(Open Questions in) Cosmology (& QUBIC)

Ken Ganga (ganga@in2p3.fr)

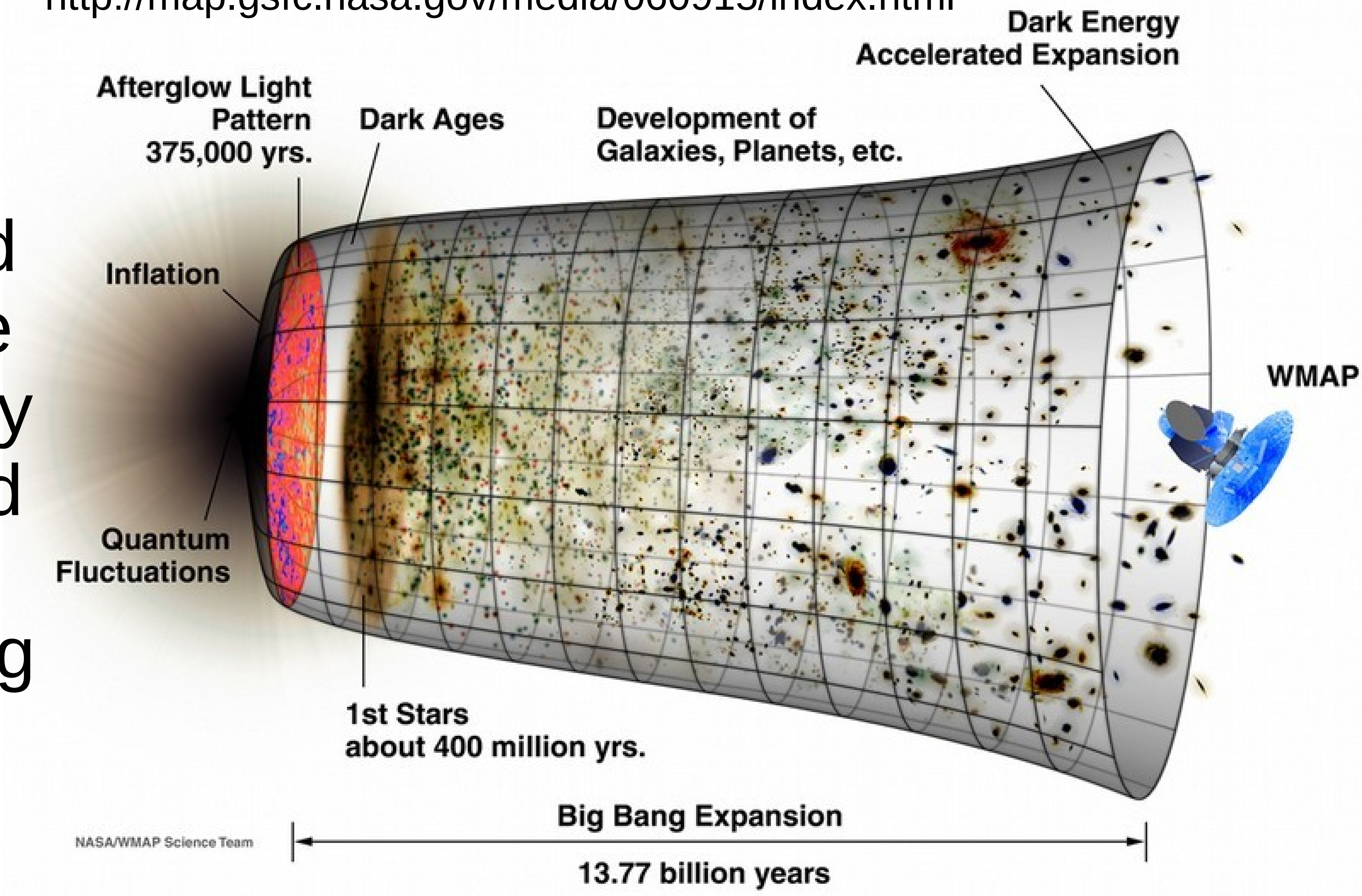
Outline :

- The CMB
- Cosmo. « Structure »
- Neutrino Masses
- Dark Matter
- Dark Energy
- Inflation

Visualize the Evolution of the Universe

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

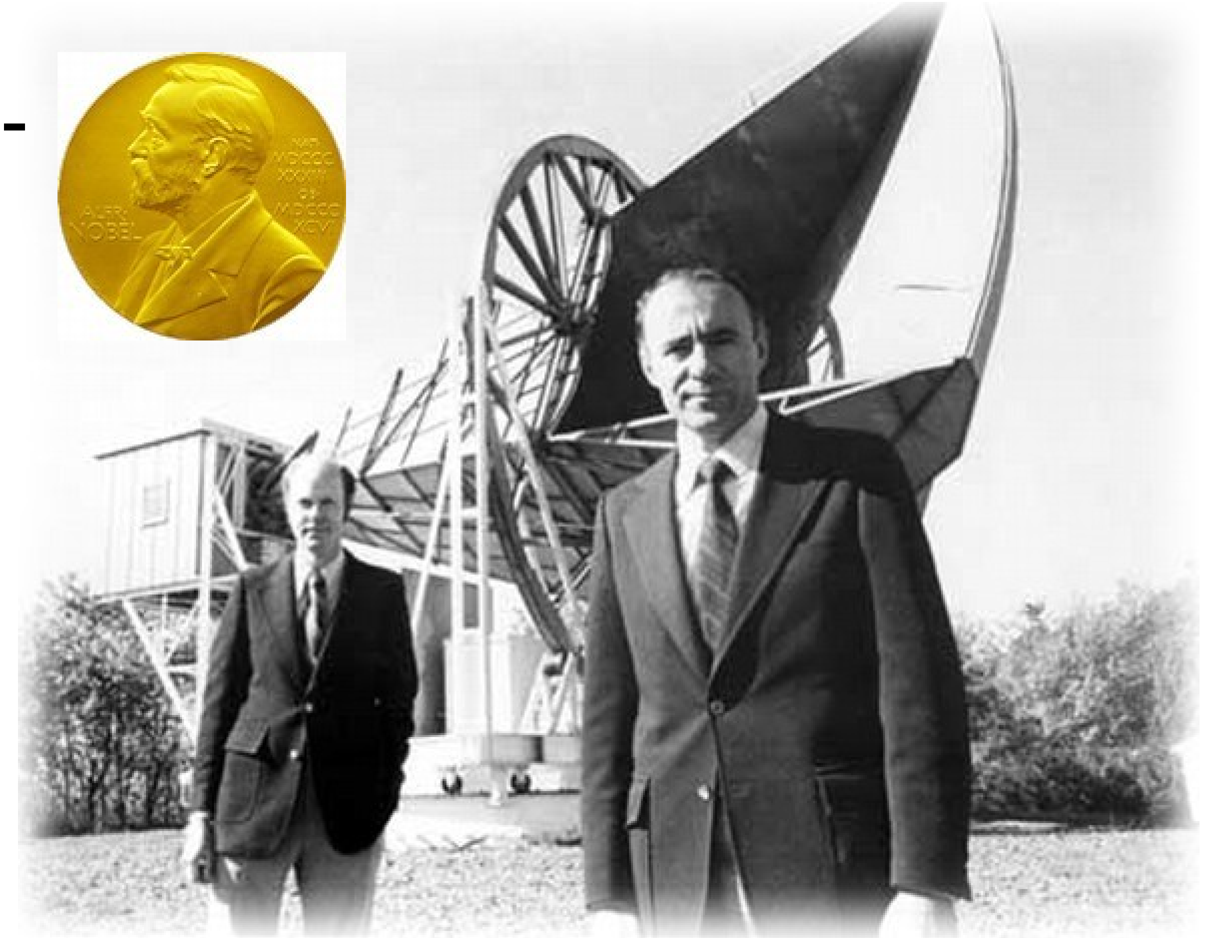
The microwave background light we are seeing today was created "just after" the Big Bang



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

CMB Discovery: Penzias & Wilson

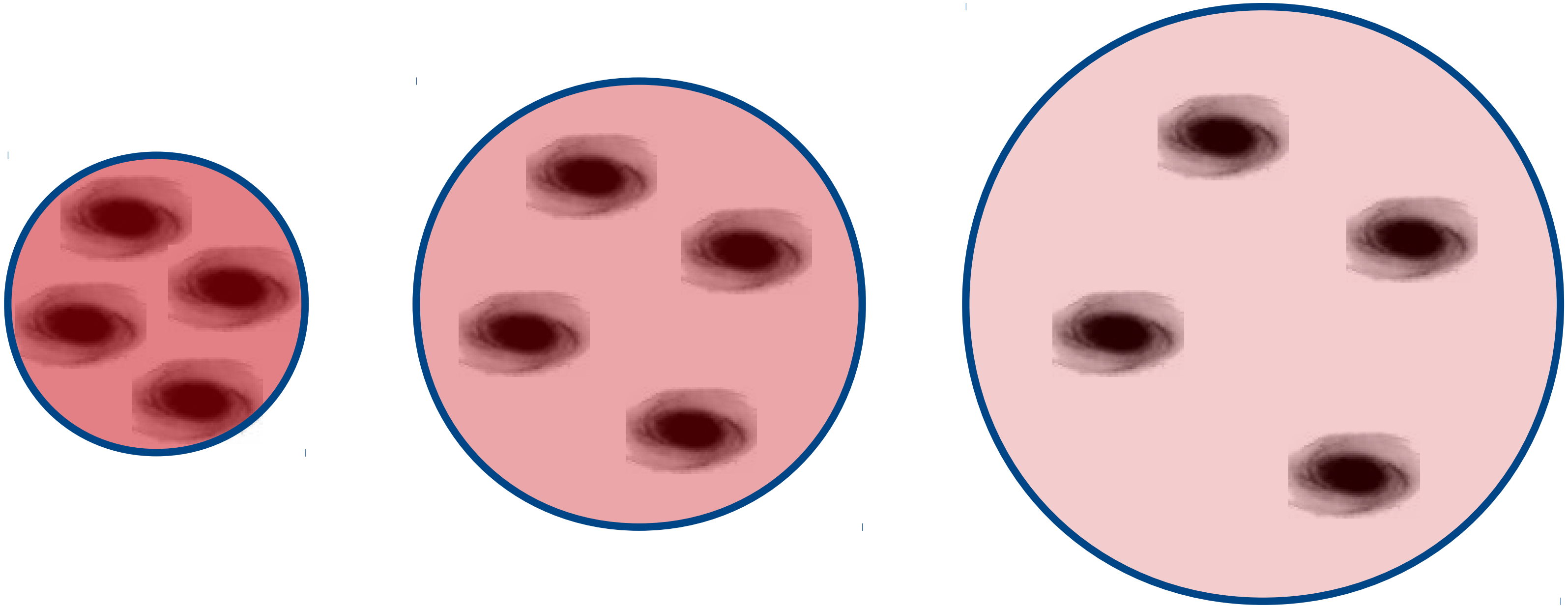
- Penzias & Wilson wanted to use a state-of-the-art telescope for radio communications.
- But they saw a small noise that they didn't understand.
- This noise was isotropic, unpolarized, and non-variable, as far as they could tell.
- This was 1964



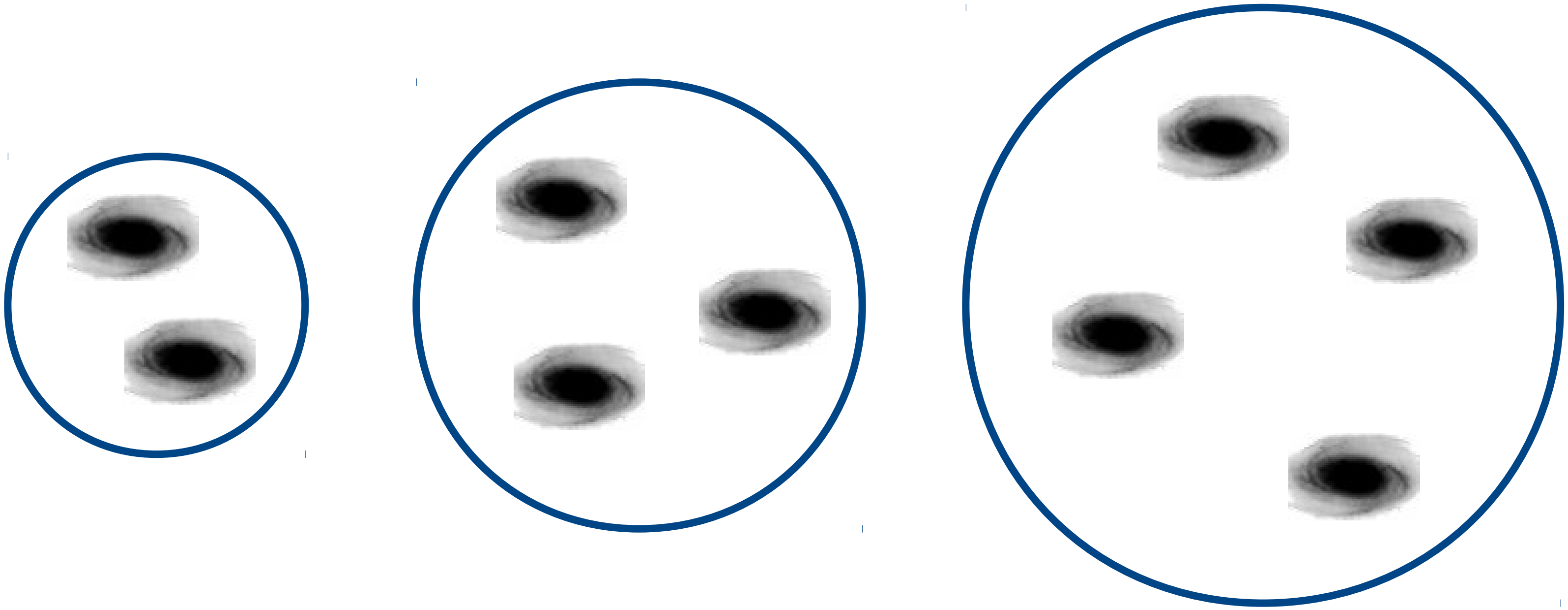
They had found the microwave background by accident!

Big Bang versus Steady State

Big
Bang
–
“Natural”
Explanation
of the CMB



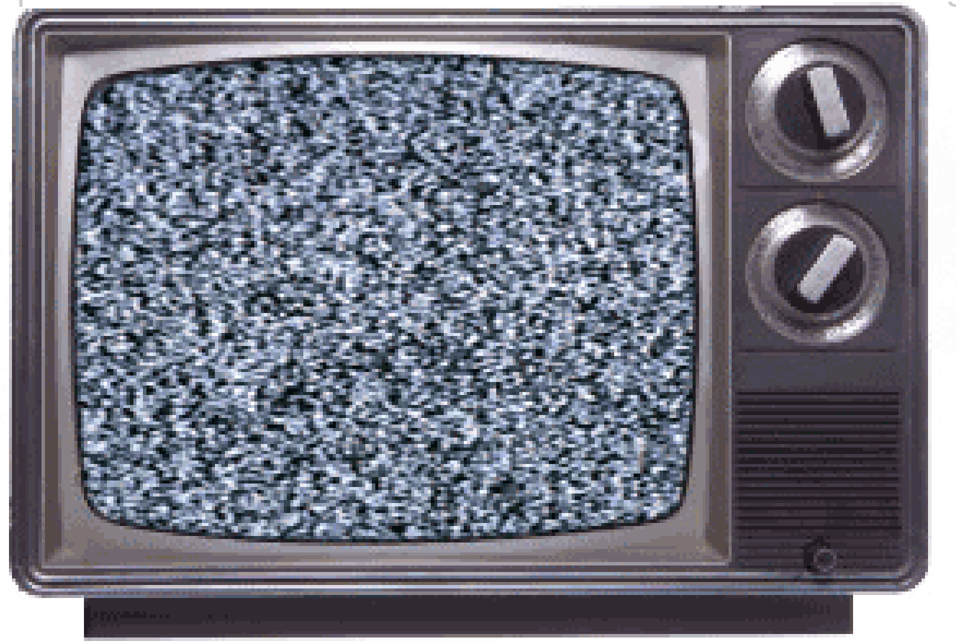
Steady
State
–
No
Explanation
for the CMB



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, $\Omega_\gamma = 5\times10^{-5}$

http://bestanimations.com/Electronics/animated-tv-static-4.gif

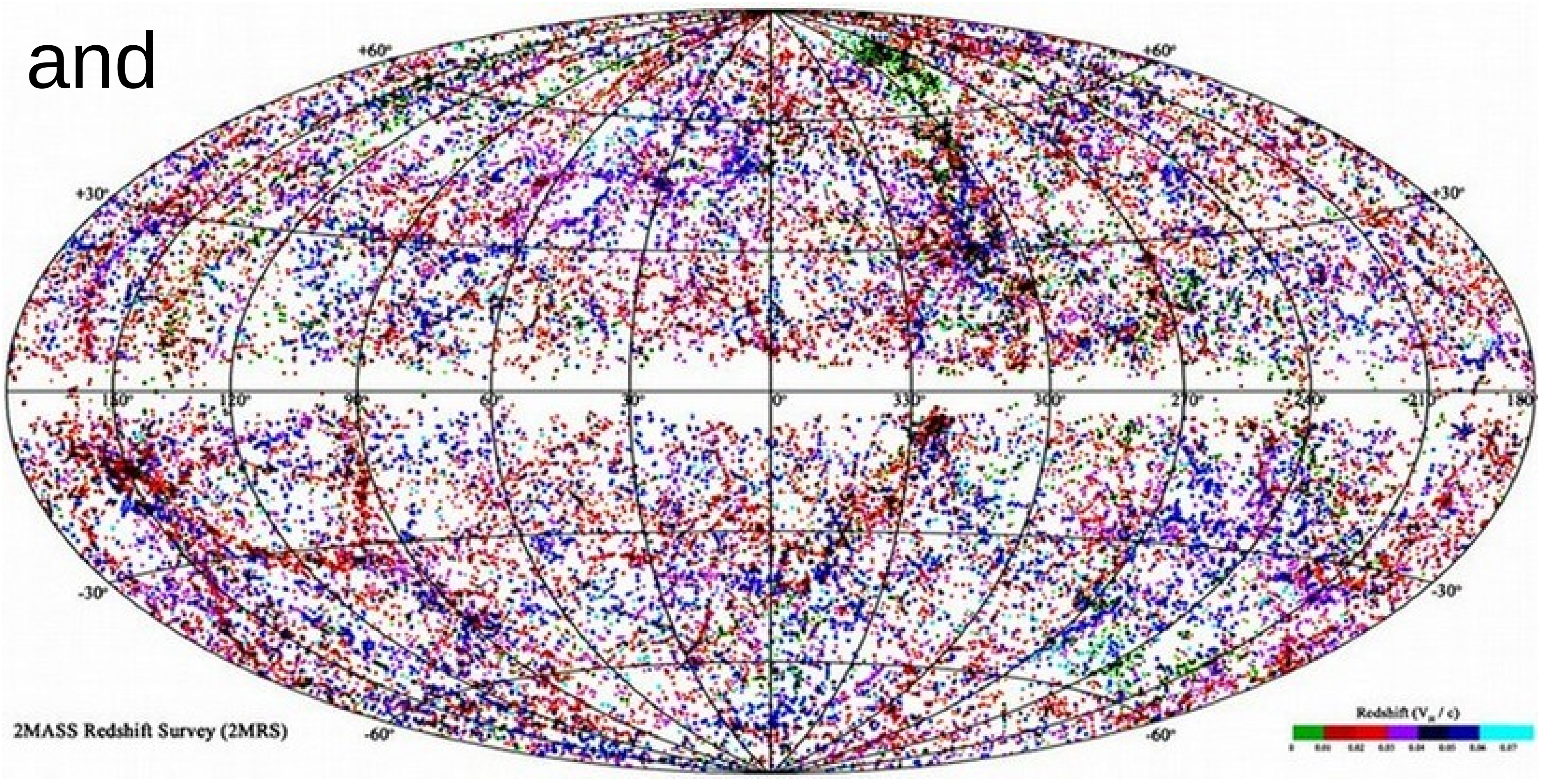


A few percent of the TV "snow" you see between channels comes from the microwave background (if you have an old, analog TV).

