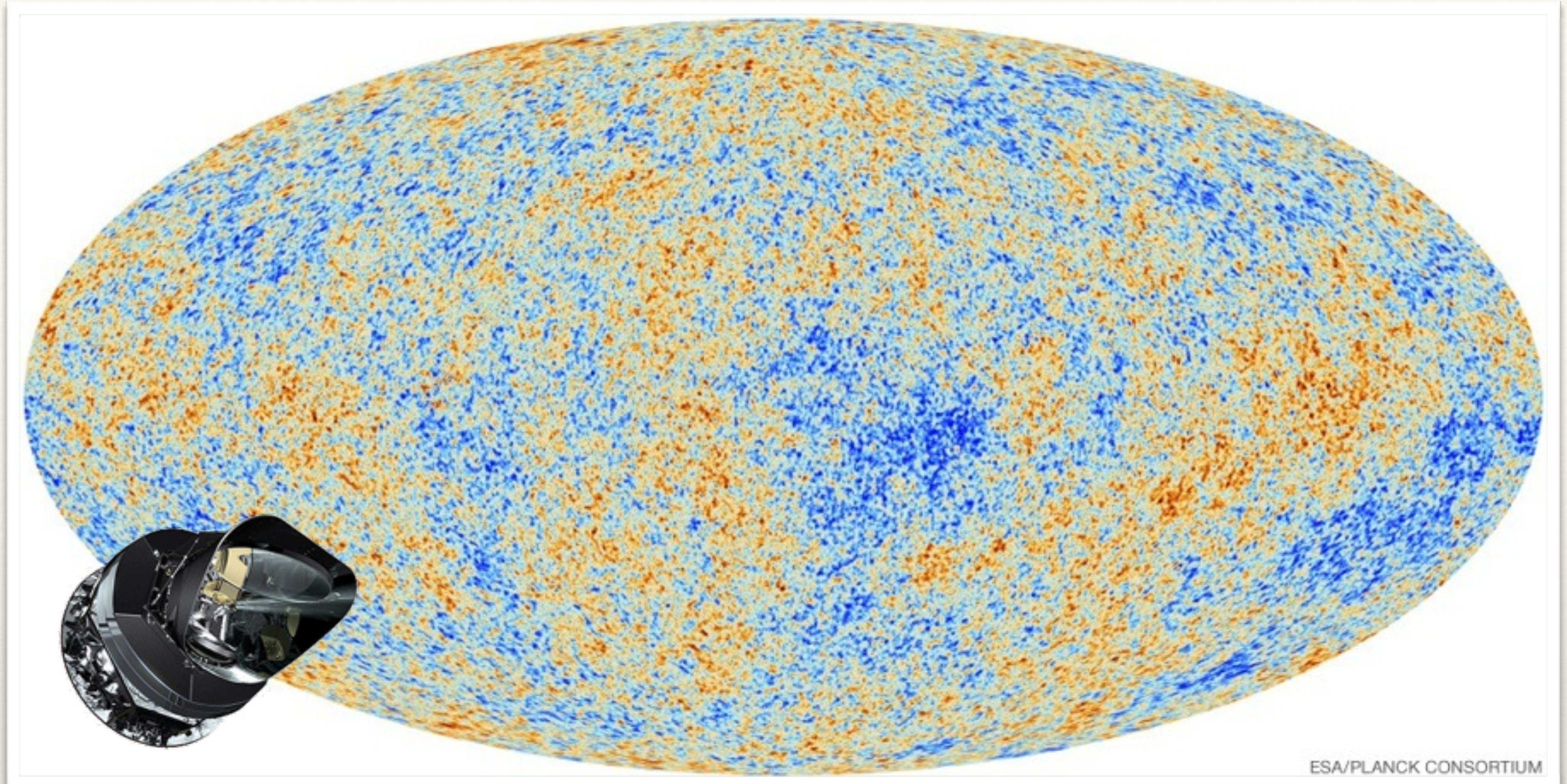


IAP Colloquium XXX: The Primordial Universe after Planck is Almost Finished

Make Better Maps not Better Parameters

IAP Medal Discourse

Albert Stebbins
2014-12-18
Paris

Parametric cosmology: H_0 Ω_0 Ω_{m0} Ω_{b0} Ω_{r0} w w' N_ν $\sum m_\nu$ σ_8 n_s r n_t τ f_{NL}

The Observational Cosmology Industrial Complex

VS

Cartography is Just Plain Useful

- Witness: Google Maps, etc.
- or SDSS which was sold on "**key projects**"
  - e.g. measure w[θ,z], P[k,z] up to and past the peak
- "**core projects**" much more important
  - e.g. in π steradians do % 5 band photometry R<25, spectroscopy R<19
- **because** the vast majority of science results (and much of the cosmological science) was not foreseen by project developers, e.g. weak lensing. They relied on the quality of the maps.

Great Trigonometric Survey of India

1802-1921

Systematic Errors to Overcome:

Refraction of atmosphere

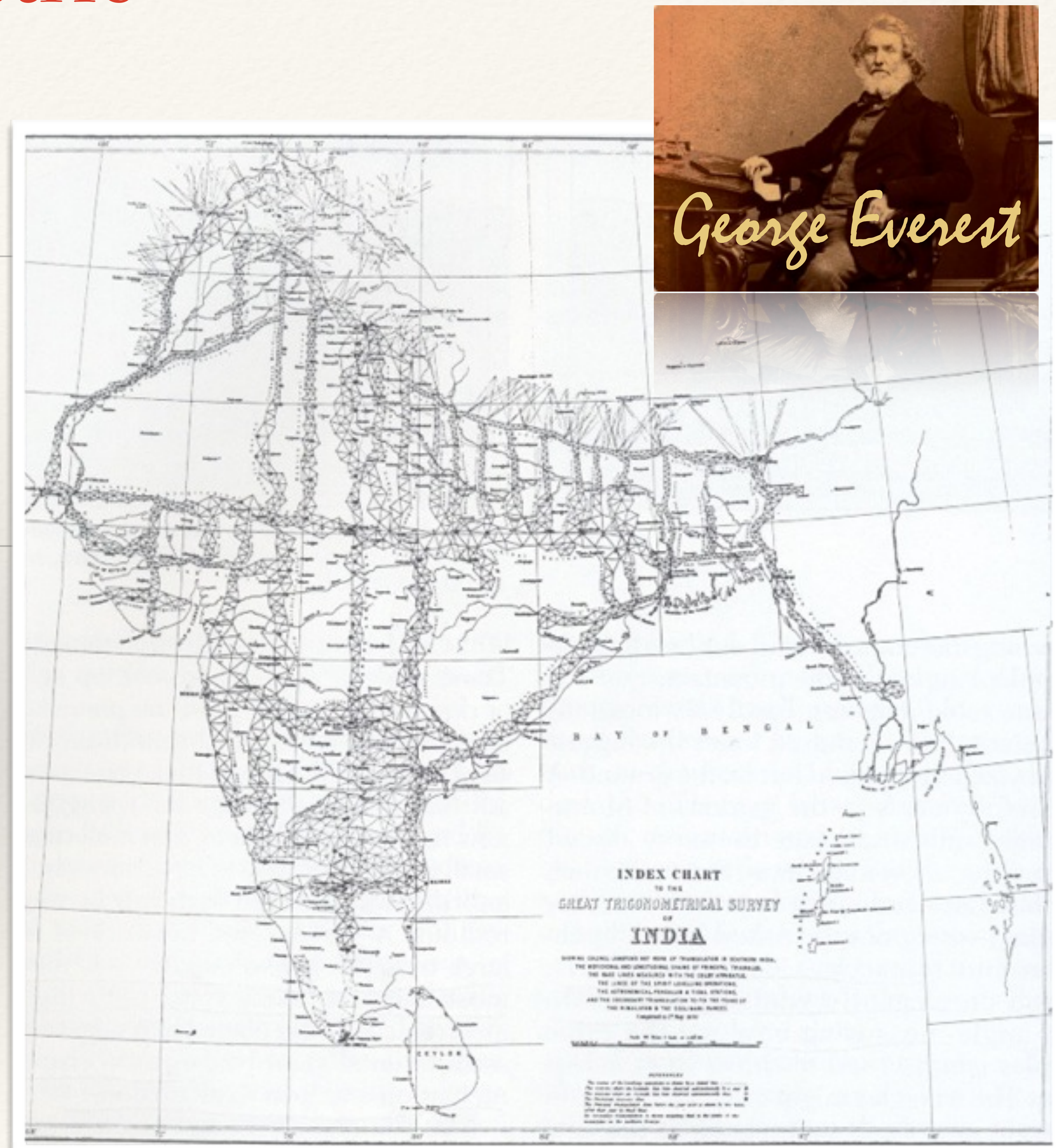
Non-spherical curvature of Earth

Gravitational attraction of mountains causing pendulums not to hang vertically

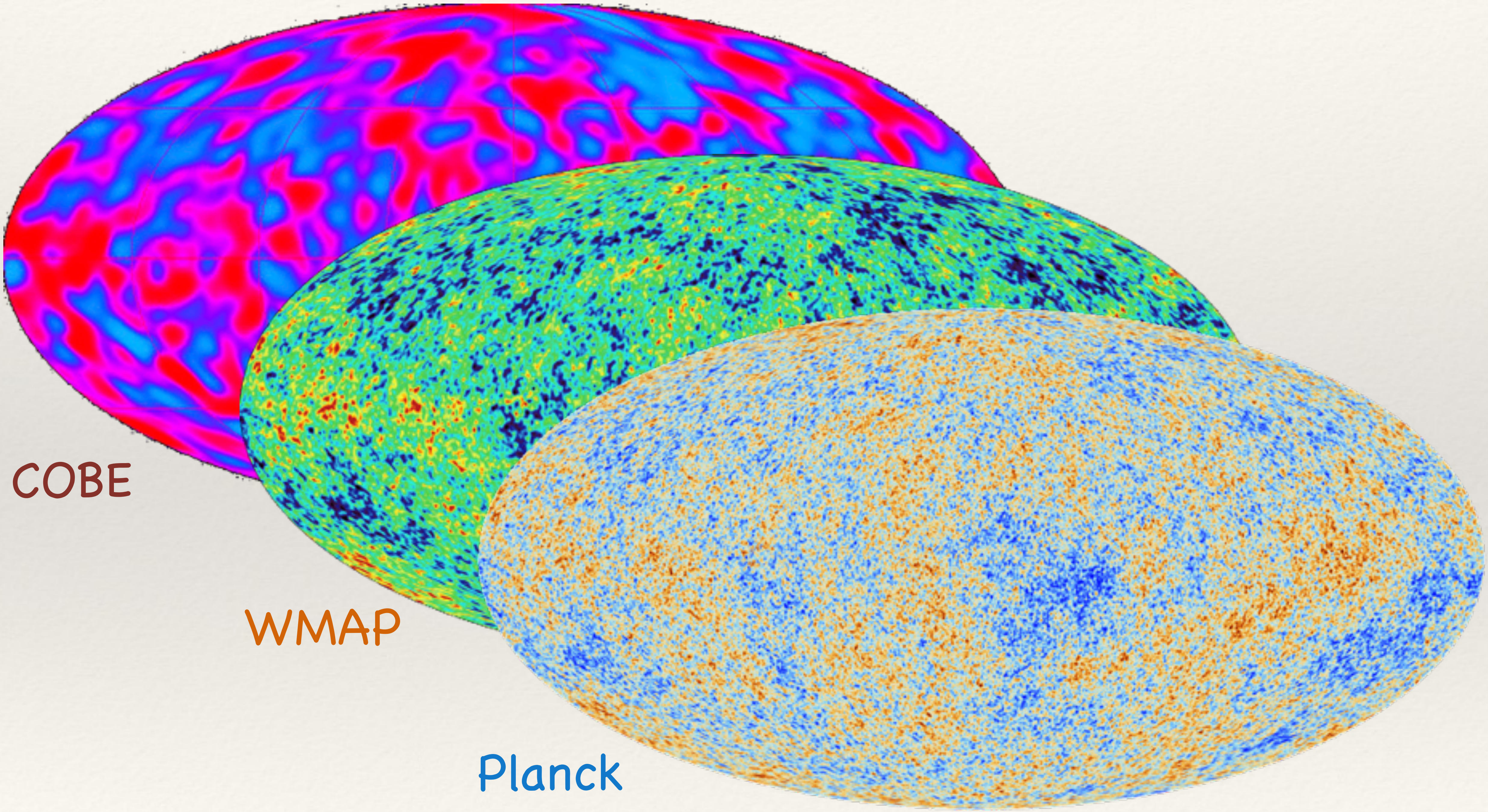
Key Project:
Measure Great Britain's Crown Jewel

Core Project:
3-D Survey of India North-to-South and East-to-West with *redundant* grid of trigonometric sitings

