The SPIDER Experiment:

Instrument review, flight performance, and preliminary results

Cosmo 15
September 8, 2015
Jon E. Gudmundsson

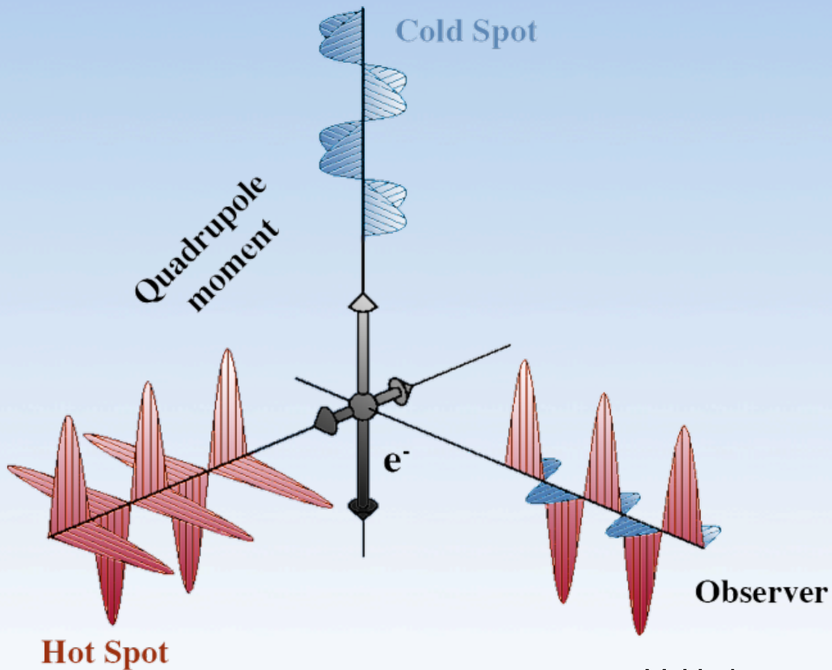
for the SPIDER collaboration

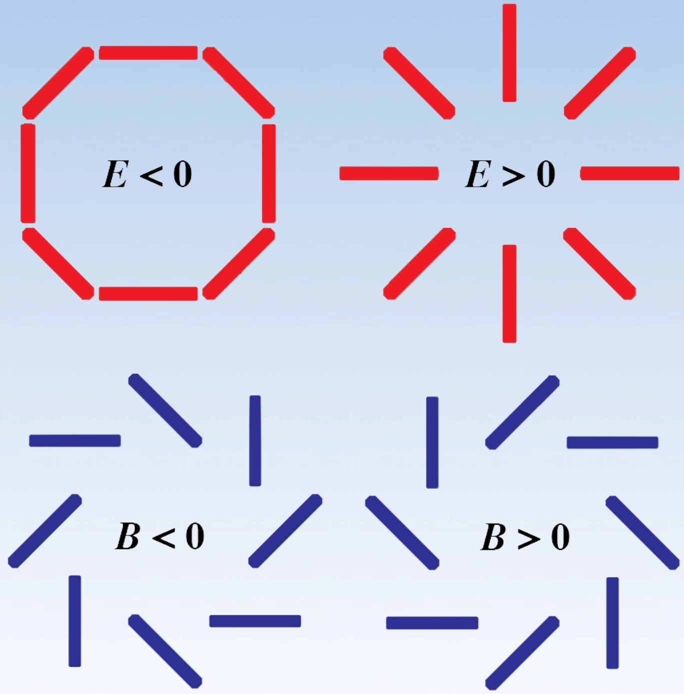
The Inflationary Paradigm

- Simplest constituents of the inflationary paradigm consistent with observations.
- Including:
  - Flat universe
  - Adiabaticity
  - Homogeneity
  - Gaussian perturbations
  - Small non-Gaussianities
  - Near scale invariance
  - Lack of exotic relics
- How can we further test early universe models?

CMB Polarization

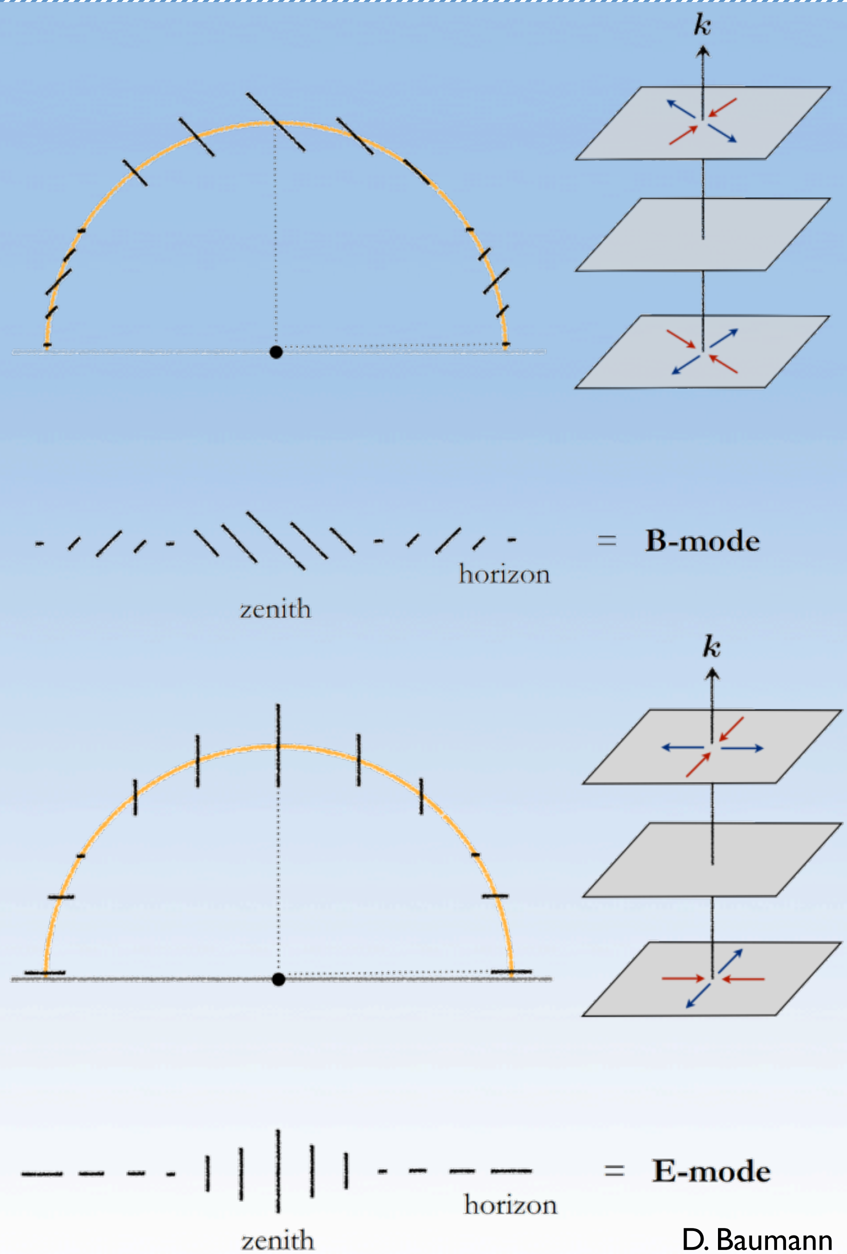
- Thomson scattering from quadrupolar density anisotropies produces polarized light.
- Polarization decomposed into *E*- and *B*-modes.
  - *E*-modes gradient "source/sink" polarization
  - *B*-modes are "swirly" or non-mirror symmetric





