Title: Probing Fundamental Physics and Cosmic Structure with CCAT-prime

Date: Jan 11, 2017 11:00 AM

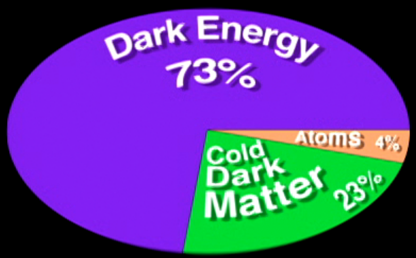
URL: http://pirsa.org/17010059

Abstract: <p>Measurements of the cosmic microwave background (CMB) have proven to be a powerful probe of the physics of our universe. CMB observations are helping to address fundamental questions, such as the nature of dark energy and dark matter, and are being used to probe the physics of inflation at energies a trillion times higher than the Large Hadron Collider. Recent measurements led to several exciting first detections, including CMB lensing, massive galaxy clusters, the large-scale velocity field, and the â€œB-modeâ€• component of the polarization field. These results have been enabled by the development of superconducting detectors and optics instrumentation, but we are now approaching the limits of current telescope facilities. Continuing advances in CMB research require greater sensitivity through major gains in optical throughput.

The CCAT-prime extreme field-of-view submillimeter telescope on Cerro Chajnantor will meet this challenge. The six-meter aperture telescope is designed to observe between 350um - 3mm and is capable of mapping the CMB roughly 10x faster than current observatories, making it a potential platform for the next generation â€œStage IVâ€• CMB survey. The first light instrument will take advantage of the unique CCAT-prime capabilities and site to characterize the large-scale velocity field and CMB polarization. In addition, CCAT-prime will enable spectroscopic intensity mapping of [CII] from early stars and galaxies during reionization and low-redshift galactic ecology. The intensity mapping measurements can be cross-correlated with upcoming neutral hydrogen surveys, and this combination may eventually characterize primordial non-Gaussianities beyond the reach of CMB measurements to provide new insights into the high-energy physics of inflation.</p>

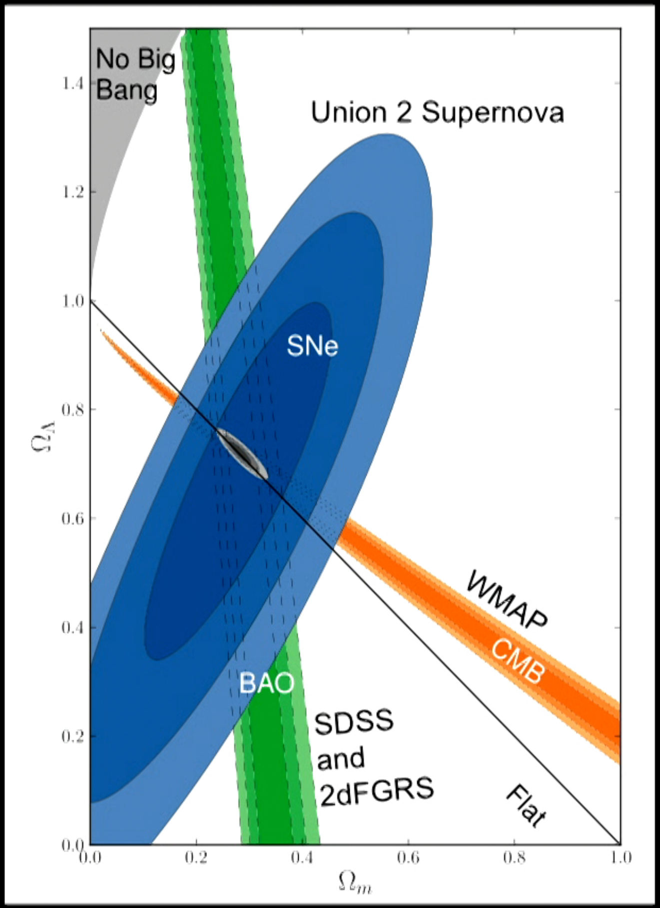
Concordance Cosmology

- Universe is flat and dominated by dark energy and dark matter



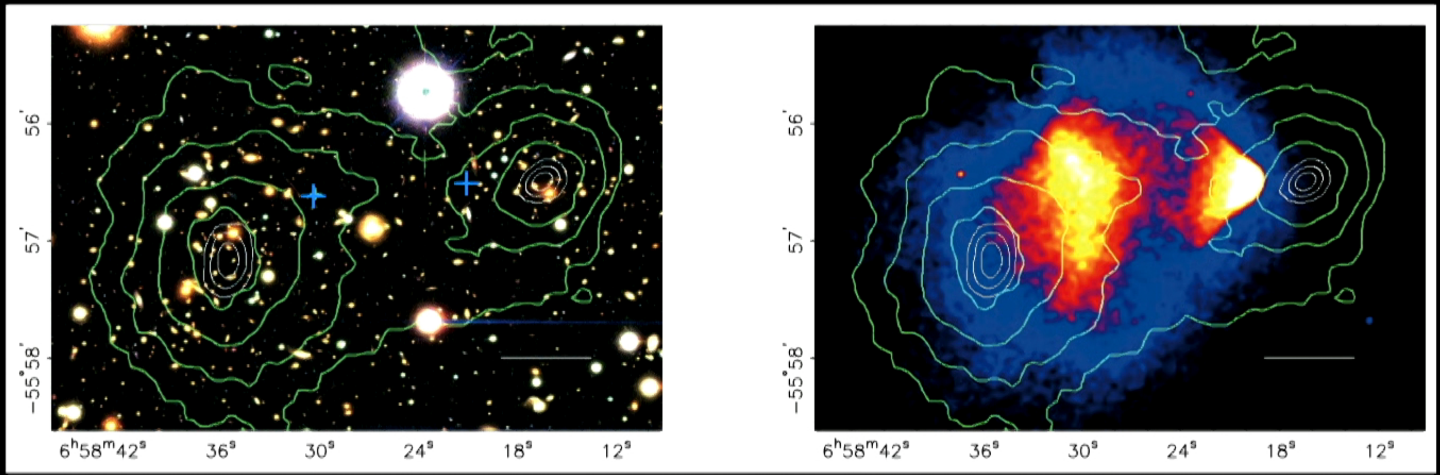
- ΛCDM confirmation spans electromagnetic spectrum

- Data fits 6 parameter model



(Suzuki et al., arXiv:1105.3470, 2011)

Proof of Dark Matter



(Clowe et al., ApJ 648 2006)

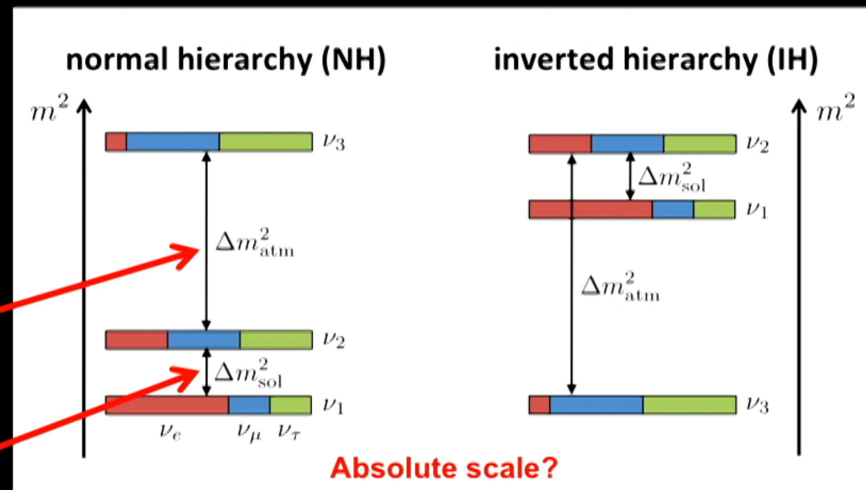
Bullet Cluster - a $z = 0.3$ cluster merger

- Separation of masses:
  - Baryonic gas (X-ray)
  - Total mass (optical lensing)
- 8σ detection

M. Niemack, Cornell Univ

Neutrinos – a Fraction of the Dark Matter

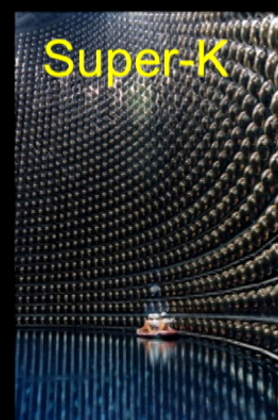
- Neutrino mass hierarchy and absolute scale unknown



- Atmospheric neutrinos
  => $\sqrt{(\Delta\, m^2_{atm})} = 0.05$ eV
- Solar neutrinos
  => $\sqrt{(\Delta\, m^2_{sol})} = 0.009$ eV

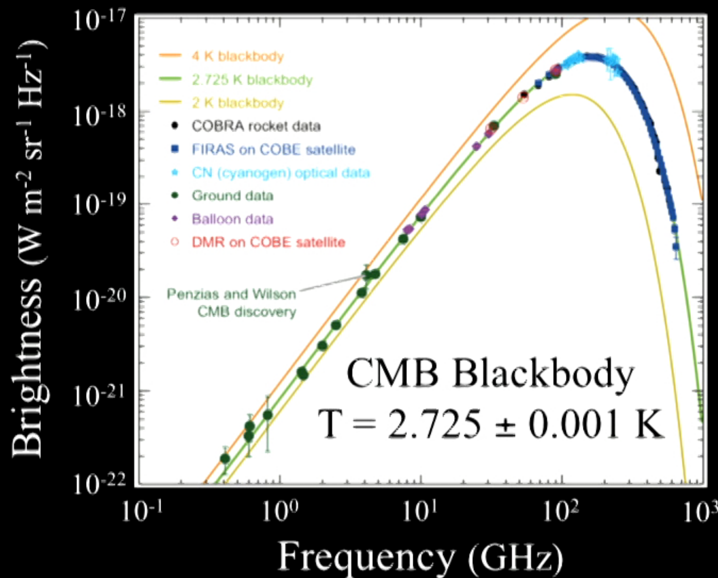
=> $\Sigma\, m_\nu > 0.05$ eV

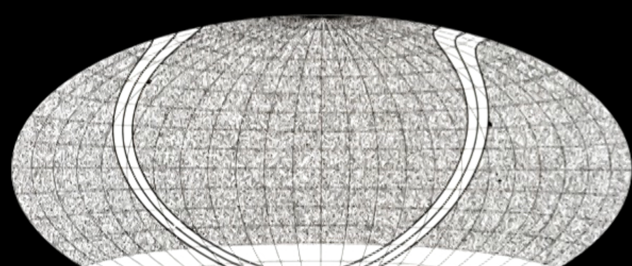
(KATRIN – $\sigma(m_{\nu_e}) \sim 0.1$ eV)



- If neutrino mass sum < 0.1 eV
  => Normal hierarchy

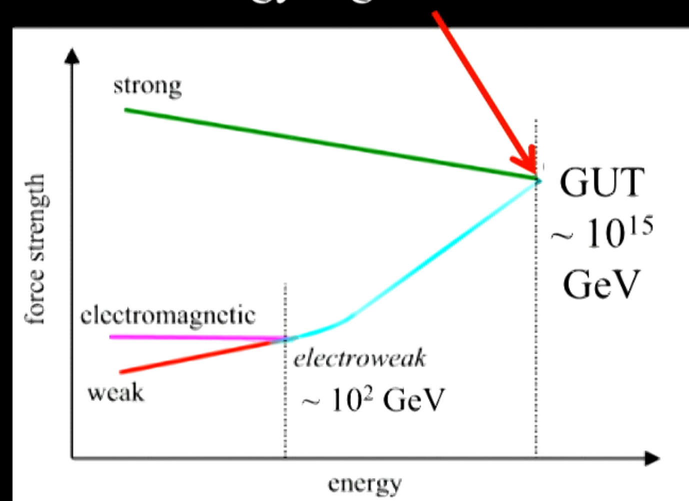
Homogeneous and Isotropic





Galaxy Survey (NVSS)

- Large scale universe in causal contact
- Inflationary epoch
  - $< 10^{-30}$ s after big bang
  - Energy ~ grand unification



- Did inflation occur? Can we learn about GUT-scale physics from cosmology?

- What is the physics of dark energy?

- What are the properties of neutrinos? And what is the rest of the dark matter?

- How did the primordial fluctuations evolve into the structure around us today?

