CMB observations from space: *Planck* and beyond

Jacques Delabrouille

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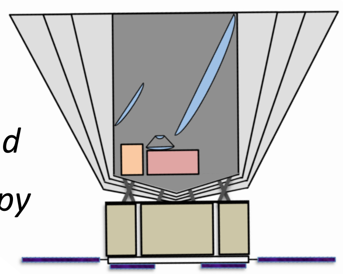
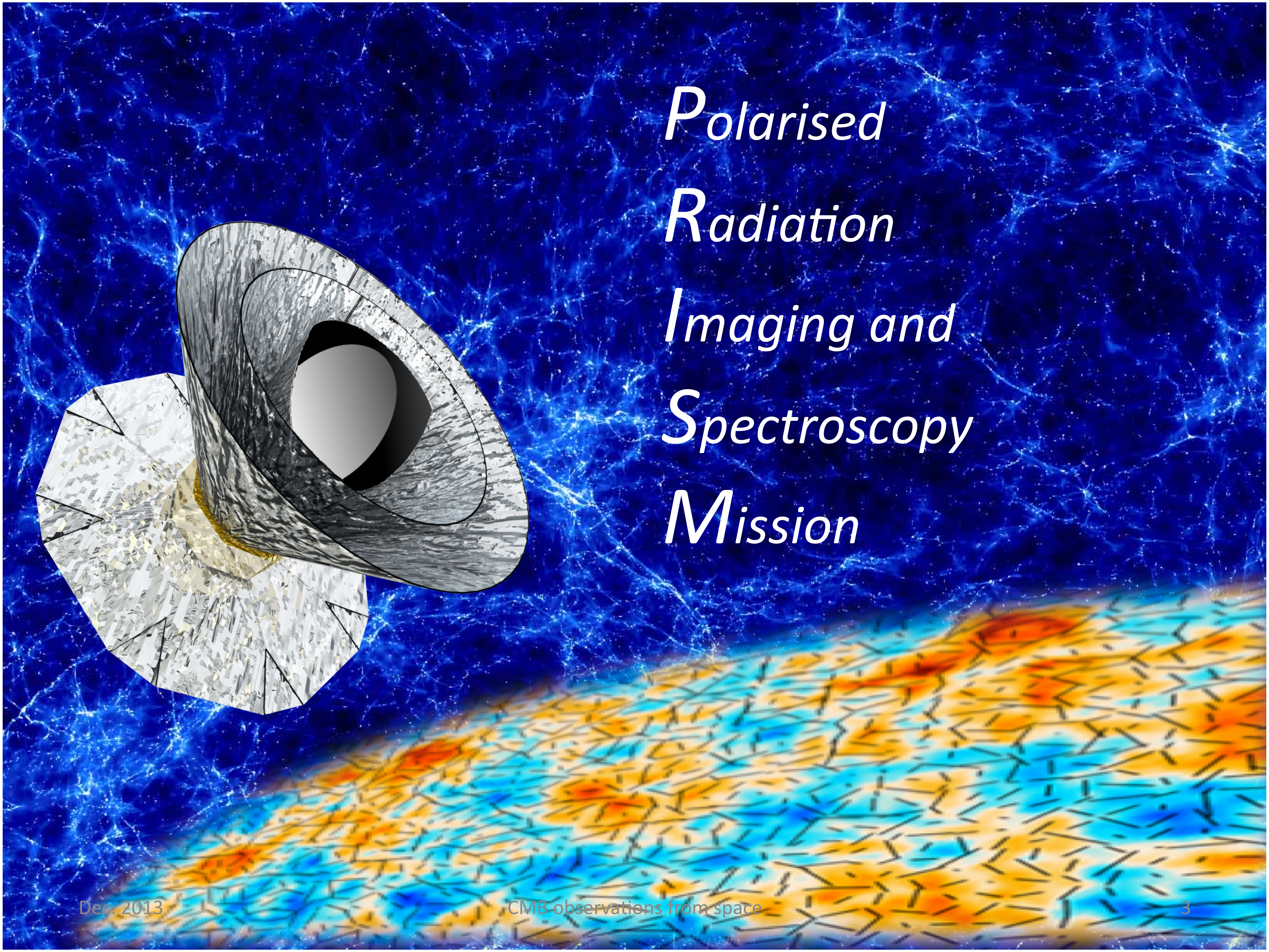
Polarized
Radiation
Imaging and
Spectroscopy
Mission



Outline

- PRISM
- CMB anisotropies and inflation
- CMB lensing
- Clusters of galaxies
- Astrophysical cosmology
- The galactic ISM
- Conclusion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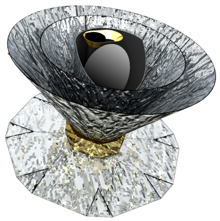


ESA L-class mission call

ESA call for proposed ***science areas*** for the next two L-class missions, L2 (≈2028) and L3 (≈2034).

Came as a surprise, with a very short calendar:

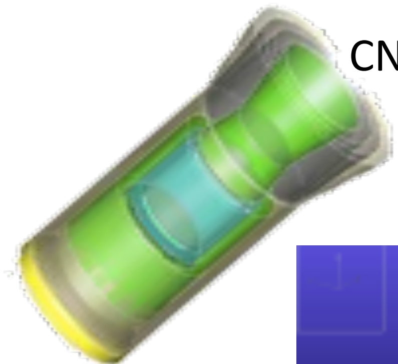
- Call issued early March 2013,
- White paper due May 24th
- Open workshop September 3rd - 4th in Paris
- Selection of two science areas for L-class missions in October
  - X-rays (Athena+) and GW astronomy (eLISA)
- *Before* the call for the next M-class mission (2014, for a launch ≈ 2025-2027)

Budget (rather ambitious):

- 900 million euro (ESA cost)
- Instruments from national space agencies
- Up to 20% foreign (non-European) participation

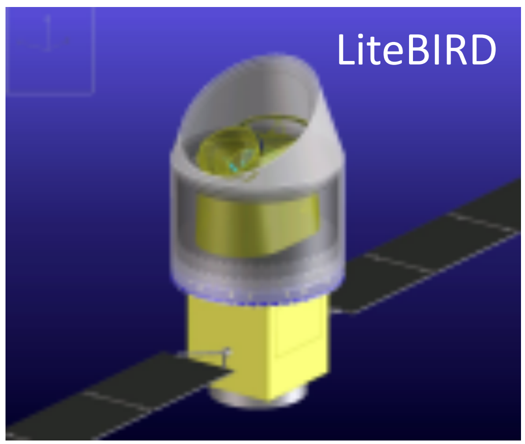
Previously proposed CMB projects

CNES 2006

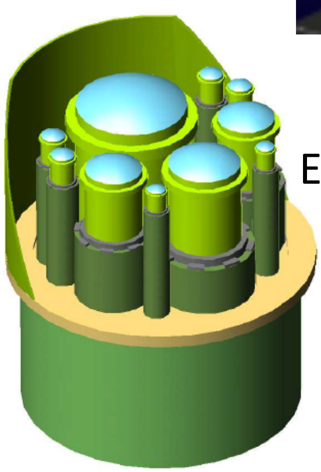


SAMPAN

JAXA 2008



ESA 2007

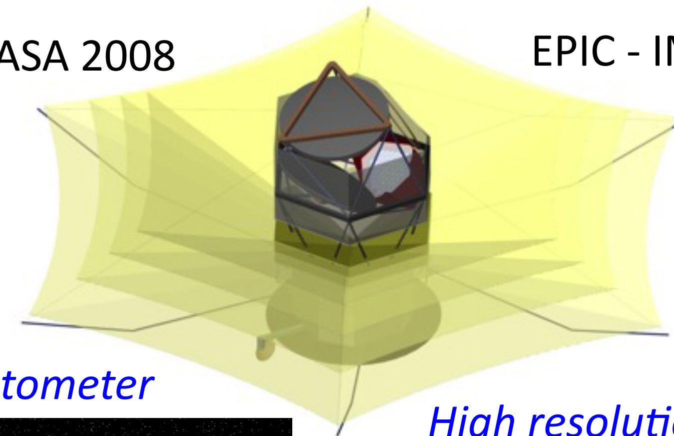


BPOL

Low resolution
Limited frequency coverage
Primary CMB B-modes

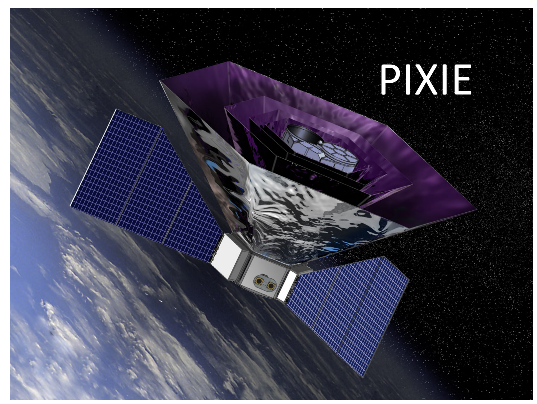
NASA 2008

EPIC - IM



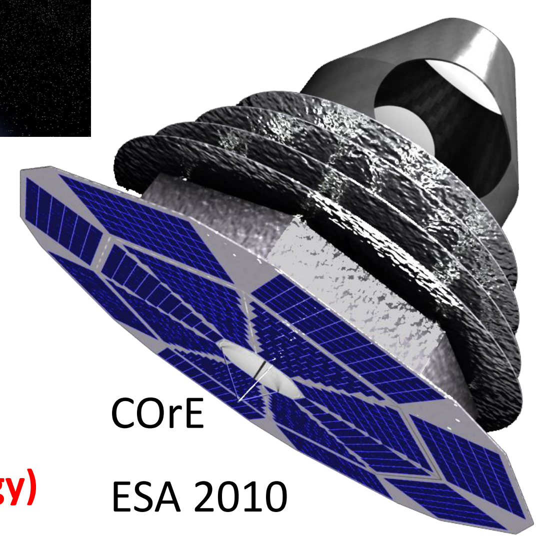
High resolution

Absolute spectrophotometer



NASA

Many frequency bands



COrE

ESA 2010

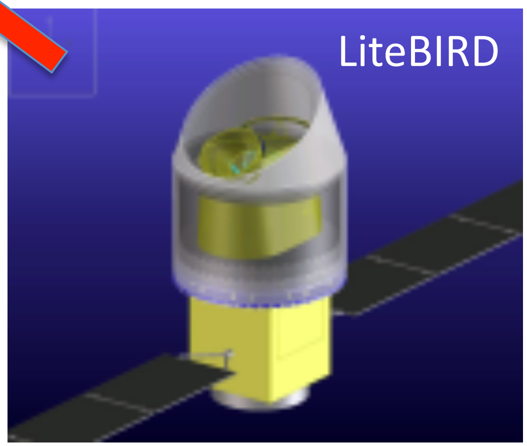
More comprehensive science cases
(sub-mm astronomy)
(astrophysical cosmology)

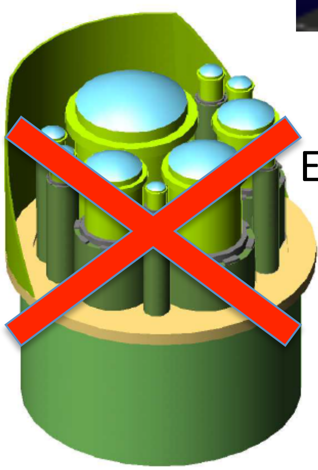
Previously proposed CMB projects

CNES 2006

SAMPAN

JAXA 2008





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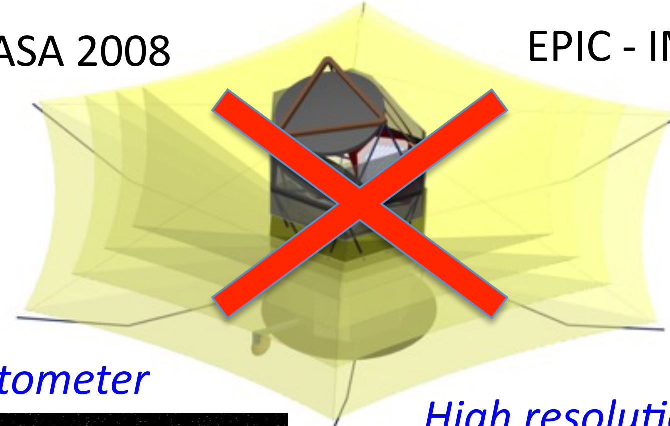
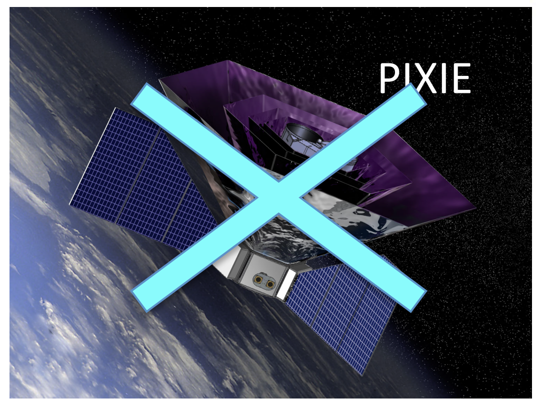


Absolute spectrophotometer

High resolution



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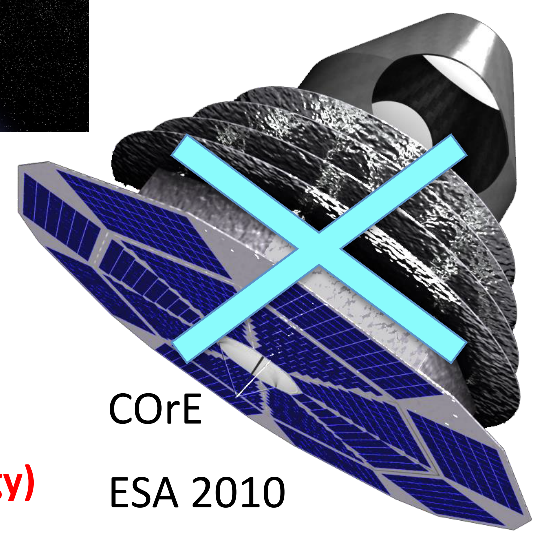

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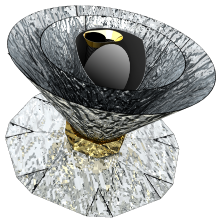

An “ideal” mission

IDEA: survey the complete sky in total intensity and polarisation from 30 GHz to 6 THz with two instruments jointly operated:

- A polarimetric imager with a 3.5 m mirror actively cooled to 4 K
  - 32 large frequency channels with $\Delta\nu/\nu \approx 0.25$
  - ≈300 narrow bands with $\Delta\nu/\nu \approx 0.025$

- An absolute spectro-photometer with a 50 cm mirror, and two operation modes ($\Delta\nu$=0.5 GHz and $\Delta\nu$=15 GHz), for two compromises between spectral resolution and sensitivity.
  - Measure the zero-level of maps at all frequencies
  - Absolute calibration of the polarimetric imager on sky data

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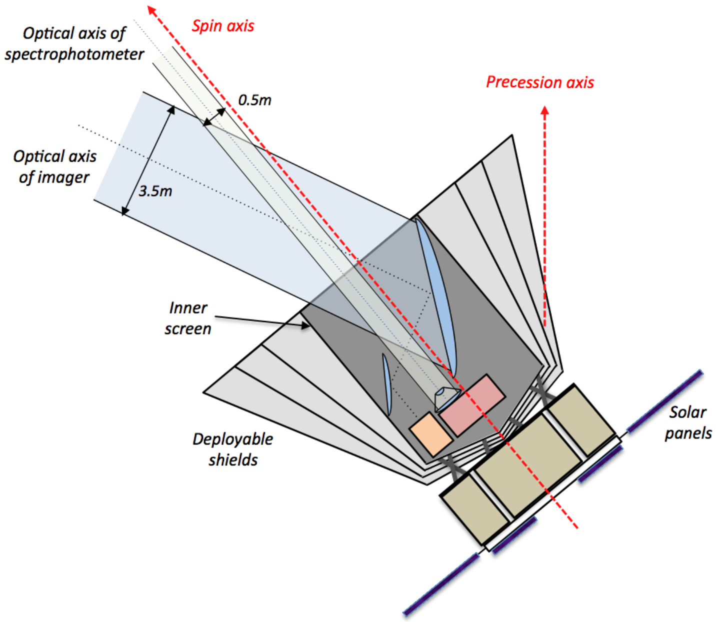
IDEA: a few well-identified areas for science breakthrough + a legacy survey useful for many scientific applications, with a very large discovery potential.

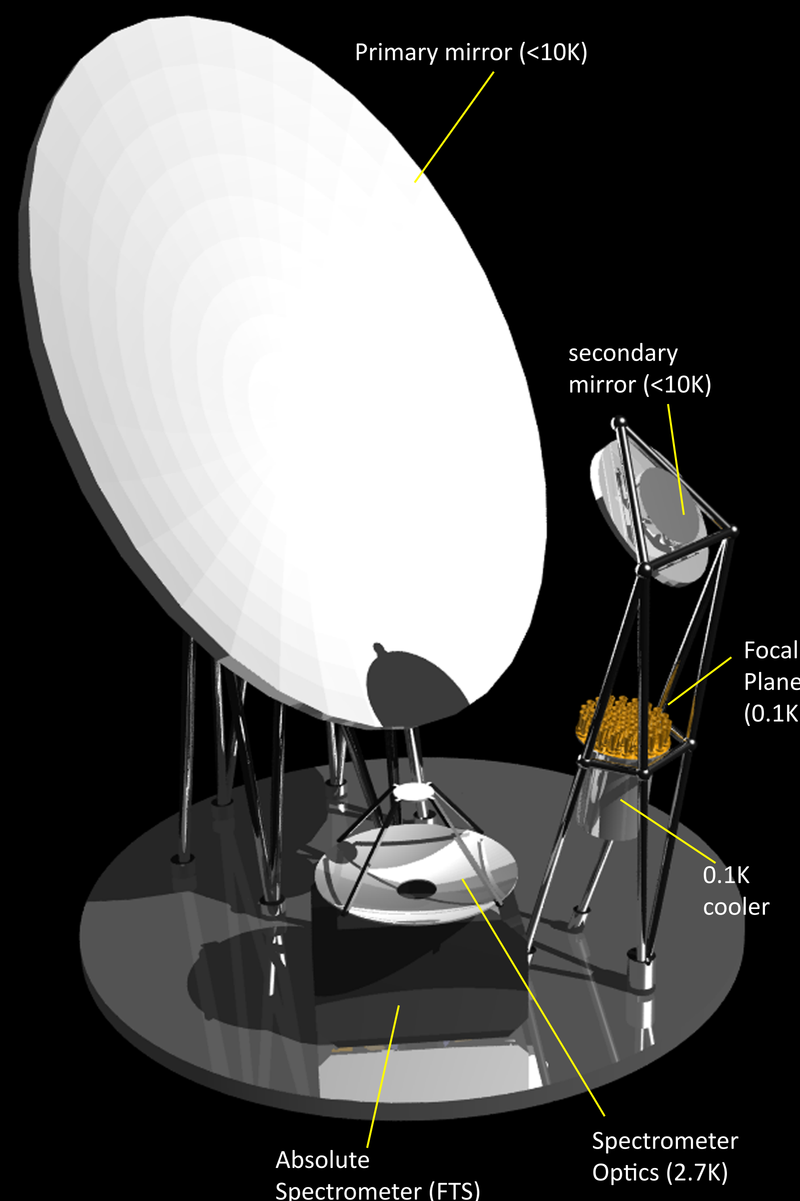


Polarimetric Imager

Think PLANCK + Full sky Herschel-SPIRE
- 10 – 100 times more sensitive
- Many more frequency channels
- Polarised
- 1-3 times better angular resolution

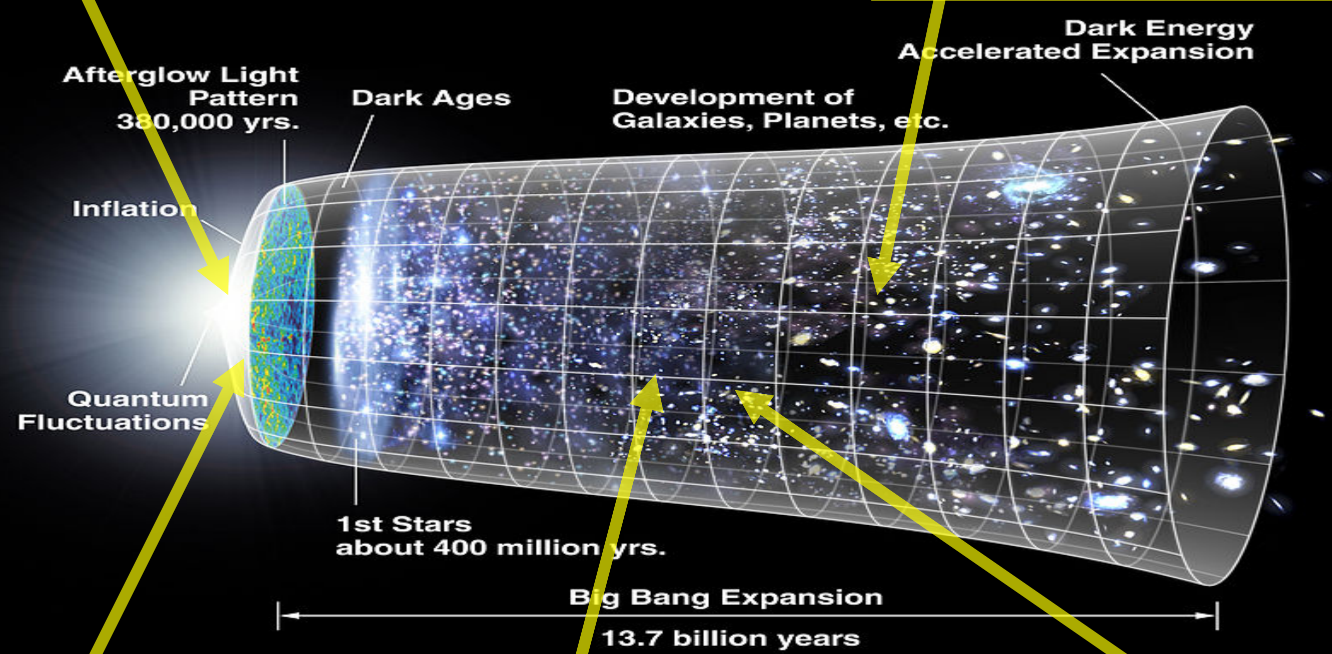
Absolute spectrophotometer

Think *COBE*/FIRAS
- 1000 times more sensitive
- 3 times better angular resolution



Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.

Ultimate galaxy cluster survey via Sunyaev-Zeldovich effect (SZ): ($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)



Probe epochs before recombination and new physics using CMB spectral distortion measurements

Map the gravitational potential all the way to z=1100 through CMB lensing

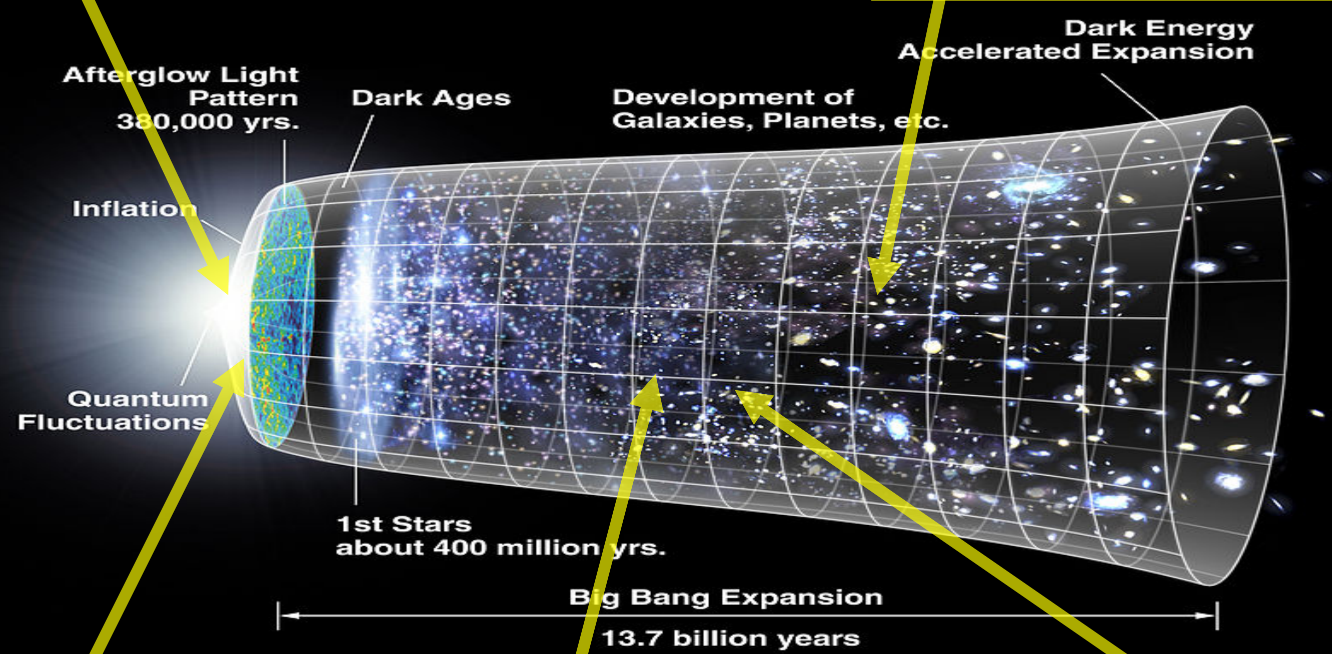
Probe early star formation and its evolution through precision characterization of the Cosmic Infrared Background (CIB)

2

Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.

4

Ultimate galaxy cluster survey via Sunyaev-Zeldovich effect (SZ):
($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)



1

Probe epochs before recombination and new physics using CMB spectral distortion measurements

3

Map the gravitational potential all the way to z=1100 through CMB lensing

5

Probe early star formation and its evolution through precision characterization of the Cosmic Infrared Background (CIB)

PLANCK

CHANNEL	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	SCANNING BEAM[c] FWHM [arcm]	Ellipticity	NOISE[d] SENSITIVITY [$\mu K_{RJ}\ s^{1/2}$]	[$\mu K_{CMB}\ s^{1/2}$]
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.0259[d]
857 GHz	4	857	4.51	1.38	1.33	0.0259[d]

PRISM

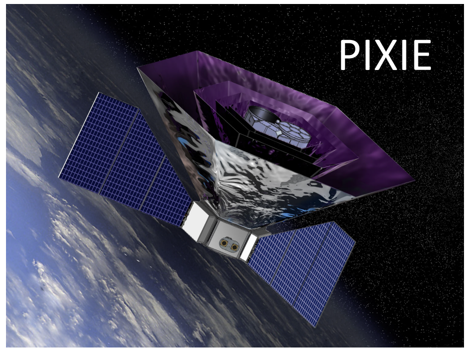
ν_0 GHz	range GHz	$\Delta\nu/\nu$	n_{det}	θ_{fwhm}	σ_I per det 1 arcmin μK_{RJ}	μK_{CMB}	$\sigma_{(Q,U)}$ per det 1 arcmin μK_{RJ}	μK_{CMB}
30	26-34	.25	50	17'	61.9	63.4	87.6	89.7
36	31-41	.25	100	14'	57.8	59.7	81.7	84.5
43	38-48	.25	100	12'	53.9	56.5	76.2	79.9
51	45-59	.25	150	10'	50.2	53.7	71.0	75.9
62	54-70	.25	150	8.2'	46.1	50.8	65.2	71.9
75	65-85	.25	150	6.8'	42.0	48.5	59.4	68.6
90	78-100	.25	200	5.7'	38.0	46.7	53.8	66.0
105	95-120	.25	250	4.8'	34.5	45.6	48.8	64.4
135	120-150	.25	300	3.8'	28.6	44.9	40.4	63.4
160	135-175	.25	350	3.2'	24.4	45.5	34.5	64.3
185	165-210	.25	350	2.8'	20.8	47.1	29.4	66.6
200	180-220	.20	350	2.5'	18.9	48.5	26.7	68.6
220	195-250	.25	350	2.3'	16.5	50.9	23.4	71.9
265	235-300	.25	350	1.9'	12.2	58.5	17.3	82.8
300	270-330	.20	350	1.7'	9.6	67.1	13.6	94.9
320	280-360	.25	350	1.6'	8.4	73.2	11.8	103
395	360-435	.20	350	1.3'	4.9	107	7.0	151
460	405-520	.25	350	1.1'	3.1	156	4.4	221
555	485-625	.25	300	55"	1.6	297	2.3	420
660	580-750	.25	300	46"	0.85	700	1.2	990

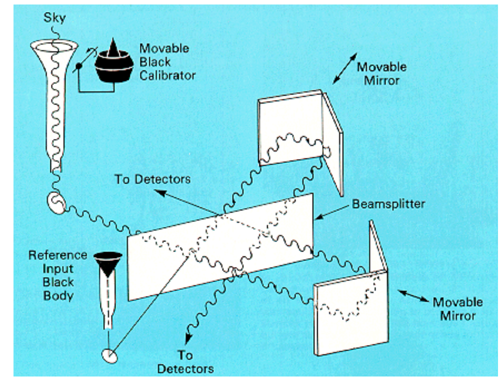
N_{det} x 100
$N_{channel}$ x 3.5 (+ narrow bands)
ν_{max}/ν_{min} x 7

Angular resolution x 2

					nK$_{RJ}$	kJy/sr	nK$_{RJ}$	kJy/sr
800	700-900	.25	200	38"	483	9.5	683	13.4
960	840-1080	.25	200	32"	390	11.0	552	15.6
1150	1000-1300	.25	200	27"	361	14.6	510	20.7
1380	1200-1550	.25	200	22"	331	19.4	468	27.4
1660	1470-1860	.25	200	18"	290	24.5	410	34.7
1990	1740-2240	.25	200	15"	241	29.3	341	41.5
2400	2100-2700	.25	200	13"	188	33.3	266	47.1
2850	2500-3200	.25	200	11"	146	36.4	206	51.4
3450	3000-3900	.25	200	8.8"	113	41.4	160	58.5
4100	3600-4600	.25	200	7.4"	98	50.8	139	71.8
5000	4350-5550	.25	200	6.1"	91	70.1	129	99.1
6000	5200-6800	.25	200	5.1"	87	96.7	124	136

The spectrophotometer

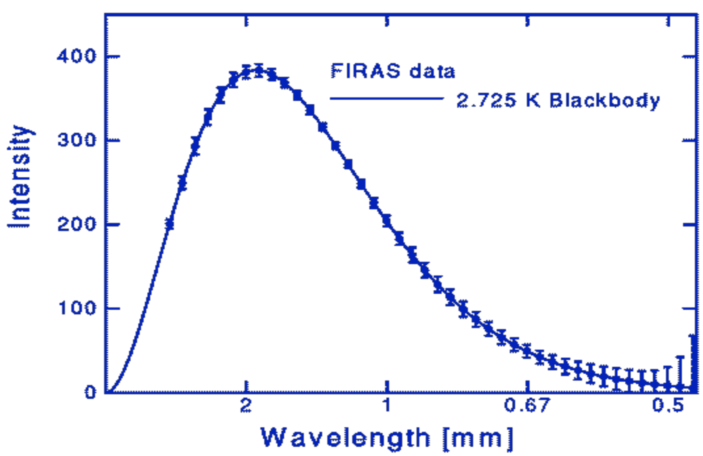


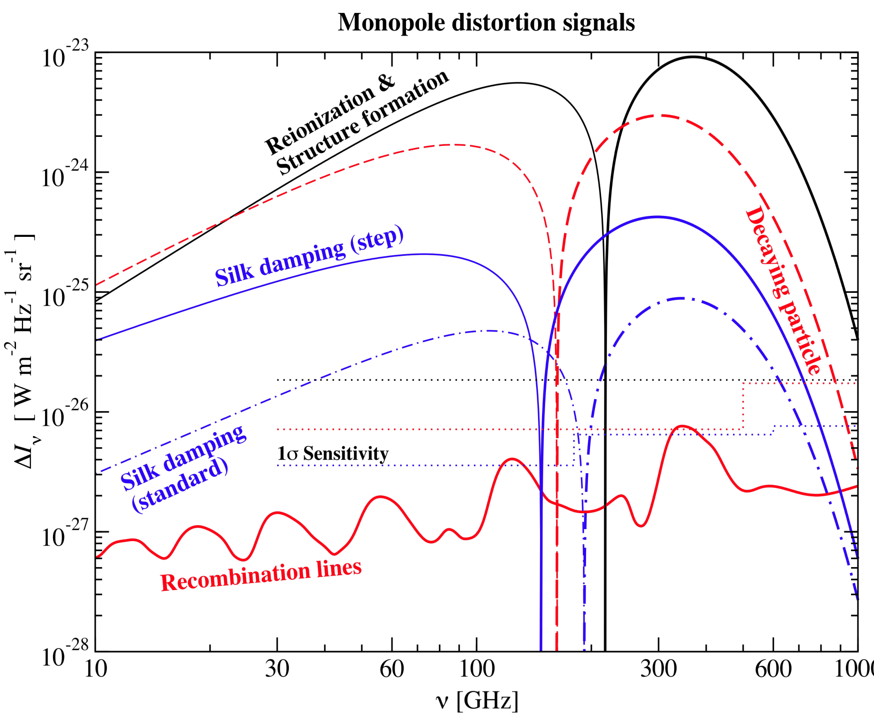


Martin-Puplett FT

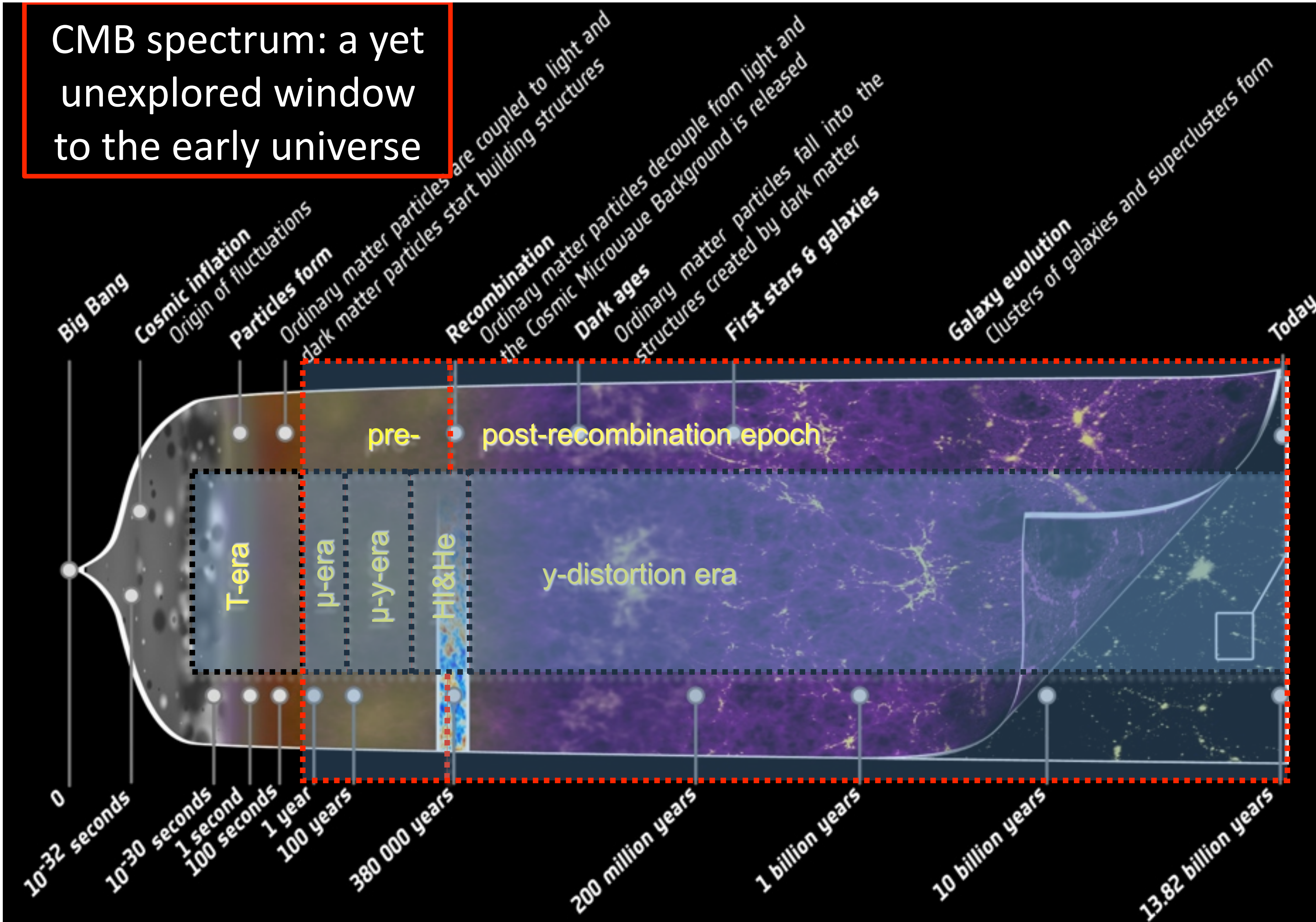
Angular resolution limited to 1.5°

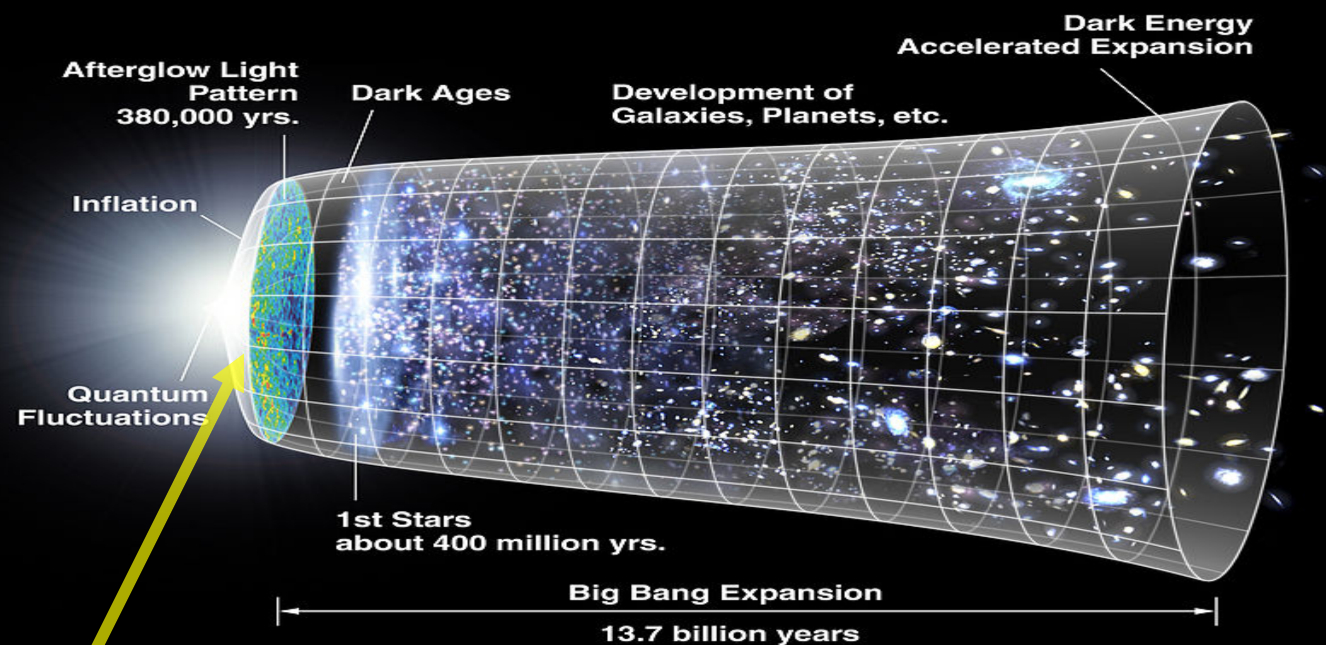
- Multi-moded for sensitivity
- Large beams for scanning / FTS limitations





CMB spectrum: a yet unexplored window to the early universe





1

Probe epochs before recombination and new physics using CMB spectral distortion measurements

- Both instruments observe through the same zodiacal emission and detect variable sources simultaneously
- Imager helps for foreground contamination in spectrophotometer data.
- Absolute spectrometer data set the zero-level of the imager maps.
- Absolute spectrometer data provide an accurate calibration of the imager channels. The absolute calibration is transferred to the imager.

