A Stage-IV CMB experiment, CMB-S4

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CSS 2013, Snowmass on the Mississippi

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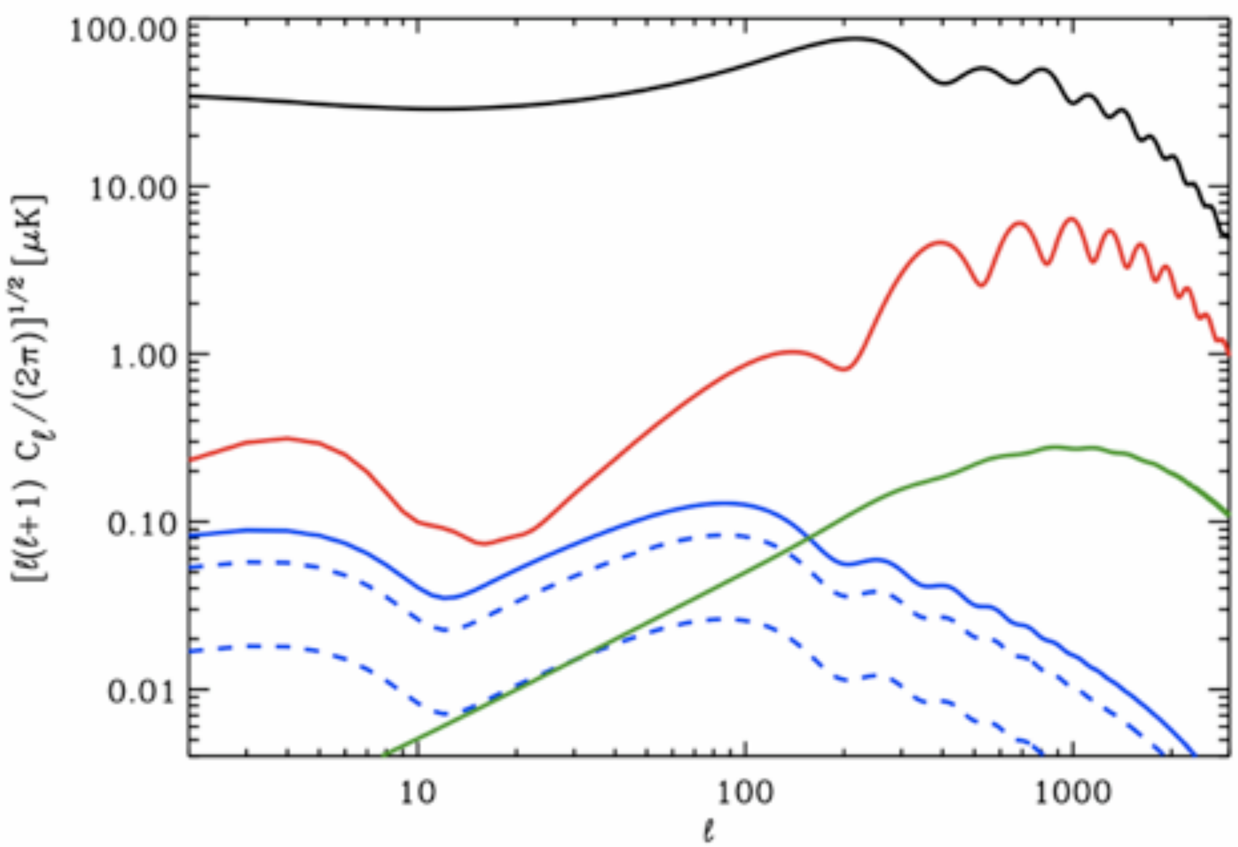
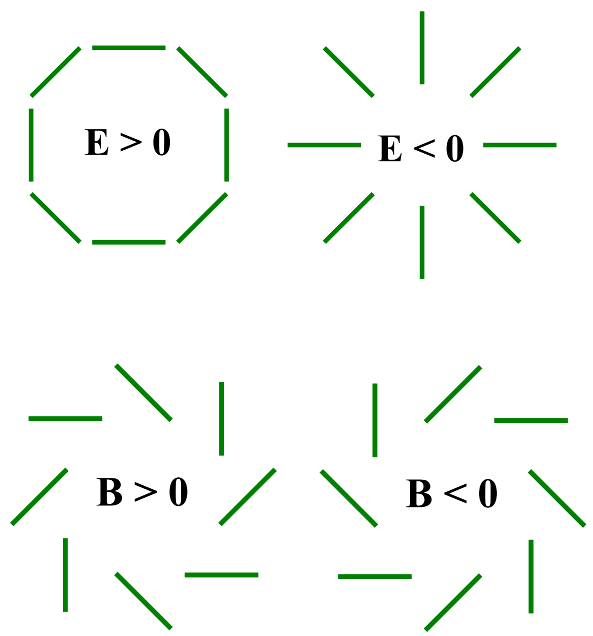
Goal: fully exploit CMB B-mode physics





