AST 1430
Cosmology

VIII

The Cosmic Microwave Background

Announcements

- Feb 15th will be a 2hr session: 10am-12pm
- Presentations!
  - Anika – Baryogenesis
  - Caleb – CMB B-modes
  - Braden – Alternative DE
  - Anna – Higgs Mechanism

Week Index	Dates	Topics
~~**Week 1**~~	~~Jan 11, 13~~	~~logistics, introduction, basic observations~~
~~**Week 2**~~	~~Jan 18, 20~~	~~Basic GR, RW metric, Distances, coordinates, Friedmann equations, cosmological models~~
~~**Week 3**~~	~~Jan 25, 27~~	~~Consistency with observations, Early Hot Universe, BBN~~
Week 4	~~Feb 1, 3~~	~~Inflation, Perturbations & Structure pre-recombination~~
Week 5	Feb 8, 10	CMB: basics, polarization, secondaries
Week 6	Feb 15 (2h)	Early-Universe Presentations
Reading Week – No Class		
Week 7	Mar 1, 3	Post-recombination growth of structure, formation of dark matter halos, halo mass function
Week 8	Mar 8, 10	The relation between dark matter halos and galaxies
Week 9	Mar 15, 17	Probing the cosmic density field / clustering
Week 10	Mar 22, 24	Late-time cosmological observations: BAO, supernovae, weak lensing, etc.
Week 11	Mar 29, 31	H0 controversy: how fast exactly is the Universe expanding today?
Week 12	Apr 5	Late Universe Presentations + Review

Keith

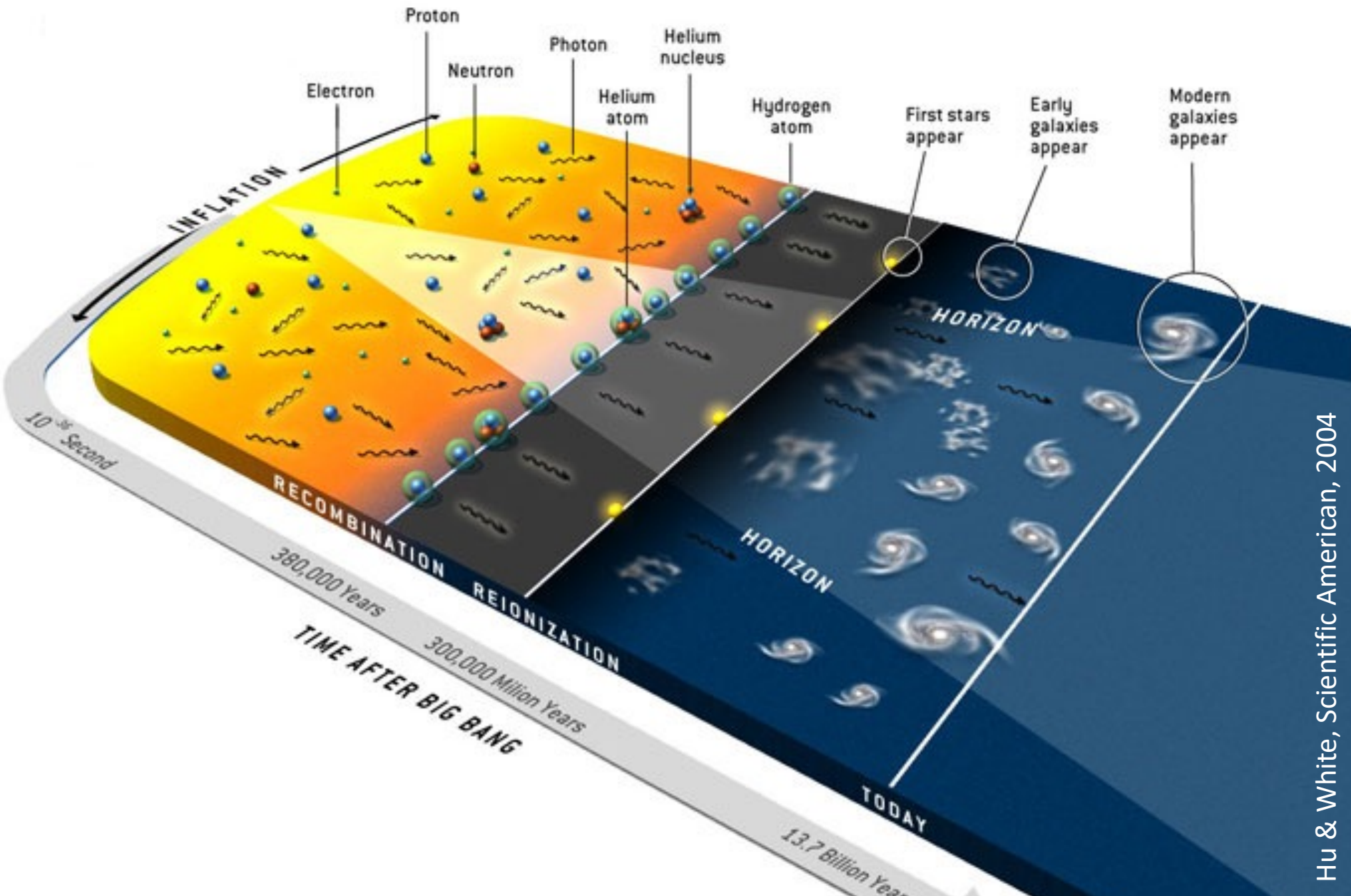
Jo

asst1

asst2

asst3

Context Reminder

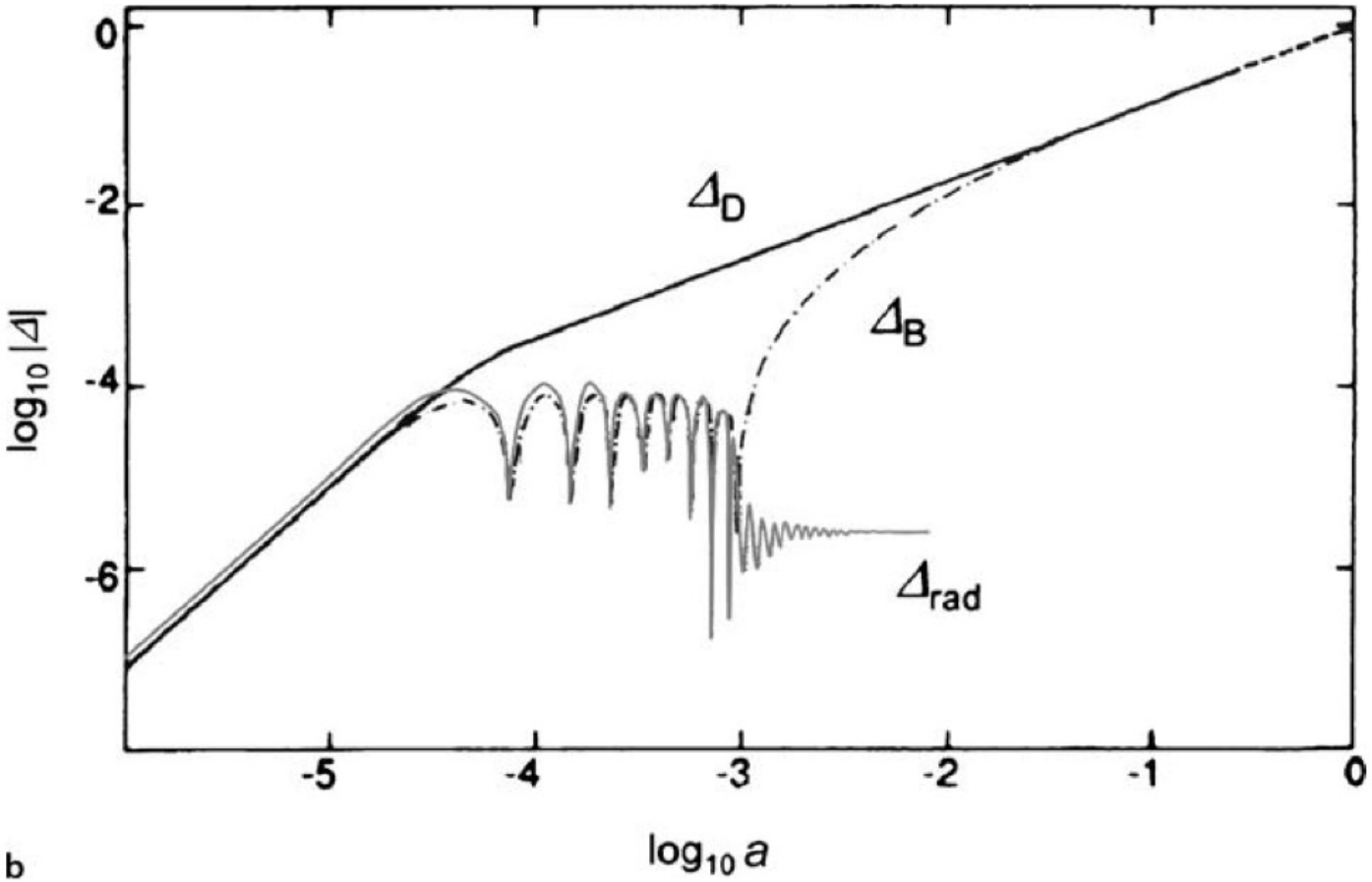


Hu & White, Scientific American, 2004

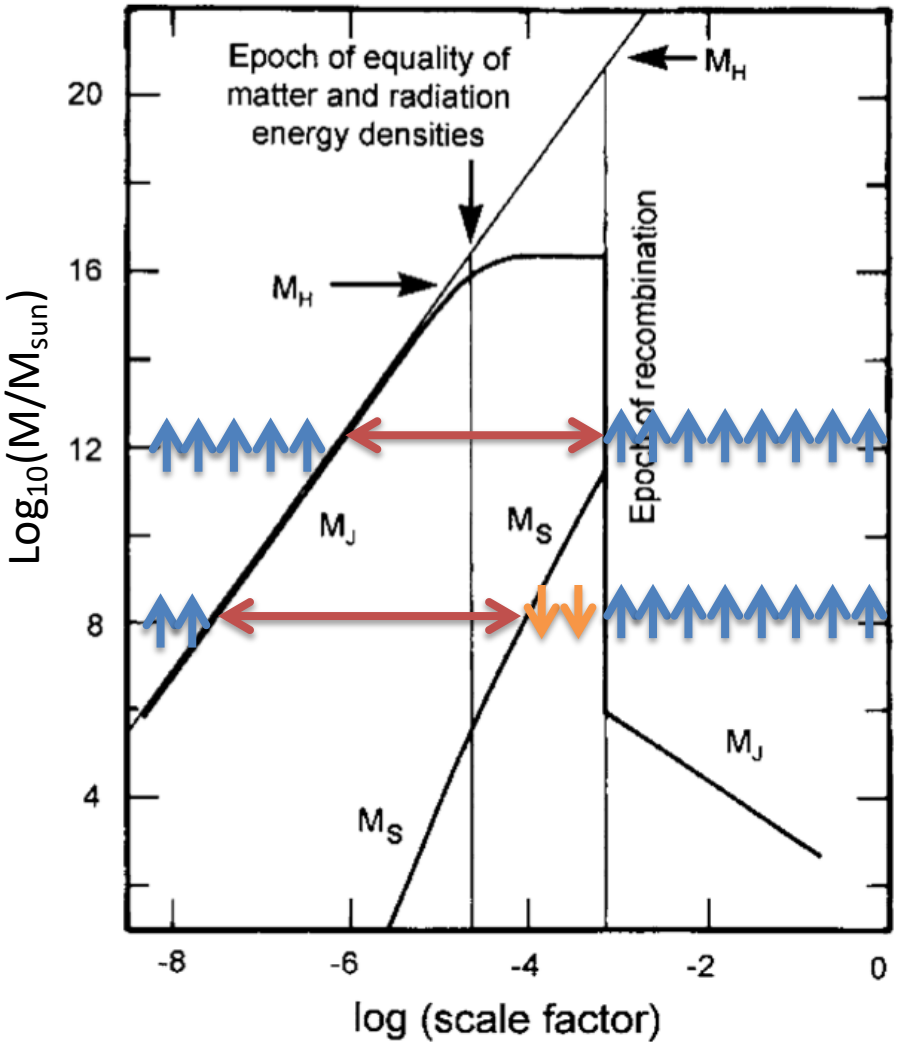
Review: Growth of Perturbations

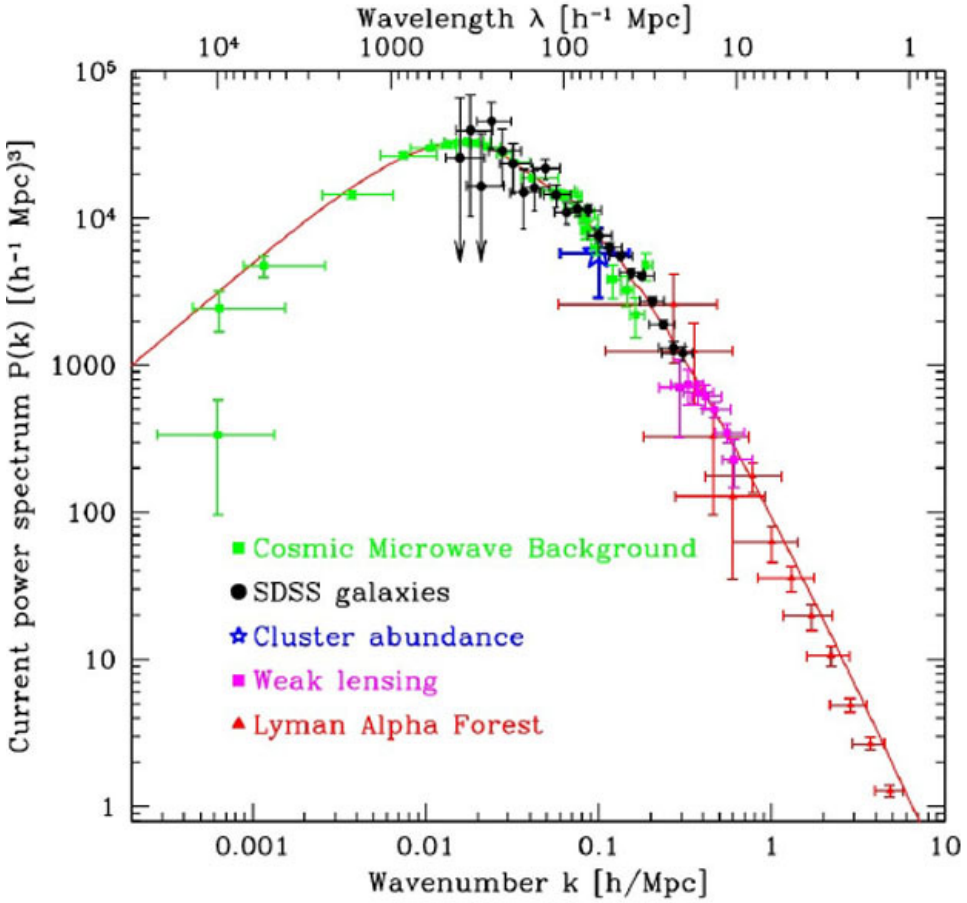
$$\ddot{\Delta} + 2\frac{\dot{a}}{a}\dot{\Delta} = \Delta\left(4\pi G\bar{\rho} - \frac{c_s^2 k^2}{a^2}\right)$$

Just a damped harmonic oscillator!

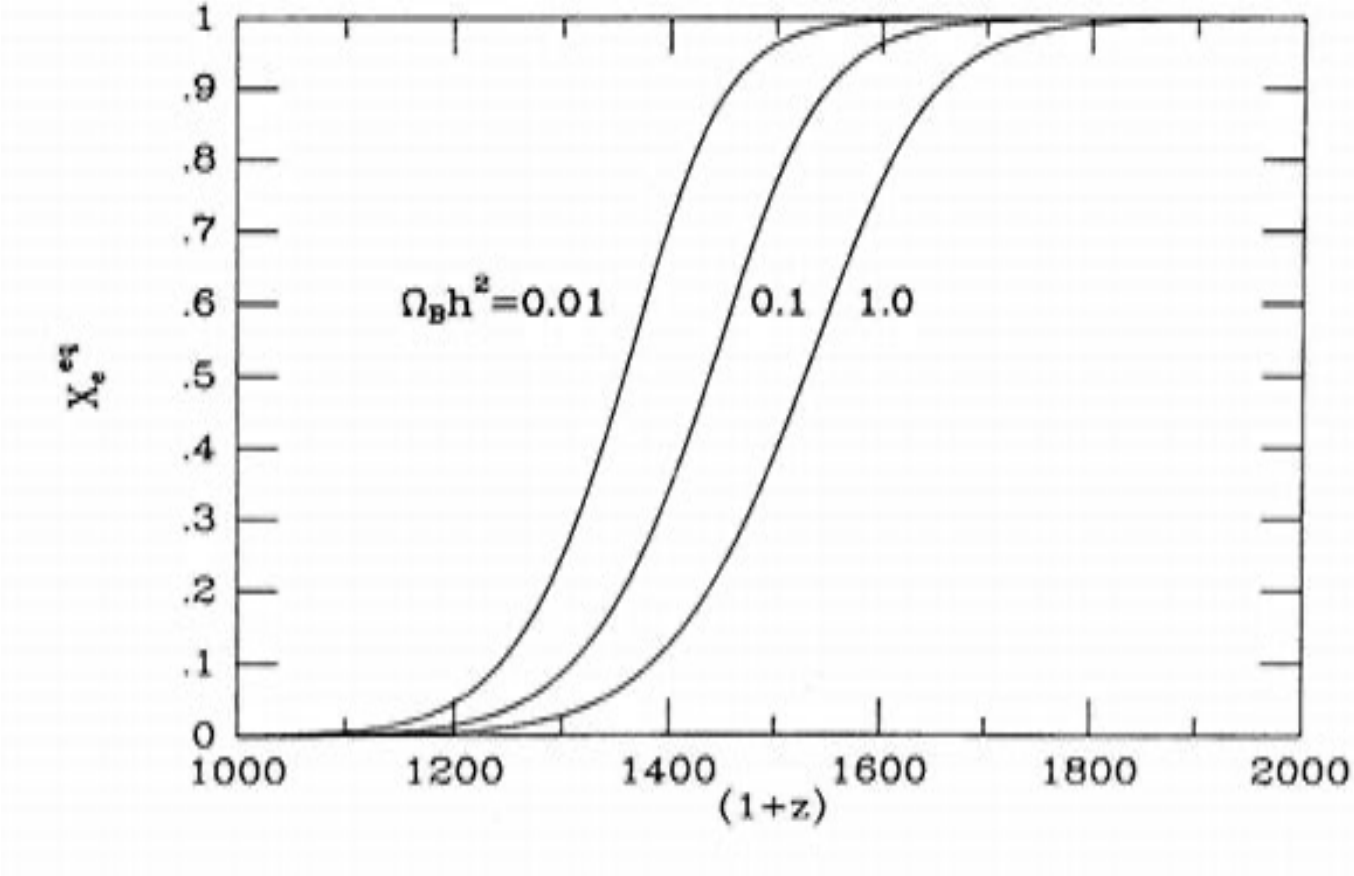


Review: Growth of Perturbations



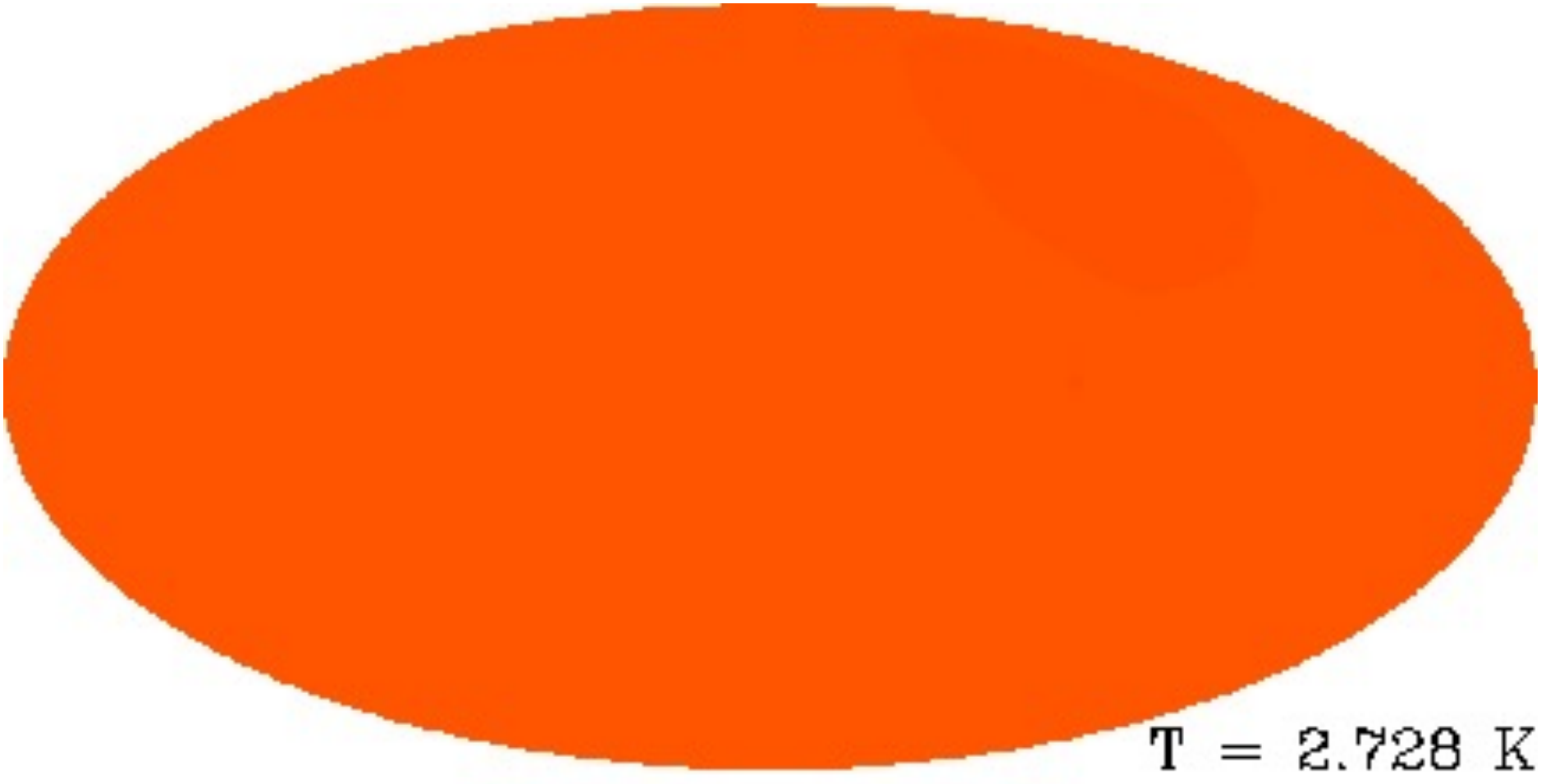


Review: Recombination, Decoupling, and the Surface of Last Scattering



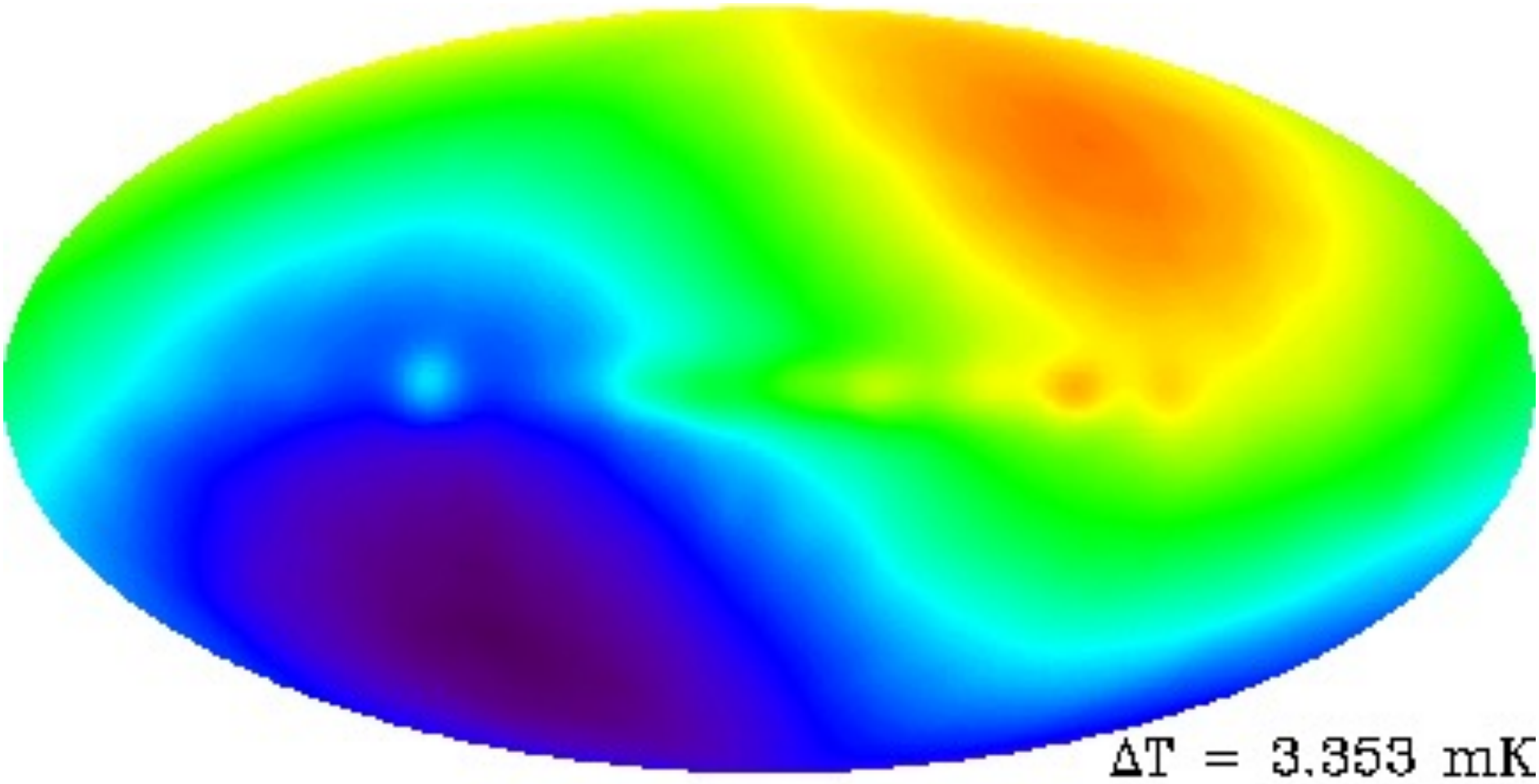
The Universe goes neutral when there are enough ionizing photons.
Mostly neutral by z≈1300; transparent around z≈1100.

