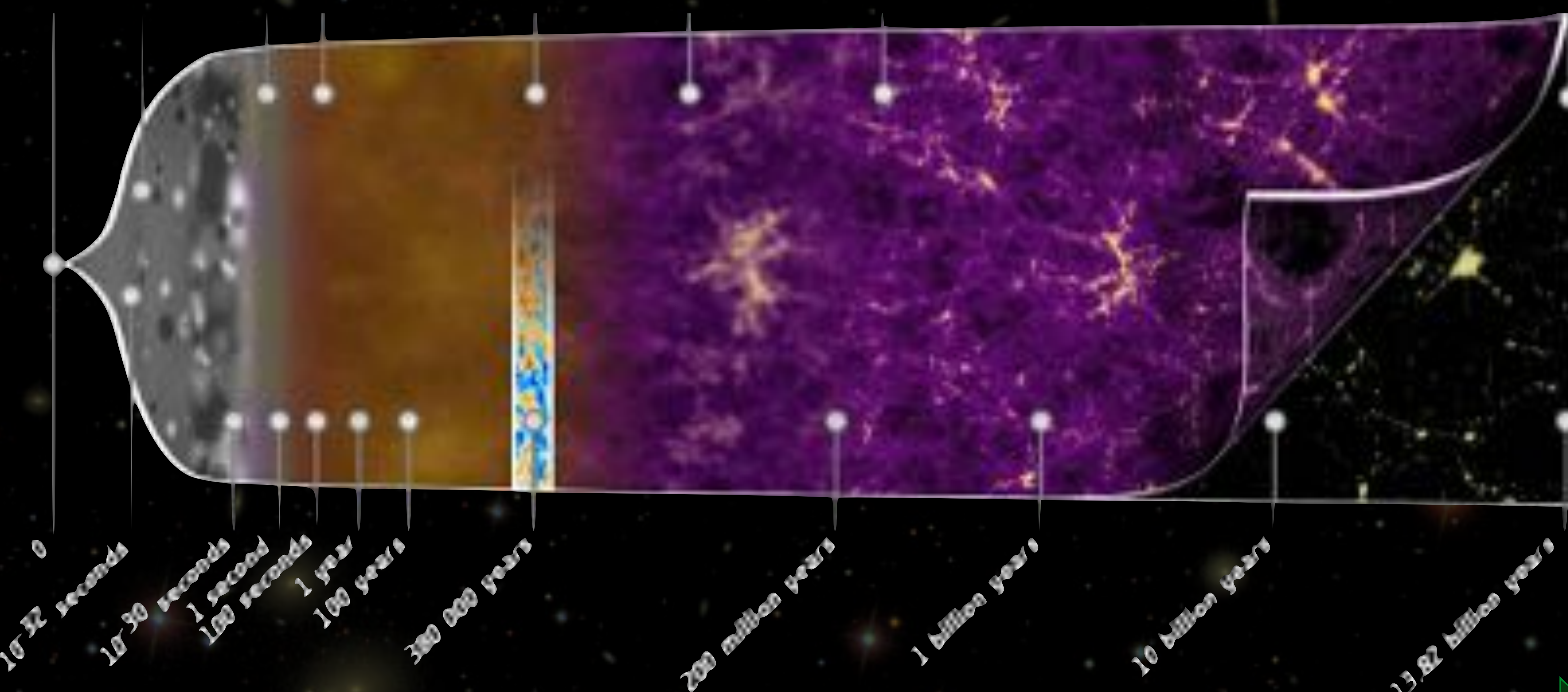
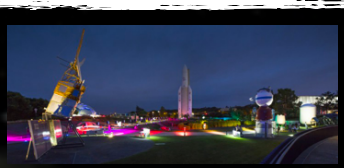
CMB: Ground and Space

J.-Ch. Hamilton
APC - Paris

A quick recap



Time increases, Universe expands, Density decreases, Temperature decreases



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hamilton@apc.in2p3.fr

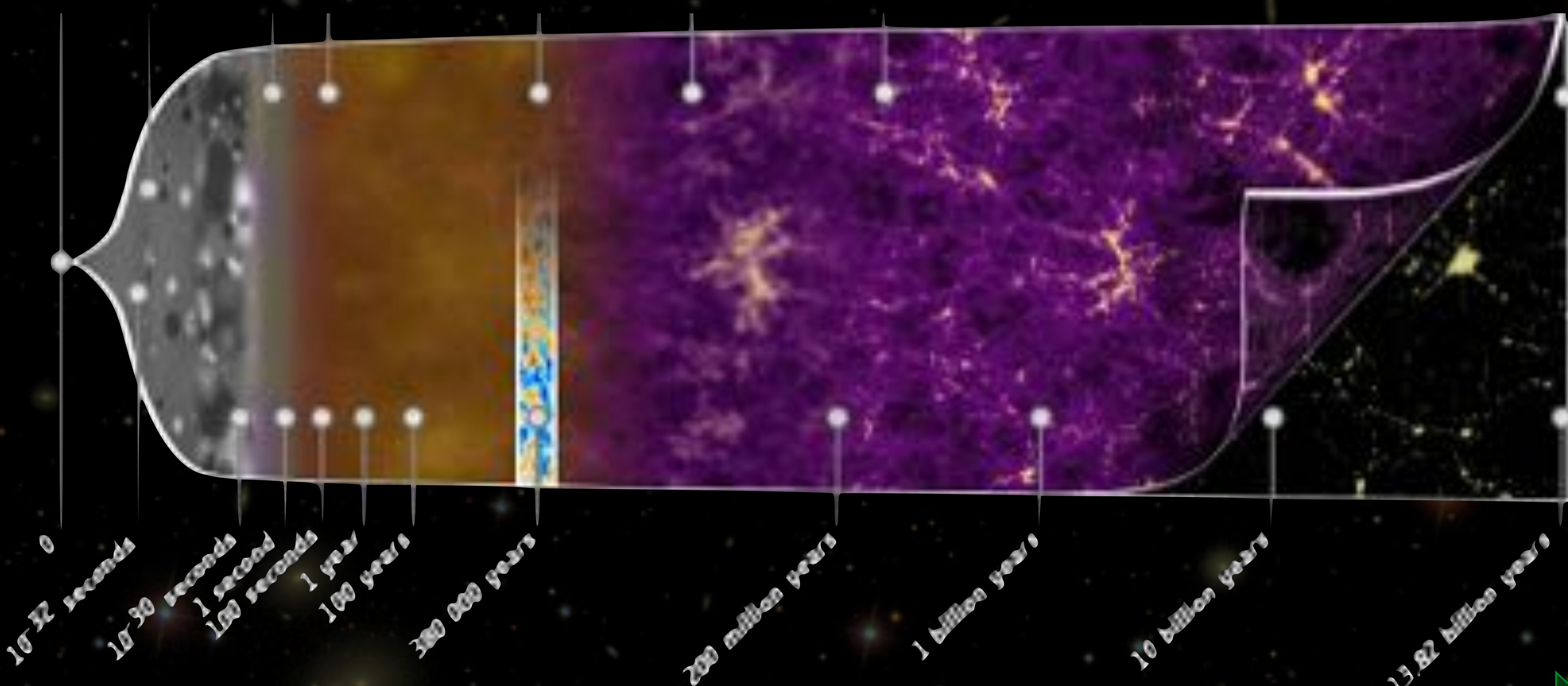
A quick recap

Ionized

Acoustic Oscillations

Primordial Nucleosynthesis

Inflation ?



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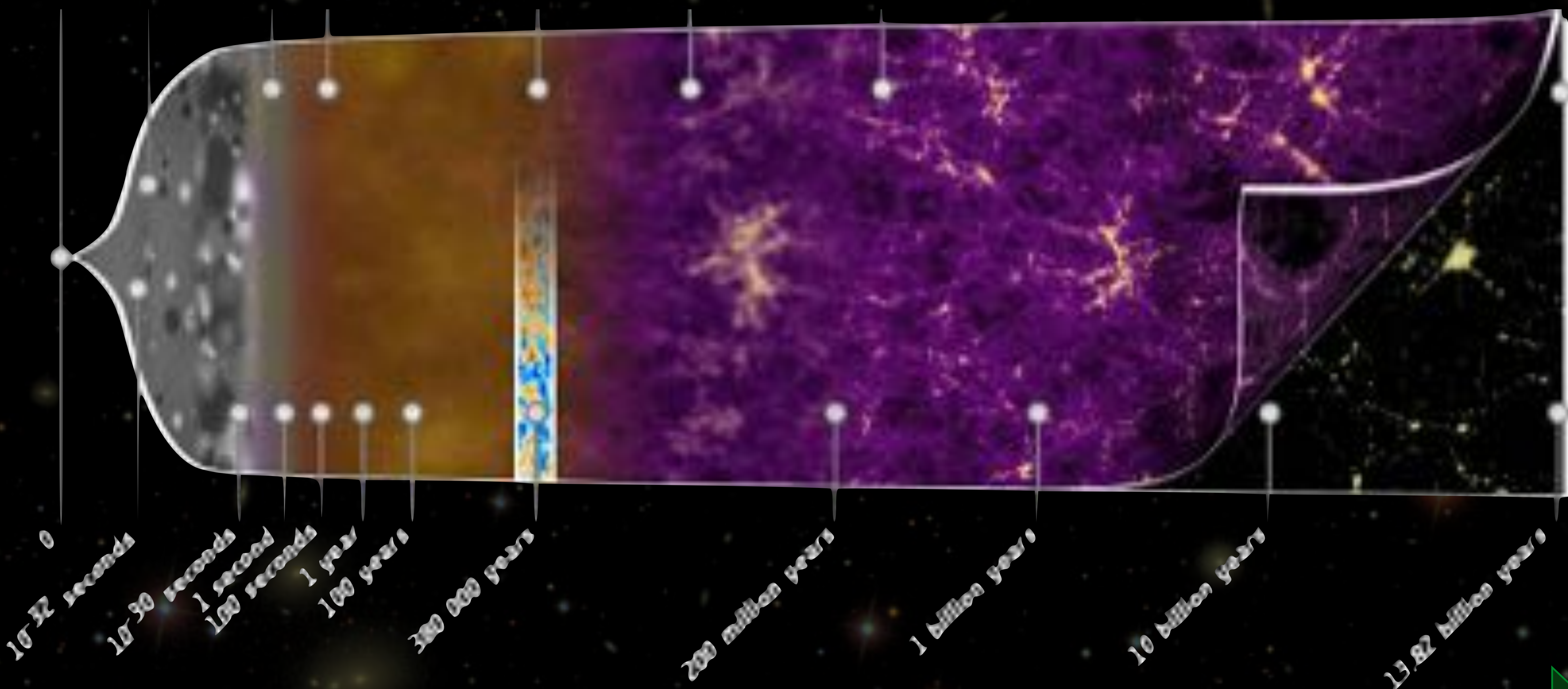
Inflation ?

Matter-Radiation decoupling CMB emission

Neutral

Matter collapses



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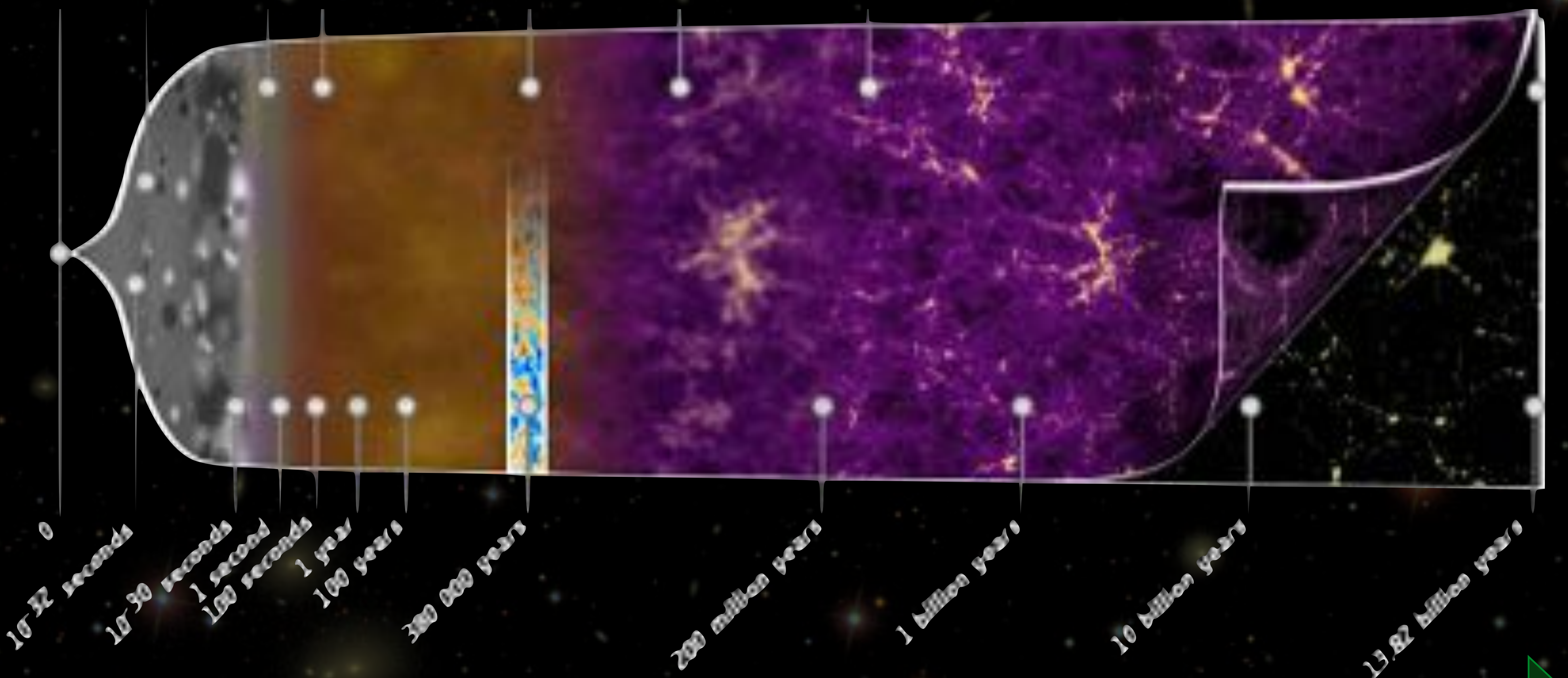
Ionized	Neutral	Re-Ionized
Inflation ? / Primordial Nucleosynthesis / Acoustic Oscillations / Matter-Radiation decoupling CMB emission	Matter collapses / First stars and quasars	Galaxies and Clusters evolution



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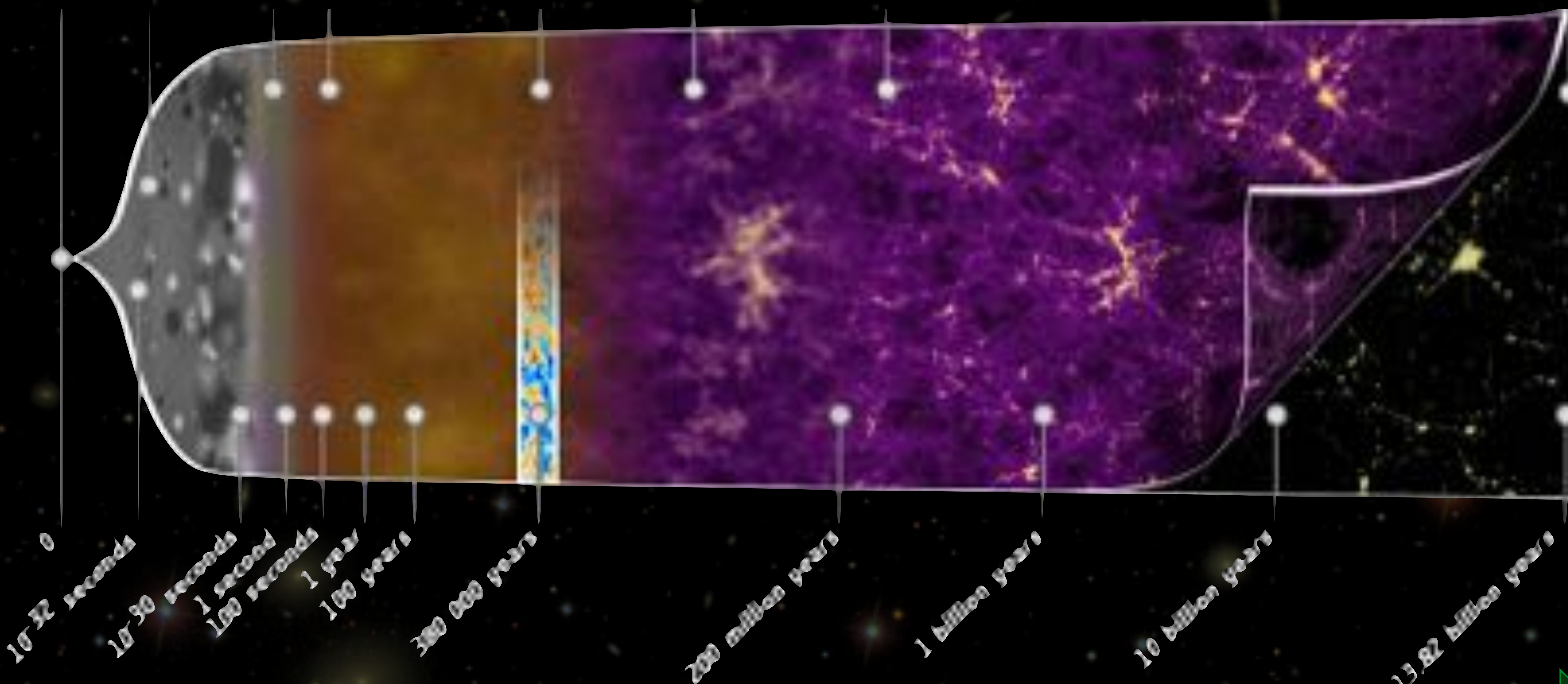

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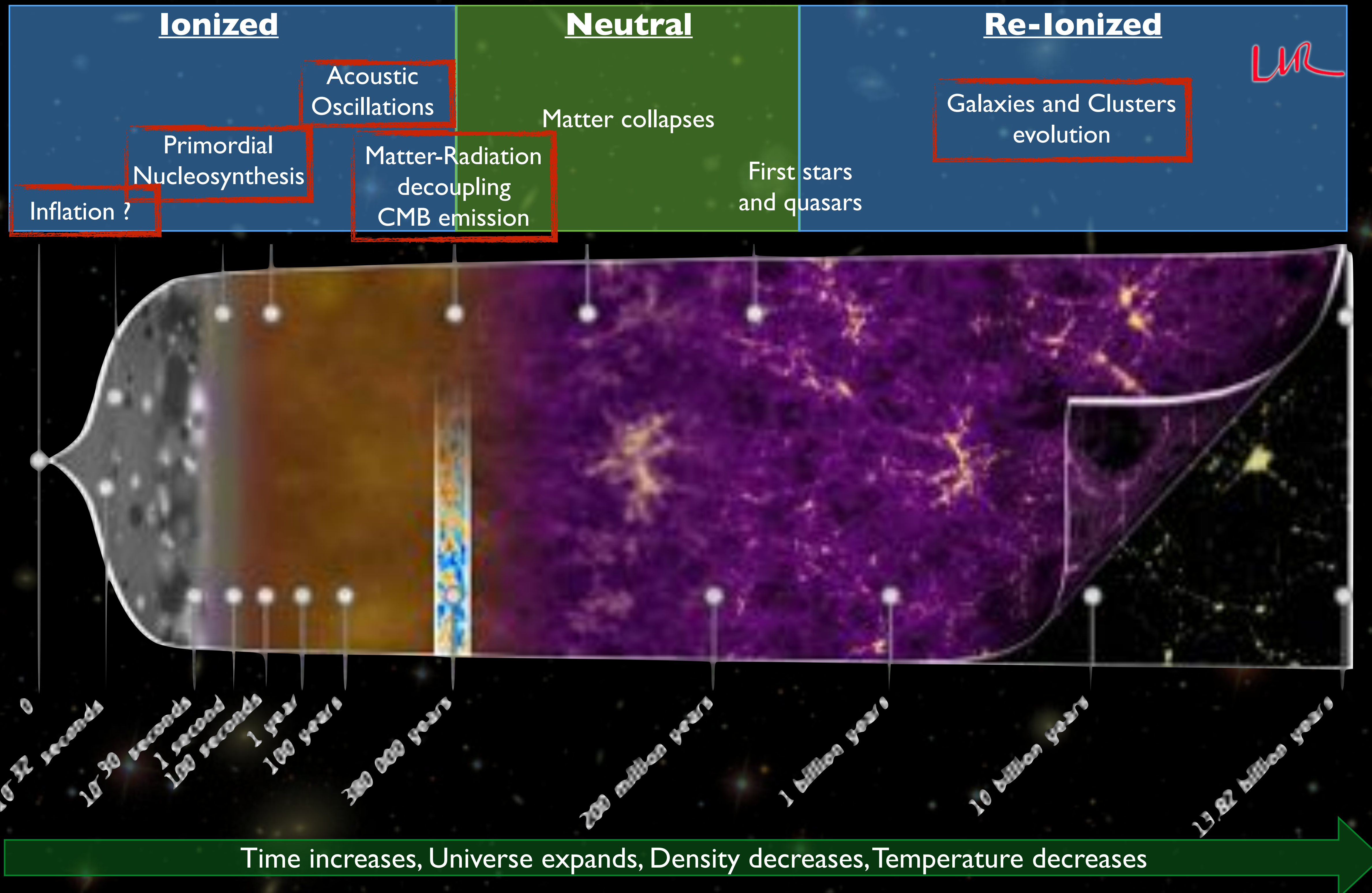

The CMB

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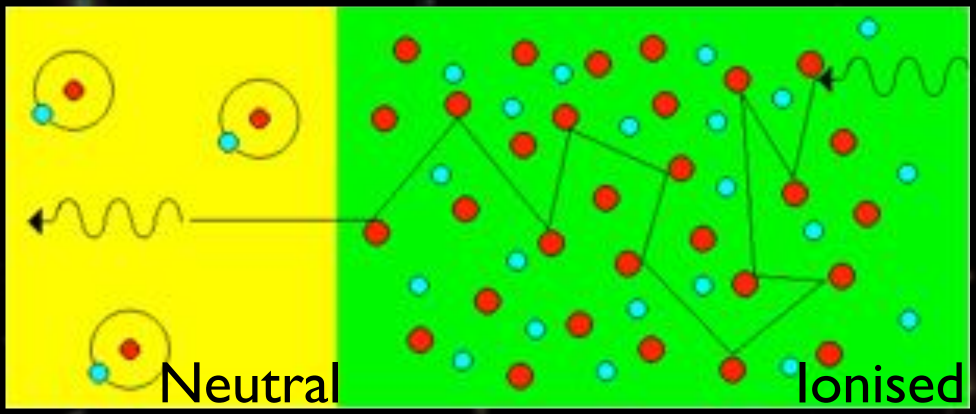

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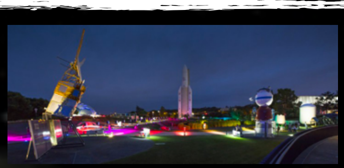

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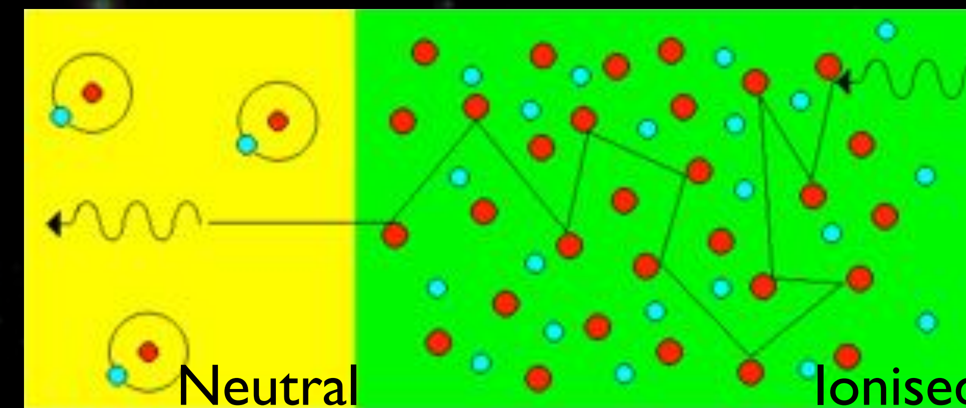

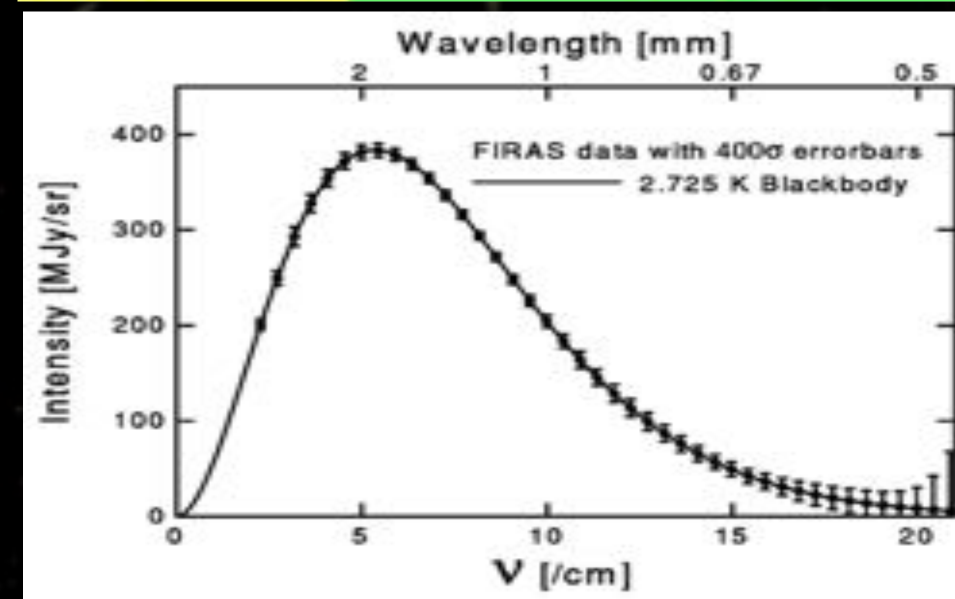

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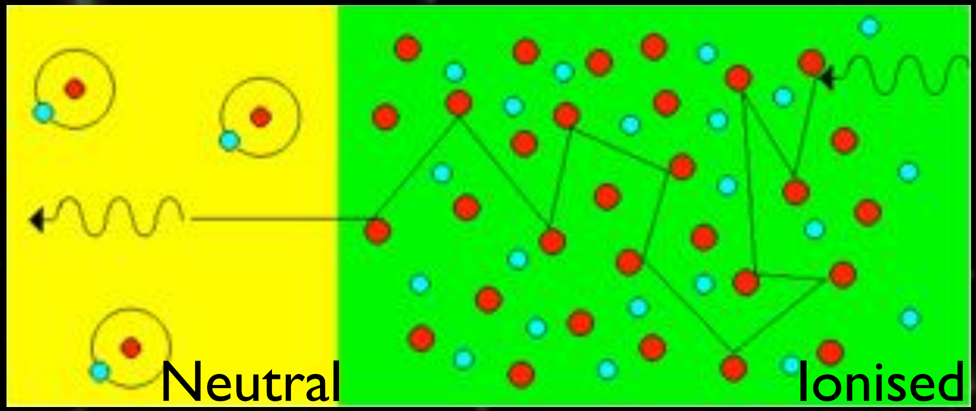

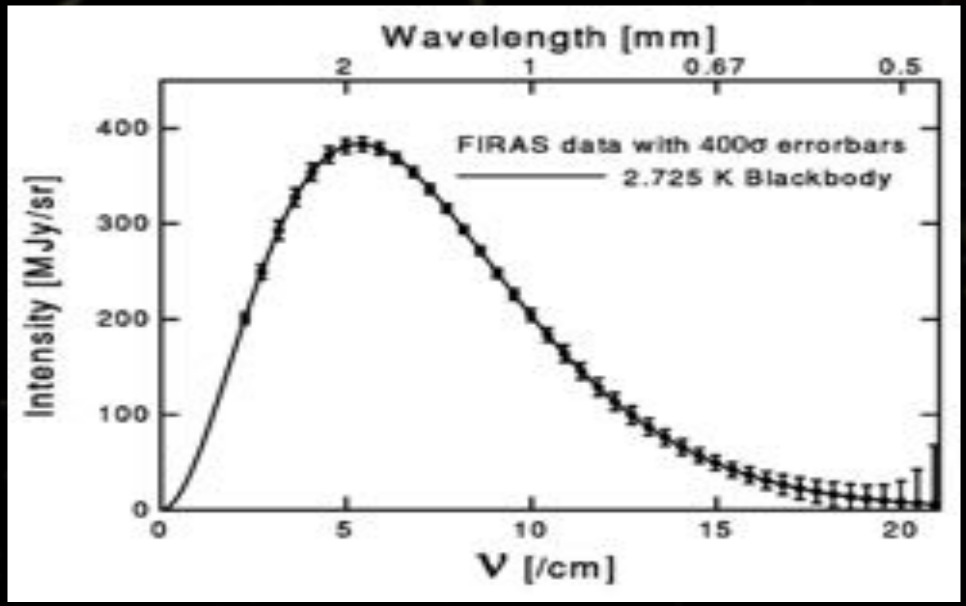

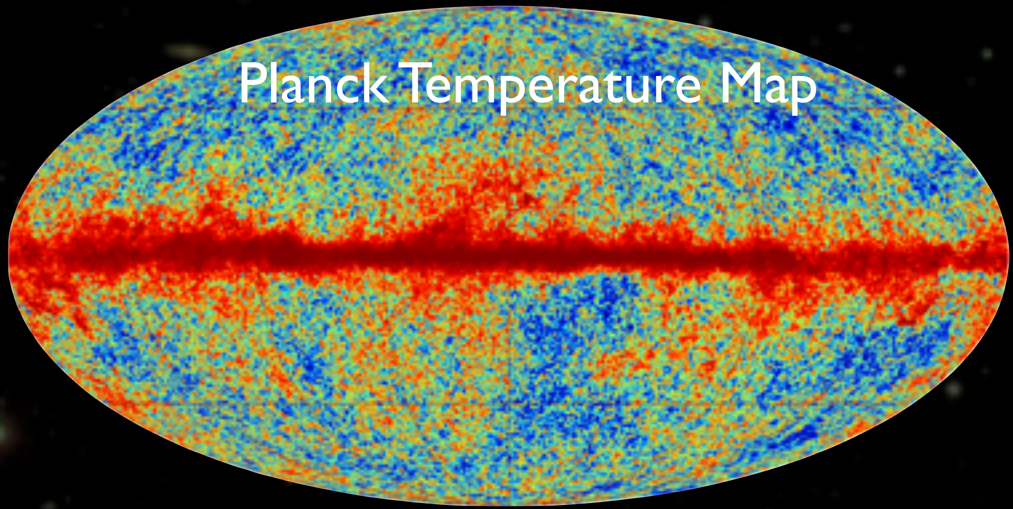

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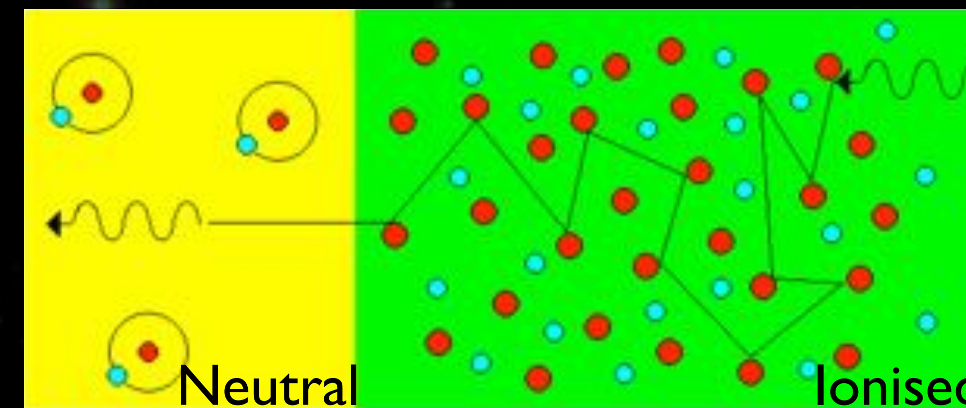

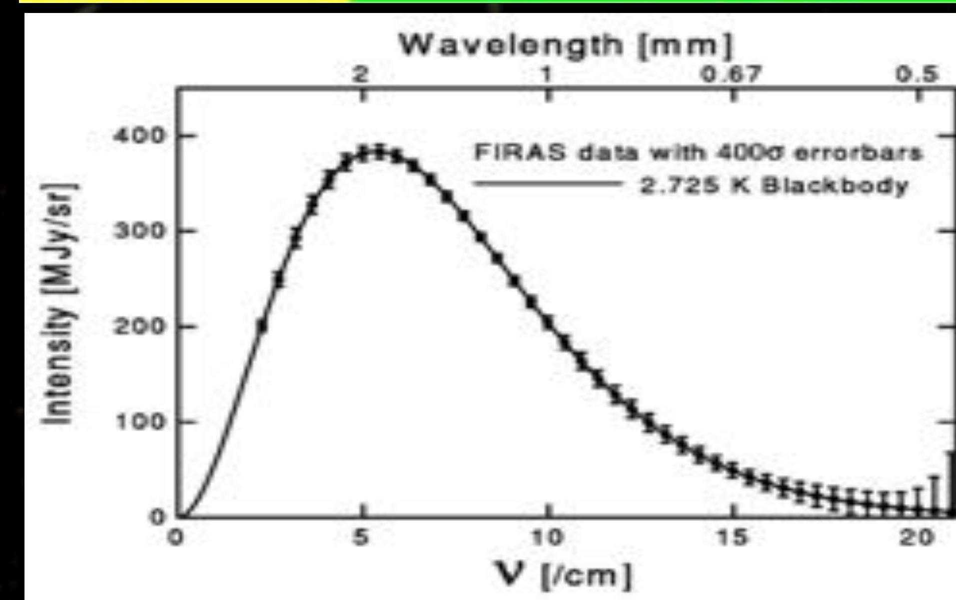

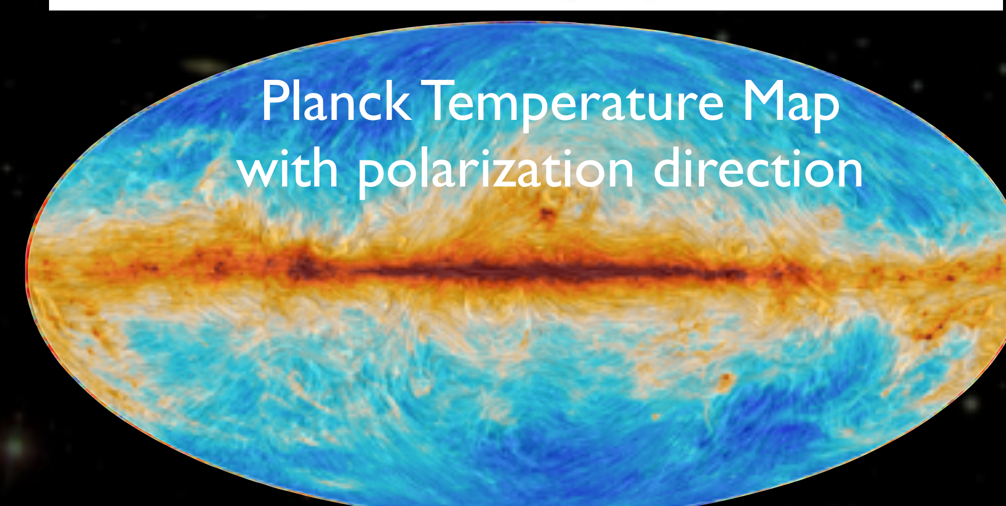

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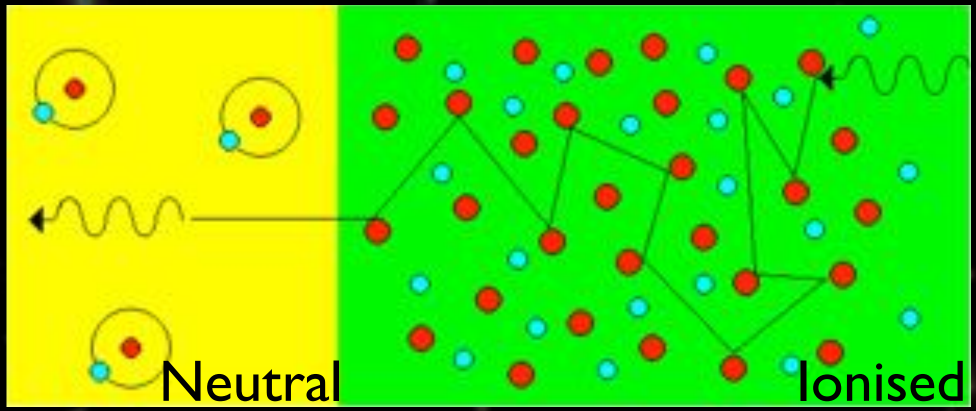

