Neutrino Masses with Lensing of the Cosmic Microwave Background

(Study of *Experimental Probe of Inflationary Cosmology*)

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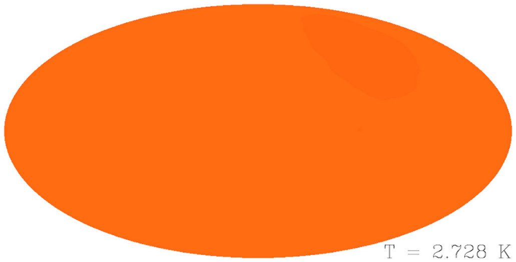
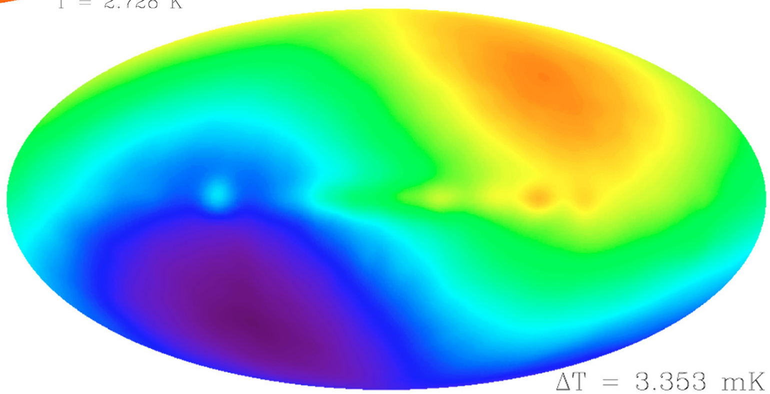


(almost) uniform 2.726K blackbody (Penzias & Wilson)

T = 2.728 K

Universe at 400kyr: the microwave sky

COBE
(Mather & Smoot)

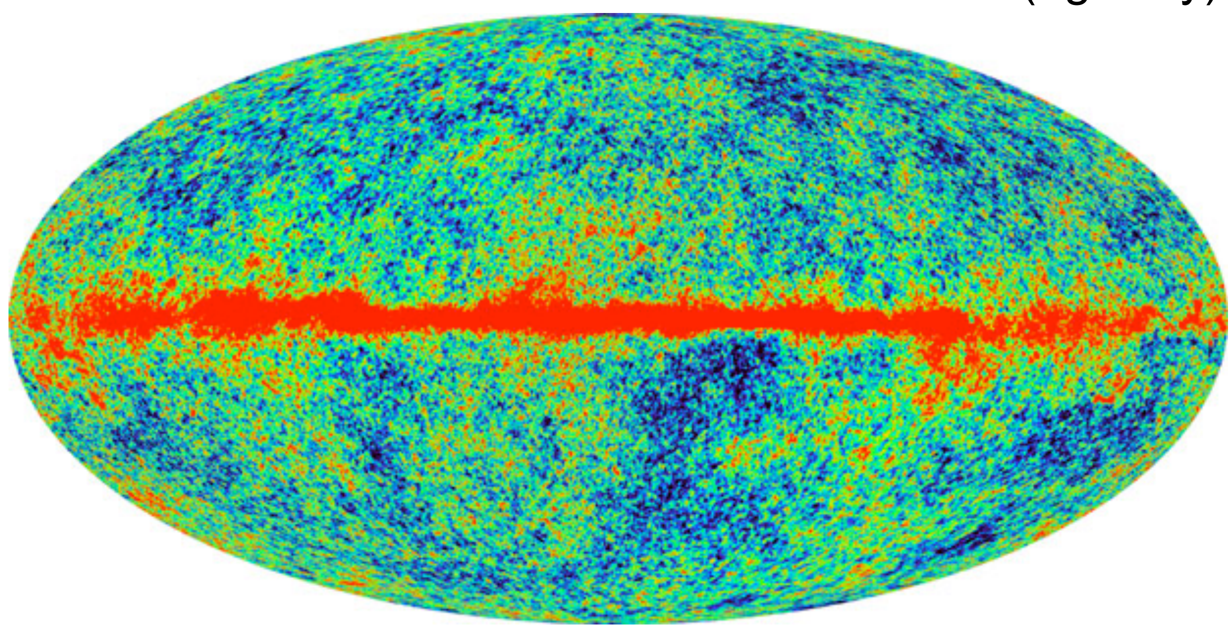


ΔT = 3.353 mK

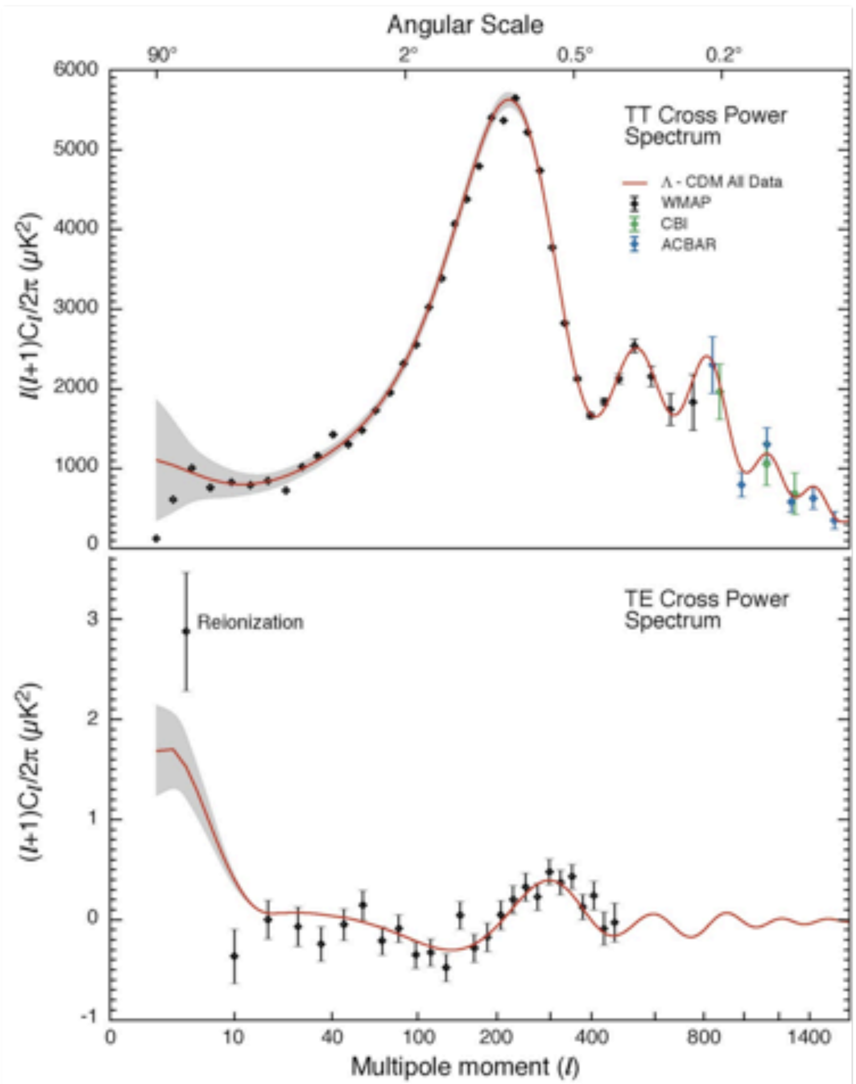
Dipole (local motion)

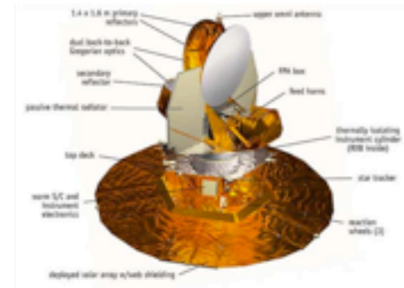
$O(10^{-5})$ perturbations
(+galaxy)

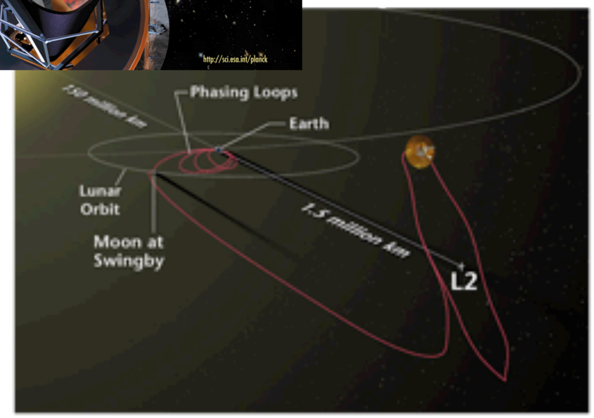
WMAP

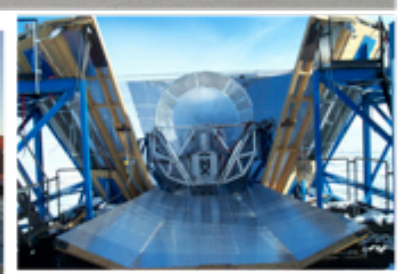


Anisotropies

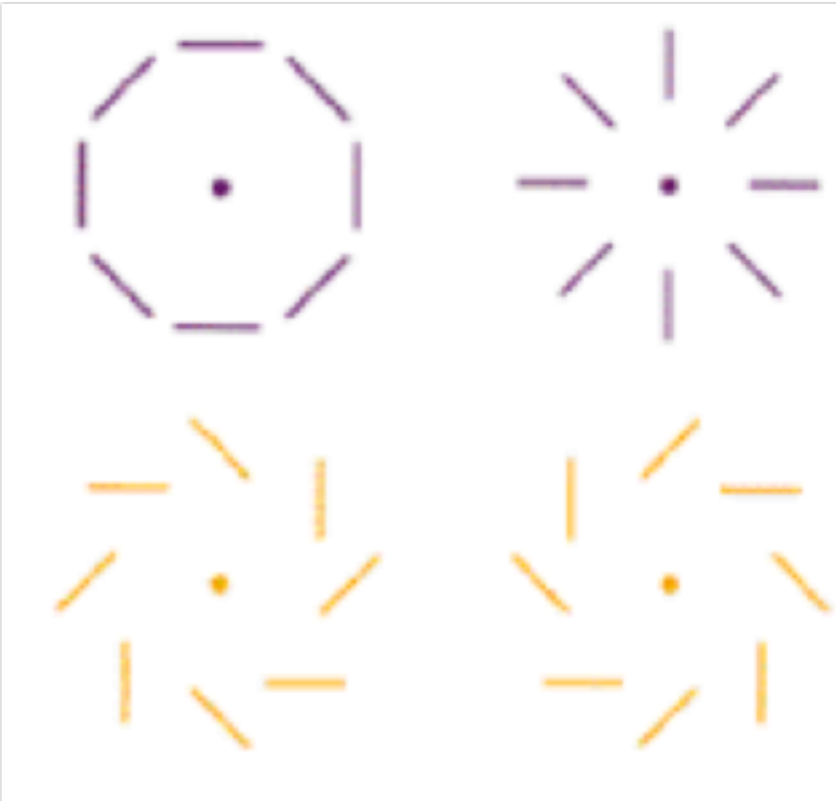








CMB Polarization

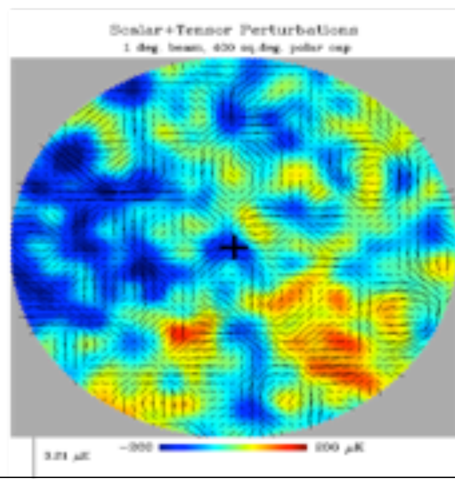


Grad (or E) modes

Curl (or B) modes

(density fluctuations have no handness, so no contribution to B-modes)

