SPIDER first flight results and beyond

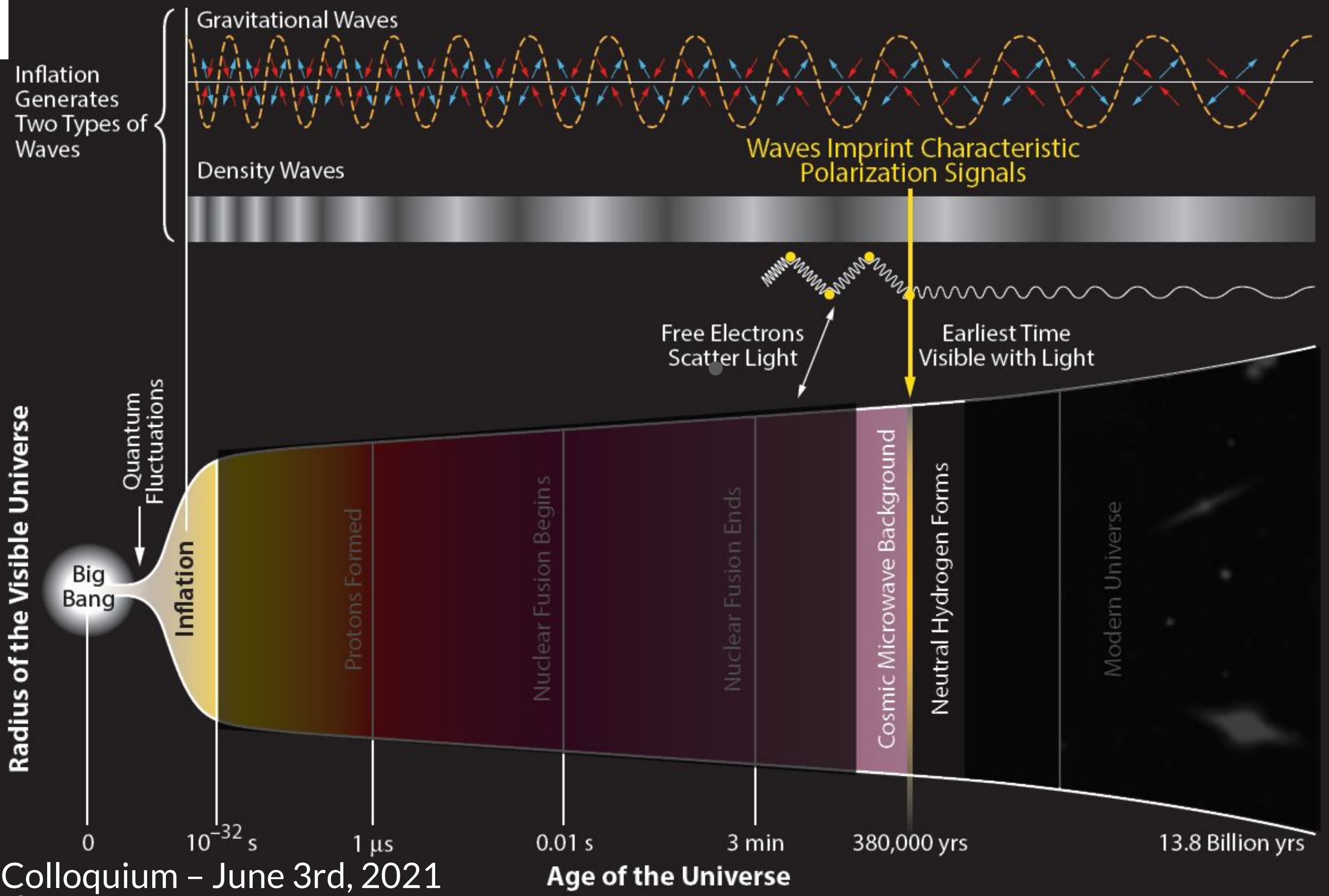
Riccardo Gualtieri, PhD on behalf of the SPIDER collaboration

National CMB Colloquium – June 3rd, 2021

Outline

- CMB B-mode polarization
  - History of the universe
  - CMB Polarization
- The SPIDER Program
  - 2015 Payload
- In-Flight Performance
  - Autonomous Detector Operations
- SPIDER results
  - Power spectra estimators
  - Null tests
  - Systematics
  - Foregrounds
  - Power Spectra
  - *r* limits
- SPIDER-2
- Conclusions

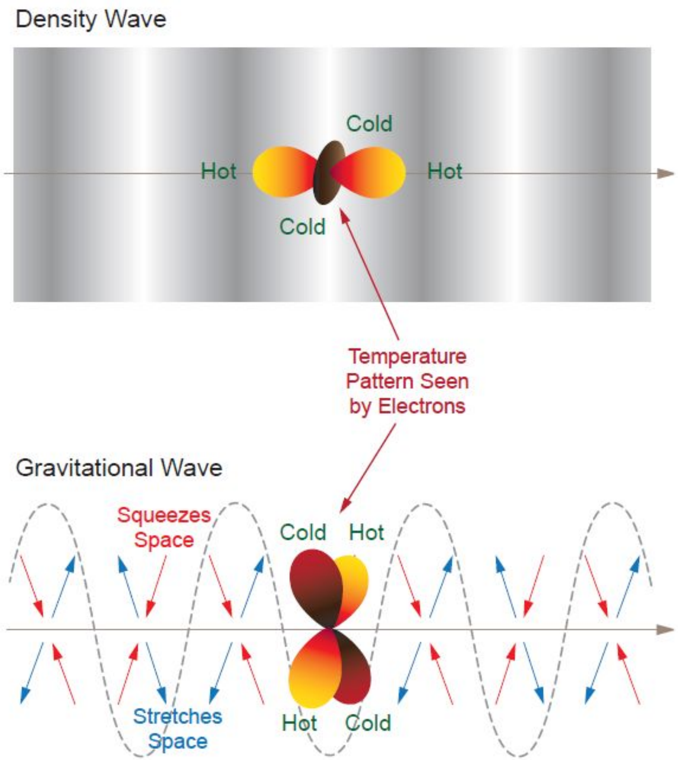
History of the Universe

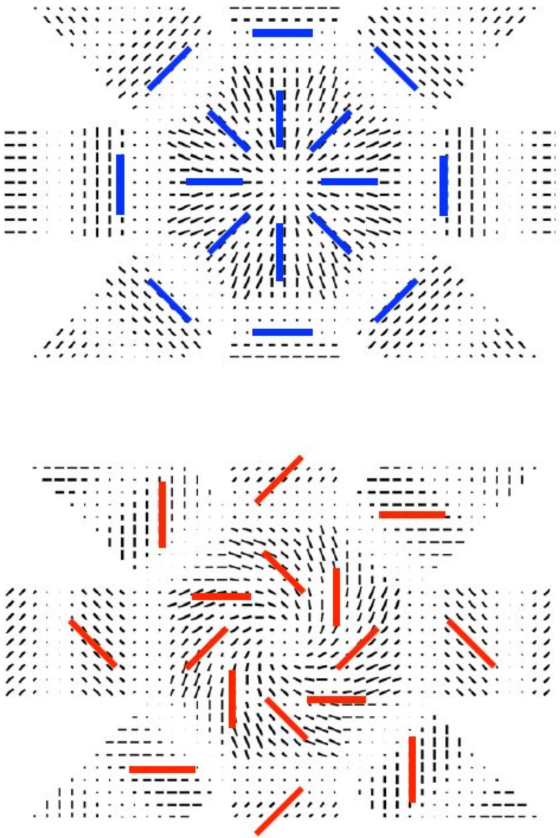


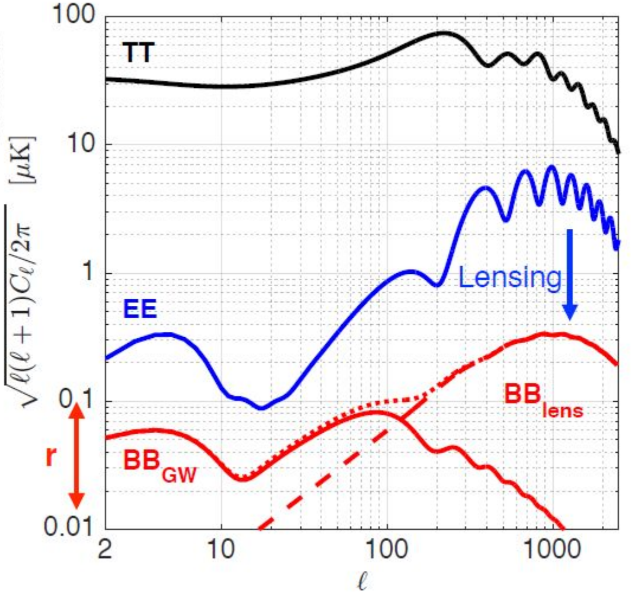
National CMB Colloquium – June 3rd, 2021