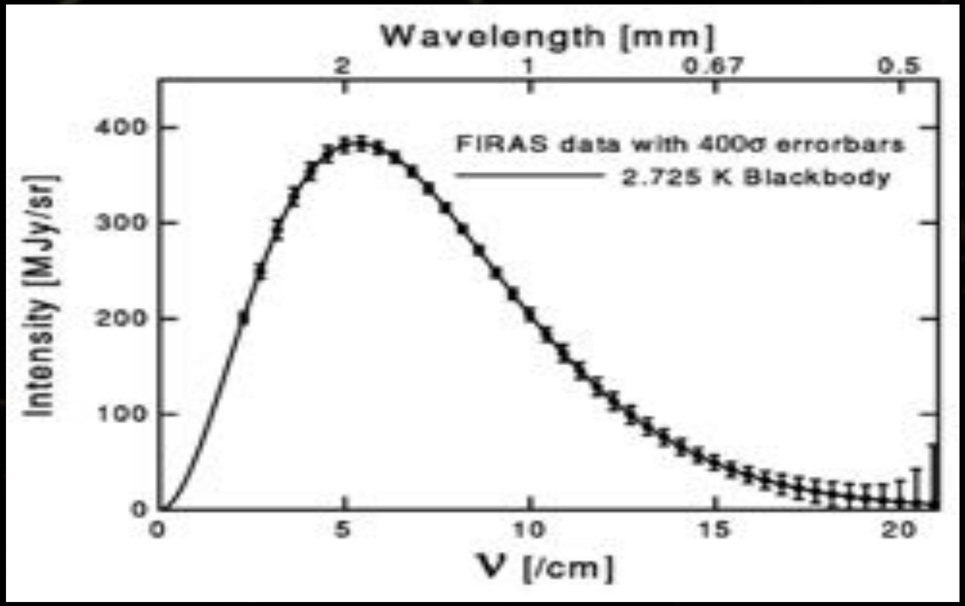

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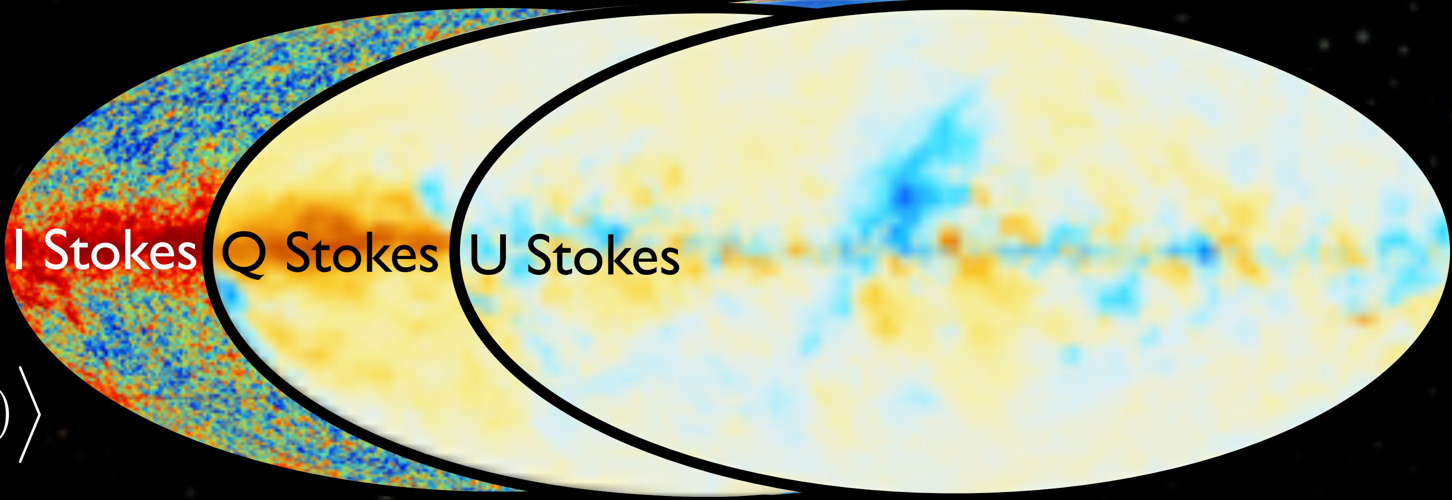

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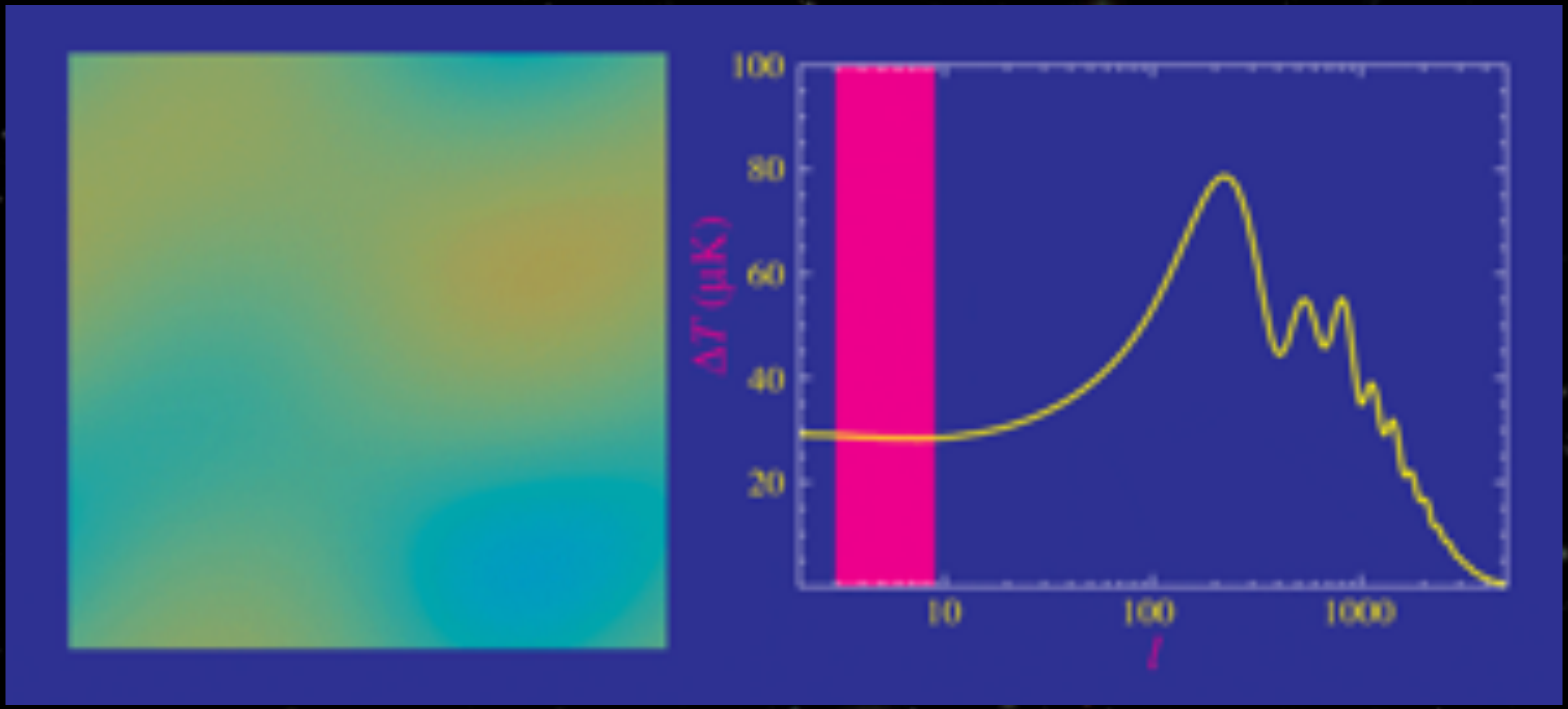
Statistical exploitation of CMB maps



Spherical harmonics expansion

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

→

Angular power spectrum

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

ℓ is the inverse of an angle

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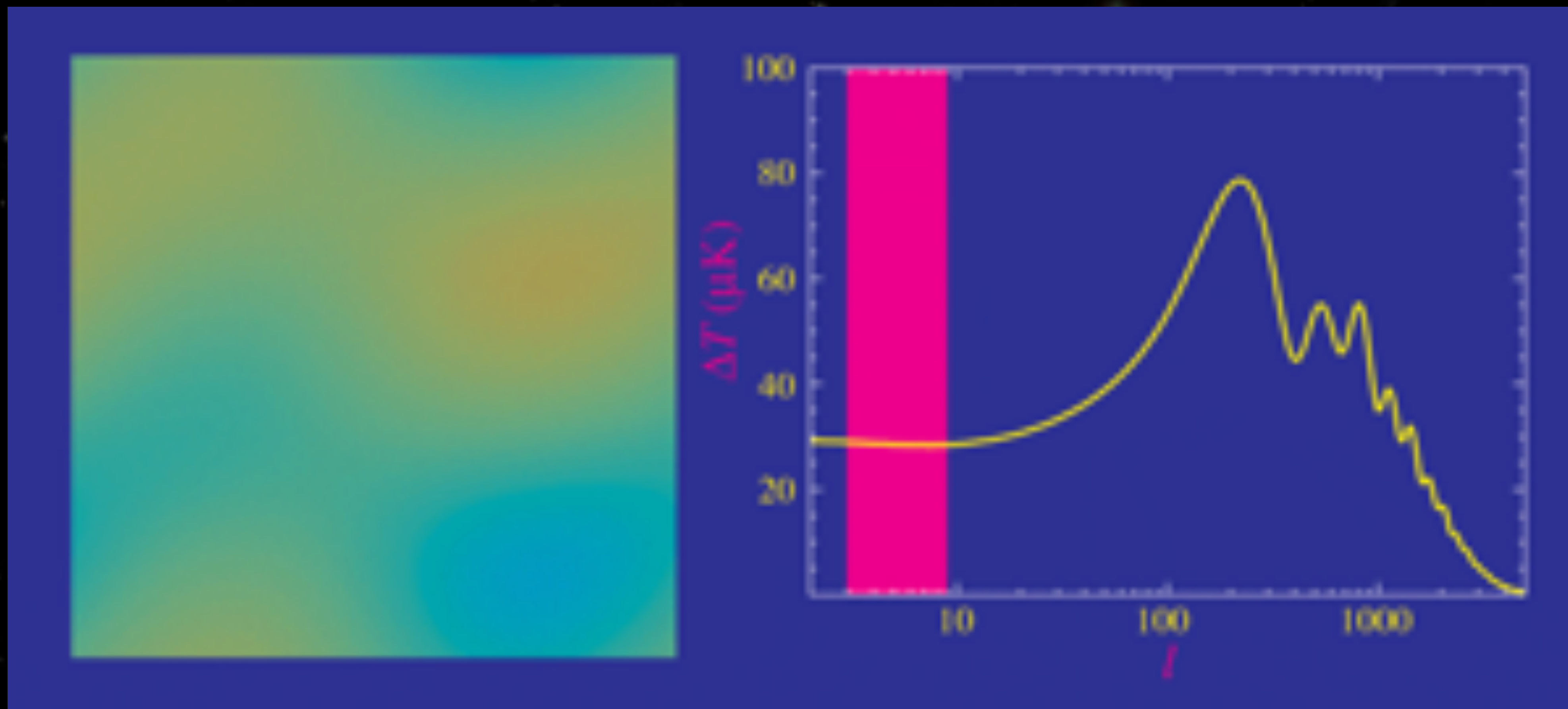

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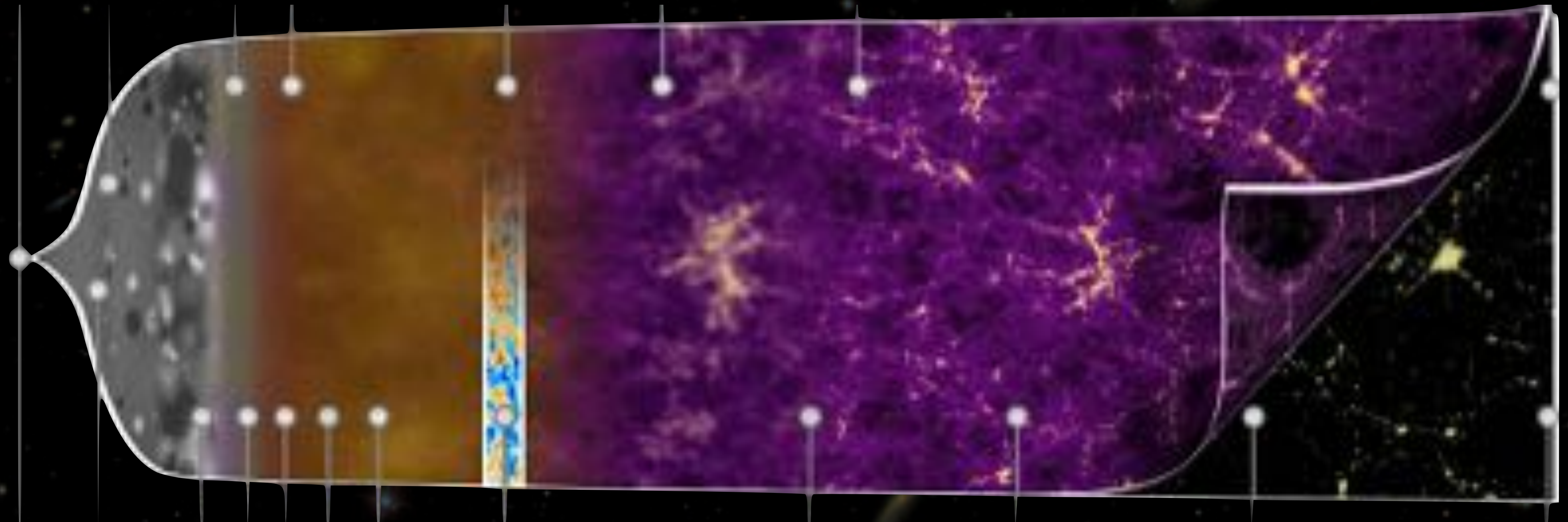
Cosmological Information from the CMB



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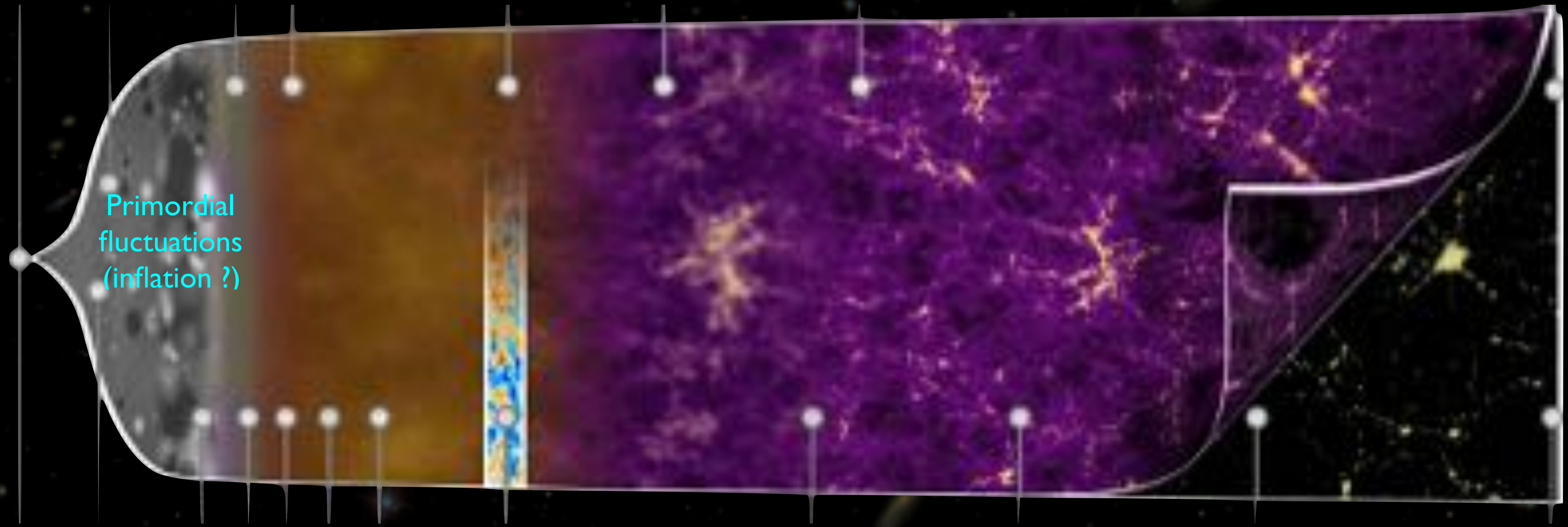

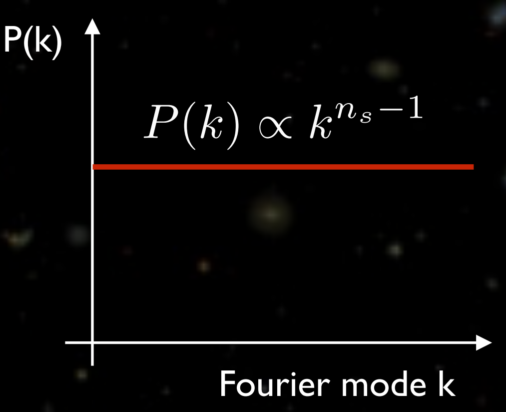

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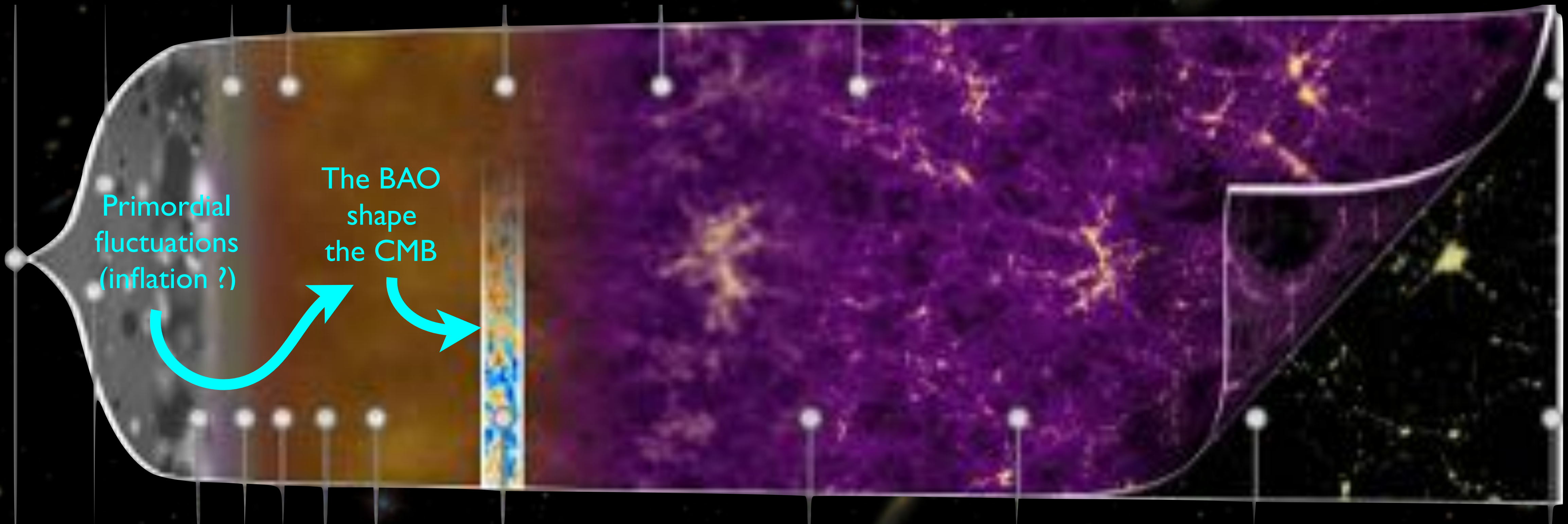

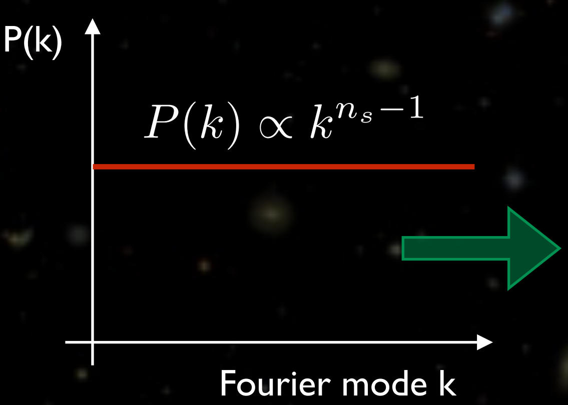

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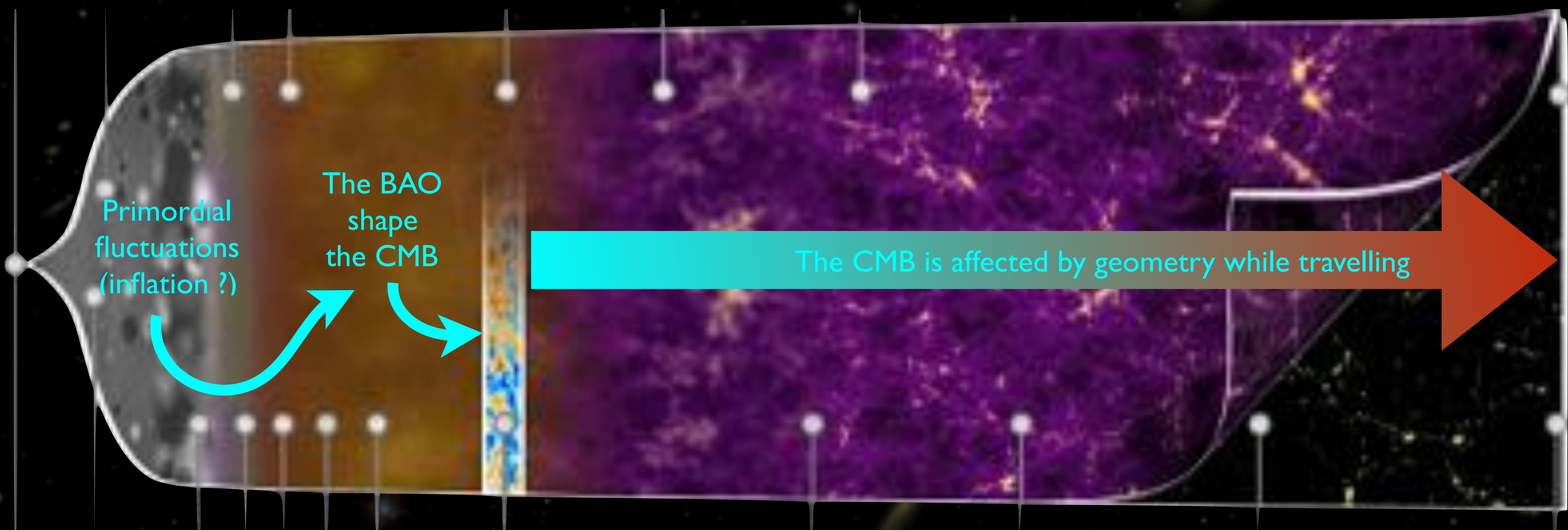

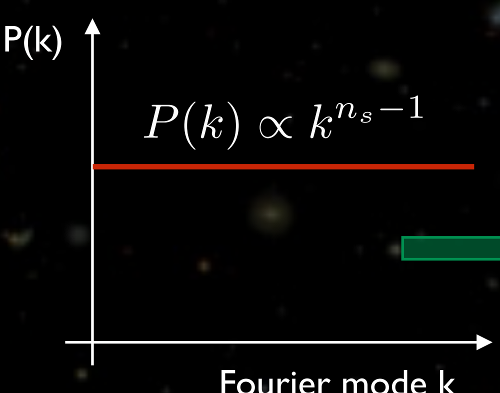

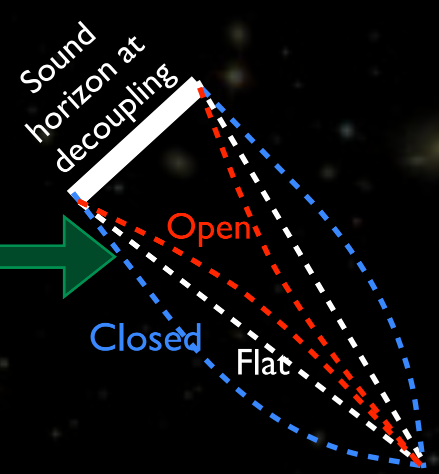

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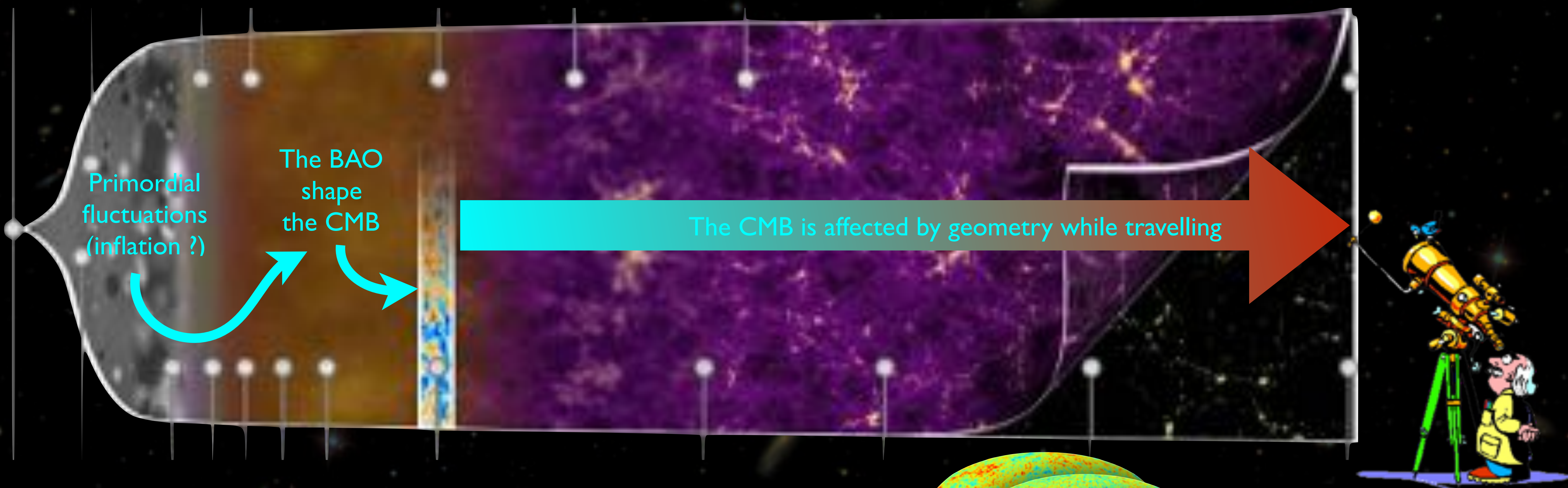

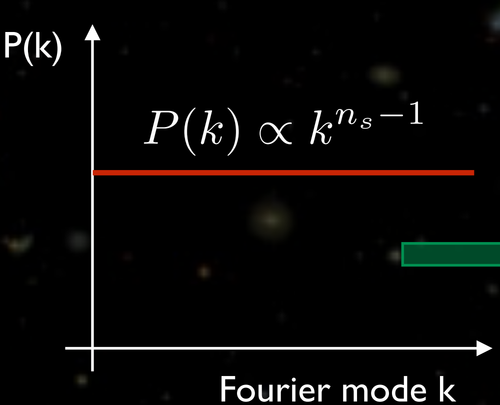

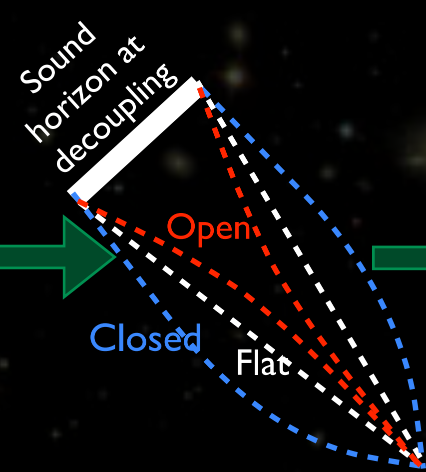

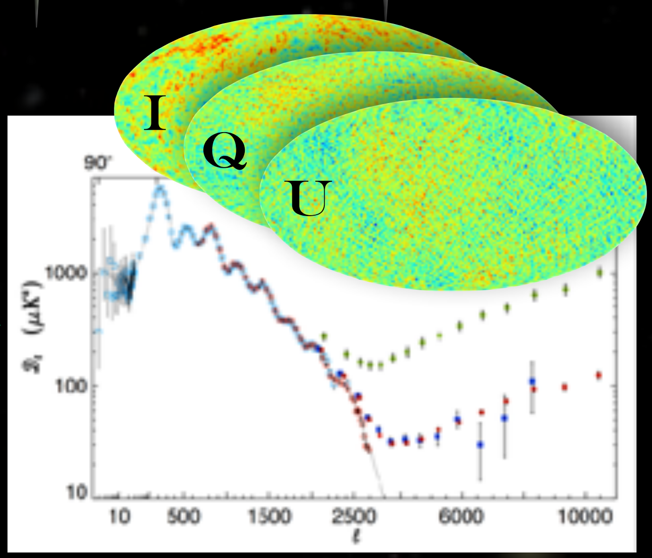

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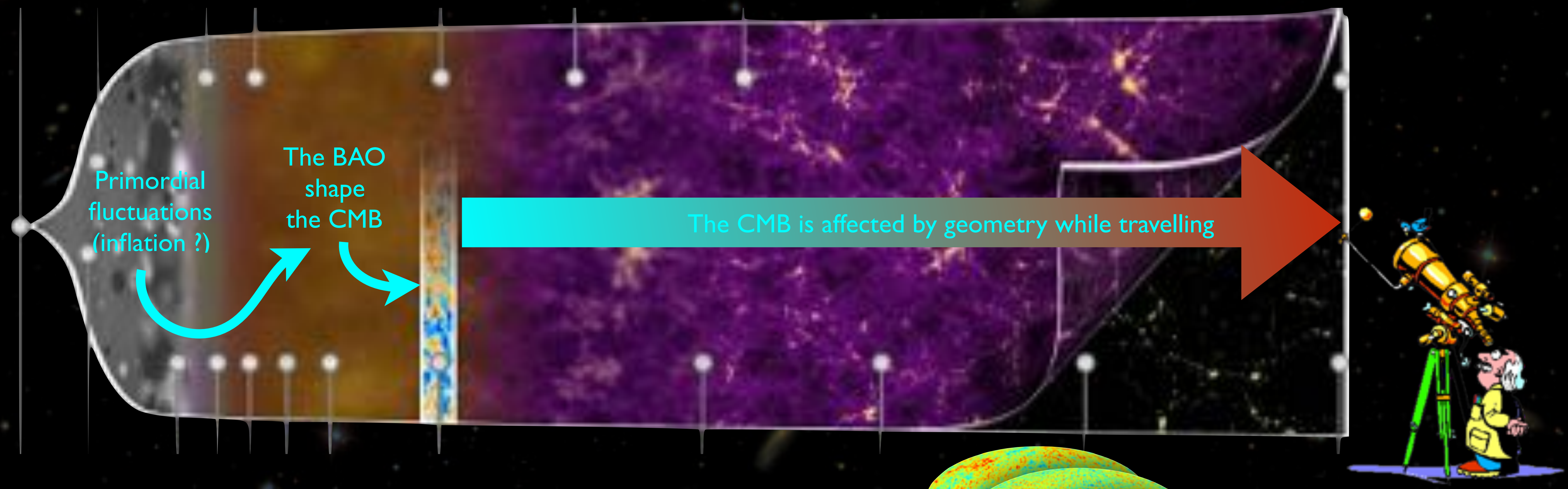

