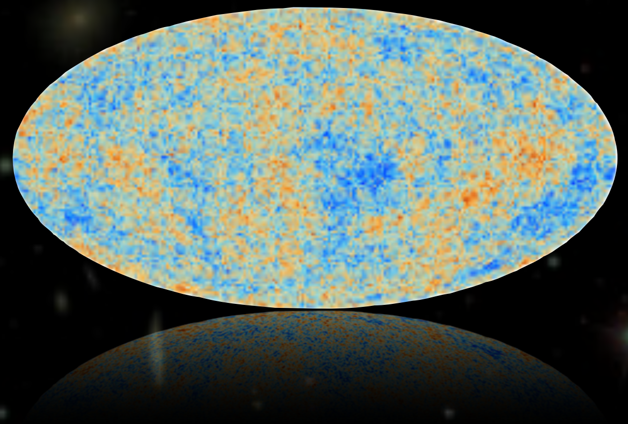
Exploring the primordial Universe with QUBIC

the Q U Bolometric Interferometer for Cosmology

J.-Ch. Hamilton (APC - Paris, CNRS/IN2P3)

Outline

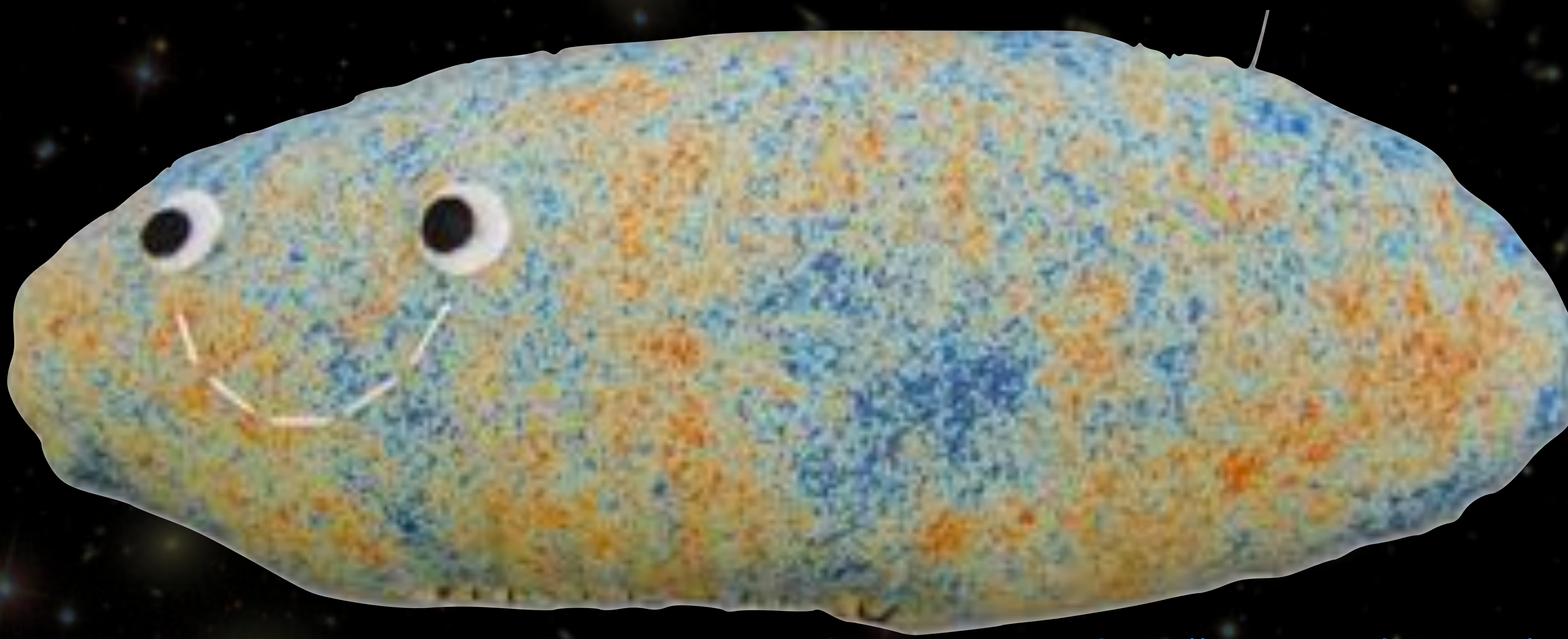
1. The CMB, its polarization and the early Universe



2. The challenging quest for the primordial B-modes

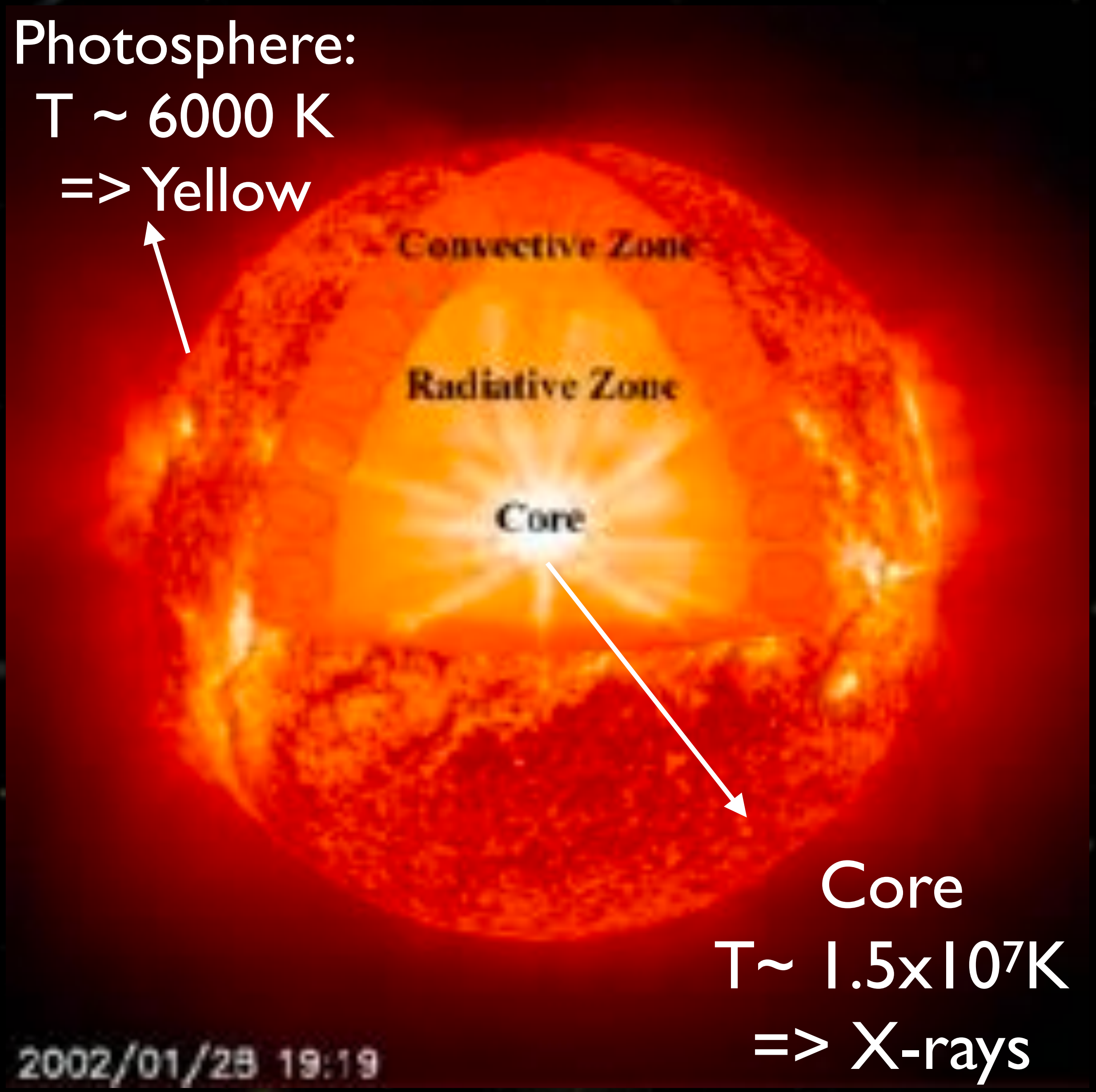
3. QUBIC overview, status and forecasts

Part 1:
The CMB, its polarization and the primordial Universe



https://www.particlezoo.net/

Matter-Radiation Decoupling



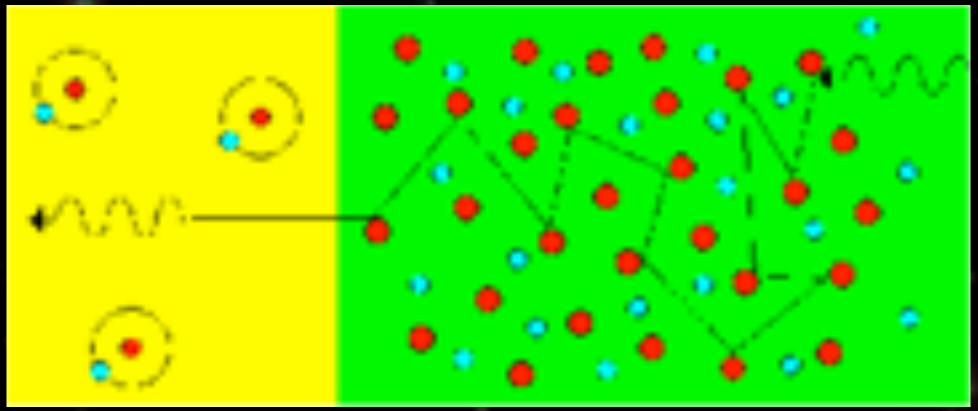
<u>Why does the sun appear yellow and not X-ray ?</u>

<u>Answer:</u>

- From the core to the photosphere, matter (Hydrogen) is ionized
  - Photons hardly propagate in a plasma
  - ➡ Energy is slowly transferred from the core to the photosphere (millions of years)
- At the Photosphere, matter becomes neutral
  - ➡ Photons propagate at the speed of light (8 minutes to the Earth)
  - ➡ <u>We only see the photosphere: yellow color</u>

The CMB

- Matter-Radiation Decoupling:
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons



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  - ★ z=1000: electrons captured by nuclei
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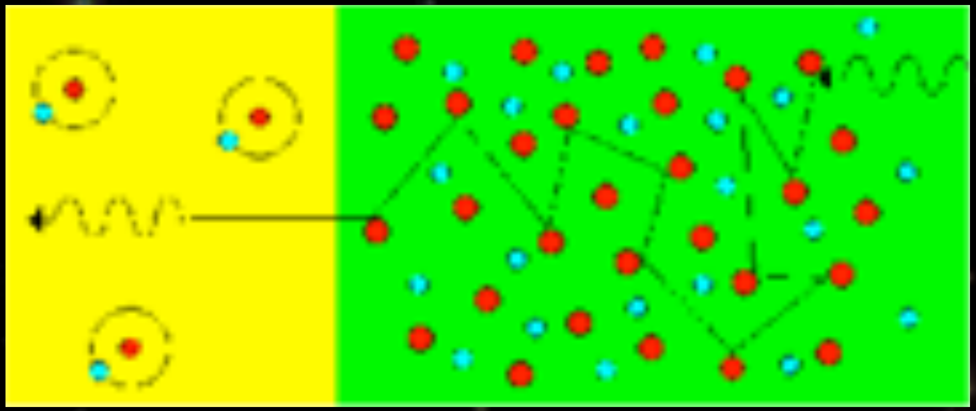
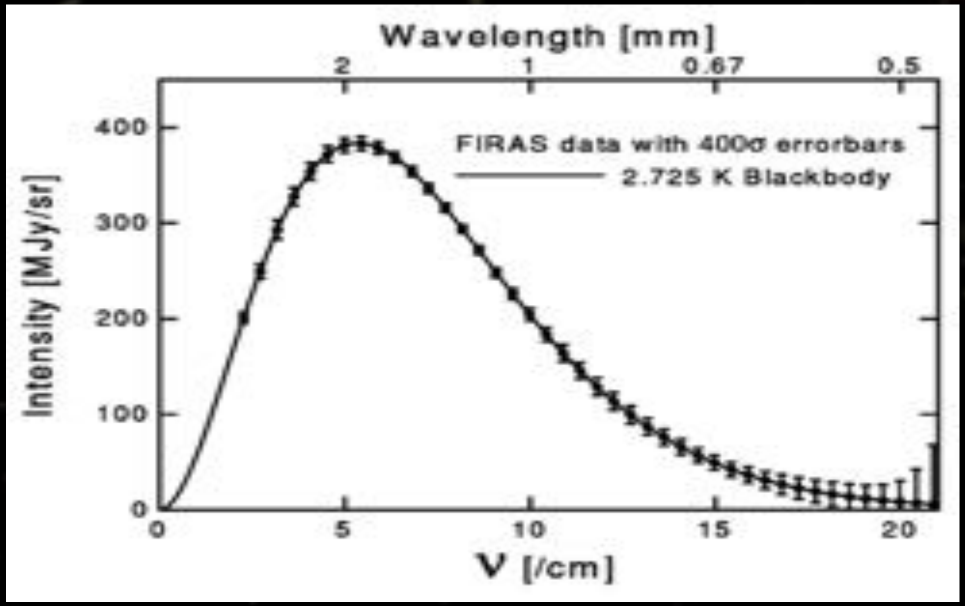
- Uniform background of photons
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky





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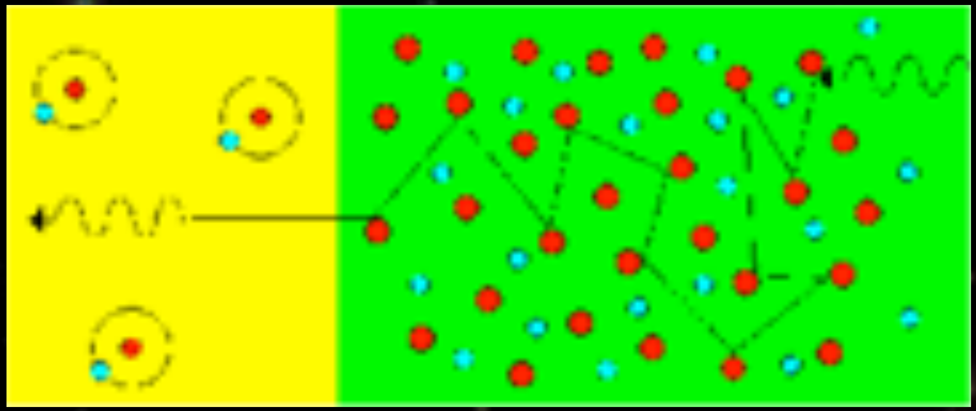
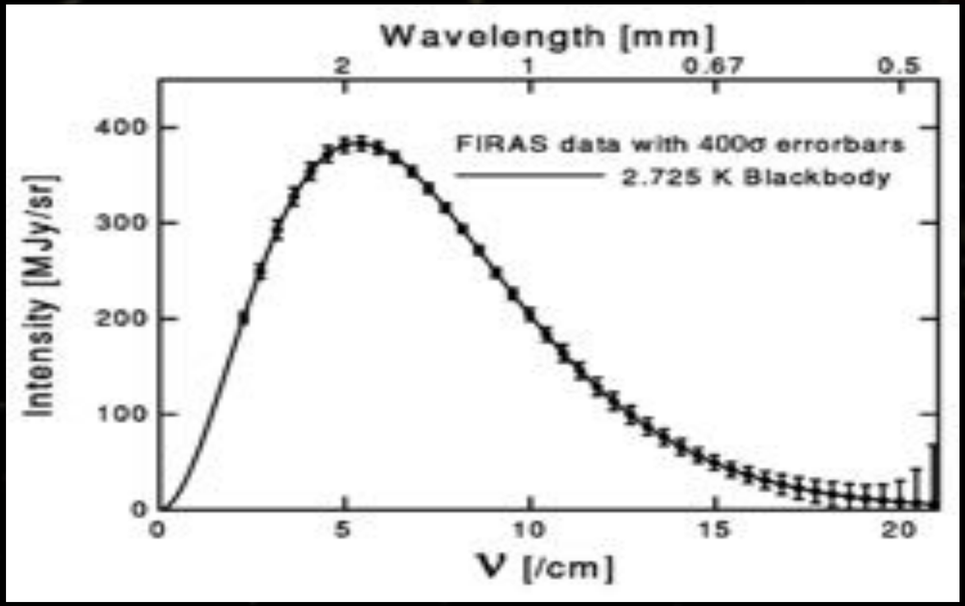
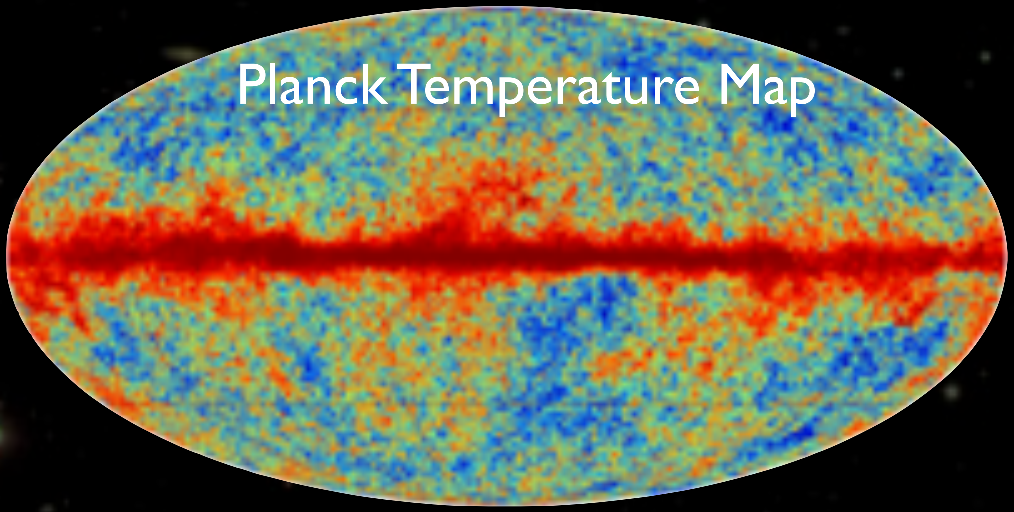
- **Picture of the Universe at z=1000**
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U







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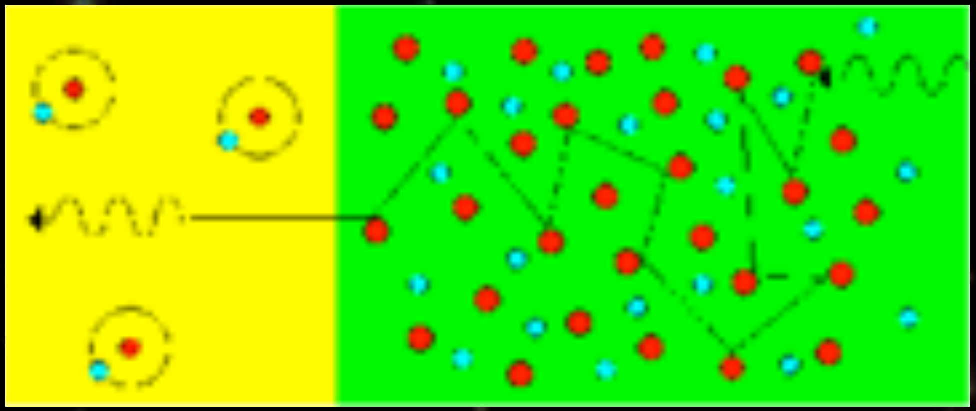

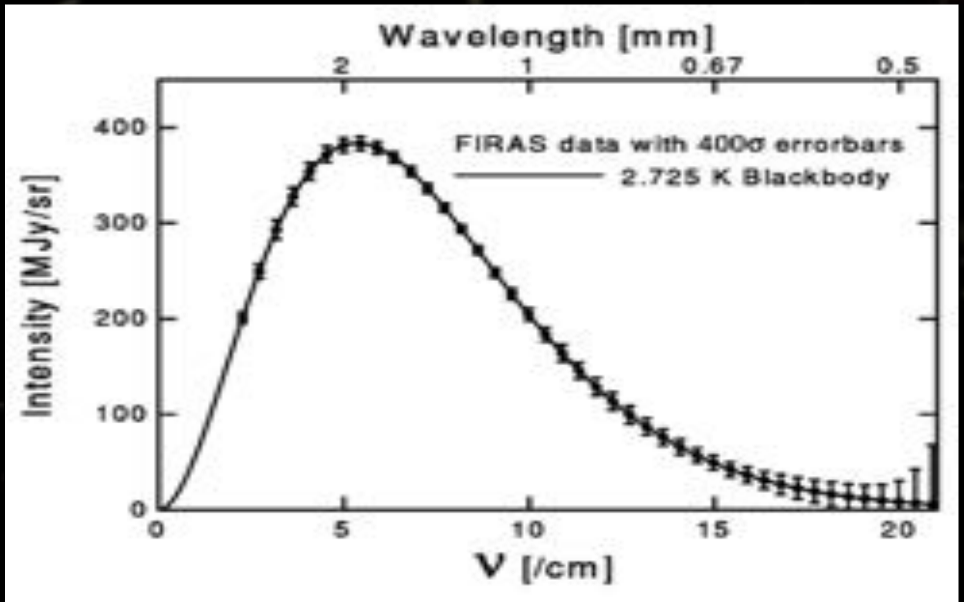

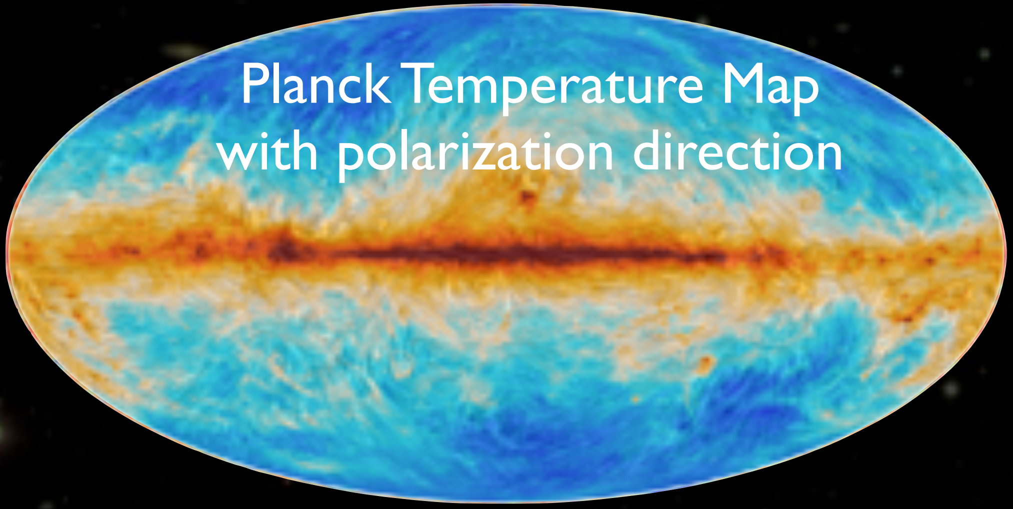

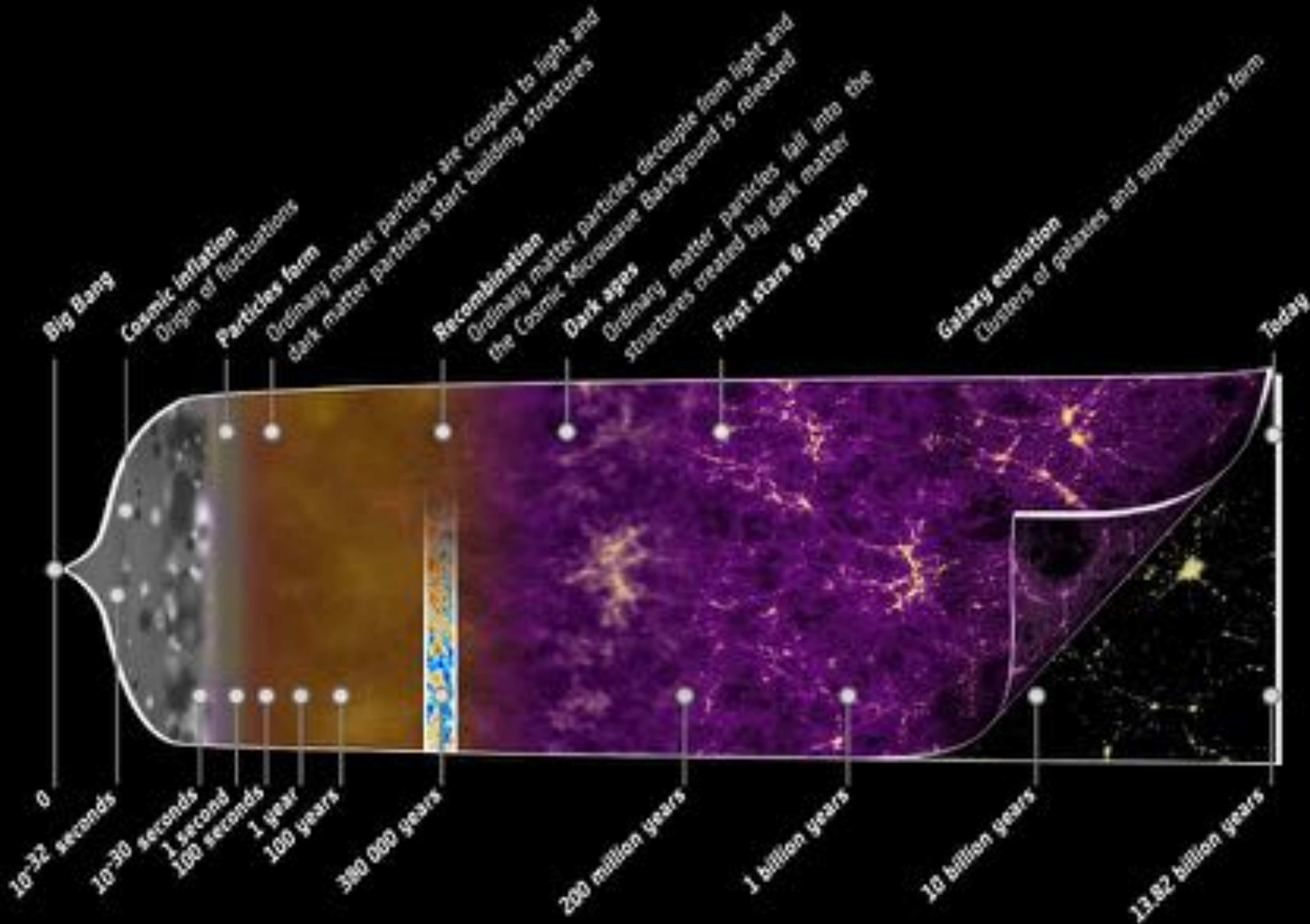

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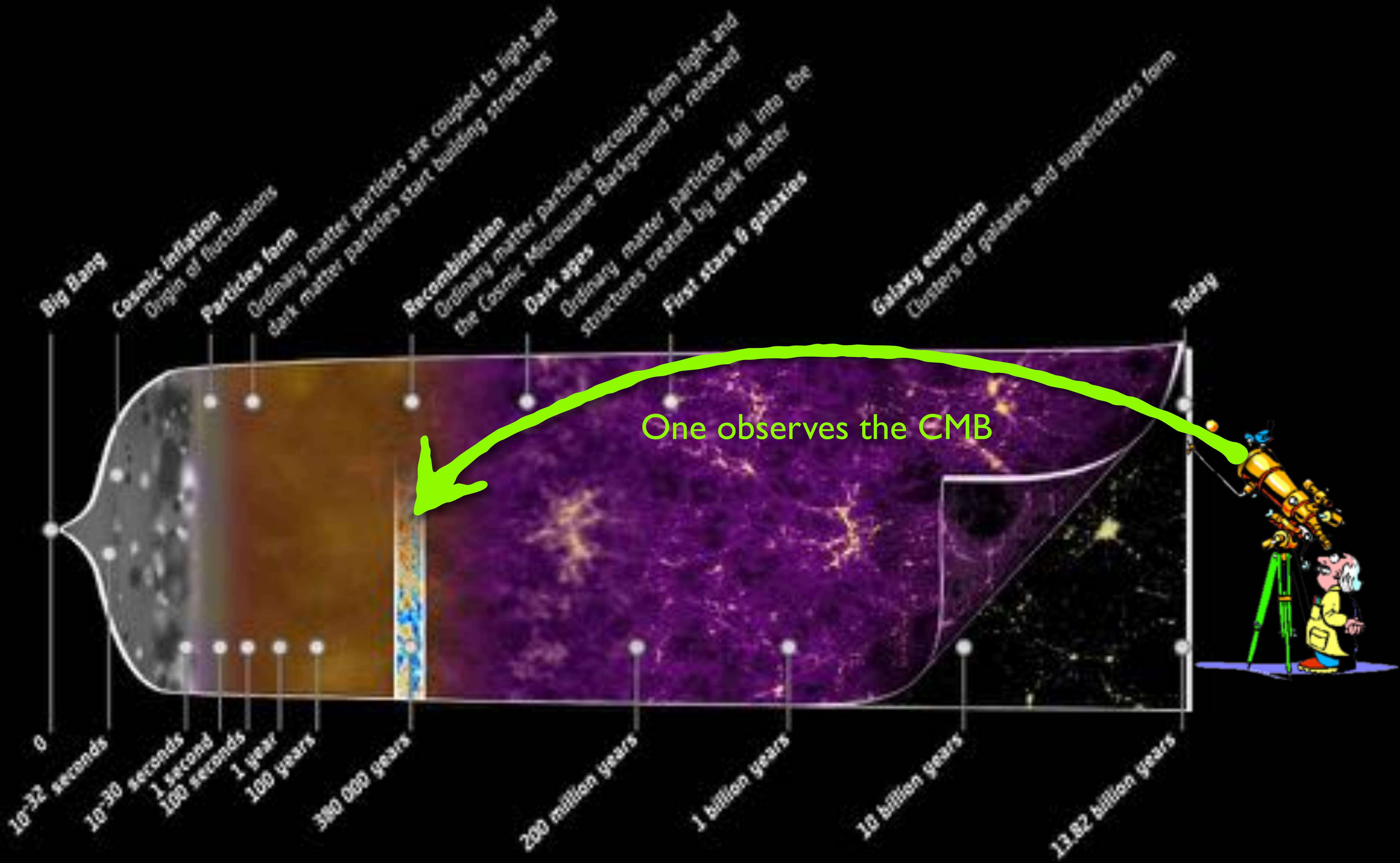

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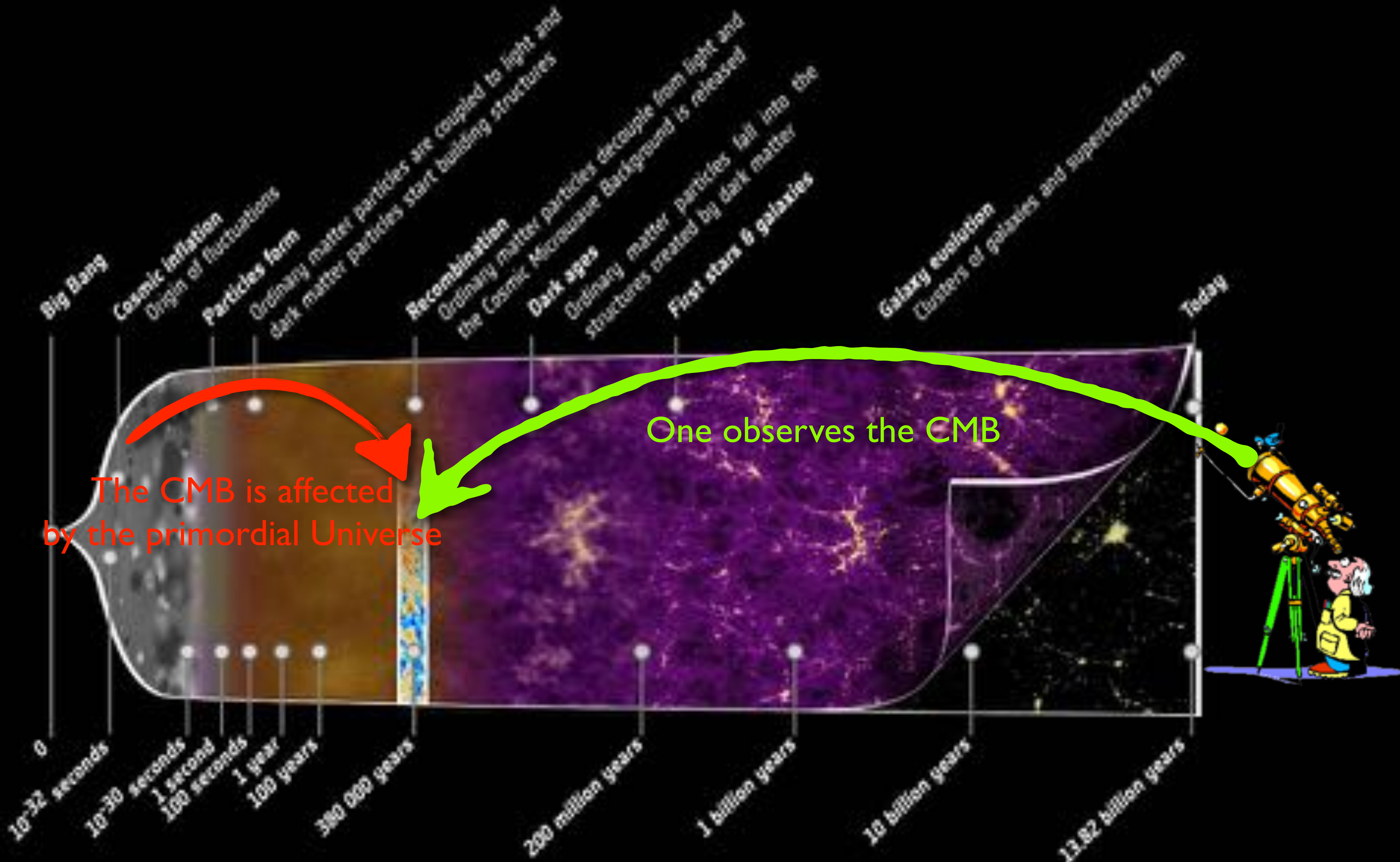

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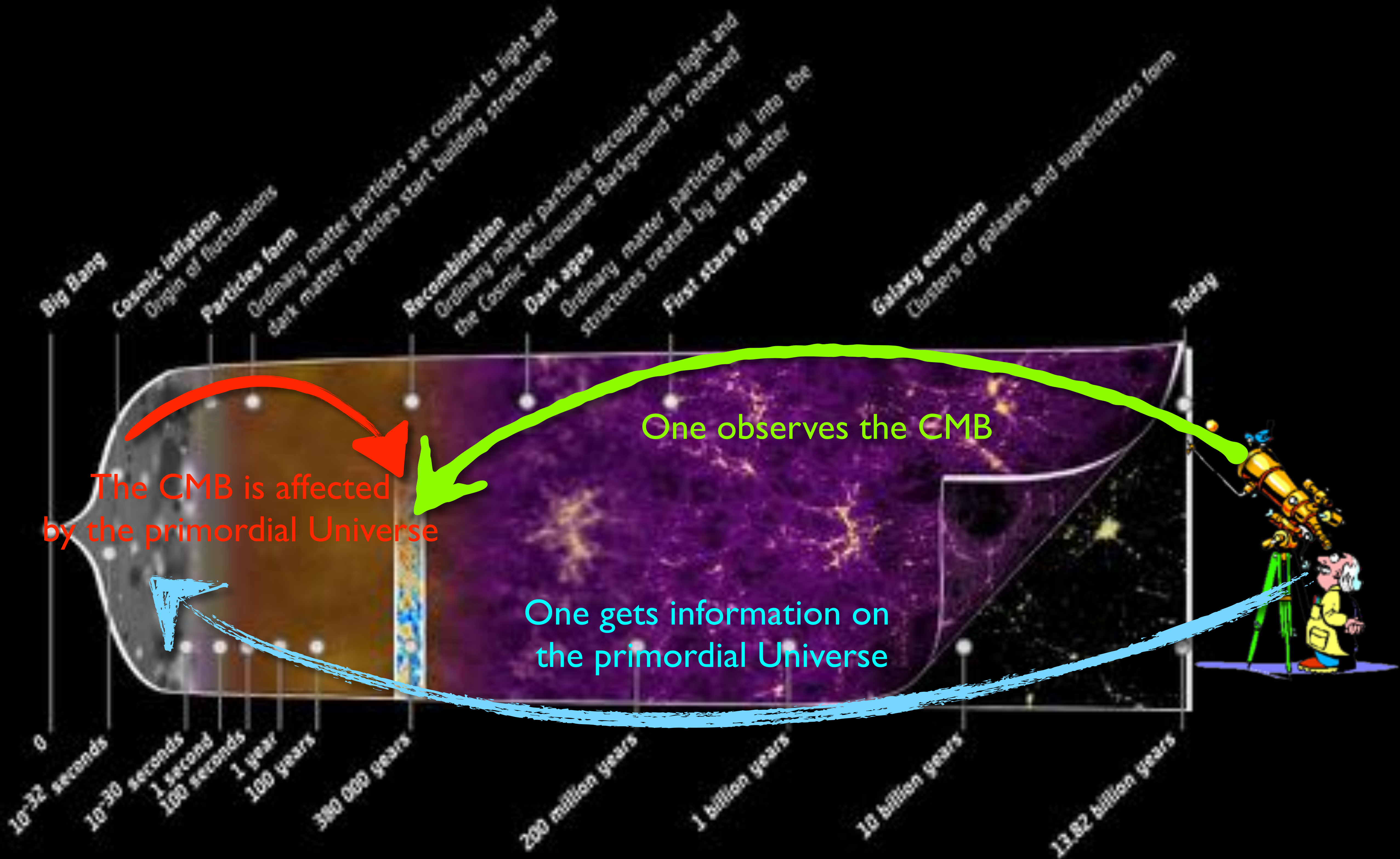

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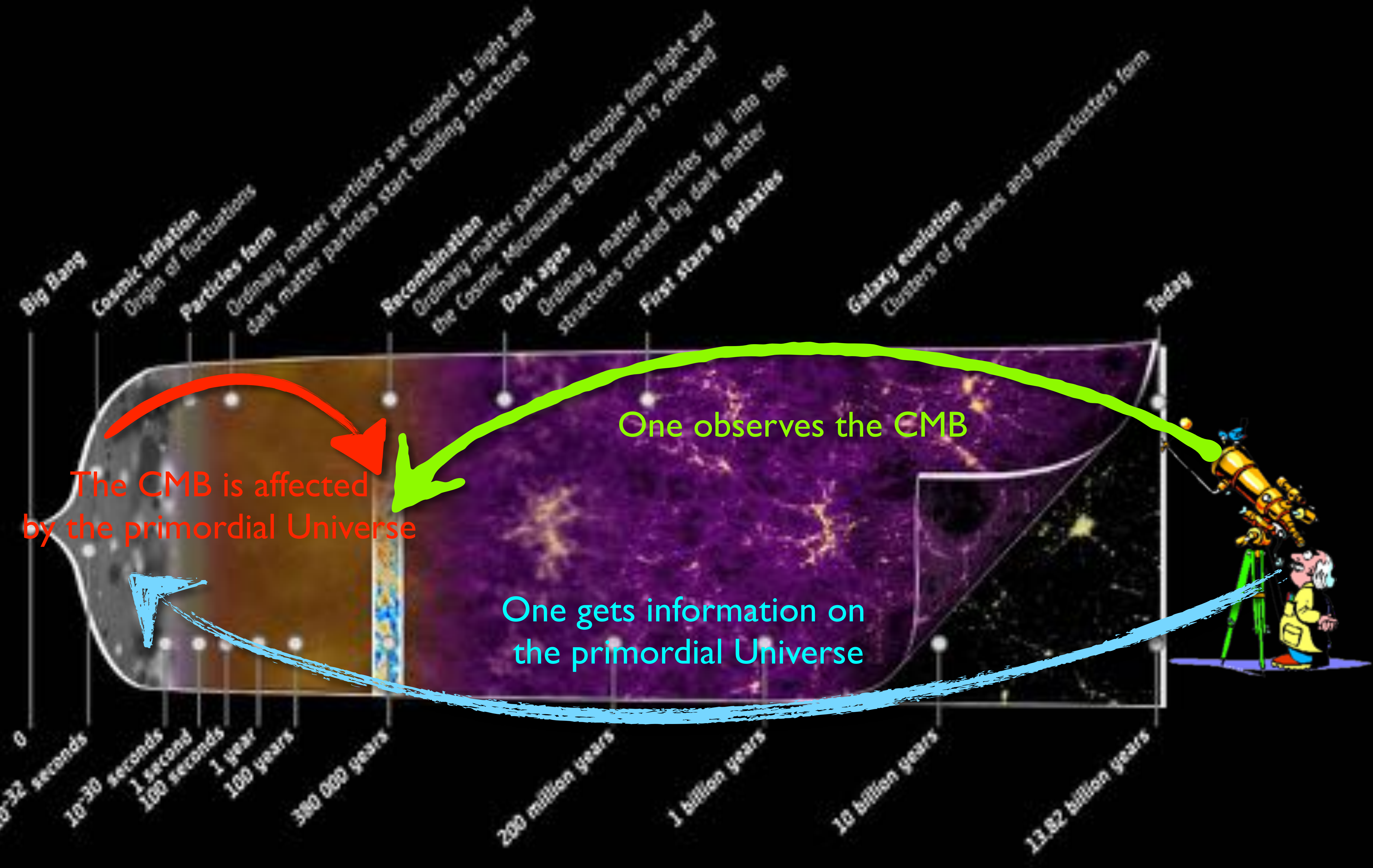


By the way… Where does all the structure come from ?

Where does all the structure come from ?

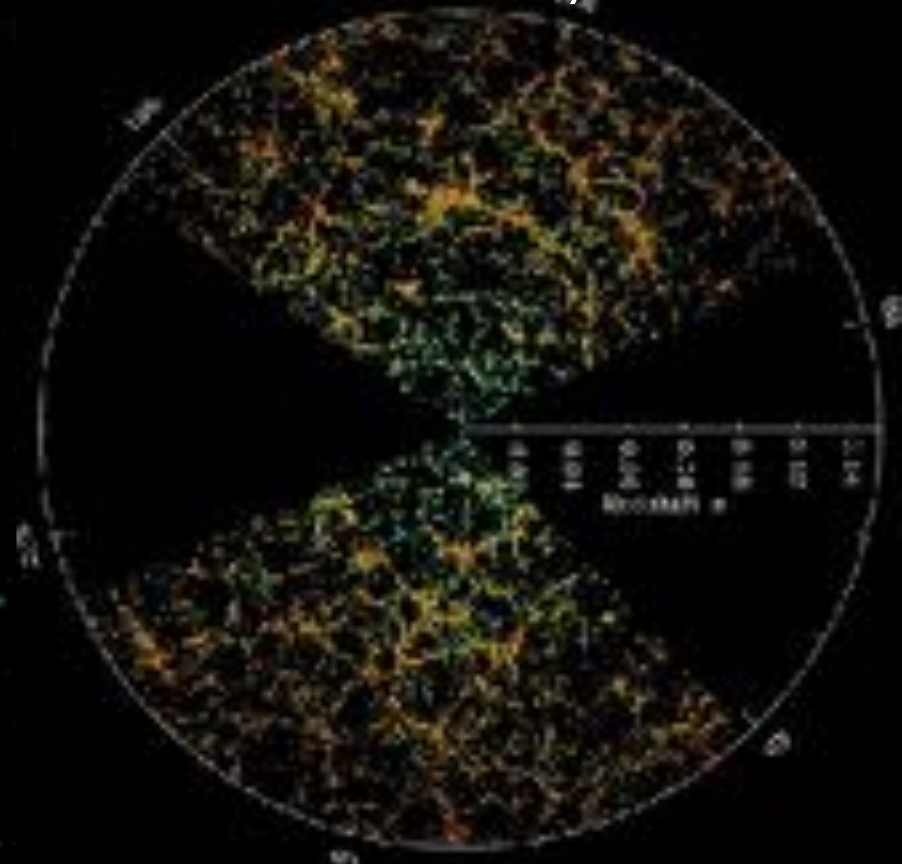
- The Universe around us appears heavily structured (clusters, superclusters, filaments)

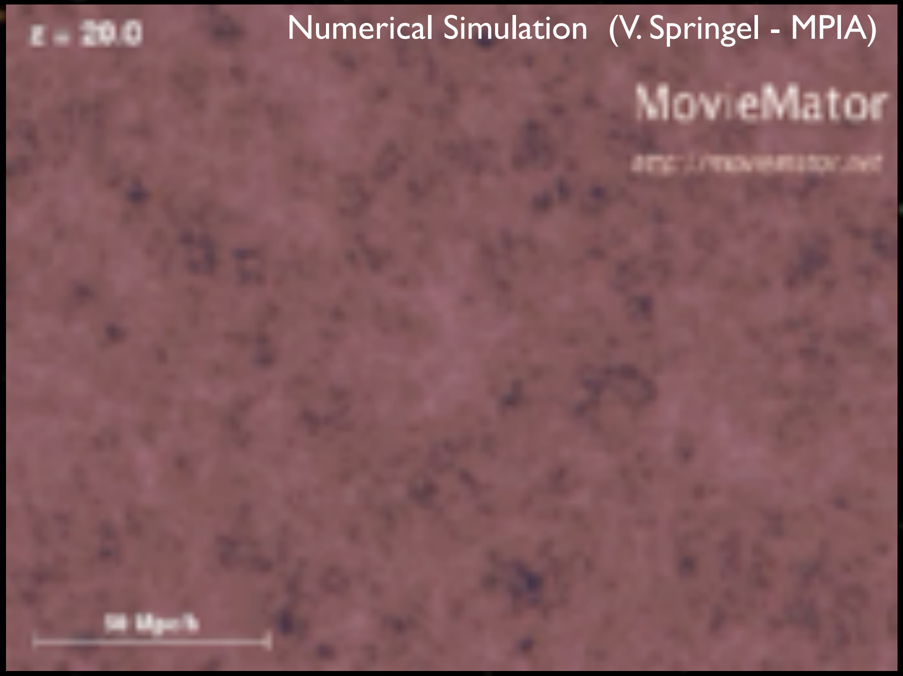
- The simple « Big-Bang » does not give any clue about the origin of this structure

- One has to assume that there were seeds of a given shape at early times

- Two possibilities :
  - ★ Ad-hoc initial conditions 
  - ★ A physical process that generates these conditions : I**nflation**

Galaxies in a declination slice in SDSS survey





Numerical Simulation (V. Springel - MPIA)

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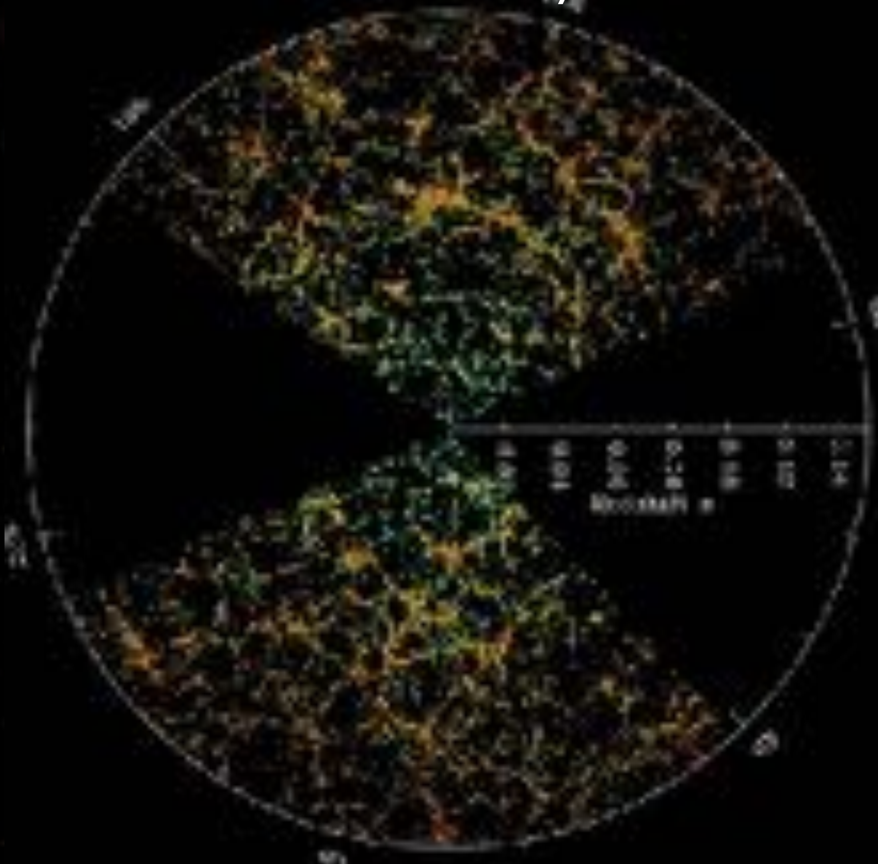

