CMB Stage 4 Update

John Carlstrom for
CMB-S4 collaboration
AAAC January 28, 2016

CMB-S4
Next Generation CMB Experiment

Stage IV CMB experiment: CMB-S4

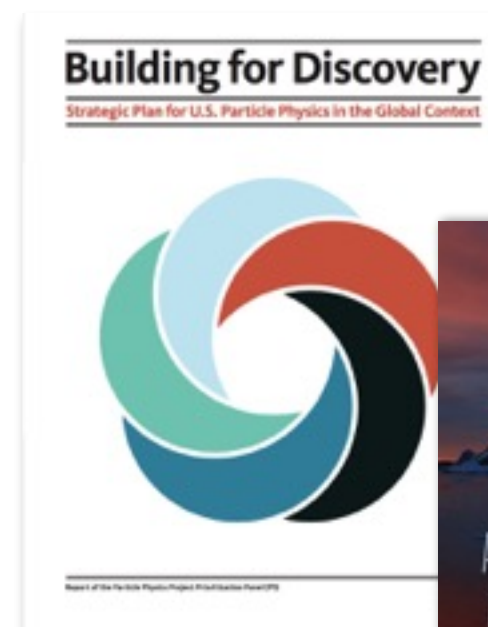
- CMB-S4: a next generation ground-based program building on CMB stage 2 & 3 projects to pursue inflation, neutrino properties, dark energy and new discoveries.

- **Targeting to deploy O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map most of the sky to provide sensitivity to cross critical science thresholds.**

- Multi-agency effort (DOE & NSF). Complementary with balloon and space-based instruments.

- Broad participation of the US CMB community, including the existing NSF CMB groups, DOE National Labs and the High Energy Physics community.

- U.S. led program; international partnerships expected.



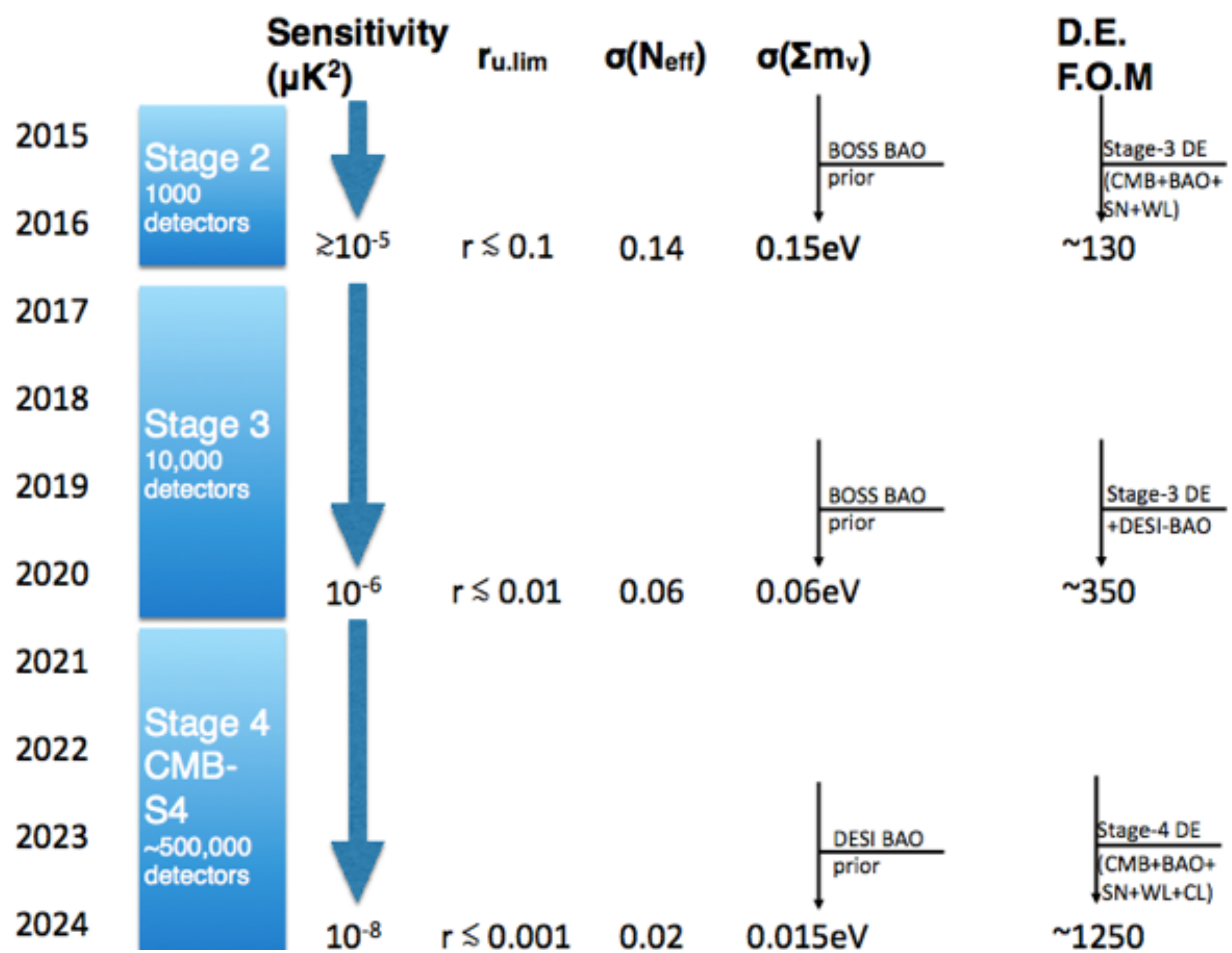
Recommended by P5 & NRC Antarctic reports

A science driven program combining the deep CMB experience of the university groups with the expertise and resources at the national labs.

Stage IV CMB experiment: CMB-S4

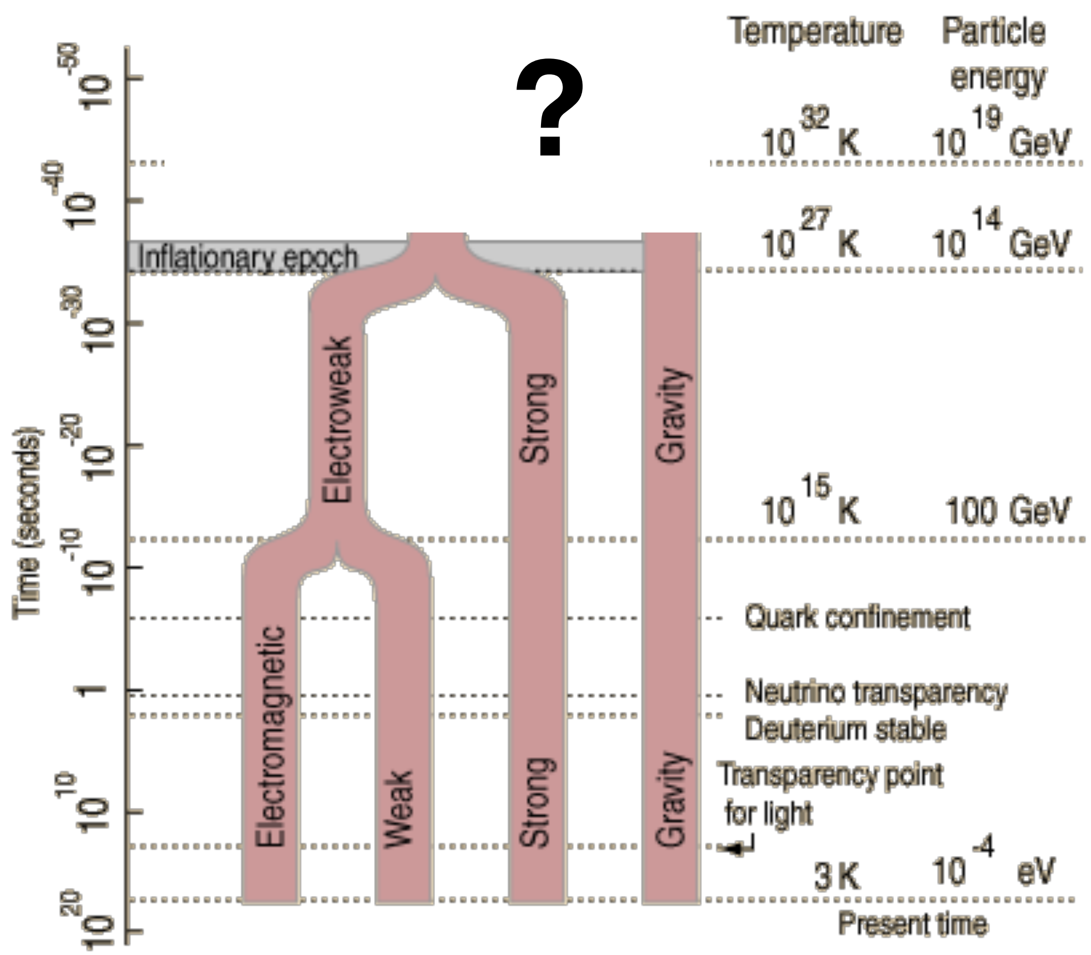
The future enabled by CMB-S4:

- Detect or rule out generic slow roll **inflation**, $E \sim 10^{16}$GeV
- Measure the sum of the neutrino masses
- Cosmological test of neutrino interactions and additional light species.
- Greatly improve **Dark Energy** constraints and test **General Relativity** on large scales.
- More fundamental discoveries?



Path Forward is clear. Required Technologies are in the pipeline.
Next Steps: Scaling to O(500,000) detectors.

The Universe as a Physics Laboratory



HyperPhysics (©C.R. Nave, 2010)

Inflation?
period of accelerated expansion at ~10^{-35} seconds generates gravitational wave background

Cosmic neutrino background at 1 second

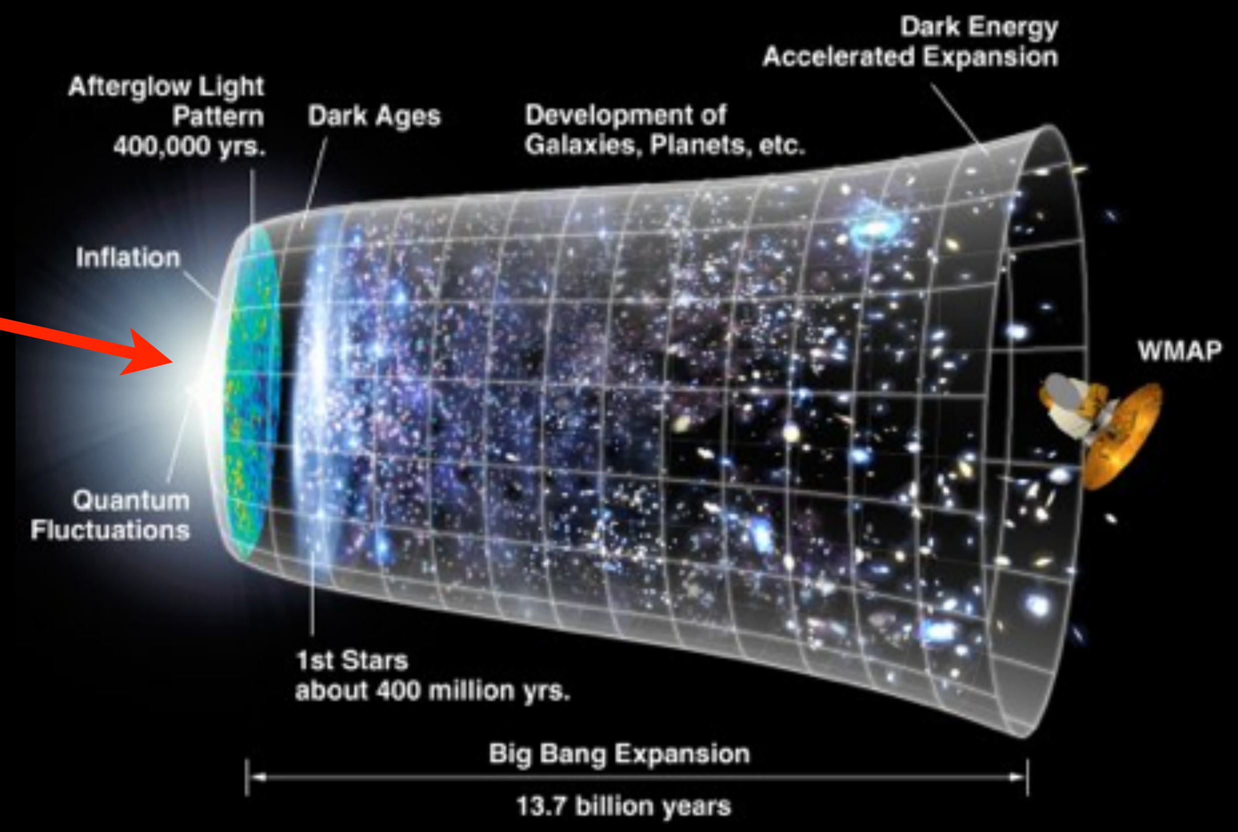
Cosmic microwave background

The CMB gains us access to energy scales of order 10^{16} GeV

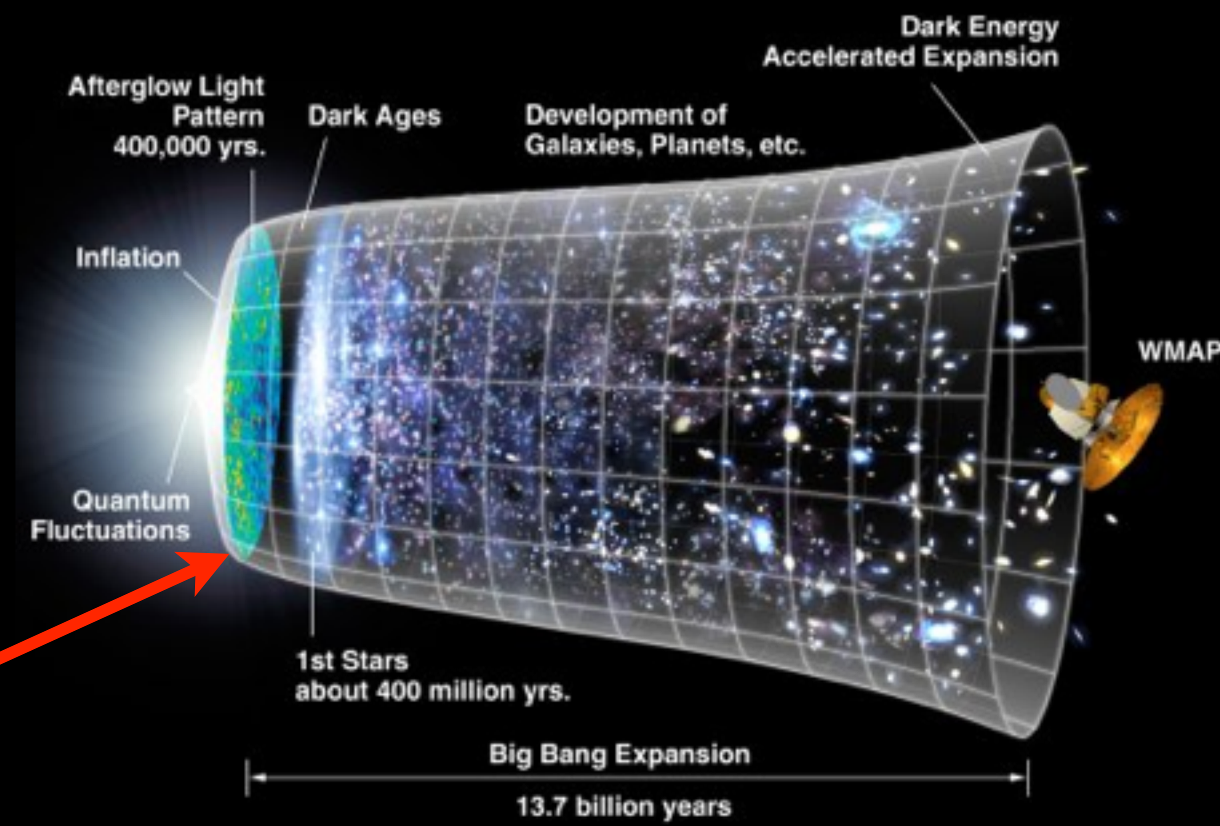
Inflation? accelerated expansion

Universe expands by $>e^{60}$

- Measure primordial fluctuations
- non-Gaussianity?
- constrain tensor to scalar fluctuations, inflationary gravitational waves?



➡ *through precision temperature and ultra-sensitive polarization measurements of the primary CMB anisotropy*



Physics at recombination

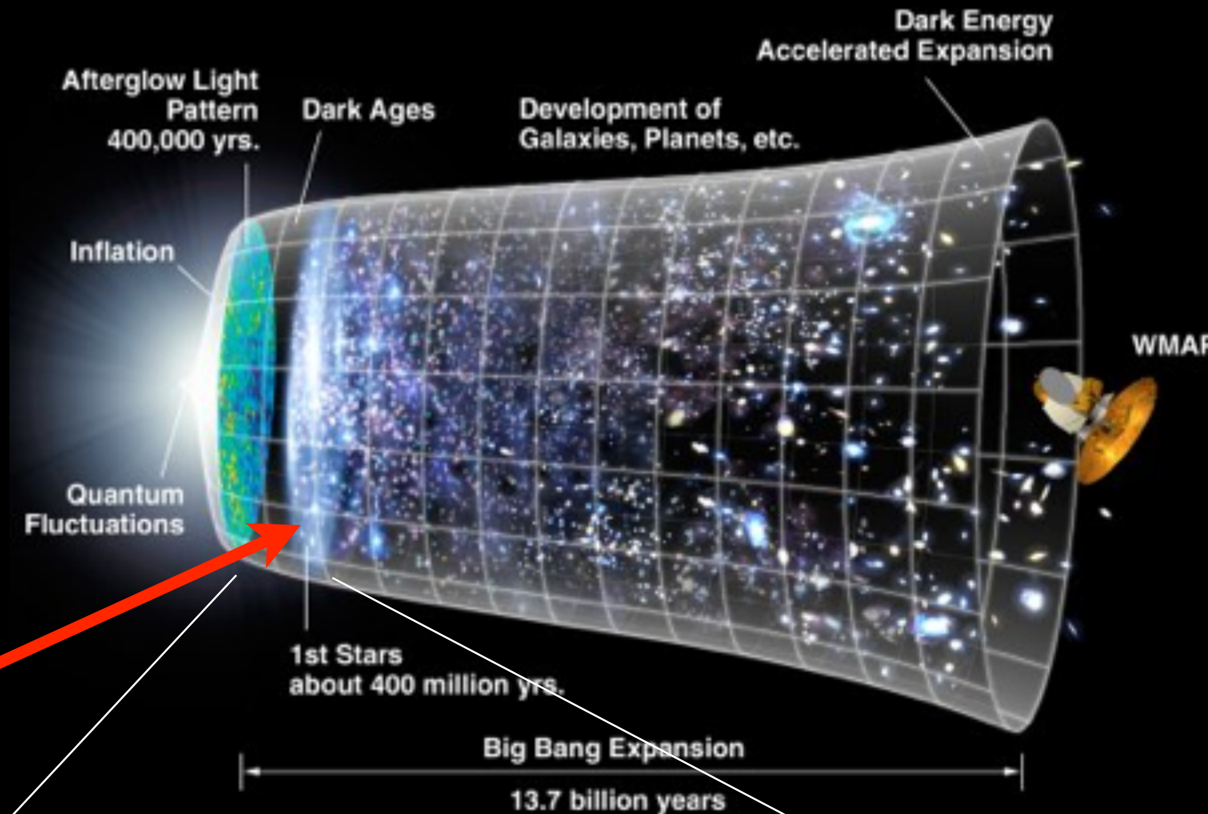
Universe cools enough to form neutral H.
Photons start free-streaming

- Measure dynamics; inventory stuff in the universe
- Number of relativistic species, helium abundance
- Recombination history; energy injection

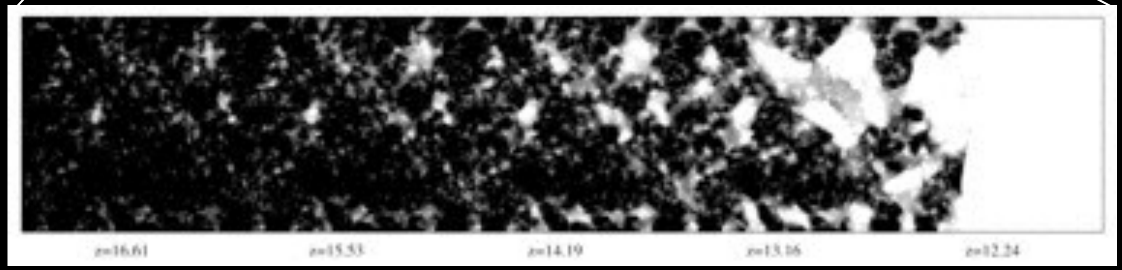
➡ *through precision measurement of CMB power spectrum to fine angular scales, i.e., covering the "damping" tail*

➡ *eventually through spectral distortions and recombination lines*

Reionization “Cosmic Dawn”

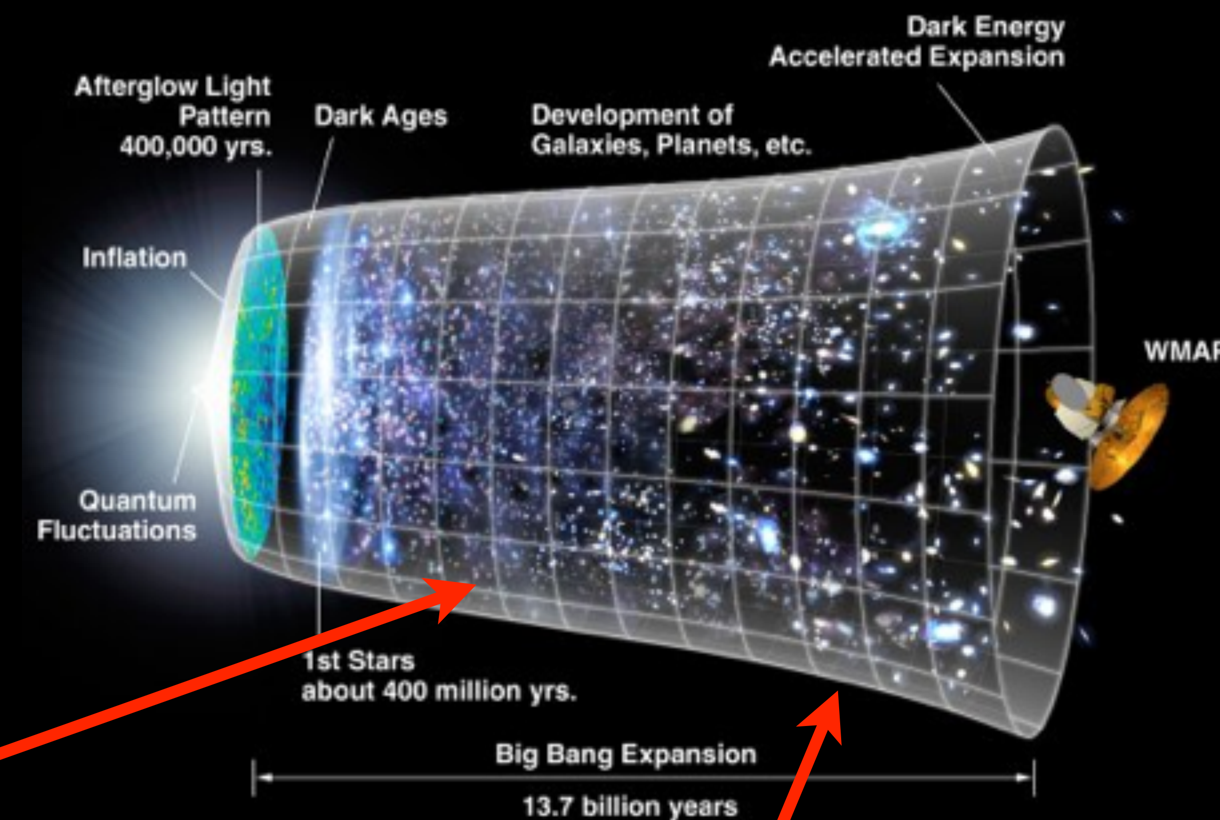


When and how did it proceed?