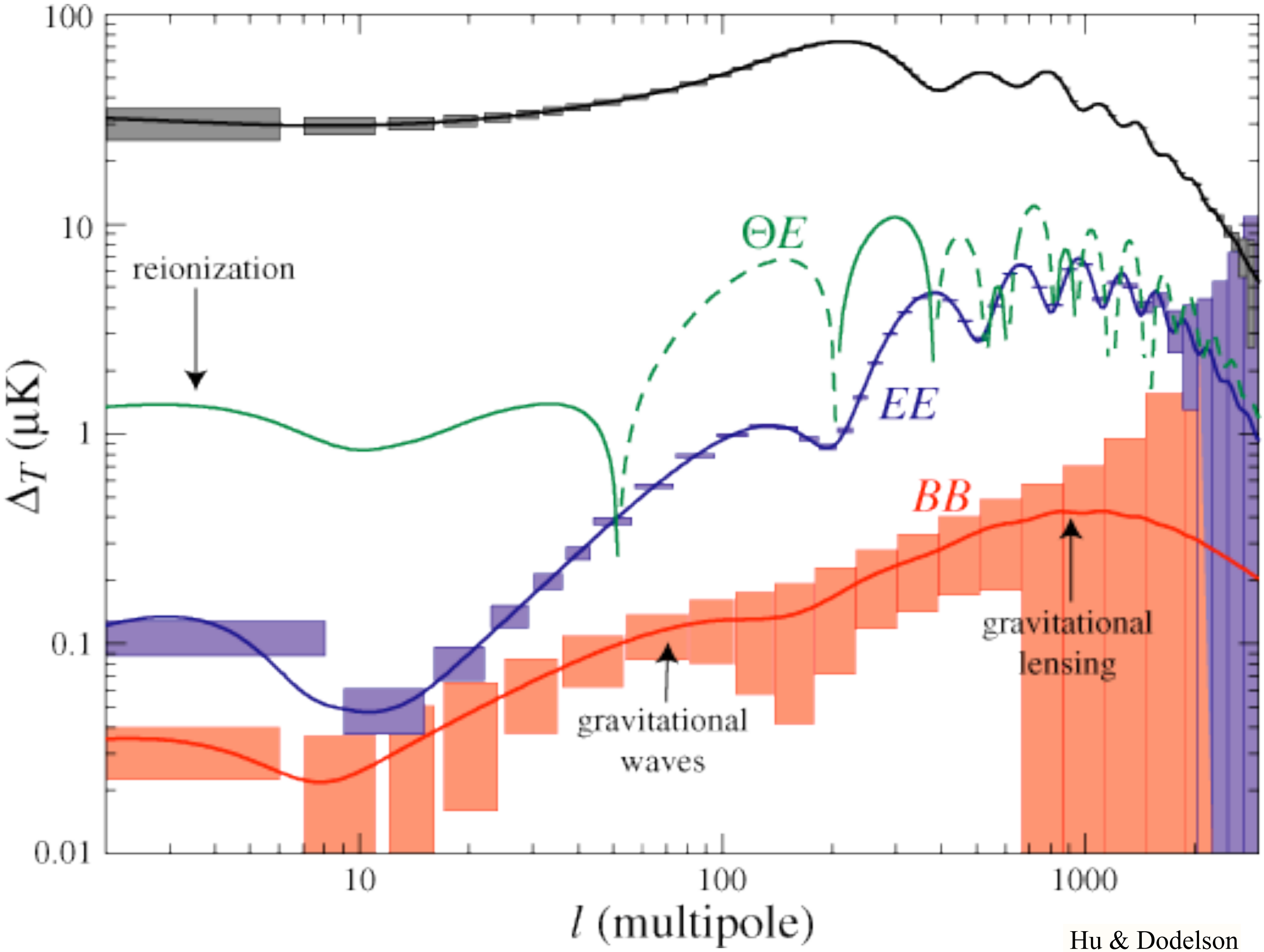
Kamionkowski et al. 1997;
Seljak & Zaldarriaga 1997



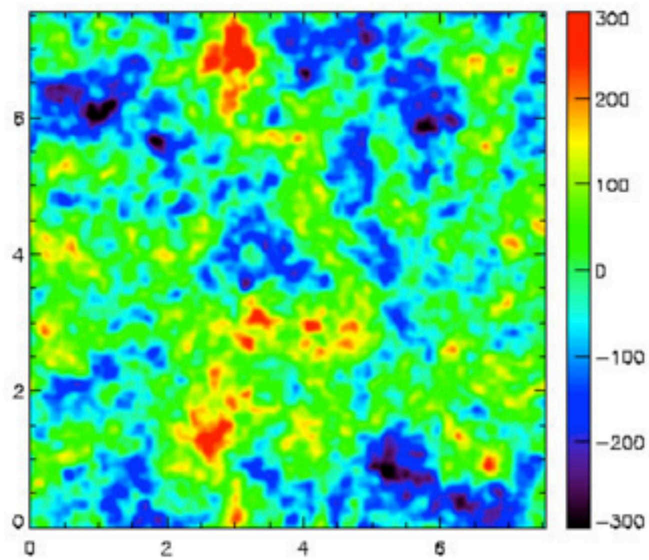
Temperature map : $T(\hat{n})$

Polarization map : $P(\hat{n}) = \vec{\nabla} E + \vec{\nabla} \times \vec{B}$

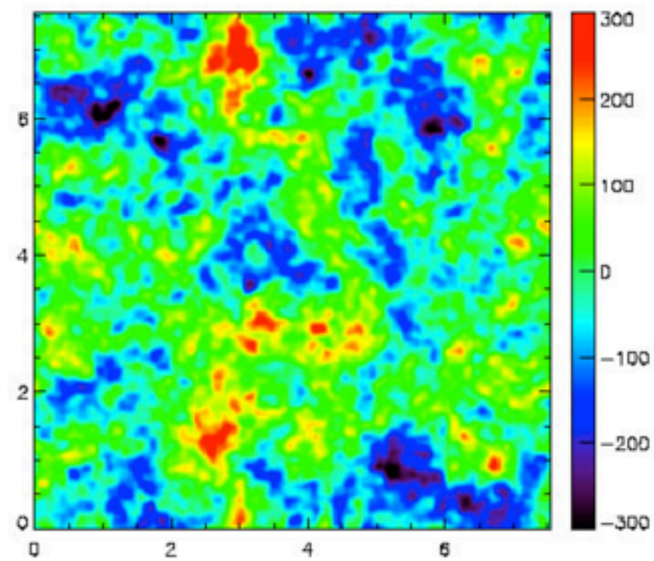
Around 2013 with Planck



Lensing in CMB - Very Weak!!!



Unlensed

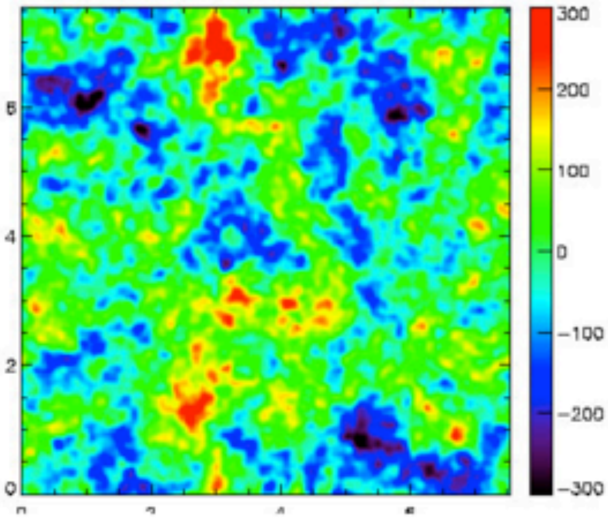


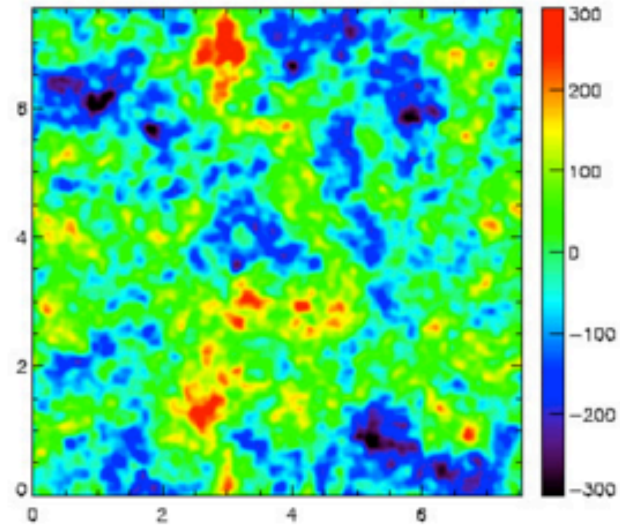
Lensed

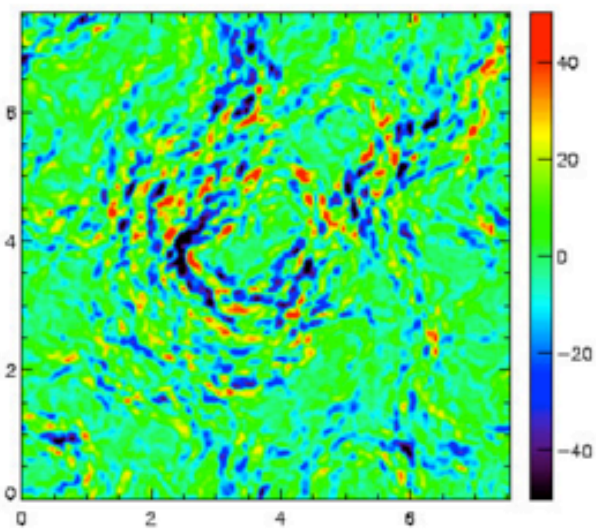
The real scenario: difference is very small!!!!

Amblard

Lensing in CMB - Very Weak!!!



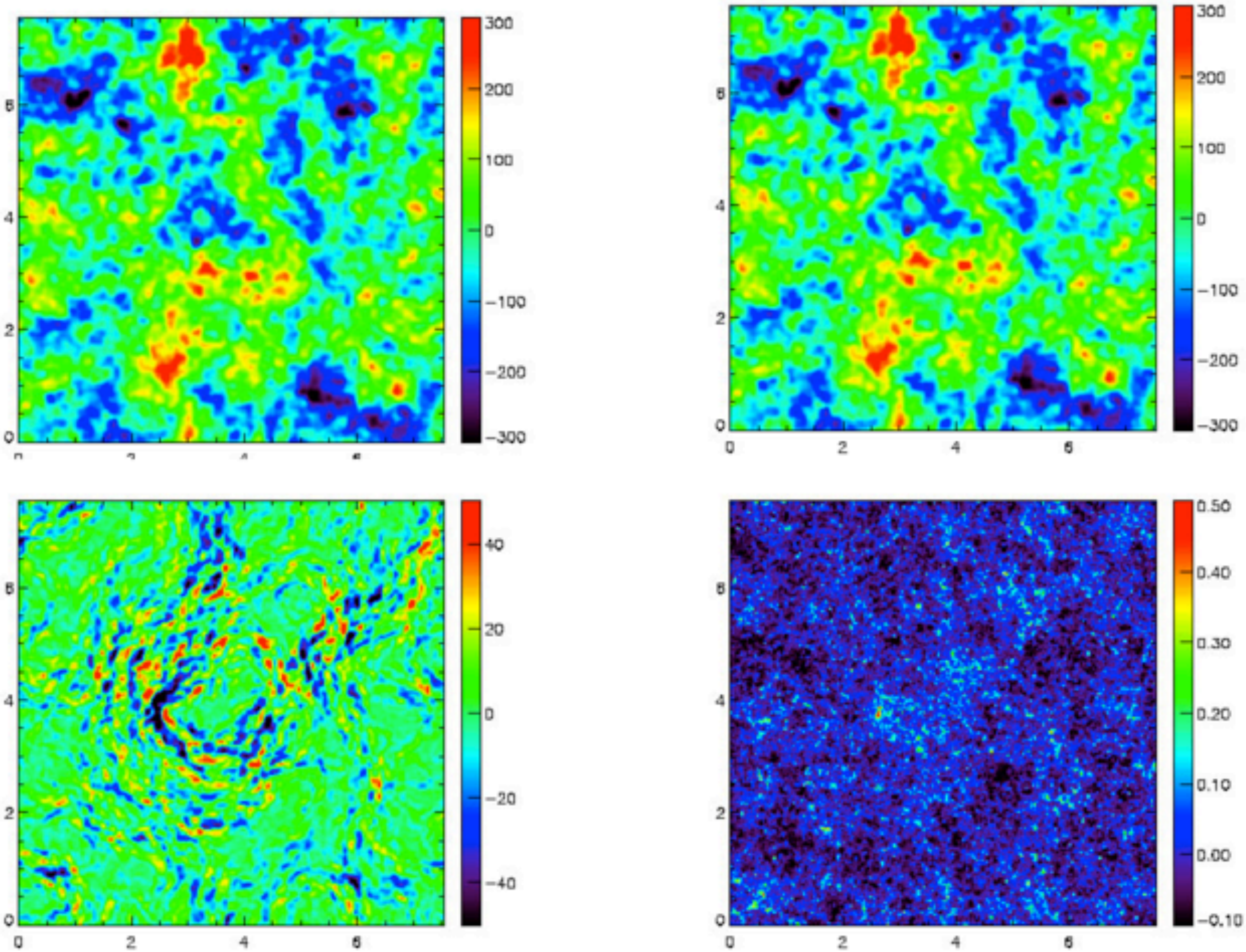




Difference between the two:

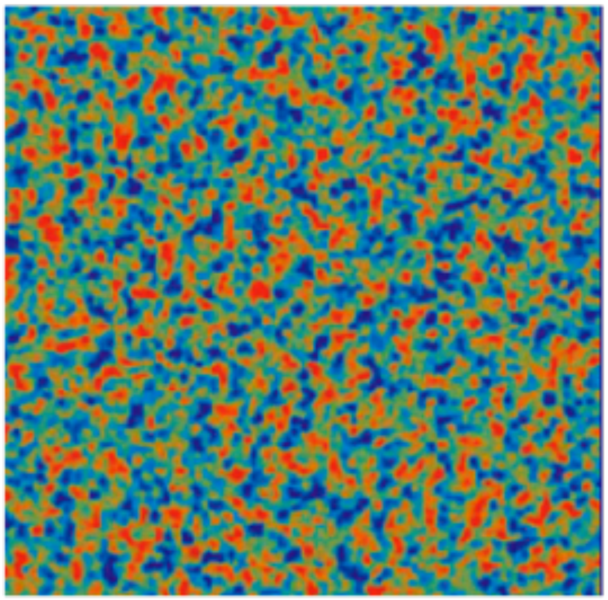
1) +/- dipolar structure

Lensing in CMB - Very Weak!!!

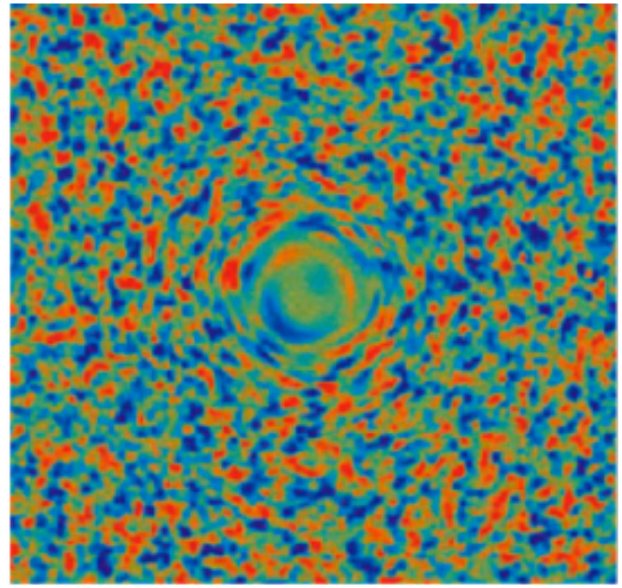


Lensing in CMB

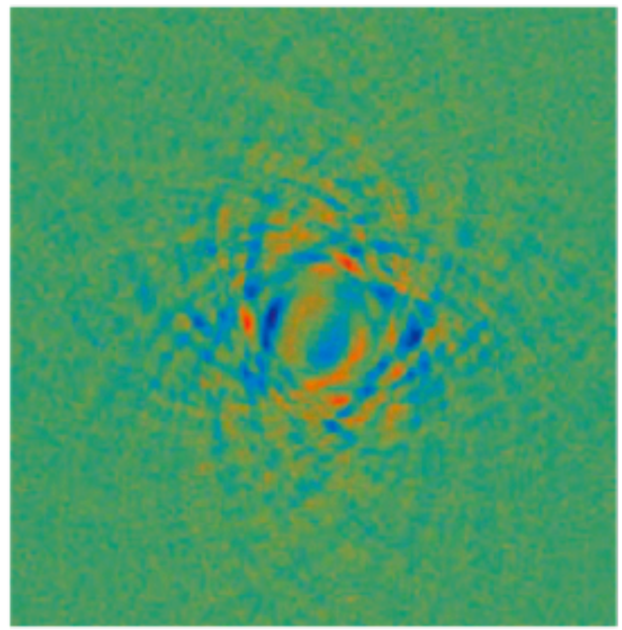
Polarization field



Input pure E-mode

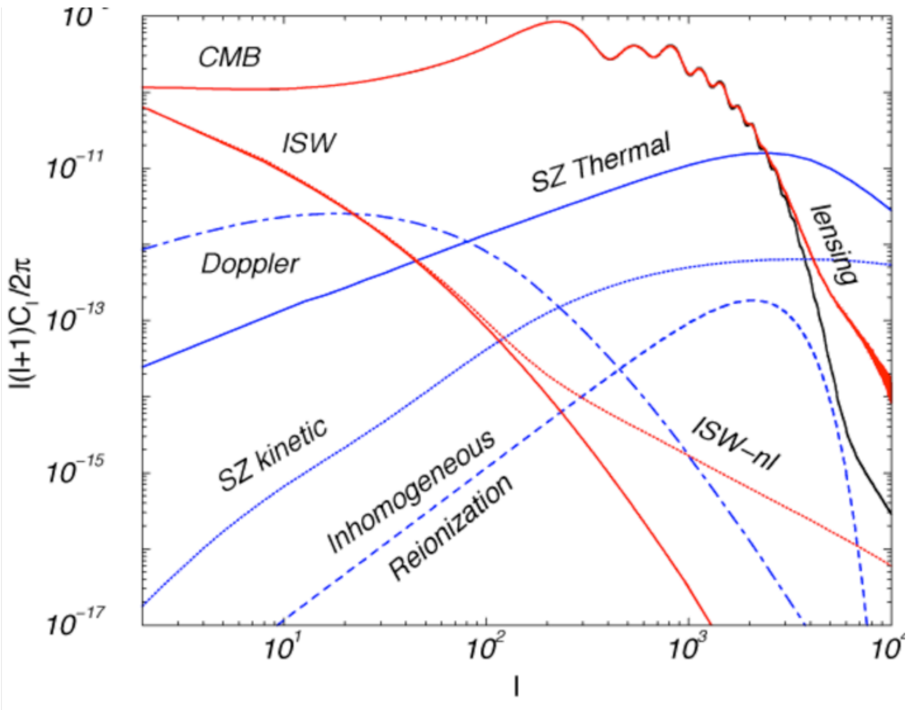


E-mode



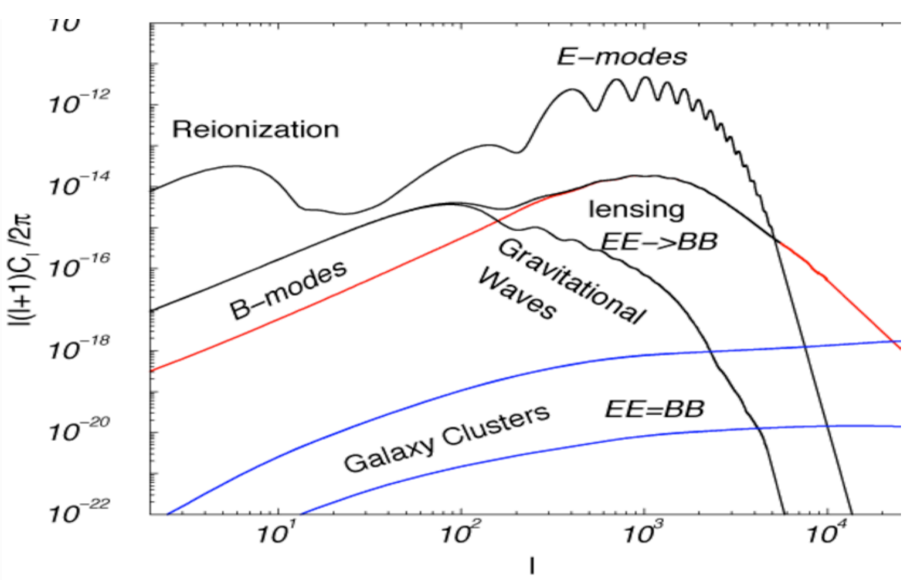
B-mode

Hu



Lensing distributes anisotropies from degree scales to damping tail and smooths acoustic peaks

In temperature hard to see because of other secondaries

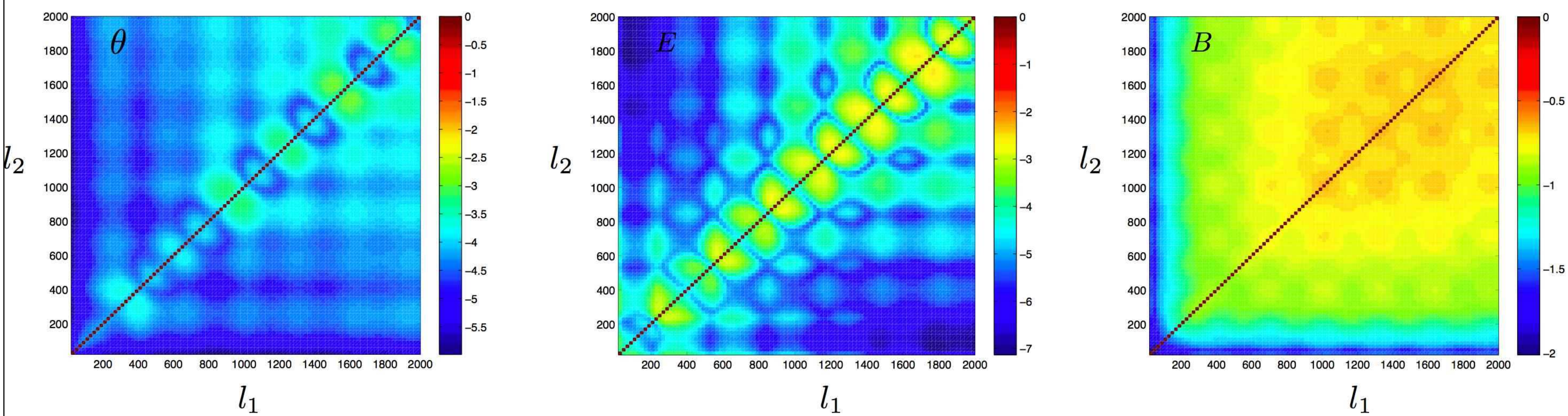


In polarization lensing mixes E & B modes. Polarization secondaries are smaller.

Non-Gaussianity of lensing

Bad: decreases information content of lensing B-modes from the case of a simple Gaussian mode counting.
(Beware of Gaussian Fisher predictions of B-modes)

Good: allows a statistical mechanism to reconstruct foreground mass distribution responsible for lensing



Non-Gaussianity of lensing

Lensing weakly correlates CMB modes with $\mathbf{l} \neq \mathbf{l}'$:

$$\langle T(\mathbf{l}) T(\mathbf{l}')^* \rangle \propto \phi(\mathbf{l} - \mathbf{l}').$$

Reconstructed field $\widehat{\phi}$ is quadratic in CMB temperature:

$$\begin{aligned}
\widehat{\phi}(\widehat{\mathbf{n}}) &= \partial^a \left[\alpha(\widehat{\mathbf{n}}) \partial_a \beta(\widehat{\mathbf{n}}) \right] \\
\alpha(\widehat{\mathbf{n}}) &= \int \frac{d^2 l}{(2\pi)^2} \left(\frac{1}{C_\ell^{TT} + N_\ell^{TT}} \right) T(\mathbf{l}) e^{i \mathbf{l} \cdot \widehat{\mathbf{n}}} \\
\beta(\widehat{\mathbf{n}}) &= \int \frac{d^2 l}{(2\pi)^2} \left(\frac{C_\ell^{TT}}{C_\ell^{TT} + N_\ell^{TT}} \right) T(\mathbf{l}) e^{i \mathbf{l} \cdot \widehat{\mathbf{n}}}
\end{aligned}$$

Second idea for detecting CMB lensing: look for extra power in $\widehat{\phi}$.

