European Low-Frequency Survey (ELFS)

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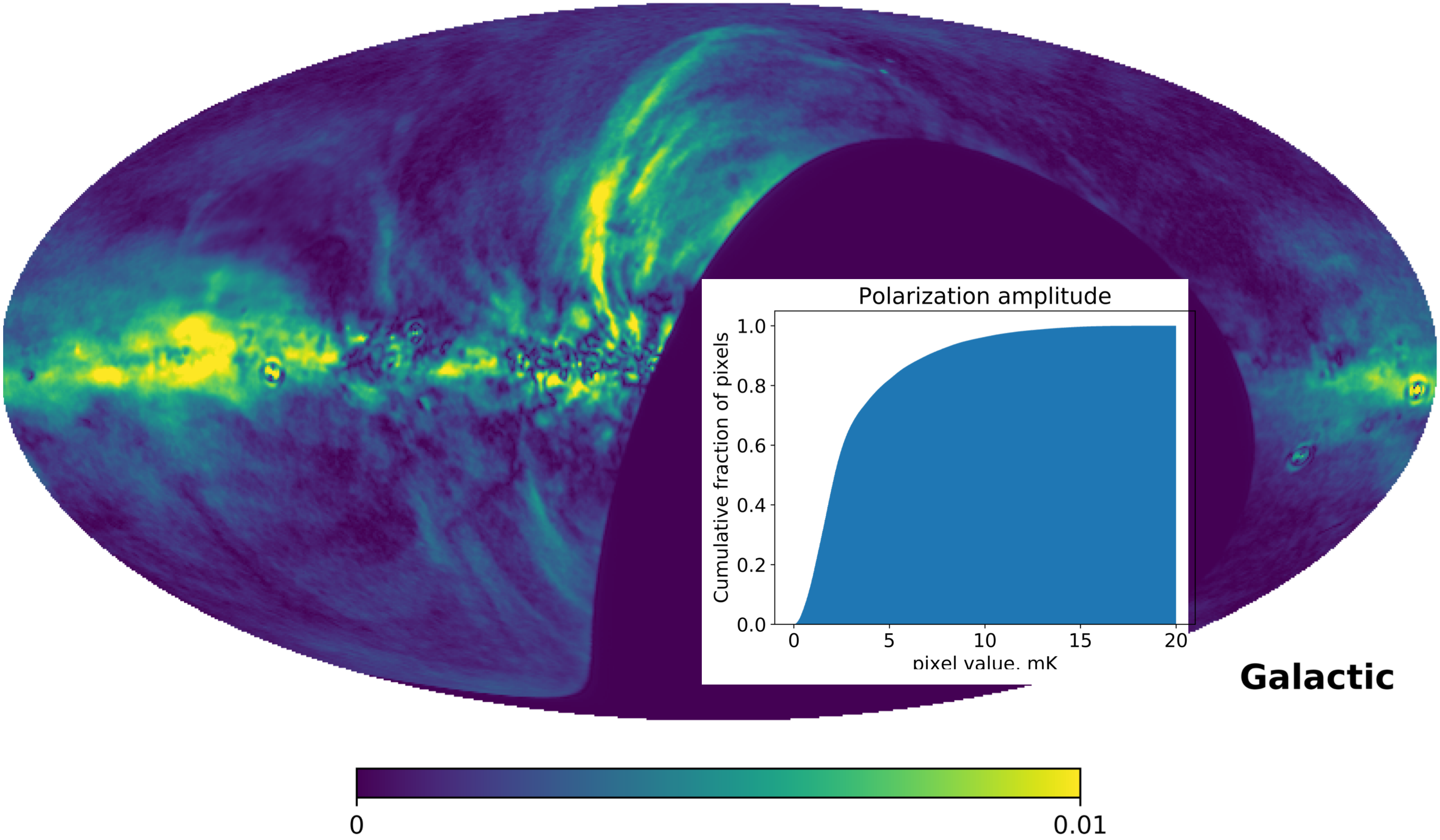
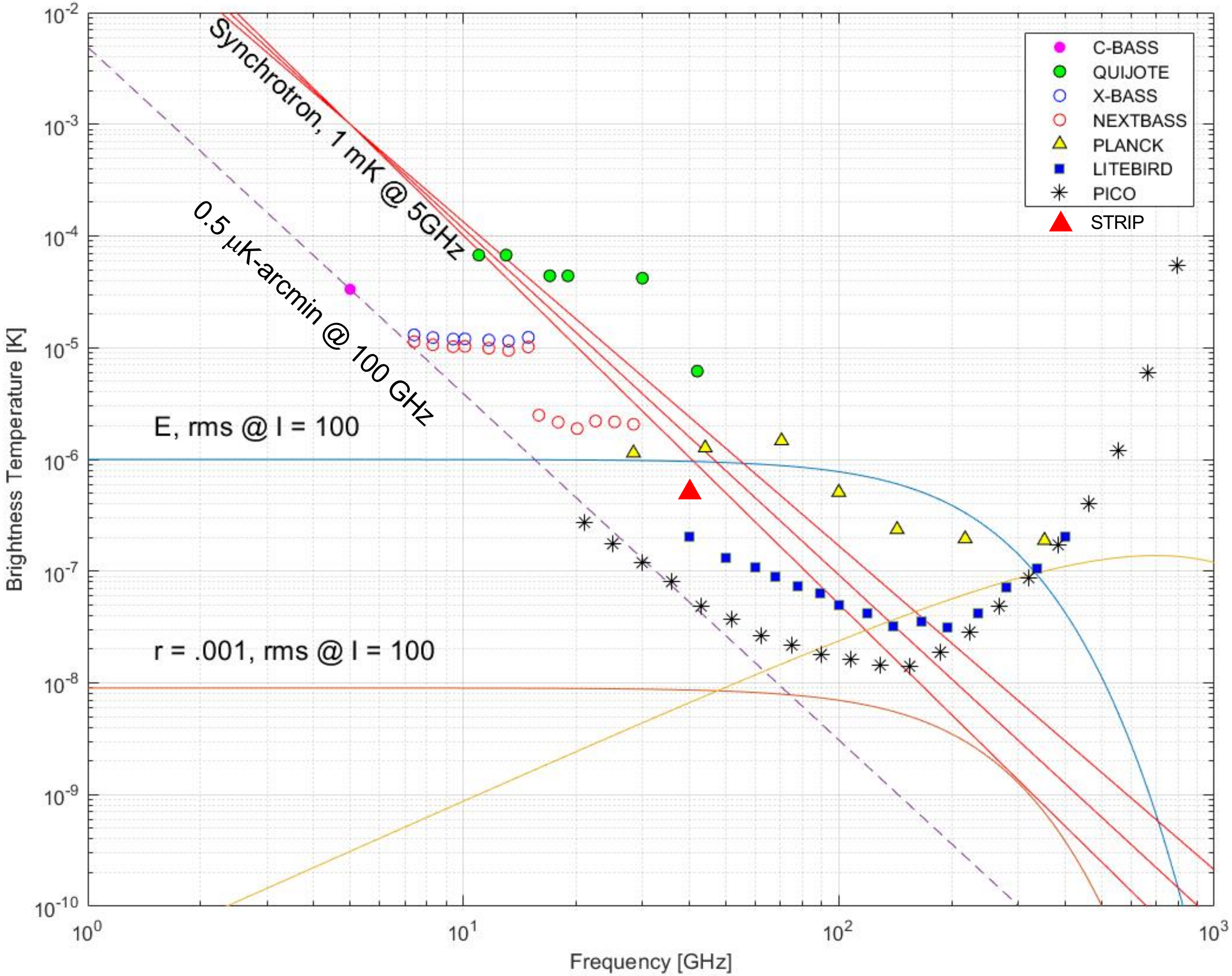
Polarized synchrotron is everywhere!



Why do we need low frequency?



The Low-Frequency Manifesto

- We will not get to $r < 10^{-3}$ just by observing at >40 GHz – low freq foregrounds are too complicated.
- The CMB community needs a 10 – 40 GHz (plus ~100 GHz) dedicated observatory
- This needs full sky coverage (to complement satellite missions) and wide l range, so
- Two sites (north and south) and low-l and high-l components
- The European community is uniquely well-placed to do this

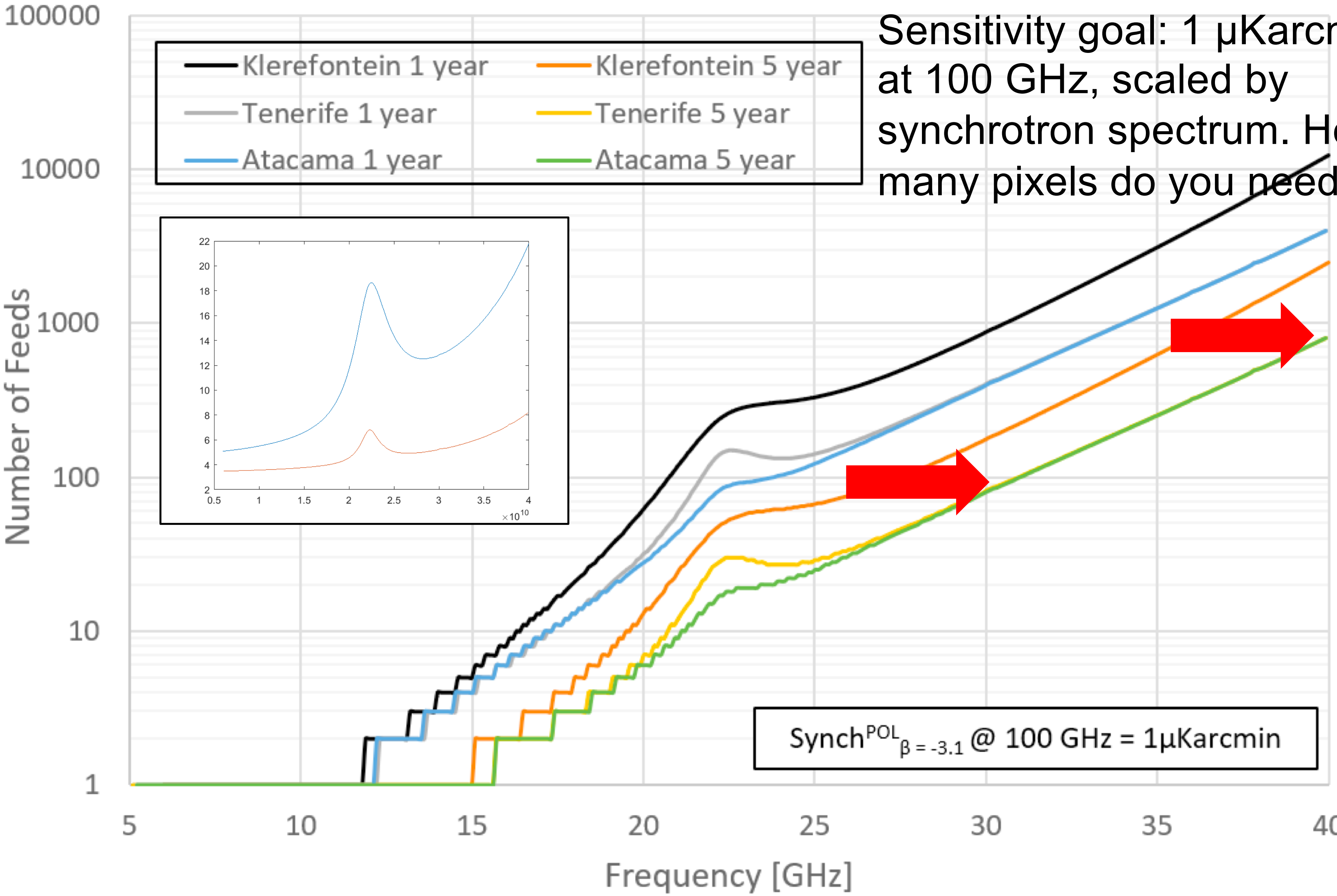
Specifications for ELFS

- Frequency: synchrotron-dominated range (from ground)
  - 10-40 (radiometer) – essential complement to CMB-S4, satellites.
  - 90-120 GHz (KIDS) – no other high-freq, high-res in north
- All-sky so two sites
- Sensitivity: 0.5-1μK-arcmin scaled to 100 GHz
  - Few elements at 5-20 GHz
  - >100 elements at 20-40 GHz
  - >1000 elements at 100 GHz
- Resolution: *l*>1000 at lowest frequency
  - ~6-m class telescope for low *l*
  - Interferometer array for higher *l*?
- Systematics: highly-shielded optics to eliminate

ELFS Proposal

- Two 6-m telescopes, shielded crossed Dragone
  - CCAT-p/SO LAT-like, but relaxed surface/pointing specs
- Two interferometer arrays, ~20 x 4-m, for high *l*?
- Sites in northern and southern hemispheres
  - Tenerife, Atacama? (or La Silla? Or Argentina? Or…?)
- 10 – 40 GHz HEMT radiometer array with *O*~100 elements
  - Two scaled octave-band corrugated feeds, 10 – 20 GHz (a few) and 20 – 40 GHz (most).
- Digital polarimeter
  - Continuous frequency coverage with high freq resolution (for RFI and science)
  - Simultaneous I, Q, U from every pixel
- KIDS array for 90 – 120 GHz
  - Sequential operation on each telescope

How much sensitivity?



