Inflation:
A Window to Ultra-high Energy Physics

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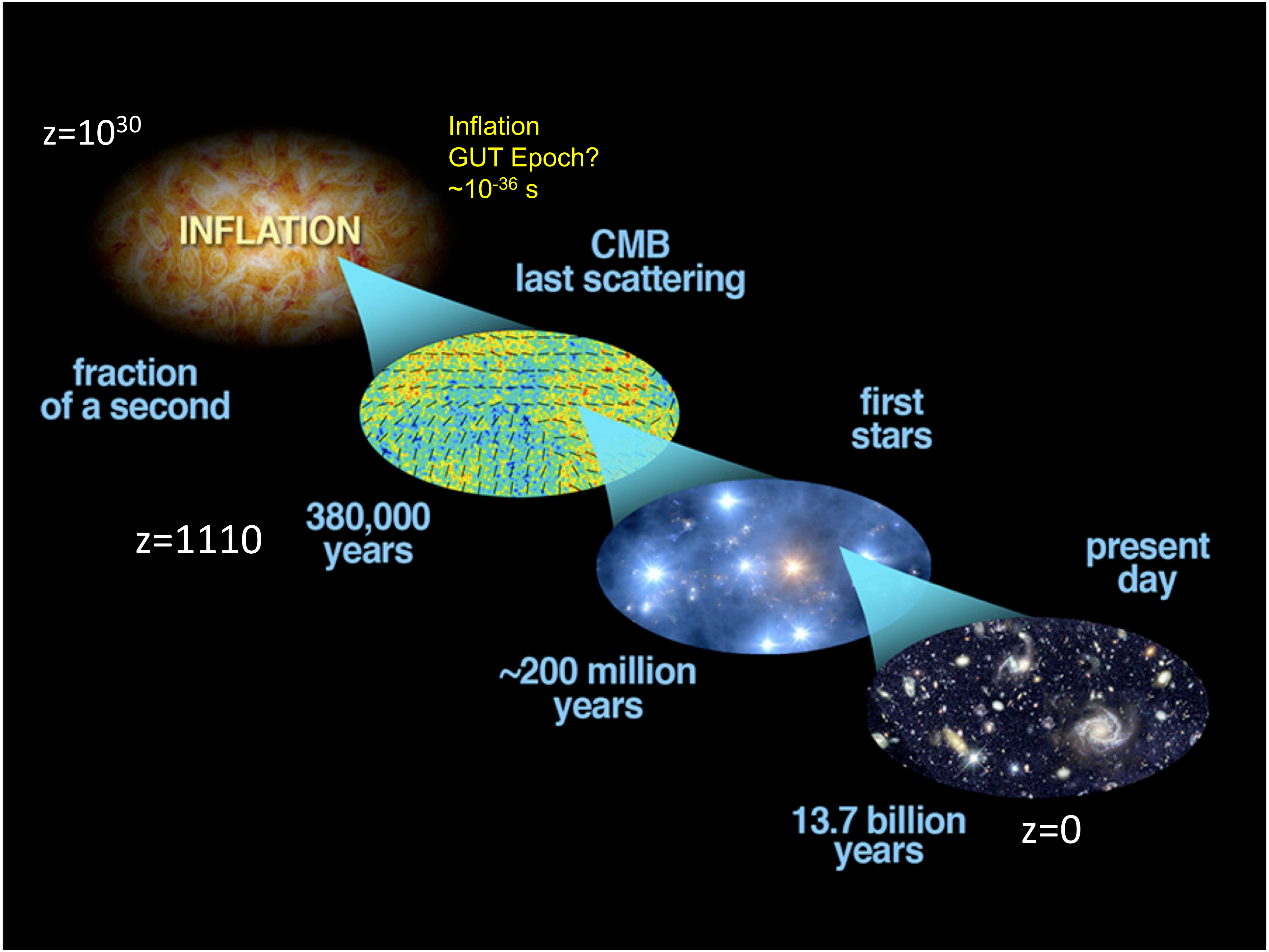


z=10^30
Inflation
GUT Epoch?
~10^-36 s
INFLATION
CMB
last scattering
fraction
of a second
first
stars
380,000
years
z=1110
present
day
~200 million
years
13.7 billion
years
z=0

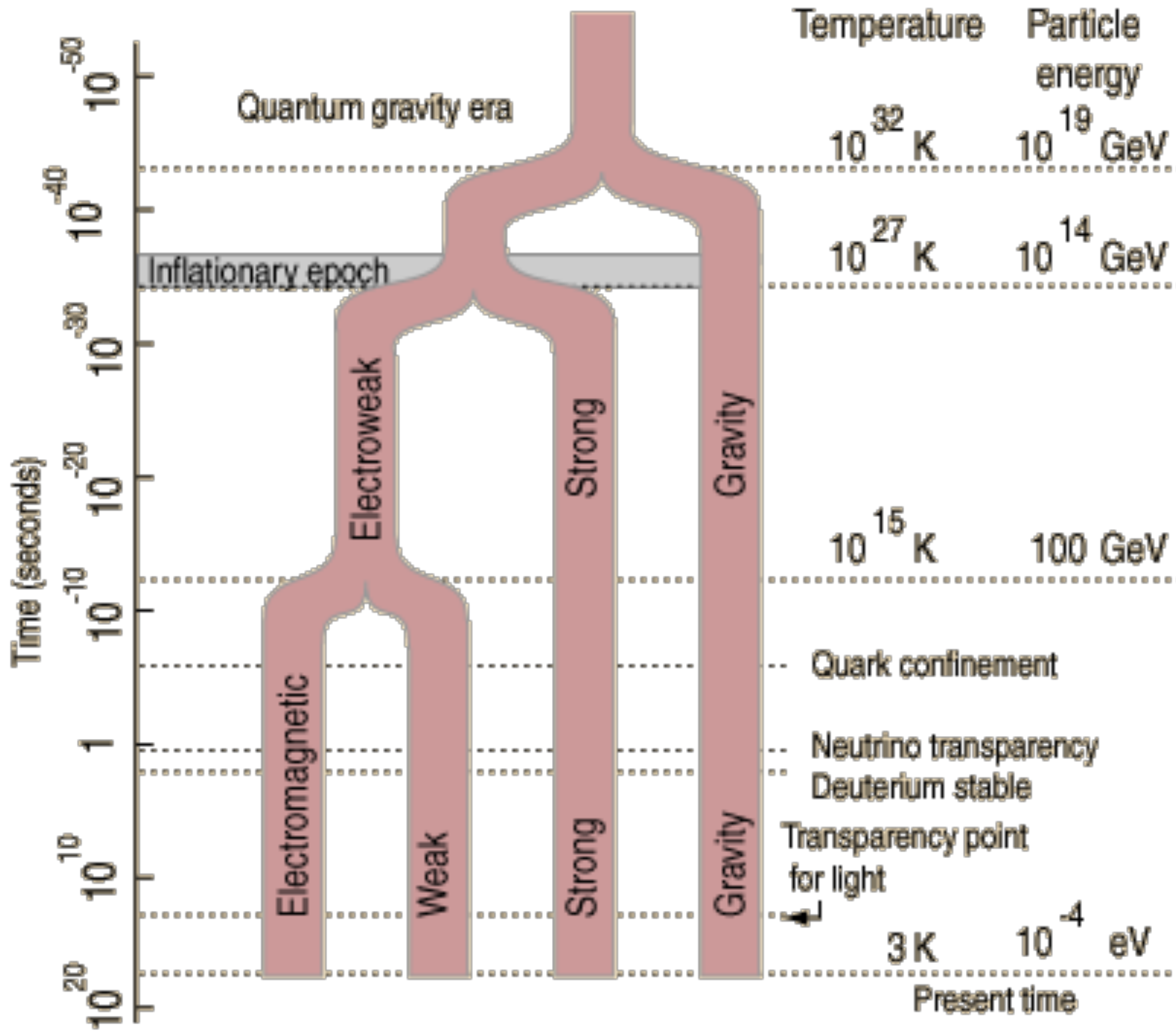
Inflation Science

- Our question: How did the universe begin?
  - What is the origin of structure in the universe?
- Present: Much data support Inflation
- Future: CMB has potential to see a direct signature of Inflation

