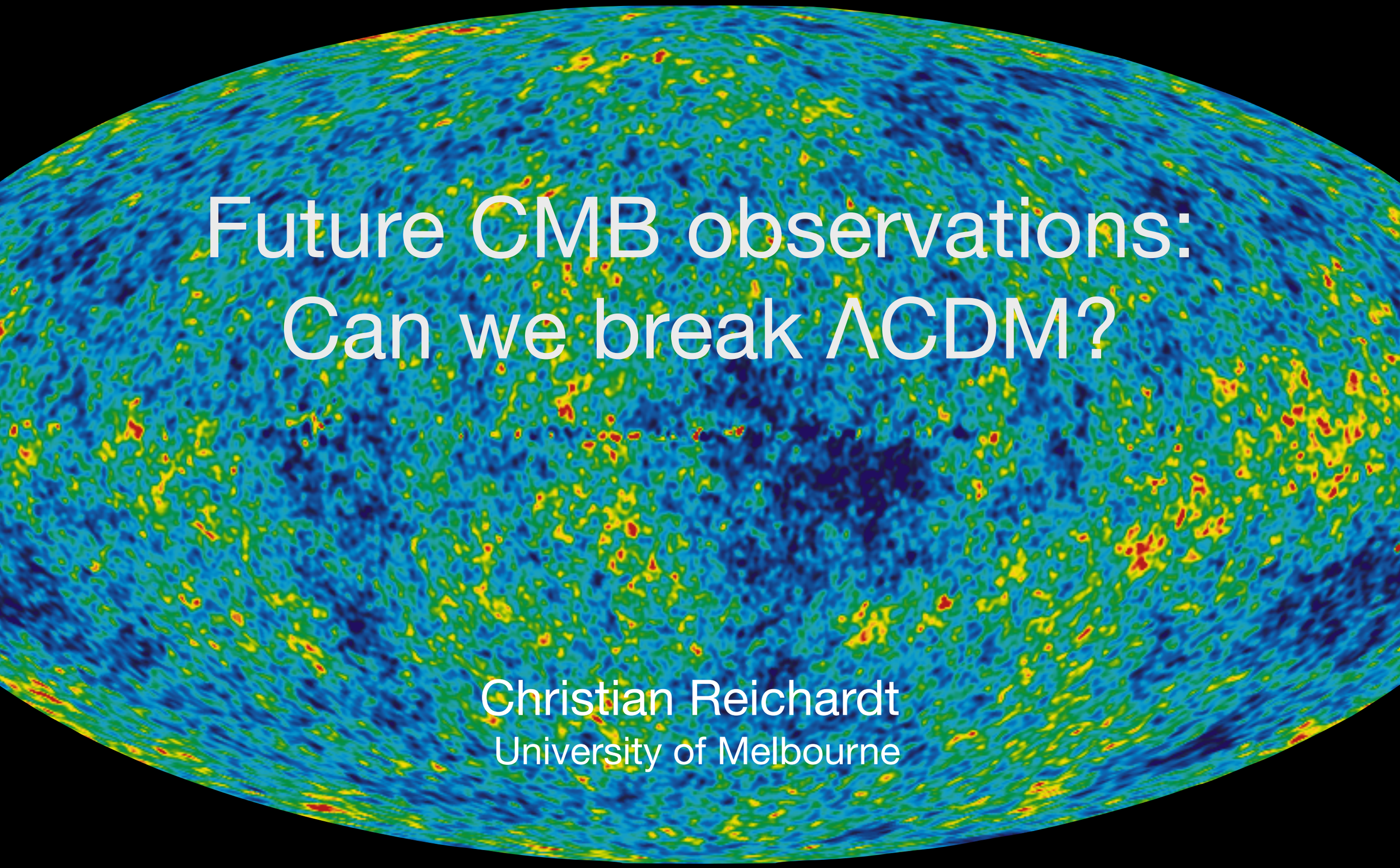


Future CMB observations: Can we break ΛCDM?

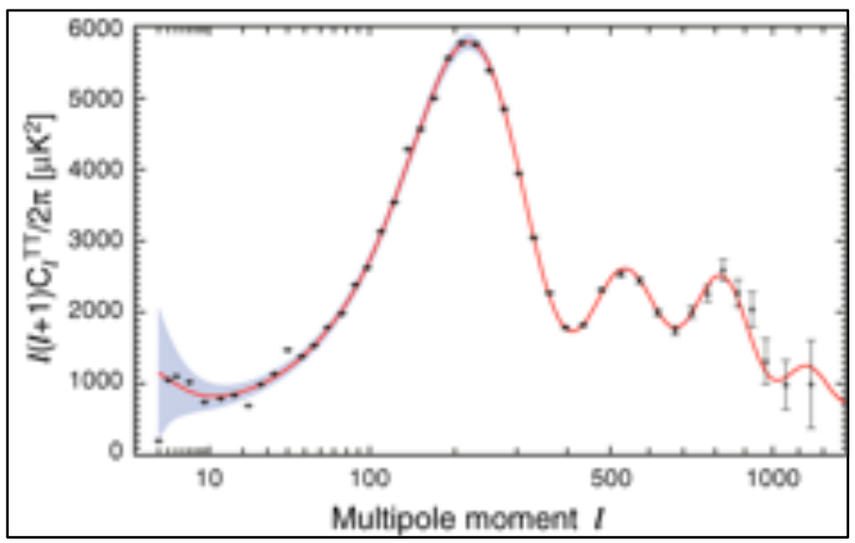
Christian Reichardt
University of Melbourne

Outline

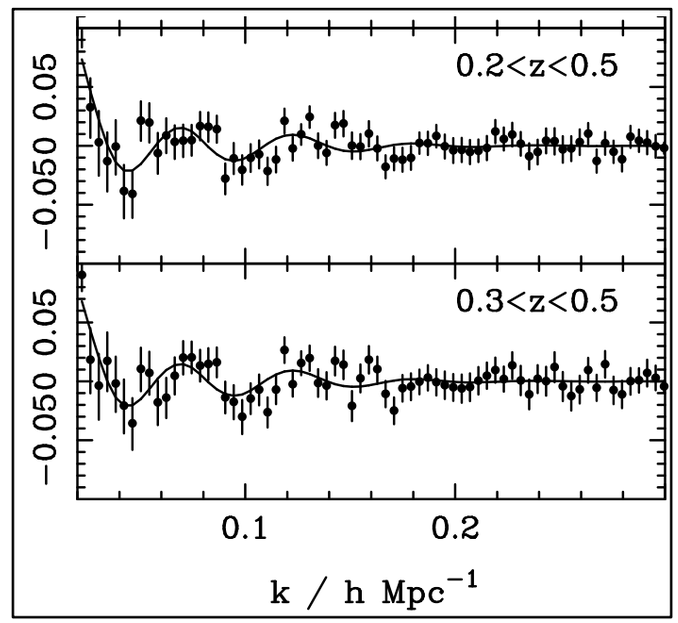
- Cosmic microwave background (CMB):
  - What are the neutrino masses?
  - What caused inflation?
- Future CMB experiments
  - Ground
  - Satellites

ΛCDM: 6 parameters fit all observations

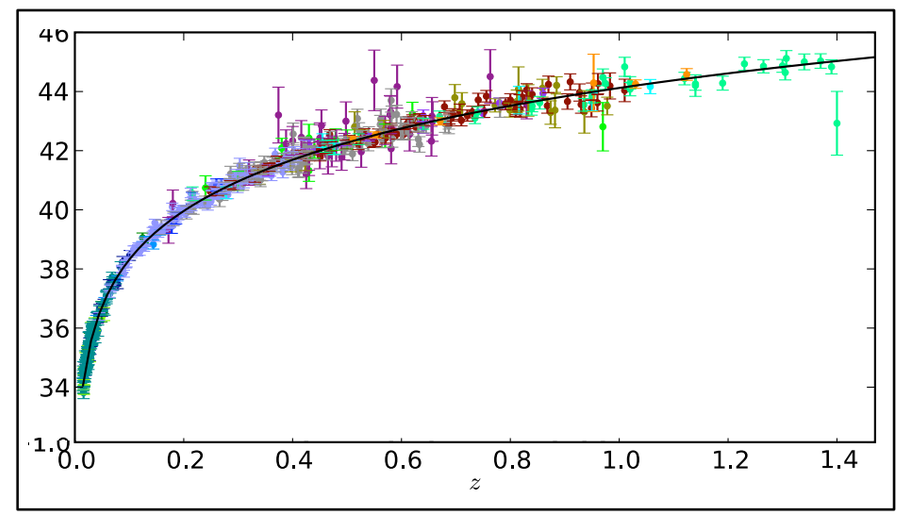
Larson et al 2011



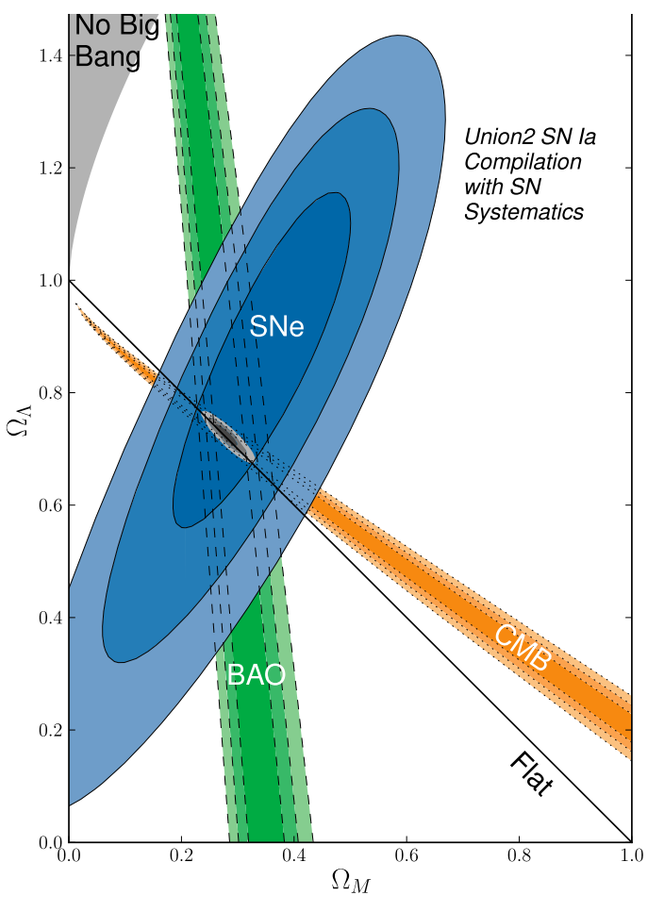
Percival et al 2010



Amanullah et al 2010



Cosmic Microwave Background + Large Scale Structure + Supernovae



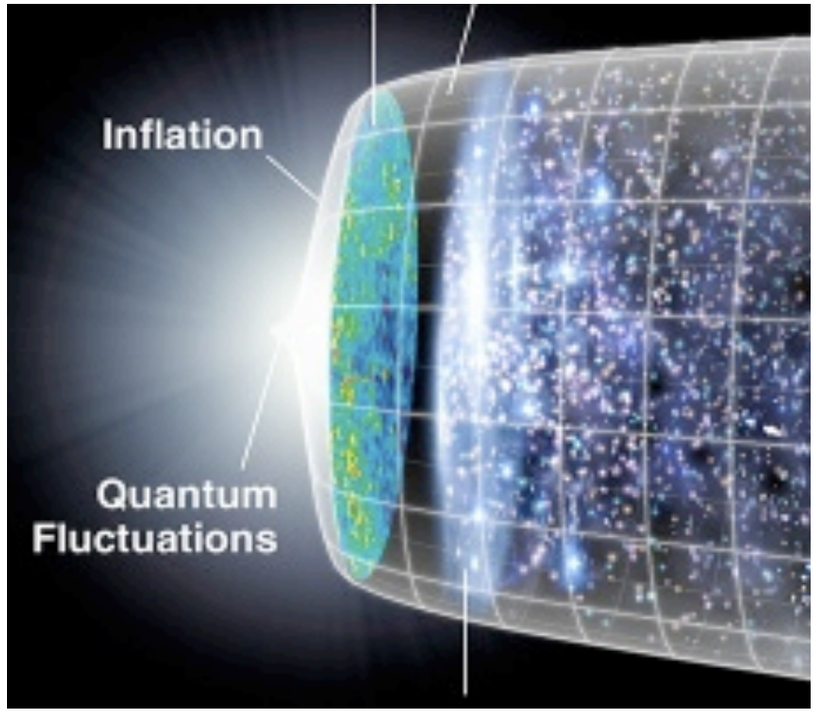
We live in a flat universe whose expansion is accelerating!

