

The Quest for B-modes: The Next Ten Years

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- B-modes in the CMB are the holy grail of inflation.
B-modes = GWB = Strongest evidence for quasi deSitter expansion in early Universe = inflation...
- cf Non-gaussianity
- Planck will not lower r limits by much...
- No funded CMB satellite mission after Planck.
- All-sky characterisation of polarisation signal will have to wait >10 years.
- What do we do until then?

1980

1990

2000



Old Inflation

1980

1990

2000



New Inflation

Old Inflation

1980

1990

2000





1980

1990

2000



Quest for B-modes

July 2011

Inflation: Scalar degeneracy

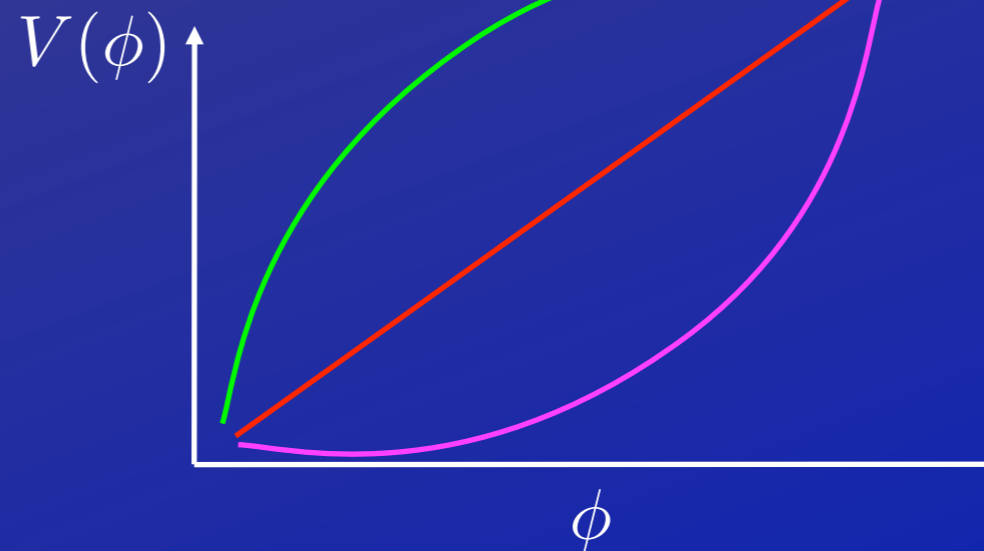
- Perturbations in curvature described by power spectrum

$$\langle \Phi(\vec{k}) \Phi^*(\vec{k}') \rangle = \delta(\vec{k} - \vec{k}') \frac{1}{k^3} A_s k^{n_s - 1}$$

???

$$A_s^{1/2} \sim 10^{-5}$$

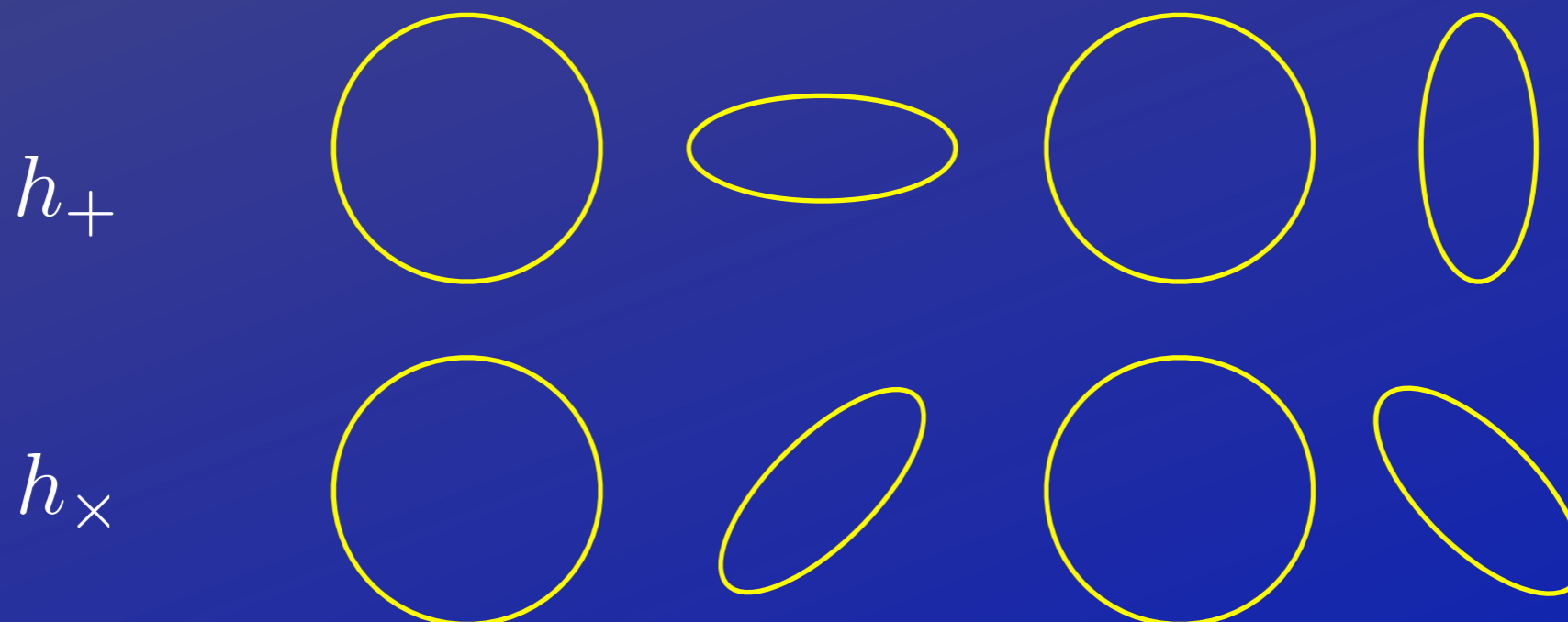
$$n_s \approx -6\epsilon + 2\eta$$



Tensor perturbations (from) Inflation

- Tensor perturbations in the background metric also evolve into super horizon scale fluctuation: we should see these as large scale gravity waves
- Relic background of gravitational waves

$$g_{\mu\nu} \rightarrow g_{\mu\nu} + h_{\mu\nu}$$



Tensor modes: Broken degeneracy

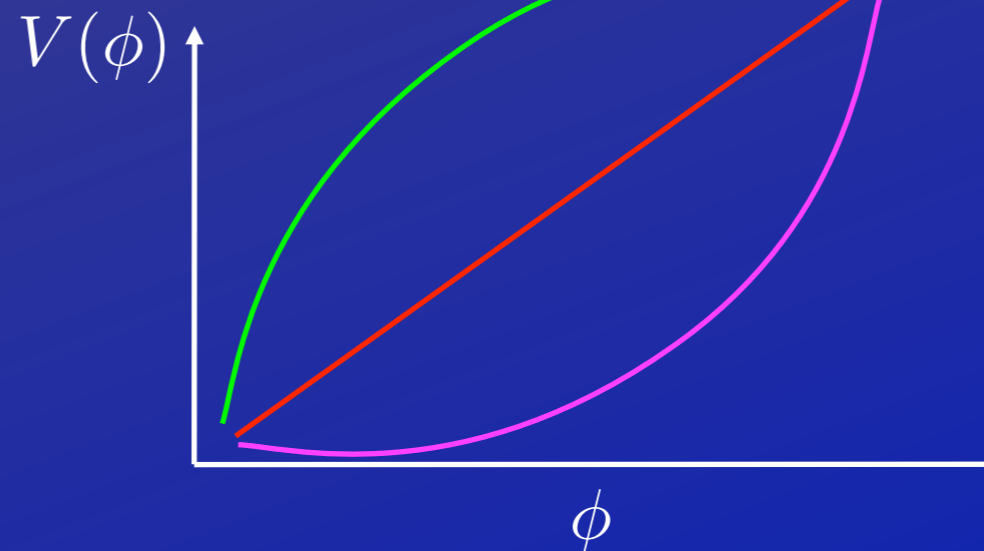
- Power spectrum of relic gravitational waves

$$\langle h(\vec{k}) h^*(\vec{k}') \rangle = \delta(\vec{k} - \vec{k}') \frac{1}{k^3} A_t k^{n_t}$$

$$r = \frac{A_t}{A_s} = 16\epsilon$$

$$n_t = -2\epsilon$$

???



Tensor modes: Broken degeneracy

- Power spectrum of relic gravitational waves

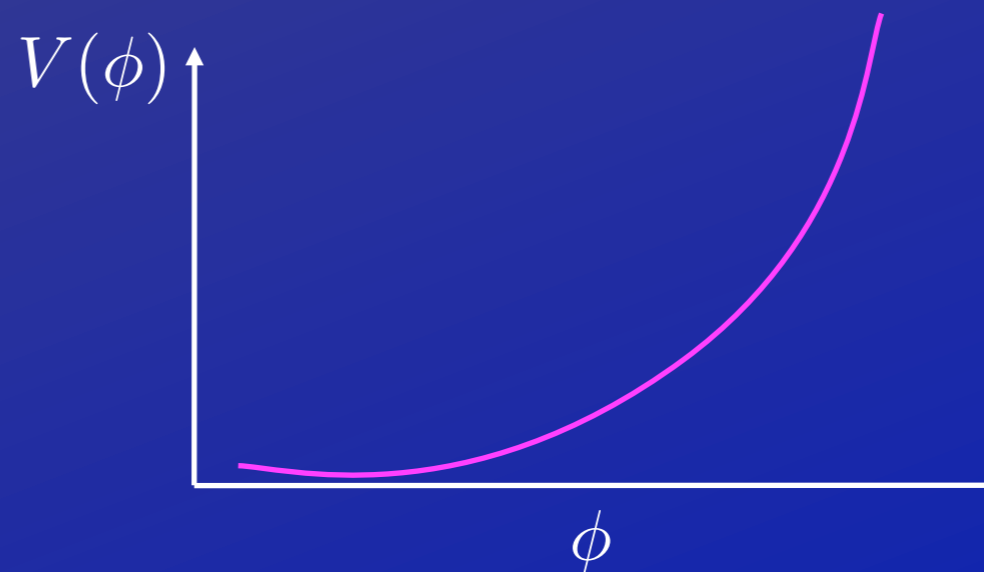
$$\langle h(\vec{k}) h^*(\vec{k}') \rangle = \delta(\vec{k} - \vec{k}') \frac{1}{k^3} A_t k^{n_t}$$

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$$n_t = -2\epsilon$$

+

$$n_s \approx -6\epsilon + 2\eta$$



Tensor modes: Broken degeneracy

- Power spectrum of relic gravitational waves

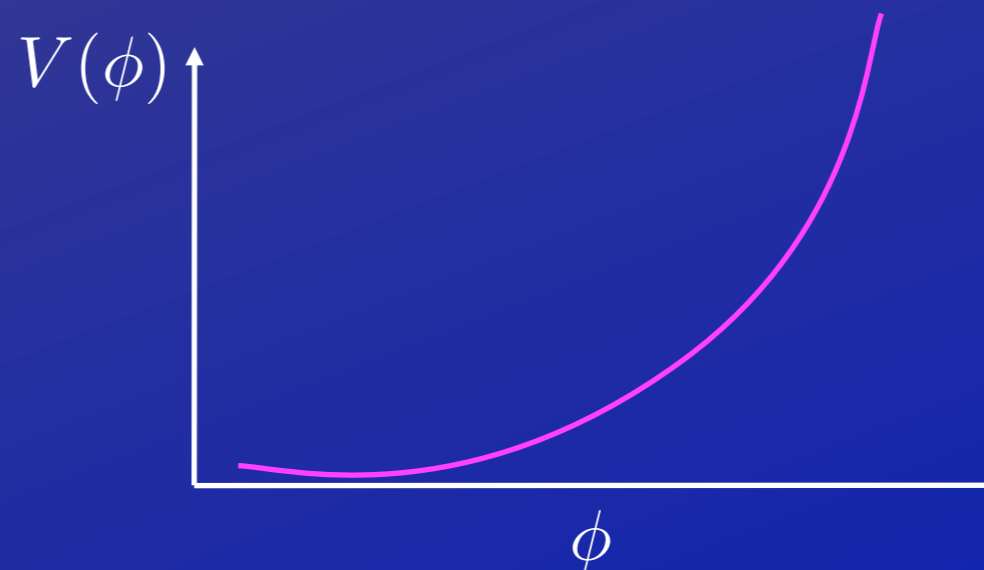
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$$r = \frac{A_t}{A_s} = 16\epsilon$$