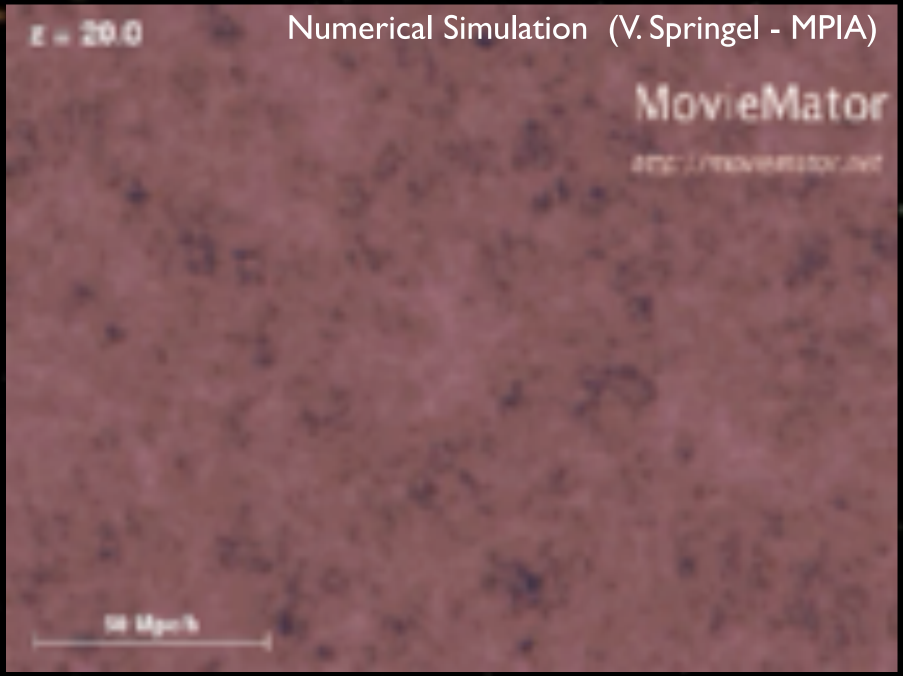

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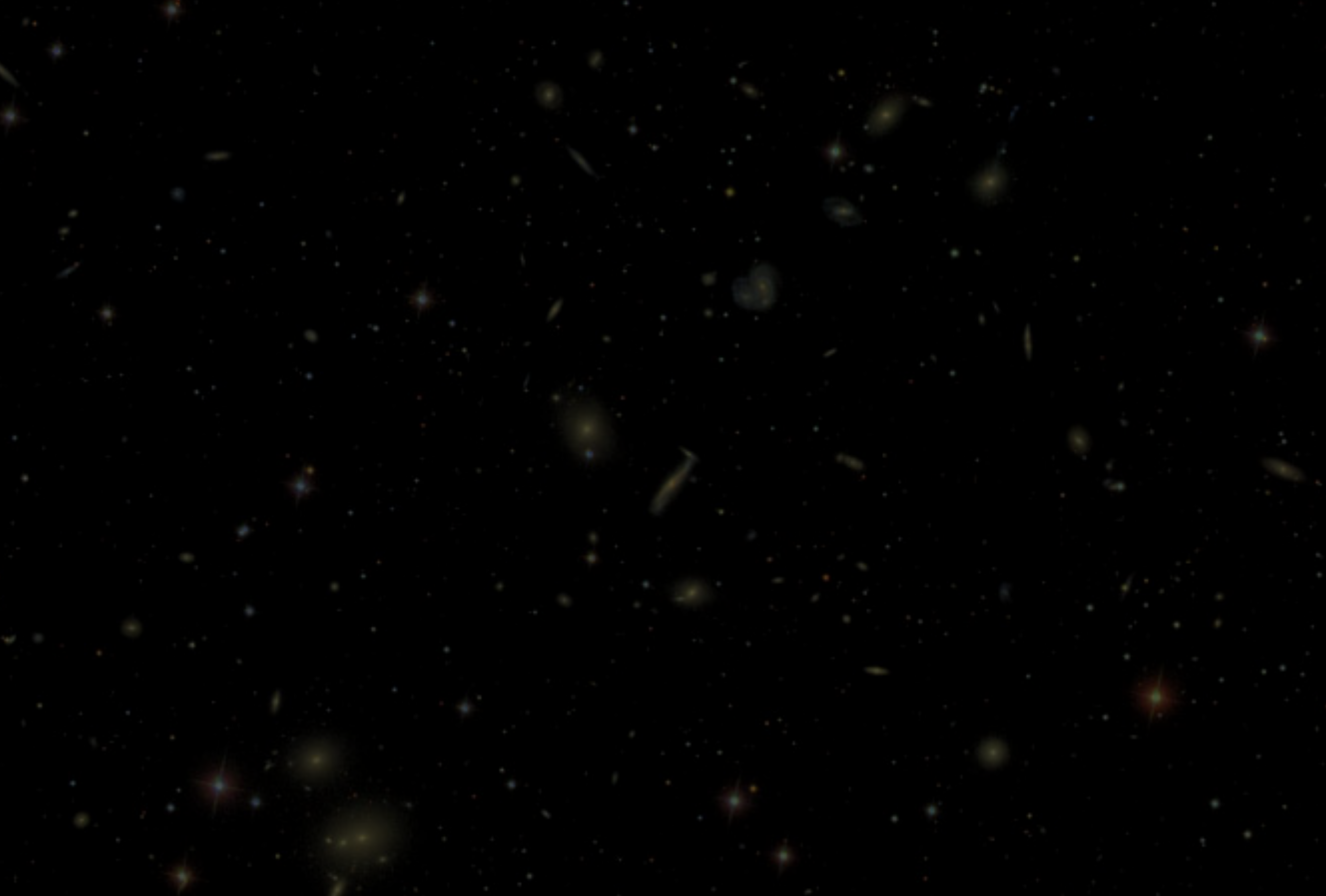
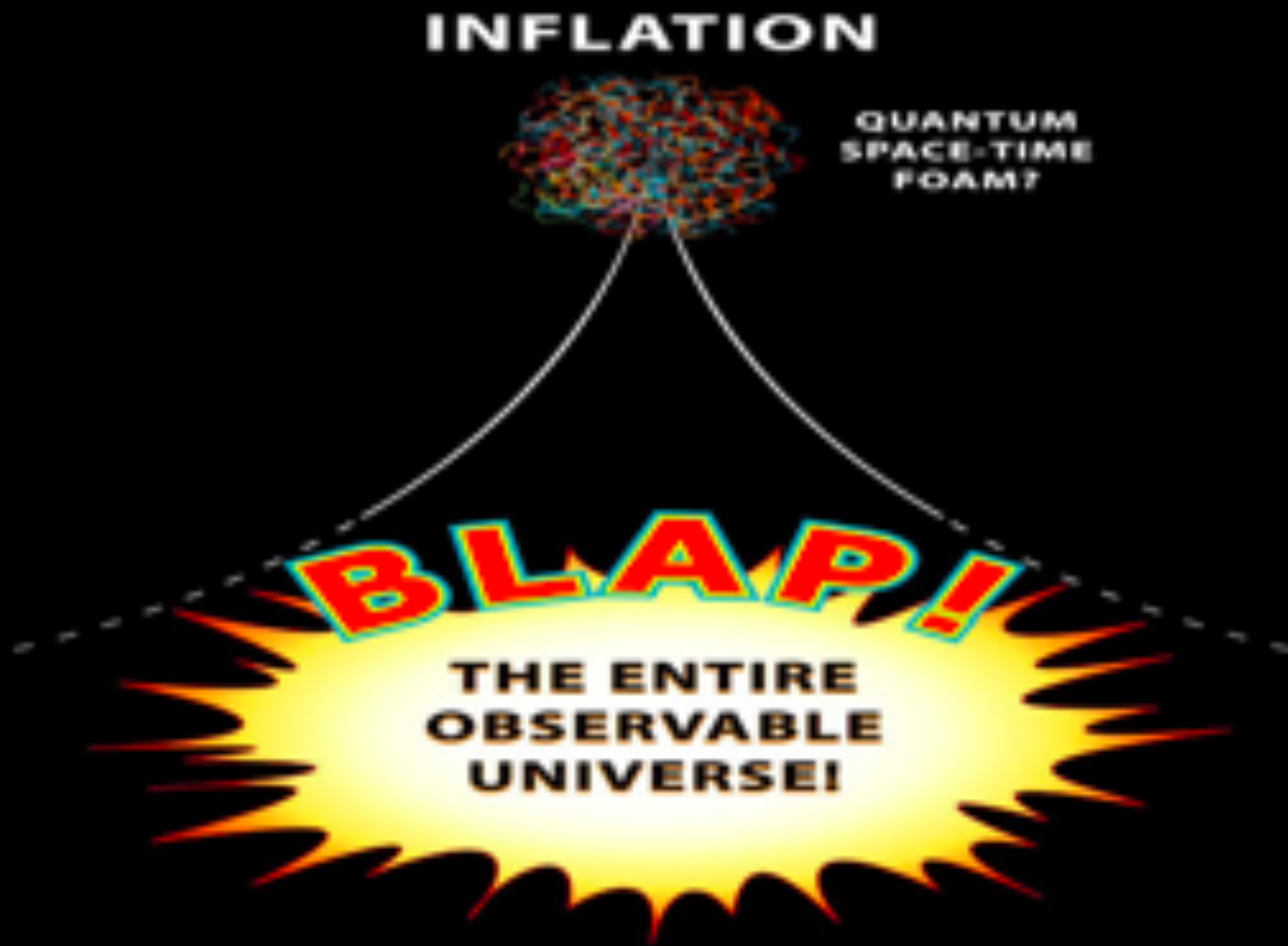
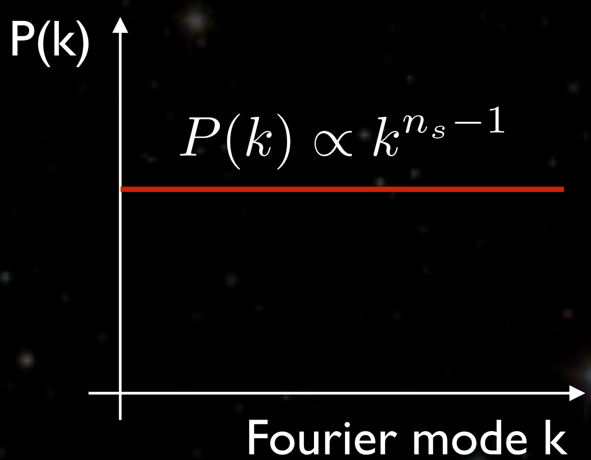




Quantum fluctuations of the « inflaton » are converted to microscopic during inflation and remain afterwards. They exactly have the required scale-invariant primordial power spectrum

Density Field Transfer Function

Early Universe
Primordial Density
Fluctuations



Density Field Transfer Function

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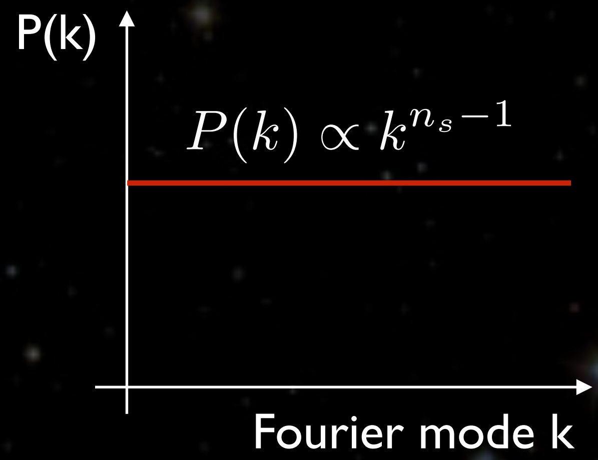
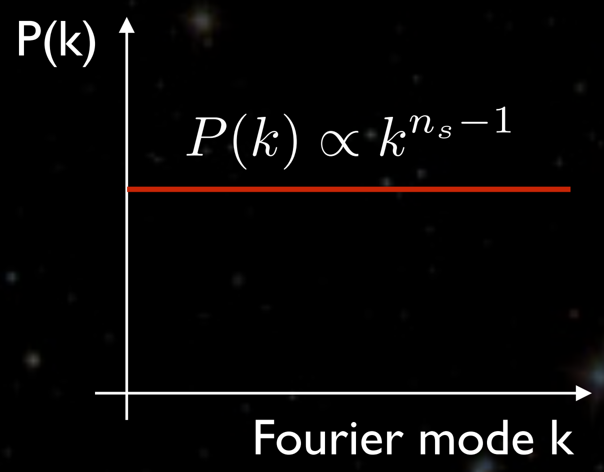
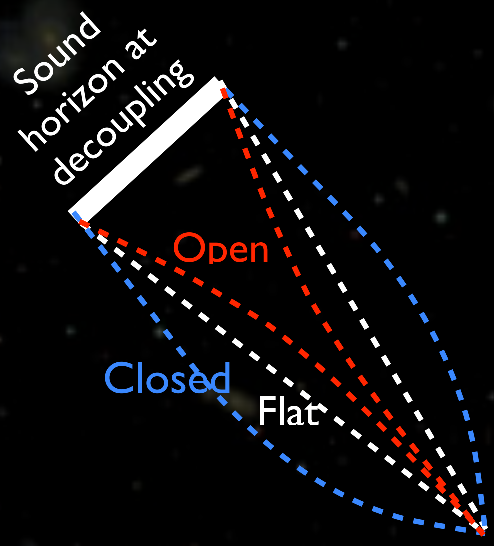
Acoustic
Oscillations



Density Field Transfer Function

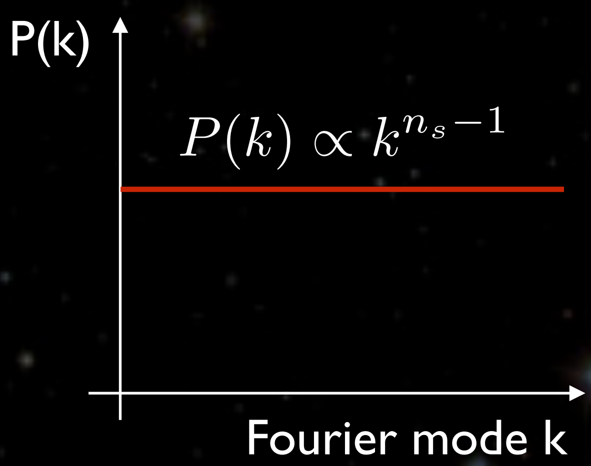
Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Geometry

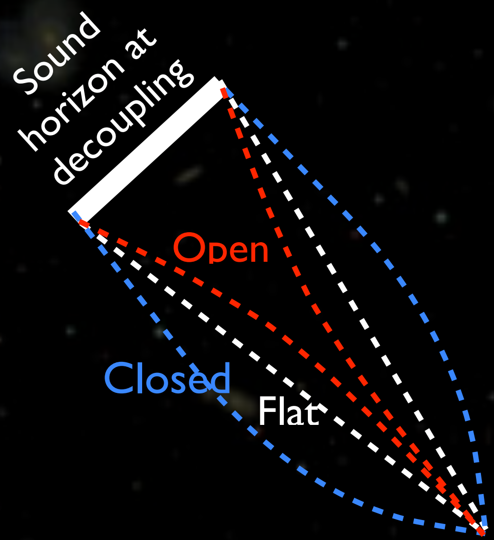


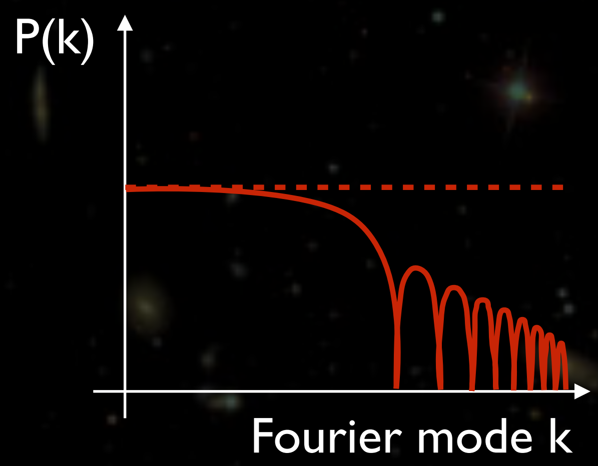


Density Field Transfer Function

Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Geometry → Evolved power spectrum







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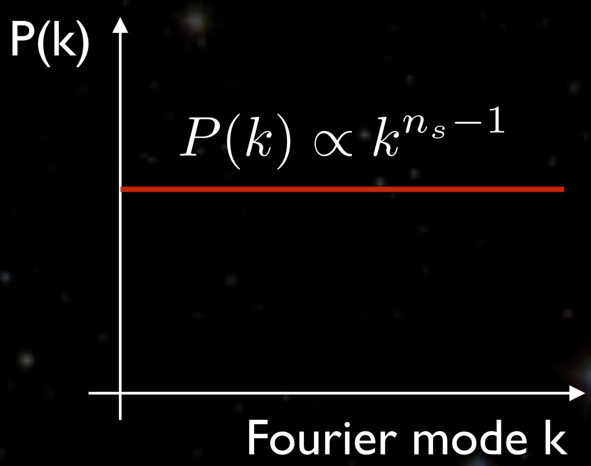
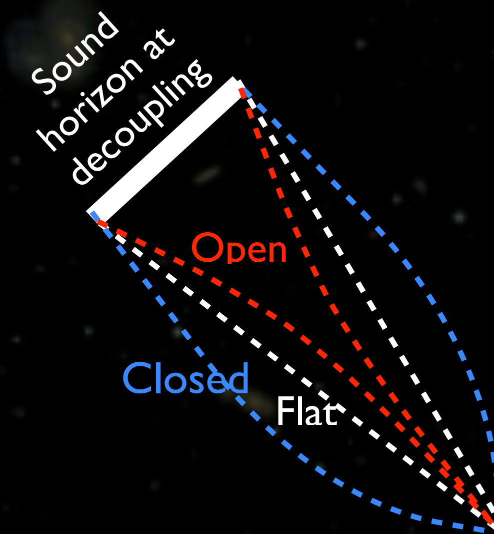
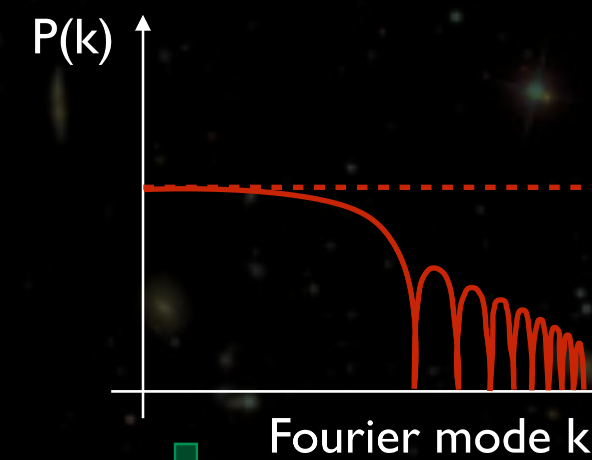
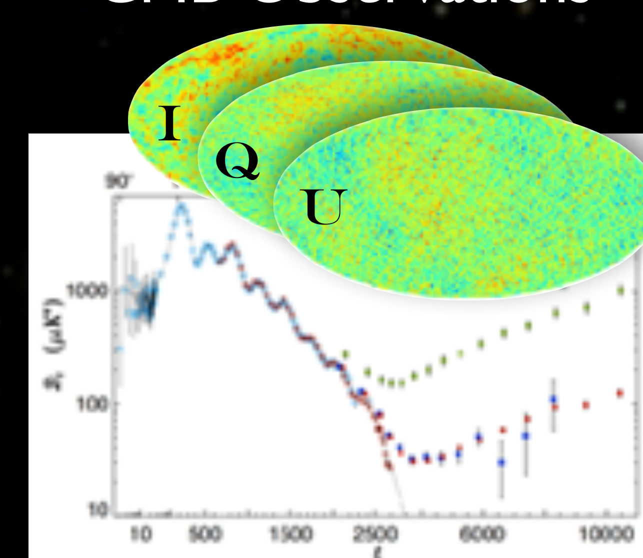






CMB Observations



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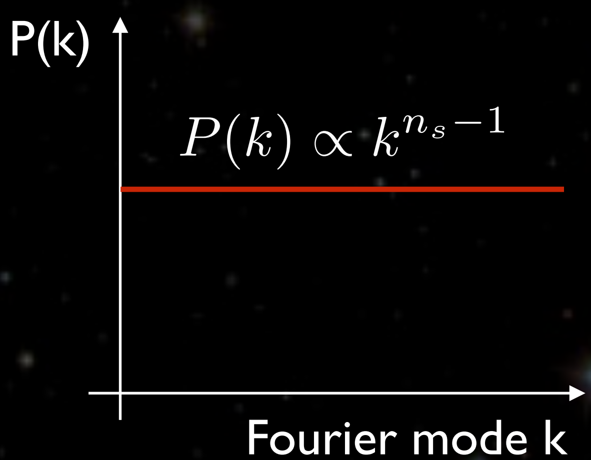

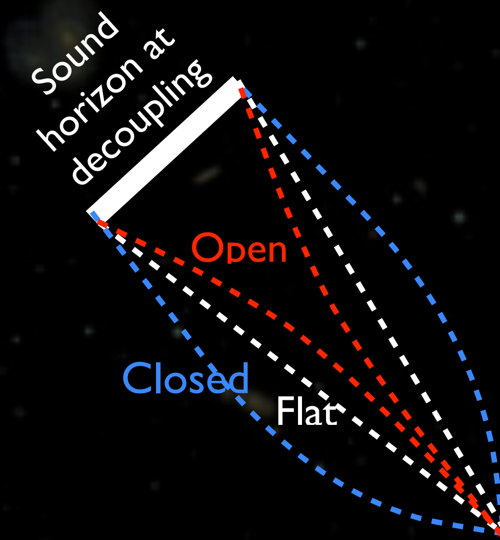

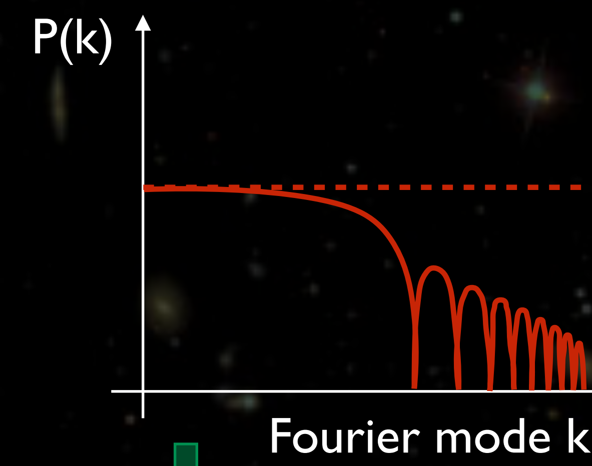

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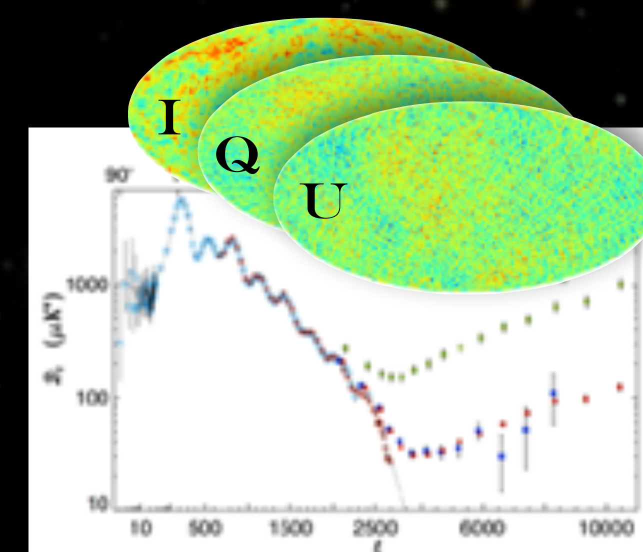
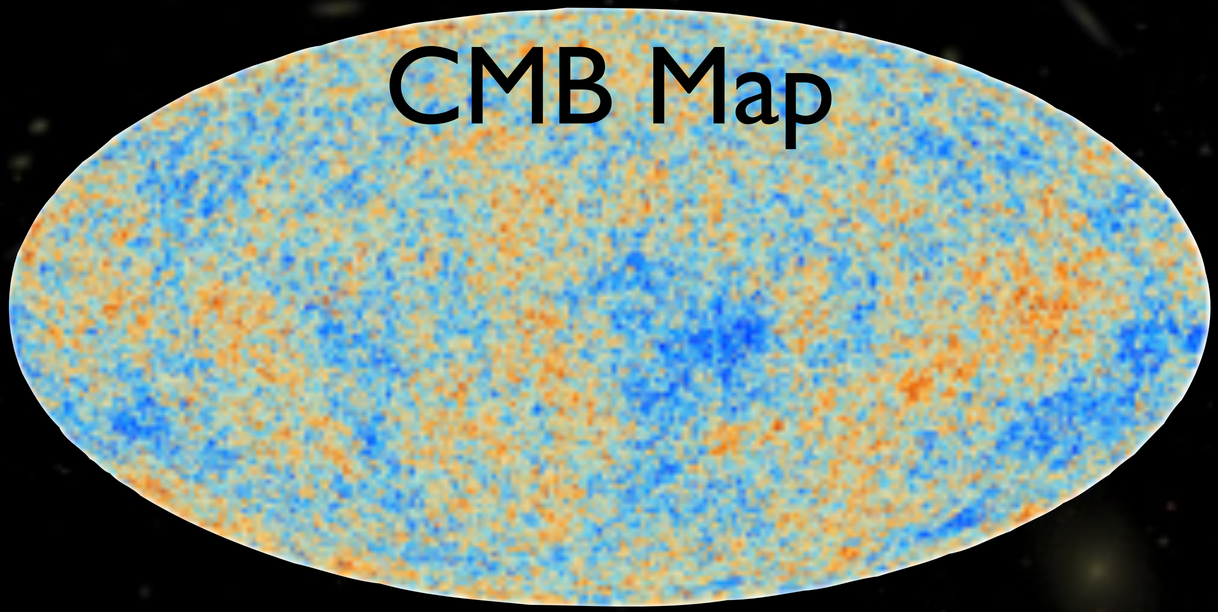


- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **transfert function** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

CMB Results (Planck)



C_ℓ = Angular power spectrum

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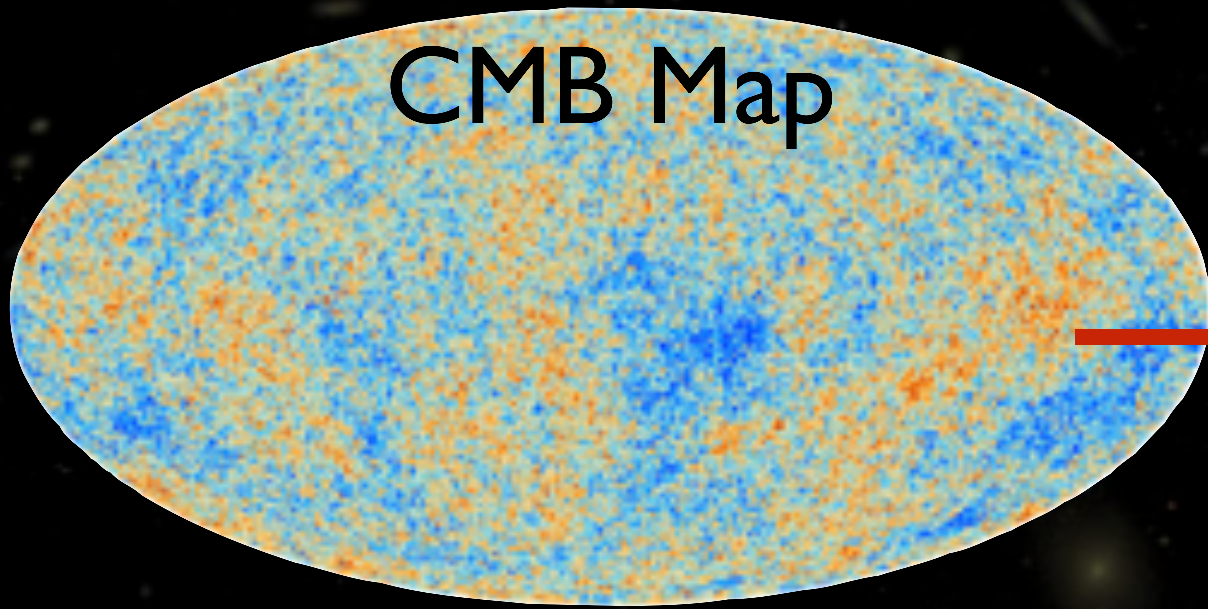

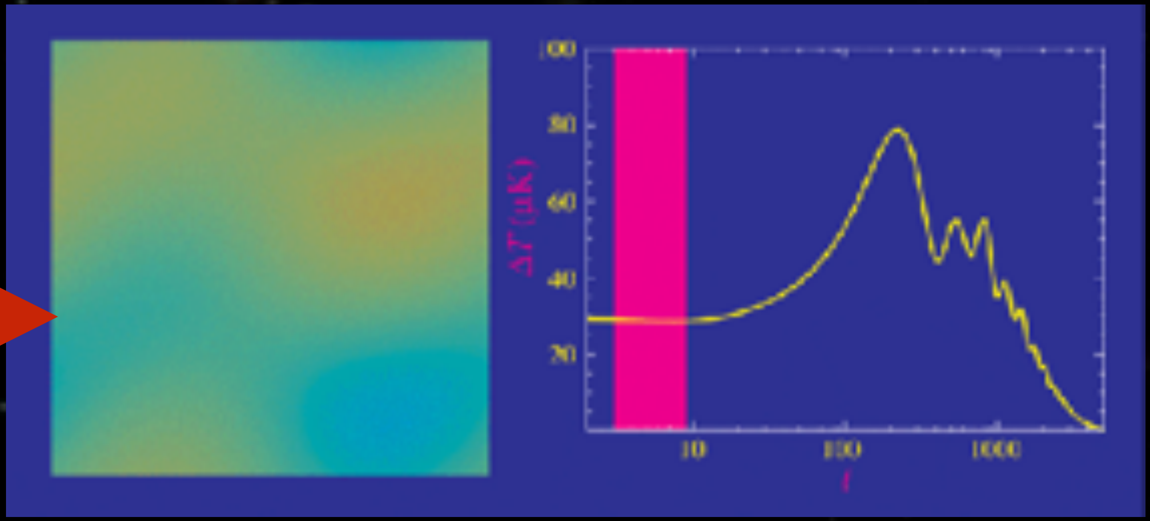

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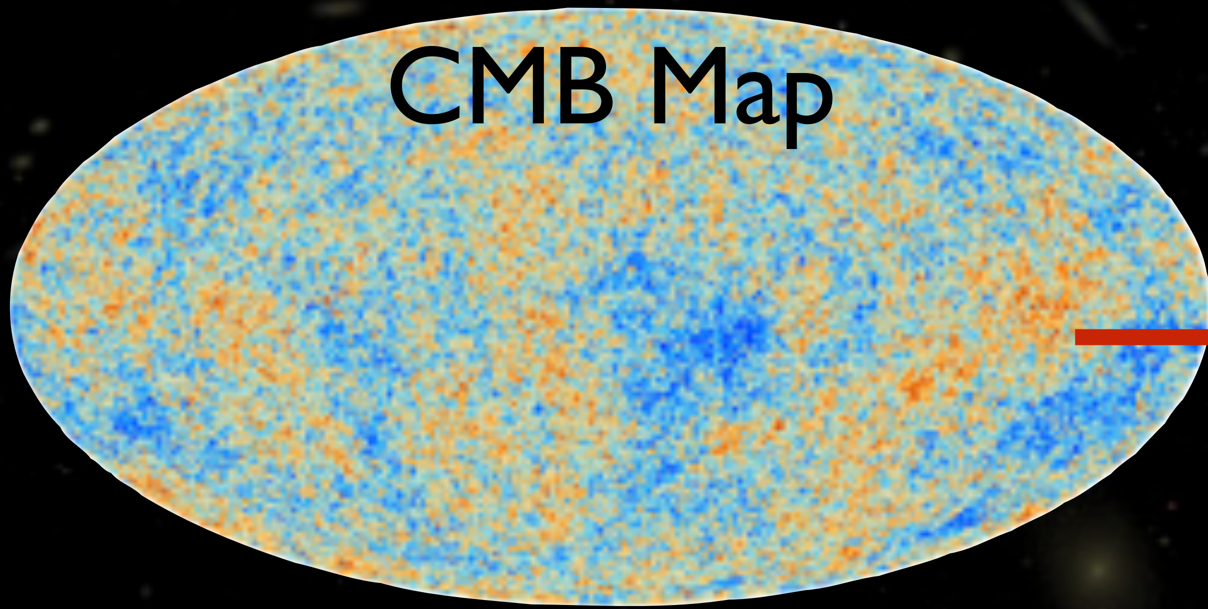

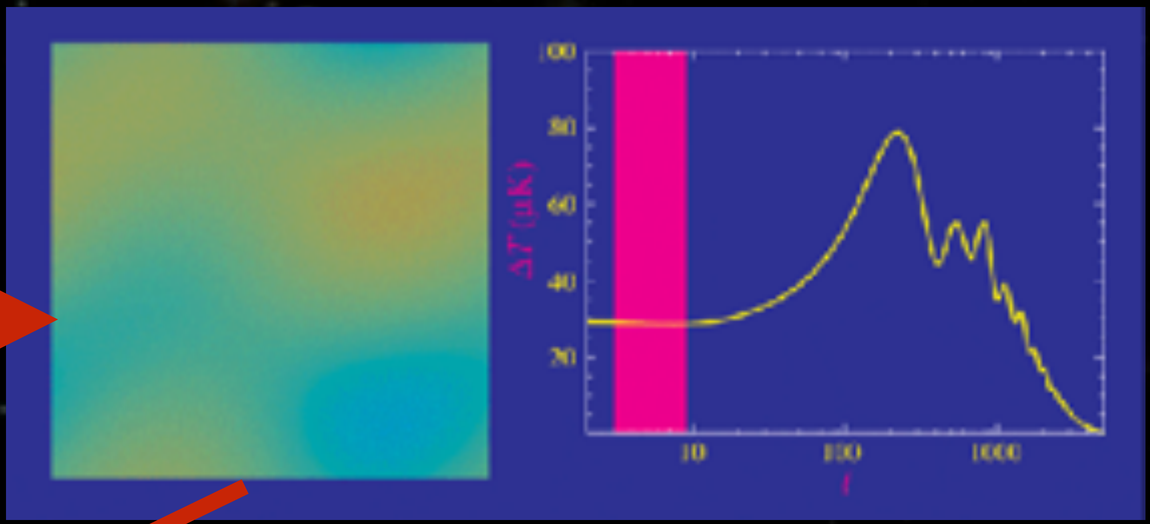

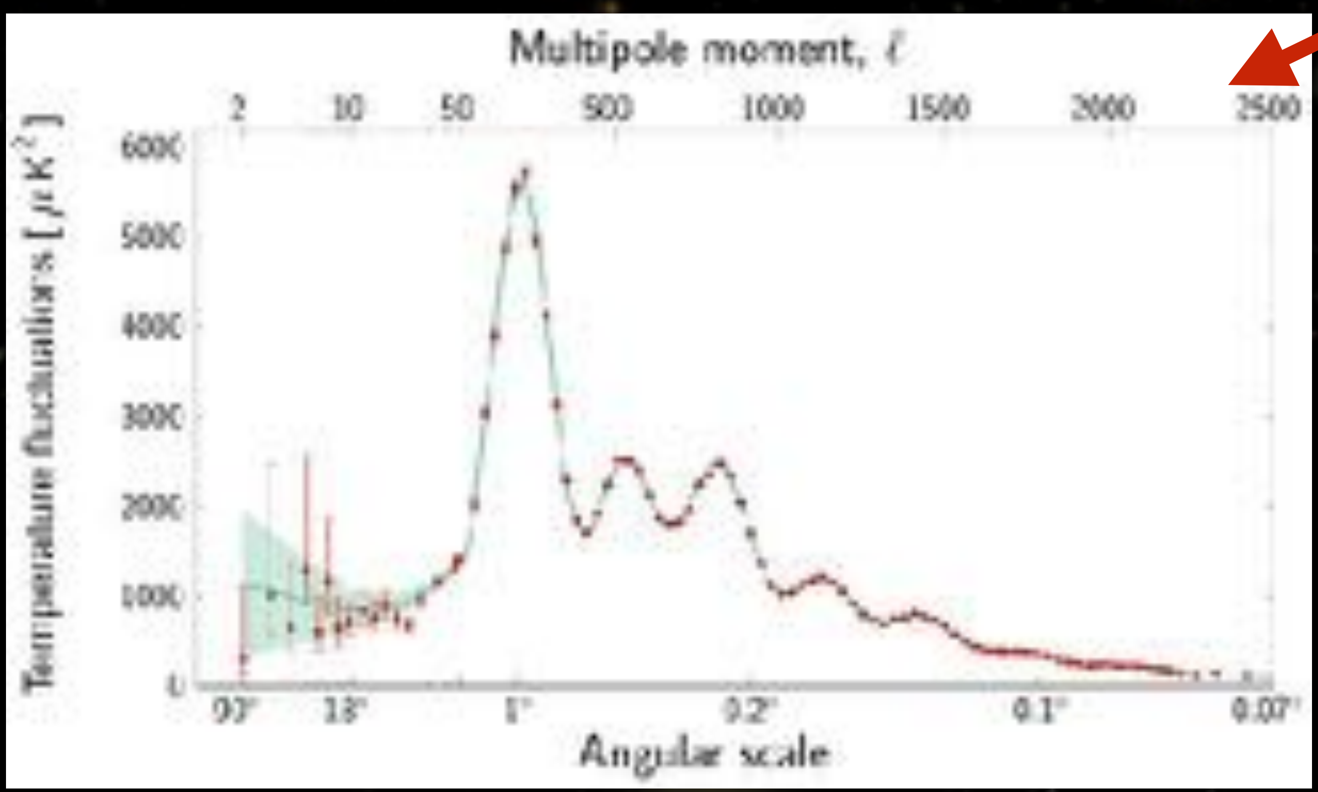

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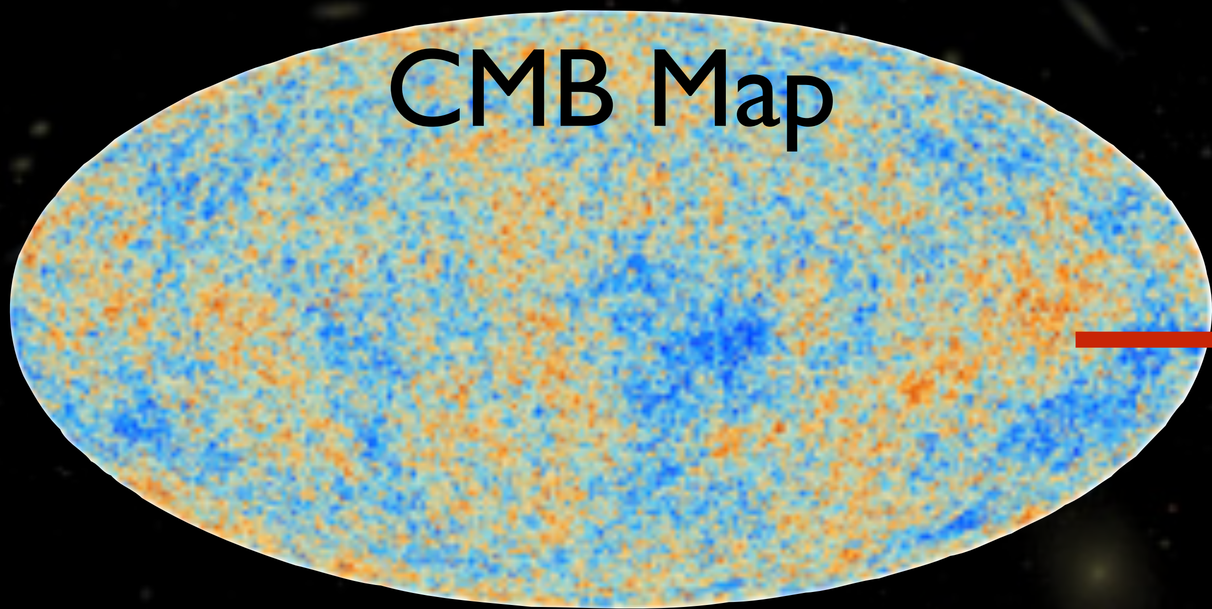
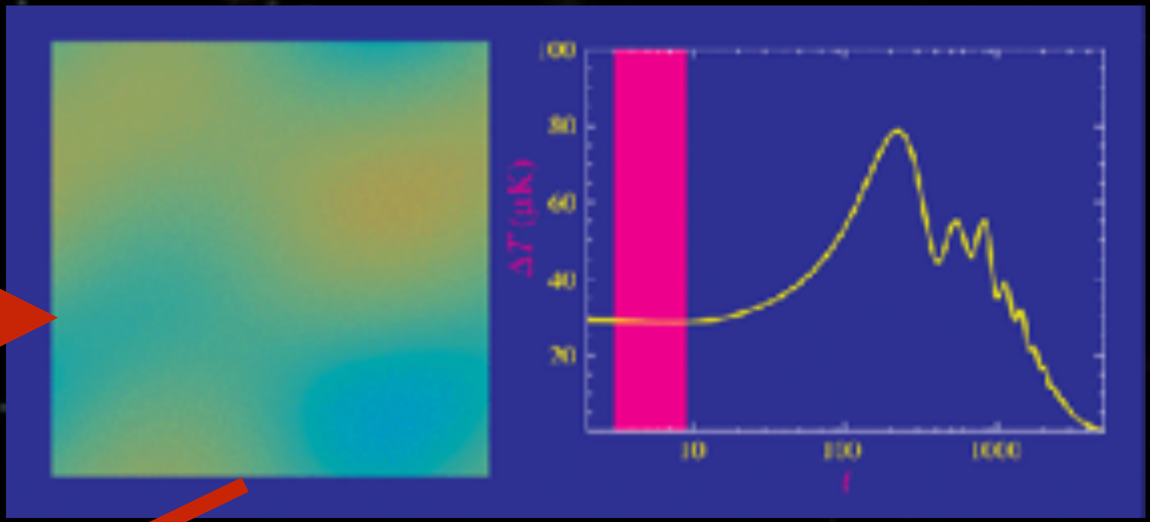
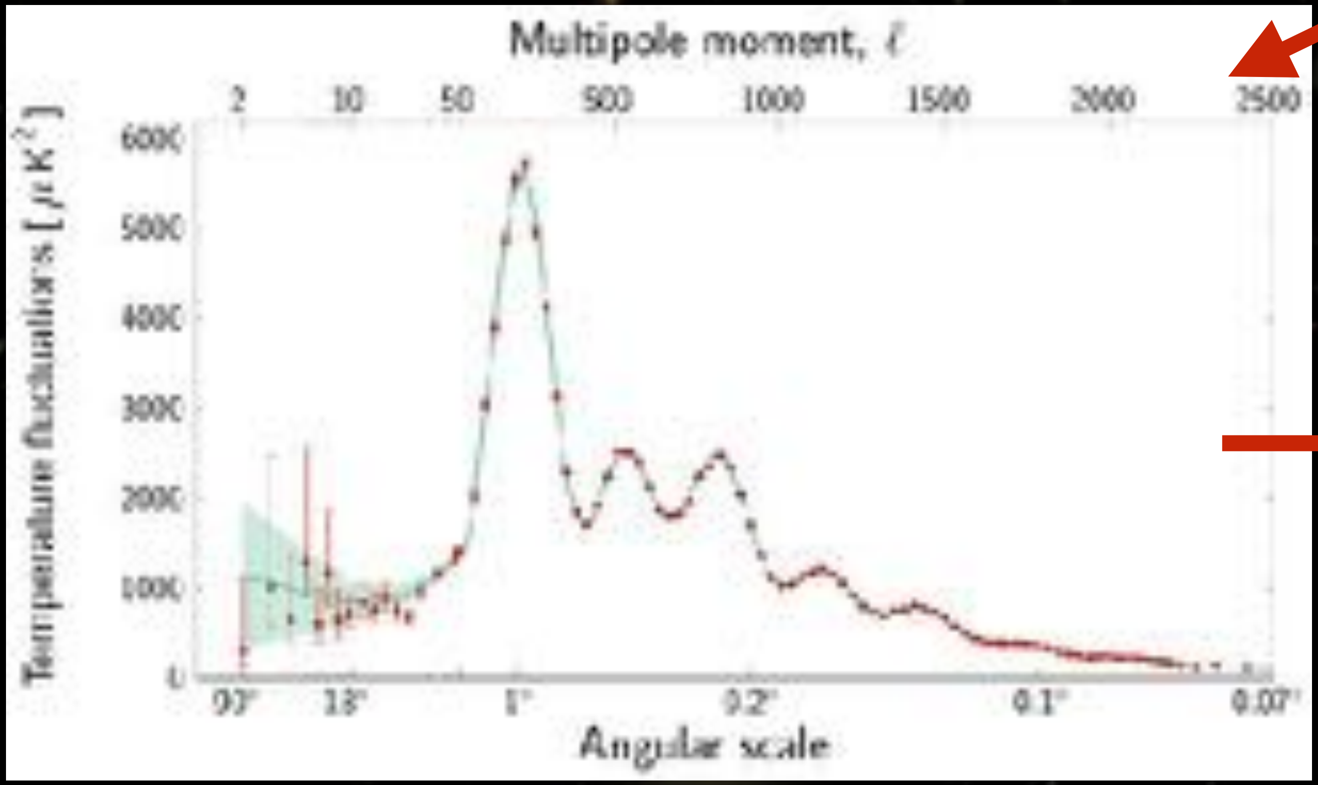
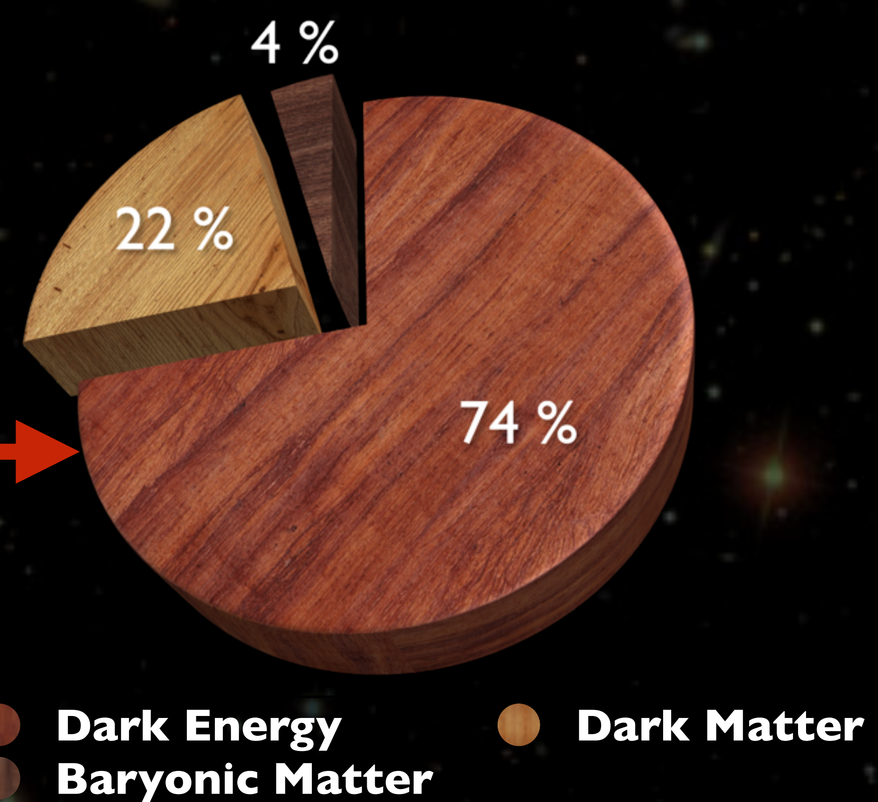






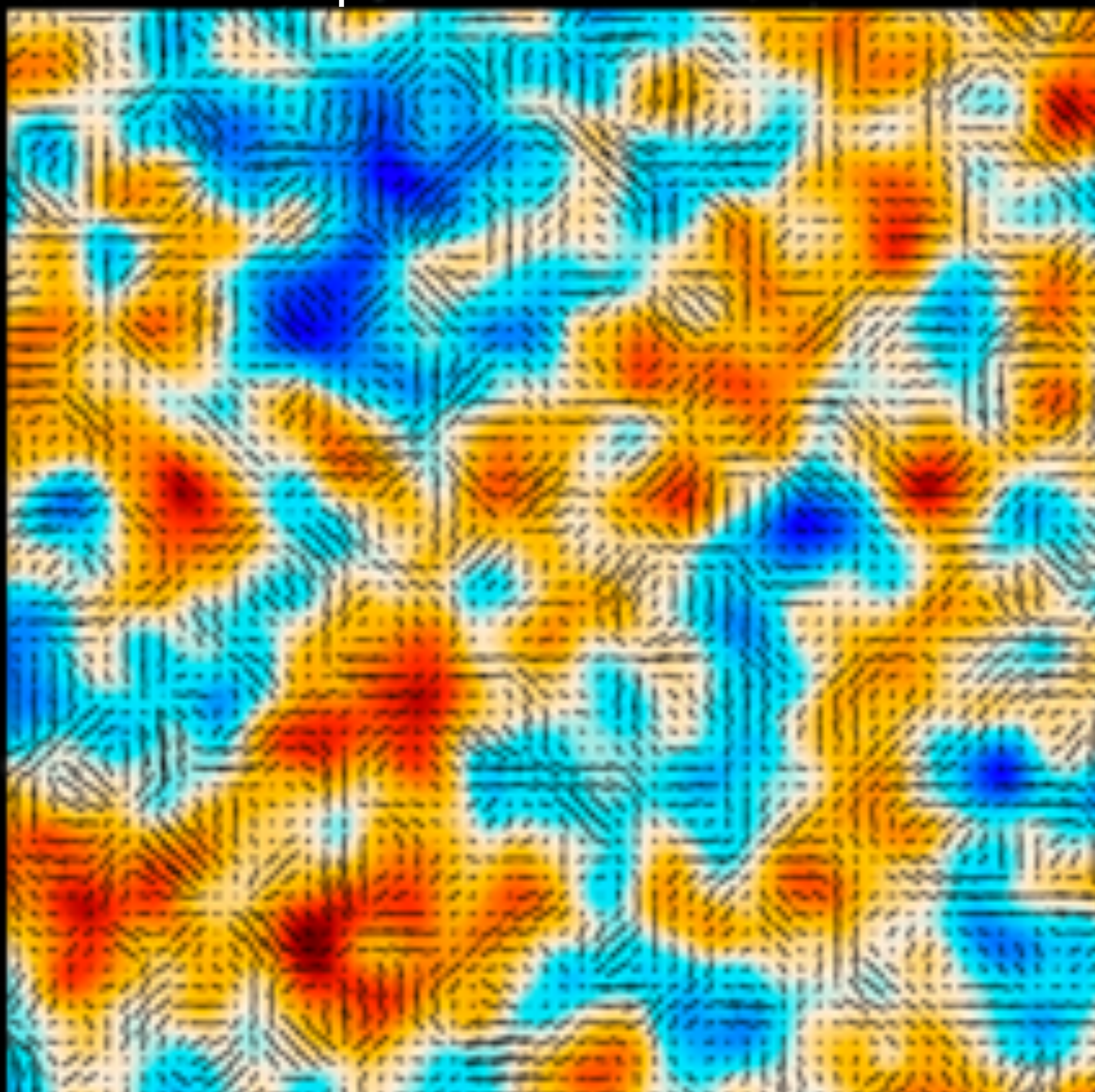


C_ℓ = Angular power spectrum

The CMB is few % polarized

CMB Sky

Color = Temperature - Vectors = Polarization



Observables

Stokes Parameters

I — Total Intensity

Detector Y + Detector X

Q — Linear Polarization

Detector Y − Detector X

U — Linear Polarization

Detector B − Detector A

Instrument

The CMB is few % polarized

CMB Sky

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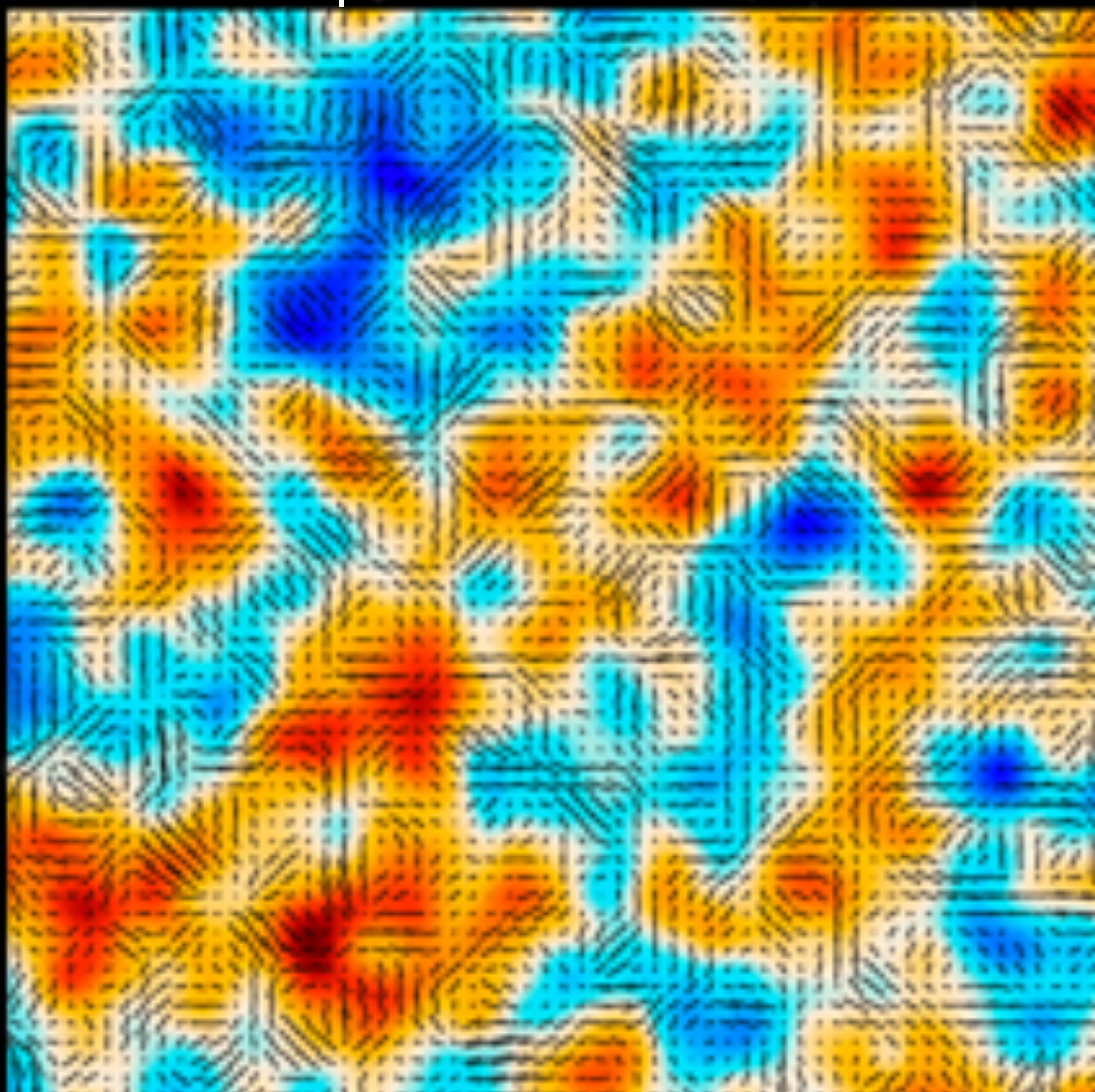

Observables

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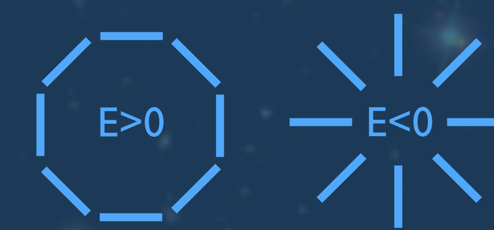
Theoretically meaningful

E-modes: curl-free



Independent from Inflation
Already observed

B-modes: curl part

Specific prediction from Inflation
Still to be observed
$r < 0.06$ (95% C.L.)

Instrument → Maths

Scalar and tensor modes - E & B polarization

- Scalar perturbations: $P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$
  - Density fluctuations
    - Temperature
    - E polarization
    - No B polarization

- Tensor perturbations: $P_r(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$
  - Specific prediction from inflation!
    = Primordial gravitational waves
    - Temperature
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$\Rightarrow$ detect B-modes is :

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale $$V^{1/4} = 1.06 \times 10^{16}\mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$$

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$$r = \frac{P_t(k_0)}{P_s(k_0)}$$

~ ratio between E and B modes

THE parameter we will talking about from now on !

