The Microwave Background

Ken GANGA

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What We See in the Sky

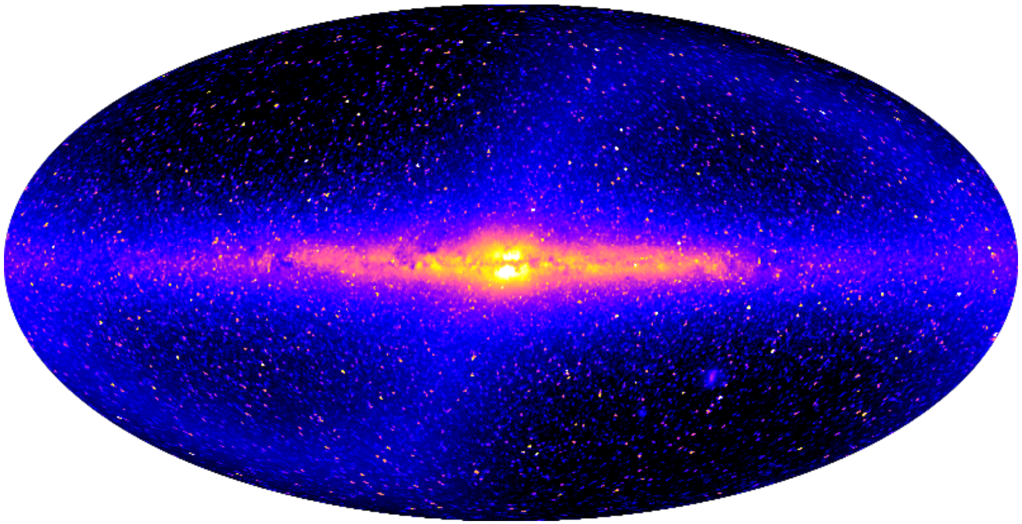
http://home.arcor-online.de/axel.mellinger/mwpan_aitoff.html

- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.

- This is an optical image, corresponding to what our eyes can see.

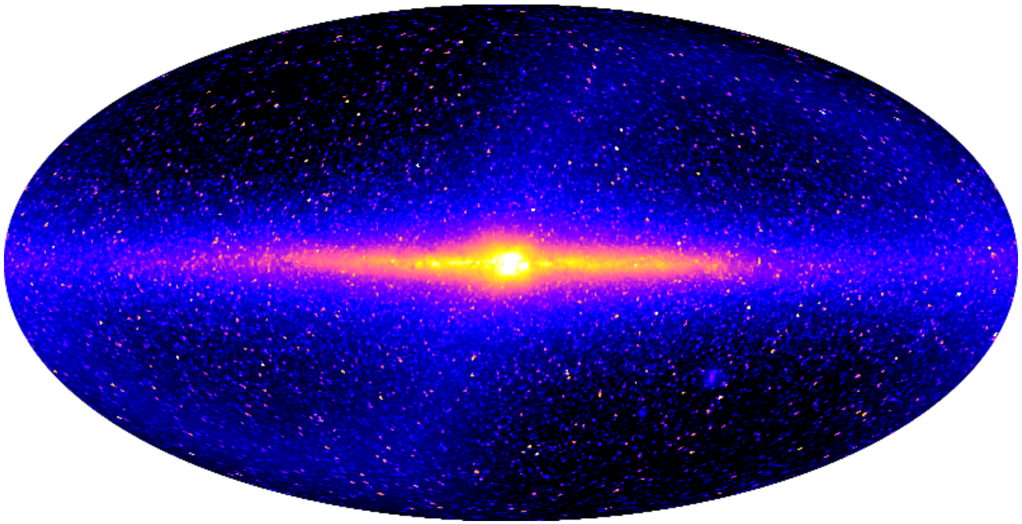
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



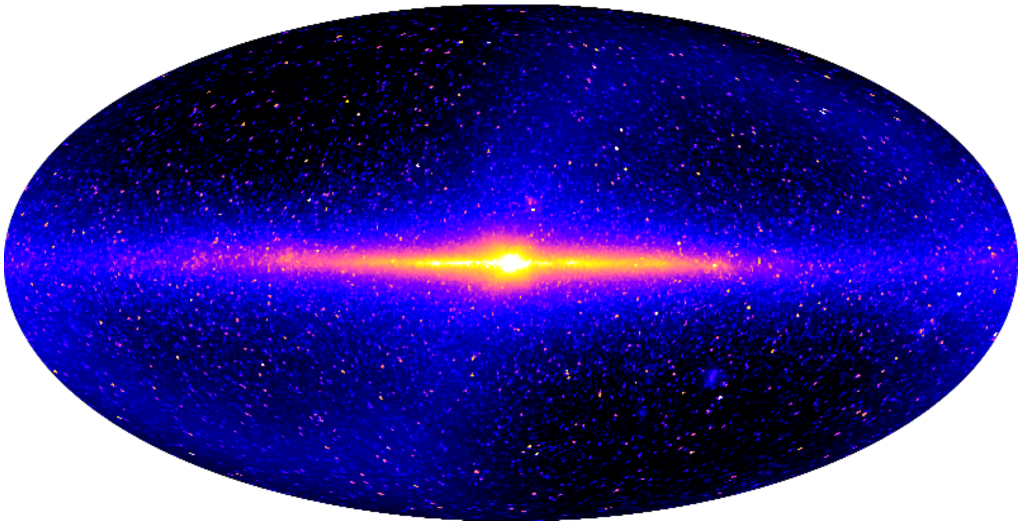
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a near infrared image – 1.25 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



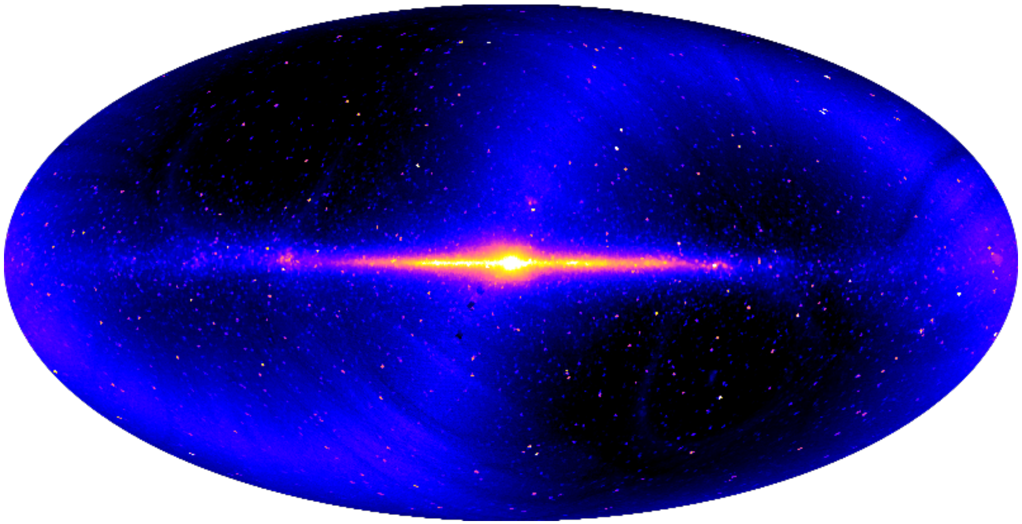
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a near infrared image – 2.2 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



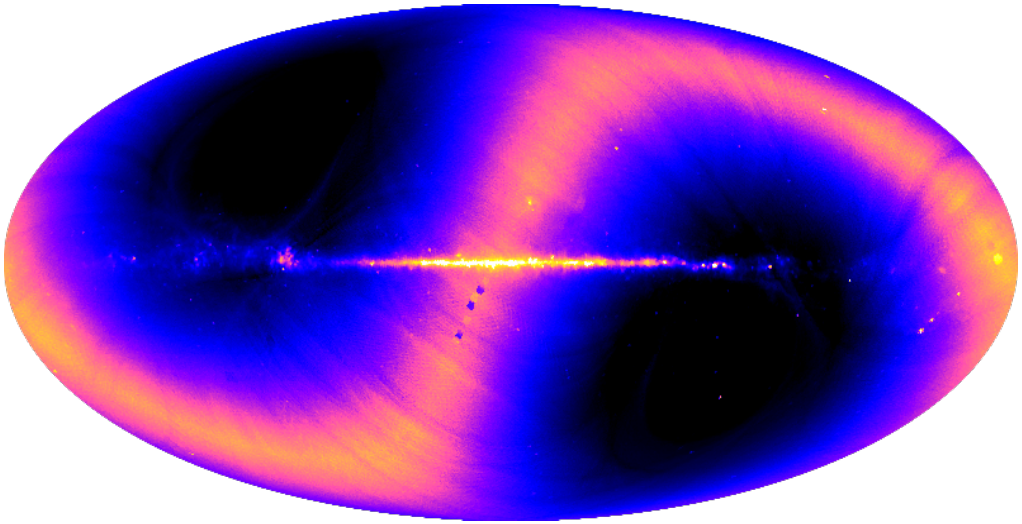
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a near infrared image – 3.5 microns – from DIRBE.
- Most of the light we see here is from "relatively nearby" stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



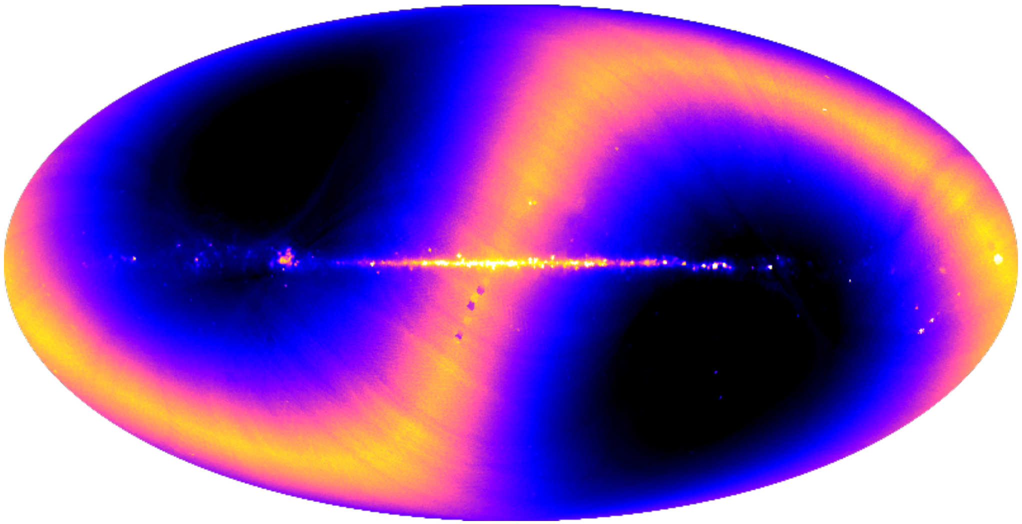
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a near infrared image – 4.9 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



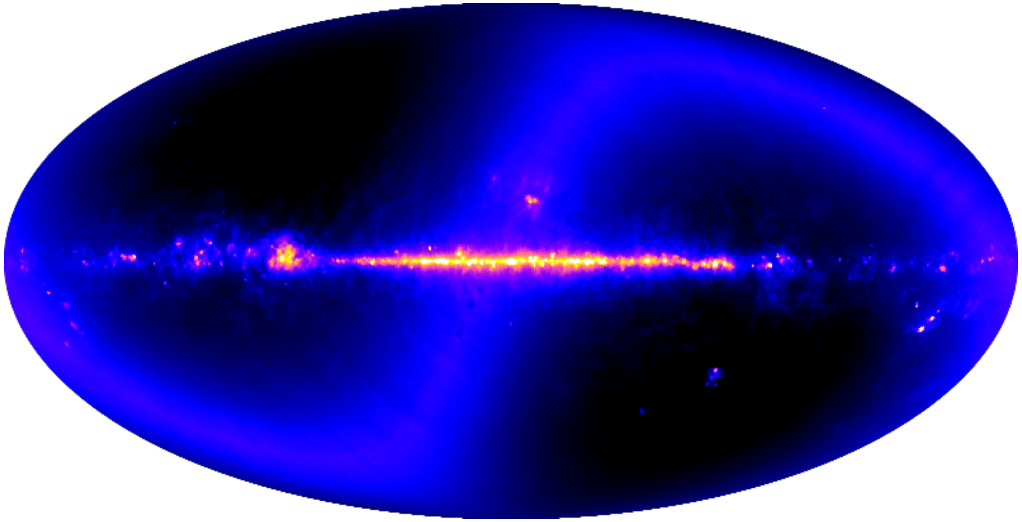
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a mid-infrared image – 12 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



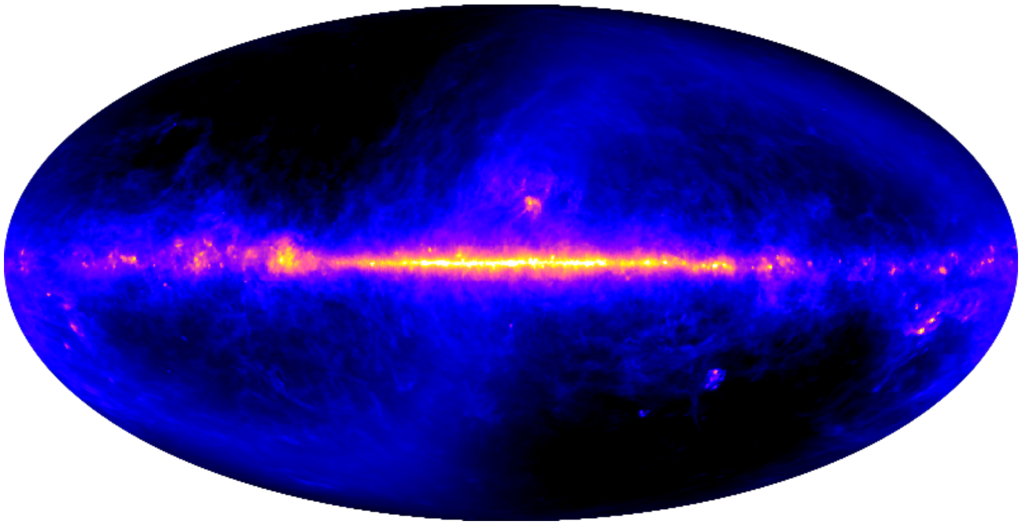
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a mid-infrared image – 25 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



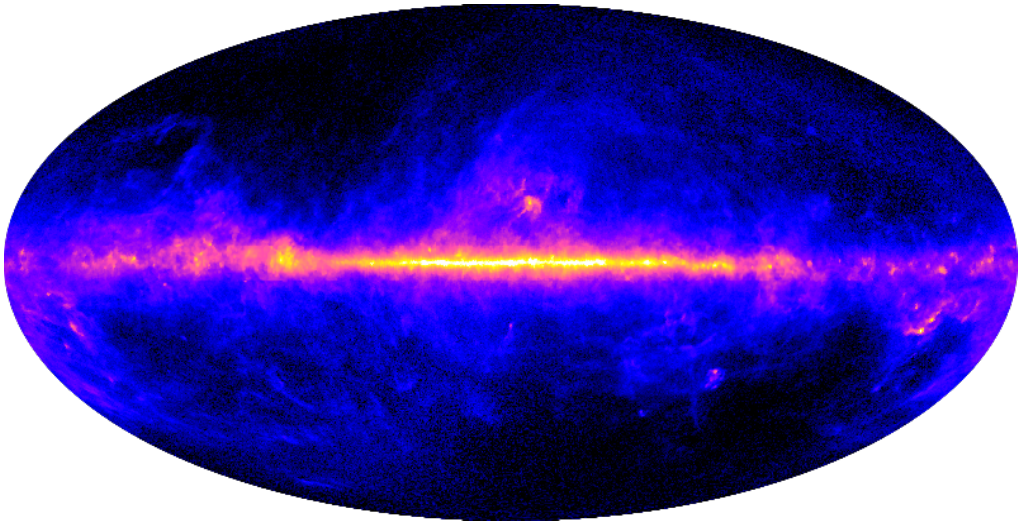
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a far-infrared image – 60 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



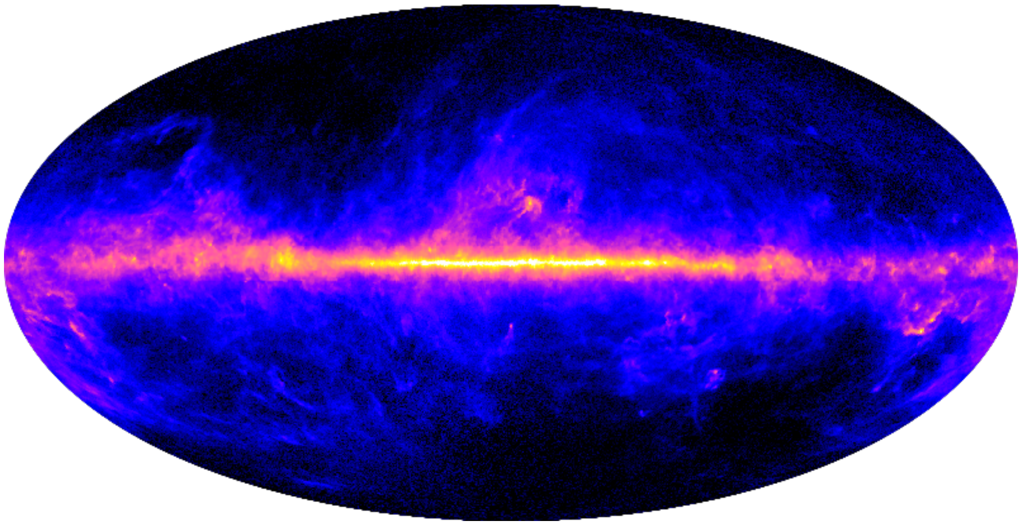
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a far-infrared image – 100 microns – from DIRBE.
- Most of the light we see here is from "relatively nearby" stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



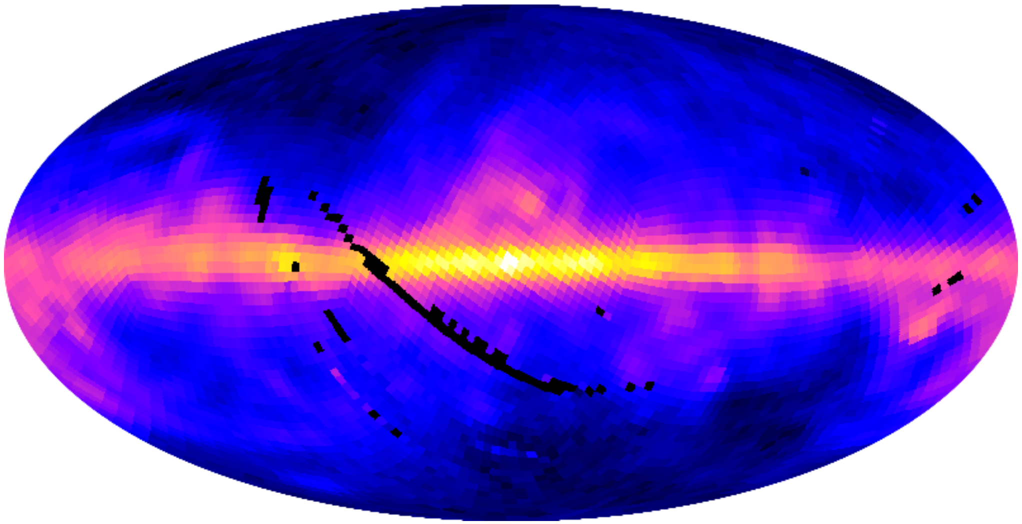
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a far-infrared image – 140 microns – from DIRBE.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



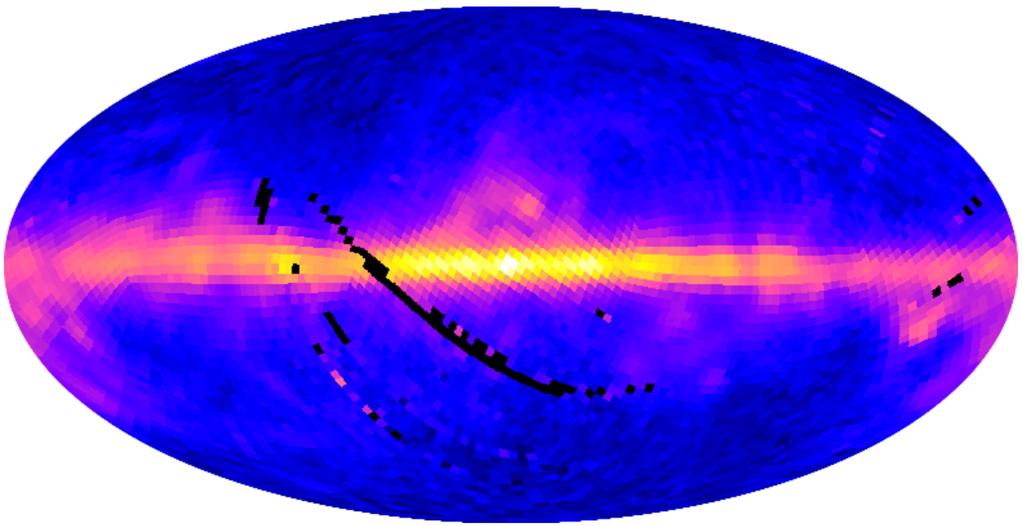
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a far-infrared image – 240 microns – from DIRBE.
- Most of the light we see here is from "relatively nearby" stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



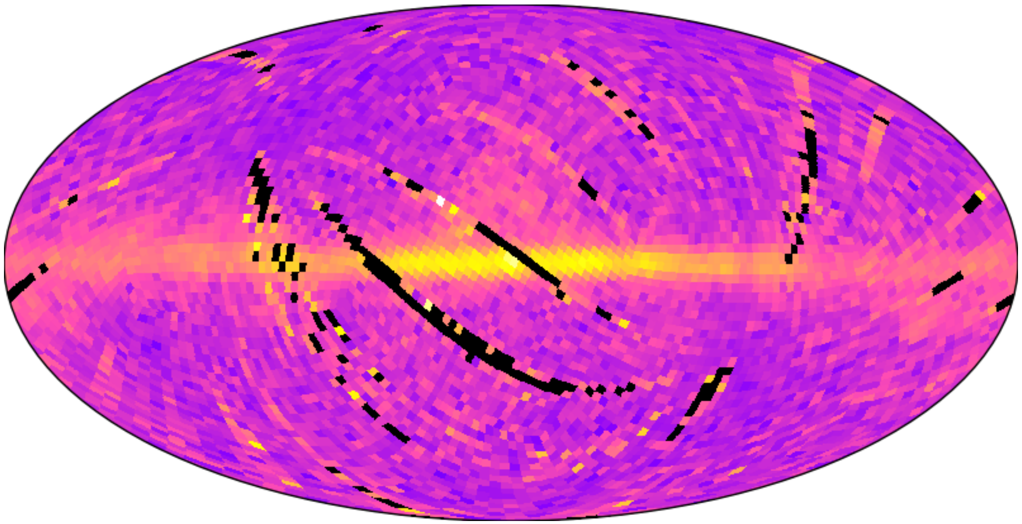
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a far-infrared image – 266 microns – from a combination of FIRAS channels.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a sub-millimeter image – 389 microns – from a combination of FIRAS channels.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky

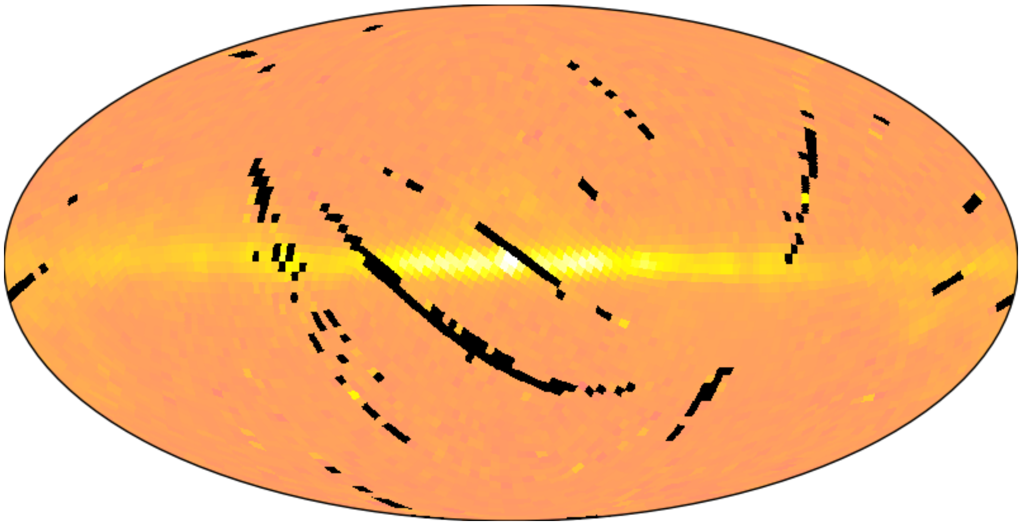


- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.

- This is a sub-millimeter image – 503 microns – from a combination of FIRAS channels.

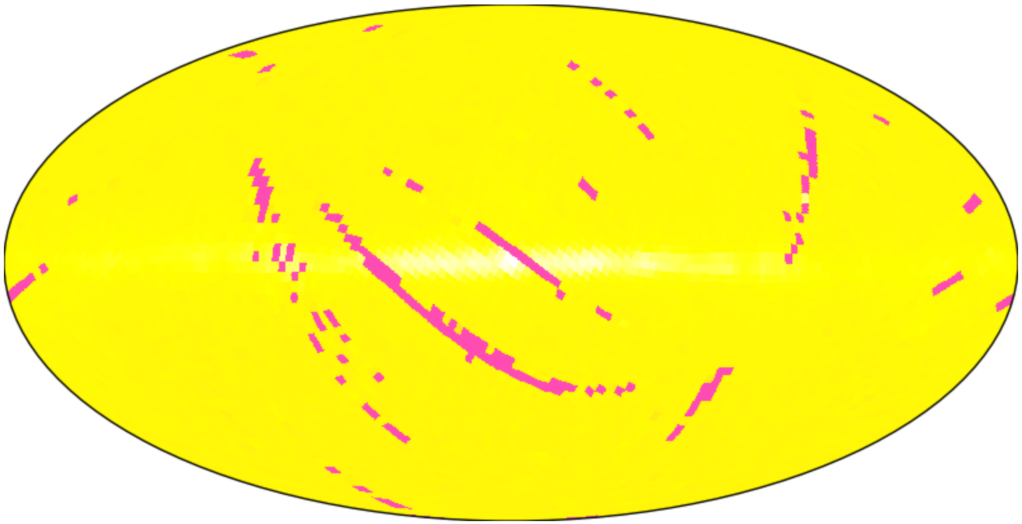
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



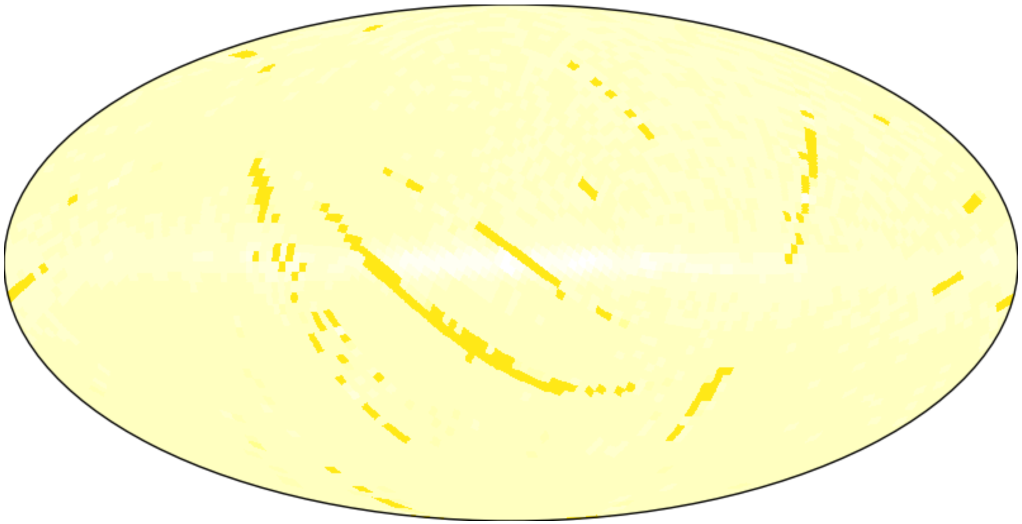
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a sub-millimeter image – 591 microns – from a combination of FIRAS channels.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



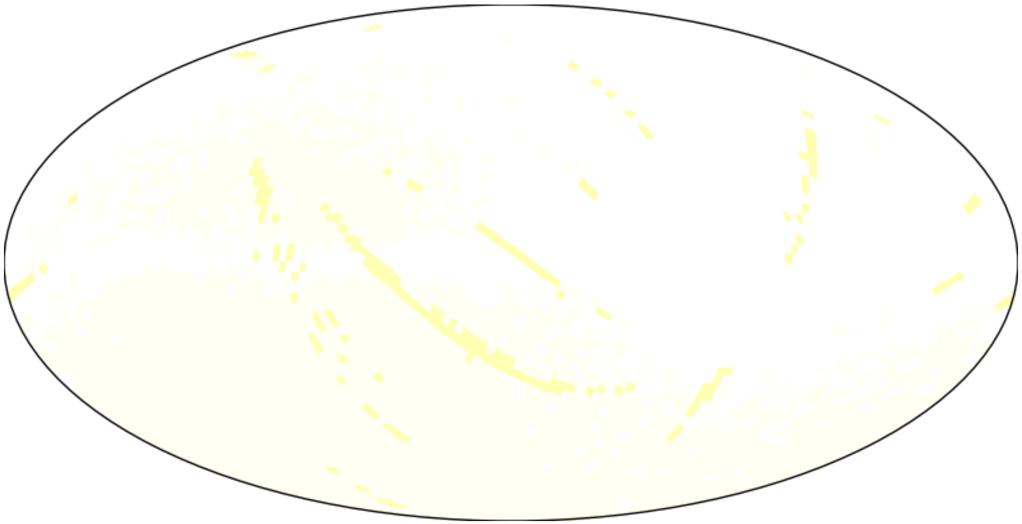
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a sub-millimeter image – 716 microns – from a combination of FIRAS channels.
- Most of the light we see here is from "relatively nearby" stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



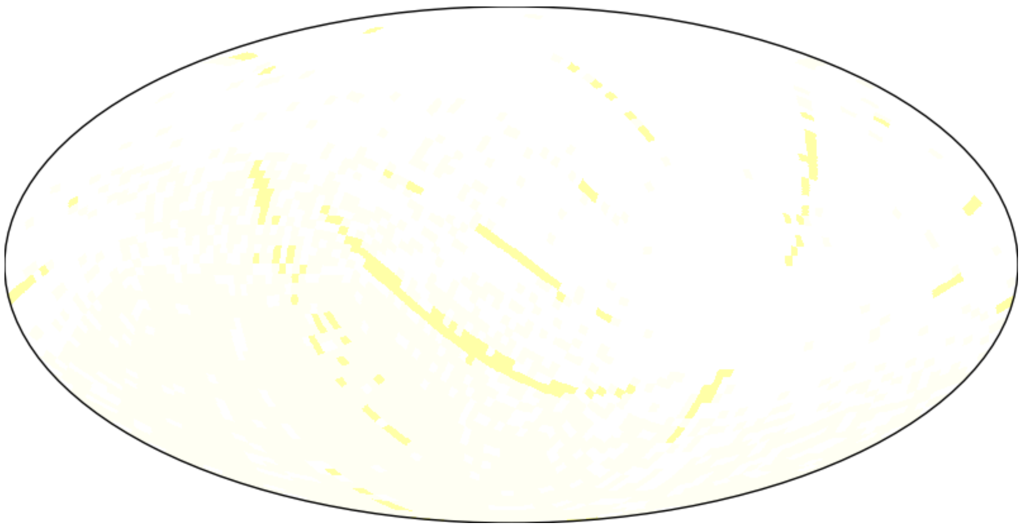
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a sub-millimeter image – 909 microns – from a combination of FIRAS channels.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



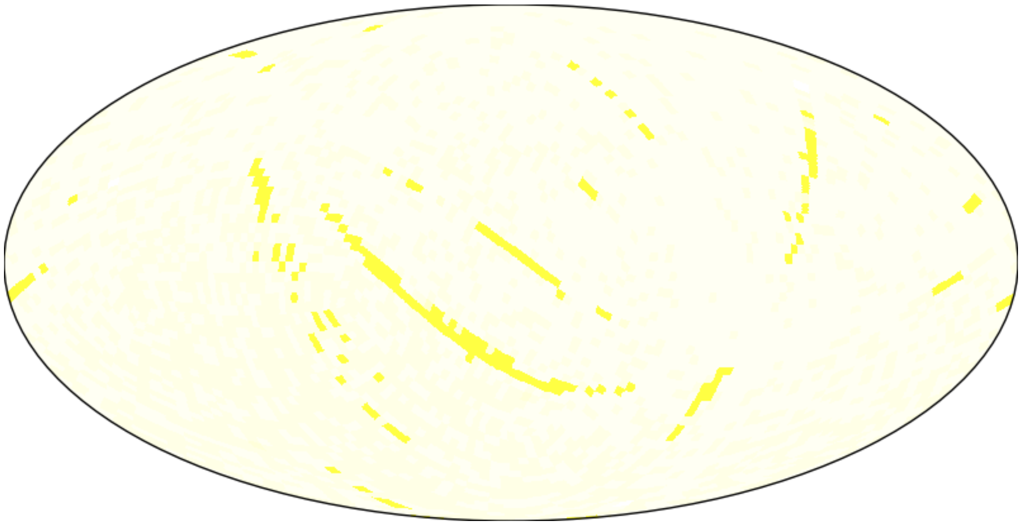
- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a microwave image – 1.246 mm – from a combination of FIRAS channels.
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky



- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.
- This is a microwave image – 1.992 mm – from a combination of FIRAS channels.
- Most of the light we see here is from "relatively nearby" stuff (at least compared to the Microwave Background – see the next page)

What We See in the Sky

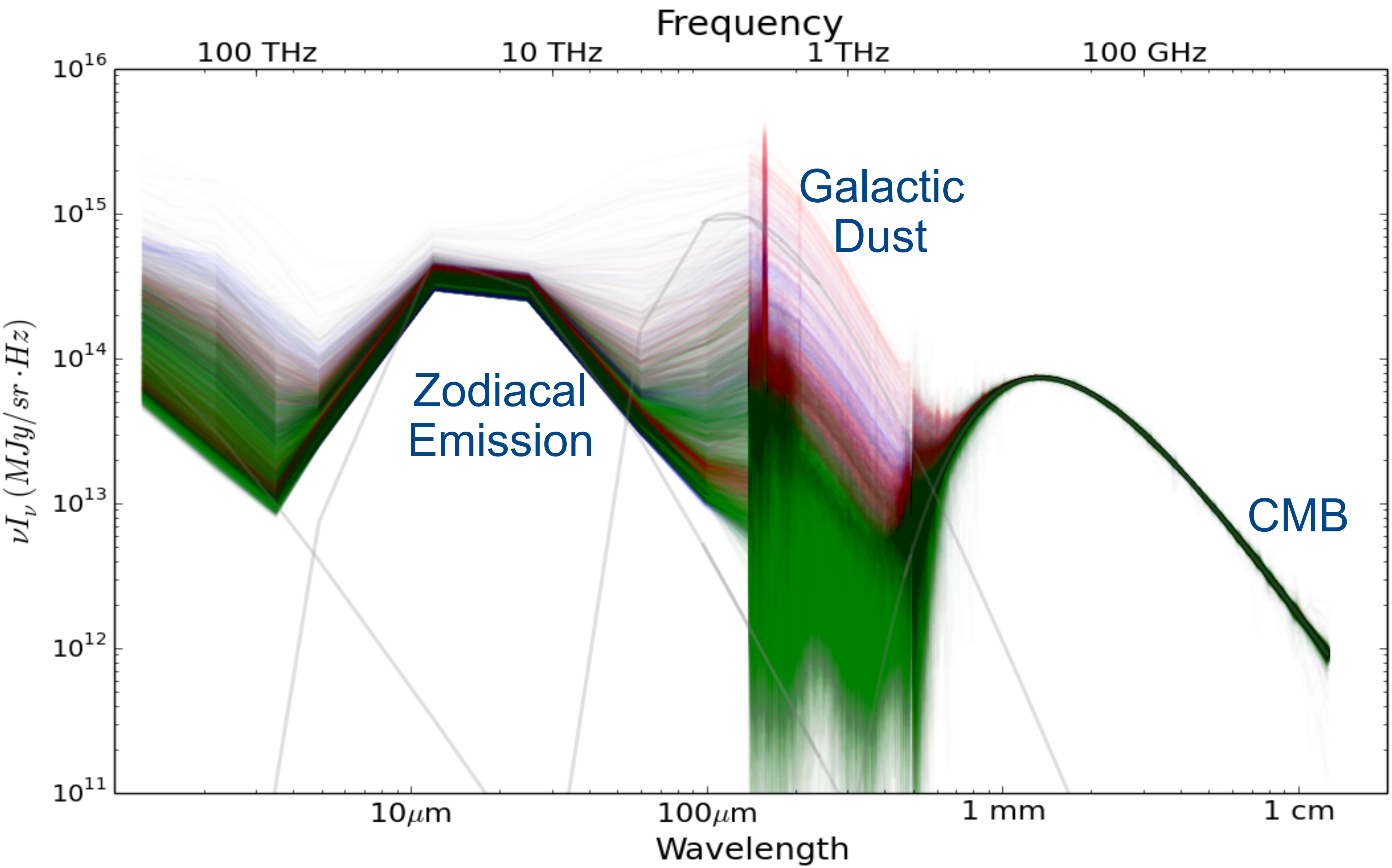


- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.

- This is a microwave image – 5.253 mm – from a combination of FIRAS channels.

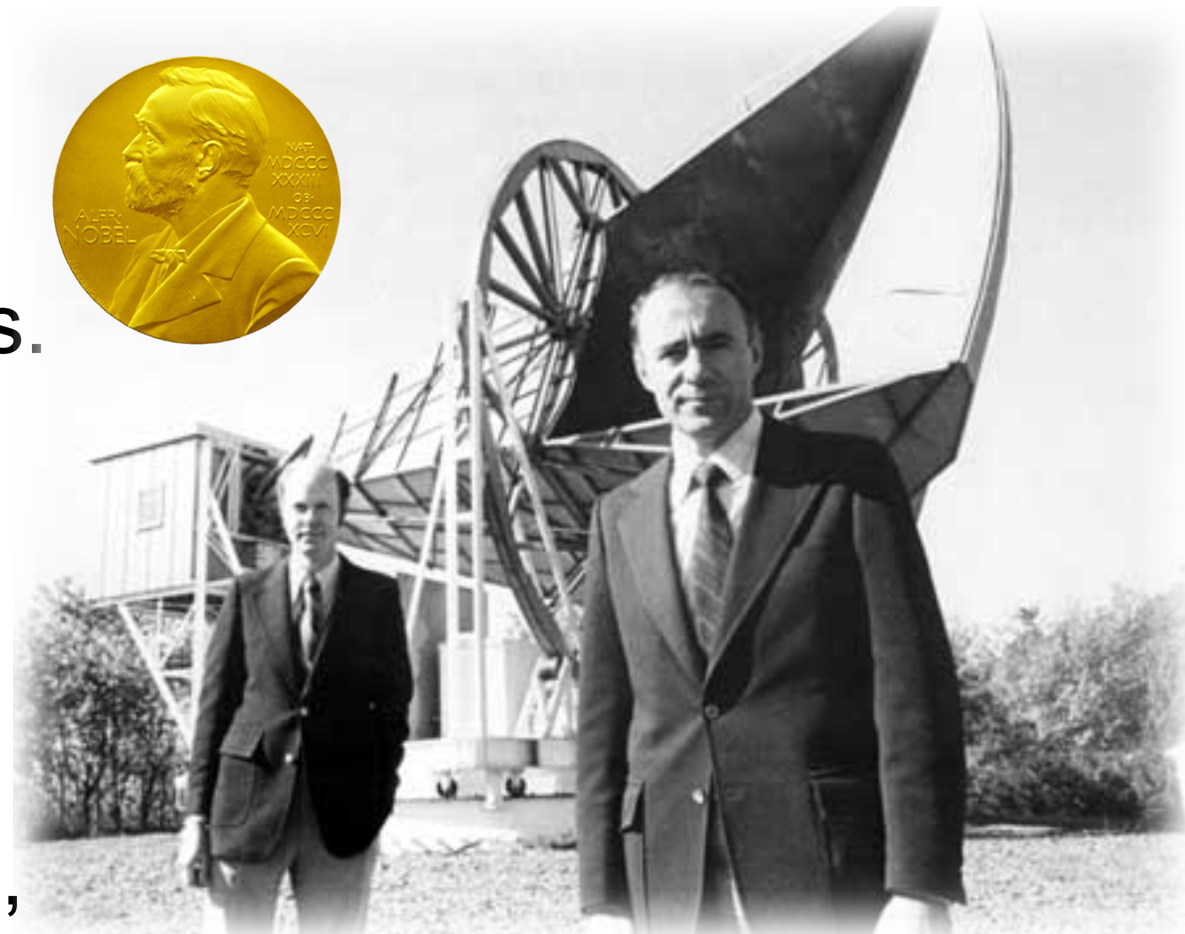
- Most of the light we see here is from “relatively nearby” stuff (at least compared to the Microwave Background – see the next page)

Sky Spectra from the IR to Microwave



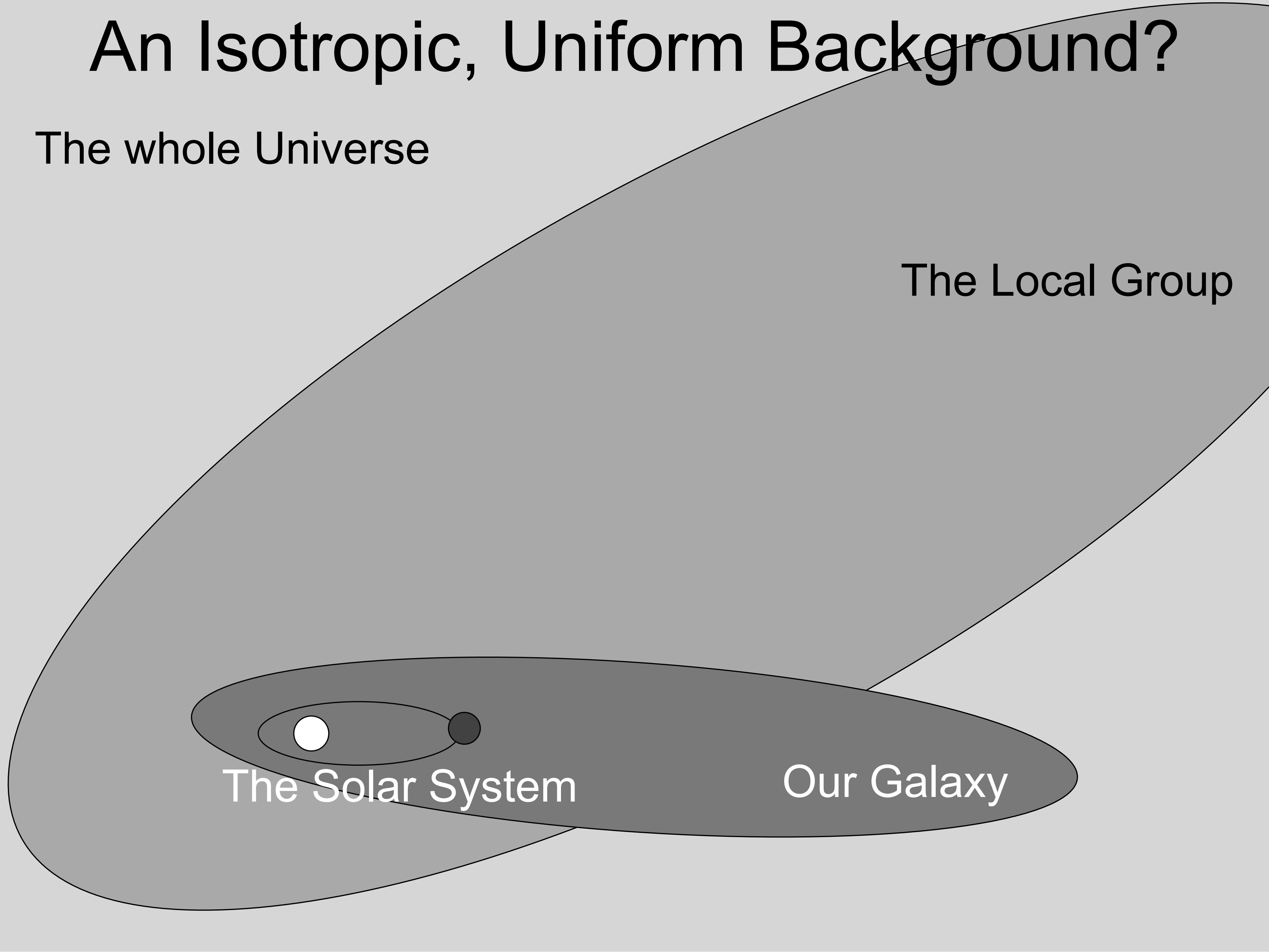
Discovery: Penzias & Wilson in 1964

- Penzias & Wilson wanted to measure "sky noise" effects on radio communications.
- But they saw a small noise that they didn't understand.
- This noise was isotropic, unpolarized, and non-variable, as far as they could tell.



They had found the microwave background by accident!

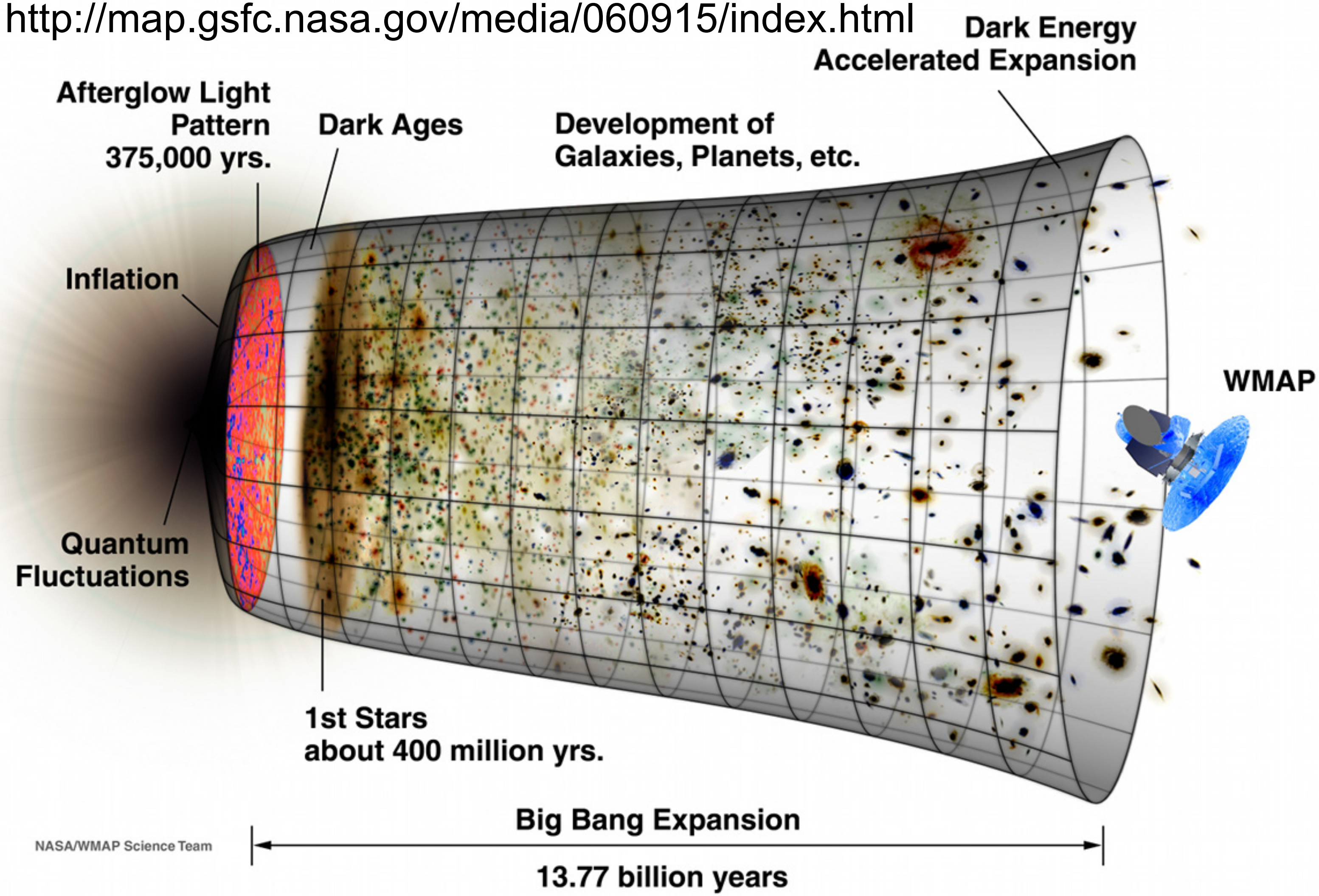
An Isotropic, Uniform Background?



