Inflation with Cosmic Microwave Background

(Study of *Experimental Probe of Inflationary Cosmology*)

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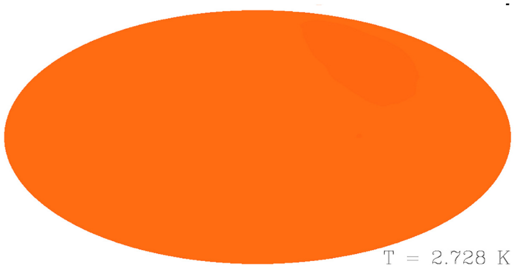
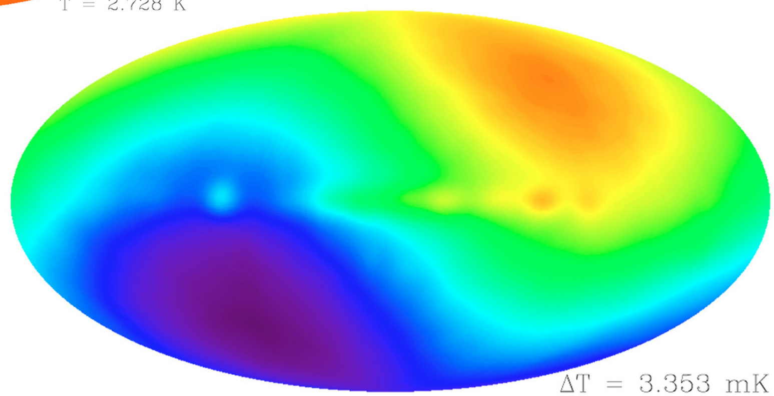
Universe at 400kyr: the microwave sky



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

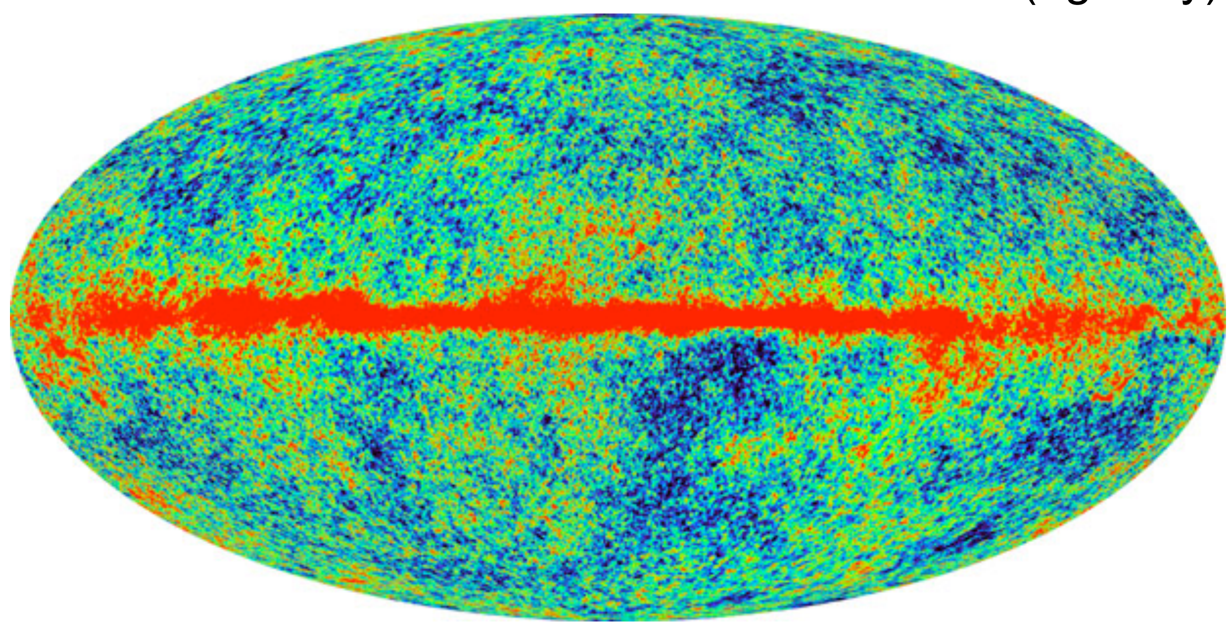
COBE
(Mather & Smoot)



Dipole (local motion)

WMAP

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

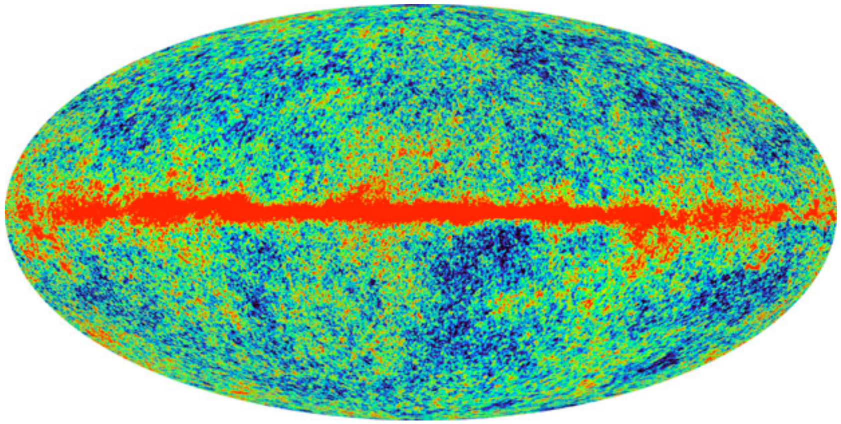


Inflation as a problem solver

Horizon Problem

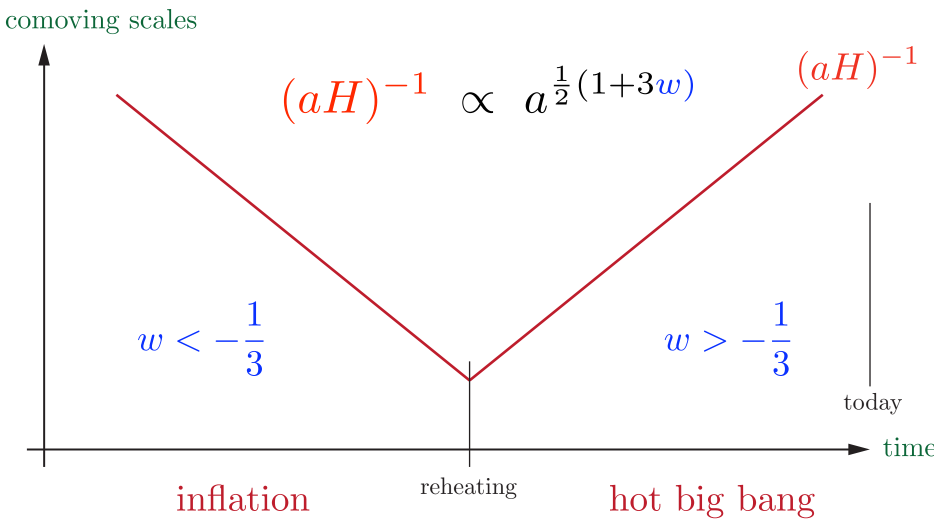
In standard cosmological expansion, horizon size at 400kyr subtends an angle of 1 deg on the sky (2 Moons)

40,000 disconnected regions in the CMB map



But, why do they all have the same temperature to within O(10^{-5})?

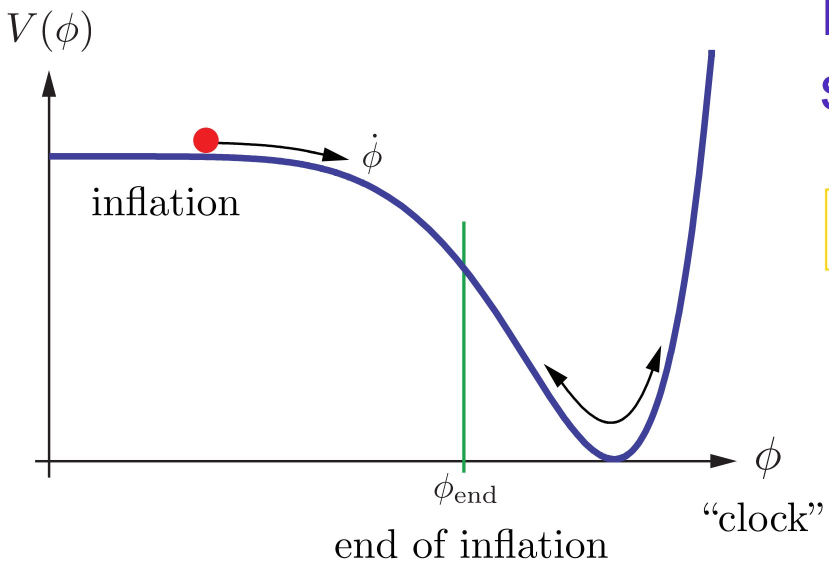
The comoving "horizon" *shrinks* during inflation
and grows after inflation



Inflation: postulate a phase of super-expansion such that independent CMB patches were once within horizon