Compute $C_\ell^{\phi\phi}$: quadratic in $\widehat{\phi}$, or four-point in CMB.

(> 50 publications)

Hint of lensing in WMAP?

3.4 σ detection, as a cross-correlation

Start

(1)

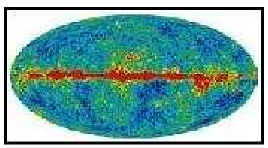
Gaussian fields $\{g_{\ell m}, \phi_{\ell m}, a_{\ell m}^{\text{unlensed}}\}$

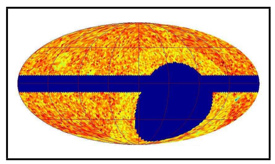
(2)

Lensed CMB $a_{\ell m}^{\text{lensed}}$

(3)

(4)





WMAP data

NVSS data

(5)

Filtered CMB $\widetilde{a}_{\ell m}$

(6)

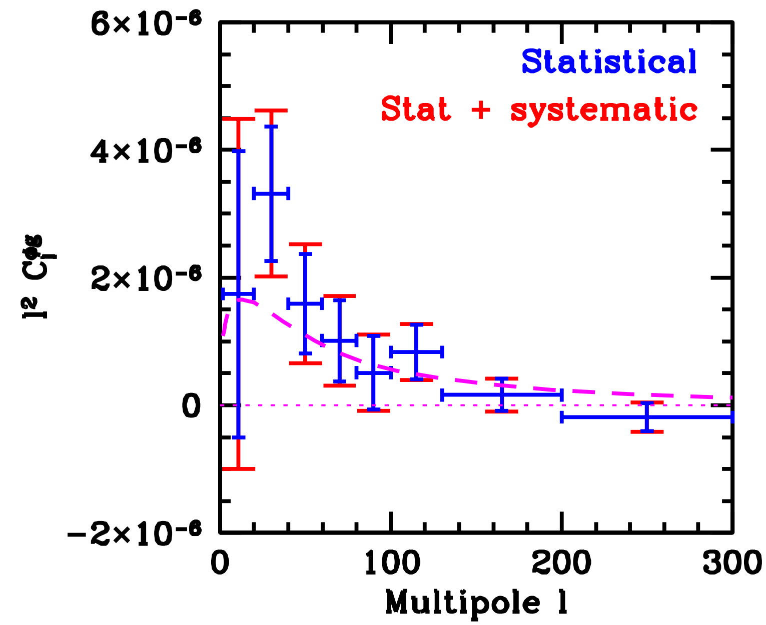
(7)

Filtered galaxy field $\widetilde{g}_{\ell m}$

Reconstructed potential $\widetilde{\phi}_{\ell m}$

(8)

Lensing estimator $\widehat{C}_\ell^{\phi g}$



$$\ell^2 C_\ell^{\phi g} = (33.2 \pm 10.5) \times 10^{-7}$$
$$(20 \leq \ell \leq 40, \mathit{stat}.)$$

Smith et al. 07

no detection limits on lensing-ISW and lensing-SZ Calabrese et al. 09

Next steps

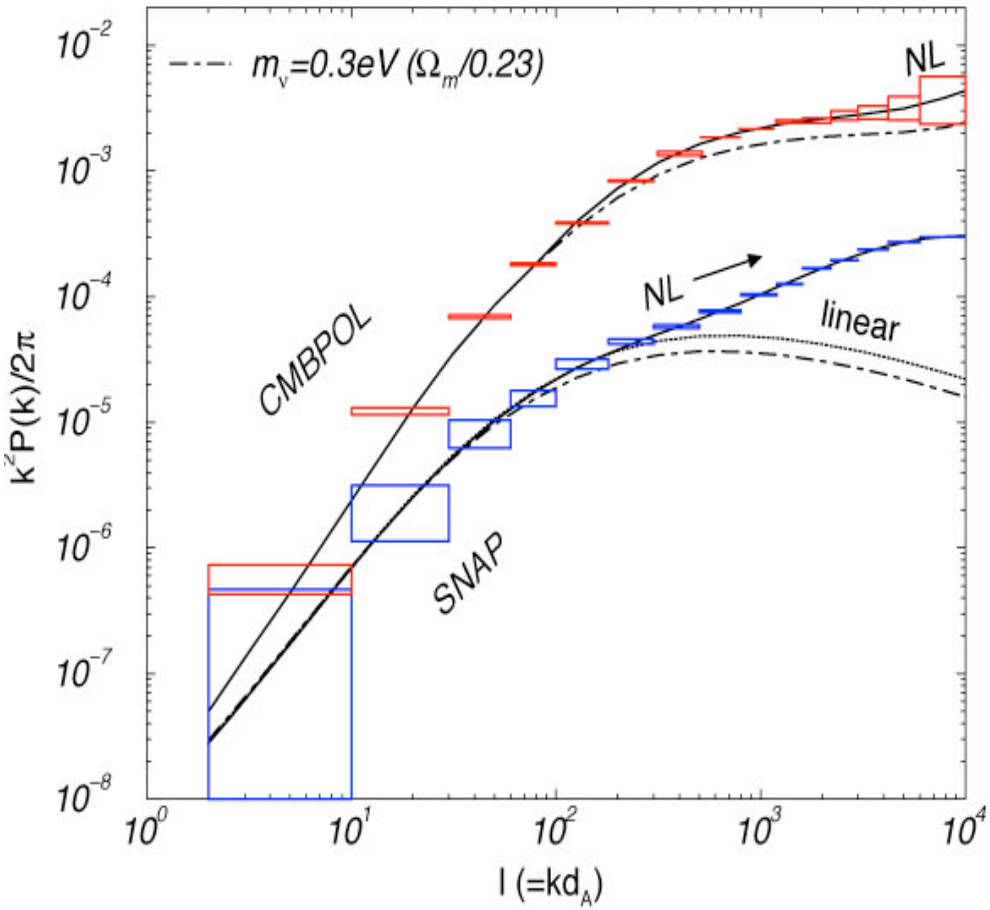
A detection of the lensing potential power spectrum with WMAP-7?
Requires a computation of the 4 point function, work started, results out soon!!! (Joseph Smidt et al. in preparation)

Existing estimators (Hu & Okamoto; Seljak & Hirata) are biased, need to properly account for the Gaussian part of the trispectrum and remove noise bias.

Fast, optimized estimators for non-Gaussianity now developed in a series of papers by Munshi, Smidt et al. *(we measured the primordial trispectrum for the first time ever in 1001.5026)*

Still requires a large number of Monte-Carlo simulations.
Limited by computational resources. Out to ell of 900,
~25,000 CPU hours. Naive estimator scales as l^4. Fast estimators scales as $l^3 \log l$.

CMB lensing



CMB lensing vs. galaxy lensing

Advantages:

1. A precisely known source
2. Linear fluctuations, there is really no need to model non-linearities down to sub-percent precision.
3. Community experience in analyses of complex CMB datasets

Disadvantages:

Finite information content!

EPIC

Selected by NASA in 2003 for a 2 to 3-year study, again in 2008-2009

In 2008-2009, EPIC was put forward as a general CMB community-supported mission concept for the CMBpol post-Planck mission.

In Europe, B-POL study (but not selected; Euclid selected for dark energy as a Cosmic Visions M class mission).

Jamie Bock (JPL), PI

Representing the EPIC-IM Mission Study Team

Abdullah Aljabri	JPL	Darren Dowell	JPL/Caltech	Elena Pierpaoli	USC
Alex Amblard	UC Irvine	Mark Dragovan	JPL	Nicolas Ponthieu	IAS, France
Daniel Bauman	Harvard U.	Sunil Golwala	Caltech	Jean-Loup Puget	IAS, France
Marc Betoule	IAS, France	Krzysztof Gorski	JPL/Caltech	Jeff Raab	NGAS
Talso Chui	JPL	Shaul Hanany	U. Minnesota	Paul Richards	UC Berkeley
Loris Colombo	USC	Warren Holmes	JPL	Celeste Satter	JPL
Asantha Cooray	UC Irvine	Kent Irwin	NIST	Mike Seiffert	JPL
Dustin Crumb	ATK Space	Brad Johnson	UC Berkeley	Meir Shimon	UCSD
Peter Day	JPL	Steve Meyer	U. Chicago	Huan Tran	UC Berkeley/SSL
Clive Dickenson	JPL	Nate Miller	UC San Diego	Brett Williams	JPL
Darren Dowell	JPL/Caltech	Hien Nguyen	JPL	Jonas Zmuidzinas	Caltech/JPL

Bock et al. 0906.1188

Post-Planck Mission Effort in US

The EPIC-IM Study Team

Abdullah Aljabri	JPL
Alex Amblard	UC Irvine
Daniel Bauman	Harvard U.
Marc Betoule	IAS, France
James Bock (PI)	JPL/Caltech
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Nate Miller	UC San Diego
Hien Nguyen	JPL
Elena Pierpaoli	USC
Nicolas Ponthieu	IAS, France
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Meir Shimon	UCSD
Huan Tran	UC Berkeley/SSL
Brett Williams	JPL
Jonas Zmuidzinas	Caltech/JPL

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Alan Kogut	GSFC
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Adrian Lee	UC Berkeley
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Samuel H. Moseley	GSFC
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Charles Lawrence	JPL
Tony Readhead	Caltech
Peter Timbie	U. Wisconsin

CMB Inflation Probe ASMCS

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Shaul Hanany	U. Minnesota
Gary Hinshaw	GSFC
Kent Irwin	NIST
Adrian Lee	UC Berkeley
Charles Lawrence	JPL
Steve Meyer (PI)	U. Chicago
Lyman Page	Princeton U.
John Ruhl	Case Western
Mike Seiffert	JPL
Matias Zaldarriaga	Harvard U.

+ 175 participants

Decadal White Papers

–*The Origin of the Universe as Revealed Through the Polarization of the CMB*, Dodelson et al. and 211 Co-signers, ArXiv 0903.3796

–*Observing the Evolution of the Universe*, Page et al. and 168 Co-signers, ArXiv 0903.0902

–*A Program of Technology Development and Sub-Orbital Observations of CMB Polarization Leading to and Including a Satellite Mission*, Meyer et al. and 141 Co-signers

CMB Community Reports

–Theory and Foregrounds: 5 Papers with 135 Authors and Co-Authors

– *Probing Inflation with CMB Polarization*, Baumann et al. 2008, ArXiv 0811.3919

– *Gravitational Lensing*, Smith et al. 2008, ArXiv 0811.3916

– *Reionization Science with the CMB*, Zaldarriaga et al. 2008, ArXiv 0811.3918

– *Prospects for Polarized Foreground Removal*, Dunkley et al. 2008, ArXiv 0811.3915

– *Foreground Science Knowledge and Prospects*, Fraisse et al. 2008, ArXiv 0811.3920