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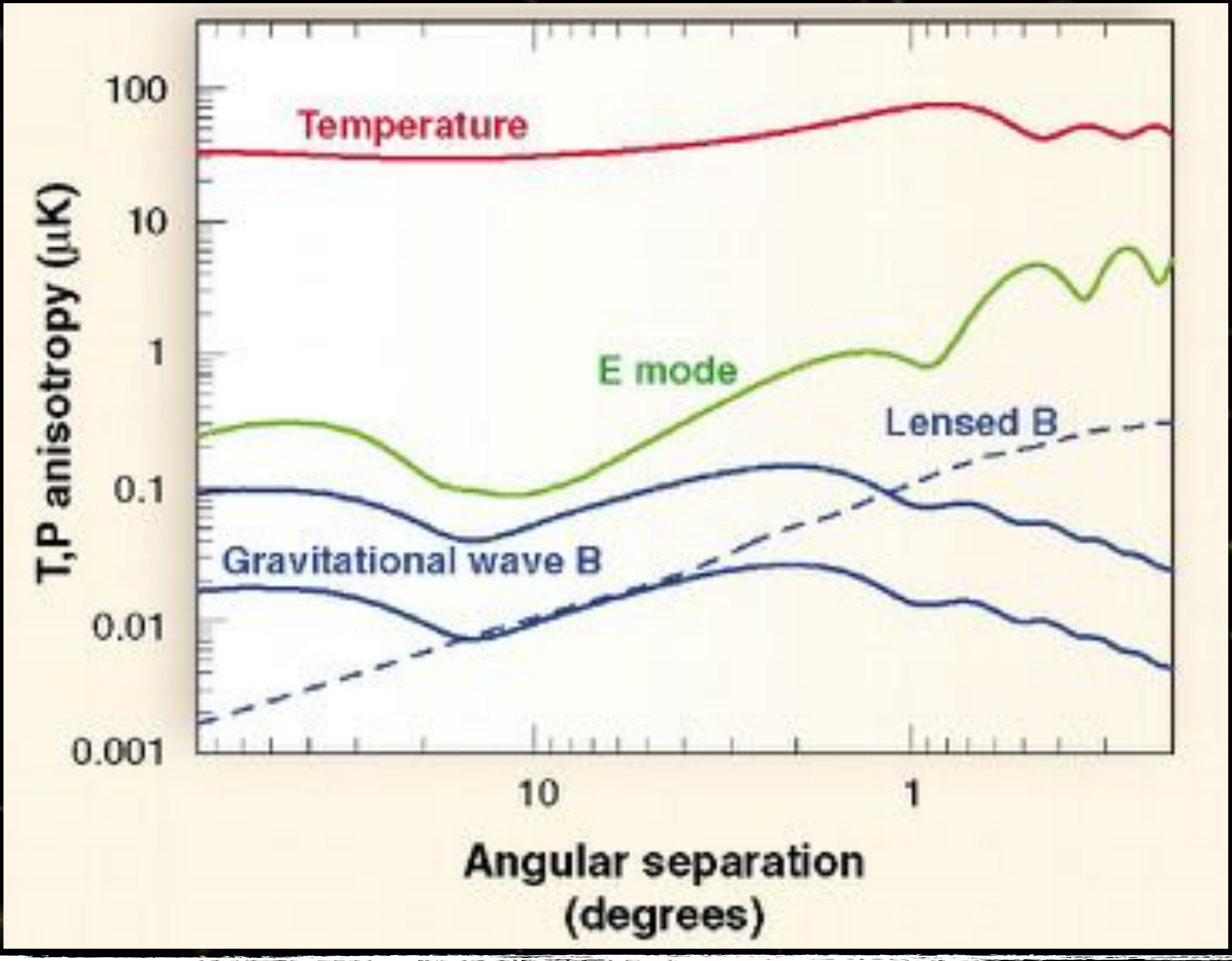
E and B spectra



Primordial Fluctuations Origin ?

Inflation Predictions

• Flatness, Homogeneity	✔
• Nature of the perturbations: ★ TT peaks at same scales as EE troughs ➡ Adiabatic perturbations	✔
• Spectral index $P(k) \propto k^{n_s-1}$ ★ Planck TT + WMAP Pol + High ℓ + BAO $n_s = 0.9608 \pm 0.0054 \; (7.2\sigma \text{ from } 1)$ ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No hint for non-Gaussianity (despite impressive efforts)	✔
• Tensor perturbations of the metric	?

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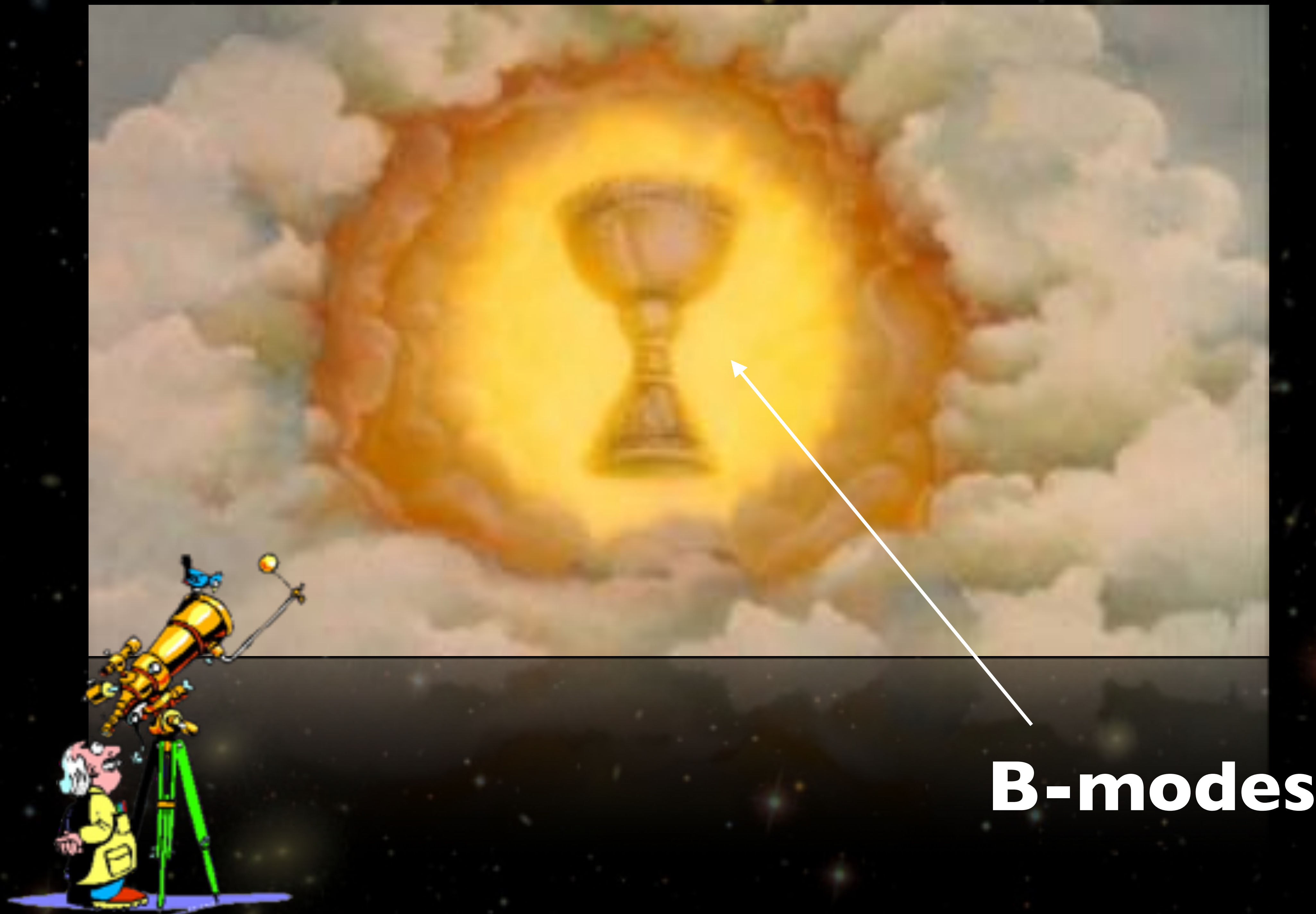
Major message



Part 2:
The difficult quest for primordial B-modes

[Monty Python - Holy Grail]

Difficulties in the Quest

- Lensing signal (by LSS and ν !)

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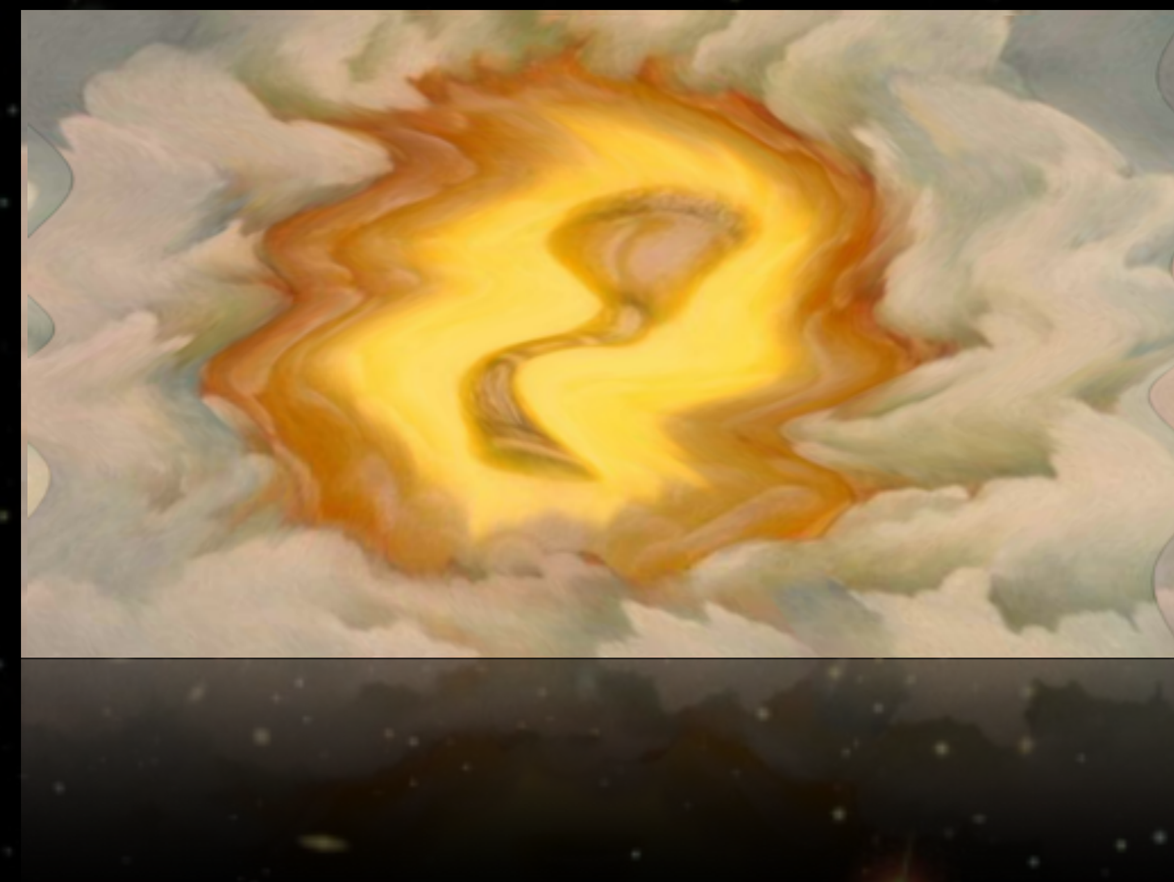
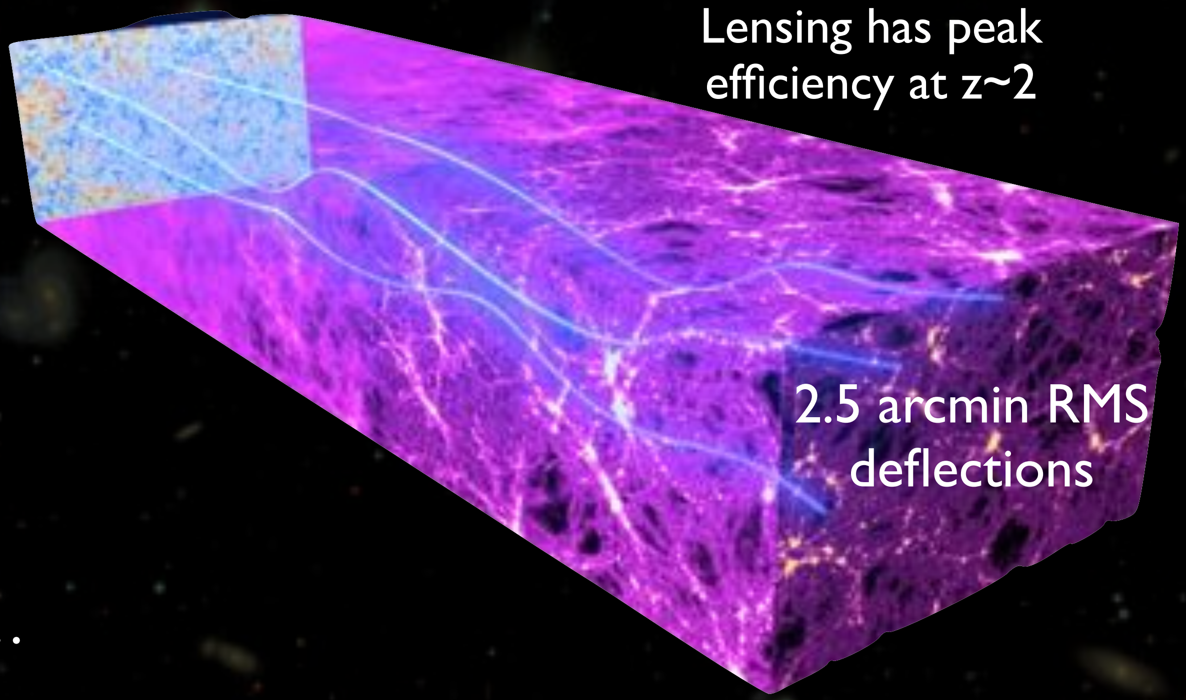


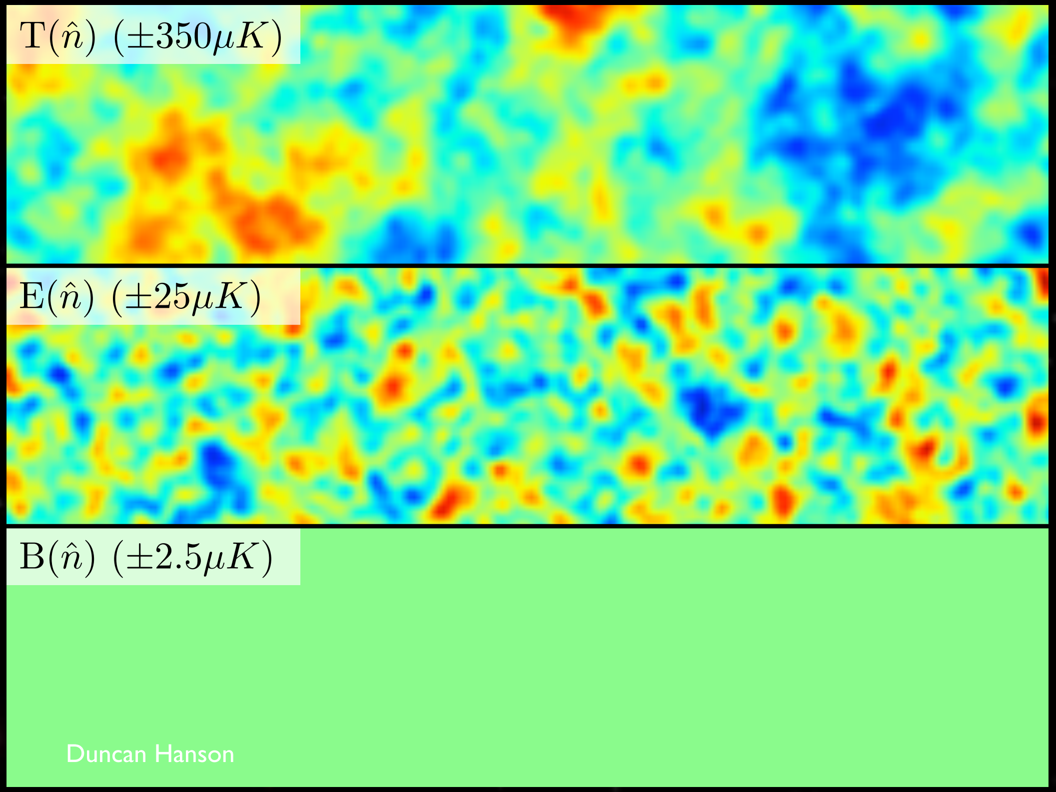
CMB Lensing by large scale structure

- Deflection field:
  - ★ Gradient of redshift-integral of LSS
- Lensing adds information
  - ★ lifts geometric CMB degeneracies
    - Curvature, sub-eV neutrino masses, Dark Energy…
- Effect on Stokes parameters

$$\begin{aligned}\tilde{T}(\vec{x}) &= T(\vec{x}+\vec{\nabla}\phi) \\ (\tilde{Q}\pm i\tilde{U})(\vec{x}) &= (\tilde{Q}\pm i\tilde{U})(\vec{x}+\vec{\nabla}\phi)\end{aligned}$$

  - Smoothes the CMB spectra
  - Adds power at arc minutes scales on TT, TE and EE
  - Generates « lensing B-modes » from E-modes…





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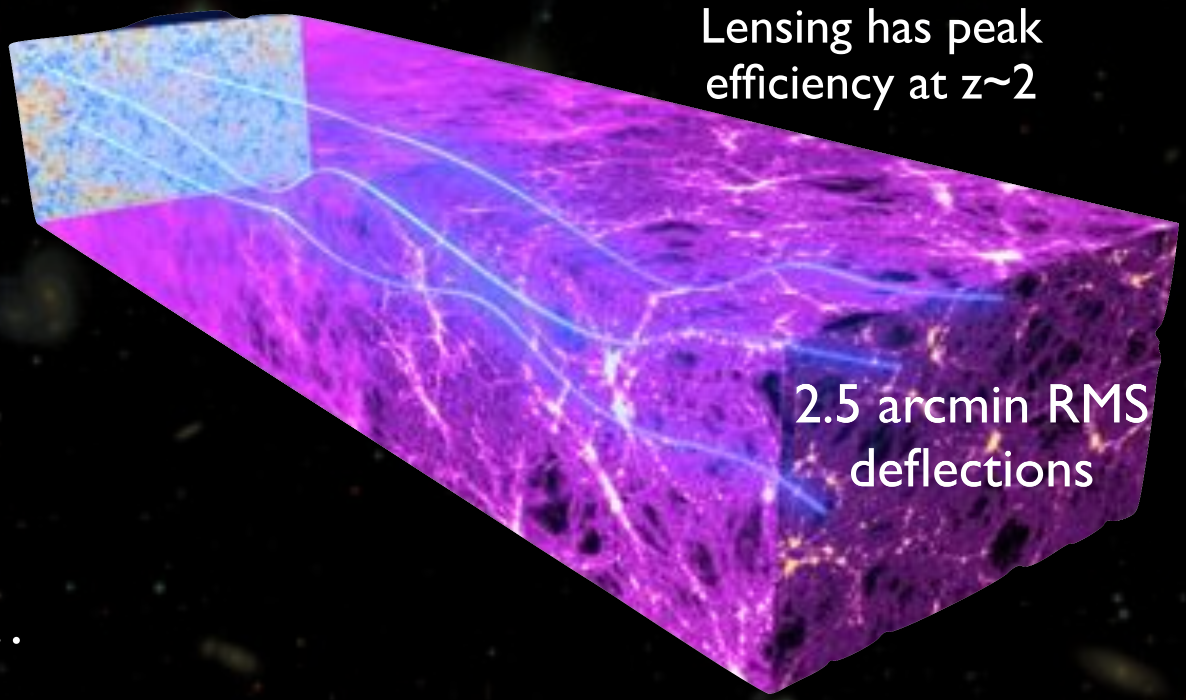

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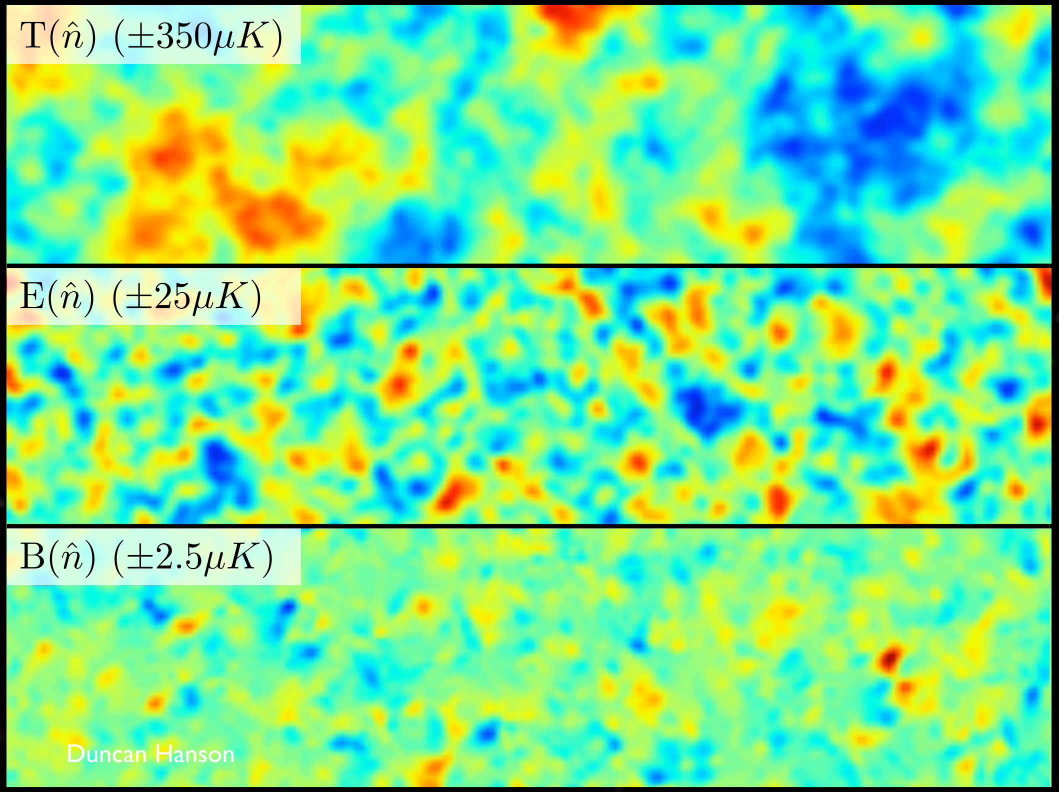
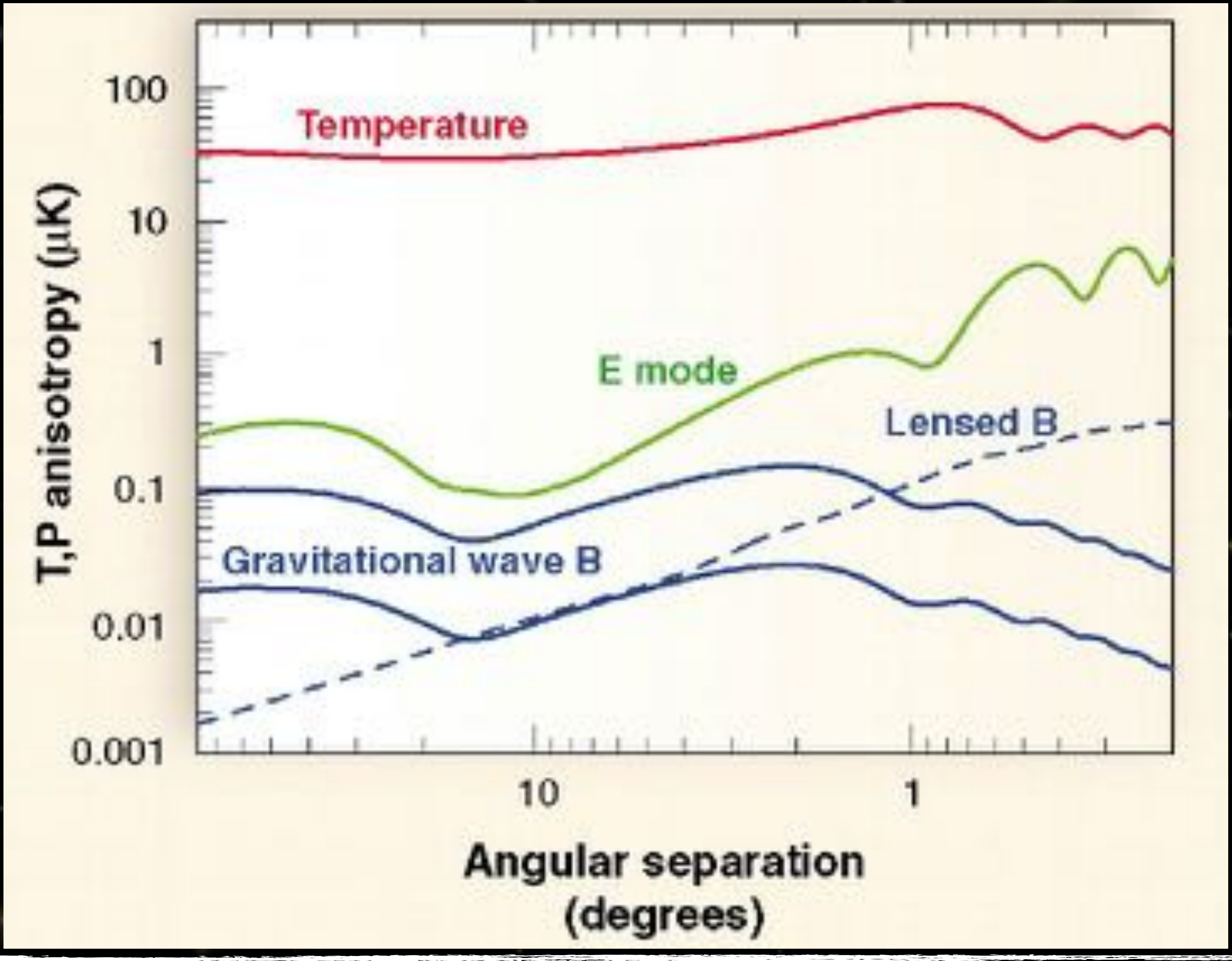


Resulting Spectrum



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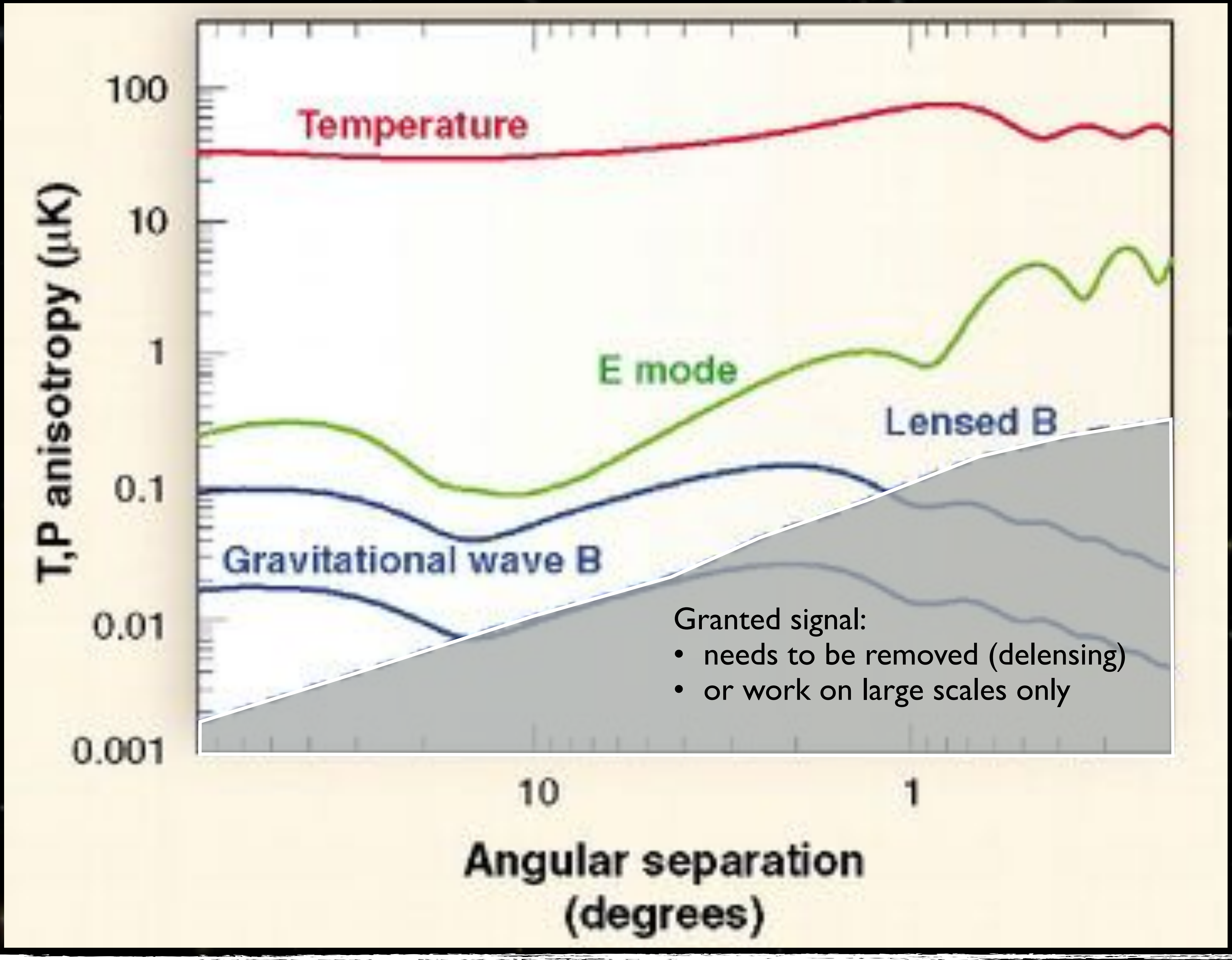

Precious Cosmological Information in lensing ! (ν masses, …)

Difficulties in the Quest

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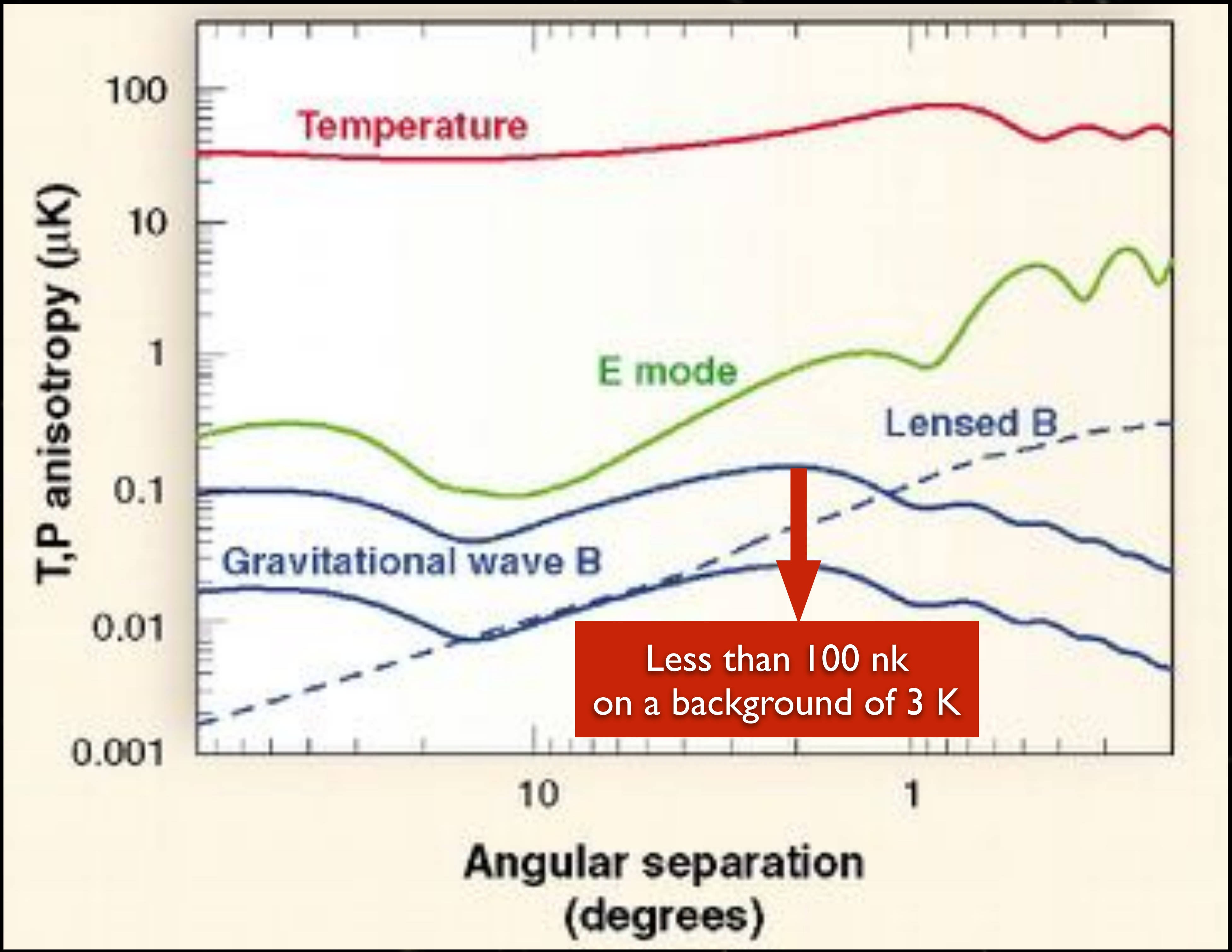
B-modes are **very** weak…



Reference Sensitivity ~ late-1990's

Sensitivity x10 ~ mid-2000's

Sensitivity x 100 ~ 2014

Sensitivity x 1000 ~ now ?

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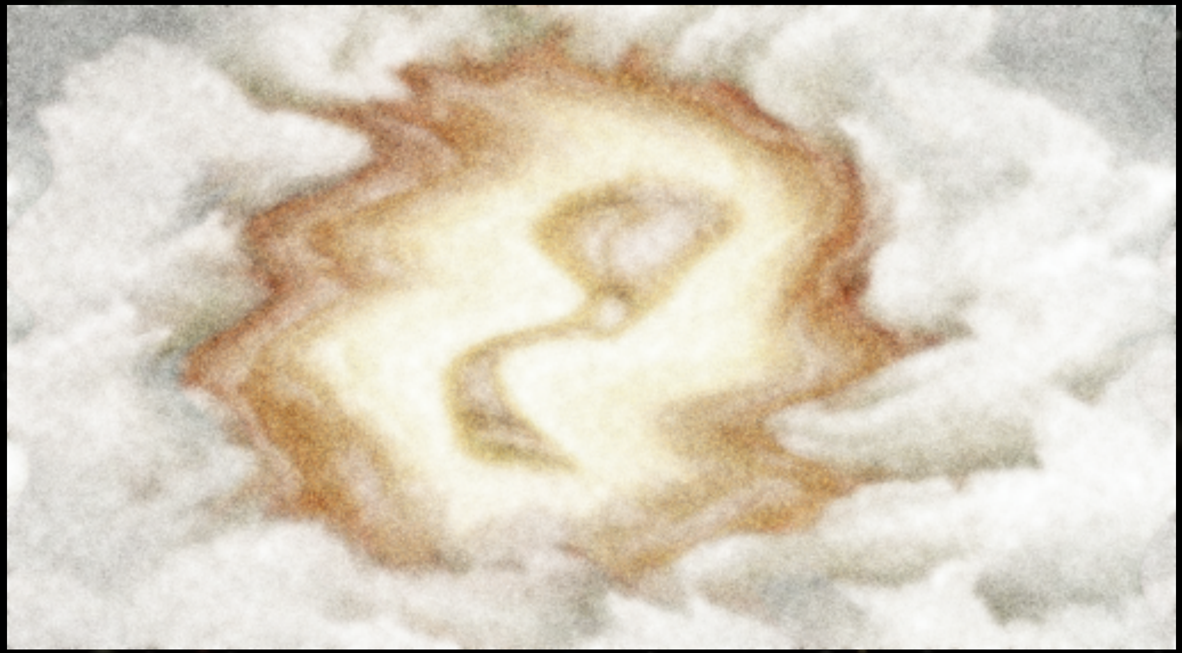

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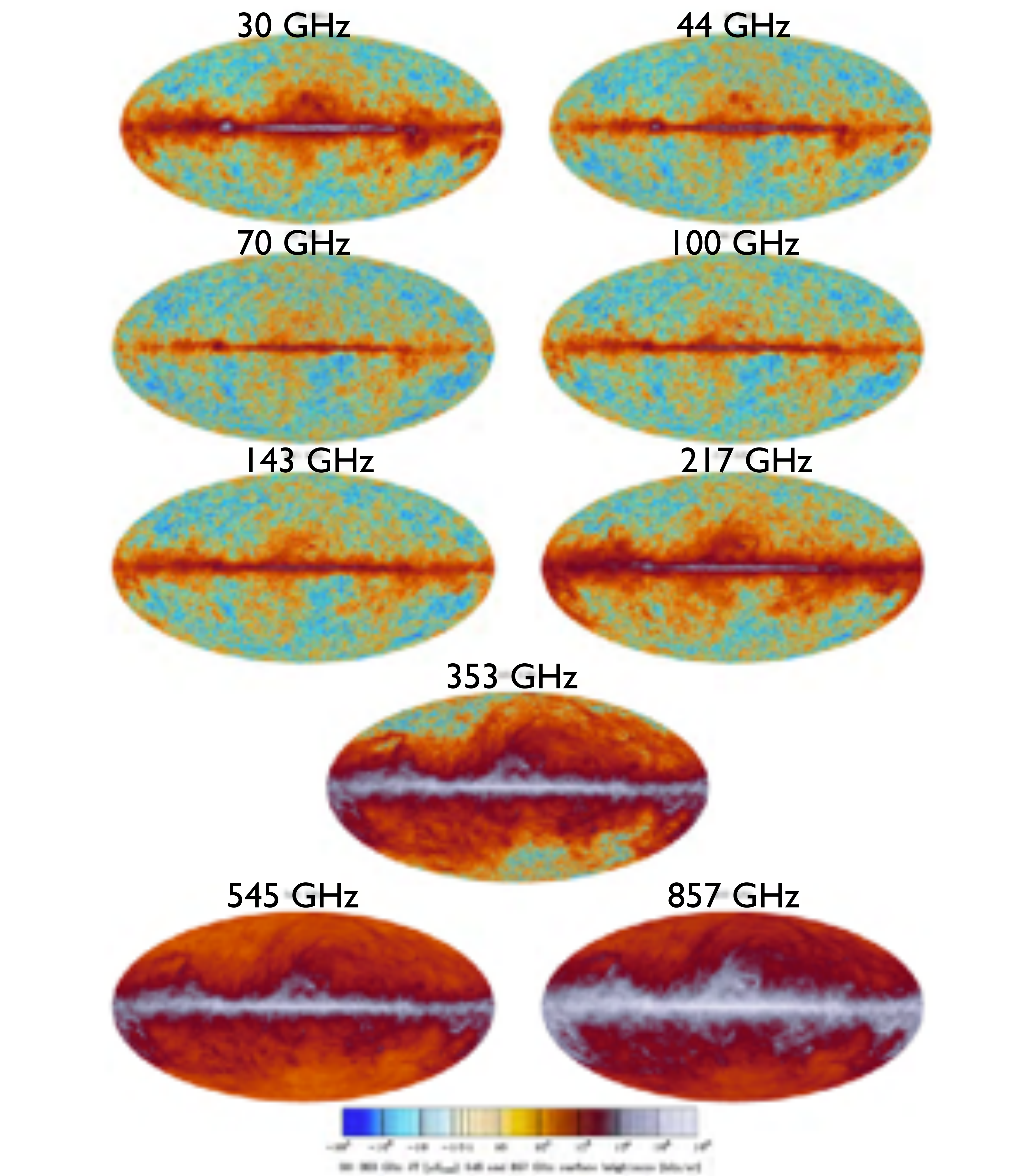
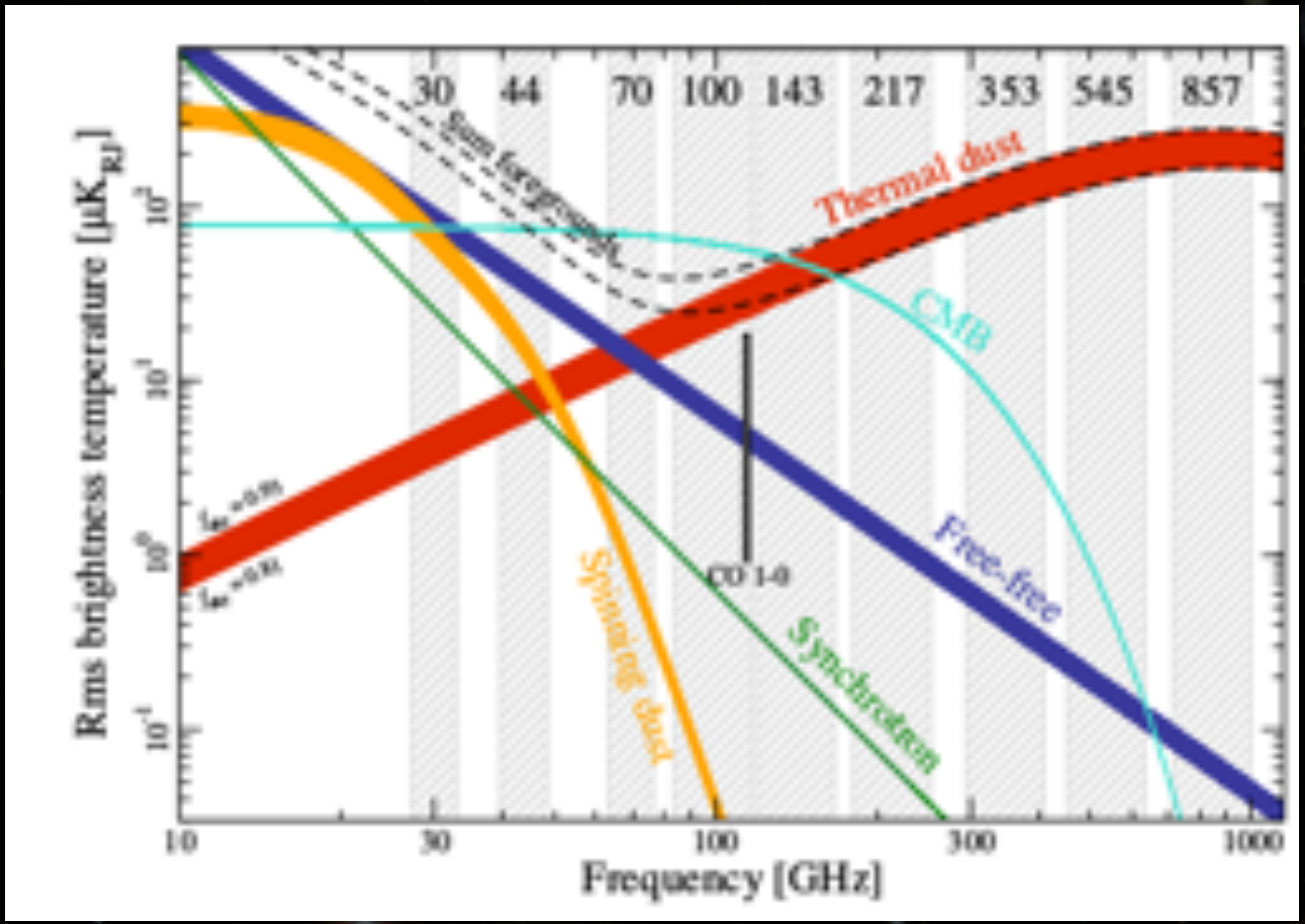
Foregrounds

Temperature Maps from Planck at various frequencies



Foregrounds

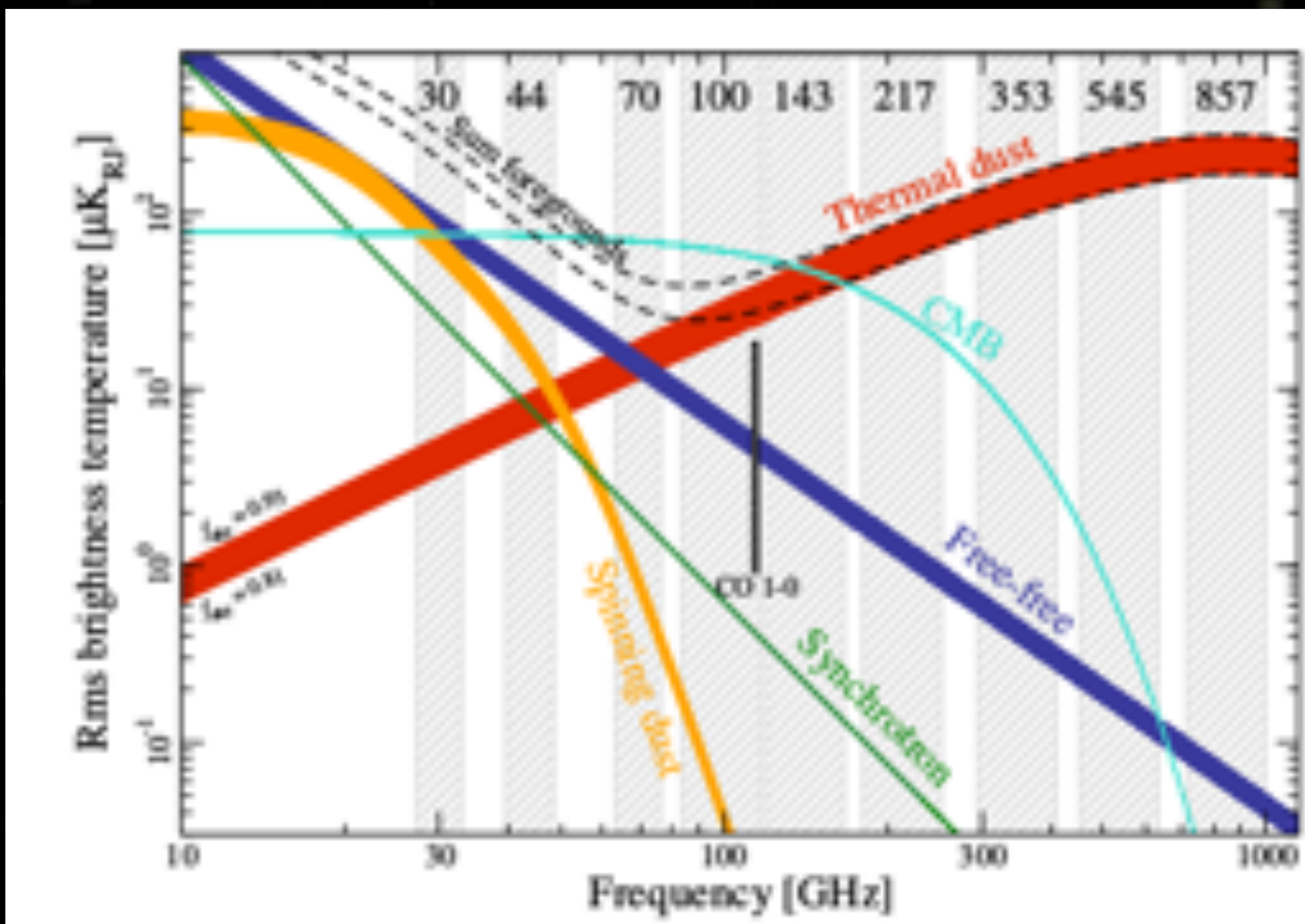
Temperature



[Planck]

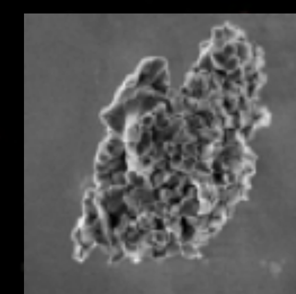
Foregrounds

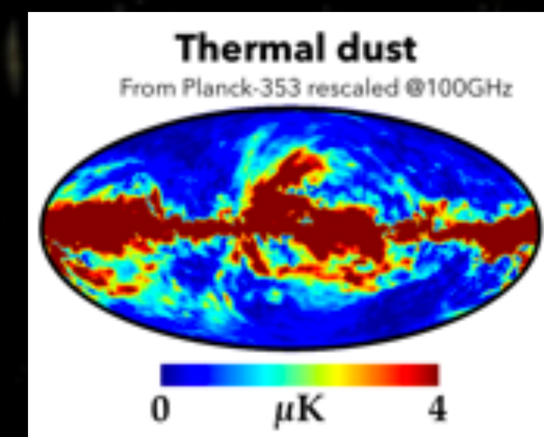
Temperature



[Planck]

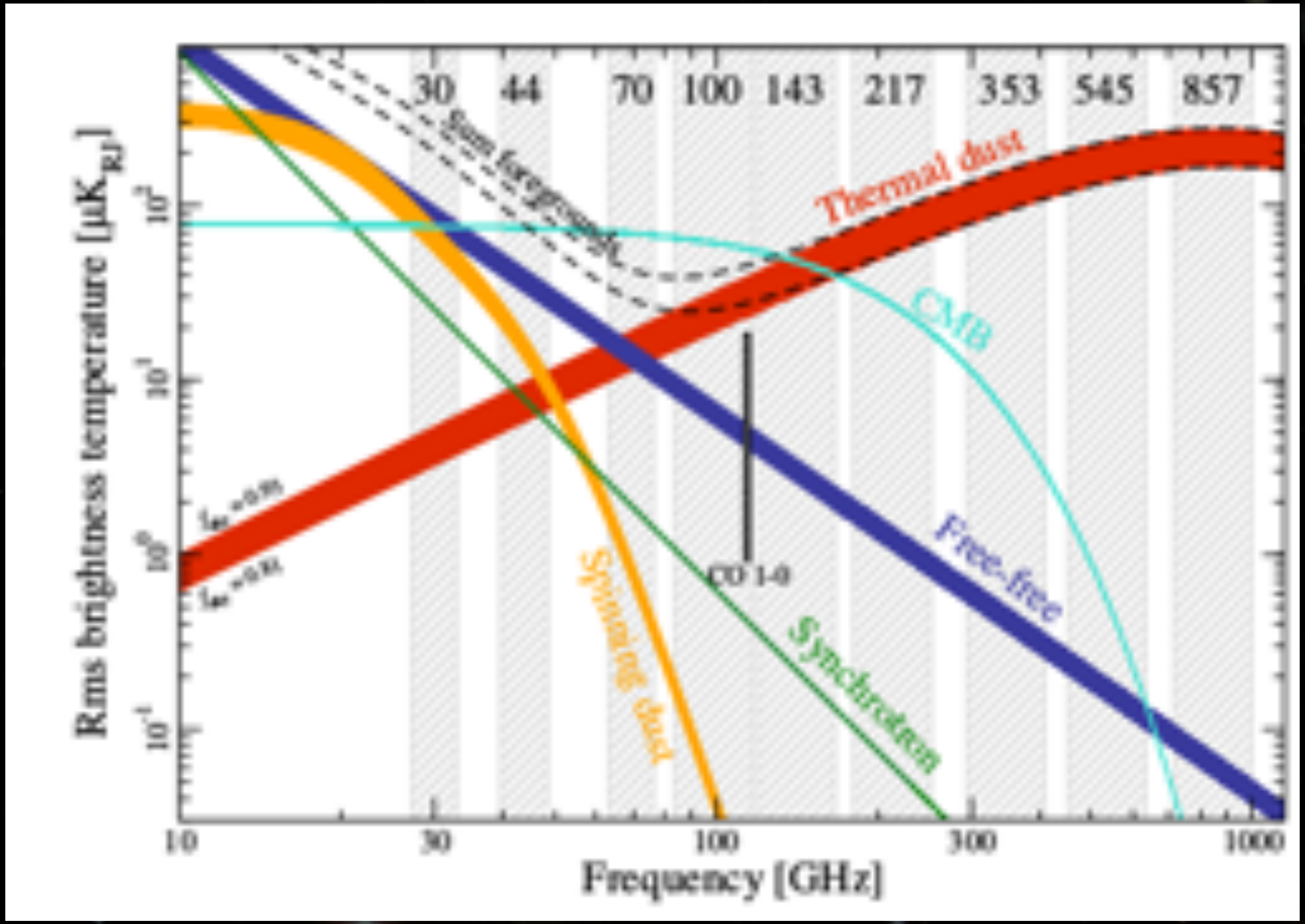
Dust grains





Foregrounds

Temperature



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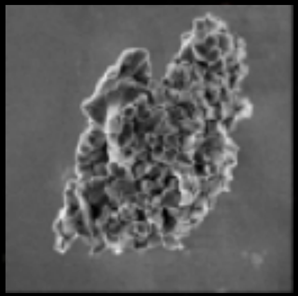
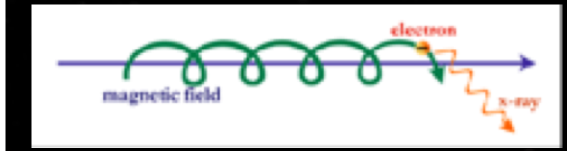
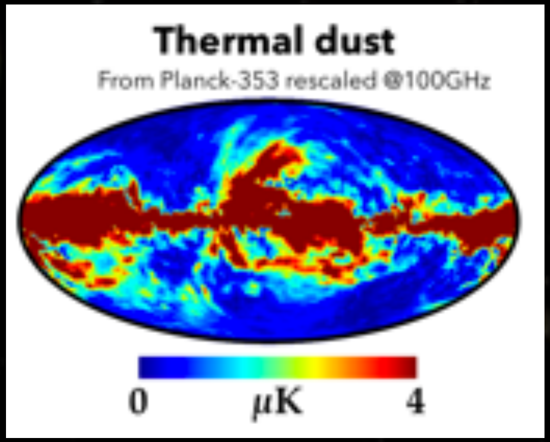
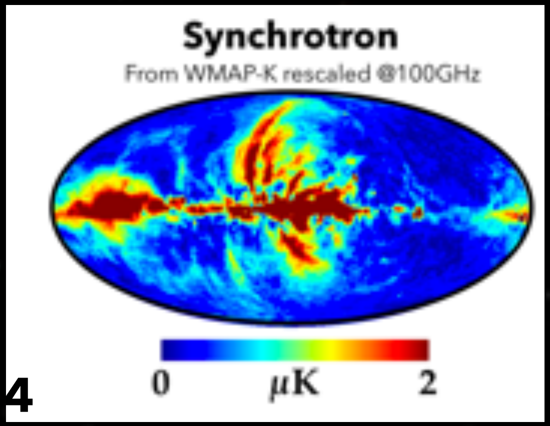