Guth 1981; Linde 1982; Albrecht & Steinhardt 1982; Sato 1981; Mukhanov 1981; Hawking 1982; Starobinsky 1982; Bardeen et al. 1983; ….. tons

Inflation: In practice, classical dynamics



Implemented as a slowly rolling scalar field evolving in a potential

Expansion rate

$$H^2 \equiv \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi}{3m_{pl}^2}\left[\frac{1}{2}\dot\phi^2 + V(\phi)\right]$$

density

Field evolution:

$$\ddot\phi + 3H\dot\phi + V'(\phi) = 0$$

Slow-roll condition:

$$\dot\phi^2 < V(\phi)$$

$$H^2 \simeq \frac{8\pi}{3m_{\rm pl}^2}V(\phi)$$

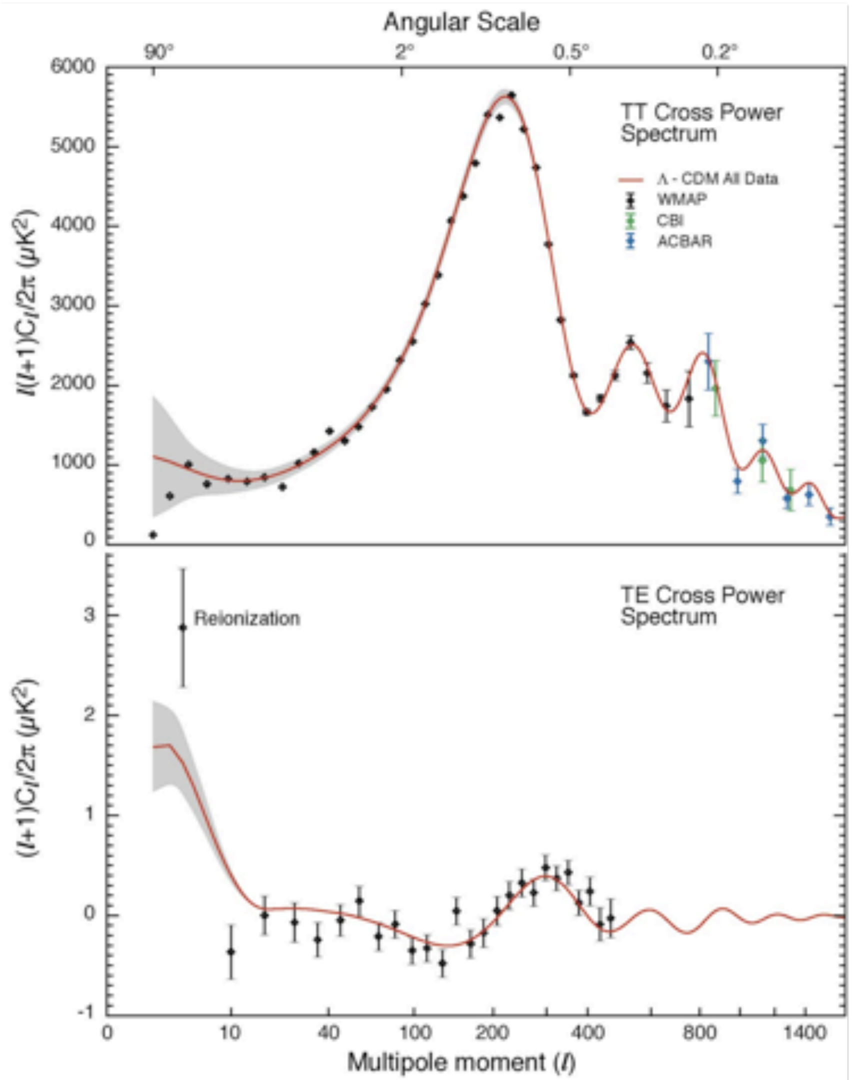
$$3H\dot\phi \simeq -V'(\phi)$$

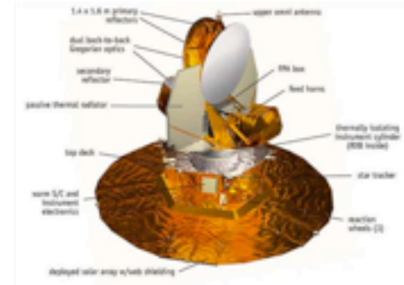
Slow-roll parameters:

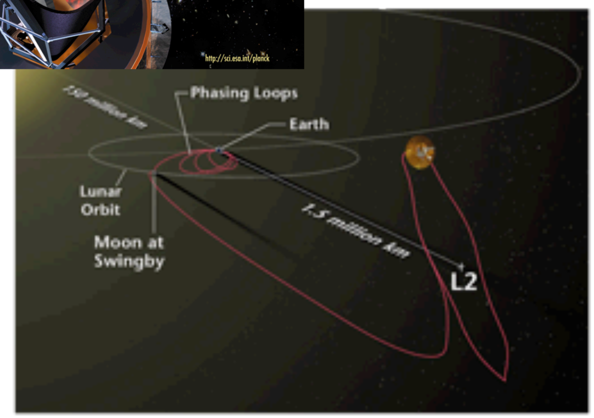
$$\epsilon \equiv \frac{m_{\rm pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 , \quad \eta \equiv \frac{m_{\rm pl}^2}{8\pi}\frac{V''}{V}$$

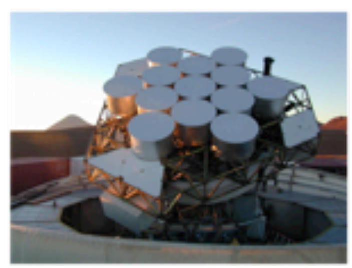
Inflate as long as ε and η << 1

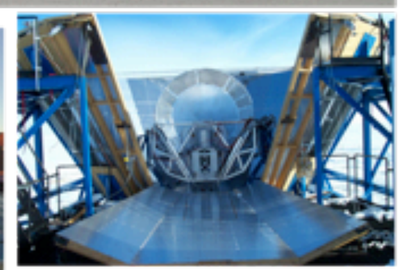
Scalar fluctuations



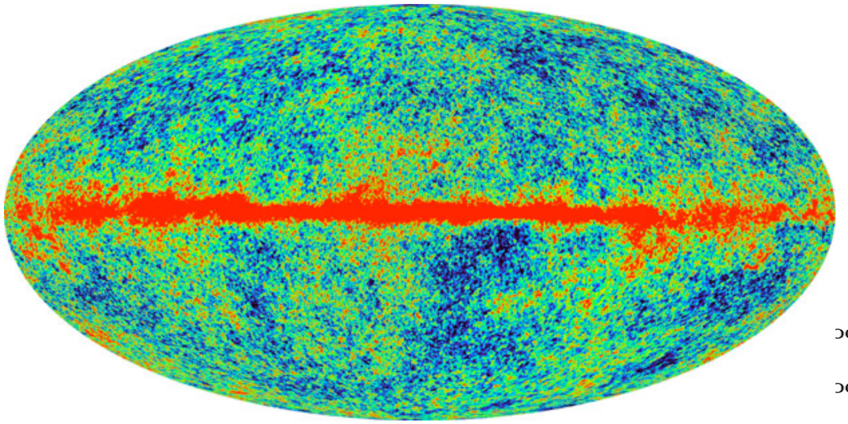




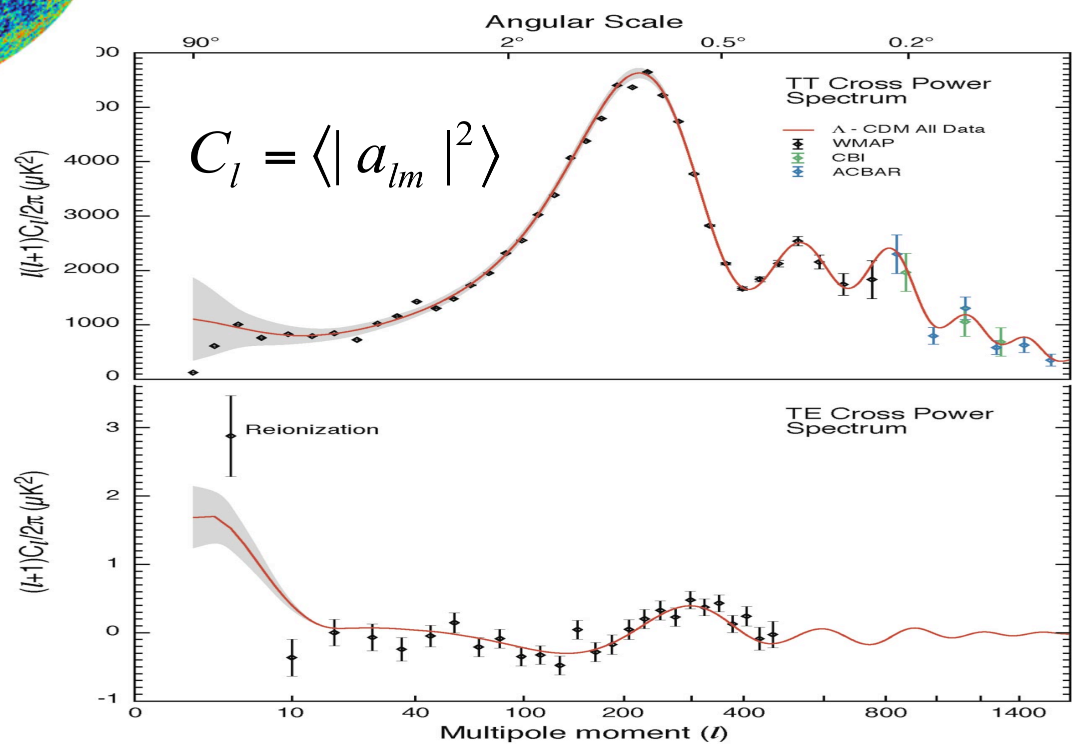




CMB as a probe of primordial physics:



$$a_{lm} = \int d\Omega \;\Delta T \; Y^*_{lm}$$



$$C_l = \langle | a_{lm} |^2 \rangle$$

Theory prediction

- -variance (average over all possible sky realizations)
- - statistical isotropy implies independent of *m* *(testable)*