Outline

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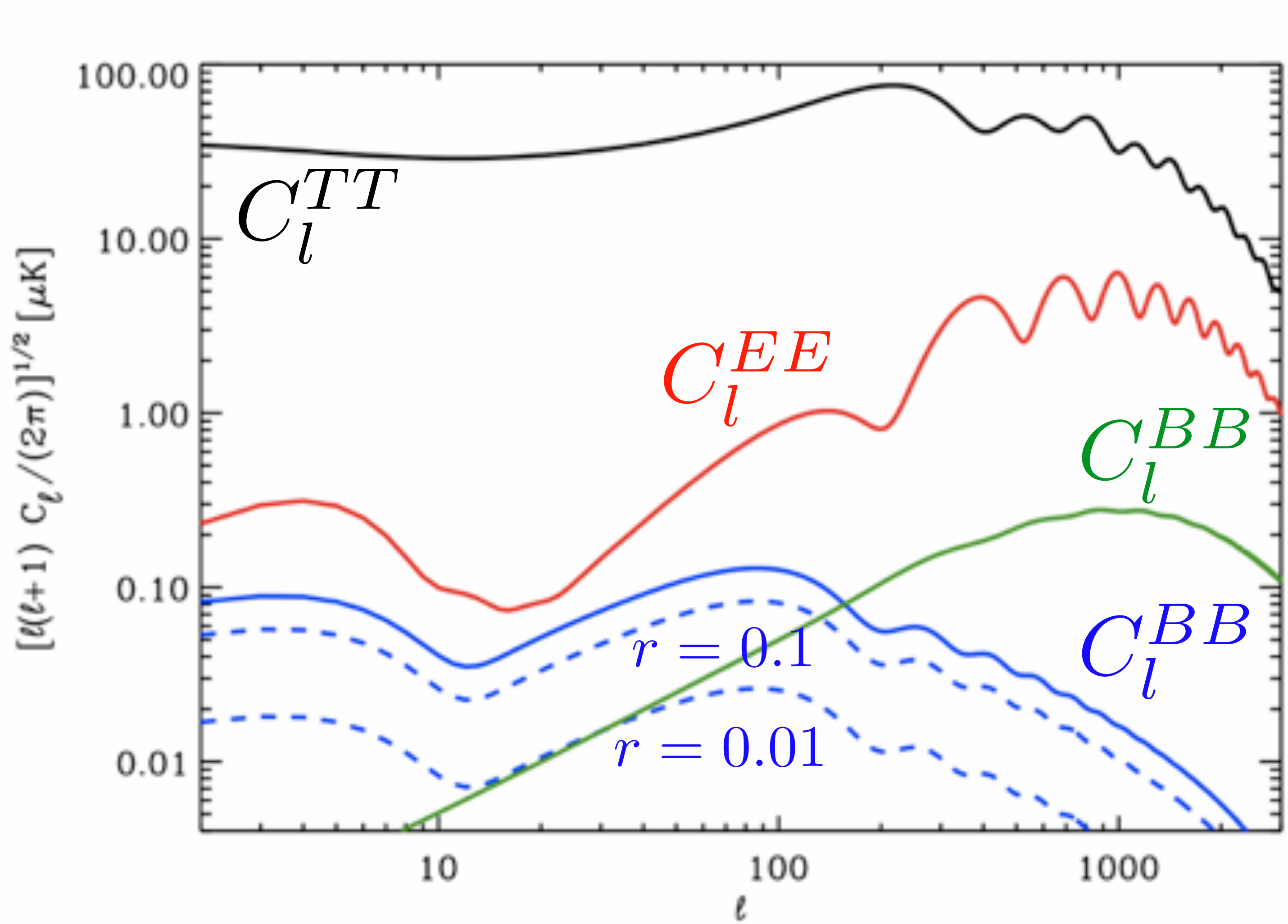
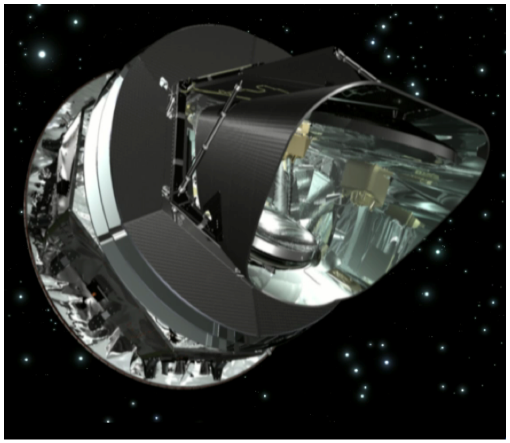
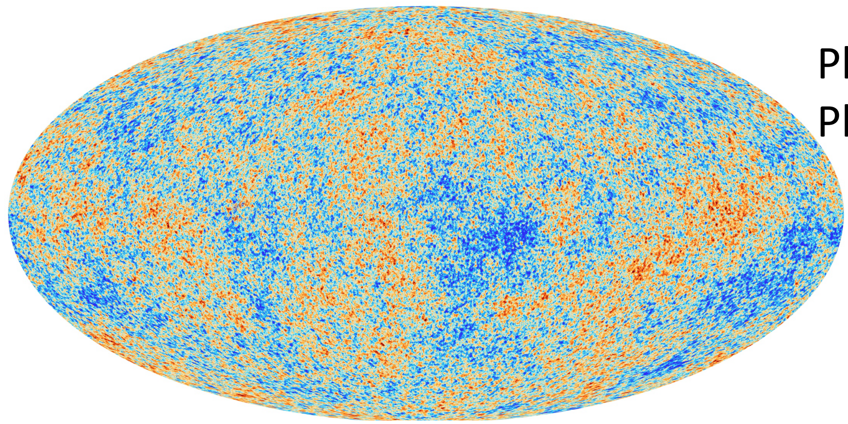
- Conclusion

Temperature & Polarisation CMB C_l

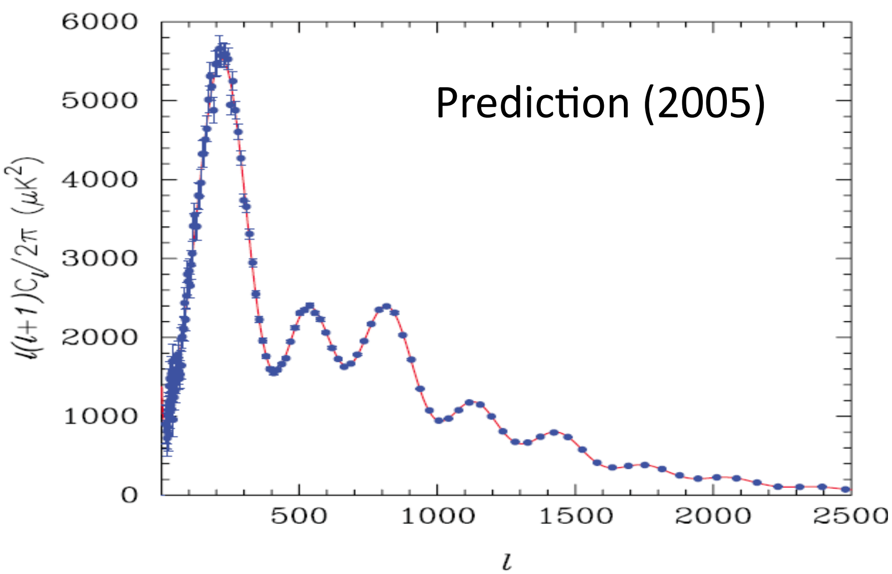


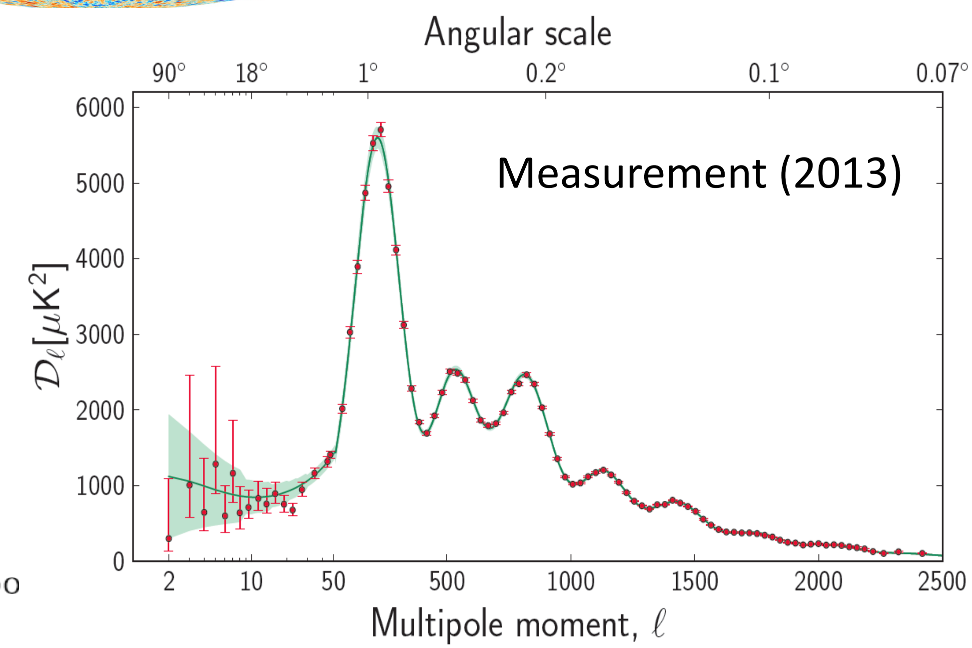
The Planck view of CMB anisotropies



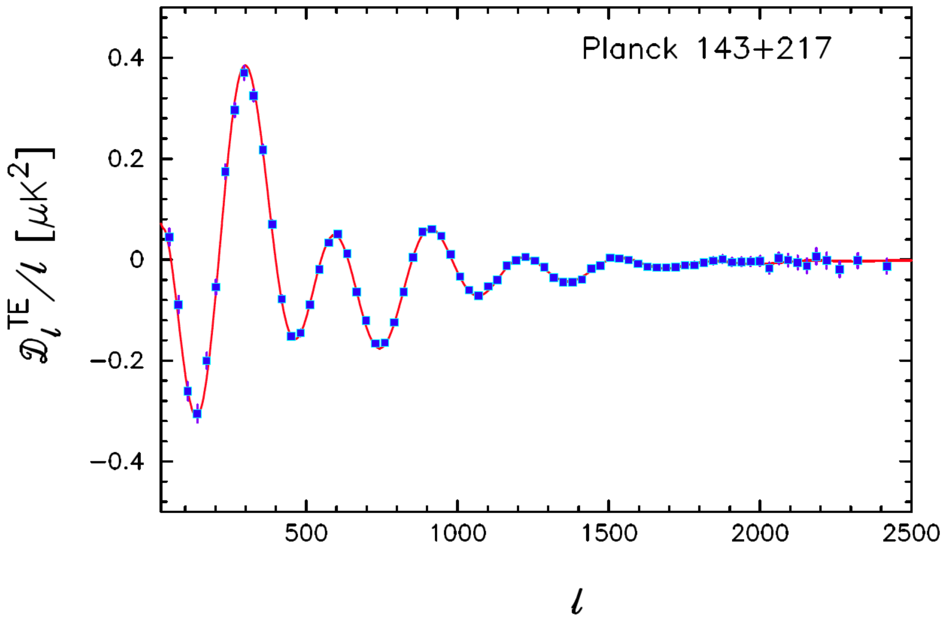


Planck 2013 results. XII.
Planck 2013 results. XV.





Polarisation spectrum in agreement



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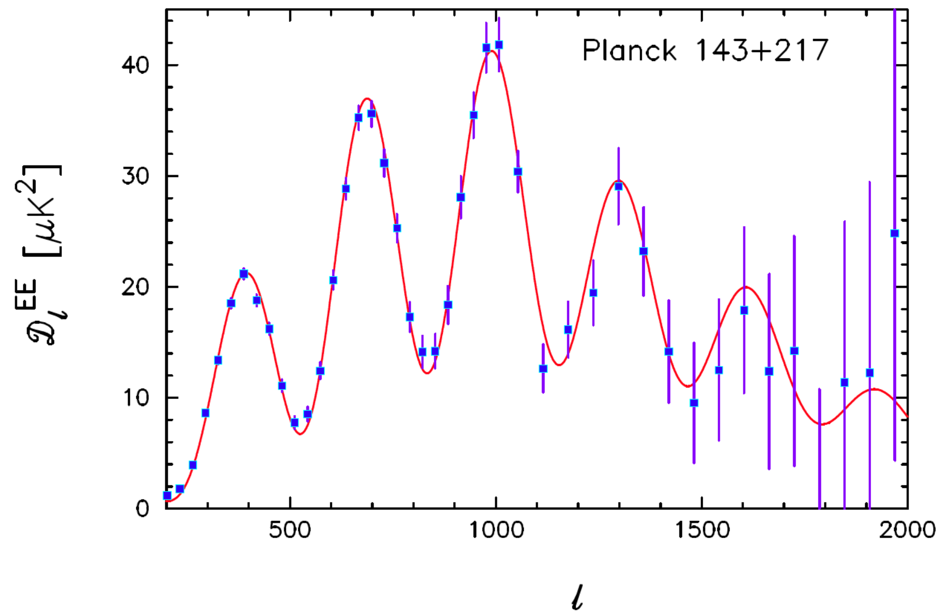
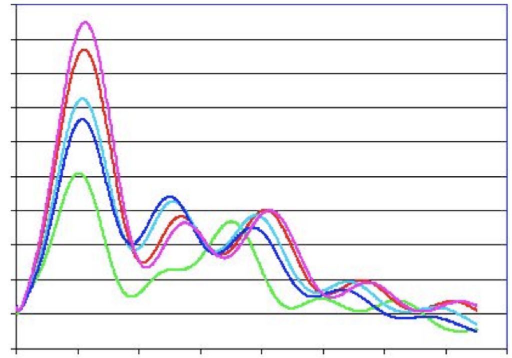
EE



Red curves: prediction based solely on the temperature best fit.

Planck: 6-parameter fit

Parameter	Planck Best fit	Planck 68% limits	Planck+WP Best fit	Planck+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14305	0.1426 ± 0.0025
Age/Gyr	13.819	13.813 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.48	1090.43 ± 0.54
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{eq}	3402	3386 ± 69	3403	3391 ± 60



- *Baryonic dark matter*
- *Cold dark matter*
- *Approx. to acoustic scale*
- *Reionisation optical depth*
- *Scalar spectral index*
- *Amplitude for k_0=0.05 Mpc^{-1}*

Derived parameters (Ω_Λ through z_{eq})

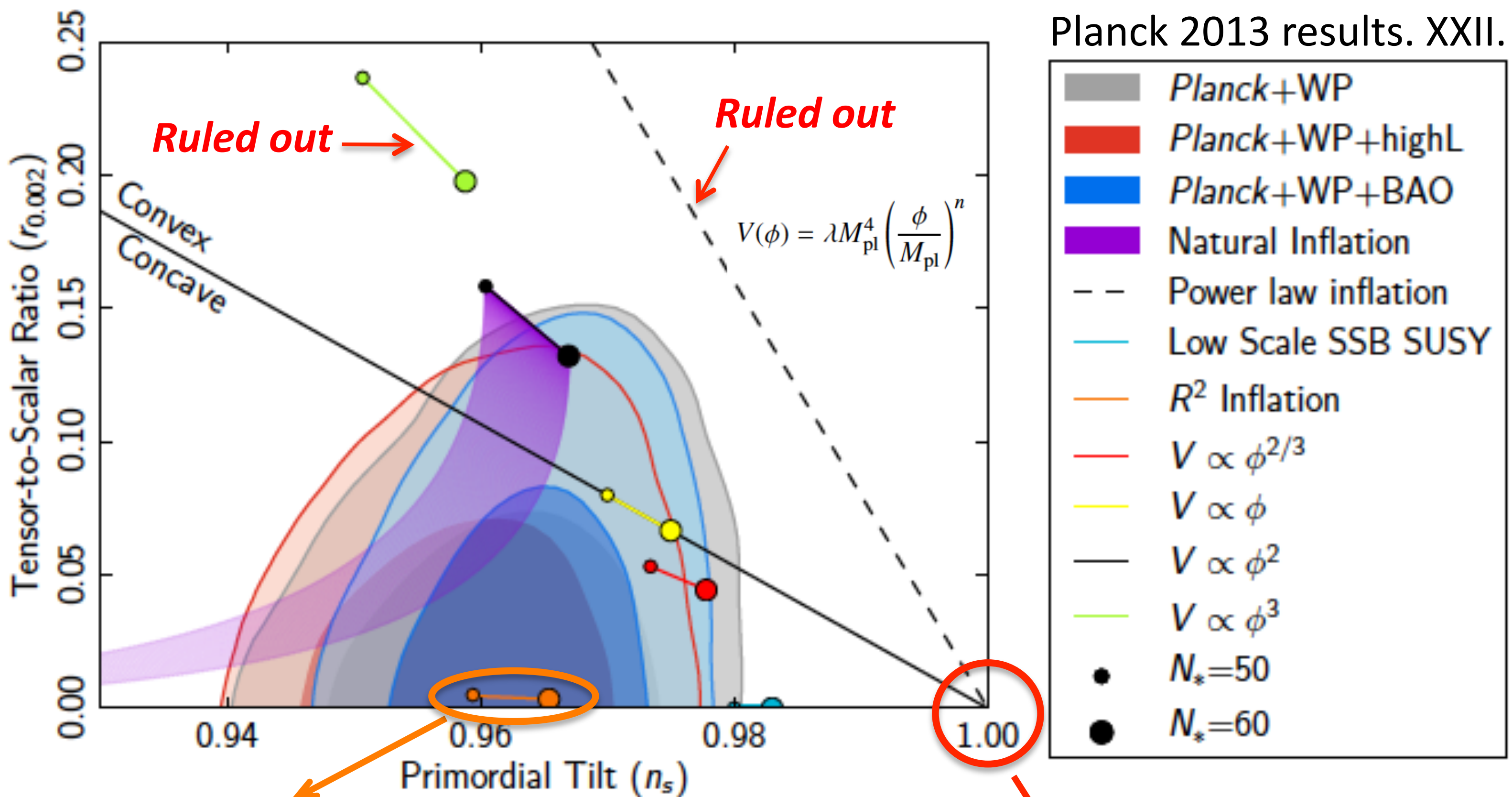
Open questions

Satisfying fit but no answers to some fundamental questions

What is the physics behind inflation ?
Did inflation really occur ?
What are dark matter and dark energy ?

A mission such as PRISM is essential
for investigating these very fundamental questions

Planck constraints on inflation

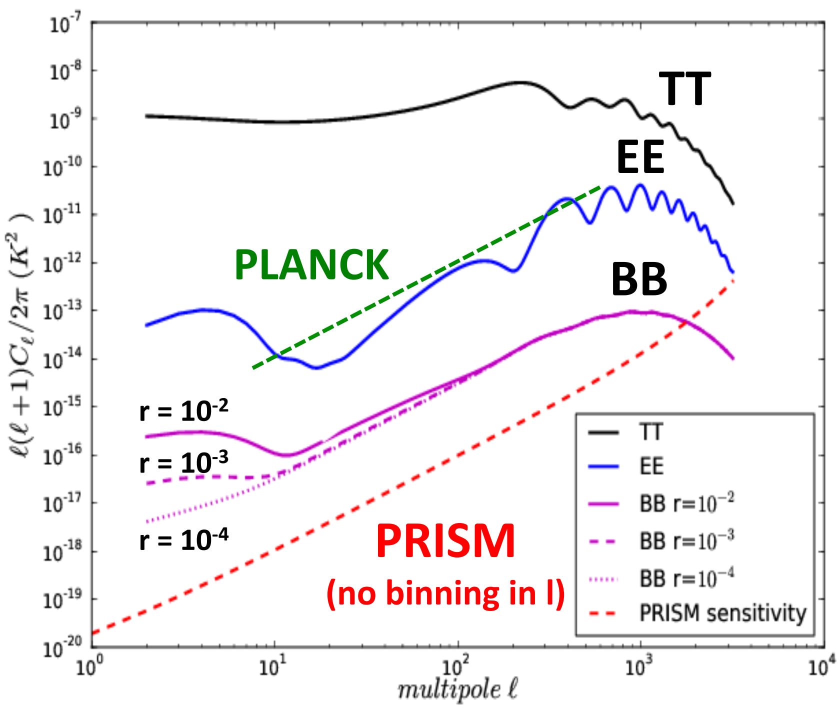


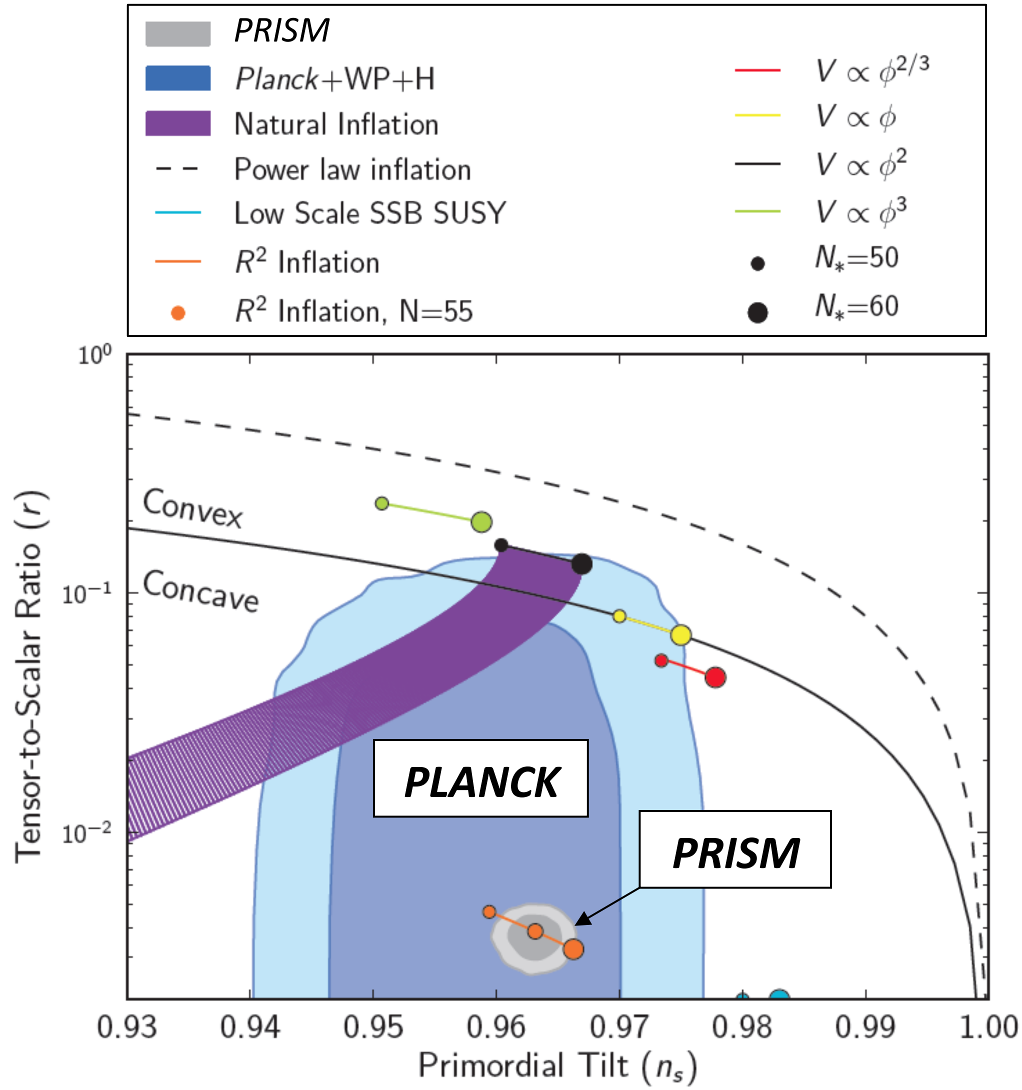
R^2 inflation: r suppressed by a factor N_* and hence low tensor modes

HZ scale invariant spectrum ***ruled out*** at more than 5σ

CMB B-modes and inflation

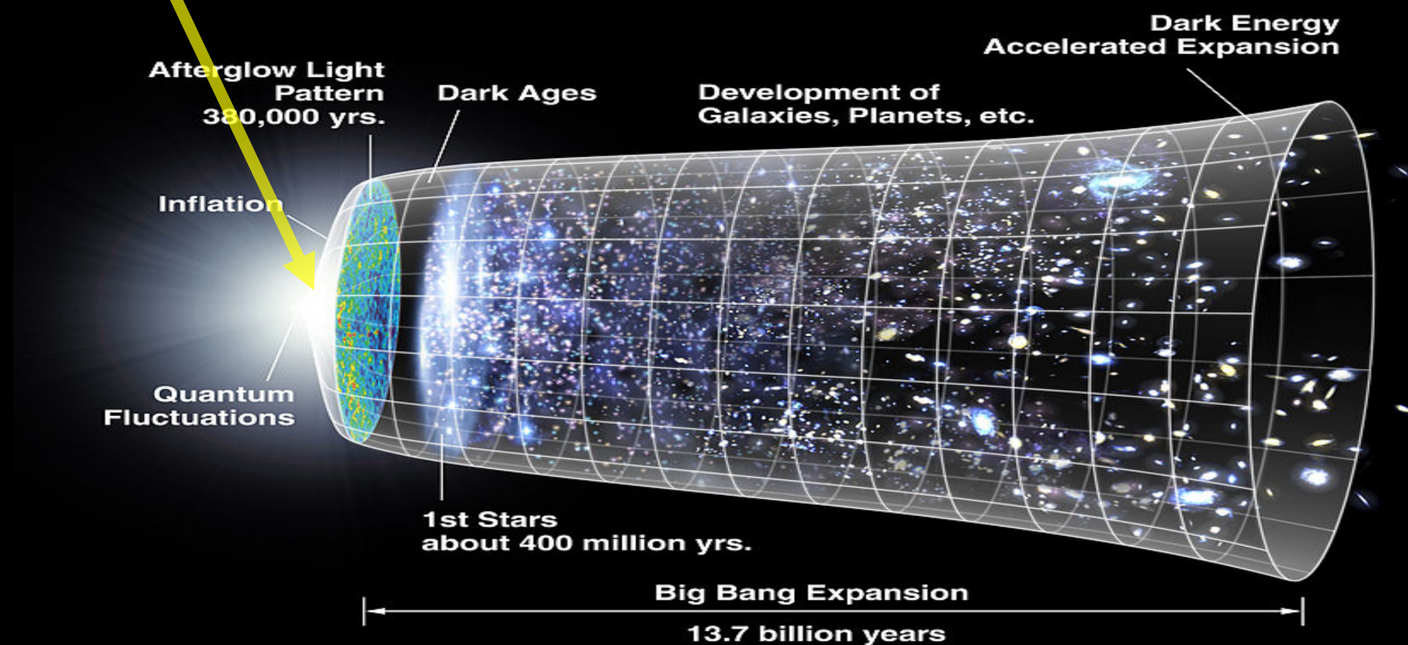
What drives inflation?





2

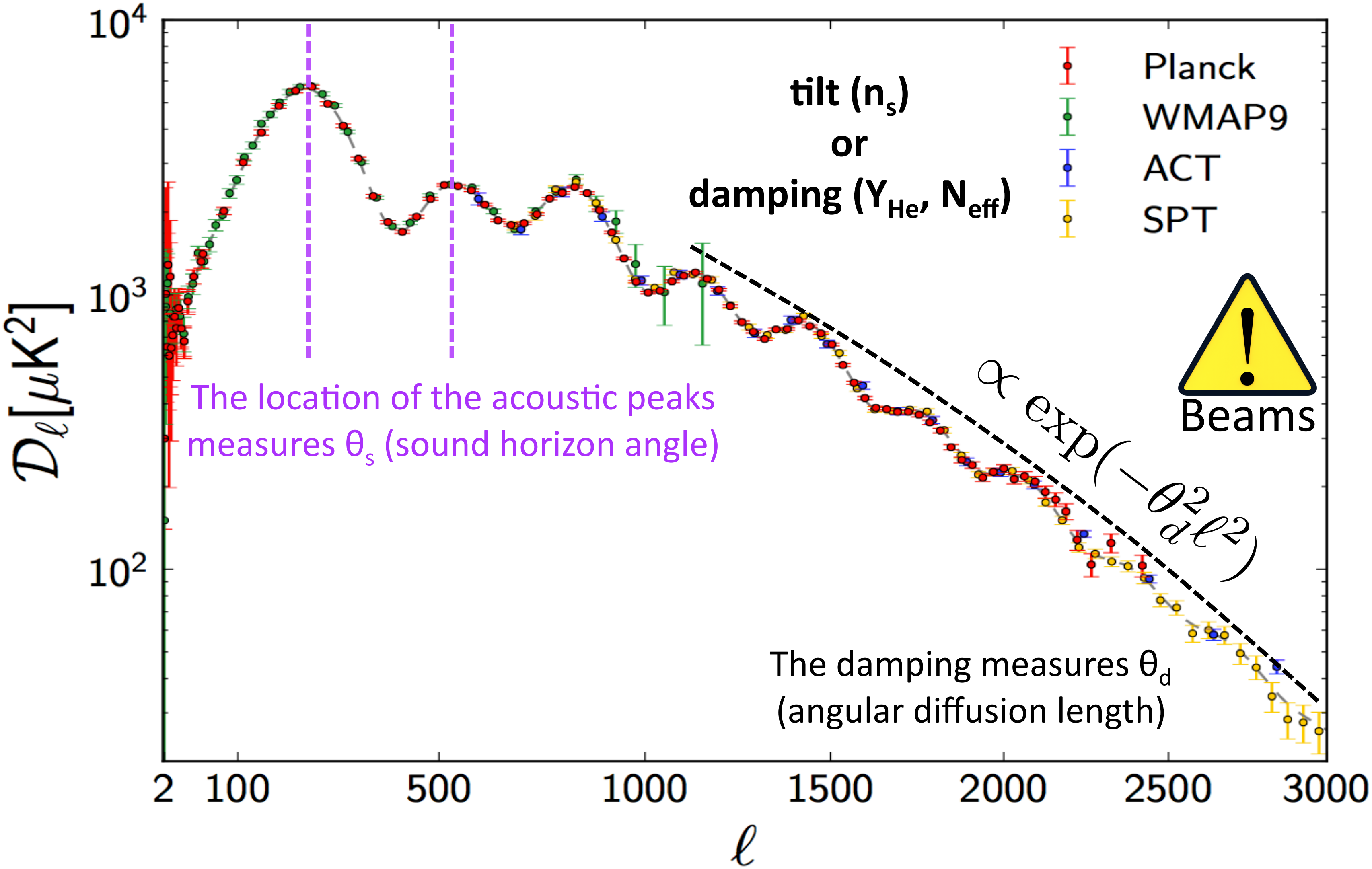
Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.



Other open questions

What about extensions such as varying N_{eff}, Σm_ν, running spectral index, varying the He fraction?

Extensions of the 6-parameter model

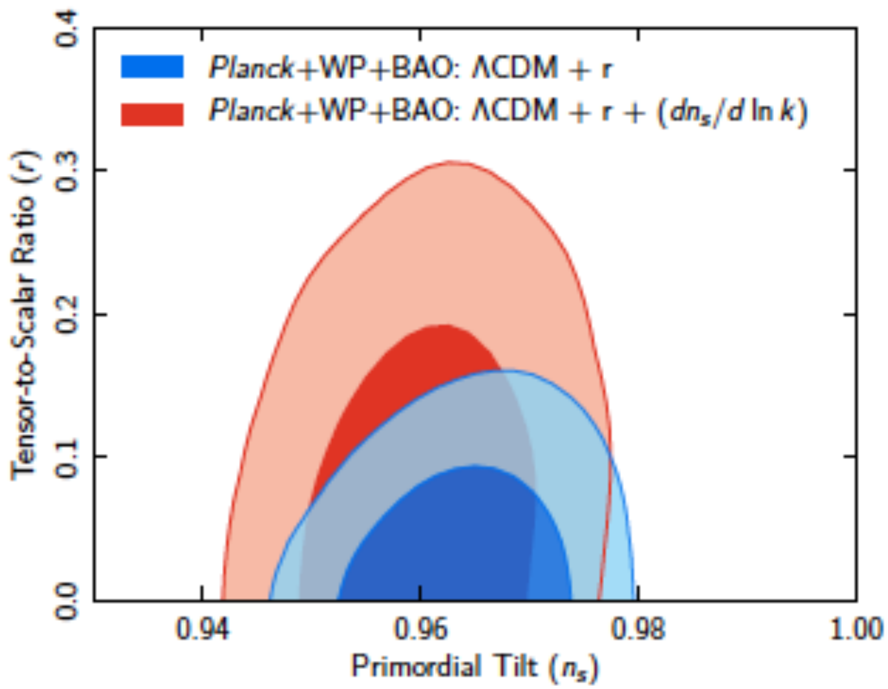


Running of the spectral index

Planck 2013 results. XXII.

$$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{(n_s-1)+\frac{1}{2}\frac{\mathrm{d}n_s}{\mathrm{d}\ln k}\ln(k/k_0)}$$

Depends on next-order slow-roll parameter



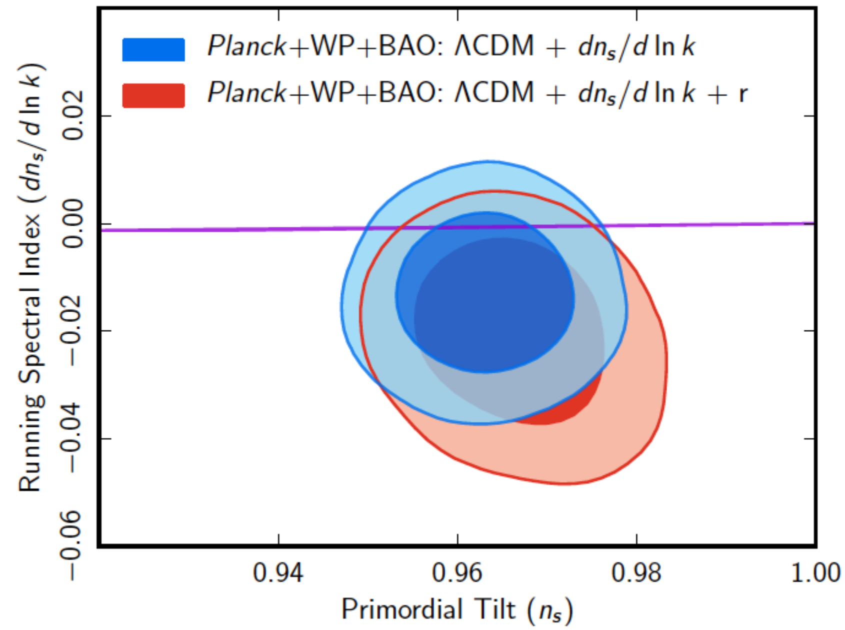
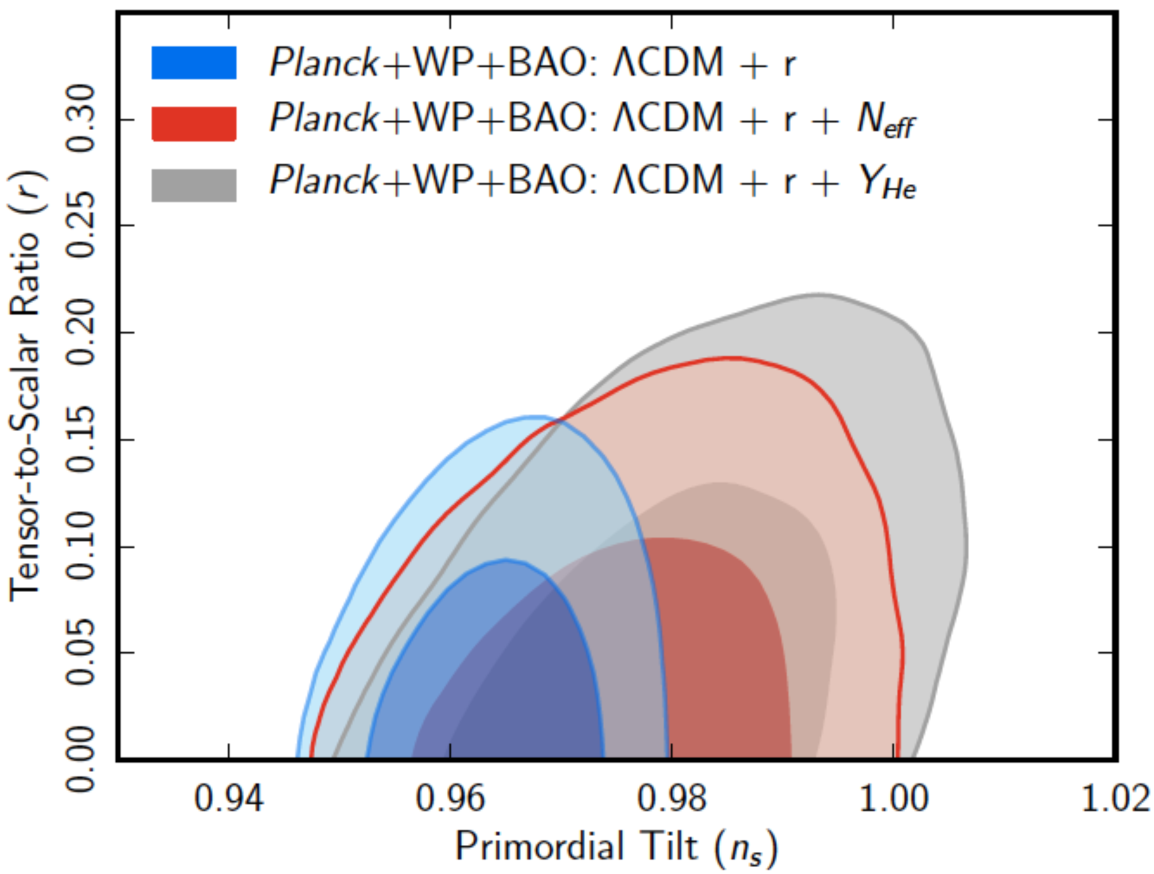


Fig. 2. Marginalized joint 68% and 95% CL for $(\mathrm{d}n_s/\mathrm{d}\ln k, n_s)$ using *Planck*+WP+BAO, either marginalizing over r or fixing $r = 0$ at $k_* = 0.038\ \mathrm{Mpc}^{-1}$. The purple strip shows the prediction for single monomial chaotic inflationary models with $50 < N_* < 60$ for comparison.

Extensions of the 6-parameter model



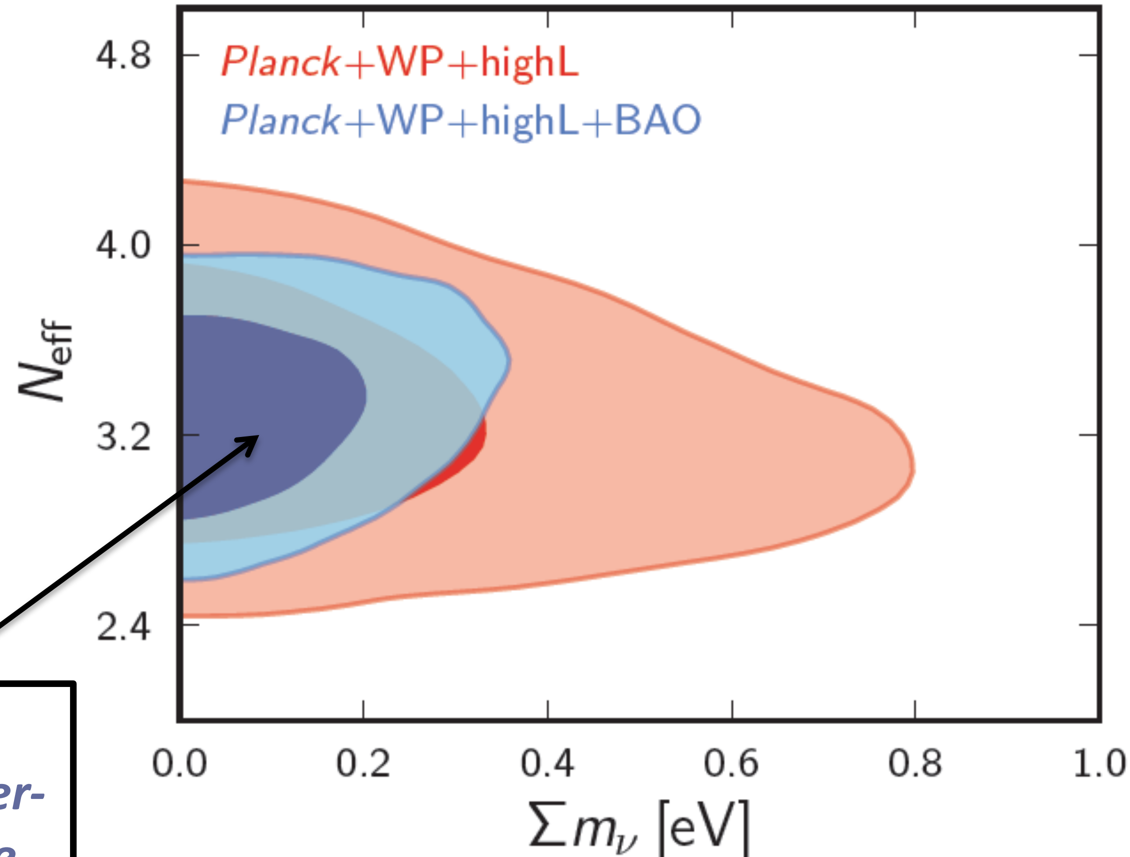
Planck 2013 results. XXII.