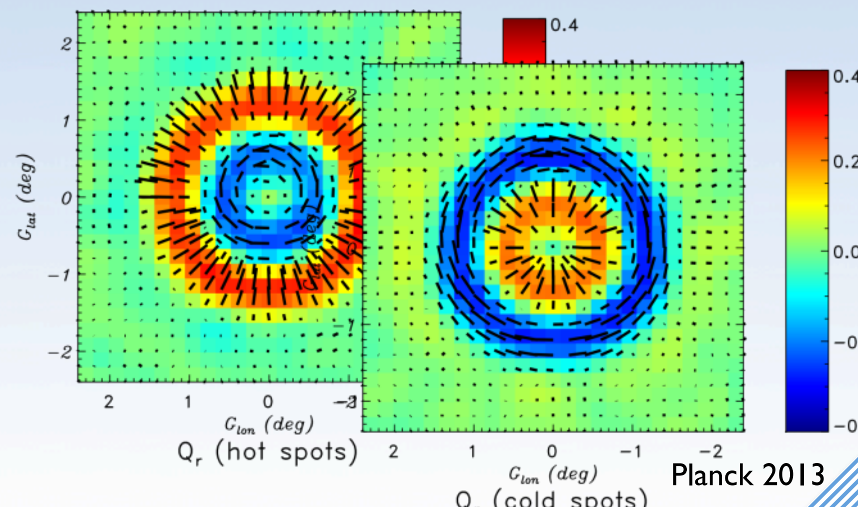
M. Hedman

Gravitational Waves Produce *E* and *B* polarization



D. Baumann

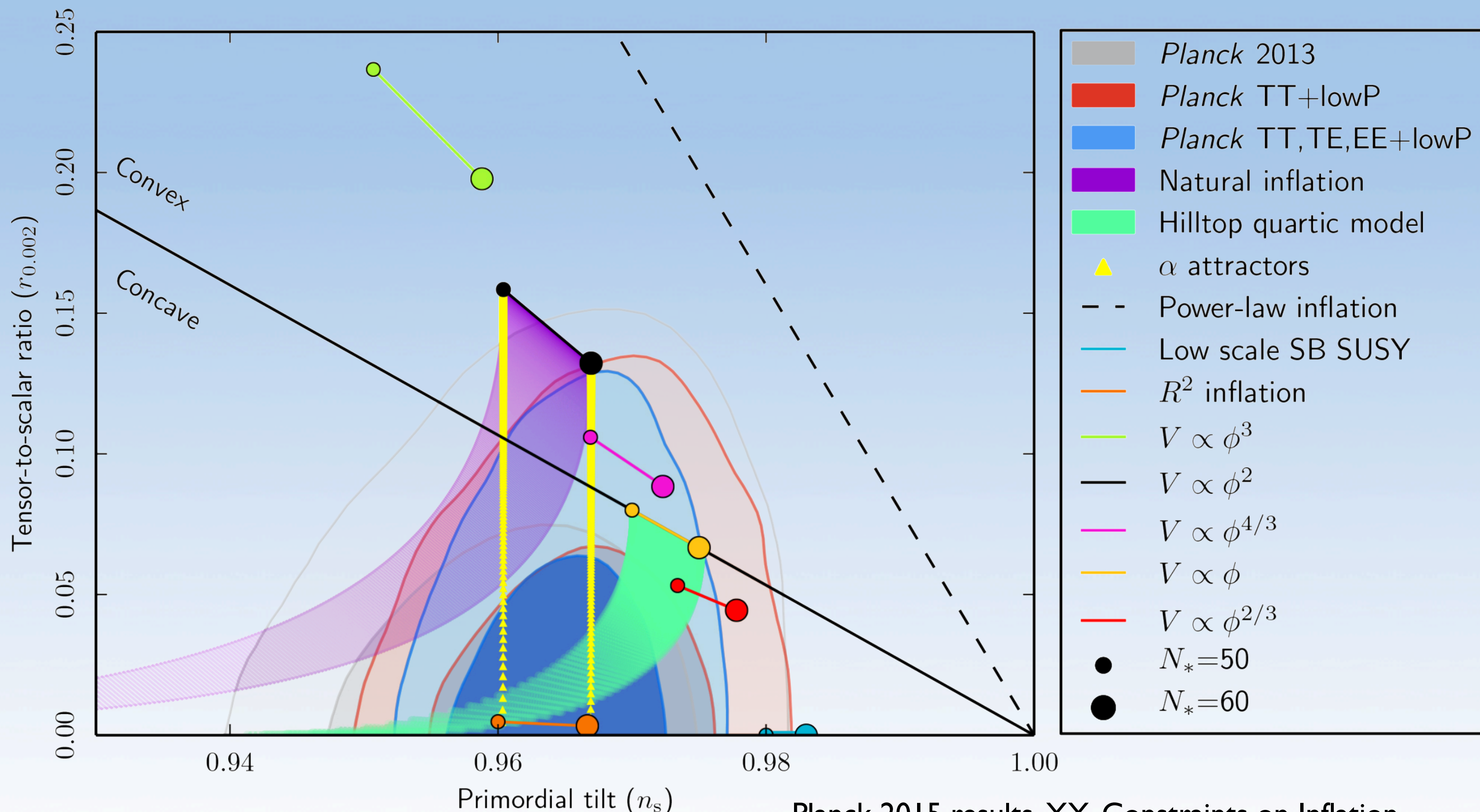
- Warping of space produces quadrupole moment perpendicular to direction of propagation.
- Unlike density waves, gravitational waves produce both *E*- and *B*-mode polarization.
- Gravitational waves are predicted by models of inflation.
- Combining many hot and cold spots on the sky we get the expected TE correlation pattern.



Planck 2013

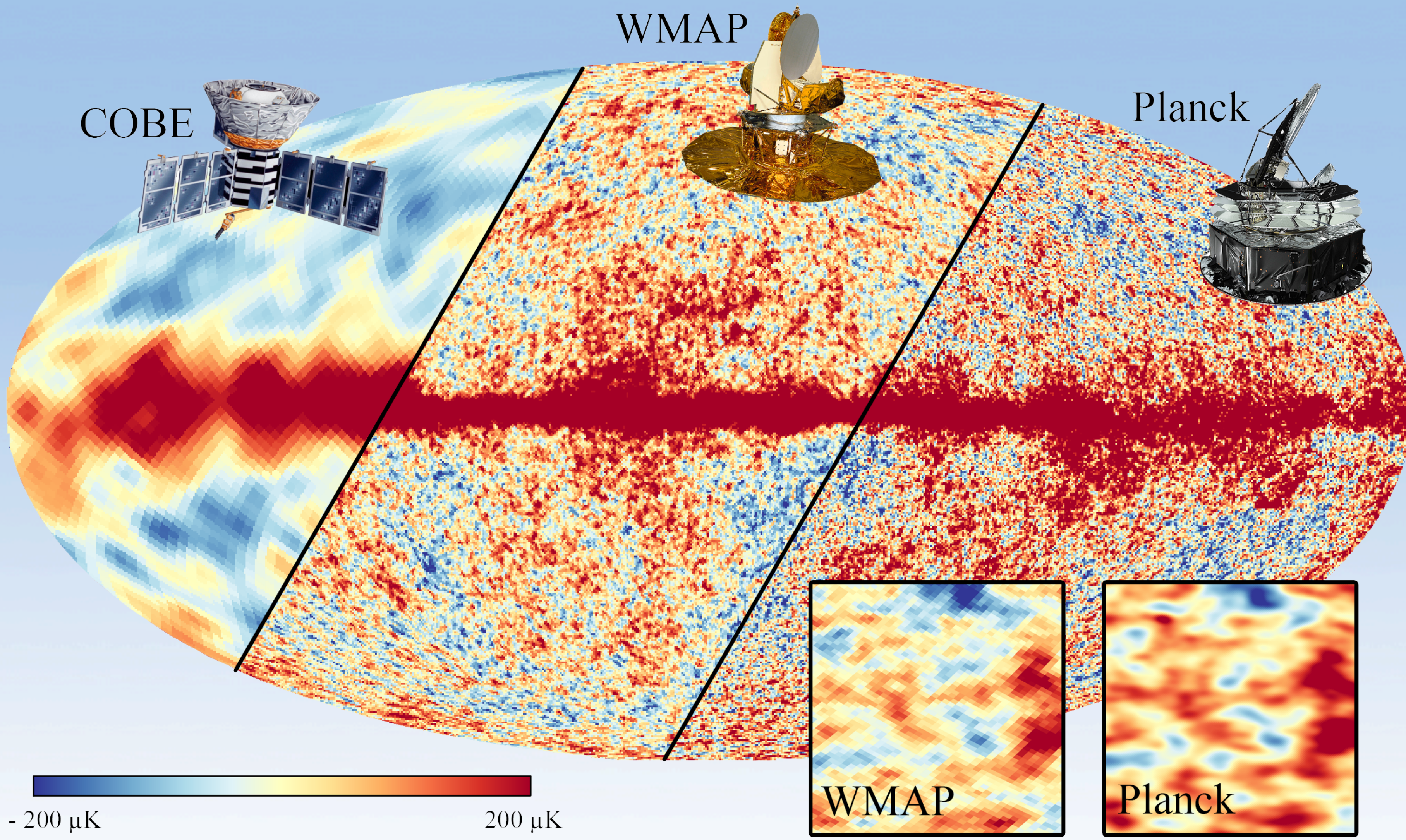
Current constraints on n_s and r

- r < 0.08 (@ 95% CL) Planck TT + low ℓ Polarization + BKP.
- r < 0.10 (@ 95% CL) same as above, but allowing for n_s running.