CMB Anisotropies

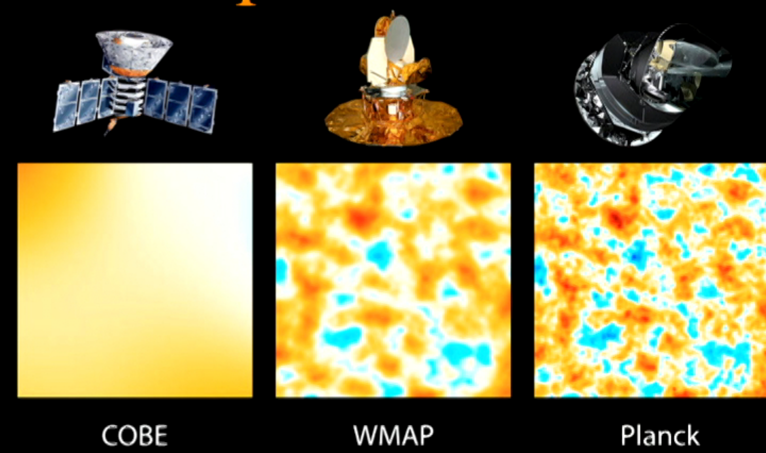
- Primordial CMB anisotropies imprint early universe physics

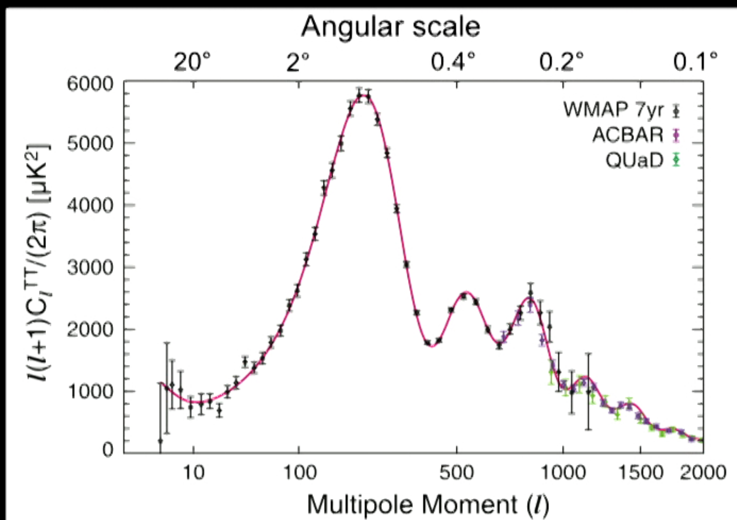
- Gaussian information is in power spectrum

$$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

$$C_l = \frac{1}{2l+1} \sum_m |a_{lm}|^2$$

- 6 parameter model fit
  – $\Omega_m h^2$, $\Omega_b h^2$, Ω_Λ, τ, n_s, Δ_R^2

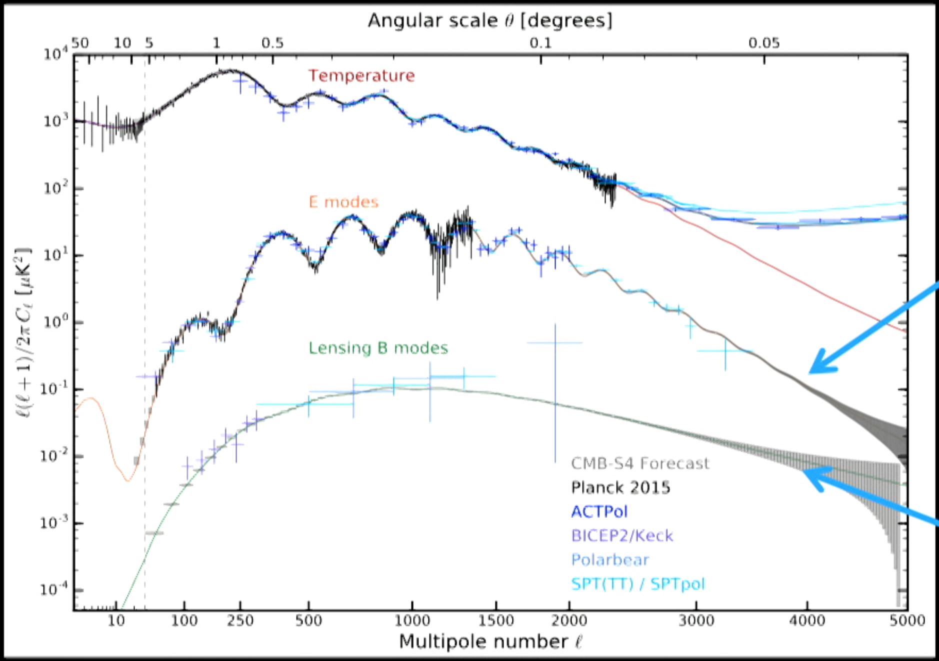




(Komatsu et al., ApJS 2011)

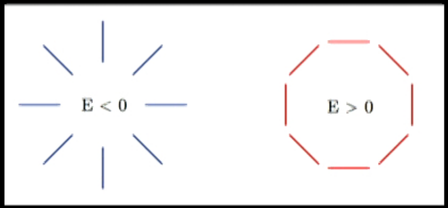
Current CMB Survey Research

Temperature & Polarization Power Spectra

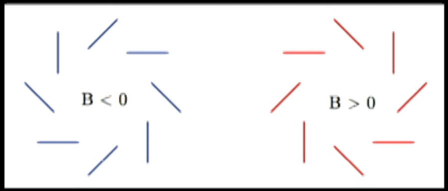


Polarization Anistotropies

Curl free 'E-modes'



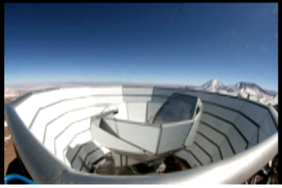
Divergence free 'B-modes'



Atacama:

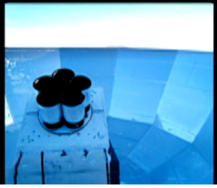
Polarbear – 2.5m

ACT – 6m



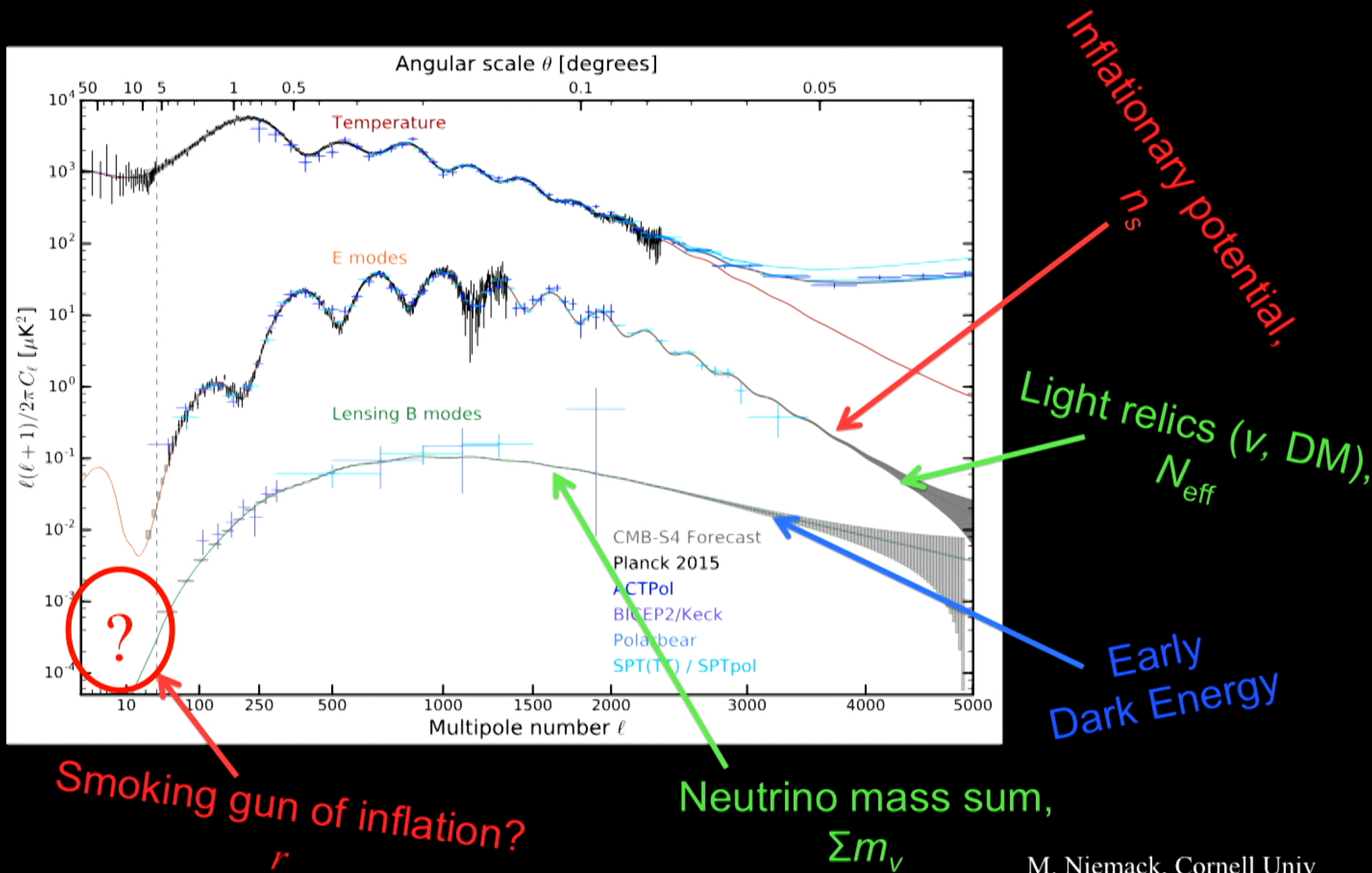
South Pole:

Keck – 0.3m



SPT – 10m

Current CMB Survey Research



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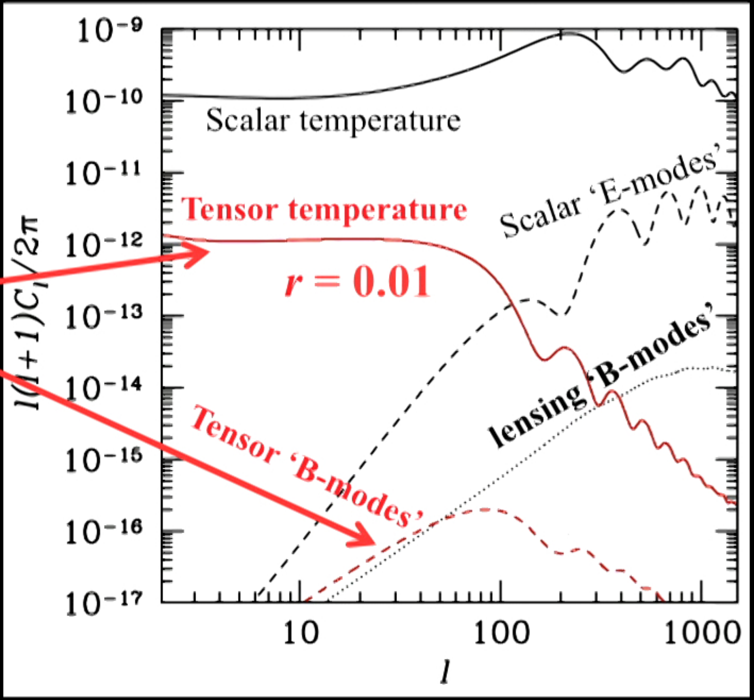
Signatures of Inflation: B-modes

- Inflationary models predict
  primordial gravity waves

- Gravity waves = tensor perturbations
  - Temp. and Pol. signatures
  - Amplitude: $r = T/S$



- Energy scale of inflation

$$V^{1/4} = 1.04 \times 10^{16}\mathrm{GeV}\left(\frac{r_*}{0.01}\right)^{1/4}$$

- $r < 0.11$ (Temperature: Planck + ACT + SPT, 2013)

  $r < 0.09$ (Polarization: BICEP2/Keck + Planck, 2015)

Natural target $r \sim 0.001$

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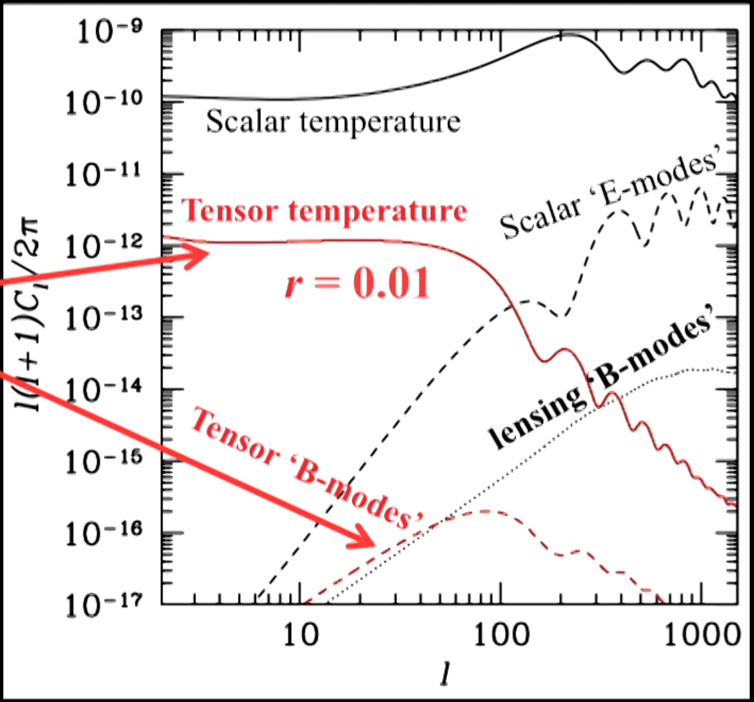

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Natural target $r \sim 0.001$

Higgs boson appears to be spin-0 => Scalar fields (like inflaton) exist!

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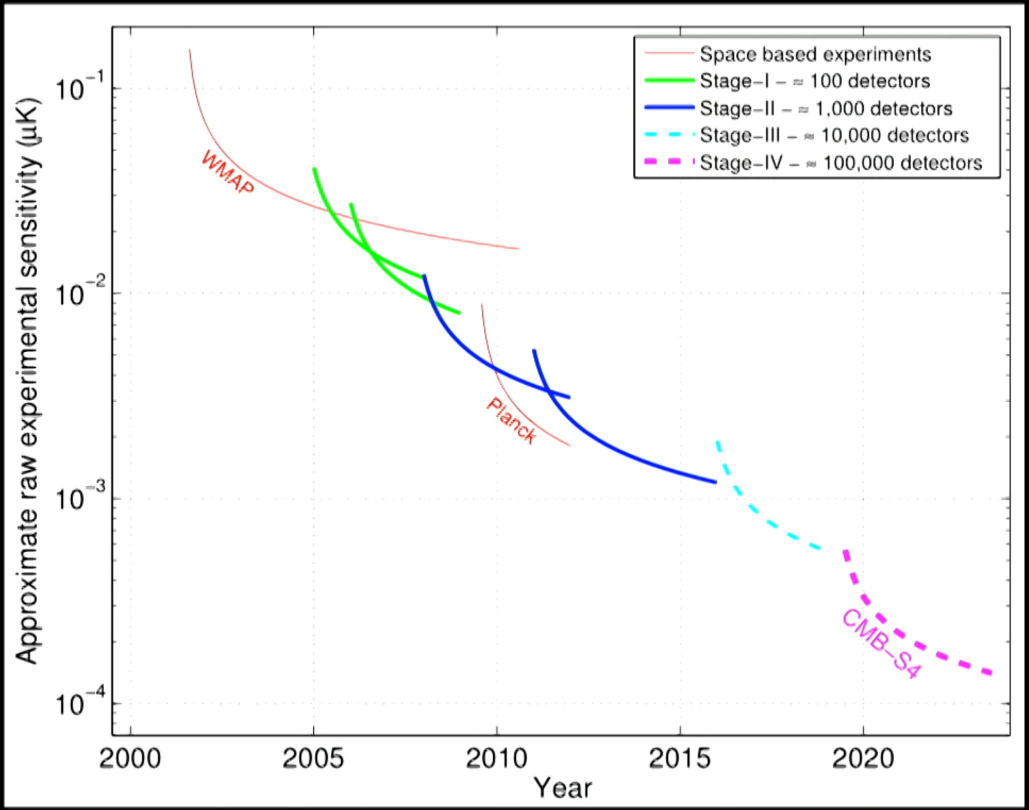
How can we get to $\sigma(r) < 0.001$?
"Stage IV" CMB Survey