Models with extensions to the energy content impacting high-l spectrum yield looser constraints on n_s (and to a lesser extent on r also)

Extensions of the 6-parameter model

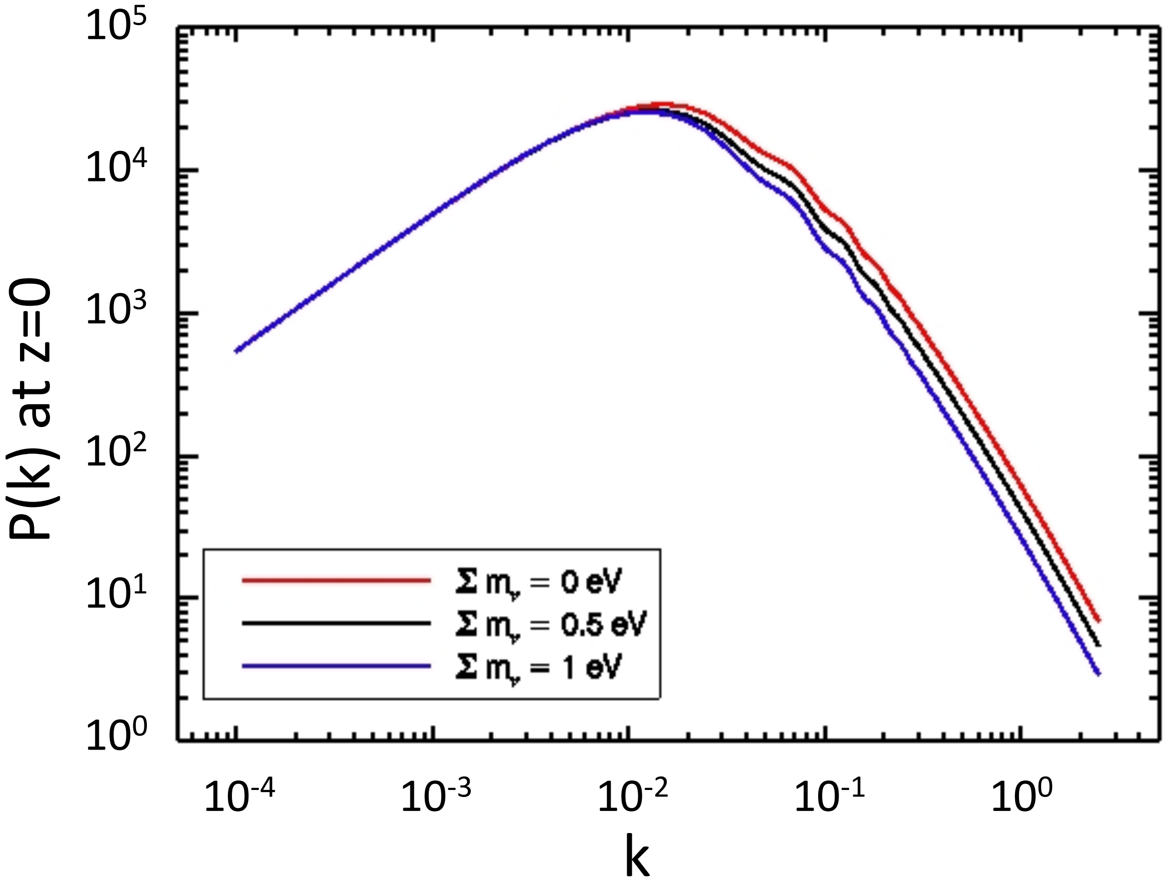
N_{eff} number of relativistic degrees of freedom (assuming here extra massless neutrino species)

Σm_ν mass of three active massive neutrinos



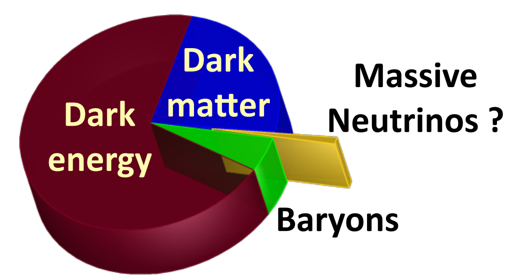
Significant improvement by adding a probe of later-time large scale structure

A handle on neutrino masses



A fundamental question:
Absolute neutrino masses

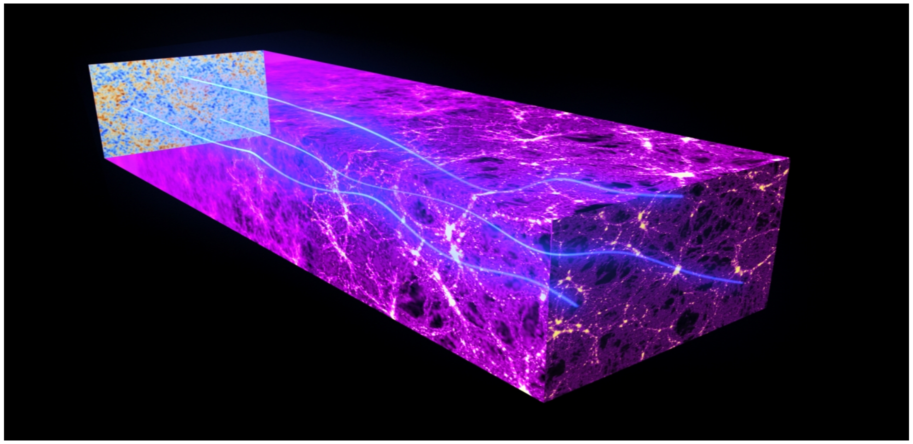
Neutrino hierarchy

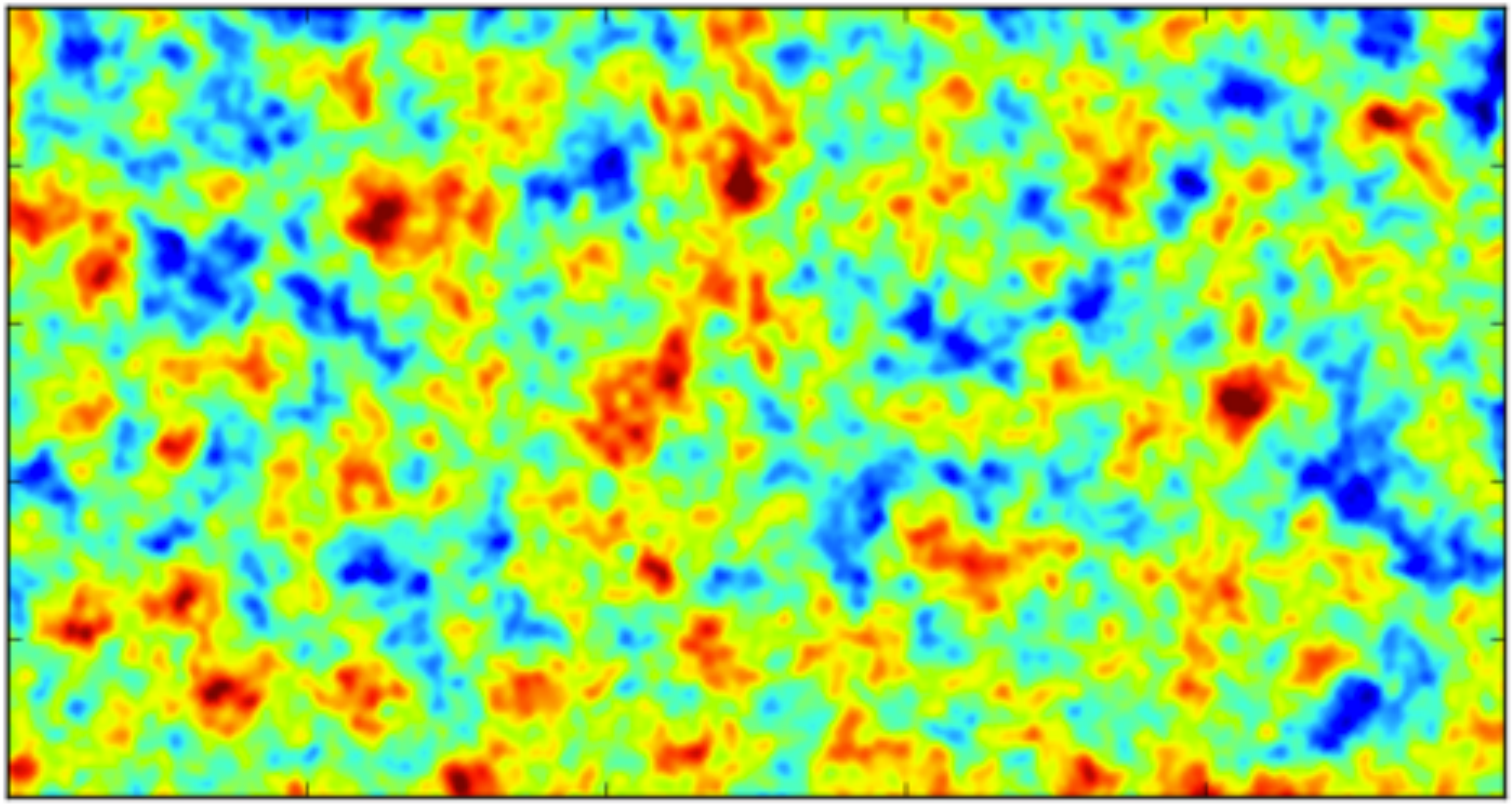


Outline

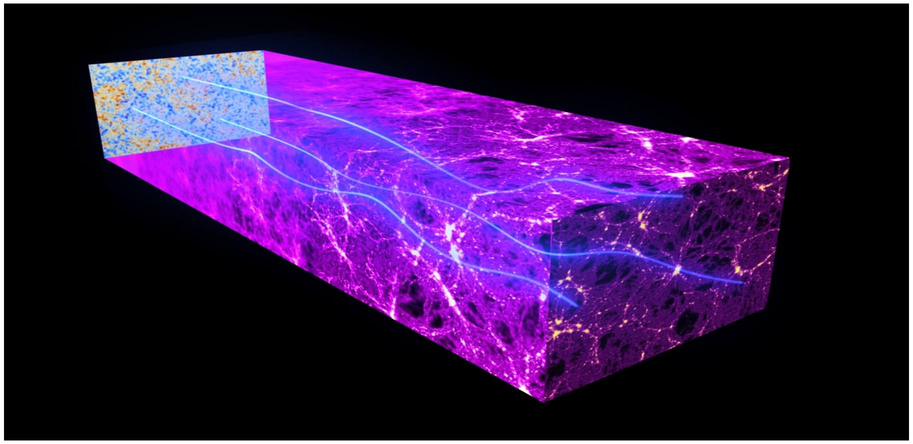
- PRISM
- CMB anisotropies and inflation
- CMB lensing
- Clusters of galaxies
- Astrophysical cosmology
- The galactic ISM
- Conclusion

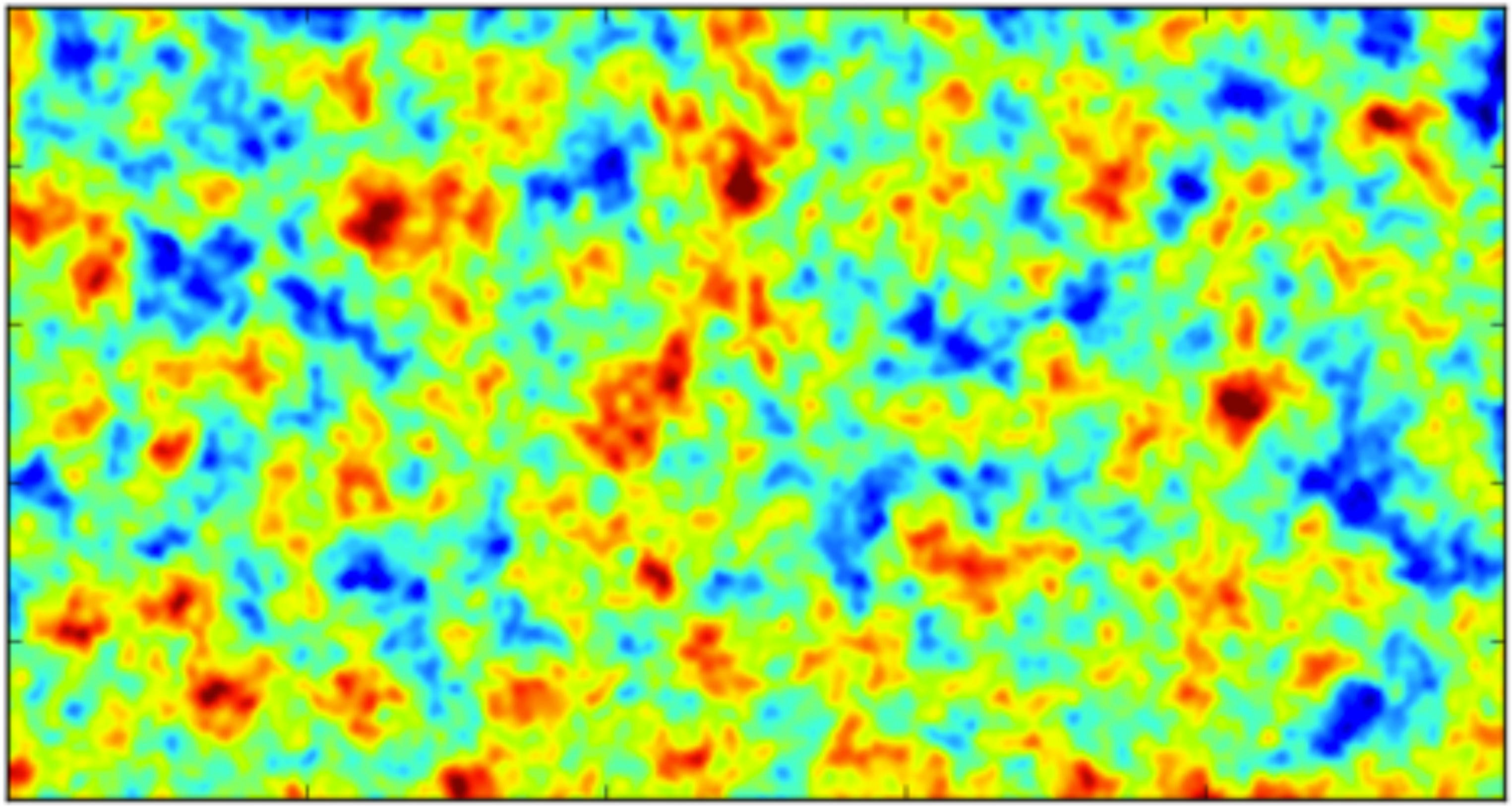
Lensing



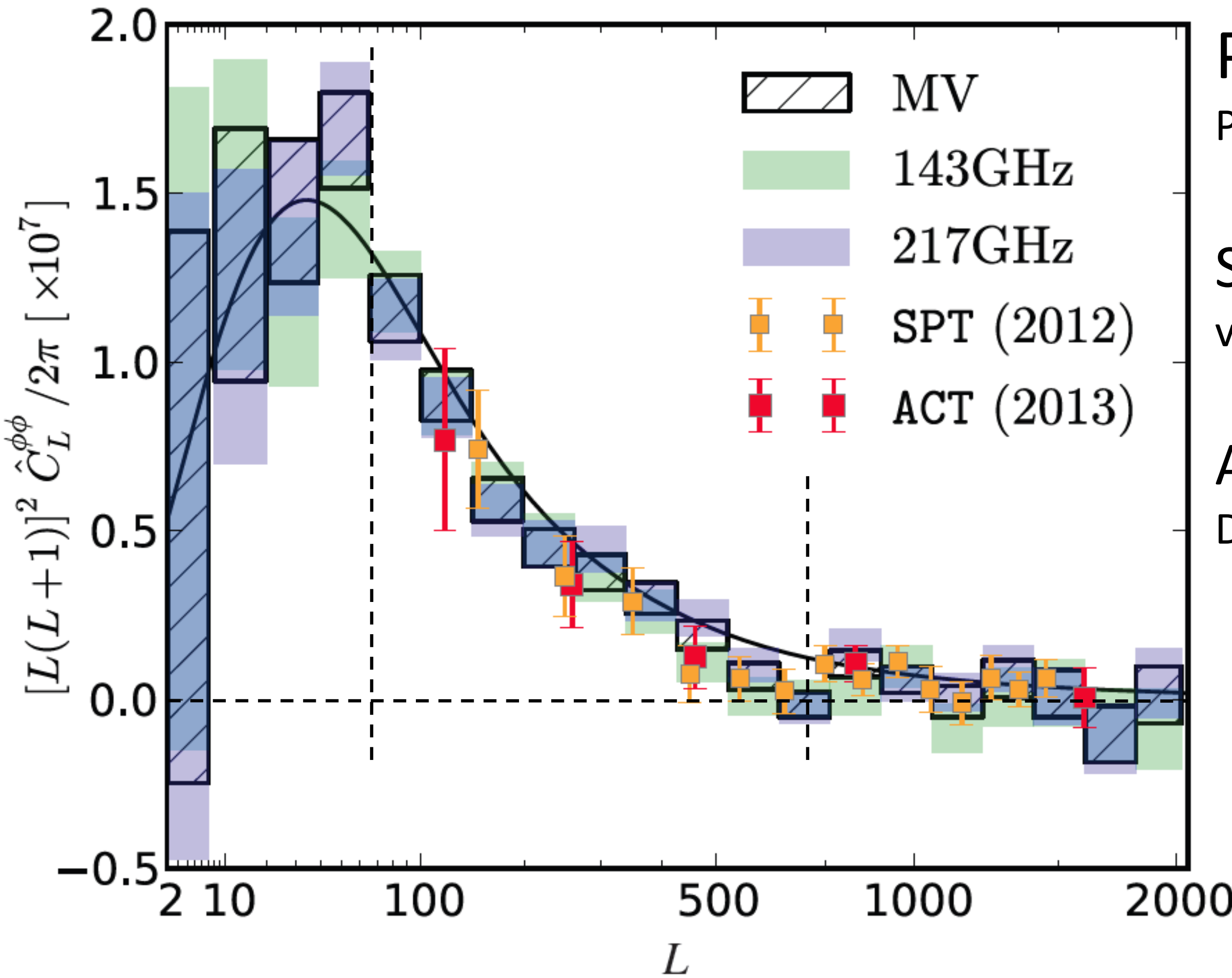


Lensing





Lensing potential power spectrum



Planck

Planck 2013 results. XVII.

SPT

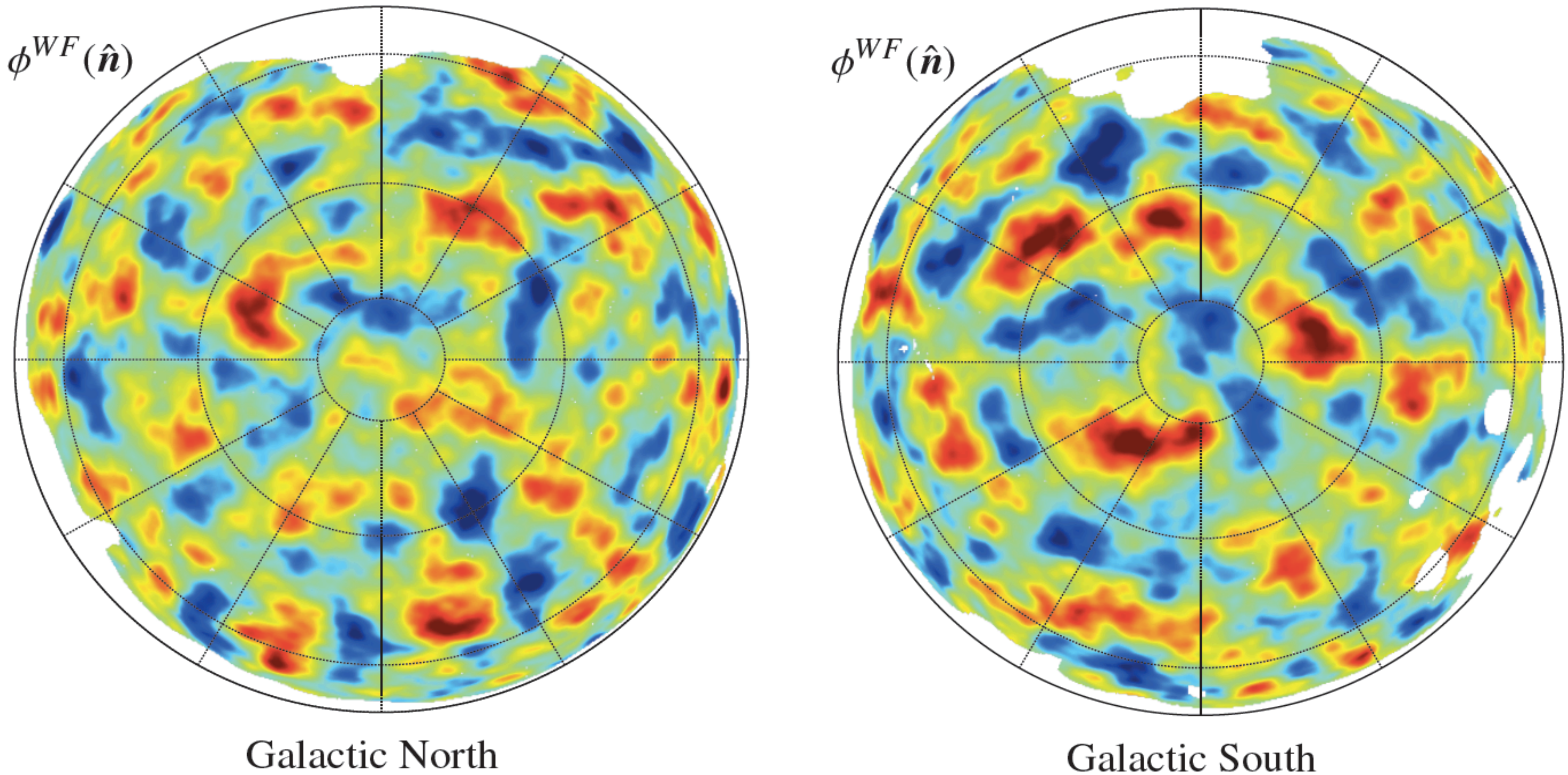
van Engelen et al 2012

ACT

Das et al 2013

Reconstruction of the lensing potential

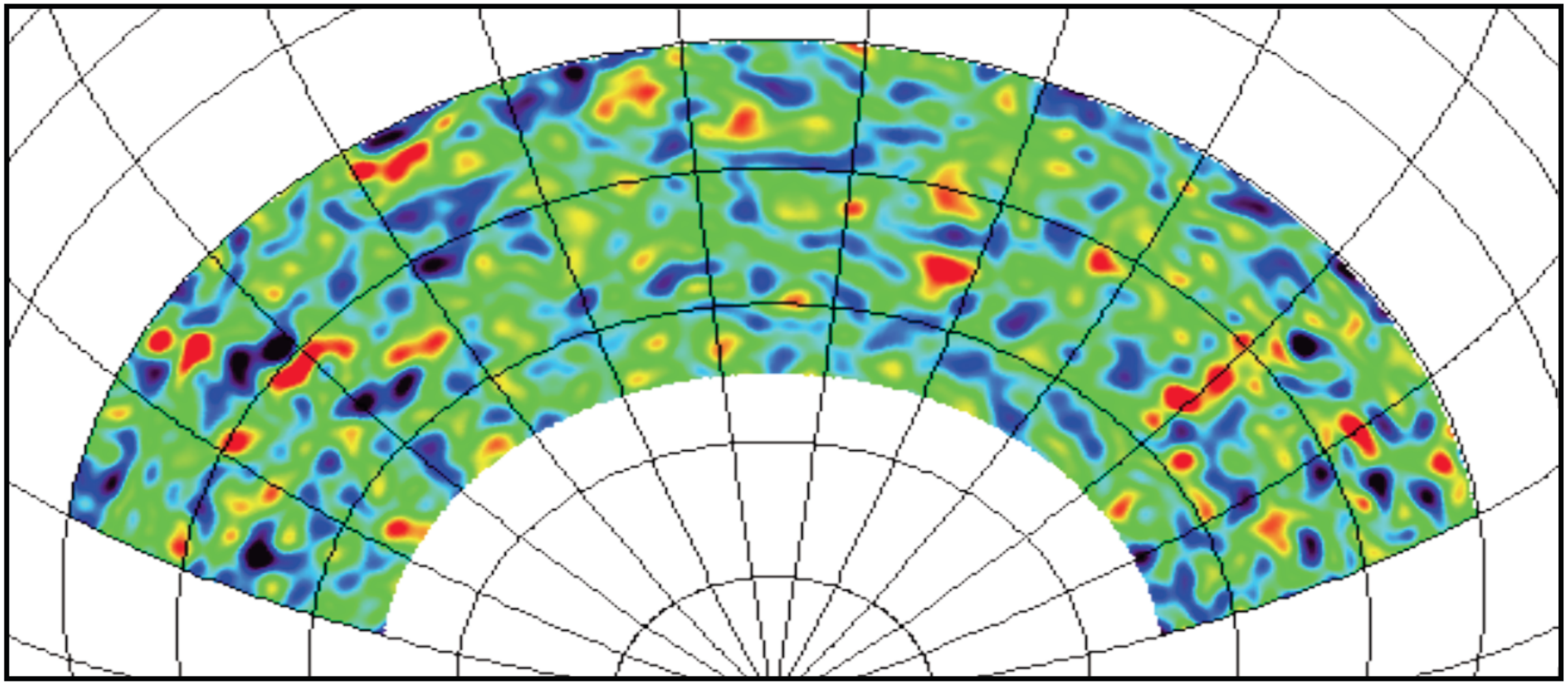
Planck 2013 results. XVII.



The reconstruction is noisy (S/N ≈0.6 – more noise than signal here)

Reconstruction of the lensing potential

With South Pole Telescope, 6% of sky



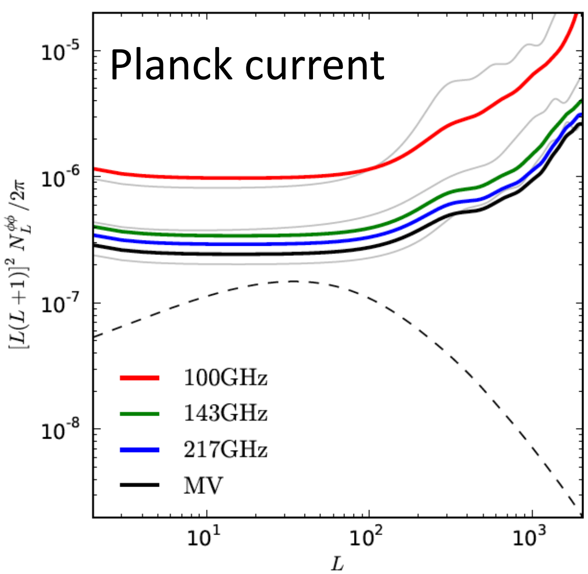
From John Carlstrom
Talk at the P5 workshop, SLAC, dec. 2013

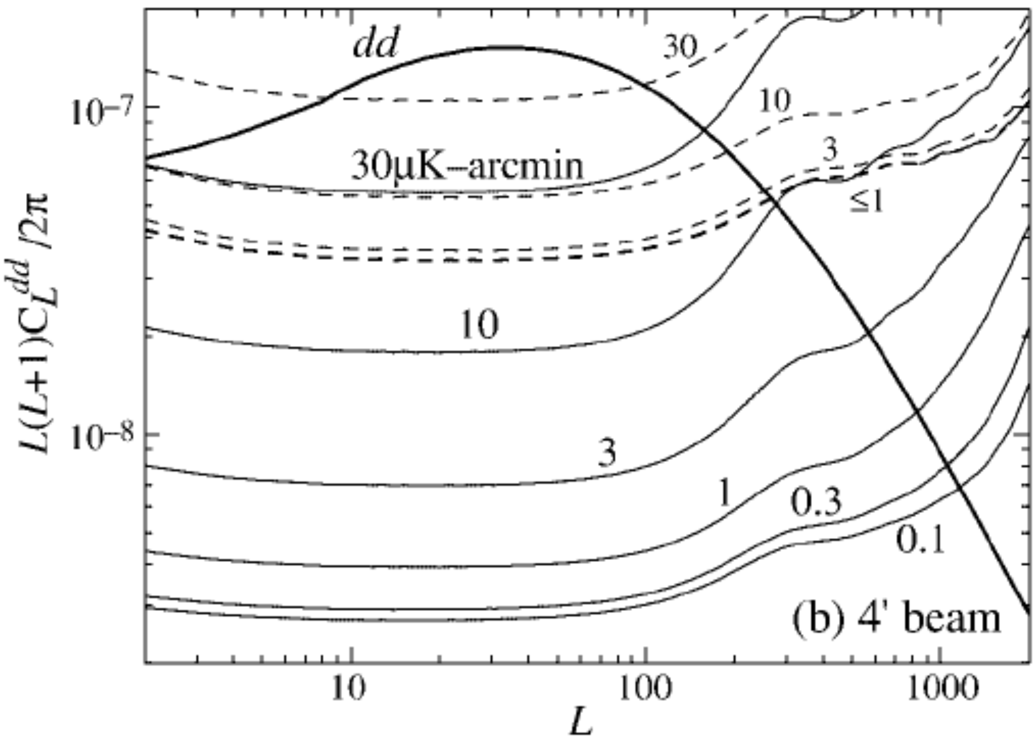
Lensing potential reconstruction

Impact of sensitivity & polarisation

Hu & Okamoto, 2002, ApJ 574, 566

- - - - - Temperature only
——— Polarisation (E-B correlation)





PRISM sensitivity
< 1 uK.arcmin

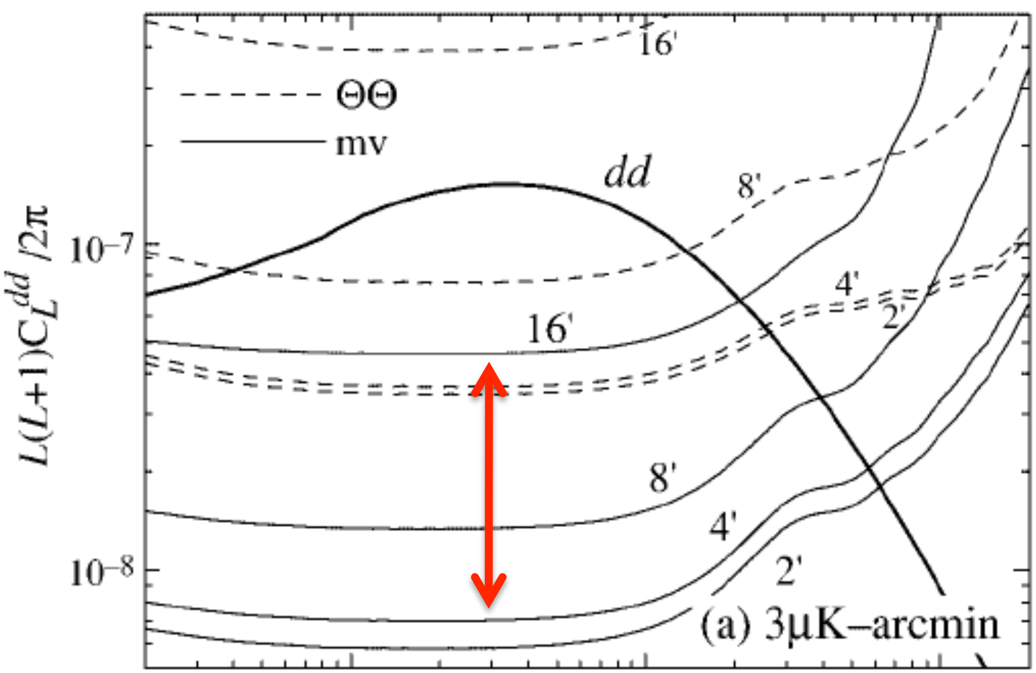
Lensing potential reconstruction

Impact of angular resolution

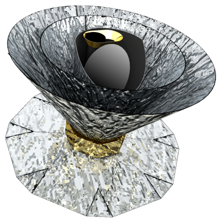
Hu & Okamoto, 2002, ApJ 574, 566

- - - - - Temperature only
——— Polarisation (E-B correlation)

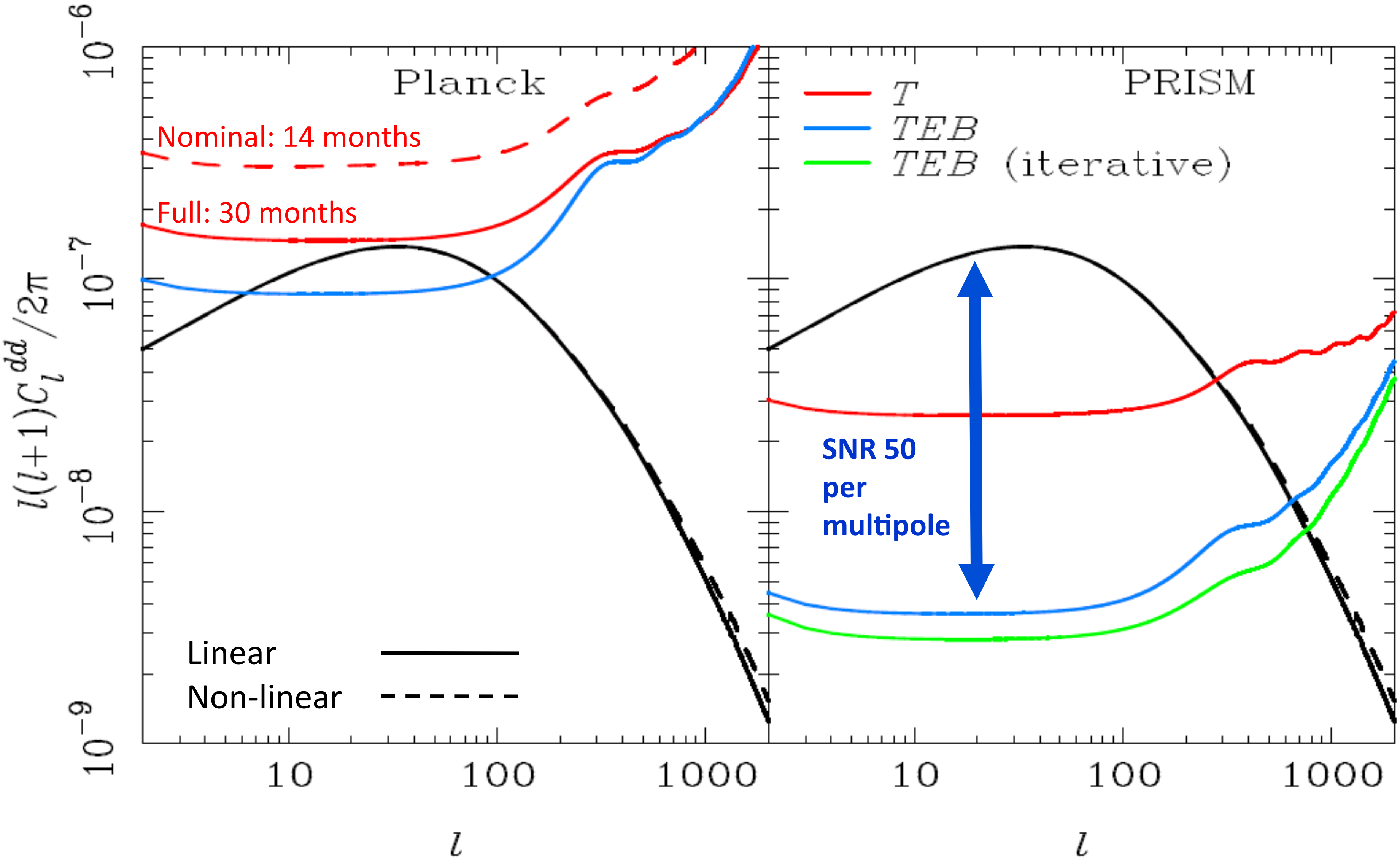
Degrading the resolution from 4 to 16' results in a loss of one order of magnitude in the lensing reconstruction



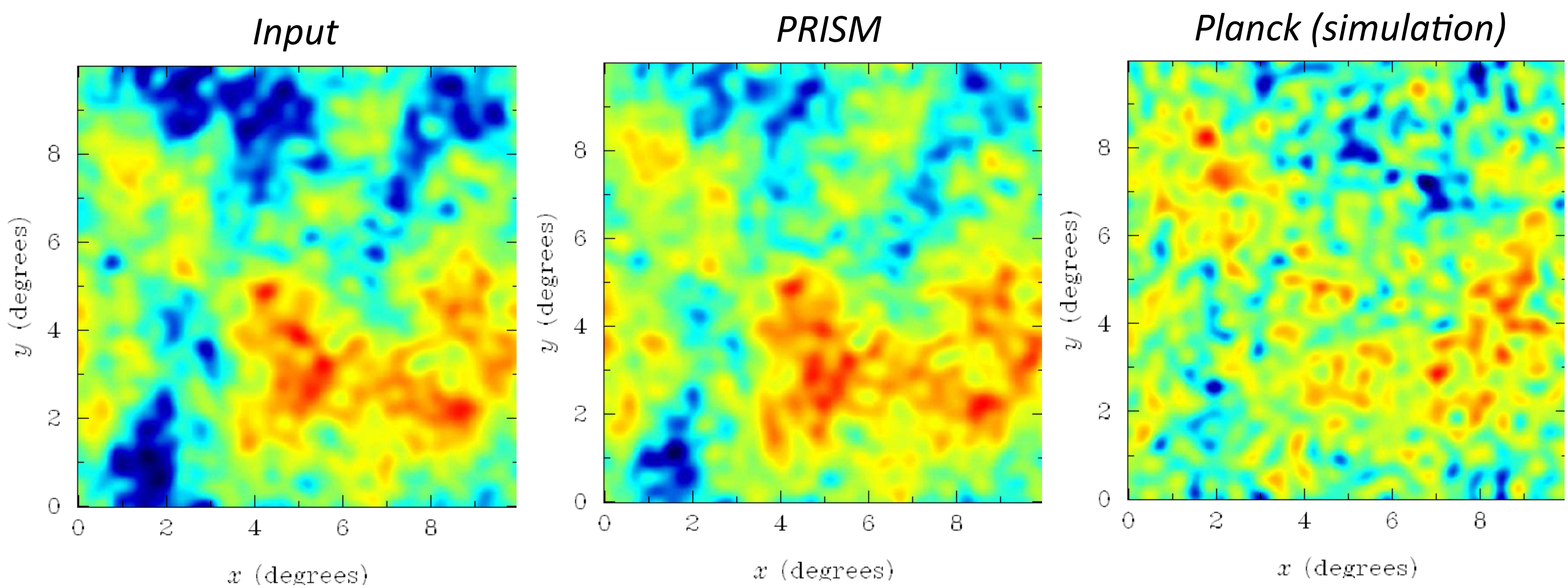
PRISM resolution
135 GHz: 3.8'
265 GHz: 1.9'



CMB lensing

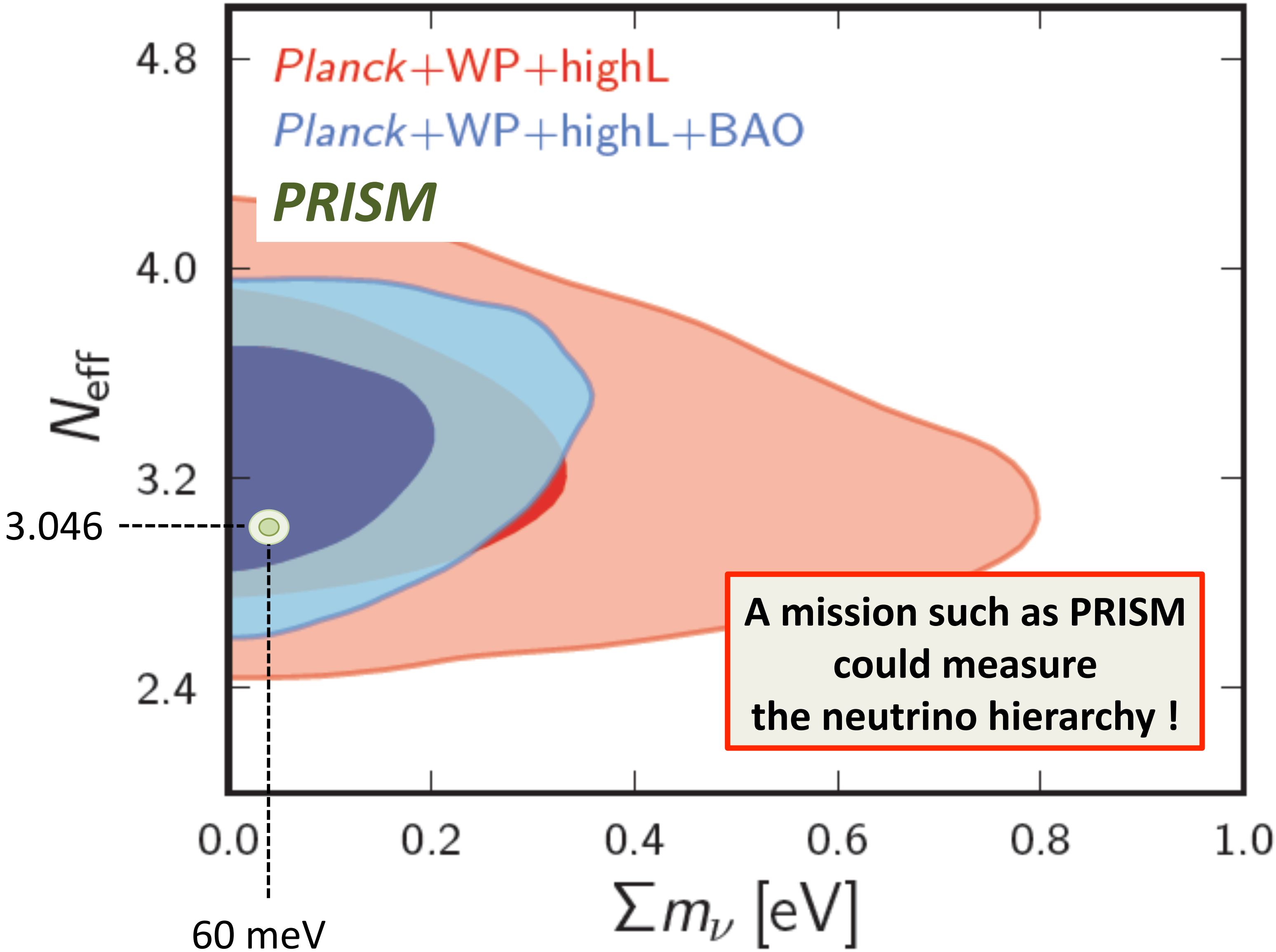

Planck
PRISM
Nominal: 14 months
Full: 30 months
T
TEB
TEB (iterative)
SNR 50
per
multipole
Linear
Non-linear
$l(l+1)C_l^{dd}/2\pi$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
100
1000
l

Reconstruction of the gravitational potential



- High-fidelity reconstruction of the LOS integral of the gravitational potential all the way to recombination.
- Connected to a map of projected mass.
- Complementary to Euclid, which is limited to redshifts < 1.5.

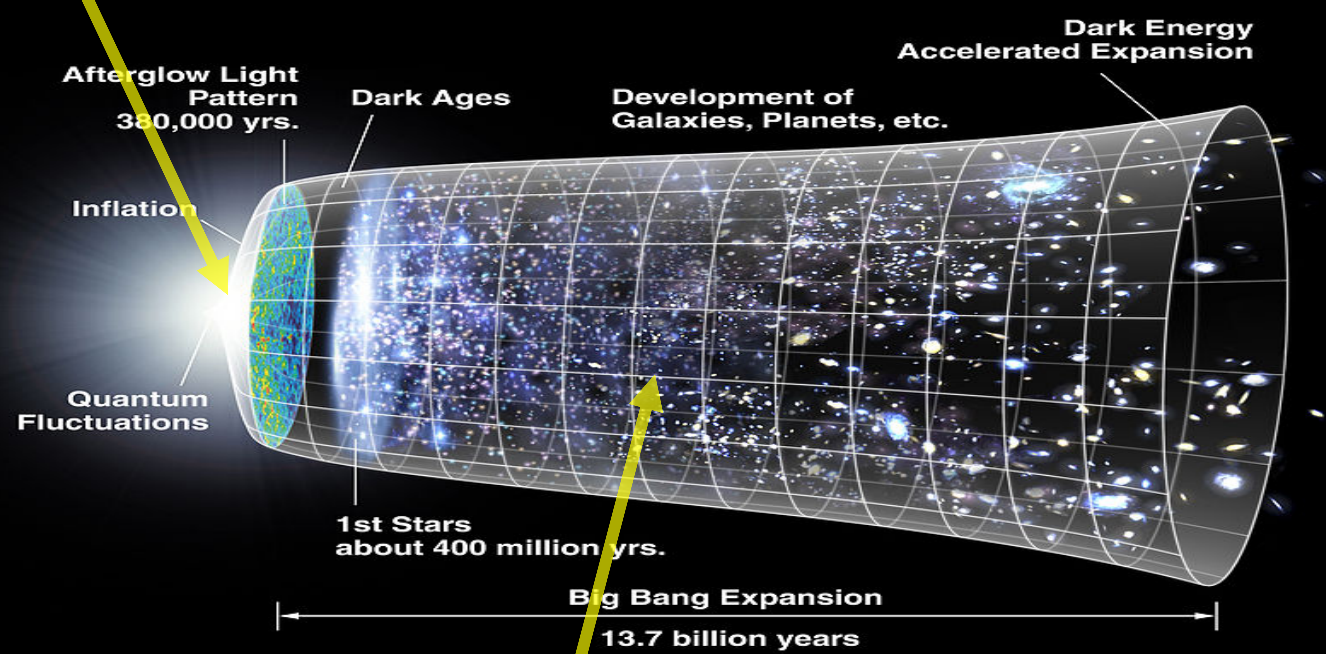
Constraining the neutrino sector



A mission such as PRISM could measure the neutrino hierarchy !