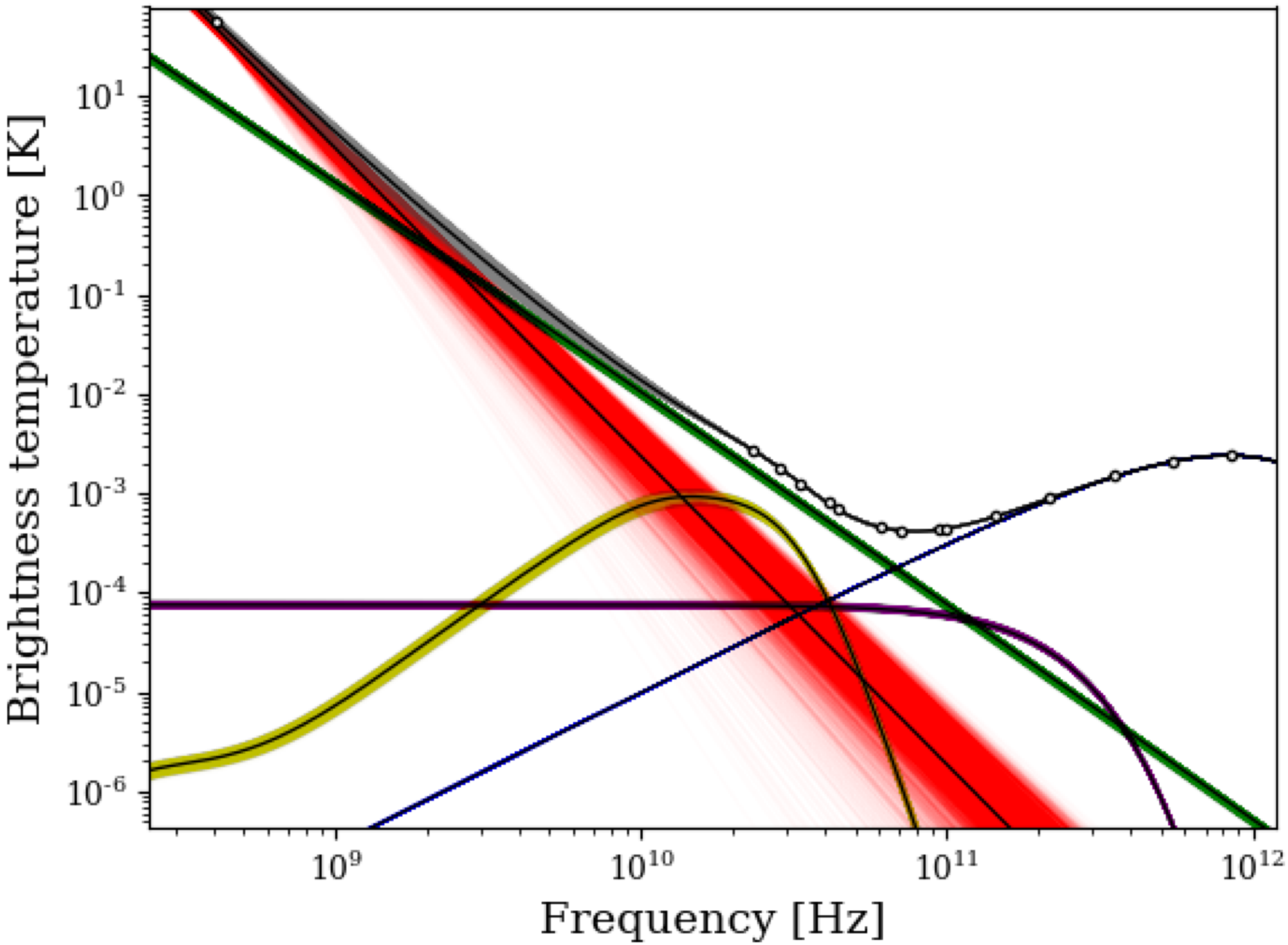
Sensitivity goal: 1 μKarcmin at 100 GHz, scaled by synchrotron spectrum. How many pixels do you need?

UNIVERSITY OF OXFORD

Sensitivity – 1/100 element array with realistic T_{sys}

frequency	beam sens (uK)	uK arcmin array	synch factor	uK arcmin scaled	multipole
7.1	35.6	850	4786	0.18	904
7.9	39.8	847	3311	0.26	1015
8.9	44.1	837	2291	0.37	1138
10.0	49.5	837	1585	0.53	1277
11.2	55.3	833	1096	0.76	1433
12.6	62.4	838	759	1.10	1608
14.1	71.1	851	525	1.62	1804
15.8	8.0	87	363	0.24	1991
17.8	9.3	90	251	0.36	2234
20.0	11.9	103	174	0.59	2507
22.4	19.9	153	120	1.27	2813
25.1	15.7	107	83	1.29	3156
28.2	16.6	101	58	1.76	3541
31.6	20.1	110	40	2.75	3973
35.5	23.7	115	28	4.17	4458
39.8	27.8	120	19	6.30	5002

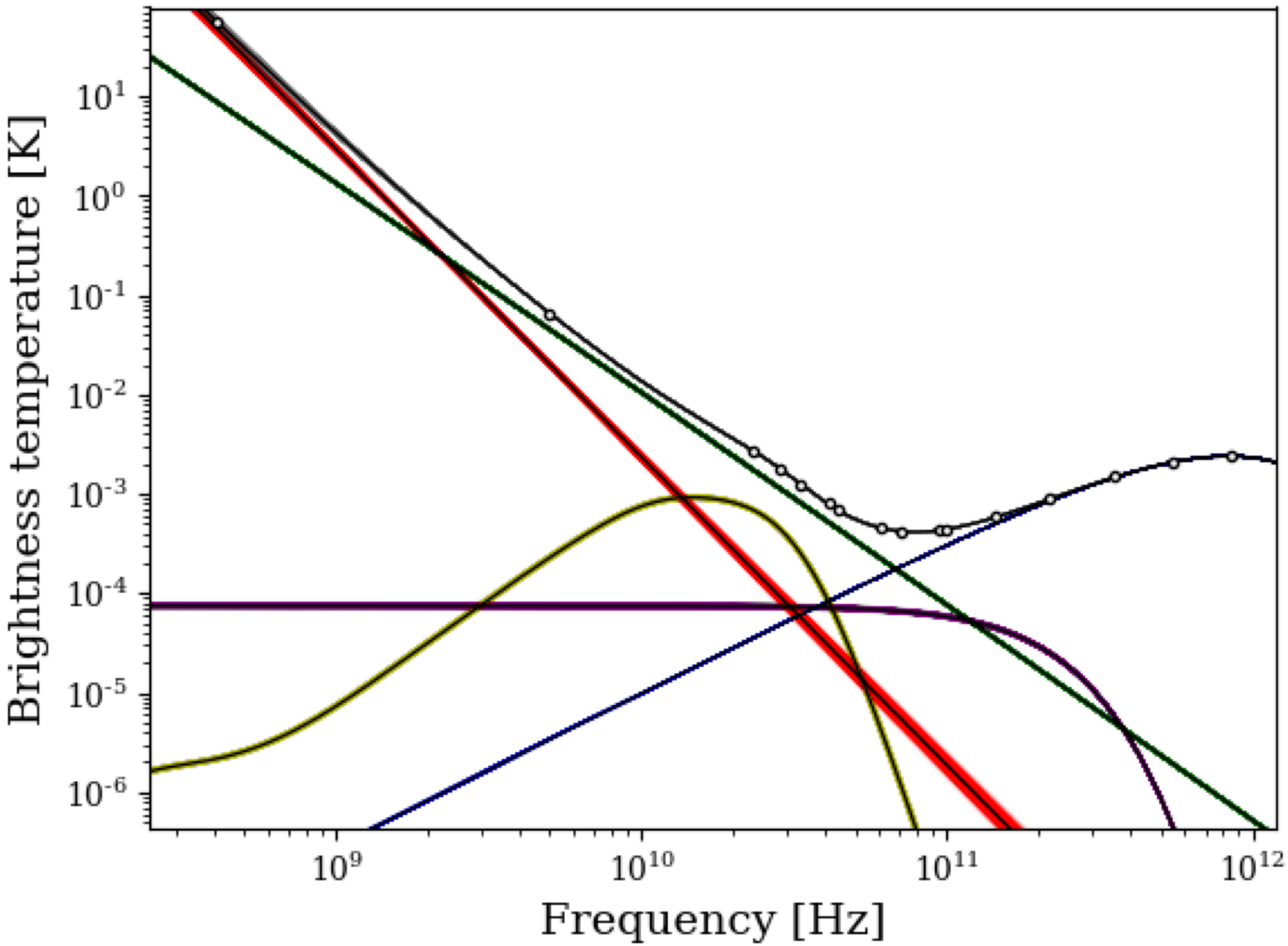
Single-pixel component separation - I



Haslam
WMAP
Planck

High-foregrounds pixel (1-deg)

