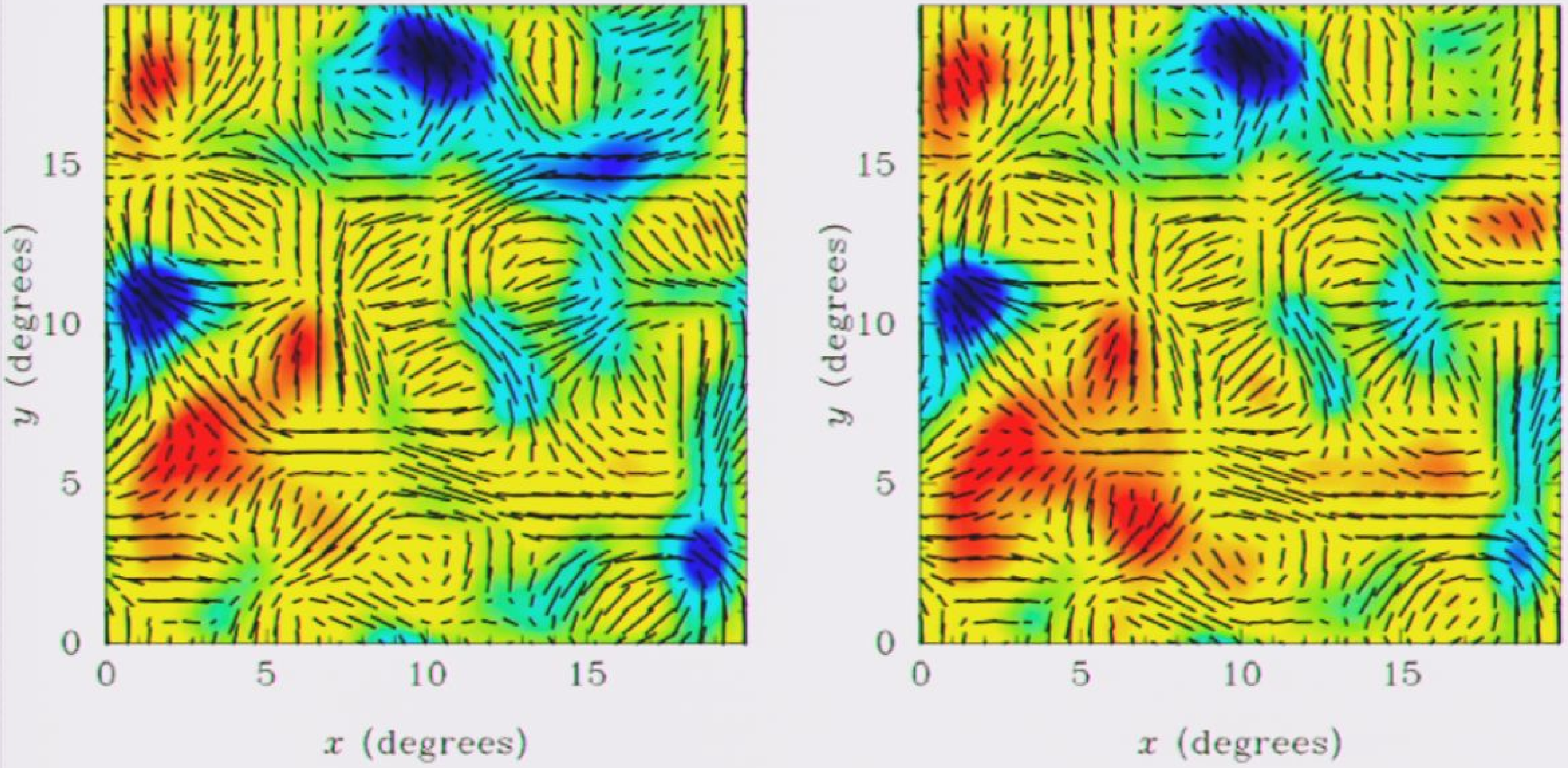

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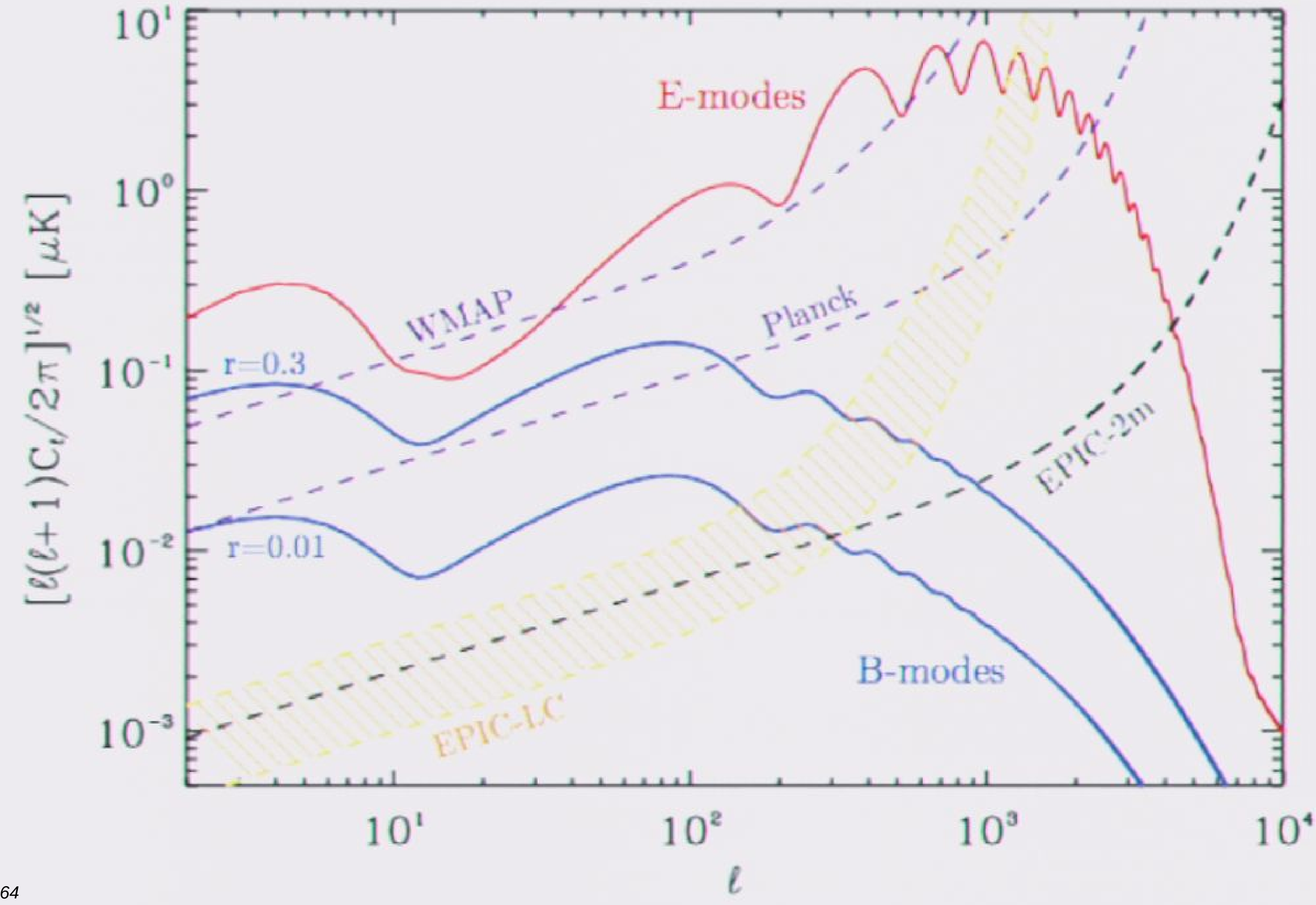
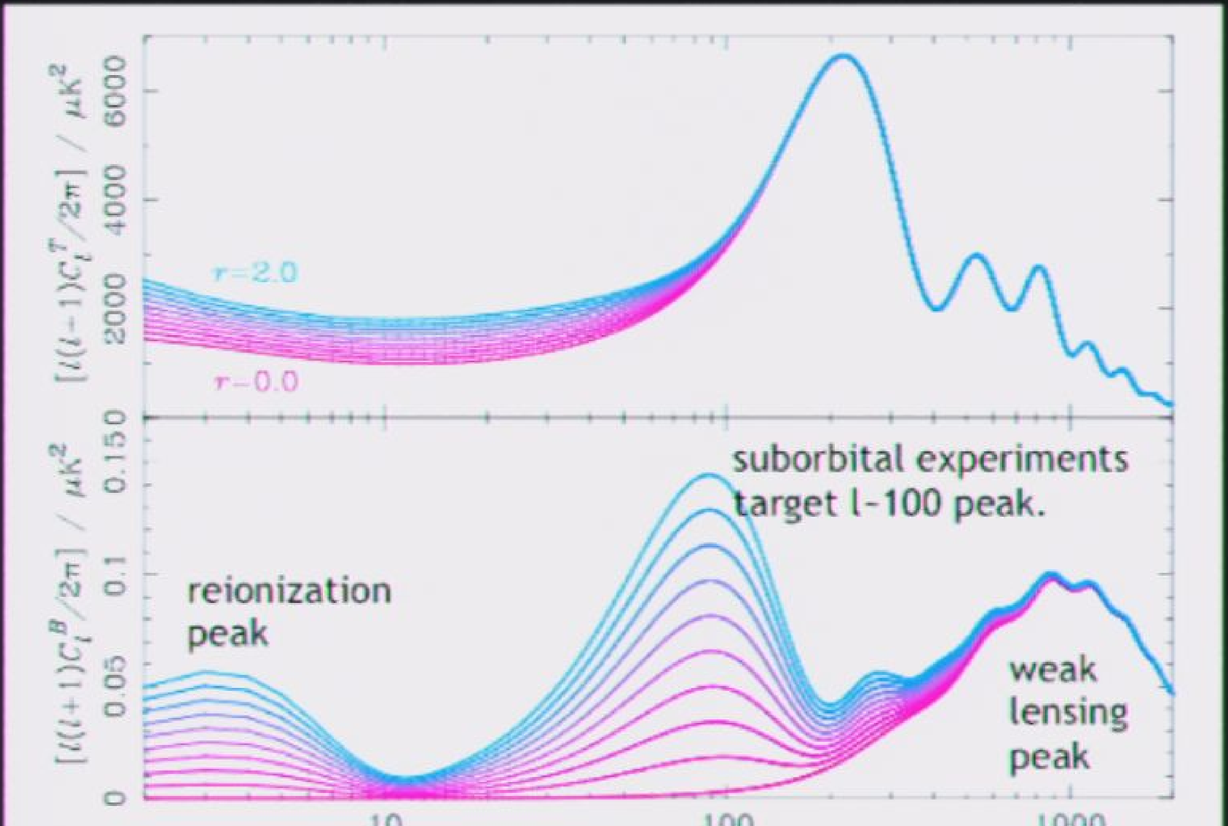
Relative Amplitudes of CMB power spectra



Challenge II: Weak Lensing

- Generated by weak lensing of the E-mode by large scale structure; subdominant on large scales, dominates on small scales. (Seljak & Zaldarriaga 1998)

- Use cross-correlation/ map non-Gaussianity to “de-lens”? (Okamoto & Hu/Lewis/Knox & Song/Smith)



suborbital experiments target l~100 peak.

Challenge III: Detectors

- Polarization-sensitive bolometers
  - -Good above ~ 100 GHz. (e.g. BOOMERanG, DASI)

- HEMT polarimeters
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$$\Delta T_{\mathrm{rms}} = \frac{T_{\mathrm{RMS}} + T_{\mathrm{receiver}}}{\sqrt{\Delta\nu\Delta t}}$$