(CMB-S4 Science Book 1st ed., arXiv:1610.02743)

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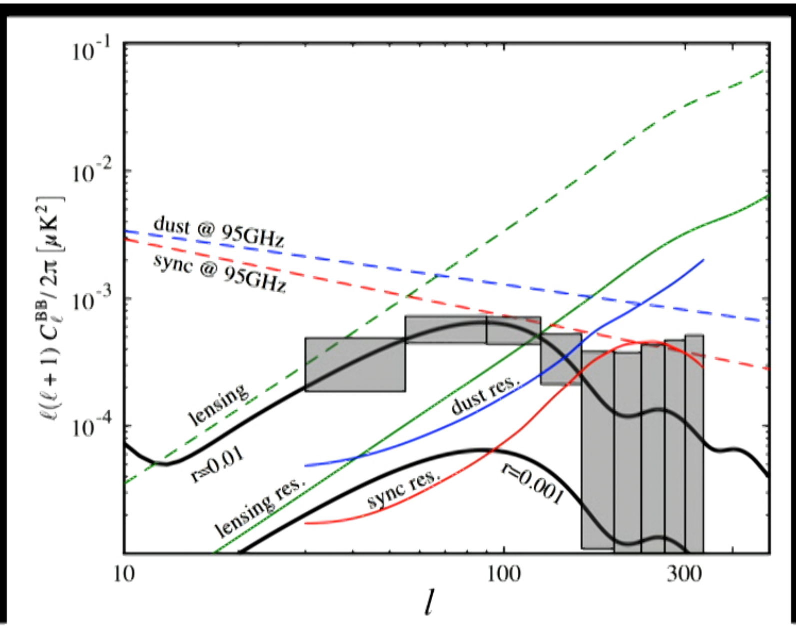
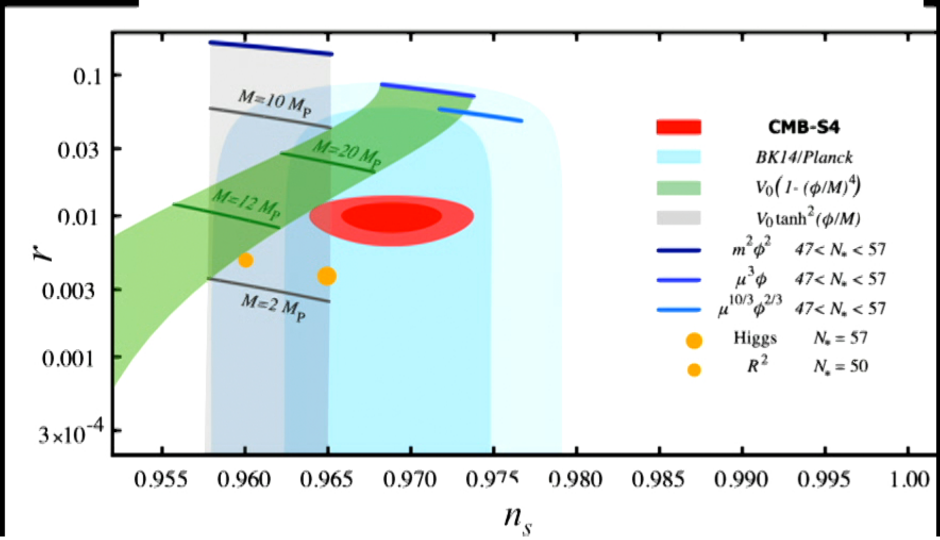
CMB-S4 Inflation Forecasts

- Must prevent false detections
- 8+ frequency bands to span foregrounds
- Resolution ~ arcmin for delensing
- Test large-field super-Planckian models

(CMB-S4 Science Book 1st ed., arXiv:1610.02743)

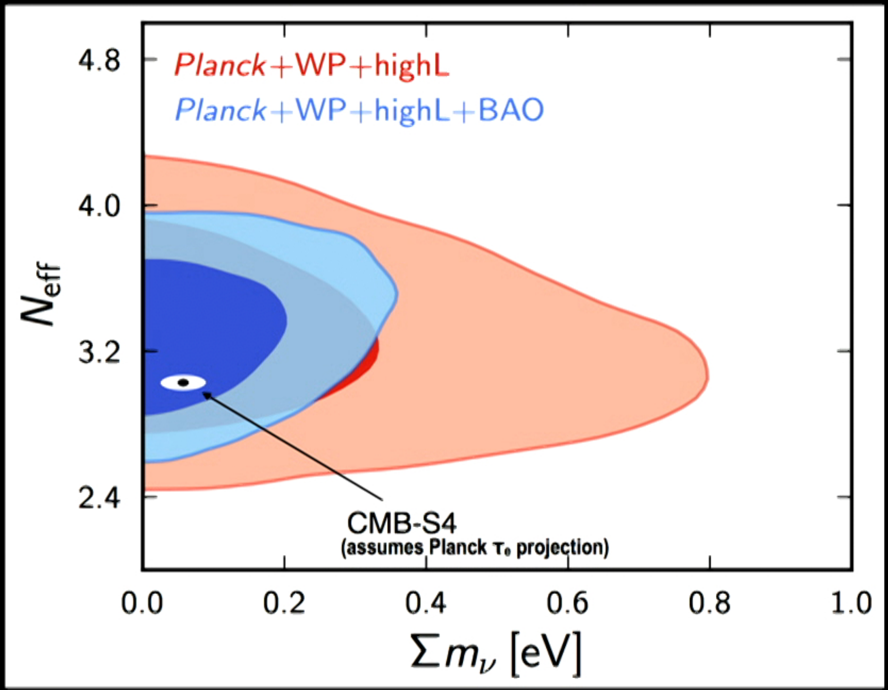




CMB-S4 Neutrino Forecasts

- Light relics add relativistic energy at early times, N_{eff}
  - Sterile Neutrinos
  - Axions
  - …
- Neutrino mass sum with BAO and τ

Clean neutrino probes: Lensing + BAO + CMB



(Abazajian et al., arXiv:1309.5381)

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CMB-S4 Survey Timeline and Targets

Years	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015, 2016	Stage 2, 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS, SPT clusters)
2017, 2018, 2019, 2020	Stage 3, 10,000 detectors	10^{-6}	0.006	0.06	0.06eV (Boss BAO prior)	~300-600 (DES + DESI, SZ Clusters)
2021, 2022, 2023, Target	Stage 4, CMB-S4, ~500,000 detectors	10^{-8}	0.0005	0.027	0.015eV (DESI BAO, $+\tau_e$ prior)	1250 (DESI +LSST, S4 Clusters)

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How can we build S4?

(CMB-S4 Science Book 1st ed., arXiv:1610.02743)

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CCAT-prime: Large Aperture Telescope to map the CMB 10x faster

CCAT-p

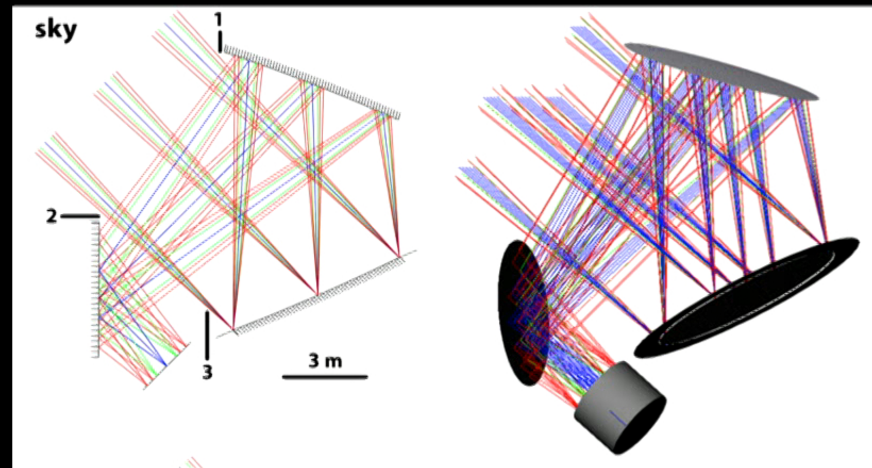
6m aperture crossed-Dragone design delivers a large, flat focal ~8 degree plane

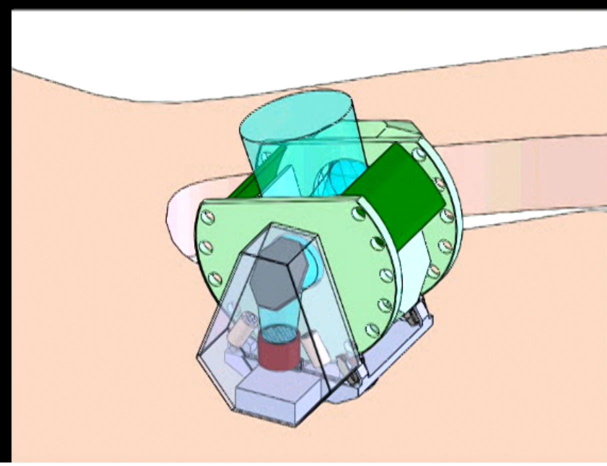
Can illuminate 10x more detectors than Stage III telescopes

(Advanced ACTPol, SPT-3G, Polarbear2)

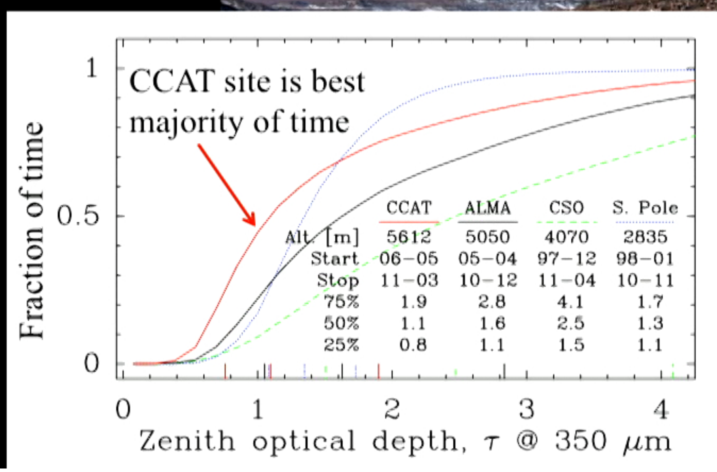
(Niemack, Applied Optics 2016)

CCAT-prime consortium:
Cornell, Cologne, Bonn, AUI
Association of Canadian Universities



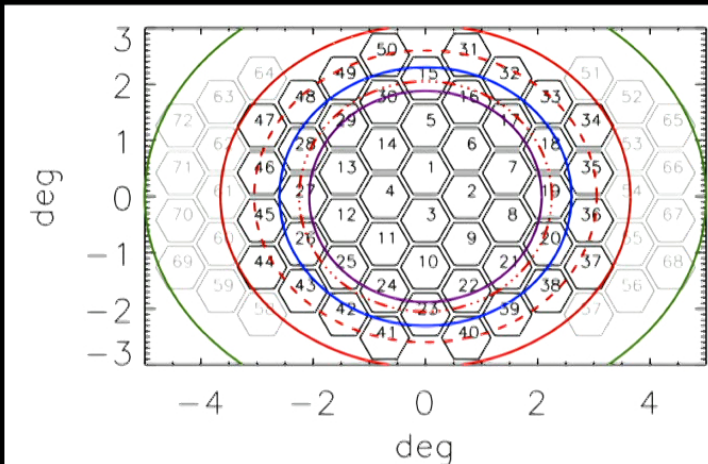


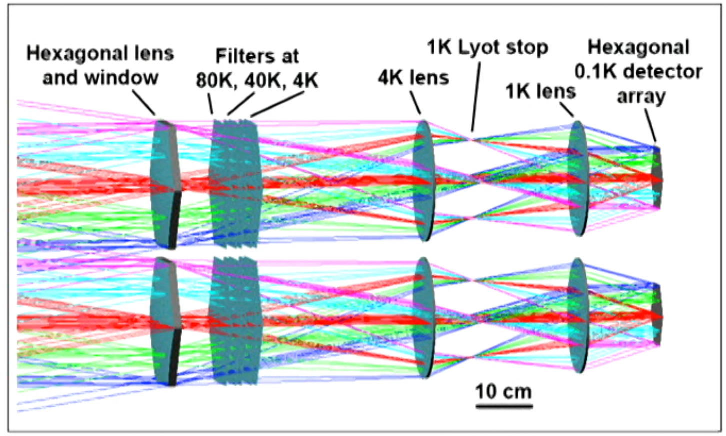
CCAT-prime site: Cerro Chajnantor at 5600 m



(Radford & Peterson, arXiv:1602.08795)

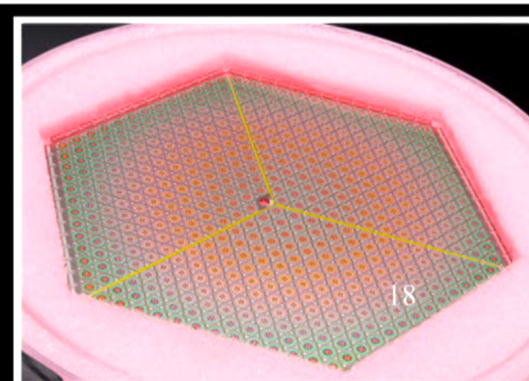
CCAT-prime: Large Aperture Telescope to map the CMB 10x faster





Close-packed reimaging optics with 30 cm diameter optics tubes are well matched to 15 cm superconducting detector fabrication capabilities.

