Space/Ground Complementarity

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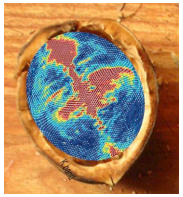
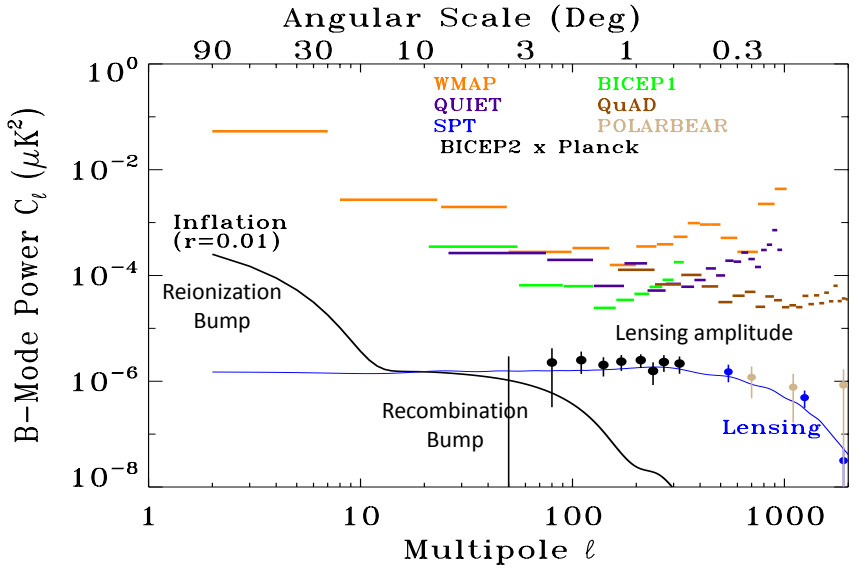
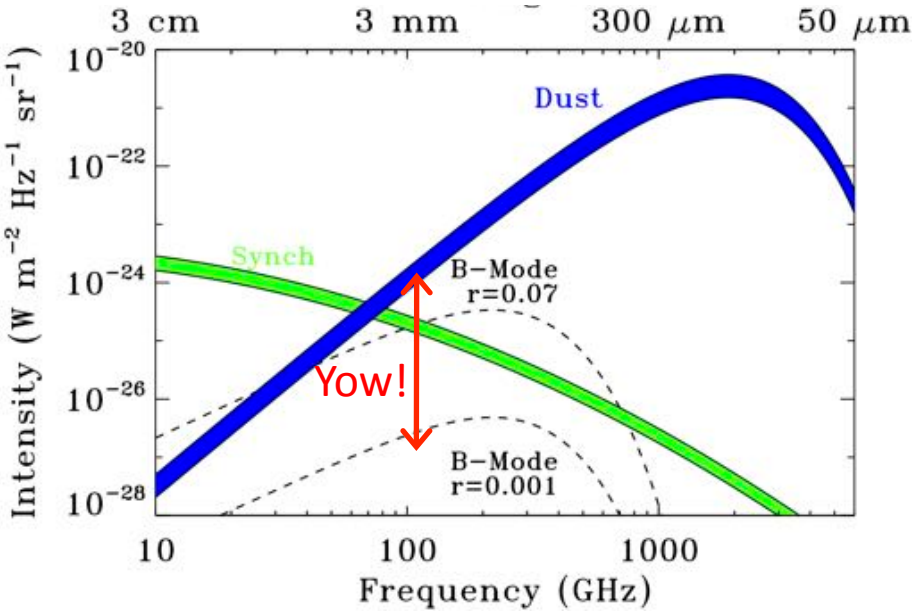