- Explore the physics of inflation. *r* = gravitational wave / density wave
- Measure the Cosmic Neutrino Background. N_{eff} and Σm_ν

Relevant numbers

- Lensing B-mode amplitude ~5 μK-arcmin
  - High S/N measurement requires very deep maps with better than 3 arcmin resolution
- Sample variance

$$\hat{C}_\ell = \langle |a_{lm}|^2 \rangle = \frac{1}{2\ell+1} \sum_m |a_{lm}|^2 \qquad \delta C_\ell \propto \frac{1}{\sqrt{(2\ell+1) f_{\mathrm{sky}}}}$$

  - Measure large areas of sky (10,000-20,000 sq deg)
- Instruments need lots of sensitivity!

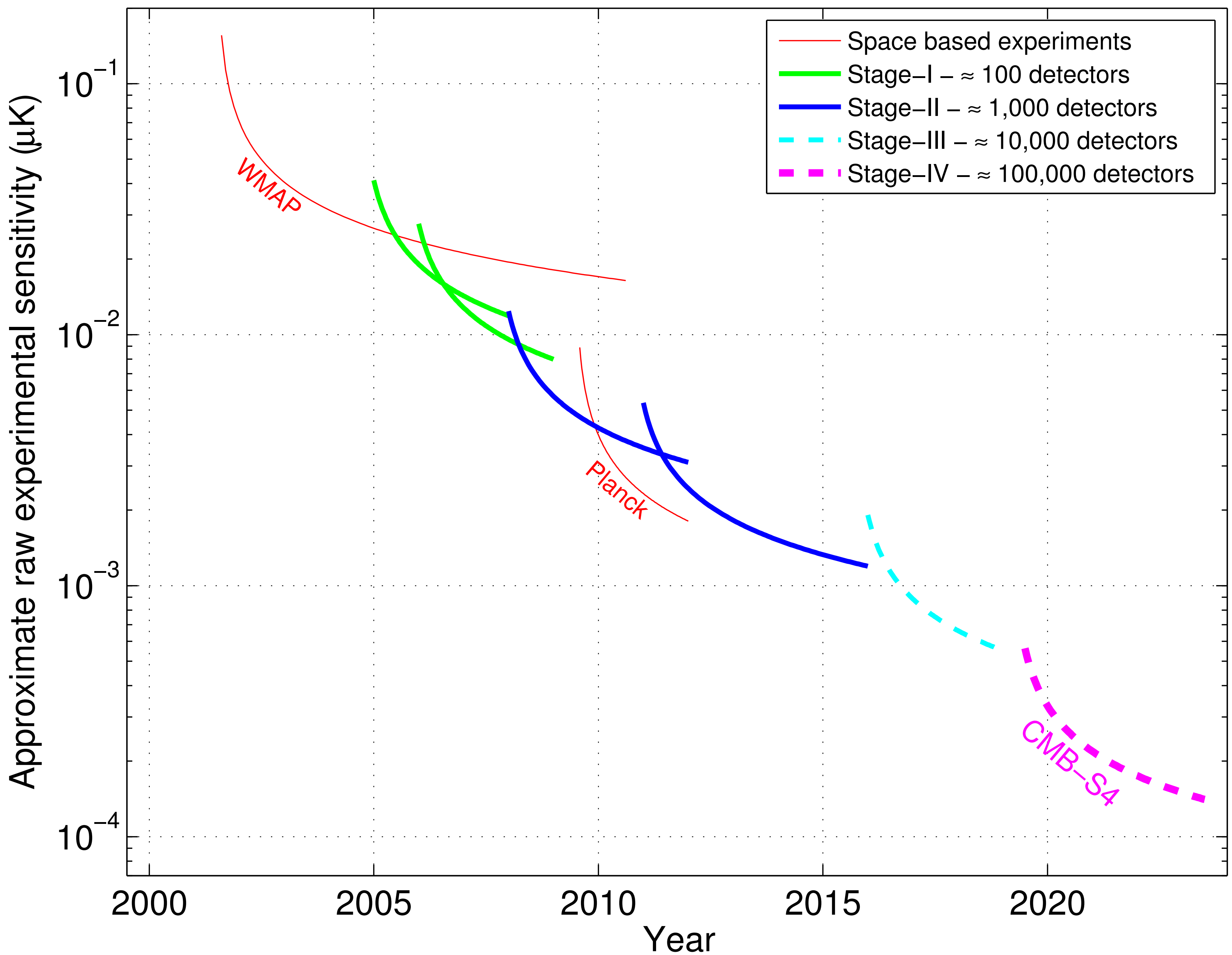
Lots of detectors

$$< n >= \frac{1}{e^{h\nu/kT} - 1}$$

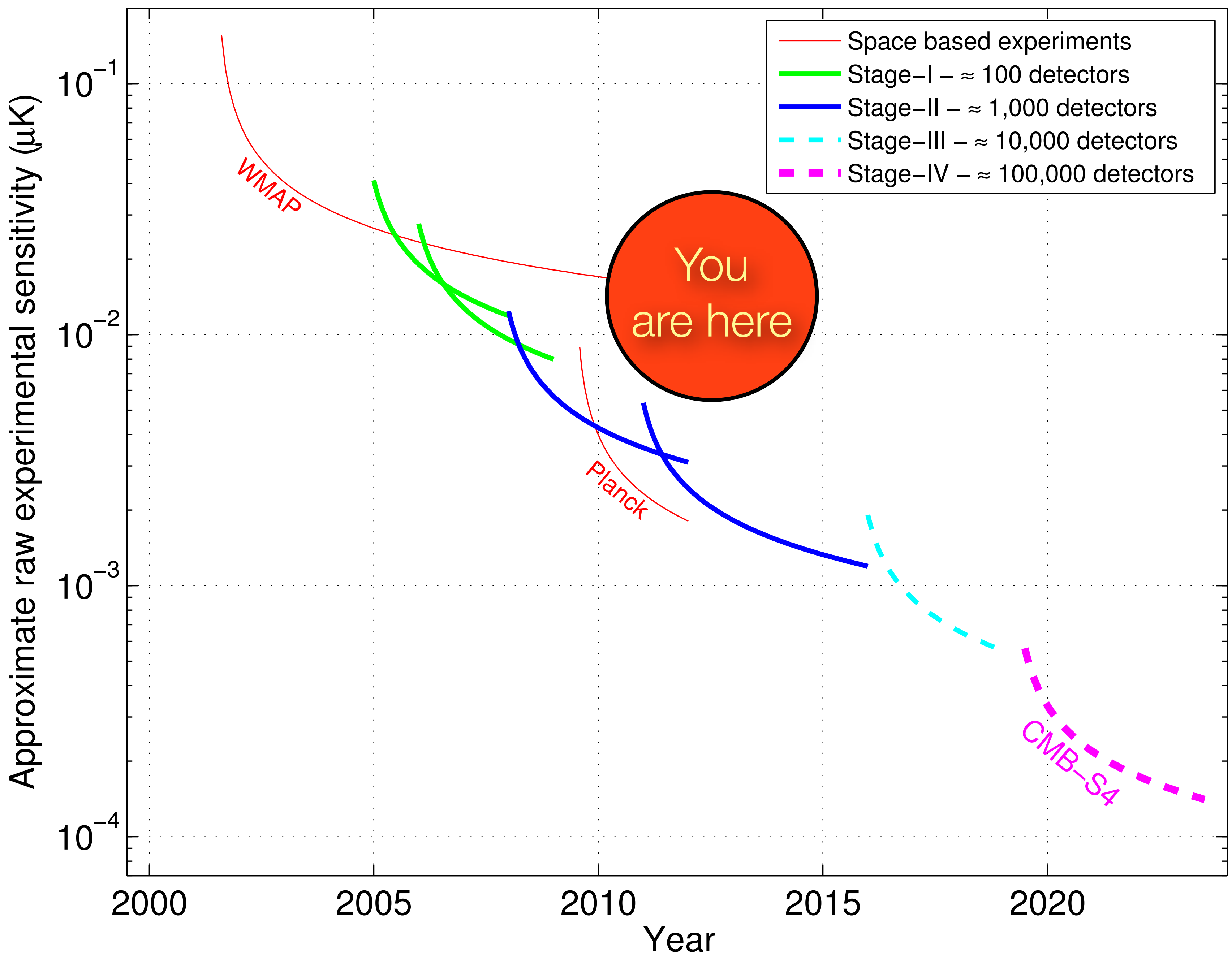
$$< n^2 >= n(n+1)$$

- Sensitivity of individual detectors is now limited by shot noise of the photon flux
- Increasing sensitivity of an experiment requires increasing the number of detectors