(Niemack, Applied Optics 2016)



Advanced ACTPol detector array

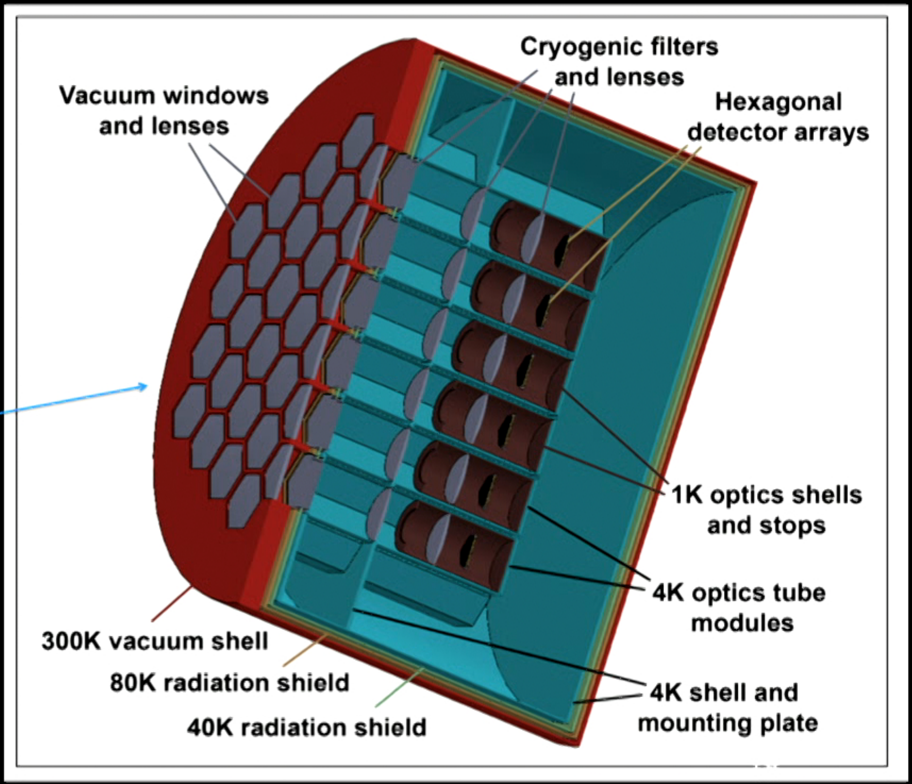
CCAT-prime: Large Aperture Telescope to map the CMB 10x faster

CCAT-p

Smaller scale instruments are natural for first light

Prototype receiver based on a 50 optics tube design

This instrument could illuminate > 10^5 CMB detectors, and **map the CMB 10x faster** than Advanced ACTPol and SPT-3G



(Niemack, Applied Optics 2016)

Simons Observatory

- Next stage of ACT + Polarbear teams: plan to build one or two ~5m scale telescope that could also be used for CMB-S4
- Crossed-Dragone telescope design is a top candidate
- CCAT-prime science goals much broader due to collaboration interests and access to short wavelengths

CMB-S4 Summary

- Science: Inflationary gravity waves, neutrinos, light relics, dark energy
- Concept Definition Task Force (CDT) study underway
- Survey outline:
  - At least ½ sky
  - Roughly 5×10^5 detectors!
  - Multiple high throughput telescopes

    CCAT-prime + Simons Observatory

    + South Pole + other?

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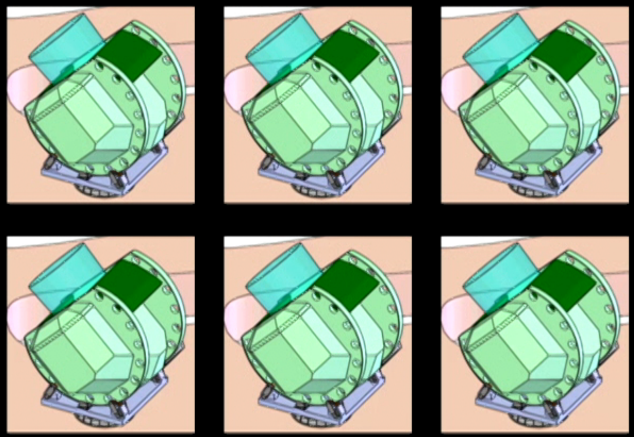

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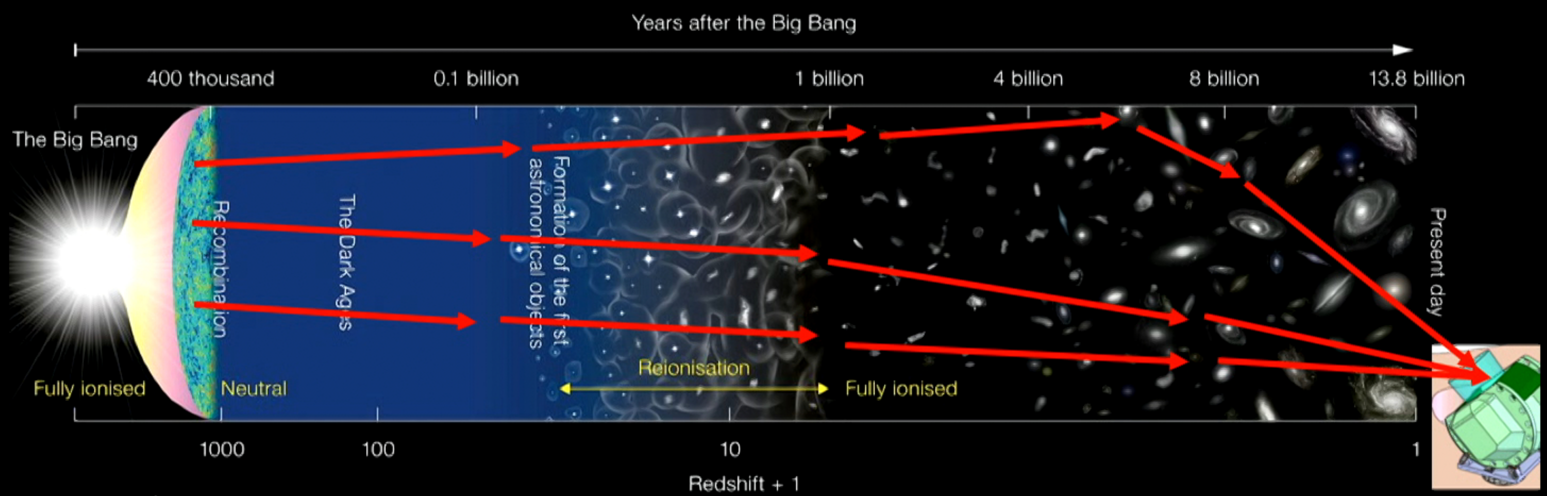
Secondary Anisotropies and Cosmic Structure



Courtesy of NAOJ

- Primary CMB anisotropy maps limited to two dimensions
- Secondary anisotropies add third dimension: structure formation

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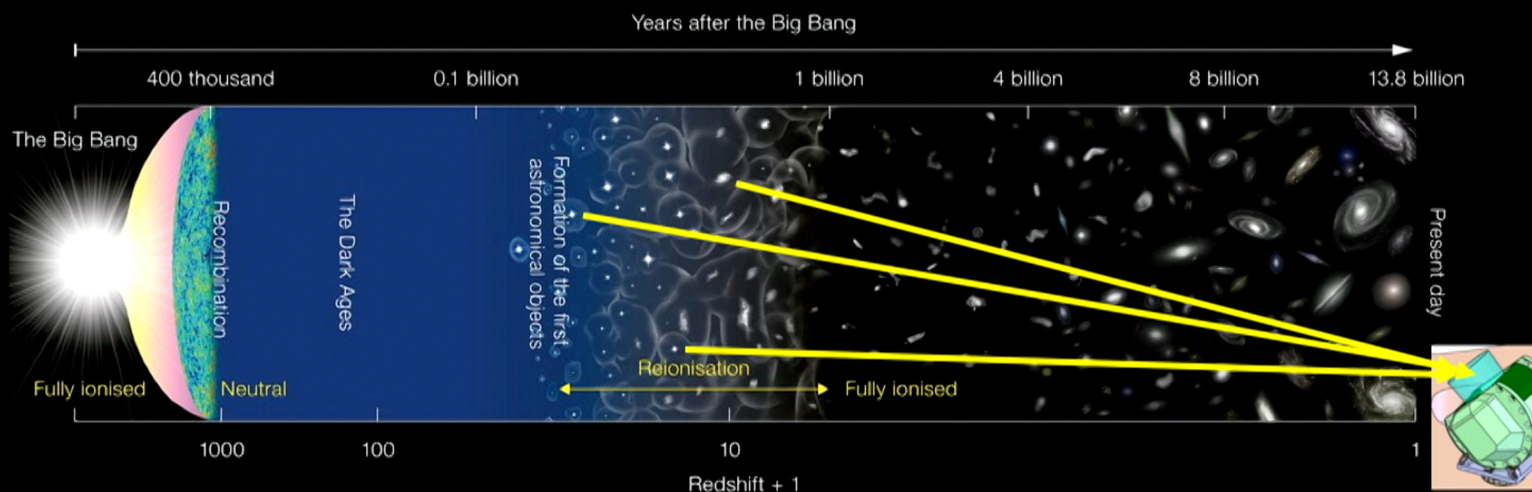
Secondary Anisotropies and Cosmic Structure



Courtesy of NAOJ

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- **Beyond CMB, 3D modes are needed to advance cosmology**

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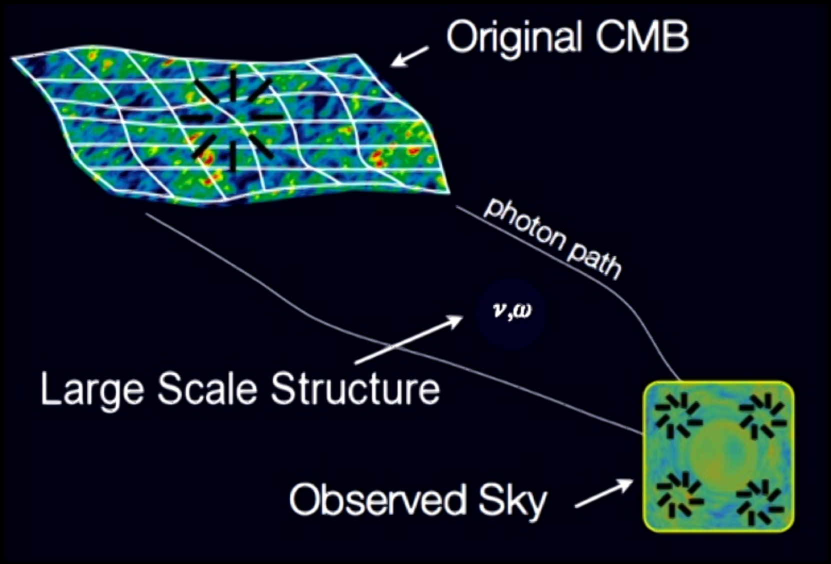
Gravitational Lensing of CMB

- Non-Gaussian effect
- Remaps temp. anisotropies
- Converts curl-free 'E-mode' polarization into 'B-modes'
- High source redshift (z ~ 1100) => lensing peaks at z ~ 2



- Constrain dark energy and map dark matter distribution
- Delens inflationary B-mode signal

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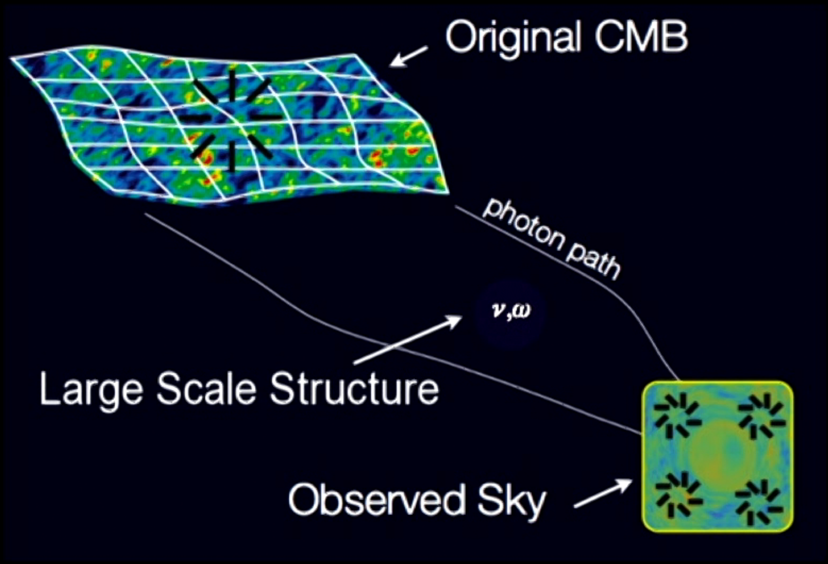

- Detection by ACT in 2011 at 4σ => Dark energy from CMB alone

  (Das et al., PRL 2011) (Sherwin et al., PRL 2011)
- Detected by SPT, then Planck at ~ 40σ

  (Planck Collab. 2015)
- B-modes from lensing in 2013-16: SPTpol, Polarbear, BICEP2, ACTPol

  (Hanson et al. PRL 2013, Polarbear Collab. 2014, BICEP2 Collab. 2014, Van Engelen et al. 2014, …)

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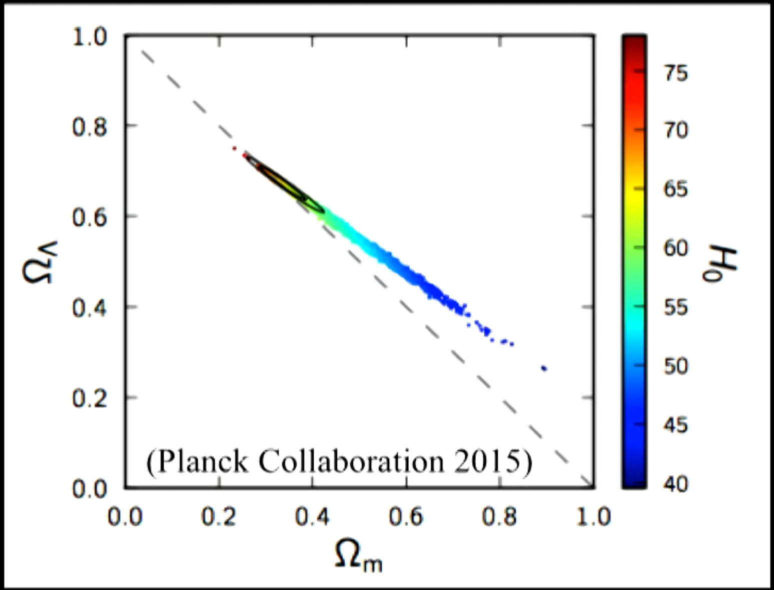