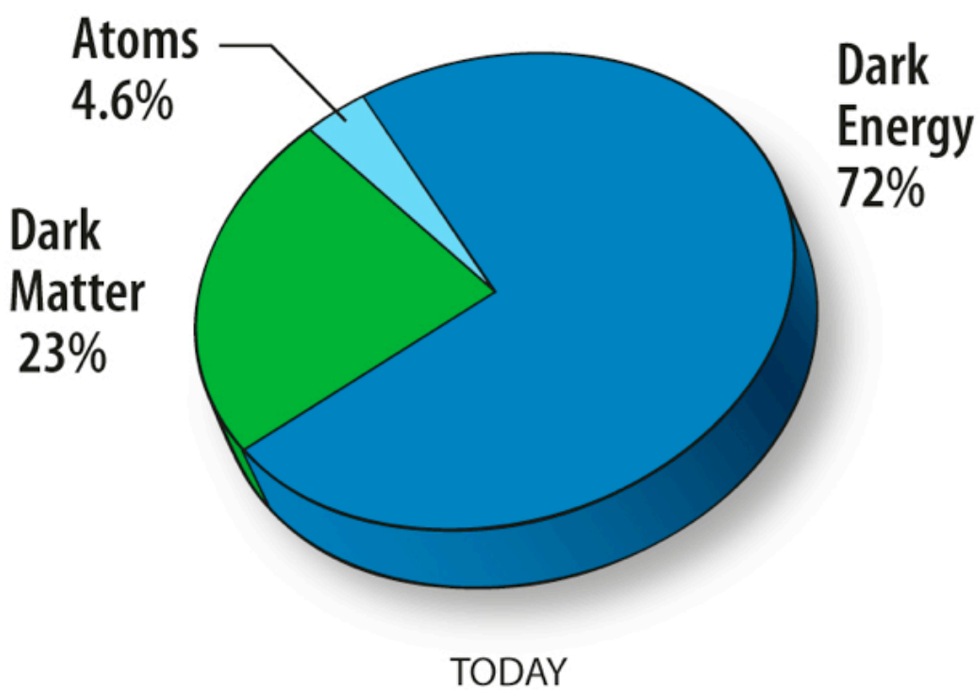
But this can’t last…

1. What are the neutrino masses?

2. What caused inflation?

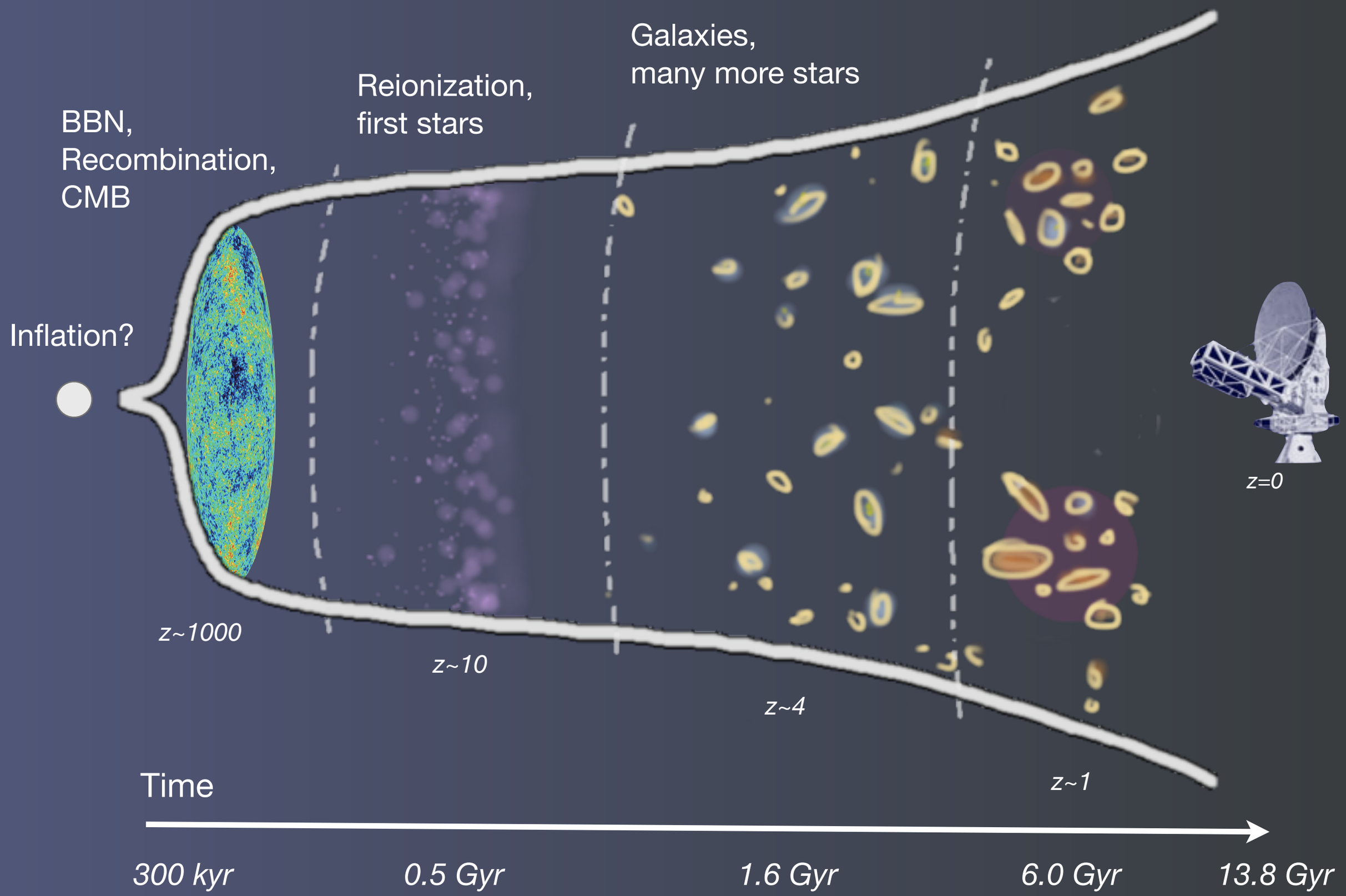
among others — is the Dark sector fully explained by 2 parameters?



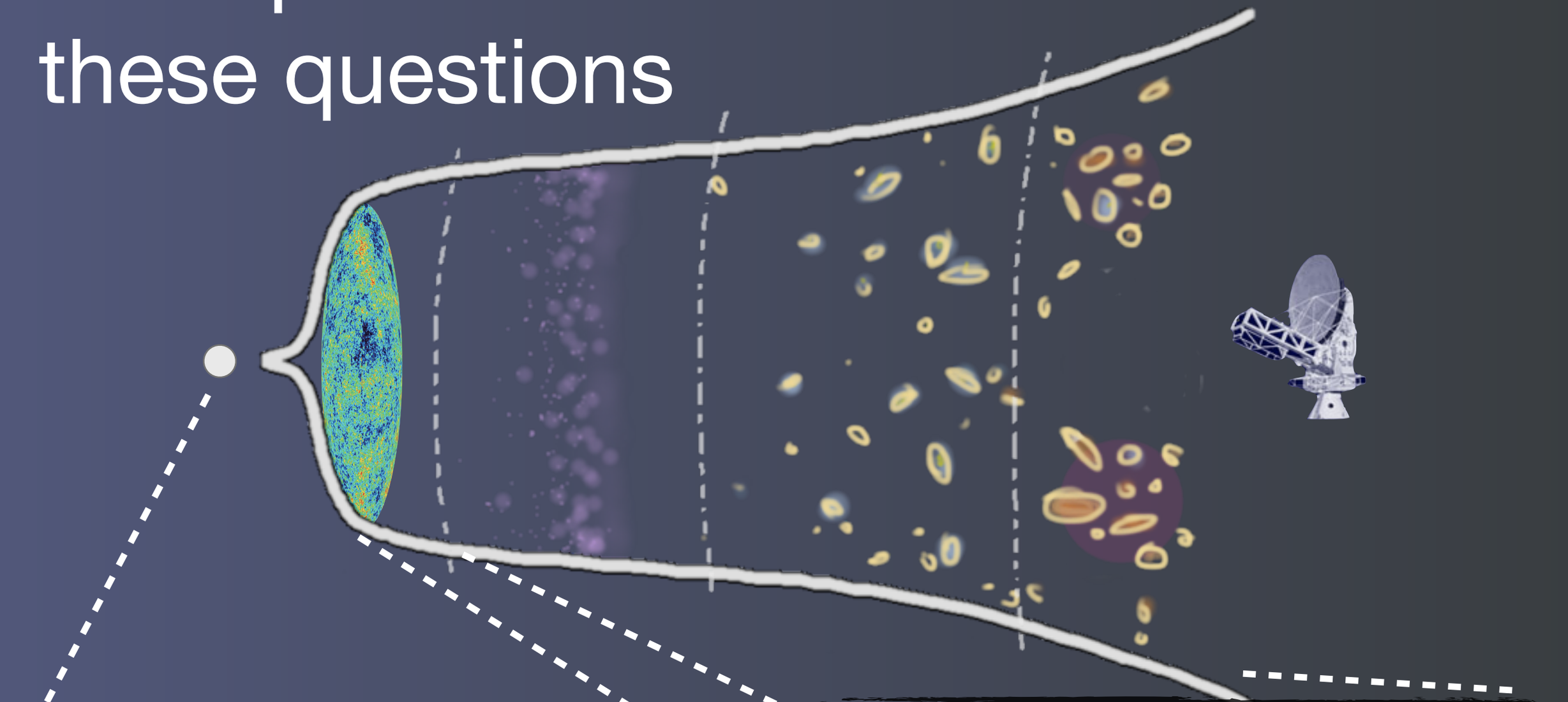


$$\Omega_\Lambda + \Omega_c = 0.9539 \pm 0.0015$$

Cosmic Timeline



CMB polarization can address these questions



CMB power spectrum:

- **What caused inflation?**
- **How many relativistic degrees of freedom (ie neutrino species) are present?**

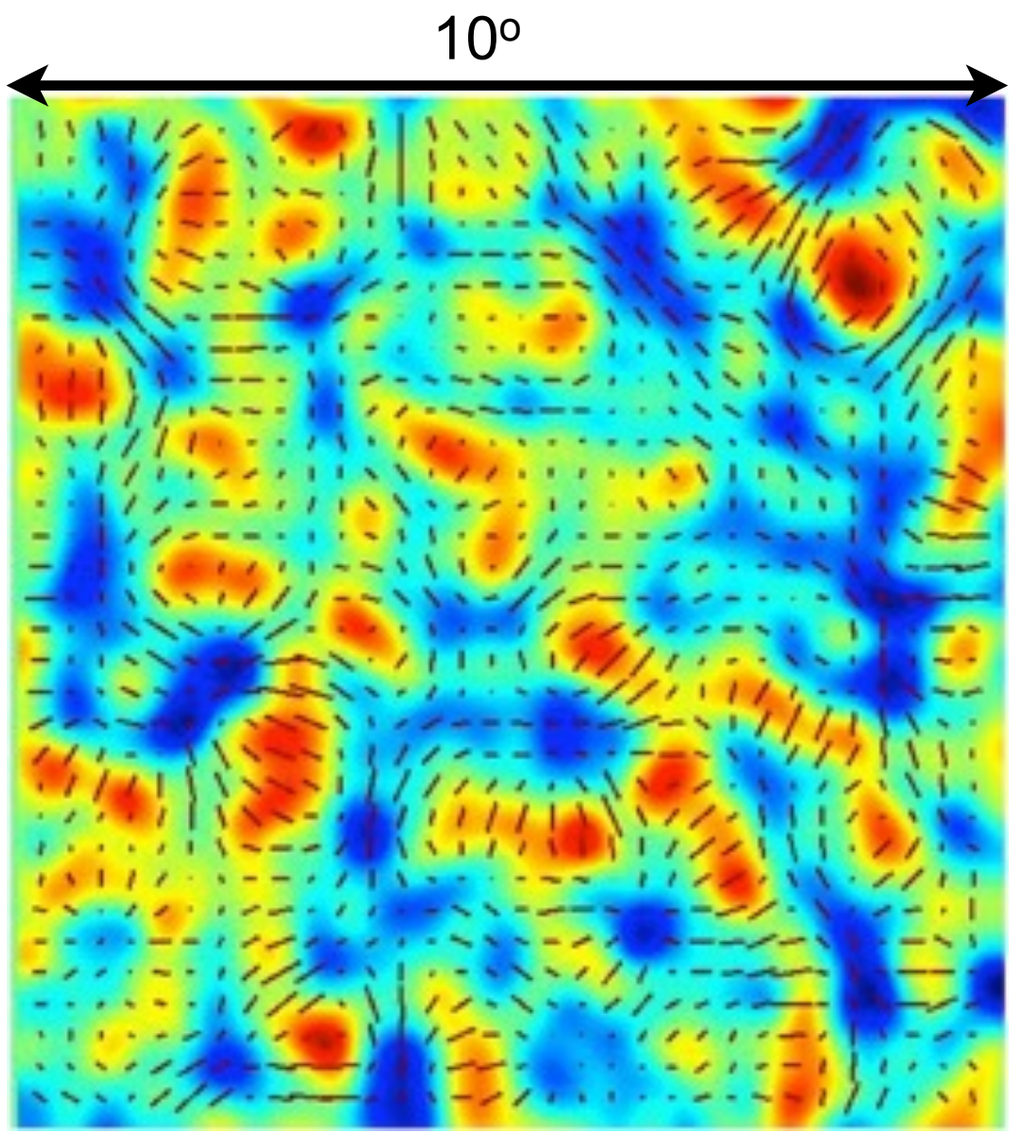
etc.