If we make a detection

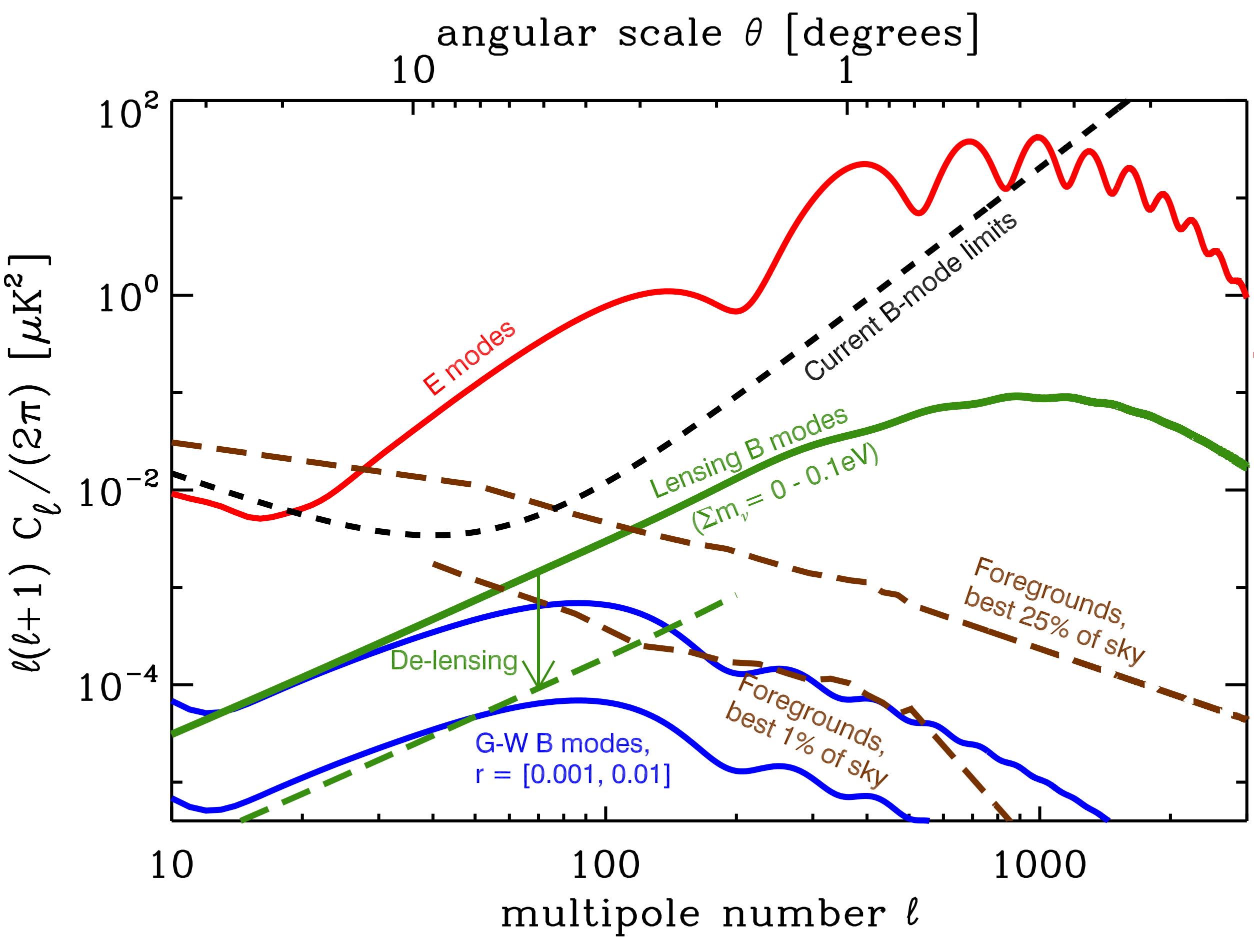
- Prove that inflation occurred
  - Measure Energy Scale
- Test Inflation models including string-motivated
- Opens a new window on Ultra-High Energy physics
  - QM fluctuations of the gravitational field
  - First experimental clue to quantum gravity
  - Large potential for discovery