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New cosmological probe

- B-modes from lensing in 2013-16: SPTpol, Polarbear, BICEP2, ACTPol

(Hanson et al. PRL 2013, Polarbear Collab. 2014, BICEP2 Collab. 2014, Van Engelen et al. 2014, …)

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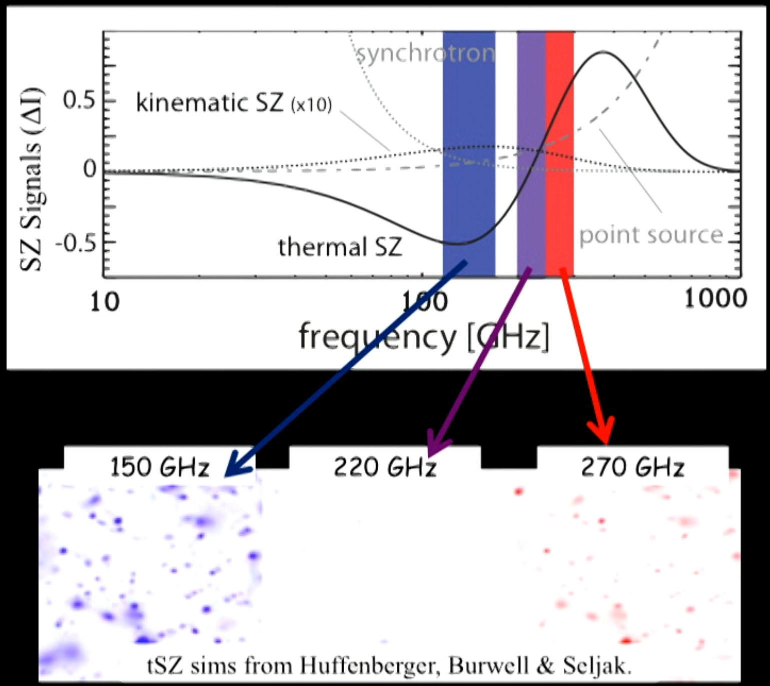
Sunyaev-Zel'dovich (SZ) Effects

- Compton scattering of CMB
- Redshift independent
  - ⇒ no $1/r^2$ cluster selection bias
- Thermal SZ Spectral Signature
- Cosmology (with redshift & mass)



tSZ sims from Huffenberger, Burwell & Seljak.

- Kinetic SZ from pairwise velocities – ACT & ACTPol + BOSS 2012/2016

  => DE, gravity, neutrino constraints

  (Mueller, De Bernardis, Bean, Niemack ApJ, PRD 2015)

Planck + BOSS 2015

SPT + DES 2016

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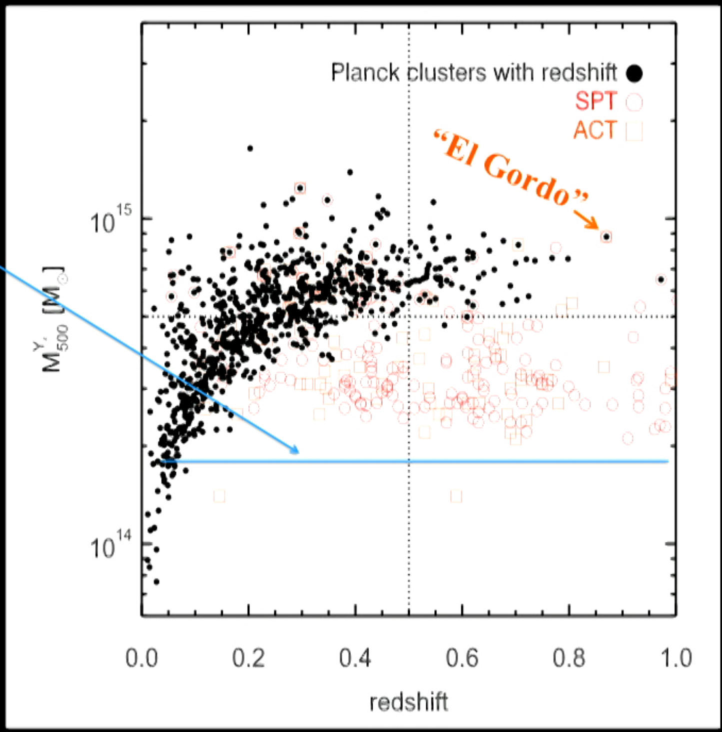
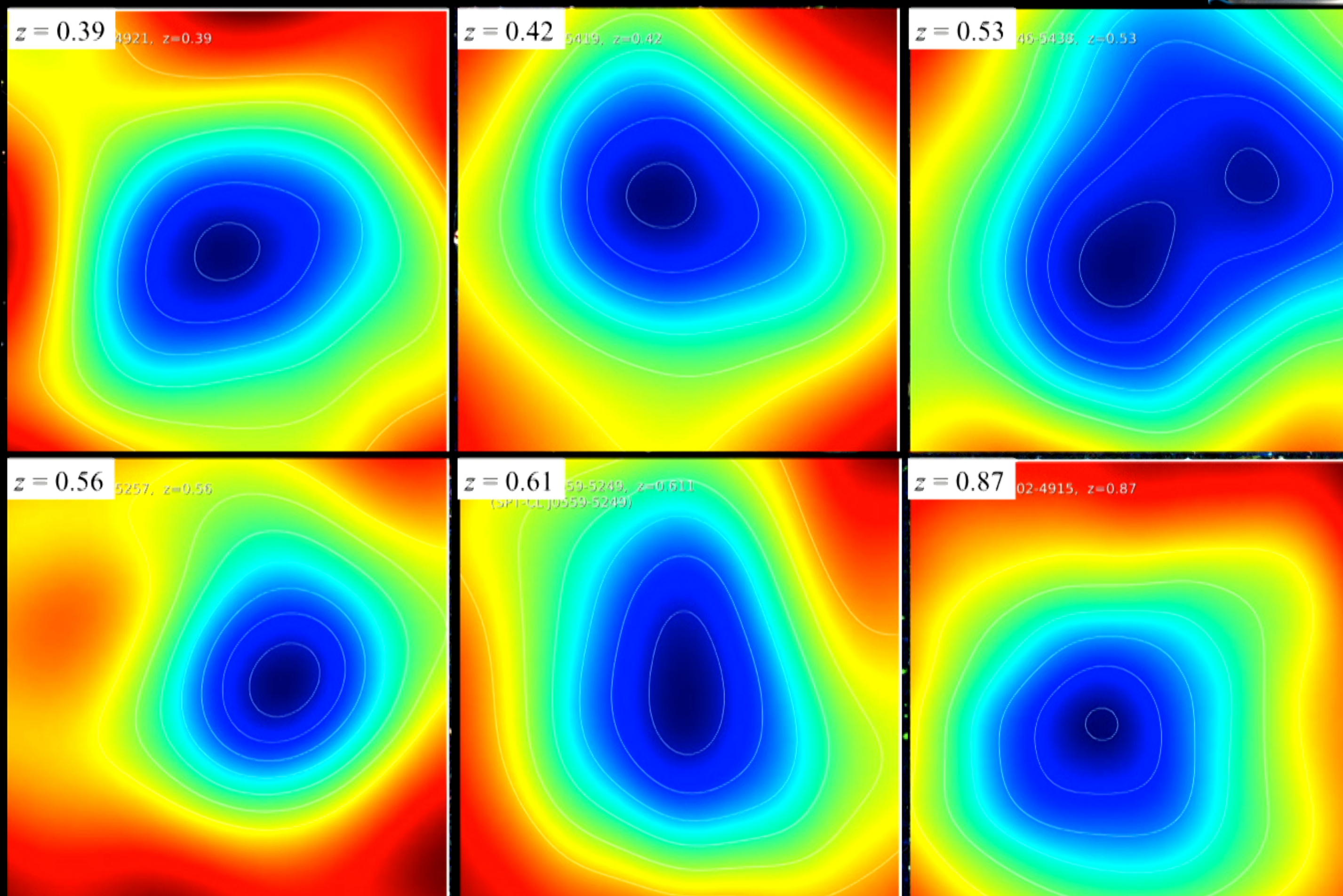
SZ Cluster Context

- 6-meter telescope is roughly optimal for SZ cluster science
- Mass-limited catalog vs. z
- Planck resolution limits sample
- Greater sensitivity needed for lower masses
- Shorter wavelengths needed to fully characterize clusters
  => CCAT-prime



(Planck 2013 results. XXIX)

ACT SZ-discovered Clusters



(Marriage et al. ApJ 2011)

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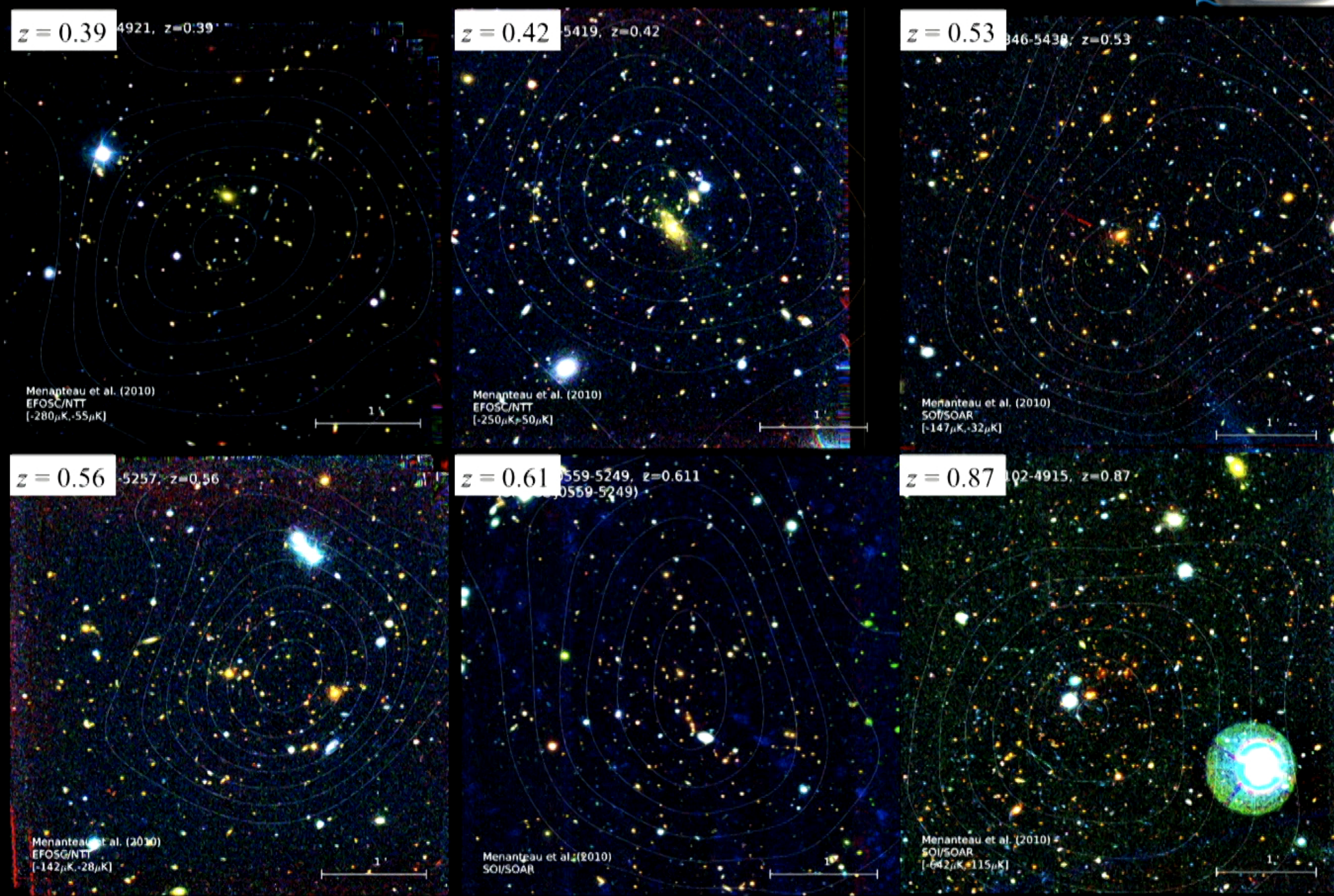
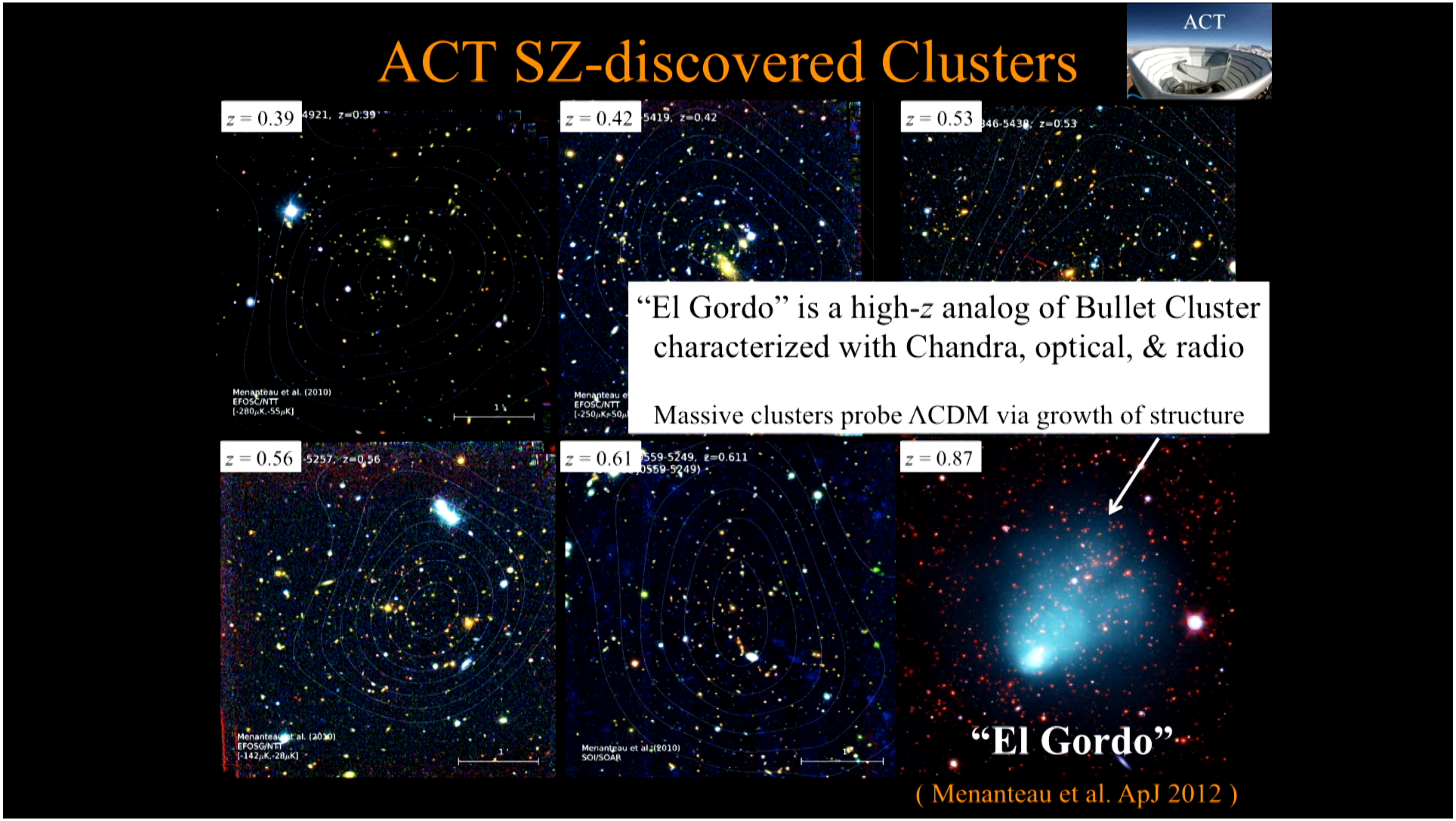
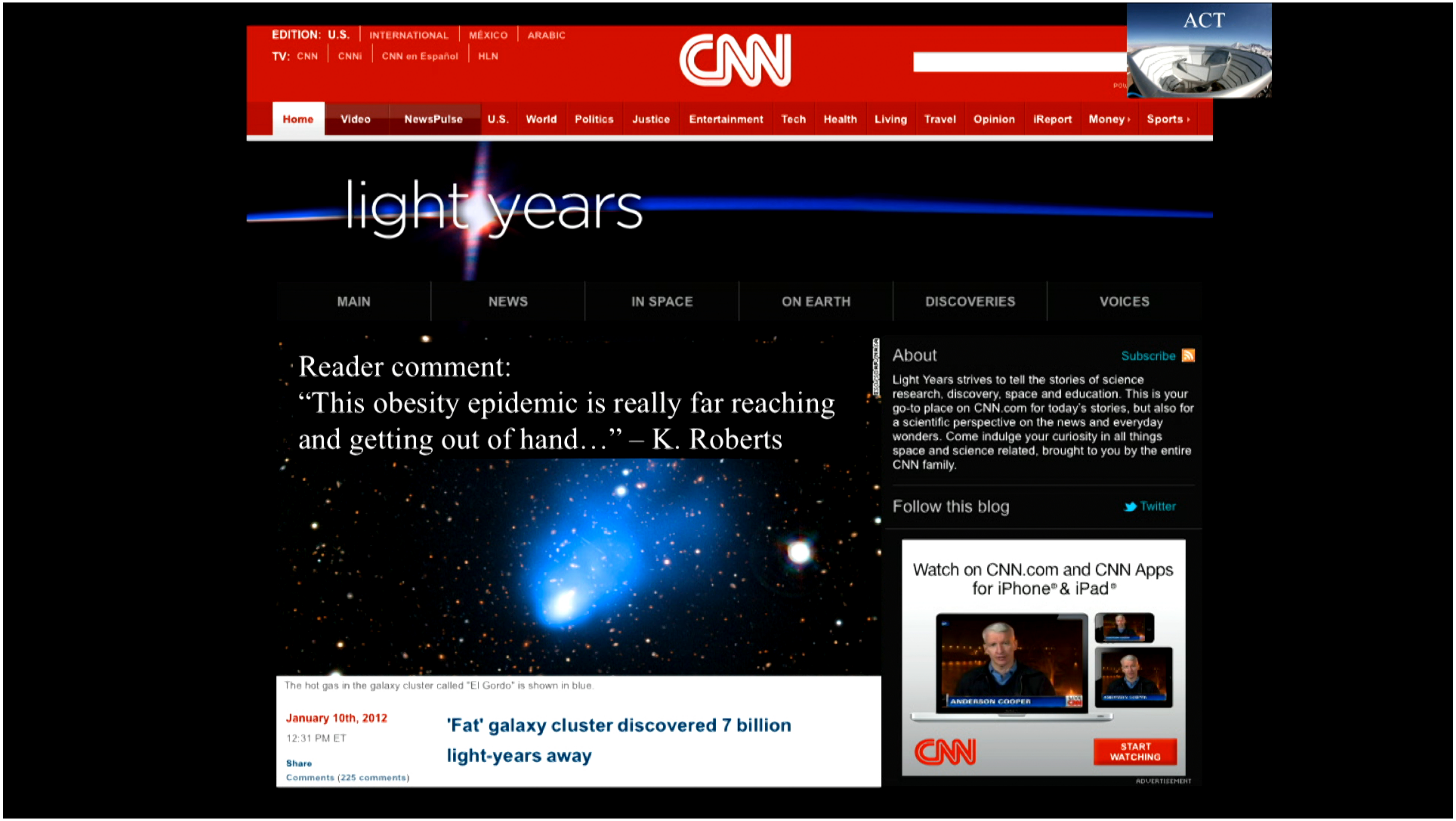