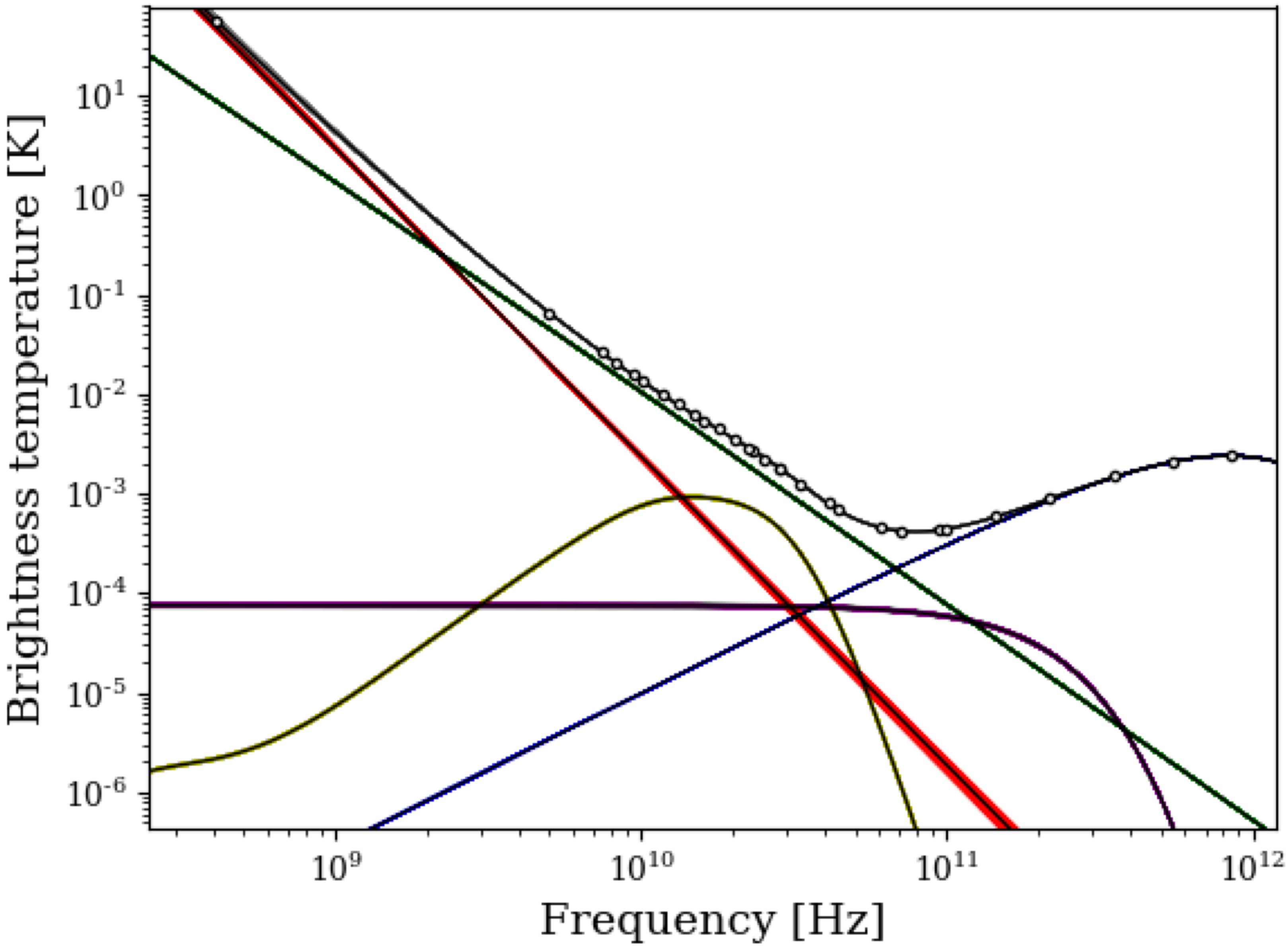
Single-pixel component separation - I



Haslam
WMAP
Planck
+ CBASS

High-foregrounds pixel (1-deg)

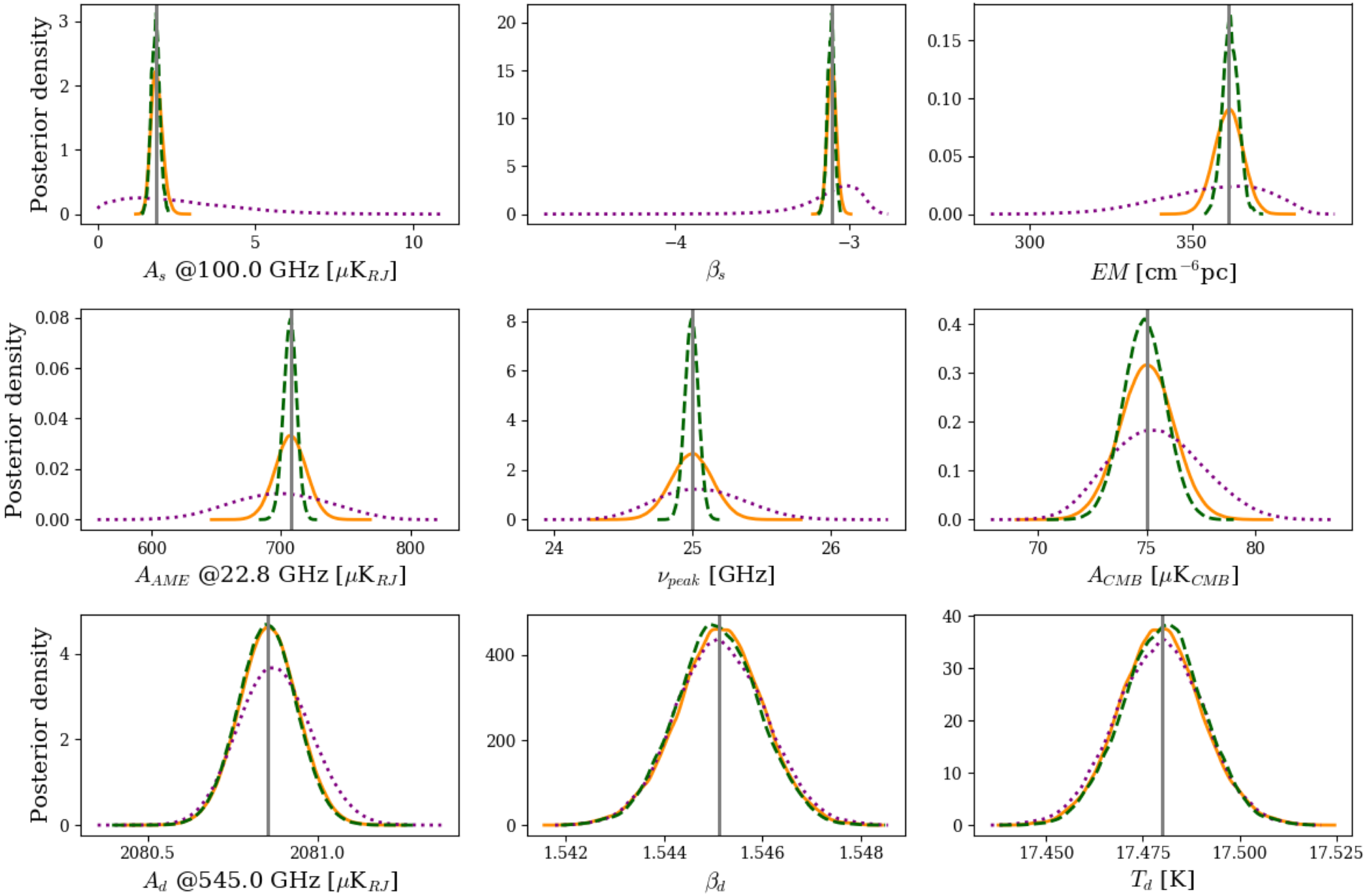
Single-pixel component separation - I



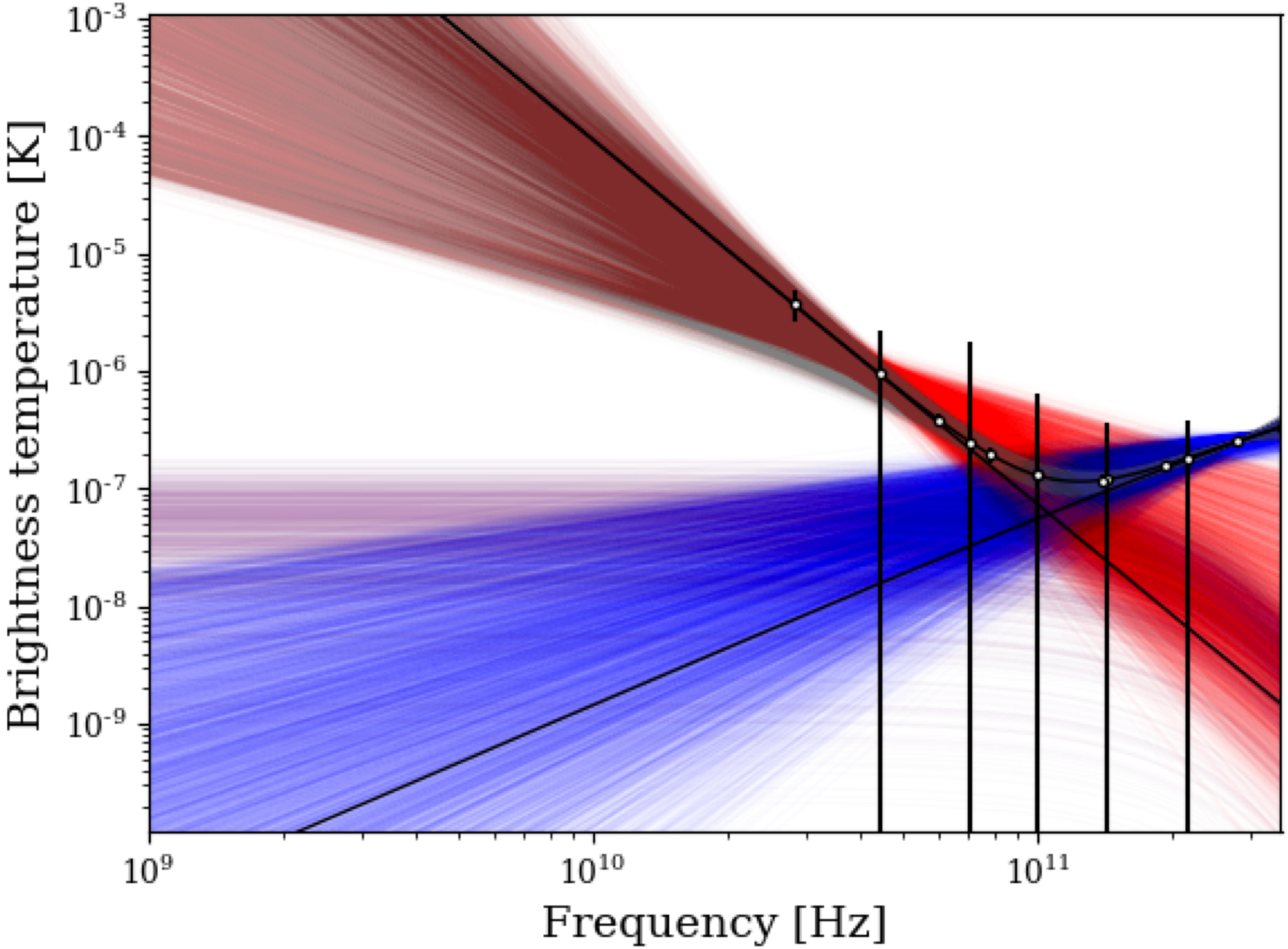
Haslam
WMAP
Planck
+ CBASS
+ ELFS

High-foregrounds pixel (1-deg)

Single-pixel component separation - I



Single-pixel component separation - P

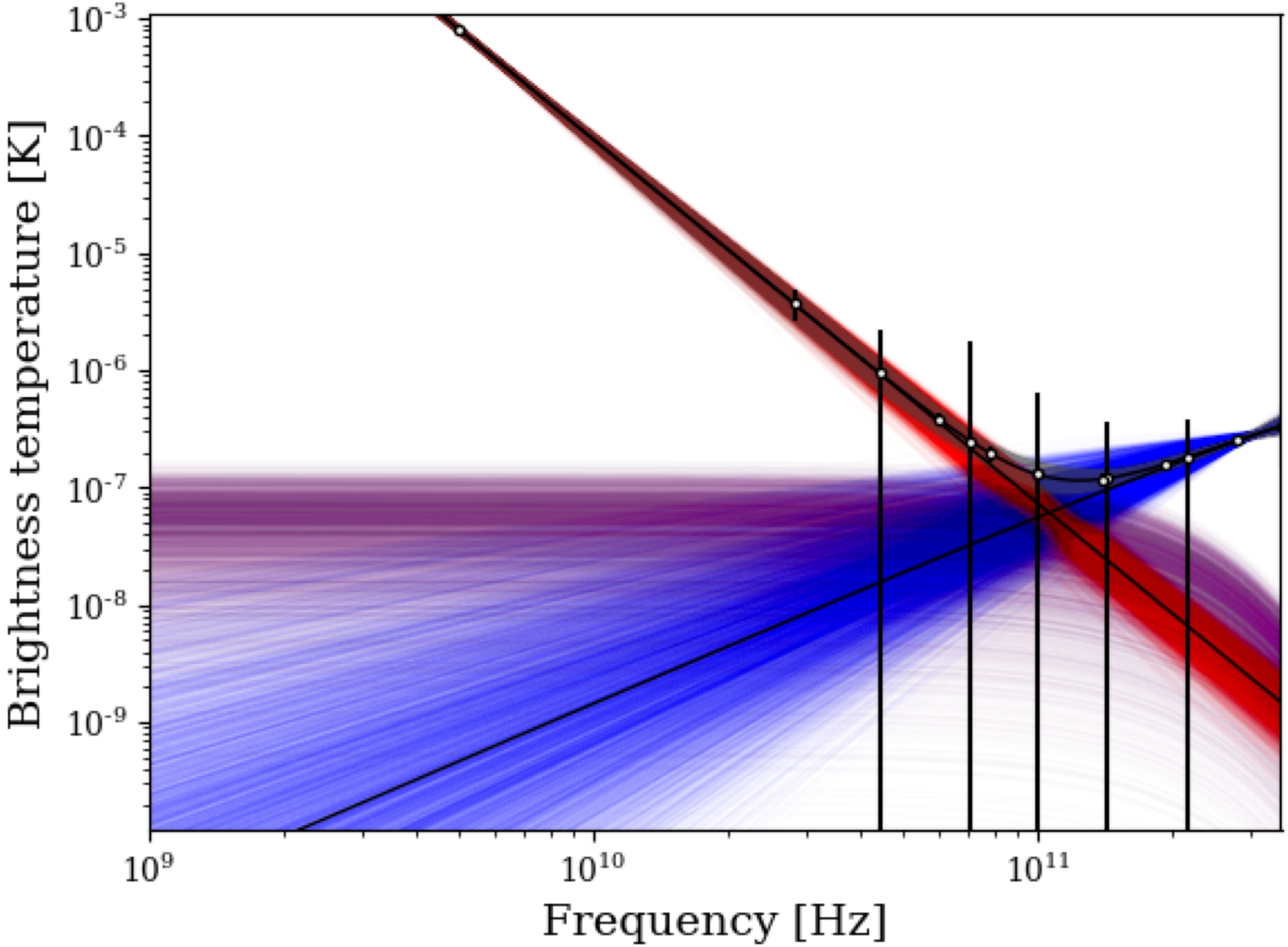


Planck
'LiteBIRD'