Gravitational lensing and the Sunyaev-Zel'dovich (SZ) effect:

- **What are the neutrino masses?**

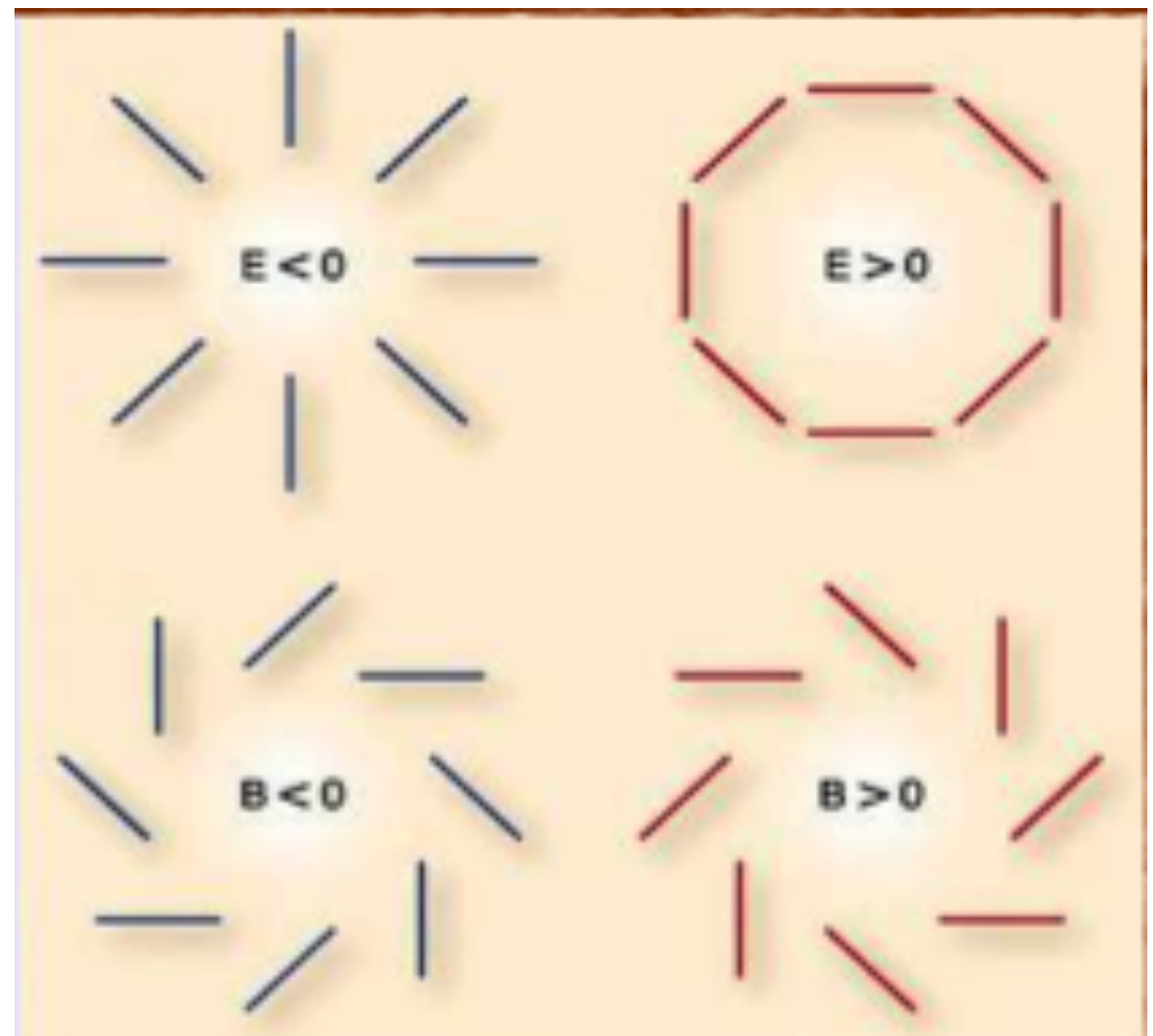
etc.

The CMB is polarized



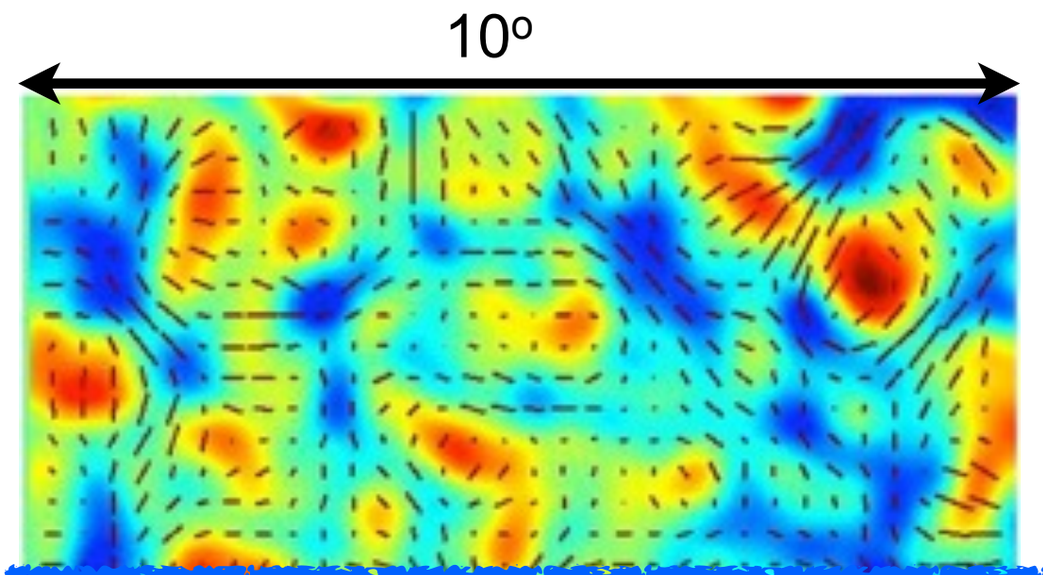
Smith et al 2008

- Any polarization pattern can be decomposed into “E” (grad) and “B” (curl) modes



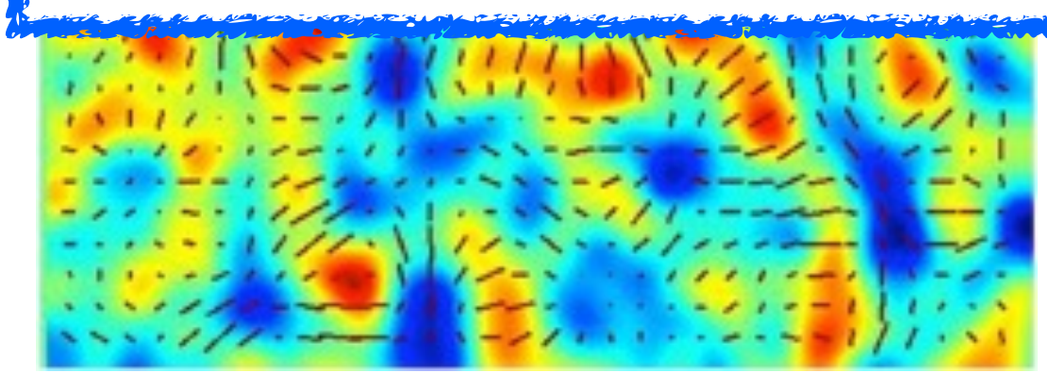
- Density fluctuations at LSS do not produce “B” modes!

The CMB is polarized

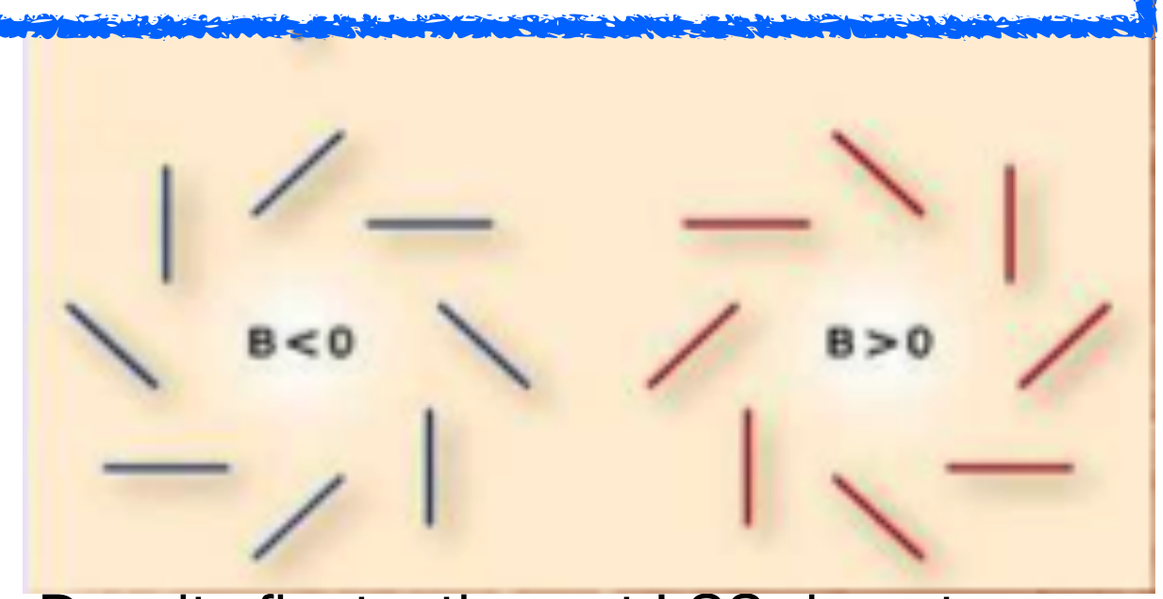


- Any polarization pattern can be decomposed into “E” (grad) and “B” (curl) modes

B-modes have a very low background!



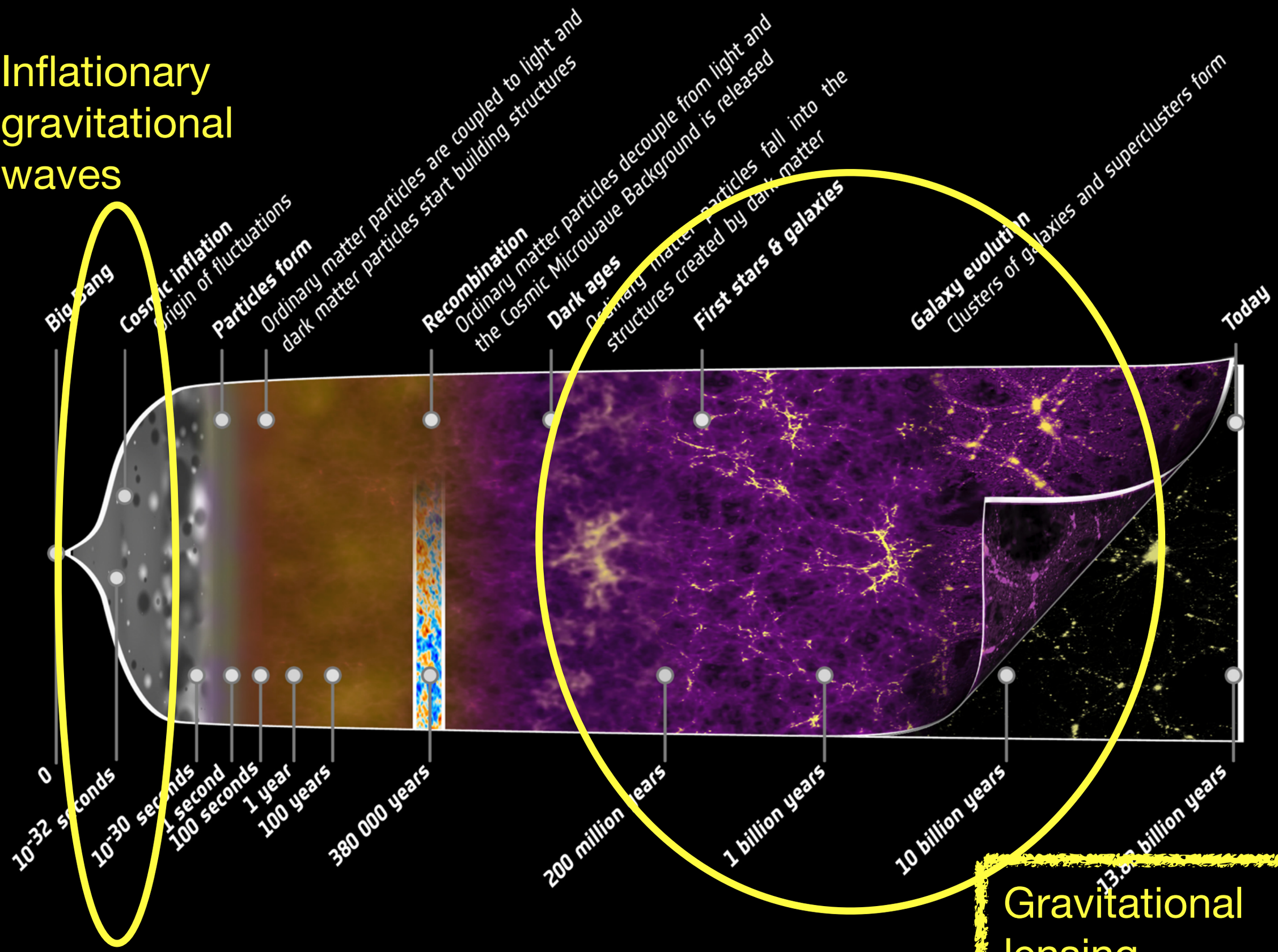
Smith et al 2008



- Density fluctuations at LSS do not produce “B” modes!

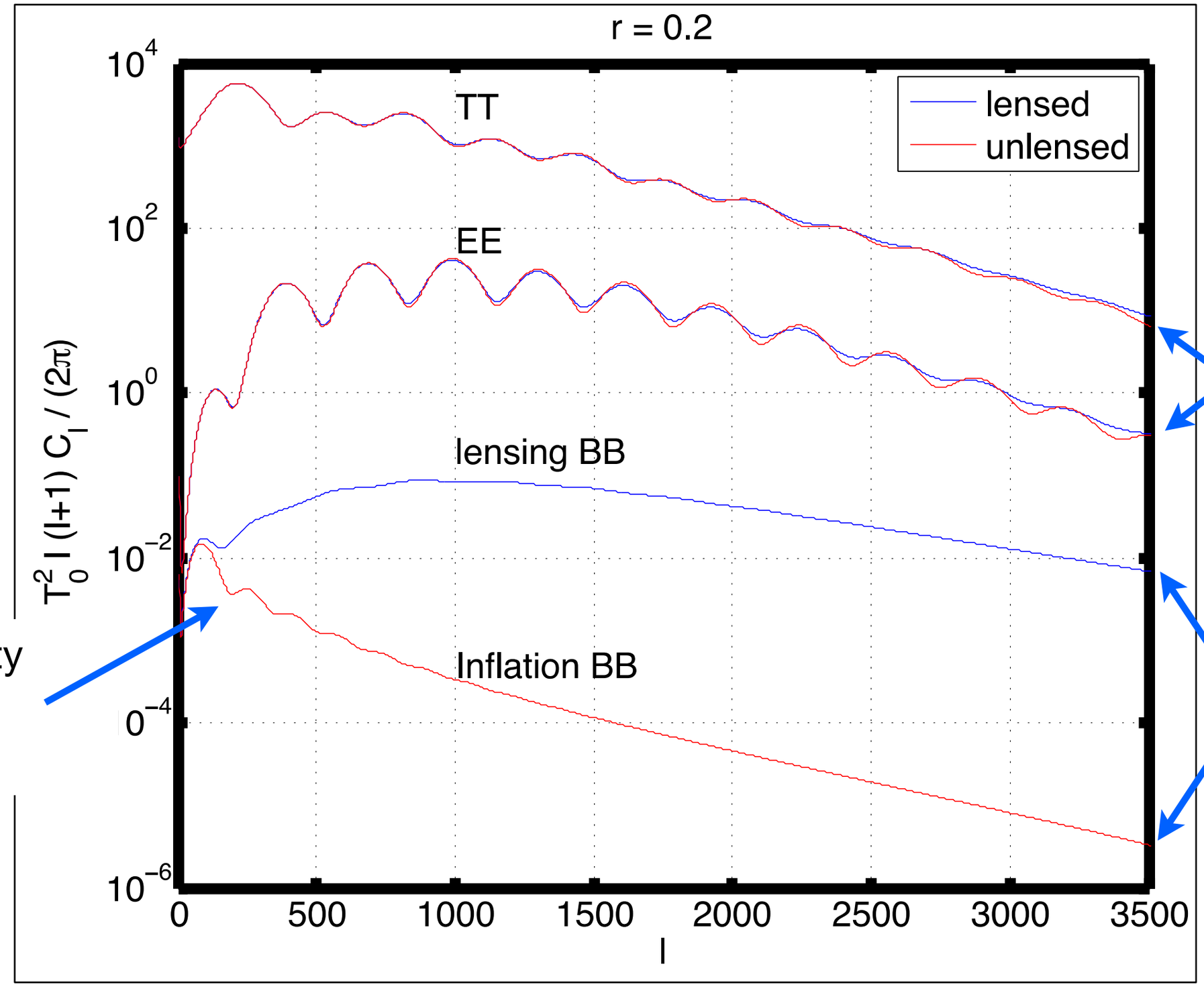
B-modes come from:

Inflationary gravitational waves



Gravitational lensing

Why look at Polarization?