Patchy reionization, Zahn et al, 2005

- ➡ *through measurement of polarization on large angular scales*
- ➡ *through measurements of the diffuse kinematic SZ effect on small angular scales*



Structure Formation

Gravitational collapse creates increasingly large structures

- Properties of dark matter
- Masses of the neutrinos

Cosmic Acceleration

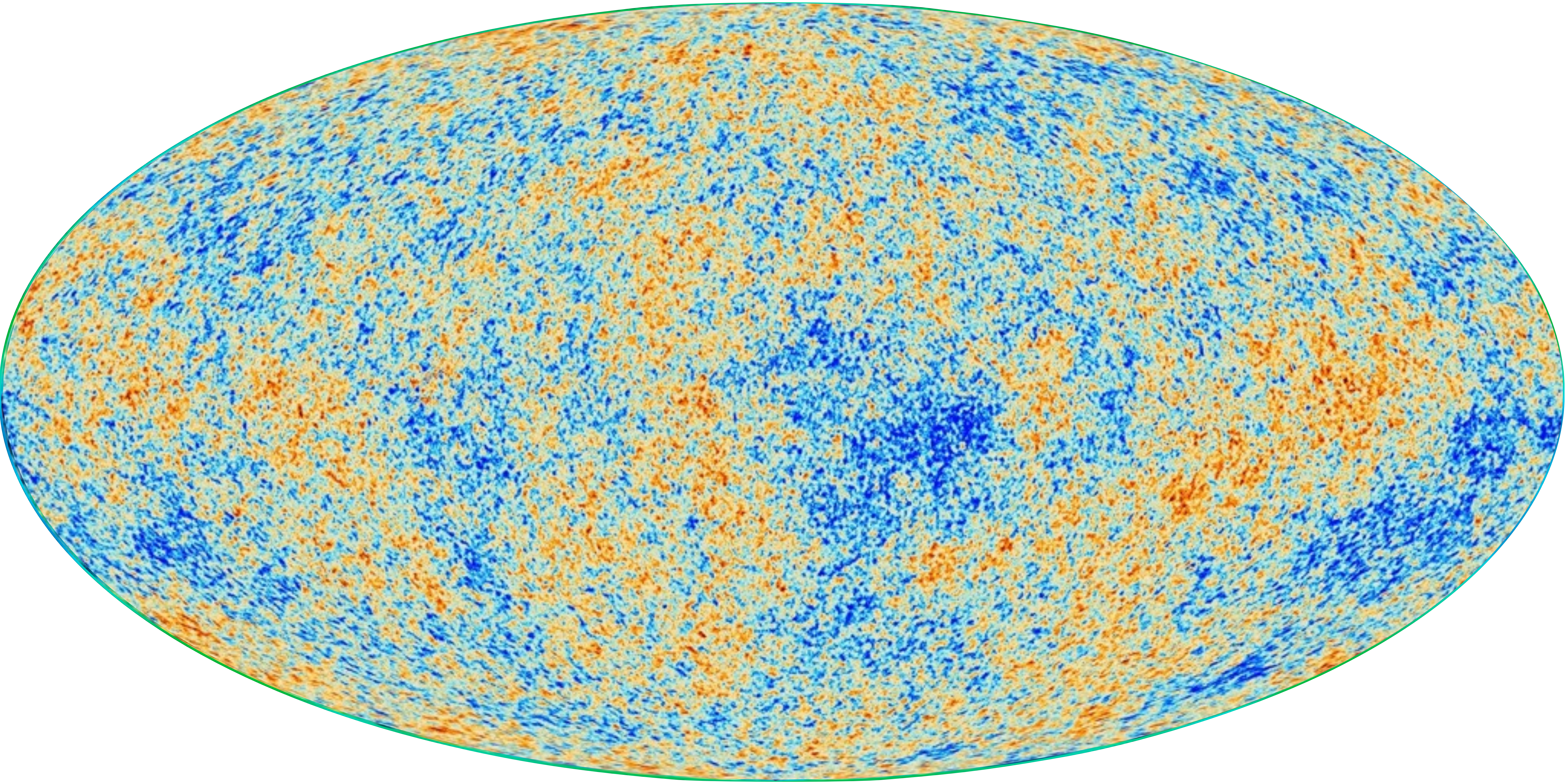
Dark energy begins accelerating the expansion of the Universe.

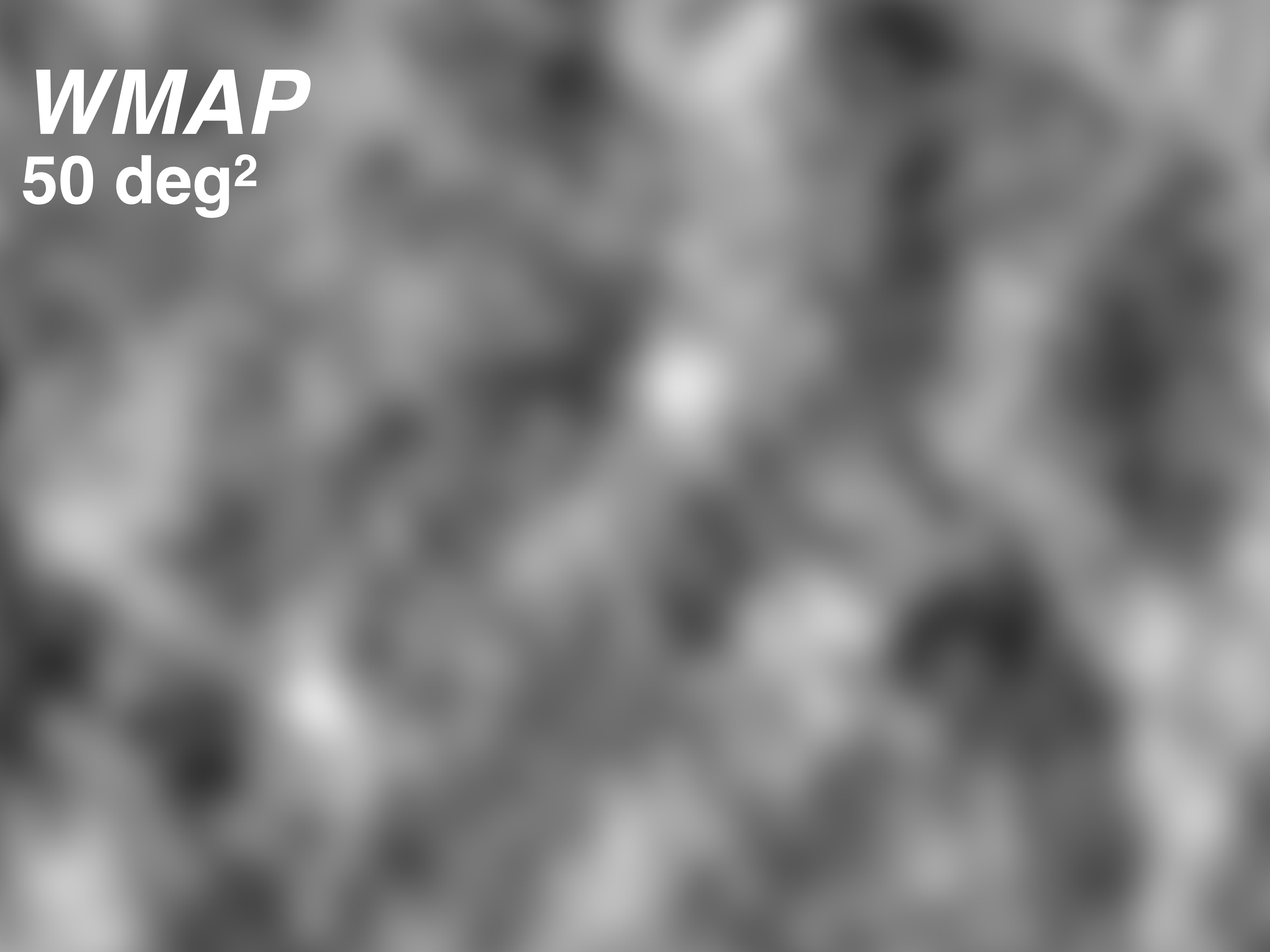
- Is dark energy dynamic or a cosmological constant?
- Is GR correct on large scales?

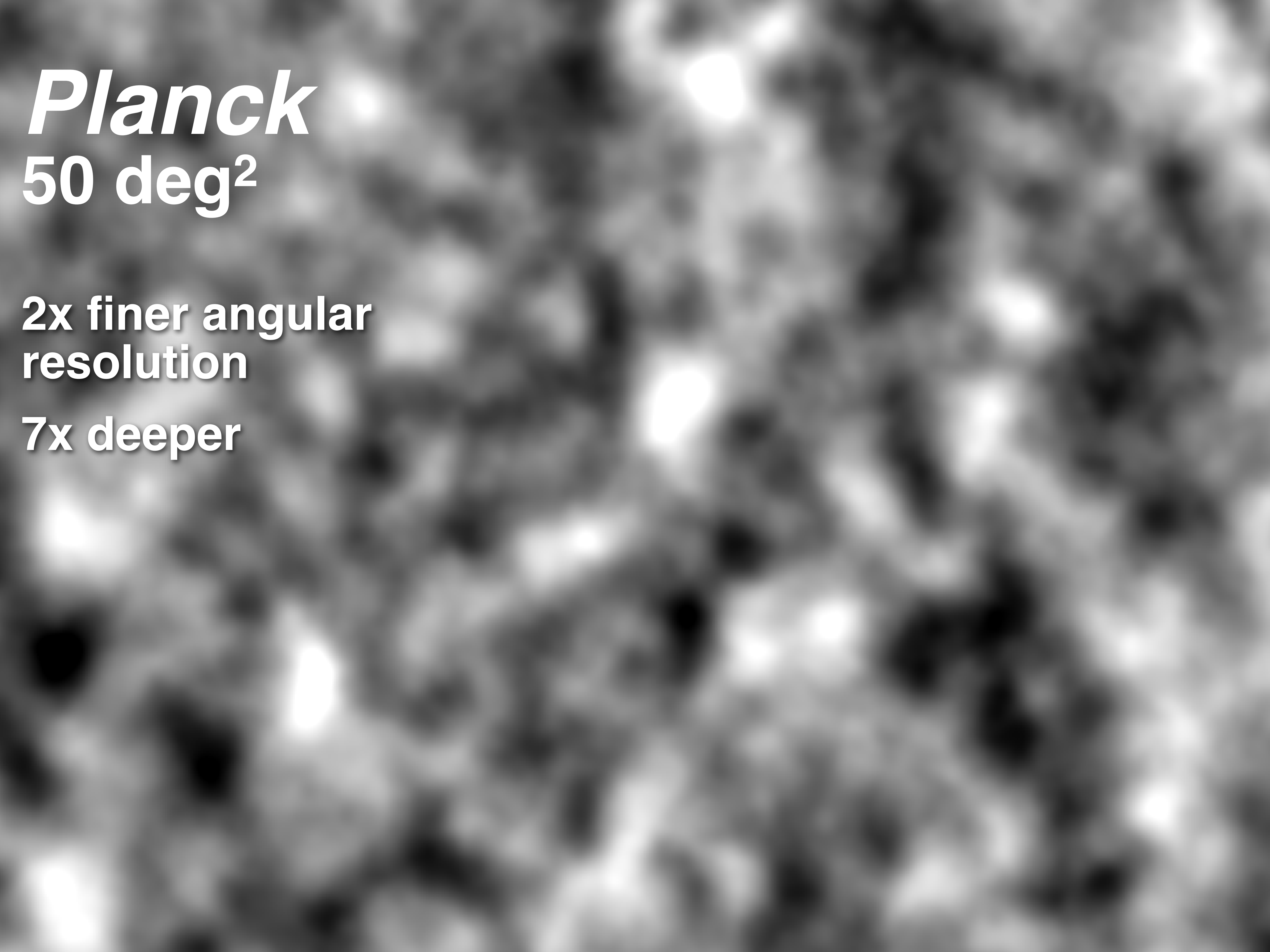
➡ *structure formation through lensing of the CMB and kinematic SZ effect*

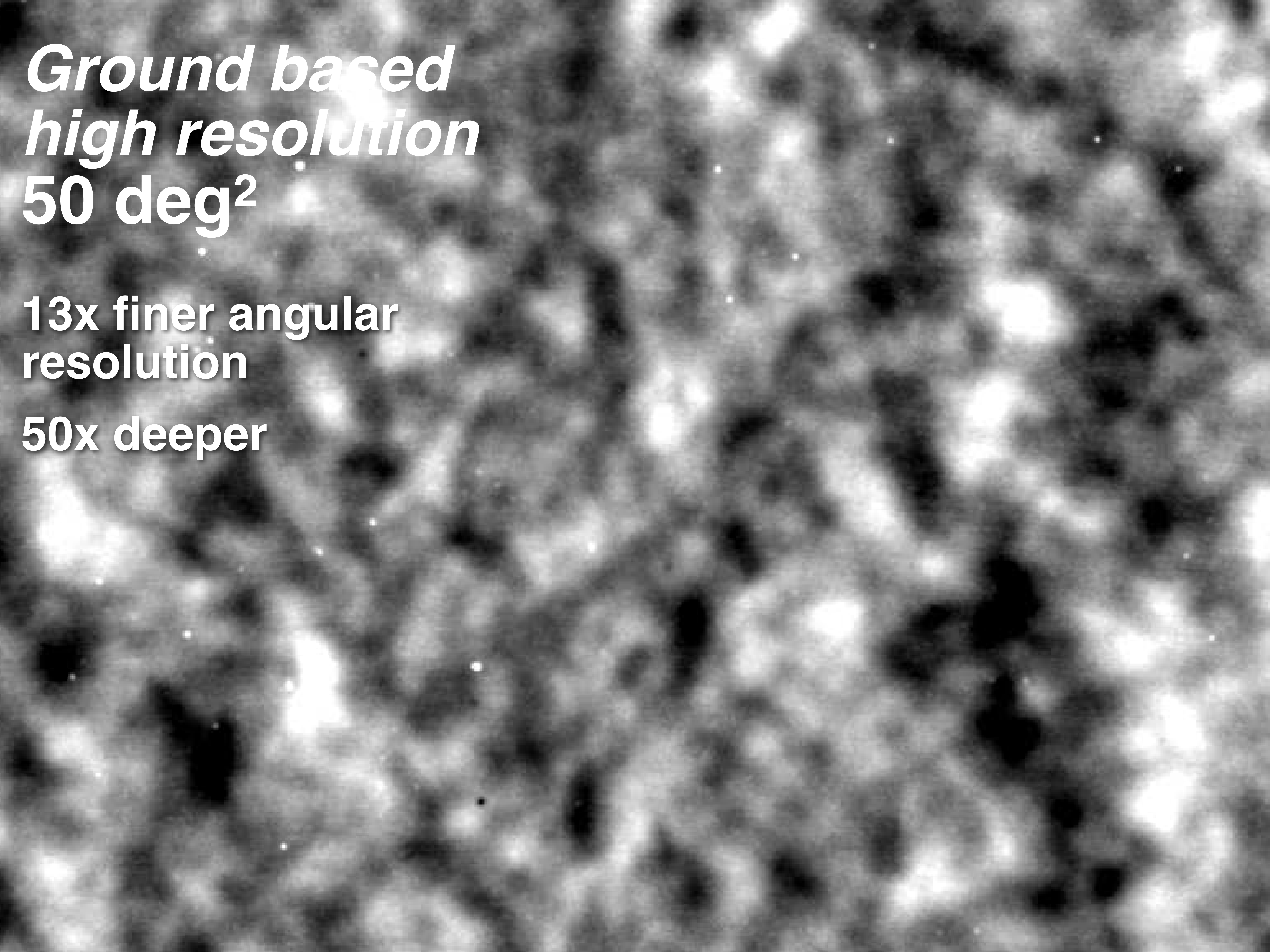
➡ *measure evolution of Galaxy Clusters through thermal SZ effect*