Need detector arrays to beat down noise limit/detector

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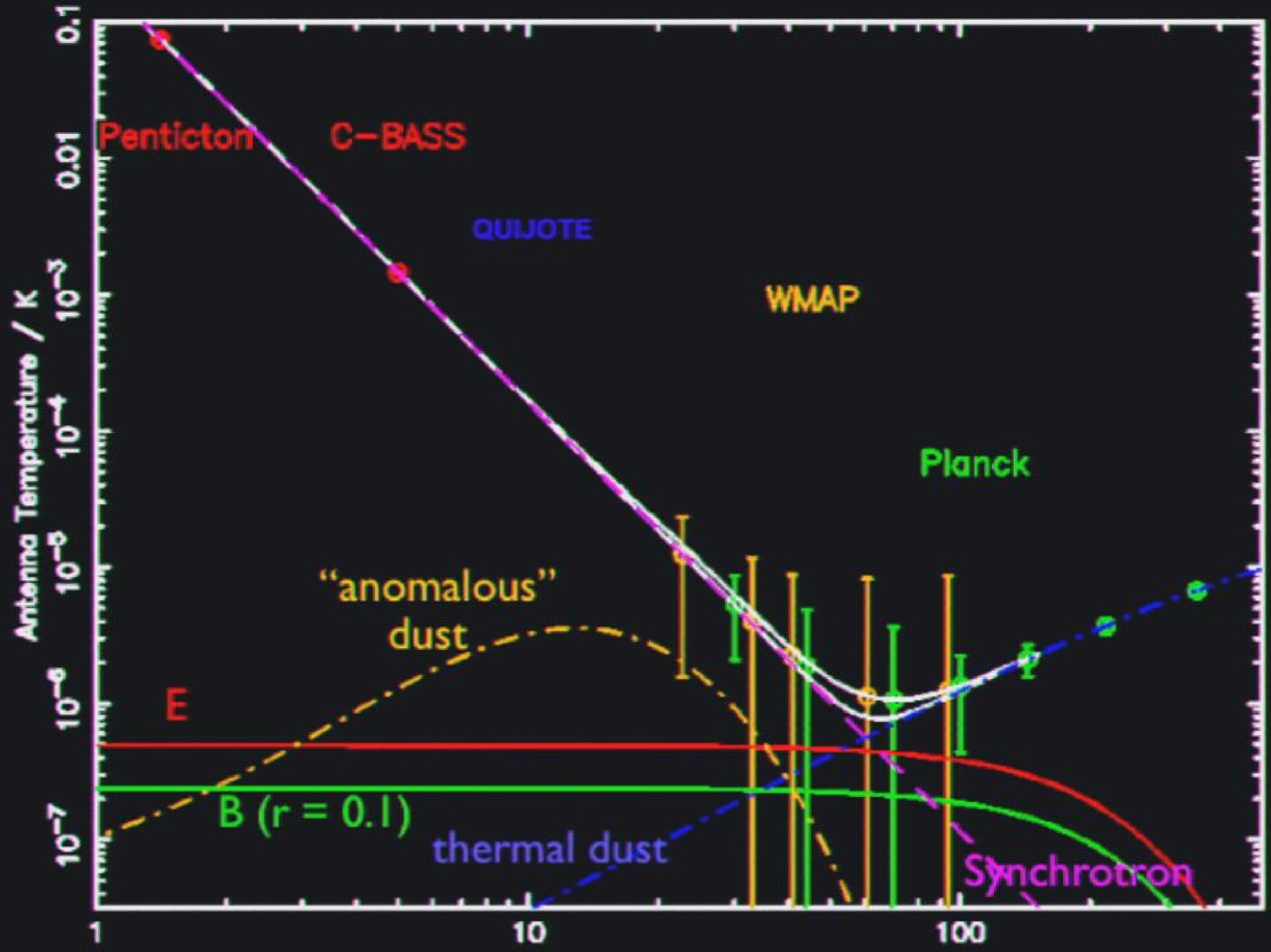
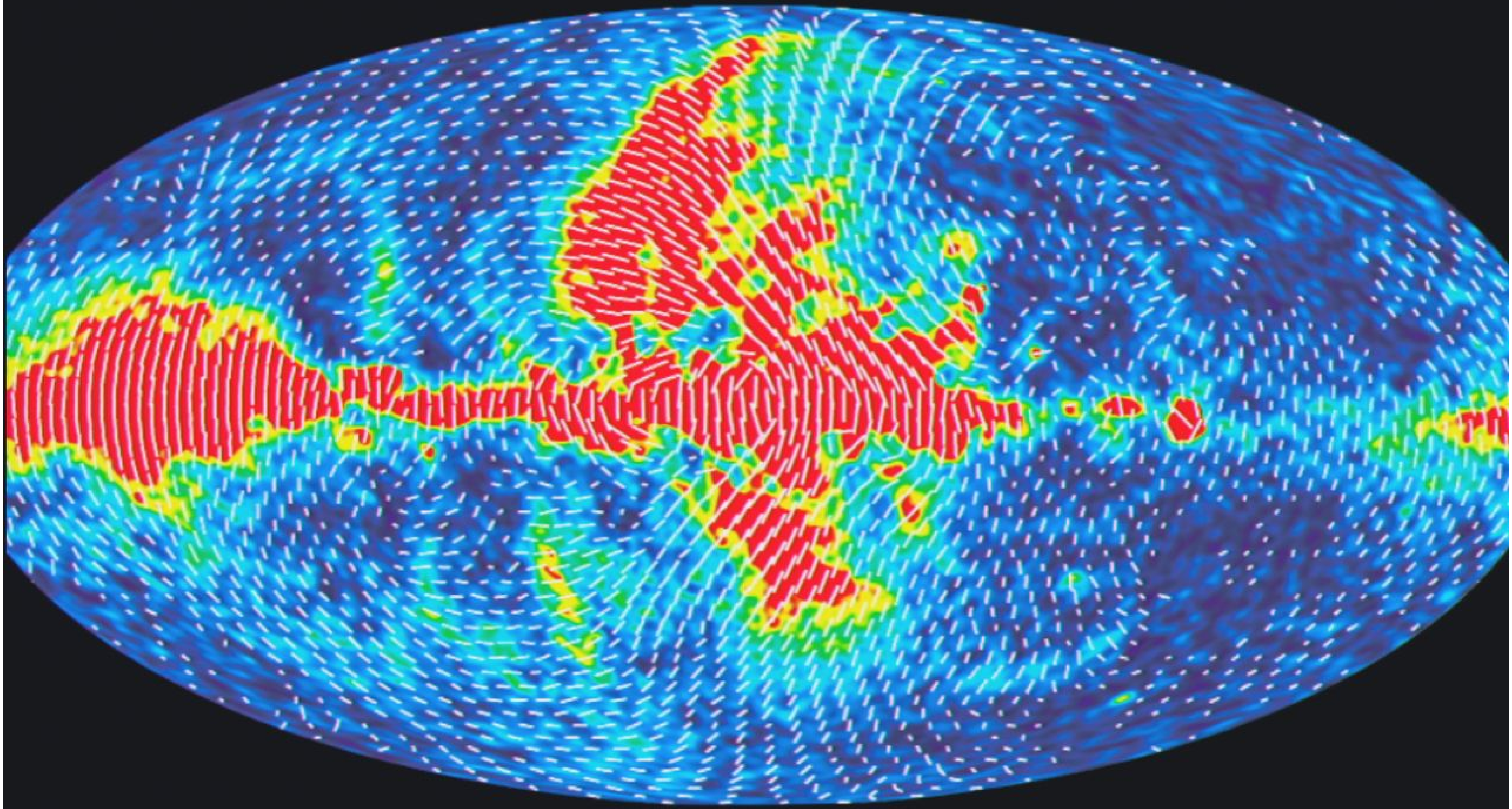
} Space → weight restrictions!

Challenge IV: we live inside a galaxy!

RMS polarized Galactic emission at 1 deg.