Ancillary Science:
Established the highest of heights: Mount Everest, K2



Other Paragons of Map Making

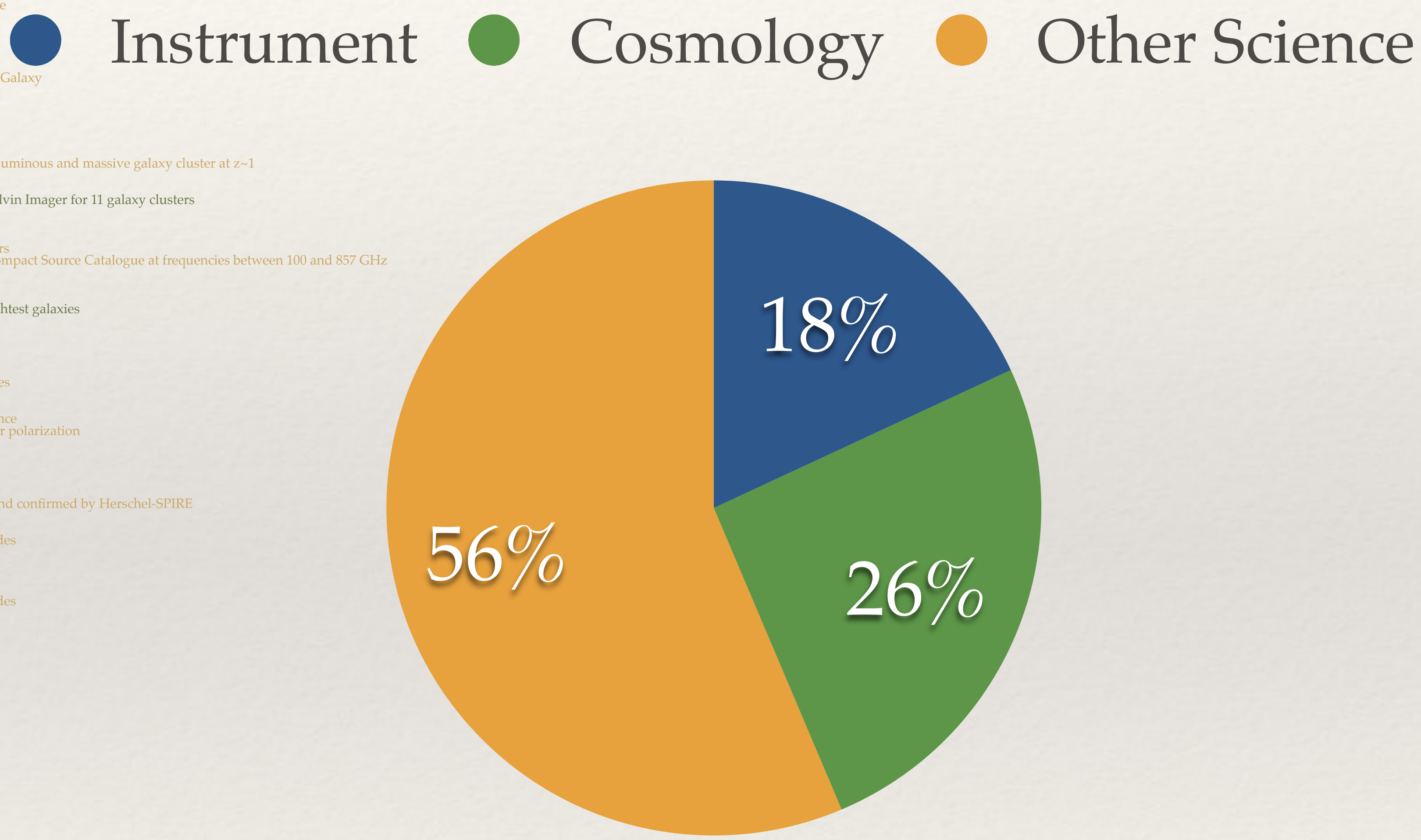


Principles for Better Mapmaking

- Better precision: statistical errors
  - lower noise and more detectors.
- Better accuracy: control of systematic errors
  - e.g. increased frequency coverage to handle foregrounds
- Better resolution:
- Measure more things:
  - e.g. temperature + linear polarization + even circular (Venumadhav's talk)
- Map greater extent (area)

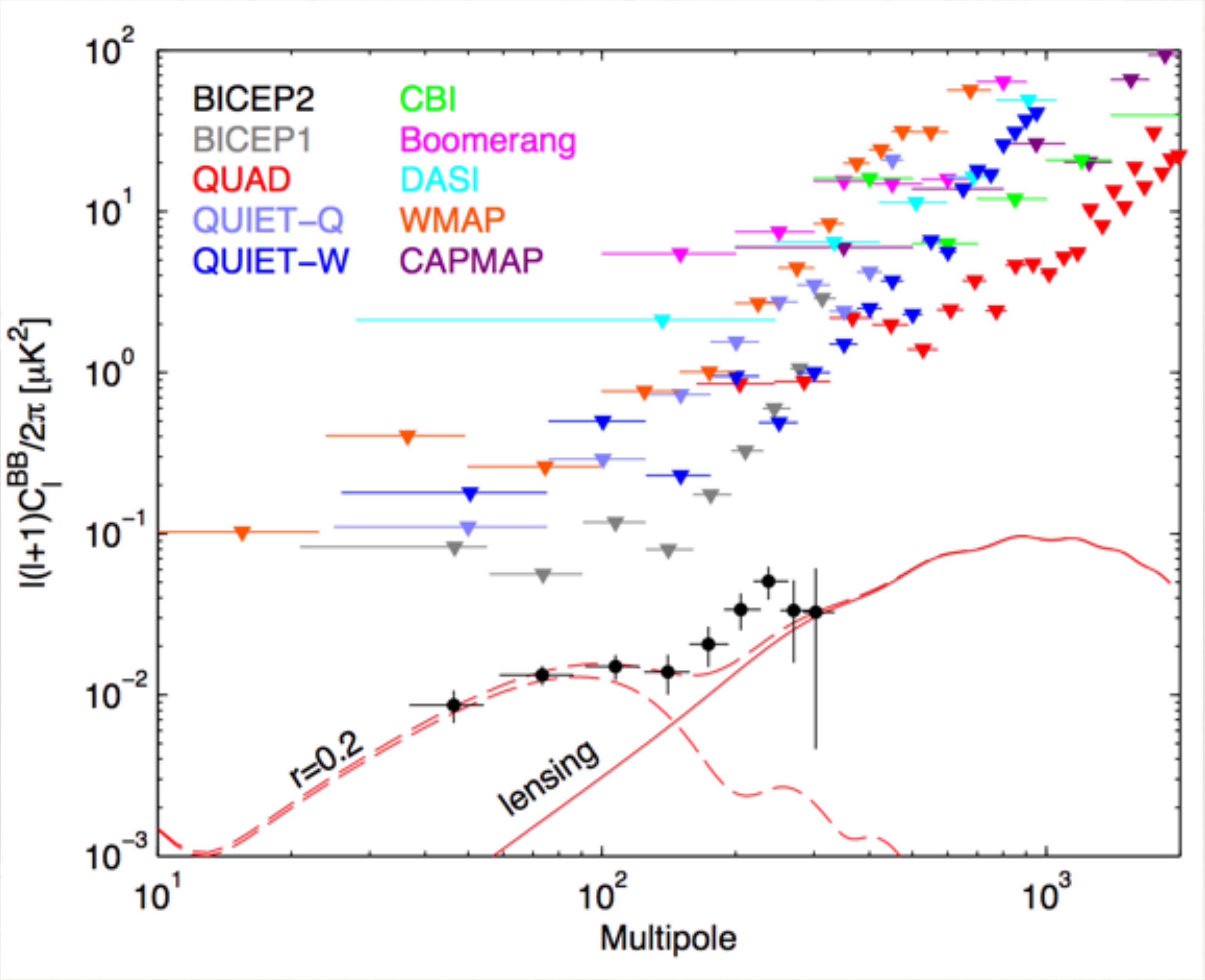
Survey Health: Diversity of Planck Science