Low-foregrounds
Pixel (3-deg)

$r = 0$

Single-pixel component separation - P

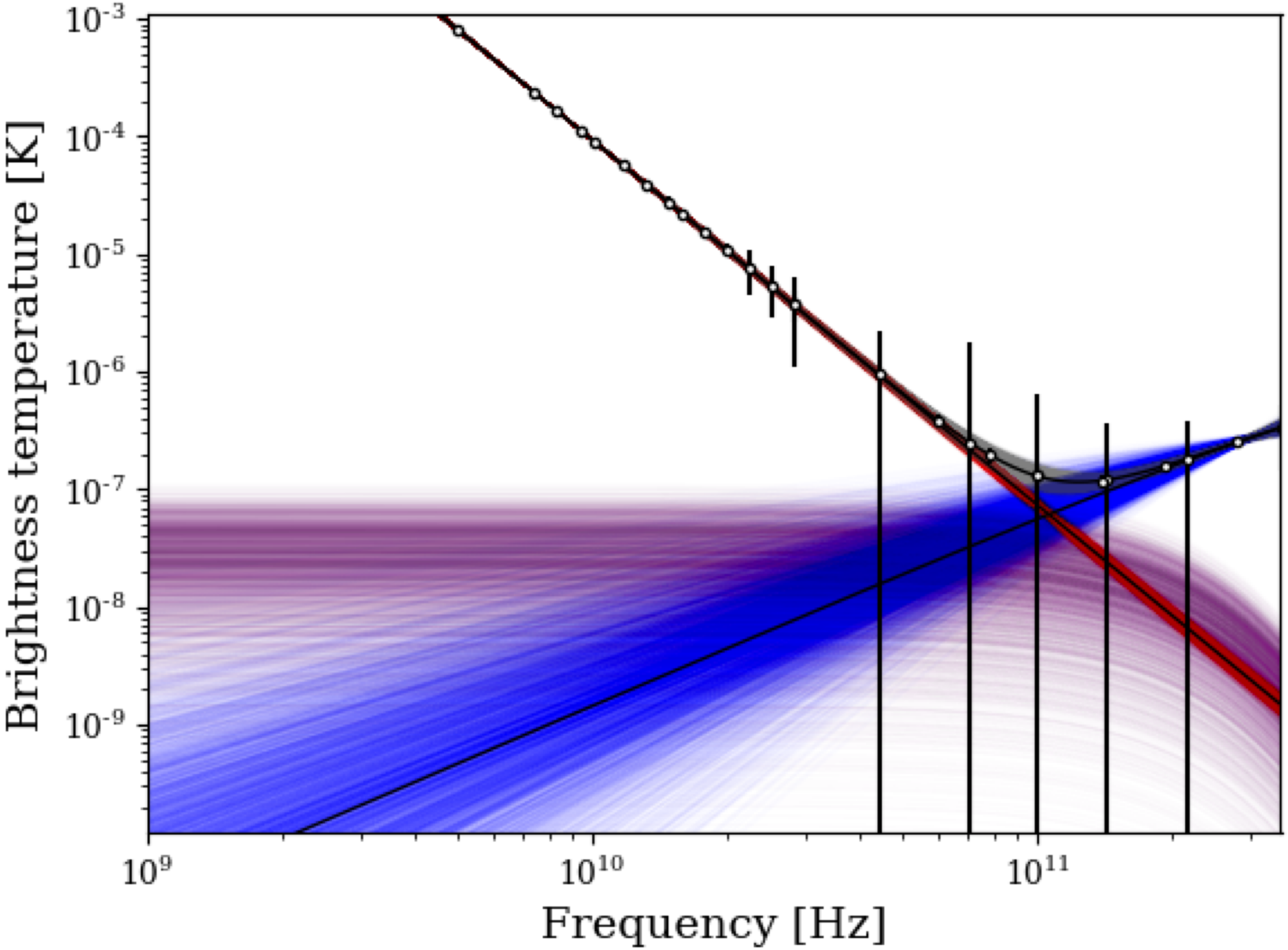


Planck
'LiteBIRD'
+CBASS

Low-foregrounds Pixel (3-deg)

$r = 0$

Single-pixel component separation - P

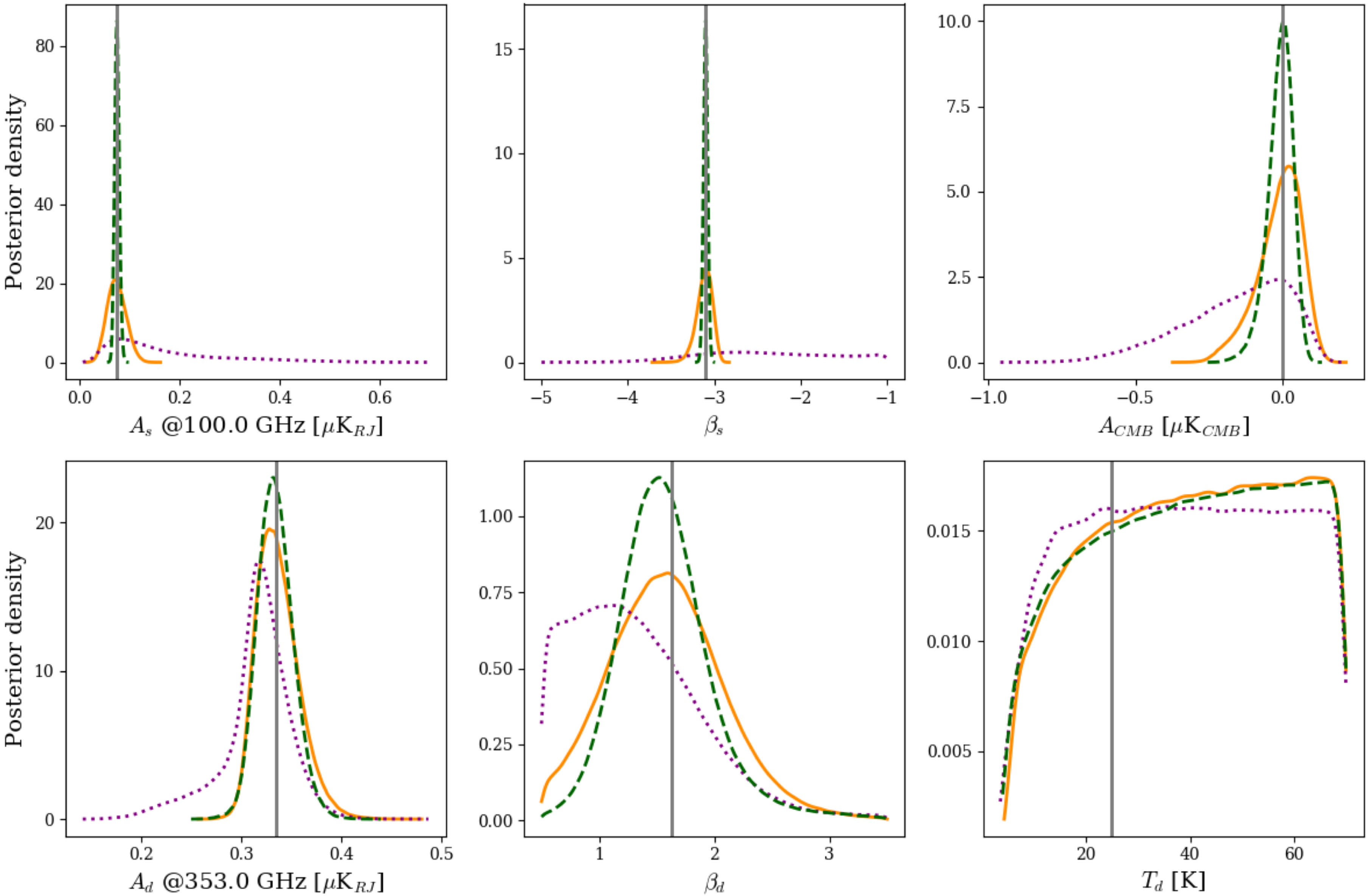


Planck
'LiteBIRD'
+CBASS
+ELFS

Low-foregrounds Pixel (3-deg)

r = 0

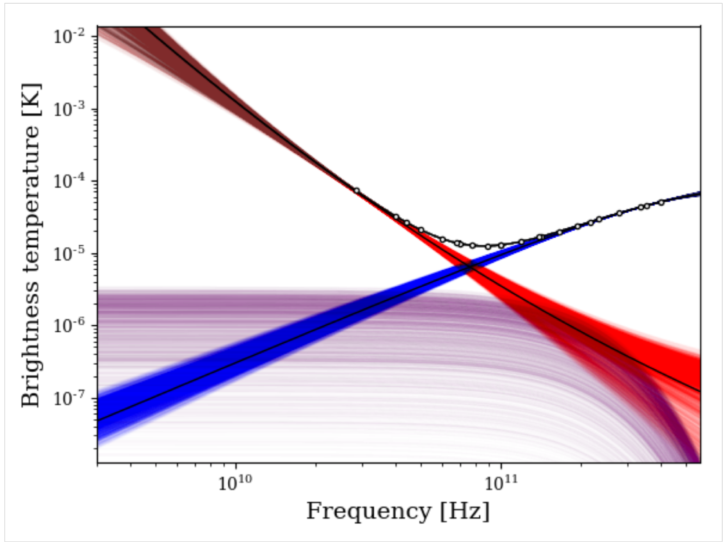
Single-pixel component separation - P



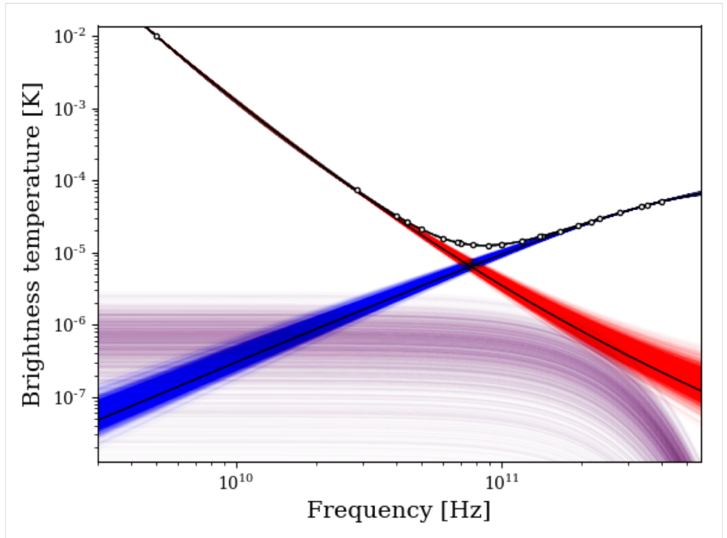
More complicated models?