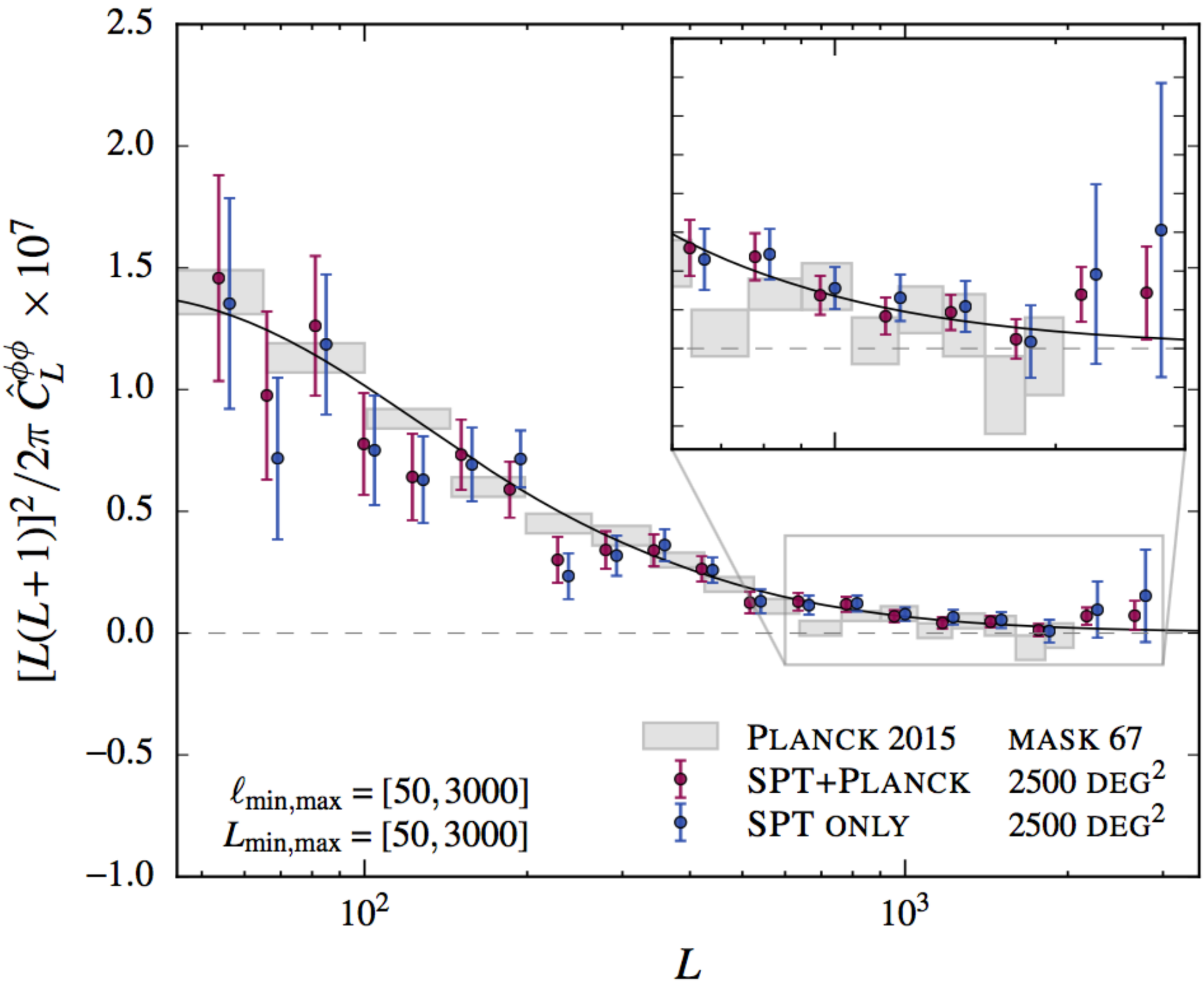
Effect of Lensing

Small Changes

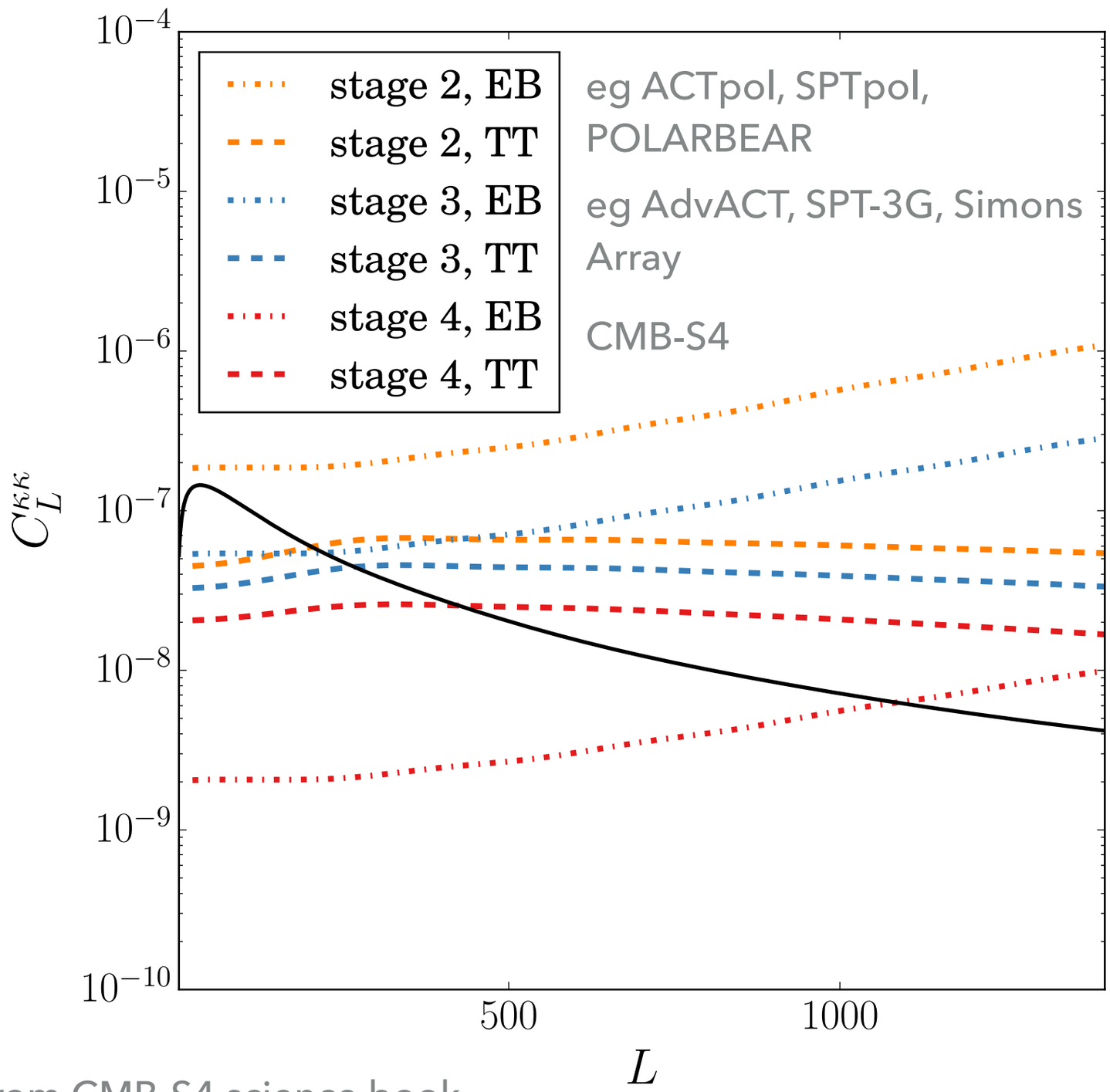
Big Changes!!!