2

Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.



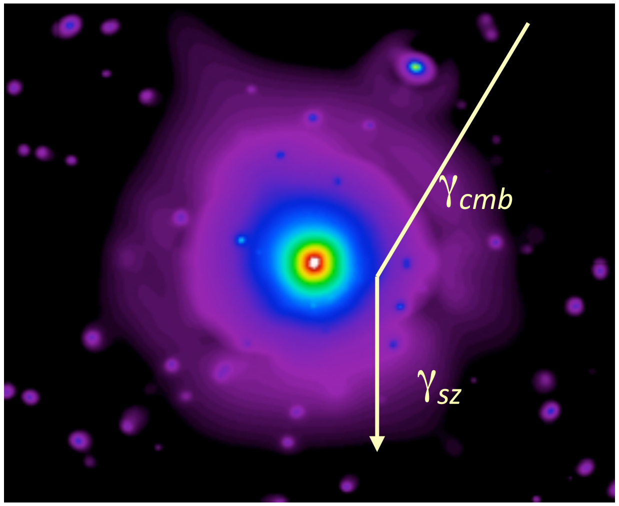
3

Map the gravitational potential all the way to z=1100 through CMB lensing

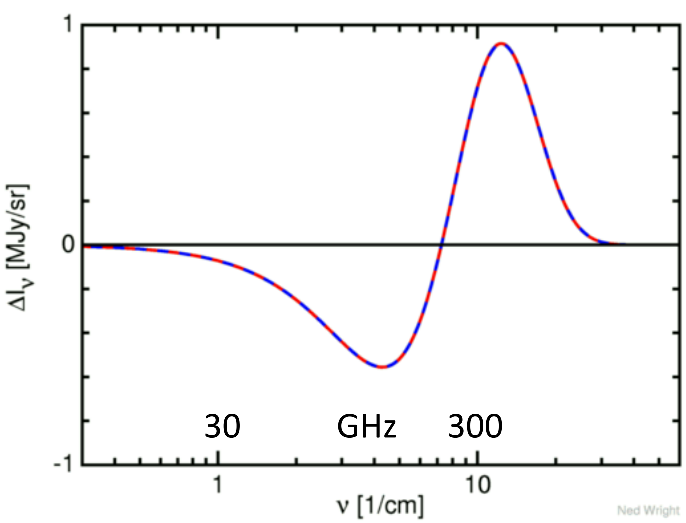
Outline

- PRISM
- CMB anisotropies and inflation
- CMB lensing
- Clusters of galaxies
- Astrophysical cosmology
- The galactic ISM
- Conclusion

Galaxy clusters



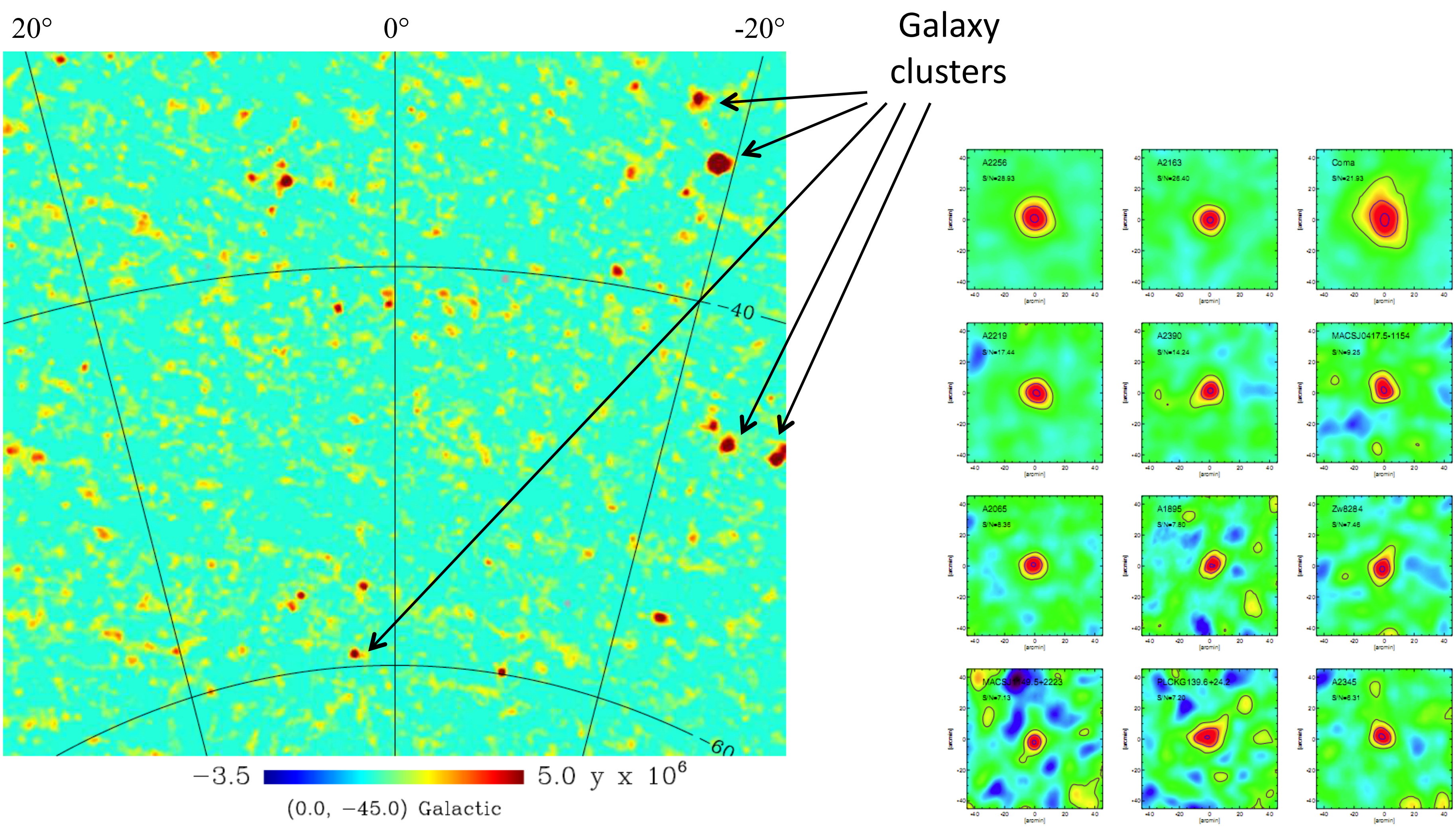
The hot gas in galaxy clusters interacts with CMB photons by inverse Compton, shifting them to higher energy.



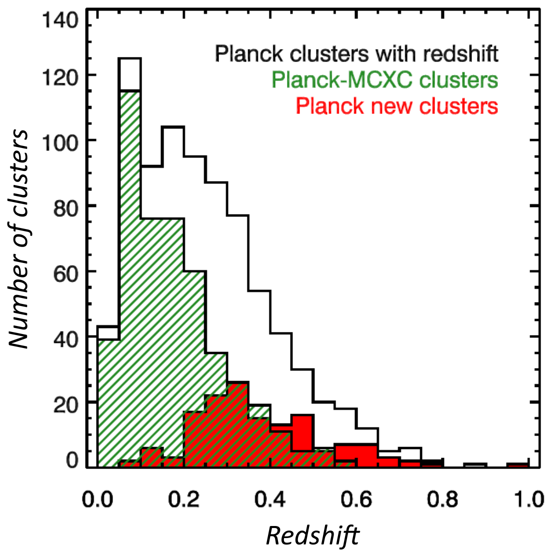
The thermal SZ effect for non-relativistic electrons has a universal frequency dependence. The amplitude is proportional to $n_e.T_e$ and is redshift independent.

Peculiar motions of clusters generate a shift of the observed CMB temperature: kinetic SZ effect

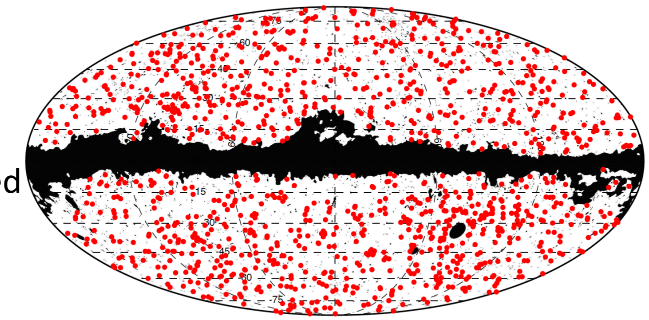
Planck detects hundreds of clusters

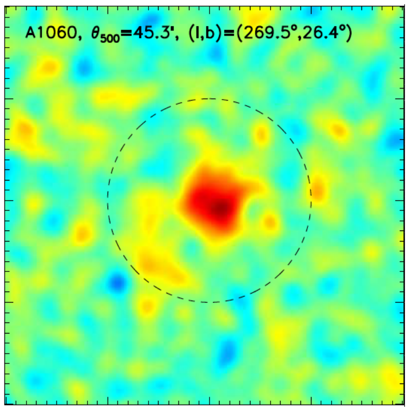


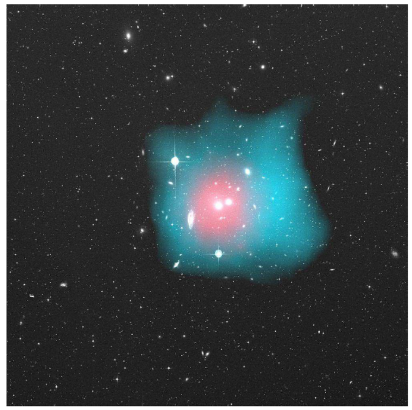
Planck detects hundreds of clusters

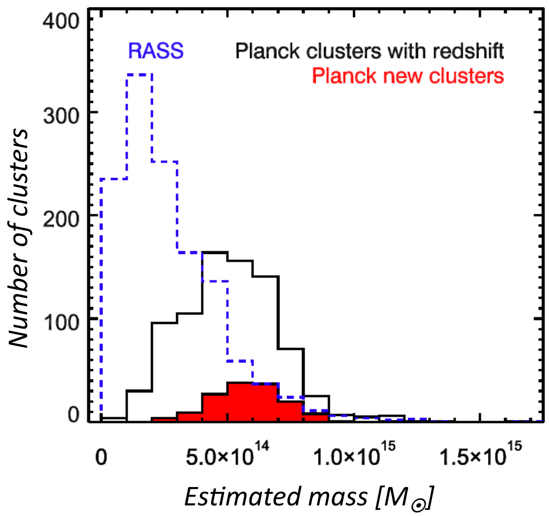


1227 + 5 detections
683 + 5 already known
178 new and confirmed
366 candidates not yet confirmed



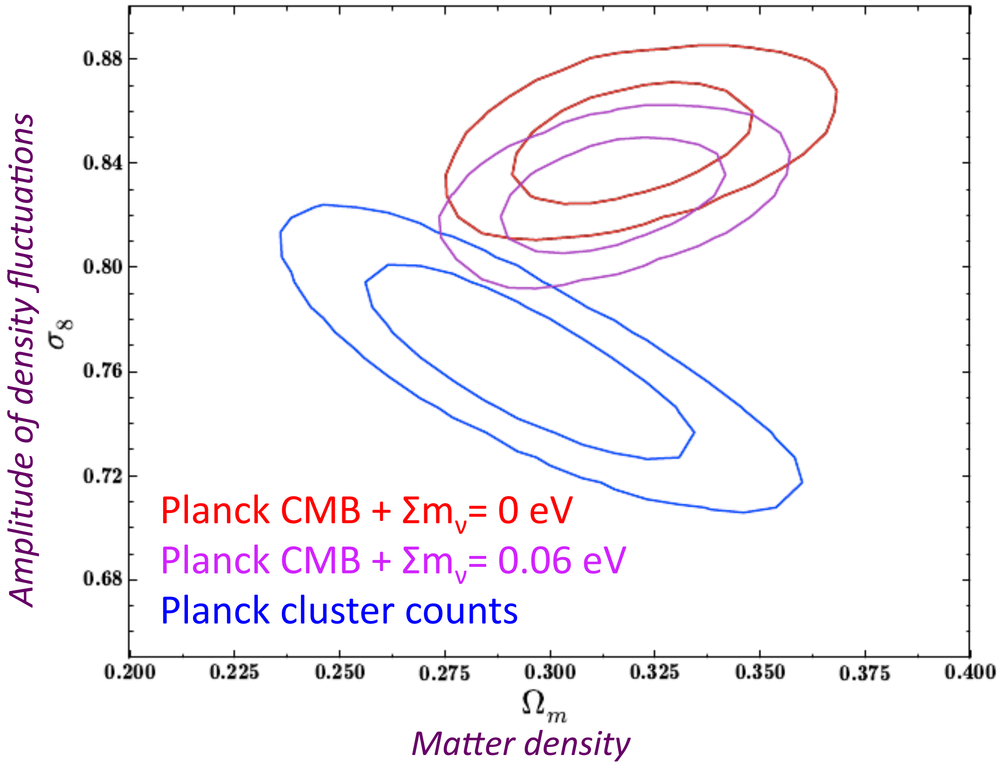


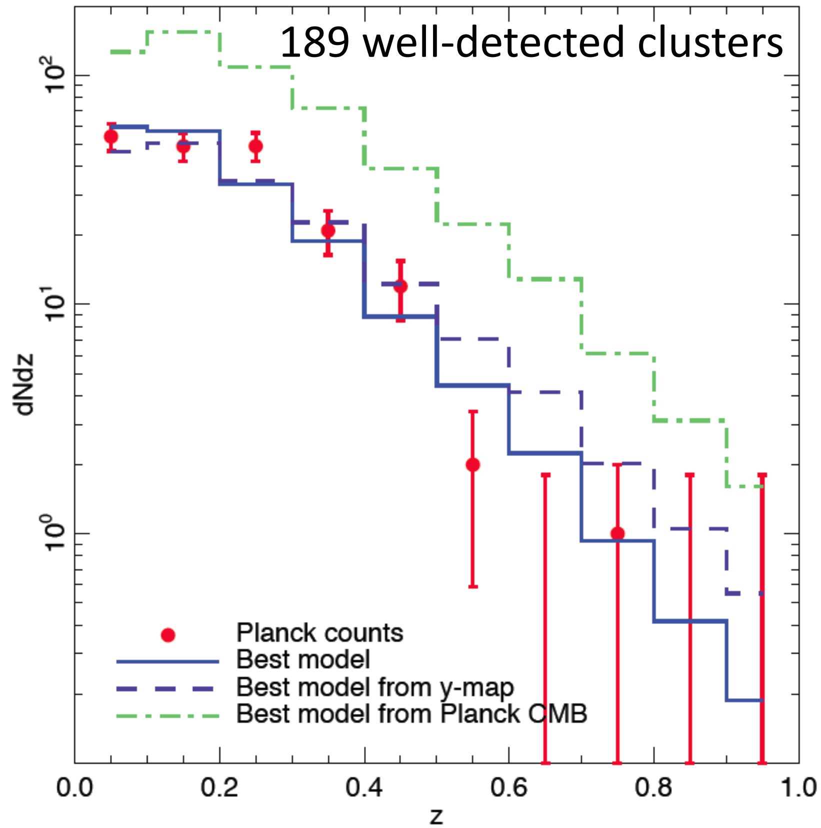




The clusters detected by Planck are farther away and more massive than previously known clusters.

Cosmological constraints from clusters

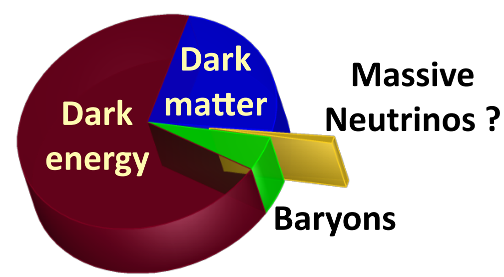




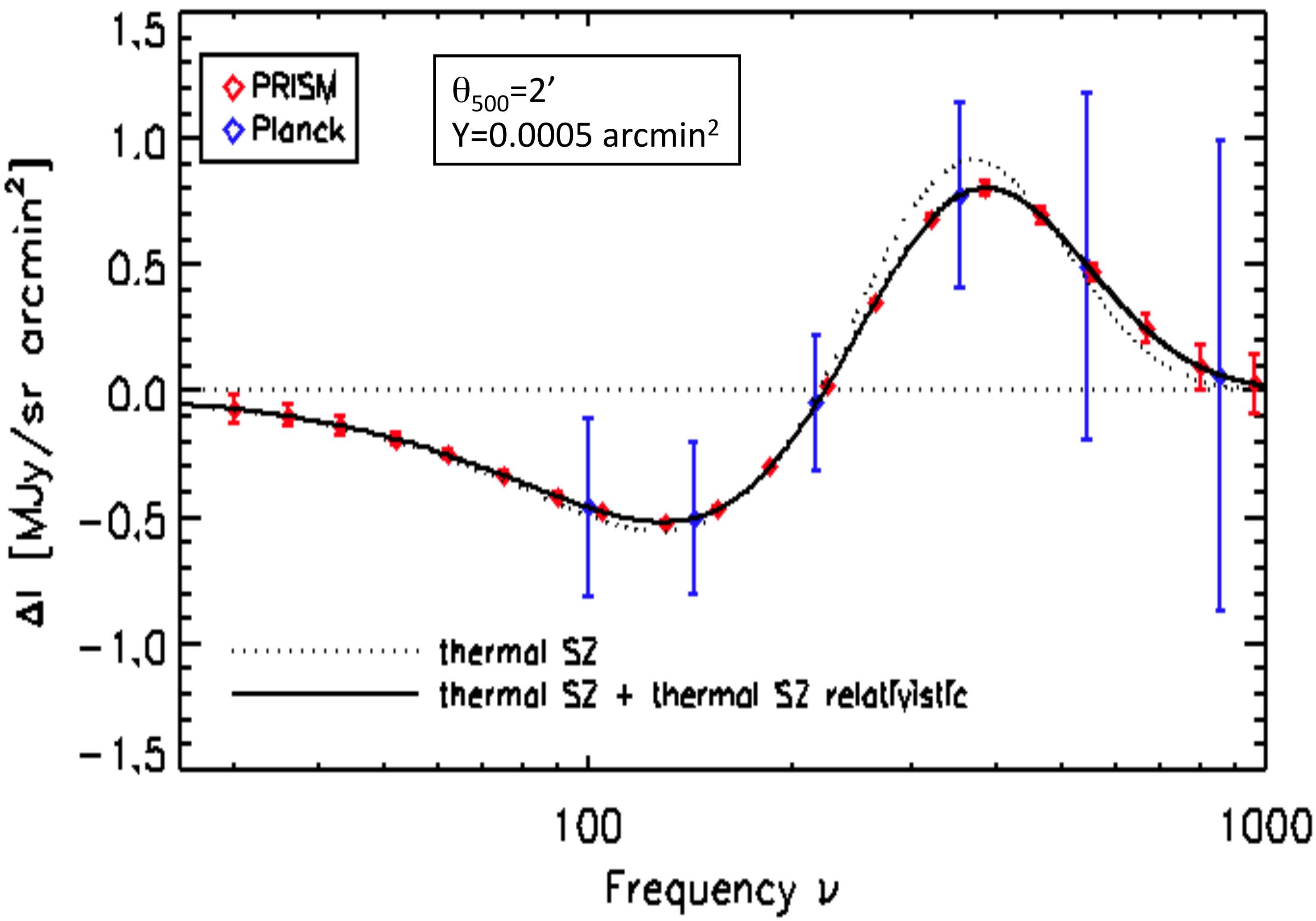
CMB best fit cosmology overpredicts the number of observed clusters

Revise cluster physics ?

Revise matter and energy content?



Probing the Universe with galaxy clusters



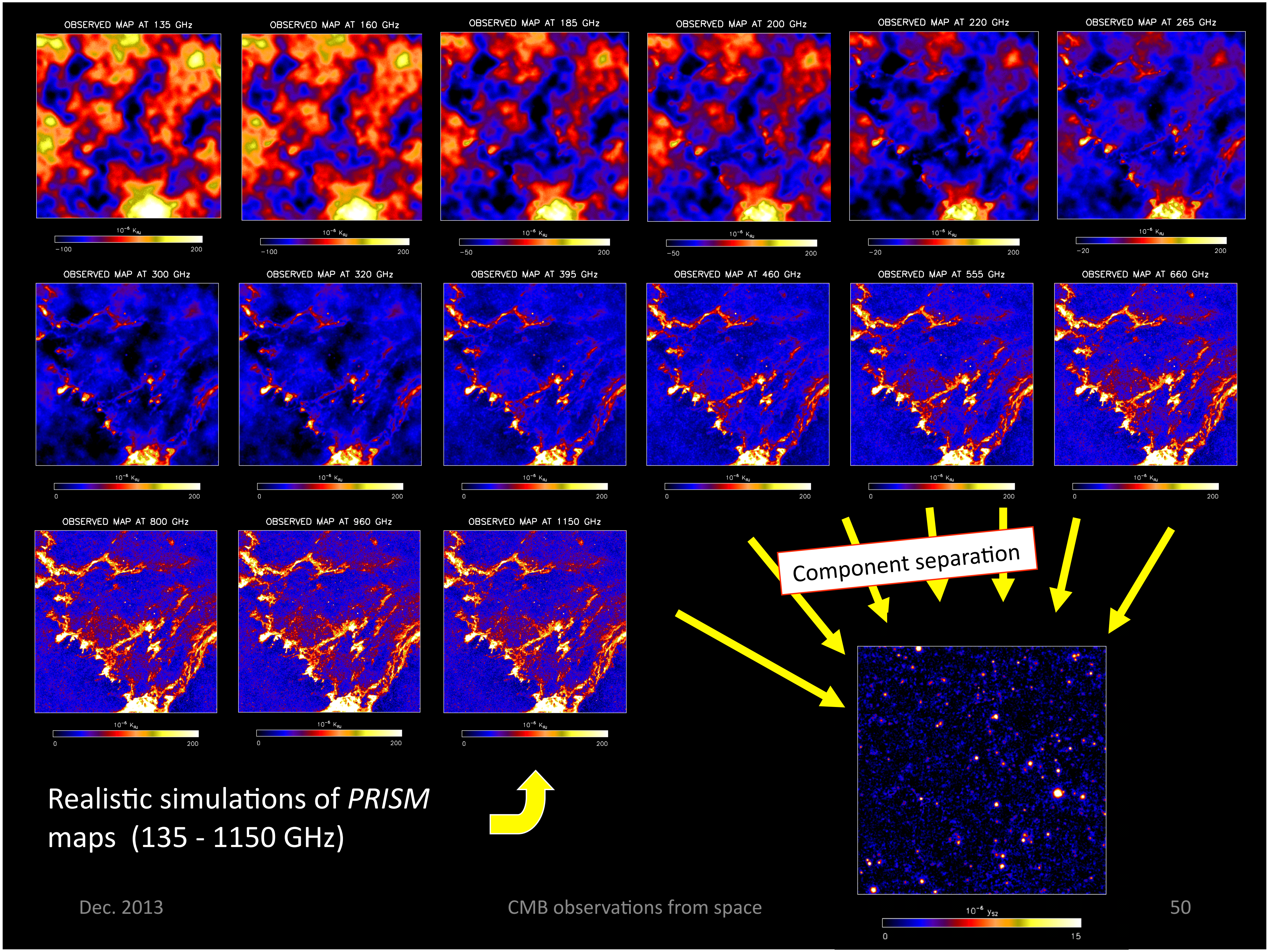
Probing the Universe with galaxy clusters

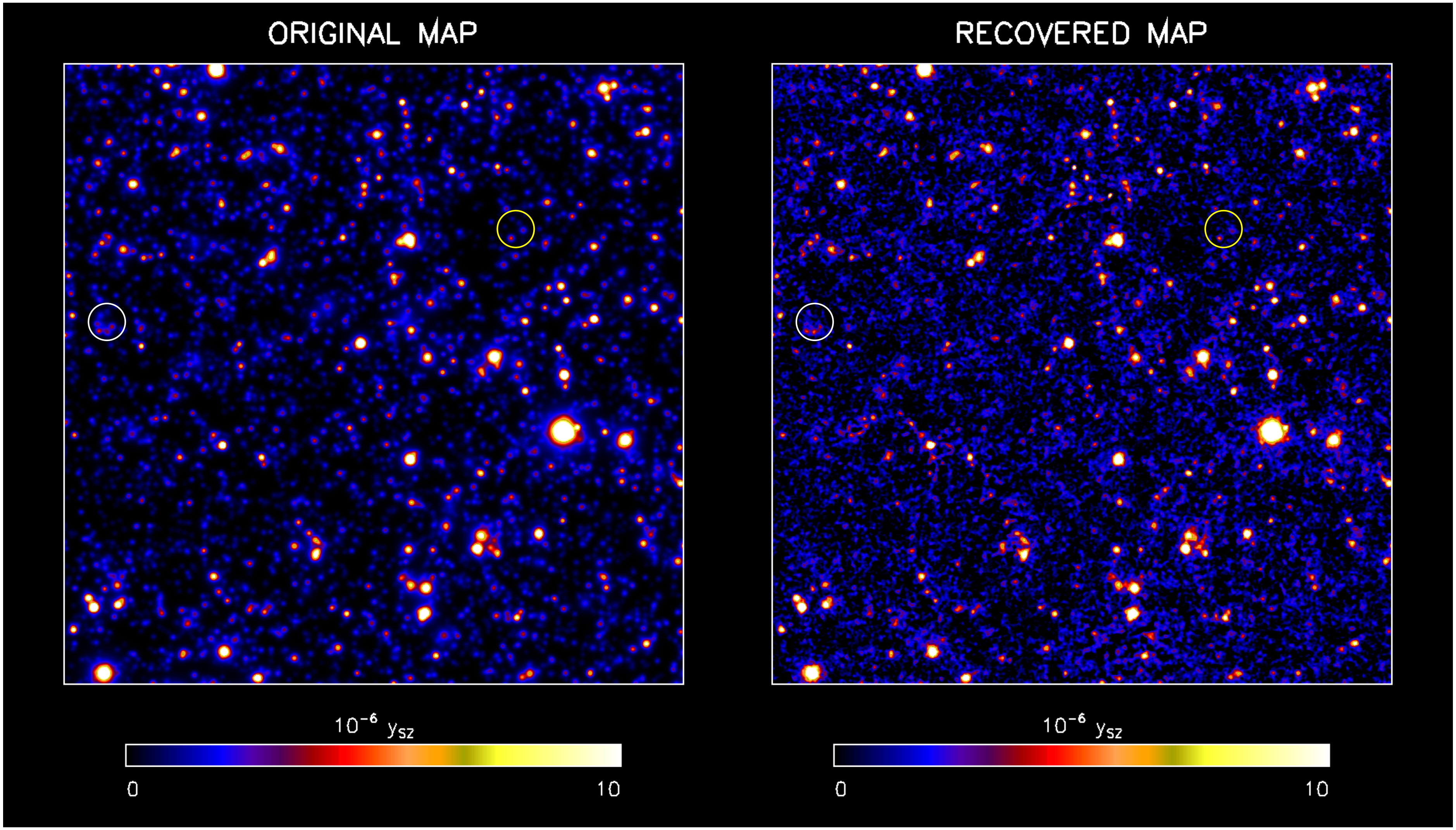
PRISM could detect more than 1 million galaxy clusters (all the galaxy clusters in the Universe) !

PRISM could measure the peculiar velocity at more than 5σ for about 200,000 clusters by kinetic SZ effect.

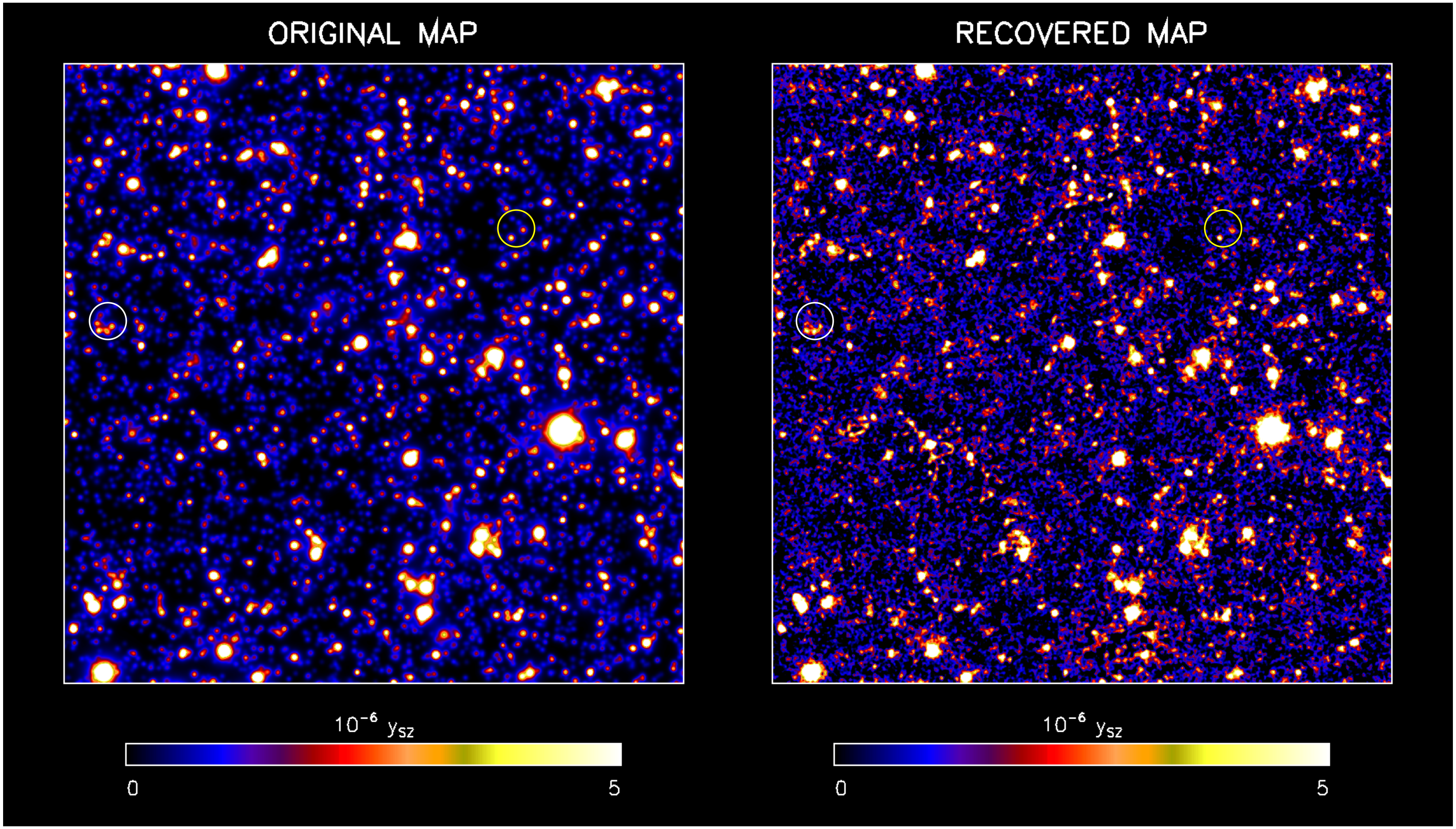
↓

Reconstruction of the cosmic velocity field !


OBSERVED MAP AT 135 GHz
OBSERVED MAP AT 160 GHz
OBSERVED MAP AT 185 GHz
OBSERVED MAP AT 200 GHz
OBSERVED MAP AT 220 GHz
OBSERVED MAP AT 265 GHz
OBSERVED MAP AT 300 GHz
OBSERVED MAP AT 320 GHz
OBSERVED MAP AT 395 GHz
OBSERVED MAP AT 460 GHz
OBSERVED MAP AT 555 GHz
OBSERVED MAP AT 660 GHz
OBSERVED MAP AT 800 GHz
OBSERVED MAP AT 960 GHz
OBSERVED MAP AT 1150 GHz
Component separation
Realistic simulations of *PRISM* maps (135 - 1150 GHz)

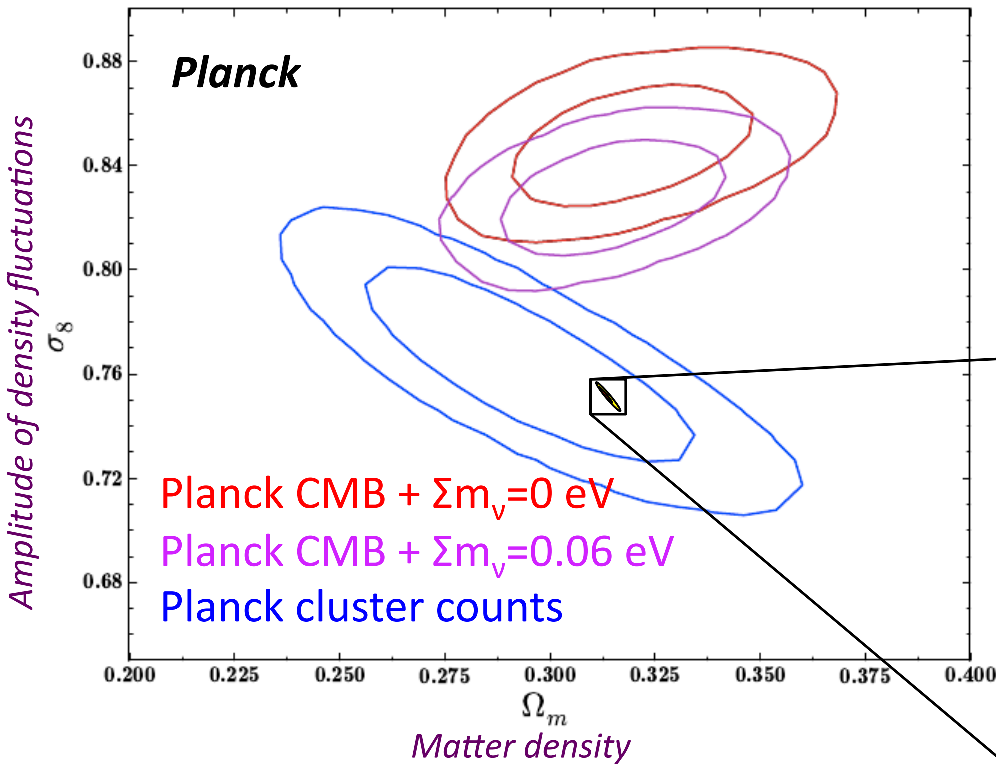


- reconstruction of the SZ effect at about 1.3’ resolution on a 3.4°x3.4° patch on the sky (only 0.025% of the actual sky coverage of PRISM).

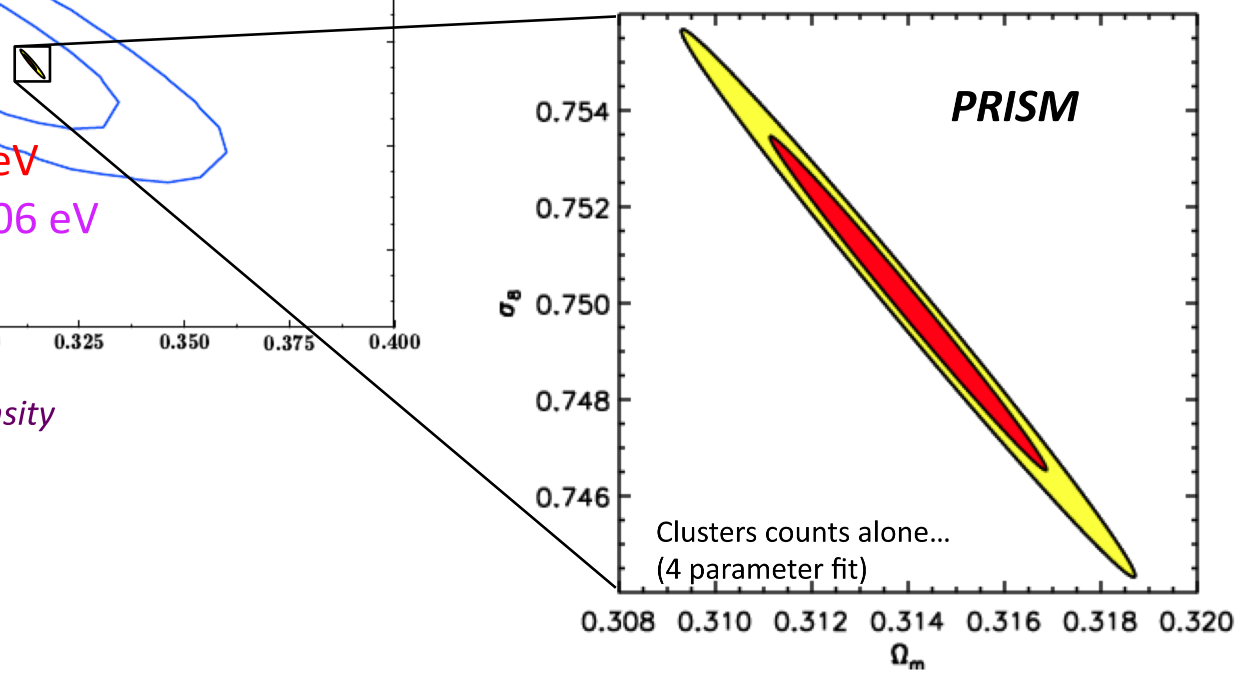


- reconstruction of the SZ effect at about 1.3' resolution on a 3.4°x3.4° patch on the sky (only 0.025% of the actual sky coverage of PRISM).

