CMB Polarization Experiments - Part II

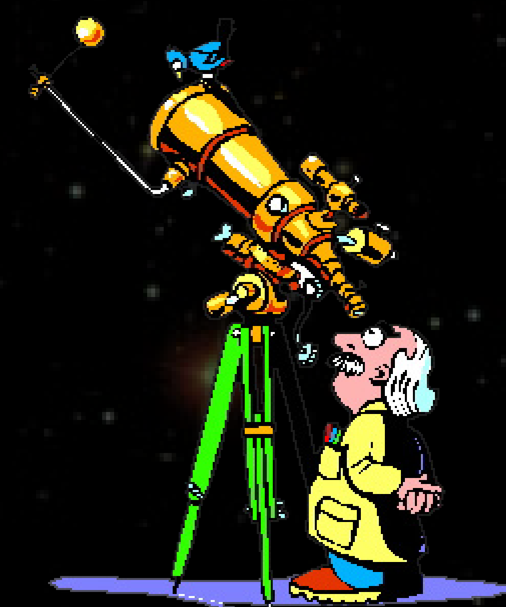
J.-Ch. Hamilton
APC - Paris

CMB Polarization

Lecture 1

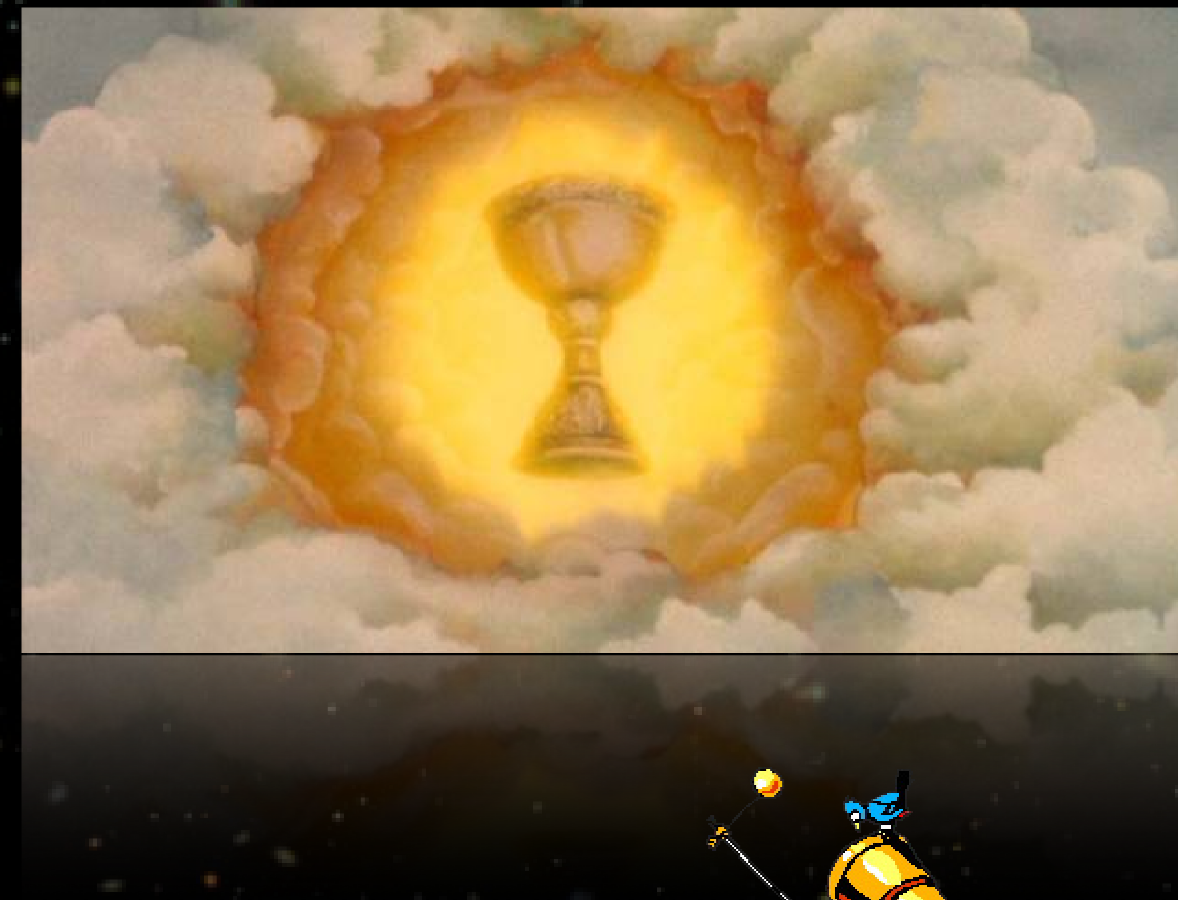
Lecture 2

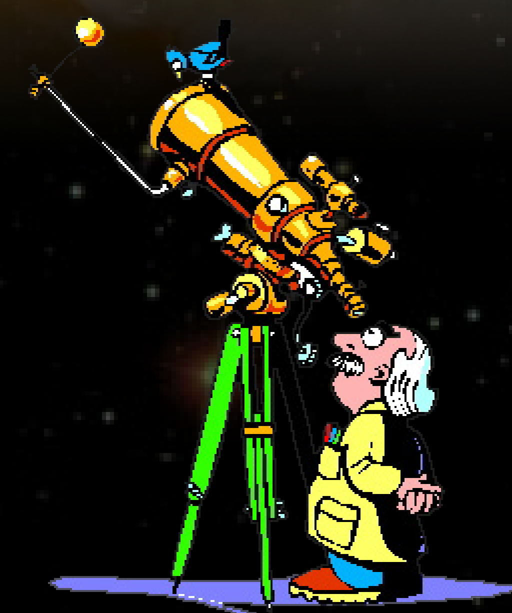
CMB Polarization



How should we proceed to find the Holy Grail ?

CMB Polarization



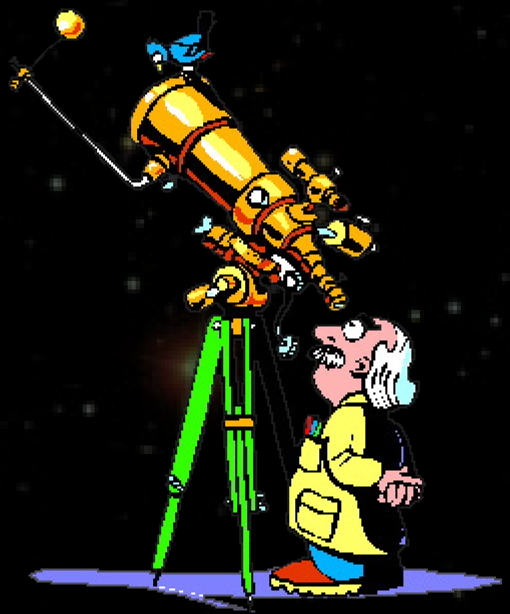


How should we proceed to find the Holy Grail ?

Expected difficulties in the Quest for the Holy Grail

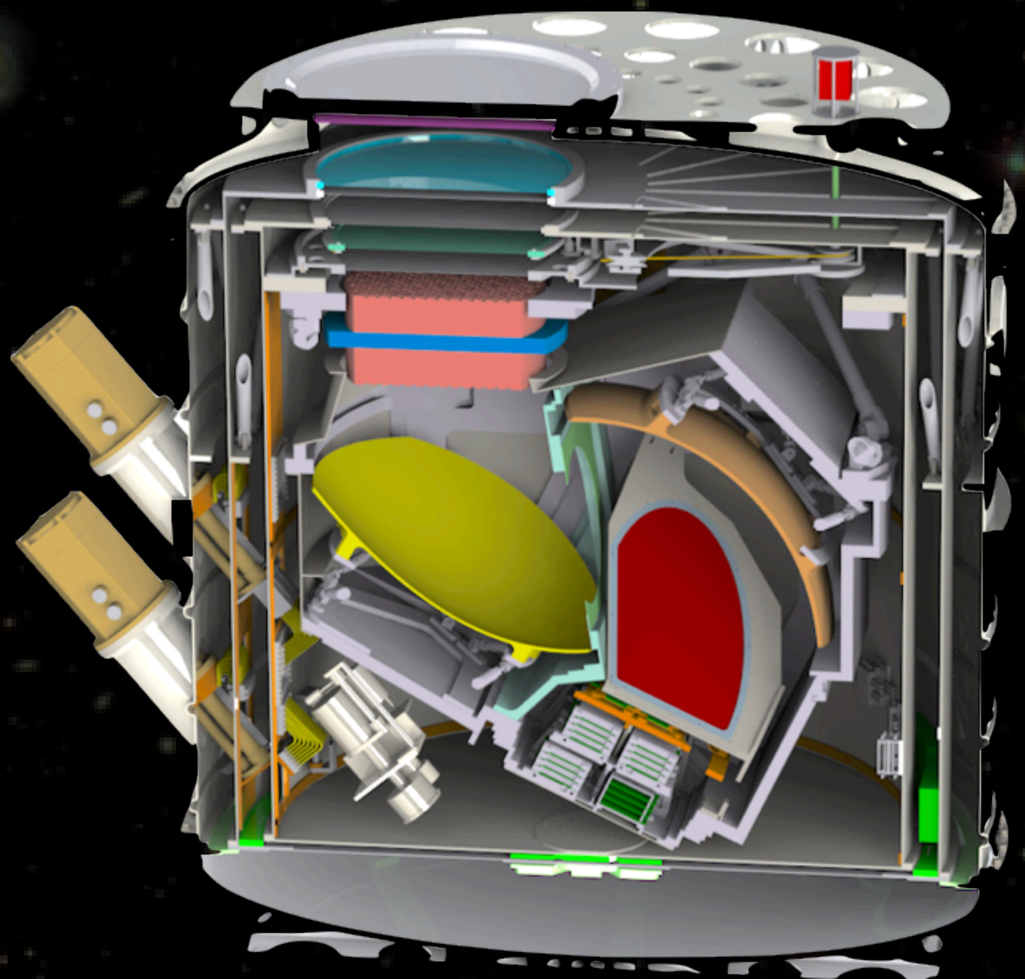
- Sensitivity :
  - ★ Low Signal: B polarization is at best ~15 times weaker than E, Amplitude could be **very** small ...
  - ★ A dedicated space mission might not be for tomorrow.
  - ➡ Need many thousands of Background limited detectors
  - ➡ Primordial B-modes peak at l~100 : 1 degree angular resolution

- Foregrounds + lensing :
  - ★ Need to remove foregrounds accurately (can't just mask: no clean region)
  - ➡ Multiwavelength detectors
  - ★ Lensing may dominate w.r.t. primordial B-modes…
  - ➡ Delensing needs high-resolution CMB Polarization maps + LSS data
- Systematic effects :
  - ★ Instrument induces leakage of T into E and B (and T>>E>>B)
  - ➡ Cross-polarization and ground pickup are major issues
  - ★ Atmospheric polarization ...
  - ➡ Need for accurate polarization modulation



Experimental Challenges and Future Instruments

- Possible designs
- Possible sites
- Optimization
- Current projects comparison
- The Future



QUBIC
(a biased choice as
an illustration)

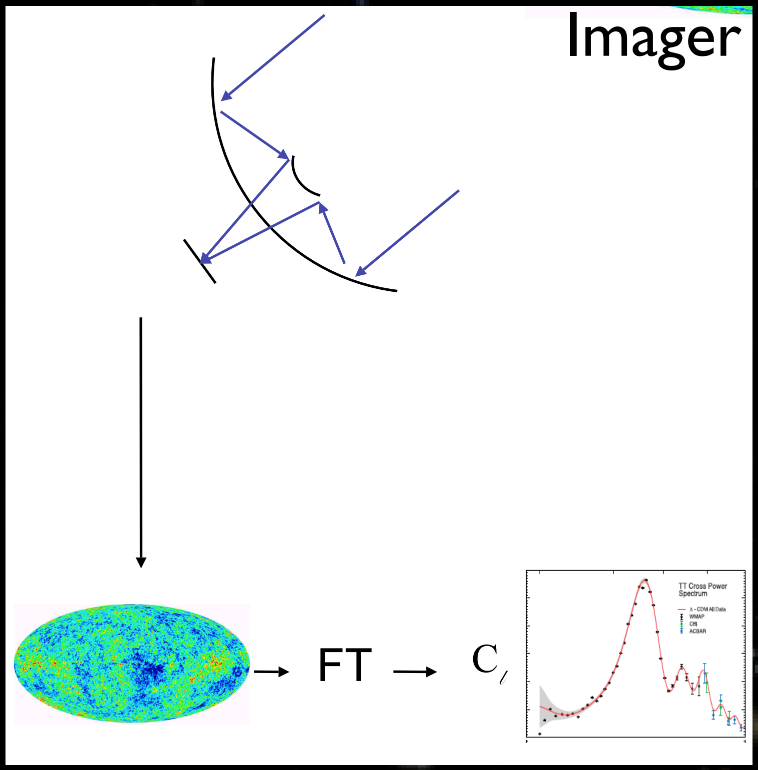
Possible instruments

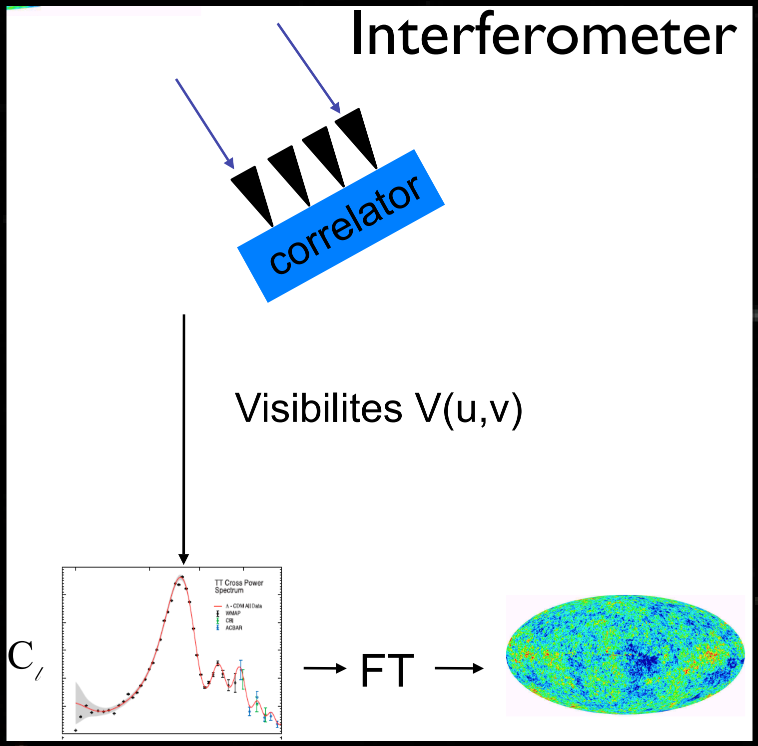
- **Imagers:**
  - ★ With bolometers (or MKIDs…):
    - Wide band & Low noise
  - ★ Coherent detectors
    - Well mastered, not too noisy from the ground, great at low-frequency
  - ★ Usually significant cross-pol & ground-pickup from telescope

- **Interferometers:**
  - ★ Long history in CMB
    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise (but reasonable from ground)
    - Correlators : hard to scale to large #channels
  - ★ Clean systematics:
    - No telescope (lower ground-pickup & cross-polarization)
    - Angular resolution set by receivers geometry (well known)

- **Bolometric Interferometry ?**
  - ➡ QUBIC

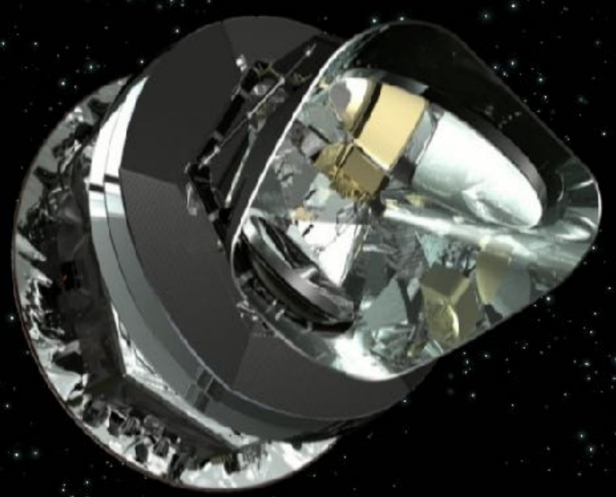
P.Timbie

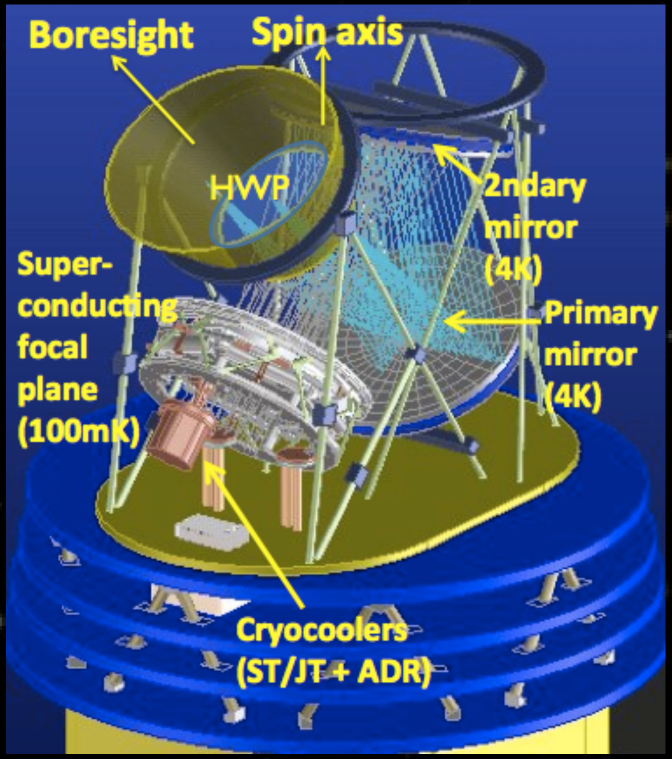




Possible sites

- Satellite
  - ★ Cool ! but expensive and rare… (nightmare ?)
  - ★ Stay tuned: LiteBIRD (Japan), Pixie (USA)
- Balloon Borne
  - ★ Sensitivity:
    - Low background
    - Short exposure: hard to do long duration flights
  - ★ Bands:
    - Easier to go to high frequency w.r.t. ground
  - ★ Weight limitations make it hard to have huge arrays
    - But some teams manage quite well !
    - SPIDER is analyzing data !
- Ground
  - ★ Can tweak the instrument
  - ★ Less logistics limitations
  - ★ Hard to go above 220 GHz
  - ★ Antarctica Vs. Chile / Argentina
    - Atmosphere Vs. logistics
  - ★ Northern hemisphere: Canary, Greenland, Tibet ?





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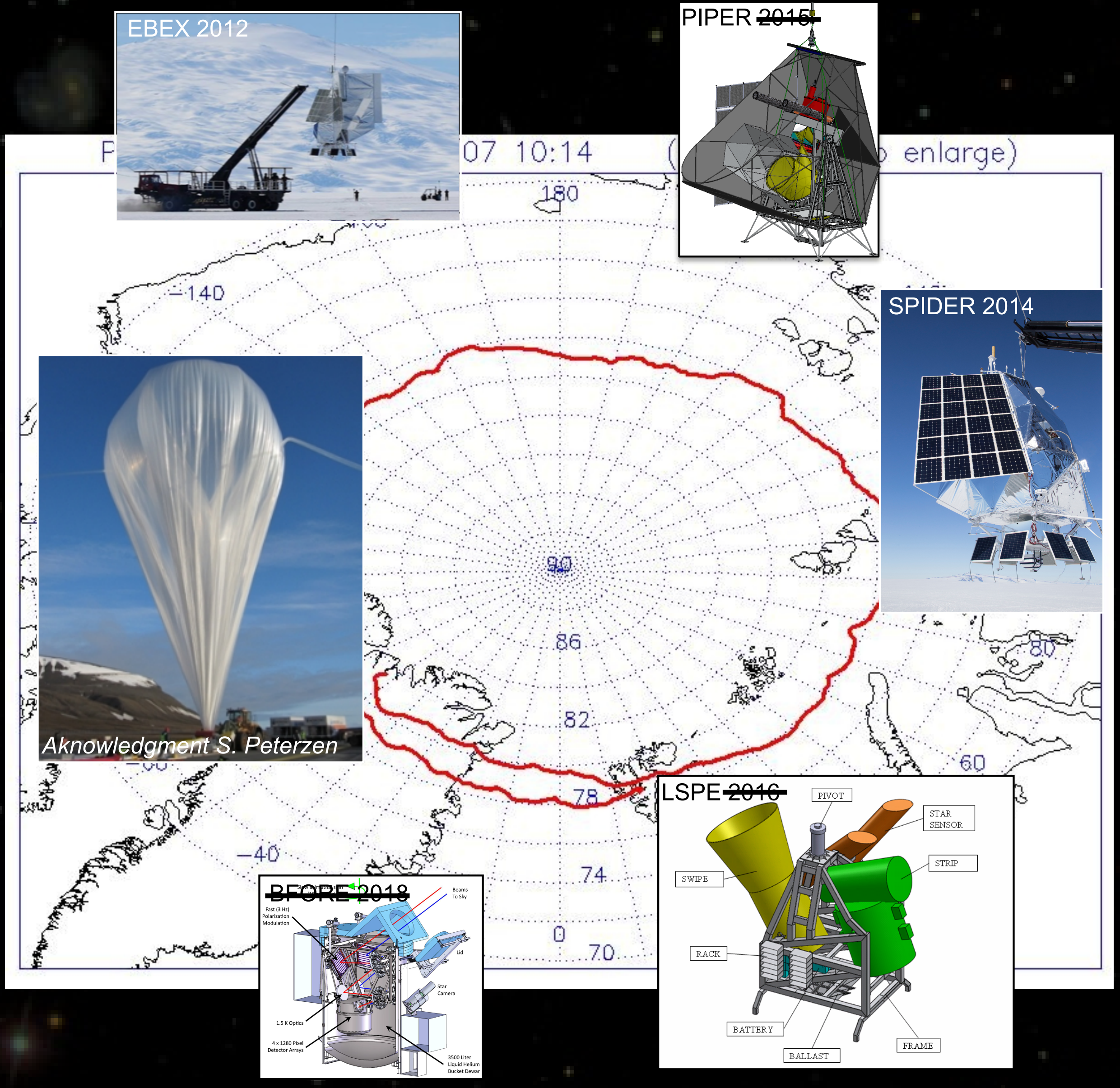
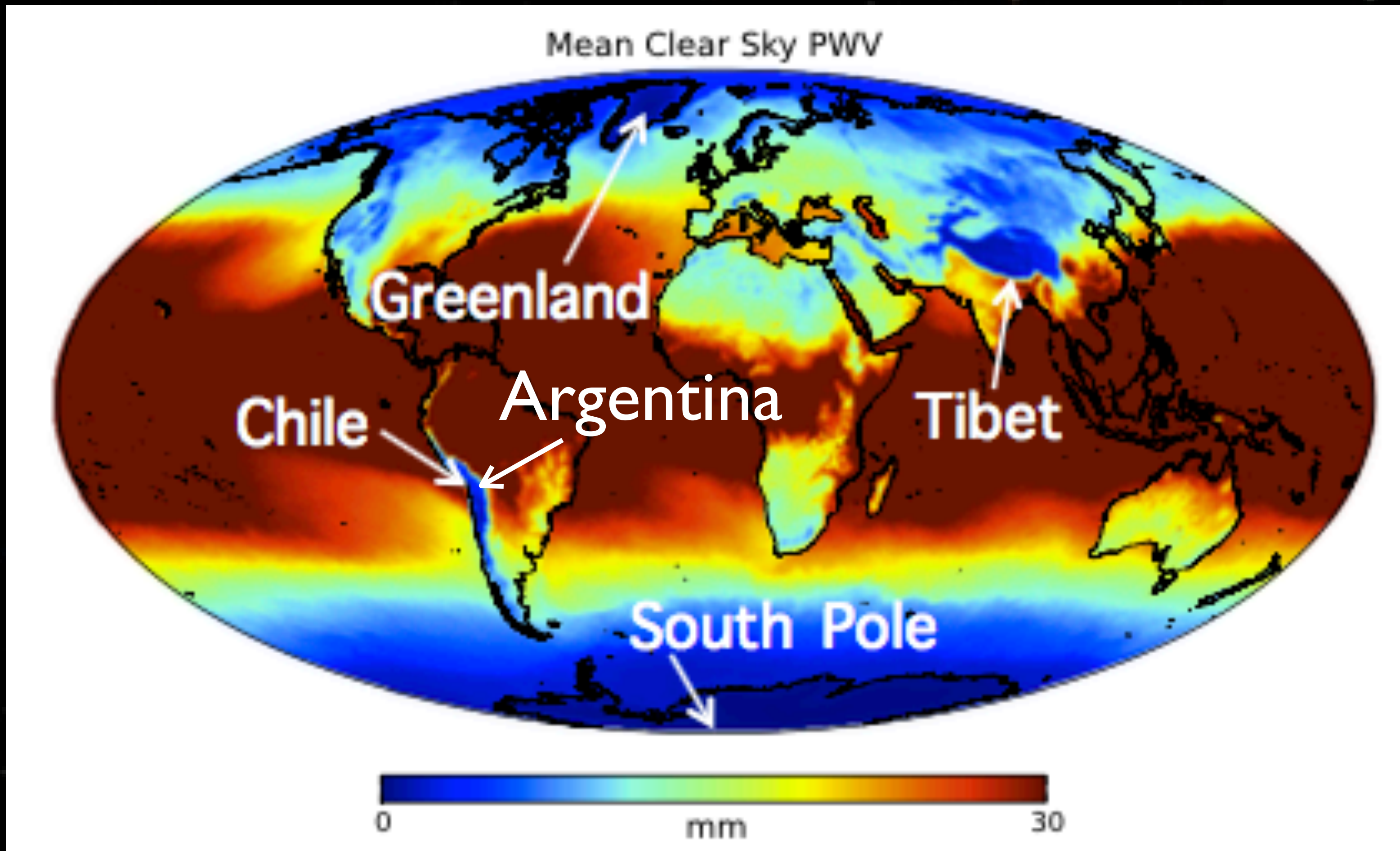


[From E. Battistelli]

Possible sites



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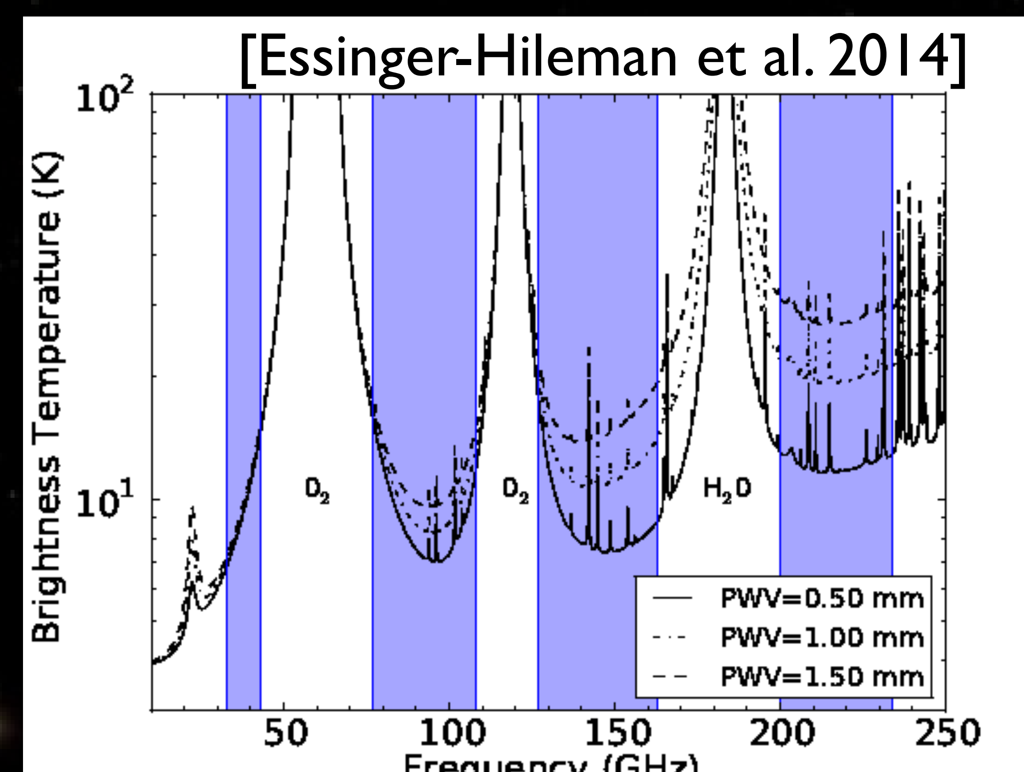
Noise in Ground-based CMB

- Detectors (TES) are Background limited
- Noise dominated by Poisson fluctuations of the incoming radiation
- Incoming radiation in dominantly atmospheric due to water content

➡ The dryer the atmosphere, the better (by significant amounts…)

➡ We seek low PWV sites



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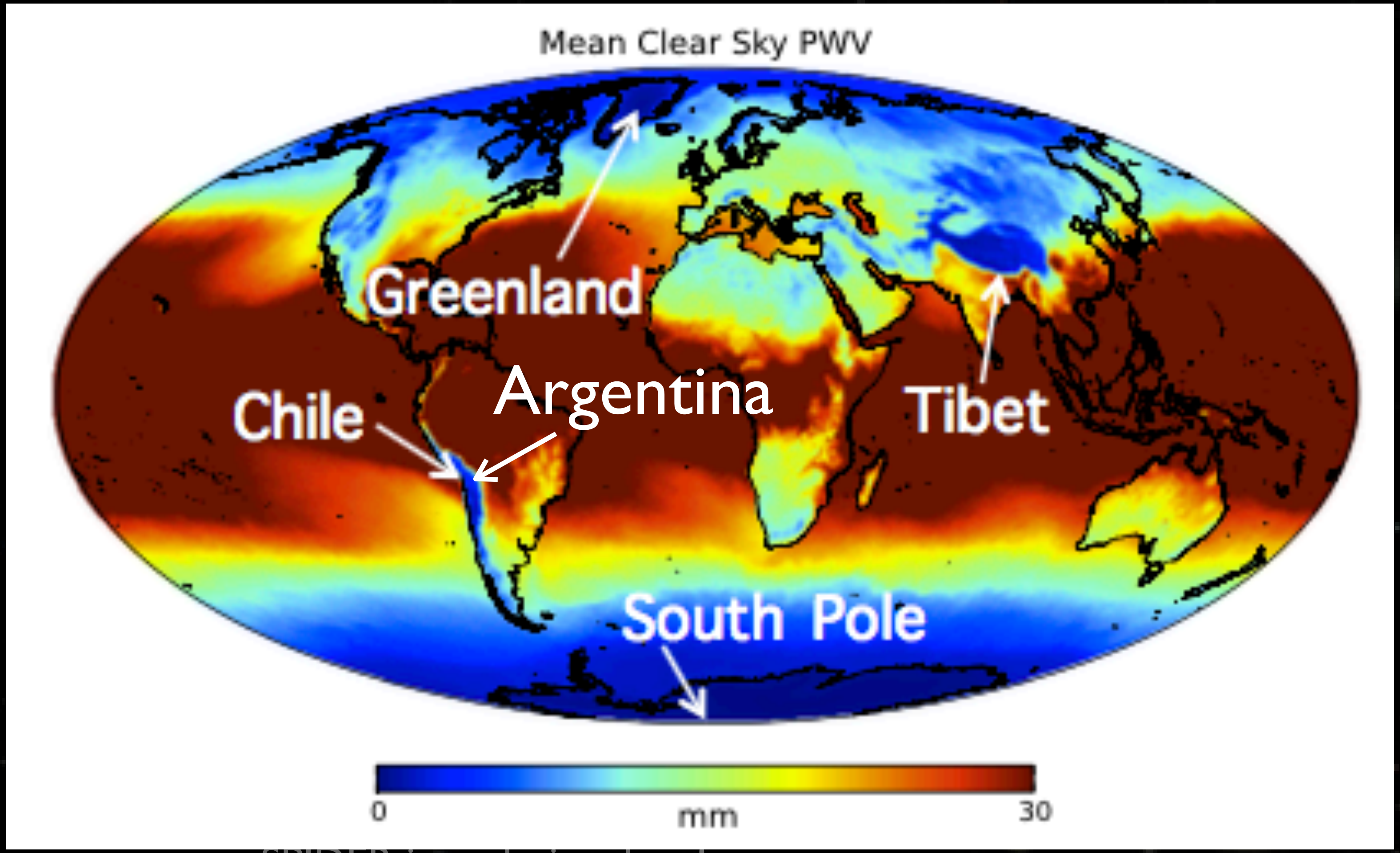