The Monopole



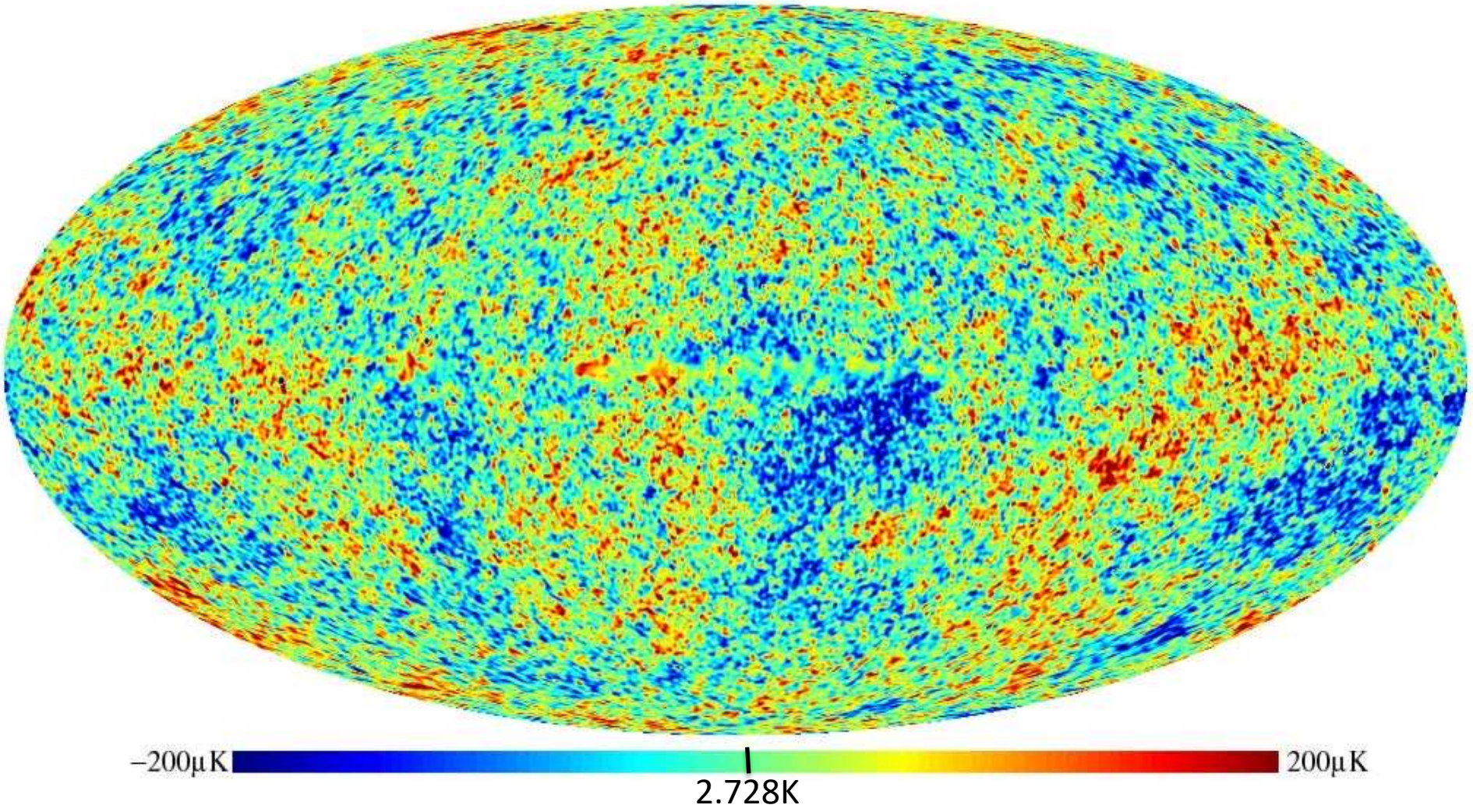
The Universe had an early hot phase, and has expanded by at least 1000x.

The Dipole



Our peculiar velocity is ≈ 600 km/s, toward the constellation Leo.

The Anisotropies



These are a little more complicated…

Structure at z ≈ 1100

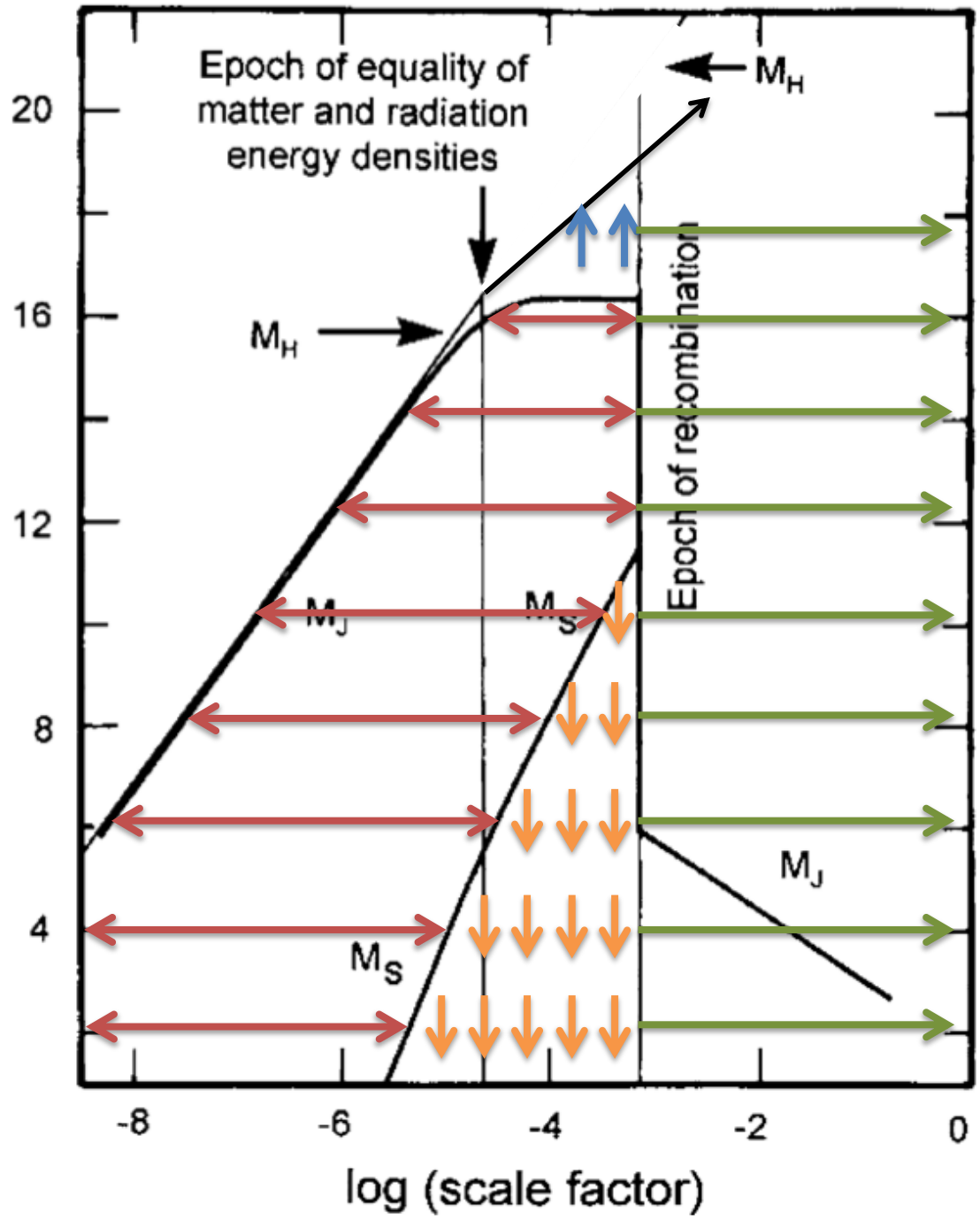
Assume Harrison-Zel'dovich, $\Delta_k(\text{hor}) = \text{const}$

Growing

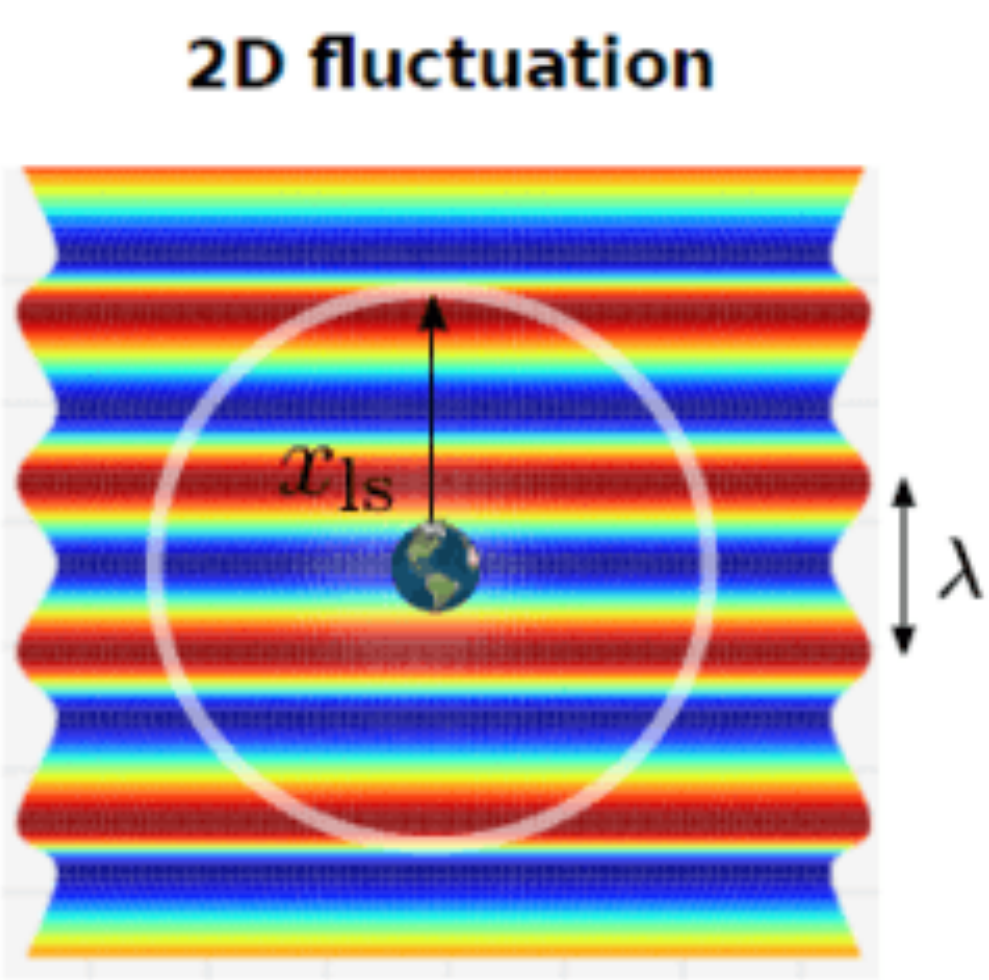
Oscillating

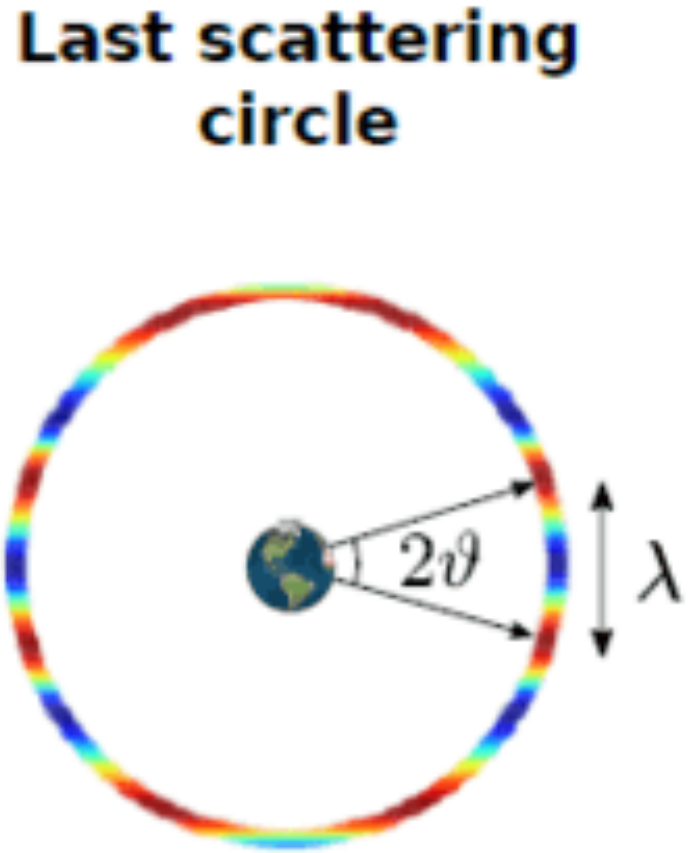
Silk Damping

Frozen In



Planes waves to Last Scattering Surface

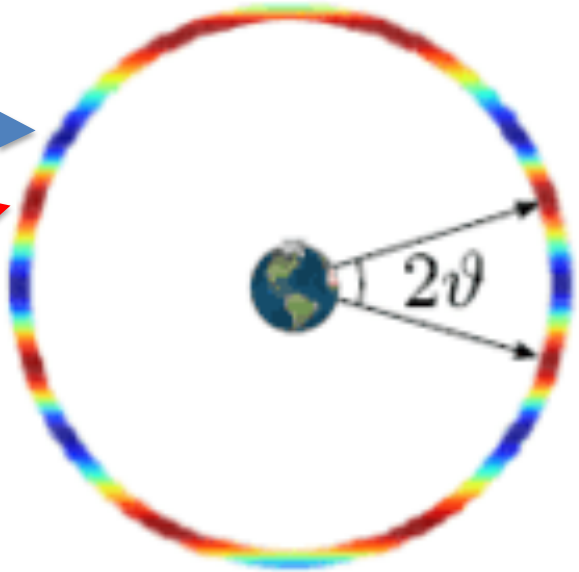




Sachs-Wolfe Effect

Overdensities
(Potential Wells)

Underdensities
(Potential Hills)



At LSS, photons:

climb out of potential wells → gravitational redshift

fall down from potential hills → gravitational blueshift

(Lose/gain energy and particle density drops/increases.)

Multipoles

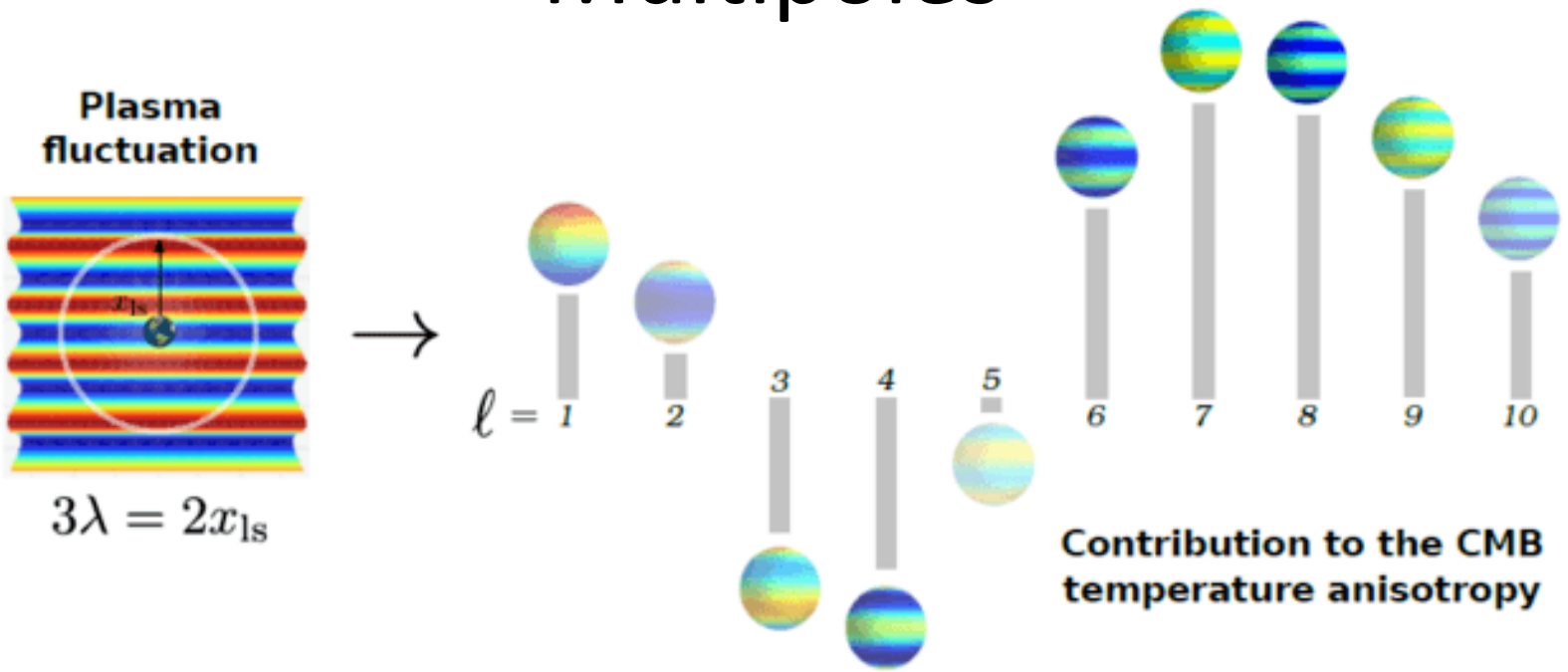
CMB gives a 2d view of the surface of last scattering, z=1100. This spherical shell doesn't *directly* probe $\Delta_k(z=1100)$.

To deal with 2d and the curved sky, we use a standard multipole decomposition, of the CMB temperature field.

$$T(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

$a_{lm} \Leftrightarrow \Delta_k$ is non-trivial, but at least somewhat local

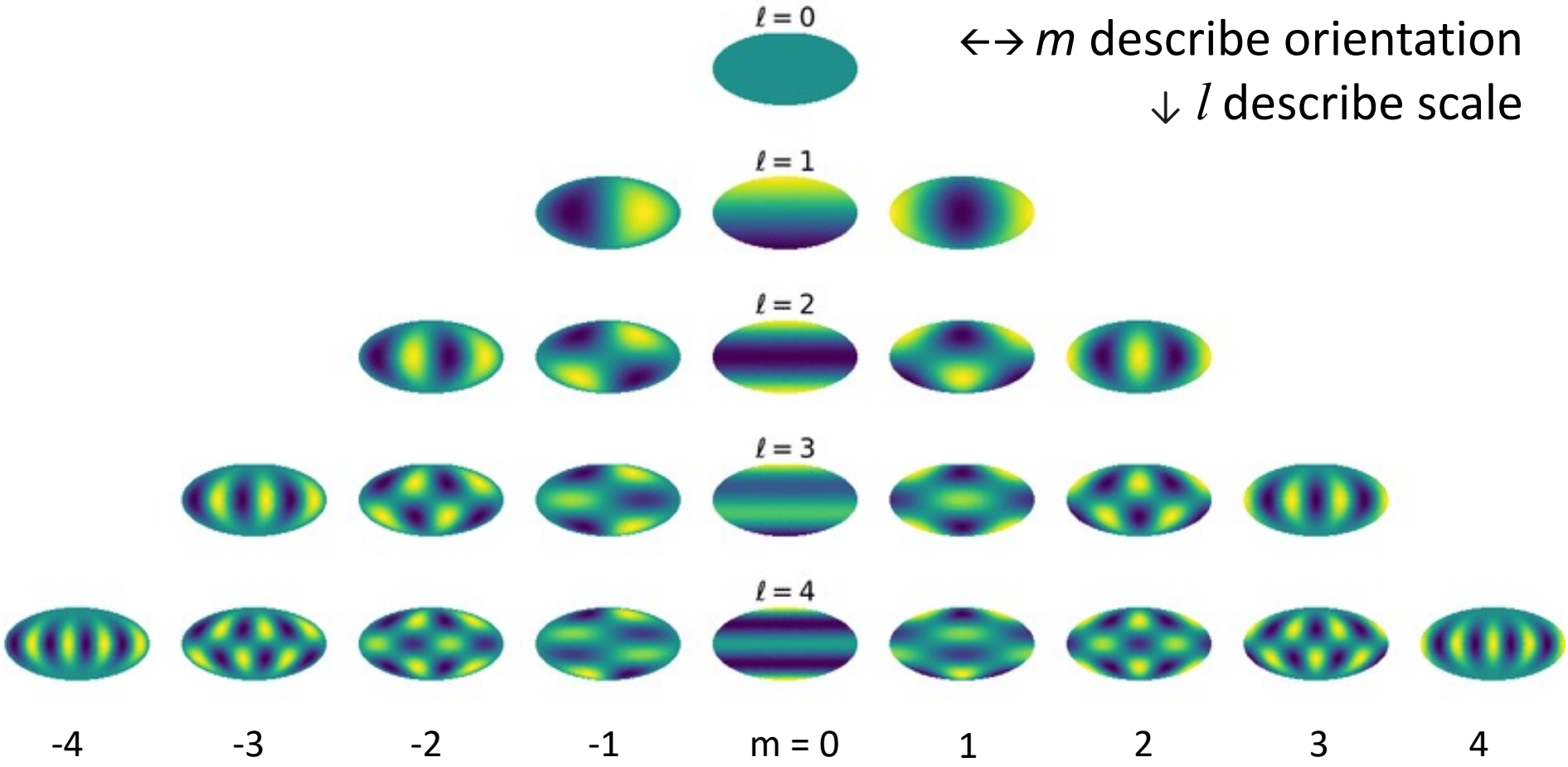
Multipoles



$$e^{i\mathbf{k}\cdot\mathbf{r}} = 4\pi \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} i^{\ell} j_{\ell}(kr) Y_{\ell m}(\hat{\mathbf{r}}) Y^{*}_{\ell m}(\hat{\mathbf{k}})$$

Spherical Bessel Function
Peaks near kr ≈ l

Multipoles



←→ *m* describe orientation

↓ *l* describe scale

Cosmological principle: no preferred axis!