(Menanteau et al. ApJ 2010)


ACT SZ-discovered Clusters
ACT
z = 0.39
z = 0.42
z = 0.53
"El Gordo" is a high-z analog of Bullet Cluster characterized with Chandra, optical, & radio
Massive clusters probe ΛCDM via growth of structure
z = 0.56
z = 0.61
z = 0.87
"El Gordo"
(Menanteau et al. ApJ 2012)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TV: CNN | CNNi | CNN en Español | HLN
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ACT
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The hot gas in the galaxy cluster called "El Gordo" is shown in blue.
January 10th, 2012
12:31 PM ET
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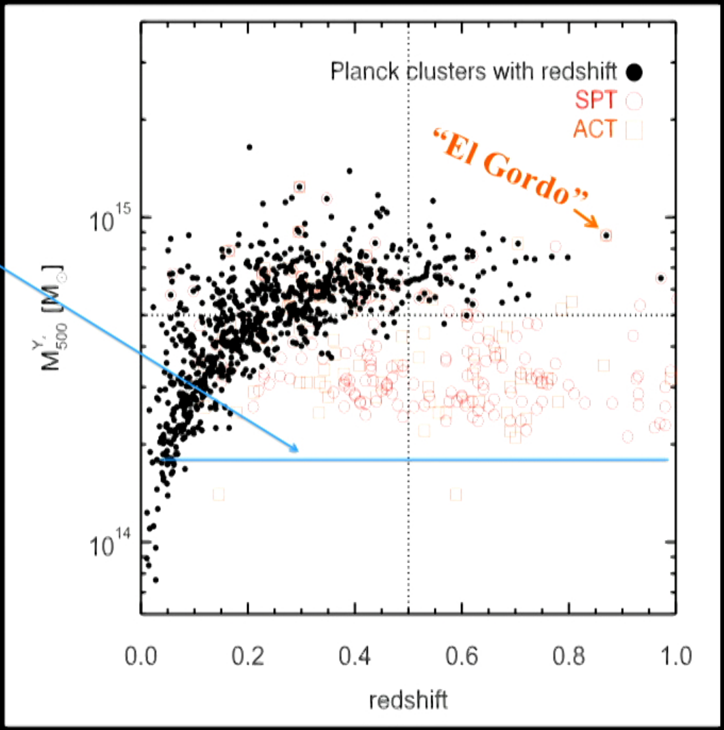
SZ Cluster Context

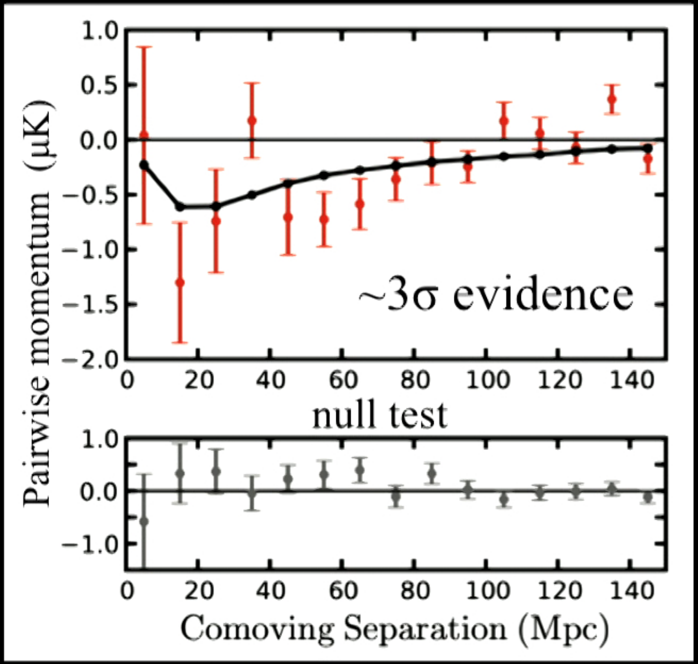
- 6-meter telescope is roughly optimal for SZ cluster science
- Mass-limited catalog vs. z
- Planck resolution limits sample
- Greater sensitivity needed for lower masses
- Shorter wavelengths needed to fully characterize clusters
  => CCAT-prime



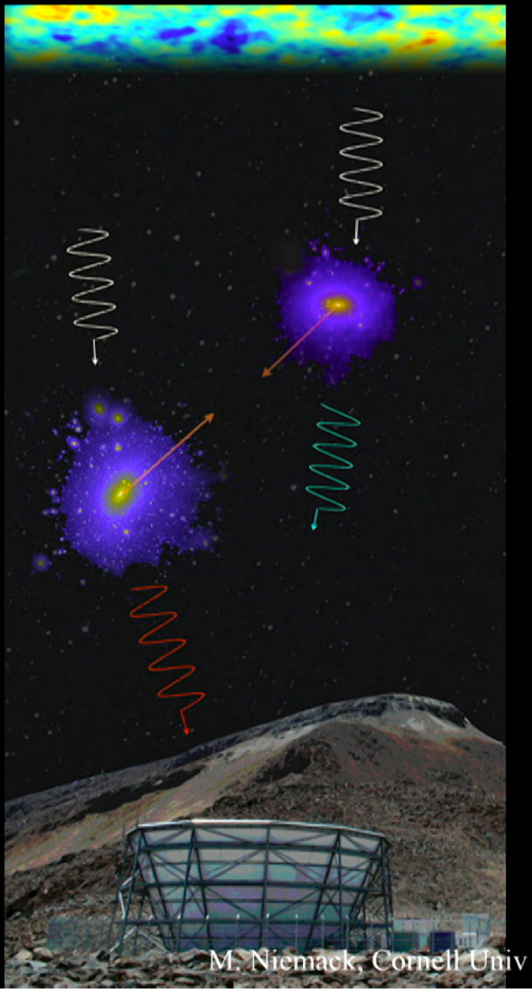
(Planck 2013 results. XXIX)

First Evidence for Pairwise kSZ Effect

ACT data plus LRG redshifts from BOSS enables measure of momentum difference between proximate cluster pairs via kSZ

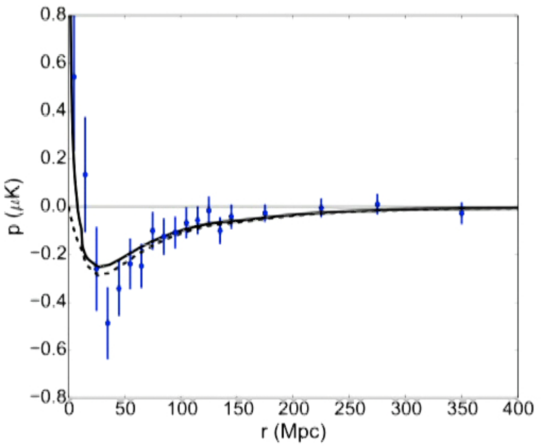


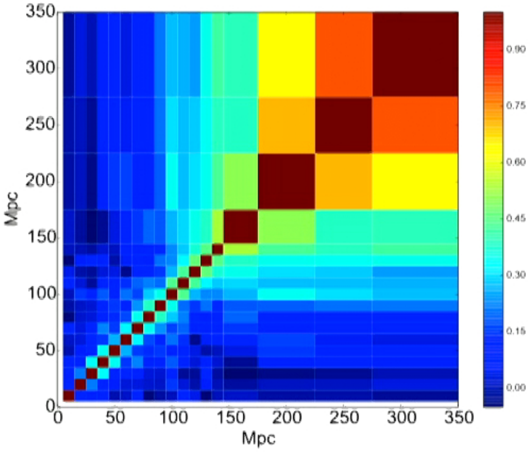
(Hand et al. PRL 2012)



Recent Pairwise kSZ Measurement

- 2 season ACTPol + BOSS
  (De Bernardis, et al. arXiv:1607.02139)
- Conservative statistical analysis => 4σ evidence
- 3 season ACTPol data has ~4x larger area
- No direct kSZ measurements of clusters yet (only substructures)