Visualize the Evolution of the Universe

http://map.gsfc.nasa.gov/media/060915/index.html

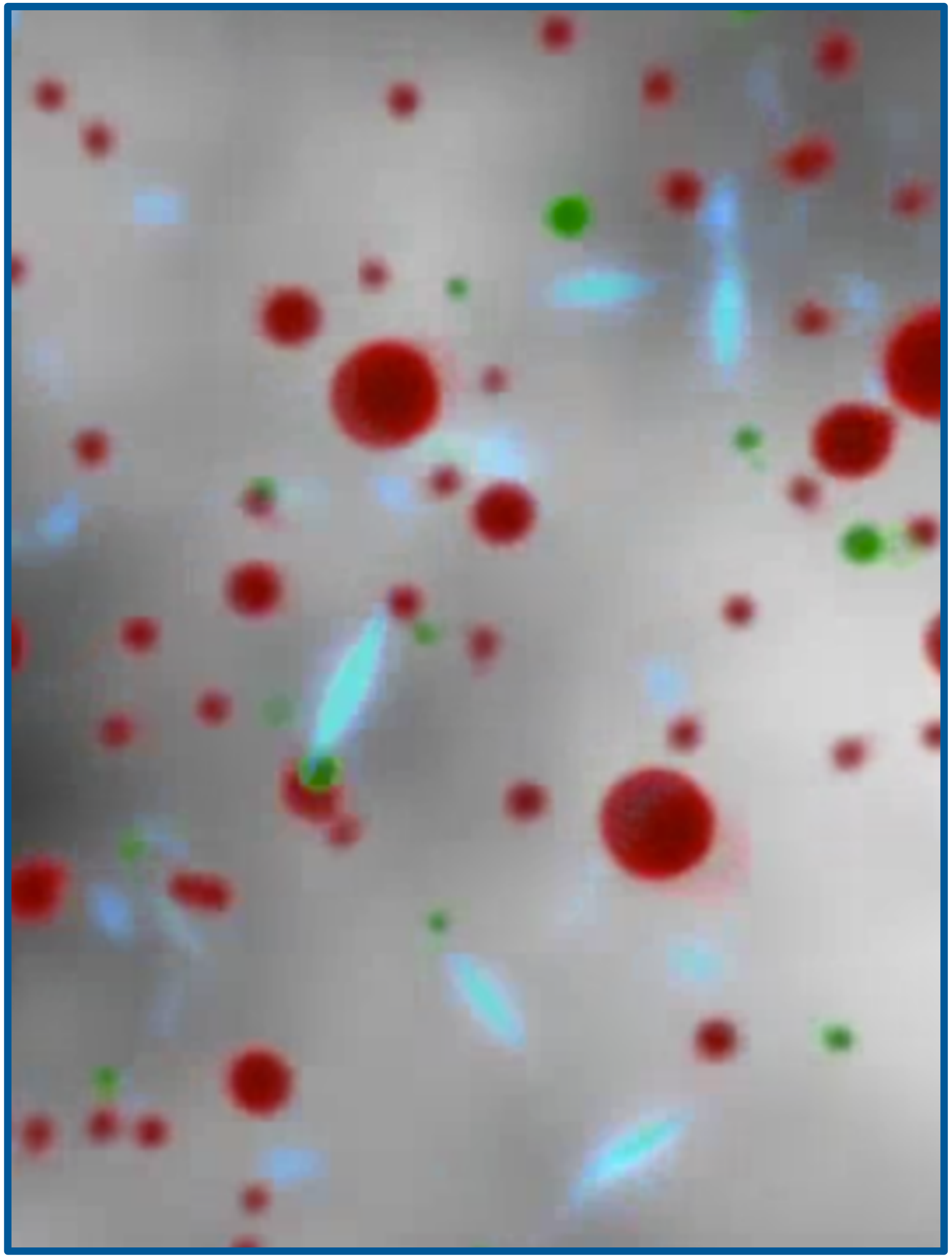
The microwave background light we are seeing today was created “just after” the Big Bang



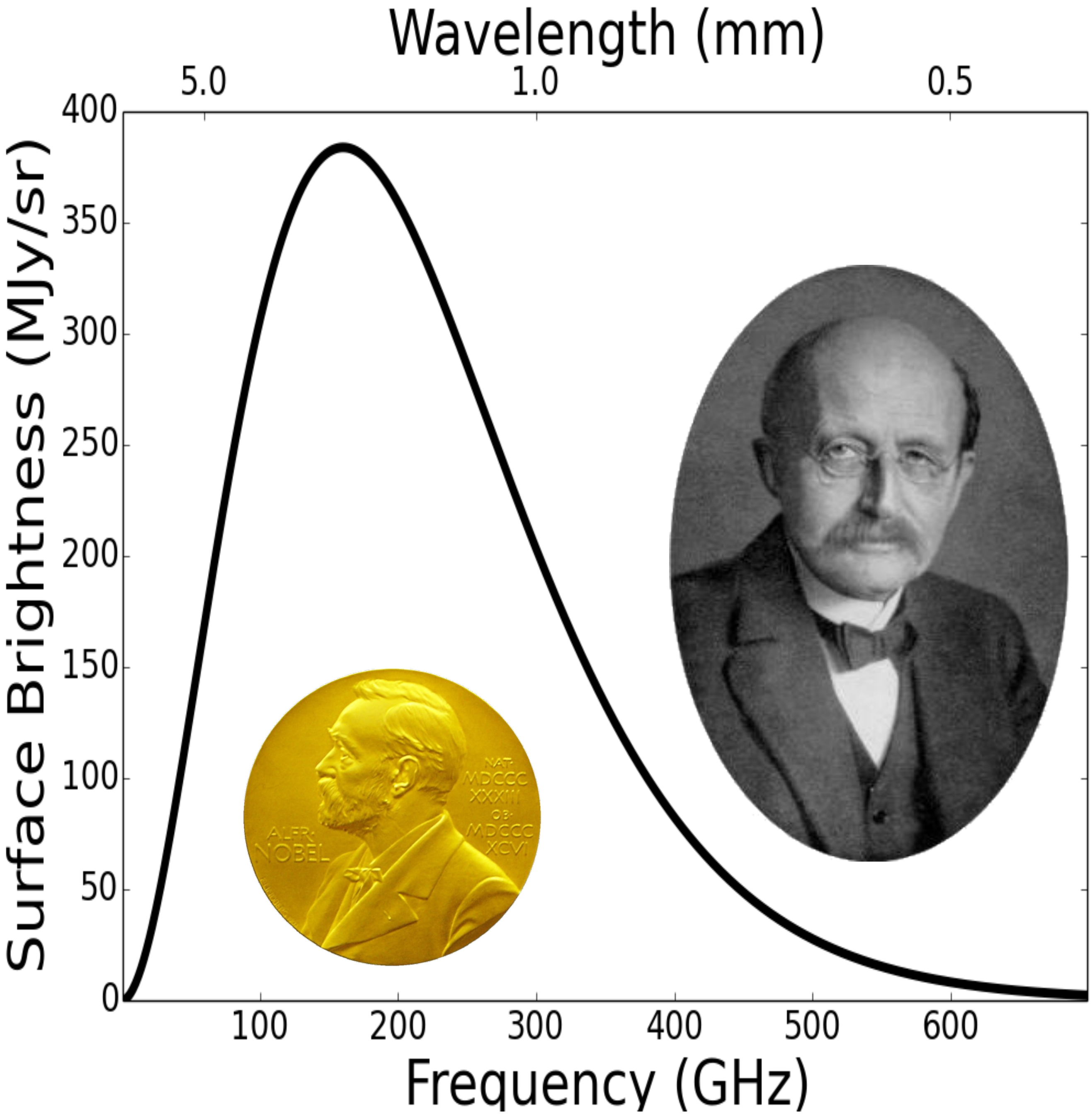
As such, it is a “baby picture” of the early Universe. By studying it, we hope to understand it's birth.

Recombination

- Happens at z~1000, when the CMB has T~3000 K
  - 3000 K ==> kT~0.26 eV; Why not 13.6 eV?
    - There are a lot of photons for each atom in the Universe – even if the average photon energy is lower than the ionization energy of Hydrogen, there are still many photons in the high-energy tail.



Planck & the Blackbody Function



Around 1900, Max Planck postulated that a perfectly absorbing body at a well-defined temperature emits with a spectrum of the form shown to the left – the "Blackbody" curve (or the Planck curve).

FIRAS & a Black Bodies

After years of work to verify that the microwave background has a blackbody spectrum, the FIRAS instrument abord the COBE satellite definitively confirmed it.

This was a major confirmation of the Big Bang theory.

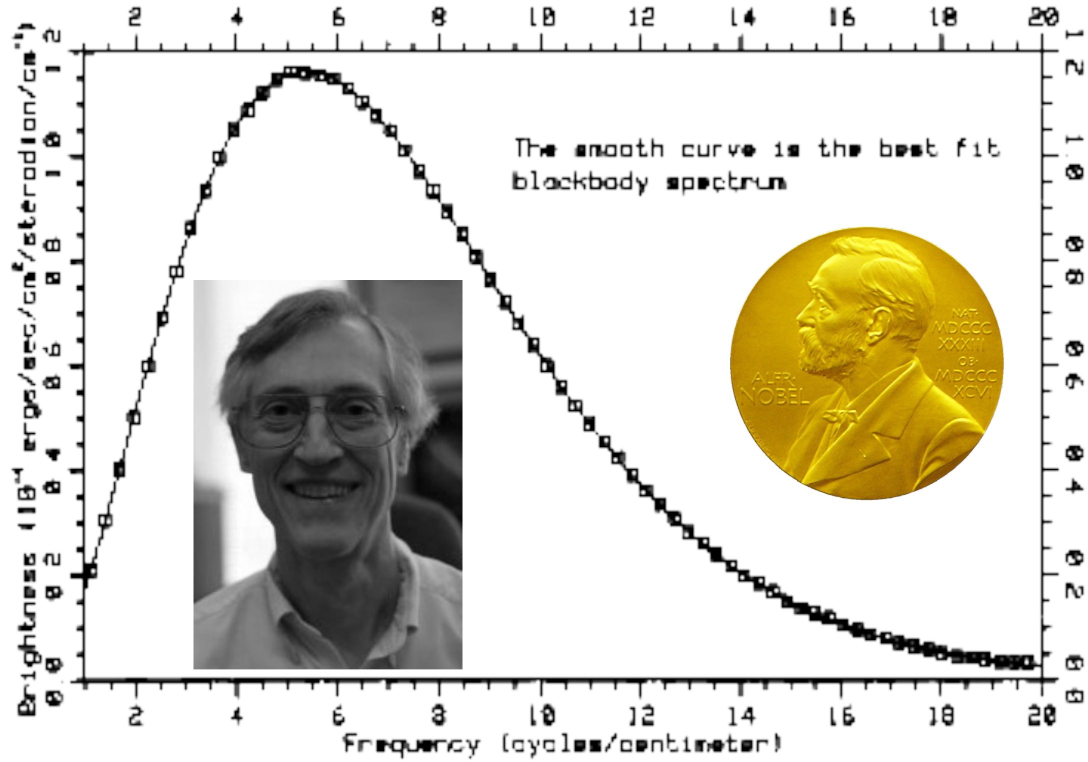
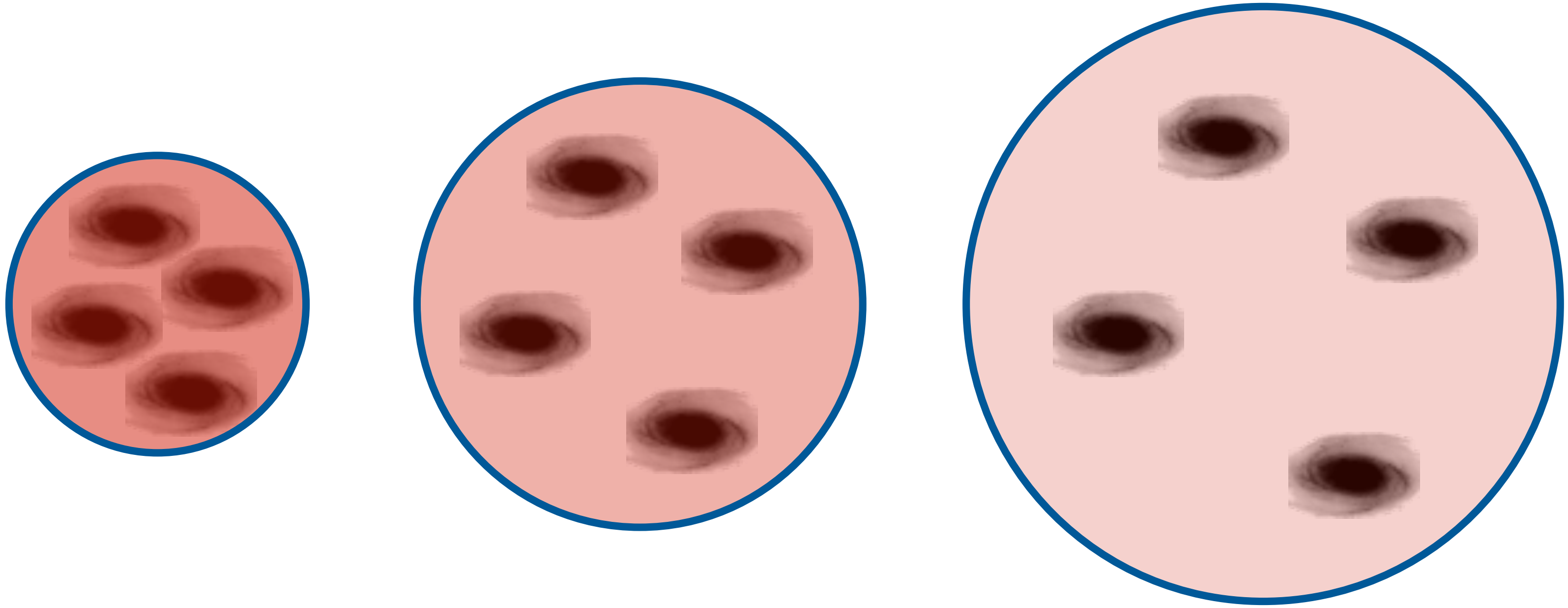


FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

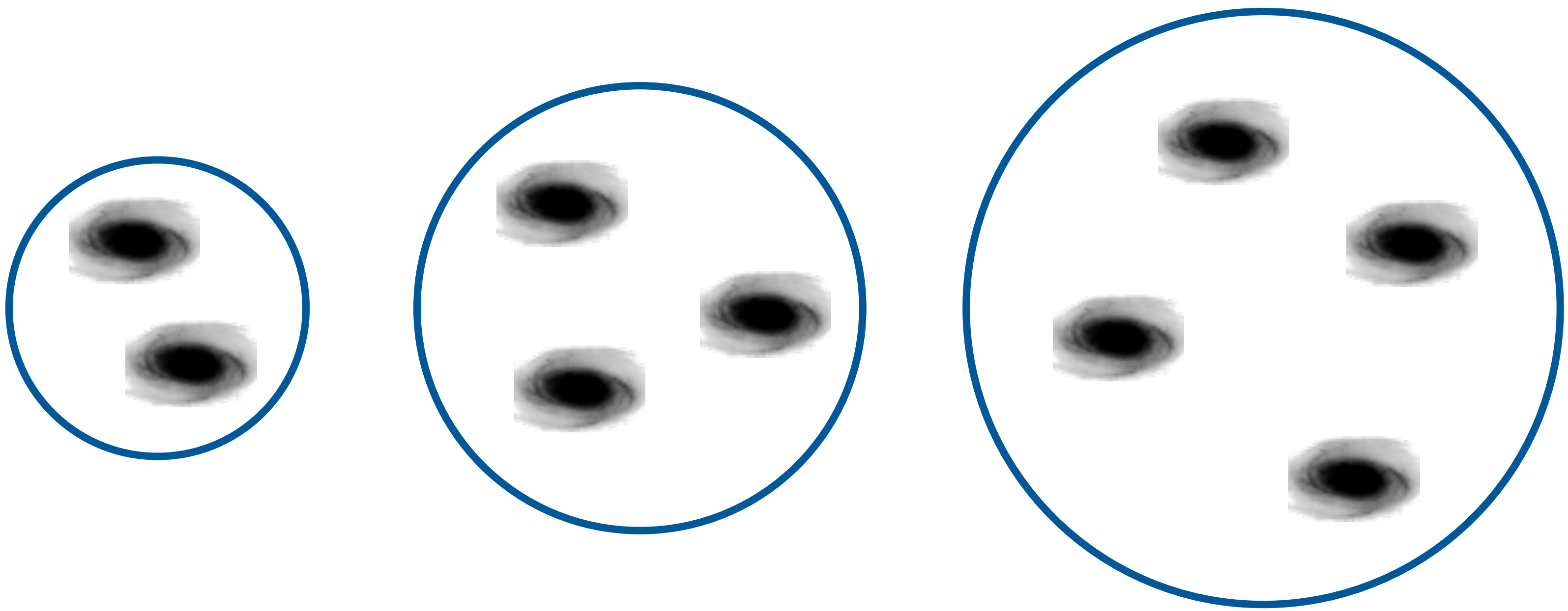
Mather *et al.*, ApJ, 1990, **354**, L37-40.

Big Bang versus Steady State

Big
Bang
–
“Natural”
Explanation
of the CMB

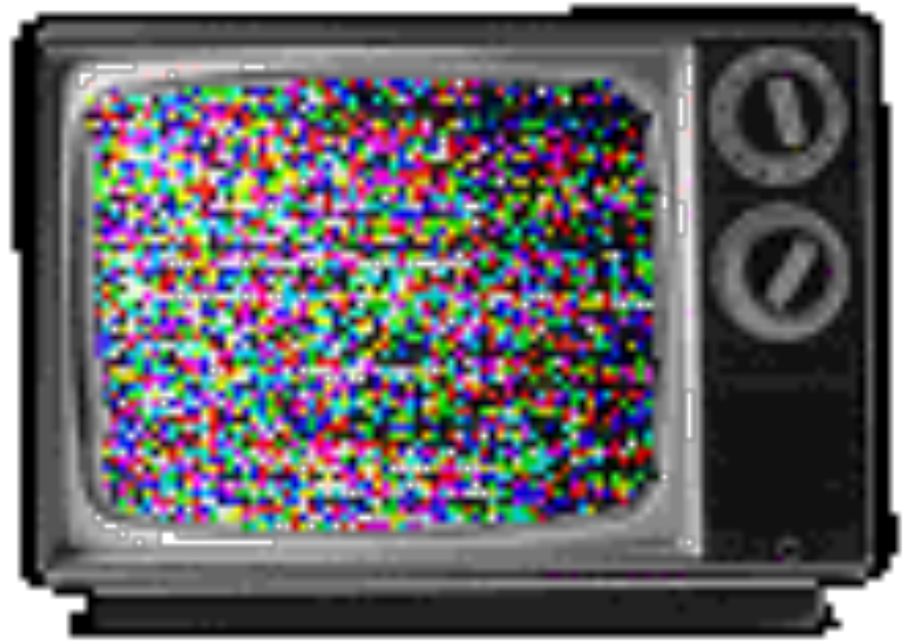


Steady
State
–
No
Explanation
for the CMB



CMB Trivia

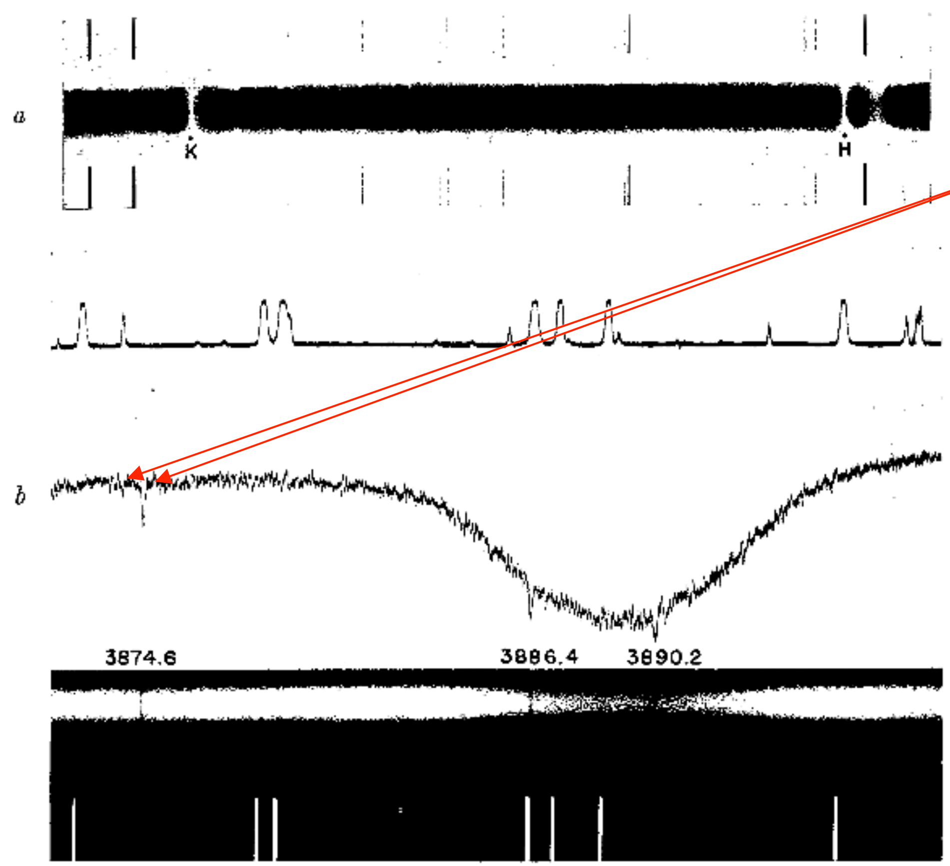
- T = 2.7255 K
- Peak freq.: $\nu_{max.}$~160 GHz
  - $\lambda_{max.}$ ~ 1 mm ($\neq c/\nu_{max.}$!)
- $\sigma T^4 \sim 4.2\times10^{-14}$ J/m^3
- 3kT ~ 10^{-22} J ~ 0.0007 eV
- 370 CMB photons/cm^3
- There are ~2 billion CMB photons for every baryon in the Universe
- But, $\Omega_\gamma = 5\times10^{-5}$



A few percent of the TV "snow" you see between channels comes from the microwave background (if you have an old, analog TV).

http://background.uchicago.edu/~whu/beginners/introduction.html

A Missed Opportunity



INTERSTELLAR LINES

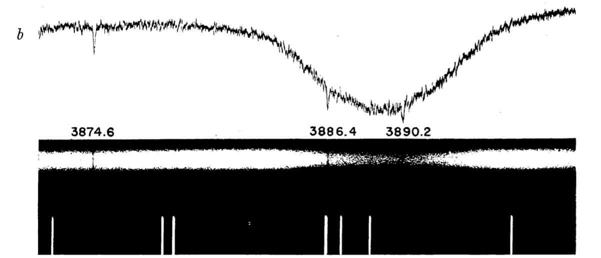
a) α Cygni showing interstellar H and K superposed upon stellar lines; b) ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of CH are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably CN.

Adams (ApJ 1941) showed excitations in CN molecules in the direction of Ophiuci

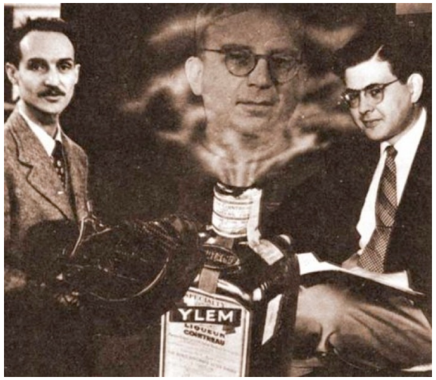
The line ratio implies an excitation temperature of ~2.3 K

But nobody had thought about the Big Bang then

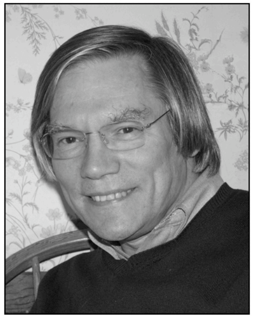
A History of the CMB in One Slide



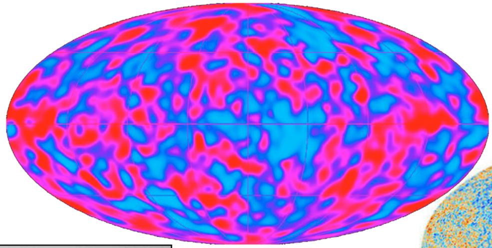
INTERSTELLAR LINES
a) α Cygni showing interstellar H and K superposed upon stellar lines; b) ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of *CH* are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably *CN*.

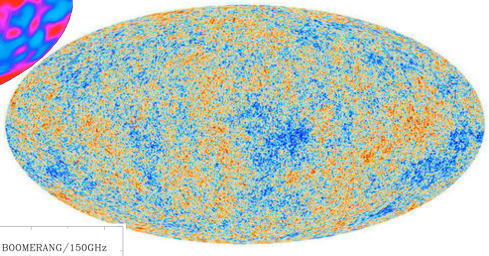


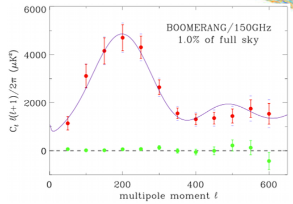
Alexei Starobinsky
b. 1948

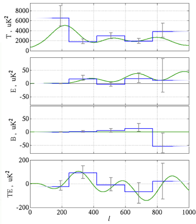


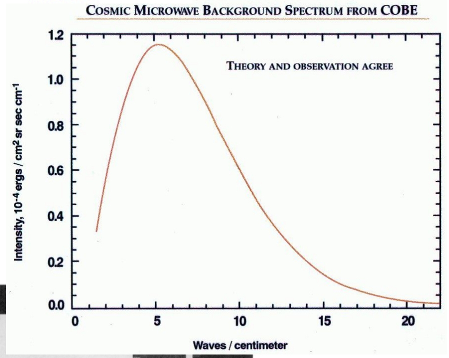
Alan Guth
b. 1947

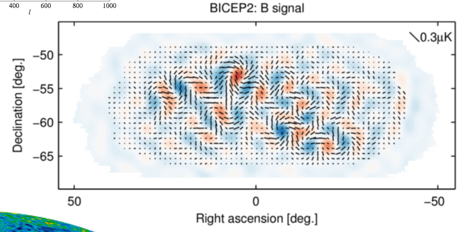




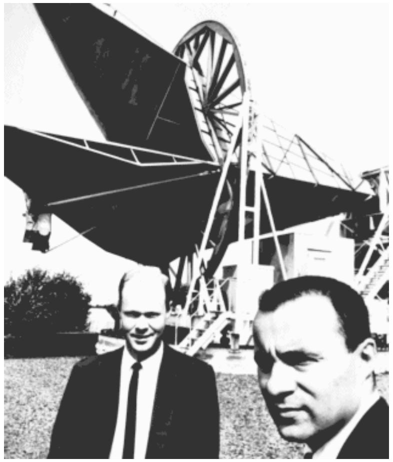


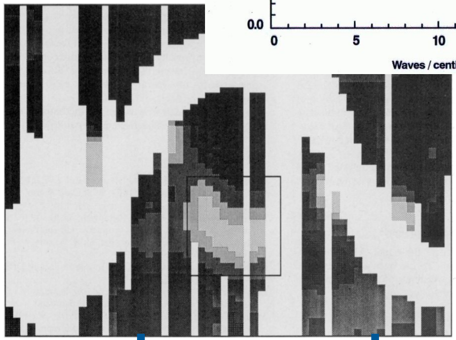


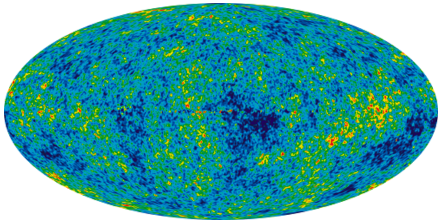




With apologies to most of the field for omissions...

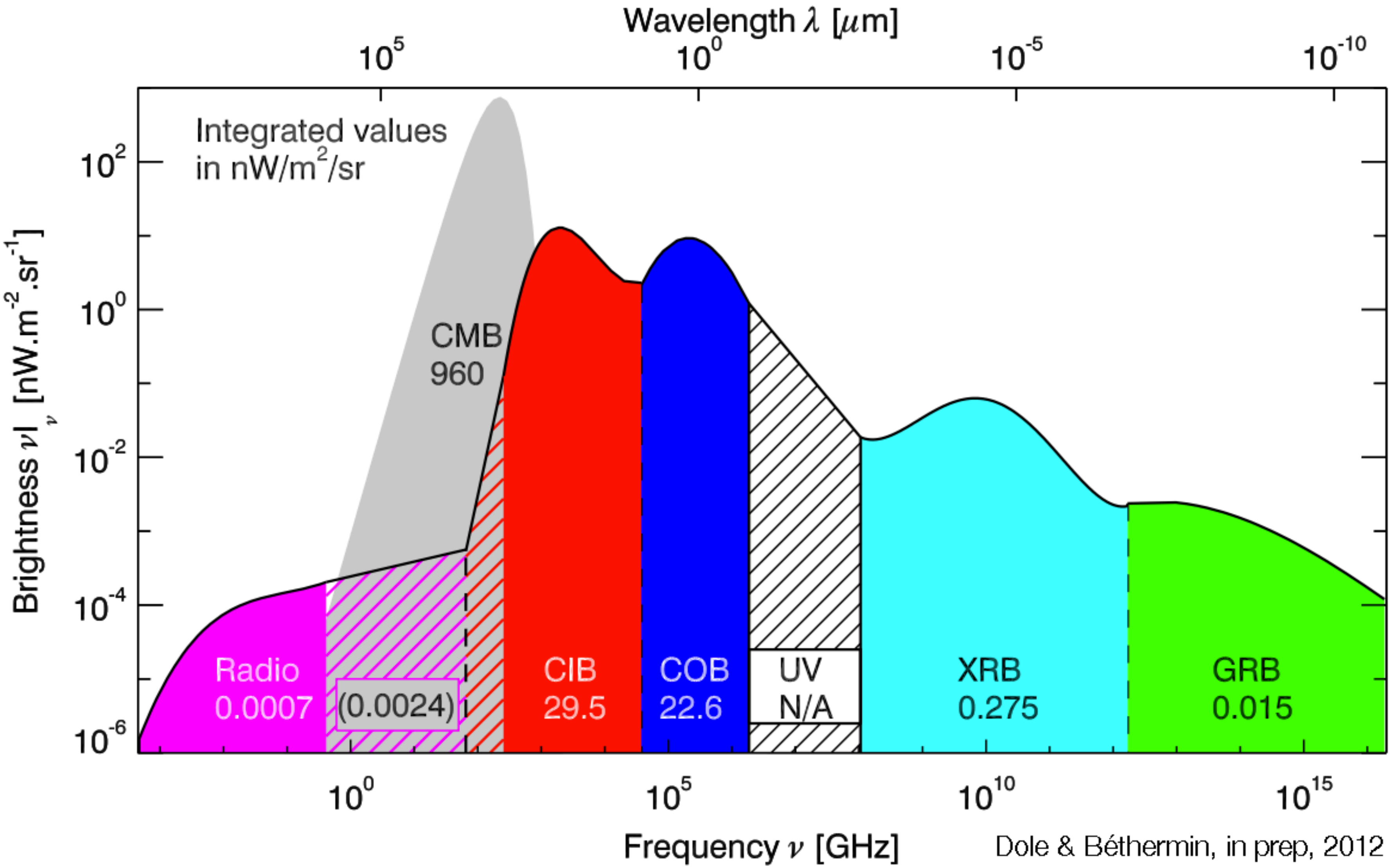






1940 1950 1960 1970 1980 1990 2000 2010 2020

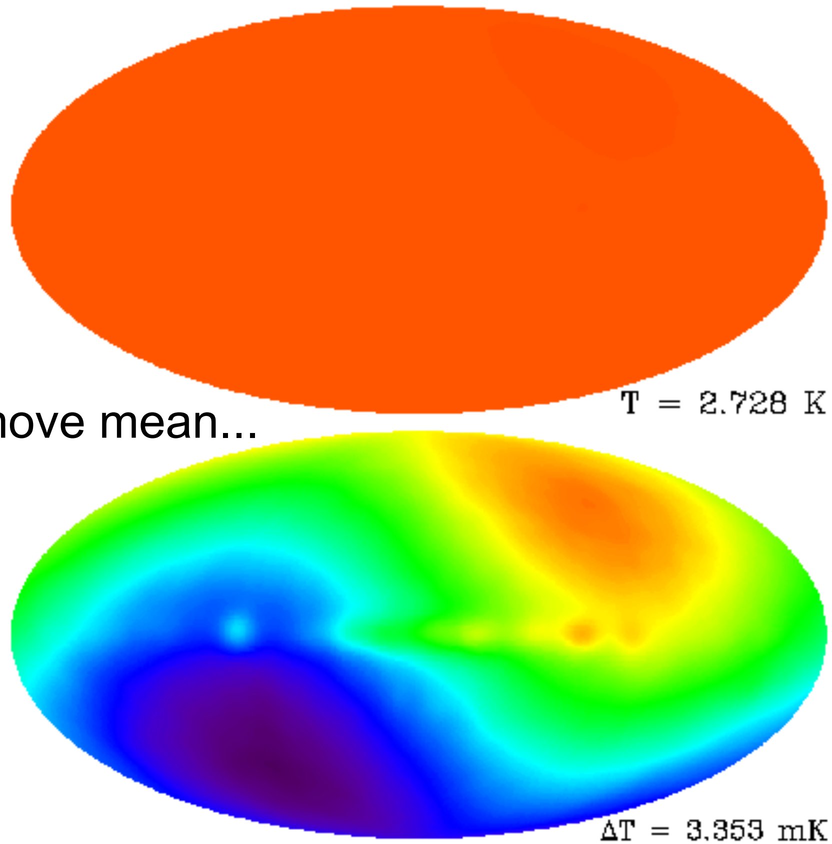
Extragalactic Background Brightnesses



The majority of photons in the Universe are from the Microwave Background.

Dipole Anisotropy

remove mean...



$\Longrightarrow$

The solar system moves with respect to the CMB rest frame

Doppler shifting results in a (mostly) dipolar anisotropy

Predicted in ~1968. First measured in the 1970s.

With this, we infer $v_{\oplus} \approx 370$ km/s with respect to the CMB

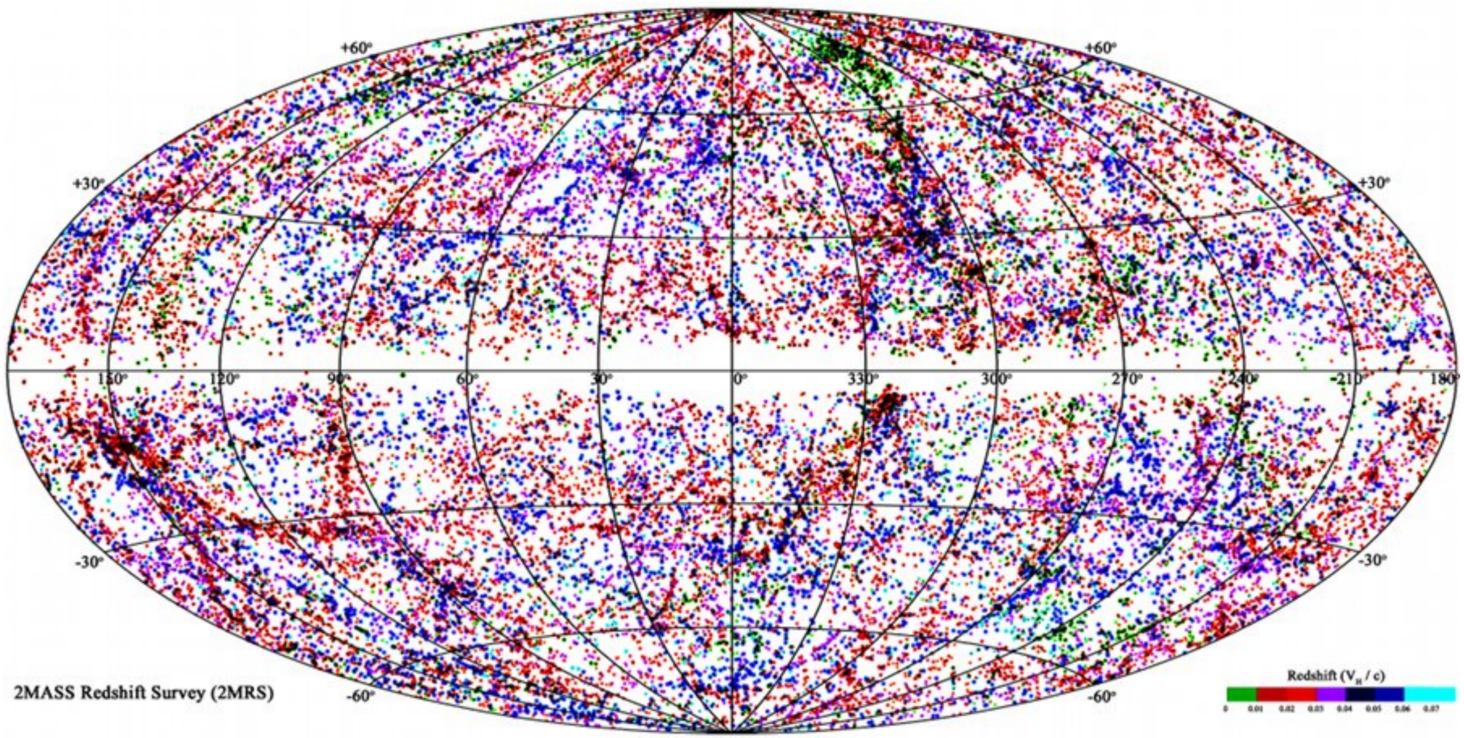
A Note on Units

The CMB temperature and “Temperature fluctuations” are not exactly the same thing…

Differentiate the Planck function to see that

What About Structure in the Universe?

- The Universe was initially very homogeneous.
- Today we see stars, galaxies, clusters of galaxies, and so on.
- How can we reconcile these points?
- To learn more, we search for small variations in the CMB

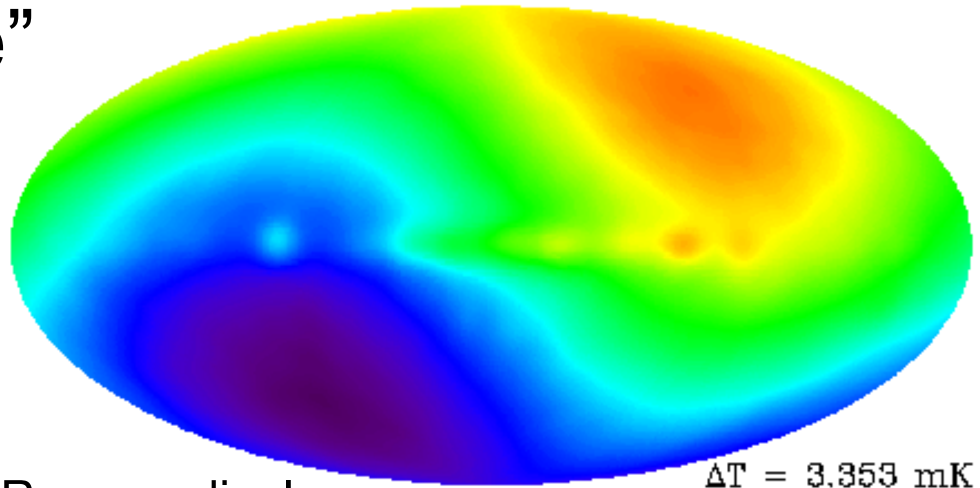


Primordial Anisotropies

Remove the CMB "monopole" and the dipole.

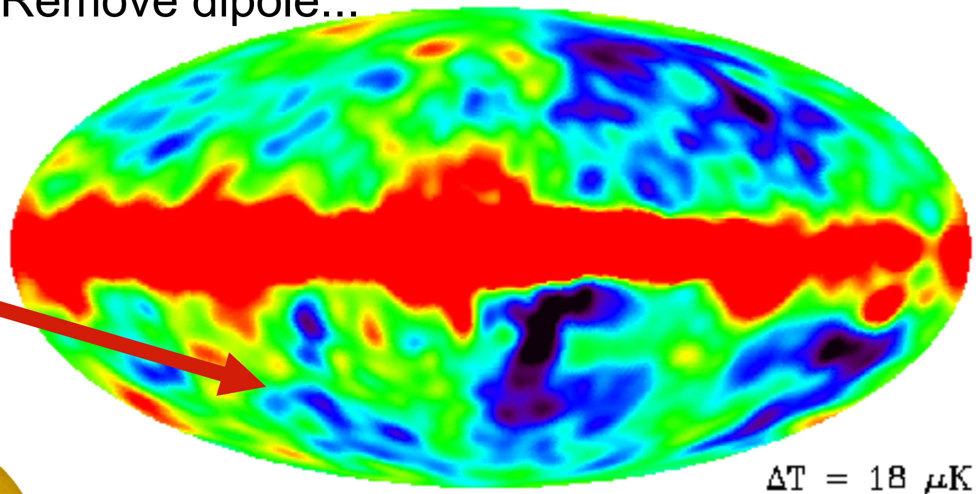
Ignore the Galaxy.

What's left are the anisotropies – the seeds of the structure in the Universe today.



$\Delta T = 3.353$ mK

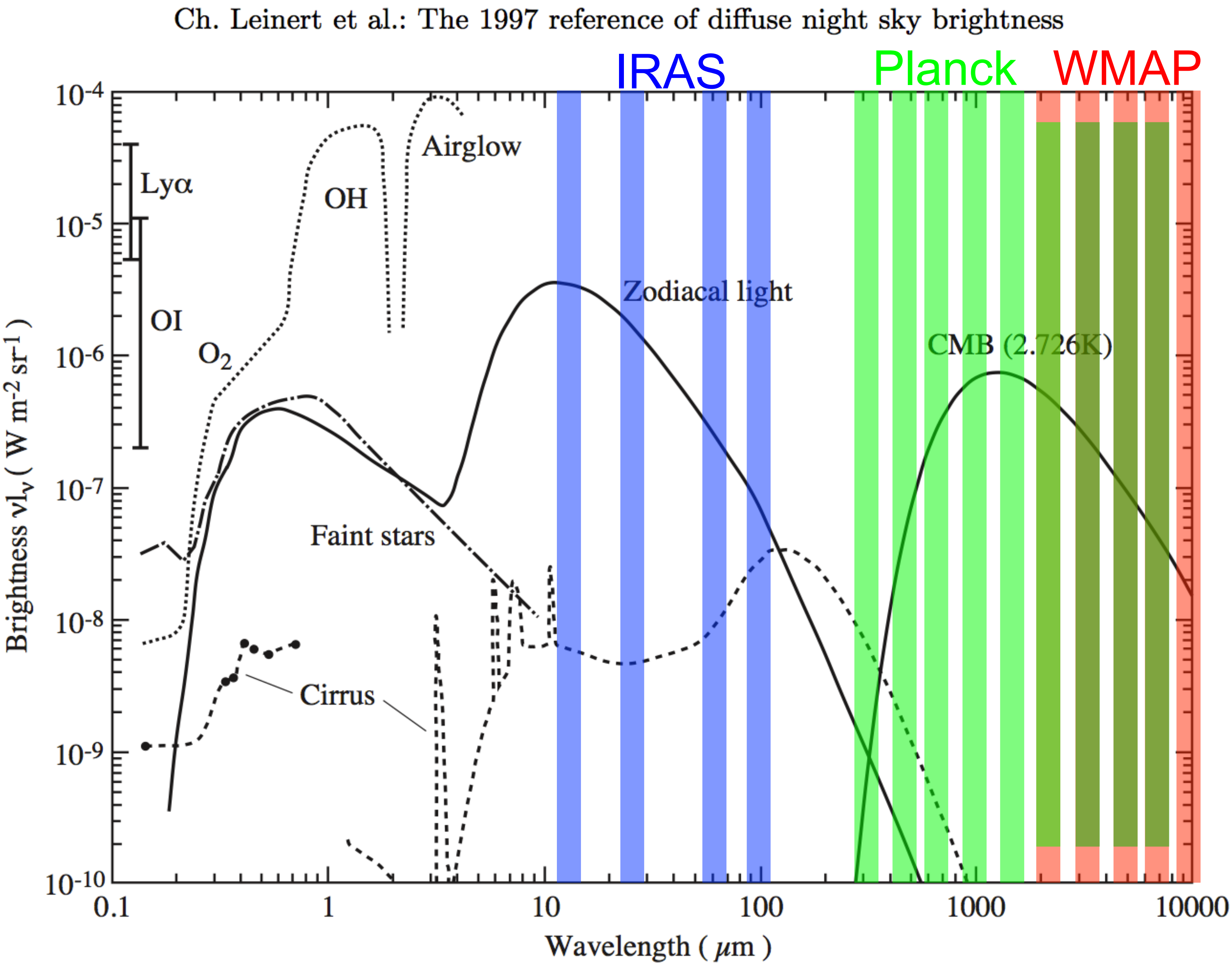
Remove dipole...



$\Delta T = 18\ \mu K$

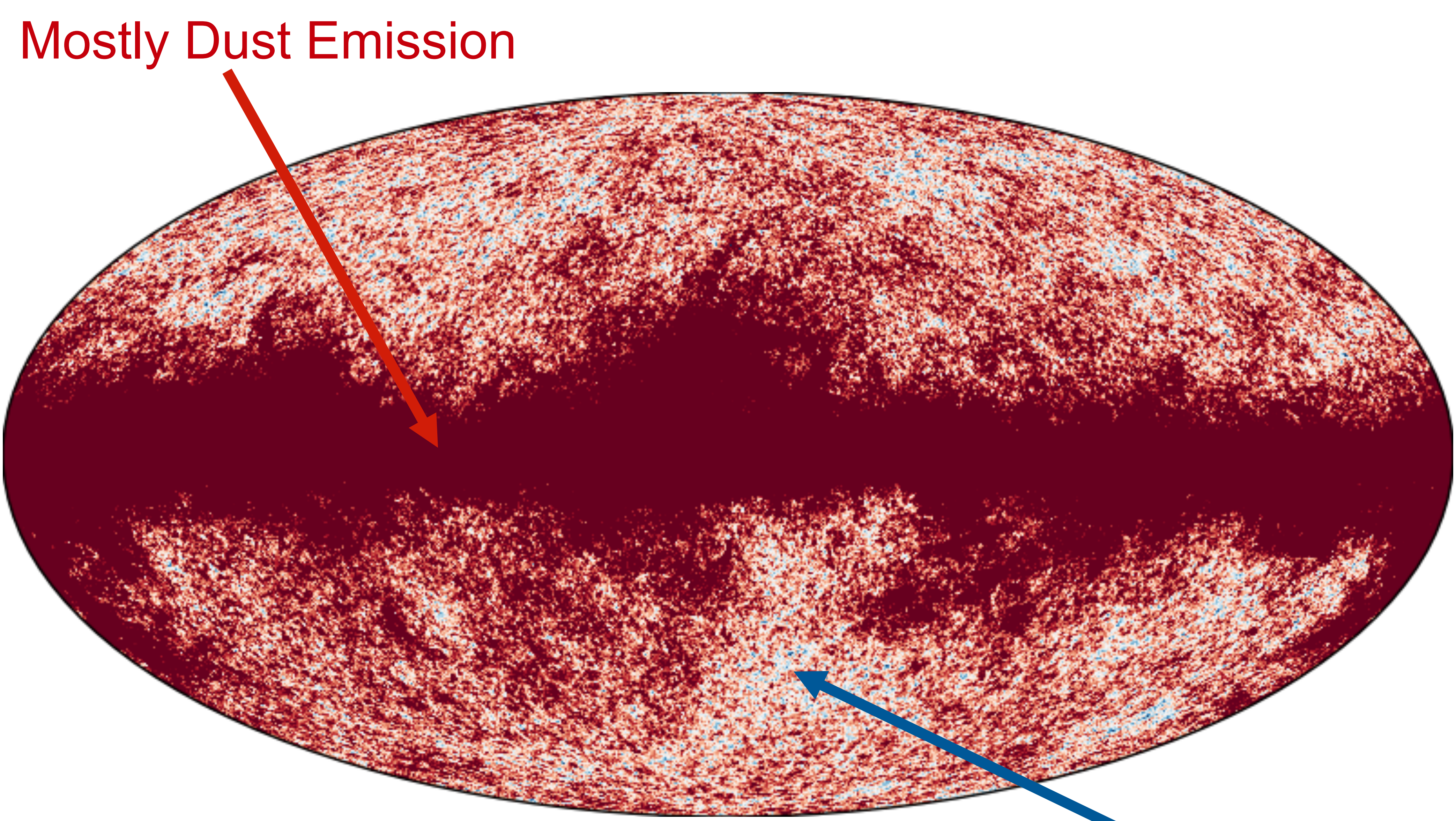
COBE/DMR & George Smoot

Frequency/wavelength coverage

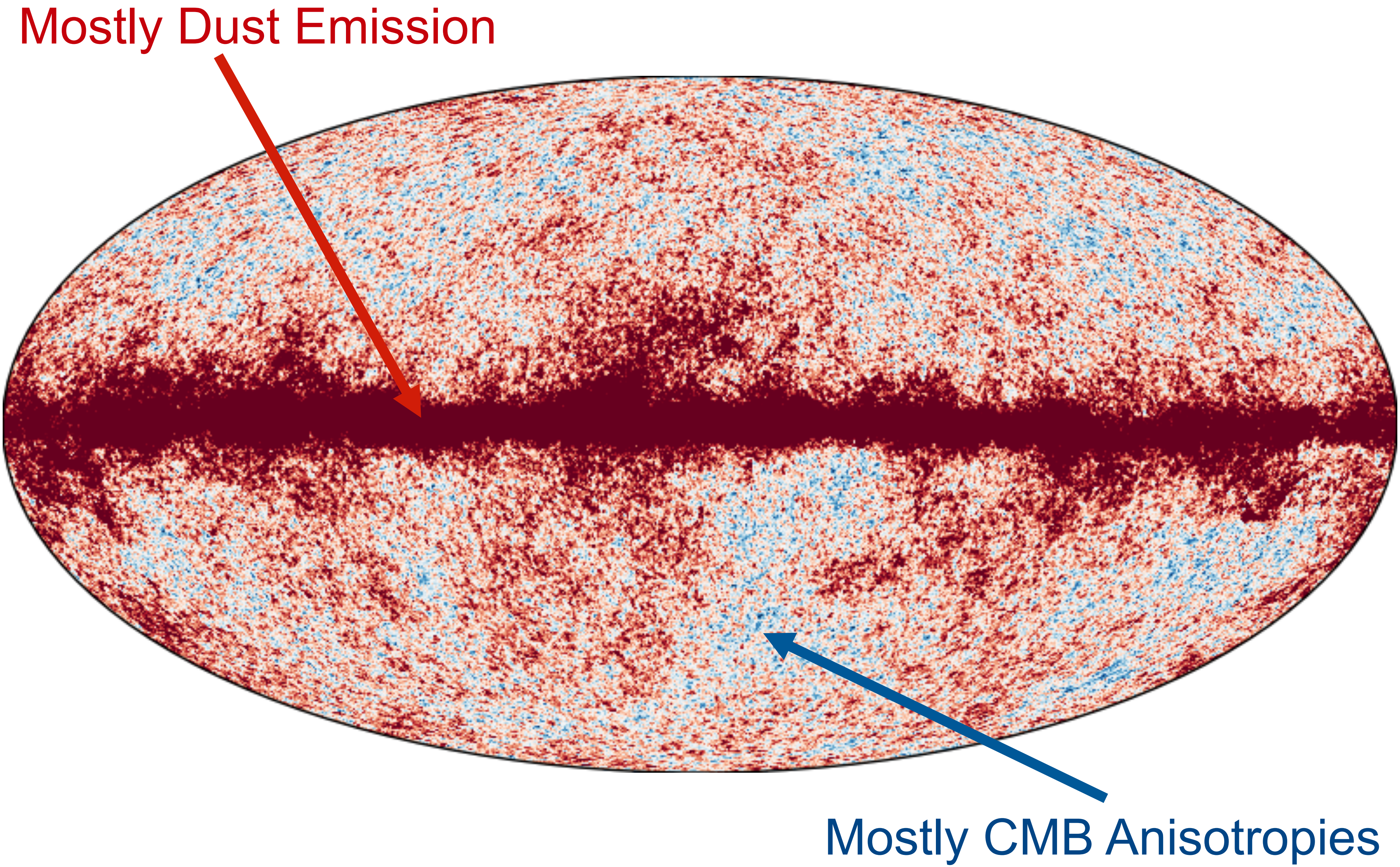


Planck fills the SubMM range, so in addition to CMB science, Planck will be able to say a lot about dust emission in our Galaxy and in others.