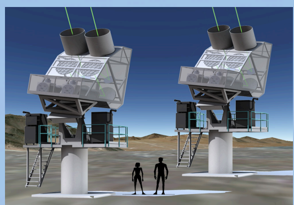


Planck 2015 results. XX. Constraints on Inflation

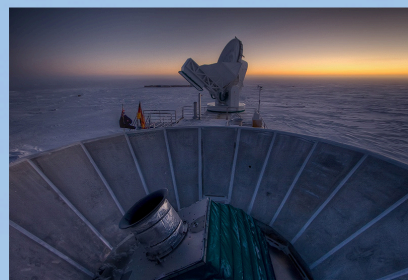
Three Full-sky Surveys



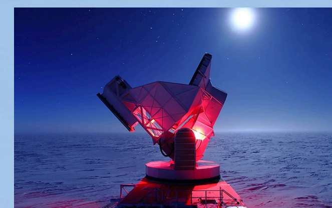
The Rest



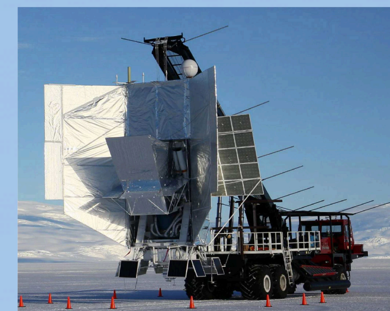
CLASS



BICEP2



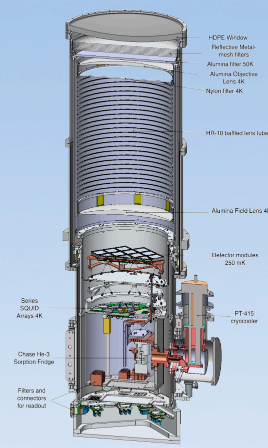
SPTpol



EBEX

QUIJOTE

Keck Array

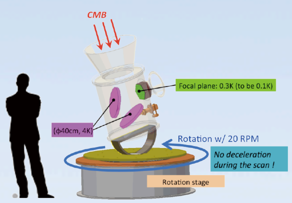


BICEP3

ACTPol

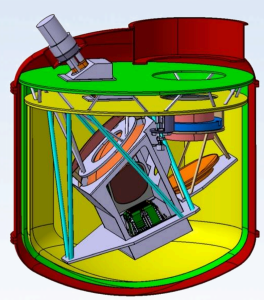
Polarbear

SPIDER

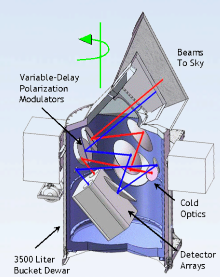


GroundBIRD

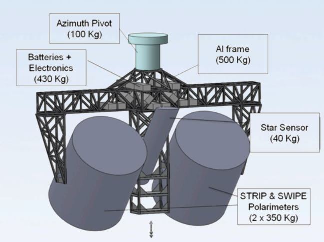
ABS



QUBIC

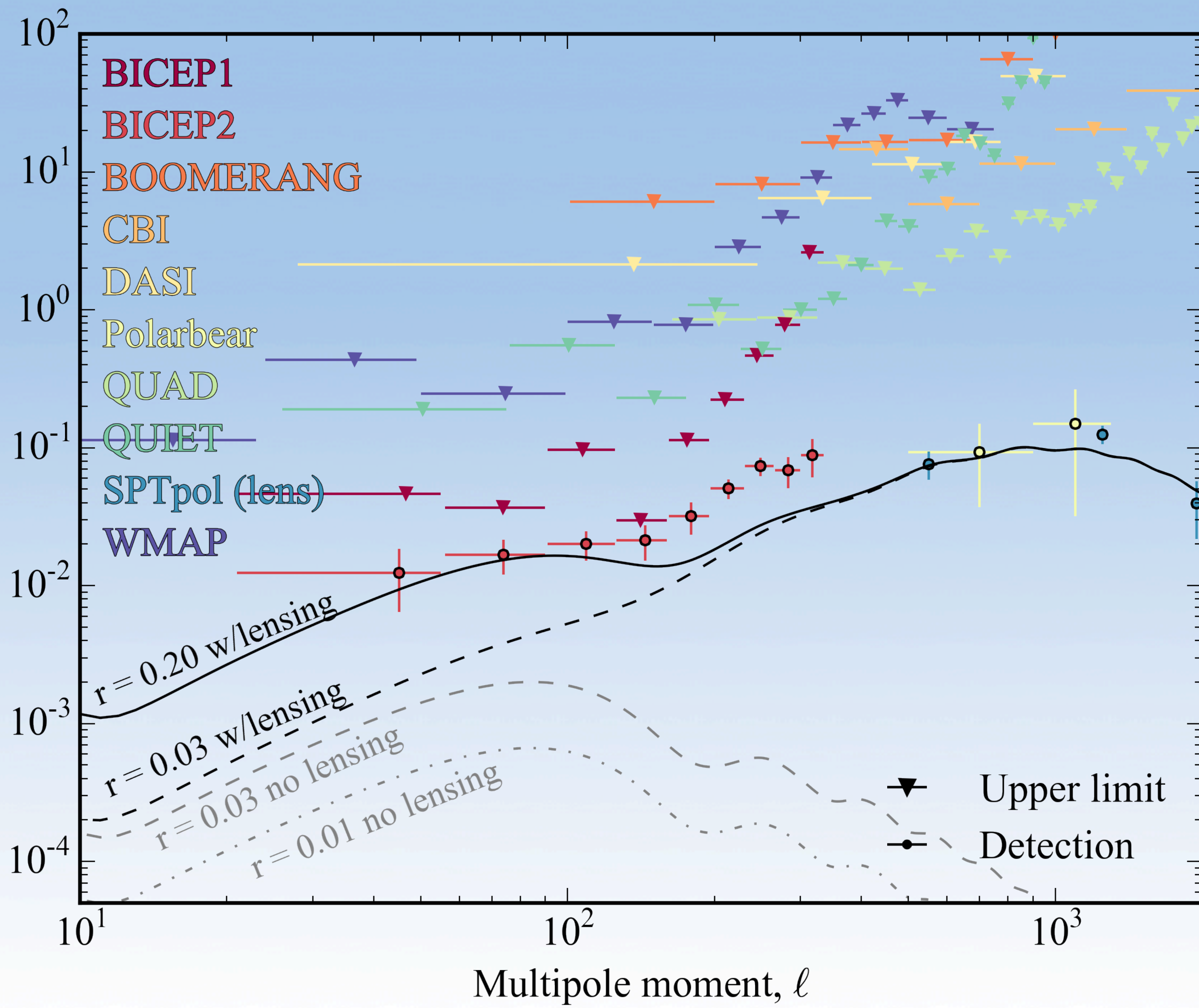


PIPER

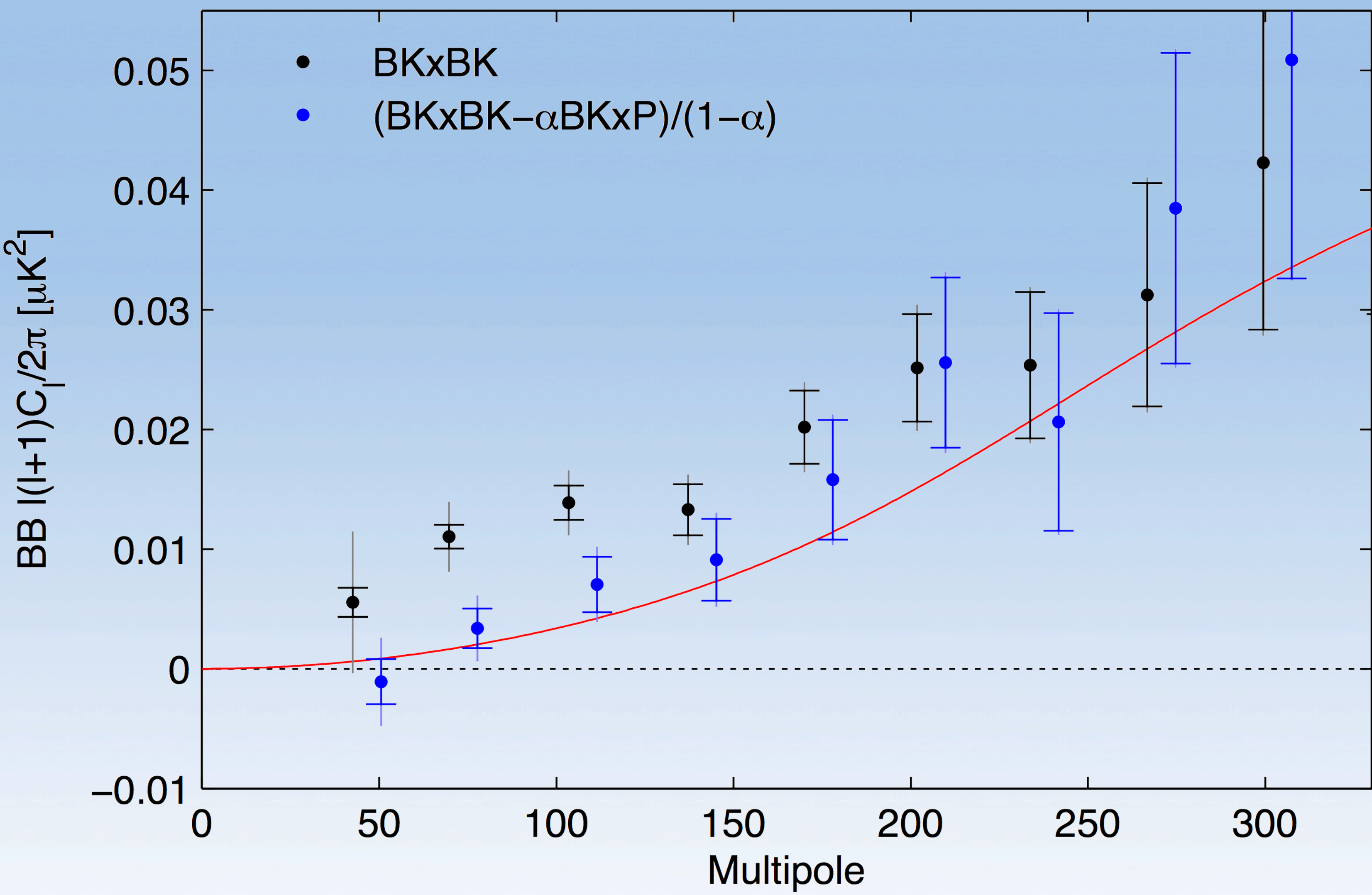


LSPE

Current *E*- and *B*-mode Measurements



Foreground Cleaned



A Joint Analysis of BICEP2/Keck Array and Planck Data

SPIDER

- A balloon-borne polarimeter.
- Mapped about 10% of the sky.
- Six telescopes, 3/3 at 95/150 GHz.
  - Approx. 2000 detectors (85% yield)
- About 0.5 deg resolution.
  - $\ell \approx 10$–300
- **Science goals:**
  - Set limits on primordial gravitational wave amplitude of $r < 0.03$ at 99% confidence (no foregrounds)
  - Characterize polarized foregrounds
  - Lensing *B*-modes
- **Questions:**
  - Are primordial *B*-modes within our reach?