- Synchrotron is not a single power law
  - Curvature/breaks due to volume averaging and intrinsic energy spectrum
  - Simplest next model is a curvature term C
- AME may not be unpolarized
  - Until you prove it isn't, need to include in models
- More parameters will need more measurements/sensitivity
  - Model with PICO freqs/sensitivity
  - 21 bands, 21 – 800 GHz, plus C-BASS, plus ELFS

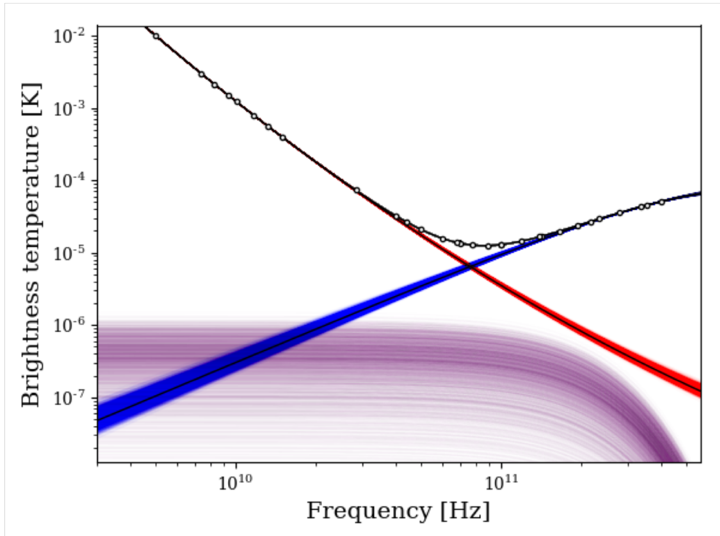
Curved synchrotron model



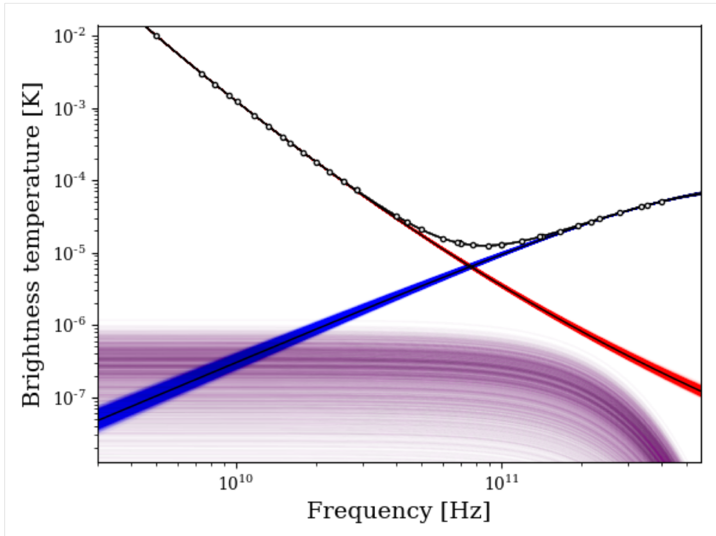
(a) PLANCK+LiteBIRD



(b) PLANCK+LiteBIRD+C-BASS

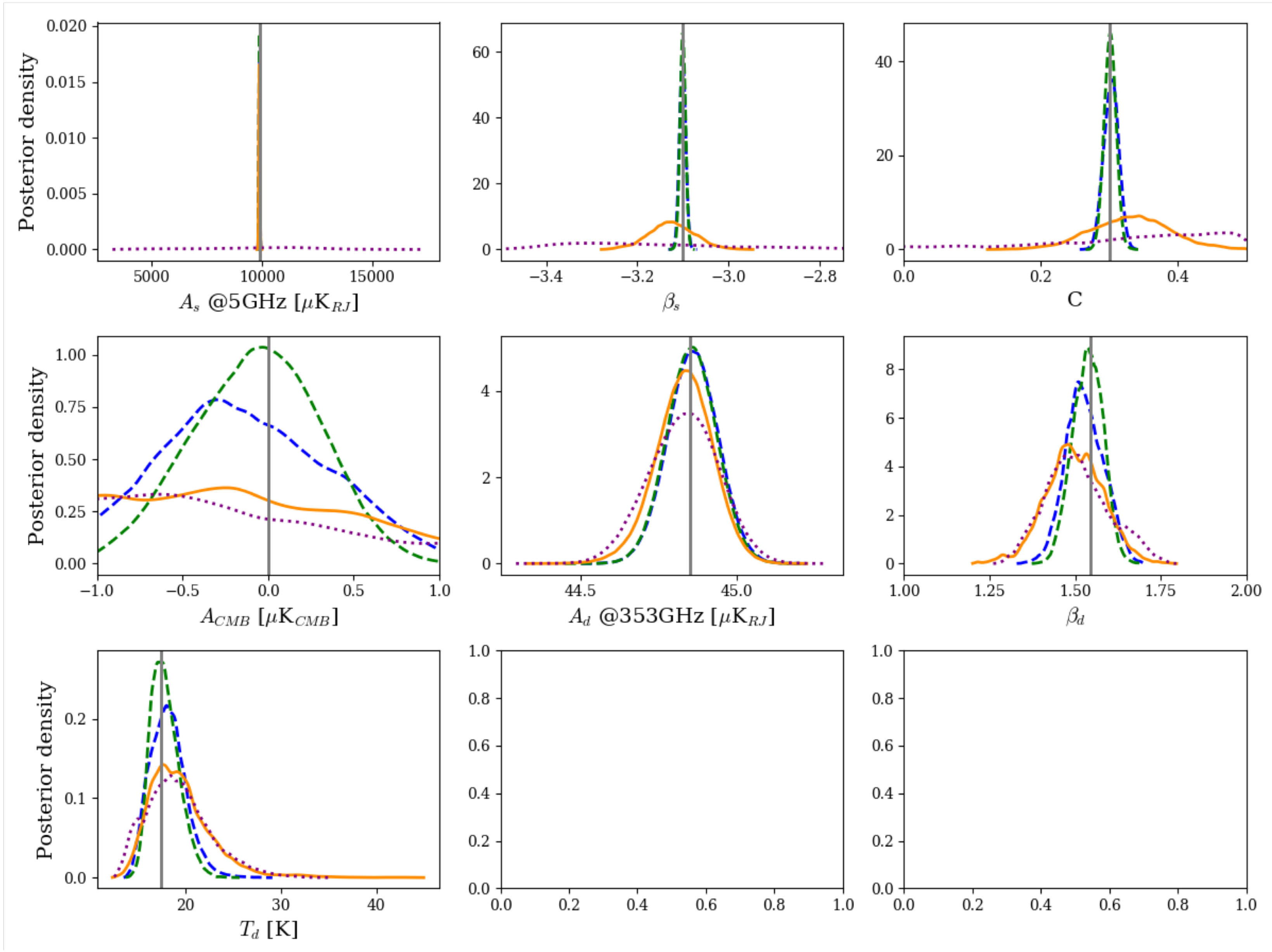


(c) PLANCK+LiteBIRD+C-BASS+X-BASS



(d) PLANCK+LiteBIRD+C-BASS+NextBASS

Curved synchrotron model



Planck+LtBIRD

…+CBASS

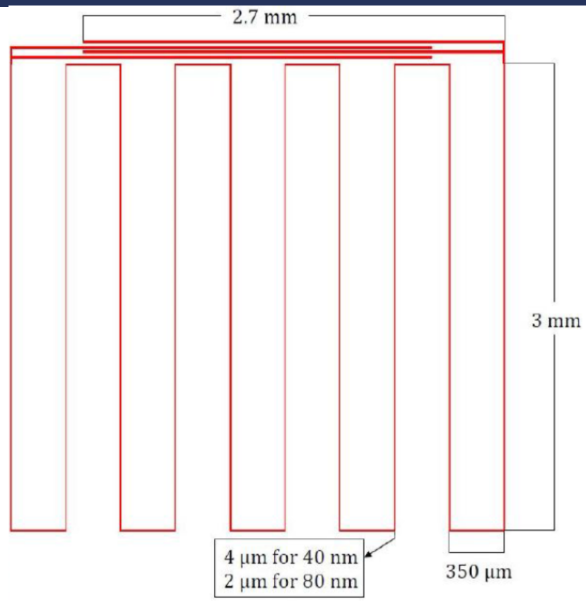
…+XBASS

…+ELFS

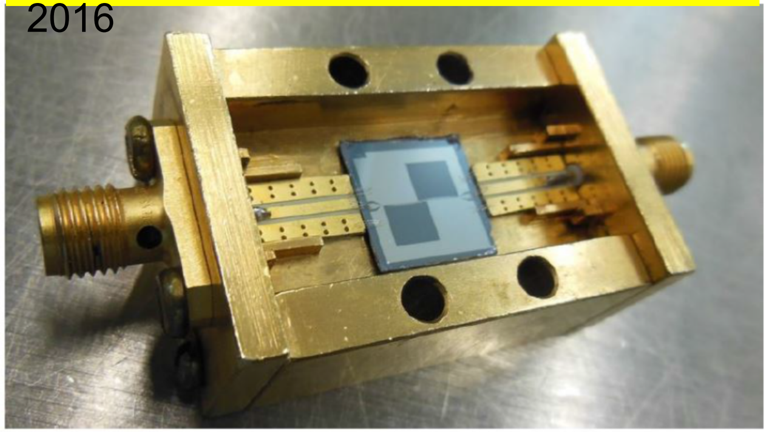
Technology status

- Telescope: CCAT-p/SO-LAT underway.
  - Investigate lower spec/cost reduced version.
  - ‘Clover’ ~2-m telescopes available now (STRIP, QUIJOTE, NextBASS)
- Receiver array: Feeds/OMTs designed. LNAs available
  - LNF LNAs with 0.25 K/GHz commercially available
- Polarimeter backend: FPGA/digitizers developed for SKA (incl firmware, software, commercially available hardware).
- Experience in systems, testing, integration, operations etc in Europe (UK, Italy, Spain…)
- KIDS array: recently flown on OLIMPO / KISS /NIKA

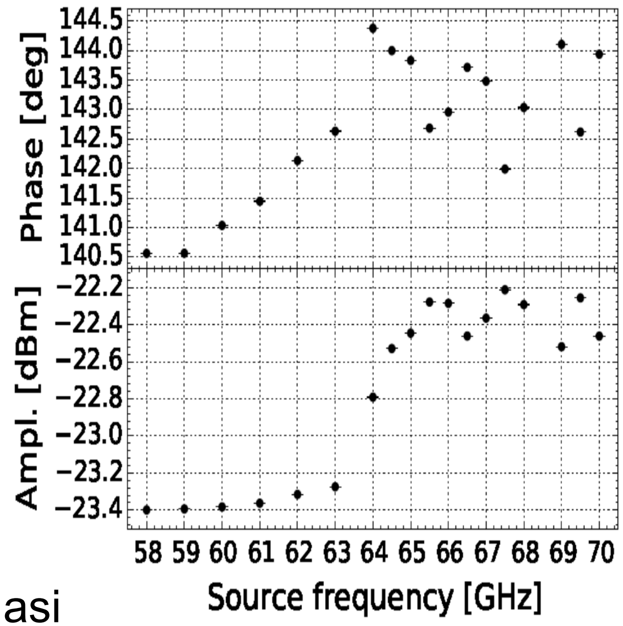
Development of Kinetic Inductance Detectors for the W-band

