Cosmology: Planck 2015 results and what's next

Christophe Ringeval
Centre for Cosmology, Particle Physics and Phenomenology
Institute of Mathematics and Physics
Louvain University, Belgium

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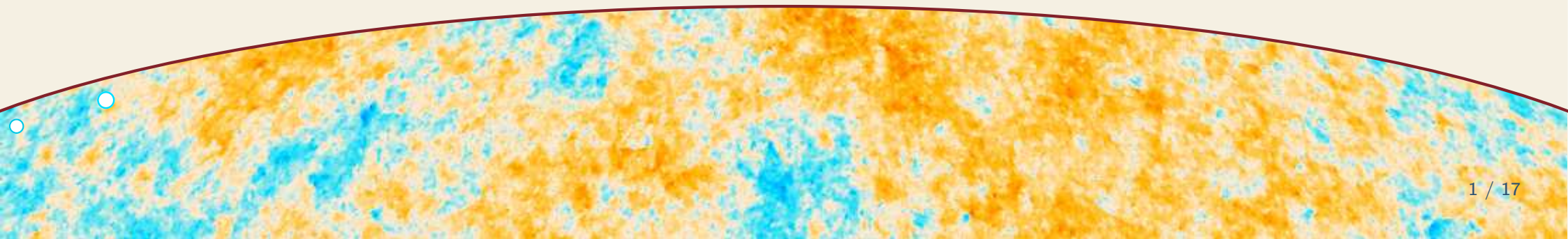
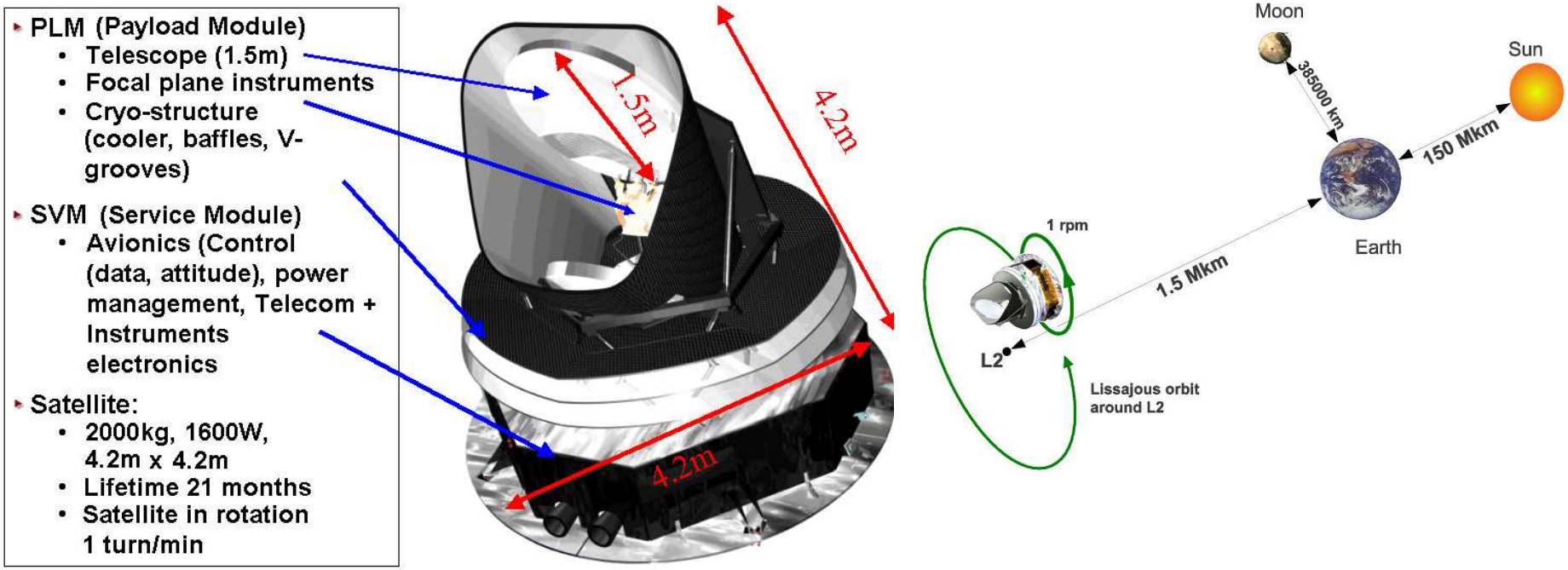


The Planck satellite was:

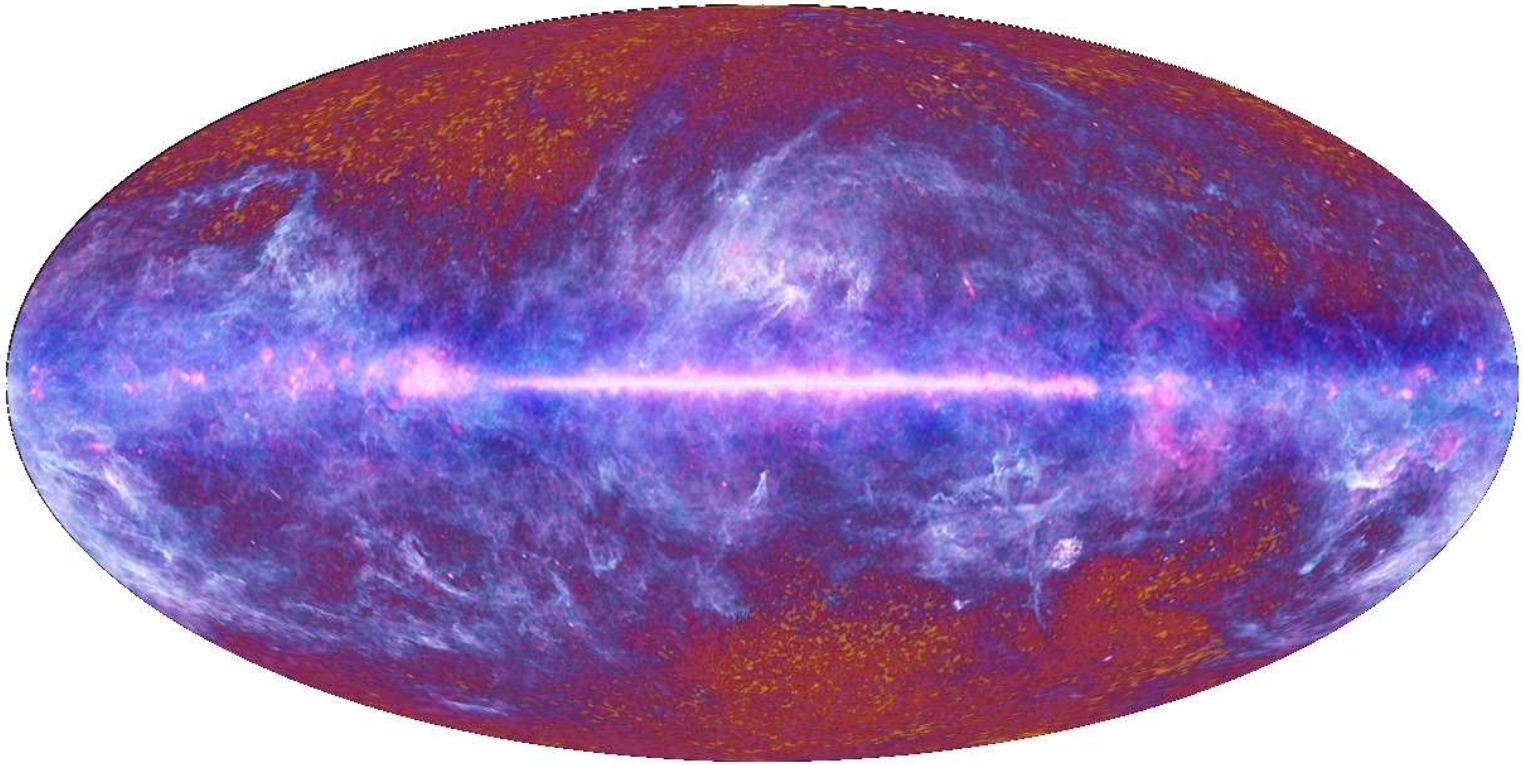
- Microwave telescope (ESA)



- Two instruments on board: LFI / HFI
  - 9 frequencies 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
  - Decommissioned since October 2013 and three data releases: 2013, 2015 and final in 2016
  - Objectives were measurements of T down to astrophysical limitation (polarization was not originally planned!)

First light (2010)

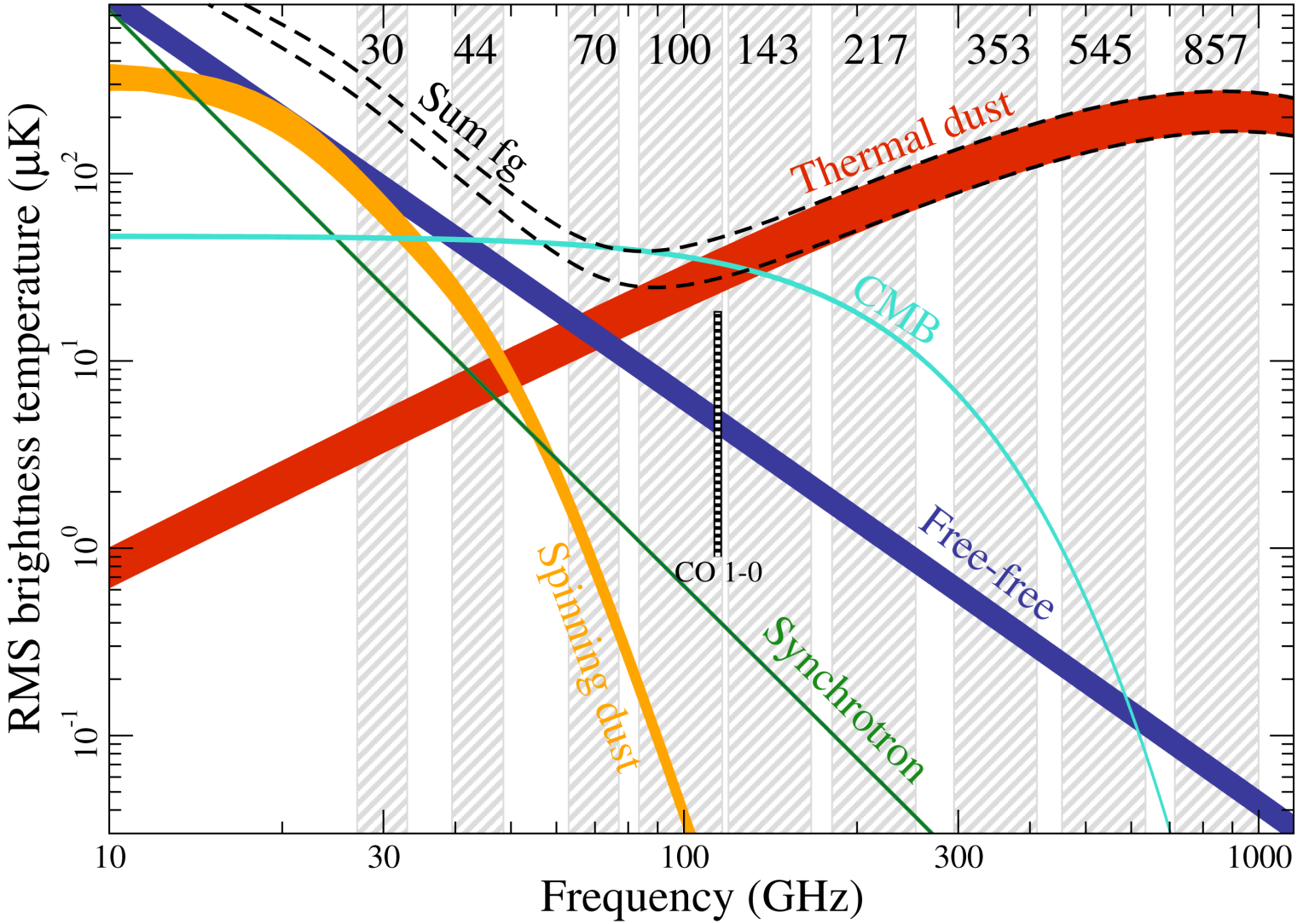
- Resolution: 50 000 000 pixels



- The CMB lies behing various astrophysical foregrounds

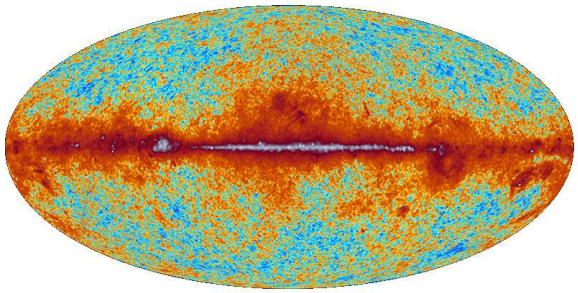
Sky maps at various frequencies

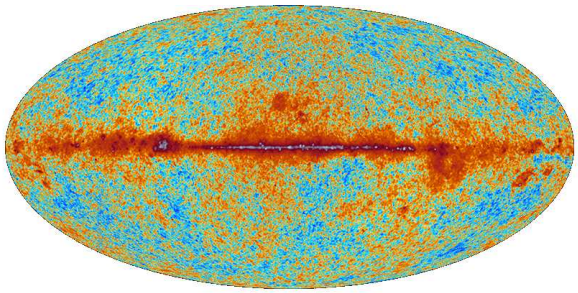
- 9 frequencies = combination of foregrounds + CMB