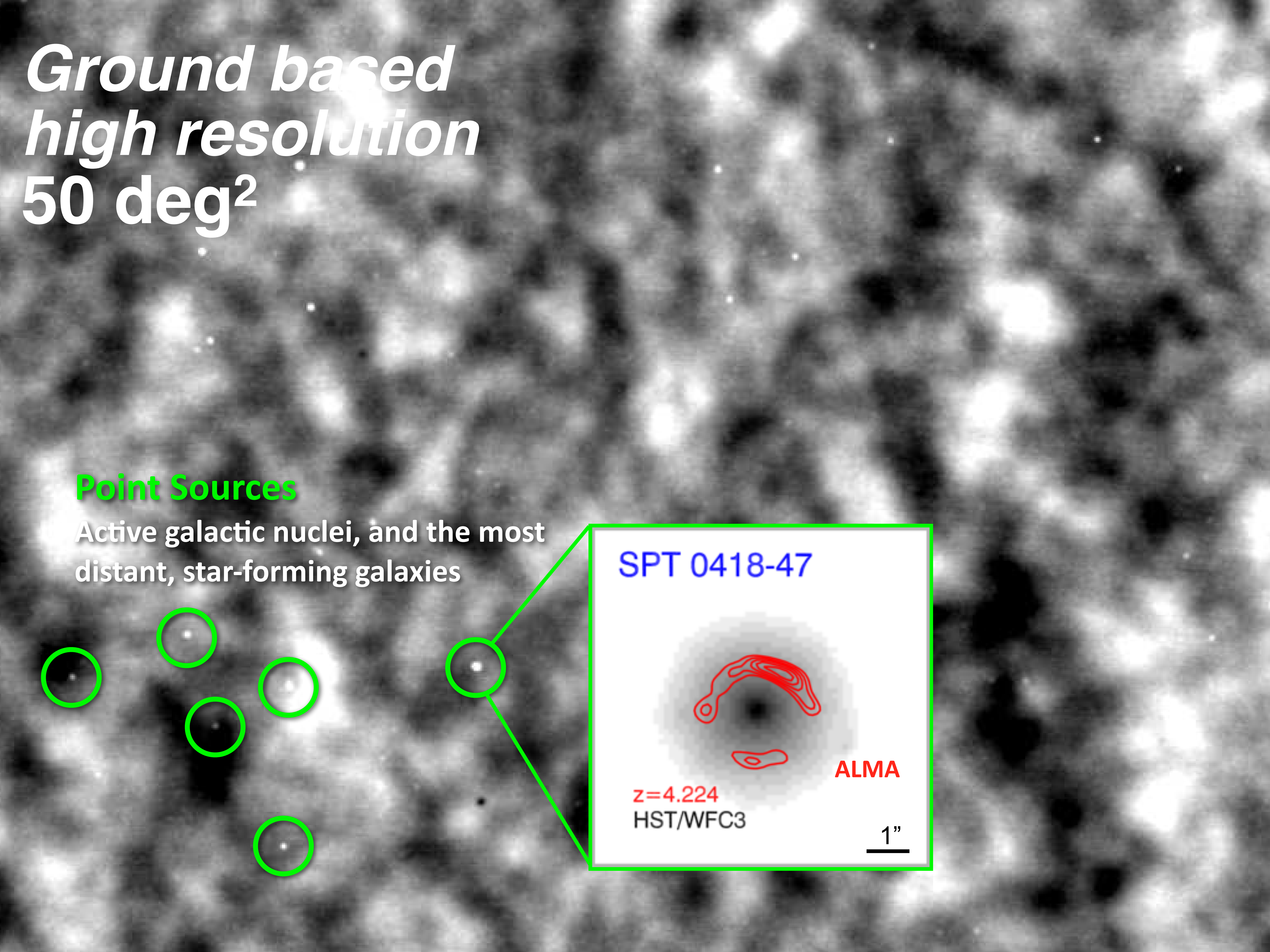
COBE → WMAP → Planck

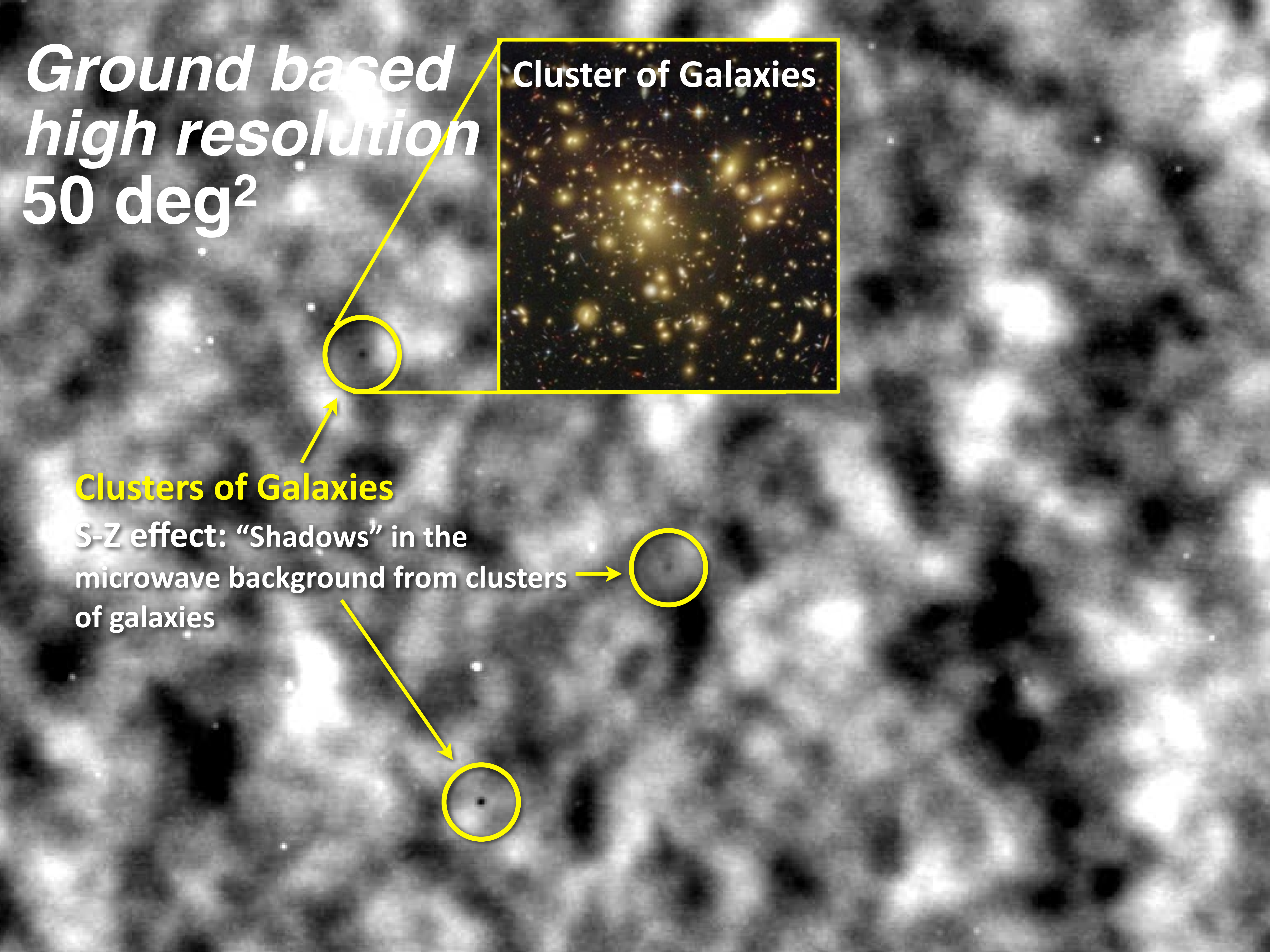


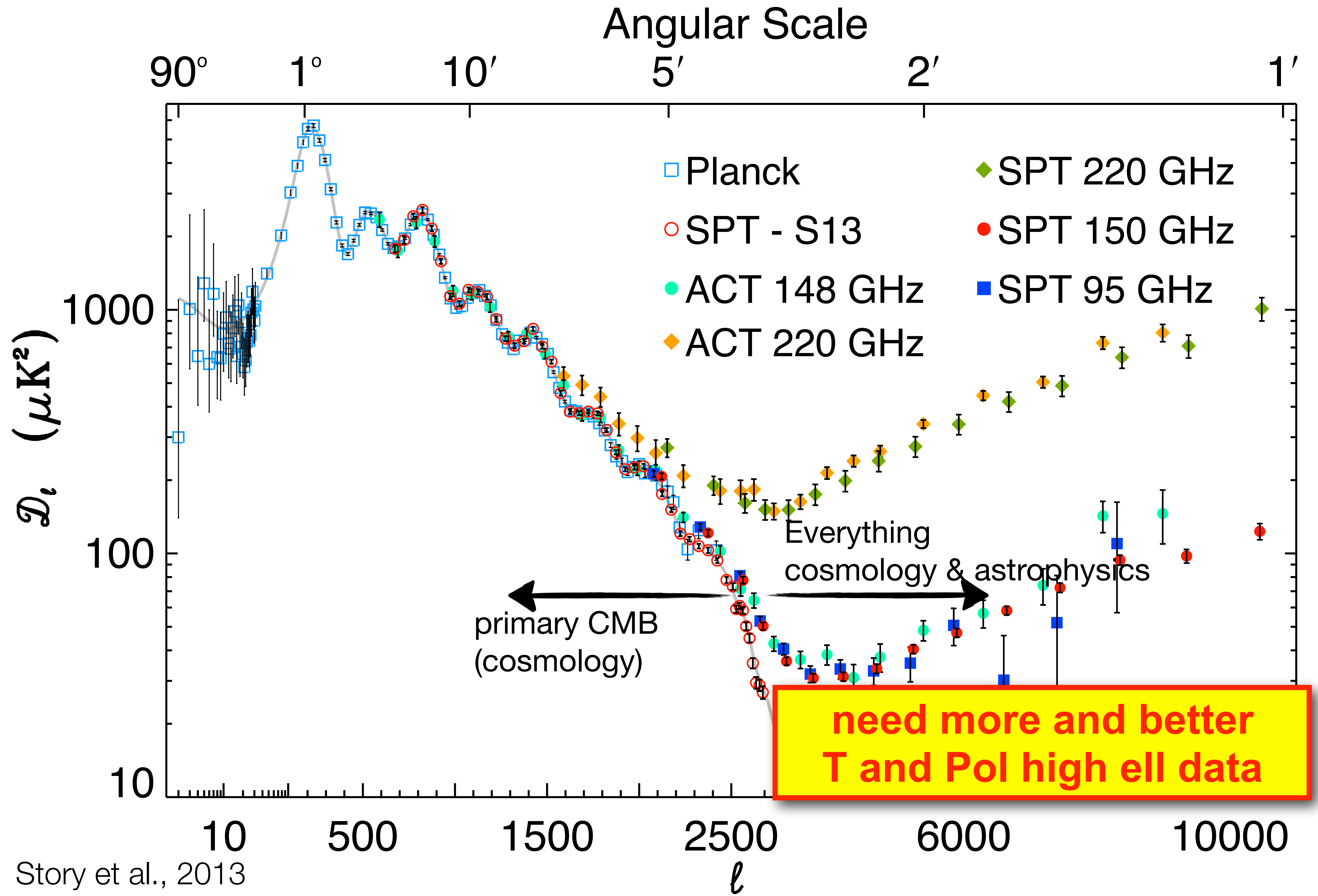

WMAP
50 deg^2


Planck
50 deg^2
2x finer angular resolution
7x deeper


Ground based
high resolution
50 deg^2
13x finer angular
resolution
50x deeper

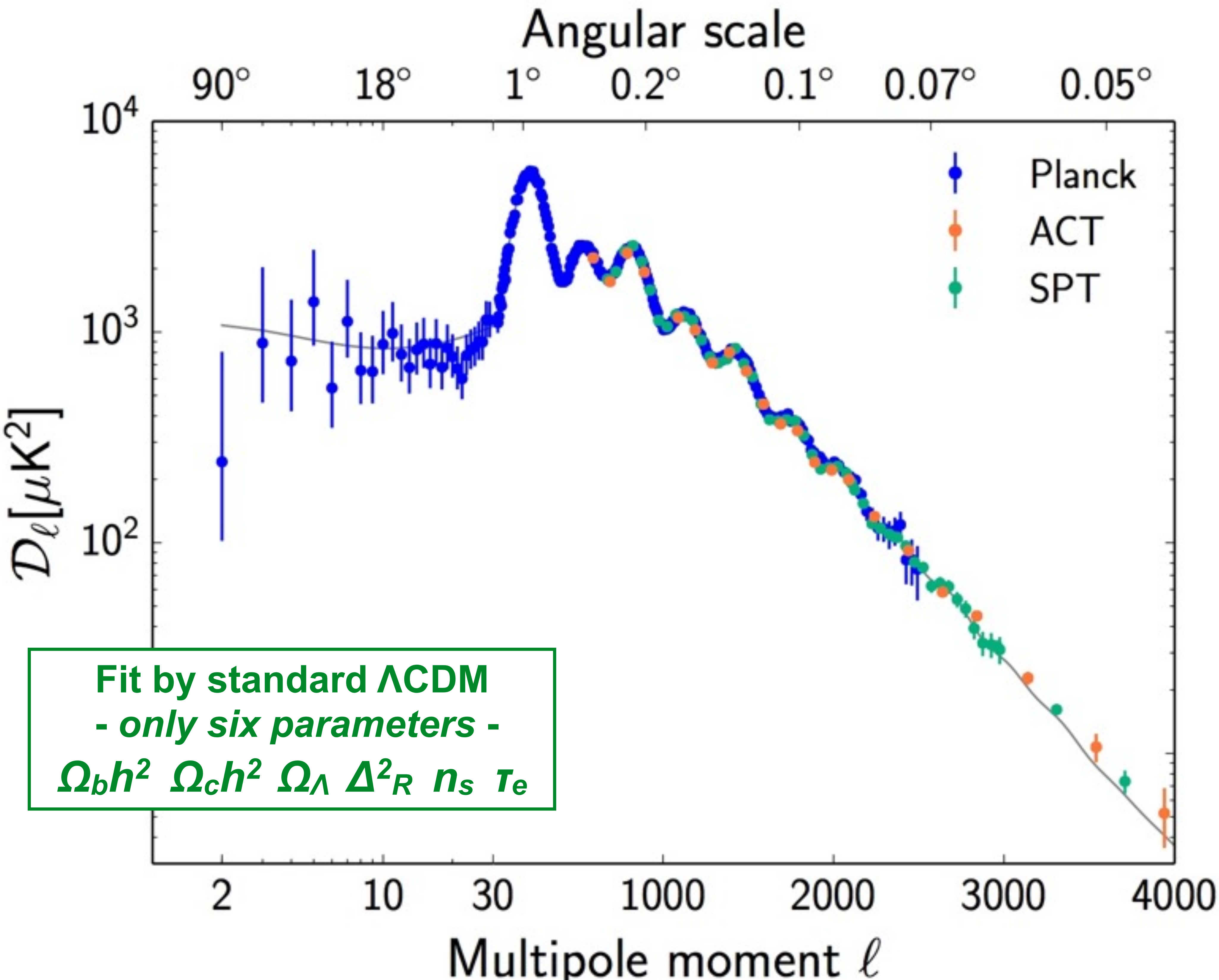

Ground based
high resolution
50 deg2
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
SPT 0418-47
ALMA
z=4.224
HST/WFC3
1”


Ground based
high resolution
50 deg2
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the
microwave background from clusters
of galaxies



Story et al., 2013
George et al., 2014
Das et al., 2014

Angular Power Spectrum



Fit by standard ΛCDM
- only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ Δ^2_R n_s τ_e

Figure from Planck 2015 Results XI

Are we finished with primary CMB Temperature anisotropy measurements?

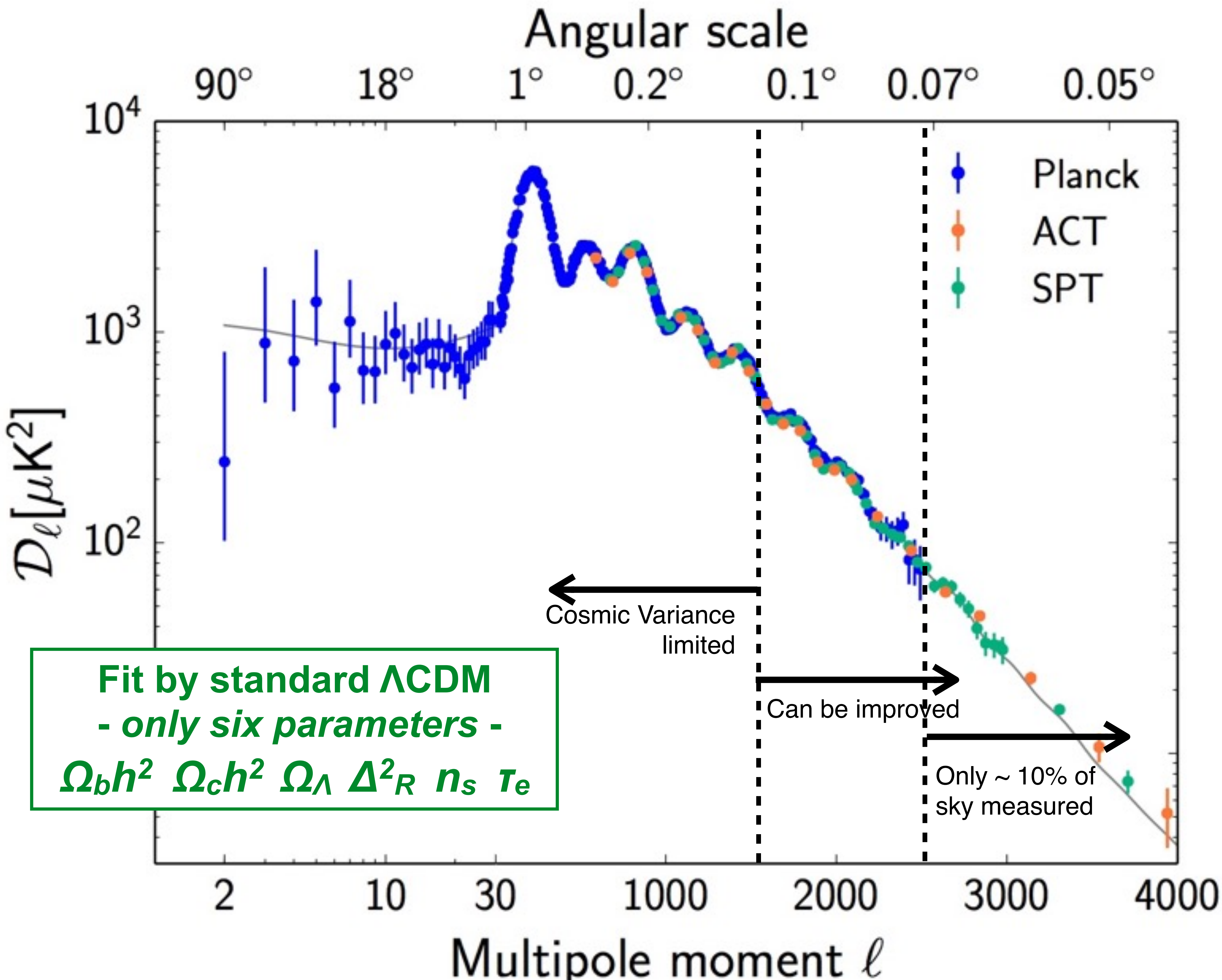
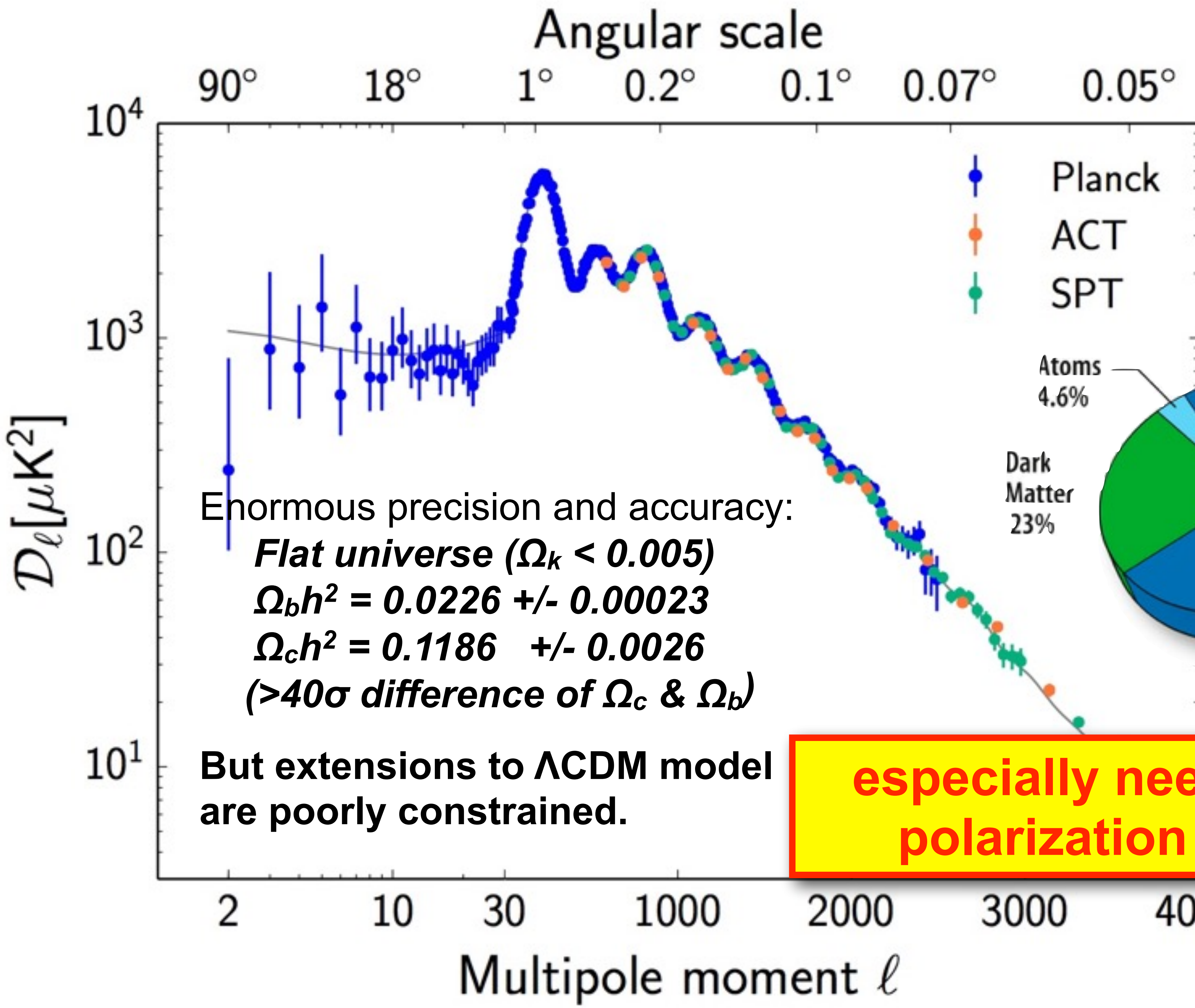
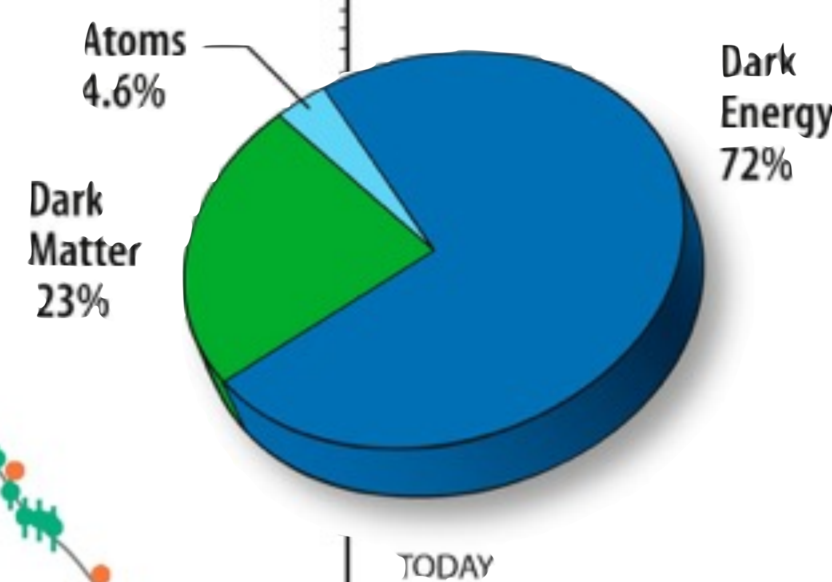


Figure from Planck 2015 Results XI

What about physics constraints? Can they be improved?





Enormous precision and accuracy:

Flat universe ($\Omega_k < 0.005$)

$\Omega_b h^2 = 0.0226$ +/- 0.00023

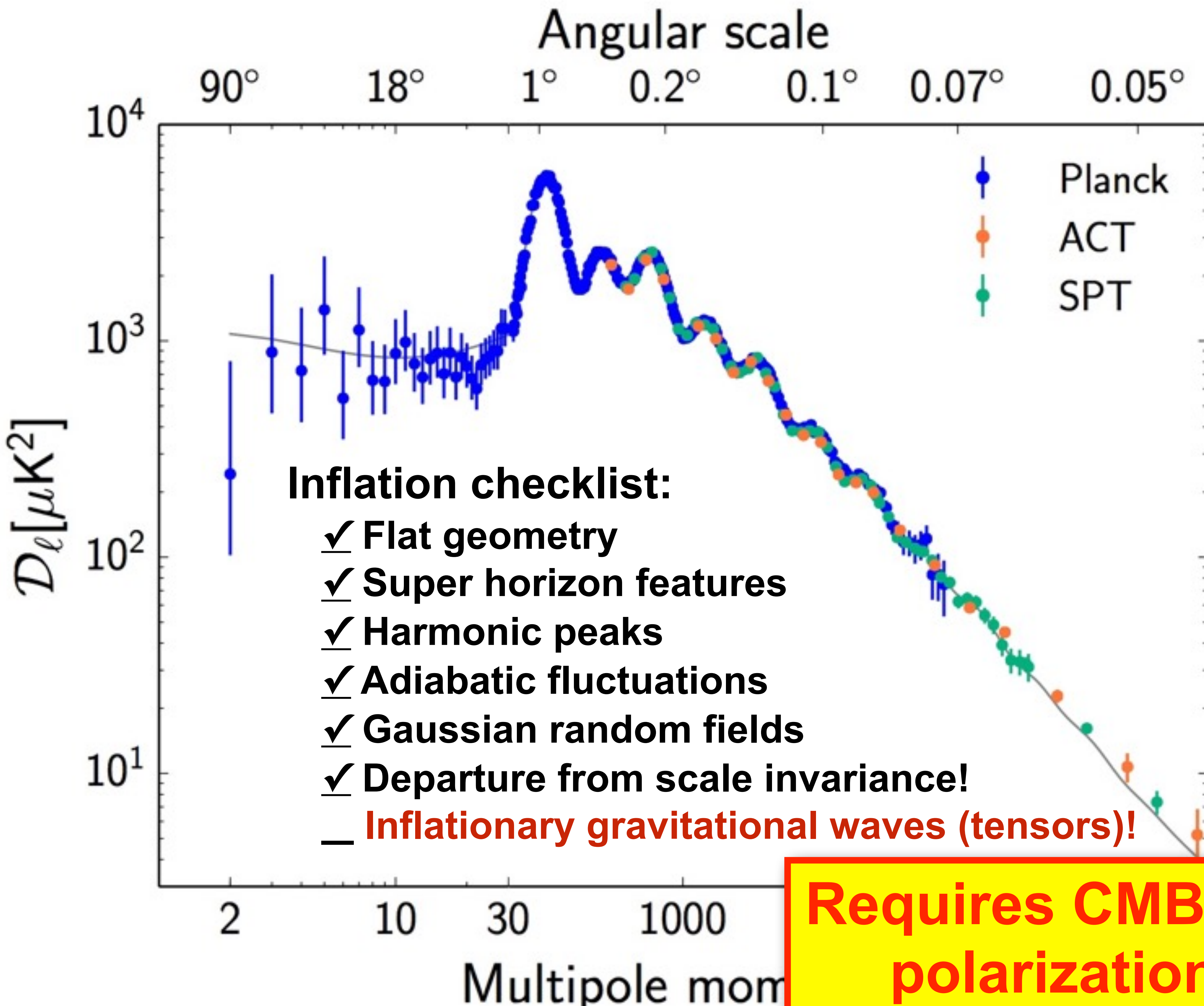
$\Omega_c h^2 = 0.1186$ +/- 0.0026

(>40σ difference of Ω_c & Ω_b)

But extensions to ΛCDM model are poorly constrained.

especially need polarization

What about physics constraints? Inflation?

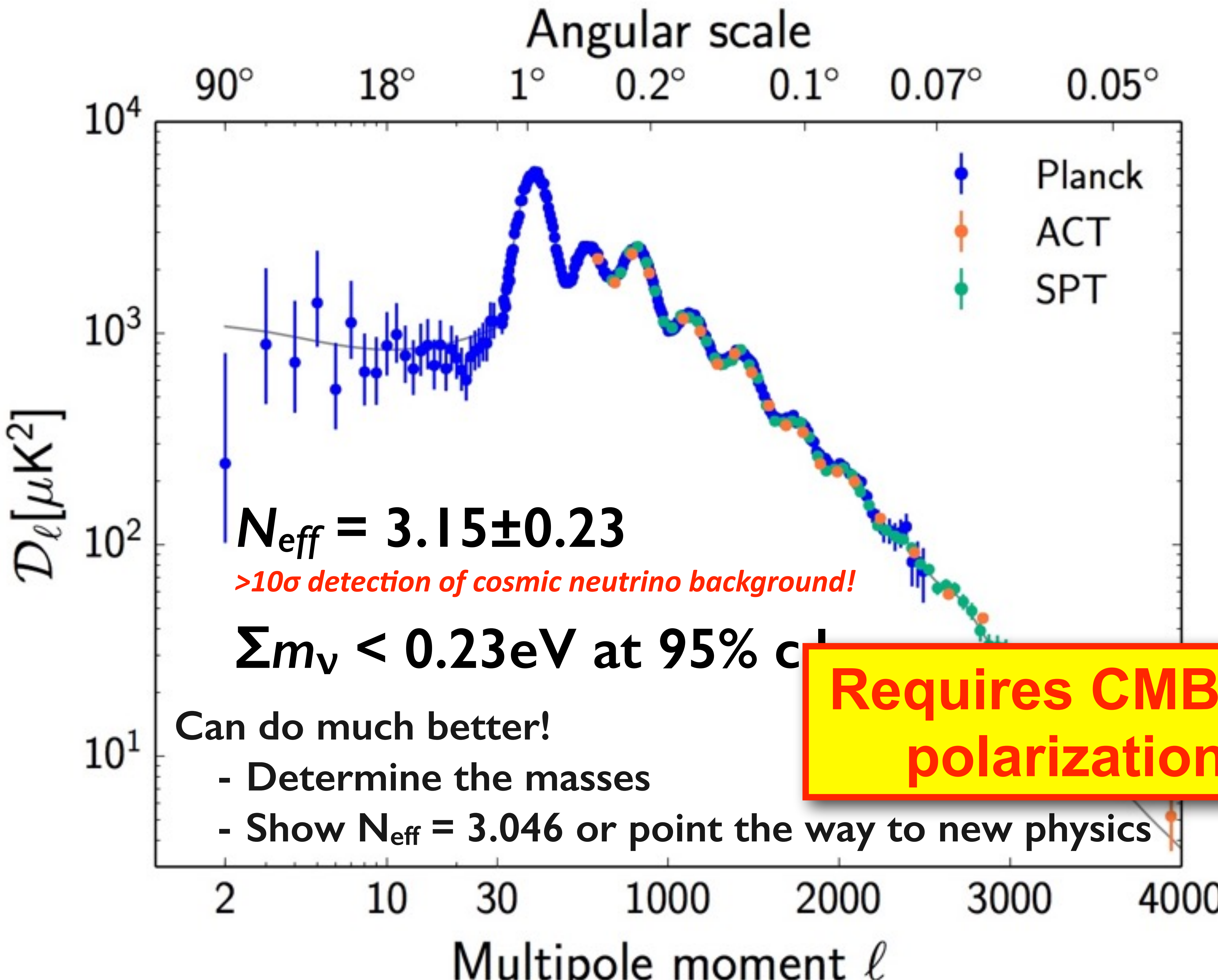


Inflation checklist:

- ✓ **Flat geometry**
- ✓ **Super horizon features**
- ✓ **Harmonic peaks**
- ✓ **Adiabatic fluctuations**
- ✓ **Gaussian random fields**
- ✓ **Departure from scale invariance!**
- __ **Inflationary gravitational waves (tensors)!**

Requires CMB B-mode polarization data

What about physics constraints? Neutrinos?



N_{eff} = 3.15±0.23

>10σ detection of cosmic neutrino background!

Σm_ν < 0.23eV at 95% c.l.

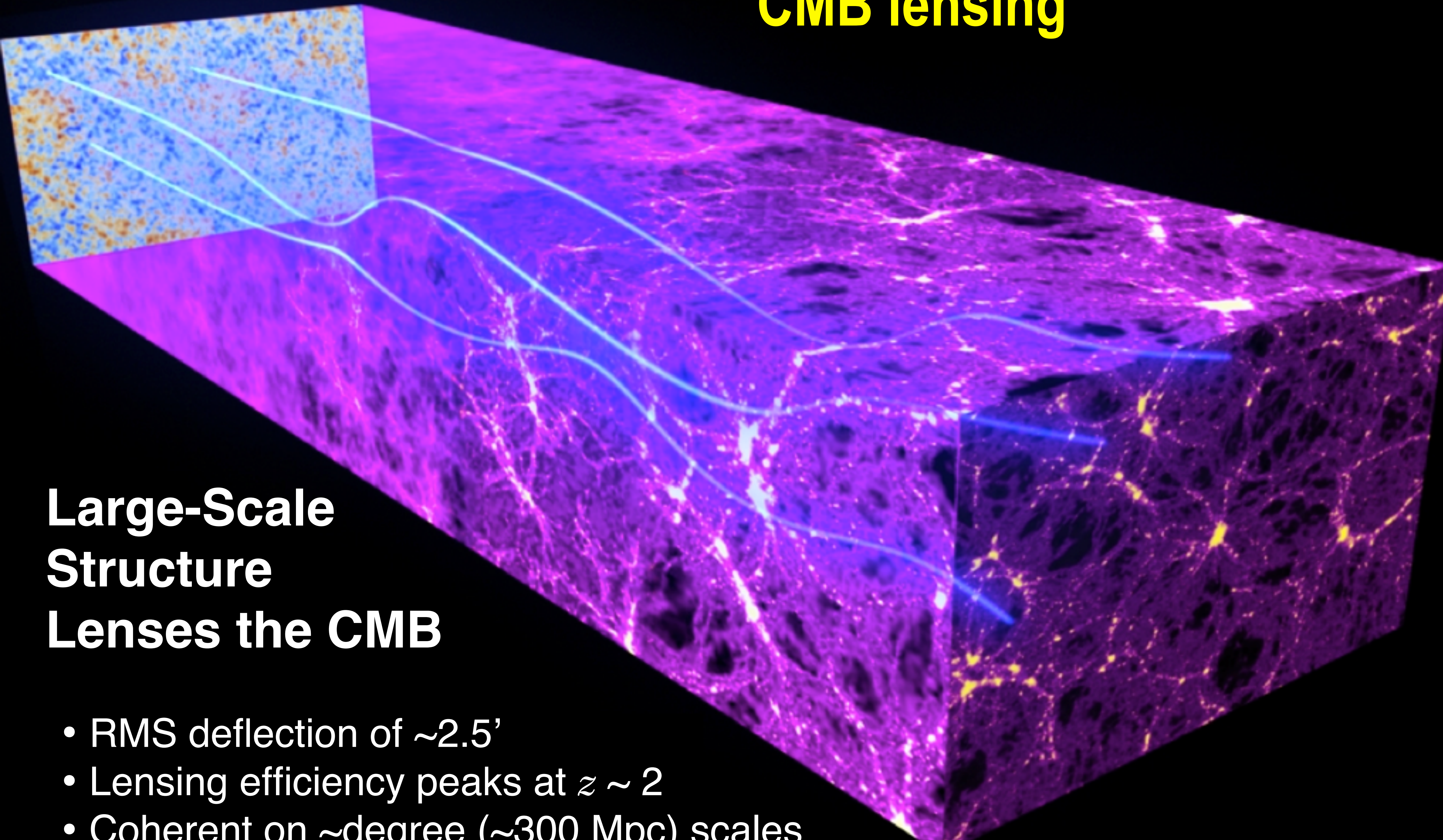
Can do much better!