Physics Ingredients

- •Thomson scattering (γ+e)
- •Recombination of H atoms
- •GR effects (Sachs-Wolfe/ISW/ Lensing)

linearized GR
+ Boltzmann equations

Primordial perturbations → C_l

COBE-Era Options for Primordial Perturbations:

Rolling scalar fields

explosions

Late-time phase transitions

Seed models

Primordial adiabatic perturbations

Global monopoles

Cosmic strings

textures

Loitering universe

Superconducting cosmic strings

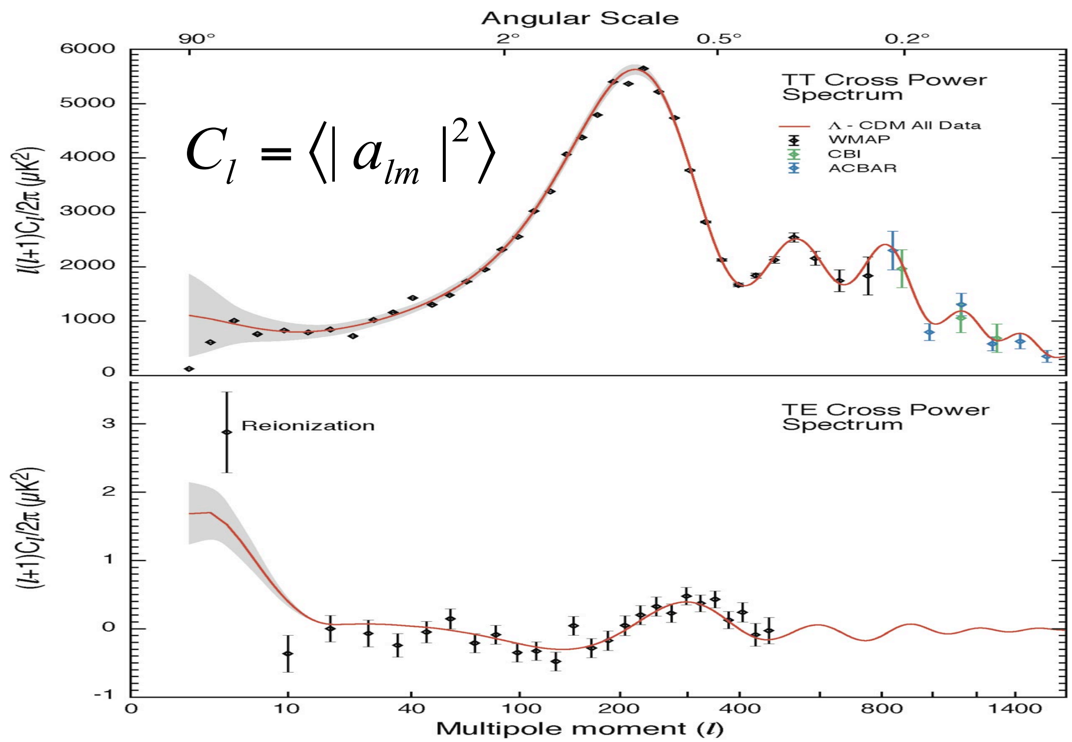
Isocurvature baryon perturbations

After Boomerang & WMAP:

Presence of harmonic oscillations: coherence of initial fluctuations

"nearly" scale invariant, adiabatic, extremely Gaussian perturbations

Adiabaticity: fluctuations in pressure are proportional to the density. Essentially, photons trace the density field.



linearized GR
+ Boltzmann equations

Primordial perturbations

C_l

What created adiabatic, nearly scale-invariant, mostly-Gaussian initial perturbations?

Standard slow-roll inflation

Hybrid inflation

Chaotic inflation

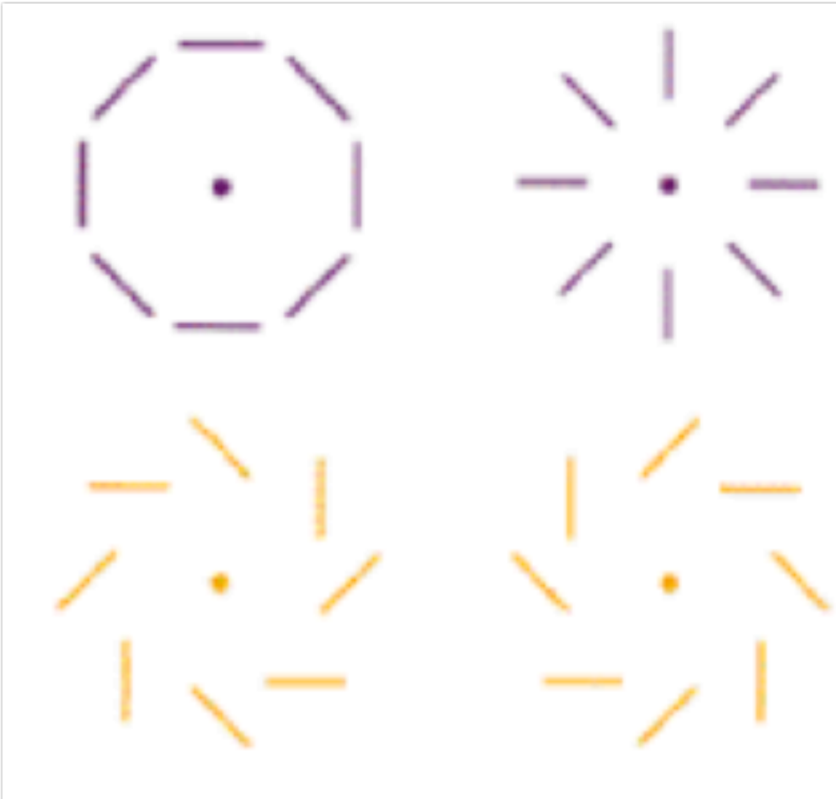
Slinky inflation

Brane inflation

Dirac-Born-Infeld Inflation

$\boxed{\text{Inflationary Paradigm}}$

CMB Polarization

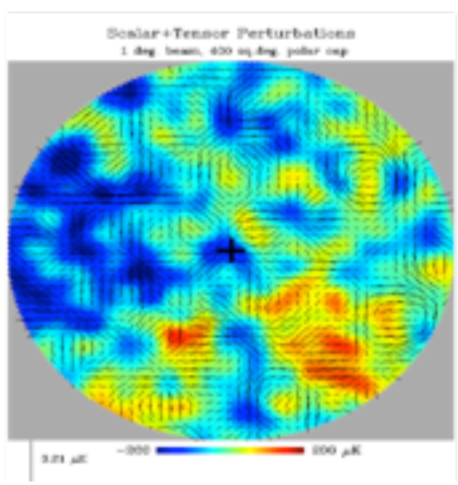


Grad (or E) modes

Curl (or B) modes

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

Kamionkowski et al. 1997;
Seljak & Zaldarriaga 1997



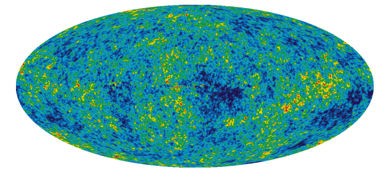
$$\text{Temperature map}: \; T(\hat{n})$$