BICEP2 collaboration

CMB Polarization

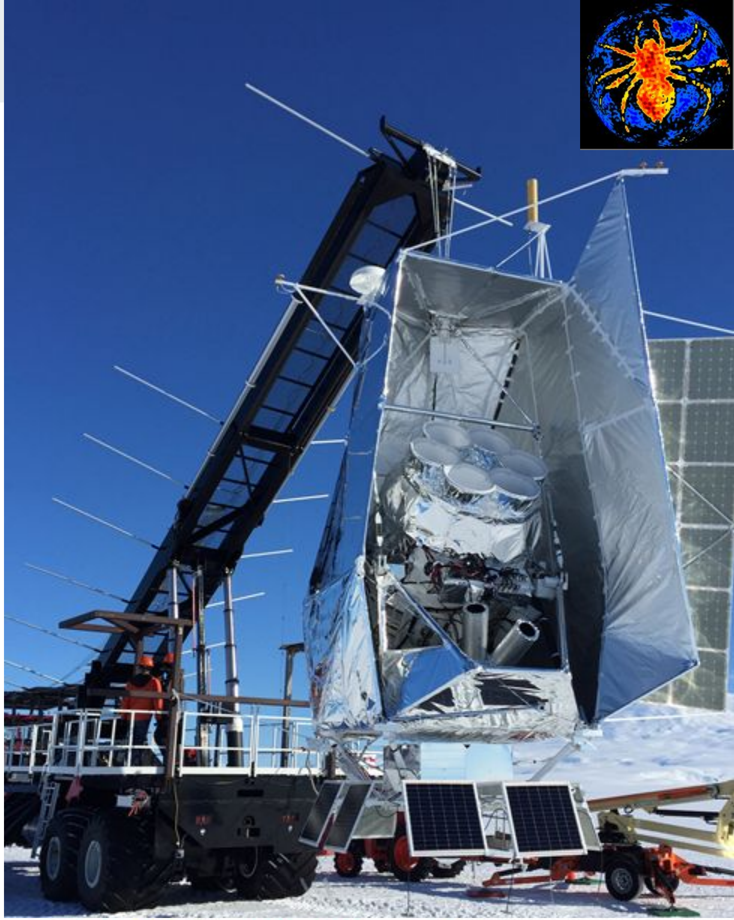






The SPIDER Program

- Balloon borne polarimeter targeting primordial gravitational waves at angular scale
- LDB flight in January 2015
- Multipole coverage: $\sim 10 < ell < \sim 300$
- ~10% of sky coverage
- 2400 antenna-coupled TESs at 90GHz and 150GHz
- SPIDER’s second flight will incorporate payload upgrades and new receivers to map the sky at 285 GHz

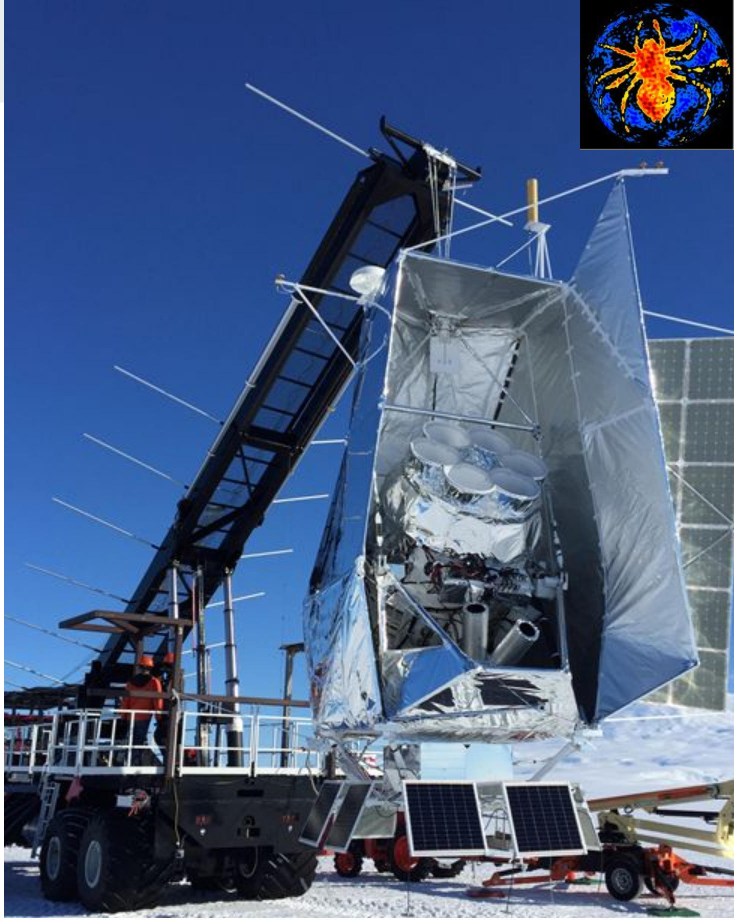


The SPIDER Program

Selected publications

- Gambrel+ arXiv:2104.01172 (2021)
- Ade+ arXiv:2103.13334 (2021): **B-mode results!!**
- Osherson+, JLTP (2020)
- **RG**+ JLTD (2018)
- Nagy+ ApJ 844, 151 (2017)
- Rahlin+ Proc. SPIE (2014)
- Fraisse+ JCAP 04 (2013) 047
- O'Dea+ ApJ 738, 63 (2011)
- Filippini+ Proc. SPIE (2010)

… and more …



The SPIDER Program

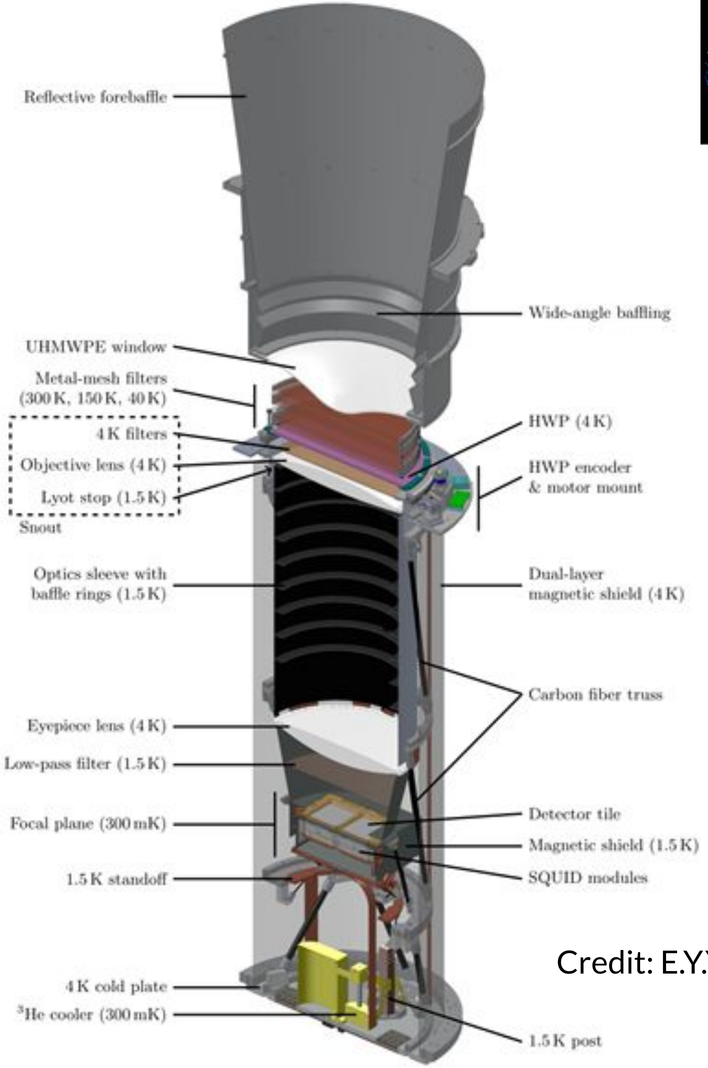
- Payload recovered
- SPIDER's data analysis completed
- All flight systems functioned nominally
- Significant data flagging due to RFI
- Cosmic rays insignificant