- Early-01 The Planck mission
- Early-02 The thermal performance of Planck
- Early-03 First assessment of the Low Frequency Instrument in-flight performance
- Early-04 First assessment of the High Frequency Instrument in-flight performance
- Early-05 The Low Frequency Instrument data processing
- Early-06 The High Frequency Instrument data processing
- Early-07 The Early Release Compact Source Catalogue
- Early-08 The all-sky early Sunyaev-Zeldovich cluster sample
- Early-00 XMM-Newton follow-up for validation of Planck cluster candidates
- Early-10 Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
- Early-11 Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
- Early-12 Cluster Sunyaev-Zeldovich optical scaling relations
- Early-13 Statistical properties of extragalactic radio sources in the Planck Early Release Compact Source Catalogue
- Early-14 ERCSC validation and extreme radio sources
- Early-15 Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources
- Early-16 The Planck view of nearby galaxies
- Early-17 Origin of the submillimetre excess dust emission in the Magellanic Clouds
- Early-18 The power spectrum of cosmic infrared background anisotropies
- Early-19 All-sky temperature and dust optical depth from Planck and IRAS – constraints on the "dark gas" in our Galaxy
- Early-20 New light on anomalous microwave emission from spinning dust grains
- Early-21 Properties of the interstellar medium in the Galactic plane
- Early-22 The submillimetre properties of a sample of Galactic cold clumps
- Early-23 The first all-sky survey of Galactic cold clumps
- Early-24 Dust in the diffuse interstellar medium and the Galactic halo
- Early-25 Thermal dust in nearby molecular clouds
- Early-26 Detection with Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an exceptionally X-ray luminous and massive galaxy cluster at z~1
- Early-27 Simultaneous Planck, Swift, and Fermi observations of X-ray and gamma-ray selected blazars
- Intermediate-01 Further validation of new Planck clusters with XMM-Newton
- Intermediate-02 Comparison of Sunyaev-Zeldovich measurements from Planck and from the Arcminute Microkelvin Imager for 11 galaxy clusters
- Intermediate-03 The relation between galaxy cluster mass and Sunyaev-Zeldovich signal
- Intermediate-04 The XMM-Newton validation programme for new Planck clusters
- Intermediate-05 Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect
- Intermediate-06 The dynamical structure of PLCKG214.6+37.0, a Planck discovered triple system of galaxy clusters
- Intermediate-07 Statistical properties of infrared and radio extragalactic sources from the Planck Early Release Compact Source Catalogue at frequencies between 100 and 857 GHz
- Intermediate-08 Filaments between interacting clusters
- Intermediate-09 Detection of the Galactic haze with Planck
- Intermediate-10 Physics of the hot gas in the Coma cluster
- Intermediate-11 The gas content of dark matter halos: the Sunyaev-Zeldovich-stellar mass relation for locally brightest galaxies
- Intermediate-12 Diffuse Galactic components in the Gould Belt System
- Intermediate-13 Constraints on peculiar velocities
- Intermediate-14 Dust emission at millimetre wavelengths in the Galactic plane
- Intermediate-15 A study of anomalous microwave emission in Galactic clouds
- Intermediate-16 Profile likelihoods for cosmological parameters
- Intermediate-17 Emission of dust in the diffuse interstellar medium from the far-infrared to microwave frequencies
- Intermediate-18 The millimetre and sub-millimetre emission from planetary nebulae
- Intermediate-19 An overview of the polarized thermal emission from Galactic dust
- Intermediate-20 Comparison of polarized thermal emission from Galactic dust with simulations of MHD turbulence
- Intermediate-21 Comparison of polarized thermal emission from Galactic dust at 353 GHz with optical interstellar polarization
- Intermediate-22 Frequency dependence of thermal emission from Galactic dust in intensity and polarization
- Intermediate-23 Galactic plane emission components derived from Planck with ancillary data
- Intermediate-24 Constraints on variation of fundamental constants
- Intermediate-25 The Andromeda Galaxy as seen by Planck
- Intermediate-26 Optical identification and redshifts of Planck clusters with the RTT150 telescope
- Intermediate-27 High-redshift infrared galaxy overdensity candidates and lensed sources discovered by Planck and confirmed by Herschel-SPIRE
- Intermediate-28 Interstellar gas and dust in the Chamaeleon clouds as seen by Fermi LAT and Planck
- Intermediate-29 All-sky dust modelling with Planck, IRAS, and WISE observations
- Intermediate-30 The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes
- Intermediate-31 Microwave survey of Galactic supernova remnants
- Intermediate-32 The relative orientation between the magnetic field and structures traced by interstellar dust
- Intermediate-33 Signature of the magnetic field geometry of interstellar filaments in dust polarization maps
- Intermediate-34 Interstellar gas and dust in the Chamaeleon clouds as seen by Fermi LAT and Planck
- Intermediate-35 The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes
- 2013-00 Overview of products and results
- 2013-01 Low Frequency Instrument data processing
- 2013-03 LFI systematic uncertainties
- 2013-04 Low Frequency Instrument beams and window functions
- 2013-05 LFI calibration
- 2013-06 High Frequency Instrument data processing
- 2013-07 HFI time response and beams
- 2013-08 HFI photometric calibration and mapmaking
- 2013-09 HFI spectral response
- 2013-10 HFI energetic particle effects: characterization, removal, and simulation
- 2013-11 All-sky model of thermal dust emission
- 2013-12 Diffuse component separation
- 2013-13 Galactic CO emission
- 2013-14 Zodiacal emission
- 2013-15 CMB power spectra and likelihood
- 2013-16 Cosmological parameters
- 2013-17 Gravitational lensing by large-scale structure
- 2013-18 The gravitational lensing-infrared background correlation
- 2013-19 The integrated Sachs-Wolfe effect
- 2013-20 Cosmology from Sunyaev-Zeldovich cluster counts
- 2013-21 Power spectrum and high-order statistics of the Planck all-sky Compton parameter map
- 2013-22 Constraints on inflation
- 2013-23 Isotropy and statistics of the CMB
- 2013-24 Constraints on primordial non-Gaussianity
- 2013-25 Searches for cosmic strings and other topological defects
- 2013-26 Background geometry and topology of the Universe
- 2013-27 Doppler boosting of the CMB: Eppur si muove
- 2013-28 The Planck Catalogue of Compact Sources
- 2013-29 The Planck catalogue of Sunyaev-Zeldovich sources
- 2013-30 Cosmic infrared background measurements and implications for star formation
- 2013-31 Consistency of the Planck data



