Future constraints on inflation (a CMB experimental view)

E.S. Battistelli
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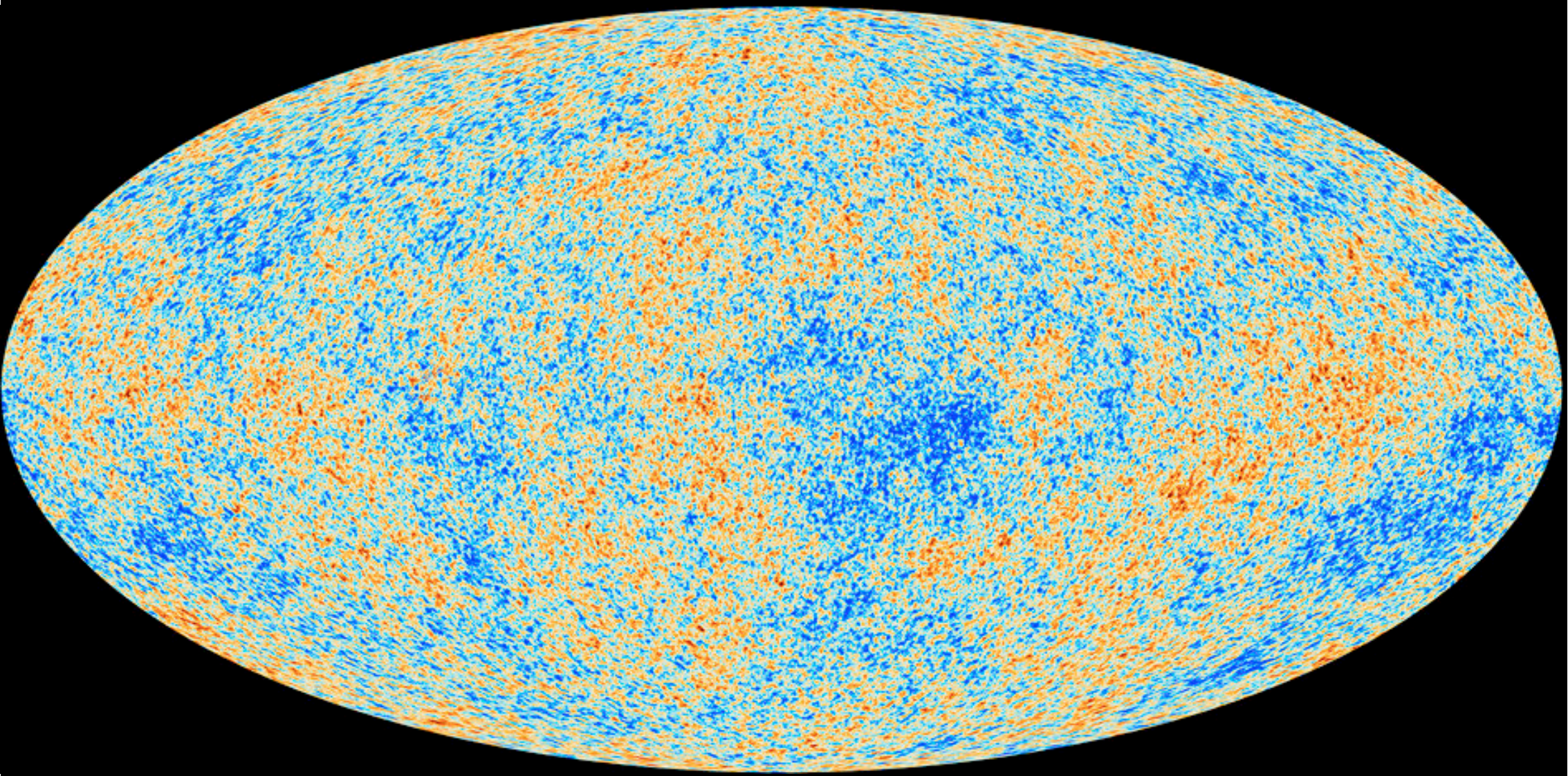
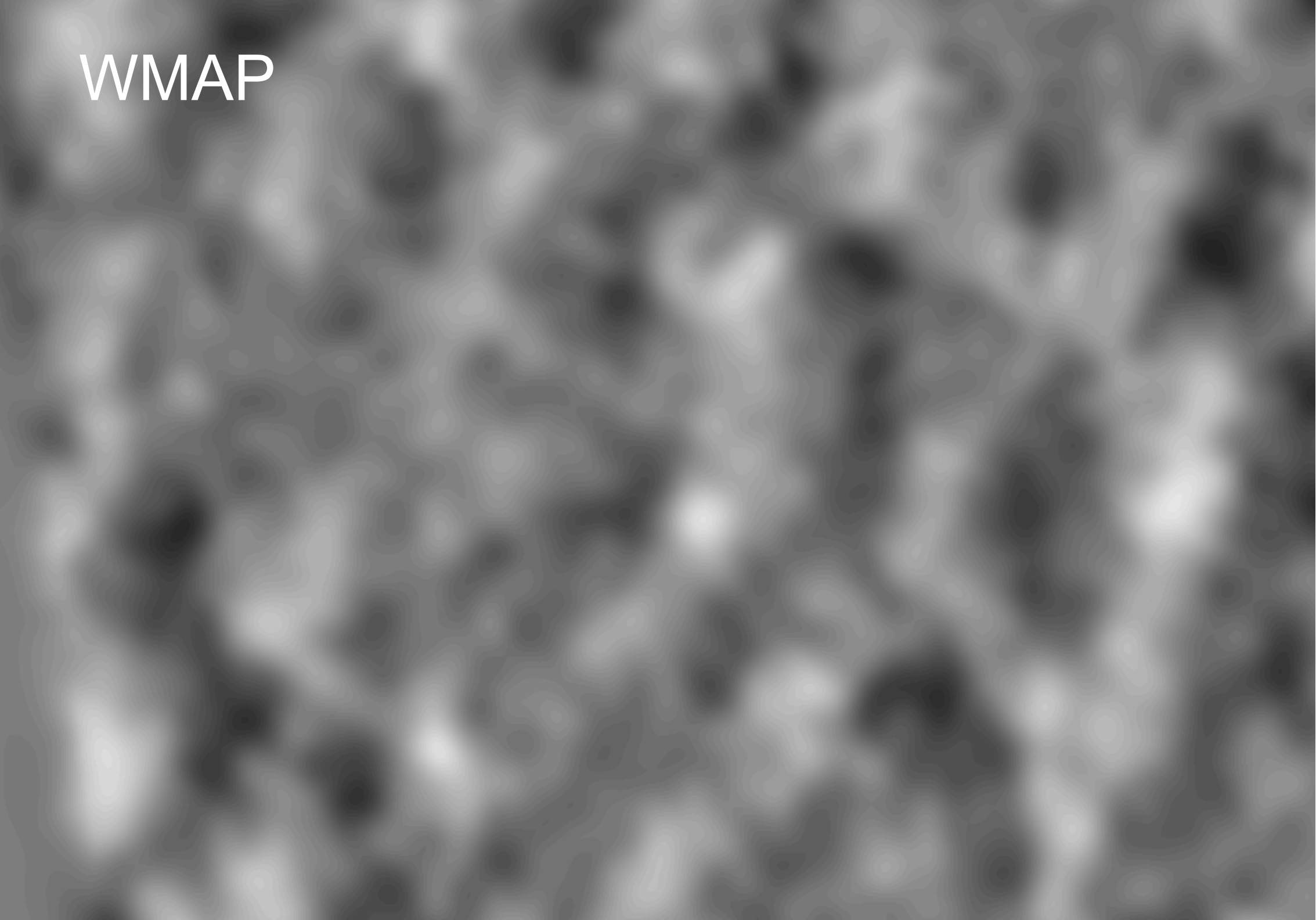
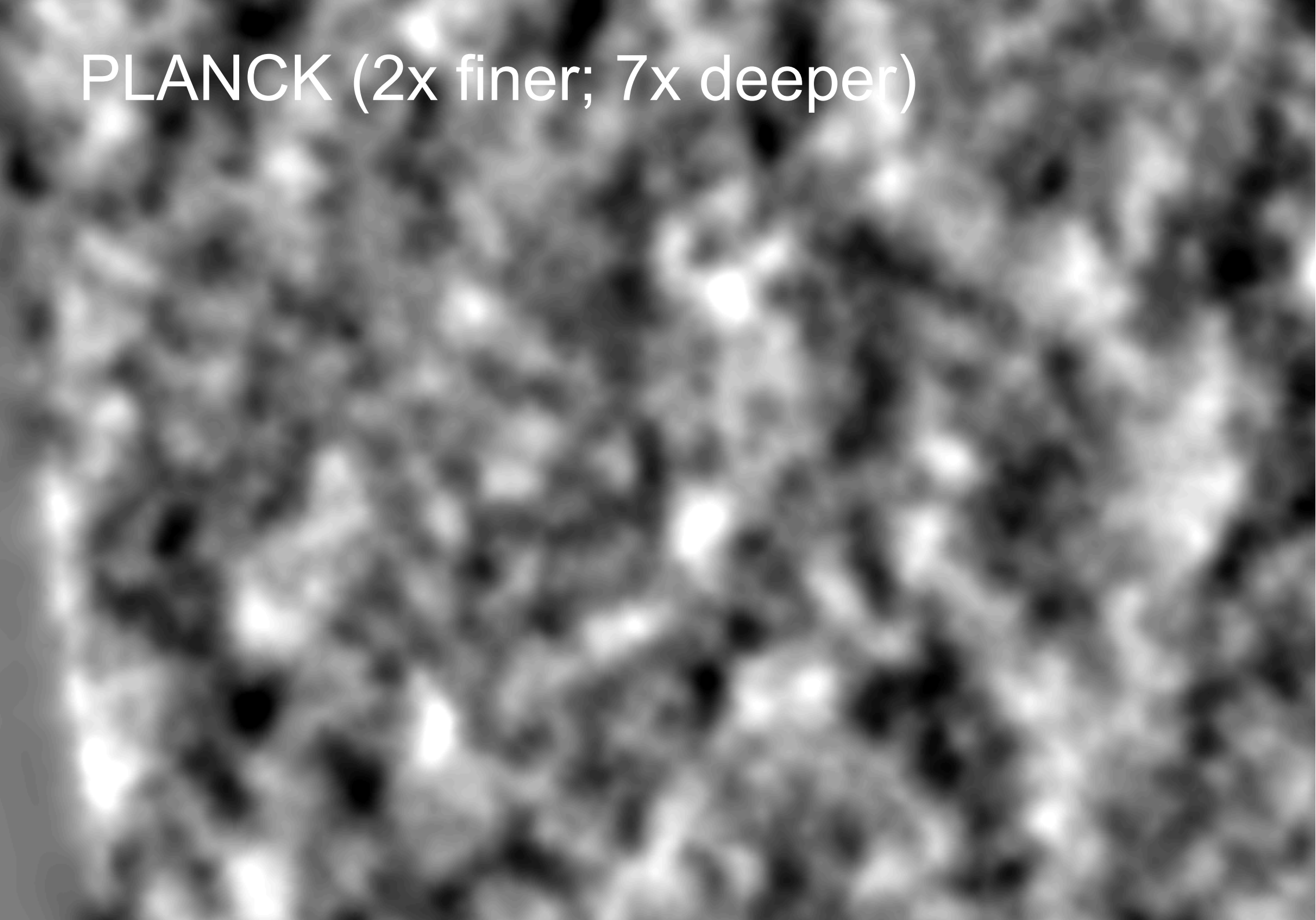
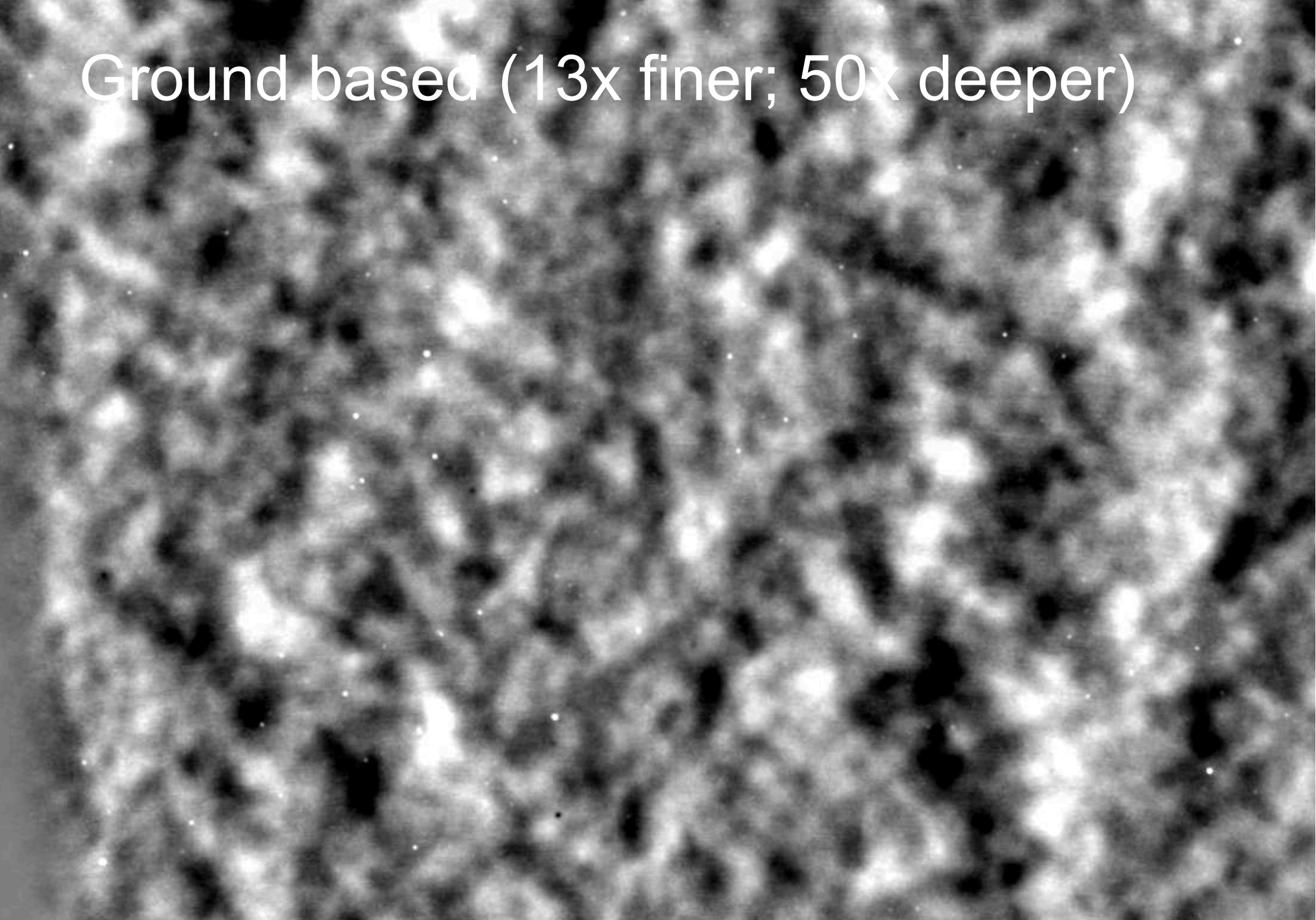
PLANCK



ESA/Planck Collaboration


WMAP


PLANCK (2x finer; 7x deeper)


Ground based (13x finer; 50x deeper)

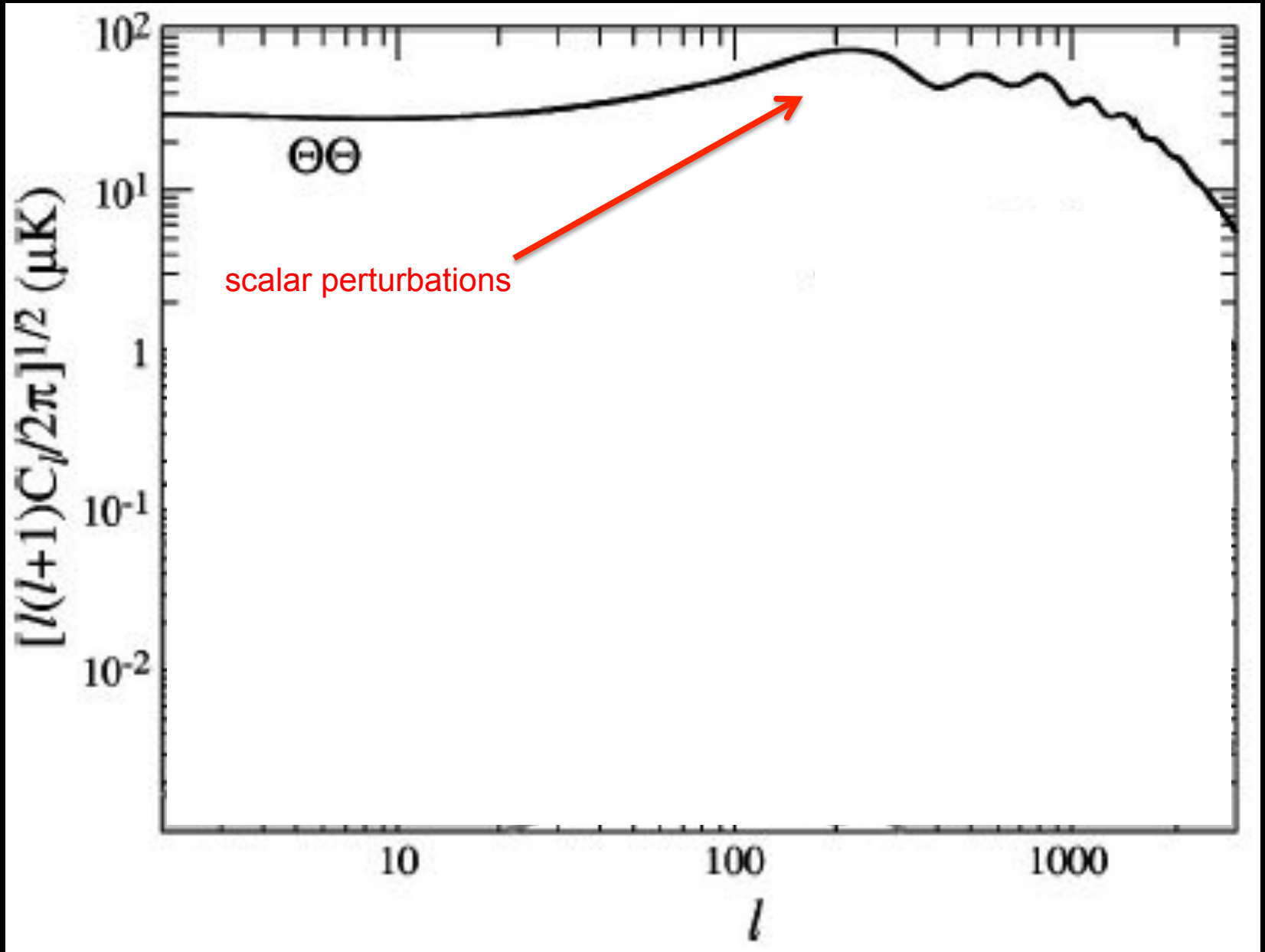
Ground based (13x finer; 50x deeper)

Galaxy Clusters

CMB anisotropies

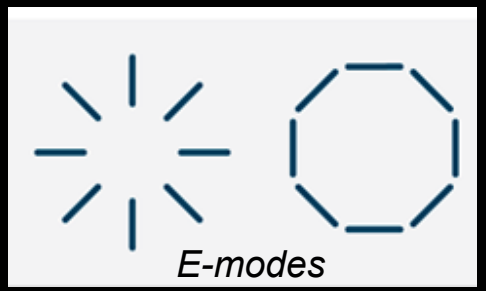
- Density perturbations produce ΔT/T
- Can be described in terms of spherical harmonics as a function of the multipole l

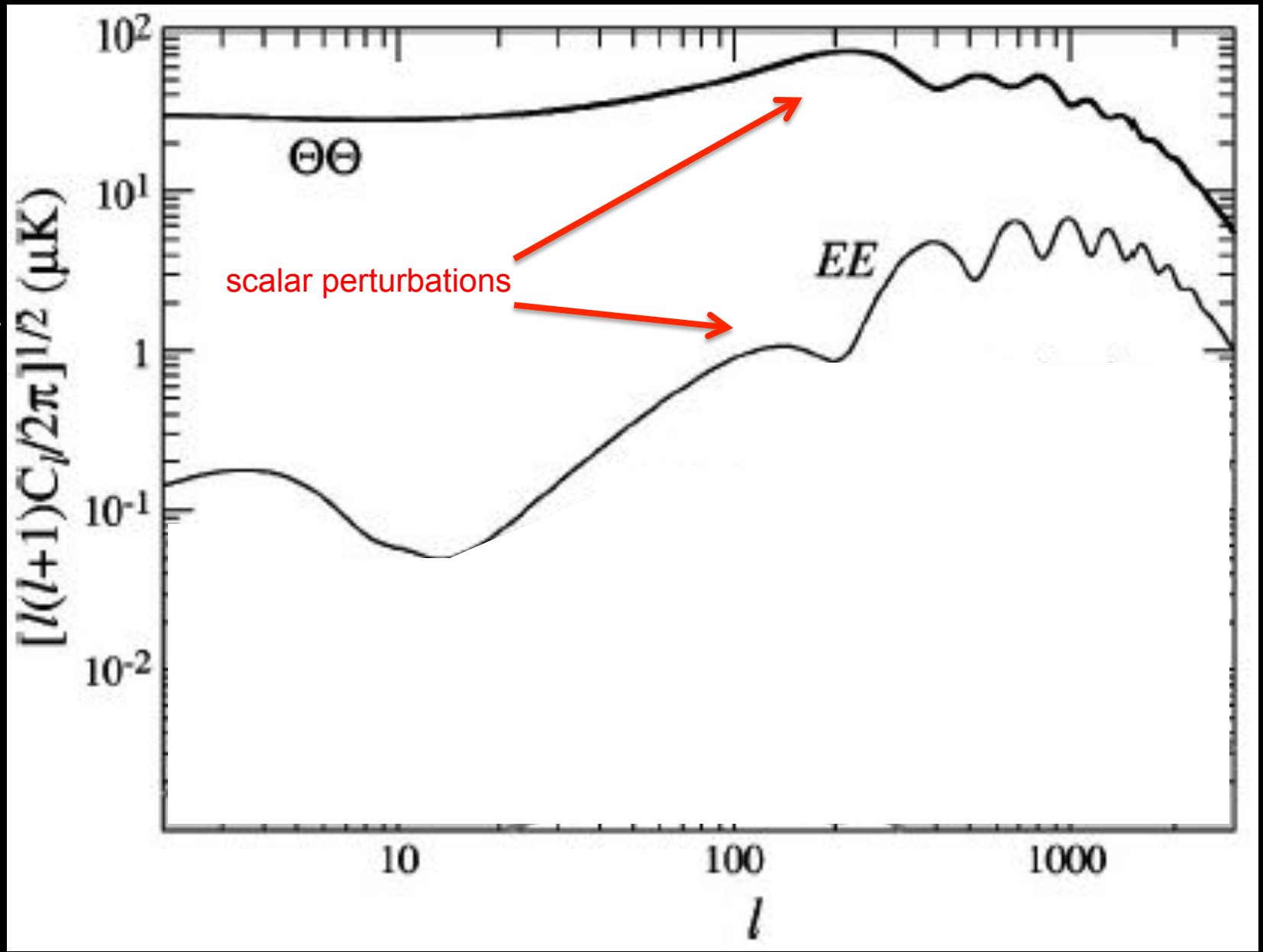
$$\frac{\Delta T}{T}(\vartheta,\varphi) = \sum_{l\,m} a_{lm}\, Y_{lm}(\vartheta,\varphi)$$



CMB polarization: E-modes

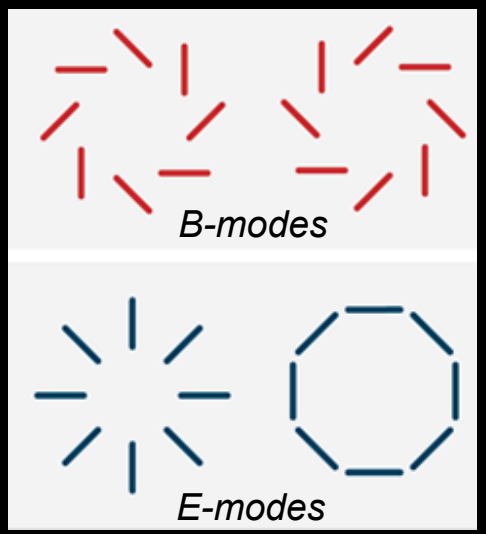
- The same density perturbations producing the temperature anisotropies also produce polarization
- Polarization is spatially correlated with temperature anisotropies
- The polarization pattern is curl-free and characterized by an even parity: E-modes

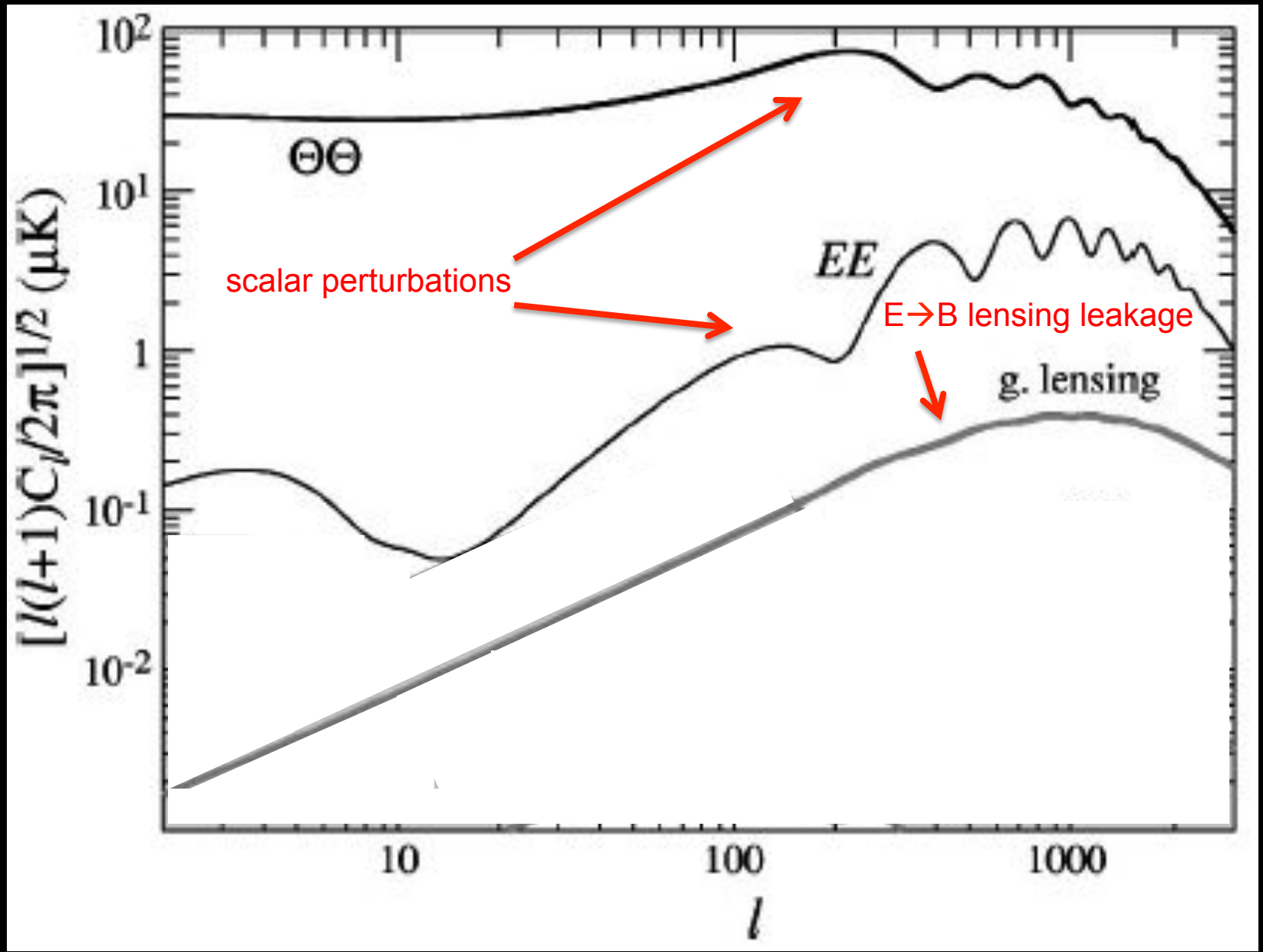




CMB polarization: E-modes and B-modes

- E-modes can be converted into a curl component whose pattern is characterized by an odd parity: B-modes
- This is due to large structures at small angular scales through gravitational lensing