Synchrotron/FreeFree



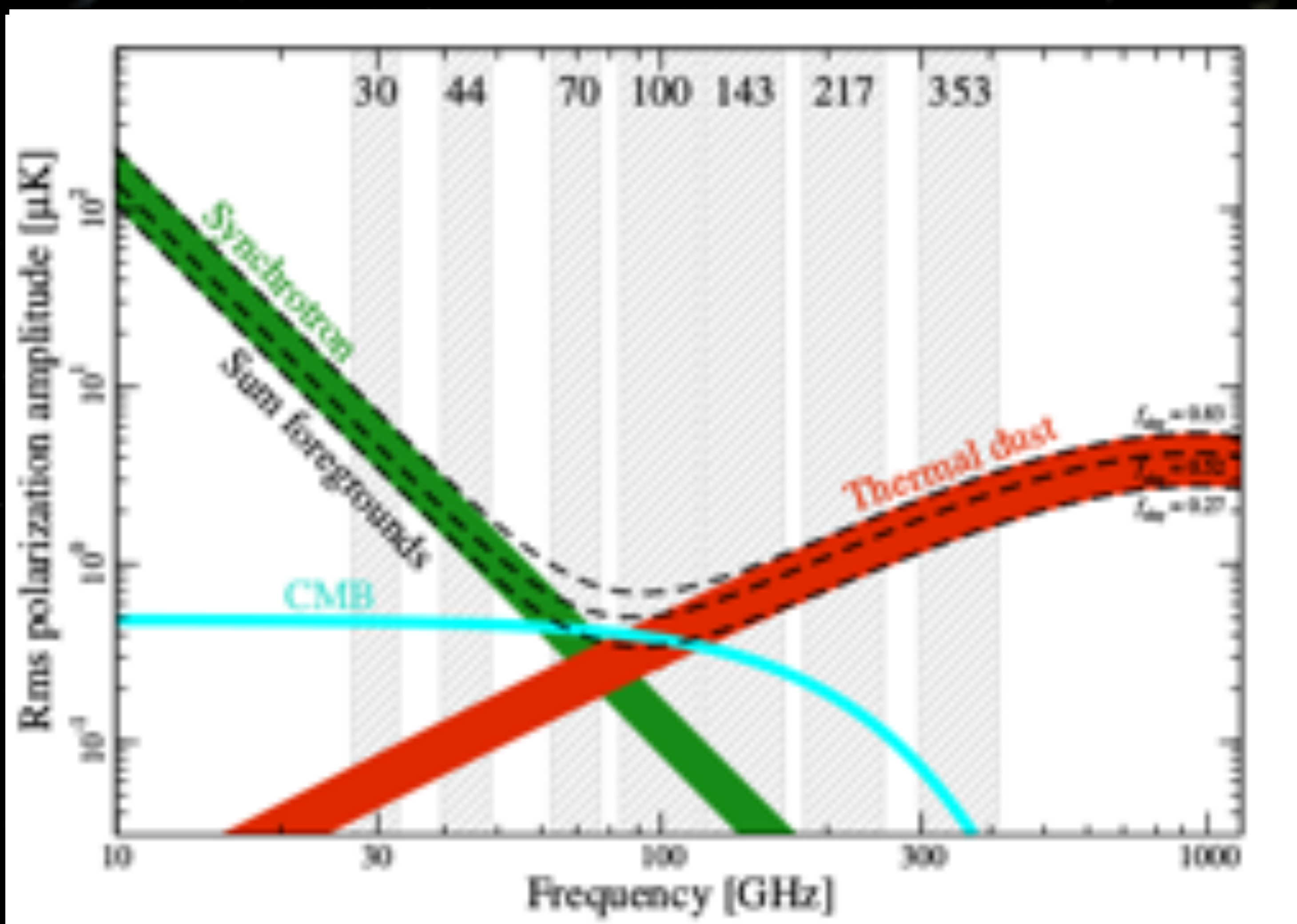




[Courtesy N. Krachmalnicoff]

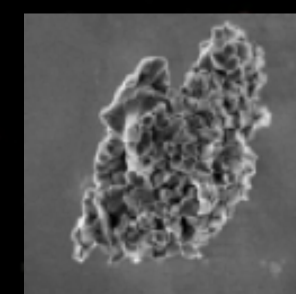
Foregrounds

Polarization



[Planck]

Dust grains



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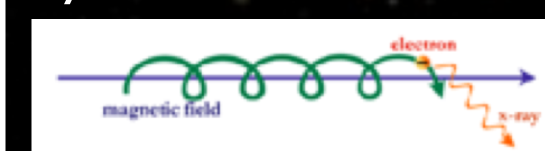
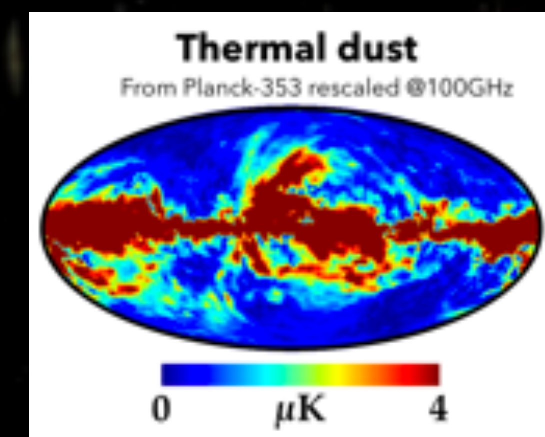
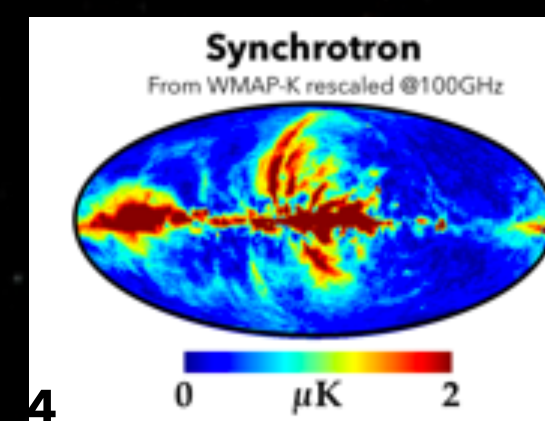






4

[Courtesy N. Krachmalnicoff]

There is no « clean » region in the sky in Polarization 😱

Foreground Separation

Sky Model:

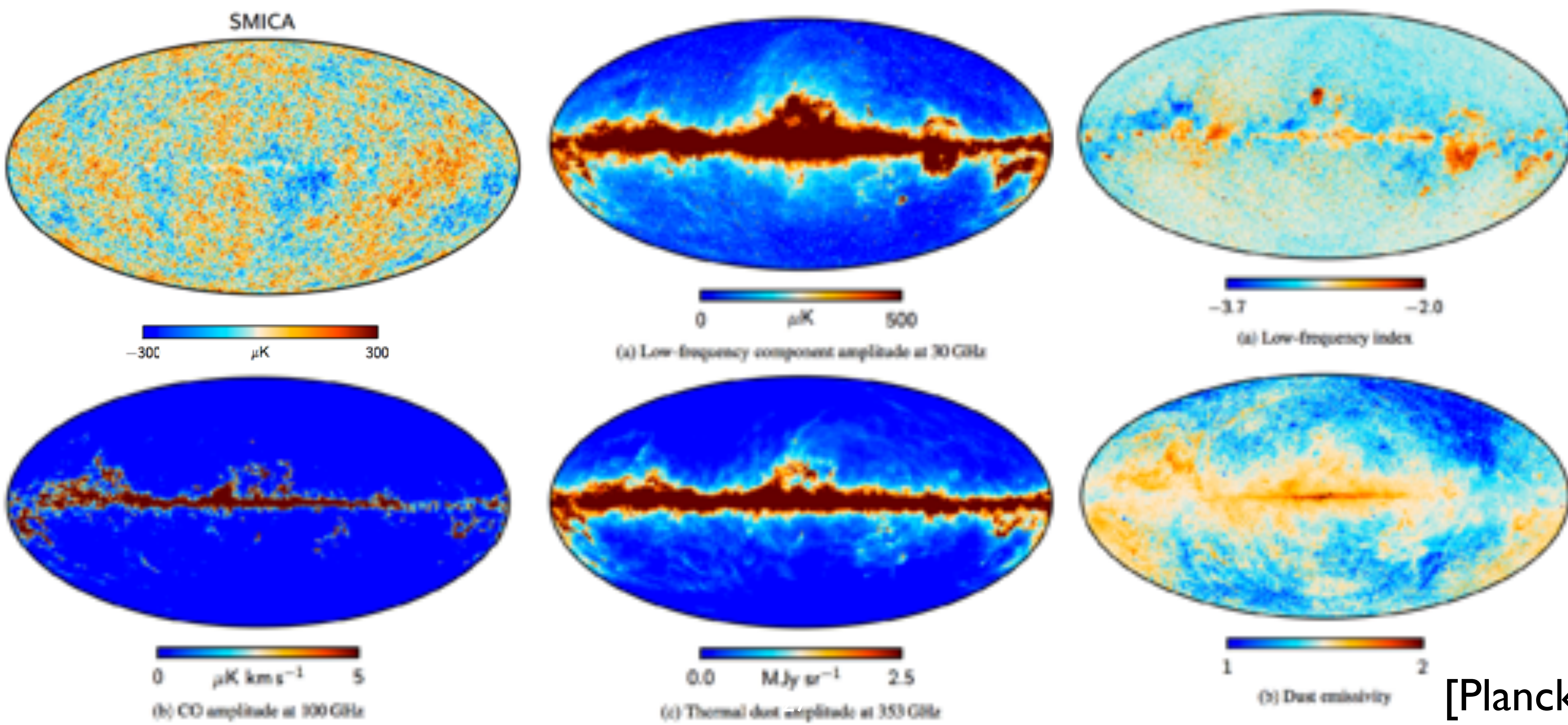
$$\vec{x}_\nu = \vec{x}_{CMB} + \vec{F}_\nu + \vec{n}_\nu$$

With $\vec{F}_\nu = A_\nu \vec{F}$

Solution:

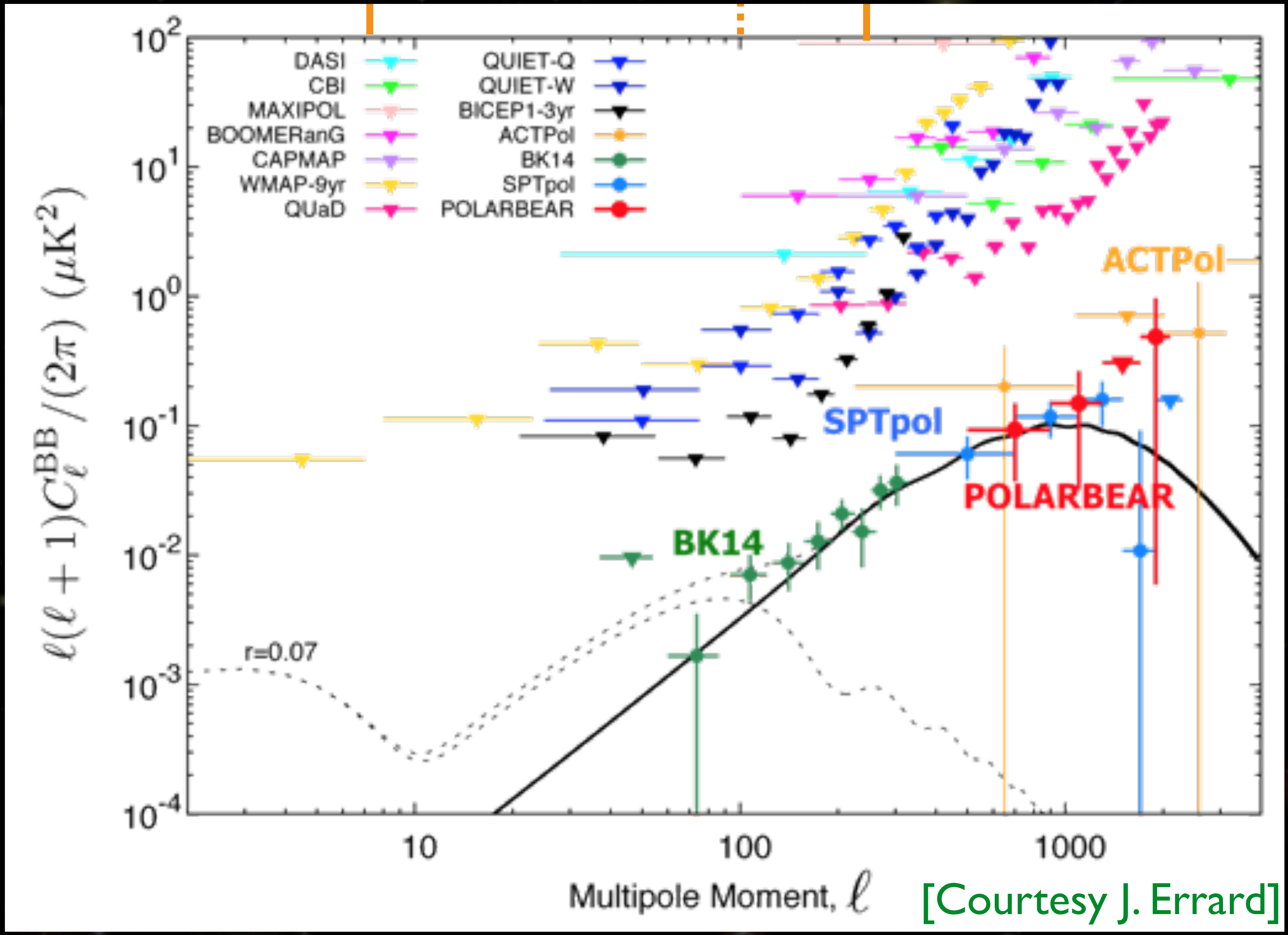
$$\hat{\vec{x}}_{CMB} = \sum_\nu w_\nu \vec{x}_\nu$$

NB: this is simple I.L.C., there are more complex algorithms



[Planck]

Recent results !!



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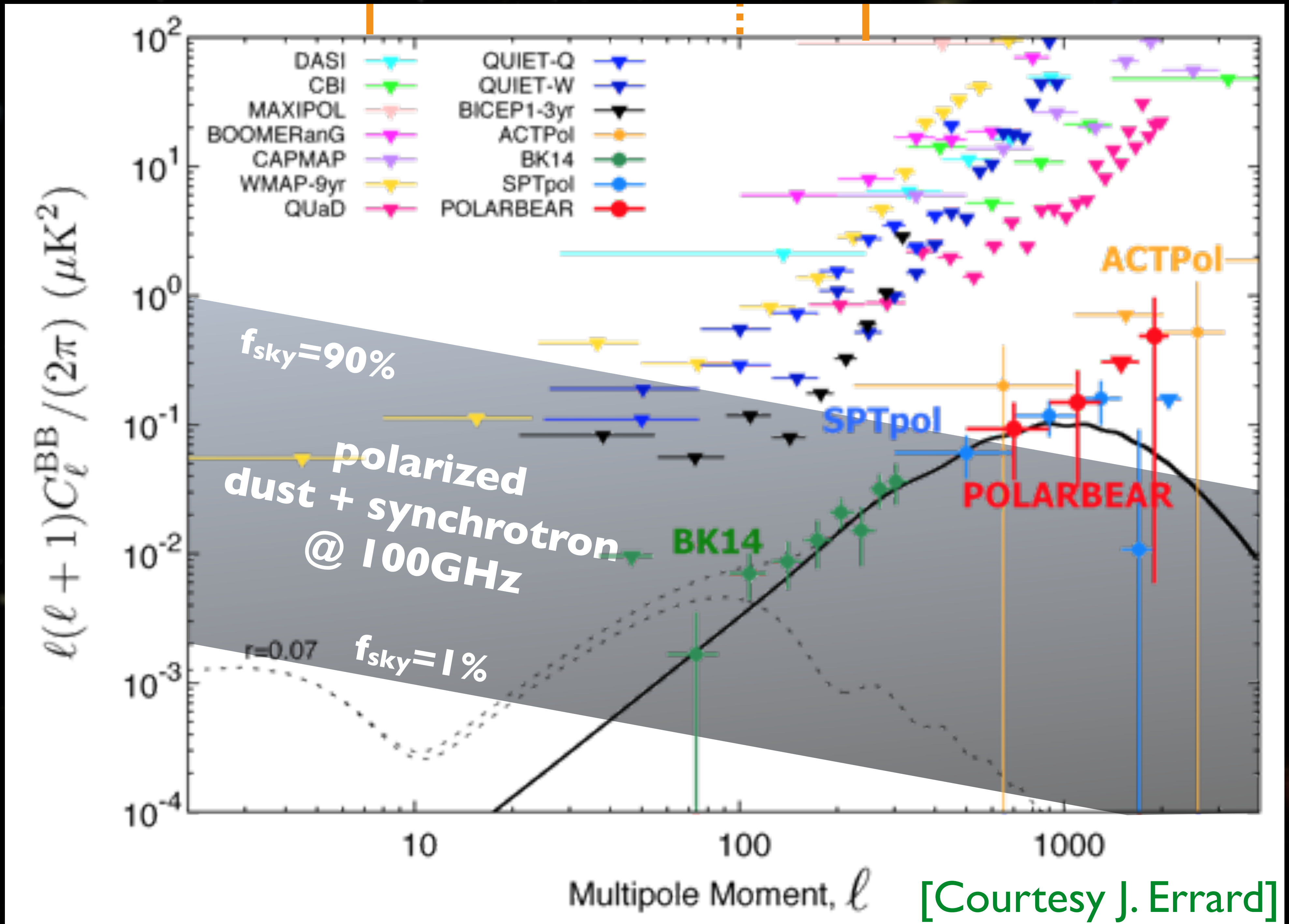

[Courtesy J. Errard]

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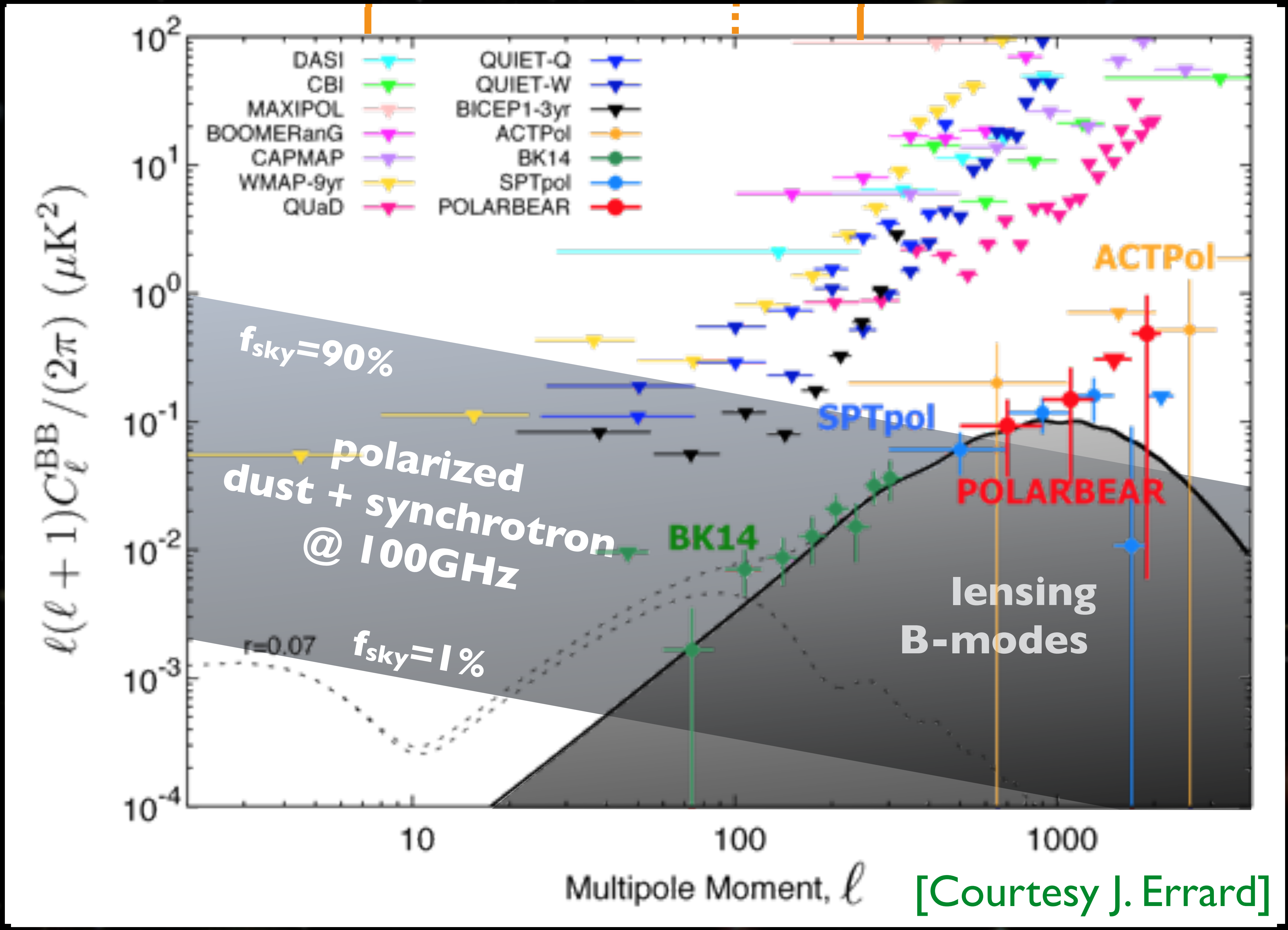

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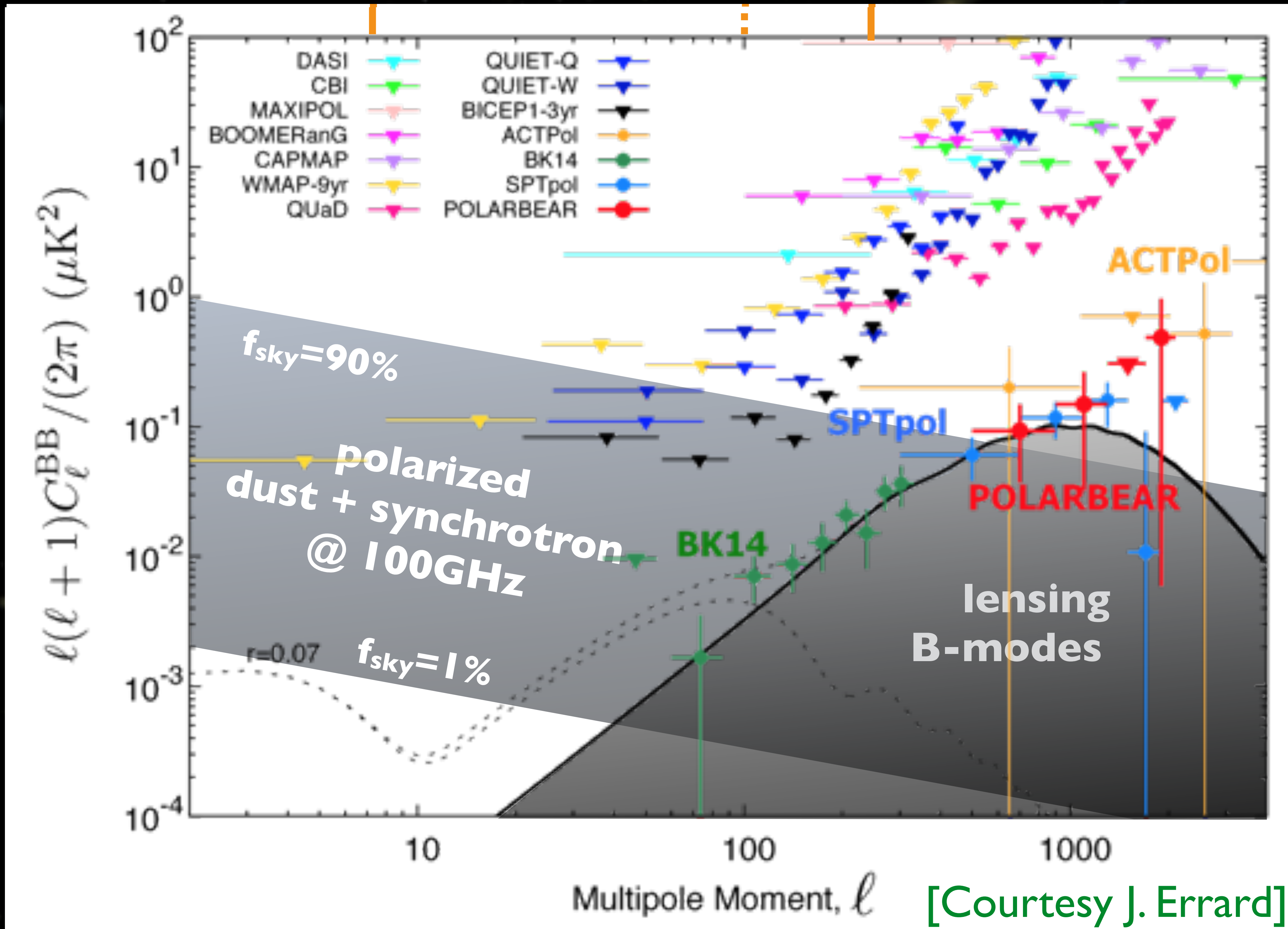
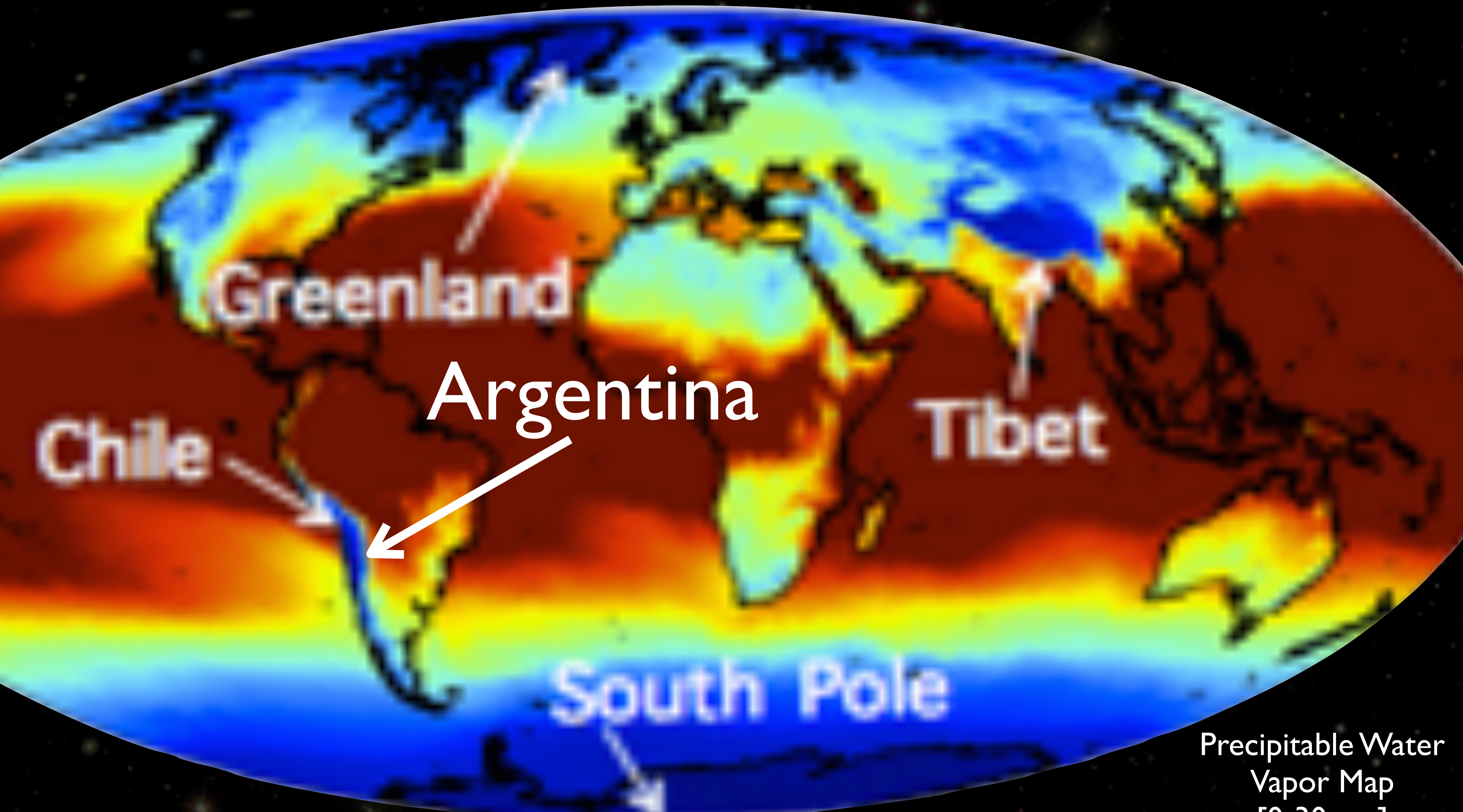


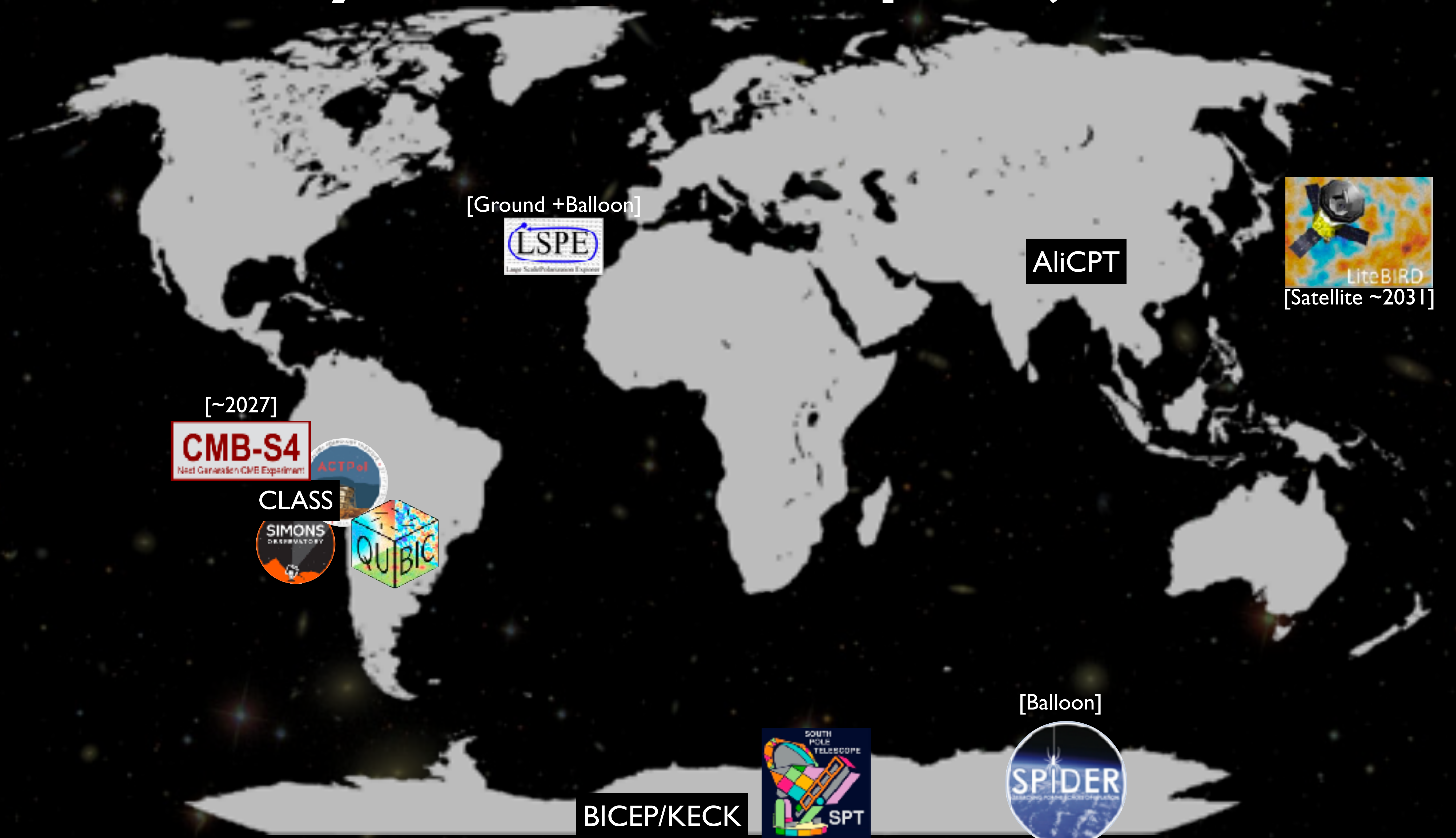
No primordial B-modes yet… Go back to work !

One needs a dry and clean sky !



Precipitable Water Vapor Map [0-30mm]

Many B-modes projects !



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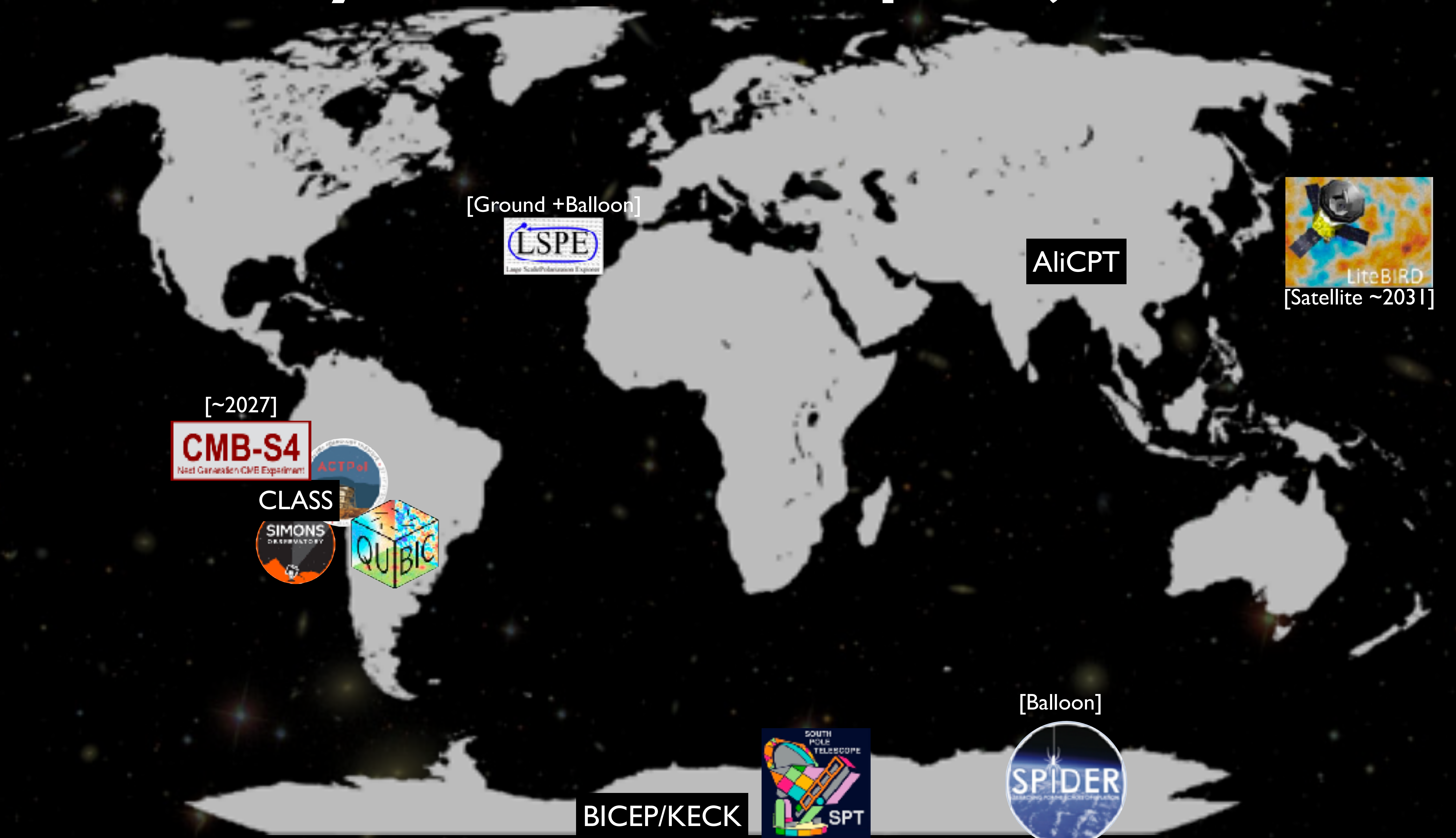


Part 3: QUBIC overview, status and forecasts

Dirección: 12 De octubre 675, Salta Capital, Argentina

QUBIC

HEALTH CLUB

[https://www.qubicsalta.com.ar/]

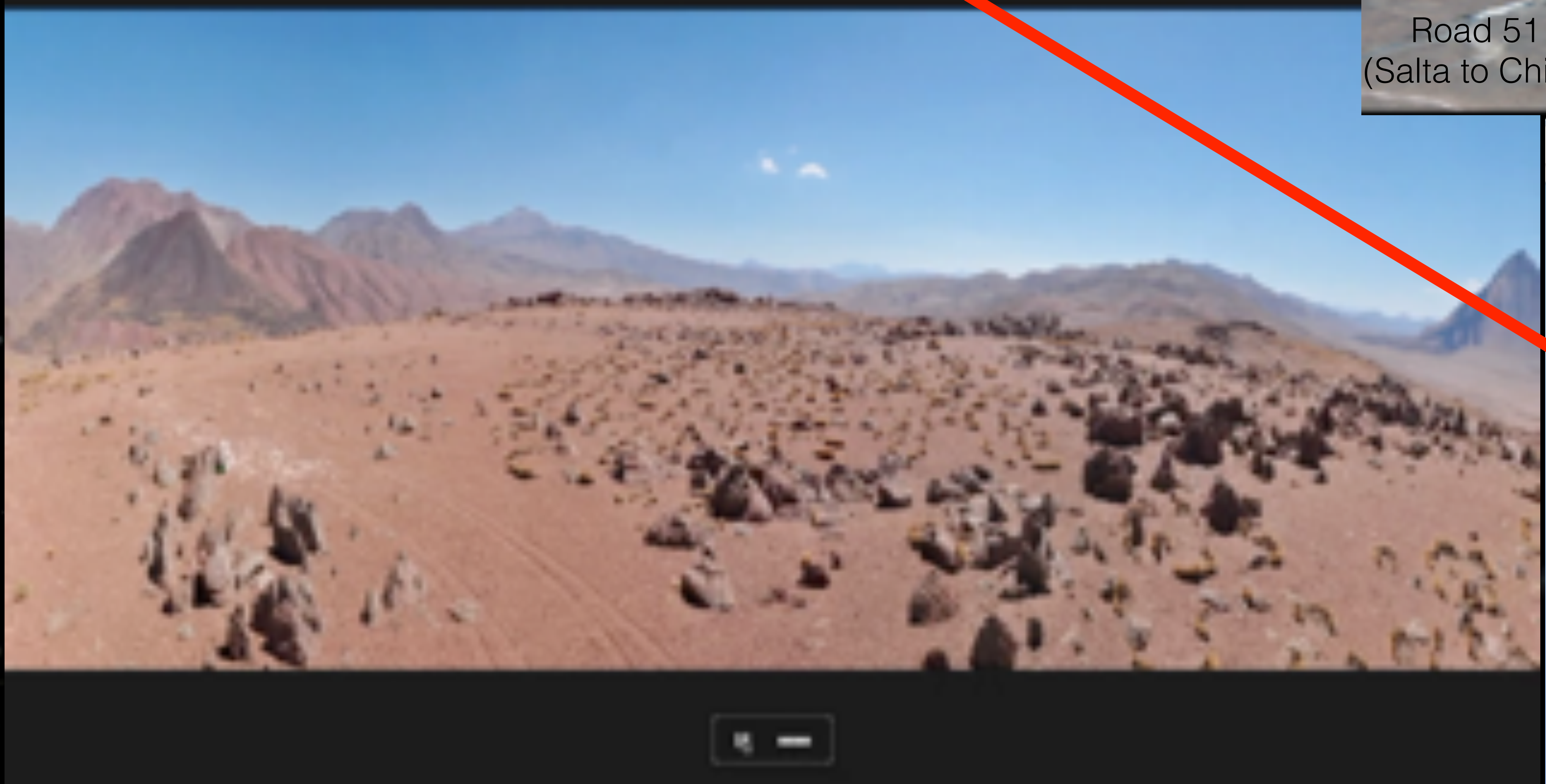
QUBIC

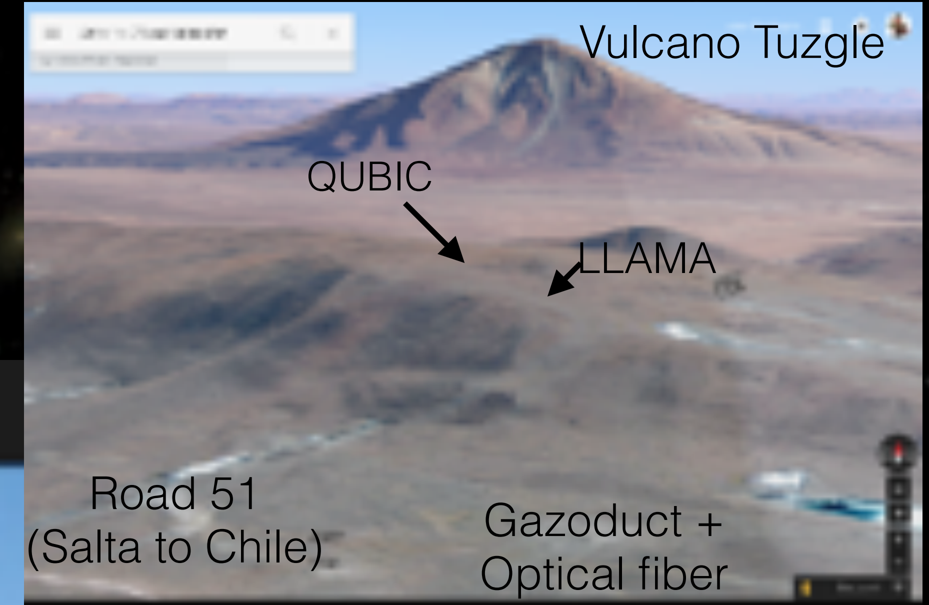
a Q&U Bolometric Interferometer for Cosmology

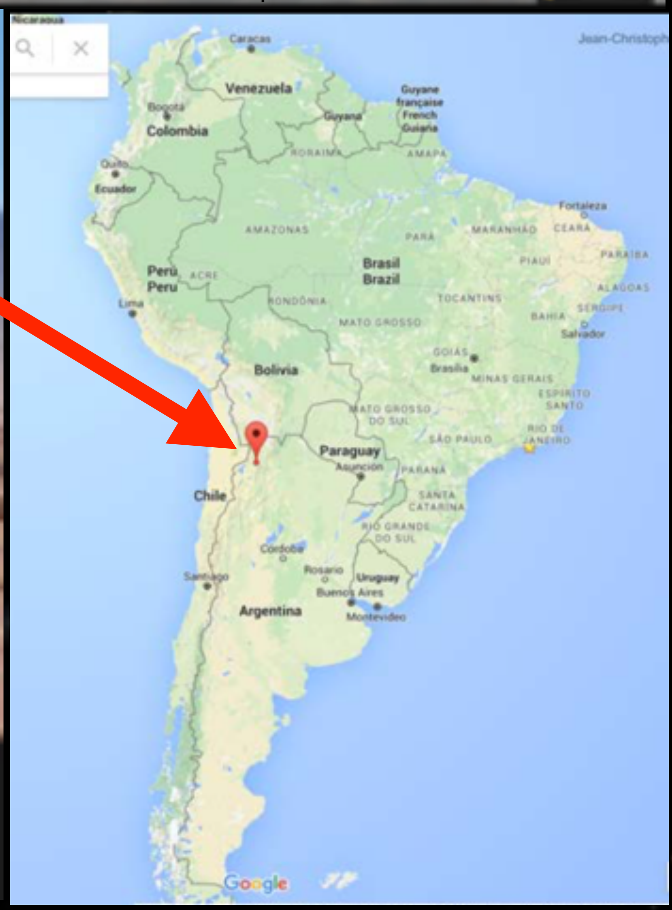
130 Collaborators
22 laboratories
6 countries

APC Paris, France
C2N Orsay, France
CSNSM Orsay, France
IAS 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
Comisión Nacional de Energía Atómica, 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

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

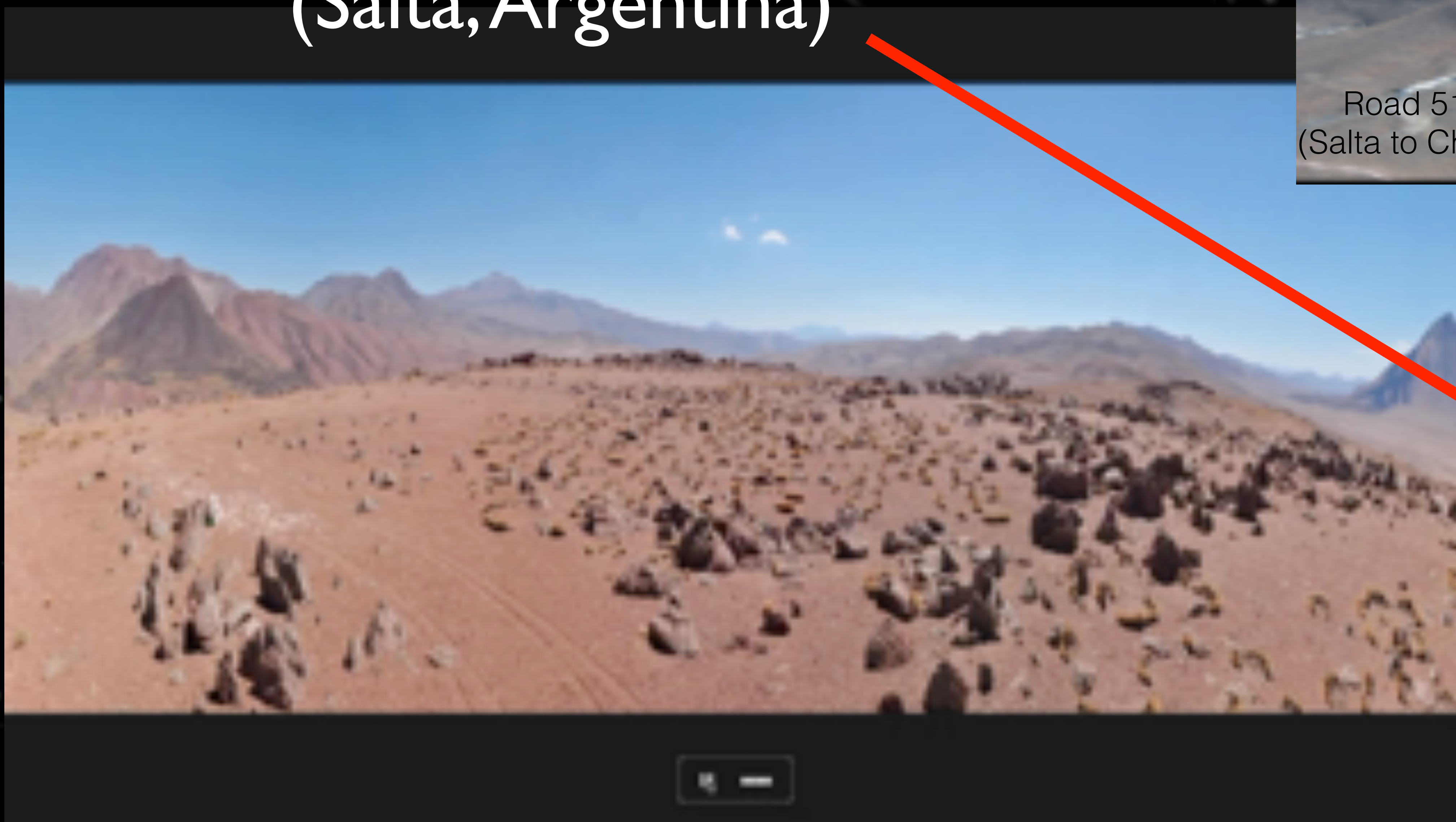


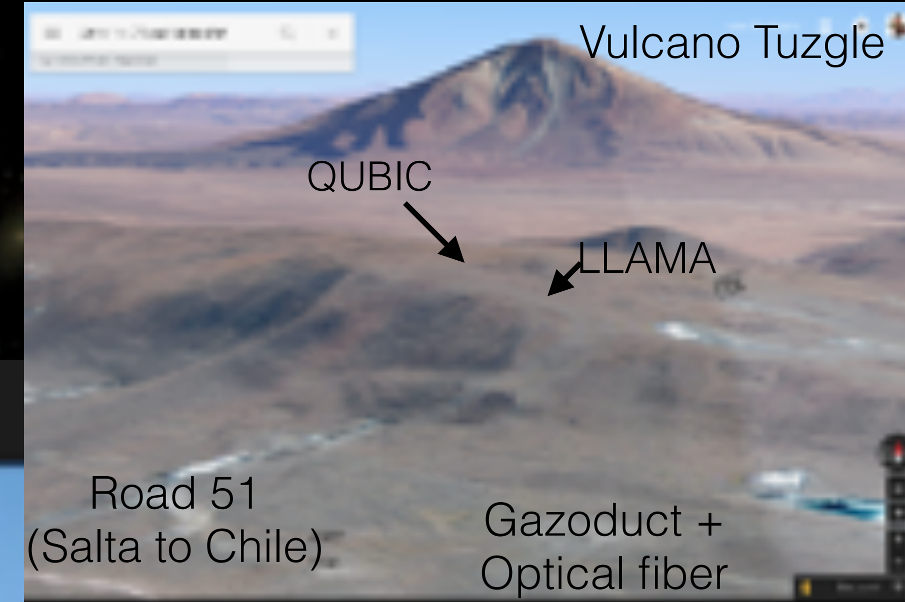




- 5000m a.s.l. - Clean and dry sky
- Next to LLAMA 12m radio antenna
- Access road built, works started on site

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





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Primordial B-modes with QUBIC

Very weak signal

- **Focal Plane:**
  - 2048 TES with NEP ~ 4×10^{-17} W.Hz$^{-1/2}$
  - 128:1 SQUIDs+ASIC Mux Readout
  - **End-To-End Sims. show σ(r)=0.01 with 2 years**

Instrumental systematics

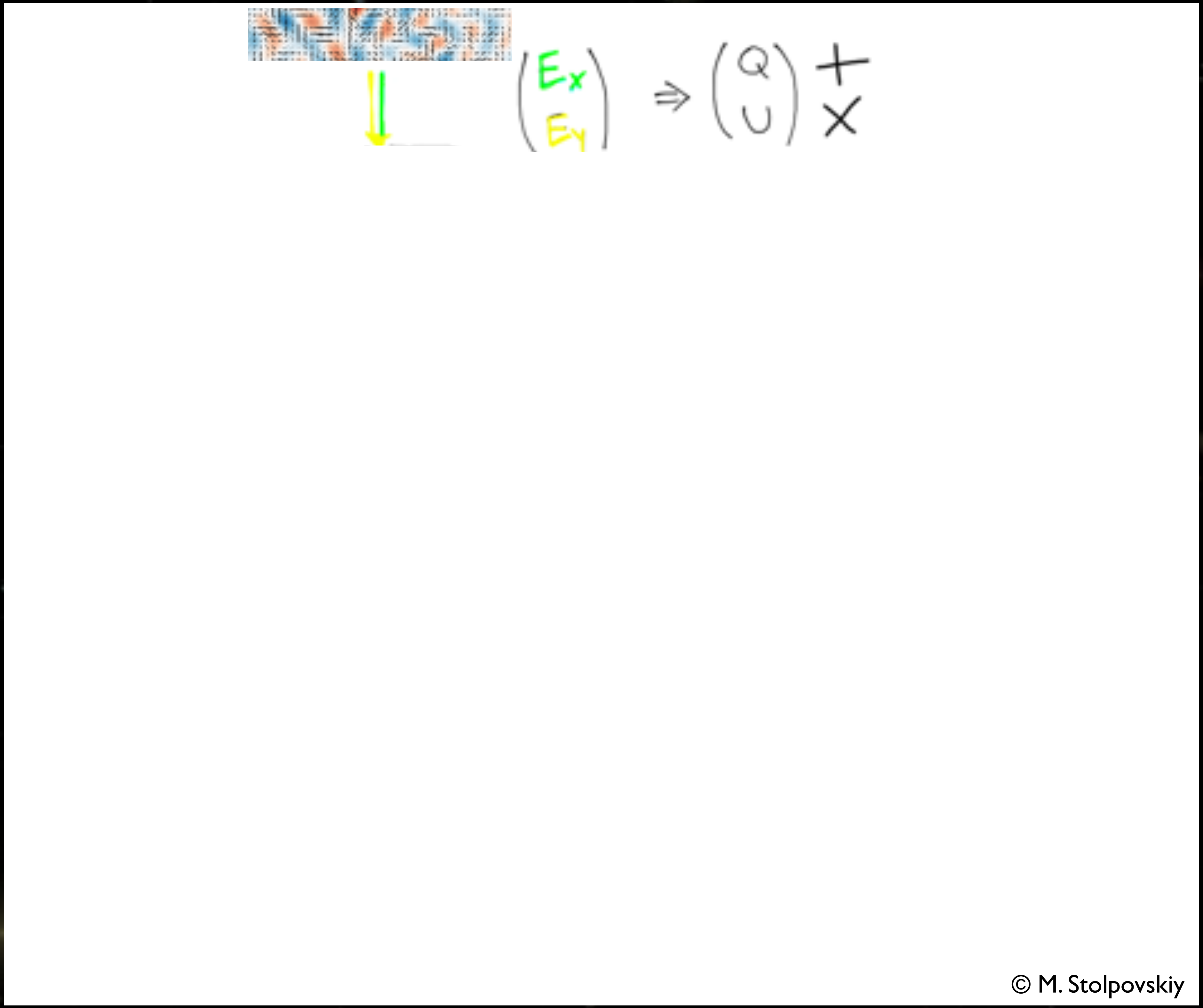
- **Cryogenic Optics after HWP and Polarizer + Full power detectors**
  - ➢ Instrumental X-Polarization has no effect