The BICEP2 Gamble

- BICEP2 took advantage of an opportunity of their own making to rapidly achieve very strong *raw* sensitivity to **r**.
- *"it's all about **r**"* (Kuo)
- but with little internal control of foreground contamination.
- "Mean and lean"
- Did it pay off?
- **Wait** (Efstathiou)

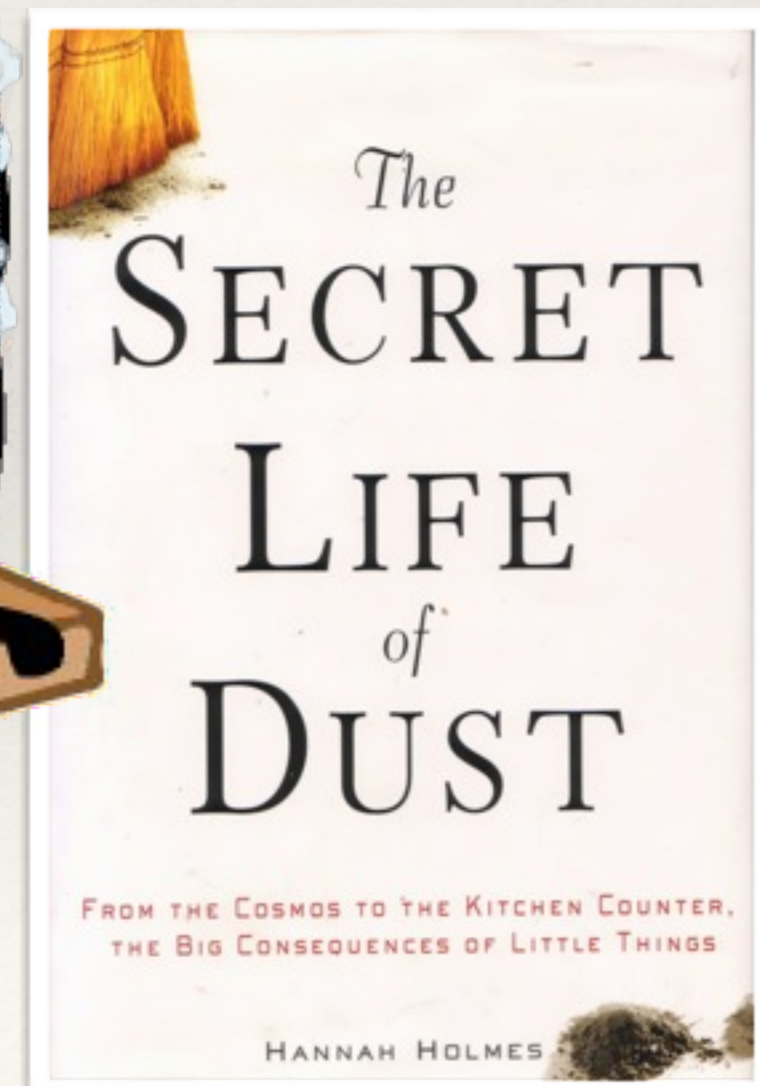


Adieu BICEP2

Modus Operandi

… dust isn't as harmless as it appears, it can be a heartless little brute …

Hannah Holmes



If we are all lean and mean then we can get into trouble

Maps in Many Spaces

- CMB - normally angular space
- but, frequency space also
  - frequency resolution WMAP<Planck<Core+<Prism
  - precision information in recombination lines frequency
  - small spectral distortions will be produced by motions and will contribute to precision measurements
  - possible energy injection in early and late universe (dark matter annihilation)
  - extent: WMAP<Planck better handle on foregrounds
  - bands above CMB band (30-200GHz) is well mapped out *but not below*
  - 10-20GHz band combined with z-surveys may help track evolution of cluster magnetic fields via Faraday rotation depolarization

Maps in Many Spaces

- 2D $\Rightarrow$ 3D:
  - LSS spectroscopic surveys
  - historically LSS maps are dirtier than CMB maps due to non-linearities and non-uniform sampling.
  - 21cm intensity mapping. In dark ages sampling will be near uniform. It might approach CMB quality.
- Time Resolution space:
  - time domain astronomy is a growing field. SNe are and Fast Radio Bursts may be important for cosmology.

Maps in Phase Space

- 2D $\Rightarrow$ 6-D:
    - Ideally we would like to map the full 6D phase space distribution of photons, neutrinos etc.
    - this quest is hindered by the fact that we only “see” things on our 3D past light cone.
    - spectral information brings us to 4D if we can redshift source.
    - however we can see a “little bit” inside our by looking at scattered light.
    - CMB polarization which is produced by scattering allows us to sample the photon phase space distribution.
    - this is what the E/B-mode thing does!