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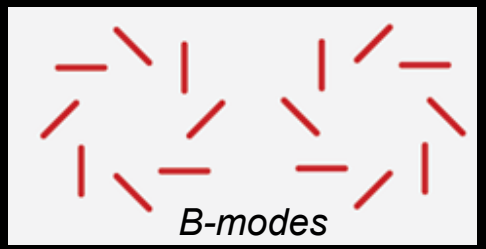
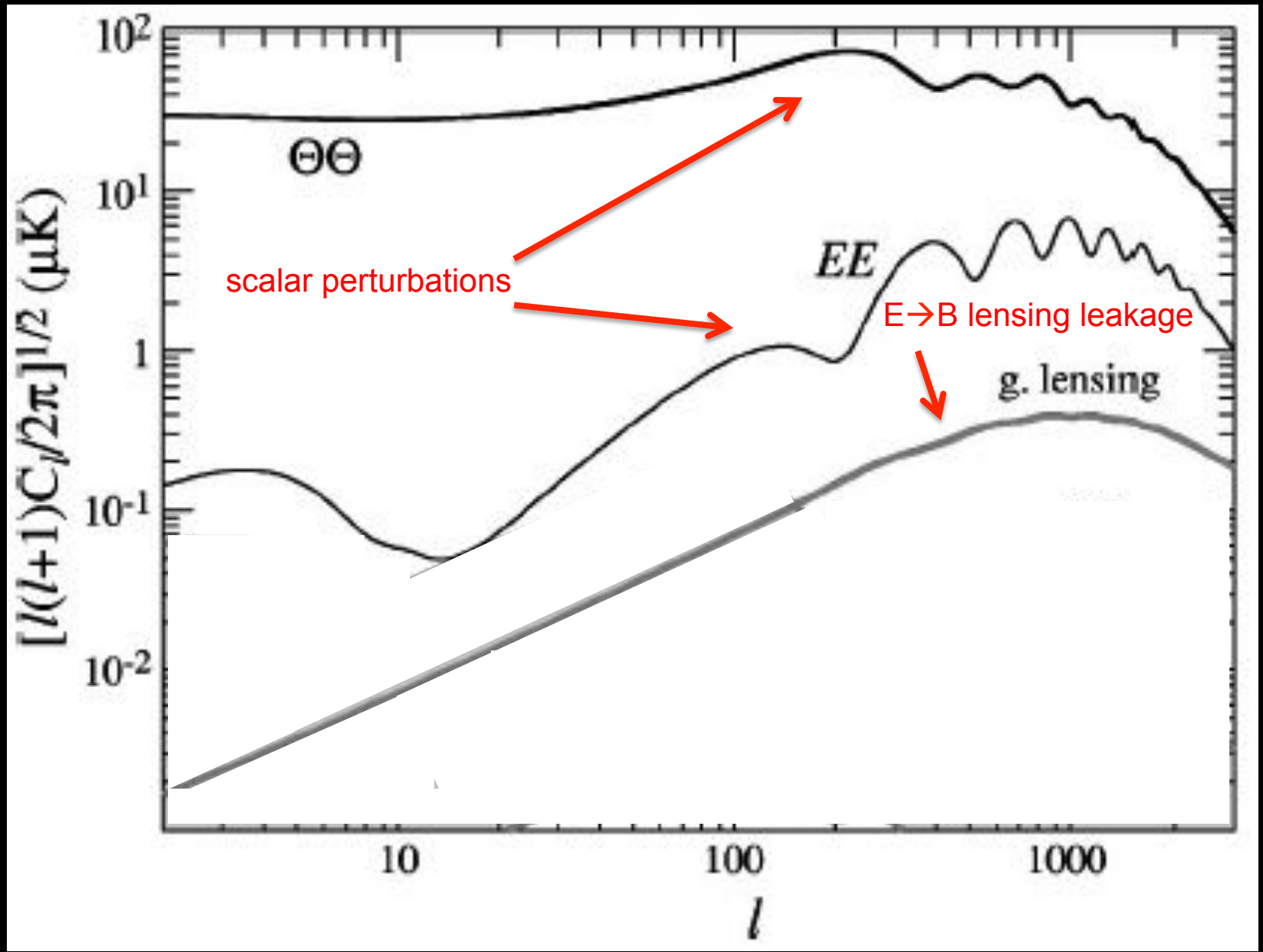
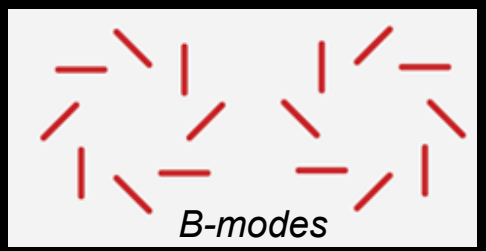


- *CAN OTHER PERTURBATIONS PRODUCE B-MODES?*



CMB polarization: E-modes and B-modes

- E-modes can be converted into a curl component whose pattern is characterized by an odd parity: B-modes
- B-modes can uniquely be produced by gravitational waves



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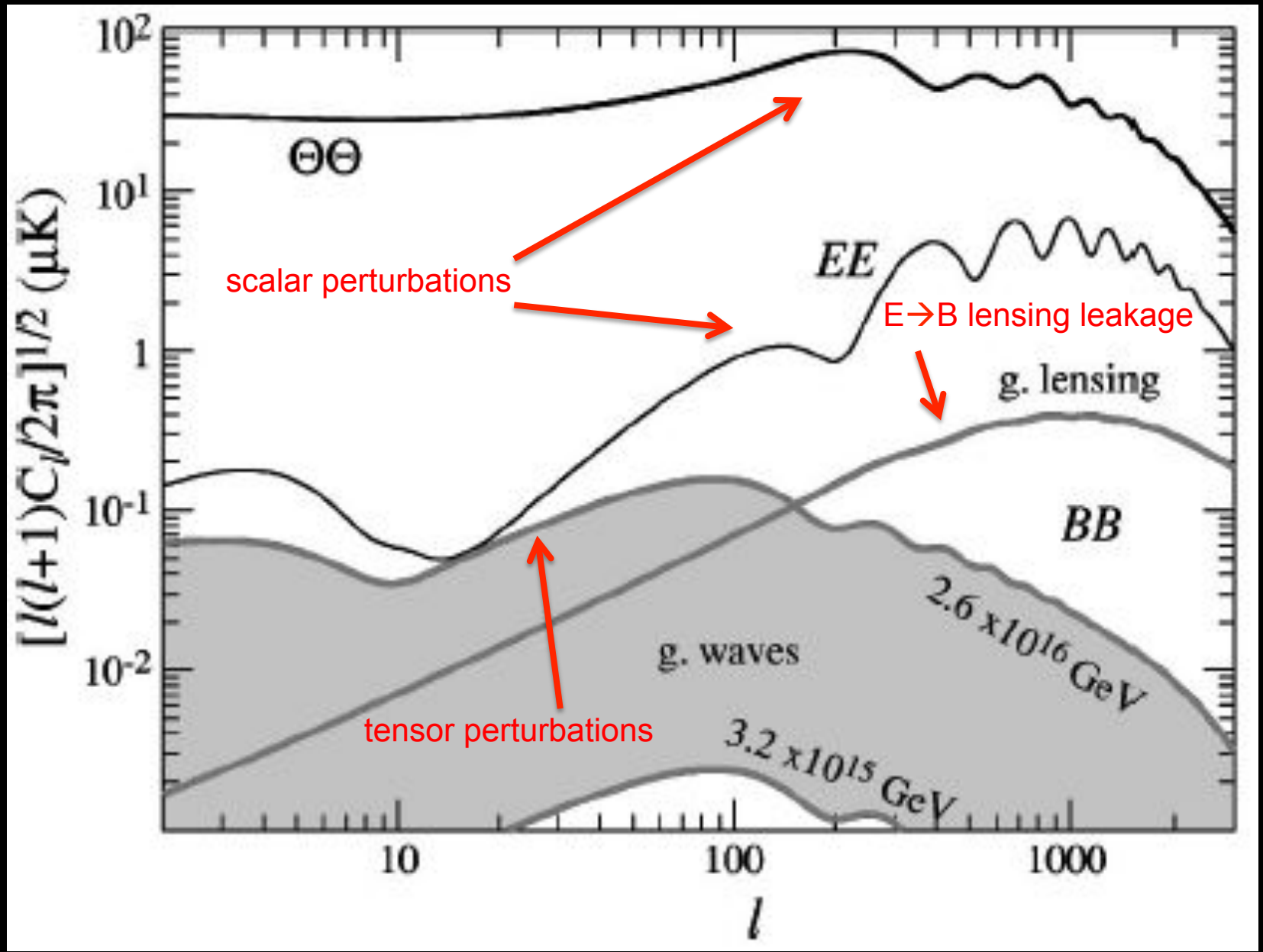
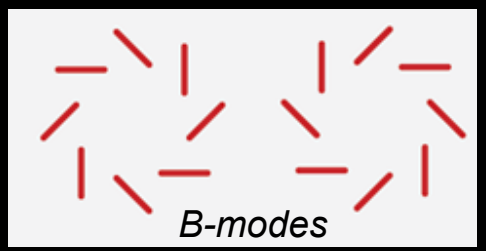


CMB polarization: E-modes and B-modes

- E-modes can be converted into a curl component whose pattern is characterized by an odd parity: B-modes
- B-modes can uniquely be produced by gravitational waves at
  - Medium scales



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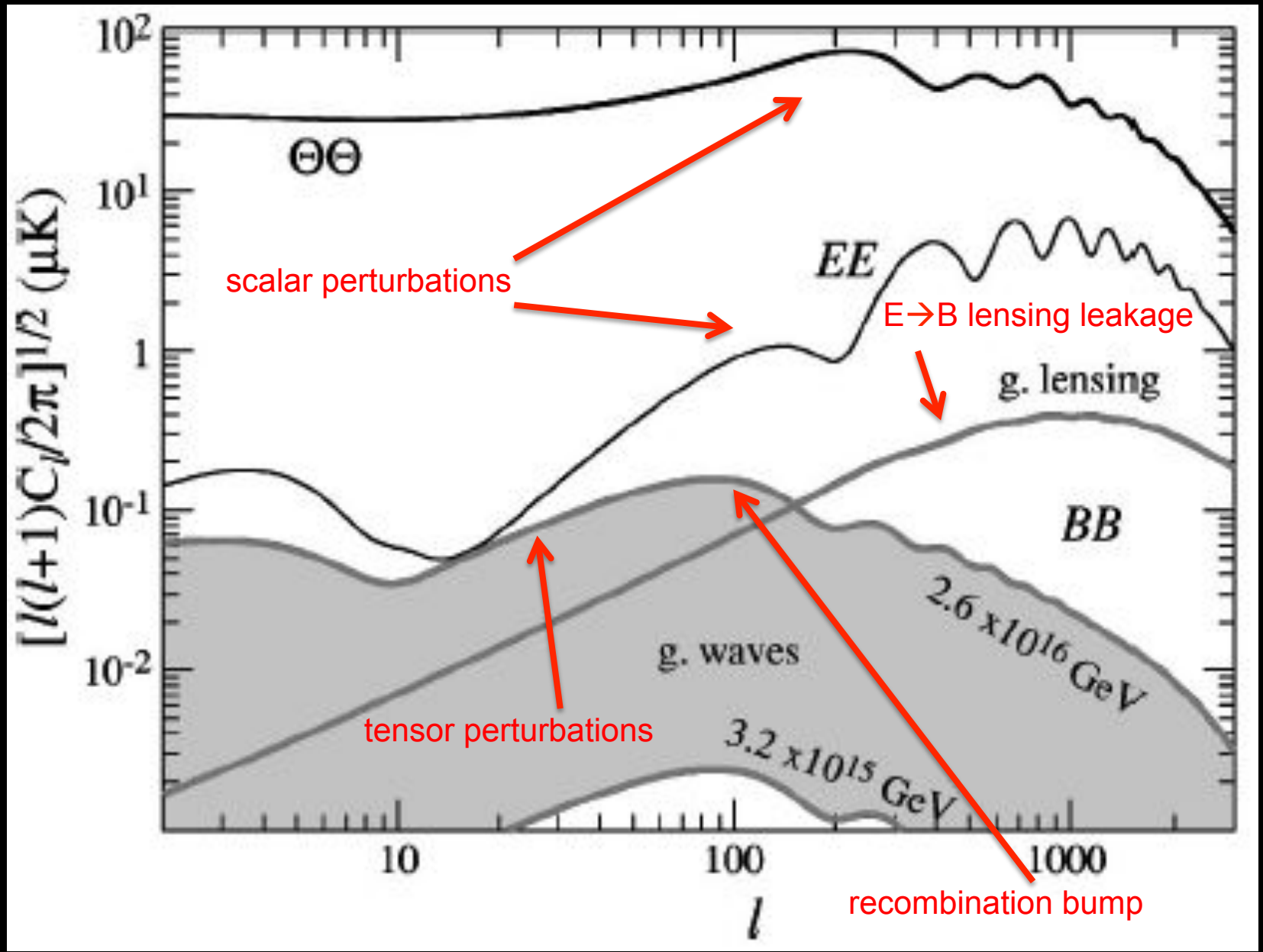
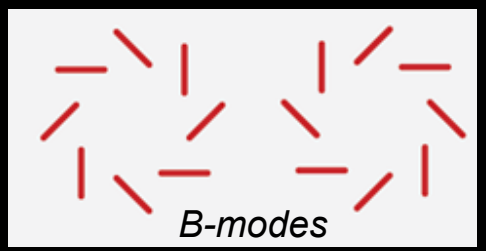


CMB polarization: E-modes and B-modes

- E-modes can be converted into a curl component whose pattern is characterized by an odd parity: B-modes
- B-modes can uniquely be produced by gravitational waves at
  - Medium scales
  - Large scales



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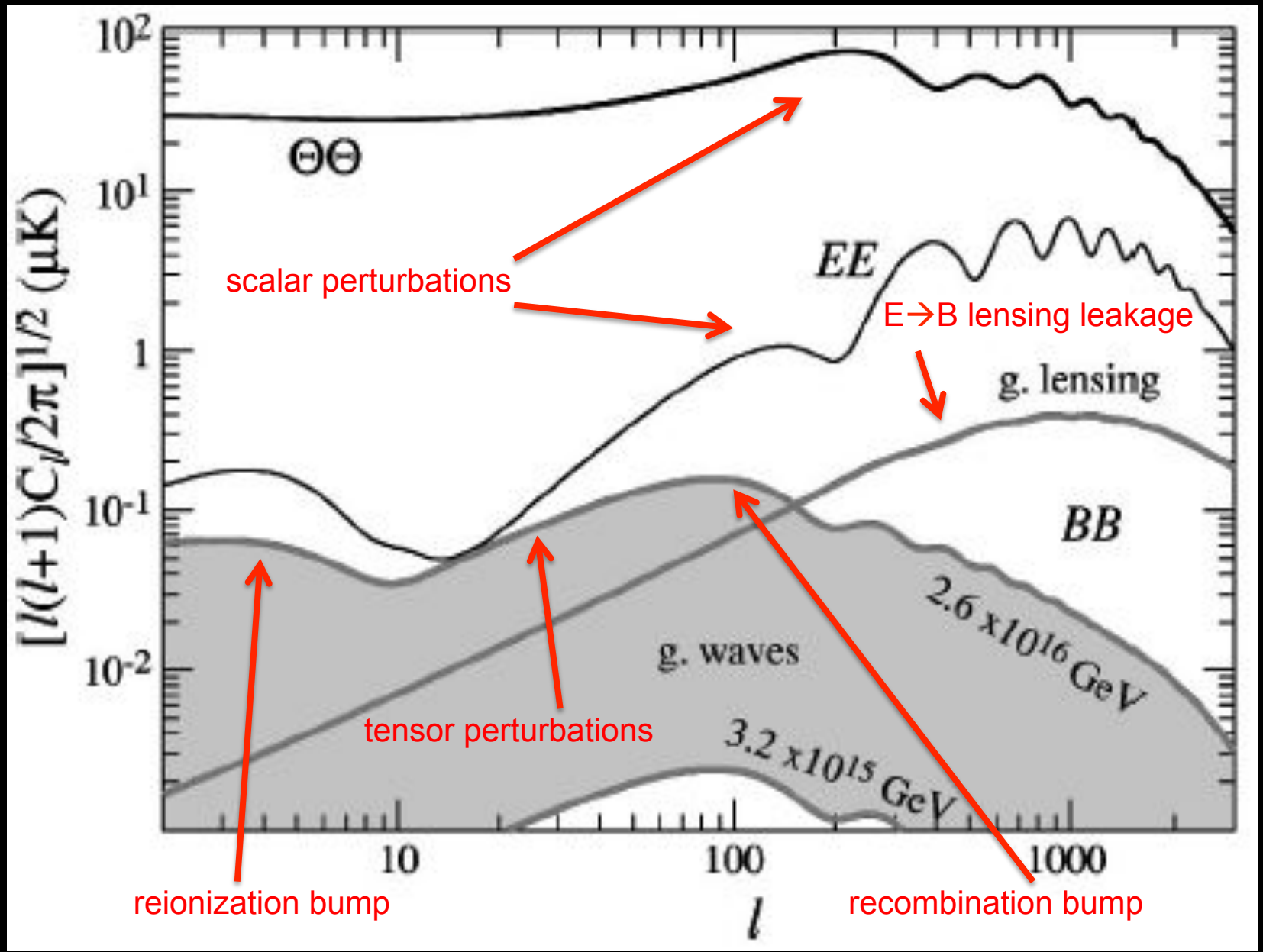
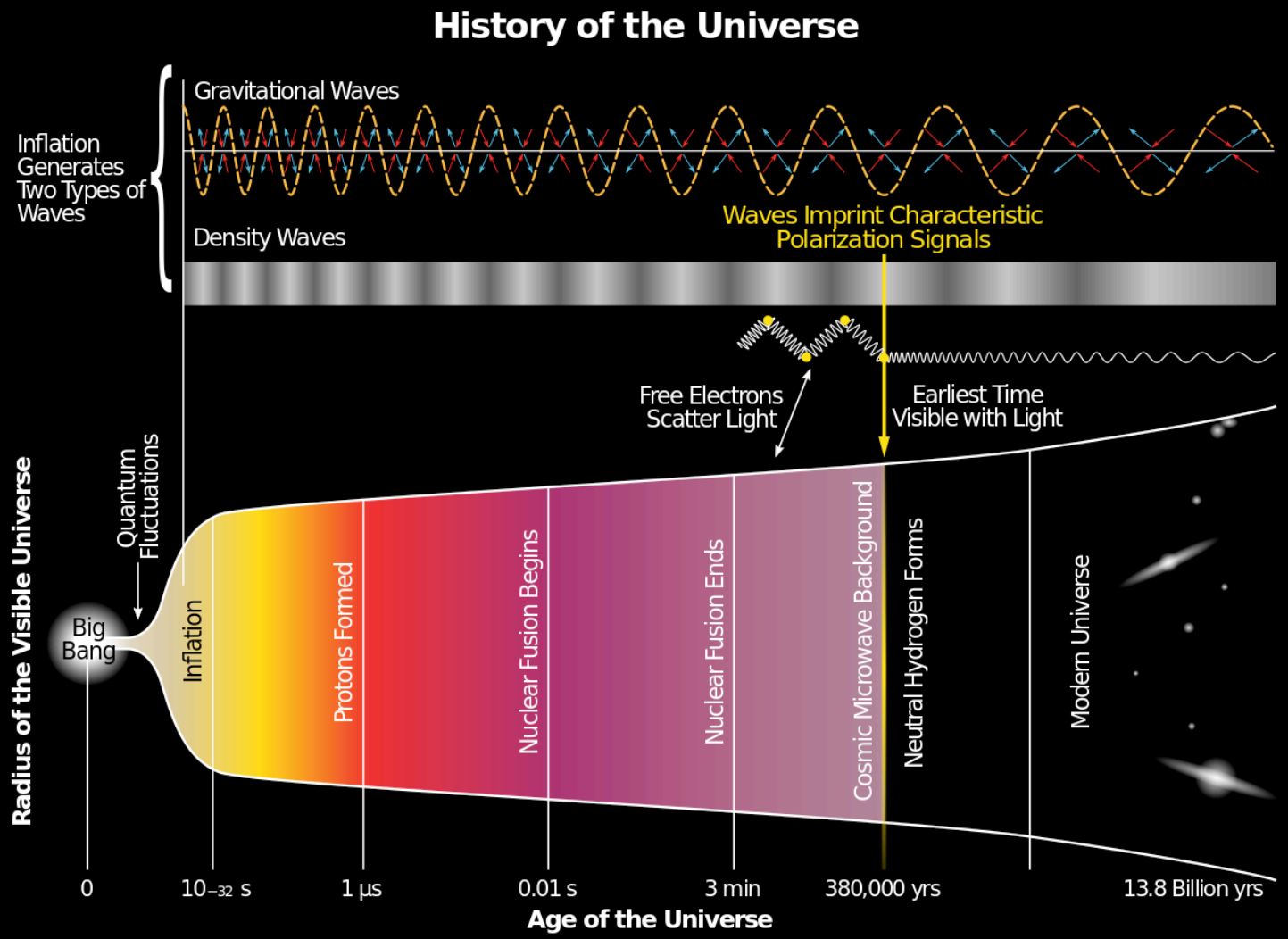


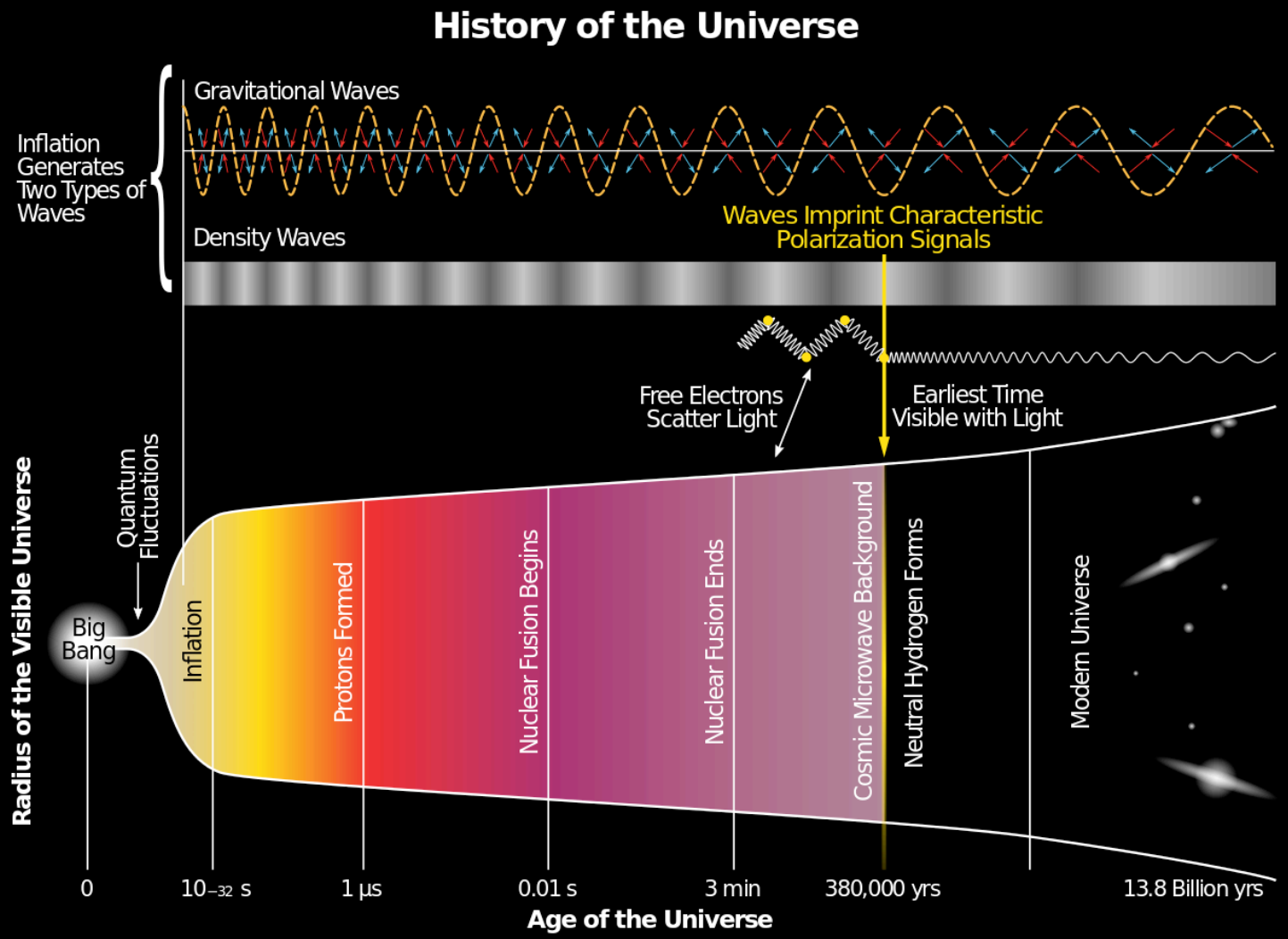
INFLATION



- Inflation is a period of exponential acceleration of the Universe at the very beginning of it (~10^{-36}s)
- It provides a theory related to the quantum gravity energy at E>10^{14}GeV
- It was invoked to explain flatness problem, super-horizon isotropy, absence of magnetic monopoles

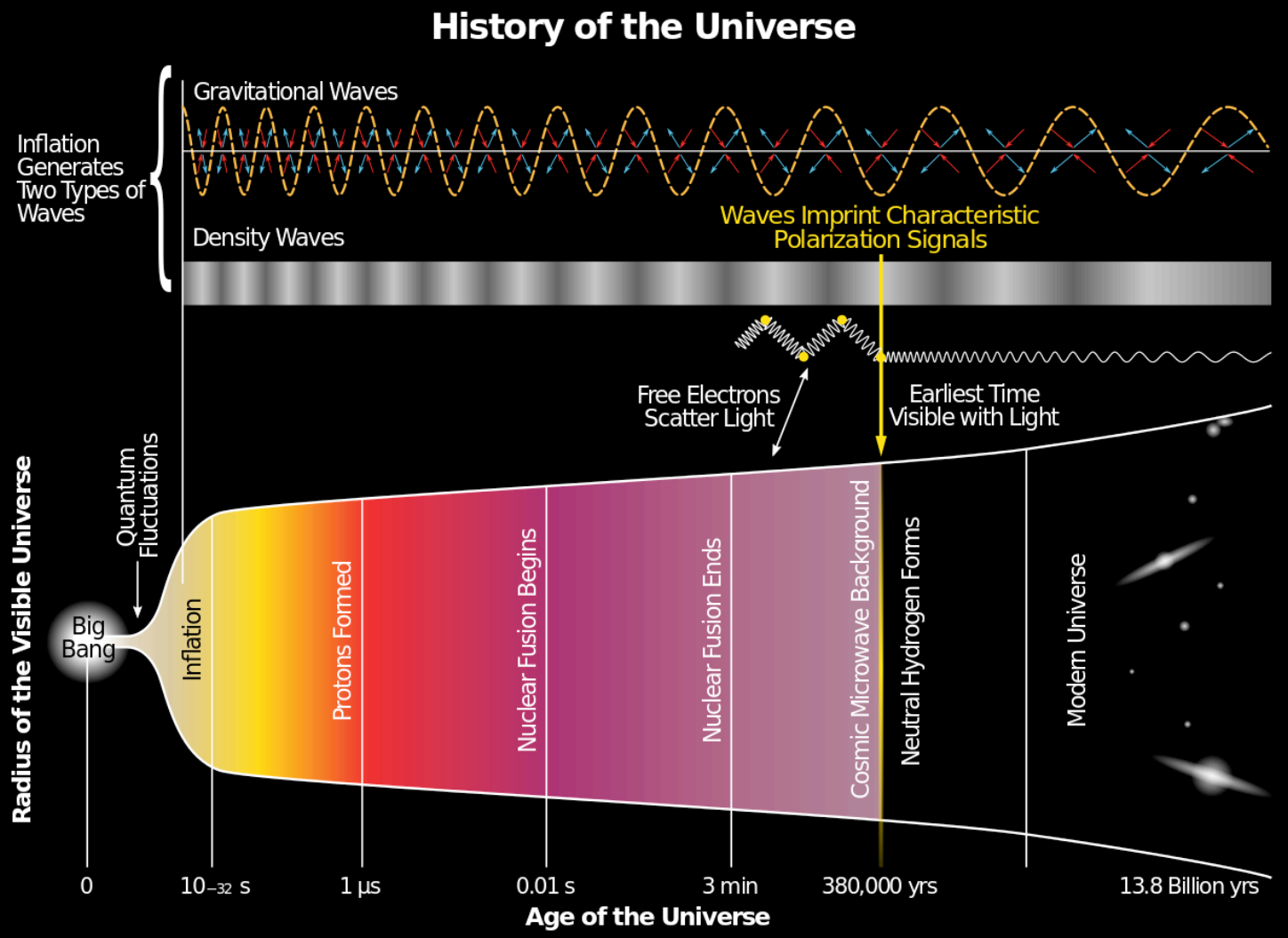
INFLATION

- INFLATION check list:



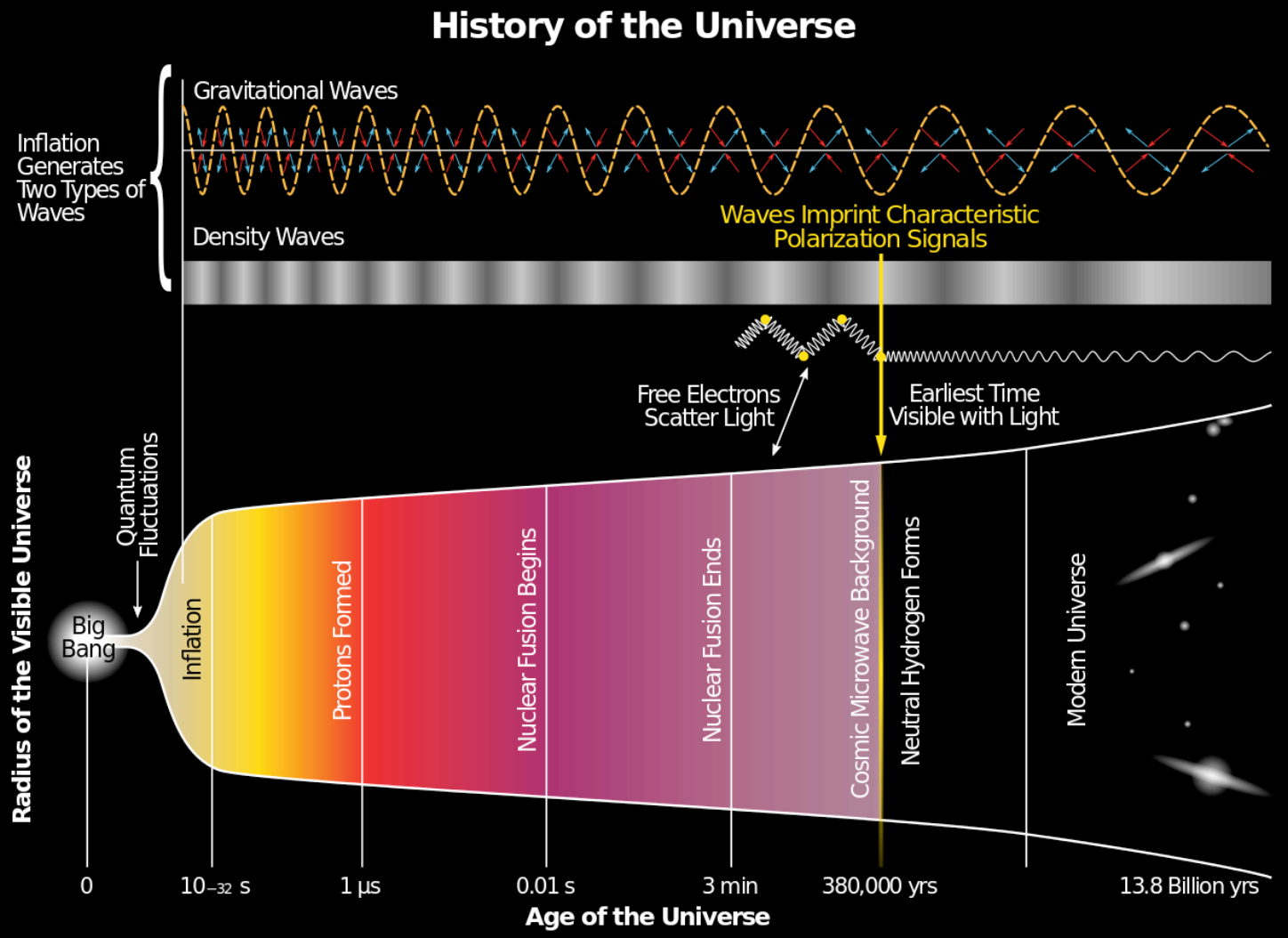
INFLATION

- INFLATION check list:
  - ☑ Flat Geometry



INFLATION

- INFLATION check list:
  - [x] Flat Geometry
  - [x] Super-horizon features



INFLATION

- INFLATION check list:

- [x] Flat Geometry
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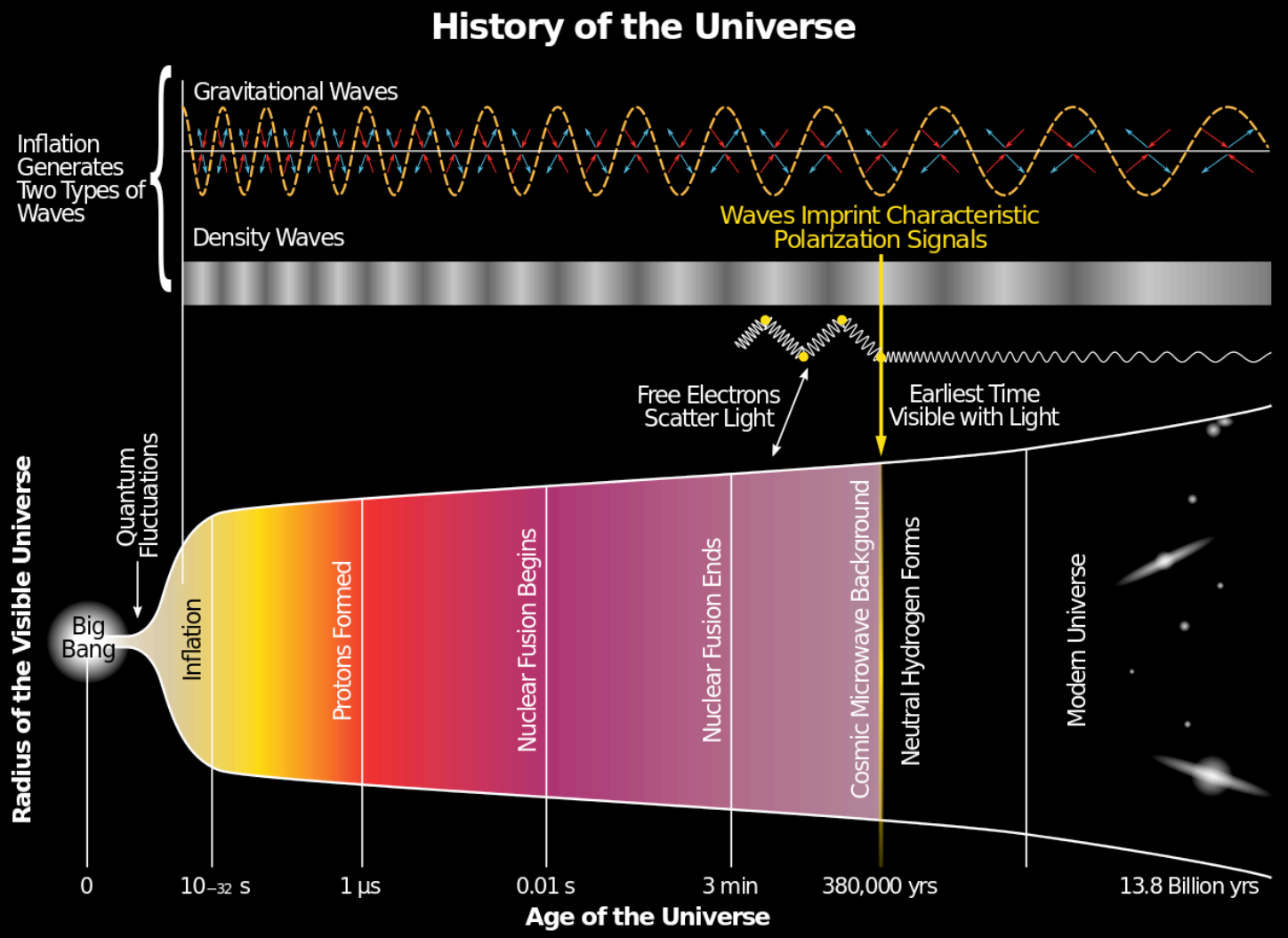

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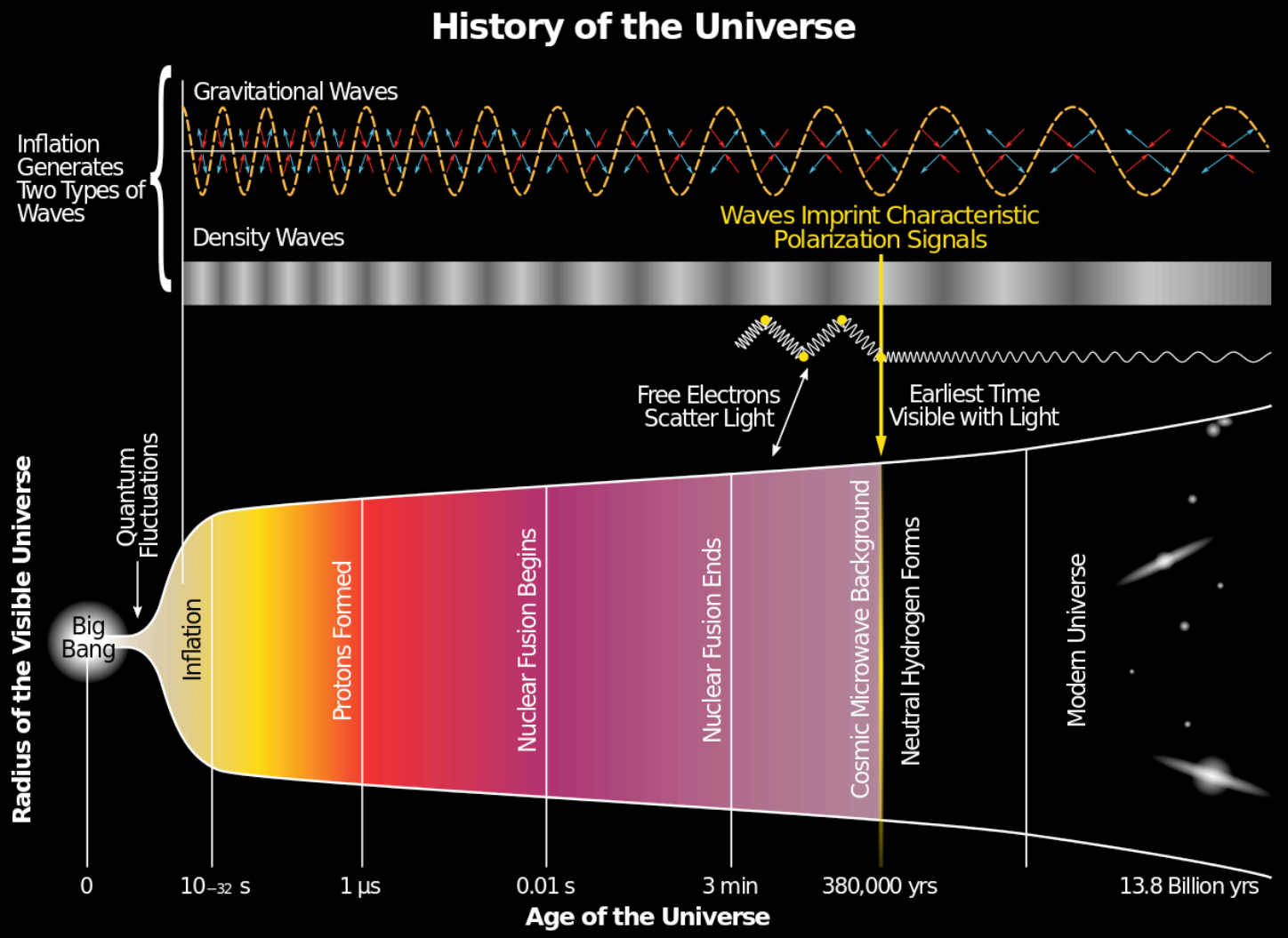

INFLATION

- INFLATION check list:

- [x] Flat Geometry
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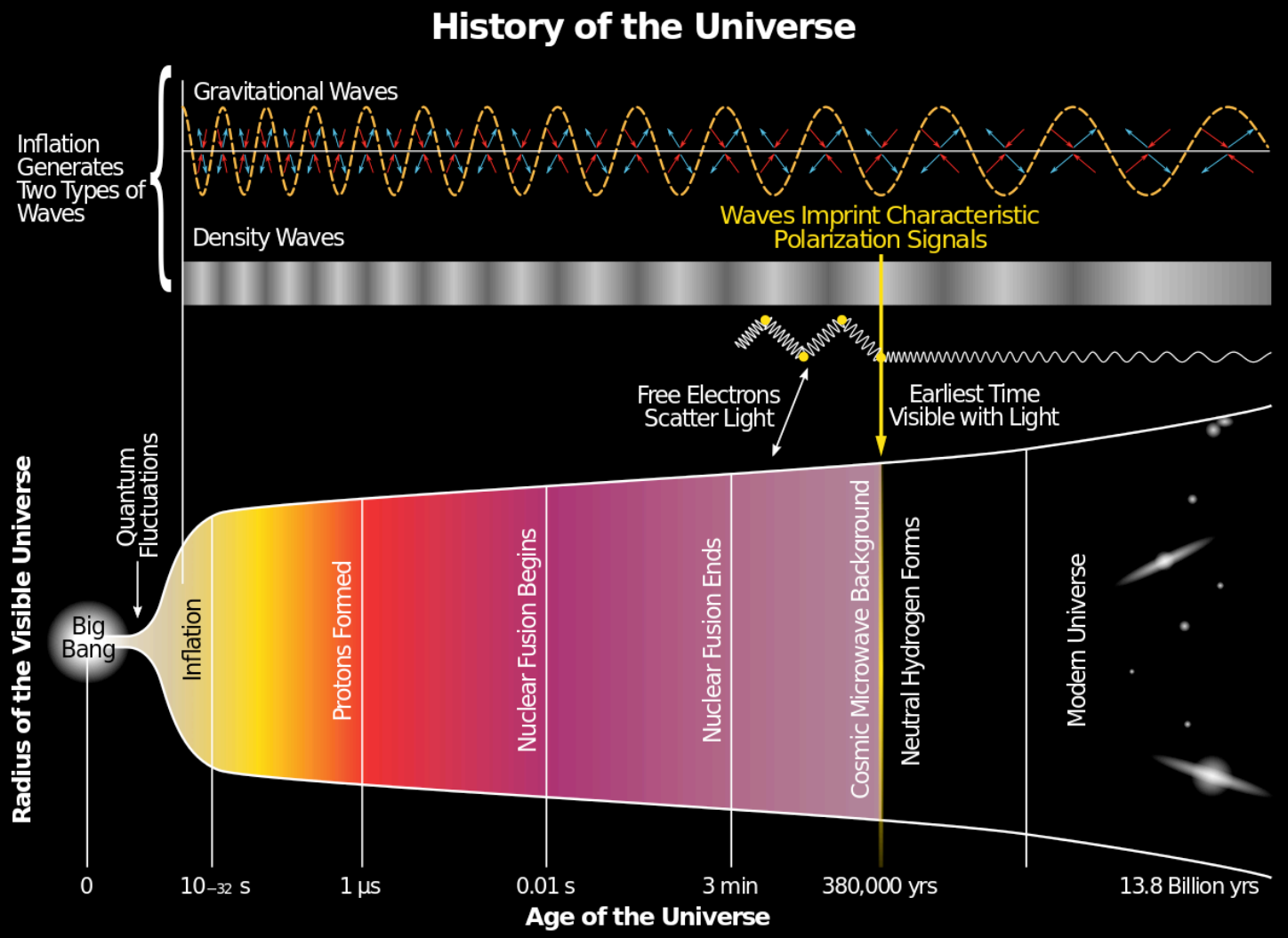
- [x] Density perturbations generated by quantum fluctuations in the spacetime metric



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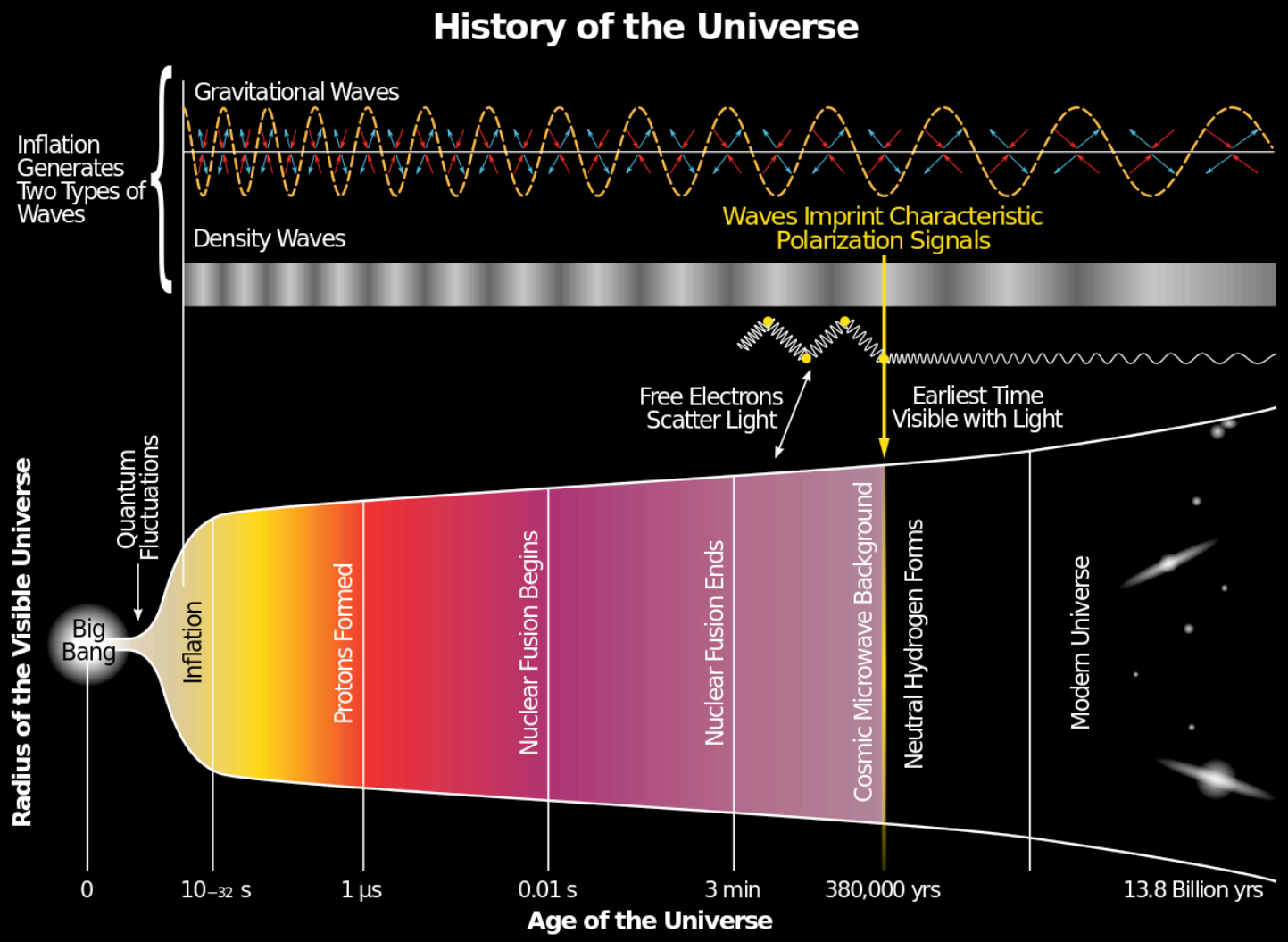

INFLATION

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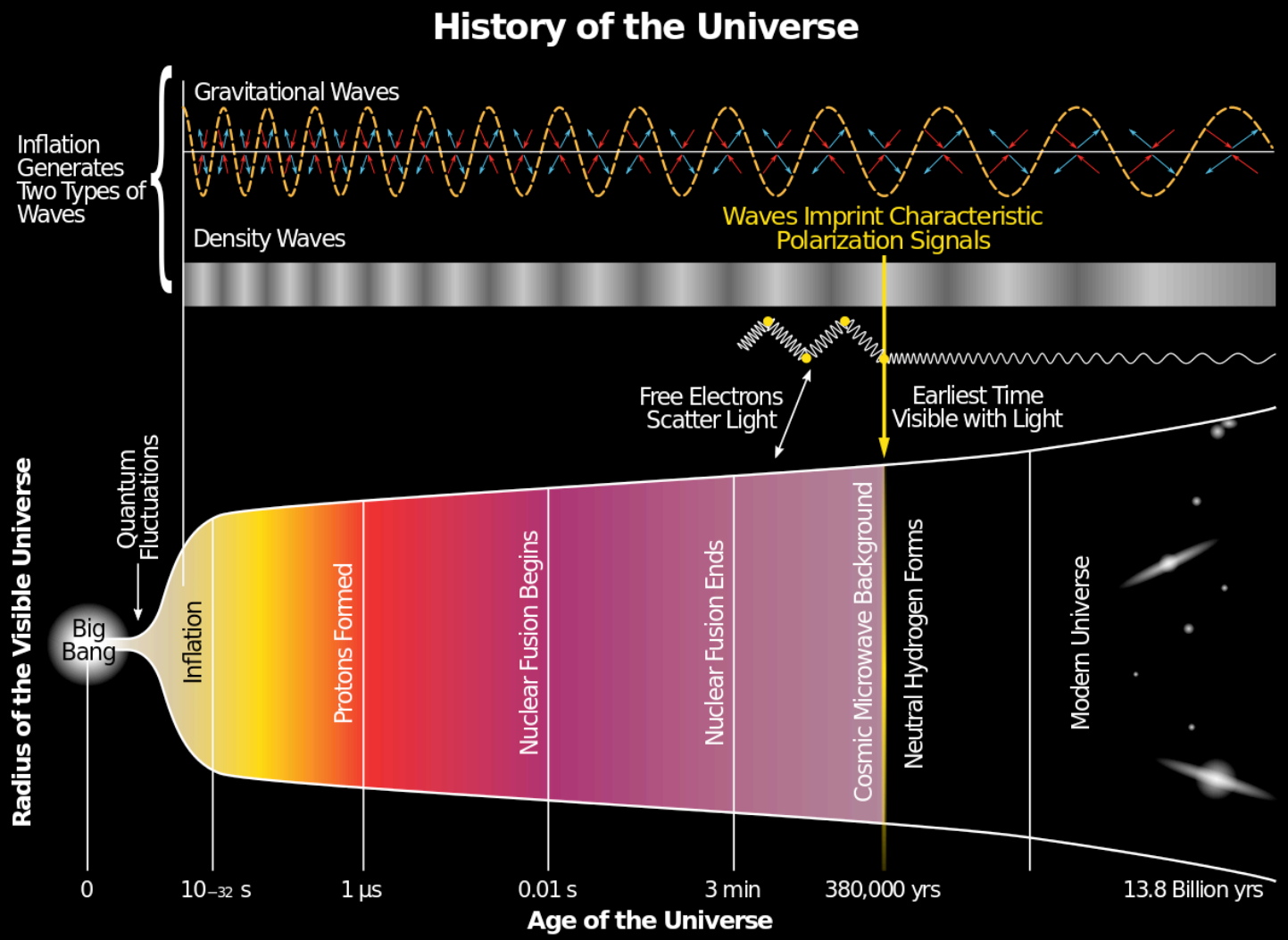
- [x] Adiabaticity and gaussianity of the perturbations



INFLATION

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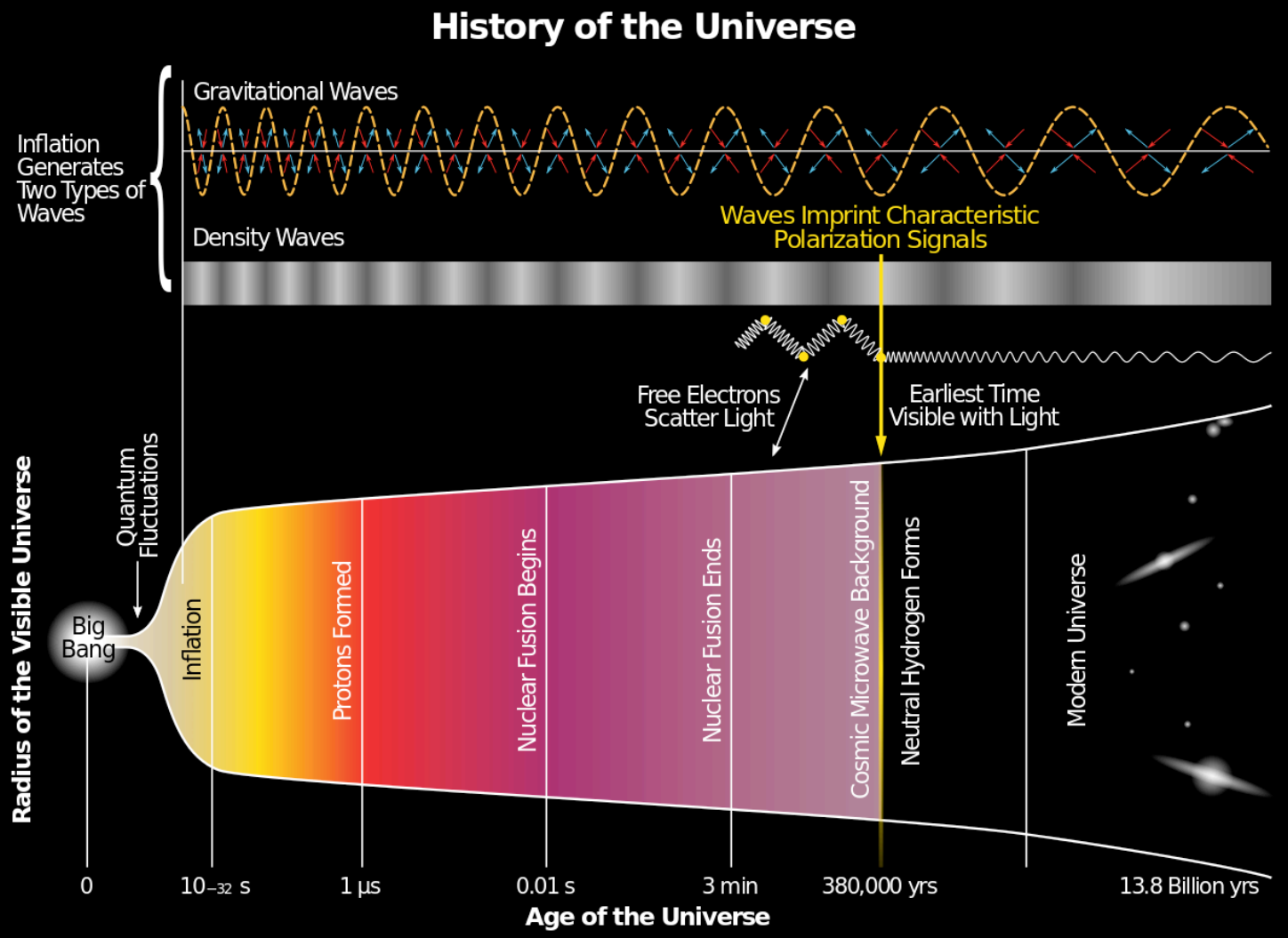
- ✓ Adiabaticity and gaussianity of the perturbations
- ? Stochastic background of Gravitational Waves



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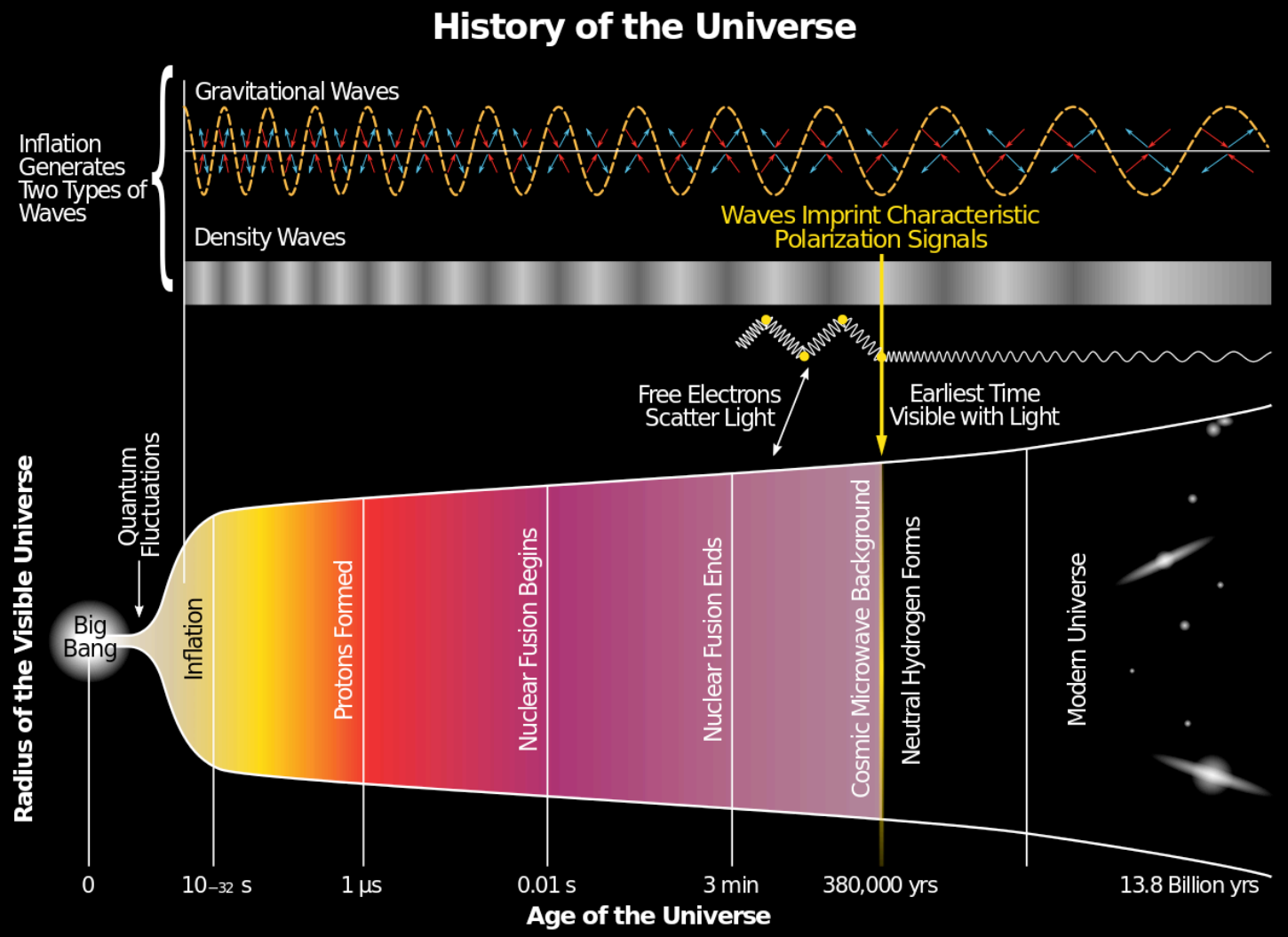