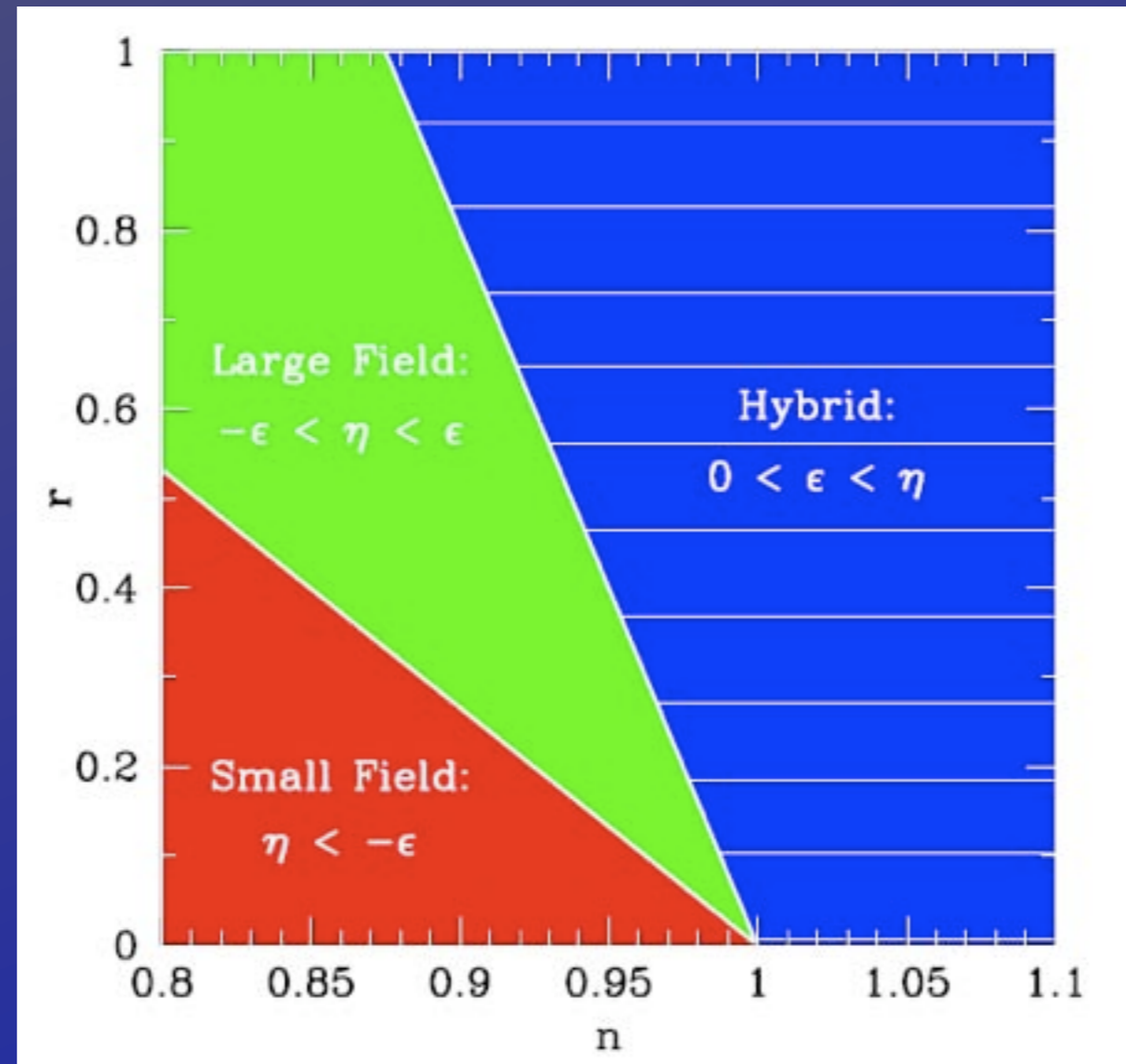
$$n_t = -2\epsilon$$

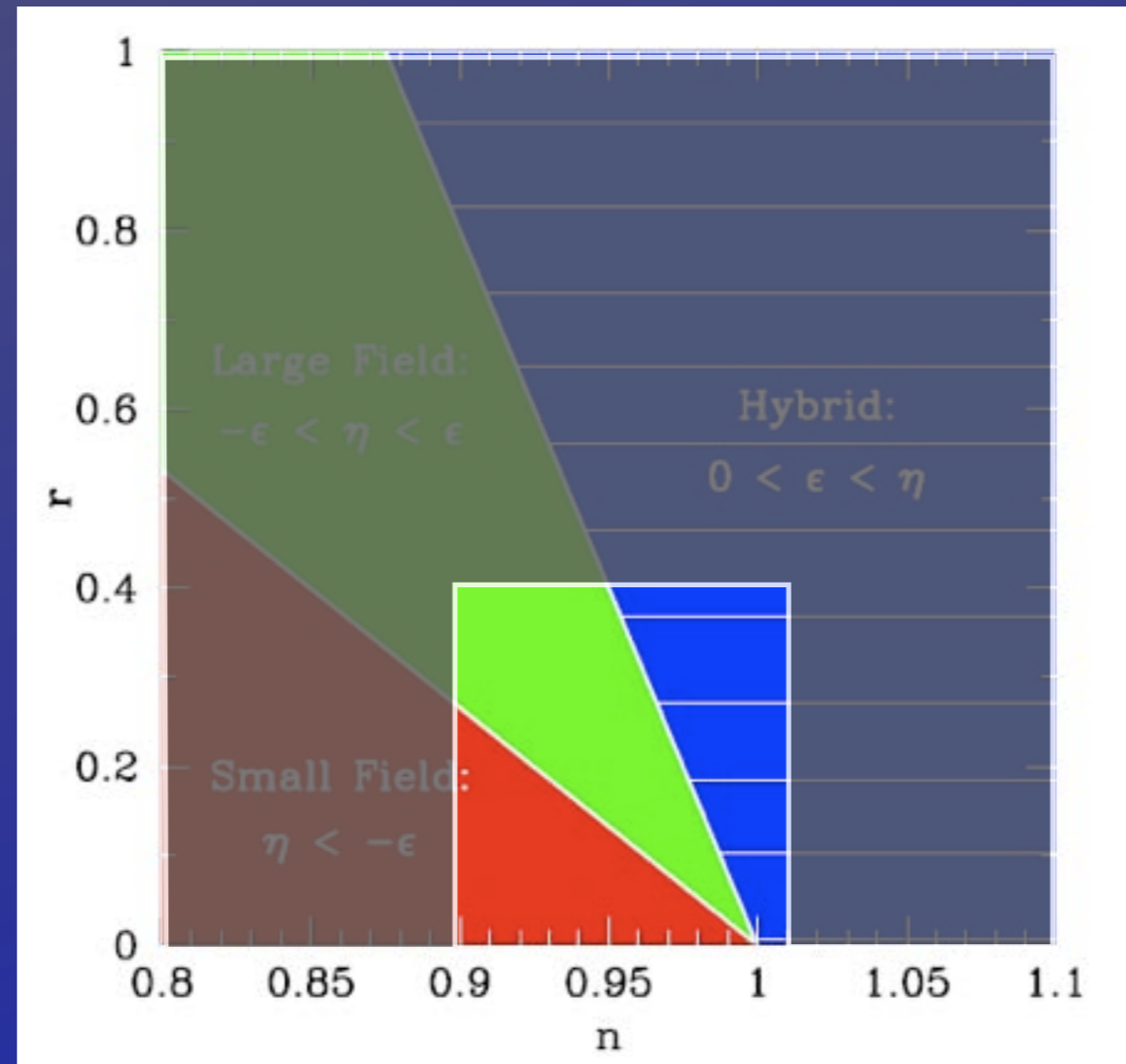
+

$$n_s \approx -6\epsilon + 2\eta$$

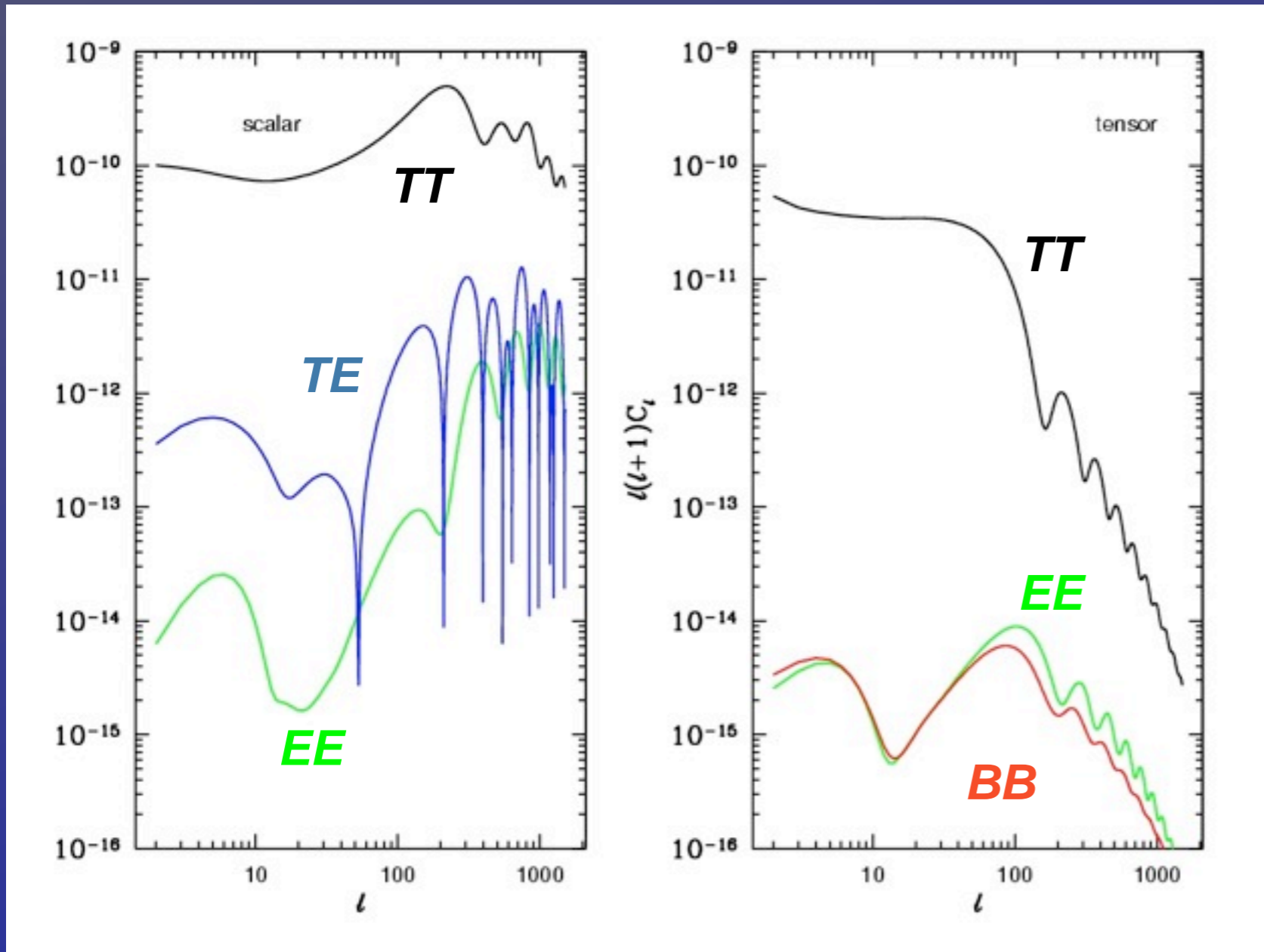


Current limits from CMB: $r < 0.36 \rightarrow 0.24$

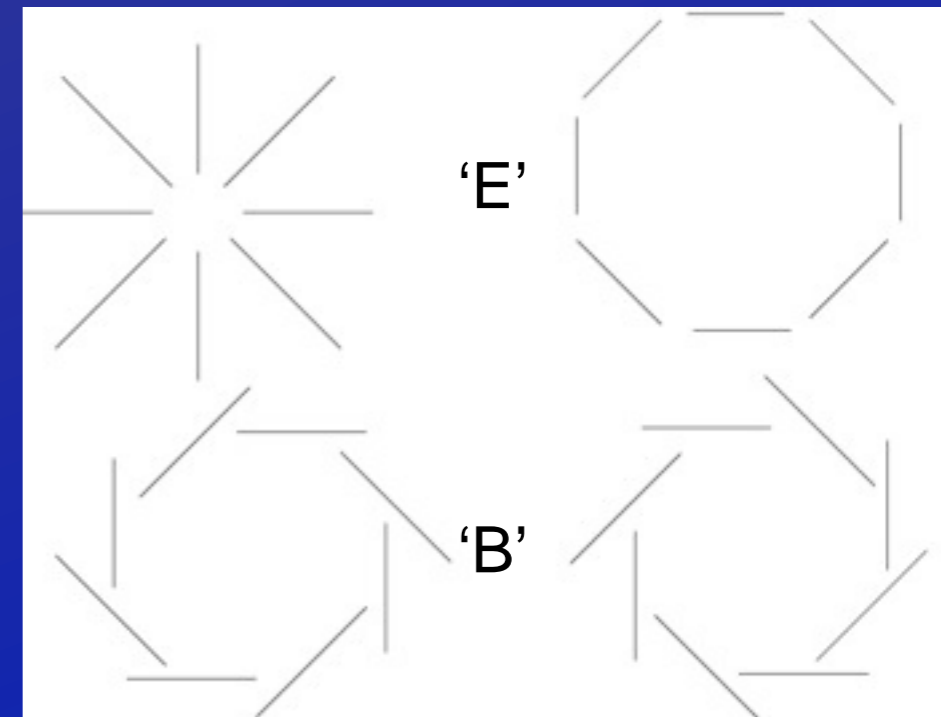




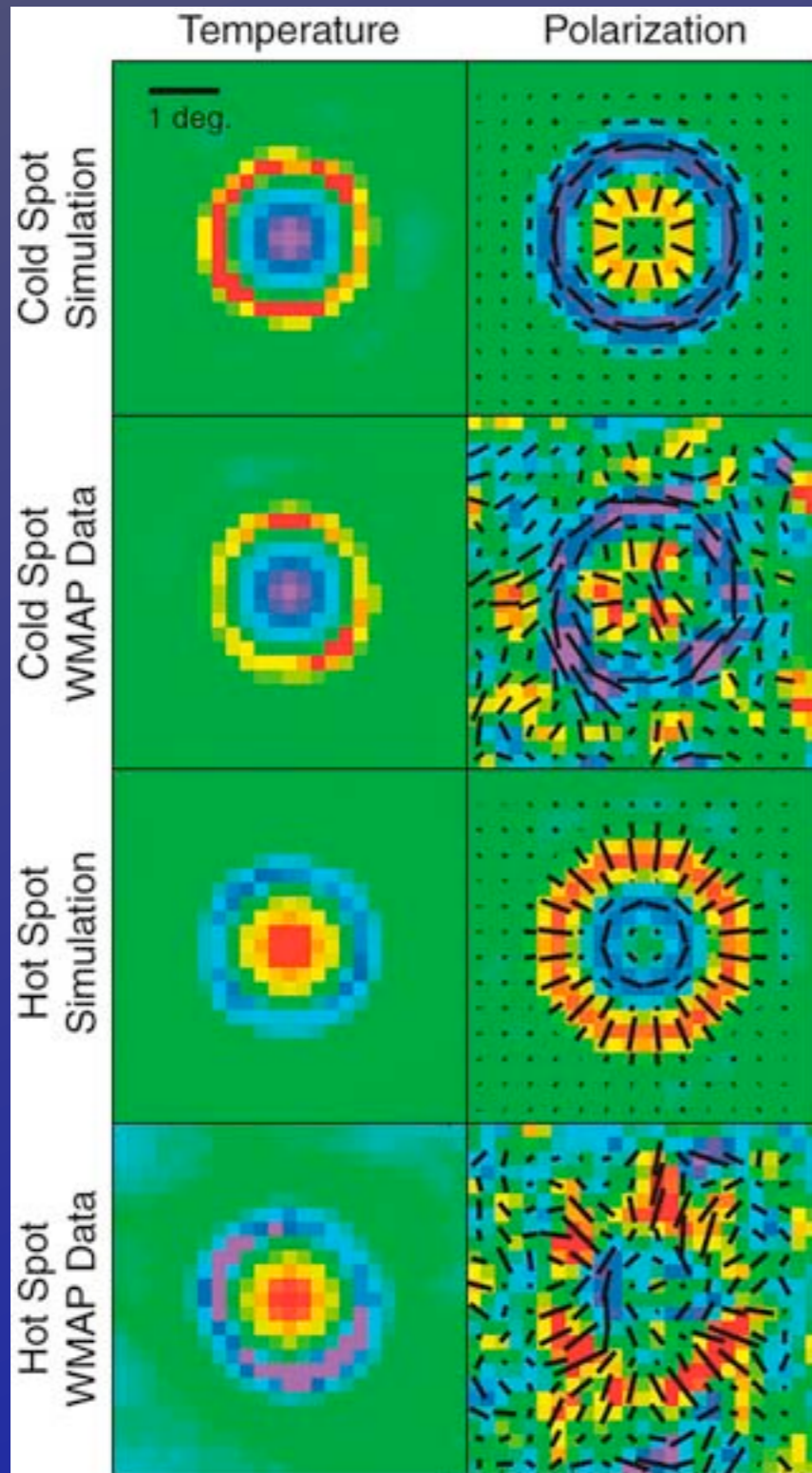
Tensors in CMB Polarization



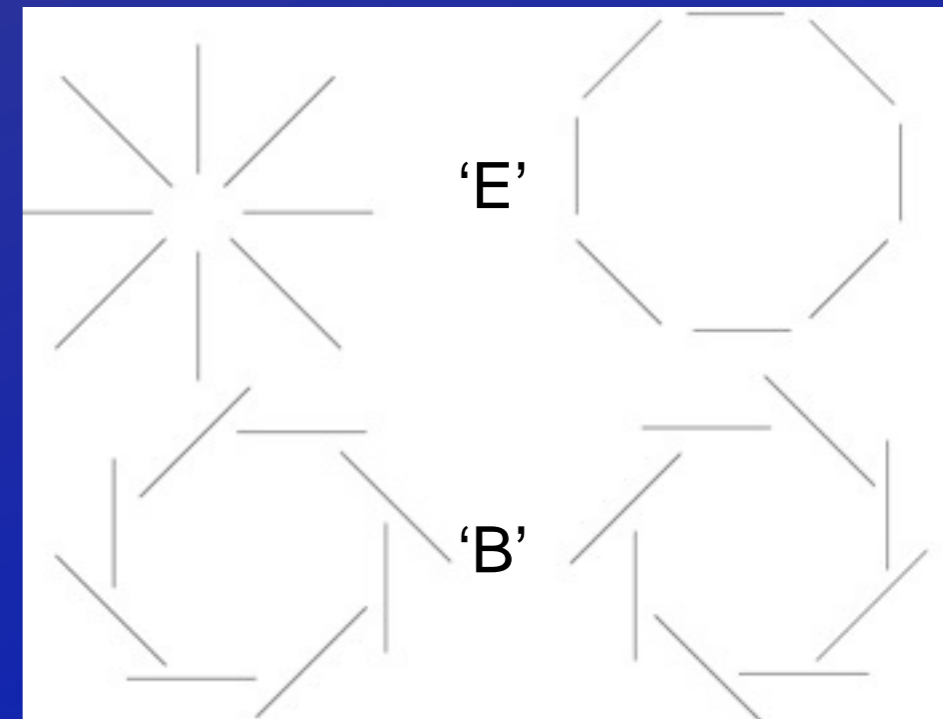
- Scalar (density) perturbations only source **E-modes**
- Tensor (GW) source both E and **B-modes**
- Detection of **clean** B-mode signal = GW background



Tensors in CMB Polarization



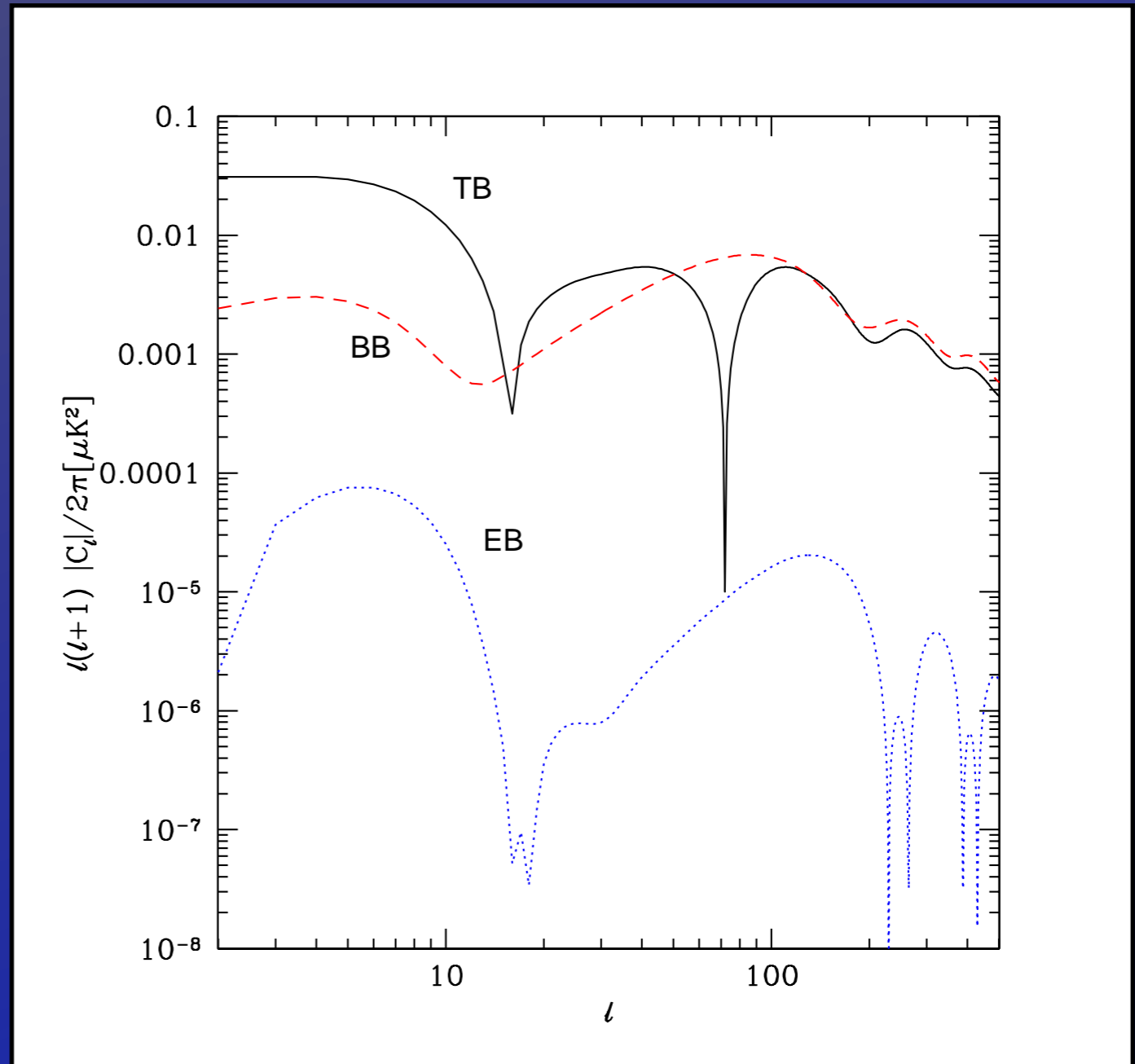
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Komatsu et al 2009

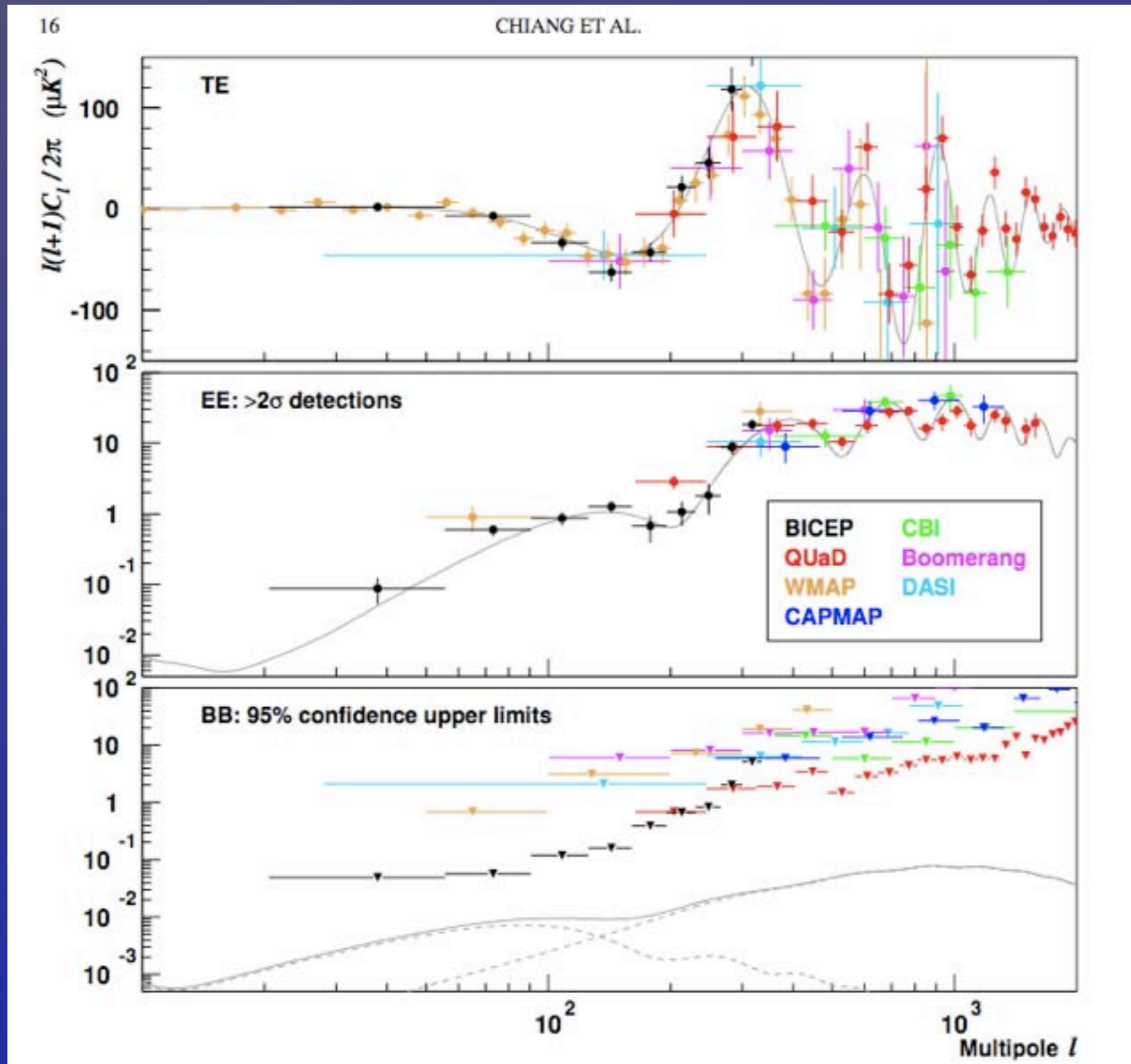
Parity Violation Signal

- Parity violating theories also produce signal in TB and EB correlations.
- e.g Chiral Gravity, polarization diffusion, photon-axion mixing along line of sight, etc...

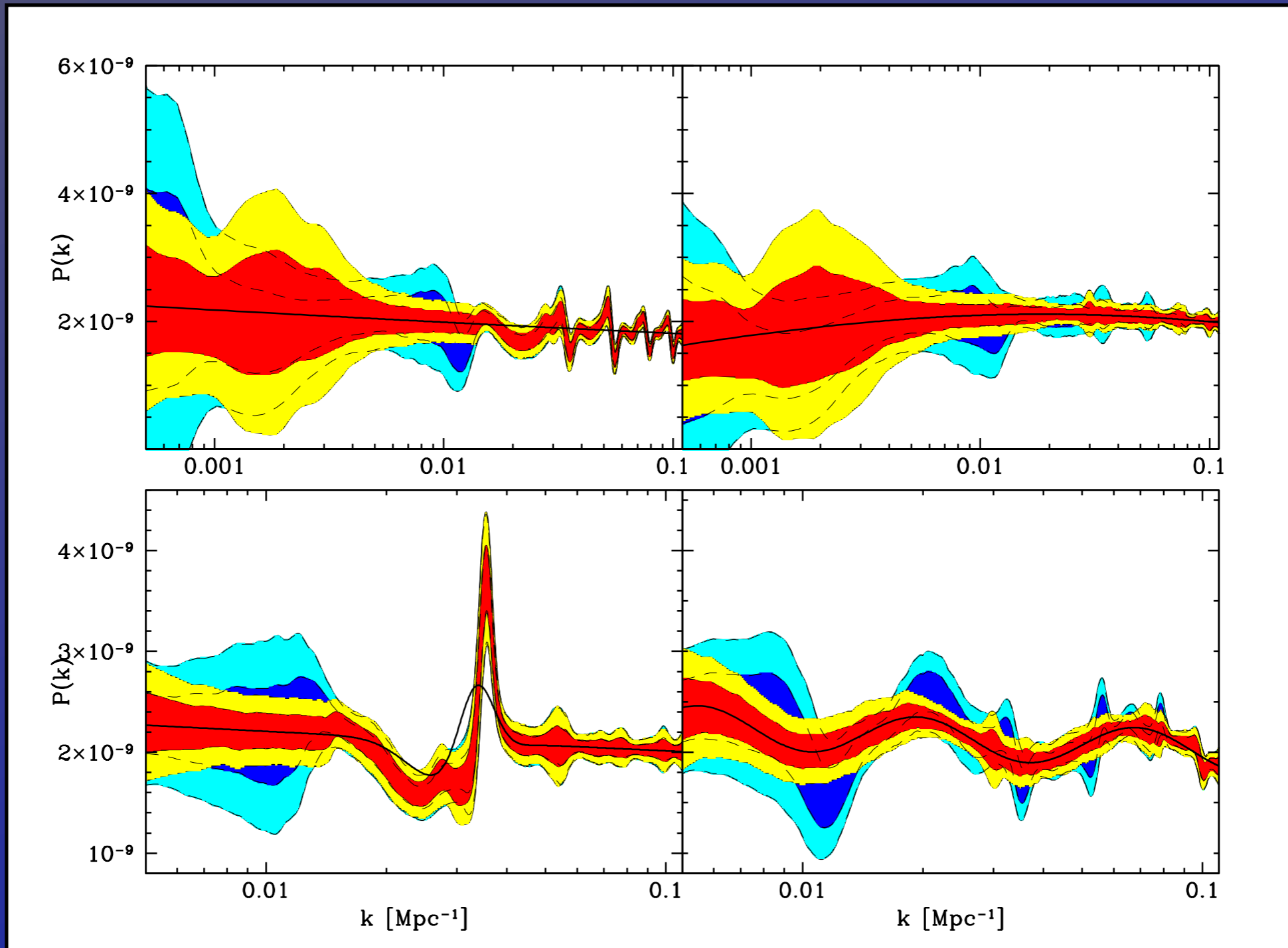


CC, Magueijo, & Smolin, PRL 2008

CC, Dowker, & Philpott, CQG 2010

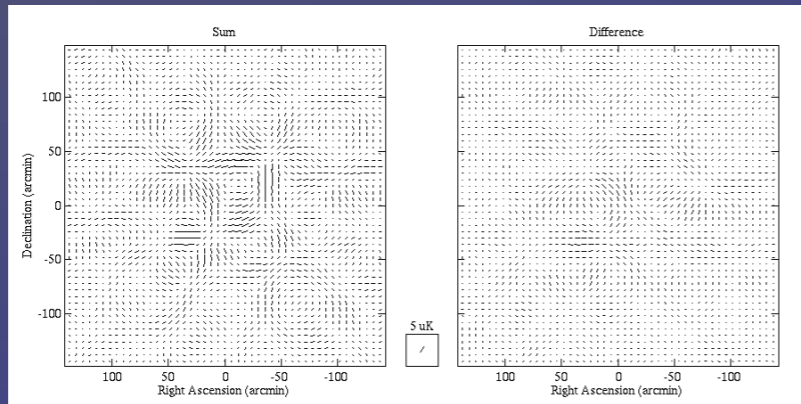


Polarisation and $P(k)$ reconstruction

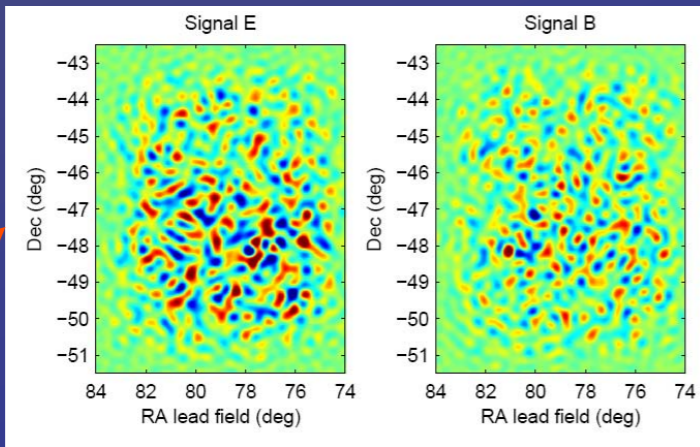
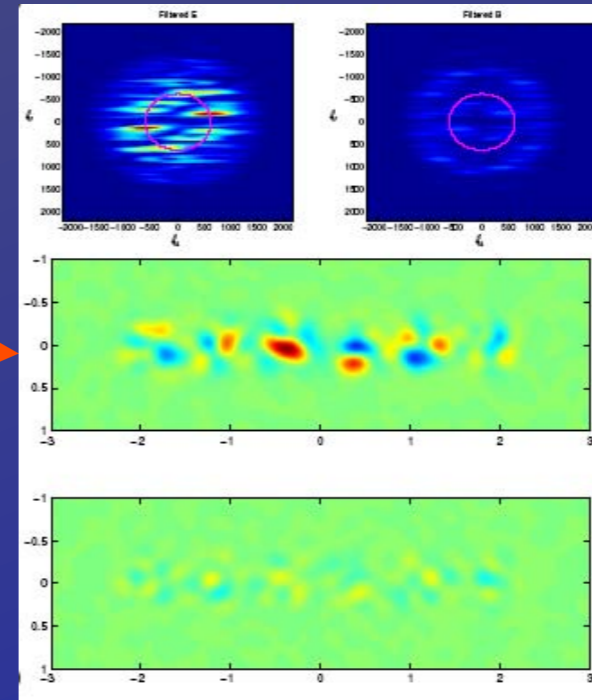