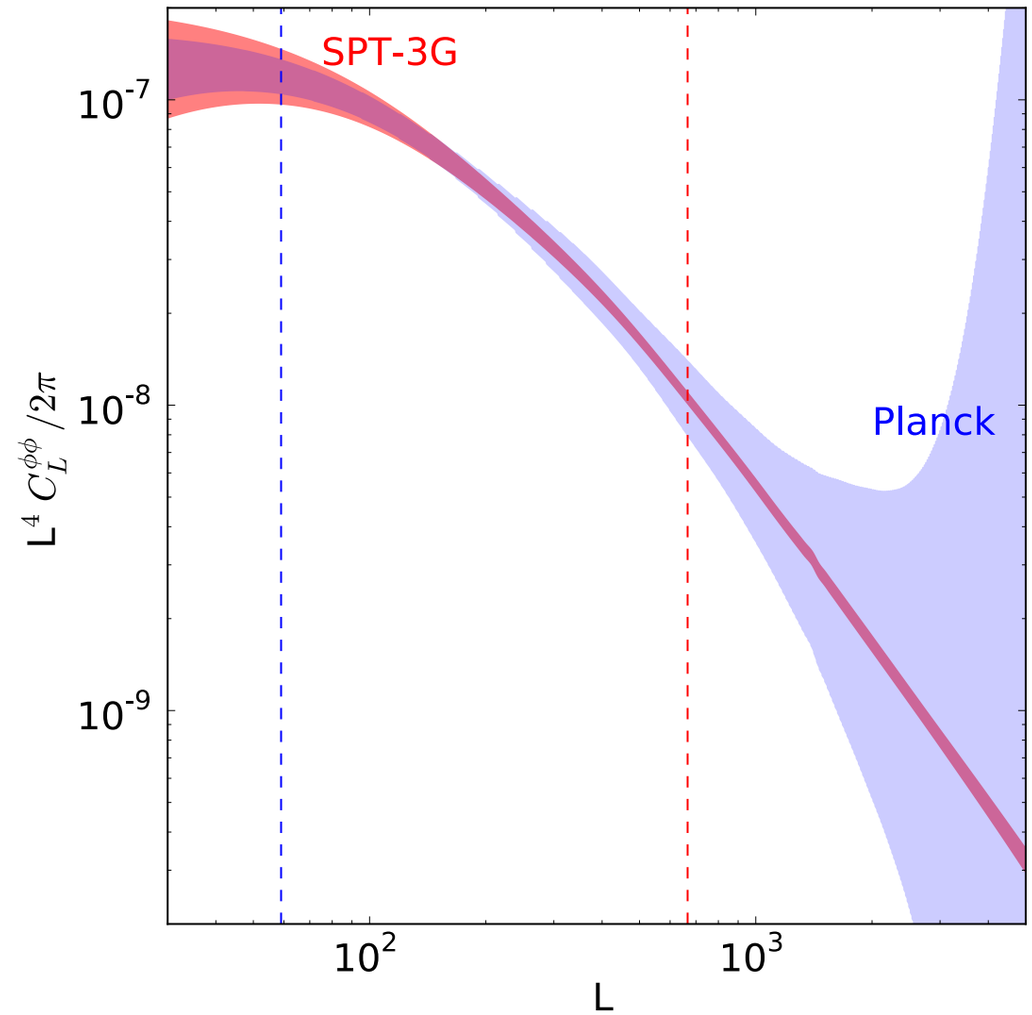
Gravity wave signal

Lensing power spectrum



Lensing power spectrum





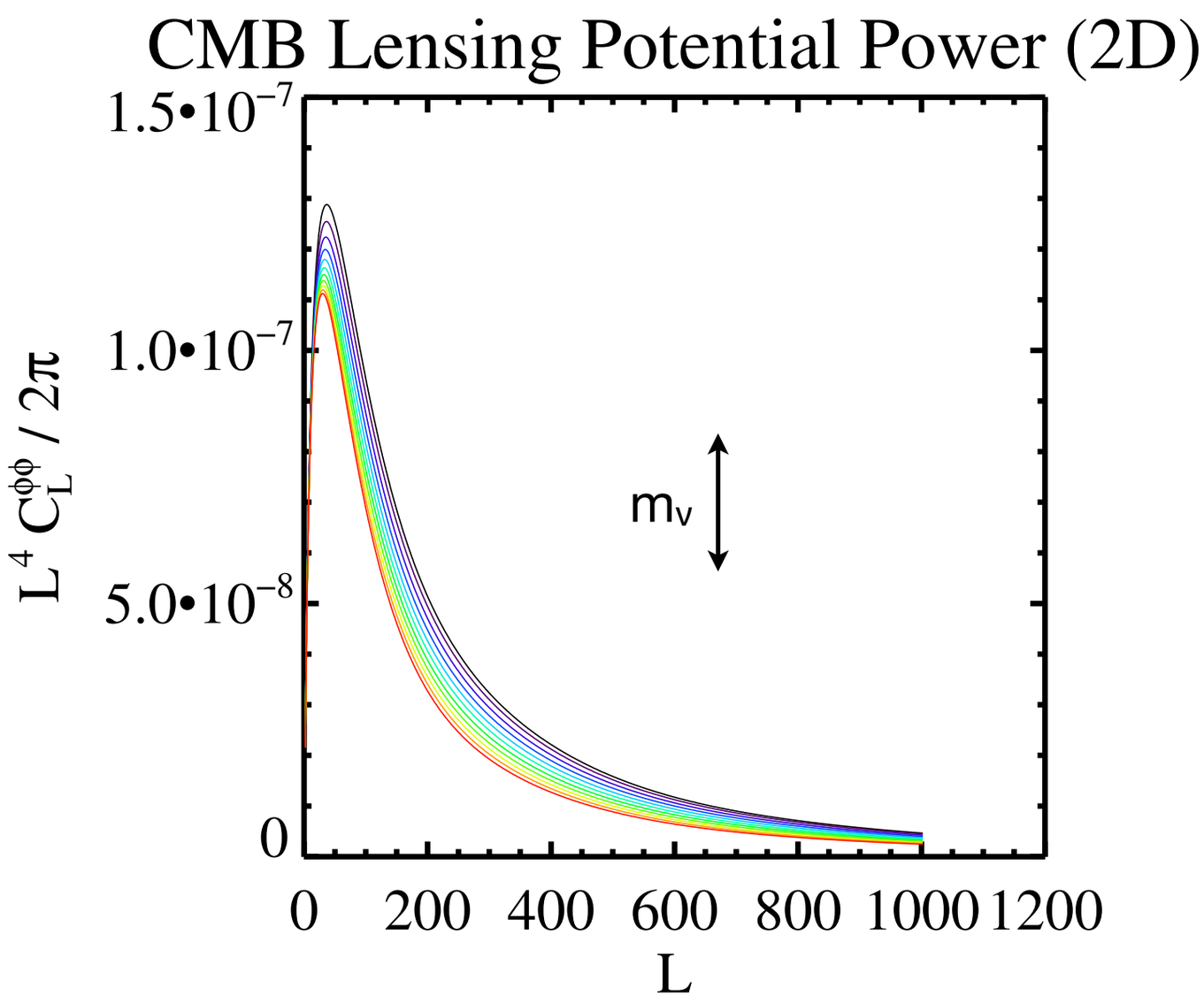
Sample variance limits:

* Planck L<40
* SPTpol, ACTpol, POLARBEAR: L < 200ish
* CMB-S4: L <1000 !

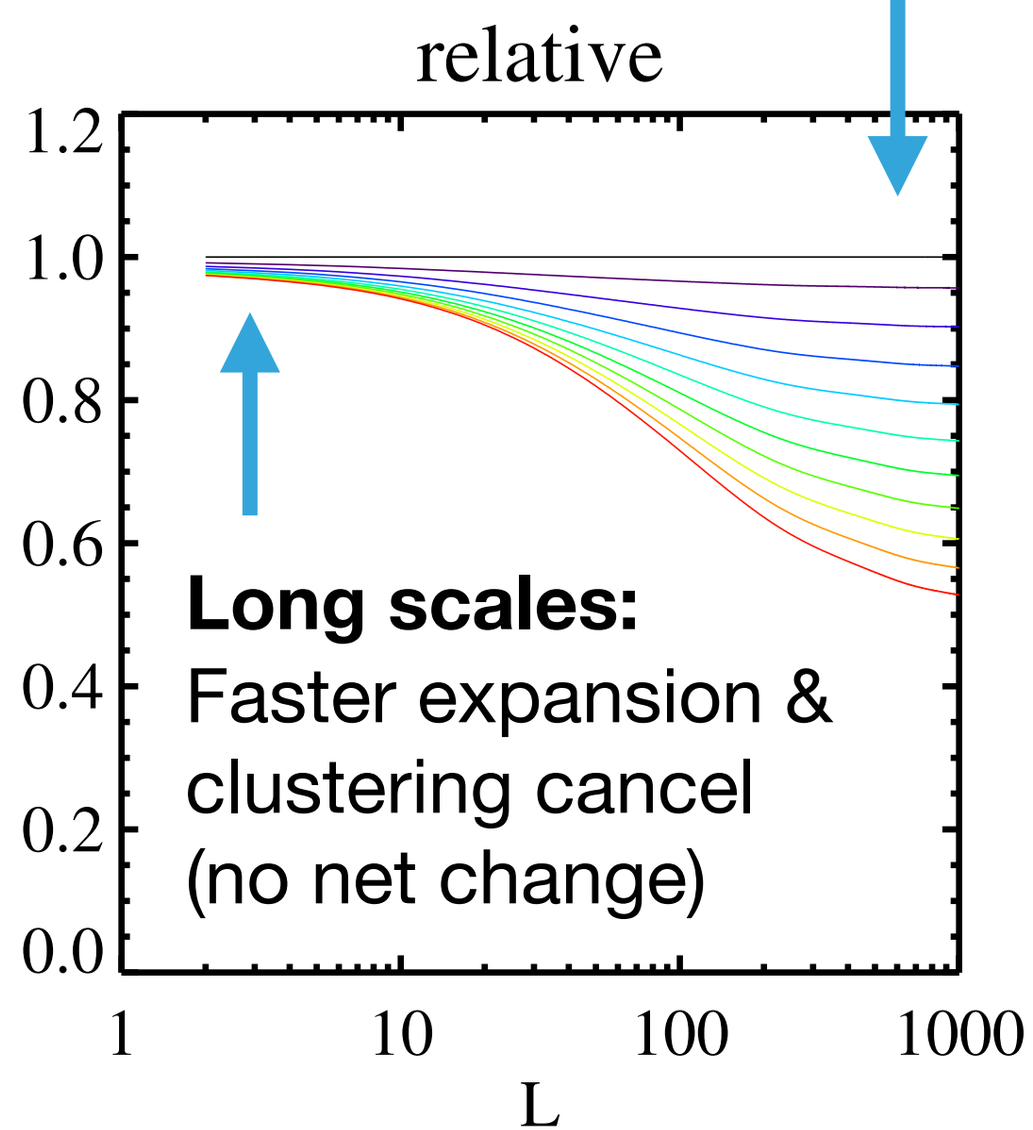
from CMB-S4 science book

Neutrinos mass from Lensing

Massive neutrinos reduce the lensing power spectrum

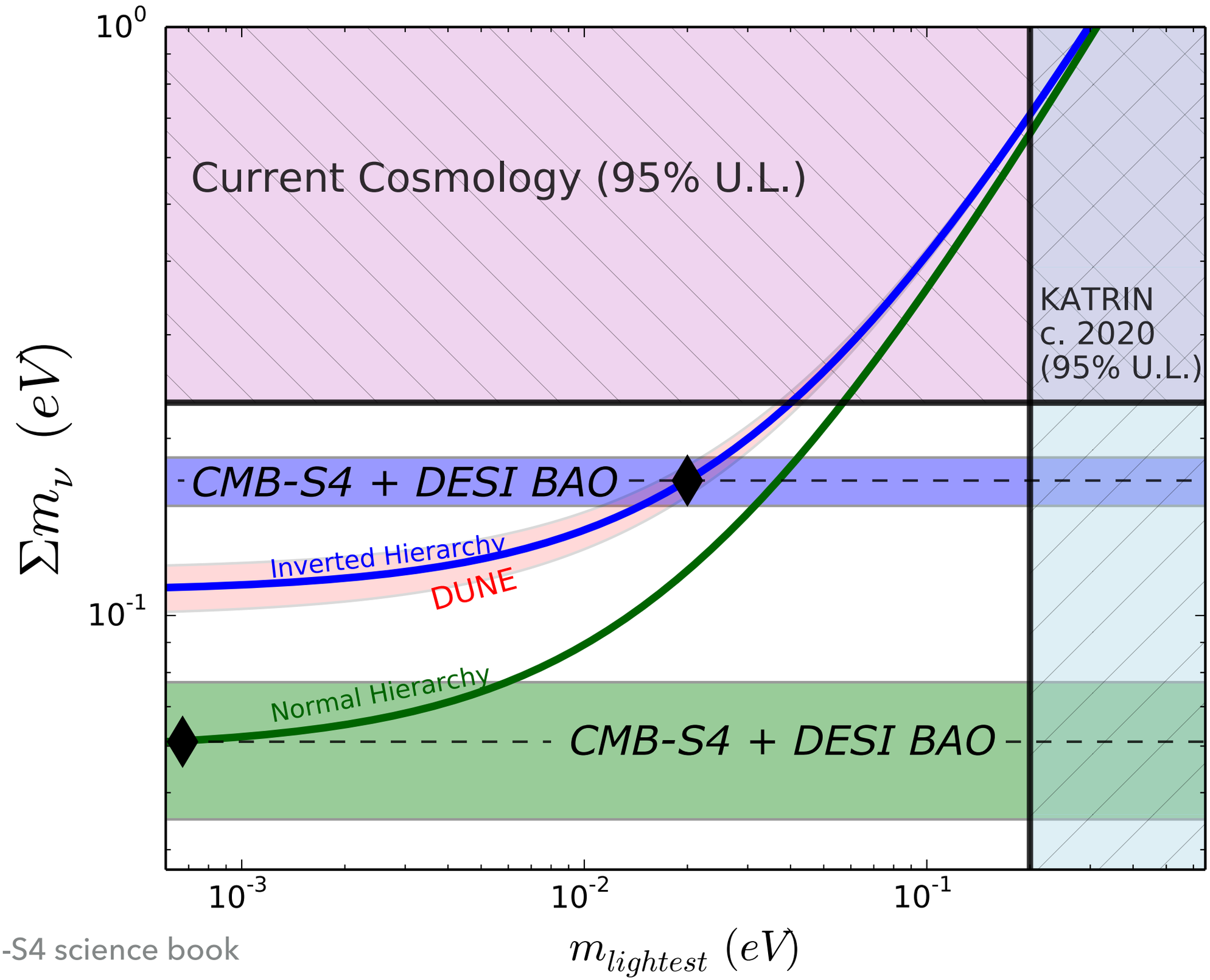


Short scales:
Faster expansion suppresses structure



Long scales:
Faster expansion & clustering cancel (no net change)

Neutrinos mass forecasts



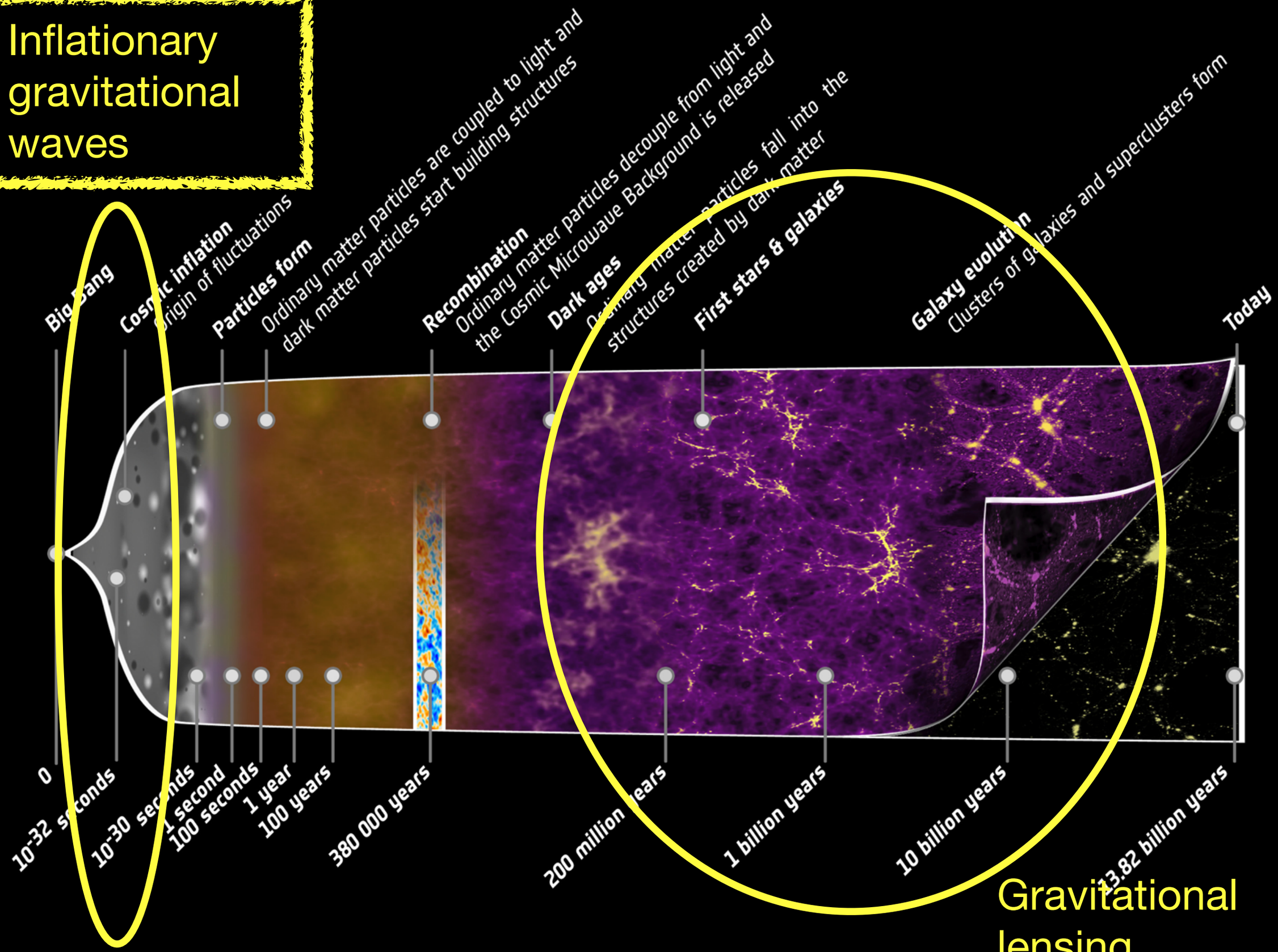
from CMB-S4 science book

Takeaway 1:

CMB lensing + BAO or H0 will measure sum of neutrino masses to 15 meV

B-modes come from:

Inflationary gravitational waves



Gravitational lensing

Tensor-to-scalar ratio (r)

Scalar perturbations

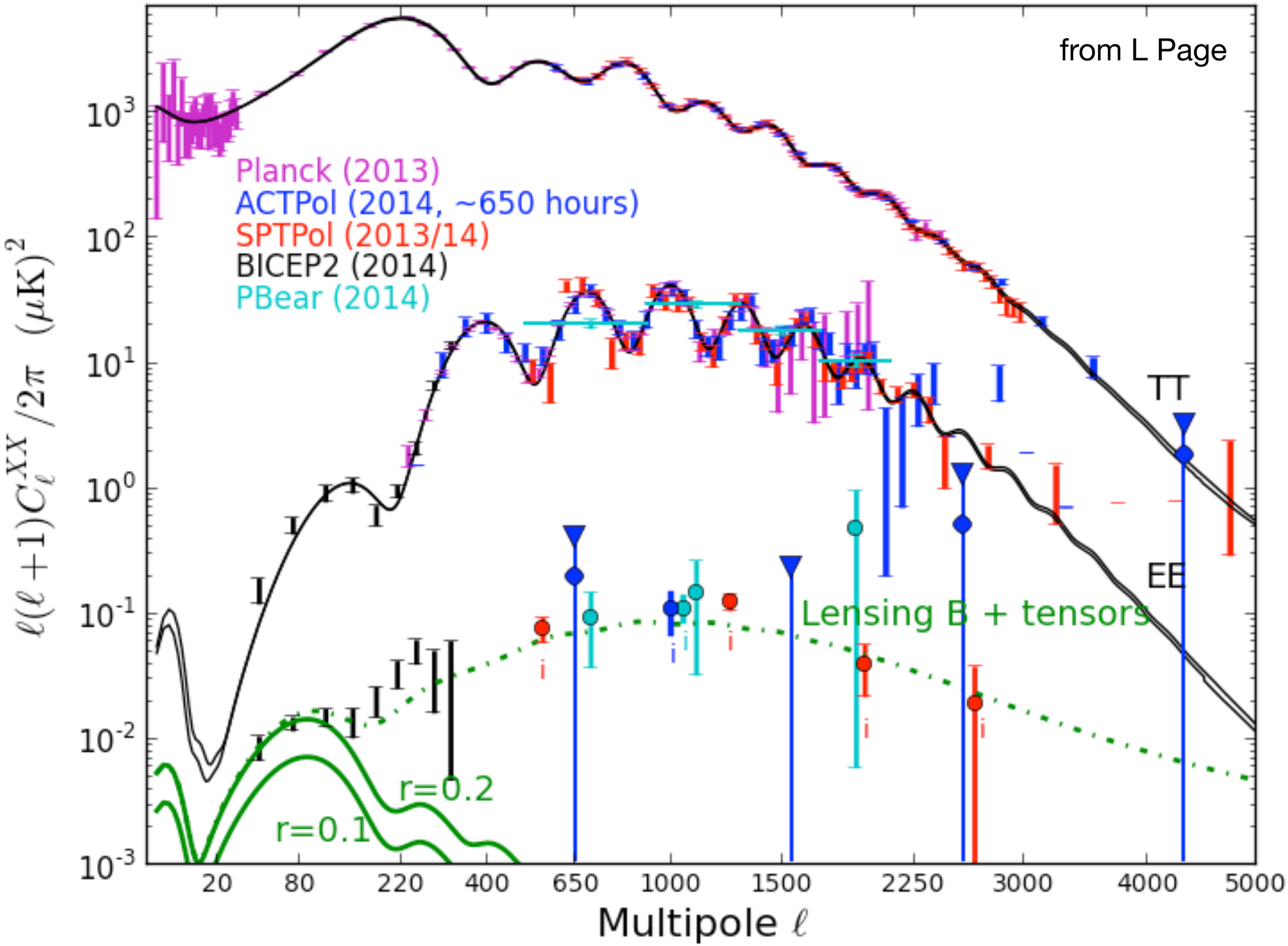
- Perturbations in the energy density.
- The *only* perturbations which form structure due to gravitational instability (therefore only ones required in a minimal model)

Tensor perturbations

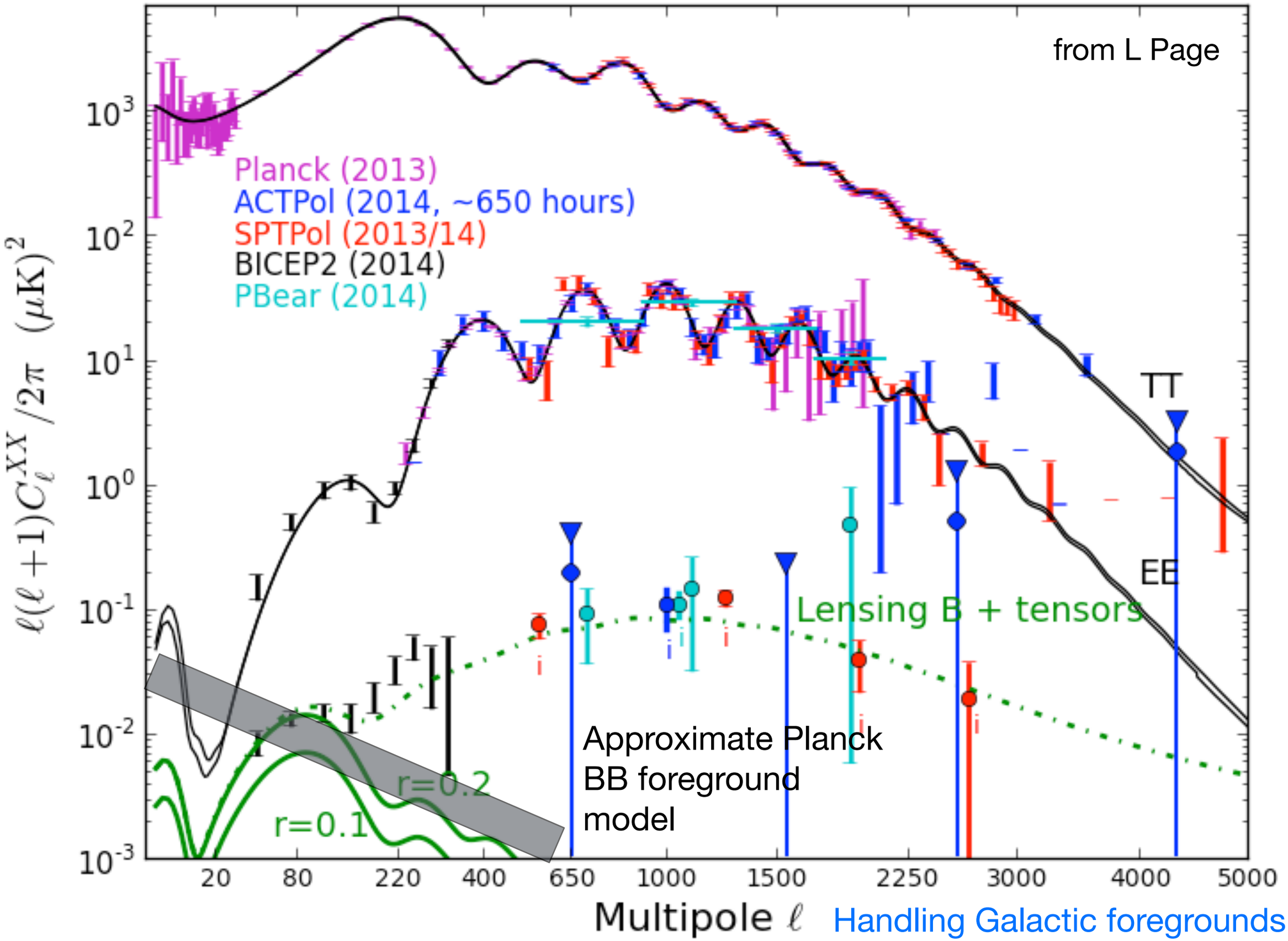
- Gravity waves - transverse-traceless metric perturbations
- Generally predicted by inflation models; amplitude related to energy scale at which inflation occurs.

r is the ratio of tensor to scalar power at a certain angular scale

Results since last Planck release

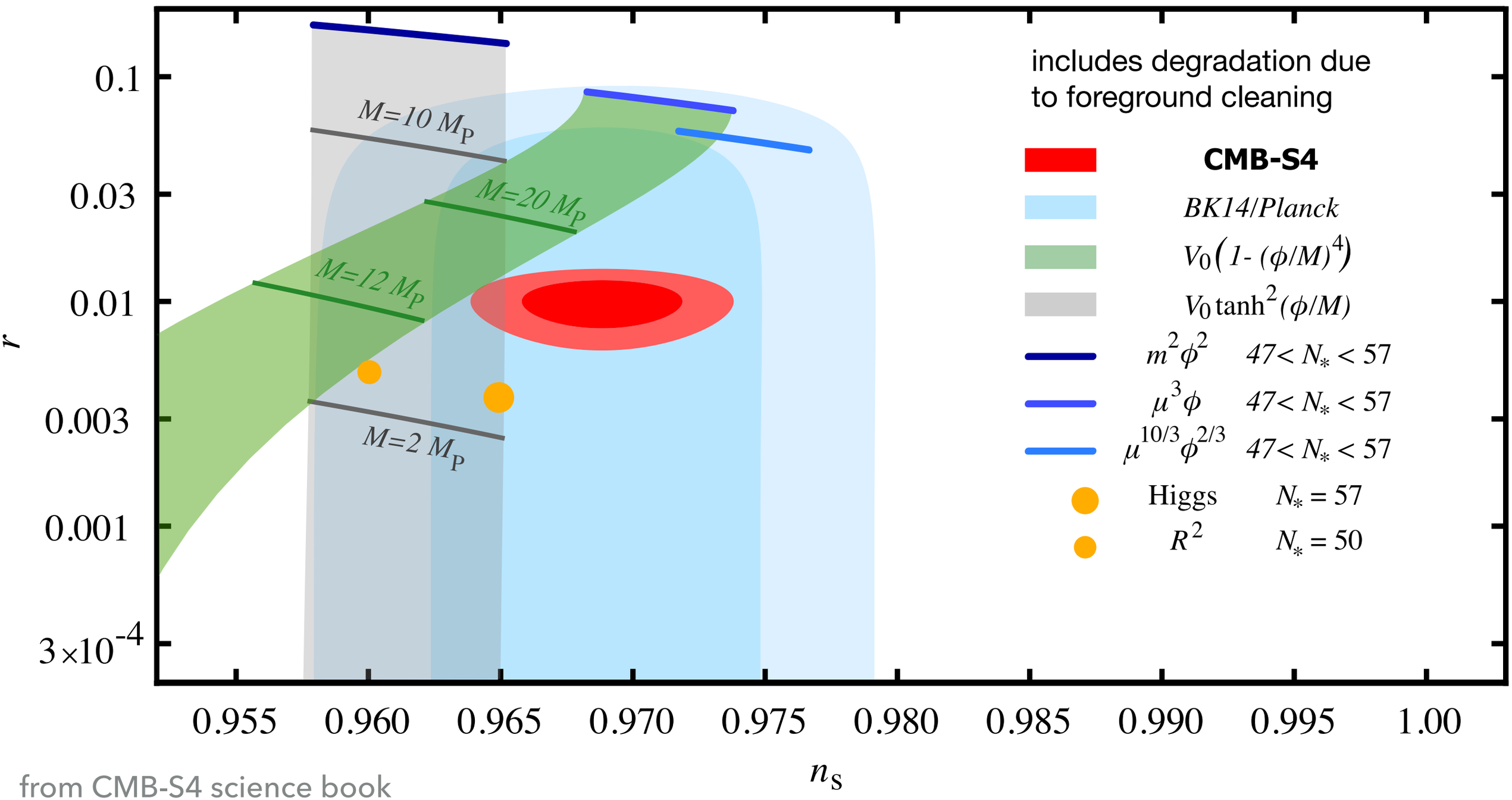


Results since last Planck release



Handling Galactic foregrounds is key!