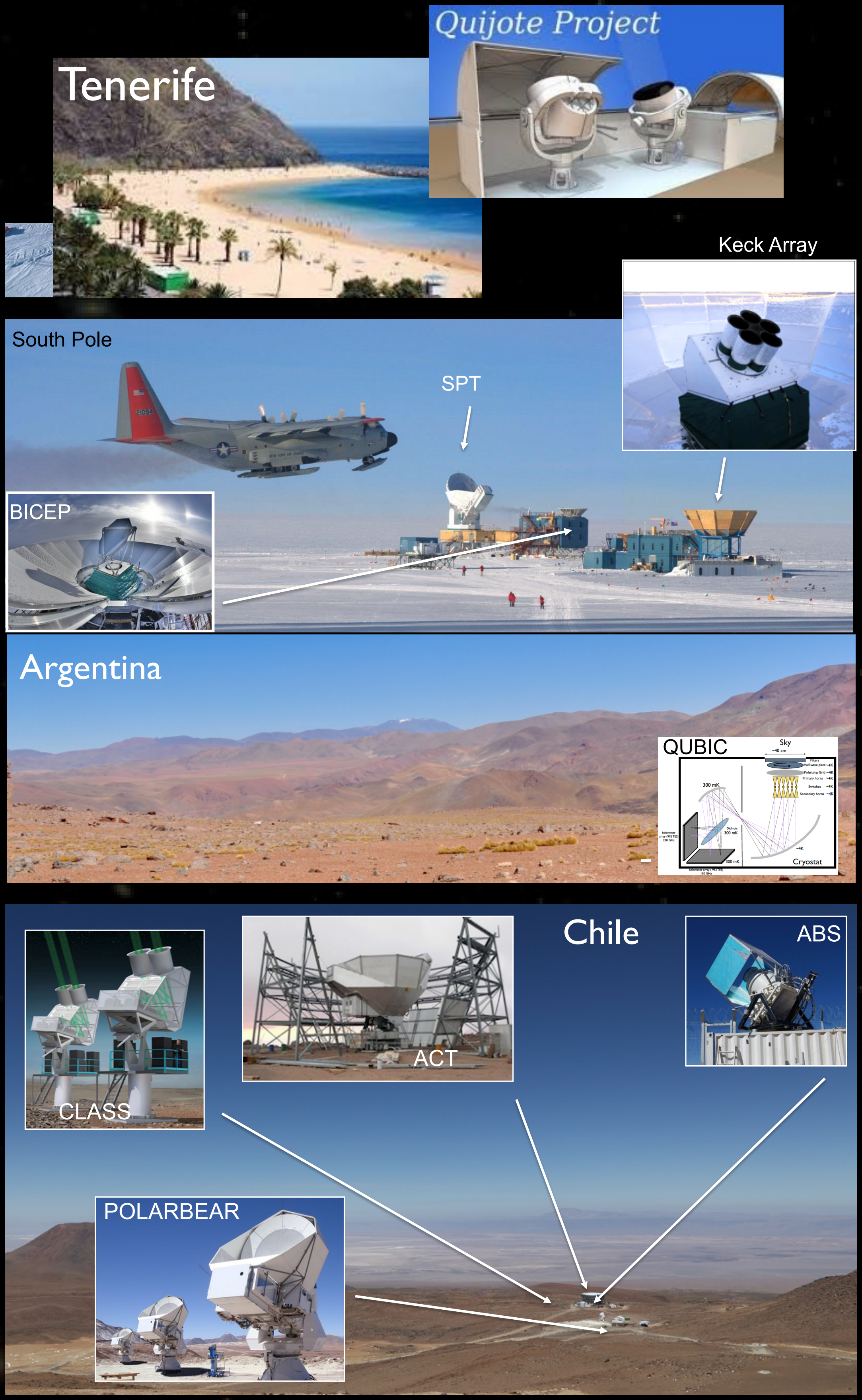

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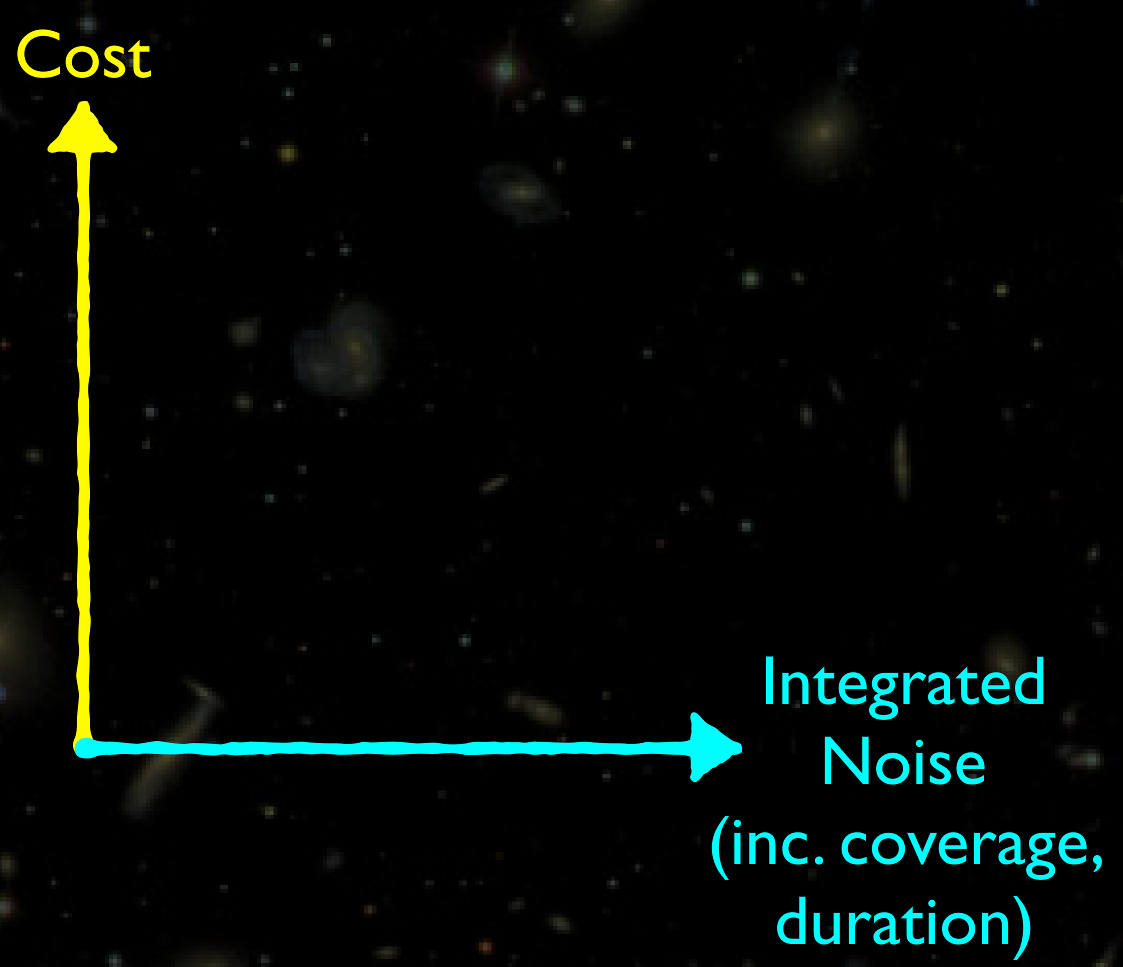
Multidimensional optimization…



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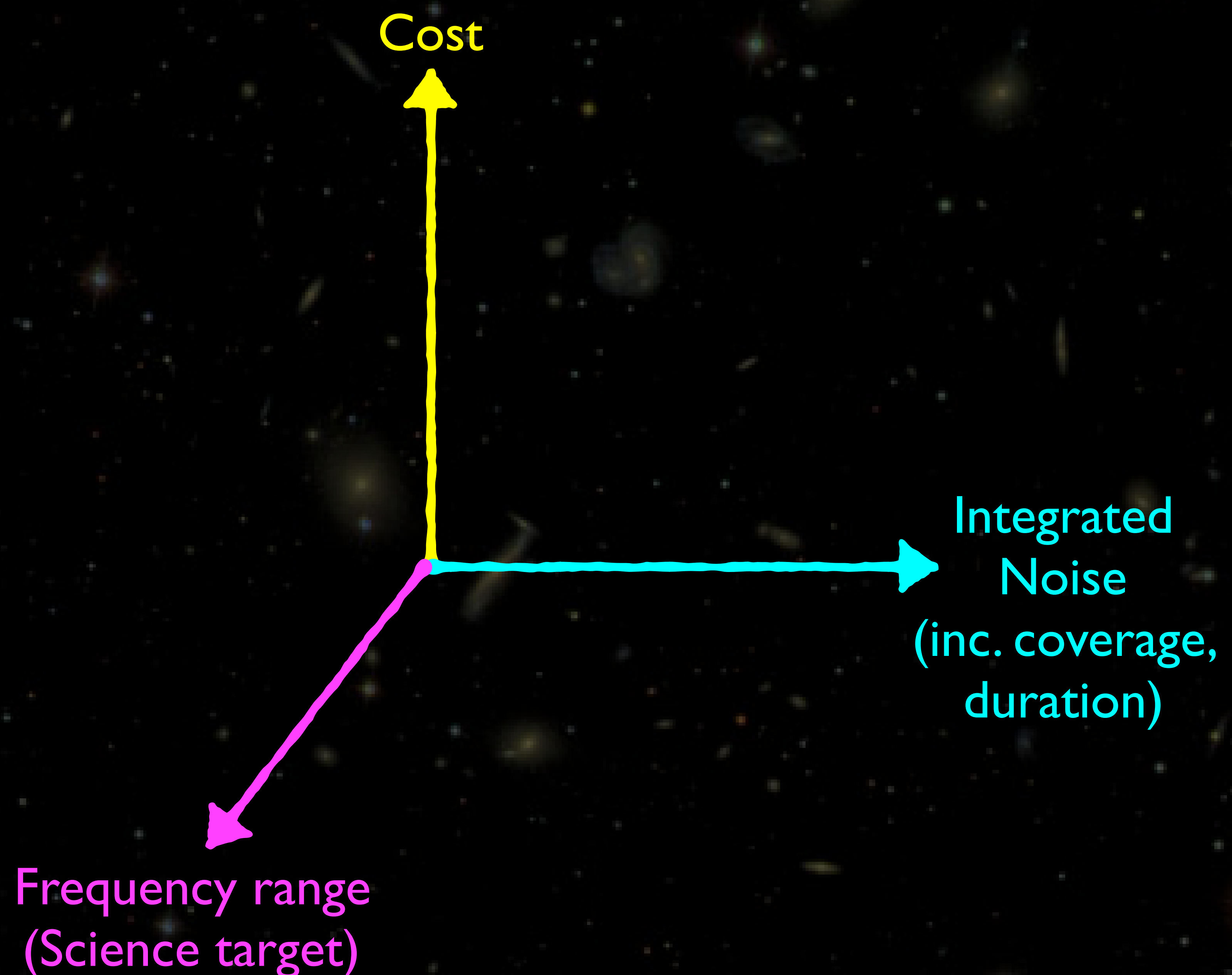

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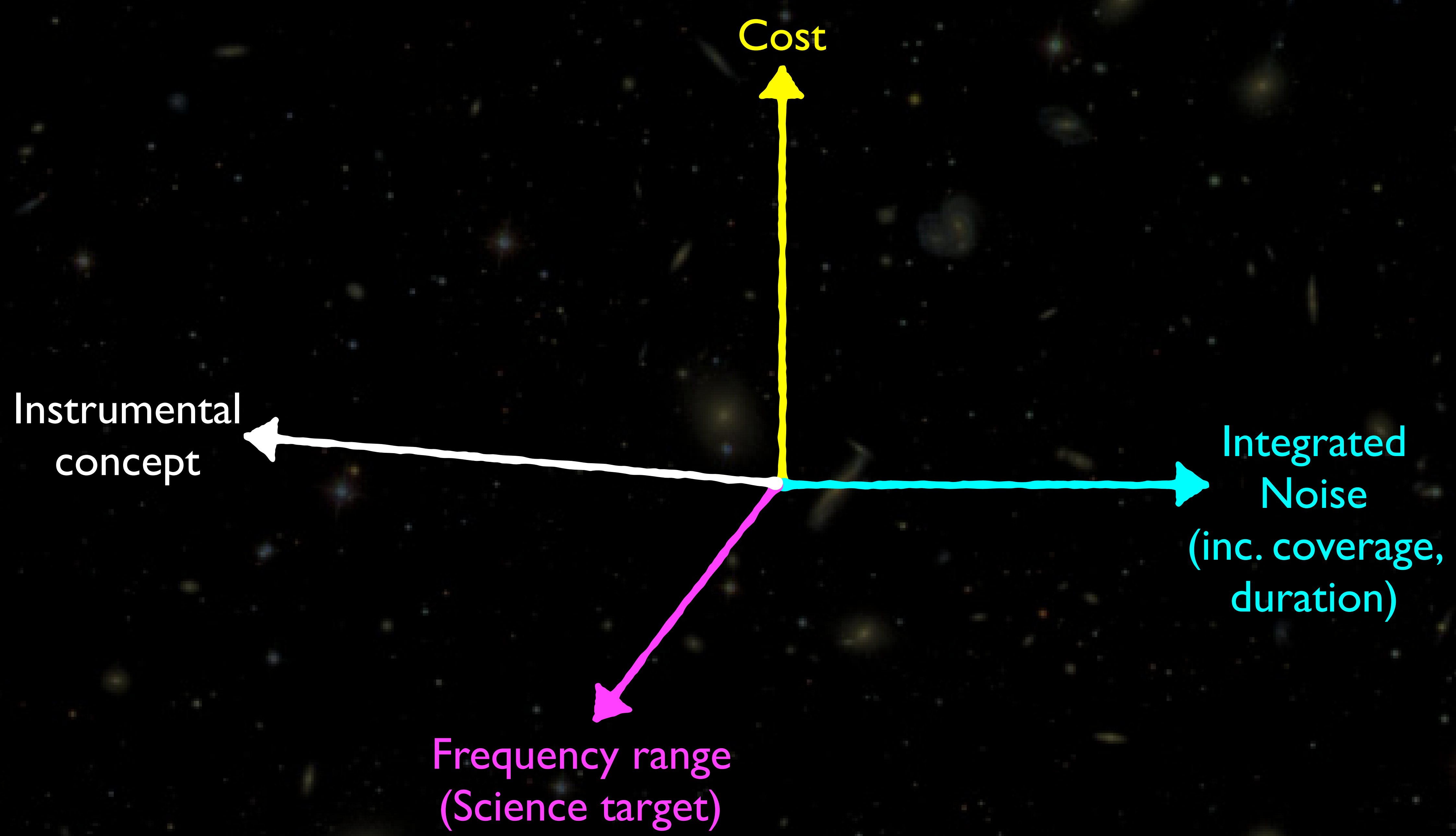

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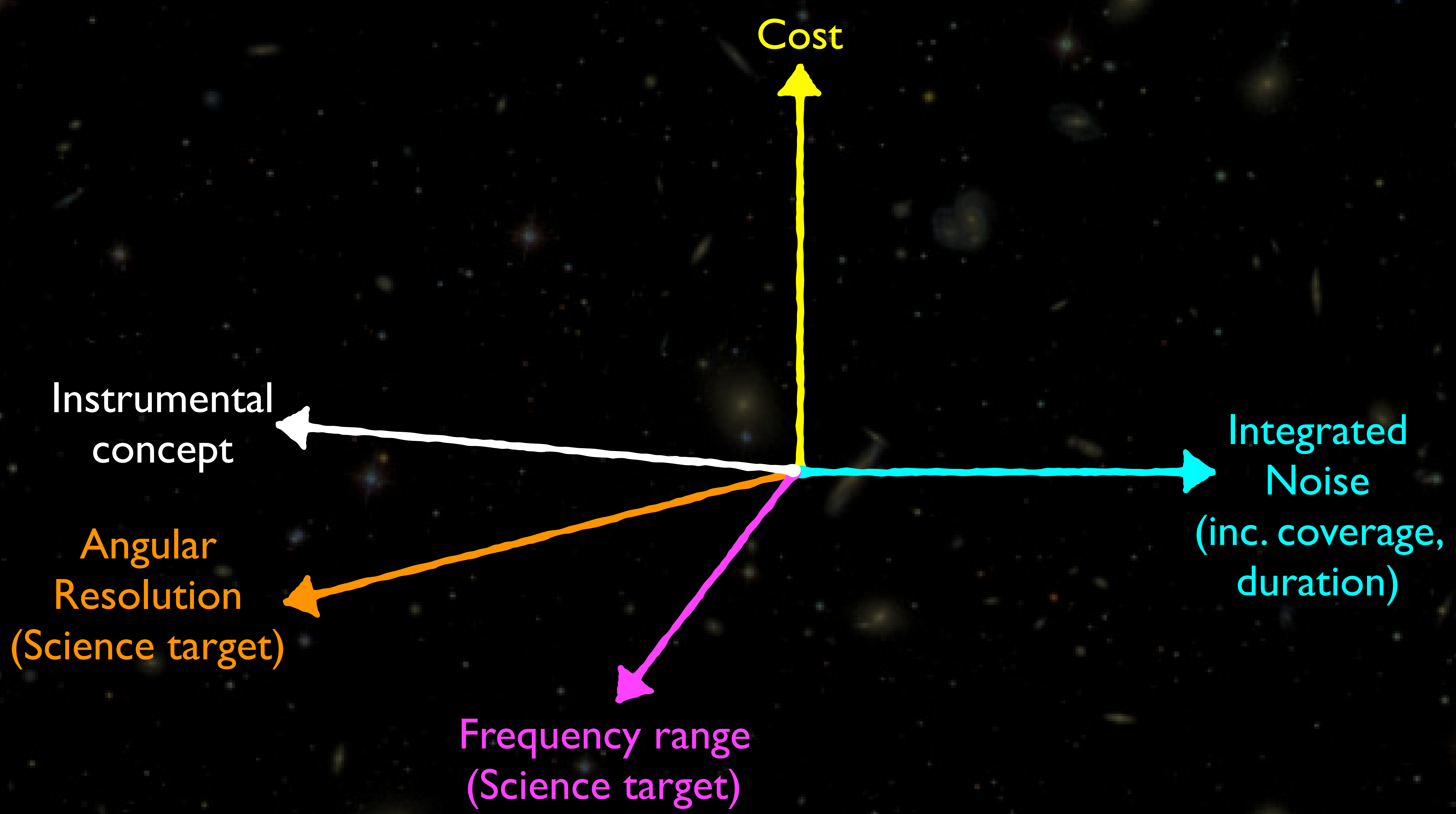

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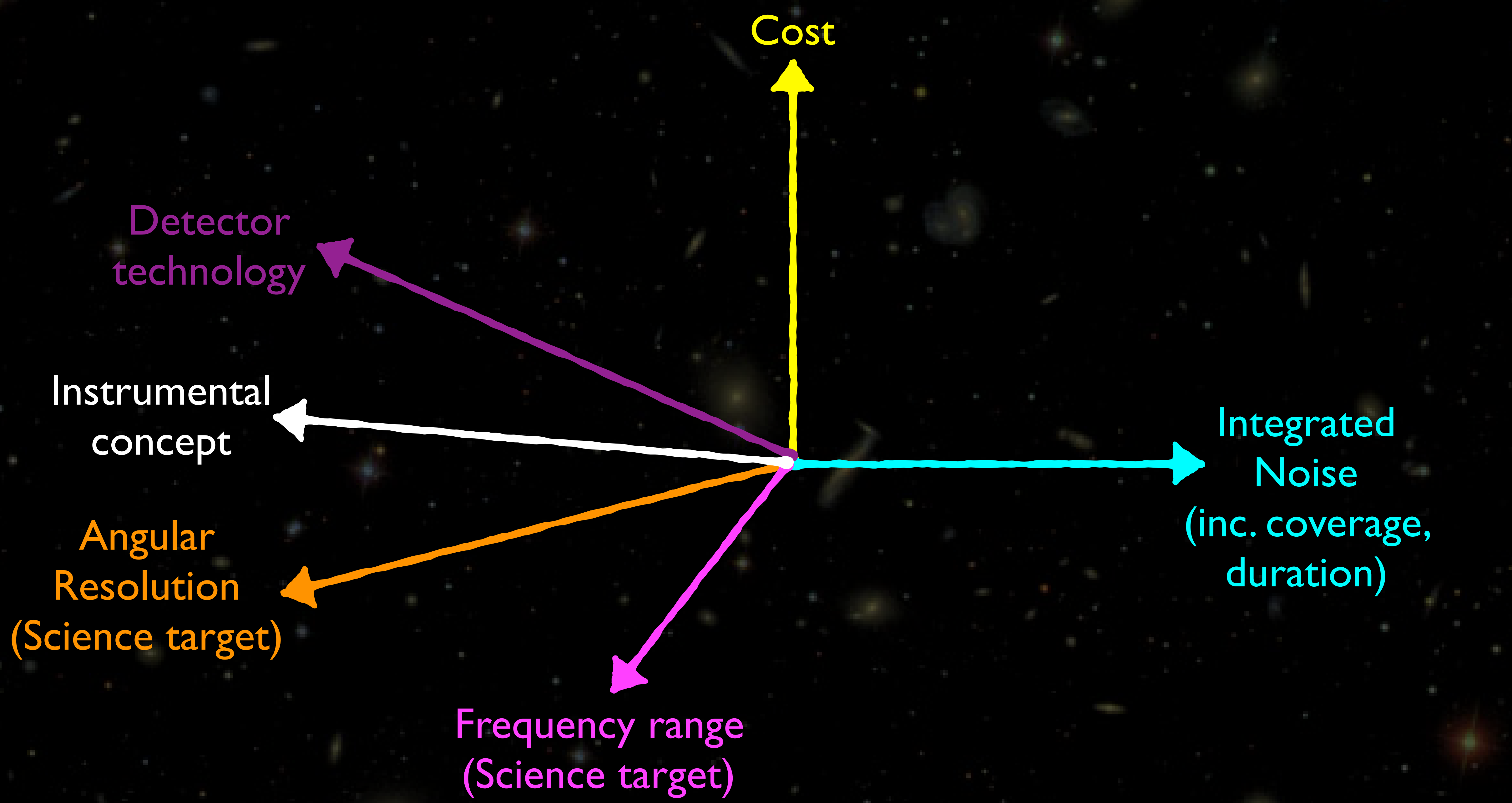

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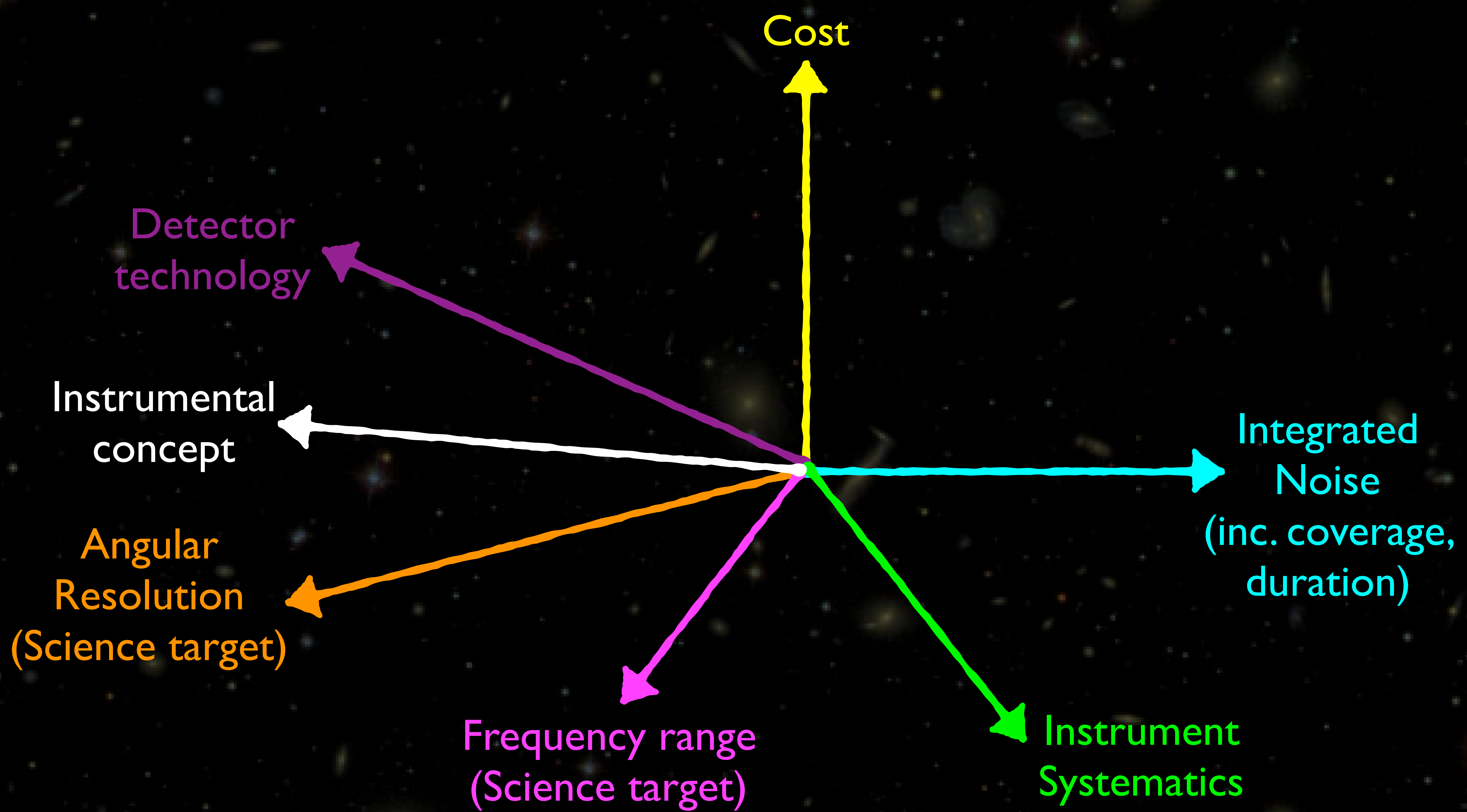

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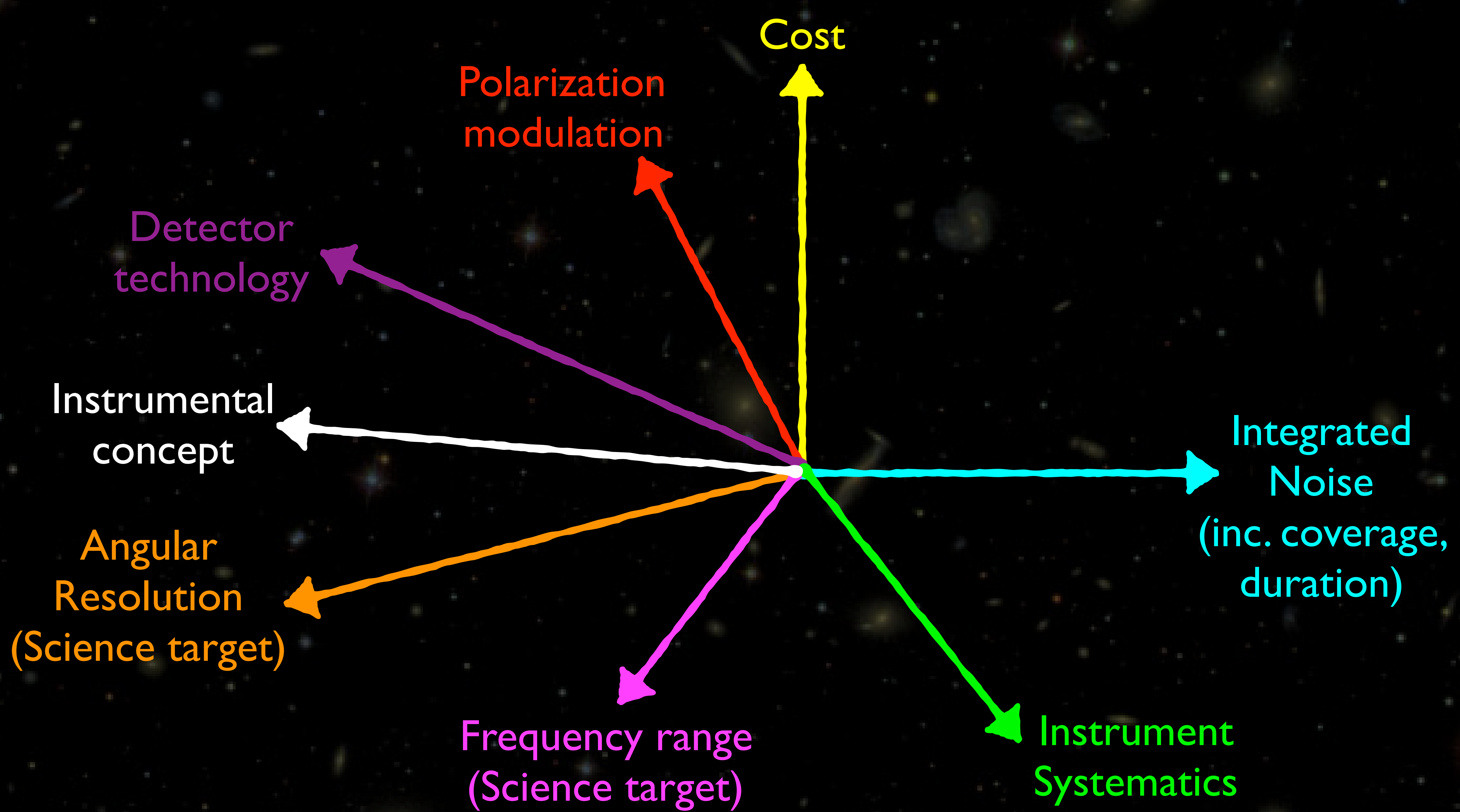

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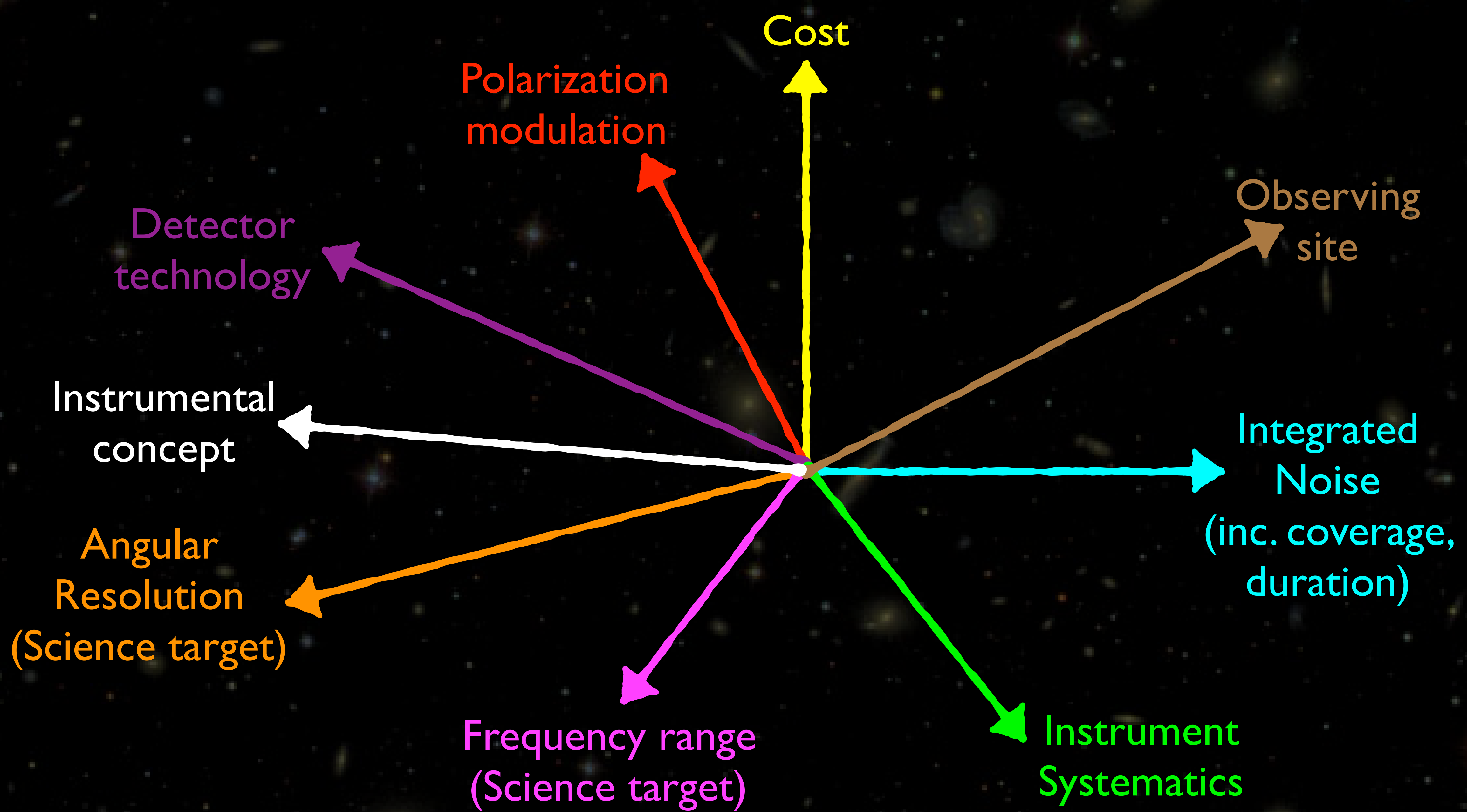