- **Determine the masses**
- **Show N_{eff} = 3.046 or point the way to new physics**

Requires CMB lensing polarization data

N_{eff} is the effective number of light relativistic species, for std model N_{eff} = 3.046

CMB lensing



Large-Scale Structure Lenses the CMB

- RMS deflection of ~2.5’
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree (~300 Mpc) scales
- Introduces correlations in CMB multipoles

graphic from ESA Website

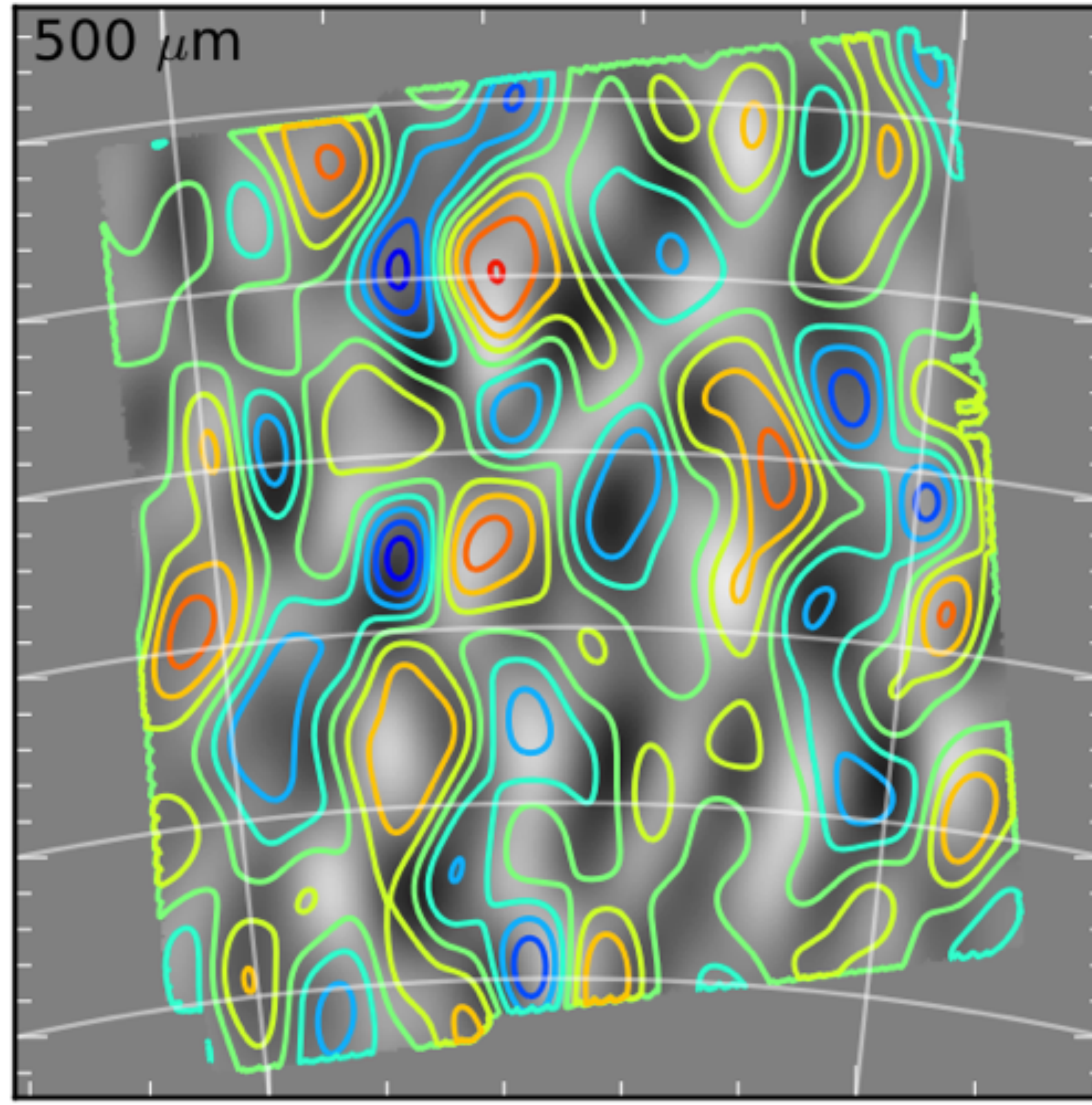
CMB lensing and optical surveys

CMB lensing reconstruction of mass maps sensitive to growth of structure, probe neutrino mass

CMB lensing will complement large optical surveys such as DES, eBOSS, LSST, DESI, Euclid, WFIRST, etc.

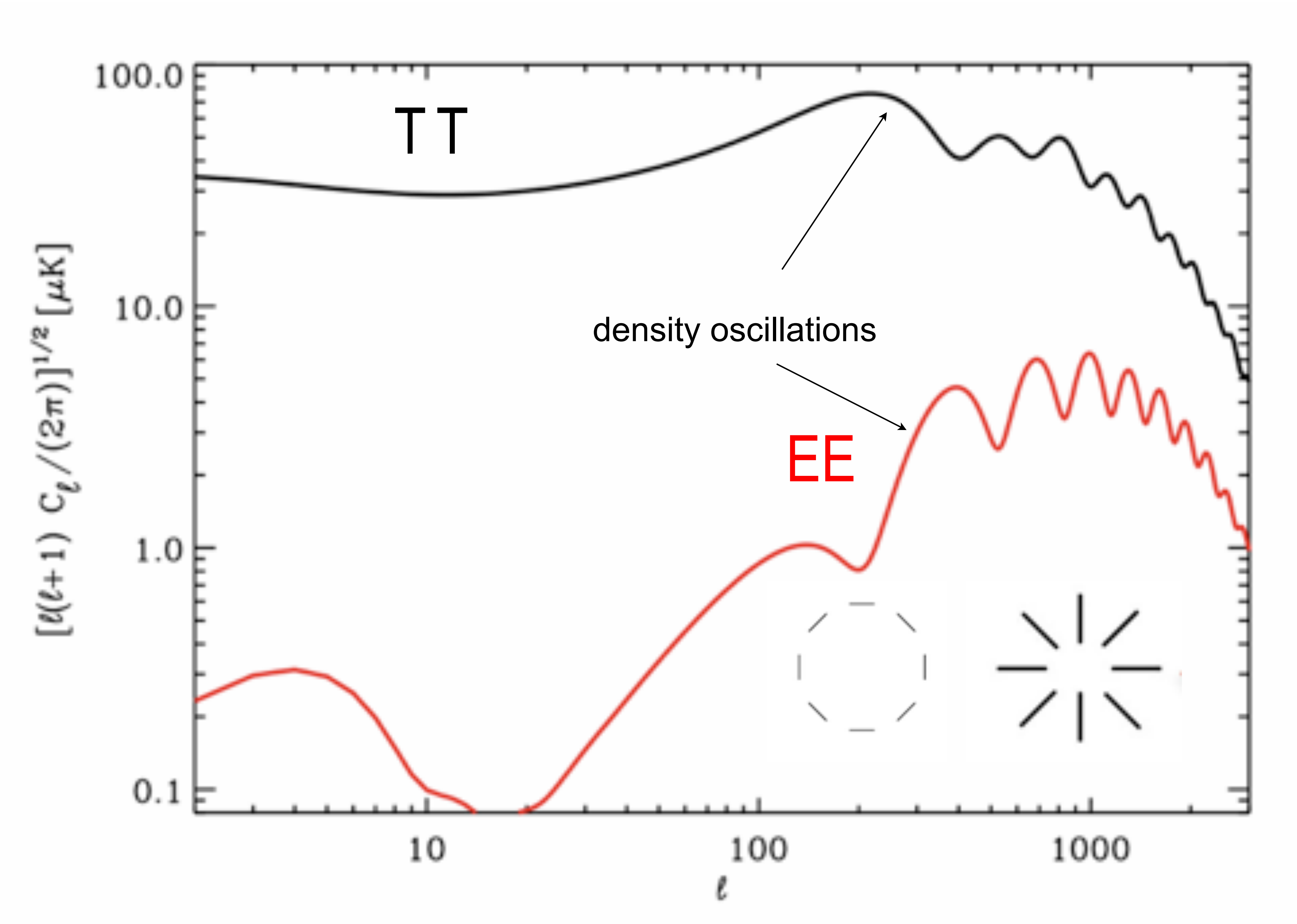
The combination leads to better shear-bias calibration and more robust constraints on Dark Energy and the properties of neutrinos. (e.g., Das, Errard, and Spergel, 2013)

Holder et al. arXiv:1303.5048

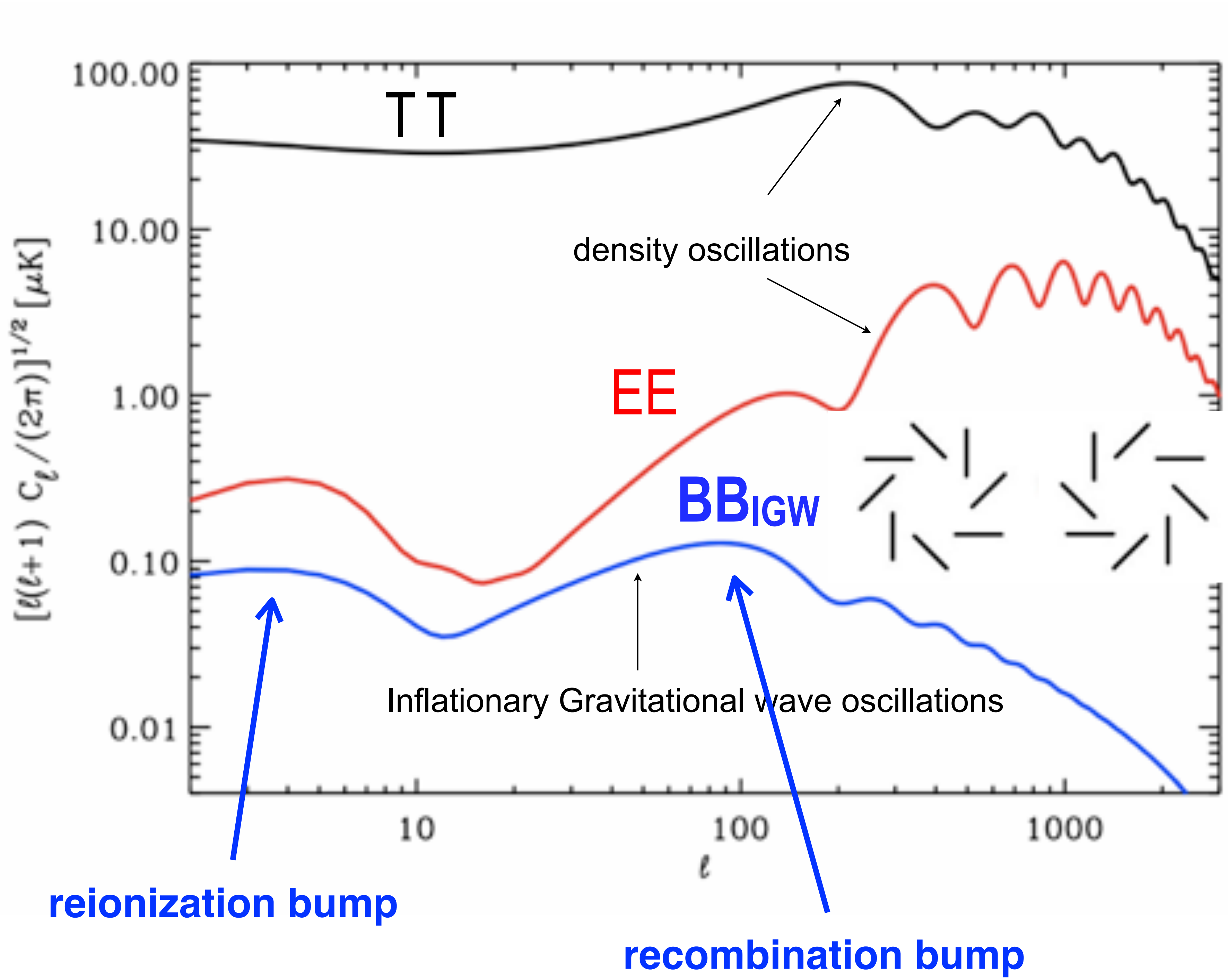


Correlation of matter traced by CMB lensing (contours) and distribution of high z galaxies (grayscale; Herschel 500 um)

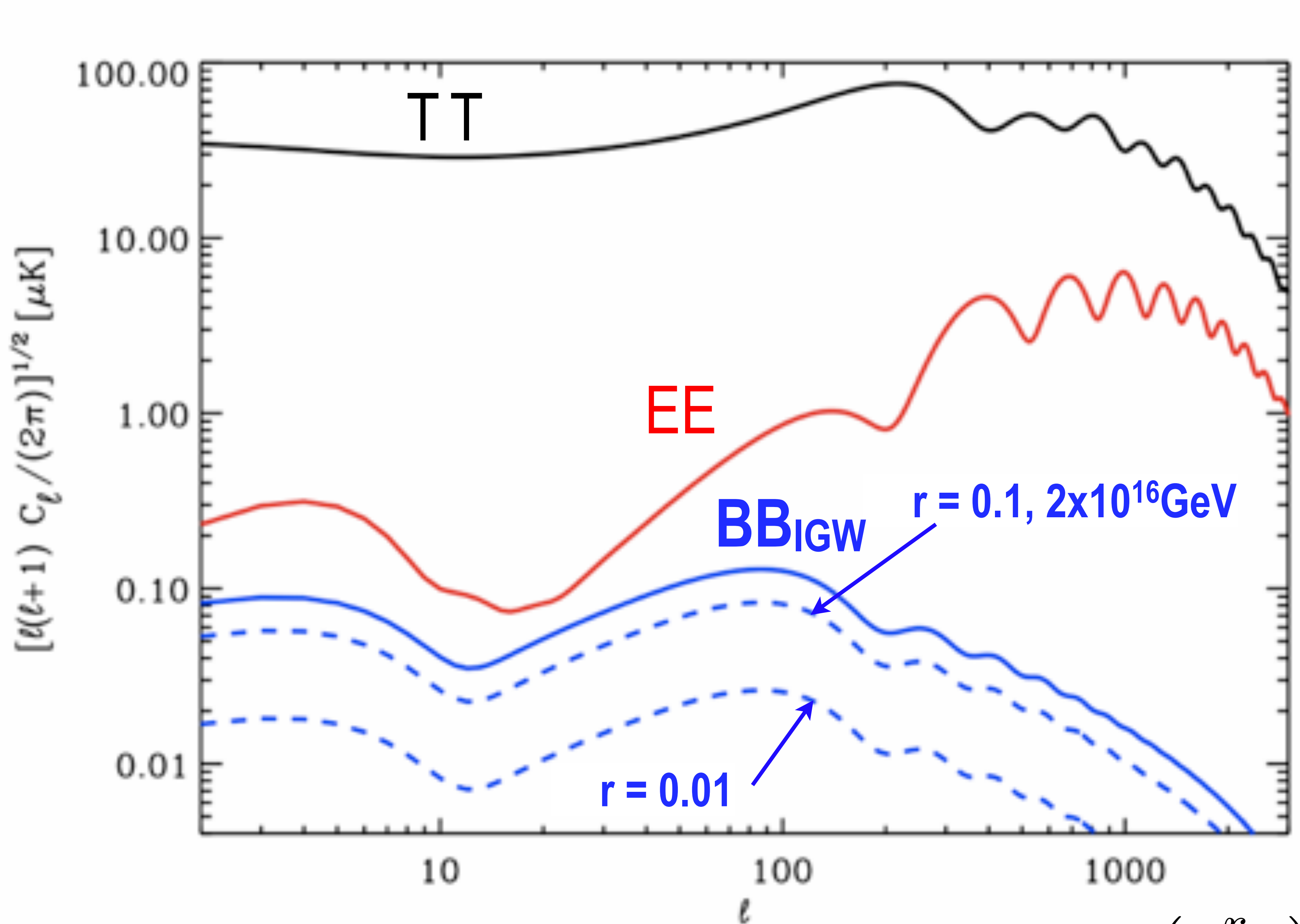
Polarization of the CMB



Polarization of the CMB



Polarization of the CMB

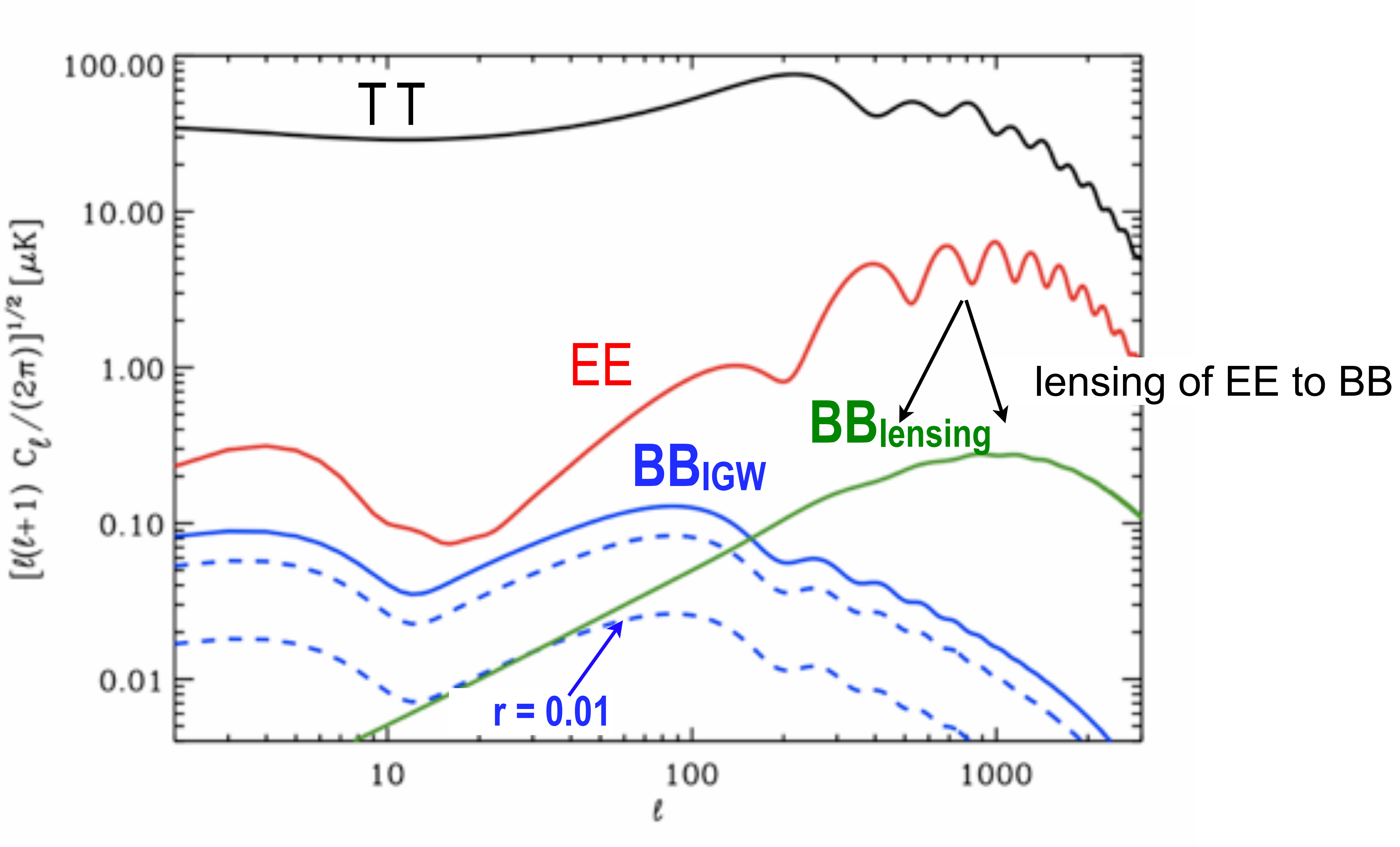


$$r \equiv \frac{\text{Tensor (gravitational) perturbation amplitude}}{\text{Scalar (density) perturbation amplitude}}$$

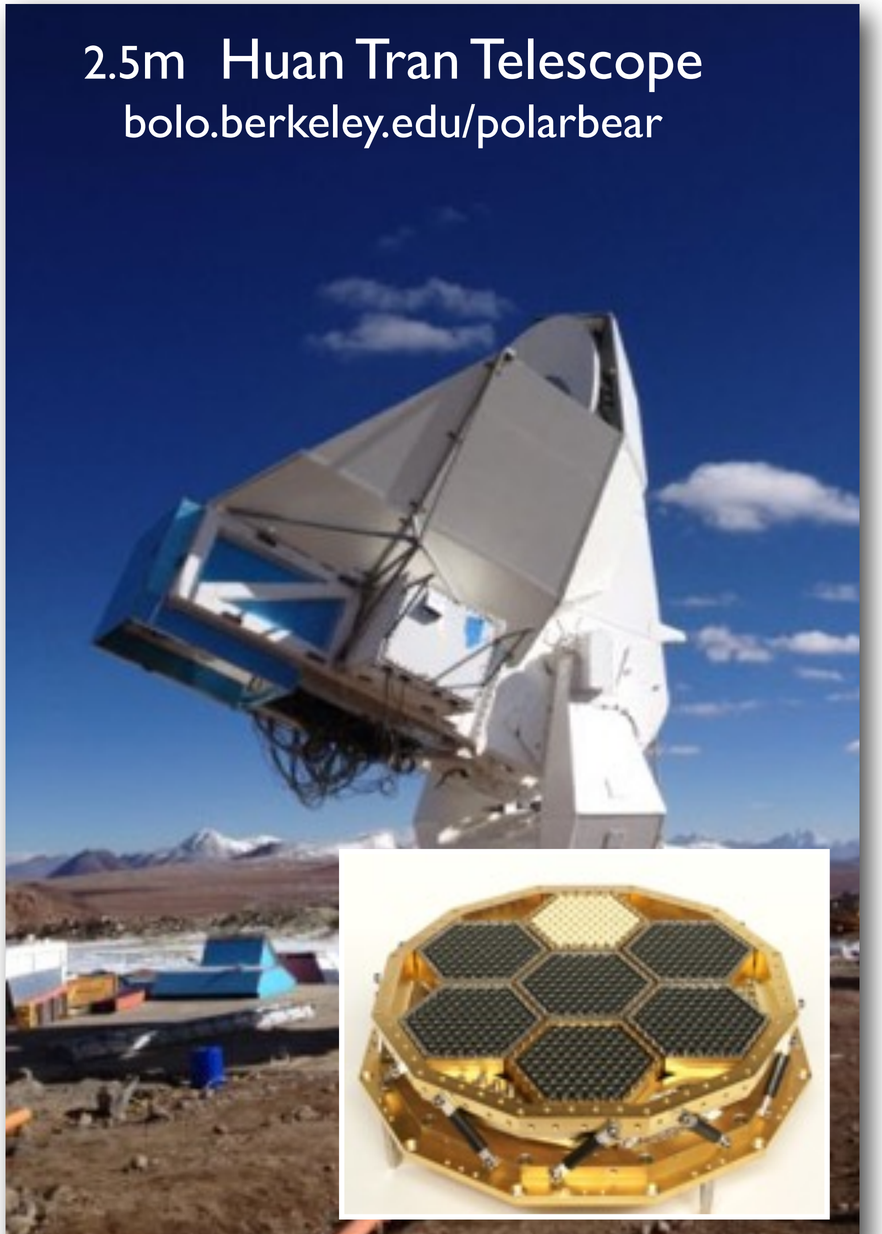
$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