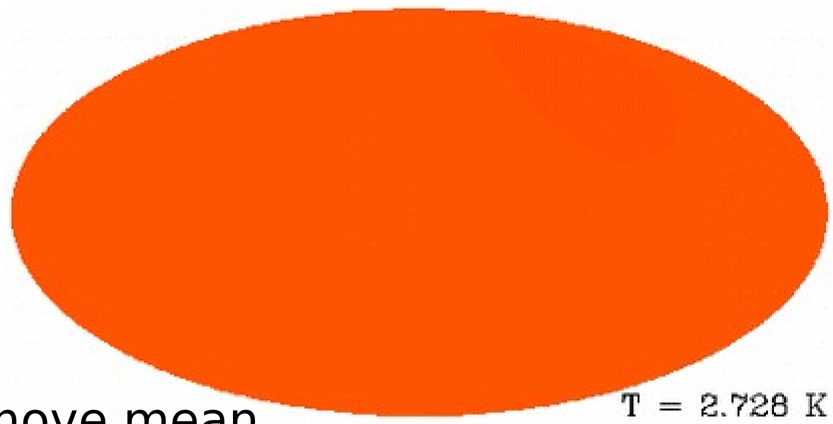
What About Structure in the Universe?

- The Universe was initially very homogeneous.
- Today we see stars, galaxies, clusters of galaxies, and so on.

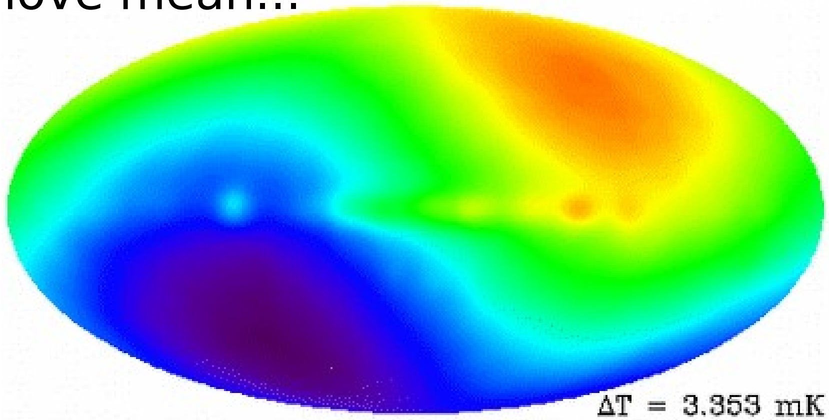
- How can we reconcile these points?
- To learn more, we search for small variations in the CMB



Dipole Anisotropy



remove mean...



$$\frac{\delta f}{f} \approx -\frac{v}{c}\cos(\theta) + O\left(\frac{v^2}{c^2}\right)$$

$$\Longrightarrow \quad v \approx \frac{\Delta T_{dipole}}{T_{cmb}} \cdot c$$

The solar system moves with respect to the CMB rest frame

Doppler shifting results in a (mostly) dipolar anisotropy

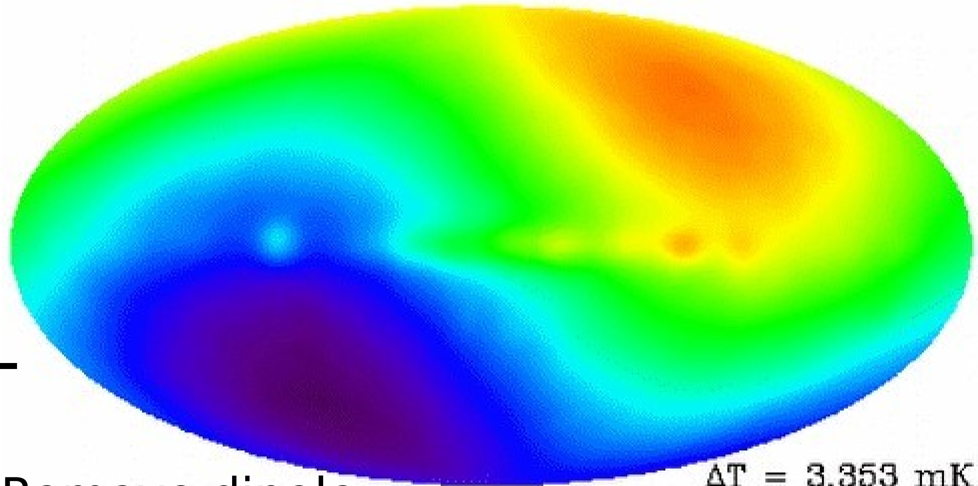
Predicted in ~1968. First measured in the 1970s.

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

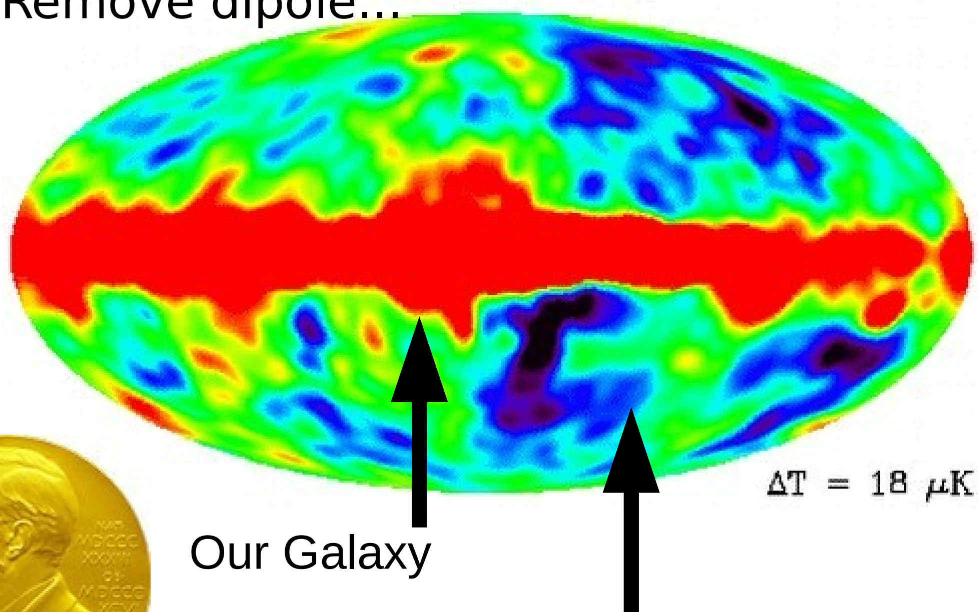
CMB « Anisotropies »

Remove the CMB “monopole”, the dipole & Ignore the Galaxy.

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



Remove dipole...



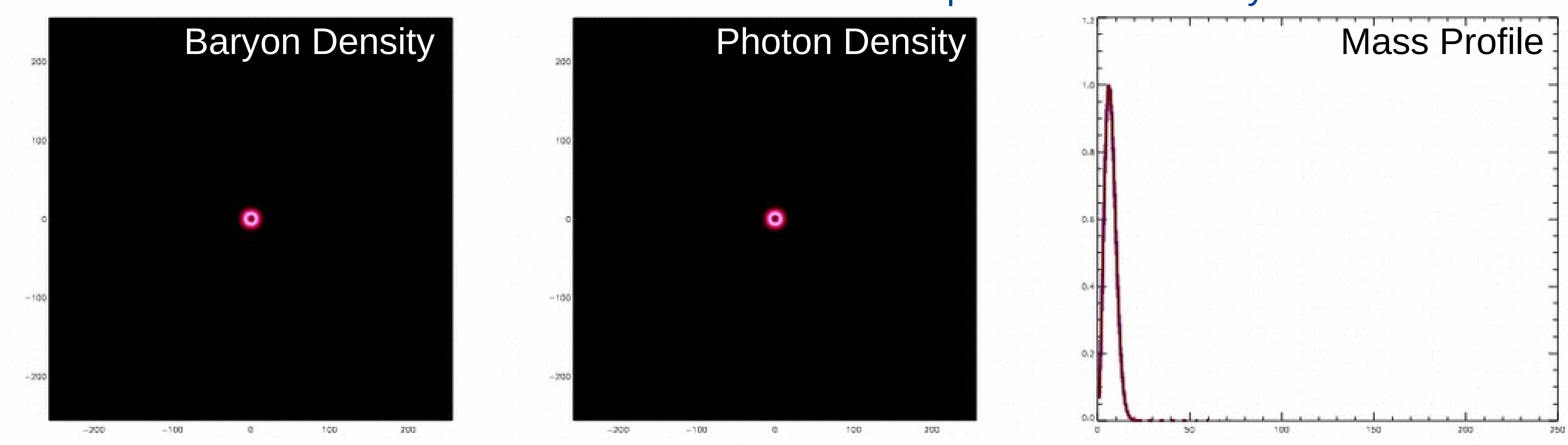
Our Galaxy

Anisotropies

COBE/DMR & George Smoot

An Initial « Perturbation »

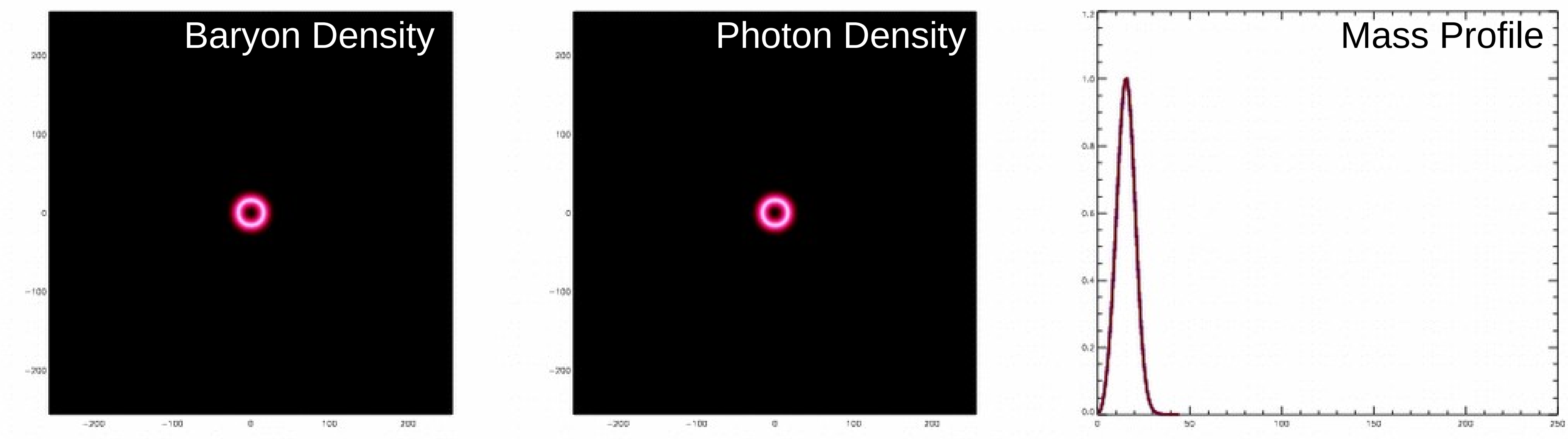
http://w.astro.berkeley.edu/~mwhite/bao/



- The plasma is totally uniform except for an excess of matter at the origin.
- High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.

Initial Expansion

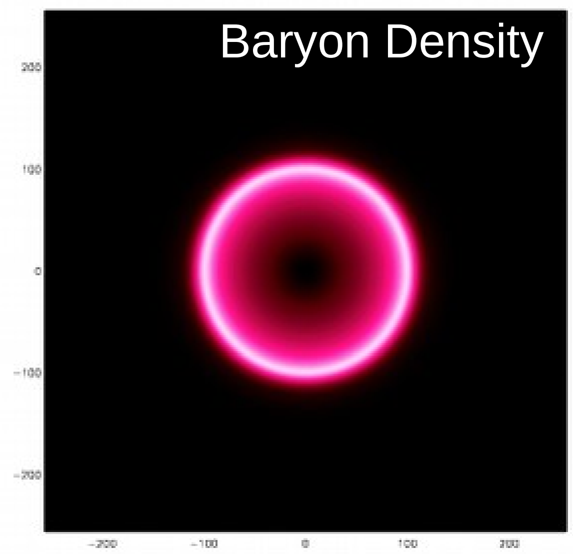
http://w.astro.berkeley.edu/~mwhite/bao/

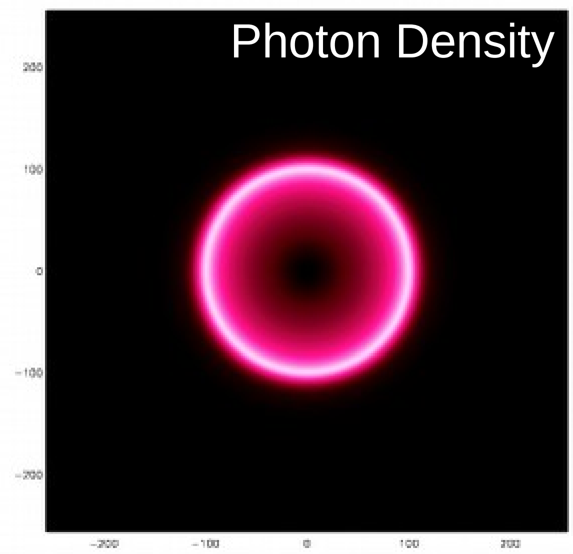


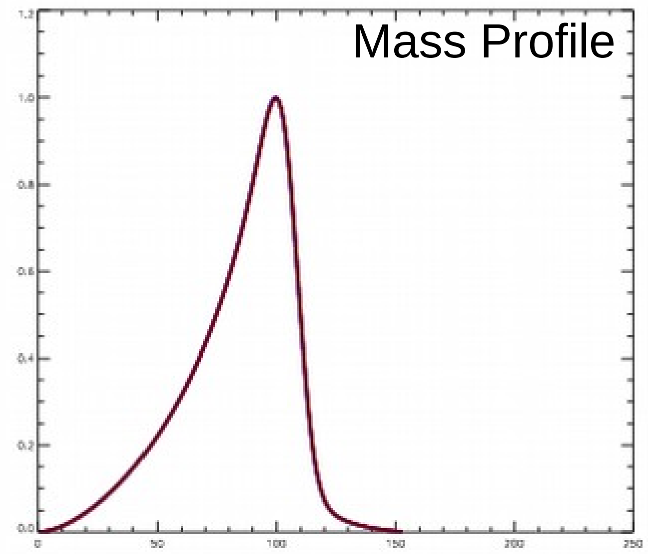
- Initially both the photons and the baryons move outward together
- The radius of the shell moving at over half the speed of light

Continued Expansion

http://w.astro.berkeley.edu/~mwhite/bao/



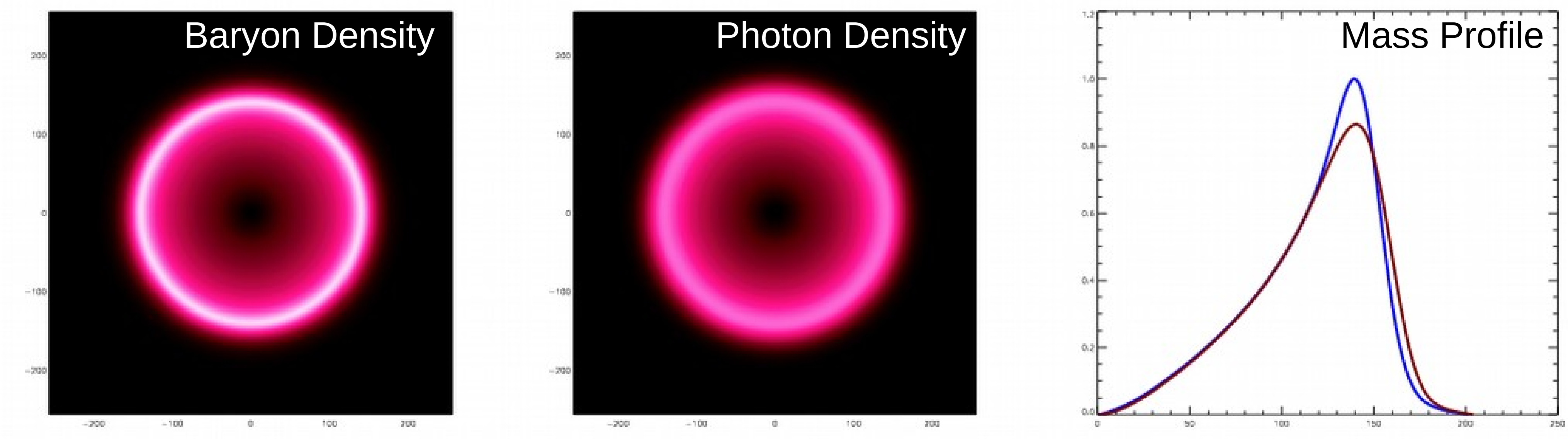




- This expansion continues for 10^5 years

« Recombination »

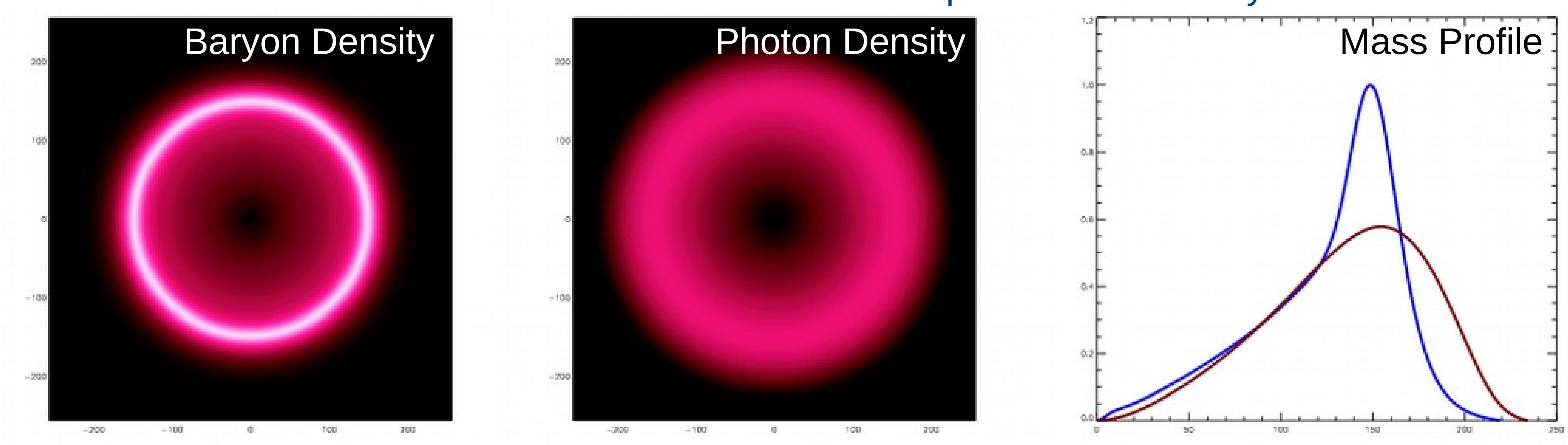
http://w.astro.berkeley.edu/~mwhite/bao/



- After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen.
- This decouples the photons from the baryons.
- The former quickly stream away, leaving the baryon peak stalled.

Photon-Baryon Separation

http://w.astro.berkeley.edu/~mwhite/bao/



- The photons continue to stream away
- the baryons, having lost their motive pressure, remain in place.