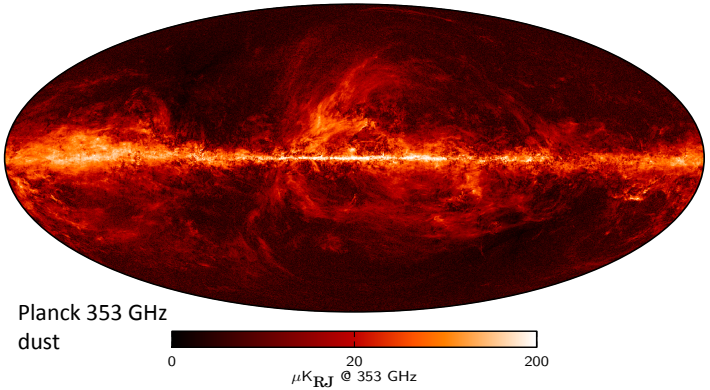
B-modes in a Nutshell

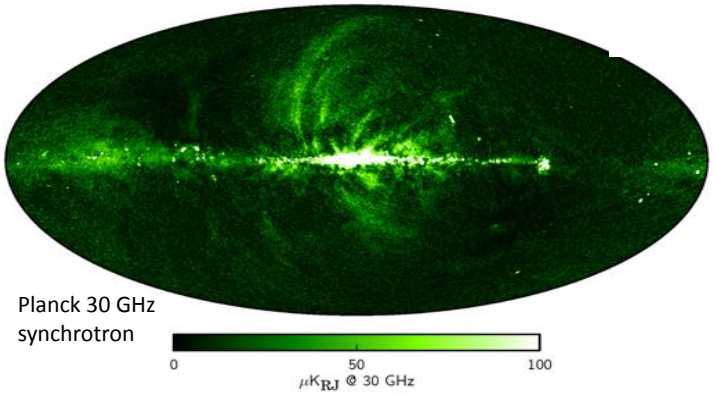




Requirements for Detection

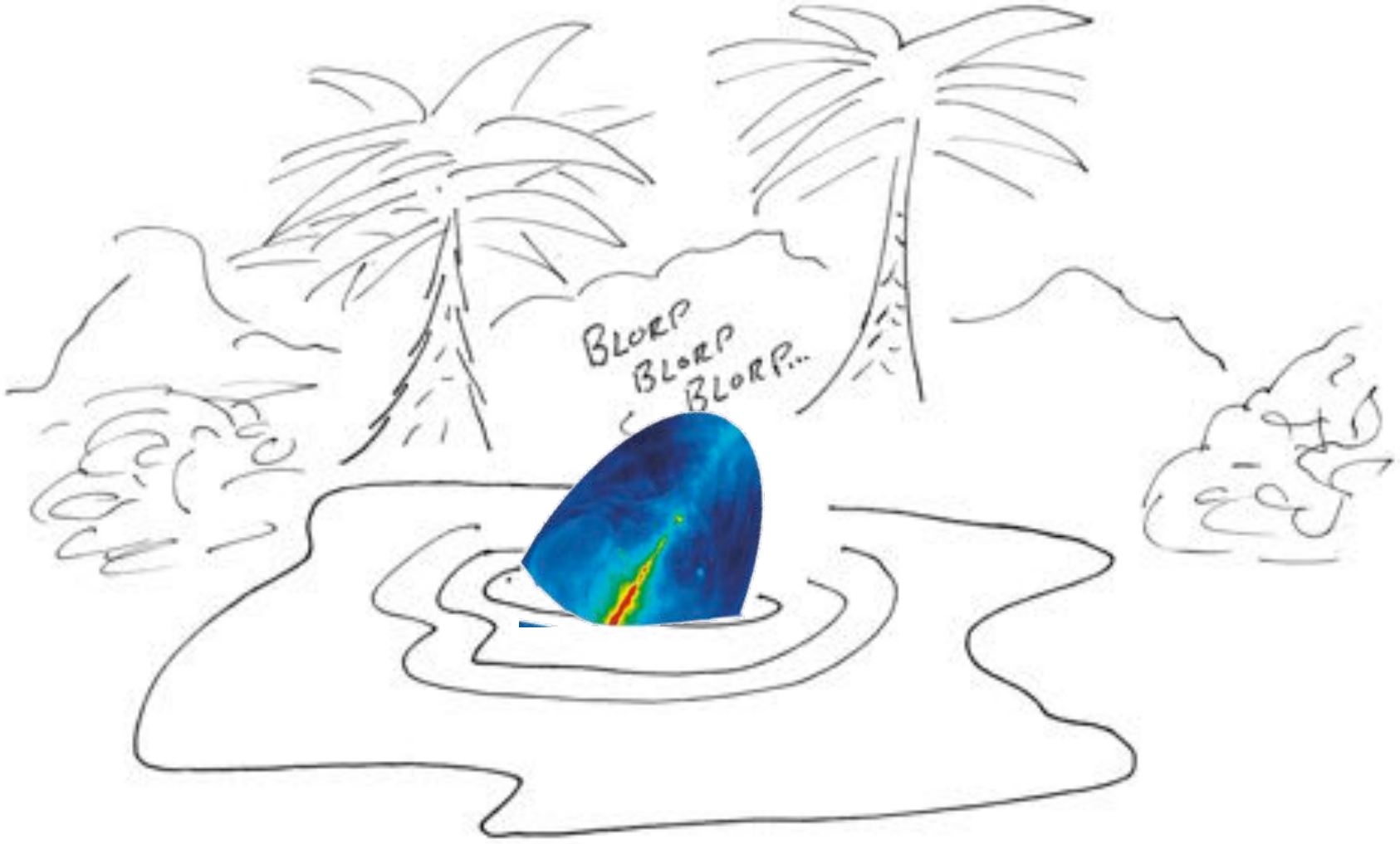
- Sub-Percent Foreground Subtraction
- Large AND small angular scales
- Immunity to Instrumental Effects





Those Annoying Foregrounds

Into The Swamp ..



Foregrounds: Size Matters!

Want Similar Angular Resolution Across Broad Frequency Range
But ...Angular Resolution $\theta \sim \lambda/D$

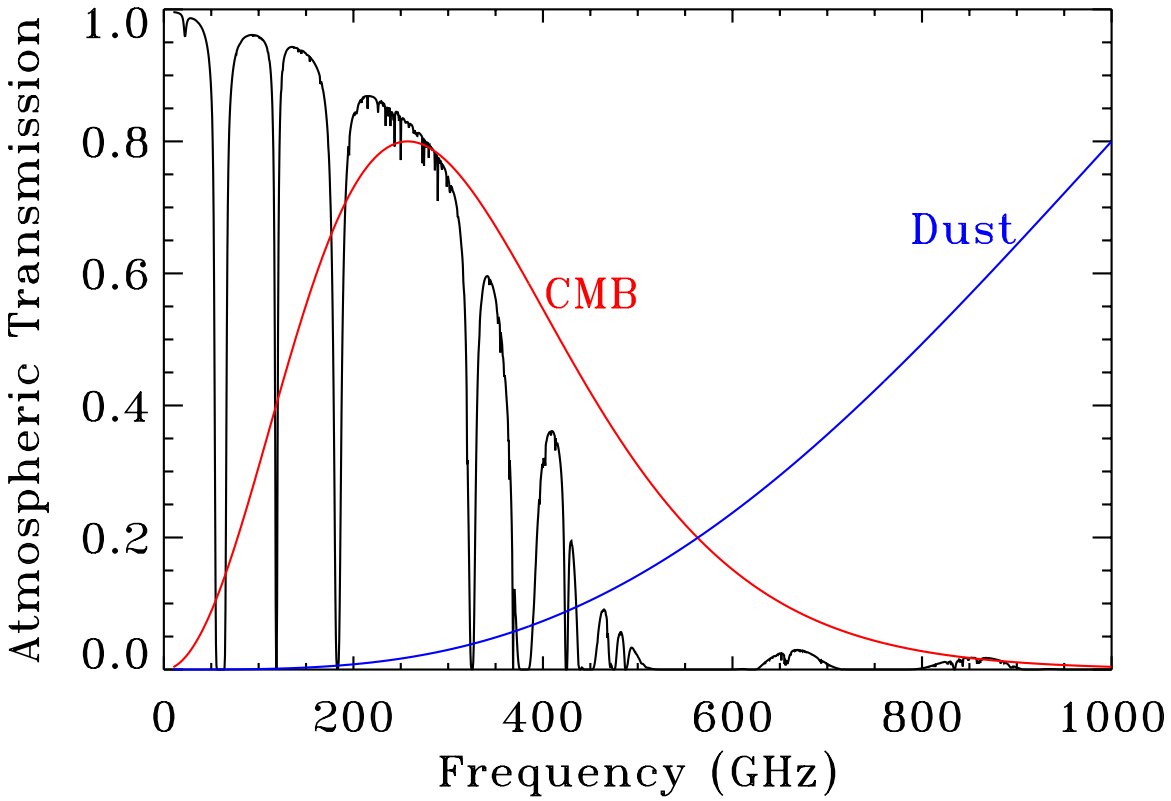
5' at 300 GHz: 80 cm primary

5' at 10 GHz: 24m primary

Cost to L2 deep-space orbit is about $250,000 / kg
Mapping low frequencies requires a ground-based observatory

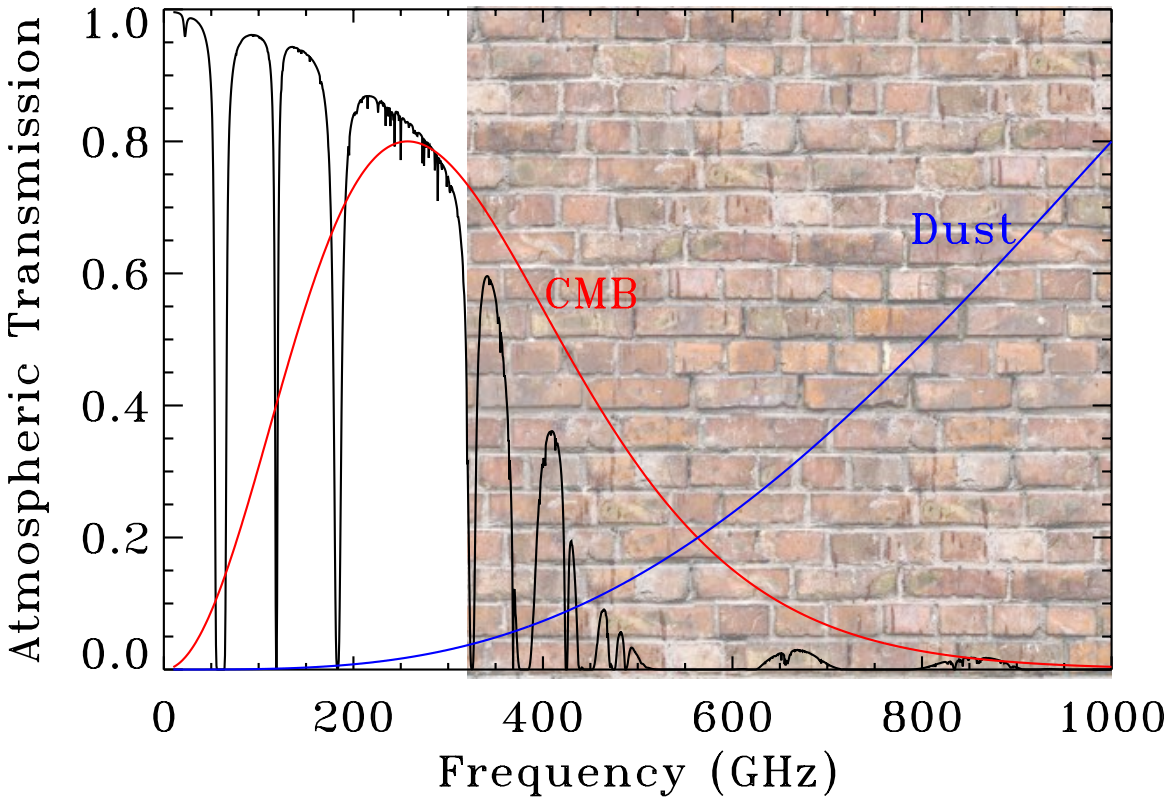
Foregrounds: Visibility Matters!