Probing the Universe with galaxy clusters



PROBING
DARK MATTER
& STRUCTURE
FORMATION



PROBING DARK ENERGY

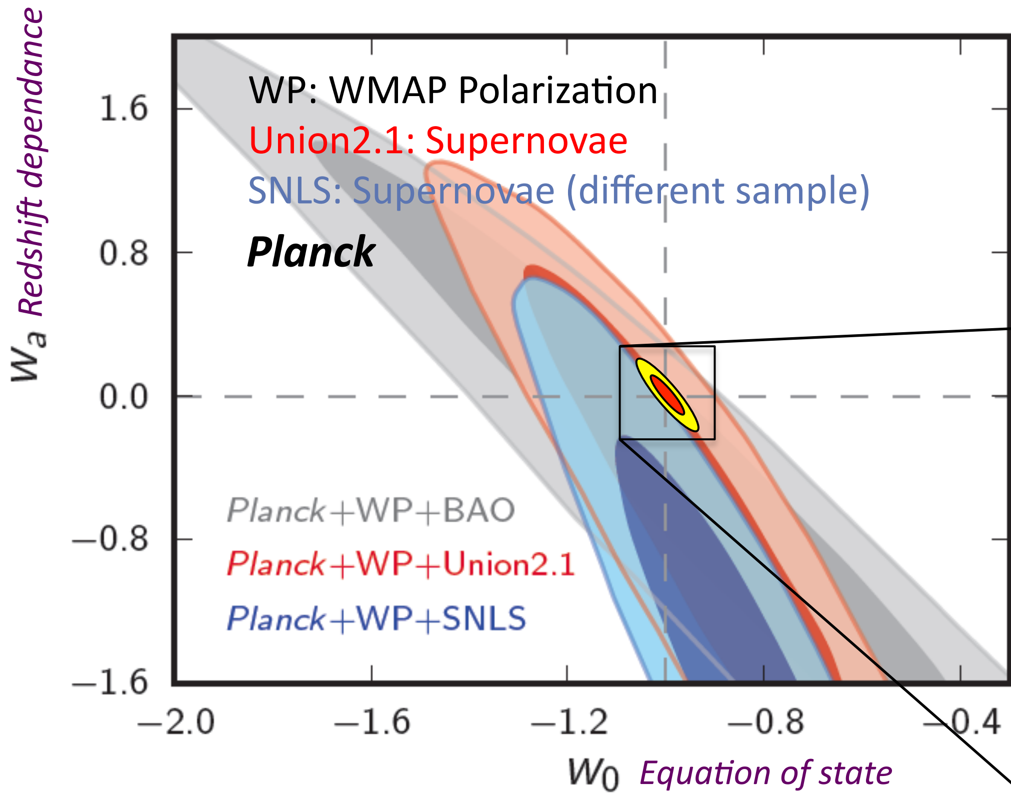
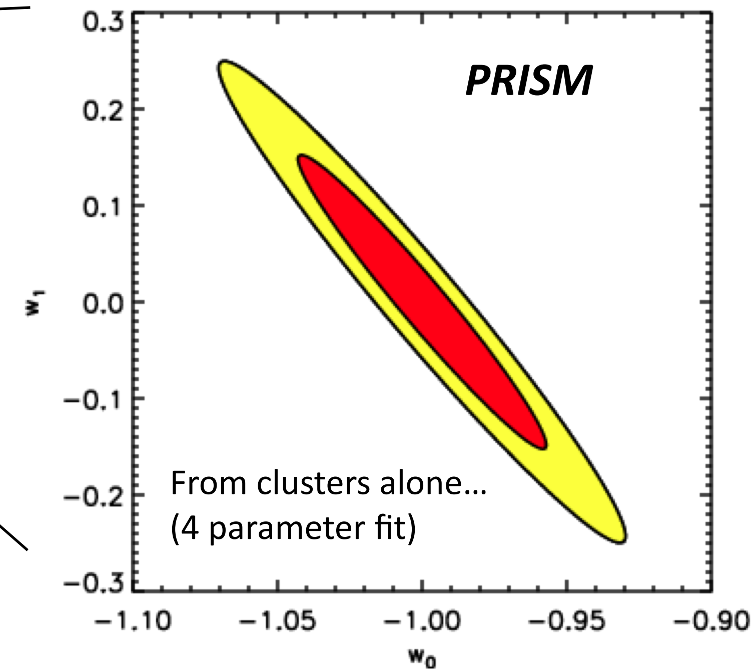
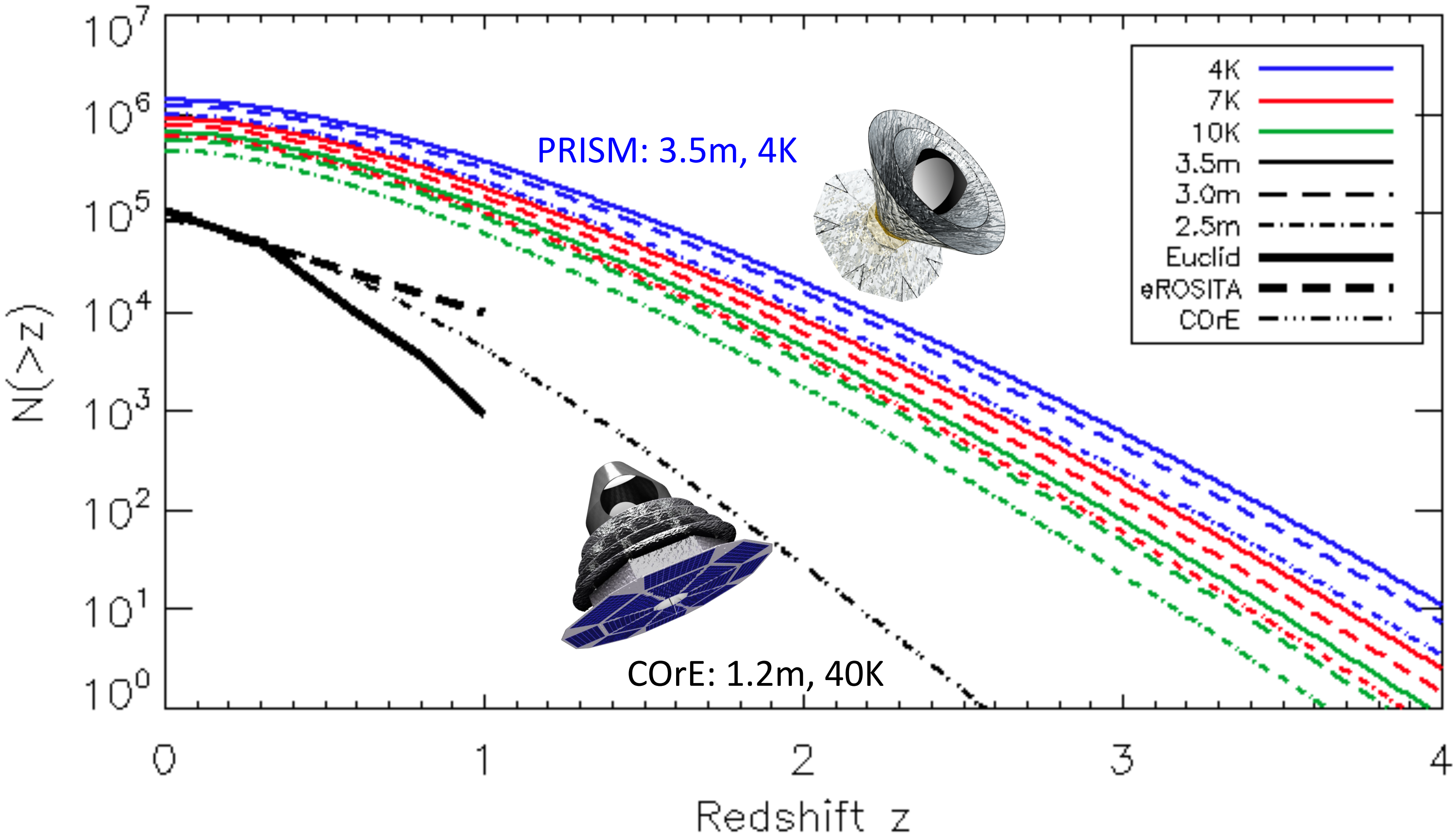


Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the cosmological constant solution.

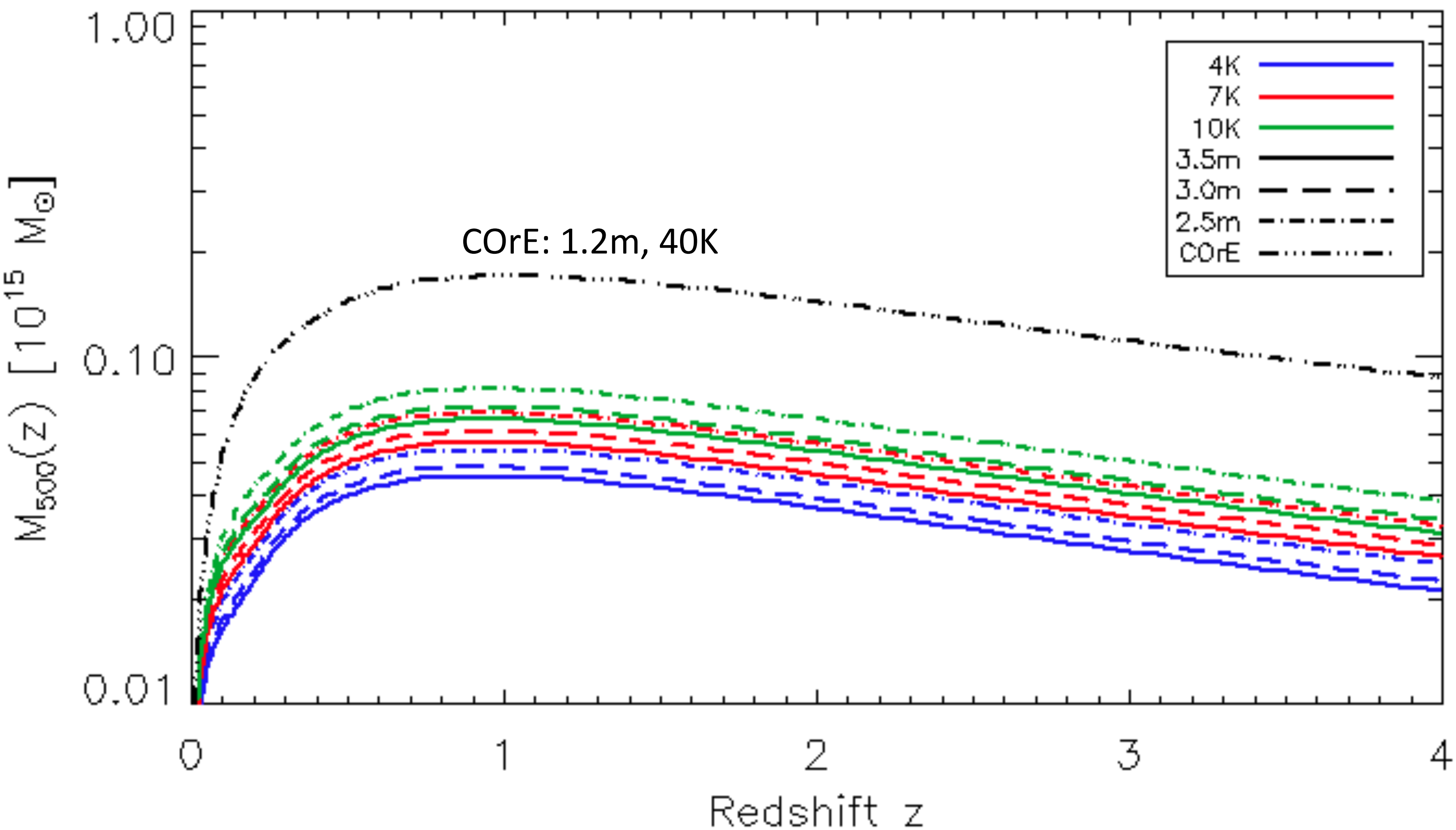


These constraints complement and improve those from other observations since they are based on a deeper (higher z) survey and have a FoM~1000 (FoM=430 for Euclid Primary)

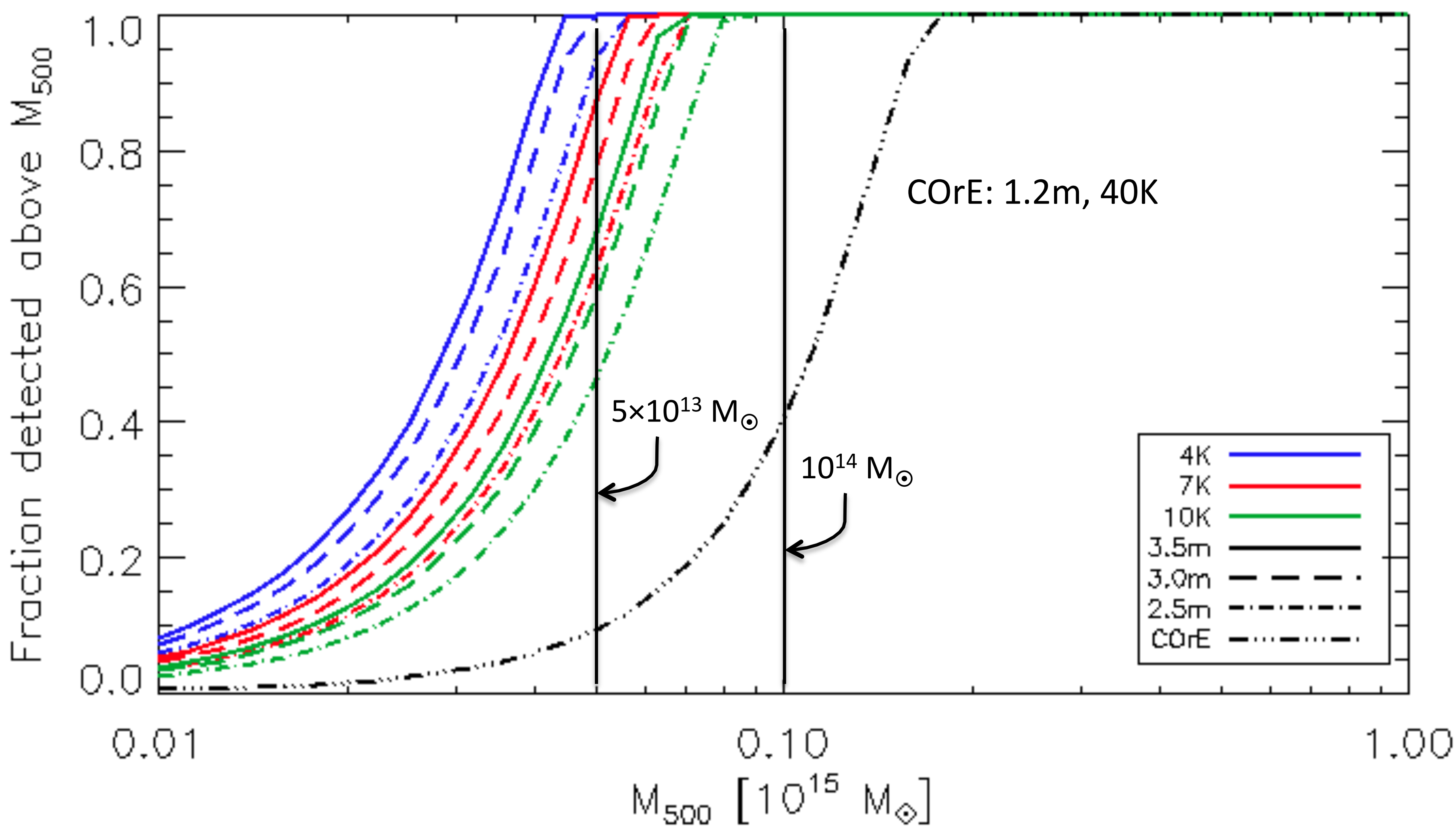
SZ cluster detection



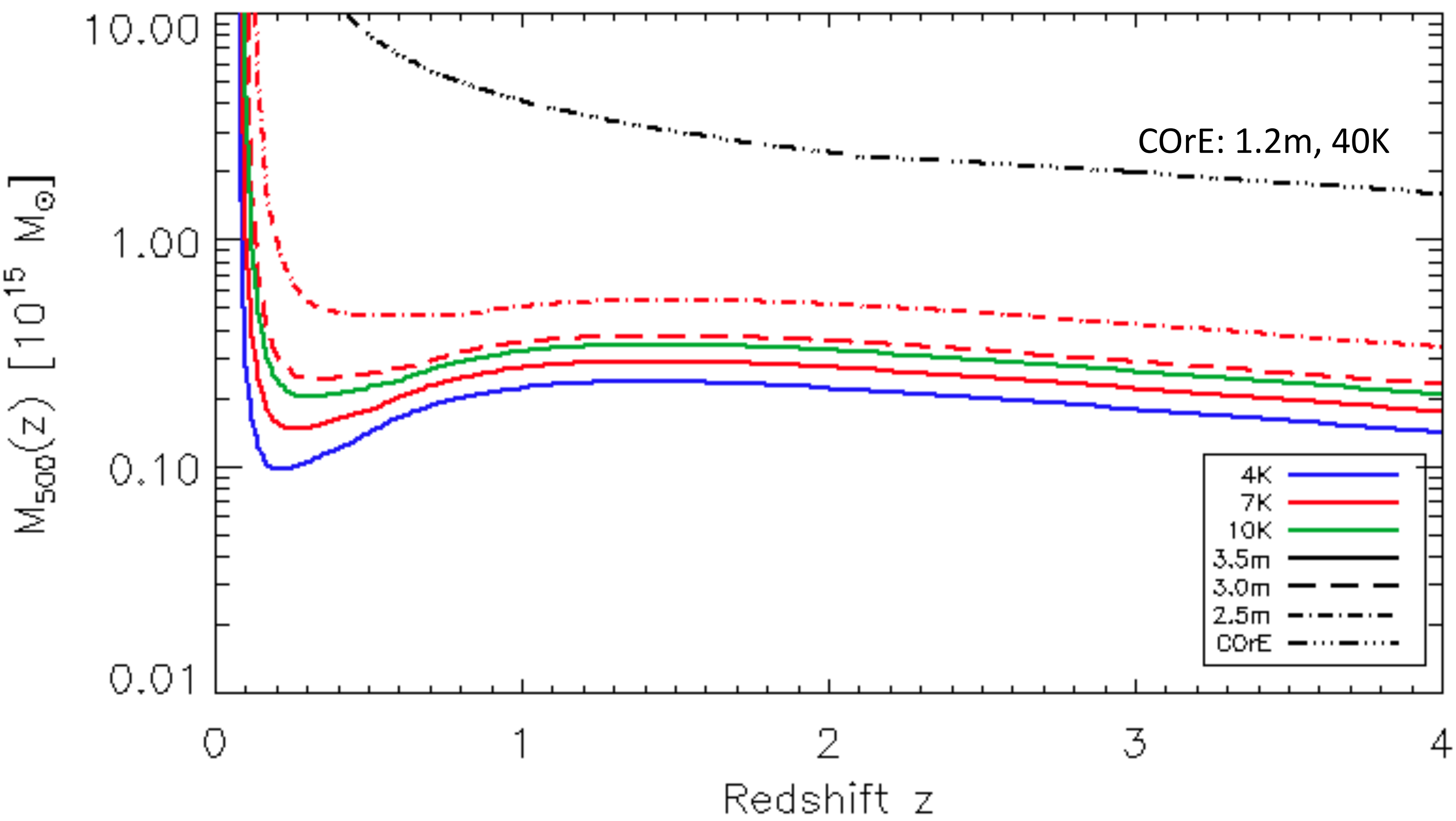
SZ cluster limit mass



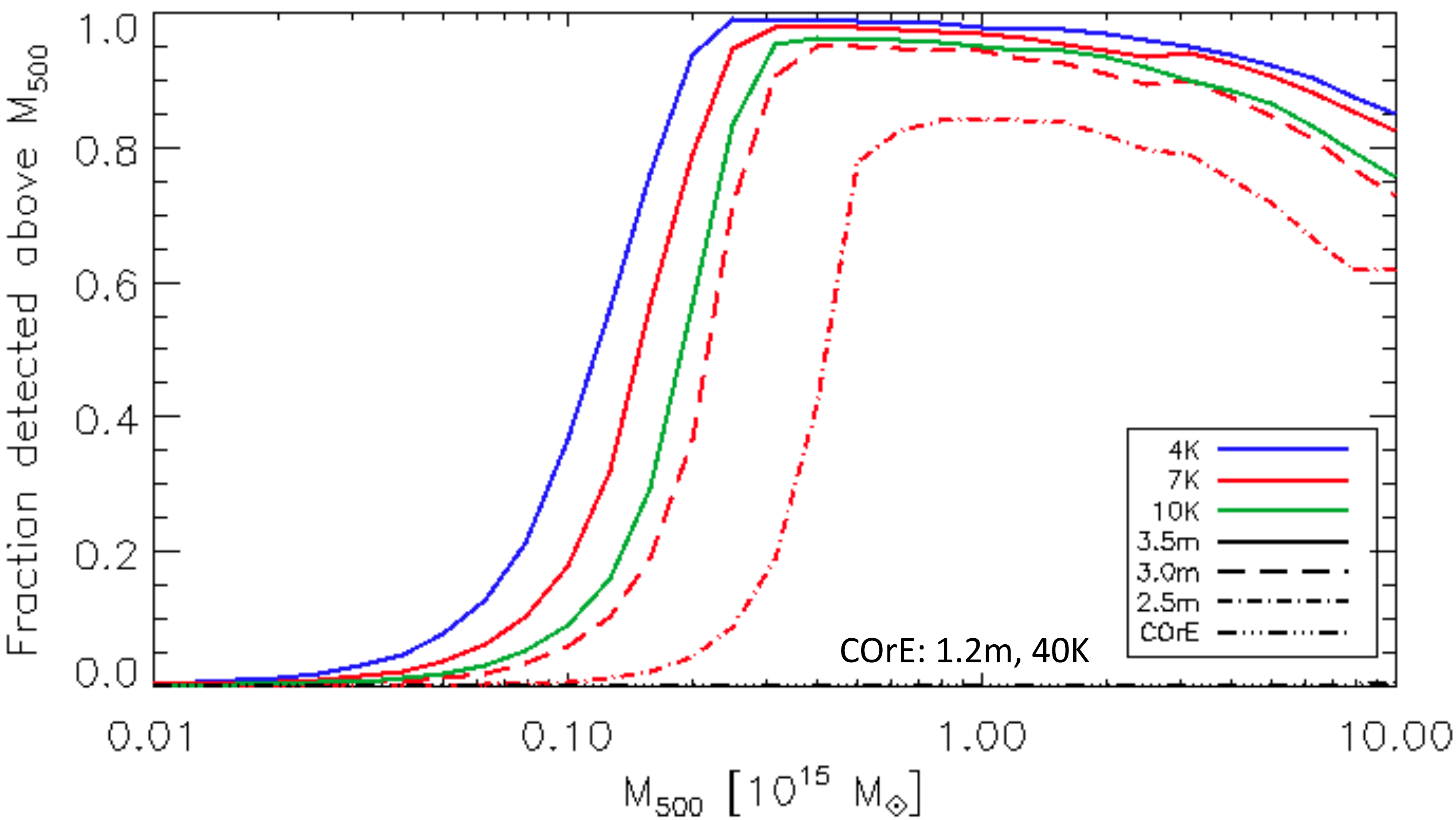
SZ cluster completeness



Velocity flows: limit mass

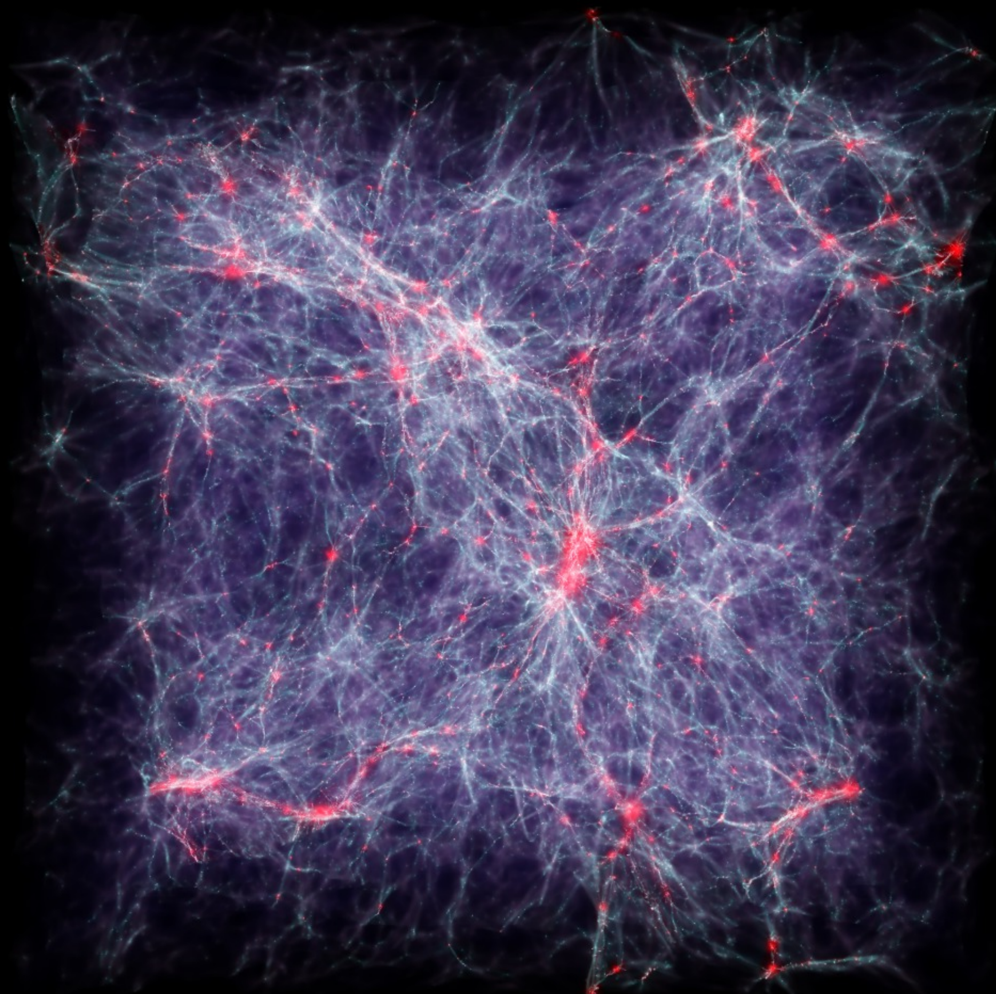


Velocity flows: completeness



Detection of the cosmic web

25 h^{-1} Mpc
Planck ΛCDM



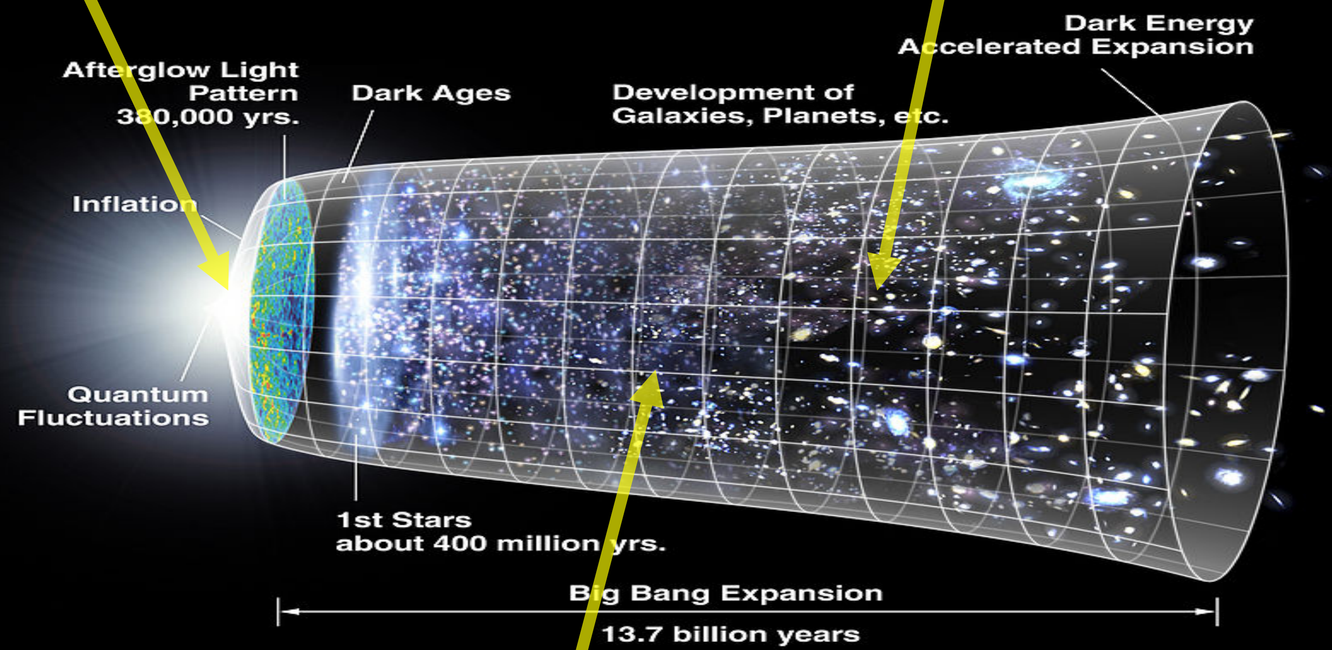
In filaments:
$T \approx 10^5$-10^7 K
$\rho_{gas} \approx 5\text{-}200 \times \rho_{gas}$

$T \approx 10^4$ K

$T \approx 10^7$ K

2 Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.

4 **Ultimate galaxy cluster survey** via Sunyaev-Zeldovich effect (SZ): ($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)



3 Map the gravitational potential all the way to z=1100 through CMB lensing

Outline

- PRISM
- CMB anisotropies and inflation
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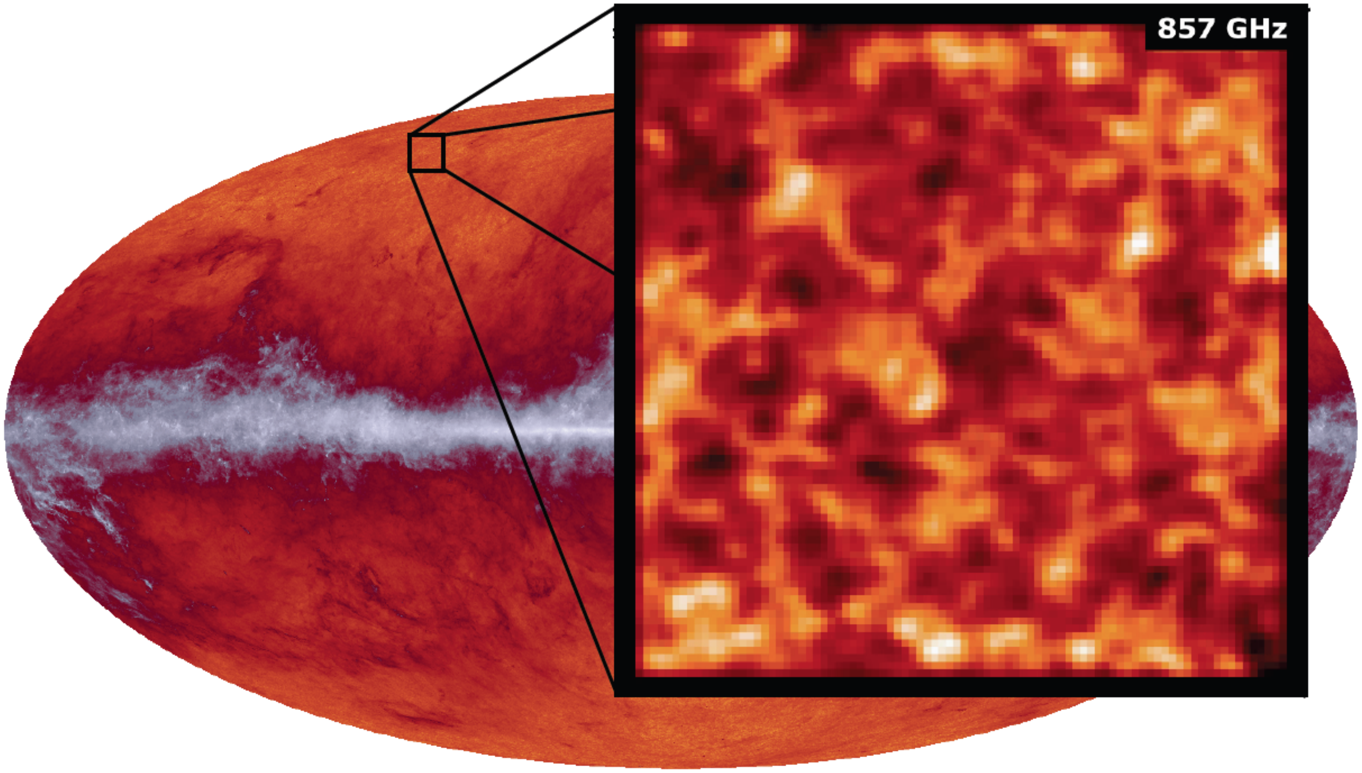
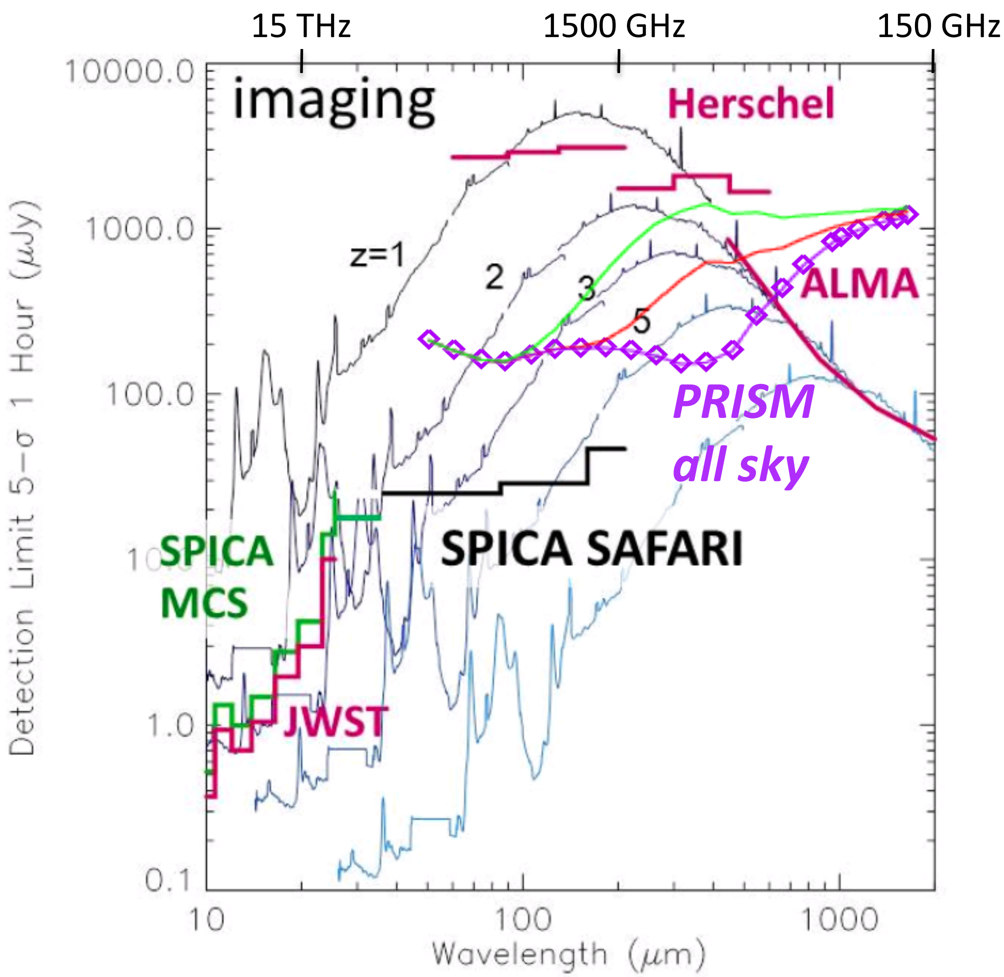
- Conclusion

CIB – 545 GHz



- At 545 GHz (~550 μm) (and all frequencies above 143 GHz), a large fraction of the signal we are mapping is composed of the Cosmic Infrared Background (CIB).
- The CIB represents the cumulative emission of high-z, dusty, star forming galaxies.
- These galaxies live in lump of (dark) matter that gravitationally lens the CMB.

Detection of dusty galaxies

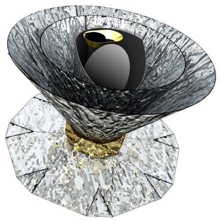


Telescope temperature

10 K

7 K

4 K



Correlations

- Between CIB maps across frequencies: separate CIB in redshift shells, push down the confusion limit
- CIB (in redshift shells) – lensing: growth of structures
- Clusters (in z-Y bins) – lensing: Y-M relations for clusters
- Clusters – sources (by types): halo population (by type)
- SZ map (after masking clusters) – CIB (by shells): sources in cosmic web, hot gas in galaxy haloes
- CMB – tracers of mass: ISW

All of this requires statistics: *case for a full sky survey*.

Correlation lensing – galaxies

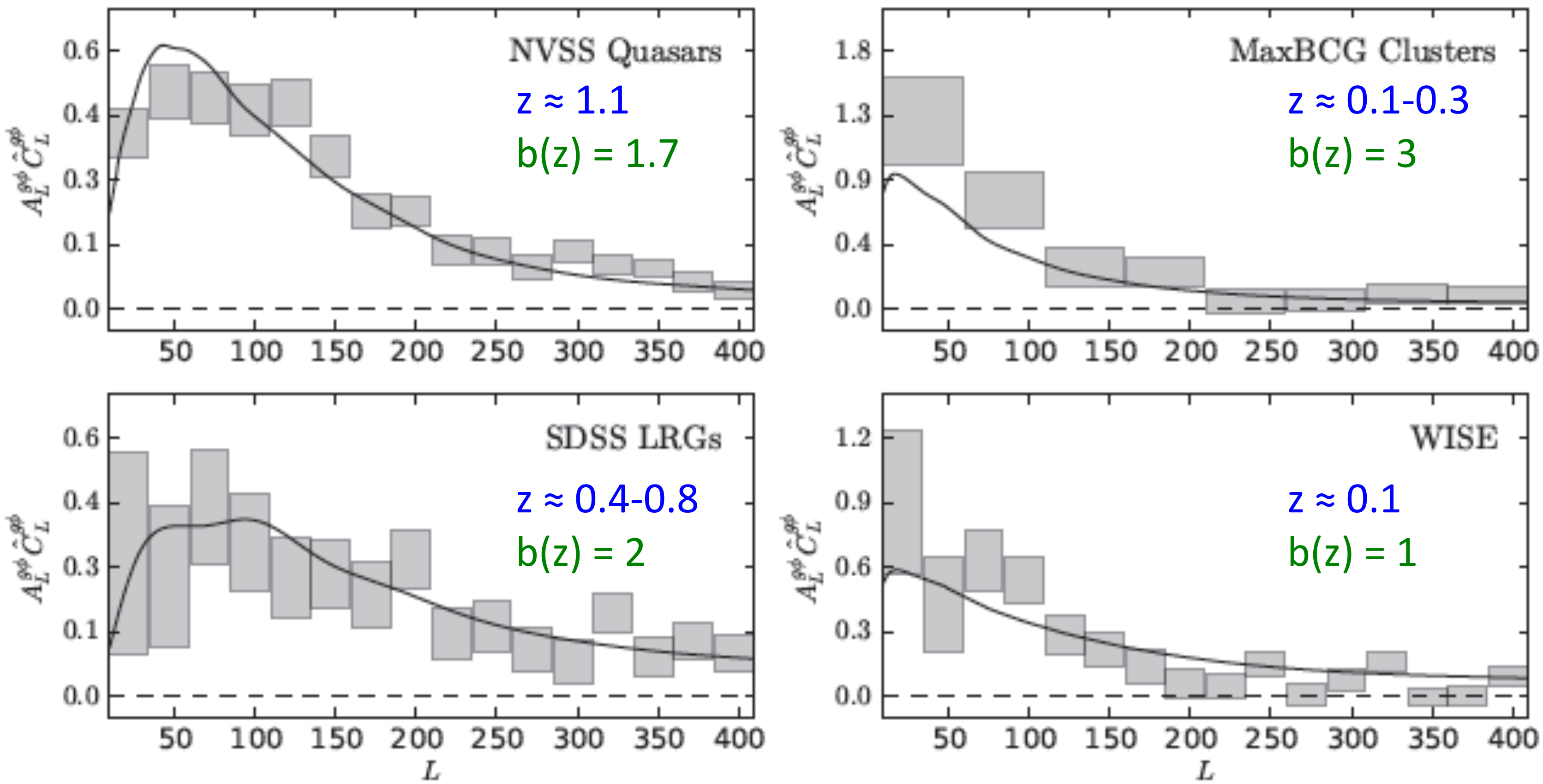
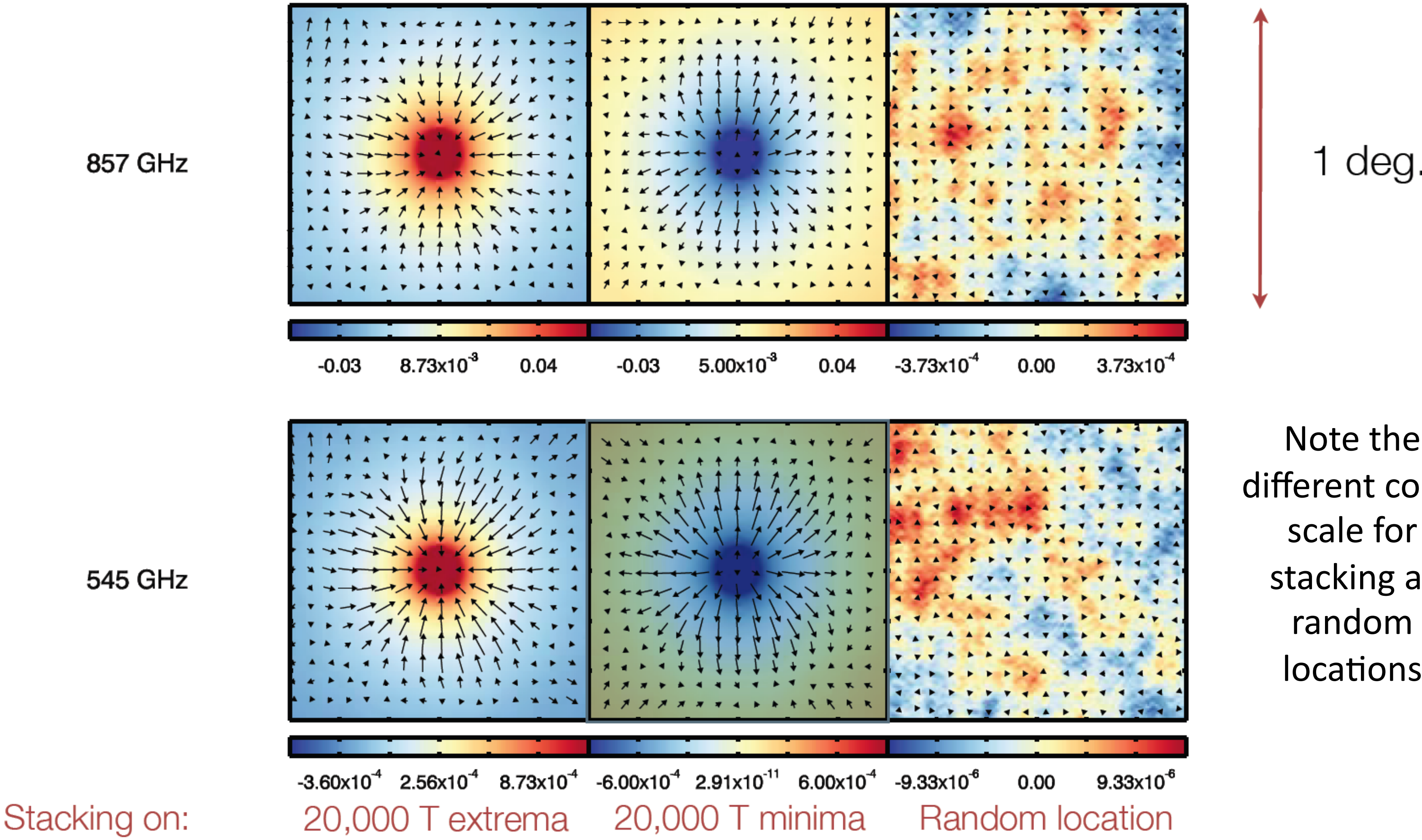


Fig. 17. Cross-spectra of the *Planck* MV lensing potential with several galaxy catalogs, scaled by the signal-to-noise weighting factor $A_L^{g\phi}$ defined in Eq. (52). Cross-correlations are detected at approximately 20σ significance for NVSS, 10σ for SDSS LRGs and 7σ for both MaxBCG and WISE.

Correlation lensing – CIB



Note the different color scale for stacking at random locations

Correlation lensing – CIB

Planck 2013 results. XVIII.

The CIB fluctuations at different frequencies originate from different redshift windows.

Powerful tool with precise, full-sky measurement of the CIB at all frequencies, and precise measurements of lensing.