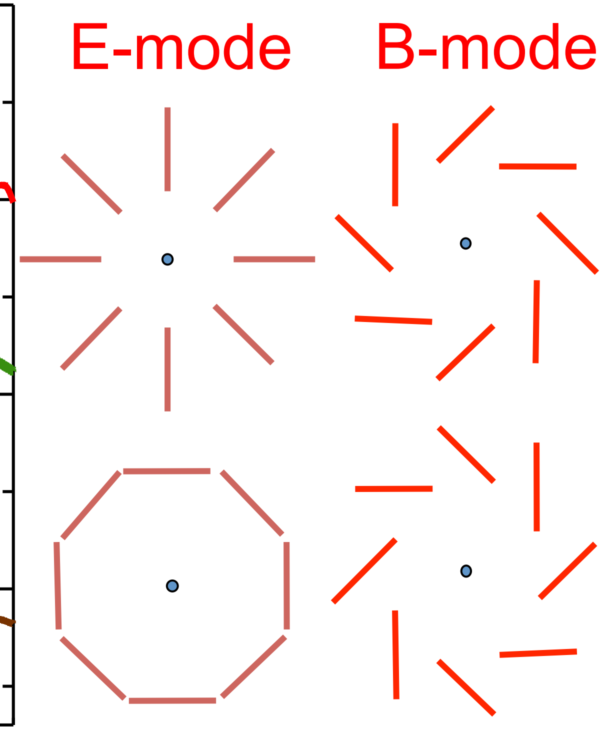
Early Universe = High Energy Laboratory



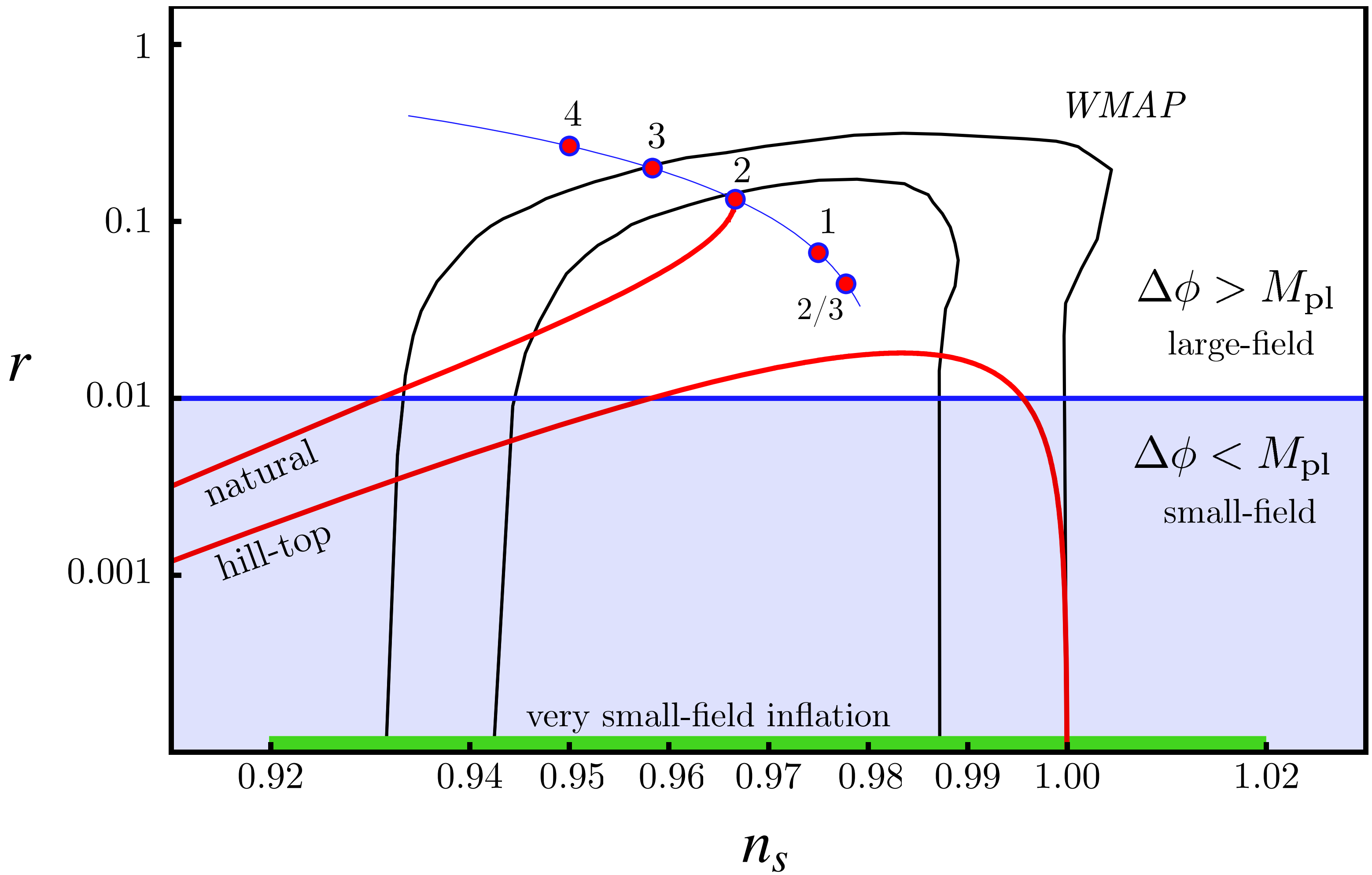
Inflation

CMB Measurements





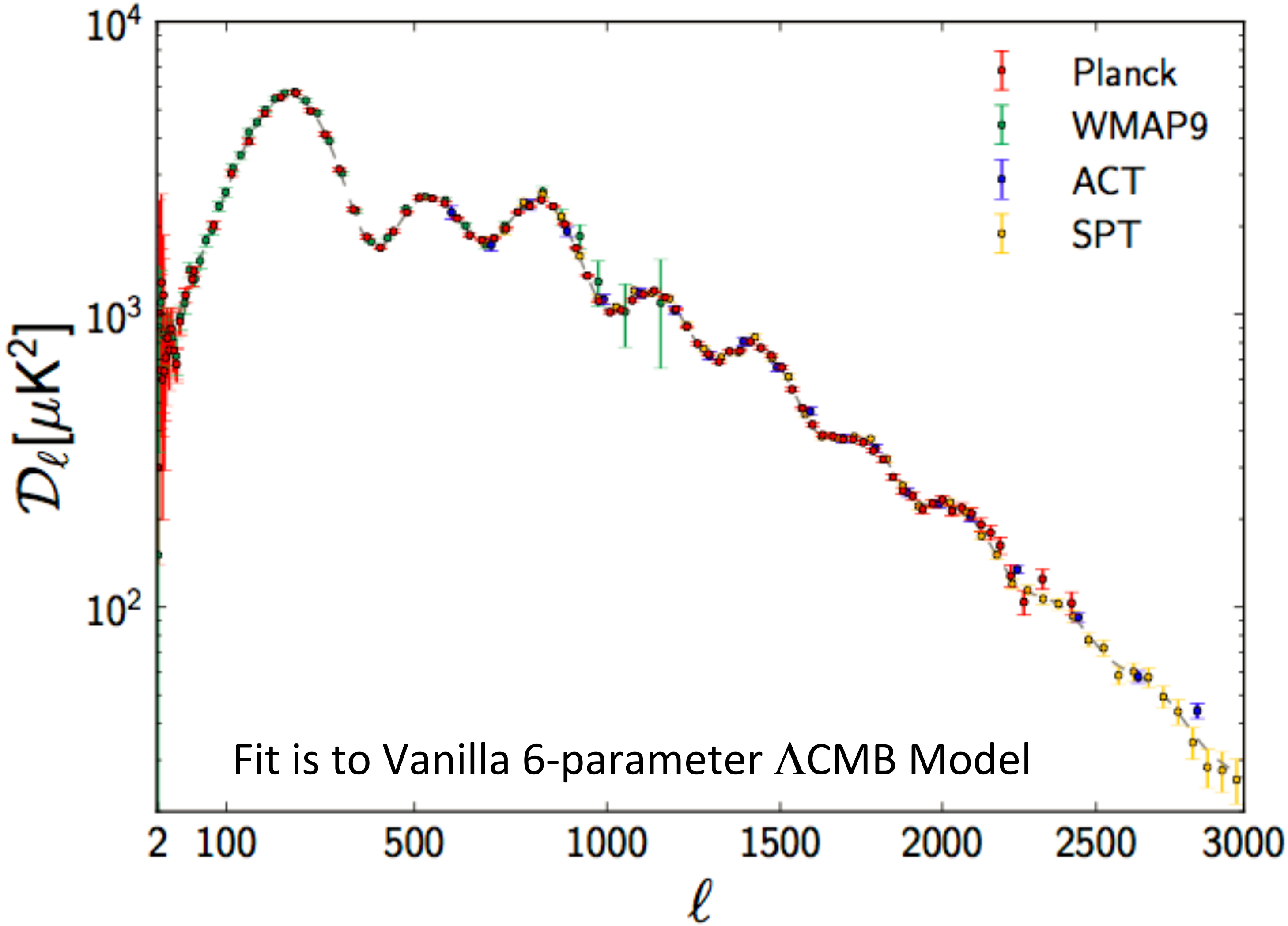
Tensor to Scalar Ratio vs. Scalar Index



Large vs. Small Field Inflation

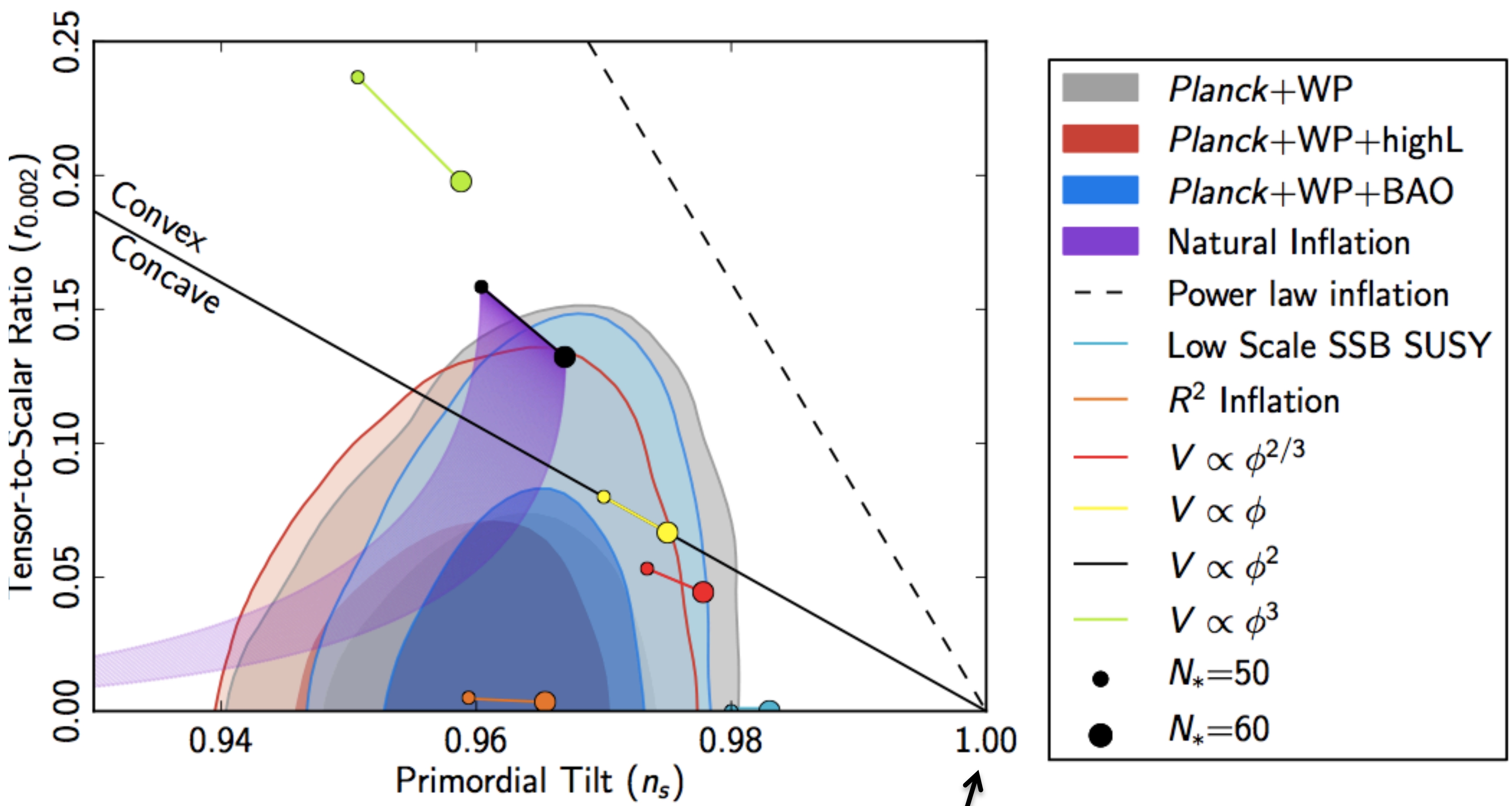
- Zoo of Inflation models fall in two classes
  - Large Field -- $\Delta\phi > m_{pl}$
    - Examples: Chaotic, Hilltop, Axion…
  - Small Field -- $\Delta\phi < m_{pl}$
    - Example: Coleman-Weinberg
- Simplest power law models predict large field
- Until recently string-motivation → small field
  - Now: Large field that obey shift-symmetry (Axion Inflation)