  - Is slow roll inflation unbreakable?
- First science flight ~~2013~~!?/2014.

SPIDER Collaboration

Caltech
J. J. Bock
B. P. Crill
O. Doré
S. Golwala
W. Holmes
V.V. Hristov
R. O'Brient
P.V. Mason
L. Moncelsi
T.A. Morford
M. C. Runyan
A. Trangsrud
R. S. Tucker
A. D. Turner

University of Oslo
H.K. Eriksen
I. Wehus

Cardiff
P. Ade
C. Tucker

CWRU
J.E. Ruhl
J. Nagy
J.A. Shariff
S. Wen

Imperial College
C.R. Contaldi

Princeton
W.C. Jones
S. Bergman
A. Fraisse
A. Gambrel
M. Hasselfield
Z. Kermish
A.S. Rahlin
E. Young

UBC
M. Halpern
M. Amiri
D. Wiebe

Stanford
K.D. Irwin

Stockholm University
A. Duivenvoorden
J. E. Gudmundsson

APC
Ken Ganga

IAS
J. Soler

UKZN
H.C. Chiang
Jon Sievers

ASU
S. Bryan

U. Toronto/CITA
C.B. Netterfield
J.R. Bond
S.J. Benton
M. Farhang
L.M. Fissel
N.N. Gandilo
M. Galloway
J. Hartley
I. Padilla

NIST
G. Hilton
C. Reintsema

University of Illinois
J. P. Filippini


December 2014
ca. Ross Island, Antarctica

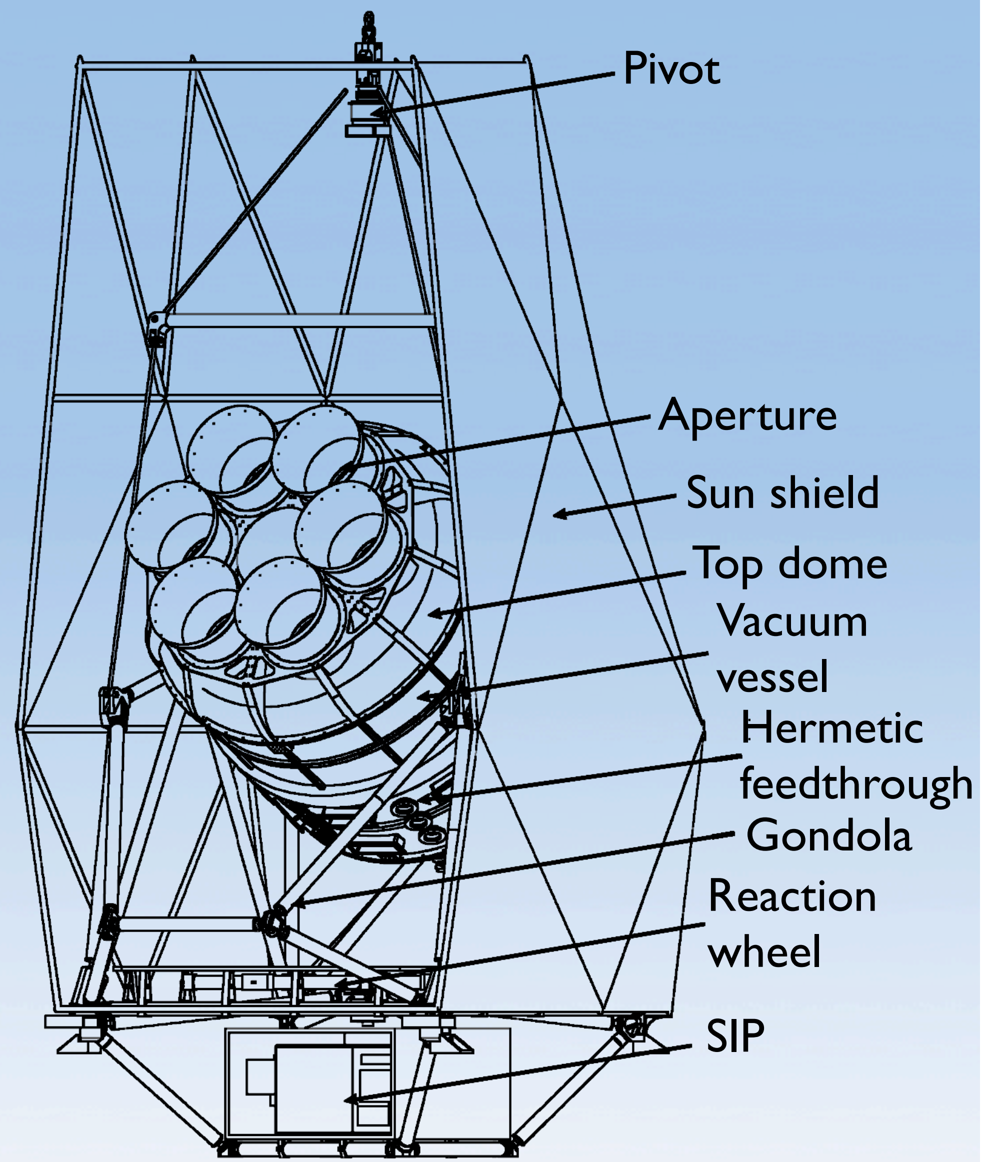
Primary characteristics

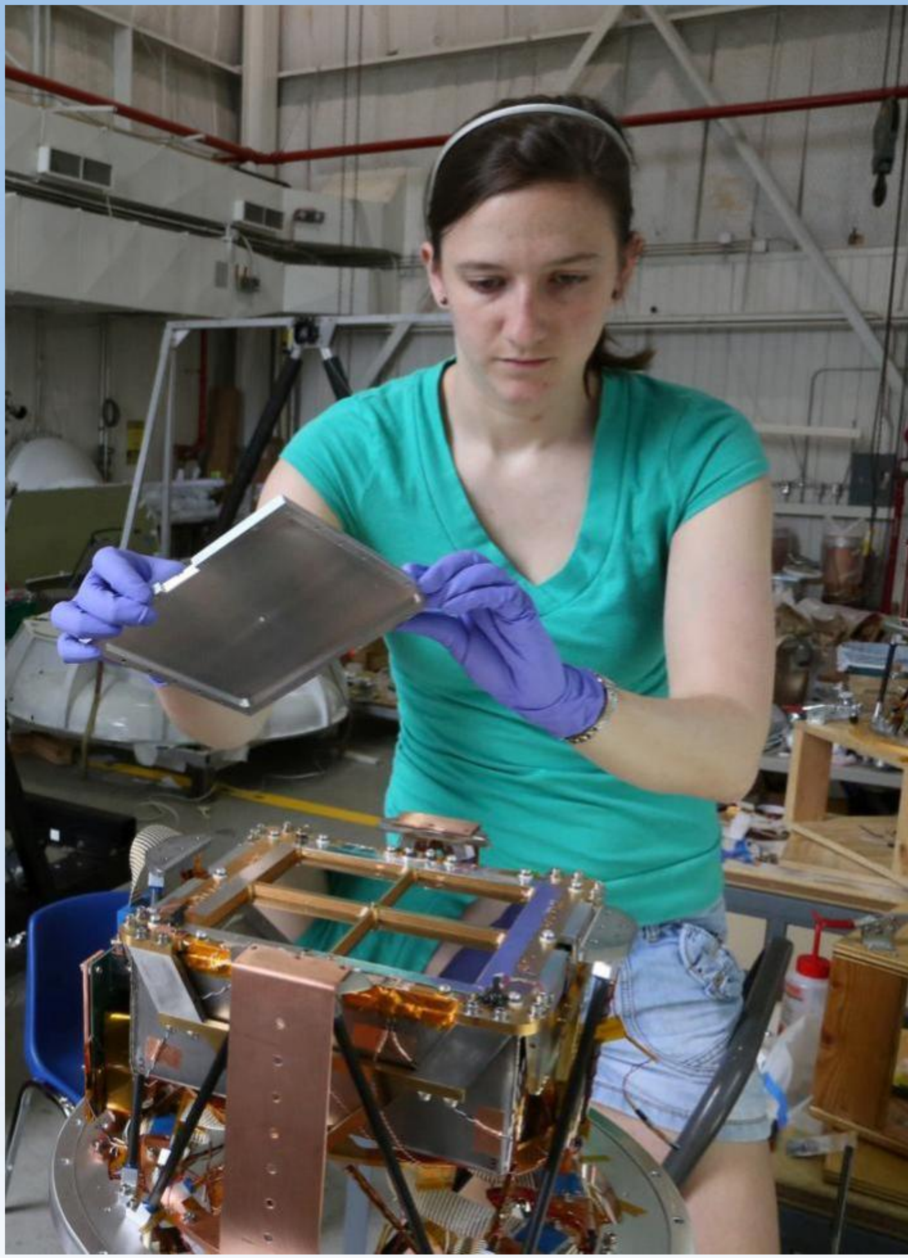
Sky coverage	About 10 %
Scan rate (az)	3.6 deg/s at peak
Polarization modulation	Stepped cryogenic HWP
Detector type	Antenna-coupled TES
Multipole range	$10 < \ell < 300$
Observation time	16 days
Limits on $r^{\dagger}$	0.03