$$r \equiv \frac{Tensor(gravitational)pert.ampl.}{Scalar(density)pert.ampl.};$$

INFLATION

- INFLATION check list:
  - ☑ Flat Geometry
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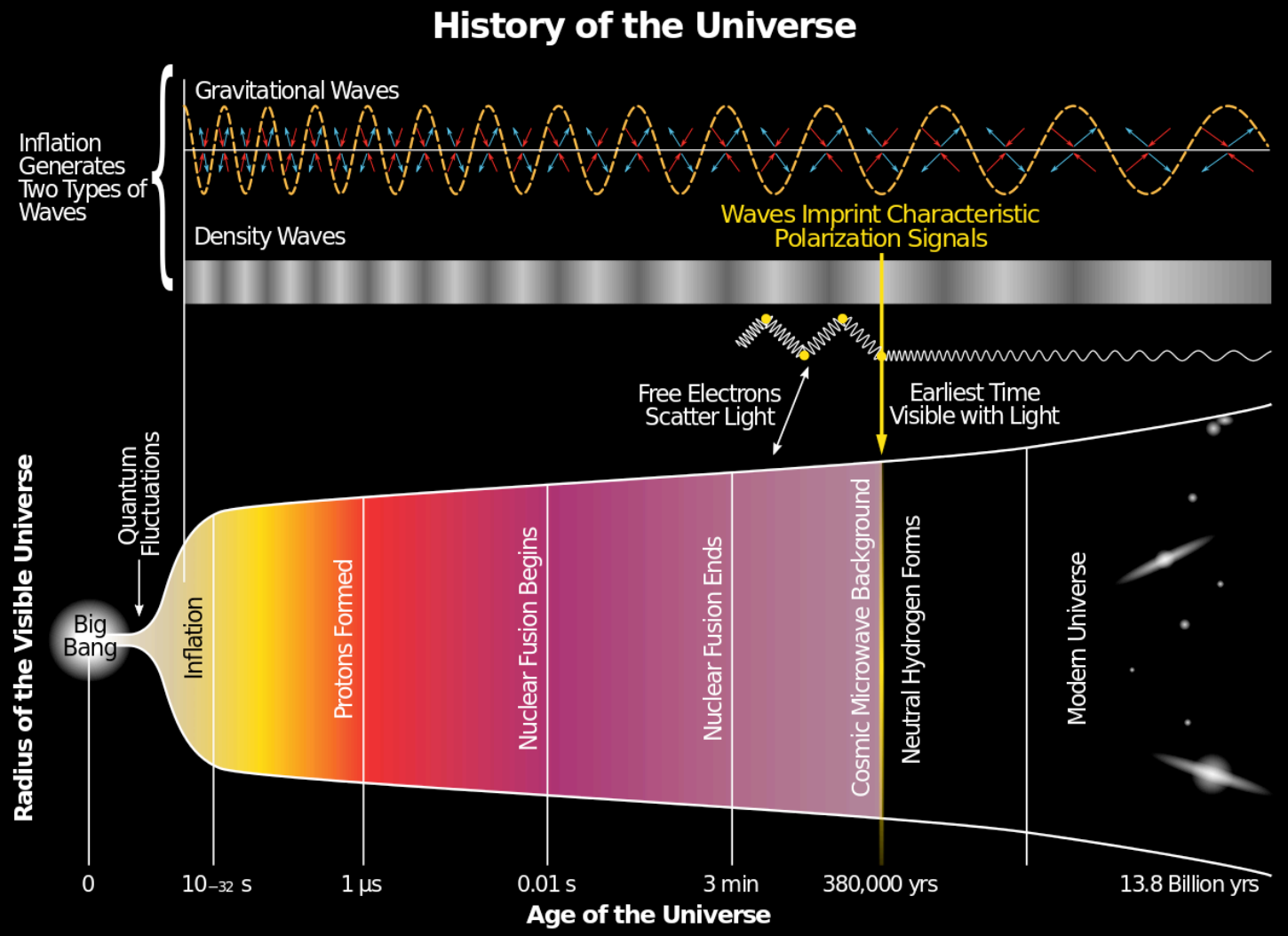
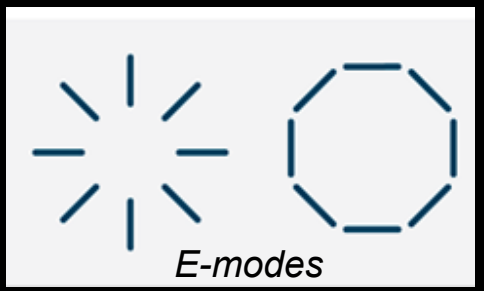
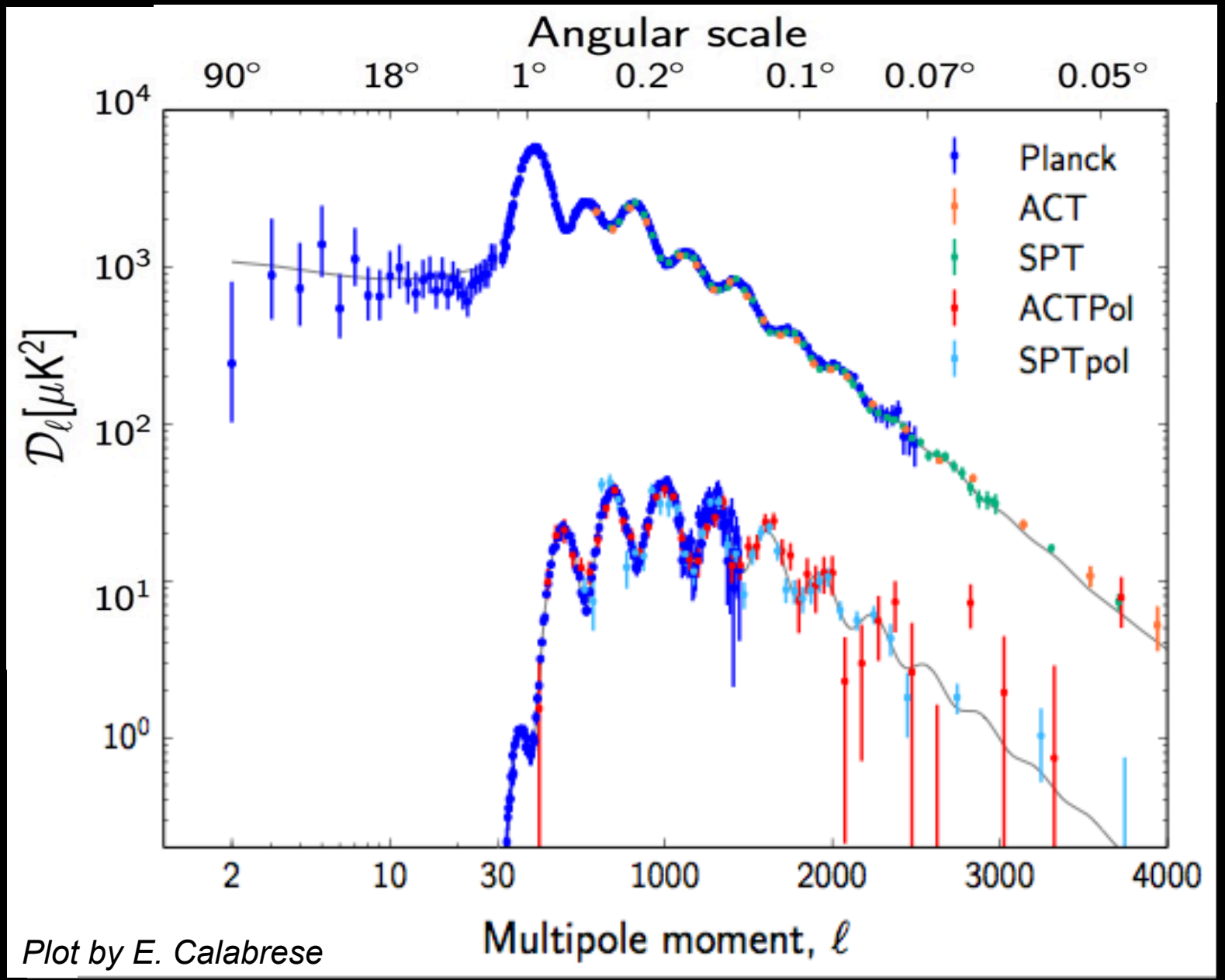


$$r \equiv \frac{Tensor(gravitational)pert.ampl.}{Scalar(density)pert.ampl.}; \qquad energy = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}} GeV; \qquad time = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}} s;$$

PLANCK+ACT+SPT

- @ l<1500 we are cosmic variance limited: Planck set the ultimate limit
- @ l>1500 things can be improved
- @ l > 2500 only 10% of the sky has been measured

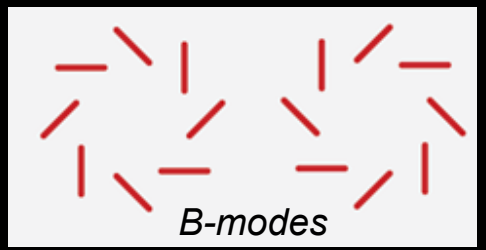




Plot by E. Calabrese

CMB polarization: E-modes and B-modes

- Current status for CMB polarization measurements: AMAZING!
- B+K/Planck: r<0.07
- Still a long way to go
- For r~0.01 de-lensing is important



B-modes

- Some models predict r≥0.002 (Starobinsky)
- If so ~10^{16}GeV (GUT)

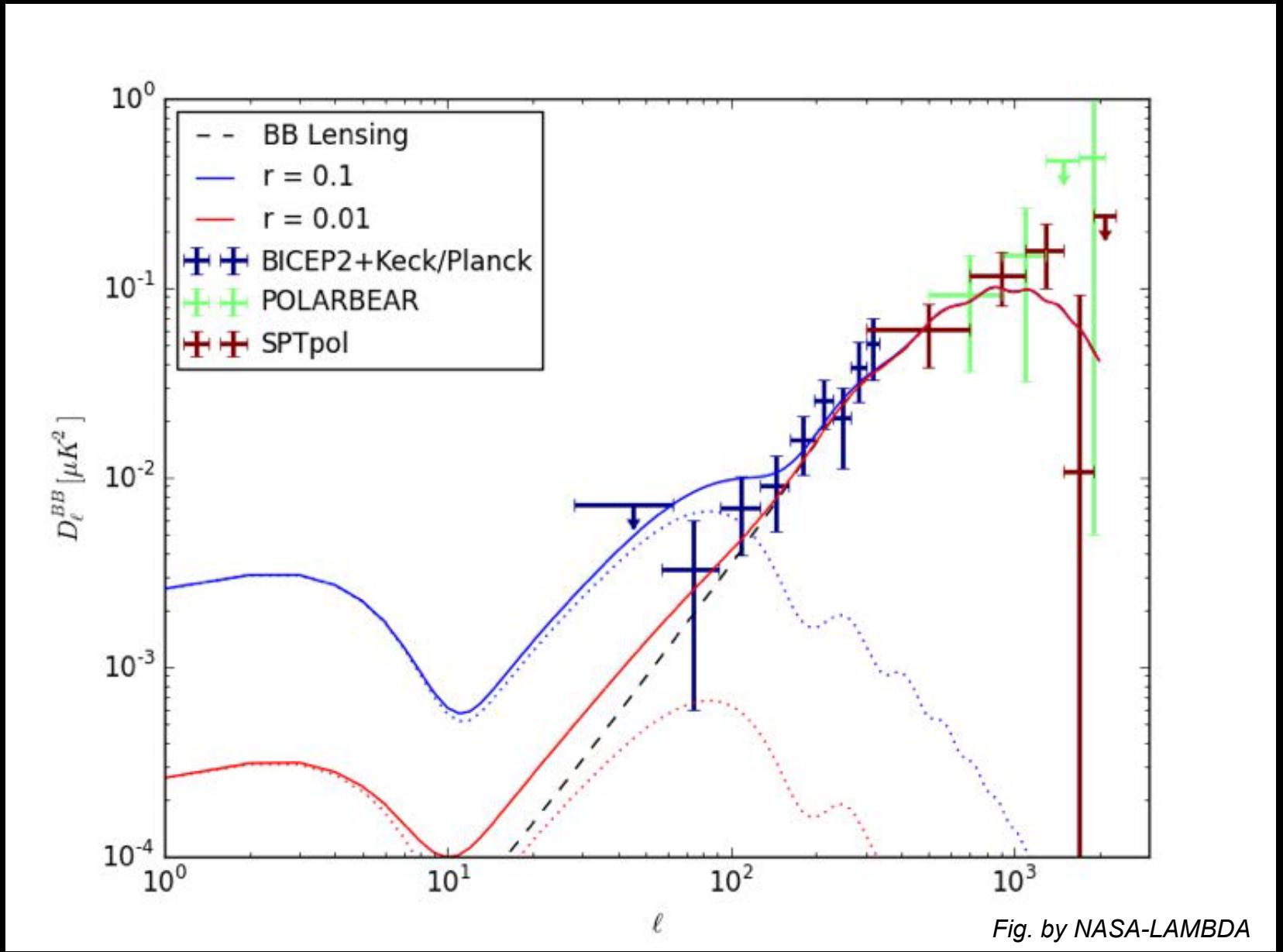


Fig. by NASA-LAMBDA

B-modes experiments

How to measure B-modes

- Complementarity:

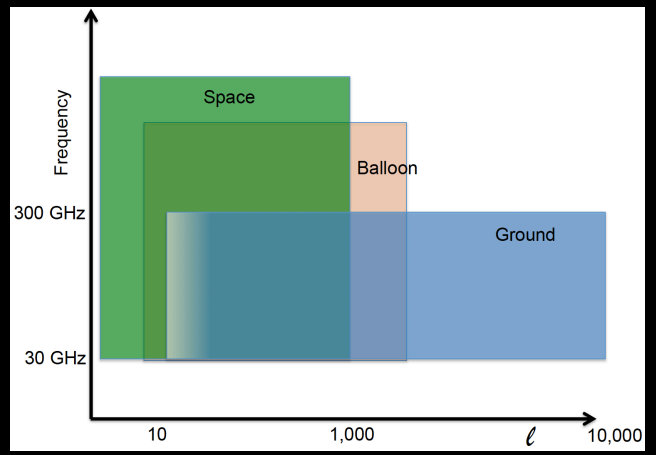
foreground

vs

sky coverage

vs

angular resolution



How to measure B-modes

- Complementarity:

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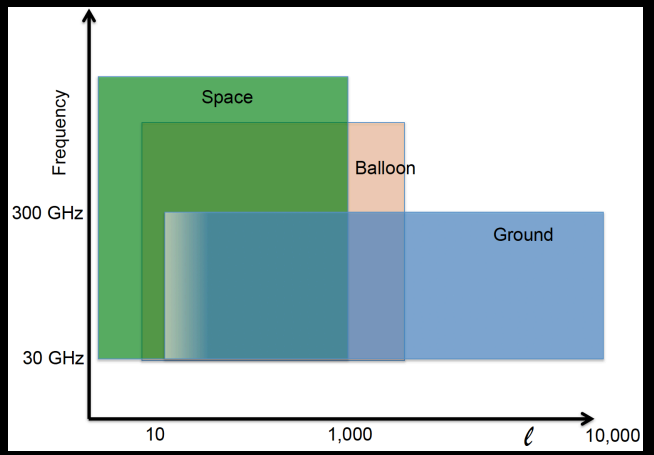
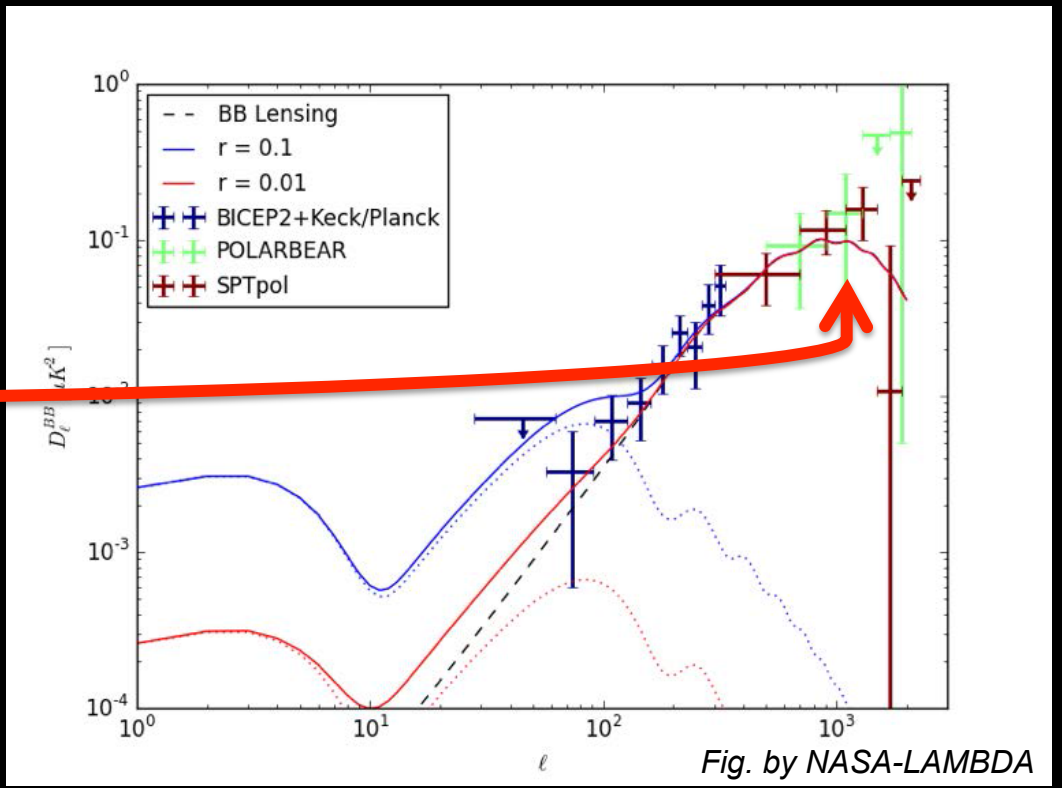
- B-modes power spectrum:

  (de-)lensing





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How to measure B-modes

- Complementarity:

  foreground

  vs

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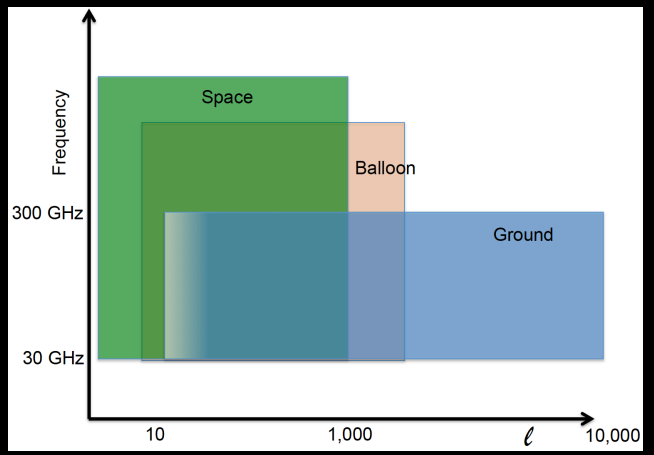
  angular resolution

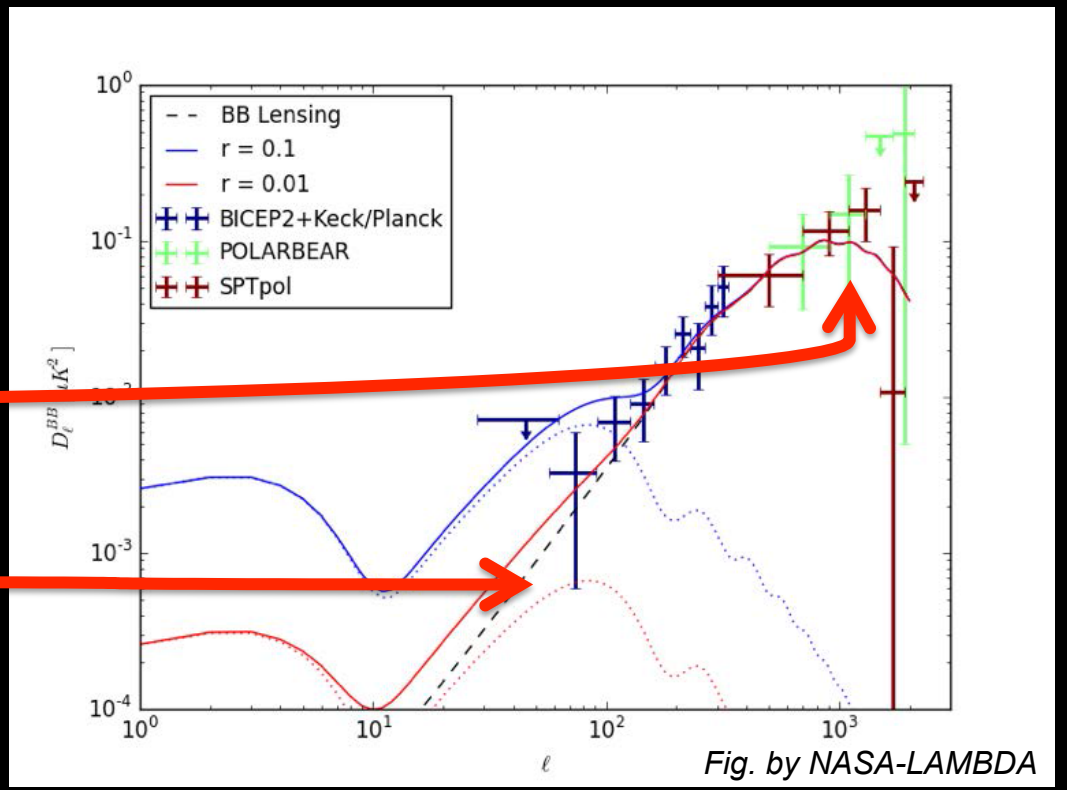
- B-modes power spectrum:

  (de-)lensing

  vs

  recombination bump





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How to measure B-modes

- Complementarity:

foreground

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sky coverage

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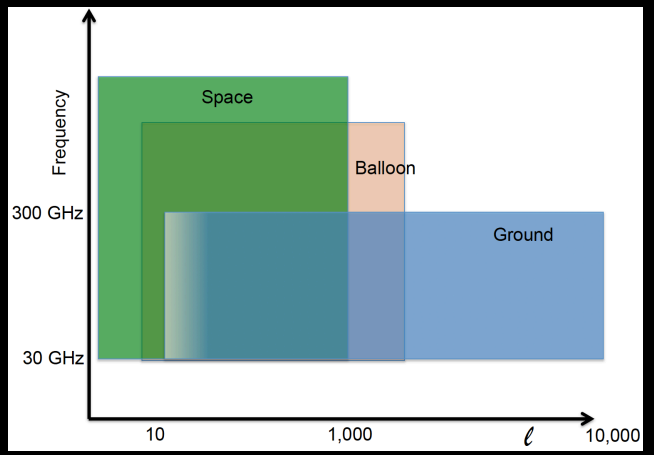
angular resolution



- B-modes power spectrum:

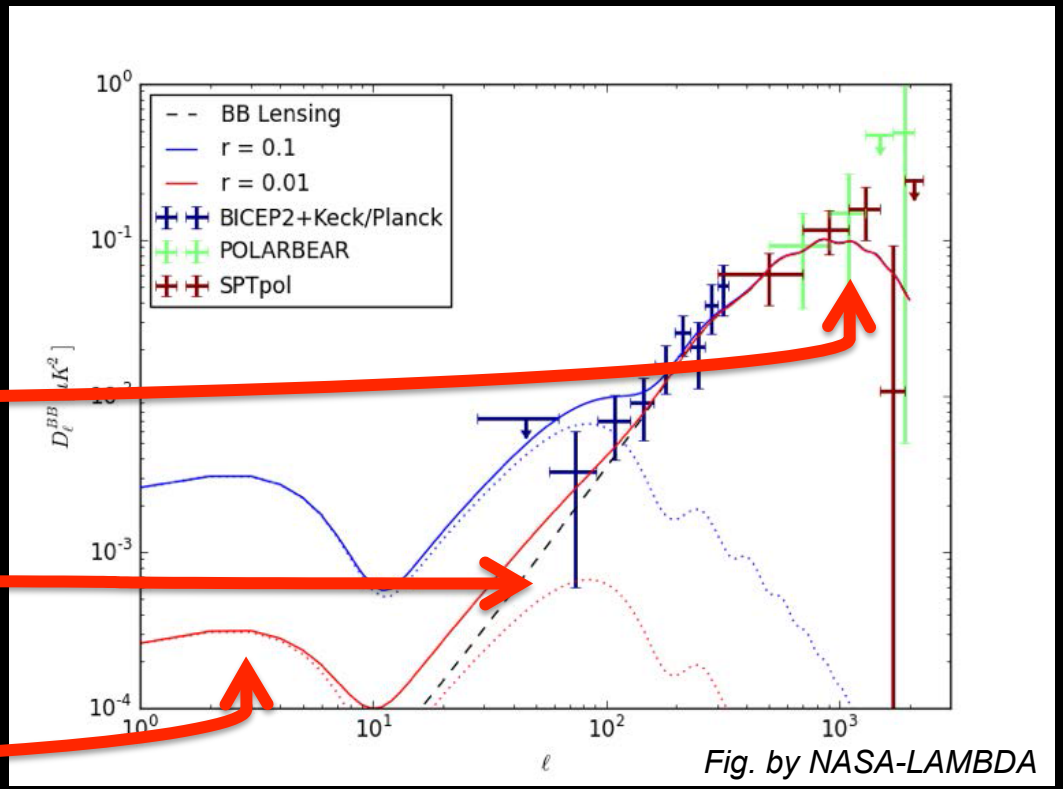
(de-)lensing

vs

recombination bump

vs

reionization bump



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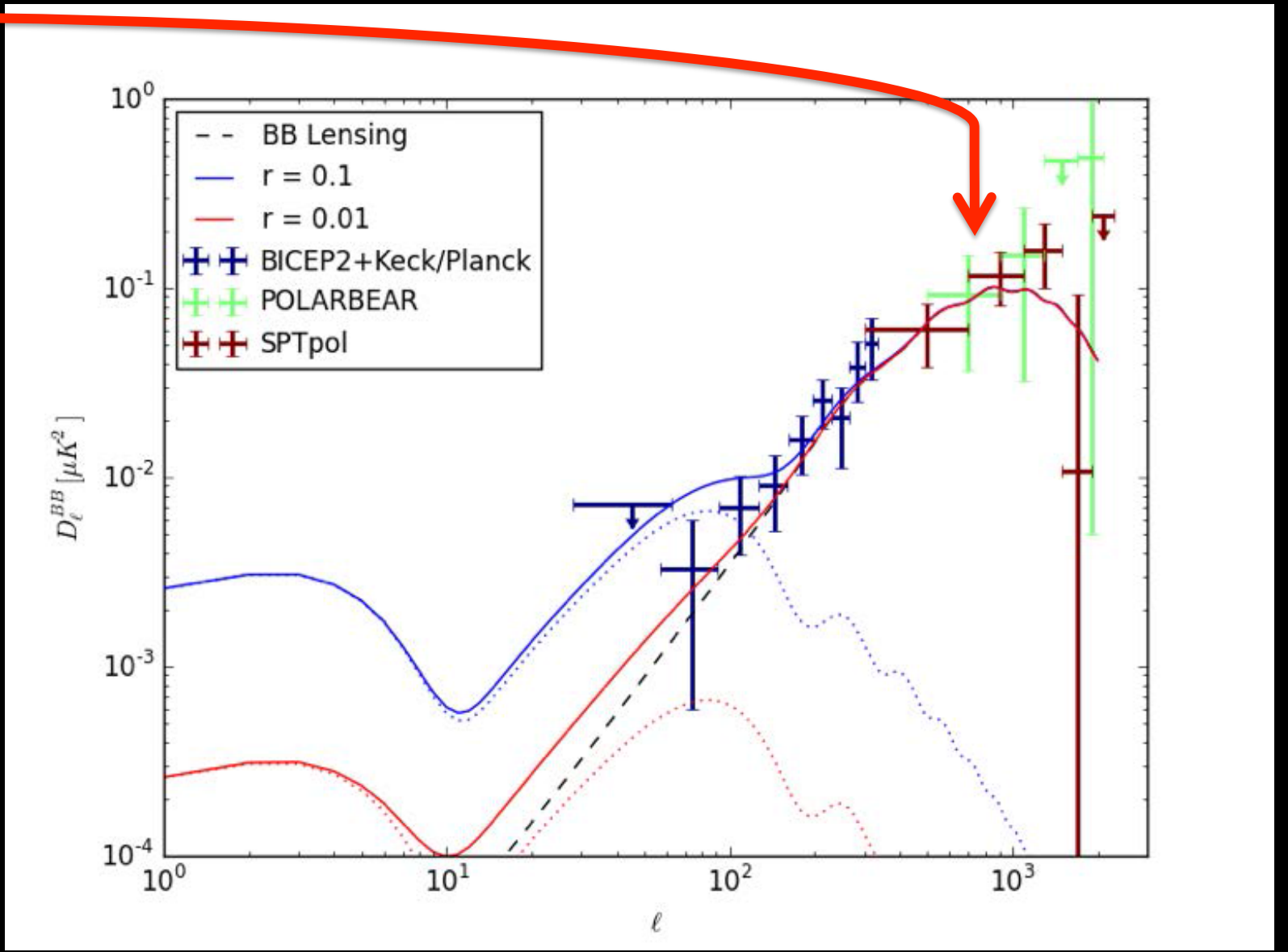
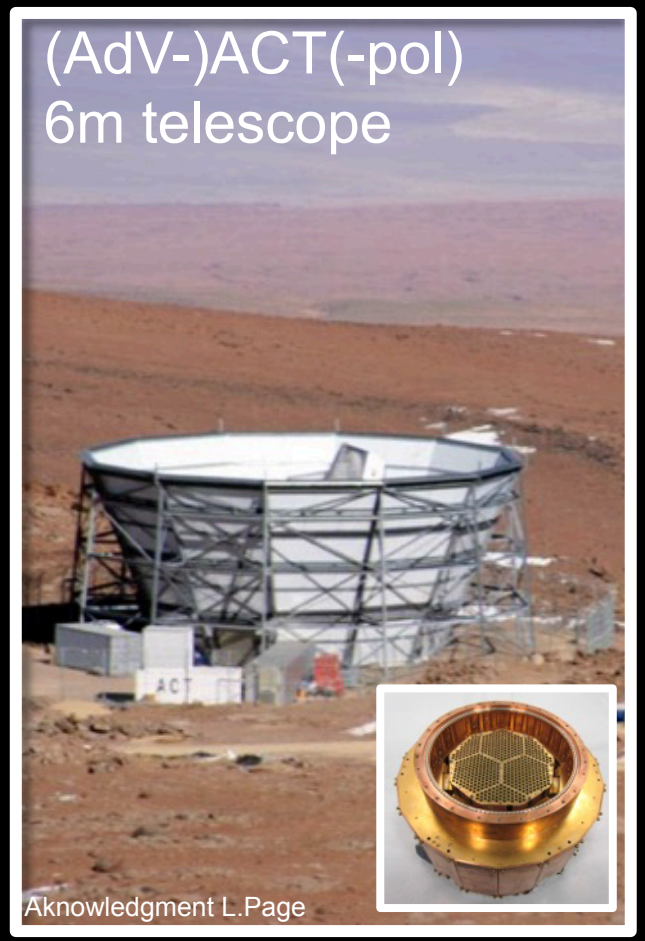
How to measure B-modes