E.Y. Young & British Antarctic Survey recovery campaign

Argonne NATIONAL LABORATORY

SPIDER 2015 Payload

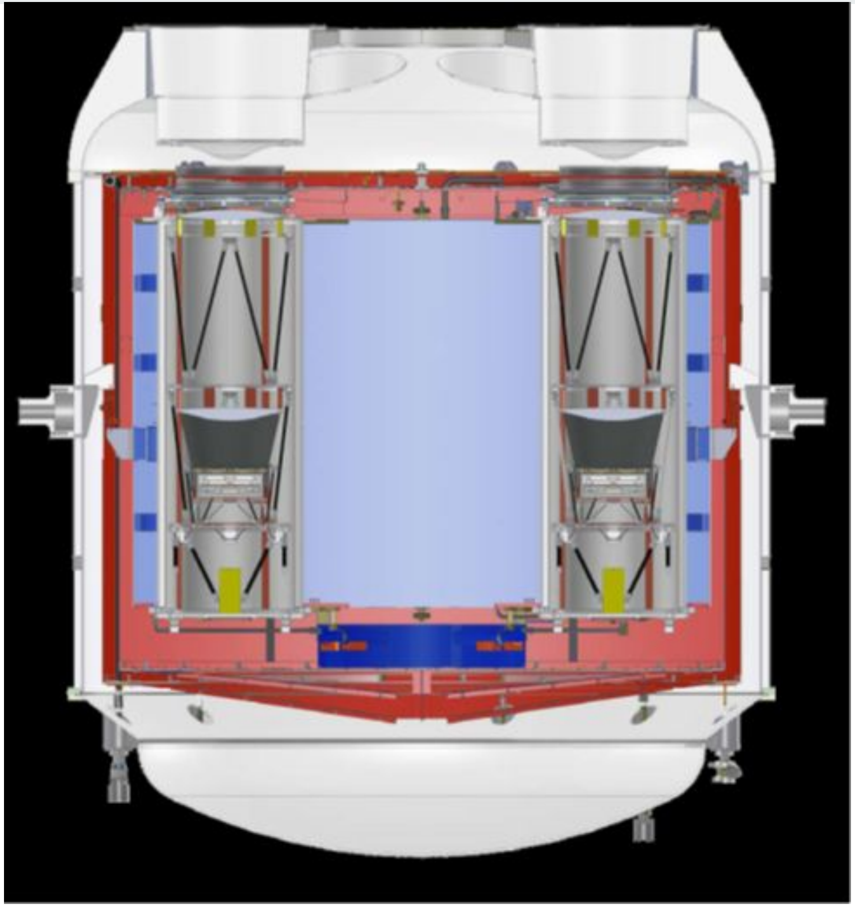
- 300mK focal plane
- Cold refractive optics at 4K
- IR blockers
- Polarization modulator: HWP
- Magnetic shielding
  - Sleeve
  - FPU



Credit: E.Y.Young

SPIDER 2015 Payload

- 1300L LHe main tank
- SF tank continuously refilled through a capillary system
- 6 3He sorption fridges
- Carbon fiber gondola
- Two axis ACS: 1’ pointing accuracy, ~6” post flight

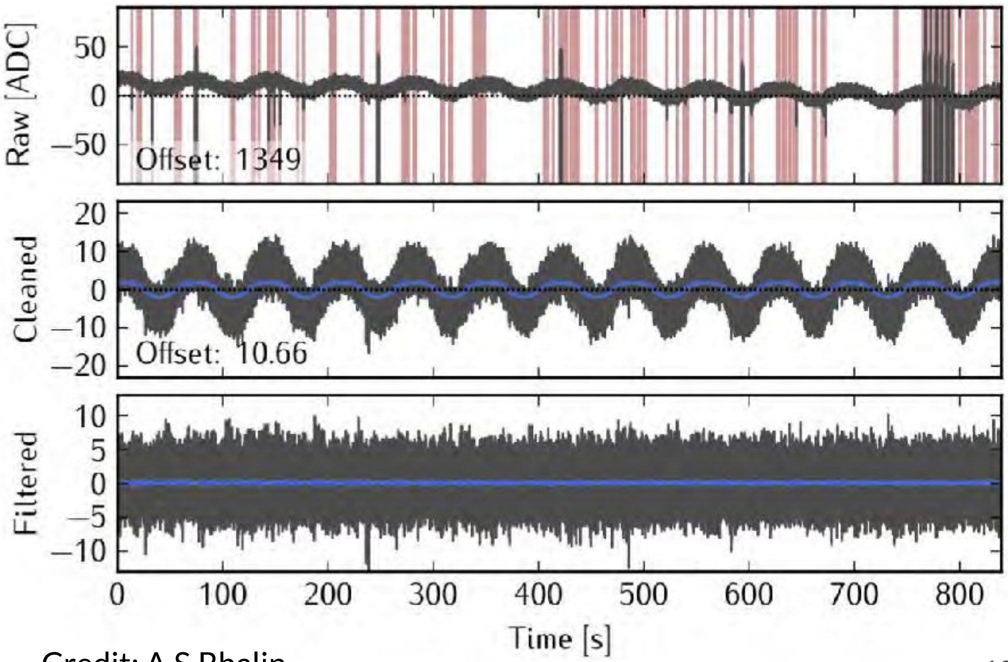


Credit: J.E. Gudmundsson

In Flight Performance

- Exceptionally low internal loading
  - 95 GHz: ≤ 0.25 pW total absorbed
  - 150 GHz: ≤ 0.35 pW total absorbed
- Flagging of samples and channels
  - Negligible from cosmic rays
    - Osherson+, JLTP (2020)
  - Significant from RFI
    - Transmitter handshake every ~1min
- Strict channel / sky cuts this analysis
  - ~1/4 of scan time outside analysis region
  - Wide exclusion around fridge cycles
  - One 150 GHz receiver excluded
- Scan-synchronous pickup (~CMB dipole)
  - Addressed with aggressive filtering

Band	Center [GHz]	Width [%]	FWHM [arcmin]	# Det. Used	NET_{tot} [$\mu K\sqrt{s}$]	Data Used [days]	Map Depth [$\mu K \cdot$ arcmin]
95 GHz	94.7	26.4	41.4	675	7.1	6.5	22.5
150 GHz	151.0	25.7	28.8	815	6.0	5.6	20.4