Photon-Baryon Separation

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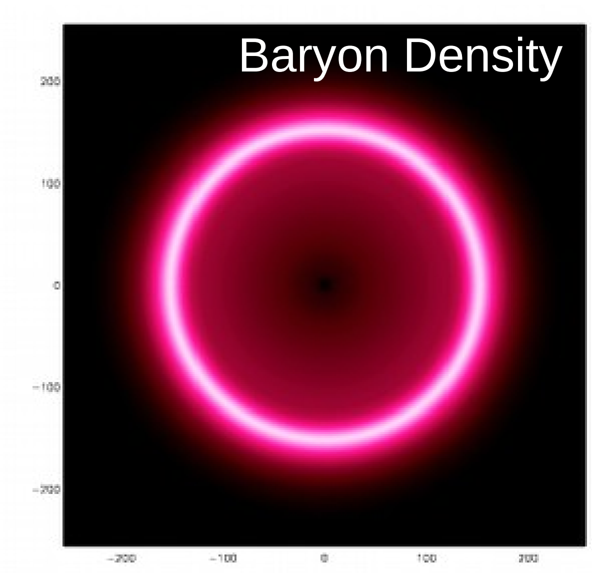

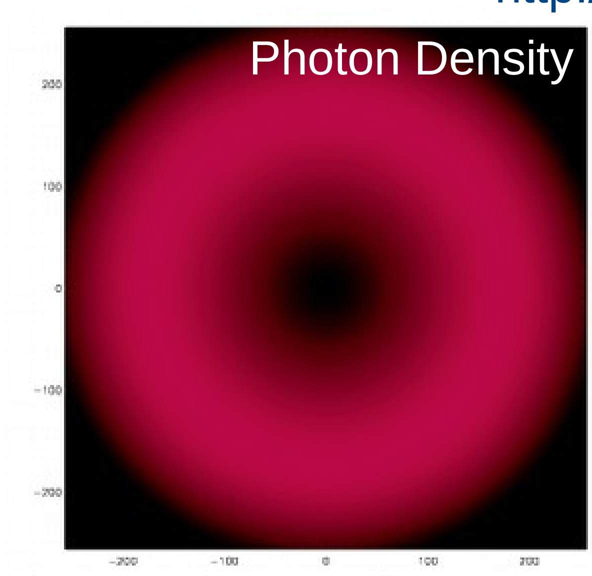

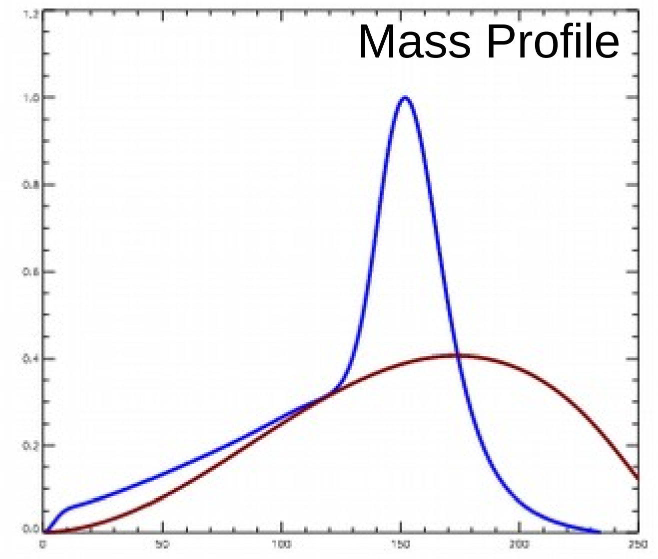

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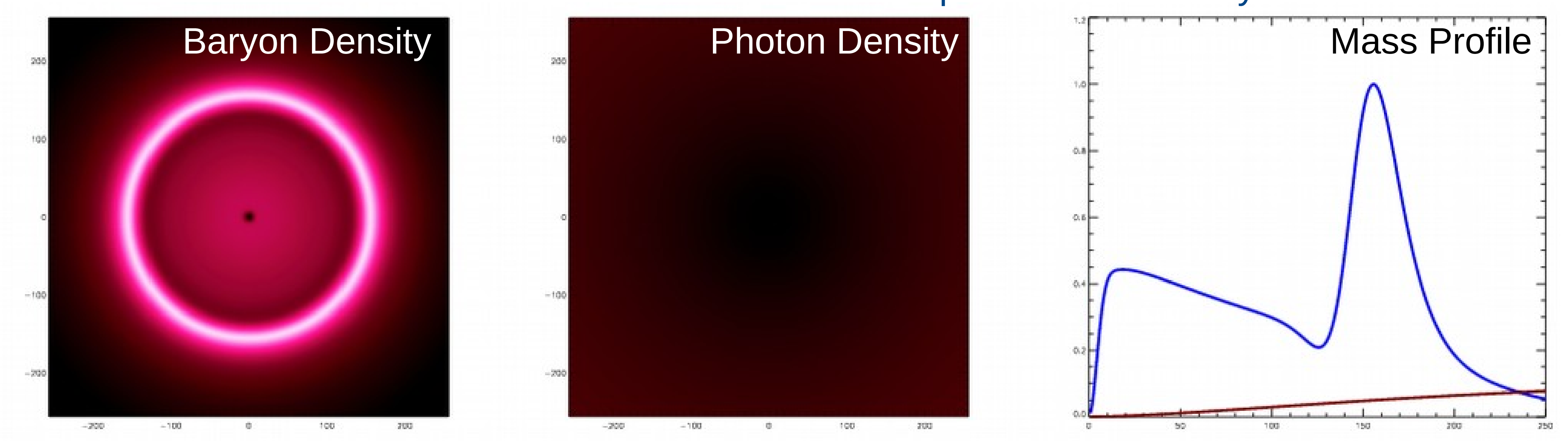
Baryonic « Shells »

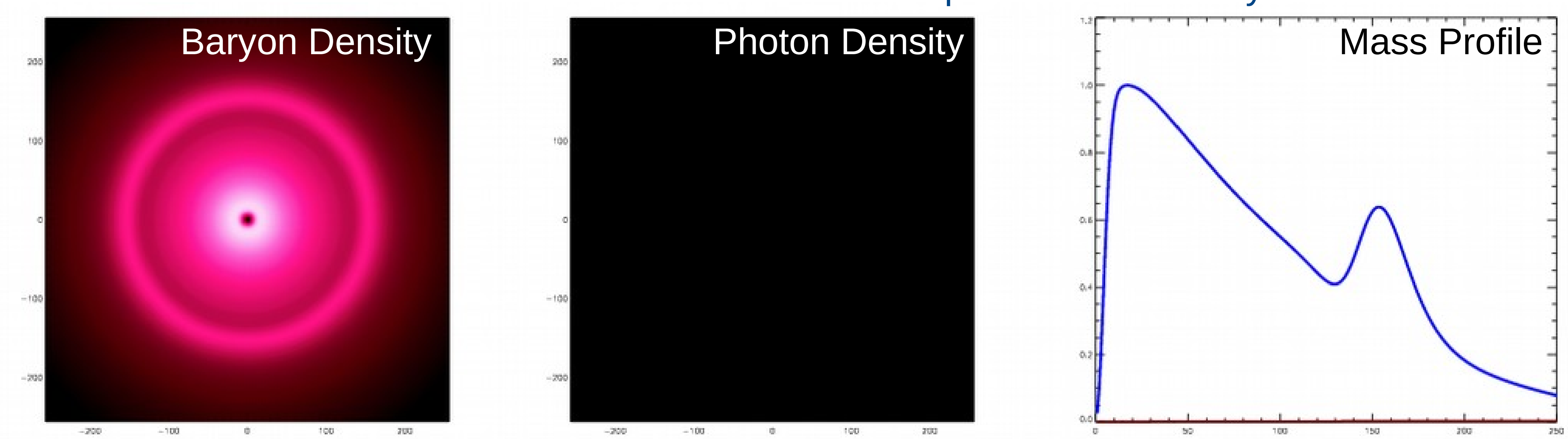
http://w.astro.berkeley.edu/~mwhite/bao/



- The photons have become almost completely uniform
- The baryons remain overdense in a shell 100Mpc in radius.
- The large gravitational potential well which we started with starts to draw material back into it.

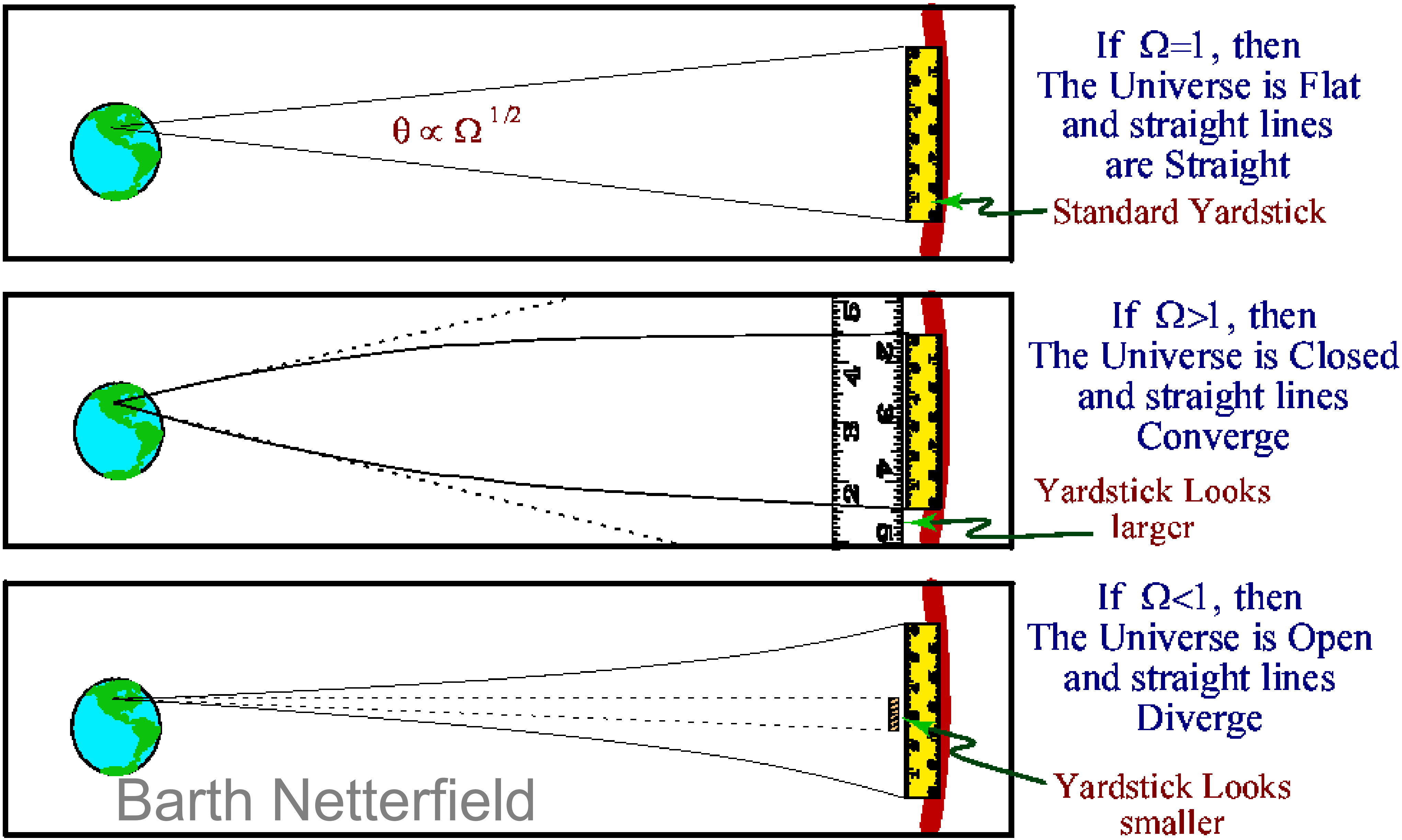
What we see today

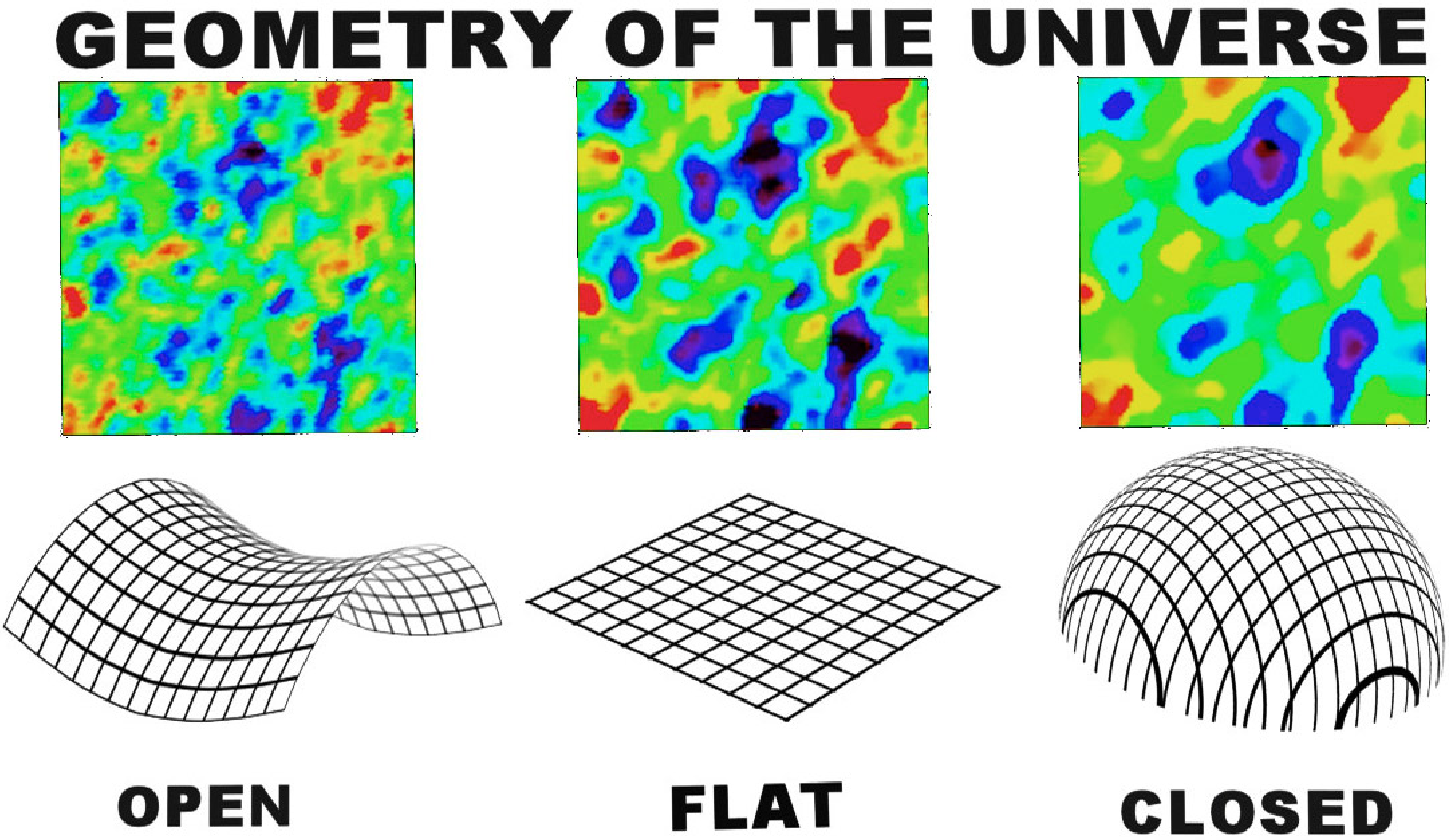
http://w.astro.berkeley.edu/~mwhite/bao/



- As the perturbation grows by O(1000) the baryons and DM reach equilibrium densities in the ratio Wb/Wm.
- The final configuration is our original peak at the center (which we put in by hand) and an echo in a shell roughly 100Mpc in radius. The radius of this shell is known as the sound horizon.

The Curvature of the Universe

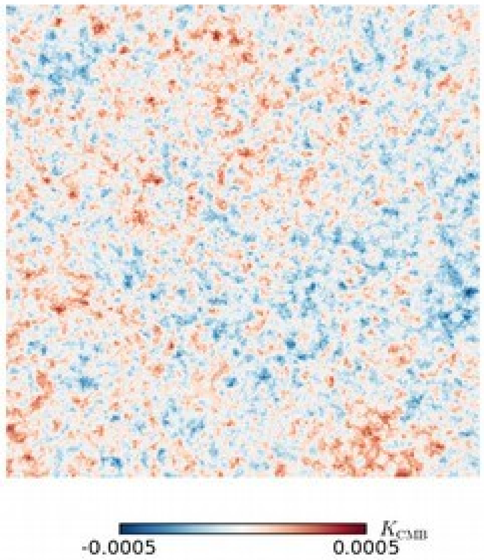




- Smaller characteristic scales indicate a closed Universe
- Larger characteristic scales indicate an open Universe

The Constituents of the Universe

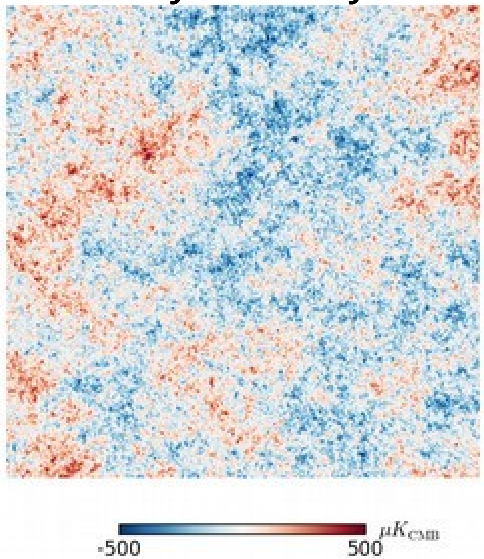
Planck



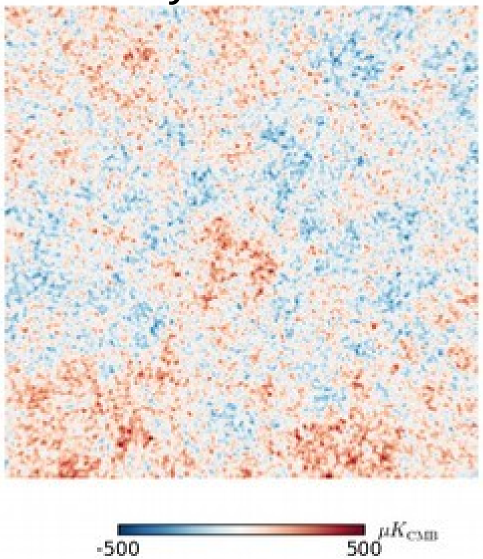
The real data resemble simulations with "normal" matter, cold dark matter and a cosmological constant than they do simulations missing any of these three components.