Helicity Decomposition of Distribution Function

Stokes Parameters: $I[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t]$, $Q[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t]$, $U[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t]$, $V[\hat{\boldsymbol{c}}, \nu, \boldsymbol{x}, t]$

- Spatial Fourier transform, e.g.

$$I[\hat{\boldsymbol{c}},\nu,\boldsymbol{x},t] = \sum_k e^{i\,\boldsymbol{k}\cdot\boldsymbol{x}}\,\tilde{I}[\hat{\boldsymbol{c}},\nu,\boldsymbol{k},t] \qquad Q[\hat{\boldsymbol{c}},\nu,\boldsymbol{x},t] + i\,U[\hat{\boldsymbol{c}},\nu,\boldsymbol{x},t] = \sum_k e^{i\,\boldsymbol{k}\cdot\boldsymbol{x}}\,P[\hat{\boldsymbol{c}},\nu,\boldsymbol{k},t]$$

- Angular decomposition: spin weighted spherical harmonics

$$\tilde{I}[\hat{\boldsymbol{c}},\nu,\boldsymbol{k},t] = \sum_\ell \sum_h Y_{(0,\ell,h)}[\hat{\boldsymbol{c}}]\,\tilde{I}_{(\ell,h)}[\nu,\boldsymbol{k},t]$$

$$V[\hat{\boldsymbol{c}},\nu,\boldsymbol{k},t] = \sum_\ell \sum_h Y_{(0,\ell,h)}[\hat{\boldsymbol{c}}]\,V_{(\ell,h)}[\nu,\boldsymbol{k},t]$$

$$P[\hat{\boldsymbol{c}},\nu,\boldsymbol{k},t] = \sum_\pm \sum_\ell \sum_h e^{i\varphi[\hat{\boldsymbol{c}},\boldsymbol{k}]}\,Y_{(\pm 2,\ell,h)}[\hat{\boldsymbol{c}}]\,P_{(\ell,h)}[\nu,\boldsymbol{k},t]$$

  - alignment of pole with $\boldsymbol{k}$.

- Note $Y_{(s,\ell,h)}$ only exists for $\ell \geq |h|, |s|$.

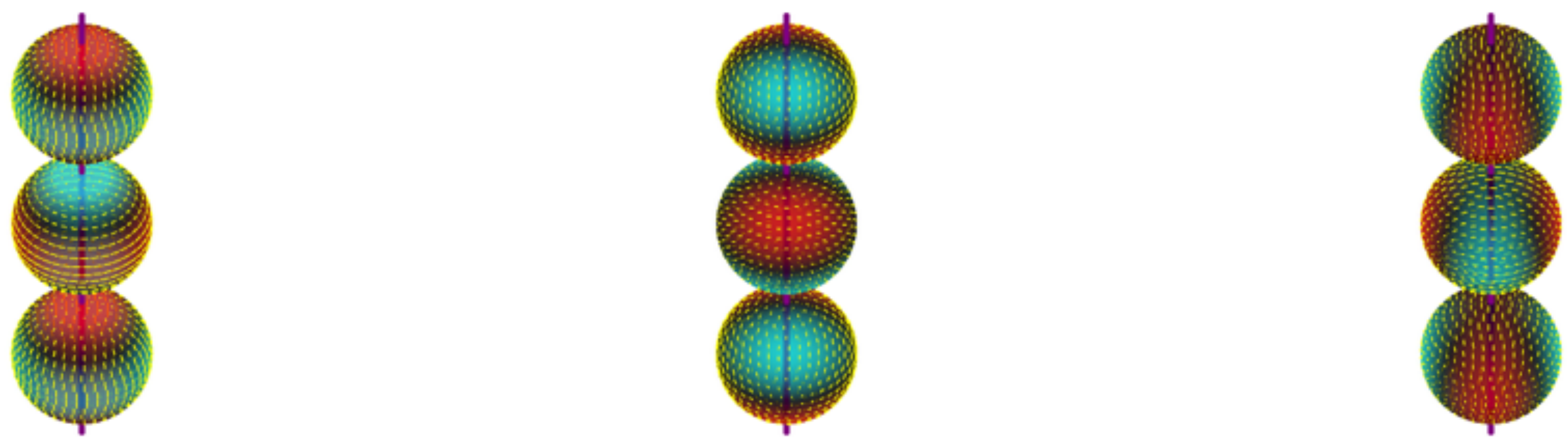
Phase Space Dynamics

Very old story from 80's

- Intense scattering erases any initial polarization / anisotropy.
- Gravity (spin 2) induces $h=\ell=0,1,2$ anisotropies
- Propagating photons then convects ℓ anisotropies to $\ell\pm1$ preserving h
- Scattering converts temperature to polarization preserving h and ℓ but only for $\ell\geq2$.
- Propagating photons then convects ℓ anisotropies/polarization to $\ell\pm1$ preserving h
- repeat …
- Polarization only produced when scattering is effective: recombination / reionization
- This old story has no mechanism to produce circular polarization

Helicity h=0,1,2 Quadrupole ℓ =2

- For large scale / super horizon modes only h=0,1,2 excited and lowest ℓ's ($\geq h$) dominate
- Since polarization is only produced for $\ell \geq 2$ the ℓ=2 h=0,1,2 dominates polarization on large scales
- These large scale modes at recombination evolve into $\ell \lesssim 200$ today, including region not contaminated by lensing, i.e. BICEP2 region.