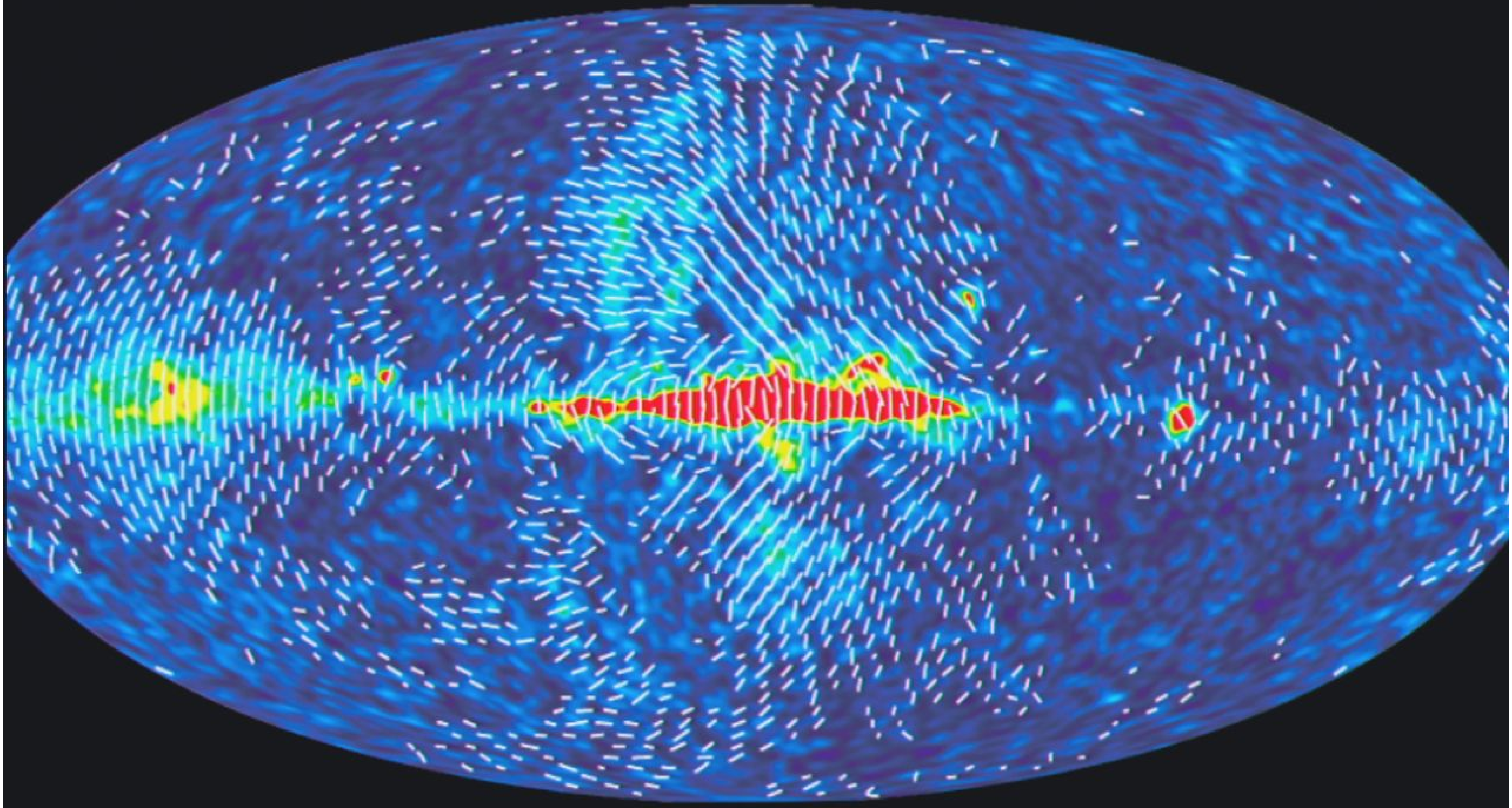


K Band (23 GHz)



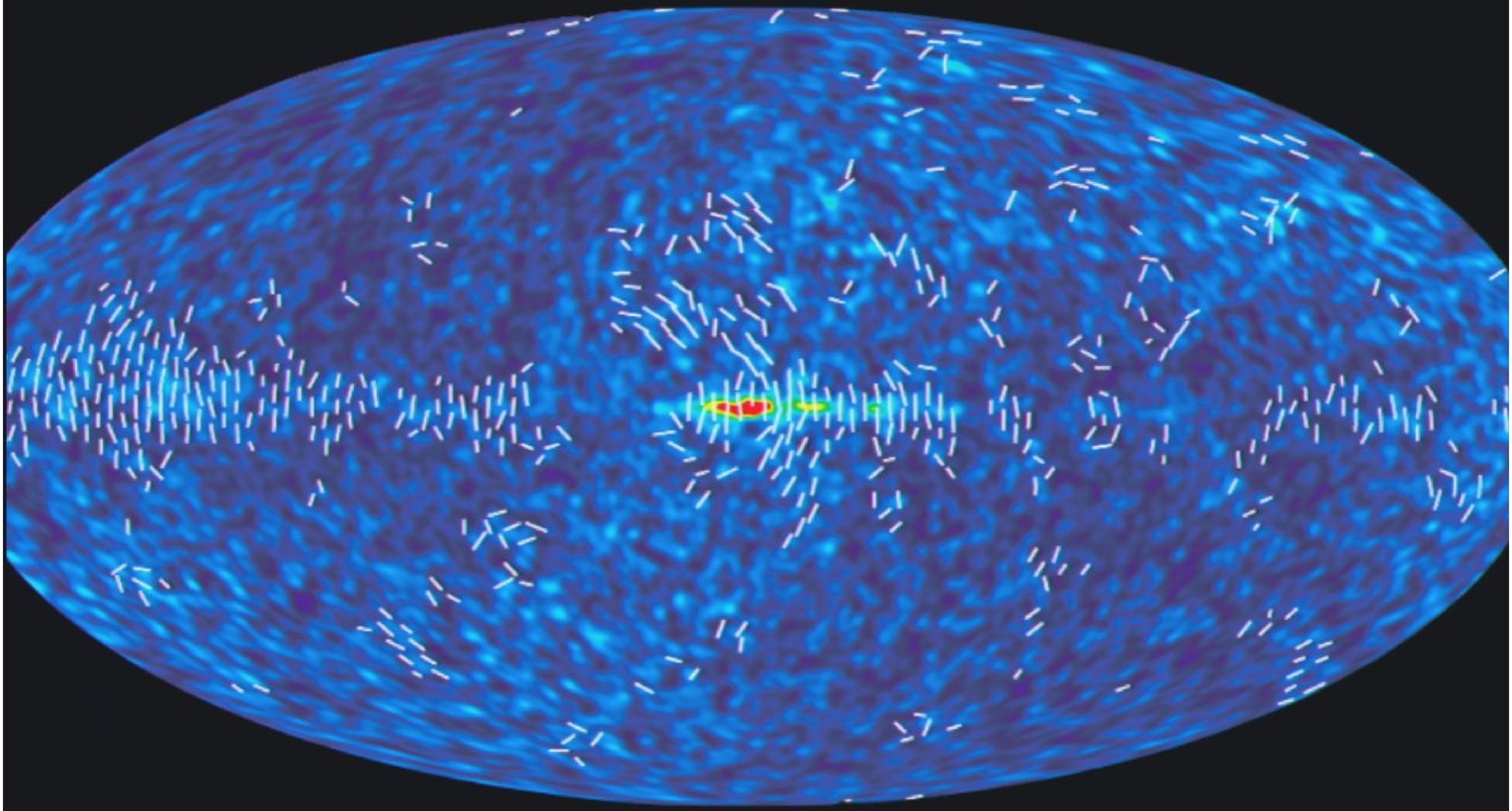
Dominated by synchrotron. Note polarization direction perpendicular to magnetic field lines