This is strong evidence for Dark Sector Physics

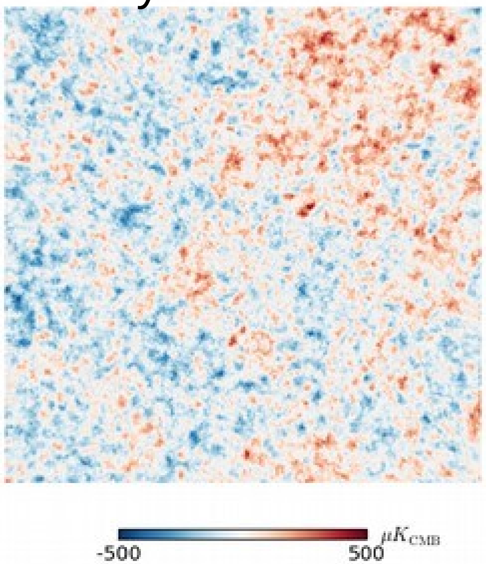
Baryons only



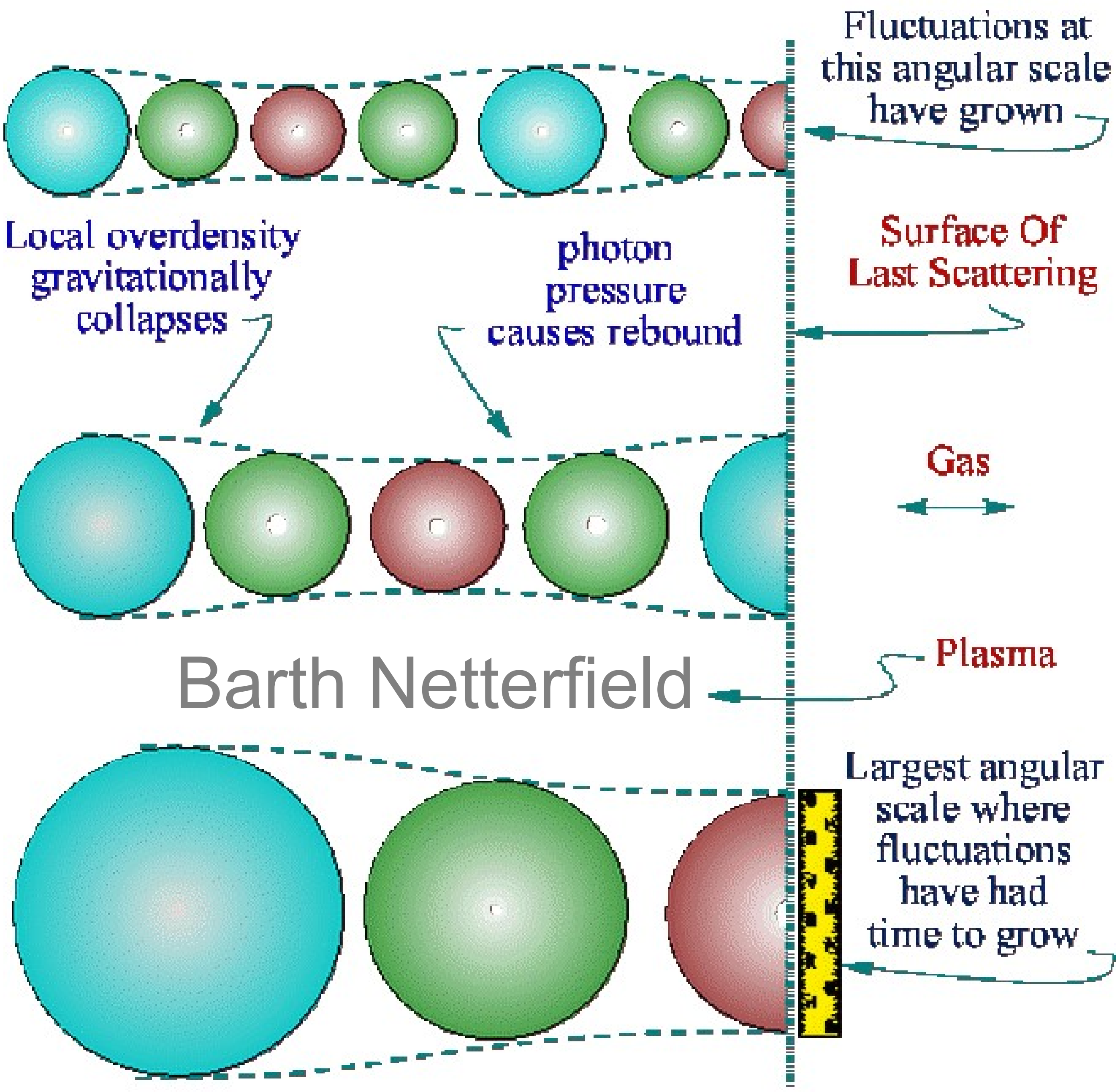
Baryons+CDM



Baryons+CDM+Λ



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 CMB Power Spectrum

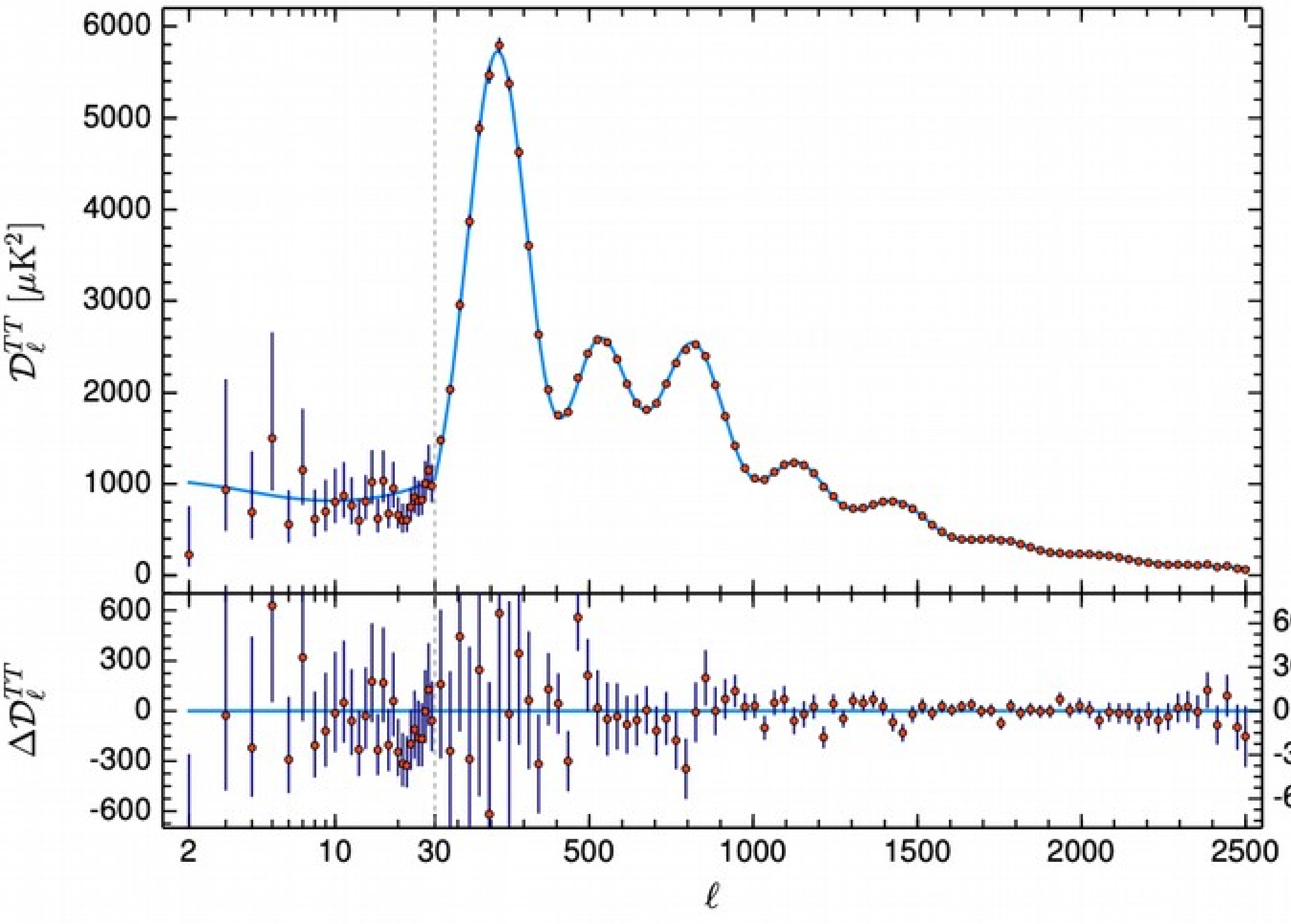
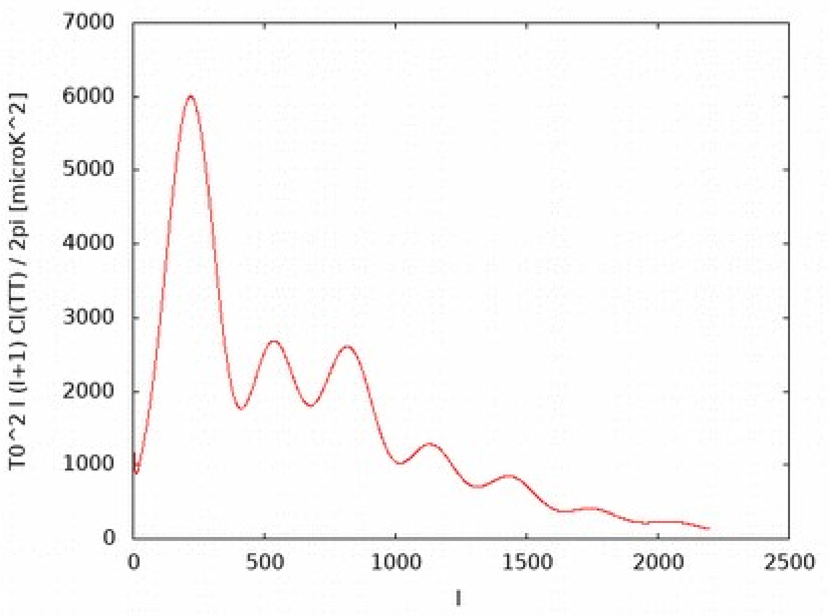
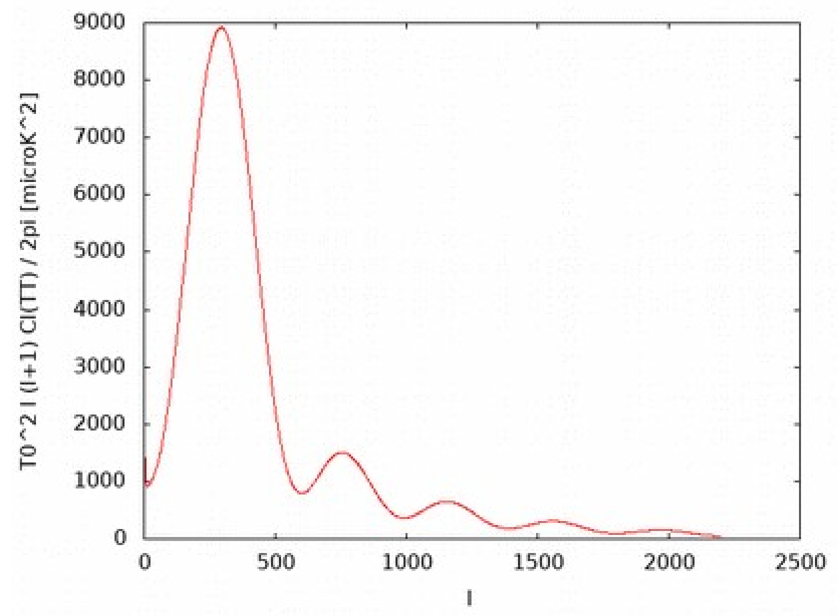


Fig. 1. *Planck* 2018 temperature power spectrum. At multipoles $\ell \geq 30$ we show the frequency-coadded temperature spectrum computed from the `Plik` cross-half-mission likelihood, with foreground and other nuisance parameters fixed to a best fit assuming the base-ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm, computed over 86 % of the sky. The base-ΛCDM theoretical spectrum best fit to the *Planck* TT,TE,EE+lowE+lensing likelihoods is plotted in light blue in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ diagonal uncertainties, including cosmic variance (approximated as Gaussian) and not including uncertainties in the foreground model at $\ell \geq 30$. Note that the vertical scale changes at $\ell = 30$, where the horizontal axis switches from logarithmic to linear.

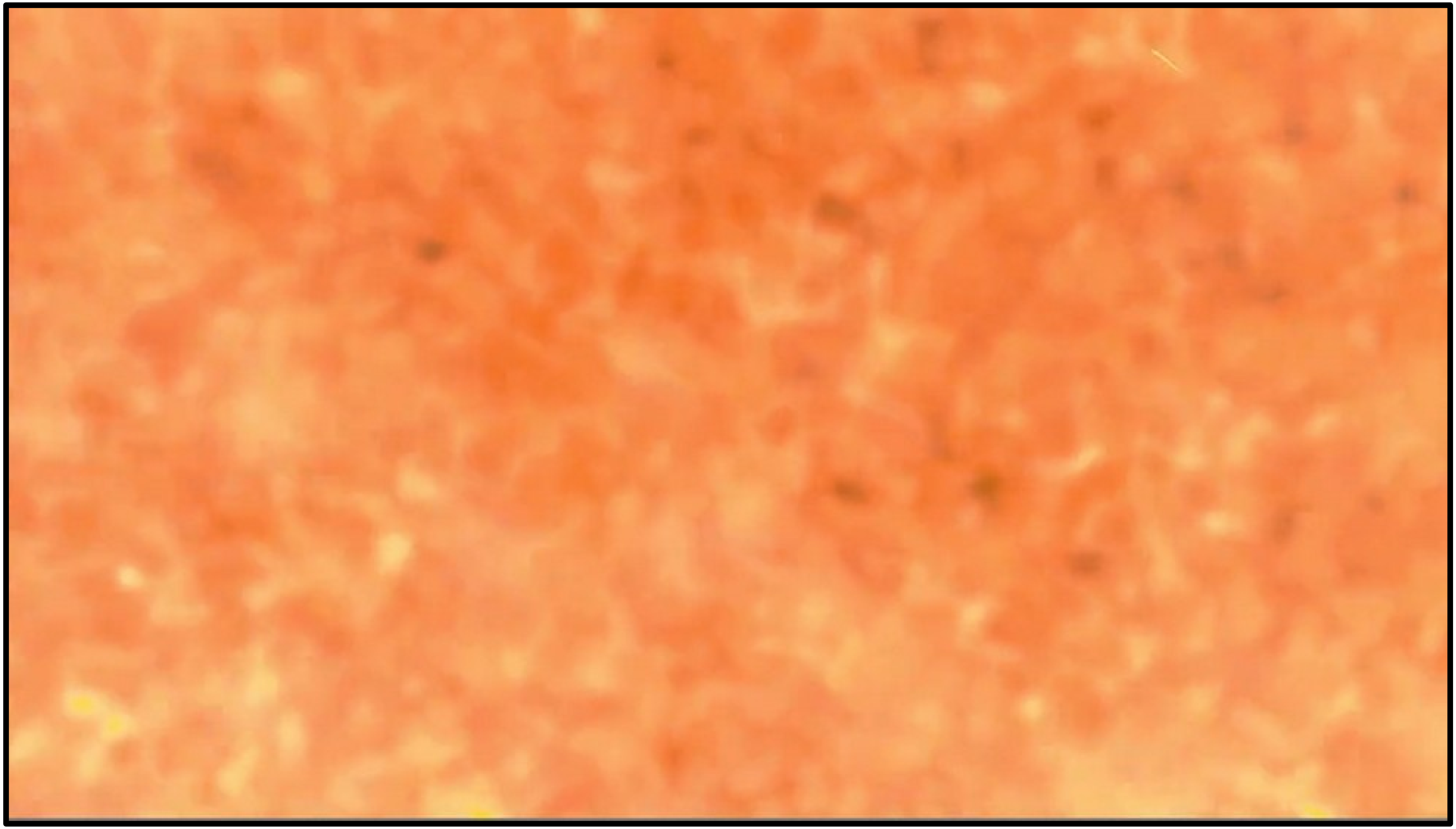
Cold Dark Matter





- If we « put » all Cold Dark Matter into Baryons, the shape of the spectrum changes drastically
- This is a very high-significance detection of Dark Matter
- But what ***is*** it ?

Visualization of the Early Universe



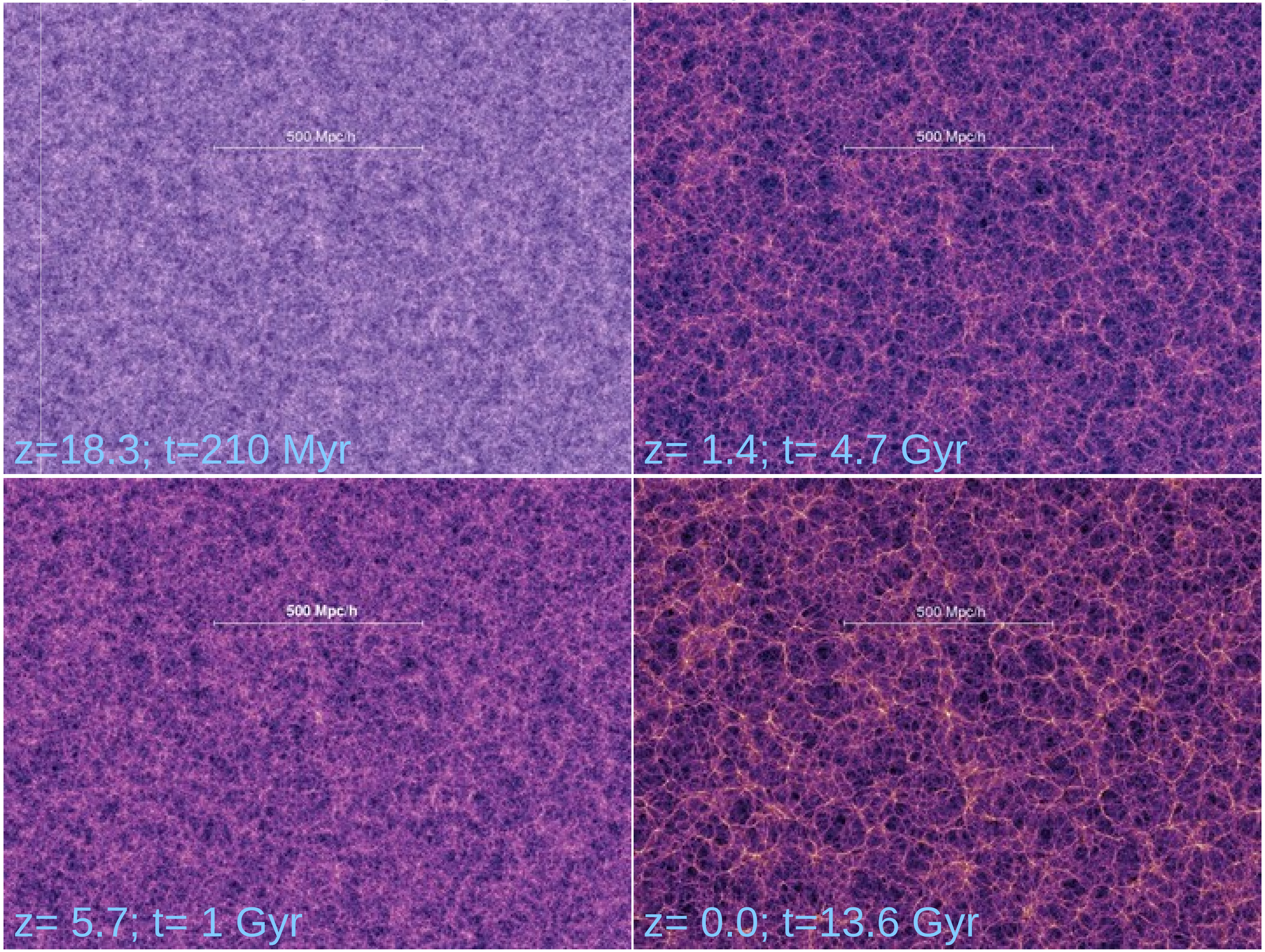
Here we see the expansion, recombination, and the start of structure formation in the Universe (from “Cosmic Voyage”)

“Structure” in the Universe

Much of what Euclid will do is look at the structure in the Universe.

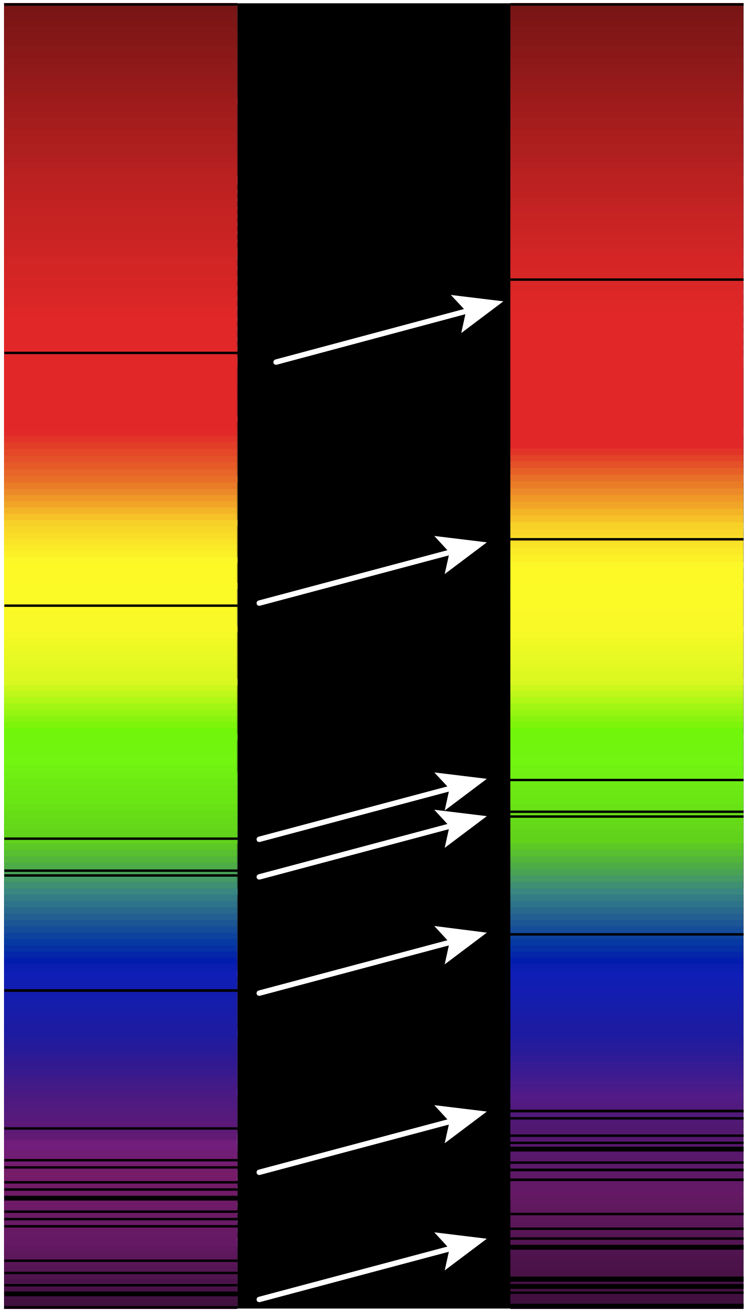
- Dark Matter “helps” structure form gravitationally
- Dark Energy accelerates expansion and increases distances between structures

http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/



We thus want to make maps (& statistics) of “structure” as a function of time to understand both.