The problem with ground-based cosmology …



Foregrounds: Visibility Matters!

The problem with ground-based cosmology …



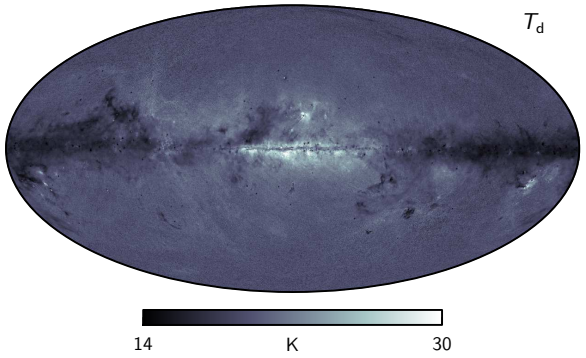
Atmosphere is opaque at frequencies above 300 GHz

Mapping high frequencies requires a space observatory

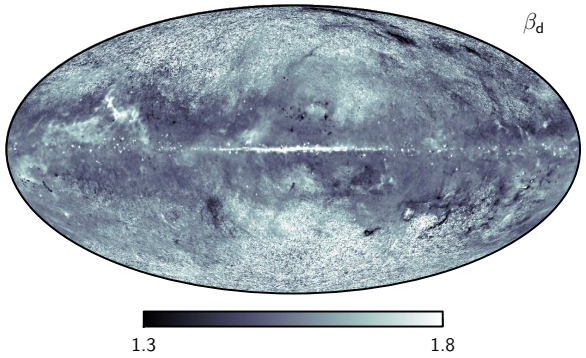
Do we need data above 300 GHz?

It depends on how well you want to do ...