Ka Band (33 GHz)



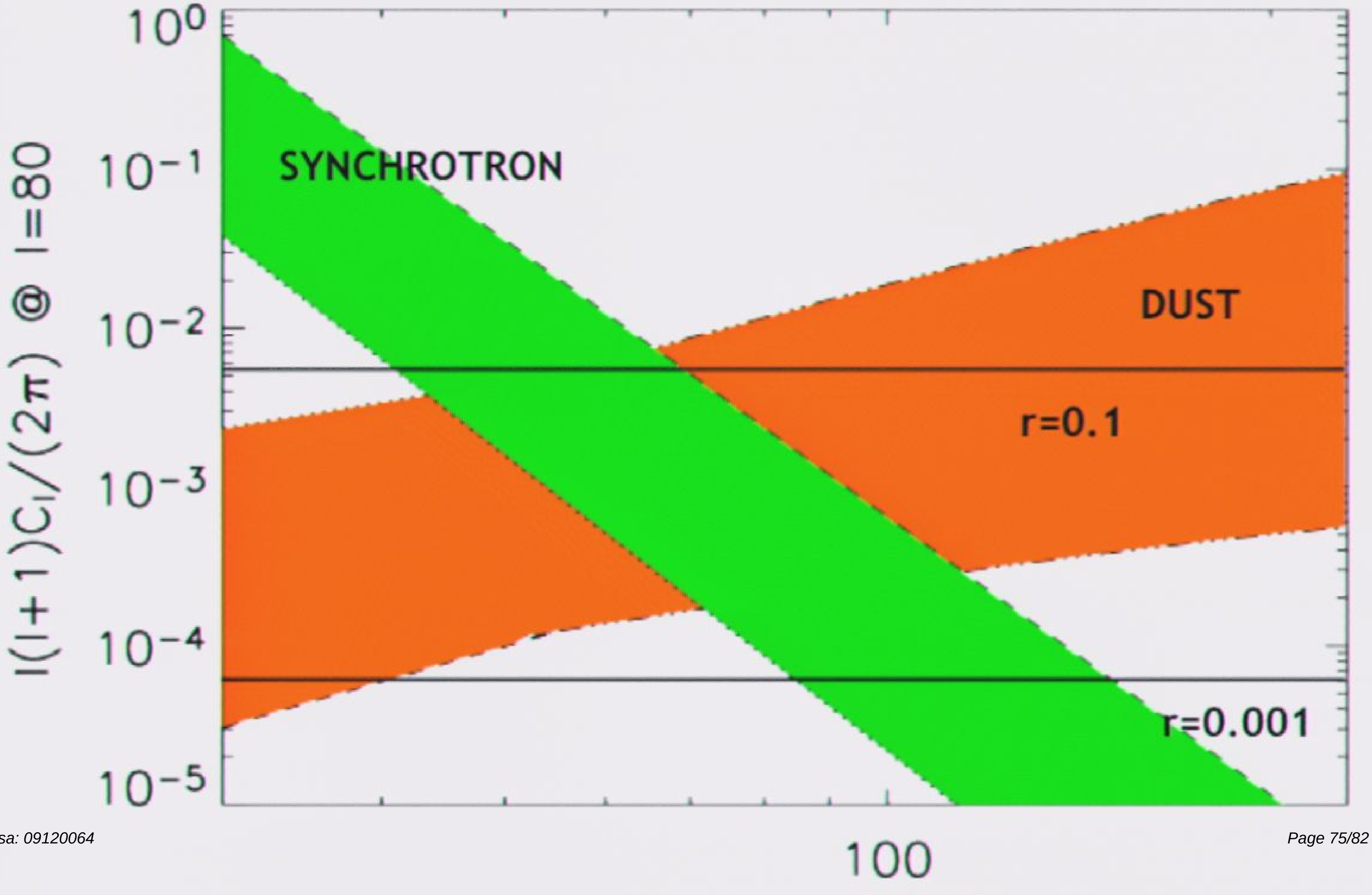
Synchrotron drops as $\nu^{-3.2}$ from K to Ka.

V Band (61 GHz)