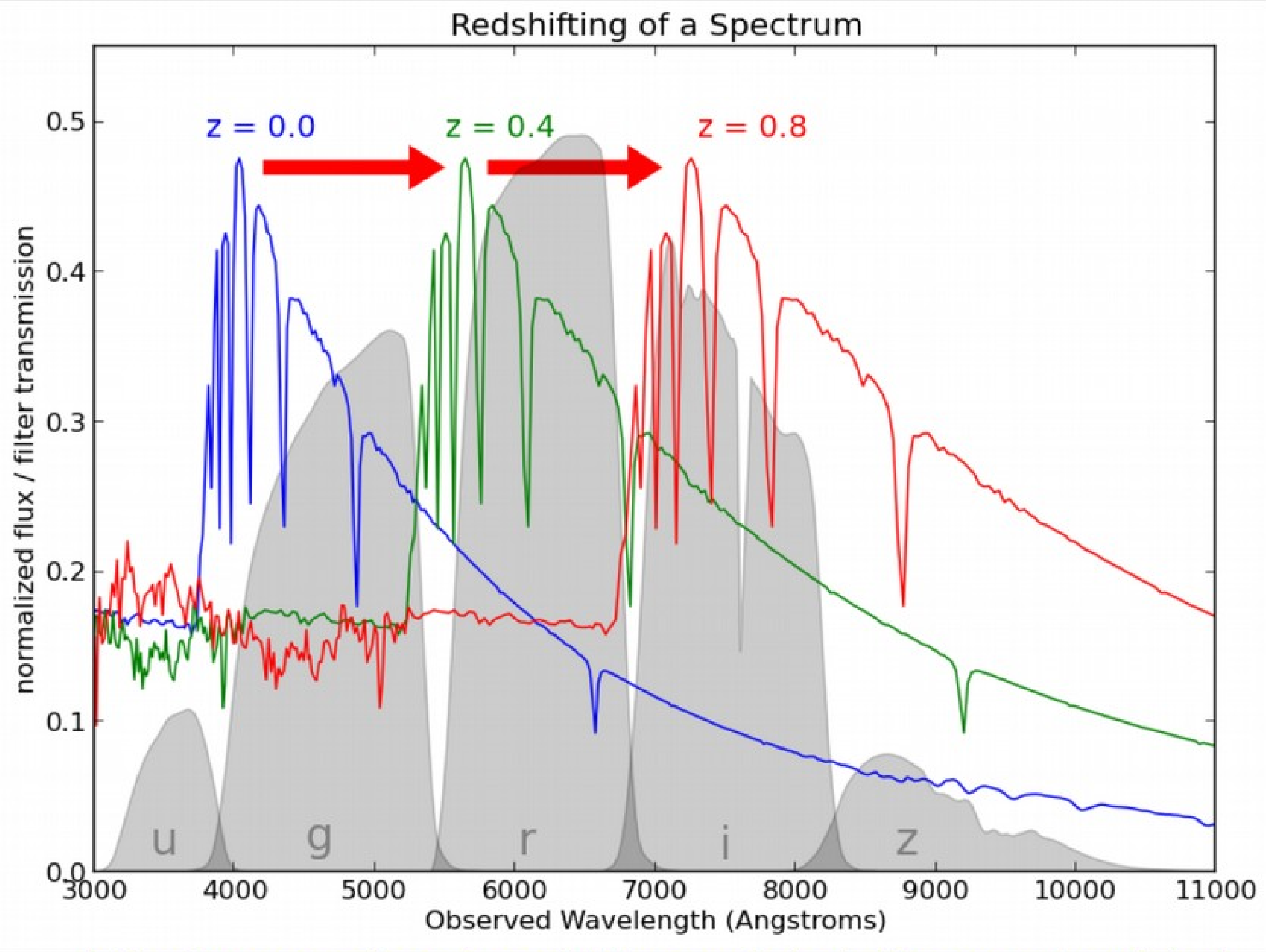
Redshifts



Absorption lines in the visible spectrum of a supercluster of distant galaxies (right), as compared to absorption lines in the visible spectrum of the Sun (left). Arrows indicate redshift. Wavelength increases up towards the red and beyond (frequency decreases).

Wikipedia

Photometric Redshifts

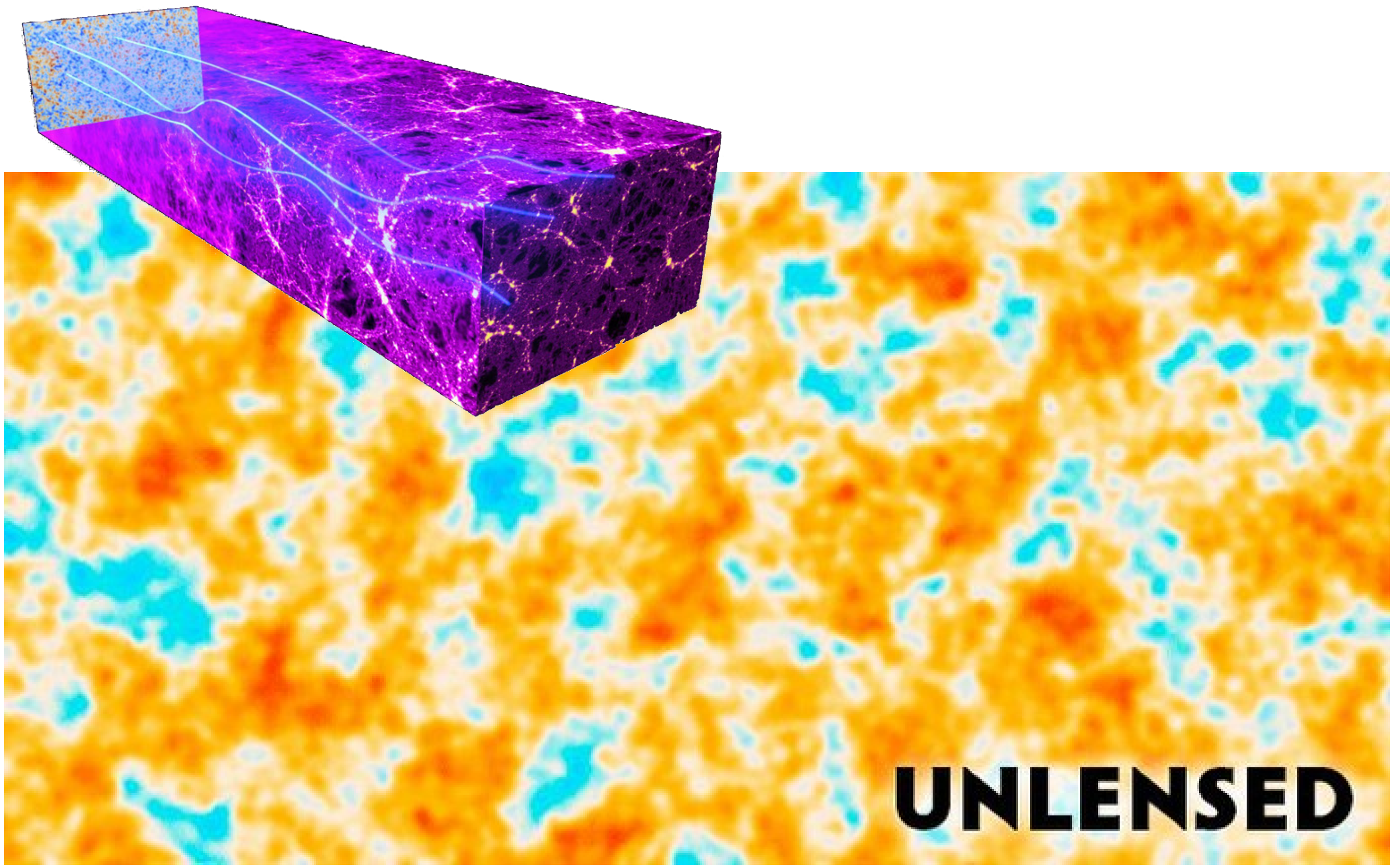


http://www.astroml.org/sklearn_tutorial/regression.html

It's difficult to do high-resolution spectrosocpy on a large number of faint sources – so some experiments are doing « Photometric Redshifts »

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



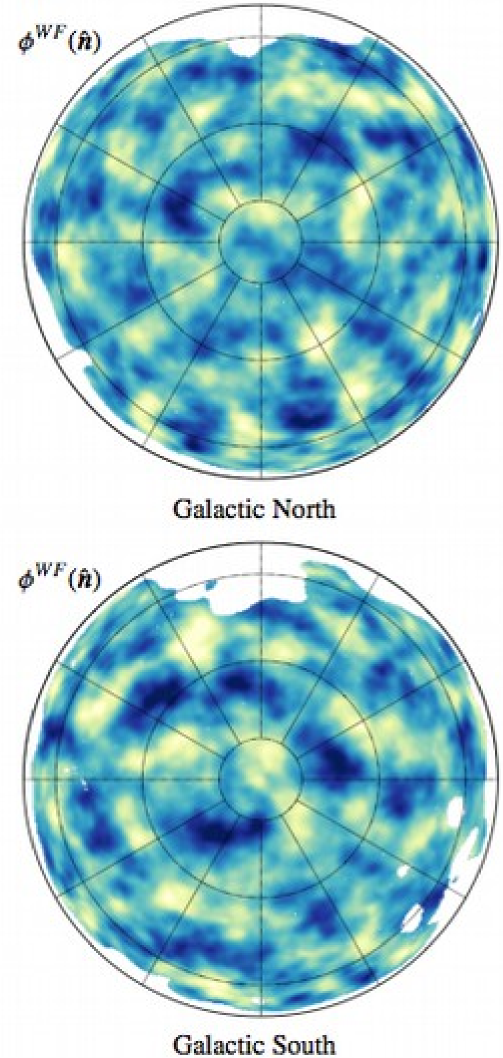


Fig. 8. Wiener-filtered lensing potential estimate $\phi^{WF}_{LM} \equiv C^{\phi\phi}_{L}(\hat{\phi}_{LM} - \hat{\phi}^{MF}_{LM})$ for our MV reconstruction, in Galactic coordinates using orthographic projection. The reconstruction is bandpass filtered to $L \in [10, 2048]$. The *Planck* lens reconstruction 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.

arXiv:1303.5078v1

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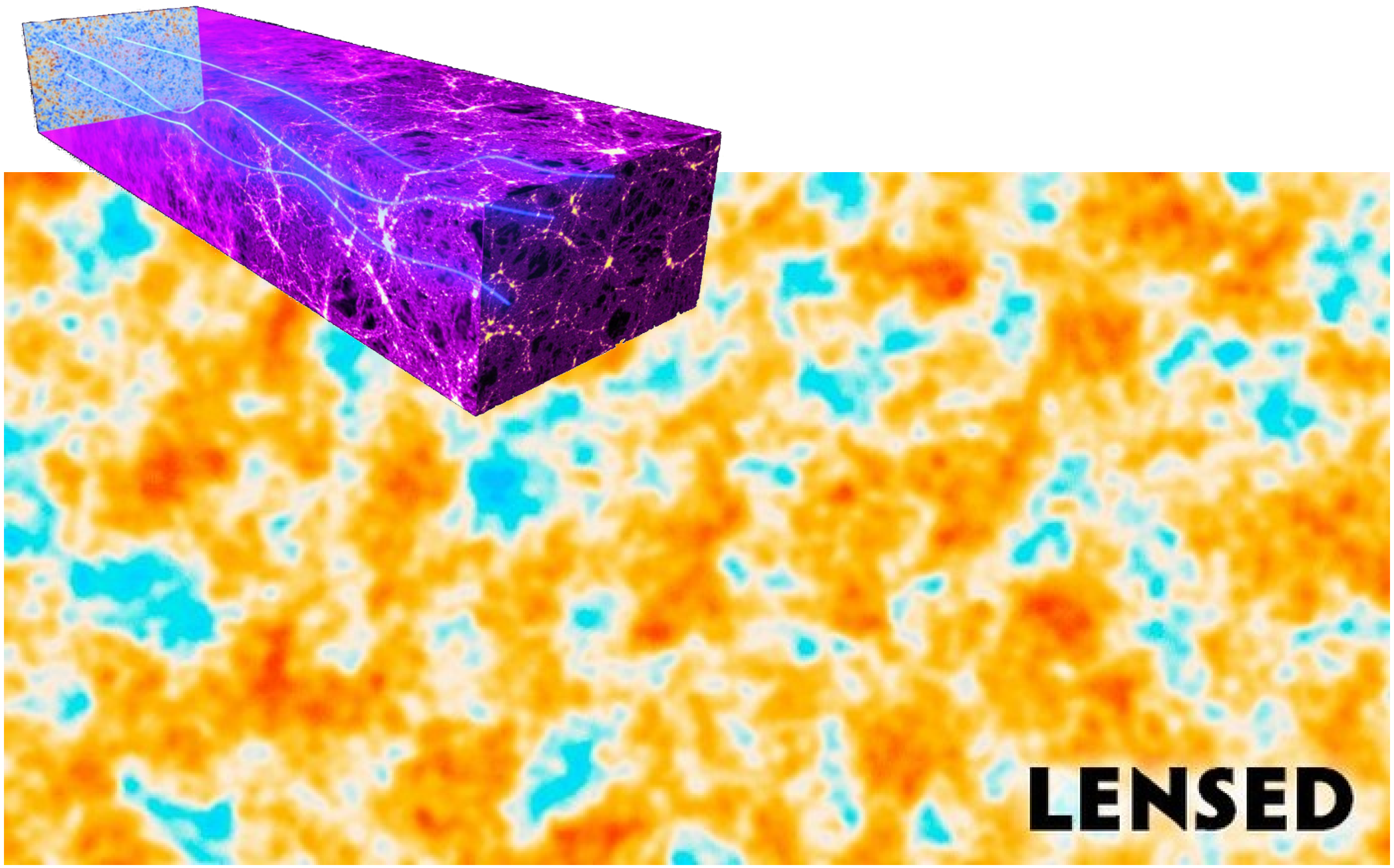

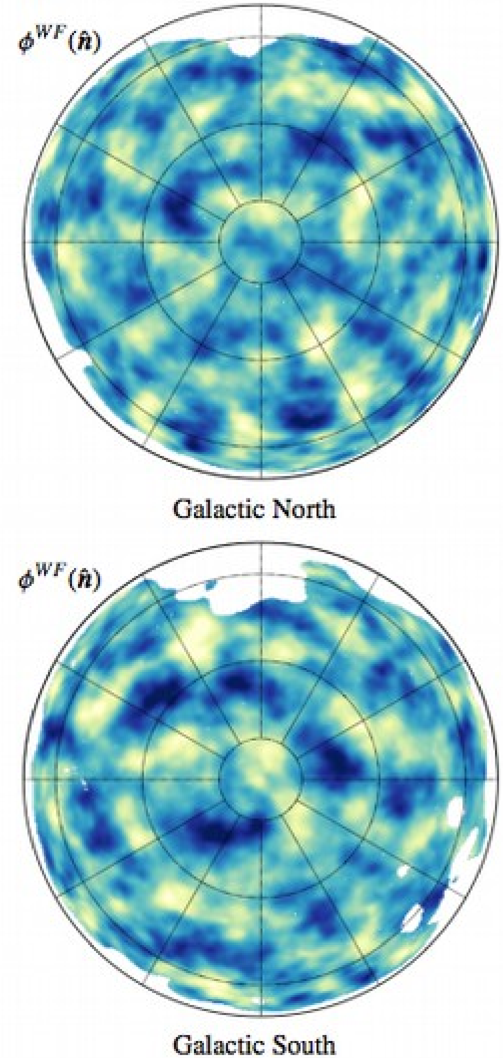

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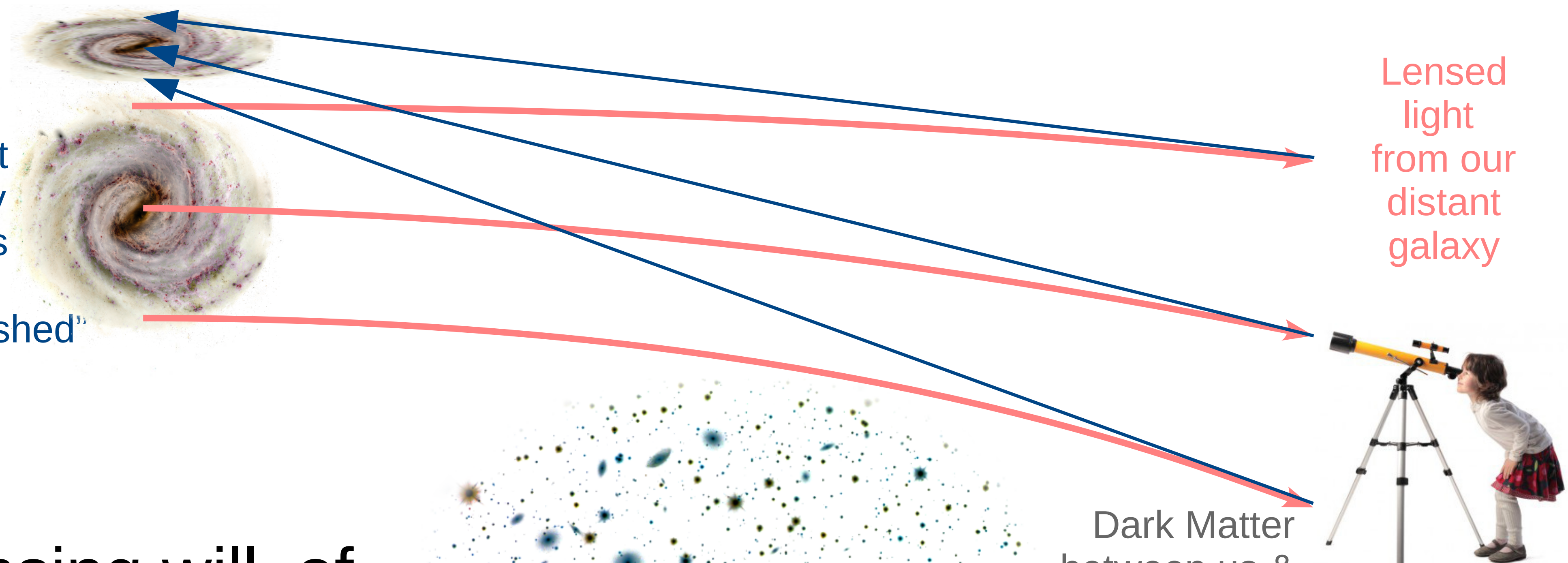
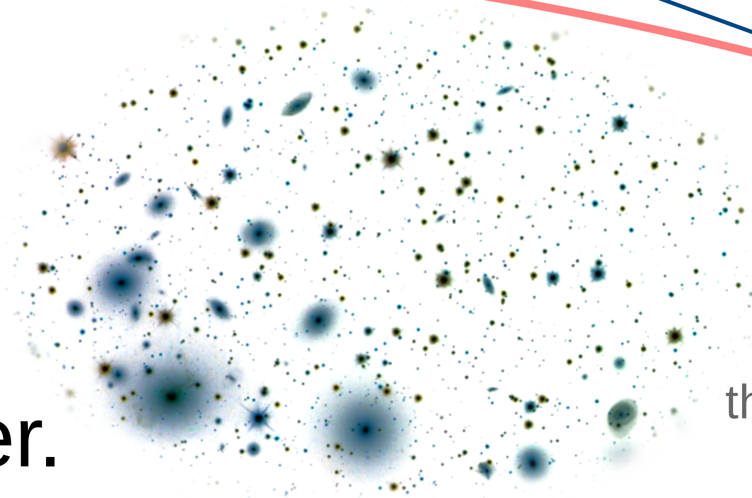
Lensing Shear



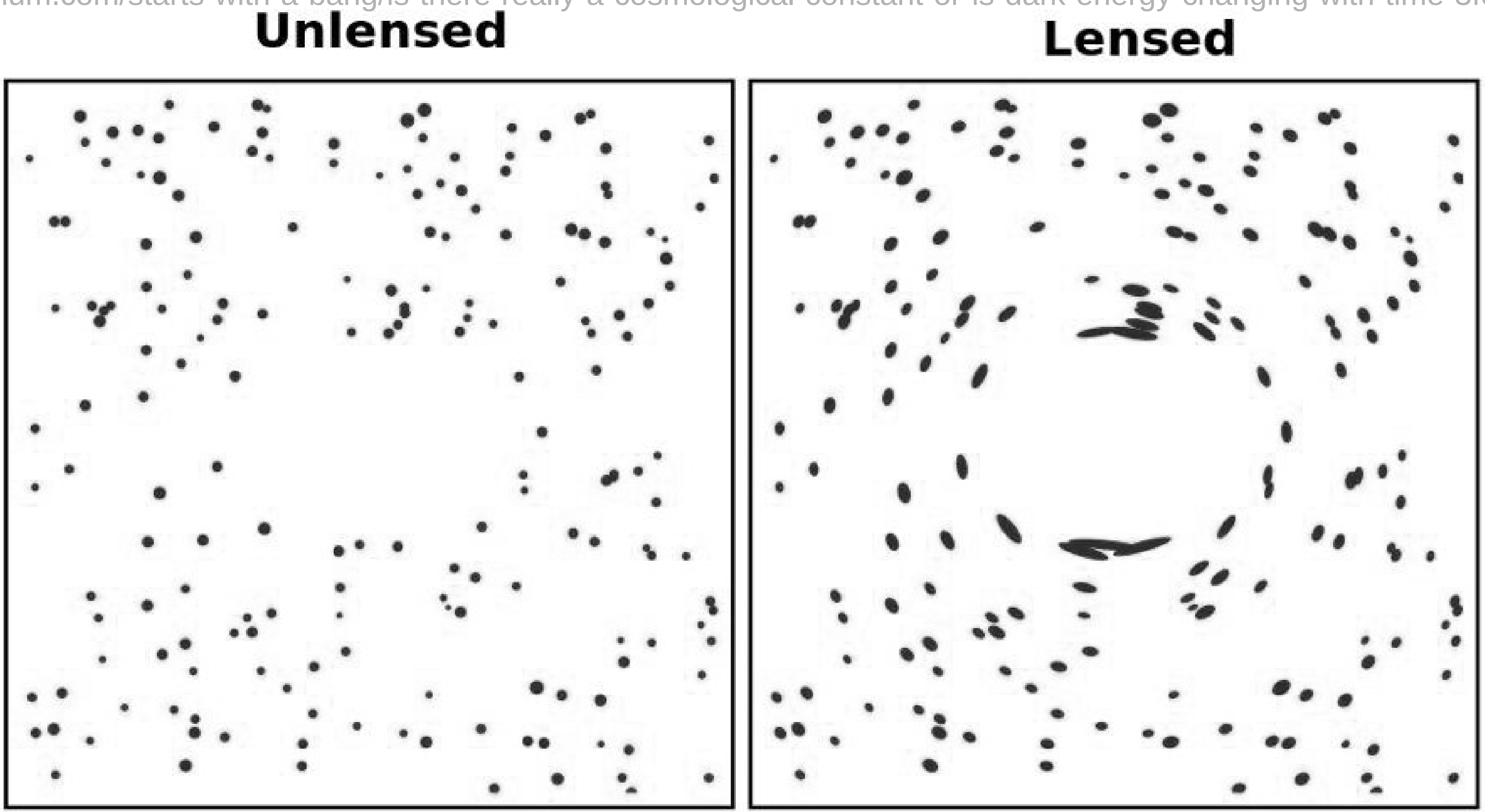


Lensing will, of course, tells us about Dark Matter.