Cosmic Microwave Background 2013



Inflation Consistency: Geometrical flat universe; Superhorizon features; acoustic peaks/adiabatic fluctuations; departure from scale invariance.

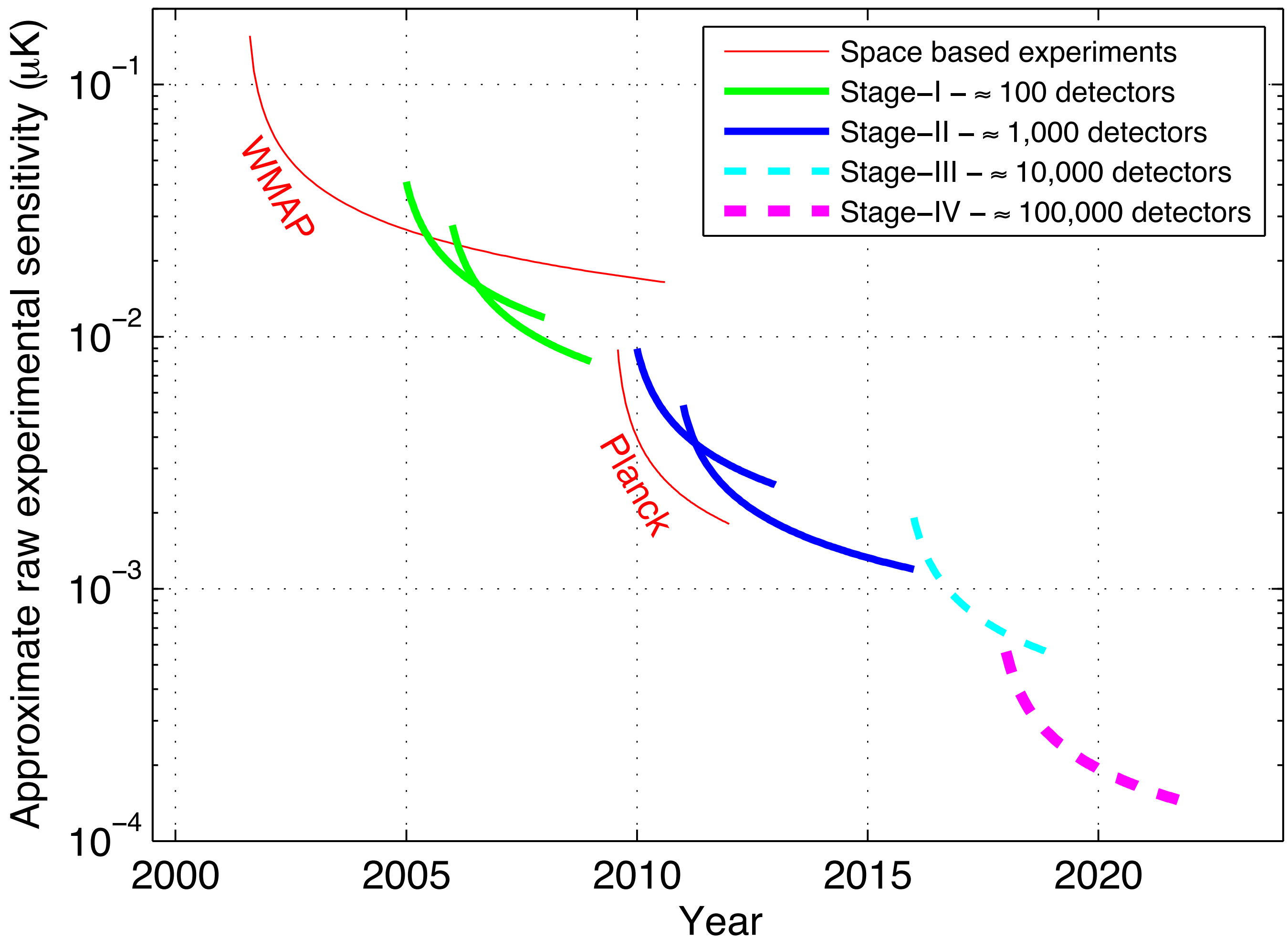
Planck Inflation Constraints



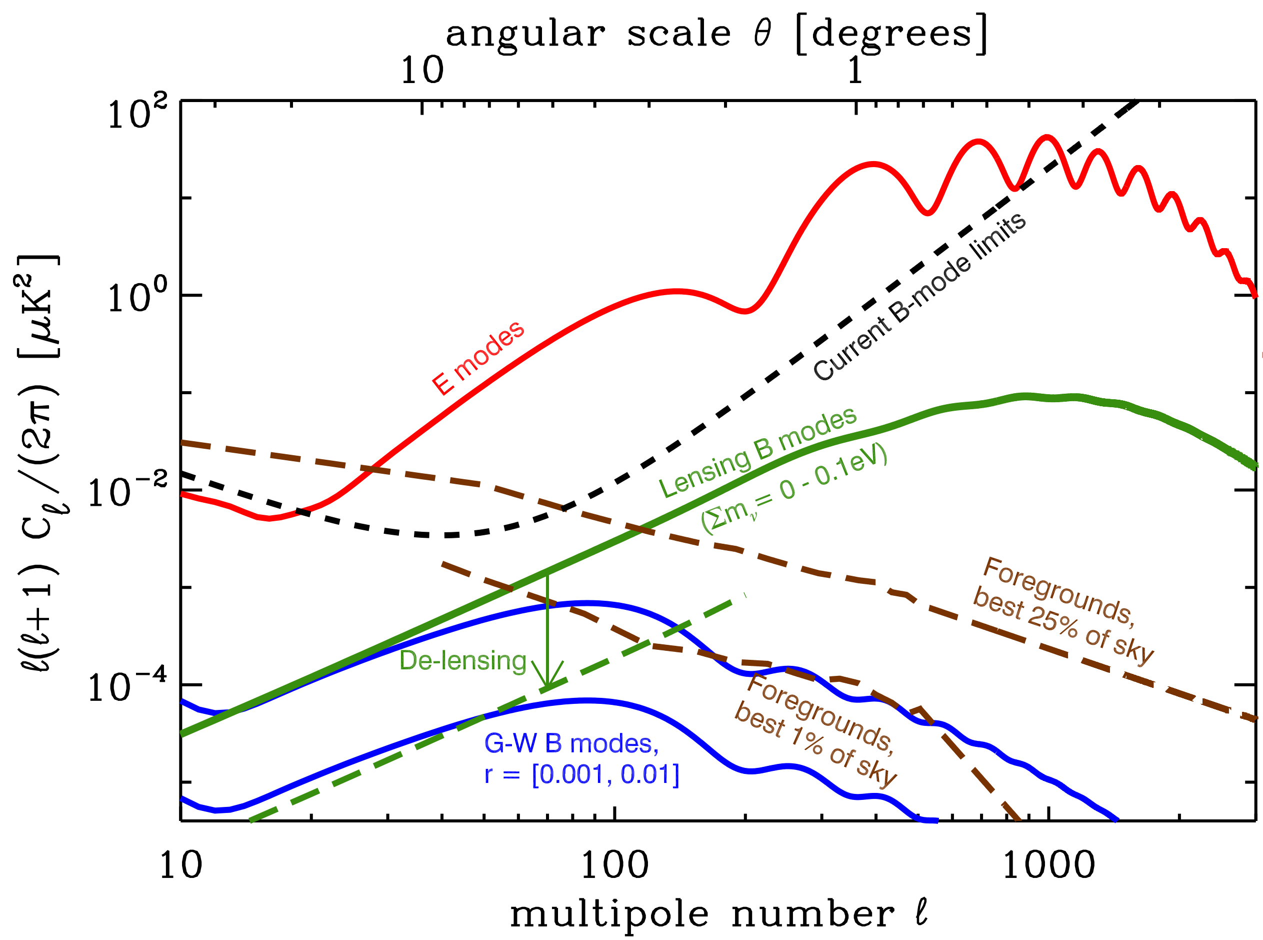
$n_s = 1$ excluded at > 5 σ

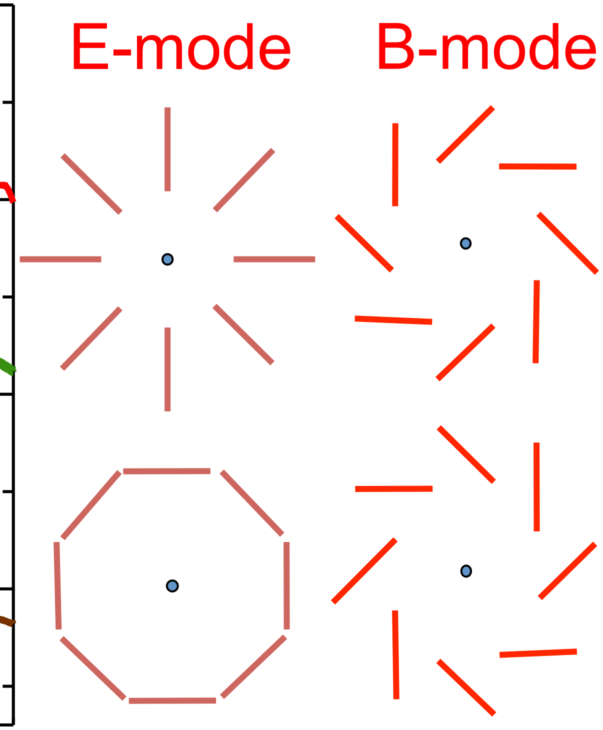
Current Work
Stage II Experiments

Experimental Evolution

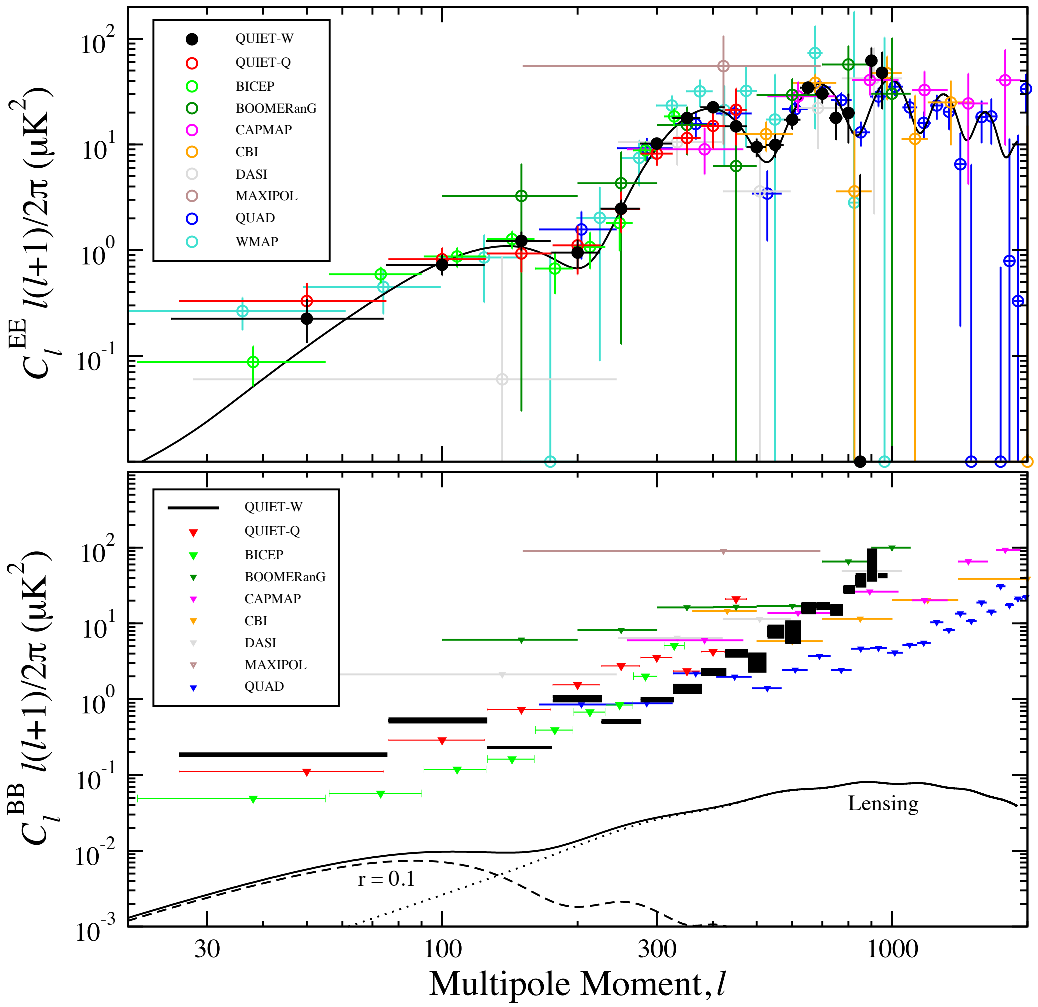


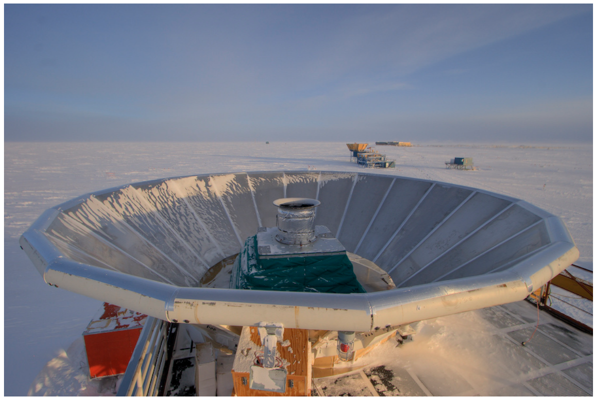
CMB Measurements





B-mode measurements





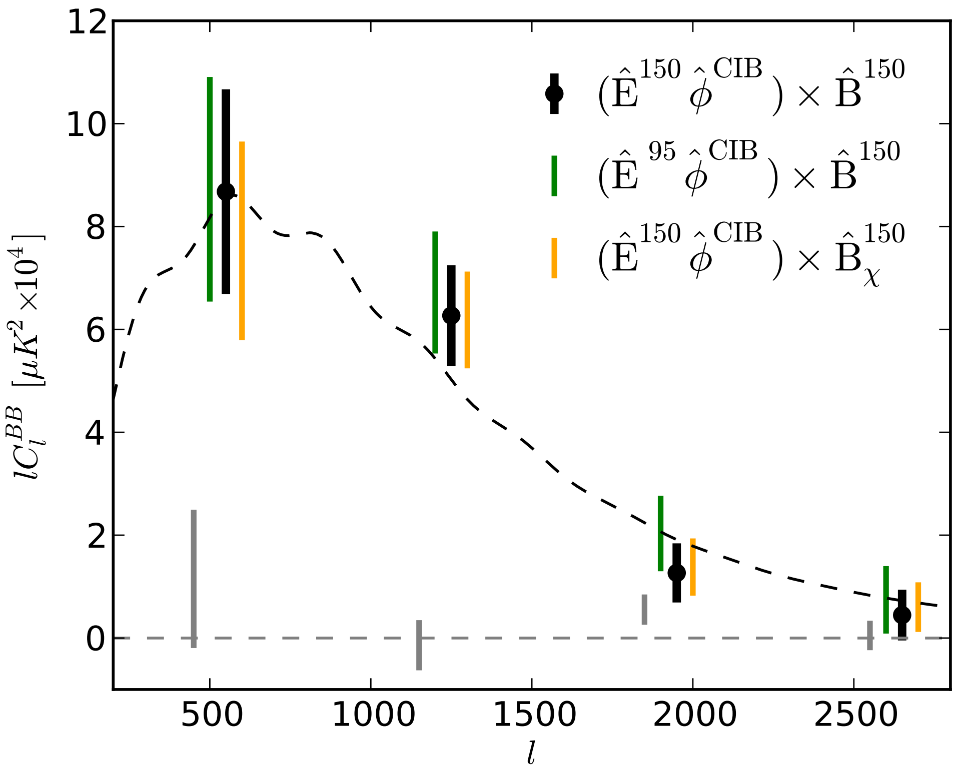
Systematic Error Requirements (Example table from BICEP)

TABLE 3
SYSTEMATIC ERRORS POTENTIALLY PRODUCING FALSE B-MODE POLARIZATION

Instrument Property	Benchmark[a]	Measured	Measurement notes	Reference
Relative gain uncertainty: $\Delta(g_1/g_2)/(g_1/g_2)$	0.9%	$<$ 1.1%	Upper limit, rms error over the array.[b]	§3.1
Differential pointing: $(\mathbf{r_1} - \mathbf{r_2})/\sigma$ [c]	1.9%	1.3%	Average, each repeatedly characterized to 0.4% precision.[d]	§3.2
Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$	3.6%	$<$ 0.3%	Upper limit, rms over the array.	§3.2