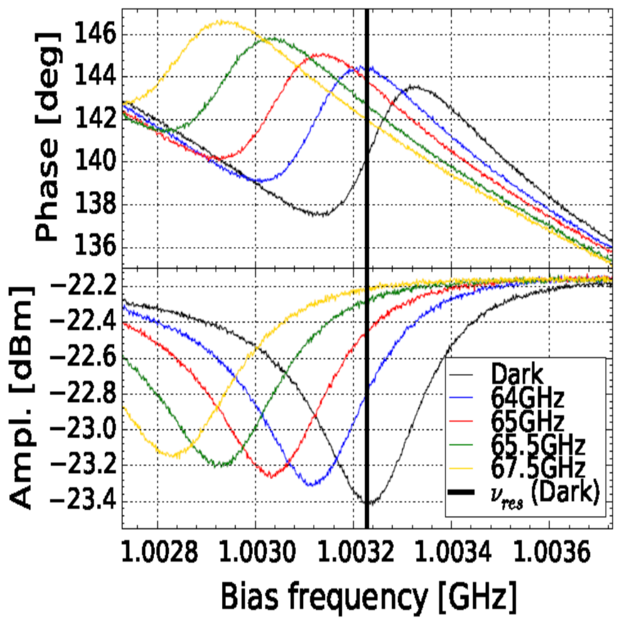


Paiella A., et al., Journal of Low Temperature Physics, **184**, 97-102, 2016



- Sapienza + IFN-CNR (Rome, Italy)
- Initially developed for a FTS spectra-imager for the 64m Sardinia Radio Telescope.
- Now considered for ground-based B-modes polarimetry
- Bi-layer LEKIDs: 25 nm Al + 10 nm Ti
- Good performance for f > 65 GHz