No useful differences across *m*!

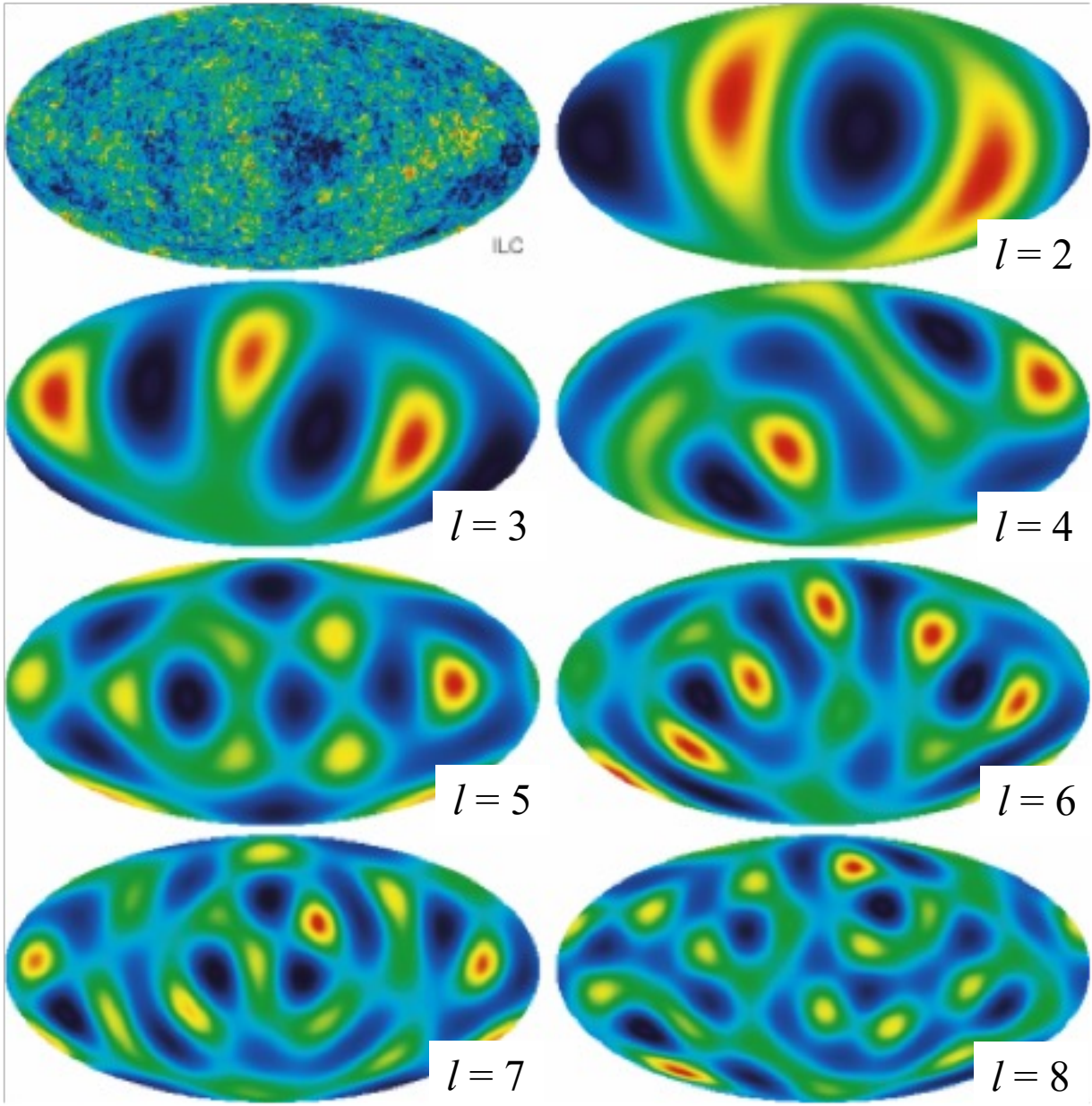
C_l Multipoles

$$T(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l \equiv \frac{1}{2l+1} \sum_m a_{lm} a_{lm}^* = \left\langle |a_{lm}|^2 \right\rangle$$

$C_{l=0}$ is the monopole
($T_{CMB} \approx 2.78K$)

$C_{l=1}$ is the dipole
($v_{pec} \approx 370$ km/s)



C_l Multipoles

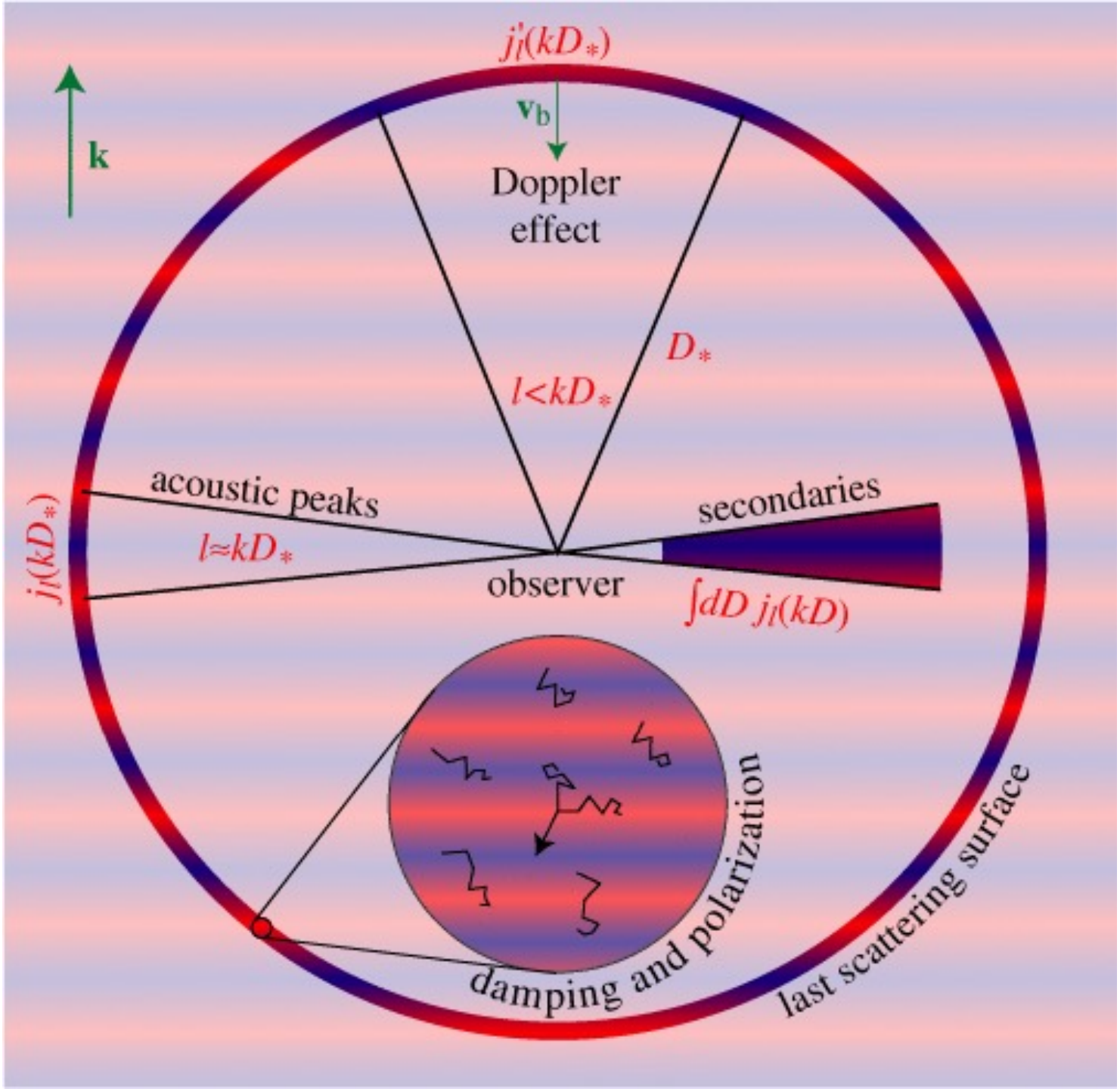
$$T(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{+l}a_{lm}Y_{lm}(\theta,\phi) \quad \rightarrow \quad C_l \equiv \frac{1}{2l+1}\sum_m a_{lm}a_{lm}^* = \left\langle |a_{lm}|^2 \right\rangle$$

$$C_l = 4\pi \int P_T(k) j_l^2(kr)\,dk$$

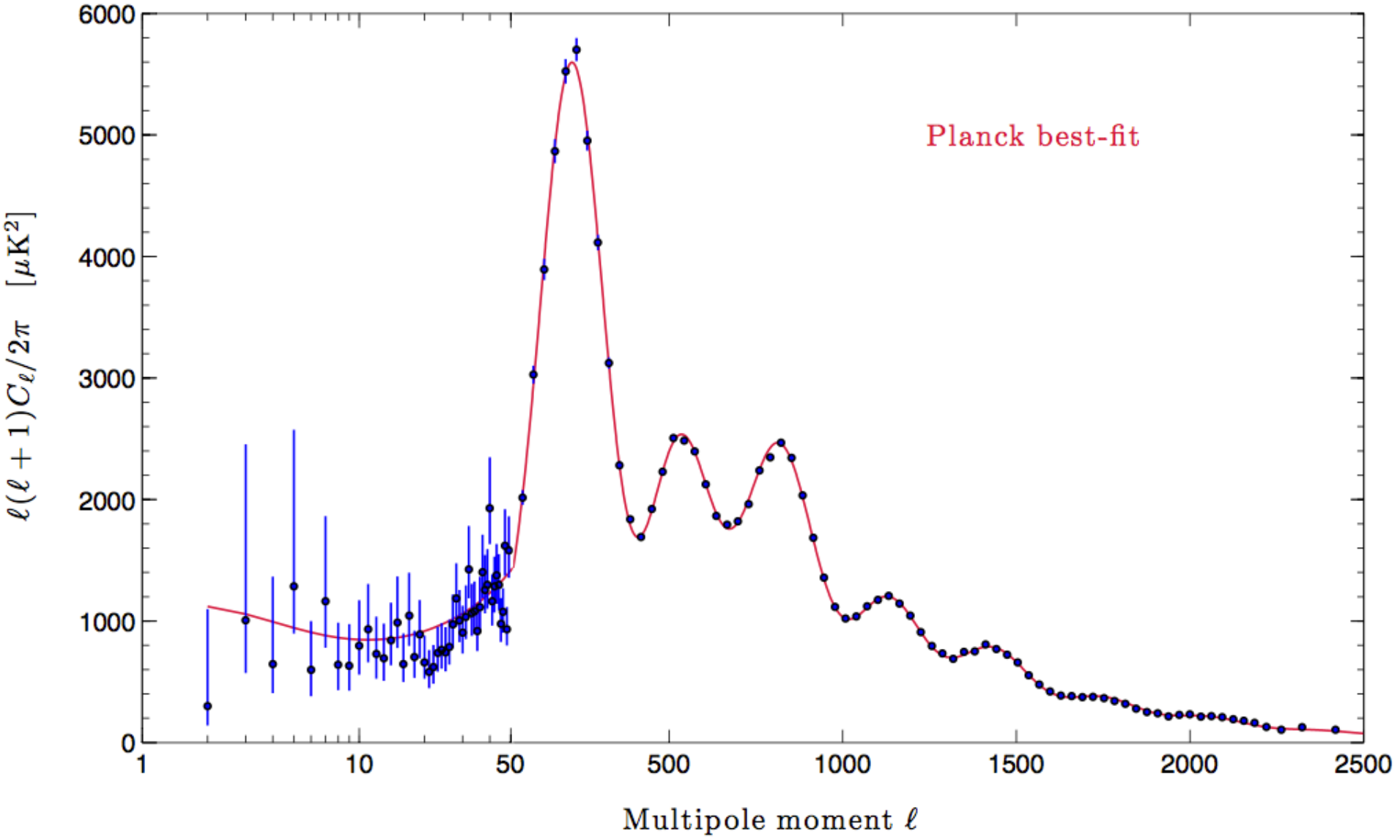
$$\Delta_T^2(k) = k\,P_T(k)$$

$$\rightarrow \quad C_l \approx \frac{2\pi}{l(l+1)}\Delta_T^2(k=l/r)$$

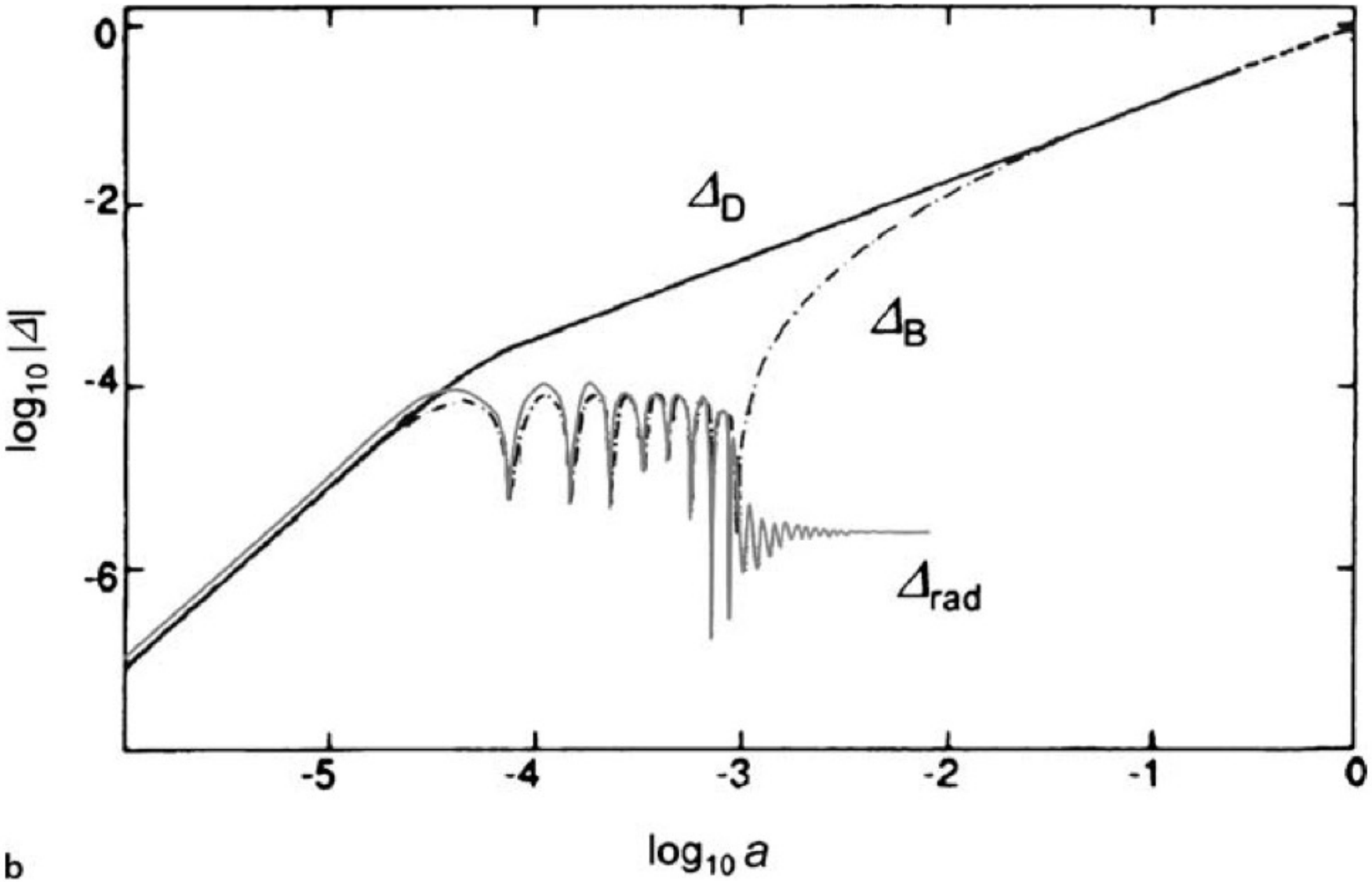
Often define & plot $D_\ell \equiv \ell(\ell+1)C_\ell/2\pi \quad (=\Delta_T^2)$


$j_l'(kD_*)$
k
v_b
Doppler
effect
D_*
$l<kD_*$
acoustic peaks
$l\approx kD_*$
$j_l(kD_*)$
secondaries
observer
$\int dD\, j_l(kD)$
damping and polarization
last scattering surface

The Power Spectrum

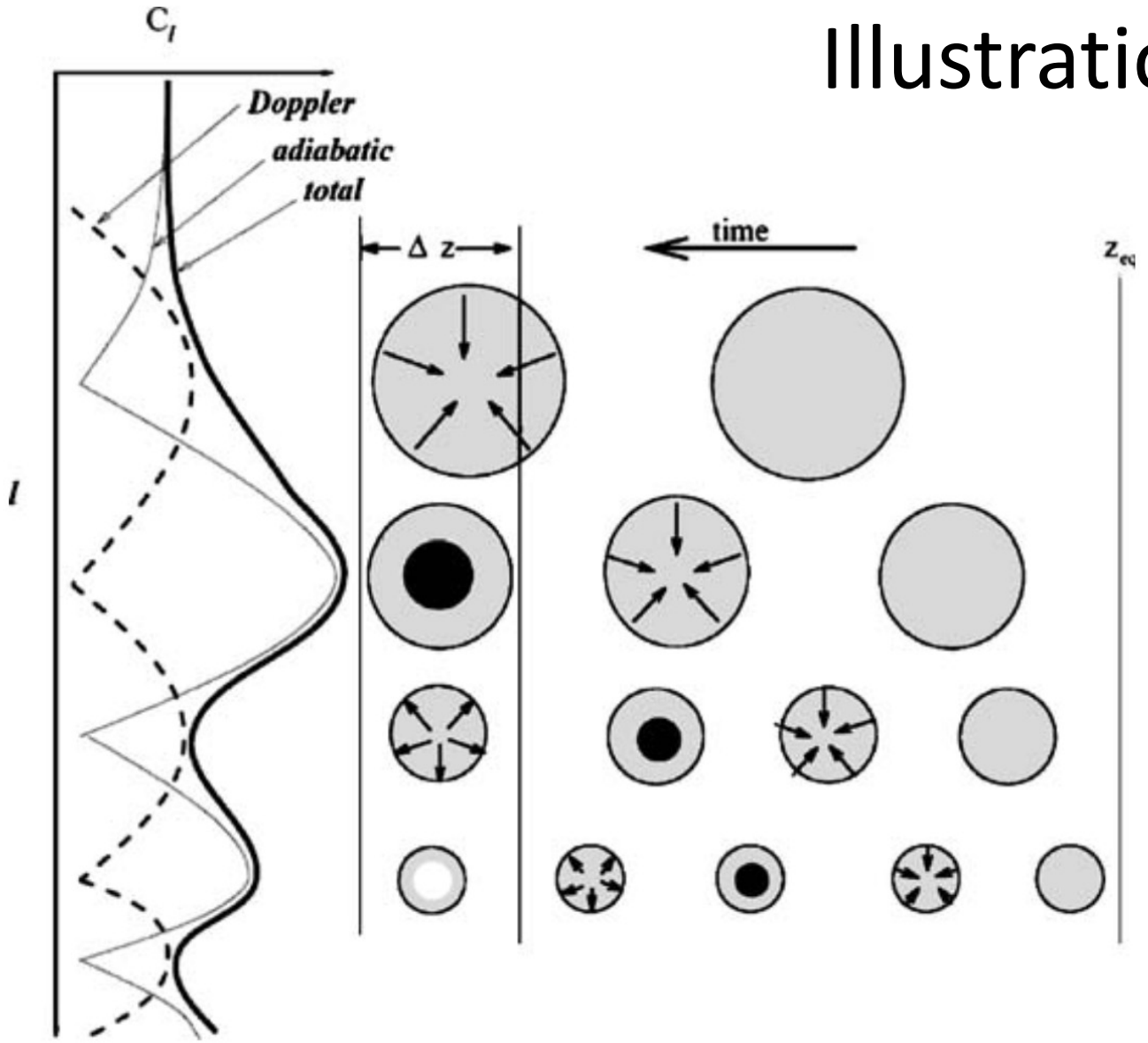


Why does it look like that?



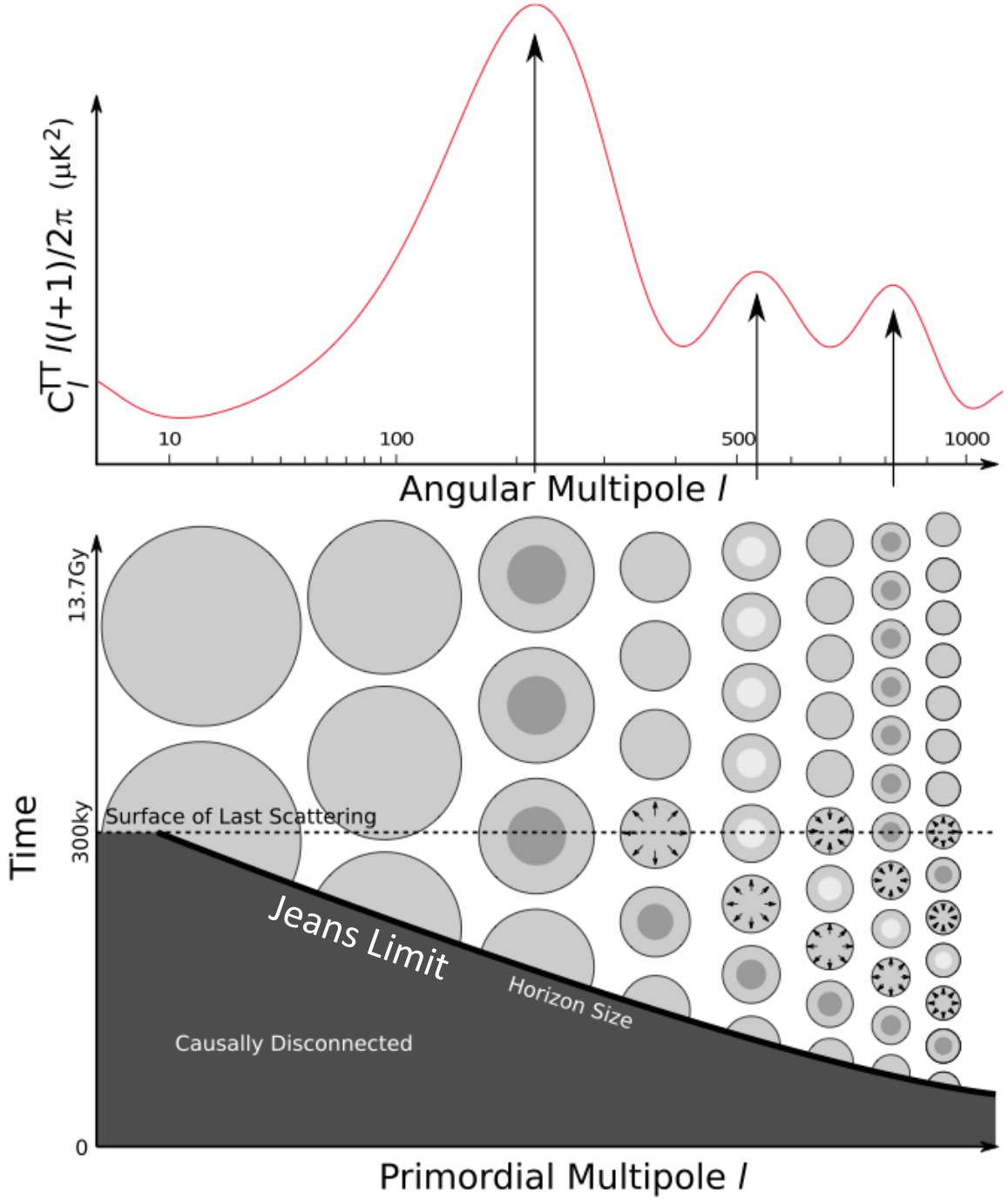
b

Beware Confusing Illustrations!