Dust properties vary across the sky

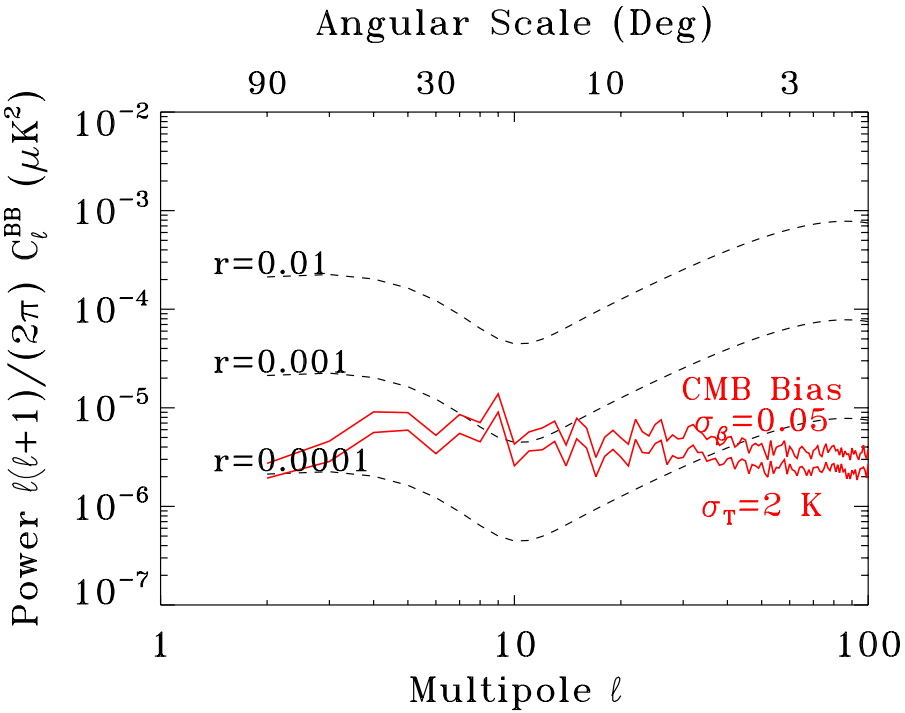


Planck temperature variation σ_T = 1.9 K

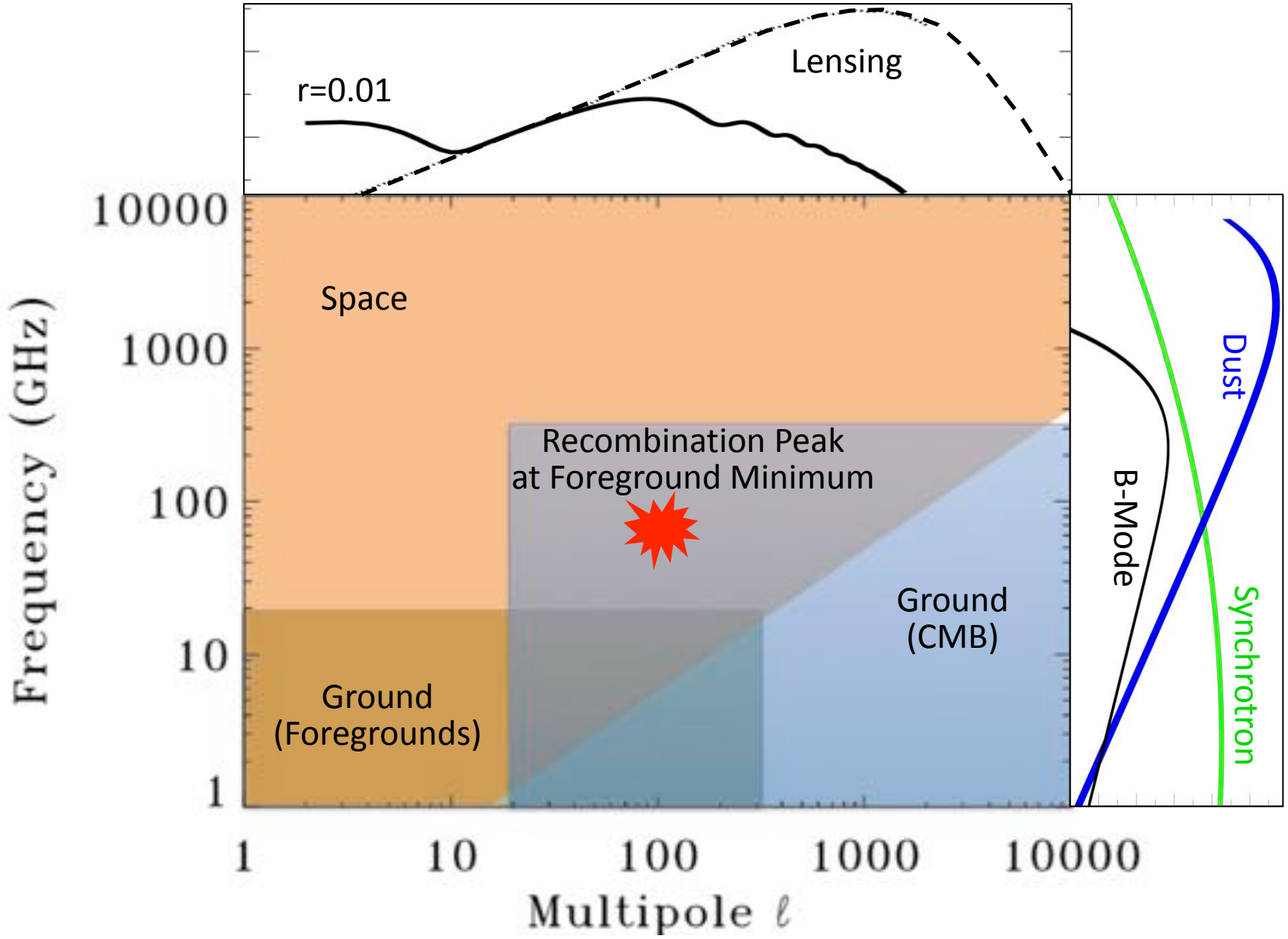


Planck spectral index variation σ_β = 0.05

Assume similar variation along line of sight
Fit dust using standard modified blackbody over frequency range [30, 250 GHz]



Foreground Complementarity

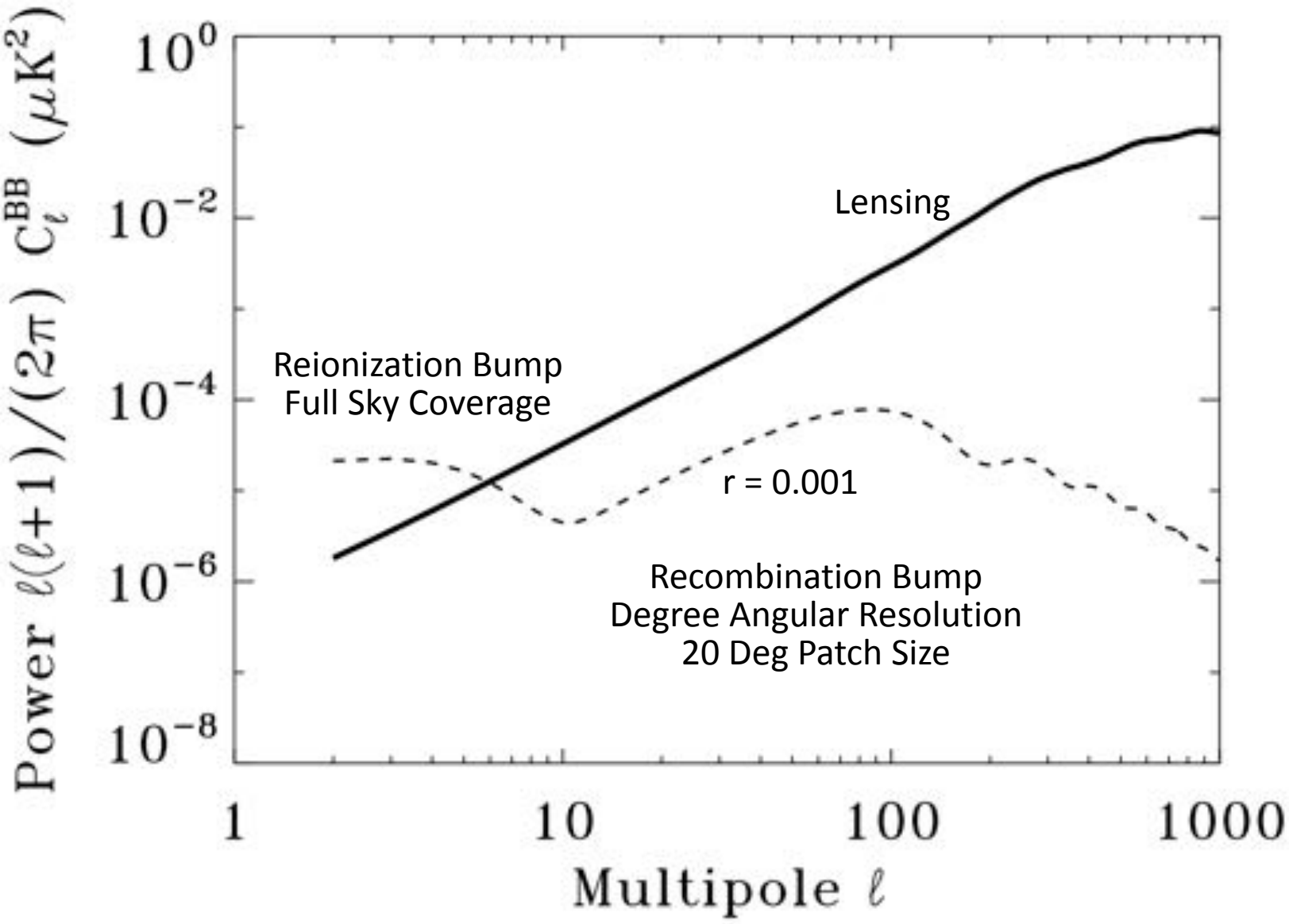


Those Difficult Angular Scales

How Big Is Big Enough?