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

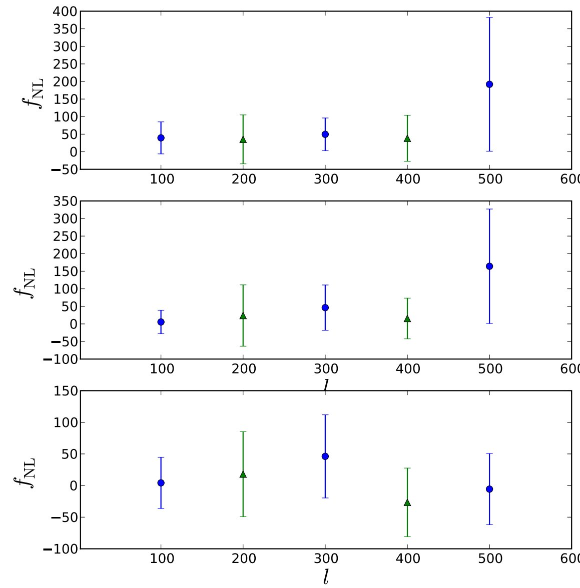
Table of Key Inflationary Observables

Amplitude of density perturbations	$\frac{\delta\rho}{\rho} \propto \frac{V^{3/2}}{V'}$	COBE
Spectral index of density perturbations	$n_s = 1 - 6\varepsilon + 2\eta$ $\varepsilon \propto \left(\frac{V'}{V}\right)^2 \quad \eta \propto \frac{V''}{V}$	WMAP +Planck
Running of the scalar index	$\frac{dn_s}{d\ln k} \propto V^{(n)} \quad n > 1$	Planck +21-cm
Gravitational-wave amplitude	$h_{ij} \propto V$	EPIC
Gravitational-wave spectral index	$n_t = -2\varepsilon$	+ direct detection
Running of the tensor index	$\frac{dn_t}{d\ln k} \propto V^{(n)} \quad n > 1$	?
Primordial non-Gaussianity	$f_{NL} \propto \varepsilon$	Planck, if lucky; 21-cm, certain

$$\Phi(\mathbf{x}) = \phi_L(\mathbf{x}) + f_{\rm NL}\left[\phi_L^2(\mathbf{x}) - \langle\phi_L(\mathbf{x})\rangle^2\right] + g_{\rm NL}\phi_L^3(\mathbf{x})$$



Observational constraints on primordial non-Gaussianity



with bispectrum (ie three-point function)

WMAP: f_{NL} = 11 ± 24 (Smidt, AC et al. 2009 PRD; arXiv:0907.4051)

(Planck: constrain f_{nl} with an error between 7 and 10)

with trispectrum (ie four-point function; measured for the first time in WMAP recently,~25,000 CPU hours)

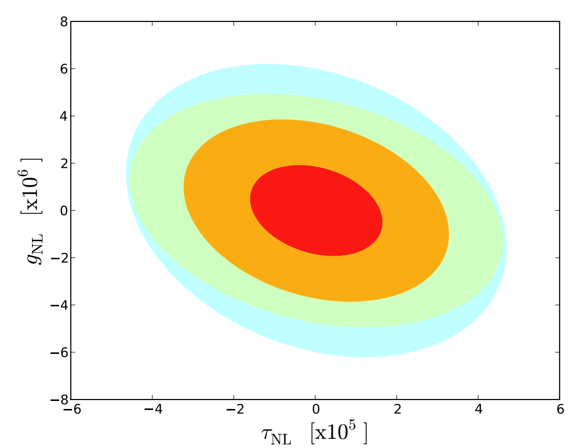
WMAP: g_{NL} = 3.9x10^4 ± 1.9x10^6

τ_{NL} = 2.7x10^4 ± 1.6x10^5 (improved COBE result by 3 OOM)

(Smidt, AC et al. 2010 PRL submitted; arXiv:1001.5026)

Consistency relation for non-Gaussianity: $\tau_{\rm NL} = 36 f_{\rm NL}^2/25$

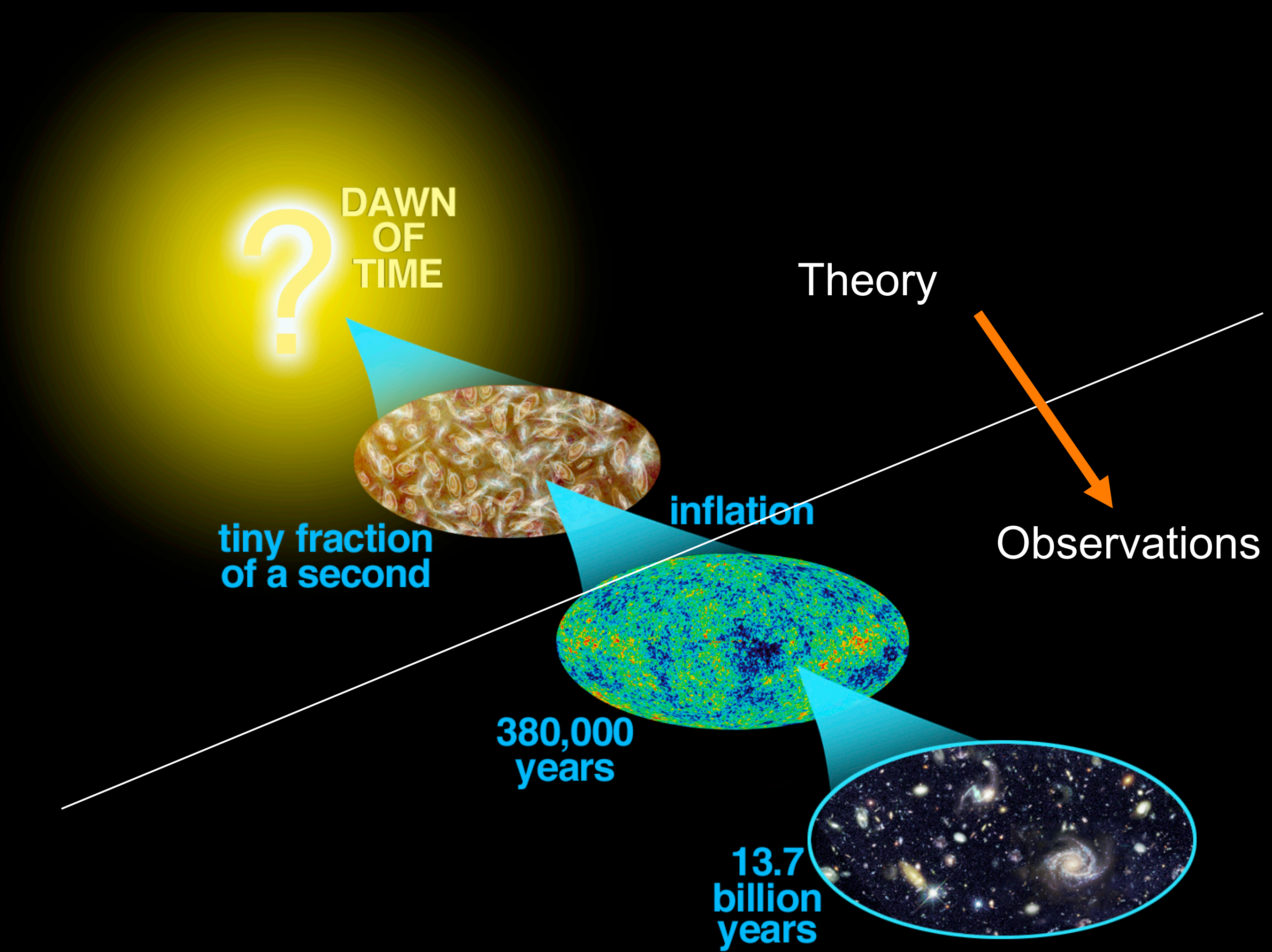
Trispectrum *Bispectrum*



The departure as a ratio now constrained for the first time to be 117 ± 657 *with WMAP data* (Smidt, AC et al. 2010 PRL).

Beyond CMB, with 21-cm fluctuations constrain f_{NL} down to 0.01

AC PRL 2006



How to measure:
"r", f_{nl} and n_{GW}

Source: NASA/WMAP Science Team

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 community-supported study under the CMBpol program for a post-Planck mission.

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

The EPIC Consortium

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Eric Hivon
Marc Kamionkowski
Tim Pearson
Anthony Readhead
Jonas Zmuidzinas

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Shaul Hanany
Michael Milligan

NIST
Kent Irwin

Stanford
Sarah Church

UC San Diego
Brian Keating (CoI)

Post-Planck Mission Effort in US

The EPIC-IM Study Team

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CMB Inflation Probe ASMCS

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Joanna Dunkley	Princeton U.
Krzysztof Gorski	JPL/Caltech
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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**