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

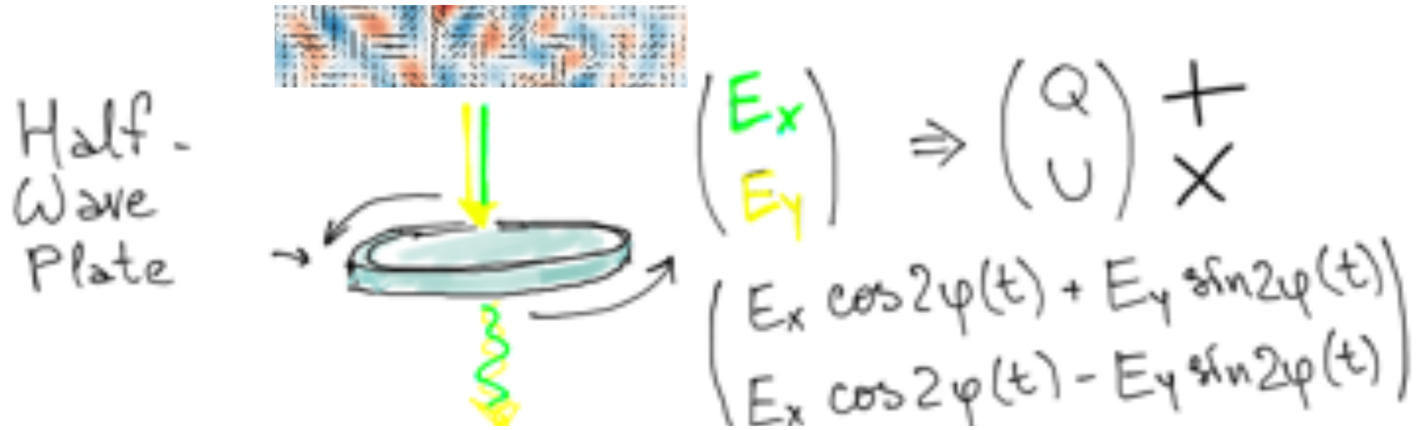
Polarized foregrounds

- **Two wide bands: 150 and 220 GHz**
  - 1 focal plane for each channel
- **Spectro-Imaging allows to form up to 5 sub-bands for each**
  - Increased Frequency Resolution
  - More Complex dust models can be constrained « locally »

QUBIC concept: Quasi optical correlator



QUBIC concept: Quasi optical correlator



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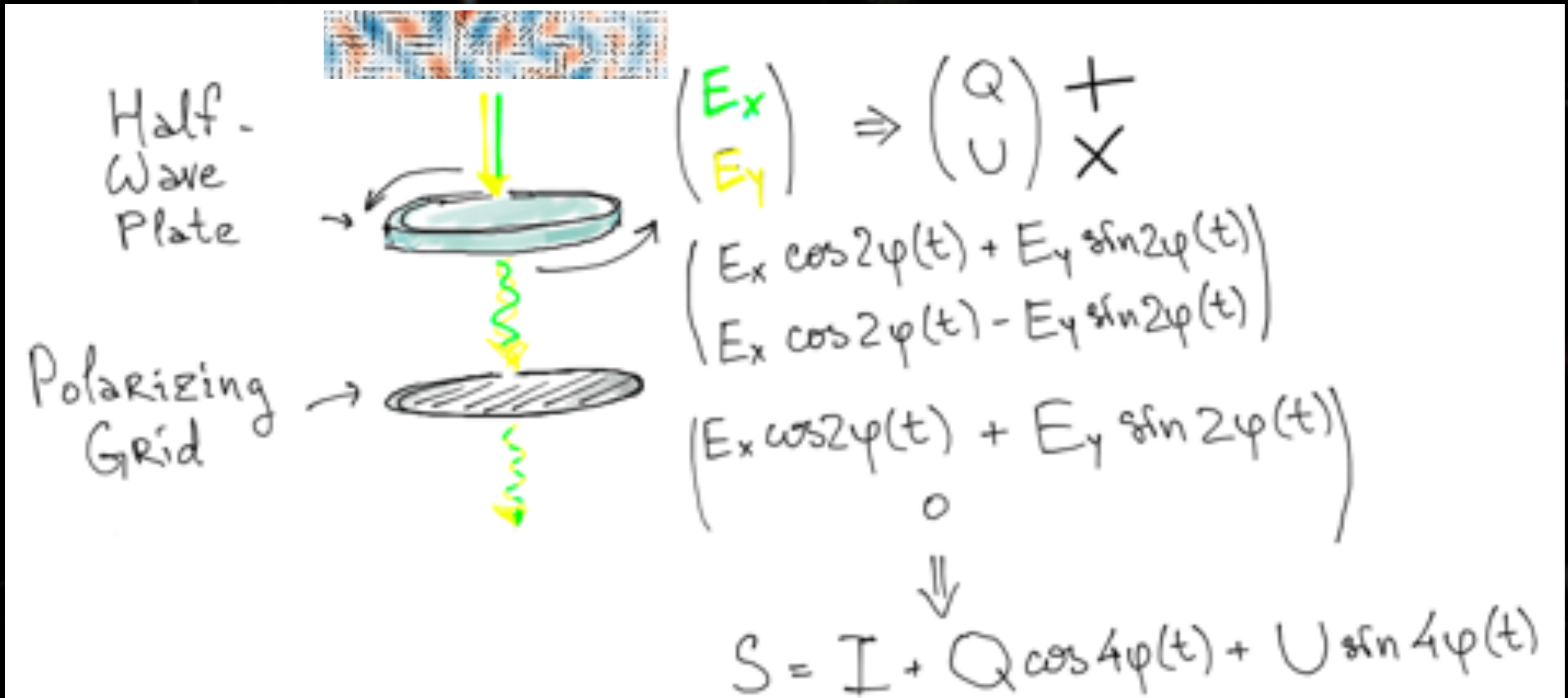

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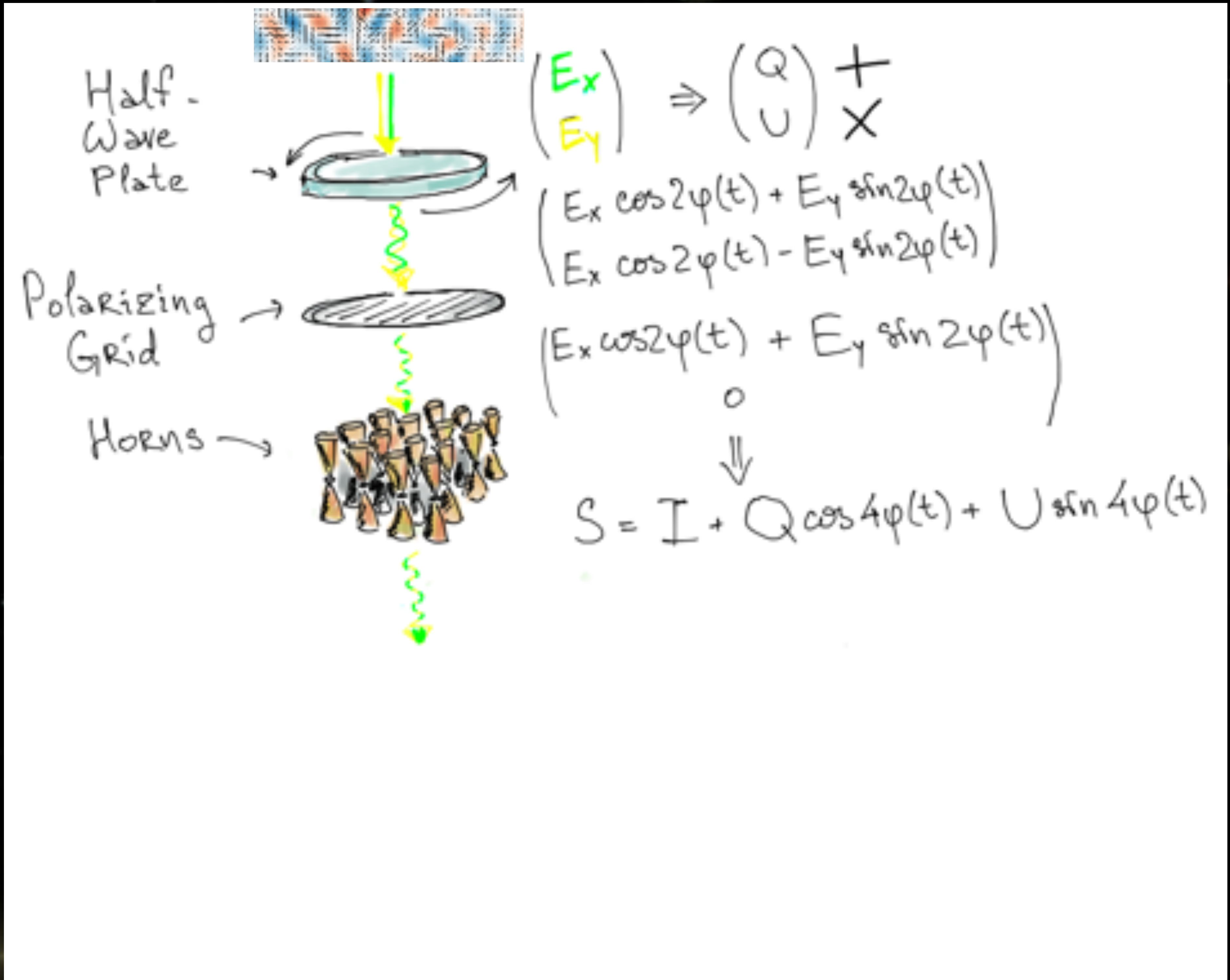

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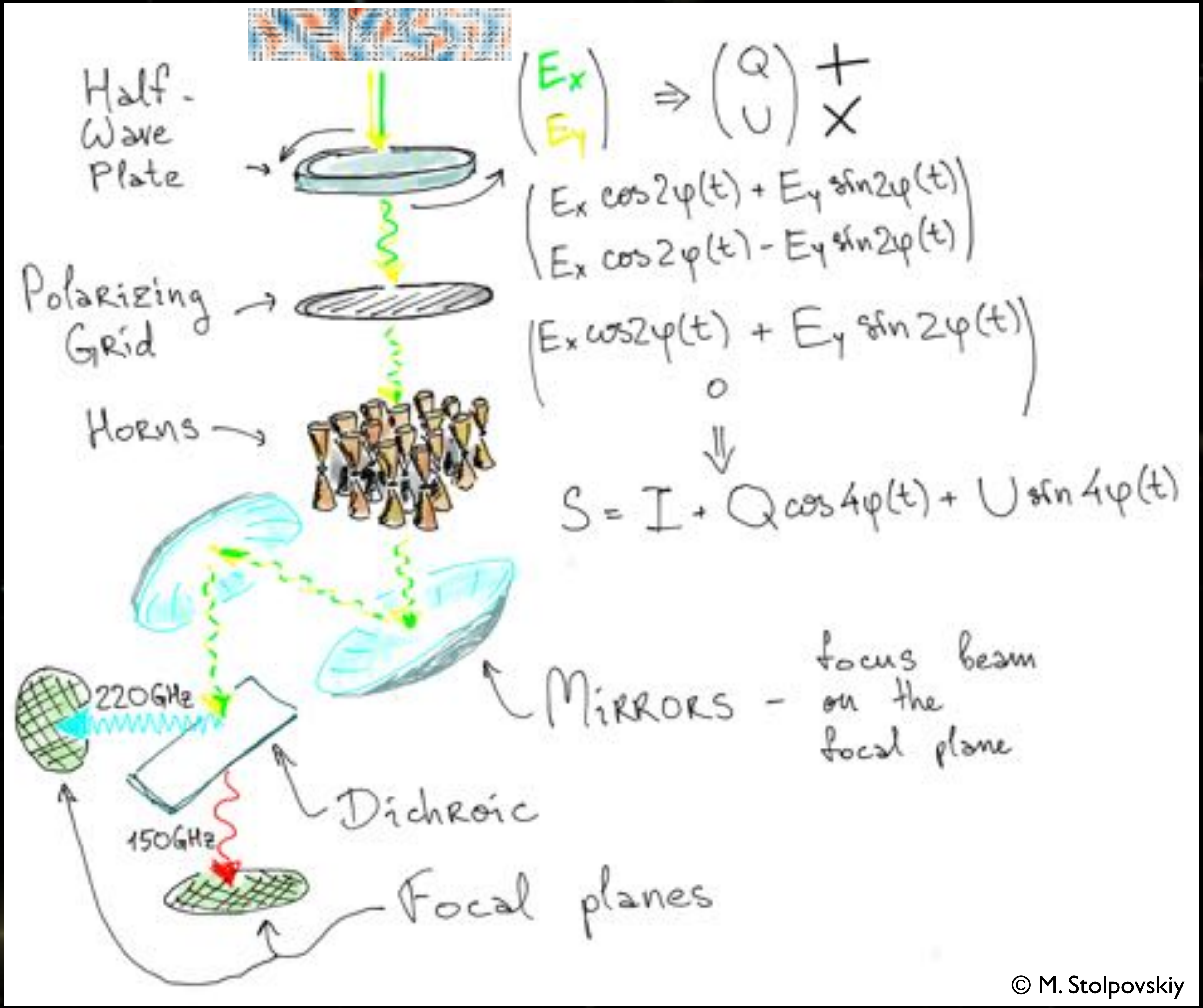

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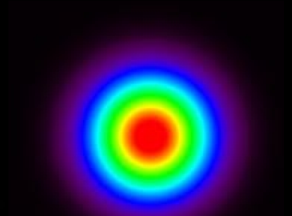
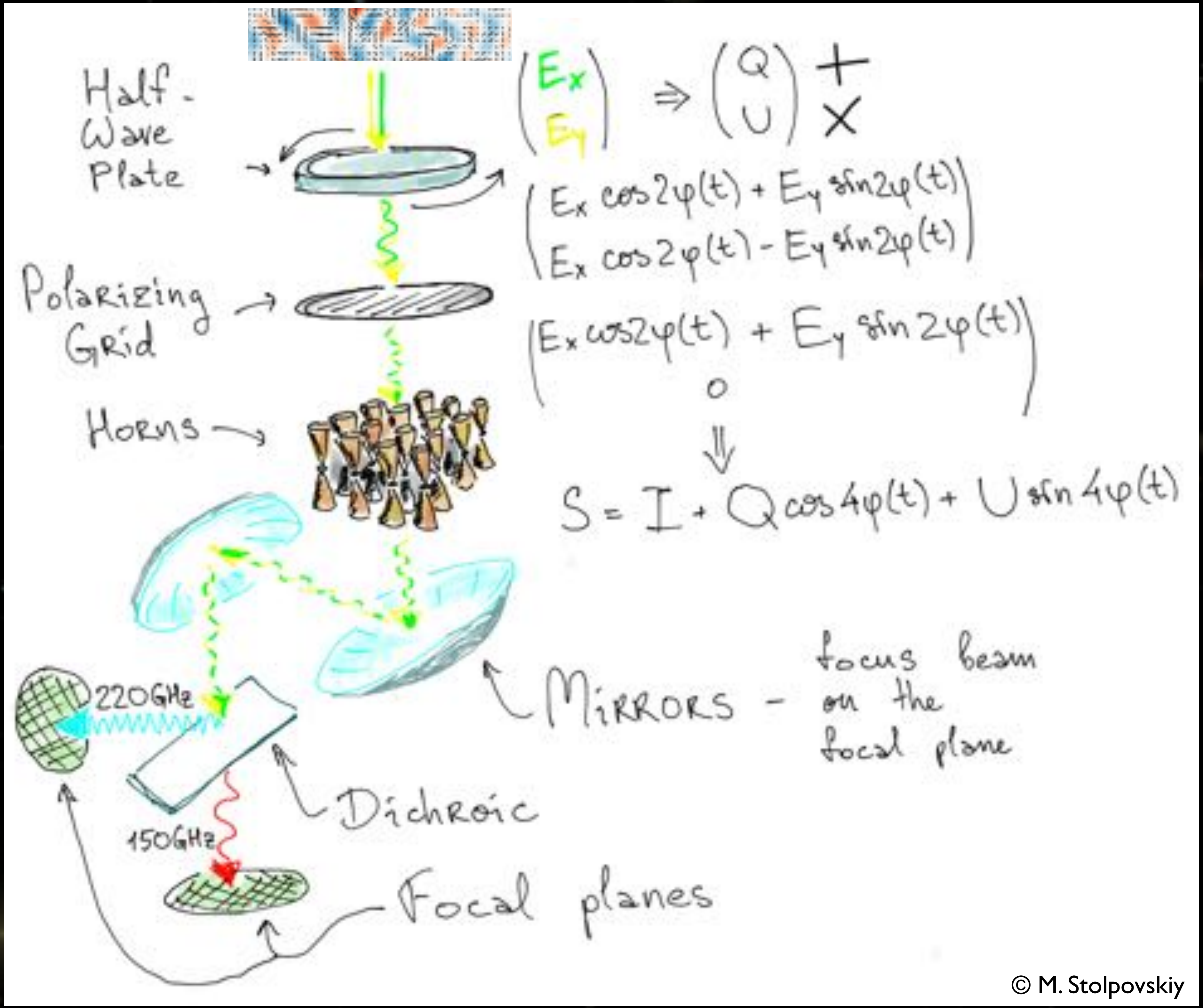


1 horn open



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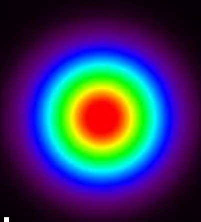

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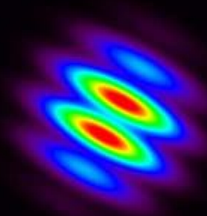
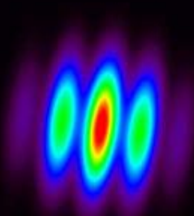


1 baseline



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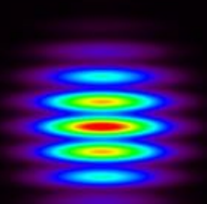

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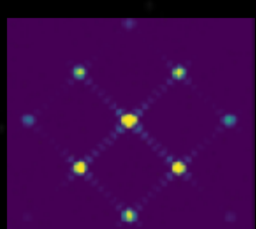
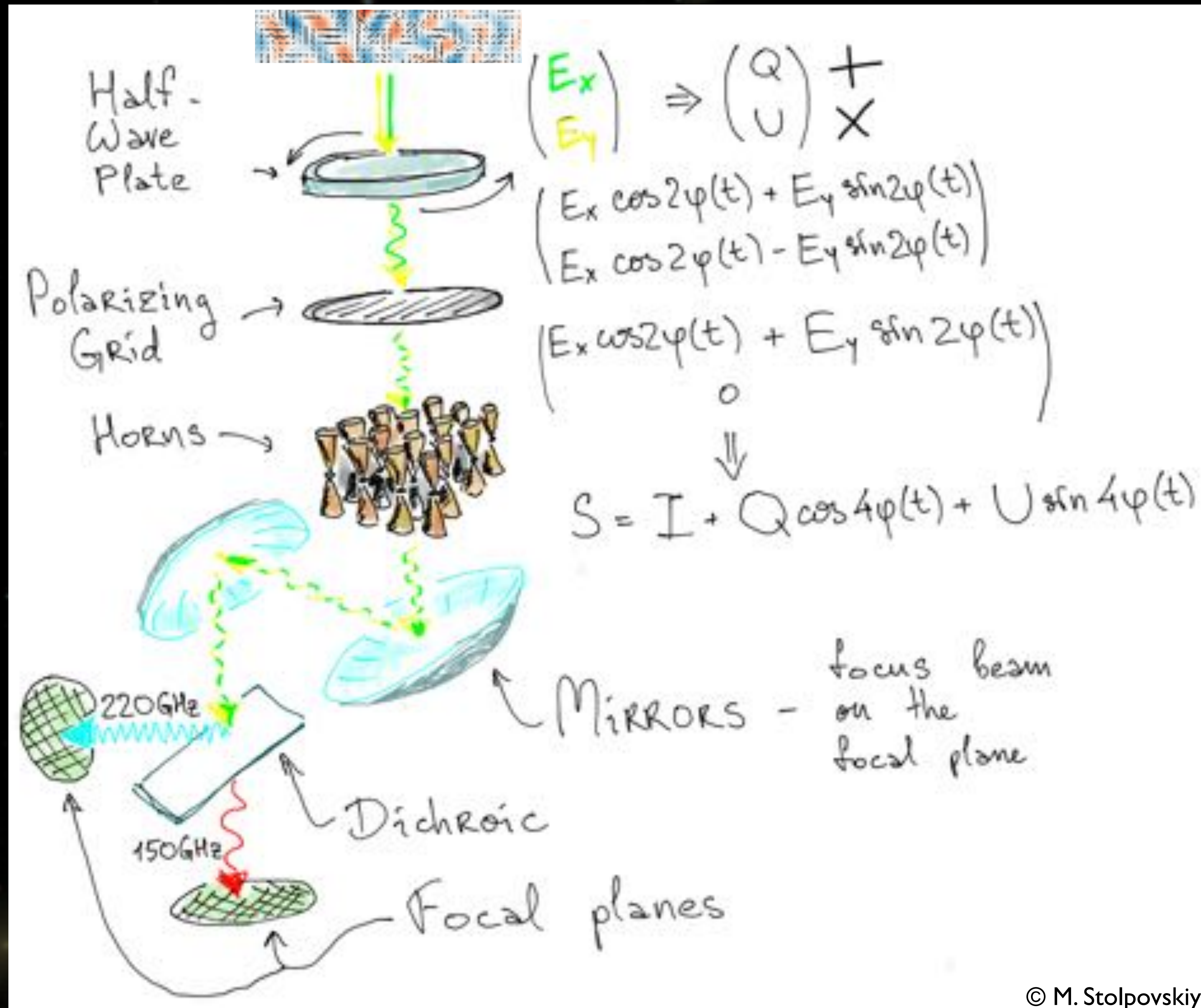


total signal
(all baselines)



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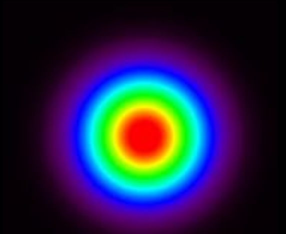

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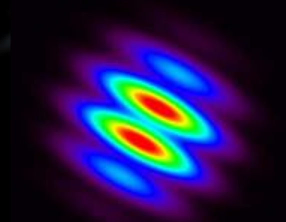

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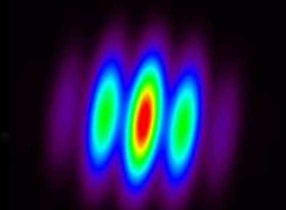

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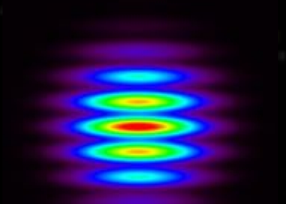

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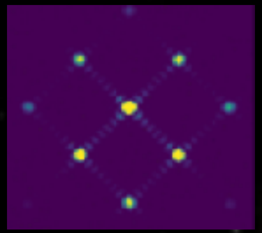

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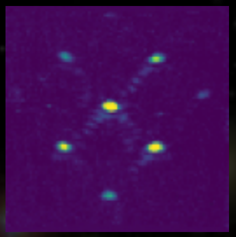
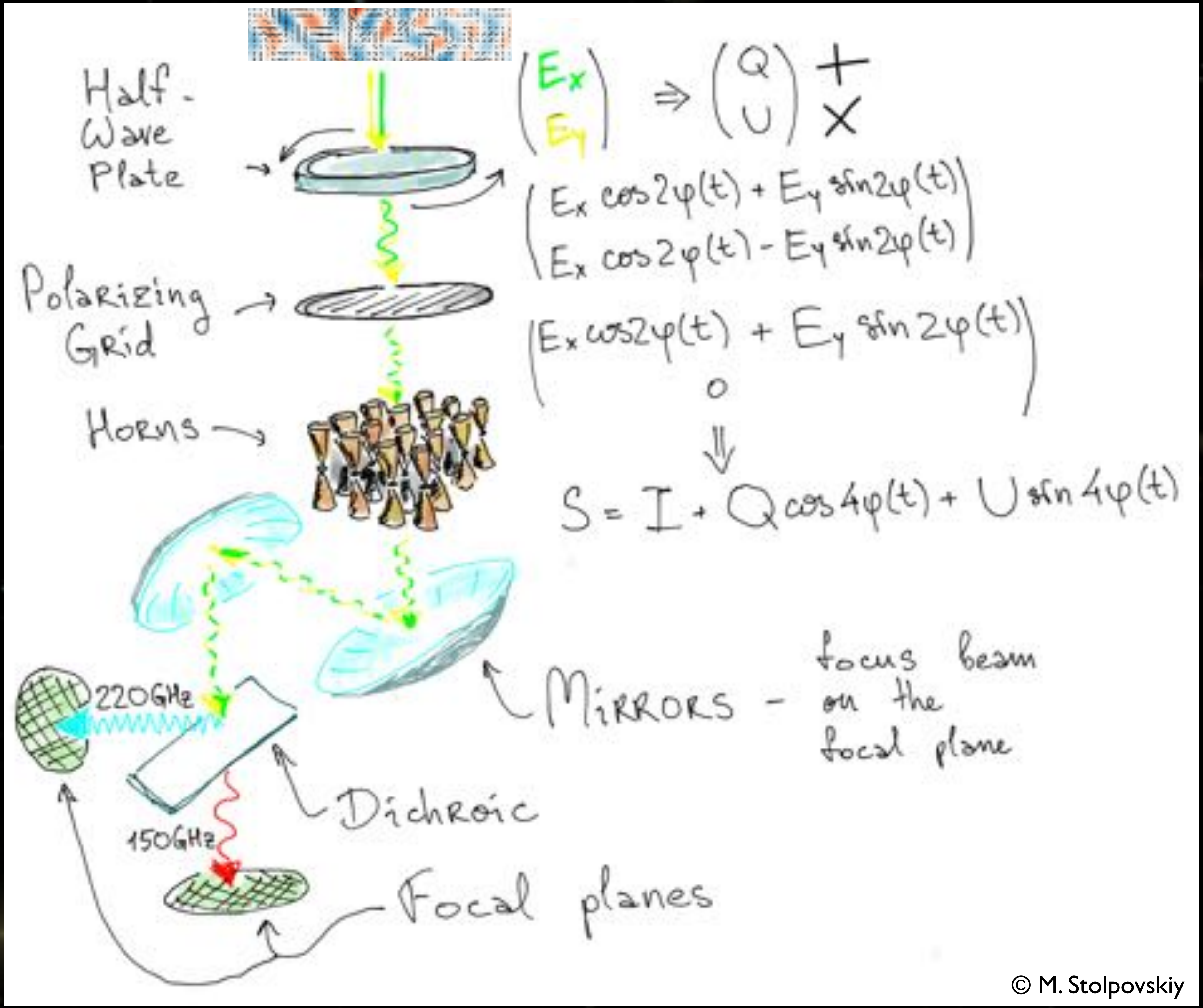
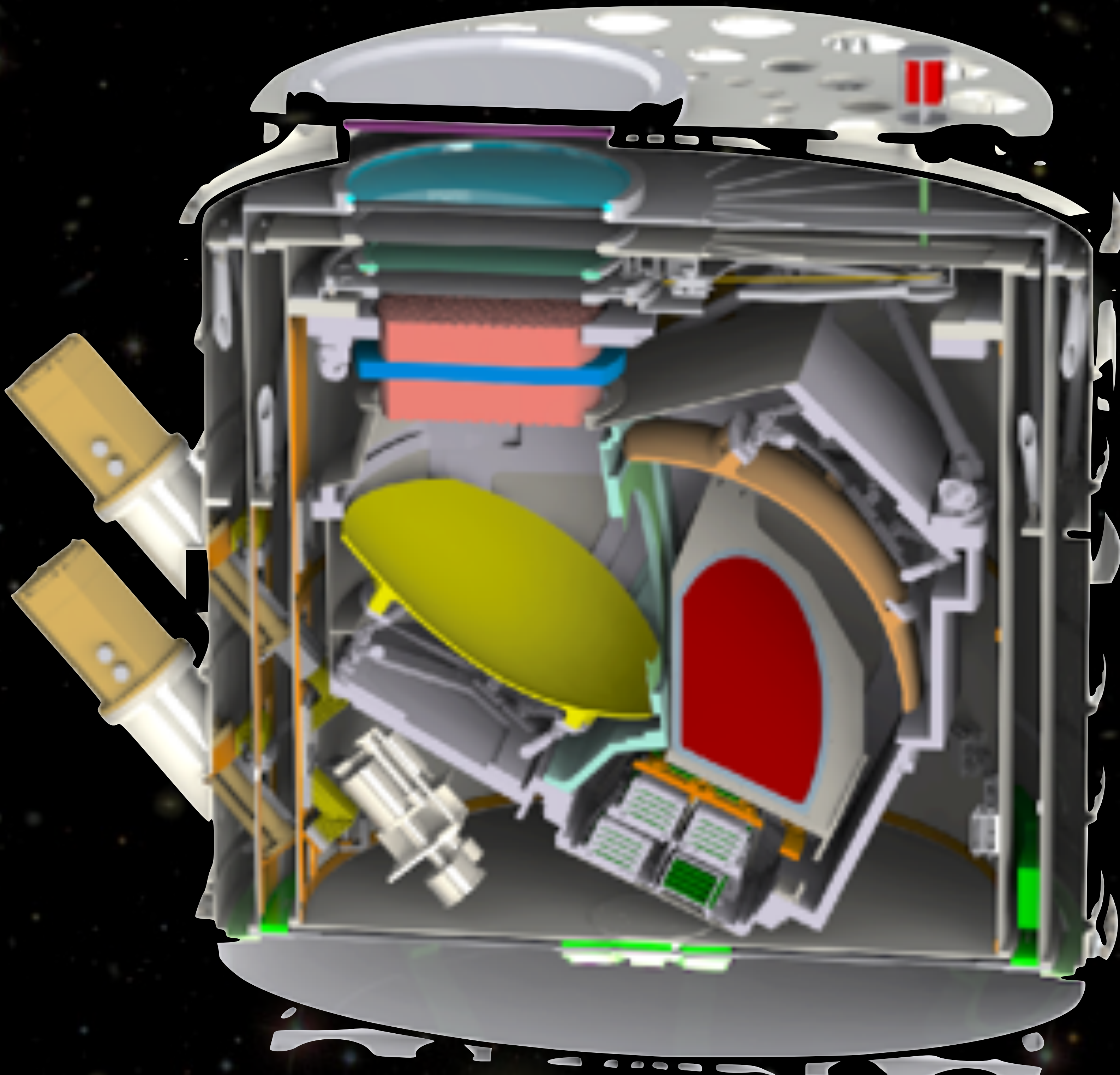
Data !





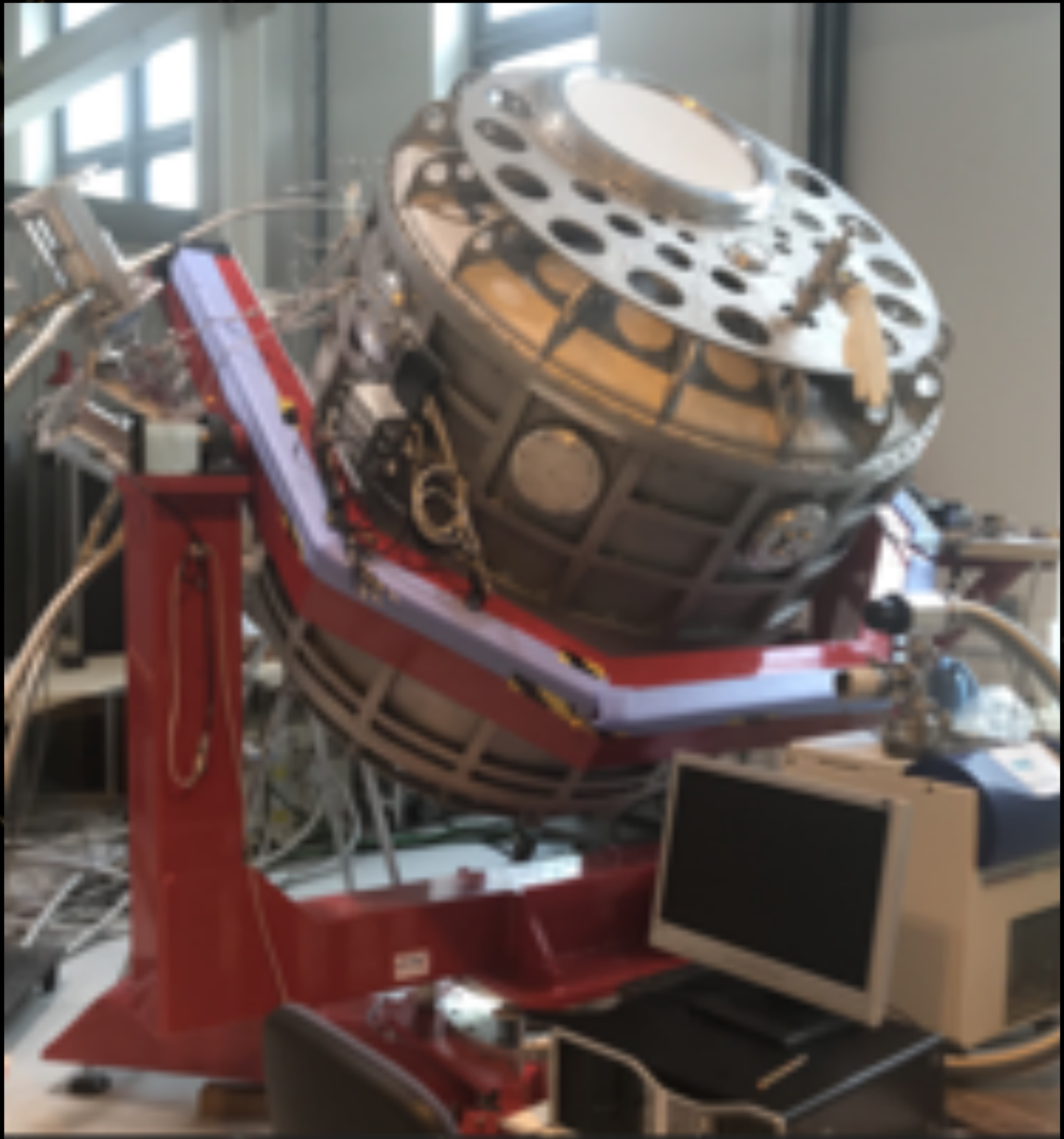
1.547m high
1.42m diameter
About 800kg



- Outer cryostat: **Roma**
- 1K Box / detectors: **APC, CSNSM / IRAP**
- Fridges: **Manchester**
- Optics: **Roma / Milano / Maynooth / Cardiff**
- Mount: **La Plata**
- Site: **CNEA**

Tests show expected behavior of the instrument !

Integrated over 2018 in Paris
Calibration 2019-2020
Ready to be Shipped !



1.547m high
1.42m diameter
About 800kg

- Outer cryostat: **Roma**
- 1K Box / detectors: **APC, CSNSM / IRAP**
- Fridges: **Manchester**
- Optics: **Roma / Milano / Maynooth / Cardiff**
- Mount: **La Plata**
- Site: **CNEA**

Tests show expected behavior of the instrument !

Integrated over 2018 in Paris
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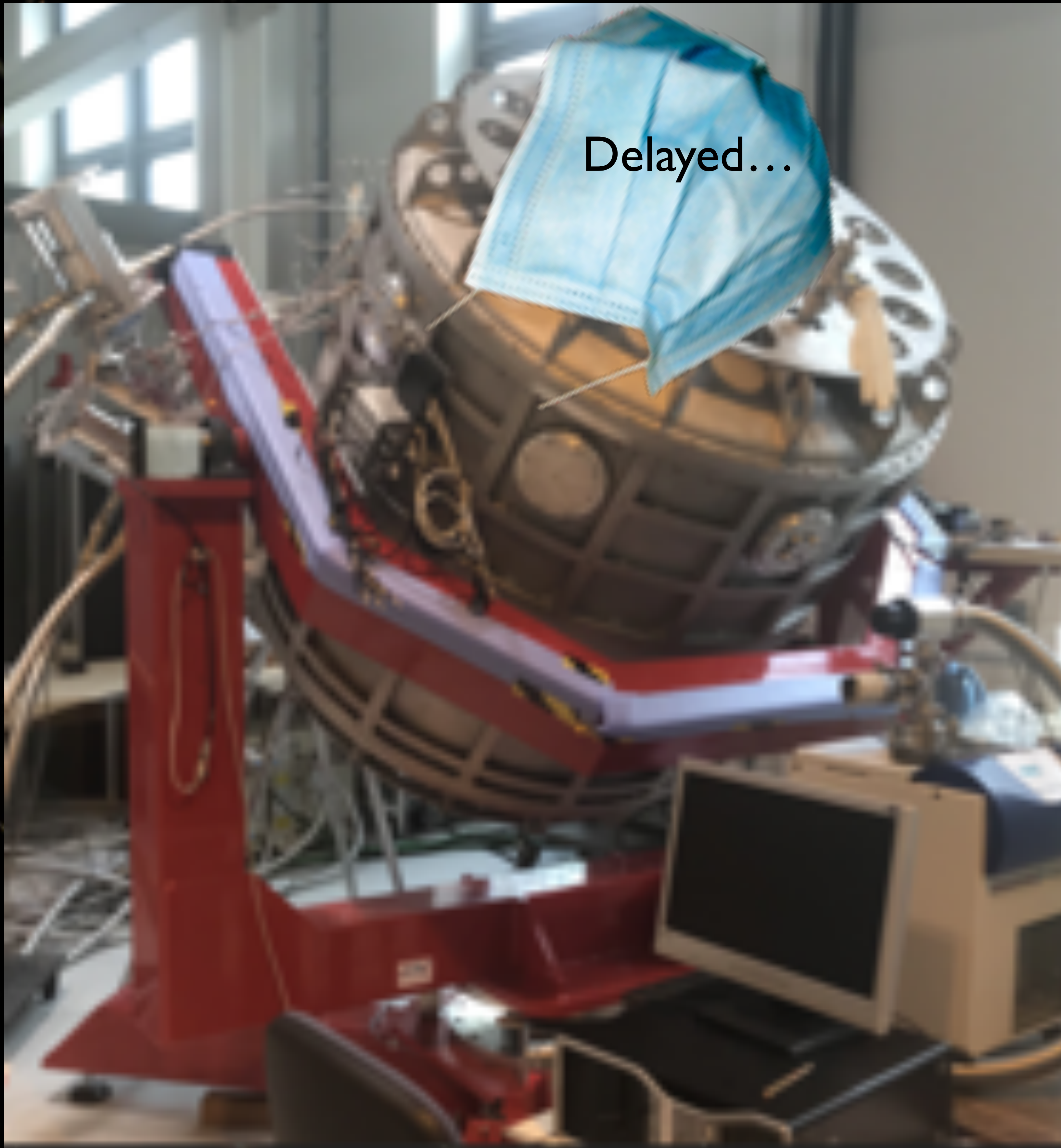

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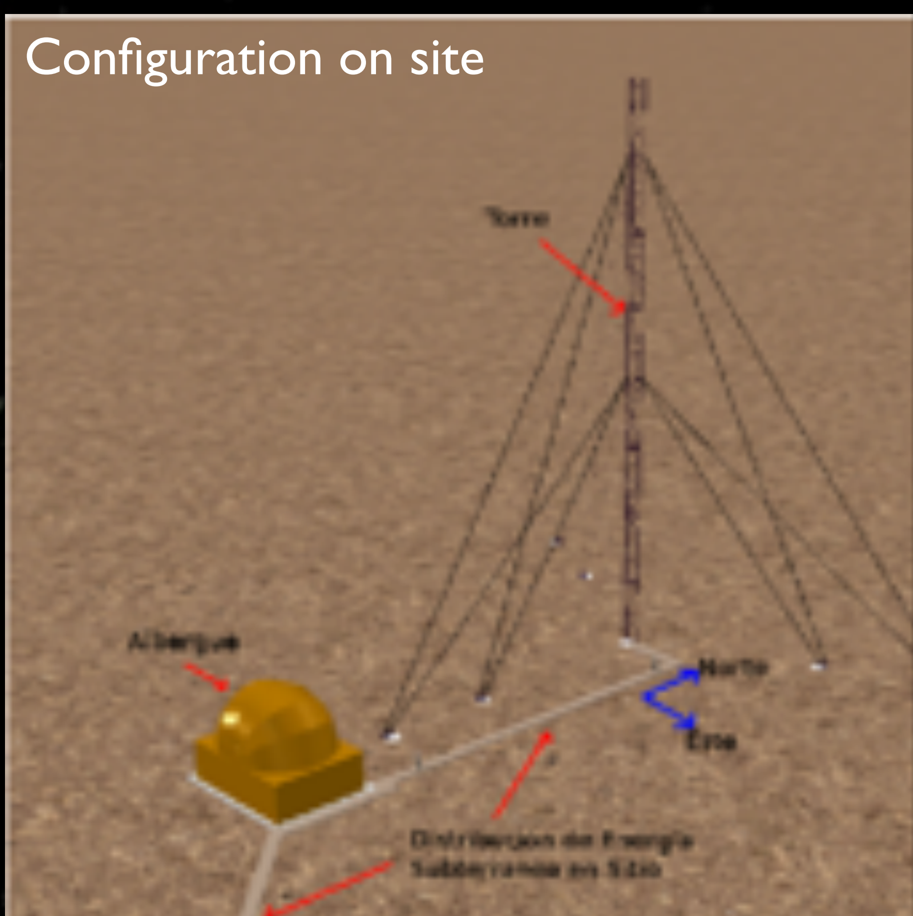
QUBIC in Argentina

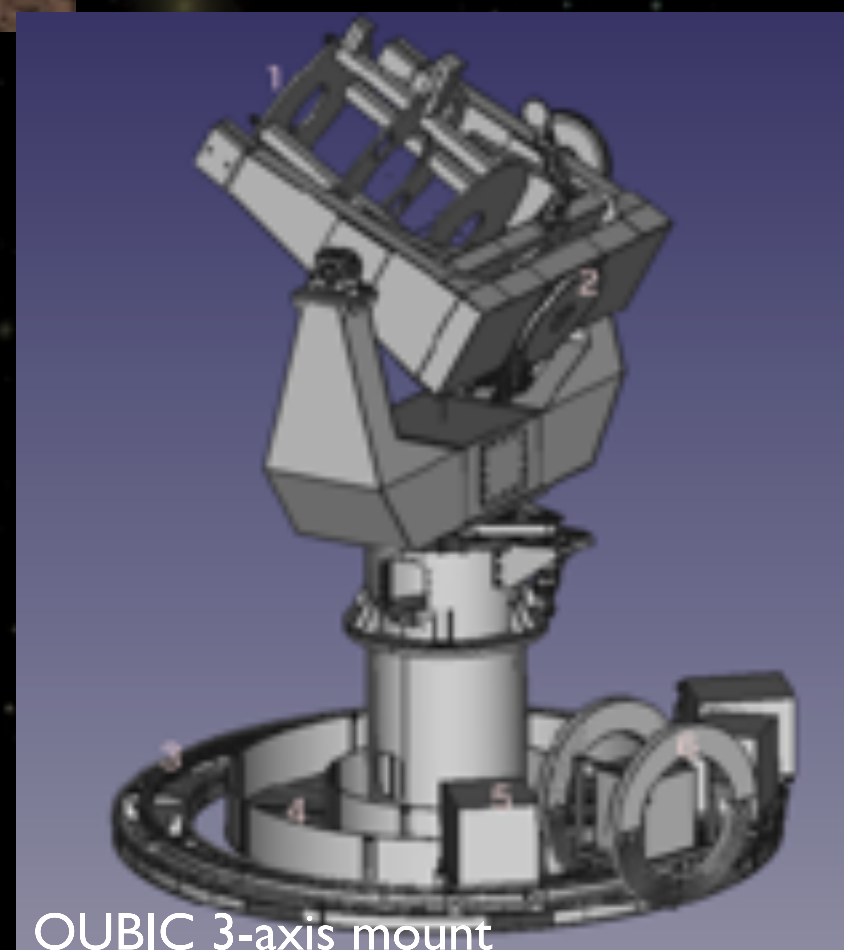

[Rendering for now…]

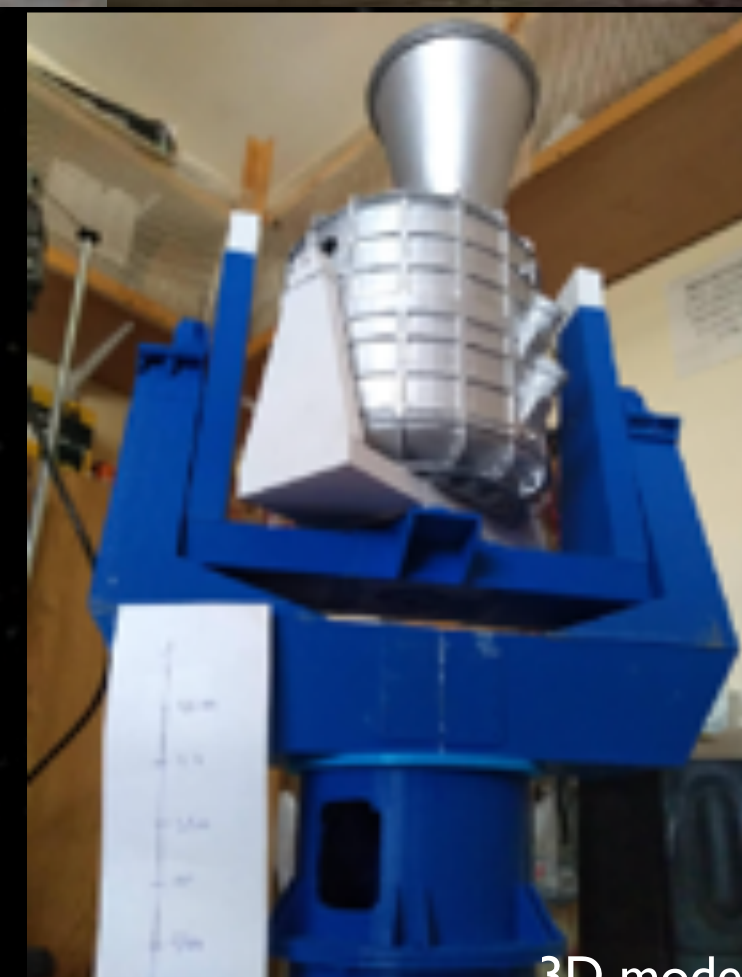


Integration Hall in Salta (CNEA Noroeste)



Configuration on site


QUBIC 3-axis mount


3D model

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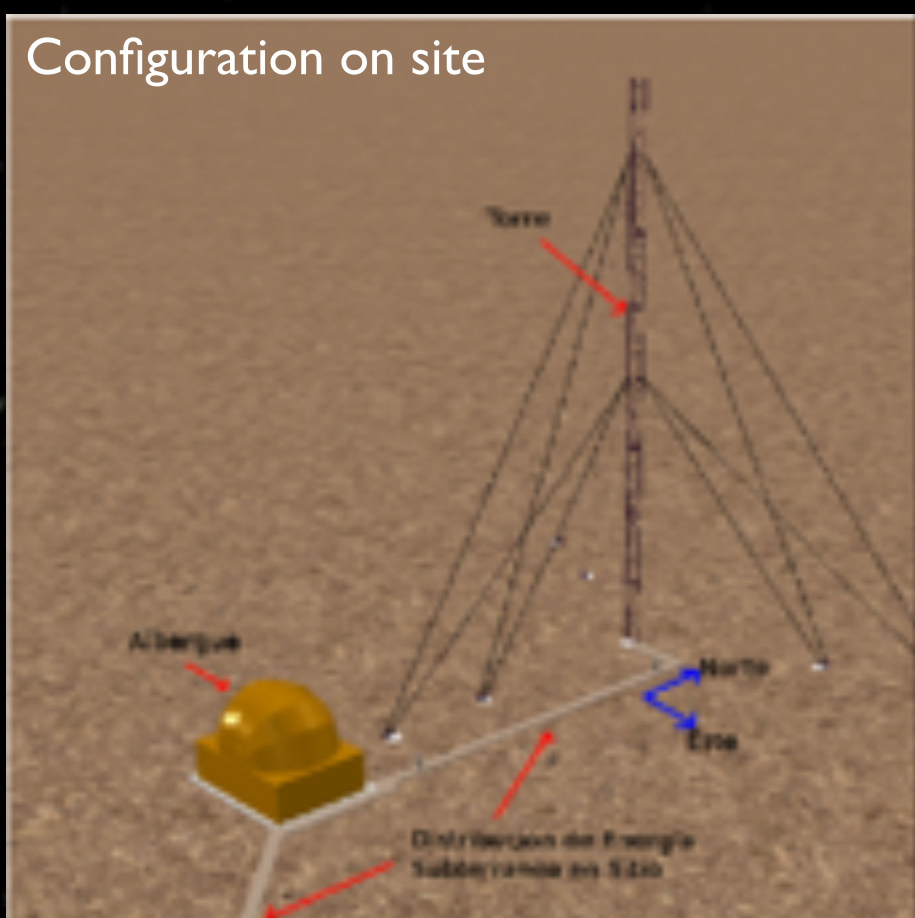

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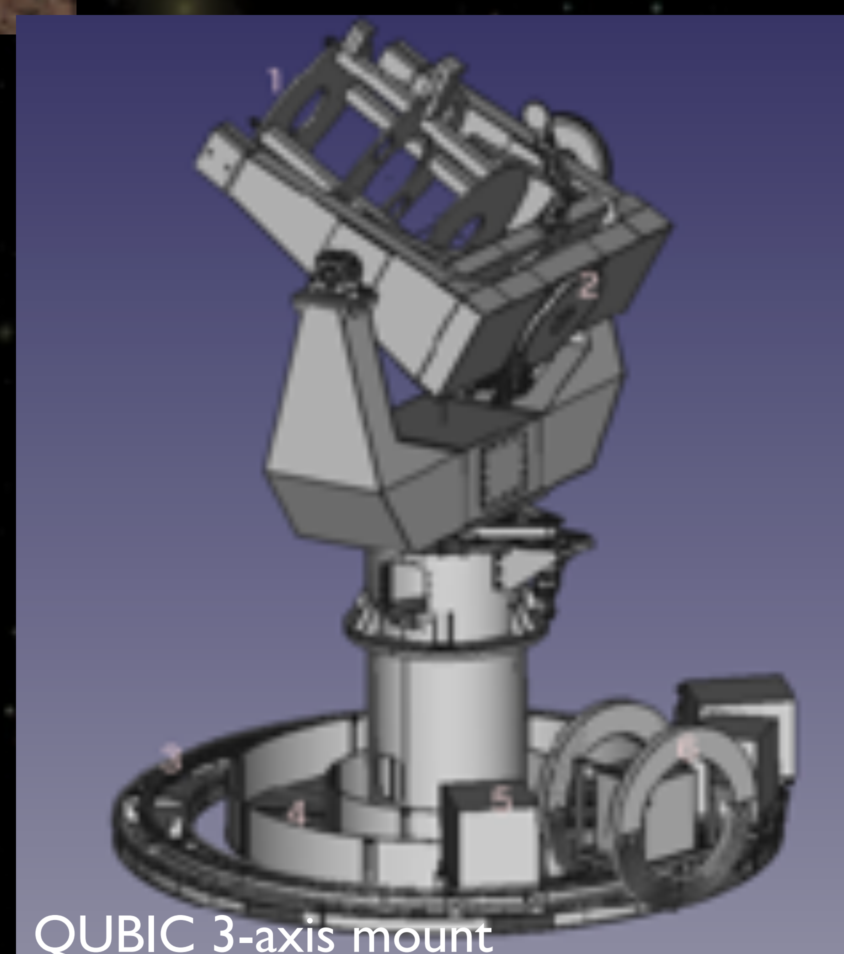
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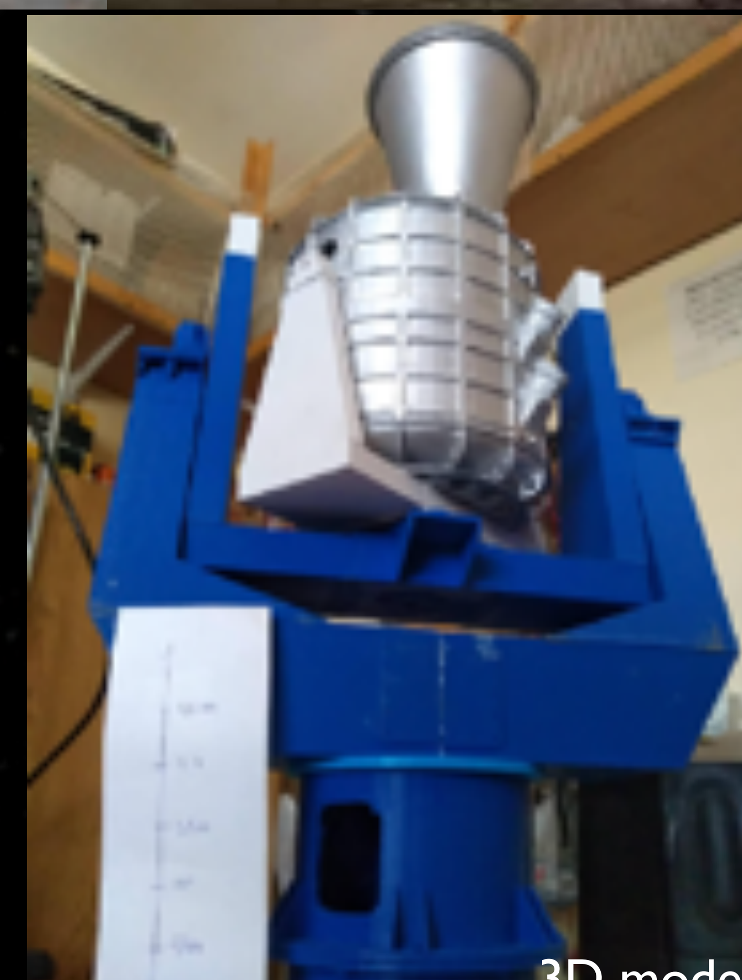
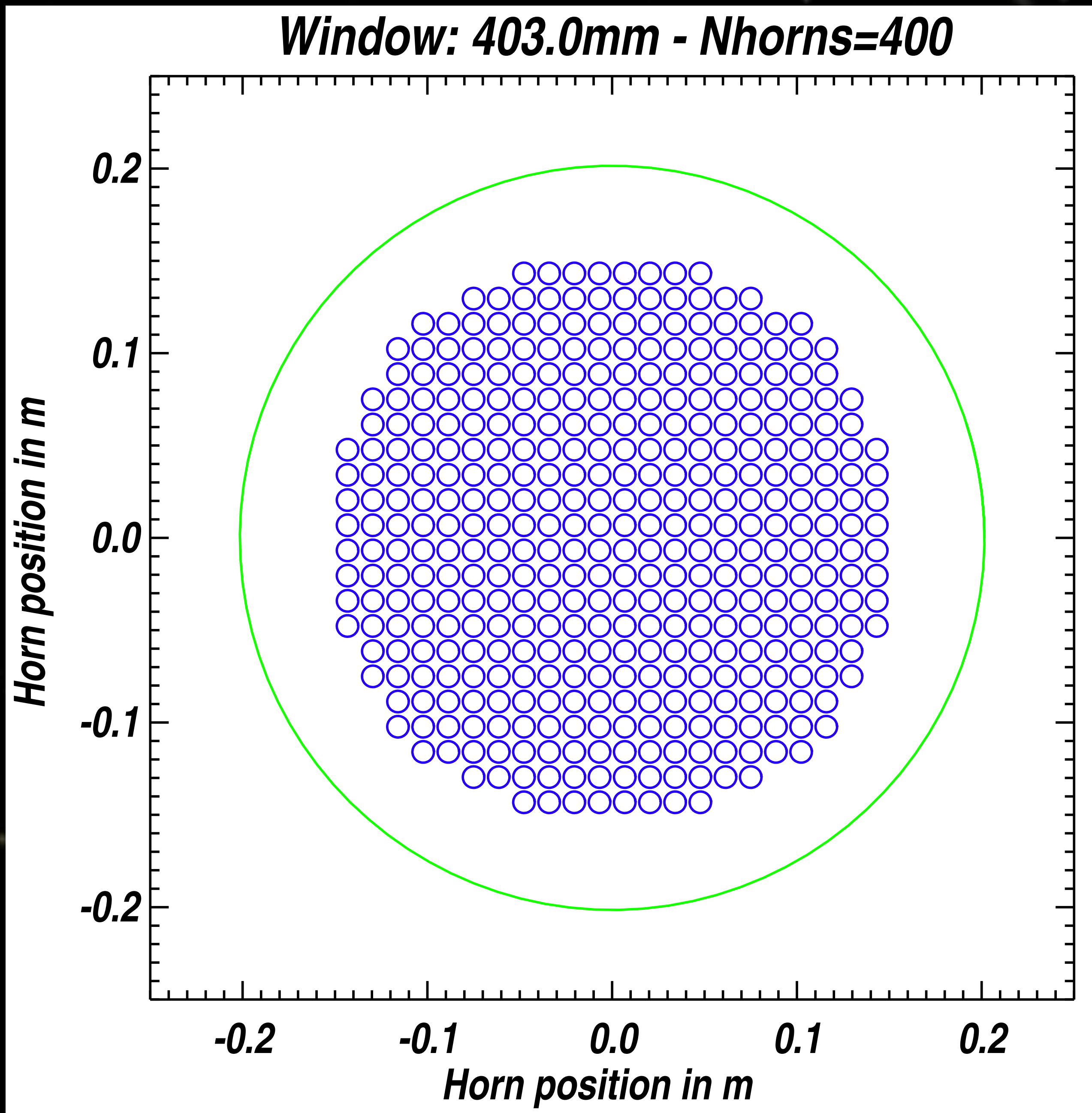