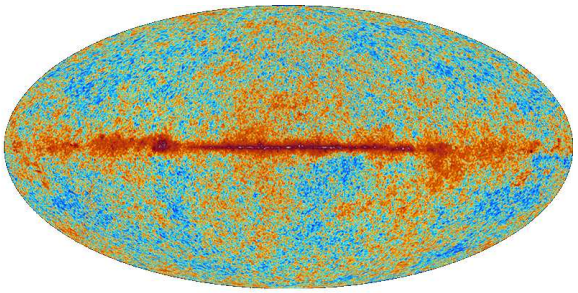


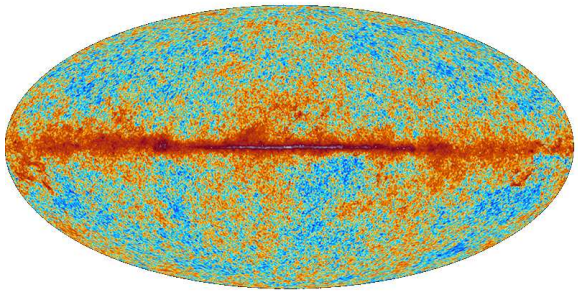
Sky maps at various frequencies

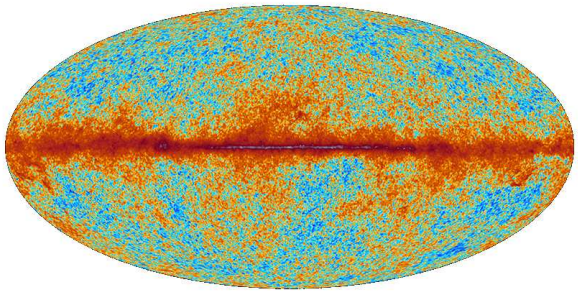
- 9 frequencies $=$ combination of foregrounds $+$ CMB