Credit: A.S.Rhalin

Autonomous Detector Operations

SQUID tuning

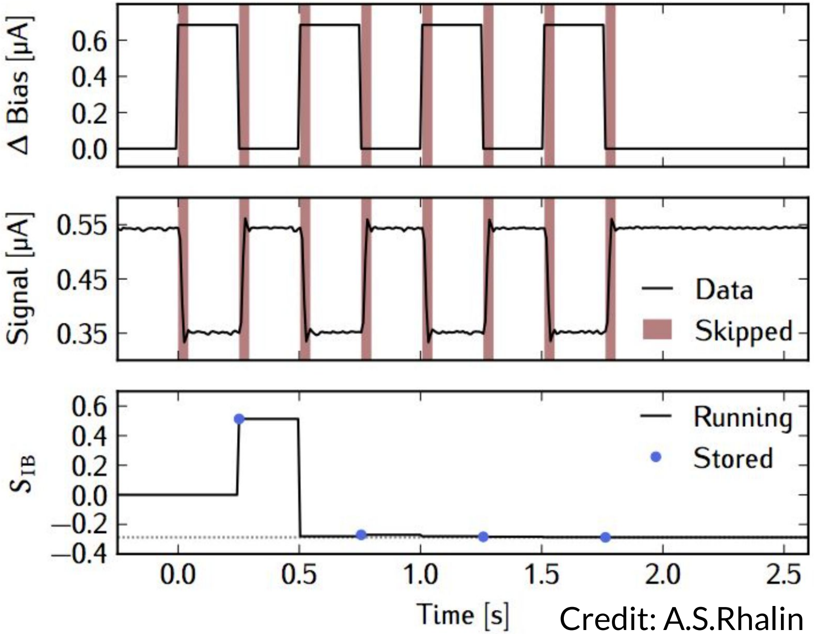
- Retuned (~5 min) after every fridge cycle
- Compares to pre-flight examples, adjusts parameters as needed

Detector responsivity

- Electrical bias step response used as proxy for optical gain variation
- 2s bias step every few turnarounds gives ~0.1% uncertainty
- Monitor loop adjusts TES biases occasionally if needed

Fully automated

- Downlinks minimal statistics to verify functionality

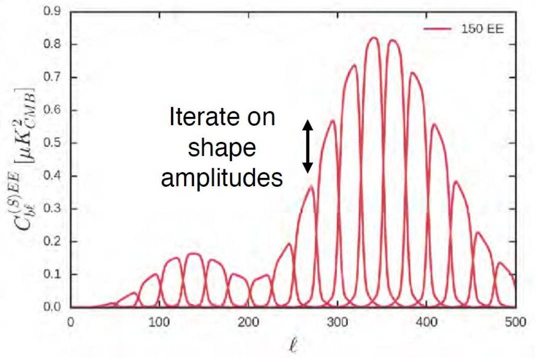


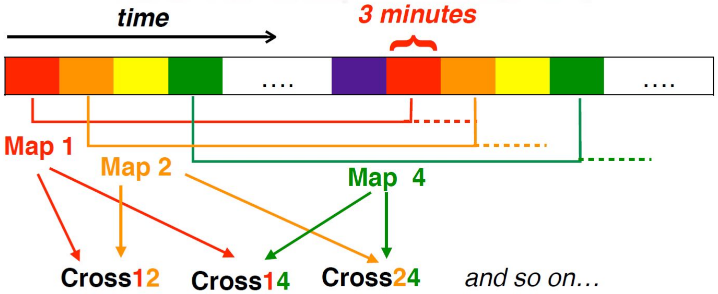
Credit: A.S.Rhalin

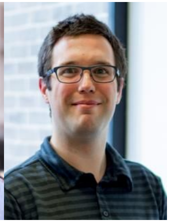
Excellent **gain stability** in flight
Electrical calibration correlates well with in-flight gain estimates

SPIDER Results: Power Spectra Estimators

Complex cross-linking, noise modeling is hard, data redundancy is limited





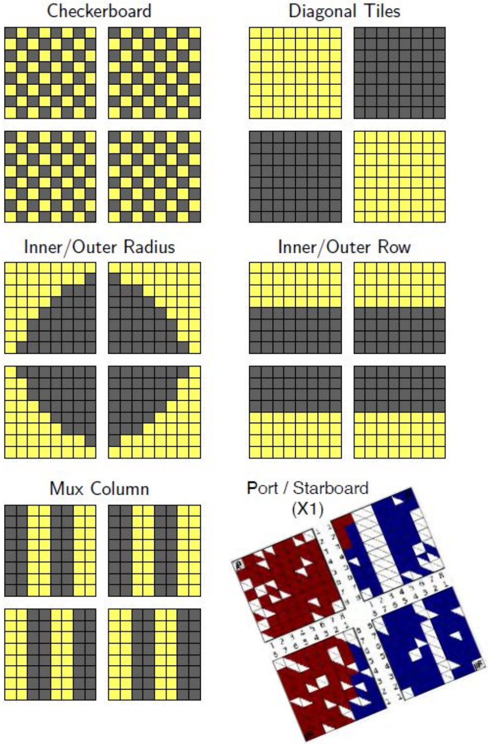
Noise Simulation Independent (NSI):

- PolSPICE pseudo-Cl Monte Carlo
- Signal-only simulation library
- Covariances from cross spectra among 14 data subsets (interleaved 3-min chunks)
  91 crosses/band, 378 total crosses
- *J.M. Nagy, J. Hartley, …*


XFaster: Hybrid maximum-likelihood

- Iterative quadratic estimator in the isotropic, diagonal approximation used by MASTER
- Solves for binned bandpowers using signal and noise simulation library
- Adapted for null tests, foreground sep in progress
- *C. Contaldi, D. Mak, A.E. Gambrel, A.S. Rahlin,arXiv:2104.01172*

SPIDER Results: Null Tests



Internal consistency tests

- Define (near-) equal data splits
  designed to amplify possible systematics / variability
- Difference split maps
- Subtract simulated signal residual
- Compute power spectra

10 data splits:

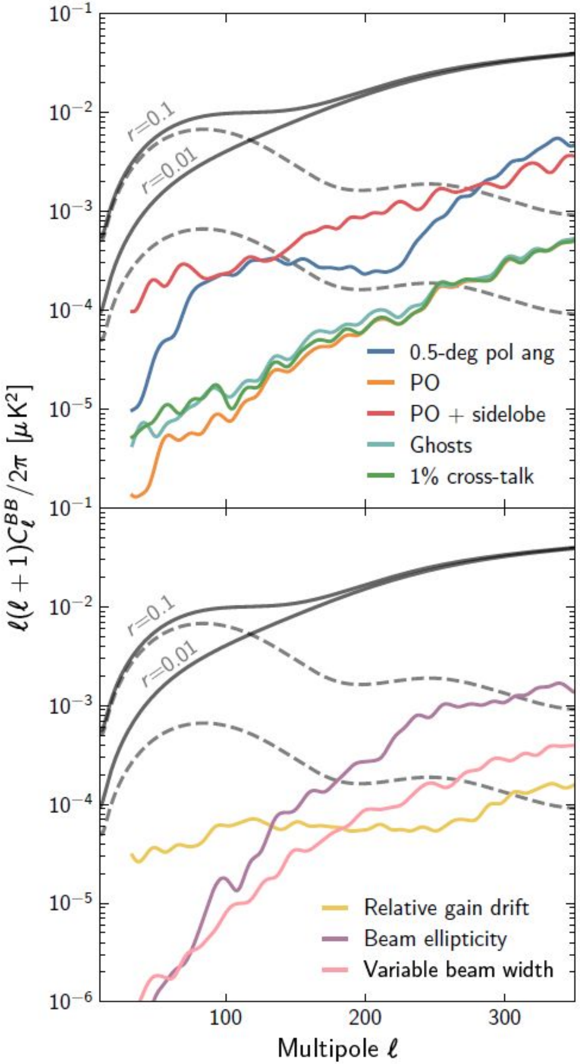
- 6 spatial detector splits (*see left*)
- Highest / lowest band centers
- Left / right-going scans
- 2 mission time splits

	Outlier Test PTE		Distribution Test PTE	
Band	XFaster	NSI	XFaster	NSI
95 GHz	0.38	0.80	0.07	N/A
150 GHz	0.34	0.20	0.21	N/A
Combined	0.78	0.34	0.56	0.50

*Consistent with zero for both pipelines, accounting for **correlations** among detector splits*

SPIDER Results: Systematics

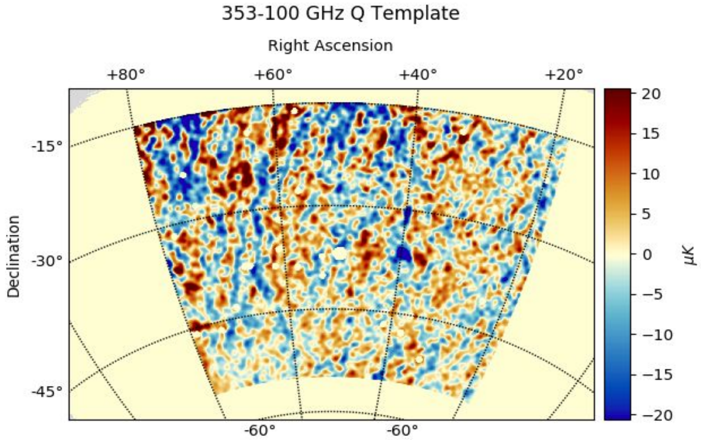
- Simulate effects of known non-idealities
  - Differential beams, gain drift (deprojected)
  - Full physical optics beam convolution
  - Beam ghosts, crosstalk above known levels
- Strong symmetrization by HWP rotation mitigates wide range of beam effects (MacTavish+ 2008)
- Known beam and readout systematics should have **negligible effect** at current sensitivities.