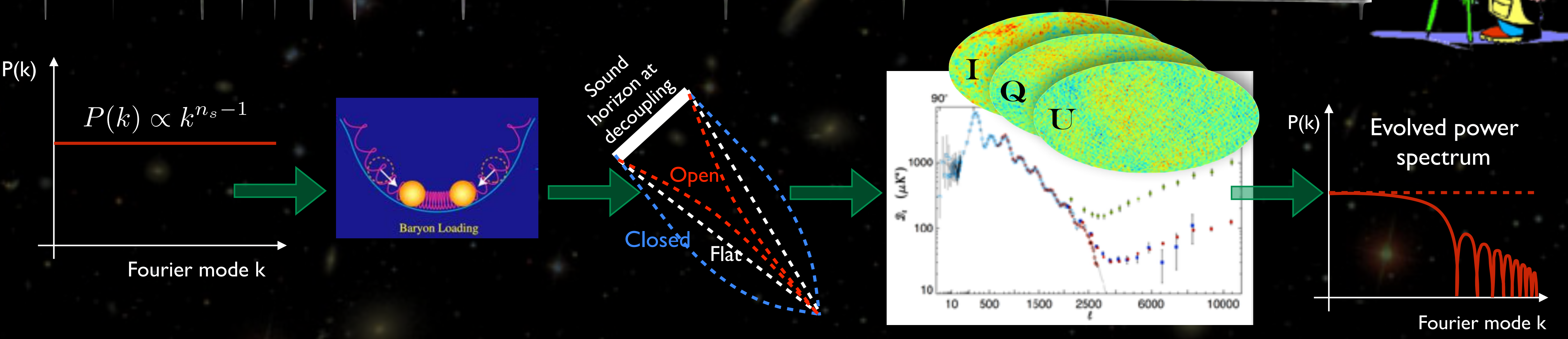

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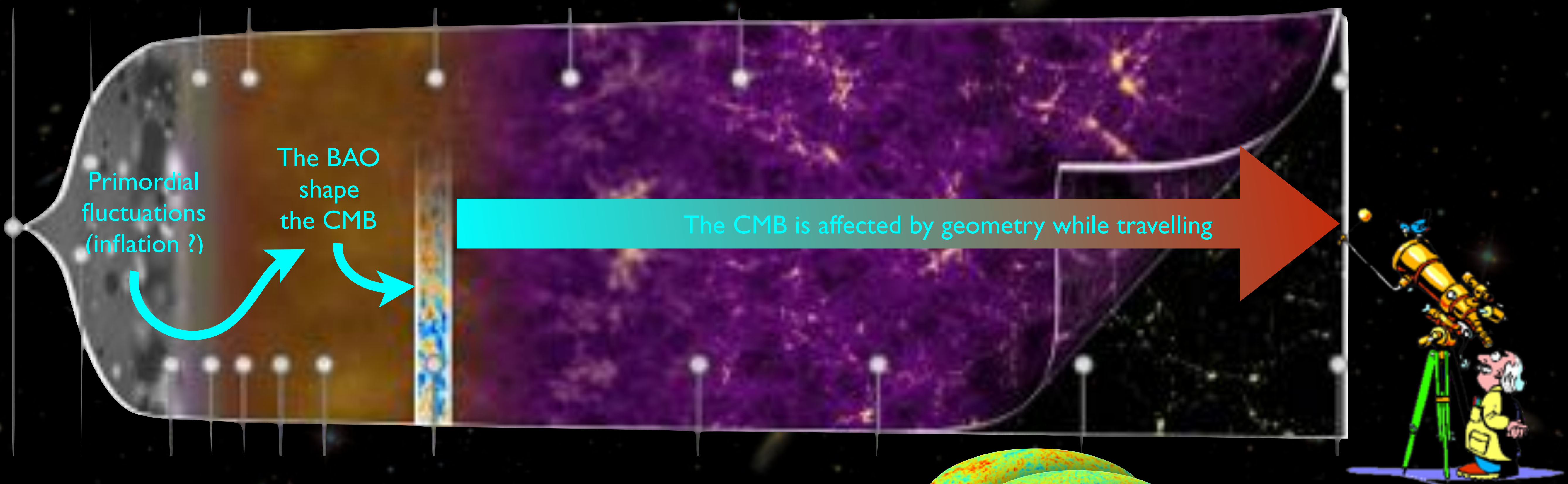
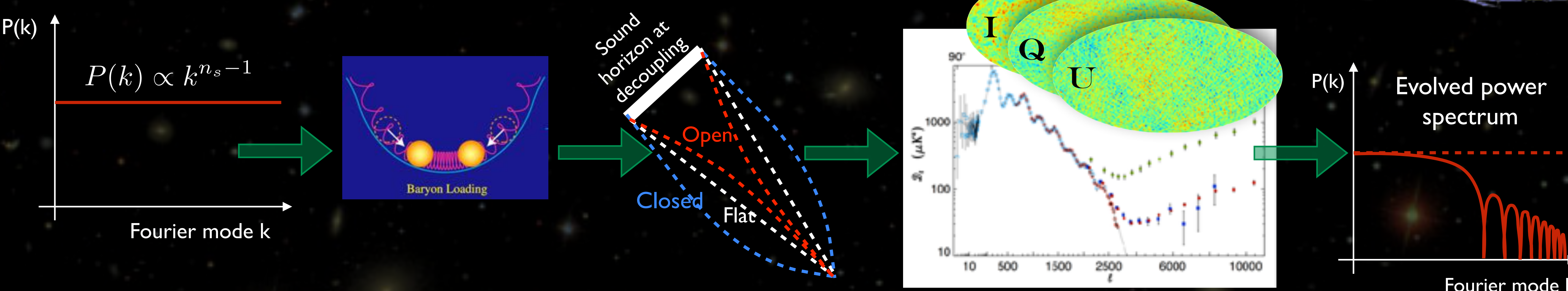
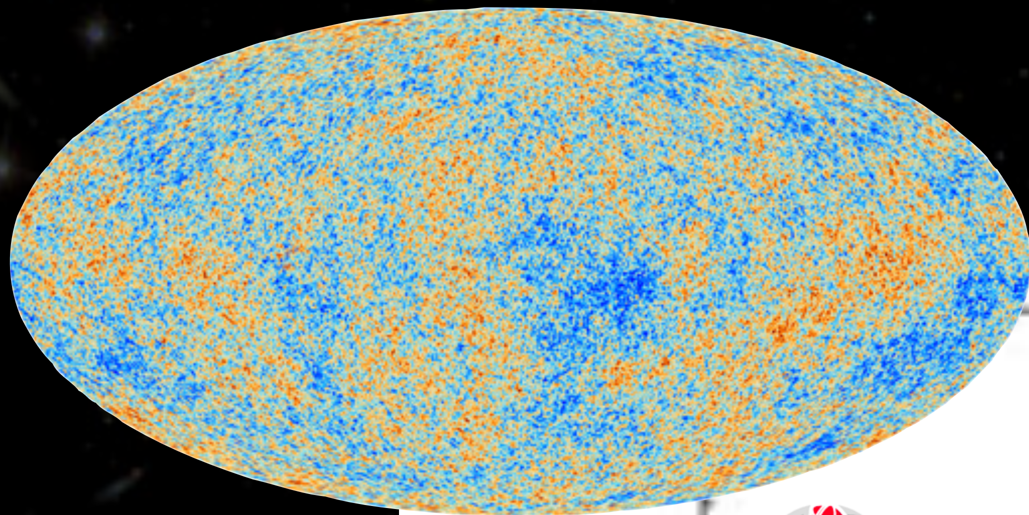
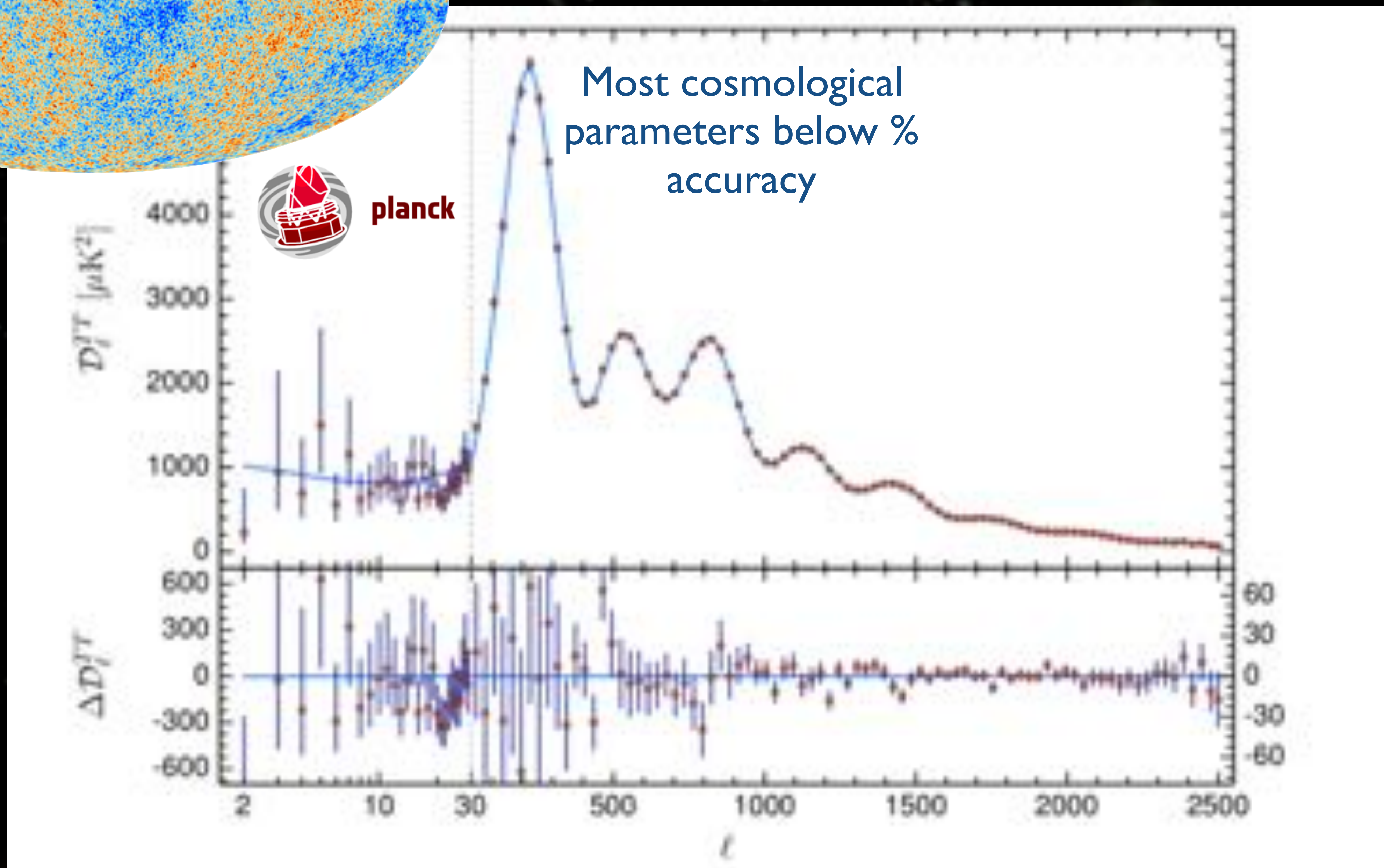




- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **transfert function** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

Planck results (2018)

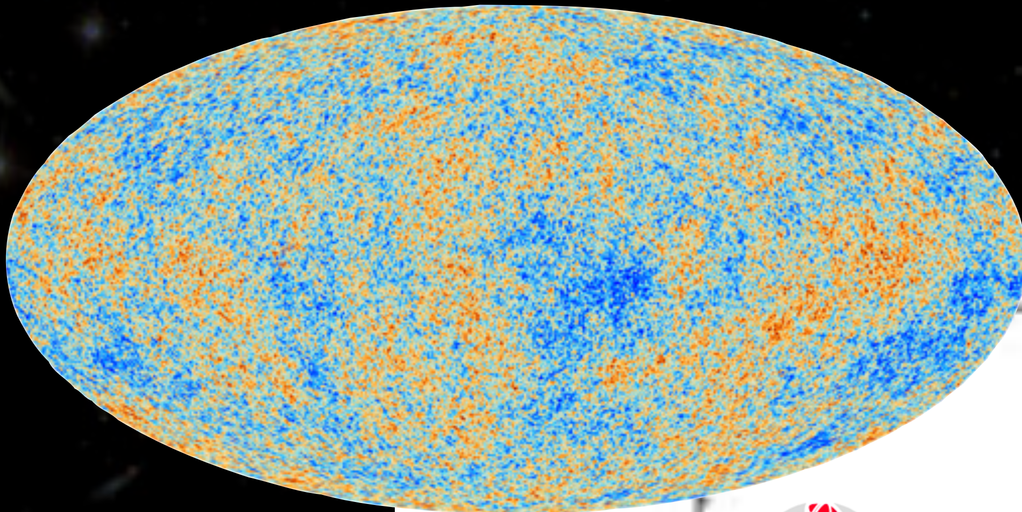


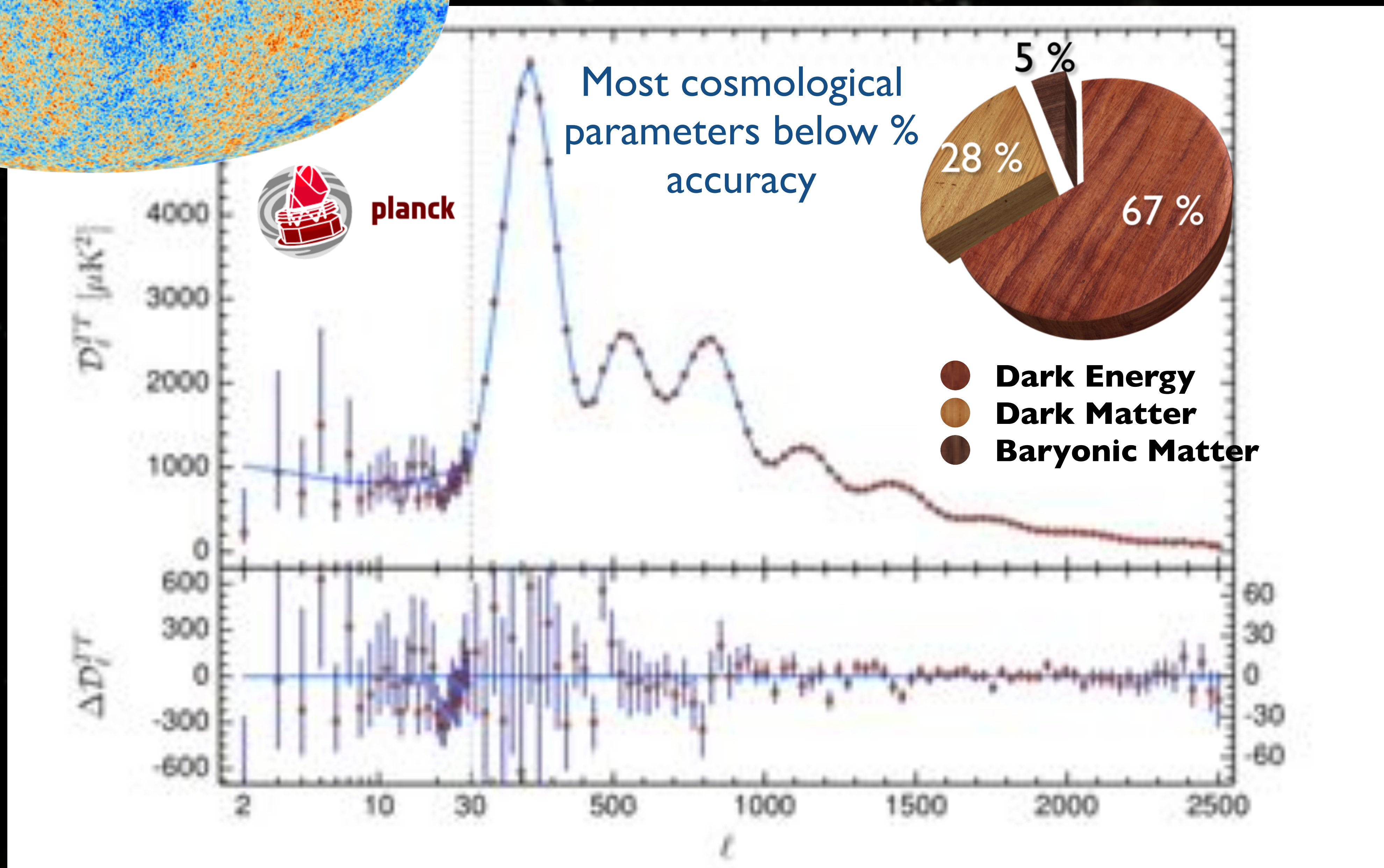


Most cosmological parameters below % accuracy

Next (current actually !) step: Inflation Physics through CMB Polarization B-modes

Planck results (2018)





Next (current actually !) step: Inflation Physics through CMB Polarization B-modes

Inflation

- Accelerated expansion in the first fractions of seconds after Planck Time ~ 10^{-35}sec
- Solves in an elegant manner well known paradoxes/issues of the initial Big-Bang Model
  - ★ Horizon
  - ★ Flatness
  - ★ Monopoles
- Predicts the shape of the primordial perturbations
  - ★ Seeds for Structure formation
  - ★ Almost perfect Gaussianity
  - ★ Presence of scalar modes AND *tensor modes*
  - ★ Spectral index slightly below 1
  - ★ Adiabatic perturbations (perturbations of the metric)
- All models adjusted to CMB or Large Scale Structure implicitly assume inflation (actually ΛCDM kind of incorporates inflation - although not « officially »…)
  - ★ Maybe it's worth checking this detail….

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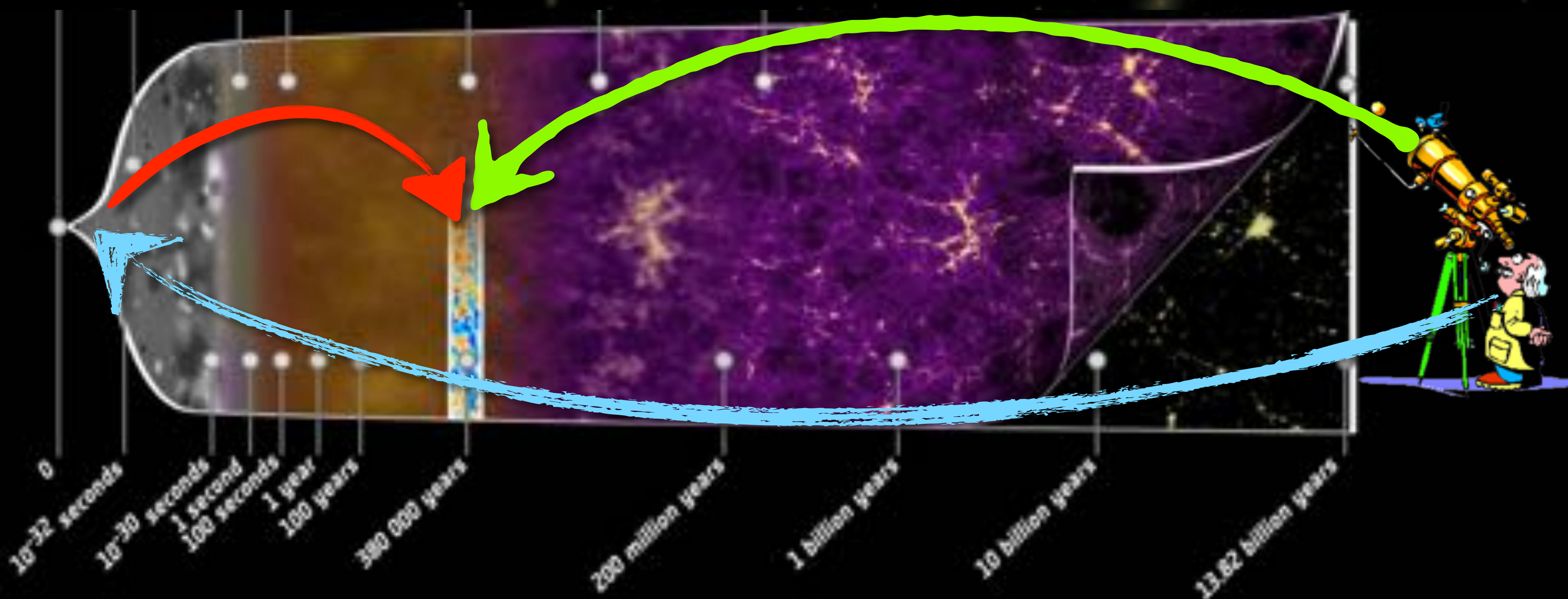
CMB B-modes and Inflation



Observing the CMB B-modes polarization gives access to the Primordial Universe physics (inflation epoch)

Difficulties:
- Sensitivity (few nK signal)
- Instrumental Systematics (I,Q,U leakage)
- Foregrounds (Polarized dust, …)

QU, EB and Inflation ?

Observables: Q,U maps

(Spin 2 quantities)

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QU, EB and Inflation ?

Observables: Q,U maps

Q — Detector Y / Detector X

U — Detector A / Detector B

(Spin 2 quantities)

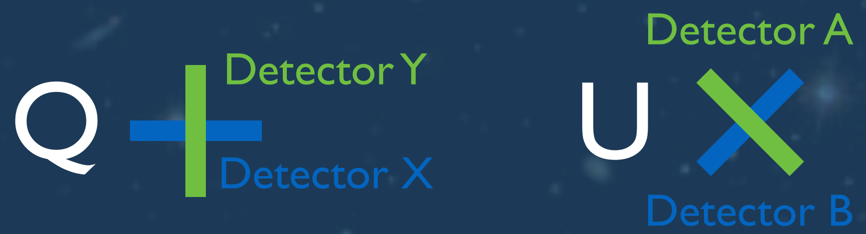
Maths →

Polarization vectors: E,B modes

(Scalar quantities)

QU, EB and Inflation ?

Observables: Q,U maps



(Spin 2 quantities)

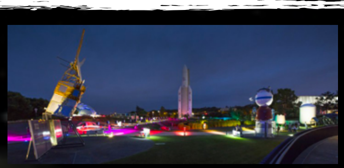
Maths

Polarization vectors: E,B modes

(Scalar quantities)

Inflation predictions:

- Scalar perturbations:
  - Density fluctuations
  - T, E, no B polarization
- Tensor perturbations:
  - Specific prediction from inflation!
    = Primordial gravitational waves
  - T, E, B polarization



CMB: Sol et espace
J.-Ch. Hamilton
hamilton@apc.in2p3.fr

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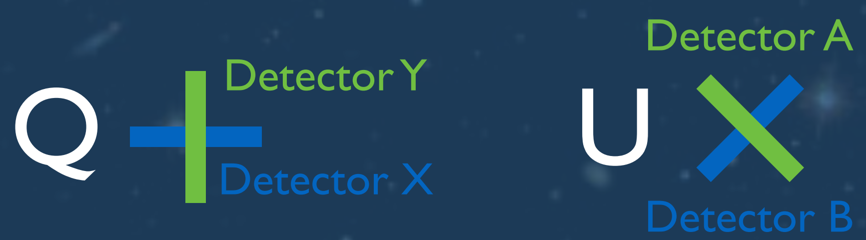

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  - Specific prediction from inflation!
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⇒ detecting B-modes is :

- Direct detection of tensor modes
- «smoking gun» for inflation
- Measurement of its energy scale

$$V^{1/4} = 1.06 \times 10^{16}\mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$$

r is the tensor/scalar ratio ~B/E

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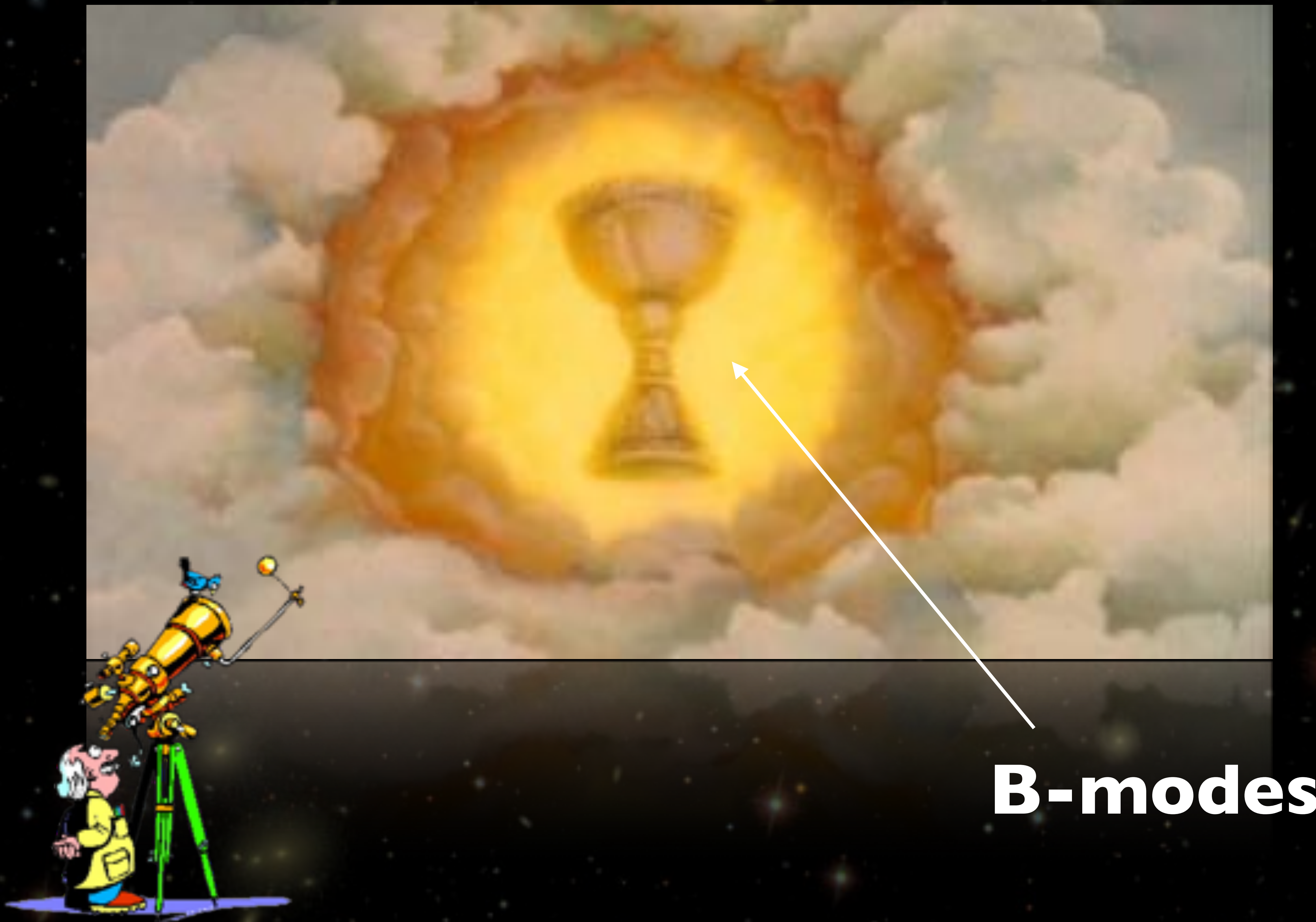
Take home message



Difficulties in the Quest

- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds

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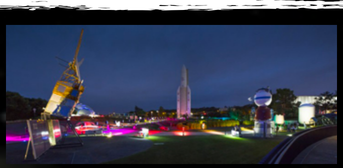

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CMB Lensing by large scale structure

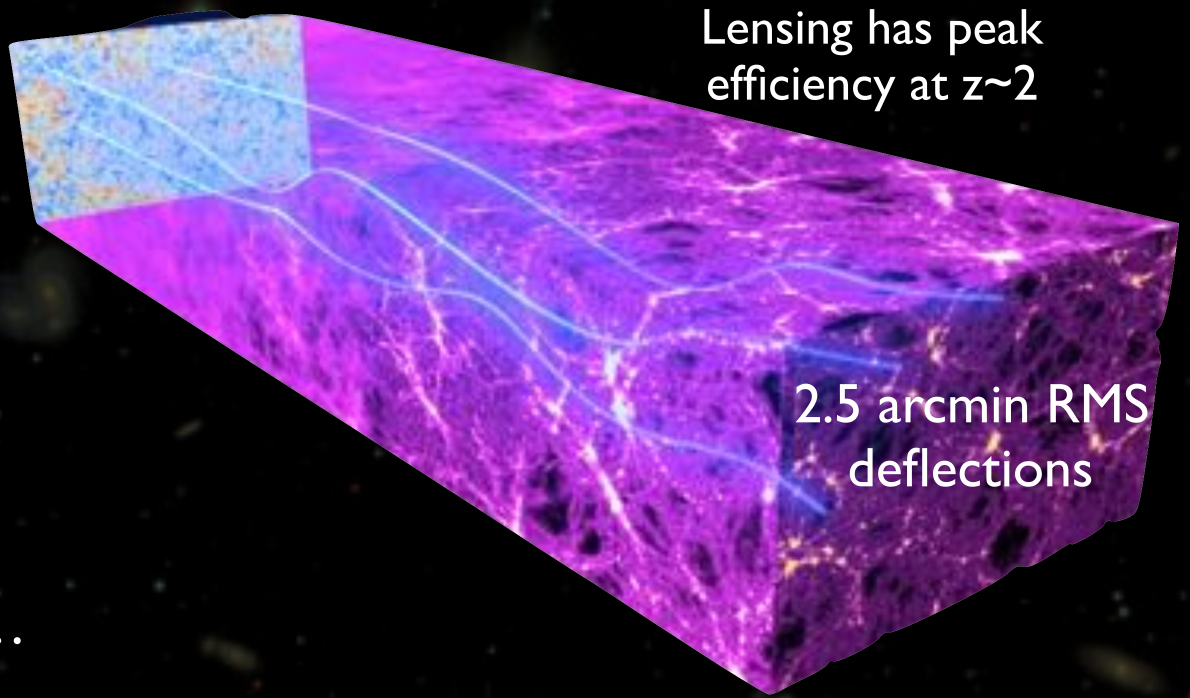
- **Deflection field:**
  - ★ Gradient of redshift-integral of LSS

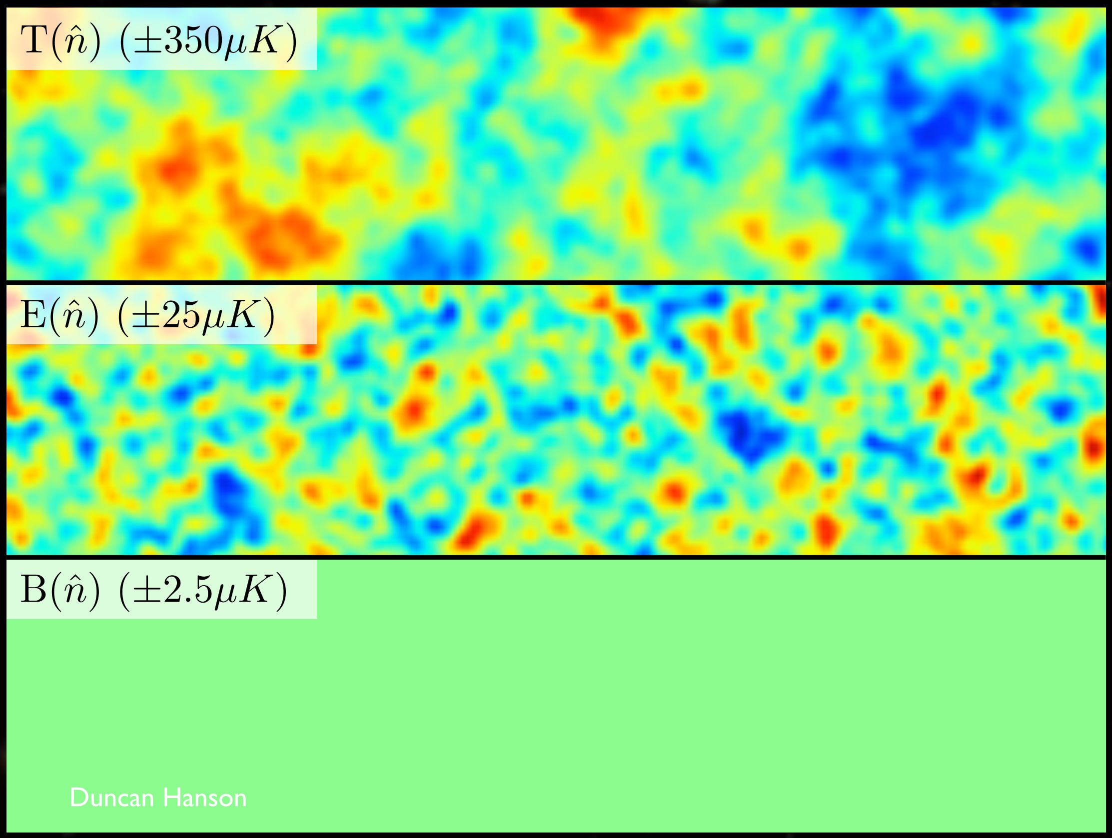
- **Lensing adds information**
  - ★ lifts geometric CMB degeneracies
    - Curvature, sub-eV neutrino masses, Dark Energy…

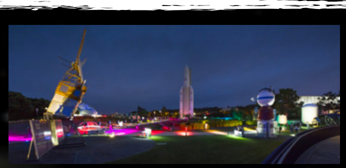
- **Effect on Stokes parameters**

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

- 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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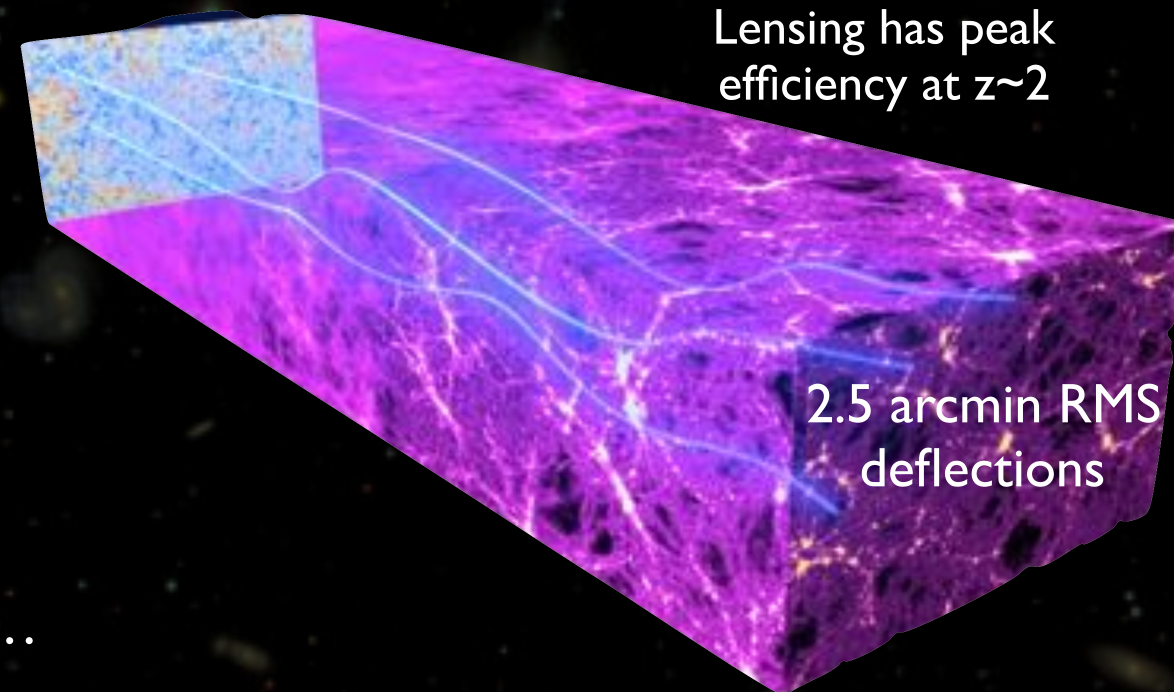