Forecast Inflaton constraints



from CMB-S4 science book

Pushing limits to r~0.001 would rule out large field inflation models

Slam dunks in the next decade

- 95% limit r < 0.001 (or detection) **ℓ < 200**
- Measure the sum of the neutrino masses to 15 meV. **200< ℓ < 4000**

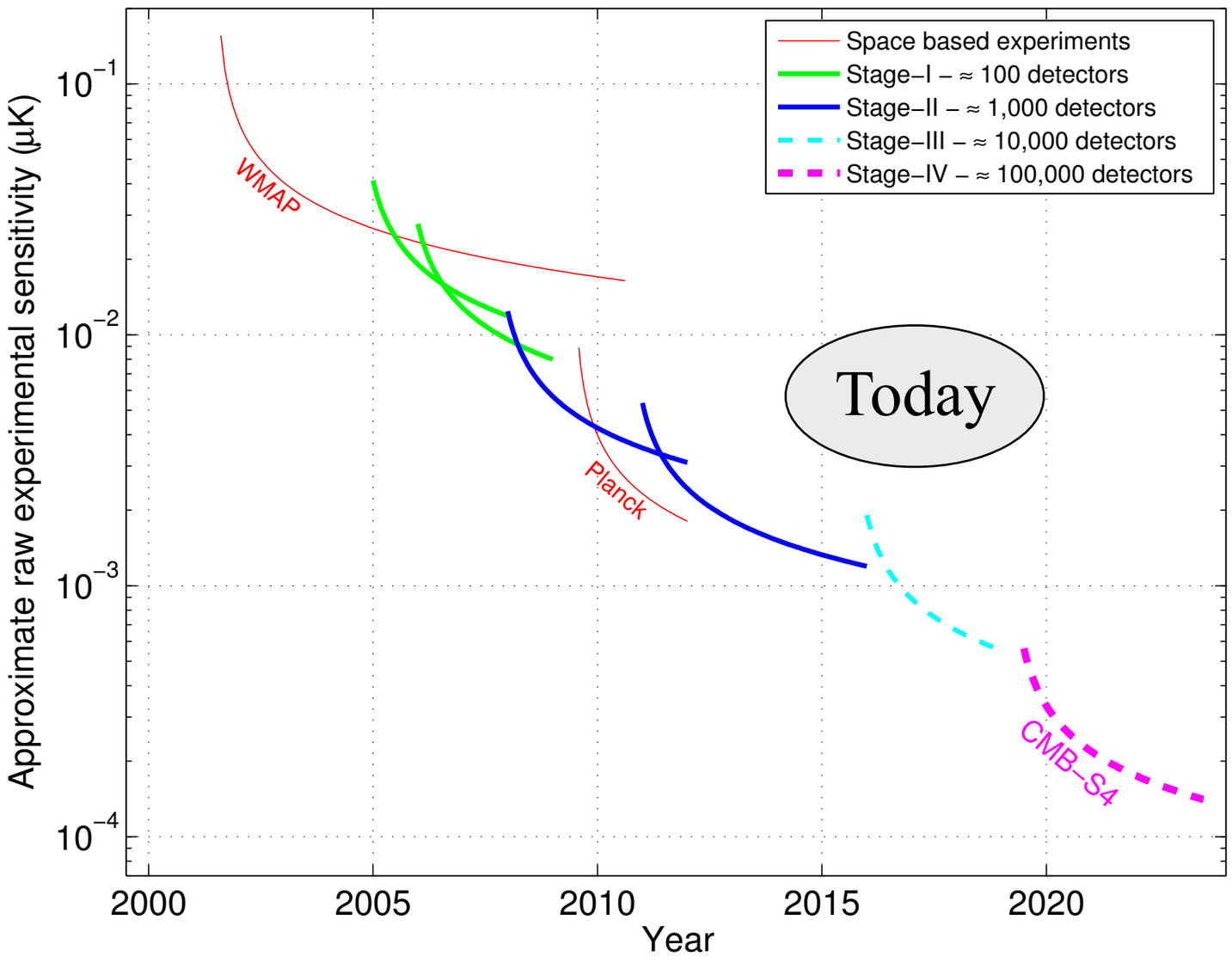
- Probes of dark energy from the abundance of galaxy clusters selected by the Sunyaev-Zel'dvich effect
- New tests of GR & the std. model through cross-correlations & growth of structure

Outline

- ☑ Cosmic microwave background (CMB):
  - What are the neutrino masses?
  - What caused inflation?
- Future CMB experiments
  - Ground-based
  - Satellites

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB Experimental Stages



Stage-III CMB experiments are starting now, e.g., BICEP3, CLASS, SPT-3G, AdvACT, Simons Array

Stage-IV CMB experiment = **CMB-S4**
~200x faster than the Stage 2 experiments that just finished

Enabling technologies:

- **First multichroic detectors on-sky in 2017.**
- **Better multiplexing**
- **Beginning to deploy tens of thousands of detectors**

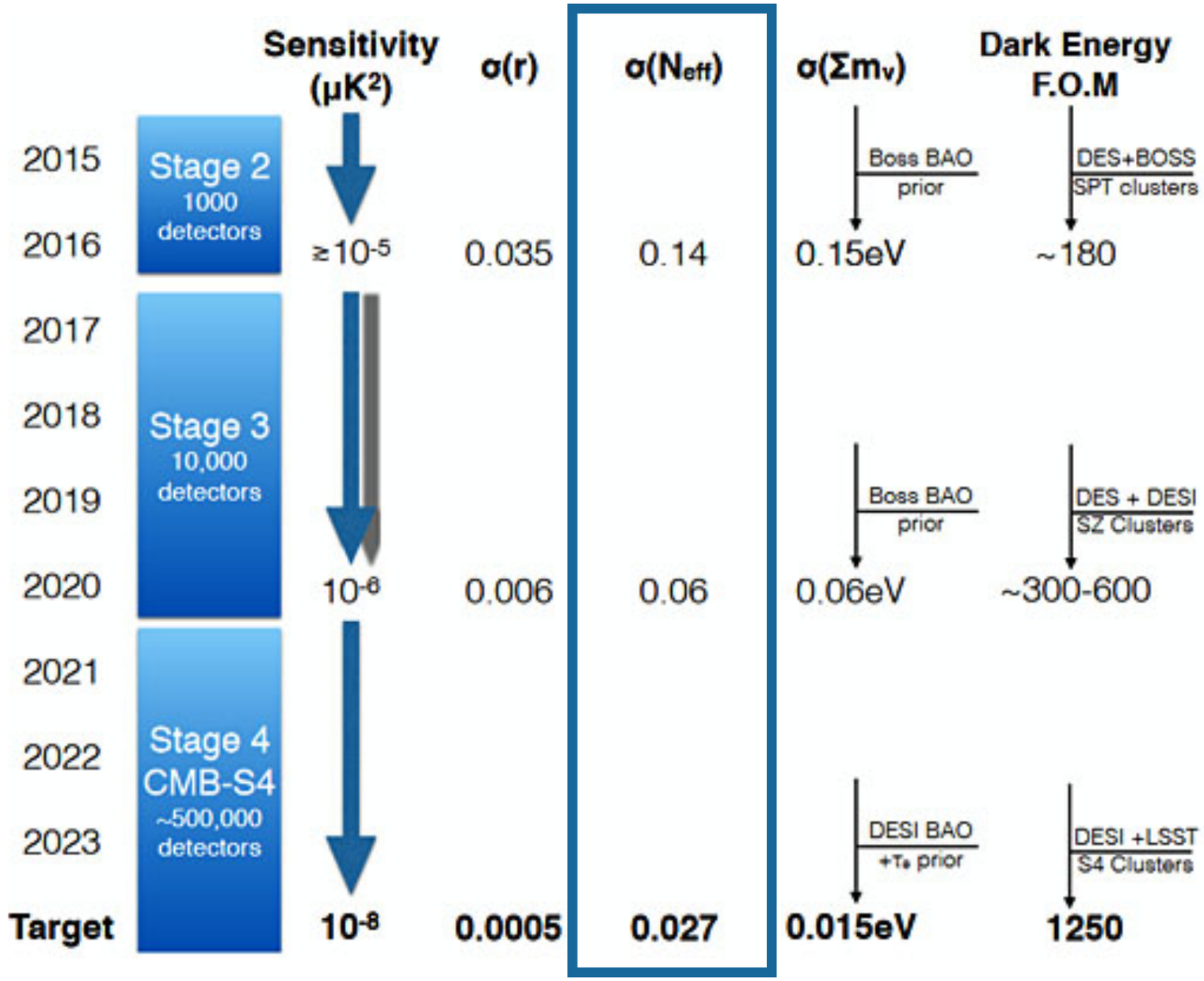
CMB-S4 Science Book

CMB Experimental Stages: Science forecasts

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\geq 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+T_\star$ prior	DESI +LSST S4 Clusters
Target		10^{-8}	**0.0005**	**0.027**	**0.015eV**	**1250**
Order of magnitude improvements compared to today:			**x70**	**x6**	**x10**	**x7**

CMB-S4 Science Book

CMB Experimental Stages: Science forecasts



Theoretical targets:

$\Delta N_{eff} \geq 0.047$ for spin 1/2, 1, or 3/2

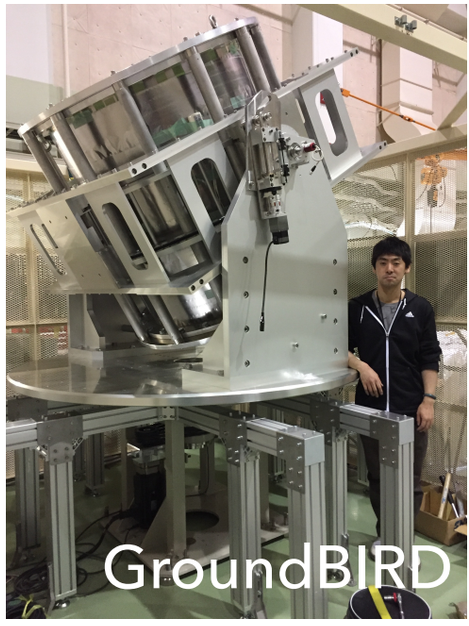
$\Delta N_{eff} \geq 0.027$ for spin 0

if in thermal equilibrium at some point

First light in 2017-2018

~10-20k detectors

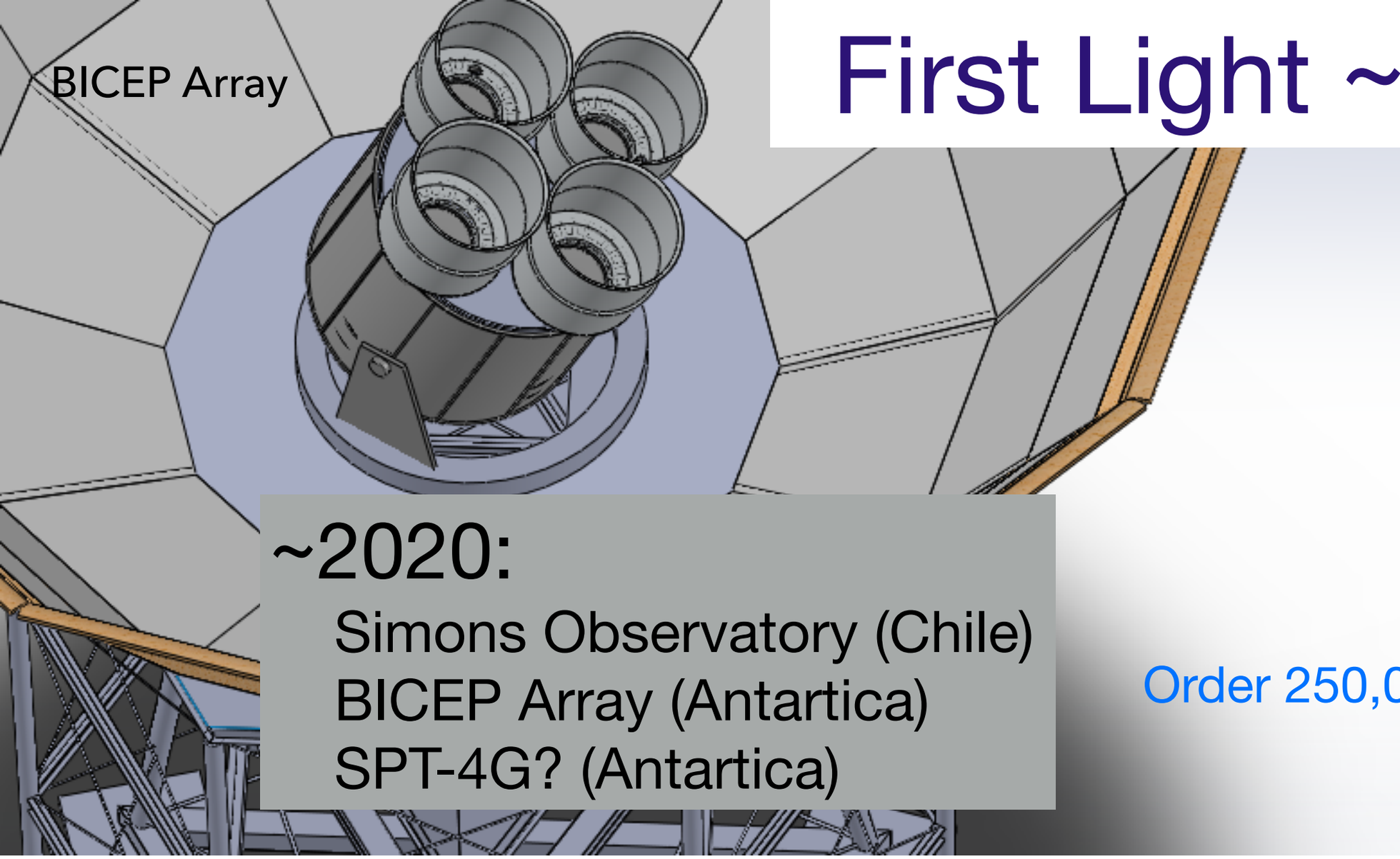
		Planned freqs
Chile		
AdvACT	+Lens	30, 40, 90, 150, 230 GHz
*Simons Array	+Lens	90, 150, 220, 280 GHz
CLASS		40, 90, 150 GHz
*GroundBIRD - *MKIDs*		150, 220 GHz
Antarctica		
BICEP3		90, 150, 220 GHz
SPT-3G	+Lens	90, 150, *220* GHz



Experiments finishing now have ~6000 detector-years

The experiments starting now plan order 70,000 detector-years

First Light ~2020+



Also Balloons:
SPIDER2
EBEX - IDS

~2020:
- Simons Observatory (Chile)
- BICEP Array (Antartica)
- SPT-4G? (Antartica)