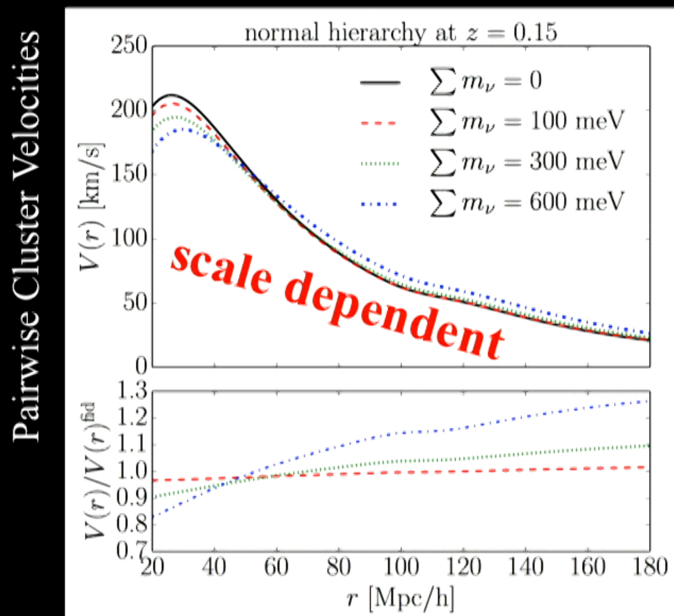




Pairwise kSZ Cosmology Forecasts

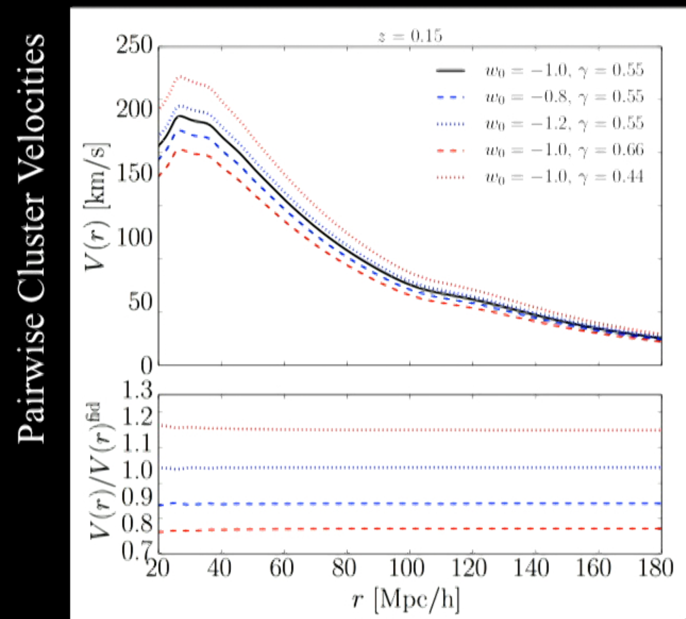
(Mueller, De Bernardis, Bean, and Niemack ApJ & PRD 2015, arXiv:1408:6248 & 1412.0592)

Neutrino Mass Sum



Cluster separation

Dark Energy & Gravity



Cluster separation

Pairwise velocity amplitude scales with cluster optical depth

M. Niemack, Cornell Univ

Pairwise kSZ Cosmology Forecasts

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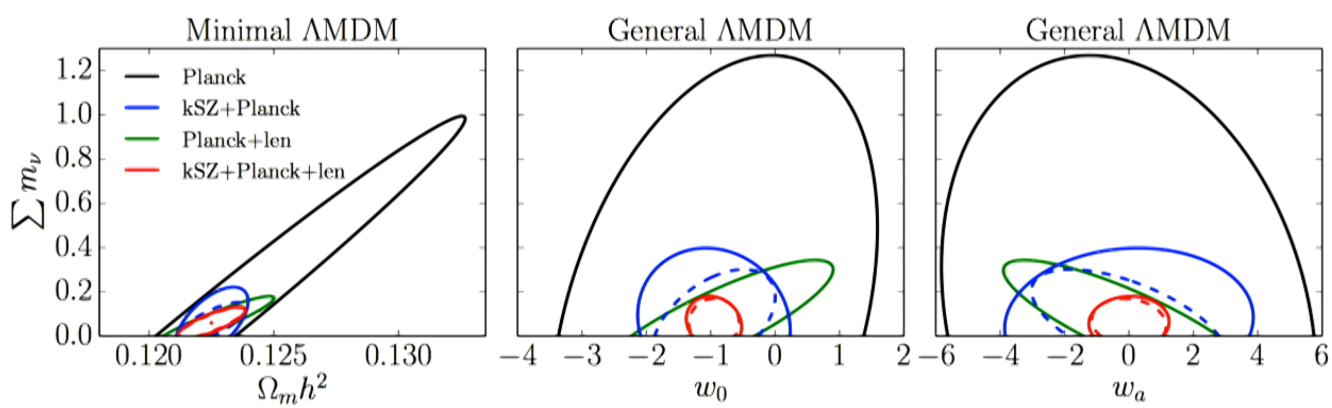


Planck priors + Pairwise kSZ (from "Stage IV" CMB + DESI)

conservative

$$\sum m_\nu < 0.096 \text{ eV}$$

optimistic

$$\sum m_\nu < 0.033 \text{ eV}$$

Complementary constraints to lensing, BAO, etc.

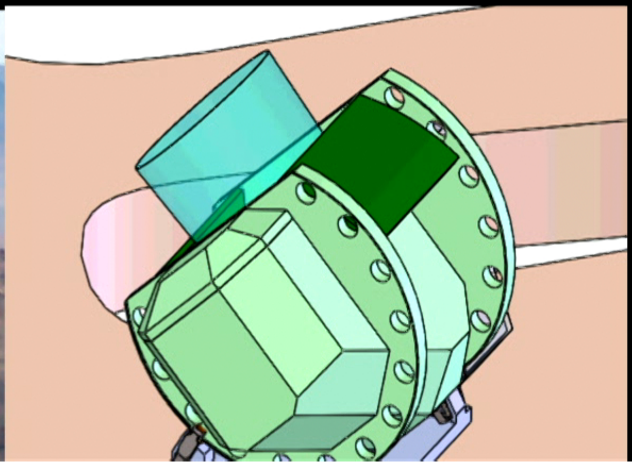
Cluster optical depth measurements important for cosmology

M. Niemack, Cornell Univ

CCAT-prime will probe transition between gravity and dark energy dominated regimes

- Direct velocity measurements of the most massive bound objects in the universe

- Constrain dark energy, gravity, and neutrinos



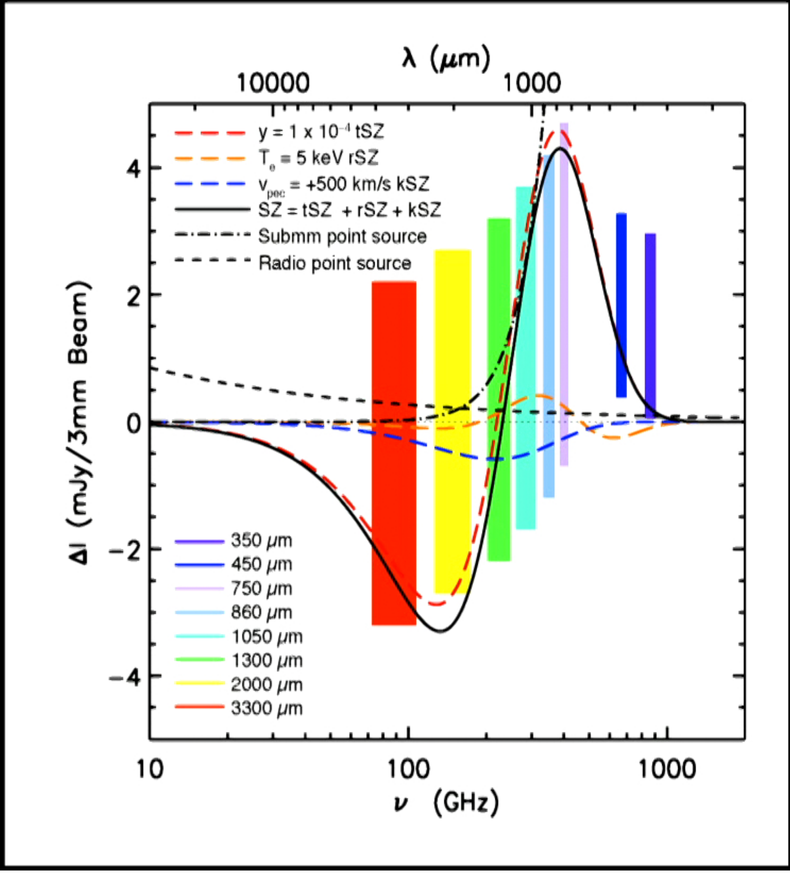
CCAT-prime SZ Survey

- Measure SZ effects with 7 bands
  - Thermal, Kinetic & Relativistic SZ
  - Constrain optical depth, velocity, and electron temperature

- Direct velocity measurements
  - Measure several thousand clusters
  - Goal ~100 km/s on ~1000 clusters
  - Break cosmology degeneracies!

CCAT-p area (deg^2)	CCAT-p time (hr)	Average mass (M_{sun})	# of clusters
1,000	3,000	2.71×10^{14}	**3,000**
1,000	10,000	2.19×10^{14}	**5,500**
10,000	3,000	3.32×10^{14}	**16,000**
10,000	10,000	3.06×10^{14}	**21,000**

CCAT-prime bands over SZ signatures



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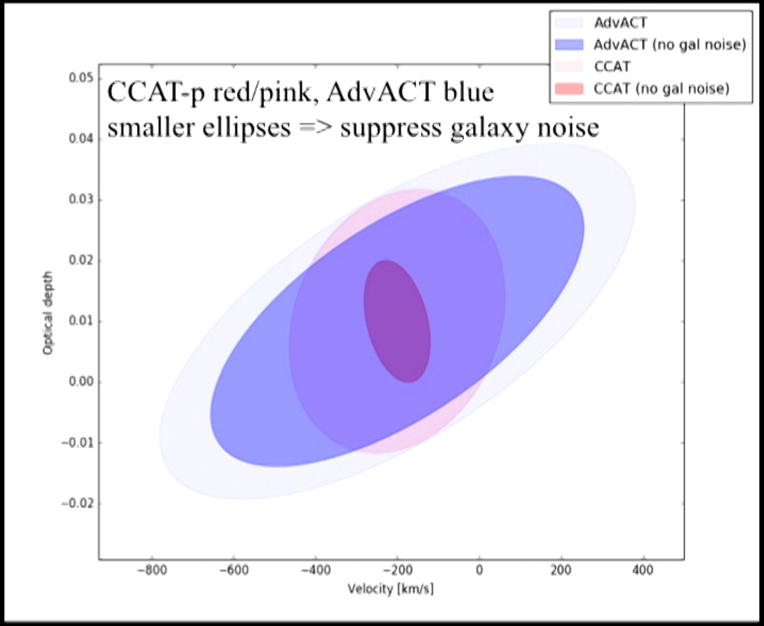
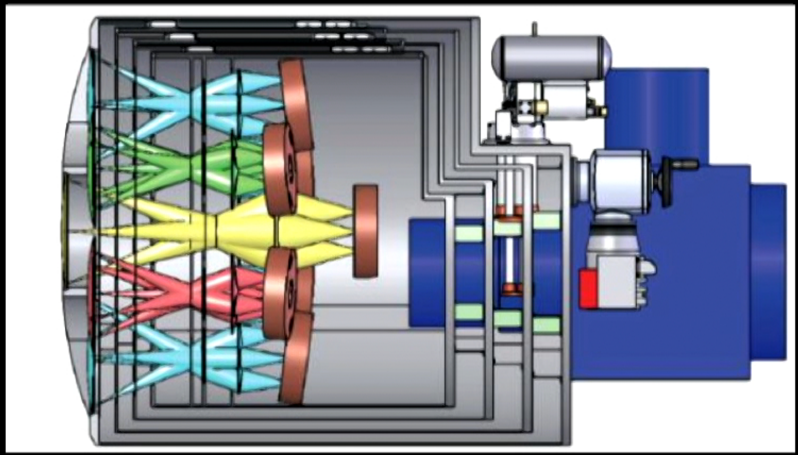
CCAT-prime velocity constraints appear much better than Advanced ACTPol



Forecasts with F. de Bernardis and A. Mittal

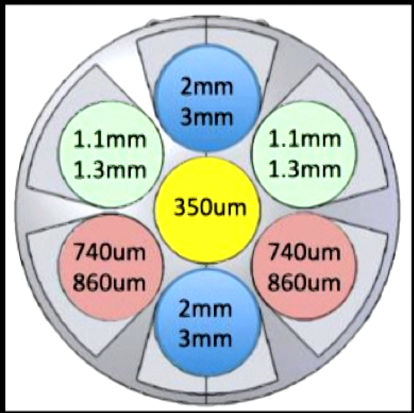
First Light Instrument Concept

- f/3 telescope, f/1.5 receiver
  Maximize sensitivity of current detector arrays
  (e.g. Niemack 2016, arXiv:1511.04506)



- Seven sub-cameras
  Forecasts assume:
  - Cam1: 350 um
  - Cam2/3: 740 & 860 um
  - Cam4/5: 1.1 & 1.3 mm
  - Cam6/7: 2 & 3 mm

- Polarization detectors at long wavelengths
  => CMB polarization to inform CMB-S4



Polarized CMB and Dust Emission

- Polarized galactic dust foregrounds limit current constraints on Inflationary Gravity Waves (e.g. BICEP2)

- Planck measurements suggest several polarized dust bands are needed to detect B-modes with $r \leq 0.01$

  (Planck intermediate results. XXII and XXXVIII 2015)

- CCAT-prime SZ instrument with polarization detectors

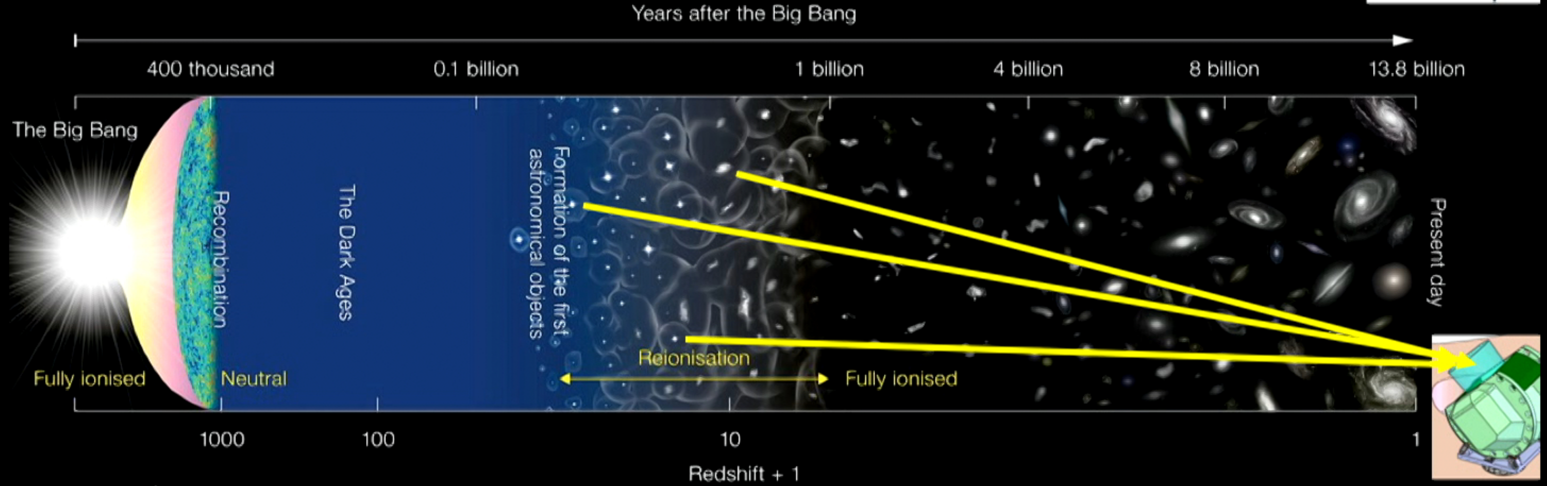
  => Unique niche in CMB community

  => Improve constraints on inflation via foregrounds

  => Understand galactic dust turbulent energy cascade

  (e.g. Caldwell, Hirata, Kamionkowski, arXiv:1608.08138)