3D model

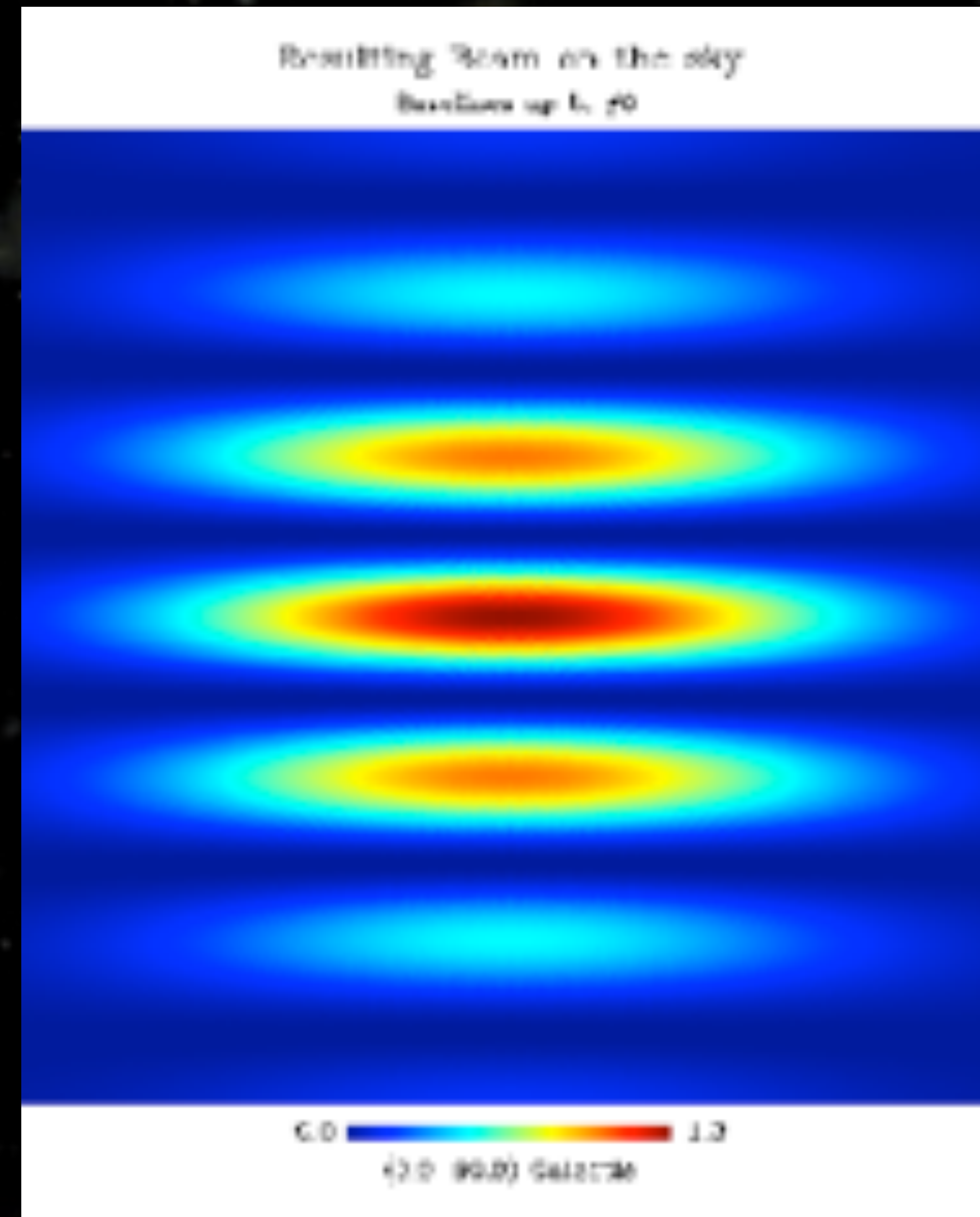
B.I. = Synthesized imager

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

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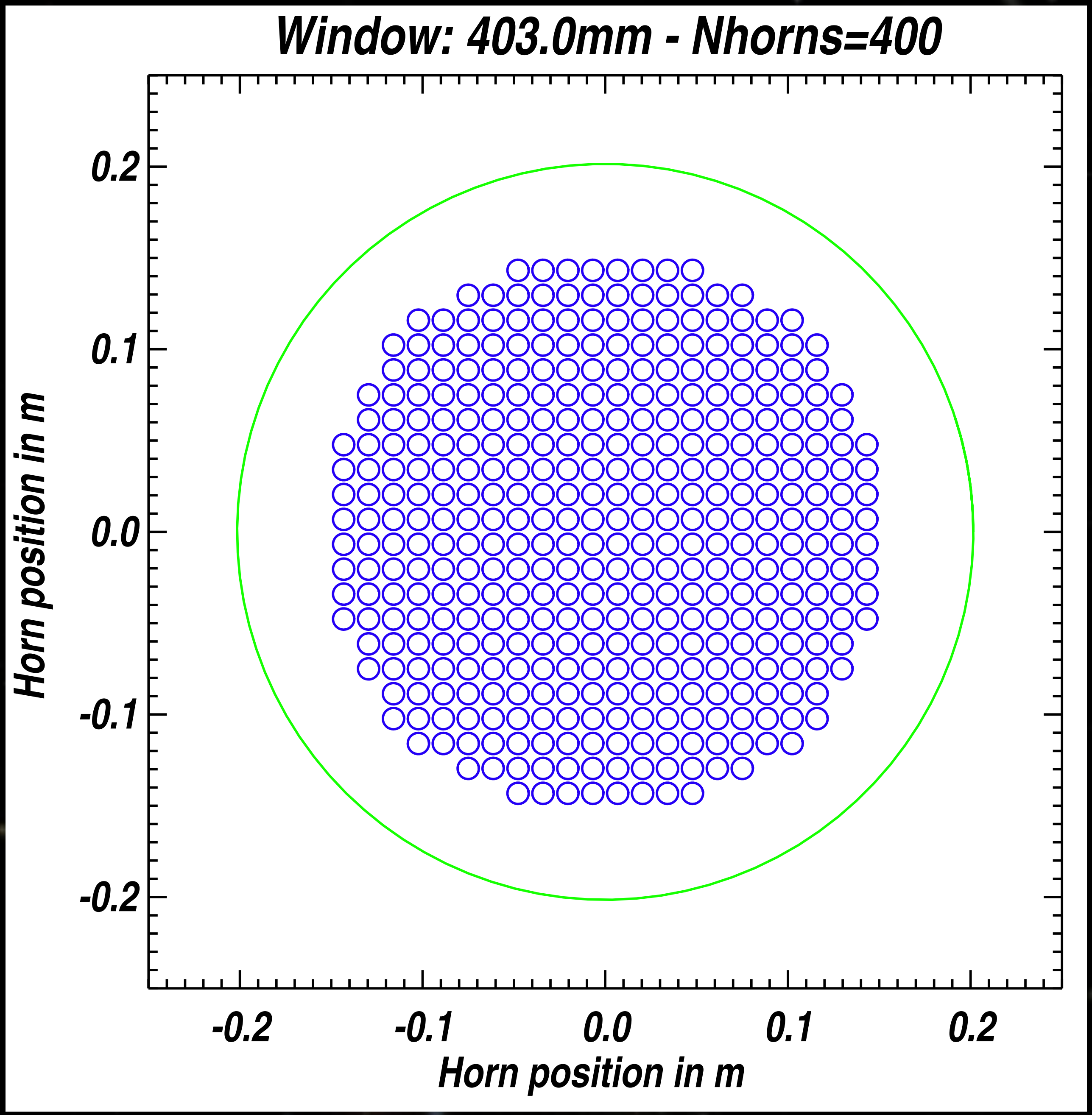

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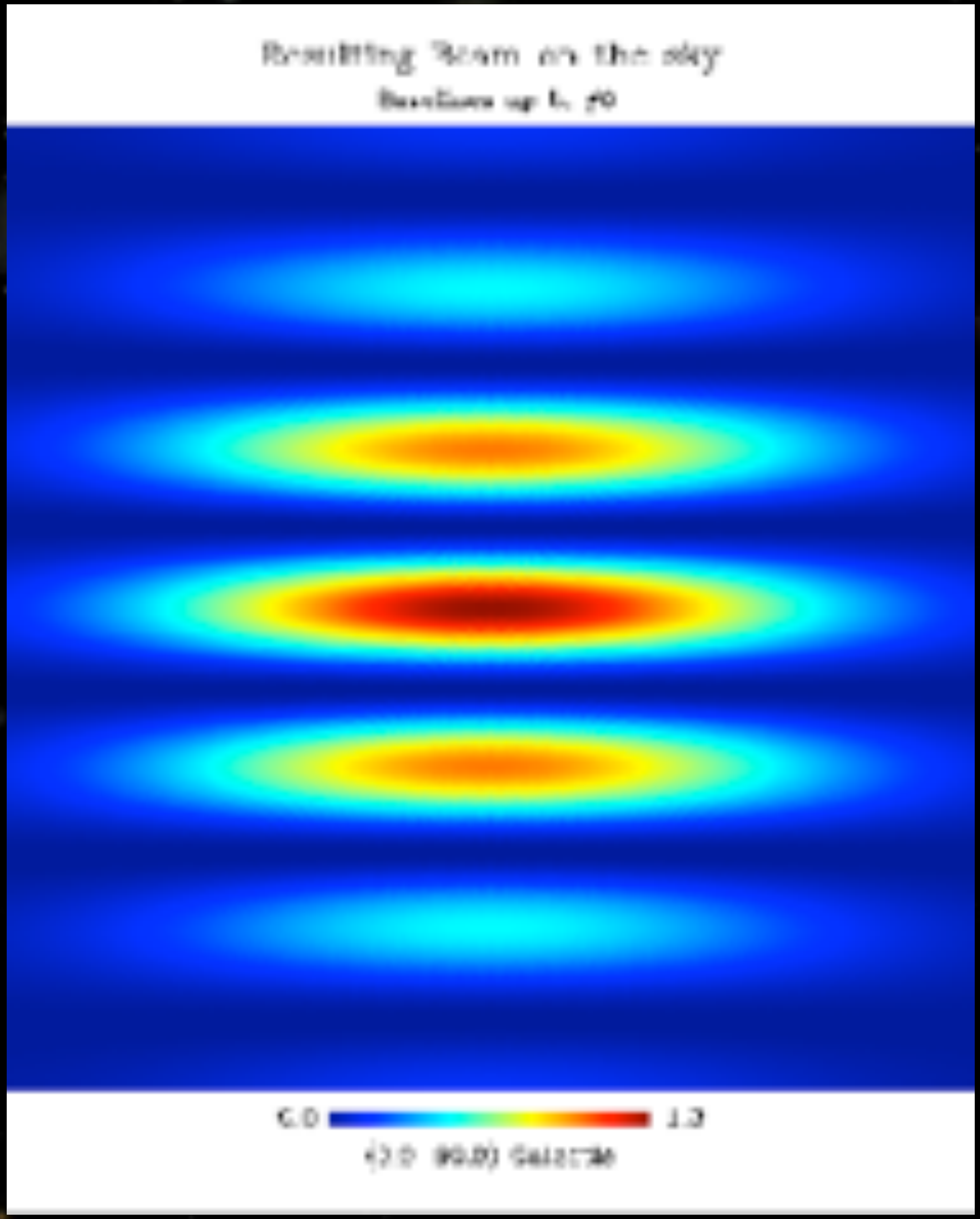

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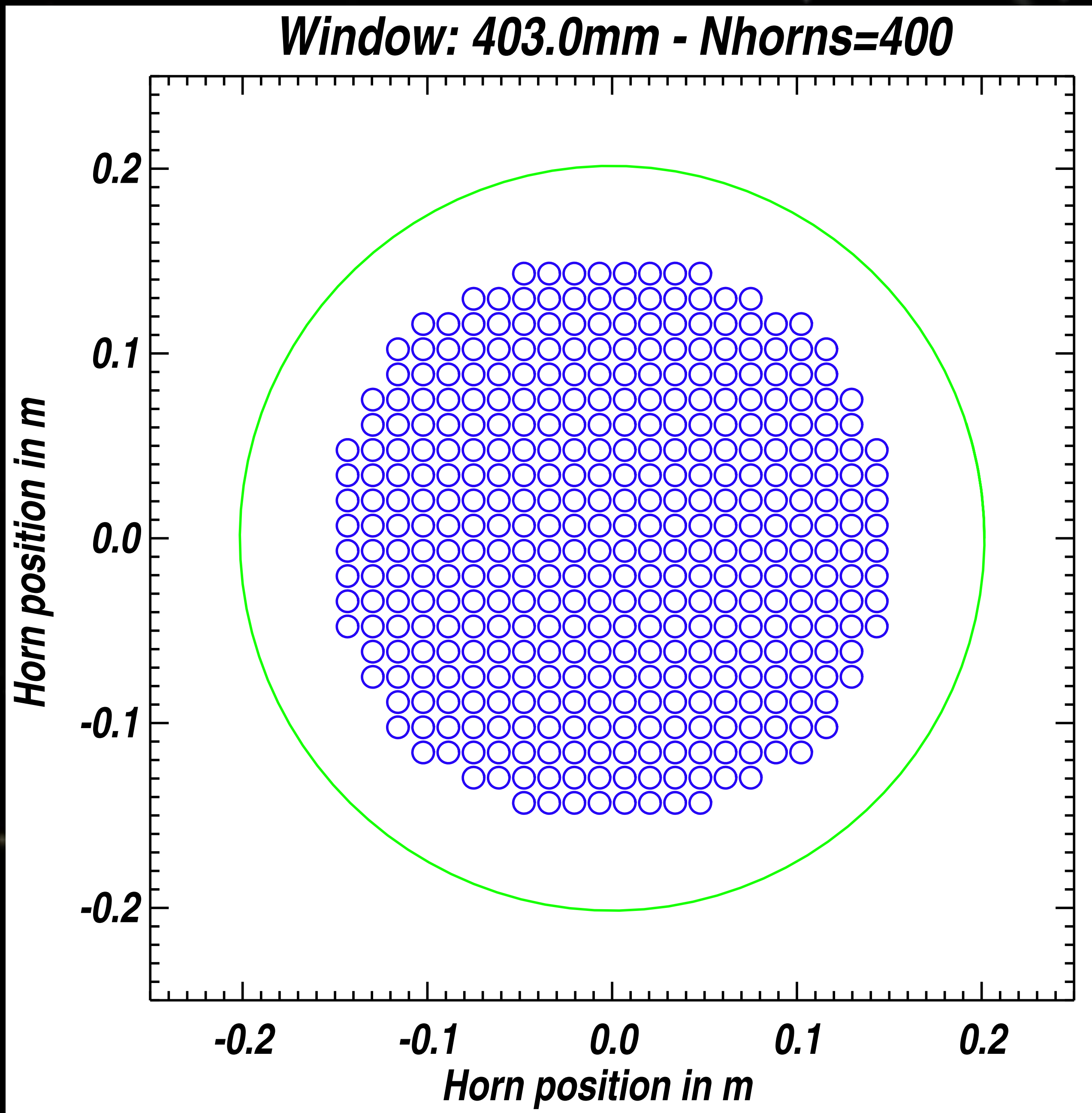

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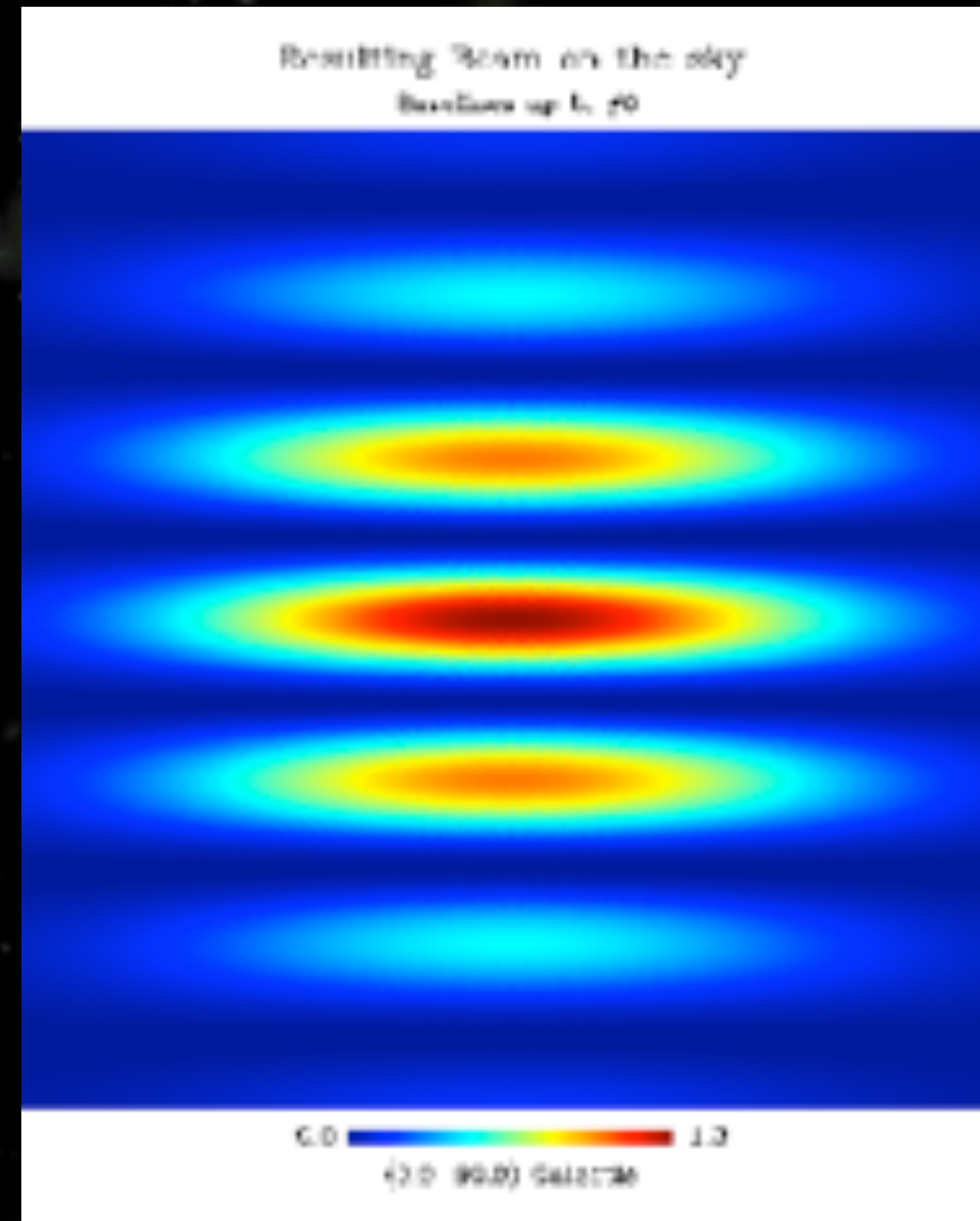

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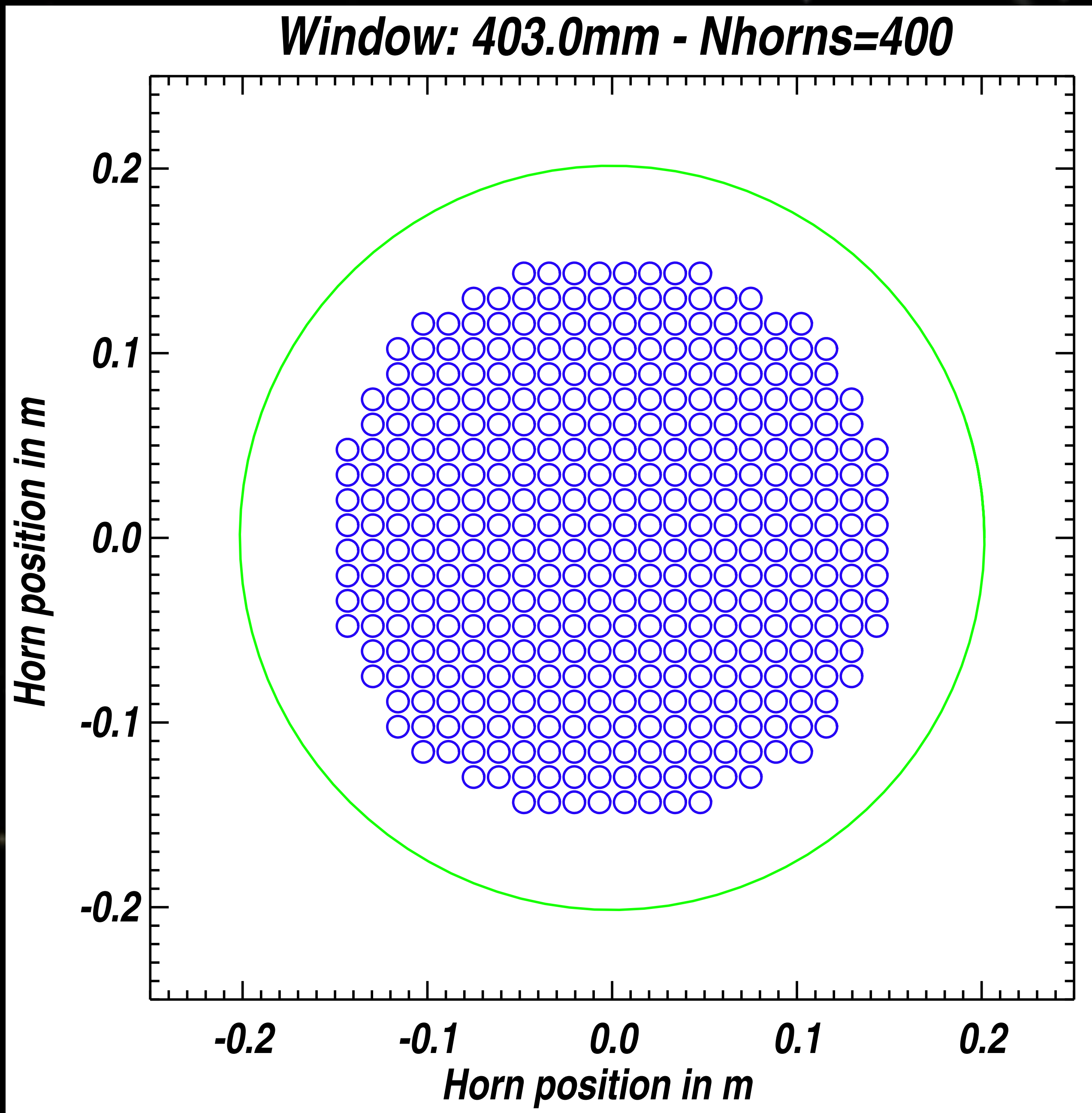

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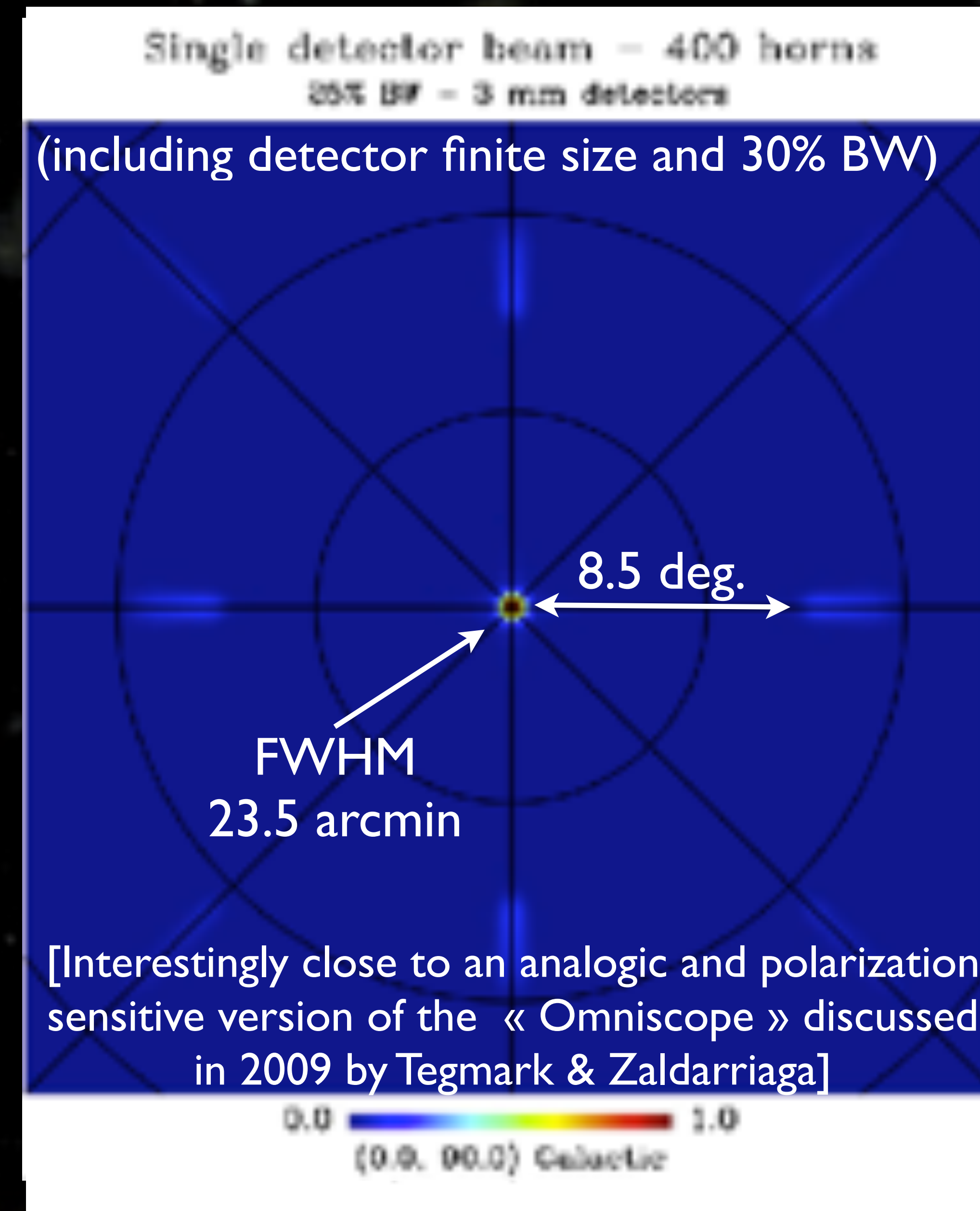
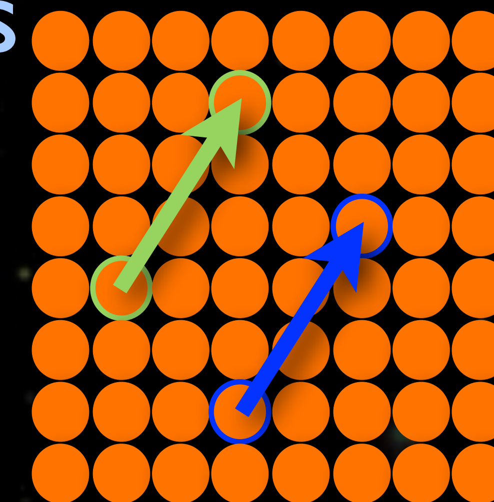


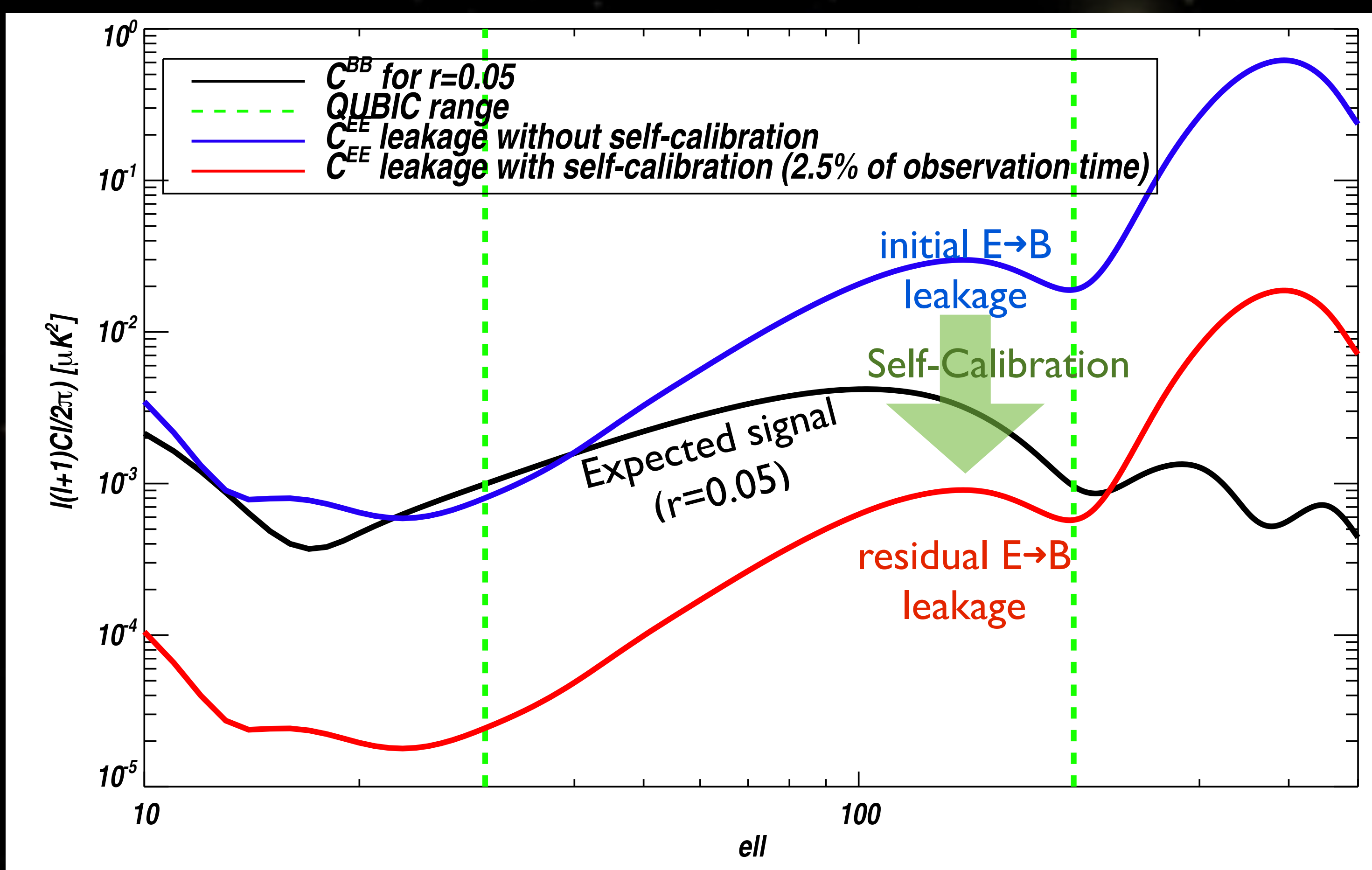
Synthesized beam used to scan the sky as with an imager

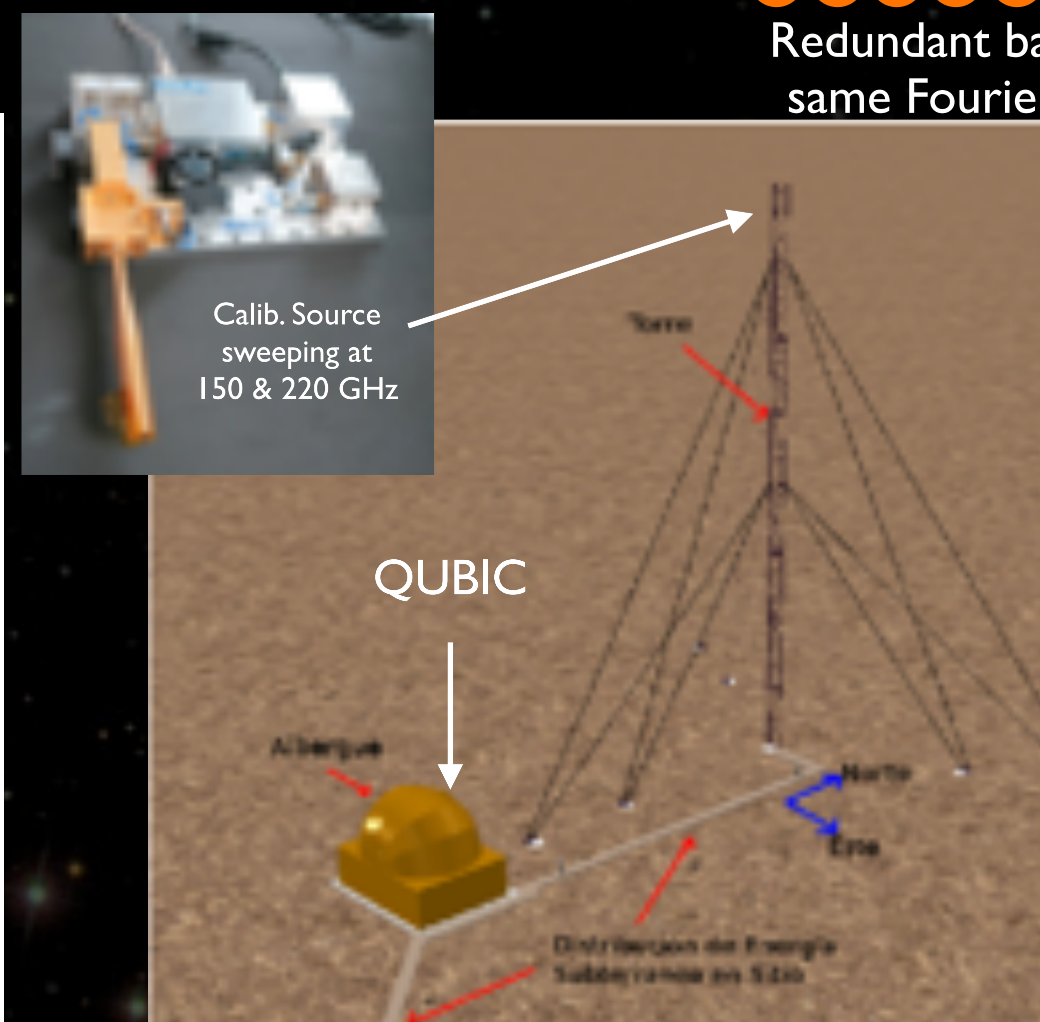
Systematics: Self-Calibration

- 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]

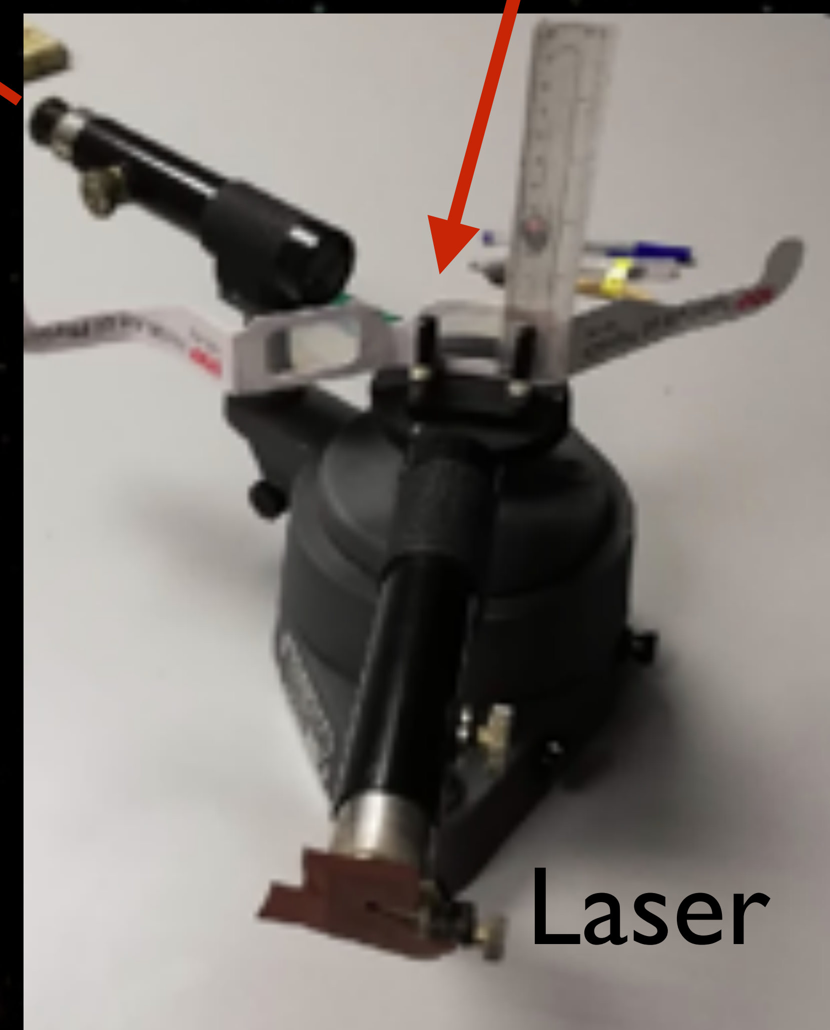


Redundant baselines : same Fourier Mode



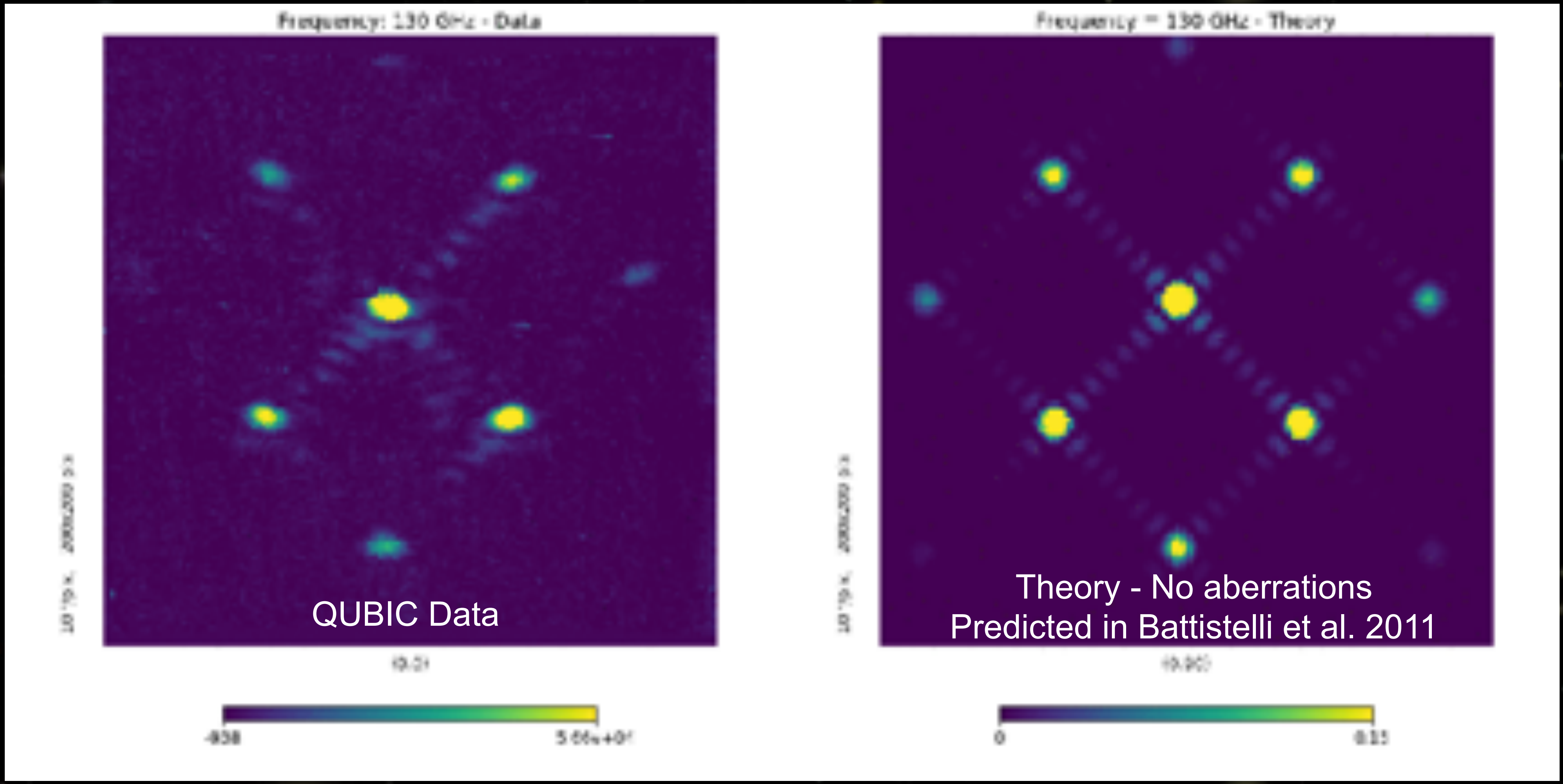


Rainbow Symphony



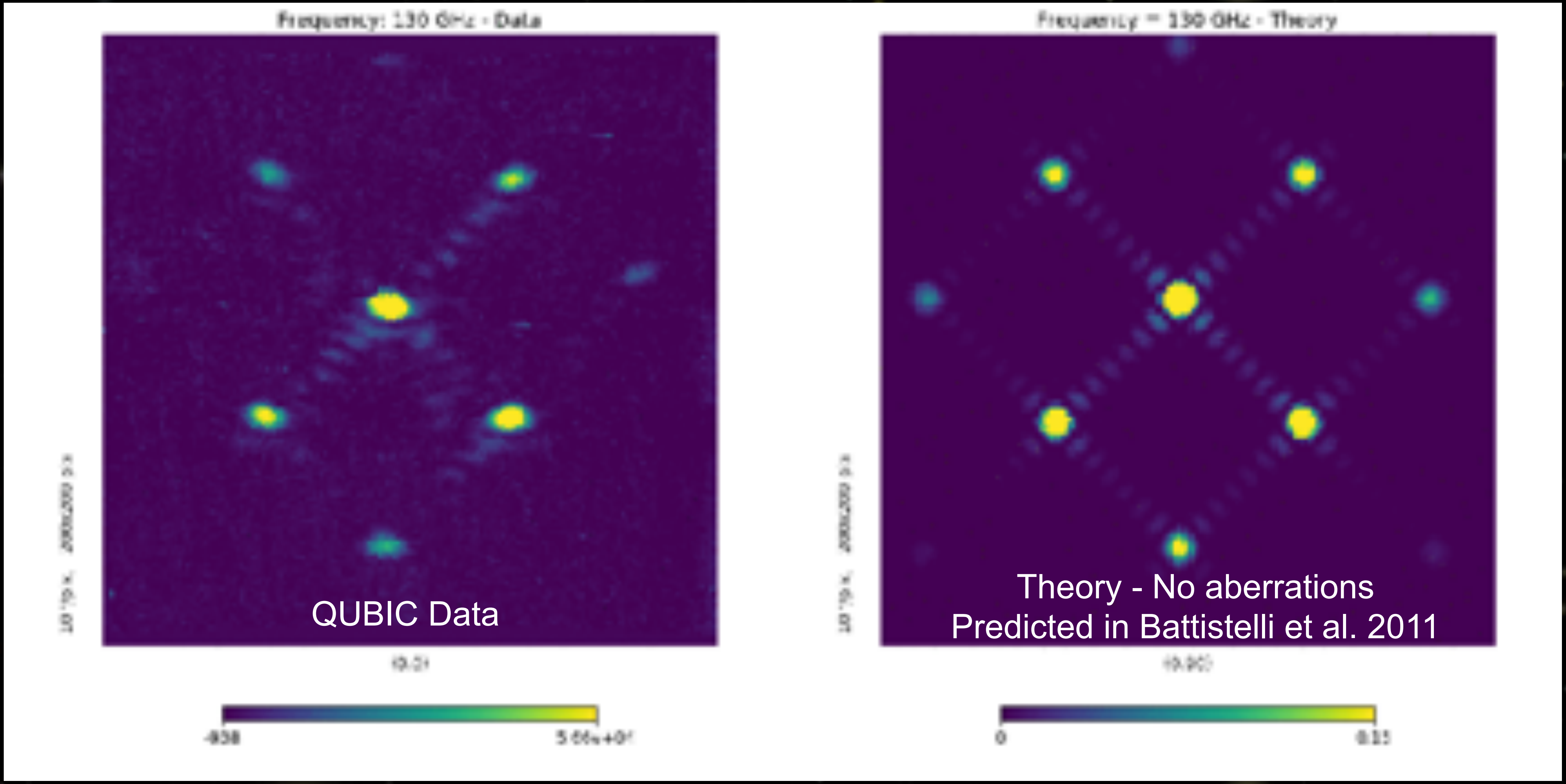
Donnacha Gayer (PhD @ Maynooth)

Frequency Evolution



Frequency scaling is the basis of Spectro-Imaging
A possibility unique to Bolometric Interferometry to constrain foregrounds

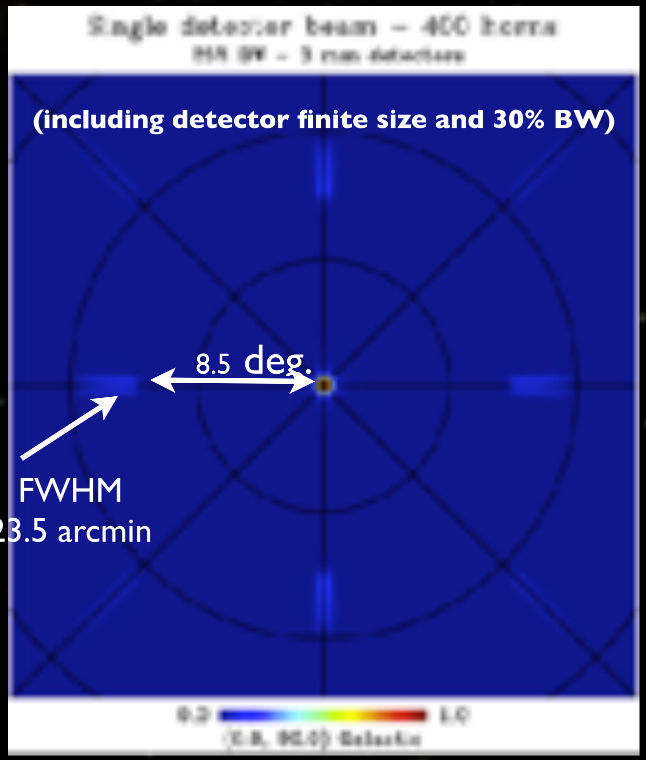
Frequency Evolution



Frequency scaling is the basis of Spectro-Imaging
A possibility unique to Bolometric Interferometry to constrain foregrounds

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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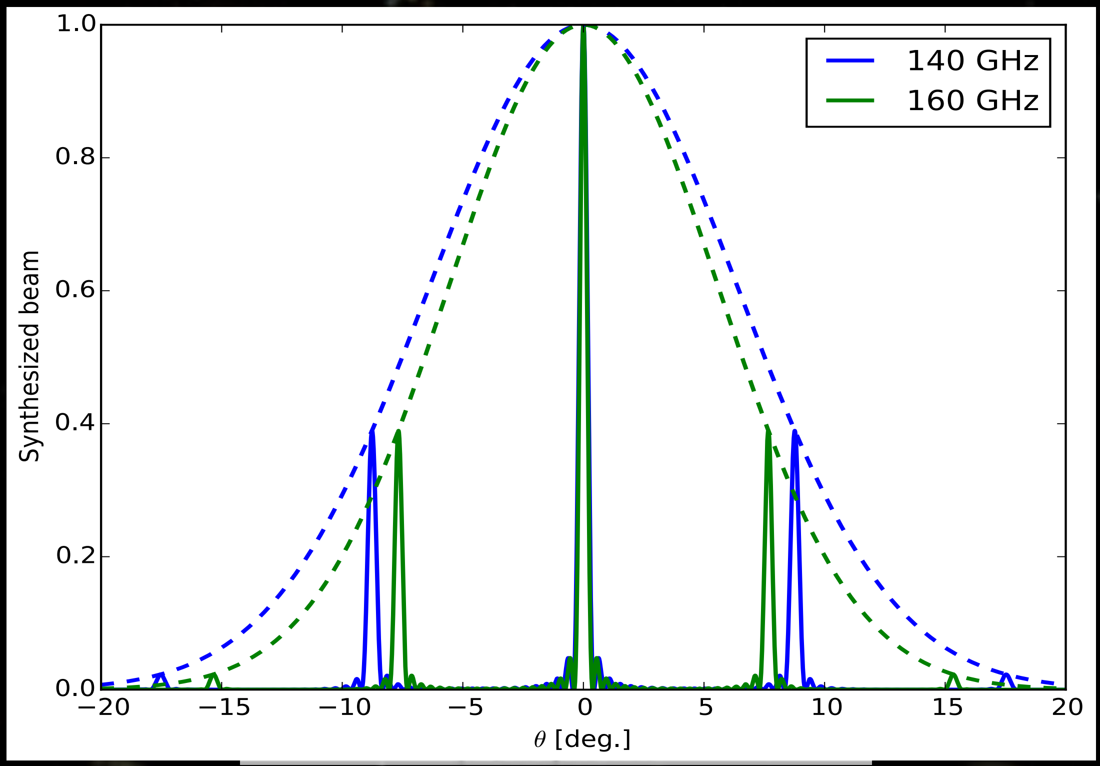

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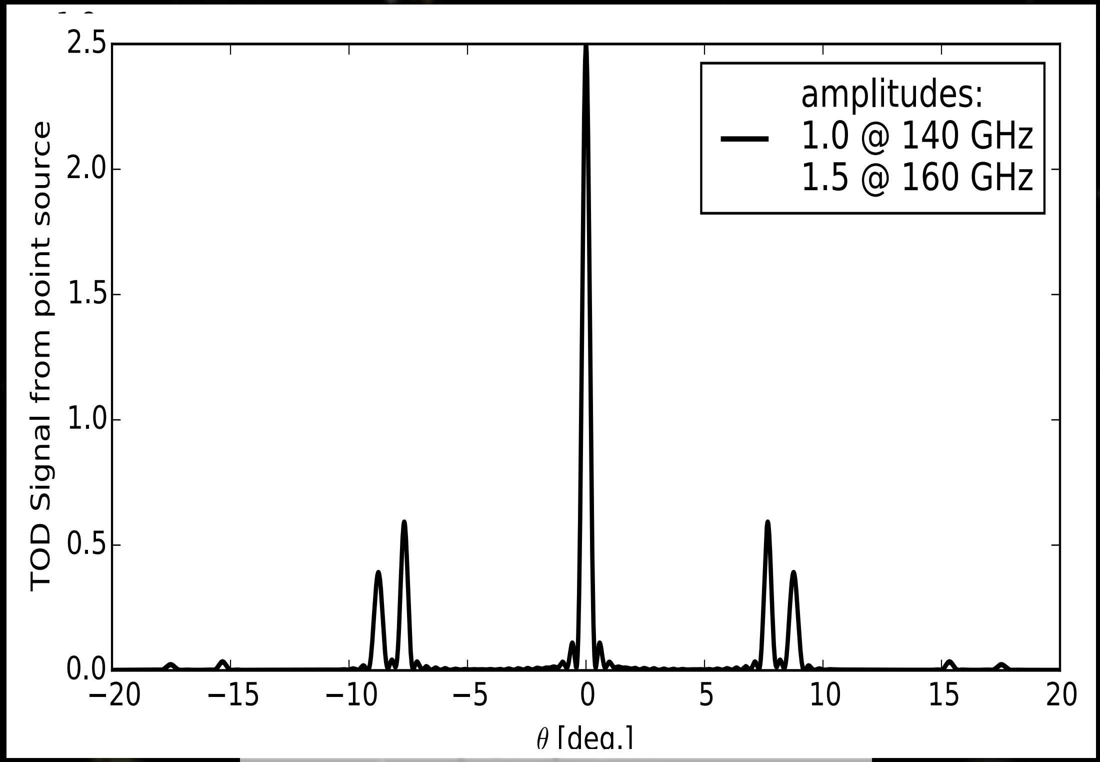

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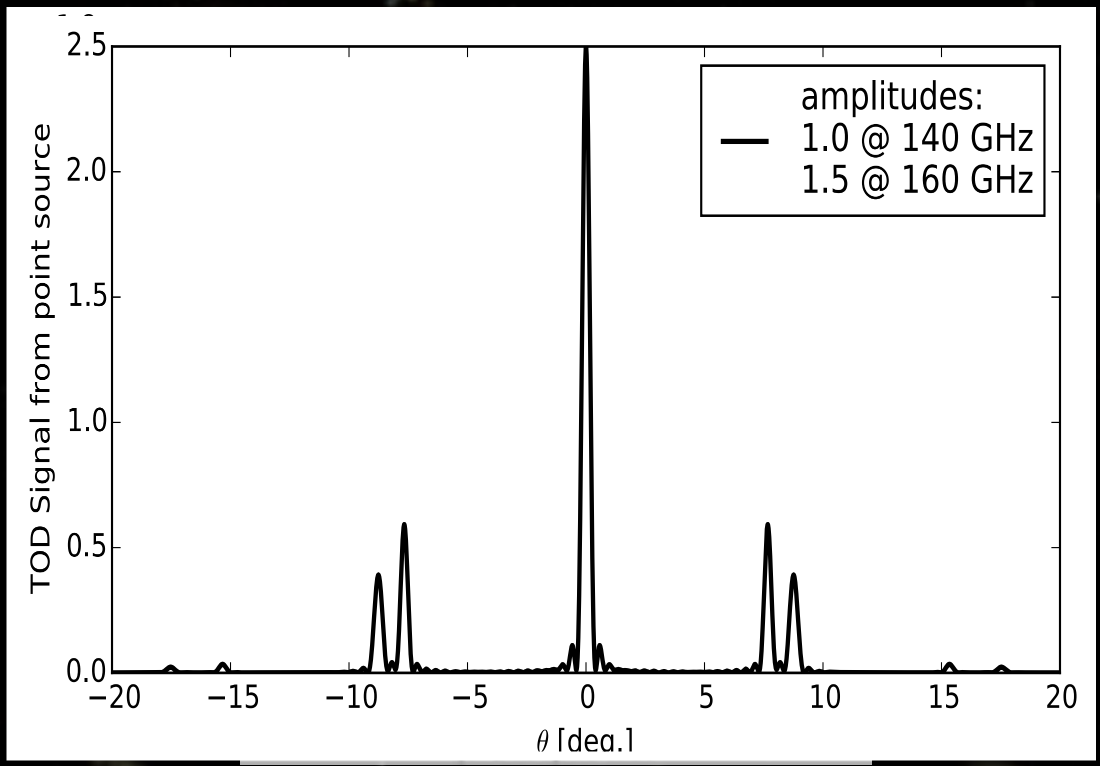

- There is spatial + frequency information !