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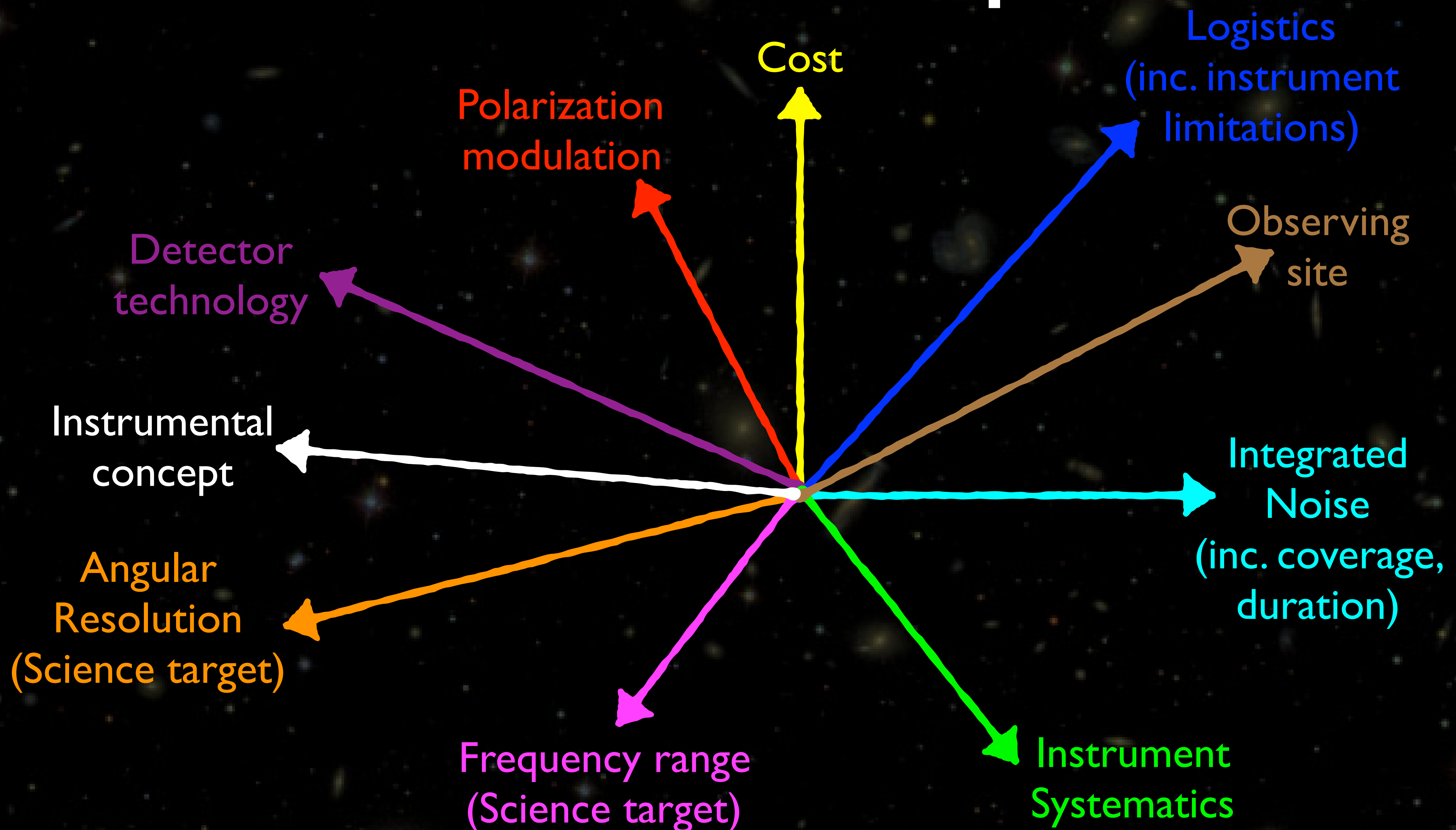

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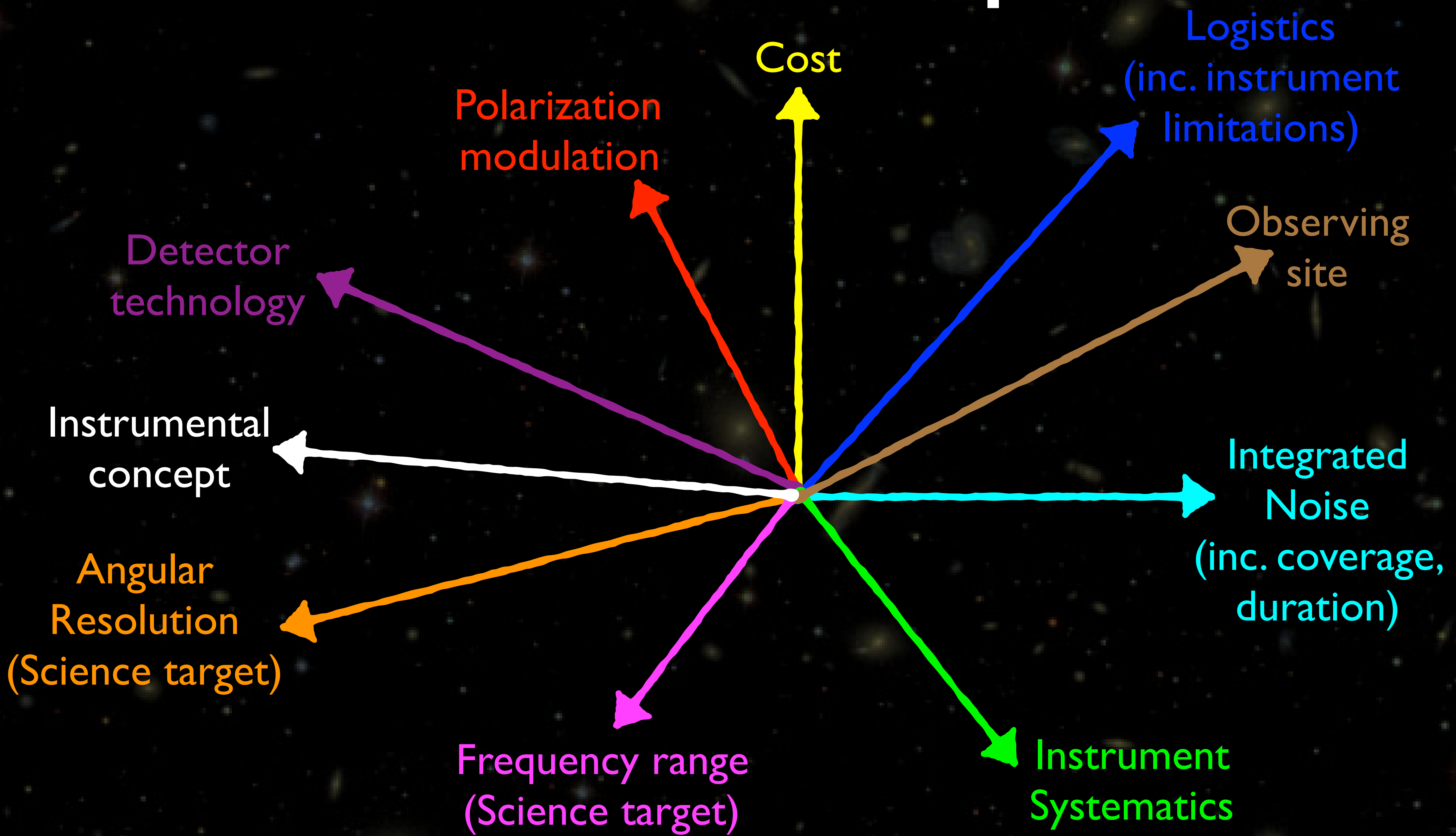

Each of the current/incoming projects has made different choices and the best combination is yet to be identified…

Contradictory requirements

- Sensitivity:
  - ★ Many thousands of detectors
  - ★ Low angular resolution (~0.5 deg) - small aperture is the best option
- Foregrounds
  - ★ At many different frequencies ranging from ~20 GHz to 300 GHz
- Lensing
  - ★ High angular resolution (~1 arcmin) - large aperture is the best option

➡ It is a tricky game…

➡ We may need a combination of instruments

Experiments…

Project	Countries	Location	Frequencies	ℓ range	σ(r) no FG	σ(r) with FG	Status
QUBIC	Fr., It., Ar., UK, Ir.	Argentina	150, 220 (+spectro-im)	30-200	6×10^{-3}	0.01	Integrating
BICEP/Keck	USA	Antarctica	95, 150, 220, 270	50-250	2.5×10^{-3}	0.01	Running
CLASS	USA	Chile	38, 93, 148, 217	2-100	1.4×10^{-3}	3×10^{-3}	Running (38)
LSPE/STRIP	It.	Canary	43, 90	30-200	0.03		Integrating
GroundBird	Jp.	Canary	150, 220 (KIDs)	6-300	0.01		?
QUIJOTE	Sp.	Canary	11,13,17,30,42	30-200	Synchrotron monitor		Commissioning
SPTPol	USA	Antarctica	95, 148, 223	50-3000	1.7×10^{-3}	5×10^{-3}	Running
ACTPol	USA	Chile	90, 150, 230	60-3000	1.3×10^{-3}	4×10^{-3}	Running
Simons Array	USA	Chile	90, 150, 220	30-3000	1.6×10^{-3}	5×10^{-3}	Running
SPIDER	USA	Antarctica	90, 150, 290	5-100	3.1×10^{-3}	12	90 GHz flew

- Large scales - Ground Based : optimized for primordial B-modes
- Small scales - Ground Based : optimized for CMB Lensing (Neutrino masses)
- Large scales - Balloon Borne : optimized for primordial B-modes
- Foreground monitor

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Large scales - Ground Based : optimized for primordial B-modes
Small scales - Ground Based : optimized for CMB Lensing (Neutrino masses)
Large scales - Balloon Borne : optimized for primordial B-modes
Foreground monitor

QUBIC

a Q&U Bolometric Interferometer for Cosmology

More than 90 members

6 countries
22 labs

APC Paris, France
CSNSM Orsay, France
IAS Orsay, France
IEF Orsay, France
IRAP Toulouse, France
LAL Orsay, France
Universita di Milano-Bicocca, Italy
Universita degli studi di Milano, Italy
Universita La Sapienza, Roma, Italy
Maynooth University, Ireland
Cardiff University, UK
University of Manchester, UK
Brown University, USA
Richmond University, USA
University of Wisconsin, USA
Centro Atómico Constituyentes, Argentina
GEMA, Argentina
Comision Nacional de Energia Atomica, Argentina
Facultad de Cs Astronómicas y Geofísicas, Argentina
Centro Atómico Bariloche and Instituto Balseiro, Argentina
Instituto de Tecnologías en Detección y Astropartículas, Argentina
Instituto Argentino de Radioastronomía, Argentina

Primordial B-modes with QUBIC

Very weak signal →

- Focal Plane: TES (APC-CSNSM-C2N-IRAP)
  - 2048 TES with NEP ~ 4x10^{-17} W.Hz$^{-1/2}$
  - 128:1 SQUIDs+ASIC Mux Readout

Polarized foregrounds →

- Two wide bands: 150 and 220 GHz
  - 1 focal plane for each channel
- Spectro-Imaging 2+3 bands

Instrumental systematics →

- Cryogenic Optics after HWP and Polarizer + Full power detectors
  - ➢ Instrumental Polarization has no effect

Instrumental systematics →

- 400 elements Interferometer
  - Synthesized Imaging (well controlled beam) – angular resolution 23.5 arcmin
  - Self-Calibration using switches + active source

QUBIC concept: Quasi optical correlator

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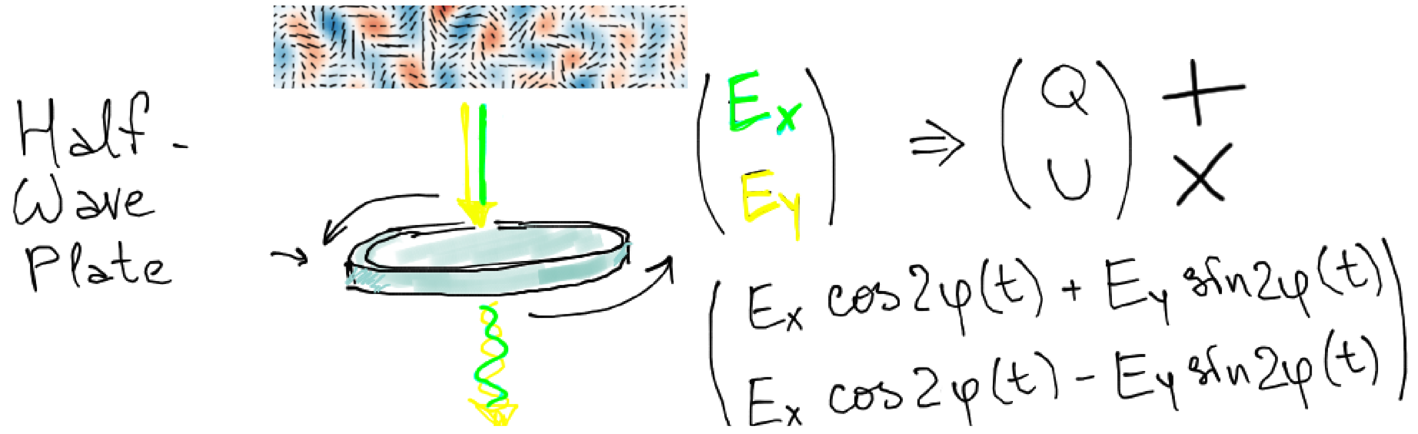
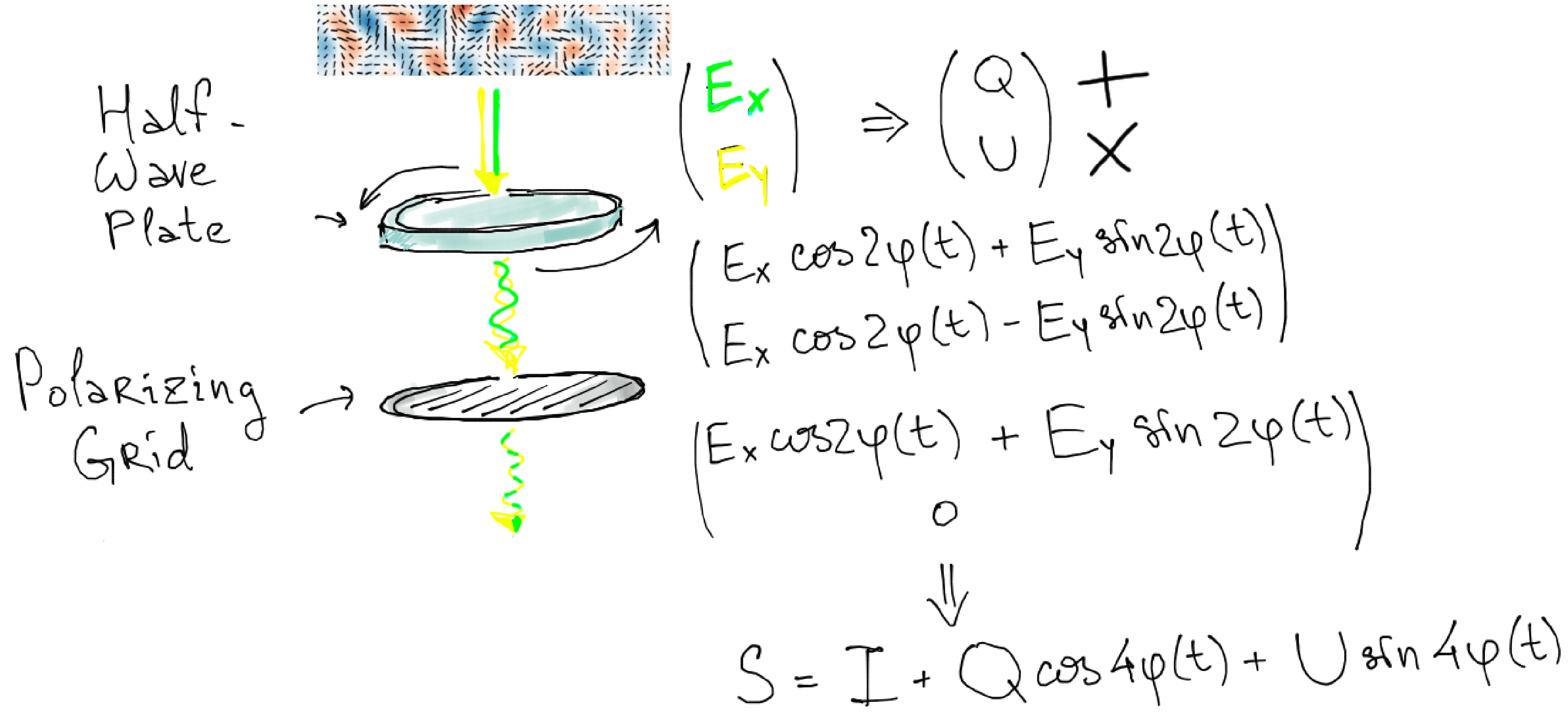


QUBIC concept: Quasi optical correlator



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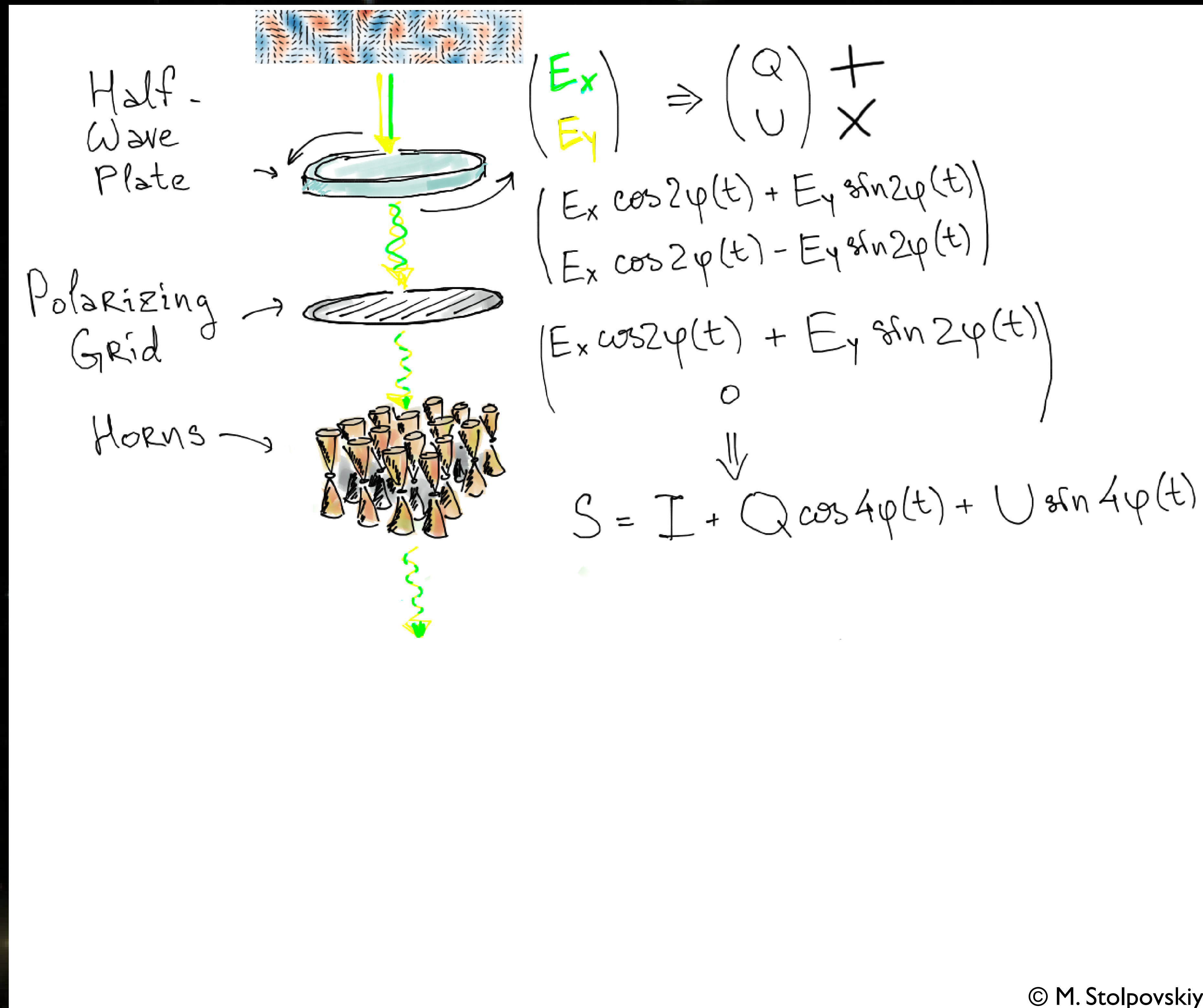

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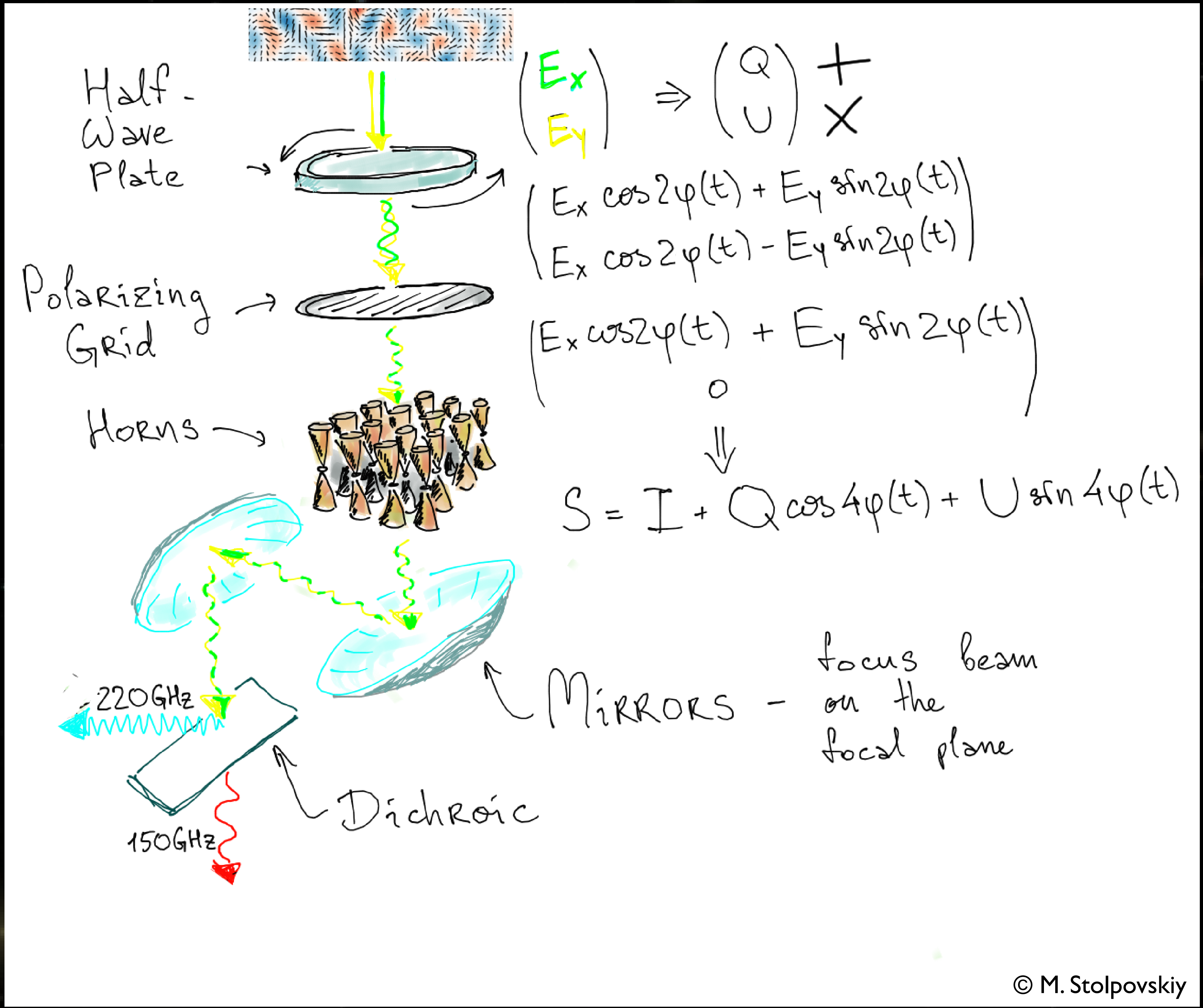

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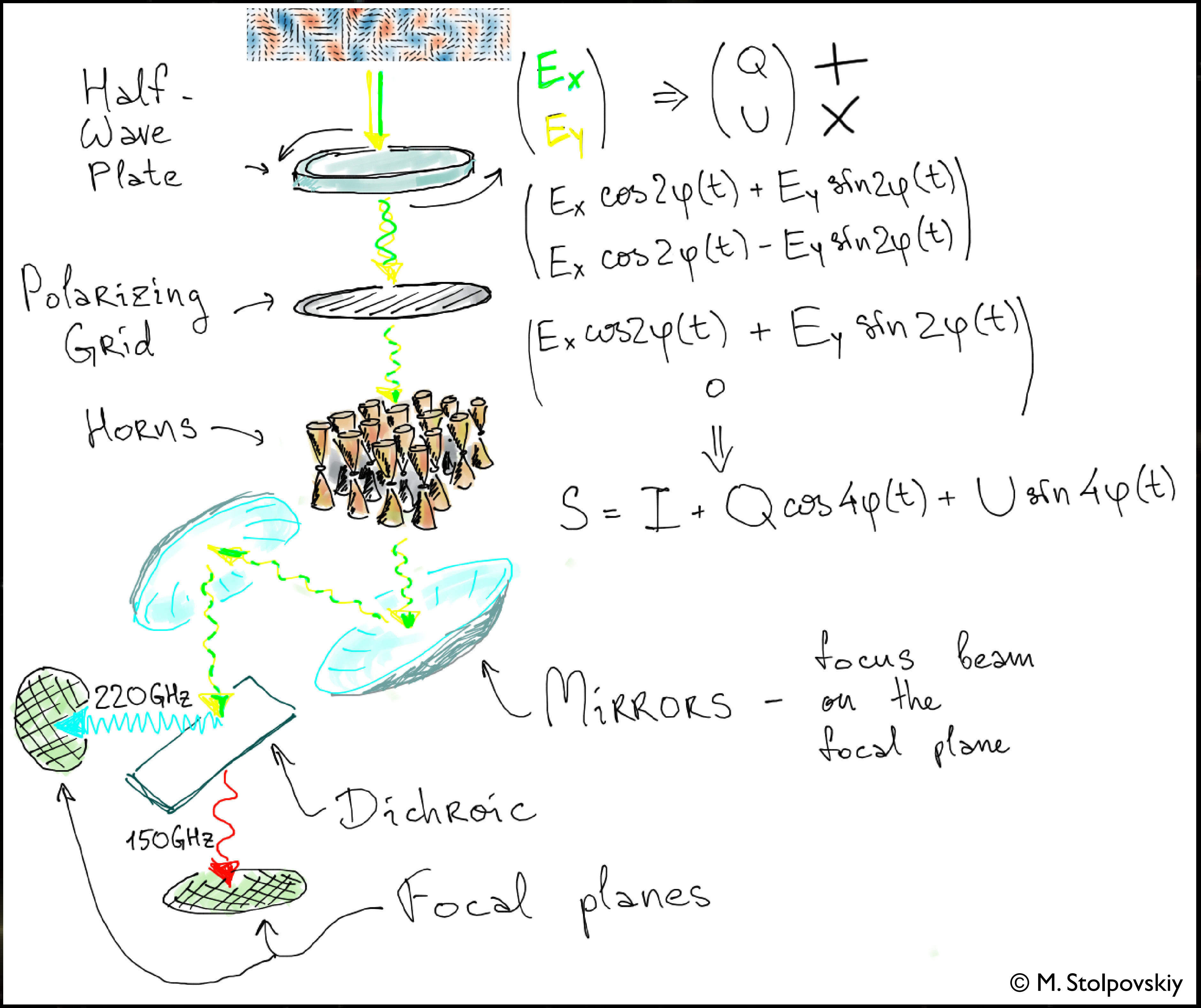

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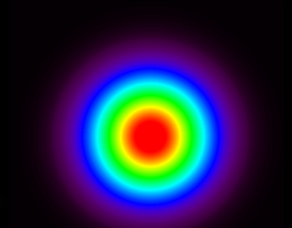
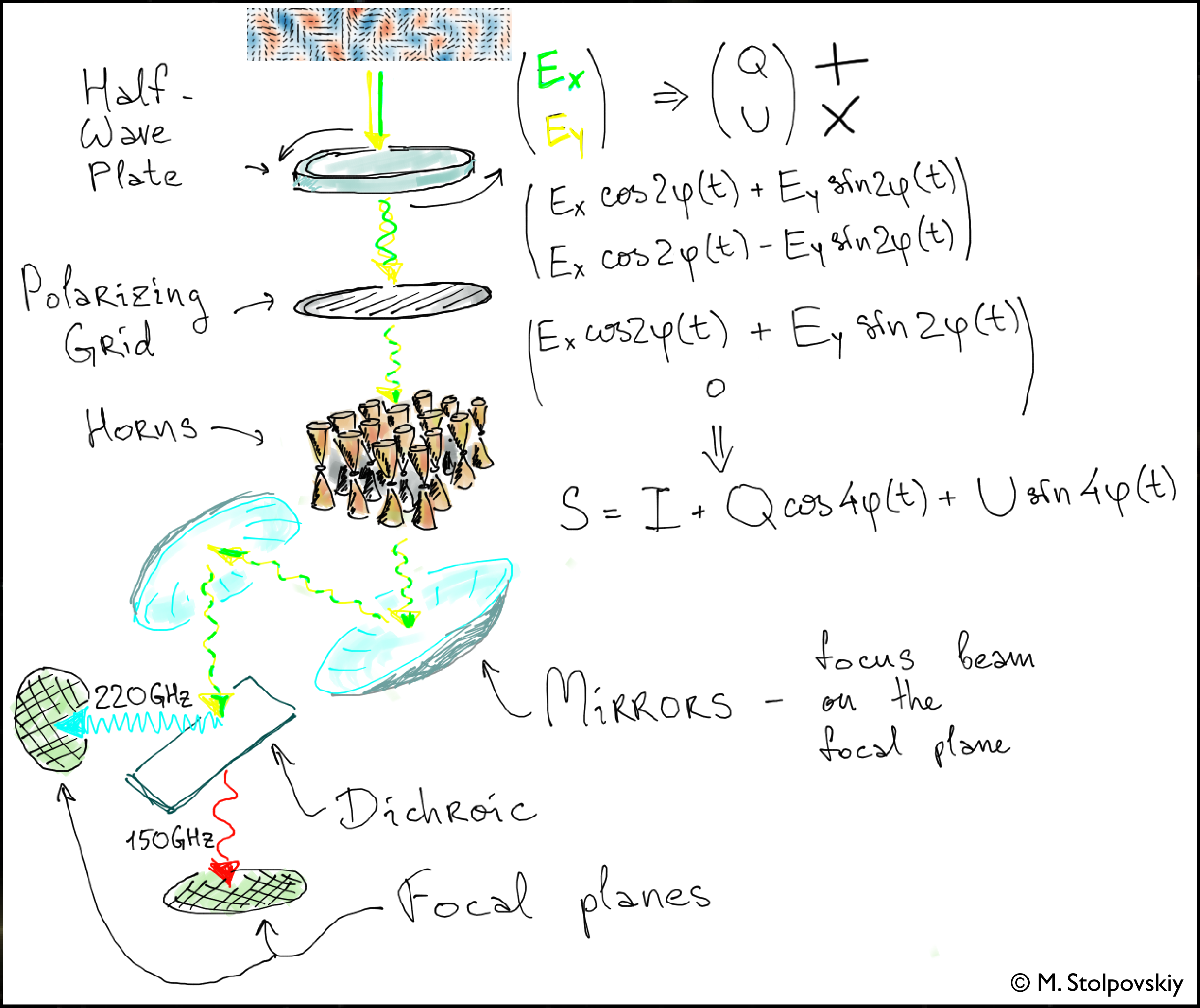