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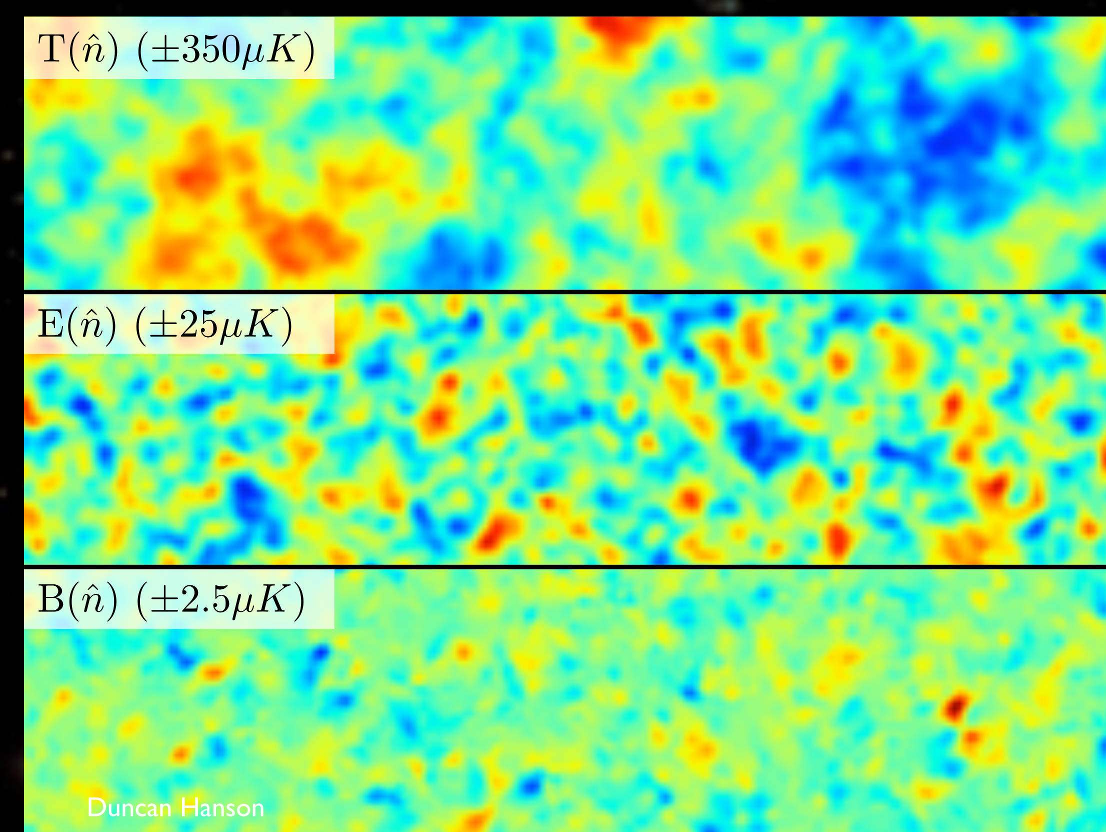
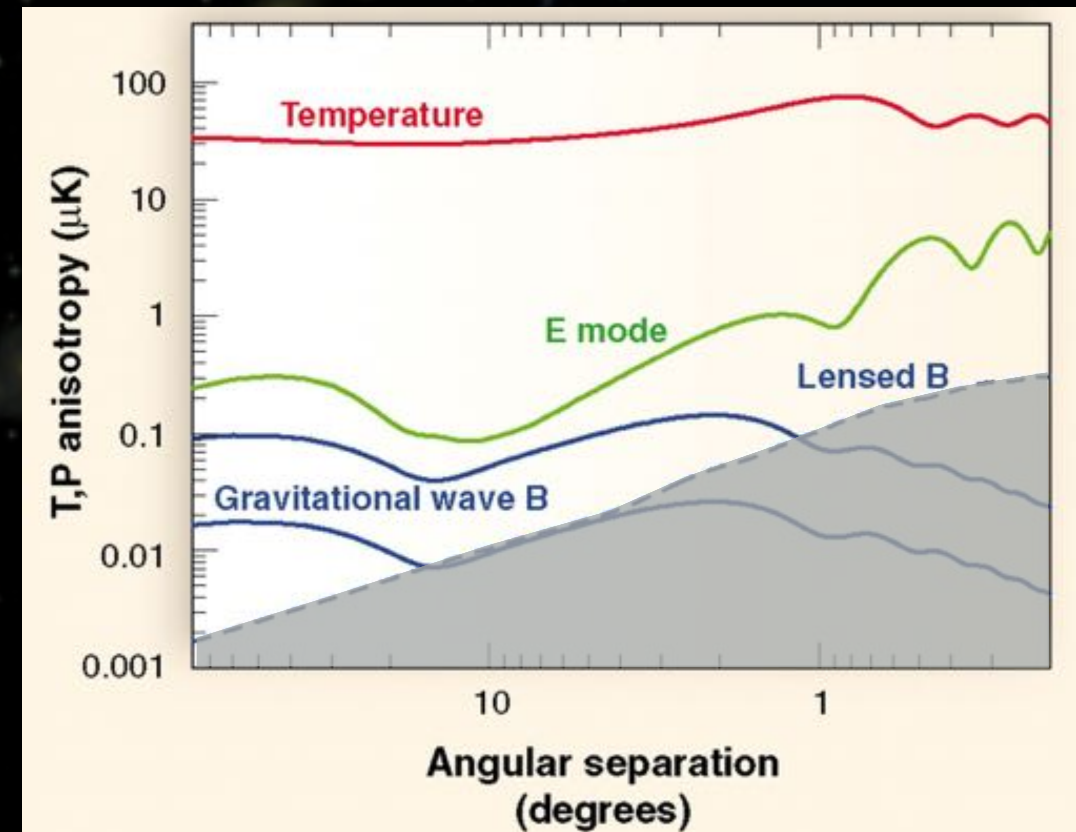
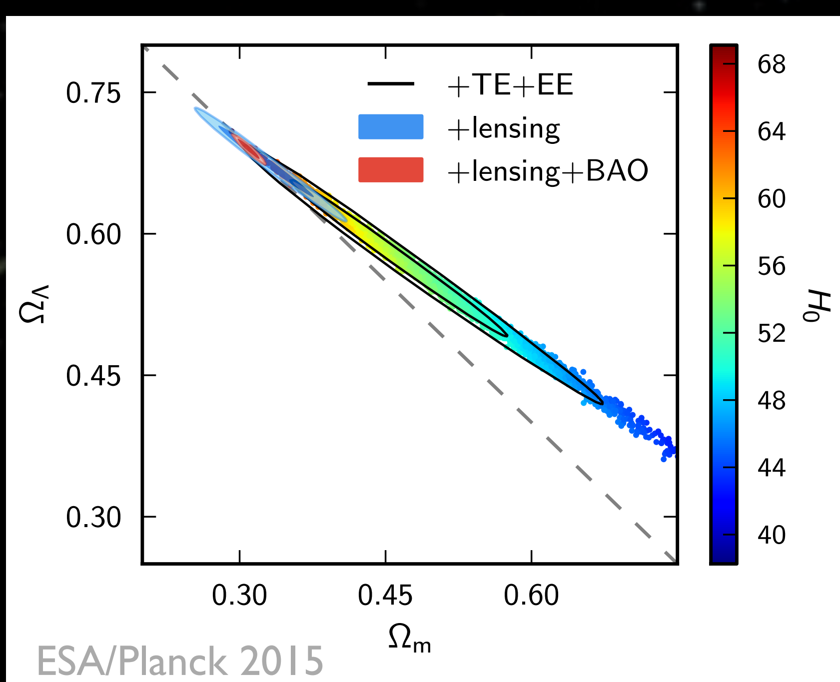


Lensing science

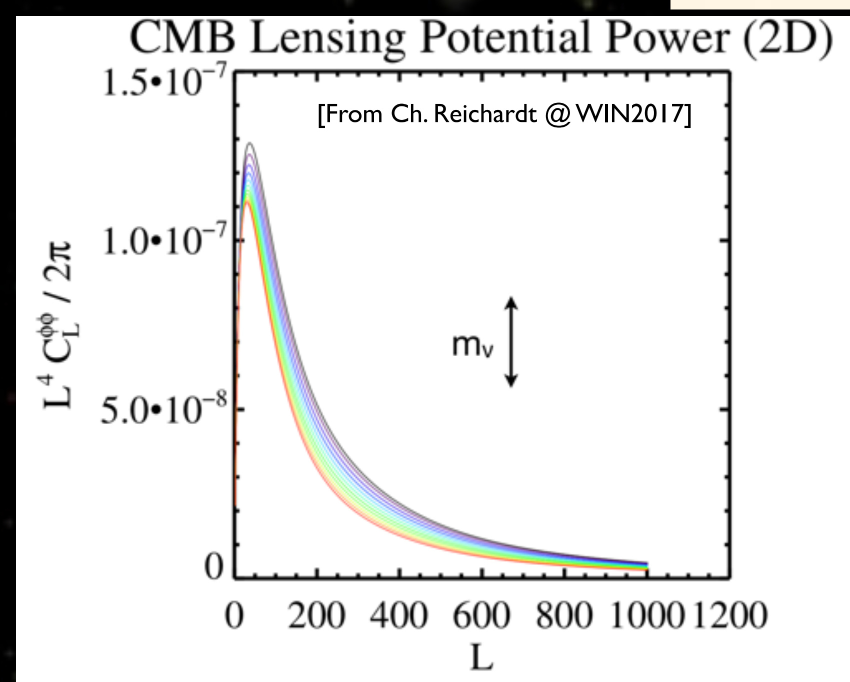
- Lensing is caused by structures at z~4 therefore highly depend on structure growth rate which in turns depends on DM, DE and ν masses and effective number

- NB: this is through a global model
  ➡ not a direct measurement…

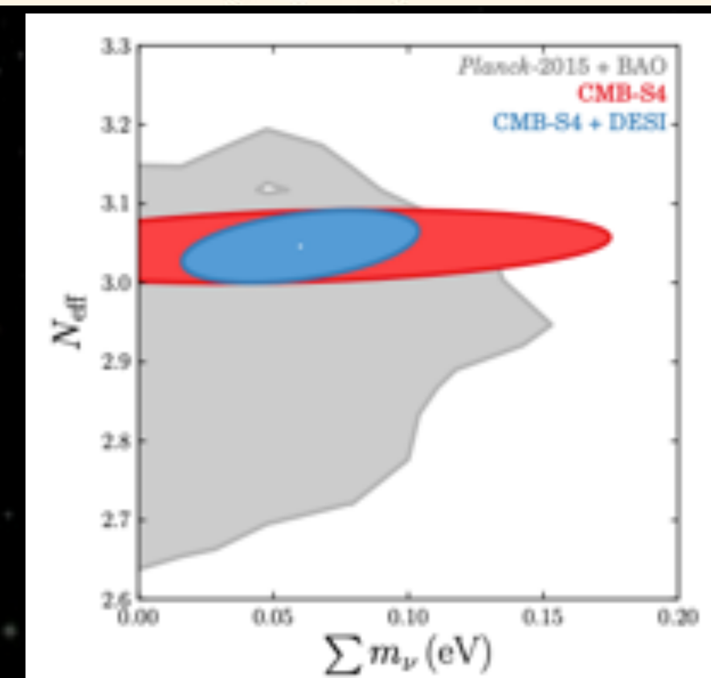




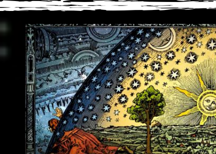
CMB-S4 + DESI + LSST: FoM ~ 1250



$\sum m_\nu$ = 0.1 eV → 5% amplitude of spectrum



CMB-S4 Forecasts



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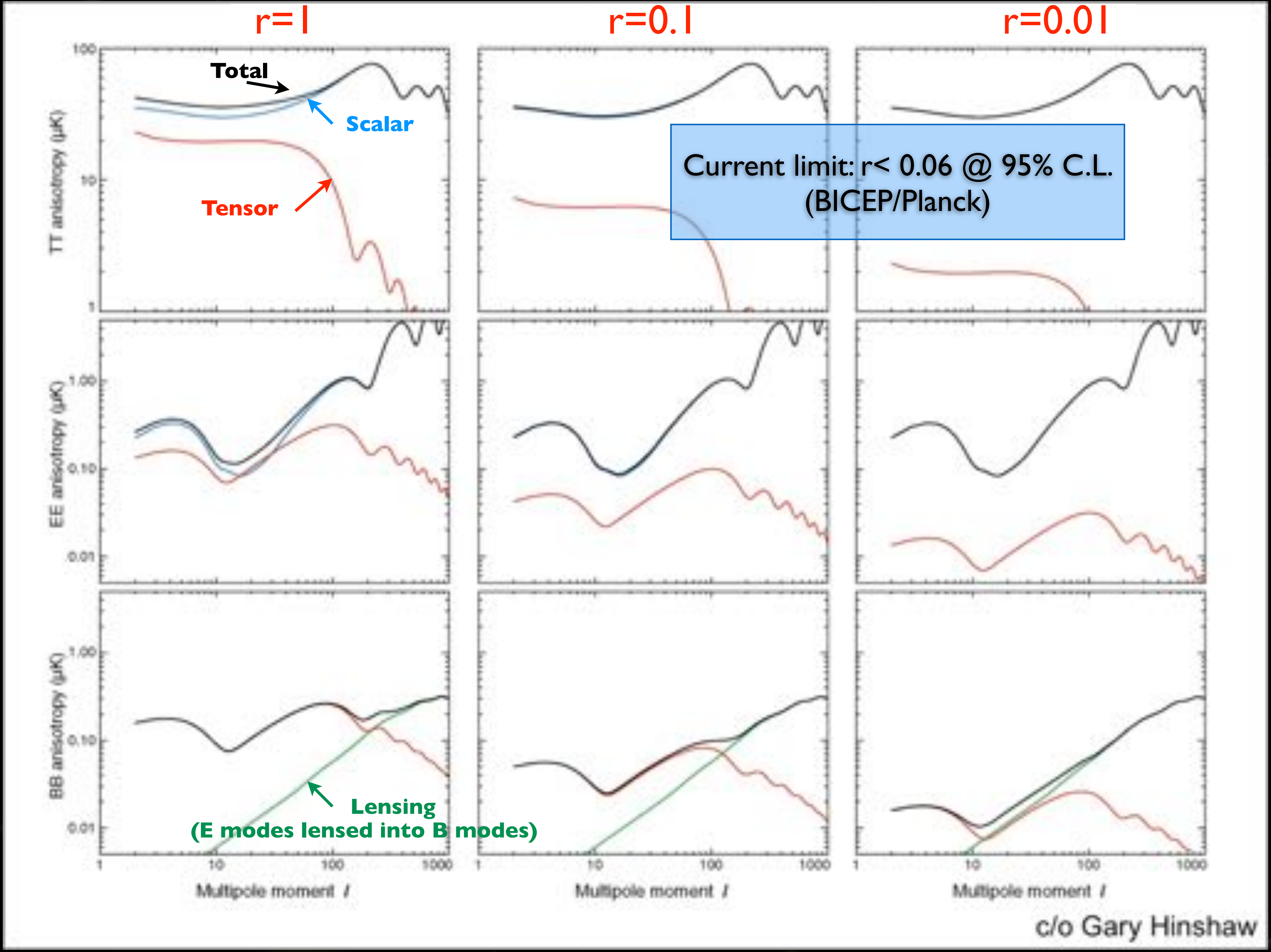

Only B modes allow to «directly observe» tensor modes

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Instrumental systematics

- Diffraction on optical elements
  - ★ Induces ground pickup + cross-polarization

Solutions:
- Ground shields
- Sky signal modulation
- Avoid having many optical elements out of the cryostat…

- Cross-Polarization

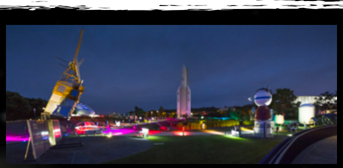
$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} 1+\rho & \epsilon \\ -\epsilon & 1+\rho \end{pmatrix} \cdot \begin{pmatrix} E_x \\ Ey \end{pmatrix} \Rightarrow \begin{pmatrix} Q \\ U \end{pmatrix}' = \begin{pmatrix} 2\rho+1 & 2\epsilon \\ -2\epsilon & 2\rho+1 \end{pmatrix} \cdot \begin{pmatrix} Q \\ U \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} C_\ell^{EE} \\ C_\ell^{BB} \end{pmatrix}' = \begin{pmatrix} 1+4\rho & 4\epsilon^2 \\ 4\epsilon^2 & 1+4\rho \end{pmatrix} \cdot \begin{pmatrix} C_\ell^{EE} \\ C_\ell^{BB} \end{pmatrix}$$

Remember: $C_\ell^{EE} \gg C_\ell^{BB}$

- ★ Therefore mixing parameter ε needs to be controlled exquisitely to allow for B-mode clean measurement.
- ★ Typically
  - if r=0.1 need better than 5% on cross-polarization
  - if r=0.01 need better than 1.5%
  - if r=0.001 need better than 0.5%

Solutions:
- Care in Instrument Design
- Care in Instrument Fabrication
- Polarization modulation (HWP, …)
- Self-Calibration in Data Analysis



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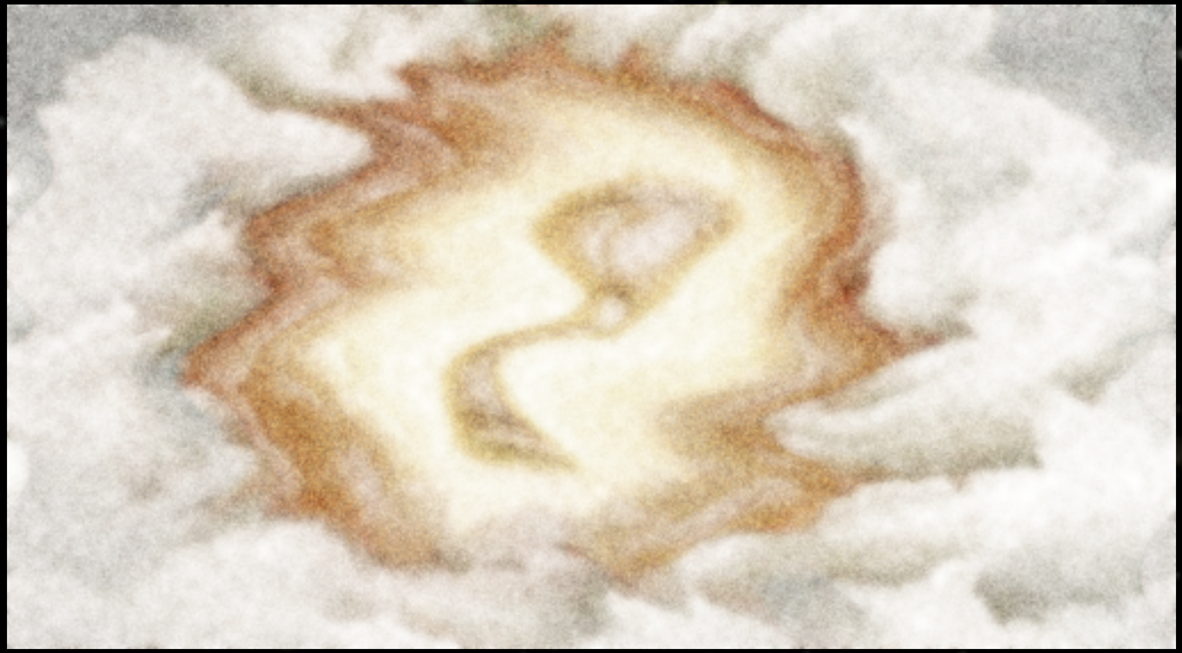

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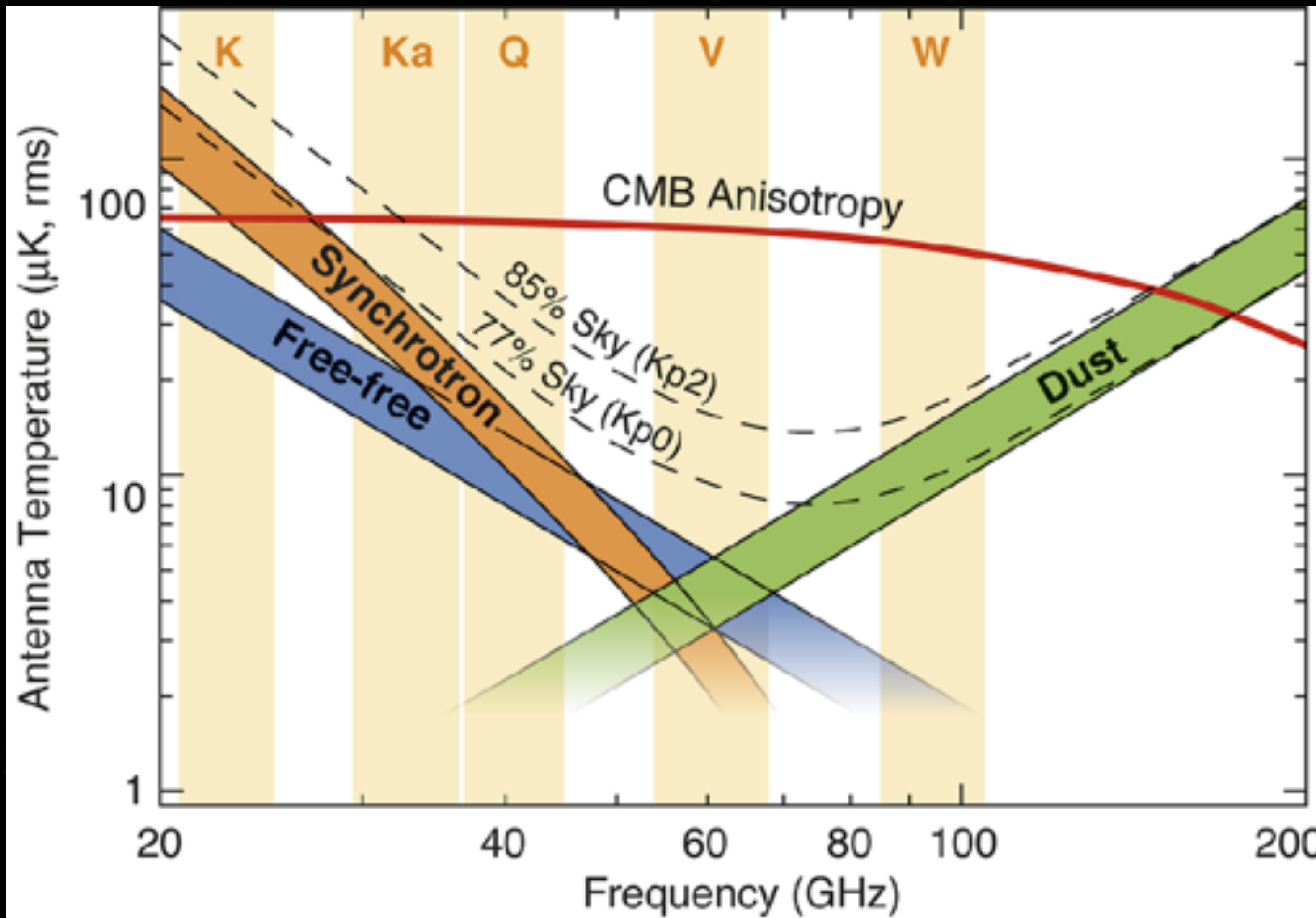
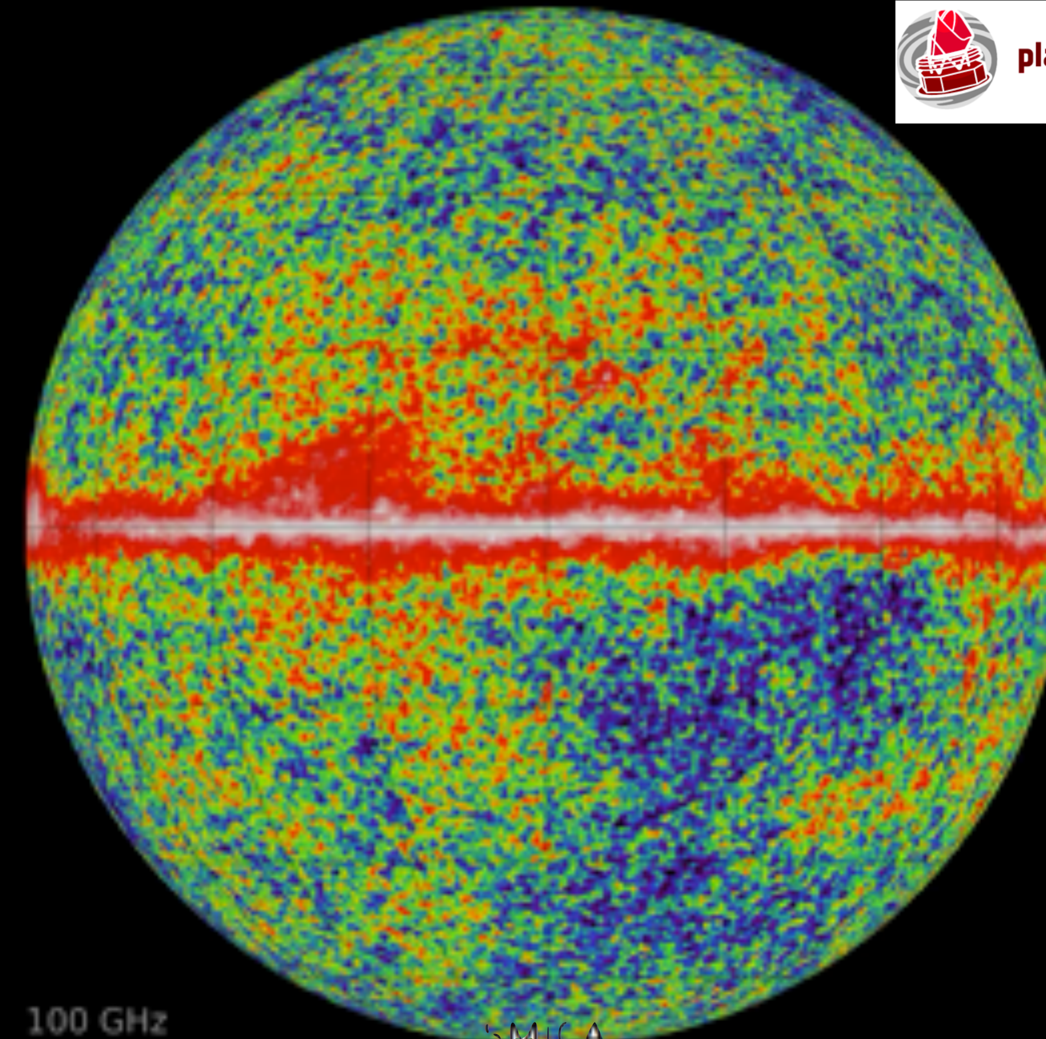




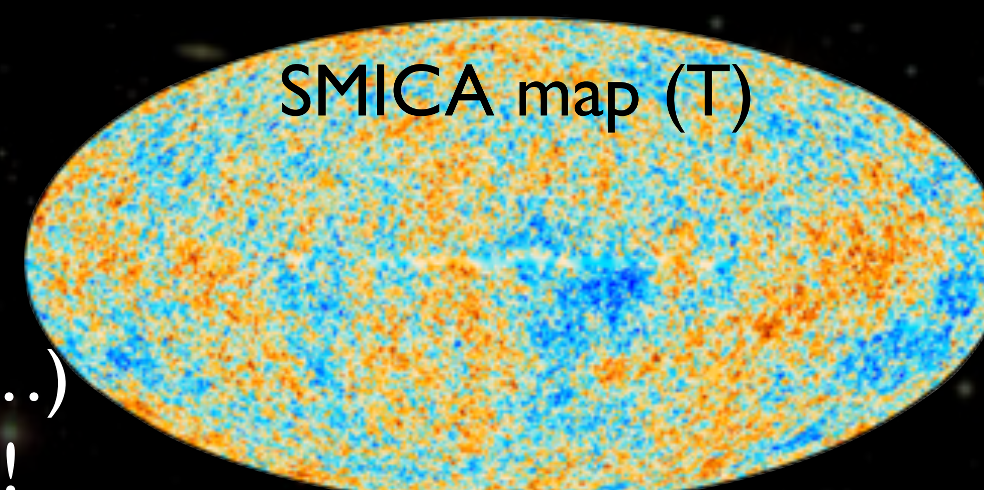
Component separation (simple ILC)

$$\vec{x}_\nu = \vec{x}_{CMB} + \vec{F}_\nu + \vec{n}_\nu \qquad \text{With} \qquad \vec{F}_\nu = A_\nu \vec{F}$$

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

Much harder with Polarization (remember BICEP2…)

NB: A lot of interesting astrophysics in foregrounds !



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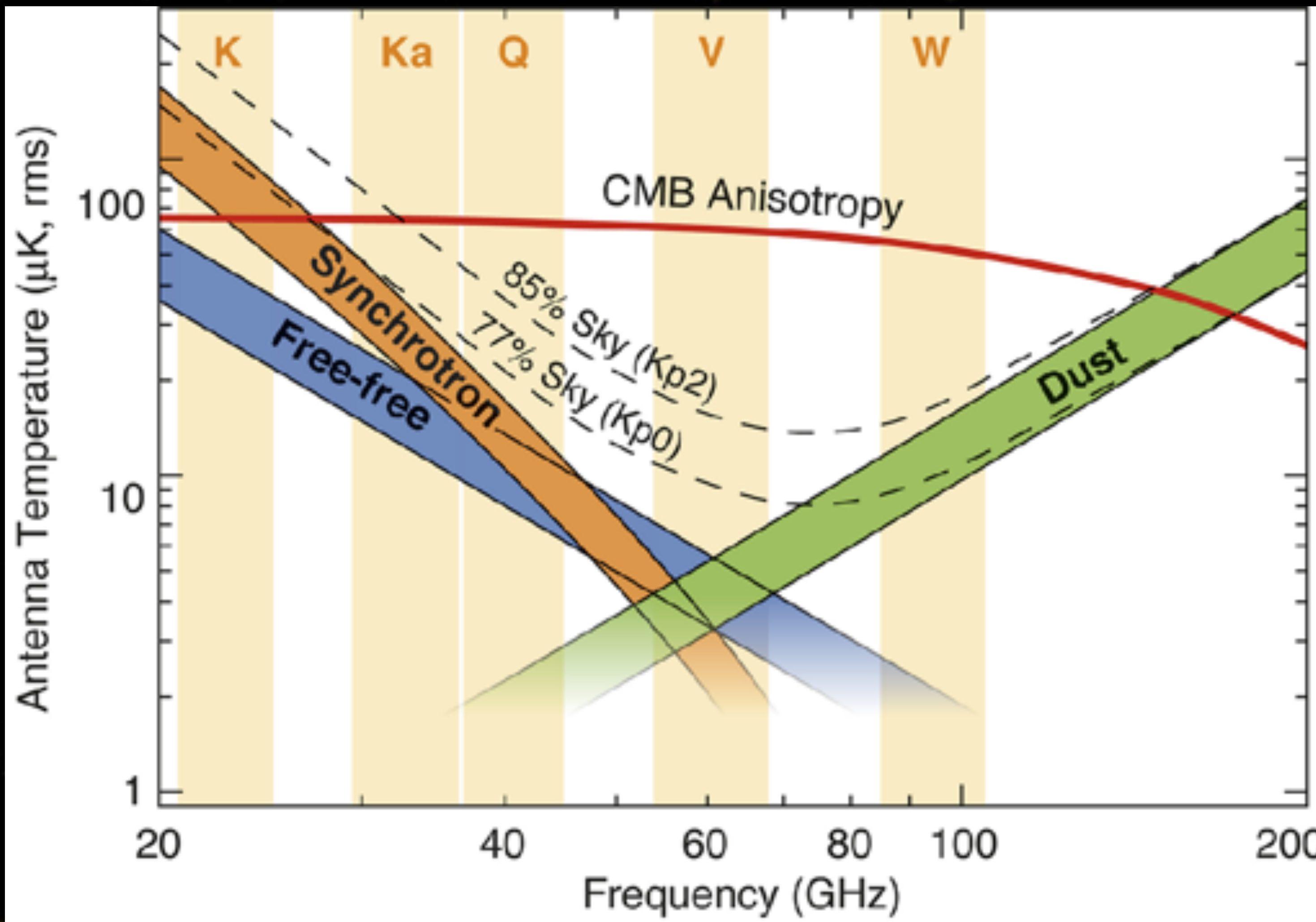

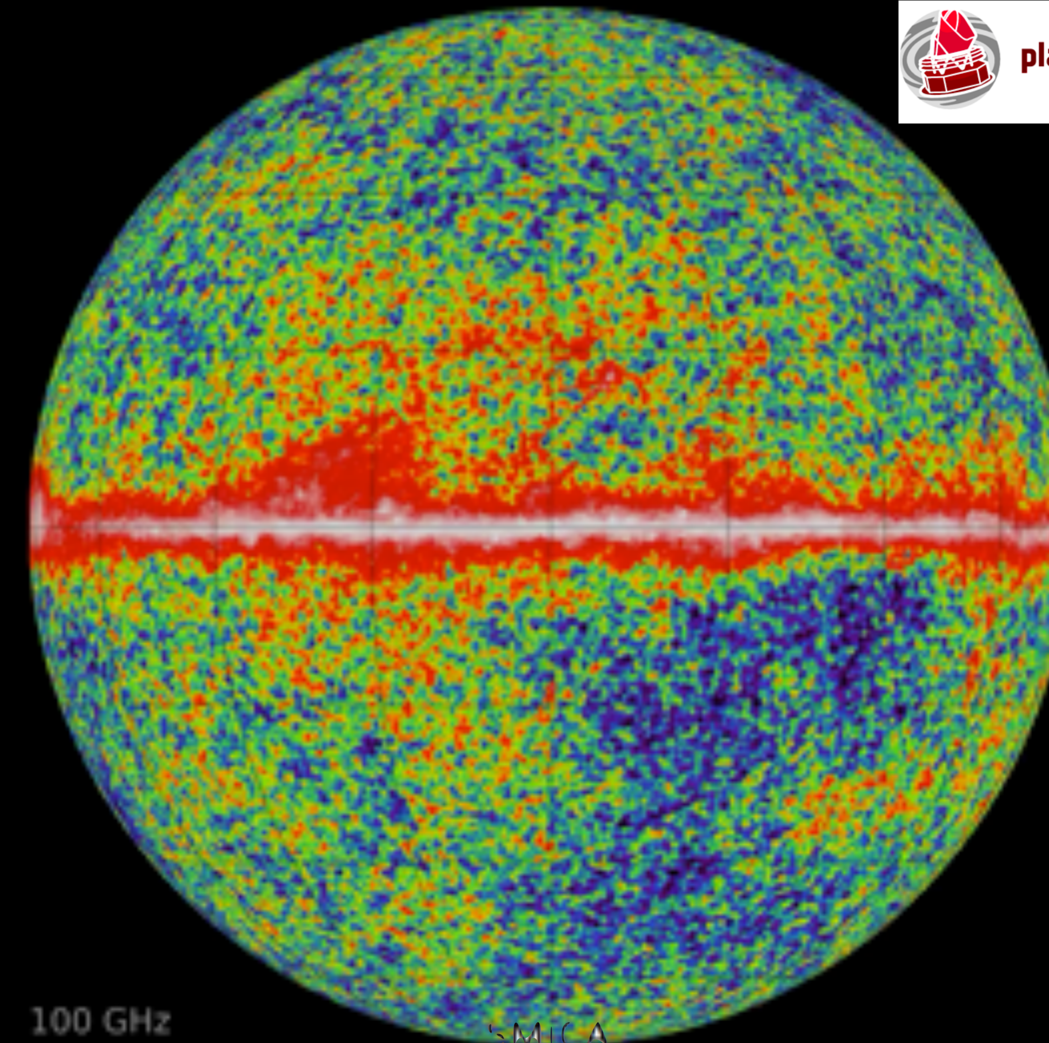

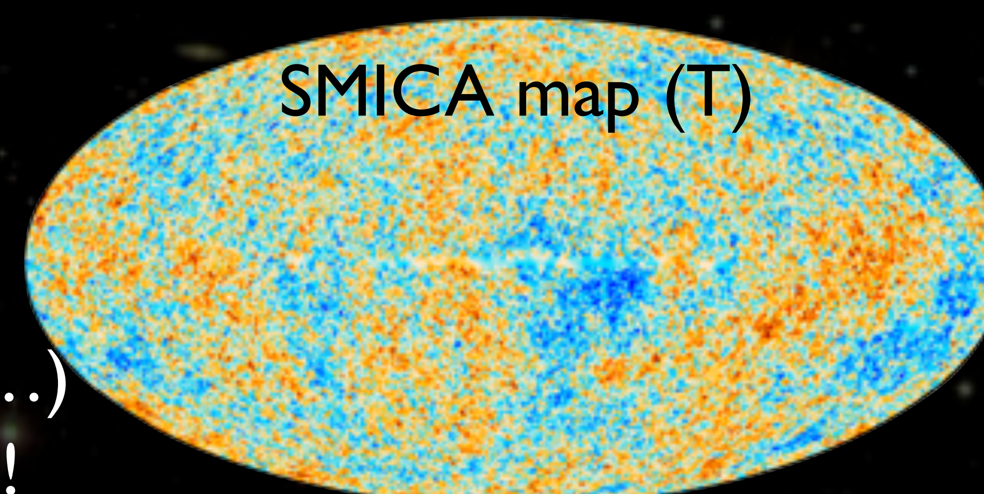

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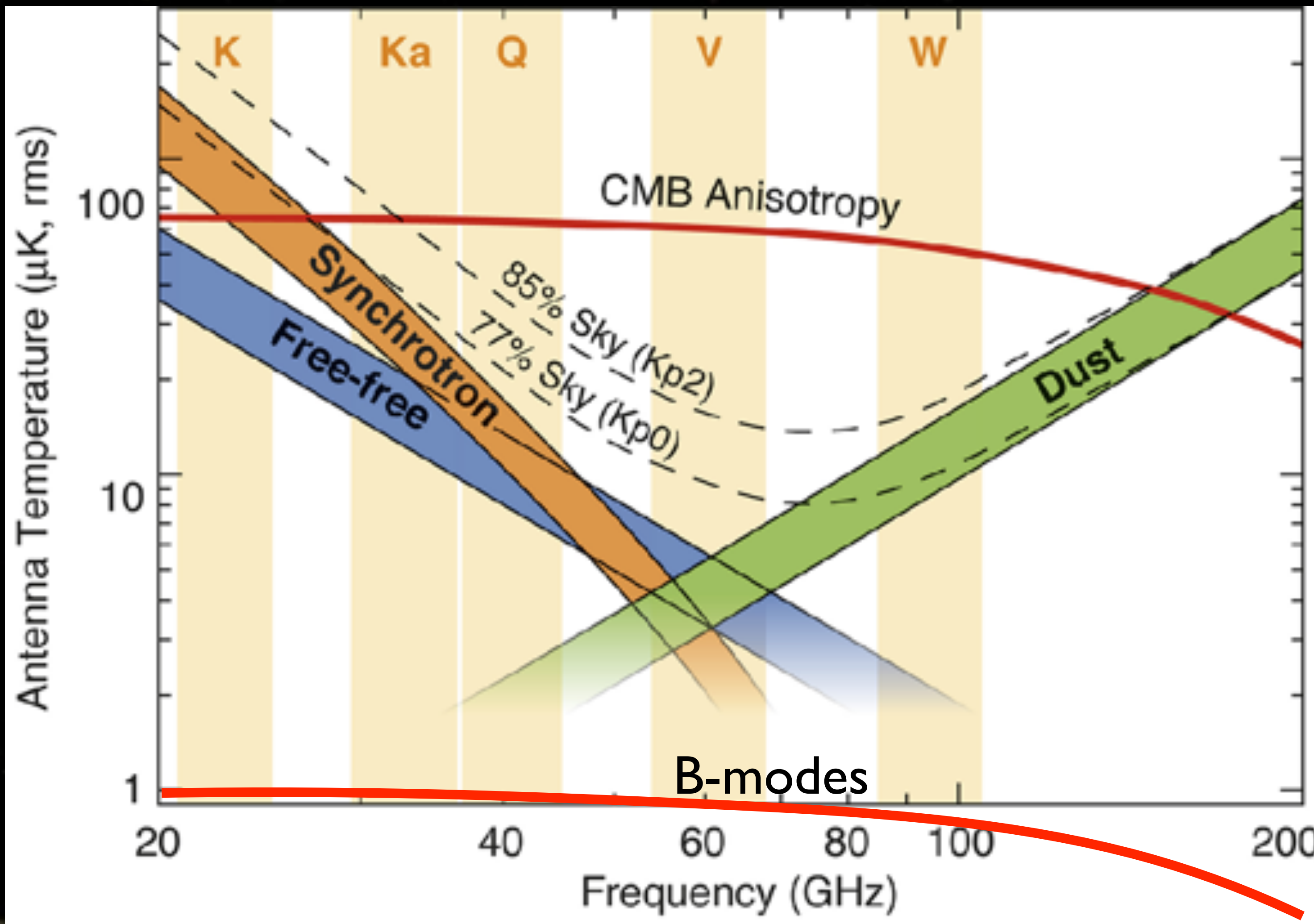