–Systematic Error Control: 10 Papers with 68 Authors and Co-Authors

–CMB Technology Development: 22 Papers with 37 Authors and Co-Authors

–Path to CMBPol: Conference on CMBPol mission in July with 104 participants

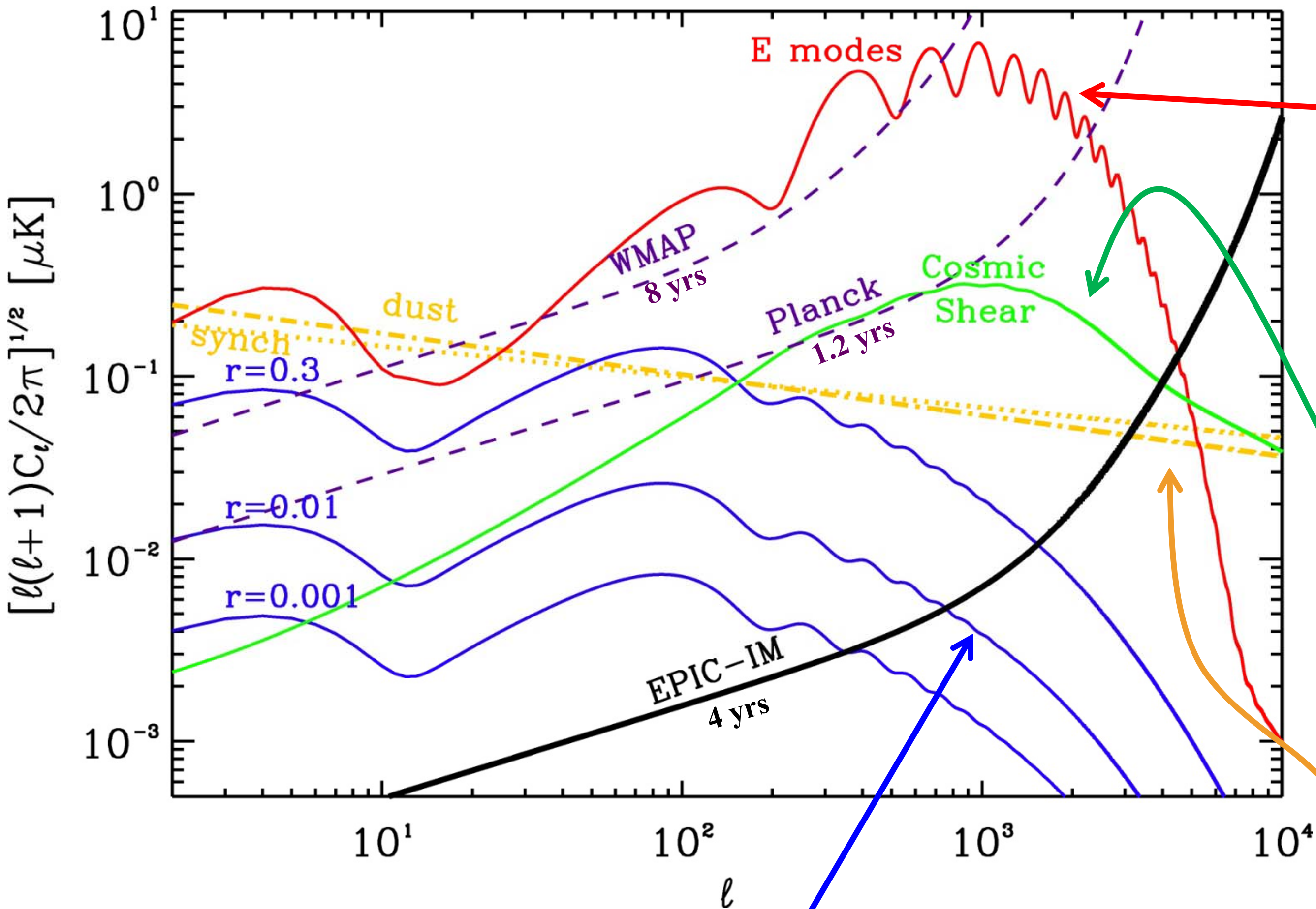
Mission Study Reports

–*Study of the EPIC-Intermediate Mission*, Bock et al. 2009, ArXiv 0906.1188

–*The Experimental Probe of Inflationary Cosmology*, Bock et al. 2008, ArXiv 0805.4207

See http://cmbpol.uchicago.edu for a full compilation

Richness of the CMB Polarization Landscape



Measure E-mode spectrum to cosmic variance to damping tail

- Precision cosmology
- Departure from scale inv.
- Reionization history

Measure B-mode cosmic shear spectrum to cosmic limits

- Neutrino mass hierarchy
- Dark energy at z > 2

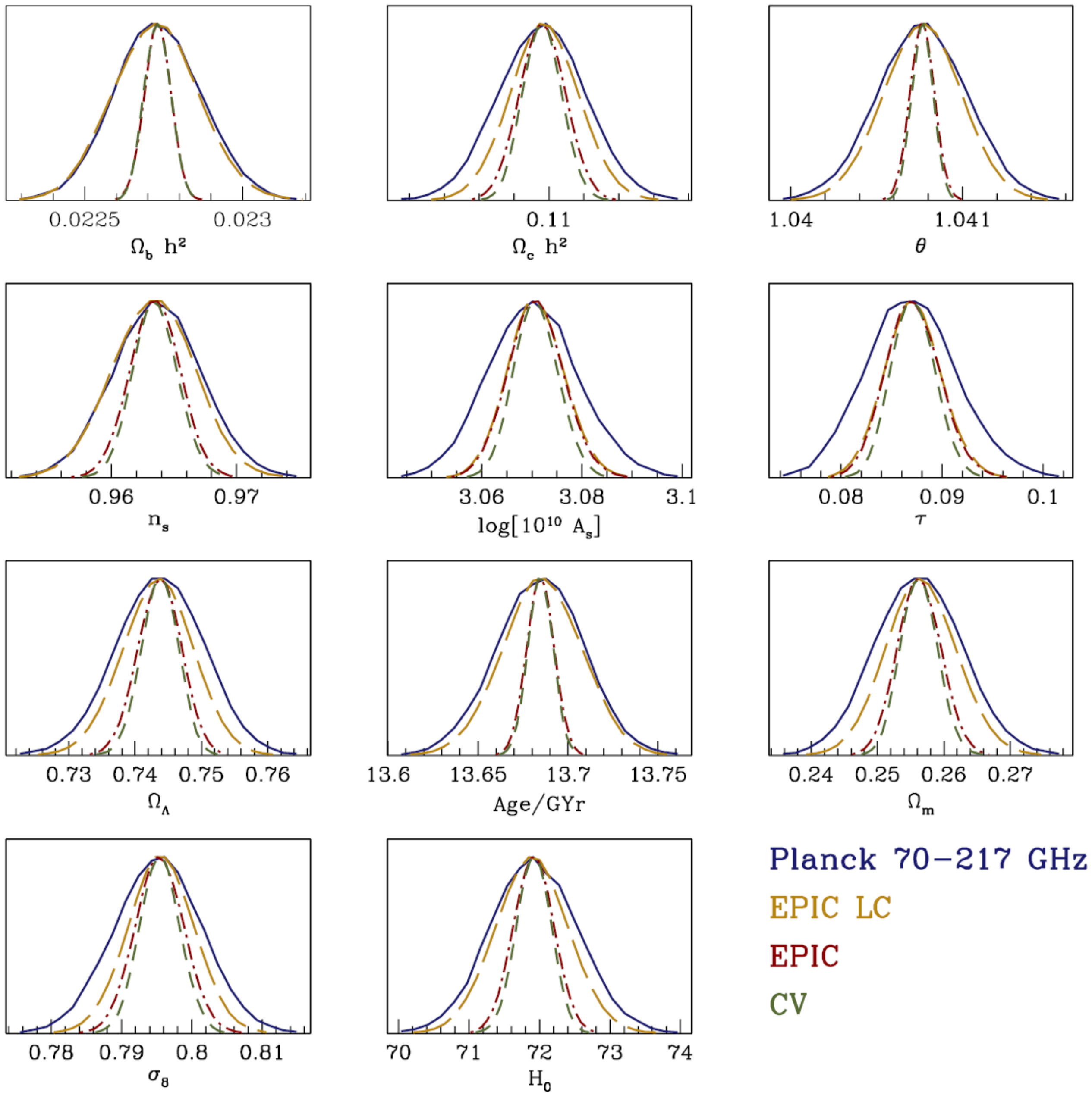
Map Galactic magnetic fields via dust polarization

- SF and large-scale B-field

Measure Inflationary B-mode spectrum at r = 0.01 to astrophysical limits

- GUT energy scale
- Large field inflation
- n_t / r consistency test

Precision Cosmology



Mapping NASA Objectives to EPIC Instrument Requirements

NASA Research Objective*	NASA Targeted Outcome*	Measurement Criteria	Instrument Criteria
What are the origin, evolution, and fate of the universe?	Test the Inflation hypothesis of the Big Bang	Measure inflationary B-mode power spectrum to astrophysical limits for 2 < _ < 200 at r = 0.01 after foreground removal	_ All-sky coverage _ $w_p^{-1/2} < 6$ μK-arcmin _ 30 – 300 GHz _ 1˚ resolution _ Control systematic errors below r = 0.01
	Precisely determine the cosmological parameters governing the evolution of the universe	Measure EE to cosmic variance into the Silk damping tail to probe primordial density perturbations	_ 10' resolution
	Improve our knowledge of dark energy, the mysterious cosmic energy that will determine the fate of the universe	Measure lensing-BB to cosmic limits to probe neutrino physics and early (z~2) dark energy density and equation of state	_ $w_p^{-1/2} < 2$ μK-arcmin _ 6' resolution
How do planets, stars, galaxies and cosmic structures come into being?	Investigate the seeds of cosmic structure in the cosmic microwave background		
	Measure the distribution of dark matter in the universe		
	Determine the mechanism(s) by which most of the matter of the universe became reionized	Measure EE to cosmic variance to distinguish reionization histories	_ Primary mission parameters above
	Study the birth of stellar and planetary systems	Map Galactic magnetic fields via dust polarization	_ 500 and 850 GHz bands