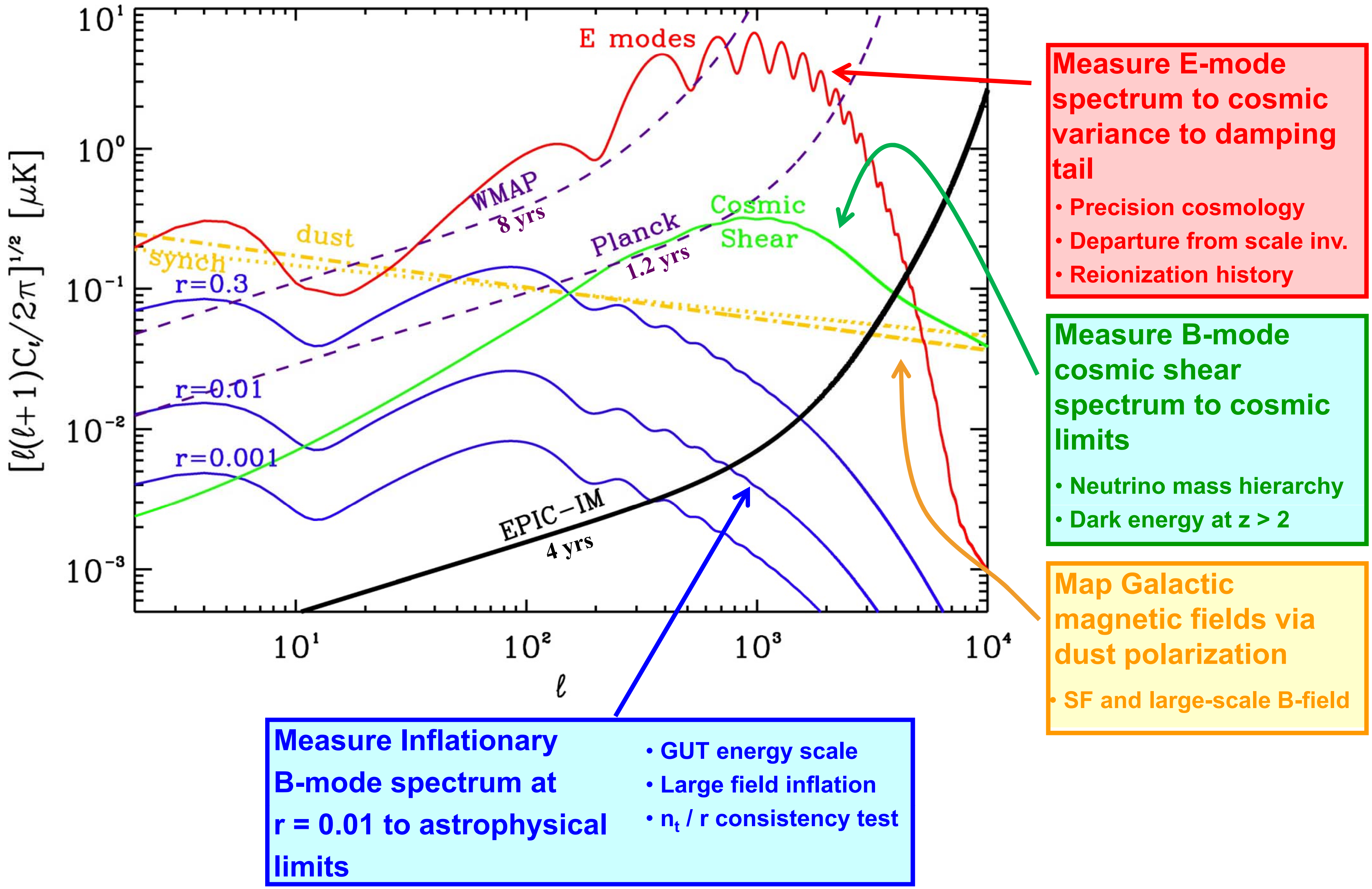
Mission Study Reports

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

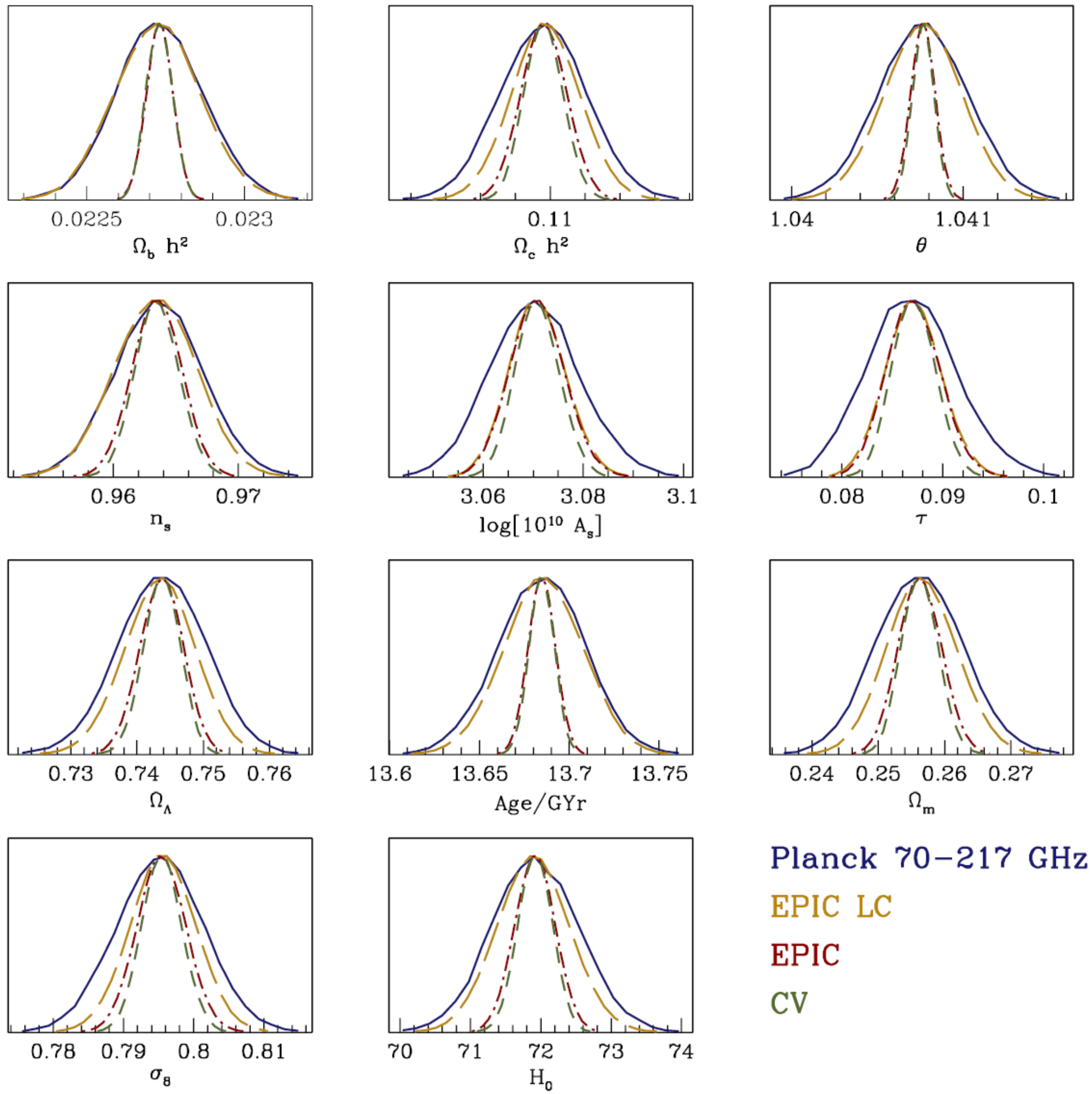
–*The Experimental Probe of Inflationary Cosmology*, **Bock et al. 2008, ArXiv 0805.4207**

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

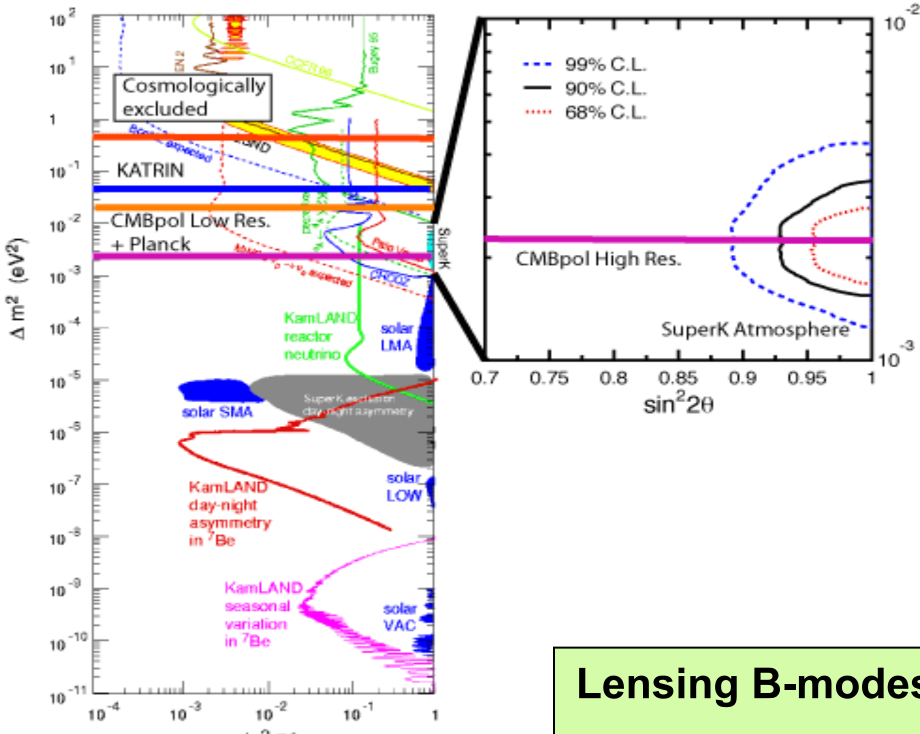
Richness of the CMB Polarization Landscape