Nicholson & CC, JCAP 2009

DASI

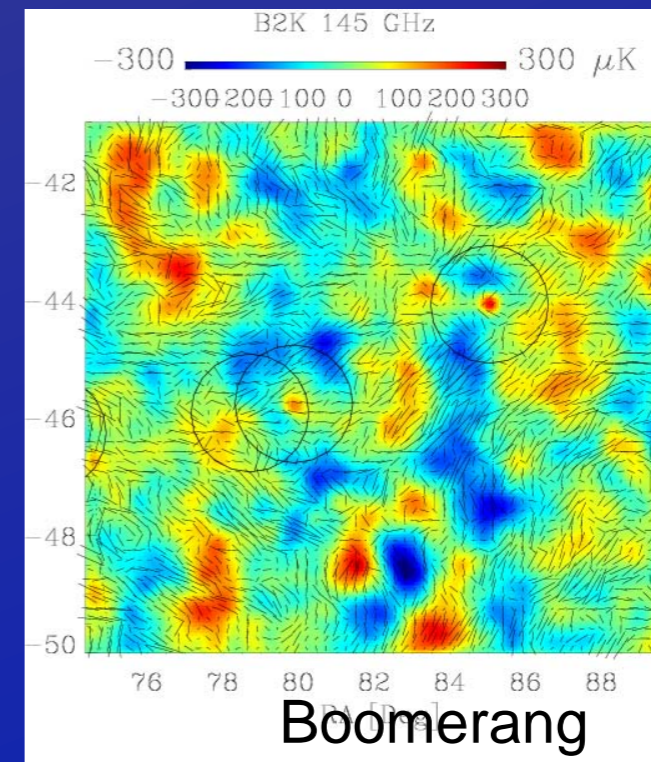
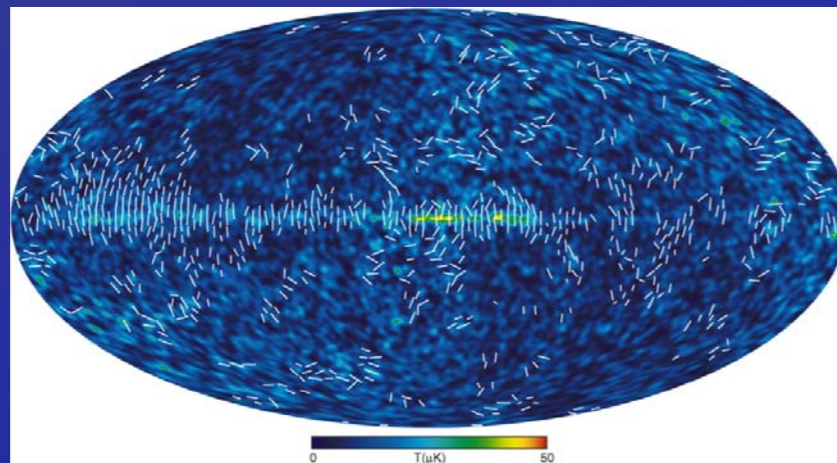


CBI

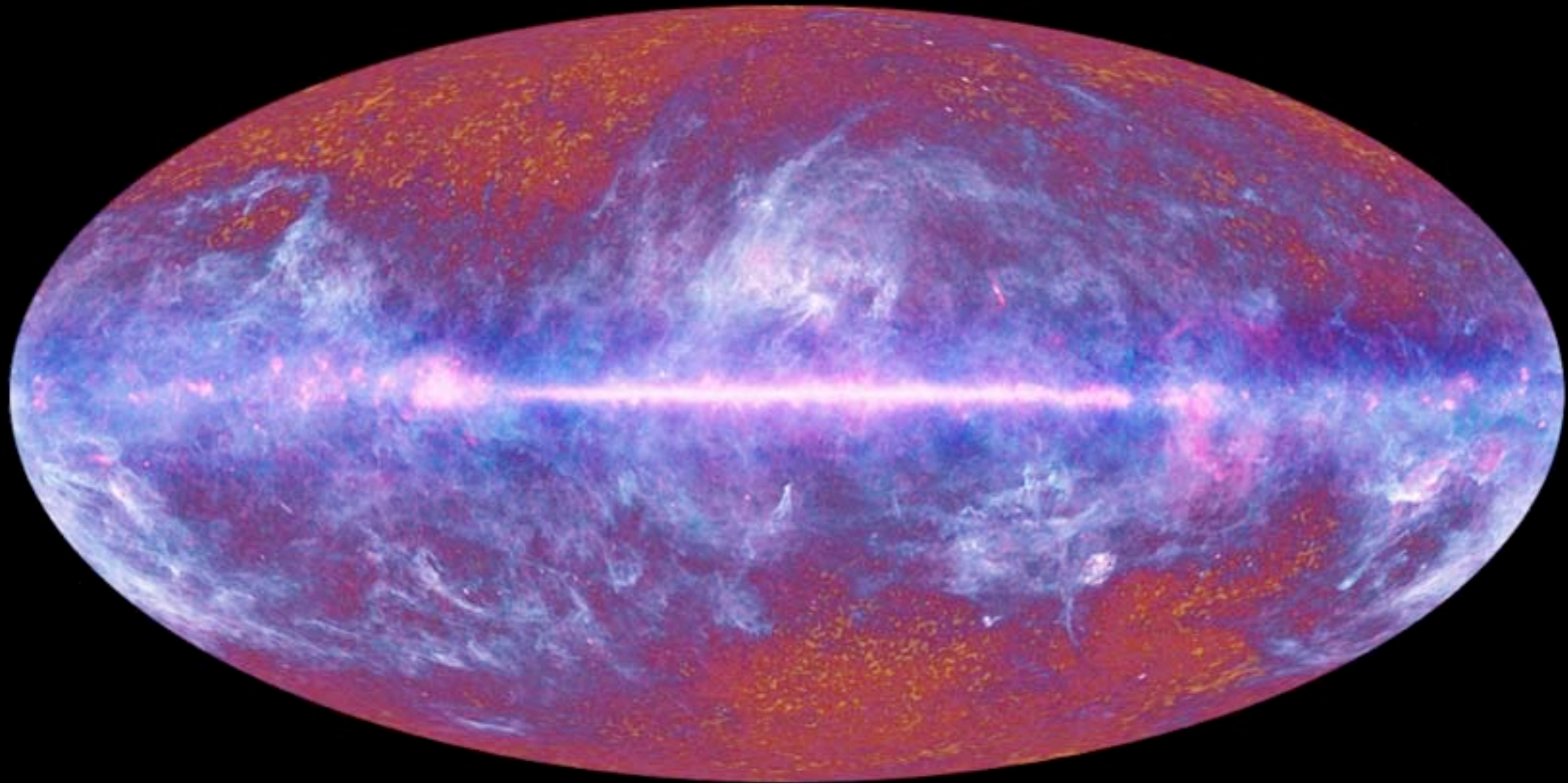


QUAD

WMAP 7yr



Foregrounds

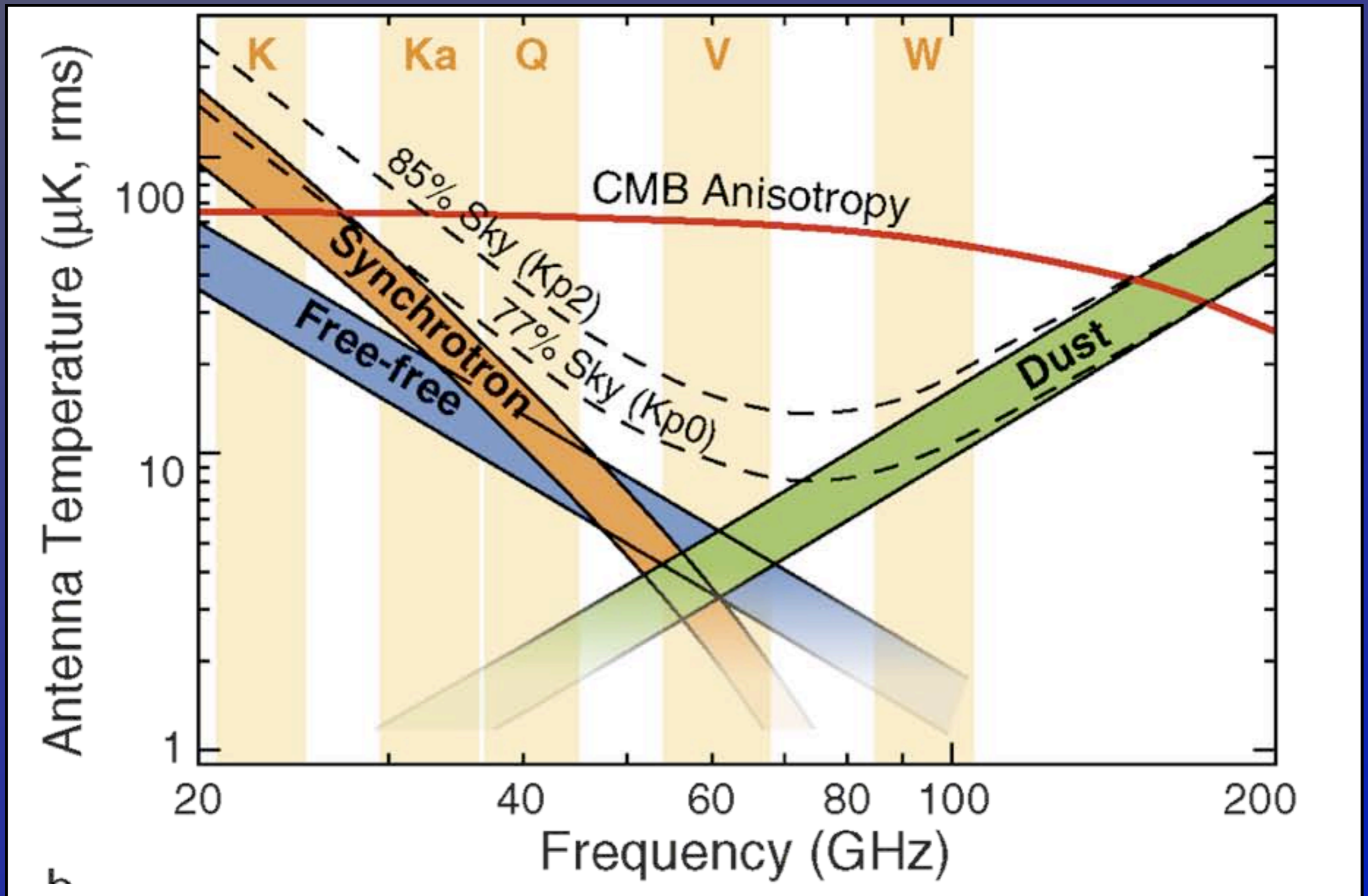


The Planck one-year all-sky survey



[c] ESA, HFI and LFI consortia, July 2010

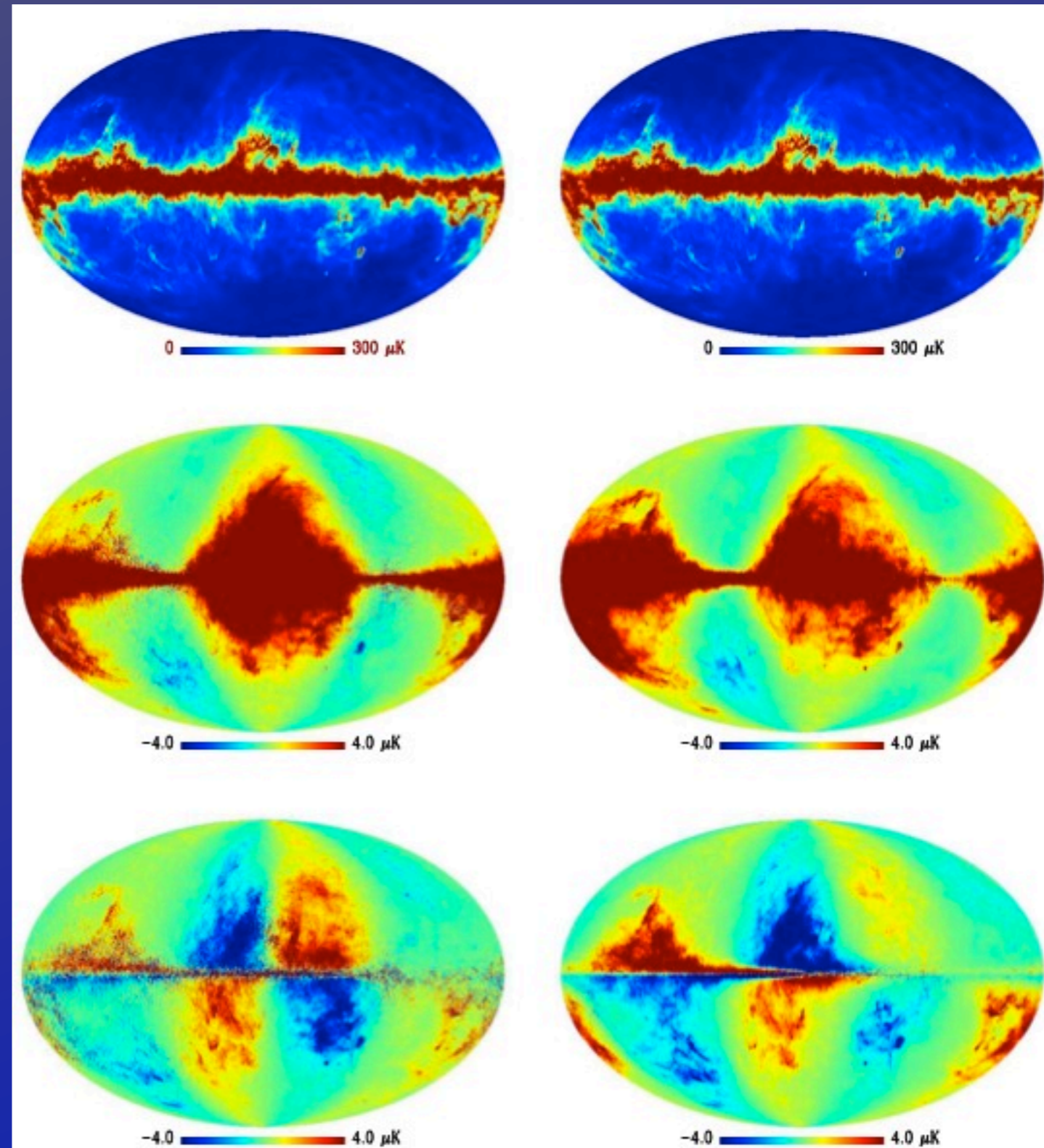
Foregrounds



C.L. Bennett, et al., 2003, ApJS, 148, 97

Foregrounds

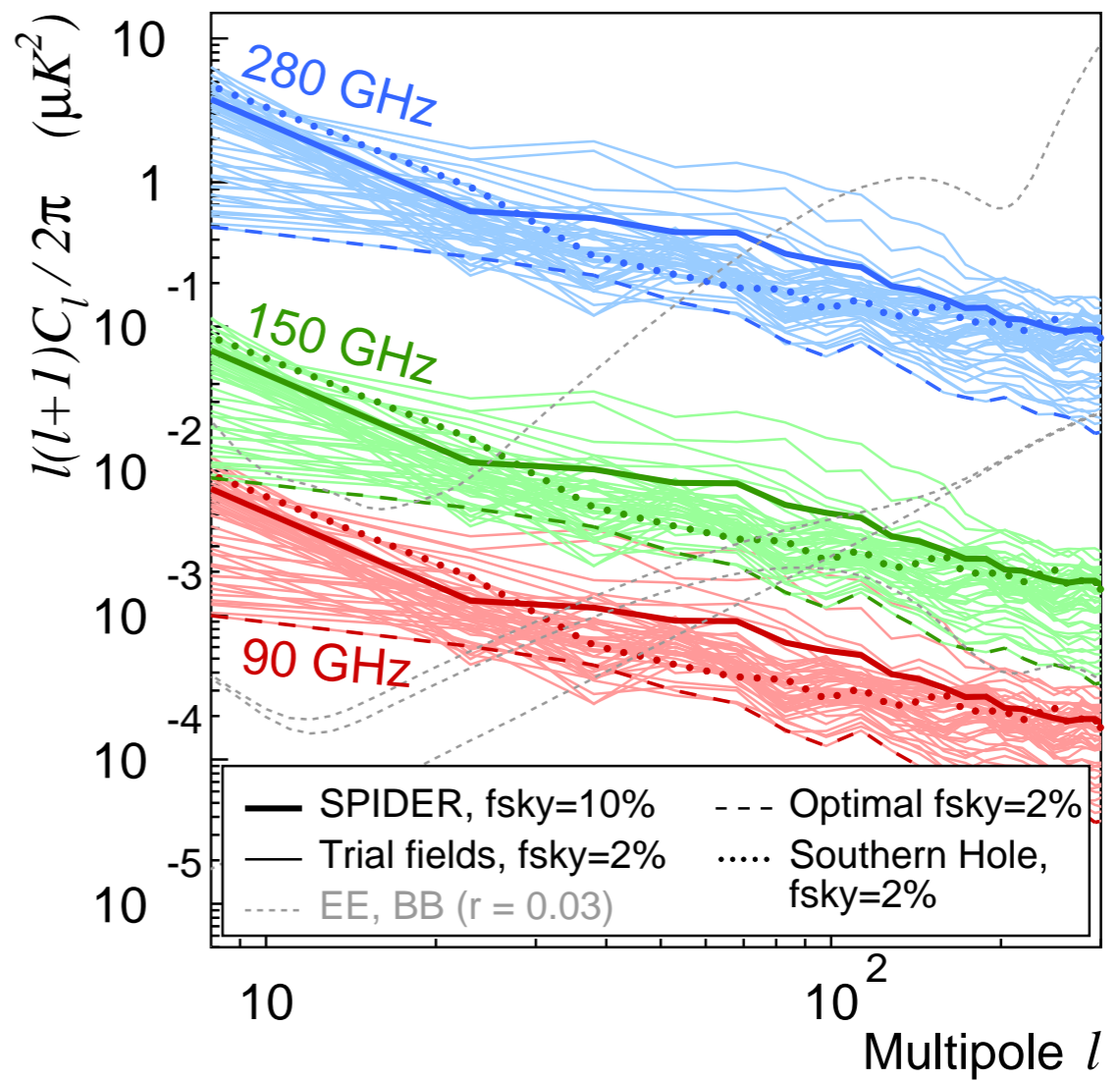
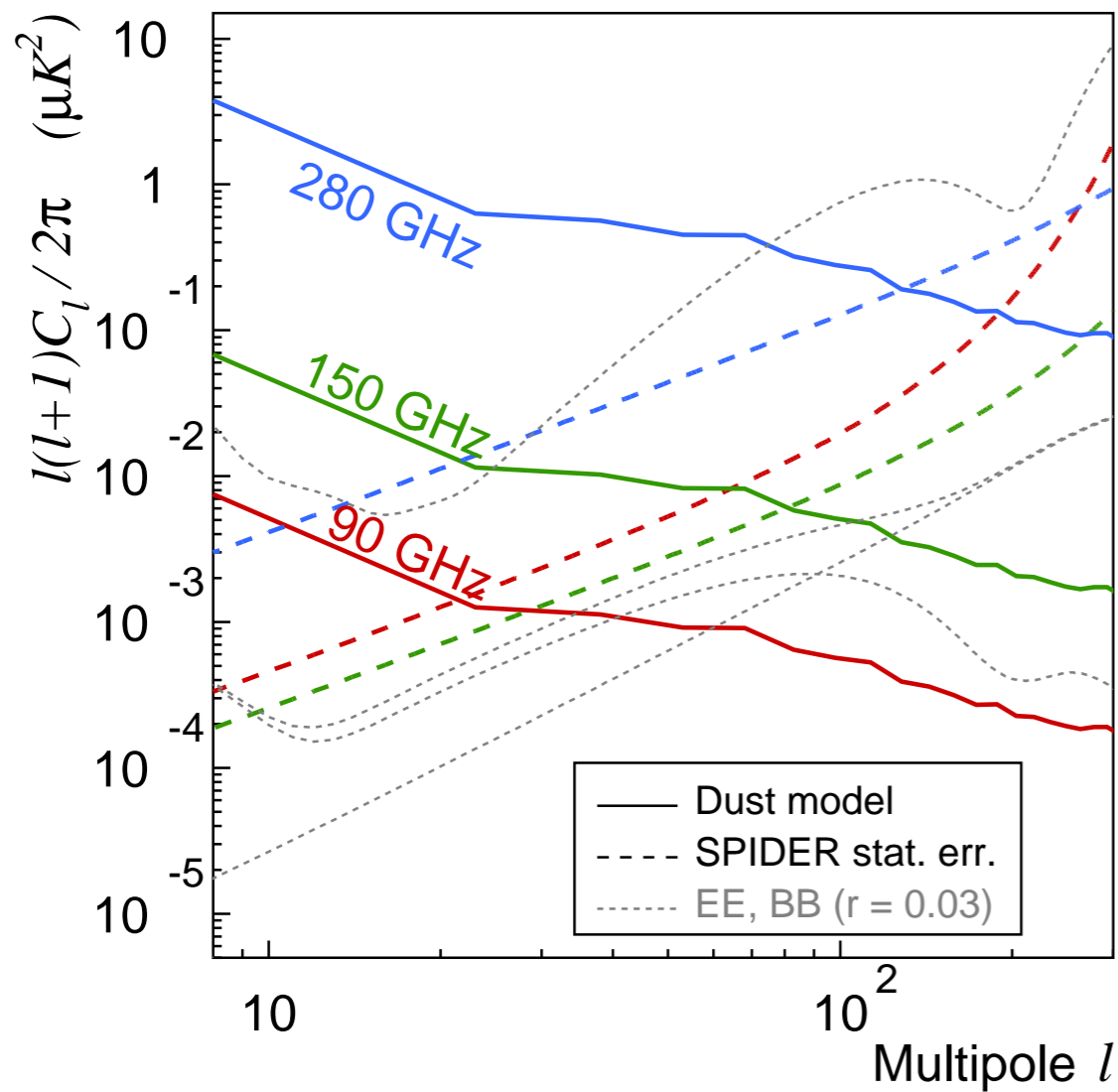
- Dust and synchrotron emission is polarised at few percent level.
- Foregrounds signal is larger than the B-mode background.
- Template cleaning/fitting will be required to detect underlying B-modes.
- Very little existing information on dust polarisation
- Accurate templates required for forecasting and subtraction