*Taken from NASA 2007 Science Plan

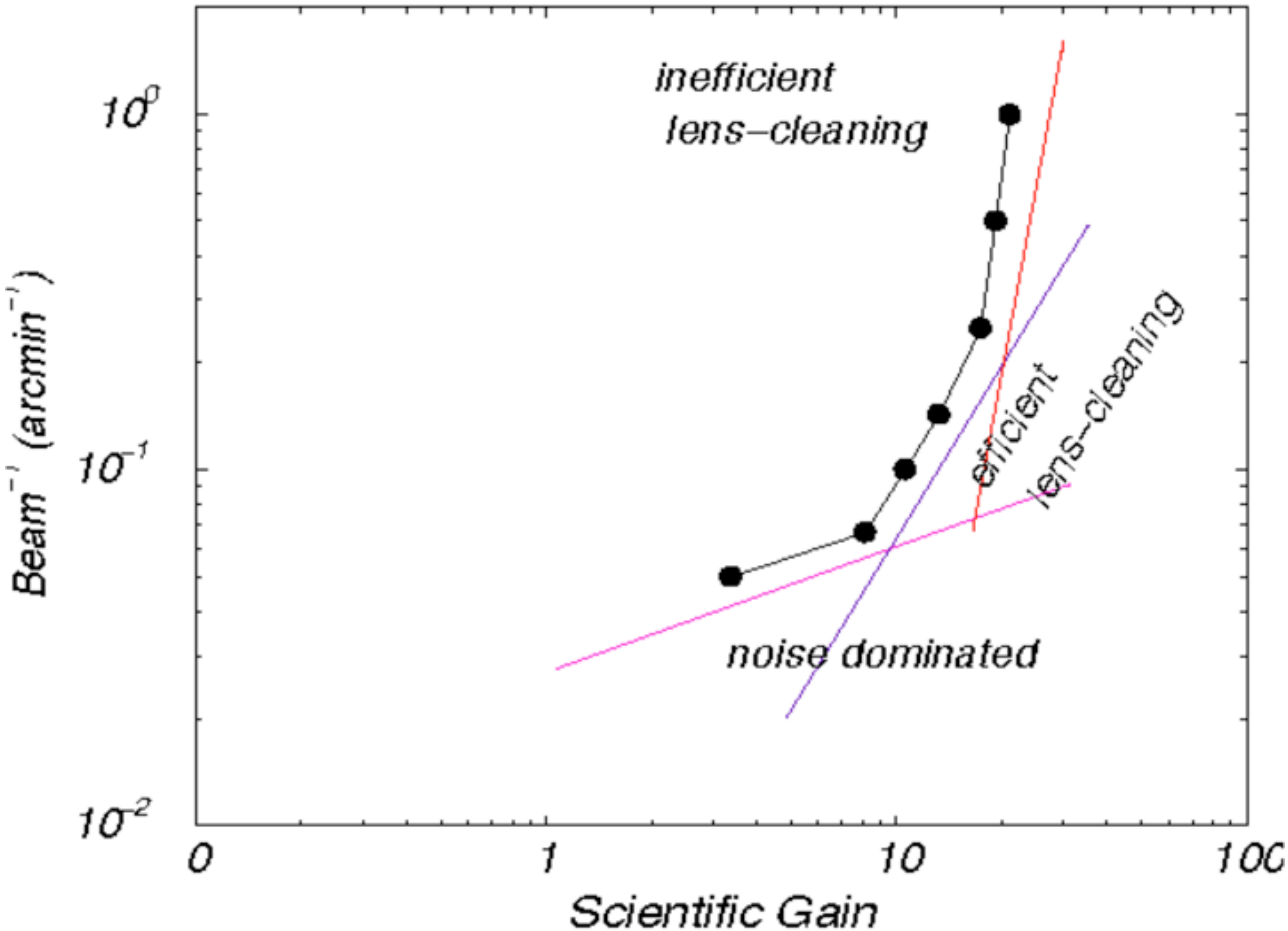
Primary Objective

Secondary Objective

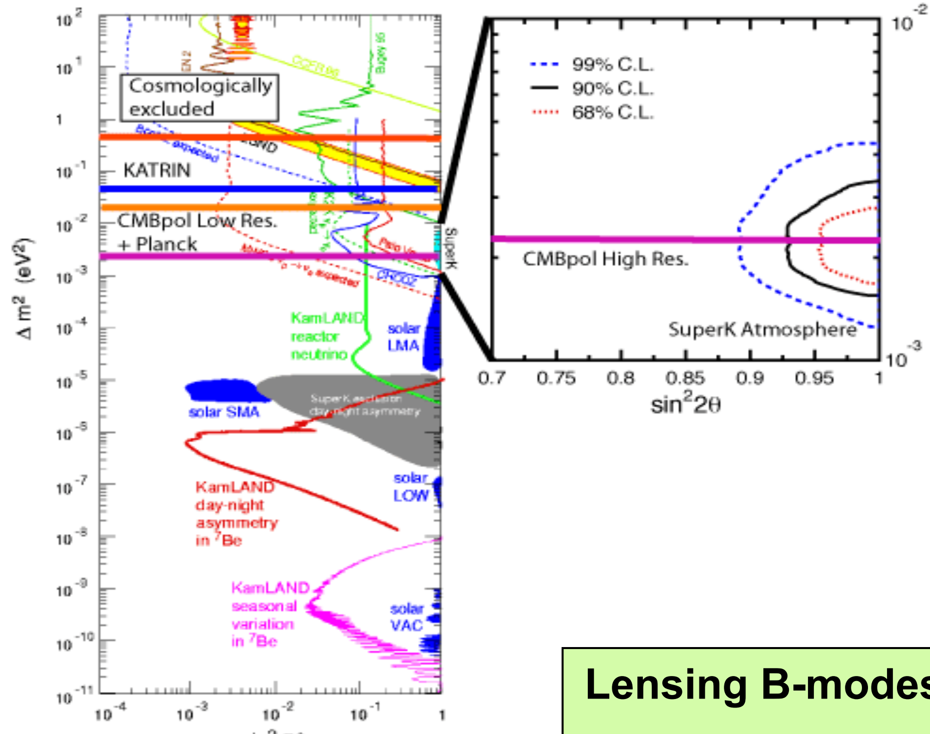
EPIC-low cost just for this

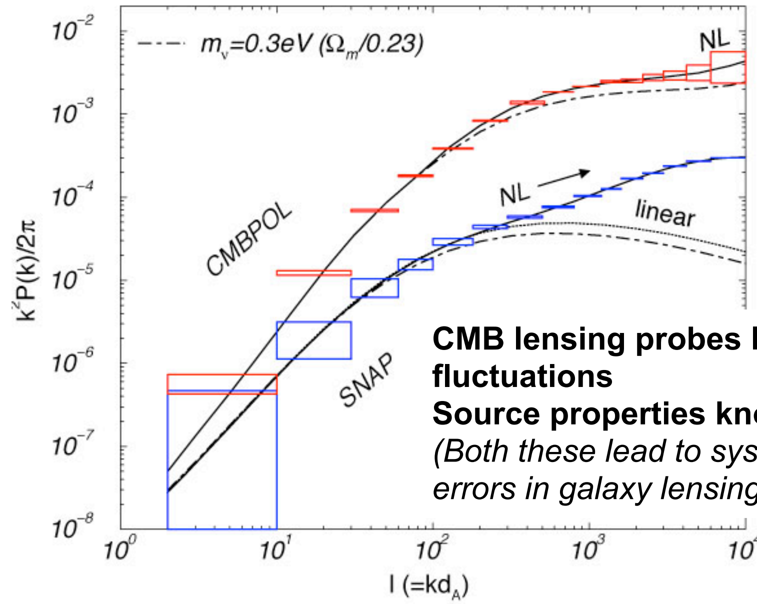
EPIC-IM optimized for the goal of measuring CMB lensing with deliverables of neutrino masses.

Optimizing an experiment for a science goal

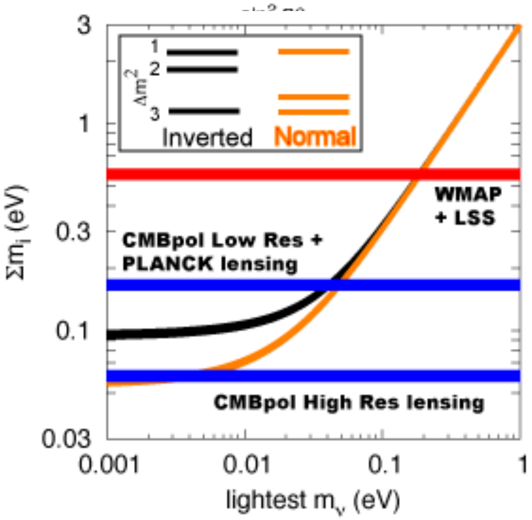


Particle physics application of EPIC





CMB lensing probes linear fluctuations
Source properties known
(Both these lead to systematic errors in galaxy lensing)



Lensing B-modes and CMB Cosmic Shear Reconstruction

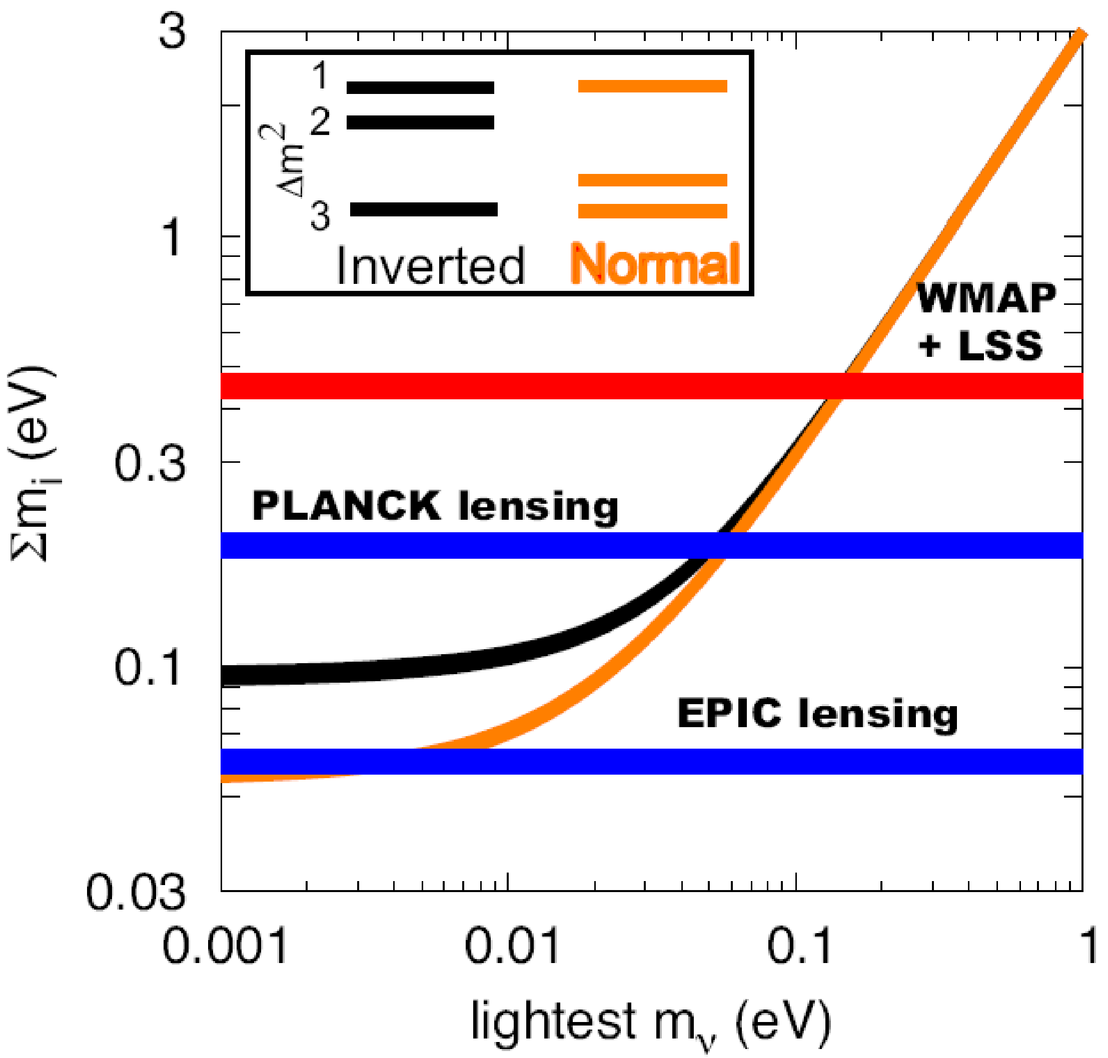
A deliverable: neutrino mass (Σm_ν < 0.05 eV or better at 95% confidence level)

Test SuperK Atmosphere oscillations that suggest $\Delta m_\nu^2 \sim 2\text{x}10^{-3}\ \text{eV}^2$

and distinguish between two mass hierarchies

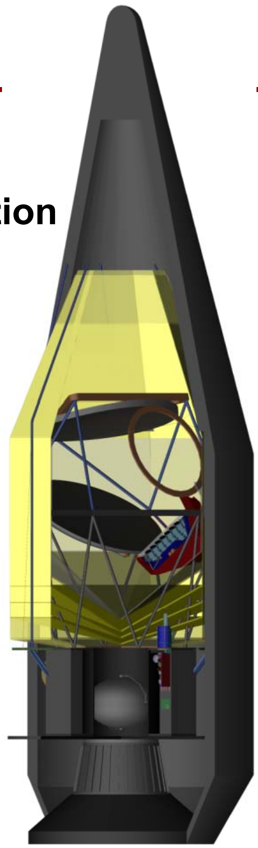
EPIC study reports

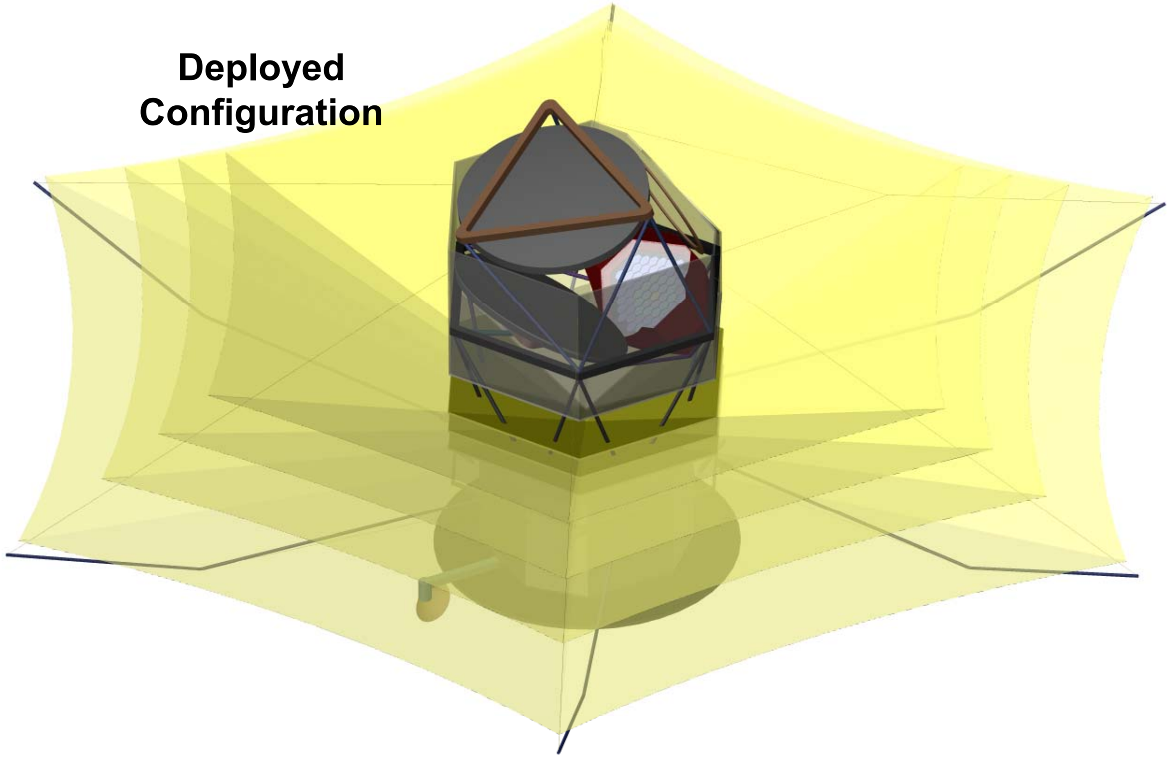
Neutrino mass hierarchy from cosmology



For the LCDM cosmological model, EPIC, as currently configured, reaches a sum of the neutrino masses of 0.042 eV and if the equation of state of dark energy is allowed to vary this constraint is at 0.047eV at the same 95% confidence level. This is not a simple Gaussian Fisher matrix estimate. It accounts for the full covariance, part of which was based on simulations.