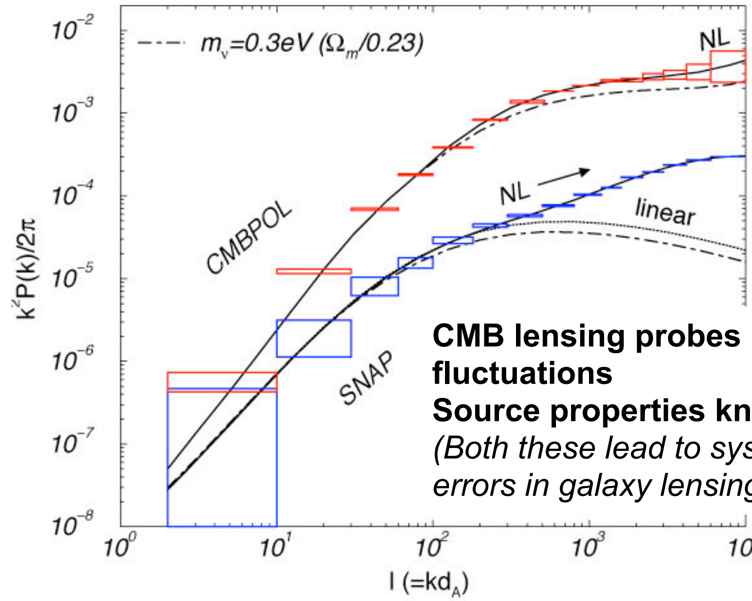


Precision Cosmology

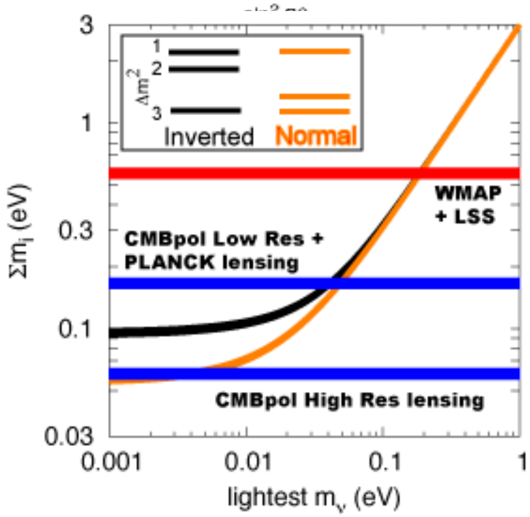


Particle physics application of EPIC





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



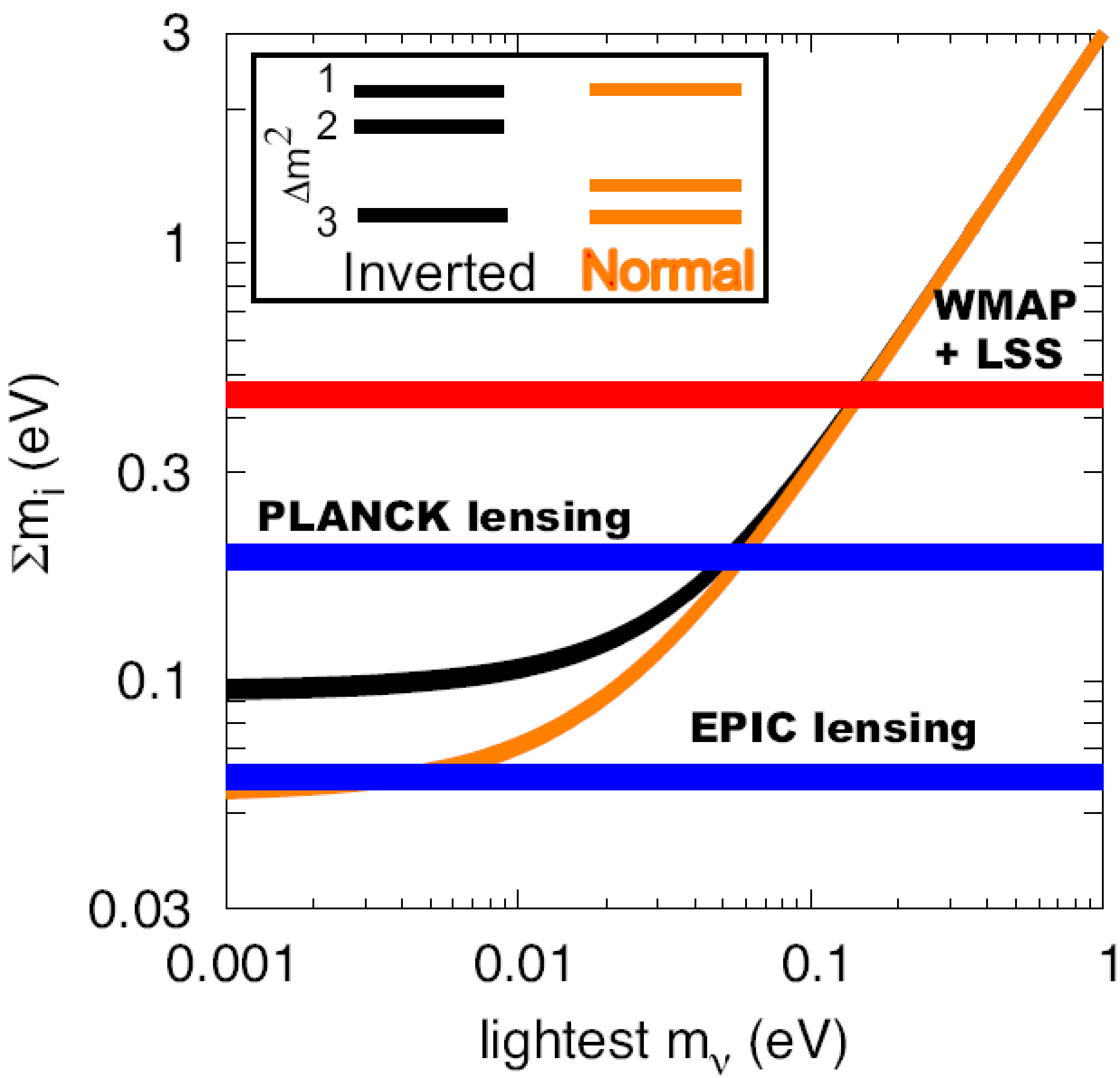
Lensing B-modes and CMB Cosmic Shear Reconstruction

neutrino mass (Σm_ν < 0.05 eV; from the linear regime)

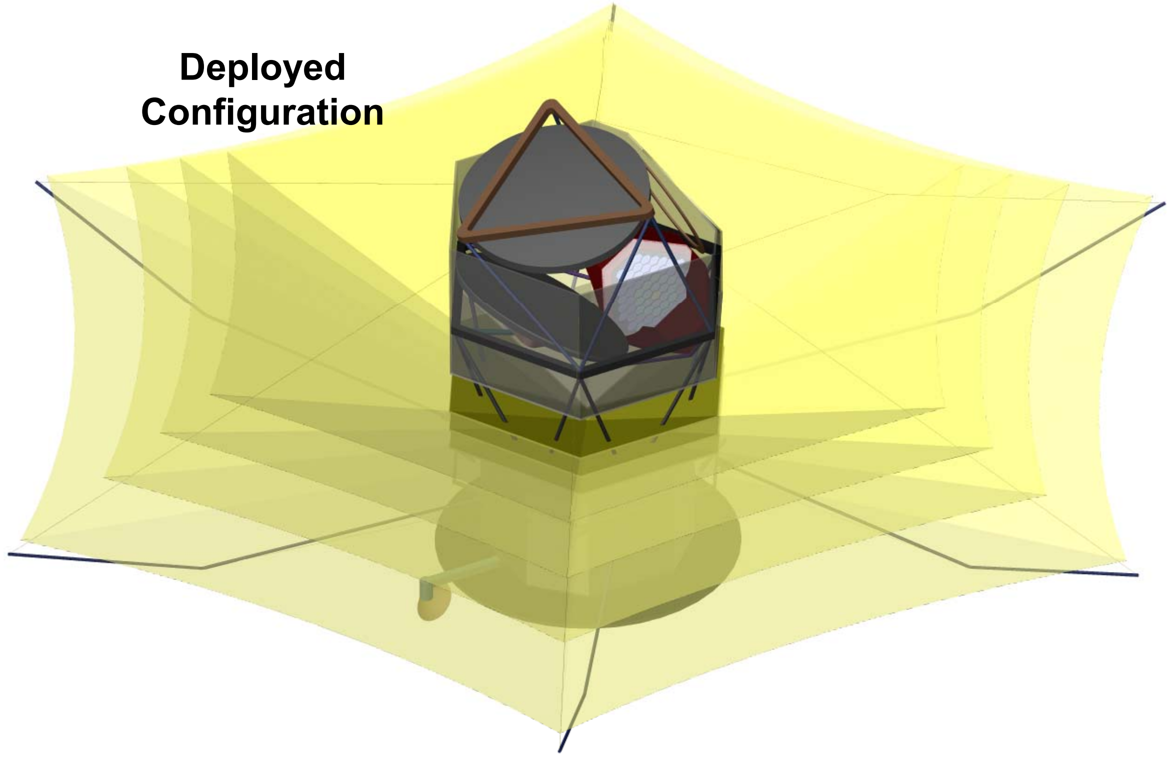
Test SuperK Atmosphere oscillations that suggest $\Delta m_\nu^2 \sim 2\text{x}10^{-3}$ eV^2 and distinguish between two mass hierarchies

AC 1999: neutrino mass from LSS lensing; EPIC study reports, Bock et al.