But in addition, by mapping the Dark Matter with lensing in many different directions and at many different distances, we can again map larger scale structure and so also investigate Dark Energy.

Weak Lensing of Galaxies

https://medium.com/starts-with-a-bang/is-there-really-a-cosmological-constant-or-is-dark-energy-changing-with-time-3fcf0e764f90

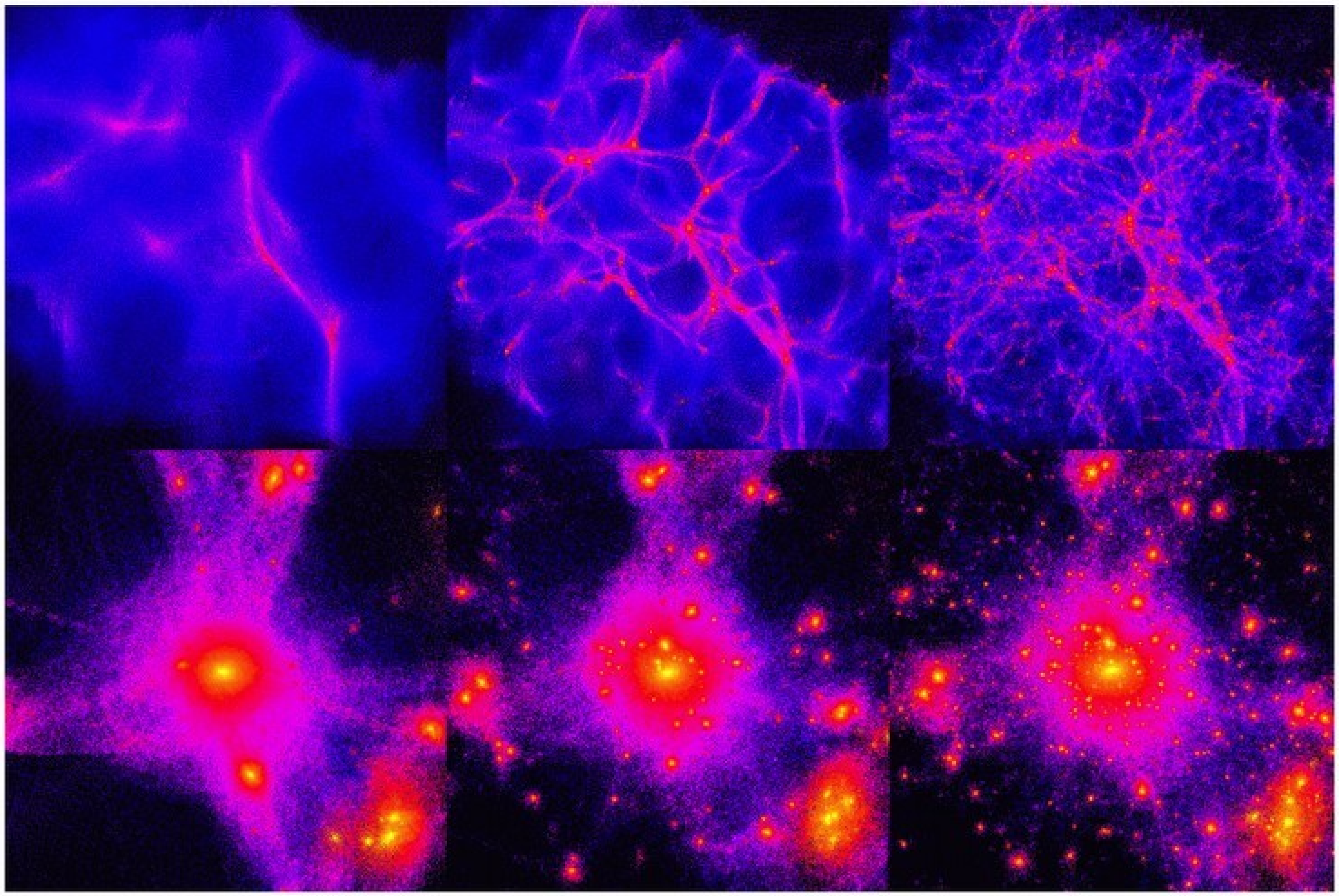


- The picture above imagines a single, compact lensing source
- Imagine a number of these lensing sources scattered in different directions (and depths!)

Neutrino Masses

Hot versus Warm vesus Cold dark matter universes (courtesy ITC @ University of Zurich):

Top row: Simulations of what structure in Hot (left), Warm (middle), and Cold (Right) dark matter universes would look like at high redshift (early times).
Bottom row: same as top row, except now as they would look at the present time (z=0).

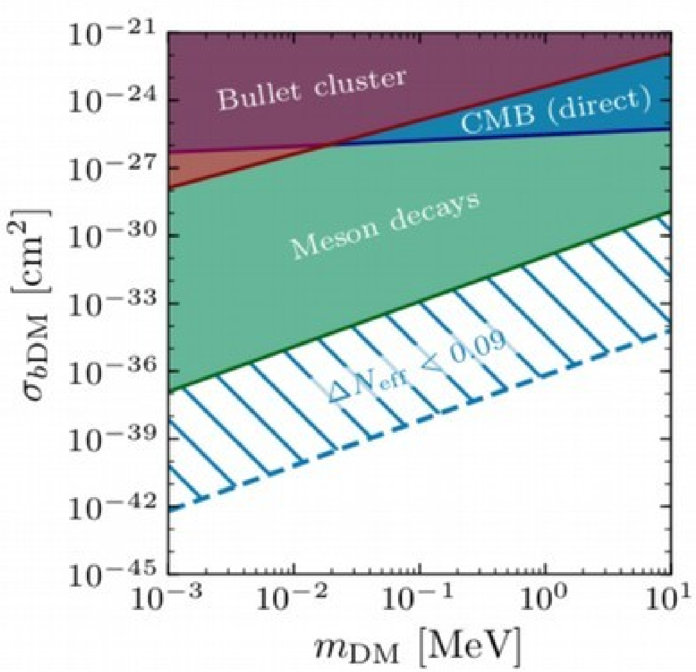


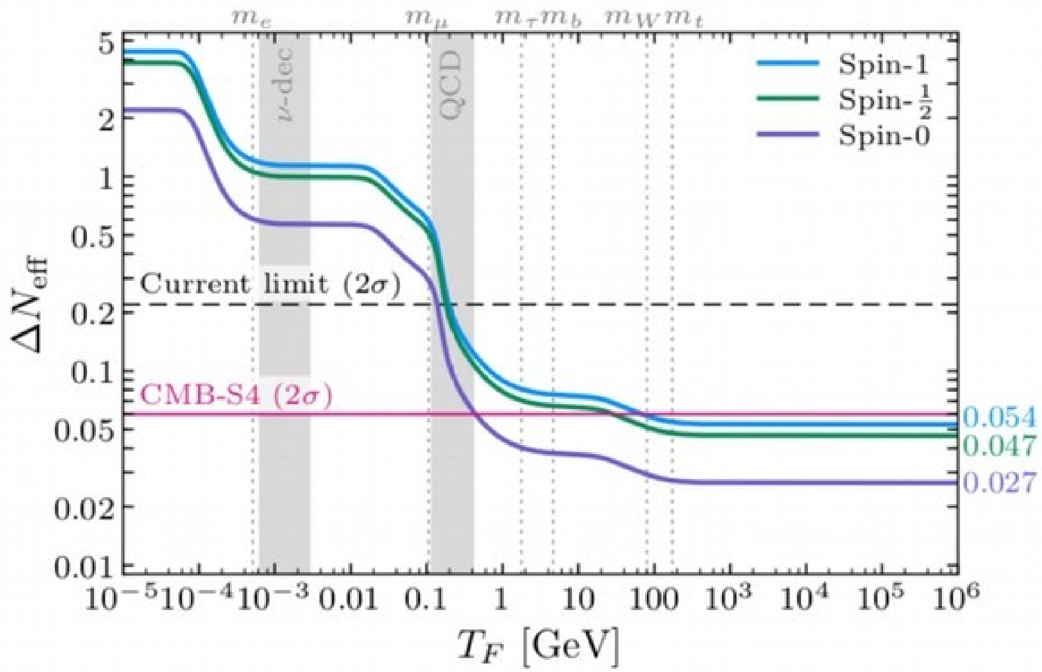
http://burro.astr.cwru.edu/Academics/Astr222/Cosmo/Structure/darkmatter.html

Massive neutrinos effectively elminate structures on small scales. Experiments that measure structure, like the CMB and optical surveys, can also measure the sum of the mass of the neutrino species.

Dark Matter & N_{eff}

- $N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_\nu}{\rho_\gamma}\right)$ = effective number of neutrinos (non-photonic free-streaming species)
- Particles which « decouple » earlier will have smaller contributions, but are detectable. Future experiments should be able to detect any particles that decoupled after the QCD transition.





CMB S4 Science Book

Structure & Dark Energy

- The Universe is expanding.
- The faster it expands, the more this expansion separates structure, again affecting the statistics of what we see on the sky today
- By studying the amount of structure we have as a function of time, we can investigate the expansion and Dark Energy (and/or alternate theories of gravity)

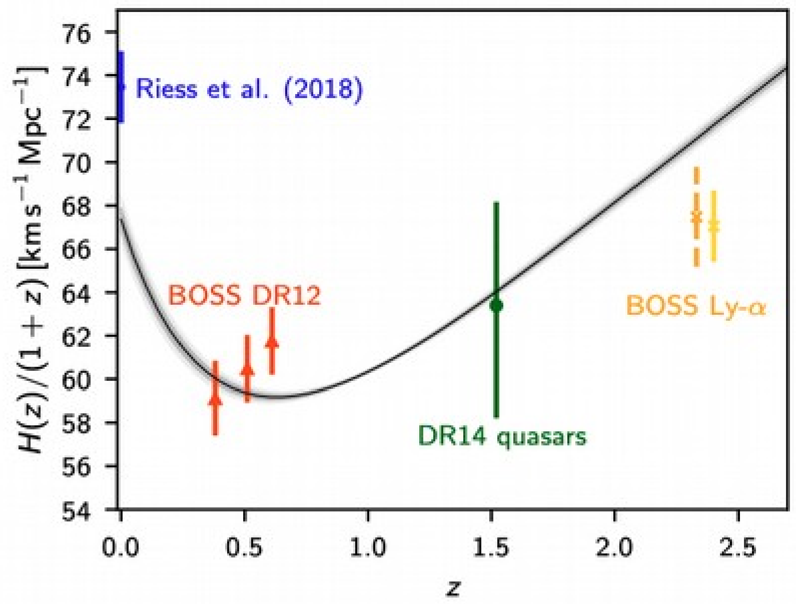


Fig. 16. Comoving Hubble parameter as a function of redshift. The grey bands show the 68 % and 95 % confidence ranges allowed by *Planck* TT,TE,EE+lowE+lensing in the base-ΛCDM model, clearly showing the onset of acceleration around $z = 0.6$. Red triangles show the BAO measurements from BOSS DR12 (Alam et al. 2017), the green circle is from BOSS DR14 quasars (Zarrouk et al. 2018), the orange dashed point is the constraint from the BOSS Ly α auto-correlation at $z = 2.33$ (Bautista et al. 2017a), and the solid gold point is the joint constraint from the Ly α auto-correlation and cross-correlation with effective redshift $z = 2.4$ (du Mas des Bourboux et al. 2017). All BOSS measurements are used in combination with the *Planck* base-model measurements of the sound horizon $r_{\rm drag}$, and the DR12 points are correlated. The blue point at redshift zero shows the inferred forward distance-ladder Hubble measurement from Riess et al. (2018a).

Hubble Constant Problem ?

- « Early » and « Late » estimates of the Hubble Constant seem to be in « tension » at the « few »-σ level.
- Is this an indication of « new physics » happening between the two ?
- Or, is this an indication of « systematics » somewhere ?

https://arxiv.org/abs/1907.10625

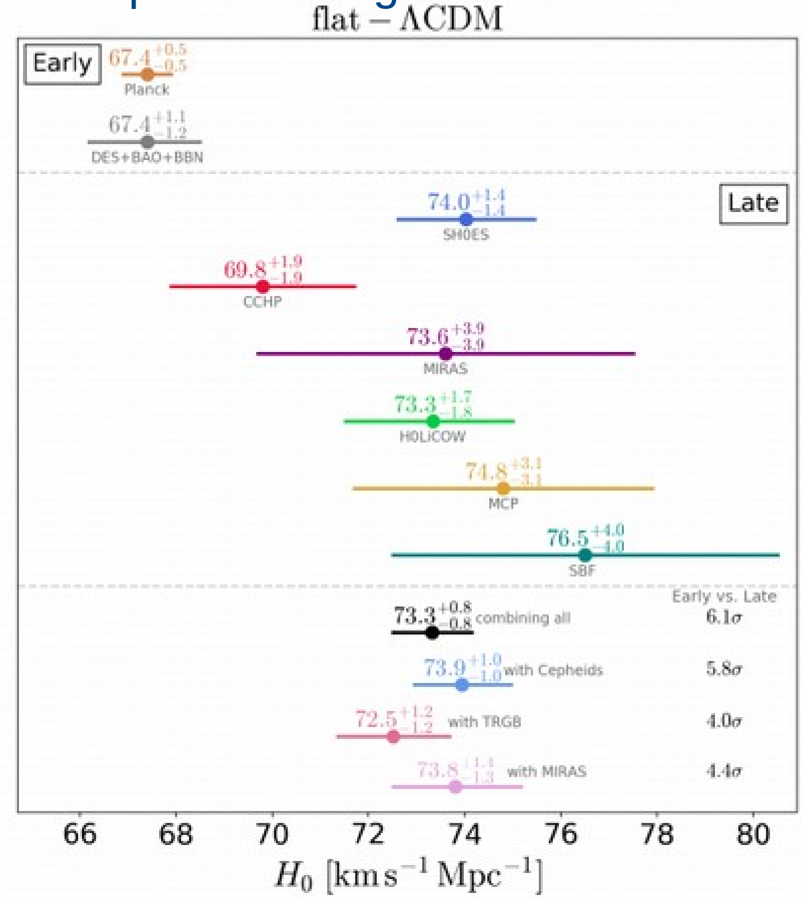


Figure 1. Compilation of Hubble Constant predictions and measurements taken from the recent literature and presented or discussed at the meeting. Two independent predictions based on early-Universe data (Planck Collaboration et al. 2018; Abbott et al. 2018) are shown at the top left (more utilizing other CMB experiments have been presented with similar findings), while the middle panel shows late Universe measurements. The bottom panel shows combinations of the late-Universe measurements and lists the tension with the early-Universe predictions. We stress that the three variants of the local distance ladder method (SHOES=Cepheids; CCHP=TRGB; MIRAS) share some Ia calibrators and cannot be considered as statistically independent. Likewise the SBF method is calibrated based on Cepheids or TRGB and thus it cannot be considered as fully independent of the local distance ladder method. Thus the "combining all" value should be taken for illustration only, since its derivation neglects covariance between the data. The three combinations based on Cepheids, TRGB, Miras are based on statistically independent datasets and therefore the significance of their discrepancy with the early universe prediction is correct - even though of course separating the probes gives up some precision. A fair summary is that the difference is more than 4 σ, less than 6 σ, while robust to exclusion of any one method, team or source. Figure courtesy of Vivien Bonvin.