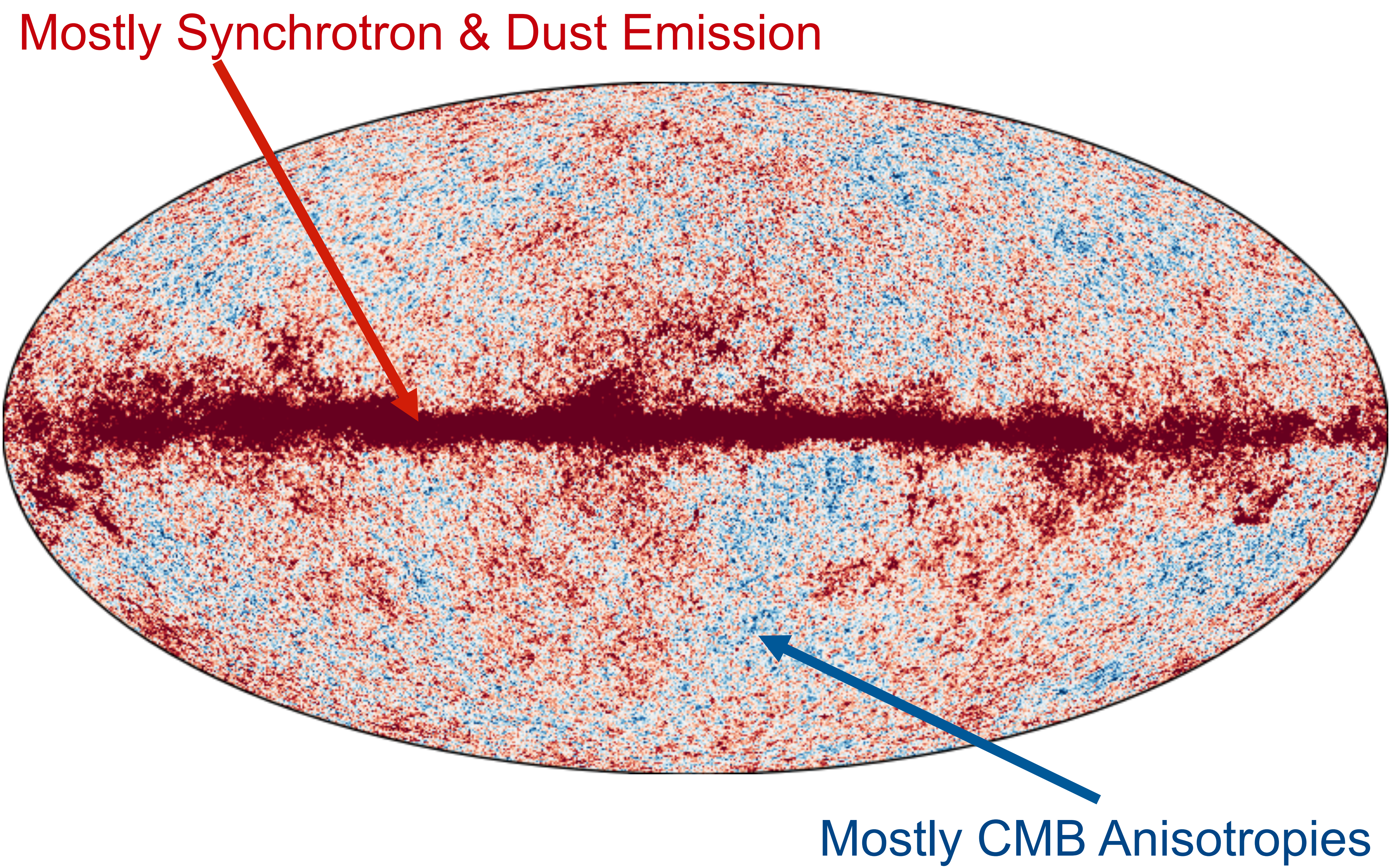
Planck@217 GHz



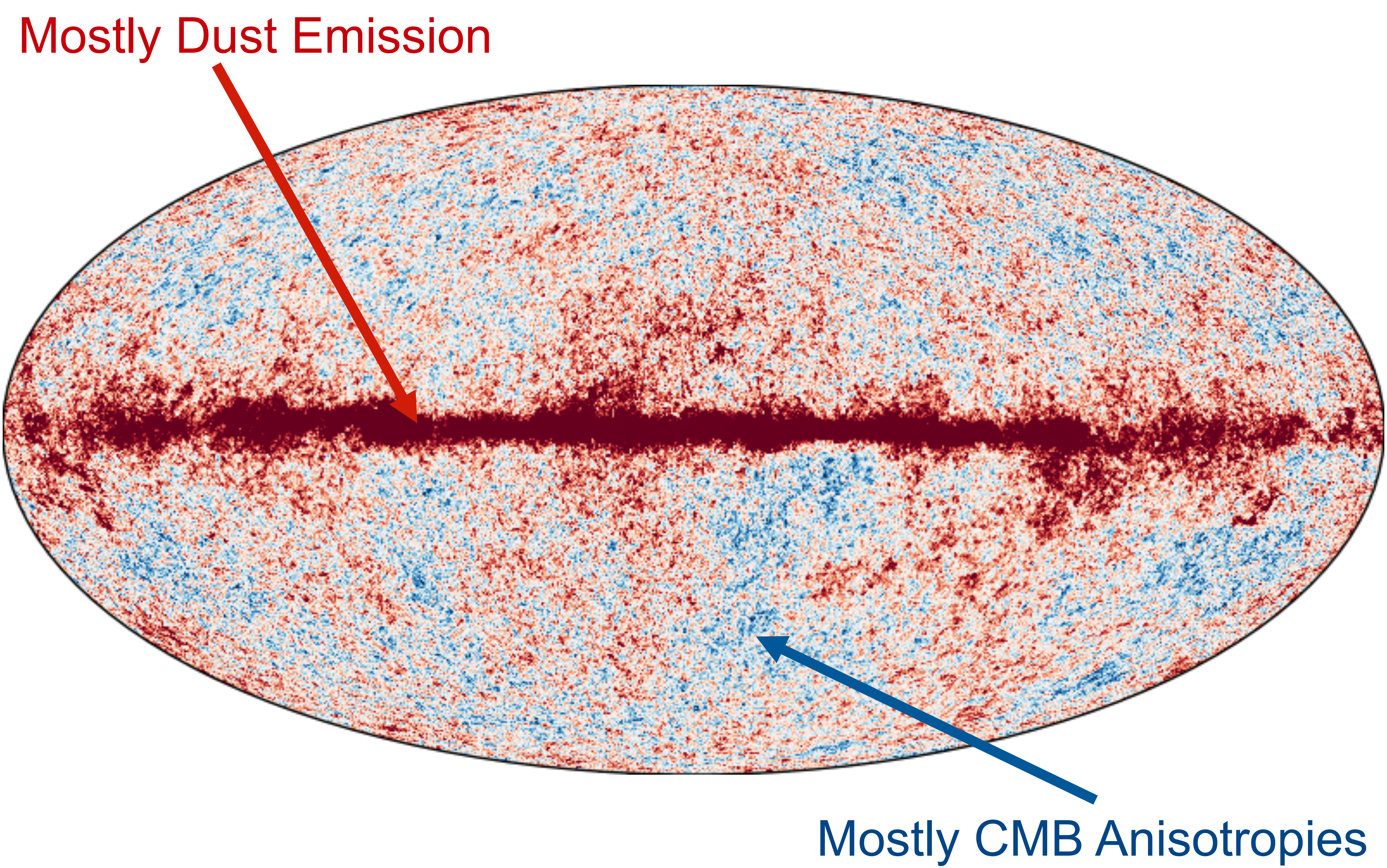
Planck@143 GHz



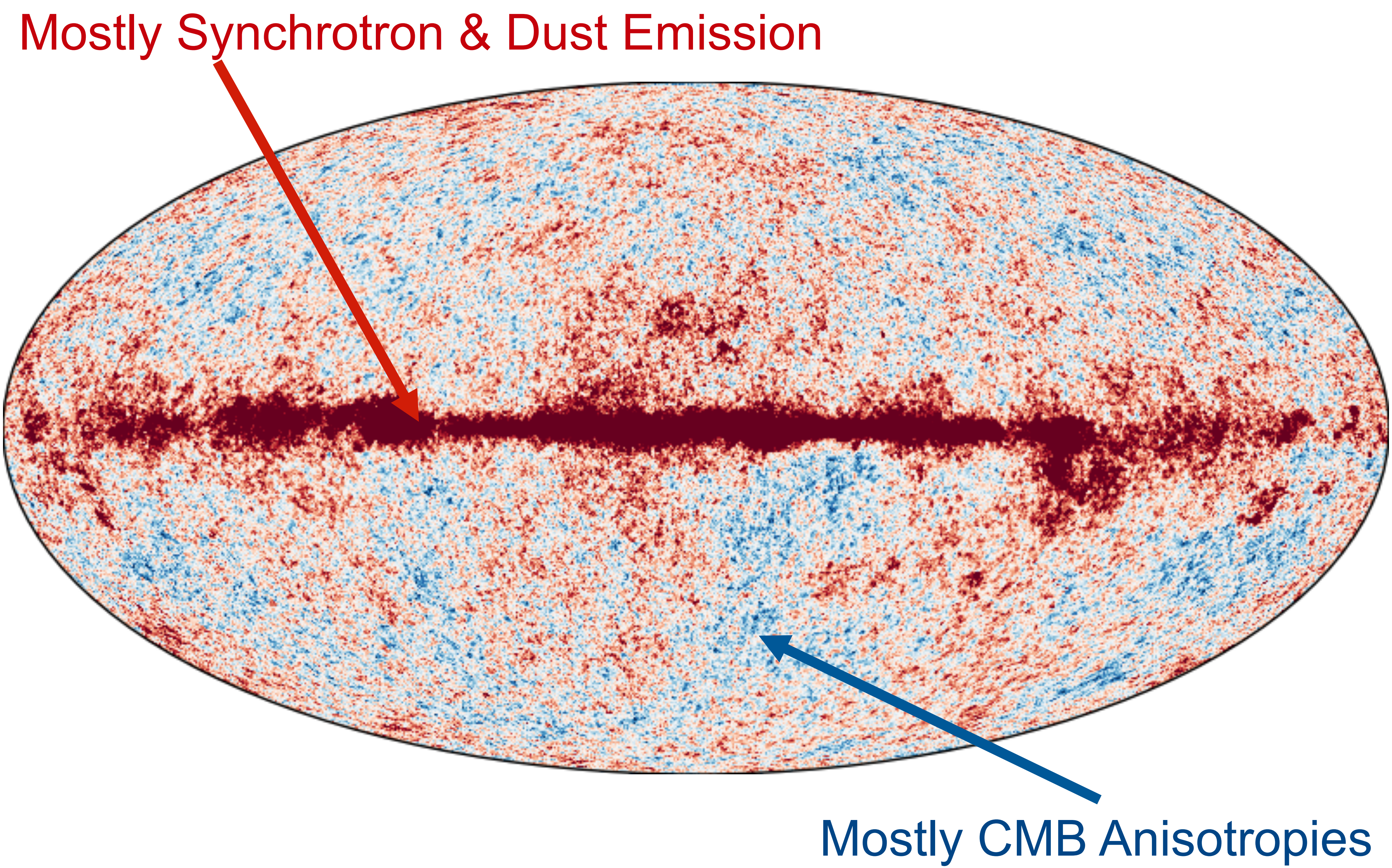
Planck@100 GHz



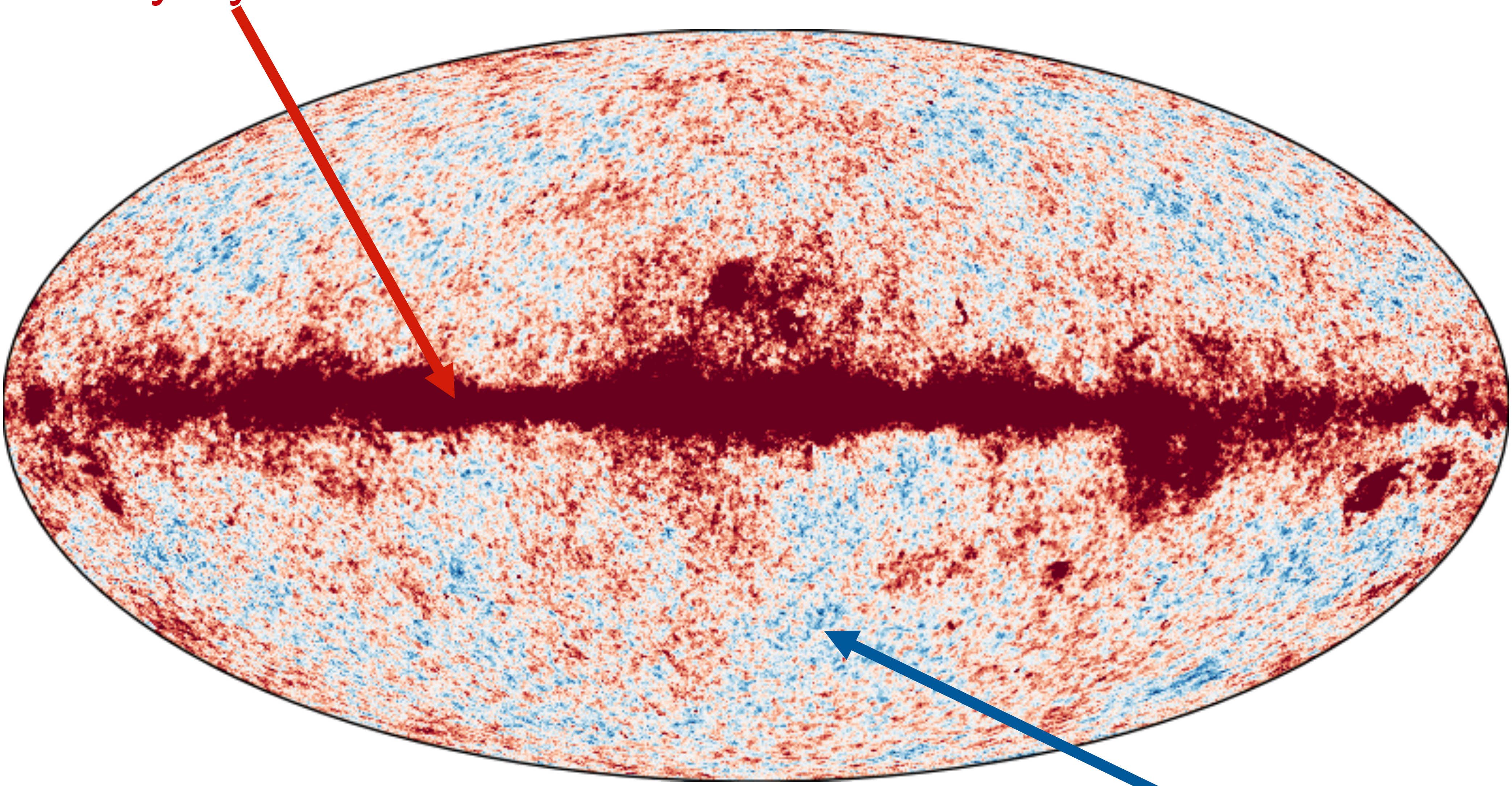
WMAP@095 GHz



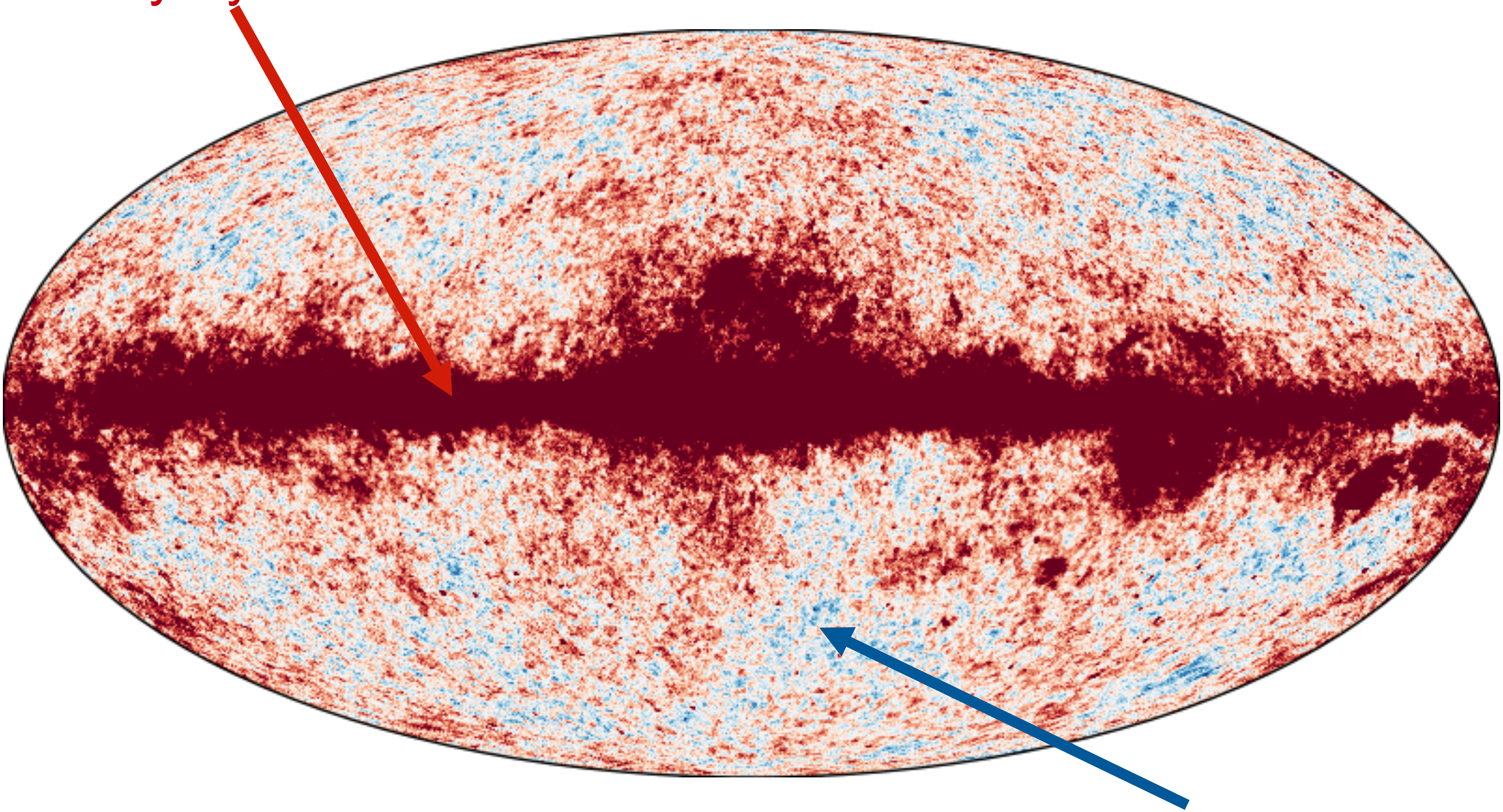
WMAP@070 GHz


Mostly Synchrotron & Dust Emission
Mostly CMB Anisotropies

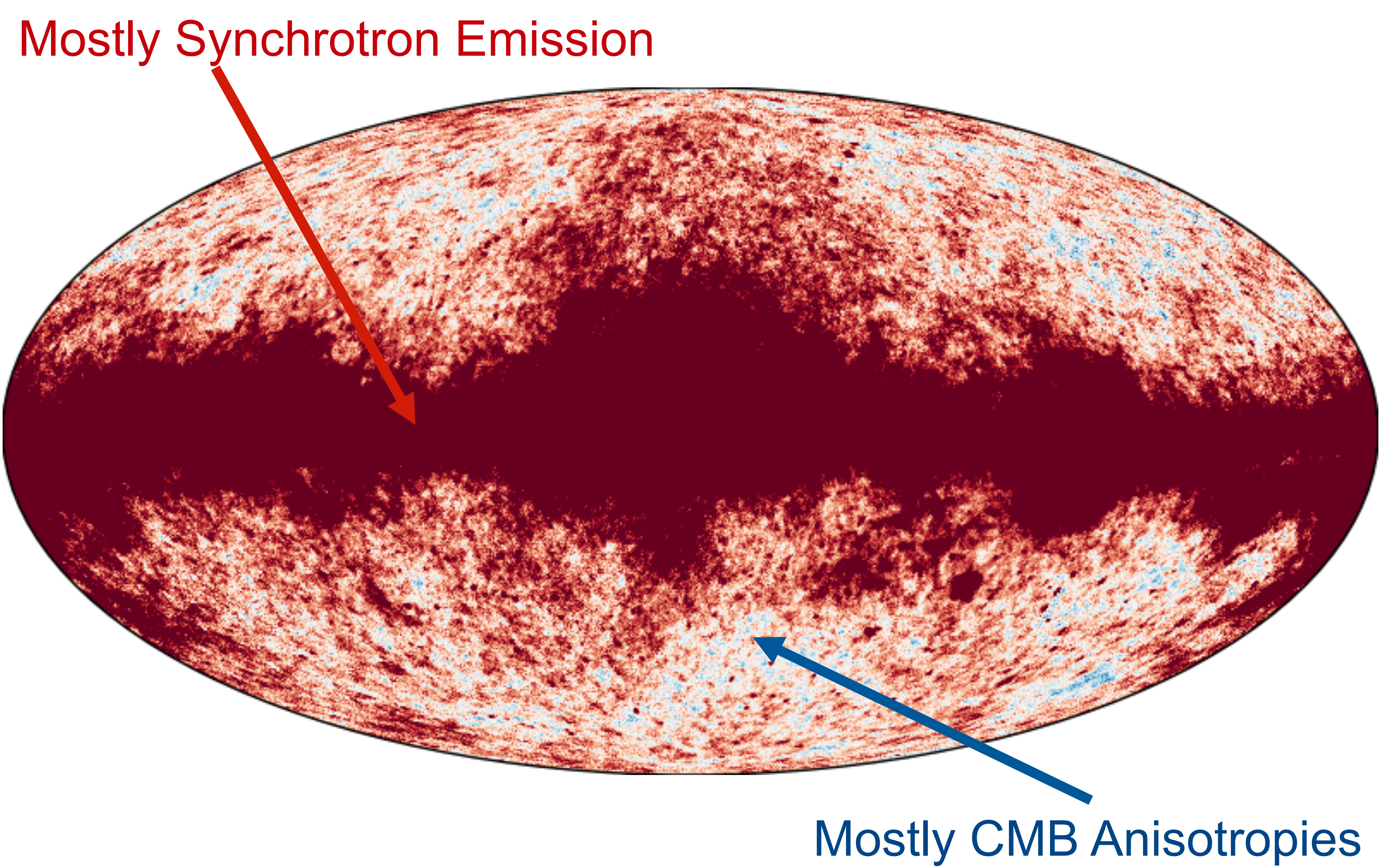
WMAP@045 GHz



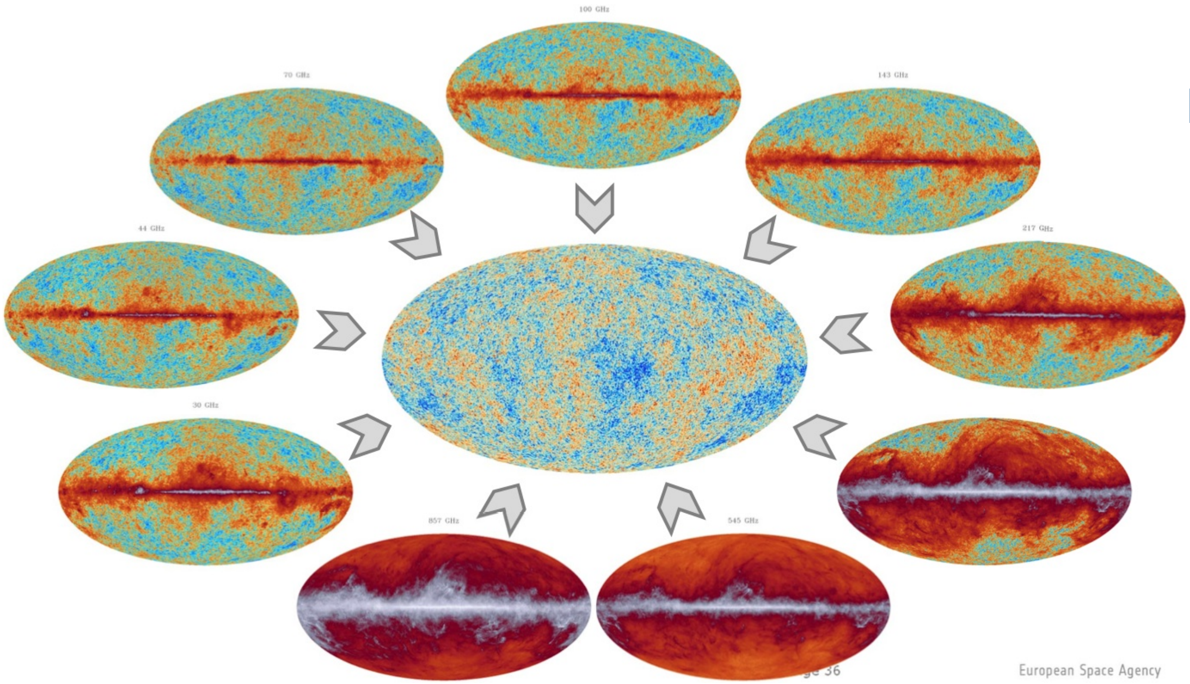
WMAP@030 GHz

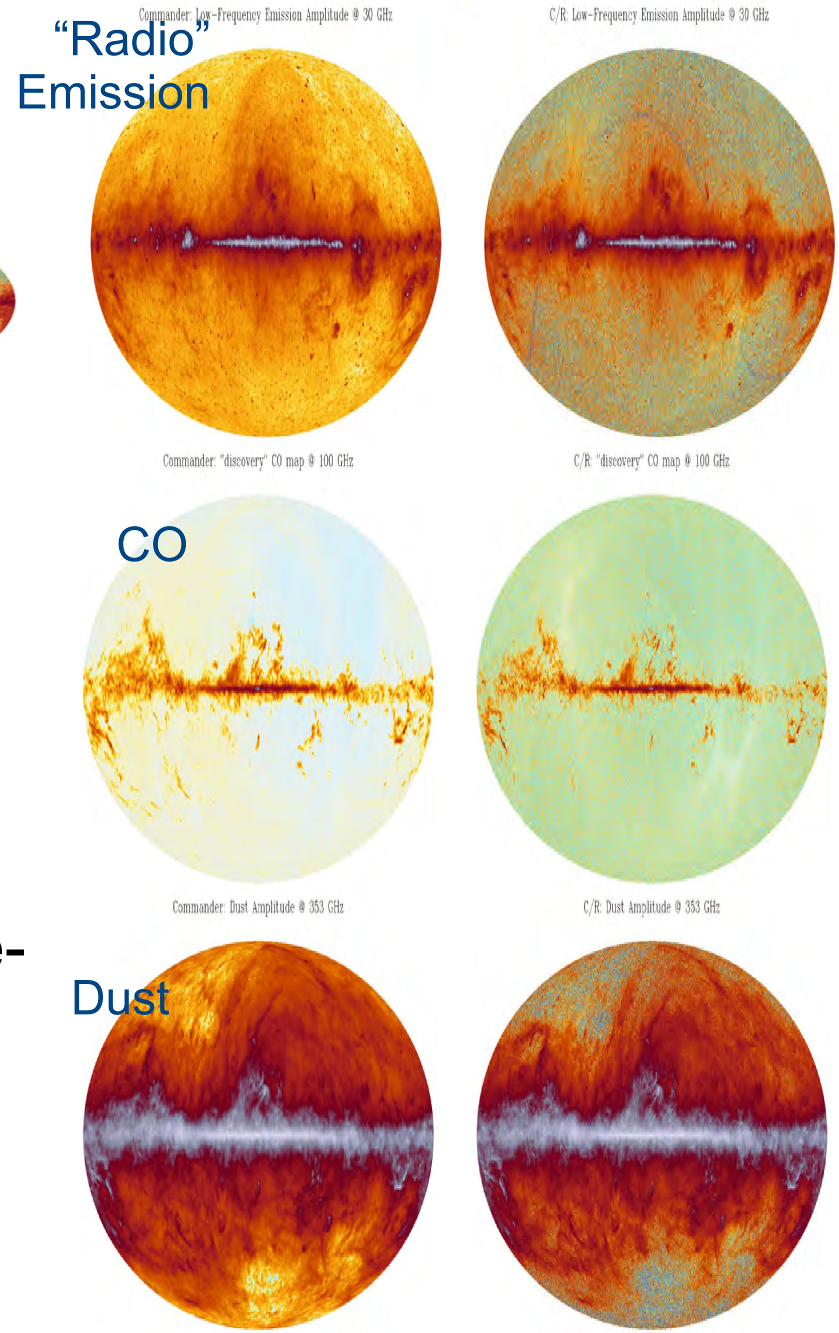


WMAP@023 GHz



“Foregrounds”

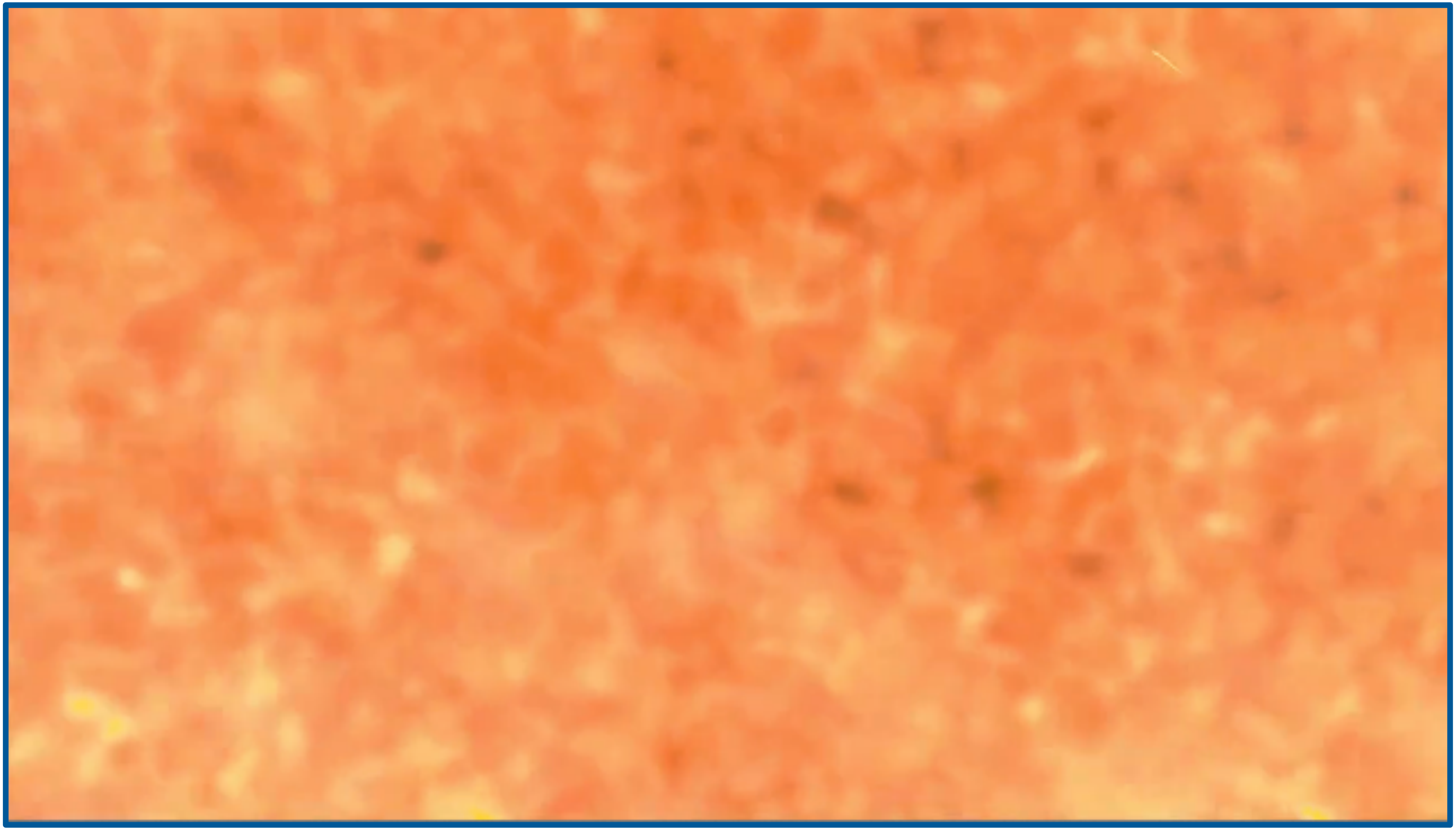




Combinations of the nine Planck channels allow us to separate the signals into CMB, CO, Dust and other components such as synchrotron, free-free and vibrational dust.

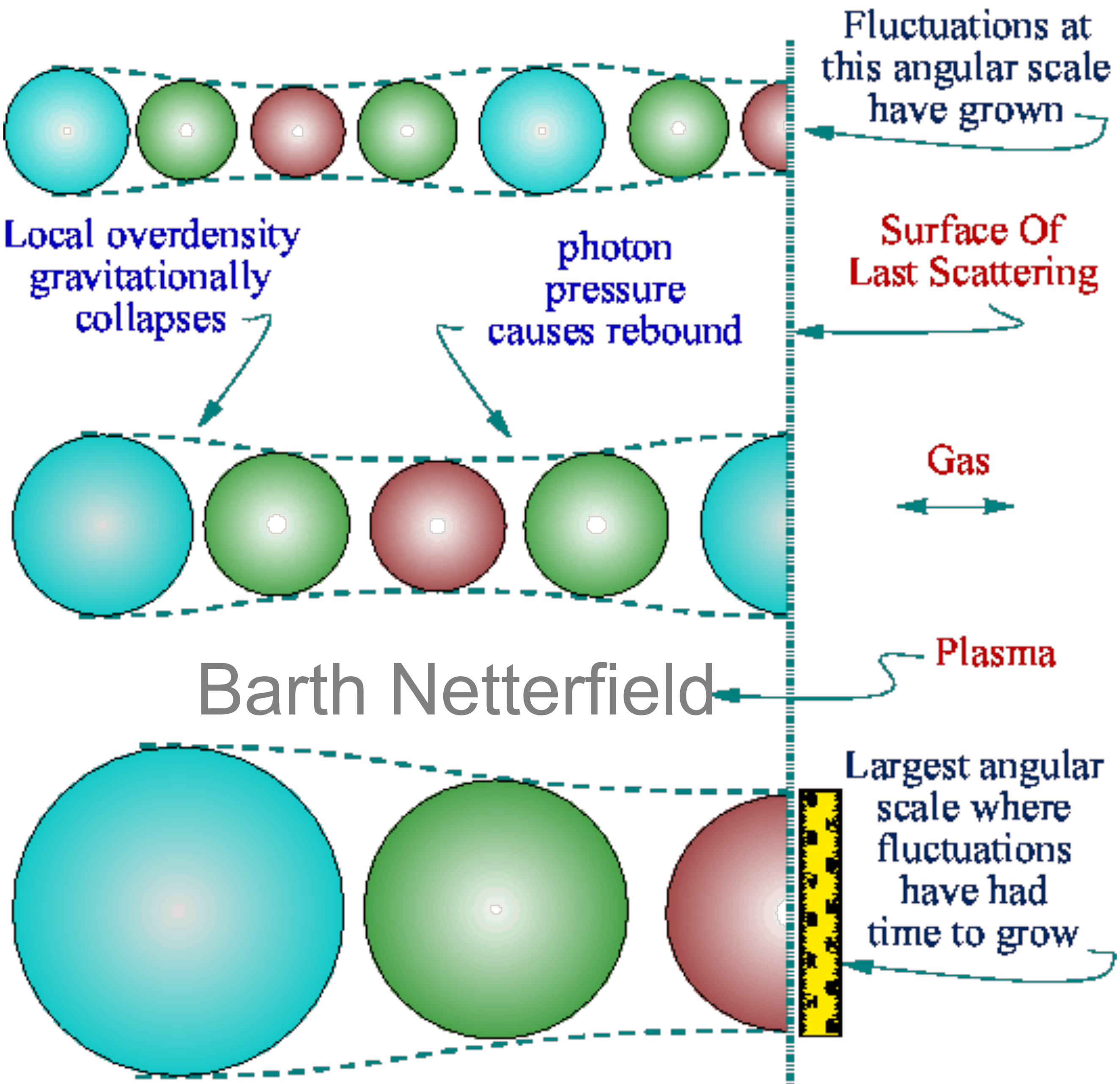
The Galactic Plane and point sources are usually masked for cosmological analyses.

Visualization of the Early Universe



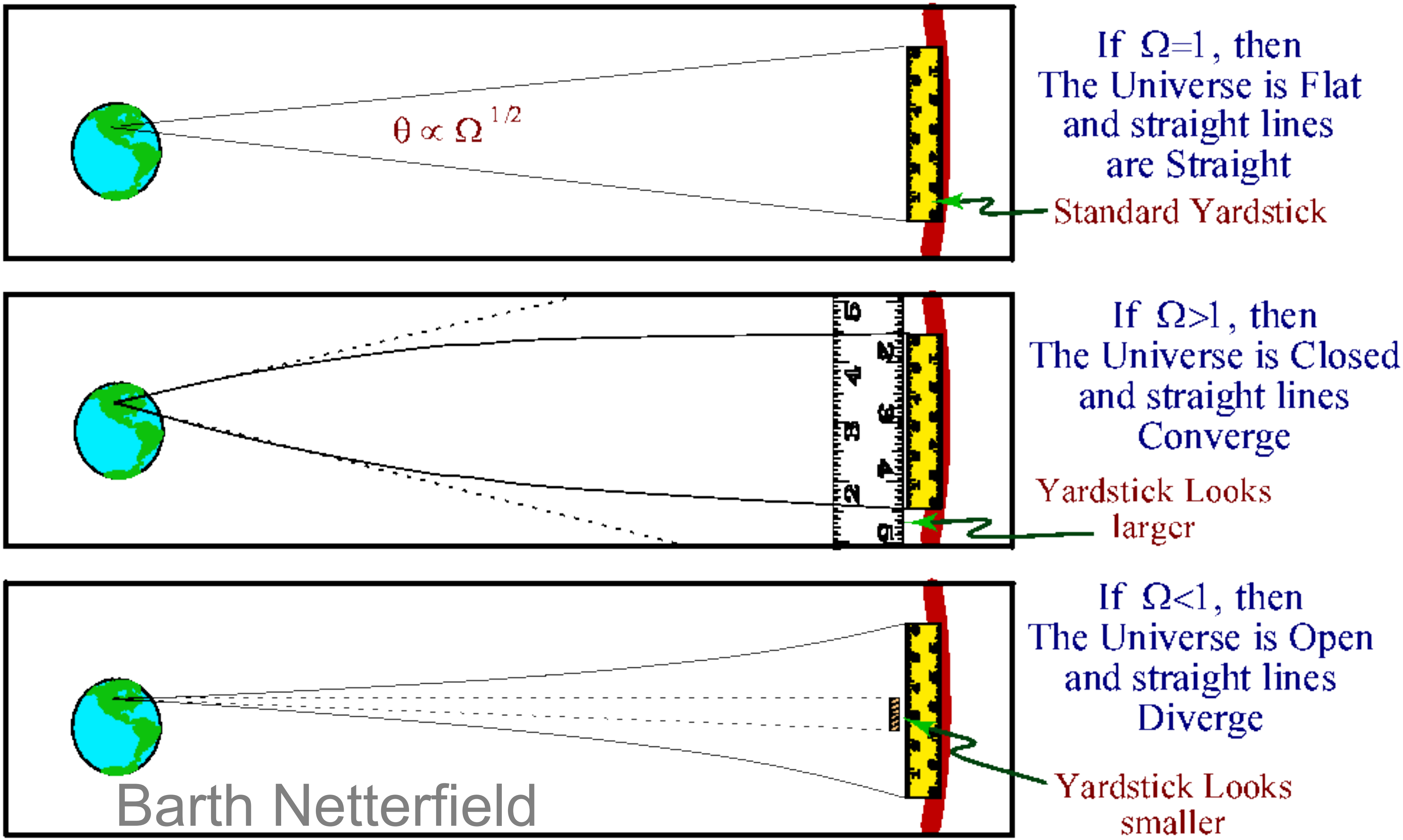
Here we see the expansion, recombination, and the start of structure formation in the Universe (from "Cosmic Voyage")

Acoustic Oscillations

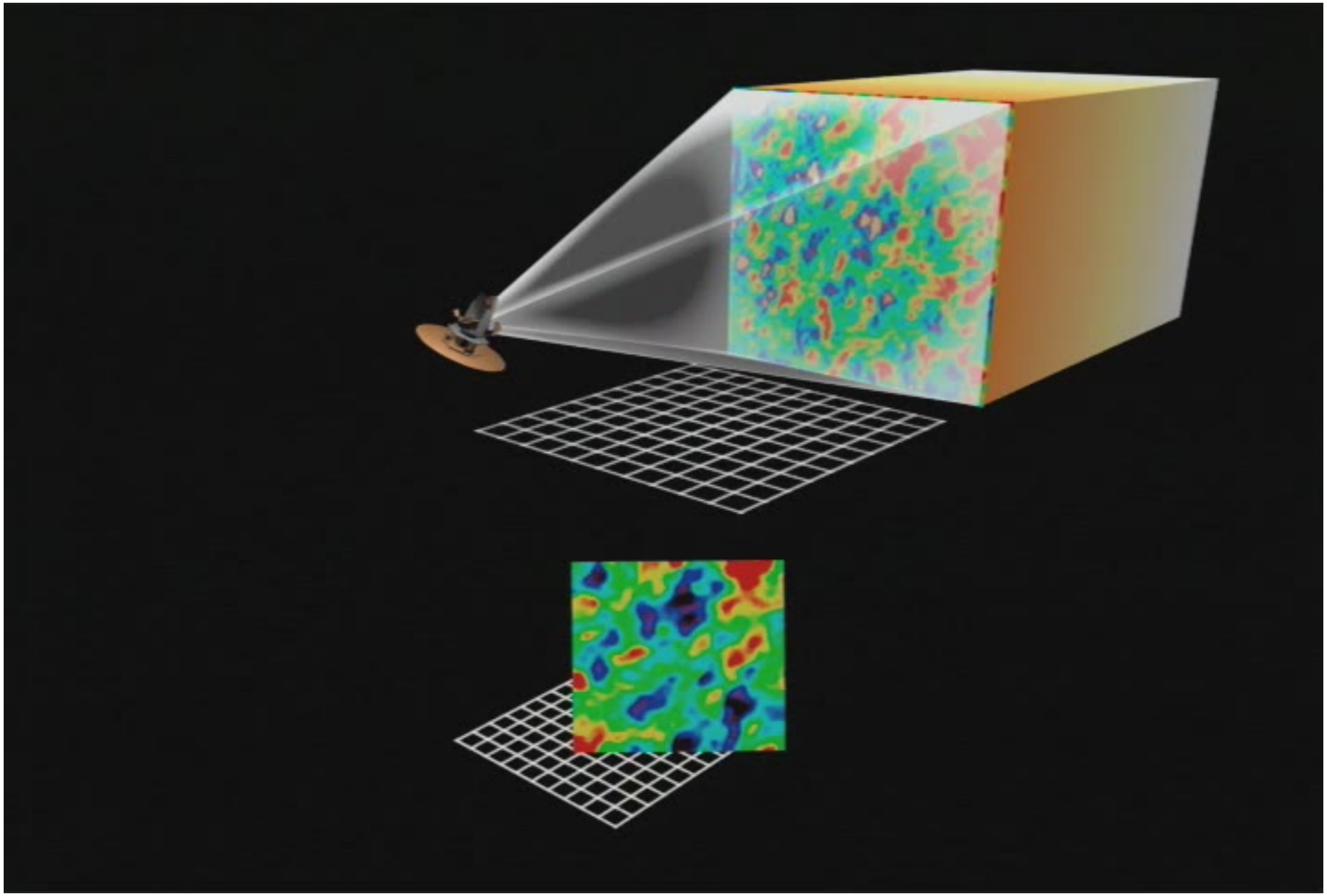


Since the speed of sound is roughly $v \sim c/3^{1/2}$ at these early times we have a "standard ruler"

The Curvature of the Universe

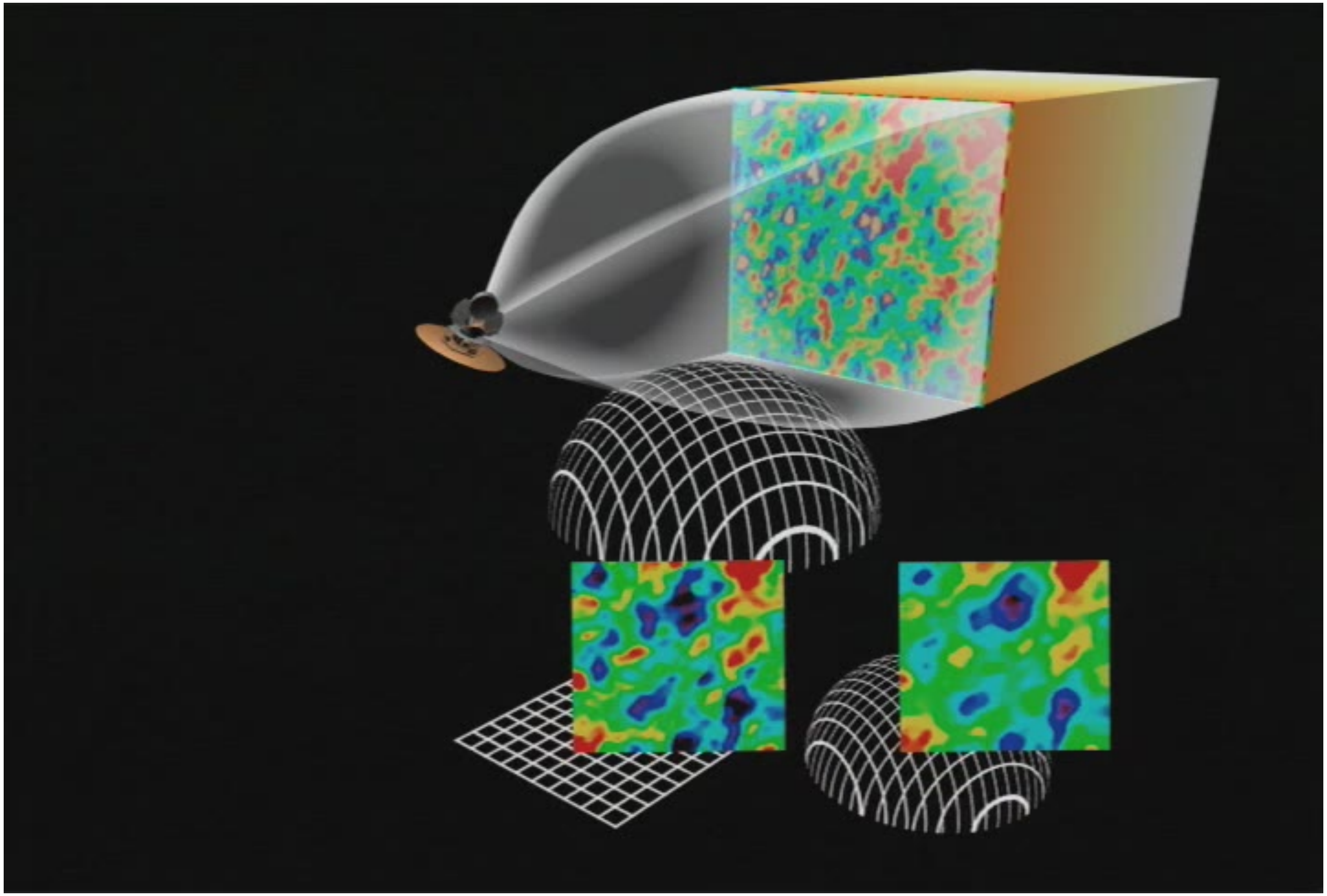


A “Flat” Universe



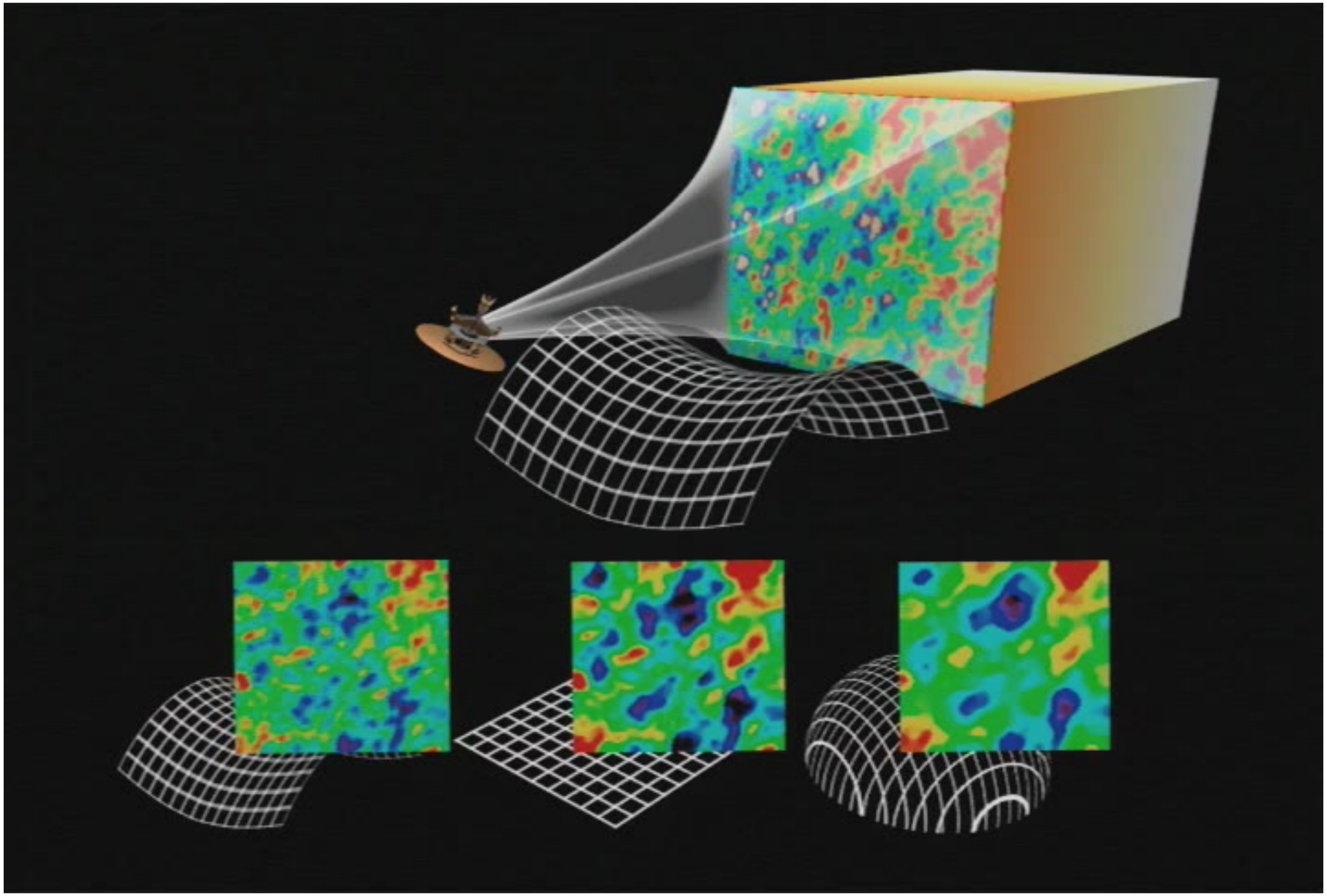
- Smaller characteristic scales indicate a closed Universe
- Larger characteristic scales indicate an open Universe

A “Closed” Universe



- Smaller characteristic scales indicate a closed Universe
- Larger characteristic scales indicate an open

An "Open" Universe



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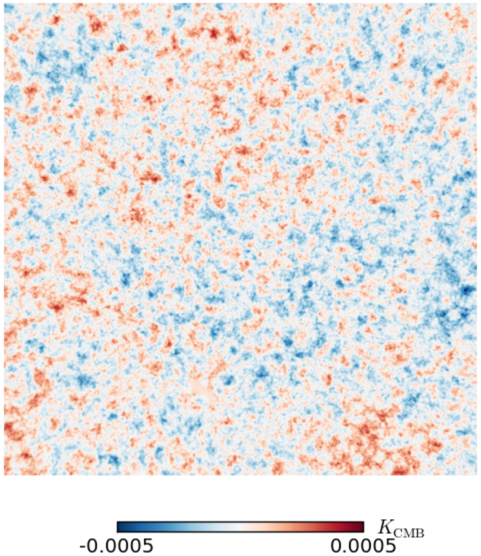
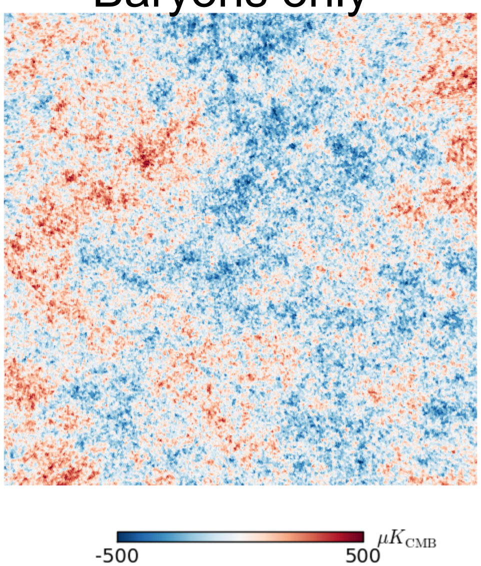
The Constituents of the Universe

Planck

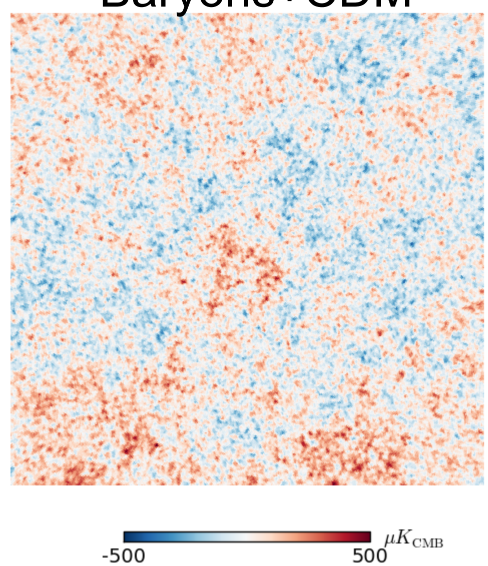


The real data resemble simulations with "normal" matter, cold dark matter and a cosmological constant than they do simulations missing any of these three components.