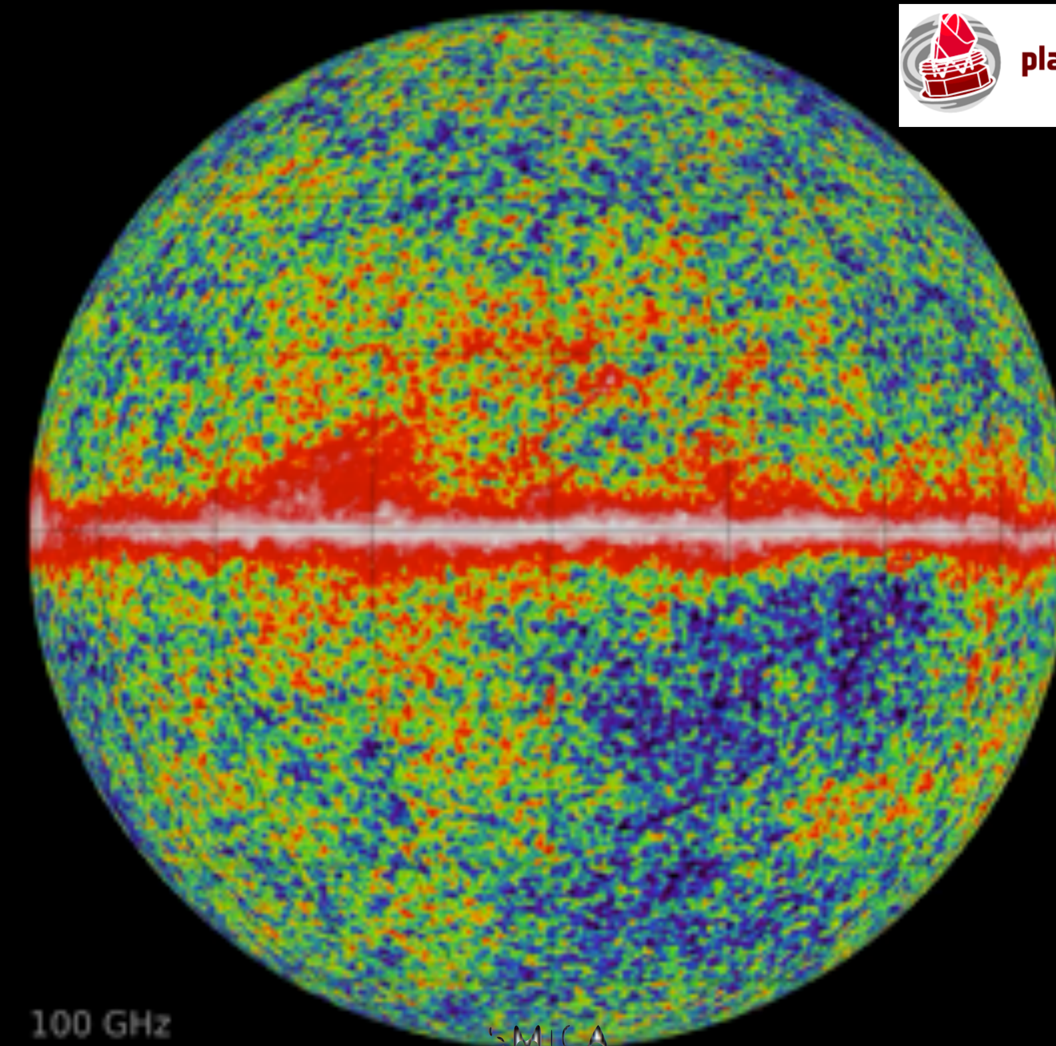

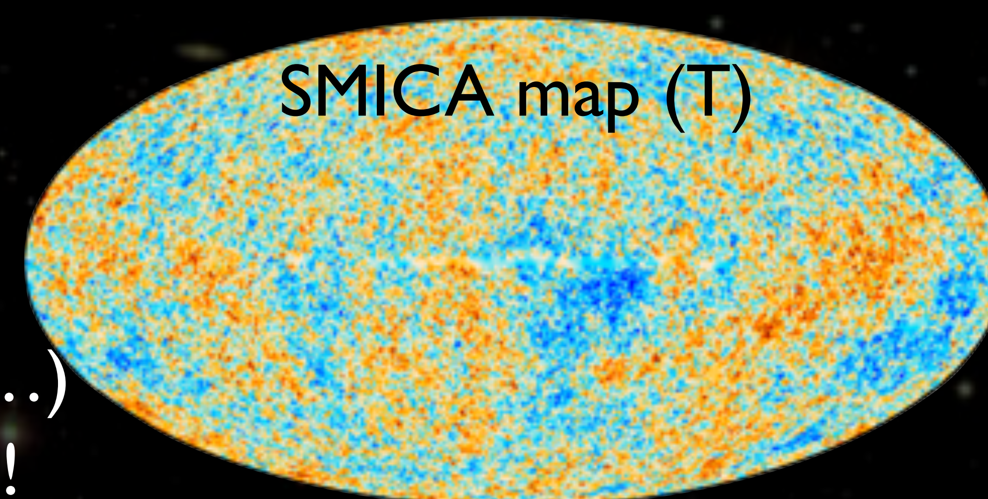

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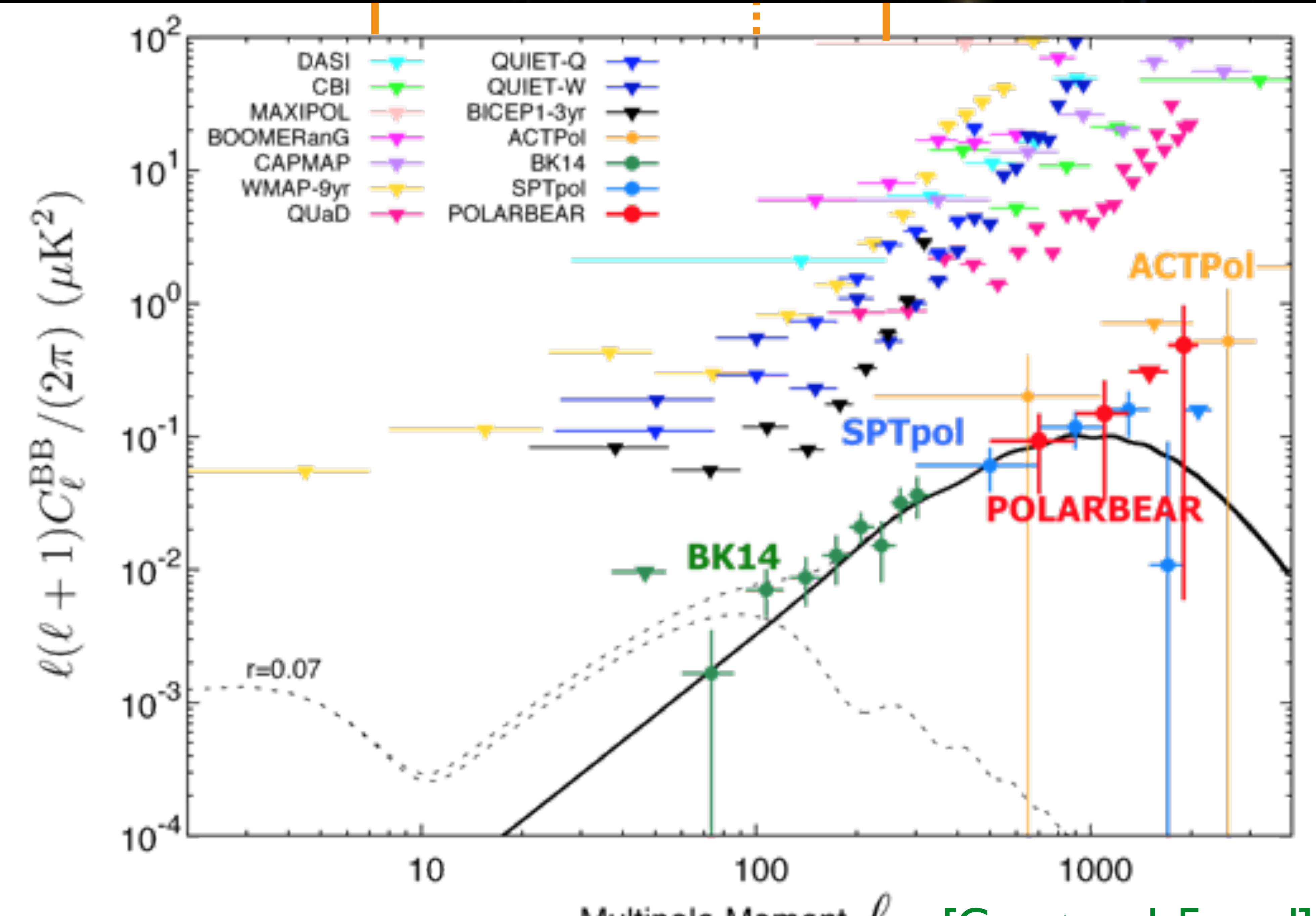
Recent results !!



[Courtesy J. Errard]

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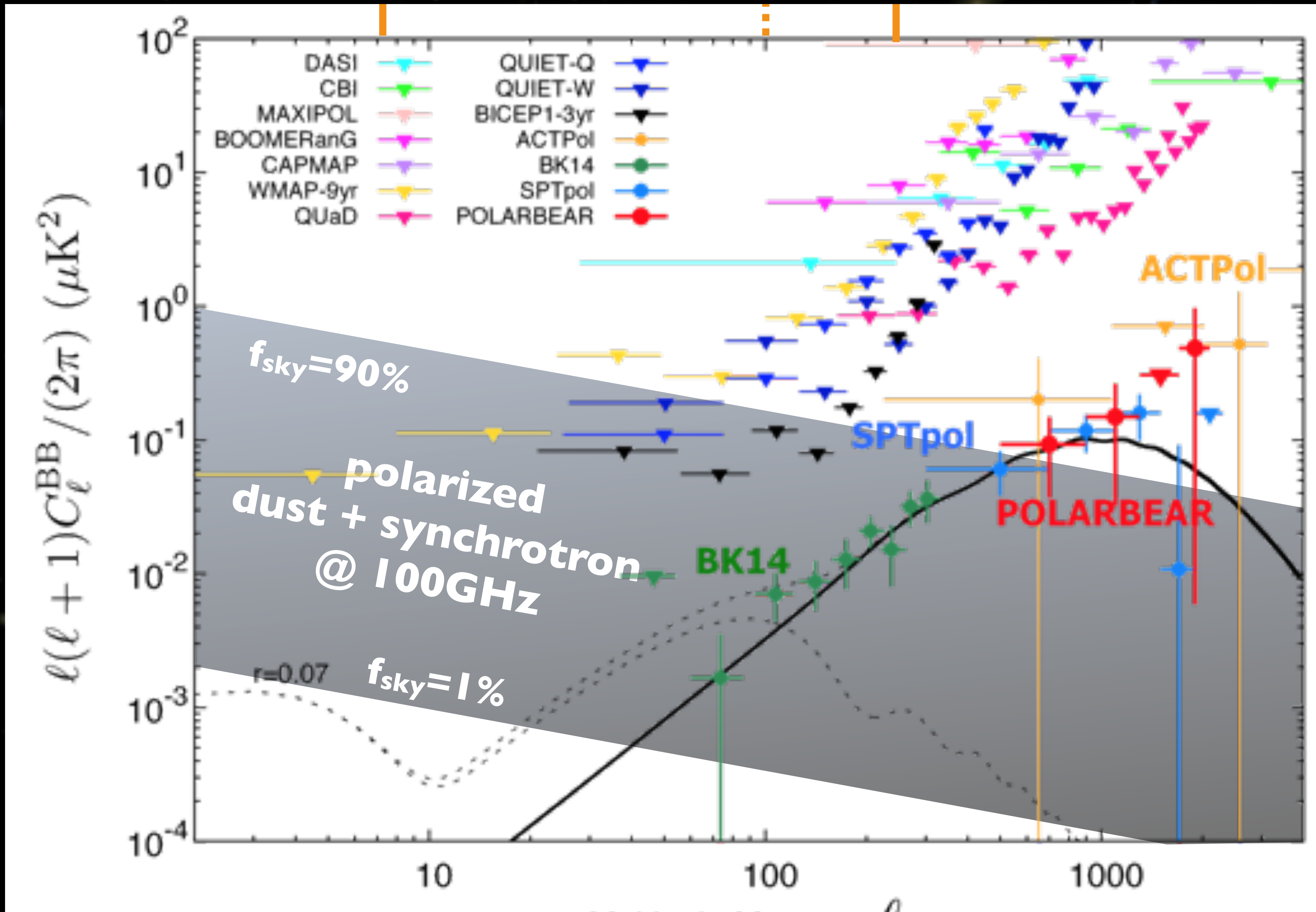

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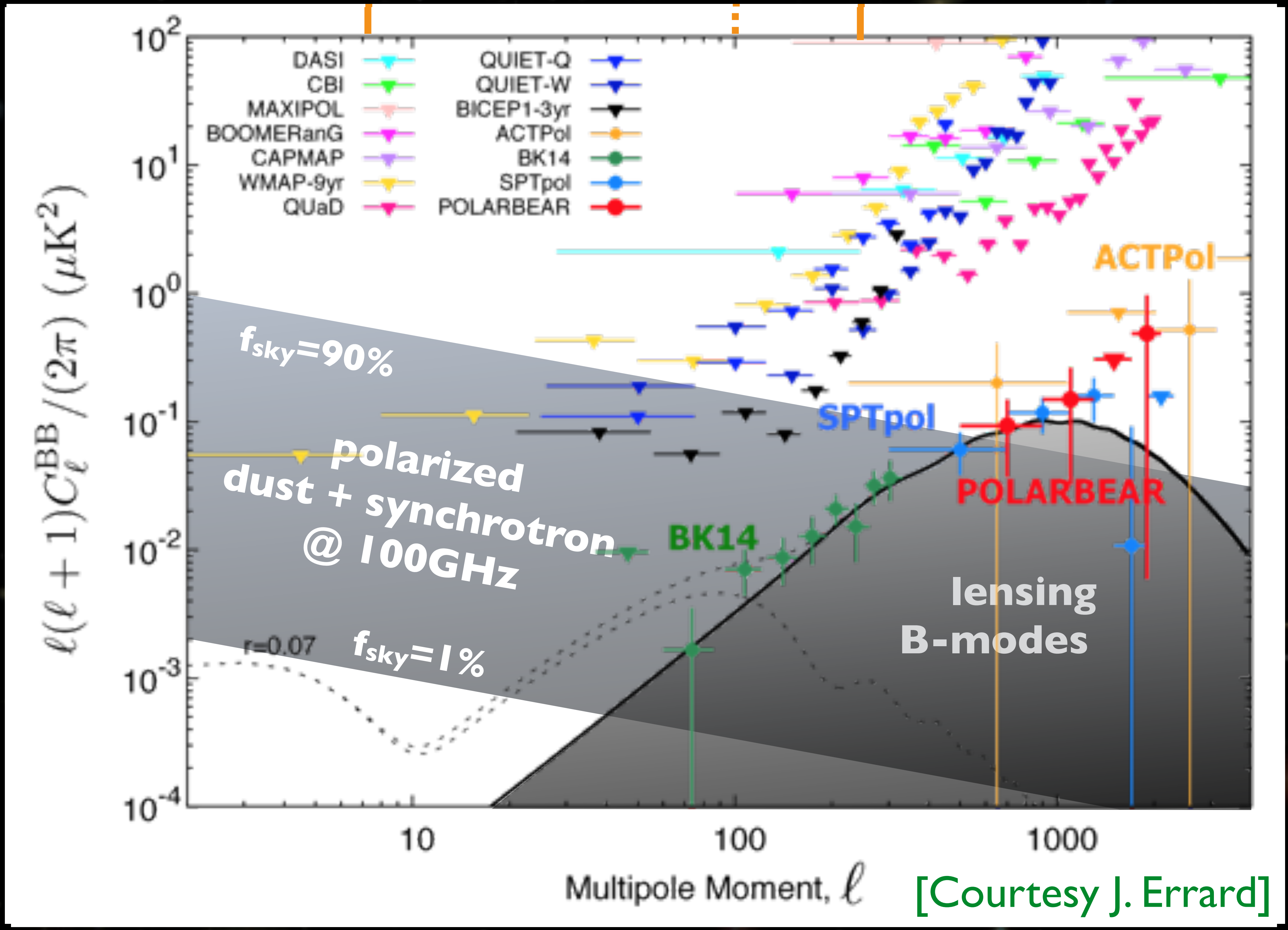

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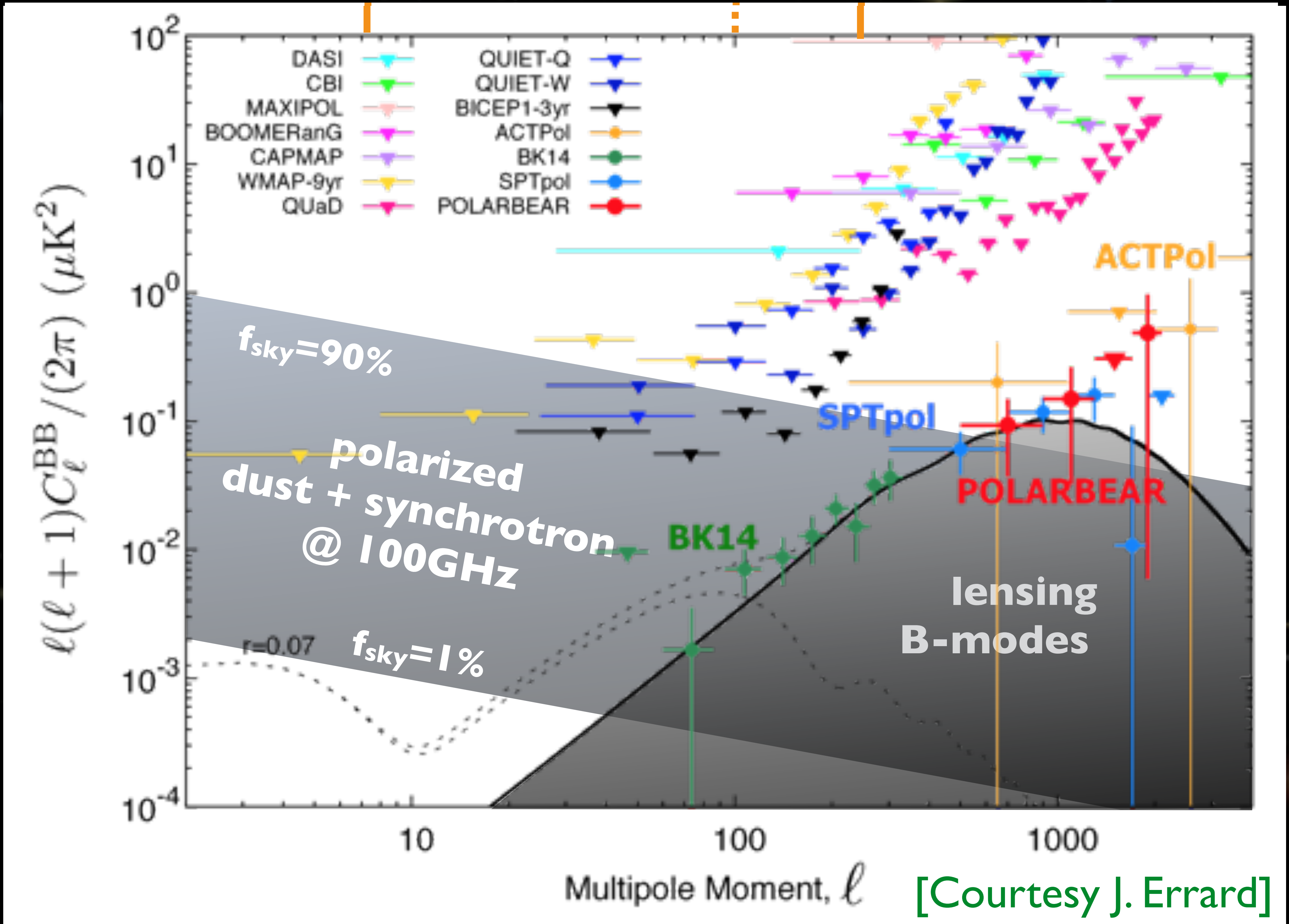

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No primordial B-modes yet… Go back to work !

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Expected difficulties in the Quest for the Holy Grail

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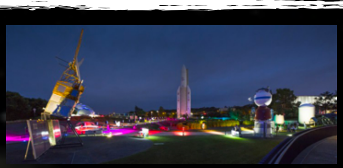
- Sensitivity :
  - ★ Low Signal: B polarization is at best ~15 times weaker than E, amplitude could be **very** small ...
  - ★ A dedicated space mission might not be for tomorrow.
  - ➡ Need many thousands of Background limited detectors
  - ➡ Primordial B-modes peak at l~100 : 0.5 degree angular resolution



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  - ★ Need to control foregrounds accurately (can't just mask: no clean region)
  - ➡ Multiwavelength detectors
  - ➡ Gives access to very interesting astrophysics
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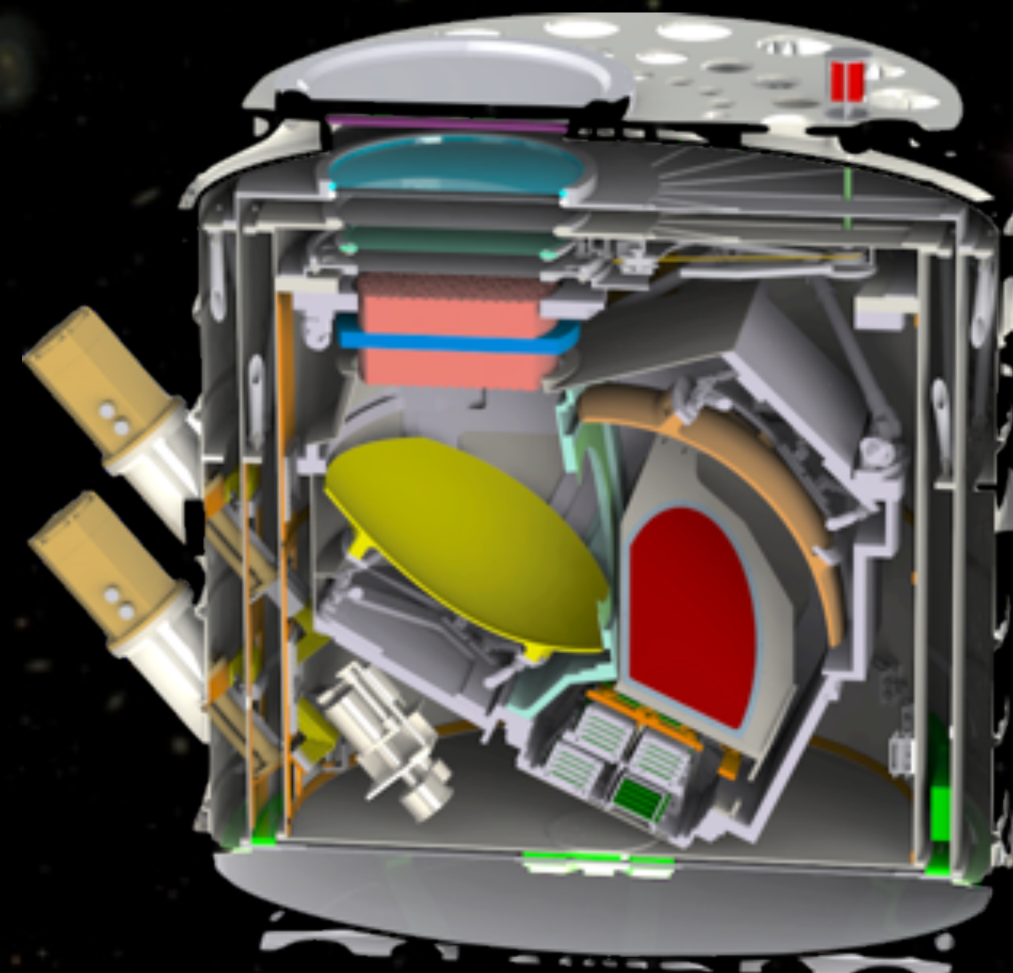
- Systematic effects :
  - ★ Instrument induces leakage of T into E and B (and T>>E>>B)
  - ➡ Cross-polarization and ground pickup are major issues
  - ★ Atmospheric polarization ...
  - ➡ Need for accurate polarization modulation

Experimental Challenges and Future Instruments

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



QUBIC
(a biased choice as
an illustration)

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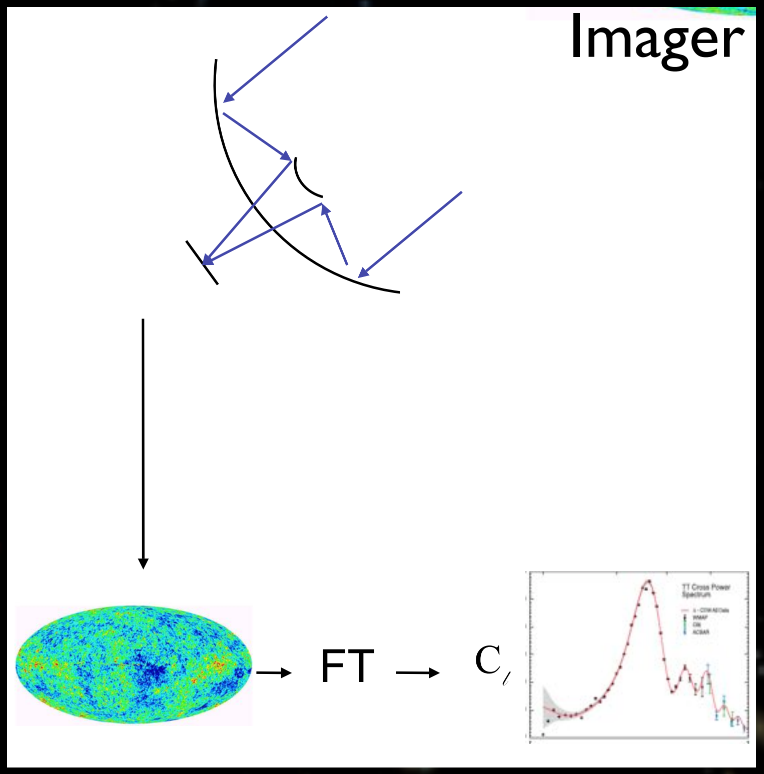
Possible instruments

P.Timbie



Possible instruments

- Imagers:
  - ★ With bolometers (or MKIDs…):
    - Wide band & Low noise
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    - Well mastered, not too noisy from the ground, great at low-frequency
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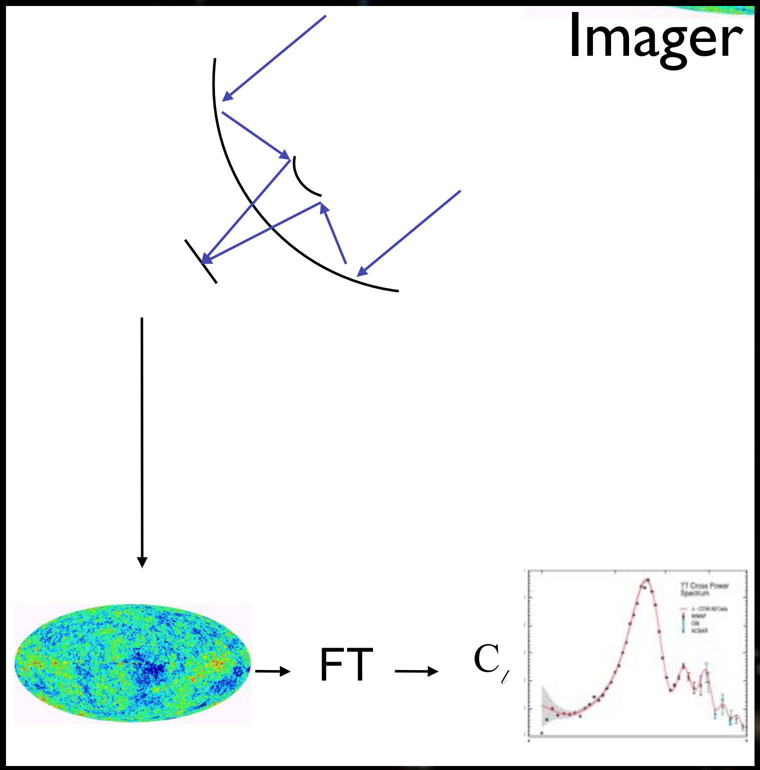

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    - CMB anisotropies in the late 90s (CAT: 1st detection of subdegrees anisotropies, VSA)
    - CMB polarization 1st detection (DASI, CBI)
  - ★ Technology used so far
    - Antennas + HEMTs : higher noise (but reasonable from ground)
    - Correlators : hard to scale to large #channels
  - ★ Clean systematics:
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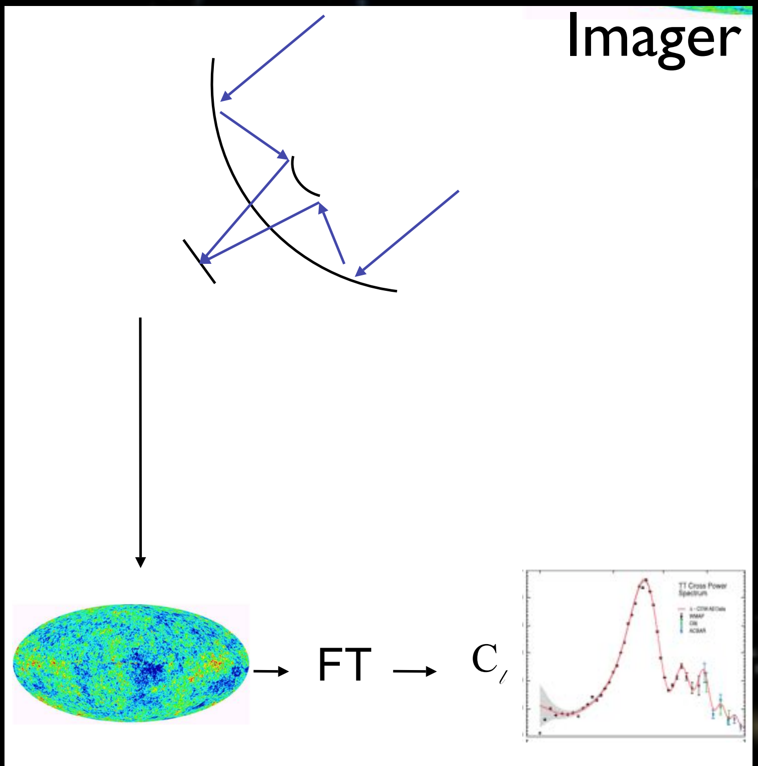
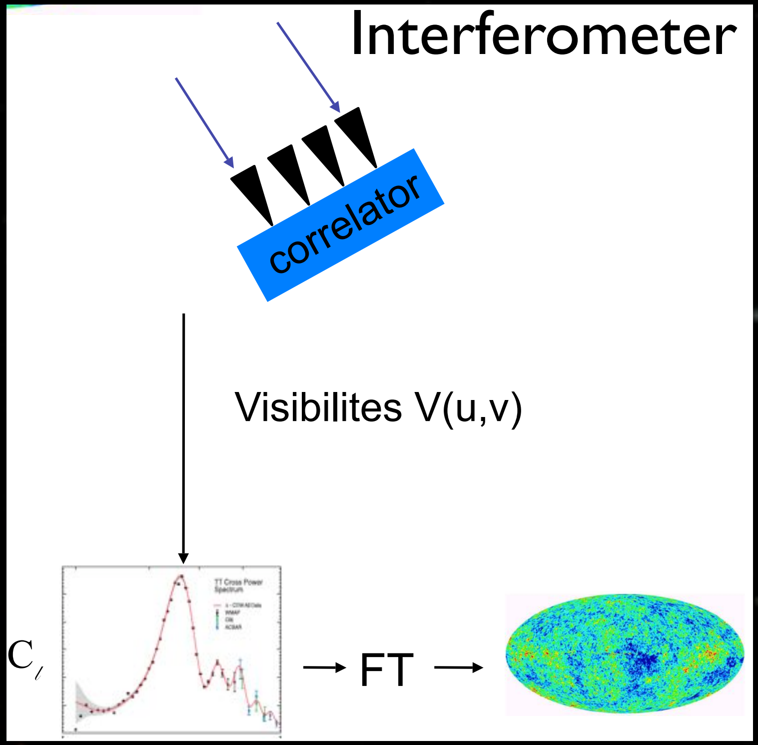
    - Angular resolution set by receivers geometry (well known)