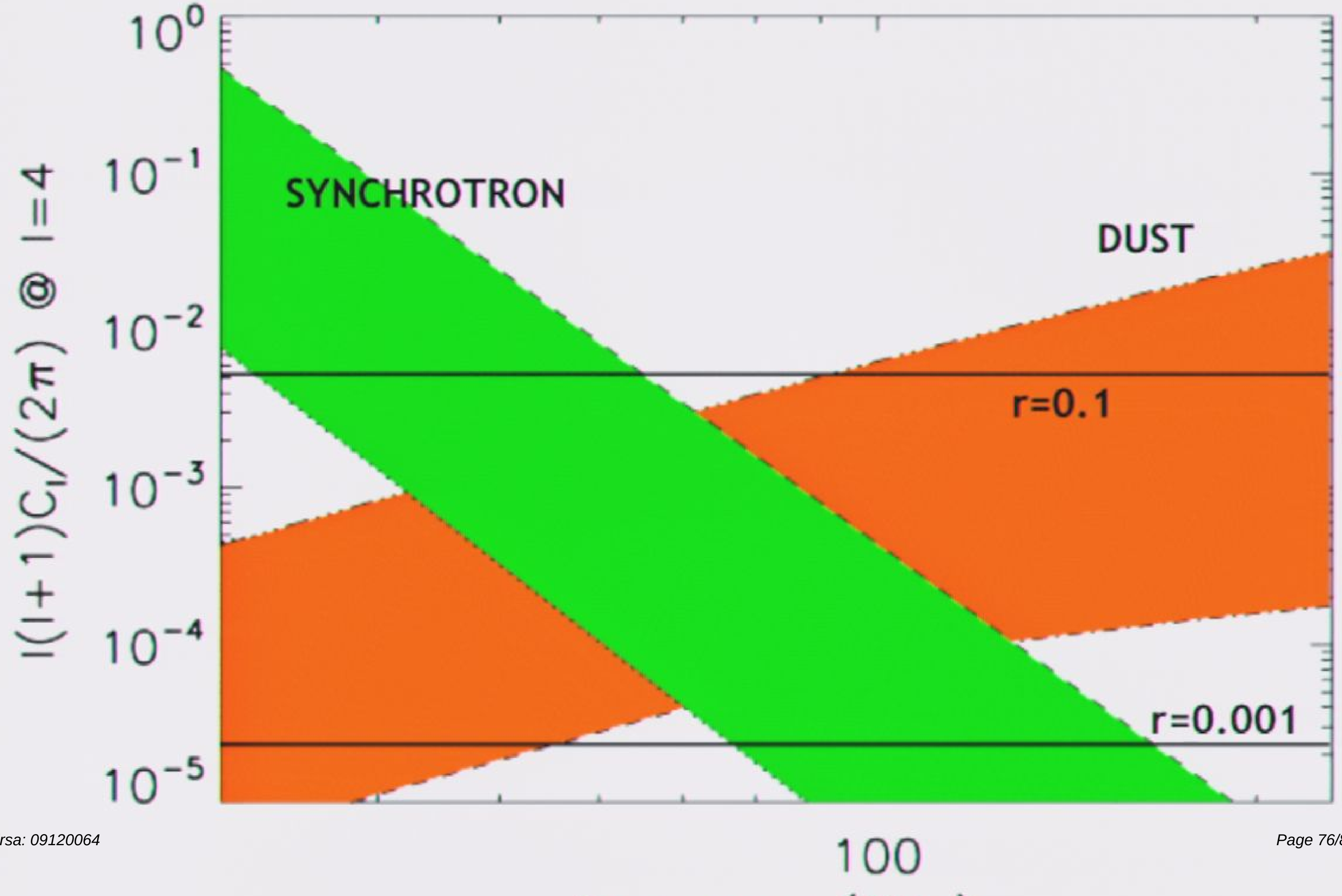


Polarized FG emission is lowest in V band (notice noise is larger in ecliptic plane).