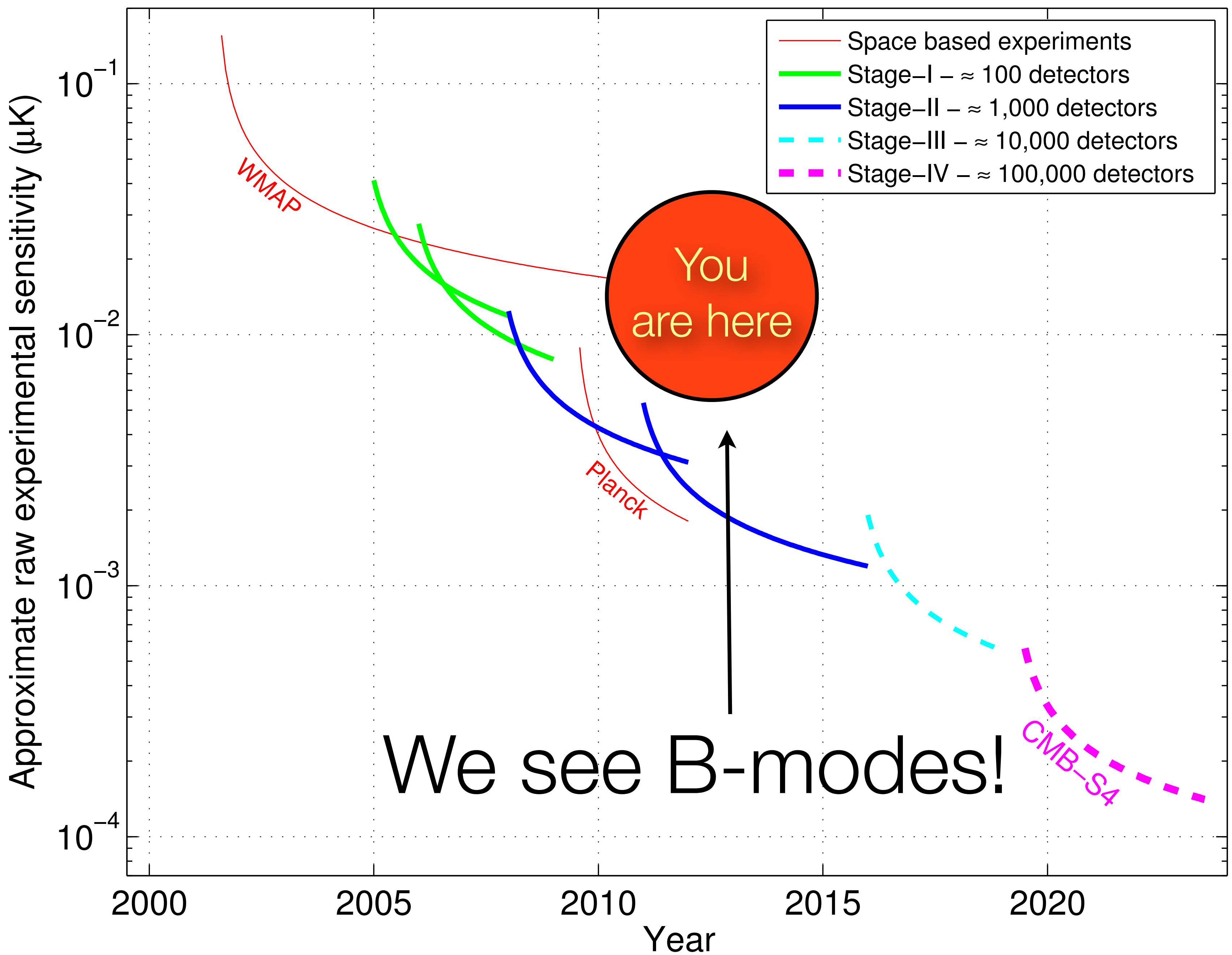
Stages of CMB experiment



Stages of CMB experiment



Stages of CMB experiment



Specs

- Large angular coverage: degree angular scales for inflation, arcmin angular scales for lensing... minimum 3 arcmin resolution
- Large sky coverage: 20,000 sq deg (f_{sky} ~0.5)
- Lots of detectors: 500,000
- Broad frequency coverage for foreground removal: 40 - 240 GHz
- Target noise of 1 μK-arcmin over 50% of the sky starting 2020, observing for 5 years

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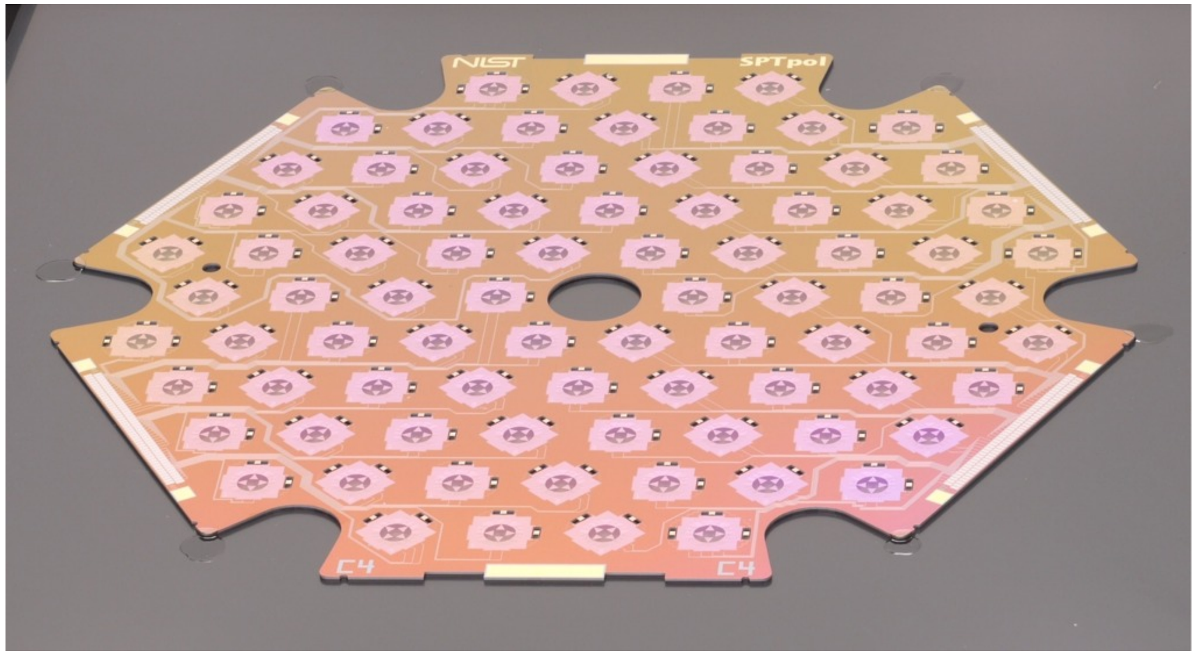
Primary technical development is one of scale

Core technology: TES bolometers

- Fabricated using thin film deposition and micromachining on Silicon wafer substrates: TES detectors are naturally manufactured as detector **arrays**
- Low impedance makes multiplexing feasible
- Strong history: Multiple detector architectures have been successfully deployed as Stage II experiments. Dominant technology for Stage II and upcoming Stage III projects
- At low frequencies (~40 GHz) MMIC or new superconducting amplifiers may also be used