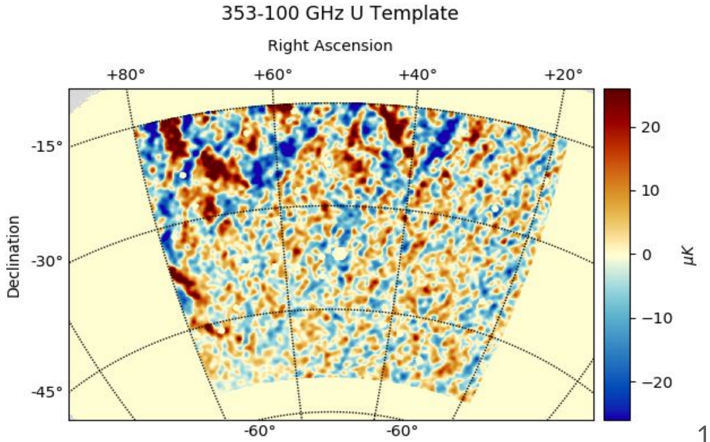


Jon Gudmundsson
Adri Duivenvoorden
Spider Collaboration

SPIDER Results: Foregrounds

- **Spatial template subtraction**
  - Planck 353-100 / 217-100 templates
- **SMICA** Harmonic domain

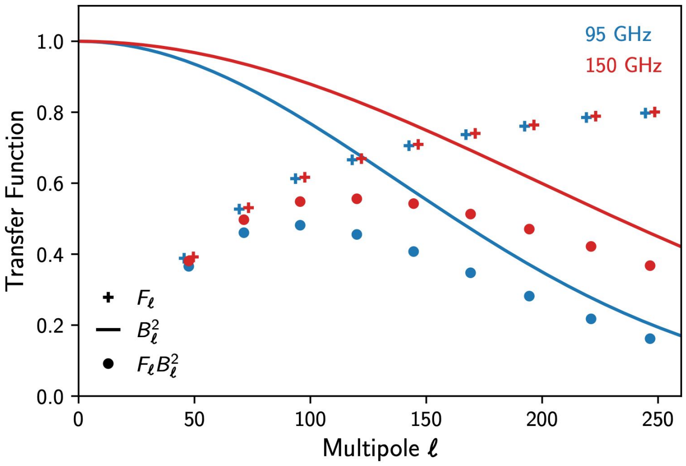


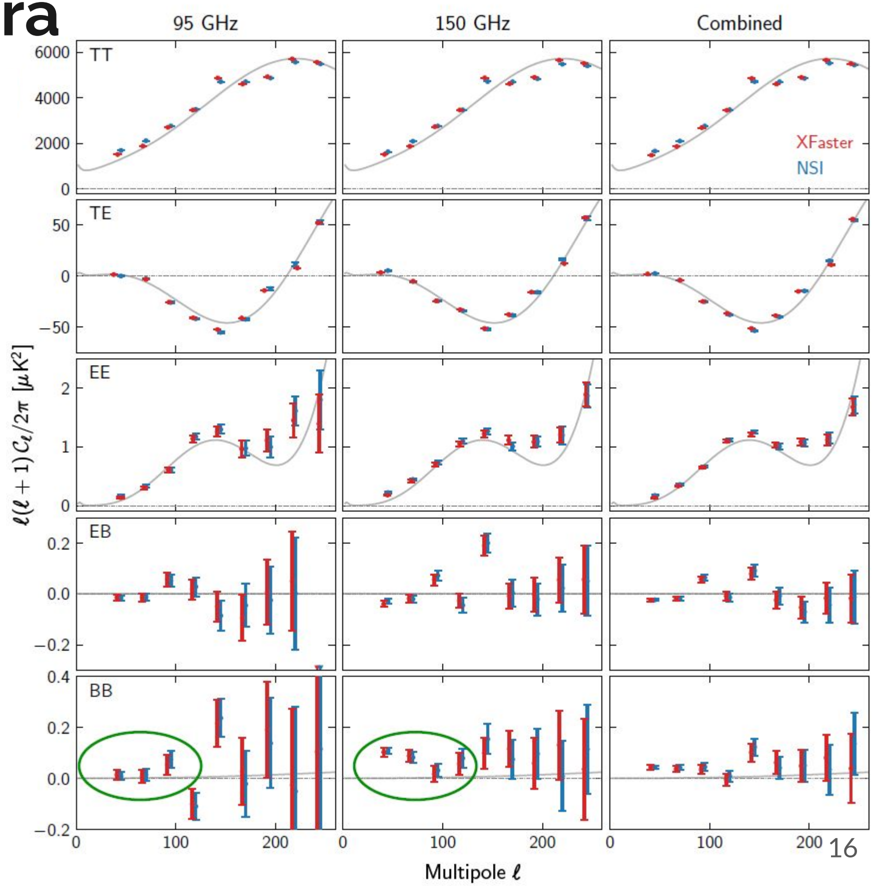


SPIDER Results: Power Spectra

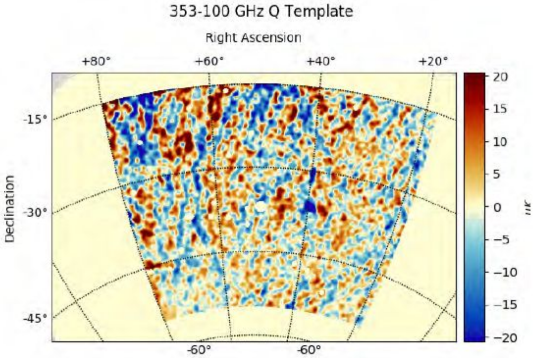
Raw power spectra

- Reduced sky mask: 4.8% sky fraction
  - Point sources removed
- Multipoles: 33<ell<257
  - 9 science bins delta_ell=25
  - Lower and higher bins accounted for leakage