Lensing vs Primordial B-Modes

Why large angular scales are important



Lensing vs Primordial B-Modes

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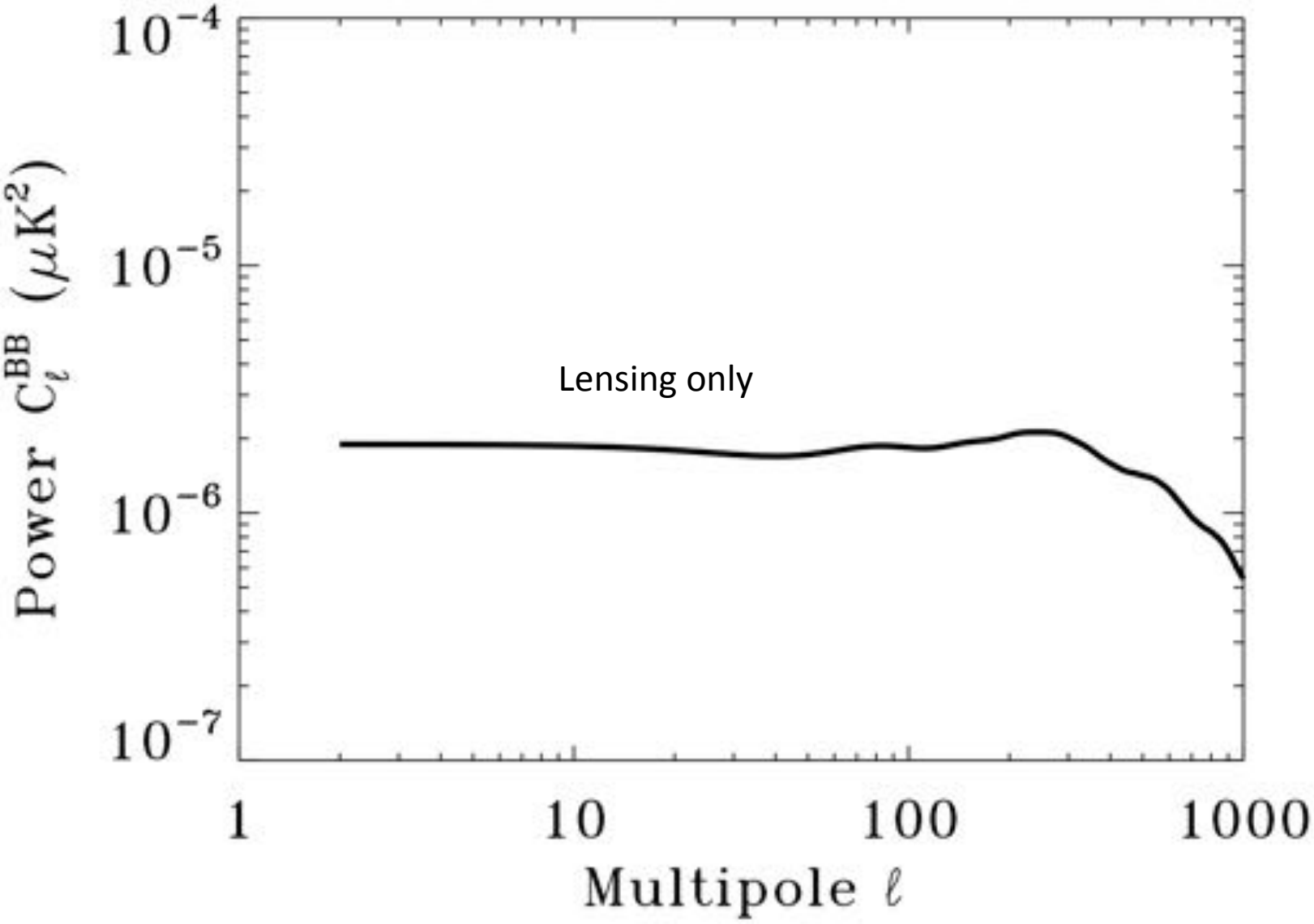

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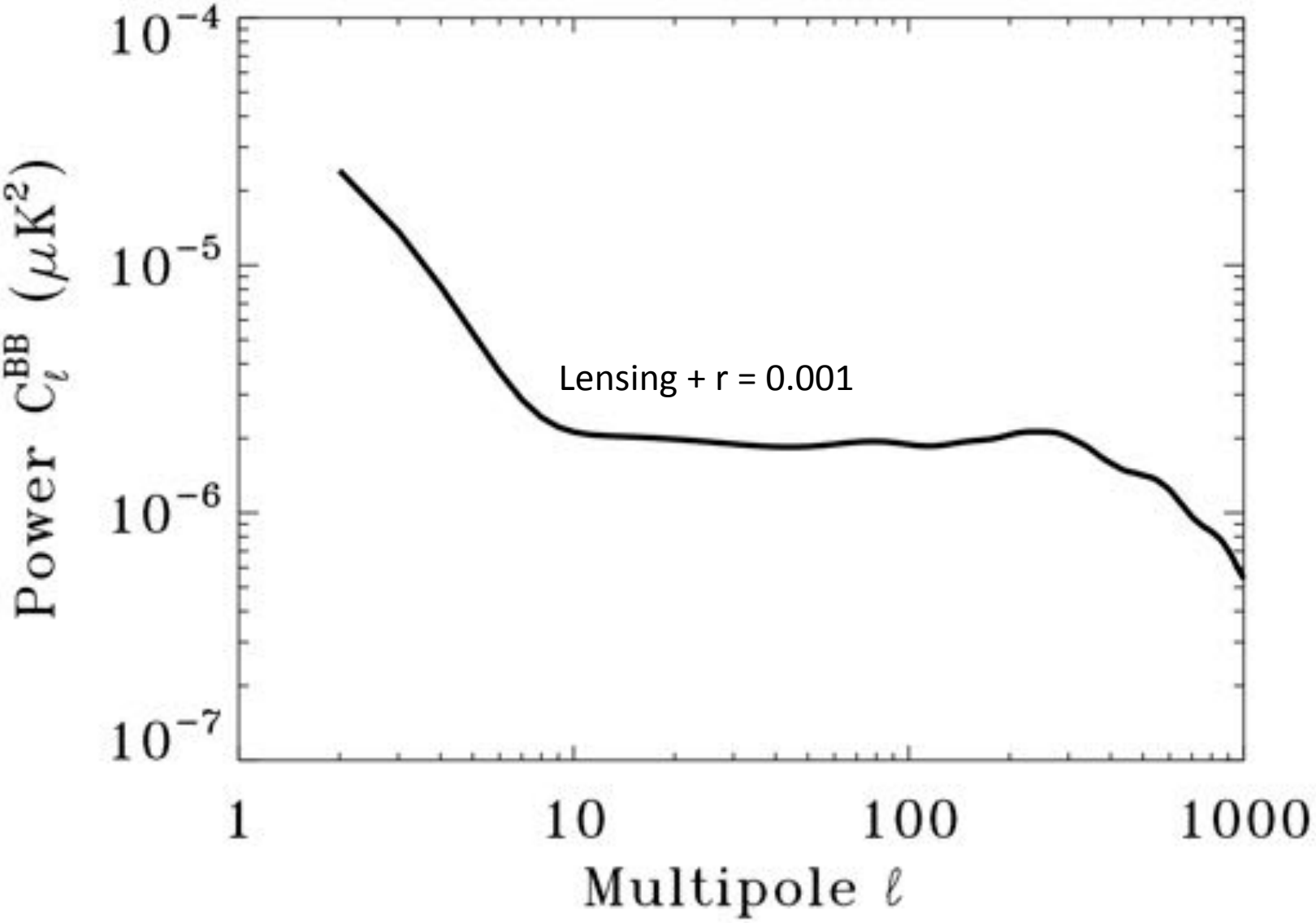
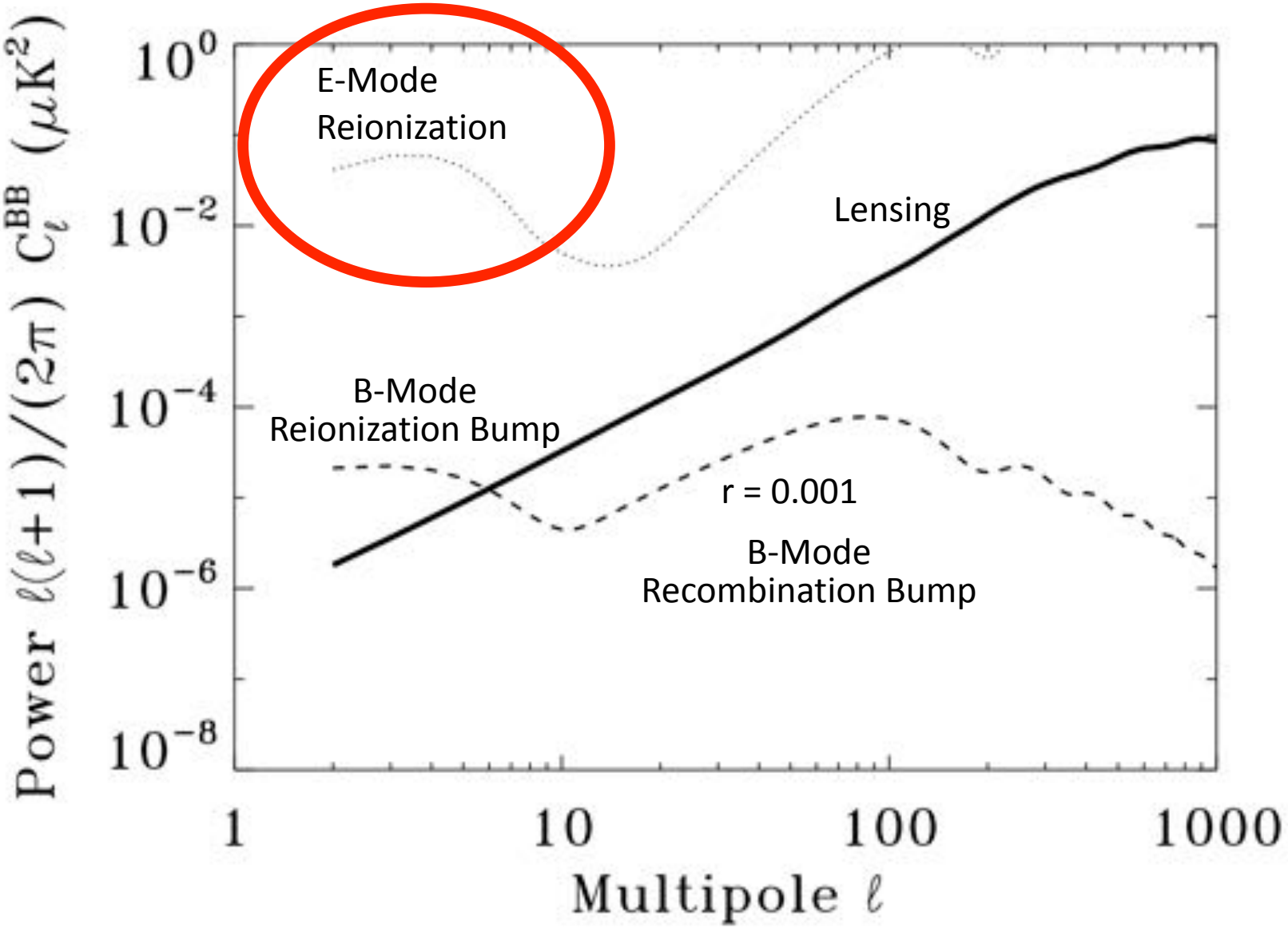