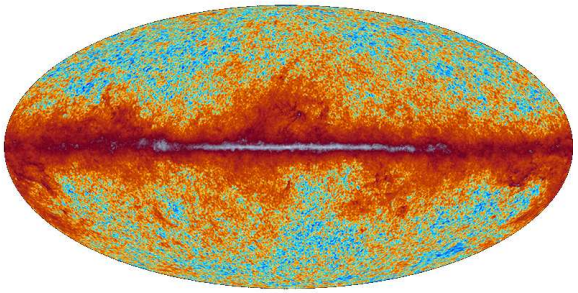

30 GHz

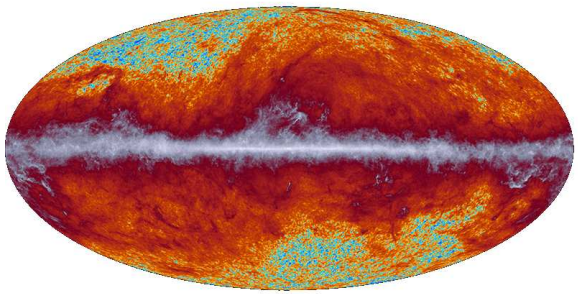

44 GHz

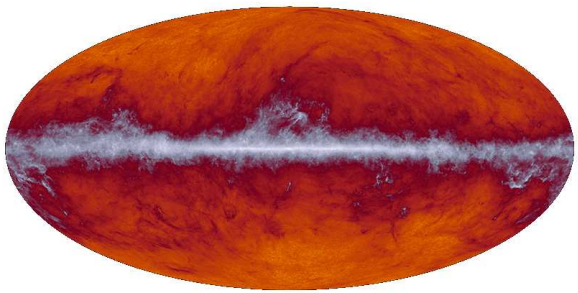

70 GHz

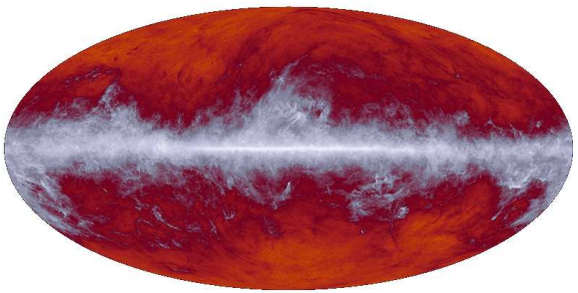

100 GHz


143 GHz


217 GHz

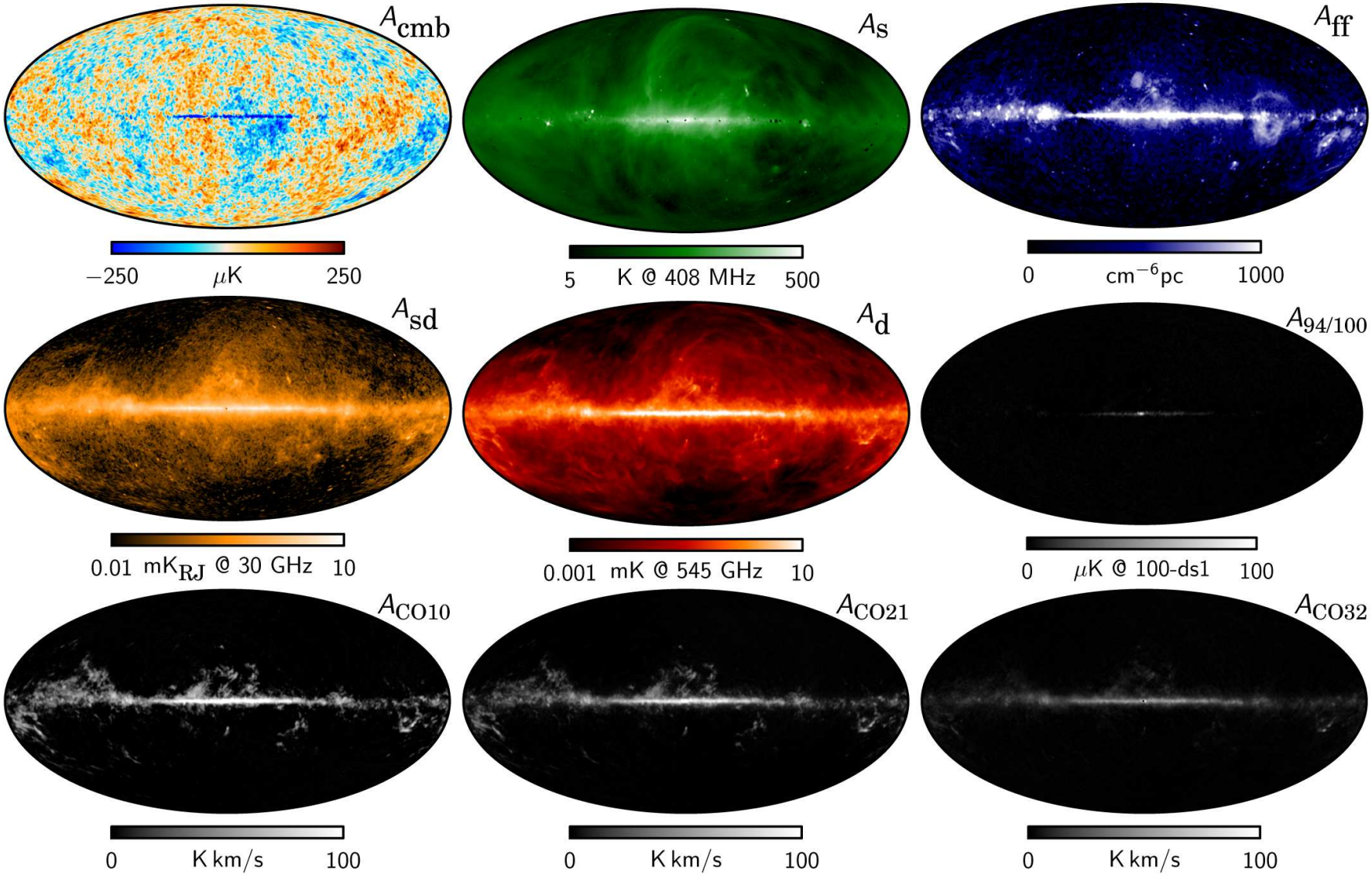

353 GHz


545 GHz


857 GHz

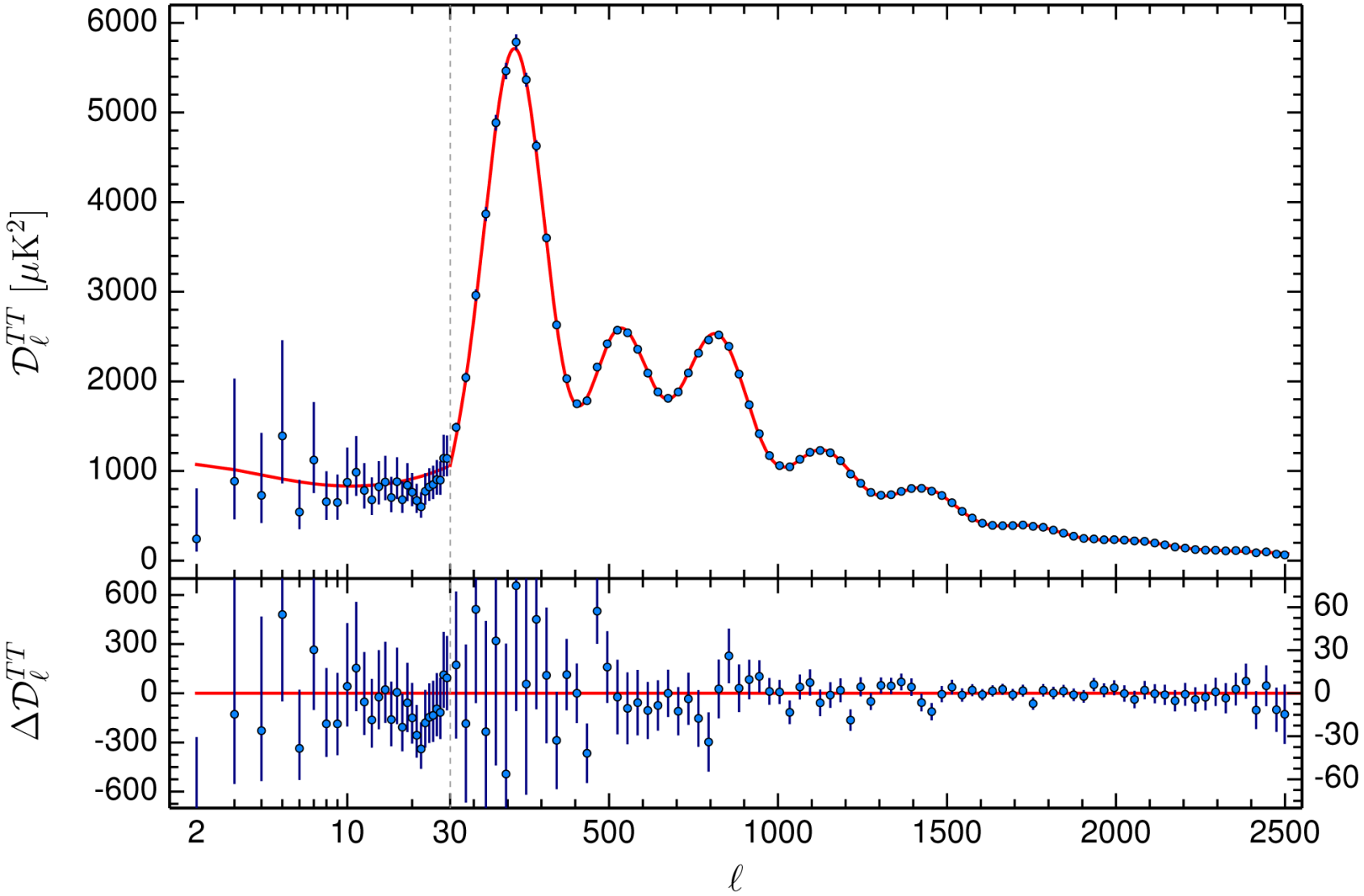
Sky maps at various frequencies

- After diffuse component separations



The CMB anisotropies in 2015

- Angular power spectrum

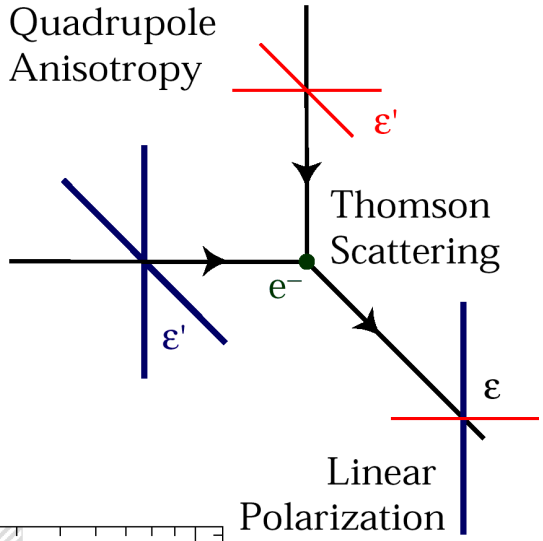


What is new since the 2013 release?

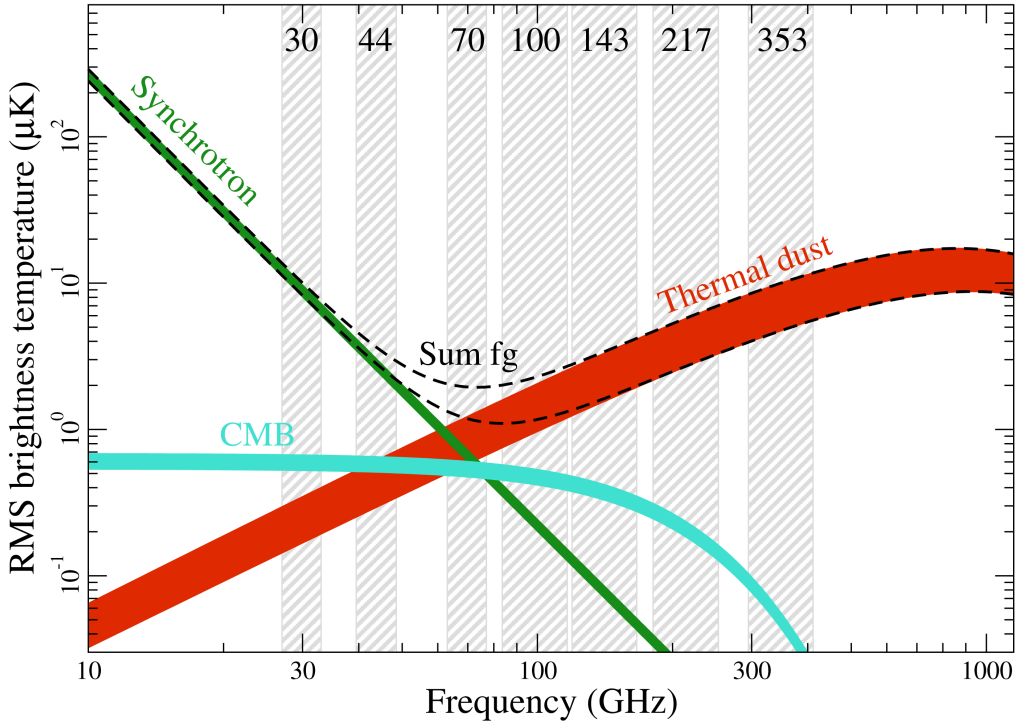
- 4 years of measurements included: twice the amount of data on T
  - Actually not used in that way: new data analysis consists of cross-correlating the first 2 years with the last 2 years to kill systematics
- Inclusion of external measurements: WMAP9 @ $23\,\mathrm{GHz}$-$94\,\mathrm{GHz}$ + Radiotelescope survey @ $0.408\,\mathrm{GHz}$
- Polarization measurements over 7 frequencies: two new observables E (and B) in addition to T
- A lot of improvements in the understanding of noise, calibration, satellite pointing, ADC, and astrophysics
- What's new for Cosmology?
  - The picture is the same: ΛCDM works very well with 6 parameters (over almost $2\,000\,000$ of modes): error bars on all cosmological parameters have been reduced by 1 to 1.5σ
  - More constraints on early universe acceptable models (in progress)
  - A lot of new results for Astrophysics and a lot of new data still unexploited for Cosmology and other fields

CMB polarisation

- Physical origin: photons-electrons interactions
  - AND anisotropies
  - Two new observables E and B (or Stokes parameters Q and U)