(de-) lensing

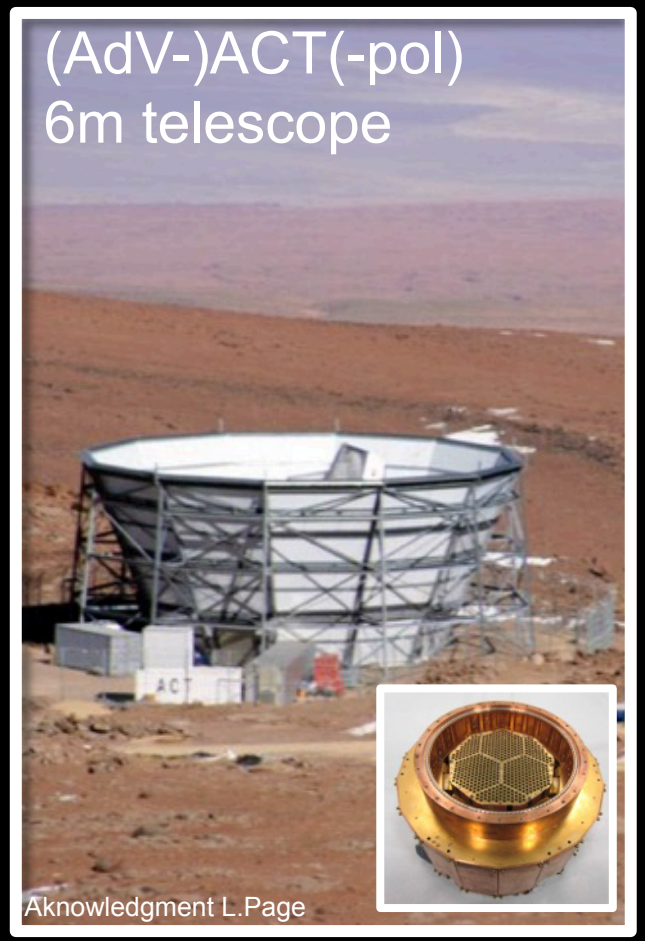


Large aperture experiments: ground



- *L. Page (Princeton) et al.*
- *Wide, deep and multifrequency survey down to r<0.01*
- *Feedhorn coupled, pol. Sensitive, multichroic, TDM'ed TES*
- *AdV-ACT: 30-230 GHz multichroic TES*

Large aperture experiments: ground



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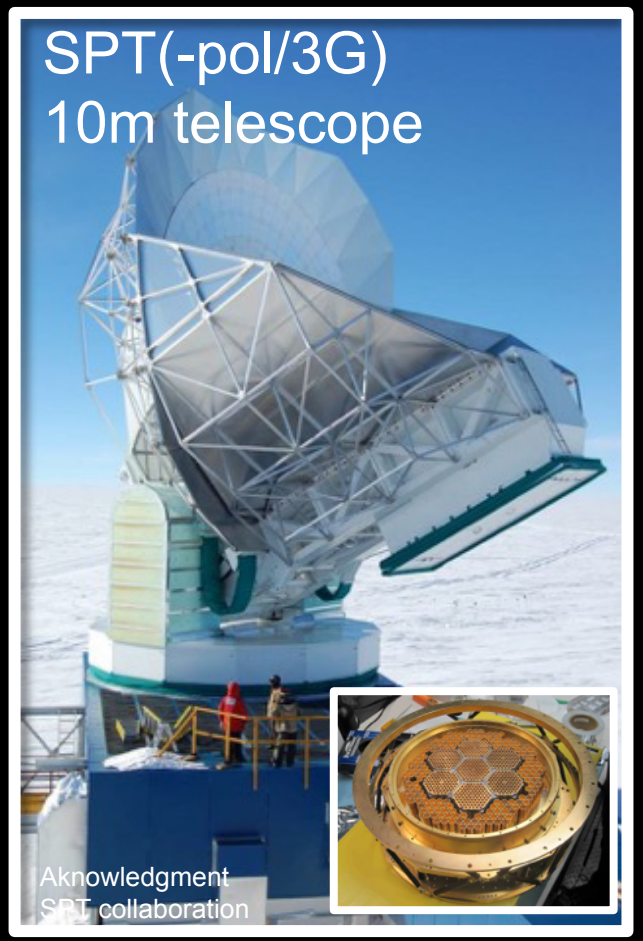
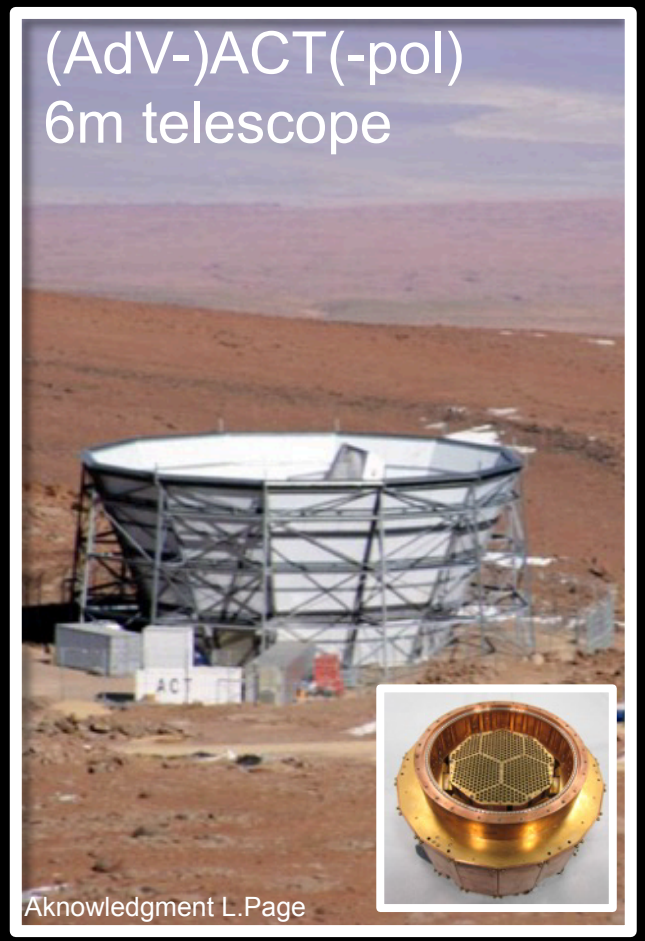


- J. Carlstrom (Chicago) et al.
- Deep, high (best!) angular res survey!
- Trial-band multichroic FDM'ed TES (90/150/220 GHz) with Sinuous Focal Plane
- SPT-3G : 16260 pixels → r<0.01

Large aperture experiments: ground



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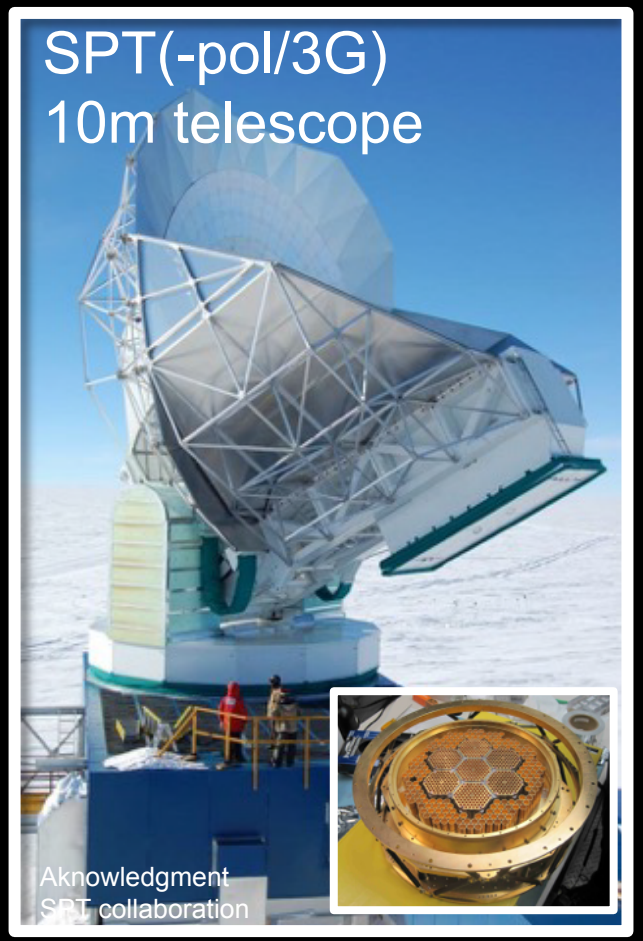
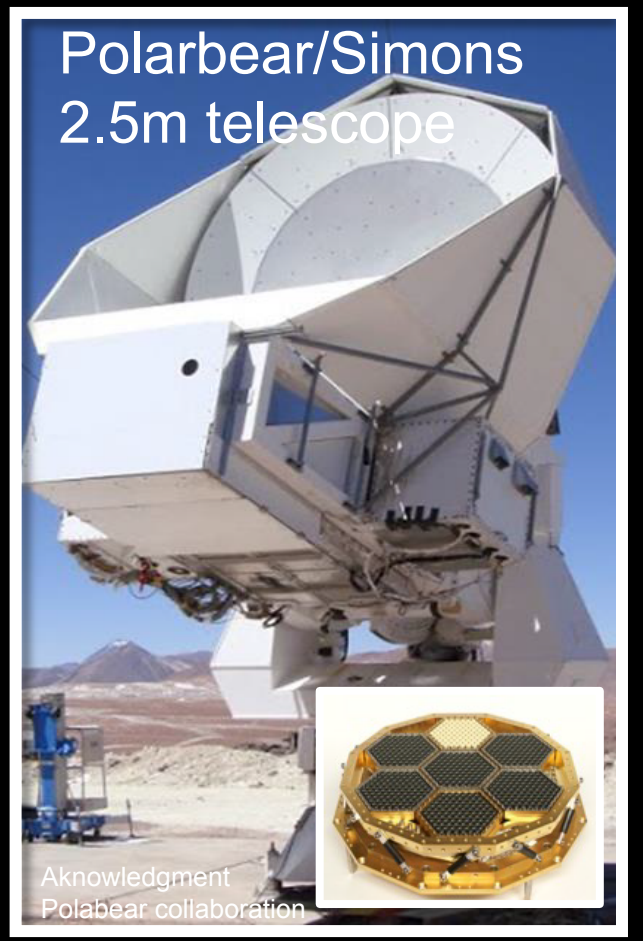


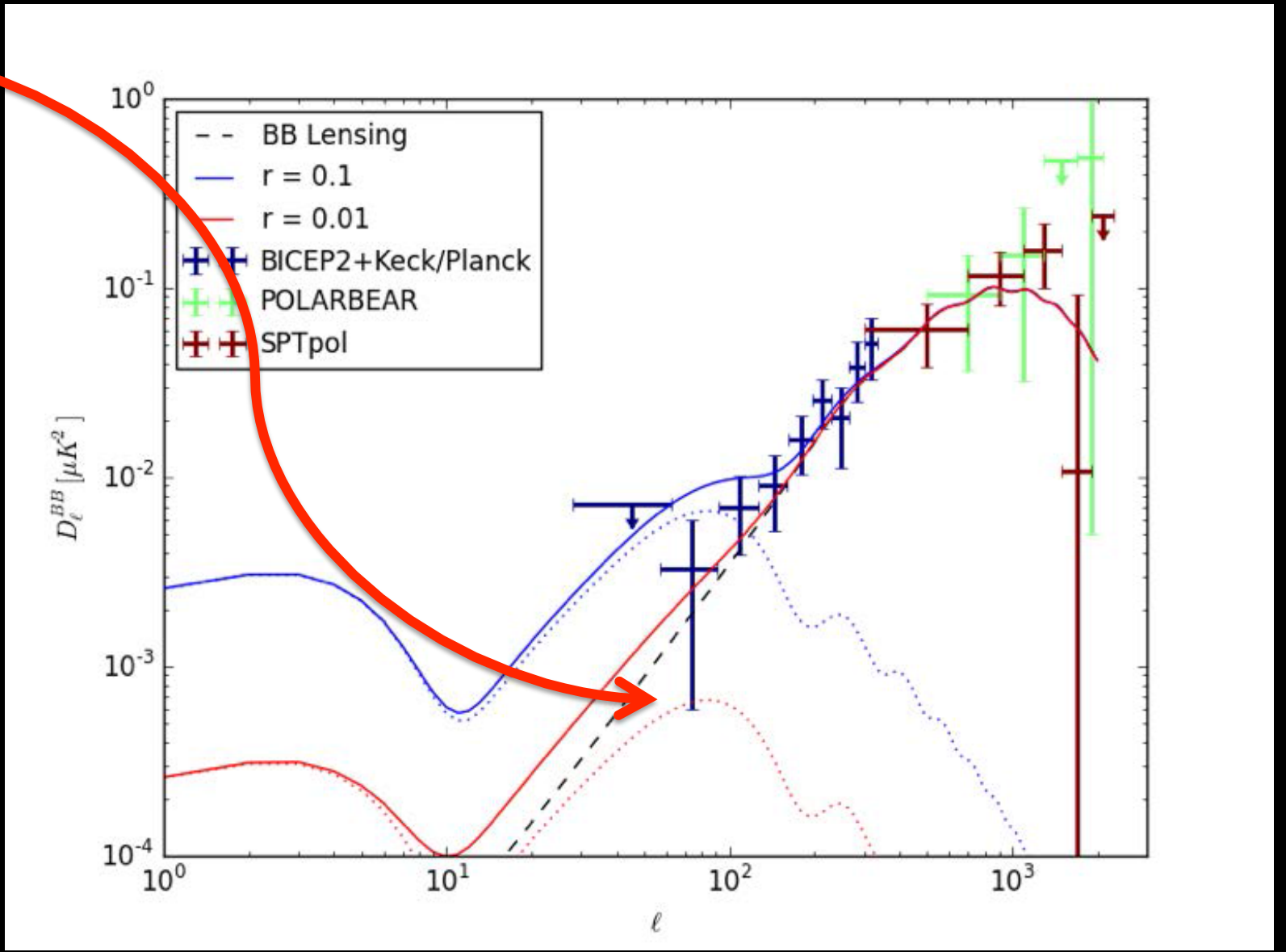
- J. Carlstrom (Chicago) et al.
- Deep, high (best!) angular res survey!
- Trial-band multichroic FDM'ed TES (90/150/220 GHz) with Sinuous Focal Plane
- SPT-3G : 16260 pixels → r<0.01



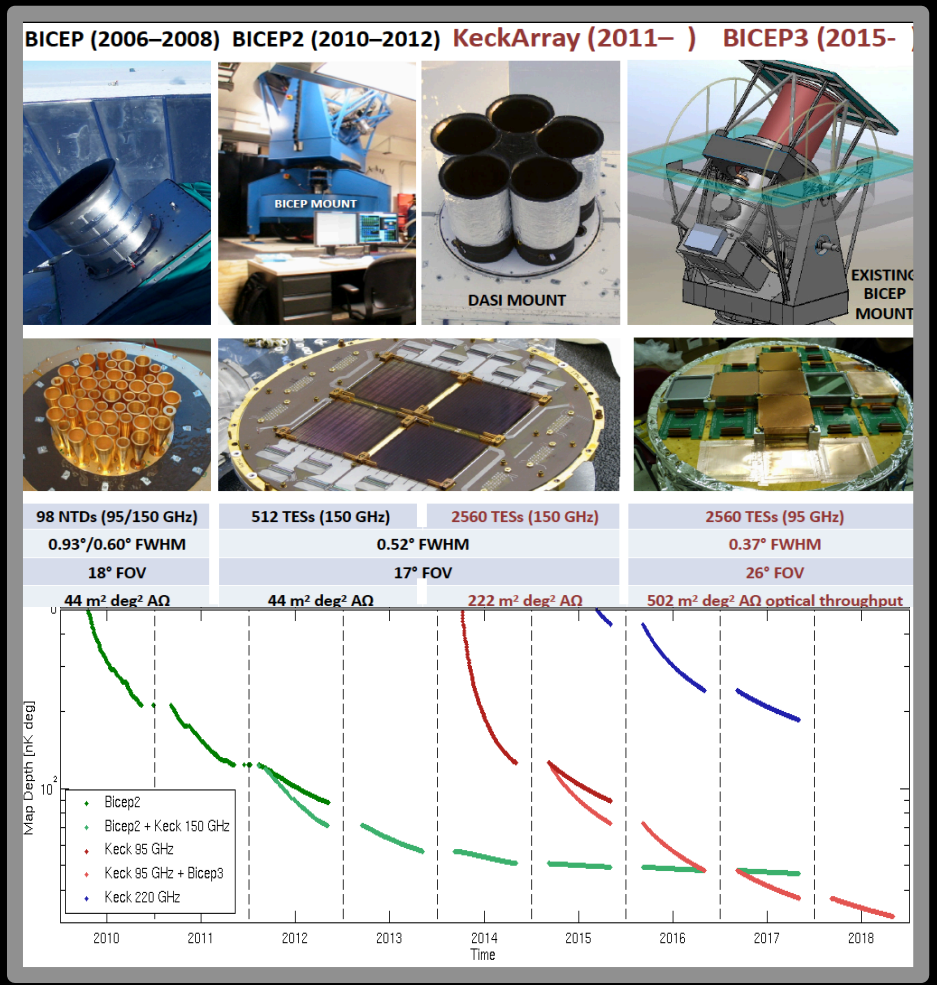
- A. Lee (Berkeley) et al.
- Deep/high angular resolution survey
- 7588 TES on POLARBEAR2
- 22768 TES on Simons Array (PB2X3)
- Dual-band multichroic pixels (90/150 and 150/220 GHz)

How to measure B-modes

recombination bump



Medium aperture experiments: ground



Aknowledgment BICEP/Keck collaboration

- Kovach (Harvard) et al.; Kuo (Stanford) et al.
- Bock (Caltech) et al.; Pryke (Minnesota) at al.
- Super deep survey: so far the most sensitive
- Primordial B-modes optimized
- Simple optics; great detectors: slot antennas, microstrip filters, load dissipation, TES, TDM

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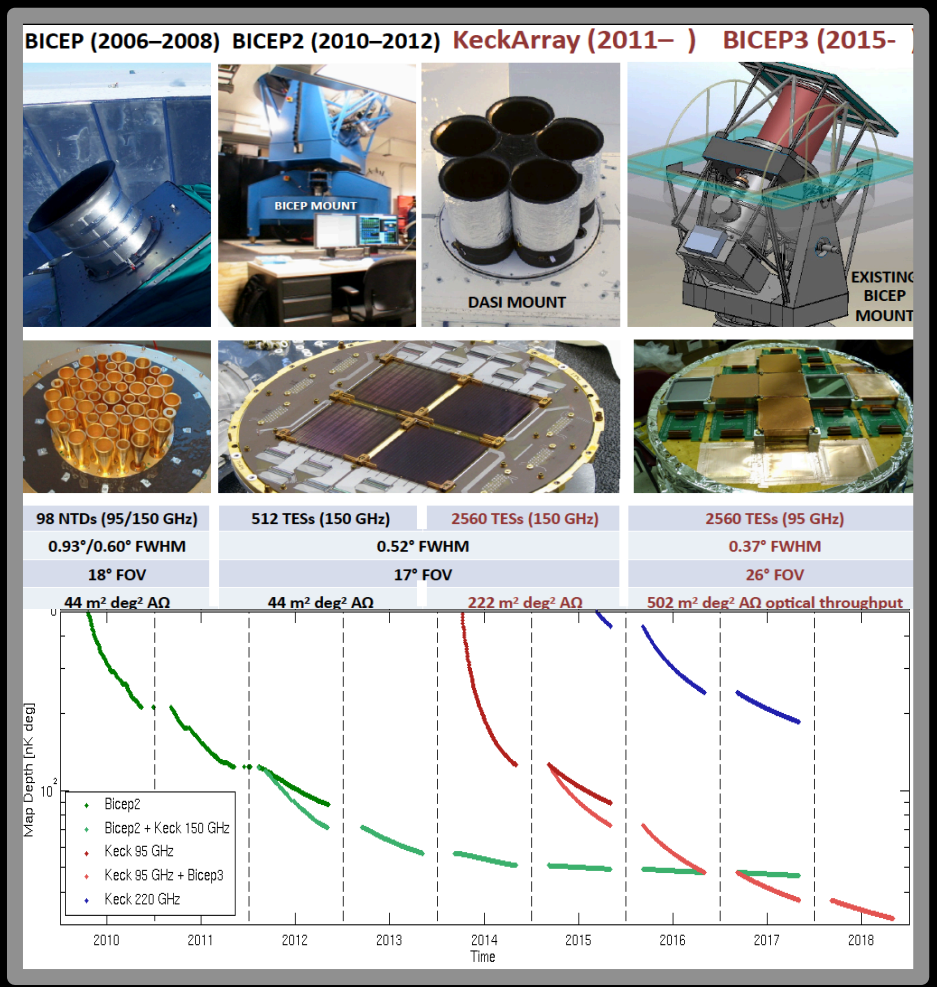

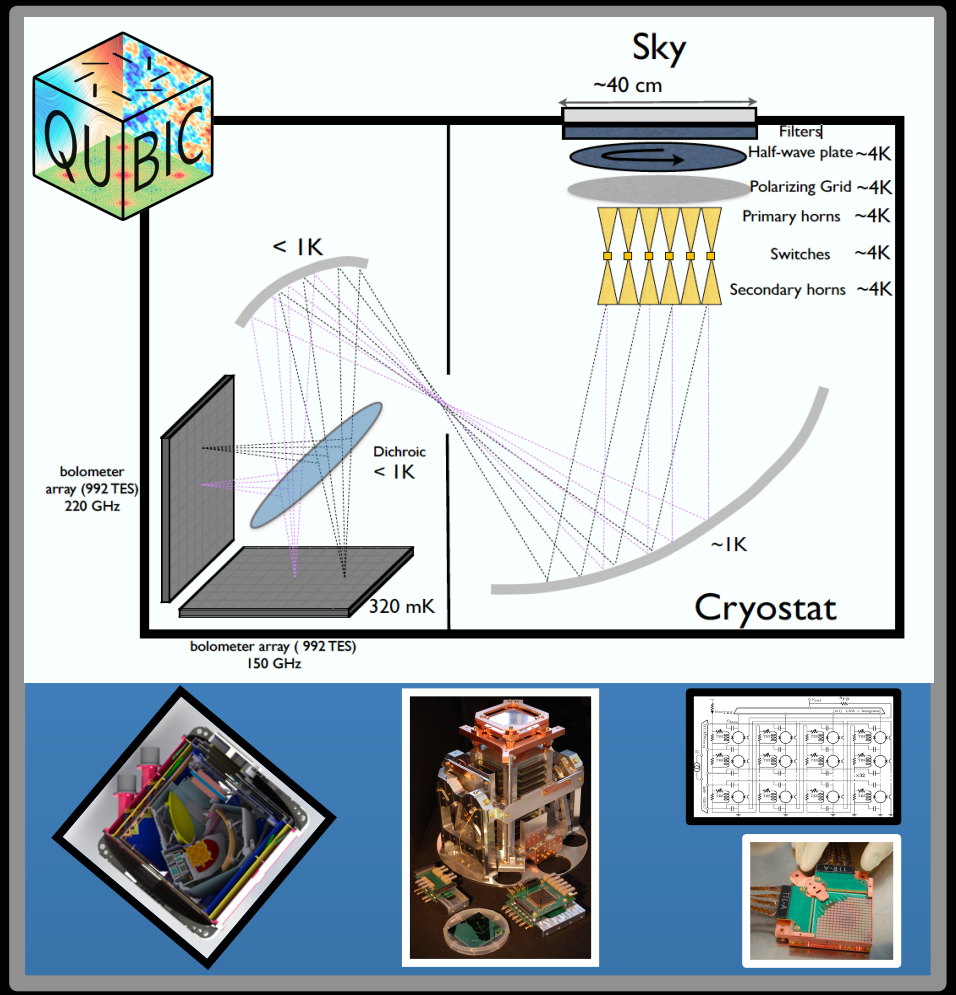

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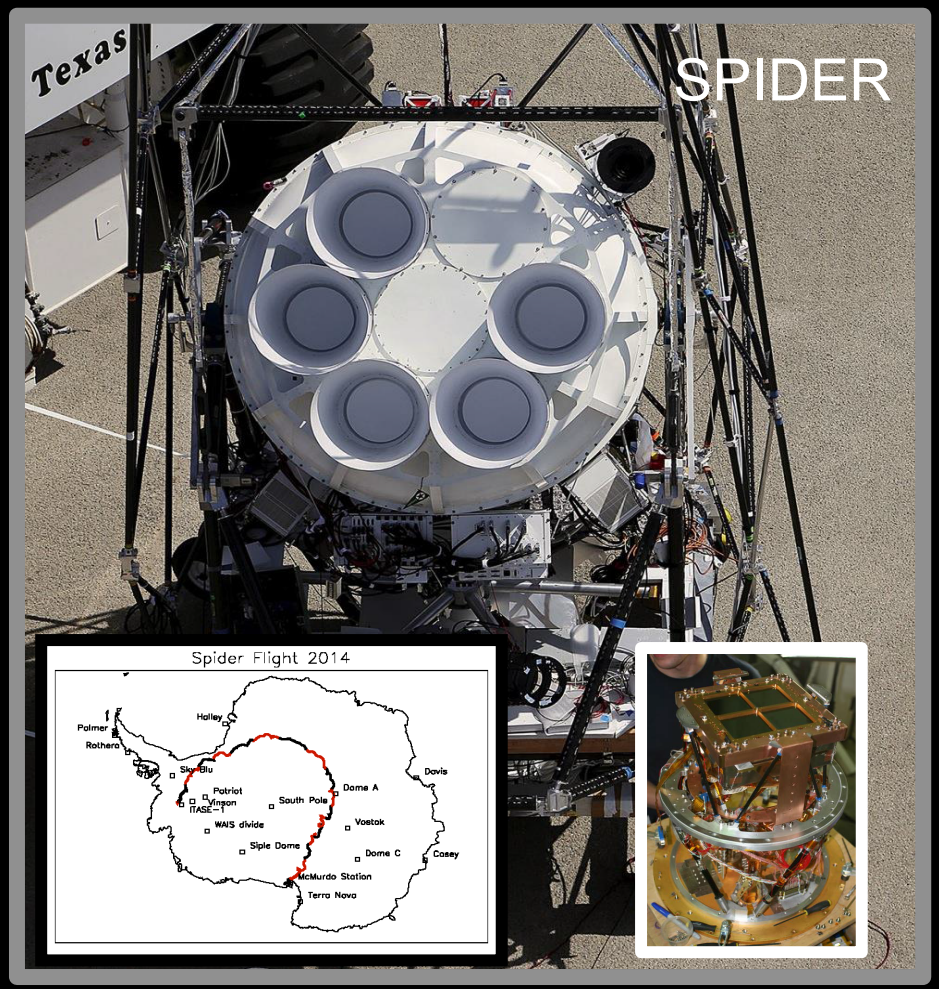
- J-C Hamilton (APC) et al. (mainly French-Italian)
- The only European ground based effort (from 2018)
- Primordial (recombination bump) B-modes: r<0.01
- Bolometric Interferometry: the systematic control of interferometers the sensitivity of bolos (2000 TES TDM)
- Next 6 module at 90-220GHz possibly from Antarctica

Medium aperture experiments: balloon



Aknowledgment W. Jones

- W. Jones (Princeton) et al.
- Balloon borne LDB: sky fraction = 10% (10<l<300)
- First flight in 2014:17 days @ 36km. The instrument worked nominally, including the (data-)recovery (and even the gopro). Great instantaneous sensitivity!
- Next flight in 2017 to go down to r<0.03

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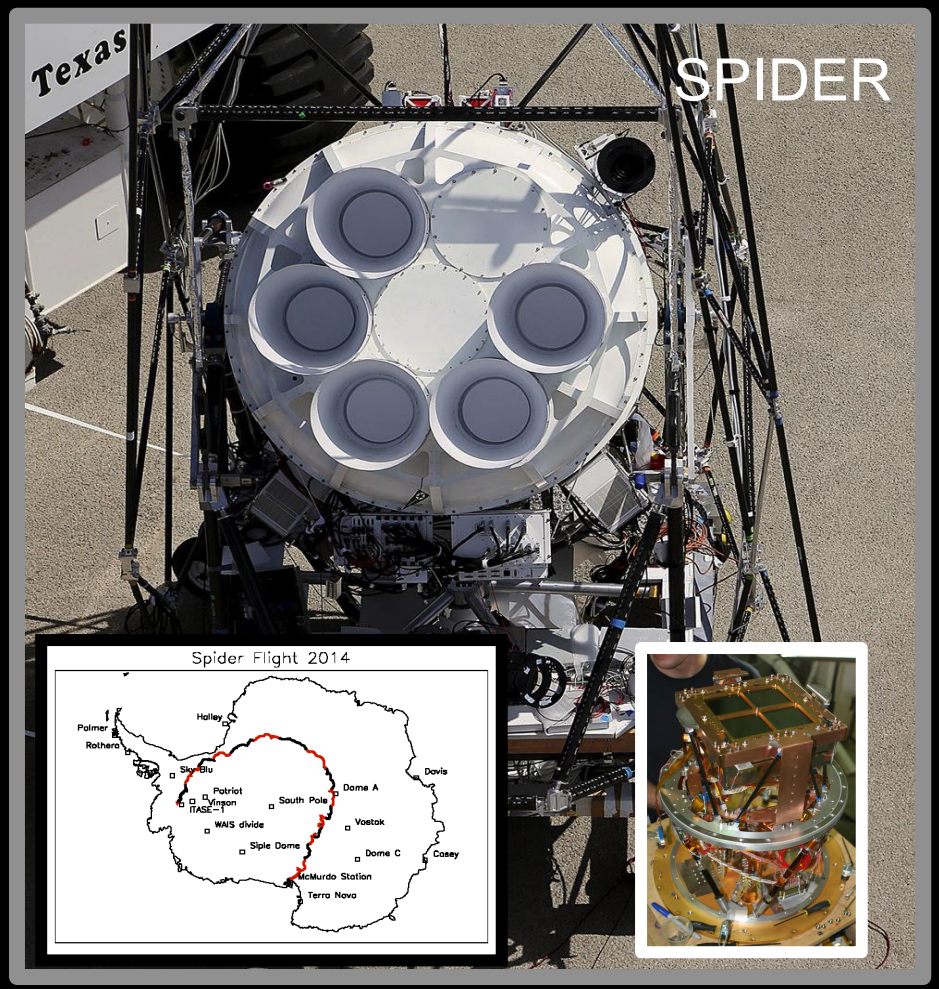