P.Timbie





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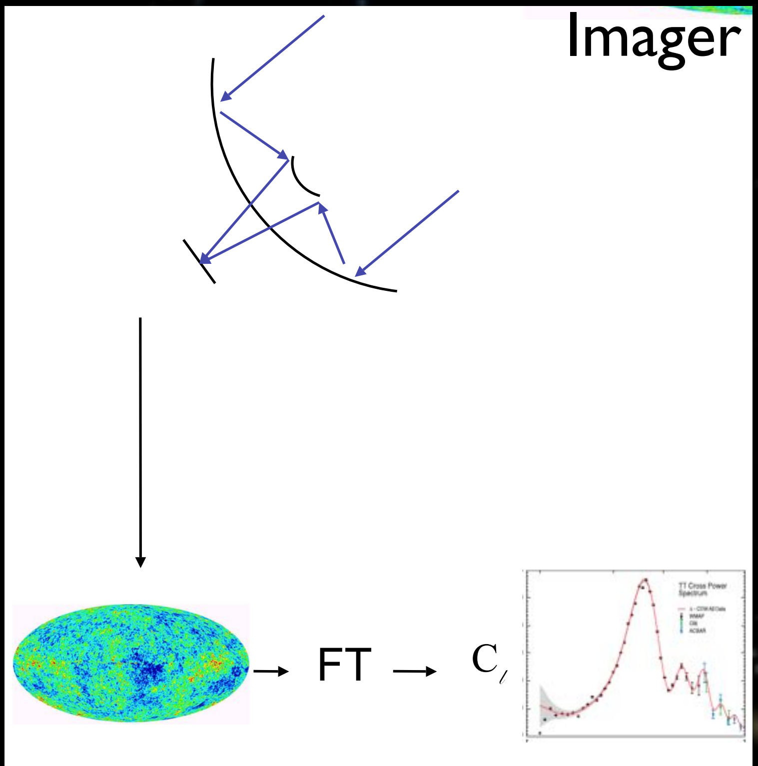
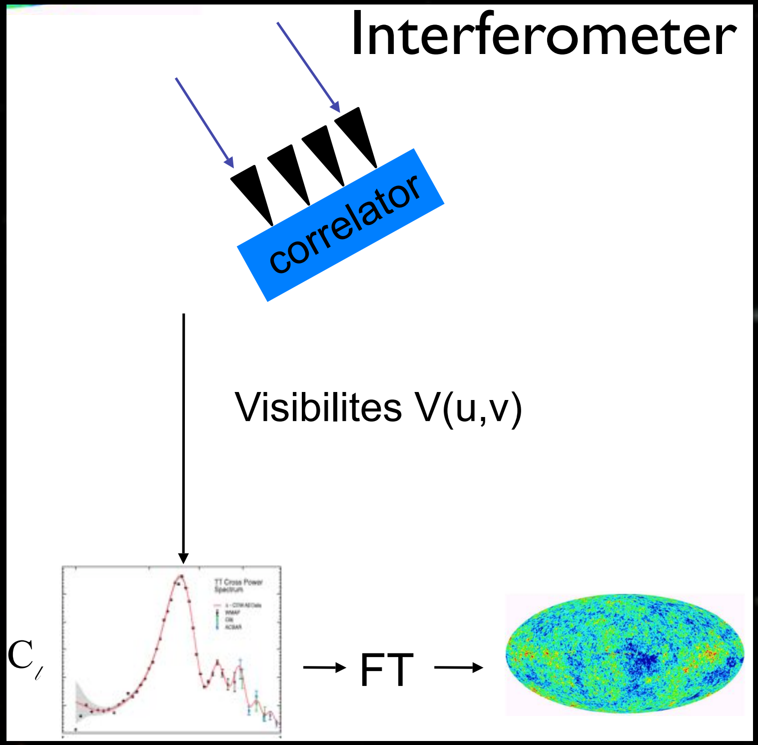
- **Bolometric Interferometry ?**
  - ➡ QUBIC

P.Timbie



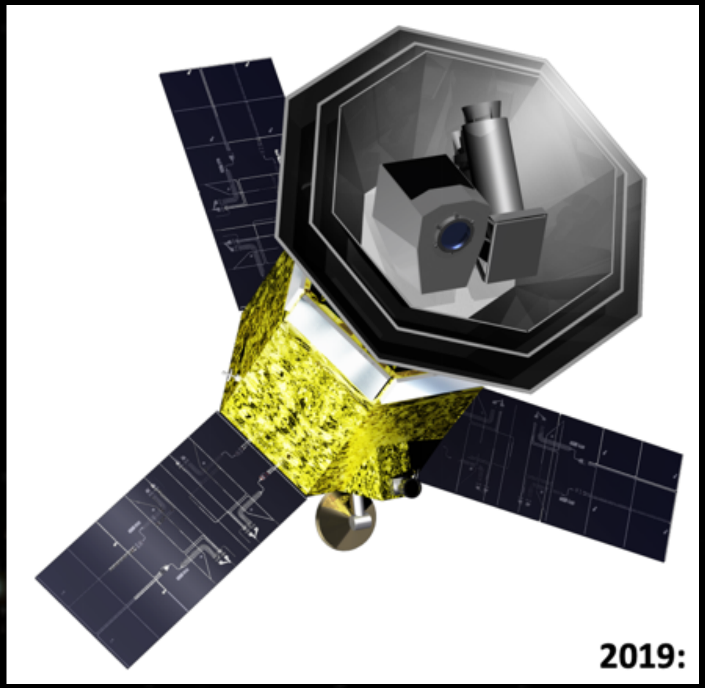


Possible sites

- Satellite
  - ★ Cool ! but expensive and rare…
  - ★ LiteBIRD (Japan with EU and USA) ~2028
- 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 250 GHz
  - ★ Antarctica Vs. Chile / Argentina
    - Atmosphere Vs. logistics Vs. sky coverage
  - ★ Northern hemisphere: Canary, Greenland, Tibet ?

Planck

LiteBIRD



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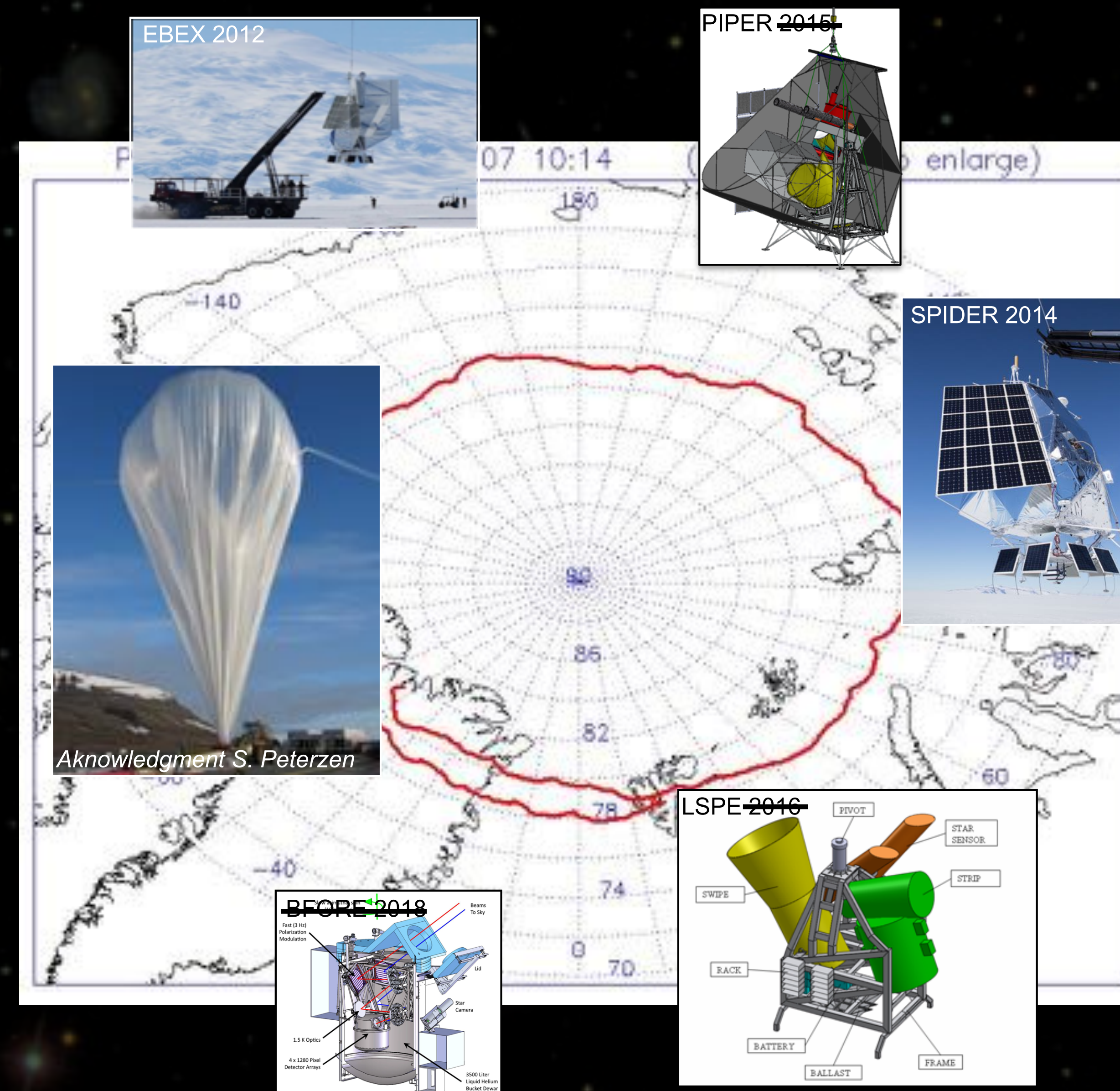
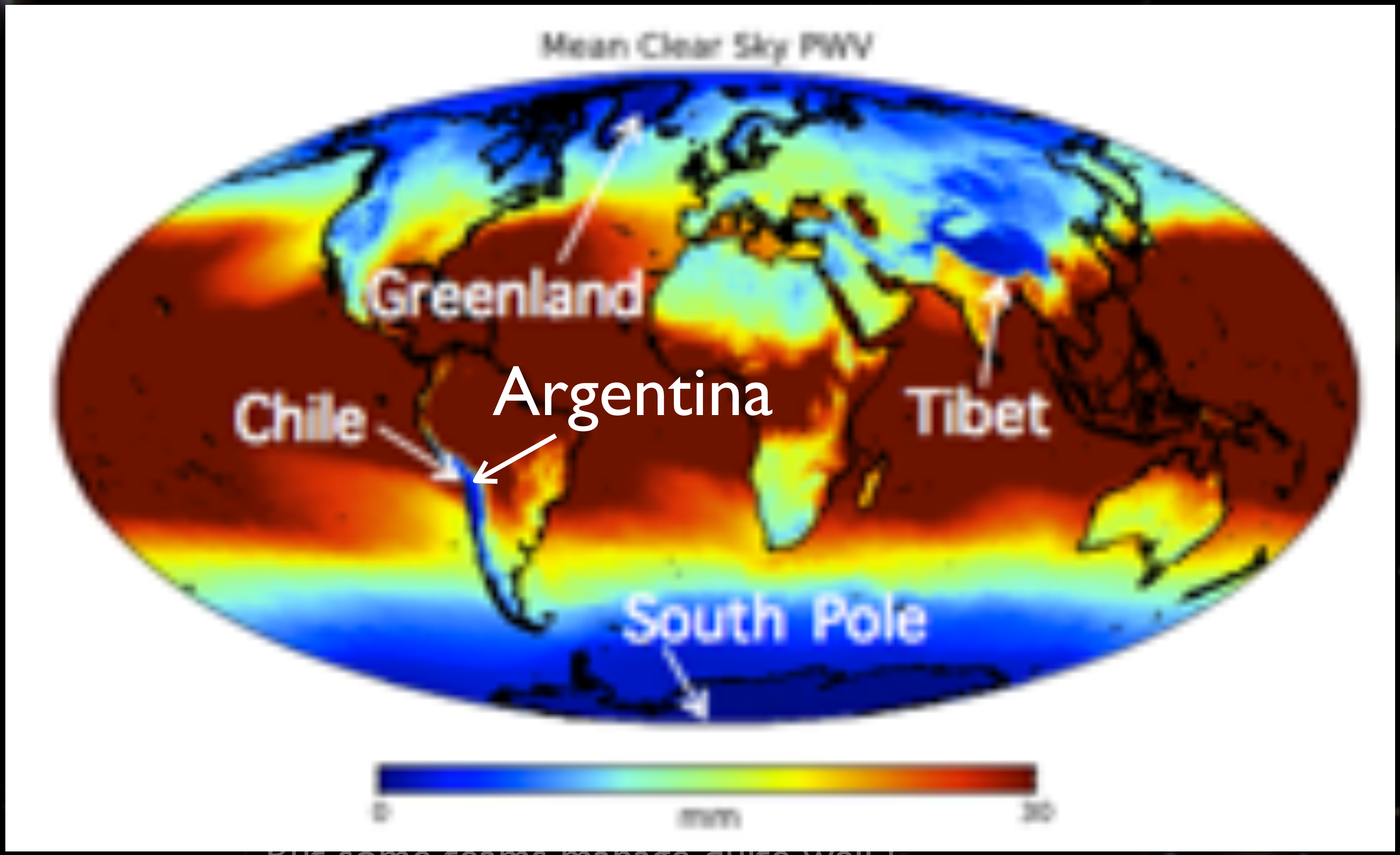
- Satellite
  - ★ Cool ! but expensive and rare…
  - ★ LiteBIRD (Japan with EU and USA) ~2028
- Balloon Borne
  - ★ Sensitivity:
    - Low background
    - Short exposure: hard to do long duration flights…
  - ★ Bands:
    - Easier to go to high frequency w.r.t. ground
  - ★ Weight limitations make it hard to have huge arrays + can't tune the device…
    - But some teams manage quite well !
    - SPIDER is analyzing data !
- Ground
  - ★ Can tweak the instrument
  - ★ Less logistics limitations
  - ★ Hard to go above 250 GHz
  - ★ Antarctica Vs. Chile / Argentina
    - Atmosphere Vs. logistics Vs. sky coverage
  - ★ Northern hemisphere: Canary, Greenland, Tibet ?



[From E. Battistelli]

Possible sites



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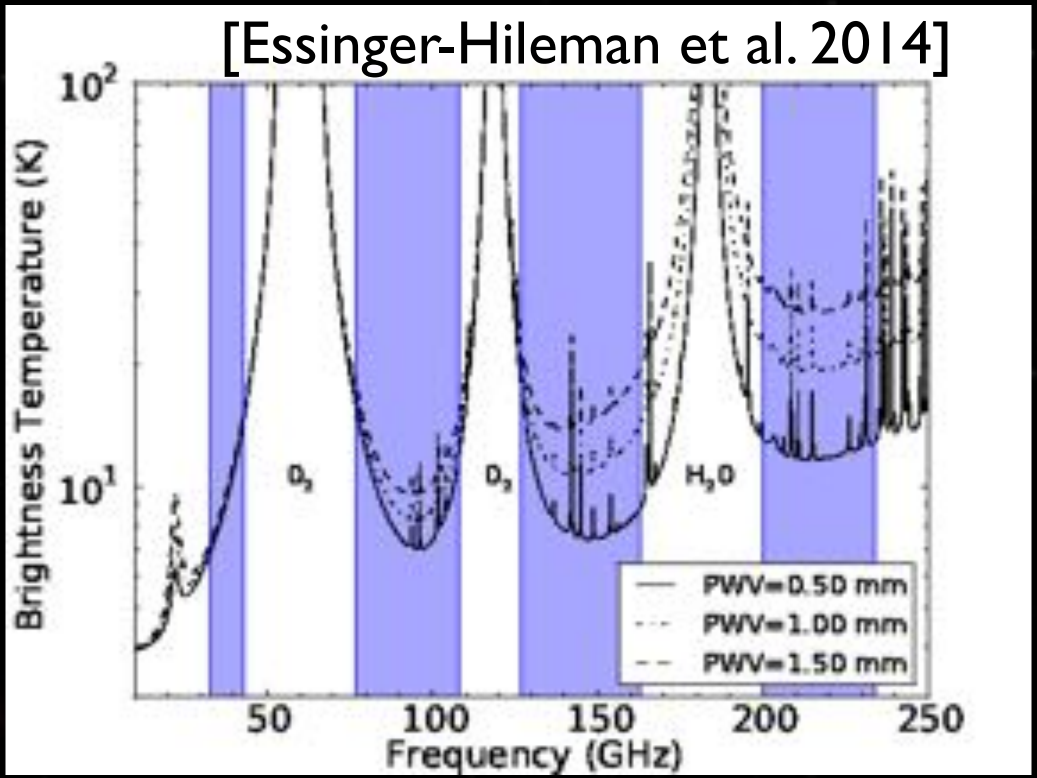
Noise in Ground-based CMB

- 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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J.-Ch. Hamilton
hamilton@apc.in2p3.fr

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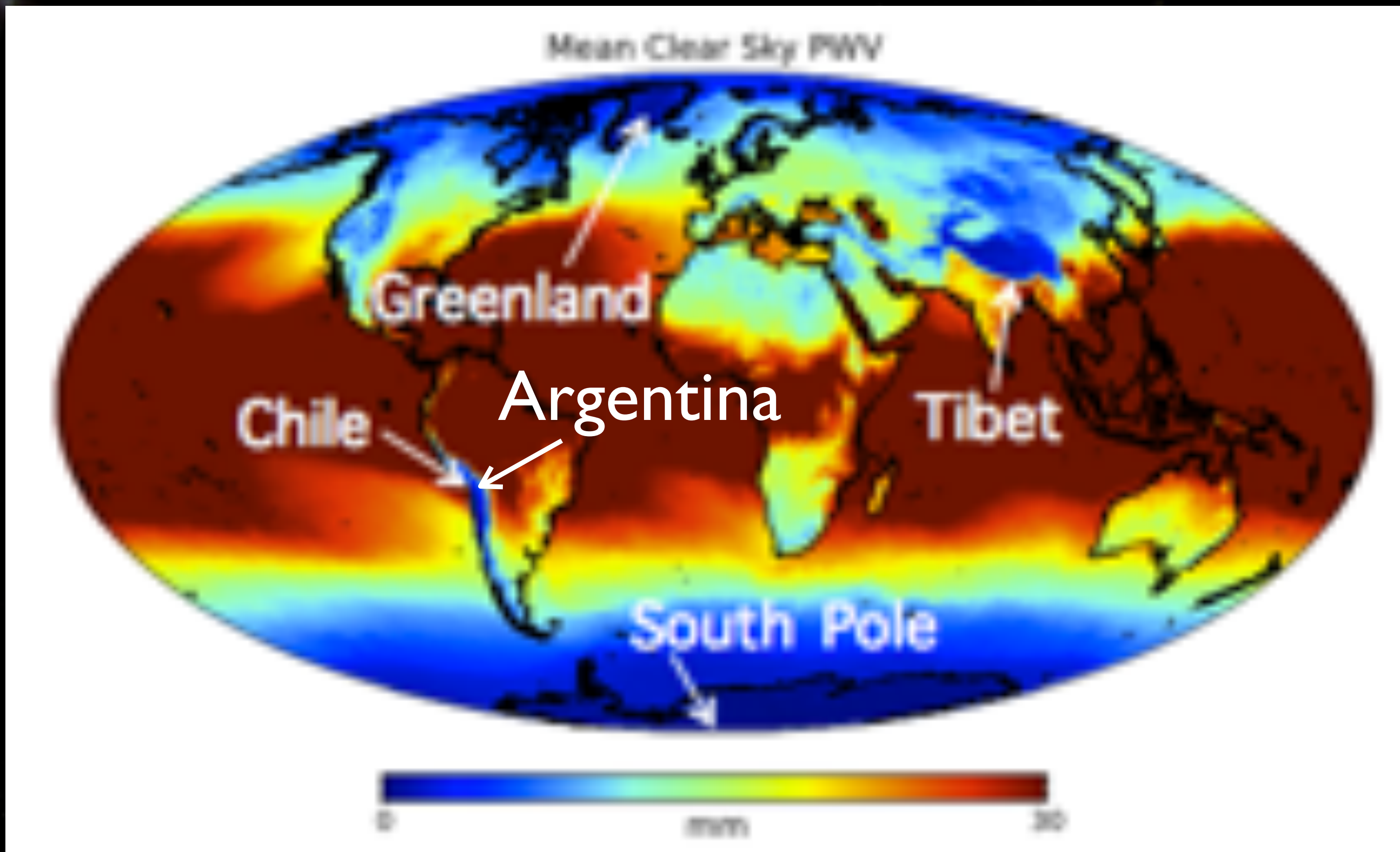

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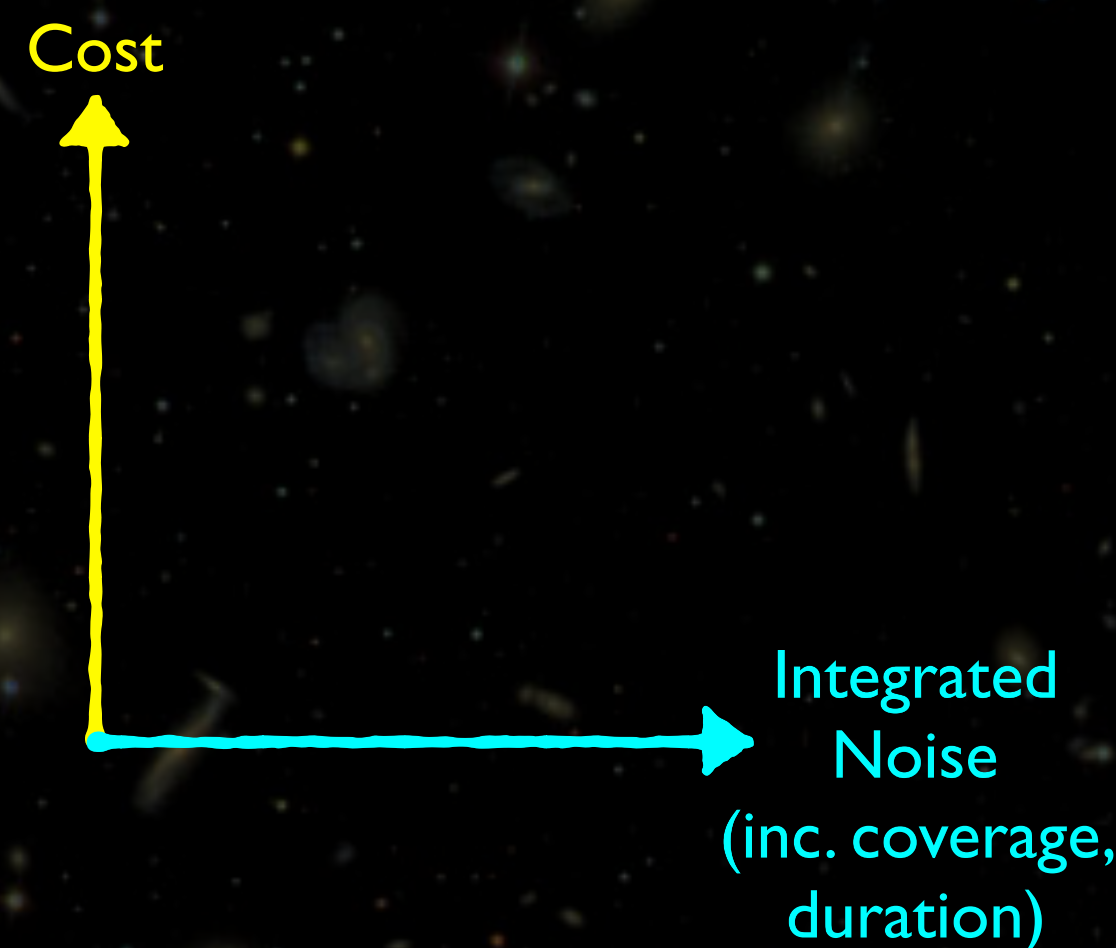

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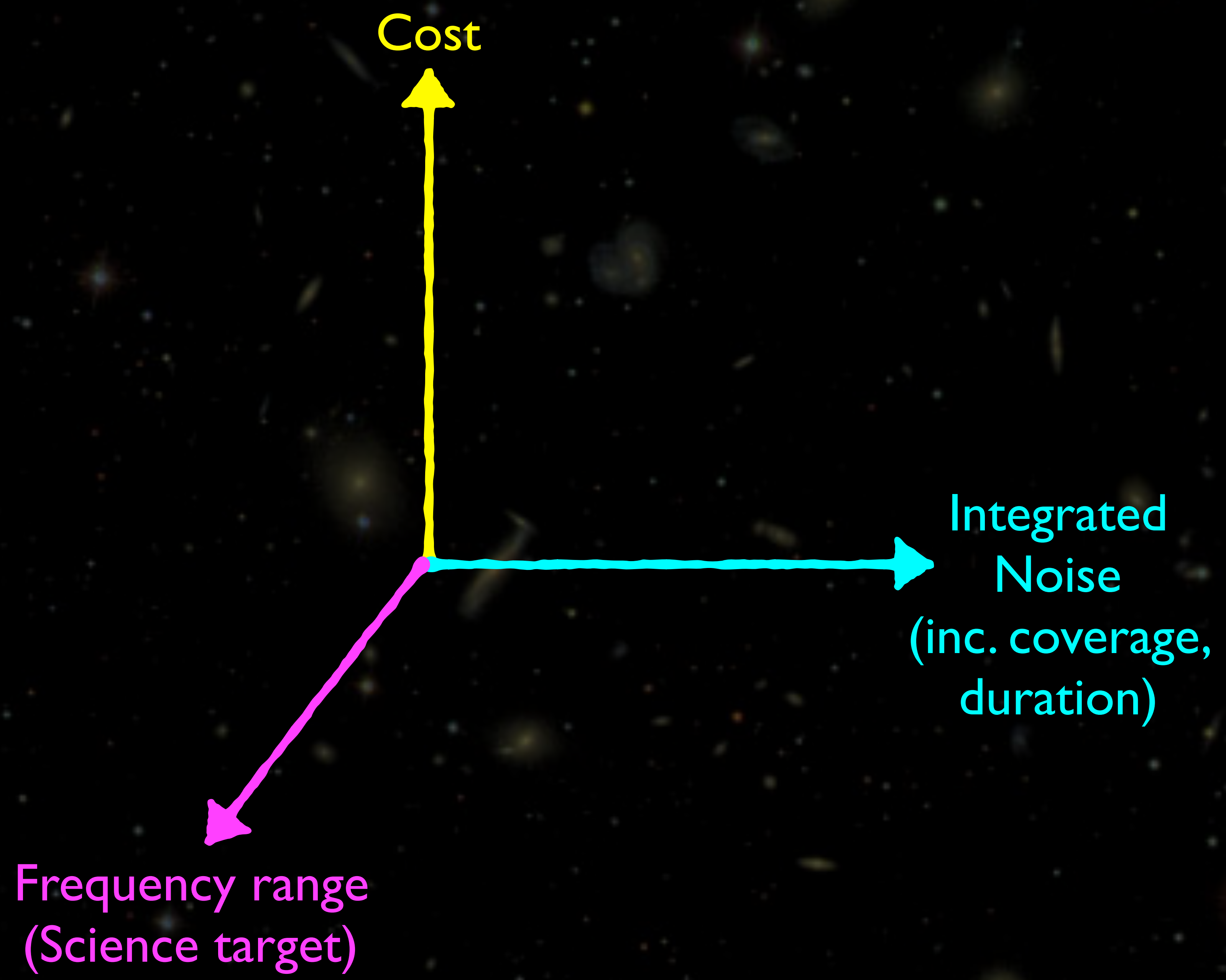

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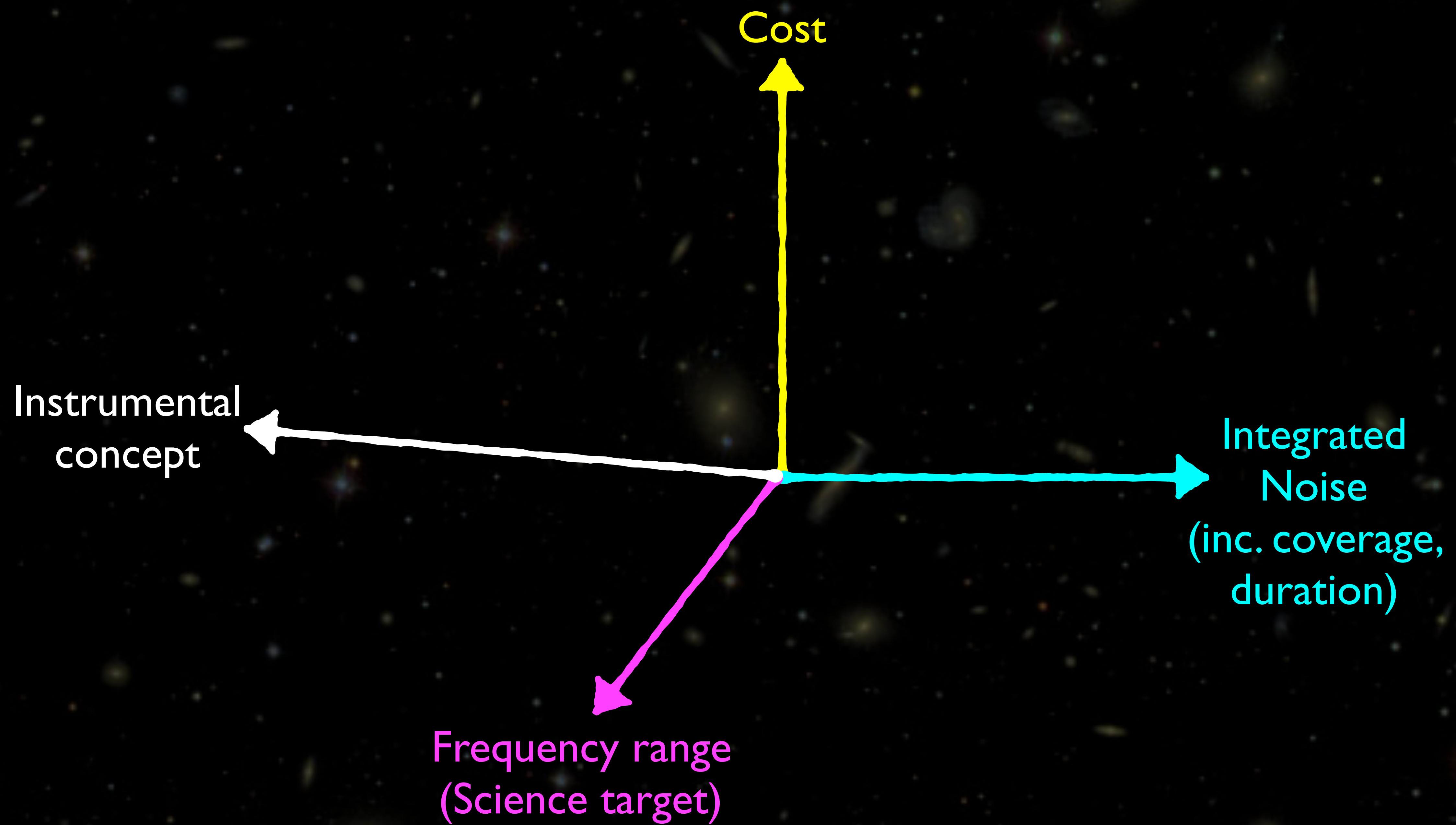

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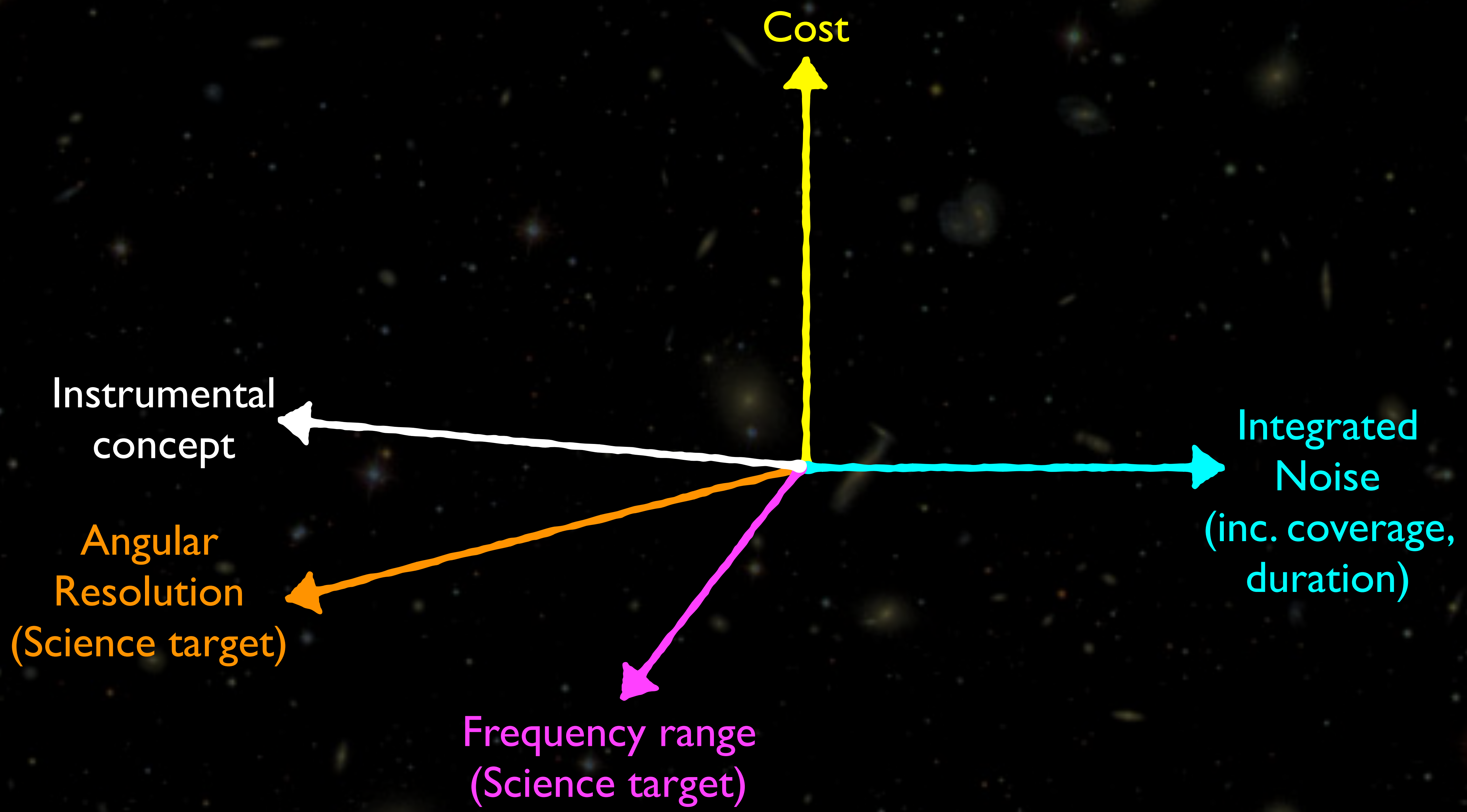