1 horn open



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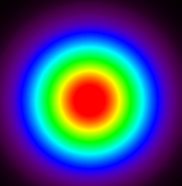

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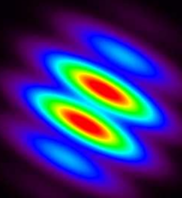
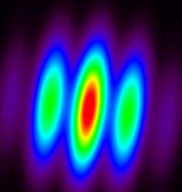


1 baseline



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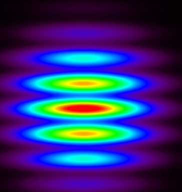

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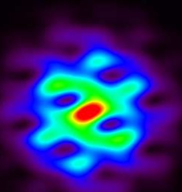
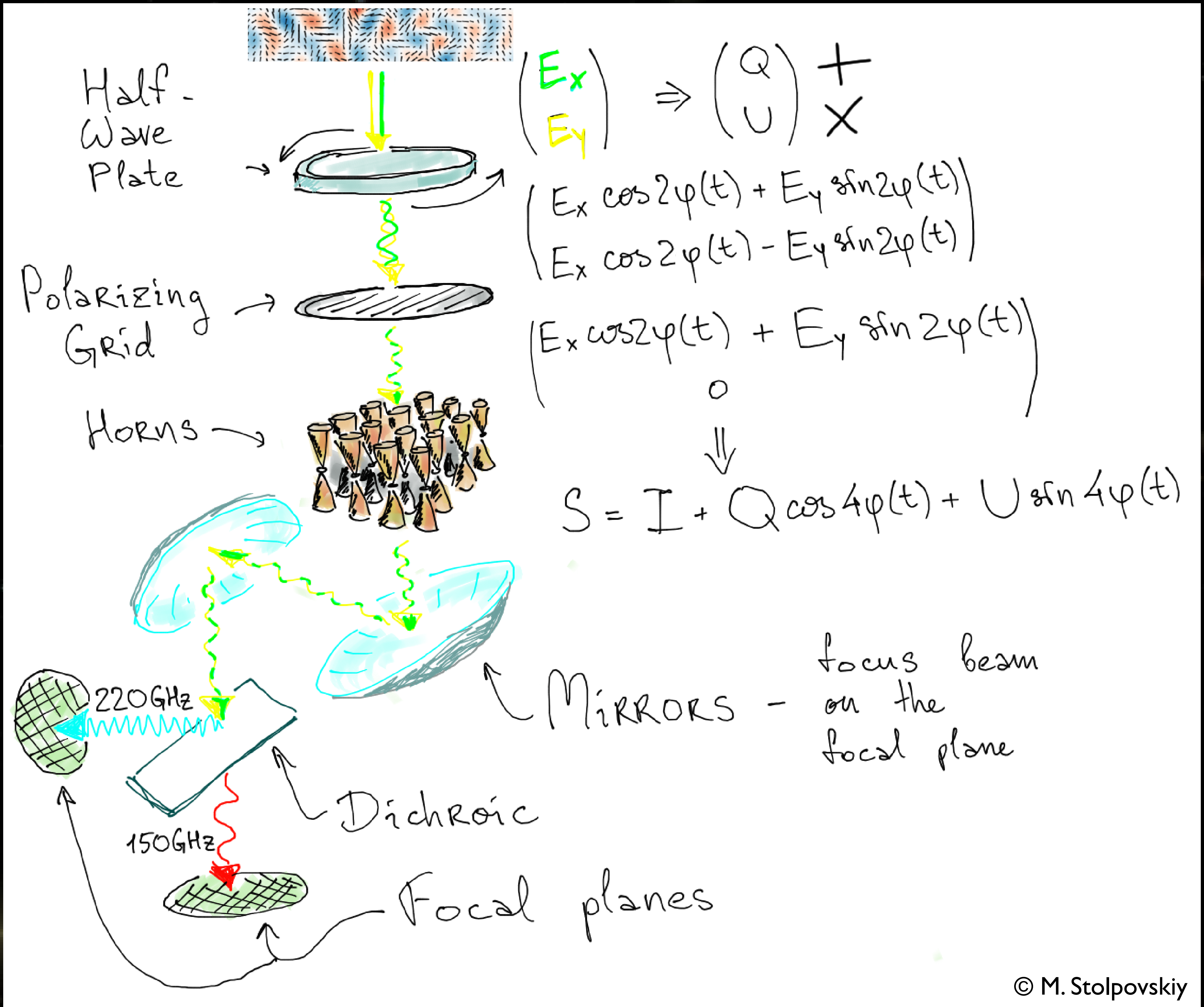
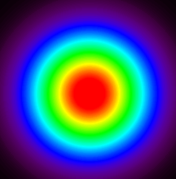


total signal
(all baselines)



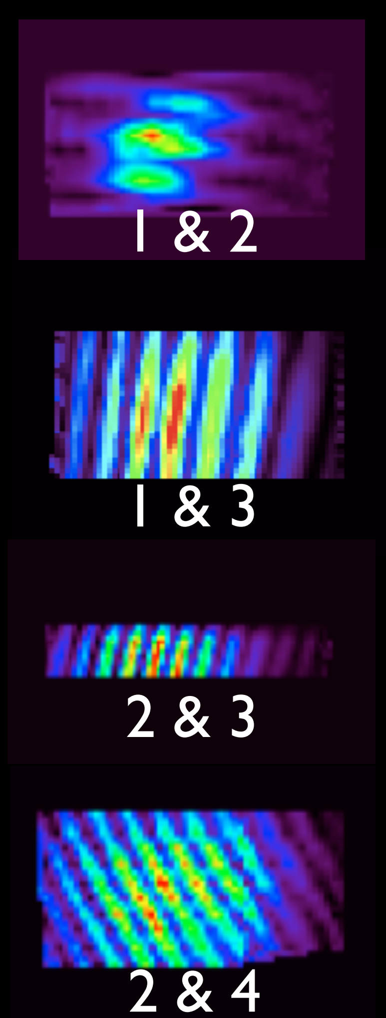
QUBIC concept: Quasi optical correlator

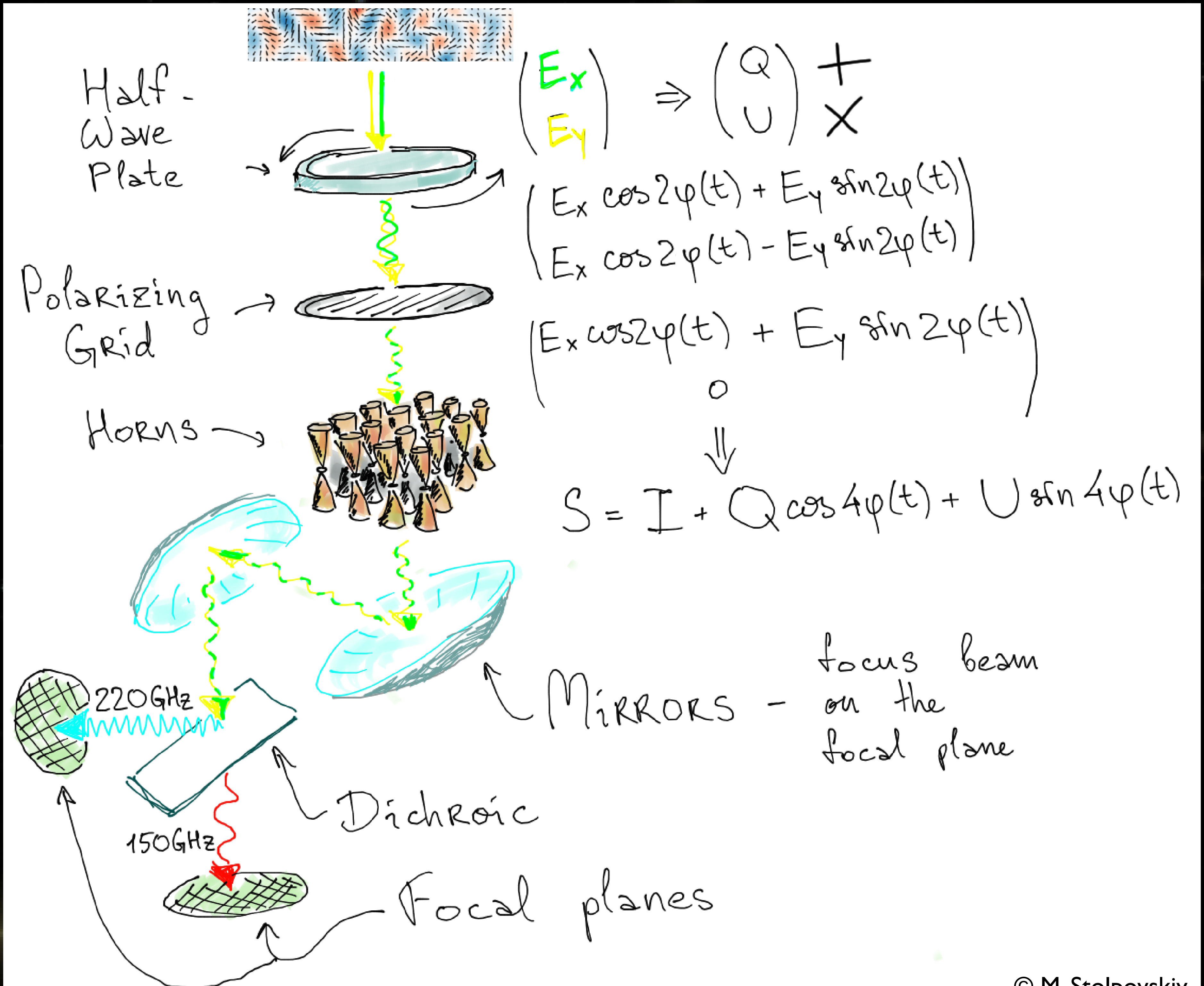
fringes successfuly observed in 2009 with MBI-4 [Timbie et al. 2006]



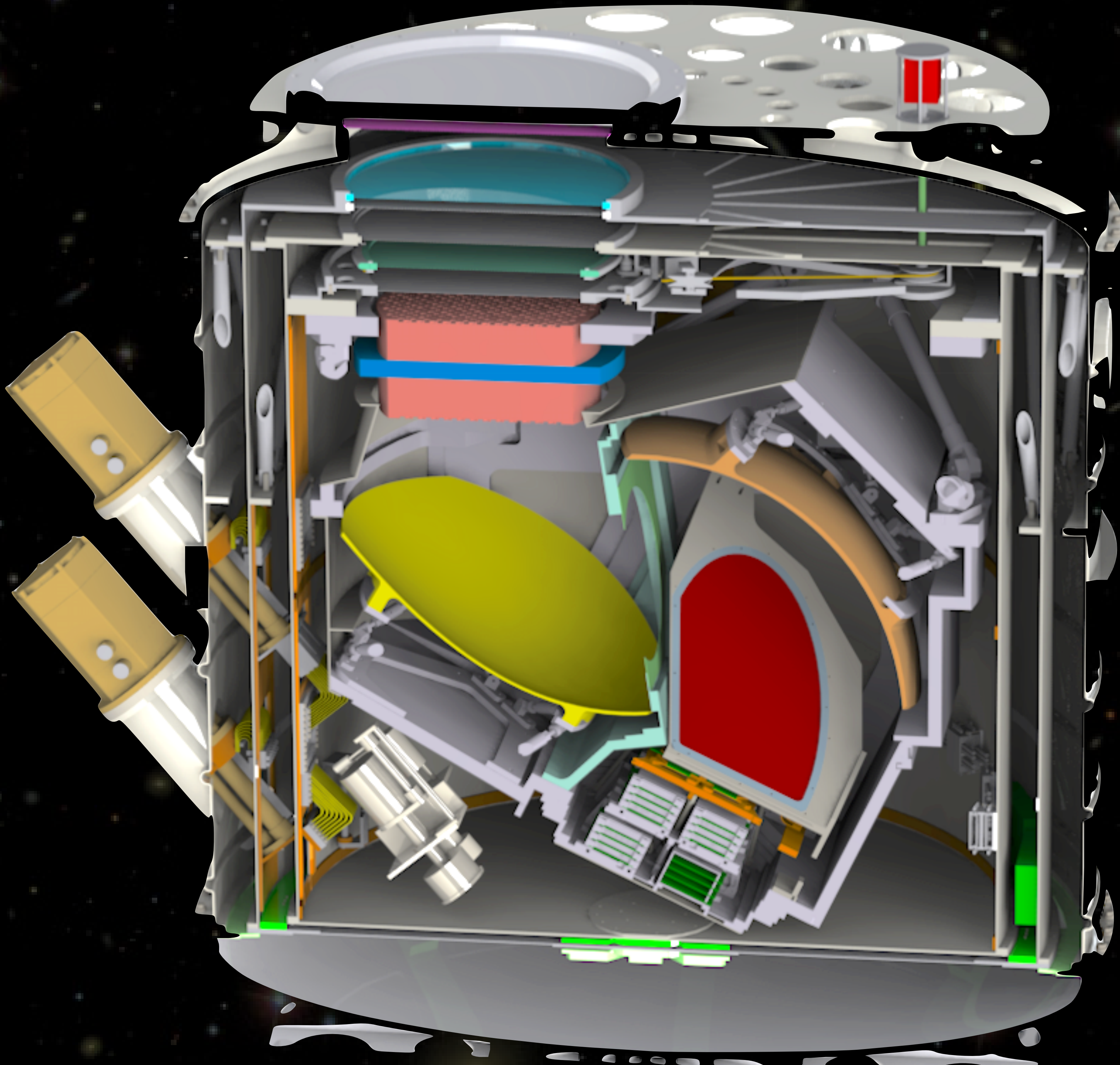
1 horn open

MBI-4 data
2009 campaign
(PBO- Wisc.)





Instrument fully designed

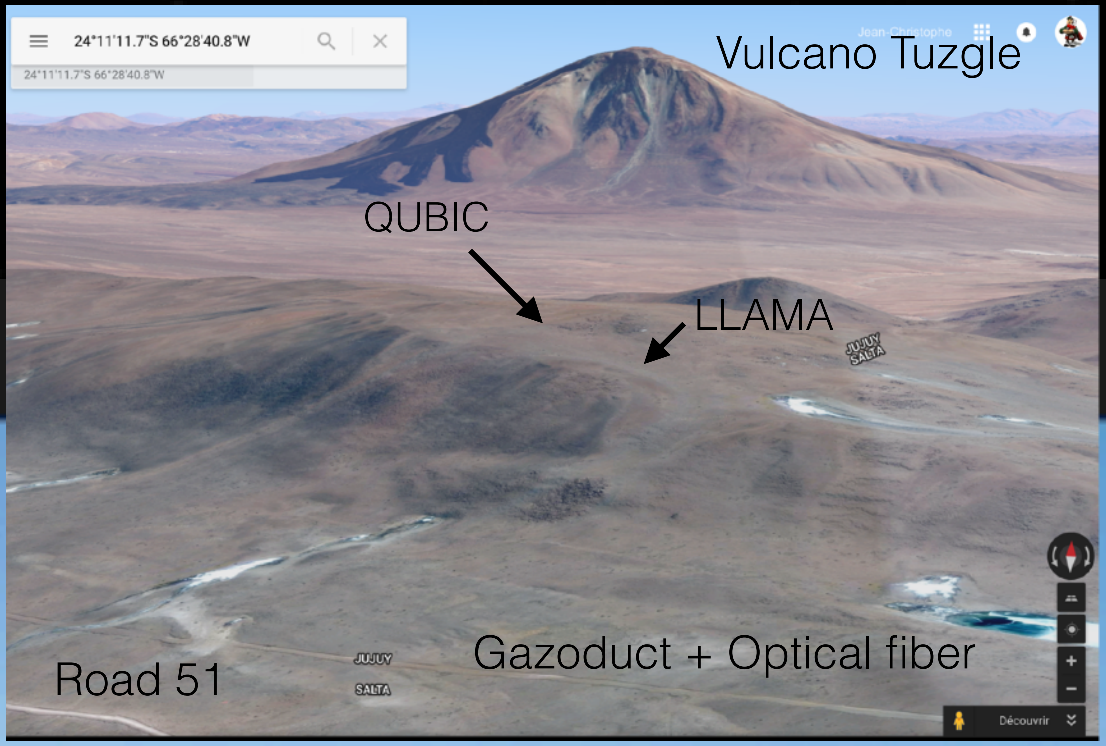


- Outer cryostat: Roma
- HWP: Manchester / Roma
- 1K Box / detectors: APC
- Fridges: Manchester
- Optics: Roma / Maynooth / Milano
- Mount: Argentina

1.547m high
1.42m diameter
About 800kg

Integration on the way !

QUBIC Site:
near San Antonio de los Cobres
(Salta, Argentina)



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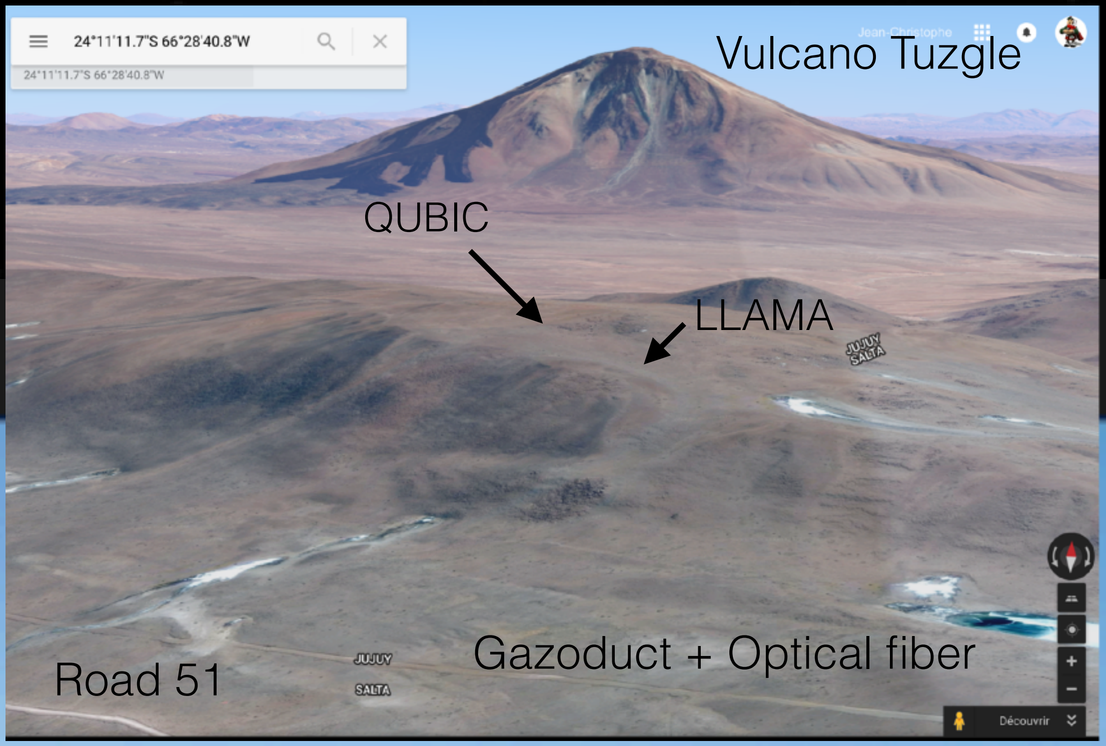
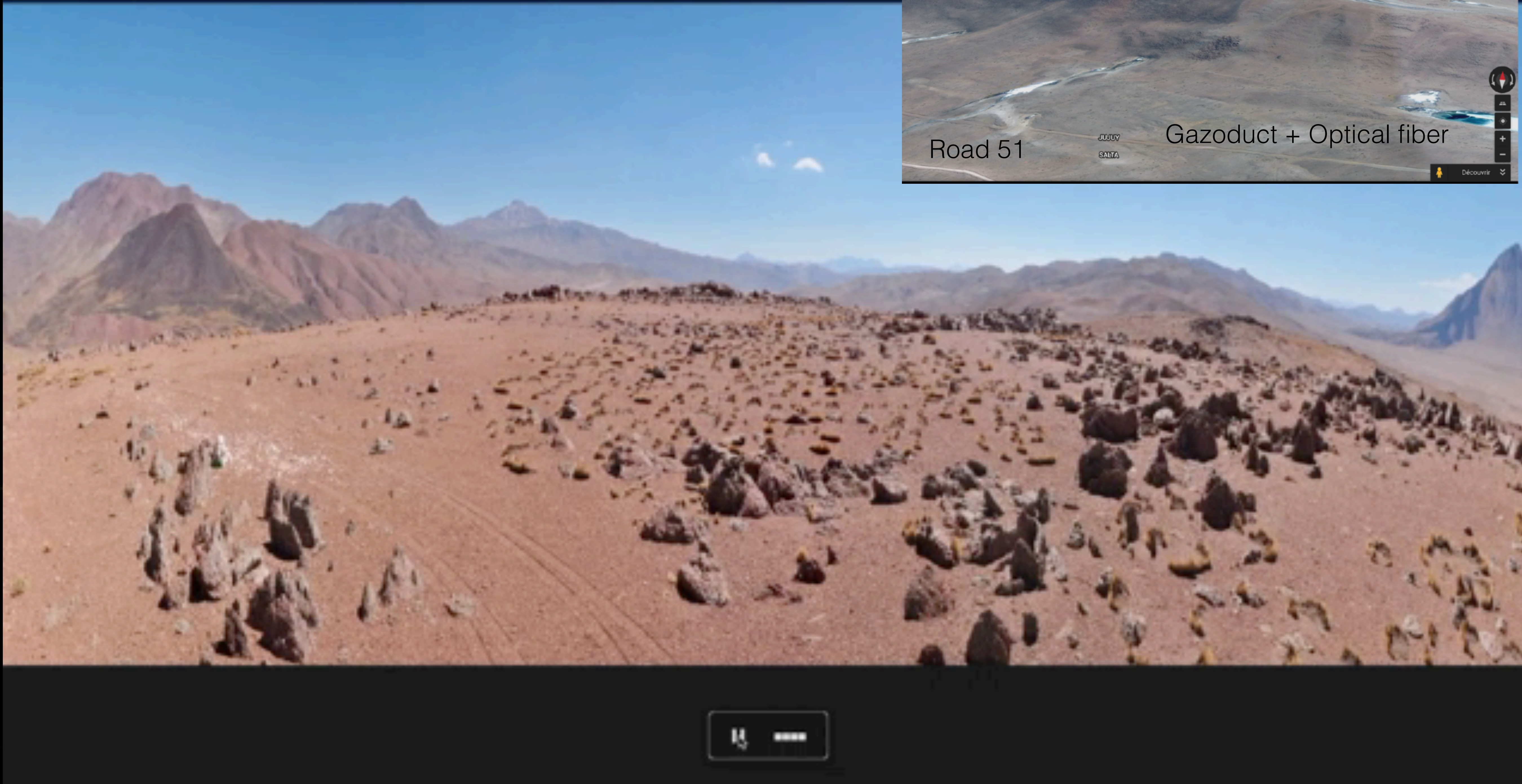
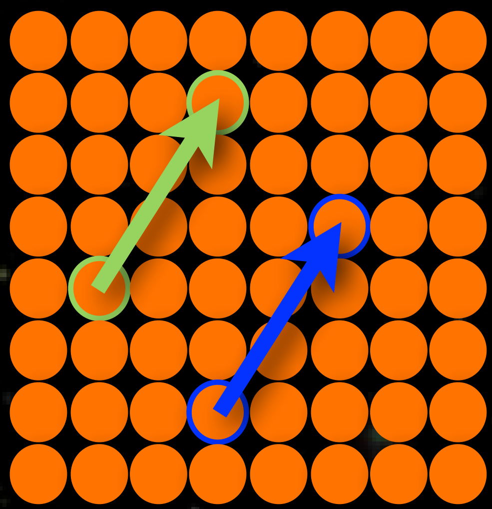


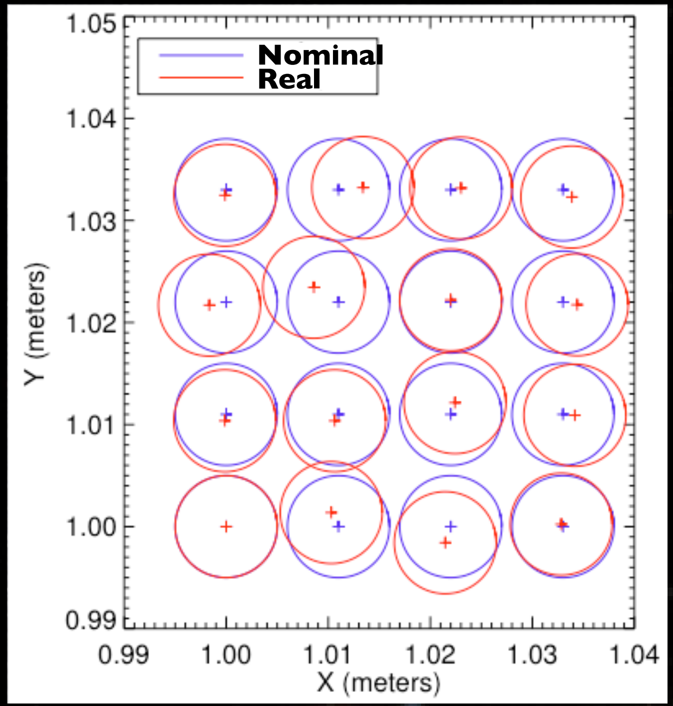


Systematics: Self-Calibration

- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique specificity of Bolometric Interferometry !
    [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]
  - ★ Example: exact horns locations (figure exagerated !!)



Redundant baselines :
same Fourier Mode



Actual horn positions (red) are not well know
One uses ideal ones (blue) in map reconstruction
⇒ Systematics in maps, E/B leakage

Systematics: Self-Calibration

- Unique possibility to handle systematic errors
  - ★ Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - ★ Unique specificity of Bolometric Interferometry !
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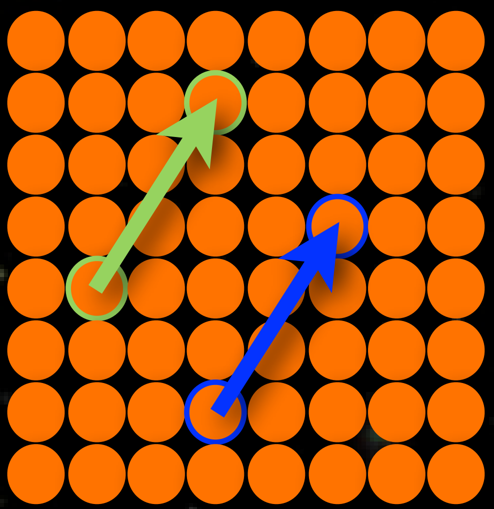

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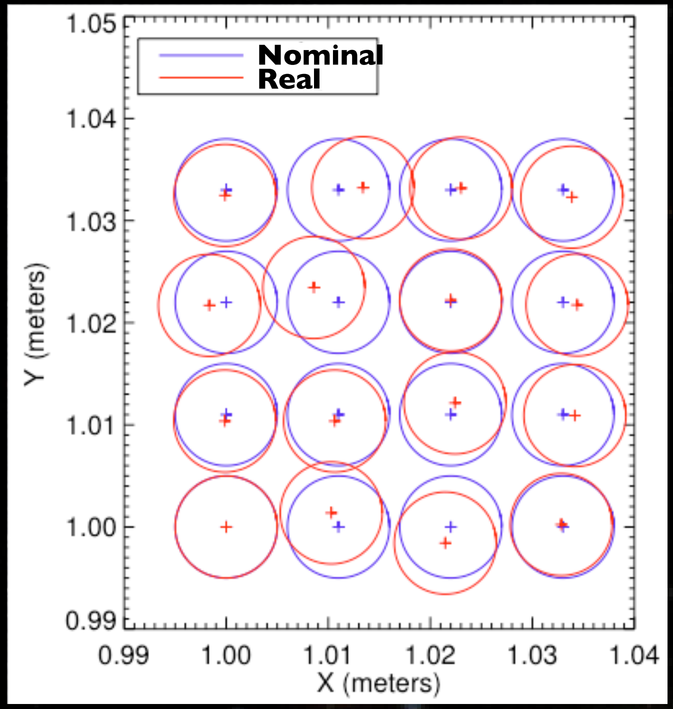

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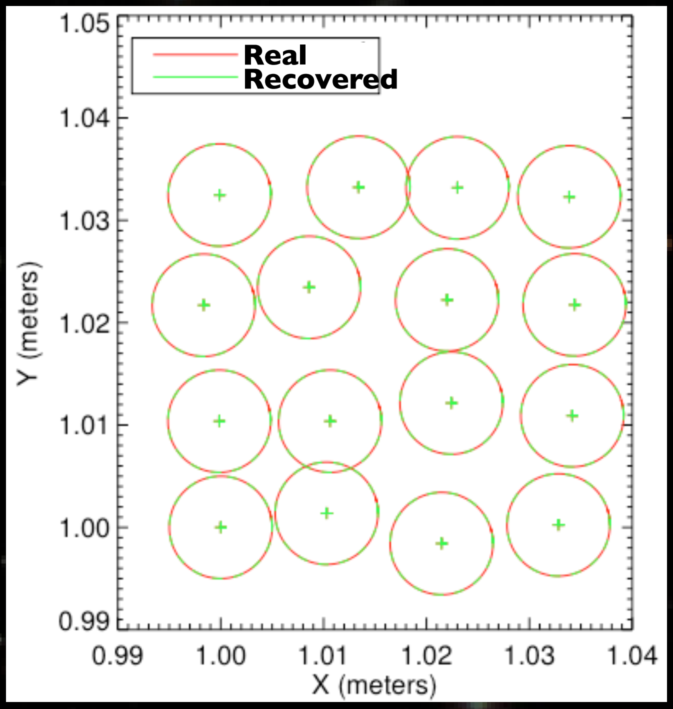

Actual horn positions (red) are recovered thanks to self calibration (green)
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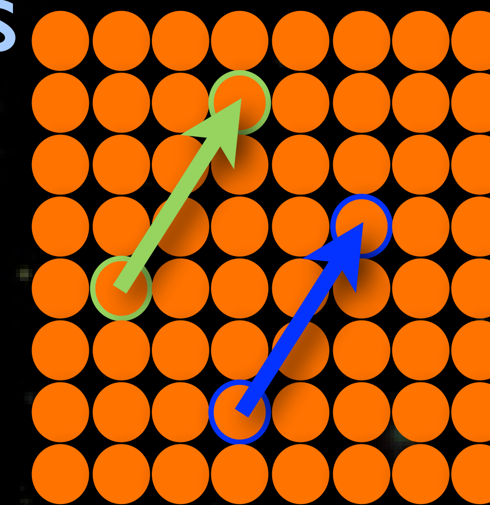

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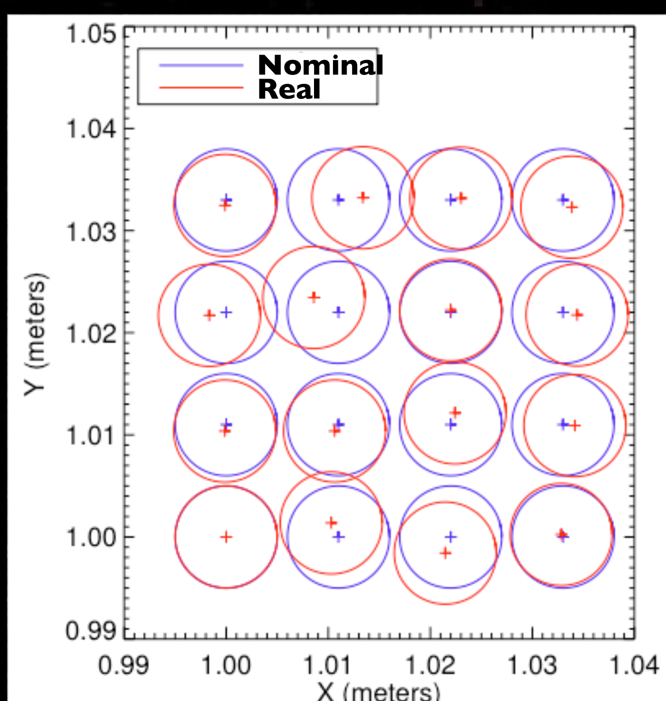