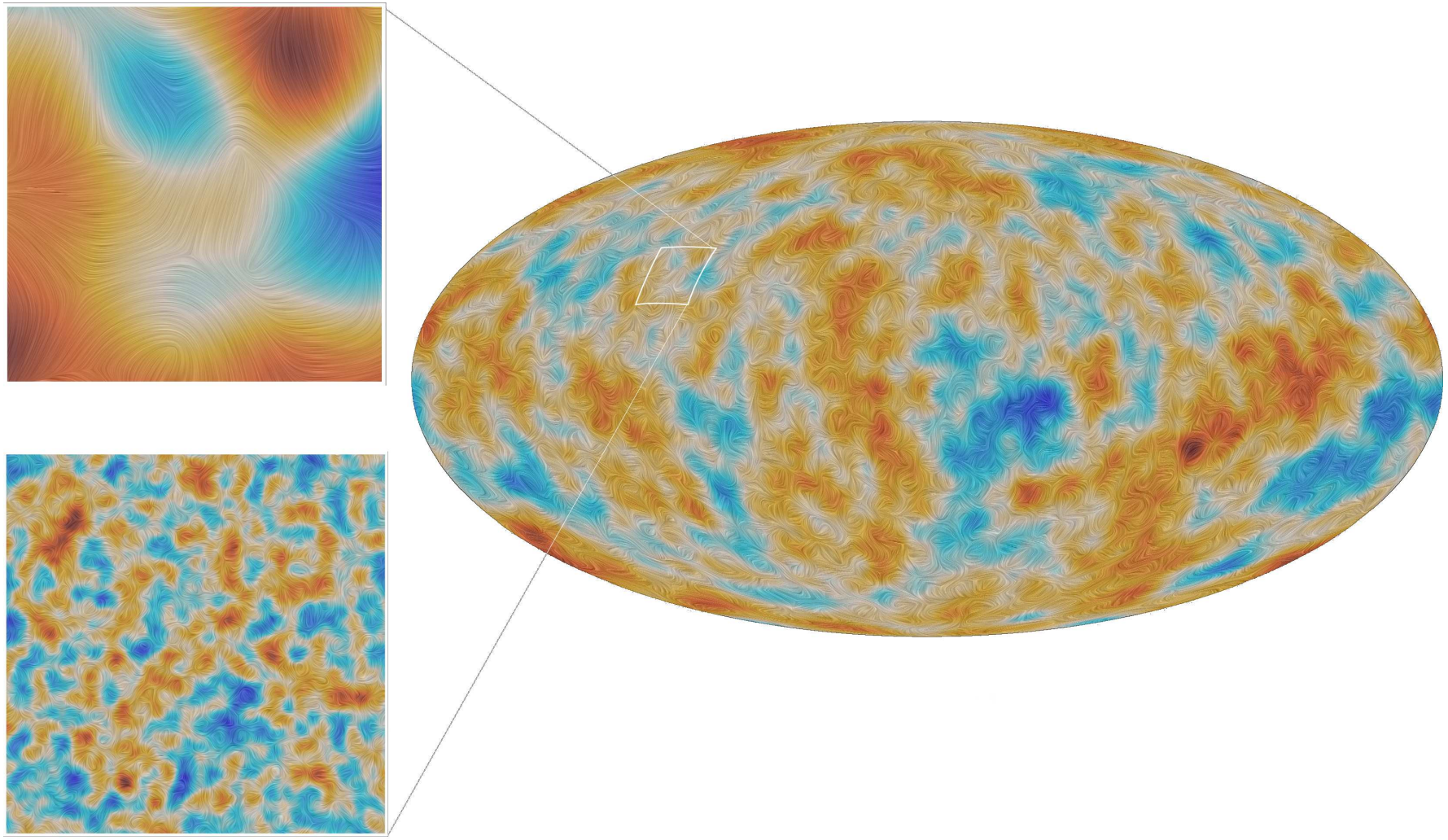


- Main issue: Signal/Foregounds < 1



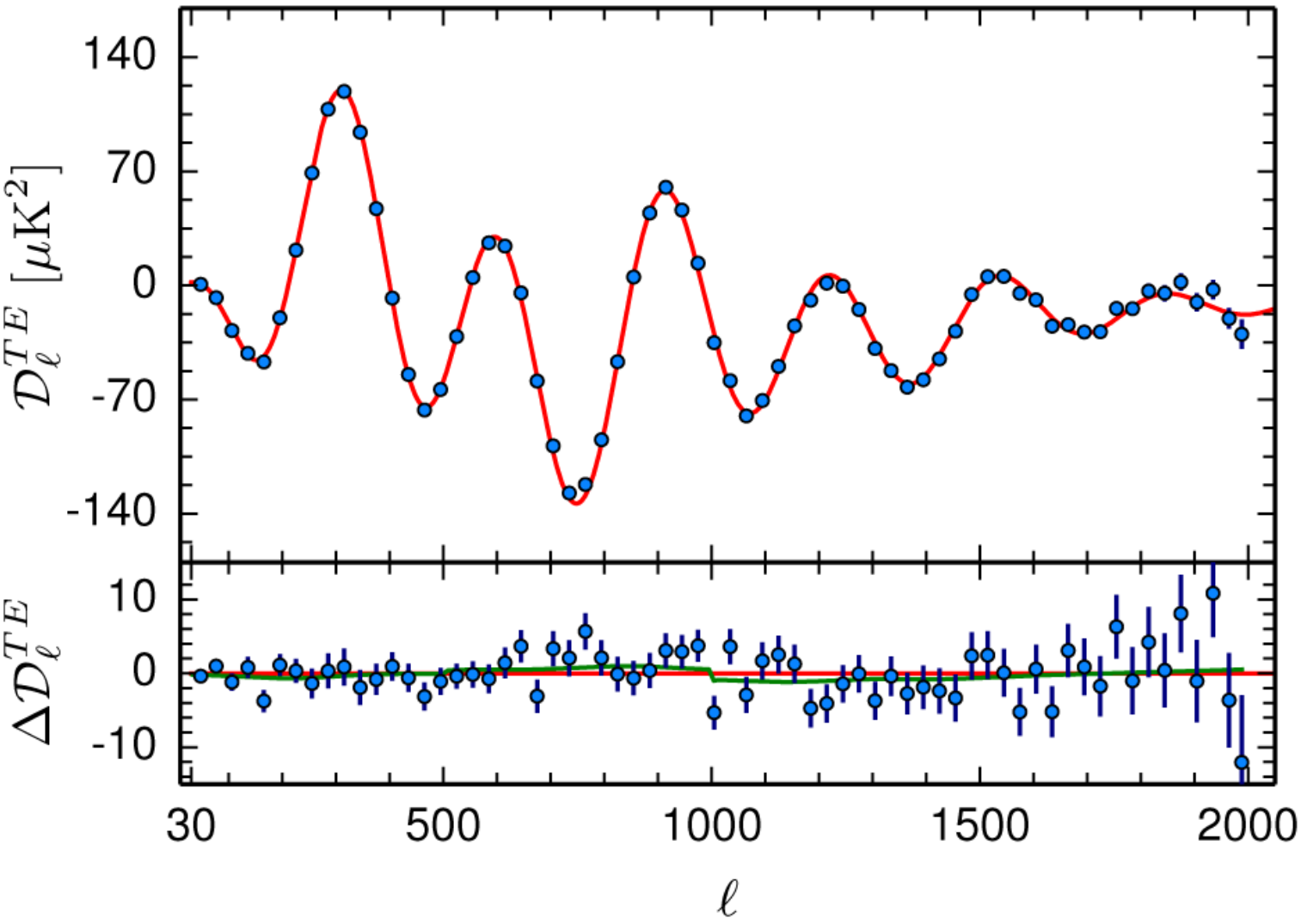
CMB polarisation with Planck 2015

- After compontent separations: intensity (color) and direction (integral lines)



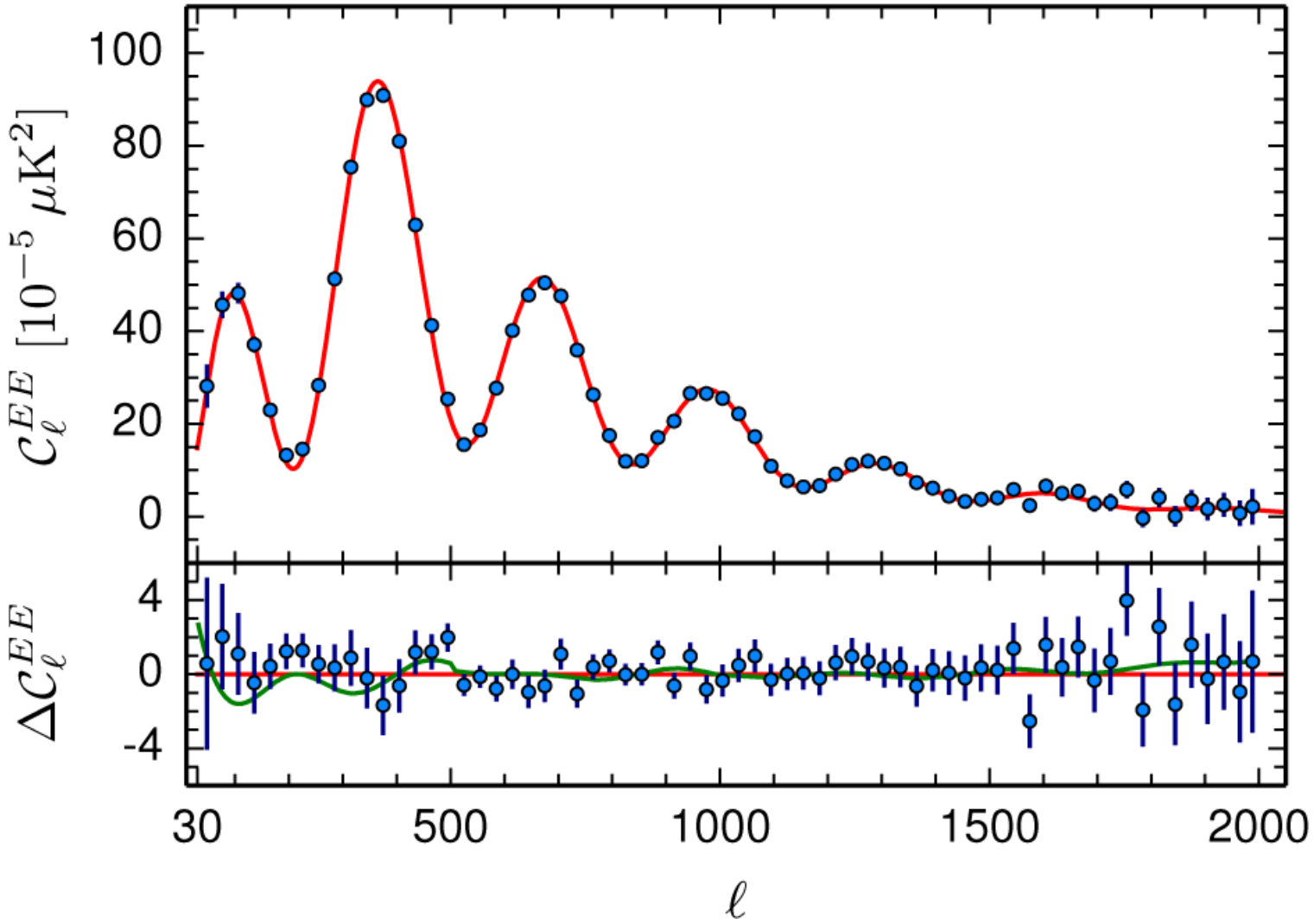
Polarisation power spectra

- Correlation intensity-direction TE



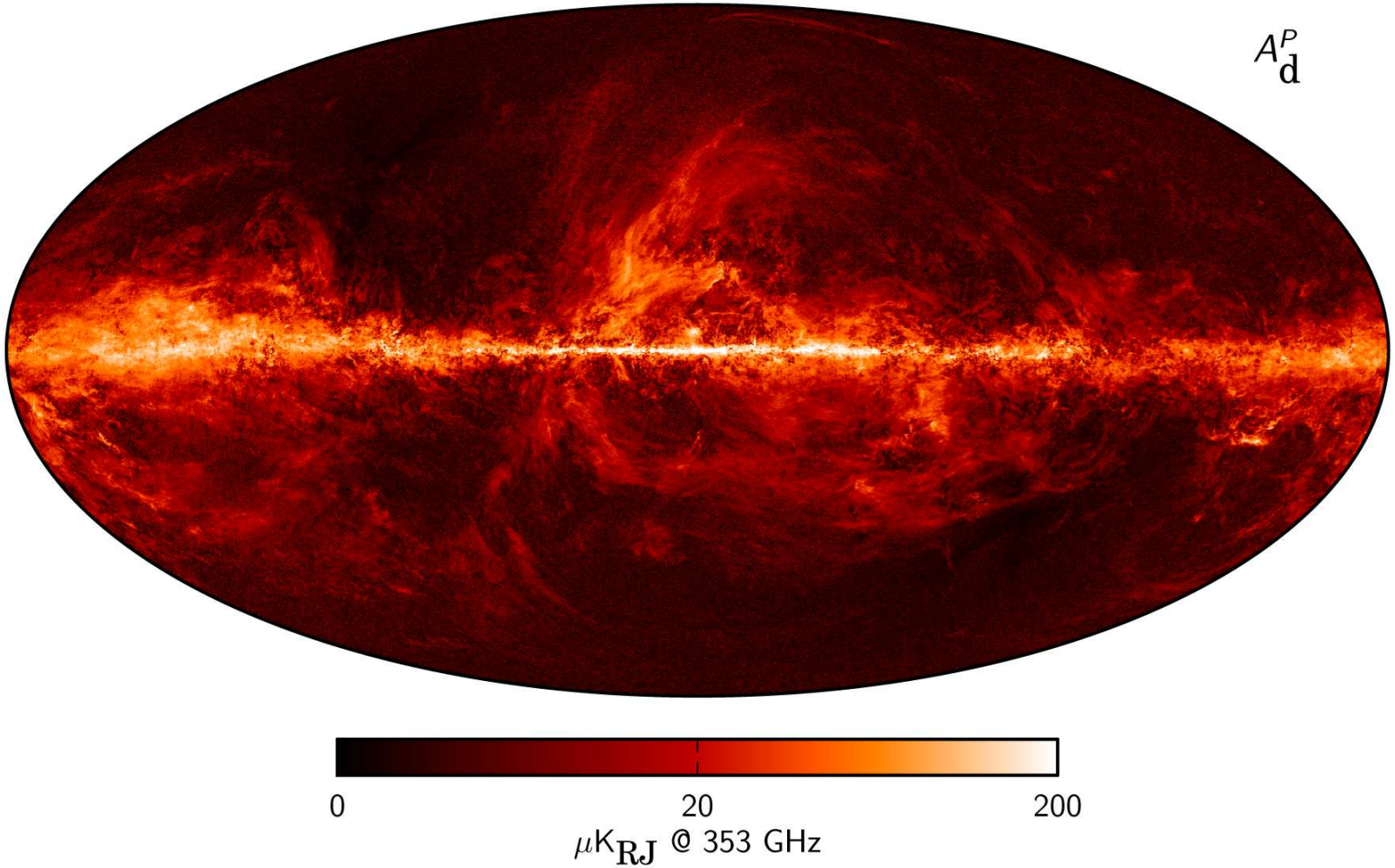
Polarisation power spectra

- Autocorrelation EE



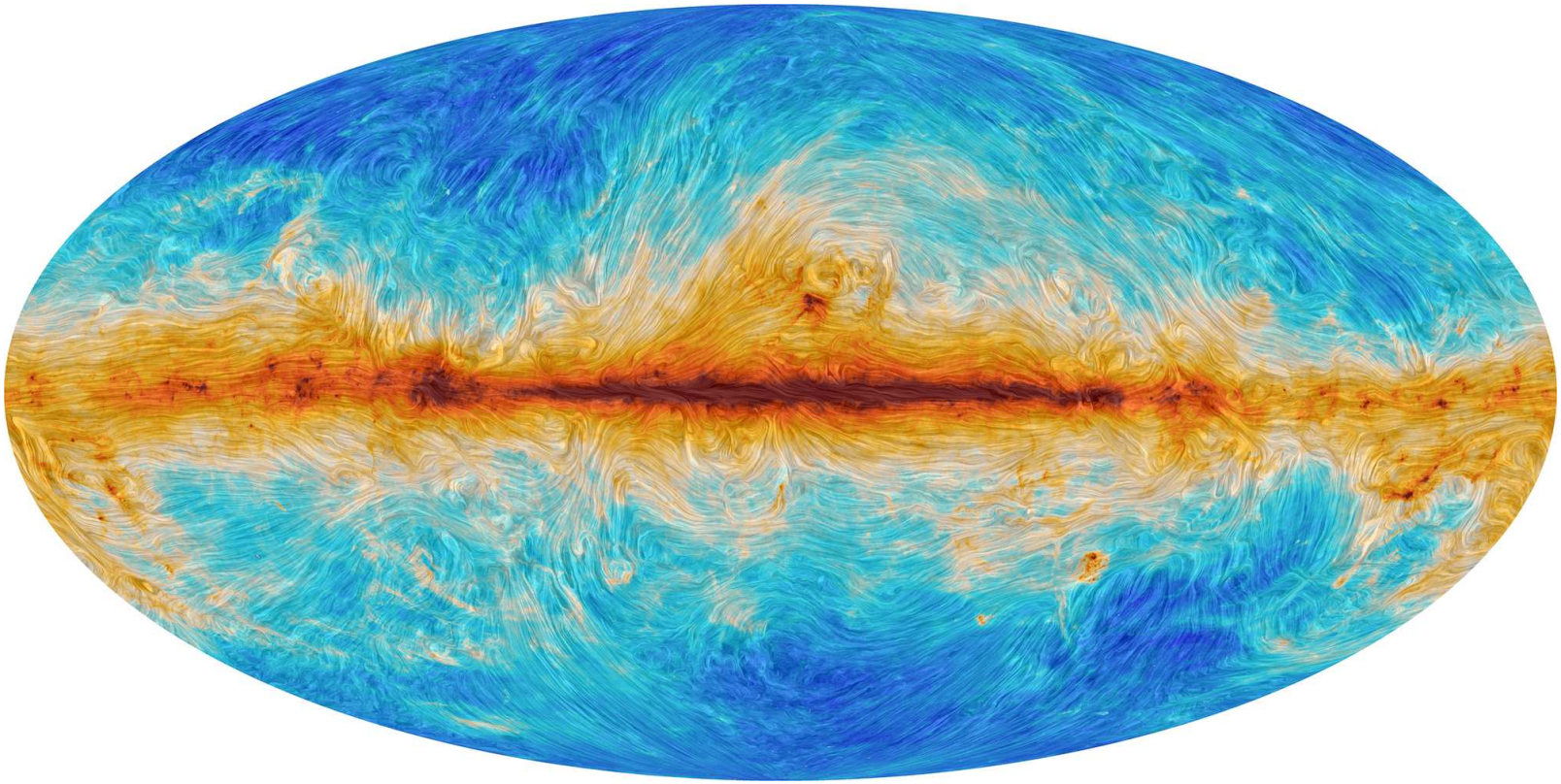
First measurement of polarised foregrounds

