Title: Planck Results and Future Prospects in Cosmology

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Abstract: In this talk I'll survey the current observational status in cosmology, highlighting recent developments such as results from the Planck satellite, and speculate on what we might achieve in the future. In the near future some important milestones will be exploration of the neutrino sector, and much better constraints on the physics of the early universe via B-mode polarization. In the far future we can hope to measure a variety of cosmological parameters to much higher precision than they are currently constrained.

Fundamental physics →

- Cold dark matter density $\rho_{c,0}$
- Baryonic matter density $\rho_{b,0}$
- Cosmological constant Λ
- Perturbation amplitude A_ζ
- Spectral index n_s
- CMB optical depth τ

→ Data analysis

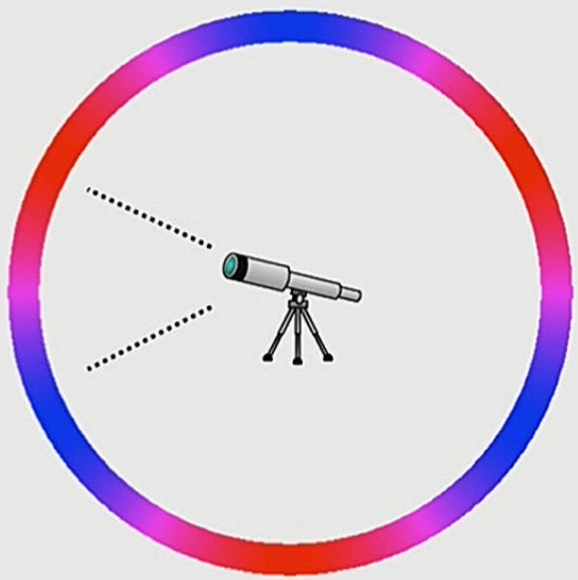
Challenge for observers: which model fits the data?

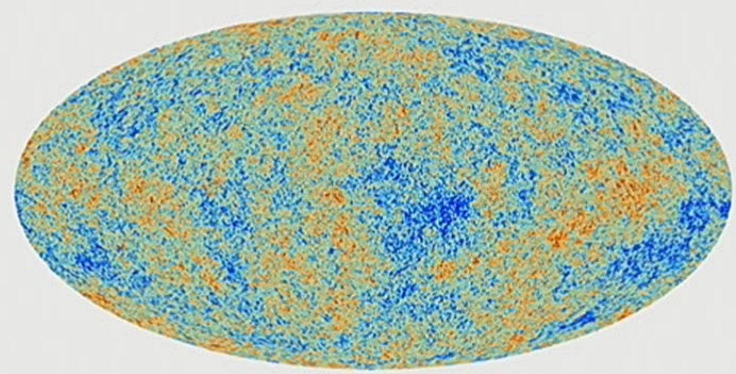
~1970: Dark matter
1992: Gaussian, nearly scale-invariant perturbations (COBE)
1998: Cosmological constant
2006: Deviation from scale invariance

Cosmic microwave background

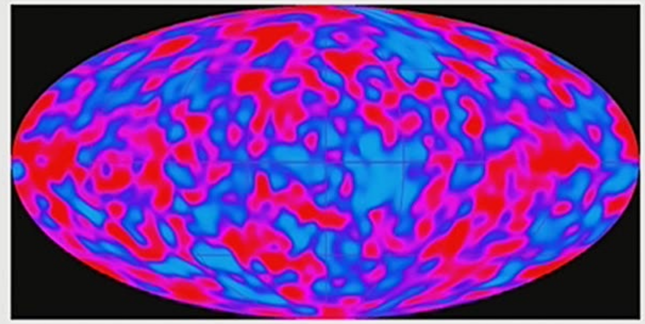
Freestreaming radiation emitted at a time close to the phase transition from p^+e^- plasma to neutral hydrogen.