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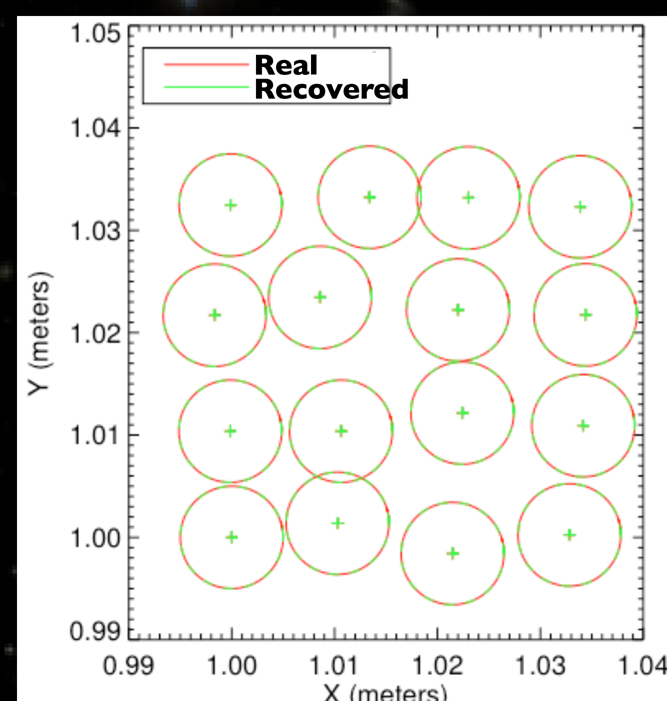

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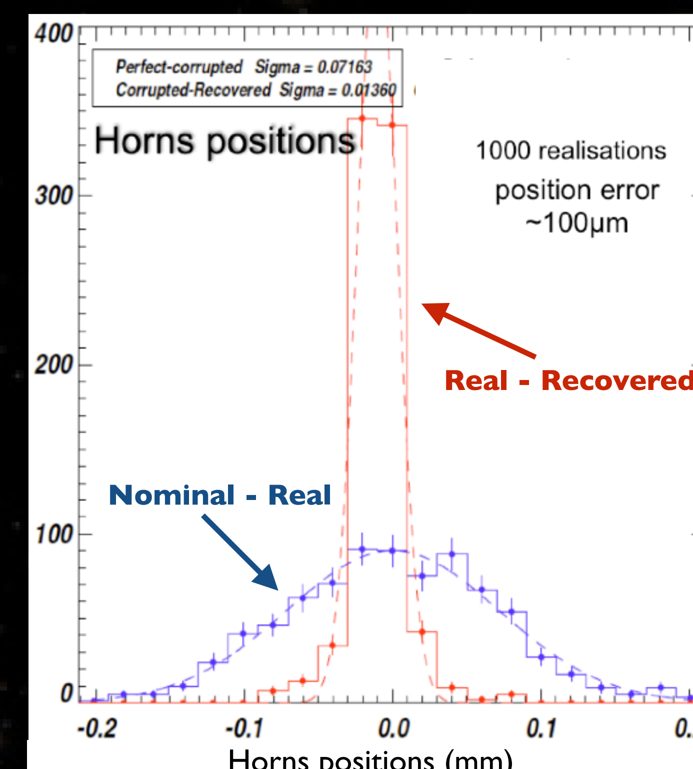
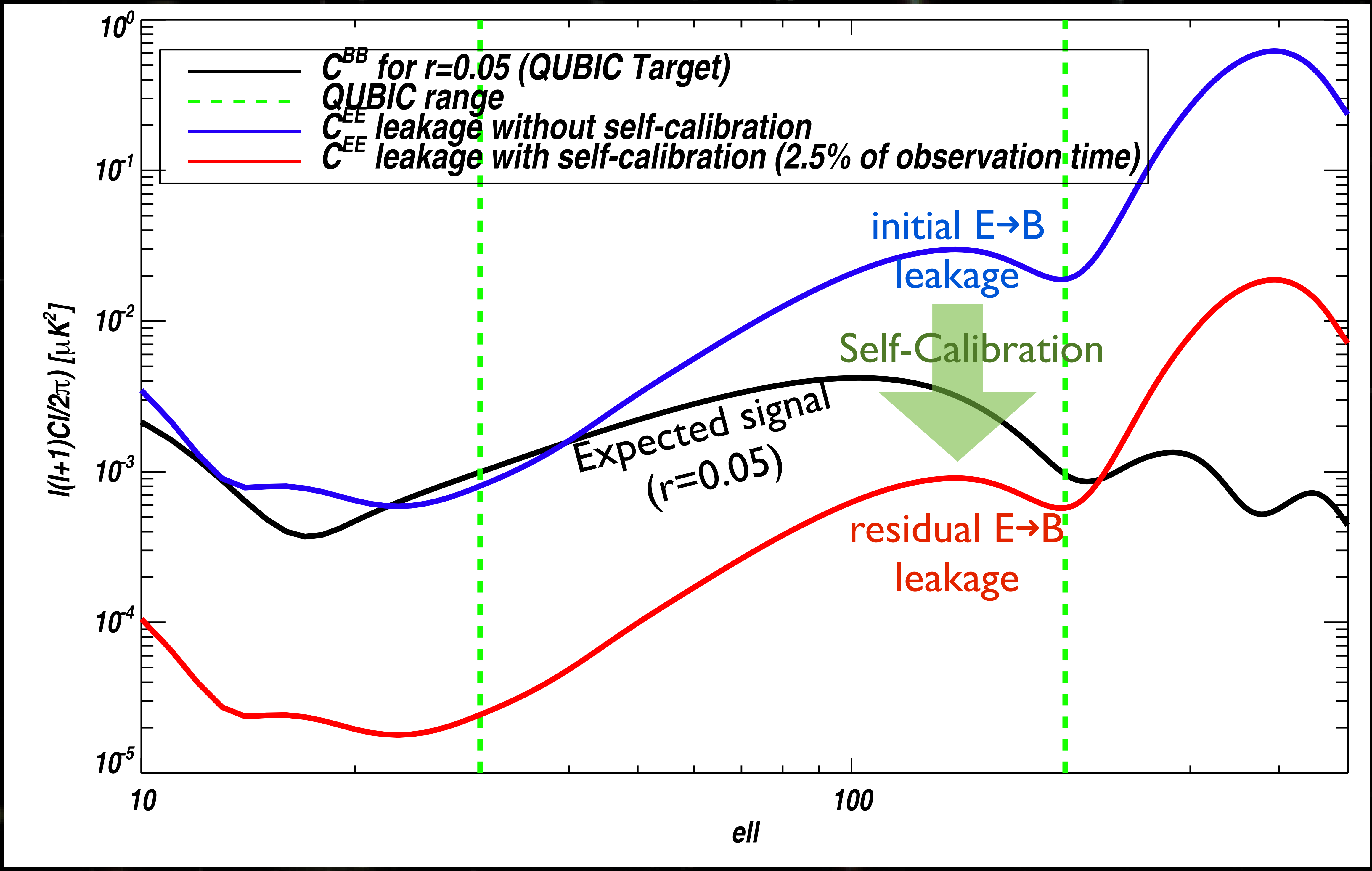


Horn position knowledge improvement

Self-Calibration results



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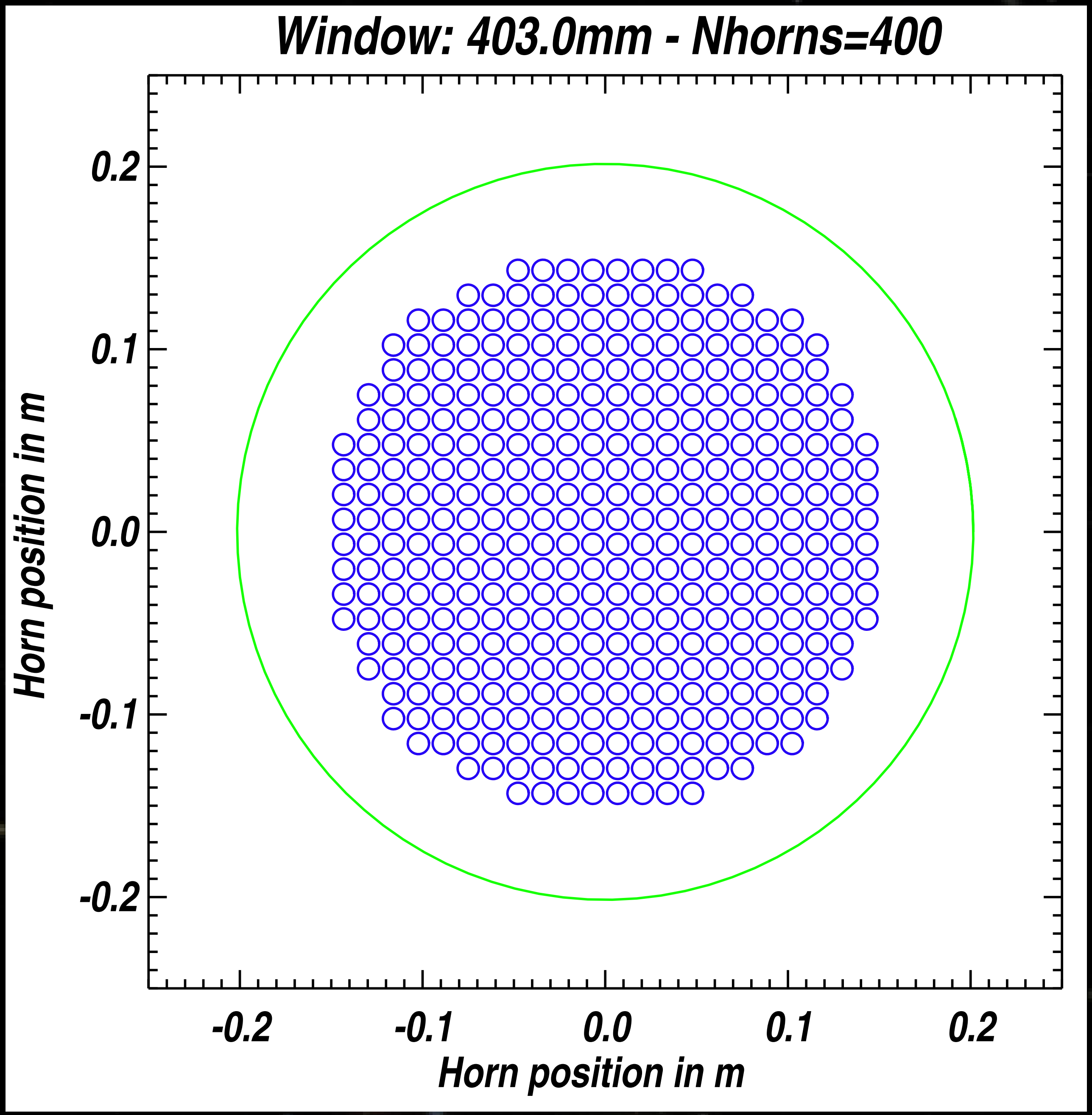
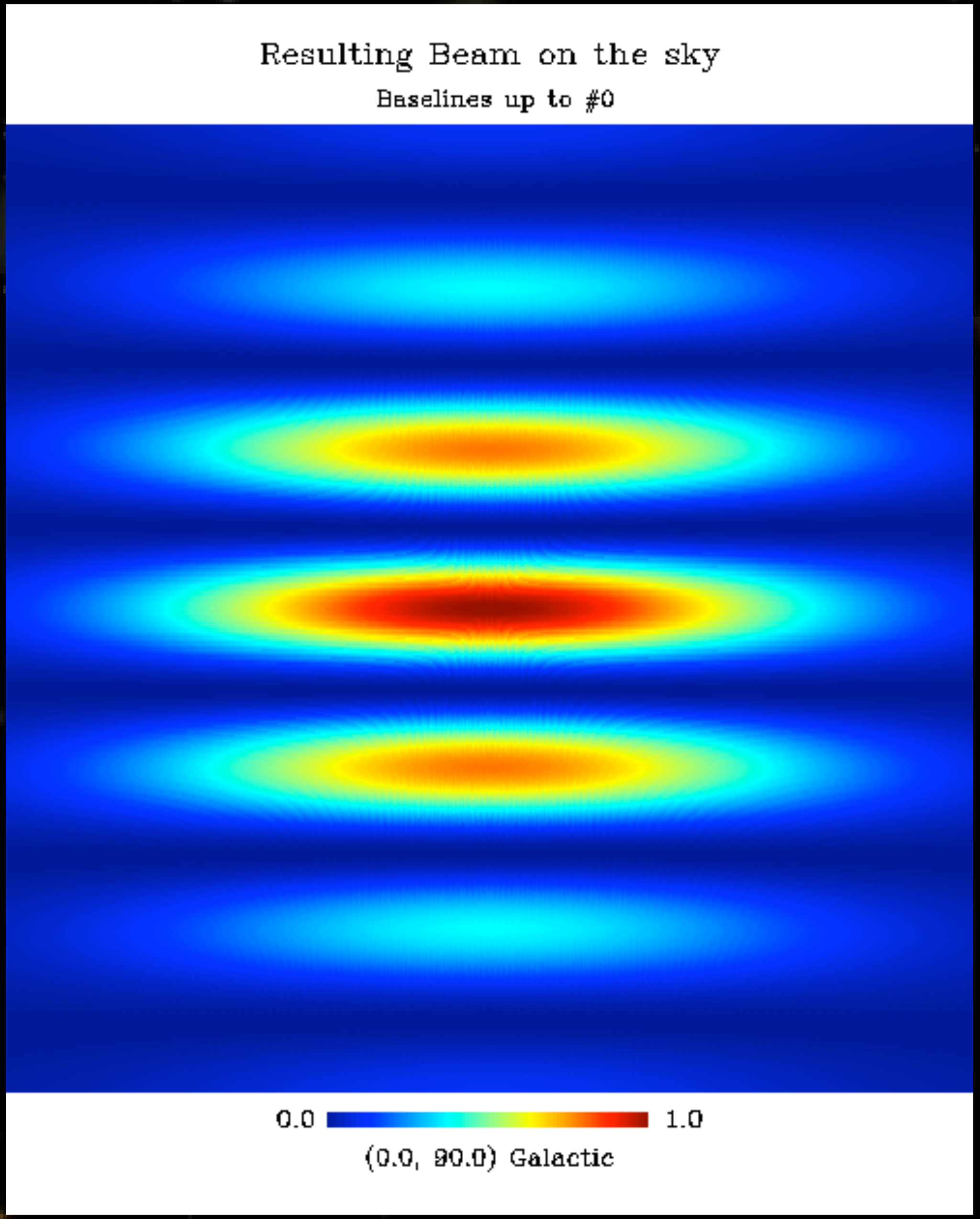
B.I. = Synthesized imager

Primary horns array



150-220 GHz, 20x20 horns,
13 deg. FWHM, D=1.2 cm

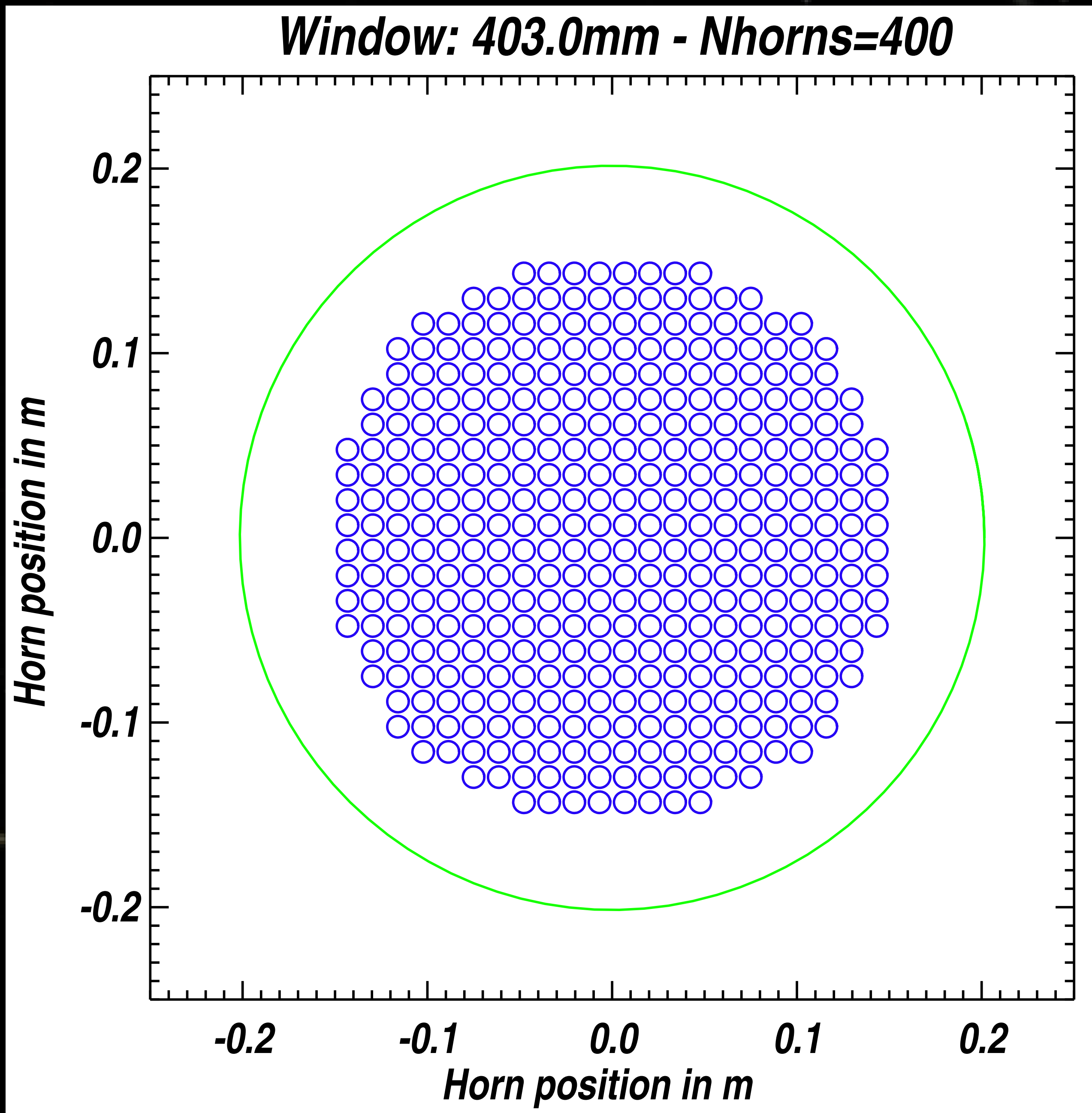
Synthesized beam (on the sky)



Synthesized beam used to scan the sky as with an imager

B.I. = Synthesized imager

Primary horns array



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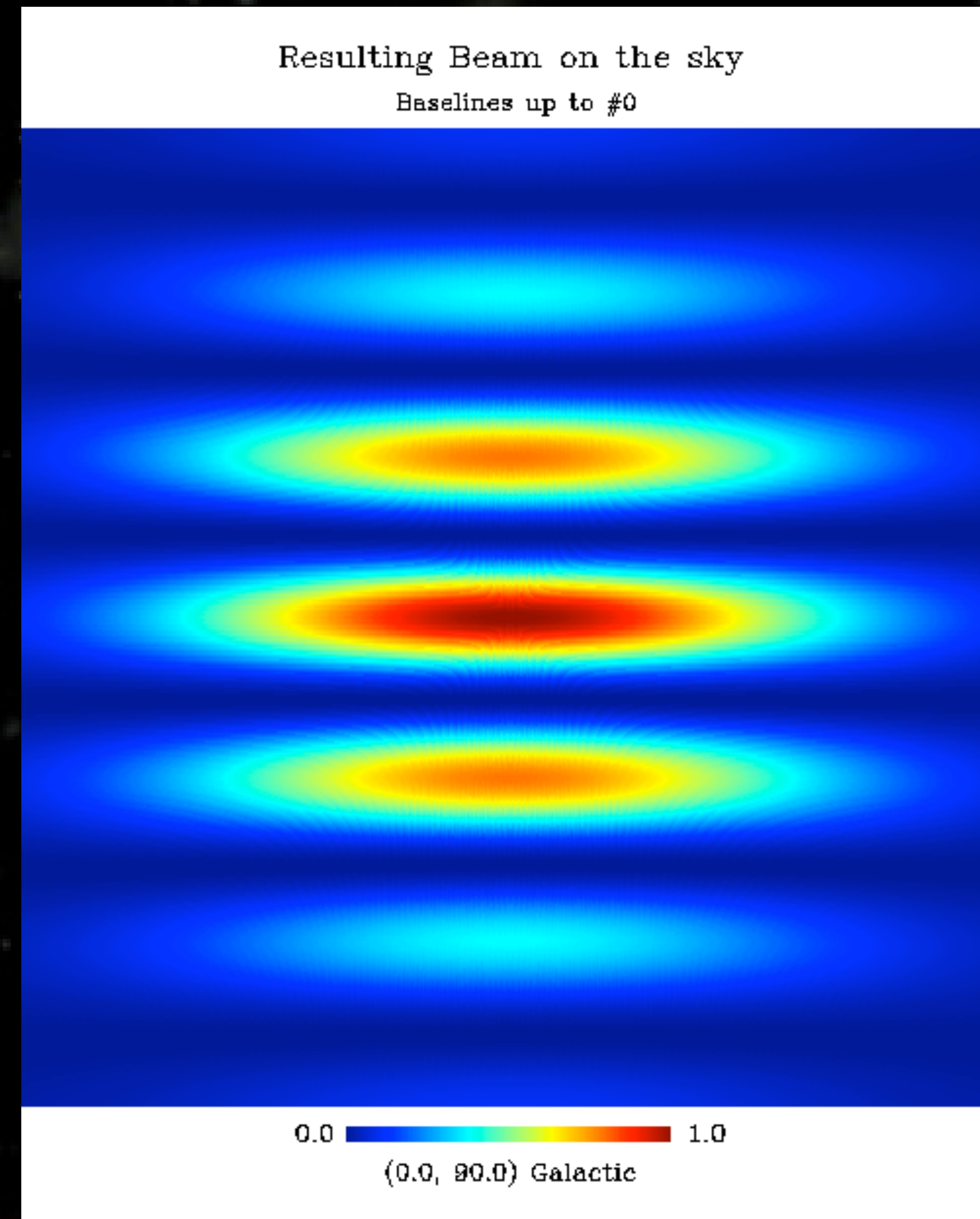

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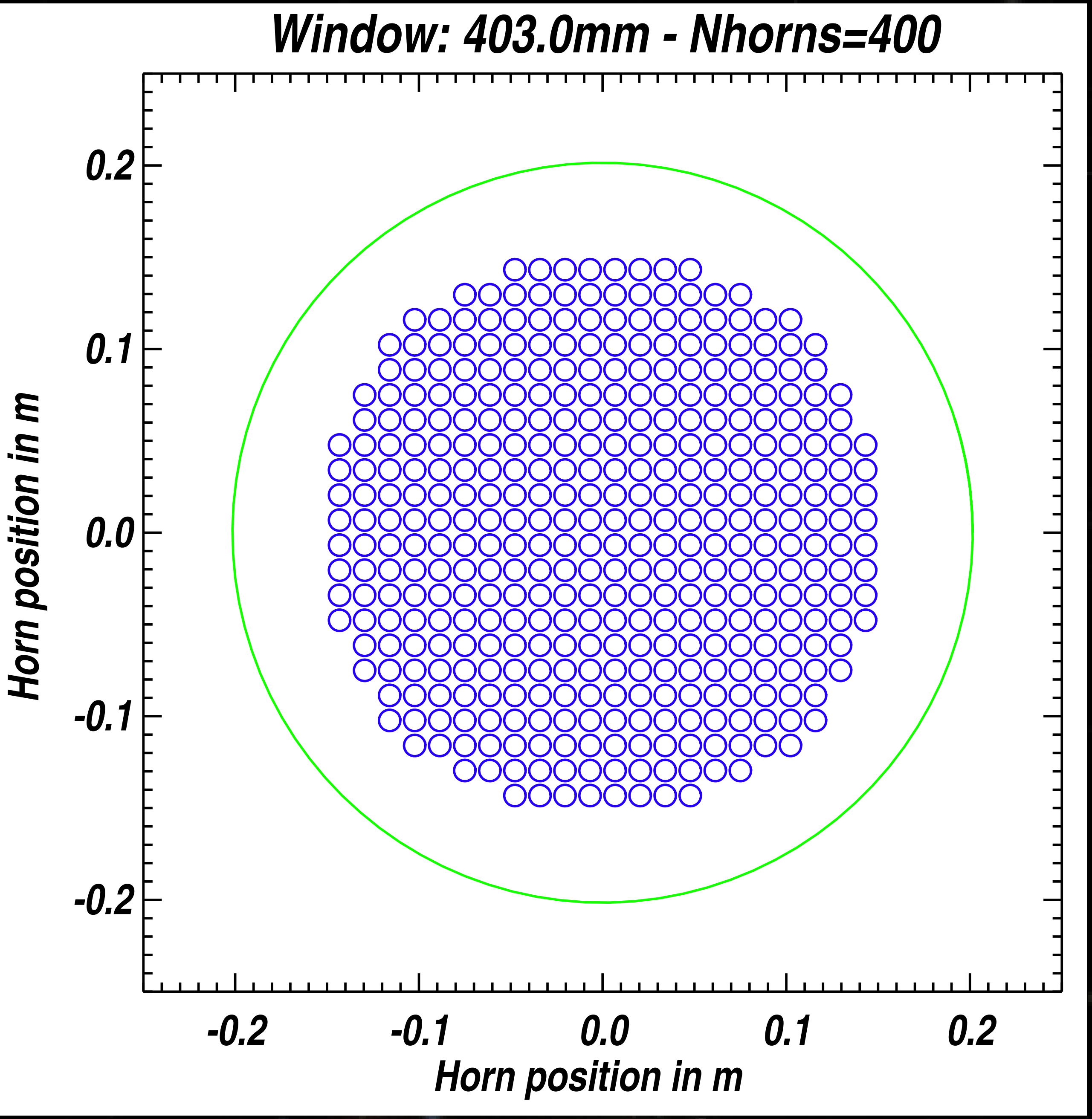

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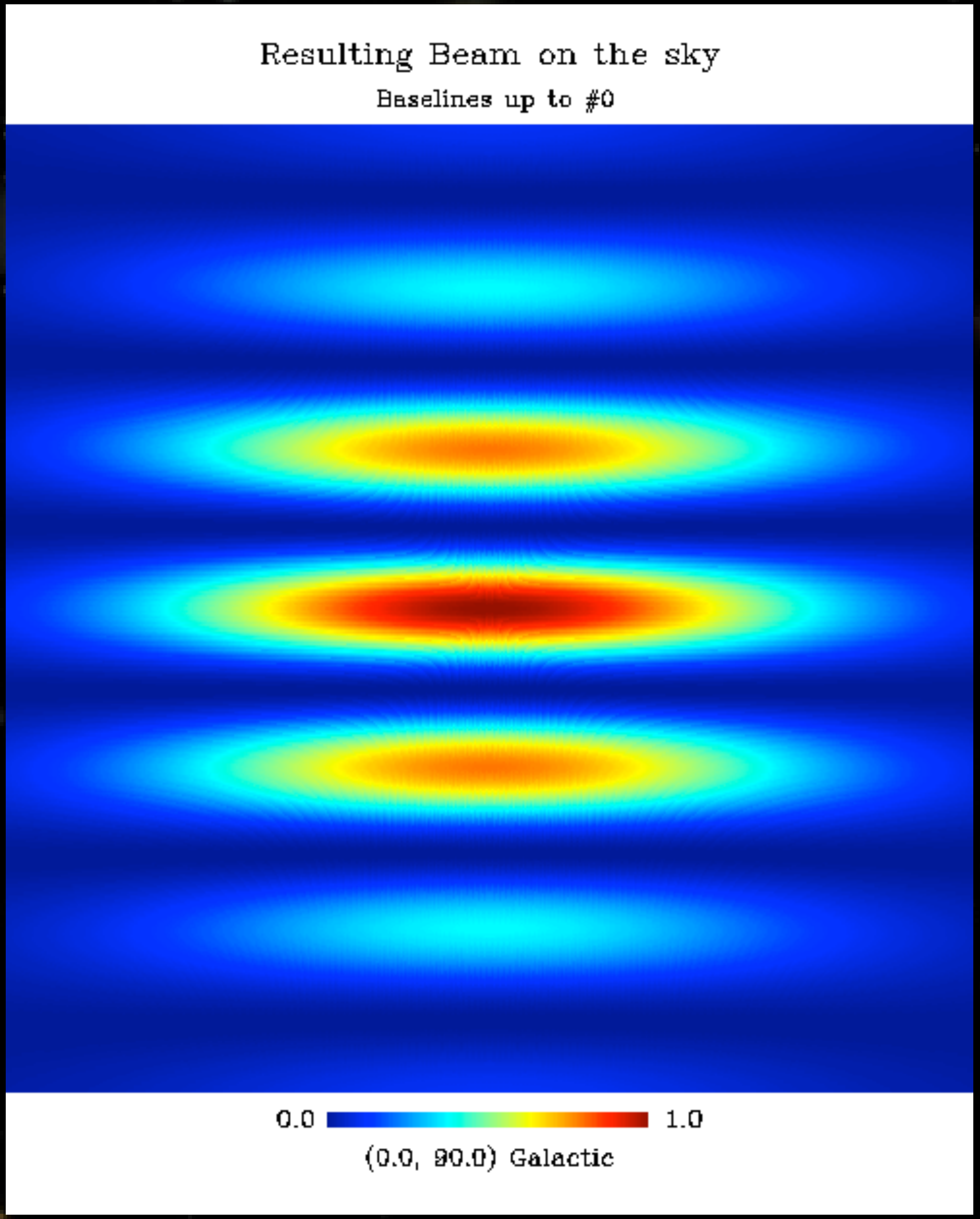

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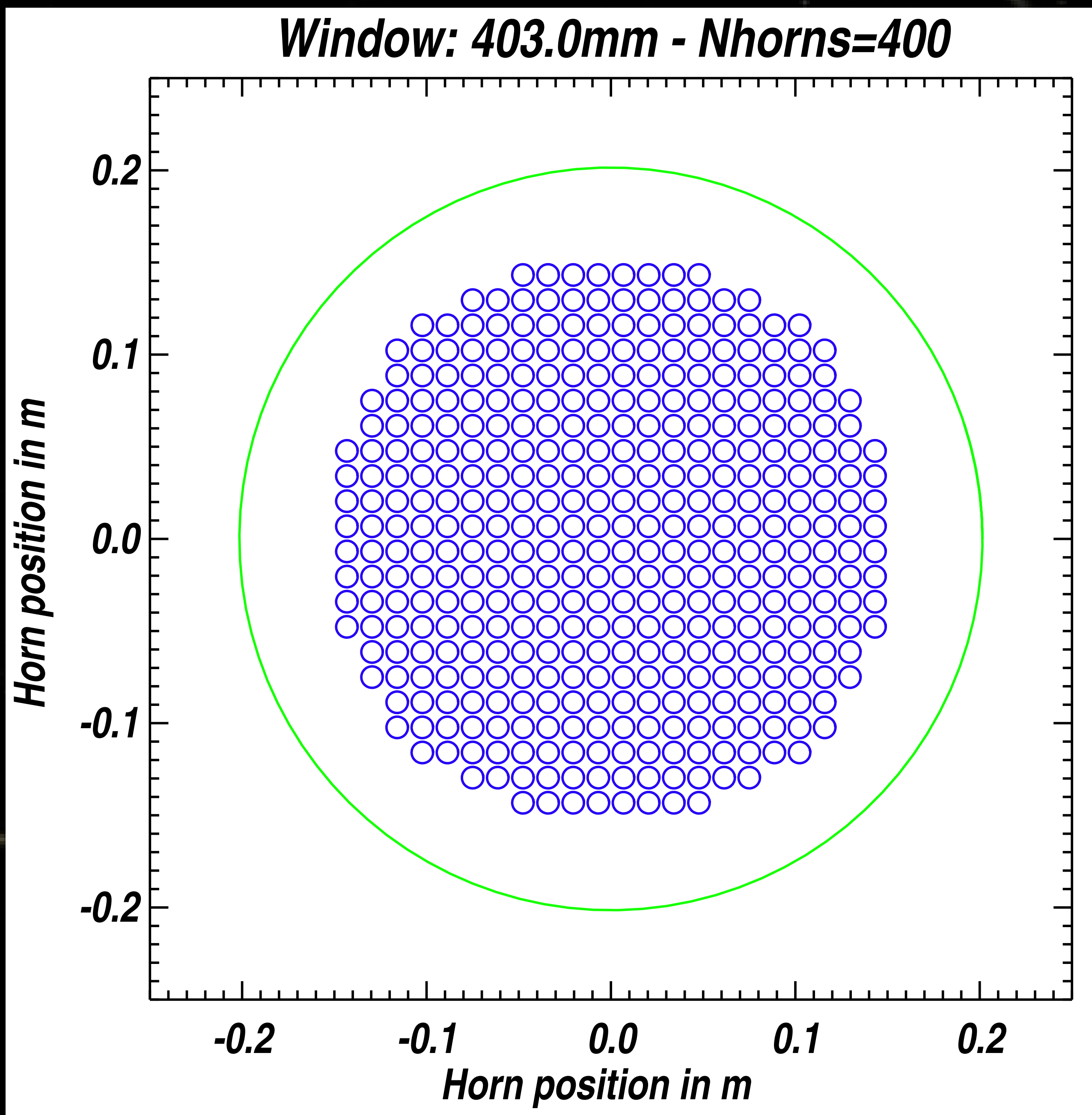