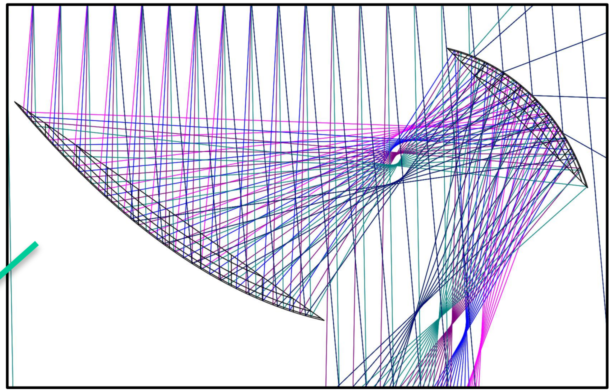


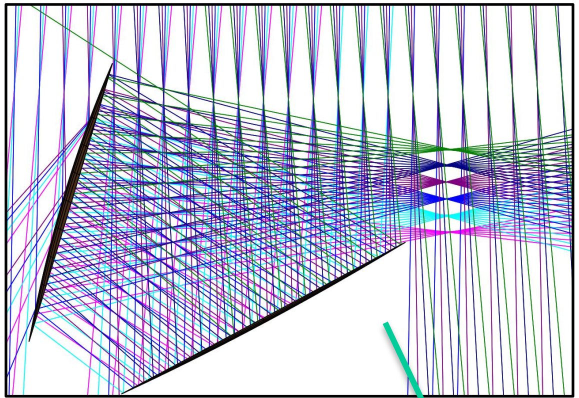


Slide from S. Masi

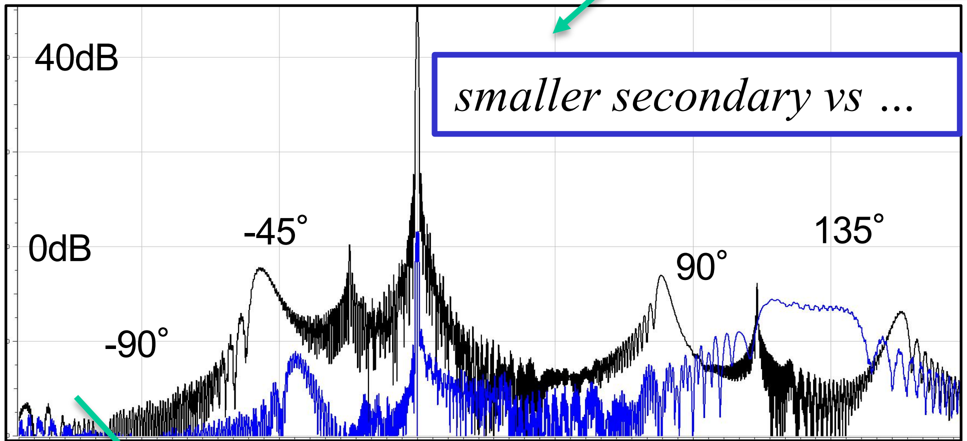
Telescope – Gregorian vs CD

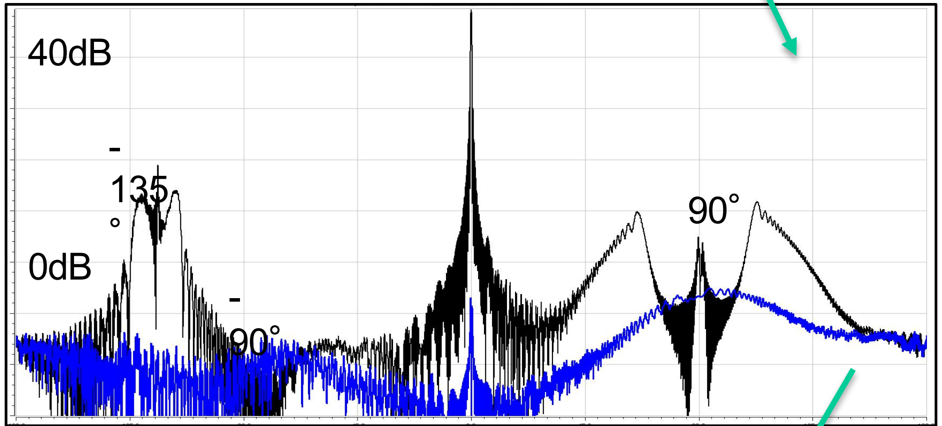
Off-axis Gregorian vs. Cross-Dragone…

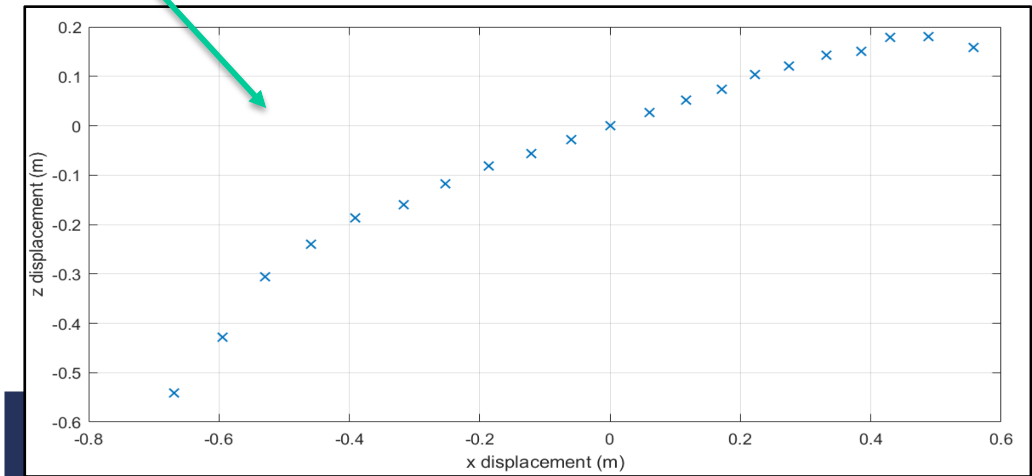


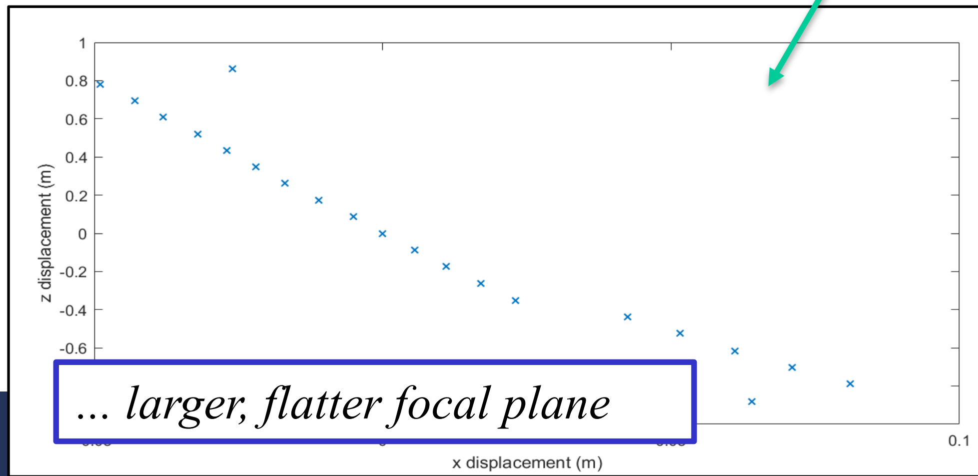


smaller secondary vs …





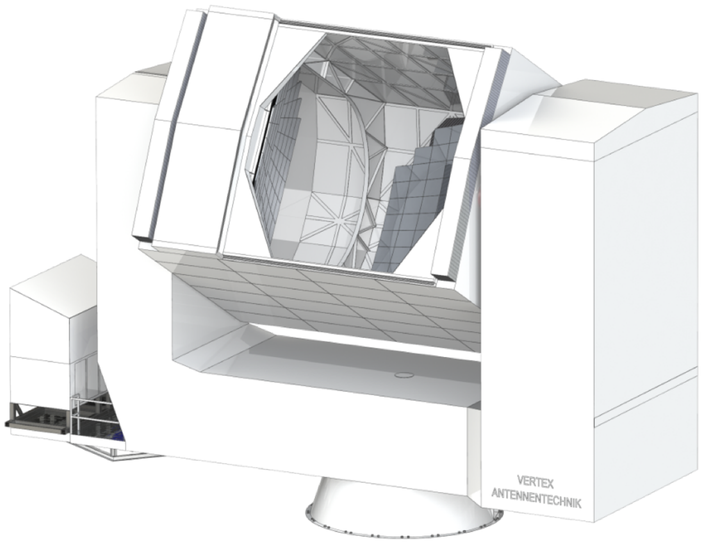


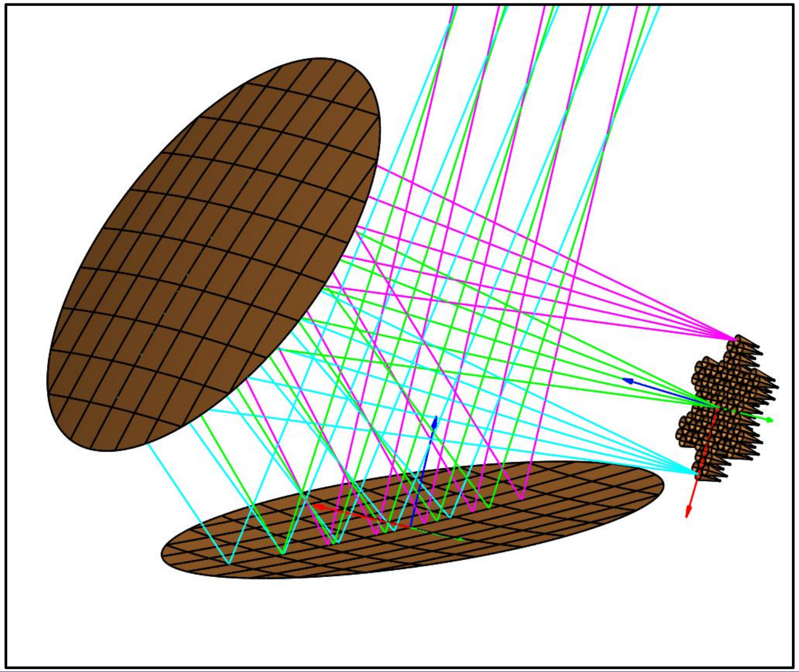


… larger, flatter focal plane

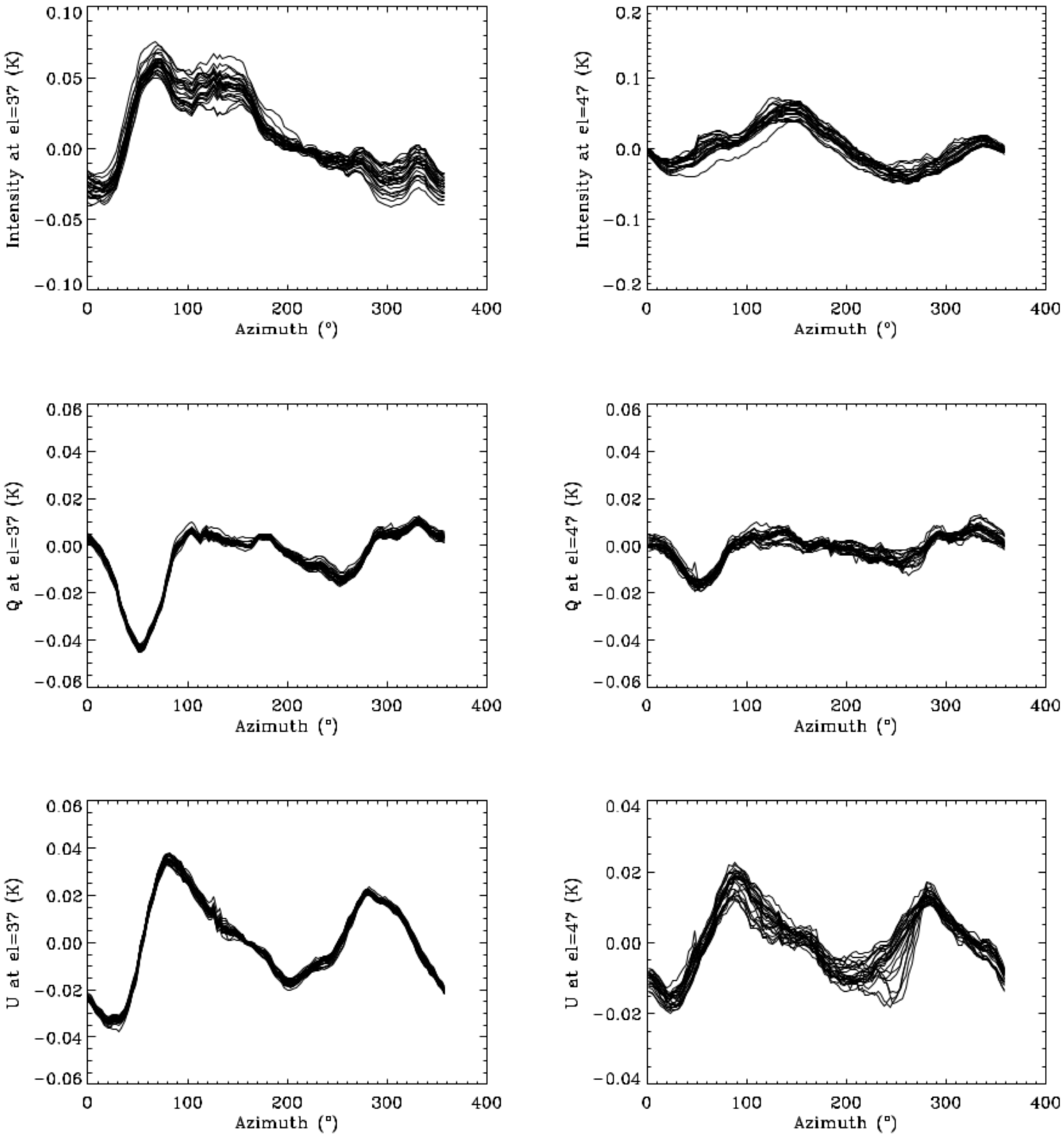
Telescope

- Gregorian is not good enough (size of focal plane)
- Shielding – ‘antenna in a box’ eg CCAT-p (but over-spec for max frequency 40/120 GHz)
- Matched optics and interfaces with SO and CMB-S4?



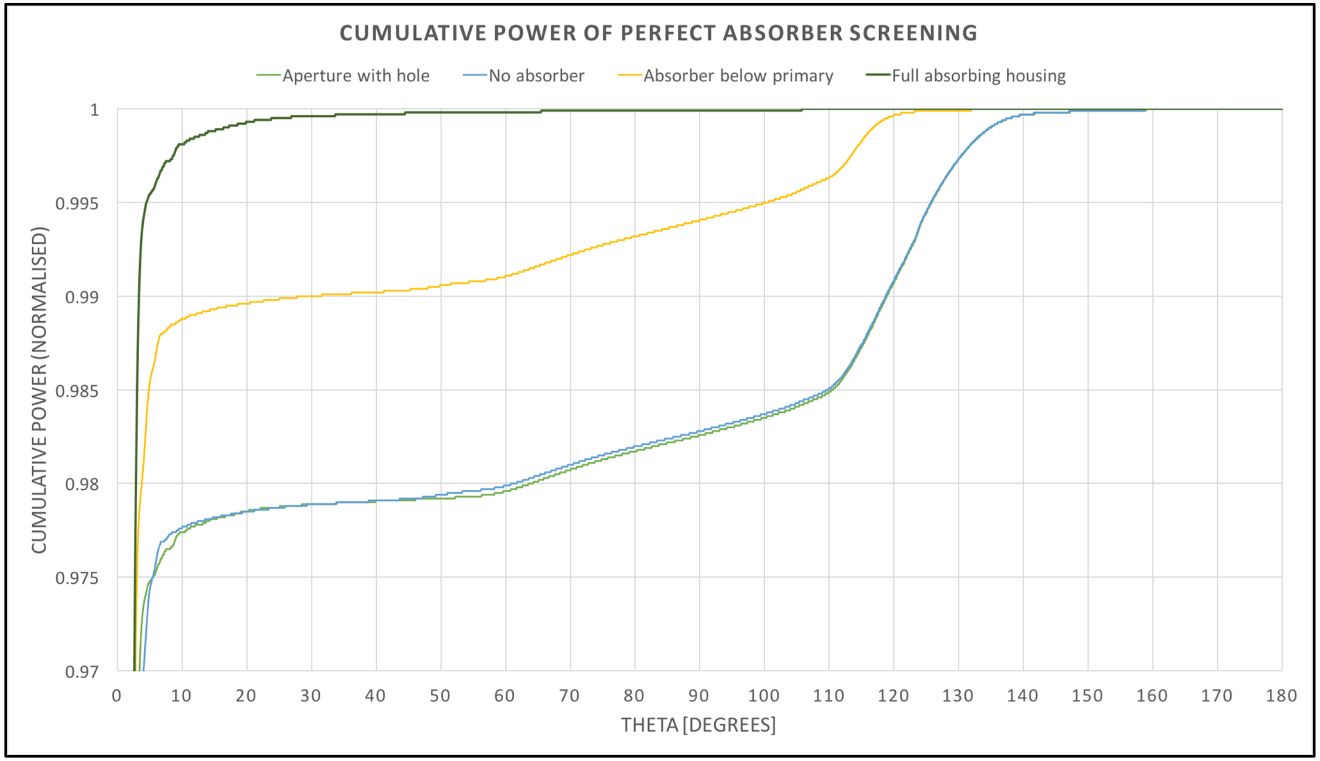


Ground pickup…

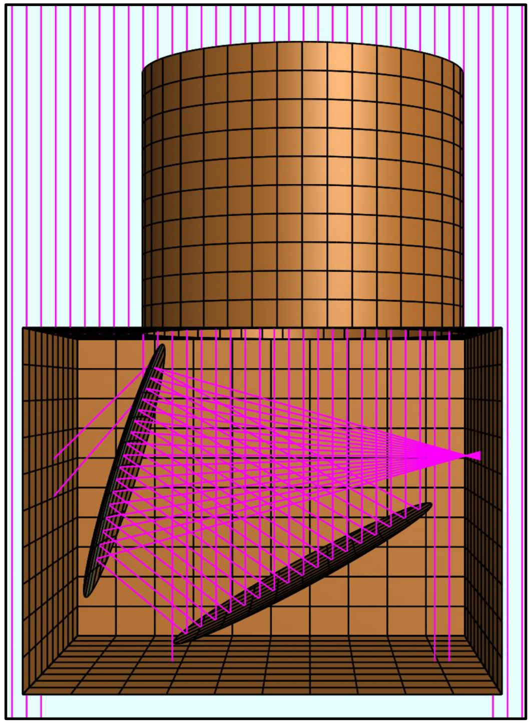


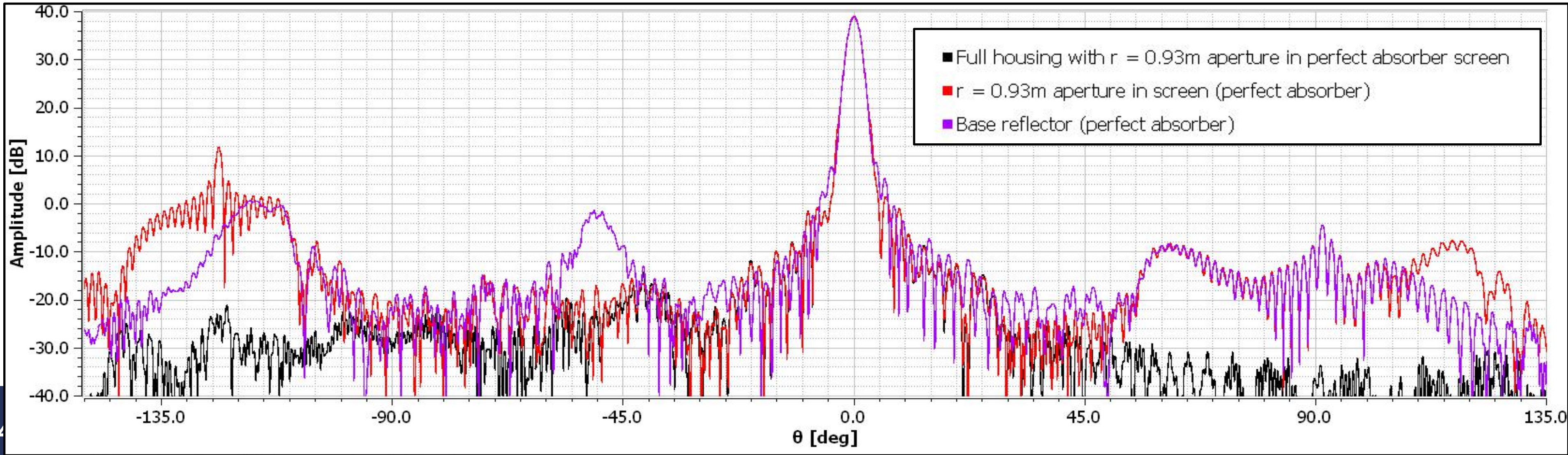
- Biggest systematic for C-BASS despite very good far-out sidelobes: ~10 mK in raw data

Baffling…



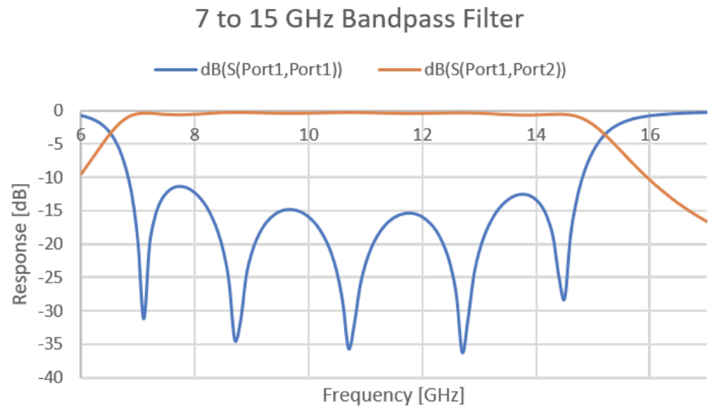
CUMULATIVE POWER OF PERFECT ABSORBER SCREENING
Aperture with hole
No absorber
Absorber below primary
Full absorbing housing
CUMULATIVE POWER (NORMALISED)
1
0.995
0.99
0.985
0.98
0.975
0.97
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
THETA [DEGREES]