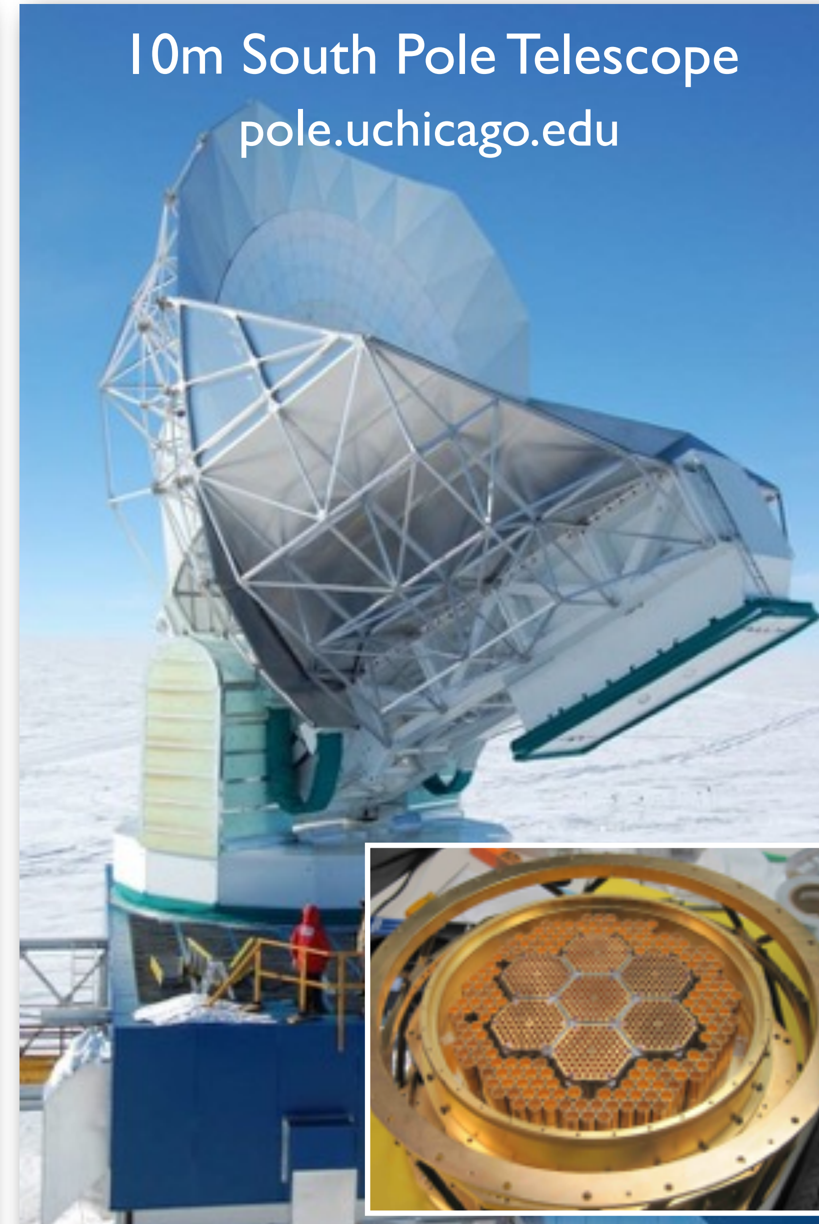
$$\text{time} = 10^{-36} \left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

Polarization of the CMB

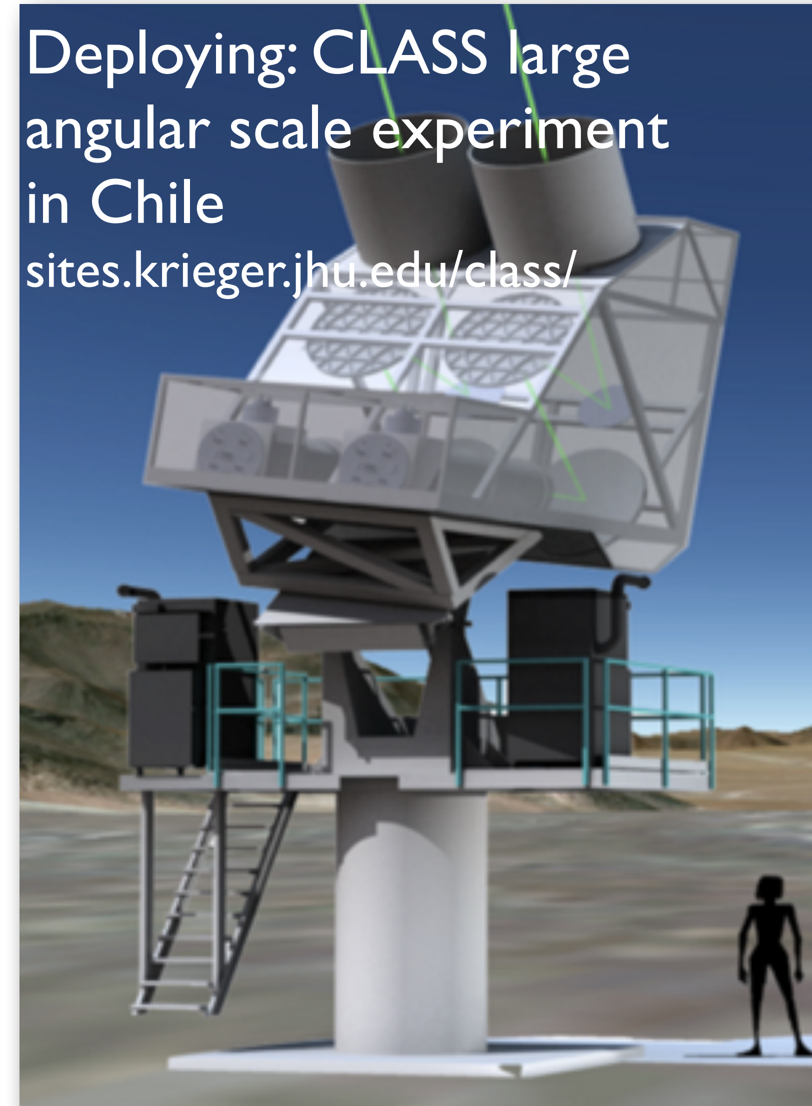


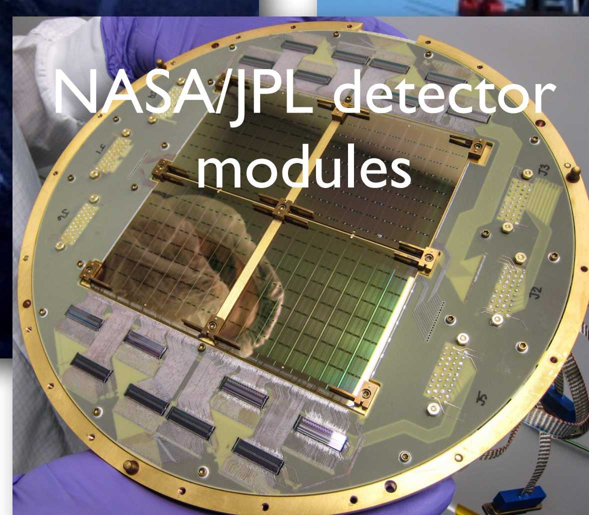
Polarization with large aperture CMB telescopes





Polarization with small aperture CMB telescopes





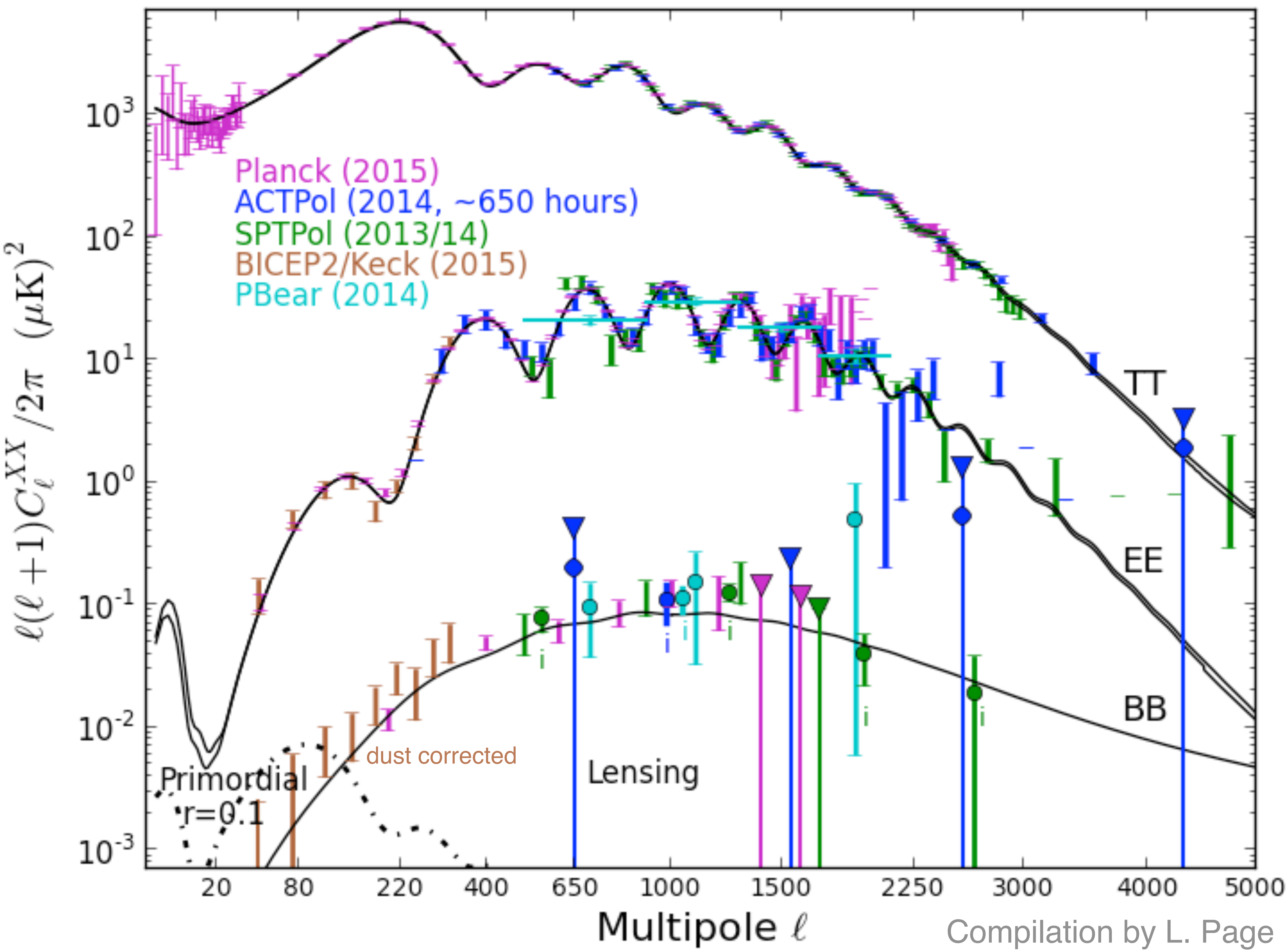
Also

Ground: ABS, QUBIC, QUIJOTE, GroundBird

Balloon: EBEX, PIPER, LSPE

Satellite proposals: LiteBird, PIXIE

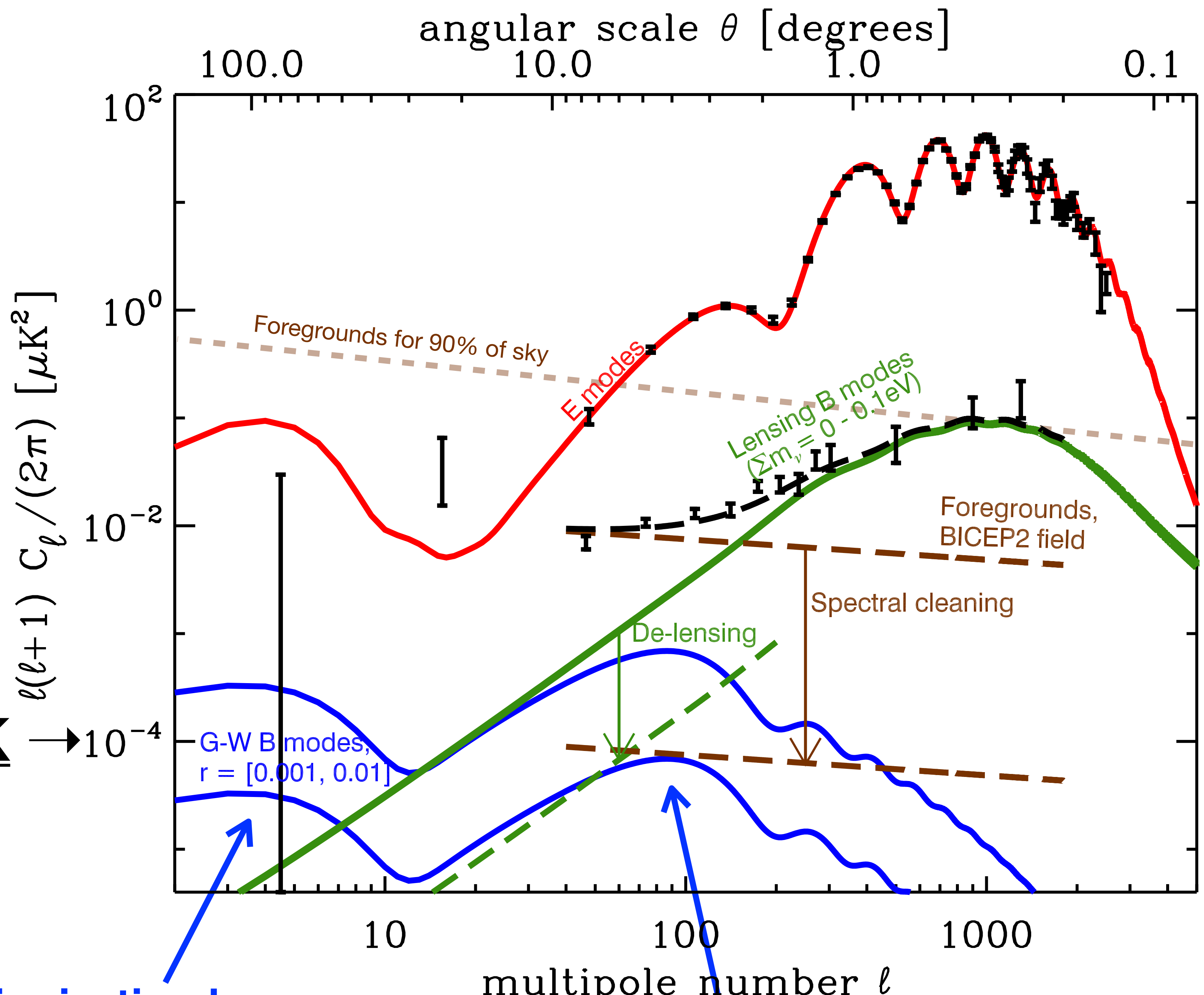
Polarization of the CMB



Rapid progress! All in last ~2 years.

Polarization of the CMB

10 nK →



Incredible progress but a still a long, long way to go… Need CMB-S4

inflationary gravity wave B modes

reionization bump
exploring if possible from the ground

recombination bump
key target of CMB-S4 for r > 0.001

Strawman CMB-S4 specifications

- **Survey(s):**

  - Inflation, Neutrino, and Dark Energy science requires an optimized survey(s) using a range of resolution and sky coverage from deep to wide.

- **Sensitivity:**

  - polarization sensitivity of ~1 uK-arcm over ≳70% of the sky, and better on deep field(s).

- **Resolution:**

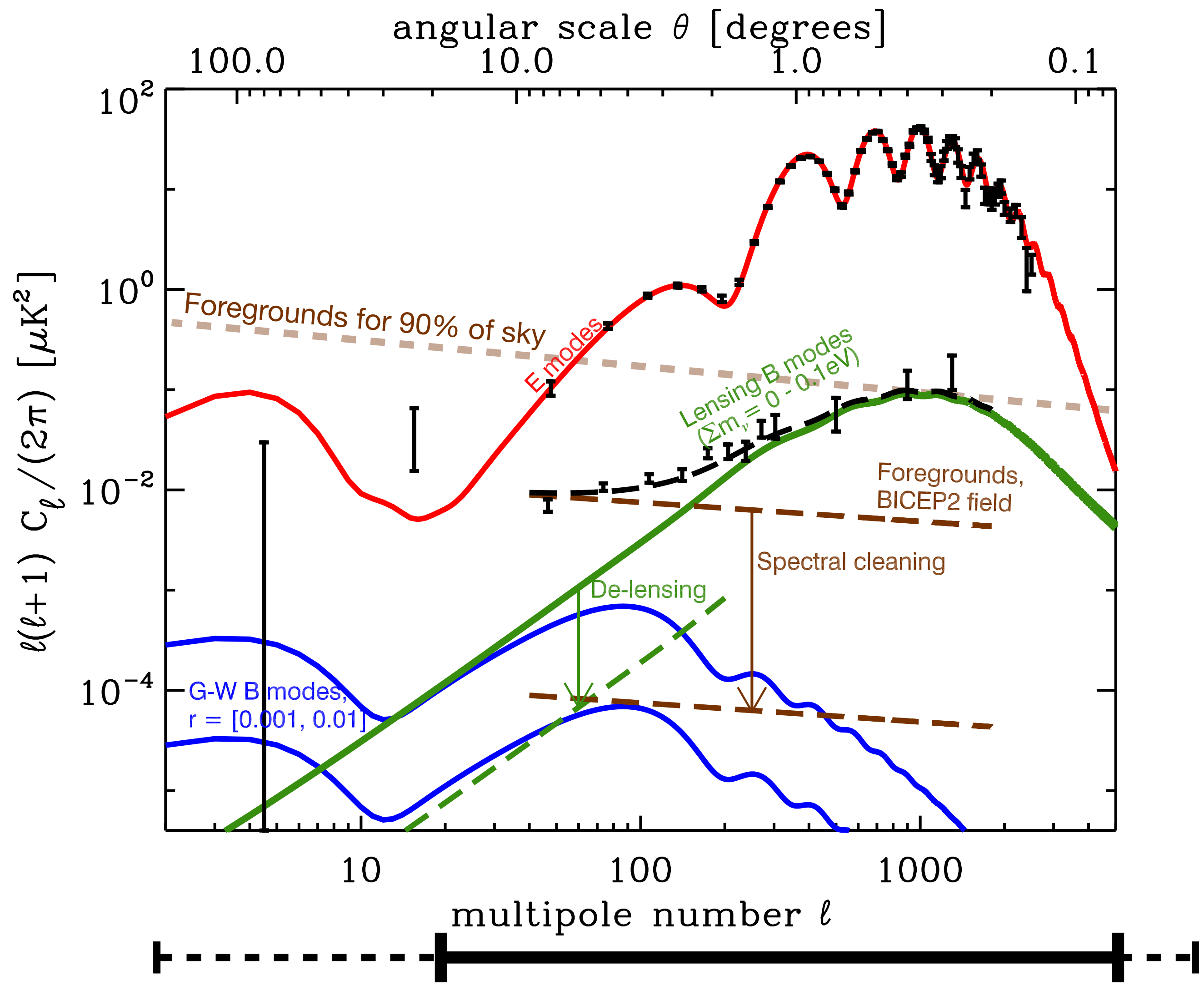
  - exquisite low-ℓ and high-ℓ coverage for inflationary B modes
  - ℓ_{max} ~ 5000 for CMB lensing & neutrino science (arc minutes)
  - higher-ℓ improves dark energy constraints, gravity tests on large scales via the SZ effects, mapping the universe in momentum, n_s, and ancillary science.

- **Configuration:**

  - O(500,000) detectors on multiple telescopes (small and large aperture)
  - spanning ~ 30 - 300 GHz for foreground mitigation

Angular range of CMB-S4

- High-ℓ for dark energy and gravity
- High-ℓ and large area for cosmic variance limited constraints on neutrino mass and N_{eff}
- Inflationary B modes search requires exquisite sensitivity **at both low-ℓ and high-ℓ** because of need for **de-lensing**.



ℓ range of CMB-S4

Angular range of CMB-S4

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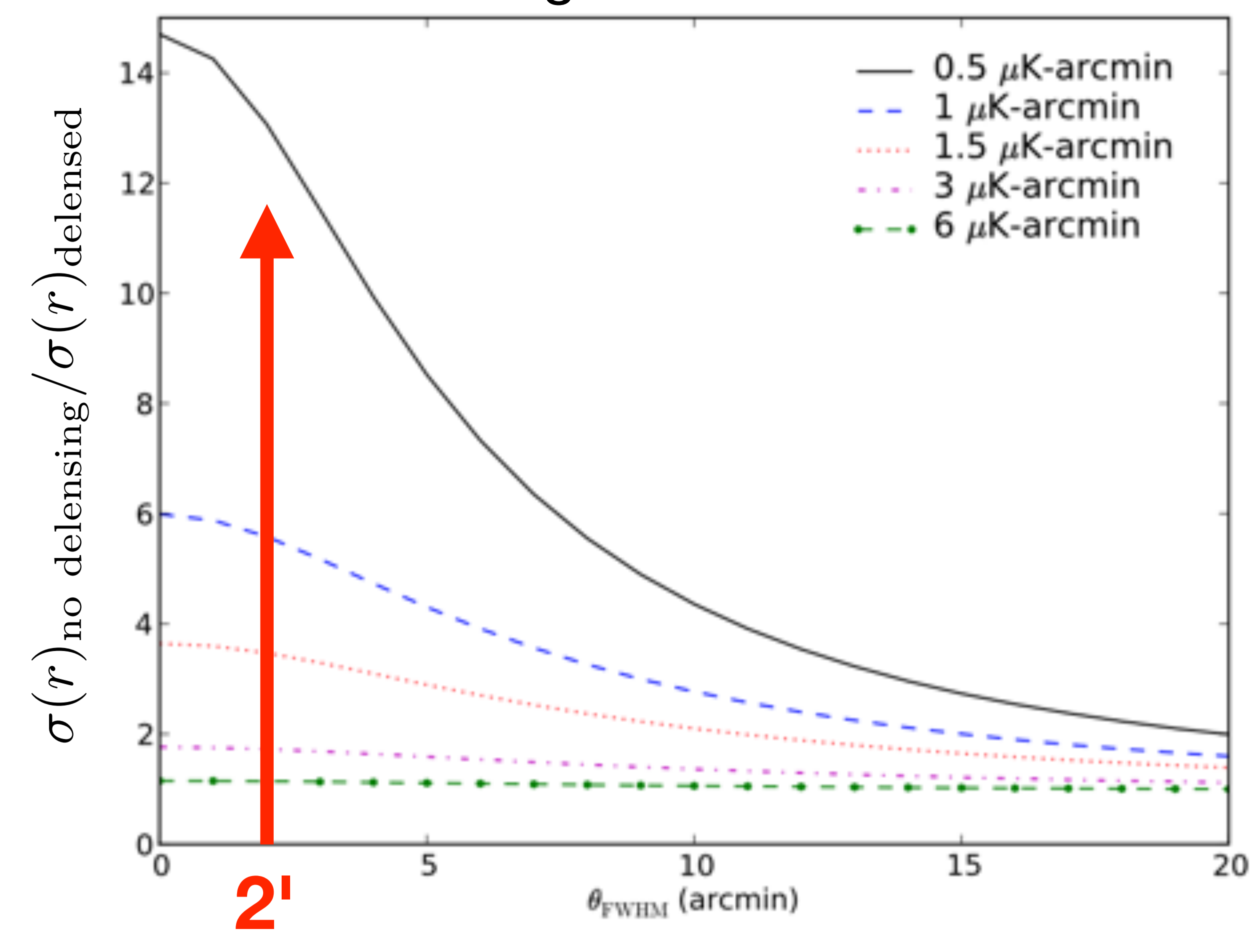
De-lensing Improvement on σ(r) vs Angular Resolution

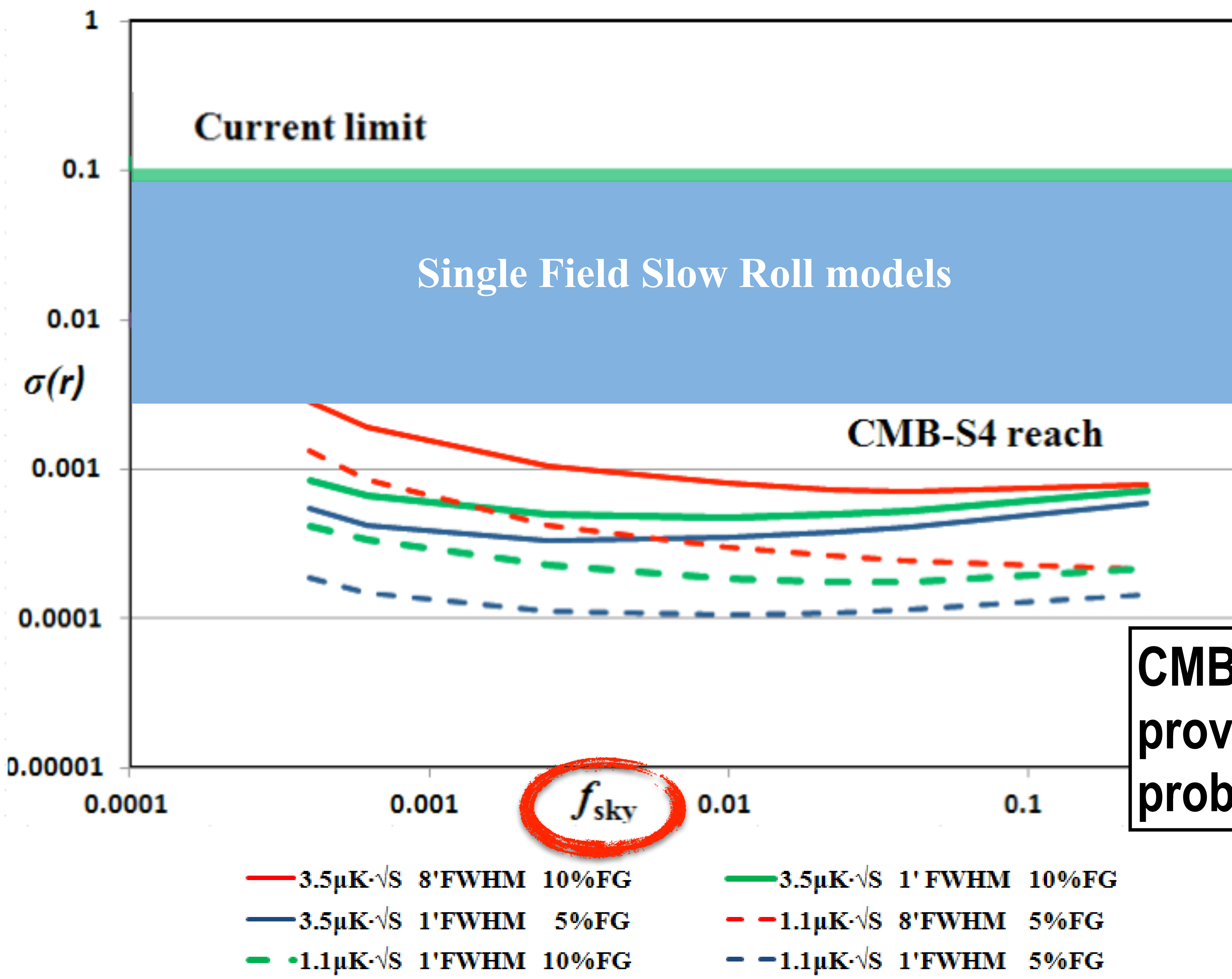


Angular resolution (arcmin)

High resolution ground-based measurements excellent for de-lensing, especially for deep fields.