EPIC-IM Specification Sheet





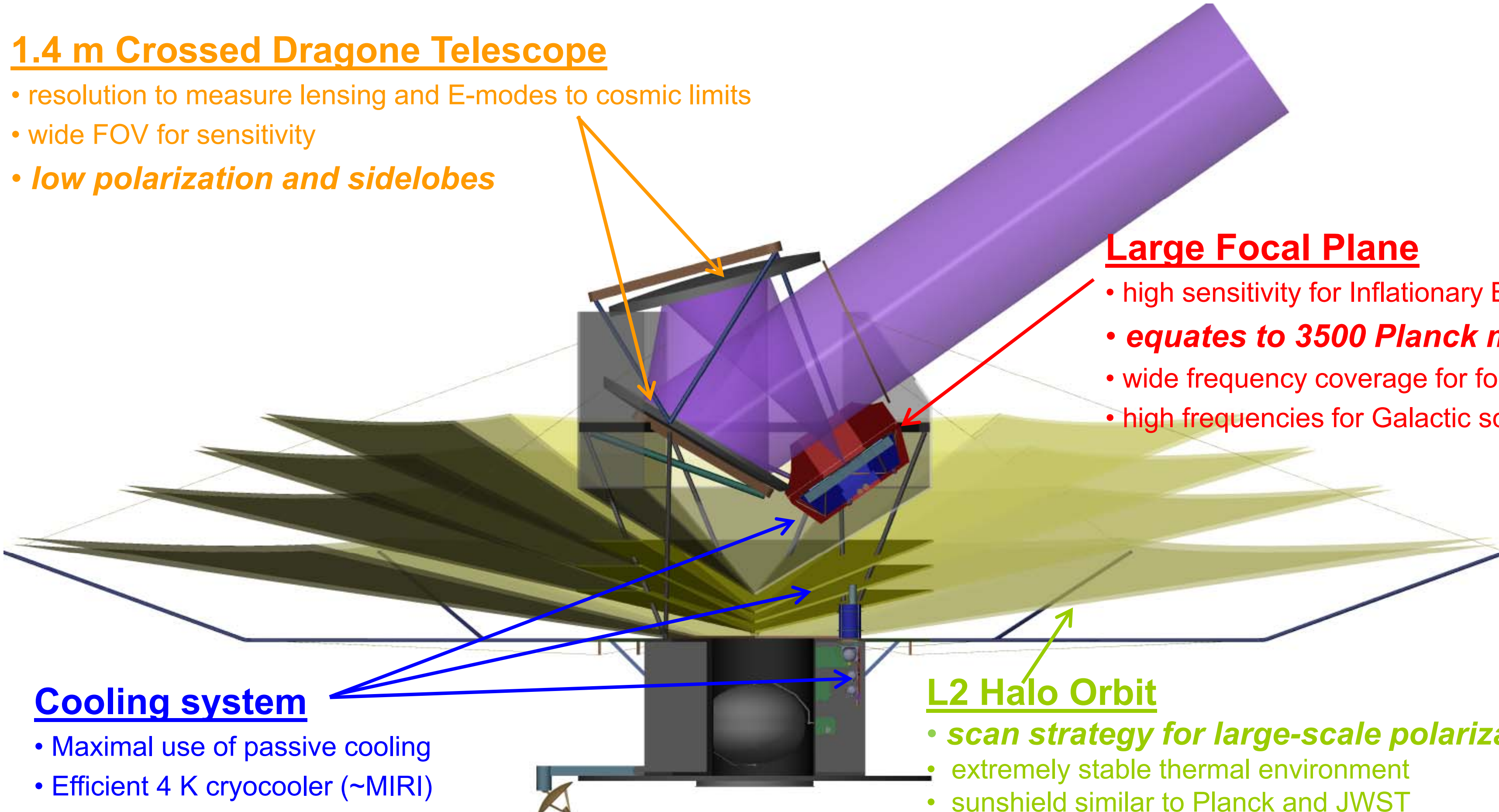
Optics	1.4 m wide-field crossed Dragone	**Total Delta-V**	170 m/s
Orbit	Sun-earth L2 halo	**Payload Power**	440 W (CBE)
Mission Life	4 years	**Spacecraft Power**	533 W (CBE)
Launch Vehicle	Atlas V 401	**Total Power**	1392 W (w/ 43 % cont.)
Detectors	11094 TES bolometer or MKID detectors	**Payload Mass**	813 kg (CBE)
Bands	30, 45, 70, 100, 150, 220, 340, 500 & 850 GHz	**Spacecraft Mass**	584 kg (CBE)
Sensitivity	0.9 mK arcmin; 3600 Planck missions	**Total Mass**	2294 kg (w/ 43 % cont.)
Spacecraft	3-axis commercial	**Vehicle Margin**	1287 kg (36 %)
Data Rate	7.7 Mbps	**Cost**	$920M FY09

Mass similar to the Planck satellite mission

Experimental Probe of Inflationary Cosmology – Intermediate Mission (Bock, JPL)

1.4 m Crossed Dragone Telescope

- resolution to measure lensing and E-modes to cosmic limits
- wide FOV for sensitivity
- ***low polarization and sidelobes***



Large Focal Plane

- high sensitivity for Inflationary B-modes
- ***equates to 3500 Planck missions!***
- wide frequency coverage for foregrounds
- high frequencies for Galactic science

Cooling system

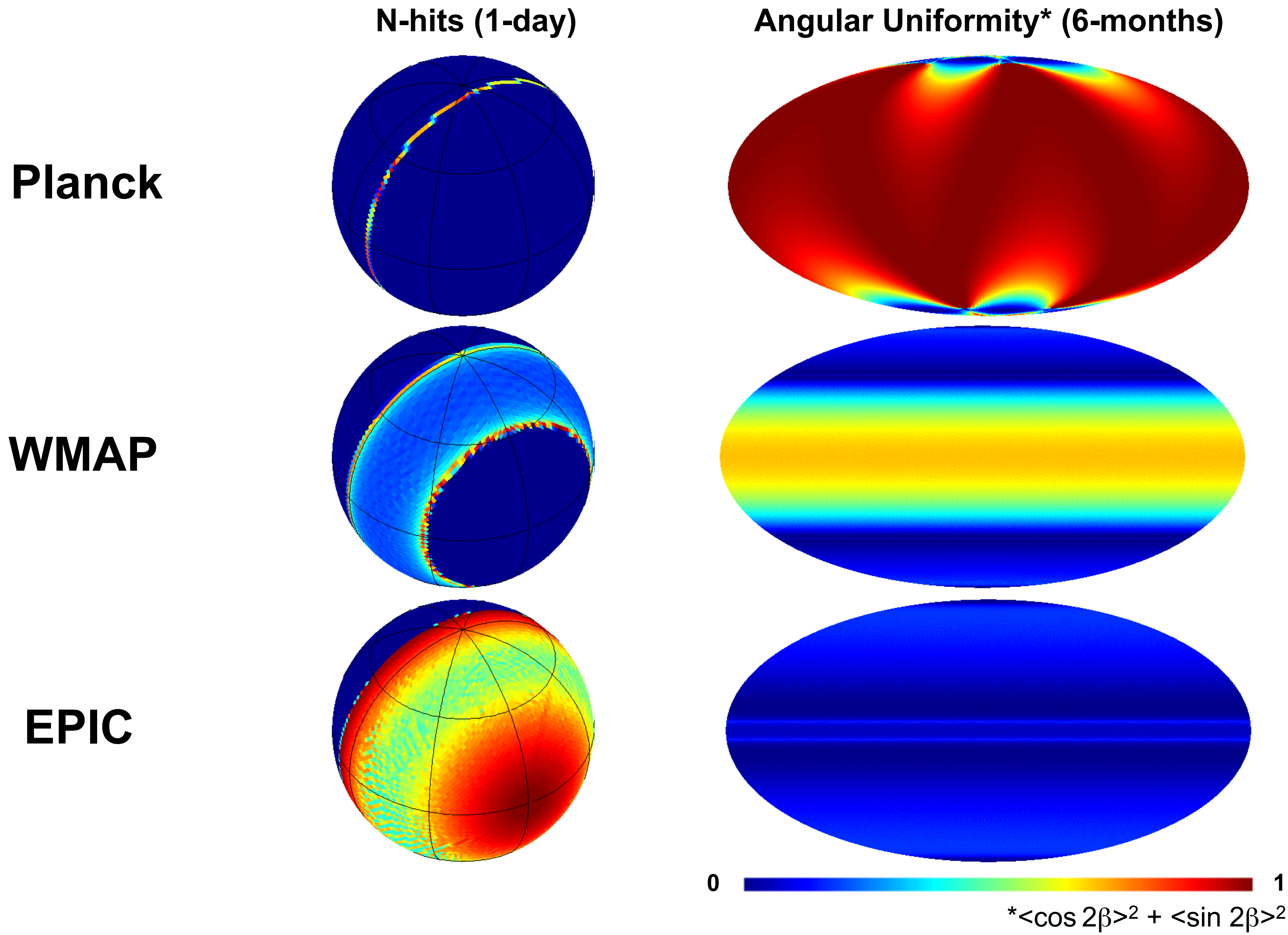
- Maximal use of passive cooling
- Efficient 4 K cryocooler (~MIRI)
- Continuous 100 mK cooler (~Planck)

L2 Halo Orbit

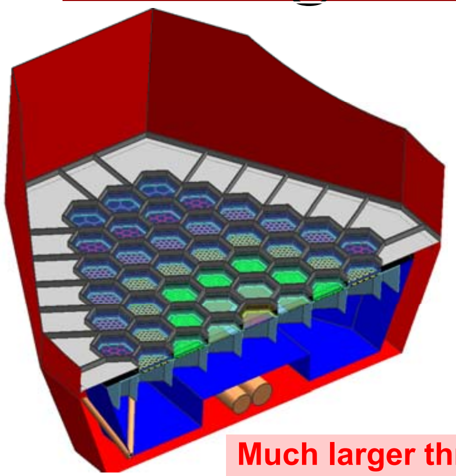
- ***scan strategy for large-scale polarization***
- extremely stable thermal environment
- sunshield similar to Planck and JWST
- ***simple operations, conventional spacecraft***

Mass similar to the Planck satellite mission

Highly Redundant & Uniform Scan Coverage

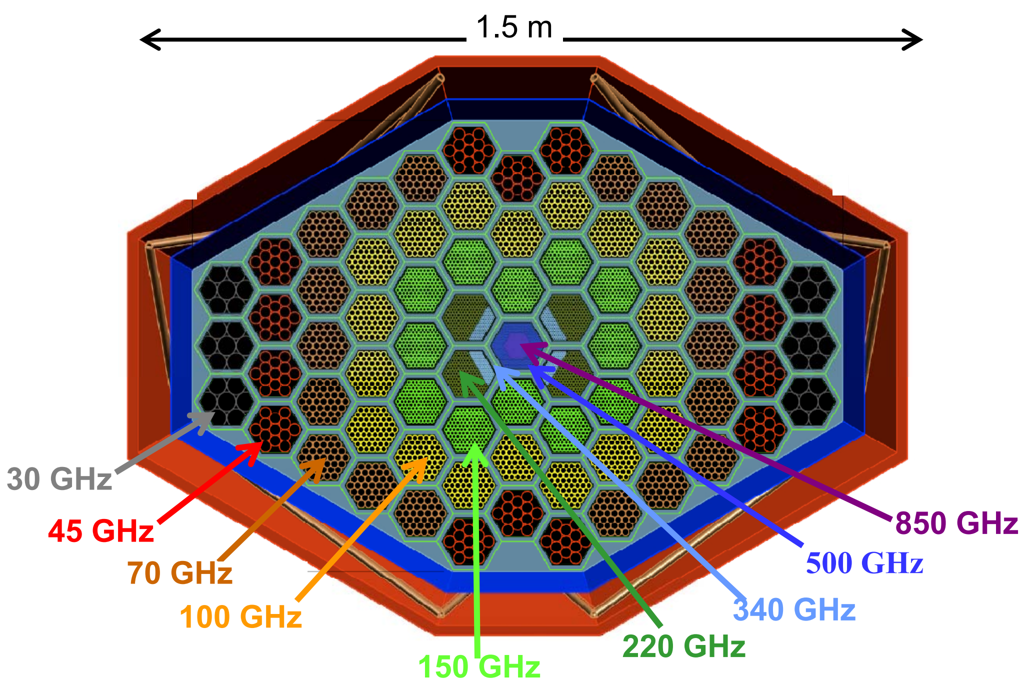


High Throughput, Multi-Band Focal Plane



- T_0 = 100 mK
- Ndet = 11,094; 5547 pixels
- All are polarization sensitive bolometers
- 9 Bands
- Including 500, 850 GHz for Galactic dust mapping