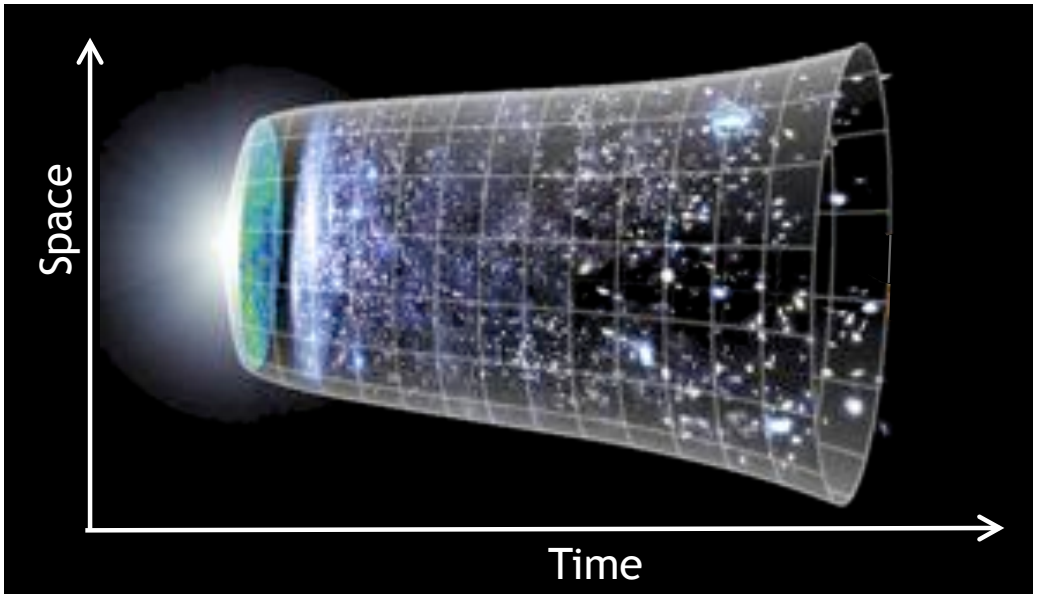
Reionization and Large Angular Scales

Guaranteed science for high-energy physics



Reionization and Neutrino Mass

Last Unknown Parameter for Standard Model of Particle Physics

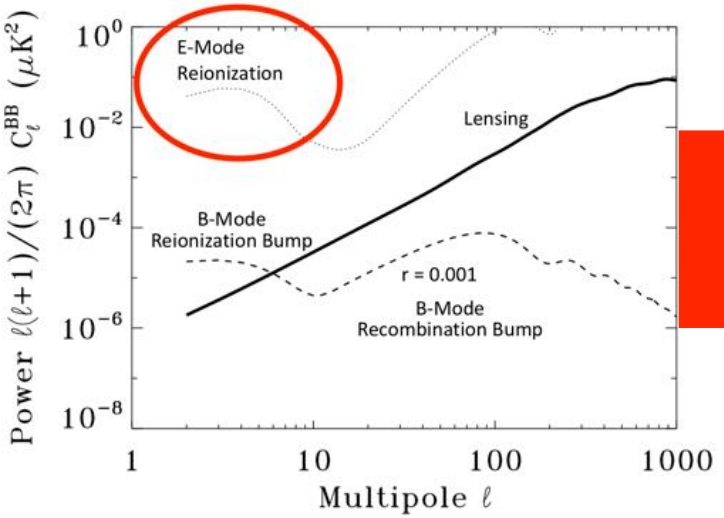


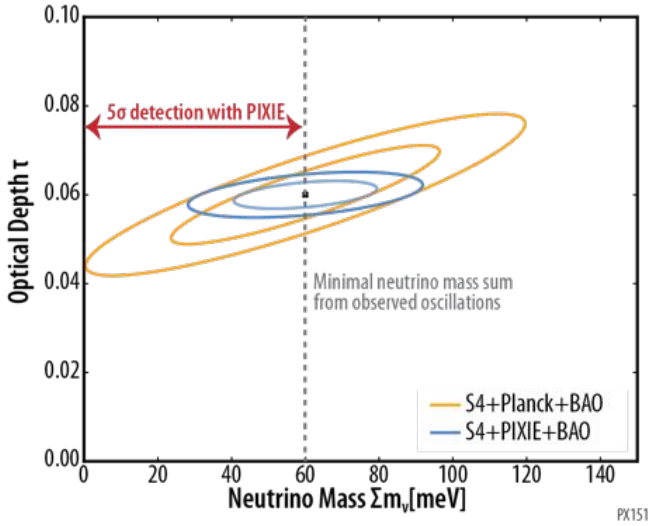
Neutrino mass affects growth of structure
Larger mass → Faster expansion → Less growth

Lensing determines structure in nearby universe

CMB density perturbations set initial structure
up to a correction for reionization optical depth

Measure E-modes on large angular scales: Cosmic-variance-limited measurement of reionization optical depth





Need a
space mission!