- Non-spherical grains aligned along galactic magnetic field
  - Polarized intensity I_p



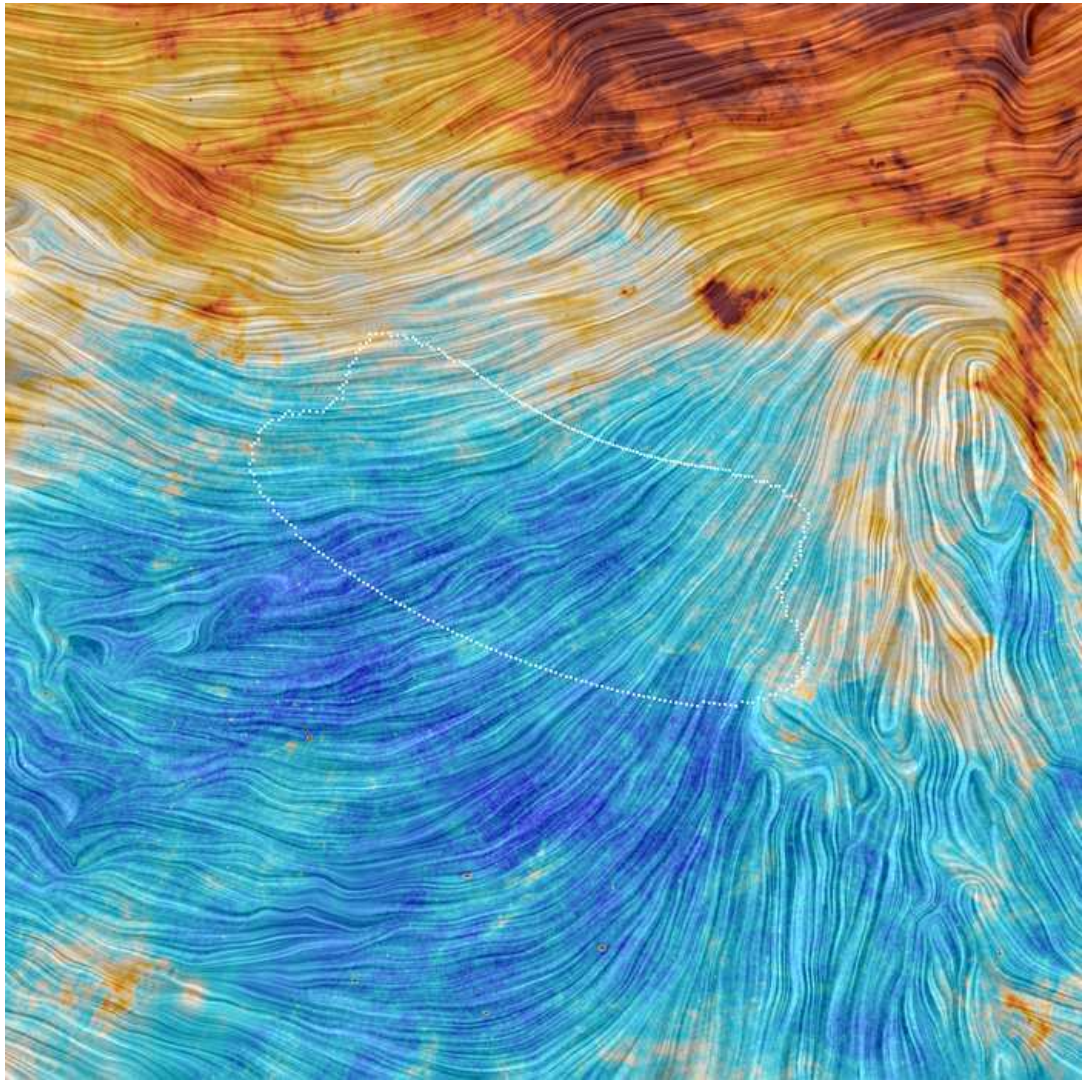
First measurement of polarised foregrounds

- Non-spherical grains aligned along galactic magnetic field
  - ✦ Direction ⇔ magnetic field direction



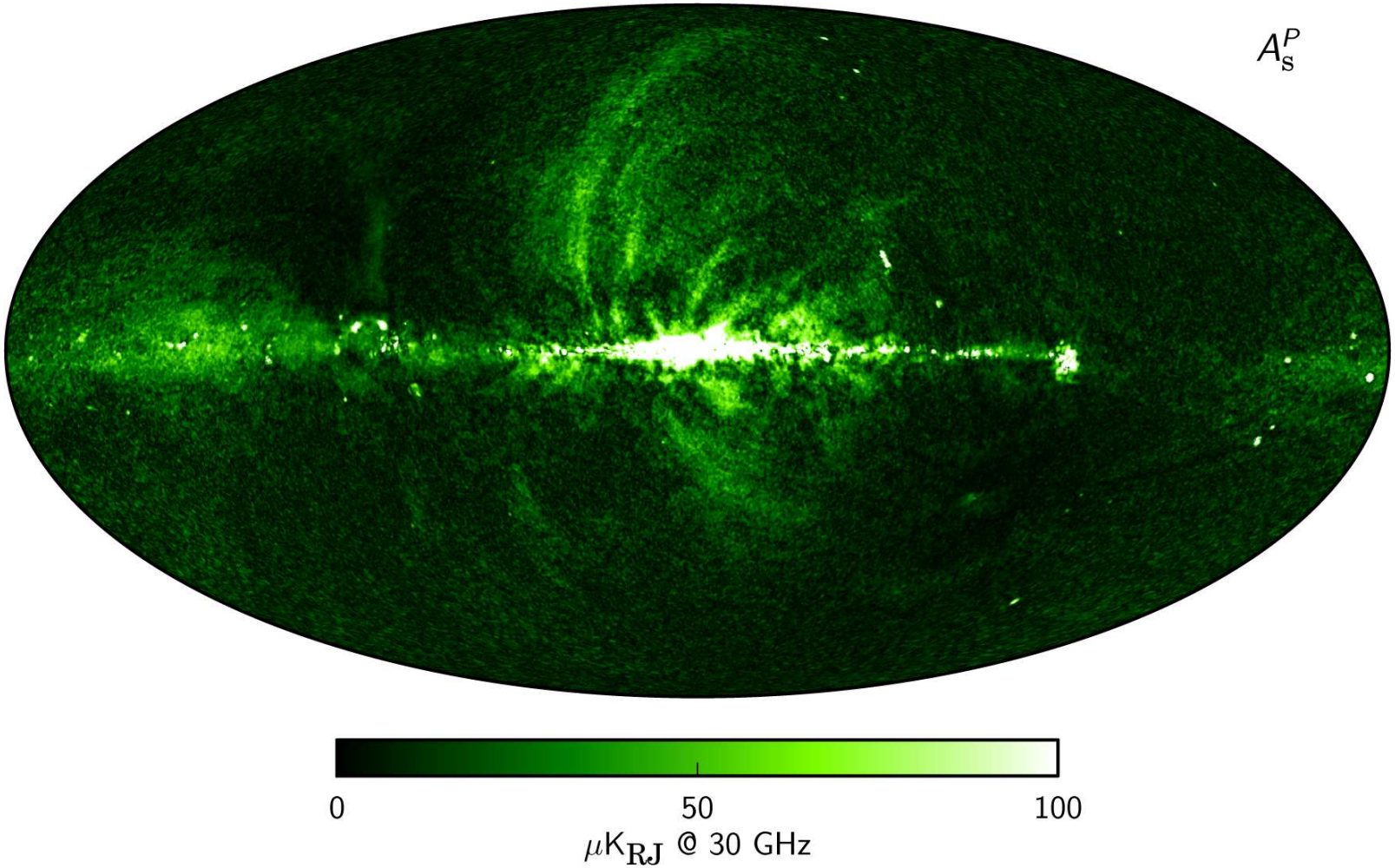
First measurement of polarised foregrounds

- Non-spherical grains aligned along galactic magnetic field
  - ✦ zoom within the BICEP2 region



First measurement of polarised foregrounds

- Polarised synchrotron emission from electrons spiraling aroung the galactic magnetic field
  - Polarized intensity I_p