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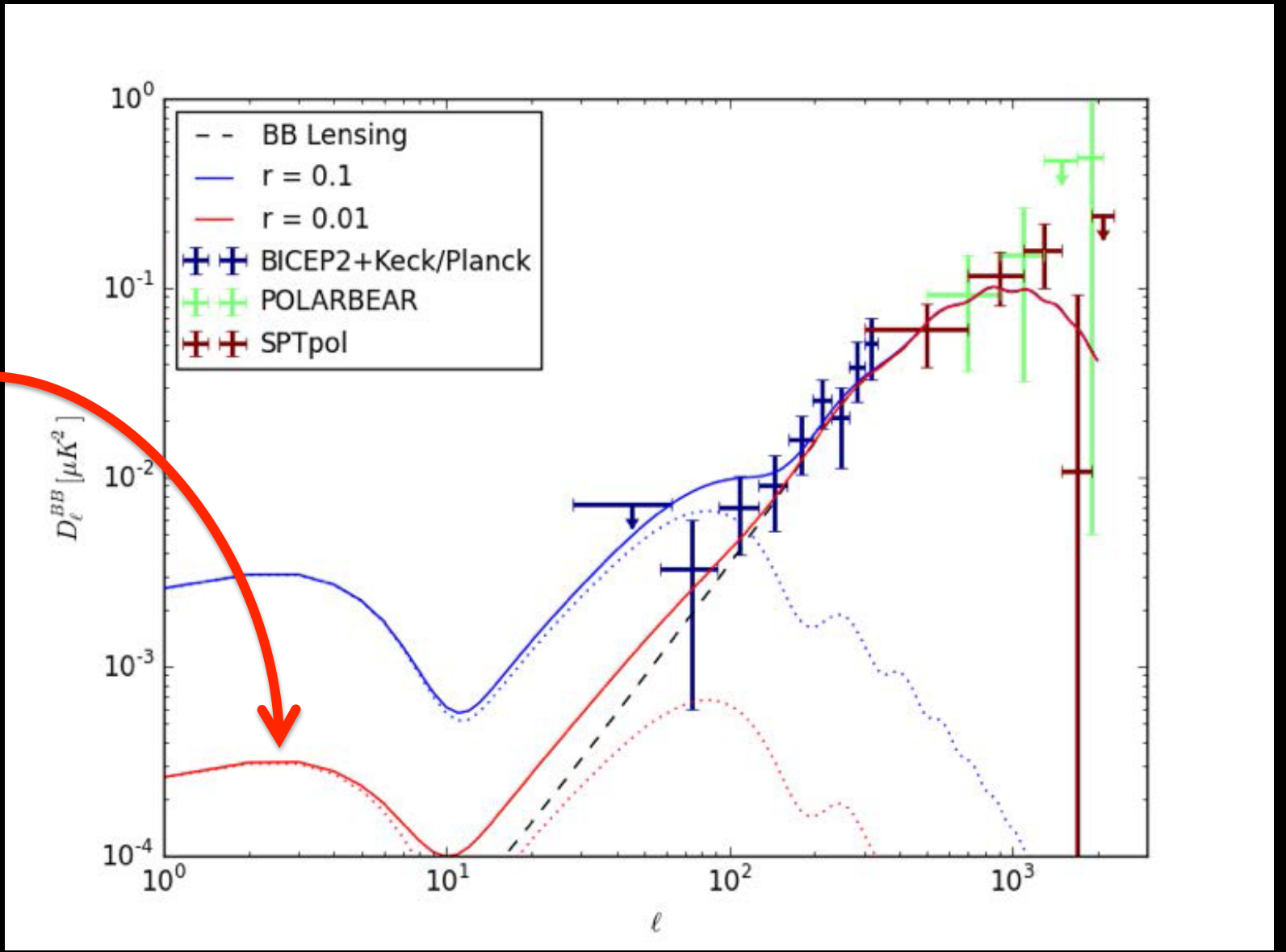
Aknowledgment PIPEr collaboration

- A. Kogut (GSFC-NASA) et al.
- 8 x single day flights (not LDB)!
- High f_sky at 200, 270, 350, and 600 GHz
- 32x40 TDM'ed 100mK TES filled arrays (5120 total)
- Innovative polarization modulators
- Flight planned for spring 2017

How to measure B-modes

reionization bump

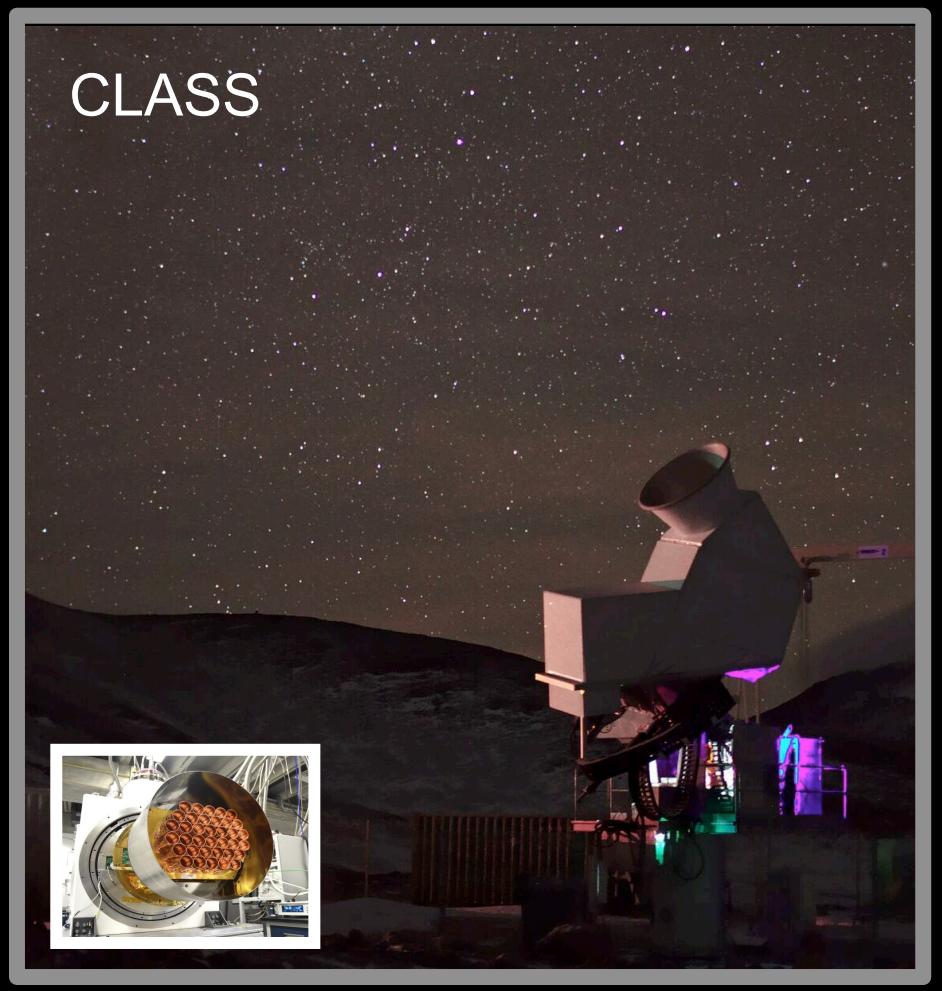


Small aperture experiments

Aknowledgment T.Marriage

- C. Bennet (John Hopkins) et al.
- Uses its particular position on the earth (Atacama) for a large (70%) sky coverage (2<l<150): unique!
- Frequency coverage 40GHz<v<220GH
- TDM'ed TES at 150mK
- First light occurred on 2016

Small aperture experiments



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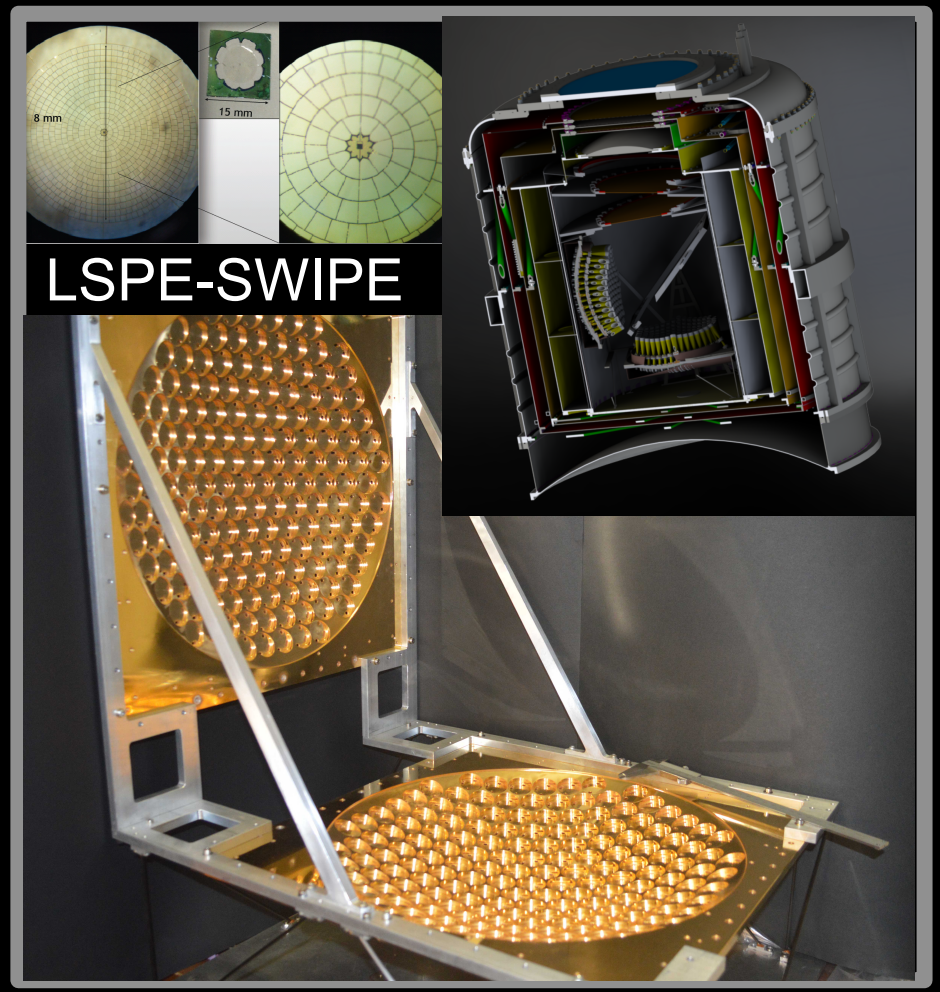
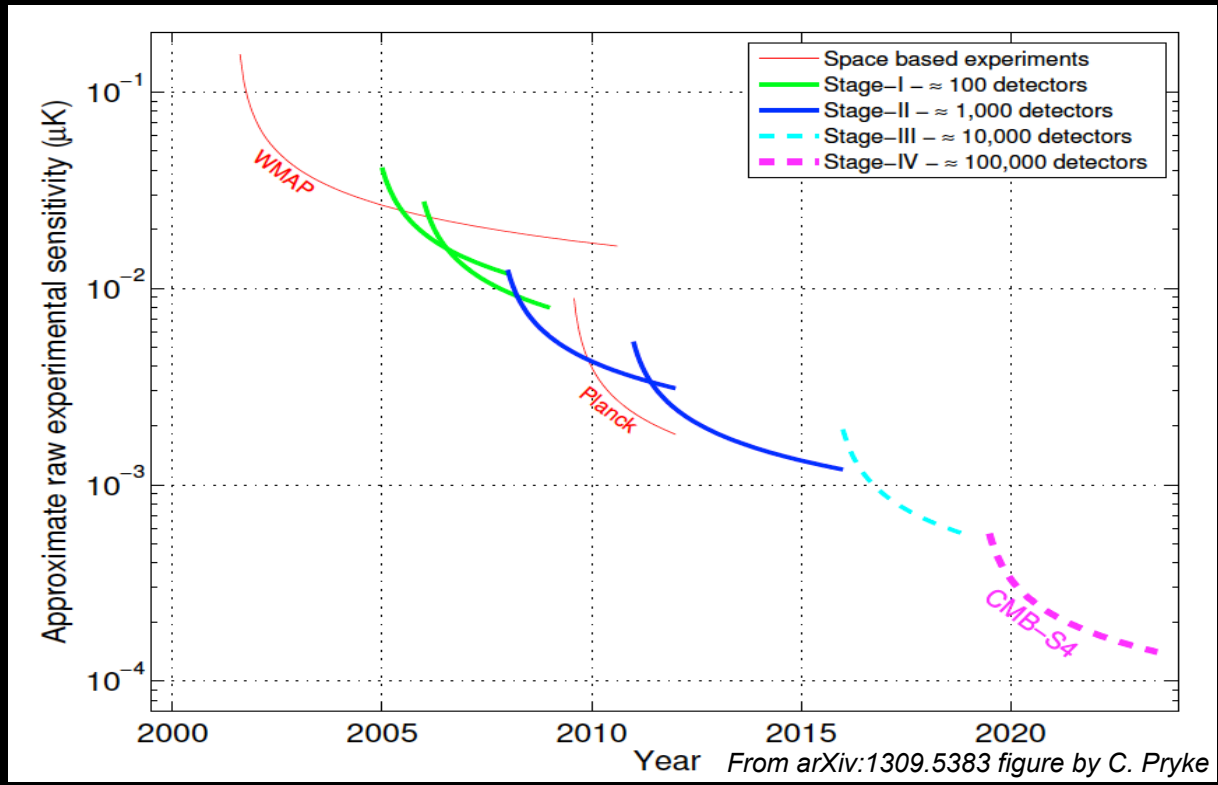
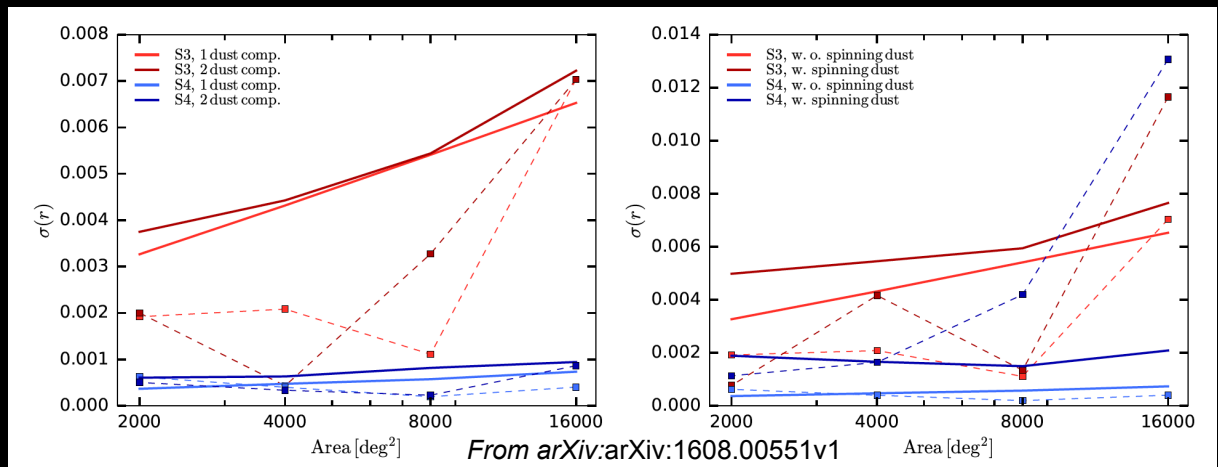


- P. de Bernardis (Rome-Sapienza) et al.
- Frequency coverage 150-250GHz → r<0.02
- Multimoded TES bolometers
- Polar night LDB flight: can spin!
- Large angular scales (>25% sky): reionization bump
- First flight planned on 2018

Sensitivity vs foreground

- More law of sensitivity: progress on detectors sensitivity just impressing
- Stage 3: σ(r) ~ few 0.01 in ~5years
- Stage 4: σ(r) ~ few 0.001 in ~10years?
- Will the systematic control be able to catch up?
- We need a fiducial model: multiple components thermal dust; synchrotron; AME will have to be understood and monitored
- If there are departures from the fiducial model than (spinning-)dust will be a problem
- Will the data-analysis effort follow?



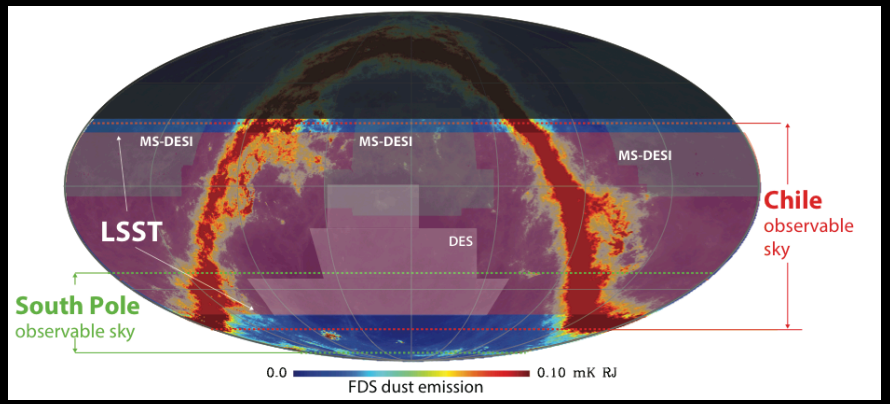


STAGE 4

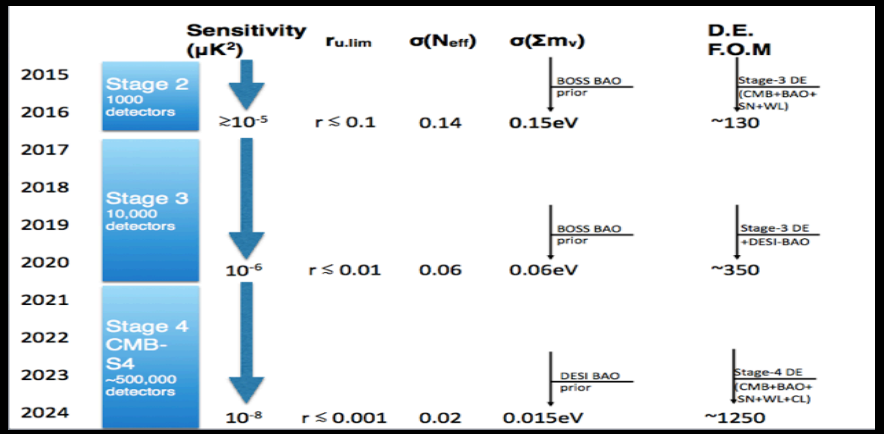
- US Community (Universities + National labs) driven progress to pursue inflation, neutrino properties, dark energy and new discovery. Multi-agency coordination.
- Joining the effort of Atacama and of South Pole:

South Pole

Atacama



- Targeting to deploy O(500.000) detectors spanning 30-300GHz
- At least ~1uK/arcmin over 70% of the sky: low l, high-l, foreground monitoring, de-lensing activity, data analysis methodology
- Aims at detecting or rule-out generic inflation (r~0.002)



Aknowledgment Stage 4 collaboration

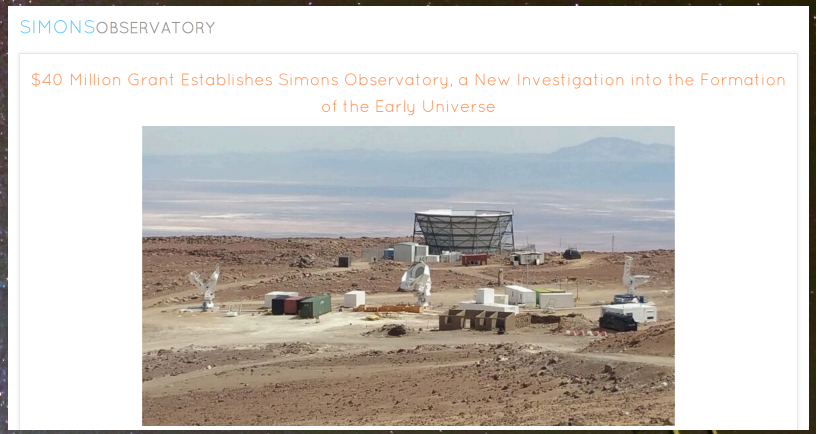
Simons Observatory: Stage 3.5?

- Large ~American collaboration already raised ~45M$

- Using existing (and growing!) facilities in Atacama to take advantage of its latitude. Stepping stone to the future CMB-S4 in Chile

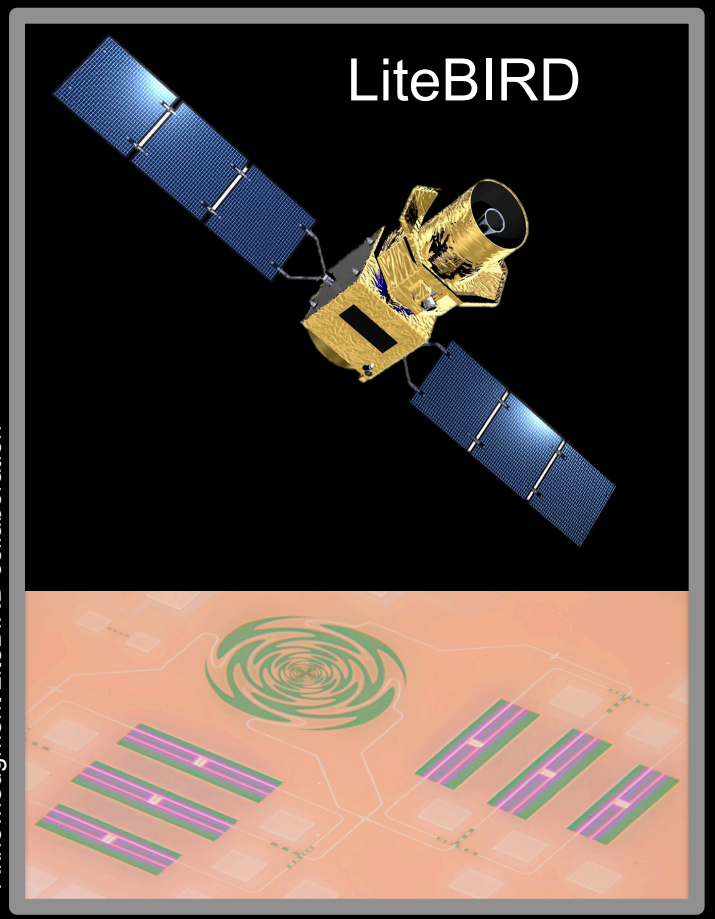
- Joining the effort of:
  - ACT: high sensitivity/high angular resolution key for de-lensing
  - POLARBEAR/SIMONS: high sensitivity medium angular resolution
  - CLASS: high sensitivity – large sky coverage

- New telescopes/technology development coordinating the telescope and receiver designs to take advantage of the scale of the project: observations will start by the end of 2020.



Aknowledgment M. Devlin

Satellites



Aknowledgment LiteBIRD collaboration

- *M.Hazumi(KEK/Kavli/SOKENDAI) et al*
- *JAXA-based to be launched 2020*
- *6-band design (60-280GHz) with trichroic TES (UC Berkeley)*
- *Now in phase A study. Will go Orbit L2*
- r < 0.001 (with fg?)
- 2<l<200 (will be synergic with S4)

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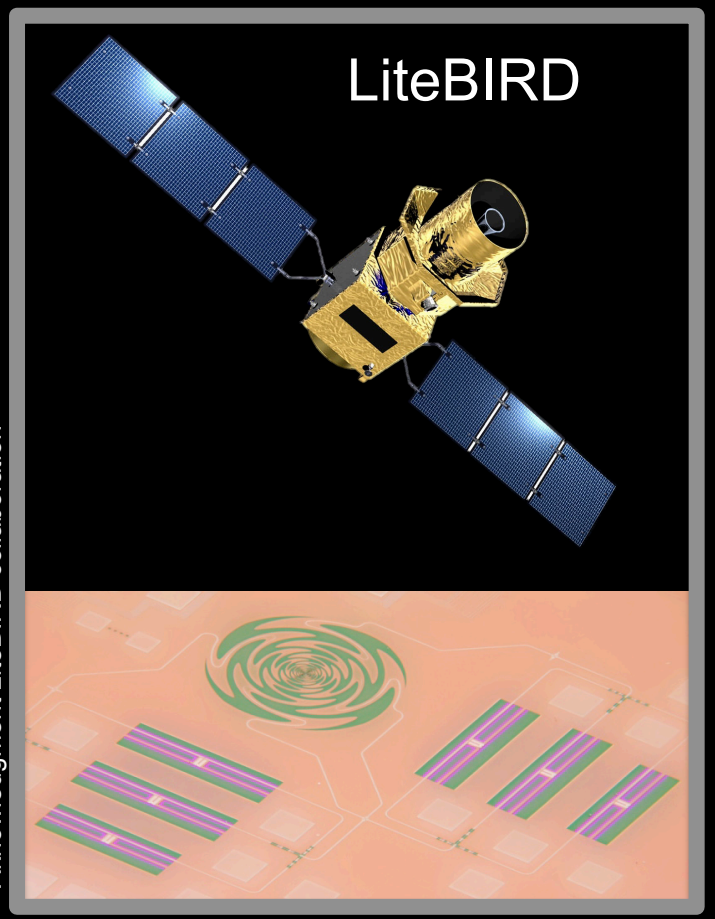

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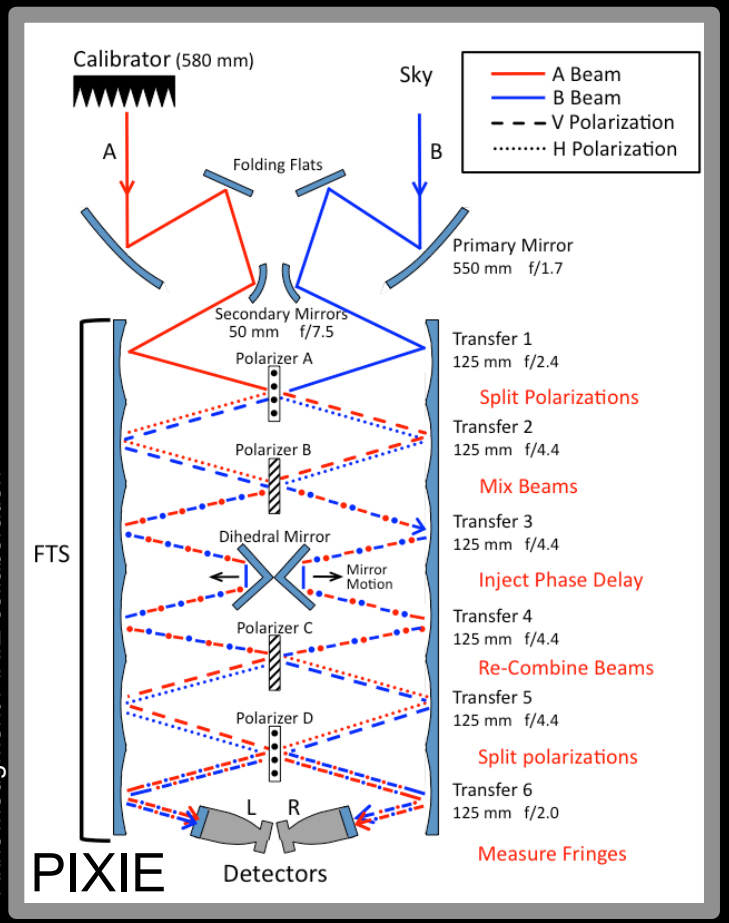

Aknowledgment PIXIE collaboration

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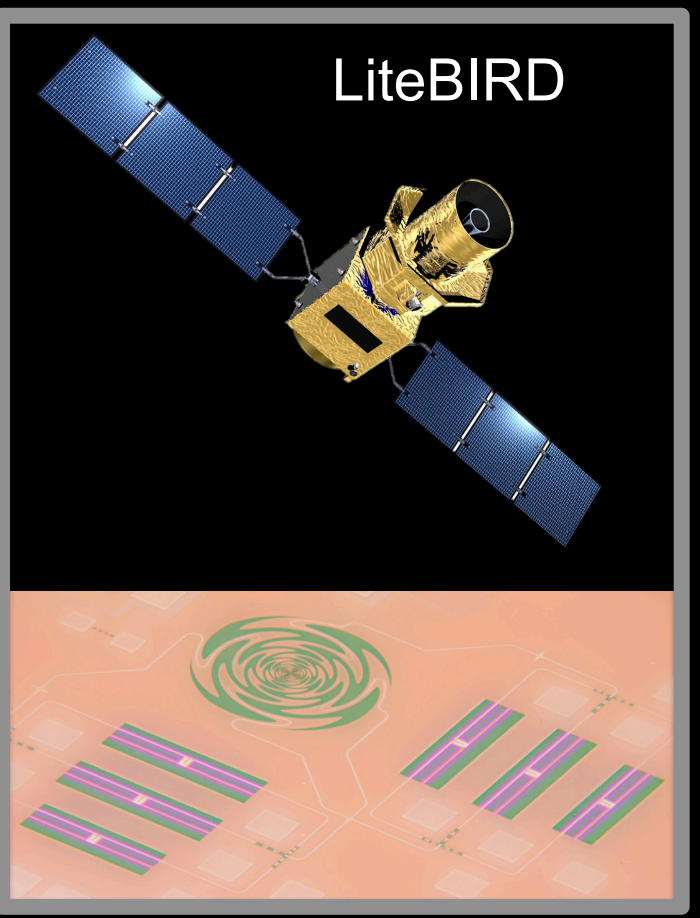
- A.Kogut (GSFC-NASA) et al.
- Spectral distortions: $|y|<2 \times 10^{-9}$; $|\mu|<10^{-8}$
- 4 multimoded detectors
- Entire instrument at 2.725K
- FTS with absolute calibrator
- r<0.001 (with fg)