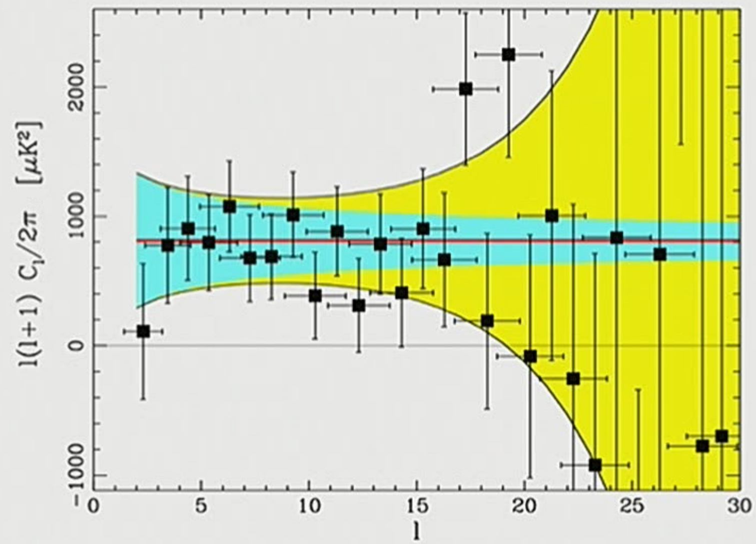
(t=380000 yr,   z=1100, T=3000 K)



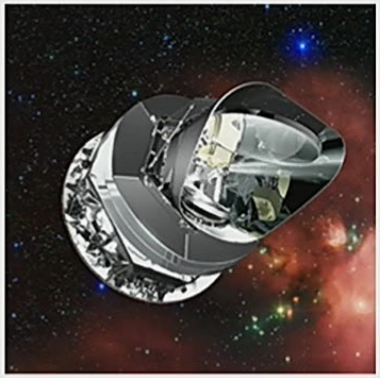


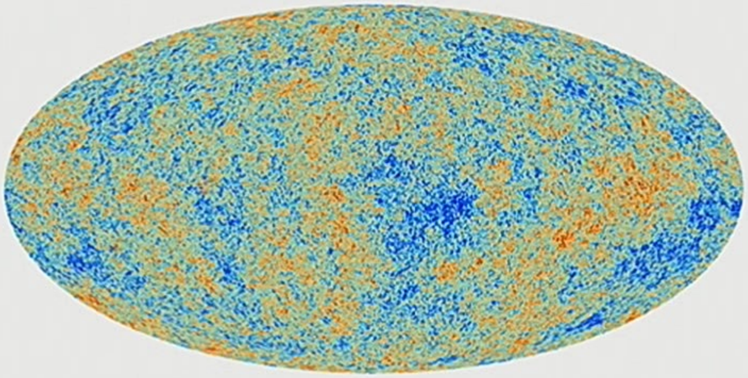
COBE satellite (1992)

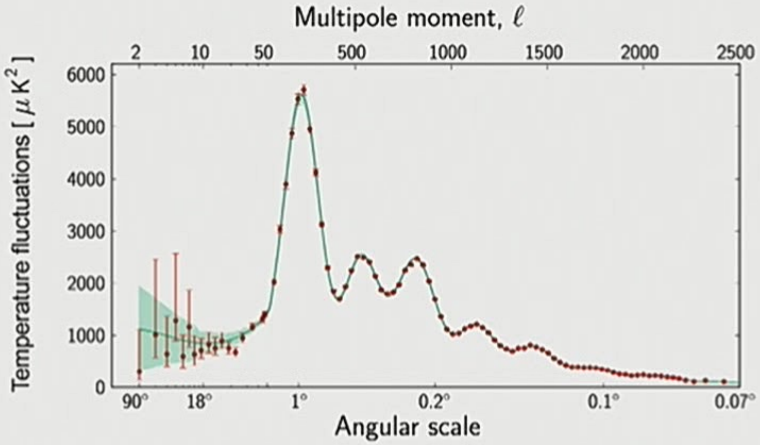




Planck satellite (2013)