QUBIC is a Synthesized Spectro-Imager

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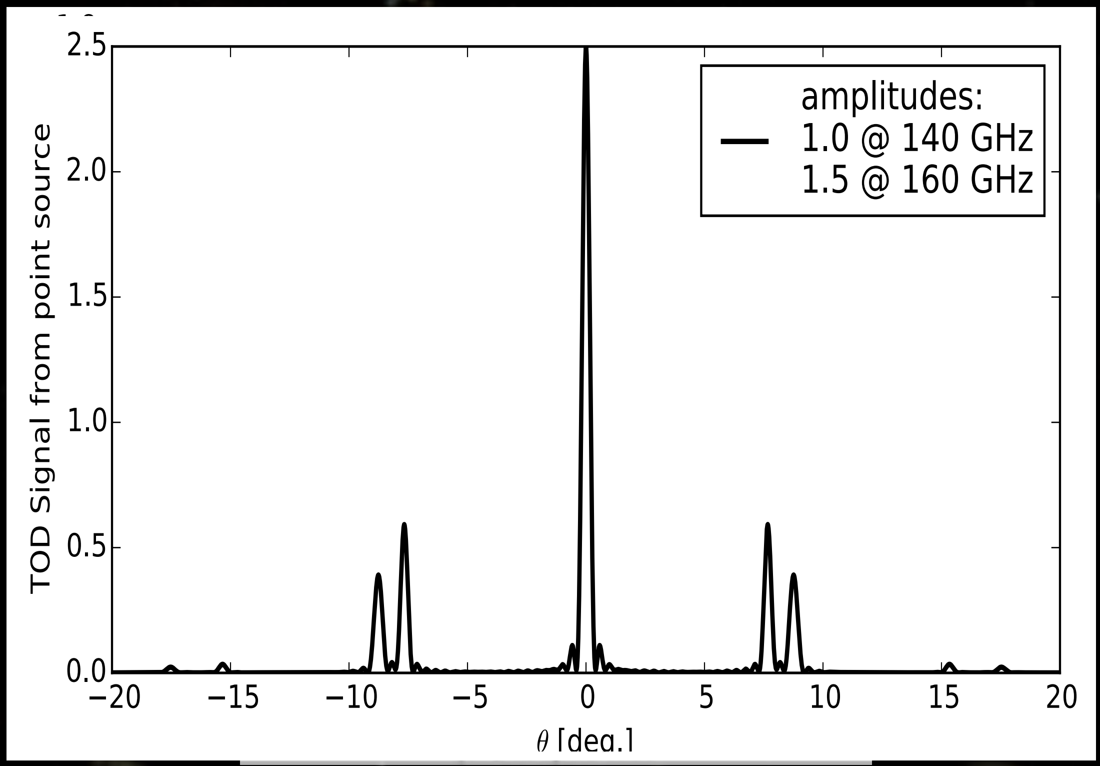
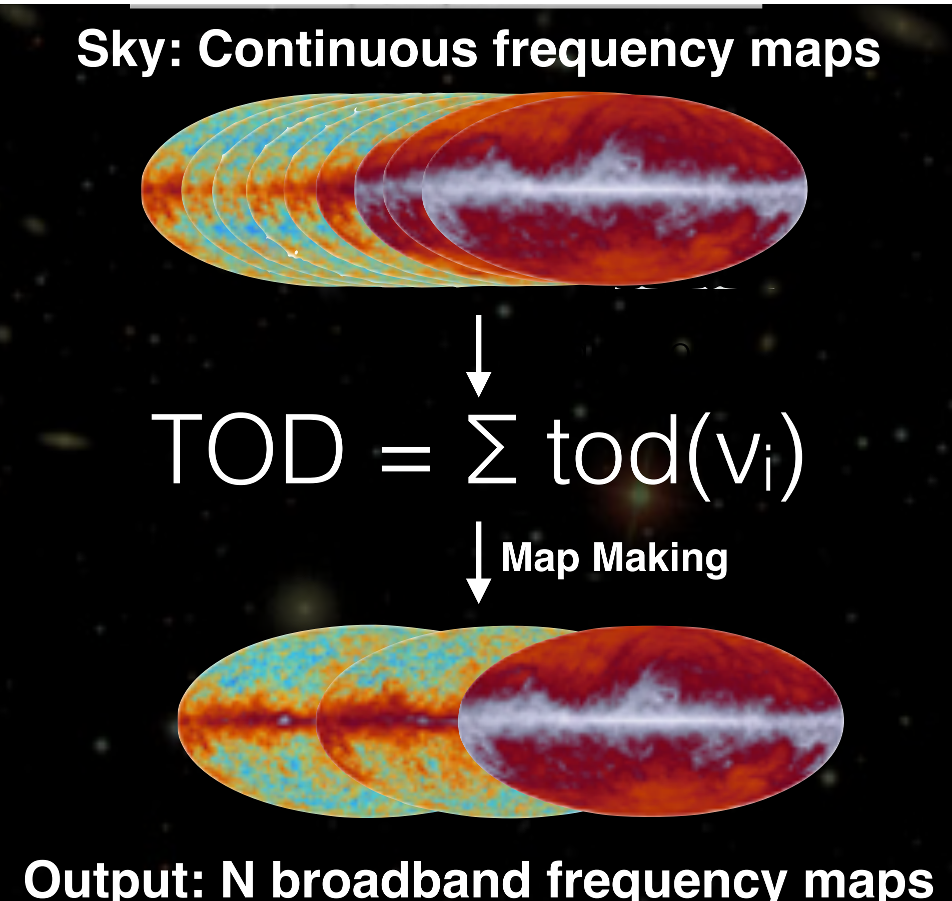
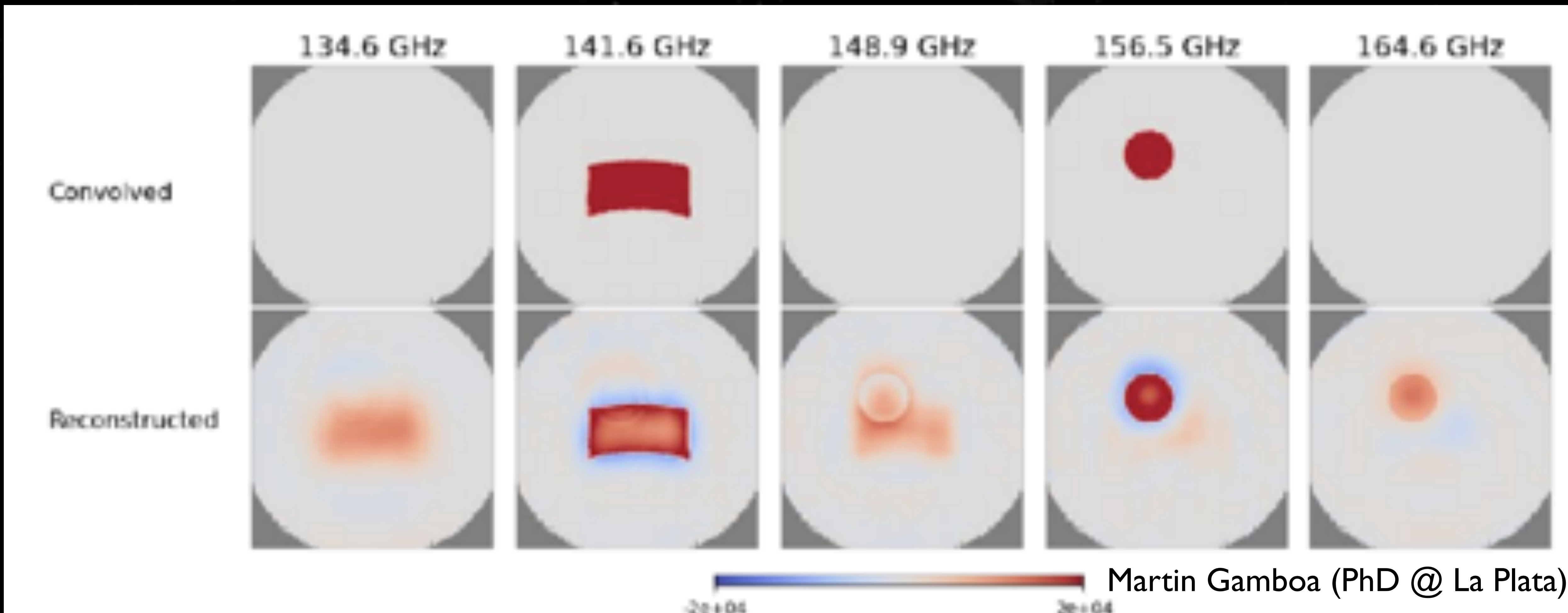
    - ex: a point source emitting at 140 and 160 GHz
- There is spatial + frequency information !
- Multi-frequency map-making with **a single wide-band TOD**
  - ★ Spectral resolution $\Delta\nu/\nu \sim 0.05$
  - ★ Shown to be quasi-optimal with simulations
  - ★ article being finalized





Spectro-Imaging toy model

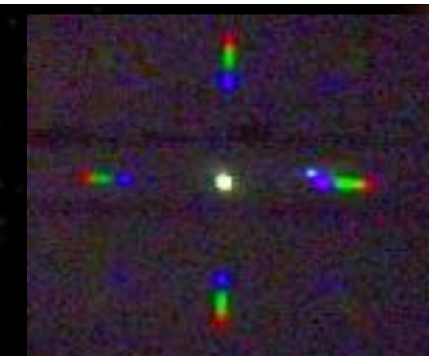
Sky signal is integrated over a single wide-band filter
But we can reconstruct sub-band information !



Martin Gamboa (PhD @ La Plata)

[Mousset, Gamboa et al., https://arxiv.org/abs/2010.15119]

White light



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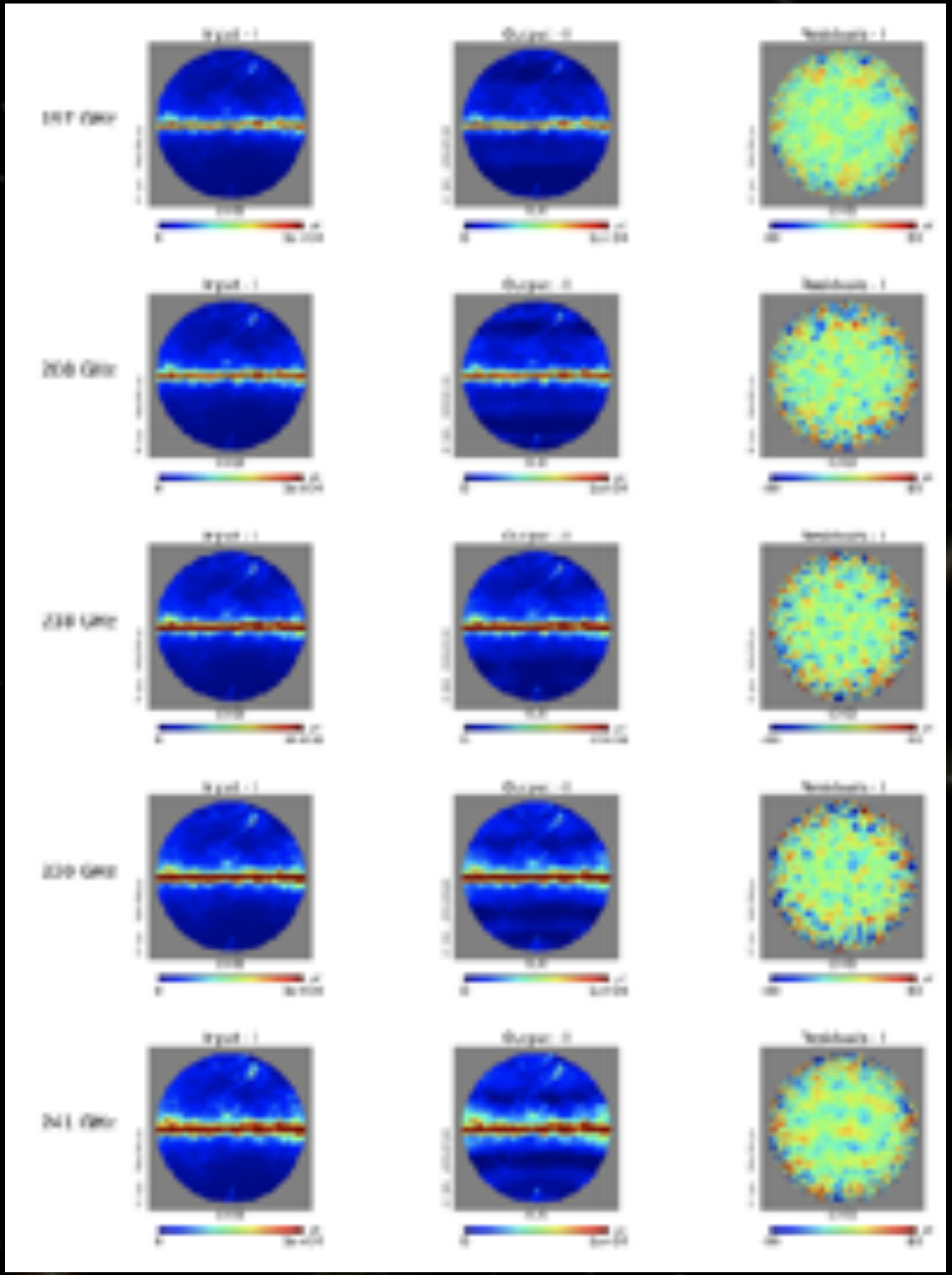
Realistic Simulations (Dust)

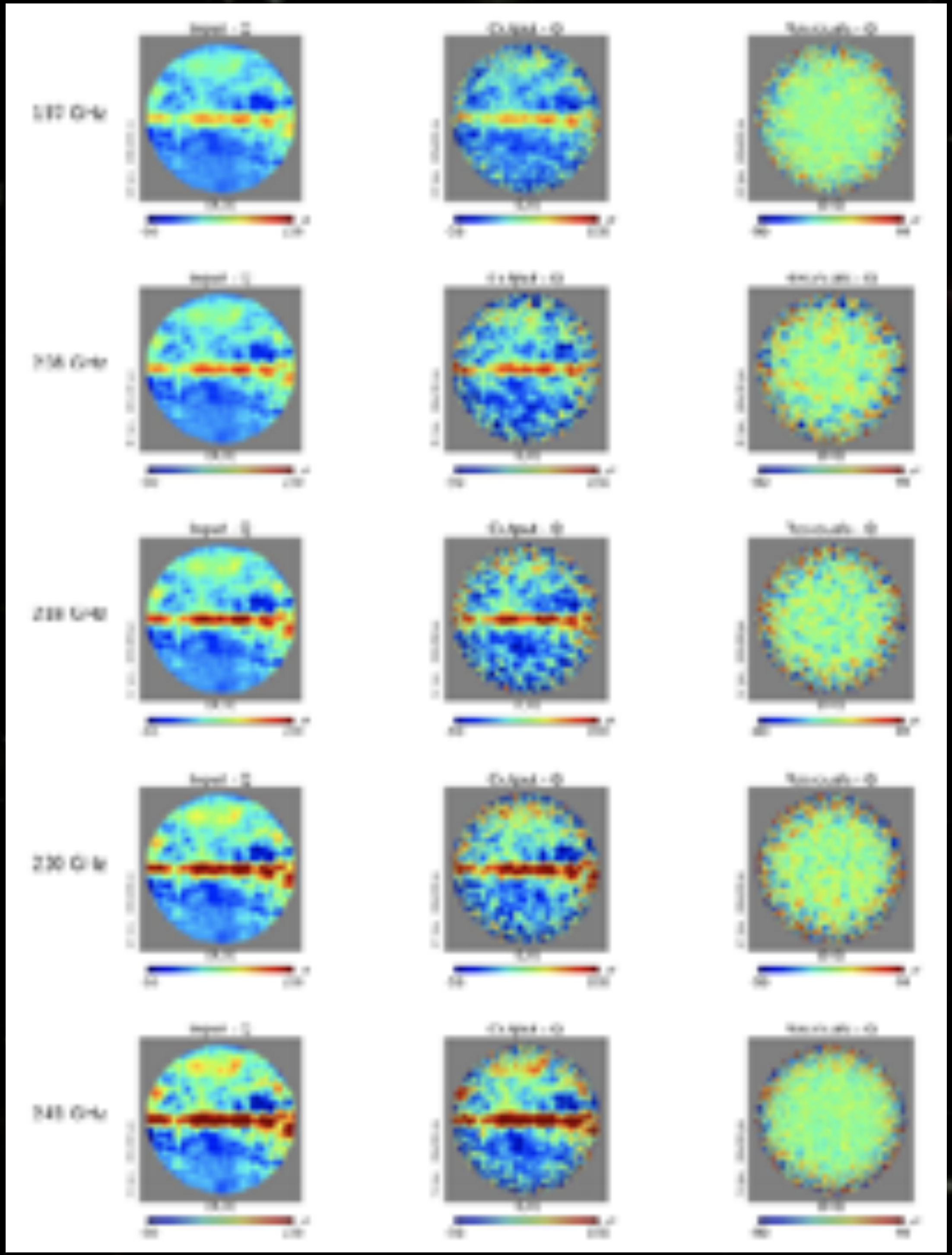
[Mousset, Gamboa et al., https://arxiv.org/abs/2010.15119]

Wide-band filter at 220 GHz

Total Intensity (Stokes I)



Polarization (Stokes Q)



Louise Mousset (PhD @ APC)

QUBIC Spectro-Imaging

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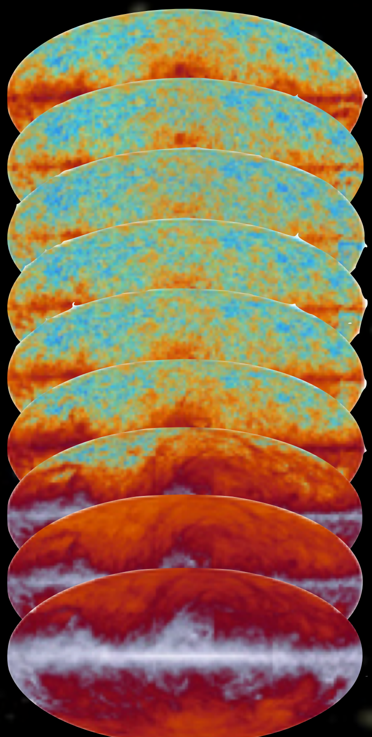
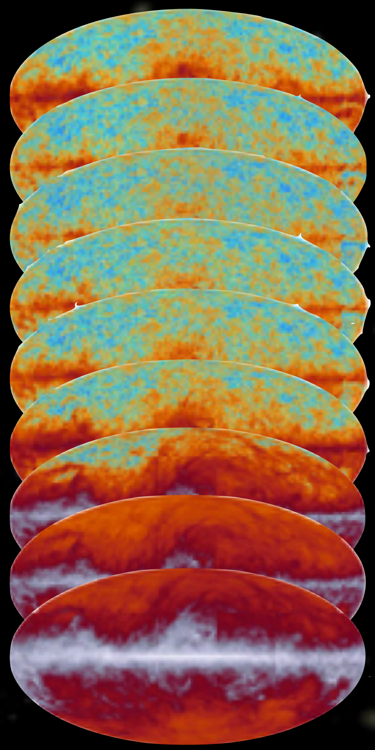
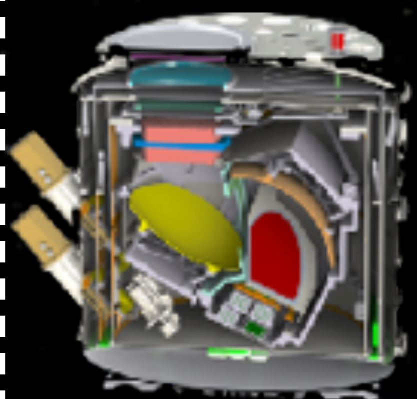


Sky:
« Infinite # bands »

QUBIC Spectro-Imaging





Sky:
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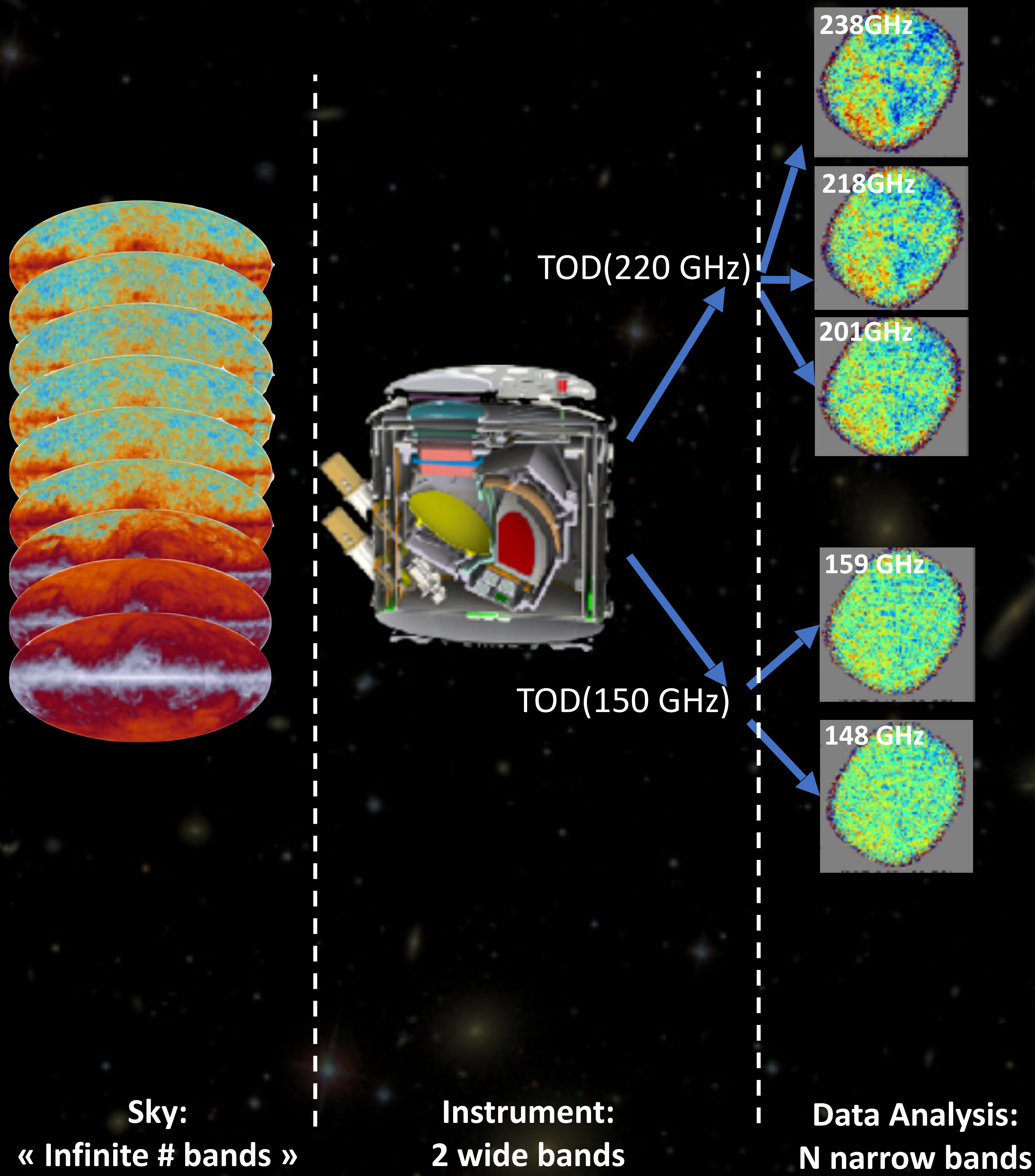
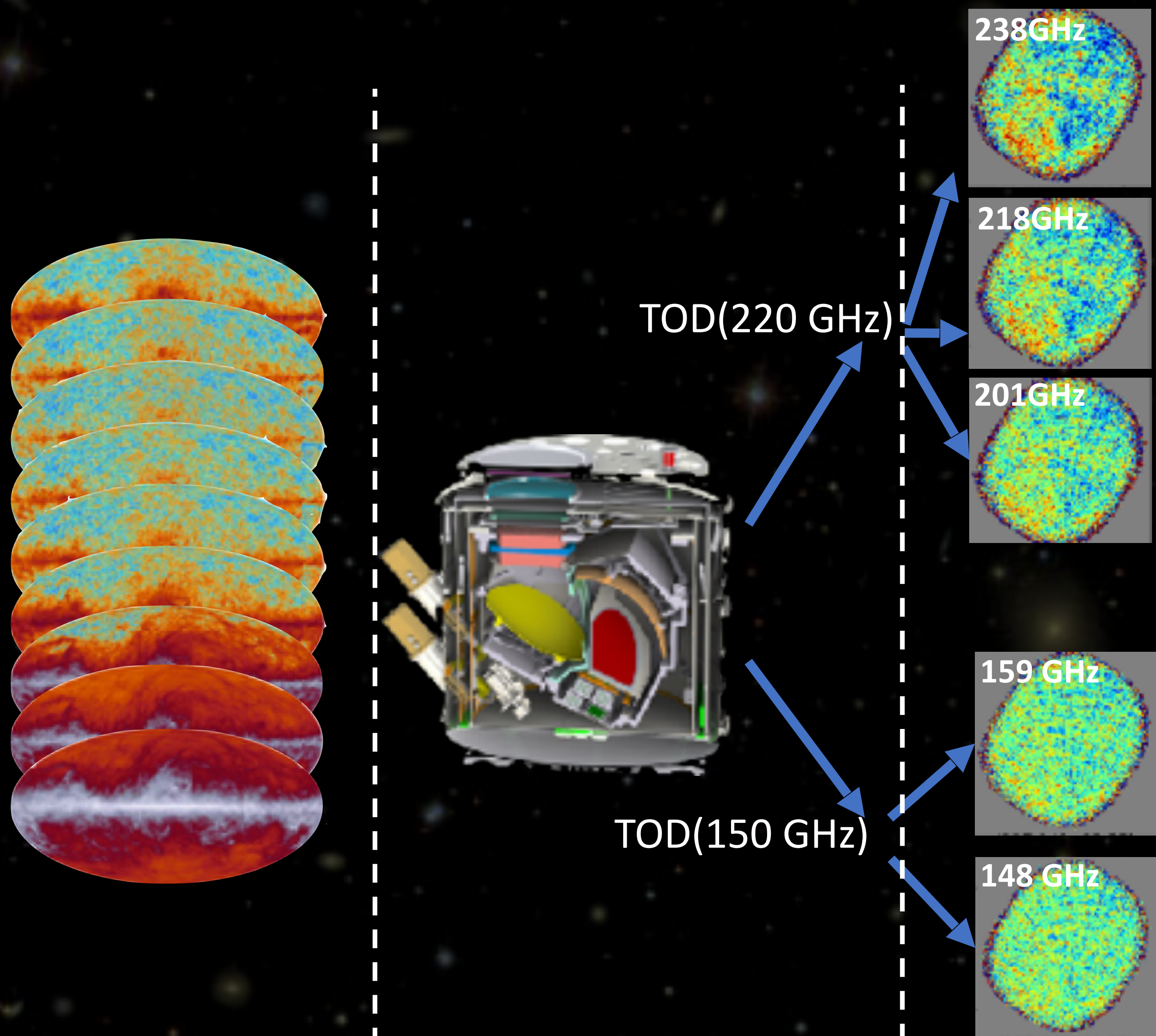
Instrument:
2 wide bands

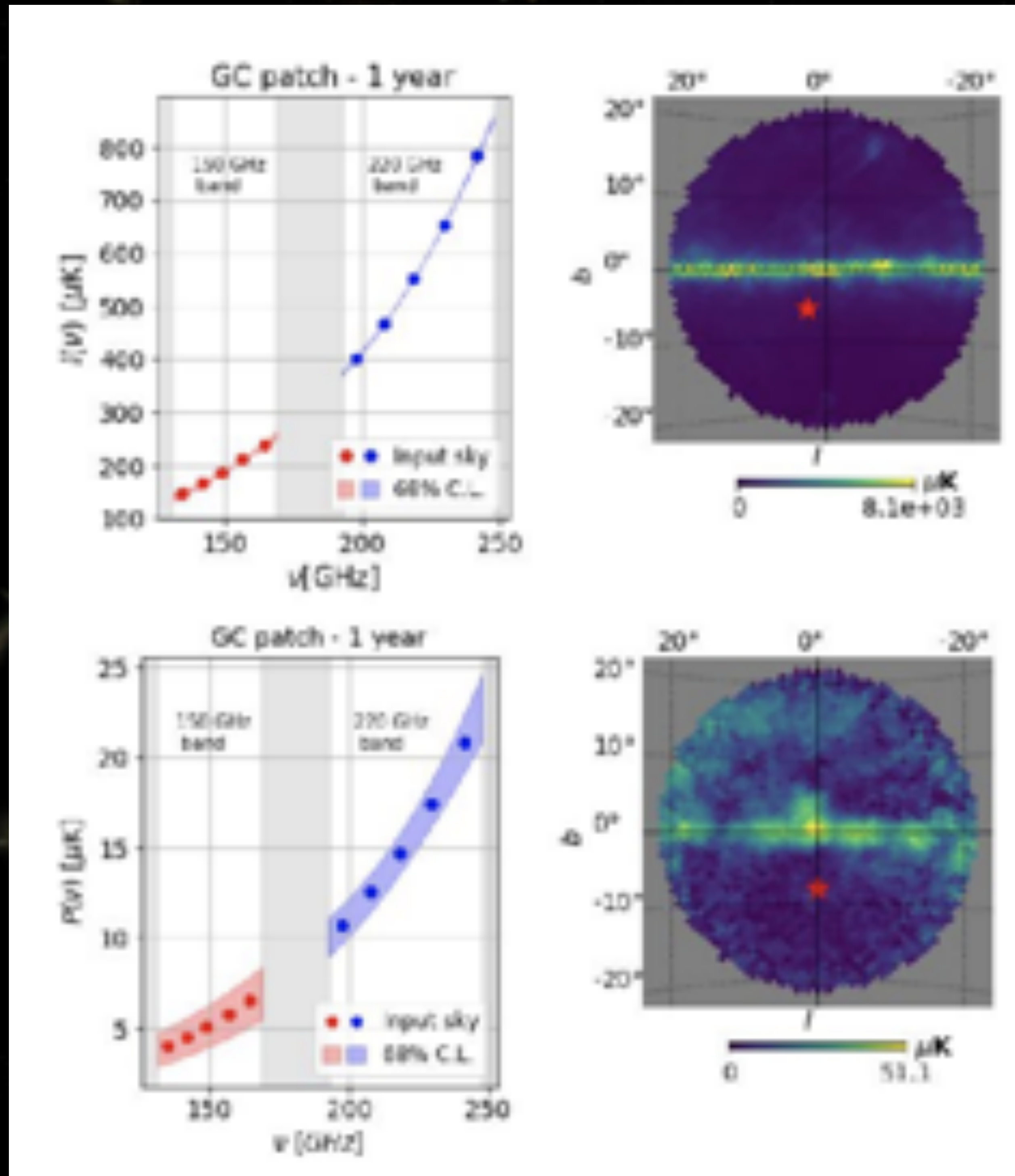
QUBIC Spectro-Imaging



QUBIC Spectro-Imaging

[Hamilton, Mousset et al., https://arxiv.org/abs/2011.02213]





Sky:
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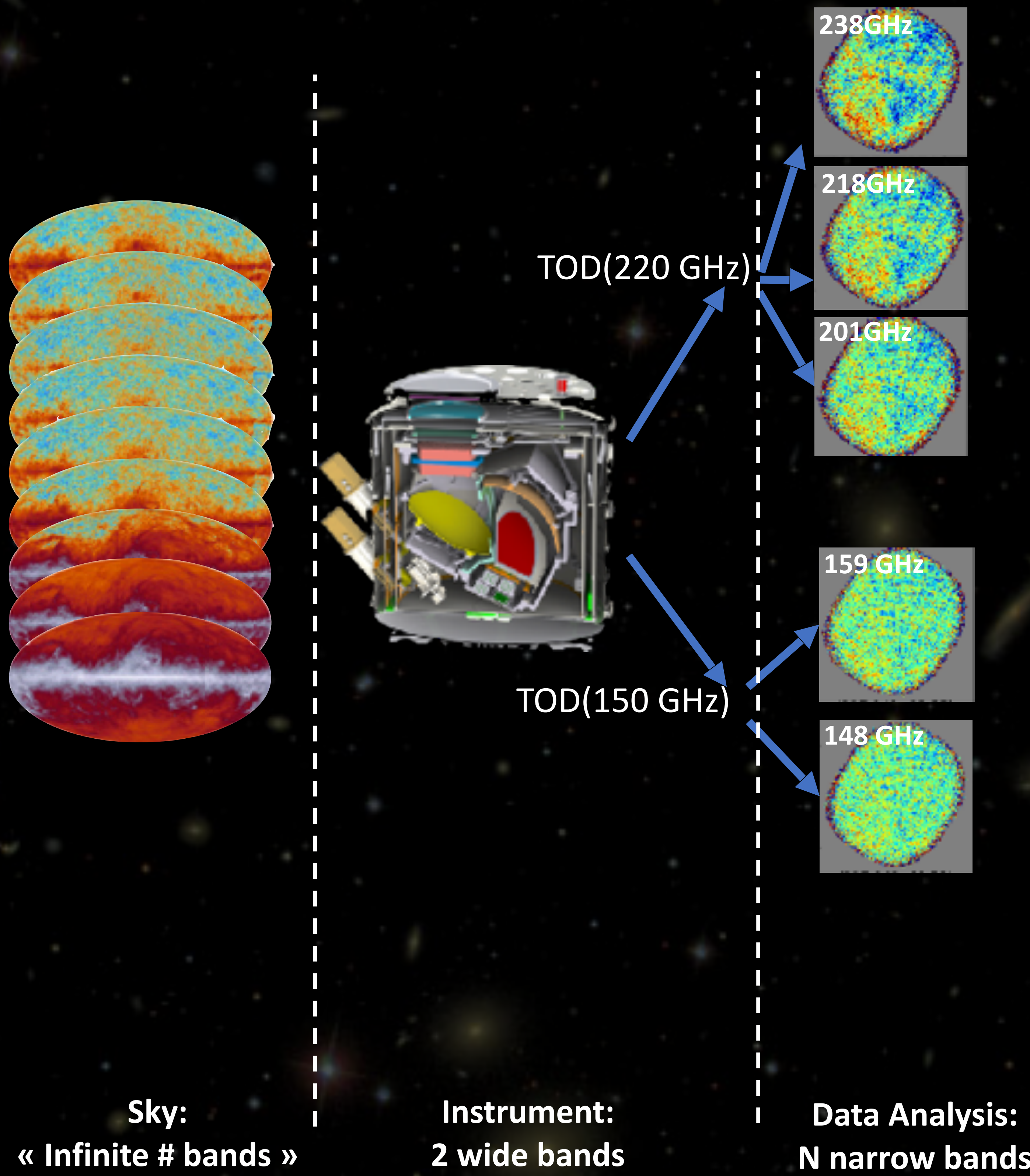
Instrument:
2 wide bands

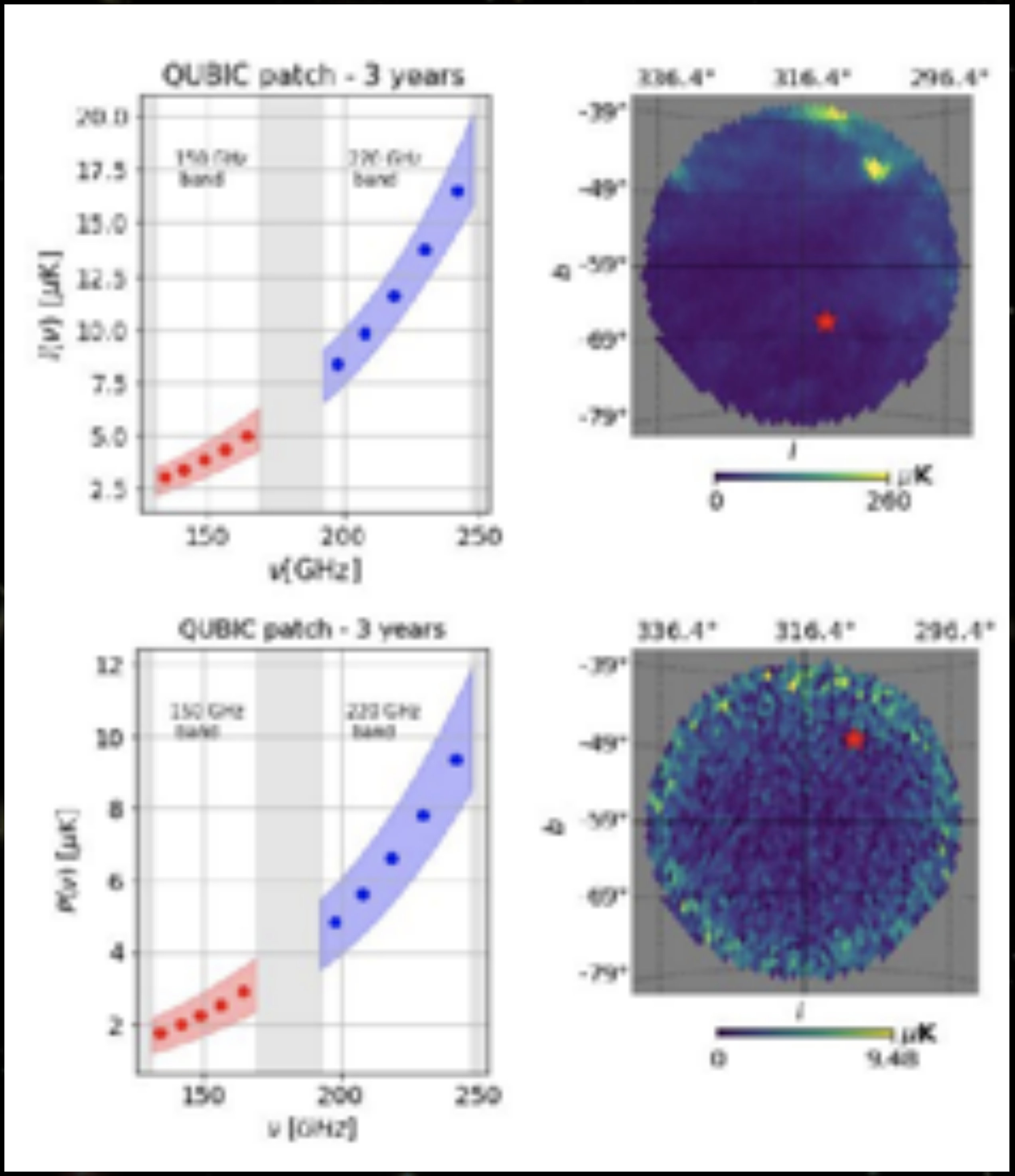
Data Analysis:
N narrow bands

Martin Gamboa (PhD @ La Plata)

QUBIC Spectro-Imaging

[Hamilton, Mousset et al., https://arxiv.org/abs/2011.02213]



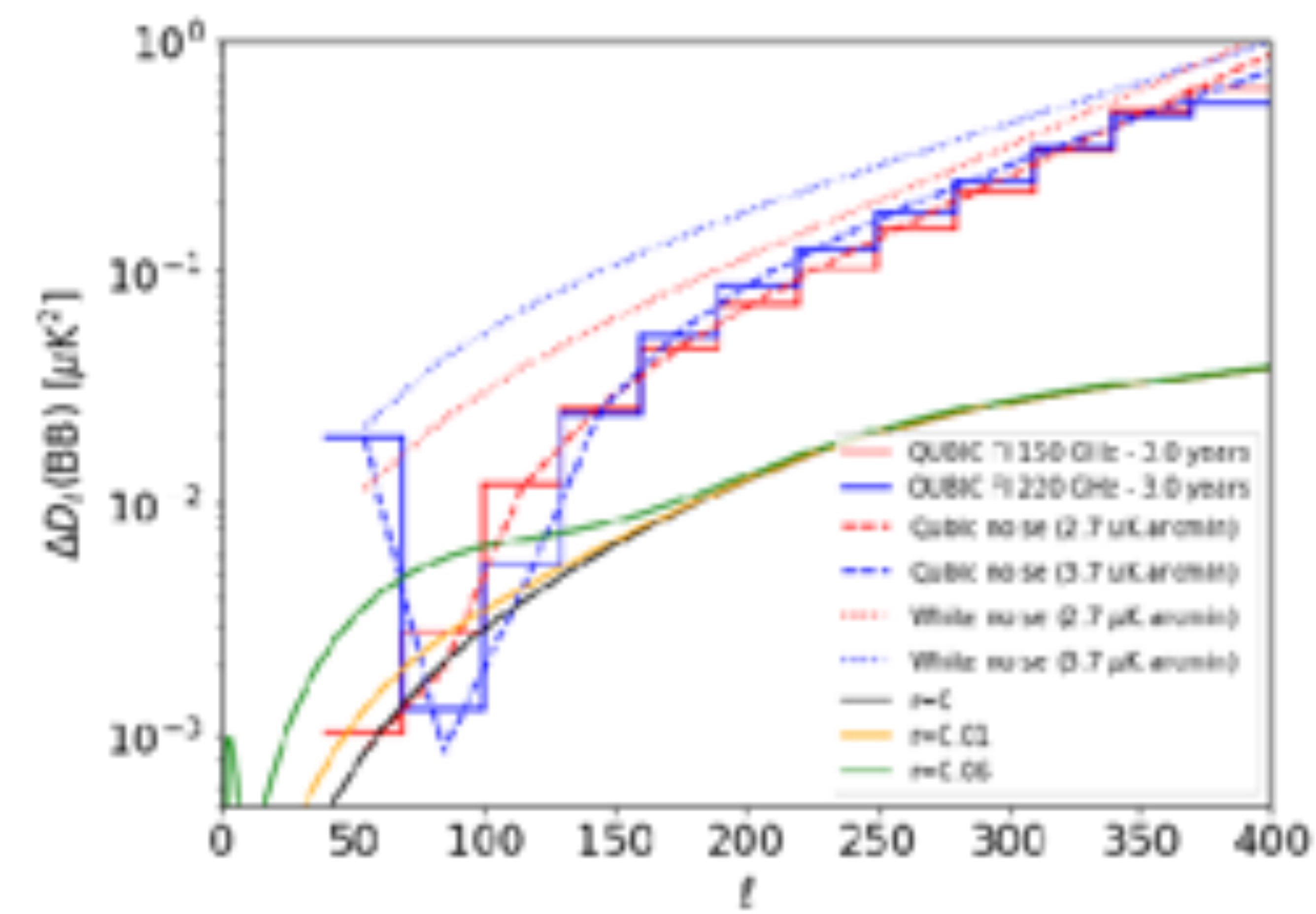


Martin Gamboa (PhD @ La Plata)

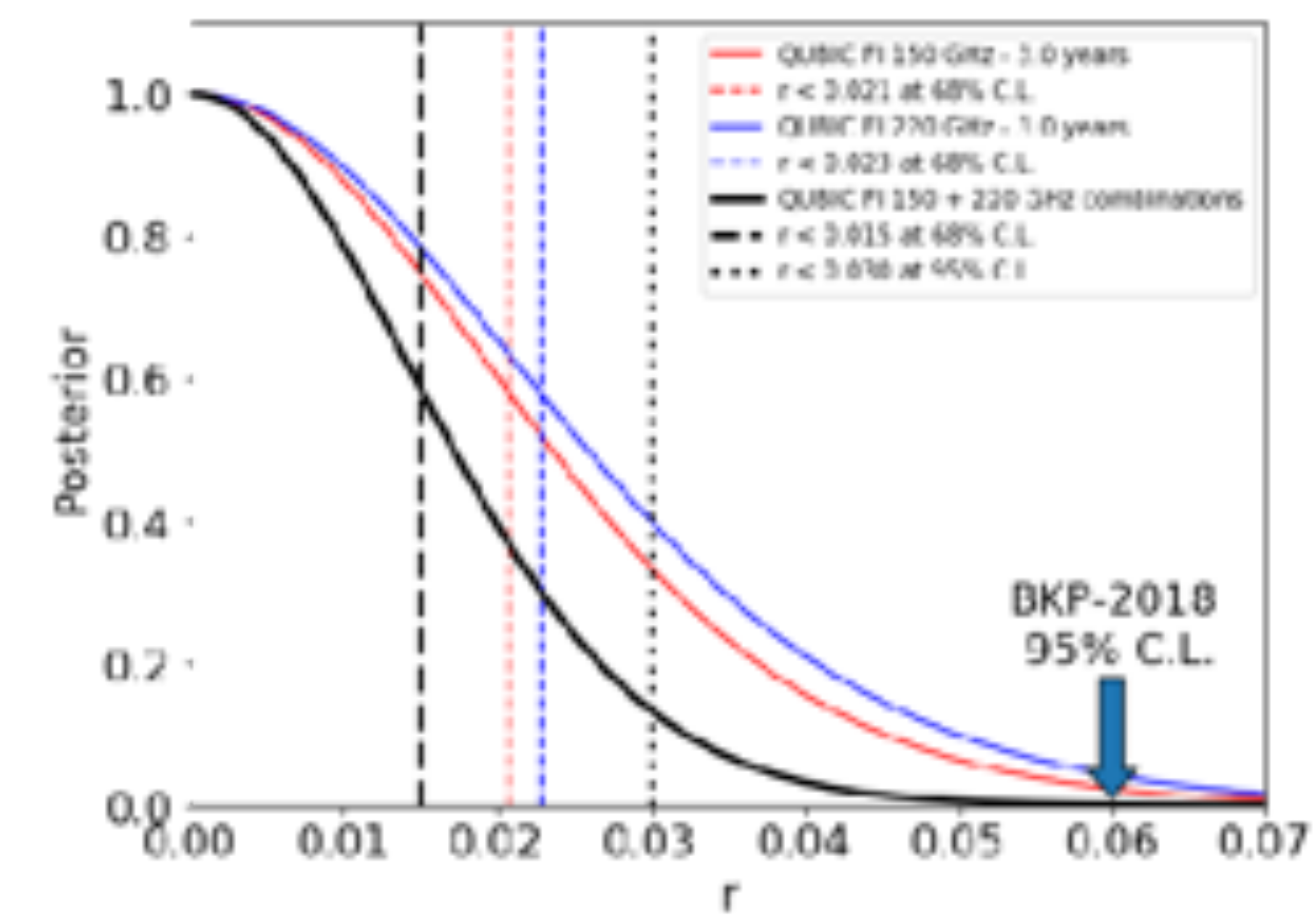
Forecast for Inflation

[Hamilton, Mousset et al., https://arxiv.org/abs/2011.02213]

Error-bars on B-modes power spectrum



Posterior likelihood on tensor-to-scalar ratio



σ(r) = 0.015 with 3 years of data
Competitive with CMB Stage III

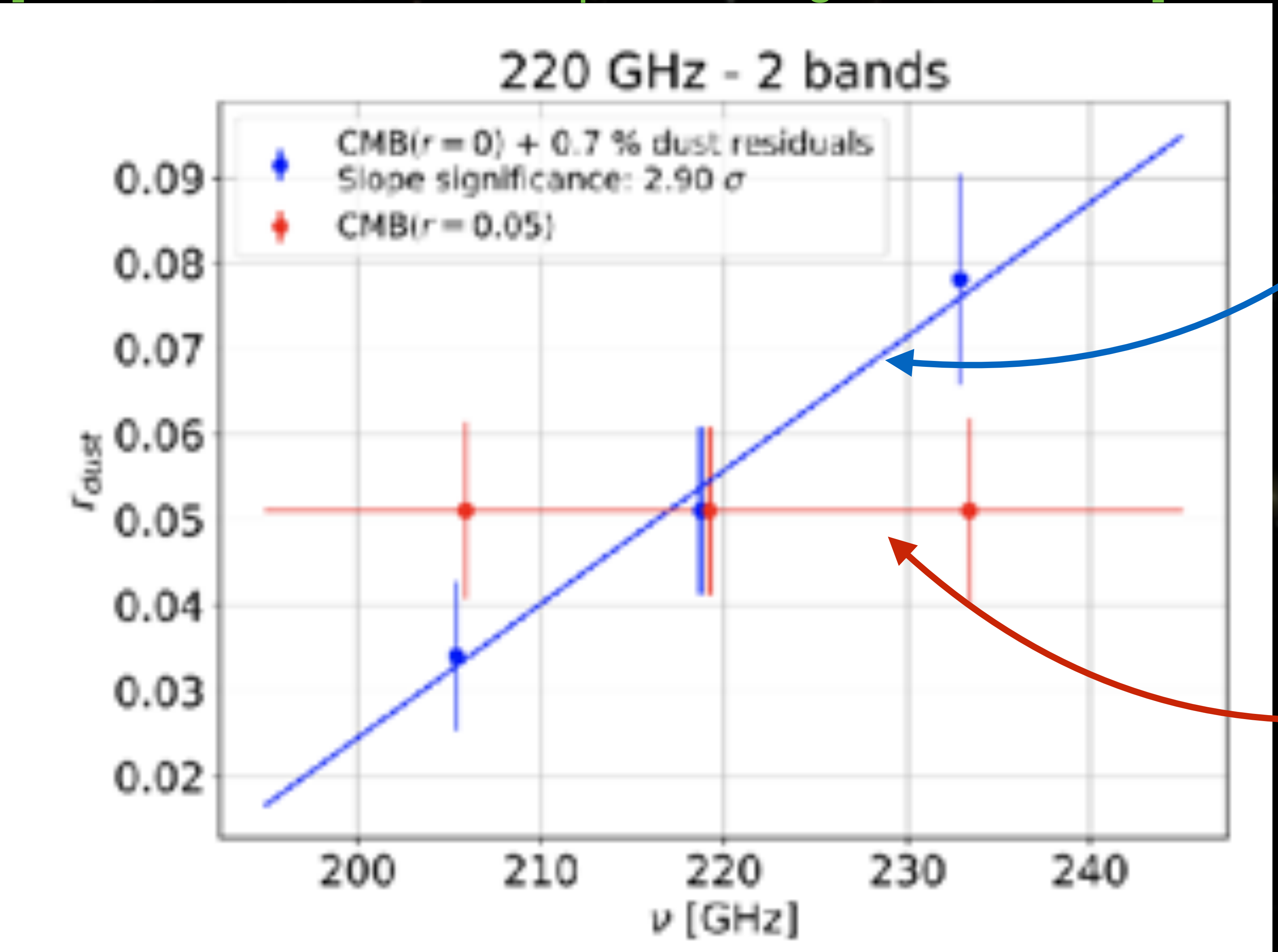
Dust contamination mitigation

[Hamilton, Mousset et al., https://arxiv.org/abs/2011.02213]