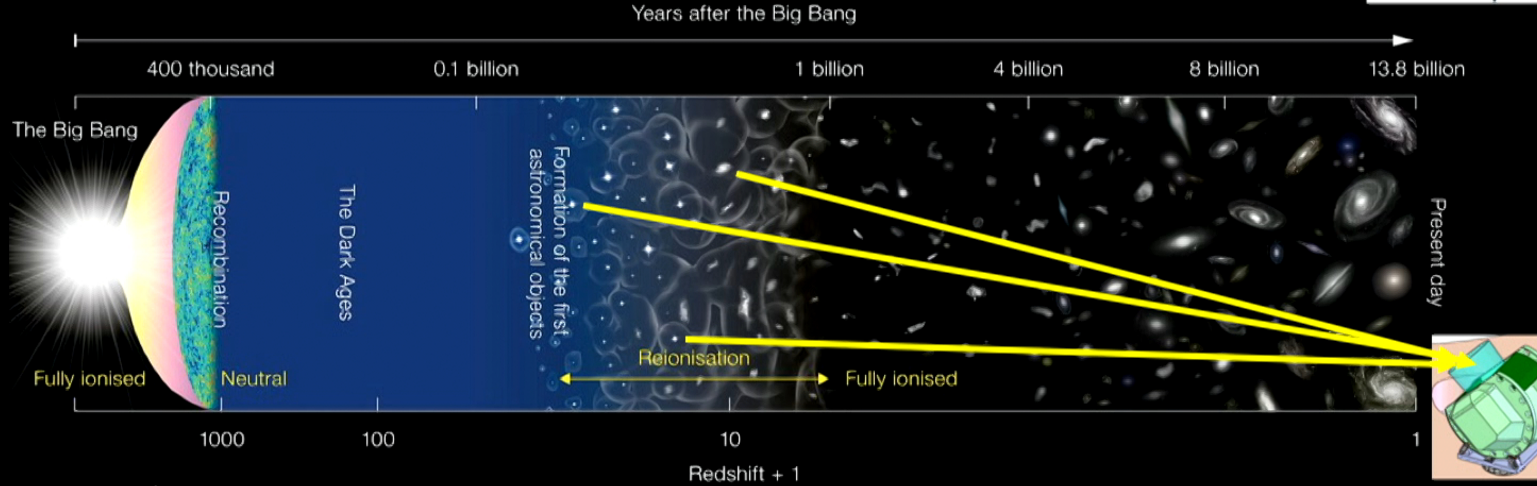
Beyond CMB:
Structure Evolution with CCAT-prime



Courtesy of NAOJ

Epoch of Reionization

Beyond CMB:
Structure Evolution with CCAT-prime



Courtesy of NAOJ

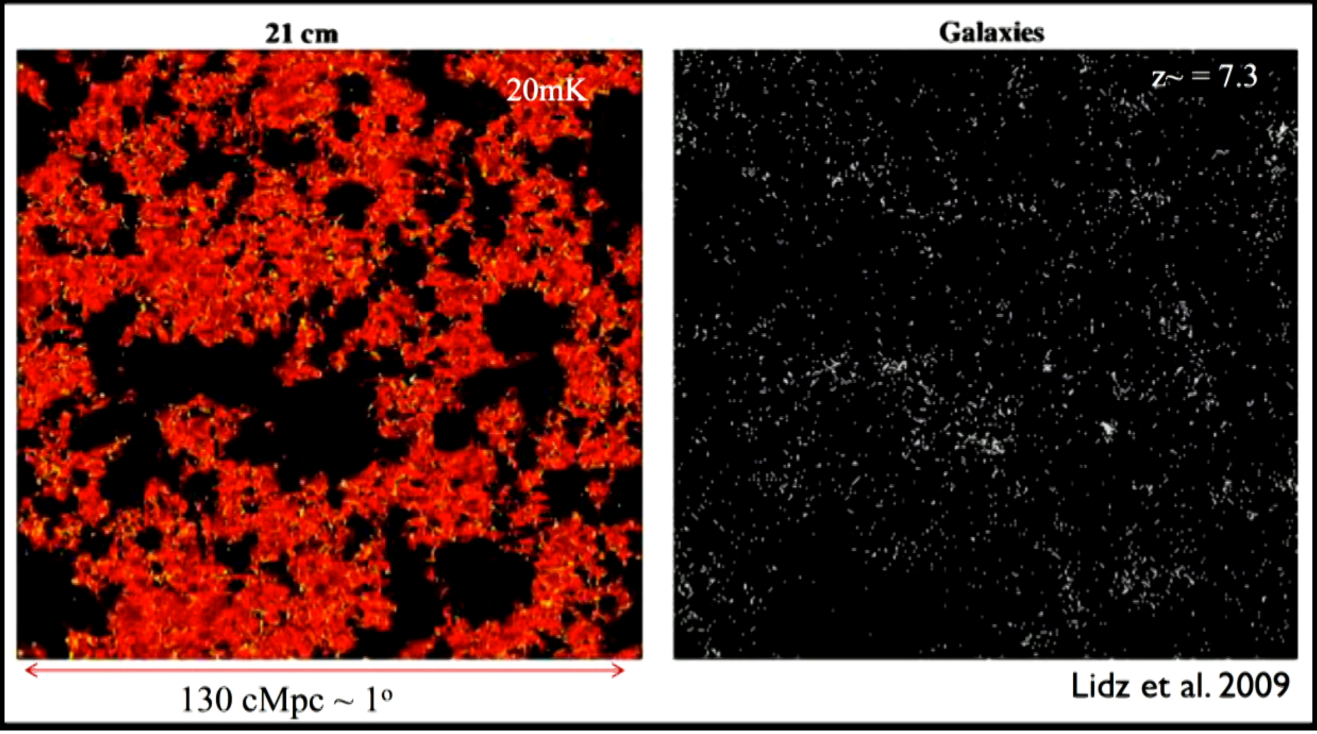
Epoch of Reionization

- How and when did the first stars and galaxies form?
- Carbon [CII] – brightest emission line in star forming galaxies

Reionization with CII line

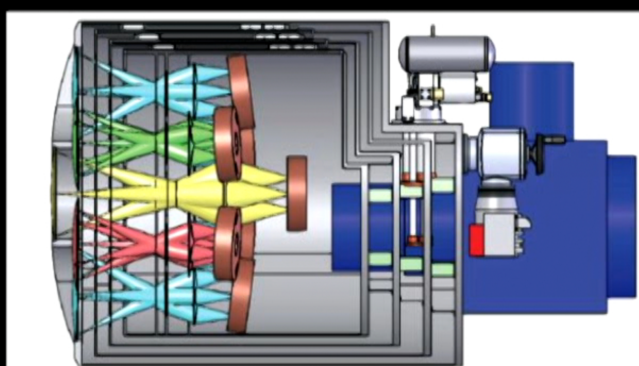
- CII emission at 158 um => 0.8 – 1.4 mm at z = 5 – 9
- Detects inverse of 21-cm on large scales
- Recent progress: high-z detections of CII with ALMA

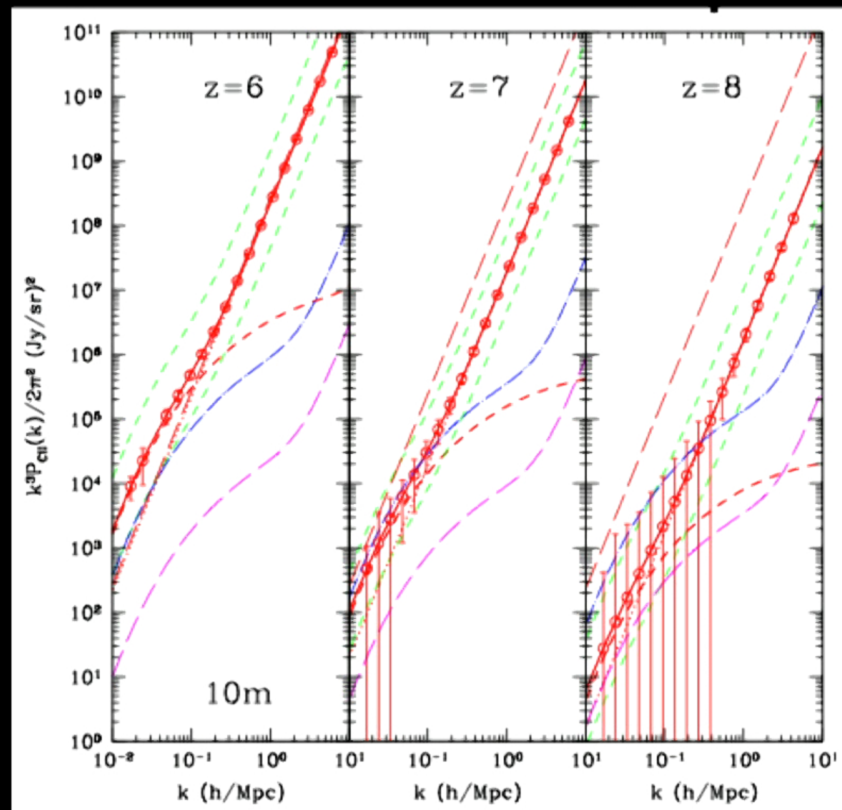
(e.g. Riechers et al. 2014, Capak et al. 2015)



Testing Models of Reionization

- Strong constraints on star formation history and reionization
- CII measurements with spectroscopic upgrade to first light instrument





(Gong et al. ApJ 2012)

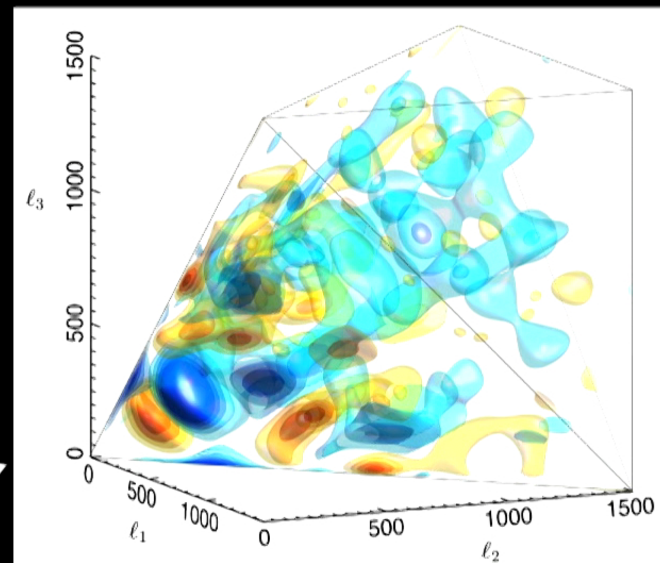
One more Signature of Inflation: Non-Gaussianity

- Requires higher-order statistics:
  3-point function with
  dimensionless amplitude f_{NL}

	$f_{NL}^{loc} \lesssim 1$	$f_{NL}^{loc} \gtrsim 1$
$f_{NL}^{eq,orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{NL}^{eq,orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

(CITA workshop review, arXiv:1412.4671)

Natural Target: $f_{NL} \sim 1$



(Planck Collaboration XVII 2015)

- Planck measurements approaching CMB limits

Type	*Planck* actual (forecast)
Local	$\sigma(f_{NL}) = 5\,(4.5)$
Equilateral	$\sigma(f_{NL}) = 43\,(45.2)$
Orthogonal	$\sigma(f_{NL}) = 21\,(21.9)$

- More modes needed to reach $f_{NL} \sim 1$
  => large-scale structure

M. Niemack, Cornell Univ

Next generation CII survey and Inflation

- Large volume spectroscopic surveys may achieve $\sigma(f_{NL}) \leq 1$

- CII and 21-cm foregrounds and bias may improve with cross-correlations
  (e.g. Gong et al. ApJ 2012)

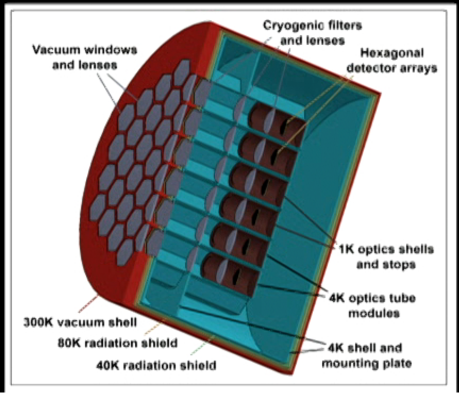
SKA 21-cm f_{NL} forecast

PNG type	$\sigma_{f_{NL}}$ (1 MHz)	$\sigma_{f_{NL}}$ (0.1 MHz)
Local	0.12	0.03
Equilateral	0.39	0.04
Orthogonal	0.29	0.03

(Munoz et al. arXiv:1506.04152)

- CCAT-prime could eventually host ~10x larger CII spectrometer than previously considered

- Could this reionization probe constrain primordial non-Gaussianity?



Summary and Status: CCAT-prime

- Significant advances in CMB probes of inflation, dark energy, and neutrinos require high-throughput telescopes
- CCAT-prime offers exciting new capabilities for CMB, galaxy cluster, intensity mapping, and more
- Telescope vendor selection in March 2017, with construction following board approval
- Additional participants welcome (at contribution)