Satellites



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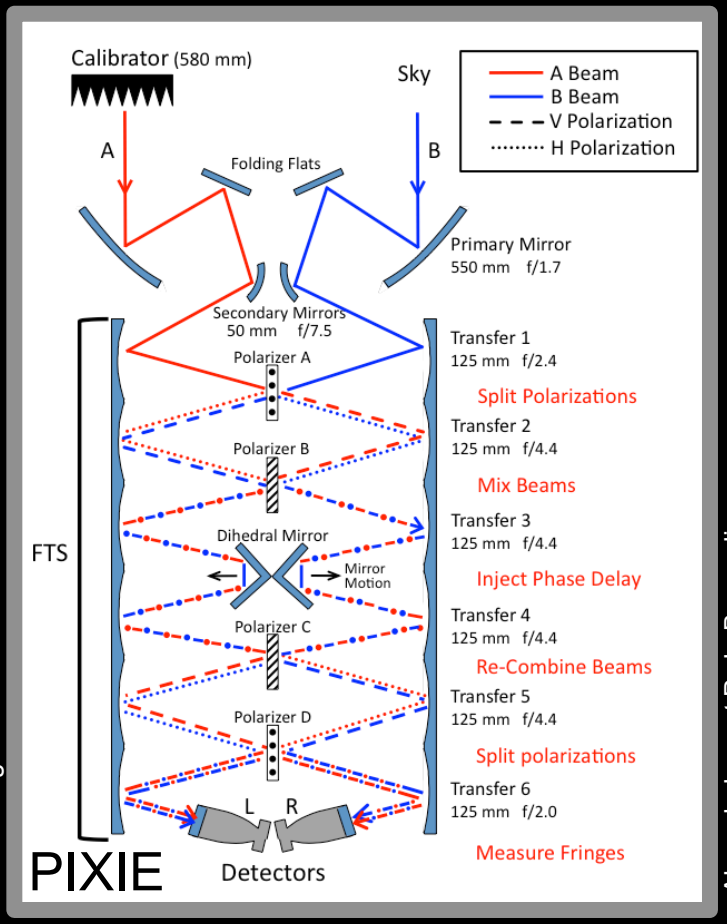

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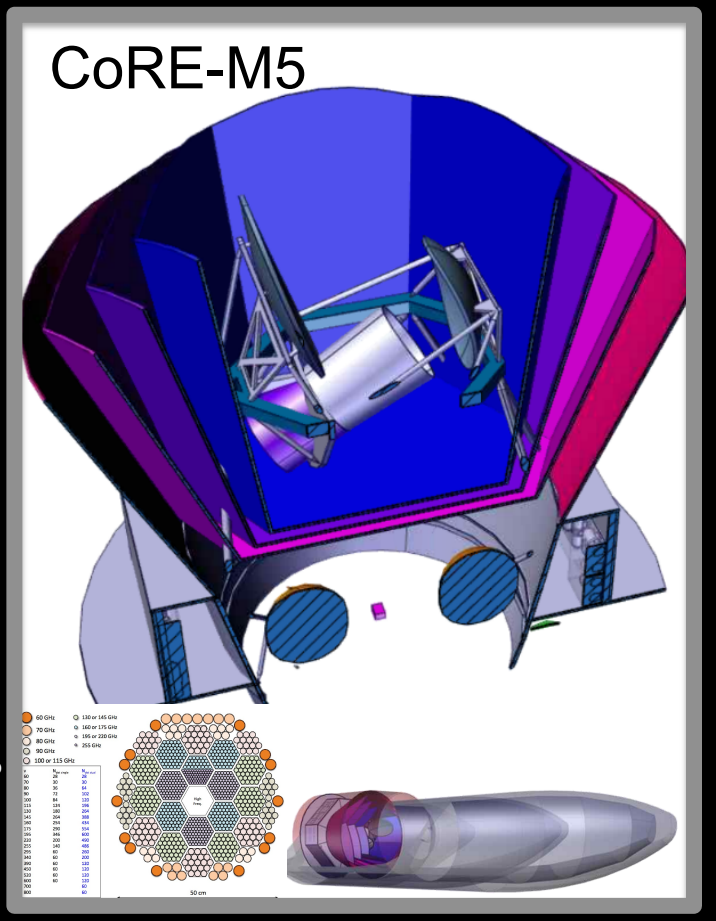
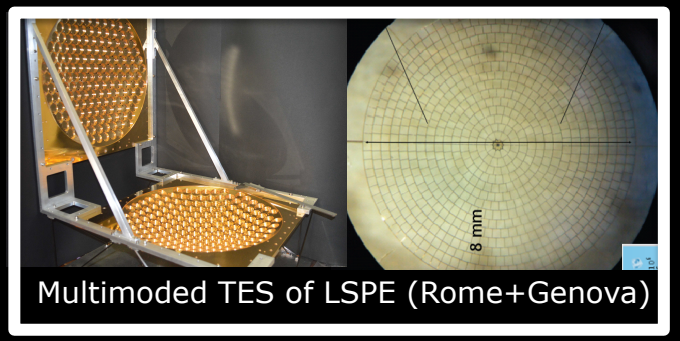


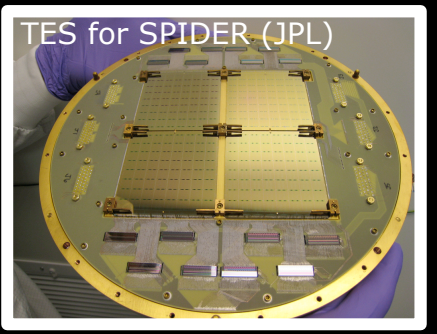
- Proposal leaders: F. Bouchet, P. de Bernardis; J. Delabrouille
- 1.2-1.5m telescope→7'-4' @ 135-200GHz
- 2500-5000 detectors
- L2 orbit for 3 yrs
- 15-20 frequency bands (60-600GHz) with stepping HWP
- r<0.001(with fg)

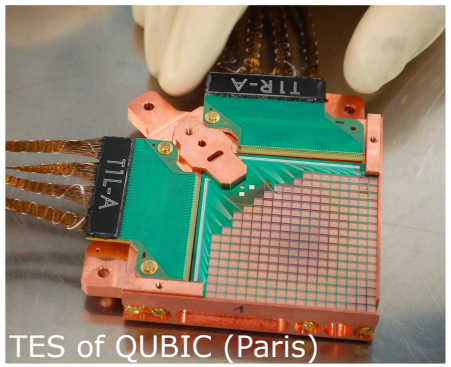
Focal plane technological effort

- Detectors need to get to few 10^{-18}W/sqrt(Hz)
- Focal planes are saturated so we need multiple telescopes and/or parallel processing or multimoded approach
- TES are the most mature technology:
  - In Europe developed in Paris, Cambridge, Genova…
  - MUX demonstrated at 128:1 for QUBIC
  - US experiments already flow them on balloons (SPIDER, EBEX)
  - LSPE will fly multimoded TES



Multimoded TES of LSPE (Rome+Genova)


TES for SPIDER (JPL)



TES of QUBIC (Paris)

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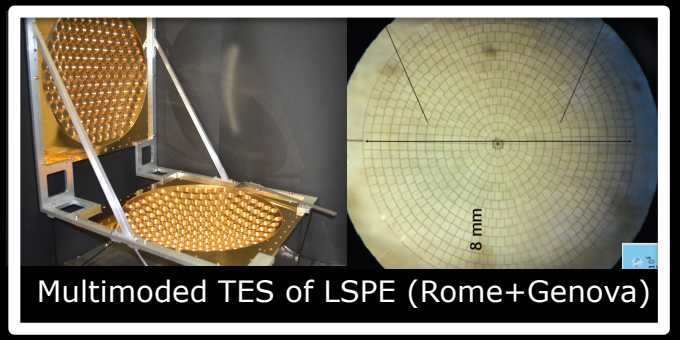
- KIDs are the most promising technique:
  - In Europe developed in Grenoble, Groningem, Cambridge, Rome,…
  - Large European array already operated at a telescope: NIKA and NIKA2
  - Promising also from the cosmic rays point of view
  - They will soon fly on balloons



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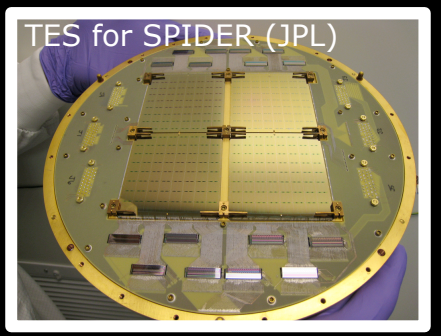
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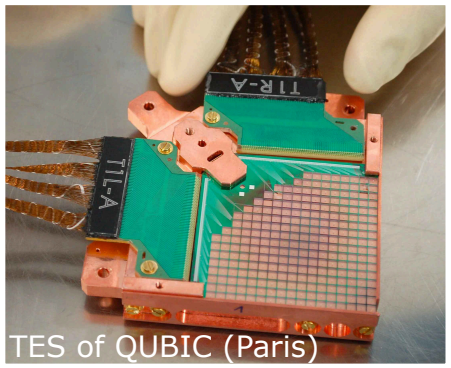
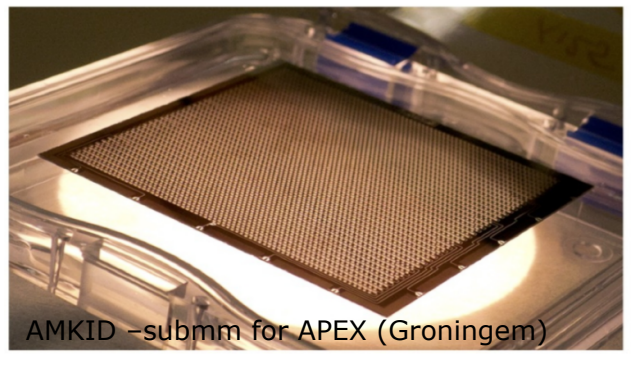
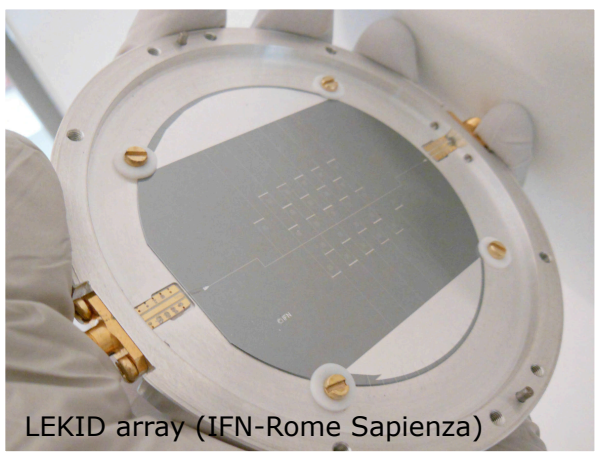


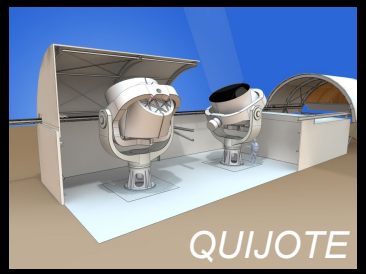
TES of QUBIC (Paris)


AMKID –submm for APEX (Groningem)


LEKID array (IFN-Rome Sapienza)


NIKA2 KIDs array (Grenoble)

Conclusions: focusing on Europe



- QUIJOTE: experiment from Tenerife (Rebolo et al.)
  - Wide sky (20000deg2) @ 10-40GHz…already taking data
  - Unique per se (r<0.05) and for synchrotron removal

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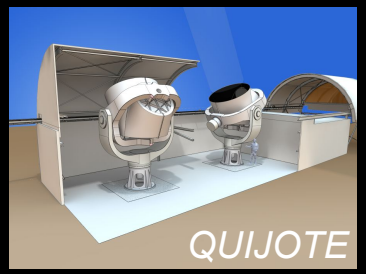

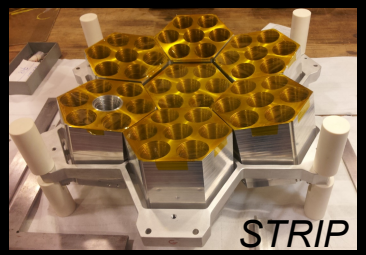

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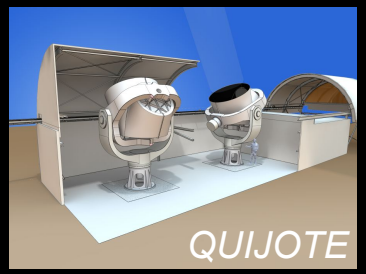

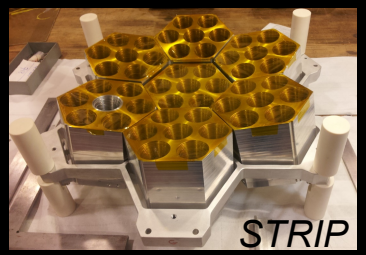

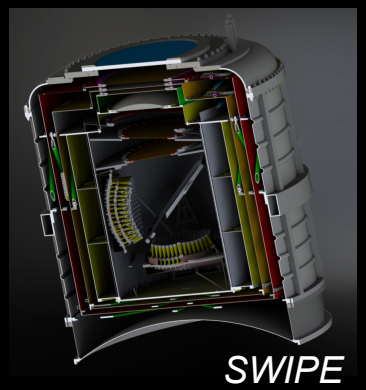

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  NB: LSPE is the only experiment planned to measure northern sky!

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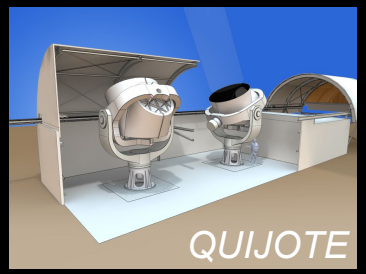

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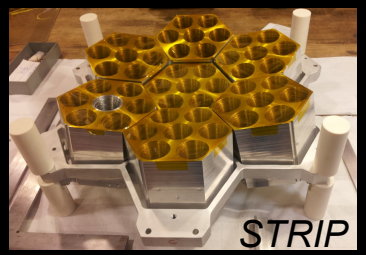

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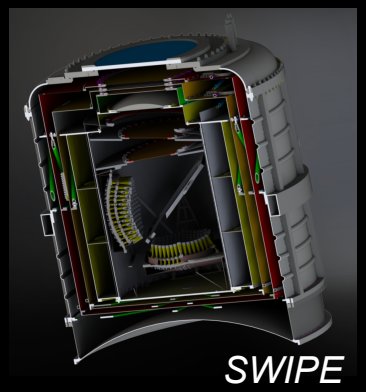

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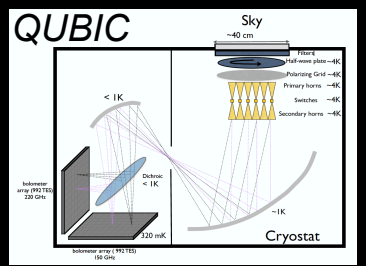
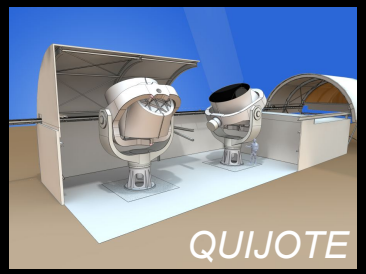
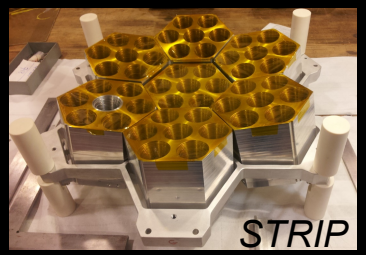


- QUBIC 1st module: from Argentina with a Bolometric interferometry. High systematic control/orthogonal wrt imagers

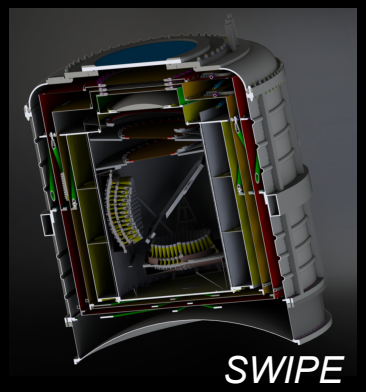
Conclusions: focusing on Europe



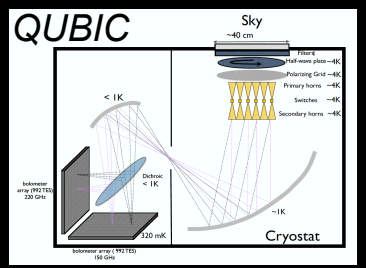
- QUIJOTE: experiment from Tenerife (Rebolo et al.)
  - Wide sky (20000deg2) @ 10-40GHz…already taking data
  - Unique per se (r<0.05) and for synchrotron removal



- LSPE-STRIP: 44GHz recently approved for ground observations from Tenerife



- LSPE-SWIPE: winter flight from Svalbard islands on 2018. It aims to measure the reionization bump.
  NB: LSPE is the only experiment planned to measure northern sky!



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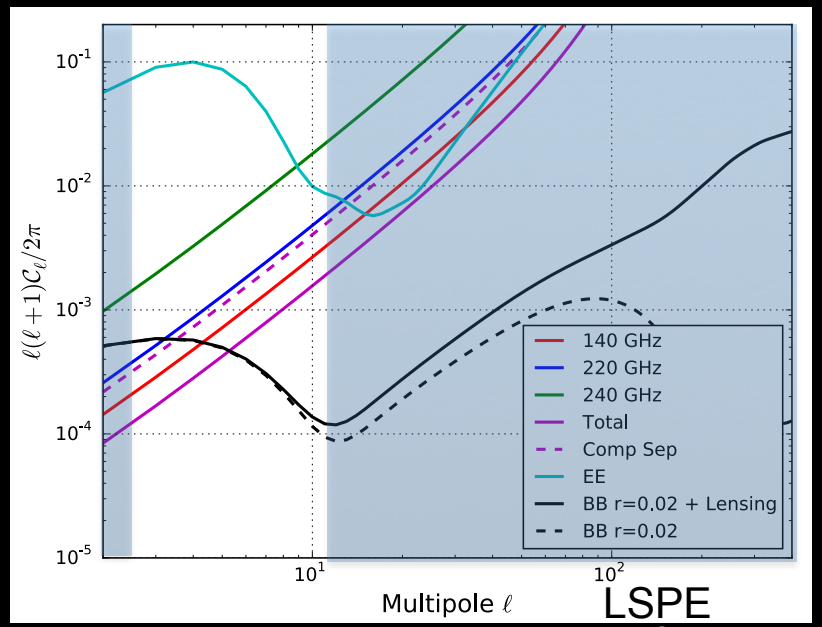
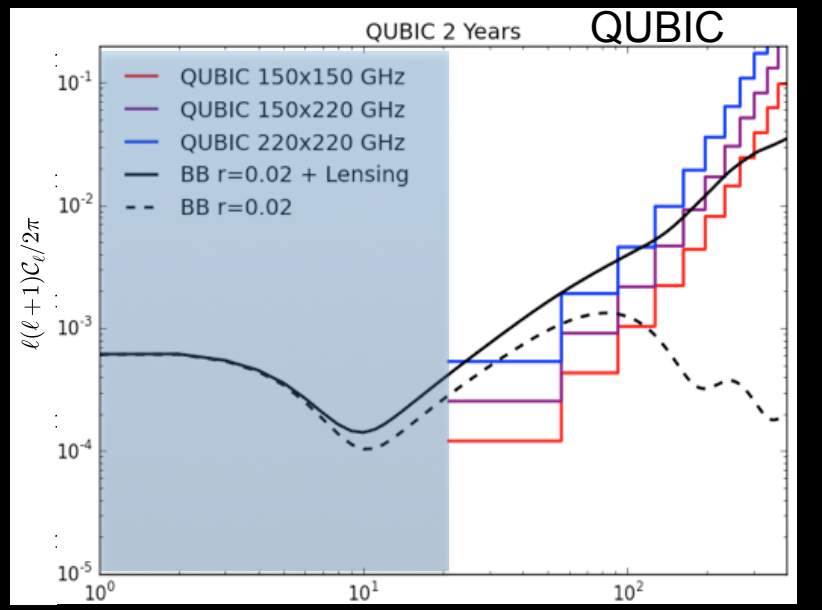


LSPE *vs* QUBIC



Aknowledgment L.Pagano and J.C. Hamilton

Conclusions: focusing on Europe (continued)

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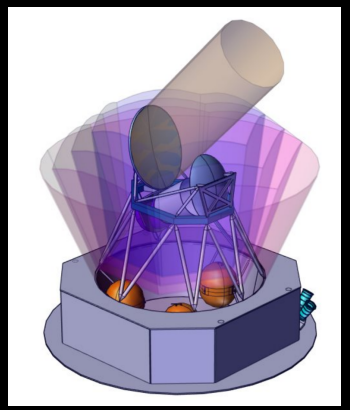
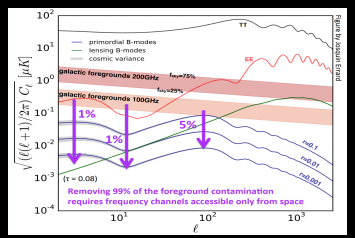
Conclusions: focusing on Europe (continued)





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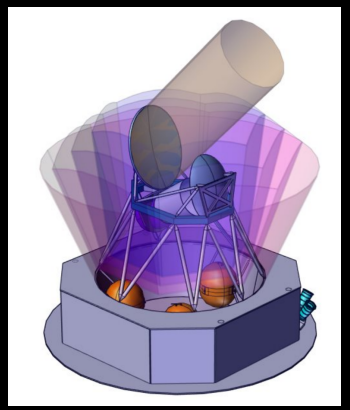

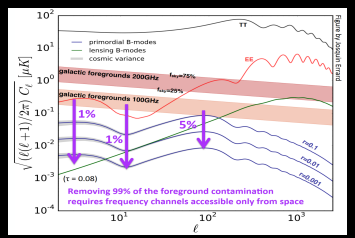

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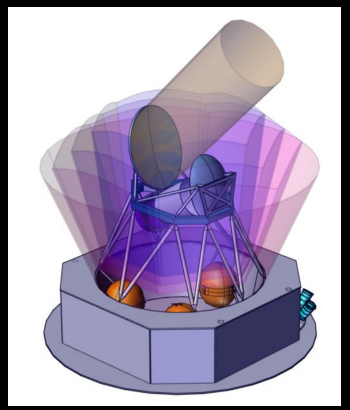

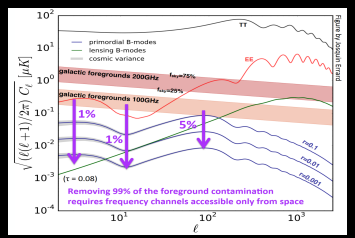

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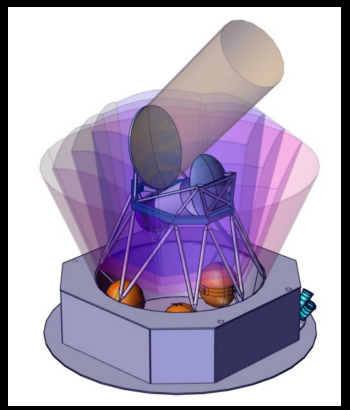

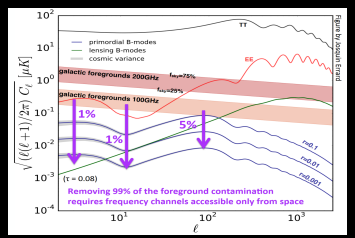

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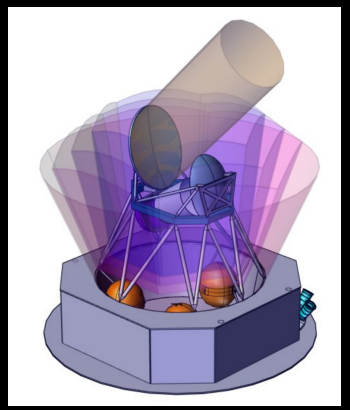

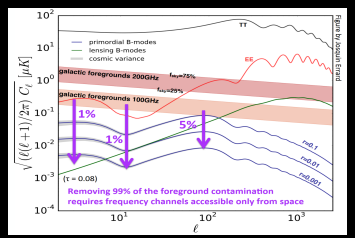

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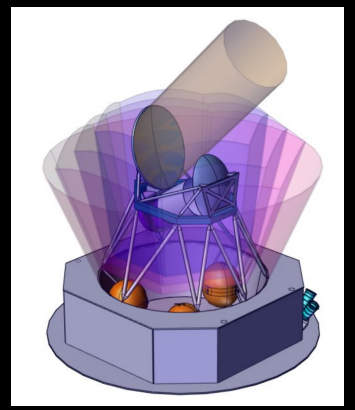

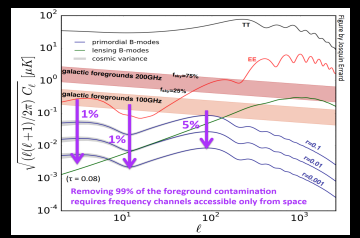

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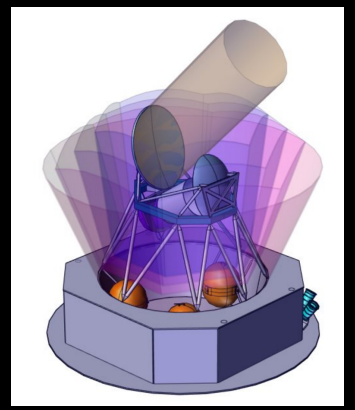
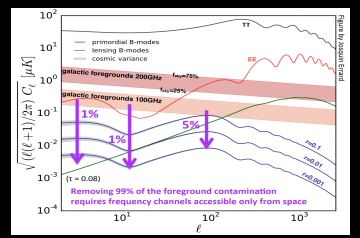
Conclusions: focusing on Europe (continued)





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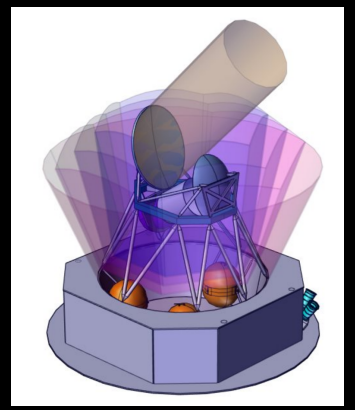

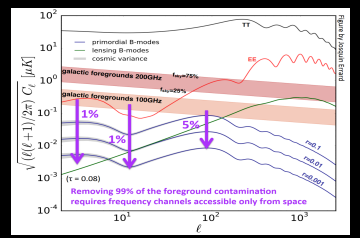

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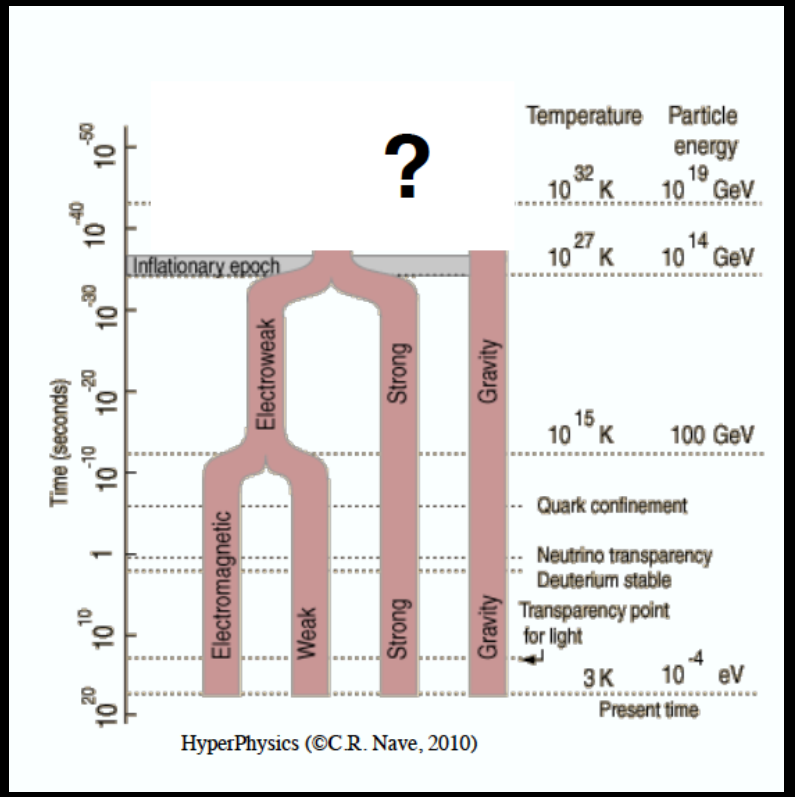
    → we need CoRE
- Tomorrow: a European CMB coordination workshop will start in Florence

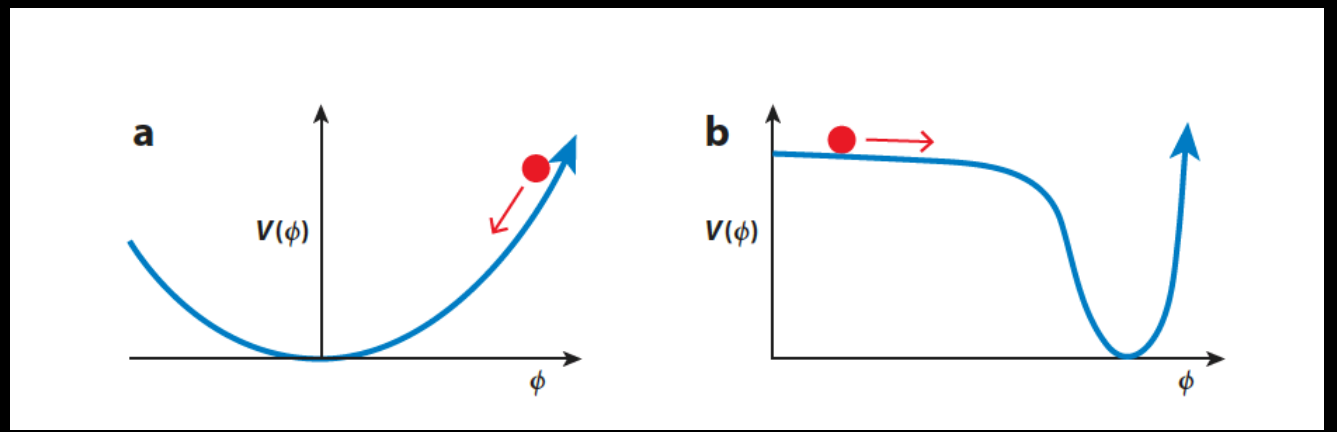
Thank you!