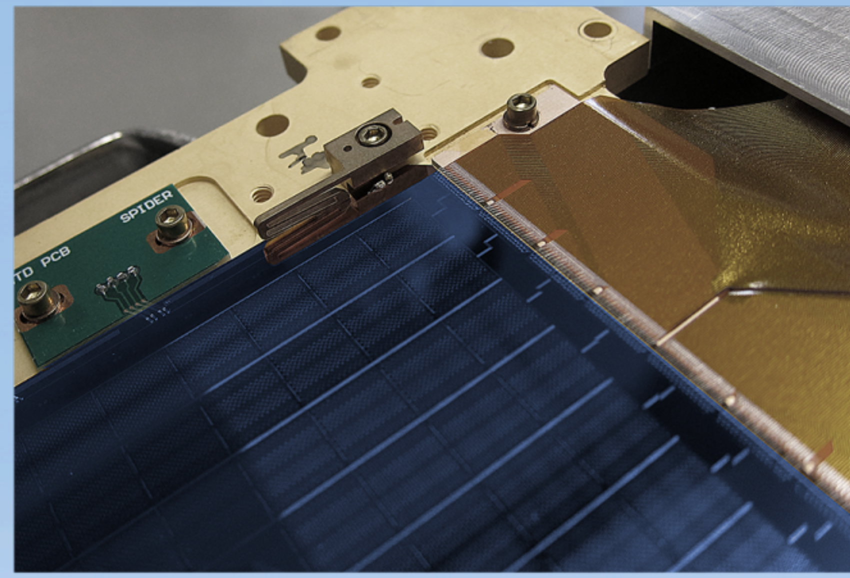
† Assuming no foregrounds, at 99% confidence

	Frequency [GHz]	
	95	**150**
Telescopes	3	3
Bandwidth [GHz]	22	36
Optical efficiency	30-45%	30-50%
Angular resolution* [arcmin]	42	30
Number of detectors†	690	1230
Internal loading‡ [pW]	≤ 0.25	≤ 0.35
NET per detector [μ K·rts]	120-150	110-150

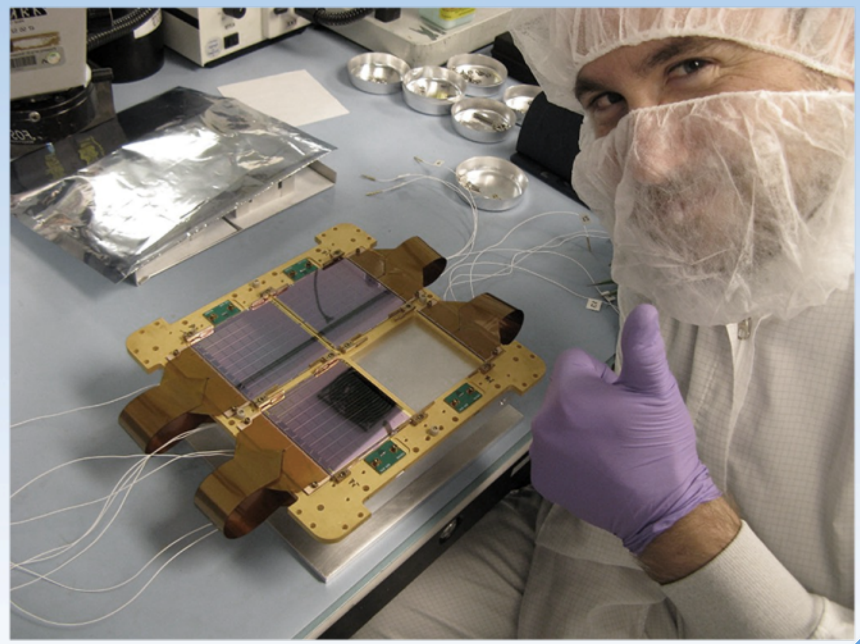
*FWHM. †Assuming 80% yield.
‡Including sleeve, window, and baffle





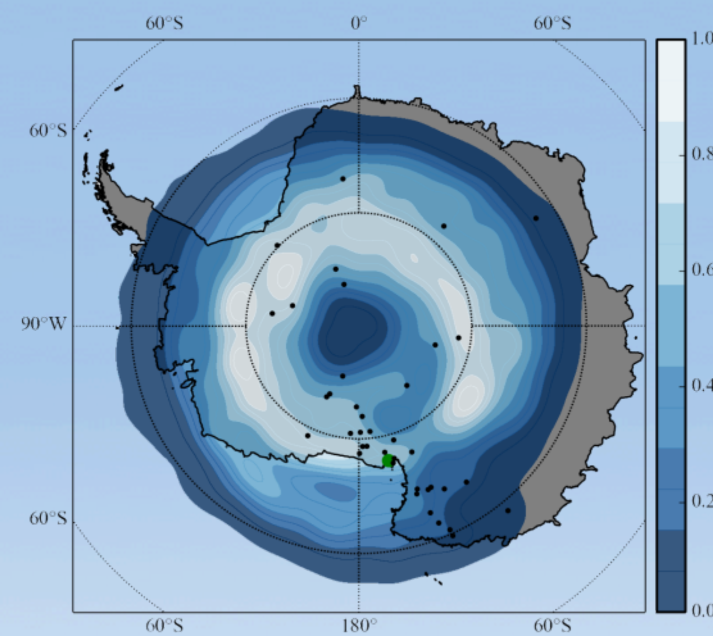


TD PCB
SPIDER

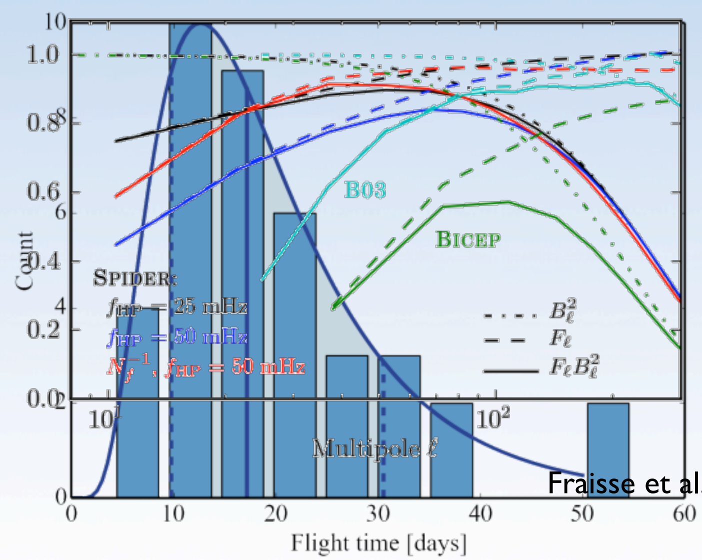


Long Duration Ballooning

- Circumpolar winds ~10 days/rev.
- On average 20 day flights at 36 km.
- **Why Ballooning?**
- Space like loading (NET).
- Access to larger angular scales.
- Wider frequency windows.
- Preparation for ULDB promised land.
- **Why Antarctica?**
- Continuous solar power.
- Long flight times.
- **At what price?**
- Narrow launch windows.
- Recovery difficulties.
- Mass, power, and automation.



Data from CSBF



Fraisse et al.