Either a helpful heuristic aid, or a disastrously confusing sidebar.

← These represent modes, not spheres.



(Keith's Thesis, circa 2007)

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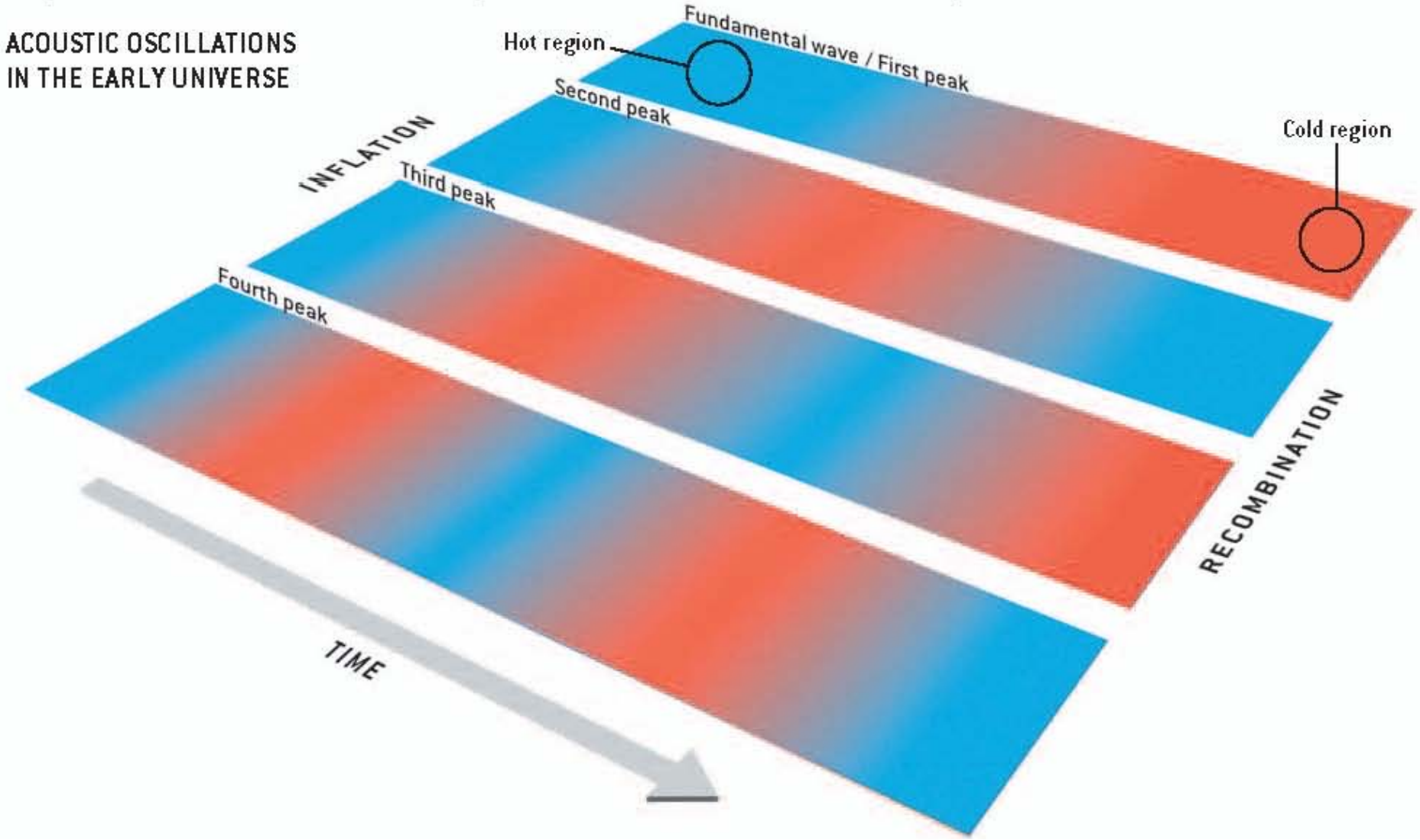
Acoustic Oscillations



Scientific American, 2004

Structure at z ≈ 1100

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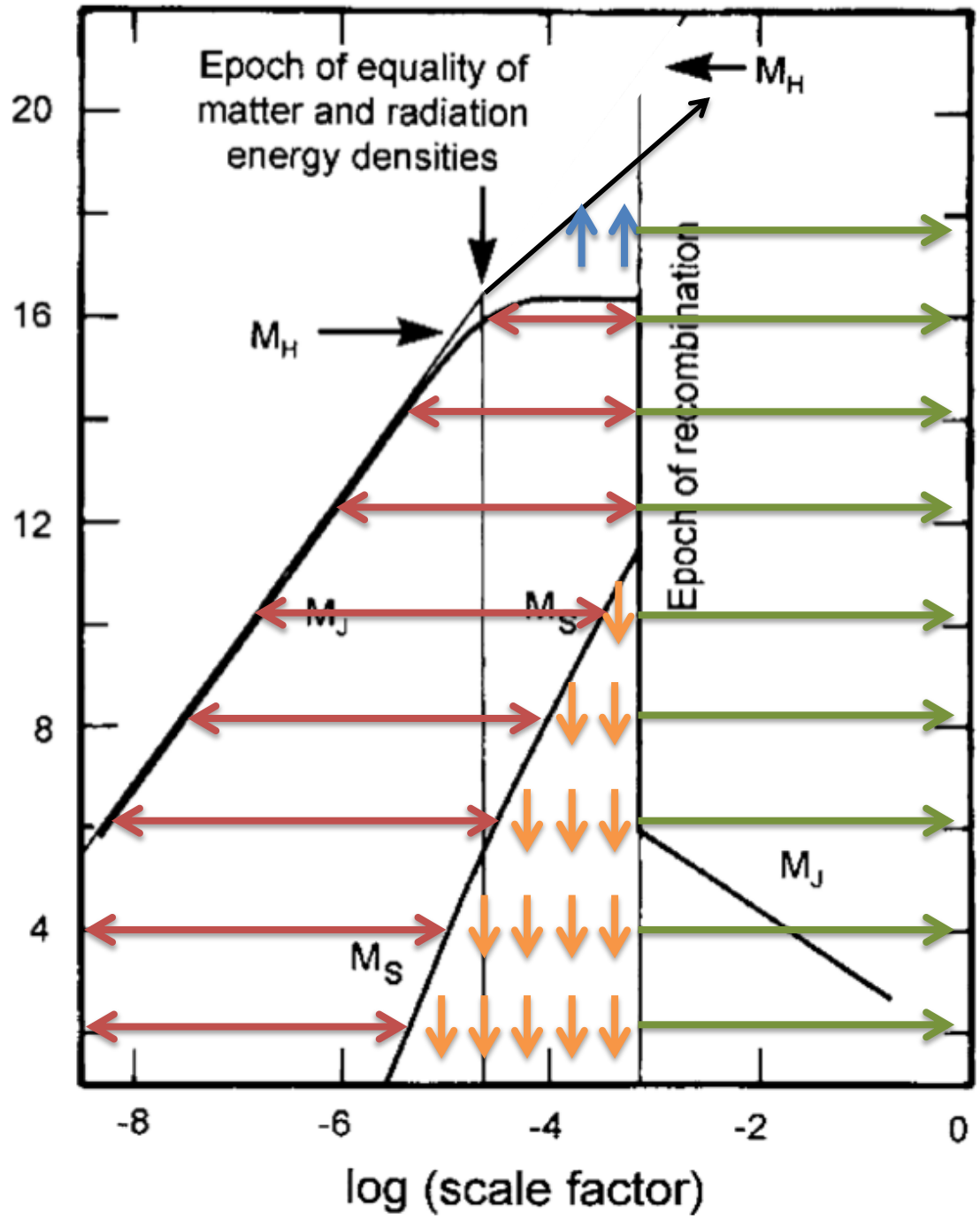
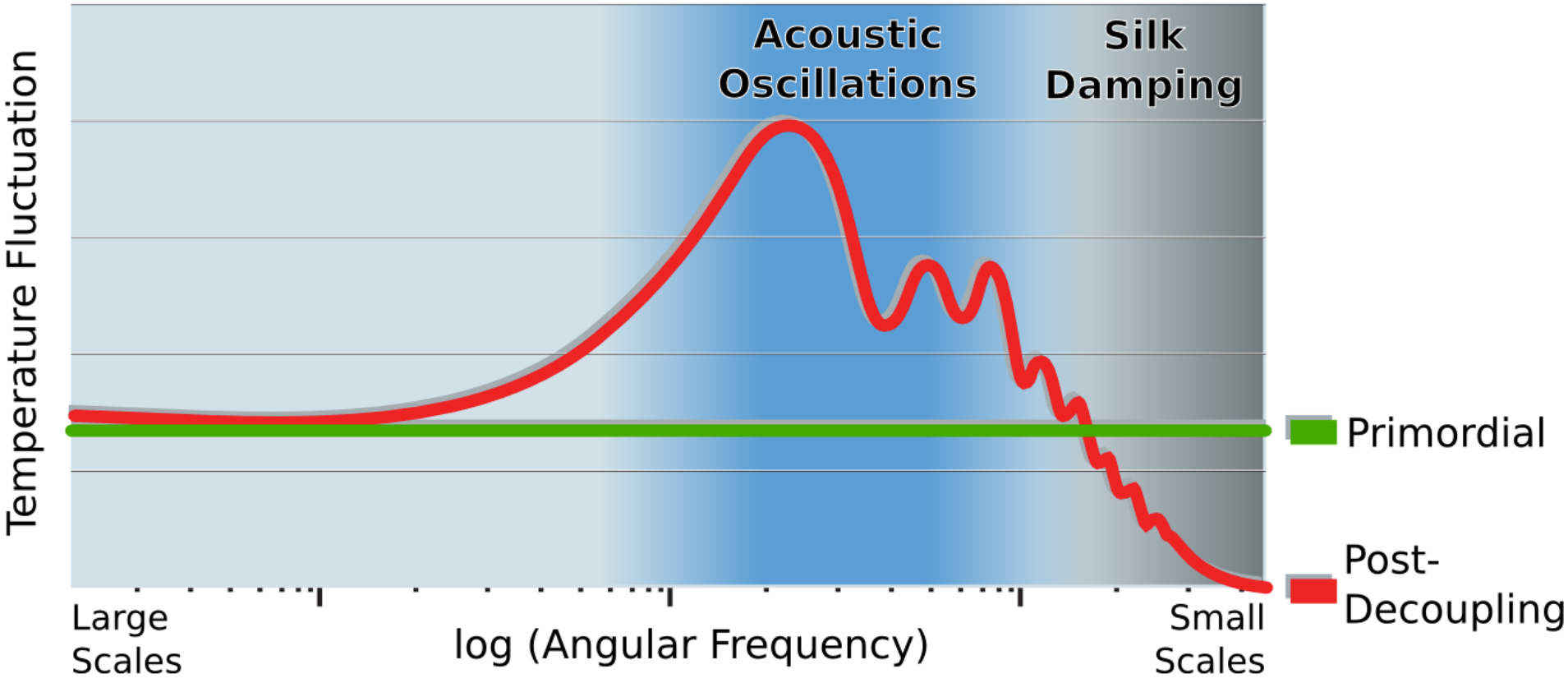
Silk Damping

Frozen In



CMB Angular Power Spectrum

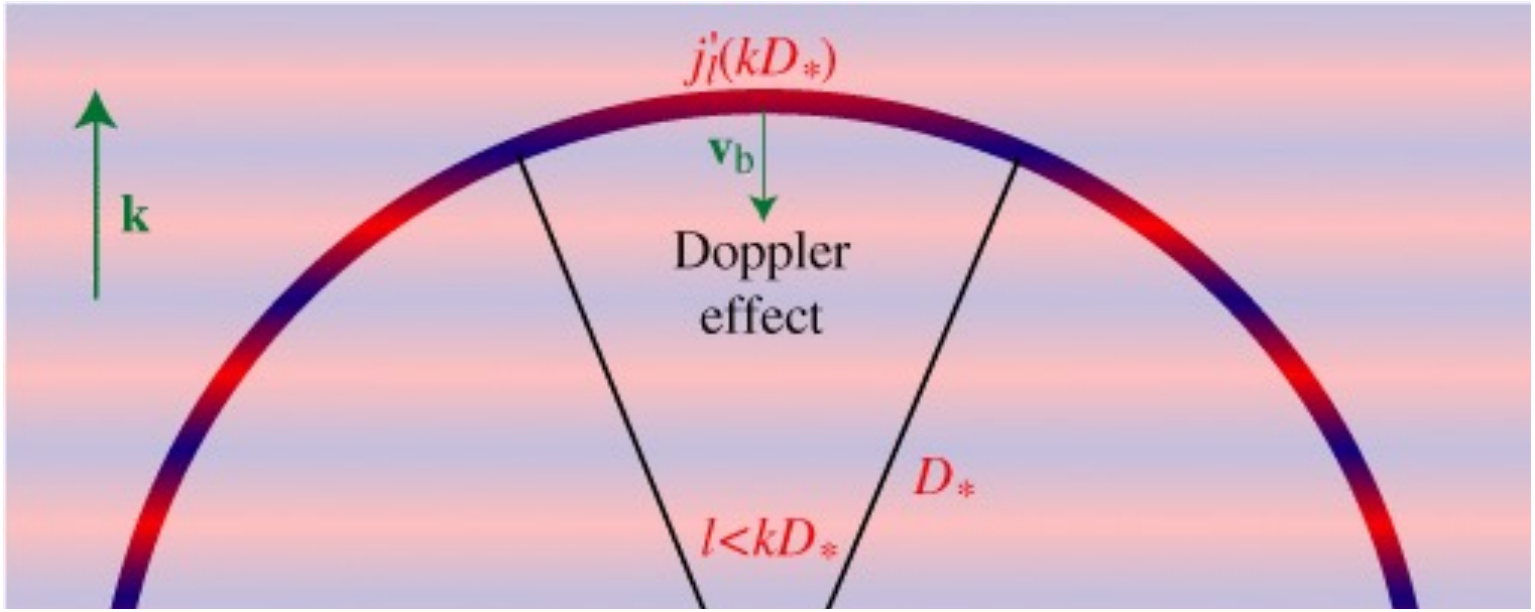


Doppler Effect

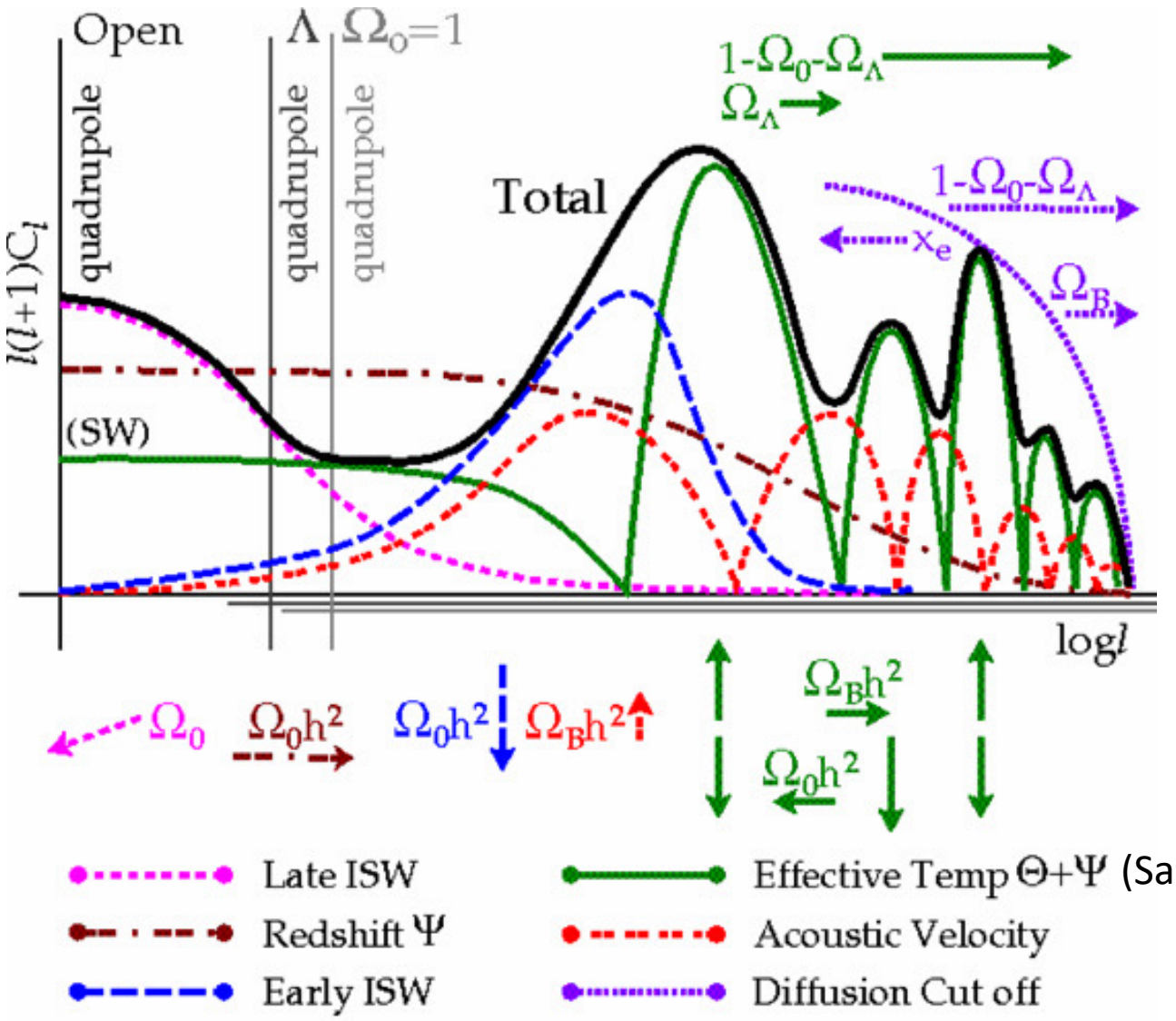
What we've been talking about is just the thermal distortion, aka the Sachs-Wolfe Effect.

Not to be confused with the *Integrated Sachs-Wolfe*, early or late.

SW depends on density. There's also a Doppler impact from material flowing into and out of potential wells. Exactly out of phase with SW.

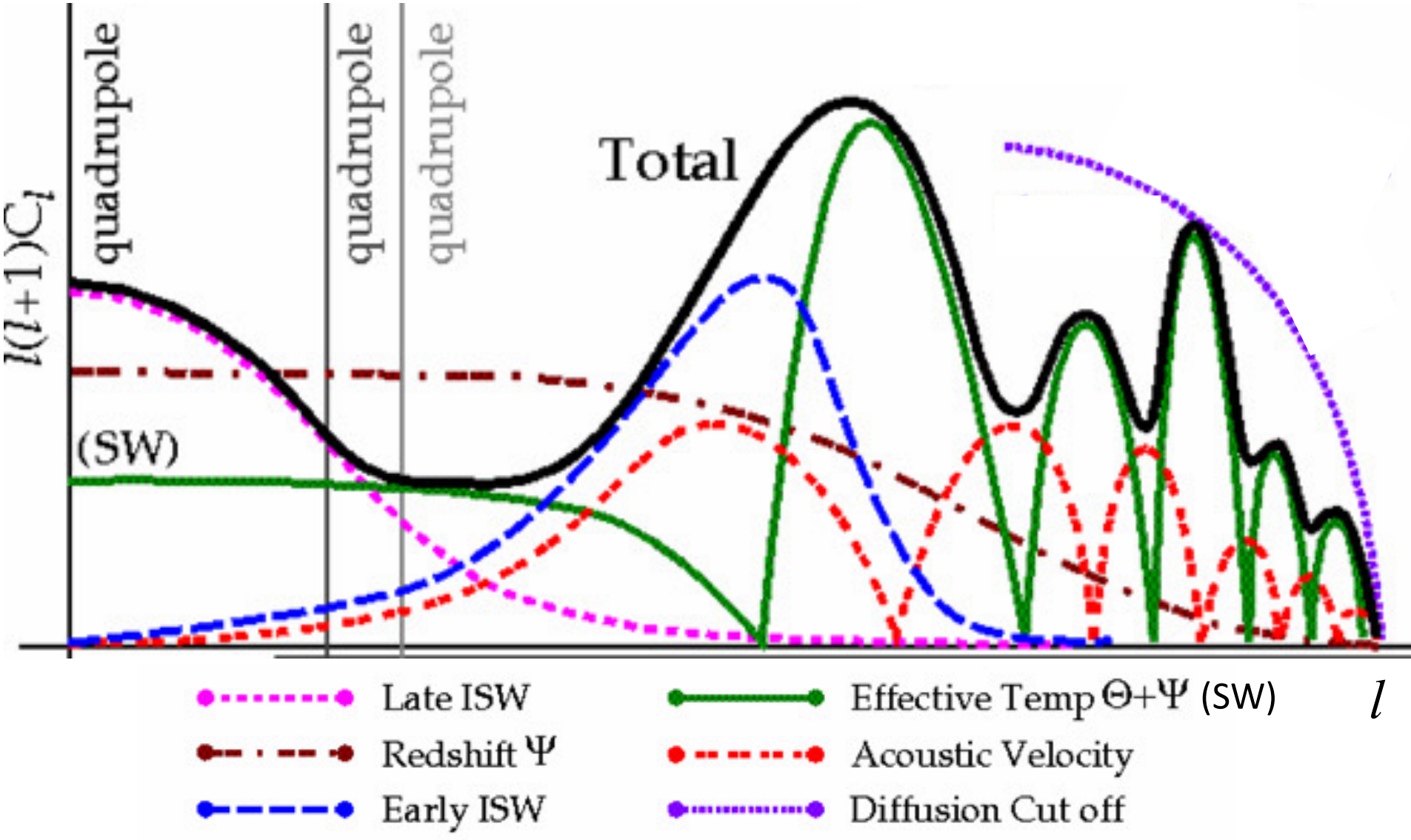


The Full Story

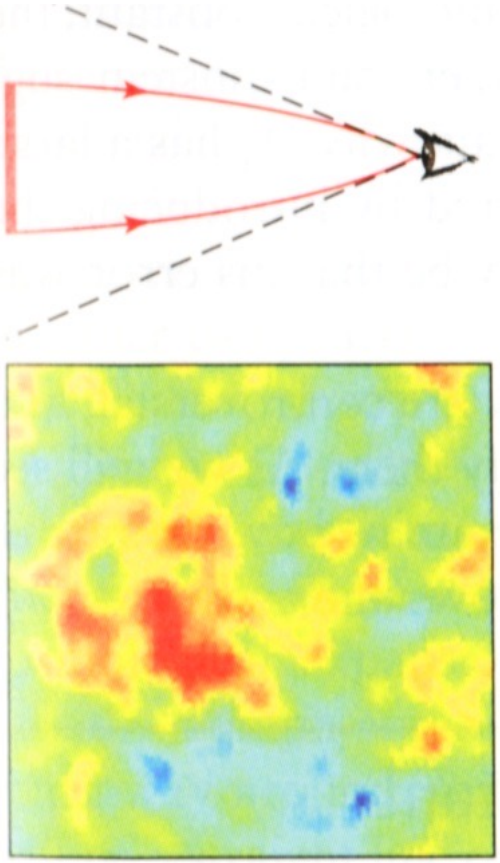


Hu, Sugiyama, & Silk (1995)