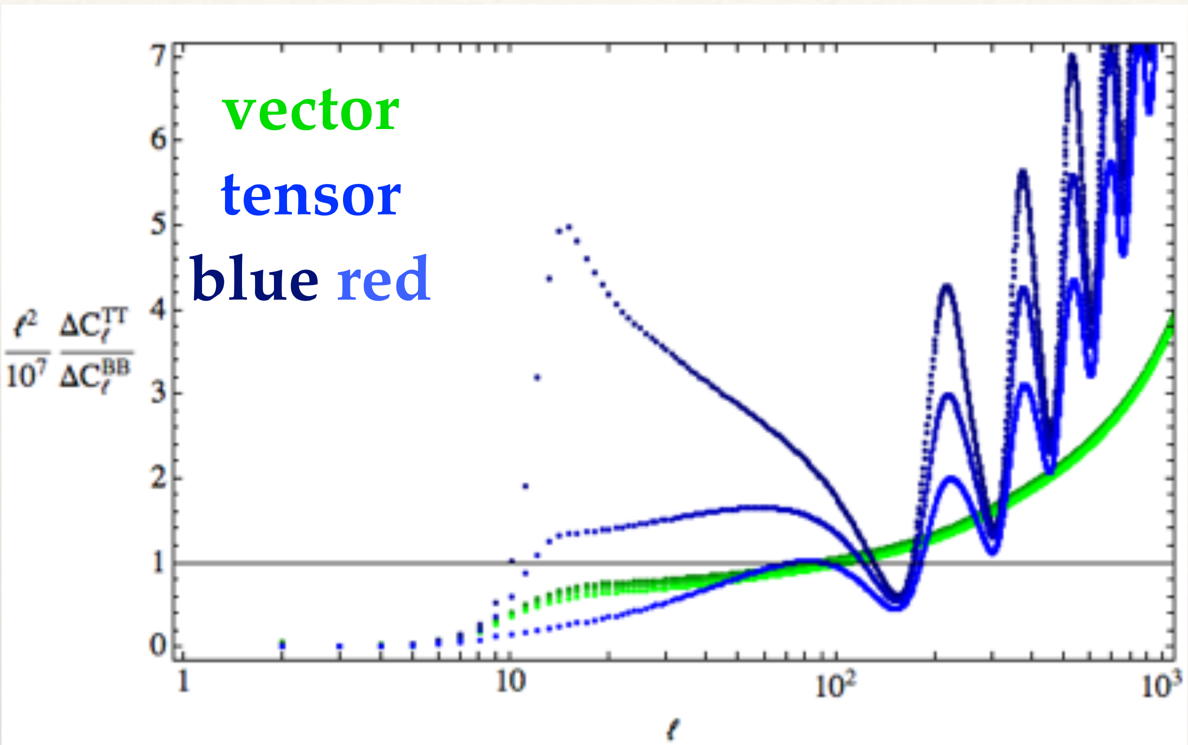
Scalar h=0 Vector h=1 Tensor h=2

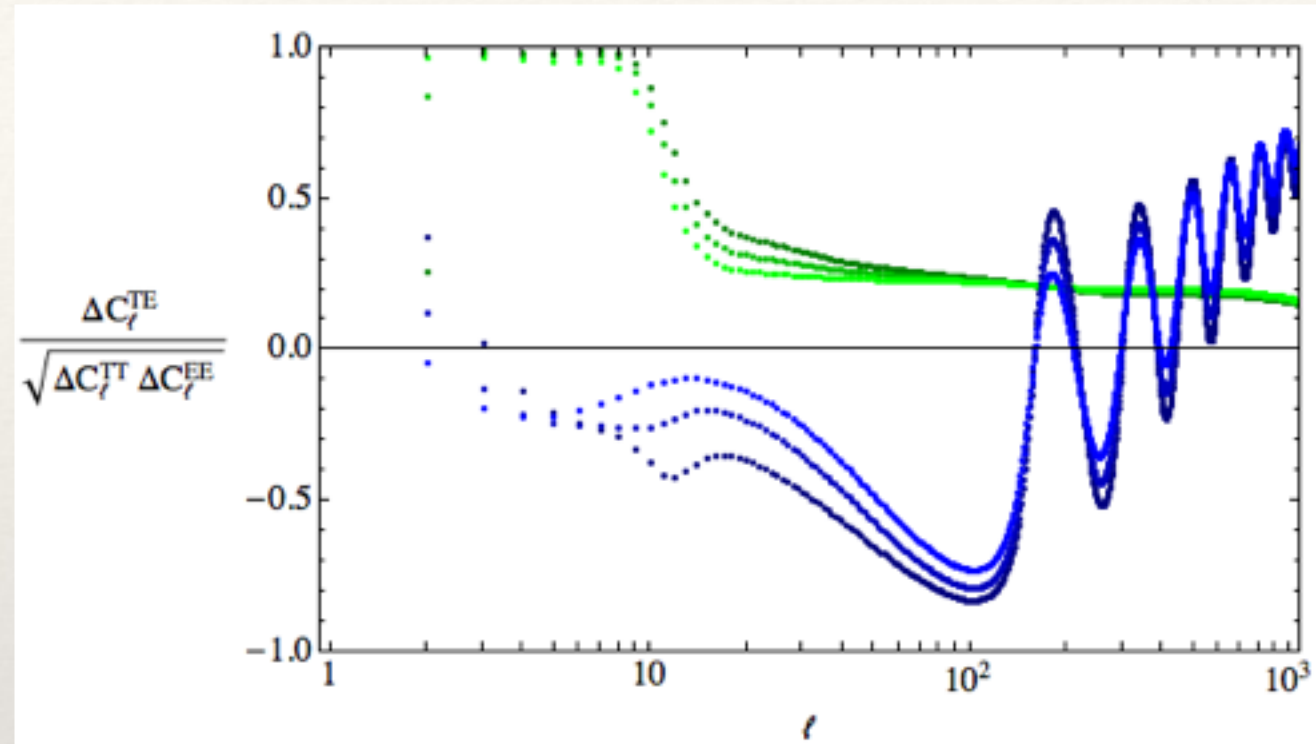
- Only thing missing from standard model is h=1 vector / vorticity modes.

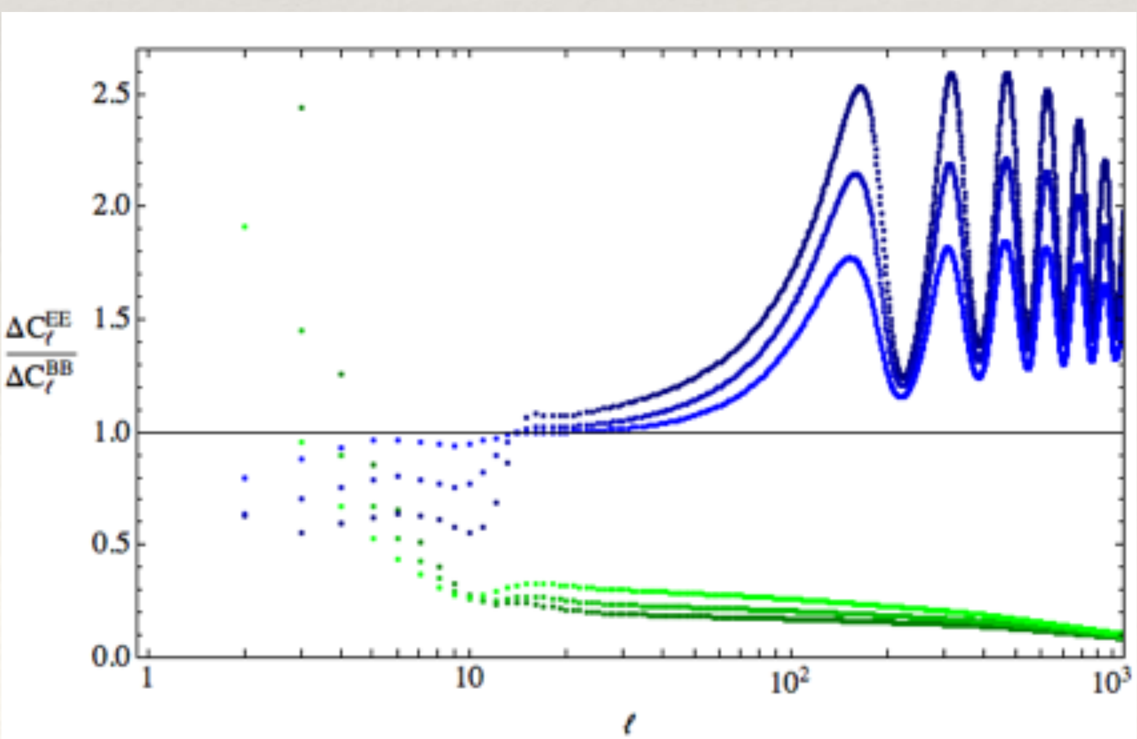
Primordial Vorticity?