Effective tensor-to-scalar ratio (can originate from CMB and from dust) measured in μK^2

Assumed to be from a map **after imperfect component separation**

⇒ **Dust residuals remain**



Louise Mousset (PhD @ APC)

We can distinguish dust residuals down to 0.7% at the ~3σ level (3 years of data)

QUBIC Deployment Plan

2018-2020 : at APC

- **Calibration successful !**
- Technological Demonstrator (reduced QUBIC)
  - 1/4 focal plane, 64 horns, small mirrors

→ In-Lab demonstration of Bolometric Interferometry

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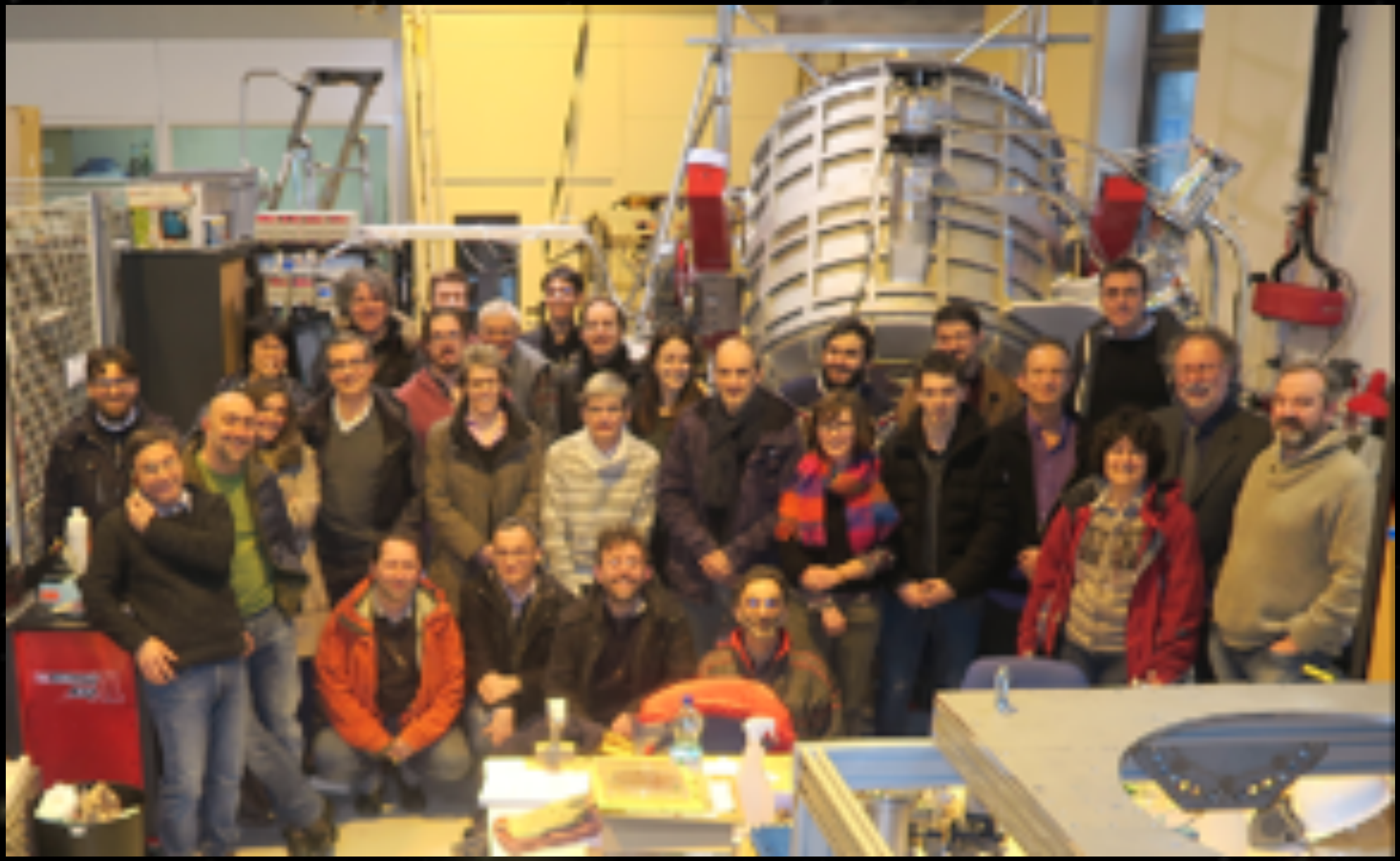
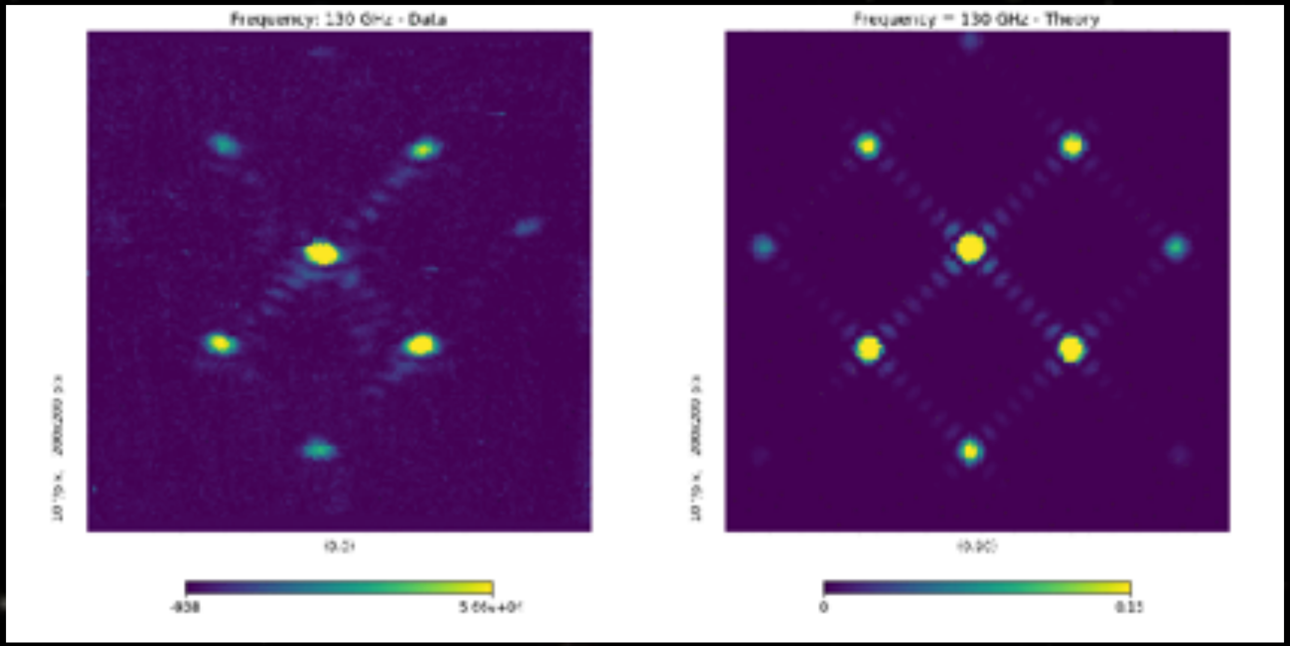


Some Lab Calibration results

[Torchinsky, Hamilton et al., https://arxiv.org/abs/2008.10056]

Synthesized beams



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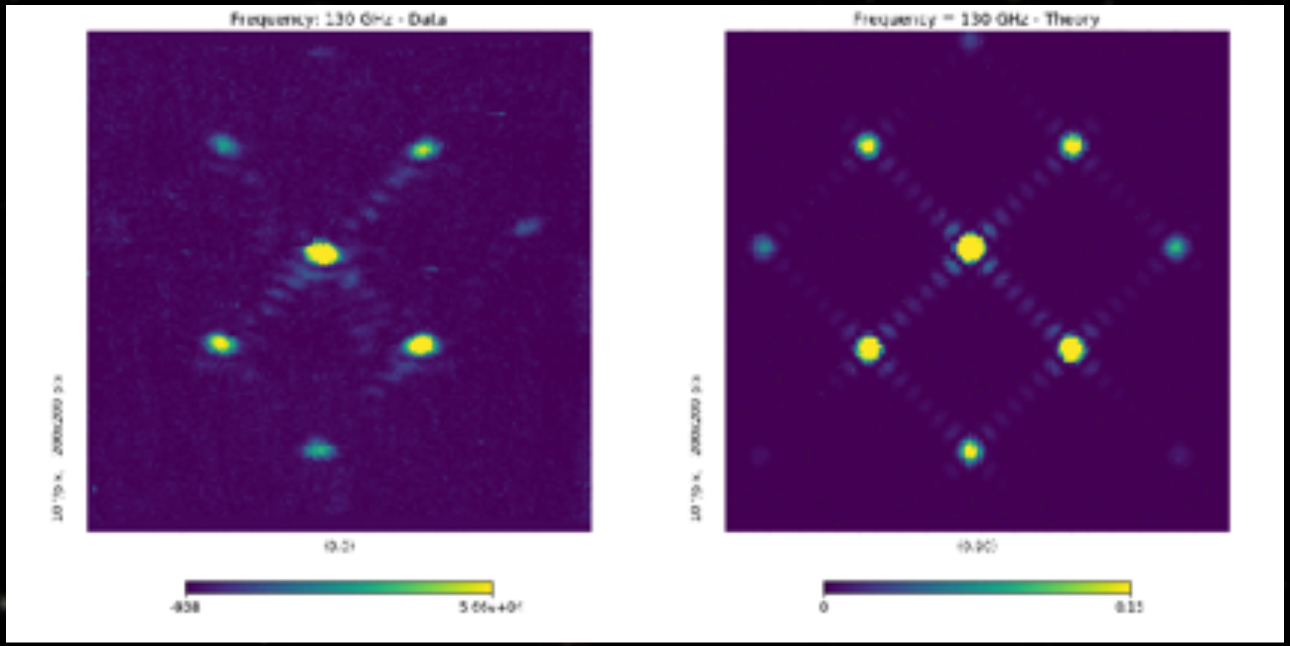

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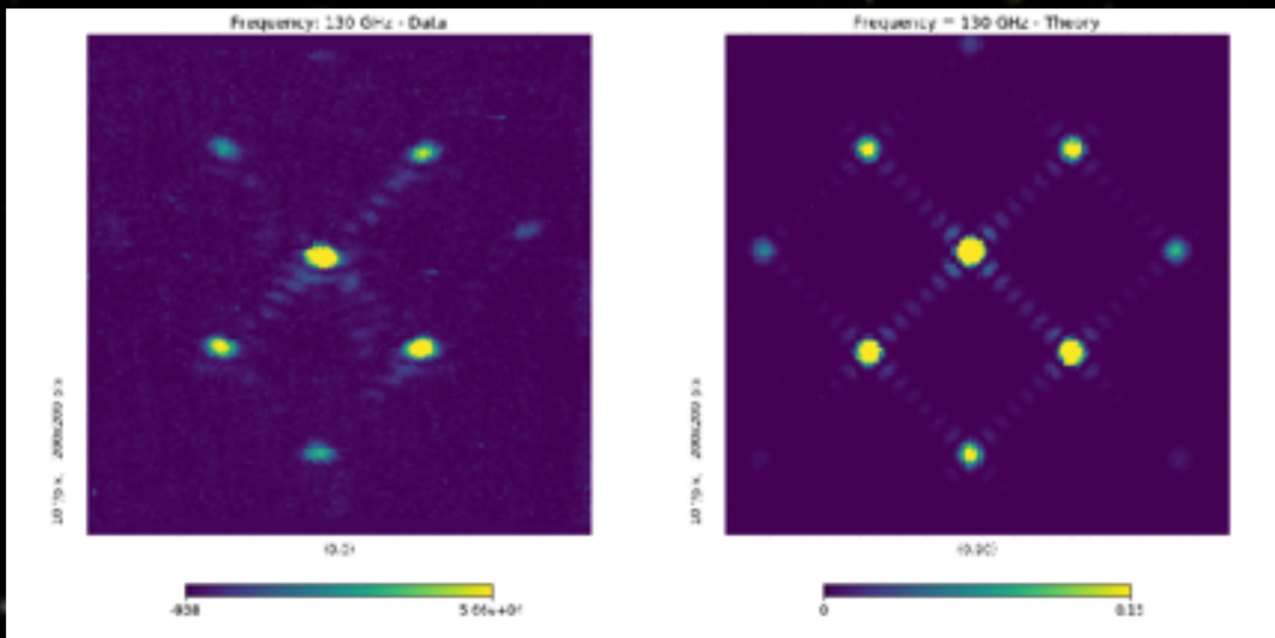
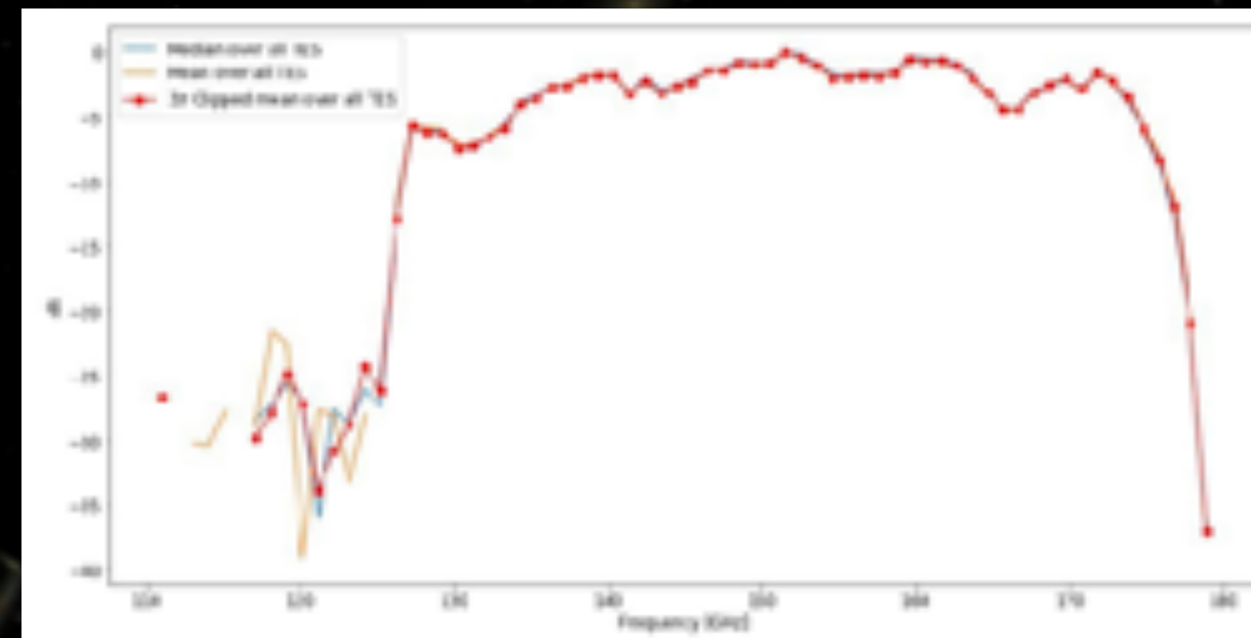


Bandwidth measurement



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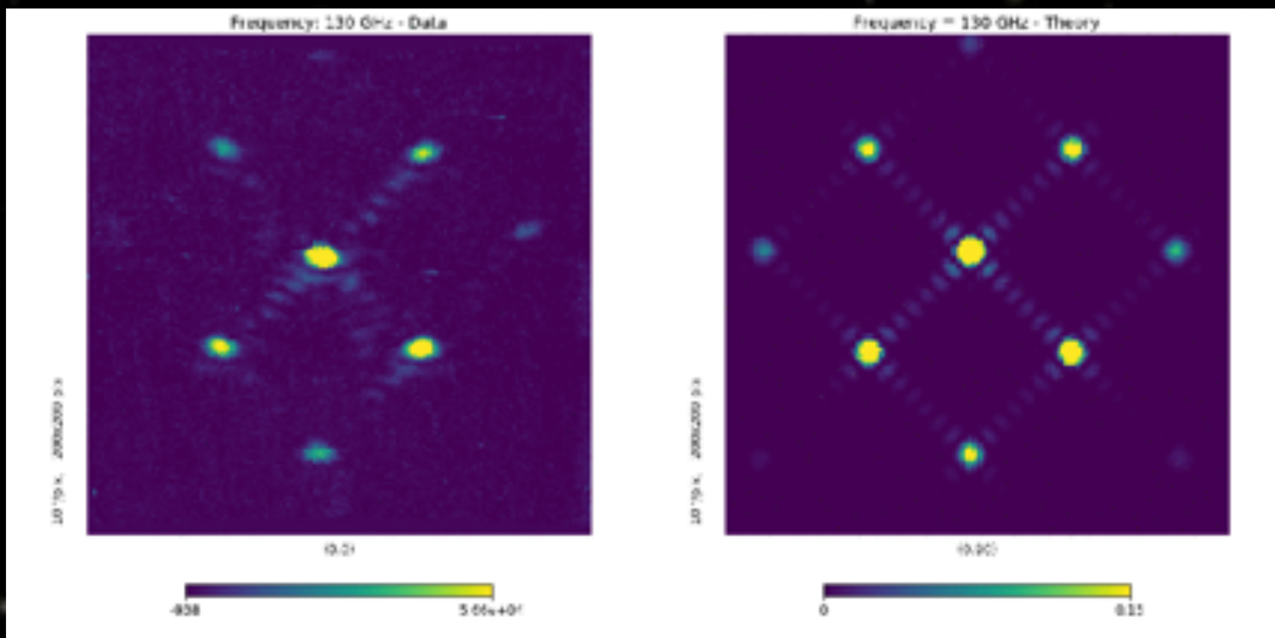

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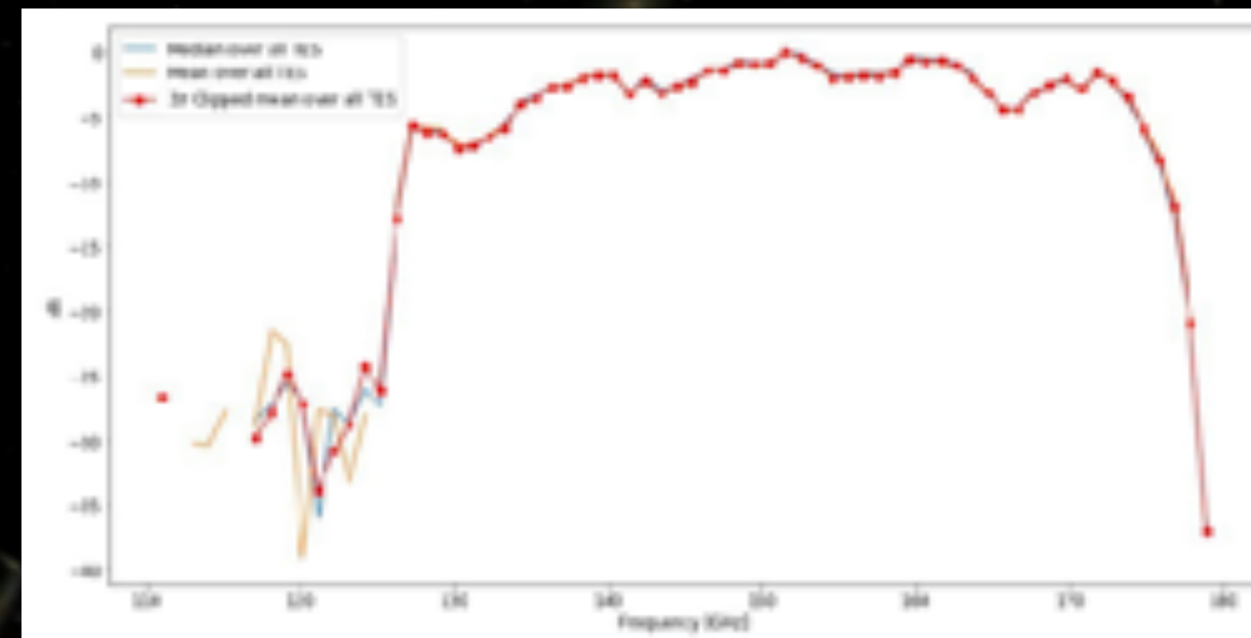
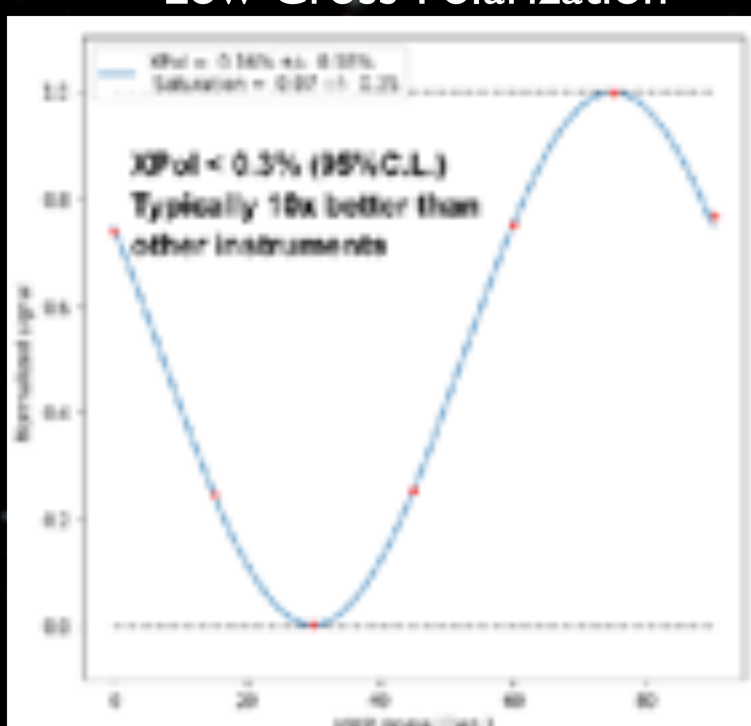


Low Cross-Polarization



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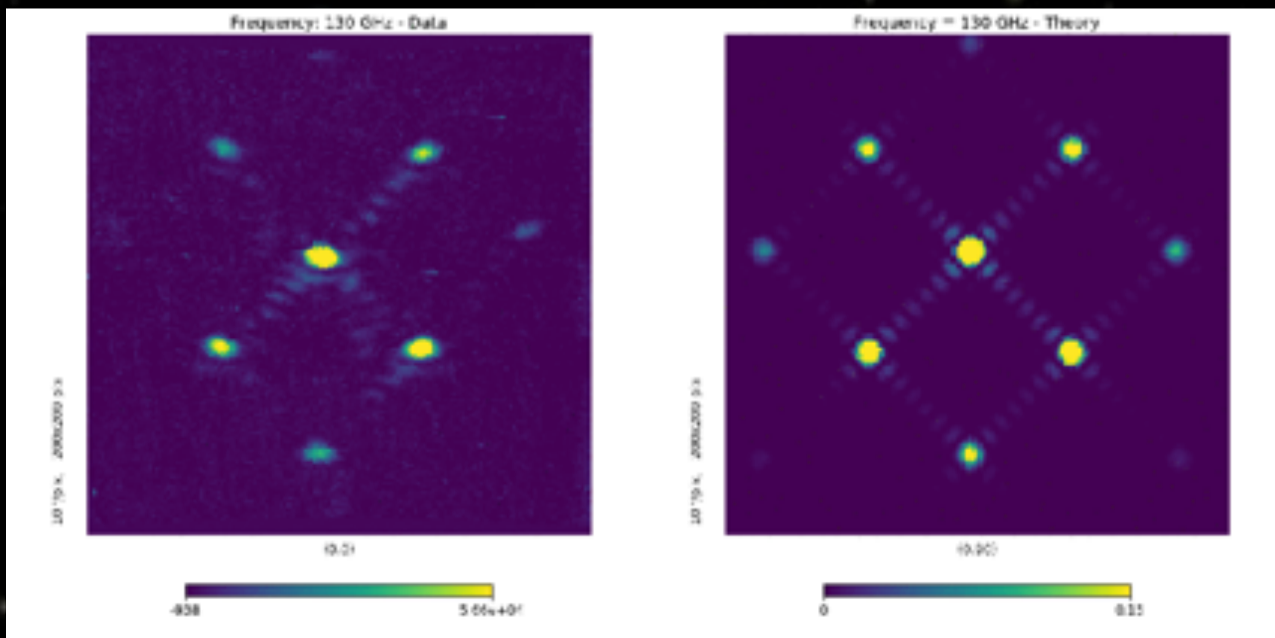

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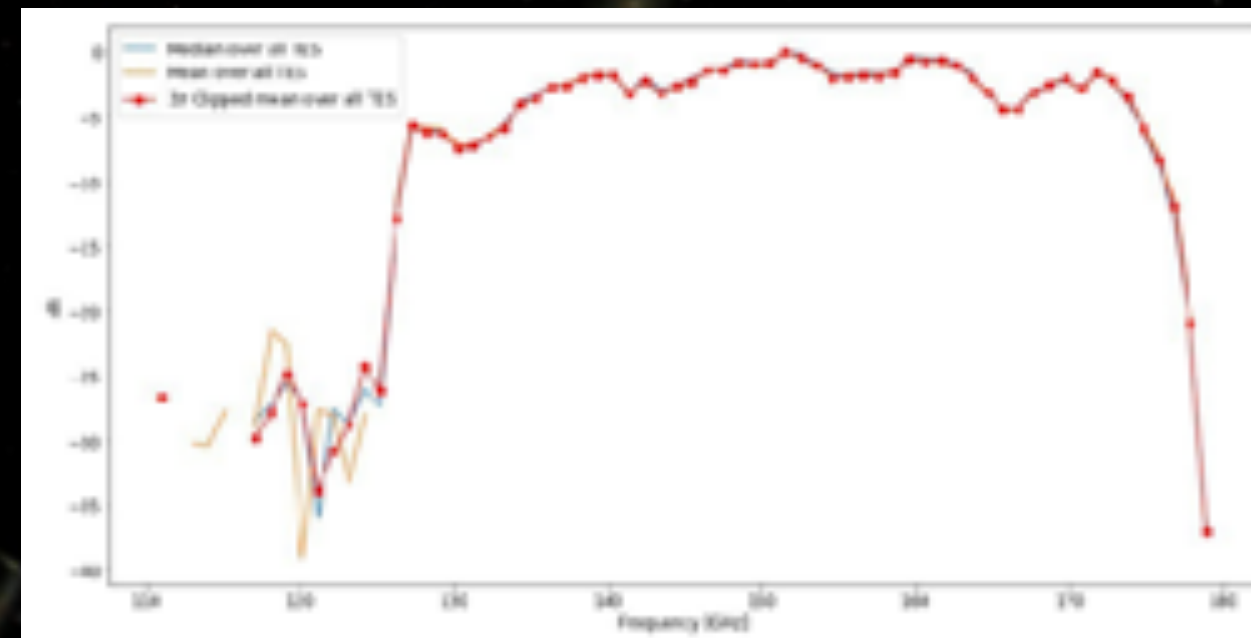

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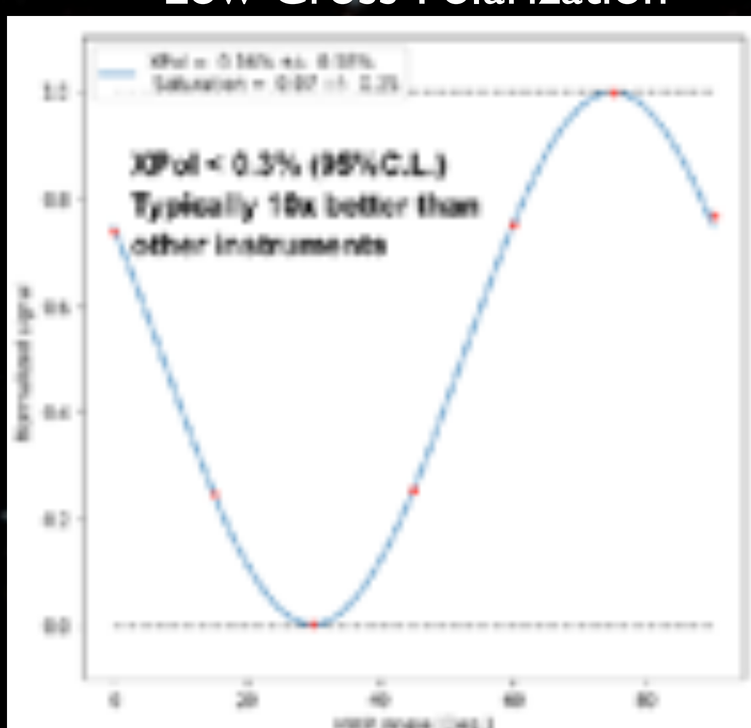
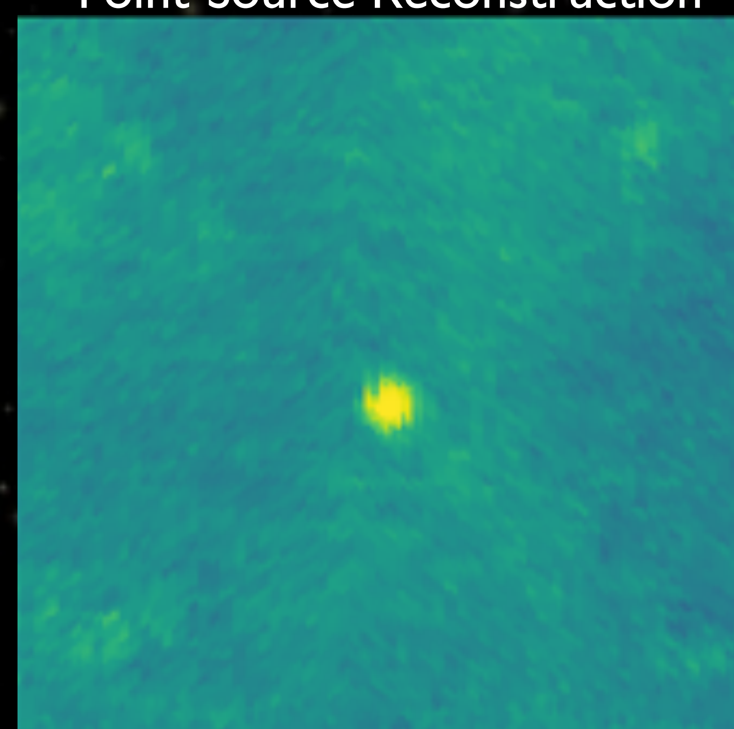


Point-Source Reconstruction



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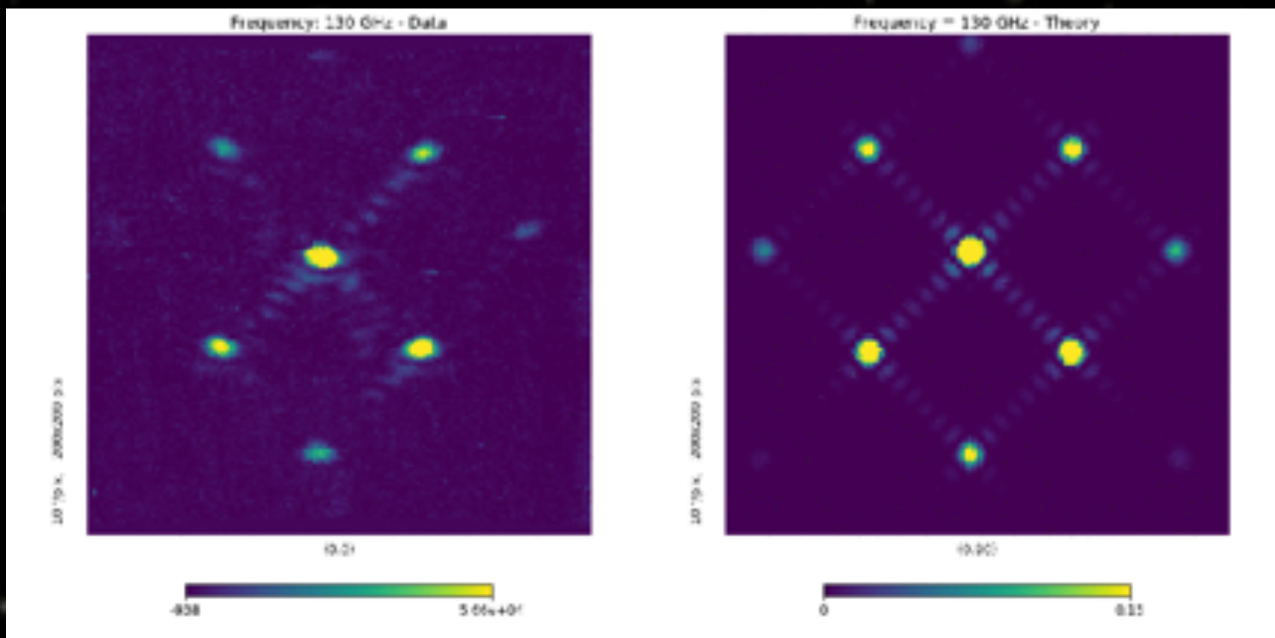

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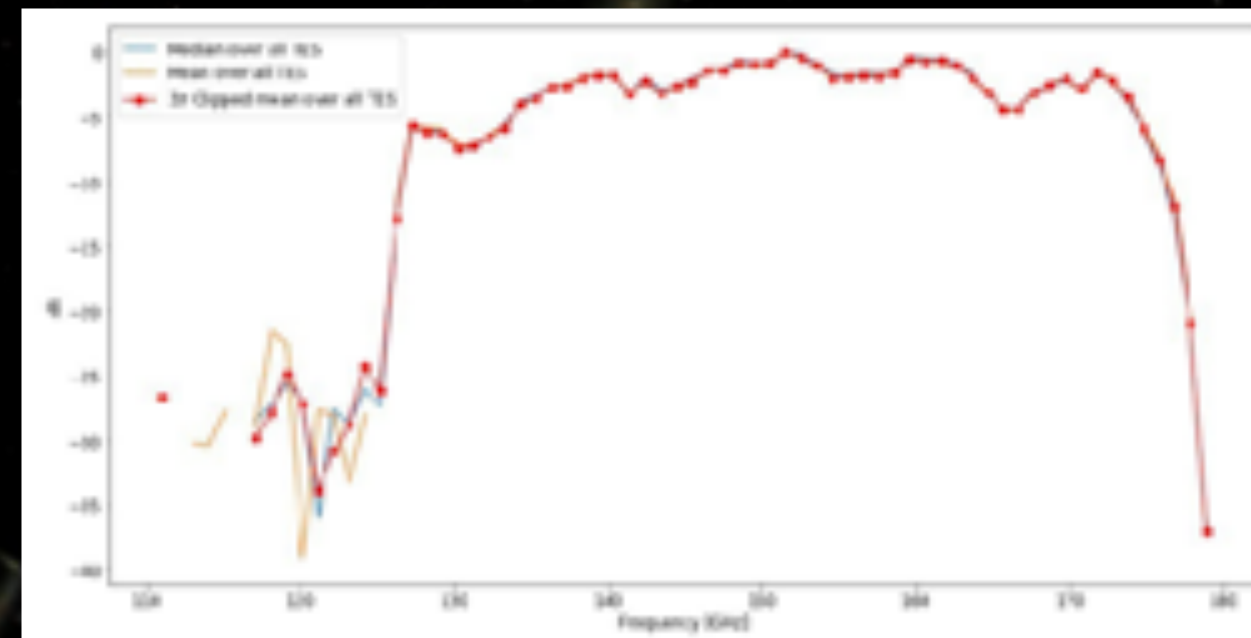
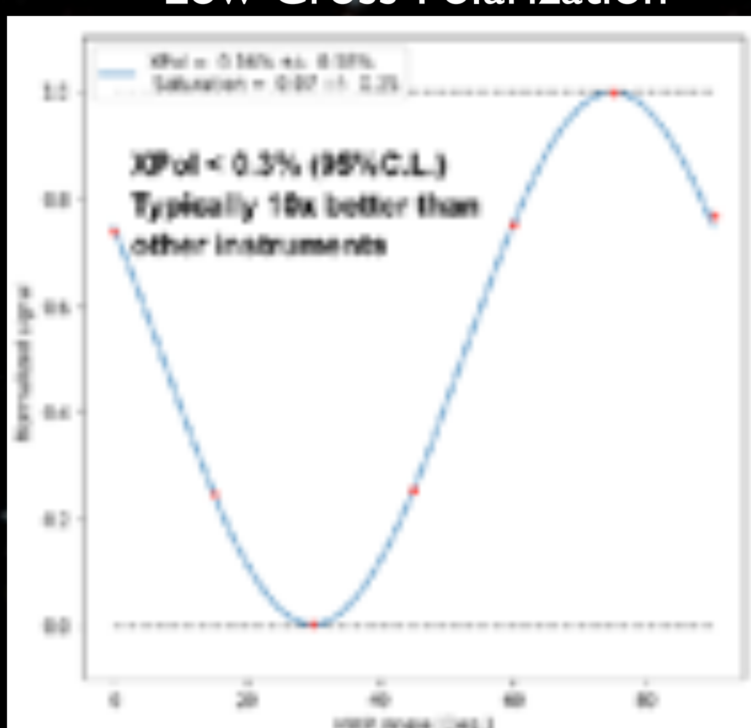
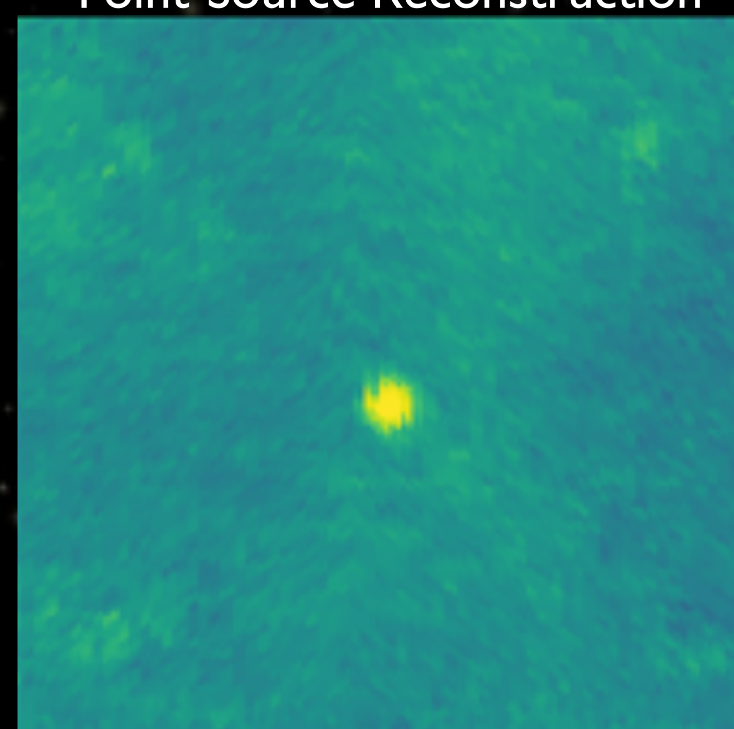


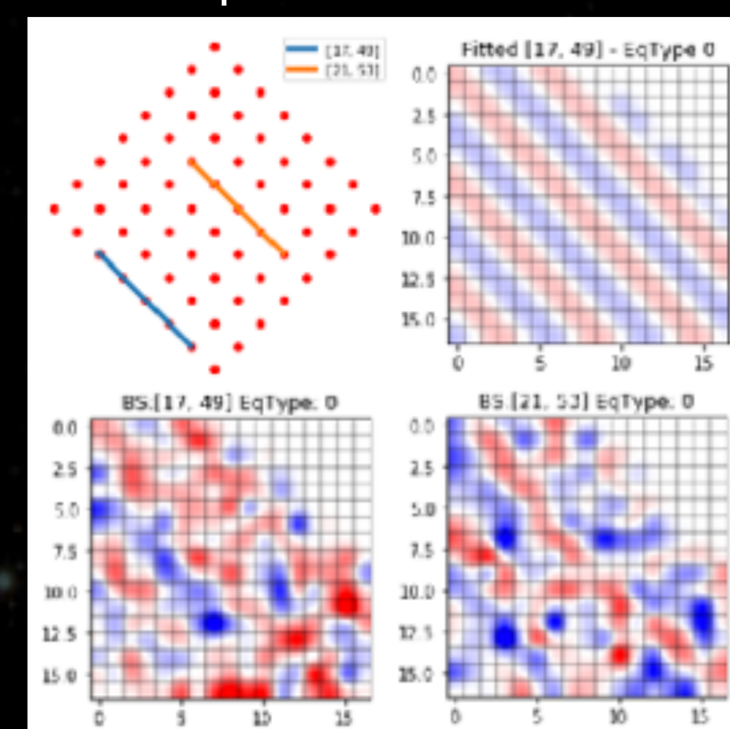
Low Cross-Polarization



Point-Source Reconstruction



Equivalent Baselines



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  - 1/4 focal plane, 64 horns, small mirrors

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In-Lab demonstration of Bolometric Interferometry

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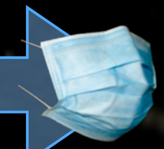

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  - Multimodes, Lower T detectors, Hex. Horn-array, ...
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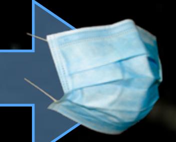

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Summary

- QUBIC is a novel instrumental concept
  - ★ First Bolometric Interferometer
  - ★ Dedicated to CMB polarimetry and inflationary physics
  - ★ High sensitivity with ~2000 TES bolometers
  - ★ Different and likely smaller instrumental systematics:
    - *Self Calibration allowed by observing individual fringe patterns (Unique to QUBIC)*
  - ★ Spectro-Imaging with two physical bands (150 / 220 GHz) and 5-10 sub-bands:
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  - ★ <u>Target :</u>
    - First module (150-220 GHz): $\sigma(r)=0.015$ (incl. dust)
    - Stage IV evolution of QUBIC $\sigma(r)=0.001$ (inc. multimodes optics, 12m LLAMA for LAT, …)

- QUBIC deployment is on the way:
  - ★ TD calibration at APC completed: Instrument compliant with expectations !
  - ★ Instrument ready to be shipped !
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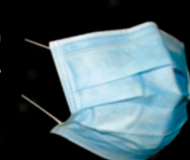
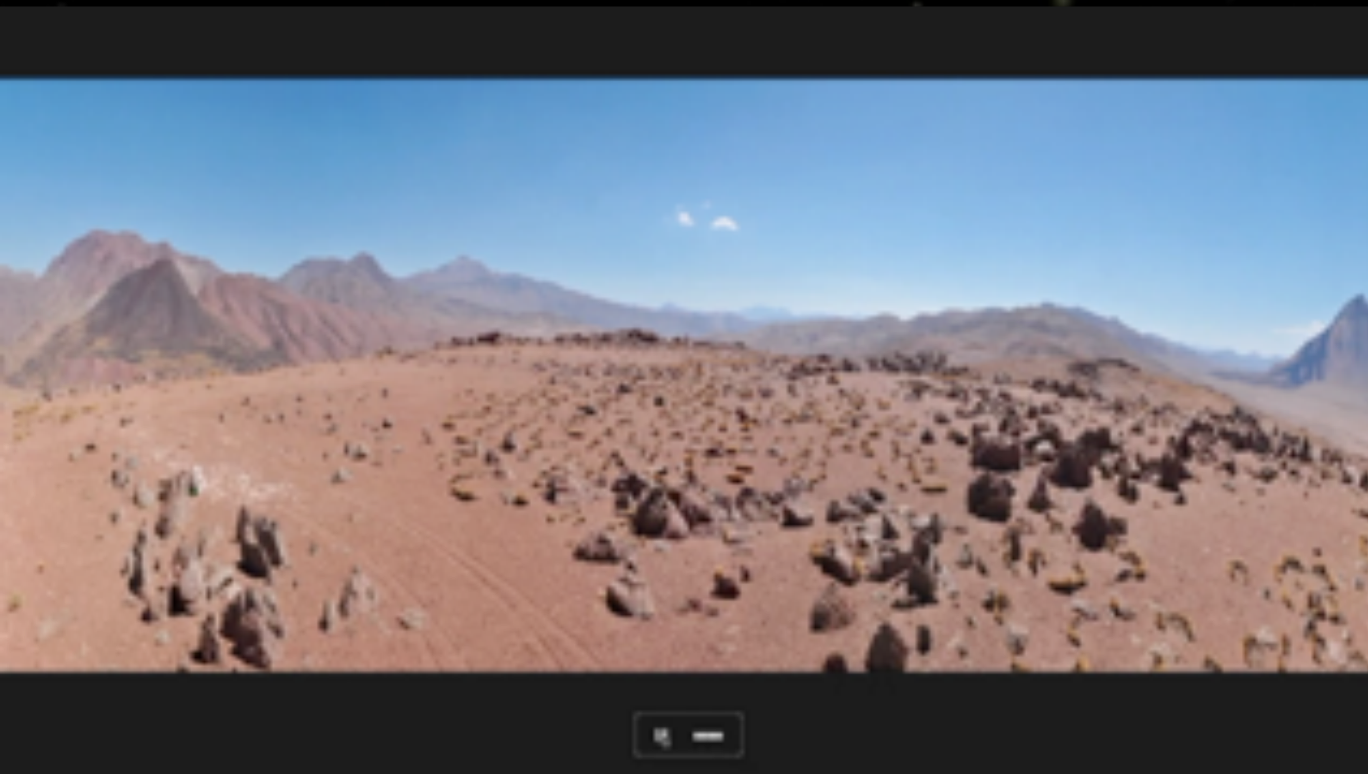


- Tired of UHECRs ? Welcome to jump-in anytime !!

Thank you

View from the site



Integration timelapse (2018)

Exciting times ahead !!!

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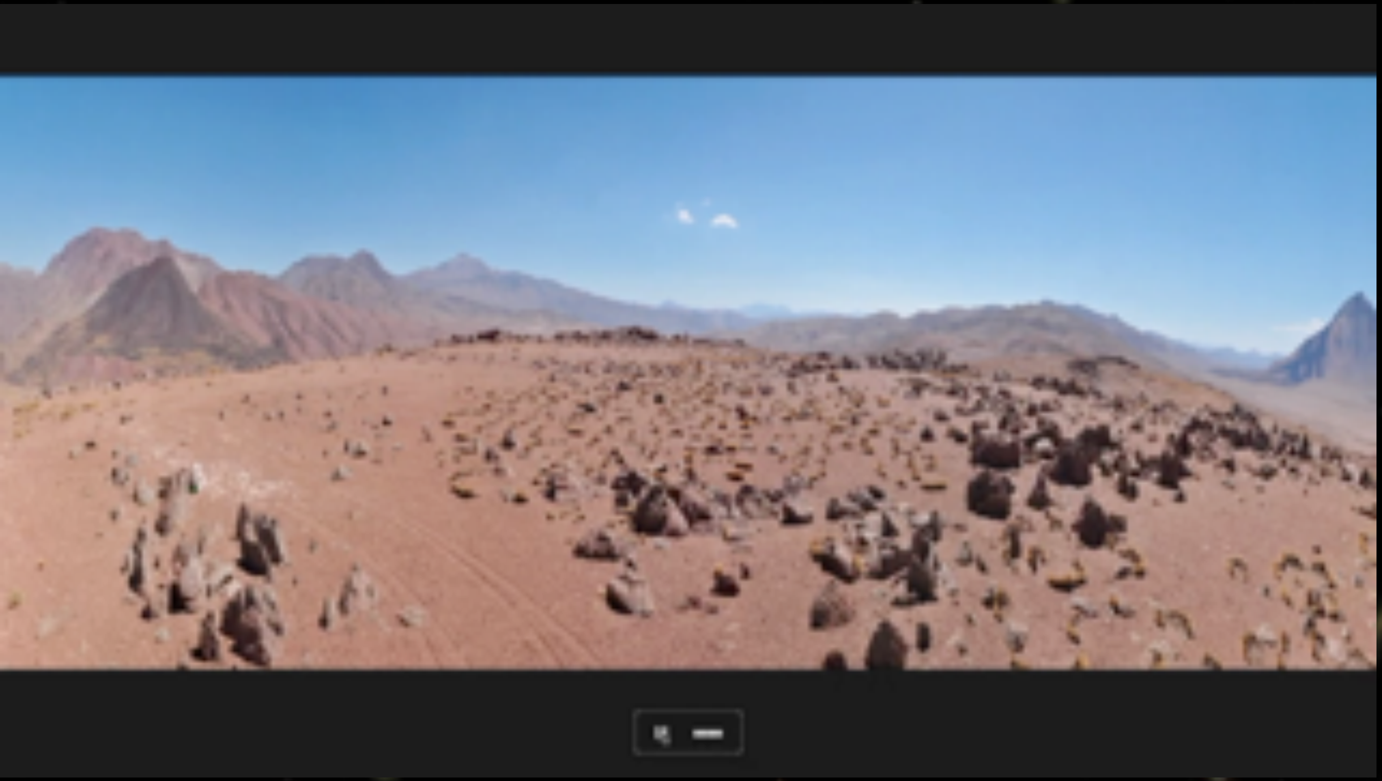

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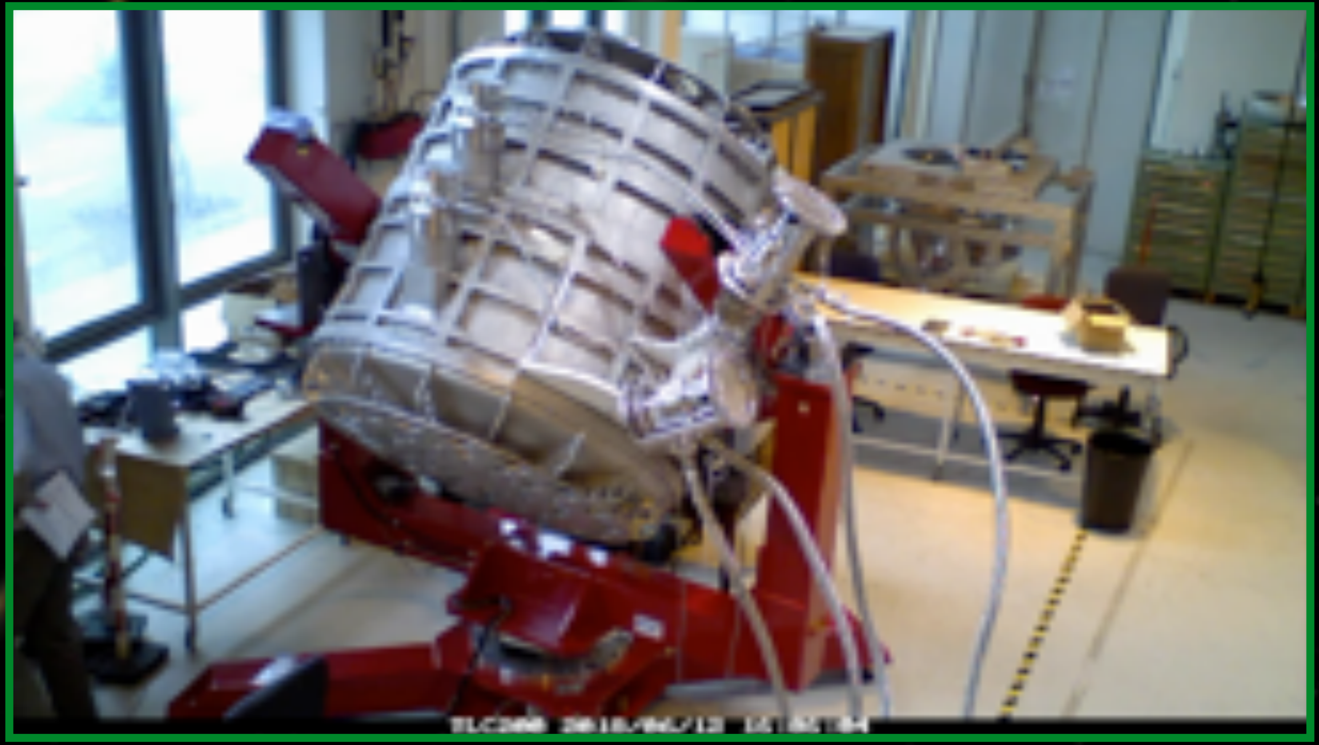

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