FGPOL (<http://www.imperial.ac.uk/people/c.contaldi/fgpol>)

O'Dea, Clark, CC, & MacTavish, arXiv:1107.4612

Foregrounds



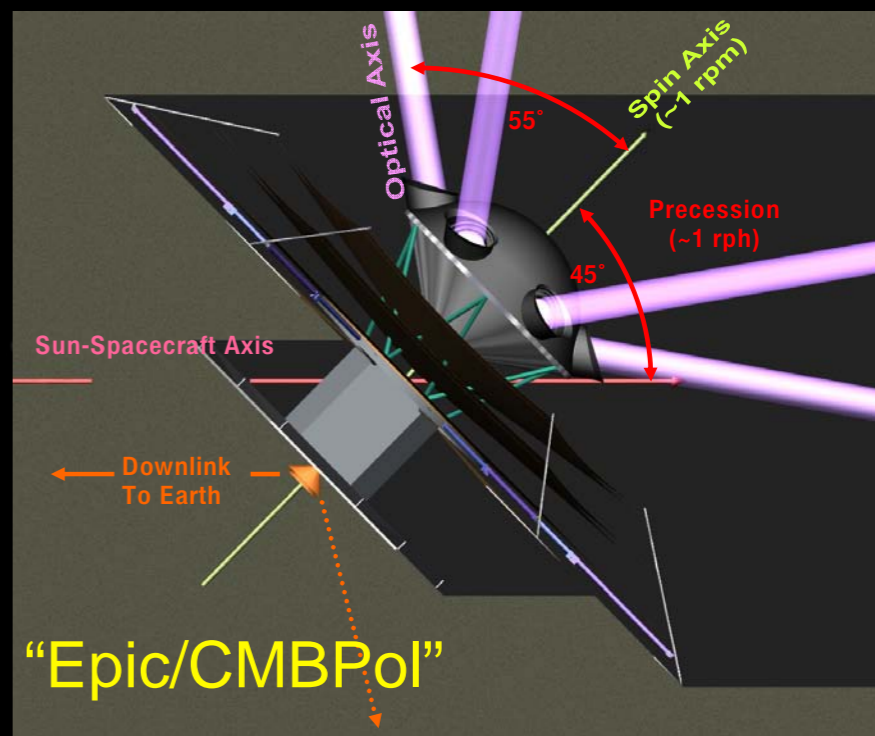
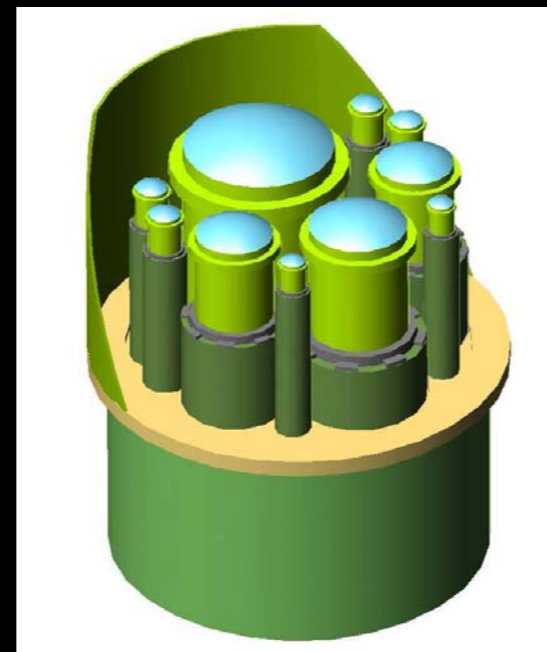
Fraisse, et al., arXiv:1106.3087

- We do not know enough about foregrounds to say at what level GWB B-modes can be detected unambiguously.
- No satellite will be funded before this question is addressed.
- This question can be addressed by sub-orbital experiments over the next 10 years.

Space



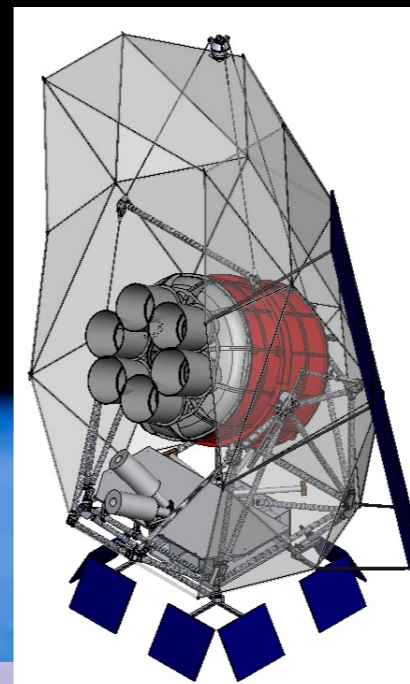
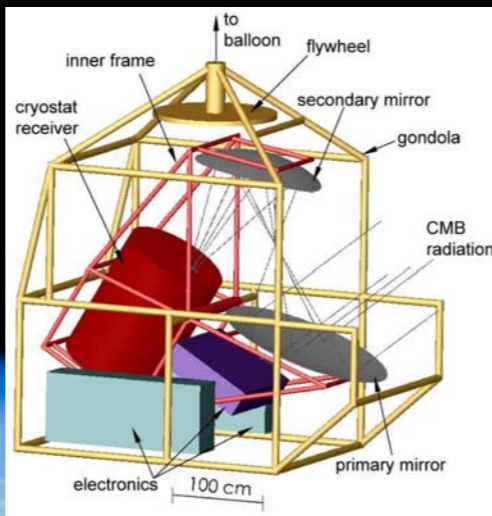
“BPol/COrE”



“Epic/CMBPol”

Balloons

EBEX



Spider

BICEP/Keck



Ground



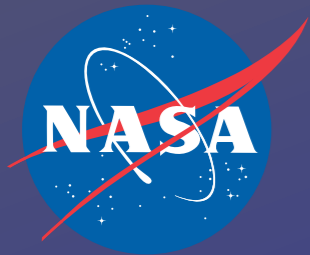
QUAD



Polarbear



The SPIDER Collaboration



California Institute of Technology

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A.E. Lange, P.V. Mason, T.A. Morford,
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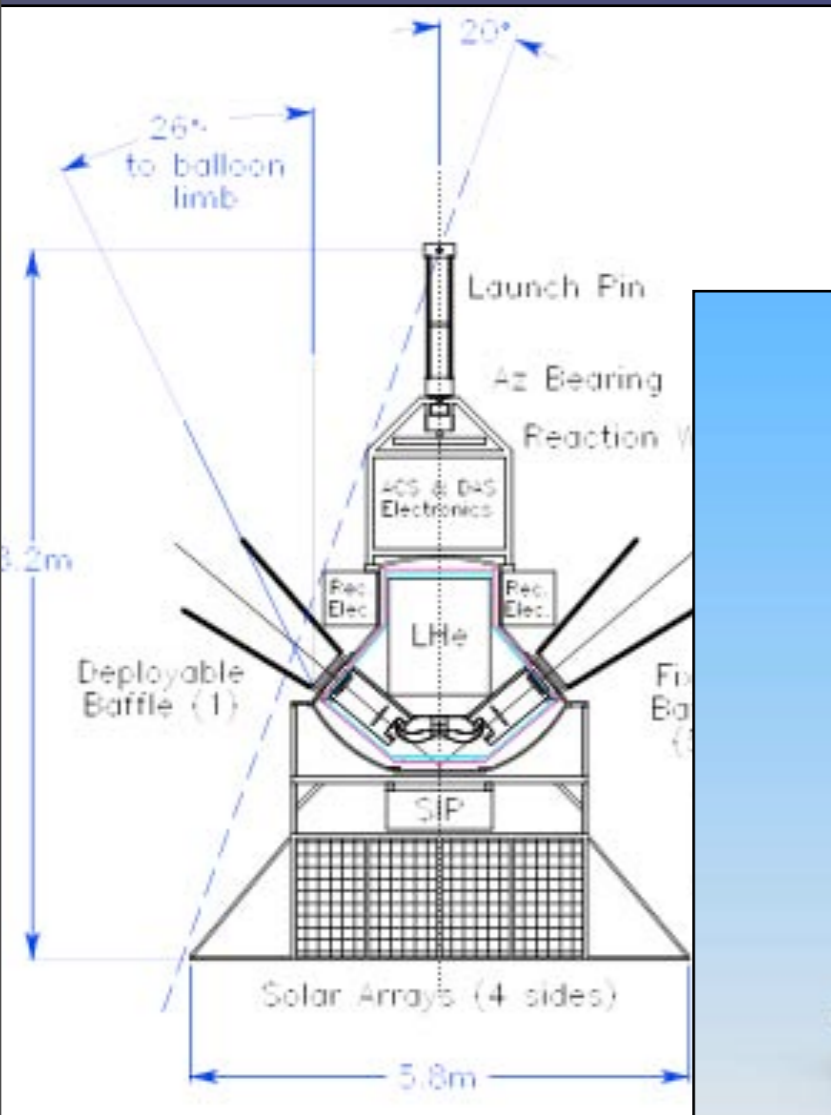
University of British Columbia

M. Amiri, B. Burger, G. Davis, M. Hasselfield,
M. Halpern, D. Wiebe

University of Toronto

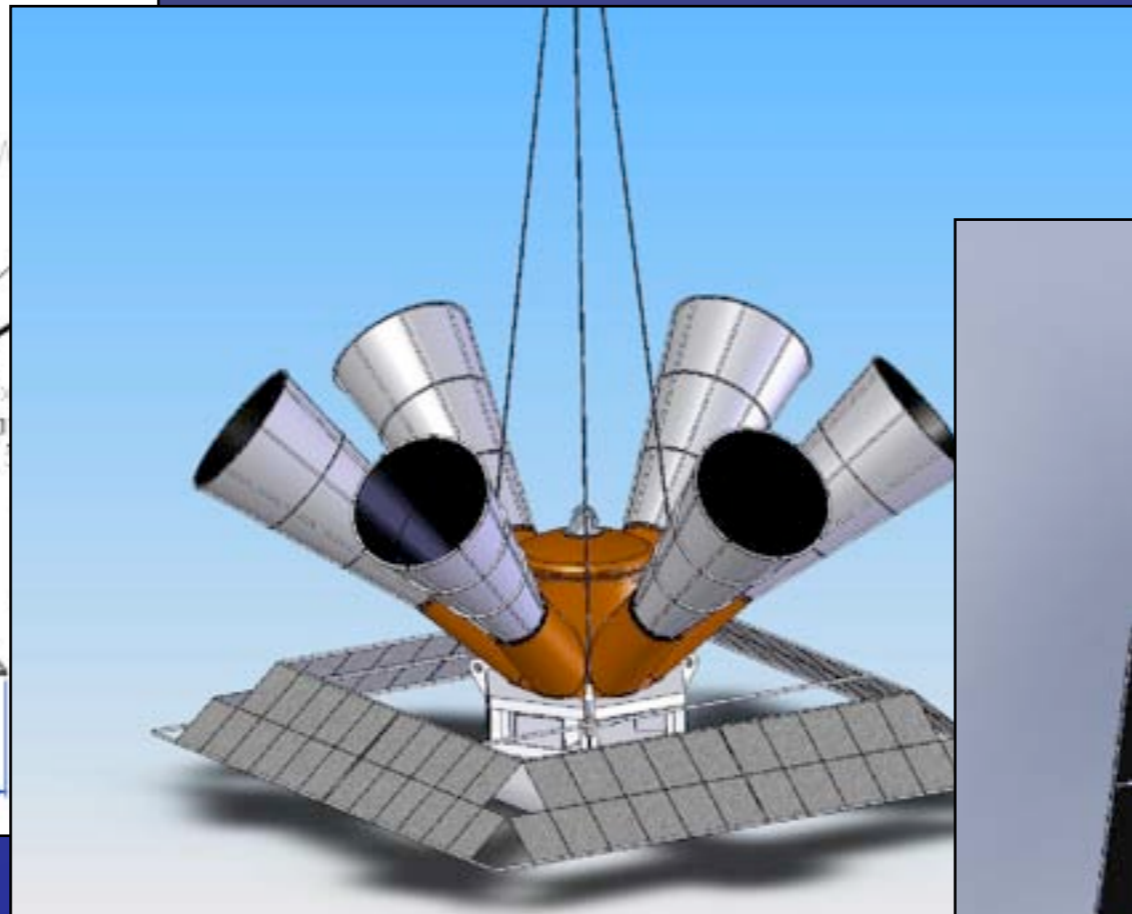
S. Benton, **J.R. Bond**, M. Farhang, L. Fissel,
N. Gandilo, **C.B. Netterfield**, J. Shariff,
J.D. Soler

The Evolution of a Spider



2005

- 8 telescopes
- let-down reel

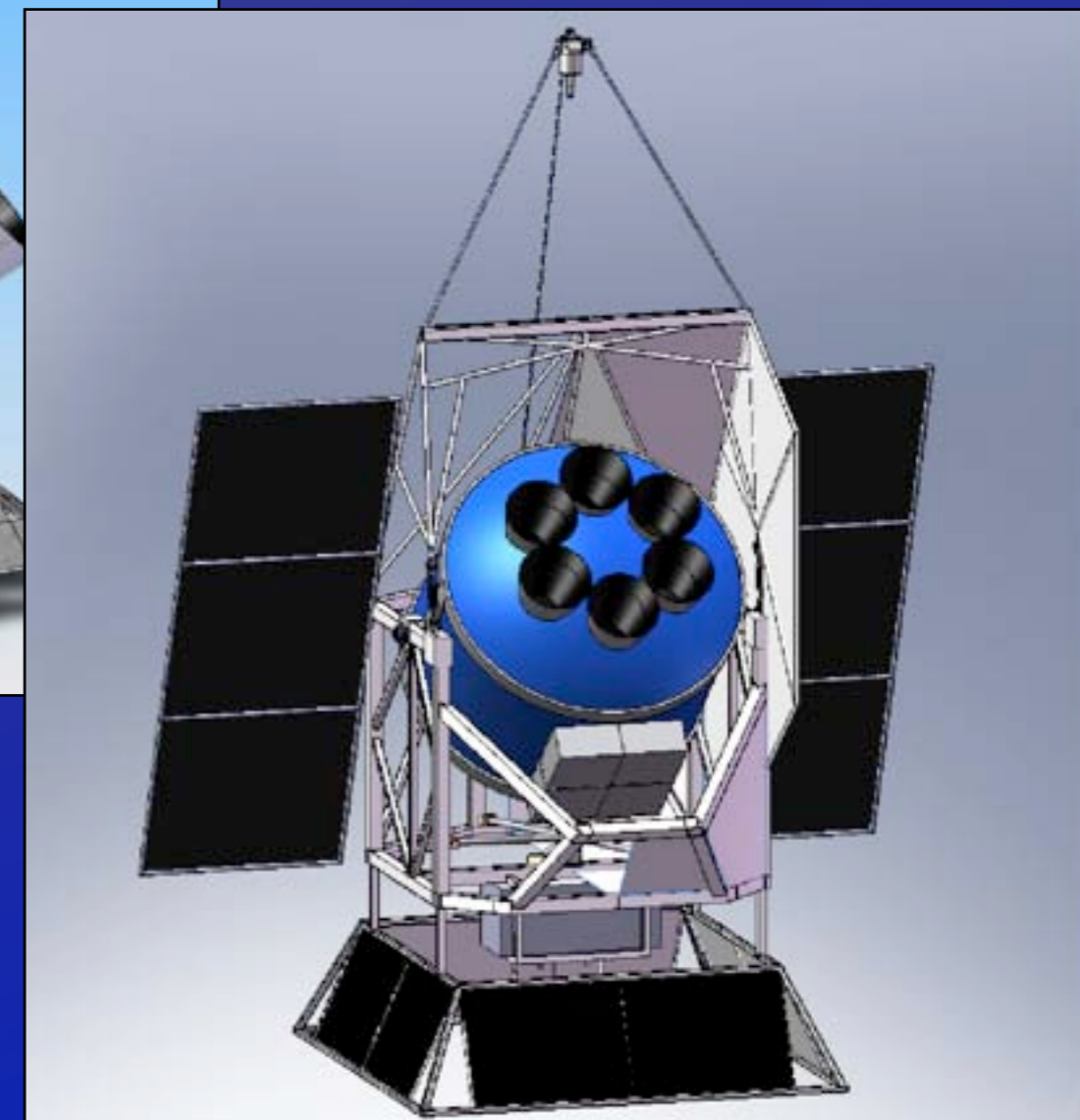


2006

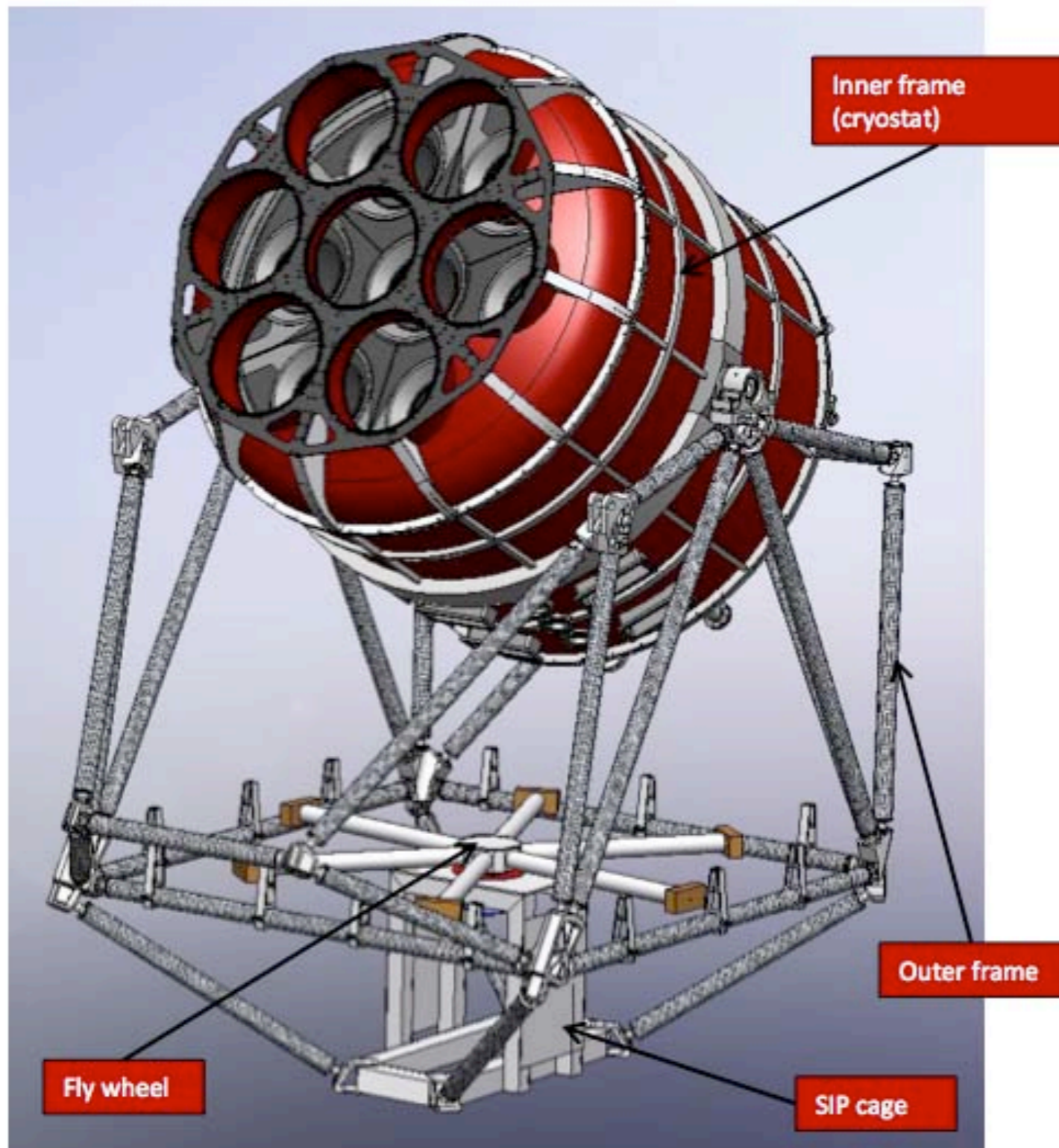
- 6 telescopes
- no let-down reel

2007

- 6 telescopes
- simplified cryostat

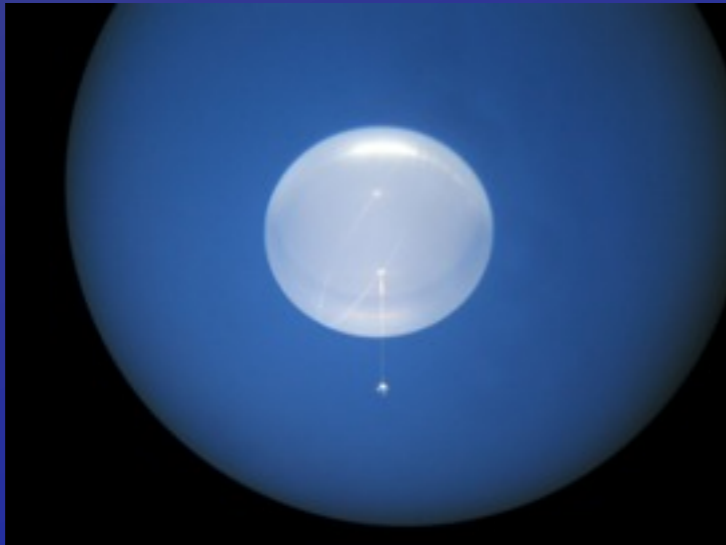


Spider 2010

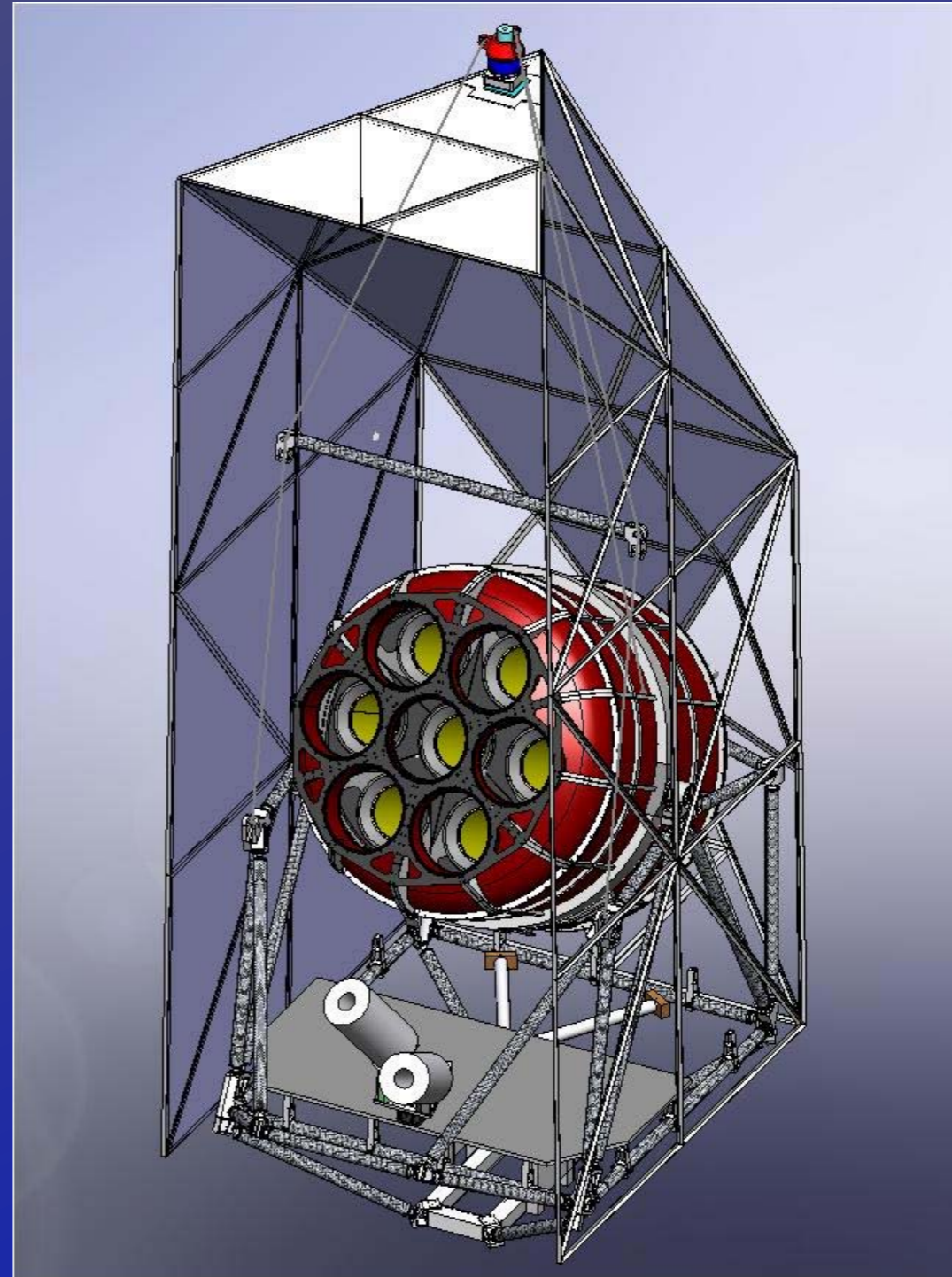


- Based on successful BLAST design
- Carbon Fibre Gondola
- Up to 7 single-frequency telescopes (LDB four different frequencies from 96 to 275 GHz)
- 35 day hold-time cryostat (2624 TES detectors cooled to 300 mK)
- Flywheel - pivot system; telescope spins or scan in azimuth
- Continuous spin mode ~ 36 dps or scan mode ~ 6 dps
- Elevation drive