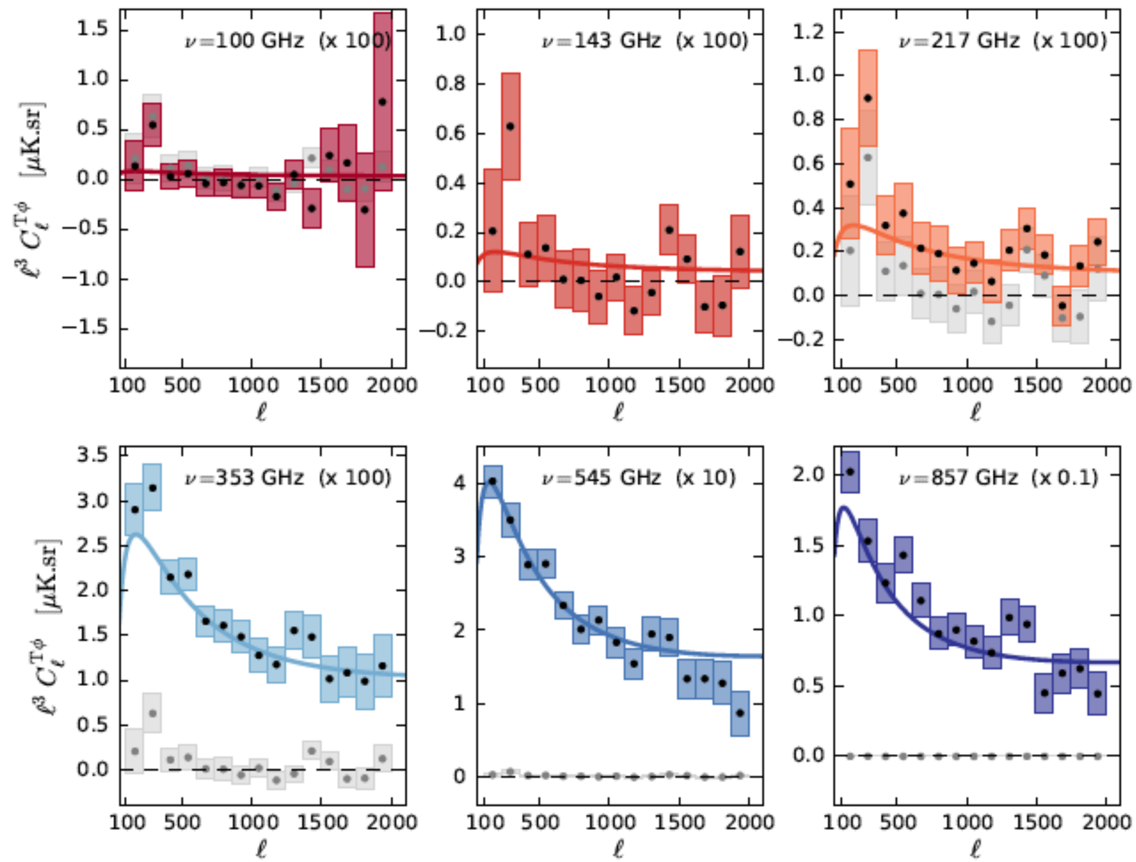


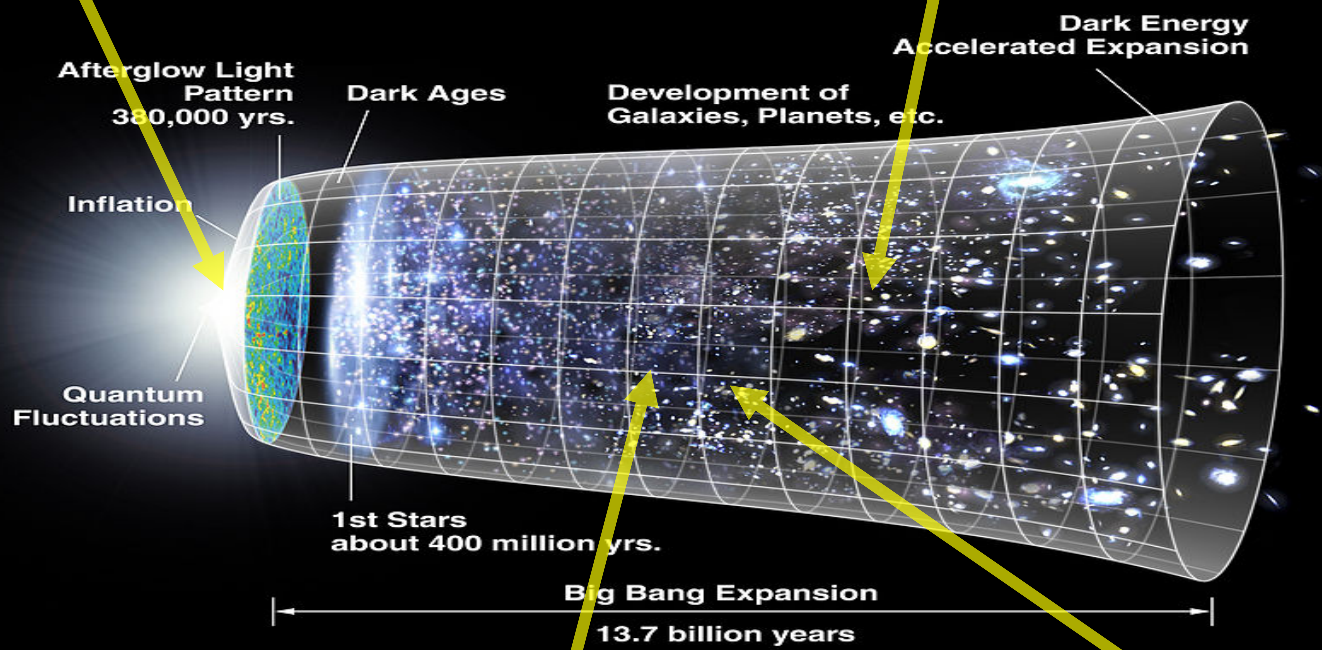
Fig. 3. Angular cross-spectra between the reconstructed lensing map and the temperature map at the six HFI frequencies. The error bars correspond to the scatter within each band. The solid line is the expected result based on the PER model and is *not* a fit to these data (see Fig. 16 for an adjusted model), although it is already a satisfying model. In each panel we also show the correlation between the lens reconstruction at 143 GHz and the 143 GHz temperature map in grey. This is a simple illustration of the frequency scaling of our measured signal and also the strength of our signal as compared to possible intra-frequency systematic errors.

1

Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.

3

Ultimate galaxy cluster survey via Sunyaev-Zeldovich effect (SZ):
($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)



2

Map the gravitational potential all the way to z=1100 through CMB lensing

4

Probe early star formation and its evolution through precision characterization of the Cosmic Infrared Background (CIB)

Outline

- PRISM
- CMB anisotropies and inflation
- CMB lensing
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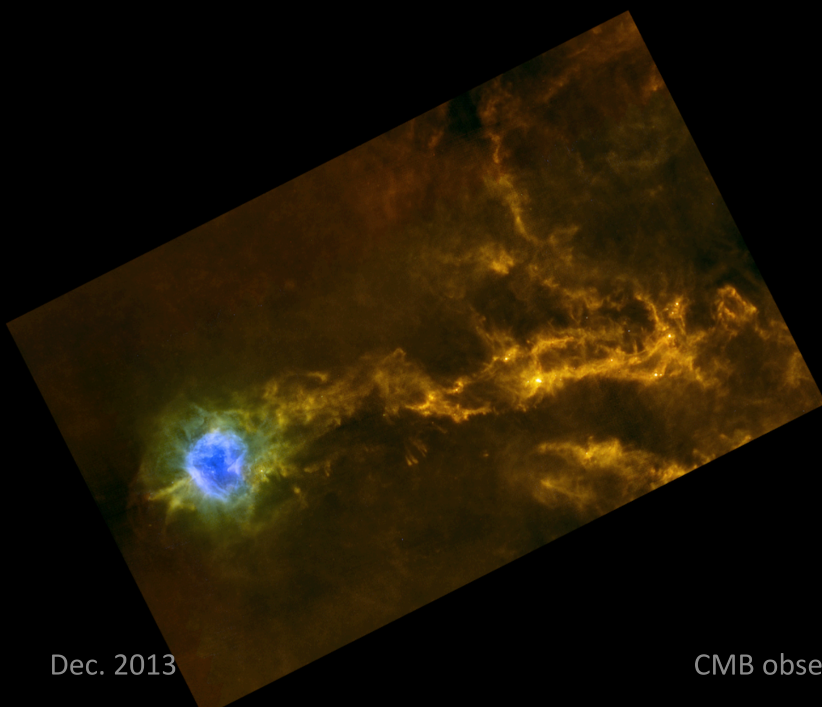
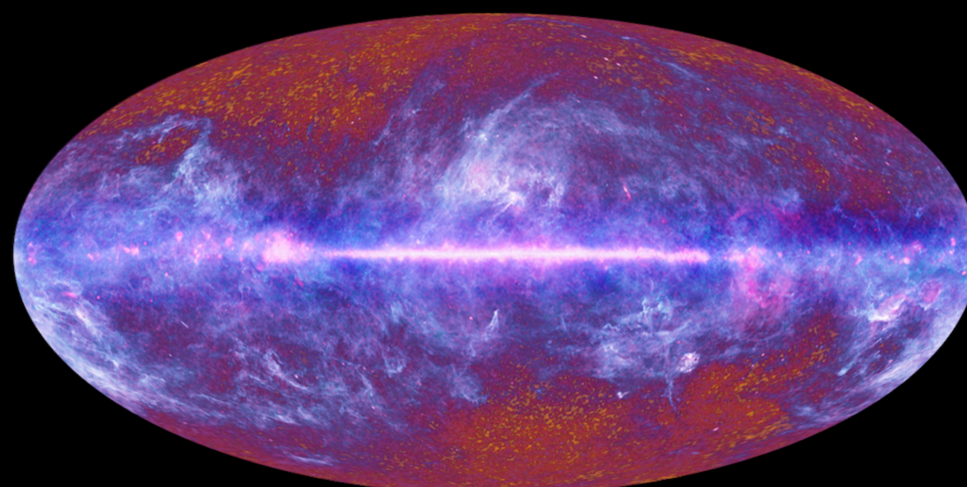
Synergy science

- Reaching these science goals require to control foreground emissions to exacting standards, which provides great additional science opportunities.
- In particular, this datasets will be well suited for unique progress in ISM understanding.

PRISM combines the power of PLANCK and Herschel for studies of the galactic ISM.

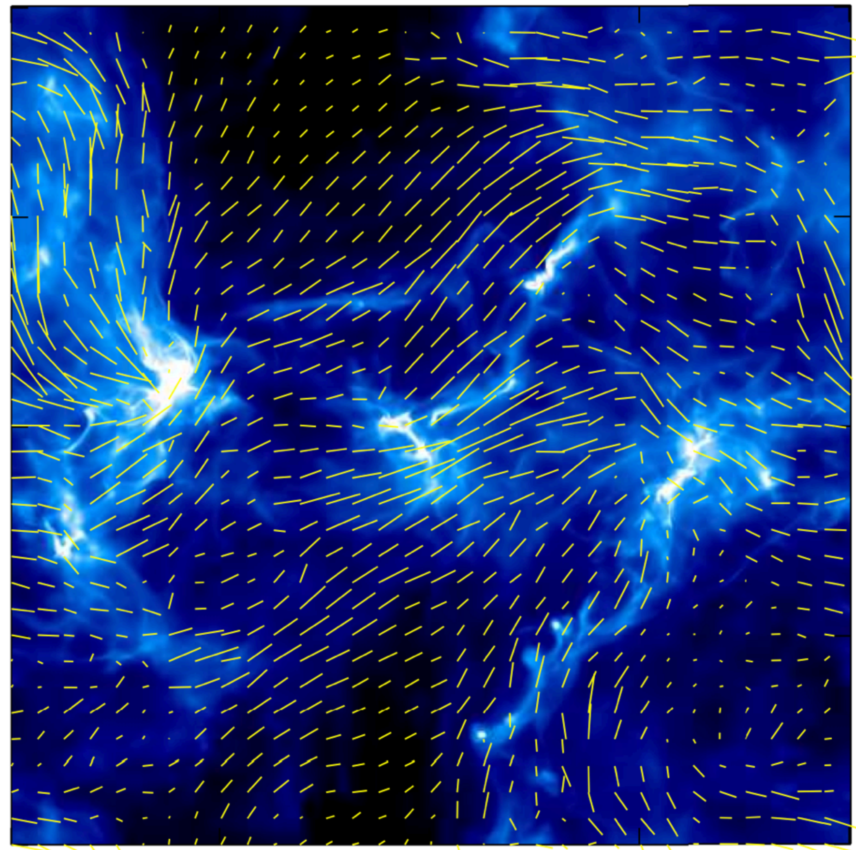
- PRISM will provide all-sky maps at Herschel resolution of
  - Dust and synchrotron emission, in intensity and polarization, tracing the density and magnetic field structures of the ISM,
  - Emission lines (CII, CI, OI, CO, H2O, NII), key to quantify ISM physical processes and to understand the transitions between ISM phases.
- PRISM will address three fundamental questions in Galactic astrophysics
  - **What are the processes that structure the interstellar medium ?**
  - **What role does the magnetic field play in the star formation process ?**
  - **What are the processes that determine the composition and evolution of interstellar dust ?**





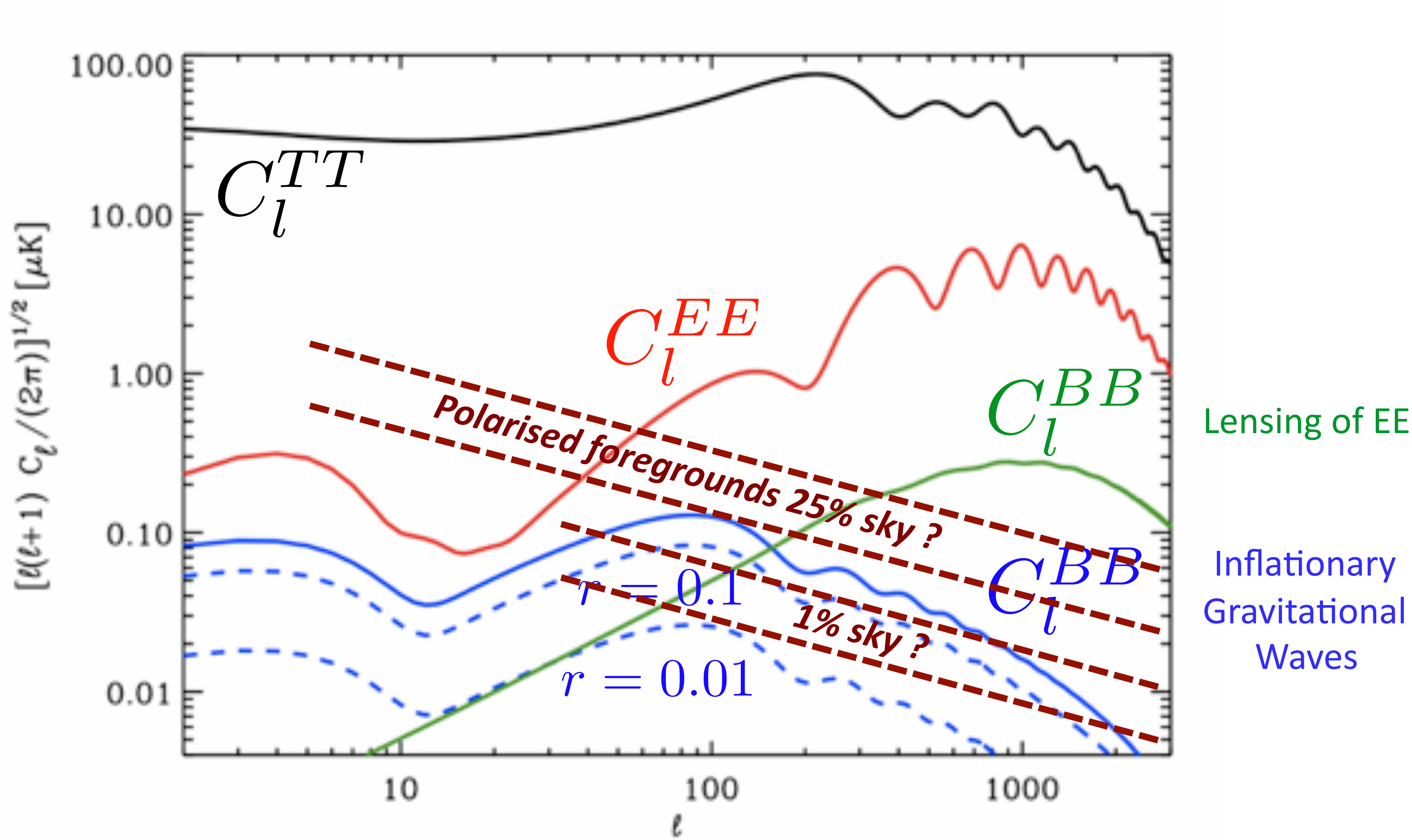
PRISM and the Galactic magnetic field

- The **magnetic field** is the final frontier in the understanding of the star formation process: gravity, turbulence and magnetic field are equally important in the structure and evolution of clouds. The balance between them is key to understanding how stars form.
  - **Polarization observations are lacking:** it is one of the rare field in astrophysics where numerical simulations are ahead of the observations.
- PRISM has the resolution and sensitivity to map the projected structure of the Galactic magnetic field over the whole sky, down to sub-arcmin resolution
  - Planck measures it over the whole sky in only one frequency, with limited sensitivity and 5 arcmin resolution
  - Ground based (e.g., ALMA) can achieve high resolution but on specific targets only
  - **Observing the whole sky is important to understand the MHD turbulence cascade and the connection of the field to the local spiral arm.**

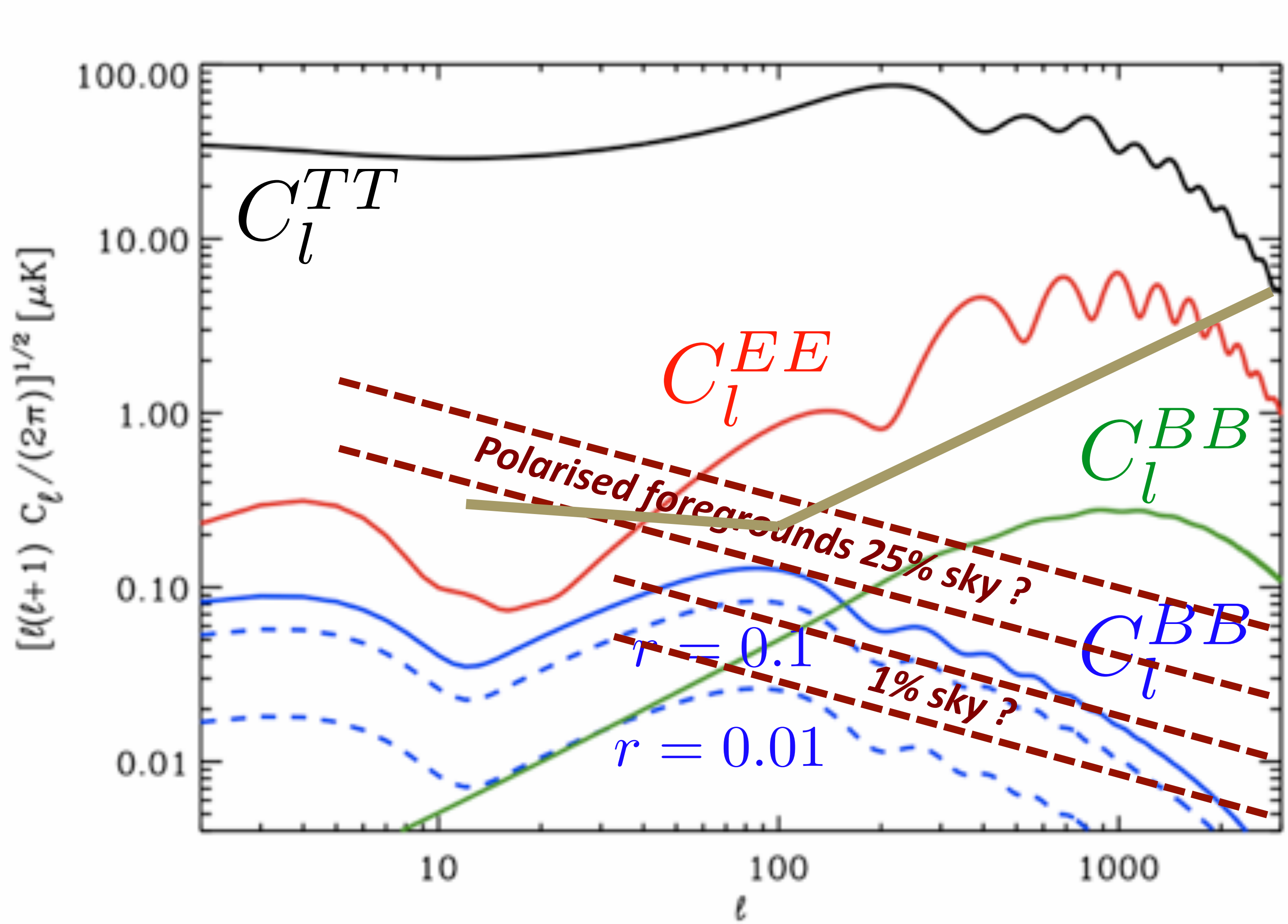


MHD simulations: link between structure and magnetic field in a molecular cloud. Soler et al. (2013)

Polarisation



Polarisation

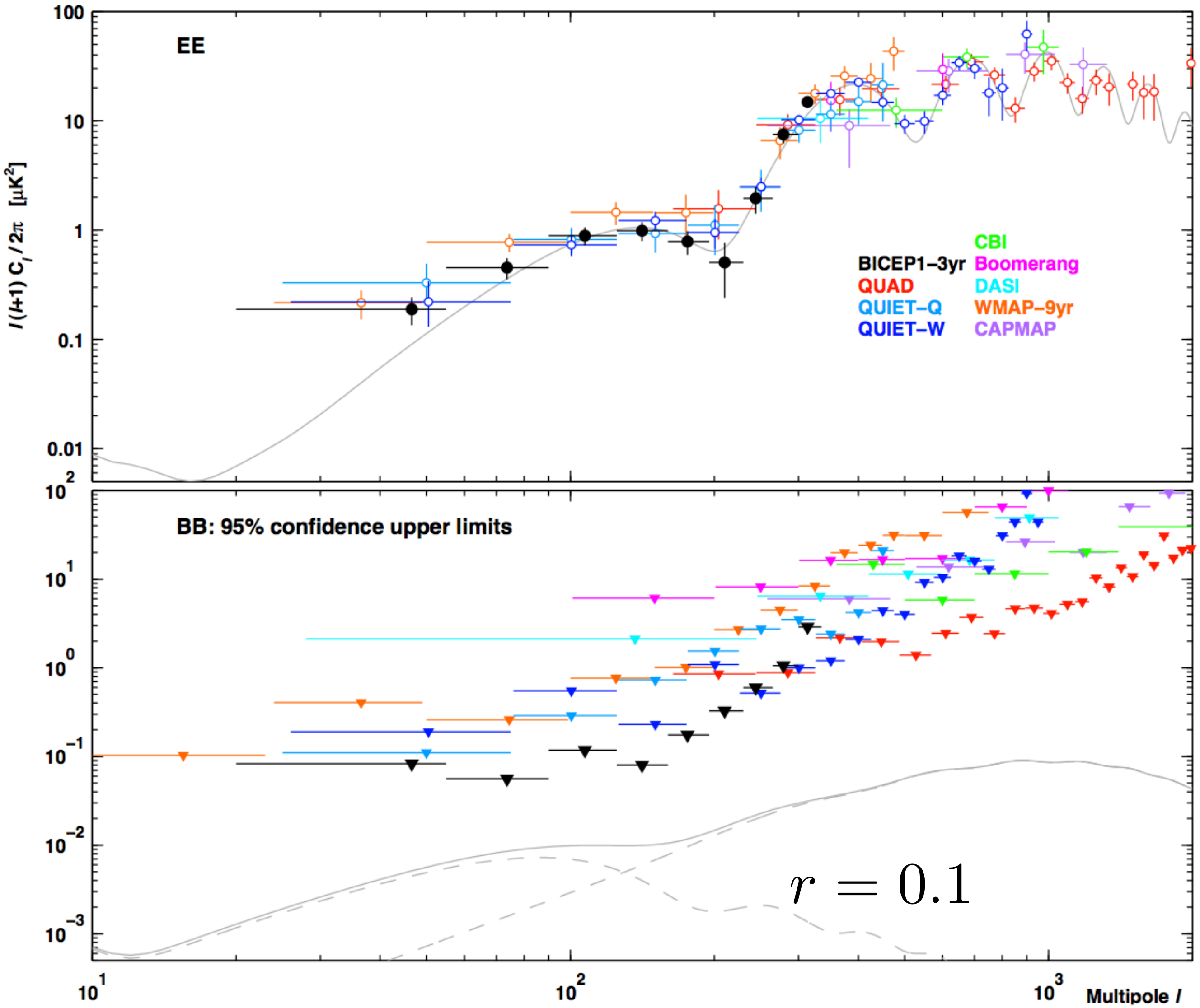


Current pol. 95% upper limits

Lensing of EE

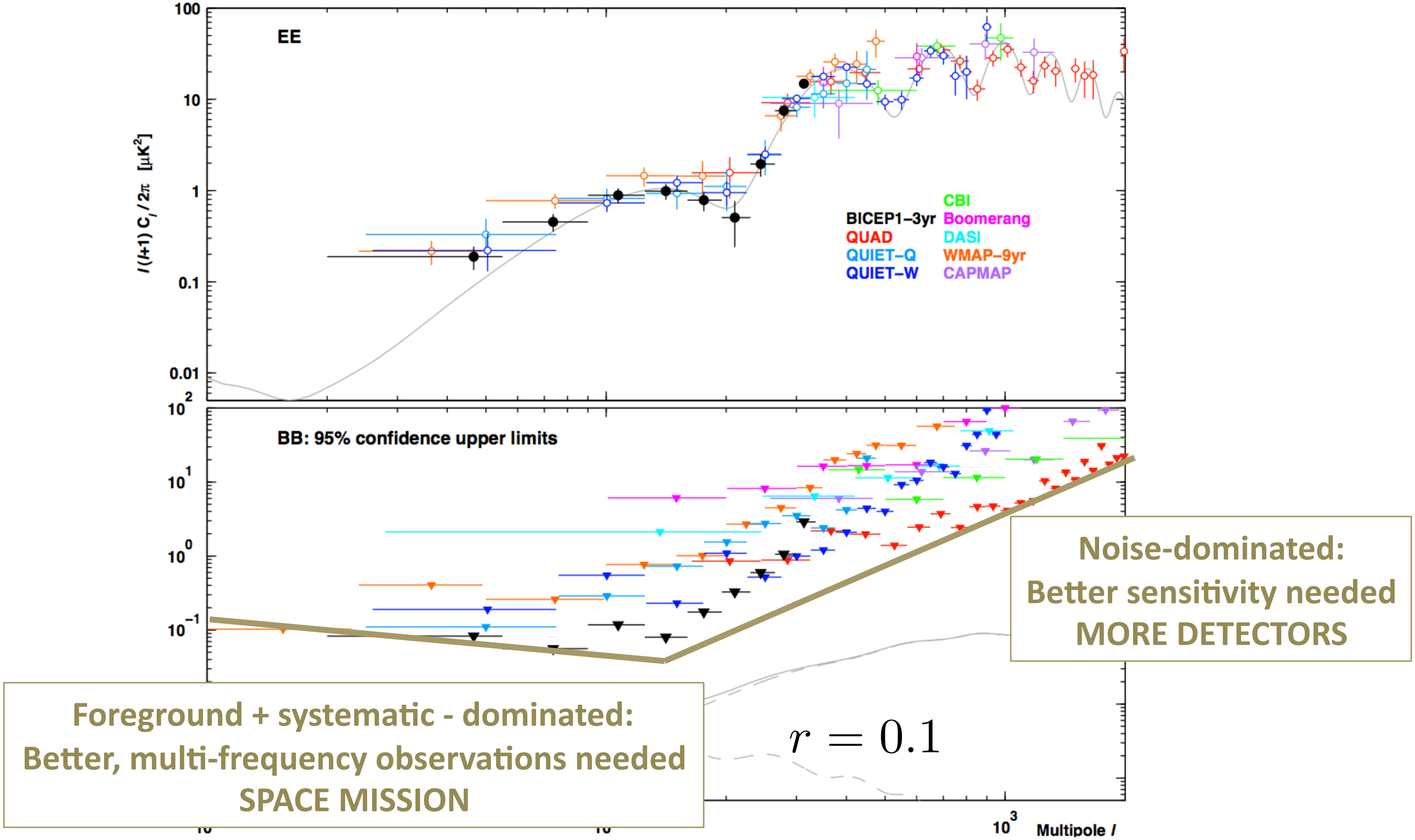
Inflationary Gravitational Waves

Current measurements

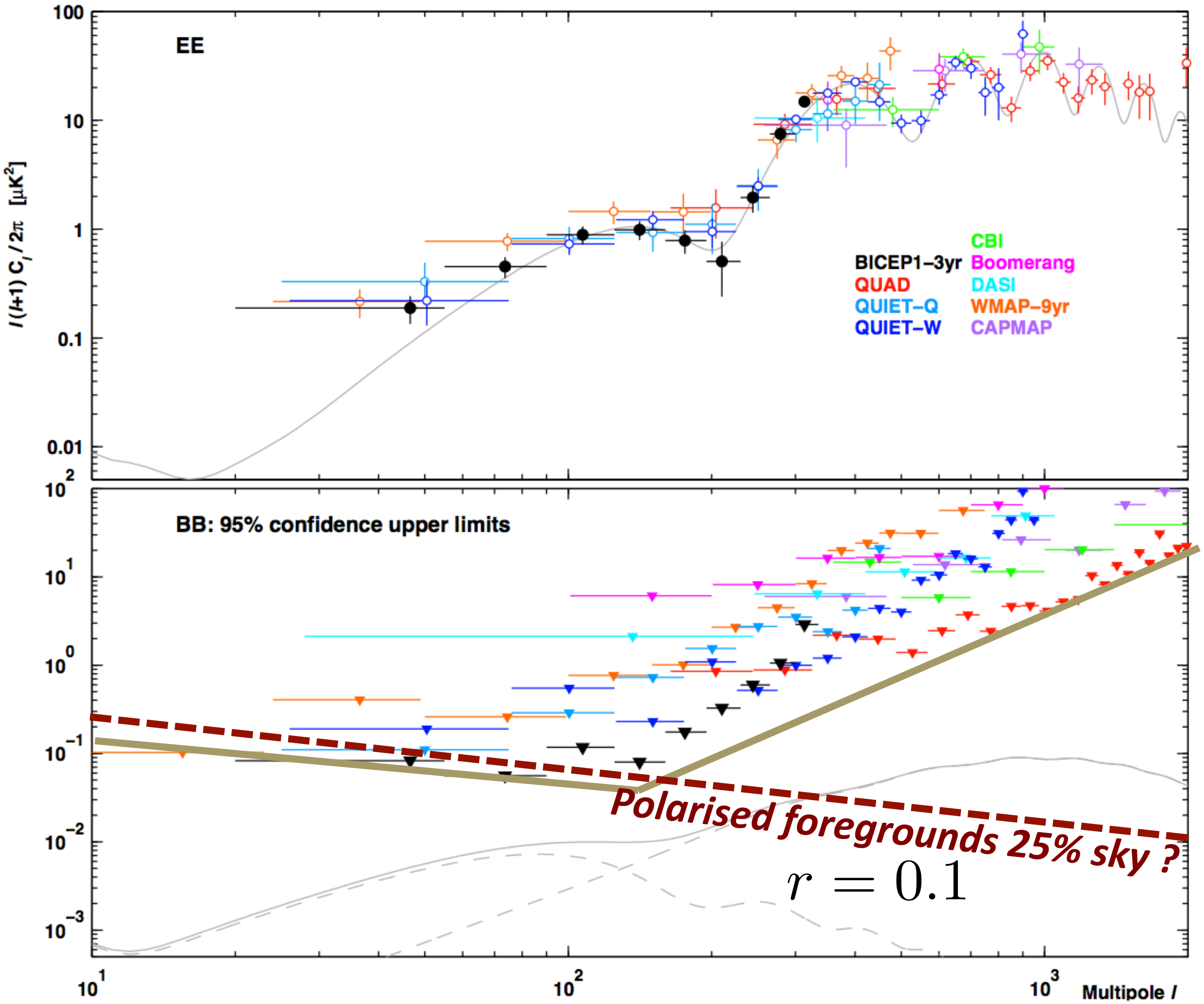


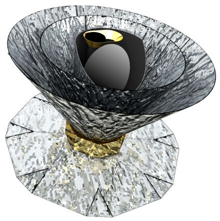
BICEP collaboration, Barkats et al., arXiv 1310.1422

Current measurements



Current measurements



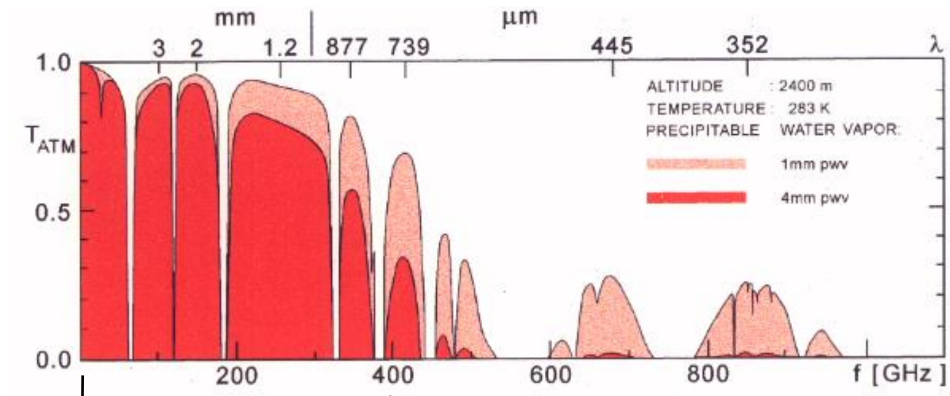


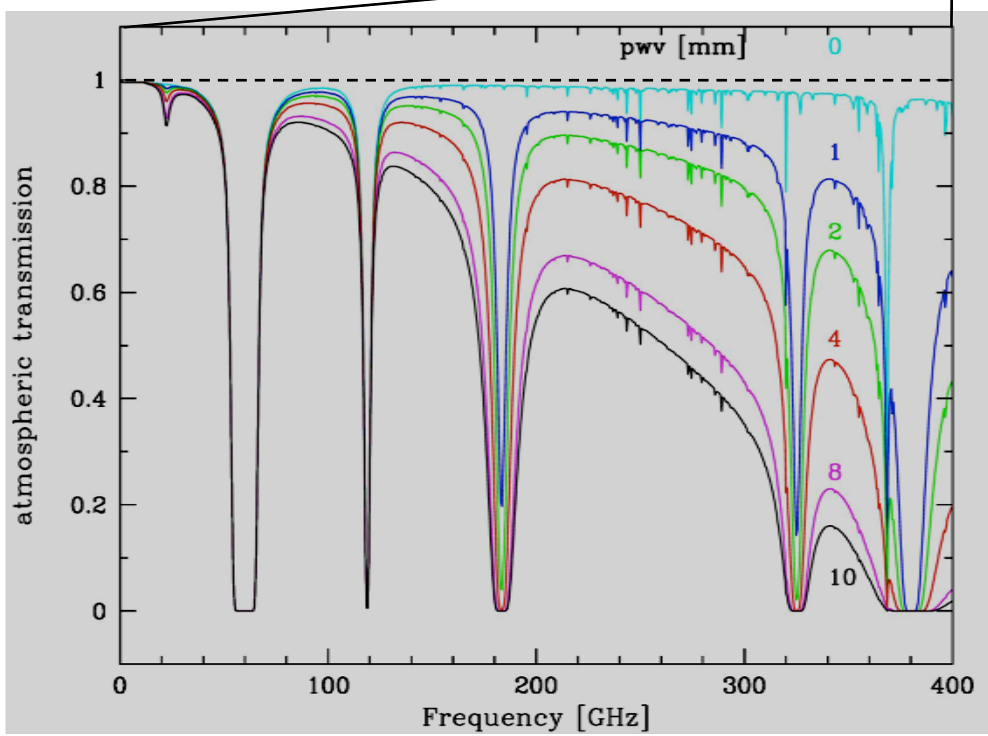
Why a space mission?

Atmospheric transmission and emission

Systematics

Complete survey

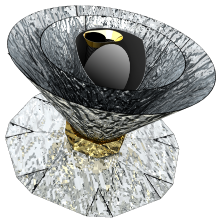




At 150 GHz a Planck detector is ≈10 × more sensitive than ground-based detectors at ATACAMA or South Pole in good observing conditions.

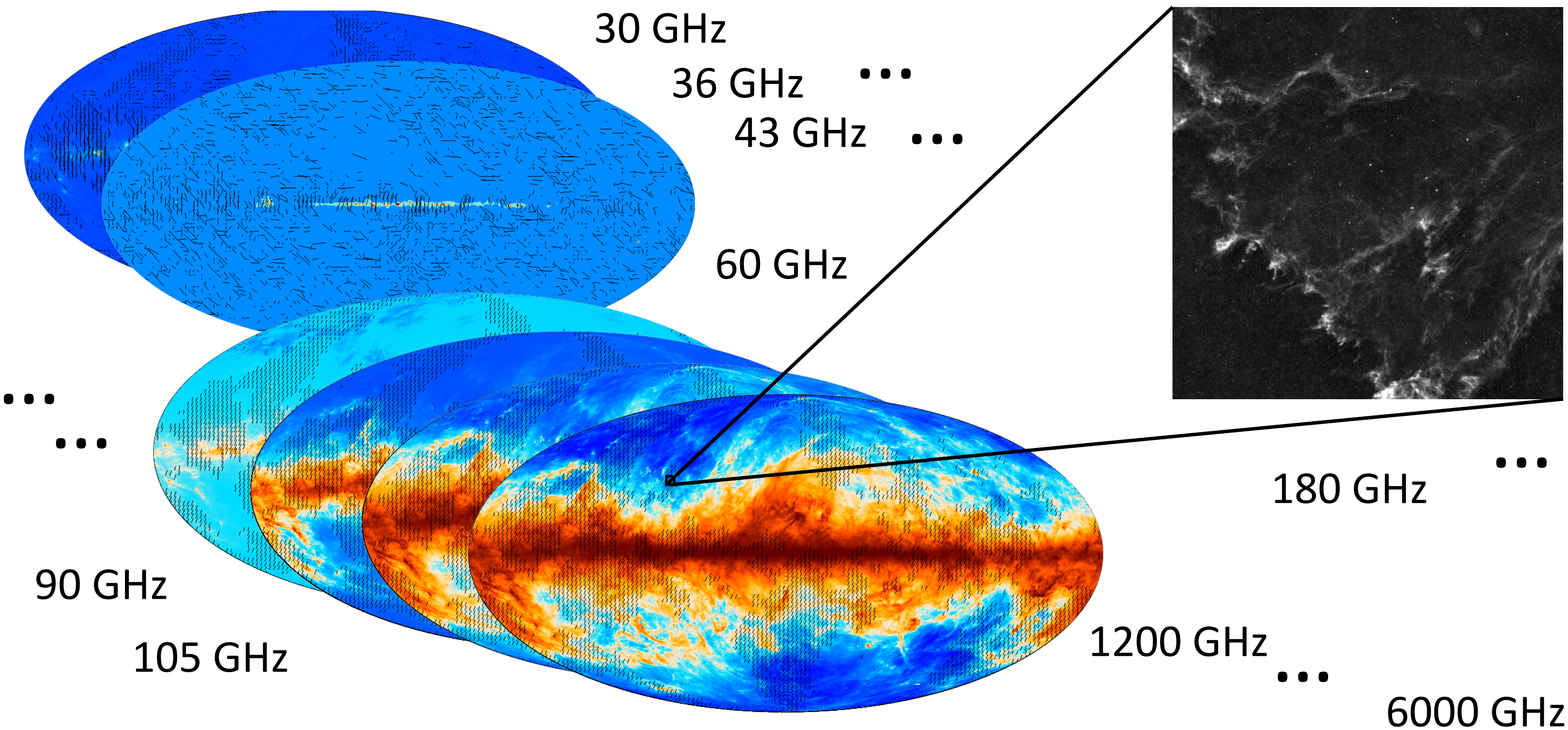
Factor of 100-400 in observing time.

The situation is much worse for ground-based observations at higher frequency.



The PRISM Legacy

PRISM would provide ***hundreds of intensity and polarization maps***, assembling a legacy archive useful for almost all branches of astronomy for decades to come. Combining low resolution spectrometer data and high resolution full-sky polarized maps, PRISM will deliver a full spectro-polarimetric survey of the complete sky from 50 μm to 1 cm.



Outline

- PRISM
- CMB anisotropies and inflation
- CMB lensing
- Clusters of galaxies
- Astrophysical cosmology
- The galactic ISM
- ➡ Conclusion

What next ?

- ESA has made its selection
  - Athena+ (X-rays) for 2028, eLISA (GW) for 2034
  - PRISM was one out of 5 pre-selected candidates
  - Feedback from selection:
    - CMB science essential, a space mission is needed
    - Non CMB science interesting but should not drive the cost
    - Submit an M mission

- Why was PRISM not selected ?
  - Strong and active competition
  - ***Contrarily to some other projects, much of this science can be done with an M-class mission !***

What next ?

- An M-class version of PRISM ?
  - Reduce the telescope size from 3.5 to 2.5m (fit in a Soyouz)
  - No active cooling of the large telescope
  - Reduce the frequency range to frequencies $< \approx$1THz

- The CMB science is essentially intact.
- Cluster survey less complete but science still very interesting.
- We still observe the CIB and dusty galaxies, but with less channels and less angular resolution…
- Much galactic science is still possible

- ***A fantastic science case !***

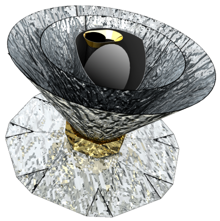
Let's do it !

That's all for today !

Thank you for your attention

BACKUP SLIDES

(for questions if necessary)



Science case: why PRISM ?