Neutrino mass hierarchy from cosmology



EPIC-IM Specification Sheet



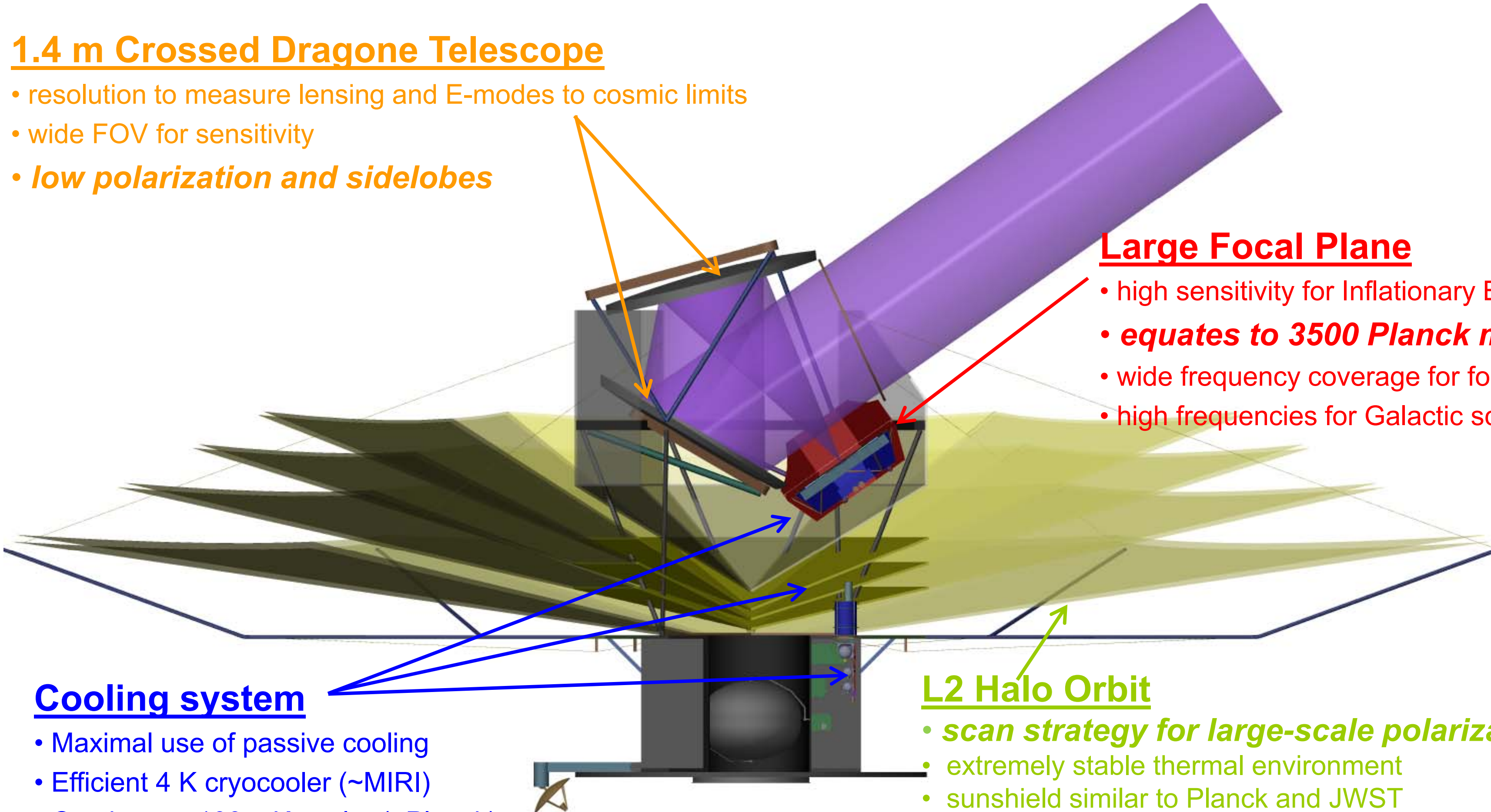
Optics	1.4 m wide-field crossed Dragone	**Total Delta-V**	170 m/s
Orbit	Sun-earth L2 halo	**Payload Power**	440 W (CBE)
Mission Life	4 years	**Spacecraft Power**	533 W (CBE)
Launch Vehicle	Atlas V 401	**Total Power**	1392 W (w/ 43 % cont.)
Detectors	11094 TES bolometer or MKID detectors	**Payload Mass**	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

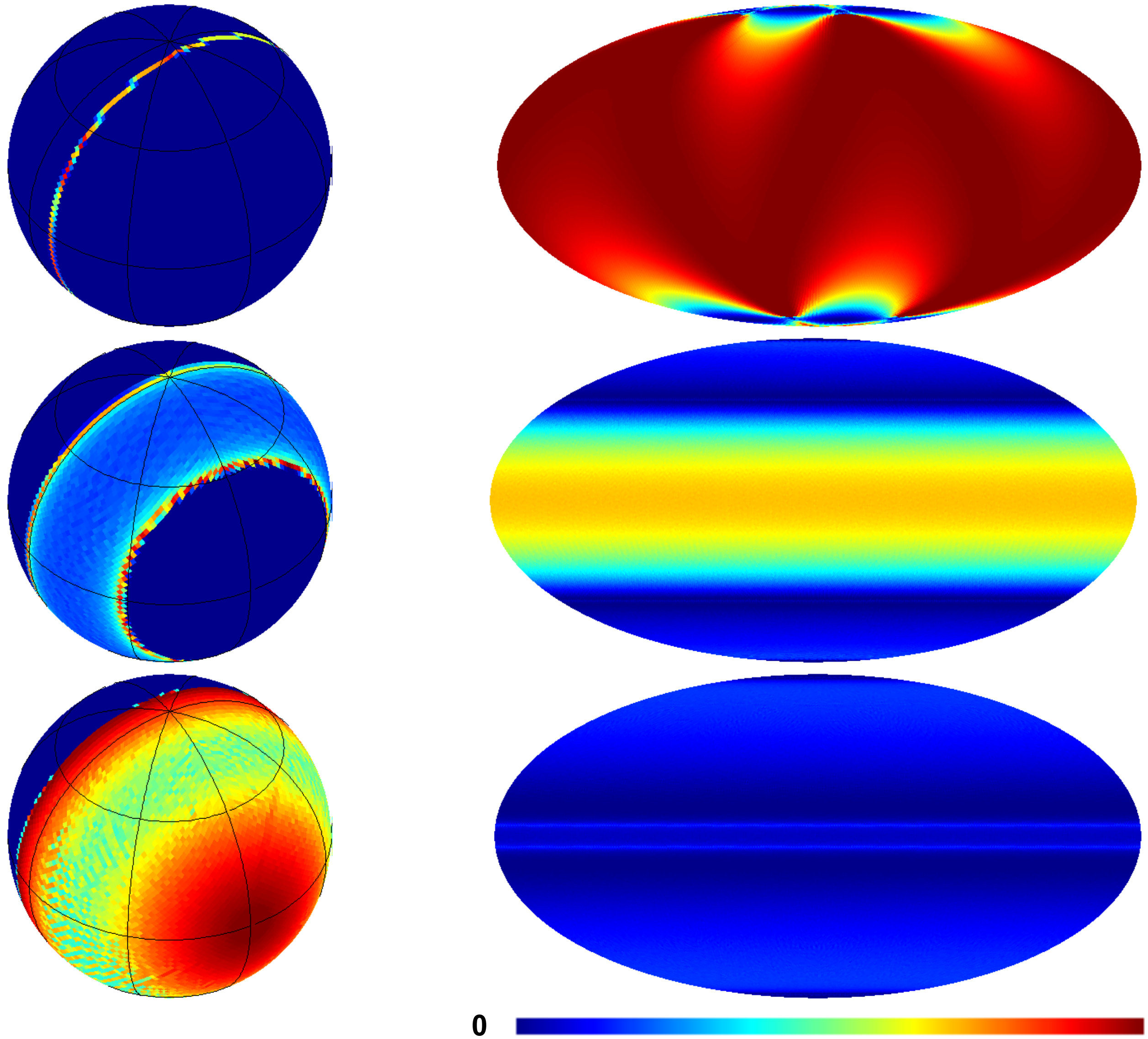
Highly Redundant & Uniform Scan Coverage

N-hits (1-day) | Angular Uniformity* (6-months)