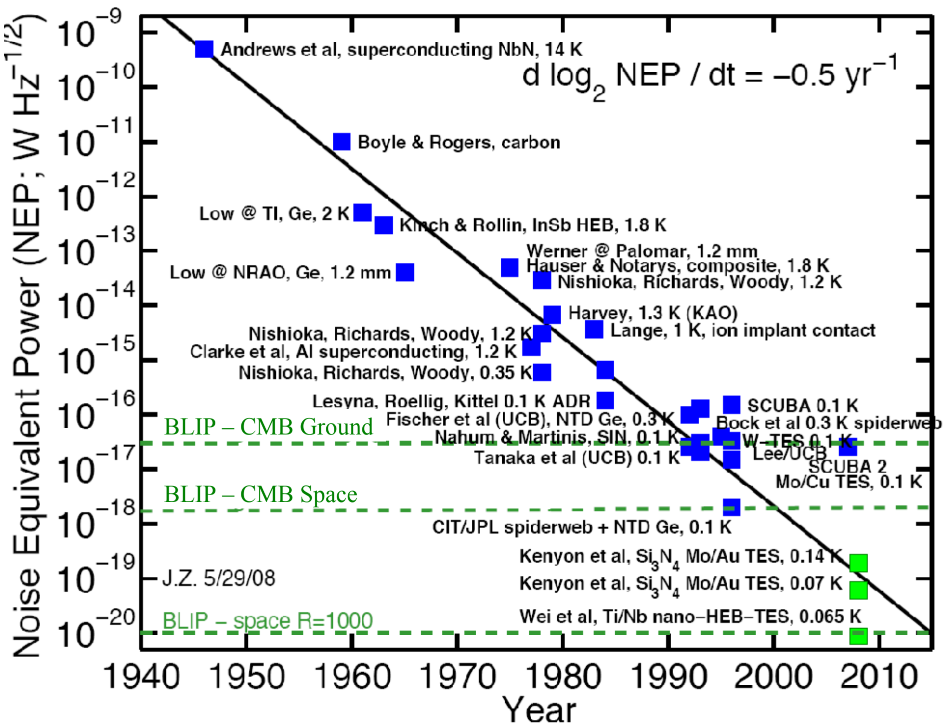
Much larger throughput and sensitivity than any planned sub-orbital experiment

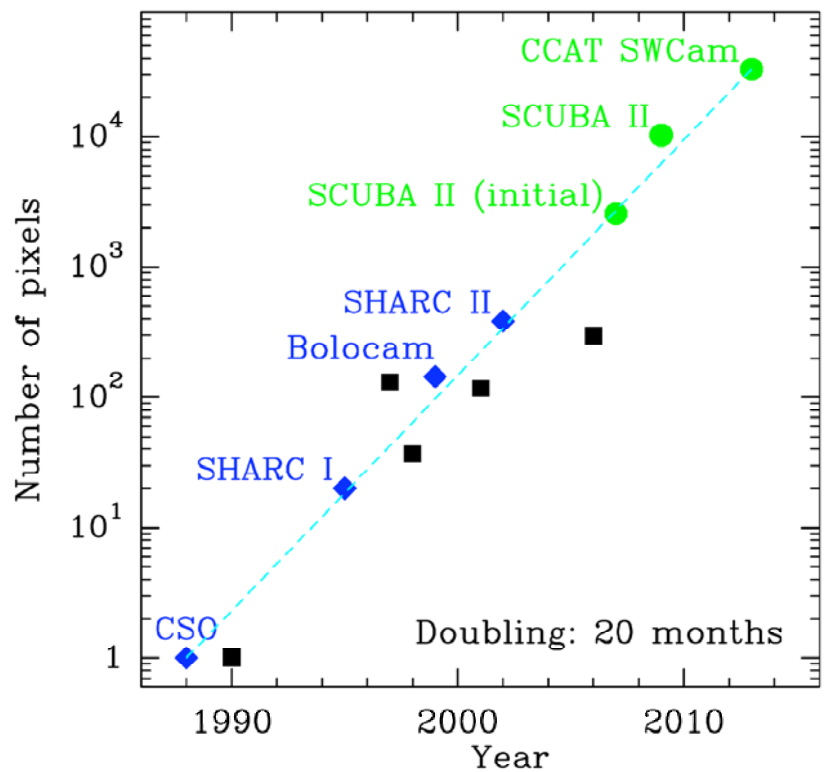


Freq [GHz]	θ_{FWHM} [arcmin]	N_{bol} [#]	$w_p^{-1/2}$ [μK-']	Planck @ 1.2 yr $w_p^{-1/2}$	δT_{pix} [nK]
30	28	84	14	350	83
45	19	364	5.7	350	34
70	12	1332	2.5	380	15
100	8.4	2196	1.8	100	10
150	5.6	3048	1.4	80	8
220	3.8	1296	2.5	130	15
340	2.5	744	5.6	400	33
500	1.7	1092	16		
850	1.0	938	740		
Total		11094	0.9	54	5.4

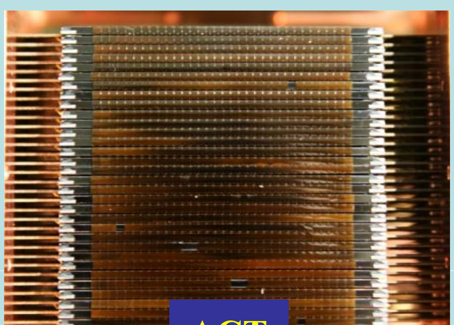
Lifetime : 4 years
Noise margin: 1.4

‘Moore’s Law’ for Sensitivity and Mapping Speed

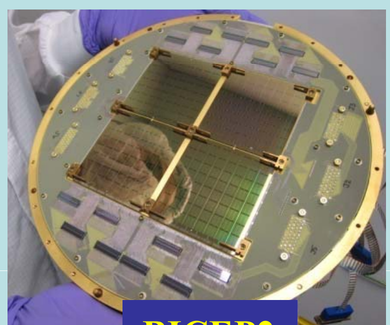




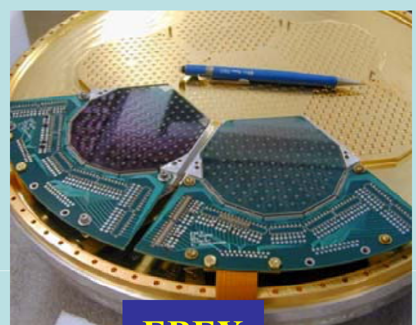
Technology & Sub-Orbital Program



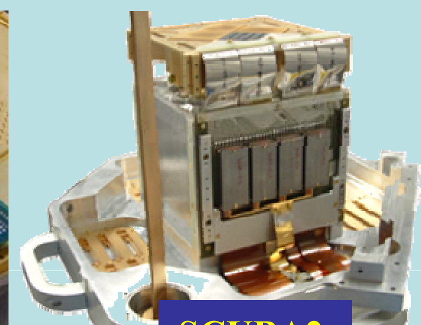
ACT



BICEP2

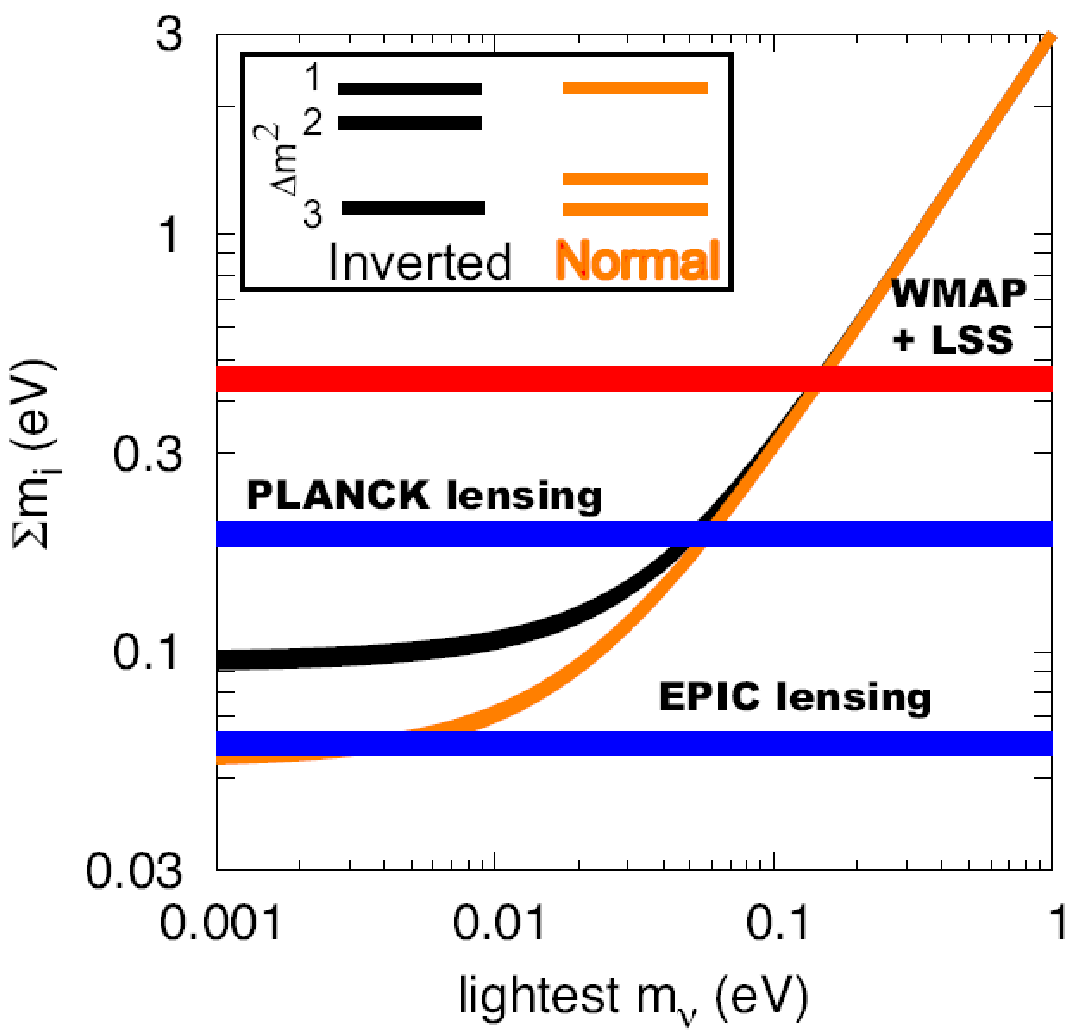


EBEX



SCUBA2

Neutrino mass hierarchy from cosmology



Can we do better?
Further optimize EPIC (at a very high cost), factor of 1.2 to 1.3 at most improvement with CMB polarization alone

Better, Combine EPIC with Euclid/JDEM-WL for a factor of ~2 to 3 improvement through z-binned lensing + a good model for non-linearities for galaxy lensing.

lensing of 21-cm: highly futuristic

Summary

• Planck should do BB lensing, and get down to ~0.2 eV level

• Post-Planck EPIC satellite for CMB polarization is well developed.

• US-based CMB community has requested NASA to start a project office after the 2010 Astronomy Decadal Survey, based on recommendations on CMB sciences.

• If started, EPIC phase-A to begin around 2015, launch around 2020-2021.

• Will Planck provide a hint of tensors and/or primordial non-Gaussianity? motivation for EPIC will be clearer then.