E.S. Battistelli
"Sapienza" University of Rome

INFLATION

- So far the picture is self-consistent but we don't know what has happened at the quantum gravity energy at $T>10^{27}K$ or $E>10^{14}GeV$
- Most models are dead: inflation (invoked to explain flatness problem, super-horizon isotropy, absence of magnetic monopoles) survives
- Inflation is a period of superluminar acceleration of the Universe at the very beginning of it ($\sim10^{-36}s$)
- A simple model is the Single-Field Slow-Roll, SFSR
- INFLATION is associated to the displacement of a scalar field Φ from the minimum of its potential V, associated to vacuum energy
- Under certain (friction) conditions INFLATION takes place

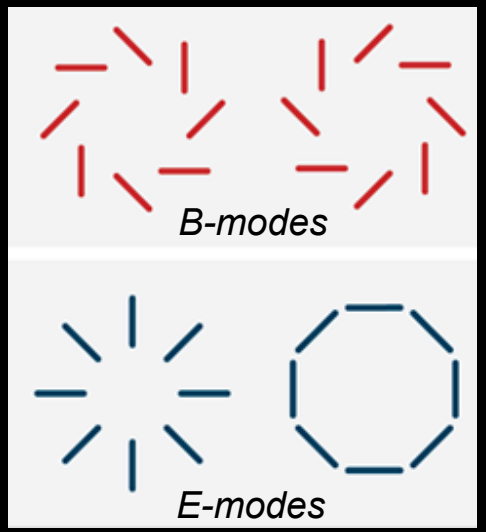




Plots from Kamionkowski et al. ARAA, 2016:1-45

CMB polarization: E-modes and B-modes

- Current status for CMB polarization measurements



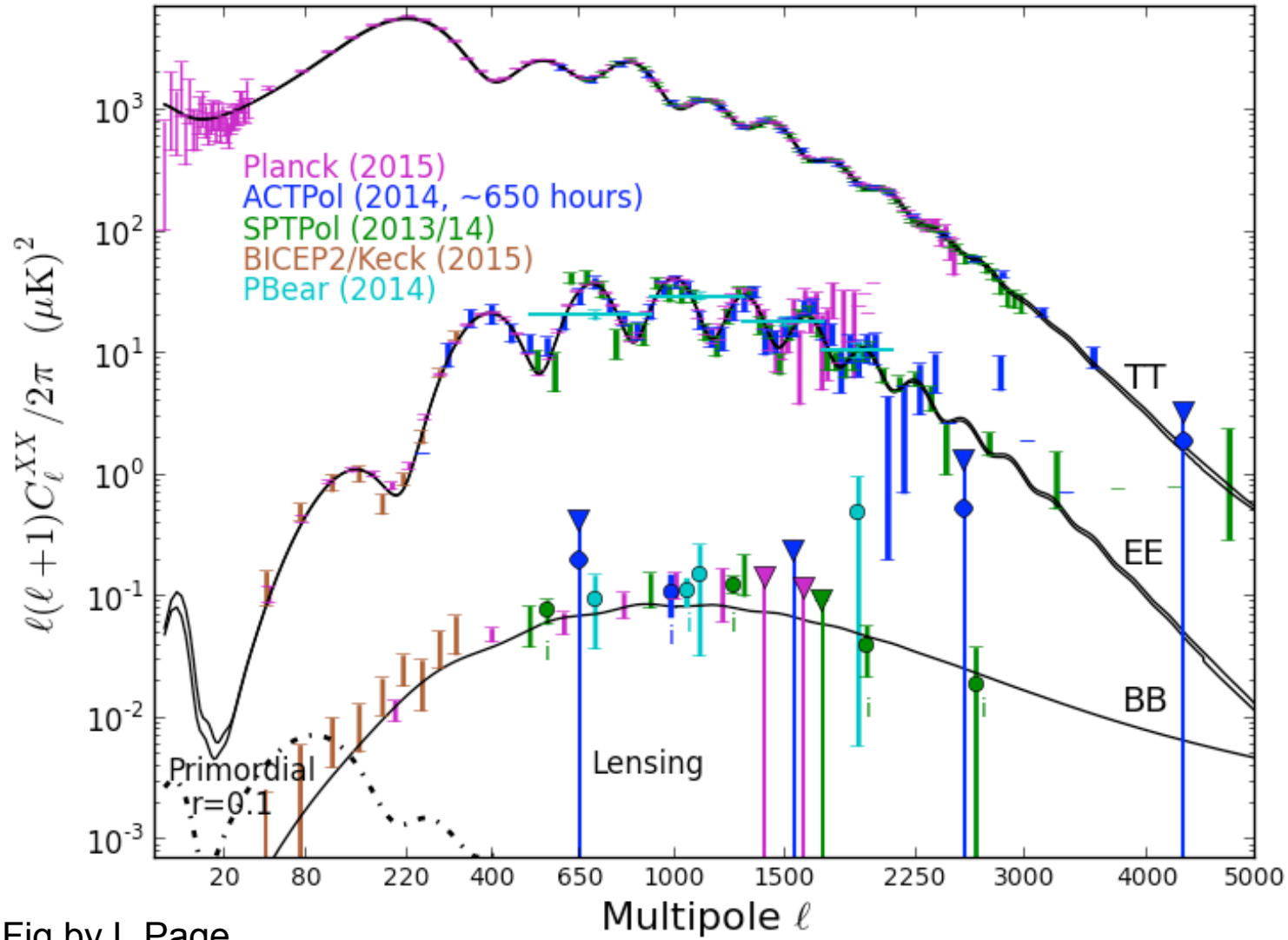
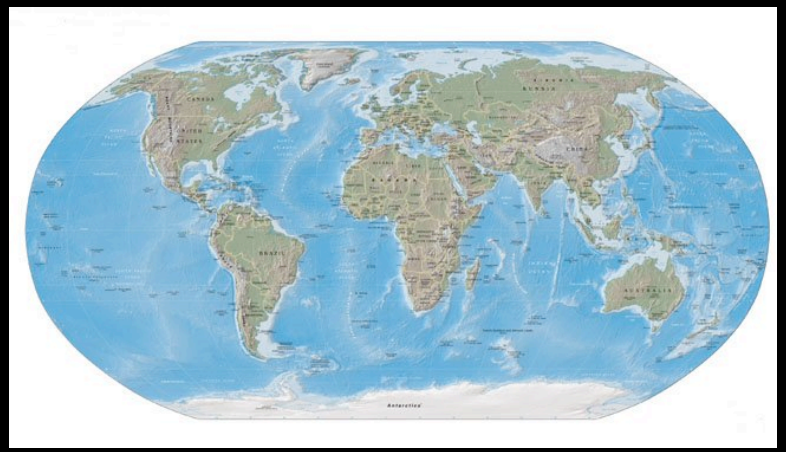


Fig by L.Page

Where to measure B-modes from



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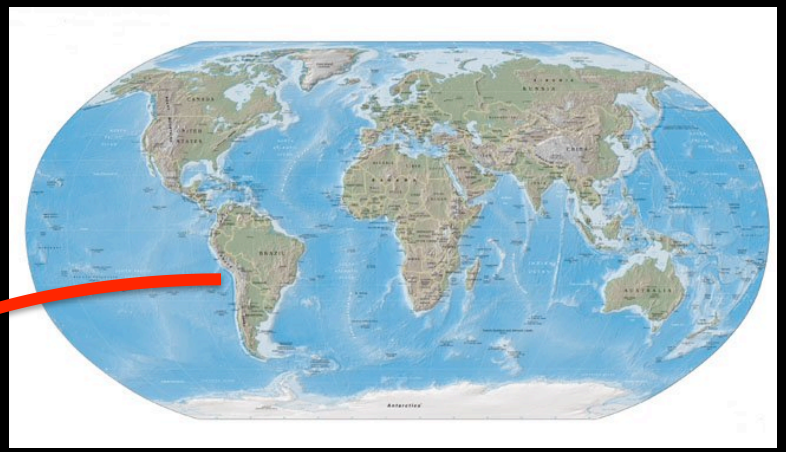
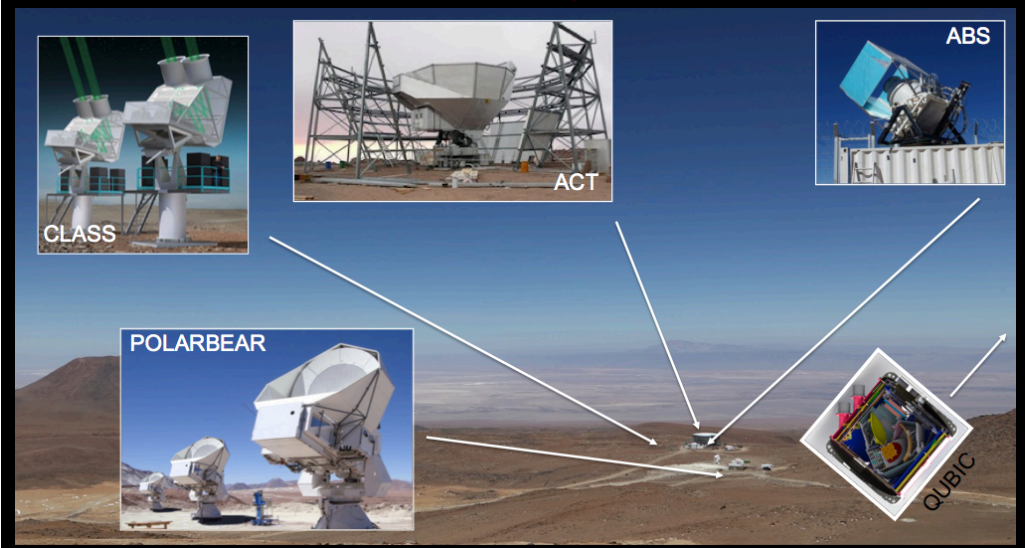


ATACAMA



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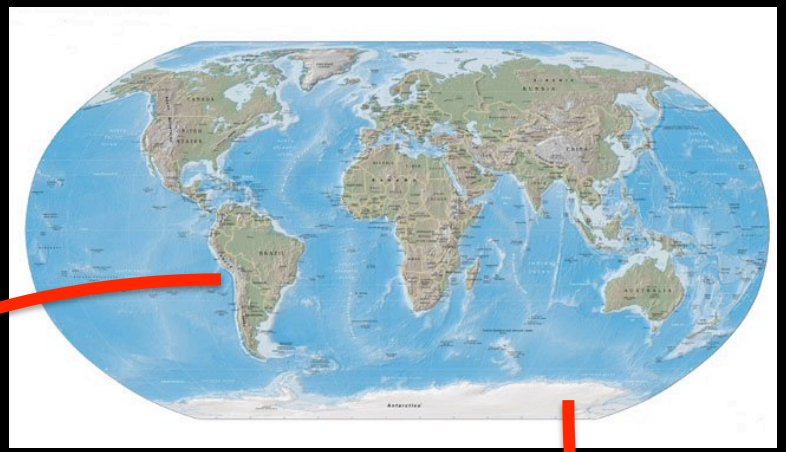

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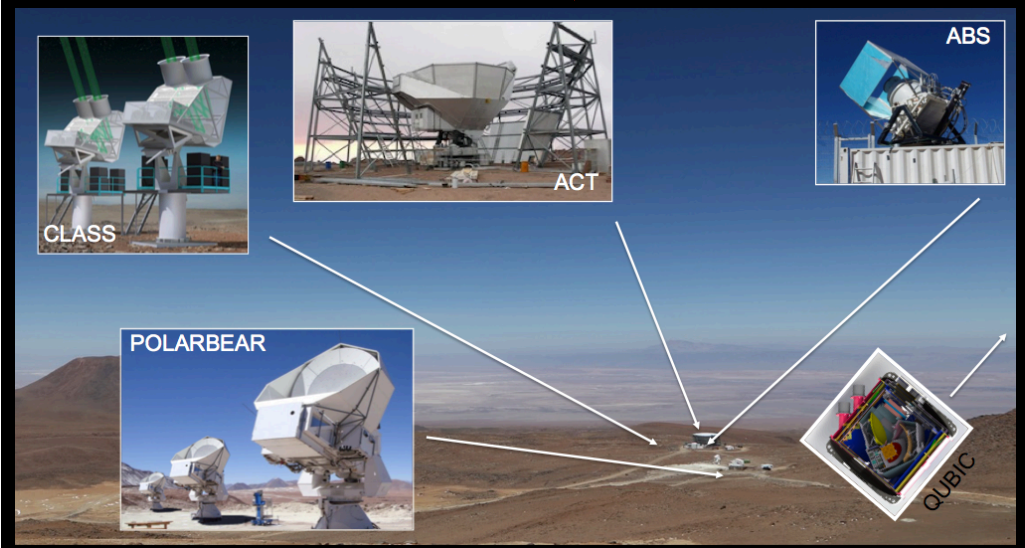
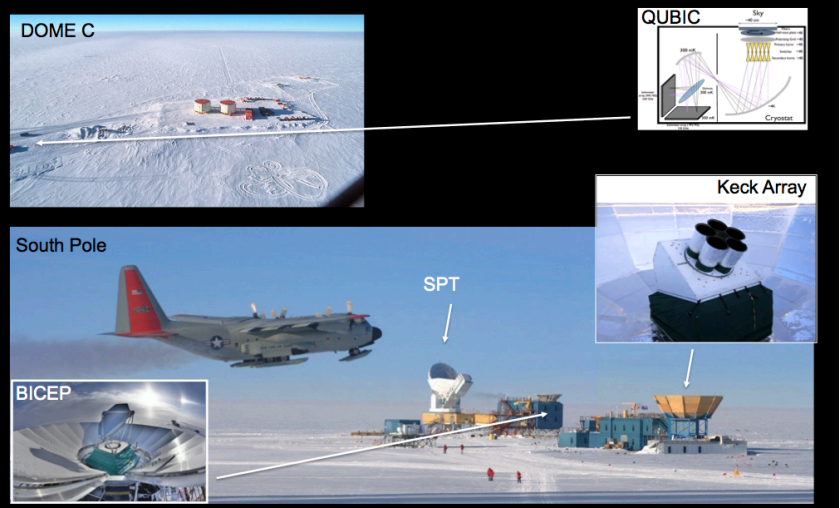


ANTARCTICA



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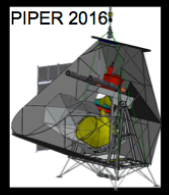
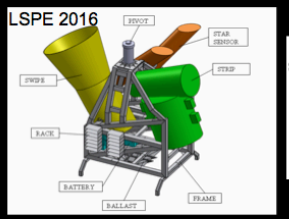
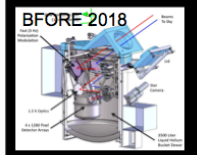
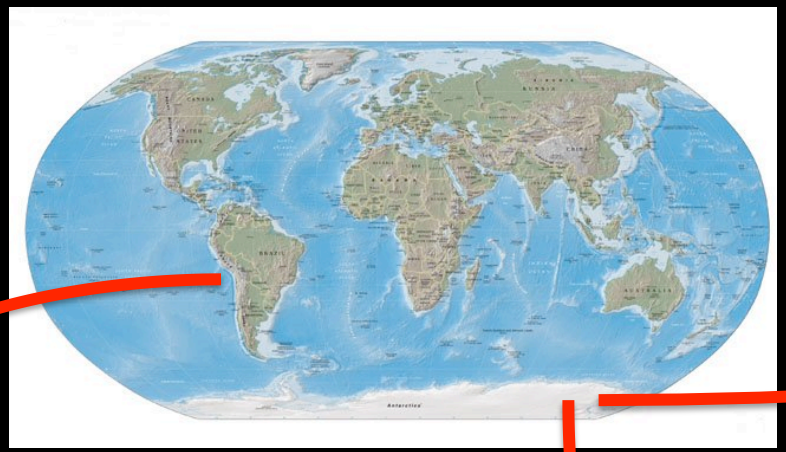
STRATOSPHERE









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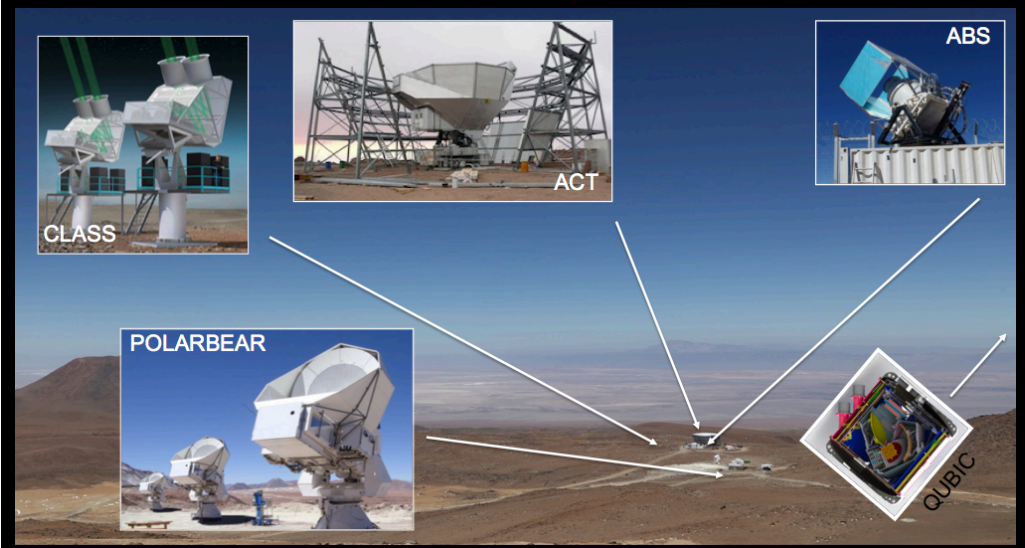

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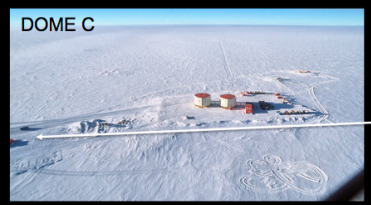

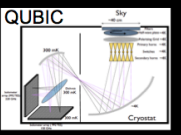

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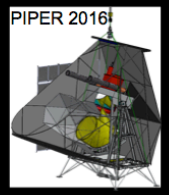

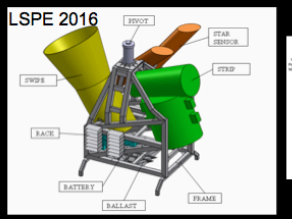

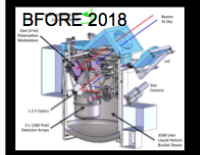

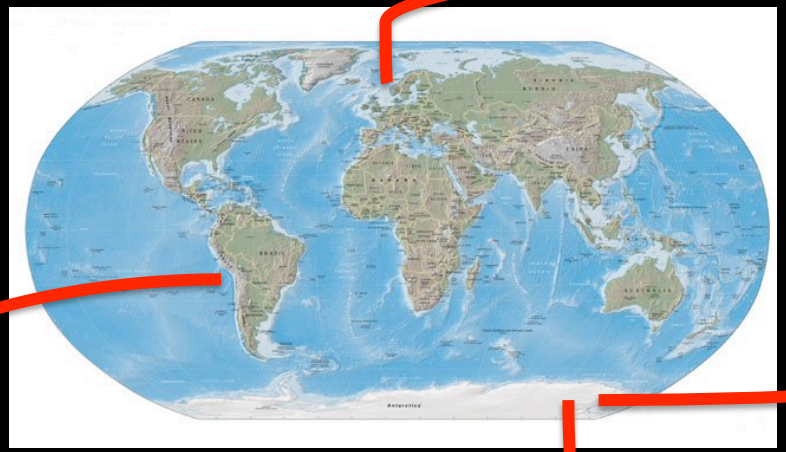

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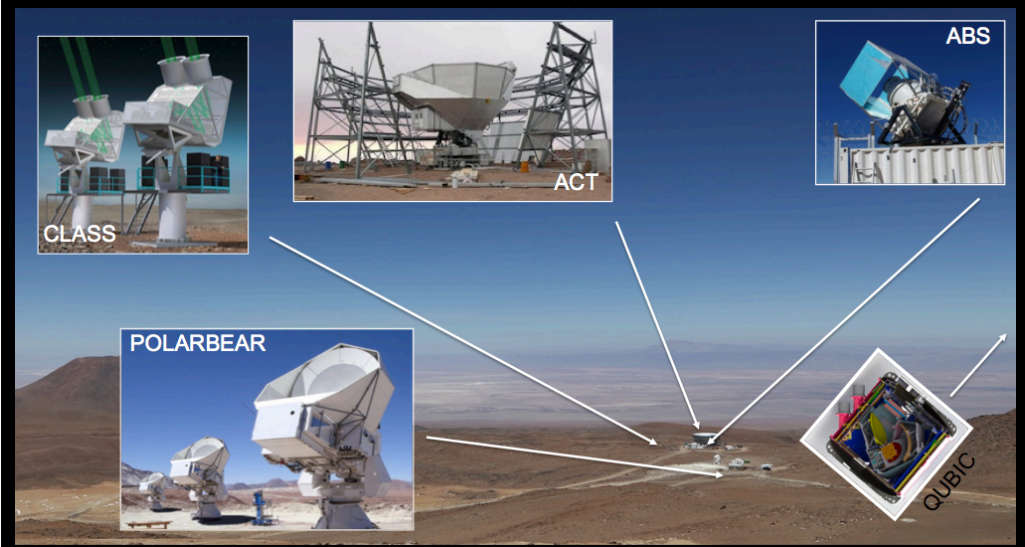

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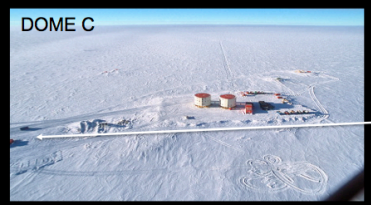

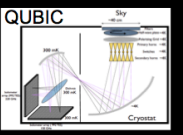

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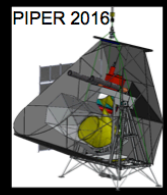
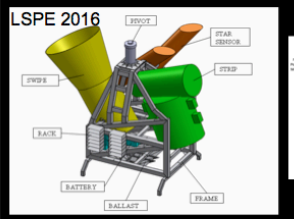
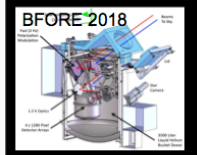
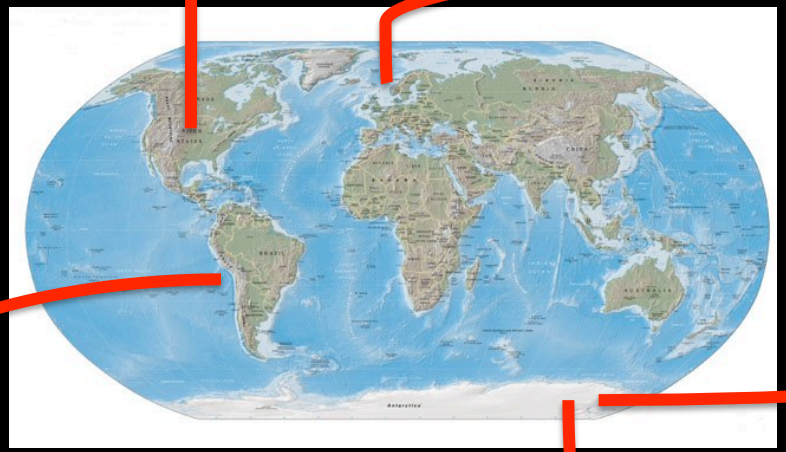
STRATOSPHERE









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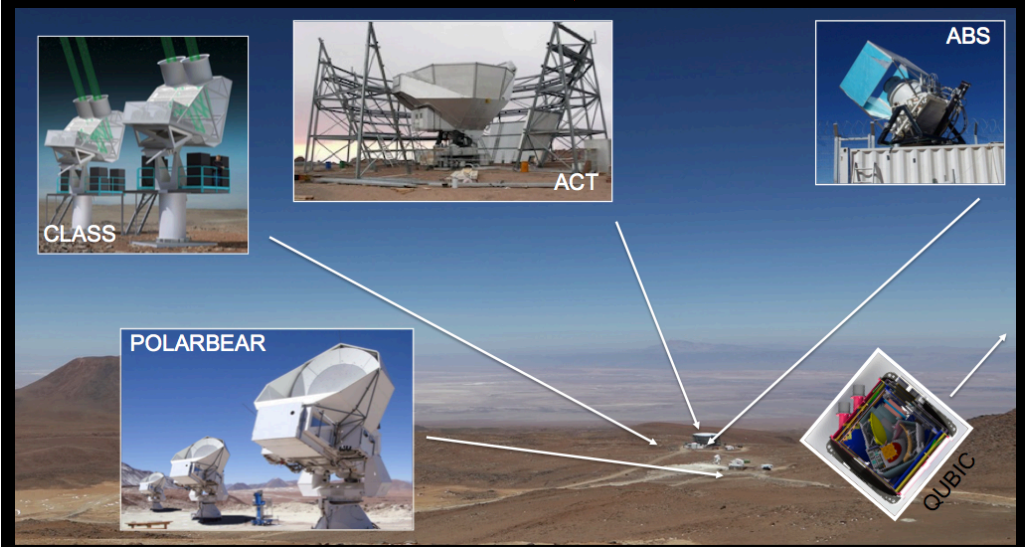

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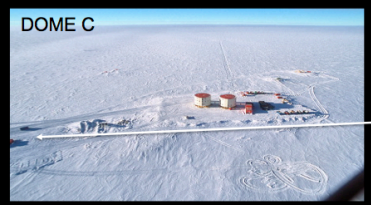
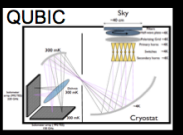
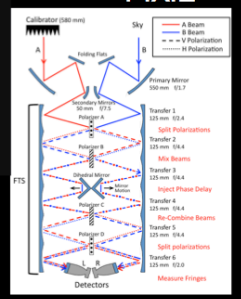




Where to measure B-modes from

SPACE

PIXIE



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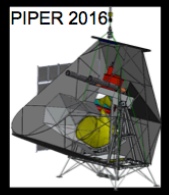

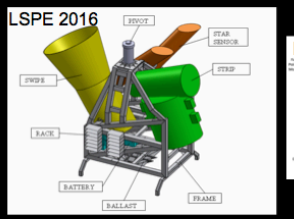

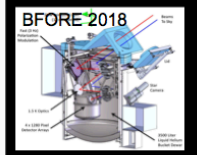

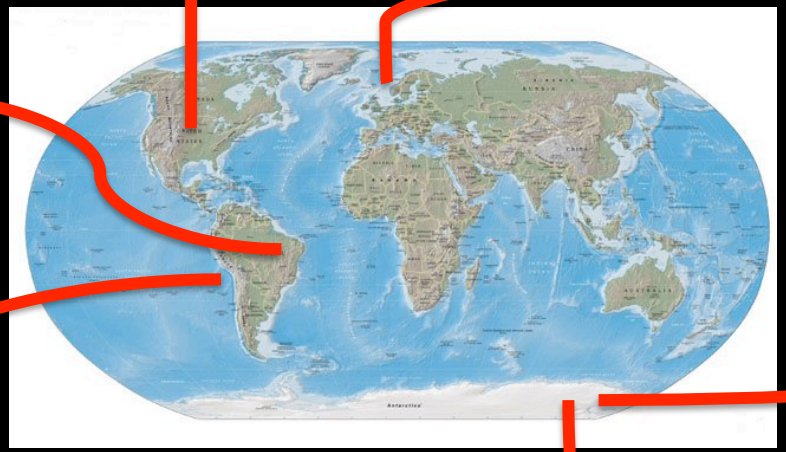

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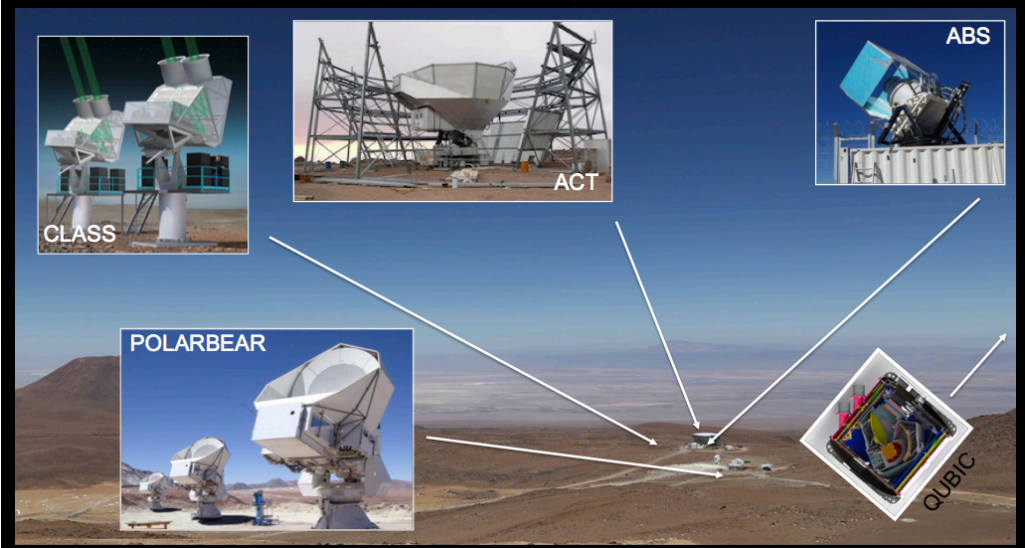

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