The Balloons

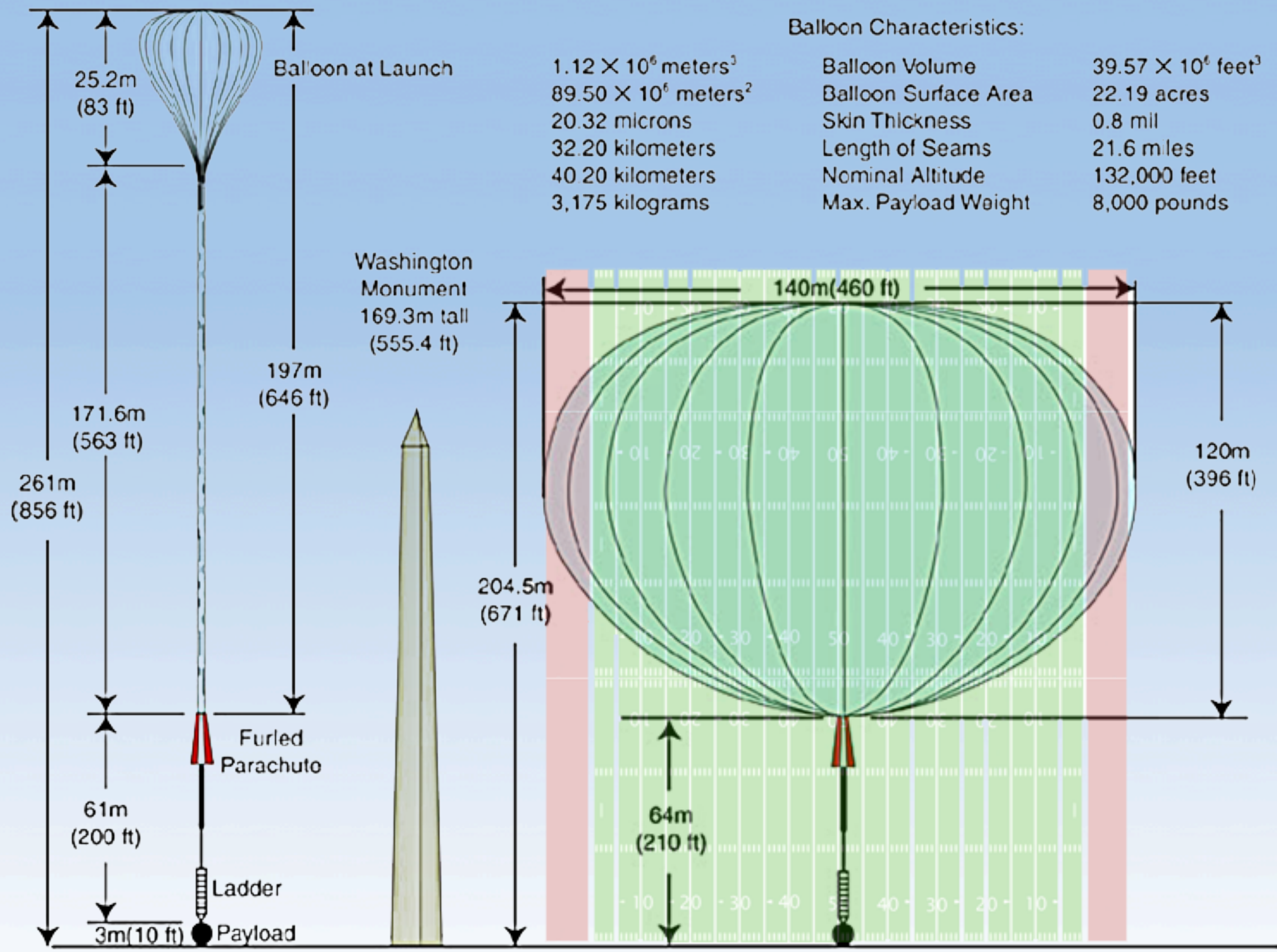
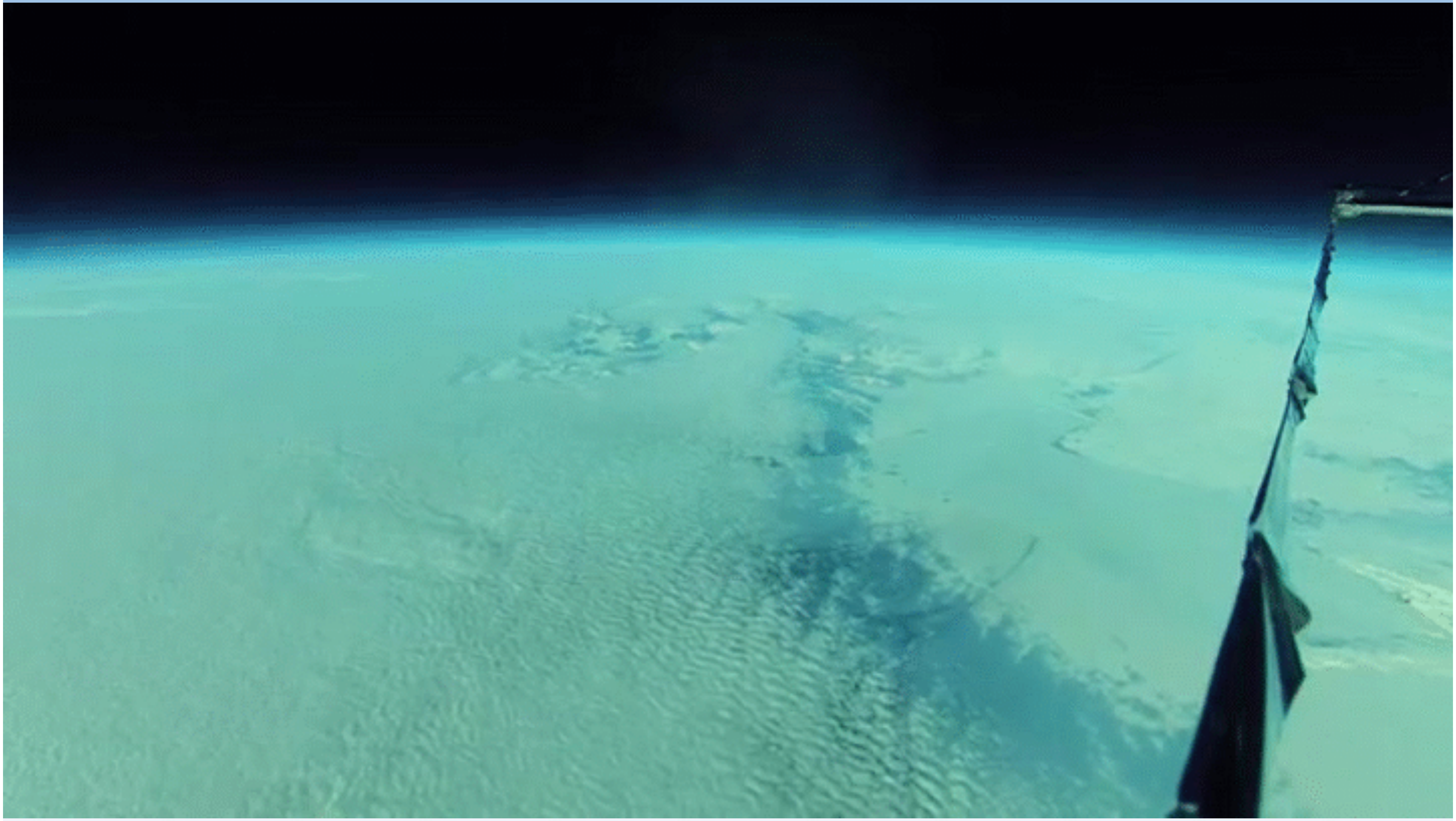