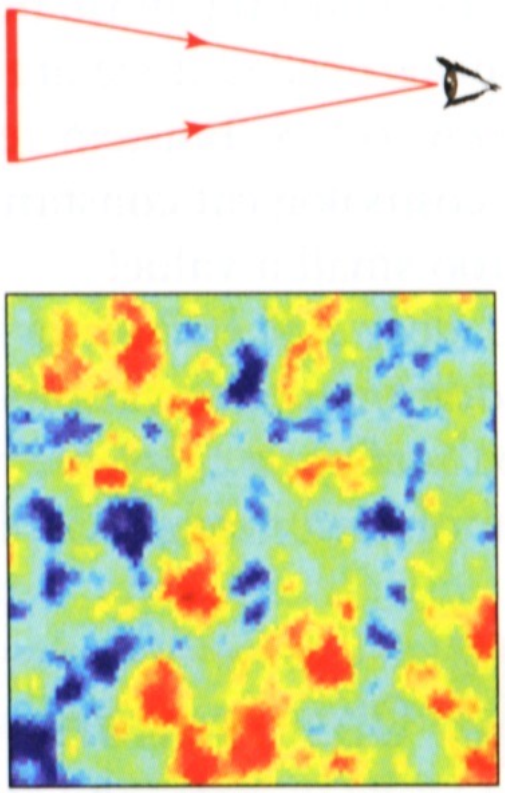
The Full Story



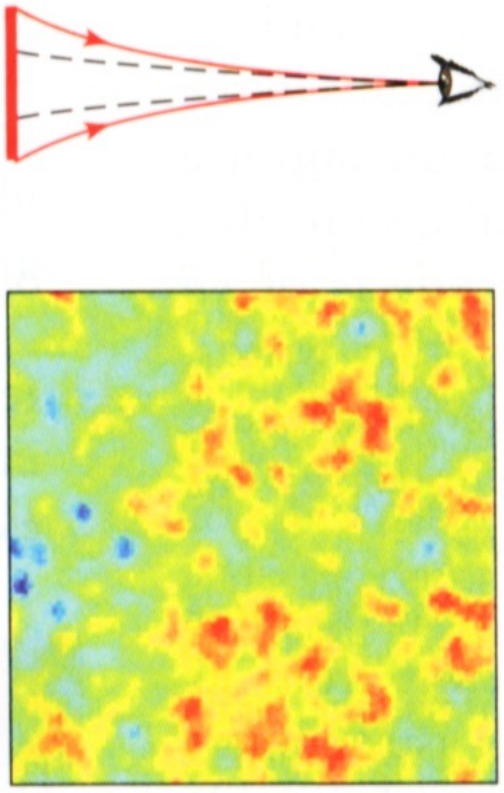
Curvature



a If universe is closed, "hot spots" appear larger than actual size

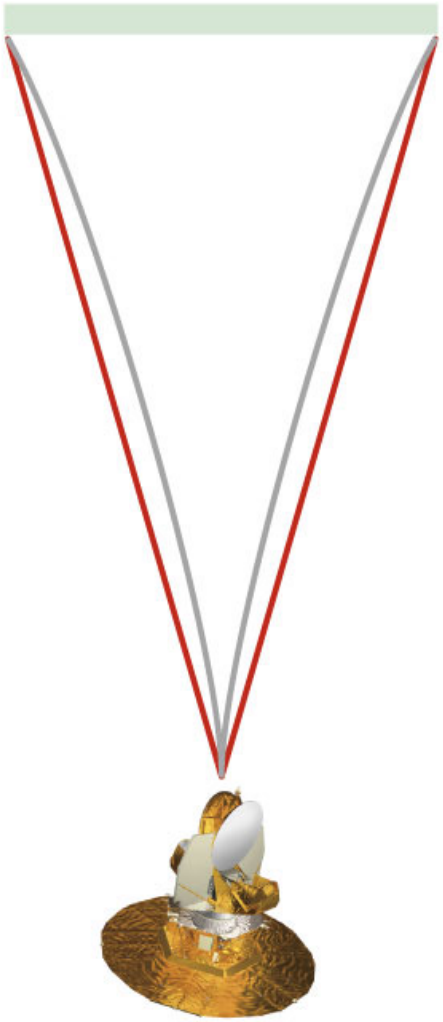


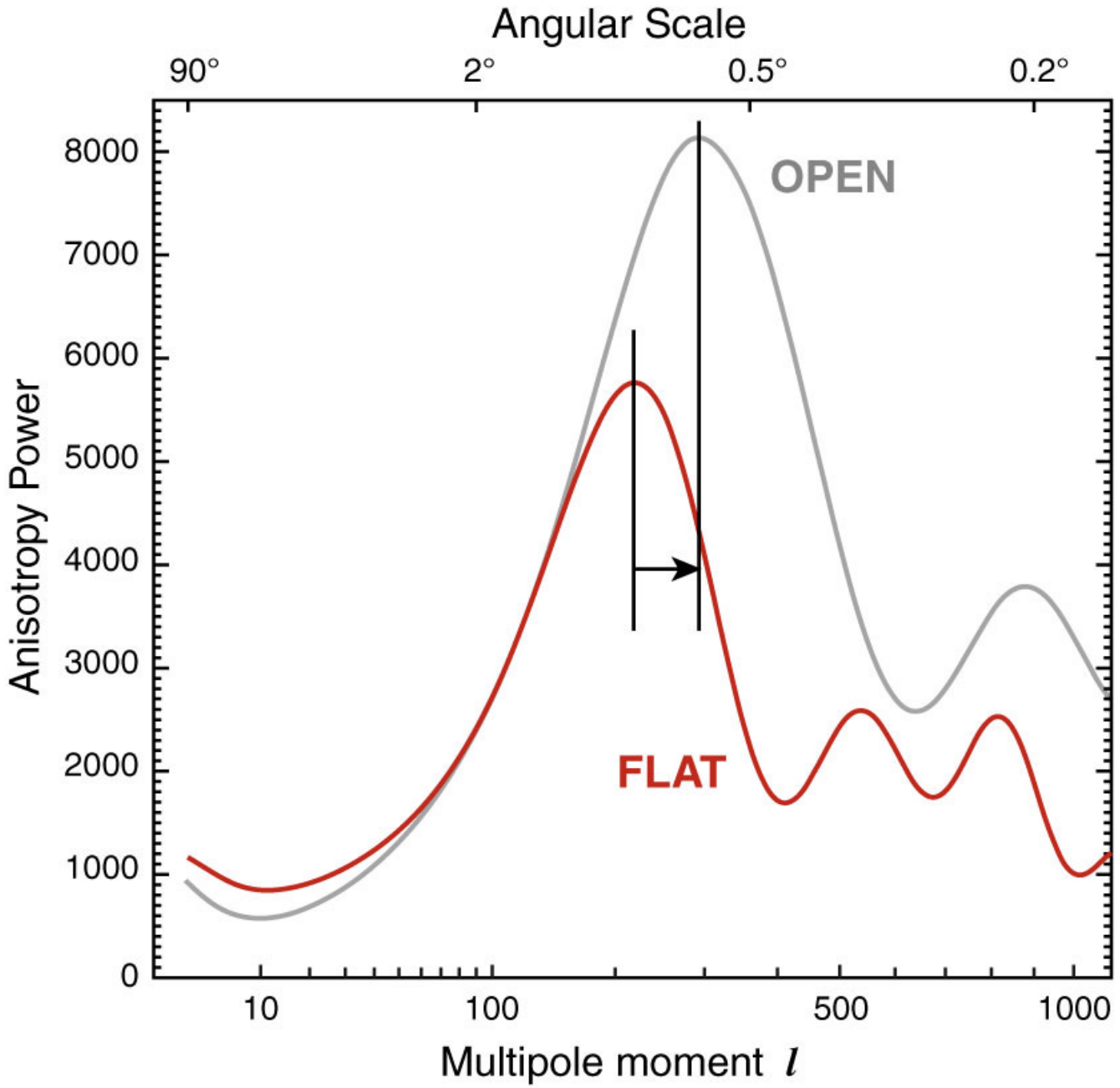
b If universe is flat, "hot spots" appear actual size



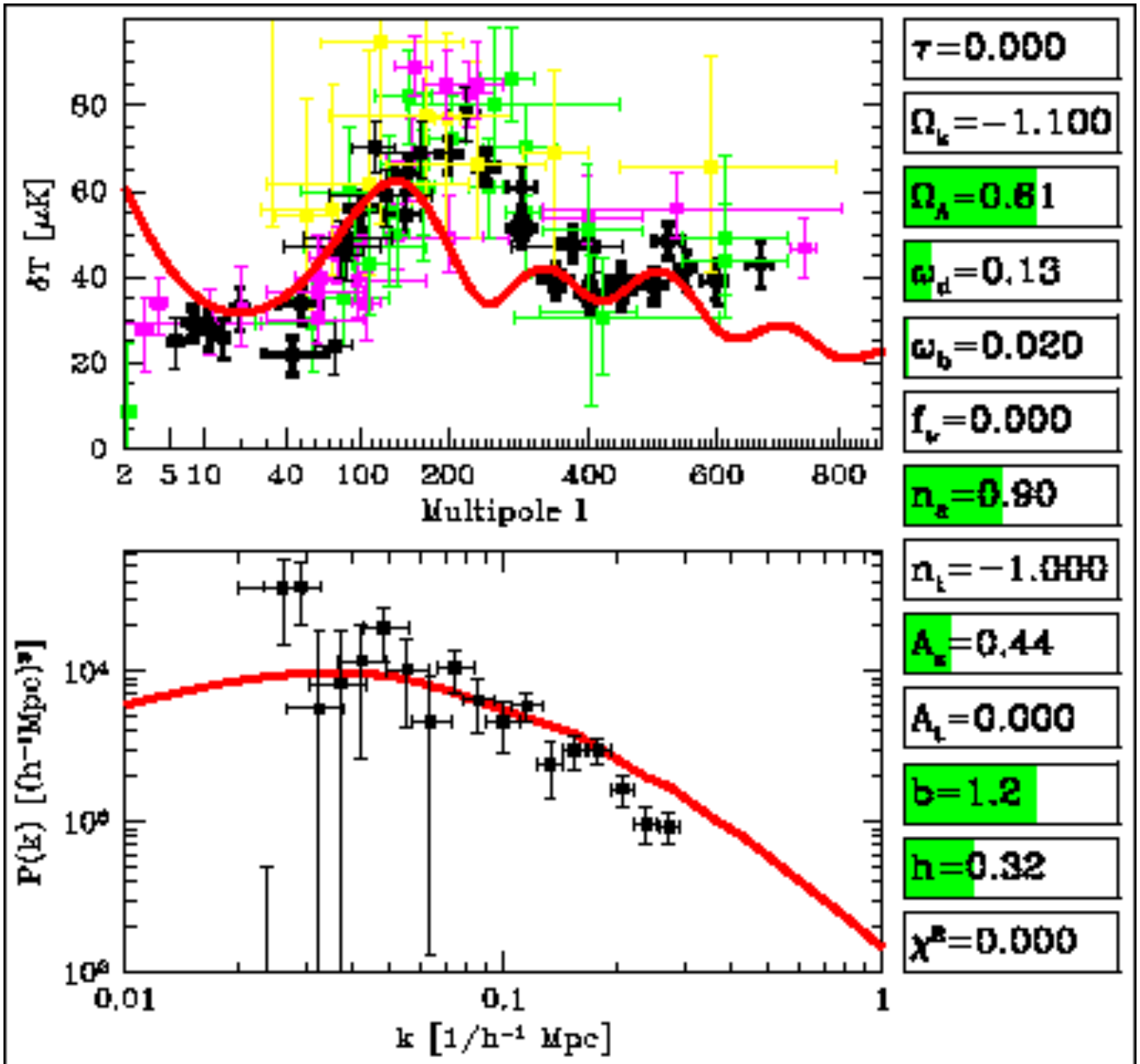
c If universe is open, "hot spots" appear smaller than actual size

Standard Ruler:
1° arc measurement of
dominant energy spike



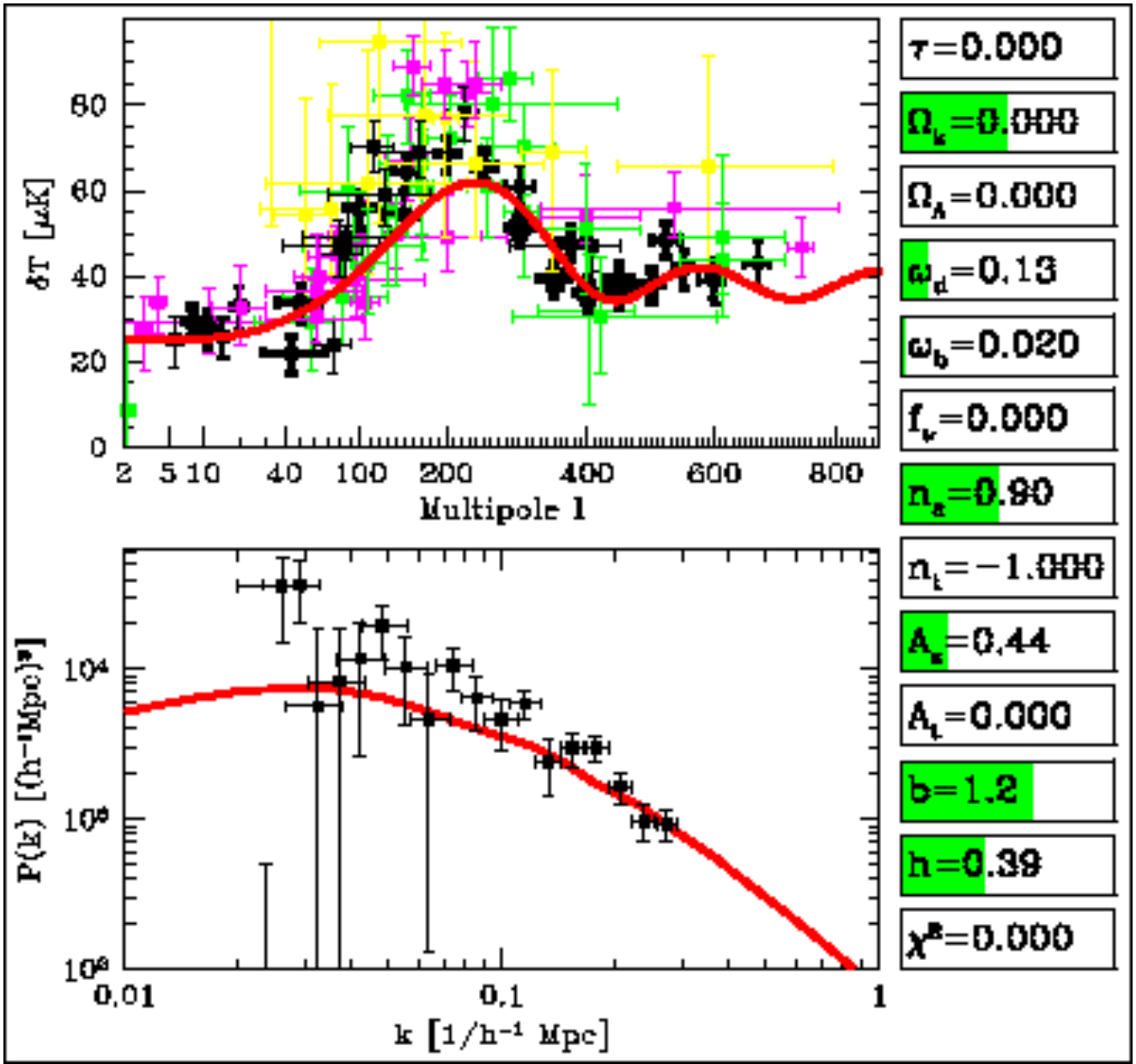


Curvature, Ω_κ



Tegmark et al.
astro-ph/0008167

Cosmological Constant, Ω_Λ



Tegmark et al.
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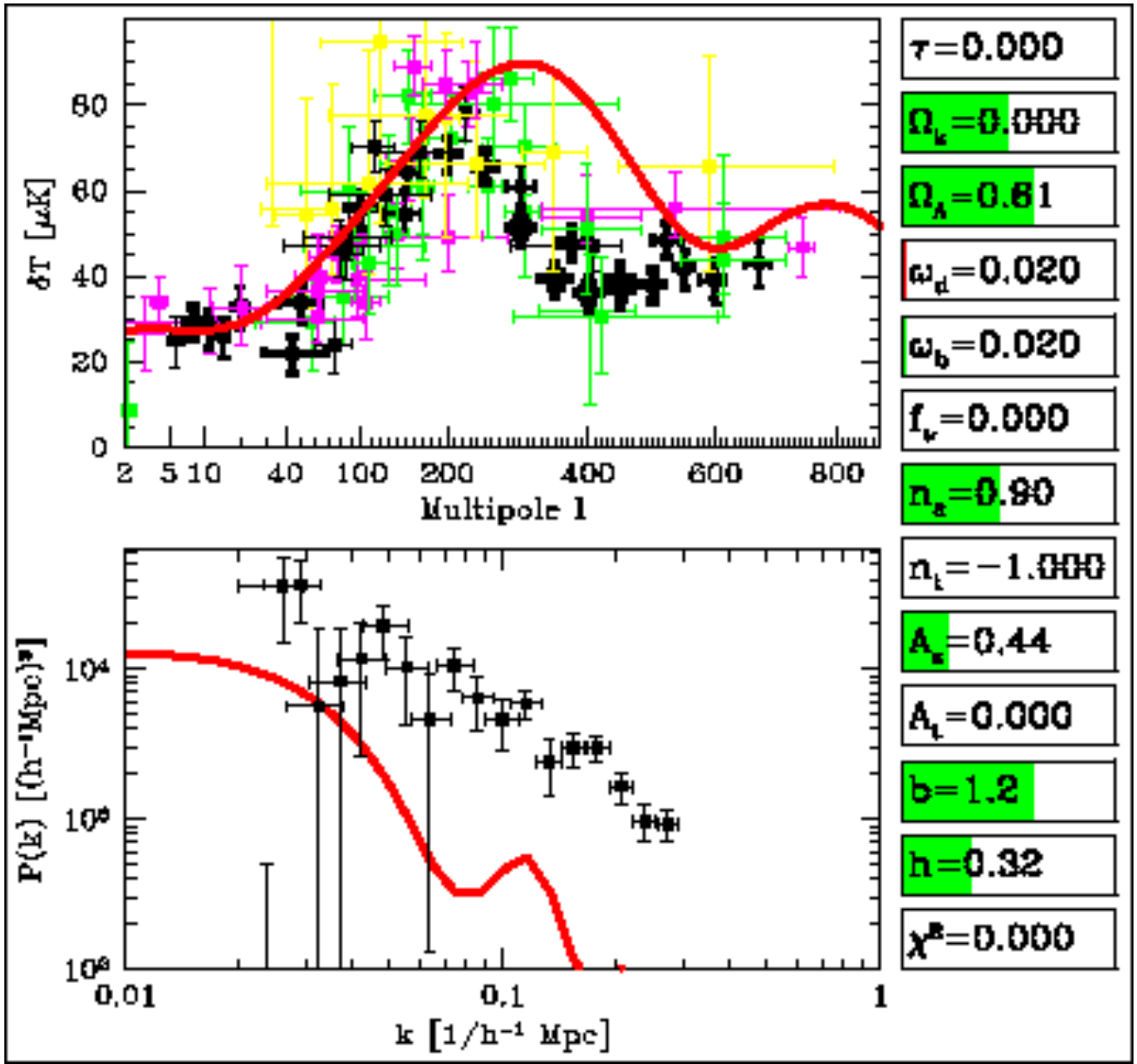
Dark Matter, Ω_D