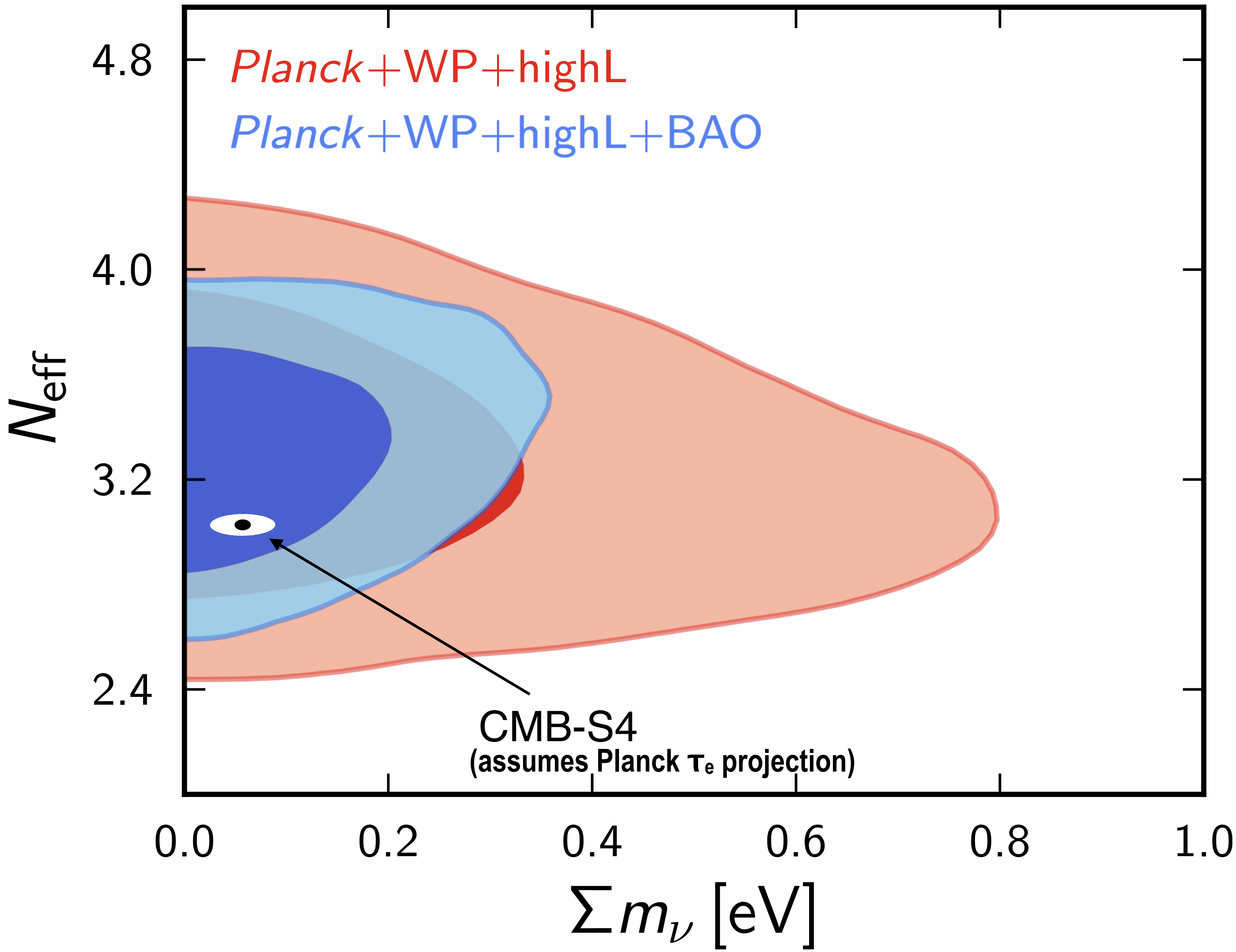
from Smith et al., CMBpol Mission Study arXiv:0811.2916

Inflation reach of CMB-S4



CMB polarization provides the only probe for r < 0.1

Initial
CMB-S4 N_{eff} - Σm_ν constraints

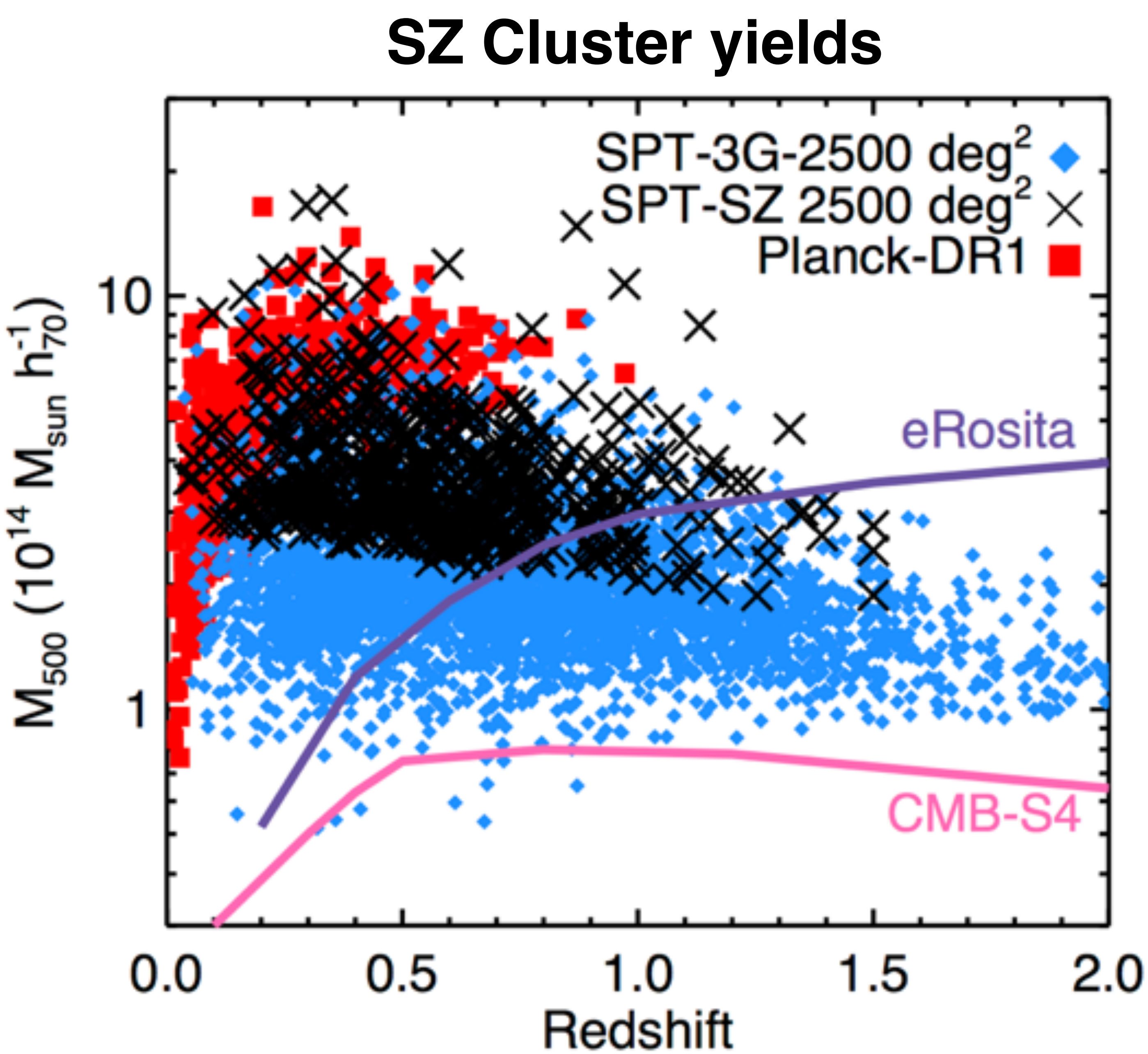


$\sigma(\Sigma m_\nu)$ = 16 meV
(with DESI BAO)

$\sigma(N_{eff})$ = 0.020
CMB uniquely probes N_{eff}

Snowmass CMB-S4 forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn
see Wu et al, ApJ 788 19 (2014)

Expectations for SZ Cluster Surveys



Stage 2: $N_{\rm clust} \sim$ 1,000

Stage 3: $N_{\rm clust} \sim$ 10,000

CMB-S4: $N_{\rm clust} \sim$ 100,000

CMB lensing will directly calibrate cluster mass SZ scaling:

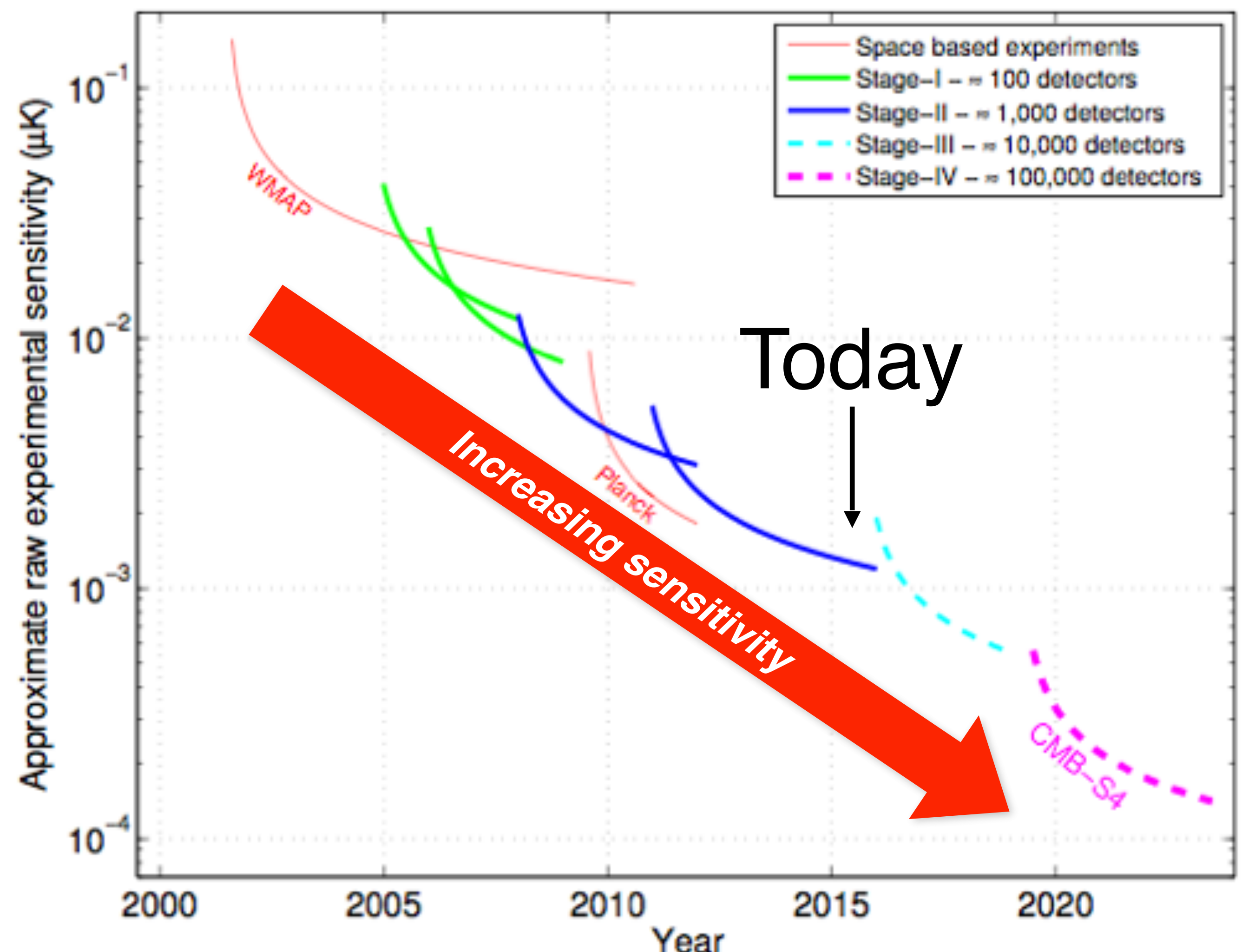
CMB-S4: $\sigma(M) \sim 0.1\%$

for an extremely powerful probe of structure formation and dark energy.

Also kSZ measurements of momentum and tests of gravity on large scales.

What's needed to realize CMB-S4

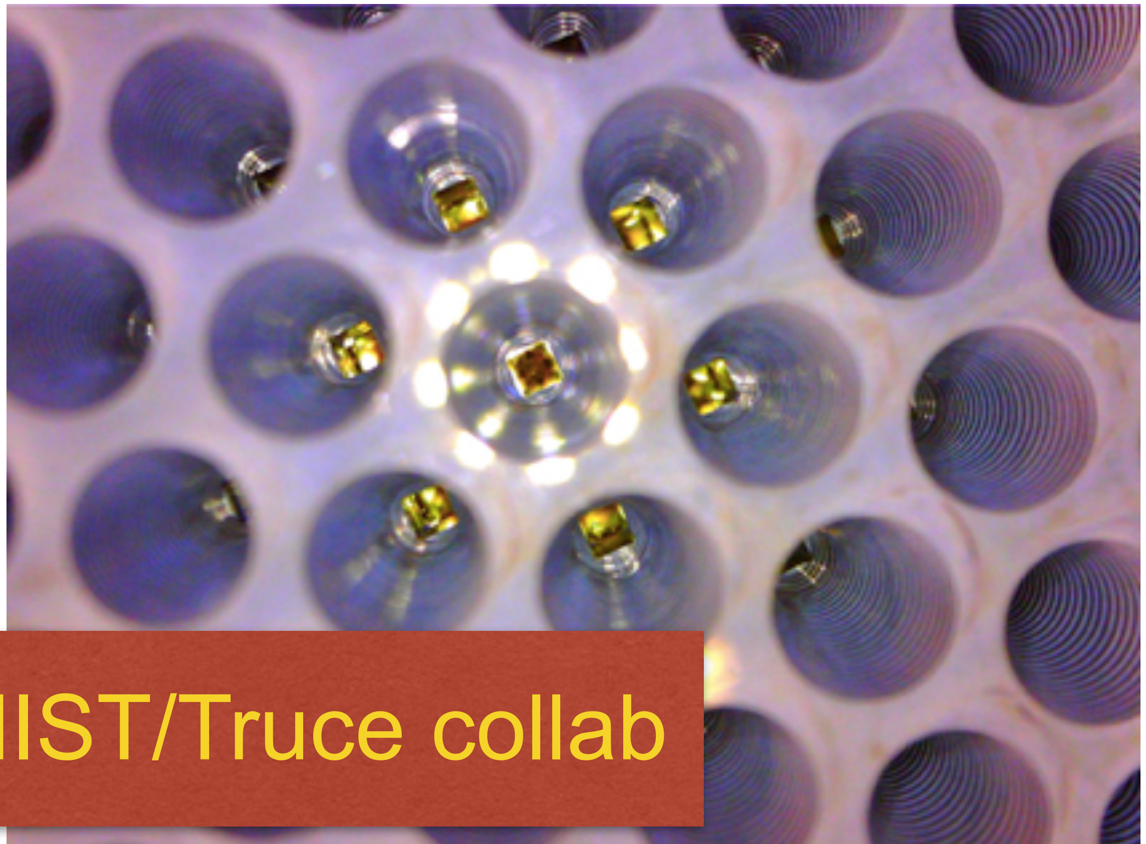
- **Scaling up:**
  - detectors, focal planes
  - sky area and frequency coverage
  - multiple telescopes; new designs
  - computation, data analysis, simulations
  - project management
- **Systematics:**
  - improved control, especially of foreground mitigation
- **Theory/phenomenology:**
  - Increased precision for analysis; new methods

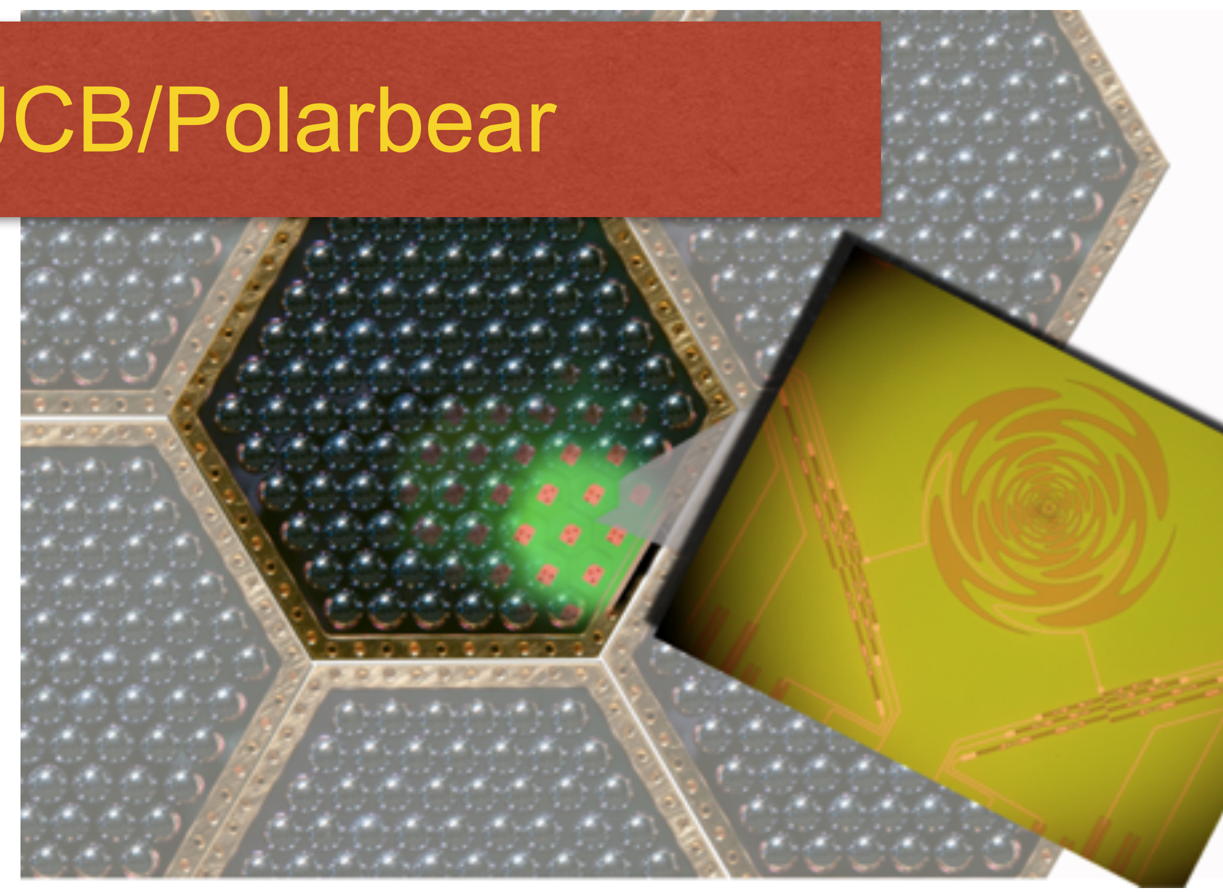


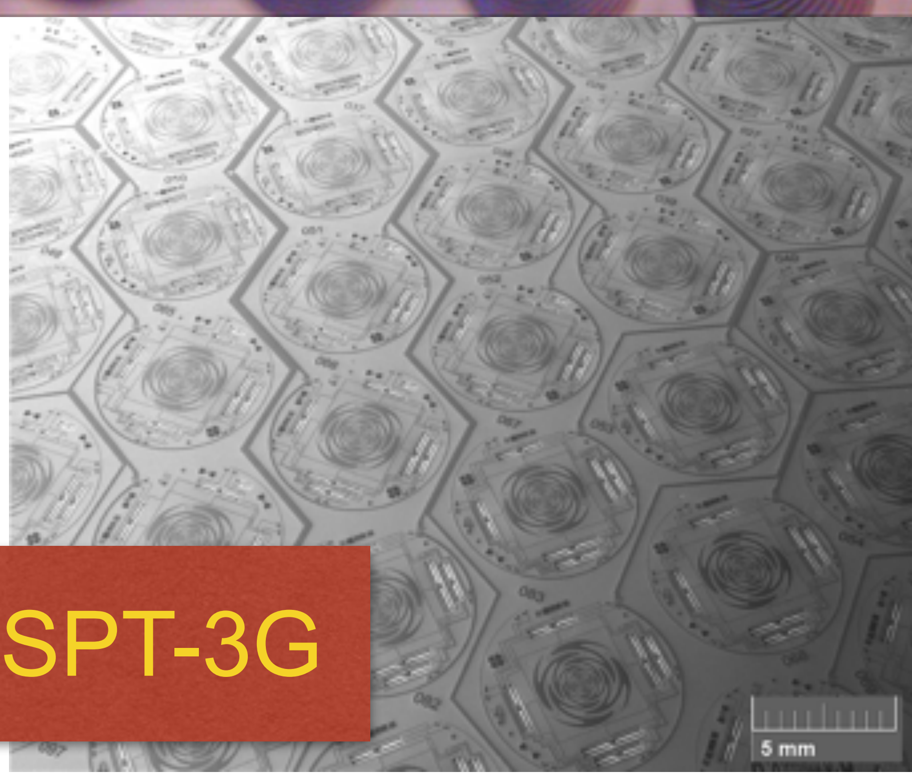
Scale of CMB-S4 exceeds capabilities of the University CMB groups.

→ Partnership of CMB community and DOE labs will do it.

<u>Scalable</u> background limited, broadband bolometric detectors.

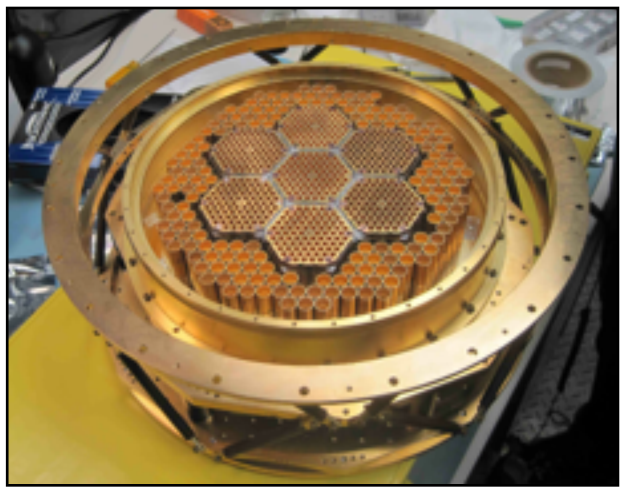




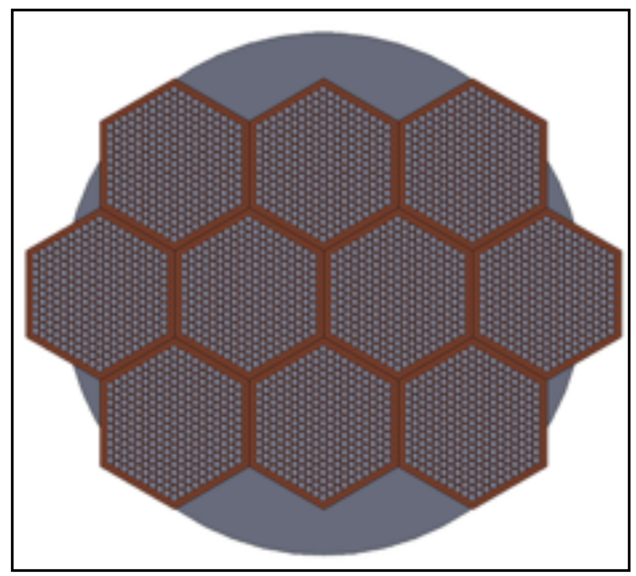


Maintaining Moore's Law: focal planes are saturated so must use parallel processing and multiple telescopes.