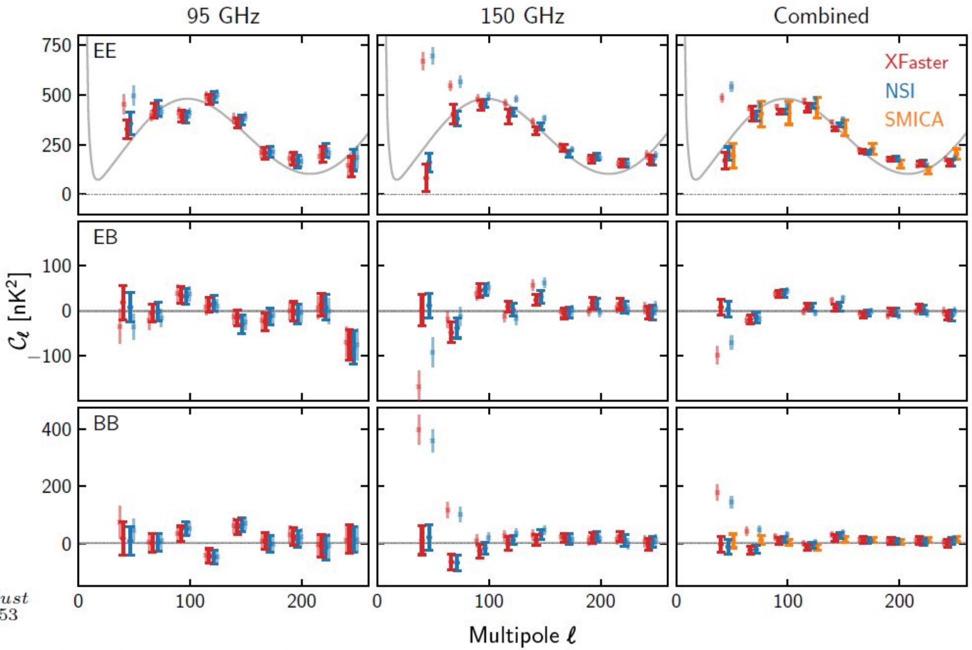


SPIDER Results: Power Spectra



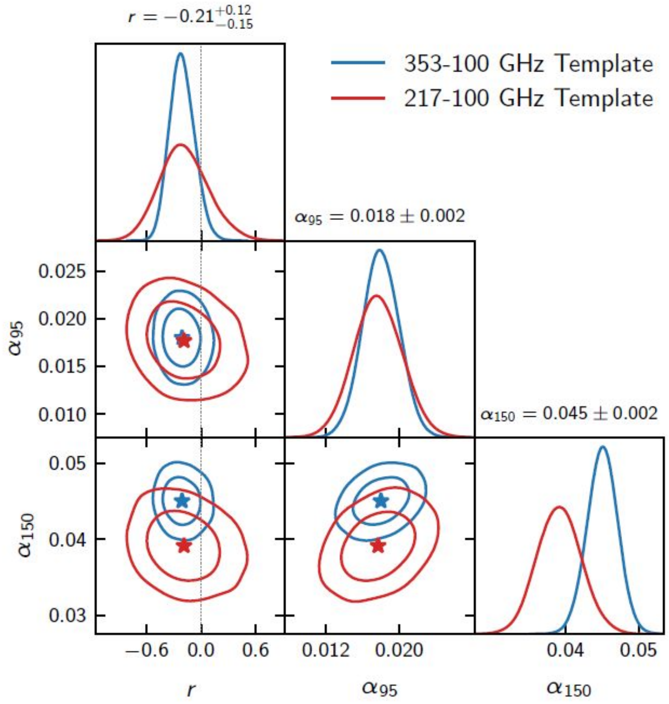
Spectra of maps cleaned by fitting out a Planck-derived template (*353 GHz - 100 GHz*)

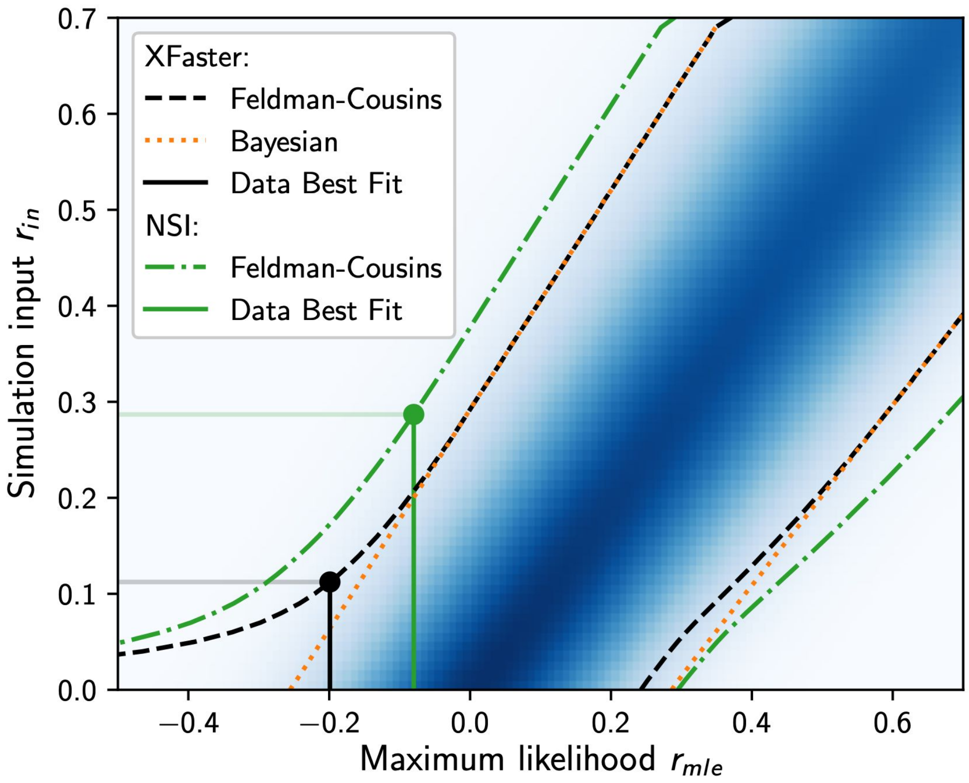
$$
\begin{aligned}
S_\nu &= S^{CMB} + A_{\nu,353} S^{dust}_{353} + n_\nu \\
S^{cleaned}_\nu &= S_\nu - \alpha S^t_{353,100} \\
&= S_\nu - \alpha \left(S_{353} - S_{100} \right) \\
&= S^{CMB} + \left(A_{\nu,353} - \alpha \left[1 - A_{\nu,100} \right] \right) S^{dust}_{353} \\
&\quad + \left(n_\nu - \alpha n^t \right)
\end{aligned}
$$