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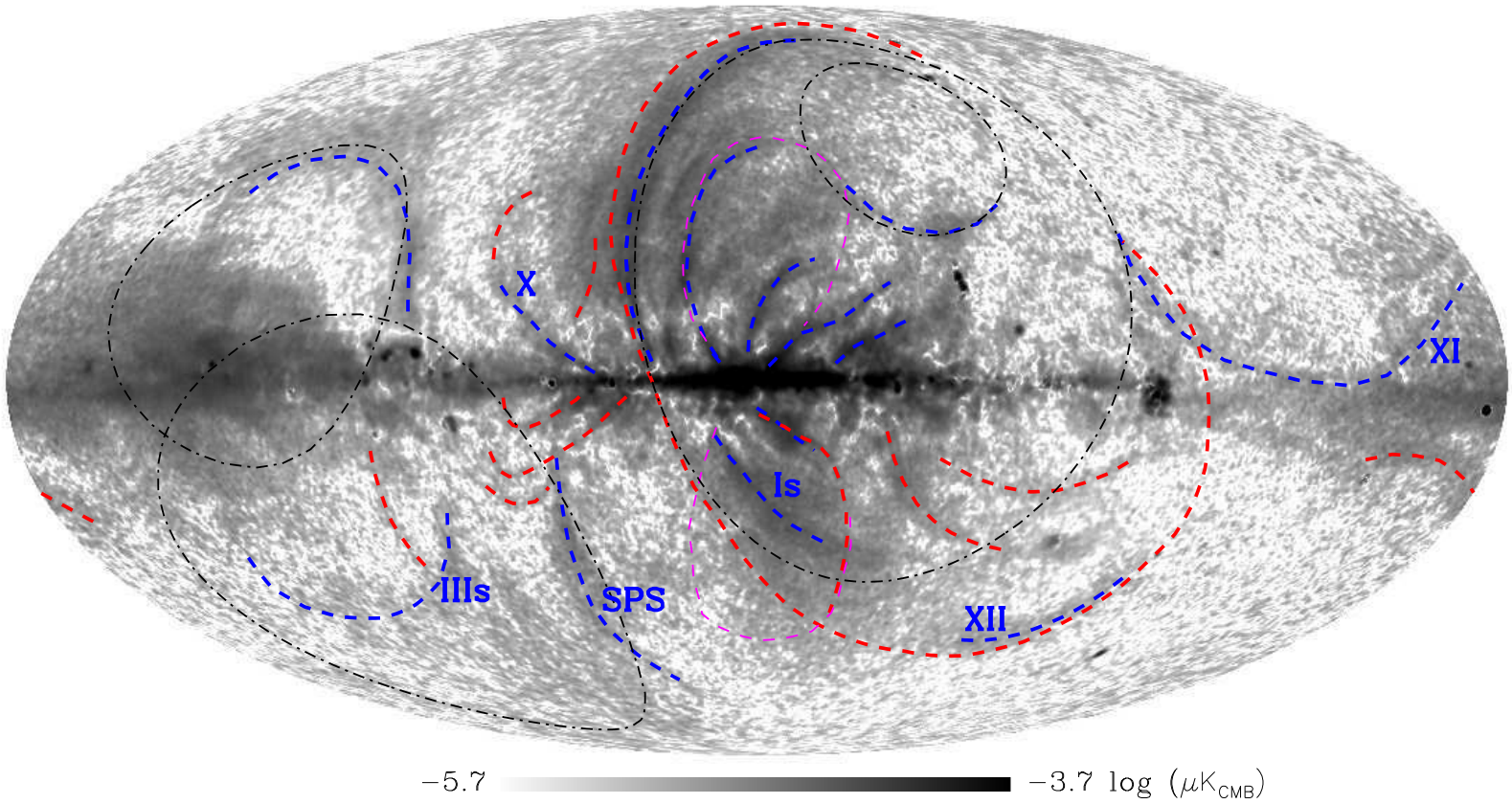
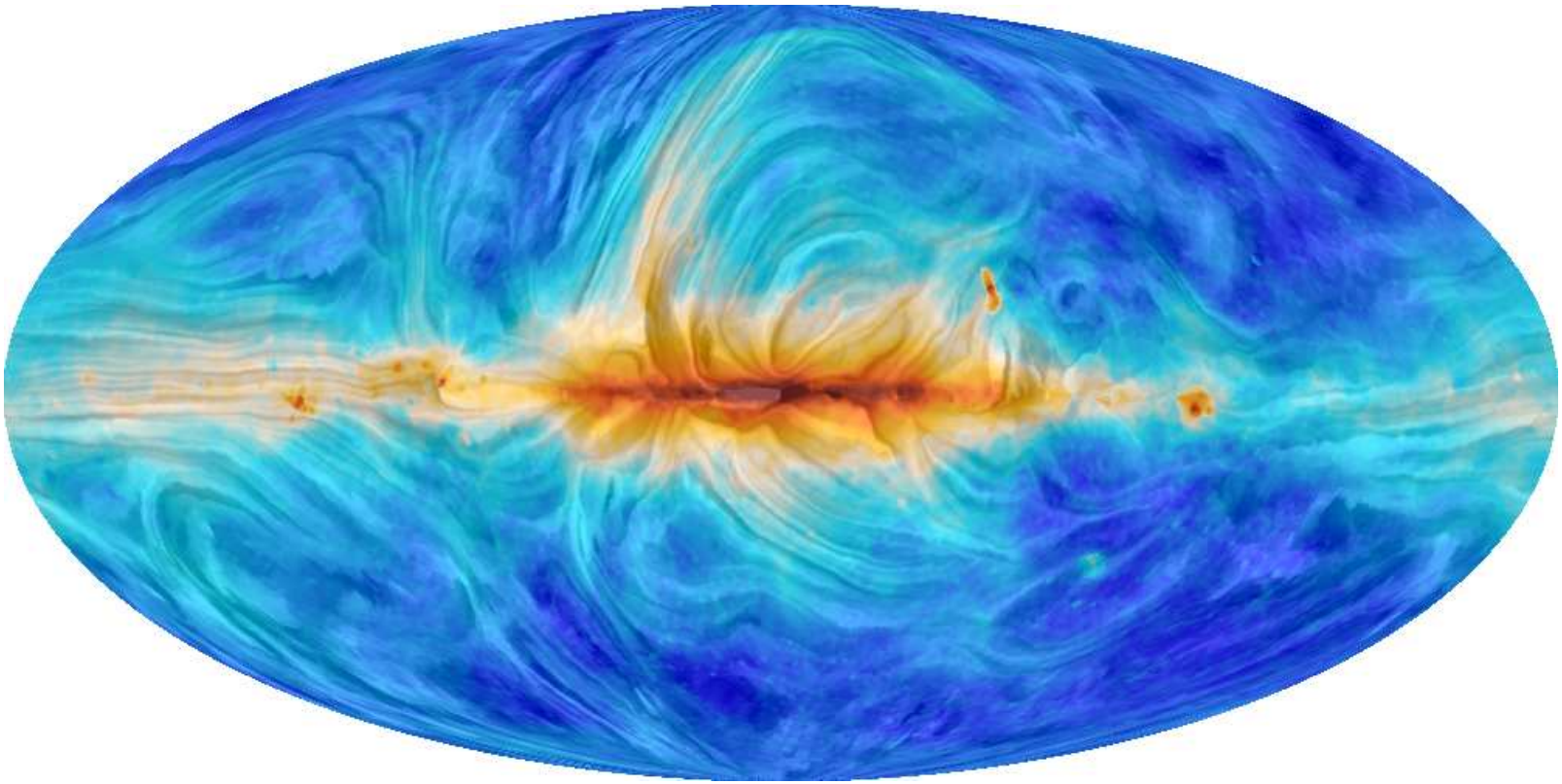


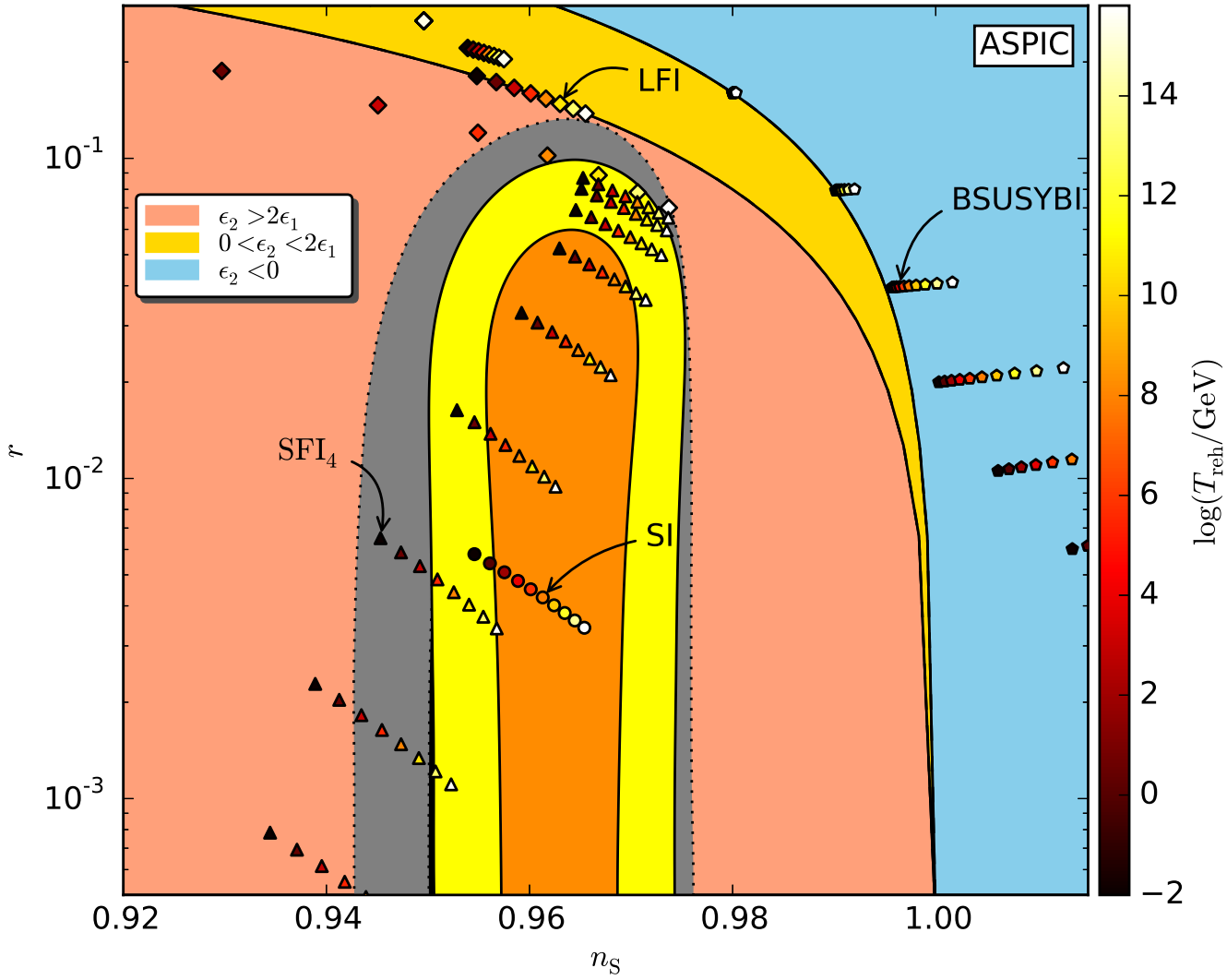
First measurement of polarised foregrounds

- Polarised synchrotron emission from electrons spiraling aroung the galactic magnetic field
  - Direction $\Leftrightarrow$ magnetic field direction



Planck 2015 bounds on Early Universe models

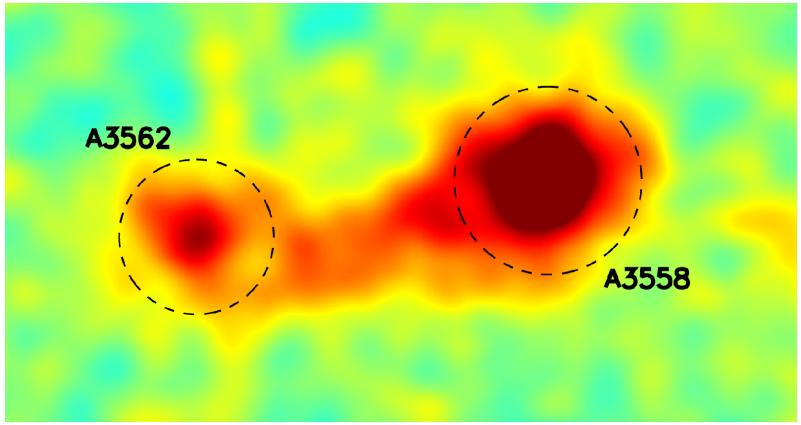
- Comparison between Planck 2013 and Planck 2015 + BICEP2



Galactic clusters as watermarks

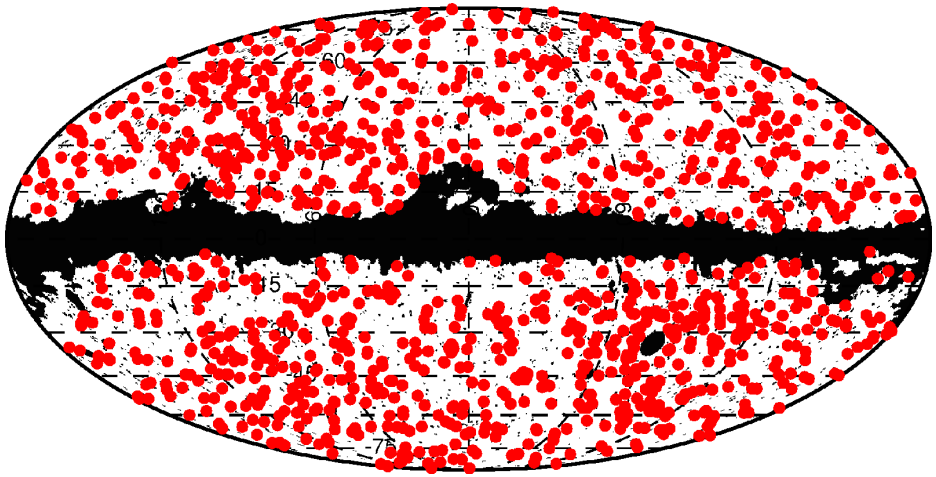
- Sunyaev-Zel'dovich effect

CMB



Optical, X-ray and SZ

- A thousand new clusters discovered: $\Longrightarrow$ new measurement of $\Omega_{\rm mat}$, σ_8