LiteBIRD, PIXIE, PICO, ...

Controlling Systematic Error

Would you rather tame a lion ...

... Or a kitten?

Potential Problem	**Ground**	**Space**
Atmospheric Turbulence		✔
Far Sidelobe Pickup		✔
Changing Thermal Environment		✔
Radio-Frequency Interference		✔
That Darned Gravity		✔

Angular Scales > 30 deg requires a space mission

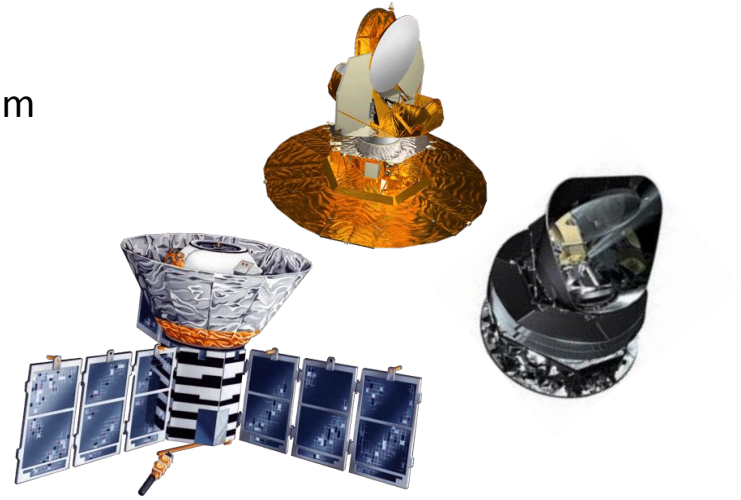
Space/Ground Complementarity

Things that space missions do very well

Measurements across entire electromagnetic spectrum
- Foregrounds outside atmospheric windows
- Ancillary science

Exceptionally stable observing environment
- Measure largest angular scales
- Calibration stability

Minimal constraints on pointing / roll
- Systematic error control



Things that ground-based missions do very well

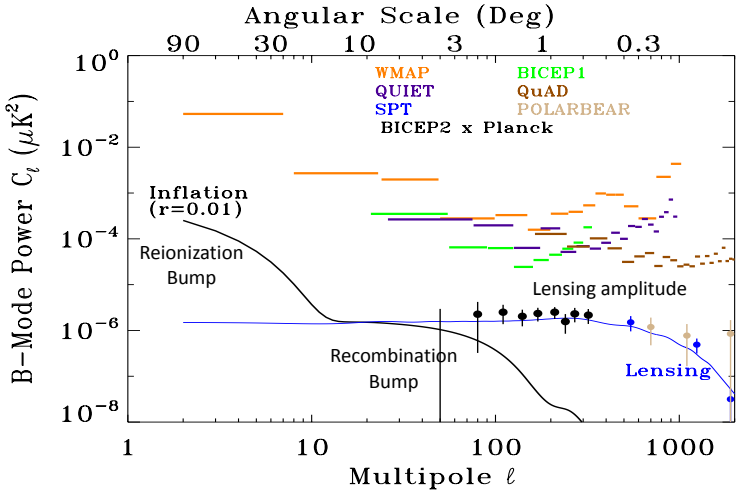
Large physical size for collecting optics
- Small angular scales
- Low-frequency foregrounds

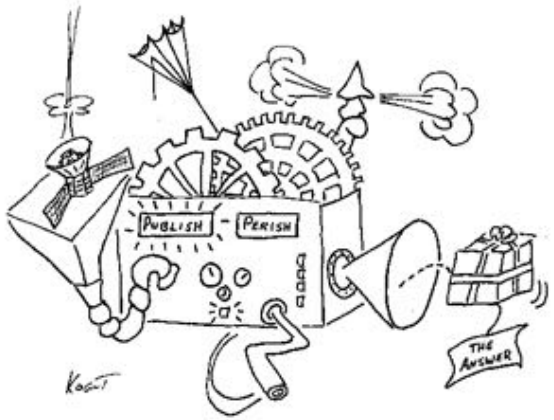
Multiple instruments / facilities
- Deep integrations
- Cross-check vs technologies, observing modes

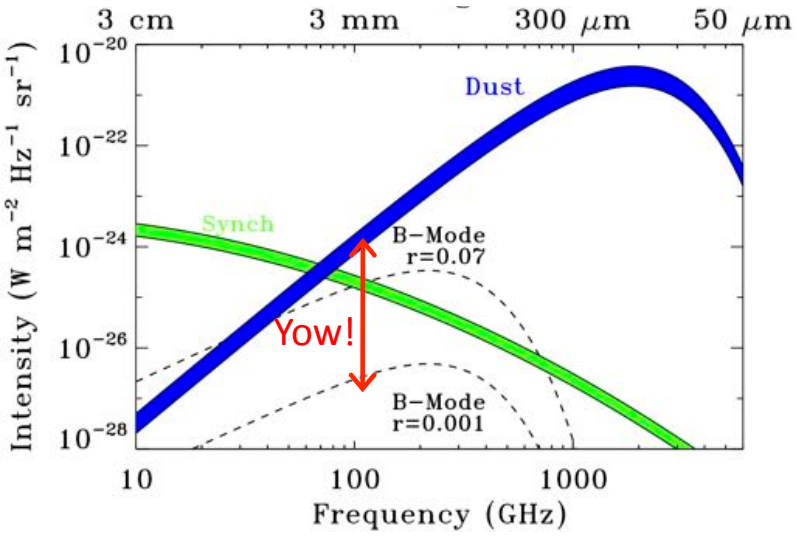
Incremental upgrades to instruments / facilities
- Cutting-edge technologies & development
- Robust reaction