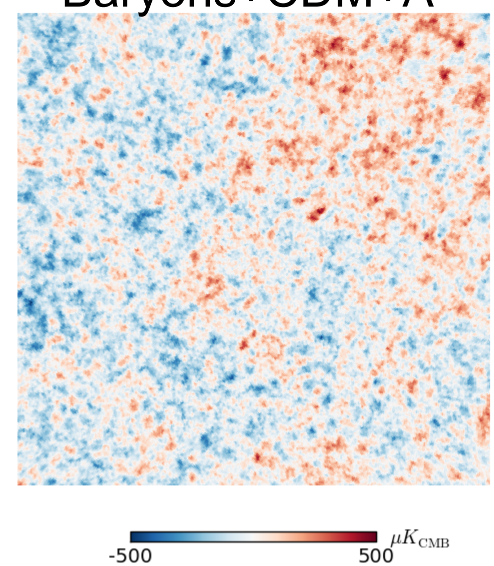
Baryons only



Baryons+CDM

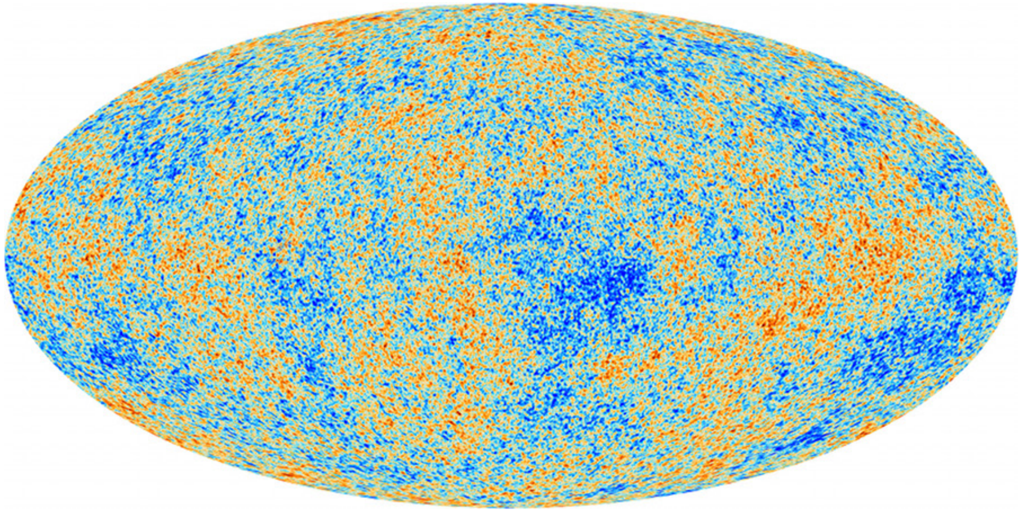


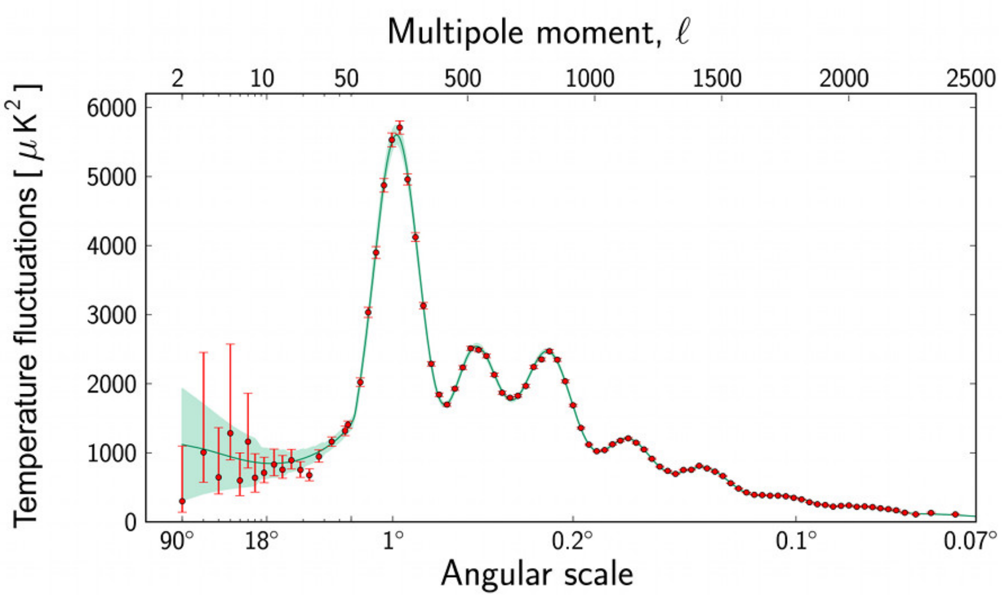
Baryons+CDM+Λ



What are Power Spectra?

http://www.esa.int/Our_Activities/Space_Science/Planck/...
...Planck_and_the_cosmic_microwave_background

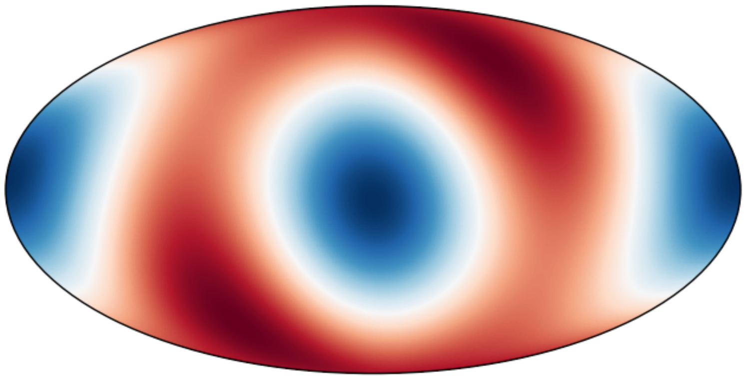


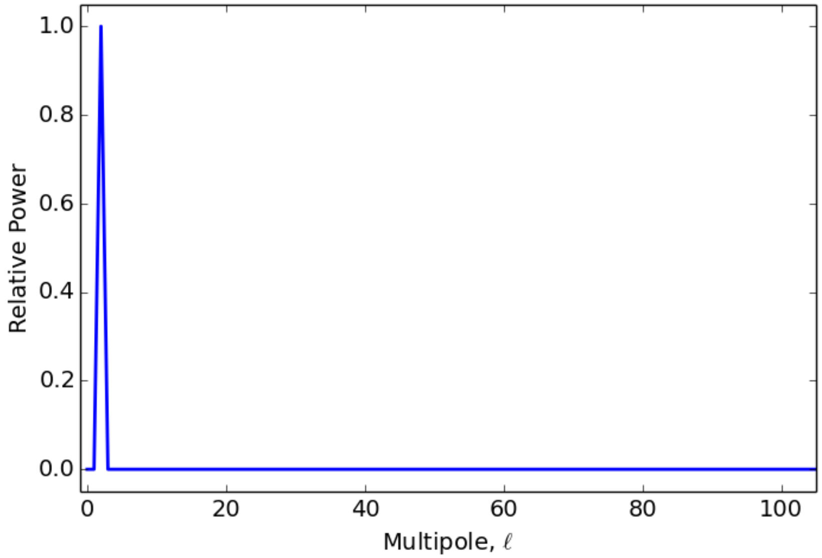


http://sci.esa.int/science-e-media/img/63/...
...Planck_power_spectrum_orig.jpg

- A power spectrum measures the amount of variations on different "scales".
- If the power spectrum is high on the left side of the plot, there's more large-scale stuff
- If the spectrum is large on the right side of the plot, there's more small-scale stuff.

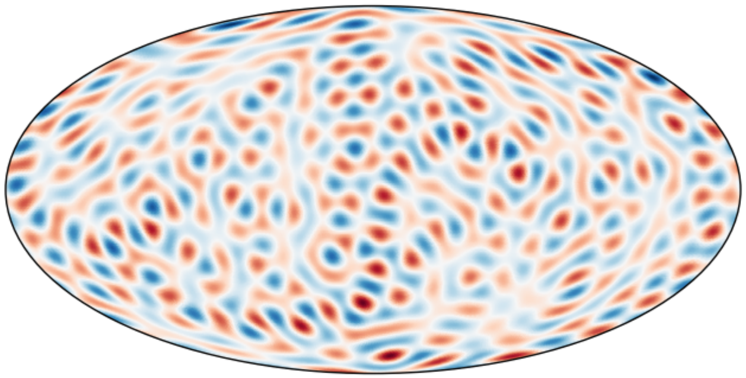
Power Spectra

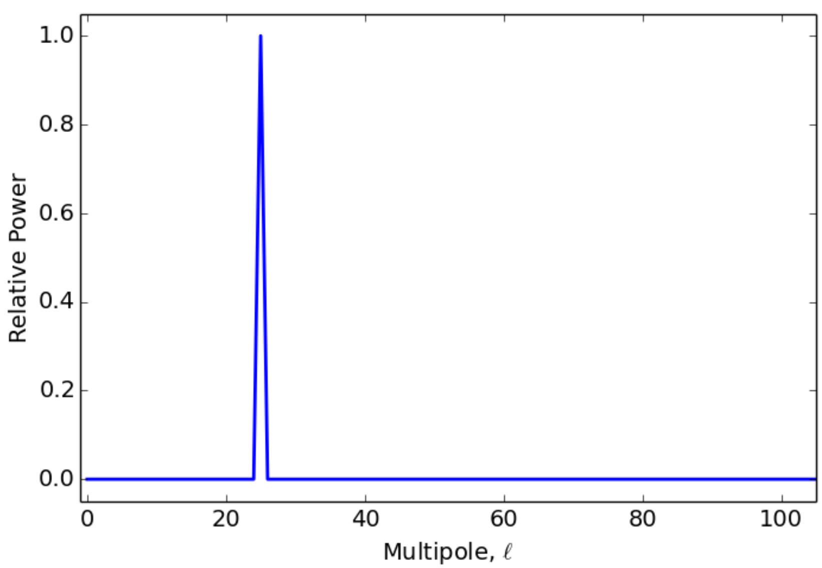




- A multipole is often denoted “ℓ”
- Small multipoles correspond to large sizes
- Large sizes correspond to small sizes.
- If you're familiar with Fourier transforms and power spectra, this is the same thing, on a sphere.

Power Spectra





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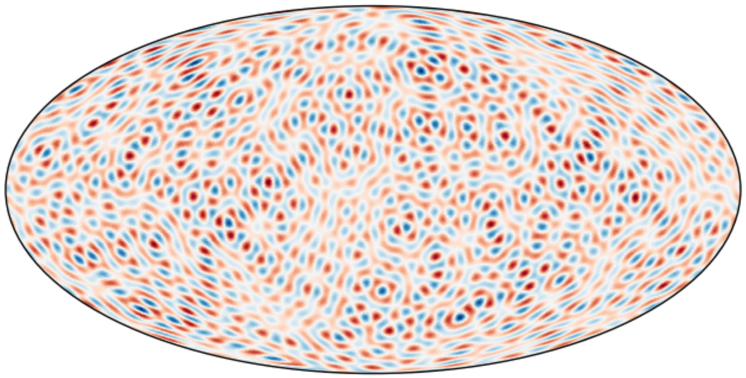

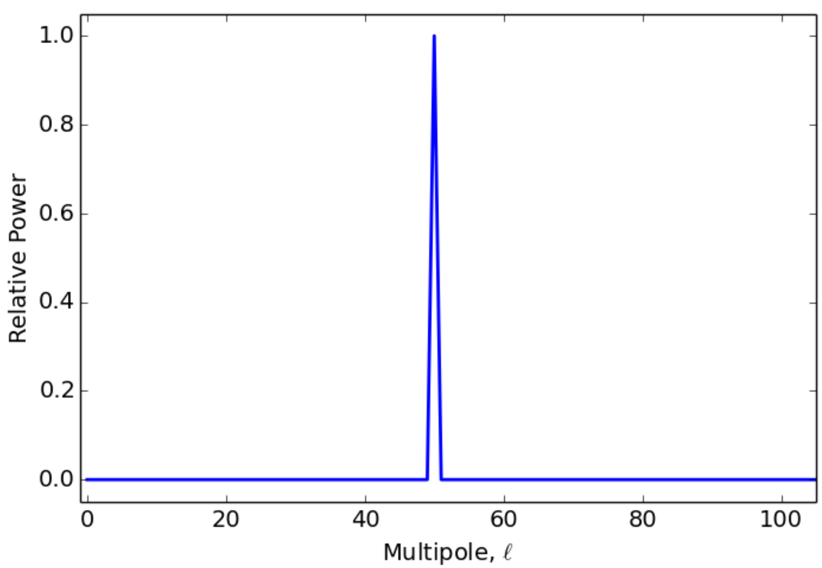

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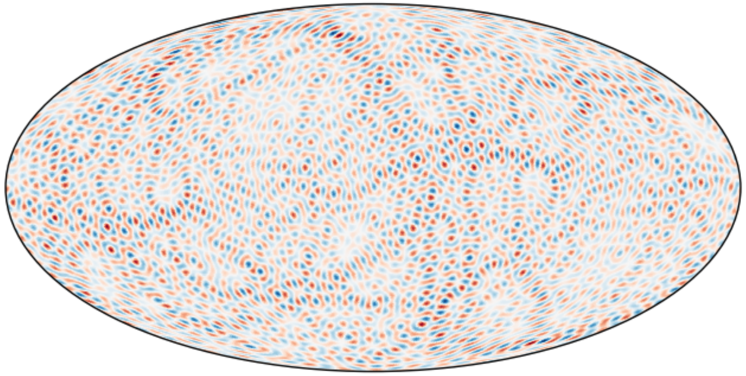

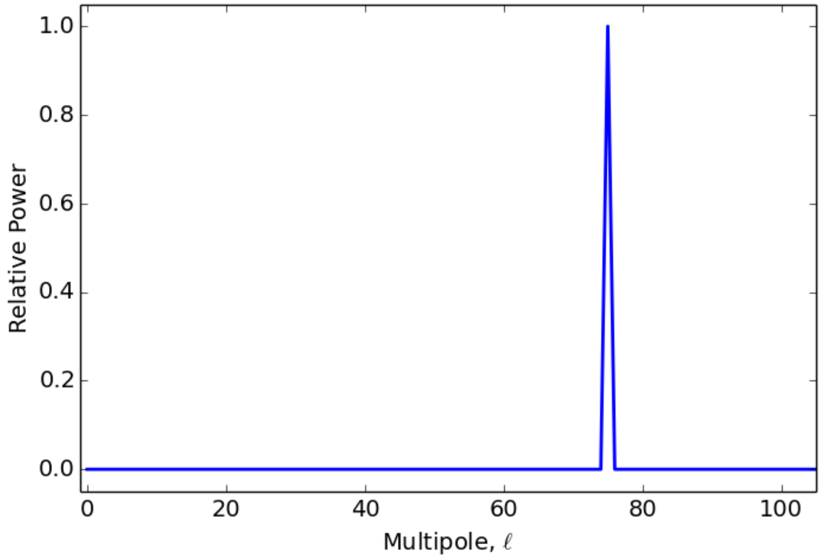

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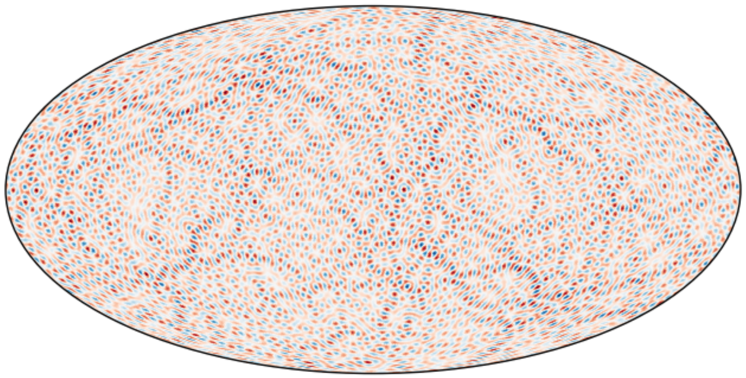

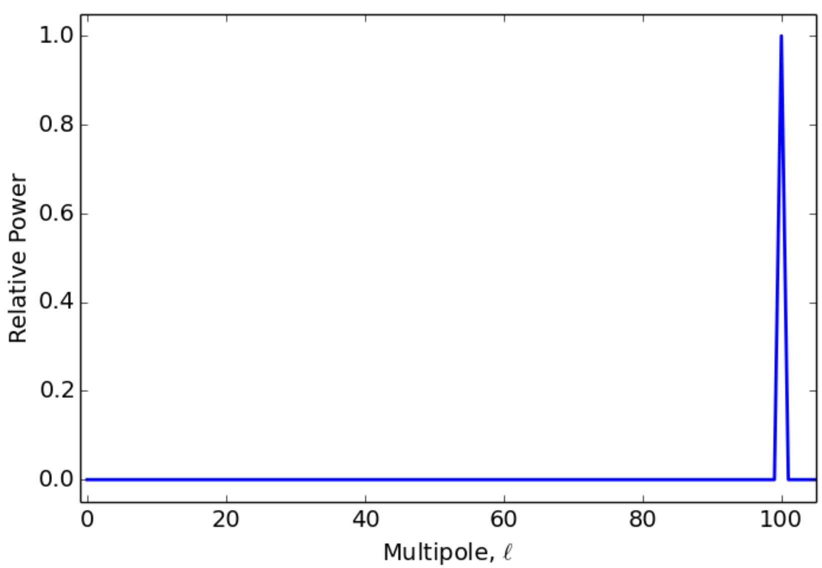

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Power Spectra

Planck Collaboration: The *Planck* mission

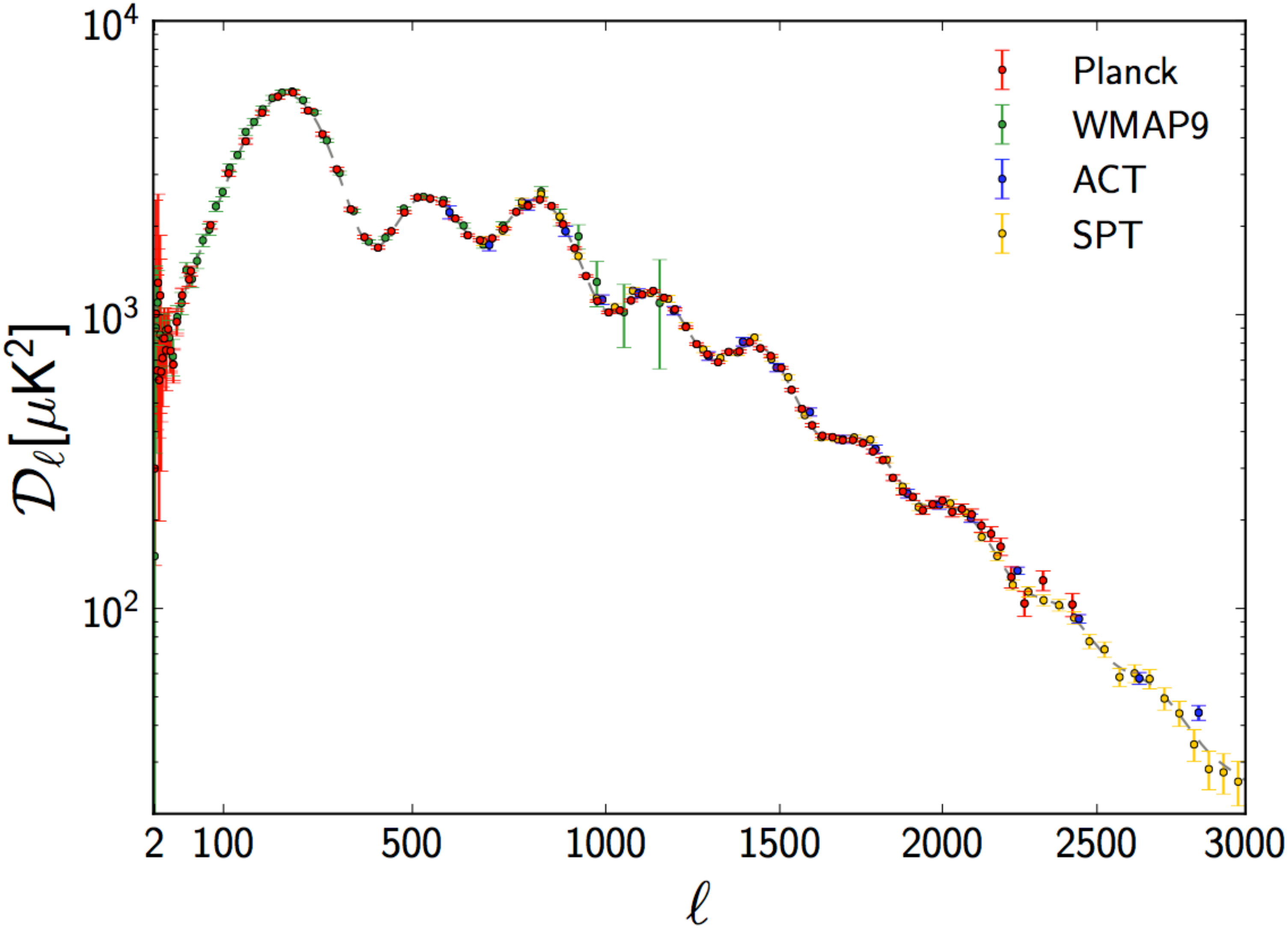
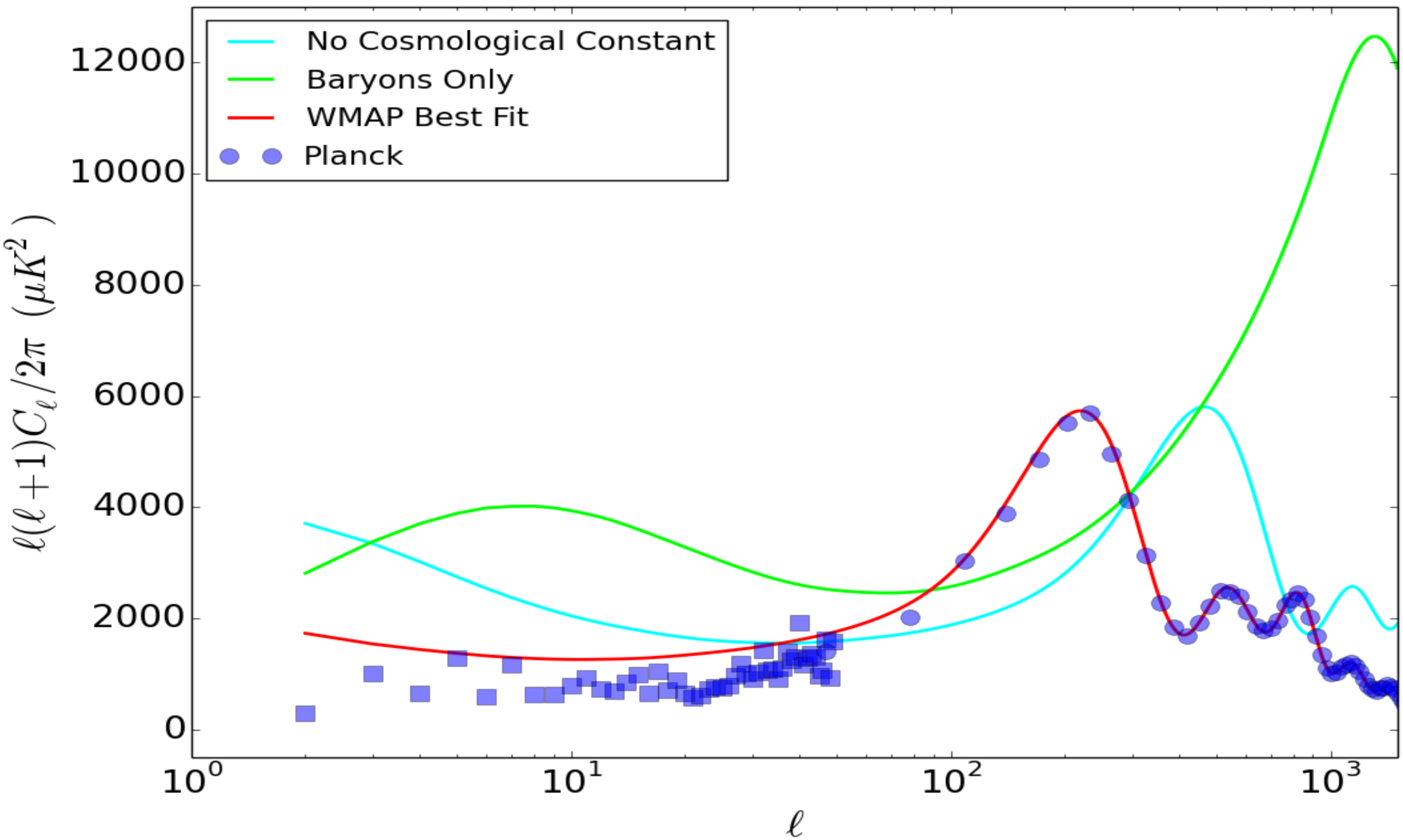


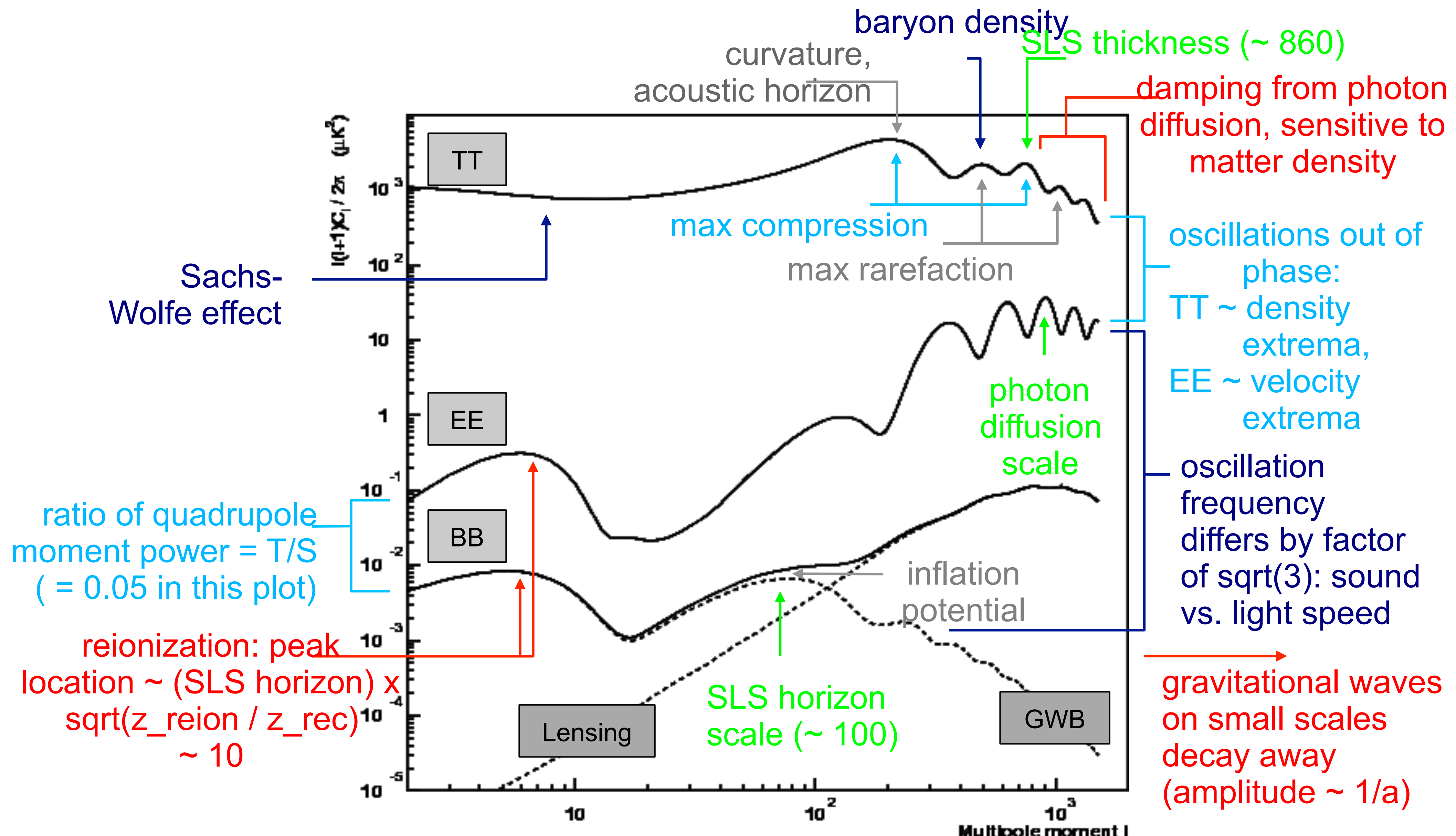
Fig. 25. Measured angular power spectra of *Planck*, WMAP9, ACT, and SPT. The model plotted is *Planck*'s best-fit model including *Planck* temperature, WMAP polarization, ACT, and SPT (the model is labelled [Planck+WP+HighL] in Planck Collaboration XVI (2013)). Error bars include cosmic variance. The horizontal axis is $\ell^{0.8}$.

Power Spectra



We use spherical power spectra to distinguish between different models and to estimate the cosmological parameters in the context of these models.

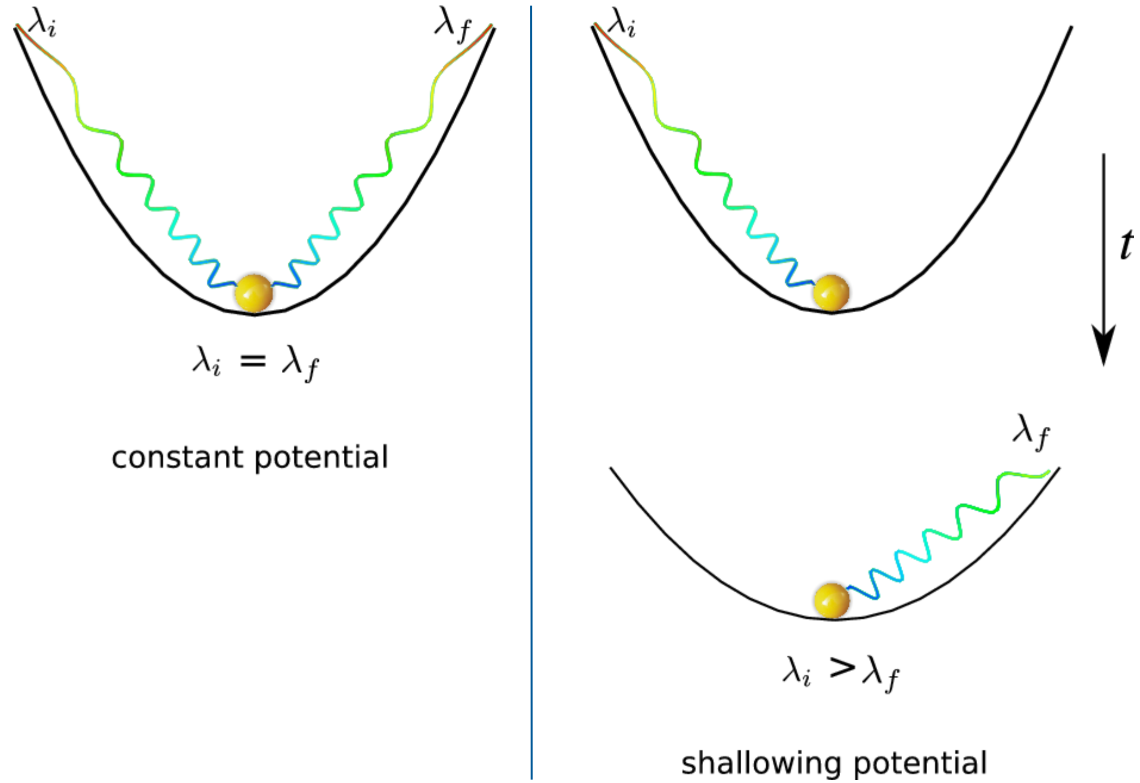
Many Different Effects Together



Cynthia Chiang

The Sachs-Wolfe Effect

Left: a photon travels through a constant potential, gaining and losing the same amount of energy while passing through the potential well.



Right: a photon travels through a shallowing potential. As the potential well from which the photon exits is shallower than the one it entered, there is an overall gain in energy. Silvestri & Trodden, Rept. Prog. Phys. 72 (2009) 096901

Degeneracies

Howlett et al. (2012);
http://arxiv.org/abs/arXiv:1201.3654

By minimizing $\chi^2_{\rm eff}$, we can find sets of parameters that give power spectra that are very close to the fiducial model. Example unlensed power spectra are shown in non-flat ΛCDM models in Fig. 1. In this case, the geometric degeneracy is within the two-dimensional space of Ω_Λ and h.

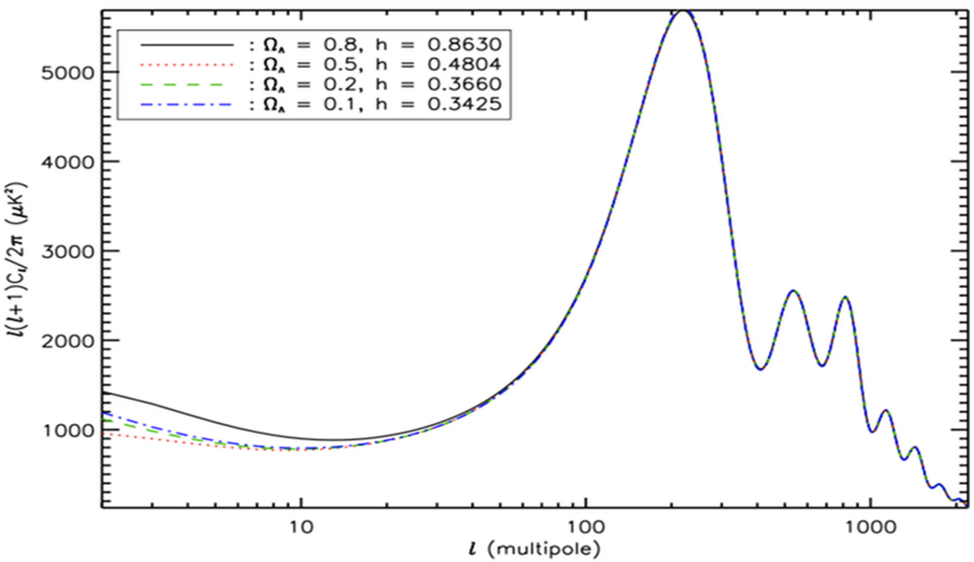


FIG. 1: CMB power spectrum obtained using CAMB for nearly degenerate geometries in non-flat ΛCDM models with no lensing (left) and the fractional differences from the fiducial-model spectrum (right). Both $\Omega_b h^2$ and $\Omega_c h^2$ were fixed to their fiducial values in all cases to preserve the pre-recombination physics. Low accuracy and values of 1 for `lSampleBoost`, `AccuracyBoost` and `lAccuracyBoost` were used for the calculations.

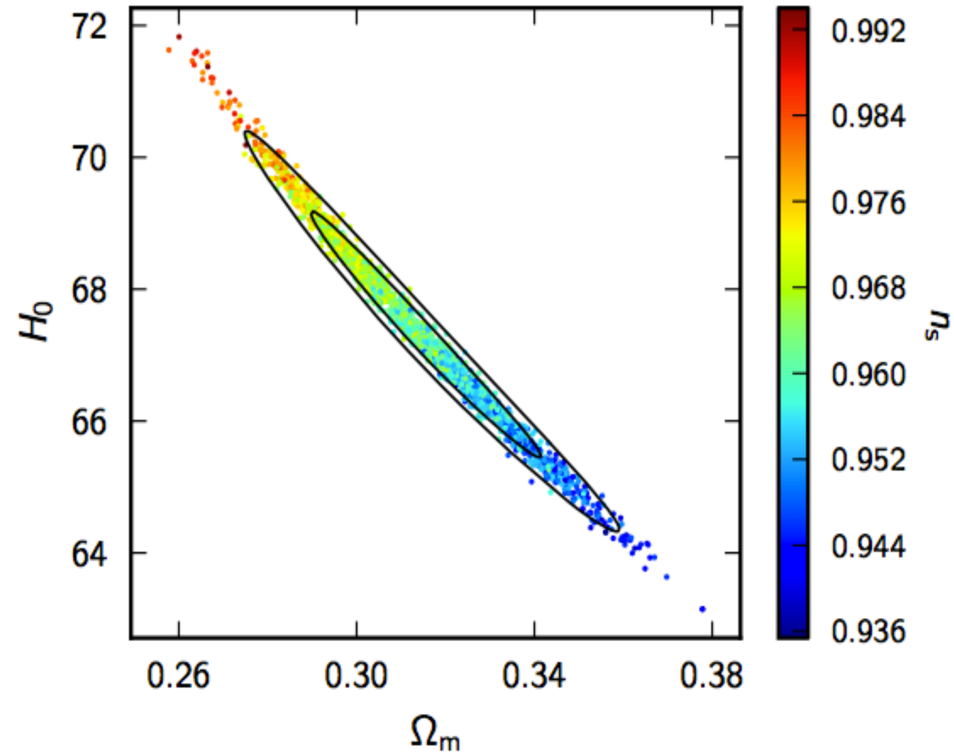
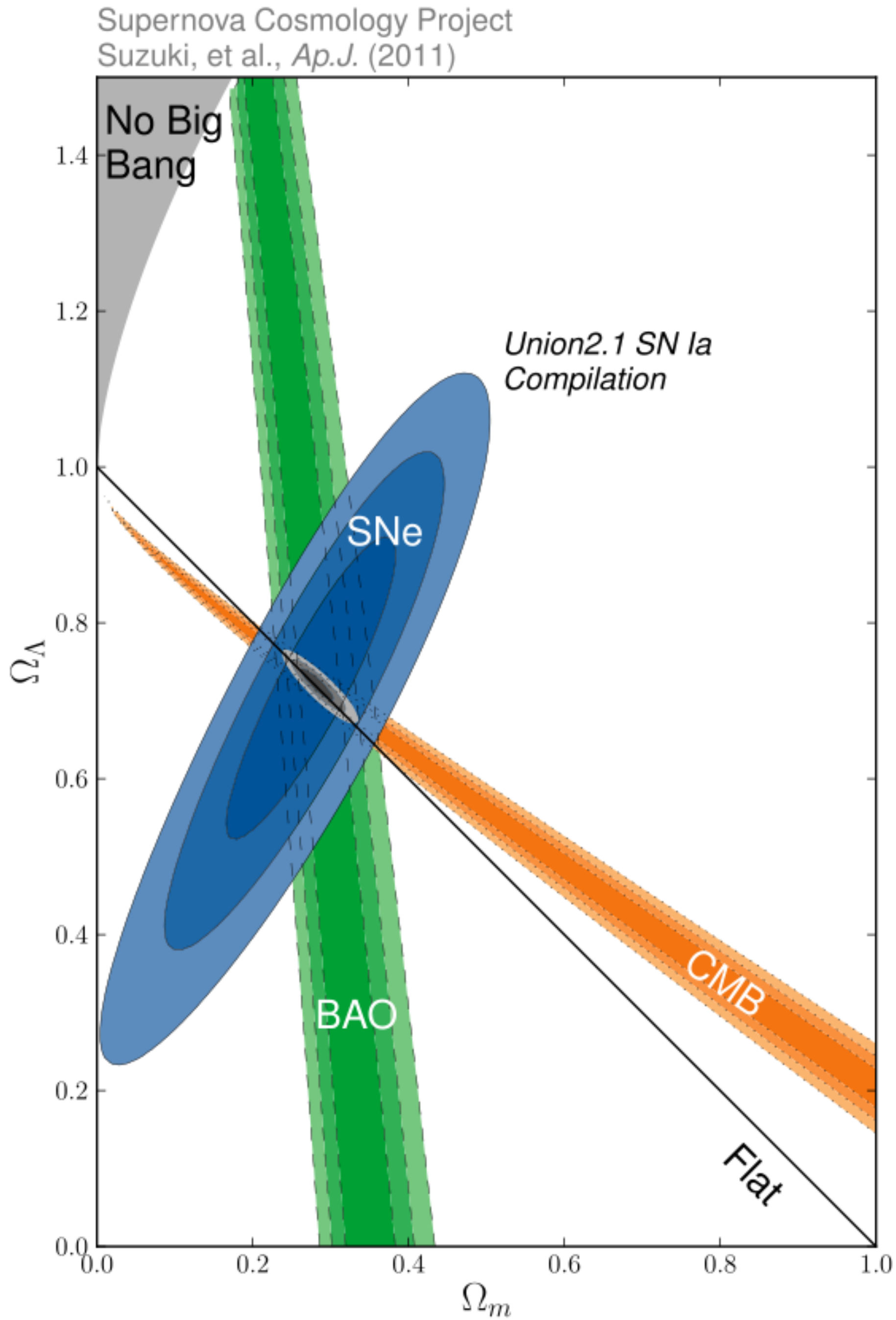


Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including WP, but the well-constrained direction of constant $\Omega_m h^3$ (set by the acoustic scale), is determined almost equally accurately from *Planck* alone.

Different sets of cosmological parameters can give us the same power spectrum (to within the error bars)

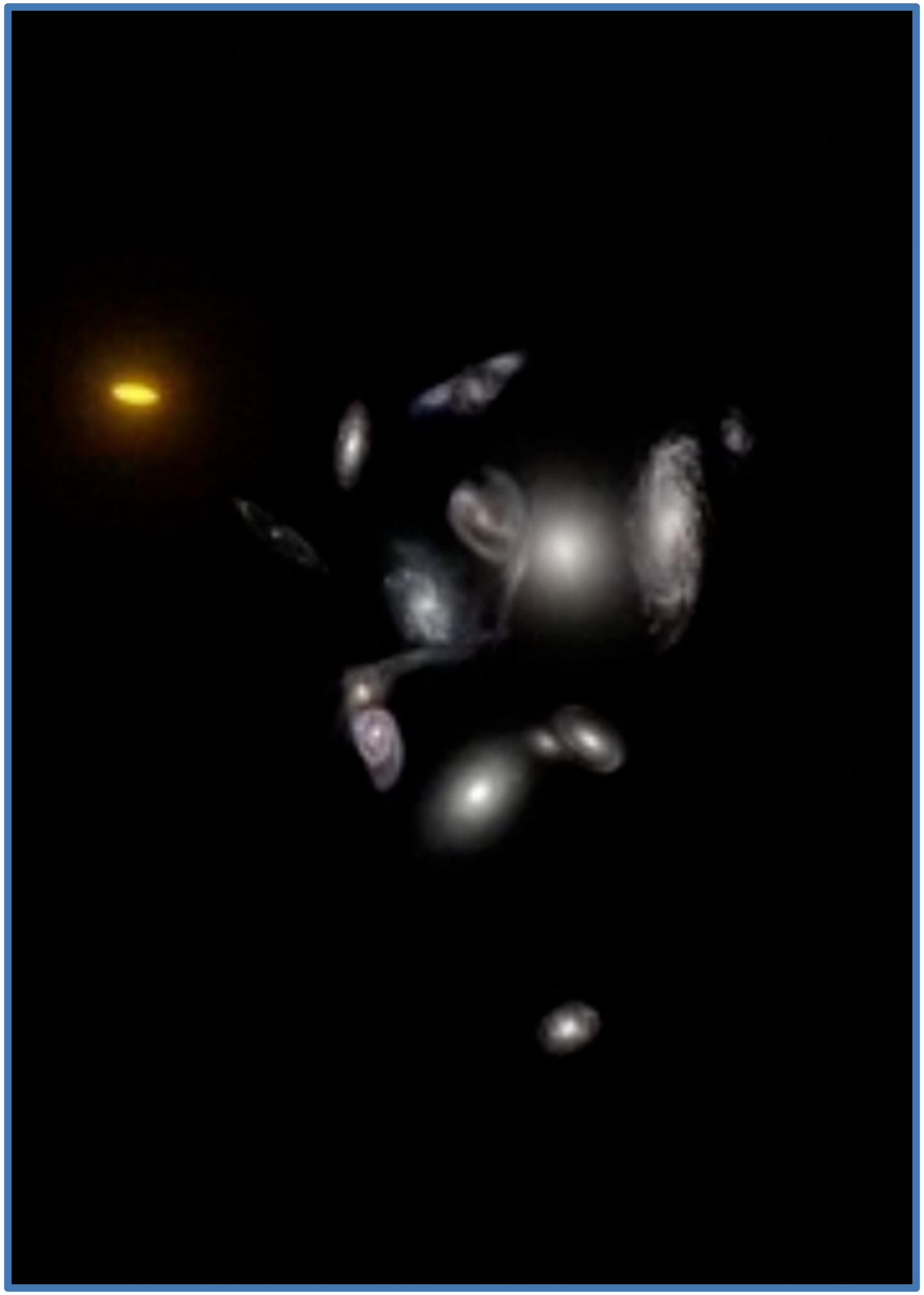
Matter, Dark Matter & Dark Energy



The CMB has helped consolidate dark matter and dark energy as real (though other probes sometimes provide somewhat more direct glimpses of their existence)

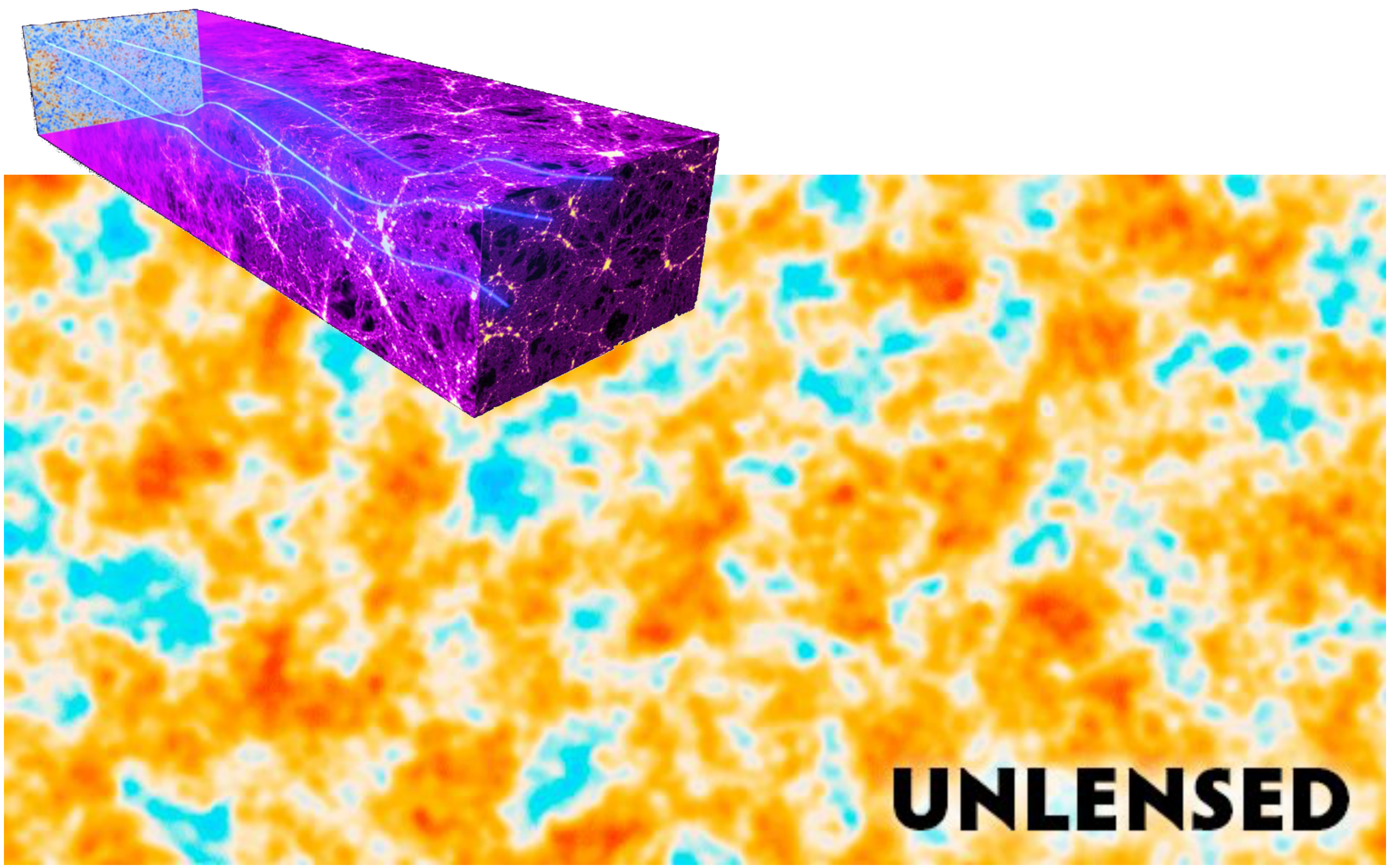
“Secondary” Effects on the CMB

Along the way to us, a number of “secondary” effects “tweak” the CMB – redshift, the Sunyaev-Zeldovich effect, the Sachs-Wolf effect, gravitational lensing, and others...



Gravitational Lensing

- Mass between the last scattering surface and us lenses the CMB
- We use the deflections to infer the effective potential seen by the CMB



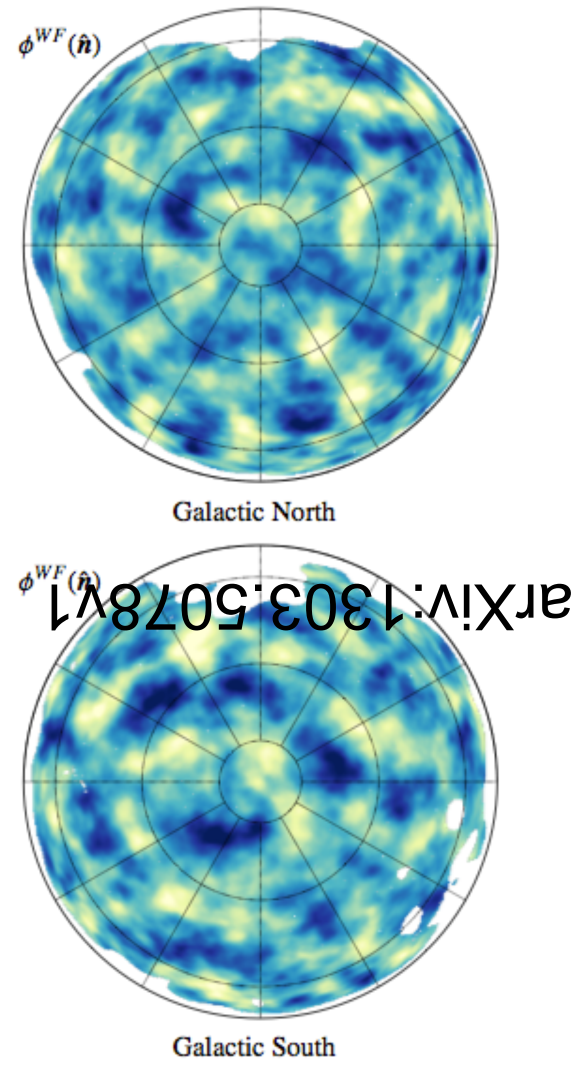


Fig. 8. Wiener-filtered lensing potential estimate $\phi^{WF}_{LM} \equiv C_L^{\phi\phi}(\bar{\phi}_{LM} - \bar{\phi}^{MF}_{LM})$ for our MV reconstruction, in Galactic coordinates using orthographic projection. The reconstruction is bandpass filtered to $L \in [10, 2048]$. The *Planck* lens reconstruction has $S/N \leq 1$ for individual modes on all scales, so this map is noise dominated. Comparison between simulations of reconstructed and input ϕ in Fig. 4 show the expected level of visible correlation between our reconstruction and the true lensing potential.