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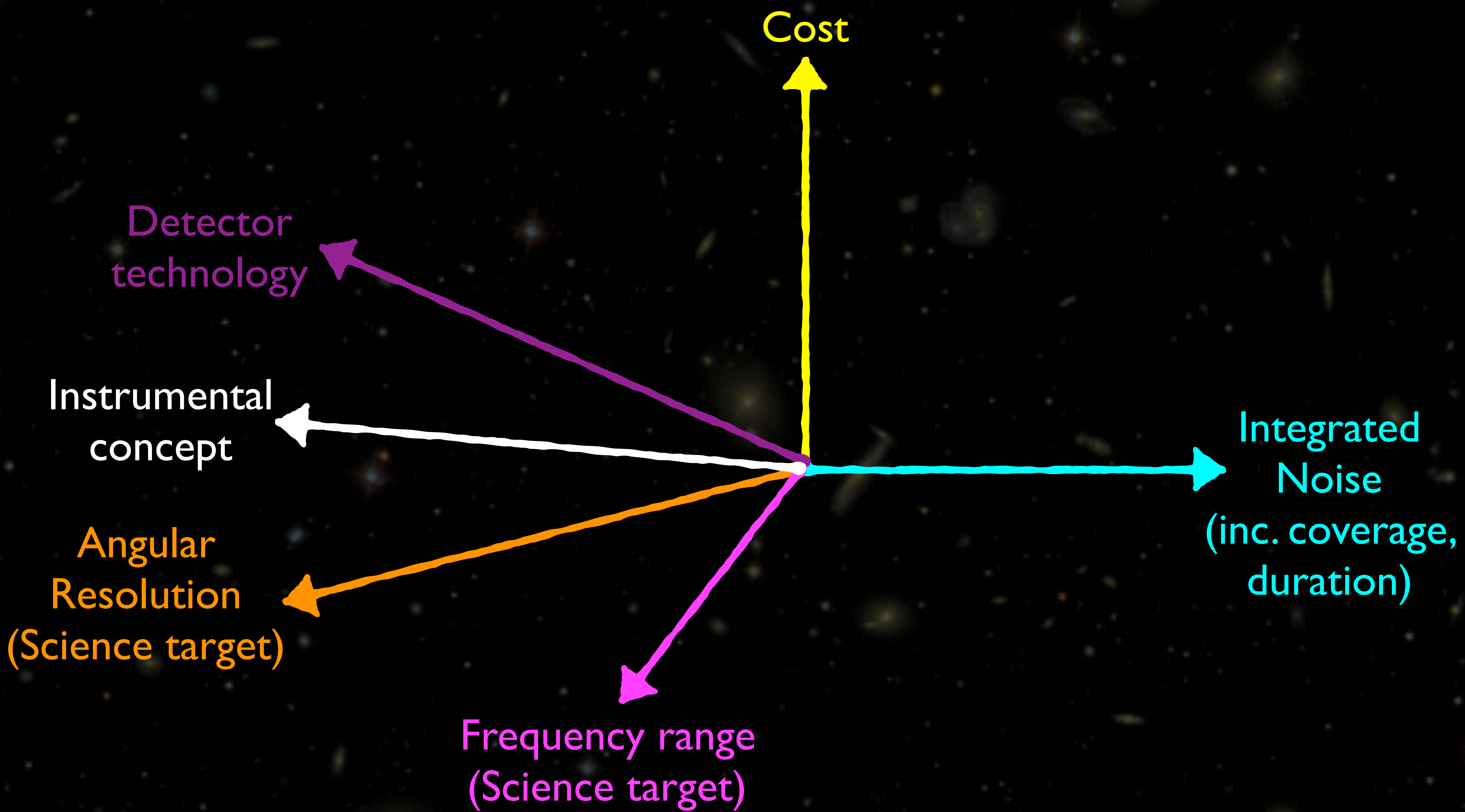

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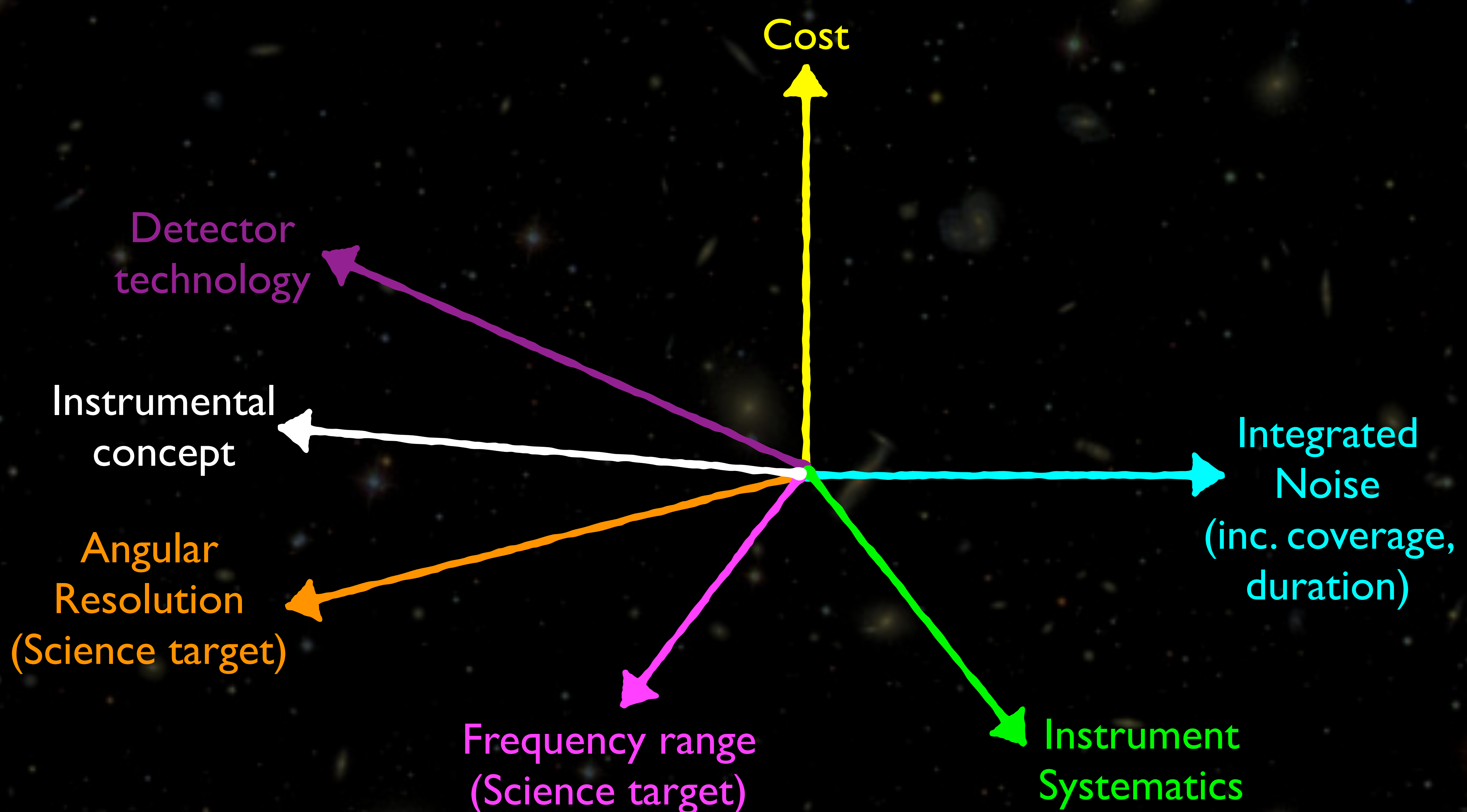

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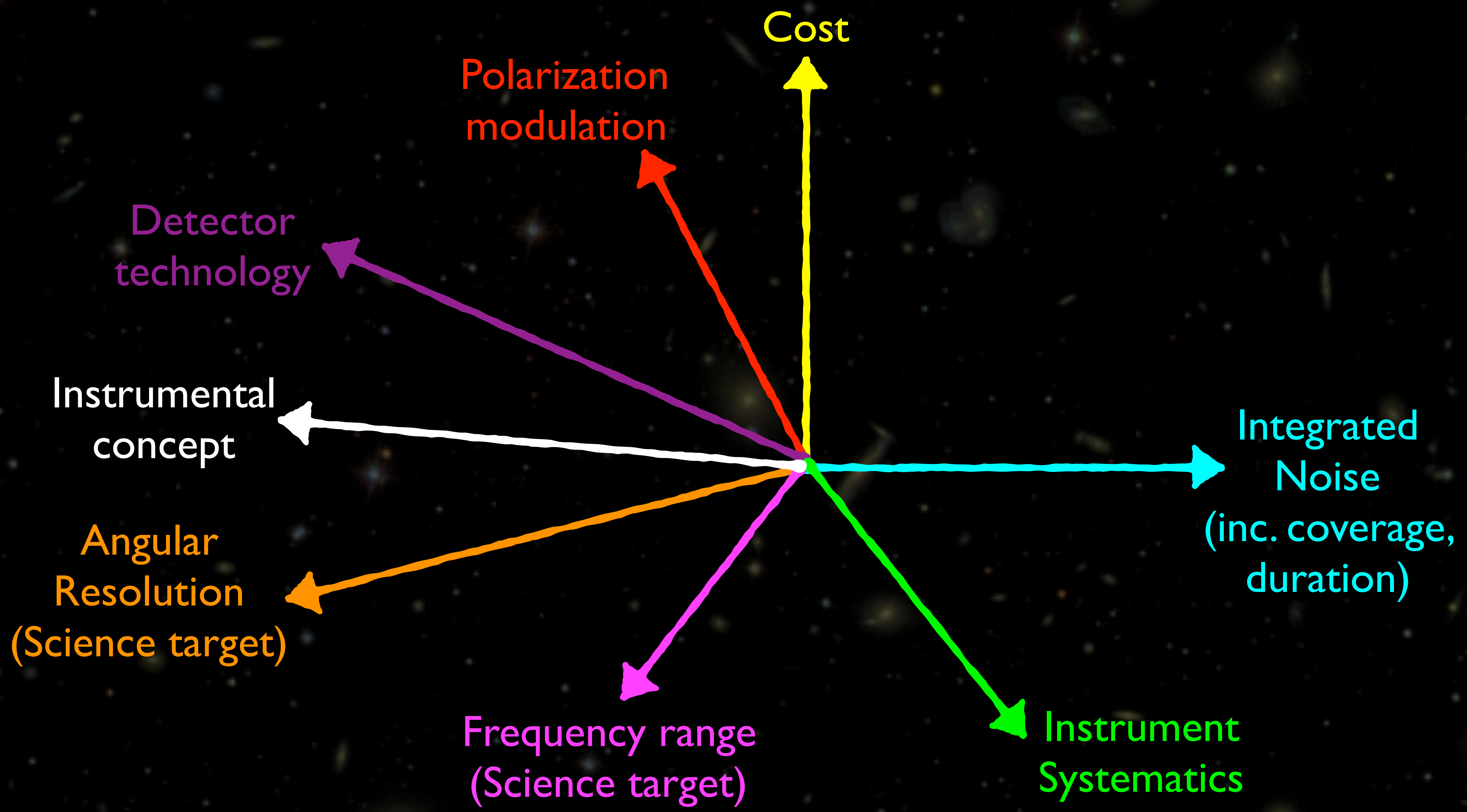

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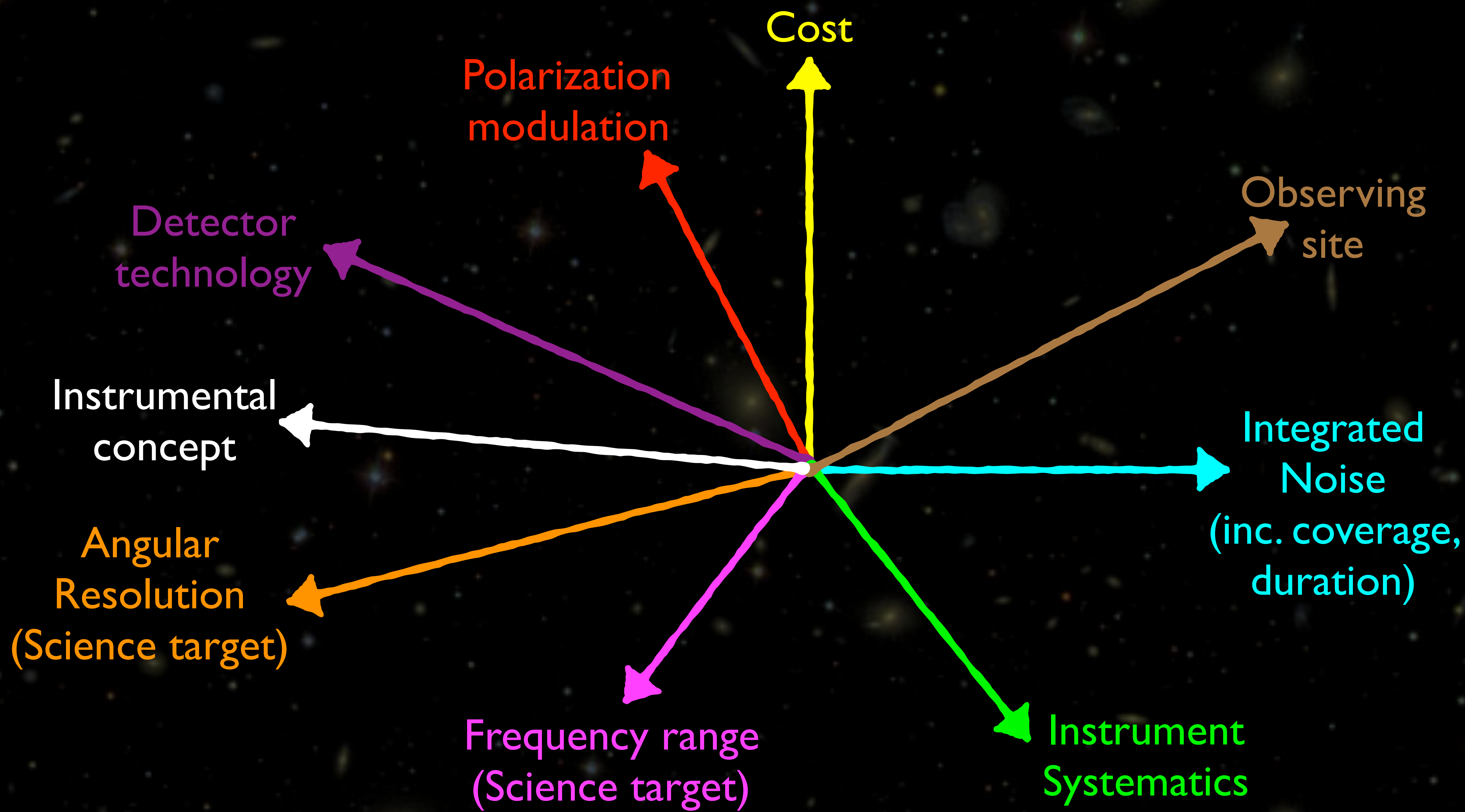

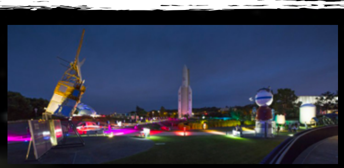

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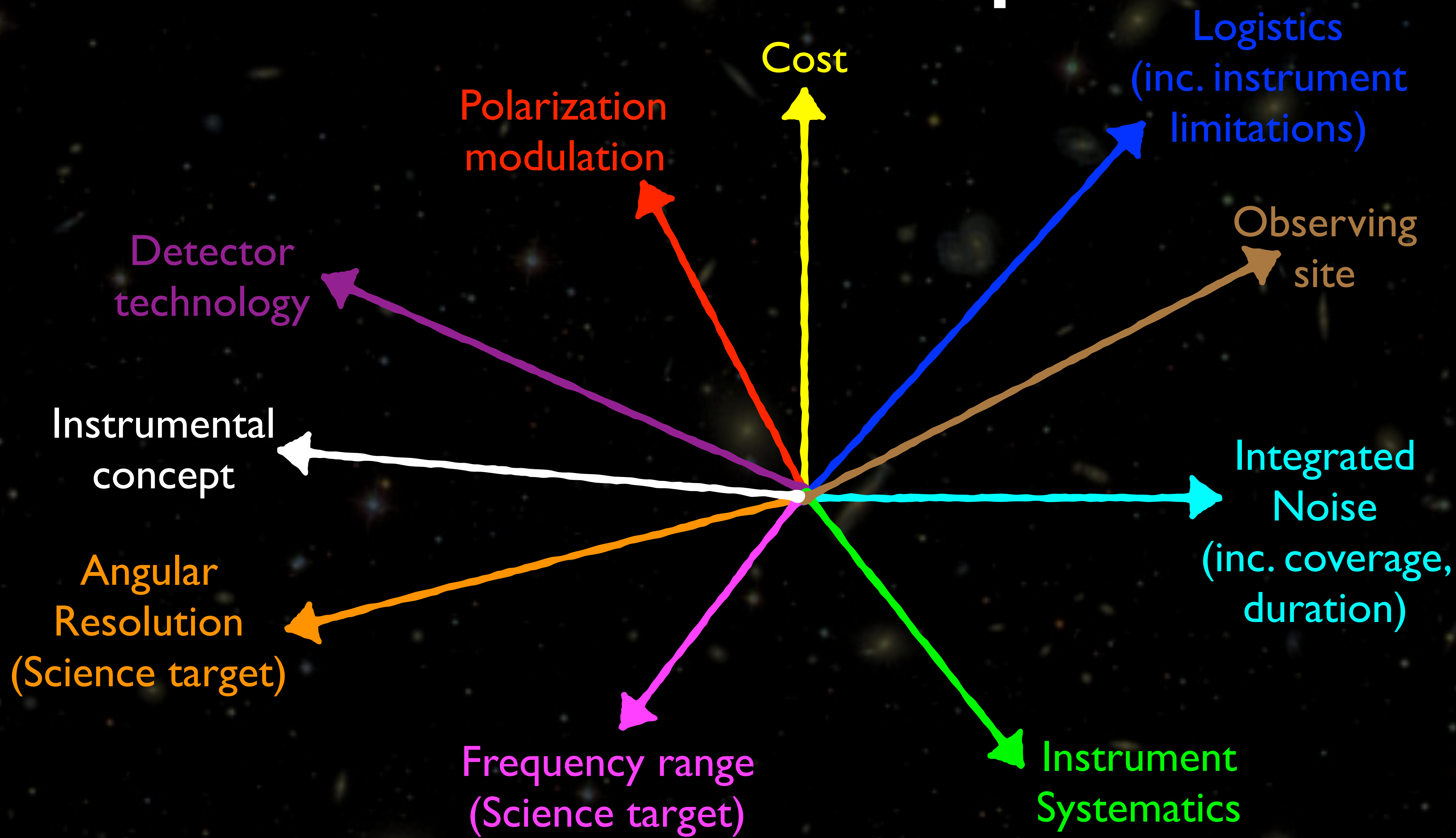

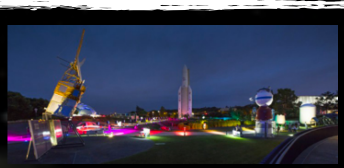

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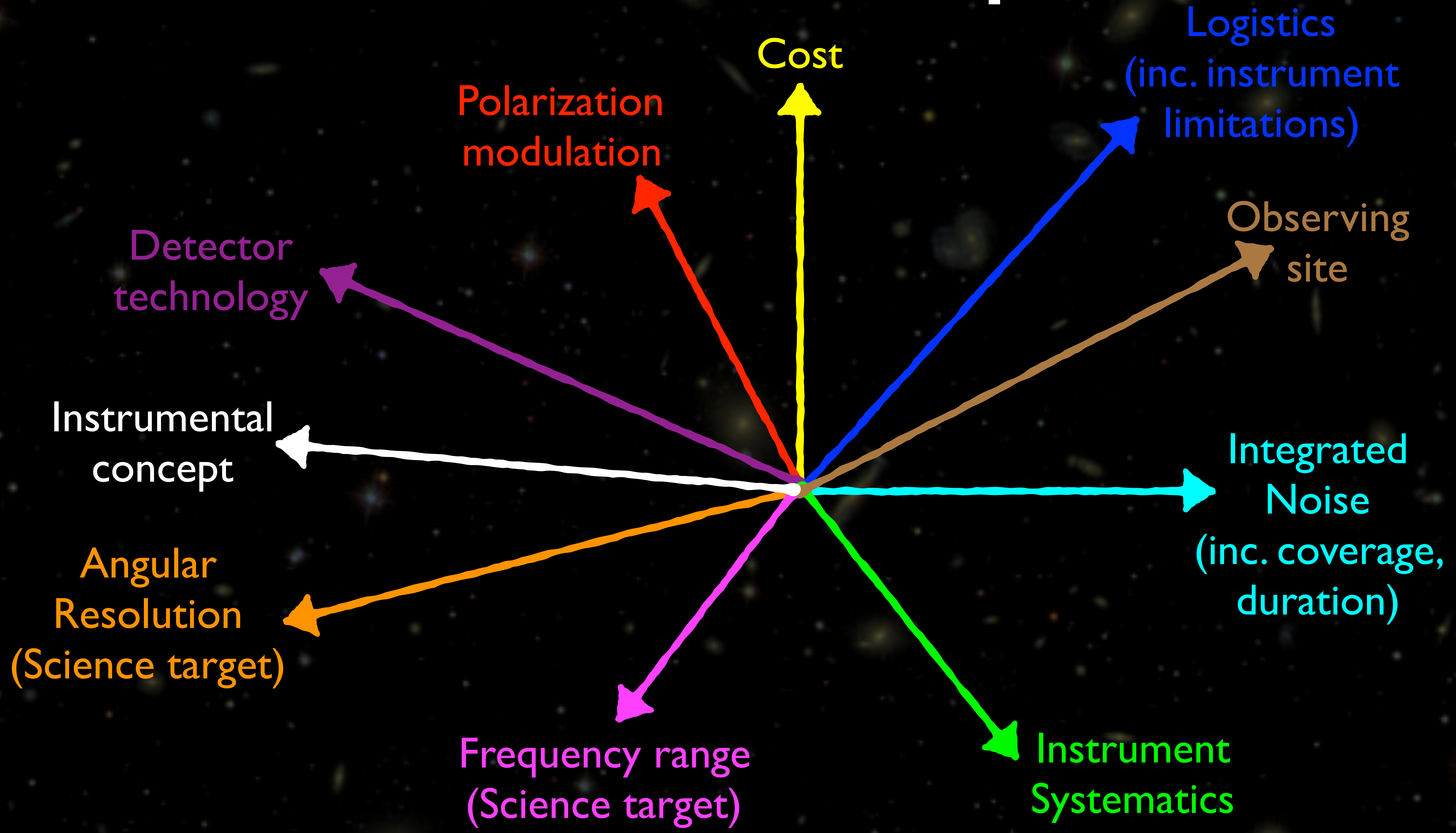
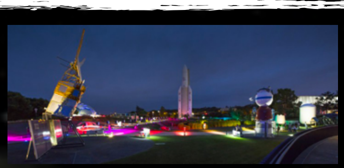


Each of the current/incoming projects has made different choices and the best combination is yet to be identified…



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Contradictory requirements

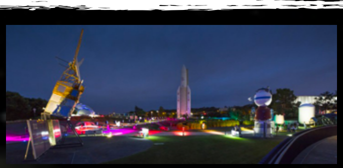
- Sensitivity:
  - ★ Many thousands of detectors
  - ★ Low angular resolution (~0.5 deg) - small aperture is the best option

- Foregrounds
  - ★ At many different frequencies ranging from ~20 GHz to 300 GHz
  - ★ Each frequency needs many detectors… (effort to have multichroic detectors or spectra-imaging like QUBIC)

- Lensing
  - ★ High angular resolution (~1 arcmin) - large aperture is the best option

➡ It is a tricky game…

➡ We need a combination of instruments



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Current Experiments…

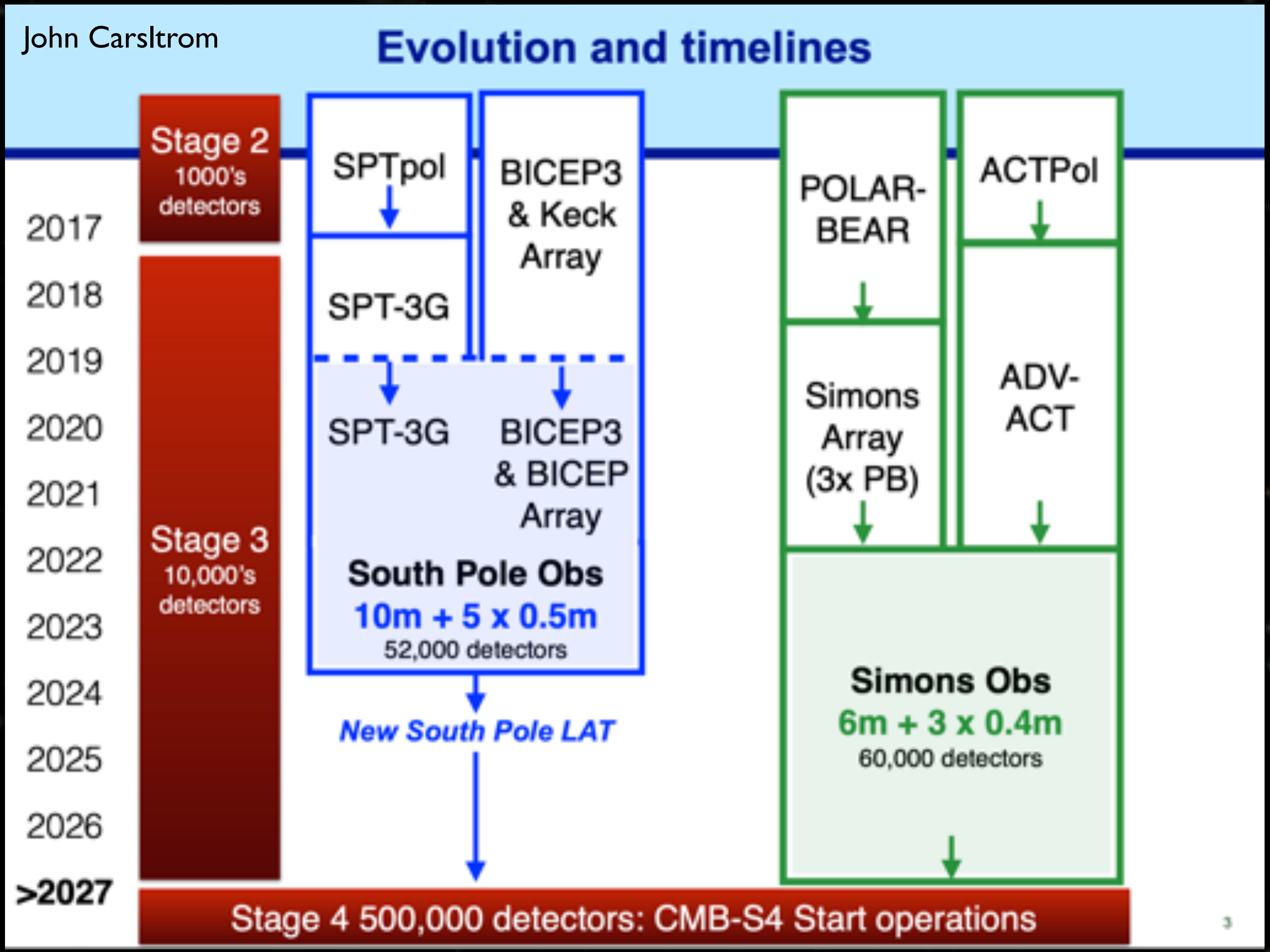
Project	Countries	Location	Frequencies	ℓ range	σ(r) no FG	σ(r) with FG	Status
SPIDER	USA	Antarctica	90, 150, 290	5-100	3.1×10^{-3}	0.01	90 GHz flew
QUBIC	Fr., It., Ar., UK, Ir.	Argentina	150, 220 (+spectro-im)	30-300	6×10^{-3}	0.01	Calibrating
BICEP/Keck	USA	Antarctica	95, 150, 220, 270	50-250	2.5×10^{-3}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

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

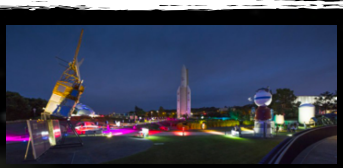
The Future (ground)

- Next efforts: Stage IV ~2027

- CMB-S4 (US) ~ 600M$…
  - ★ Many TES: ~ 500 000 !
  - ★ More frequencies (foregrounds)
    - 8 bands: 20 - 270 GHz
  - ★ Small AND Large apertures
    - 0.5 and 5 meters (30 to 1 arcmin)



- Forecasts
  - ★ Primordial B-modes
    - $r<0.001$ @ 95% C.L.
  - ★ Lensing:
    - $\sigma(N_{eff})\sim 0.03$
    - $\sigma(\Sigma m_\nu)\sim 0.02$ eV (with DESI)
    - Dark Energy : F.O.M. ~ 1250 (with DESI, LSST, SZ)



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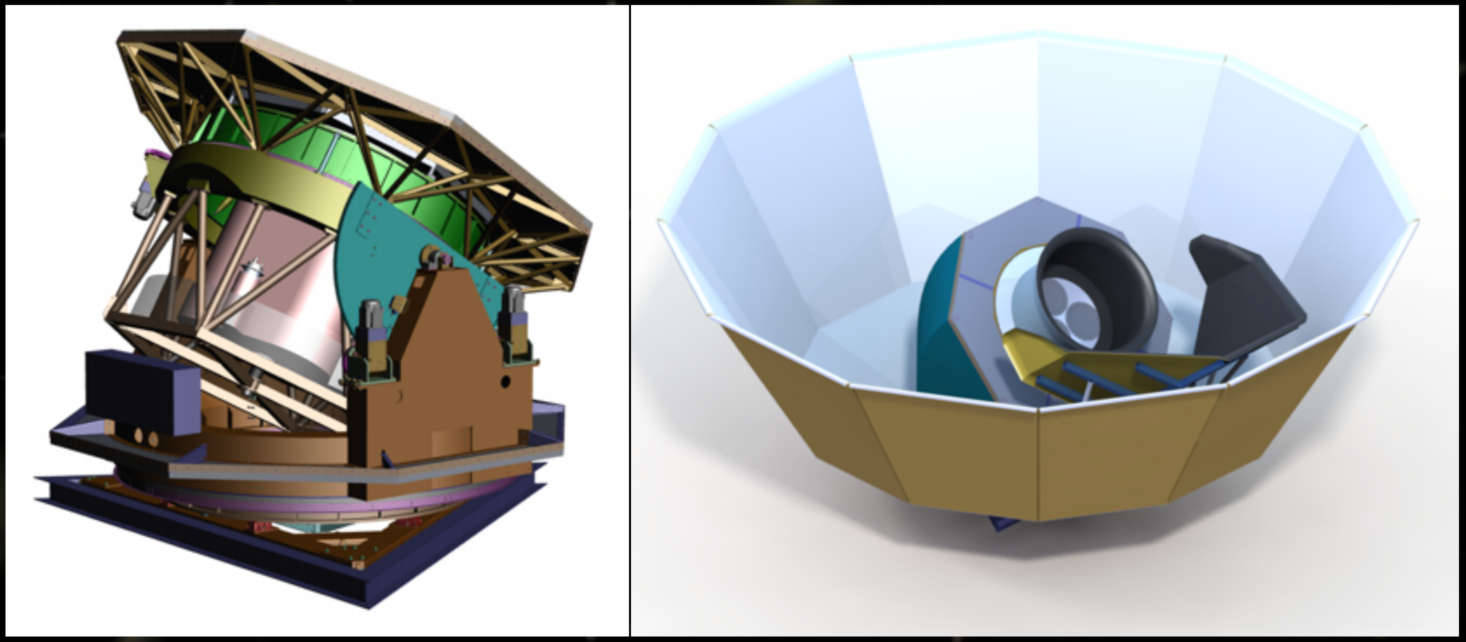
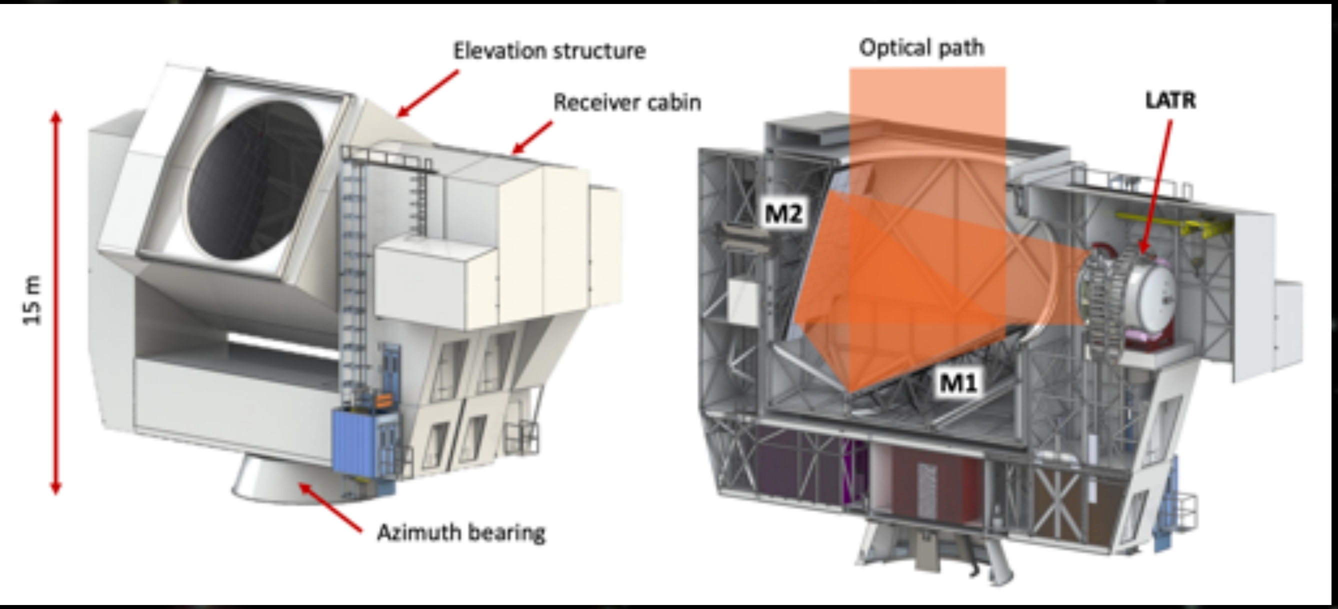
Small aperture (large scales)