A Mix of Methods

Don't assume a single mission must do it all





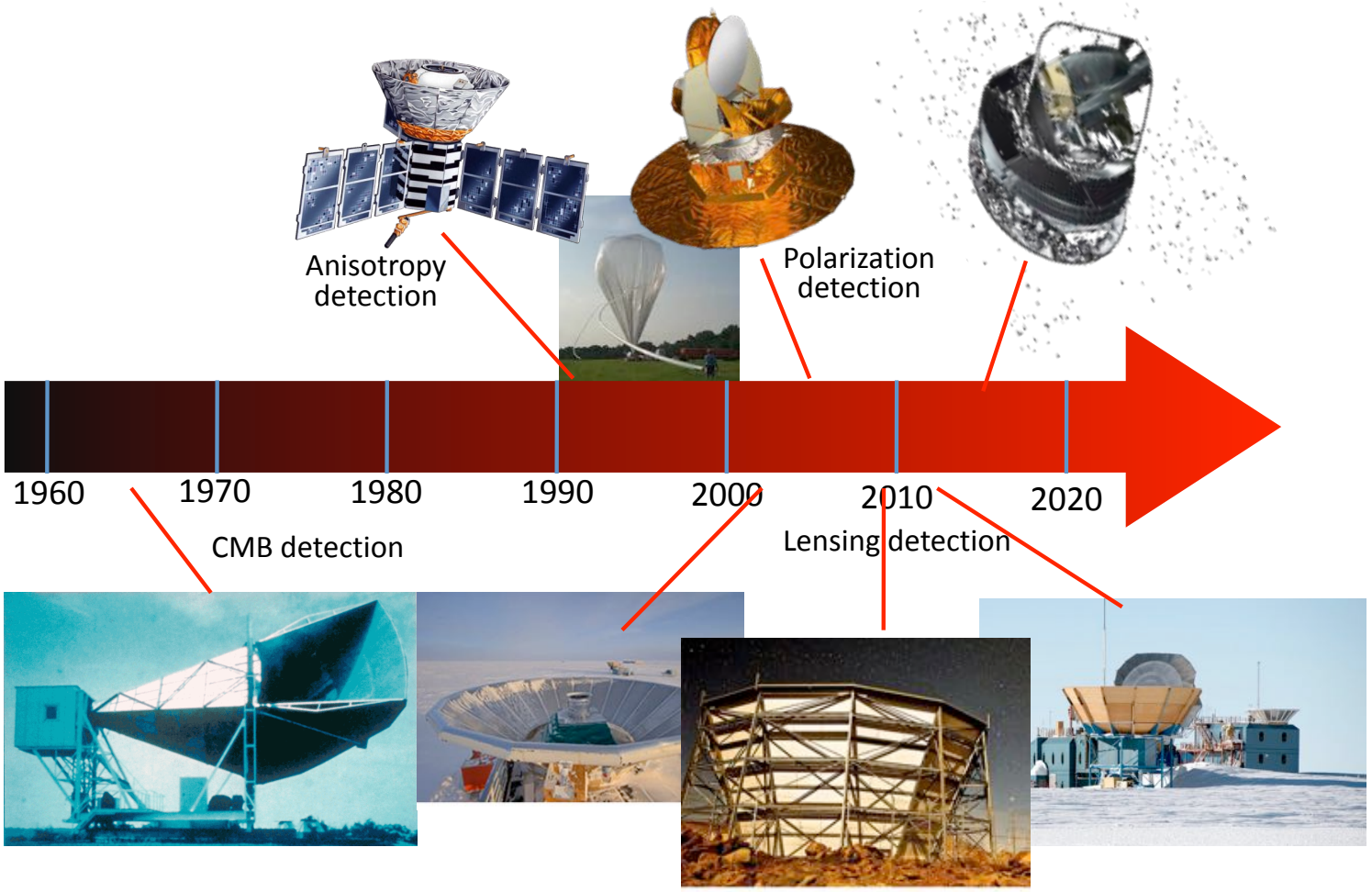


Goal	Requirement	Location
Detect reionization bump	Access large angular scales	Space
Detect recombination bump	0.5 to 1 deg resolution over ~20 deg patch	Space Ground
Remove lensing	Arcmin resolution over relevant patch of sky	Space Ground
Clean dust foreground	ν > 300 GHz	Space
Clean synchrotron foreground	ν < 30 GHz	Ground

The Past as Prologue

Long track record of space/ground complementarity

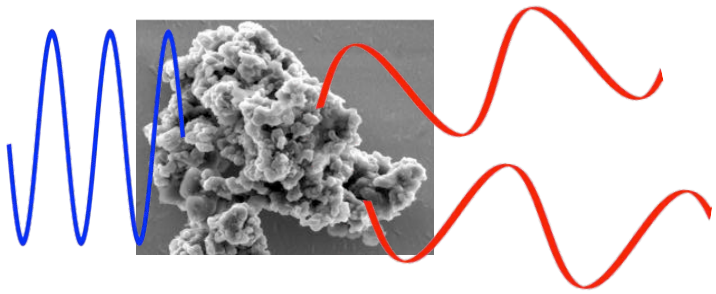
Space missions have been indispensable for precision cosmology



Ground-based measurements have been indispensable pathfinders

Do we need data above 300 GHz?

Simple models OK for now, but we want to do 50x better



Absorb UV photon

Emit FIR photons

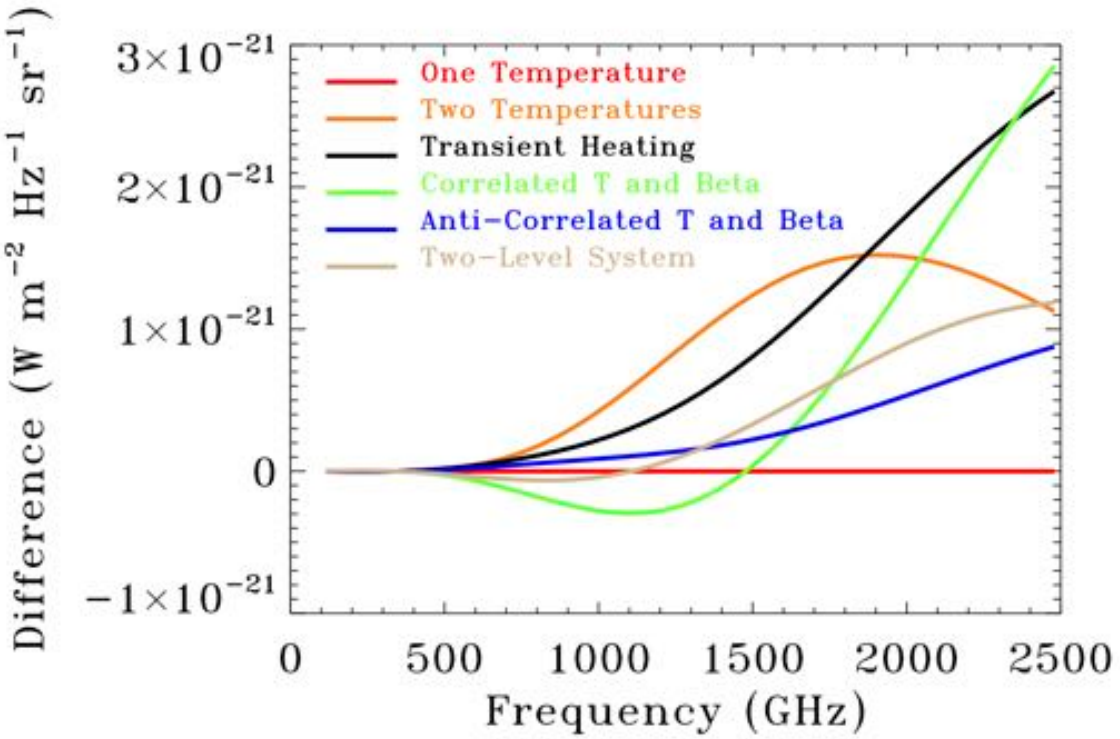
Dust far-IR emission depends on ...

- Local radiation field
- Dust chemical composition
- Dust physical composition
- Elapsed time since UV absorbtion

All of which vary everywhere!

There are a lot of possible models

Distinguish them at THz frequencies inaccessible to ground!



Reionization and Large Angular Scales

Neutrino mass: Last unknown parameter for Standard Model