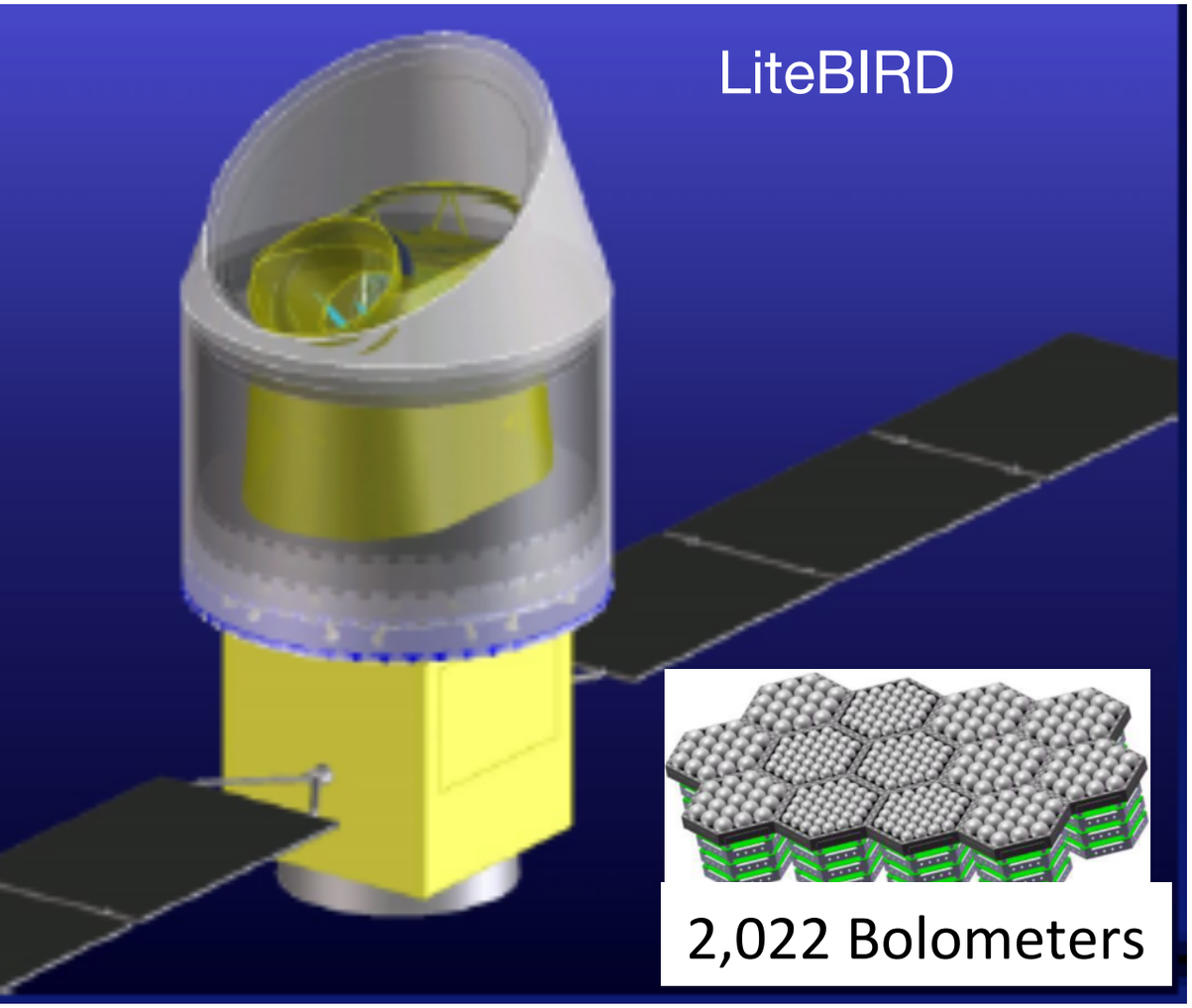
Order 250,000 detector-years

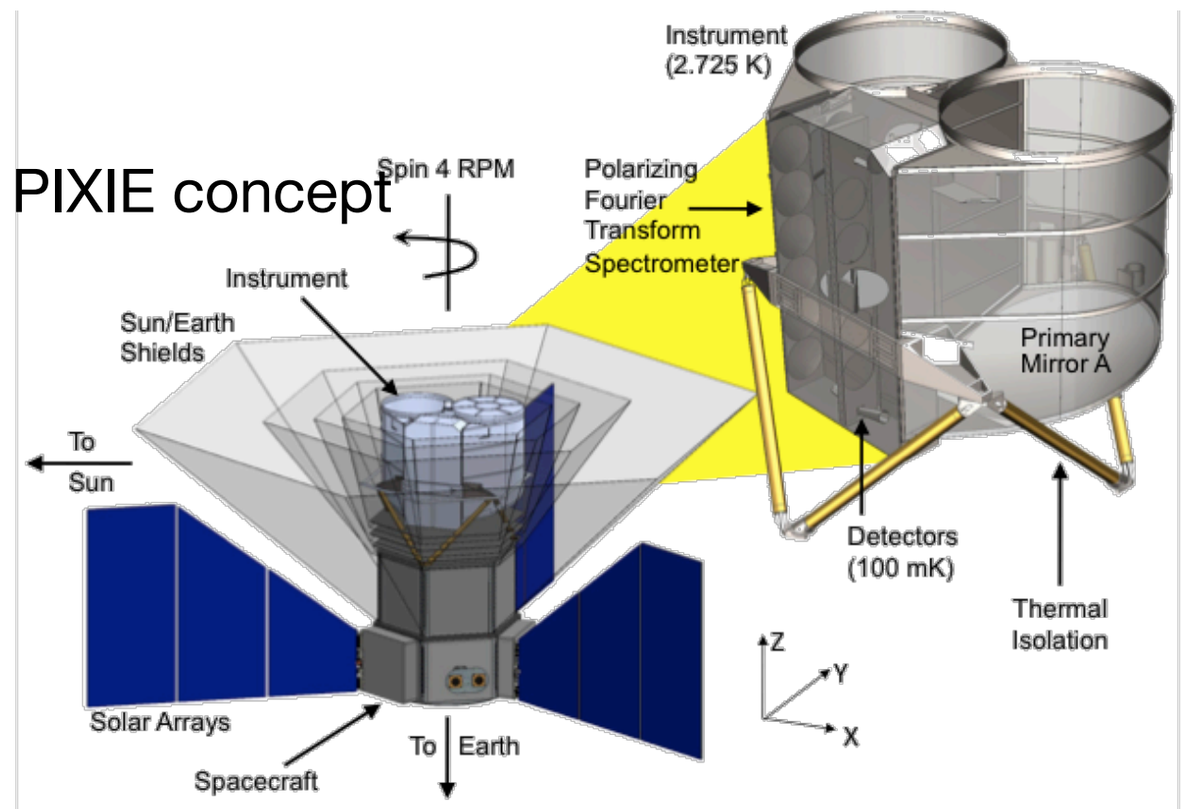
early-mid 2020s

CMB-S4 (Chile, Antartica)

Goal: 2 million detector-years

Future Satellites

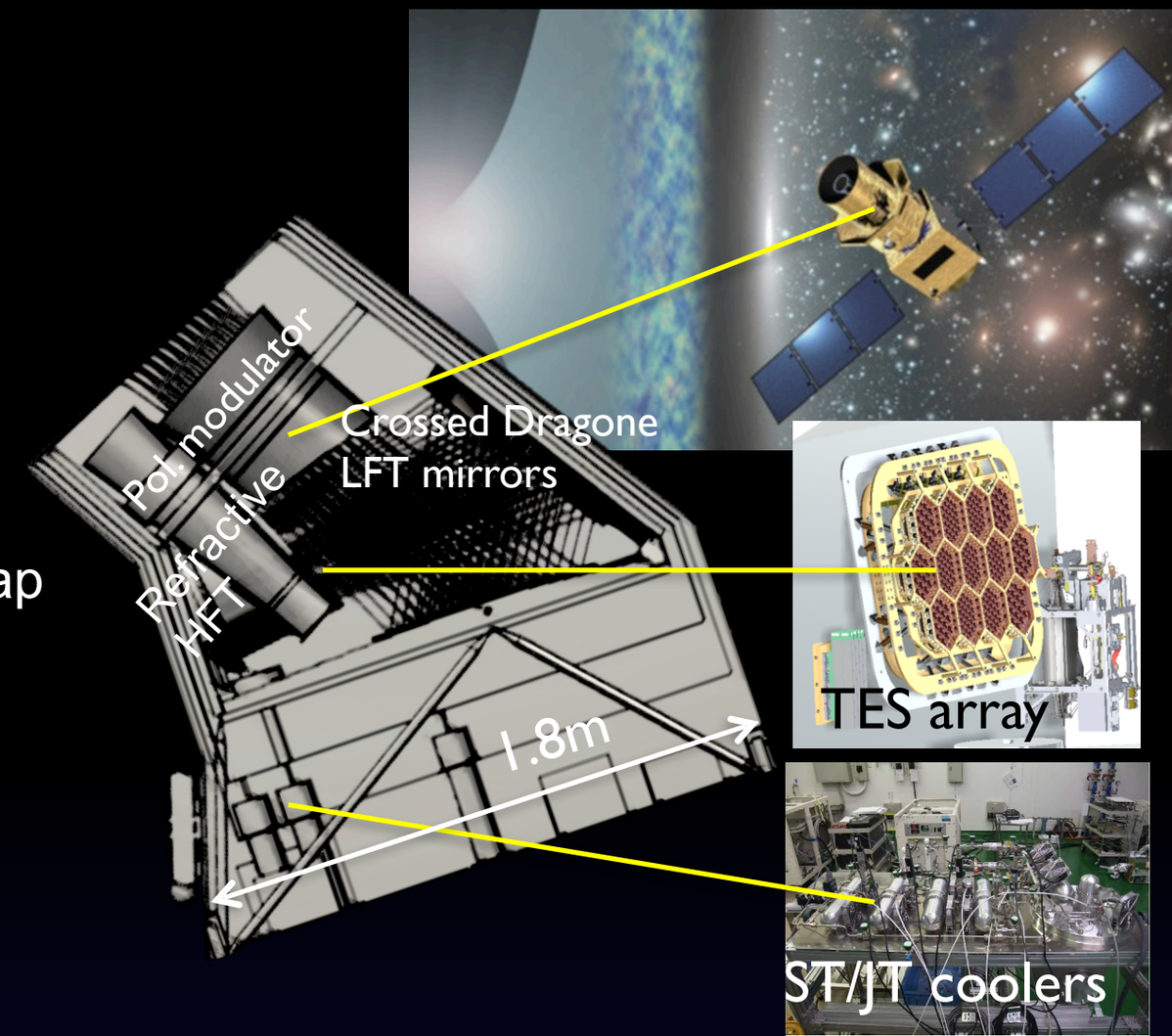


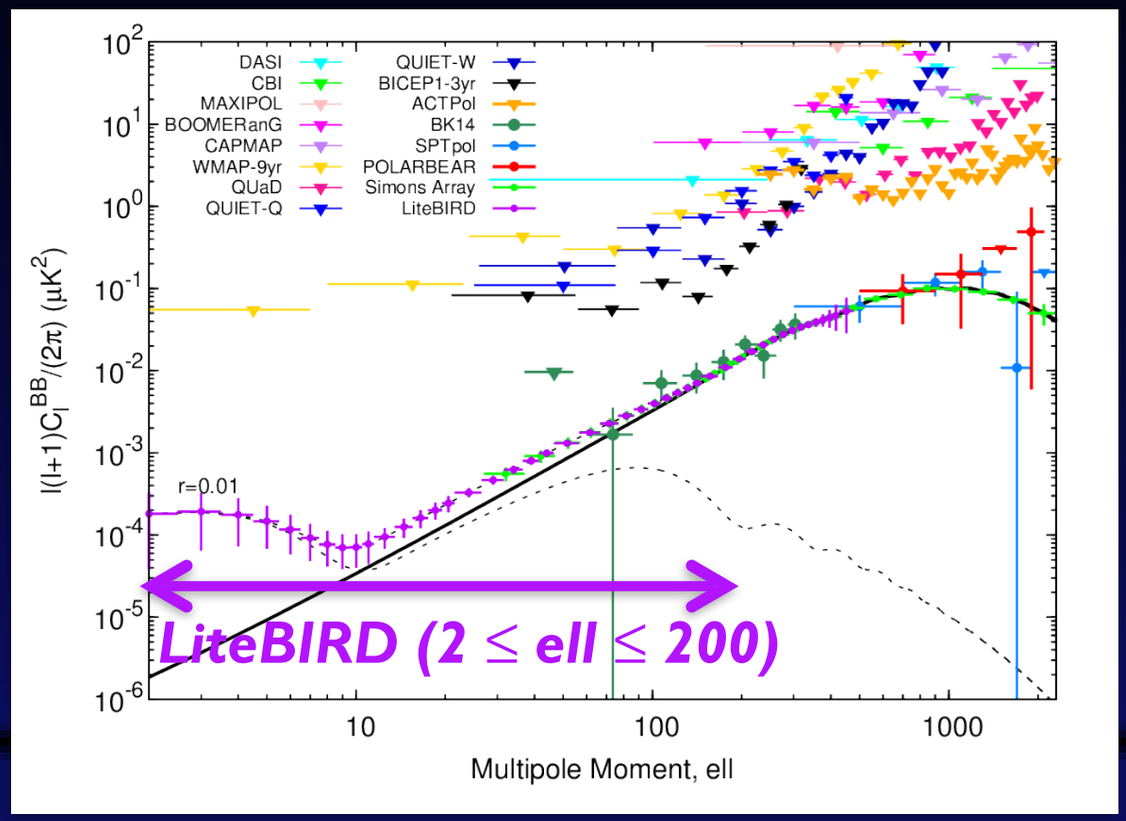


- **LiteBIRD** (Japan) - launch in 10 years
- **PIXIE** (recently reviewed for Phase B), **CMBpol** (concept study) (US)
- **COrE** (EU)

LiteBIRD

- JAXA's strategic large mission candidate
  - In Phase-A1 (~2 years) for concept development
- CMB polarization all-sky surveys for testing cosmic inflation
  - One of top-priority science goals in JAXA roadmap
  - $\delta r < 0.001$ for full success (w/o delensing)
- Launch in 2026-27 w/ JAXA's H3 rocket for 3-year observations at L2
- Heritages from JAXA's cryogenic satellites
- JAXA Phase-A1 team experience:
  - X-ray satellites, CMB exp., large-scale projects (in high energy physics, ALMA)
- Strong support from community in Japan
  - Listed as a top-priority large-scale project in Master Plan 2017 of Science Council of Japan
- International project
  - Expertise of US team in CMB projects
  - Expertise of readout electronics in Canada
  - Planck legacies/lessons learned (Europe+US)





In conclusion

- CMB experiments have detected the B-mode polarization signal, enabling:
  - Searches for inflationary gravitational waves "Smoking gun of inflation"
    - Must deal with Galactic foregrounds
  - Precision mass maps through gravitational lensing (neutrino masses)

- Experimental sensitivities are improving rapidly with diverse technology base
  - Order of magnitude improvements with each generation