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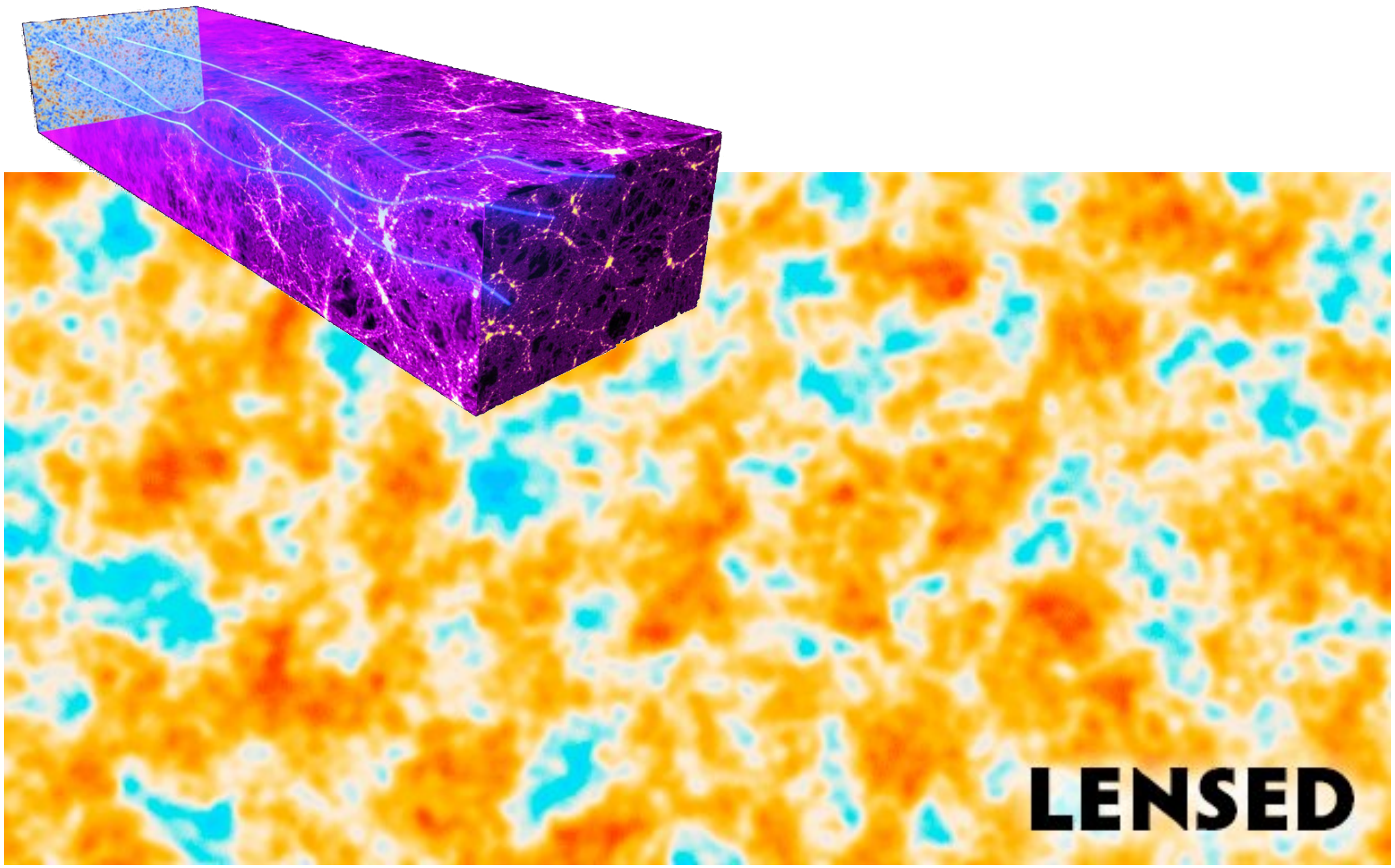

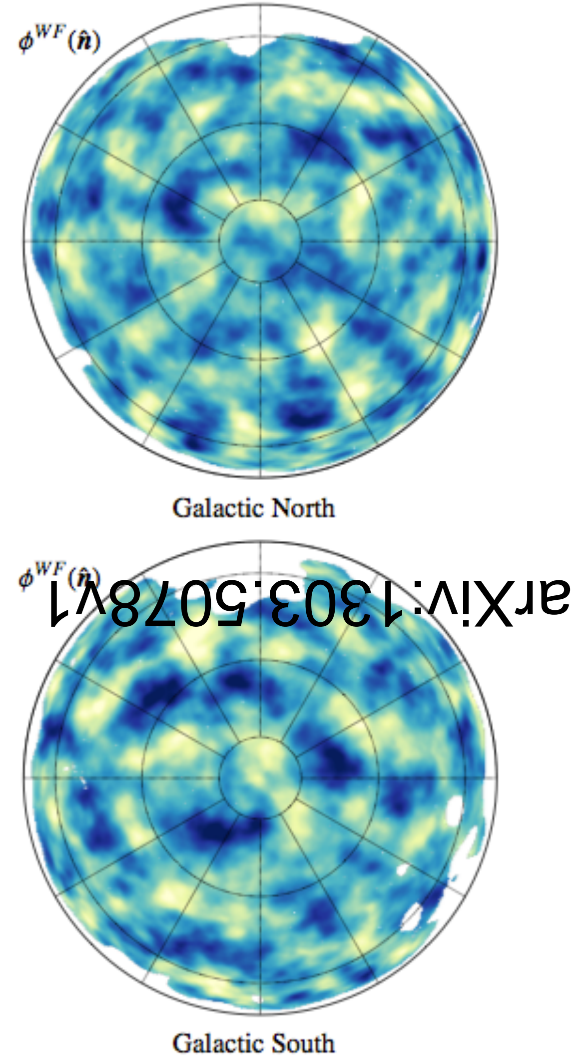

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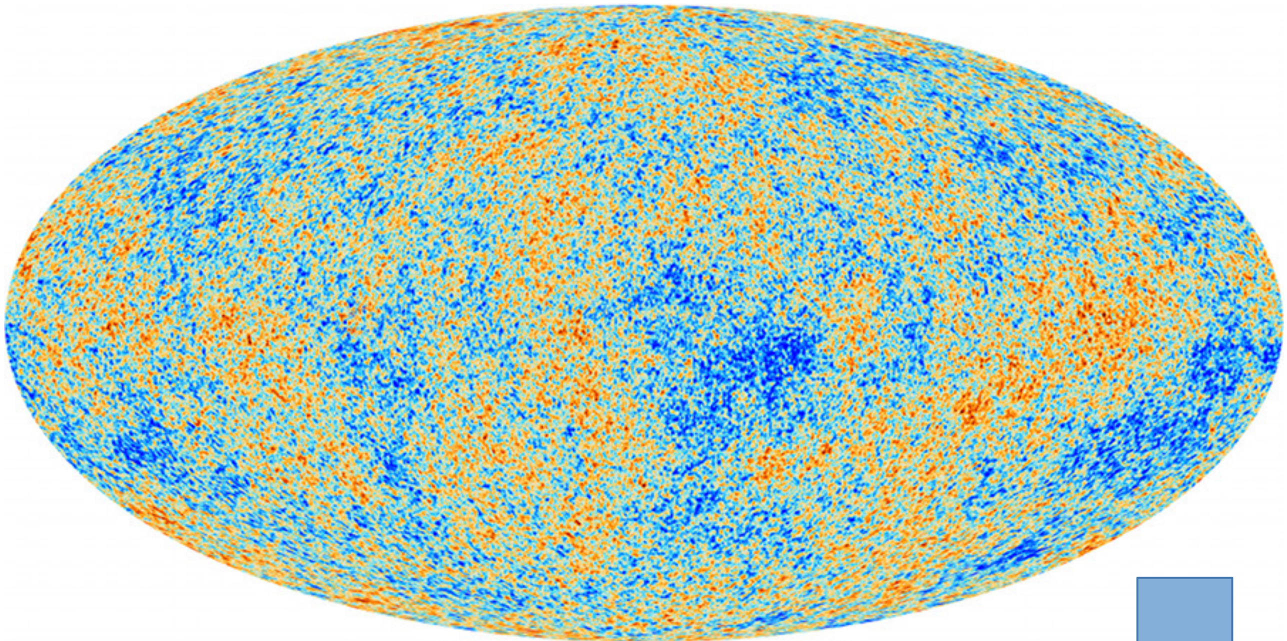
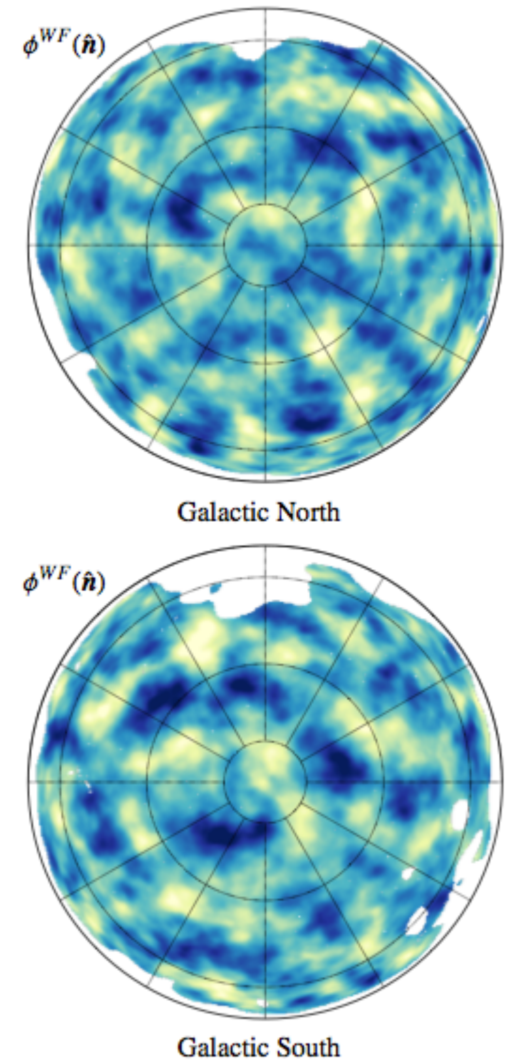
From CMB to Lensing Maps



We can use the non-Gaussianity induced by lensing to reconstruct the integrated gravitational potential a photon sees along its journey.



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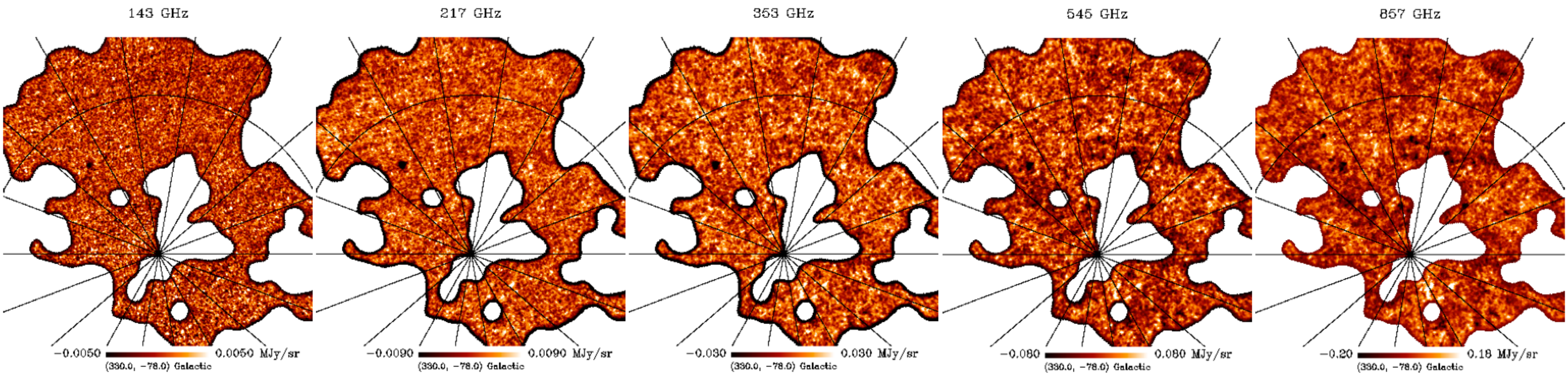
Cosmic Infrared Background

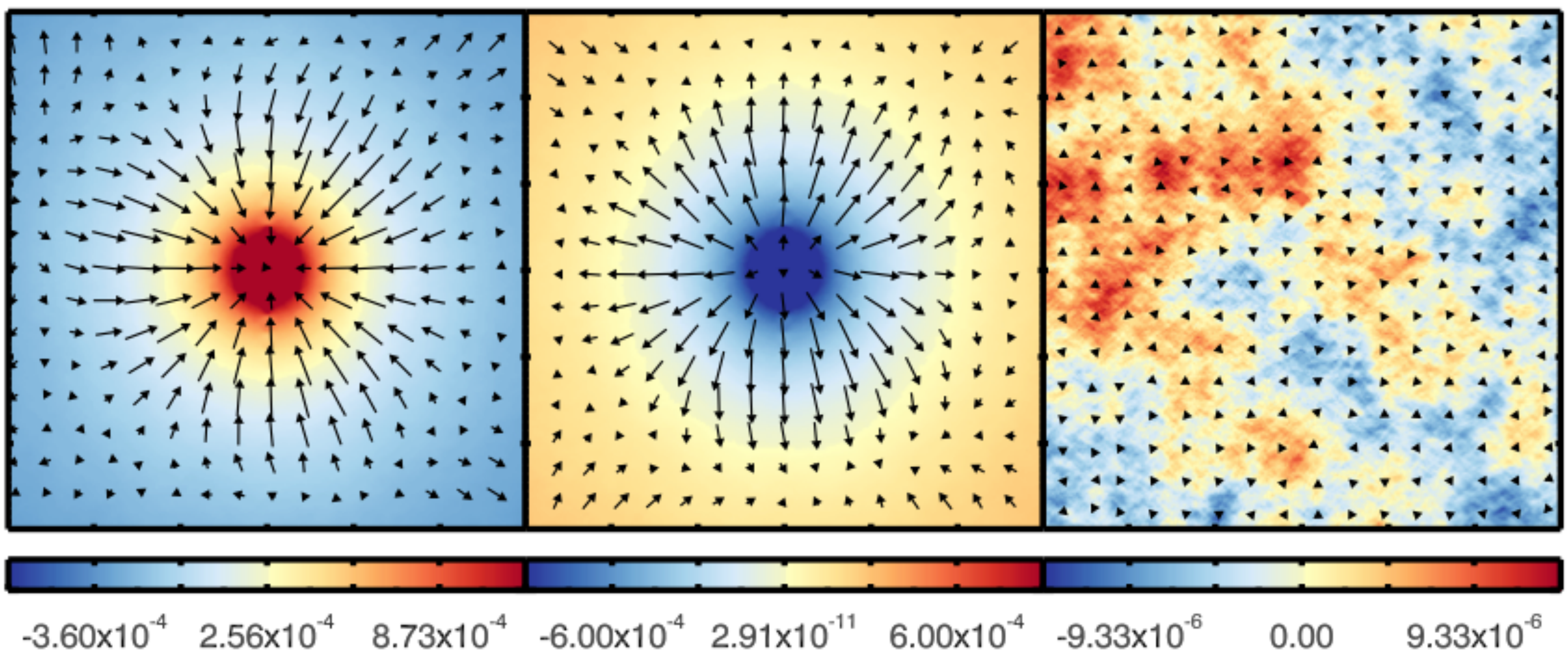


- Dominates the extragalactic sky in the higher Planck frequencies
- Has a spectrum similar to Galactic dust
- Tracer of star formation, much of it around z~2.
- Represents material at higher redshifts than many catalogs
- arXiv:1309.0382v1

CIB × Lensing Potential

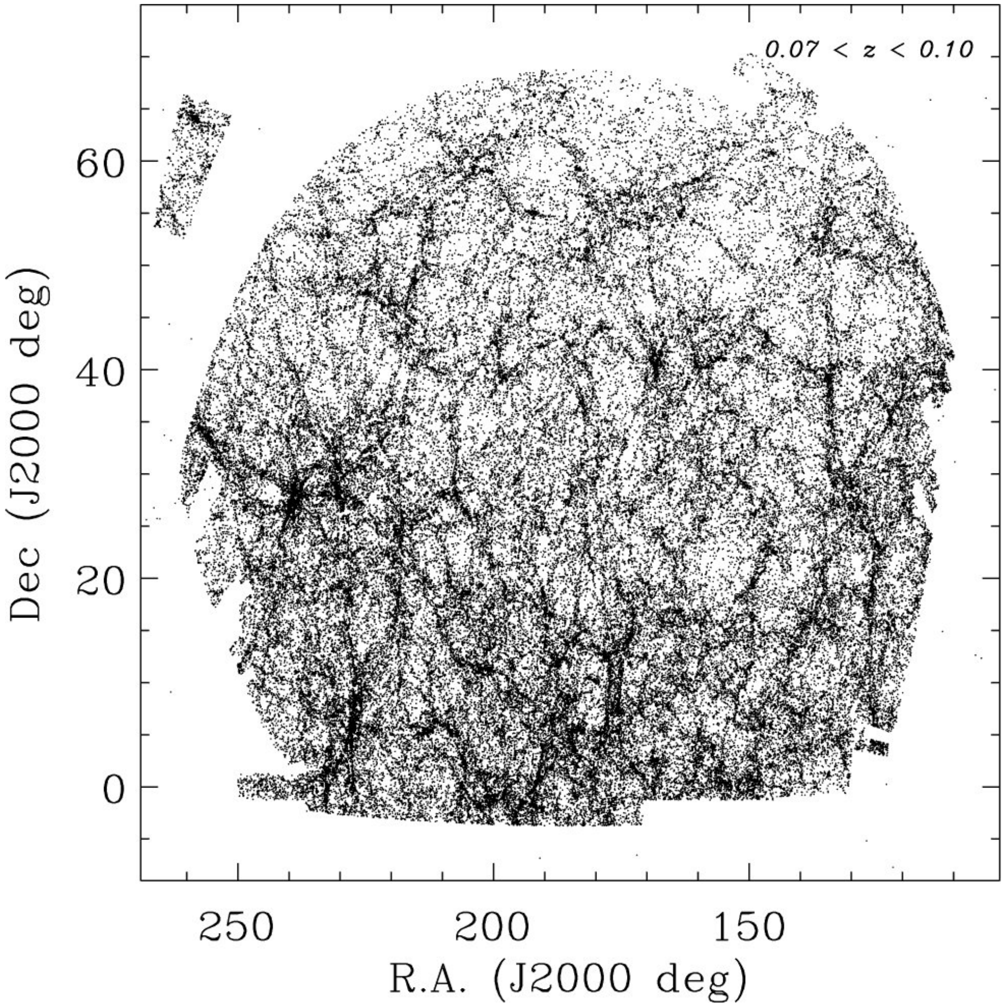
- The CIB is the remnant of star formation, much around z~2
- This material lenses the CMB
- A cross-correlation shows this:
- Correlations can also be done with your favorite catalog of sources, or other tracers of mass

545 GHz × Φ



ArXiv: 1303.5078v1

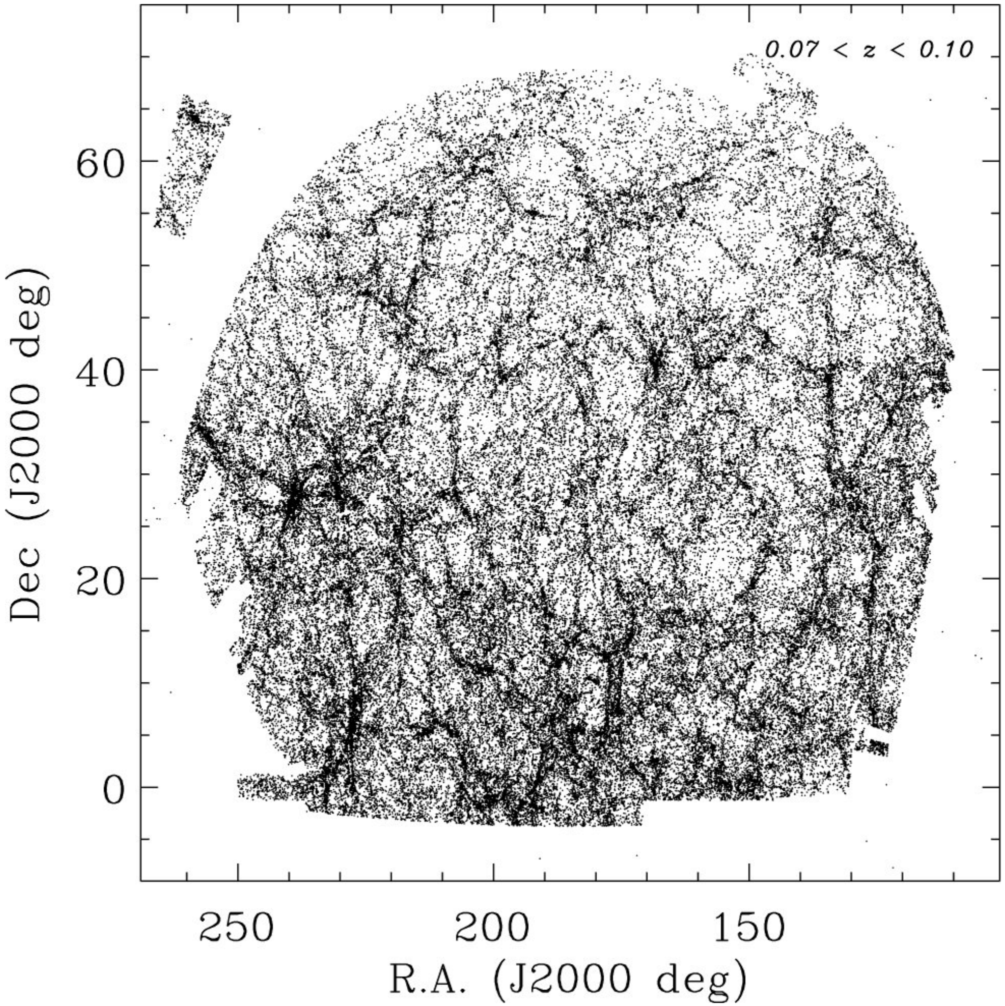
Late Integrated Sachs-Wolfe Effect



NYU-VAGC: http://sdss.physics.nyu.edu/vagc/

Large-Scale surveys trace matter. The Sachs-Wolfe effect comes from matter. There should be a correlation.

Late Integrated Sachs-Wolfe Effect



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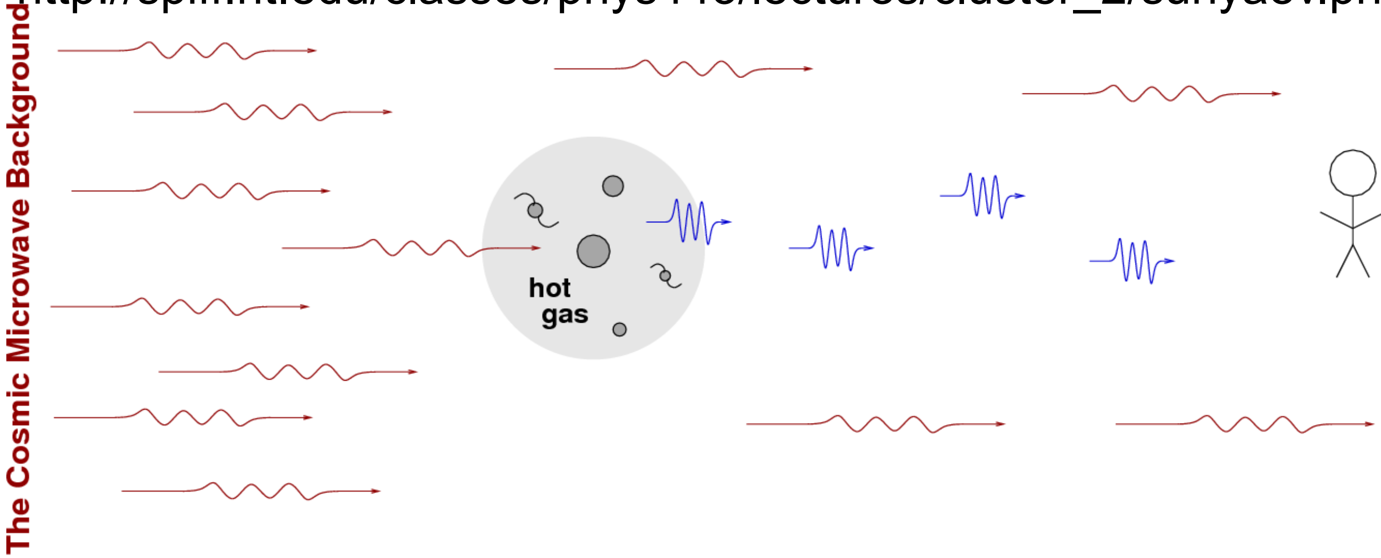
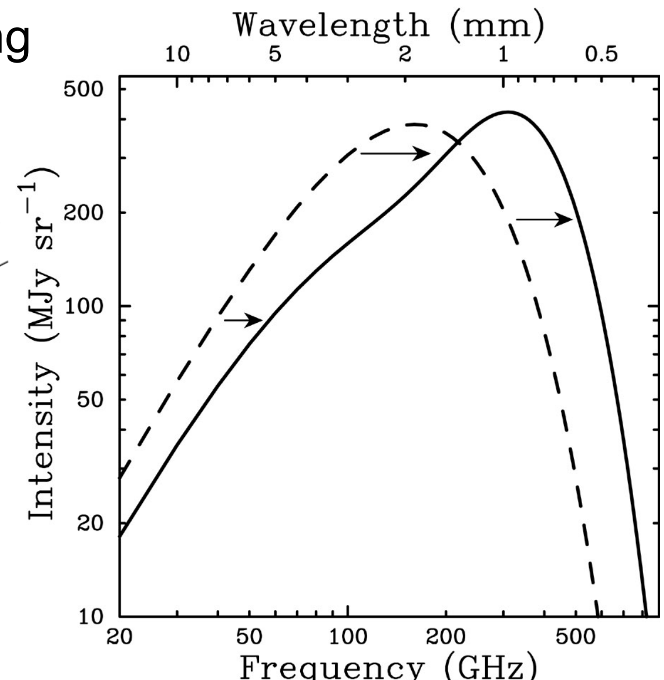
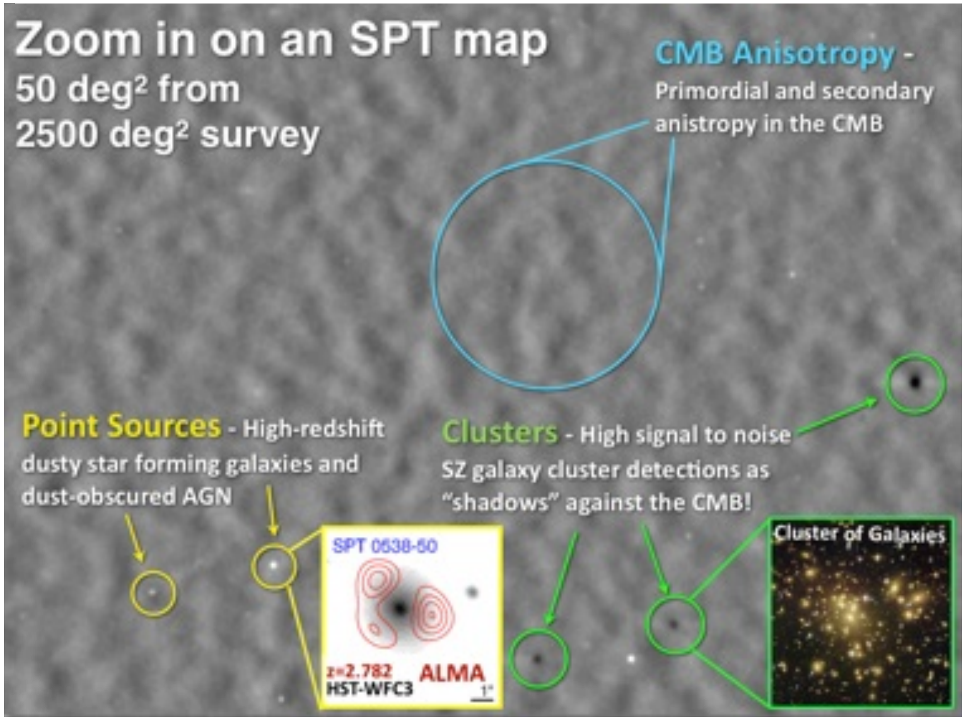
Jackson Pollock-http://www.moma.org/collection_images/resized/805/w500h420/CRI_223805.jpg

The Sunyaev-Zeldovich Effect

http://spiff.rit.edu/classes/phys443/lectures/cluster_2/sunyaev.png







Galaxy Clusters are the largest known gravitationally bound structures in the Universe. Comparing the SZ effect and the CMB teaches about cosmology and clusters

Neutrinos

Massive neutrinos change large-scale anisotropies in the CMB through the early integrated Sachs-Wolfe effect. Most limits on neutrino masses to this point have used this effect.

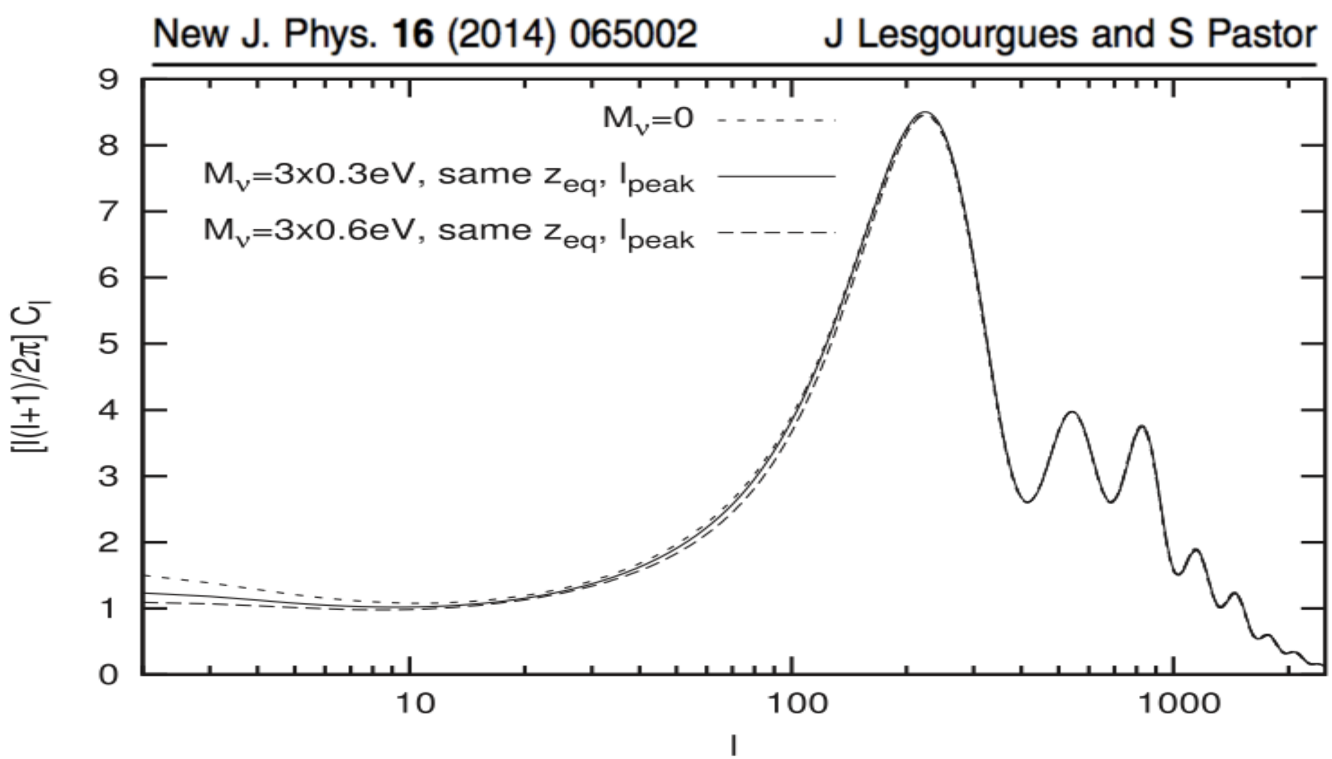


Figure 4. CMB temperature spectrum with different neutrino masses. Some of the parameters of the Λ MDM model have been varied together with M_ν in order to keep fixed the redshift of equality and the angular diameter distance to last scattering.

Neutrinos

In addition to the Early Sachs-Wolfe Effect, neutrinos change "small"-scale structure through free-streaming, which is visible through weak gravitational lensing

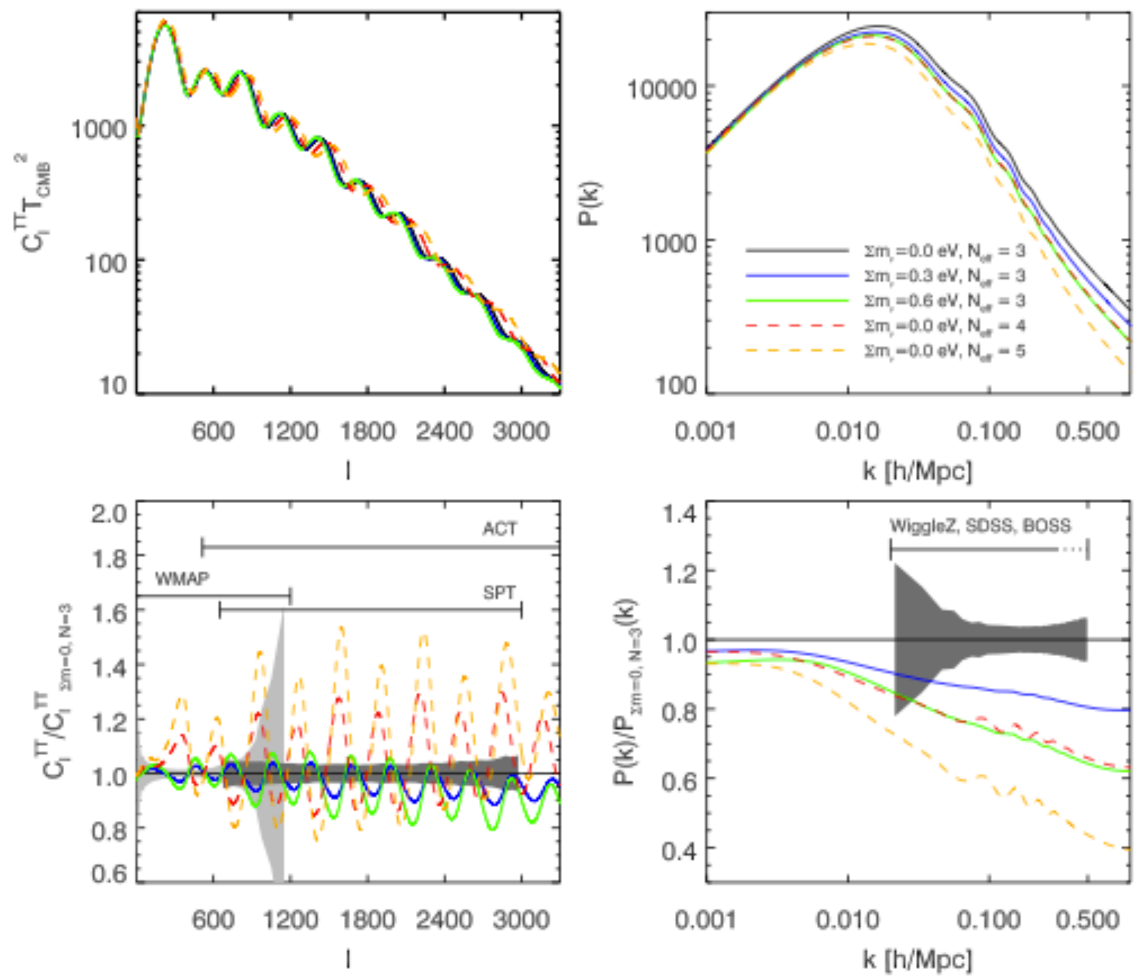
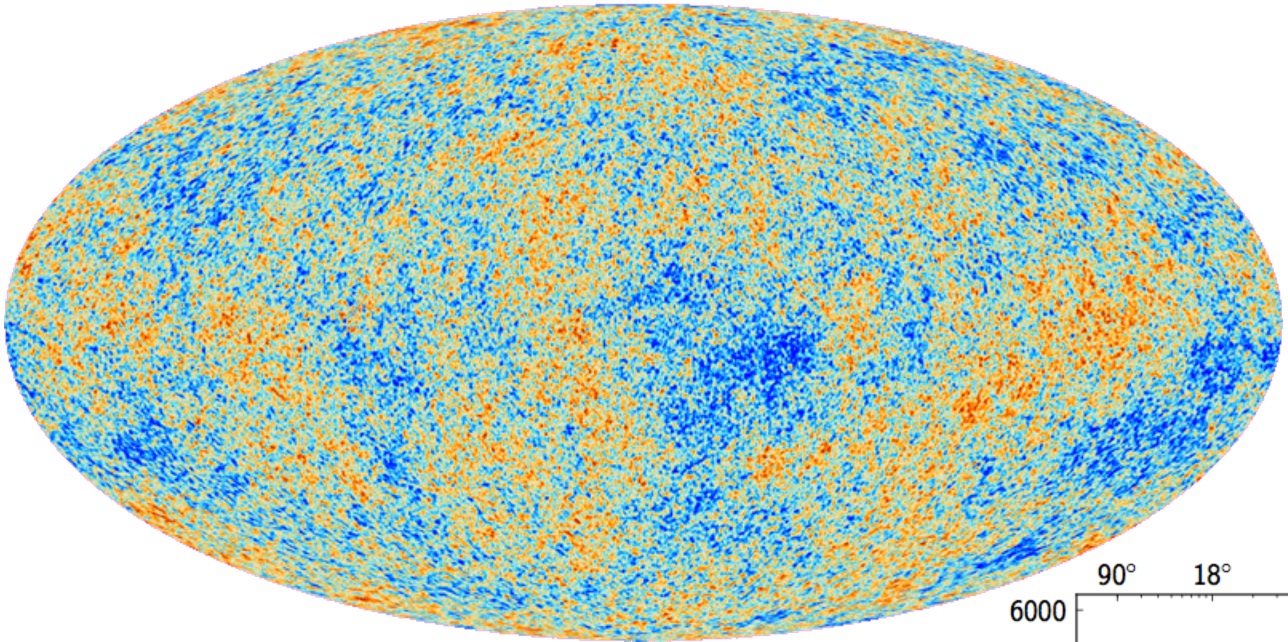


Figure 3: Illustration of the CMB (left) and matter (right) power spectra for a fiducial cosmology and how they change for varying neutrino mass (solid lines, we vary $f_\nu = \Omega_\nu/\Omega_m = \sum m_\nu/(93.14\ \mathrm{eV}\Omega_m h^2)$), and effective number of neutrinos (dashed lines) fixing all other parameters. The bottom two plots show the ratio of the power spectra when varying $\sum m_\nu$ and $N_{\rm eff}$ relative to $\sum m_\nu$=0 eV, $N_{\rm eff}$=0. $\sum m_\nu$ does not affect the CMB power spectrum much, but changes the matter power spectrum. The effect of $N_{\rm eff}$ is clearly visible for small scales (high values of l) in the CMB power spectrum, and the two parameters are clearly degenerate for the matter power spectrum unless the peak position is very precisely measured. The horizontal lines indicate the coverage by current and near future experiments, and the shaded areas indicates the relative magnitude of the uncertainties for WMAP (light grey) and SPT (dark grey) in the CMB plot, and WiggleZ (dark grey) for galaxy surveys.

Anomalies



- Alignments
- Hemispheric Anomaly
- Parity Anomaly
- Large Scale Decrement
- Seen by WMAP too

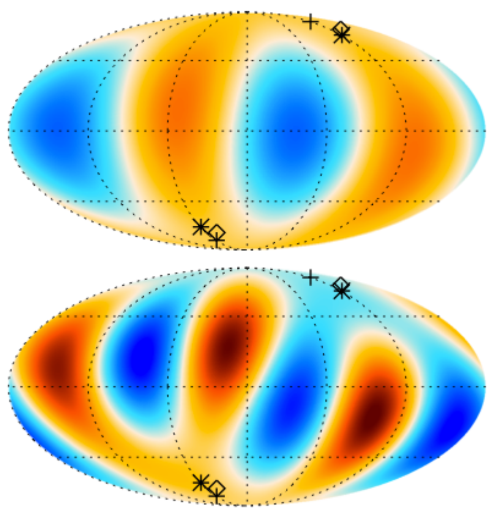


Fig. 17. *Upper*: Wiener-filtered SMICA CMB sky (temperature range ± 400 μK). *Middle*: derived quadrupole (temperature range ± 35 μK). *Lower*: derived octopole (temperature range ± 35 μK). The plus and star symbols indicate the axes of the quadrupole and octopole, respectively, around which the angular momentum dispersion is maximized. The diamond symbols correspond to the quadrupole axes after correction for the kinematic quadrupole.

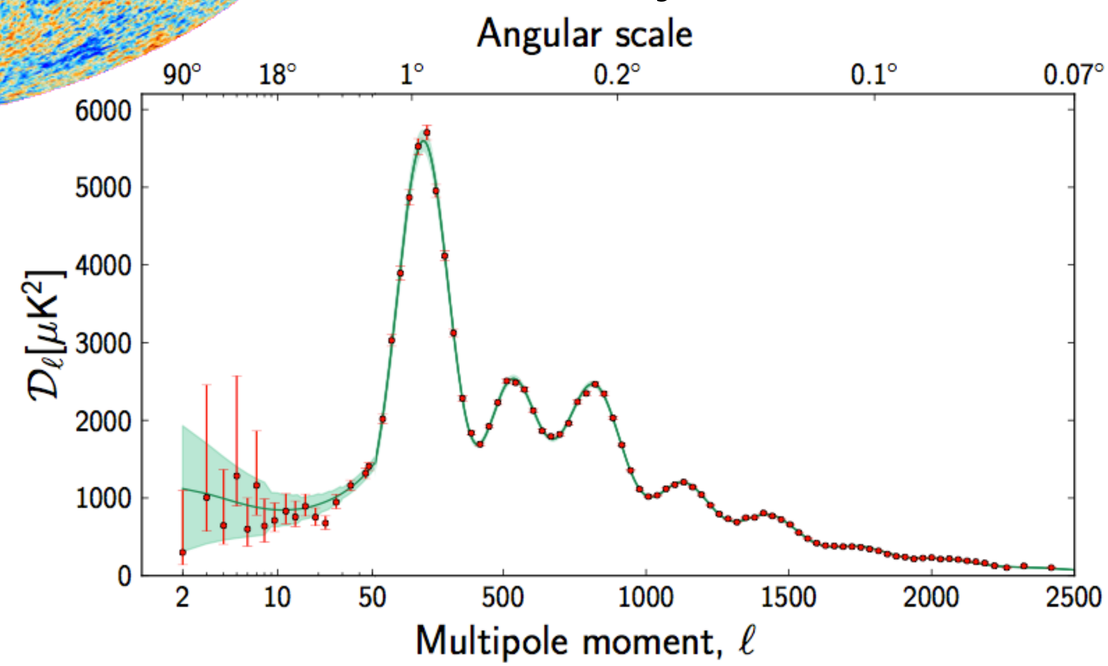
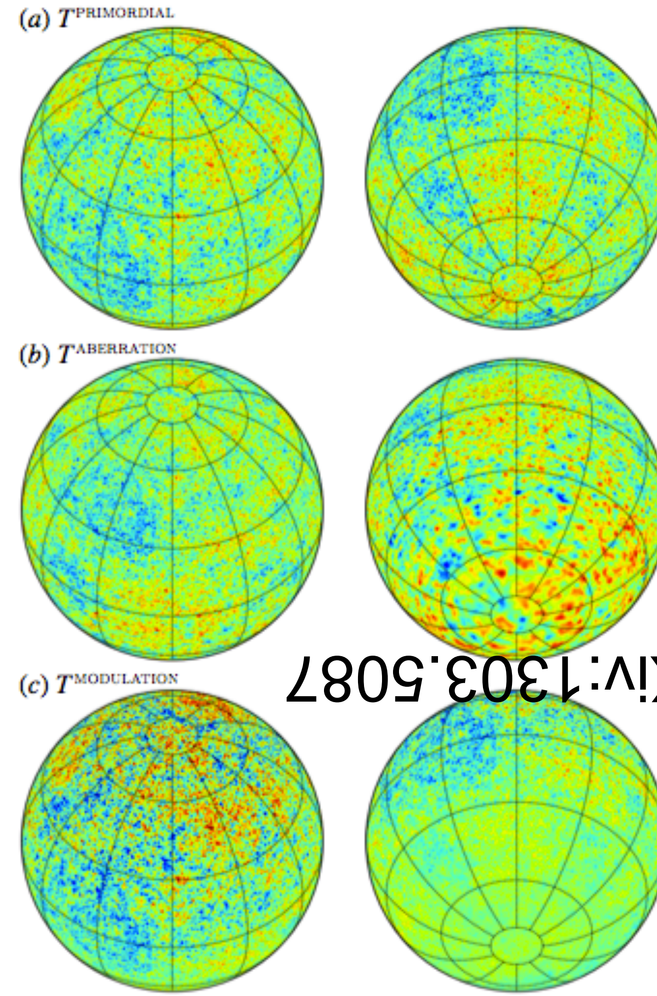


Fig. 20. Temperature angular power spectrum of the primary CMB from *Planck*, showing a precise measurement of seven acoustic peaks that are well- fitted by a six-parameter ΛCDM model (the model plotted is the one labelled [Planck+WP+highL] in Planck Collaboration XVI 2014). The shaded area around the best-fit curve represents cosmic/sample variance, including the sky cut used. The error bars on individual points also include cosmic variance. The horizontal axis is logarithmic up to $\ell = 50$, and linear beyond. The vertical scale is $\ell(\ell+1)C_l/2\pi$. The measured spectrum shown here is exactly the same as the one shown in Fig. 1 of Planck Collaboration XVI (2014), but it has been rebinned to show better the low-ℓ region.

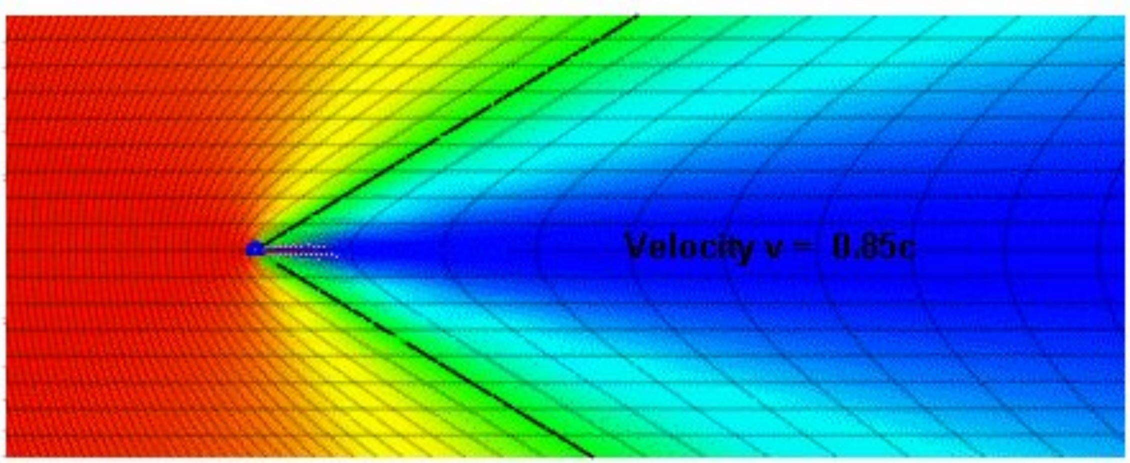
Higher-Order Doppler Effects

- "Dipole" is now a bit of a misnomer, as higher-order relativistic Doppler effects have been detected by Planck (and are mixed up with the so-called "anomalies")



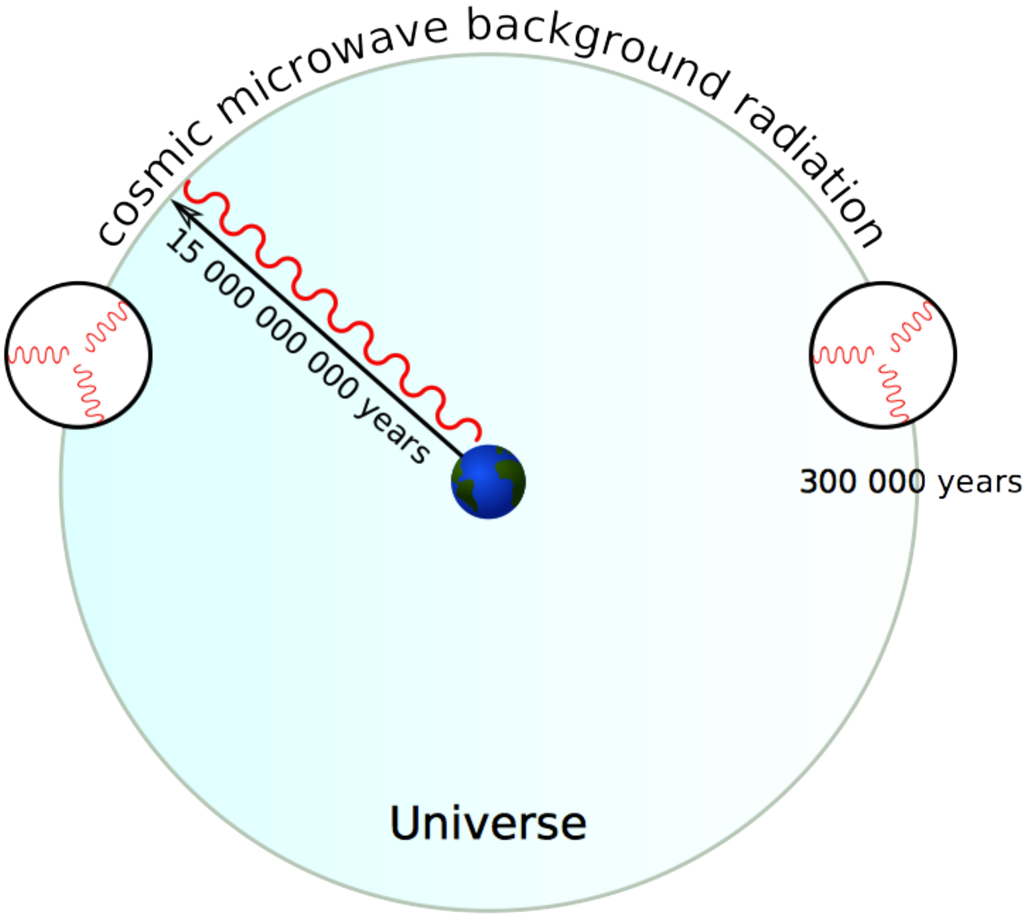
arXiv:1303.5087

Fig. 1. Exaggerated illustration of the Doppler aberration and modulation effects, in orthographic projection, for a velocity $v = 260\,000\,\mathrm{km\,s^{-1}} = 0.85c$ (approximately 700 times larger than the expected magnitude) toward the northern pole (indicated by meridians in the upper half of each image on the left). The aberration component of the effect shifts the apparent position of fluctuations toward the velocity direction, while the modulation component enhances the fluctuations in the velocity direction and suppresses them in the anti-velocity direction.



http://en.wikipedia.org/wiki/File:XYCoordinates.gif

The Horizon Problem



http://upload.wikimedia.org/wikipedia/…
…/commons/c/ce/Horizon_problem.svg

There are also “flatness” and “monopole” problems

Look left; the CMB photons reaching you come from the opposite end of the Universe as those coming from the right – they have never interacted, ever.