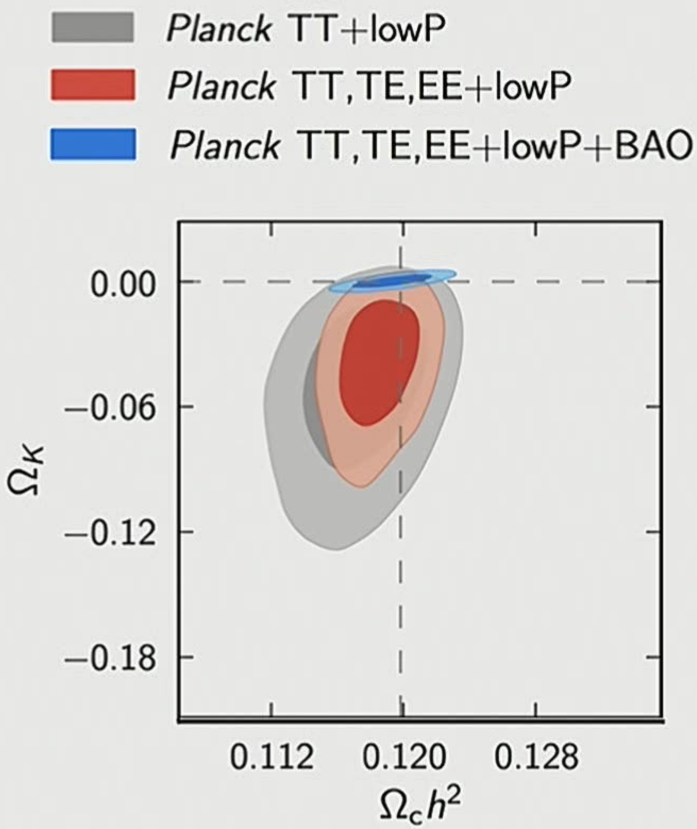




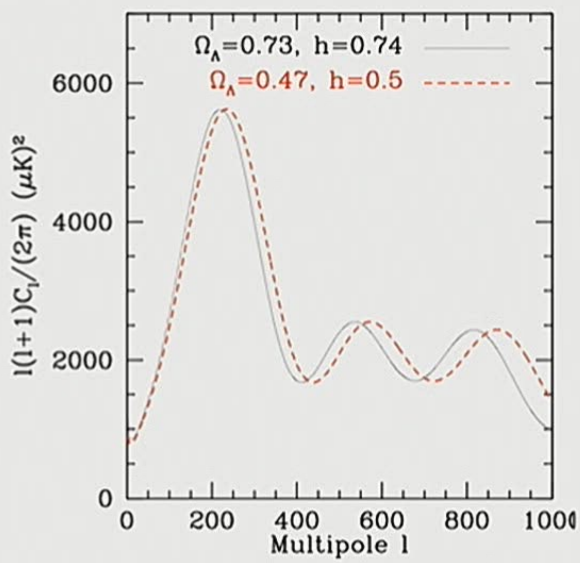


In many interesting parameter spaces, non-CMB datasets play an important role by breaking degeneracies in the CMB

E.g. spatial curvature



BAO data is breaking the CMB distance degeneracy



Some observational predictions

First let's pause to appreciate the amazing progress of the last few decades:

- Sandage (1970): "Cosmology is a search for two numbers" $[H = \dot{a}/a \text{ and } q = -\ddot{a}a/\dot{a}^2]$
- Peebles: "I did not continue (with computation of CMB anisotropy), in part because I had trouble imagining that such tiny disturbances could be observed"
- Sunyaev: "I did not think that the acoustic oscillation would ever be observed"
- Mukhanov: "I thought it would take 1000 years to detect the logarithmic dependence of the power spectrum"

Some observational predictions

Based on this historical perspective, I'll adopt a perspective of cautious optimism for the future

Example: Tegmark (1999) forecasts for Planck, very futuristic at the time

Parameter	Forecasted uncertainty (1999)	Reported uncertainty (2015)
ρ_b	0.94%	0.72%
$(\rho_b + \rho_c)$	1.6%	0.9%
n_s	0.0076	0.0048
$\Lambda/\rho_{\rm tot}$	0.022	0.0087

Physics of the early universe

Hundreds of inflationary models have been proposed:

S-dimensional assisted inflation
anomaly-induced inflation
assisted inflation
assisted brane inflation
assisted chaotic inflation
boundary inflation
brane inflation
brane-assisted inflation
brane gas inflation
brane-antibrane inflation
braneworld inflation
Brans-Dicke chaotic inflation
Brans-Dicke inflation
bulky brane inflation
chaotic inflation
chaotic hybrid inflation
chaotic new inflation
D-brane inflation
D-term inflation
dilaton-driven inflation
dilaton-driven brane inflation

and many more!

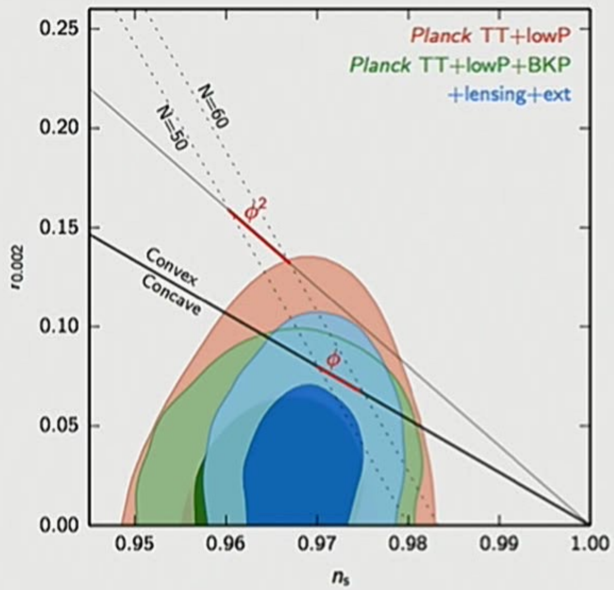
More interestingly, alternatives to inflation have emerged:

- Ekpyrotic/cyclic models
- Galilean genesis
- Pseudo-conformal universe

The dream: can we reduce this long list of possibilities to 1 model?