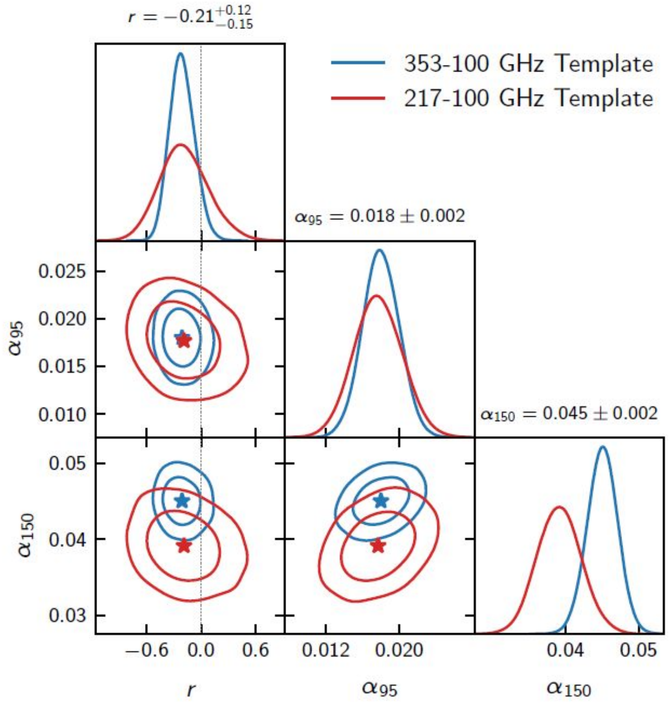
Sample variance included

SPIDER Results: ‘r’ limits





SPIDER Results: *r* limits



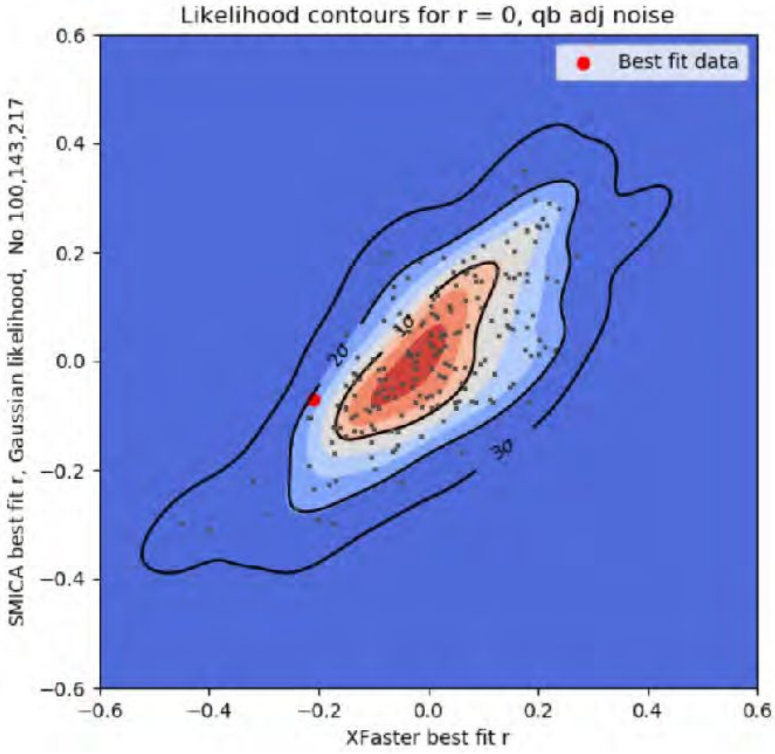
Point estimate	$r = -0.21^{+0.12}_{-0.15}$
Feldman-Cousins (*frequentist*) constraint	$r < 0.11$
Bayesian constraint	$r < 0.19$

Pipeline	Description	r_{mle}	$r \leq 95\%$
XFaster	Nominal, Feldman–Cousins	-0.21	**0.11**
	Nominal, Bayesian	-0.21	**0.19**
	NSI-like:		
	(*a*) *r* from *BB* only	-0.19	–
	(*b*) Independent *EE* & *BB* noise	-0.19	–
	(*a*) + (*b*)	-0.15	–
NSI	Nominal, Feldman–Cousins	-0.09	0.23
	Nominal, Bayesian	-0.09	0.27
SMICA	Nominal, Bayesian	0.06	0.24
	Template-like:		
	Excl. *Planck* inputs < 353 GHz	-0.07	–

SPIDER Results: *r* limits

- Results paper explores *r* estimates derived from **XFaster**, **NSI**, **SMICA**
- All estimators found to be unbiased on simulations
- Choice of data (Planck maps, etc.) and method found to move r_{mle} by O(0.1)
- Largely consistent with simulations

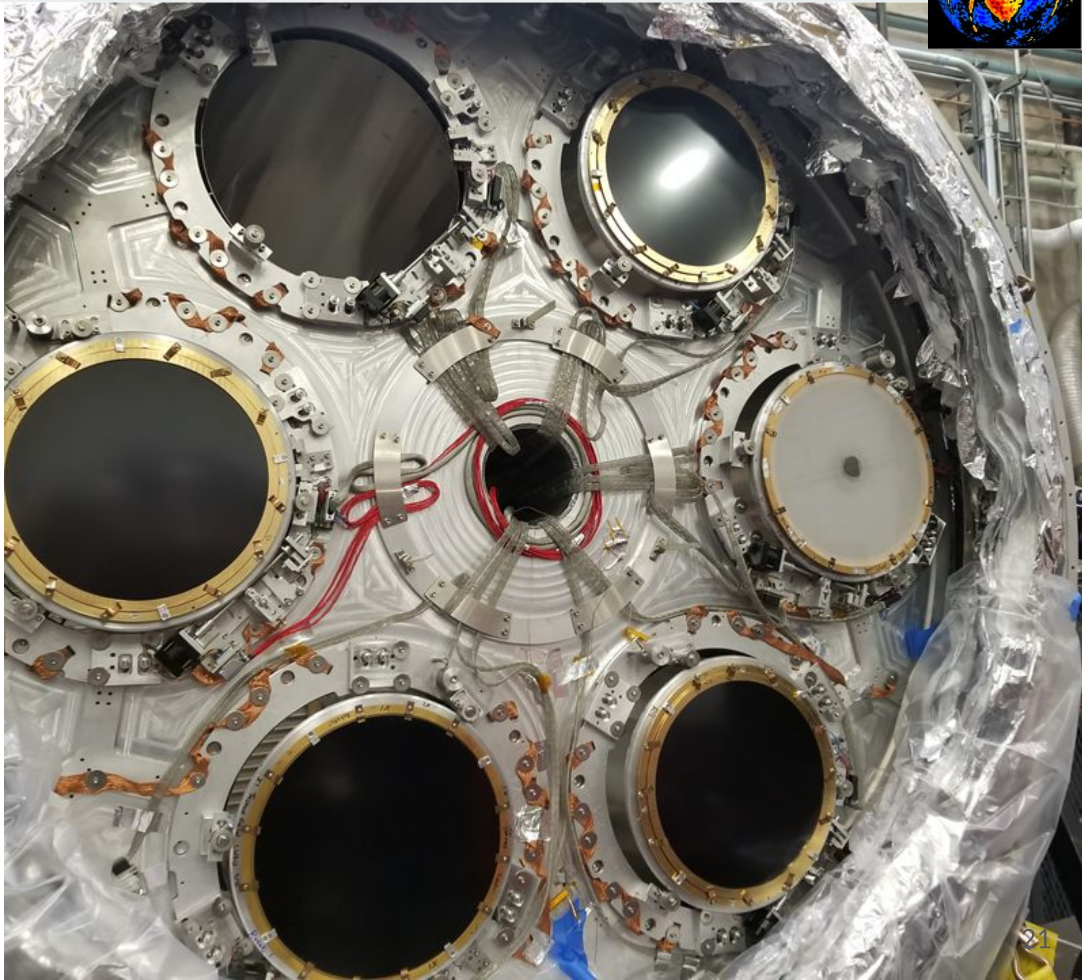
Much more detail in the results paper!



SPIDER 2

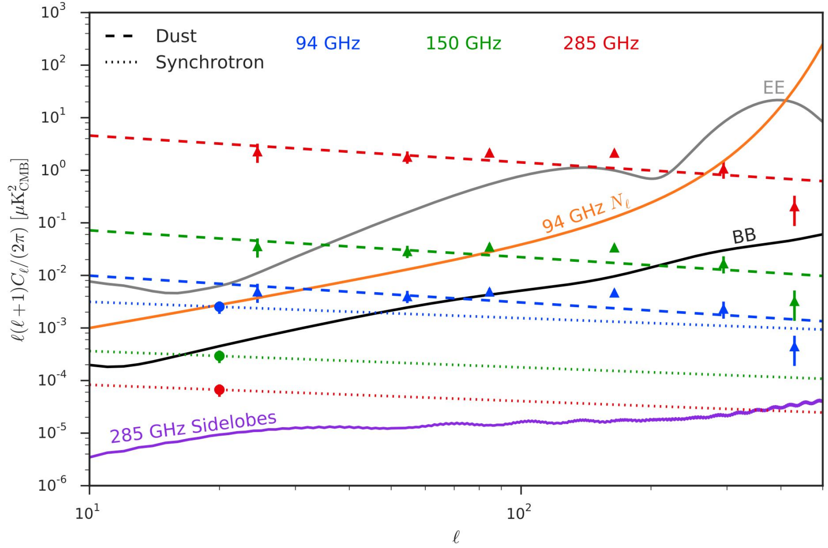
- Lightweight LHe cryostat
- 3 X 150GHz inserts
- 3 X 285GHz "Dust Monitors"
- 285GHz feedhorn coupled detectors by NIST
- New low noise design SSAs