- Because of conservation of momentum super horizon vorticity has horizon problem just like scalar and tensor: in need of inflation / bounce / … .
- Vorticity is not produced in standard models of inflation.
- Physically relevant amplitude is velocity (in units of *c*).
- Velocity is constant in radiation dominated universe but does during matter domination (e.g. reheating, late universe).
- **An *unbiased* approach to cosmology would include vorticity in analysis of cosmological data.**

Vector / Tensor Polarization Phenomenology



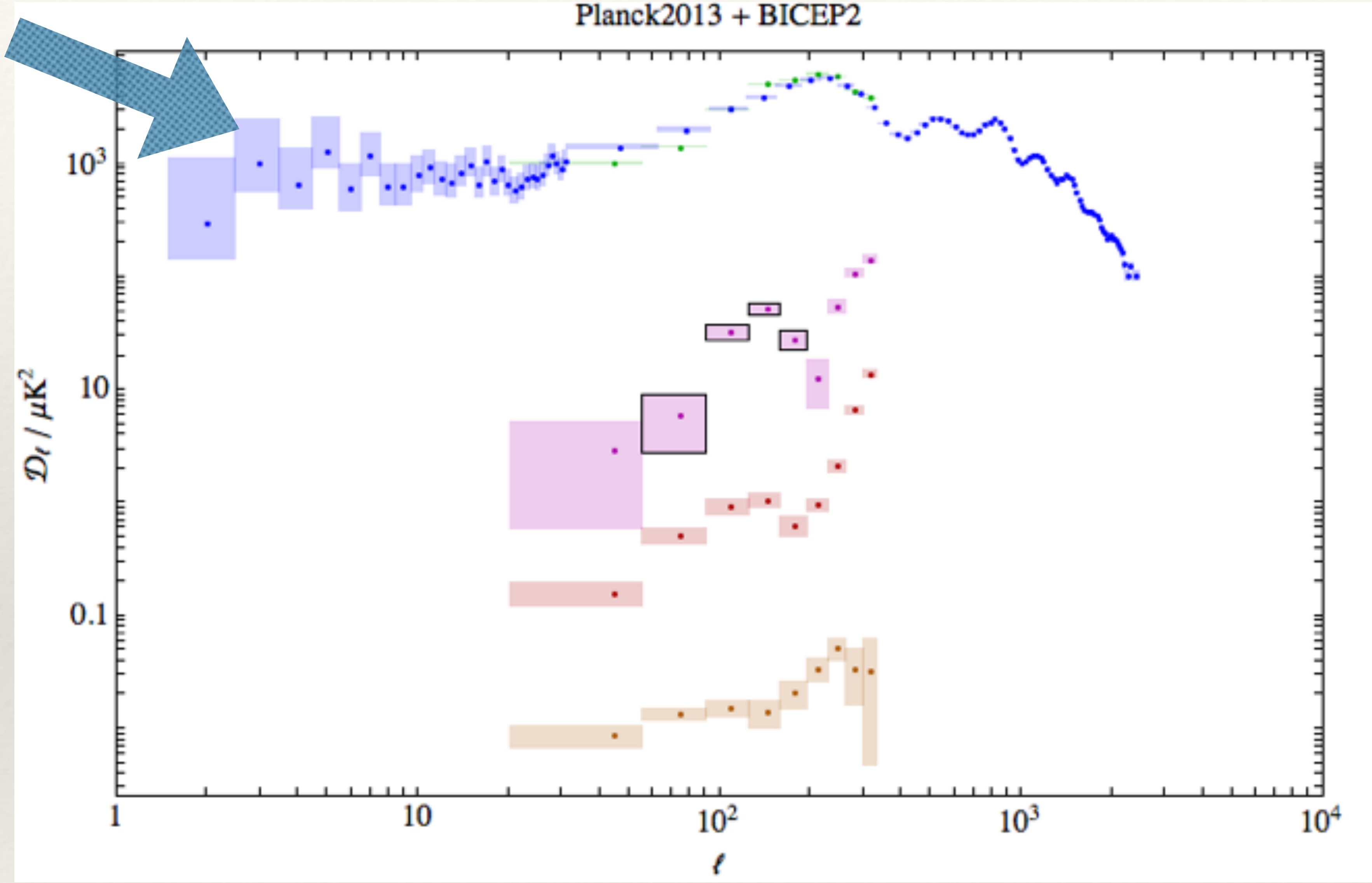




Understood geometrically in terms of components of $Y_{(s,\ell,h)}$

	$\frac{\ell_\star^4 c_\ell^{EE}}{\ell^4 c_\ell^{QQ}}$	$\frac{c_\ell^{BB}}{c_\ell^{EE}}$	$\frac{c_\ell^{EQ}}{\sqrt{c_\ell^{QQ} c_\ell^{EE}}}$	$\frac{c_\ell^{ED}}{\sqrt{c_\ell^{DD} c_\ell^{EE}}}$	$\frac{c_\ell^{EM}}{\sqrt{c_\ell^{MM} c_\ell^{EE}}}$
h=0	1	0	$\frac{1}{\sqrt{6}}$	0	$-\sqrt{\frac{5}{6}}$
h=±1	$\frac{1}{6}$	5	1	0	n/a
h=±2	$\frac{7}{12}$	$\frac{5}{7}$	$-\frac{3}{\sqrt{14}}$	n/a	n/a

BICEP2 is a Tight Squeeze for Tensors



not enough room in TT for tensors that produce BB: blue tensors $n_t > 0$ helps

since vector T/B, E/B are smaller than tensor T/B, E/B it is easier to fit in vectors

see Saga, Shiraishib, Ichikia JCAP **10** 4 (2014)

The Vector Way Forward

- TT, TE, EE, BB allows fitting of 4 types of perturbations
- in current era of CMB polarization measurement we should take advantage of this freedom
- good choice: adiabatic, isocurvature, vector, tensor
- geometrical differences make vectors and tensor easily distinguishable
- if large BB persists this gives strong motivation for theoretical exploration of vorticity production during inflationary epoch.

Large observational parameter spaces remain to be explored.

These may contain important new phenomena.

Some may be relevant to cosmology.

Make Better Maps not Better Parameters

Thanks for these curious, astounding results