Fig. Courtesy of CSBF

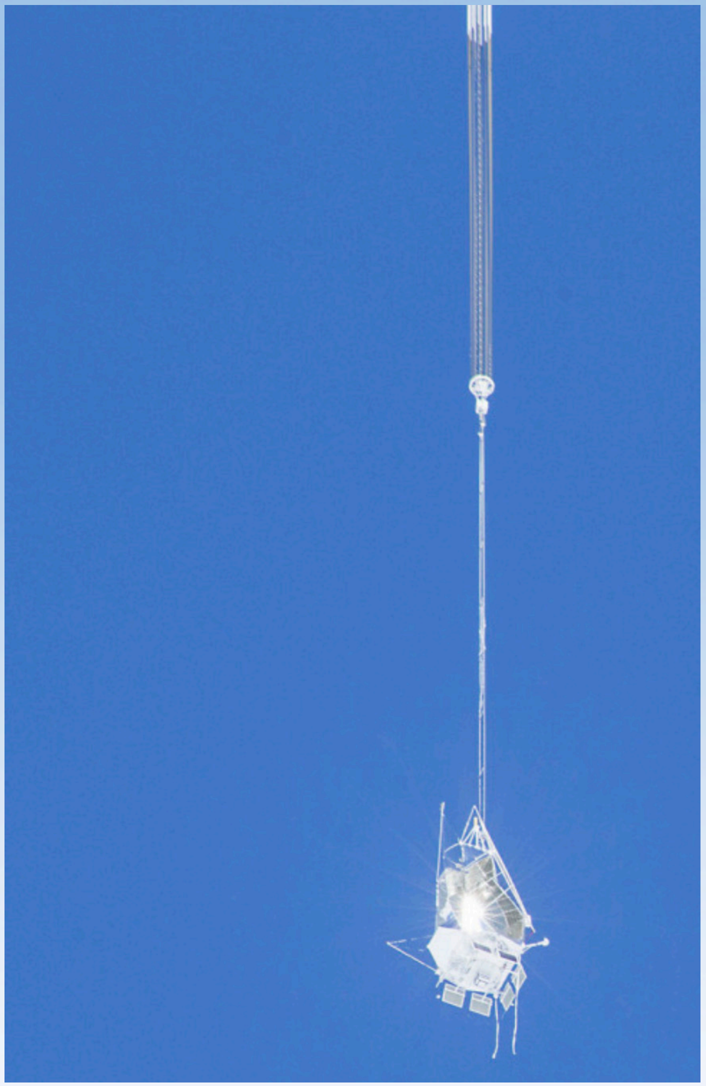
Launch

Made it to Space



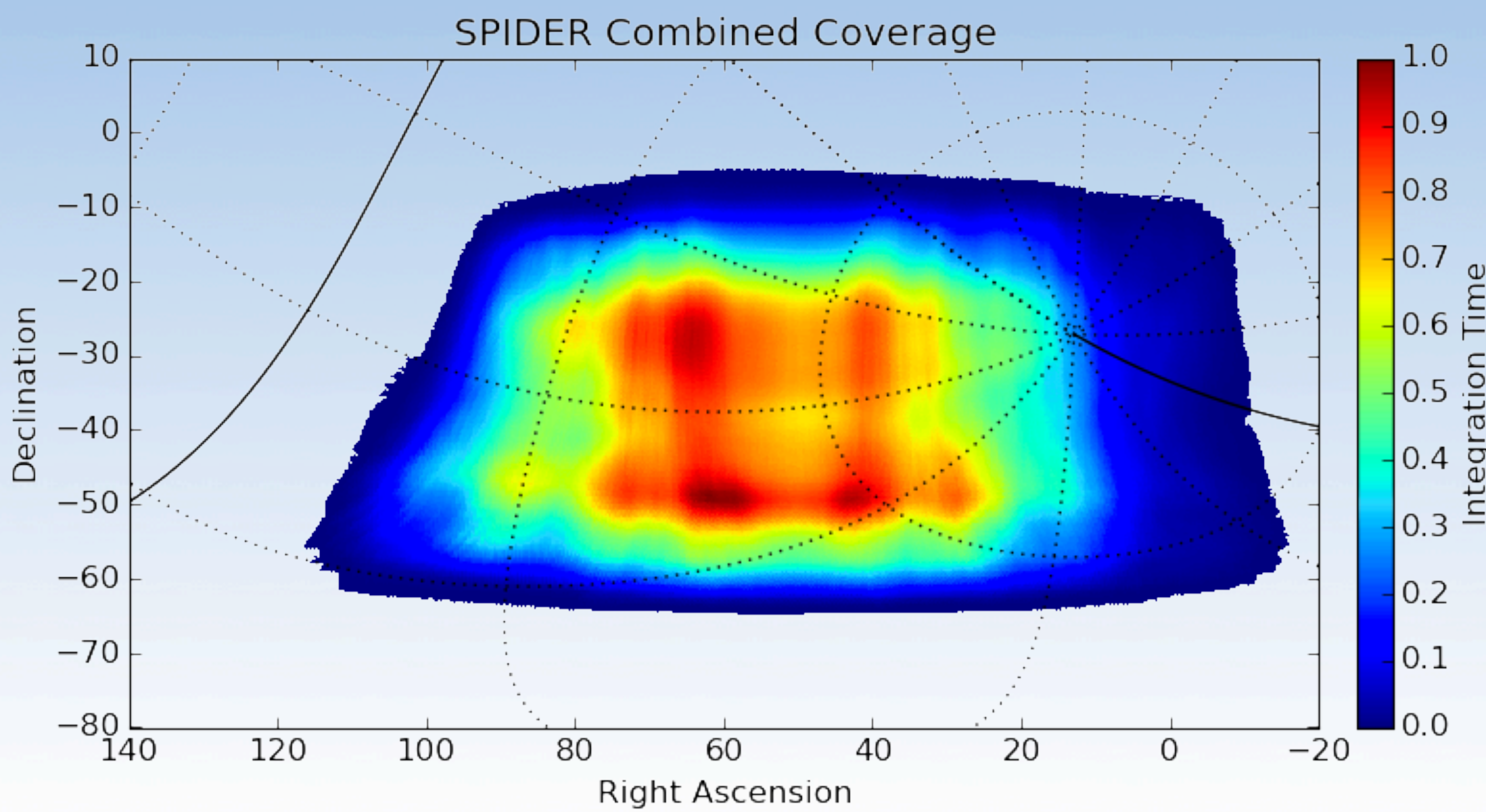
Flight Summary

- Launched on 1/1/2015.
- All systems functional.
- Around 16 days of science data.
- Stable at 35.5±0.5 km.
- Expected flagging fraction < 10 %.
- A total of 1.56 TB of data.
- Cosmic rays minimal.
- No indication of magnetic pickup.
- NET's in line with expectation.
- In-band loading:
  - ≤ 0.35 pW at 150 GHz
  - ≤ 0.25 pW at 95 GHz



Scan Strategy

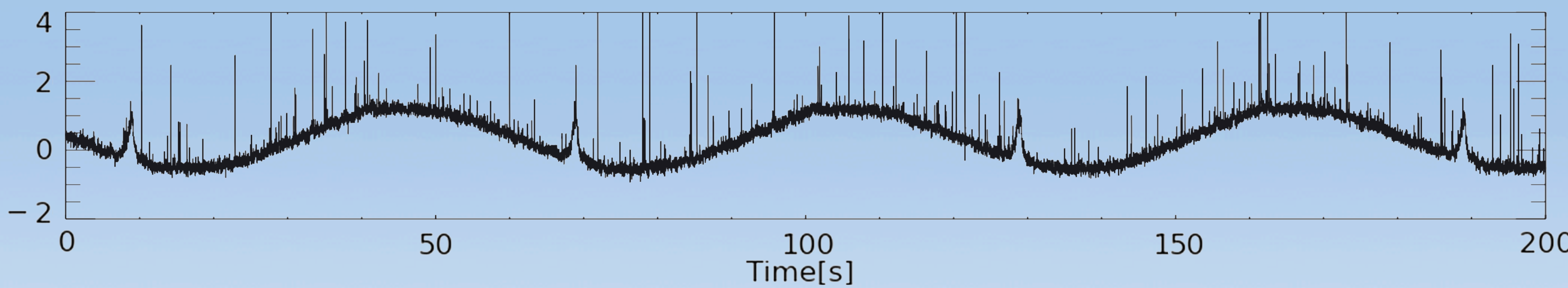
- Sinusoidal angular velocity profile with 3.6 deg/s max scan rate.
- Full map generated each sidereal day.
- Geometric / Hits weighted f_{sky}= 12.3 / 6.3 %.
- HWP stepped by ~ 22.5 deg every 0.5 sidereal days.



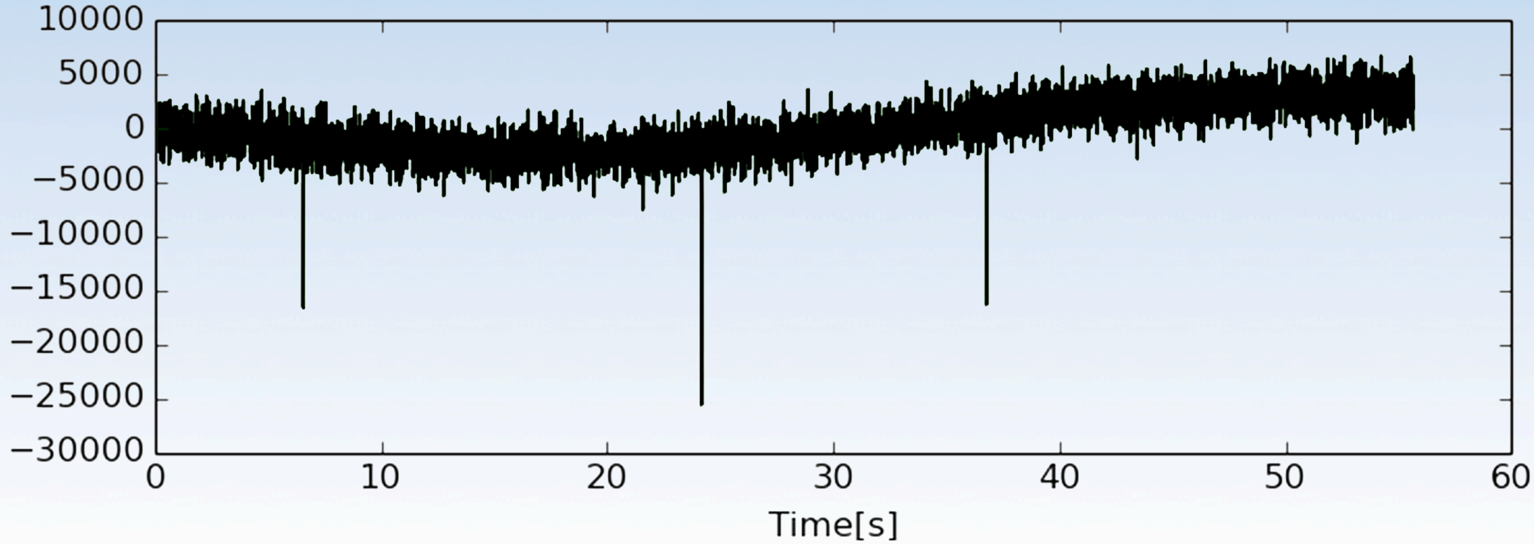
Cosmic Rays

- For SPIDER, cosmic rays appear manageable.