Tegmark et al.
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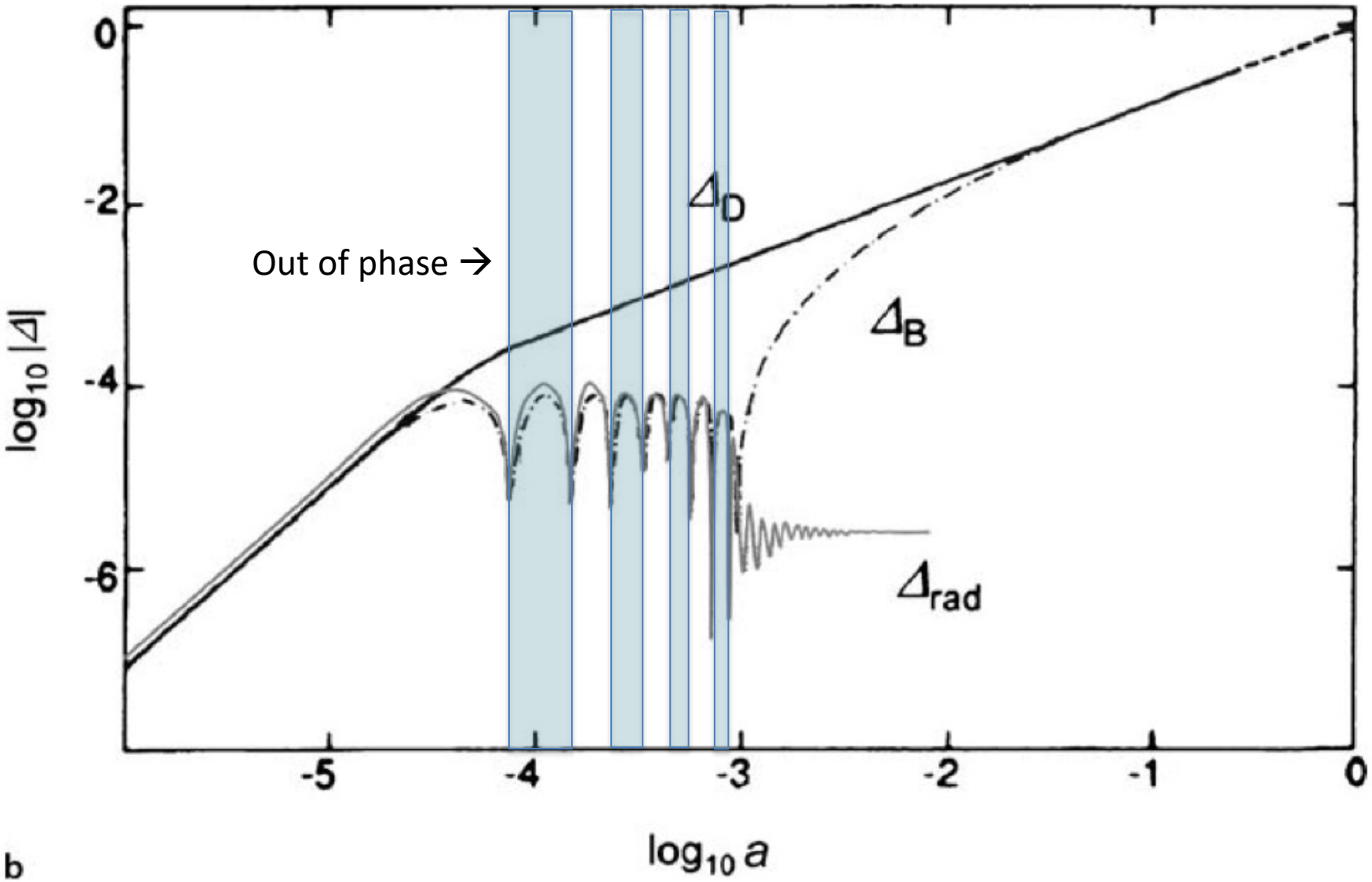
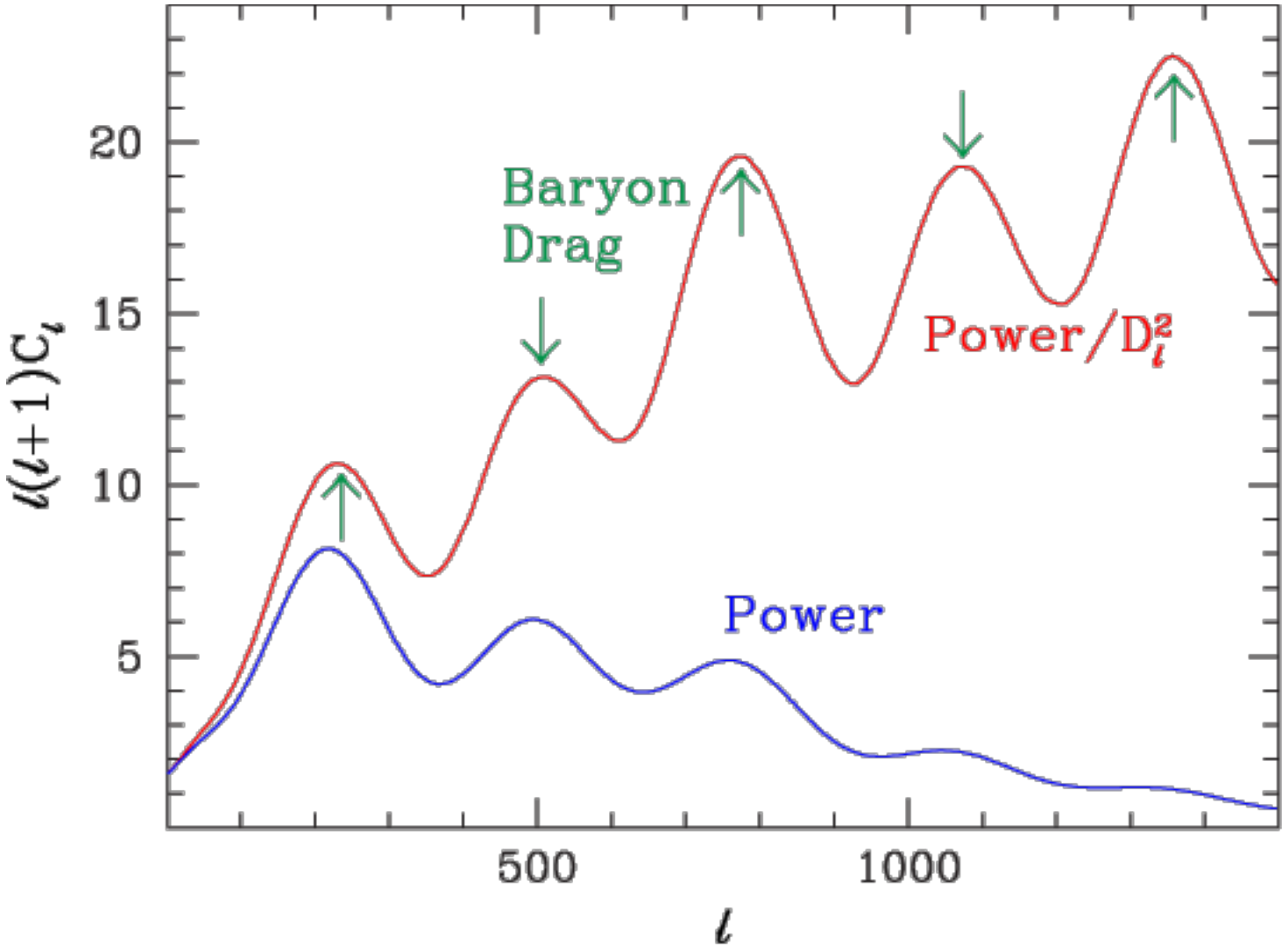
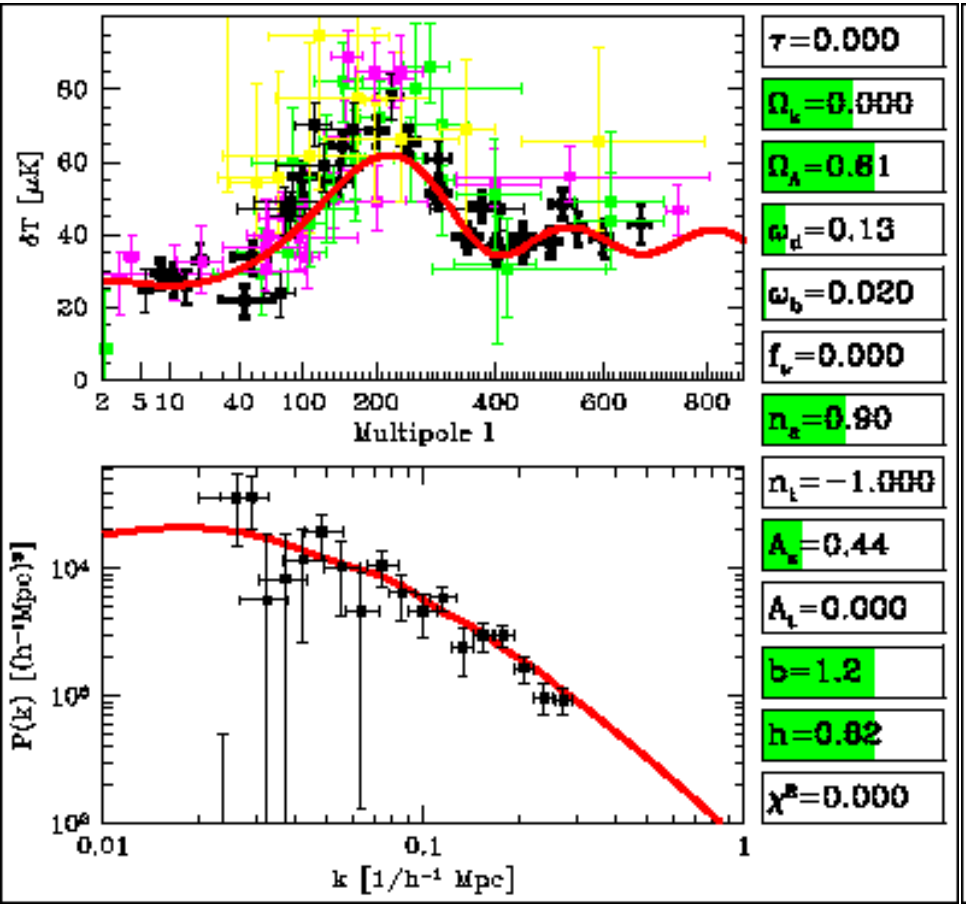
Why does it look like that?

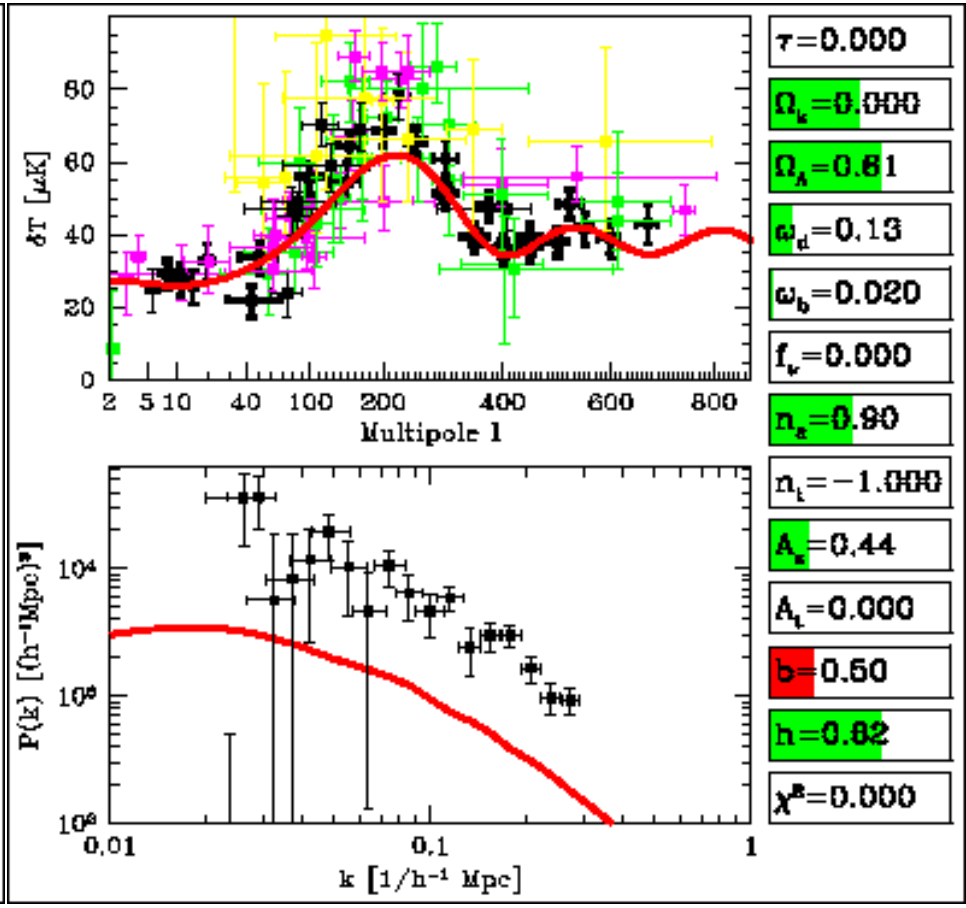


Why the 3rd Peak?