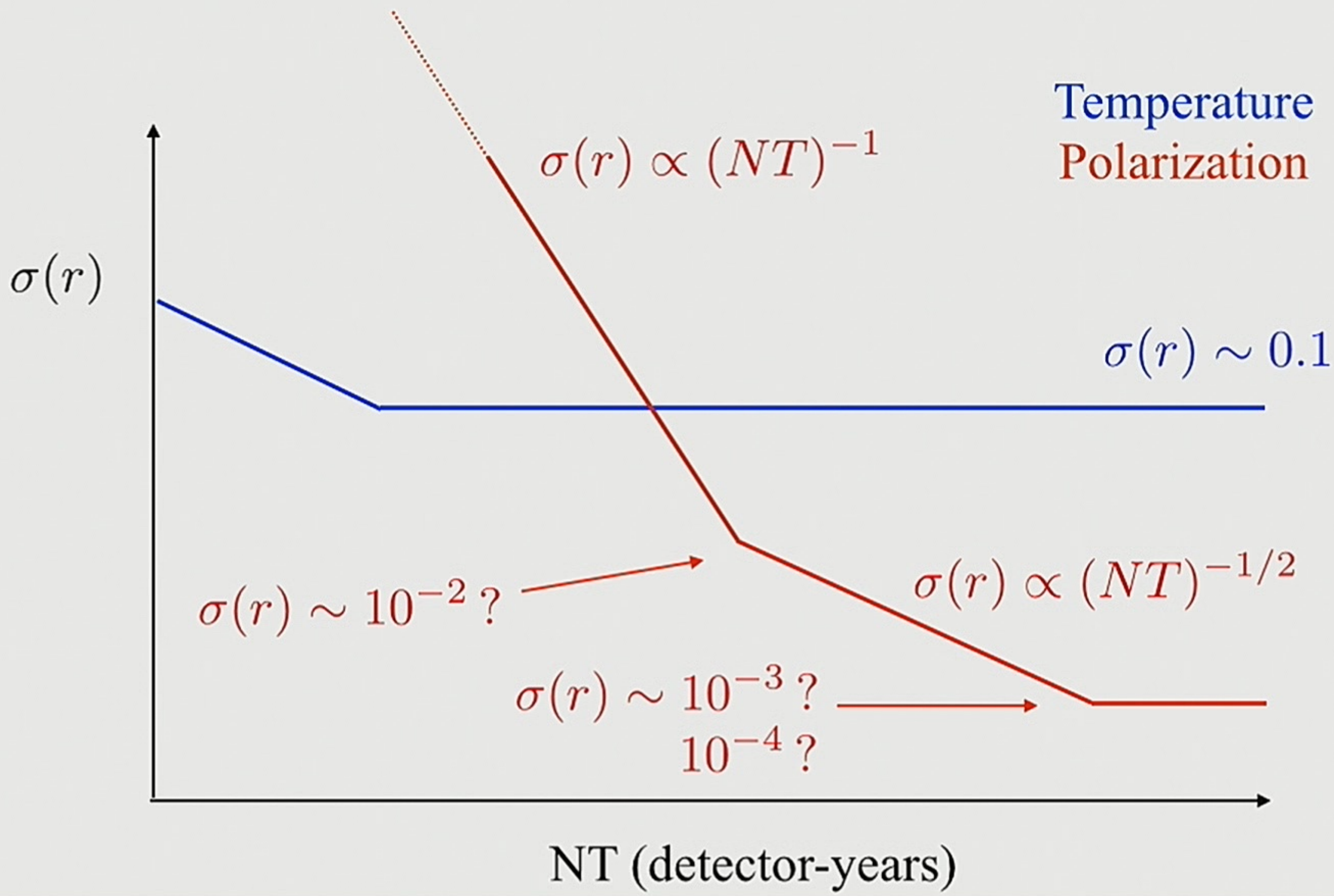
Gravity waves: the time is now!