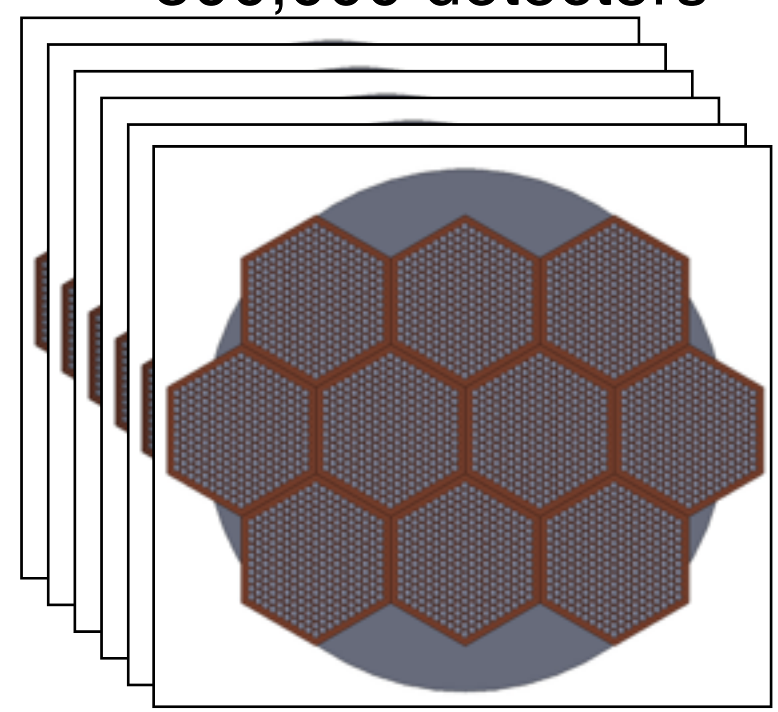
Stage 2
Now
~1000 detectors

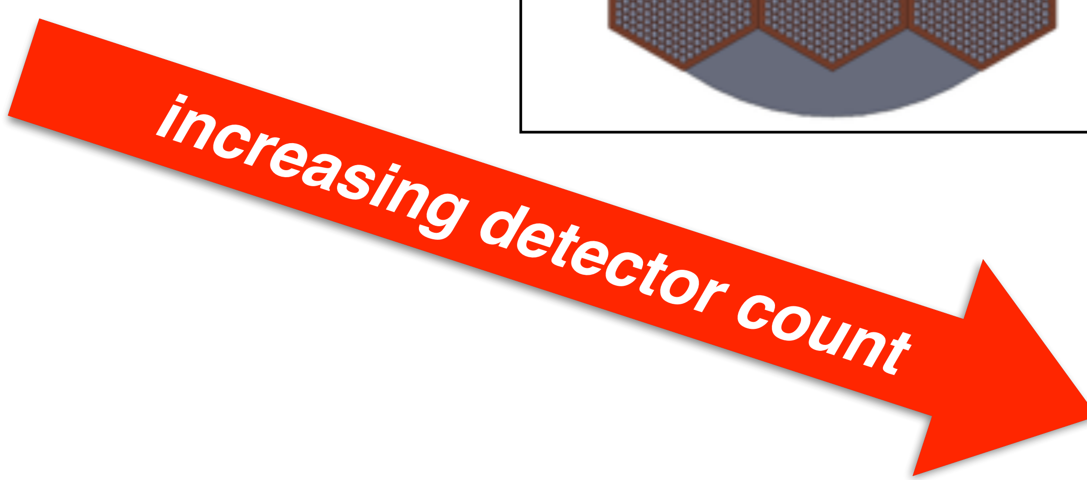


Stage 3
ramping up
~10,000 detectors



Stage 4
CMB-S4
~500,000 detectors

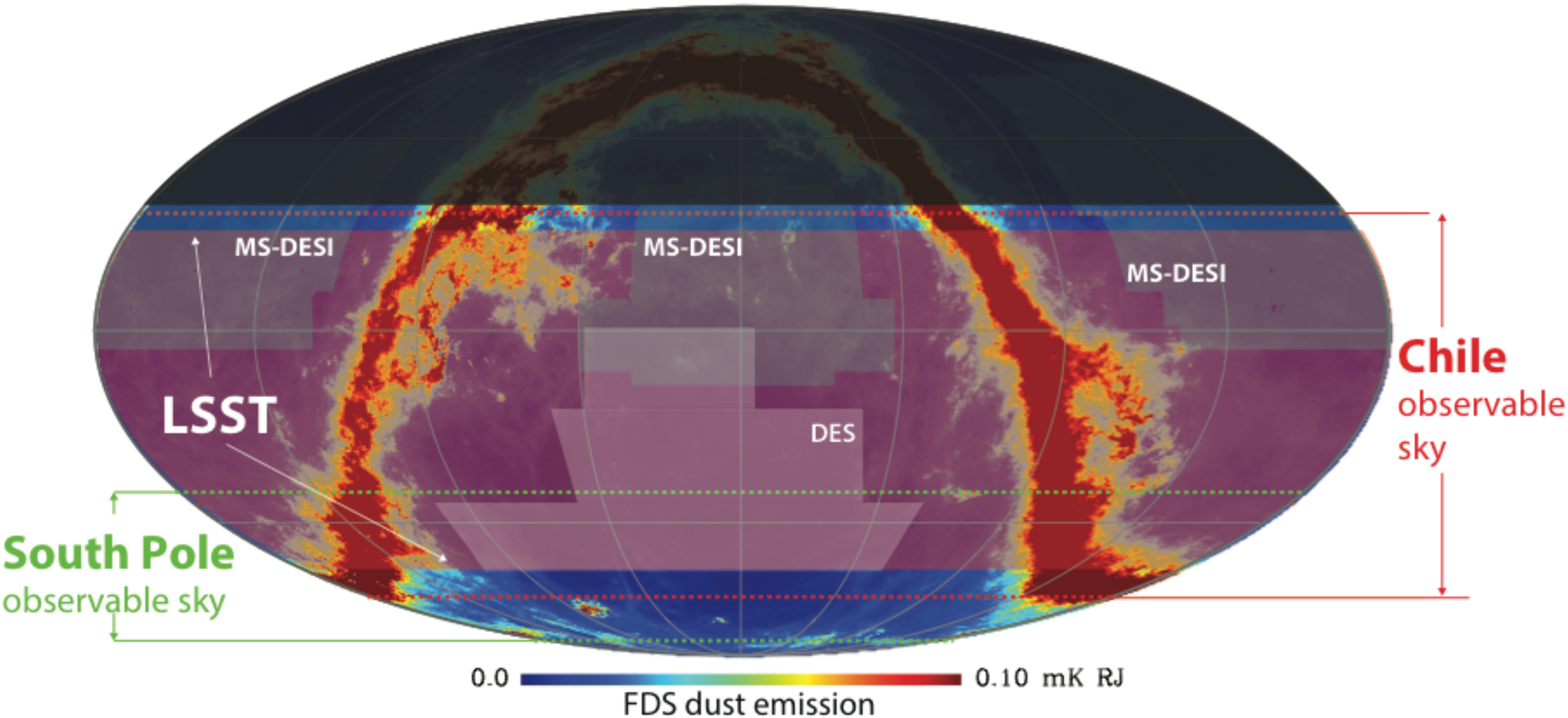




Coverage from Chile and South Pole

70% of the sky, overlapping the large optical surveys

Greatly enhance DES, DESI and LSST science by overlapping sky



Possibly add northern site for full sky coverage: Tibet? Greenland?
May provide opportunity for international partner.

Recent South Pole CMB experiments at NSF's Amundsen-Scott Research Station

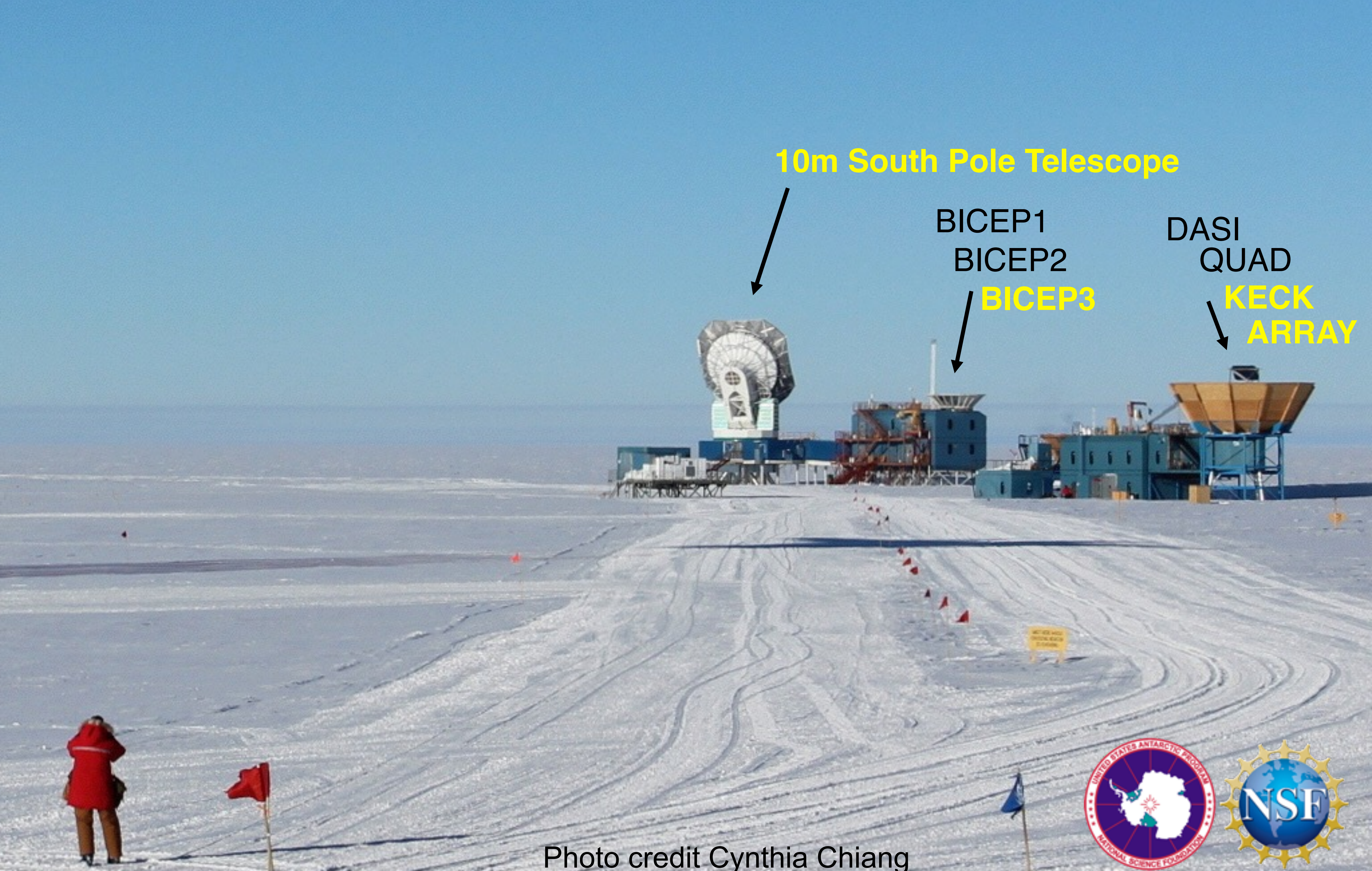


Photo credit Cynthia Chiang

Recent & upcoming Atacama CMB experiments

Moving CMB-S4 forward

Community driven progress

- 2013: Community came together to produce and endorse Snowmass documents and need for stage 4 ground based project.

Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure

Topical Conveners: K.N. Abazajian, J.E. Carlstrom, A.T. Lee

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Includes appendix on:

“A Stage-IV CMB experiment, CMB-S4”

arXiv:1309.5383

Inflation Physics from the Cosmic Microwave Background and Large Scale Structure

Topical Conveners: J.E. Carlstrom, A.T. Lee

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arXiv:1309.5381

Community driven progress

- 2013/2014: Major US ground based CMB groups and DOE lab representatives came together to provide input on CMB-S4 to the Particle Physics Project Prioritization Panel (P5).
- 2014: The P5 report, "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context" endorses CMB science and the CMB-S4 project.
- 2014: Proposed for NSF STC "Center for Microwave Background Research (CMBR)" co-directed by J. Carlstrom and Lyman Page. Included 67 senior US scientists. Not funded.
- 2015: CMB-S4 one of only three priorities identified in the NRC report "A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research."
- 2015 - Ongoing DOE Cosmic Visions CMB group made up of representatives from the DOE CMB scientists, management and from the major ground-based CMB projects.

  C-V group provides DOE with link to CMB community and input for DOE planning (monthly telecons with K. Turner and E. Linder). Produced three "planning" documents on CMB-S4: Science; Technical; and Programmatic.

Community driven progress

- 2015 - **CMB-S4 Community workshops** every ~six months.
  - "Cosmology with the CMB and its Polarization" at UMN January 16, 2015. Day dedicated to CMB-S4 discussion.
  - "Cosmology with CMB-S4" at the University of Michigan September 21-22, 2015. Worked on CMB-S4 science reach and organizing science book, captured on wiki: https://cosmo.uchicago.edu/CMB-S4workshops/index.php?title=Cosmology_with_CMB-S4&oldid=1081
  - "Cosmology with CMB-S4 Collaboration Workshop" at the LBNL, Berkeley, March 7-8, 2016.
  - "CMB-S4" at the University of Chicago ~Sep 2016.

Community driven progress

- Now: Initial writing teams producing first draft of the Science Book "science" chapters based on output of Michigan workshop. Will distribute to entire CMB-S4 community for feedback prior to March Berkeley workshop.

Inflation:
R. Flauger
J. Dunkley
J. Kovac
L. Knox*
C-L Kuo
M. Peloso
S. Shandera
E. Silverstein
L. Sorbo
K. Wu
(building on SnowMass)

Neutrinos:
K. Abazajian
G. Fuller
A. Friedland
D. Green*
A. Kusaka
M. Loverde
A. Slosar
(building on SnowMass)

D.E. & Gravity
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Agency roles in CMB-S4

NSF

- Funds the world leading ground based CMB efforts (AST, PHY & PLR).
- Leads Stage 2 and 3 efforts, with small but key contributions from DOE
- Critical role in sustaining university efforts into CMB-S4
  - possibly capital investment from NSF in new CMB telescopes

DOE

- Key contributions to Stage 2 & 3 efforts
  - Detectors, Readout, Computing, large cryogenic components
- Critical role for DOE in scaling up for CMB-S4

NSF and DOE activities will need to be carefully coordinated for CMB-S4.

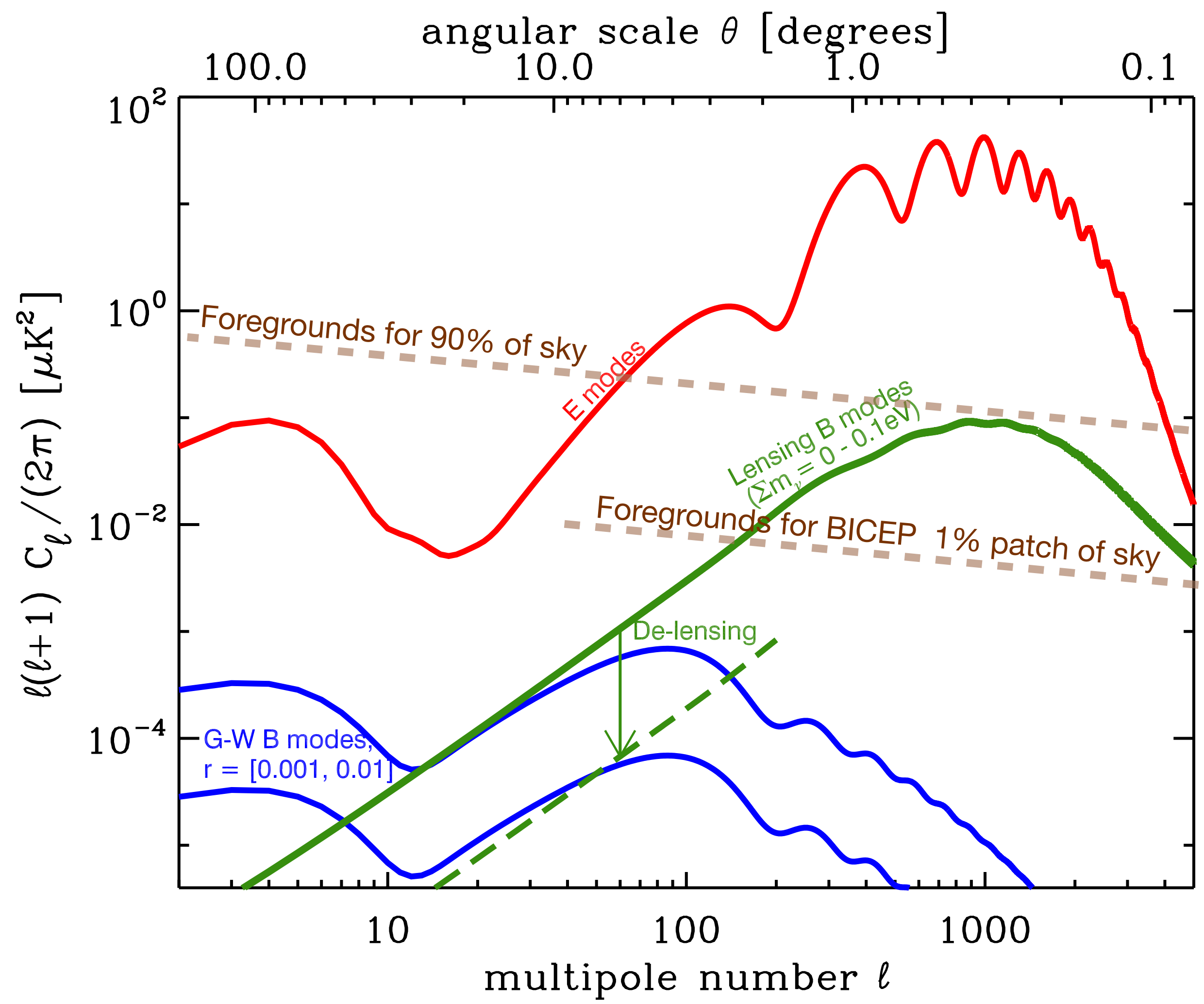
Agency roles in CMB-S4

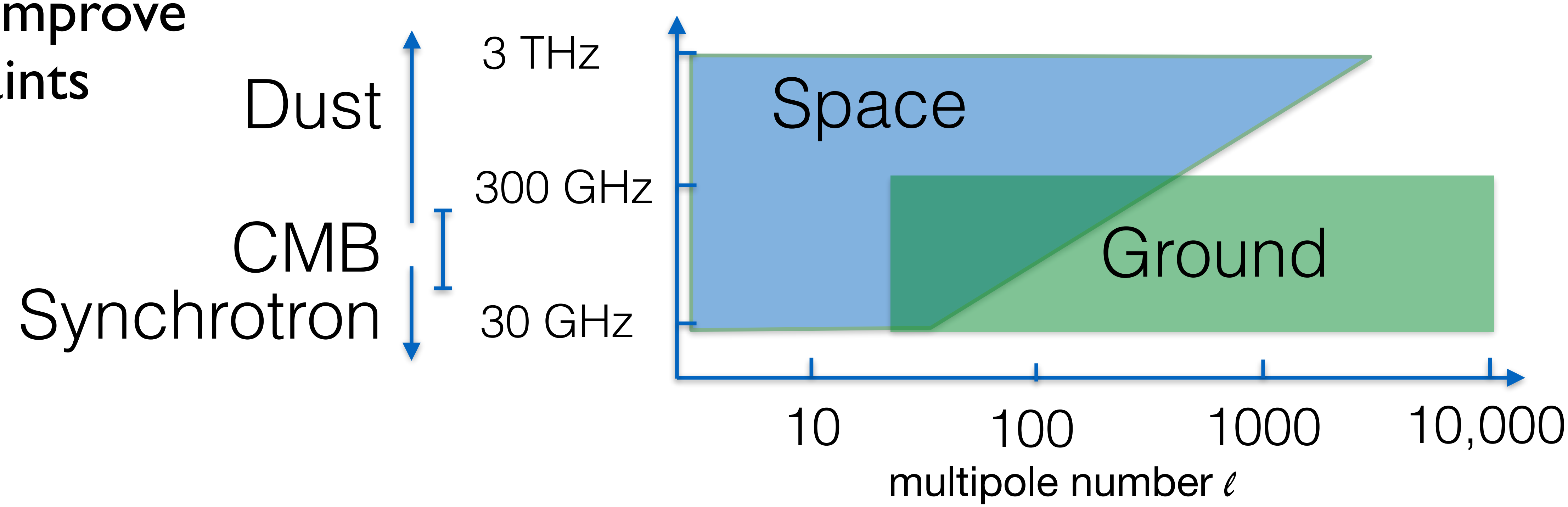
NASA

- Independent of planned CMB-S4 effort, but fundamentally complementary:
  - Complementary detector technology (JPL, GSFC)
  - Ballooning program → high-ν, low-ℓ: foregrounds, possibly reionization bump
  - Involvement in possible Japanese (JAXA) satellite Litebird
    → high-ν, low-ℓ; foregrounds, reionization bump, τ_e
  - PIXIE satellite possibility → spectral coverage, low-ℓ; foregrounds, reionization bump, τ_e

Complementarity strengths of ground and space

- **Ground:** Resolution required for CMB lensing (+delensing!), damping tail, clusters….
- **Space:** All sky for reionization peak; high frequencies for dust.
- Combined CMB-S4 and NASA mission data would improve constraints





Last words

CMB-S4 will be a great leap for CMB measurements, cosmology and astrophysics.

The community is behind it and we are moving forward. The biggest challenge is scaling up.

The CMB is the gift that keeps on giving. With the next generation CMB measurements we will be searching for inflationary gravitational waves and rigorously testing single field slow roll inflation, determining the neutrino masses, mapping the universe in momentum, investigating dark energy, testing general relativity and more.

backup slides

CMB-S4 FAQs

1. Why not do it all from space?

- CMB-S4 is the next logical step for U.S. ground-based CMB. All the pieces are in place.
- CMB-S4 program could flow seamlessly from Stage 3, continuing science output.
- It would take an extremely ambitious and expensive mission to do it all from space. CMB-S4 can obtain its goals from the ground much sooner and cheaper.
- CMB-S4 could inform a future space mission.

CMB-S4 FAQs

2. Why not wait to see what Stage 3 does (and downselect technology)?

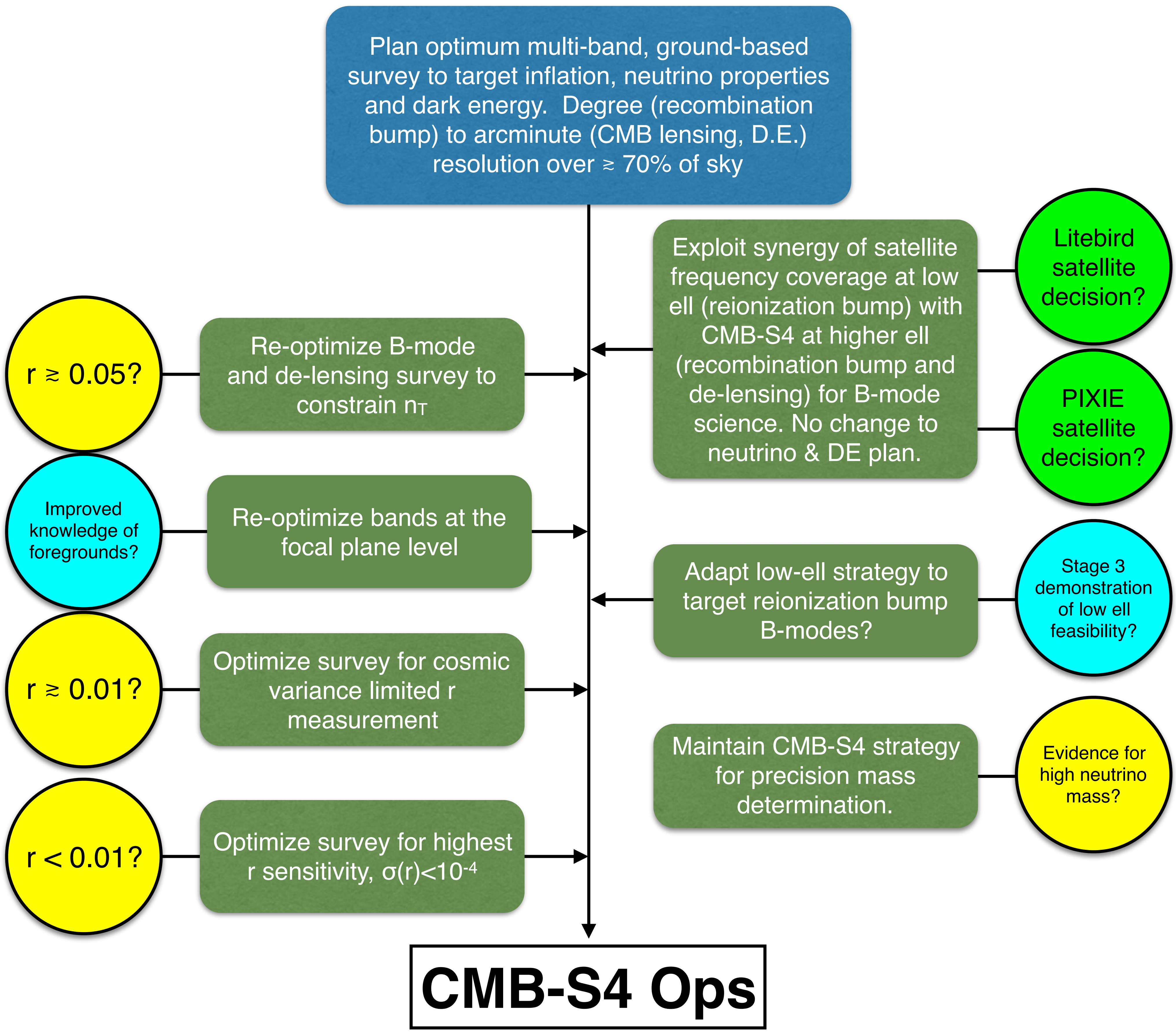
- The Stage 3 groups and the extended community are planning CMB-S4 and developing the technology. They will optimize the technology, especially for scaling up, but no major downselects are expected. The basic technologies are in place, and so are the people.
- CMB-S4 goals are beyond the reach of Stage 3 experiments (but not the aspirations of the Stage 3 groups!).
- Information learned from Stage 3 (e.g., foregrounds, *r*) can be easily incorporated into CMB-S4 (see planning flow chart).
- CMB-S4 is timely because it will enhance the science return from other cosmic surveys (e.g., LSST, DESI).