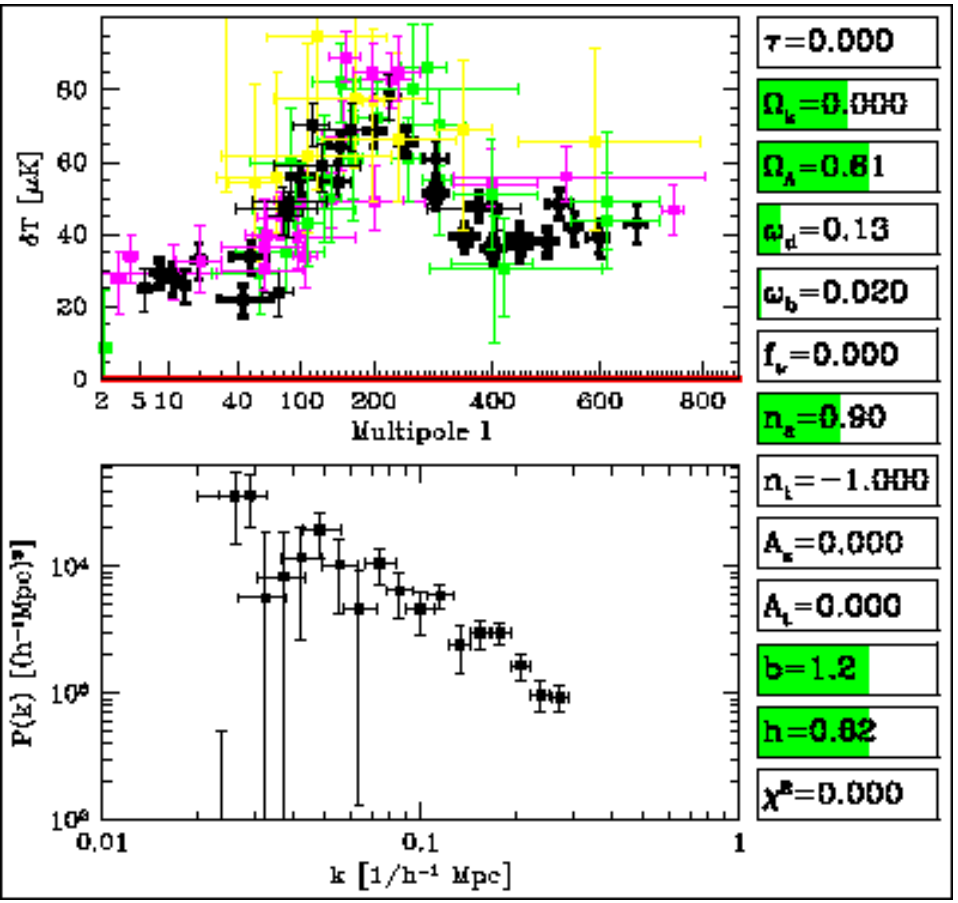
Optical Depth & Galaxy Bias



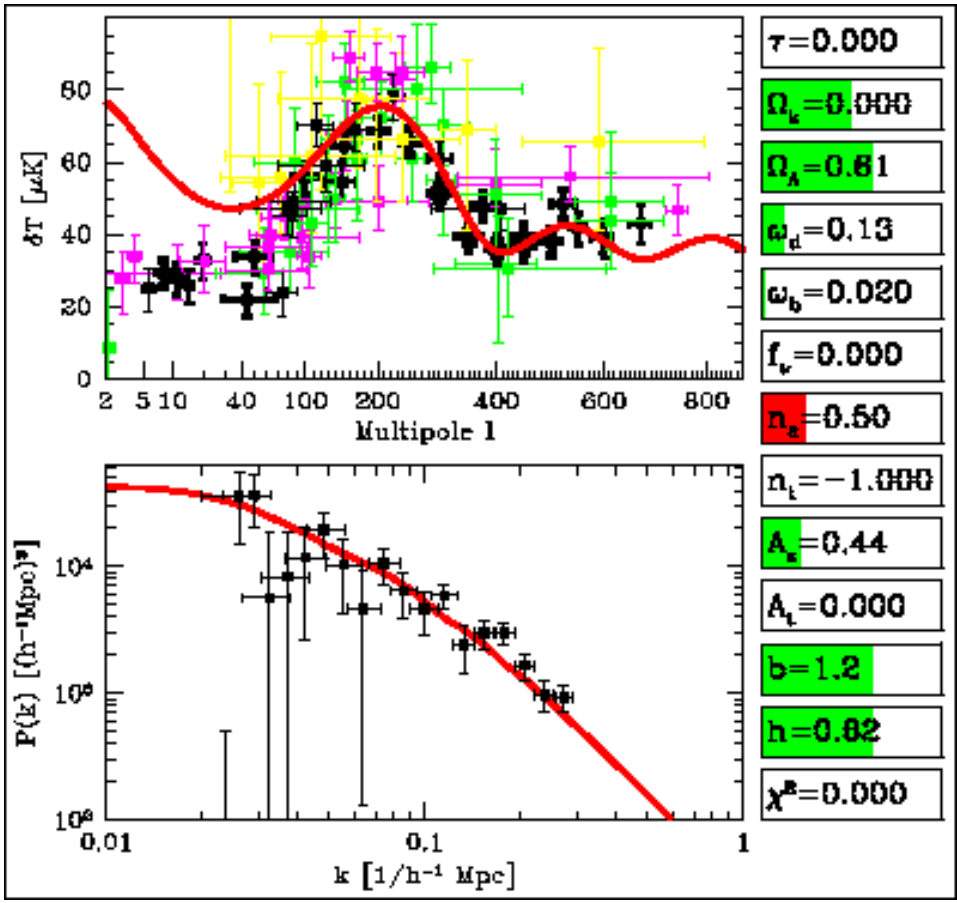


Tegmark et al.
astro-ph/0008167

Initial Conditions



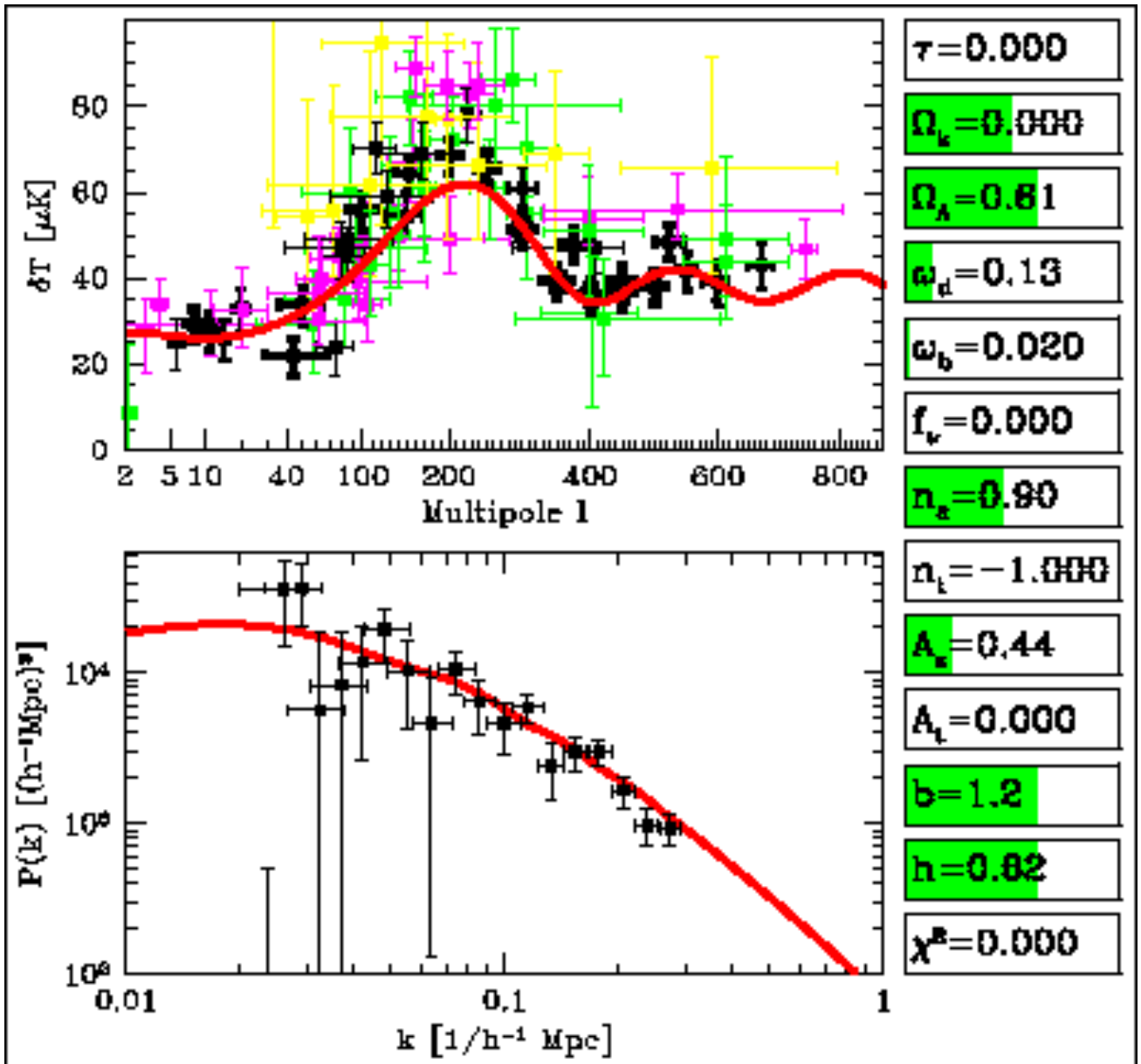
Amplitude of H-Z Spectrum



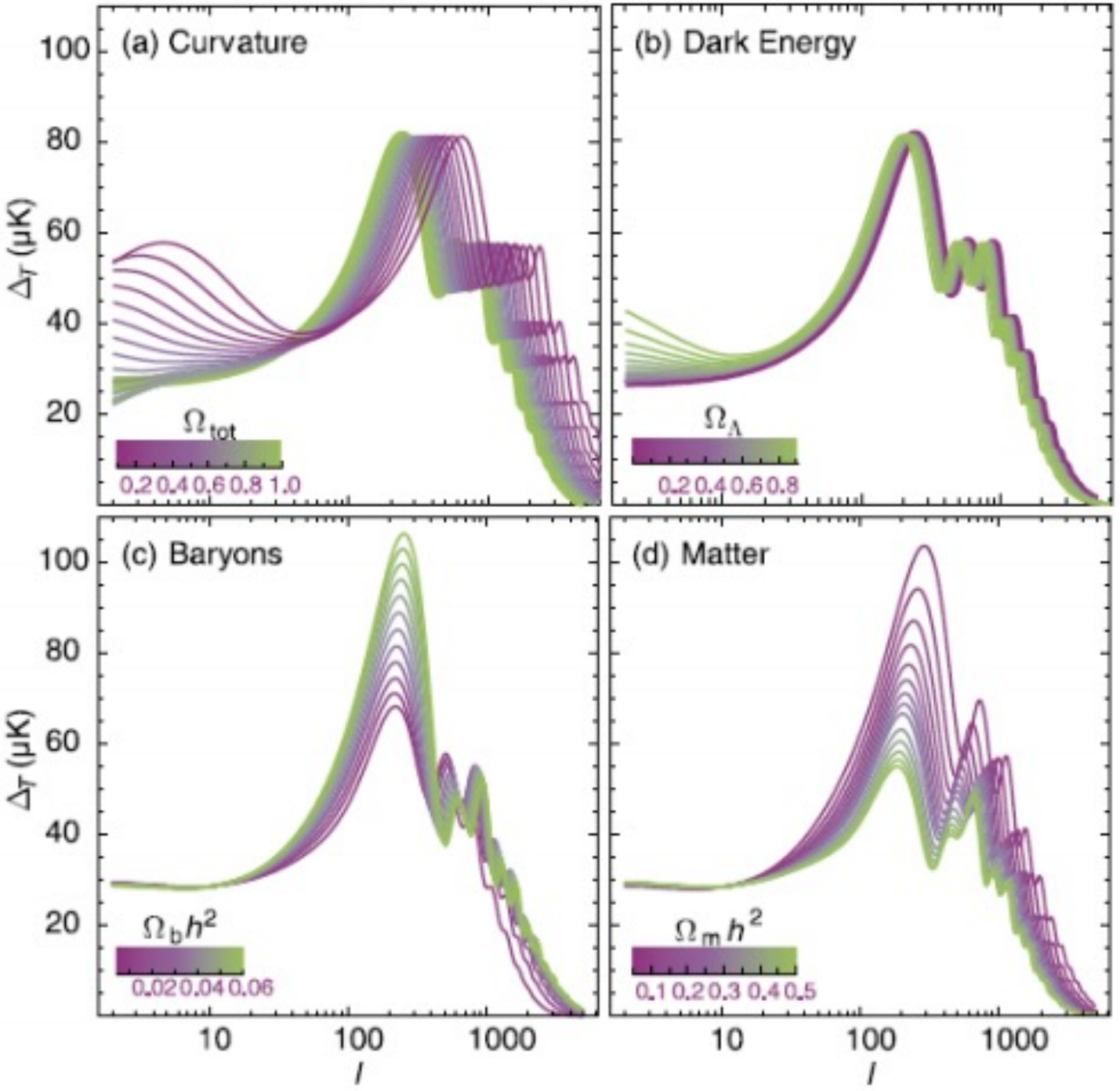
Departure from Scale Invariance

Tegmark et al.
astro-ph/0008167

Hot vs Cold Dark Matter

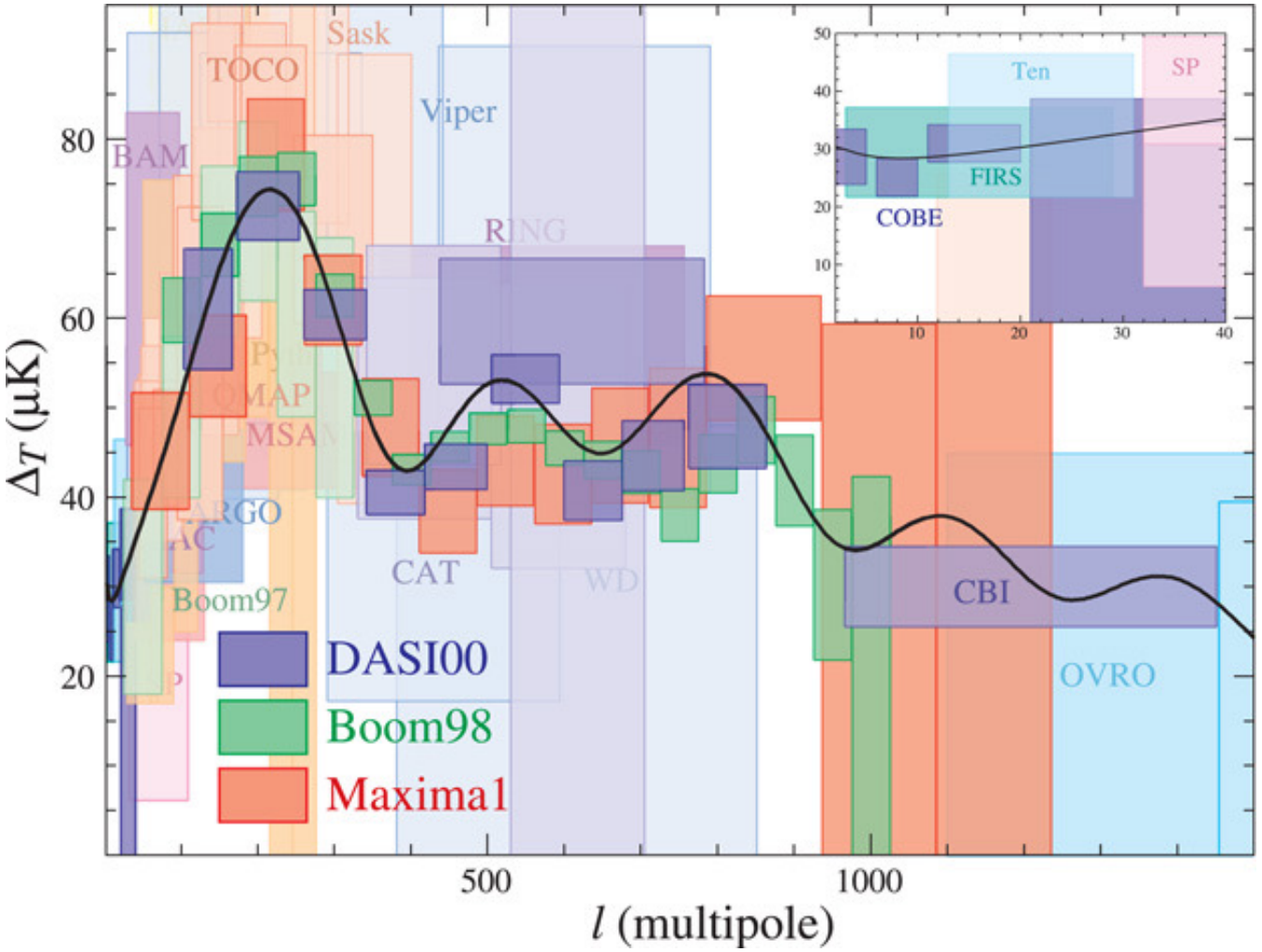


Tegmark et al.
astro-ph/0008167

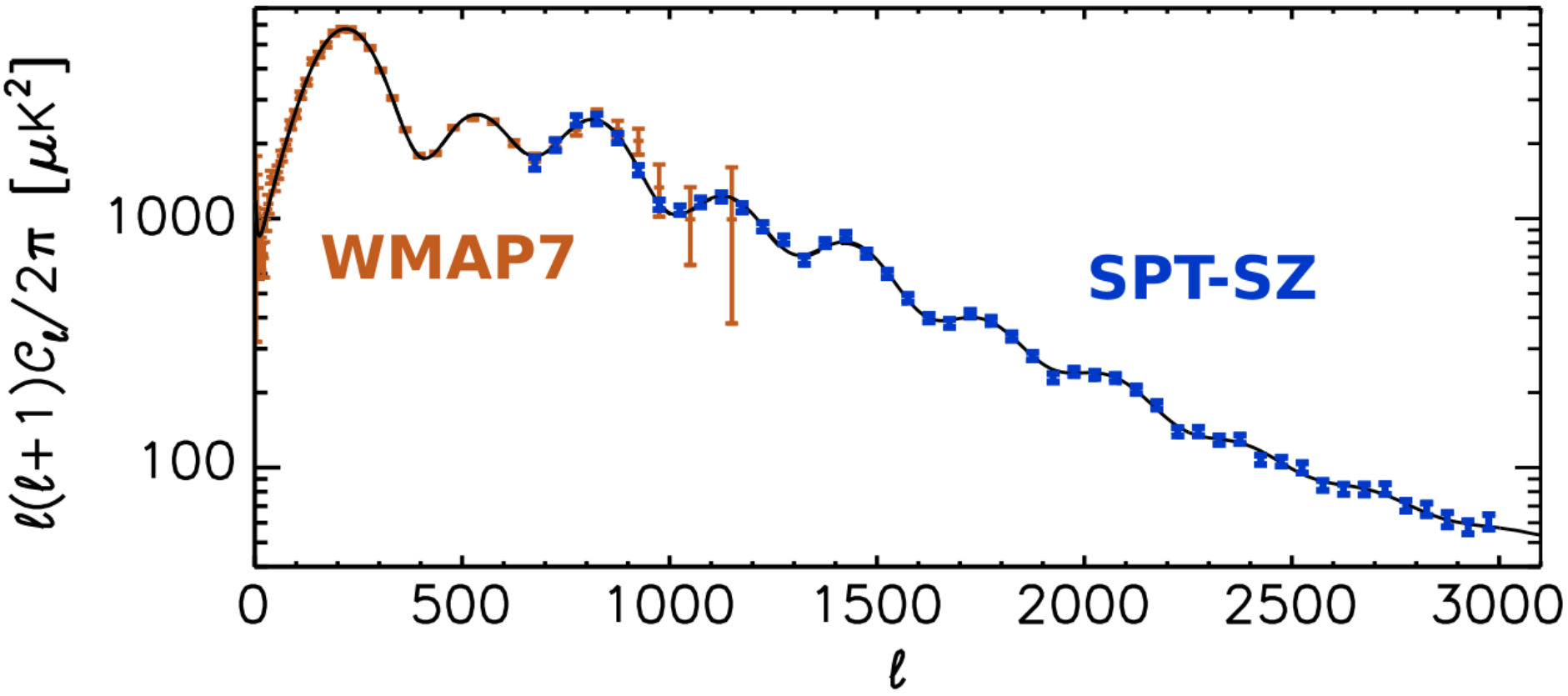

(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
100
80
60
40
20
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
10
100
1000
l

CMB Anisotropy circa 2002

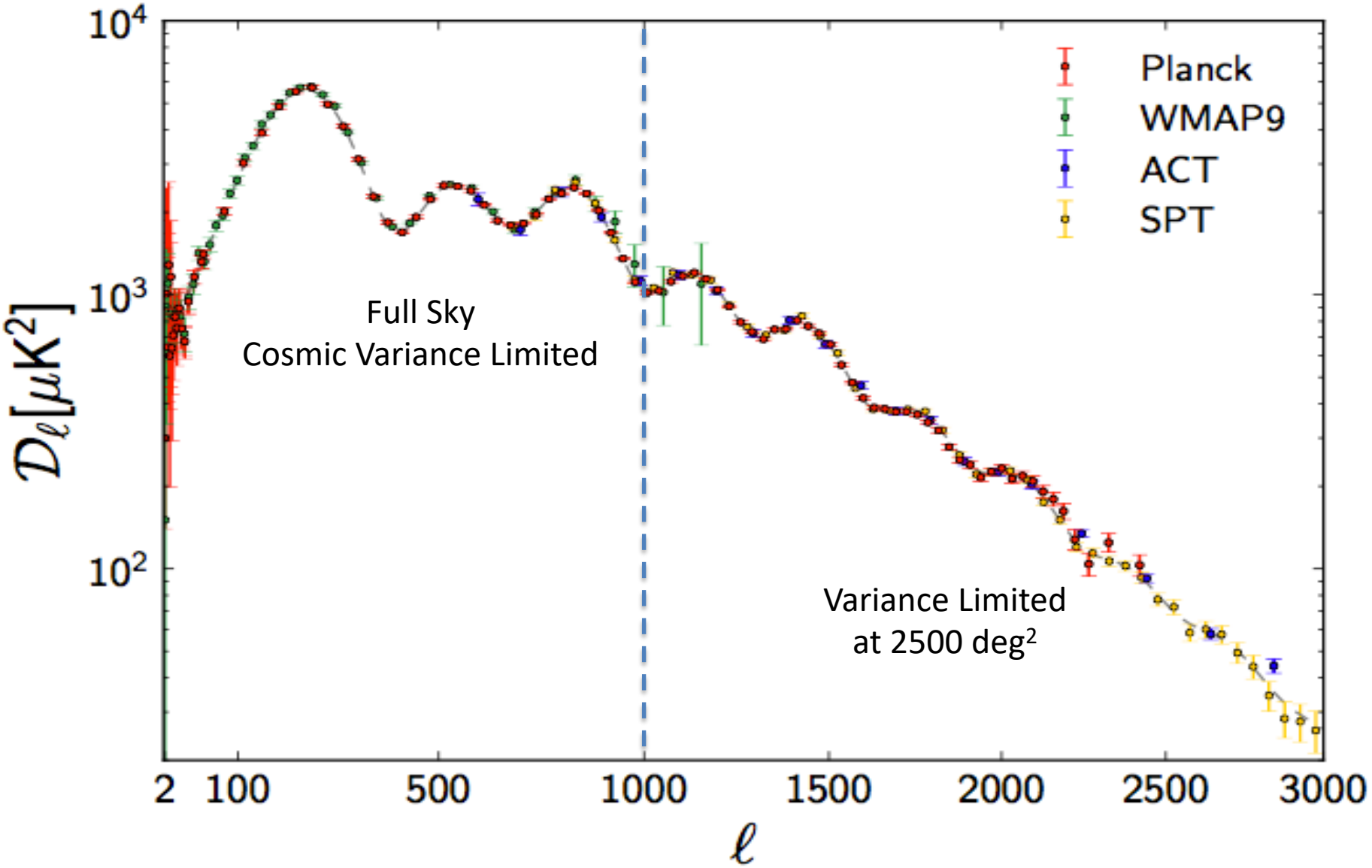
Circa 2002



CMB Anisotropy circa 2012



CMB Data Circa 2020



Cosmic Variance

Each mode Δ_k, and hence each a_{lm} is a (quantum-mechanically) random realization of the primordial power spectrum.

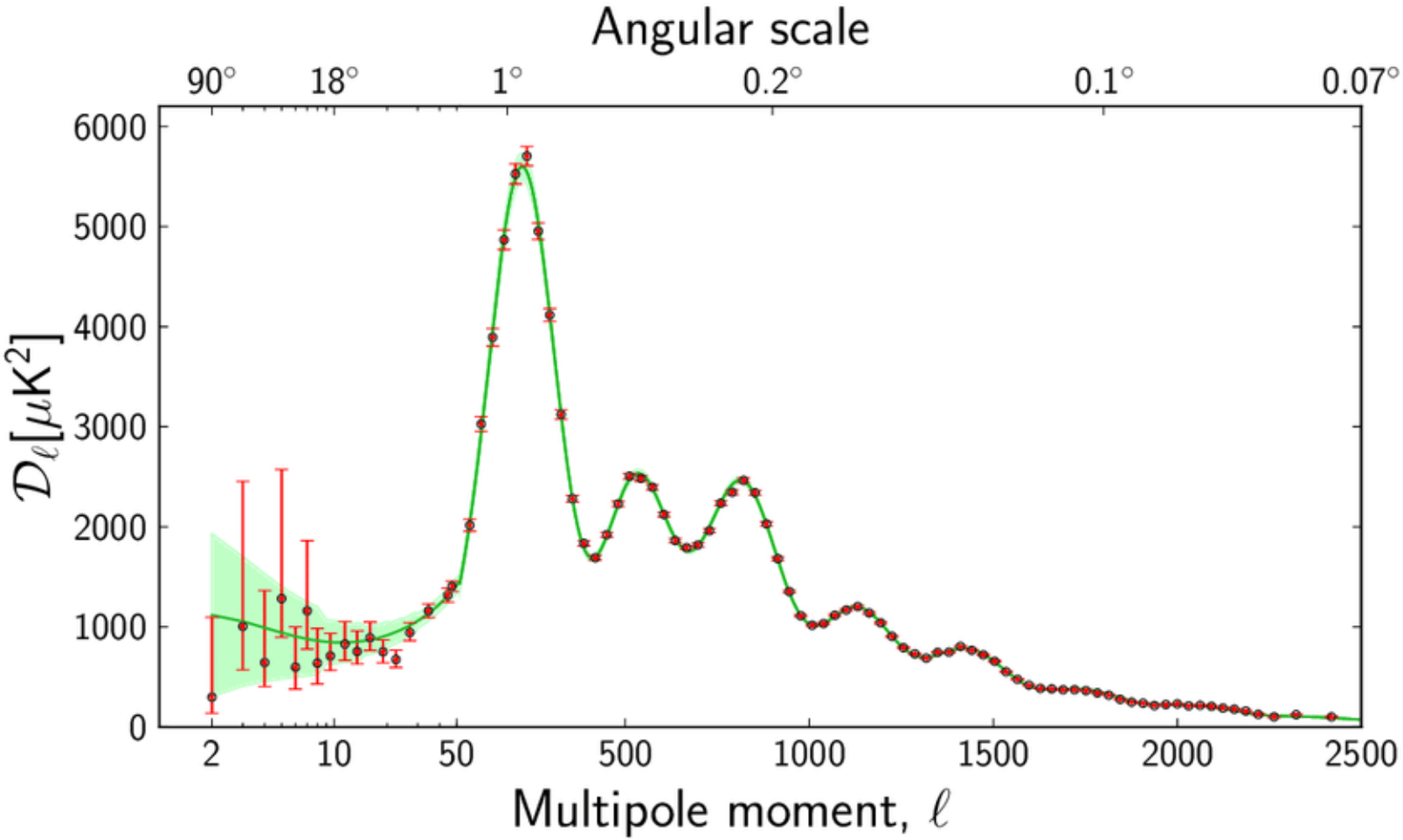
Strictly speaking, the a_{lm} are generated from a Gaussian process with variance $<|a_{lm}|^2>$. Isotropy says this is independent of m.

We thus expect each C_l to be drawn from a χ^2 distribution of a_{lm} describing *2l+1* degrees of freedom. Variance = $2C_l^2/(2l + 1)$

Cosmic Variance is the uncertainty from this. No matter how well we measure the modes in our Universe, the underlying model which gave rise to them is limited by this random uncertainty.

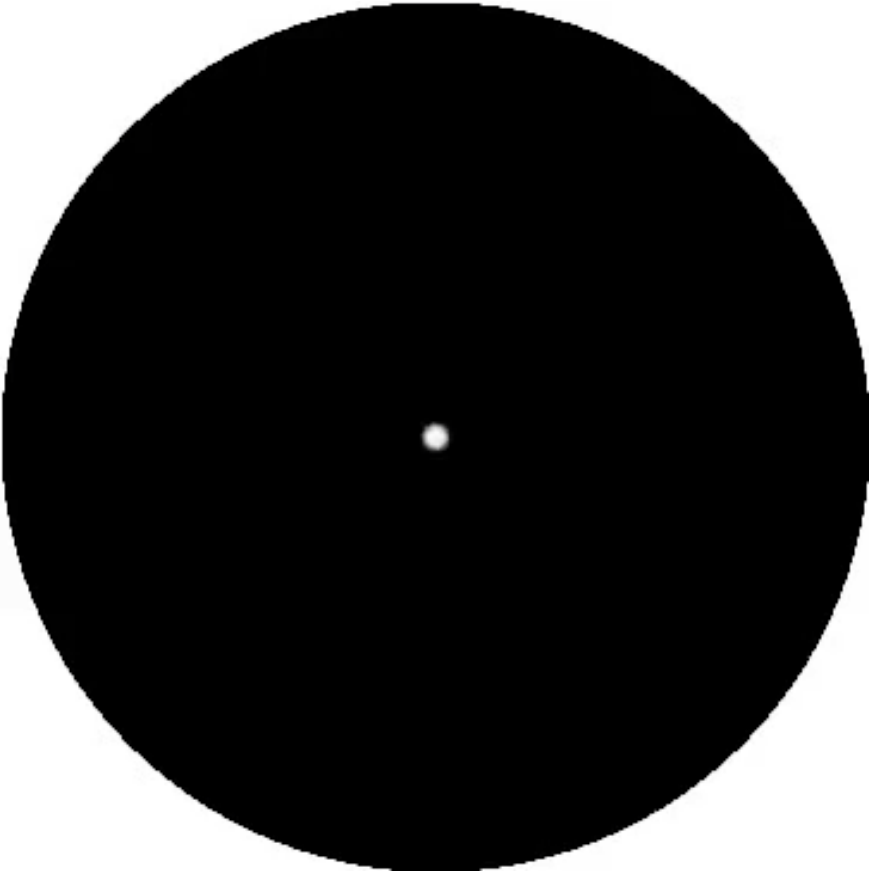
(We only have 1 Universe, finite modes to study)