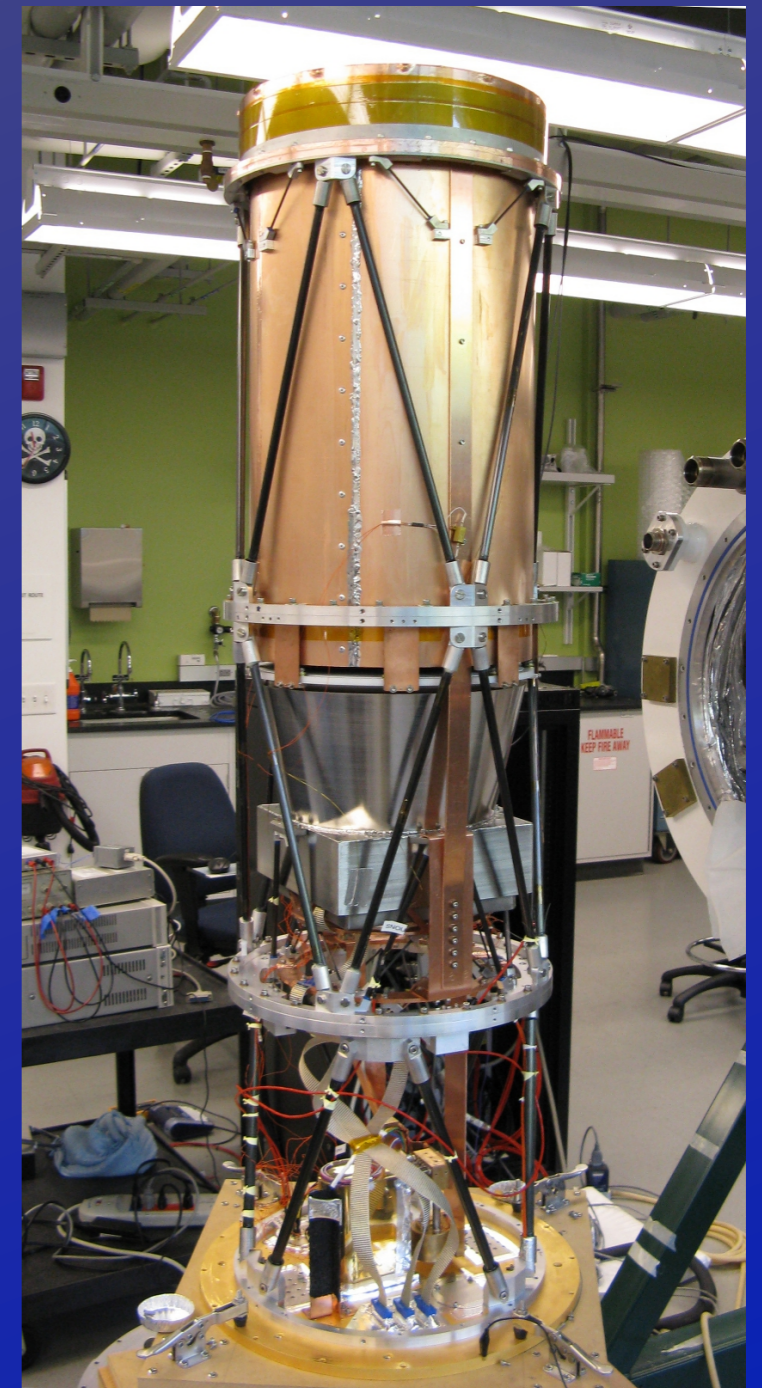
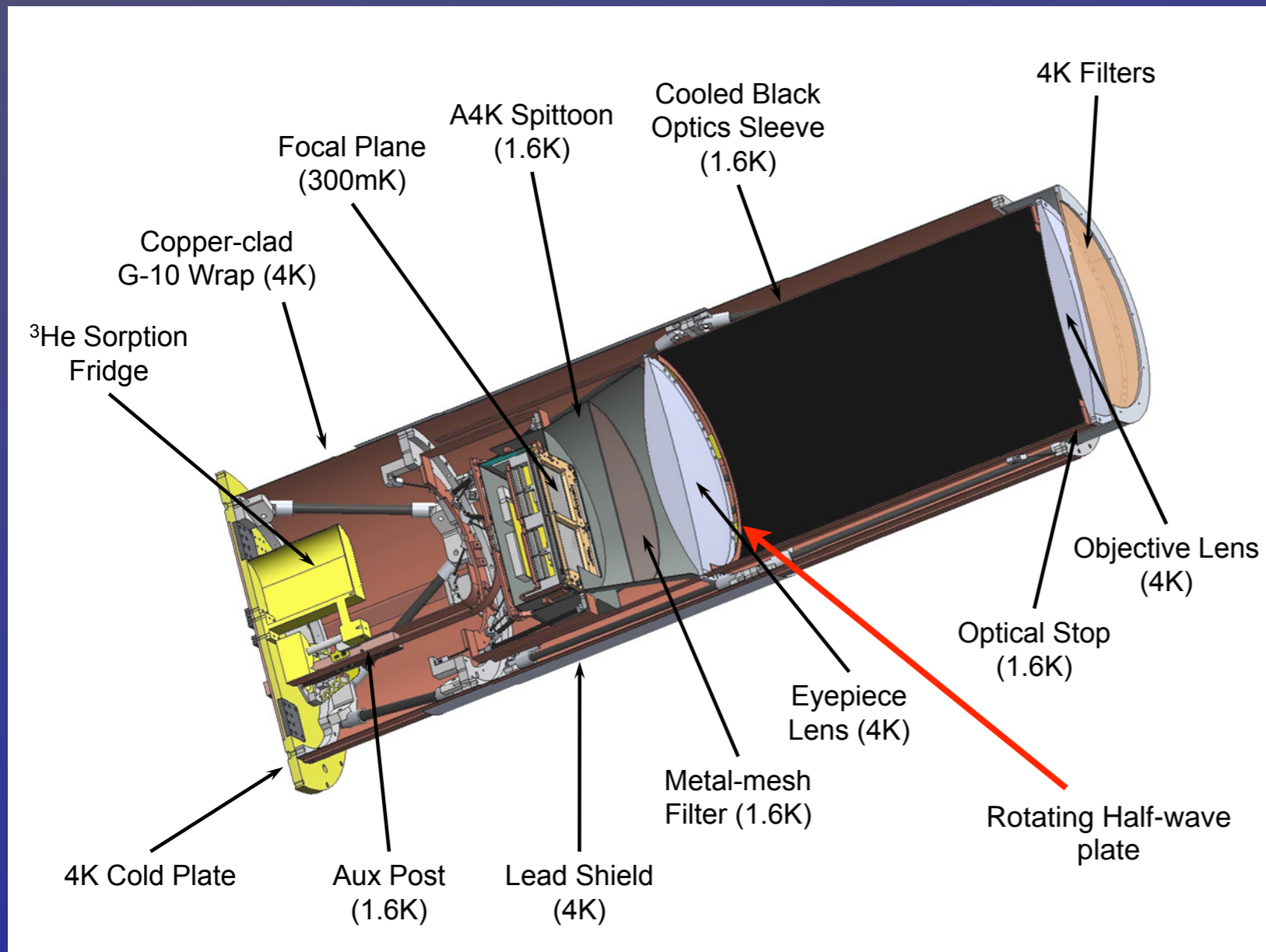
- CMB Ballooning, lots of experience now: Boomerang, Maxima, Saskatoon, Tophat,...
- Fly at edge of atmosphere: atmospheric noise (loading) reduced by many orders of magnitude
- @ 20 km; power of CMB \sim 60% of space
- Testbed for next generation orbital experiment



Image, taken through a telescope, of super pressure balloon at float altitude over Antarctica. Columbia Scientific Balloon Facility

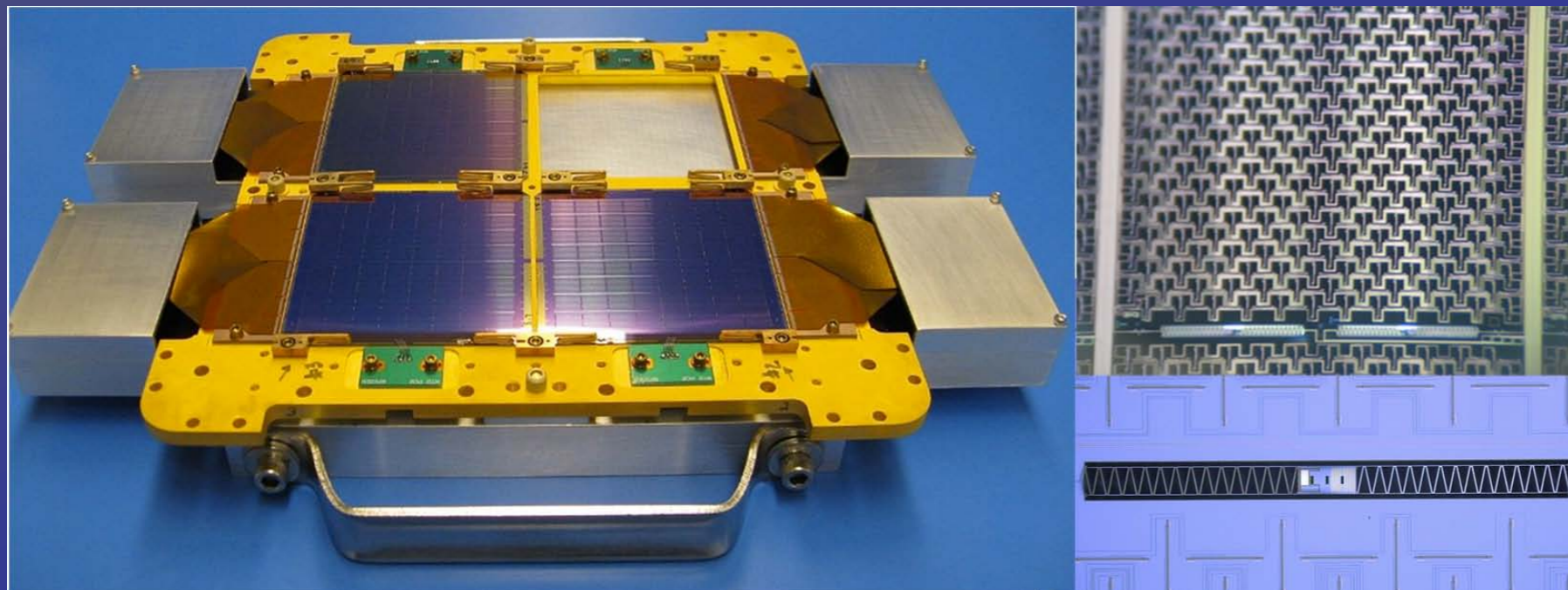


Spider Optics

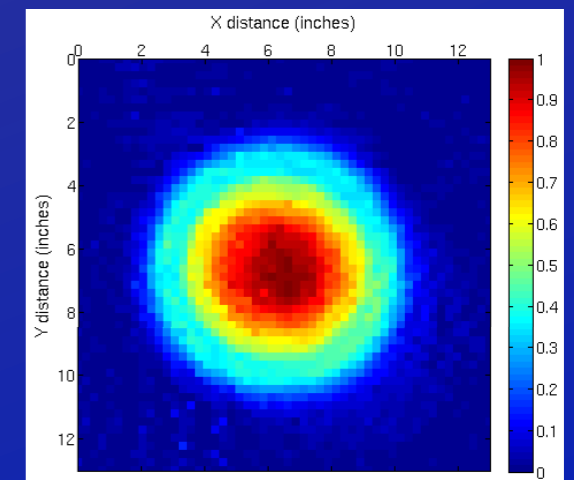


Spider Detectors

- New antenna-coupled bolometer array technology
- Each pixel a phased array of dual-polarization antennas

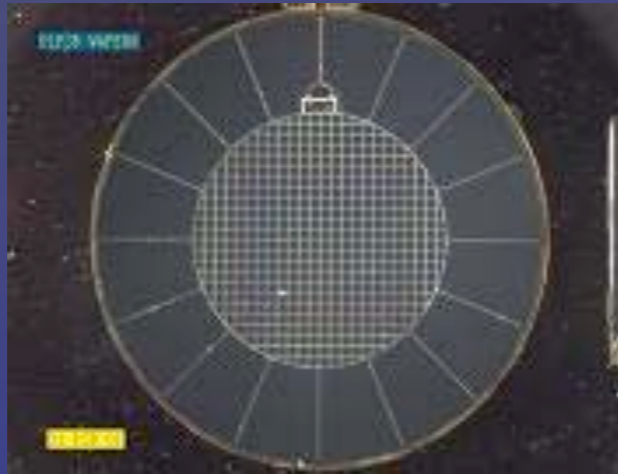


- Single 145 GHz sensitivity $100\mu\text{K}\sqrt{\text{s}}$
- Beam pattern from coherent interference of antenna elements
- 2624 for LDB flight

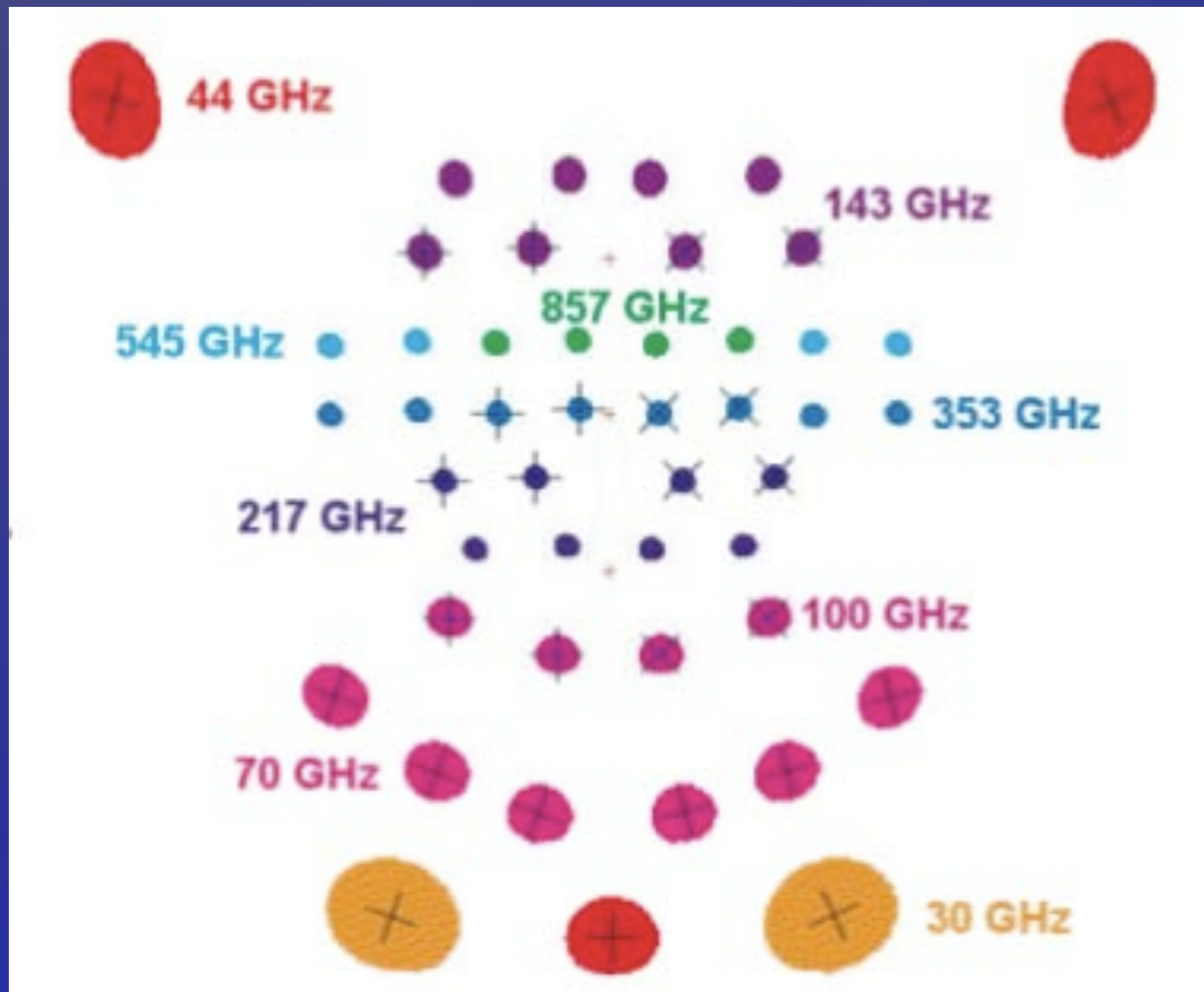


| Band Center (GHz) | Bandwidth (GHz) | Beam FWHM (arcmin) | Number of Spatial Pixels | Number of Detectors | Single-Detector Sensitivity ($\mu\text{K}_{cmb}\sqrt{\text{s}}$) | Instrument Sensitivity ($\mu\text{K}_{cmb}\sqrt{\text{s}}$) |
|-------------------|-----------------|--------------------|--------------------------|---------------------|--|---|
| 90 | 22 | 51 | (2×)144 | (2×) 288 | 110 (96) | 5 (4) |
| 150 | 36 | 31 | (2×) 256 | (2×) 512 | 130 (80) | 4 (3) |
| 280 | 67 | 17 | (2×) 256 | (2×) 512 | 470 (90) | 16 (3) |

Planck Comparison



- NTD Bolometers.
- Passively cooled to 50K; actively cooled to 20K (LFI) and 0.1K (HFI)
- 74 detectors split between 9 frequencies in LFI HEMPTs and HFI bolometers
- All of LFI (22-channel) pol. sensitive, HFI 32 PSBs
- Focal plane projected on the sky max. 8 deg across

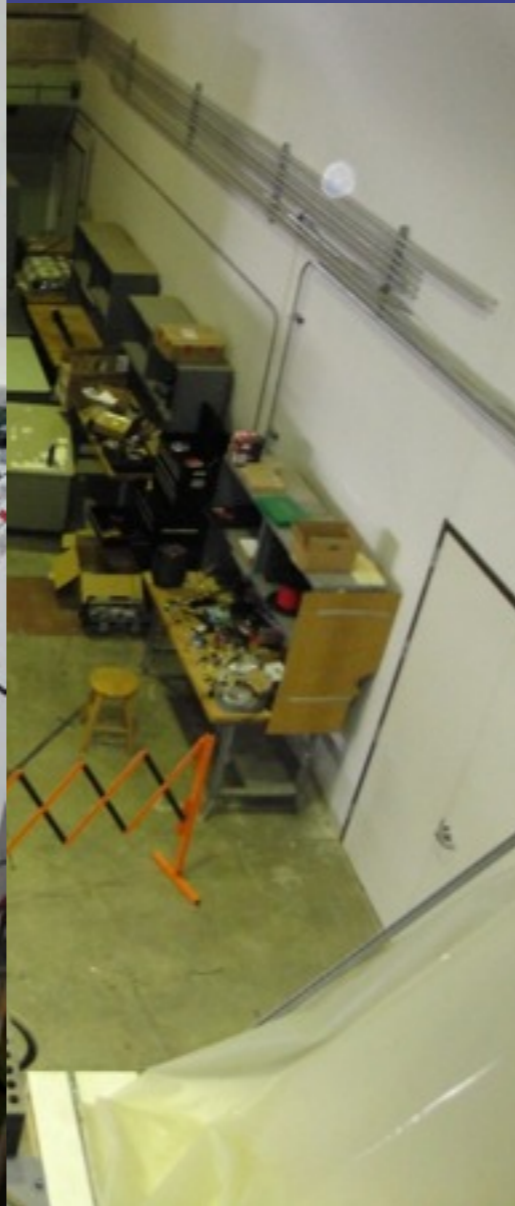


Spider Cryostat

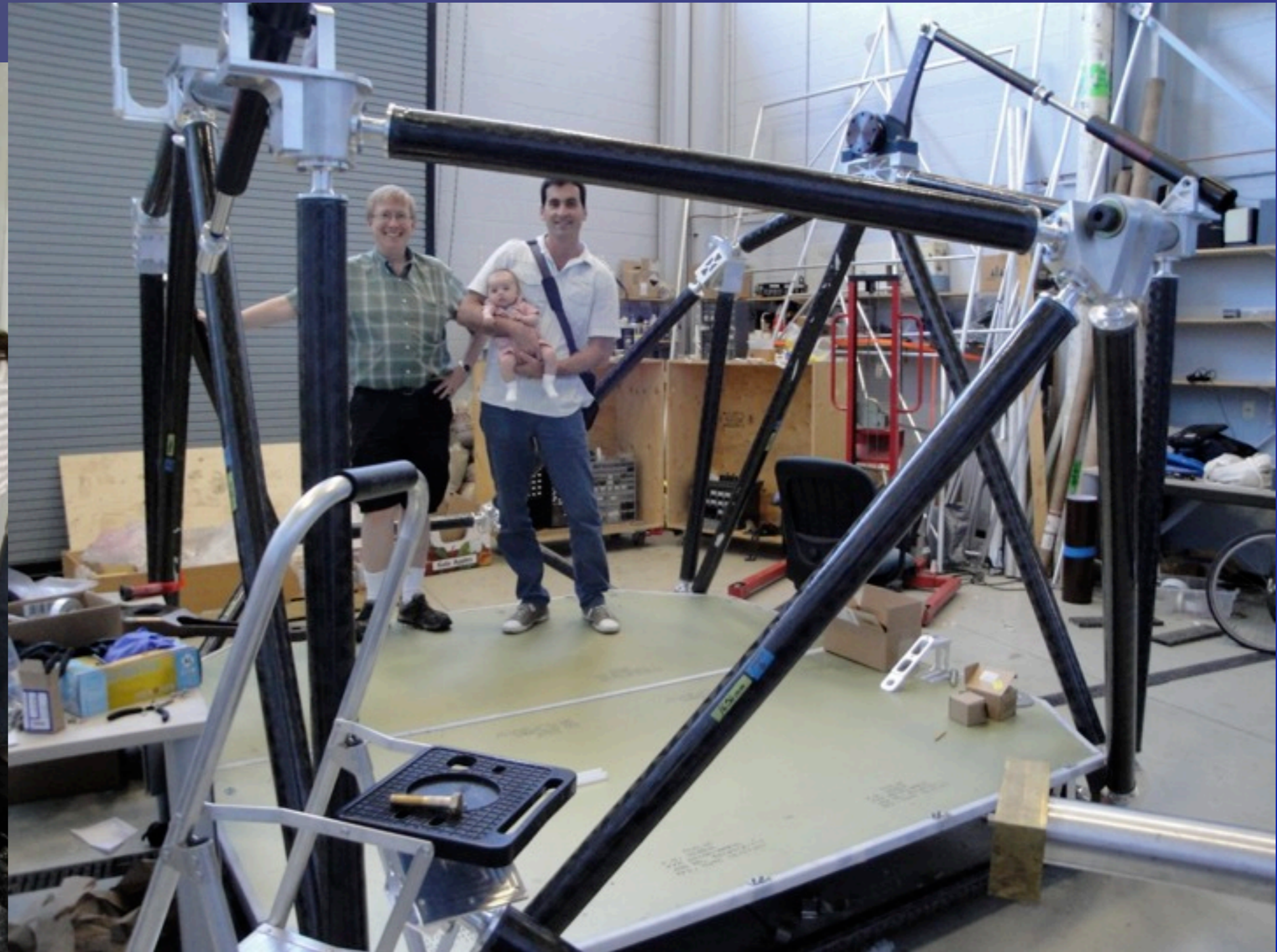




- Weight ~900kg
- Empty cryostat ~1/4 payload weight
- Net cryogen volume > 1000 litres
- 35 day hold-time cryostat with detectors cooled to 300 mK
- Passed preliminary 77K leak check