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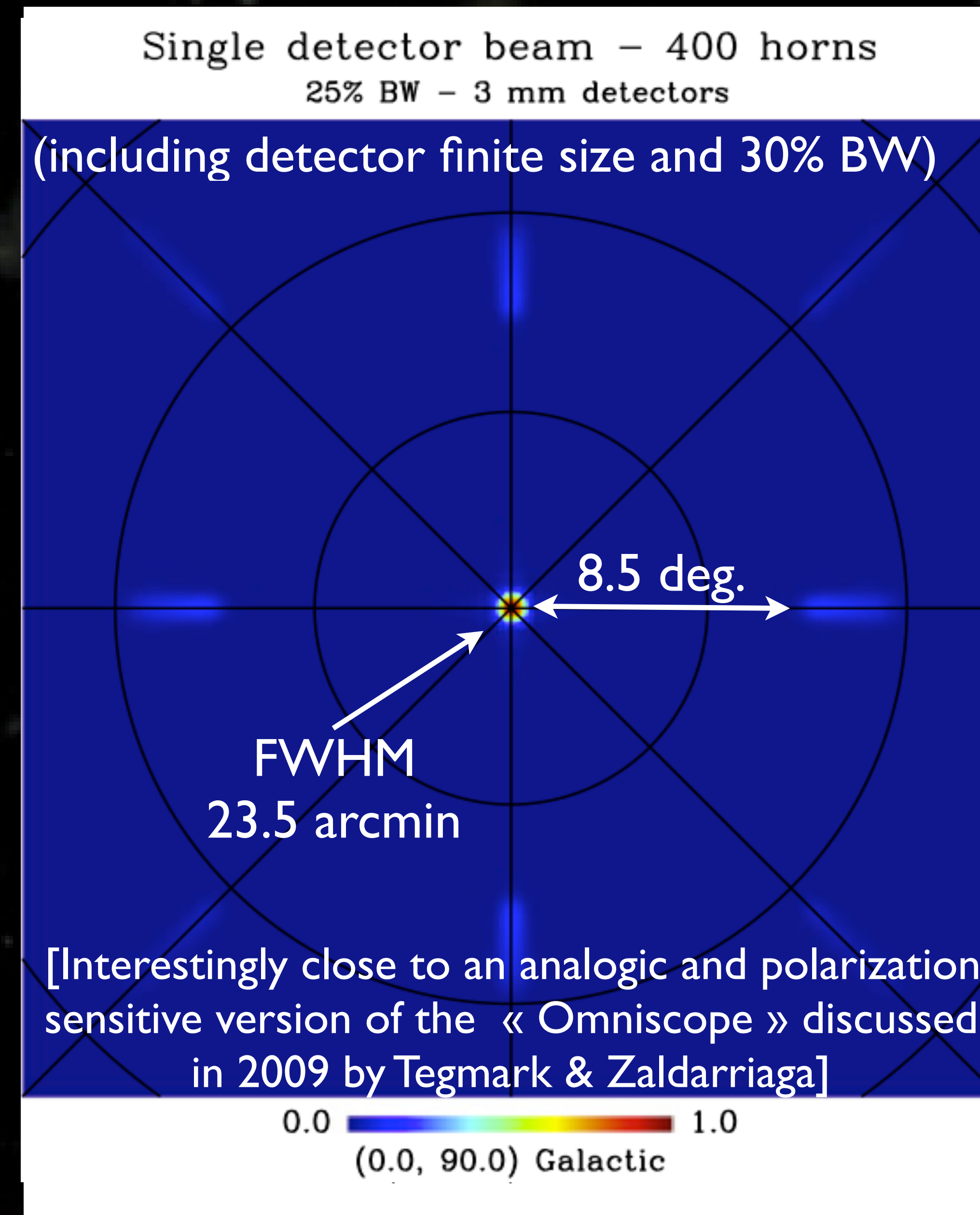

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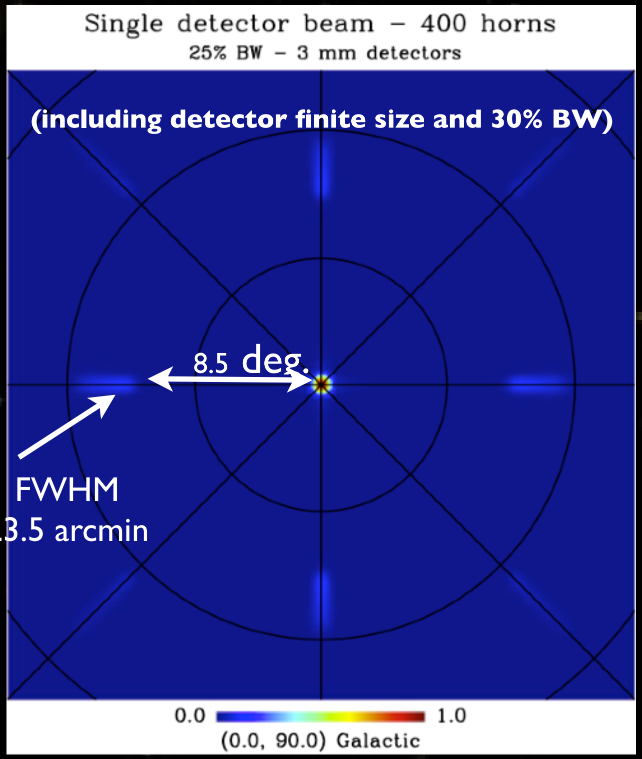
QUBIC is a Synthesized Spectro-Imager

- Synthesized beam:
  - ★ Depends on horns configuration
  - ★ AND on frequency !
    - ex: a point source emitting at 140 and 160 GHz



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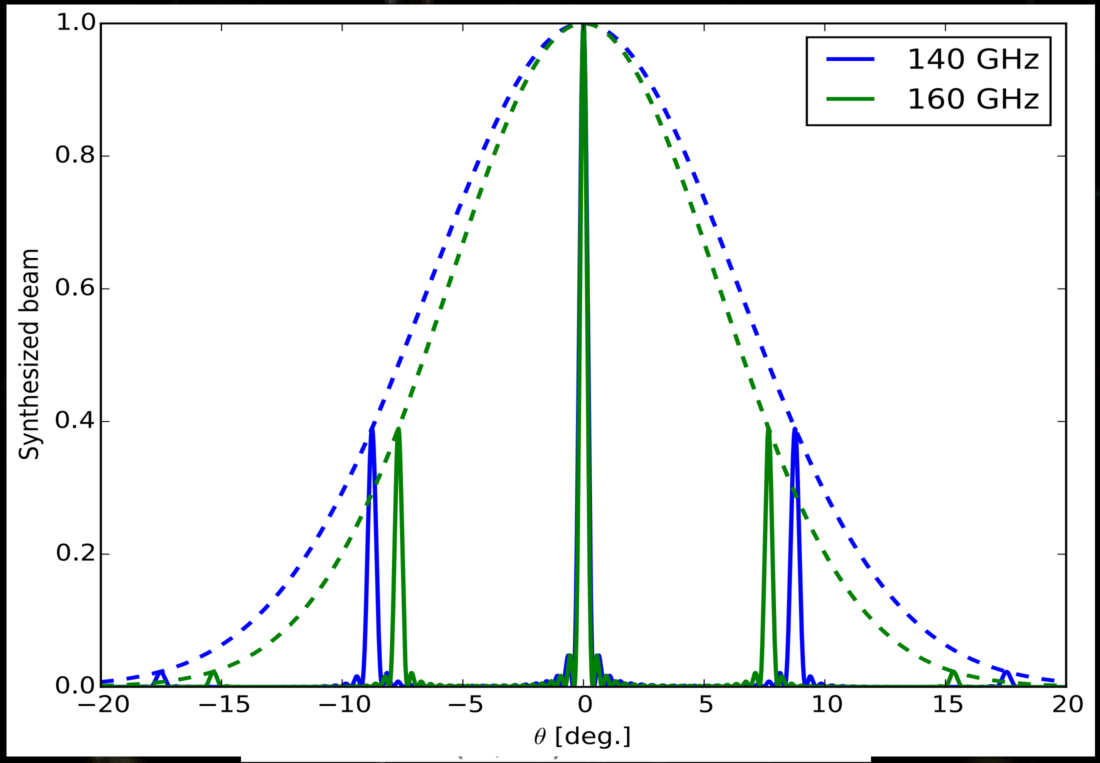

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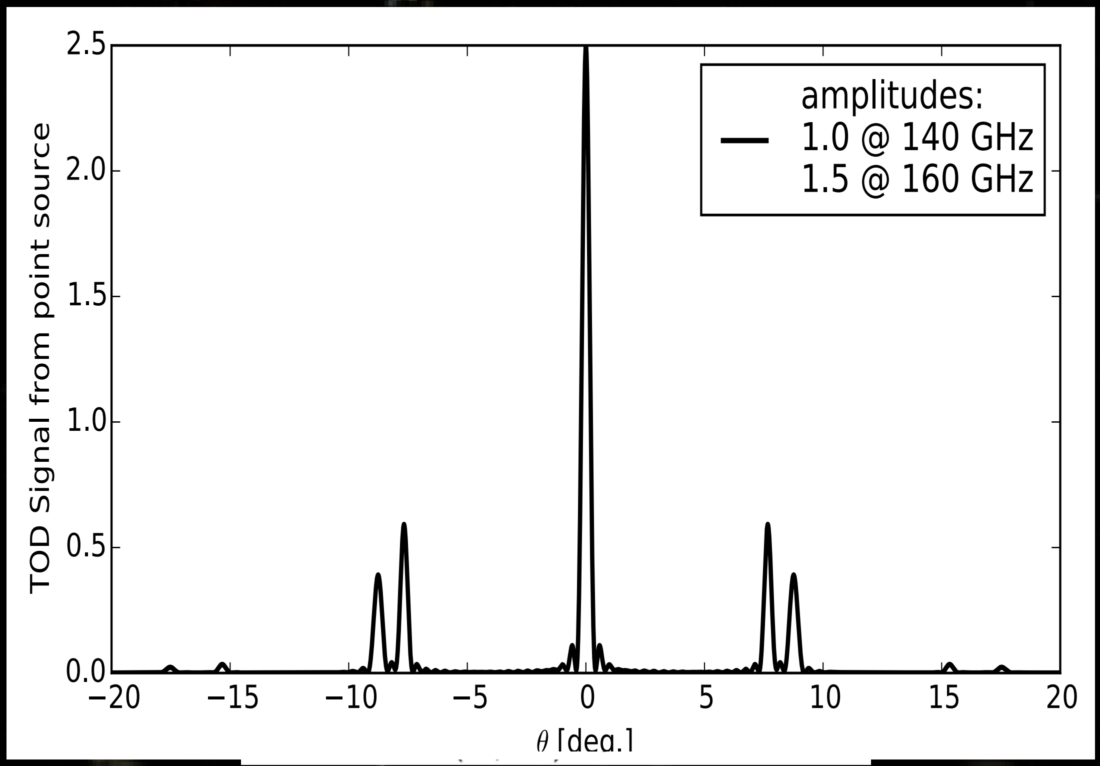

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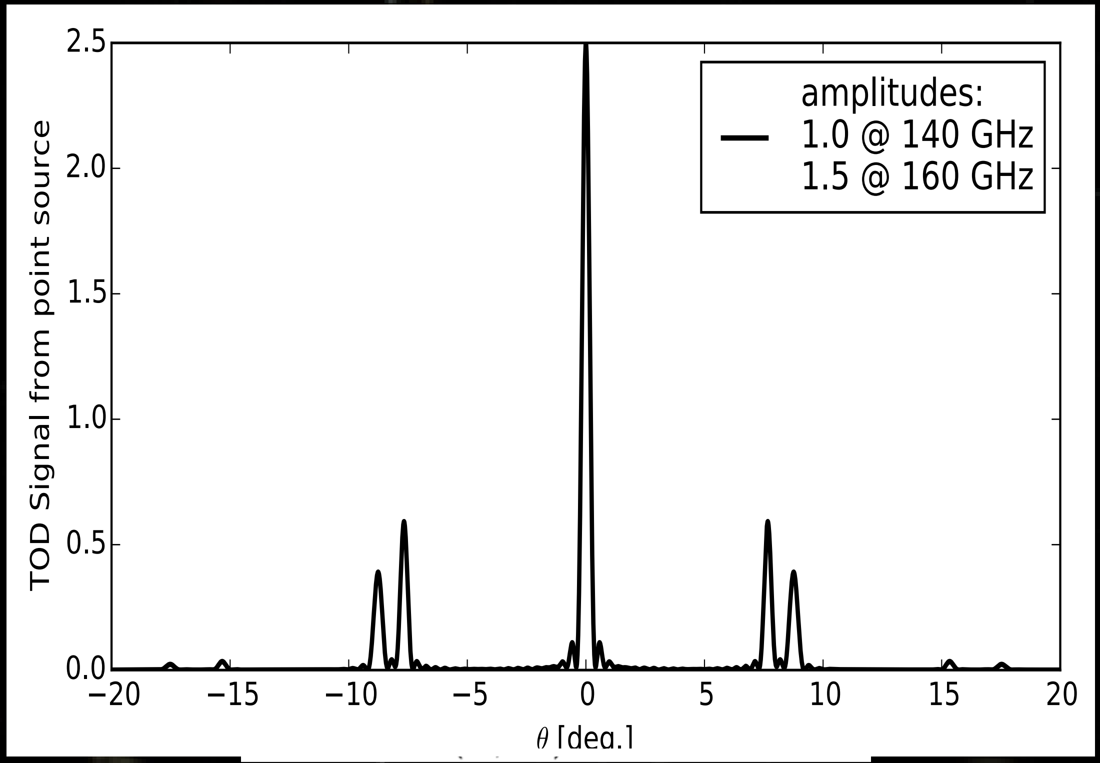

- There is spatial + frequency information !

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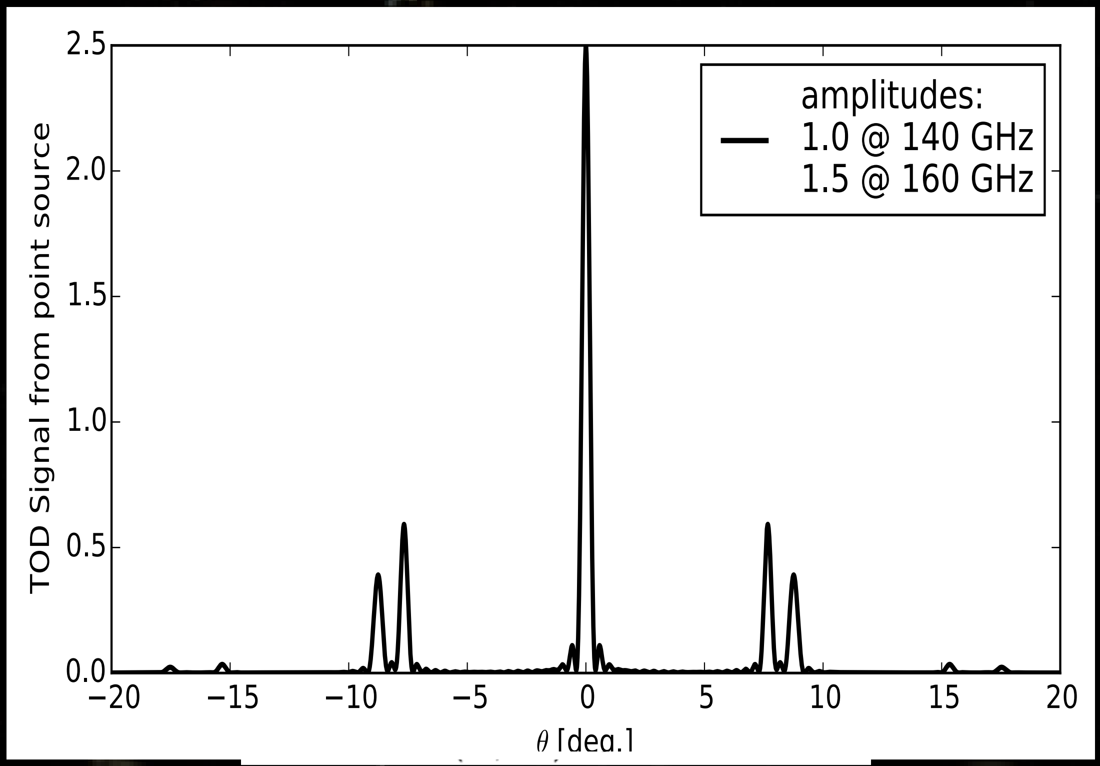
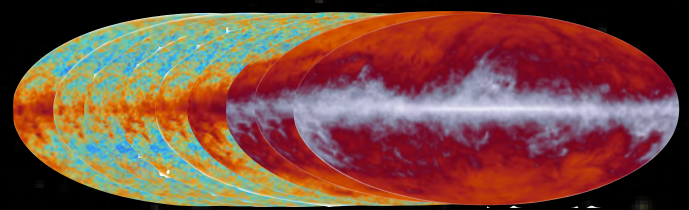
- Synthesized beam:
  - ★ Depends on horns configuration
  - ★ AND on frequency !
    - ex: a point source emitting at 140 and 160 GHz
- There is spatial + frequency information !
- Multi-frequency map-making with the same TOD
  - ★ Spectral resolution $\Delta\nu/\nu \sim 0.05$
  - ★ Shown to be quasi-optimal with simulations
  - ★ article being finalized

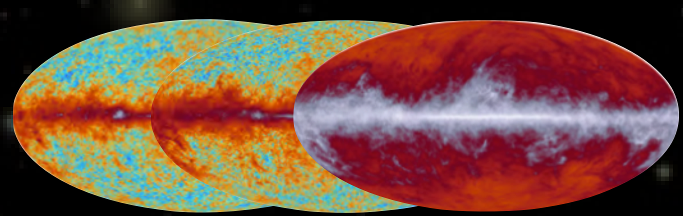


Sky: Continuous frequency maps



$$\text{TOD} = \Sigma\, \text{tod}(\nu_i)$$

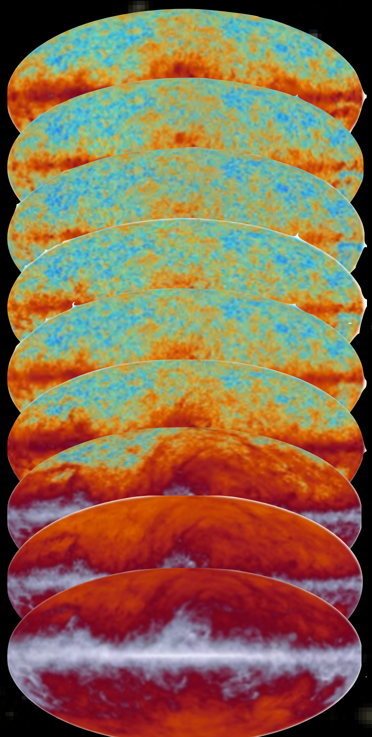
Map Making



Output: N broadband frequency maps

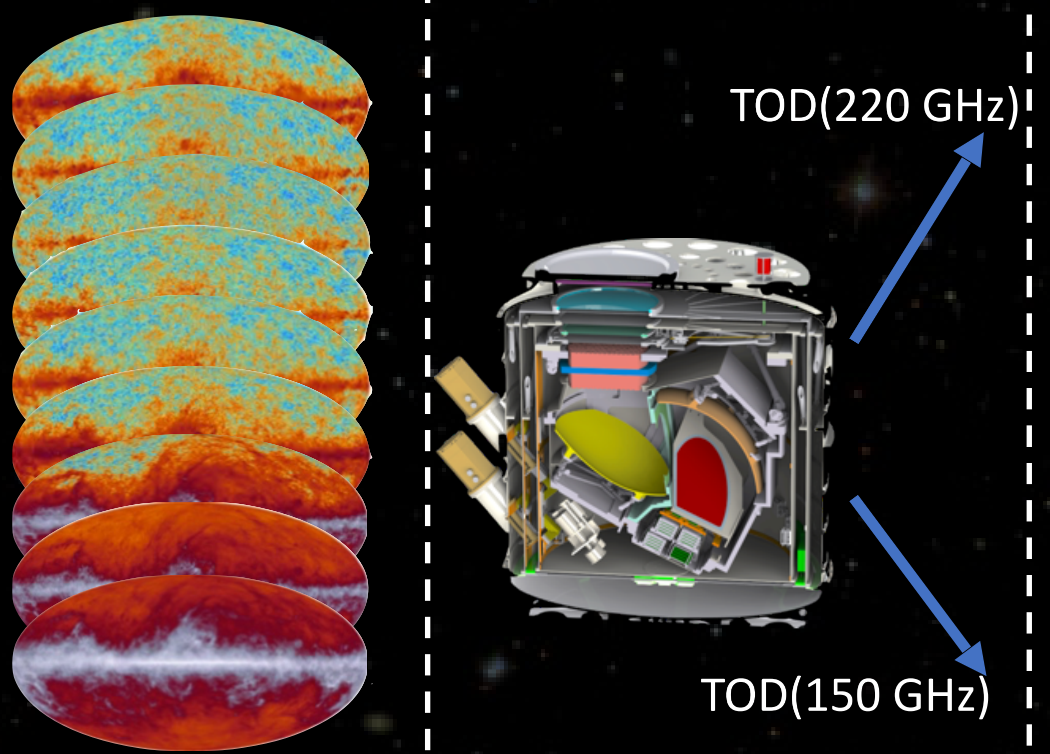
QUBIC Spectro-Imaging

QUBIC Spectro-Imaging



Sky:
« Infinite # bands »

QUBIC Spectro-Imaging



Sky:
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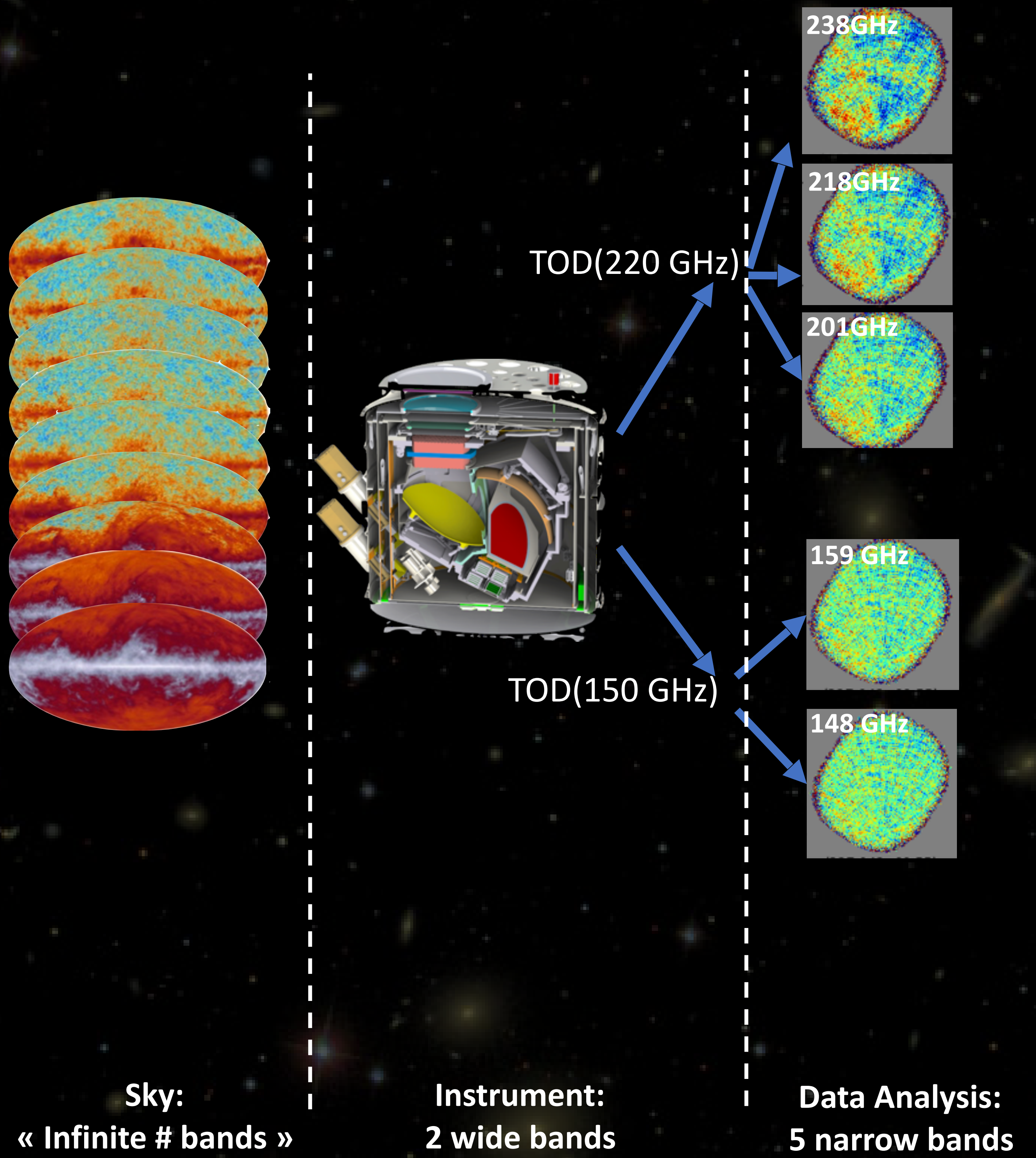
Instrument:
2 wide bands

QUBIC Spectro-Imaging



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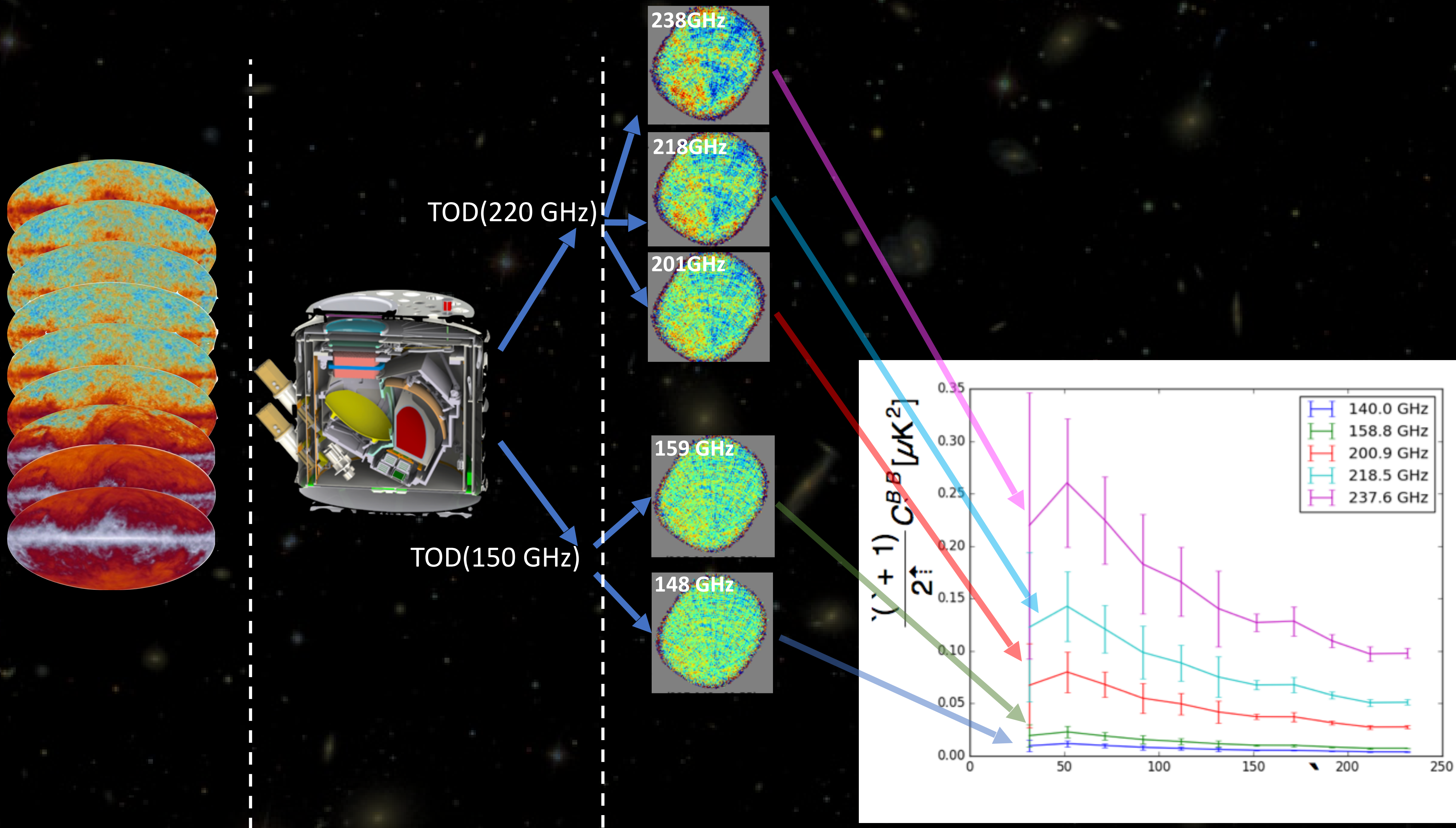