Differential ellipticity: $(e_1 - e_2)/2$	1.5%	$<$ 0.2%	Upper limit, rms over the array.	§3.2
Polarization orientation uncertainty: $\Delta\psi$	2.3°	$<$ 0.7°	Upper limit, rms absolute orientation error over the array.	§3.3
Telescope pointing uncertainty: $\Delta\mathbf{b}$	5′	0.2′	Fit residual rms in optical star pointing calibration.	§3.4
Polarized sidelobes (100, 150 GHz)	-9, -4 dBi	-26, -17 dBi	Response at 30° from the beam center.	§3.5
Focal plane temperature stability: ΔT_{FP}	3 nK	1 nK	Scan-synchronous rms fluctuation on $\ell \sim 100$ time scale.	§3.6
Optics temperature stability: ΔT_{RJ}	4 μK	0.7 μK	Scan-synchronous rms fluctuation on $\ell \sim 100$ time scale.	§3.6

Lensing Measurements/Delensing

- SPTPOL: Lensing B-modes detected in correlation with LSS Paves way for lensing measure and delensing



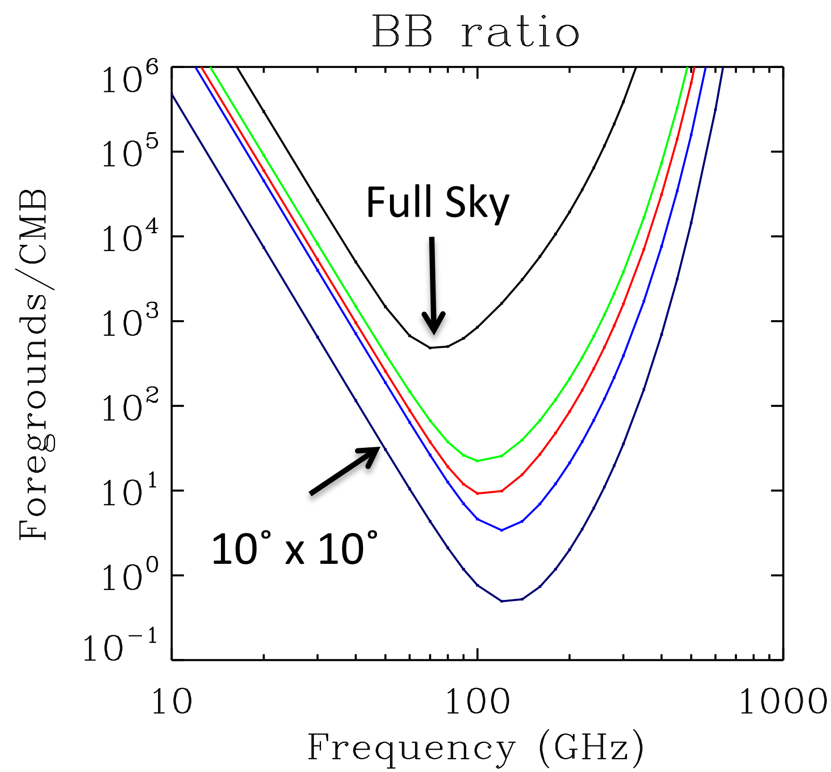
Hanson et al. 2013

Stage IV CMB Experiment
CMB-S4

The Stage-IV experiment: CMB-S4

- Builds on extensive experience from earlier generation experience
  - Technology
  - Systematic Error Control
- Two surveys
  - Inflation Scan (few % of the sky)
  - Neutrino mass Scan (50% of the sky)
- Experiment configuration
  - 500,000 detectors
  - 3’ or better resolution for lensing