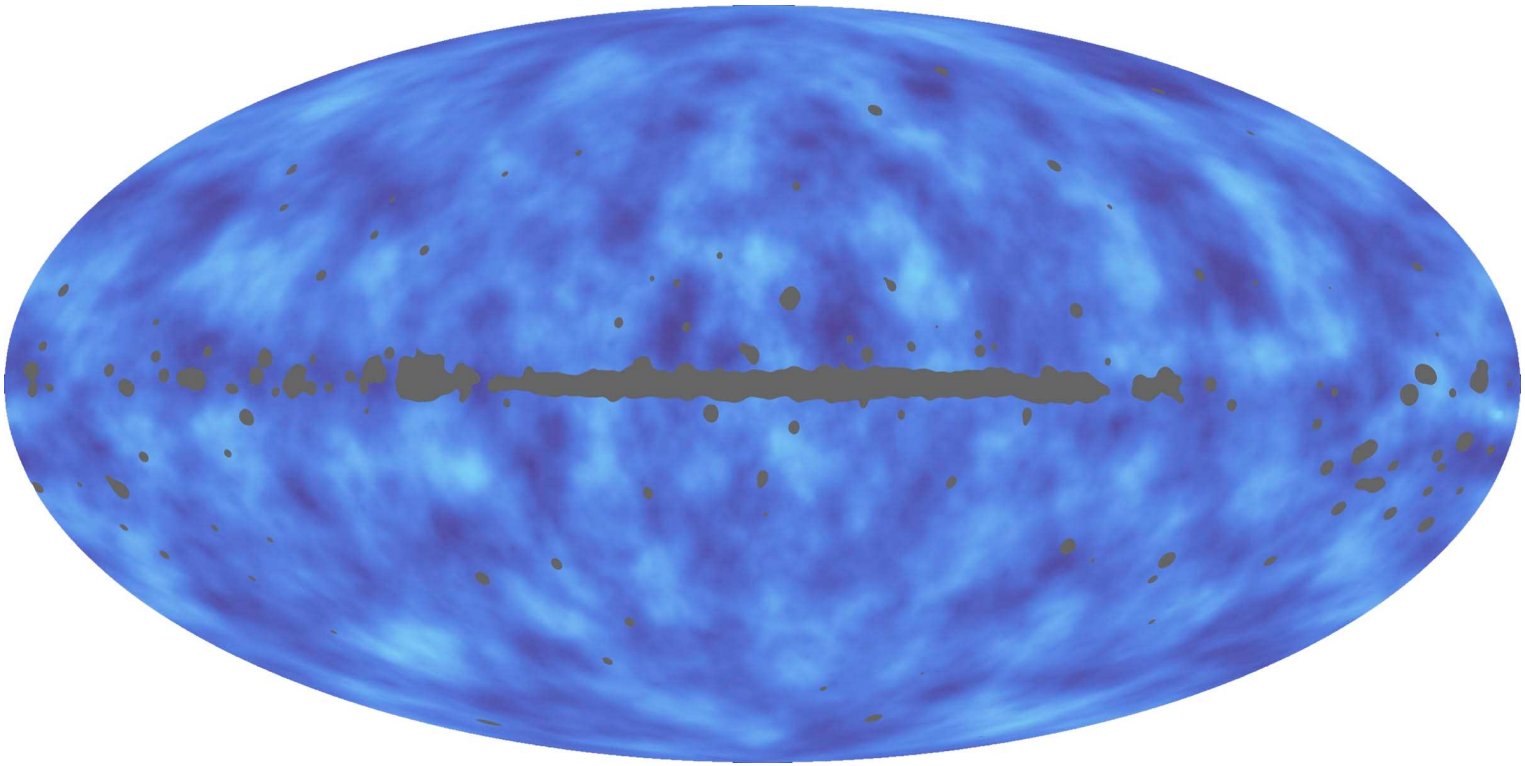


Gravitational lensing

- CMB is deflected by structures and dark matter

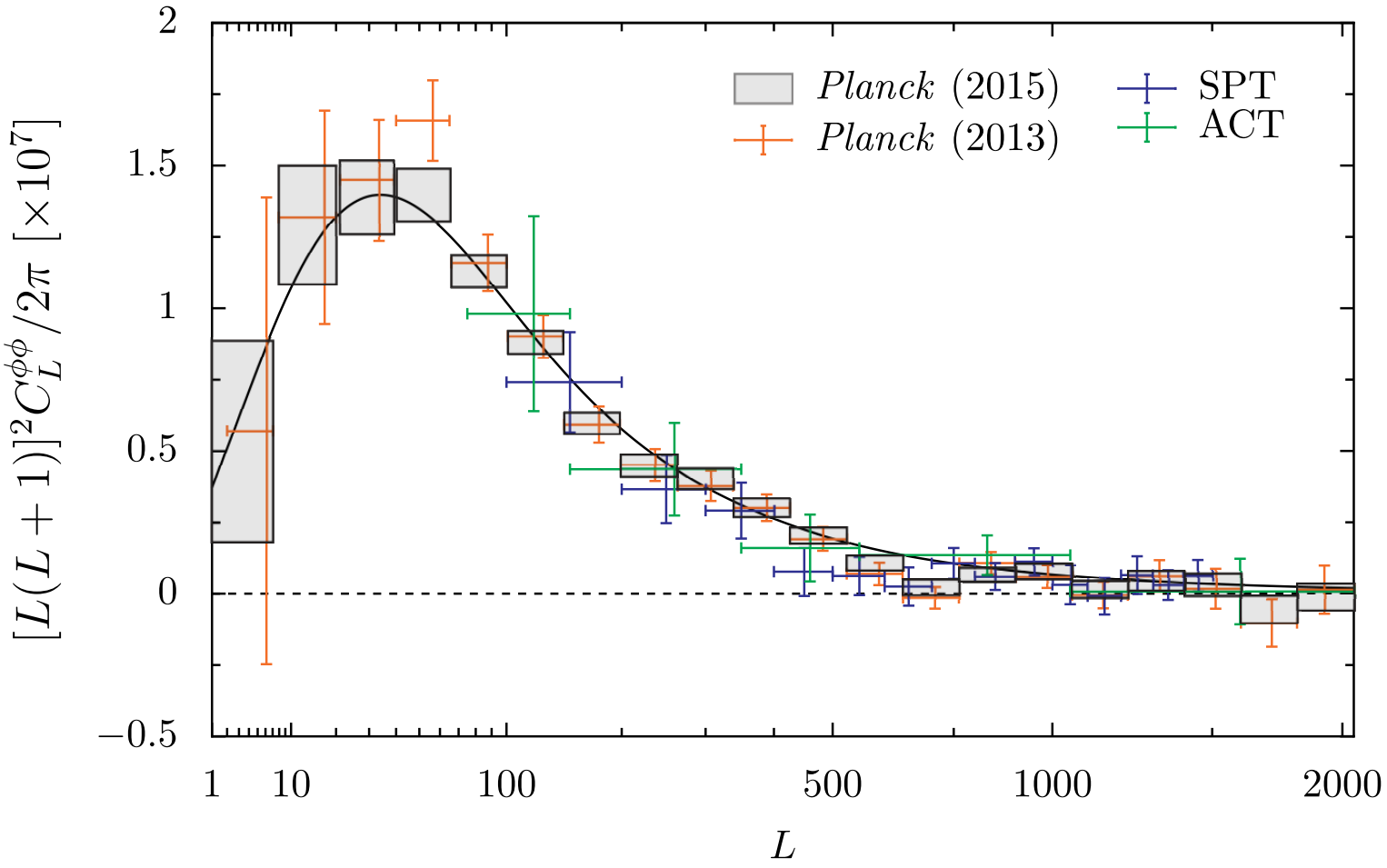
$$\tilde{T}(\boldsymbol{n}) = T\left[\boldsymbol{n} + \nabla\phi(\boldsymbol{n})\right] \simeq T(\boldsymbol{n}) + \nabla^i\phi(\boldsymbol{n})\nabla_i T(\boldsymbol{n})$$

- Deflexion map $\simeq$ projected map of dark matter distribution



Lensing power spectrum

- Compared to the DM + GR predictions



Some other results

- Neutrino masses (TT+lowP+lensing+H_0+BAO+JLA)

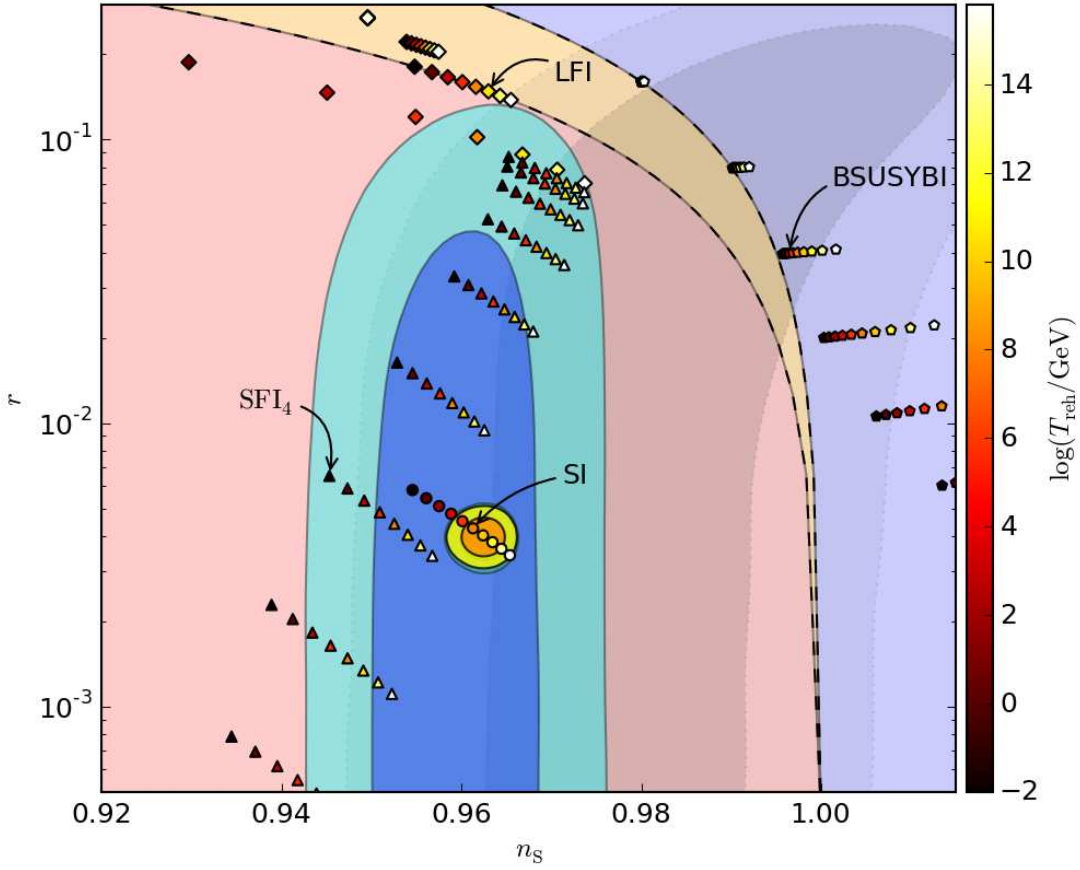
$$\sum_\nu m_\nu < 0.23\,\mathrm{eV} \quad (95\%)$$

- Extra relativistic degrees of freedom at $T \ll \mathrm{MeV}$

$$\rho \equiv \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\,\rho_\gamma \qquad N_{\mathrm{eff}} = 3.15 \pm 0.23 \qquad (\mathrm{TT{+}lowP{+}BAO})$$