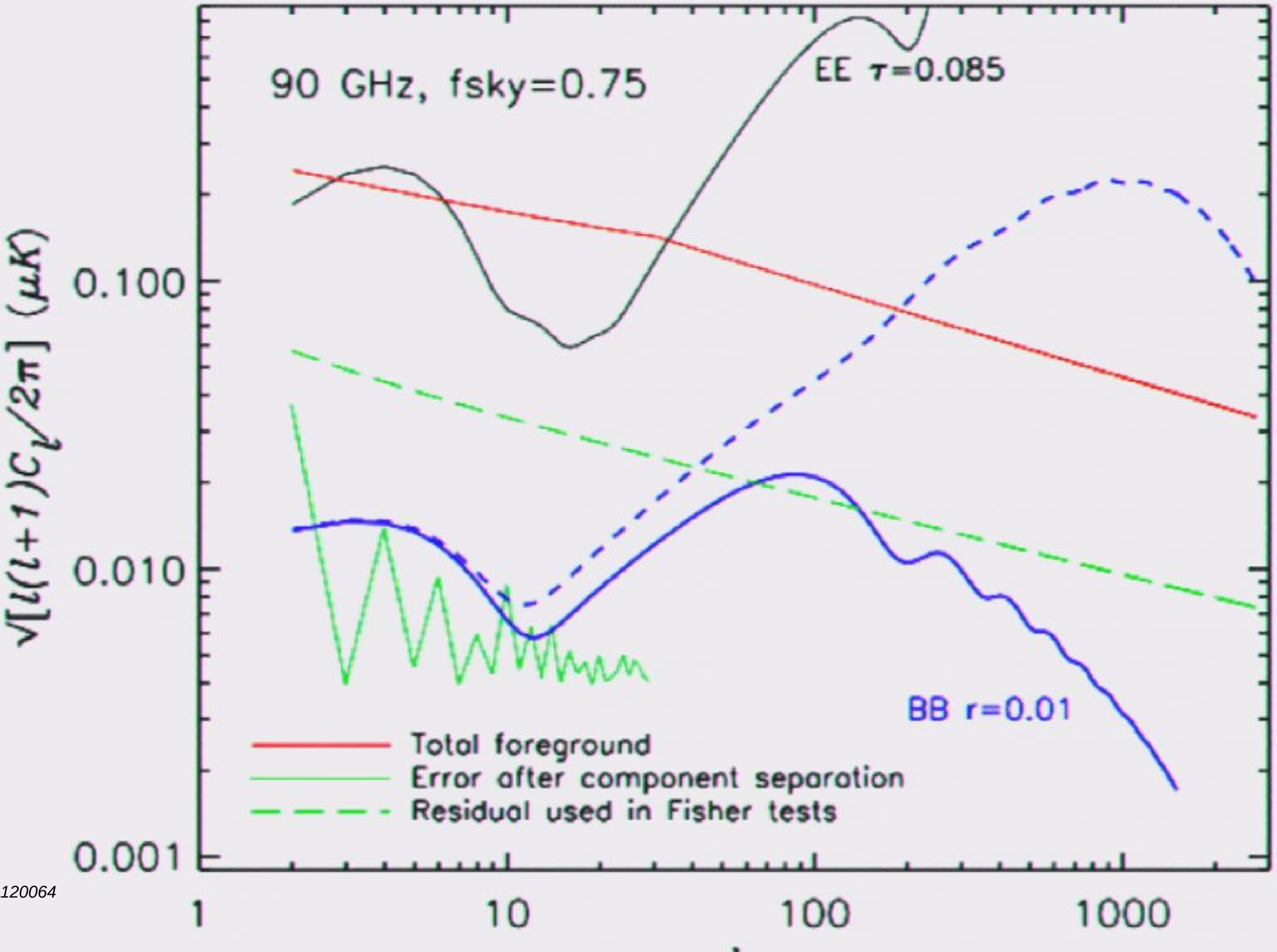
Foreground uncertainties vs CMB at l=80



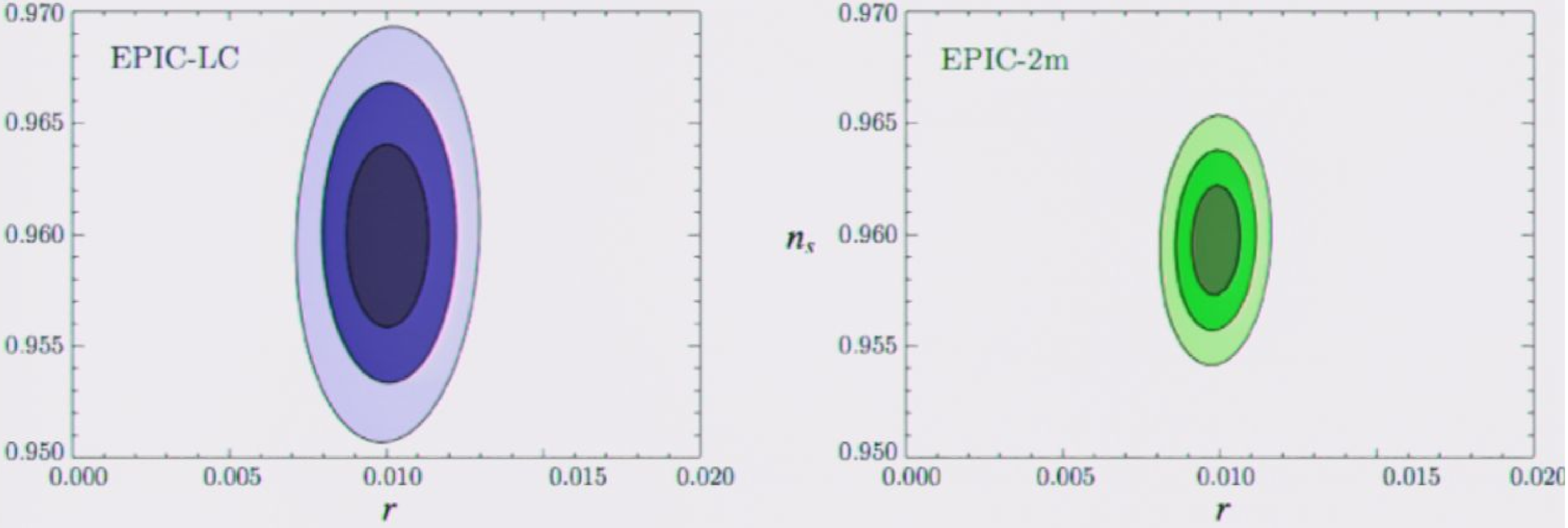
Foreground uncertainties vs CMB at l=4



FG cleaning residuals from simulated maps



Forecasted CMBpol constraints for r=0.01



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- *EPIC-2m*: “mid cost” CMBpol proposal

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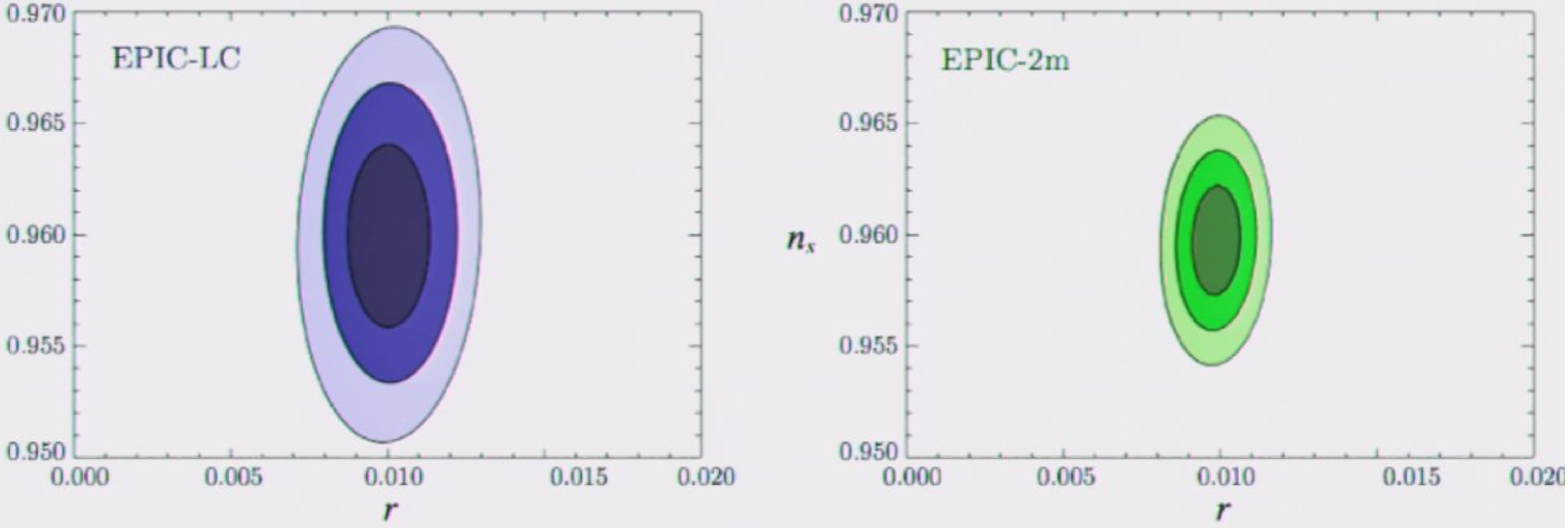