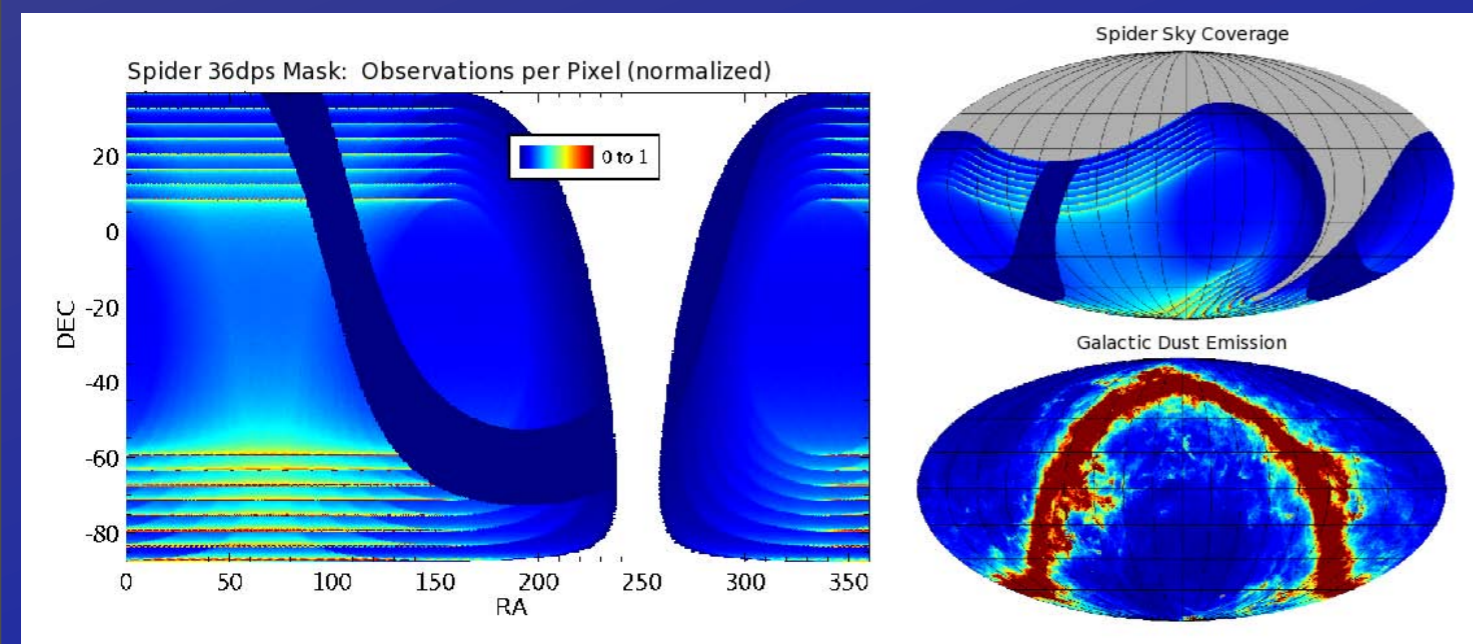
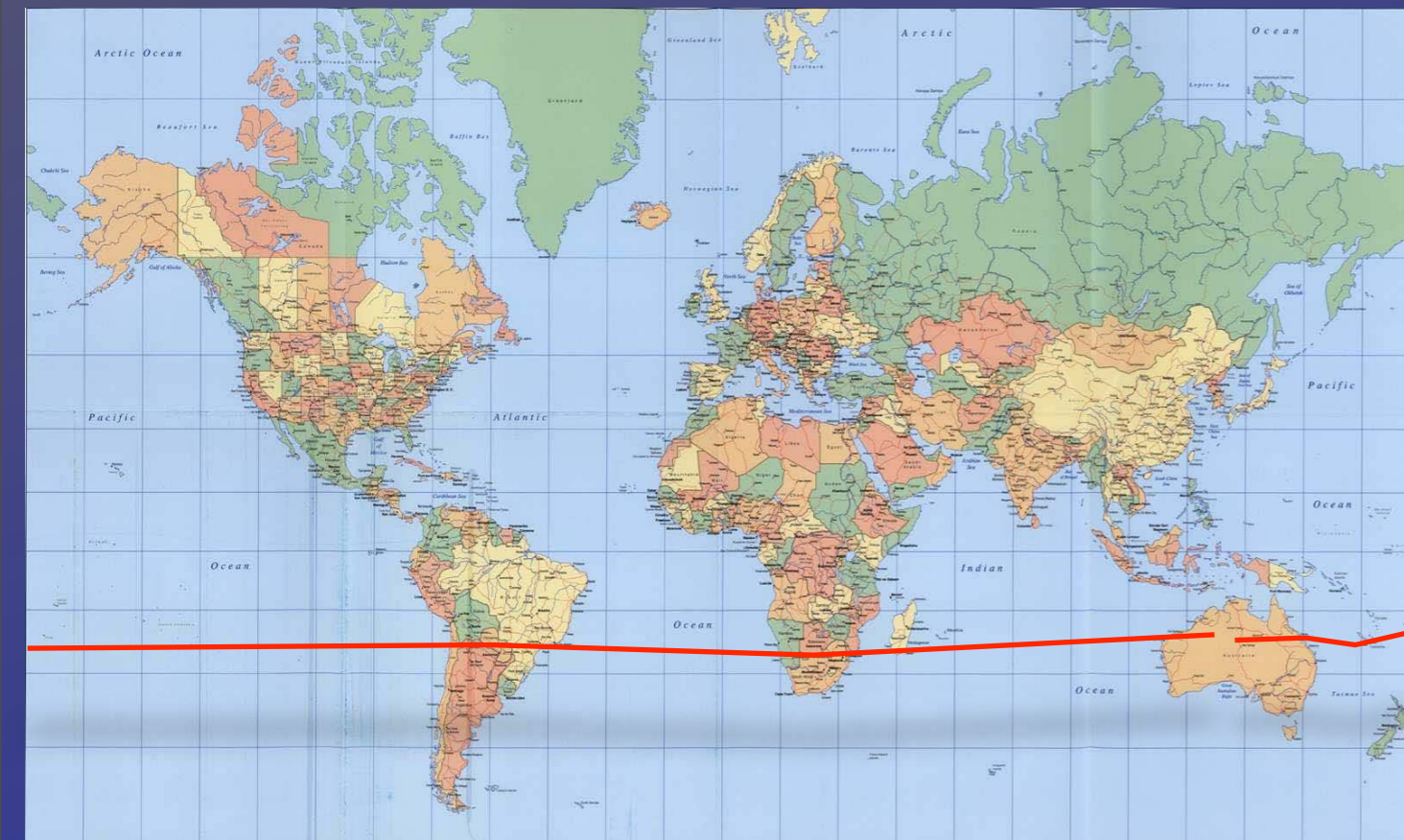


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Spider: The original plan...

- Around the world, mid-latitude (-23°S) flight ~ 25 days
- Spin in azimuth at fixed elevation; night observation only
- $>50\%$ of the sky with good cross-linking
- Target large angular scales, $\ell < 100$
- Turnaround test-flight spring 2011; LDB fall 2012





Antarctica ULDB Flight

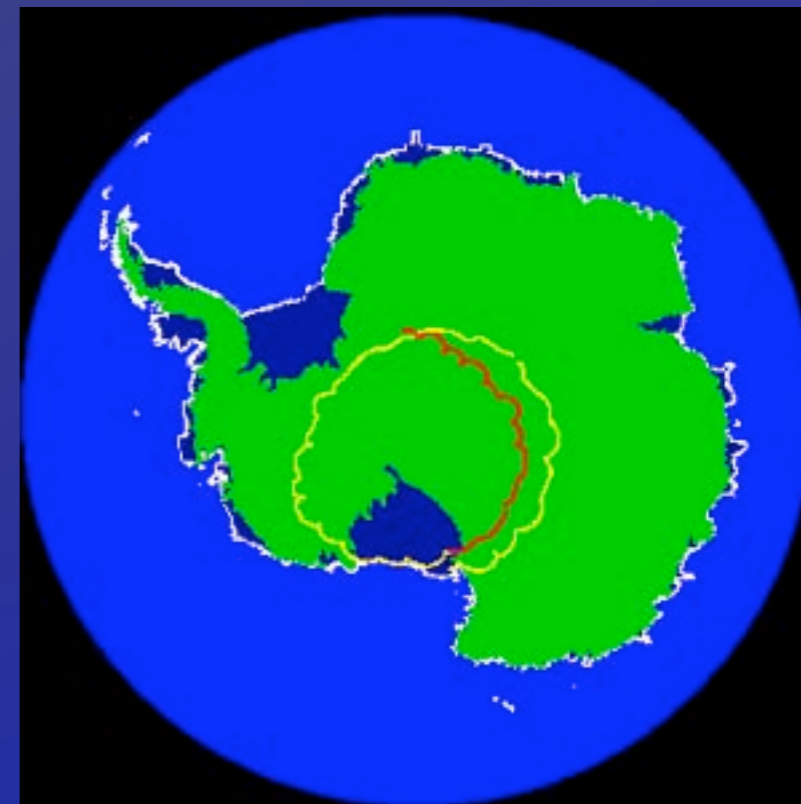
- Jan. 08, 2009

NEW NASA BALLOON SUCCESSFULLY FLIGHT-TESTED OVER ANTARCTICA

WASHINGTON -- NASA and the National Science Foundation have successfully launched and demonstrated a newly designed super pressure balloon prototype that may enable a new era of high-altitude scientific research. **The super-pressure balloon ultimately will carry large scientific experiments to the brink of space for 100 days or more.**

This seven-million-cubic-foot super-pressure balloon is the largest single-cell, super-pressure, fully-sealed balloon ever flown. When development ends, NASA will have a 22 million-cubic-foot balloon that **can carry a one-ton instrument to an altitude of more than 110,000 feet**, which is three to four times higher than passenger planes fly.

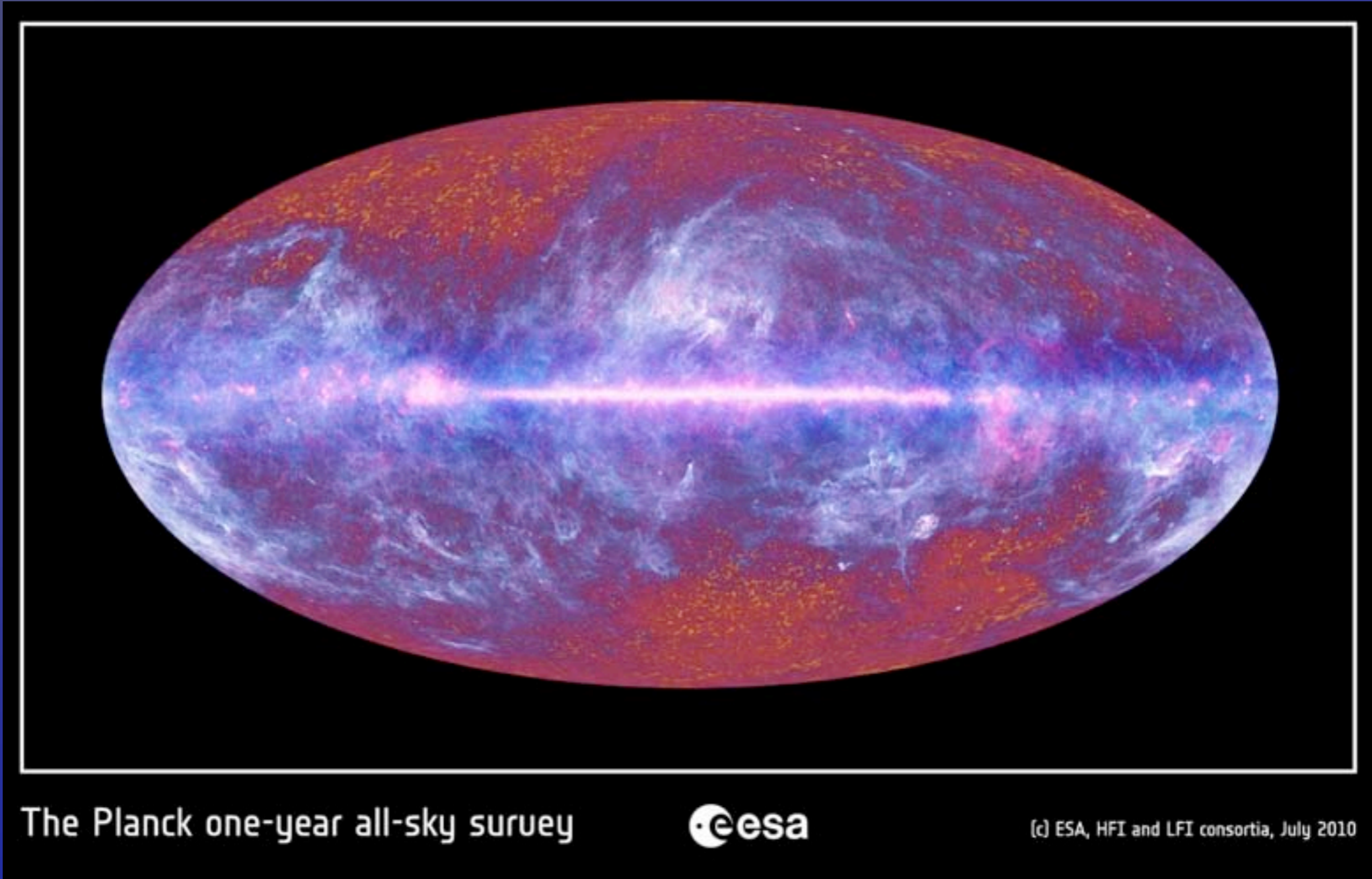
http://www.nasa.gov/topics/earth/features/superpressure_balloon.html



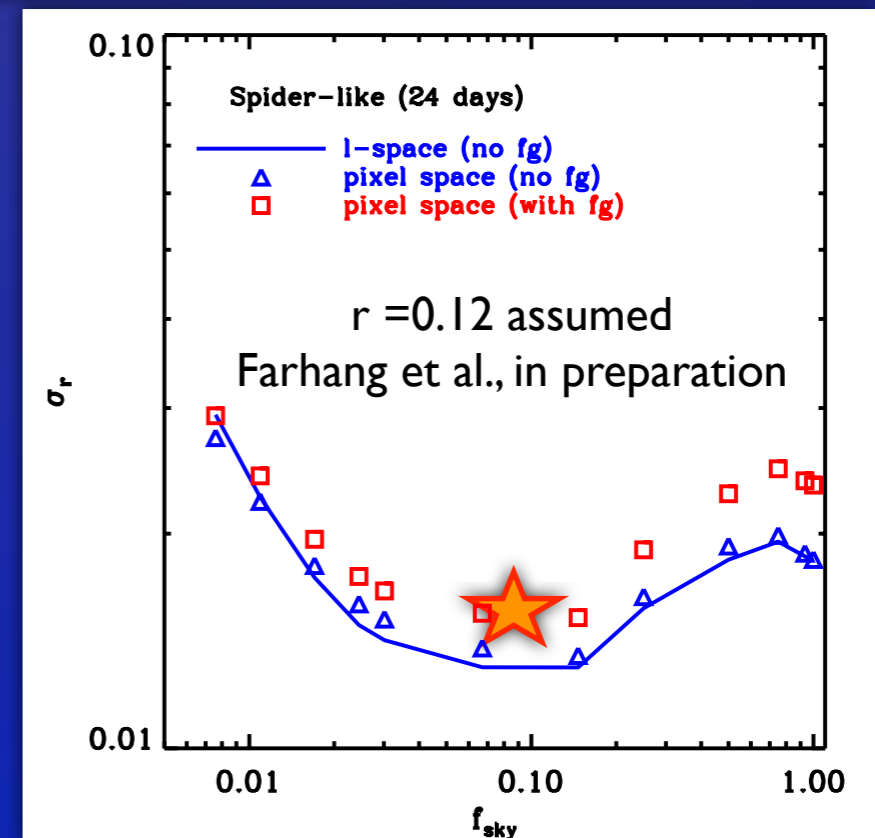
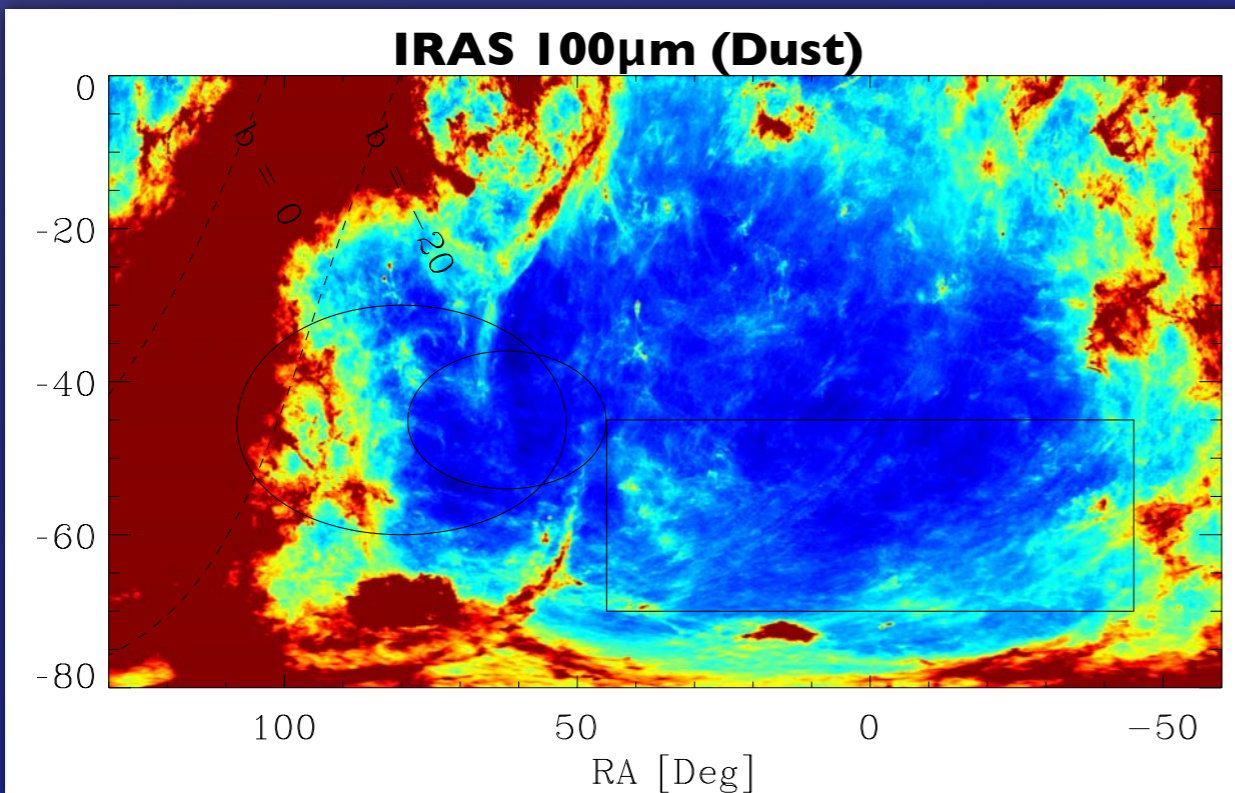
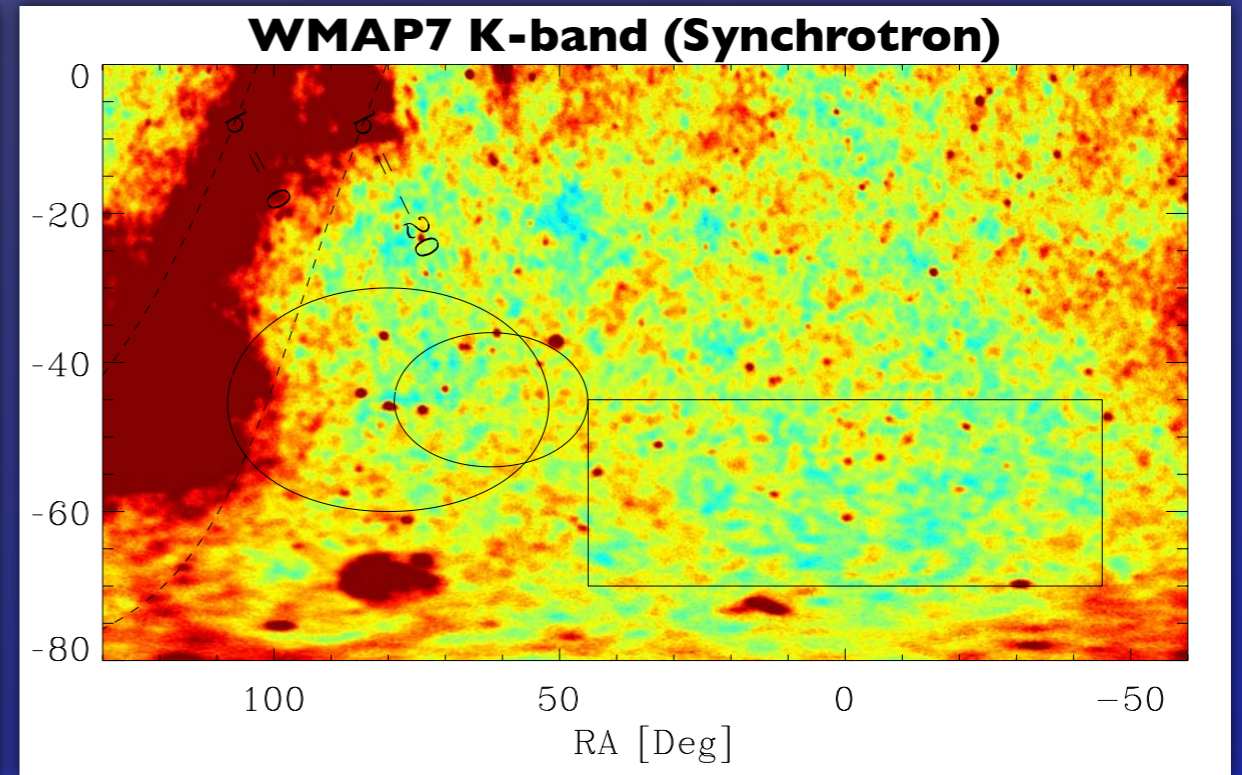
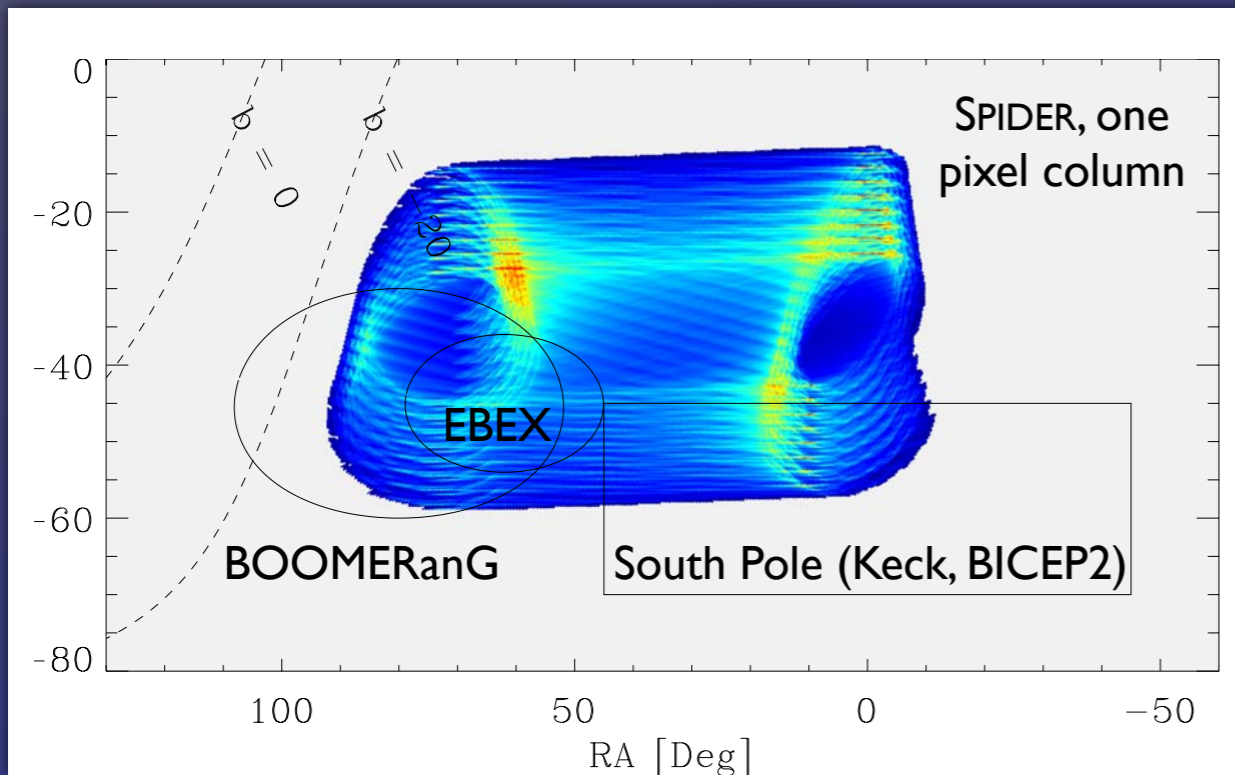
Payload position as of:
15:53:15Z 01/14/09
**Columbia Scientific
Balloon Facility**