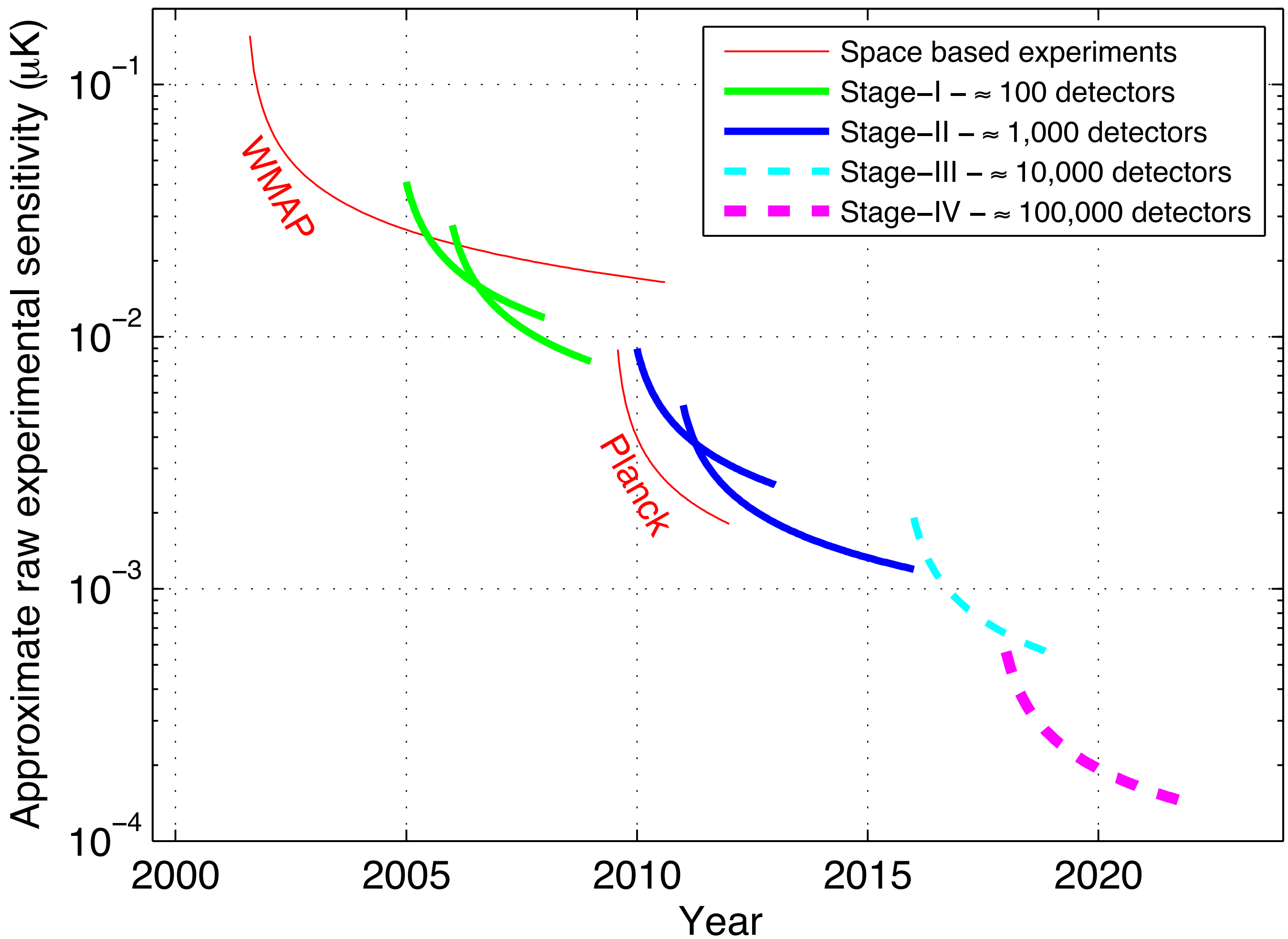
Foregrounds on small sky area



CMB here => r = 0.01 (80 < ell < 120)

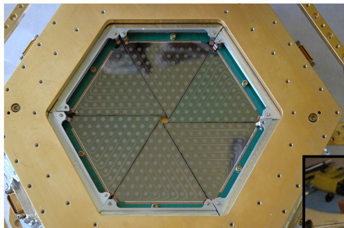
Dunkley et al. (2008)

Experimental Evolution

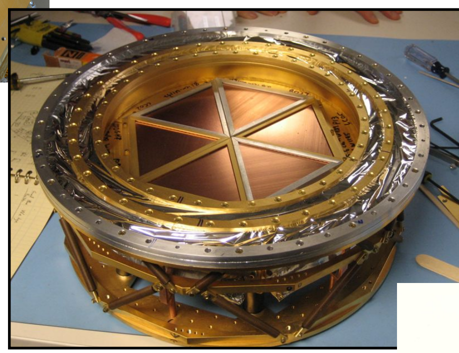


Experimental Evolution

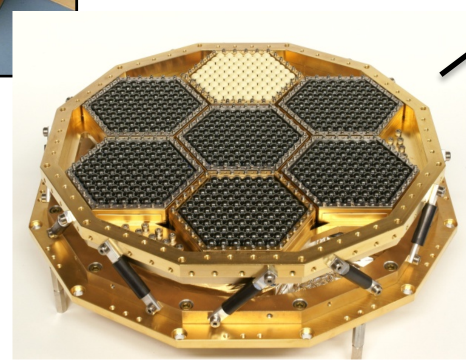
16 cm



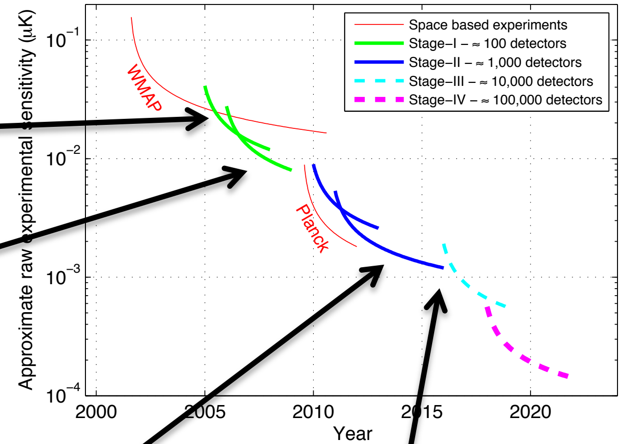
APEX-SZ
330 detectors



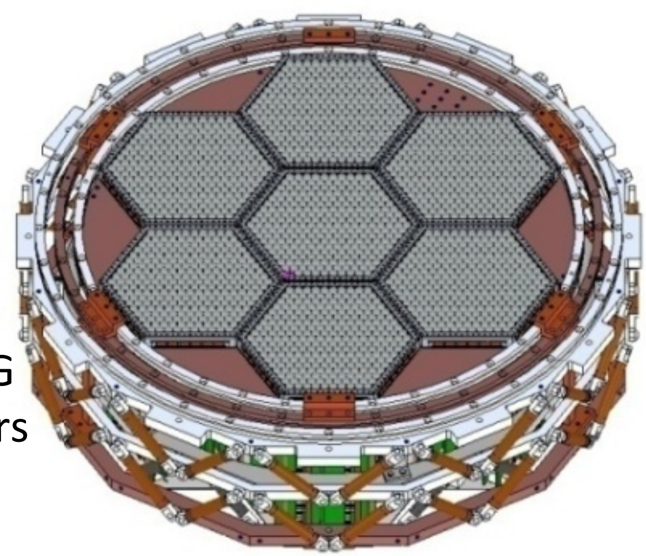
SPT-SZ
960 detectors



POLARBEAR-1
1274 detectors
Dual-Polarization



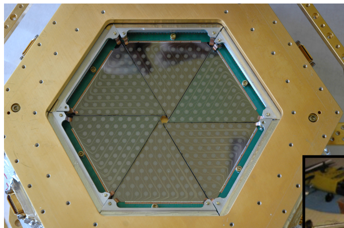
38 cm



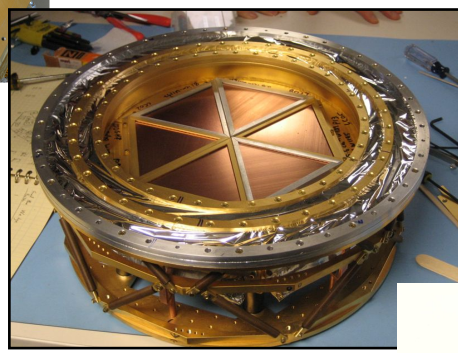
POLARBEAR-2/SPT-3G
8,000/15,000 detectors
Dual-Polarization
2/3 Color/pixel