Planck

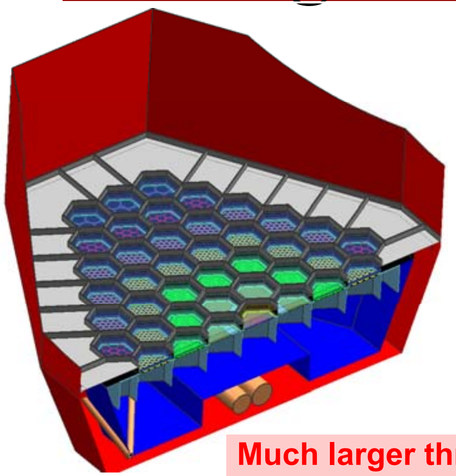
WMAP

EPIC



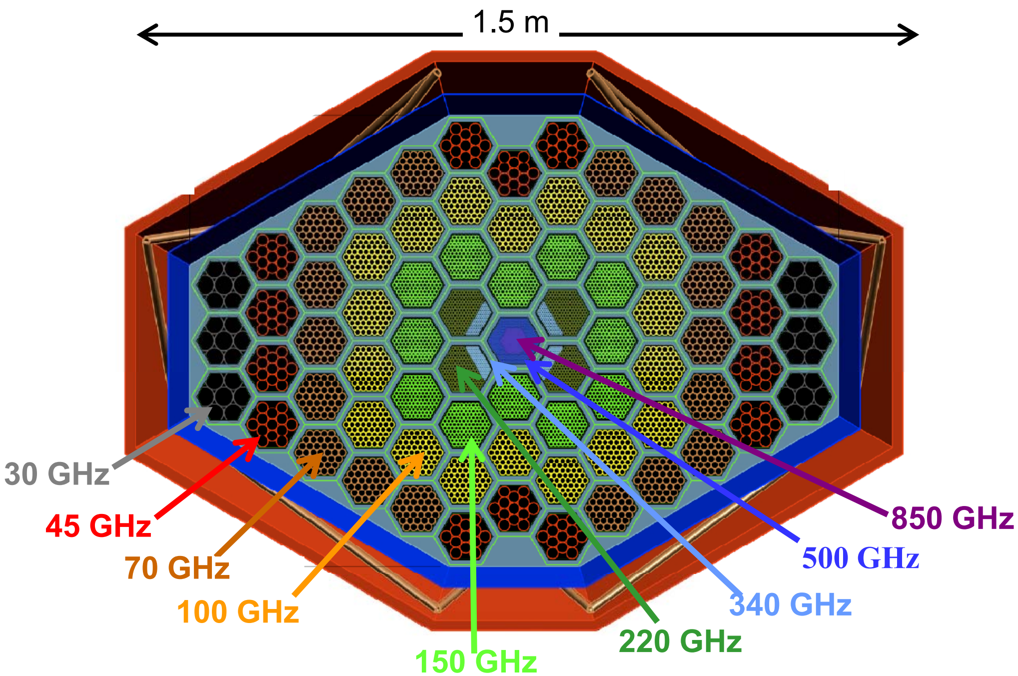
$*\langle\cos 2\beta\rangle^2 + \langle\sin 2\beta\rangle^2$

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

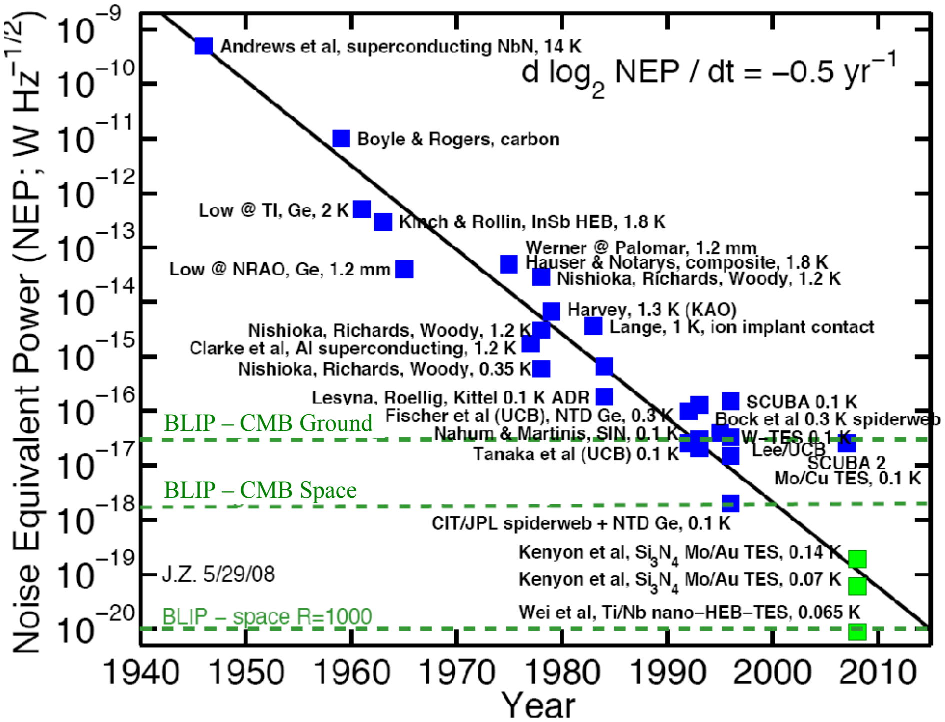
Much larger throughput and sensitivity than any planned sub-orbital experiment

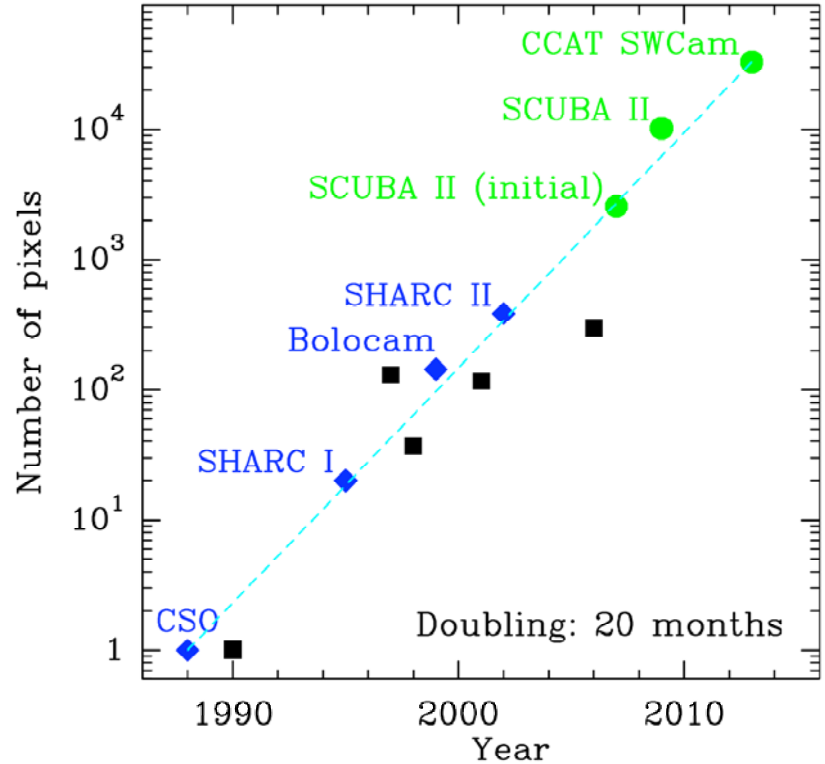


Freq [GHz]	θ_{FWHM} [arcmin]	N_{bol} [#]	$w_p^{-1/2}$ [μK-']	Planck @ 1.2 yr $w_p^{-1/2}$	δT_{pix} [nK]
30	28	84	14	350	83
45	19	364	5.7	350	34
70	12	1332	2.5	380	15
100	8.4	2196	1.8	100	10
150	5.6	3048	1.4	80	8
220	3.8	1296	2.5	130	15
340	2.5	744	5.6	400	33
500	1.7	1092	16		
850	1.0	938	740		
Total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

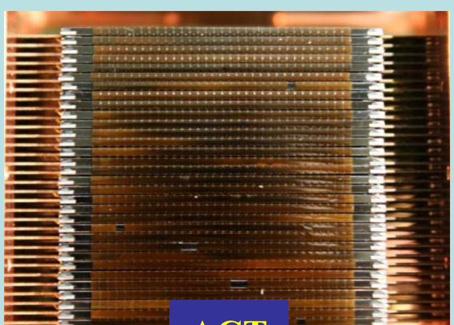
Lifetime : 4 years
Noise margin: 1.4

'Moore's Law' for Sensitivity and Mapping Speed

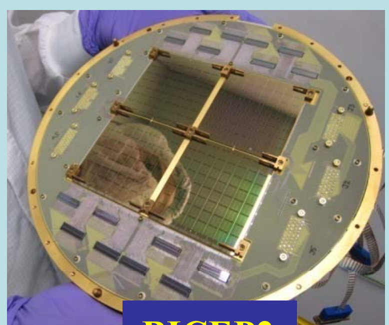




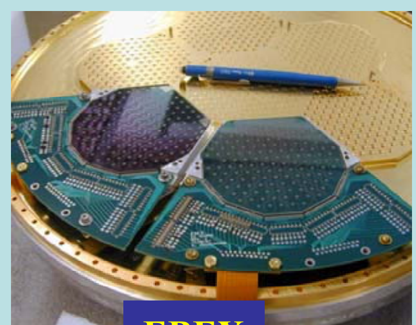
Technology & Sub-Orbital Program



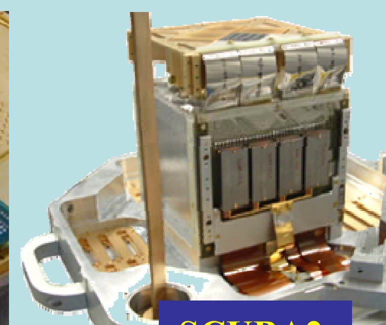
ACT



BICEP2



EBEX



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