Invented by HEP for Dark Matter detection

Technical Path for CMB-S4

- **Improved Production Reliability:** develop fabrication processes which control and stabilize material properties to achieve consistent high yield
- **Increased Production Volume and Throughput:** requires facilities with dedicated tooling and mass production throughput. Extensive QA testing program.
- **Multiplexed TES Readout:** modest improvements of existing successful multiplexer technologies. New microwave-based multiplexers may provide lower cost options with broader applicability
- **Large Cryogenic Optics:** large aperture, large optical bandwidth cryogenic optics. Incremental improvement over Stage-III
- **Computing:** data rate ~1 TB per day. ~10,000-times more observations per pixel compared to Planck

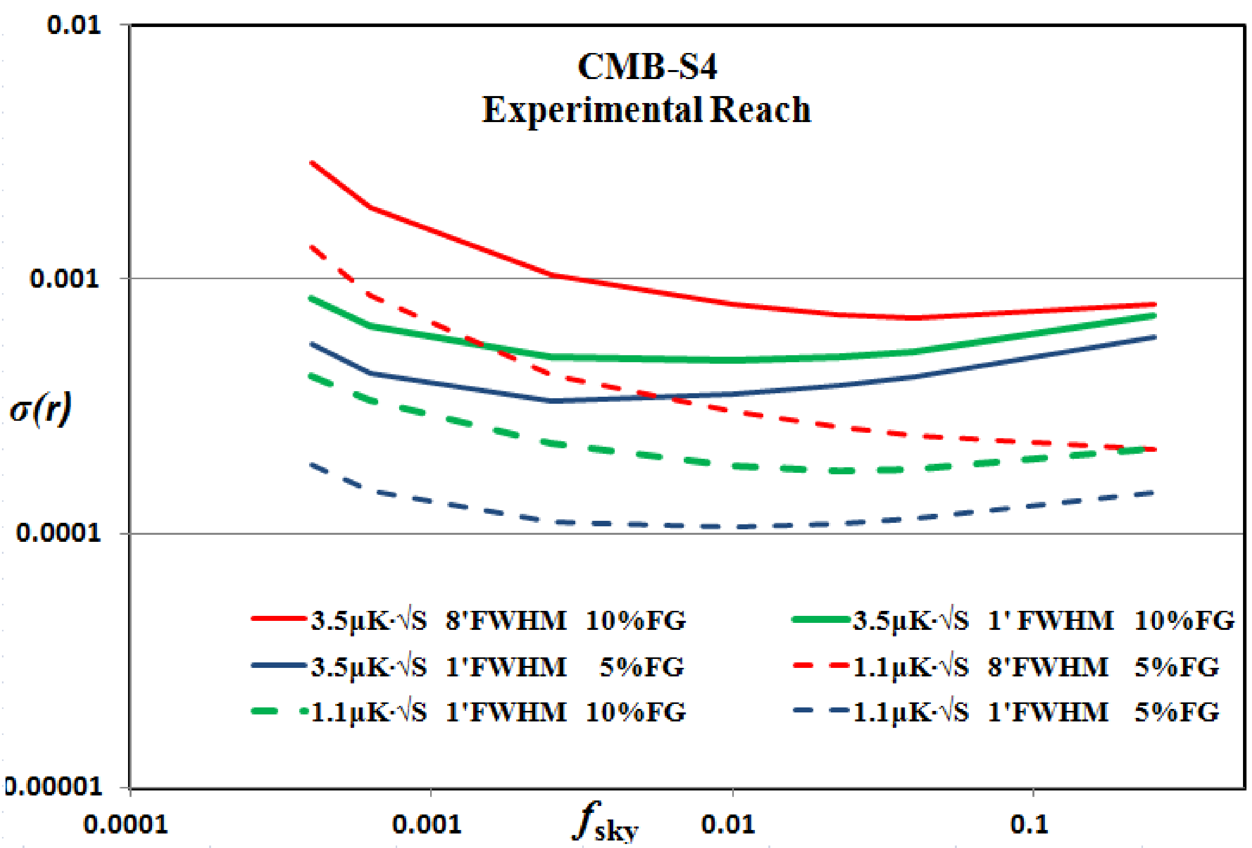
Evolution of CMB experiment

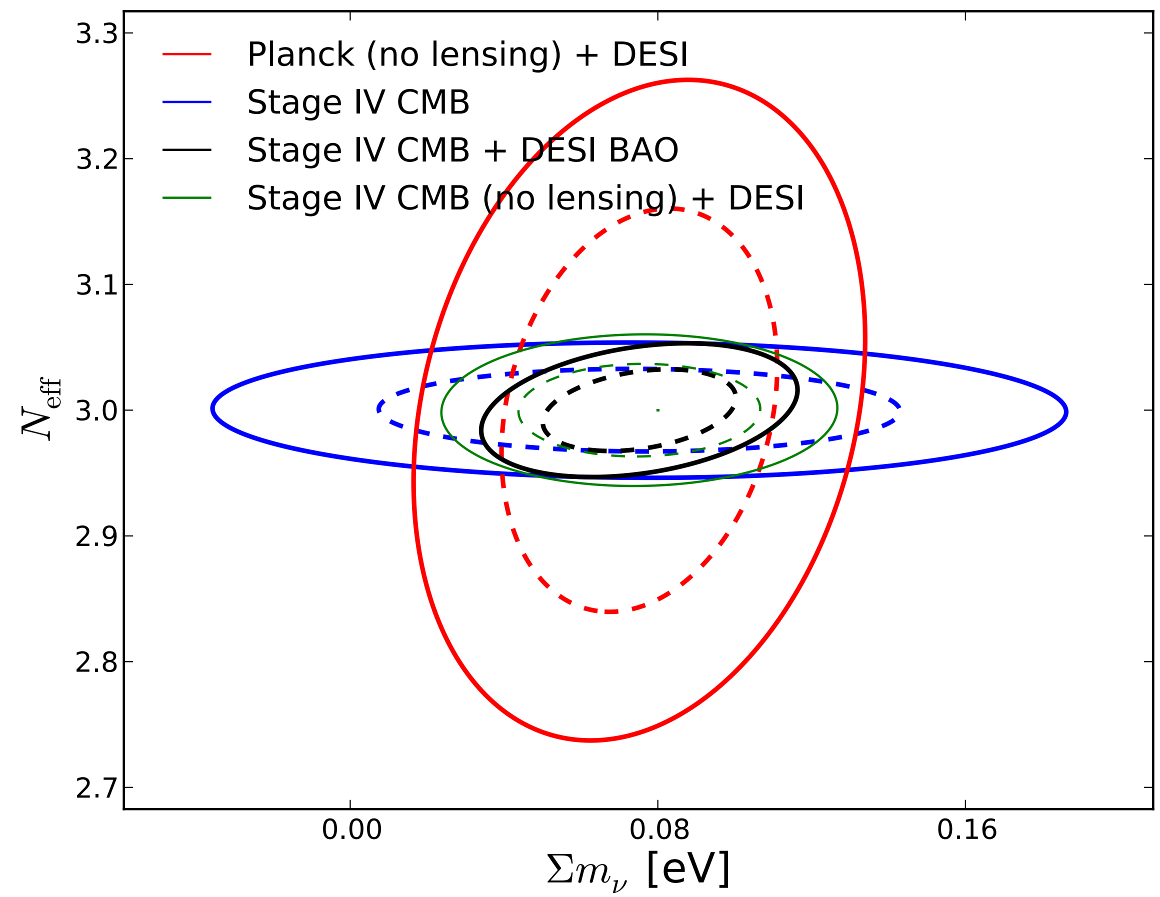
- HEP involvement in CMB has historically been small efforts focused on specific technical contributions (e.g.: multiplexing, detector fabrication and development, broadband antennas, MMICs)

- Moving from Stage-II to Stage-III and beyond, there is a consolidation of effort from multiple small experiments towards a few larger experiments

- There is increased involvement and impact from national lab resources

Science reach of CMB-S4





σ(r) = 0.001; large field vs small field inflation?

σ(N_{eff}) = 0.02; CvB just SM neutrinos?

σ(Σm_ν) = 16 meV (including DESI) mass hierarchy?

Summary

- CMB-S4 will fully exploit B-mode measurement. Primary challenge is one of scale.

- TES Core technology. HEP invented technology. Major impact on Stage-II incl. first lensing B-mode detection. Focus on mass production for CMB-S4.

- Change from historical *Modus Operandi*... consolidation of effort. Increased contribution/leadership from national labs.

- Impact: $\sigma(r) = 0.001$; $\sigma(N_{eff}) = 0.02$; $\sigma(\Sigma m_\nu) = 16$ meV

- CMB-S4 will continue US leadership in CMB science over the next 10 years.