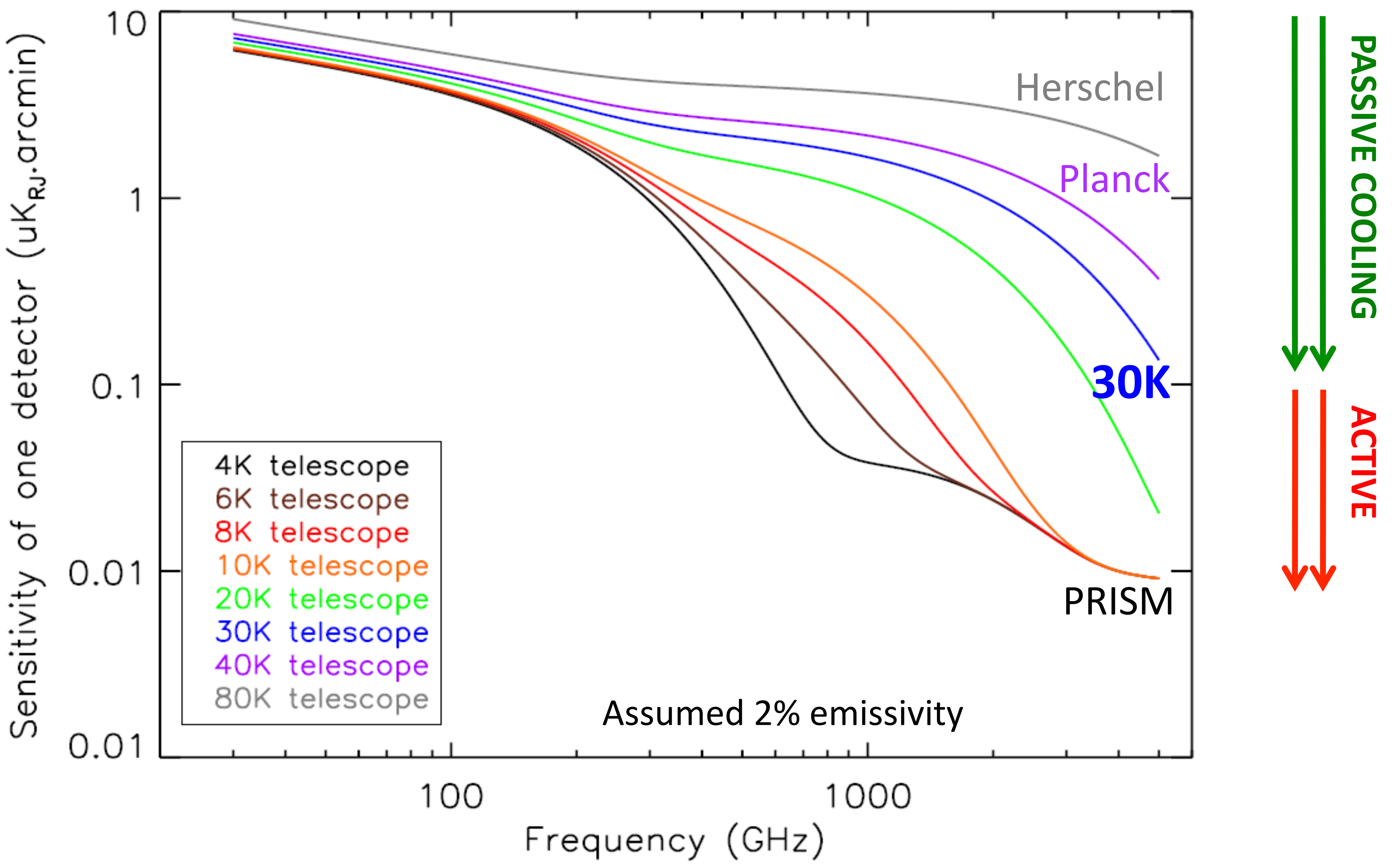
- Primordial CMB B-modes, high precision CMB T (absolute!) and E

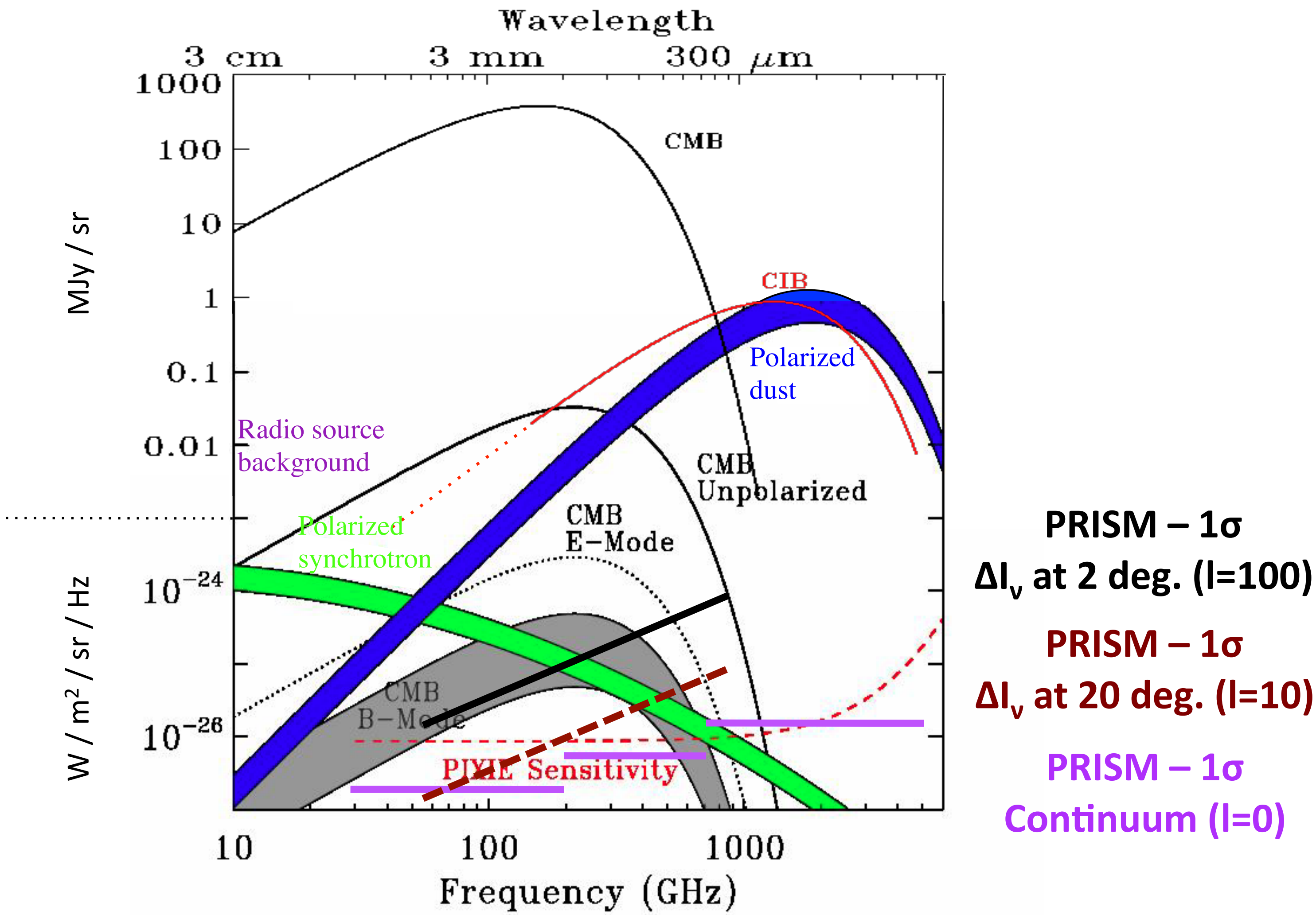
- 3D structures and velocity flows:
  - A complete census of galaxy clusters (hot baryons and mass up to z>3)
  - CMB lensing (projected mass)
  - The CIB and dusty galaxies (up to z>6) – dust, AGNs and interplay, P(k) in shells
  - 3D cosmic velocity flows

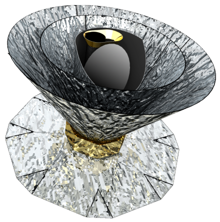
- All phases of the galactic interstellar medium (CMB foregrounds):
  - Dust (thermal, spinning, size and chemical composition)
  - Cosmic rays (synchrotron components)
  - Gas (neutral and ionised), free-free, atoms and molecules, molecular clouds,
  - Magnetic field via polarisation of dust (and synchrotron)

- CMB spectral distortions
  - thermal history, energy exchanges between CMB and matter
  - reionisation, decaying dark-matter particles, small scale primordial P(k)

A cold telescope




Wavelength
3 cm
3 mm
300 μm
1000
100
10
1
0.1
0.01
MJy / sr
CMB
CIB
Polarized dust
Radio source background
CMB Unpolarized
CMB E-Mode
Polarized synchrotron
10^{-24}
10^{-26}
W / m^2 / sr / Hz
CMB B-Mode
PIXIE Sensitivity
10
100
1000
Frequency (GHz)
PRISM – 1σ
ΔI_ν at 2 deg. (l=100)
PRISM – 1σ
ΔI_ν at 20 deg. (l=10)
PRISM – 1σ
Continuum (l=0)



CMB spectral distortions

✓ Current observations consistent with Blackbody & Standard Big-Bang Model… BUT:

◆ Several processes lead to inevitable distortions

❖ Comptonization & free-free distortion associated with reionization / structure formation & hot galaxy clusters: clearly detectable with PRISM ($\gtrsim 100\sigma$!)

❖ Dissipation of acoustic modes at small scales ($1\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$):

→ complementary probe of inflation over additional ~10 e-folds!

→ signal for standard power spectrum detectable with PRISM

❖ Hydrogen and Helium recombination lines from $z \simeq 10^3$

→ HI Balmer & Paschen-α lines detectable with PRISM

→ additional anisotropic signal detectable with PRISM!

❖ Resonant scattering signals of metals during the dark ages

◆ CMB spectrum also is a probe of new physics: Discovery potential Lifetime and abundance of decaying particles (complementarity with BBN)

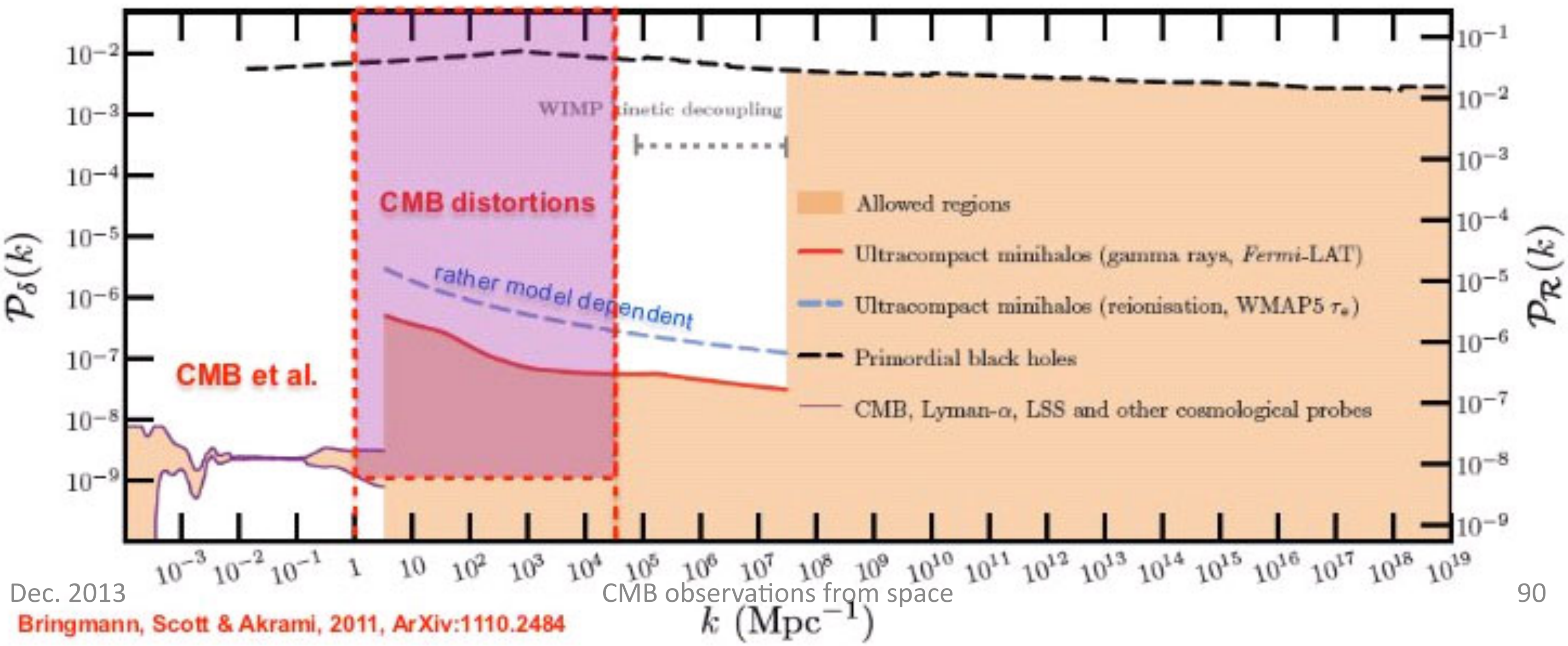
❖ Constraints on annihilating particles (both from CMB anisotropies & spectrum!)

❖ Cosmic strings, primordial black holes, primordial magnetic fields, axions...

5

Probing primordial power spectrum on very small scales using spectral distortion

- Current constraints on the power spectrum (and the spectral index n_s) are limited by the size of current horizon (CMB quadrupole) on large scales, and by nonlinearity and Silk damping on small scales.
- Little improvement can be expected from galaxy surveys and SKA because of these fundamental limitation.
- The small scale primordial power dissipated by Silk damping does not disappear completely, but leaves its imprint in **spectral distortions** from the perfect CMB blackbody spectrum. **Important target for the PRISM spectrometer.**

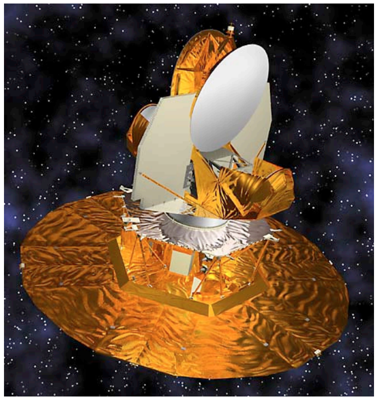


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

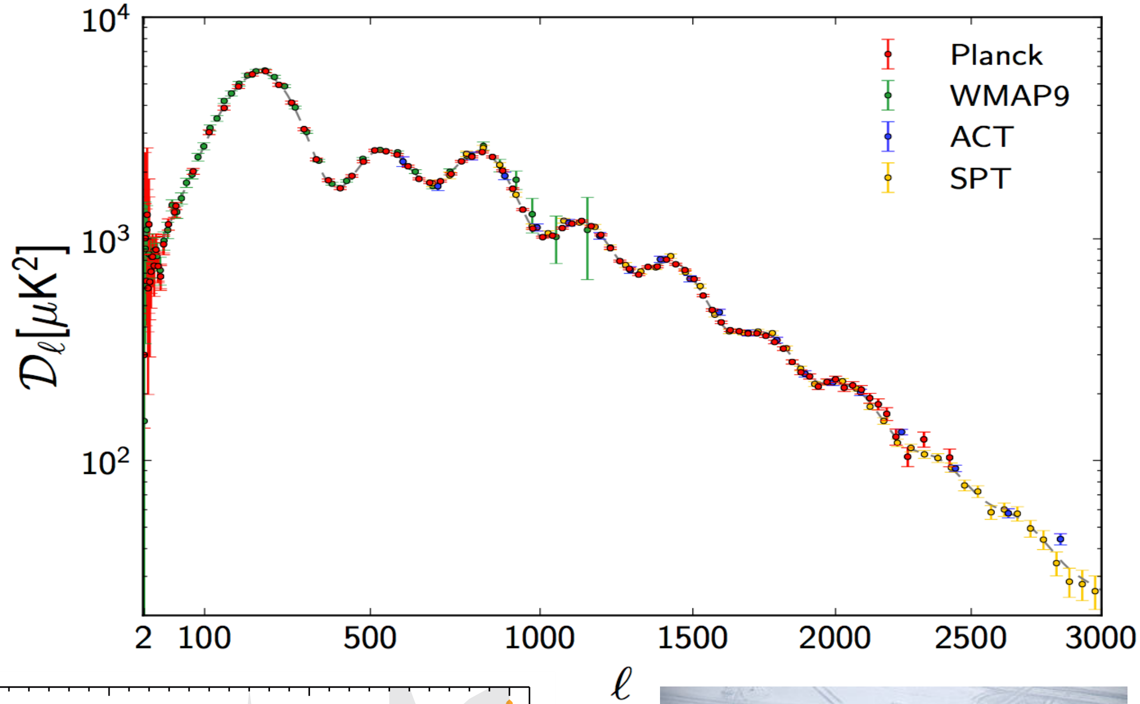
Planck parameters: limitations

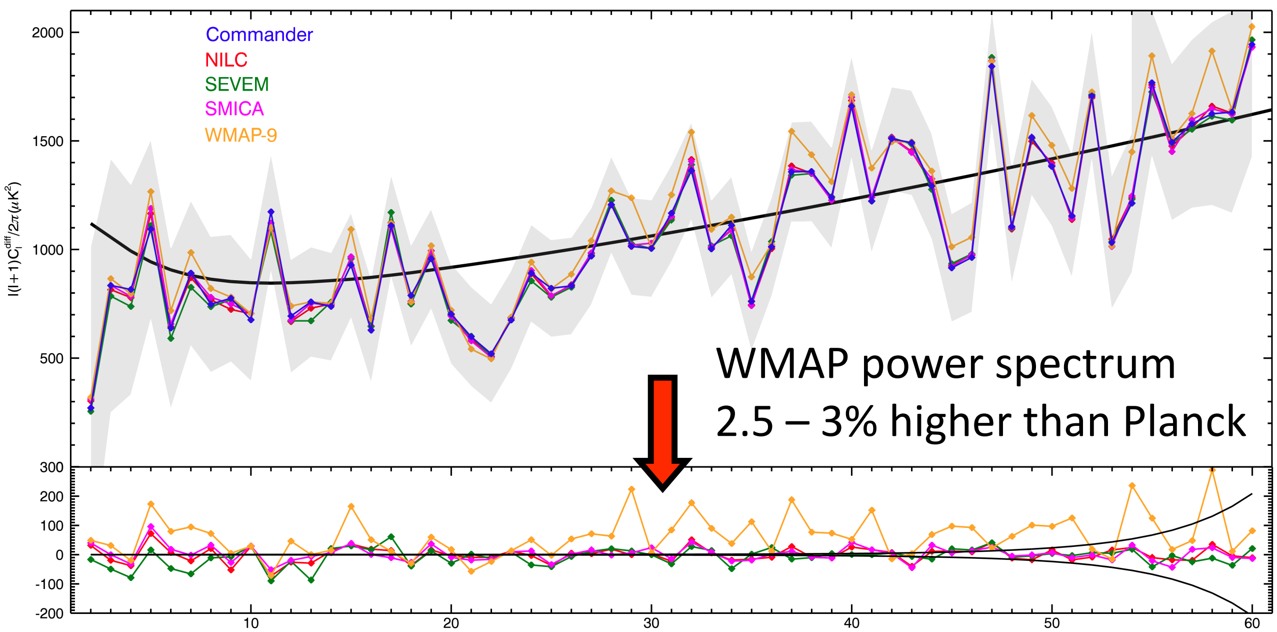
- The baseline parameter fit for Planck uses 4 cross spectra: 100x100, 143x143, 217x217, 143x217. We fit for:
  - ***6 cosmological parameters***
  - ***11 model-dependent*** astrophysical parameters
    - Amplitudes of spectra of foreground emission
    - spectral indices
    - correlation coefficients
  - **2** calibration parameters
  - Up to ***20*** beam parameters
- With ACT and SPT data, 17 additional foreground and nuisance parameters, for a total of 50.
- Use only ***57.8%*** of sky at 100 GHz, and ***37.3%*** of sky at 143 - 217 GHz
- Temperature anisotropies only so far…

Consistency and discrepancy



WMAP





WMAP power spectrum
2.5 – 3% higher than Planck

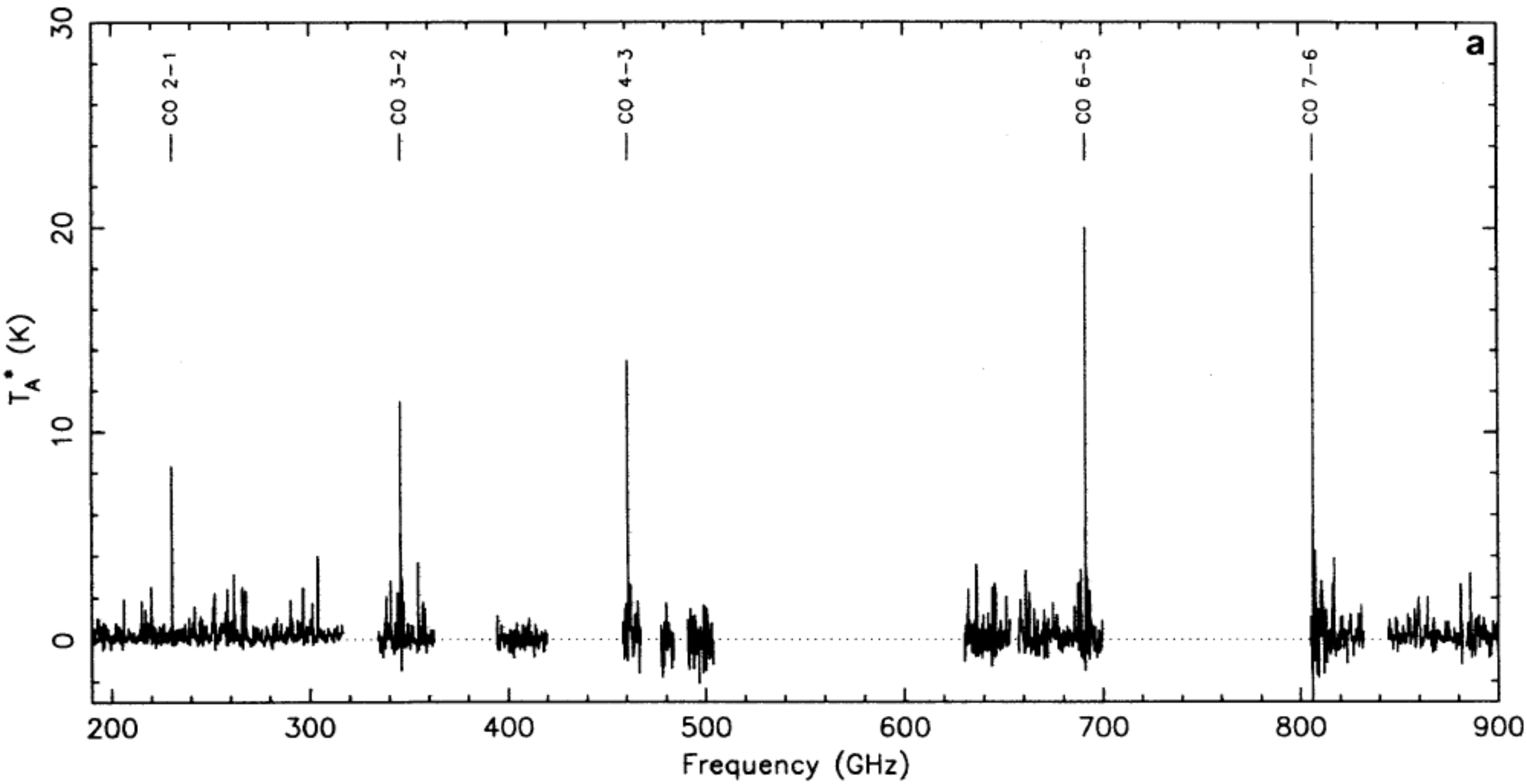
SPT

ACT

Additional science …

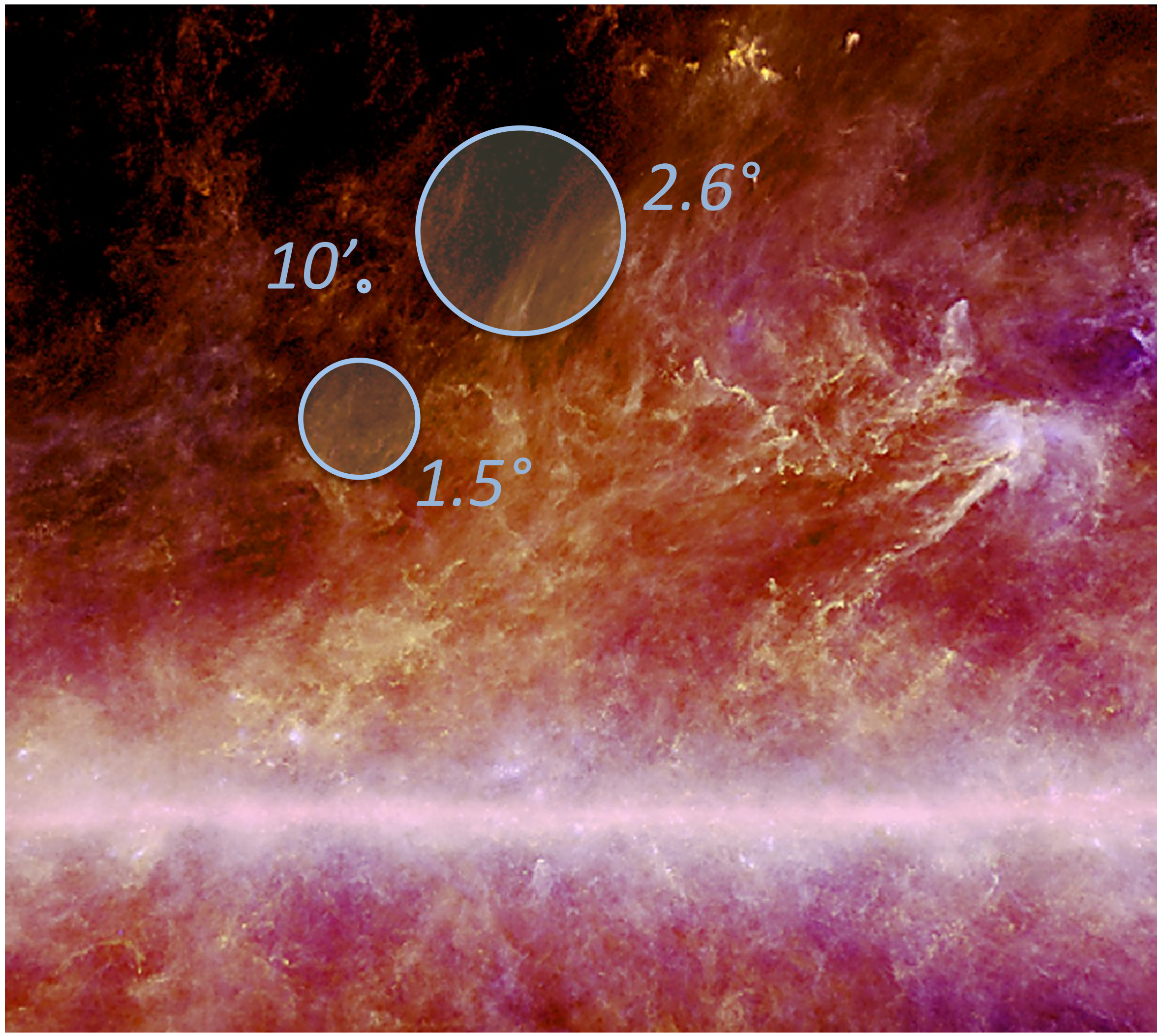
- Non Gaussian perturbations
- Cluster temperatures
- Neutrino masses: determining neutrino hierarchy
- Interacting dark matter
- Decaying dark matter
- CMB Rayleigh scattering
- Modified gravity
- Topological defects
- Zodiacal emission & solar system bodies
- … … …

Line monitor – SED spectroscopy

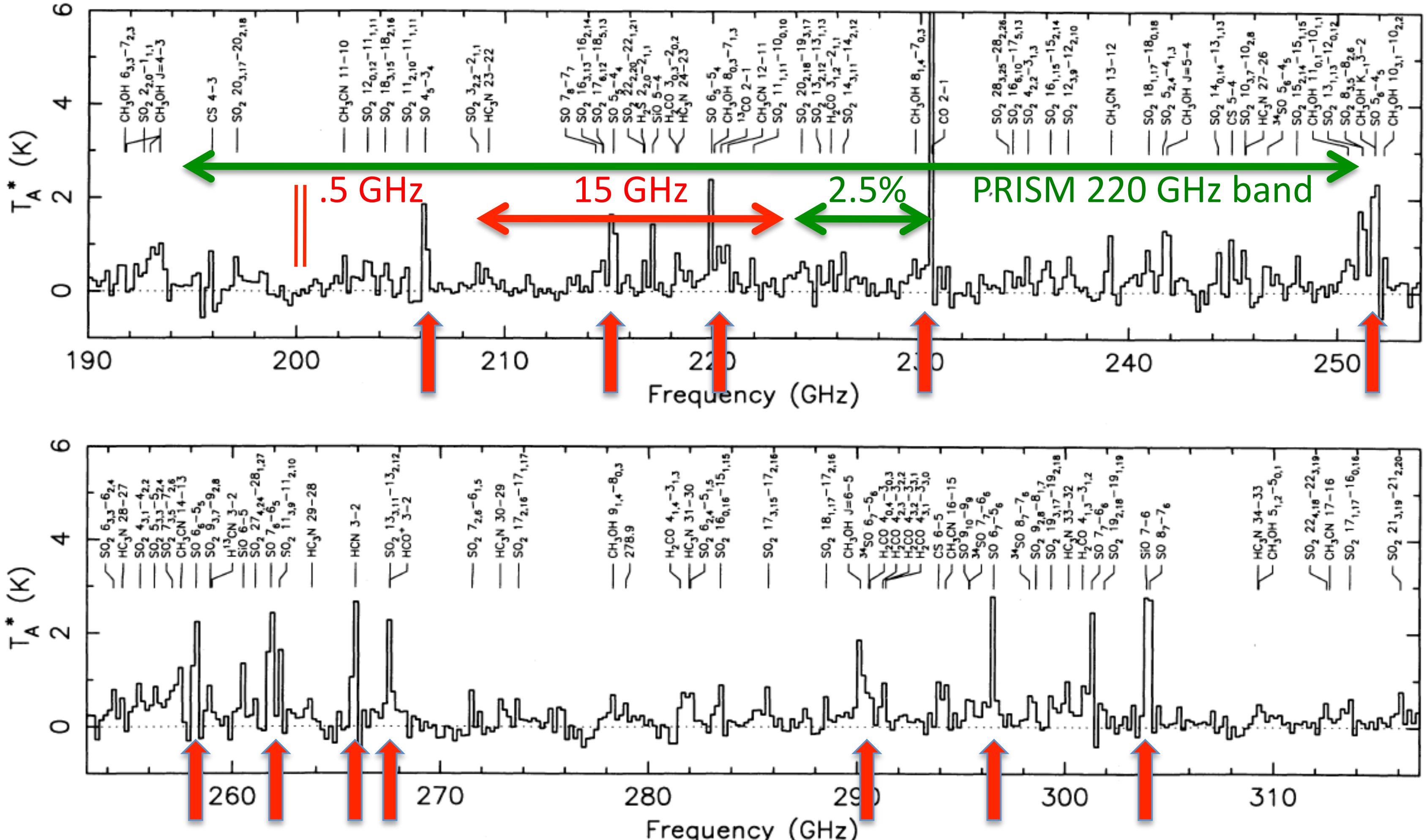


Serabyn & Weisstein, ApJ, 451, 238 (1995)

Confusion in large beams



Line monitor – SED spectroscopy

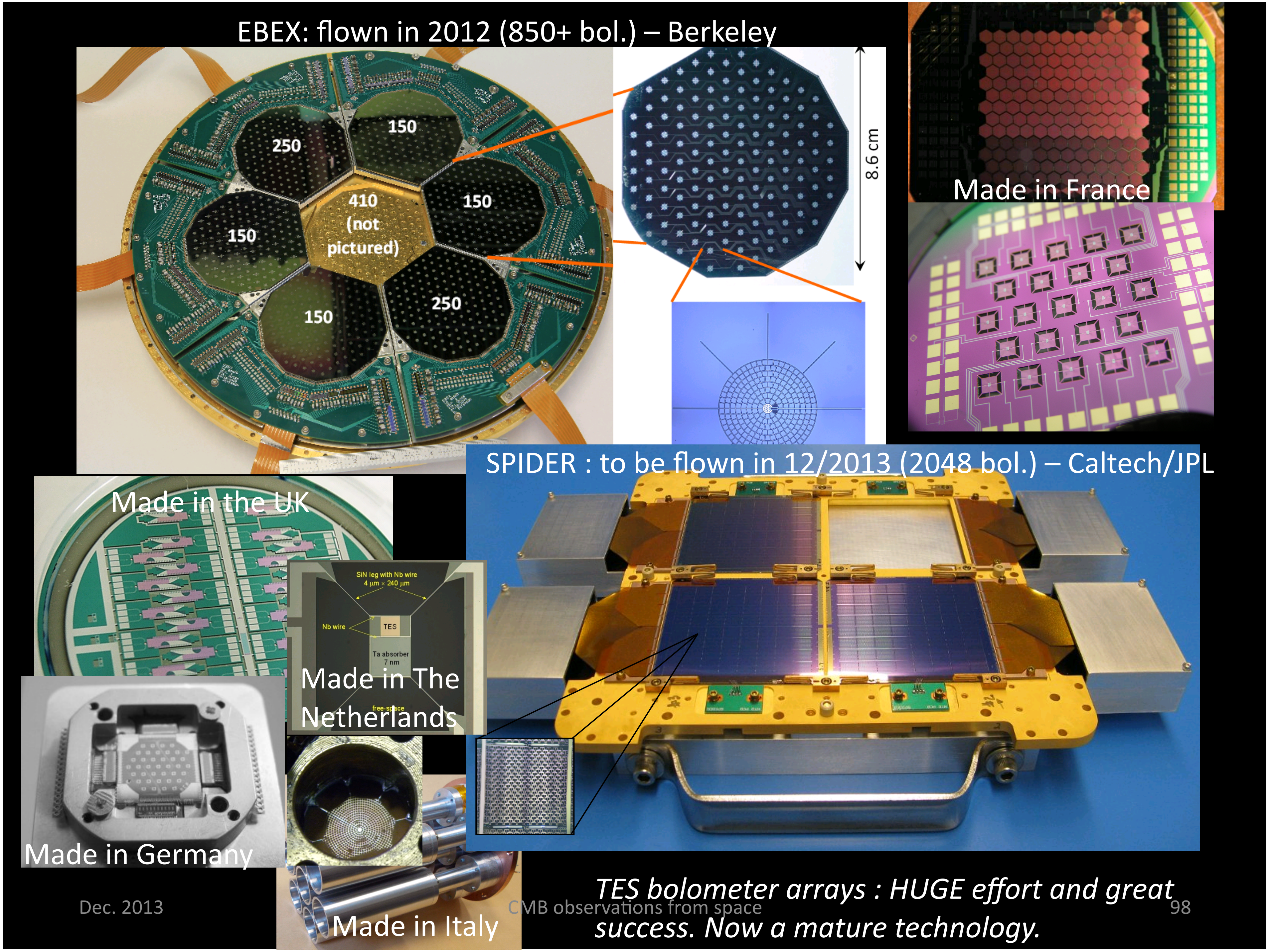


Here binned in 200 MHz bands

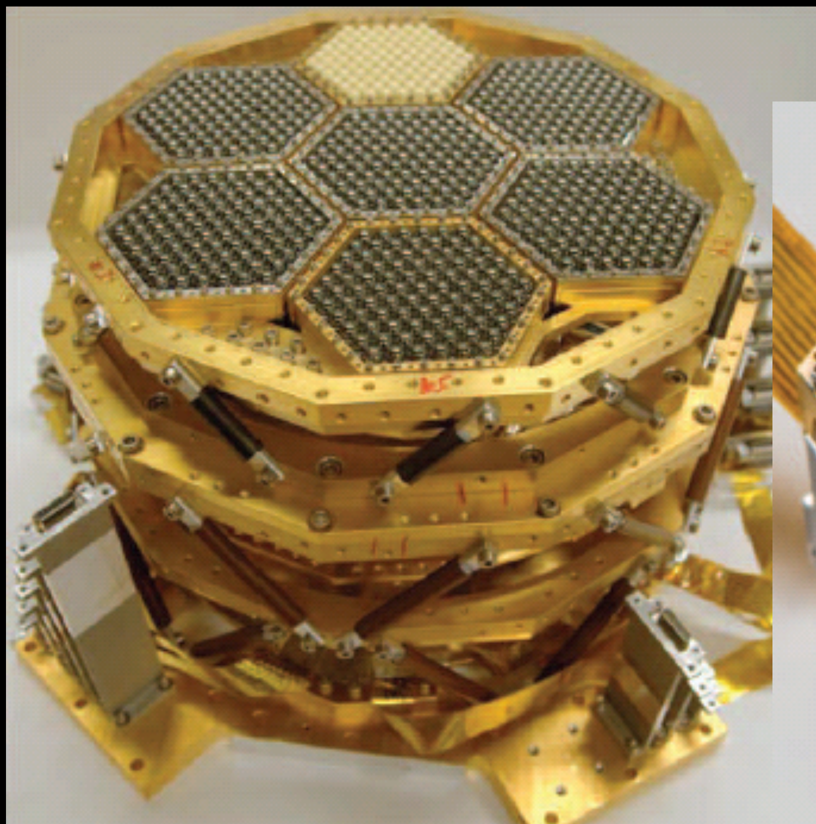
Serabyn & Weisstein, ApJ, 451, 238 (1995)

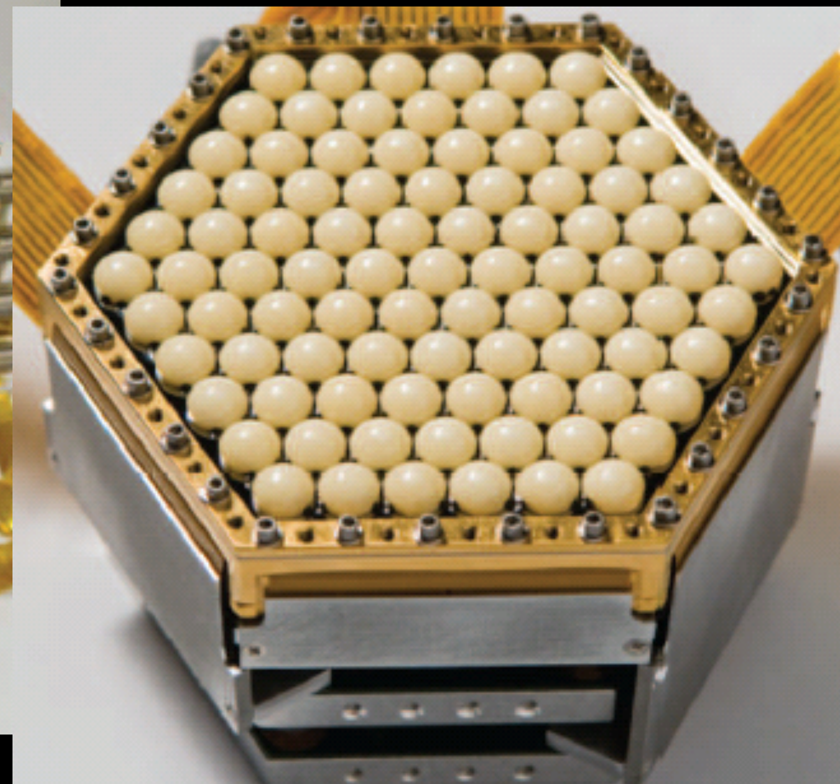
Line monitor – SED spectroscopy

- Not critical for CMB polarisation nor SZ studies
- Useful but not critical for precise CMB temperature anisotropies measurements
- Some line monitoring necessary for galactic astrophysics (dust SED physics)
- Some line monitoring necessary for precise CMB spectral distortion measurement
- Line measurement critical for some galactic astrophysics


EBEX: flown in 2012 (850+ bol.) – Berkeley
250
150
150
410
(not
pictured)
150
150
250
8.6 cm
Made in France
SPIDER : to be flown in 12/2013 (2048 bol.) – Caltech/JPL
Made in the UK
SiN leg with Nb wire
4 µm × 240 µm
Nb wire
TES
Ta absorber
7 nm
Made in The Netherlands
Made in Germany
Made in Italy
TES bolometer arrays : HUGE effort and great success. Now a mature technology.