So why are they at the same temperature?

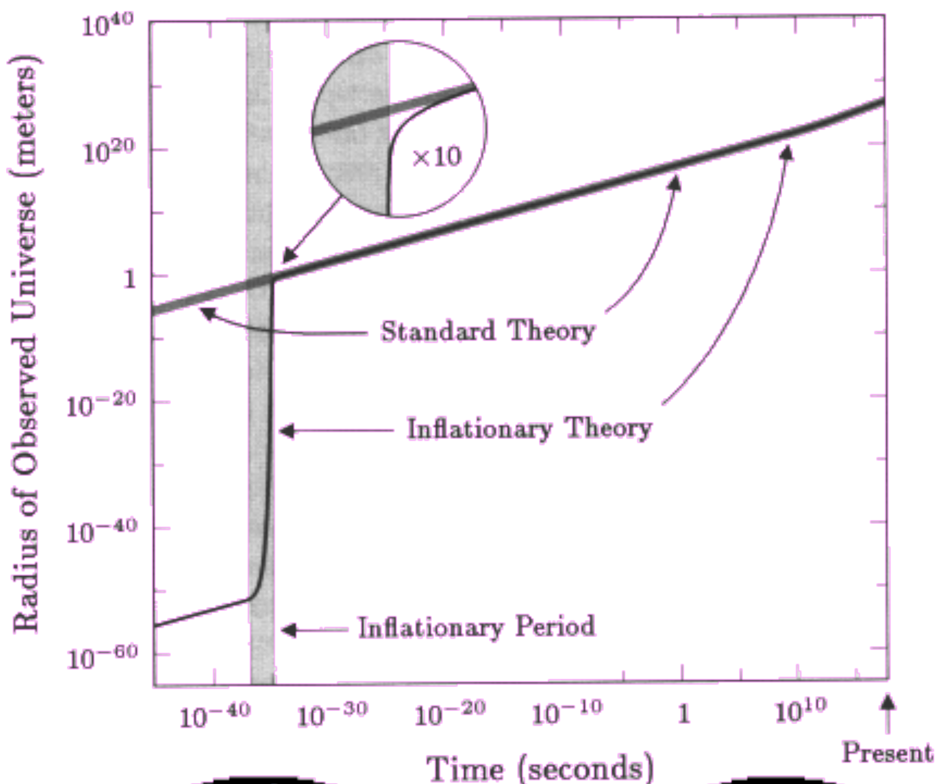
These issues led to the development of Inflation

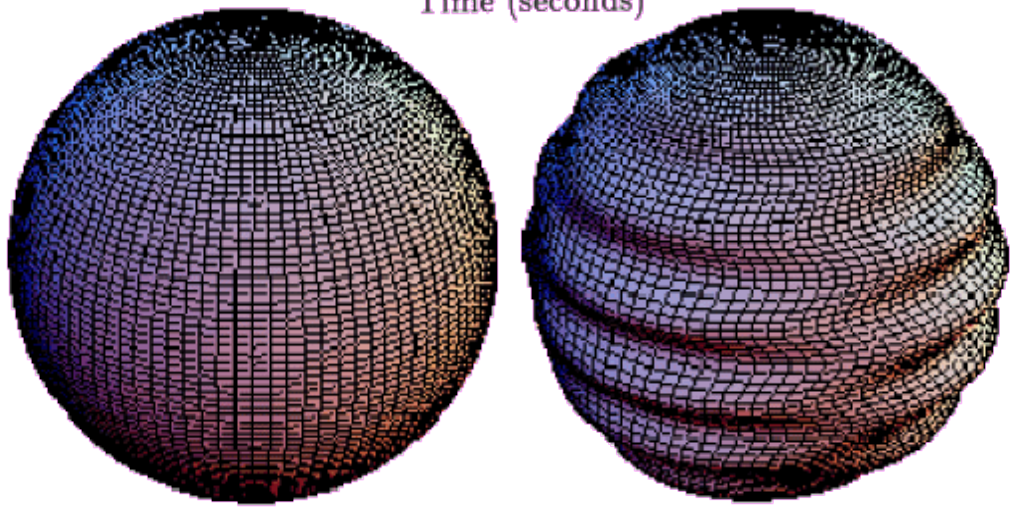
Inflation

Period of *very* fast expansion

Solves monopole, flatness and horizon problems

Implies gravitational waves, but they may be vanishingly small.

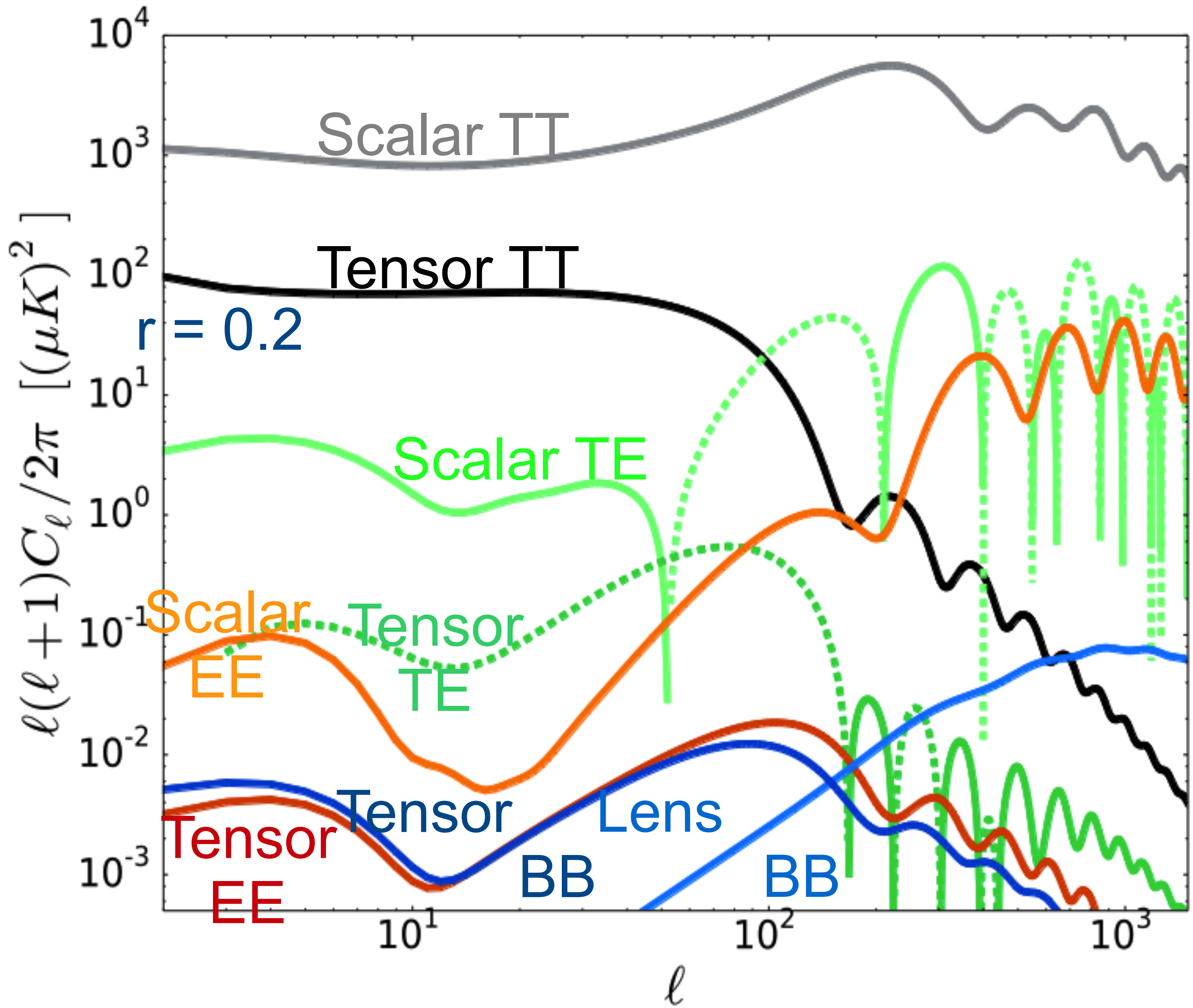




Spectra Zoo

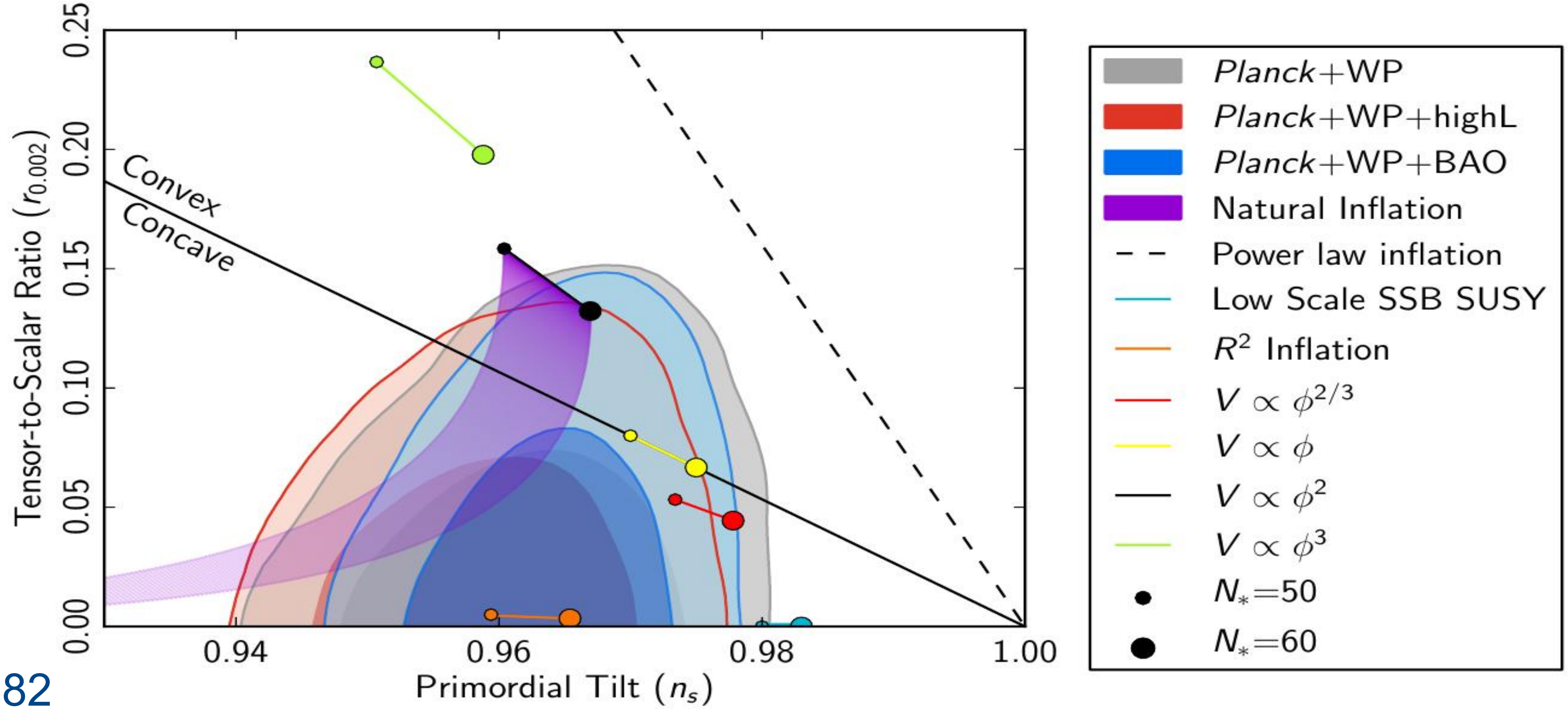
Scalar & Tensor TT, TE, EE & BB Spectra

'r' quantifies the fraction of power in tensors versus scalars



Inflation

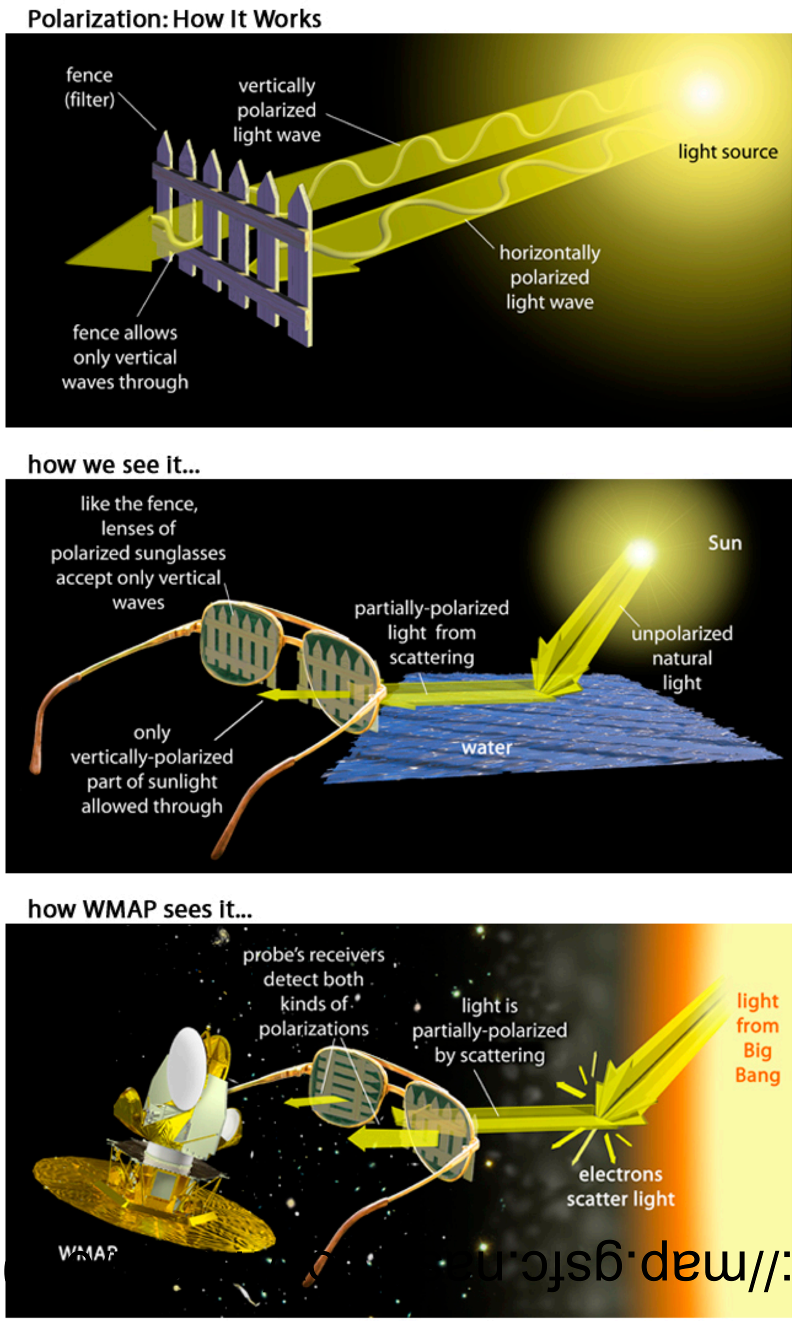
- $n_s = 0.9603 \pm 0.0073$ (Note: $n_s<1$ at $>5\sigma$)
- Tensor-to-scalar ratio: $r < 0.11$
  - In the future, with polarization, we hope to be able to reduce this to ~0.05
- B-mode polarization will allow us to improve limits on "r"



arXiv:1303.5082

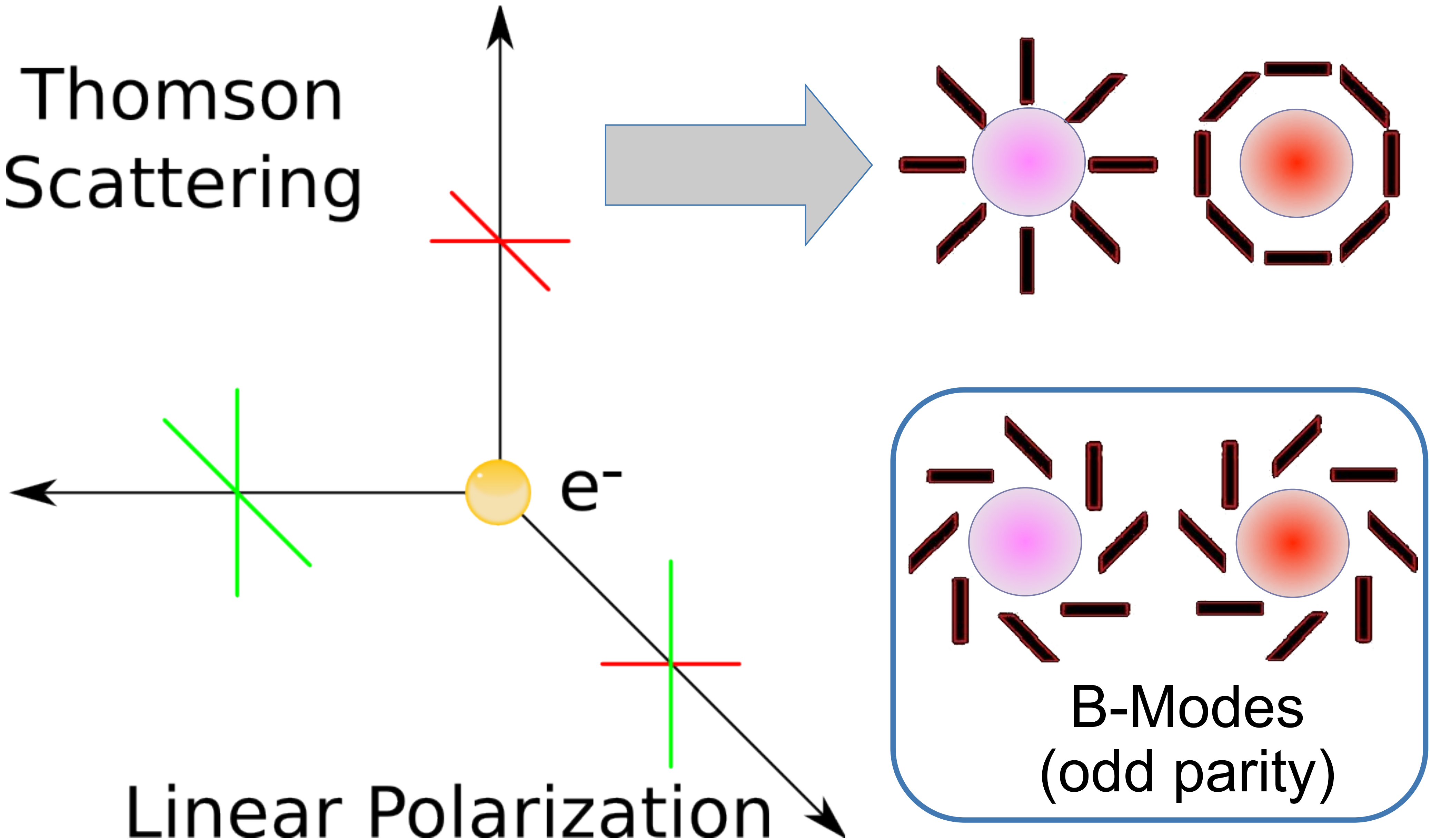
About Polarization

- Light can be polarized, giving it not only a direction it travels, but also an orientation, or "angle" around the direction of travel.
- We don't usually worry about this, but this detail is exploited by sunglasses, among other things (like modern microwave background experiments)



http://map.gsfc.n … 666/030666b.jpg

Polarization of the CMB



SPT/Herschel Polarization Lensing

- Using an SPT E-Mode map and a Herschel map of the CIB, the predicted what B-Modes should be there and found a correlation.
- This is analogous to what Planck did using maps of temperature lensing and its own 545 GHz channel

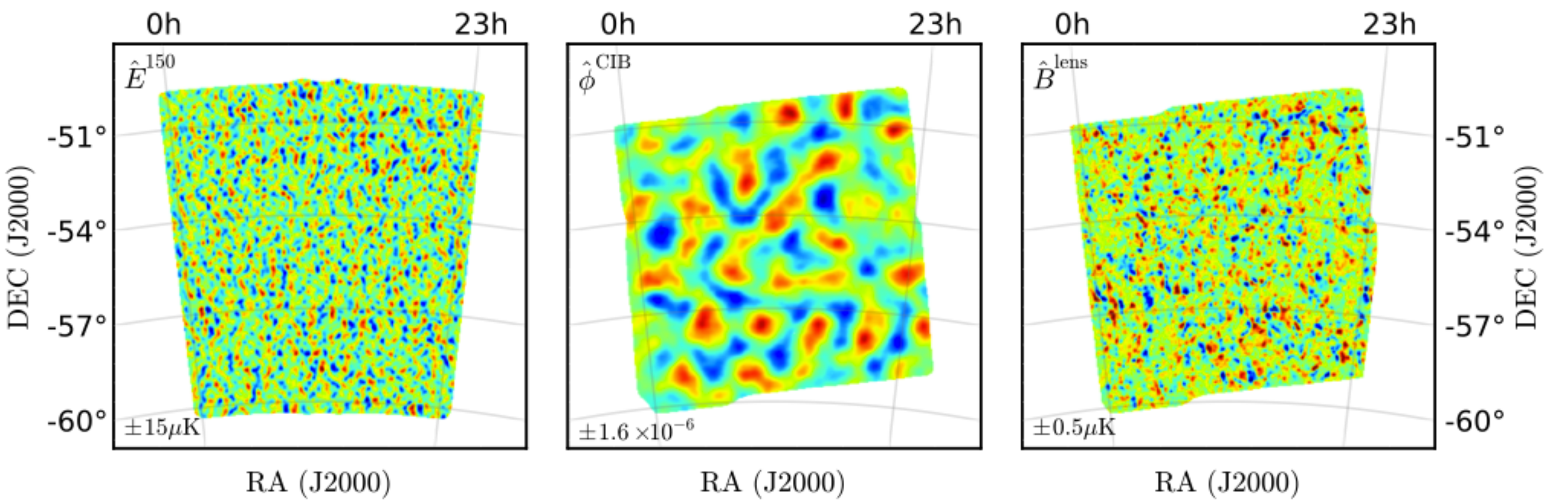
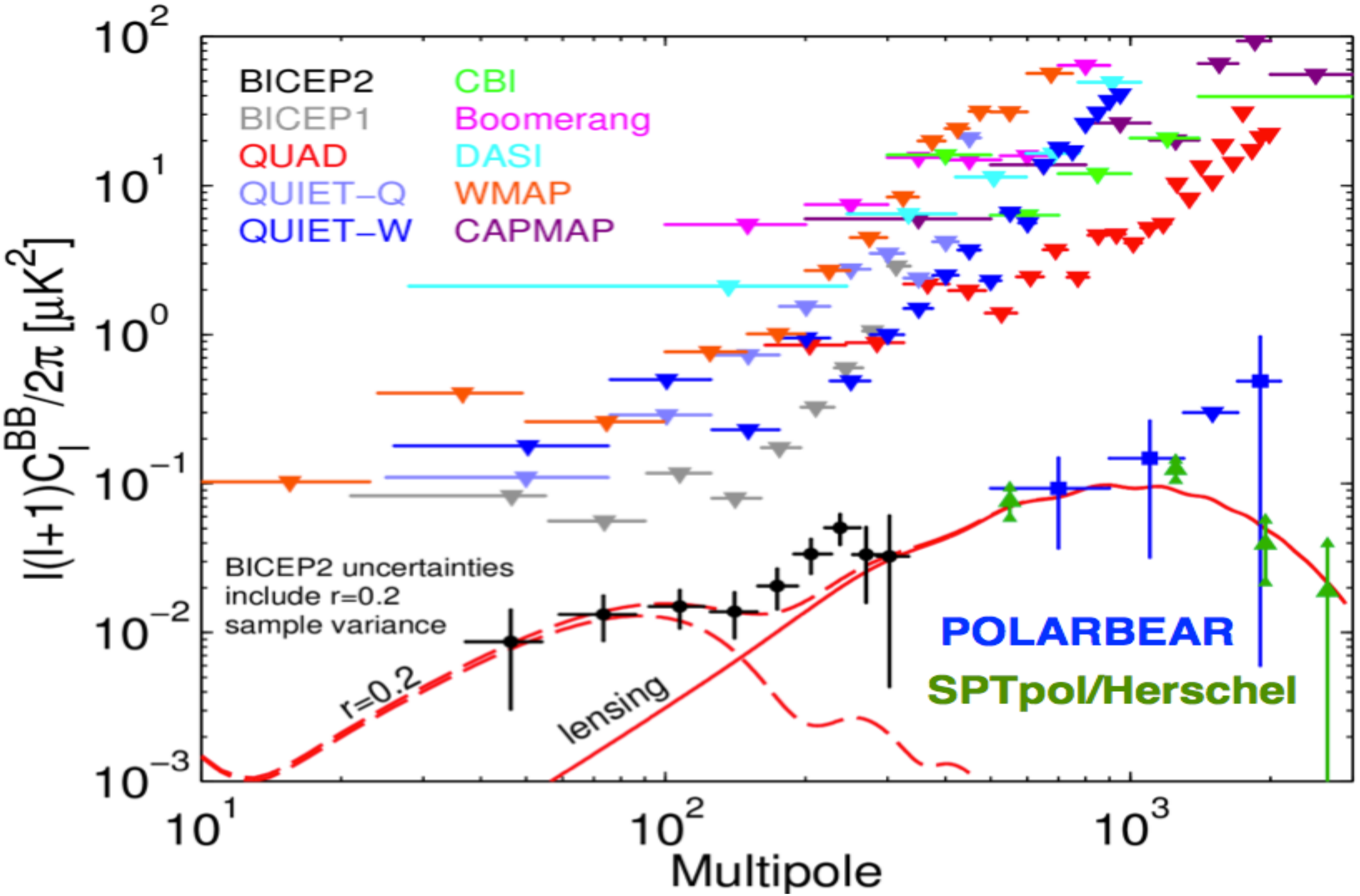


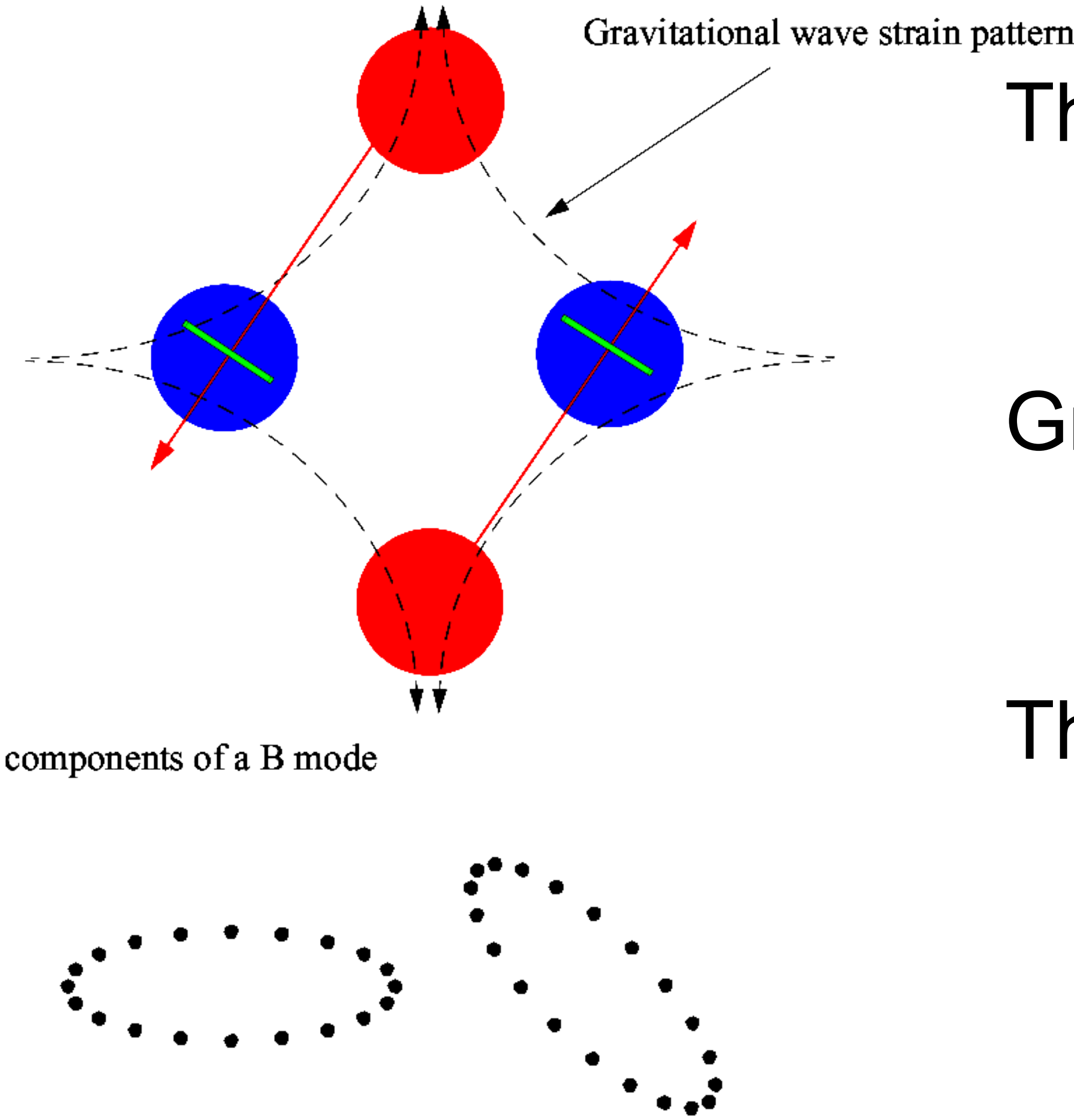
FIG. 1: Left: Wiener-filtered E-mode polarization measured by SPTpol at 150 GHz. Center: Wiener-filtered CMB lensing potential inferred from CIB fluctuations measured by *Herschel* at 500 μm. Right: gravitational lensing B-mode estimate synthesized using Eq. (1). The lower left corner of each panel indicates the blue(-)/red(+) color scale.

B-Mode Measurements



Stolen from Jeff Filippini; https://indico.cern.ch/event/296546/session/1/contribution/5

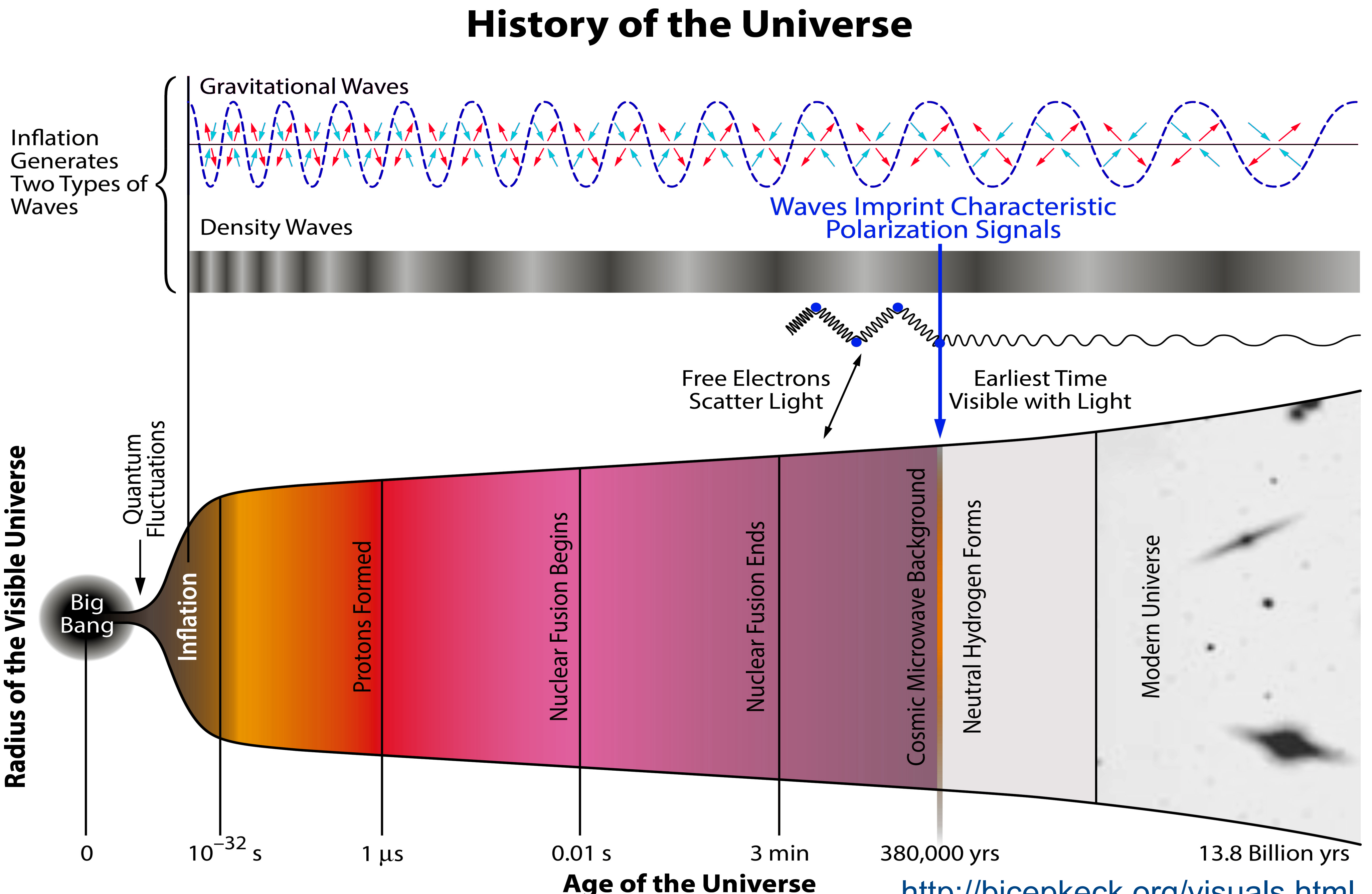
Grav. Waves Convert E Modes to B



- Thomson scattering creates E-mode polarization
- Gravitational Waves can break the symmetry and create B-modes
- This is a very small effect compared to what has been measured with the CMB to date

Rai Weiss – 2005 CMB Task Force Update

Relic Gravitational Waves – B-Modes



http://bicepkeck.org/visuals.html

BICEP Sees r ~ 0.2

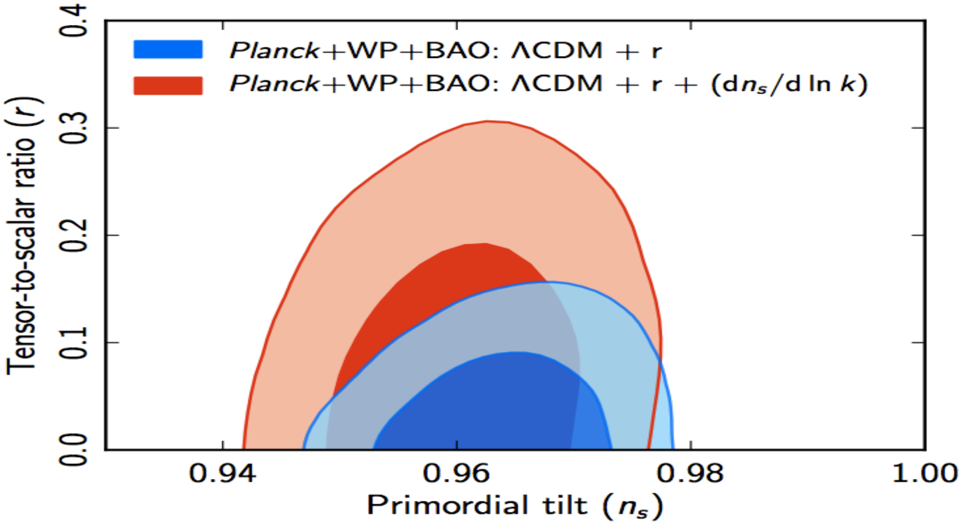
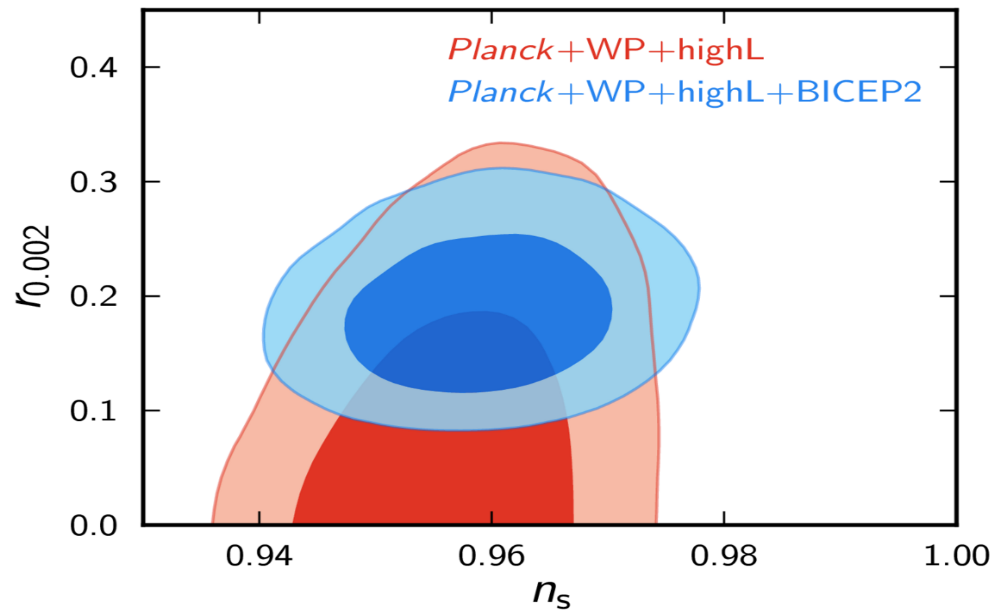


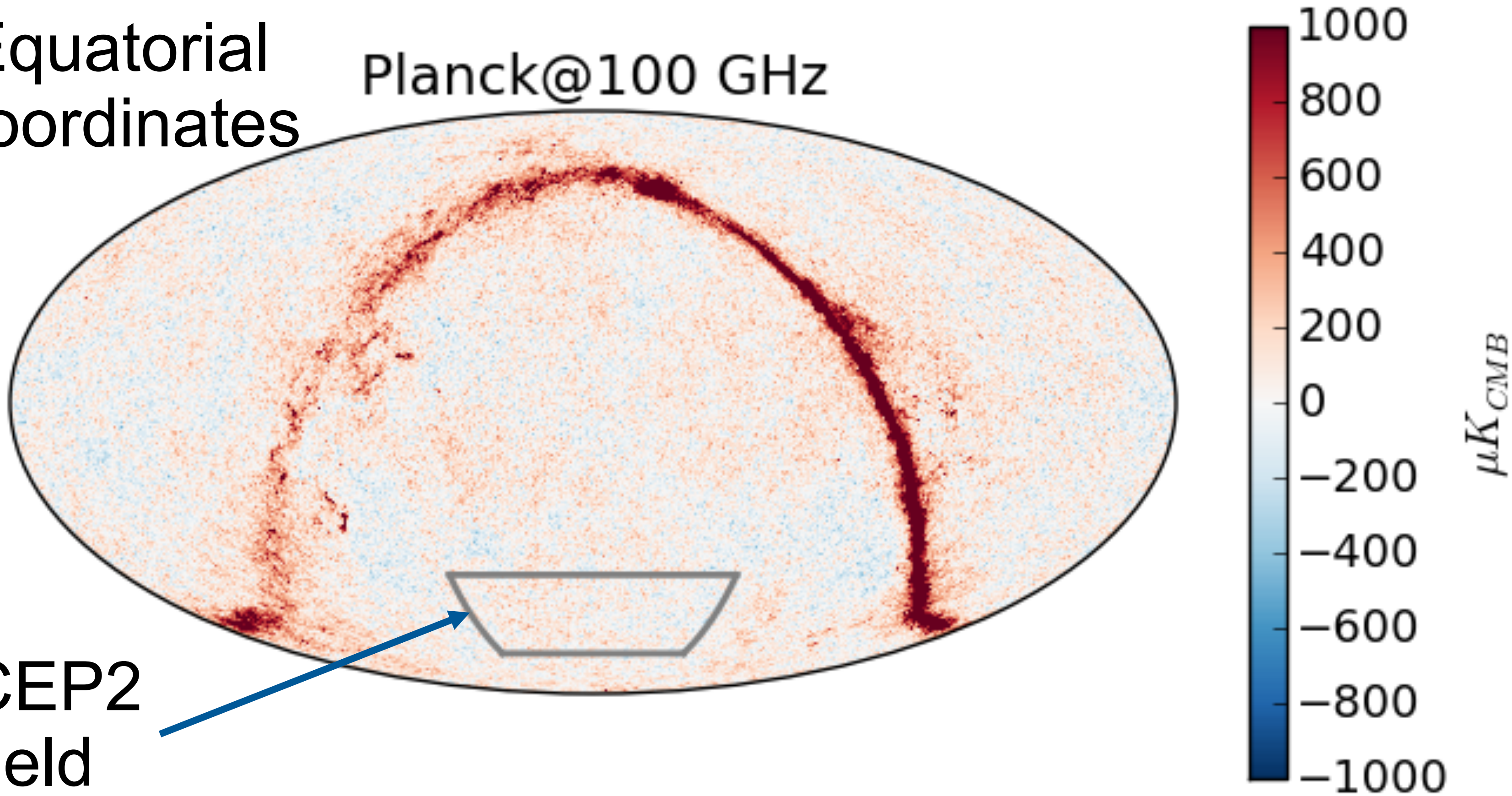
Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.



- "... the fractional contribution of tensor modes is limited to r < 0.13 (95% CL)" -- *Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results (2012)*
- "Planck establishes an upper bound on the tensor-to-scalar ratio of r < 0.11 (95% CL)." -- *Planck 2013 results. XXII. Constraints on inflation.*
- "The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio $r=0.20^{+0.07}_{-0.05}$." -- *BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales (2014)*
- We were looking for a needle in a haystack, but instead we found a crowbar. -- *Clem Pryke*

Planck 143 GHz Temperature Map

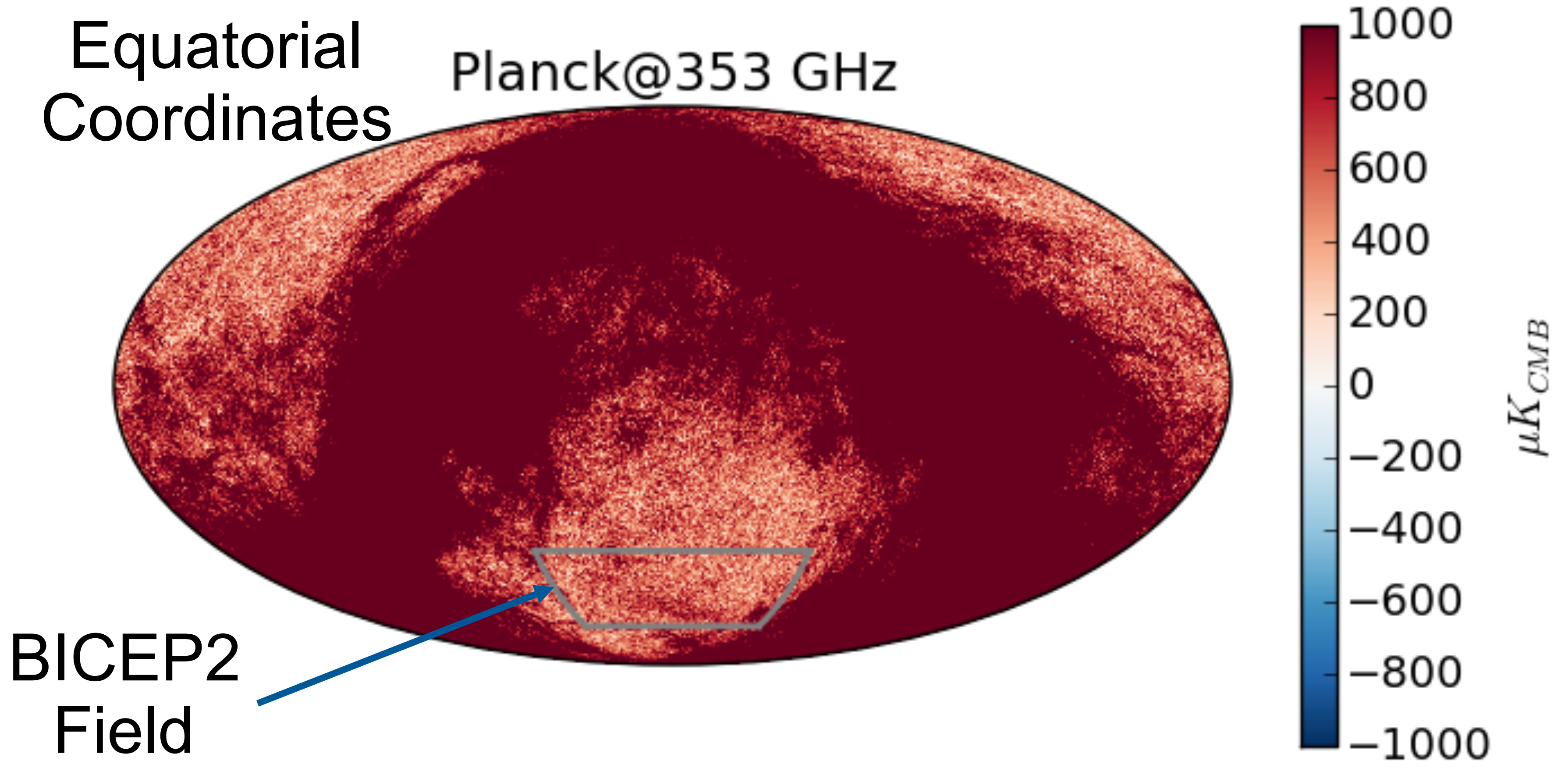
Equatorial Coordinates



BICEP2 Field

This is a *temperature* map. Planck has not yet released full-sky polarization maps.

Planck 353 GHz Temperature Map



This is a *temperature* map. Planck has not yet released full-sky polarization maps.

What Planck is Working on Now

Stokes Q & U at 353 GHz from Planck

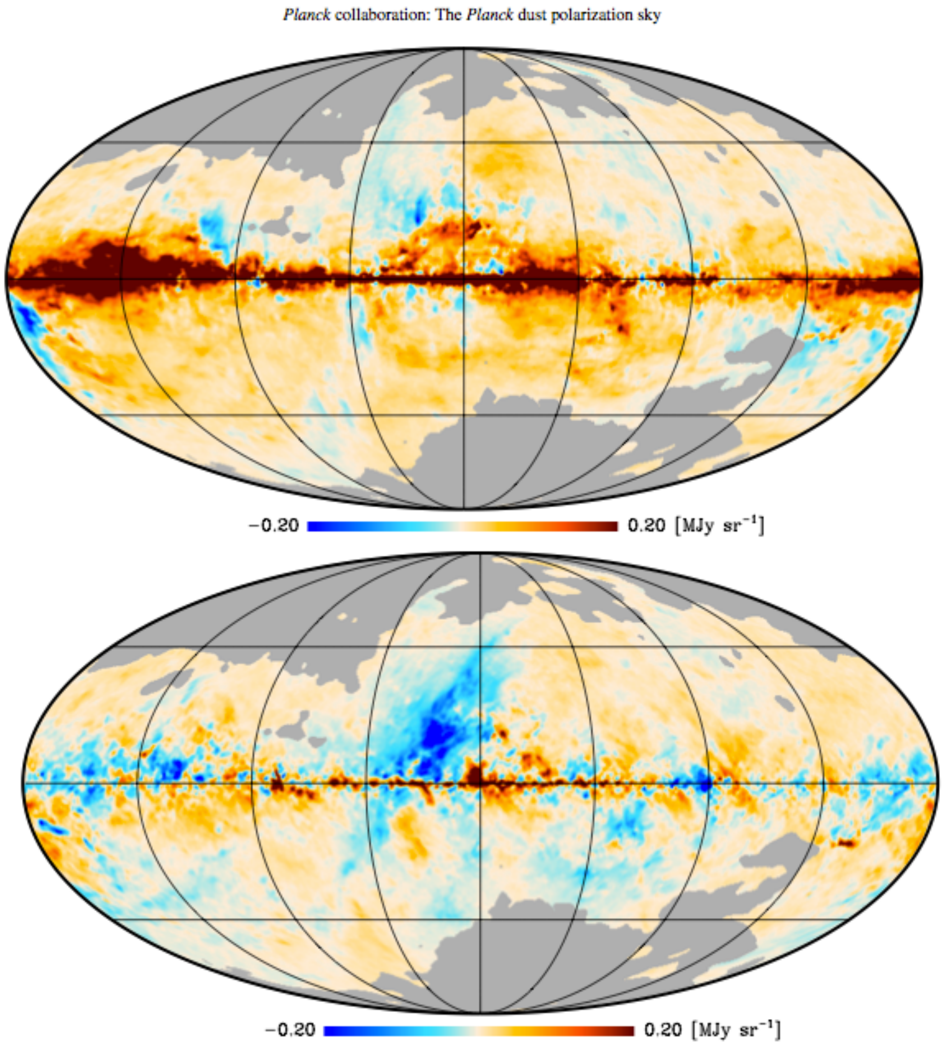


Fig. 1. *Planck* 353 GHz polarization maps at 1° resolution. *Upper*: *Q* Stokes parameter map. *Lower*: *U* Stokes parameter map. The maps are shown with the same colour scale. High values are saturated to enhance mid-latitude structures. The values shown have been bias corrected as described in Sect. 2.3. These maps, as well as those in following figures, are shown in Galactic coordinates with the galactic center in the middle and longitude increasing to the left. The data is masked as described in Sect. 2.4.

arXiv:1405.0871v1 5 May 2014

- BICEP has more sensitivity than Planck in their field at 150 GHz
- But Galactic dust is much brighter at 353 GHz than at 150 GHz
- Planck finds that at 150 GHz, dust must be carefully addressed, even in the cleanest regions of the sky

B-Mode Spectrum on the BICEP Field

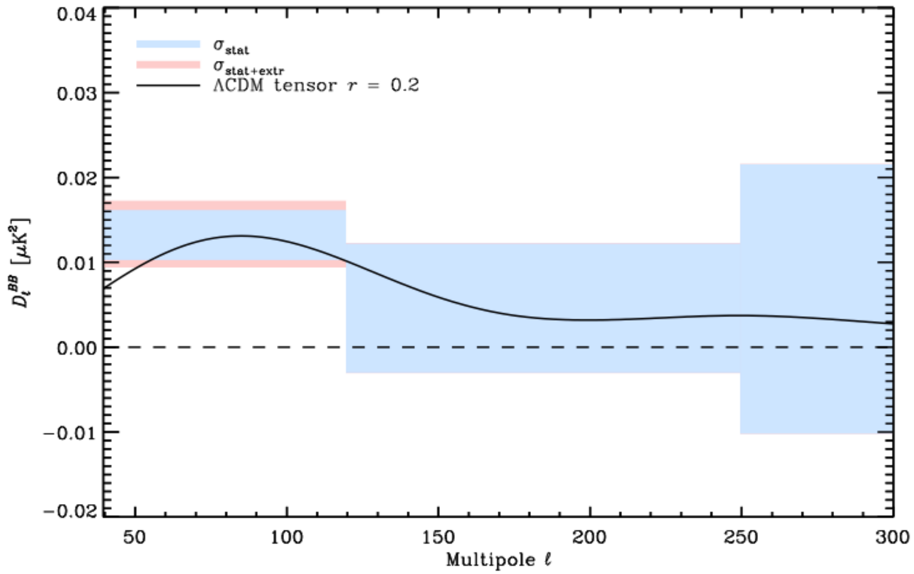


Fig. 9: *Planck* 353 GHz $\mathcal{D}_\ell^{BB}$ angular power spectrum computed on M_{B2} defined in Sect. 6.1 and extrapolated to 150 GHz (box centres). The shaded boxes represent the $\pm 1\,\sigma$ uncertainties: blue for the statistical uncertainties from noise; and red adding in quadrature the uncertainty from the extrapolation to 150 GHz. The *Planck* 2013 best-fit ΛCDM $\mathcal{D}_\ell^{BB}$ CMB model based on temperature anisotropies, with a tensor amplitude fixed at $r = 0.2$, is overplotted as a black line.