Sky:
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Instrument:
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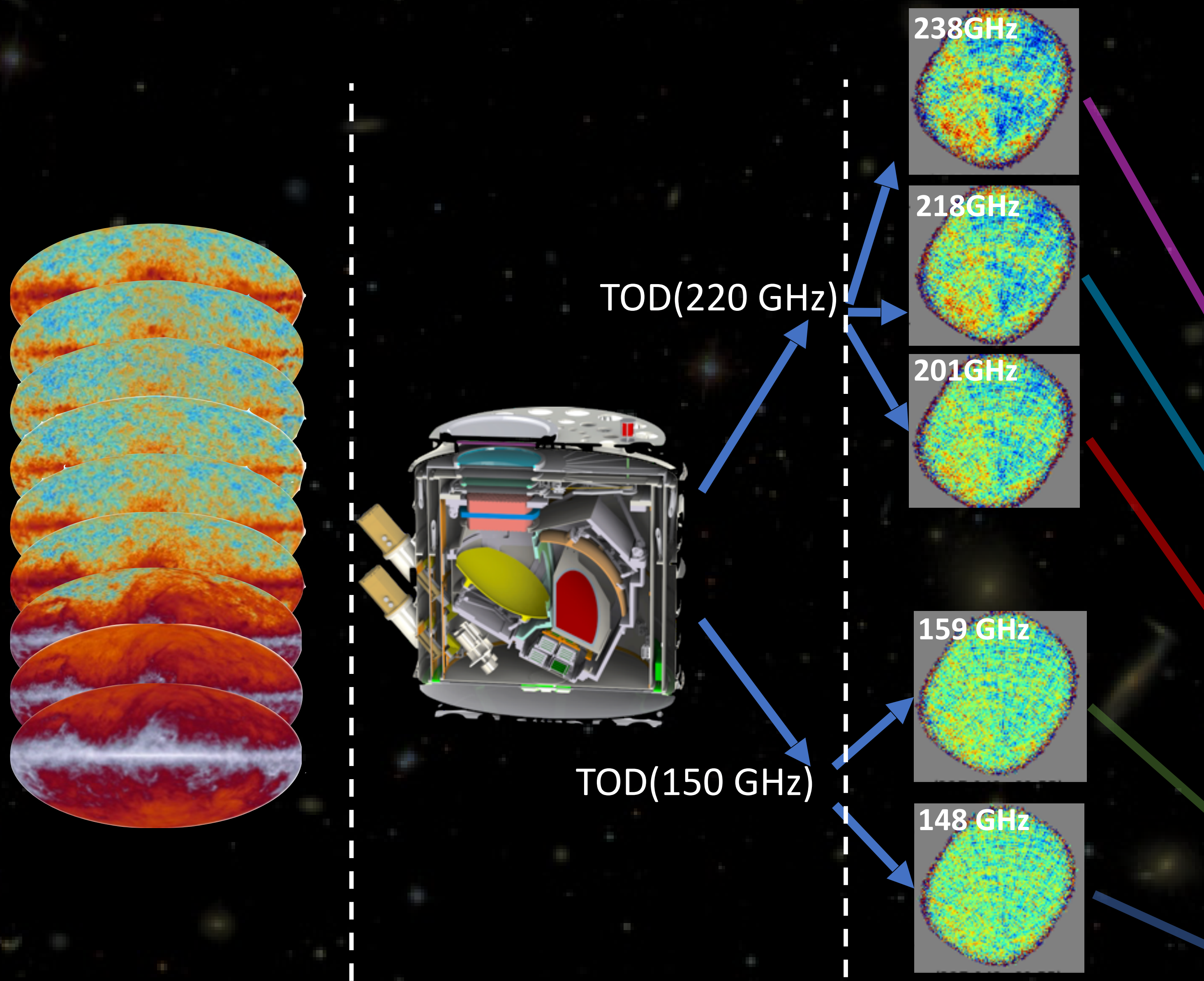
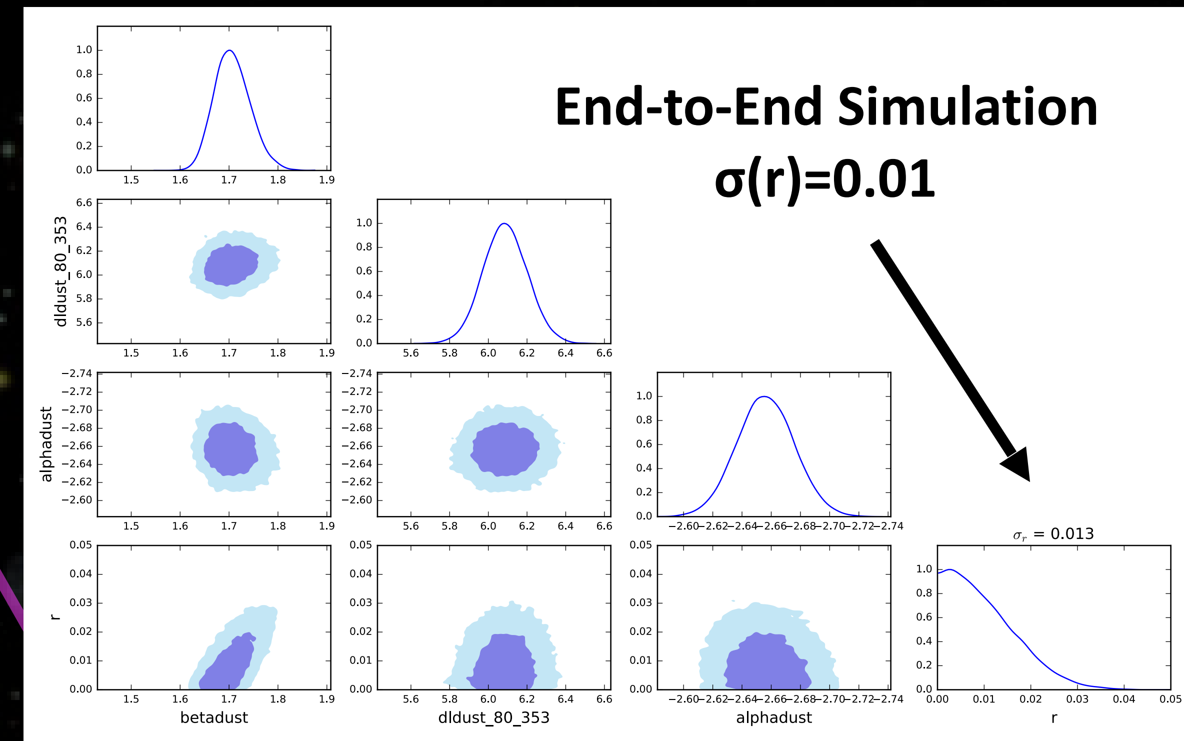
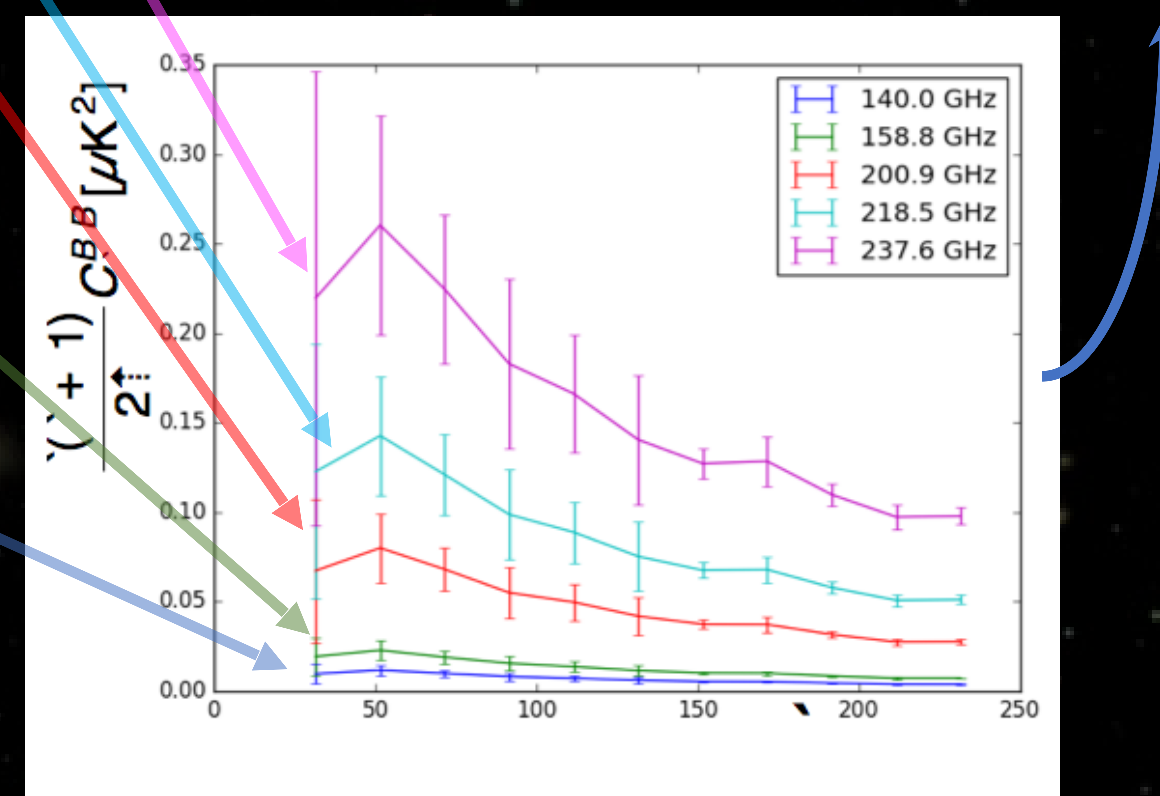
Data Analysis:
5 narrow bands

=> Increased Spectral Resolution
=> Dust subtraction

QUBIC Spectro-Imaging







Sky:
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Instrument:
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=> Increased Spectral Resolution
=> Dust subtraction

Data Analysis more complex but richer than with a classical imager

Complex shape of synthesized beam

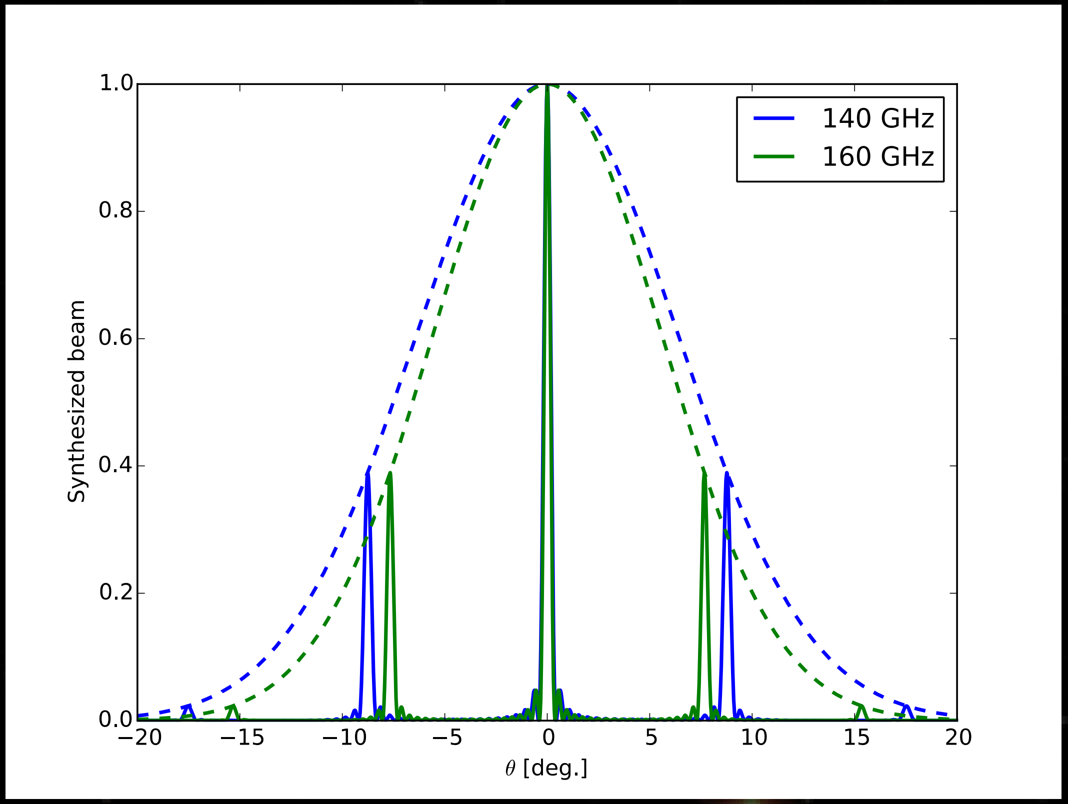
Map-making more complex

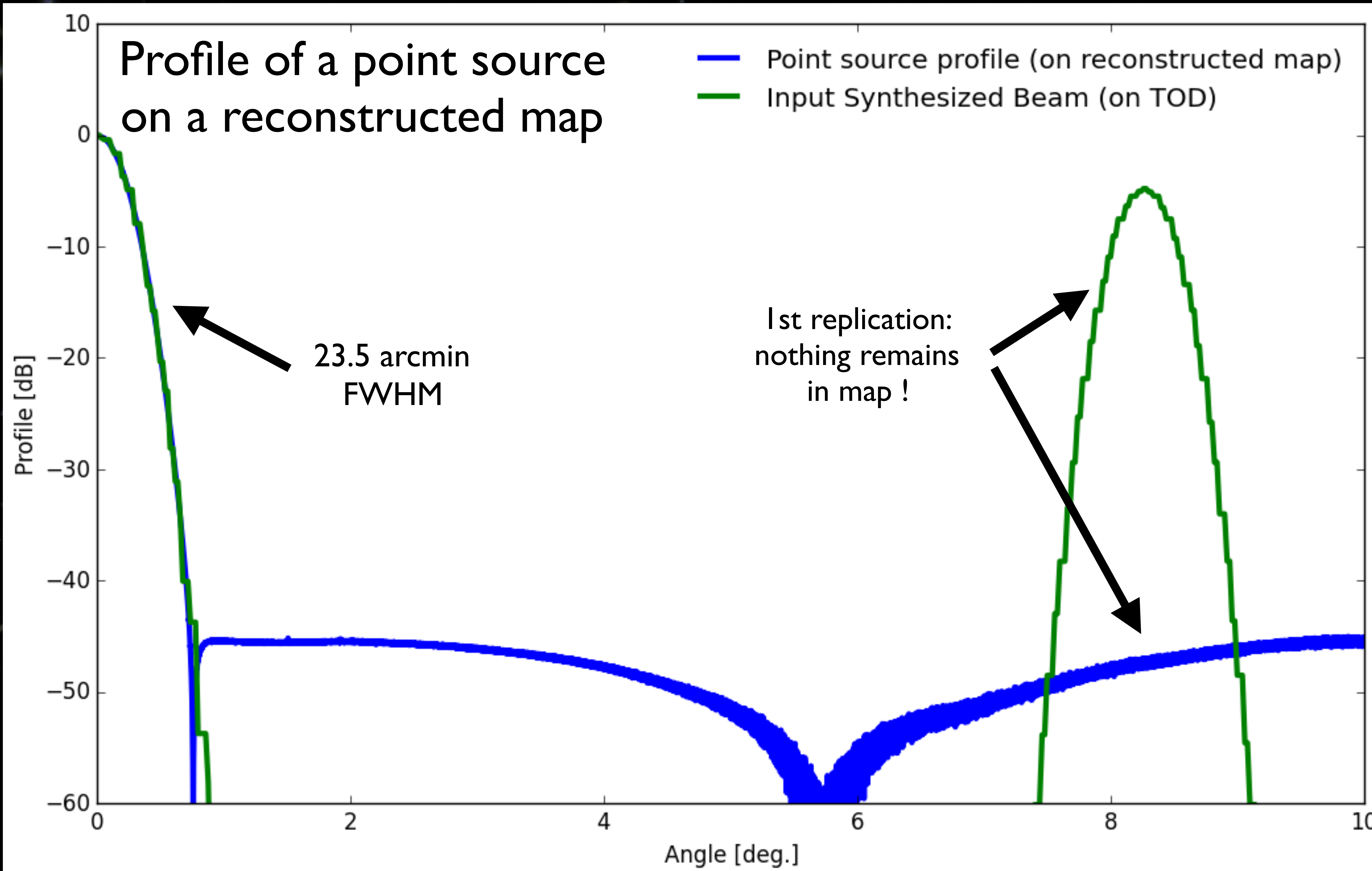
CPU...

Frequency dependence of synthesized beam

Spectro-Imaging

Foregrounds!




Profile of a point source
on a reconstructed map
Point source profile (on reconstructed map)
Input Synthesized Beam (on TOD)
23.5 arcmin
FWHM
1st replication:
nothing remains
in map !
Profile [dB]
Angle [deg.]
10
0
−10
−20
−30
−40
−50
−60
0
2
4
6
8
10

QUBIC Deployment Plan

2017-2018 : at APC

- Integration on the way !
- 1st half 2018: Technological Demonstrator (reduced QUBIC)
  - 1/4 focal plane, 64 horns, small mirrors
- Followed by: Upgrade to full size mirrors and 400 horns

→ In-Lab demonstration of Bolometric Interferometry

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- Late-2018: Integration with mount, Installation on site
- First Light Late 2018 with ¼ focal plane

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- Data taking: 2-3 years $\sigma(r)=0.01$

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- European extension of the collaboration
- Improved designs already being investigated
- Excellent quality site open to development

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→ Evolution to Stage IV $\sigma(r) = 0.001$

QUBIC
Integration
On the way !

QUBIC Integration On the way !

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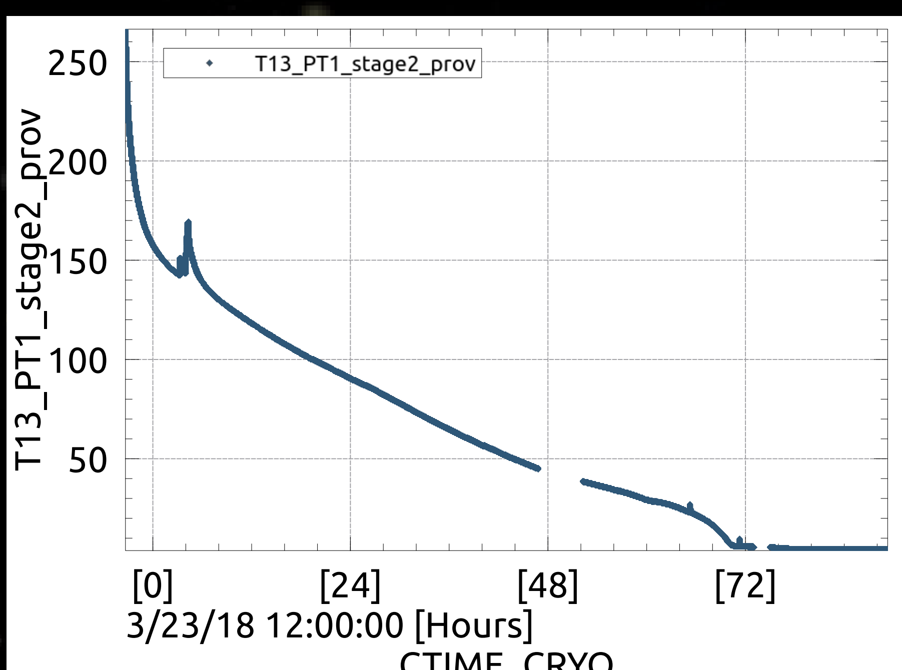
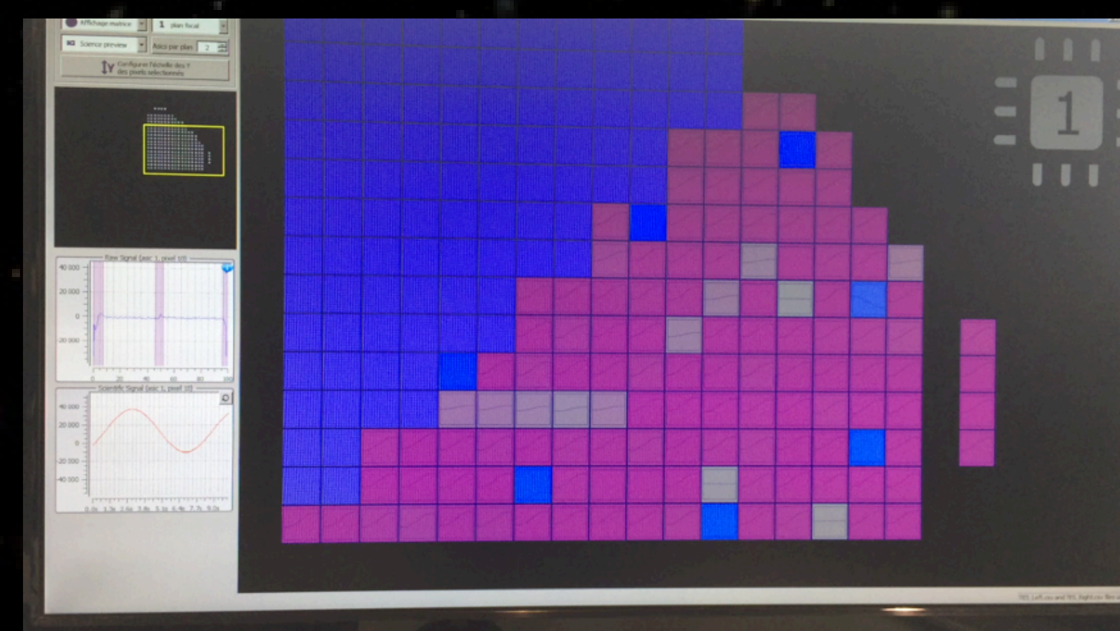
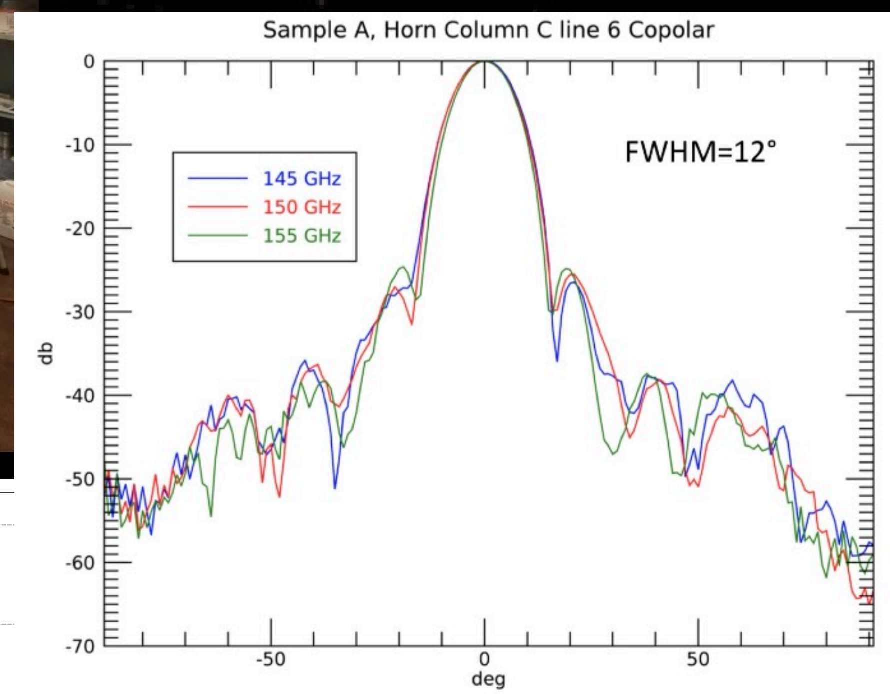
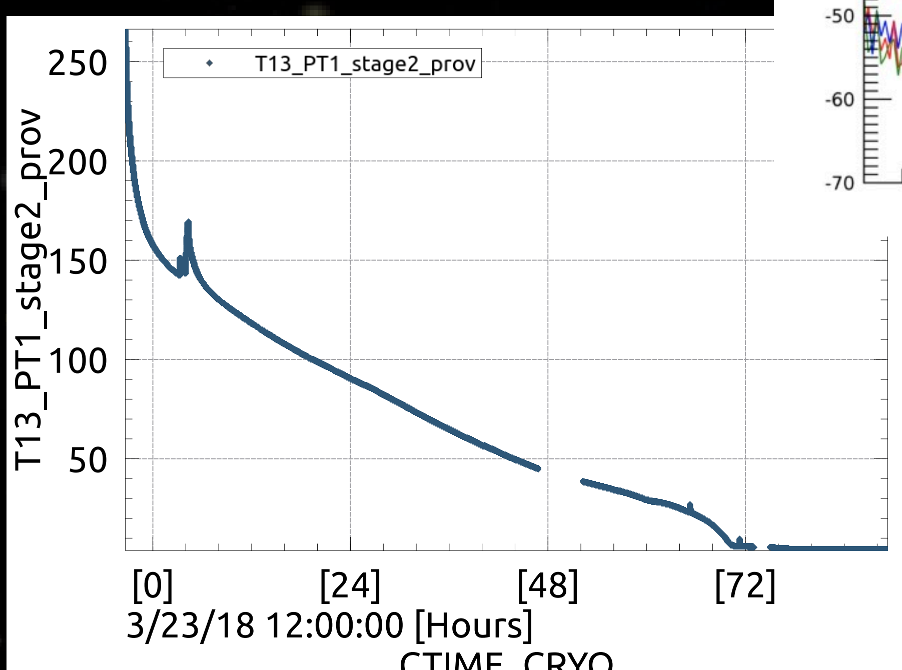
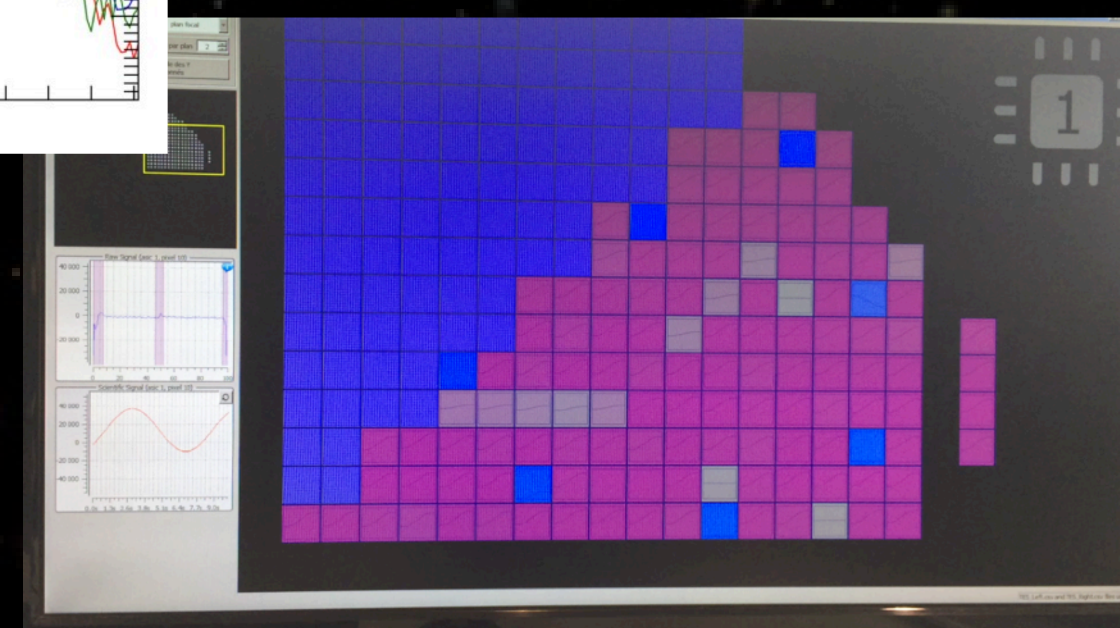


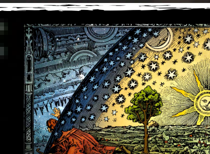


QUBIC Integration On the way !







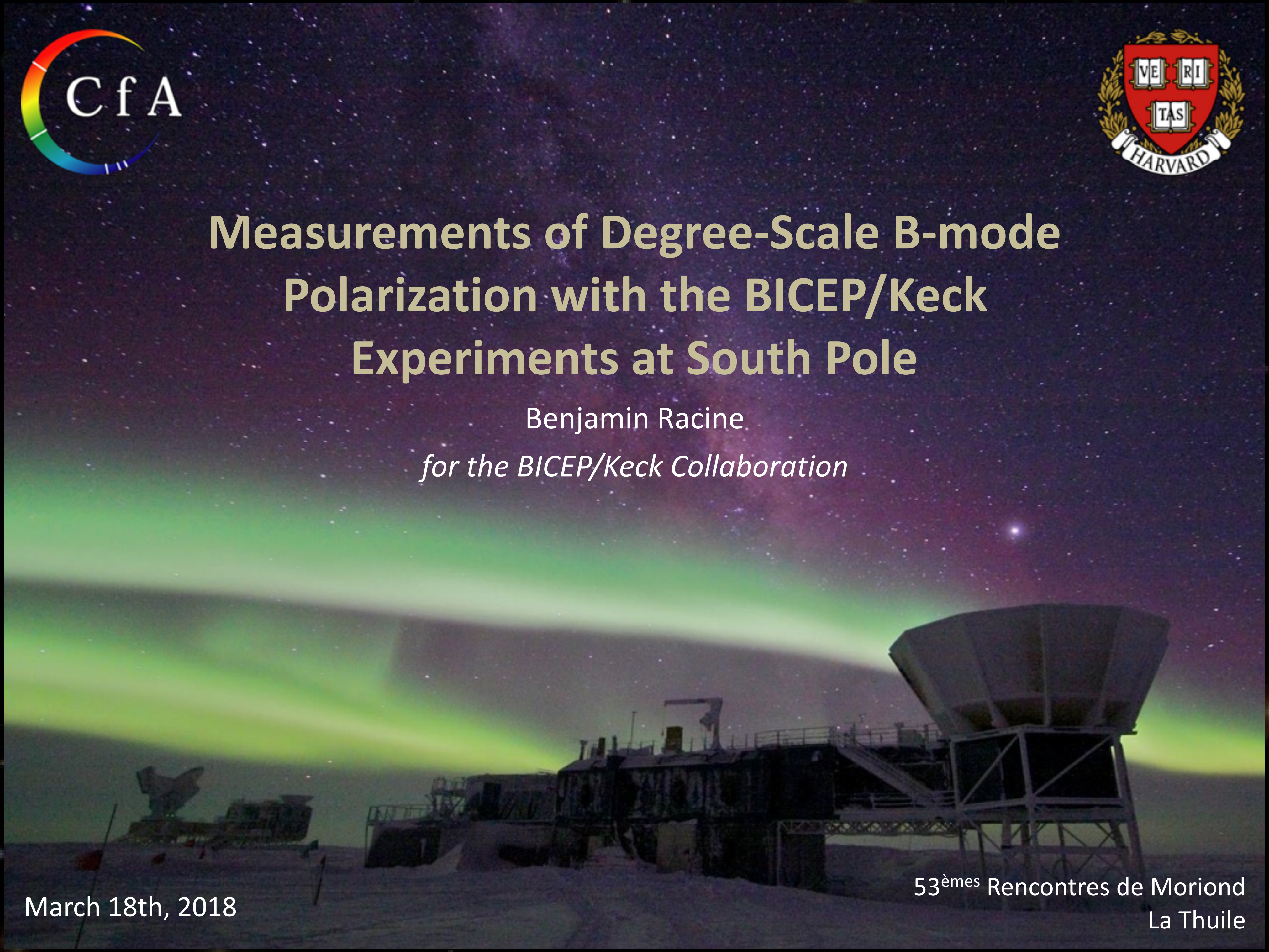


Experiments…

Project	Countries	Location	Frequencies	ℓ range	σ(r) no FG	σ(r) with FG	Status
QUBIC	Fr., It., Ar., UK, Ir.	Argentina	150, 220 (+spectro-im)	30-200	6×10^{-3}	0.01	Integrating
BICEP/Keck	USA	Antarctica	95, 150, 220, 270	50-250	2.5×10^{-3}	0.01	Running
CLASS	USA	Chile	38, 93, 148, 217	2-100	1.4×10^{-3}	3×10^{-3}	Running (38)
LSPE/STRIP	It.	Canary	43, 90	30-200	0.03		Integrating
GroundBird	Jp.	Canary	150, 220 (KIDs)	6-300	0.01		?
QUIJOTE	Sp.	Canary	11,13,17,30,42	30-200	Synchrotron monitor		Commissioning
SPTPol	USA	Antarctica	95, 148, 223	50-3000	1.7×10^{-3}	5×10^{-3}	Running
ACTPol	USA	Chile	90, 150, 230	60-3000	1.3×10^{-3}	4×10^{-3}	Running
Simons Array	USA	Chile	90, 150, 220	30-3000	1.6×10^{-3}	5×10^{-3}	Running
SPIDER	USA	Antarctica	90, 150, 290	5-100	3.1×10^{-3}	12	90 GHz flew

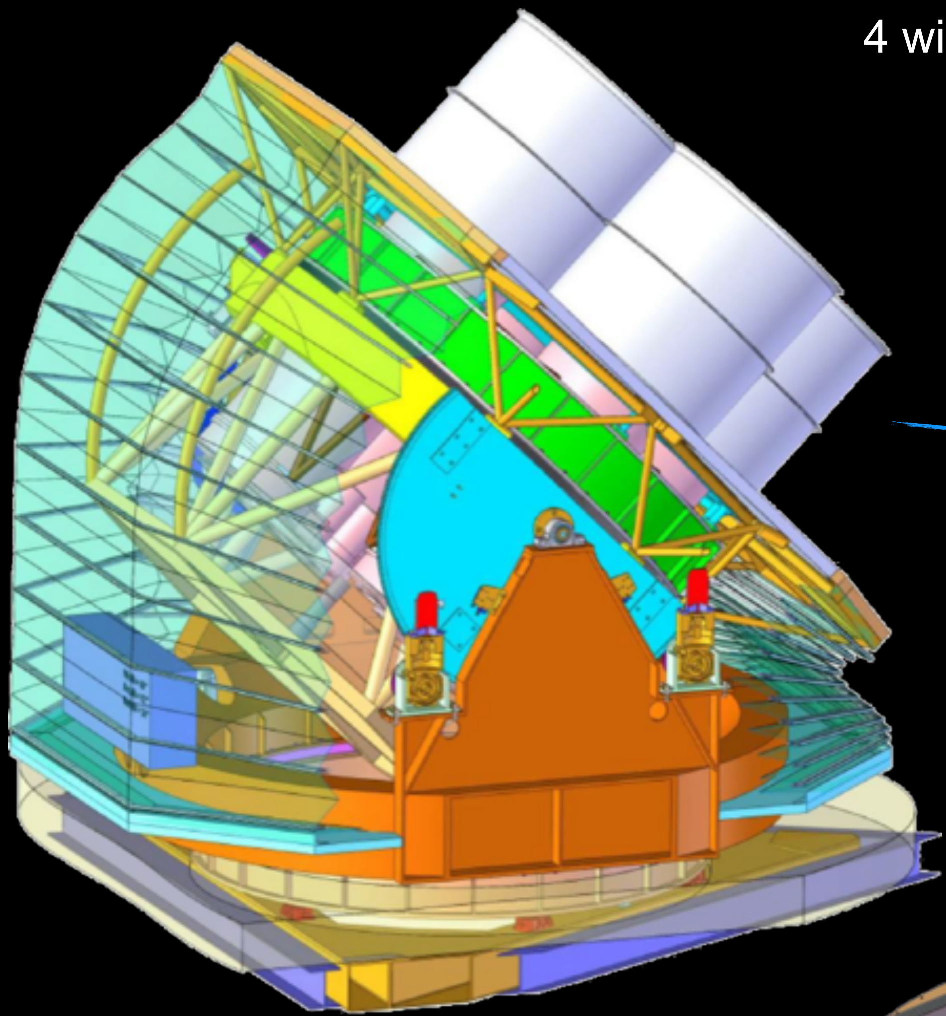
- Large scales - Ground Based : optimized for primordial B-modes
- Small scales - Ground Based : optimized for CMB Lensing (Neutrino masses)
- Large scales - Balloon Borne : optimized for primordial B-modes
- Foreground monitor