Experimental Evolution

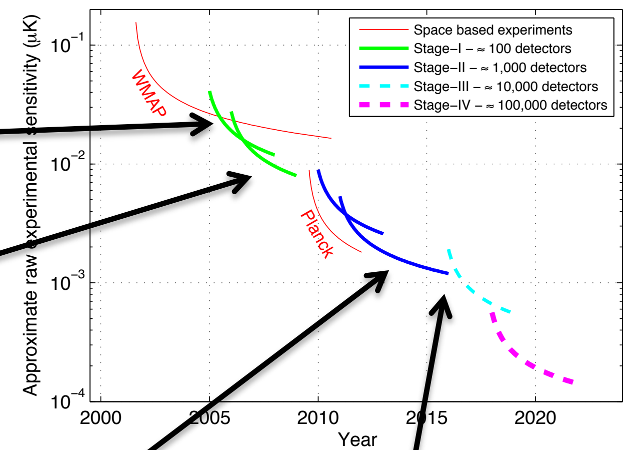
16 cm

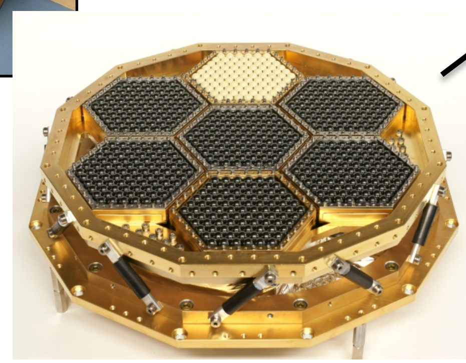


APEX-SZ
330 detectors

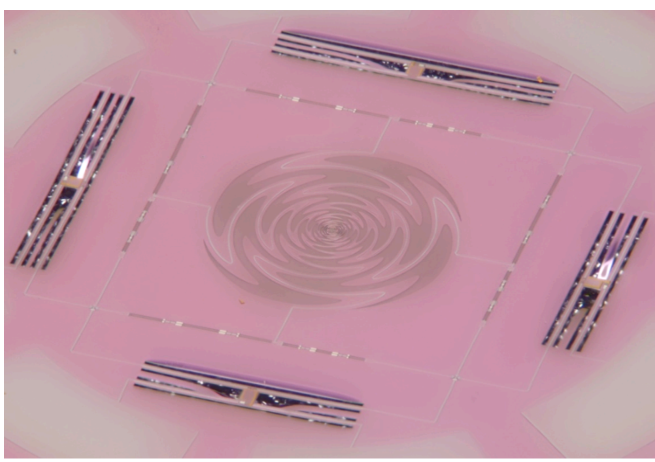


SPT-SZ
960 detectors

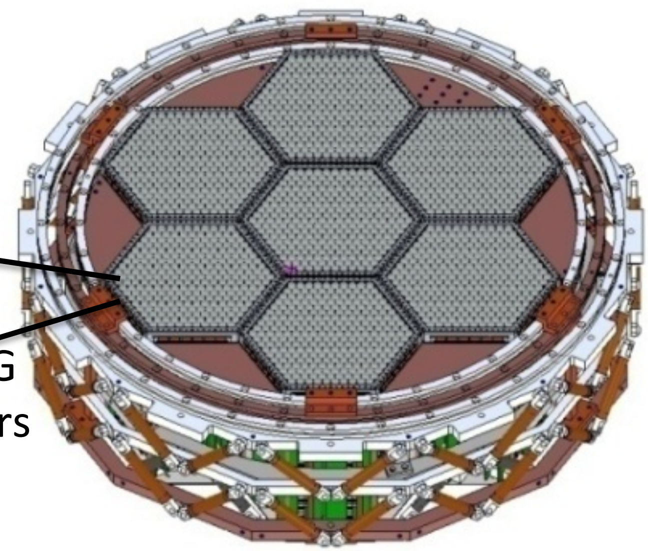




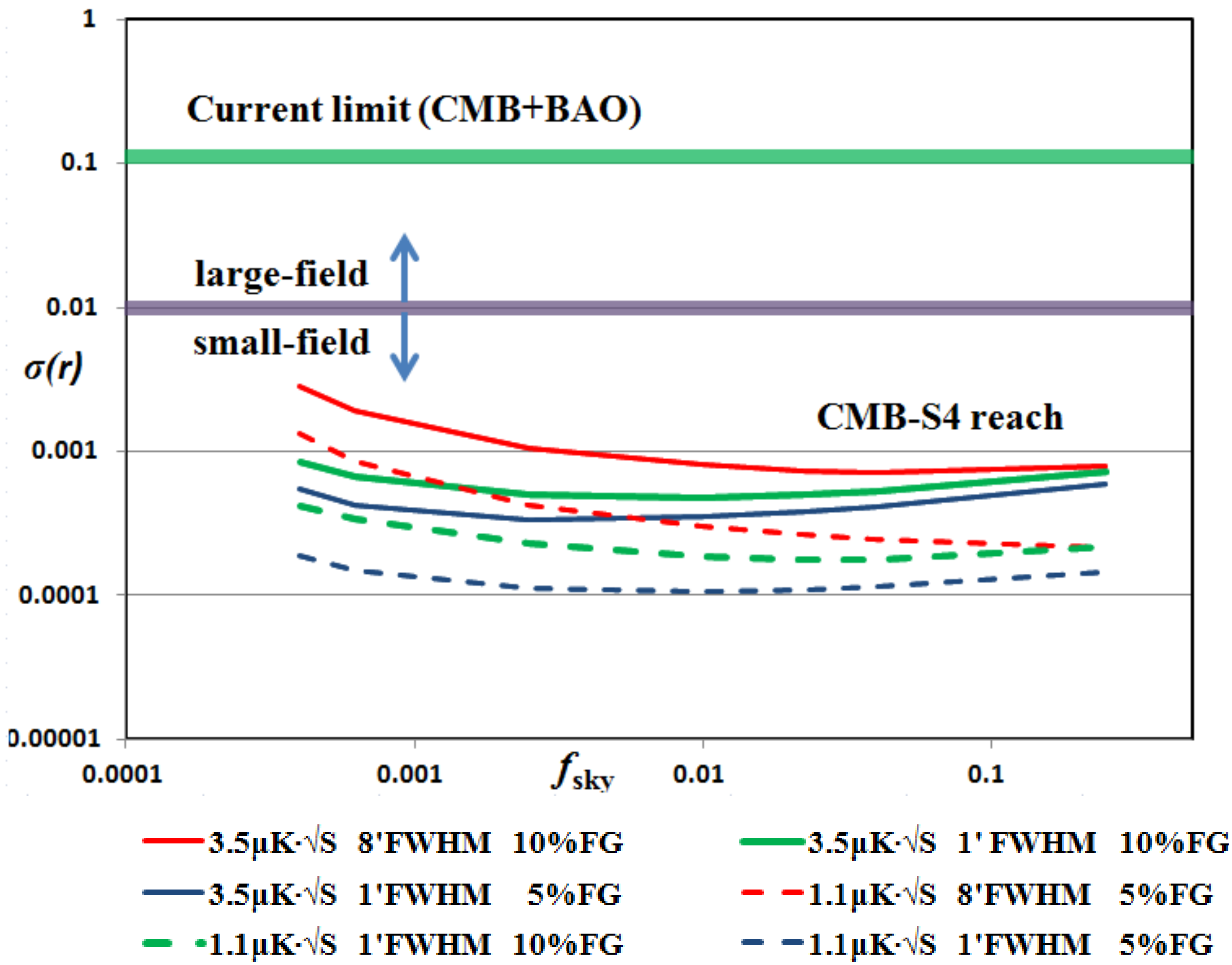
38 cm



POLARBEAR-2/SPT-3G
8,000/15,000 detectors
Dual-Polarization
2-3 Color/pixel



CMB-S4 Sensitivity



Role of National labs

- CMB-S4 requirements exceed capabilities of University-based experiments
  - Focal-plane Arrays and Readout
    - Improved Production Reliability
    - Increased Production Volume and Throughput
      - 500,000 detectors ~ 300 silicon arrays
    - Multiplexed TES Readout
    - Large Cryogenic Optics
  - Computing Infrastructure and Analysis tools
    - ~10,000 x planck data size (~ 3 TB/day)
  - Project Organization/Management

Conclusions

- Detection of Inflationary gravitational waves would be a *profound* discovery.
  - Proves Inflation Occurred
  - Opens a new window on Planck-scale Physics
- Present: Stage II → Stage III
  - Control systematic errors
  - Develop technology
- A new scale of experiment is required
  - ➔ Stage IV CMB – CMB-S4
  - HEP multilab scale project

EXTRA