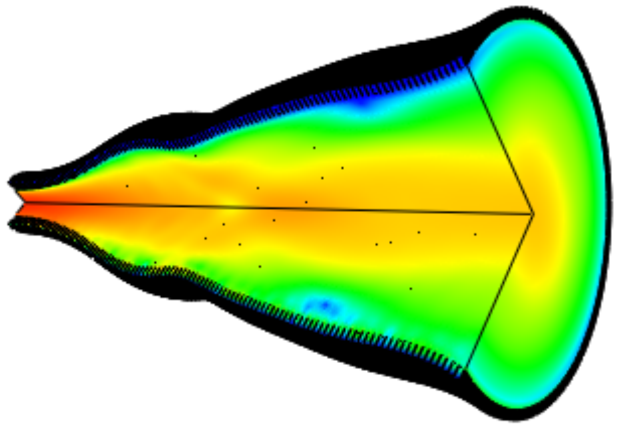


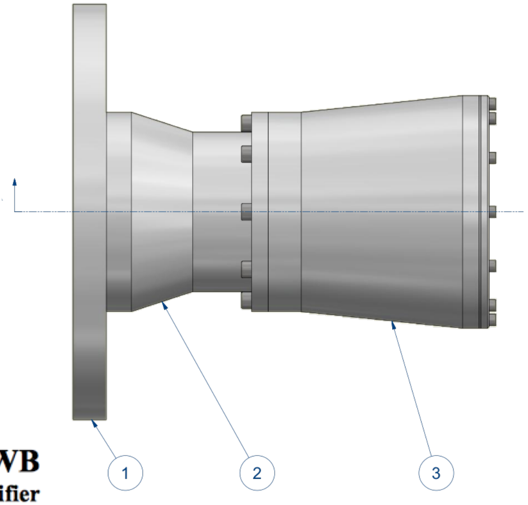


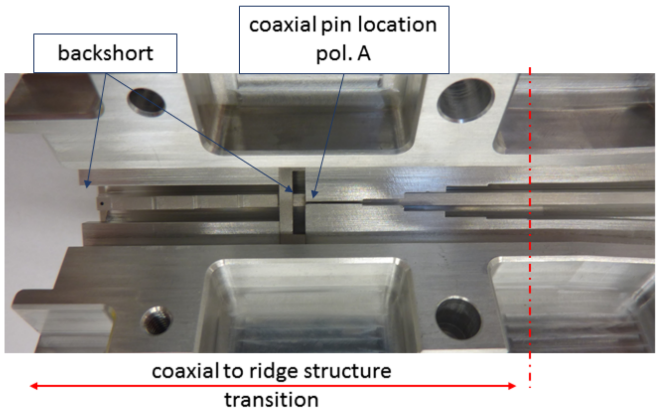
Full housing with r = 0.93m aperture in perfect absorber screen
r = 0.93m aperture in screen (perfect absorber)
Base reflector (perfect absorber)
Amplitude [dB]
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-135.0 -90.0 -45.0 0.0 45.0 90.0 135.0
θ [deg]

Feeds/OMTs/LNAs/Filters…









LOW NOISE FACTORY
www.lownoisefactory.com

LNF-LNC23_42WB
23-42 GHz Cryogenic Low Noise Amplifier

Rev: Jan 2018

Absolute maximum ratings

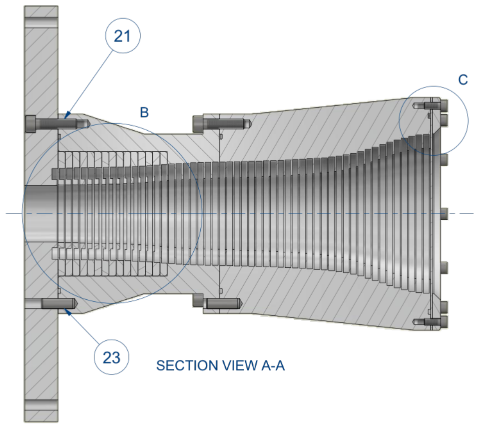
Parameter	Min	Max
V_{ds}	-0.5 V	2 V
I_{ds}		100 mA
V_{gs}	-20 V	+20 V
RF Input drive level		-10 dBm

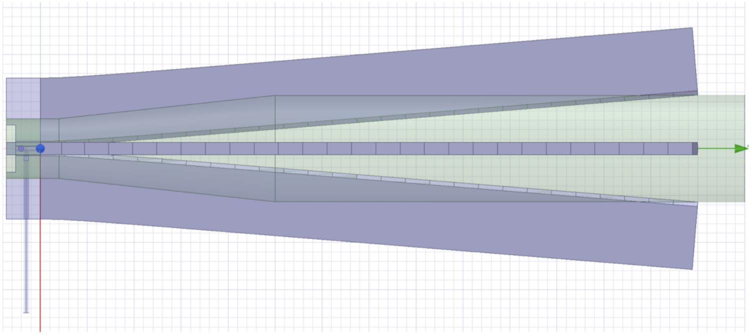
Product features

- RF bandwidth: 23-42 GHz
- Noise Temperature: 7.9 K typical
- Noise Figure: 0.12 dB typical
- Gain: 28 dB
- DC-power: V_d=1.00 V, I_d= 9 mA
- One gate and one drain supply only
- RF connectors: WR28, UG-599/U
- DC-connector: 9-pin female Nano-D

Typical RF Characteristics

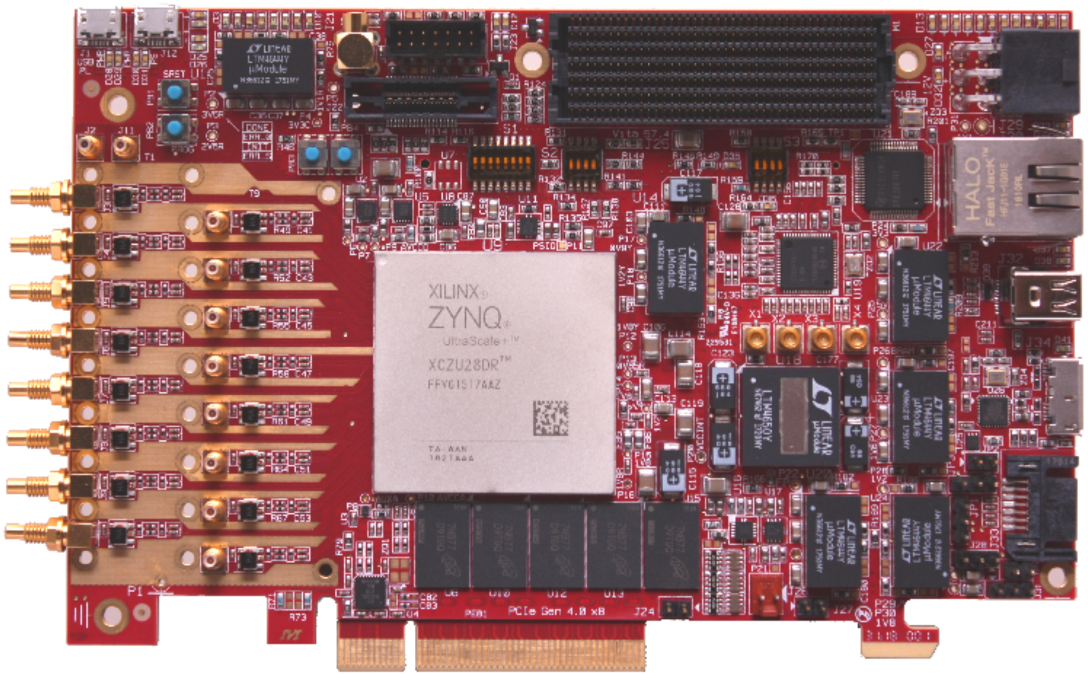
Parameter	Test Condition	Value	Unit
Gain	23-42GHz	28	dB
Noise	23-41GHz	7.9	K
IRL	23-42GHz	13	dB
ORL	23-42GHz	17	dB
P_{1dB}	23-42GHz	-10	dBm
OIP3	23-42GHz	0	dBm





Digital radiometer/polarimeter

- Downconvert and sample IF signals
- 4 GS/s-12b ADC integrated with FPGA now off-the-shelf: 8GHz dual-pol pixel per board
- Channelize – essential for RFI (much finer than for science)
- *Q/U* from x-correlation of *R/L* *(no polarization modulators needed)*
- *I* from autocorrelation of *R,L*, stabilized with calibration signal
- On-board DAC for generation of coherent calibration signals



- Firmware/software control being done now for SKA/other projects
- Cost ~€8k per board.

Interferometer array for higher l

freq GHz	FOV (deg)	Sensitivity uKarcmin	Projected uKarcmin	lmin	lmax
10.0	0.43	162	0.13	837	4,186
11.2	0.38	129	0.15	939	4,697
12.6	0.34	102	0.17	1,054	5,270
14.1	0.30	81	0.19	1,183	5,913
15.8	0.27	64	0.21	1,327	6,635
17.8	0.24	51	0.24	1,489	7,444
20.0	0.22	41	0.27	1,671	8,353
22.4	0.19	32	0.31	1,874	9,372
25.1	0.17	26	0.35	2,103	10,515
28.2	0.15	20	0.40	2,360	11,798
31.6	0.14	16	0.46	2,648	13,238

- Example for 10 x 4m antenna, 20m max baseline
- Same sampler/FPGA boards provide correlator

Technology Summary

ELFS is doable now, except…

- 6-m shielded telescope 🙂
- Large cryostat with ~50-100 cm window 😀
- Octave-band feeds and OMTs 😀
- Very low noise LNAs 😀
- Digital polarimeters capable of many 10s of GHz 😀
- Correlator technology with many 10s of GHz 😀
- Money 😔

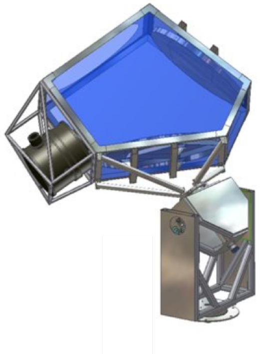
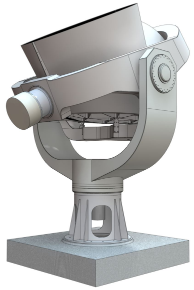
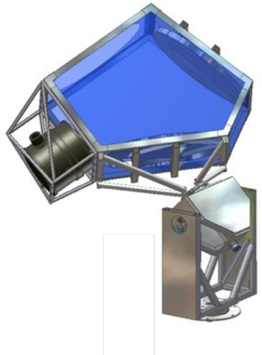
ELFS Proposal - costs

Very approximate at present!

- Two telescopes: 2 x €5M = €10M
- Site infrastructure: 2 x €1M = €2M
- Operations: 2 x (€0.5M/yr) = €5M
- Interferometer array x2 = €10M
- Polarimeter array: €5M
- Polarimeter backend: €5M
- KIDS array receiver: €10M
- Staff for construction, operations, analysis: €10M
- Computing: €3M
- Total: €60M (times π)

Timescale: Could start immediately funding is available

Steps on the way

- X-BASS (STFC grant application, 2018 😔)
  - Single 7-15 GHz pixel on C-BASS South
  - S4 equivalent sensitivity (if thermal noise limited)
- STRIP
  - 40/90 GHz, Tenerife
- QUIJOTE South
  - 10-20 GHz (South Africa/Chile?)
- NEXTBASS (ERC grant application, 2018 😔)
  - 31-element 15-30 GHz array on ex-Clover 2-m telescope
  - C-BASS South site
  - S3+ equivalent sensitivity
  - Proves all technology
- ELFS-p (ERC Synergy application 2019?)
  - 6-m telescope, Tenerife
  - ~100-element array 10 – 40 GHz

Summary

- Low-frequency full-sky coverage is essential to complement CMB-S4 and satellites.
- Two 6-m telescopes, north and south
- Additional small interferometer array for high l?
- Radiometer arrays 10 – 40 GHz with ~100 elements plus KIDS arrays at 90 – 120 GHz.
- Europe has lead in these areas
- A European Low-Frequency Survey should be a key part of the European CMB strategy.
- Discuss!