Planck 143 GHz timeline

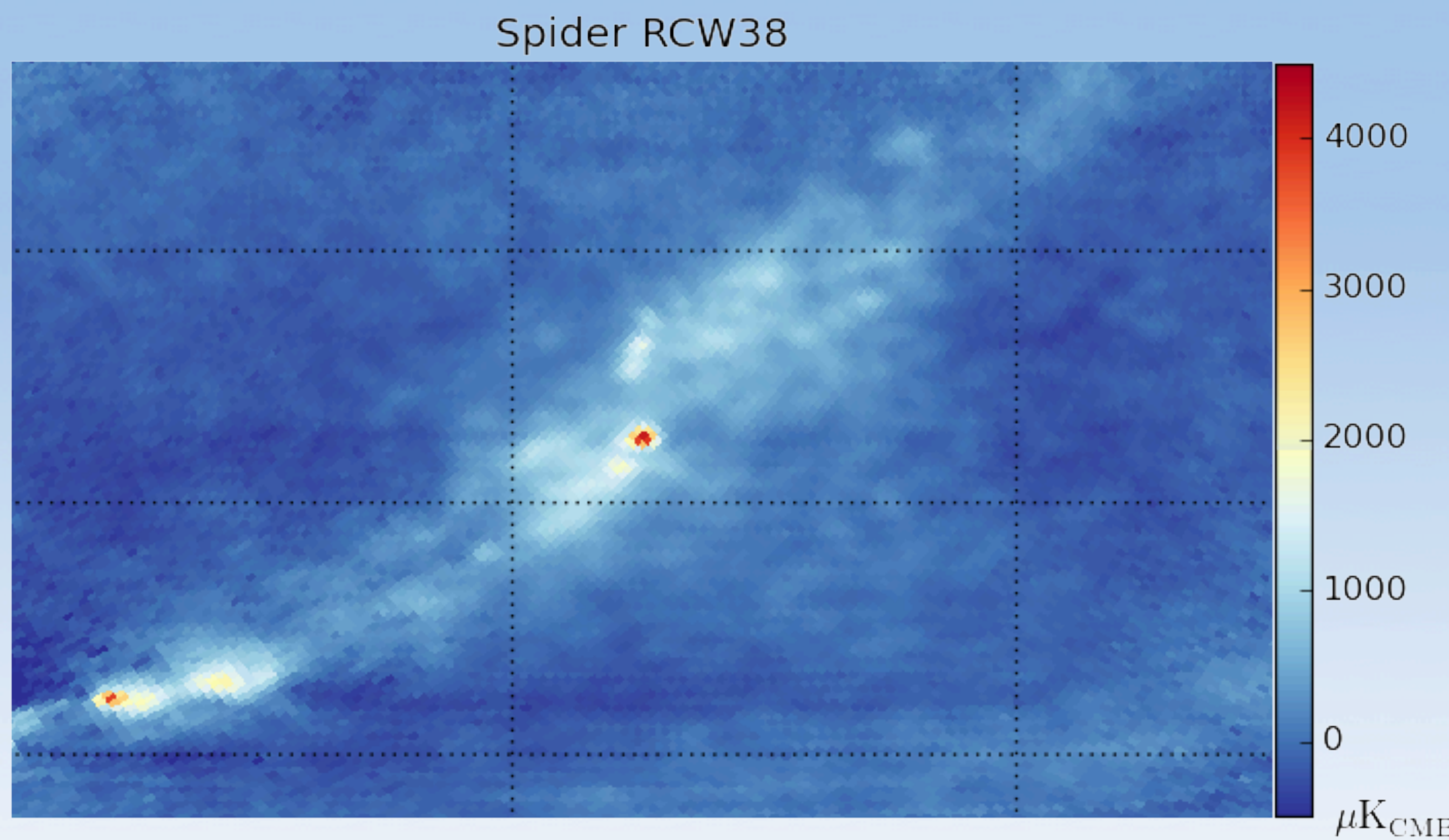


SPIDER 150 GHz timeline



Early Maps

- Minimally cleaned maps of RCW38 are promising.



- Stay tuned for CMB analysis results!

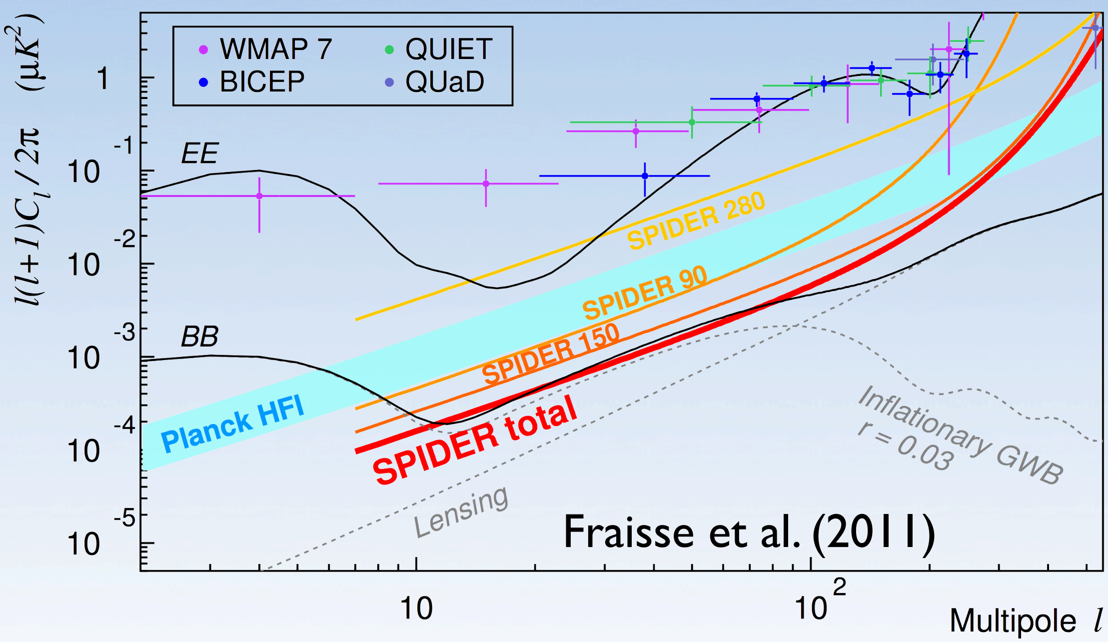
Recovery

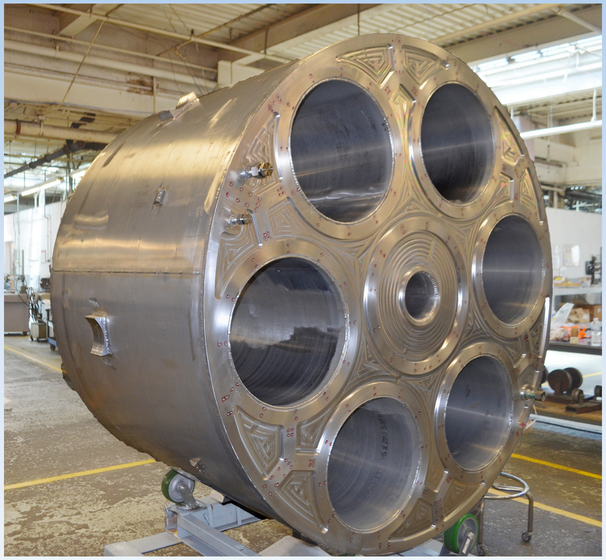
- Hard Drive (data) recovered by the British Antarctic Survey. Thanks!

- Full payload recovery expected Nov ’15.
  - Arriving in the USA spring 2016
- Refurbishing work and preparation for subsequent flight.

Next Flight

- Aiming for a second flight in 2017-2018 season.
- Adding 285 GHz dust channels (NIST).
  - Complimentary to Planck's frequency coverage (between 217 and 353 GHz)
- Aiming for 3σ detection of r = 0.03 (with foregrounds).
- Building new flight cryostat.





Concluding Remarks

- SPIDER successfully completed its first flight.
  - The most instantaneously sensitive instrument on the sky
  - Approximately 16 days of observation
  - Data analysis ongoing
- Payload recovery scheduled for Nov '15.
- Preparing for a subsequent flight in 2017-2018.
  - Adding a 280 GHz band