Mission Complete
54 Days 1 Hour 29 Min

Sky coverage



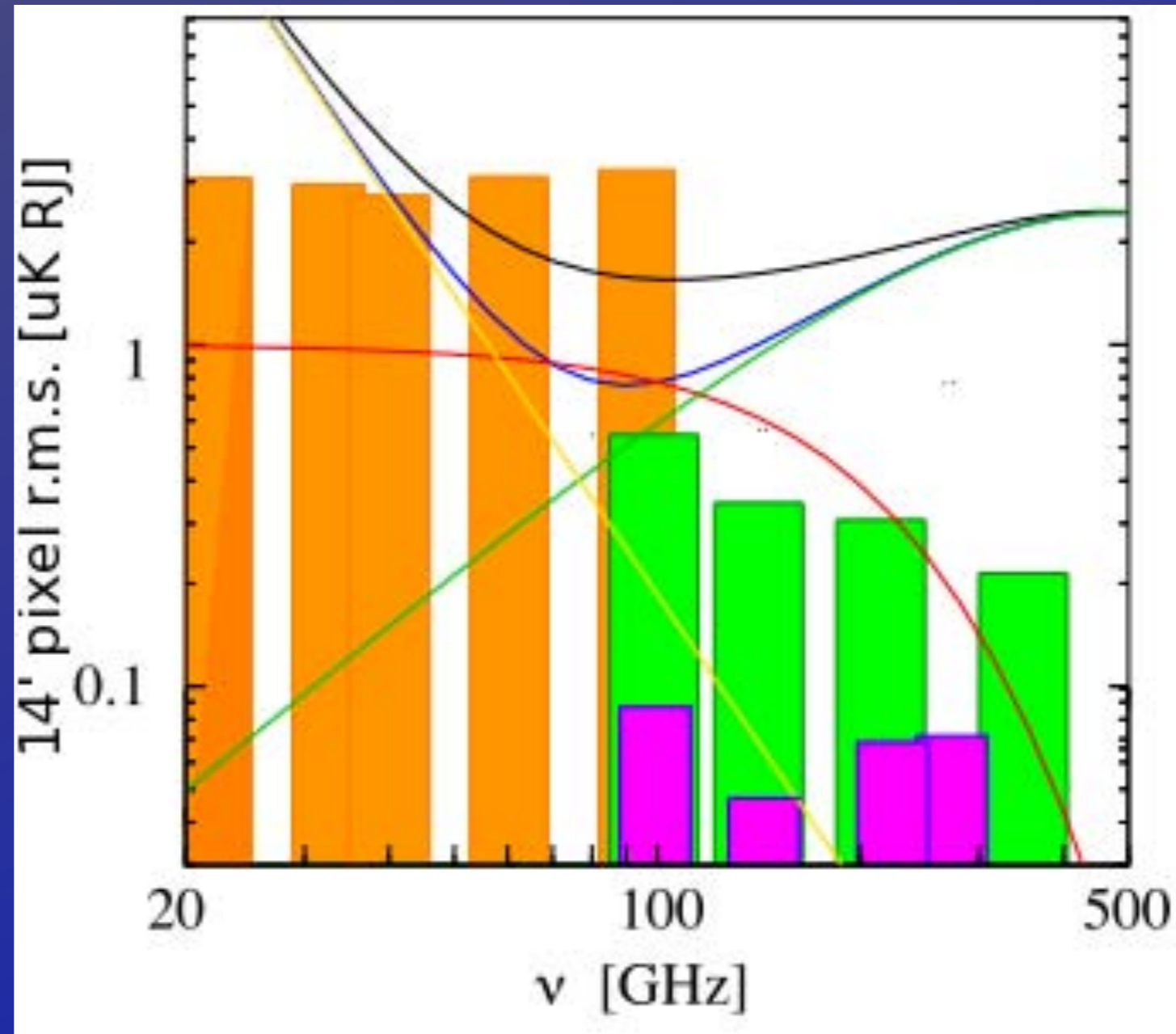
Sky coverage



Frequency Coverage

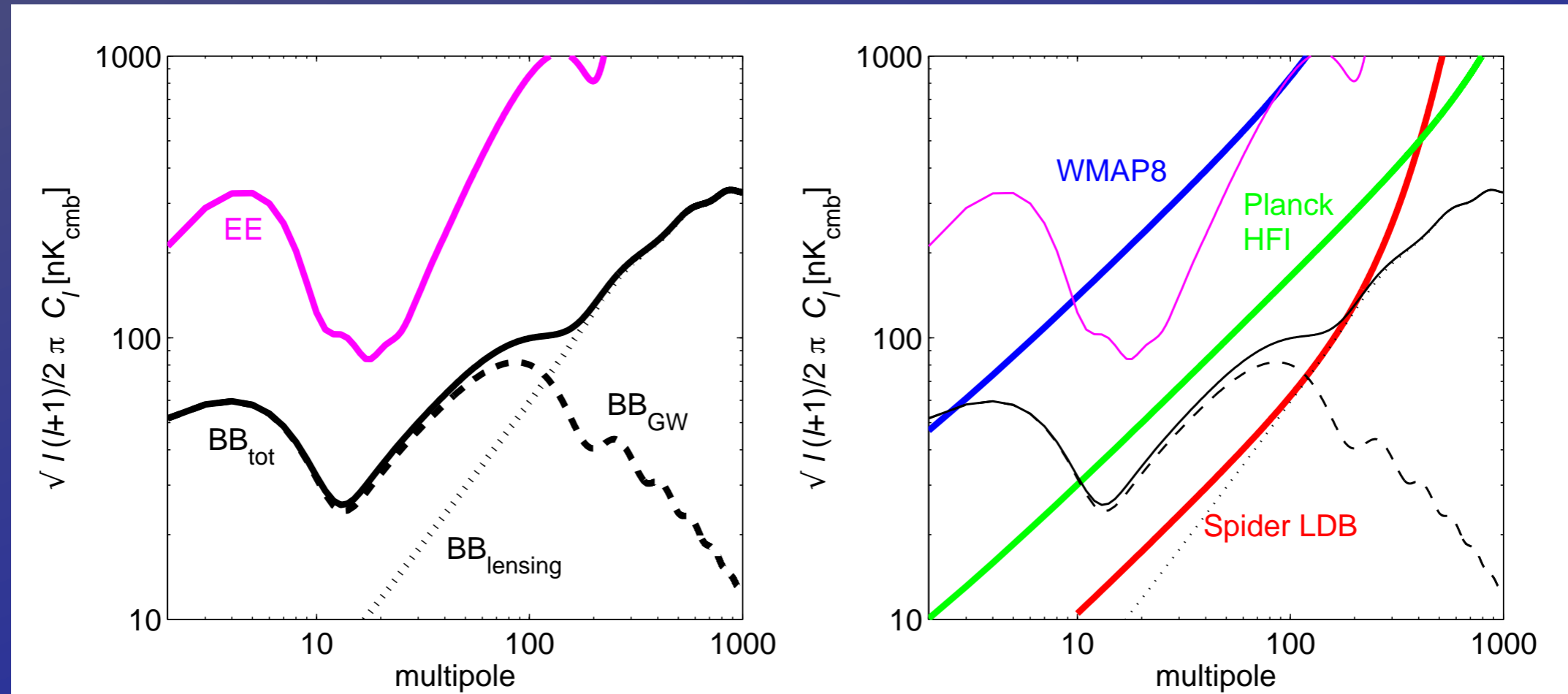
WMAP
Planck
SPIDER

CMB
WMAP synchrotron
FDS model 8 comp. 1 dust
total foregrounds
total foregrounds + CMB



Systematics

- Impact of systematics and foregrounds must be minimised by correct choice of scan strategy and observing mode
- Lots of work done using hi-fidelity end-to-end timestream simulations (MacTavish et al 2009, O'Dea et al 2010);
 - Half-wave plate filtering effects
 - TES Magnetic field susceptibility
 - Foreground residuals
 - Beam asymmetries/offsets & ghosts
 - etc.
- Residuals < 0.01 of signal @ $r \sim 0.1$

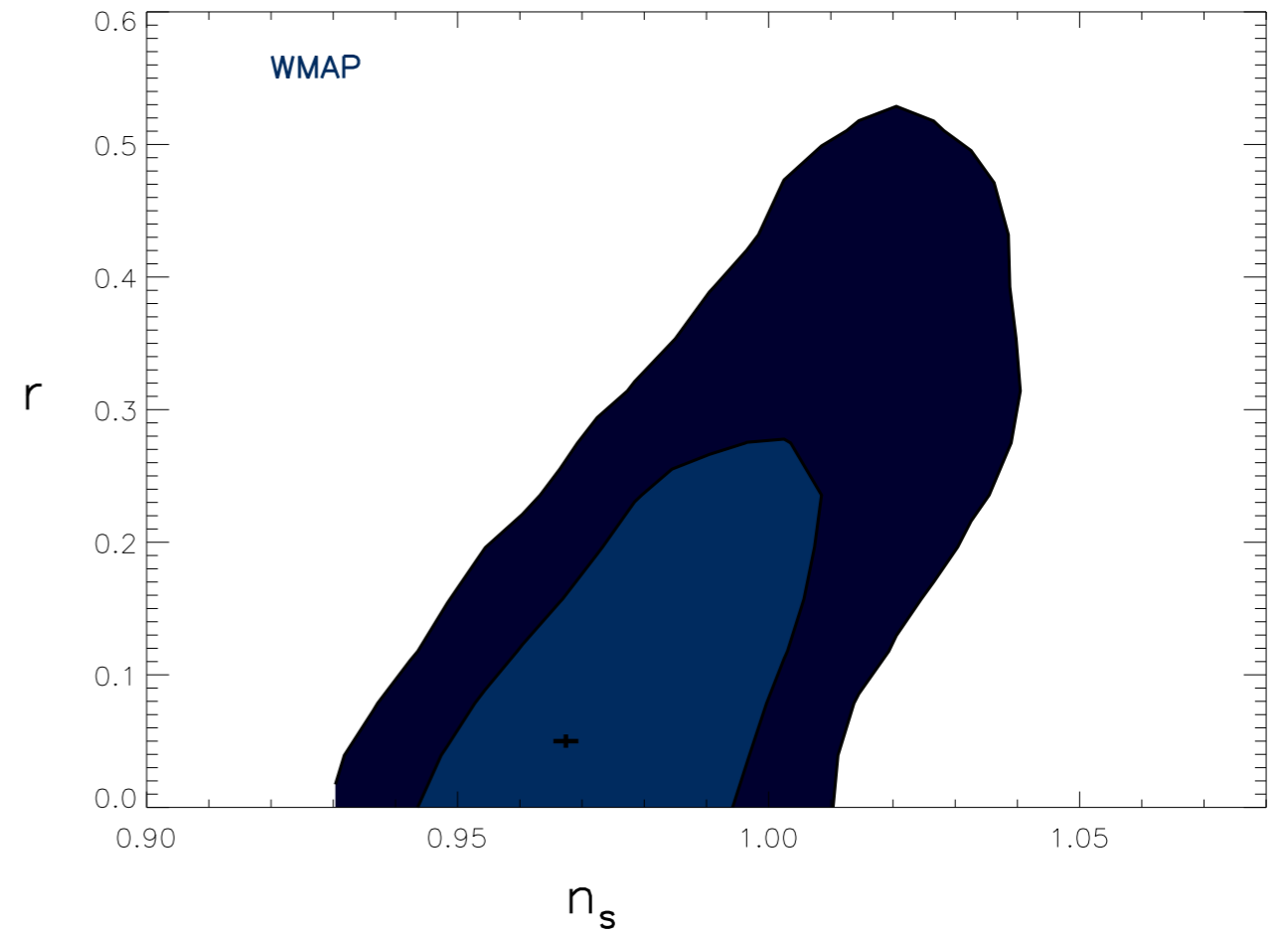
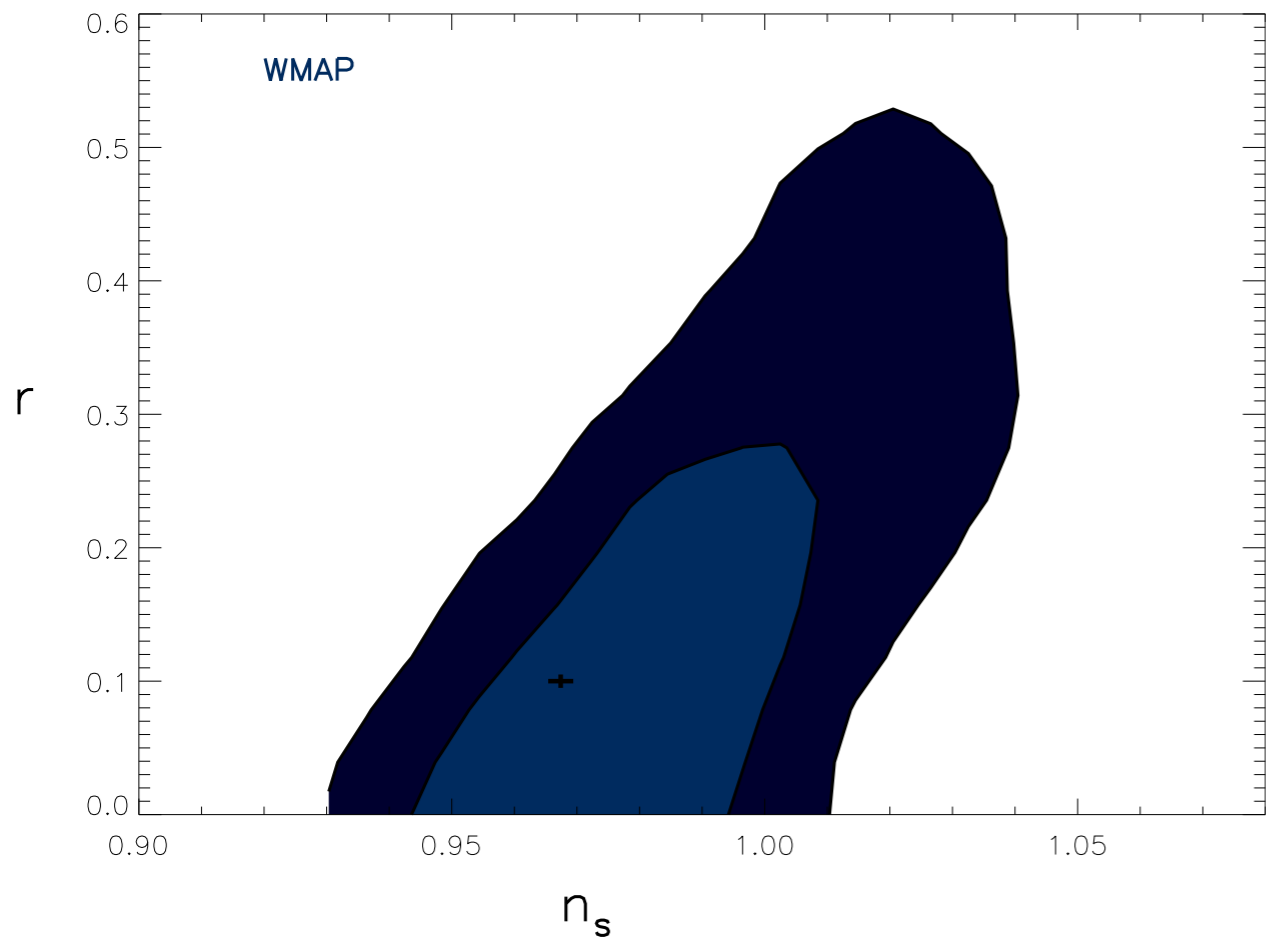