CMB-S4 FAQs

3. Why not have another CMB task force report?

- P5 has endorsed CMB and CMB-S4. The NRC report "A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research" chose CMB-S4 as one its three priorities.
- CMB-S4 is the natural next step. We do not feel another review of the field is necessary for planning the future ground-based program.
- The U.S. leaders and practitioners of the field are working to optimize the science and the technology of CMB-S4. It is an open community effort. It will undergo a more exhaustive examination and optimization than can be achieved by a task force.
- The people who would serve on a task force for ground based CMB are a subset of the people already involved in CMB-S4.

CMB-S4 planning flow chart



Scheduling considerations for CMB-S4

Experiment		bands (GHz)	# det	θ' (GHz)	2016	2017	2018	2019	2020	2021	2022	2023	2024
Ground based (ongoing/funded):													
ACT:	*ACTpol*	90/150	3108	1.3' (150)									
	Adv-ACTpol	28/41/90/150/230	5792	1.3' (150)									
Polarbear:	*PB2*	90/150	7588	3.5' (150)									
	Simons Array	90/150/220	22,764	3.5' (150)									
SPT:	*SPTpol*	90/150	1536	1.0' (150)									
	SPT-3G	90/150/220	16,260	1.0' (150)									
BICEP:	*KECK*	90/150/220	2560	30' (150)									
	BICEP3	90	2560	25' (90)									
CLASS:		40/90	590	40' (90)									
		40/90/150/220	5108	24' (150)									
CMB-S4		**30/ / / / /300**	**~500,000**	**≳1.0' (150)**									
Balloon based (ongoing/funded):													
SPIDER2		150/280	2000	30' (150)									
PIPER		200/270/350/600	1200	21' (150)									
Satellite (pending):													
Litebird		15-bands from 40-400	2276	30' (150)									
Pixie		400-bands from 30-6000	multi-moded	100' (all)									

Steady stream of science on way to CMB-S4 achieving critical thresholds in inflation and neutrinos.

CMBR participants

Directorship					
Carlstrom, John	*U. Chicago*	Director			
Page, Lyman	*Princeton*	Co-Director			
Meyer, Stephan	*U. Chicago*	Associate Director			
Basri, Gibor	*U.C. Berkeley*	Diversity Officer			
TBD		Center Manager			
Internal Guiding Board					
Staggs, Suzanne [c]	*Princeton*	Irwin, Kent	*Stanford*	Miller, Amber	*Columbia*
Borrill, Julian	*LBL*	Knox, Lloyd	*U.C. Davis*	Padin, Steve	*Caltech*
Devlin, Mark	*U. Penn*	Kovac, John	*Harvard U.*	Ruhl, John	*Case Western*
Holzapfel, Bill	*U.C. Berkeley*	Lee, Adrian	*U.C. Berkeley*	Stassun, Keivan	*Fisk U.*
Coordinators					
Stassun, Keivan	*Fisk*	Education, Diversity and Outreach (EDO)			
TBD		EDO Executive Coordinator			
Lloyd Knox	*U.C. Davis*	Physics & Cosmology			
Padin, Steve	*Caltech*	Tehnology and Methods			
Center Council					
Arnold, Kam	*UCSD*	Hu, Wayne	*U. Chicago*	Niemack, Mike	*Cornell*
Bean, Rachel	*Cornell*	Johnson, Bradley	*Columbia*	Partridge, Bruce	*Haverford*
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Benson, Bradford	*FNAL*	Kamionkowski, Marc	*JHU*	Pryke, Clem	*UMN*
Bock, Jamie	*Caltech*	Keating, Brian	*UCSD*	Readhead, Anthony	*Caltech*
Burger, Arnold	*Fisk U.*	Kosowsky, Arthur	*Pitt*	Schaffer, Kathryn	*SAIC*
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Flauger, Raphael	*CMU*	LoVerde, Marilena	*Stony Brook*	Spergel, David	*Princeton*
Halverson, Nils	*CU Boulder*	Lubin, Phil	*UCSB*	Timbie, Peter	*UW Madision*
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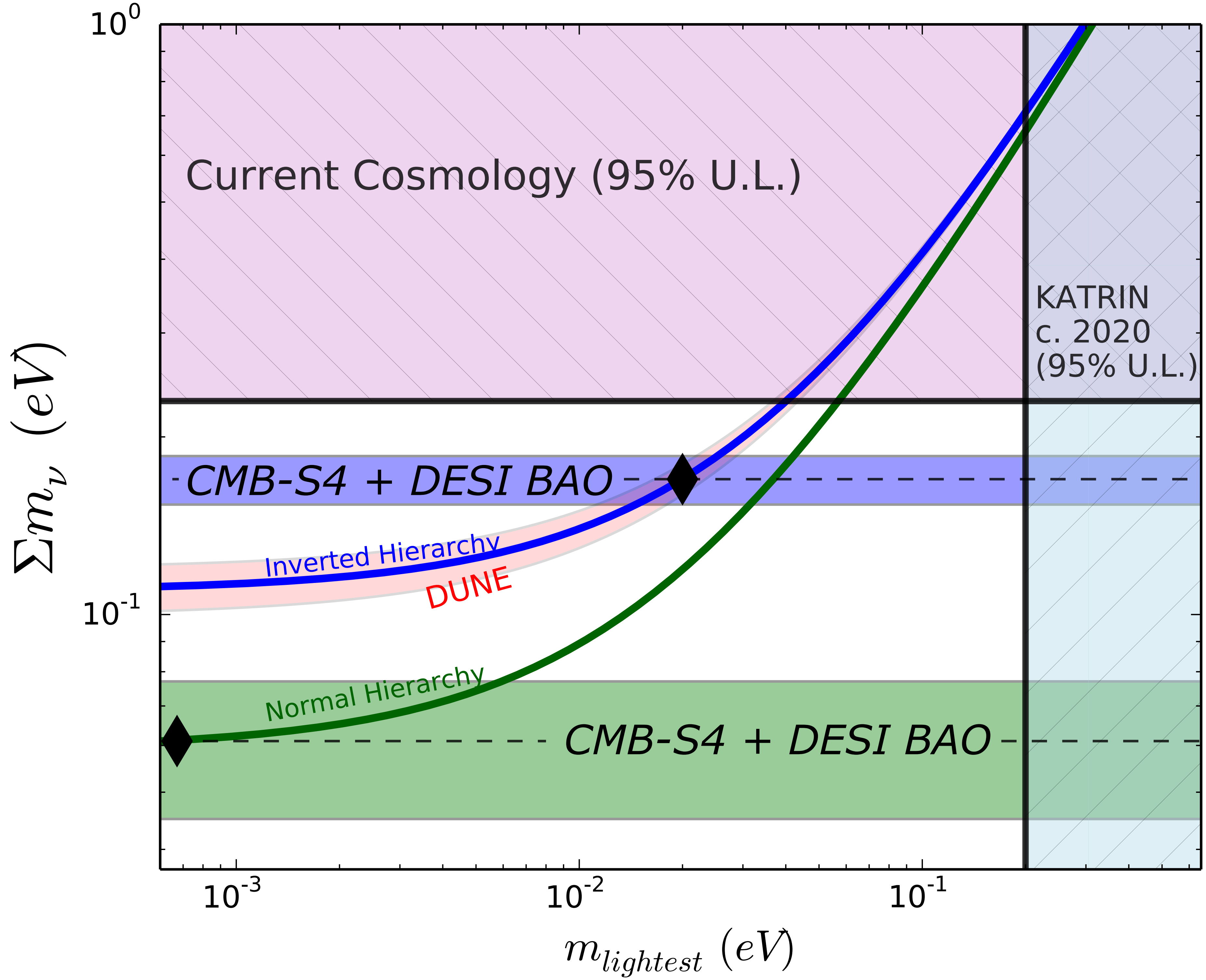
Heitmann, Katrin	*ANL*	Mauskopf, Phil	*Arizona State*	Vieregg, Abigail	*U. Chicago*
Hirata, Chris	*OSU*	McMahon, Jeff	*U.Michigan*	White, Martin	*U.C. Berkeley*
Ho, Shirley	*CMU*	Meinhold, Peter	*UCSB*	Zaldarriaga, Matias	*IAS*

Technology Status, Next Steps & Needs

Technology area	Critical next steps	Ongoing lab efforts	Needs
High Performance Computing (HPC)	Scale current CMB mission simulation & analysis capability to: - 1000x data volume - next-generation HPC architectures	LBNL is simulating & mapping full CMB mission data sets; ANL, FNL, LBNL & SLAC (and many university groups) are performing various S3 analyses.	Invest in computational science (transitioning from Planck). Continue to provide significant HPC resources.
Detectors	Develop plans for increasing fab throughput to ~100 wafers/yr (requires multible fab facilities)	SLAC, LBNL & ANL are building fab facilities; ANL is fabricating detectors for SPT-3G	Major investment in fab resources
	Develop plans for detector testing to match fab throughput	FNAL, SLAC, LBNL & ANL are testing materials and building detector test facilities; (several university groups can each test ~2 wafers/month)	Invest in test facilities
	Demonstration of new bands (for foreground removal)	FNAL, SLAC, LBNL & ANL are working on detector designs; (ongoing effort in several university groups)	Invest in detector design work
Optics	Demonstration of large lenses with broadband anti-reflection coatings	SLAC is making lenses for SPT-3G; SLAC & LBNL are working on AR coatings; (ongoing effort in several university groups)	Invest in lens development
Platforms, shields, pol modulation, camera configuration, cryogenics, detector readout electronics, camera integration, control architecture	Choose candidate technologies from S2 & S3 experiments	LBNL is developing pol modulators; FNAL is integrating the SPT-3G camera; LBNL is working detector module integration; (ongoing effort in several university groups)	Continue LDRD & Start DOE HEP office support

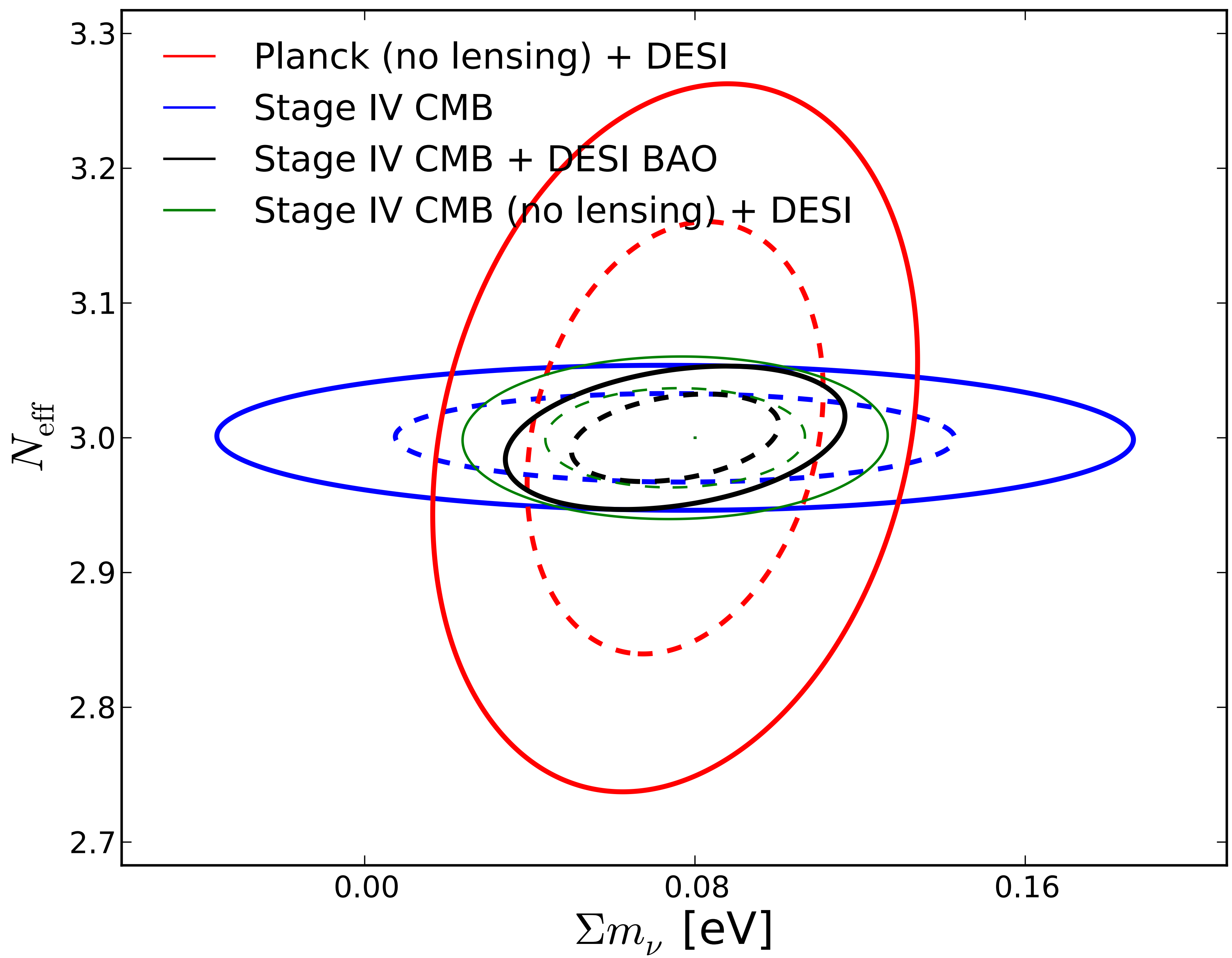
green=low risk
yellow=moderate risk
red=high risk

Snowmass combined Neutrino mass constraints



"use cosmology to tighten the noose" Boris Kayser

Snowmass joint projections N_{eff} - Σm_ν



σ(N_{eff}) = 0.020

CMB uniquely probes N_{eff}

σ(Σm_ν) = 16 meV

(with DESI BAO)

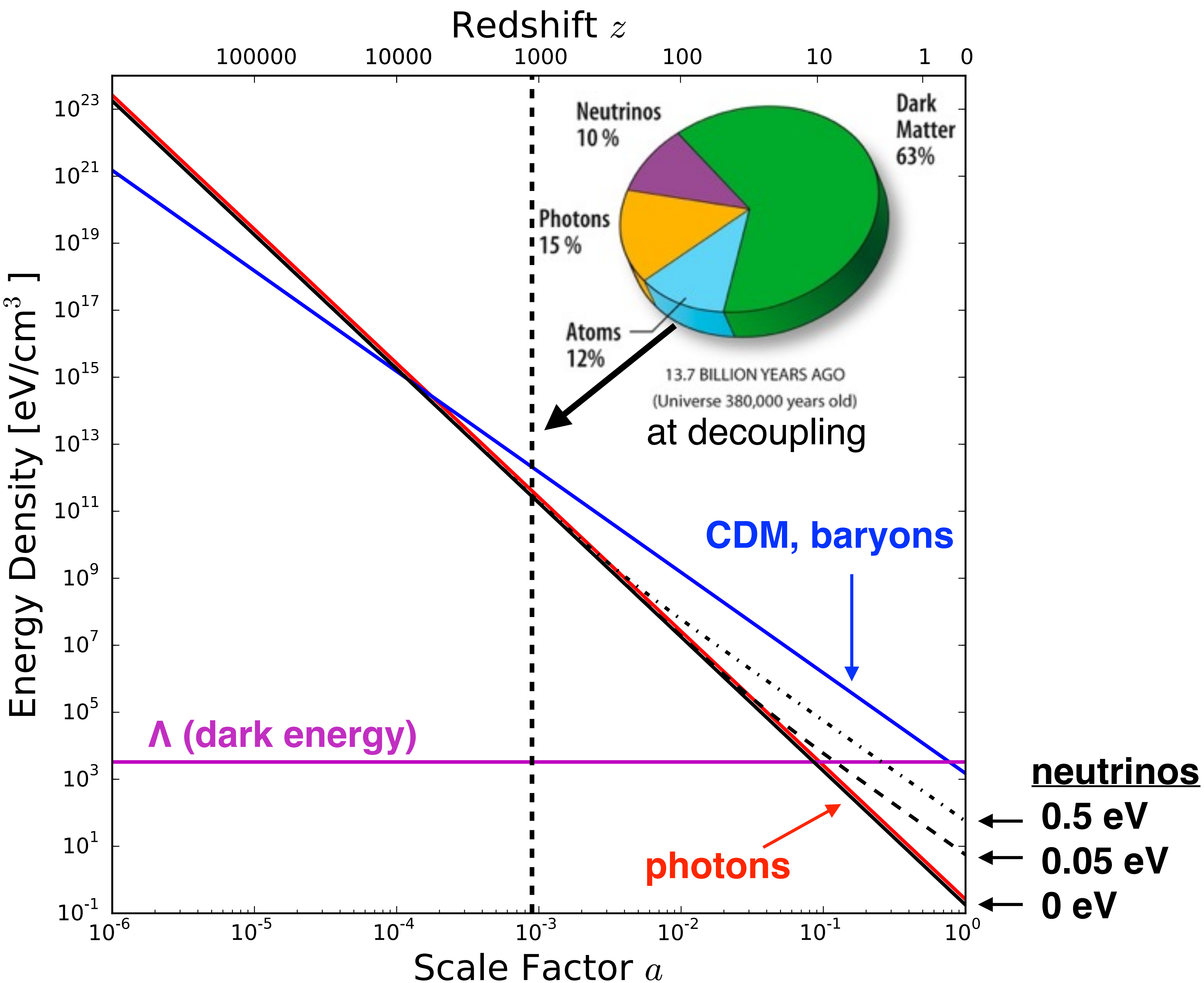
P5 Summary of Scenarios

Project/Activity	Scenarios			Science Drivers					
	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓	?	C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I

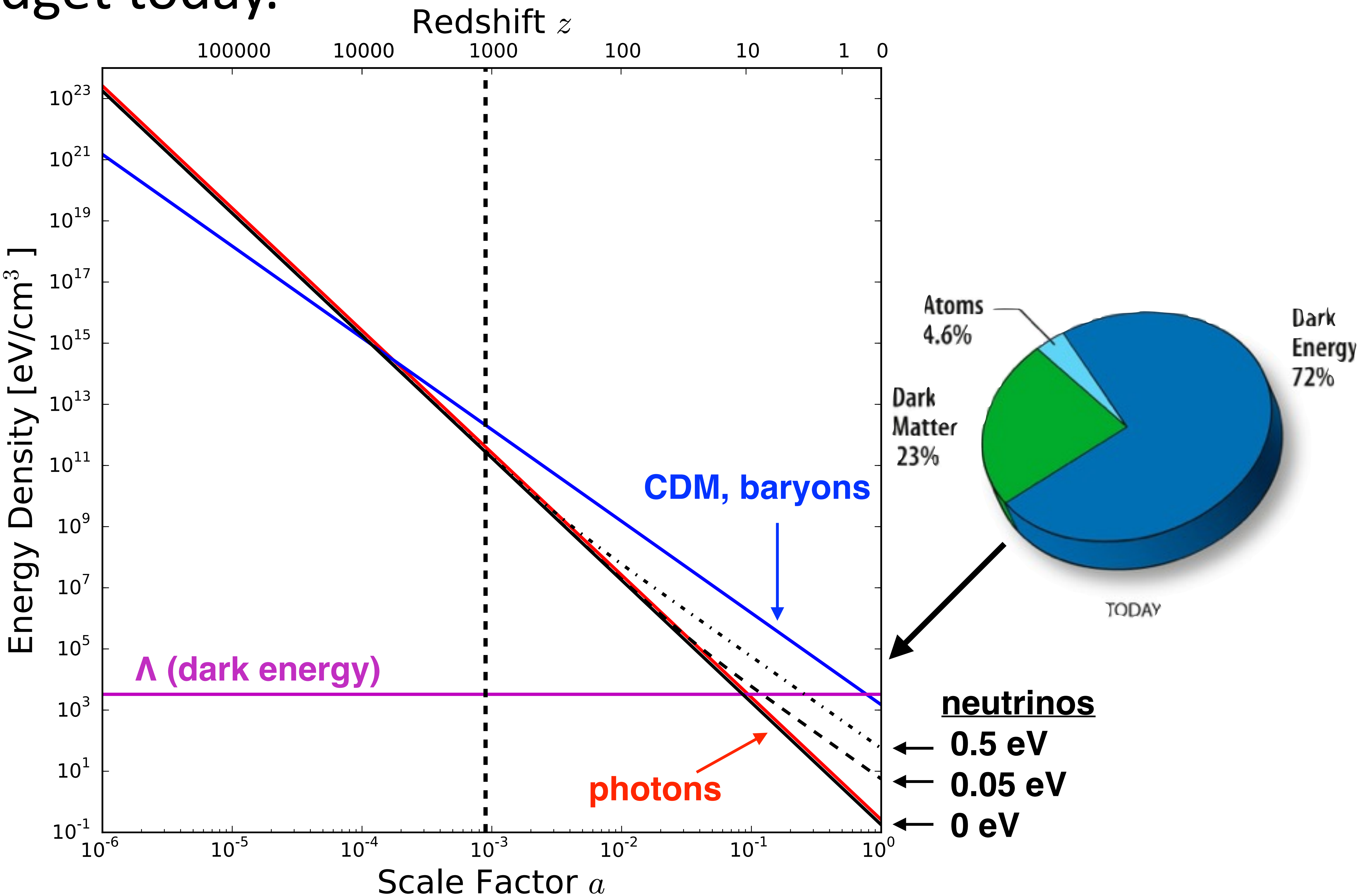
P5's timelines

CMB-S4 ramps up as LSST ramps down

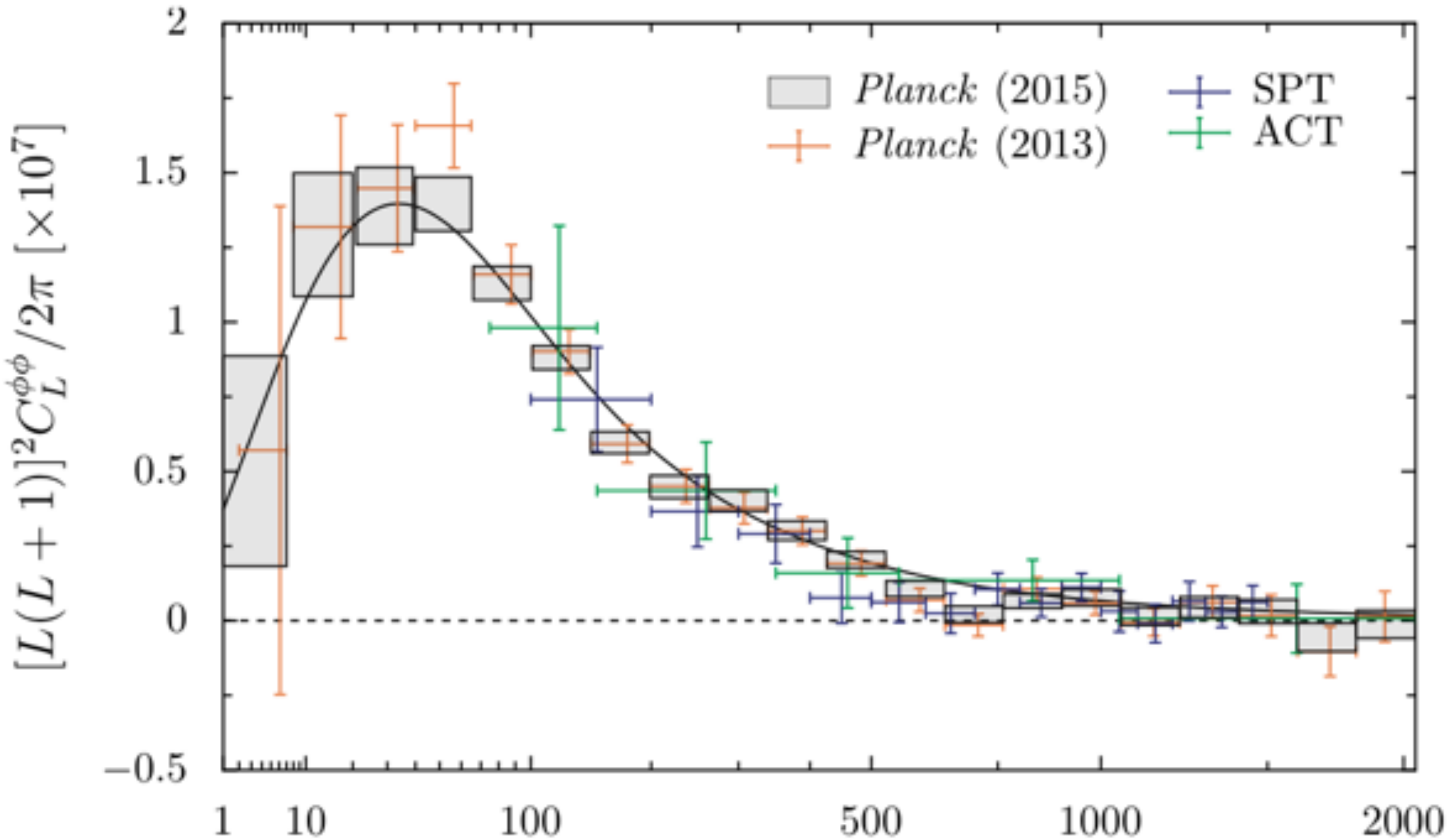
Neutrinos - fully relativistic at decoupling



Neutrinos - transition to become part of matter budget today.



CMB lensing power spectrum



Sensitive to the neutrino masses, Σm_ν