Degeneracies

- For the CMB, the Hubble constant and the matter density are « degenerate »
- But in this case, the degeneracy doesn’t seem to be a solution to the difference

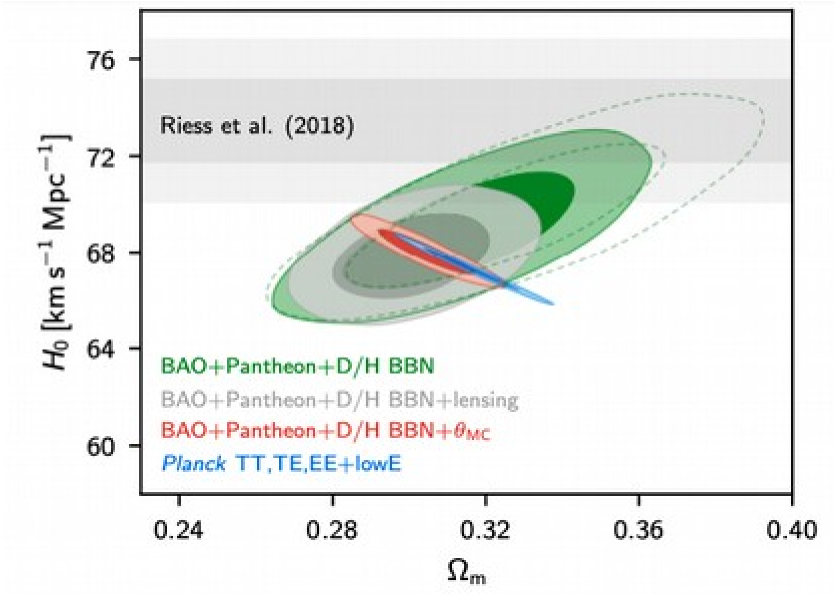
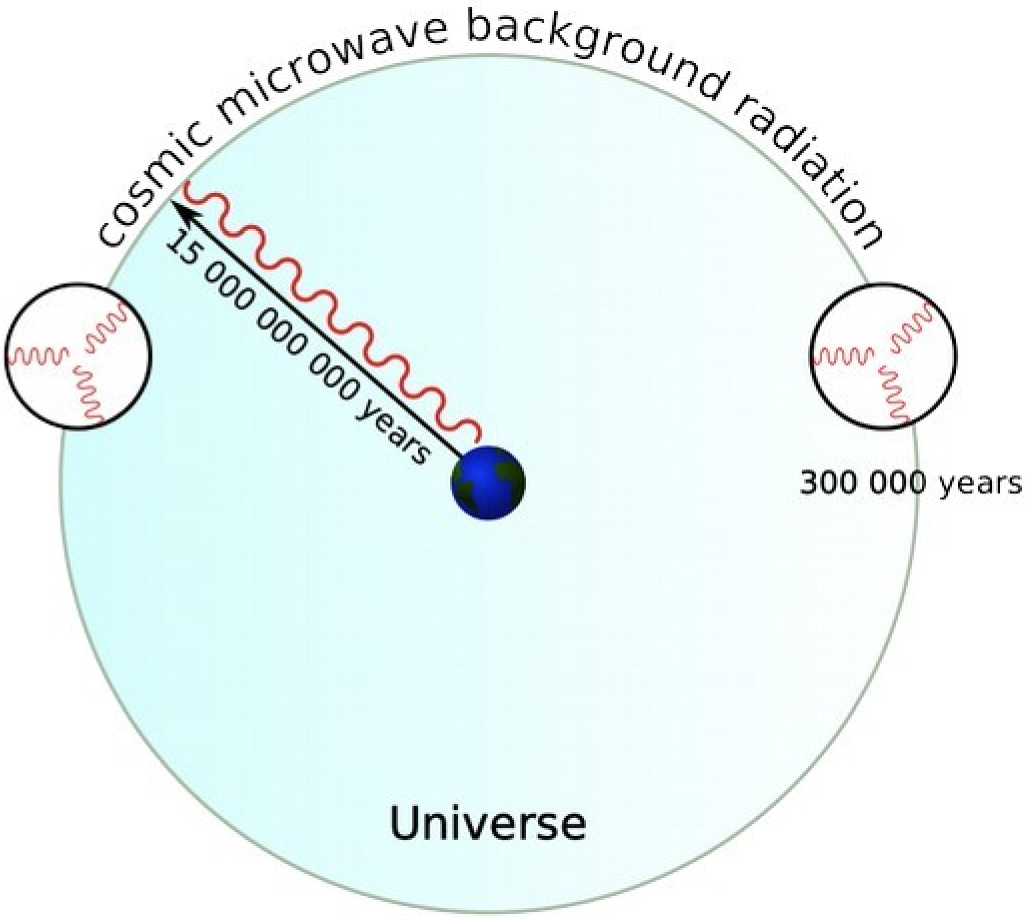


Fig. 17. Inverse distance-ladder constraints on the Hubble parameter and Ω_m in the base-ΛCDM model, compared to the result from the full *Planck* CMB power spectrum data. BAO constrains the ratio of the sound horizon at the epoch of baryon drag and the distances; the sound horizon depends on the baryon density, which is constrained by the conservative prior of $\Omega_b h^2 = 0.0222 \pm 0.005$, based on the measurement of D/H by Cooke et al. (2018) and standard BBN with modelling uncertainties. Adding *Planck* CMB lensing constrains the matter density, or adding a conservative *Planck* CMB “BAO” measurement ($100\theta_{MC} = 1.0409 \pm 0.0006$) gives a tight constraint on H_0, comparable to that from the full CMB data set. Grey bands show the local distance-ladder measurement of R18. Contours contain 68 % and 95 % of the probability. Marginalizing over the neutrino masses or allowing dark energy equation of state parameters $w_0 > -1$ would only lower the inverse distance-ladder constraints on H_0. The dashed contours show the constraints from the data combination BAO+JLA+D/H BBN.

The Horizon Problem



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

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

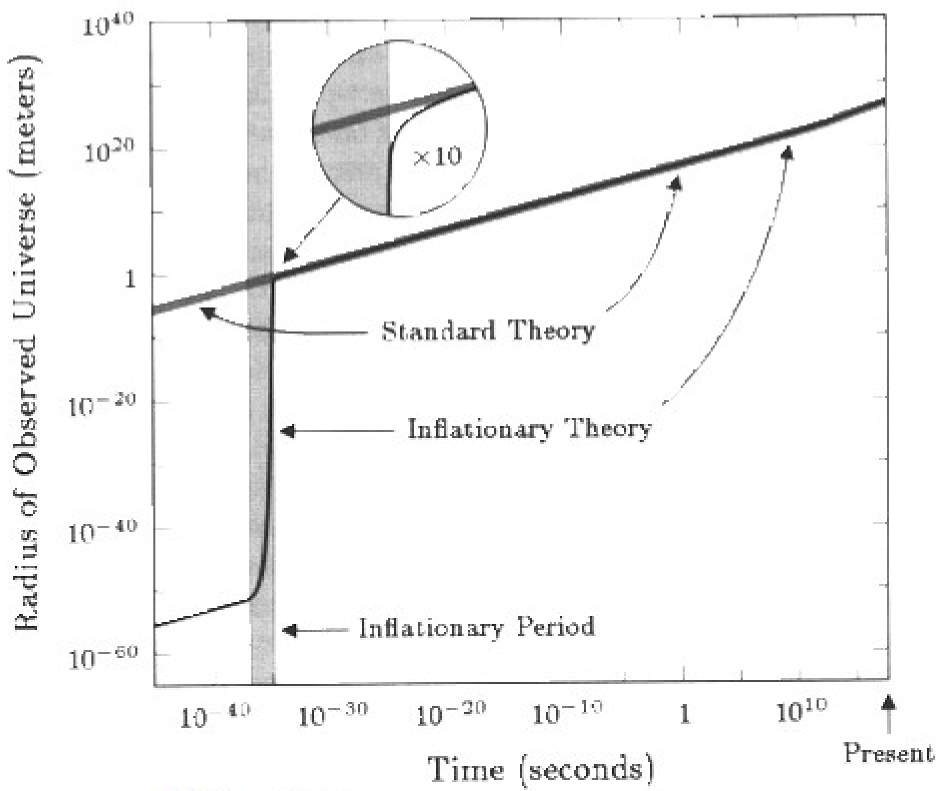
There are also “flatness” and “monopole” problems

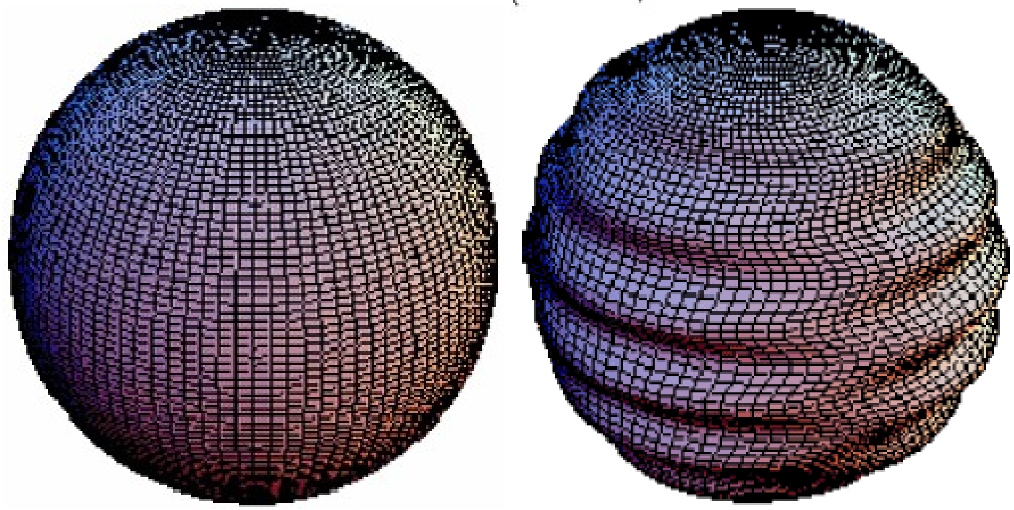
Inflation

Period of *very* fast expansion

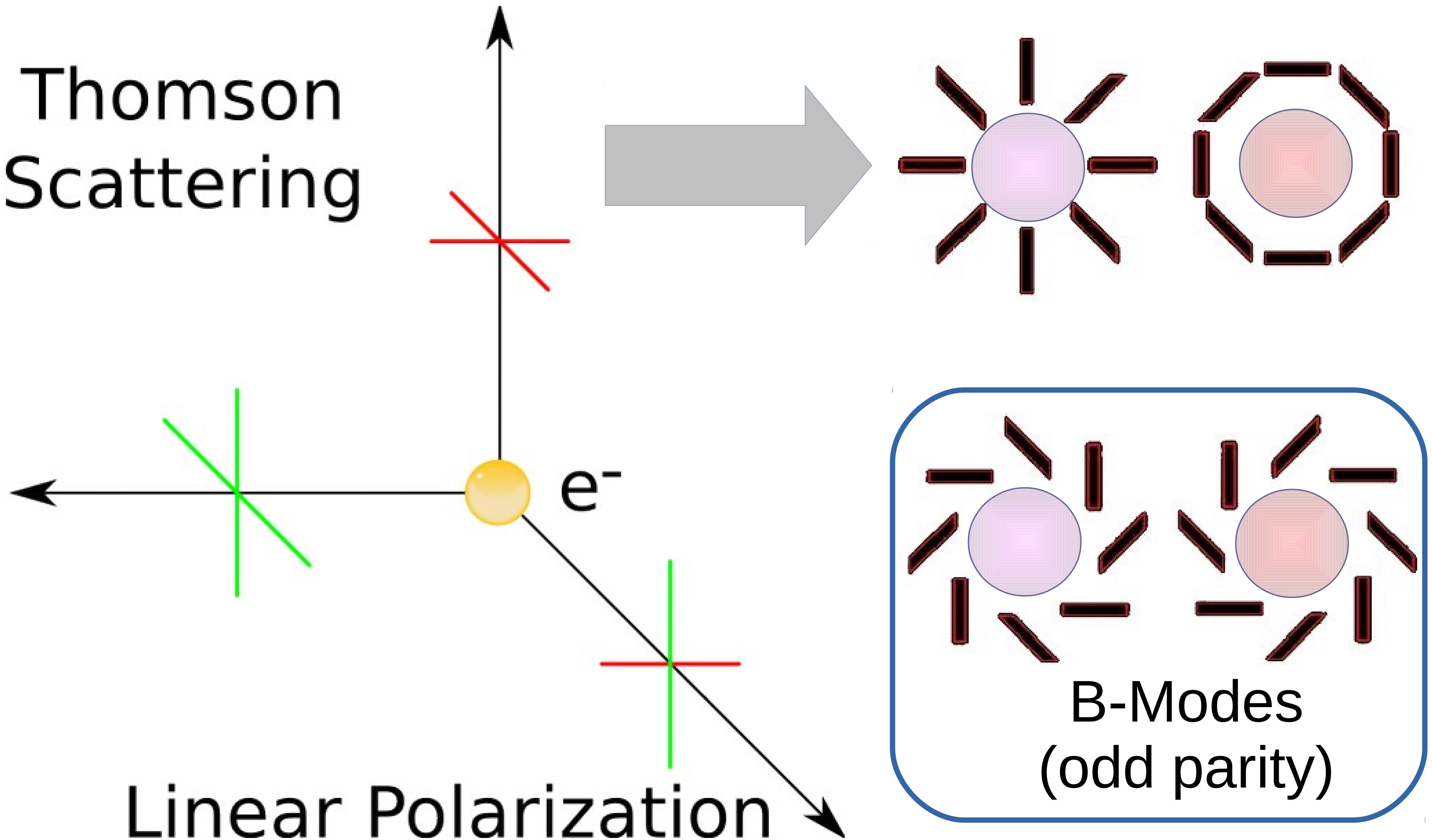
Solves monopole, flatness and horizon problems

Implies gravitational waves, but they may be vanishingly small.

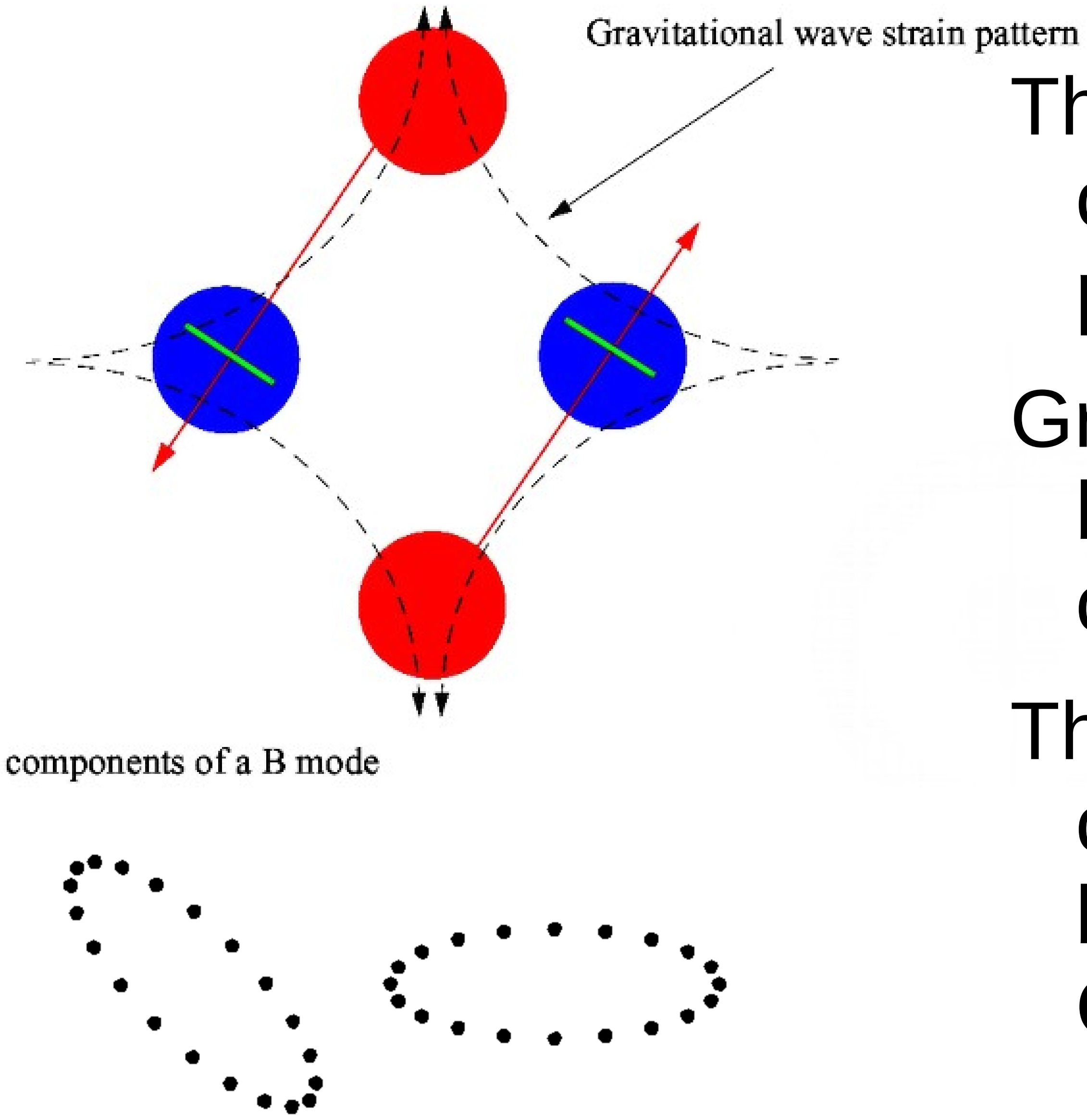




Polarization of the CMB



Grav. Waves Convert E Modes to B



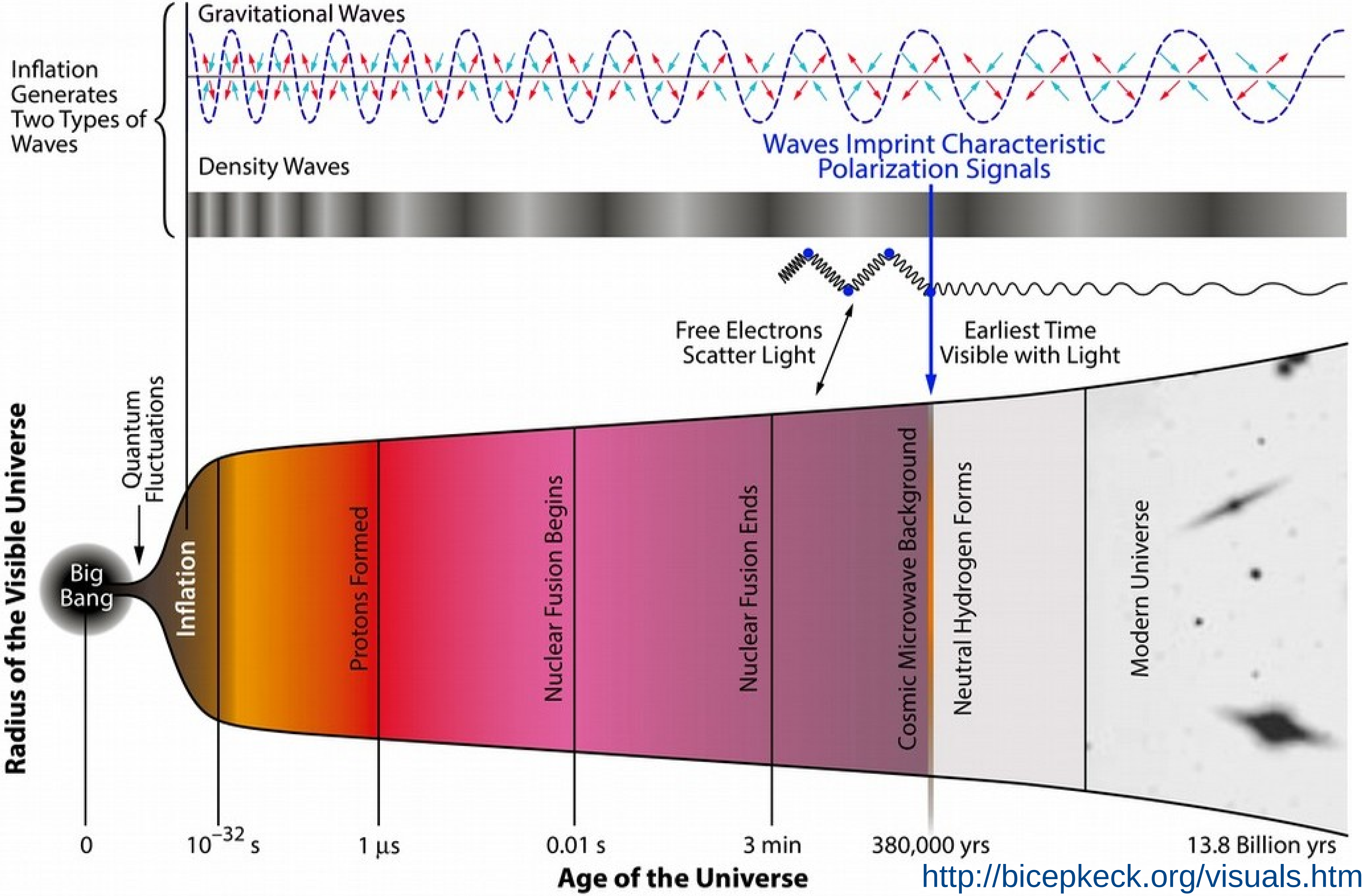
Thomson scattering creates E-mode polarization