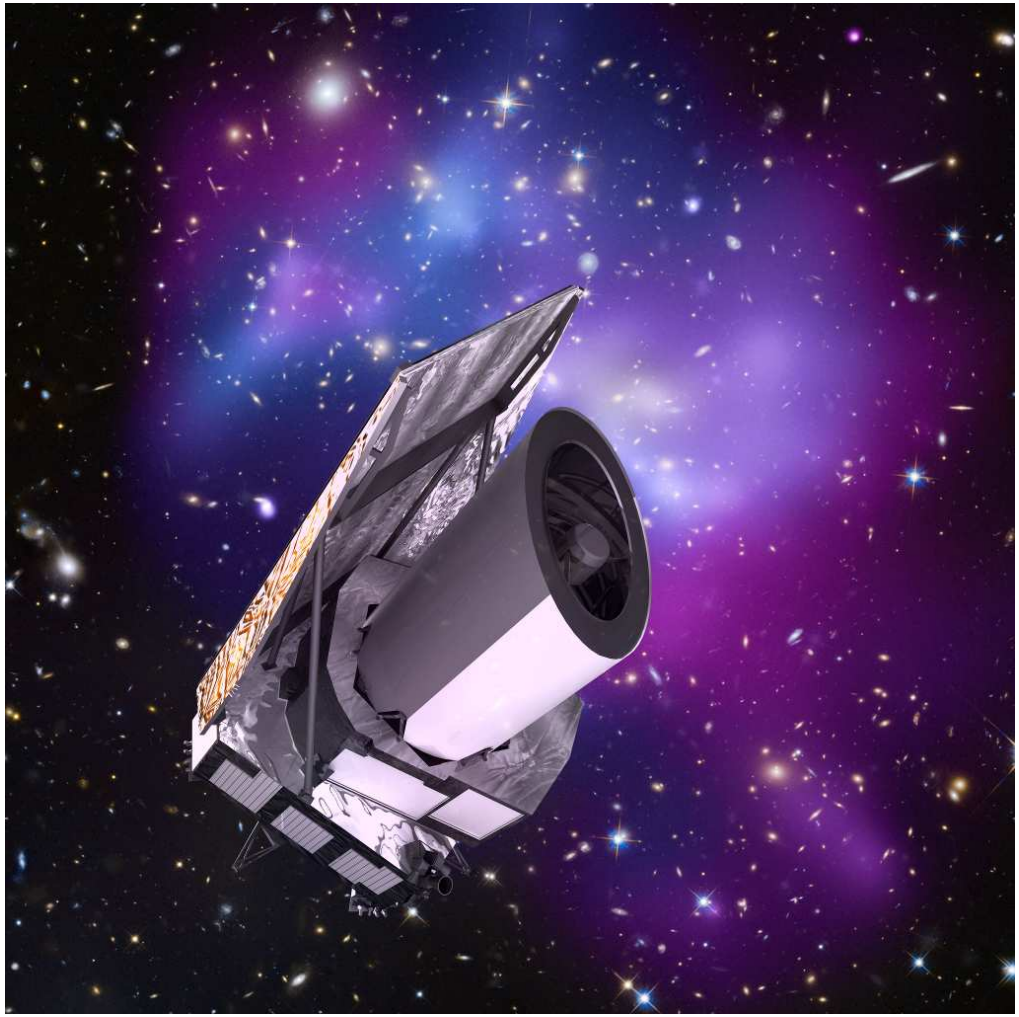
After Planck?

- CMB: intensity measurements are over, but not polarization
- New detectors (as BICEP2) currently deployed in telescopes + balloons: CLASS, SPIDER, ABS, KECK, BICEP3 (2560 detectors)...
- Next step is spatial missions: Core+, LiteBird (Japan)



Cosmology after the CMB?

- Galaxy surveys: SDSS IV (2014-2020), LSST (2019), EUCLID satellite (first light 2020)



Cosmology after the CMB?

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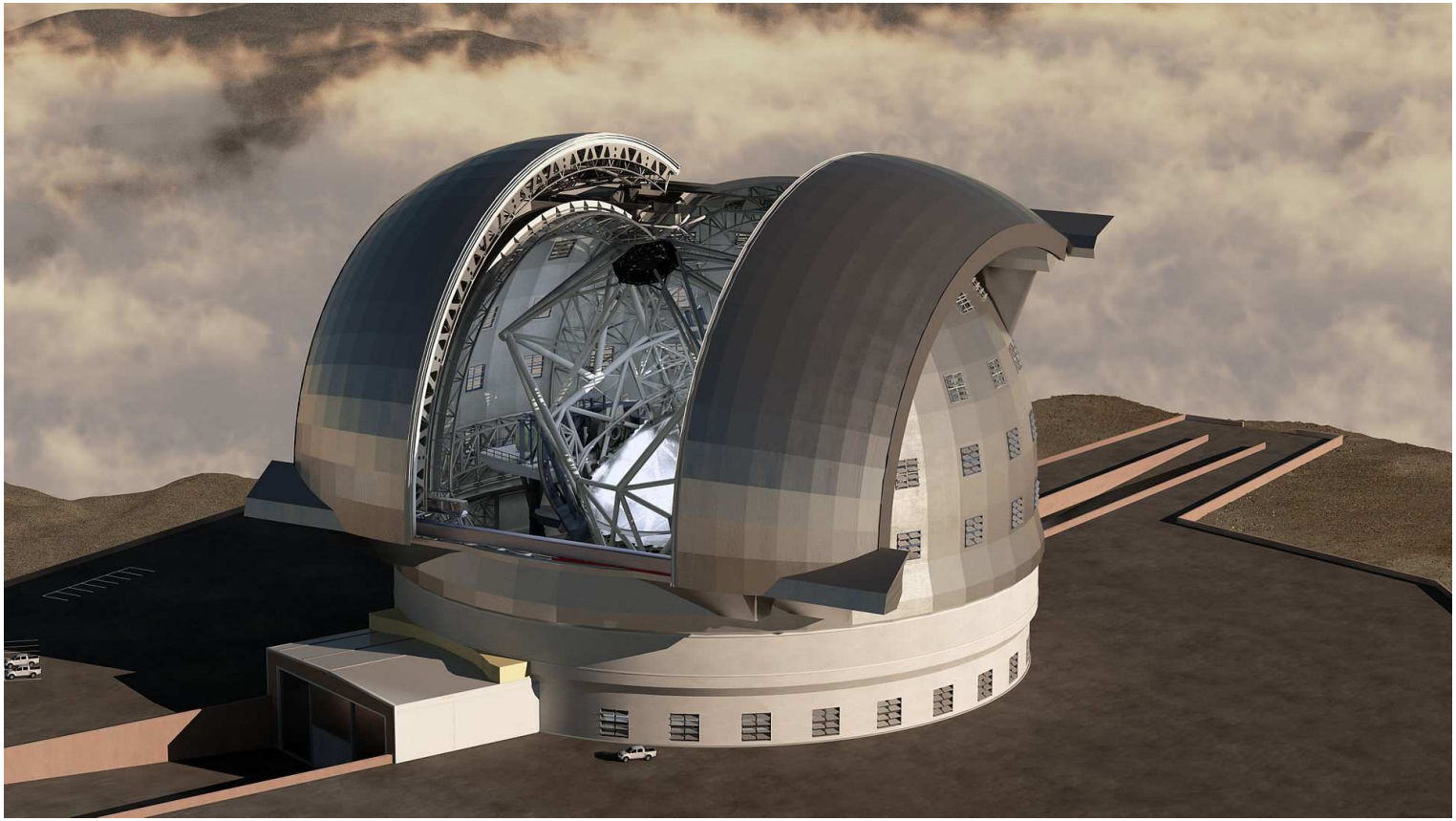
- 3 Extremely Large Telescopes in construction (first light 2024)



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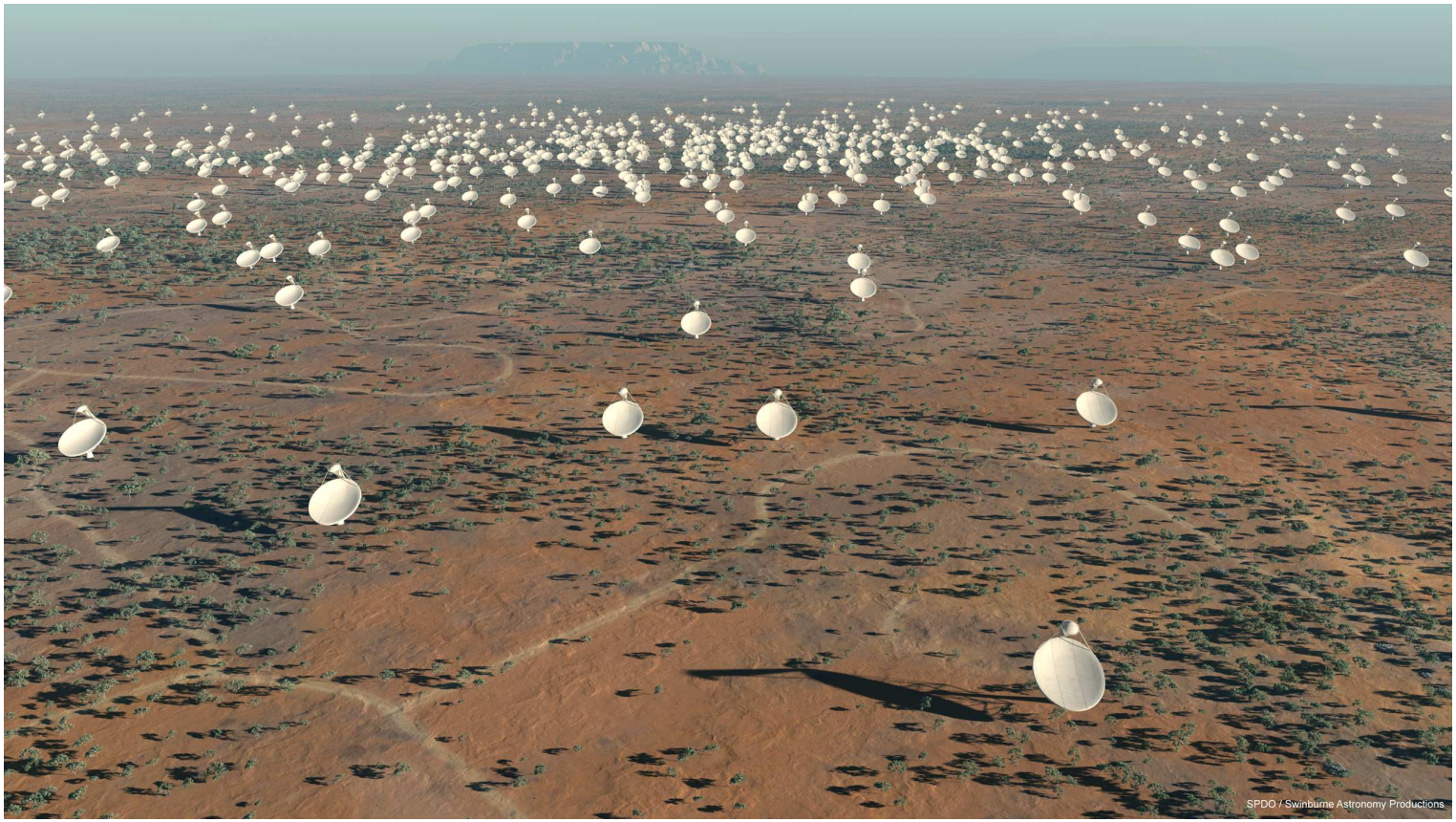
- 21cm interferometric arrays: SKA (construction 2018)



Cosmology after the CMB?

- Galaxy surveys: SDSS IV (2014-2020), LSST (2019), EUCLID satellite (first light 2020)
- 3 Extremely Large Telescopes in construction (first light 2024)
- 21cm interferometric arrays: SKA (construction 2018)
- Direct detection for GW with VIRGO/LIGO (2016-2017?)
  - ✦ eLISA has been accepted (2034!) while LPF will be launched soon 27/11