Blue: Statistical Uncertainty
Pink: 353-150 Extrapolation Uncertainty

Cross-Correlations between BICEP2 and Planck are happening now...

- Measured at 353 GHz and extrapolated to 150 GHz
- Note that there are only three bins here...
  - The first band is the most relevant to the primordial B-Modes...
- The filtering and processing that BICEP has actually done is not accounted for here.

Fig. 8: Best Parts of the Polarized Sky

- Value of BB spectrum at ℓ=80, normalized to a spectrum with r=1.
  - Deep red is r~10
  - Orange/red is r~1
  - Blue/cyan is r~0.1
  - Deep blue is r~0.01
- Computed from the 353 GHz data and extrapolated to 150 GHz using power law above

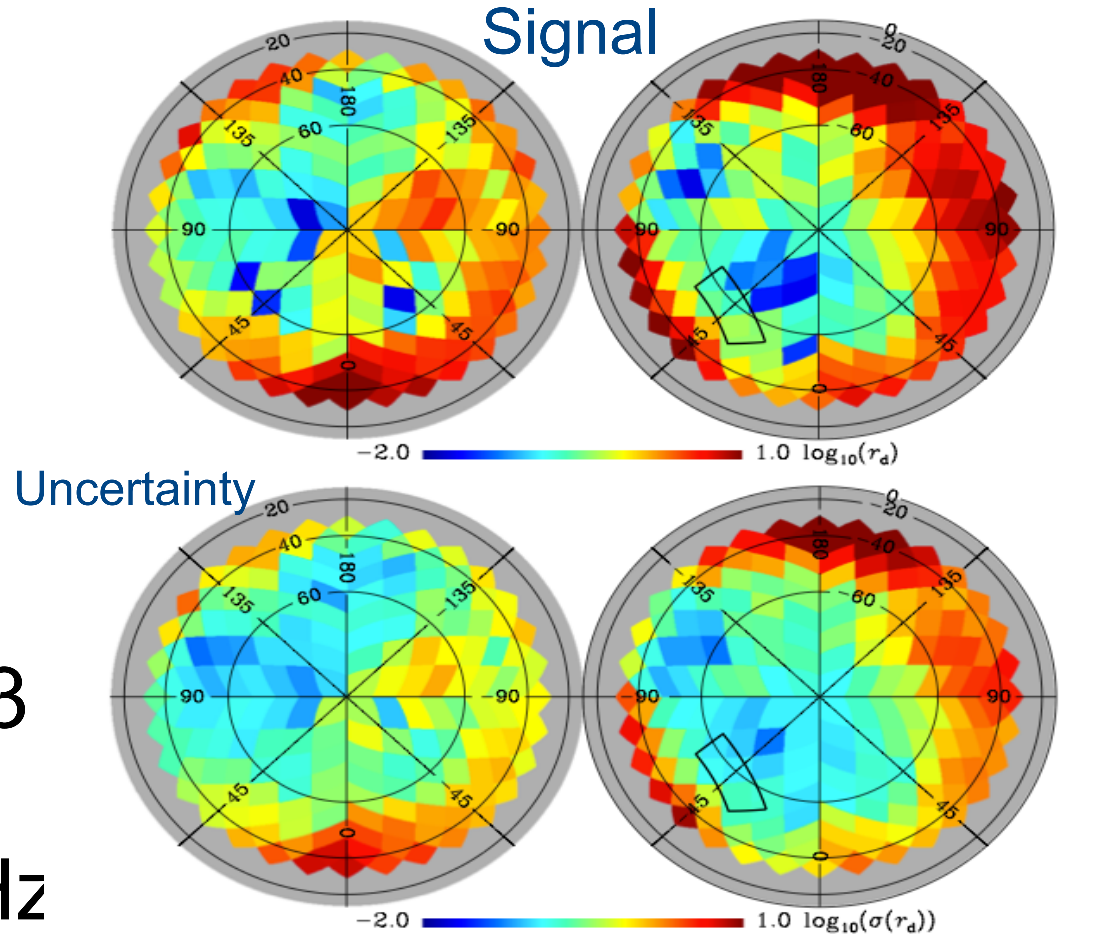


Fig. 8: *Top*: map in orthographic projection of the 150 GHz $\mathcal{D}_\ell^{BB}$ amplitudes at $\ell = 80$, computed from the *Planck* 353 GHz data, extrapolated to 150 GHz, and normalized by the CMB expectation for tensor-to-scalar ratio $r = 1$. The colours represent the estimated contamination from dust in r_d units (see details in Sect. 5.3). The logarithm of the absolute value of r_d for a 400 deg^2 patch is presented in the pixel on which the patch is centred. As described in Sect. 3.3.2, the patches overlap and so their properties are not independent. The northern (southern) Galactic hemisphere is on the left (right). The thick black contour outlines the approximate BICEP2 deep-field region (see Sect. 6). *Bottom*: associated uncertainty, $\sigma(r_d)$.

Future

Near-Term Experiments

B-Mode Search Projects Underway

GroundBird MuSE

Ground-Based (Chile):

POLARBEAR: Polarization of Background Radiation

ACTPOL: Atacama Cosmology Telescope – Polarization

ABS: Atacama B-mode Search

CLASS: Cosmology Large Angular Scale Surveyor

Ground-Based (Antarctica):

SPTPOL: South Pole Telescope's polarization-sensitive camera

BICEP2: Background Imaging of Cosmic Extragalactic Polarization (and Keck Array)

QUBIC: Q&U Bolometric Interferometer for Cosmology

Ground-Based (Canary Islands):

QUIJOTE: Q-U-I JOint TEnerife

Balloon Experiments:

EBEX: E and B Experiment

SPIDER: Suborbital Polarimeter for Inflation

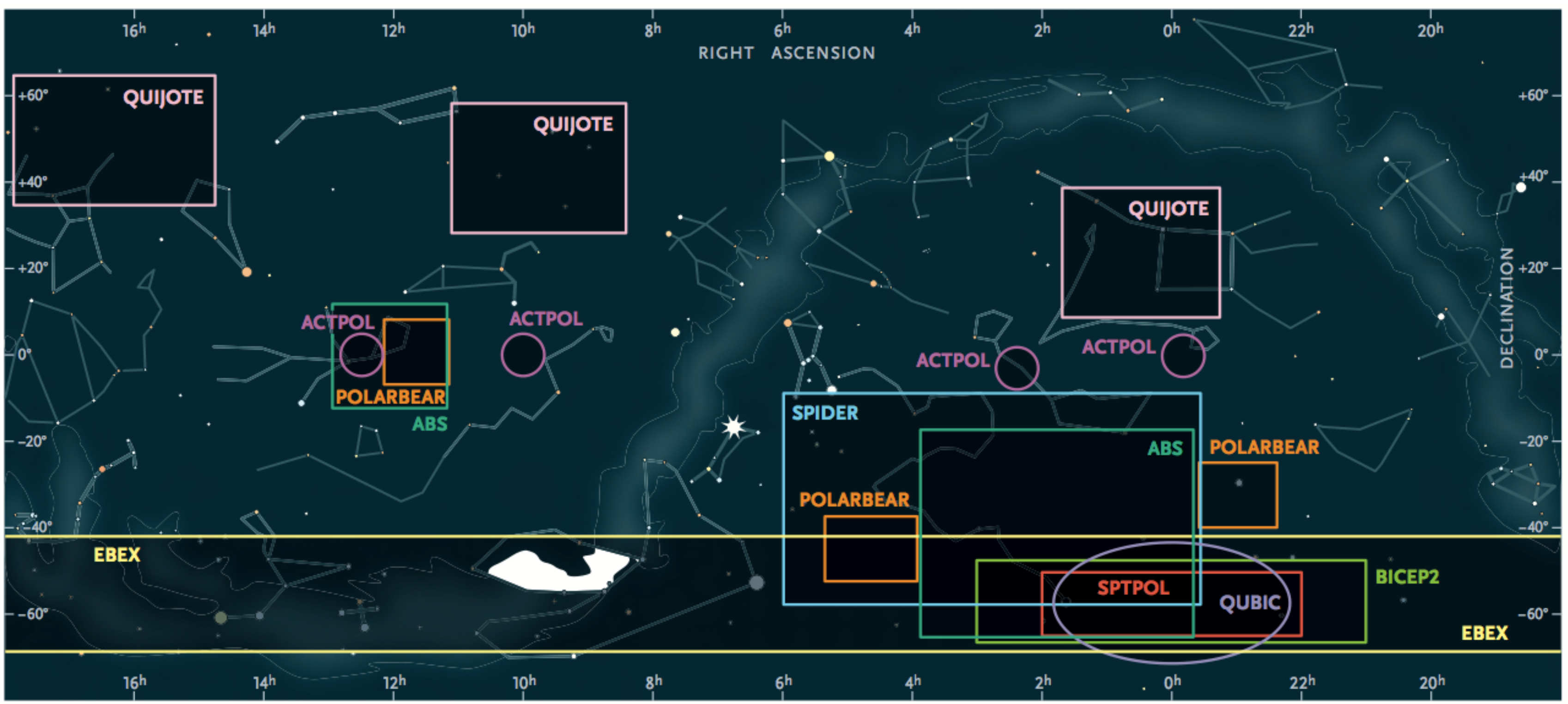
LSPE: Large-Scale Polarization Explorer

PIPER: Primordial Inflation Polarization Explorer

ESA Satellite Mission:

PLANCK

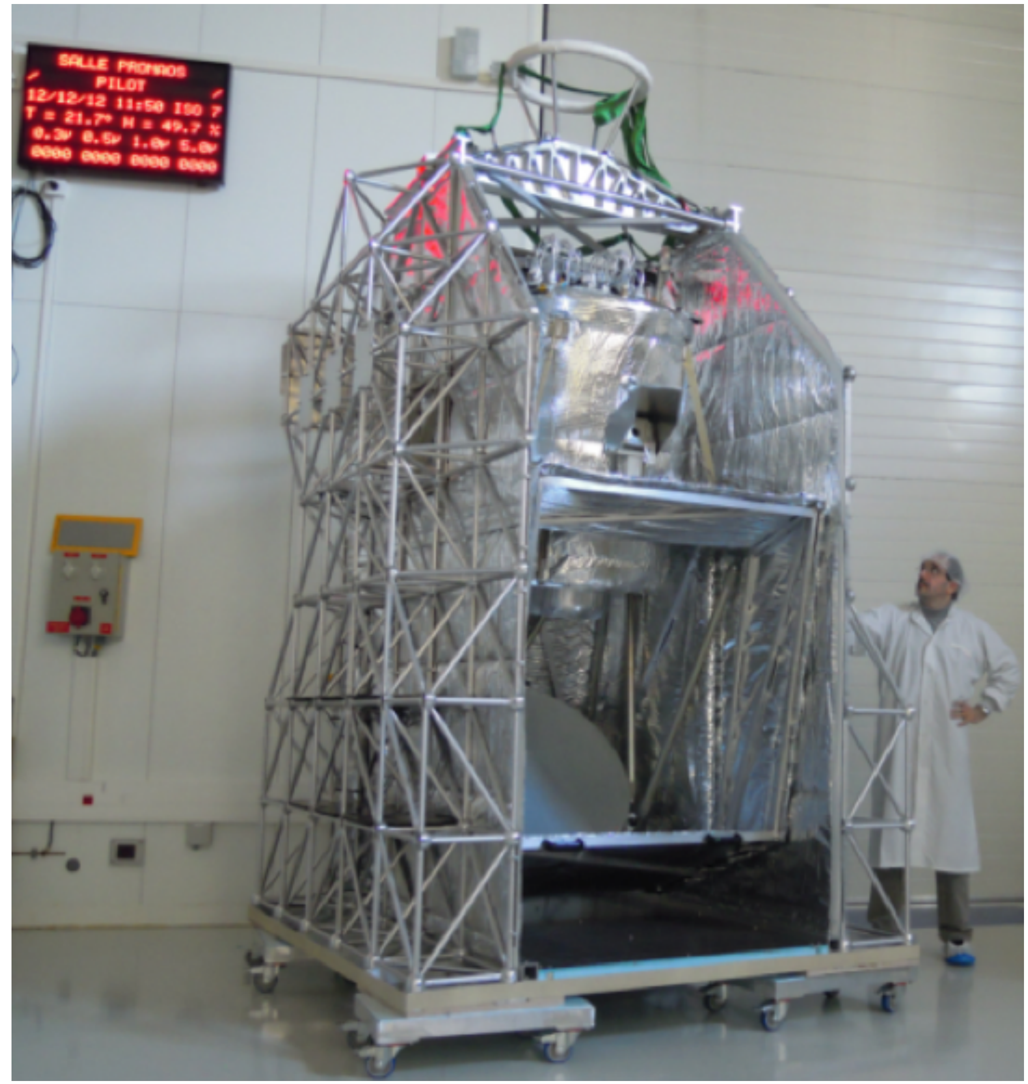
RACE TOWARD THE BIG BANG Several projects are currently hunting for the polarization signature of inflation. Shown below are the fields of view for active projects (except for Planck, which is all-sky). Fields are approximate and distorted by projection at high declinations.



SkyandTelescope.com *October 2013* 27

PILOT Advertisement

- Balloon to measure linear polarization of Galactic dust emission at 240 & 550 microns (<Planck; 10-50 times more sensitive than for dust)
- Initially Galactic Plane observations, but coverage of CMB fields possible.
- Flight readiness review in autumn; 1st flight in 2015.



J.P. Bernard

Ground-Based Plans

For reference, Planck/HFI has ~50 detectors

CMB timeline

O(100) detectors ==>

- 2009: $r < 0.7$ (BICEP) Chiang et al, 0906.1181

O(1000) detectors ==>

- 2013: $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013-2016: Stage II experiments
  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV;

O(100000) detectors ==>

- 2020-2025: **Stage IV goal to reach**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.025$, $\sigma(\Sigma m_\nu) = 16$ meV

Taken from a pre-BICEP2 presentation by John Carlstrom
Note: 2**(15 years/1.5 year "Moore" doubling time) ~ 1000

Neutrino Limits from Polar. Lensing

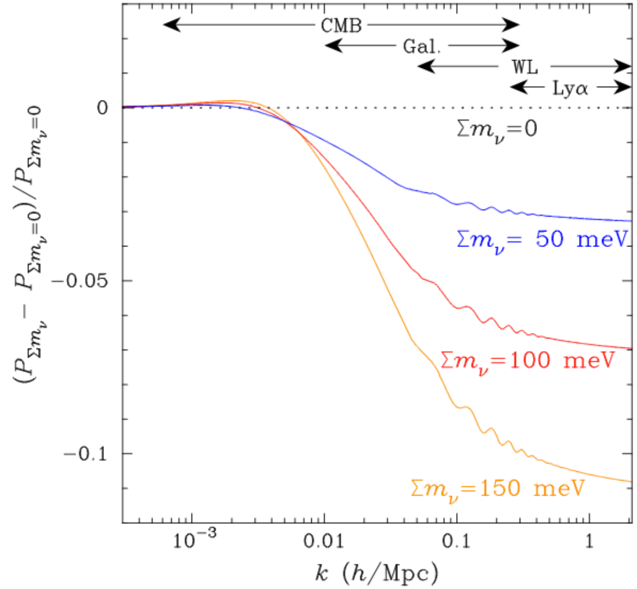


Figure 1. *Fractional change in the matter density power spectrum as a function of comoving wavenumber k for different values of $\sum m_\nu$. Neutrino mass suppresses the power spectrum due to free streaming below the matter-radiation equality scale. The shape of the suppression is highly characteristic and precision observations over a range of scales can measure the sum of neutrino masses (here assumed all to be in a single mass eigenstate). Also shown are the approximate ranges of experimental sensitivity in the power spectrum for representative probes: the cosmic microwave background (CMB), galaxy surveys (Gal.), weak lensing of galaxies (WL), and the Lyman-alpha forest (Lyα). The CMB lensing power spectrum involves (an integral over) this same power spectrum, and so is also sensitive to neutrino mass.*

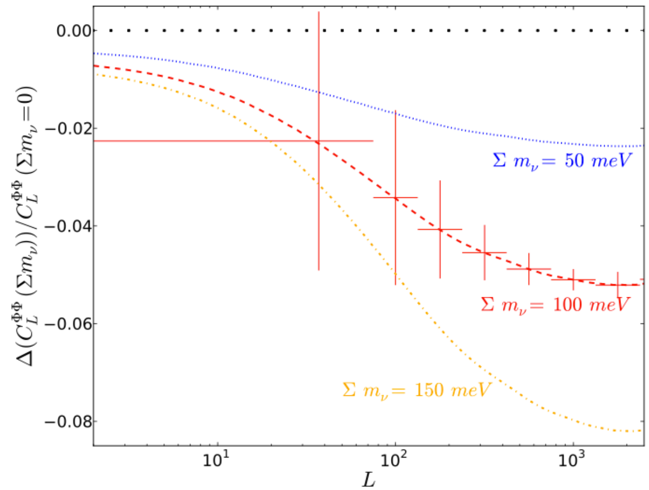


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrum $C_L^{\Phi\Phi}$. The fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero neutrino mass. Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu$ = 100 meV. Here we have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total matter density $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drops to 16 meV when combined with other probes.*

- Neutrinos suppress structure; This changes CMB lensing
- By measuring lensing we measure N_{eff} & Σm_ν

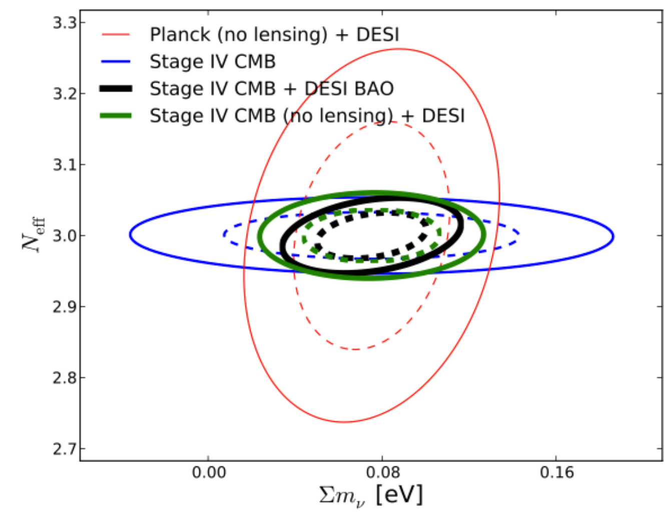
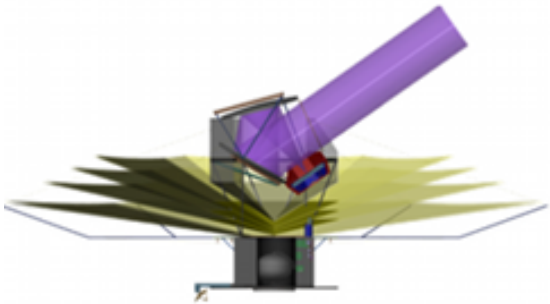


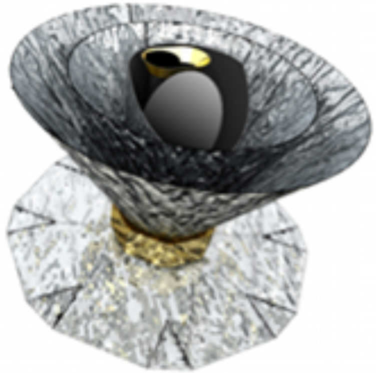
Figure 4. *The same as Figure 3, but showing forecasts in the Σm_ν - $N_{\rm eff}$ plane for a model including the effective number of neutrino species as a free parameter. A Stage-IV CMB experiment will not be able to distinguish between the standard model value of $N_{\rm eff}$ = 3.046 and the integer value of 3 at high statistical significance, but it will indicate a preference for one over the other at the $\sim$ 2 σ level.*

CMB Mission Concepts in the Current Environment

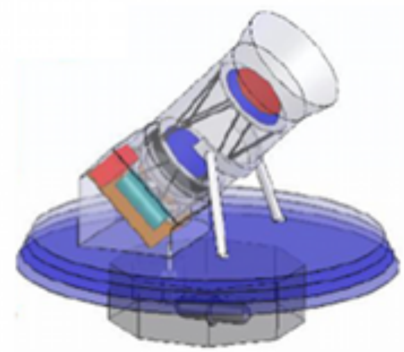
EPIC-IM



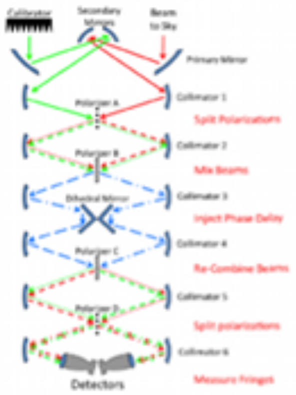
PRISM



LITEBIRD



PIXIE



Can we fit a CMB concept into a ~$220M Explorer cost cap?

Any concept seems very cost challenged at this cap

L2 concepts have a high launch cost

Will the science community accept a single-purpose satellite designed to discover inflationary B-modes?

In the US, the answer from Decadal planning exercise is clearly "No"

We need a detection from the ground first to justify a satellite for full characterization

What about an absolute spectrum instrument?

Absolute spectrum science is interesting and should be considered in its own right

No heritage for polarization measurements is worrisome

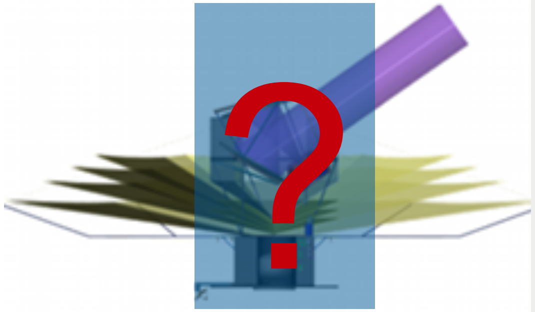
Is there a window for a large CMB mission?

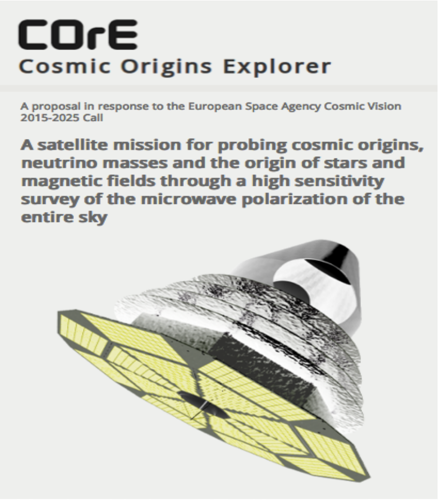
Not in the US this decade. We'll see how PRISM fares in Europe.

- Stolen from J. Bock; see: http://www-conf.kek.jp/cmb/2013/

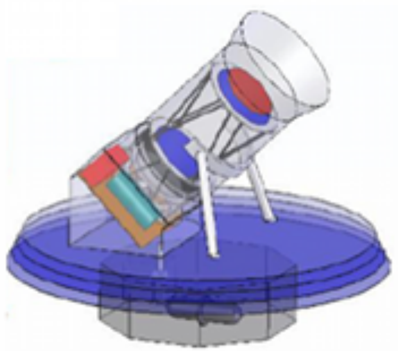
CMB Mission Concepts in the Current Environment

EPIC-IM





LITEBIRD



PIXIE

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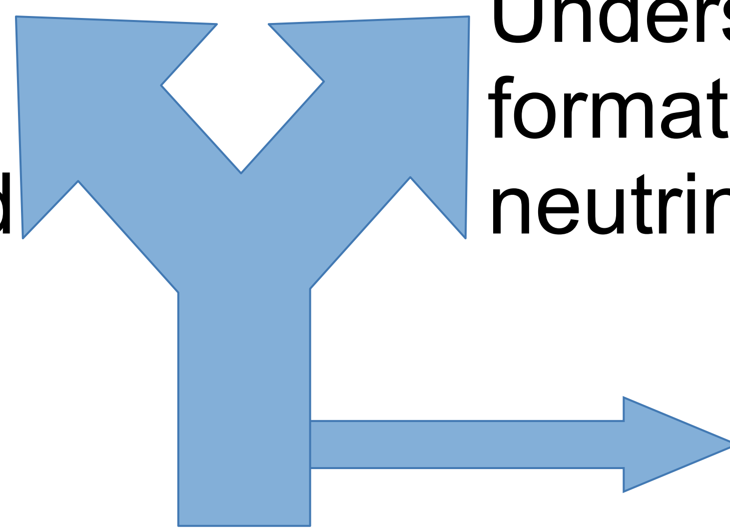
Will the CMB Field Split/Change?

"Primordial" CMB:
E.g., Polarized B-Modes.
Traditionally "aligned" with astrophysics.
May soon become even more dependent on "Galactic" astronomy to remove polarized foregrounds.

"Late" CMB:
Use the CMB not as a probe of the early Universe, but as a well-understood tool to probe astro- and particle-physics. E.g. Understand cluster formation and/or neutrino masses.



Spectrum?

CMB Now

Some References

- **An introduction to Modern Cosmology**, by A. Liddle
  - An undergraduate introduction with some math
- **The First Three Minutes**, by S. Weinberg
  - The science is somewhat dated (there's no indication of a cosmological constant, for example), but there's a nice discussion of the historical reasons why it took so long to detect the CMB

Acknowledgments

We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science.

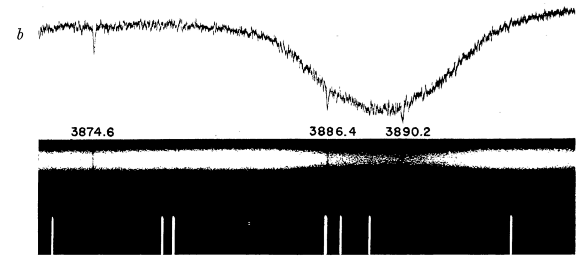
Some of the work here is from the Planck scientific collaboration. Planck is an ESA project with instruments funded by ESA member states (in particular the PI countries: France and Italy), and with special contributions from Denmark and NASA (USA).

Some plots here were made using CAMB and some using CMBFast.

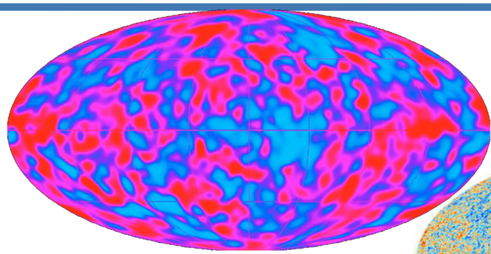
Some plots here were made using HEALPix (healpix.jpl.nasa.gov)

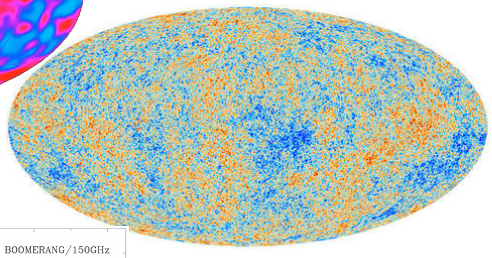
Backup

A History of the CMB in One Slide

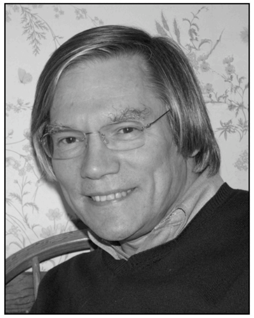


INTERSTELLAR LINES
a) α Cygni showing interstellar H and K superposed upon stellar lines; *b)* ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of *CH* are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably *CN*.

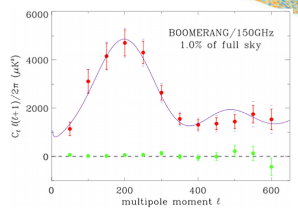


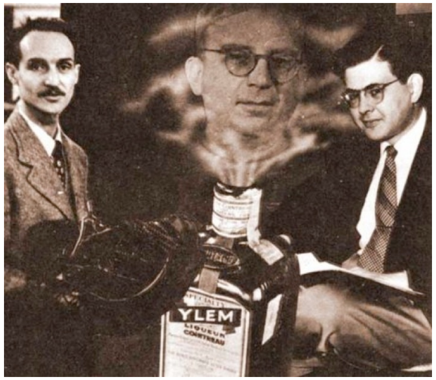


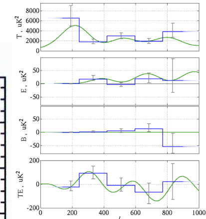
Alexei Starobinsky
b. 1948

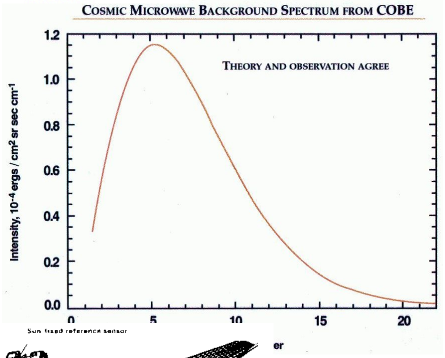


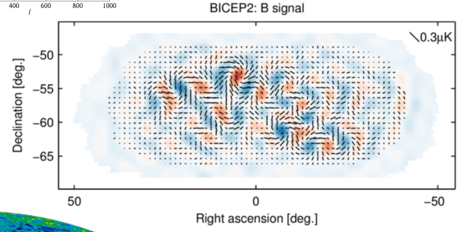
Alan Guth
b. 1947



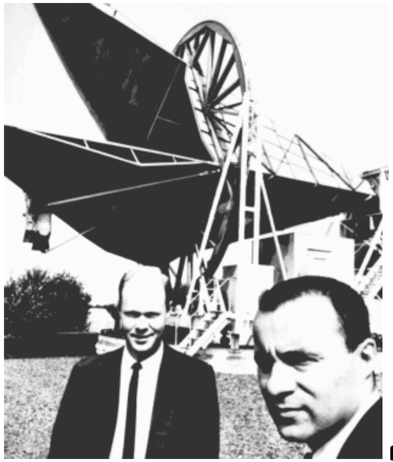


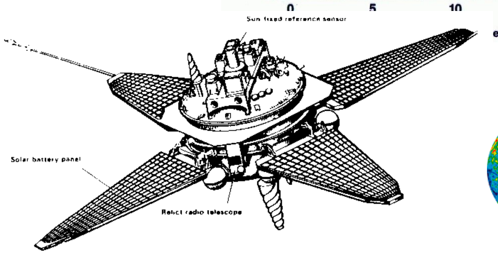




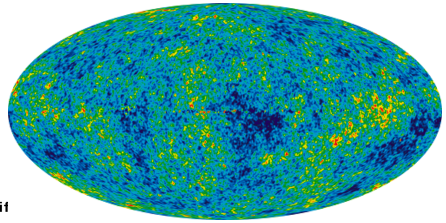


With apologies to most of the field for omissions...





http://rammb.cira.colostate.edu/dev/hillger/Prognoz-9_sketch.gif
Prognoz 9's Relikt 37GHz radiometer



1940 1950 1960 1970 1980 1990 2000 2010 2020

ApJ, 142: 419-421

A Measurement of Excess Antenna Temperature at 4080 Mc/s
A.A. Penzias & R.W. Wilson

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value of about 3.5 K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 - April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

Other Possible Detections

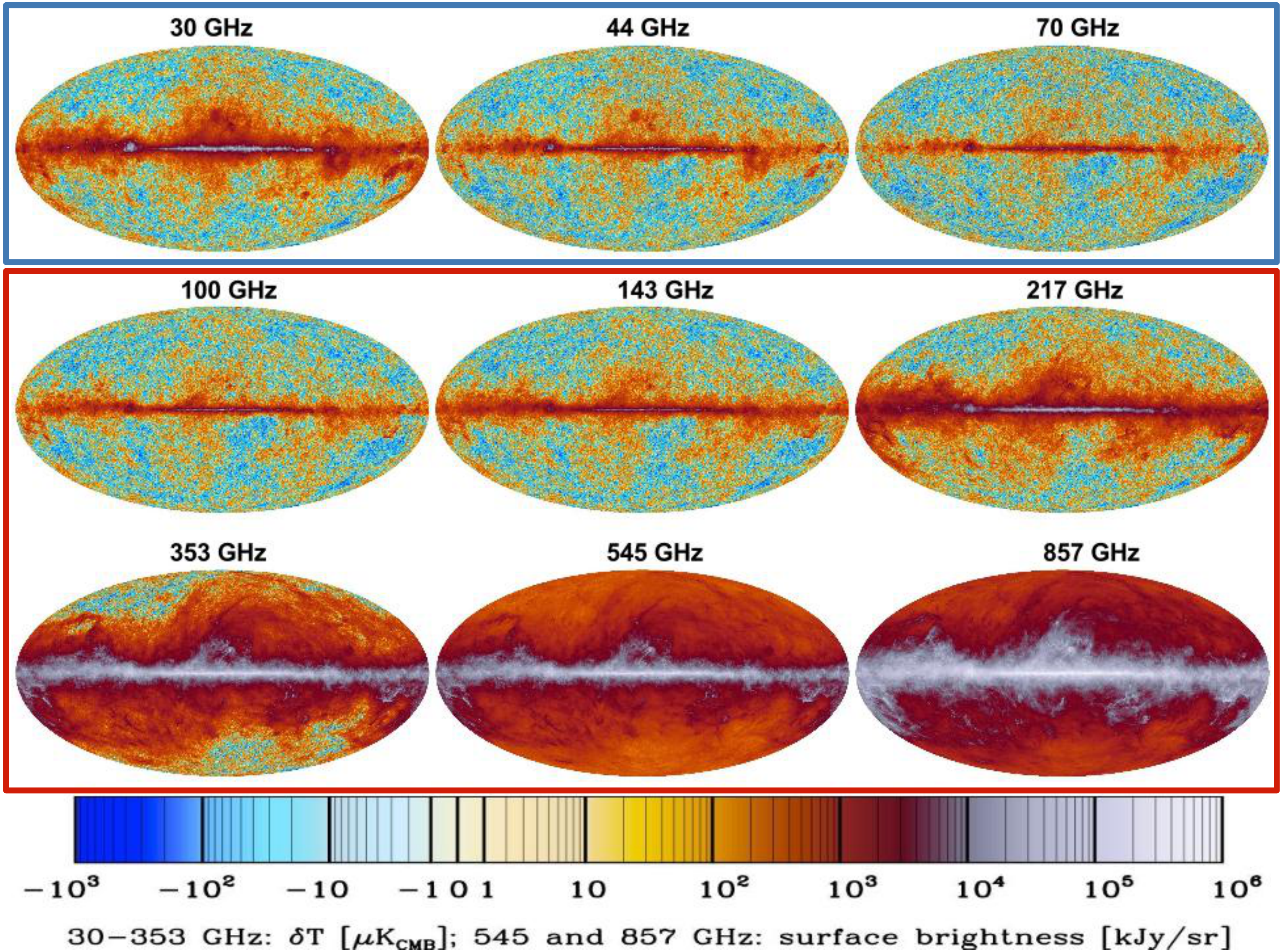
- Japanese in the early 1950s?
- T. Shmaonov in 1957.
- French?
- Others?

Planck Maps

Planck has two instruments:

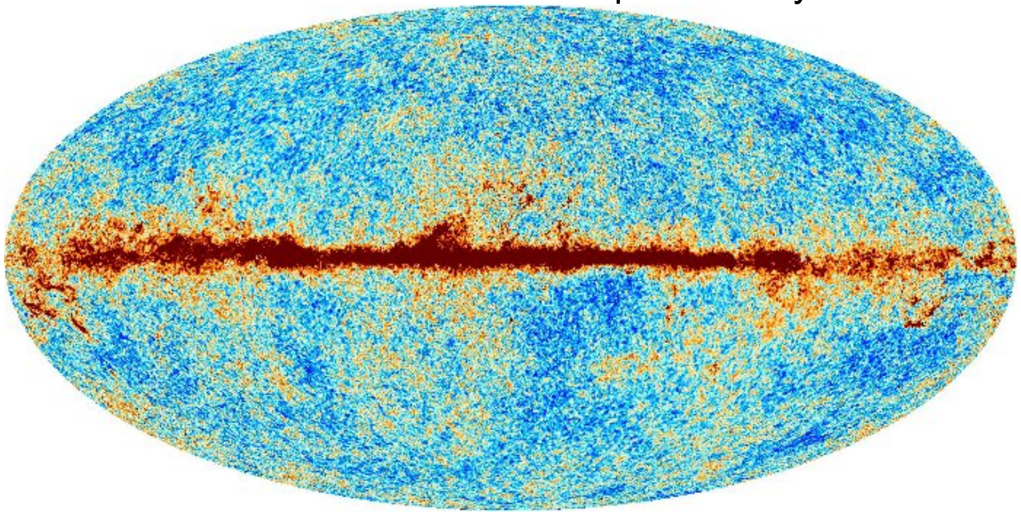
- LFI:
-- 30,
-- 44,
-- 70 GHz

- HFI
-- 100,
-- 143,
-- 217,
-- 353,
-- 545,
-- 857 GHz



But if We Could See Microwaves...

Planck/HFI 100 GHz Map of the Sky



http://arxiv.org/abs/1303.5067

- This is a microwave image. Apart from the Galaxy (the red band), most of this emission comes from the Microwave Background

- This map is in Galactic coordinates, so our Galaxy shows up as the band that spans from the left to the right of the image.

- The Microwave Background was emitted when the Universe was 0.00003 of its present age.

All the Cosmology You Need Here

- The CMB was emitted when the Universe was ~400000 years old
- The Universe is ~1000 times larger than it was when the CMB was emitted
- 70% of the “energy density” of the Universe is “Dark Energy”, 25% is “Dark Matter” and 5% is stuff we understand.

Degeneracies

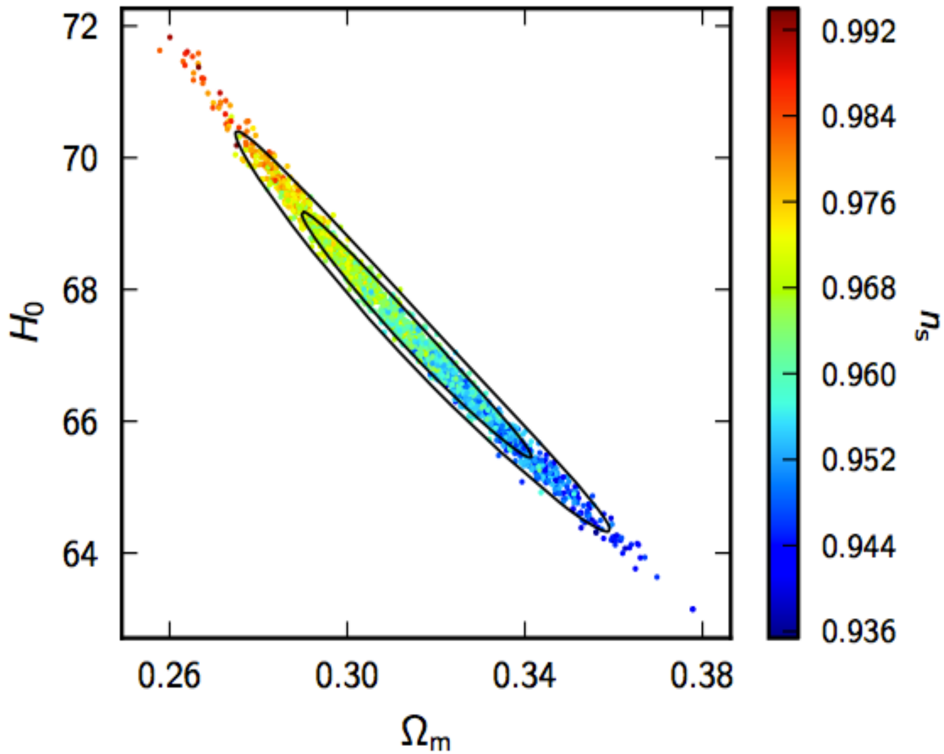
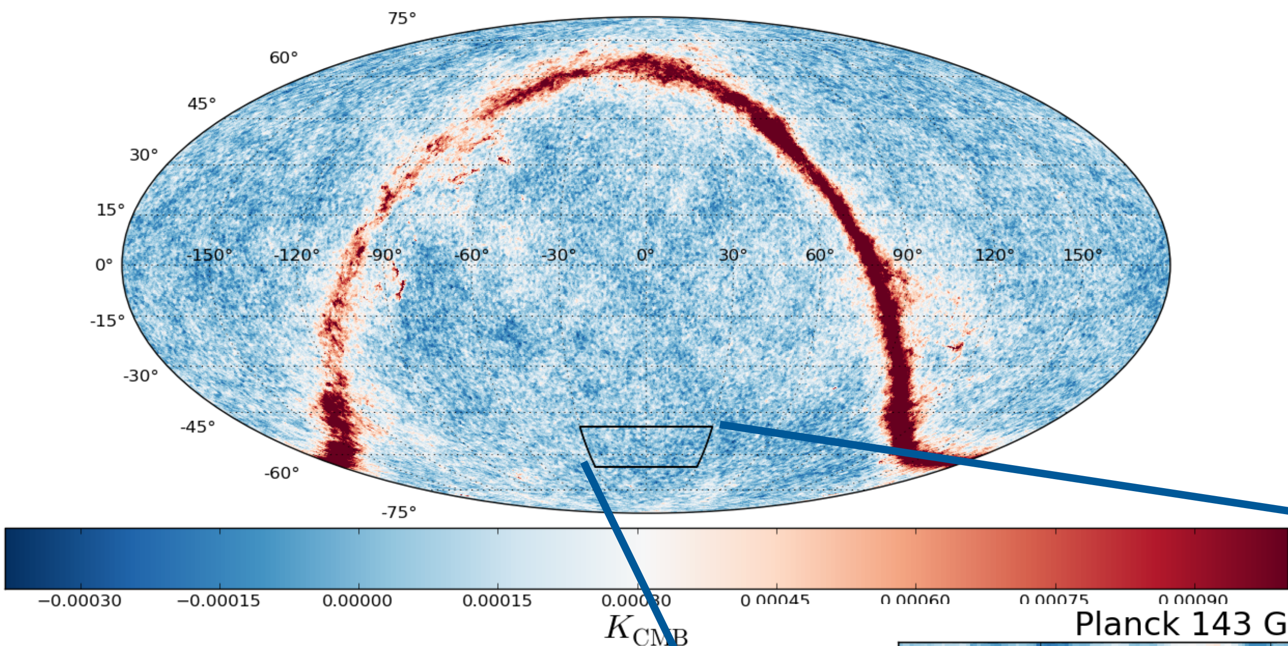


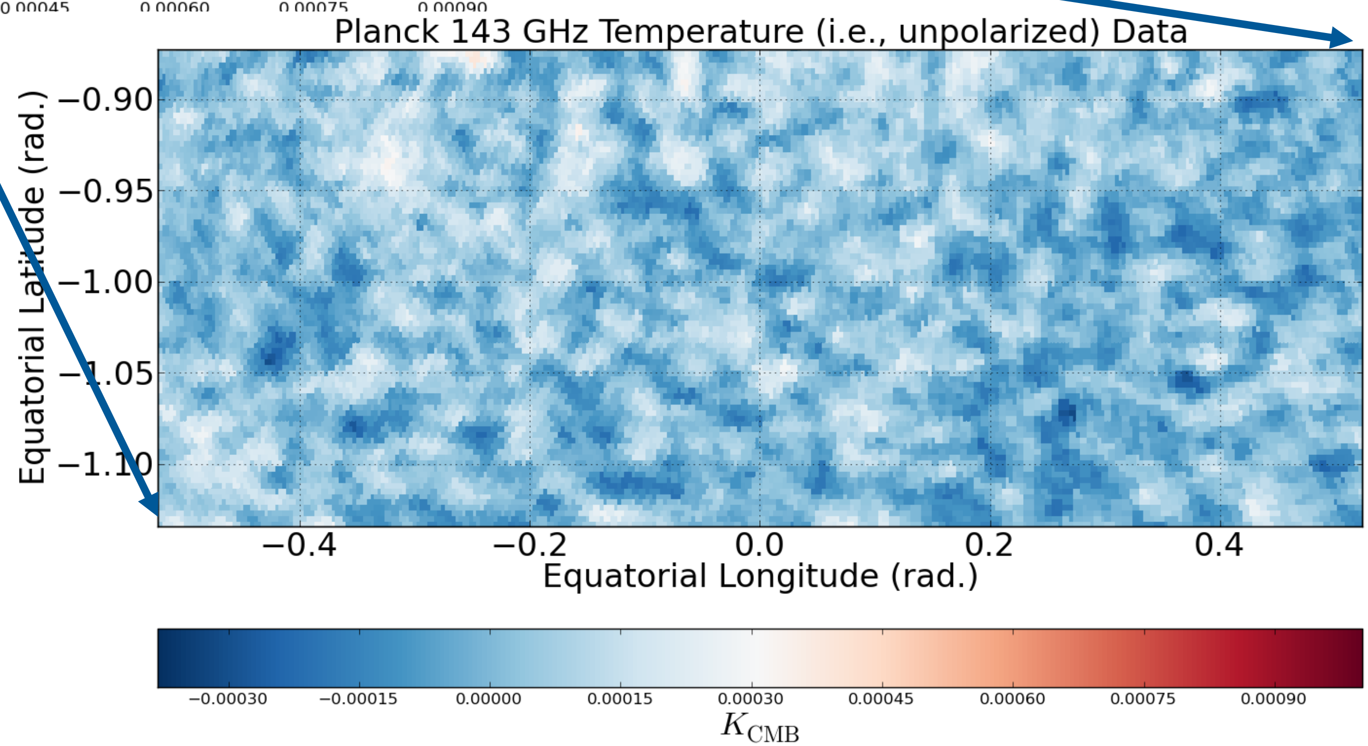
Fig. 3. Constraints in the Ω_m–H_0 plane. Points show samples from the *Planck*-only posterior, coloured by the corresponding value of the spectral index n_s. The contours (68% and 95%) show the improved constraint from *Planck*+lensing+WP. The degeneracy direction is significantly shortened by including WP, but the well-constrained direction of constant $\Omega_m h^3$ (set by the acoustic scale), is determined almost equally accurately from *Planck* alone.

- Omega$_m$ & H$_0$ are degenerate, so an increase in the latter evokes a decrease in the former.
- The scalar spectral index is also affected.
- Many of the "differences" may have a single "root cause"

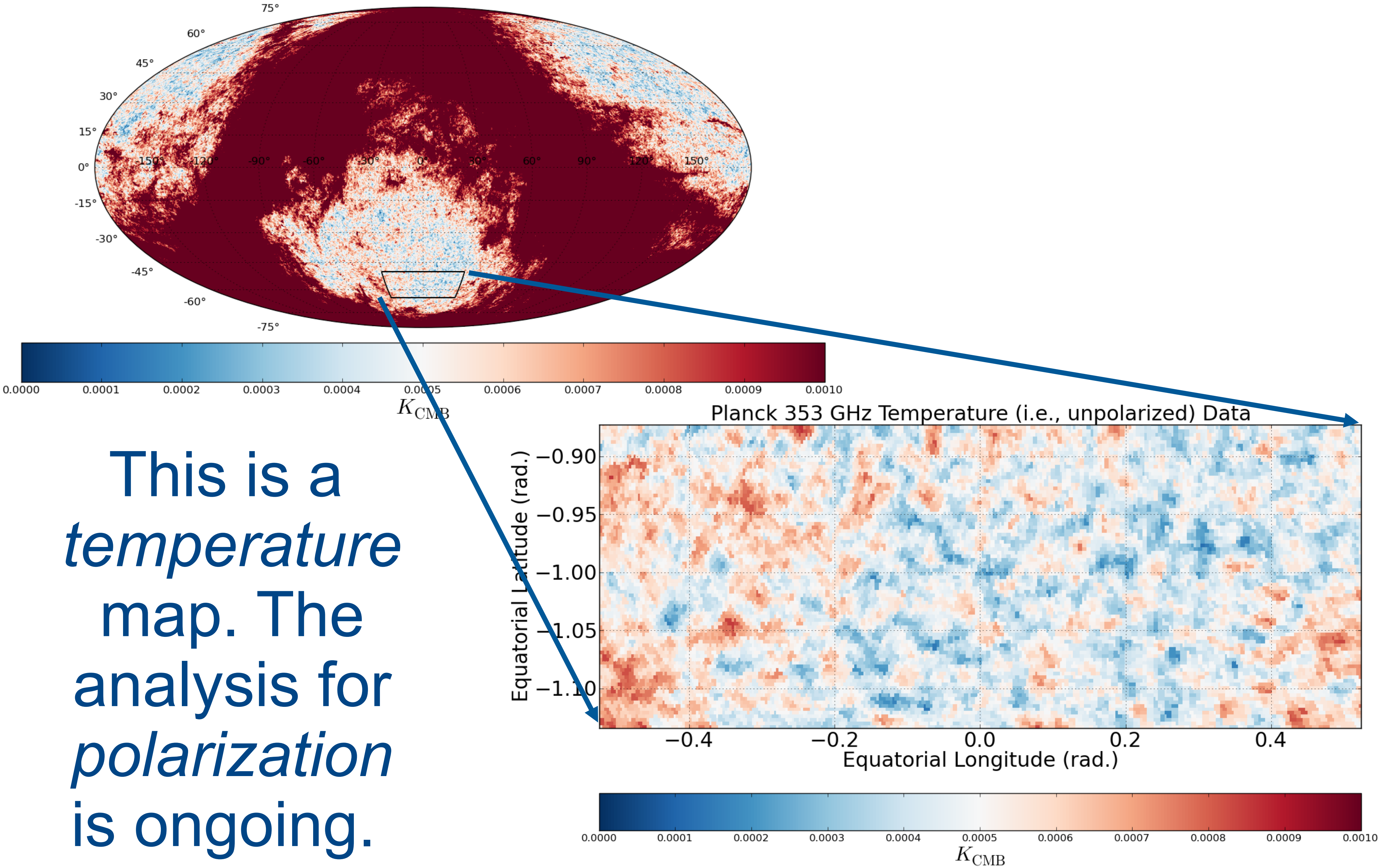
Planck 143 GHz Temperature Map



This is a *temperature* map. The analysis for *polarization* is ongoing.