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

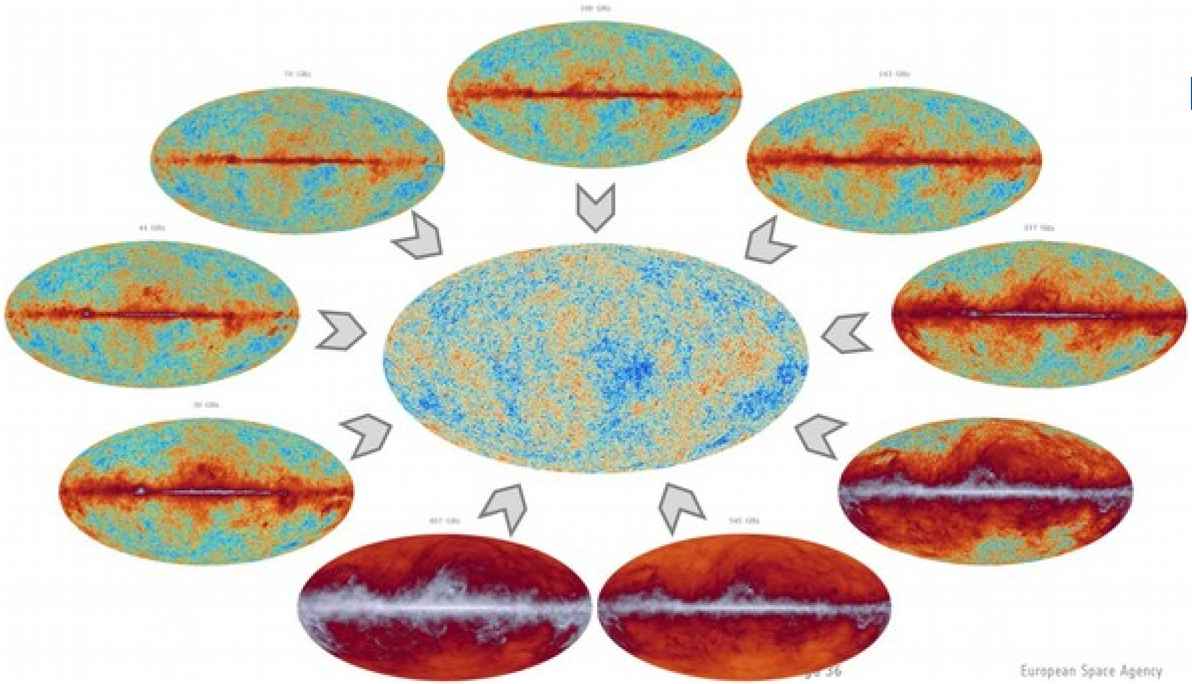
Rai Weiss – 2005 CMB Task Force Update

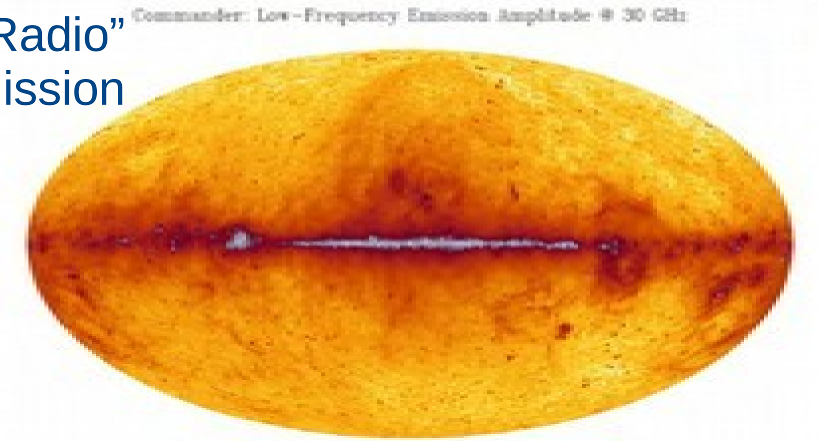
History of the Universe – in Log Scale

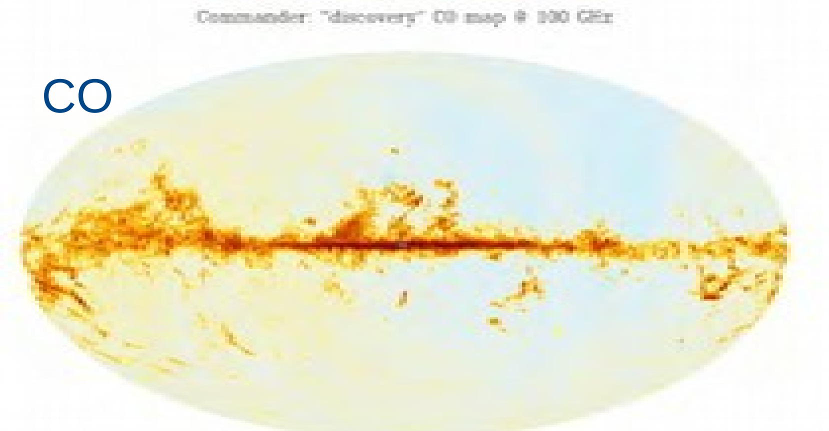


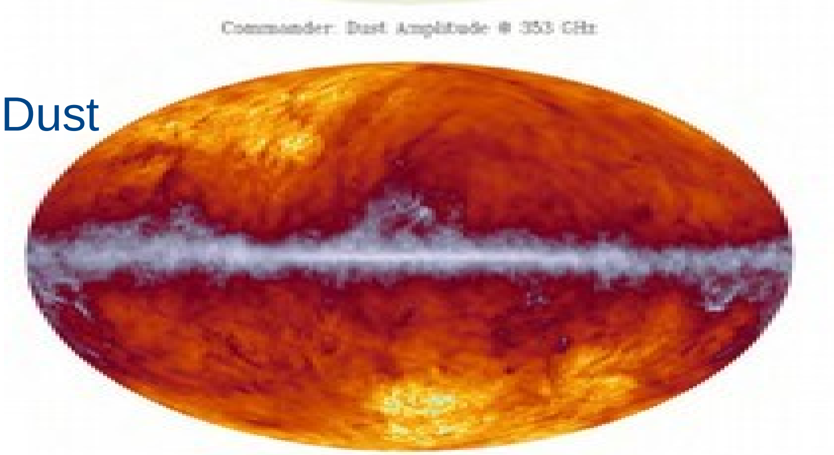
http://bicepkeck.org/visuals.html

“Foregrounds”





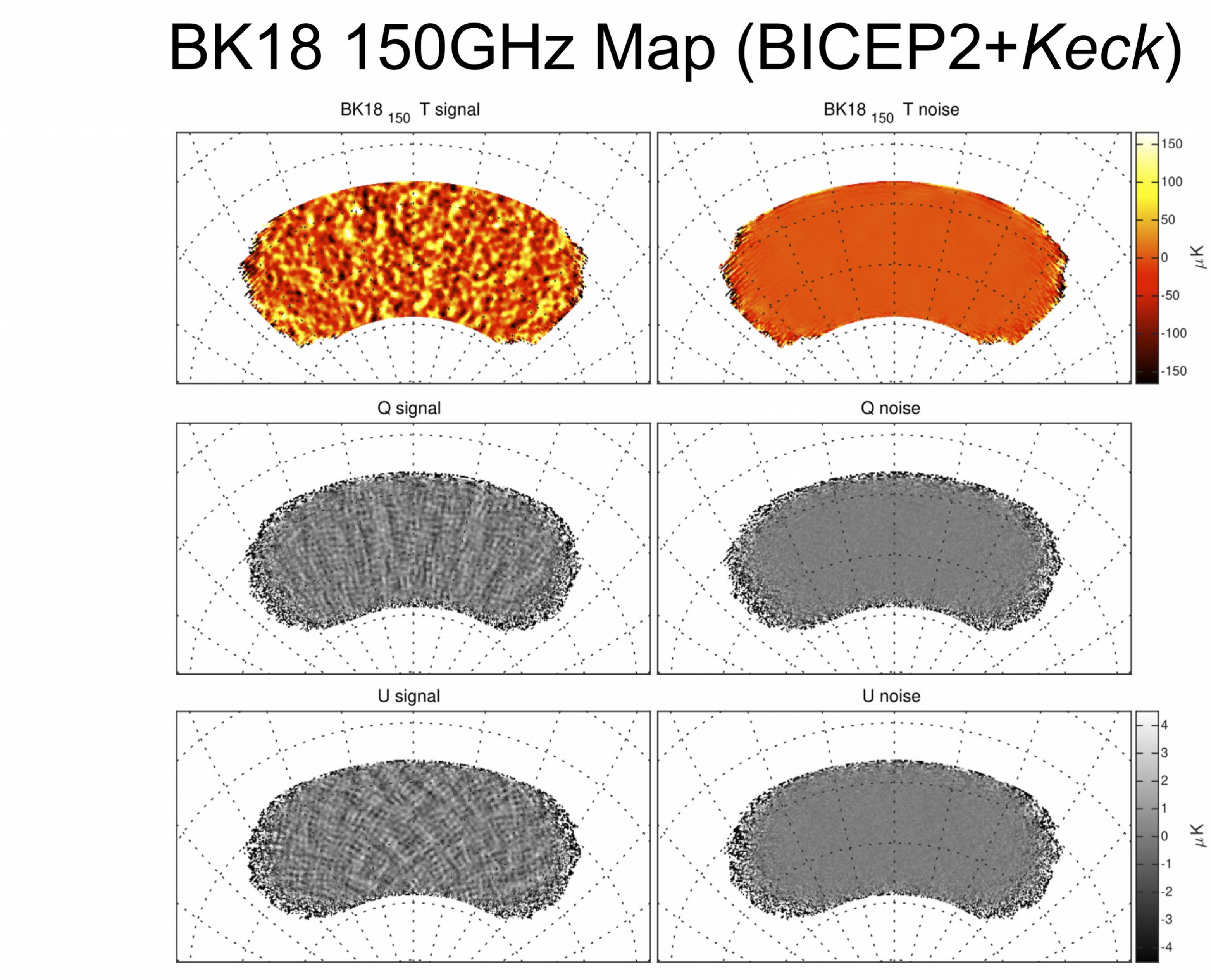




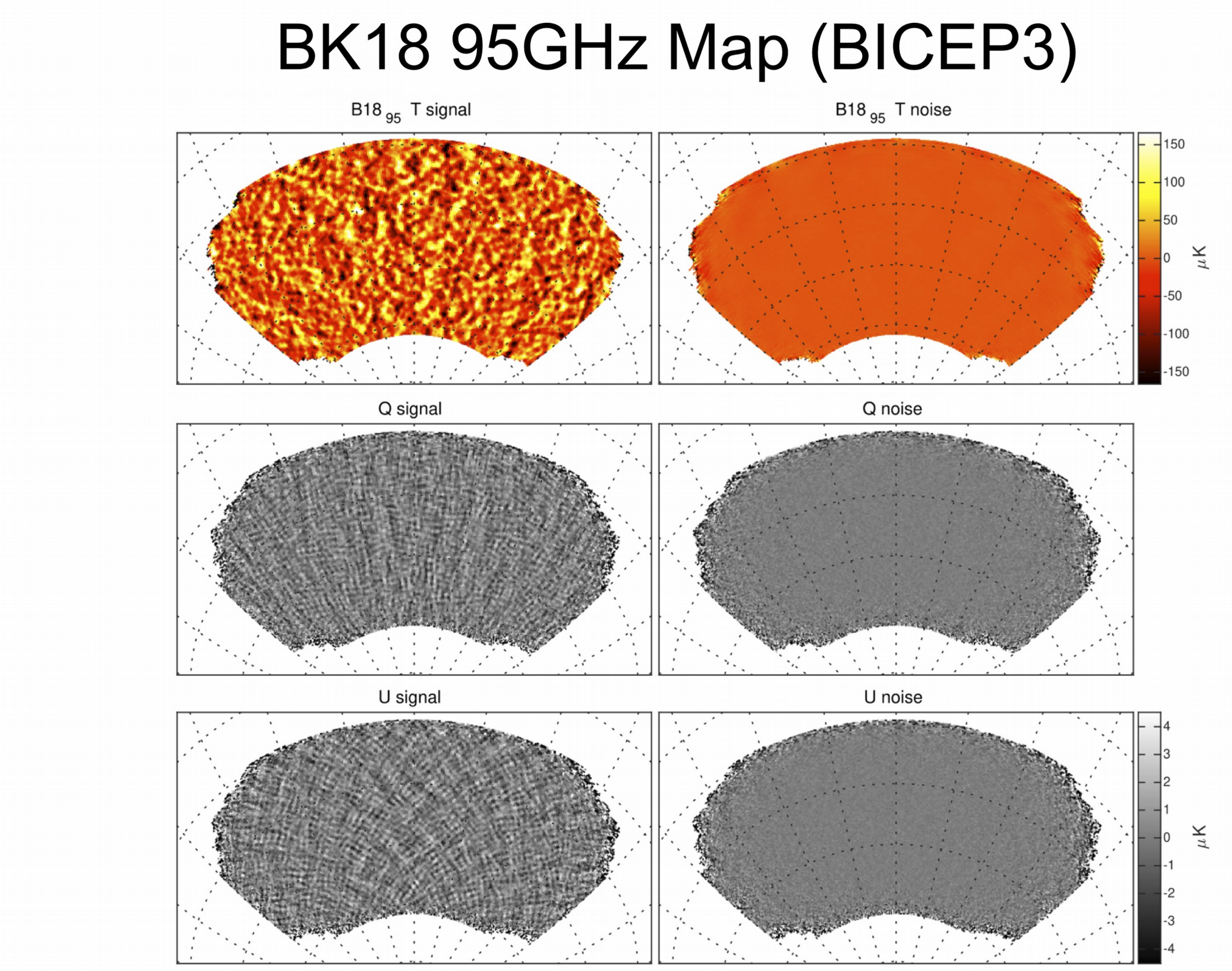
Combinations of the nine Planck channels allow us to separate the signals into CMB, CO, Dust and other components such as synchrotron, free-free and vibrational dust.

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

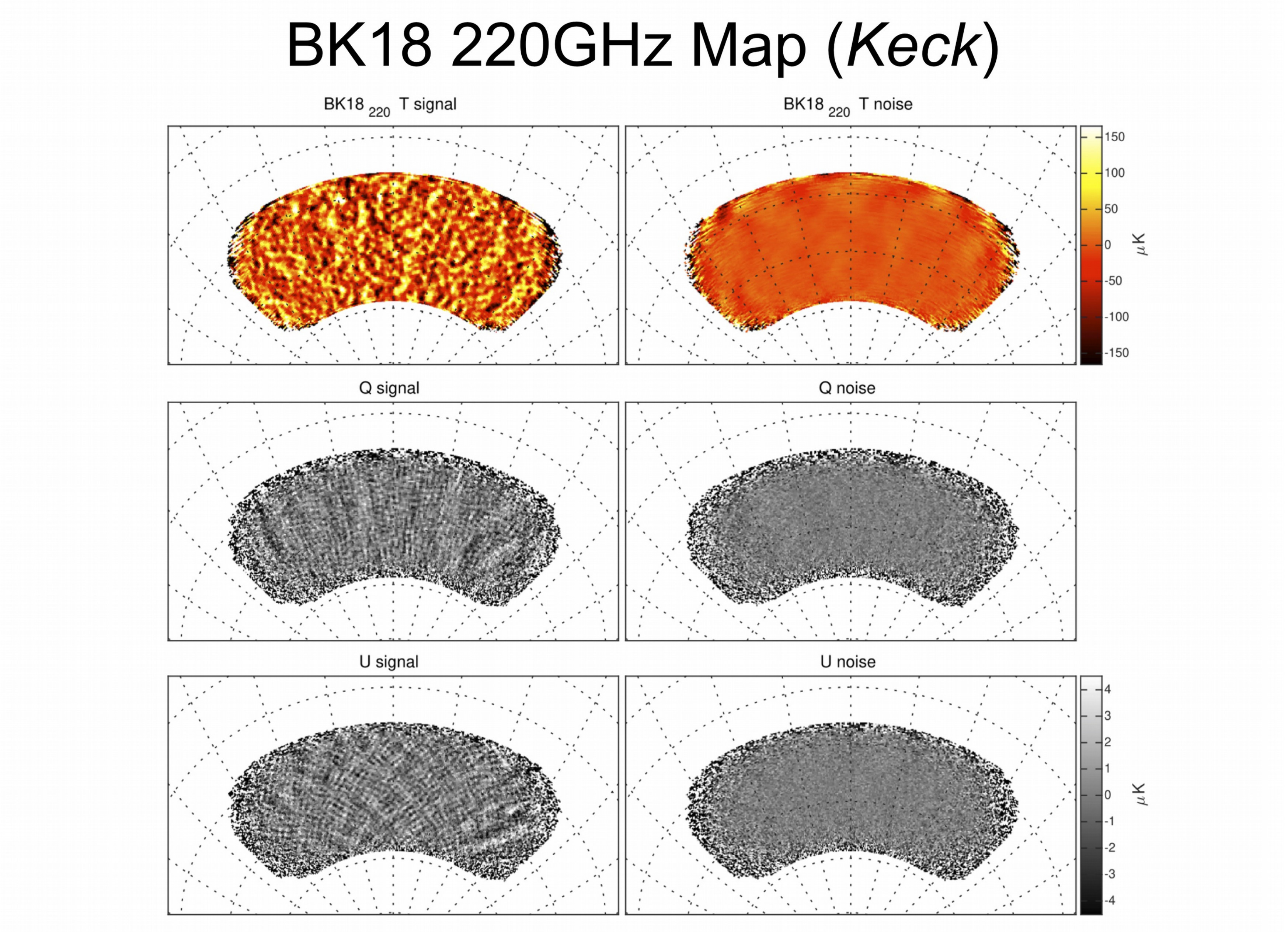
BICEP 150 GHz Map



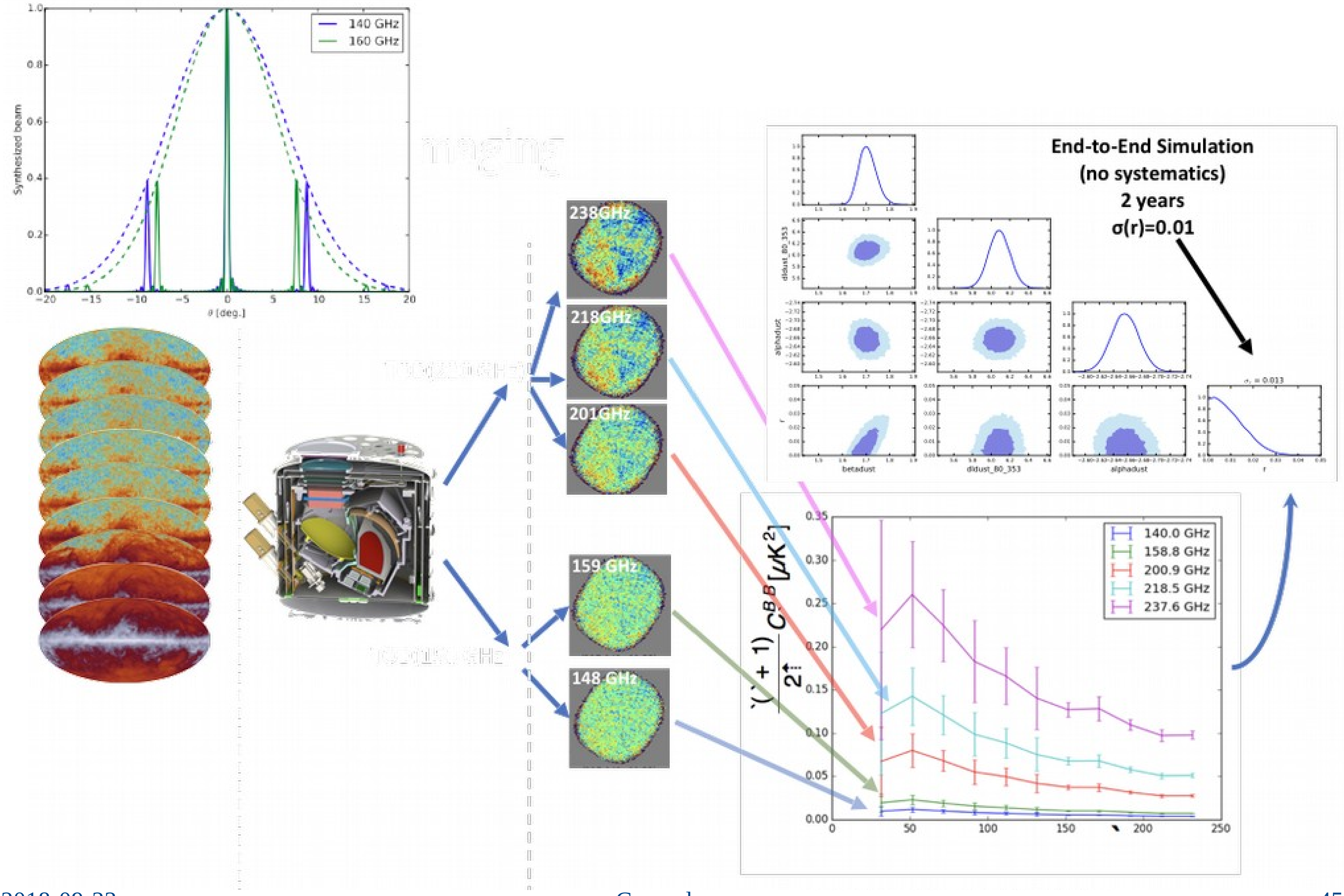
BICEP 090 GHz Map



BICEP 220 GHz Map



QUBIC Spectro-Imaging



A Small Sample of Open Questions...

A_{lens}: Smoothing of the spectrum and estimation from maps give different answers

- σ_8 vs. Ω_M : Planck sees different fractions than some other experiments

Missing Baryons : Yes, baryons are only a fraction of the Universe's content, but we **still** can't find them all...

- Why is the Cosmological Constant « so small » ?

- Baryon Asymmetry : Why are there more particles than anti-particles ?

- Why is there anything at all ?