The Present

$r=0.10$

$r-n_s$

$r=0.05$

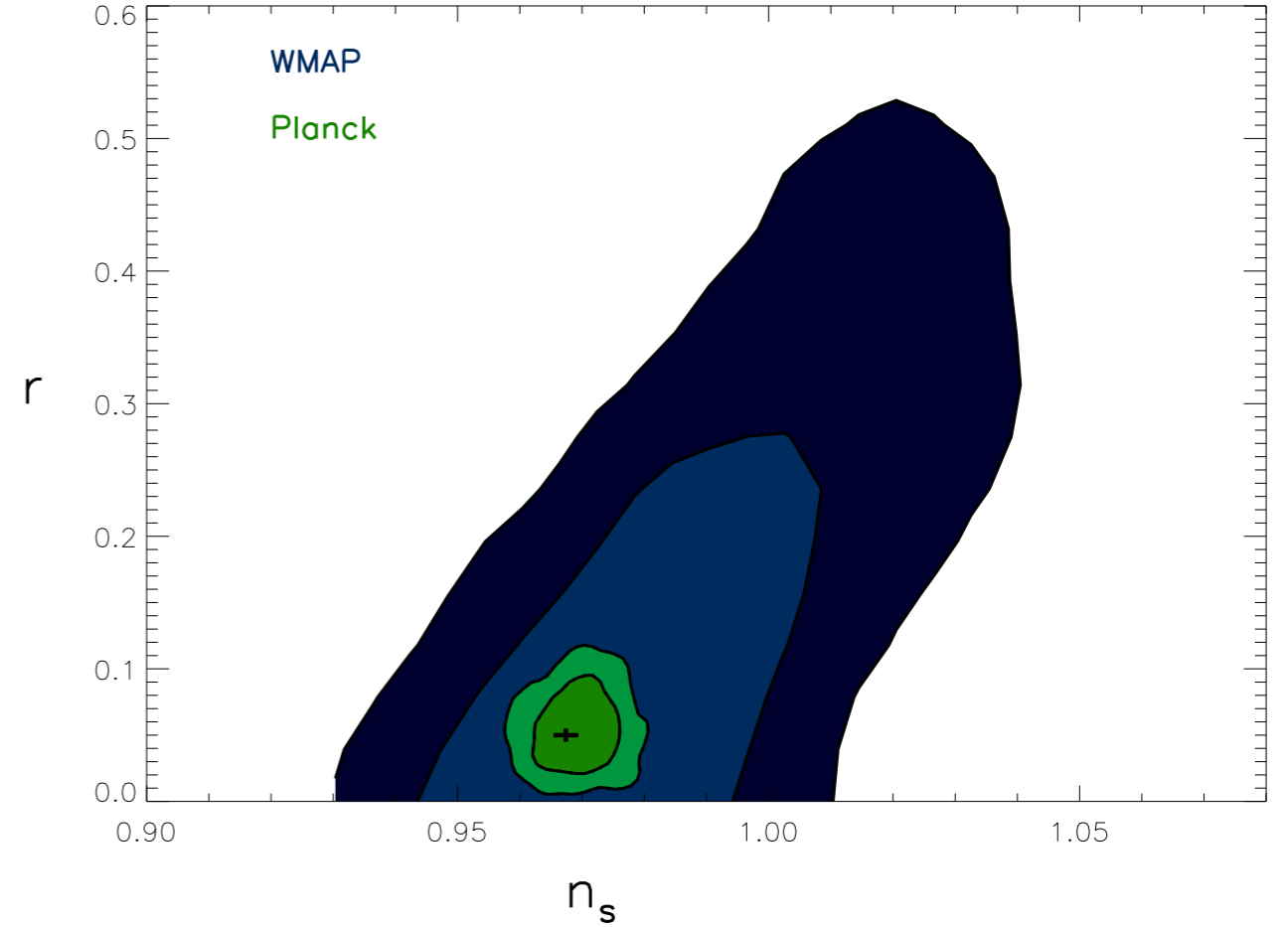
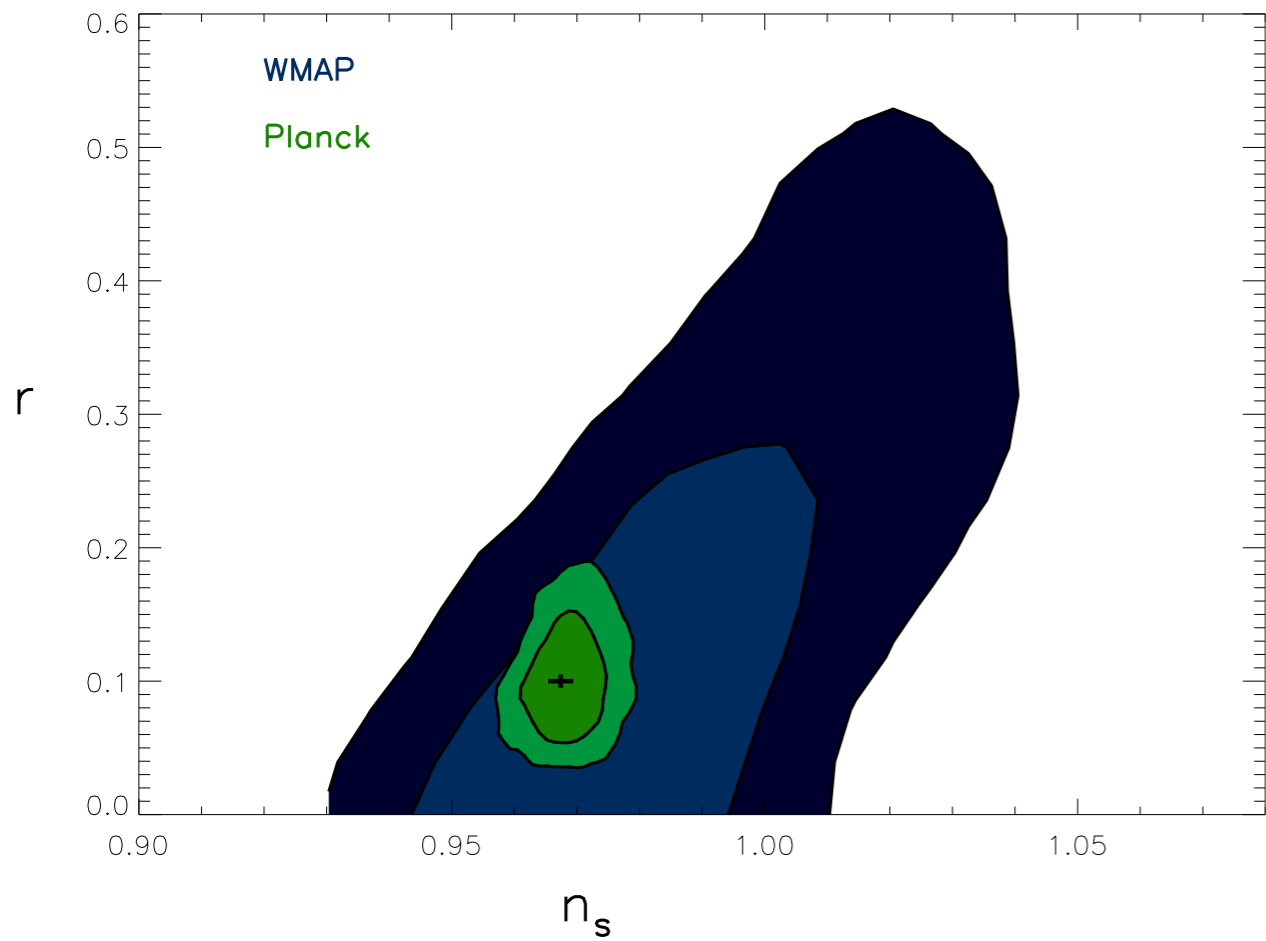


The Future

$r=0.10$

$r-n_s$

$r=0.05$

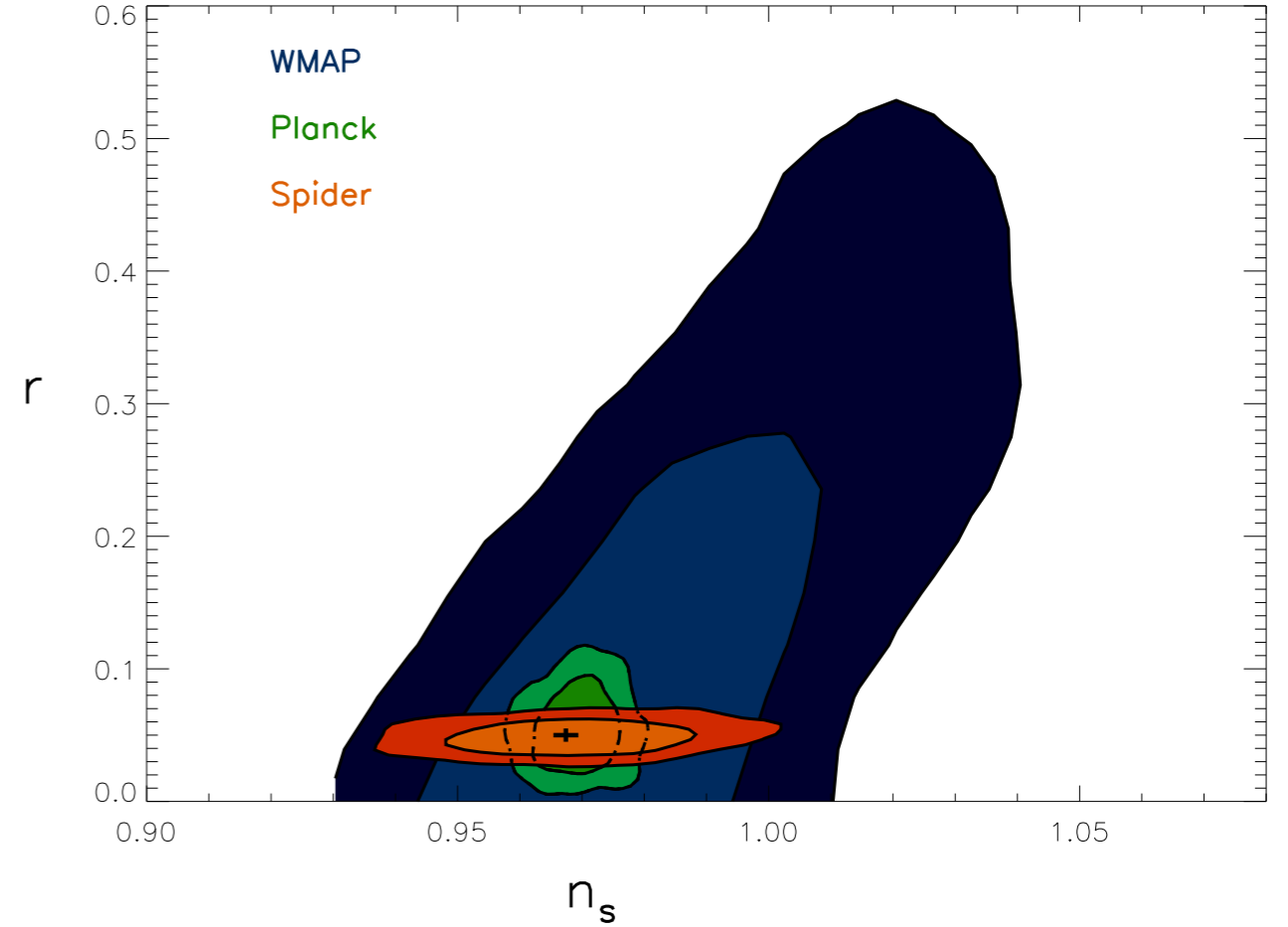
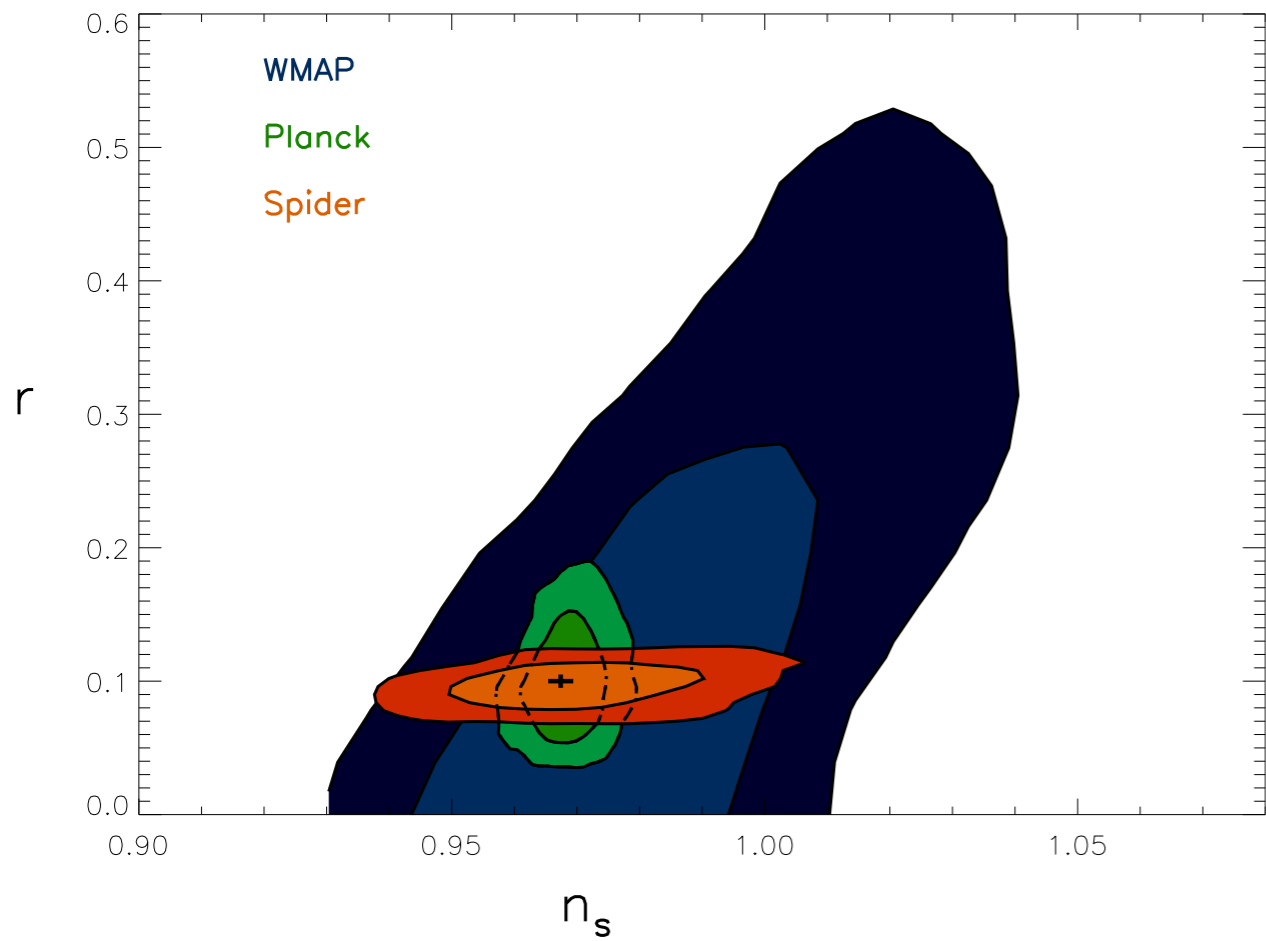


The Future

$r=0.10$

$r-n_s$

$r=0.05$

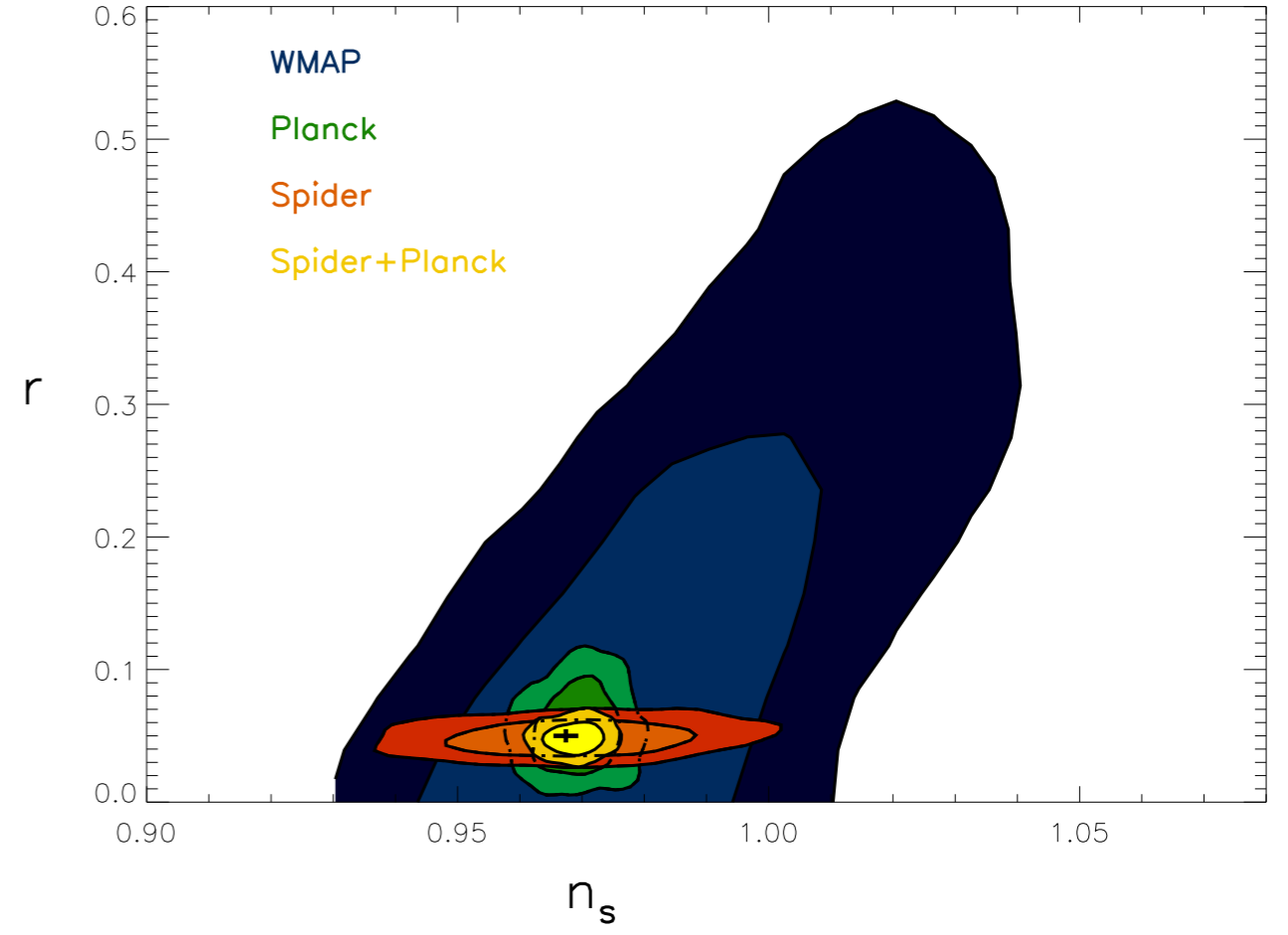
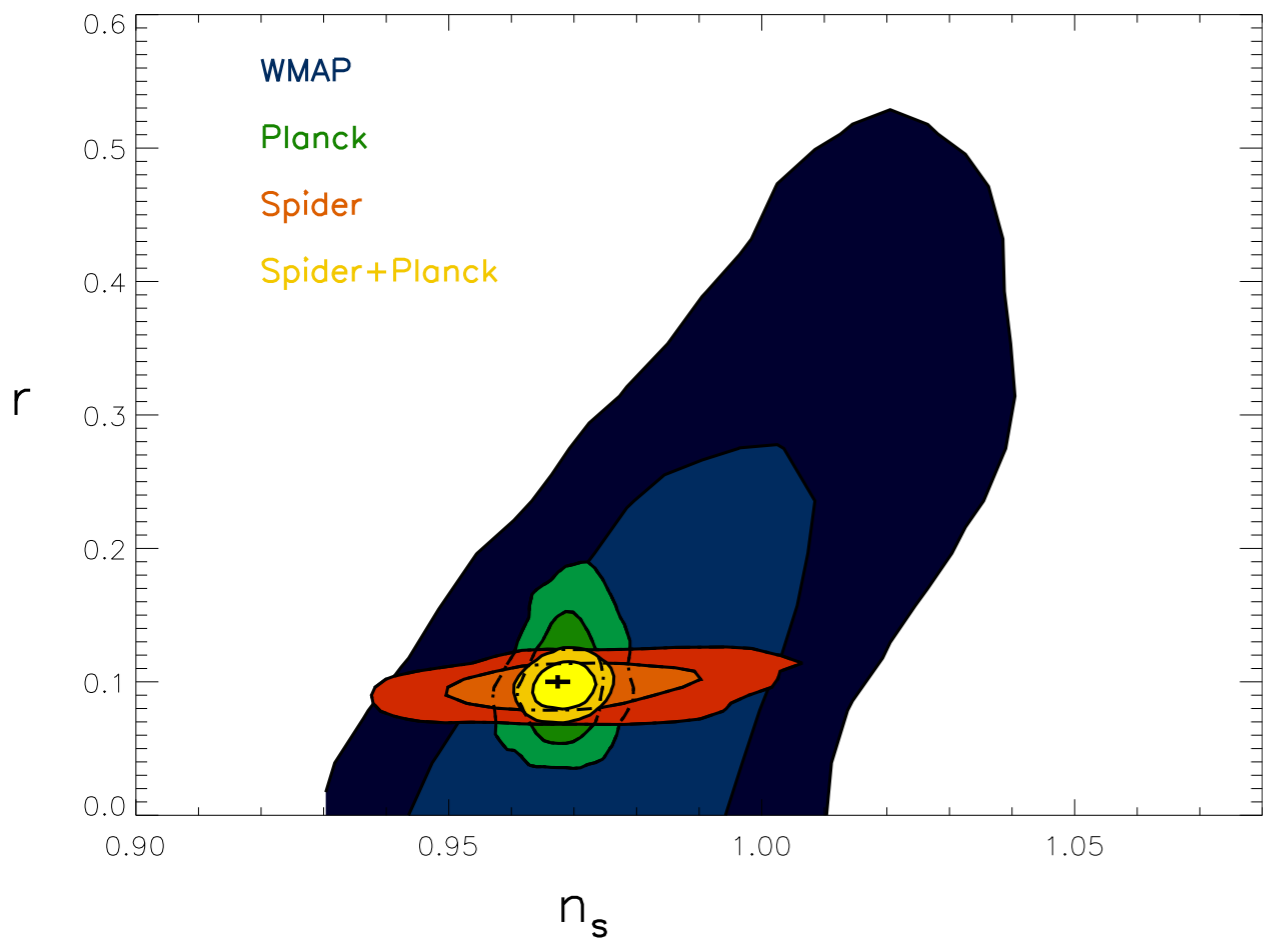


The Future

$r=0.10$

$r-n_s$

$r=0.05$





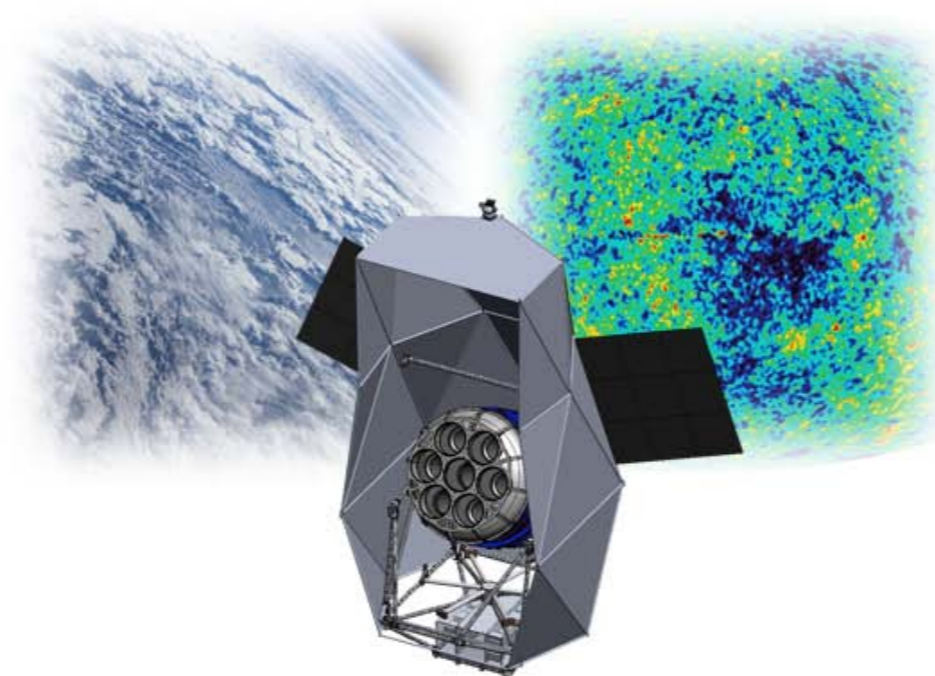
SCIP

the Suborbital Cosmic Inflation Probe



**MISSION OF
OPPORTUNITY**

*A Long-Duration Balloon
Experiment to Explore
Cosmic Origins*



Summary

- The next decade will see 2-3 generations of sub-orbital experiments characterising “small” patches of sky.
- Detector technology will mature and stabilise.
- Foregrounds will be characterised, particularly at high frequencies (dust).
- Lensing signal will be observed, lots of interesting science/ cosmology. Difficult to extract GWB component to claim detection.
- Low & high angular scale approaches complementary (Spider vs Ebex)
- If $r > 0.05-0.03$, “fair” chance of detection over the next decade from sub-orbital telescopes.
- Otherwise, the pathway to a quick turn around mission proposal ca 2020 will be defined clearly.