Recent development: CMB polarization is starting to improve constraints on “r” from CMB temperature



…but CMB polarization constraints will improve by 1-2 orders of magnitude very soon!!

Gravity waves: the time is now!



A more likely possibility: we will end up measuring a few parameters in a many parameter space. E.g.

- We might measure the potential V and its first two derivatives V', V'' but not third and higher derivatives

- We might find signatures of multifield inflation ($f_{NL} \neq 0$) but not have much information beyond the existence of multiple fields

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In this case, further progress will be outside the scope of observational cosmology, and will have to come from elsewhere (new ideas in theoretical physics? collider experiments?)

Neutrino mass: the time is soon!

Constraints in the neutrino sector will also be very interesting.

Note: cosmology mainly constrains sum of neutrino masses $\sum_\nu m_\nu$ whereas oscillation experiments constrain mass-squared differences $(m_\nu^2 - m_{\nu'}^2)$.

The minimum mass consistent with oscillation experiments is $\sum_\nu m_\nu = 58$ meV

Current constraints (Planck + several external datasets):

$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$

$$N_{\text{eff}} = 3.04 \pm 0.18$$

Neutrino mass: the time is soon!

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$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$ (guaranteed signal at 58 meV)

$$N_{\text{eff}} = 3.04 \pm 0.18$$

Some forecasts for experiments starting on or before 2020:

CMB-S4 + DESI-BAO $\sigma\left(\sum m_\nu\right) = 16 \text{ meV}$

Planck + Euclid $\sigma\left(\sum m_\nu\right) = 25 \text{ meV}$

CMB-S4 $\sigma\left(N_{\text{eff}}\right) = 0.02$

More futuristic experiments may even measure individual masses, not just the sum. We are not far away from probing the neutrino sector in some detail with cosmological observations!

More observational predictions

Dawn of the 21-cm era in cosmology?

A particular type of observation which is still in its infancy:
"21-cm intensity mapping": mapping the density of neutral hydrogen throughout the universe, using the redshifted spectral line at λ=21 cm (radio frequencies).

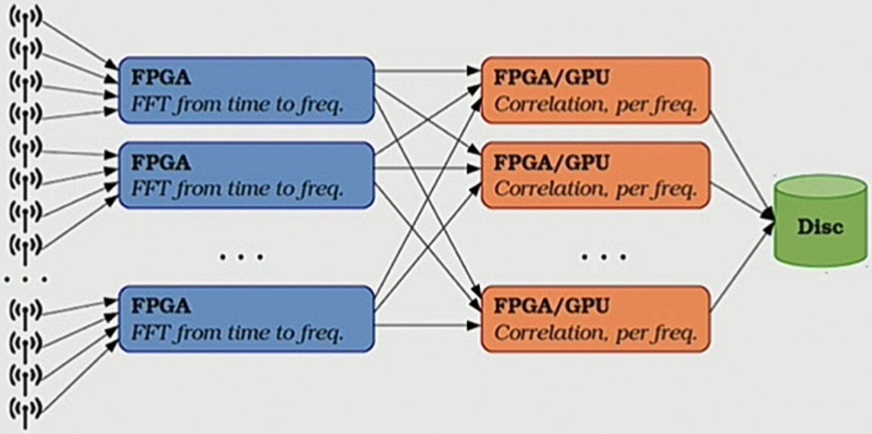
Futuristic forecasts show that it may eventually be our most powerful cosmological probe, essentially due to the huge number
of modes which are potentially measurable at high redshift.

A provocative statement: there is no fundamental limit to how well we might measure most cosmological parameters!

CHIME

Pathfinder (running!)

2 x 40m cylinders
128 dual-pol feeds
400-800 MHz ($0.8 < z < 2.5$)
Beam size ~0.7 deg



Full CHIME

4 x 80m cylinders
1024 dual-pol feeds
400-800 MHz ($0.8 < z < 2.5$)
Beam size ~0.3 deg

More observational predictions

Observation: we will be crossing some natural thresholds soon, and this will make the next few years particularly interesting!

- Gravity waves: $r \sim (\text{few} \times 10^{-2})$
- Neutrino mass: 58 meV
- Deviations from Gaussian statistics (primordial non-Gaussianity)

On the other hand, the cosmological constant was gradually discovered by surprise, by simply shrinking error bars on "natural" quantities such as expansion history and galaxy counts.

We are in an era where error bars are still rapidly improving, so there is plenty of scope for unexpected discoveries!