Shaw+ 2020
Bergman+ 2018
RG+ 2018
Hubmayr+ 2016

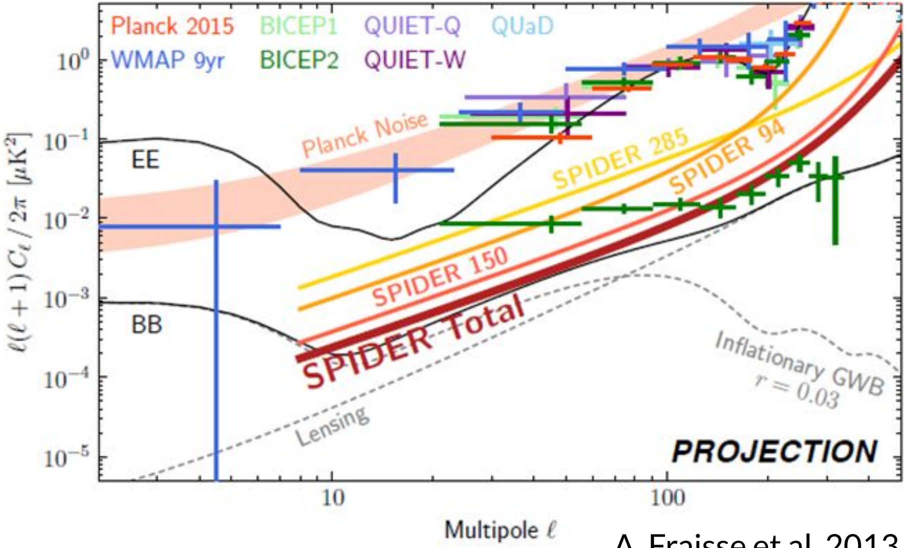


SPIDER 2

Commander foreground estimate

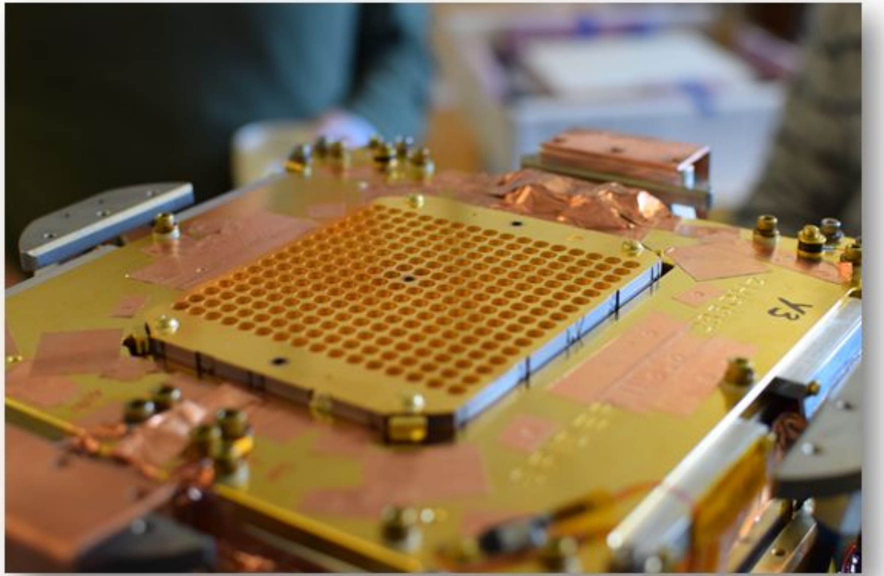


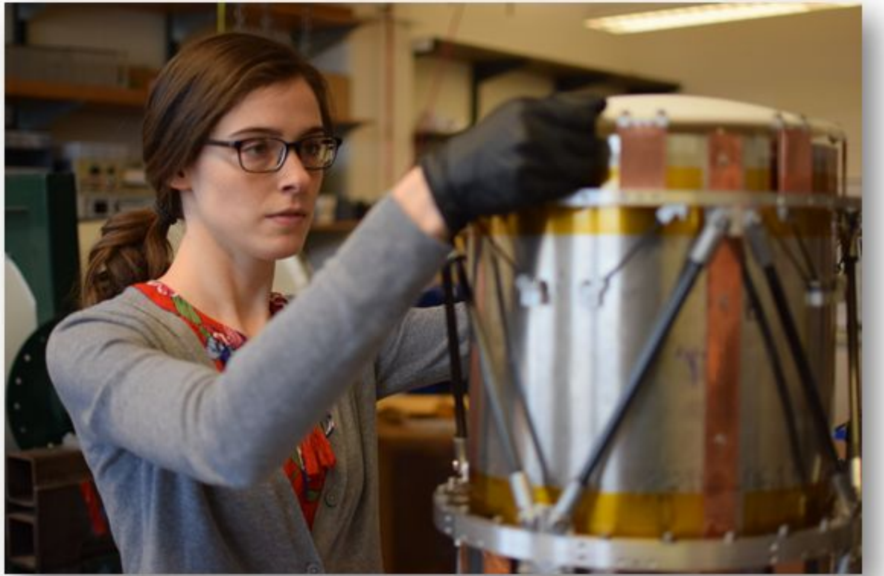
Proposal sensitivity - 2 flights



A. Fraisse et al. 2013

SPIDER 2

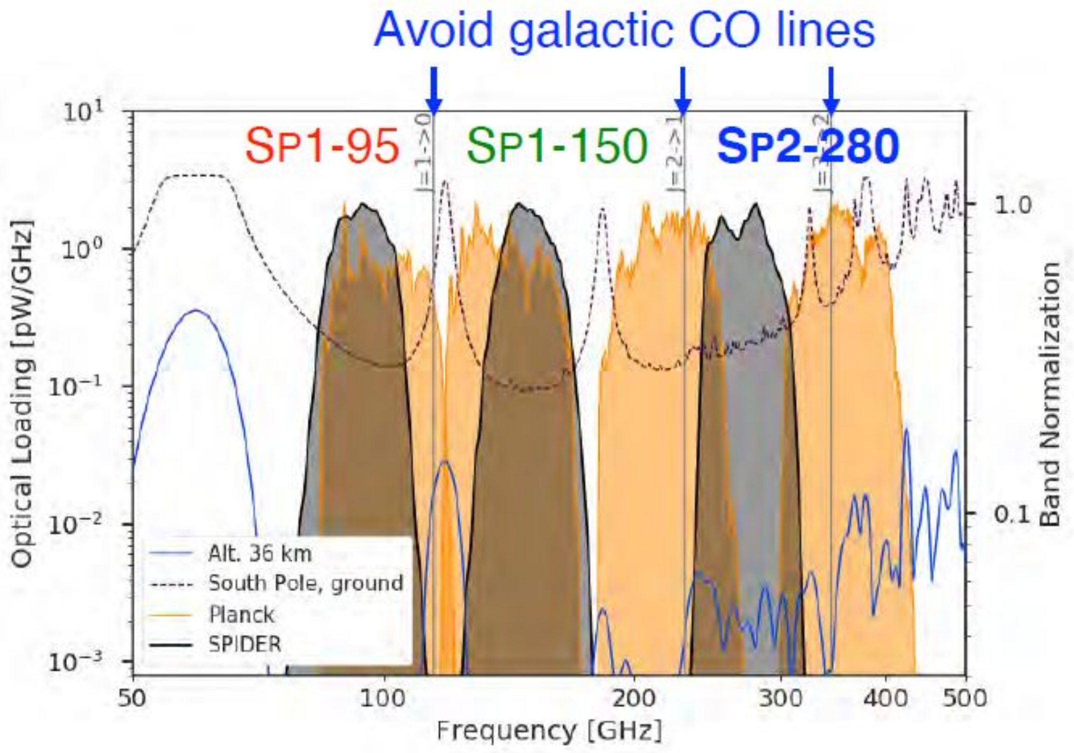




E.C.Shaw assembling the 280 receiver at UIUC

SPIDER 2

- Expanded frequency coverage to resolve foregrounds with post-Planck sensitivities
- 3x 280 GHz receivers, new optical design
- Best 95/150 receivers from first flight
- Second flight targeting ~~2018/19~~ ~~2019/20~~ ~~2020/21~~ (🦠) 2022/23? austral summer



Conclusions

SPIDER's first voyage to near-space was very successful!

Primordial gravitational waves remain elusive

95/150 GHz, 6% of the sky: $r < 0.11$ (0.19)

More to come on foregrounds and analysis techniques

SPIDER-2 is ready to map the sky at 280 GHz

Upcoming papers on:

- Low-level processing
- NSI transfer function
- Foregrounds phenomenology