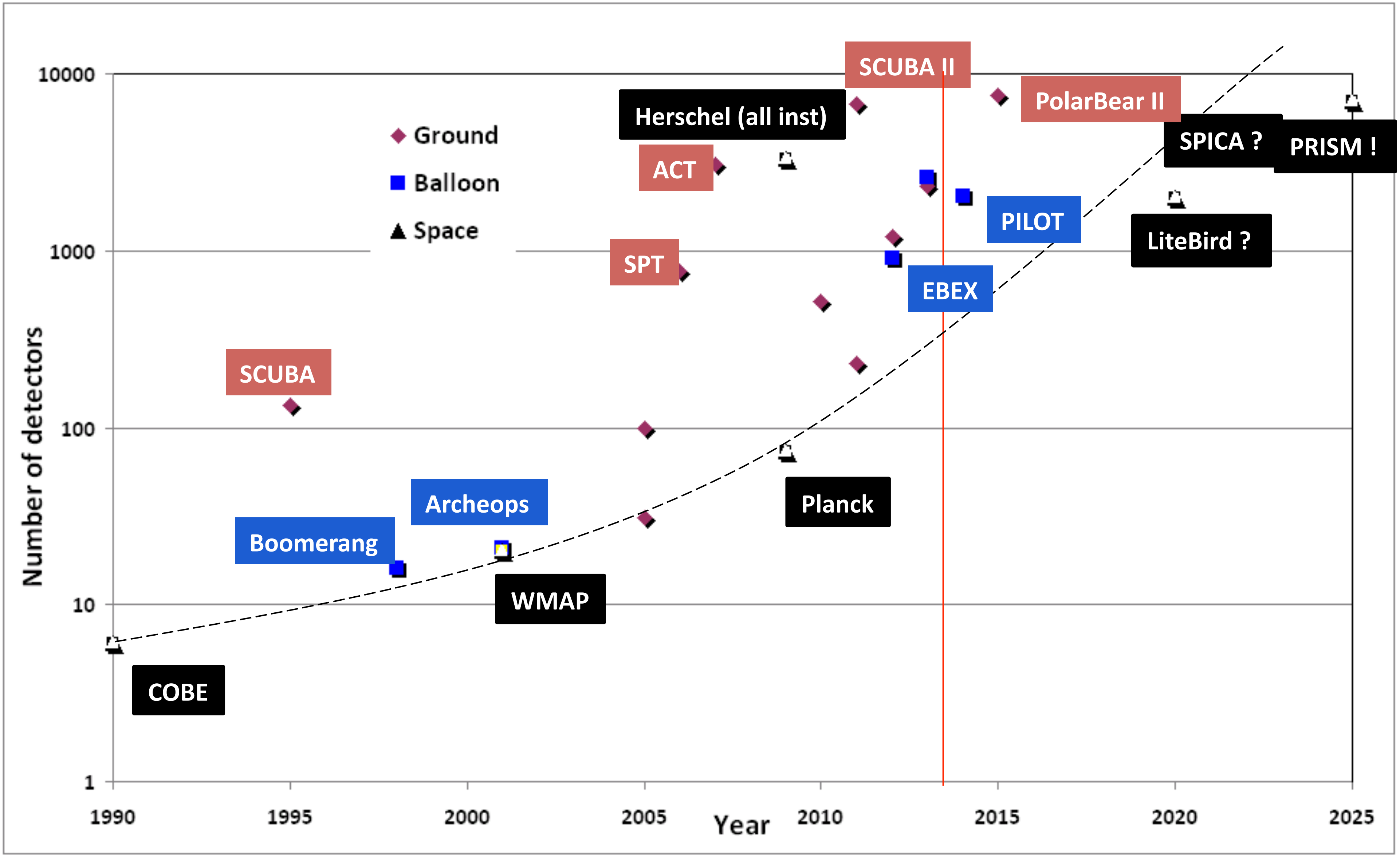
The trend :





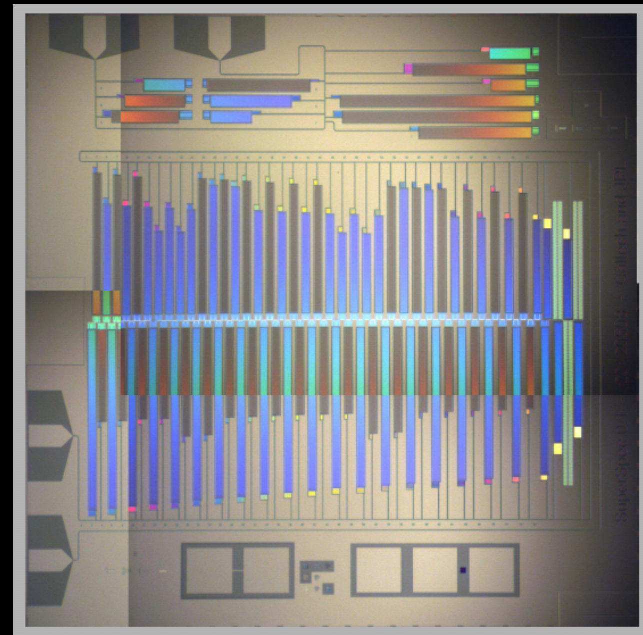
- Large arrays of multichroic pixels: 6000+ detectors for polarbear2, SPTpol, litebird …
- ESA ITT for compact focal planes (Maynooth)

Evolution of number of detectors in mm-wave / sub-mm projects

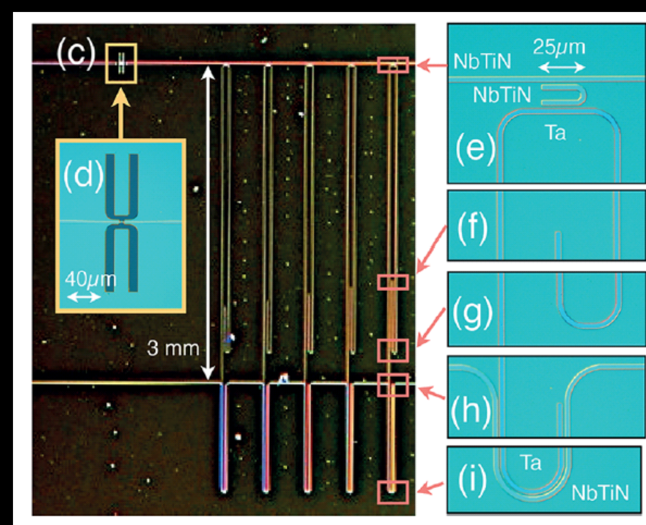


Lines monitors

- Need R=40 @ sub-mm
  - Monitor Galactic lines
  - Get redshifts from C+ line
- Either single pixels with narrow-band filters
- Or narrow-band channelizers
- or filter-bank on chip (Superspec, Deshima, and similar)
- Very promising !



Superspec, astro-ph/1211.1652
Kovacs et al. SPIE 8452 (2012)

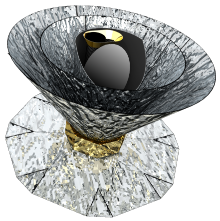


Deshima, Endo et a. APL 103 (2013)

Polarimetric Imager : telescope

- Off-axis telescope (sidelobes and correct focal plane size)
- Correct all the way to
  - Requirement: 3 THz (100 μm) : 5 μm surface accuracy
  - Goal: 6 THz (50 μm) : 2.5 μm surface accuracy **(Herschel)**
- Aperture:
  - This is a large mission, and we plan to exploit its power using the largest mirror fitting the Ariane-5 fairing. We have assumed 3.5m of projected aperture (similar to Herschel and SPICA).
  - Science output degrades gradually with smaller apertures (# of detected clusters, resolved fraction of the CIB, resolution in ISM studies). Optimization science vs cost to be studied in the implementation phase.
- Temperature:
  - Requirement: 10K
  - Goal: 7 K

Requires active cooling of shield and mirror

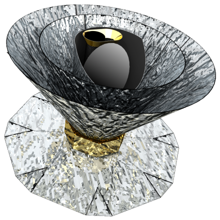


The polarimetric imager

- The polarimetric imager (PIM) is designed to map the full sky brightness fluctuations in intensity and polarisation
  - in as many bands as possible between 30 GHz and 6 THz
  - with the best possible angular resolution and sensitivity

- Compromise between sensitivity and spectral resolution
  - 50% of detectors in 32 broad-band channels with $\Delta\nu/\nu \approx 0.25$
  - 50% of the detectors in 300 narrow-band channels with $\Delta\nu/\nu \approx 0.025$

- Compromise between sensitivity and angular resolution
  - For the moment, angular resolution is preferred (single mode detectors at the diffraction limit).
  - Can be reconsidered for the narrow-band detectors (to map faint spectral lines at high frequency)

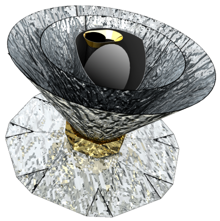


The spectrophotometer

- The absolute spectrophotometer (ASP) is designed both to
  - measure the absolute sky emission between 30 GHz and 6 THz
  - serve as an absolute on-sky calibrator for the PIM

- Main idea: complementarity
  - The spectrophotometer measures the l=0 mode
  - Both the ASP and the PIM measure modes from l=1 to l≈100 (Intensity)
  - The PIM measures modes up to l≈6000 or more in Intensity and Polar

- Compromise between sensitivity and spectral resolution
  - Two operating modes: high resolution for matching band with PIM (by coadding ASP high-res channels) and for spectral line survey, low resolution for sensitivity to CMB.



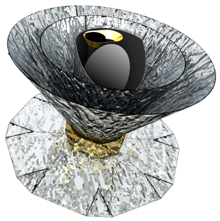
Synergies

- Cross-correlations / complementarity with other *surveys*
  - Euclid (population of cluster haloes, lenses of high-z FIR galaxies)
  - SKA (complementarity in frequency, reionisation, radio sources, neutral hydrogen - redshifts of objects)
  - eROSITA (common clusters at $z<1$, X-ray stacking at $z>1$)
  - LSST

- Follow-up with and large ground-based facilities *pointed observations*
  - Cluster substructures at high resolution from the ground
  - ALMA: complementarity in scales, follow-up spectra
  - CCAT: cluster velocities and substructures, temperatures (pointed + survey)
  - Validation of separation of CIB in redshift shells on patches at high resolution

- Follow-up with other space missions
  - X-rays (e.g. Athena or US equivalent)
  - SZ effect (e.g. Millimetron)
  - Galactic and extragalactic infrared targets (future FIR interferometer)

- PRISM: a very complete survey by itself, + an enhancer/improver of other instruments



Is it *feasible* ?

- ✓ Full design still TBD/TBC, but nothing very complicated – no deployable telescope, no formation flight, no futuristic designs, no moving parts.

- ✓ Detectors
  - Technologies exist at TRL = 5+
  - Arrays of thousands of TES detectors, antenna coupling, channellizers
  - Build on Planck and Herschel experience + ground-based & balloon-borne exp.

- ✓ Cold telescope
  - Developed for SPICA for flight in early 20s, detailed cooling chain still TBD

- ✓ Scan strategy
  - Similar to WMAP, EPIC, SAMPAN designs

- ✓ Simple deployable screens + one solid inner shield – TBD

- ✓ Small ancillary spacecraft (optional, TBC)
  - Data transmission 40+ Mbit/s (e.g. Gaia, phased array)
  - In flight calibration

Inflation in a nutshell

Posited period of nearly exponential (superluminal) expansion in the very early universe, driven by a scalar field (the inflaton) for which the equation of motion and Friedmann equation are:

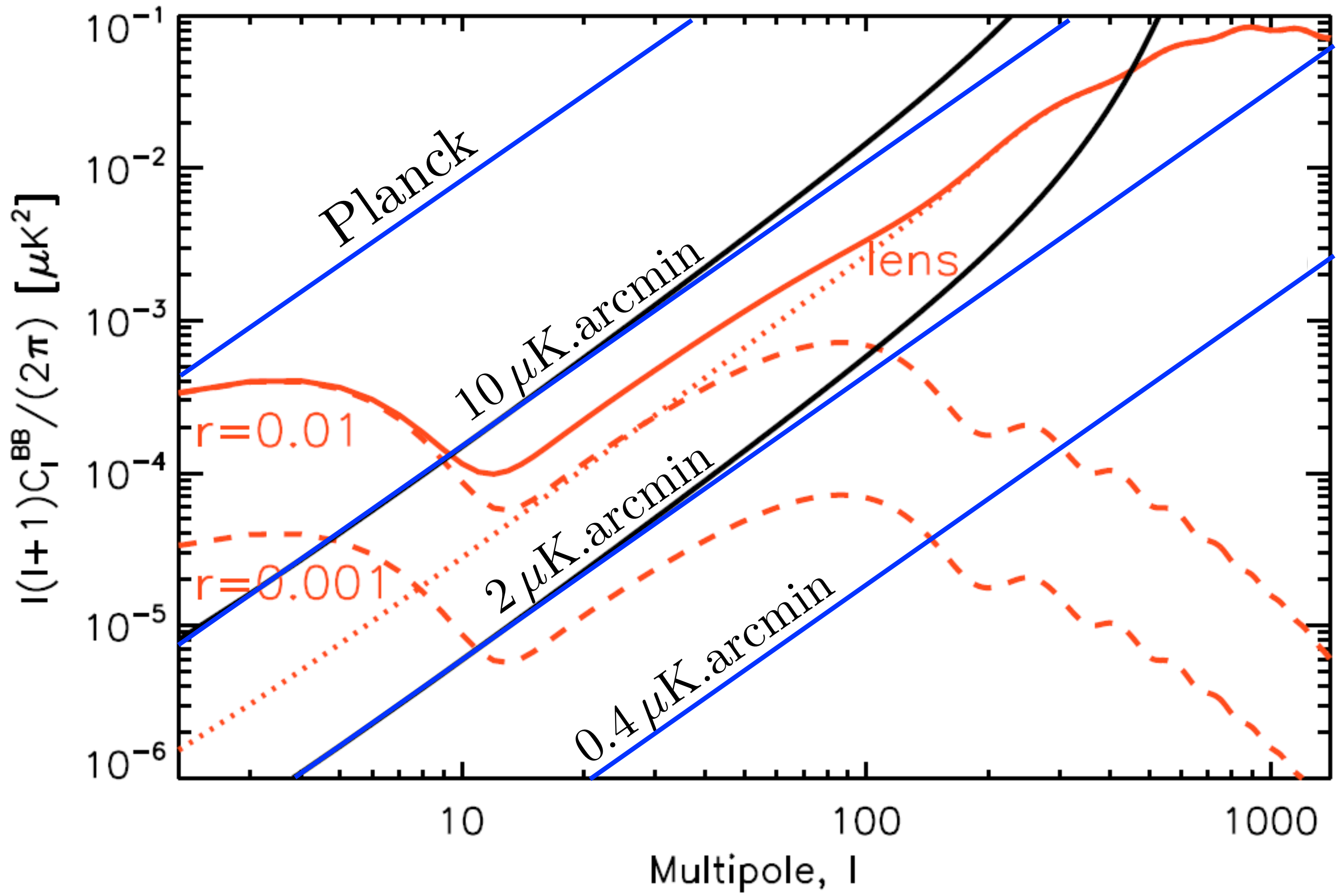
$$\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + V_\phi = 0 \qquad H^2 = \frac{1}{3M_{\mathrm{Pl}}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

Quantum fluctuations seed scalar and tensor perturbations of the metric with power spectra:

$$P_s(k) = A_s\left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_t(k) = A_t\left(\frac{k}{k_0}\right)^{n_t}$$

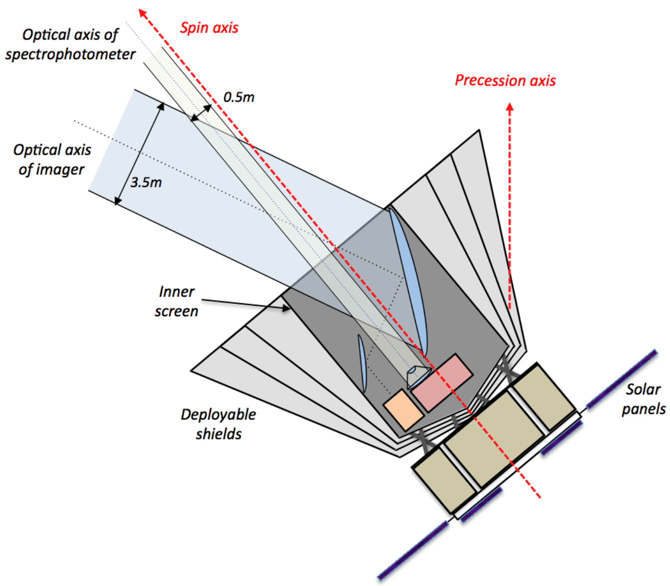
$$A_t \rightarrow rA_s$$

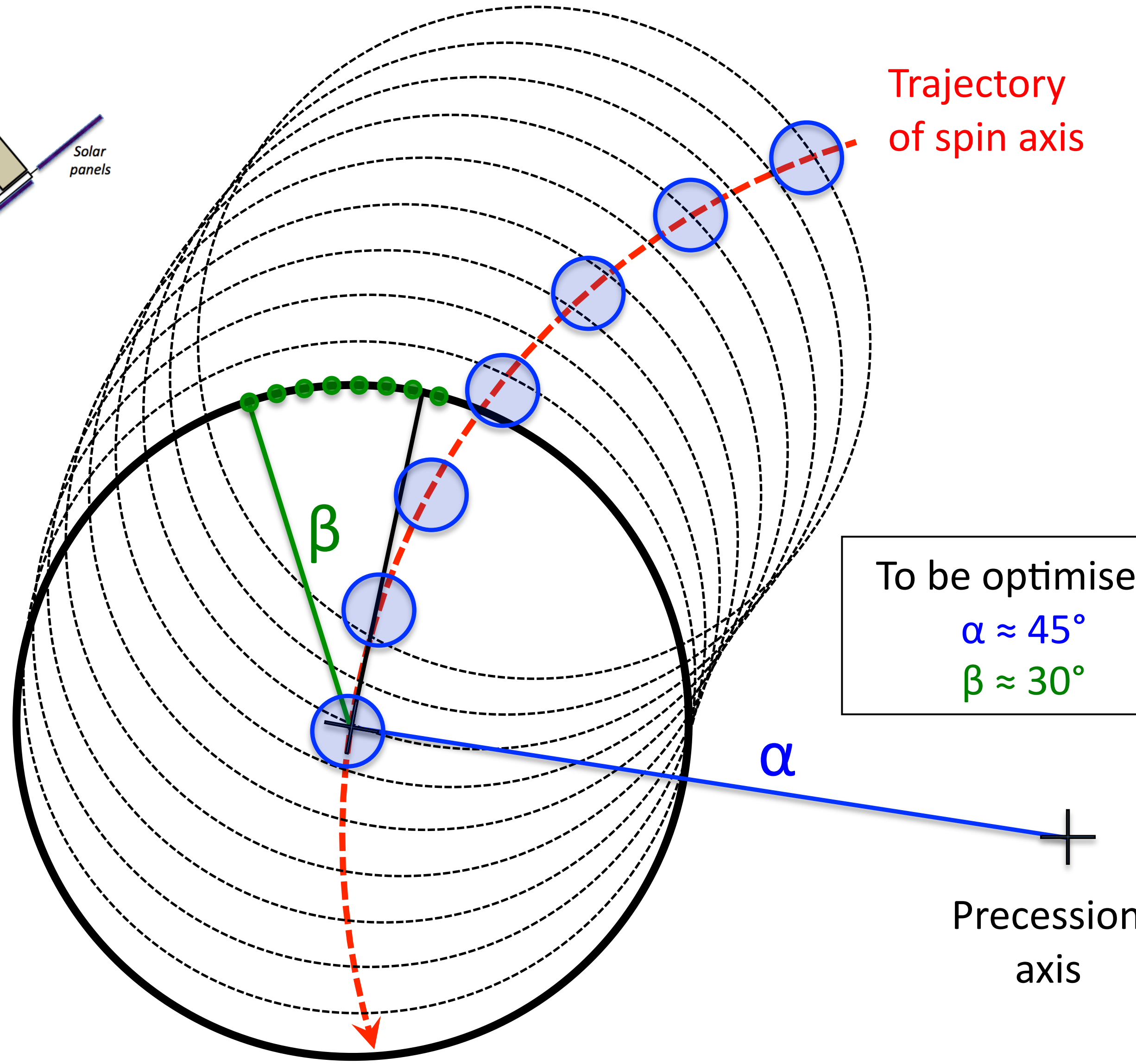
B modes



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$l(l+1)C_l^{BB}/(2\pi)$ [μK^2]
Planck
10 μK.arcmin
2 μK.arcmin
0.4 μK.arcmin
lens
r=0.01
r=0.001
10
100
1000
Multipole, l

Scanning strategy

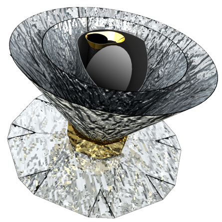




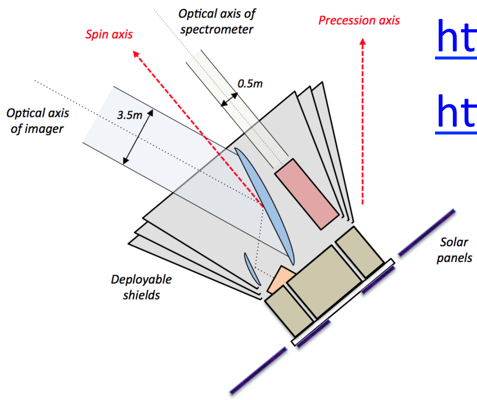
Imager
≈ 1' beam

Spectrometer
≈ 1.4° beam

To be optimised:
α ≈ 45°
β ≈ 30°

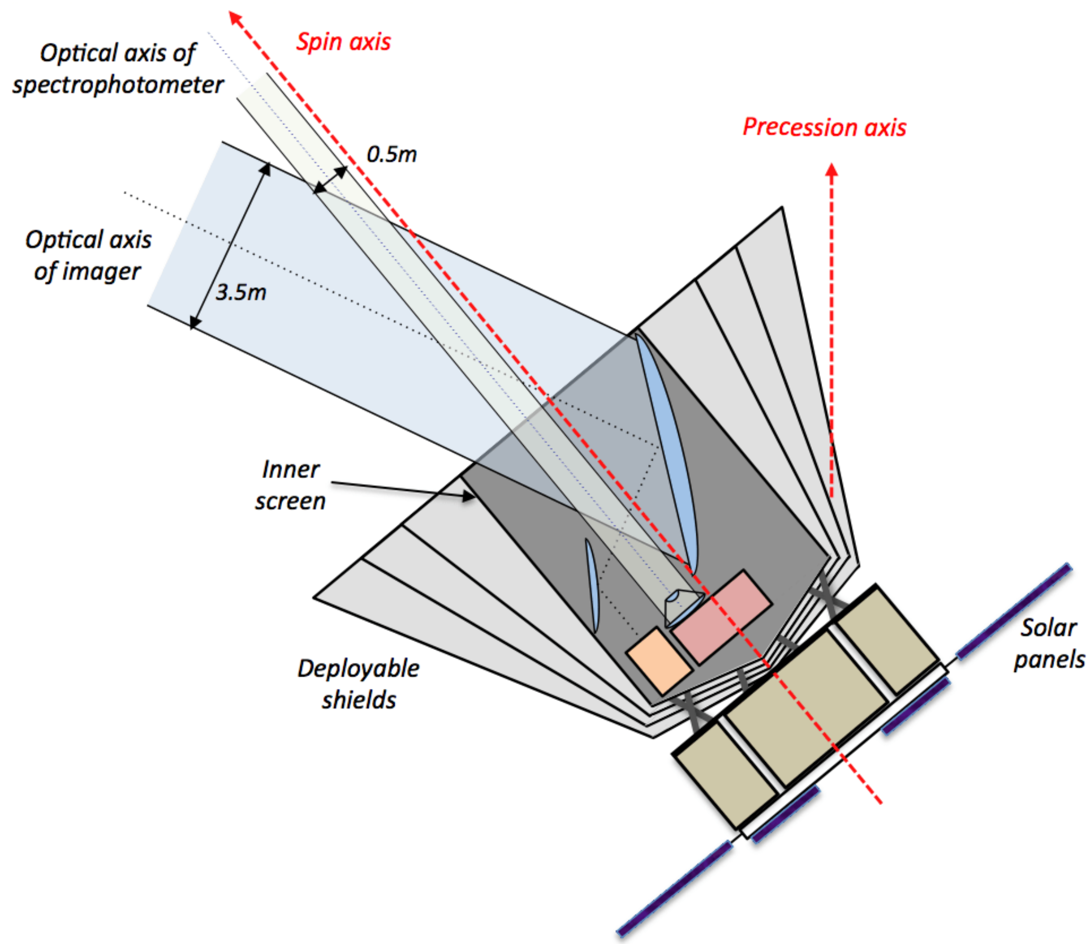


The PRISM mission concept



http://arxiv.org/abs/1306.2259

http://arxiv.org/abs/1310.1554



Polarised

Radiation

Imaging and

Spectroscopy

Mission

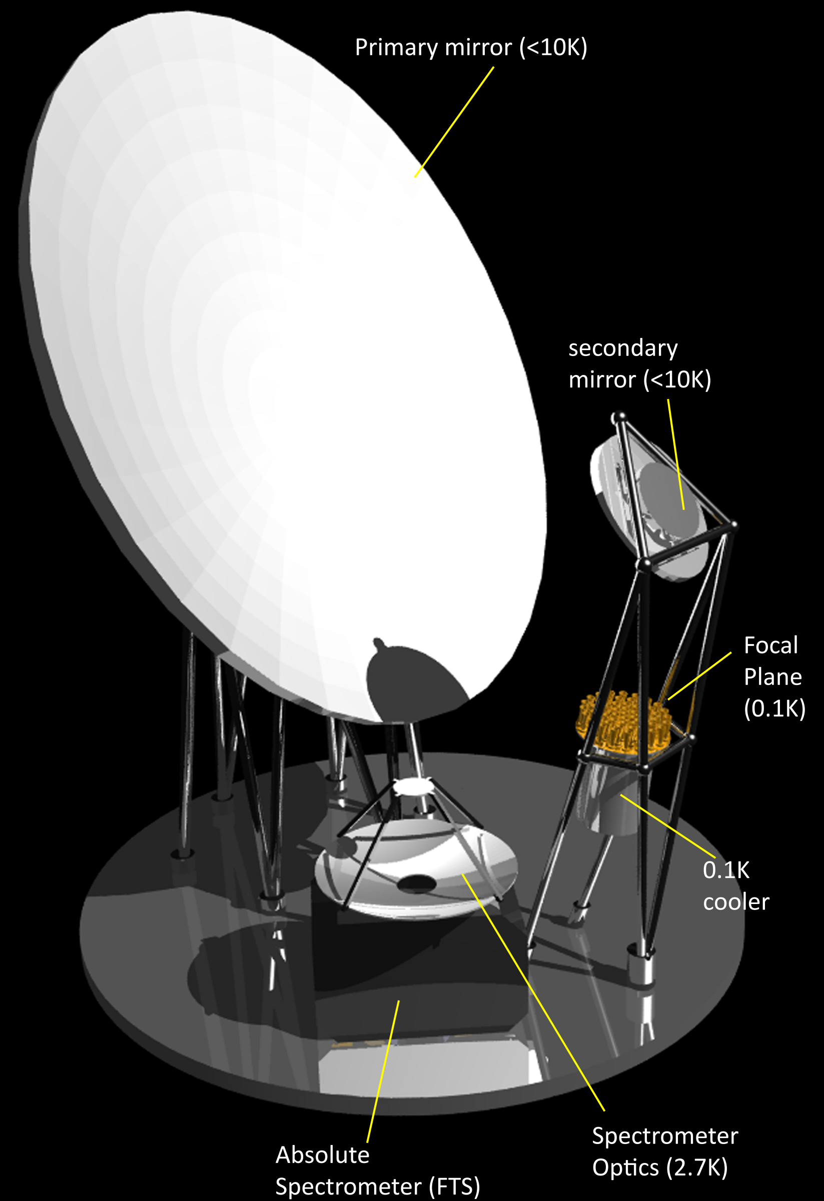
Polarimetric Imager

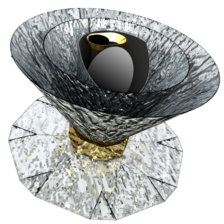
Think PLANCK + Herschel-SPIRE
- 10 – 100 times more sensitive
- Many more frequency channels
- Polarised
- 1-3 times better angular resolution

Absolute spectrophotometer

Think *COBE*/FIRAS
- 1000 times more sensitive
- 3 times better angular resolution

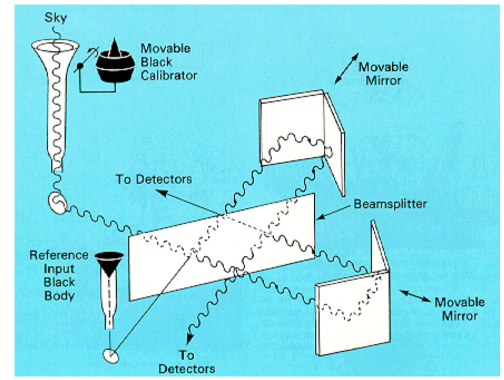
1+1 > 2
- Absolute calibration of the imager
- Cleaning FTS data from foregrounds





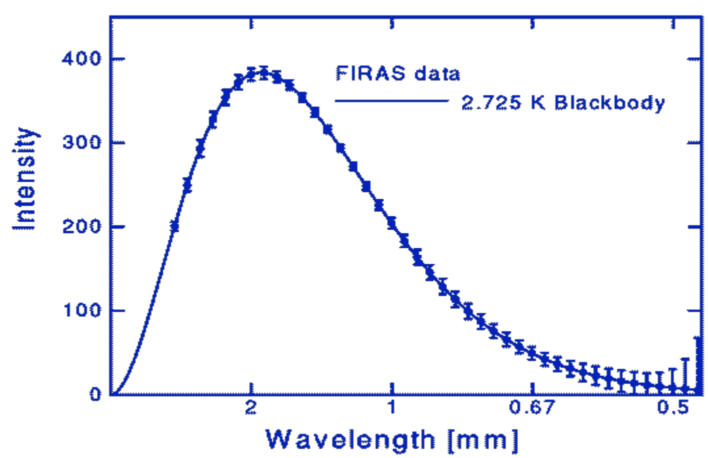
The spectrophotometer

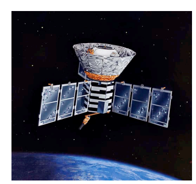
band (GHz)	resolution (GHz)	$A\Omega$ ($cm^2 sr$)	background (pW)	NEPν ($W/m^2/sr/Hz \times \sqrt{s}$)	global 4-yr mission sensitivity ($W/m^2/sr/Hz$)
30-6000	15	1	150	1.8×10^{-22}	1.8×10^{-26}
30-500	15	1	97	7.0×10^{-23}	7.2×10^{-27}
500 - 6000	15	1	70	1.7×10^{-22}	1.7×10^{-26}
30-180	15	1	42	3.5×10^{-23}	3.6×10^{-27}
180-600	15	1	57	6.3×10^{-23}	6.5×10^{-27}
600-3000	15	1	20	7.4×10^{-23}	7.6×10^{-27}
3000-6000	15	1	28	1.6×10^{-22}	1.6×10^{-26}

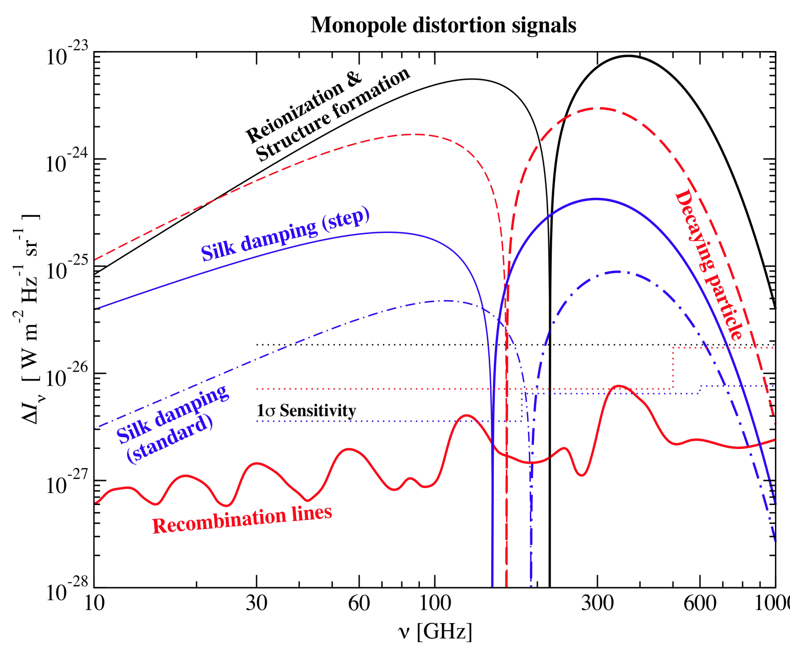


Martin-Puplett FTS, three possible configurations, best option TBD

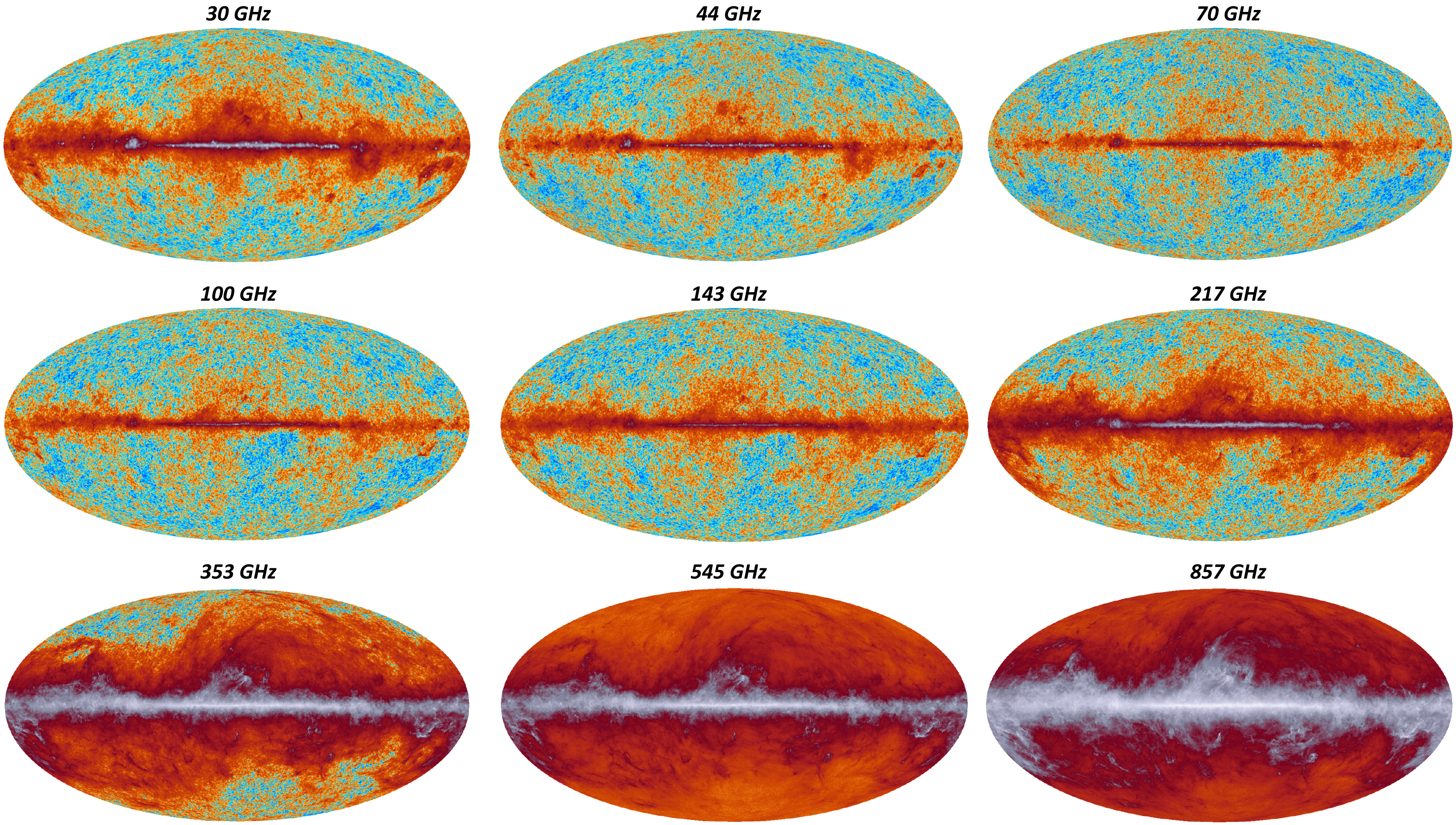
Angular resolution limited to 1.5°
- Multi-moded for sensitivity
- Large beams for scanning / FTS limitations



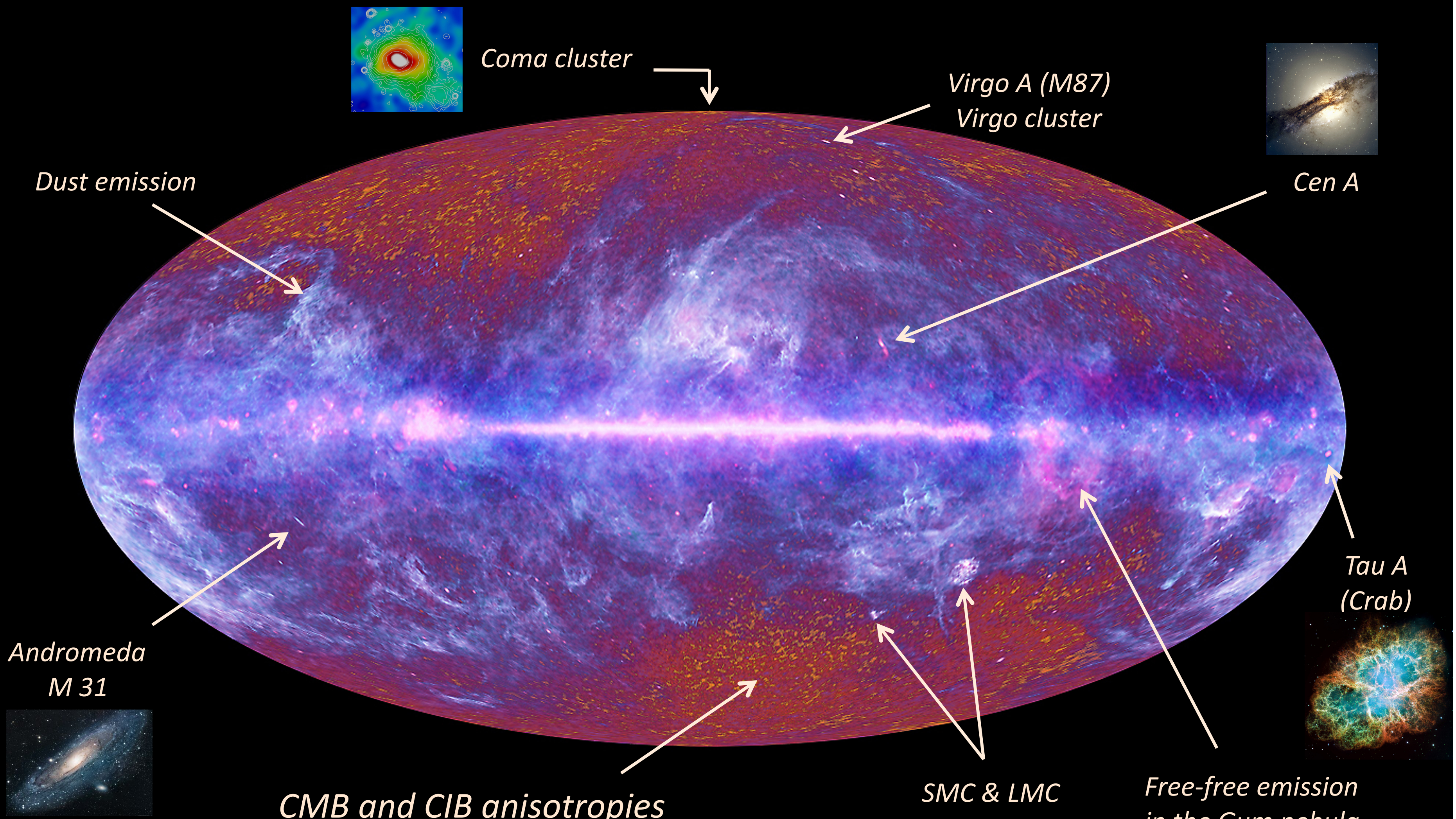




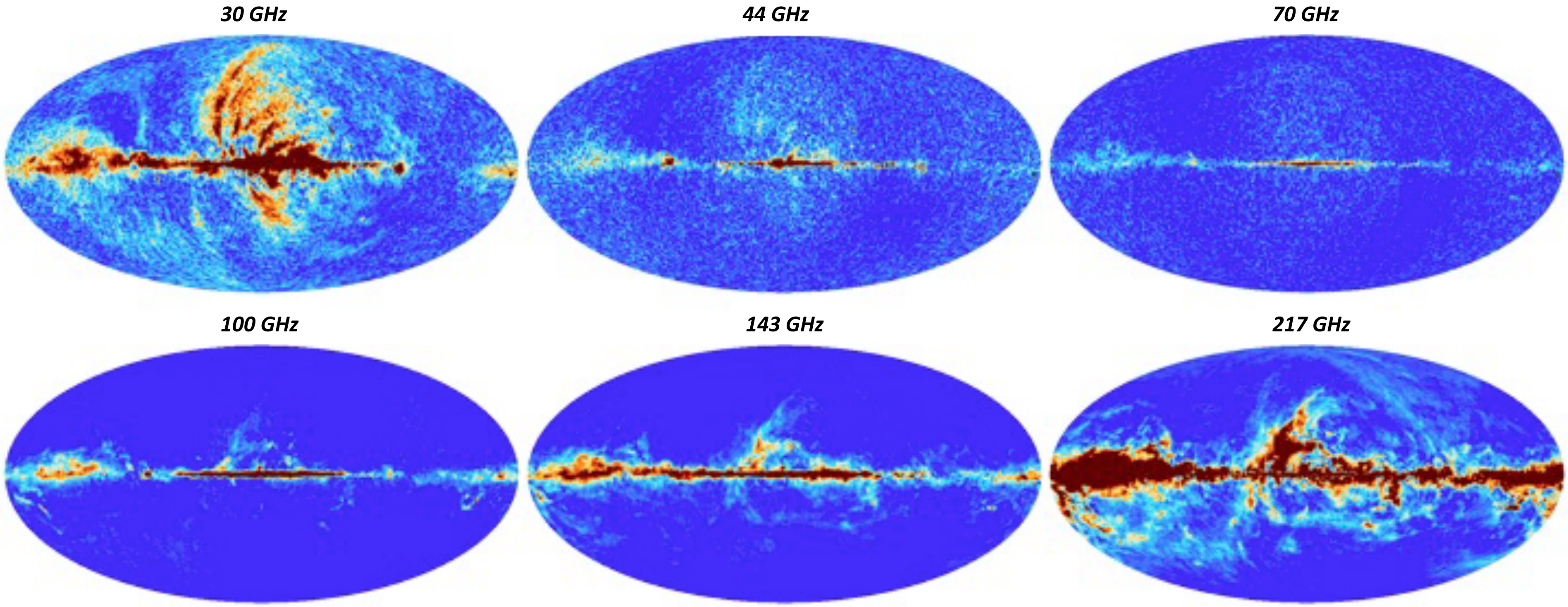
Planck observed maps at 9 frequencies

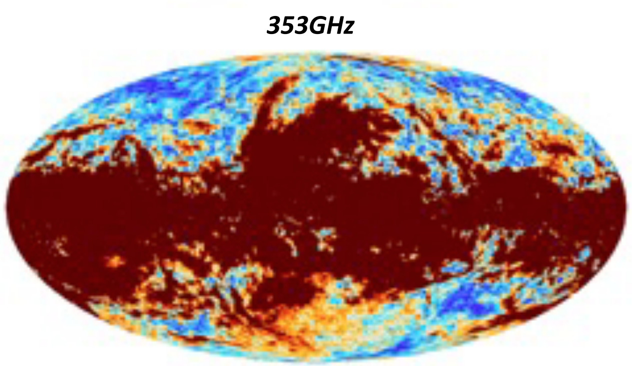


The sub-millimetre sky seen by *Planck*



Planck polarisation maps





Galactic polarisation fraction is larger than that of CMB
- Synchrotron (up to 75% theoretically, 20-30% in practice)
- Dust (10-20% - more than expected at high galactic lat.)

Polarisation analysis mid 2014