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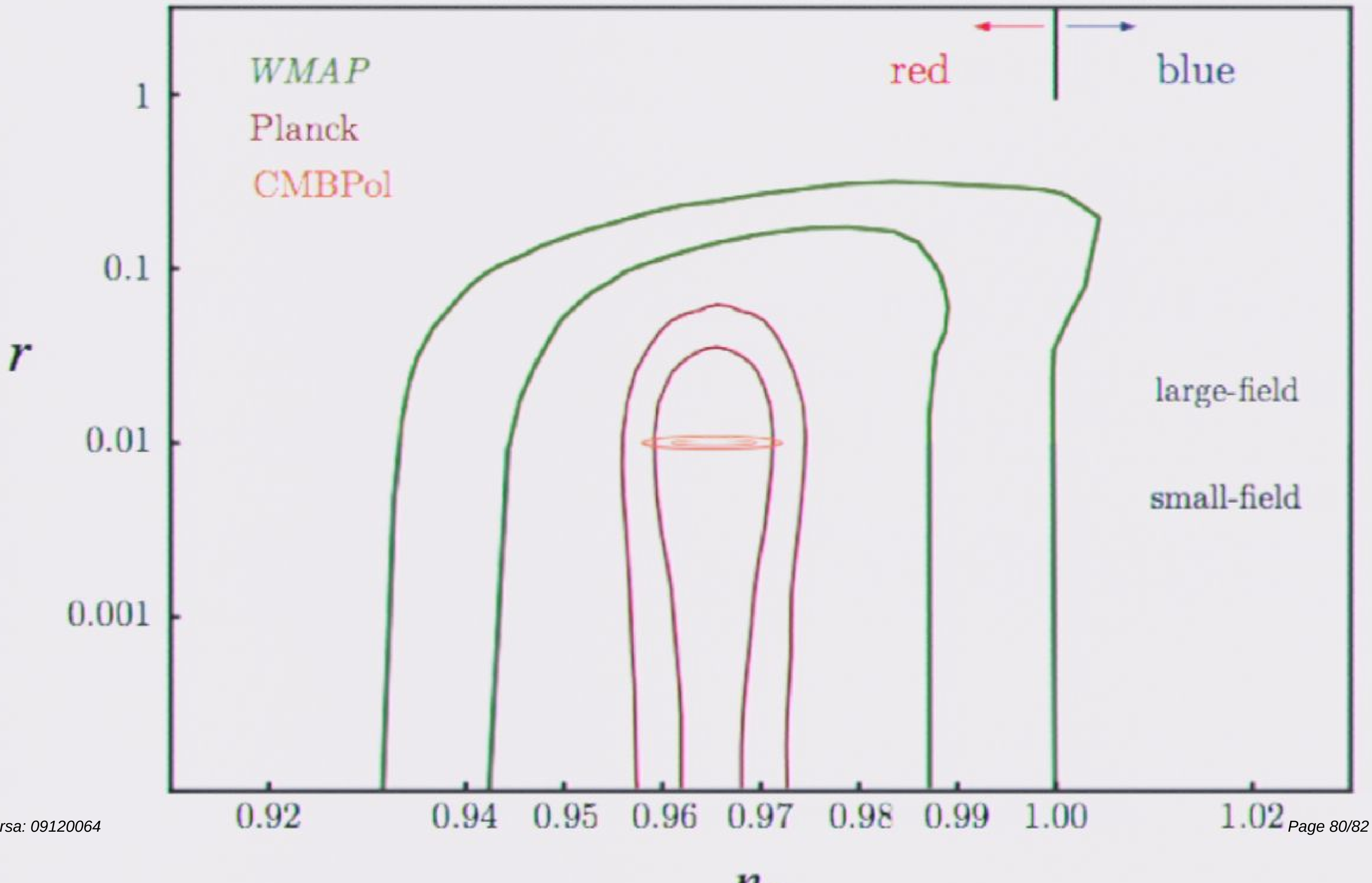
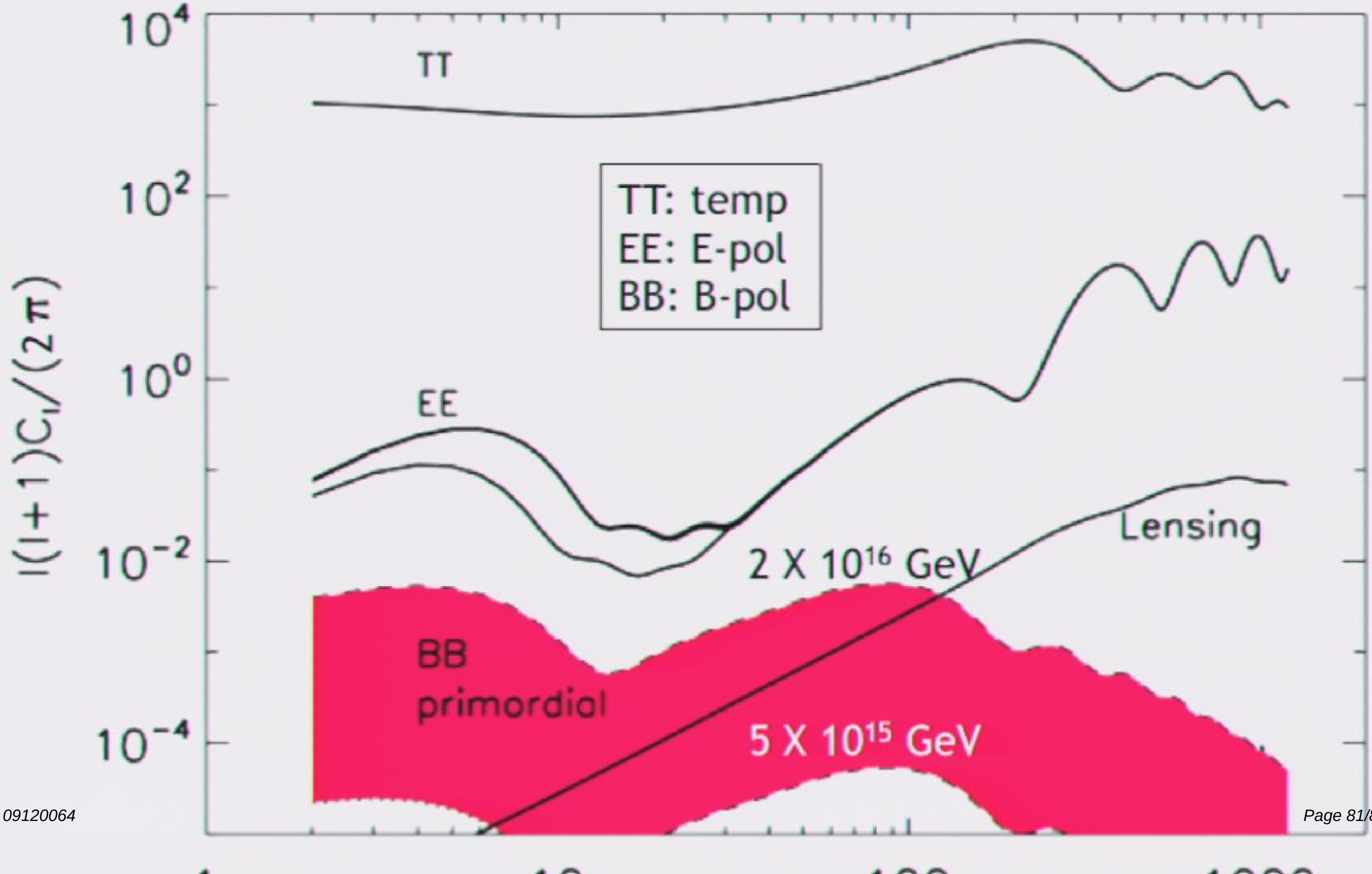


Approximate range of primordial tensors accessible to upcoming experiments

$$V^{1/4} \simeq 3.3 \times 10^{16} r^{1/4} \text{ GeV}$$



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