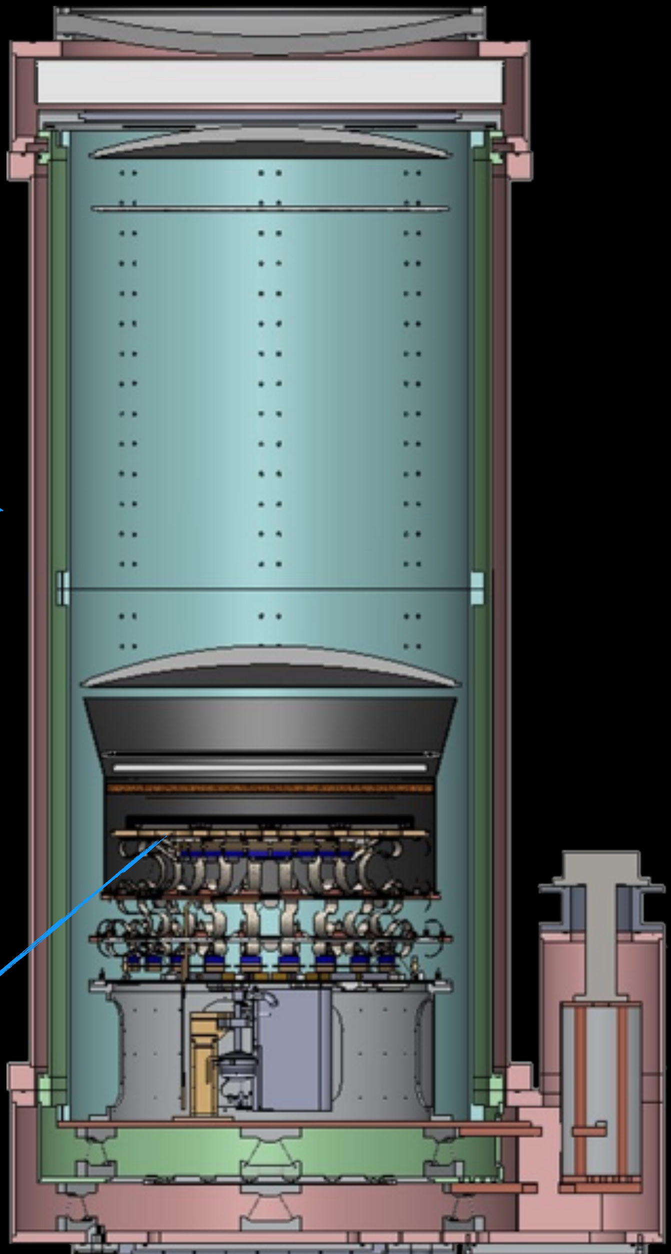
BICEP

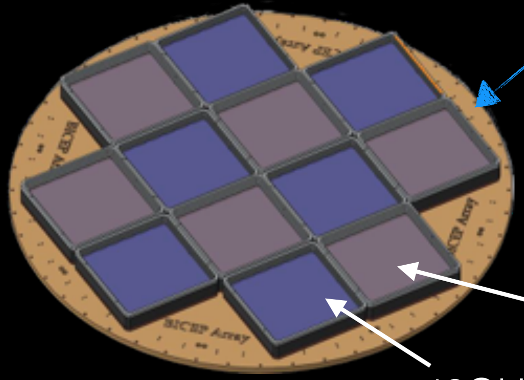

CfA
VE RI TAS
HARVARD
Measurements of Degree-Scale B-mode Polarization with the BICEP/Keck Experiments at South Pole
Benjamin Racine
for the BICEP/Keck Collaboration
March 18th, 2018
53èmes Rencontres de Moriond
La Thuile

BICEP Array Under Construction

4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



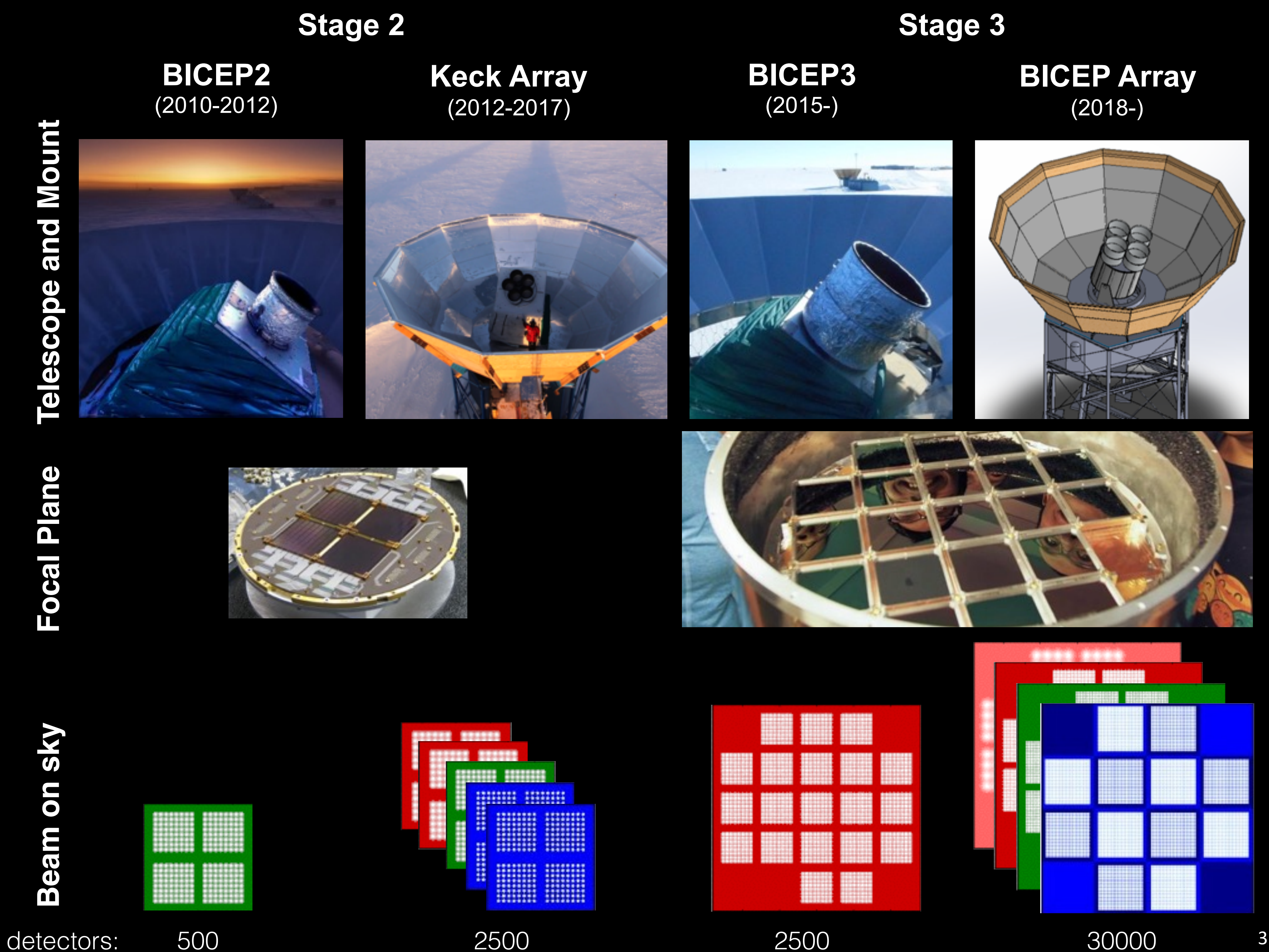




Focal plane layout

33

[Slides from B. Racine @ Moriond 2018]



[Slides from B. Racine @ Moriond 2018]

J.-Ch. Hamilton
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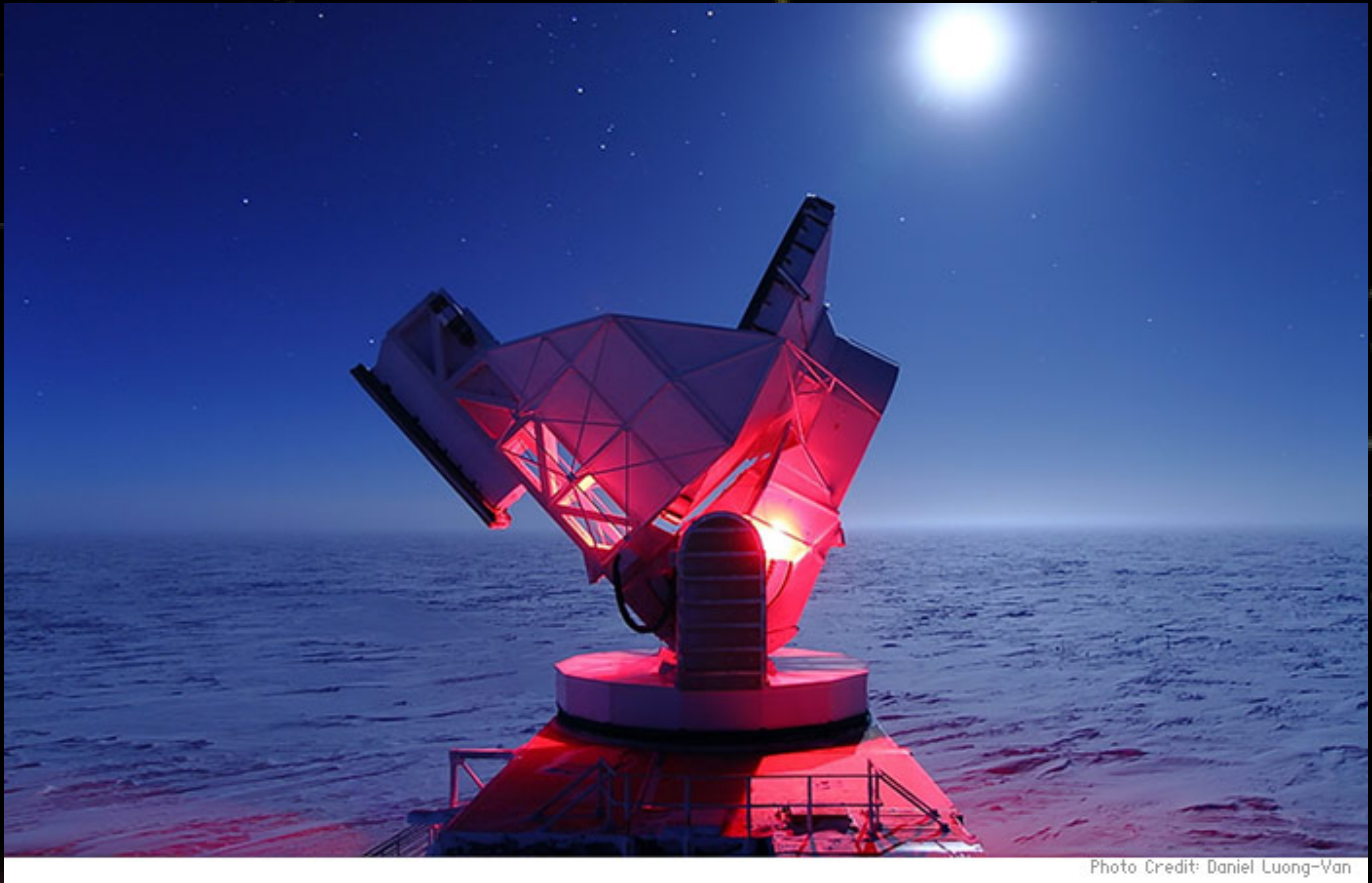
Experiments...

Project	Countries	Location	Frequencies	ℓ range	σ(r) no FG	σ(r) with FG	Status
QUBIC	Fr., It., Ar., UK, Ir.	Argentina	150, 220 (+spectro-im)	30-200	6×10^{-3}	0.01	Integrating
BICEP/Keck	USA	Antarctica	95, 150, 220, 270	50-250	2.5×10^{-3}	0.01	Running
CLASS	USA	Chile	38, 93, 148, 217	2-100	1.4×10^{-3}	3×10^{-3}	Running (38)
LSPE/STRIP	It.	Canary	43, 90	30-200	0.03		Integrating
GroundBird	Jp.	Canary	150, 220 (KIDs)	6-300	0.01		?
QUIJOTE	Sp.	Canary	11,13,17,30,42	30-200	Synchrotron monitor		Commissioning
SPTPol	USA	Antarctica	95, 148, 223	50-3000	1.7×10^{-3}	5×10^{-3}	Running
ACTPol	USA	Chile	90, 150, 230	60-3000	1.3×10^{-3}	4×10^{-3}	Running
Simons Array	USA	Chile	90, 150, 220	30-3000	1.6×10^{-3}	5×10^{-3}	Running
SPIDER	USA	Antarctica	90, 150, 290	5-100	3.1×10^{-3}	12	90 GHz flew

Large scales - Ground Based : optimized for primordial B-modes
Small scales - Ground Based : optimized for CMB Lensing (Neutrino masses)
Large scales - Balloon Borne : optimized for primordial B-modes
Foreground monitor

SPTPol



SPTPol

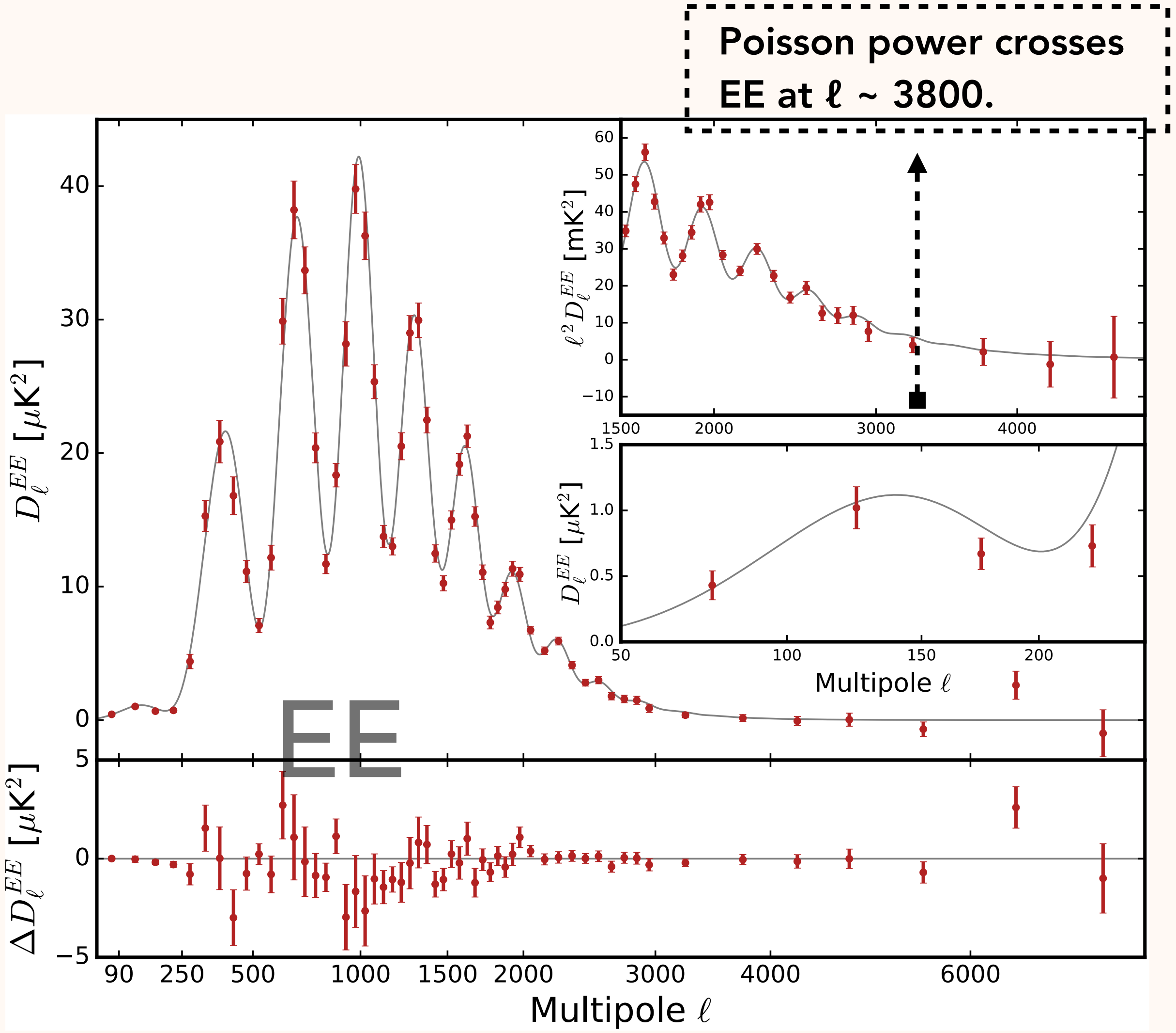
9 PEAKS (50 < ℓ < 3000) AND 4 TIMES TIGHTER UPPER LIMITS ON FOREGROUNDS

- D_ℓ^{PS} < 0.1 μK2 at 95% confidence

  (Contributes < 1 μK-arcmin to rms map noise).

  Source cut at > 50 mJy in T.

Bandpowers and likelihood available on LAMBDA!

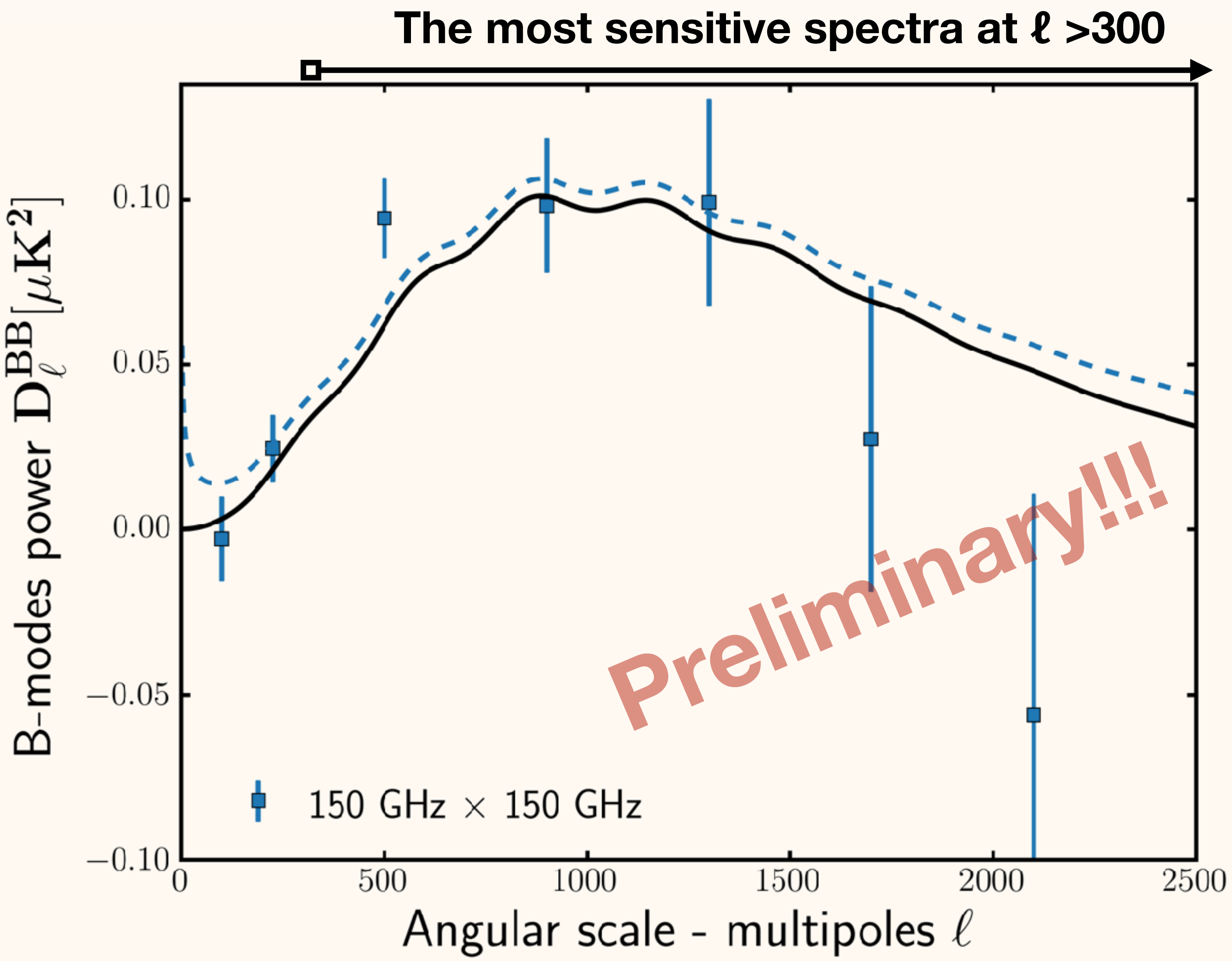


JW Henning et al. 1707.09353

[Slides from A. Manzotti @ Moriond 2018]

SPTPol

SPTPOL 500^2 B-MODES, THE BEST CURRENT B-MODE POWER AT ELL>300



[Slides from A. Manzotti @ Moriond 2018]

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POLARBEAR

Simons Array

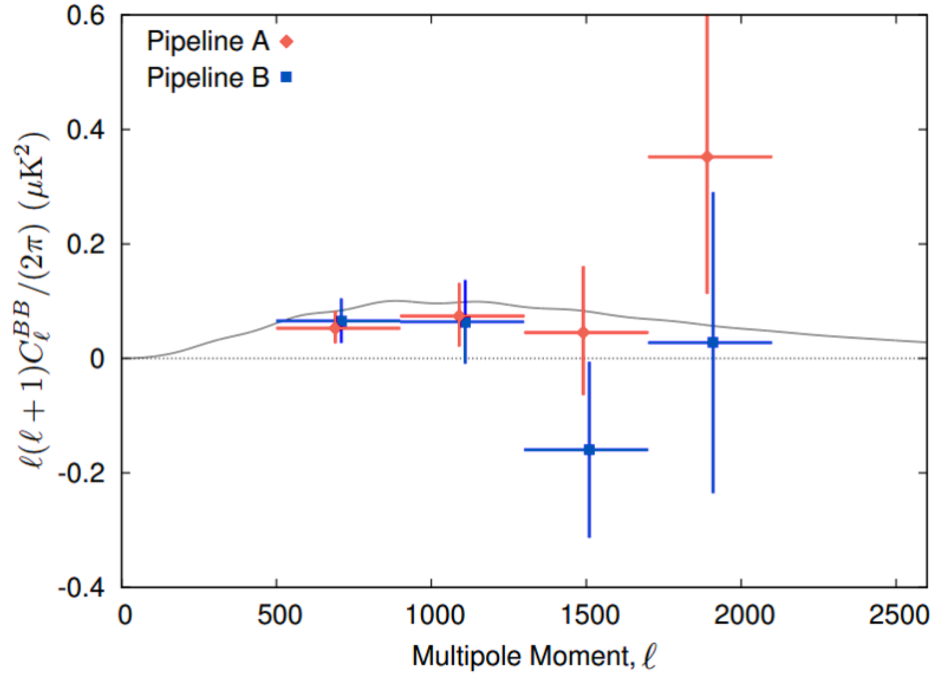
- 3 receivers, 22,764 bolometers total, observing in four frequency bands
- Full array projected to achieve ~ 2.5 $\mu K_{CMB}\sqrt{s}$

[Slides from D. Beck @ Moriond 2018]

POLARBEAR

POLARBEAR-1 Second Season Results

POLARBEAR Collaboration ApJ 848, 121 (2017)



3.1σ rejection of no B-modes

Reduced band-power uncertainties by factor two

Measured amplitude of lensing B-modes:

$$A_{BB} = 0.60^{+0.26}_{-0.24}(\text{stat.})^{+0.00}_{-0.04}(\text{inst.}) \pm 0.14(\text{foreground}) \pm 0.04(\text{mult.})$$

Lensing auto power spectrum in preparation

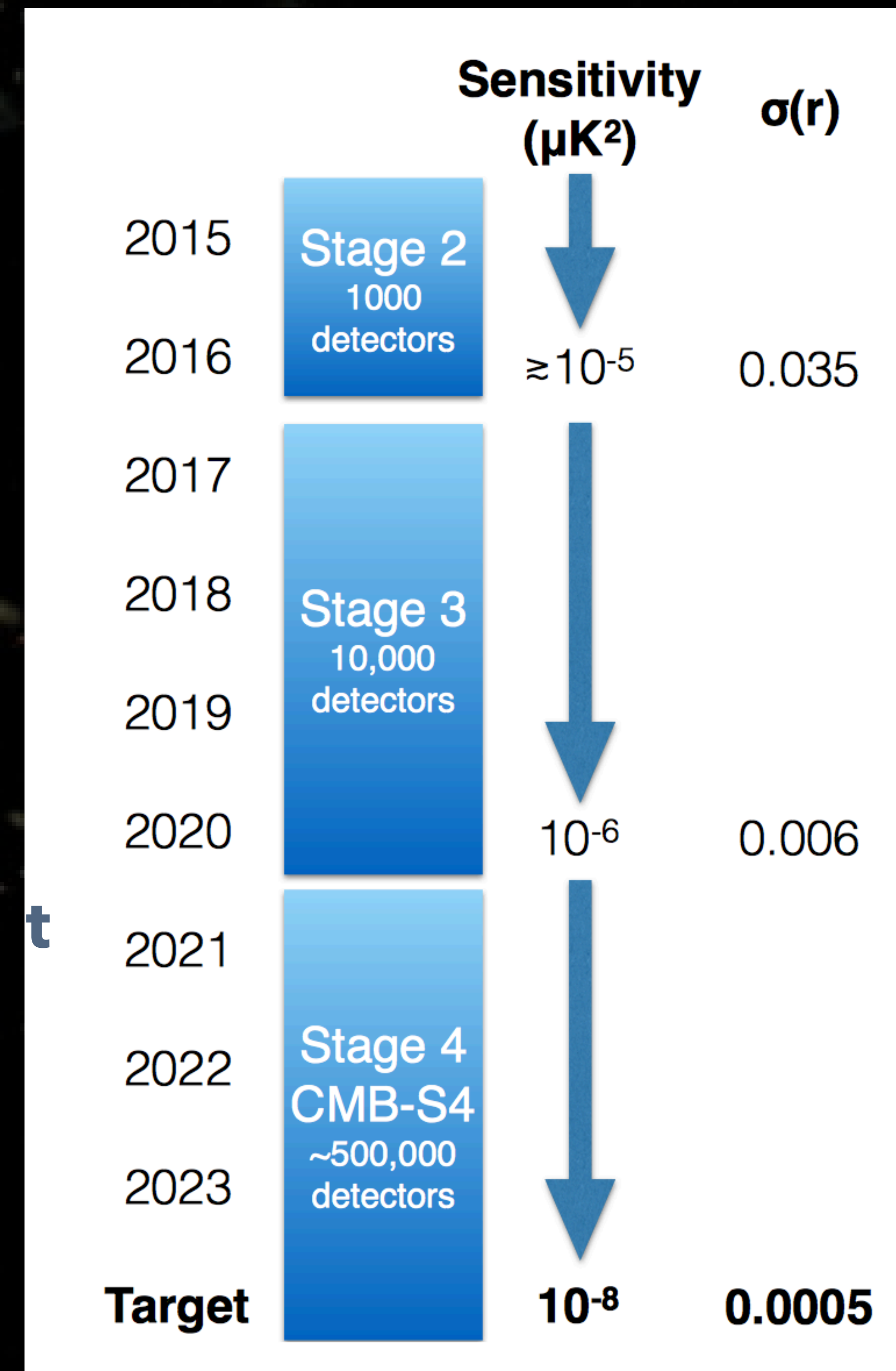
10

[Slides from D. Beck @ Moriond 2018]

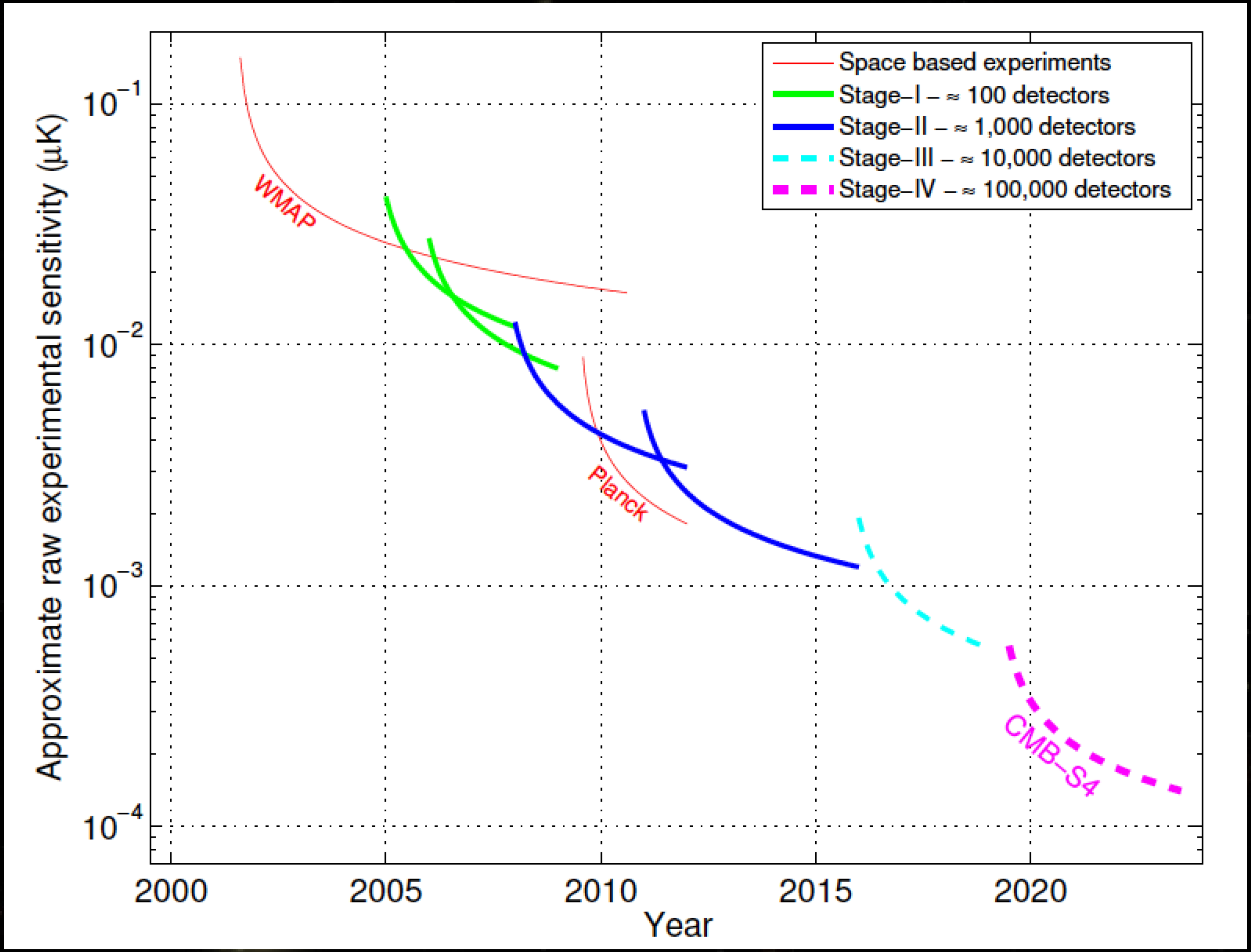
The Future

- Current effort: Stage III
  - ★ Investigating various designs, sites, detectors
  - ★ (relatively) small collaborations
  - ★ Little delensing / foreground removal capabilities Should reach σ(r)~0.01 by 2020

- Next efforts: Stage IV
  - ★ Very large collaboration(s): CMBS4 (US) and possibly E4 (Europe)
  - ★ Small + large scales (delensing)
  - ★ More frequencies (foregrounds)
  - ★ could reach σ(r)~0.001 by 2025
  - ★ also target
    - Neutrino physics (through lensing & damping tail):
      - $\sigma(N_{eff})$~0.027
      - $\sigma(\Sigma m_\nu)$~0.015 eV (with DESI)
    - Dark Energy : F.O.M. ~ 1250 (with DESI, LSST, SZ)



from CMB-S4 Science Book


Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
Approximate raw experimental sensitivity (μK)
10−1
10−2
10−3
10−4
2000
2005
2010
2015
2020
Year

Summary

- Primordial B-modes are the Holy Grail for Cosmology

- Their detection is an amazing experimental challenge:
  - ★ Weak signal on the large scales
  - ★ Foregrounds (Dust at high frequency and Synchrotron at low frequency)
  - ★ Lensing (requires small scales CMB Polarization + LSS)
  - ★ Instrumental Systematics

- A huge effort is currently undertaken towards r~0.01
  - ★ Massively in the US, but also in elsewhere with original concepts
  - ★ Ground based and Balloon Borne

- At the 2025 horizon: Stage IV target r~0.001
  - ★ Ground based: a combination of instrumental designs ?
  - ★ Satellite projects ?

- If B-modes are sufficiently high: we will have seen them by 2030…

Gracias