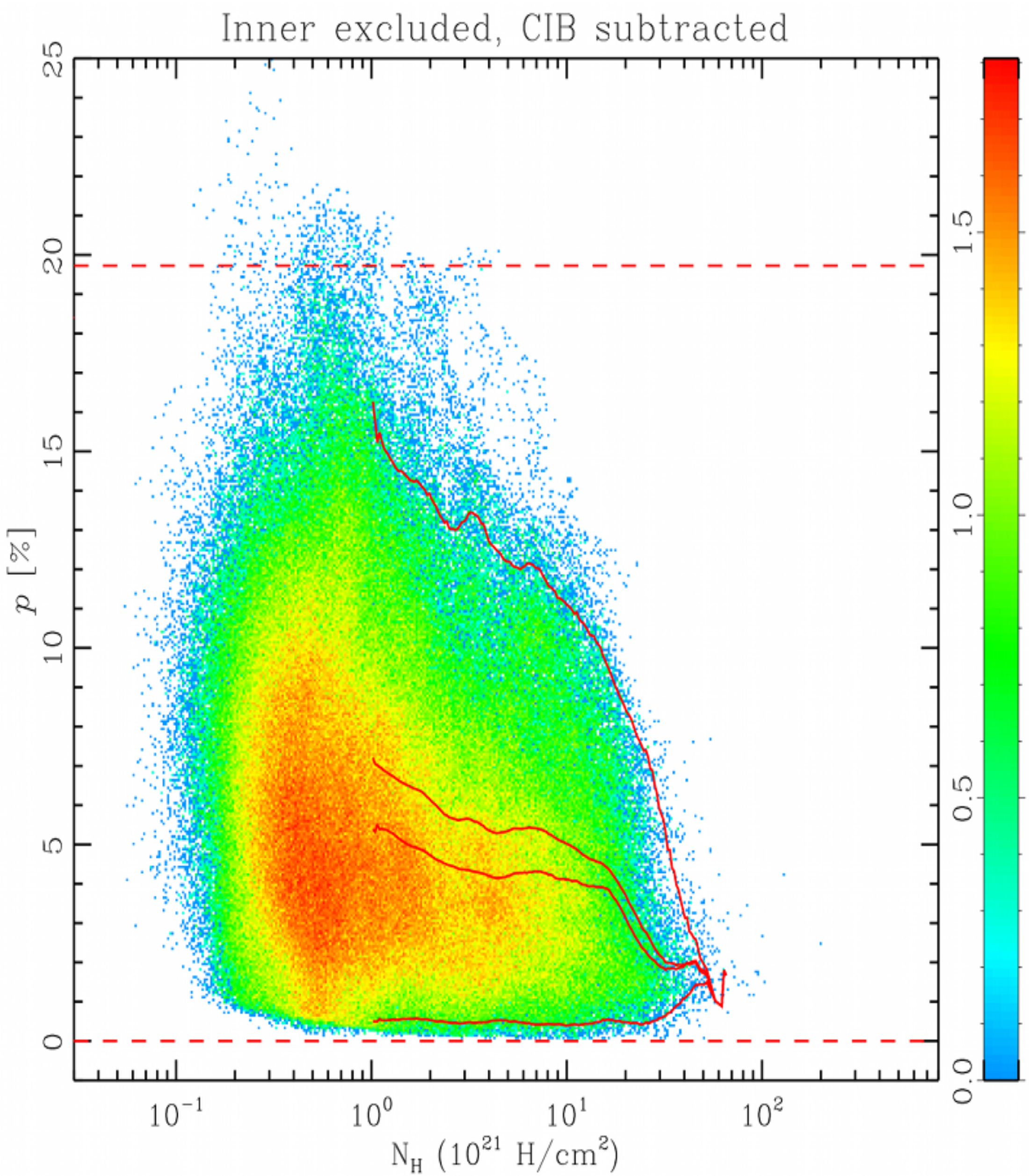


Planck 353 GHz Temperature Map



This is a *temperature* map. The analysis for *polarization* is ongoing.

Polarization vs. Optical Depth



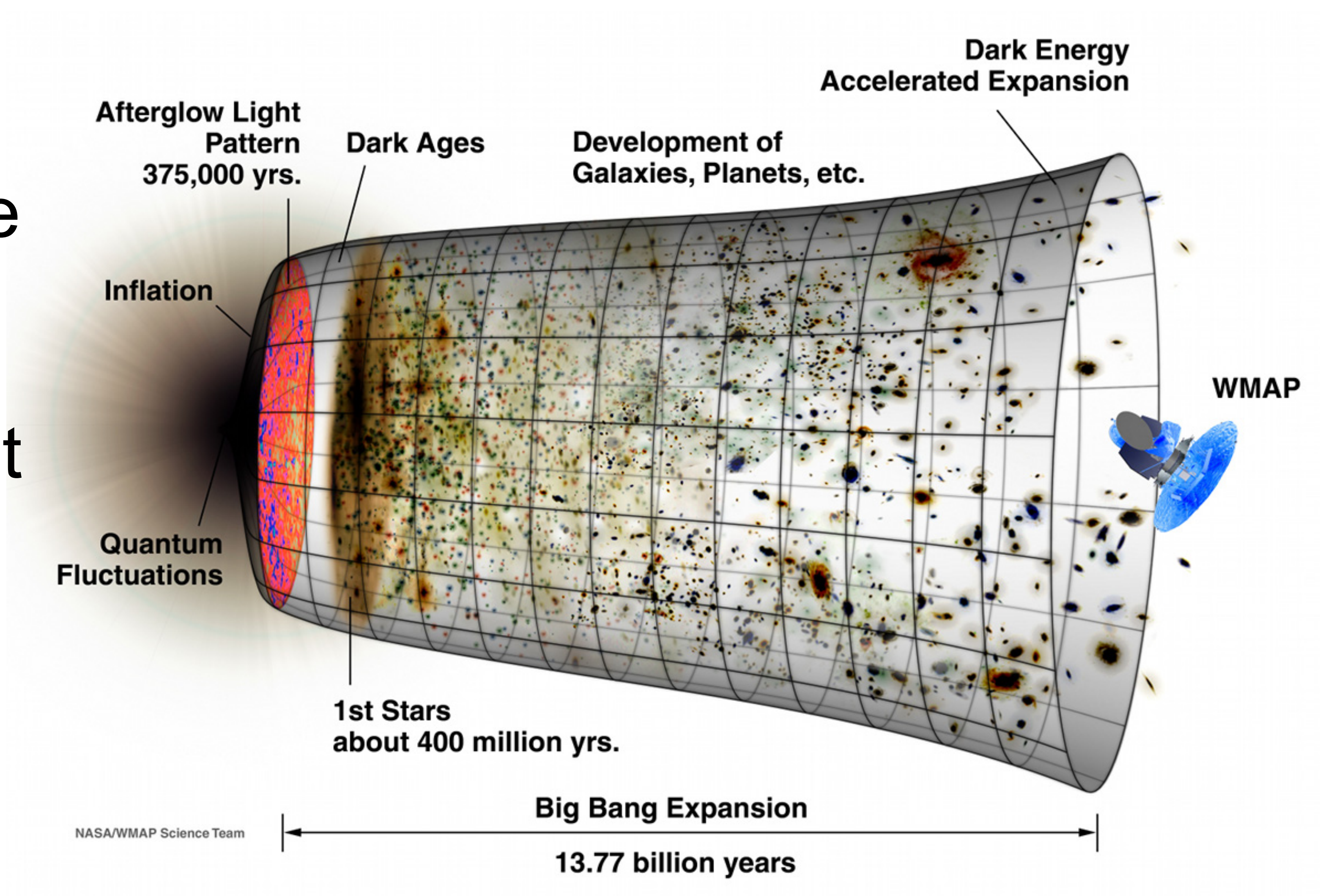
arXiv:1405.0871v1 5 May 2014

- Historically, the CMB world has used a canonical 5% polarization figure for dust
- These are based on the only regions we could measure – bright regions
- Lower column-depth regions are less complicated, have less depolarization and so seem have higher

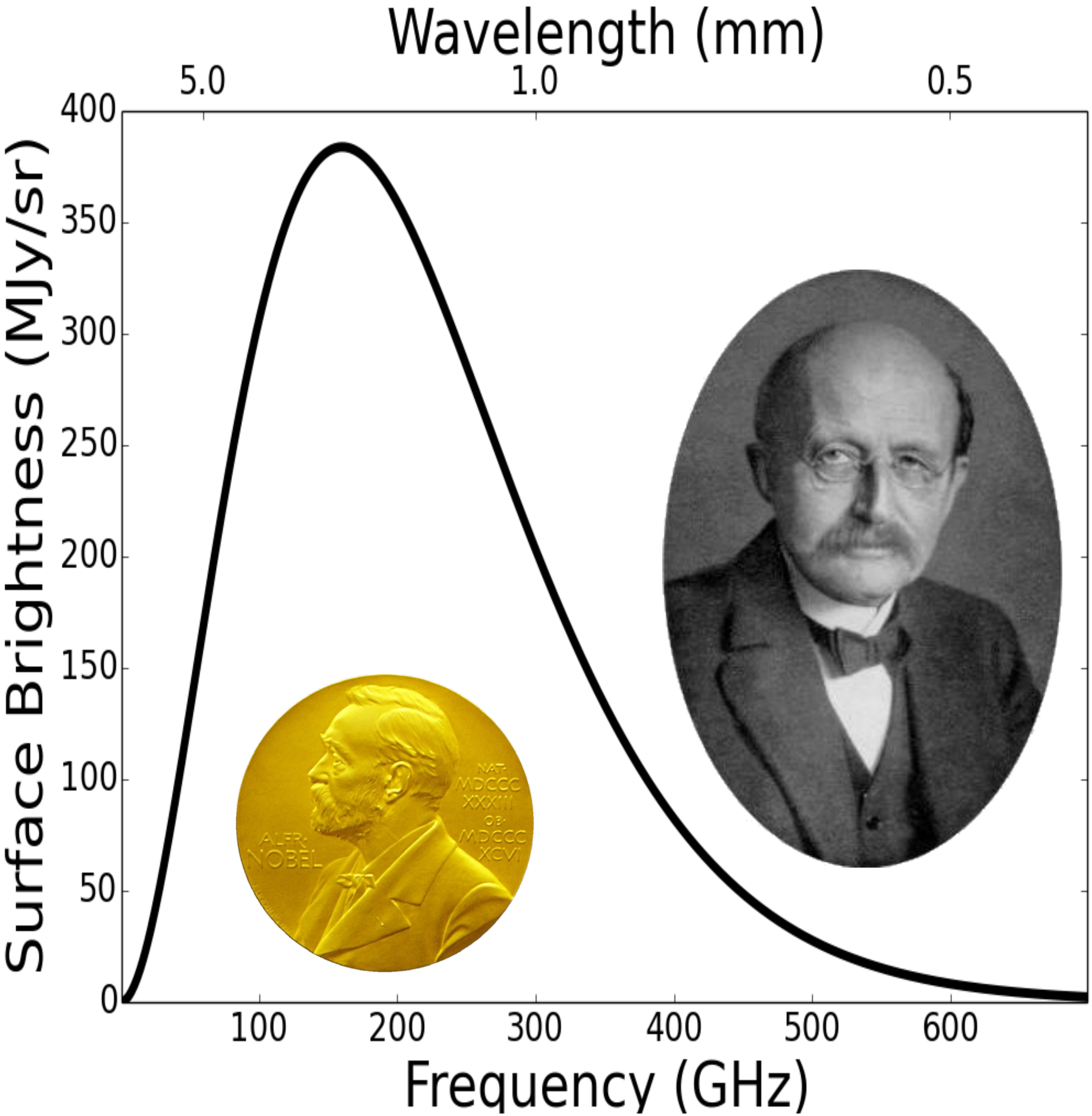
French

L'évolution de l'Univers

Le fond cosmologique était émis quand l'Univers avait ~3·10-5 de son age aujourd'hui.

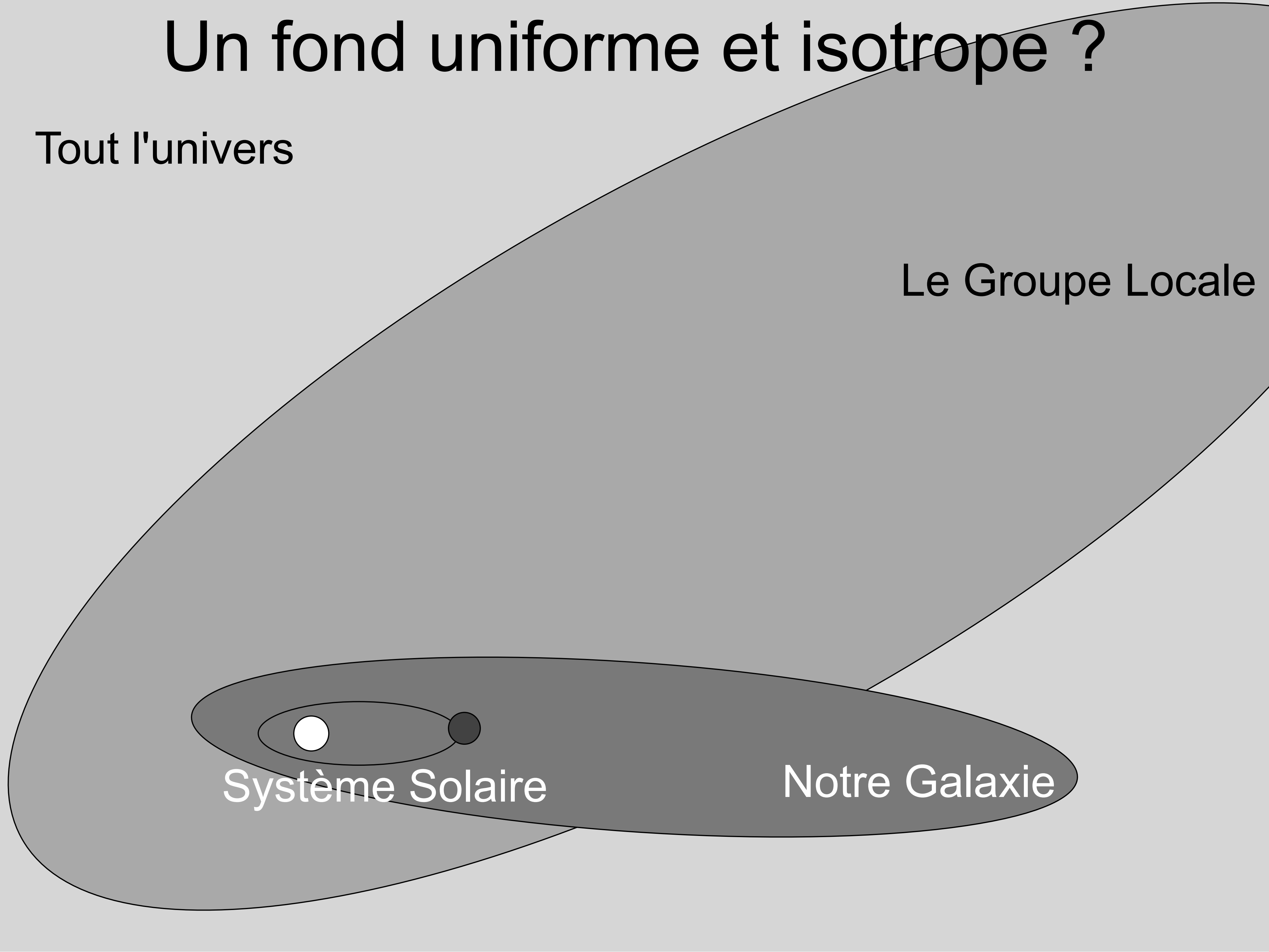


Planck & la courbe de corps noir



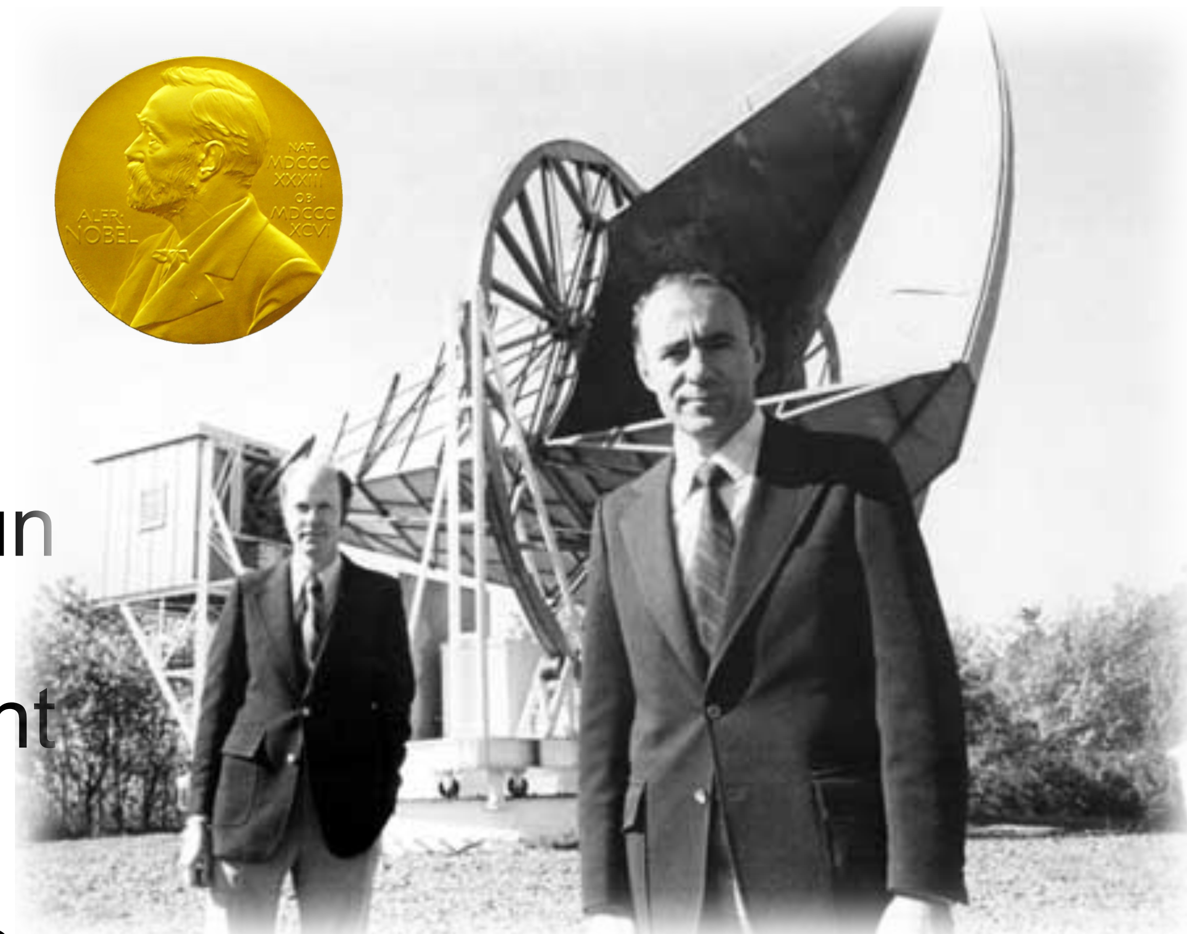
Max Planck a postulé vers 1900 qu'un corps parfaitement absorbant avec une température bien précis émettrait avec une spectre de la forme à gauche – la courbe de corps noir (ou la courbe de Planck).

Un fond uniforme et isotrope ?



Découverte : Penzias & Wilson en 1964

- Penzias & Wilson voulaient mesurer le bruit du ciel pendant communication à la radio.
- Mais ils ont mesuré un petit bruit uniforme qu'ils ne comprenaient pas.
- Ce bruit était isotrope, non-polarisé et non-variable



Ils avaient trouvé le fond cosmologique de micro-ondes par hasard

FIRAS & le corps noire

Après plusieurs années de travail pour vérifier que le Fond Cosmologique avait une spectre du forme corps noir, l'instrument FIRAS abord la satellite *COBE* l'a vérifié dans une façon définitive.

Ceci était une confirmation majeur de la théorie du Big Bang.

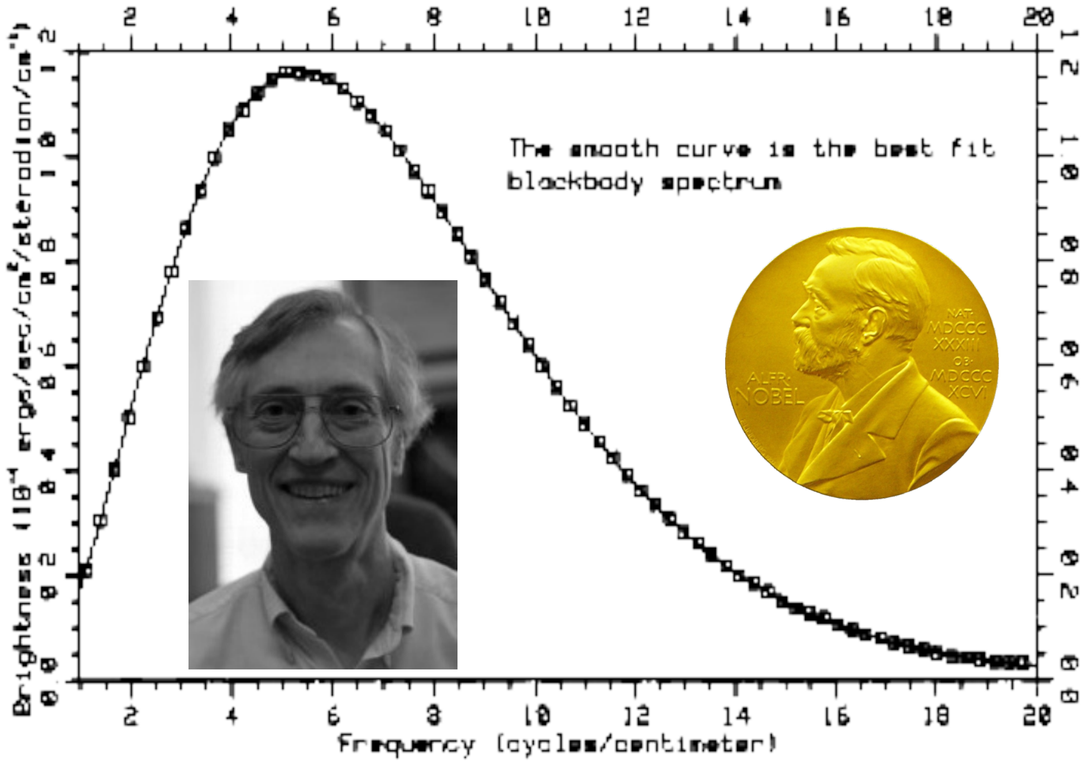
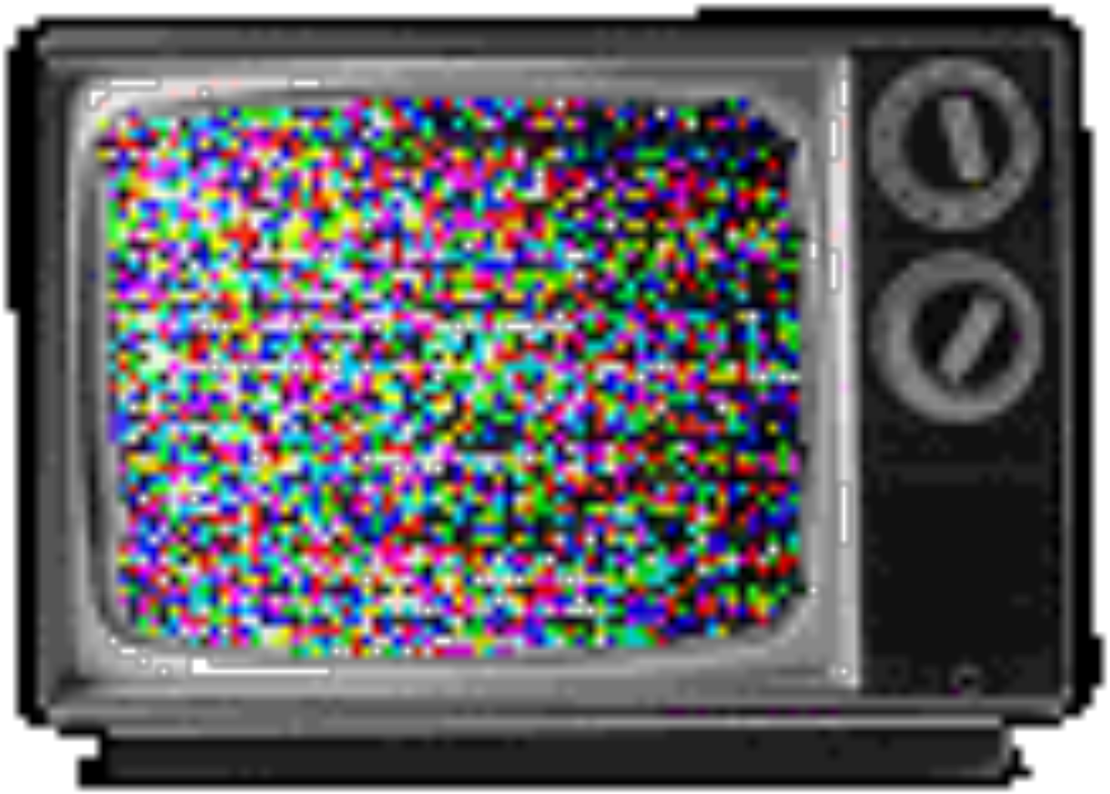


FIG. 2.—Preliminary spectrum of the cosmic microwave background from the FIRAS instrument at the north Galactic pole, compared to a blackbody. Boxes are measured points and show size of assumed 1% error band. The units for the vertical axis are 10^{-4} ergs s^{-1} cm^{-2} sr^{-1} cm.

Mather *et al.*, ApJ, 1990, **354**, L37-40.

Le fond cosmologique est partout

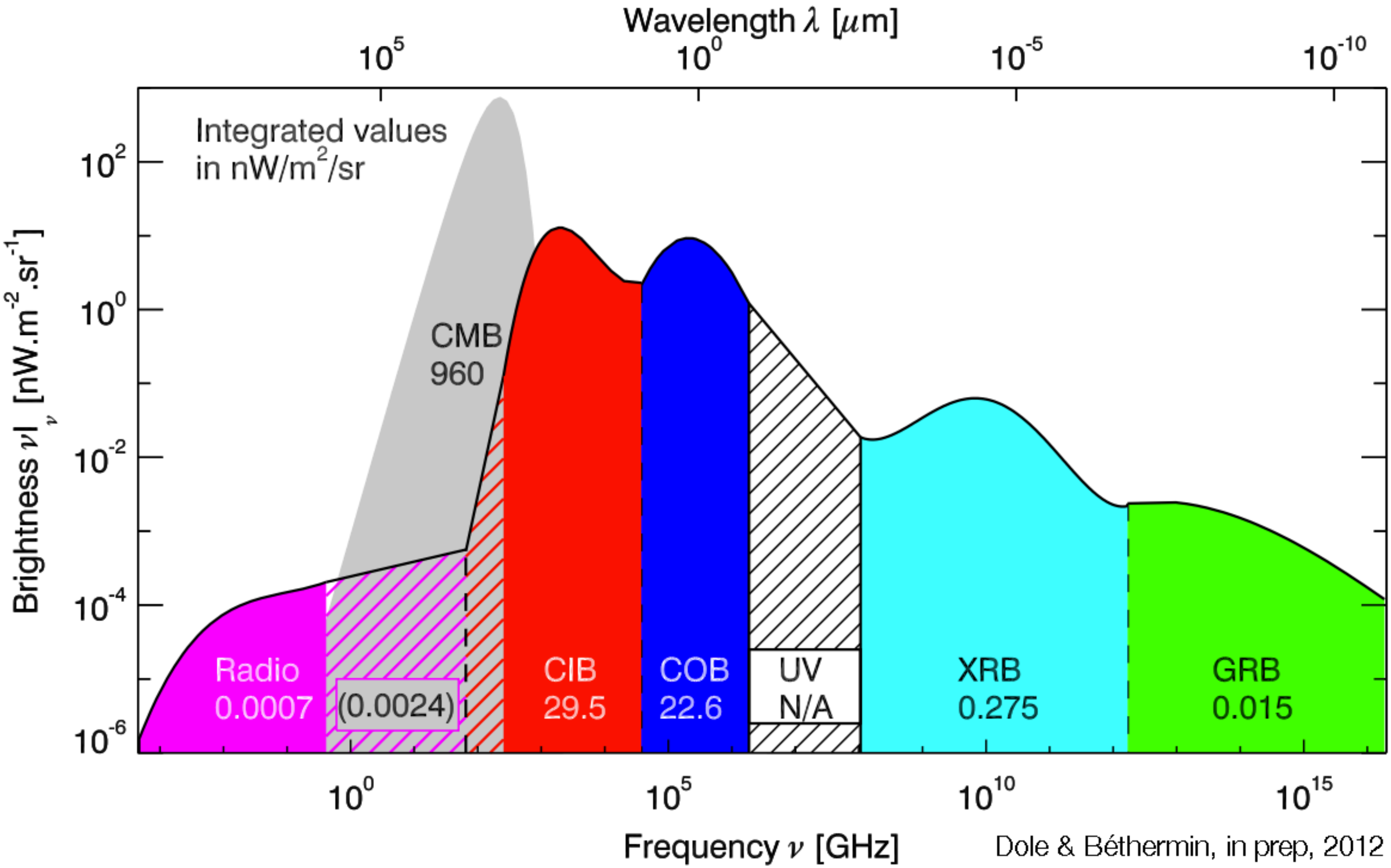
Il y a en environ de 400 photons du fond cosmologique par cm³, ou ~$4 \cdot 10^{-14}$ J/m³.



Quelques pourcents de la « neige » qu'on voit entre deux chaines (analogiques) sont du au fond cosmologique.

http://background.uchicago.edu/~whu/beginners/introduction.html

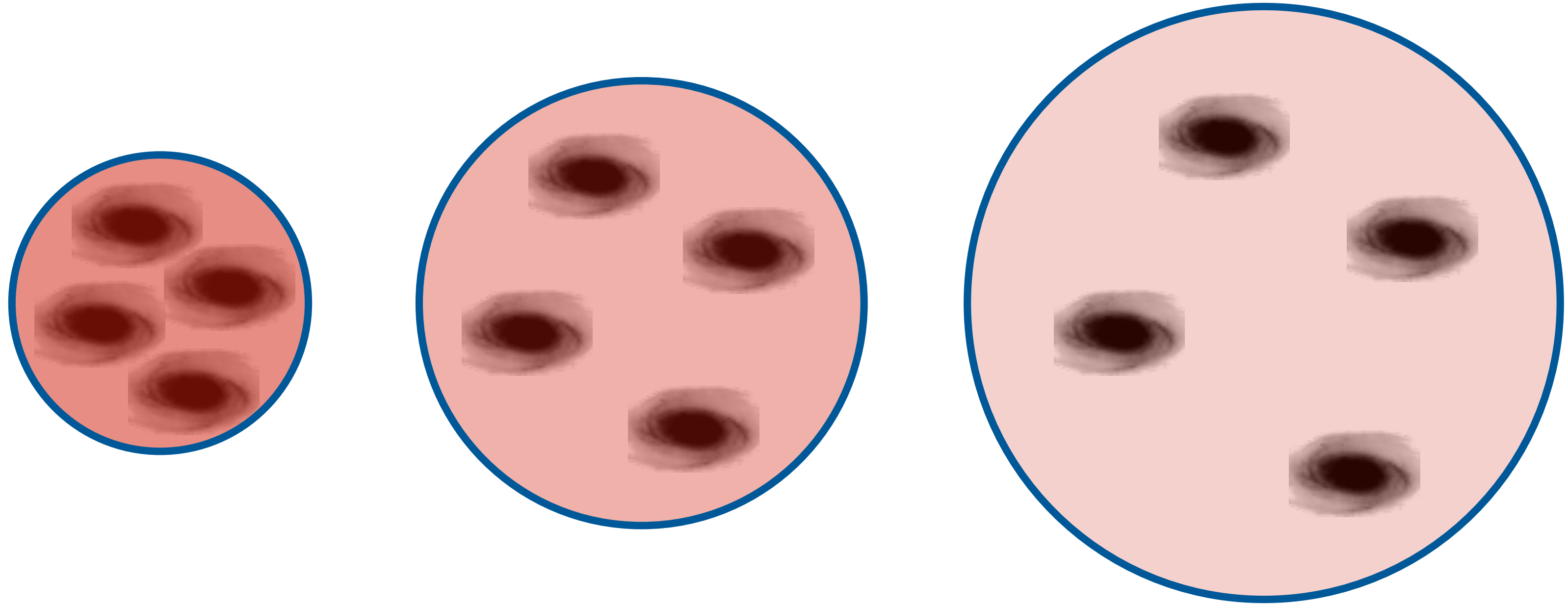
Brillances des Fonds



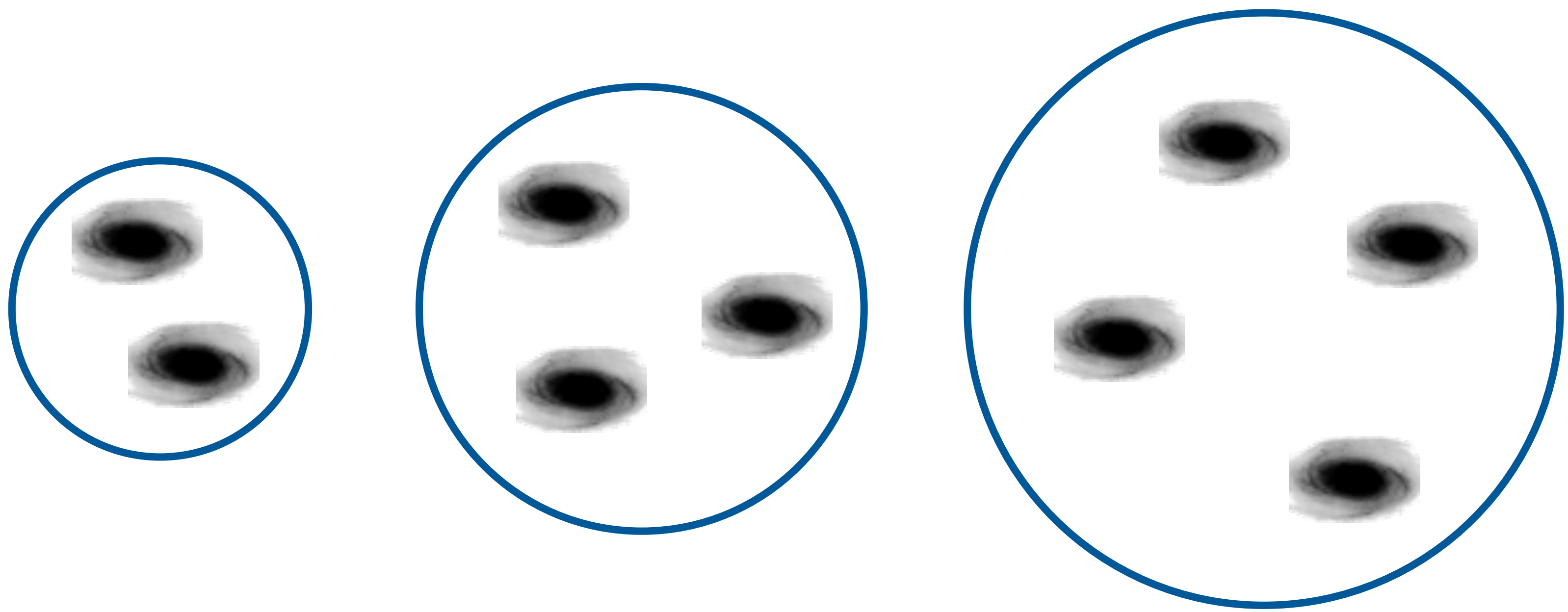
Le fond cosmologique fait la majorité de la lumière dans l'Univers.

Big Bang contre Steady State

Big
Bang
–
Explication
« naturelle »
du CMB

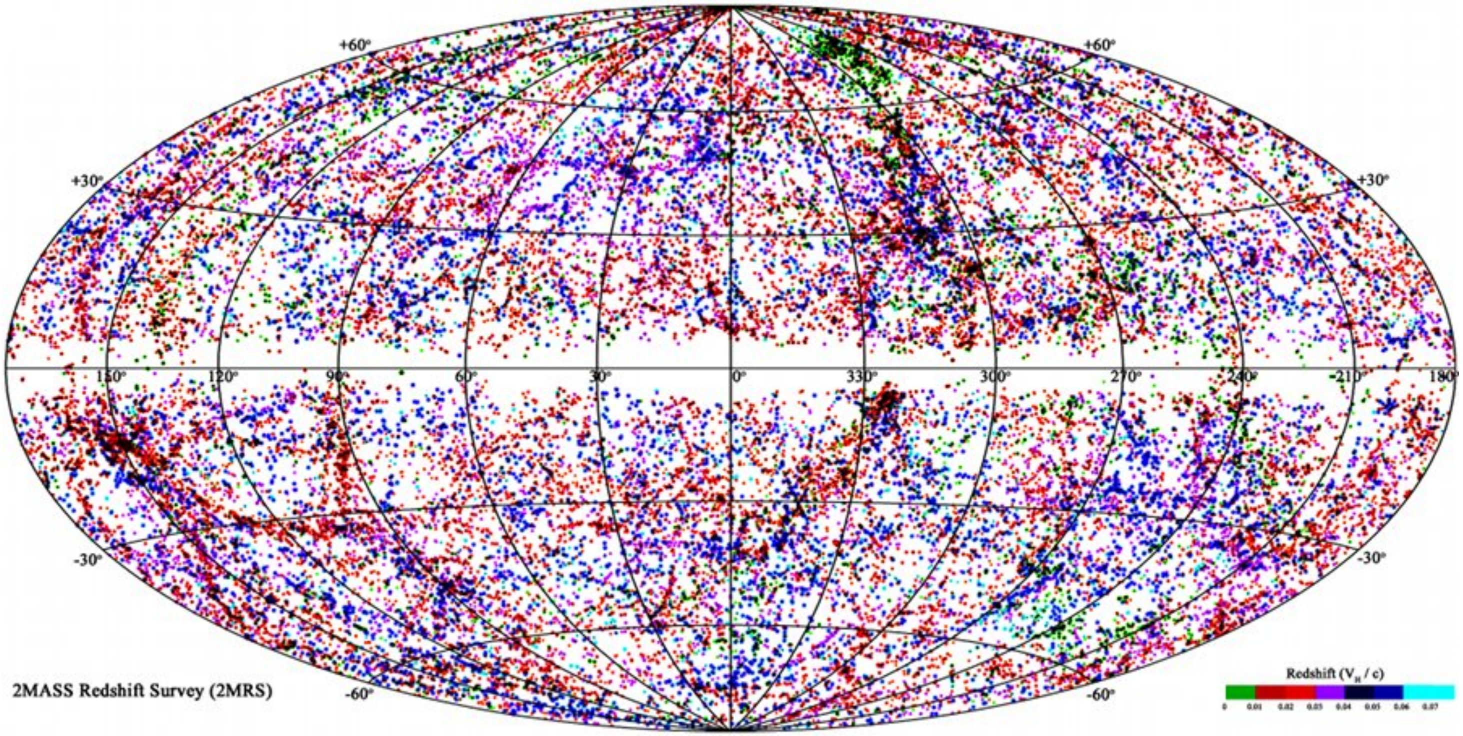


Steady
State
–
Pas
d'explication
pour l'CMB

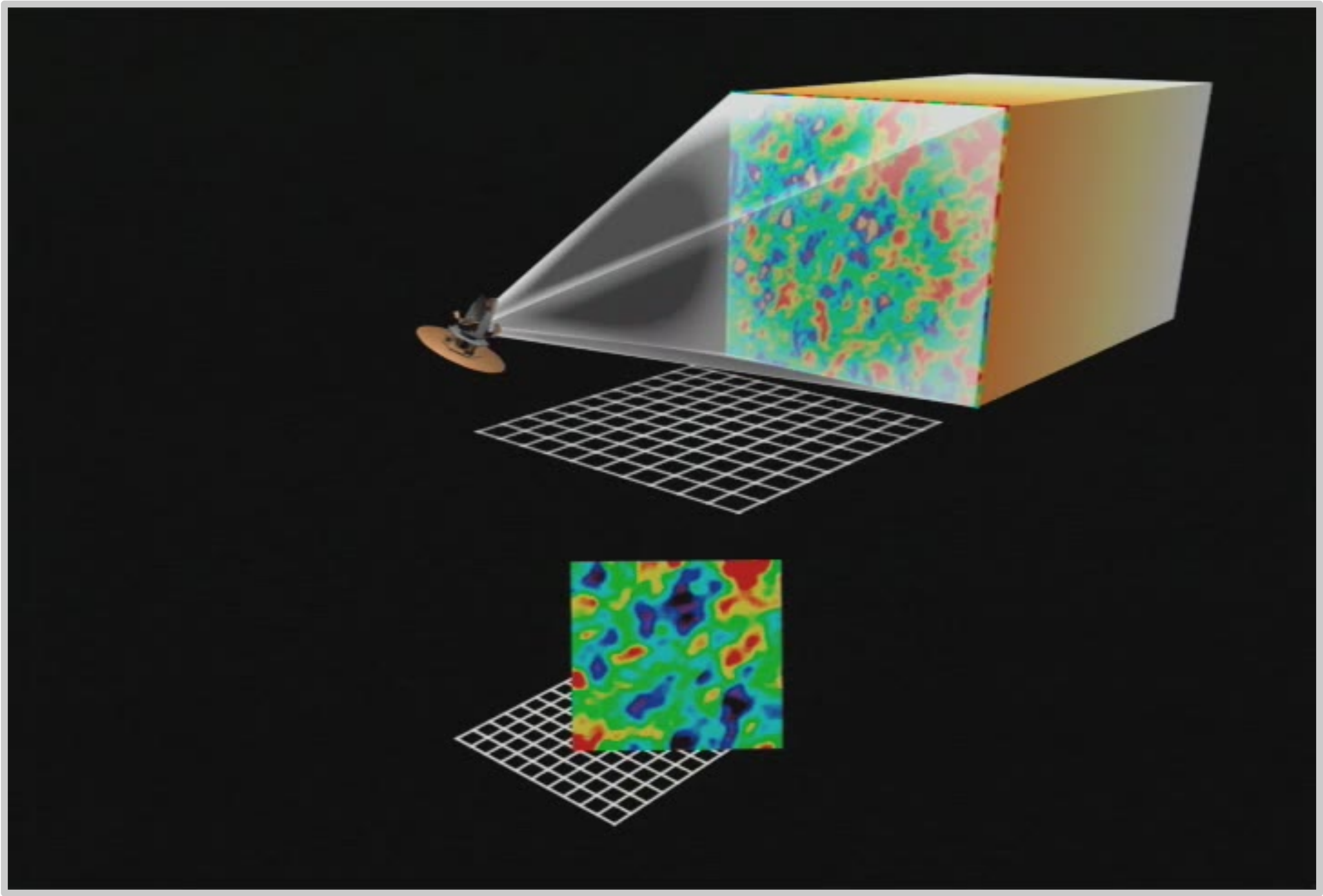


D'ou vient la « structure » de l'Univer ?

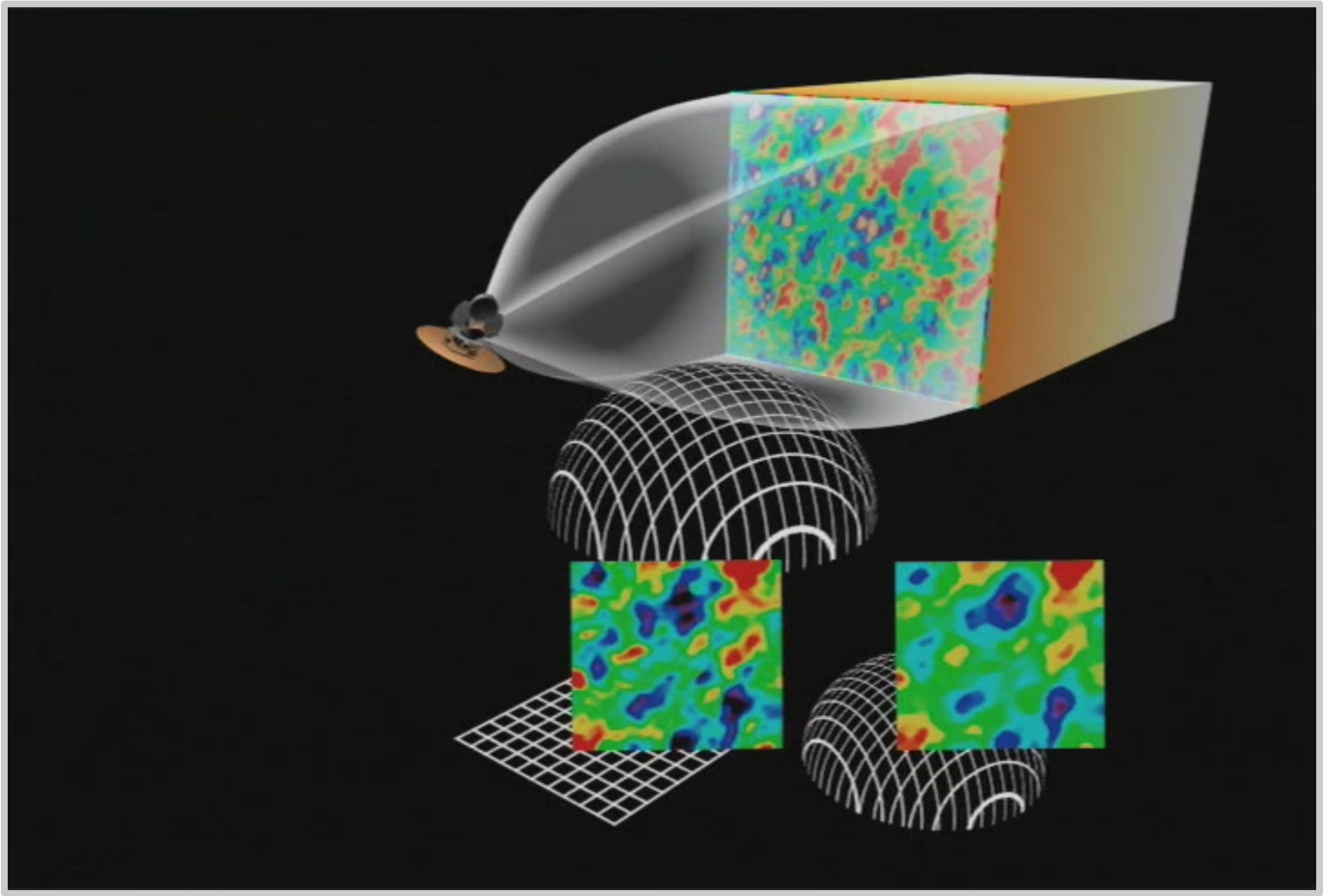
- L'Univers était très homogène au début
- Maintenant, nous voyons des étoiles, galaxies, amas de galaxies, etc.
- Comment est-ce qu'un est arrivé ici de cette situation de debut ?
- Nous pouvons chercher des faibles structures dans le fond cosmologique



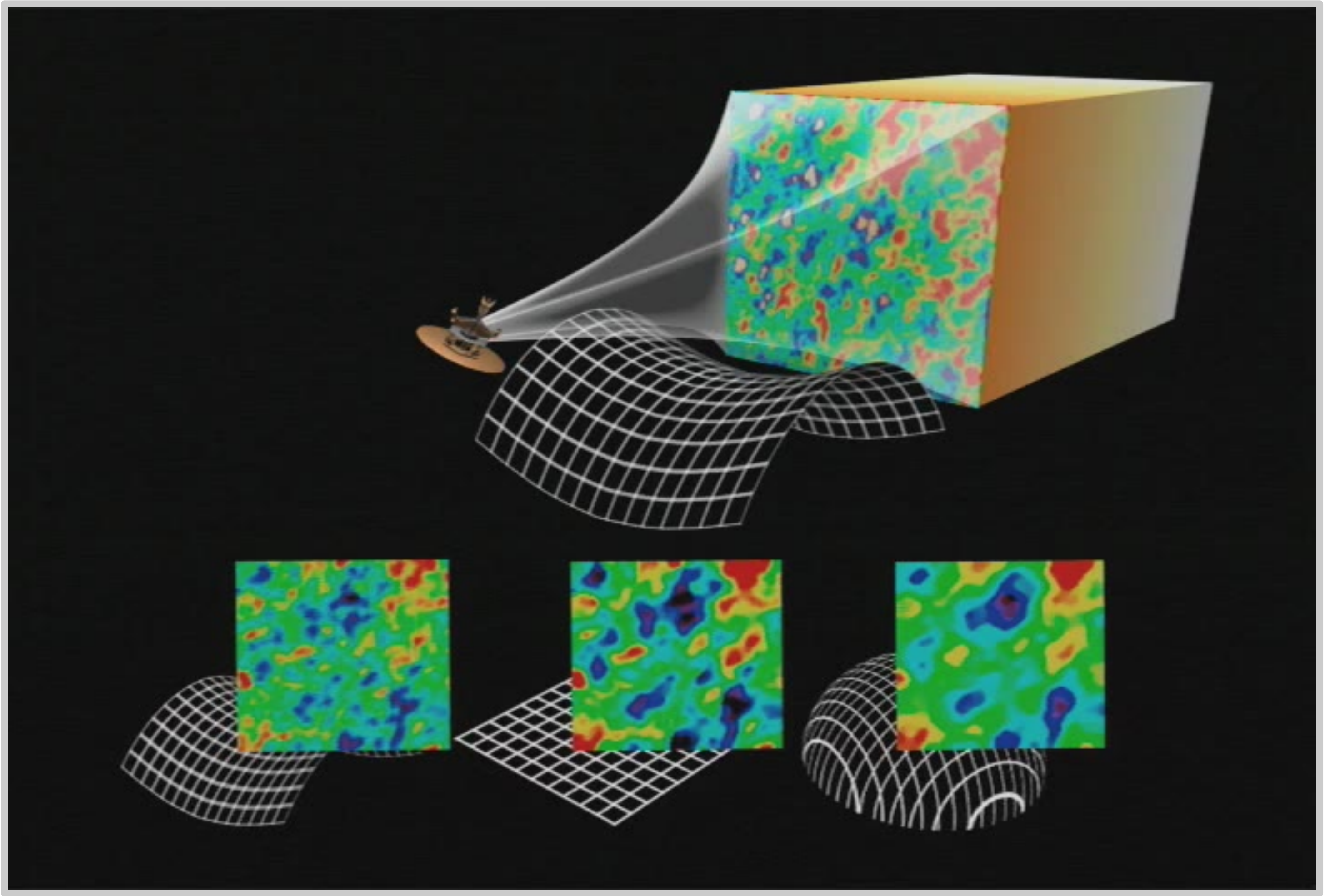
Un Univers « Plat »



Un Univers « fermé »

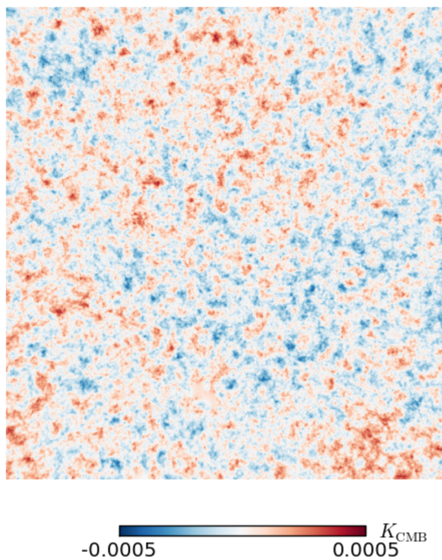


Un Univers « ouvert »



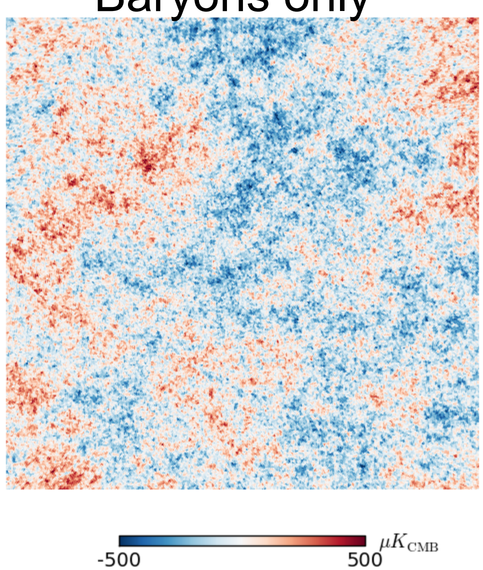
Les Composants de l'Universe

Planck

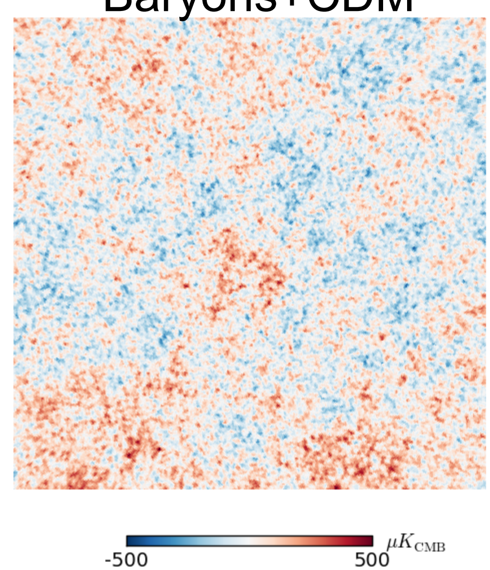


Si on ignore le bruit, les vrais donnes rassemble plus de simulations avec baryons, matière sombre et un constant cosmologique que de simulations sans un constant cosmologique ou matière non-baryonique.

Baryons only



Baryons+CDM



Baryons+CDM+Λ