Large aperture (small scales)

arXiv:1907.04473

The Future (ground)

arXiv:1907.04473

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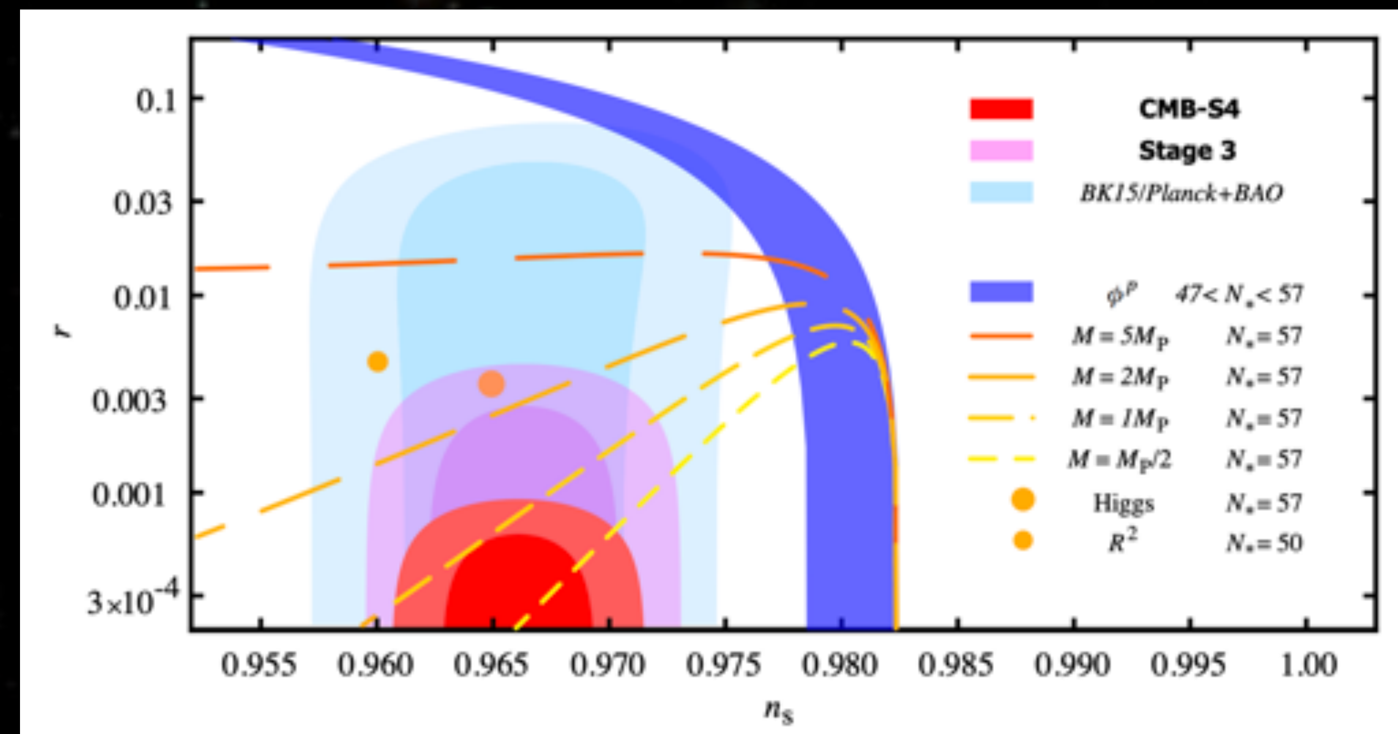

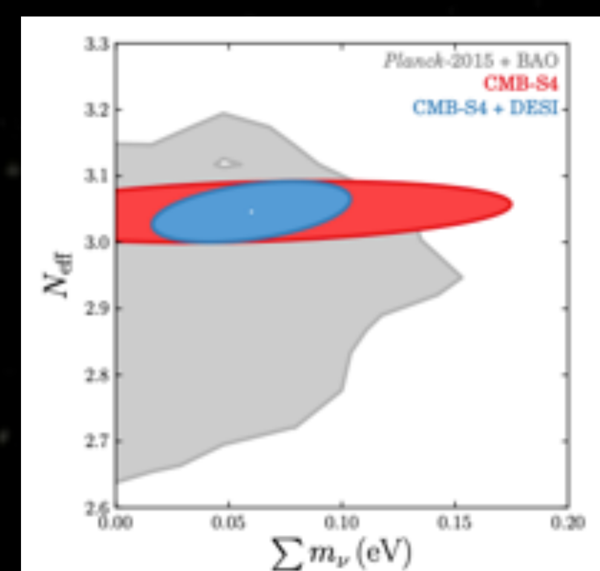

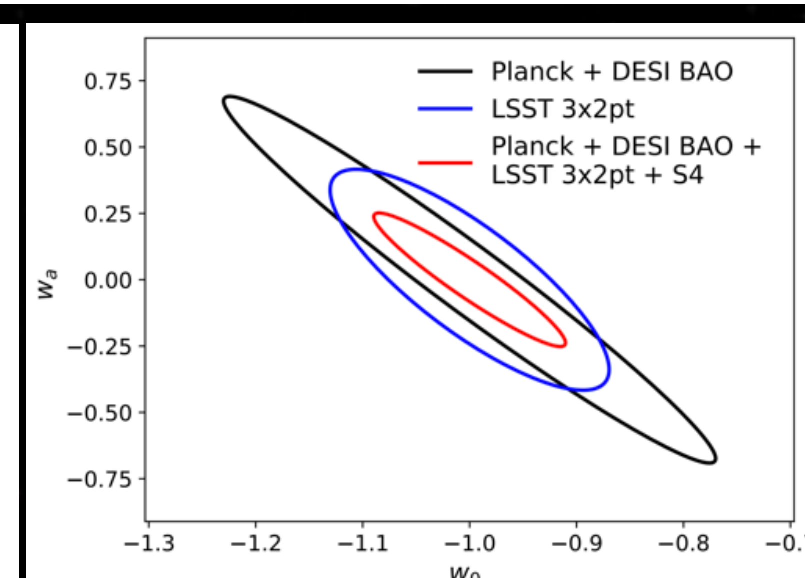

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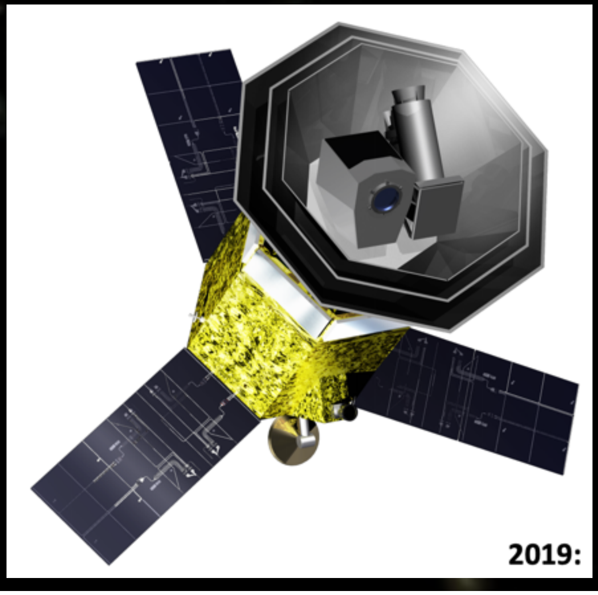
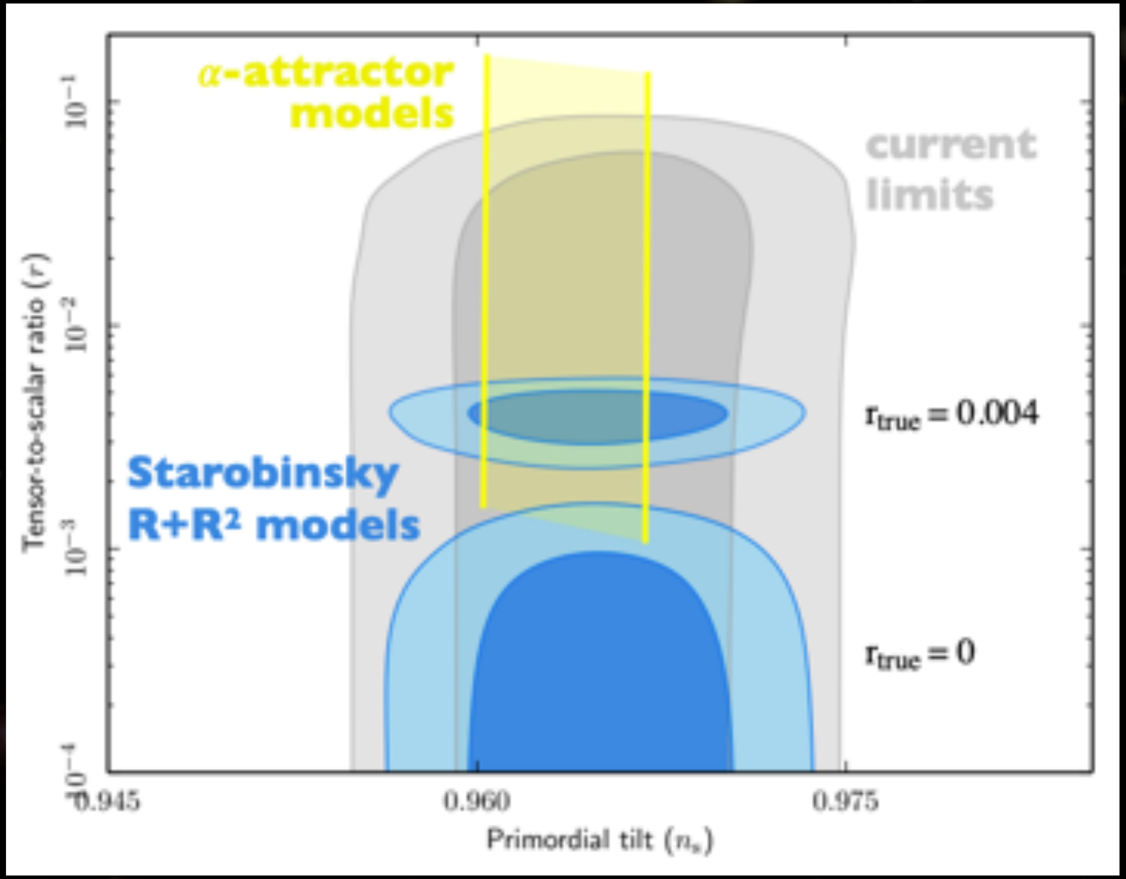
The Future (space)

- LiteBIRD ~2028
- JAXA Mission
  - ★ 4600 TES
  - ★ 3 telescopes
    - LFT: Japan
    - MFT and HFT: Europe + US
    - 15 bands from 34 to 448 GHz
  - ★ Resolution:
    - 10-70 arcmin
- Forecasts
  - ★ Primordial B-modes
    - r<0.001 @ 95% C.L.

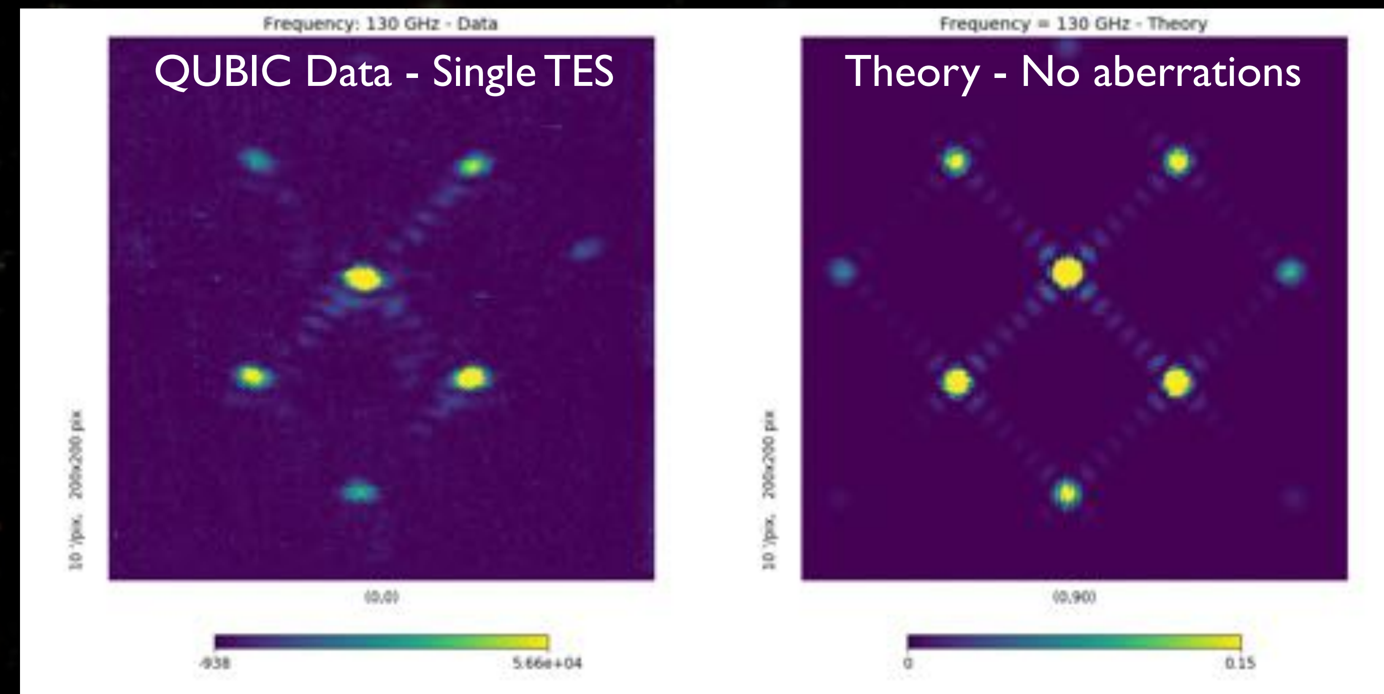




[LiteBIRD Science Objectives - Journées LiteBIRD France - M. Tristram]

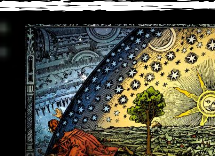
The Future (QUBIC)

- Calibration at APC started Nov. 2018
  - ★ All predictions from Bolometric Interferometry confirmed
  - ★ Now repairing the 1K fridge
  - ★ Next steps:
    - Review this autumn
    - Shipment to Argentina late 2019
    - Upgrade from TD to FI through 2020
    - 3 years operation $\sigma(r)=0.01$
  - ★ Future plans:
    - Upgrade to multimodes (x5)
    - Larger cryostats, more BW
    - Install a B.I. on LLAMA 12m antenna
      - Enter small scales physics
  - ★ Discussion with CMB-S4 to join the collaboration with B.I.



Frequency scaling is the basis of Spectro-Imaging

A possibility unique to Bolometric Interferometry to constrain foregrounds



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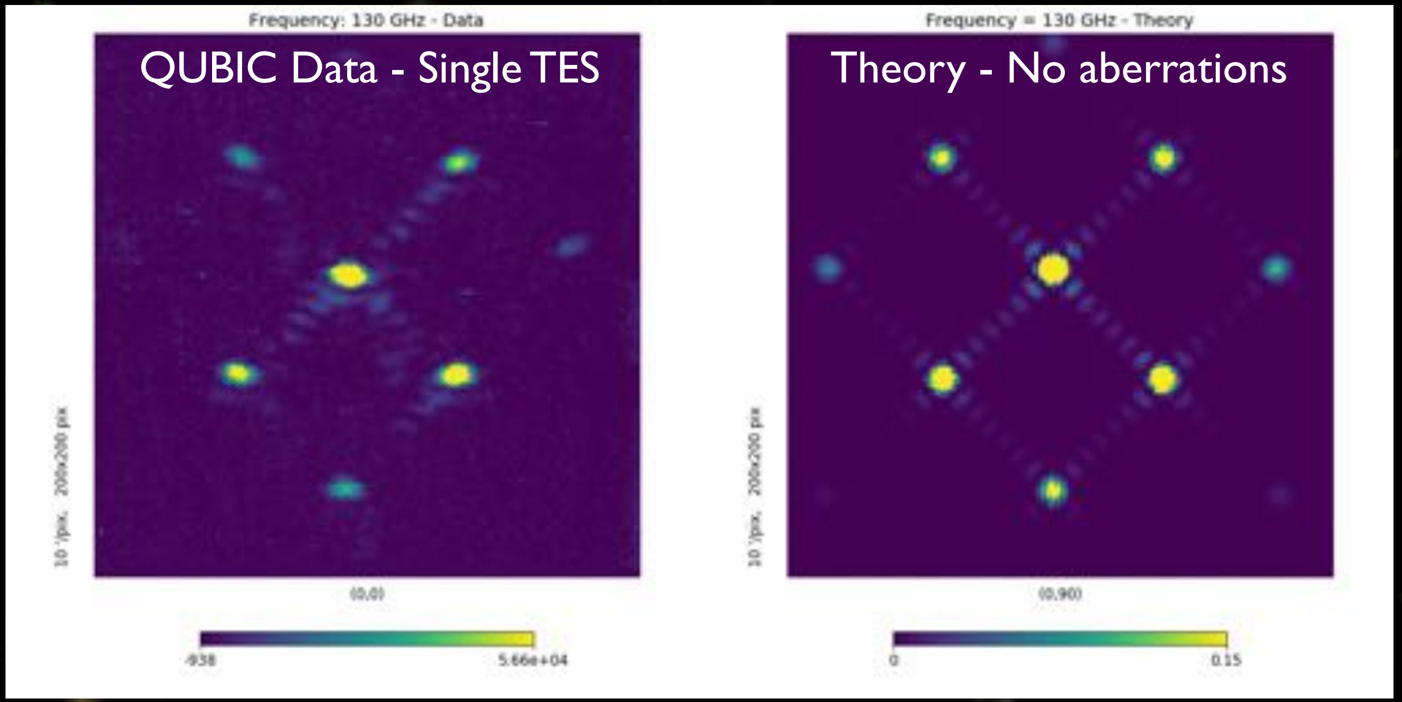

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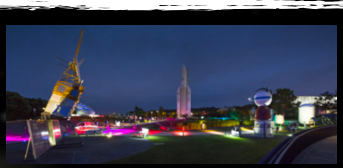

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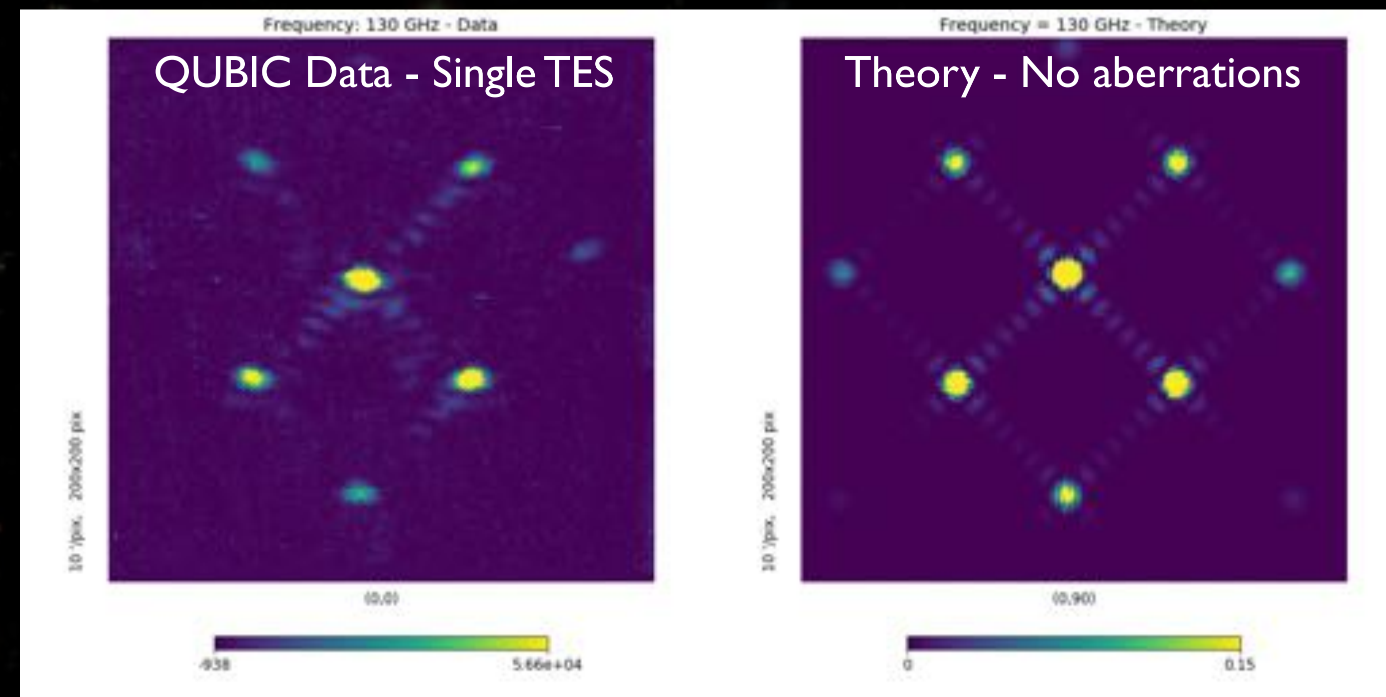

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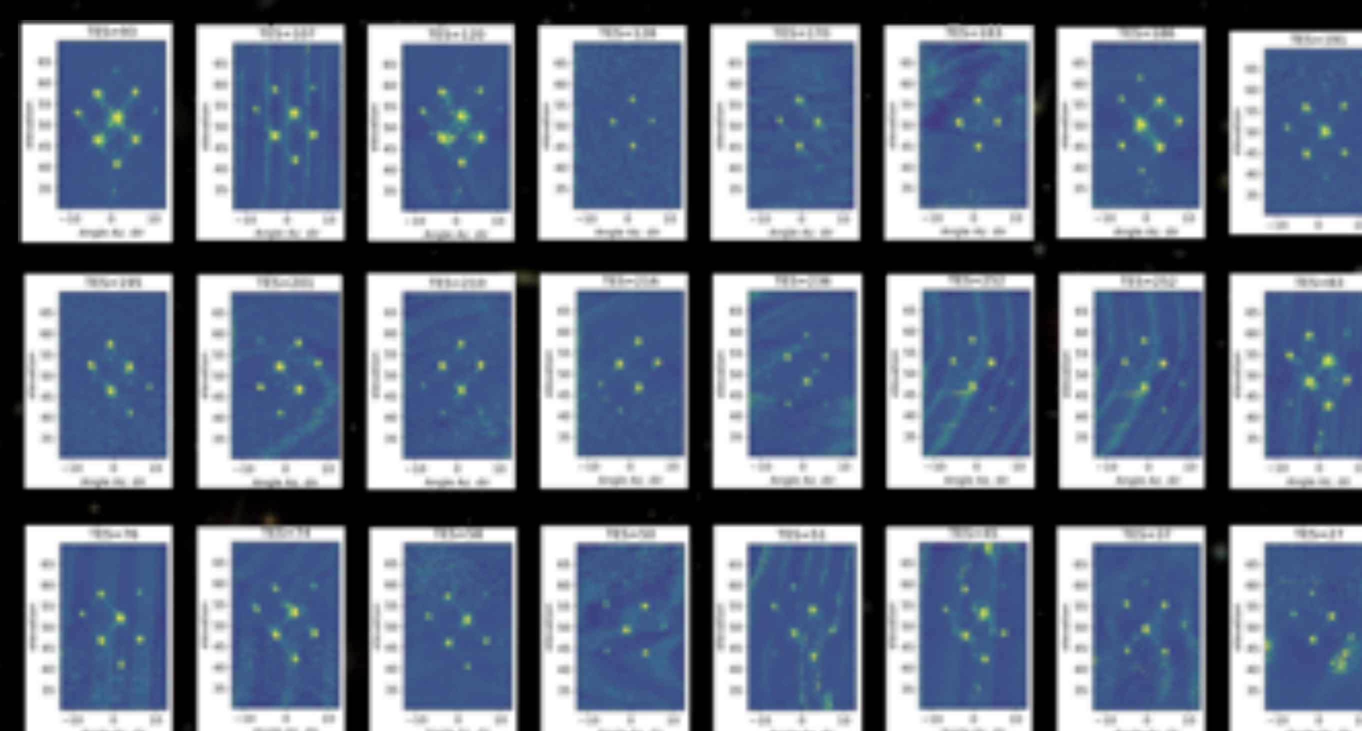

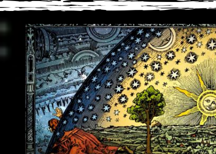

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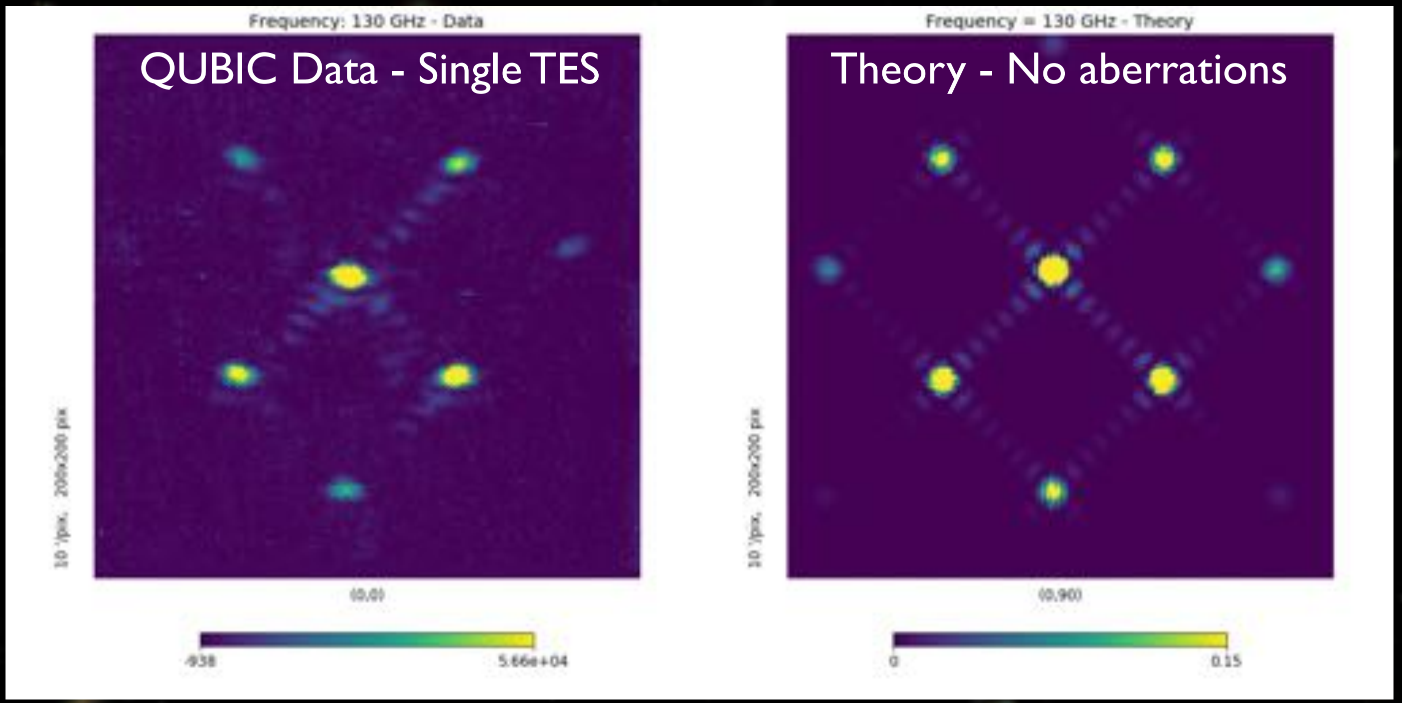

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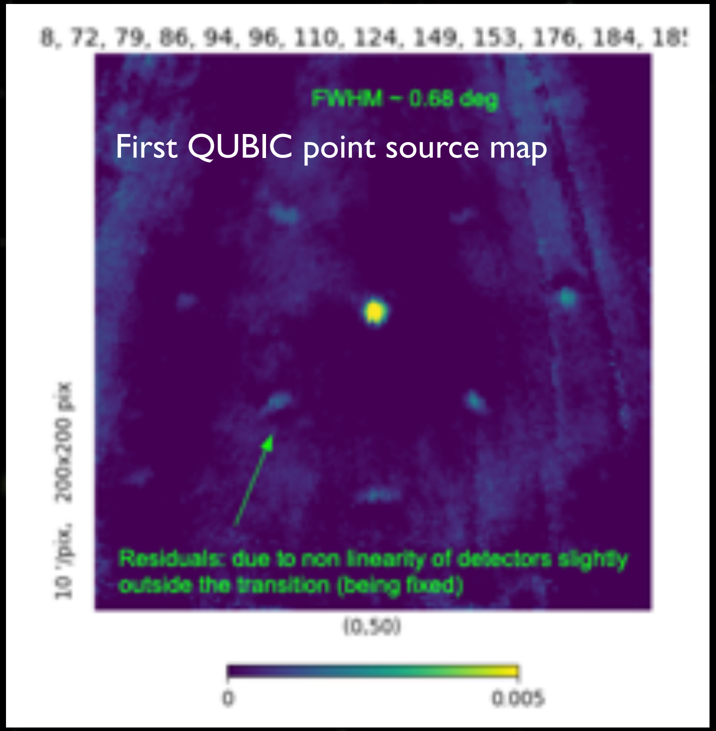

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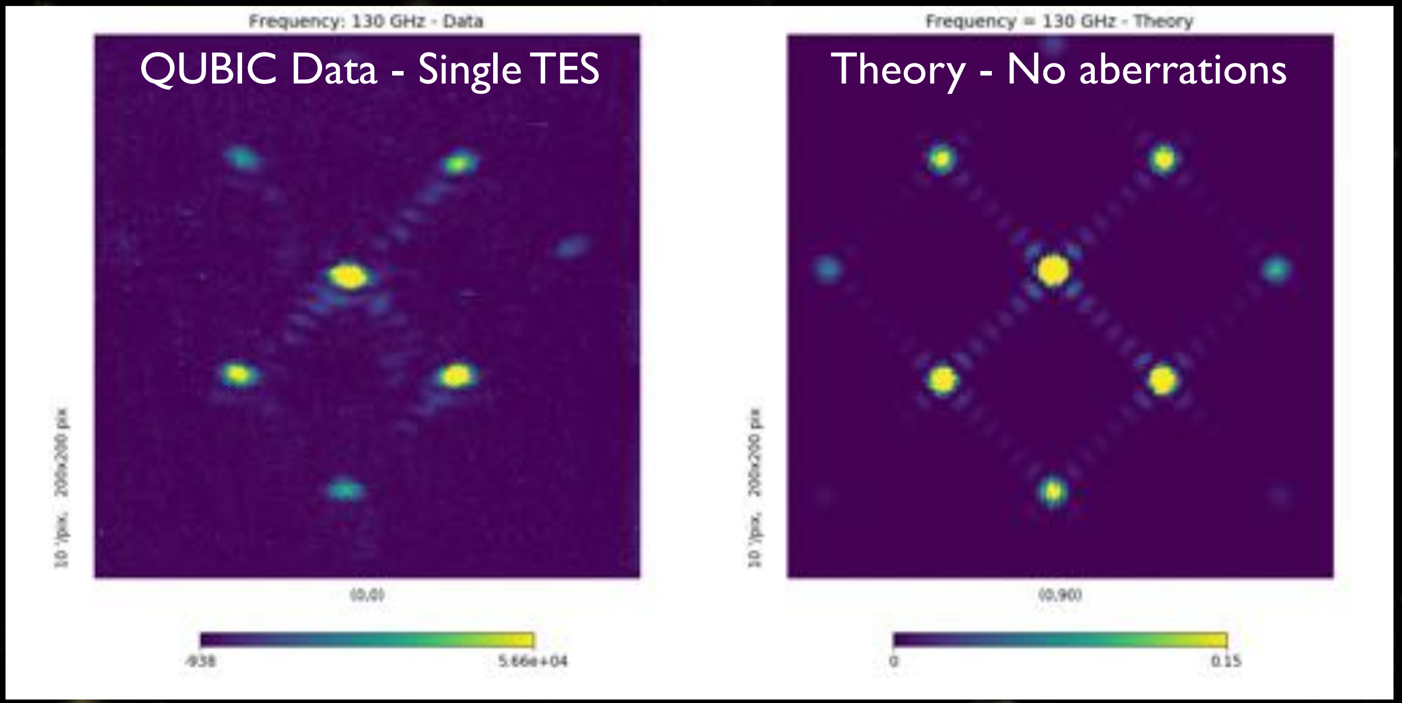

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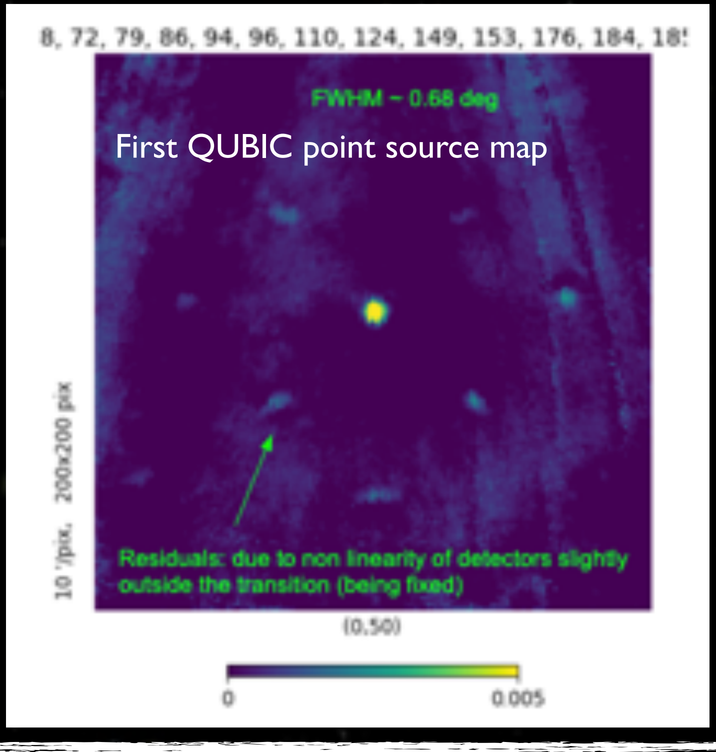

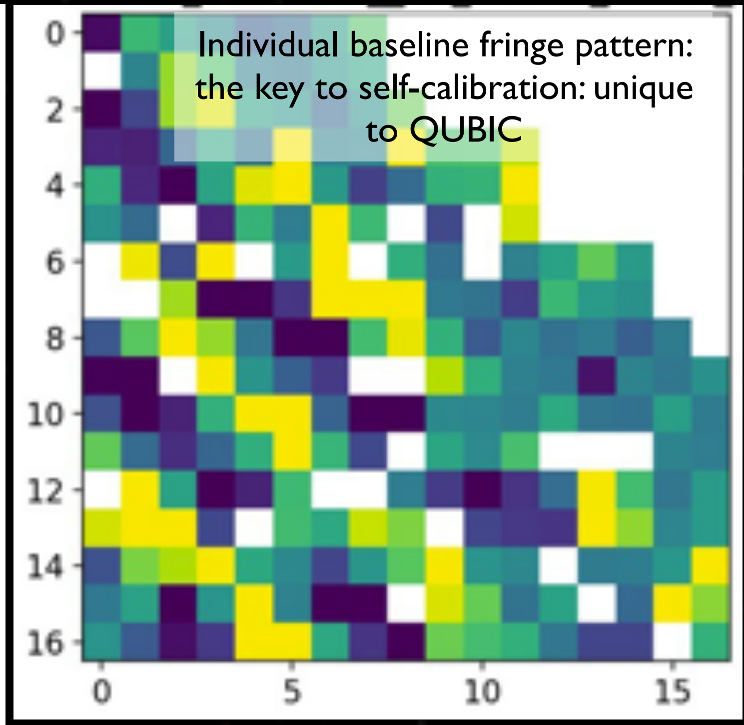

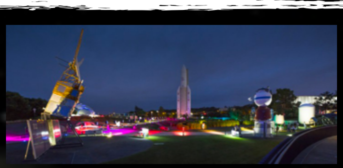

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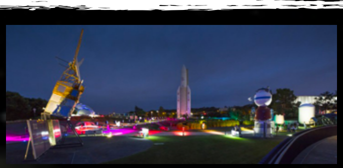
Summary

- CMB has offered cosmologists an amazing tool to understand the Universe
  - ★ Wonderful results so far…
  - ★ ΛCDM confirmed in great details
- A lot more to come with CMB Polarization in the next decade
  - ★ Large scales:
    - Inflation physics: $\sigma(r)=0.01$ by 2025 and $\sigma(r)=0.001$ by 2030…
  - ★ Small scales:
    - Neutrino physics: $\sigma(N_{eff})\sim0.03$ and $\sigma(\Sigma m_\nu)\sim0.02$ eV (with DESI)
    - Dark Energy: F.O.M. ~ 1250 (with DESI, LSST, SZ)
- In France
  - ★ QUBIC
  - ★ CMB-S4
  - ★ LiteBIRD
  - ★ [+ NIKA2, KISS, CONCERTO (Clusters, Spectral Distorsions, …)]
- « I hope some day you'll join us… » (J. Lennon)



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