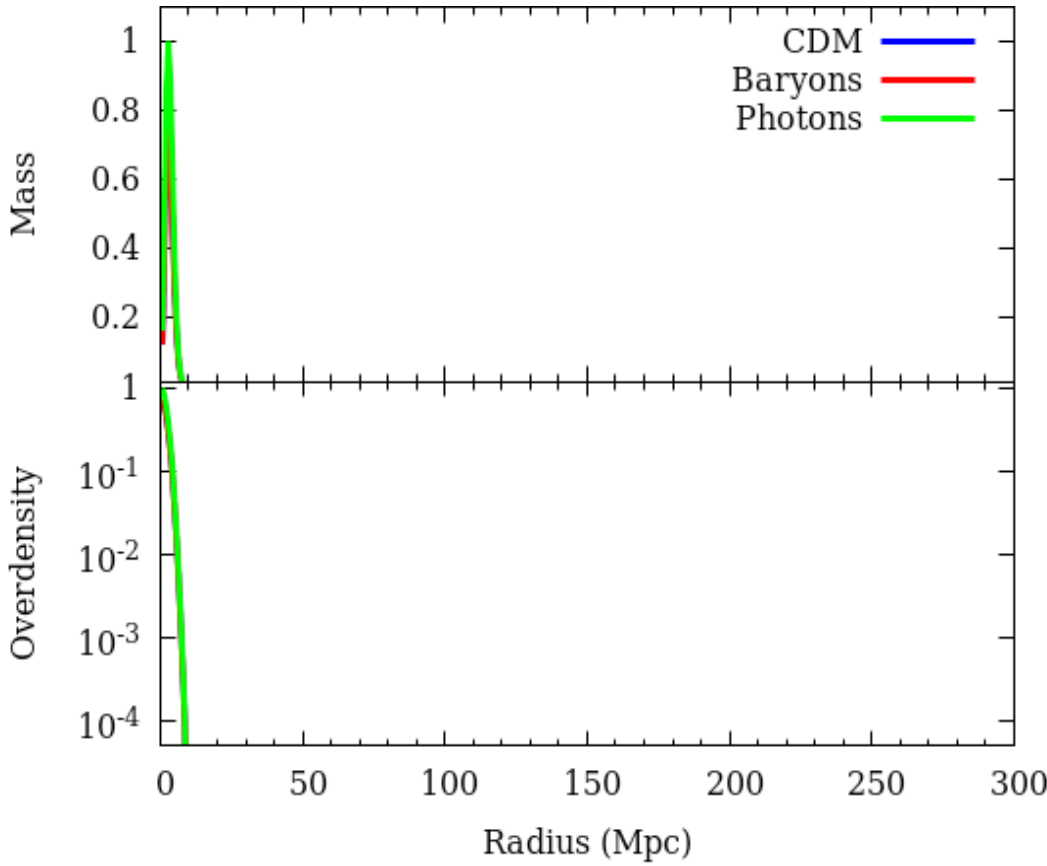
Cosmic Variance



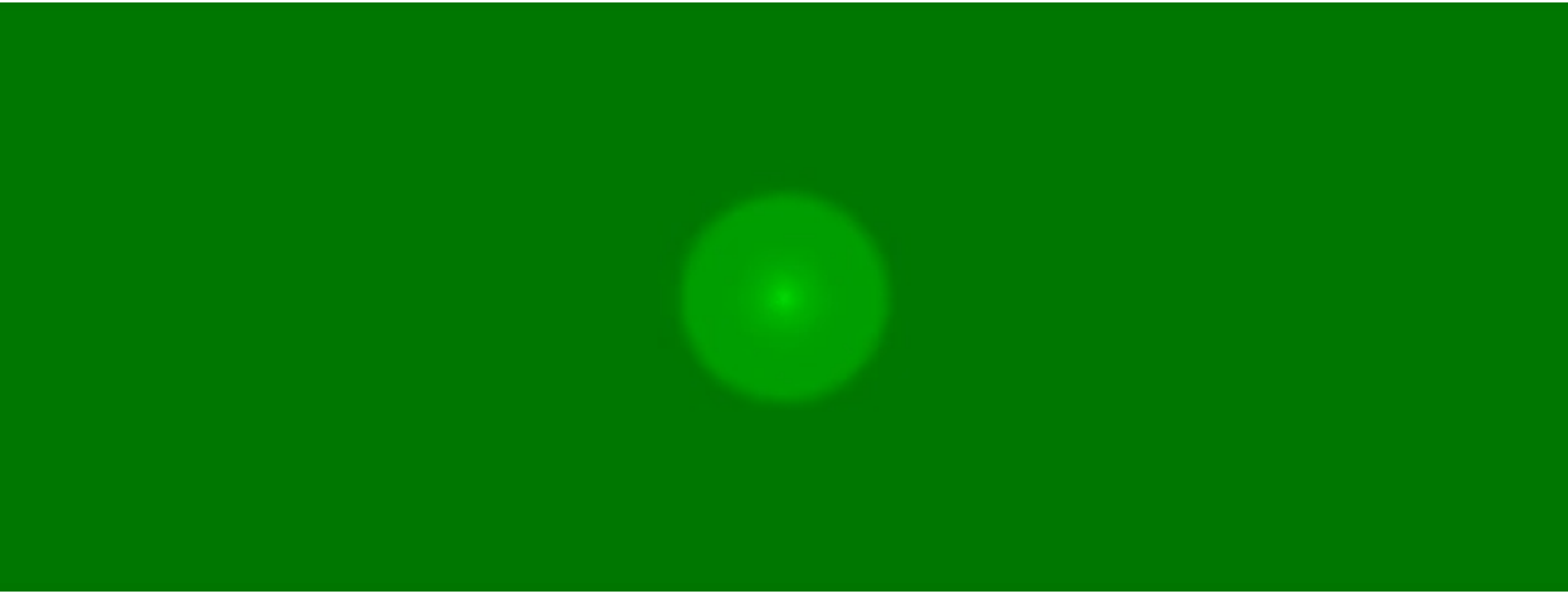

INTERMISSION

In Real Space



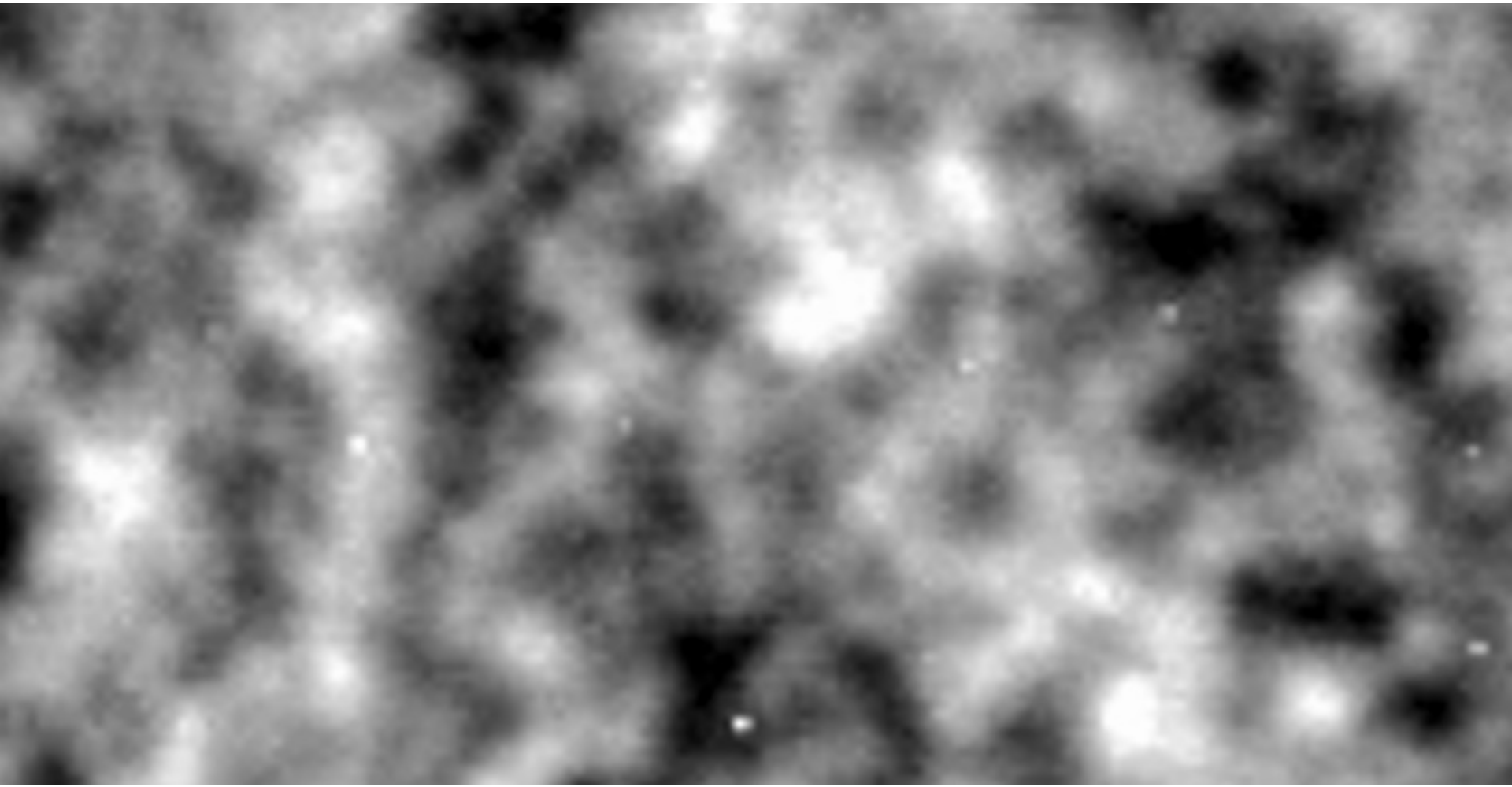


From BAO to CMB



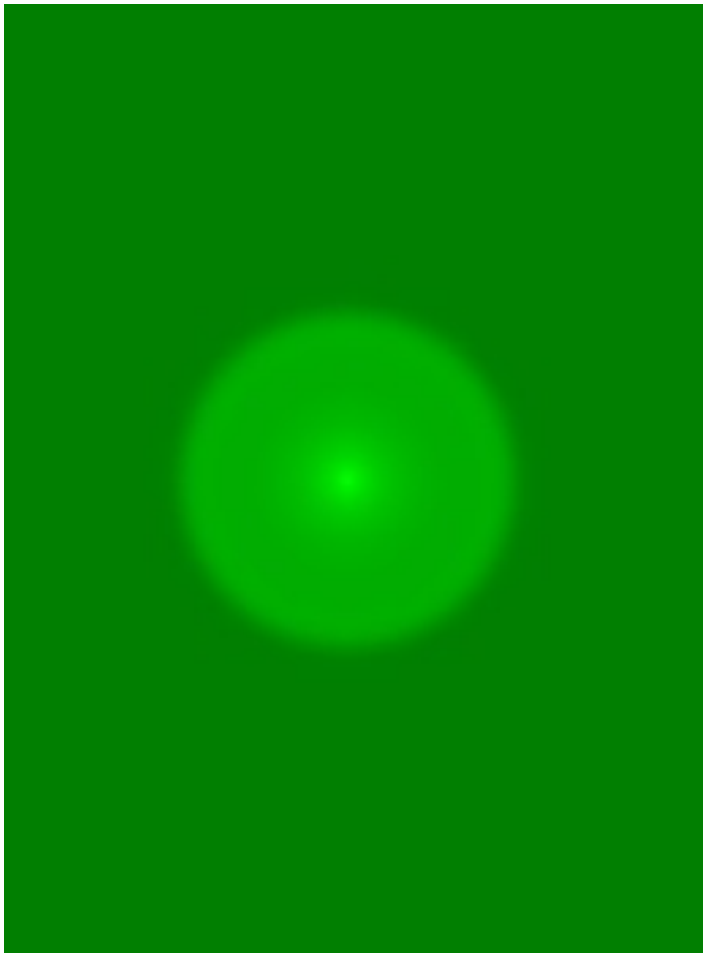
From BAO to CMB

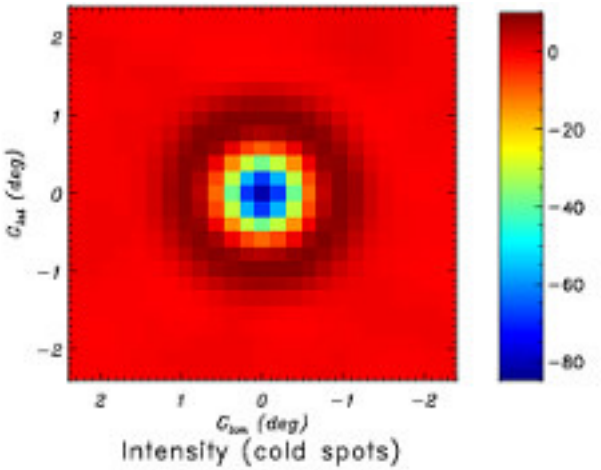
From BAO to CMB



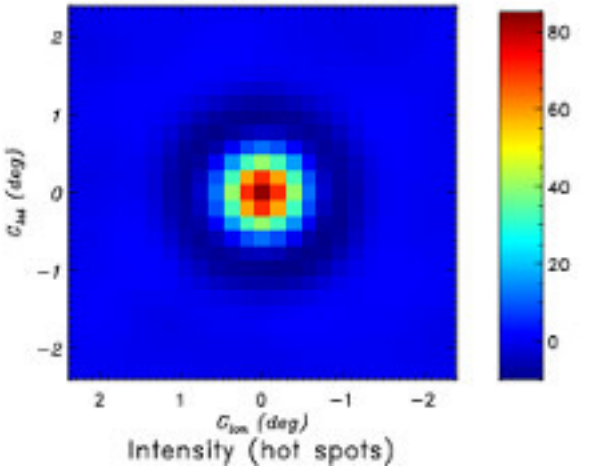
Planck Stacks

BAO Simulation



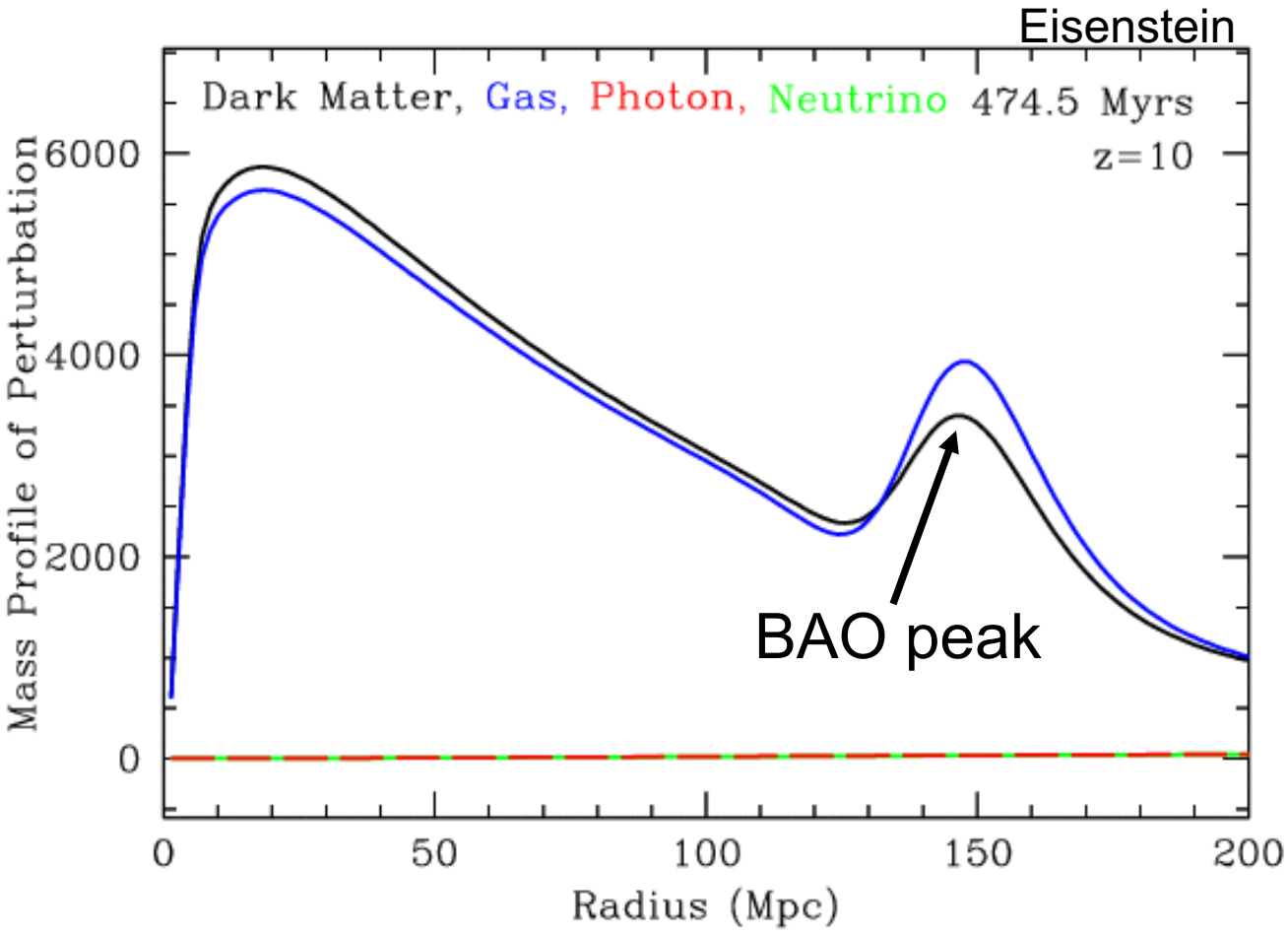


Cold Spots



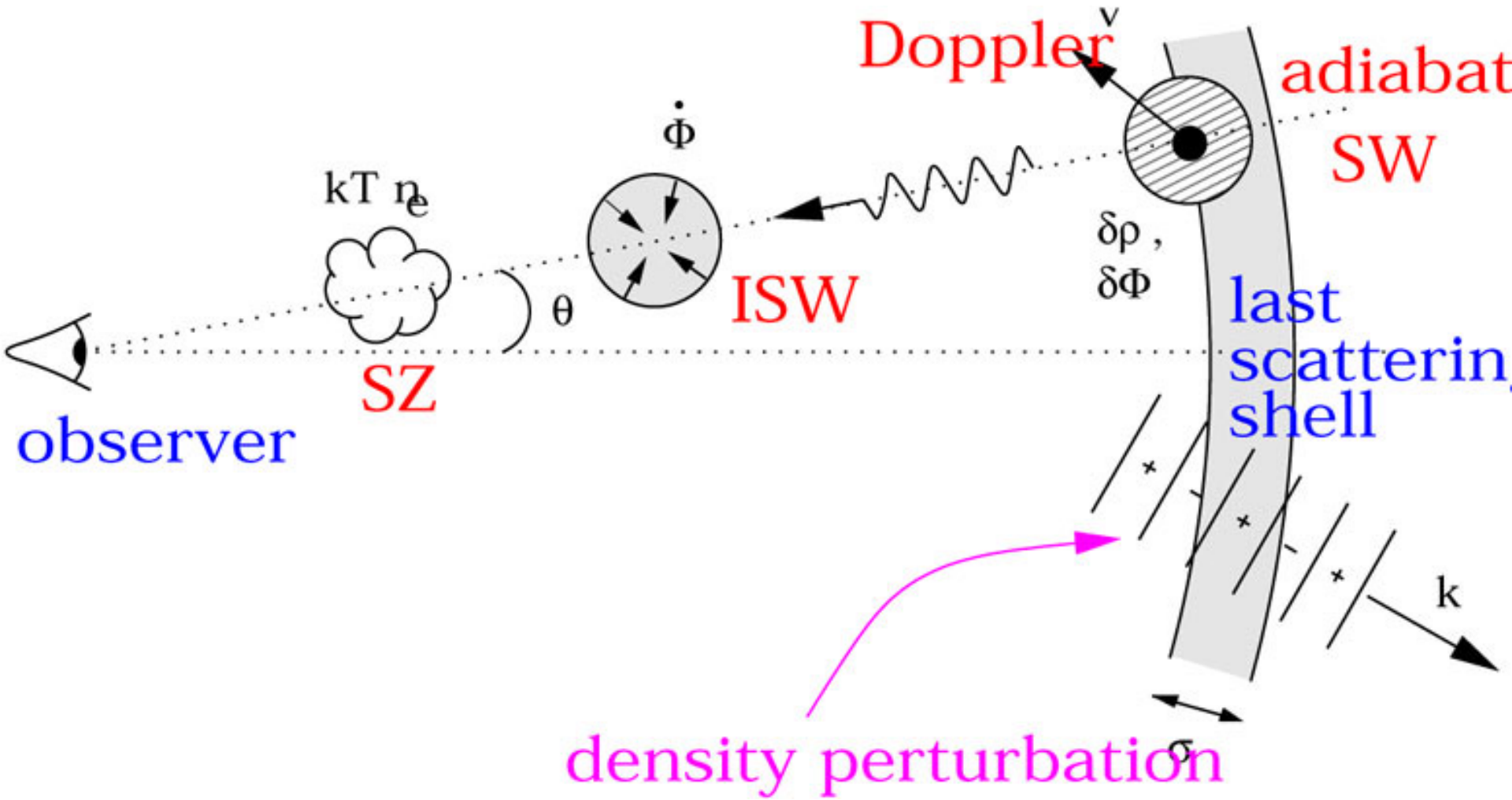
Hot Spots

Late-Time Radial Profile

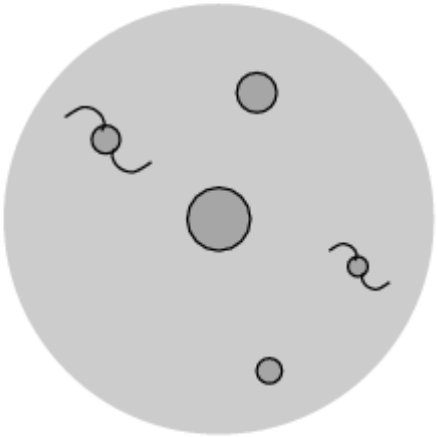


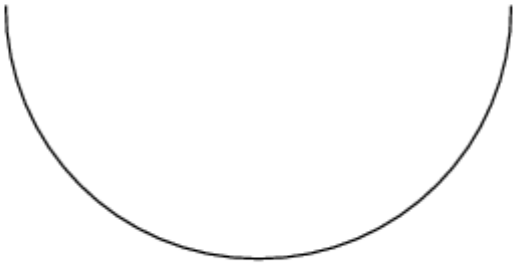
BAO are “frozen in” ≈150 co-moving Mpc.

Secondaries

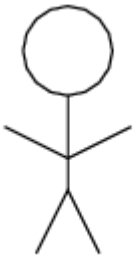


Integrated Sachs-Wolfe

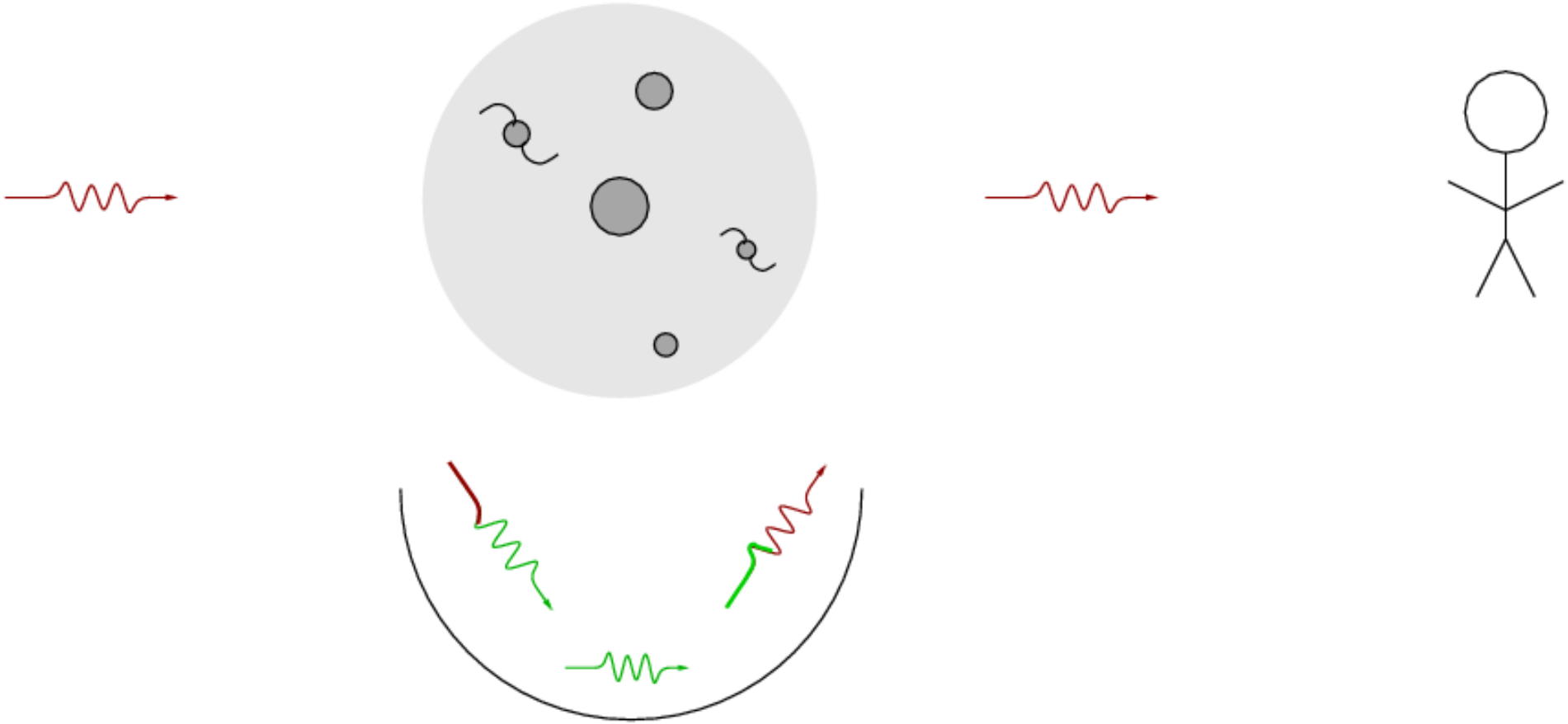




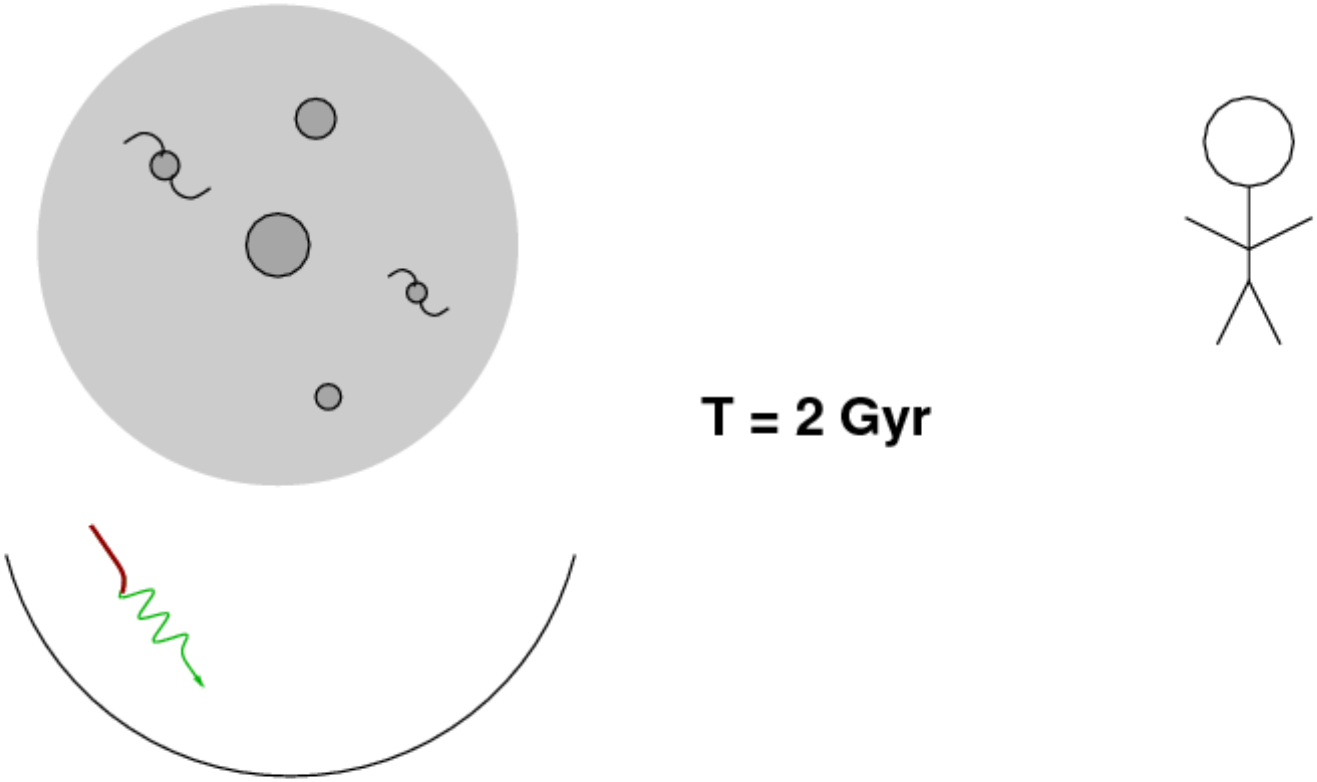
T = 1 Gyr



Late-time Potential Wells

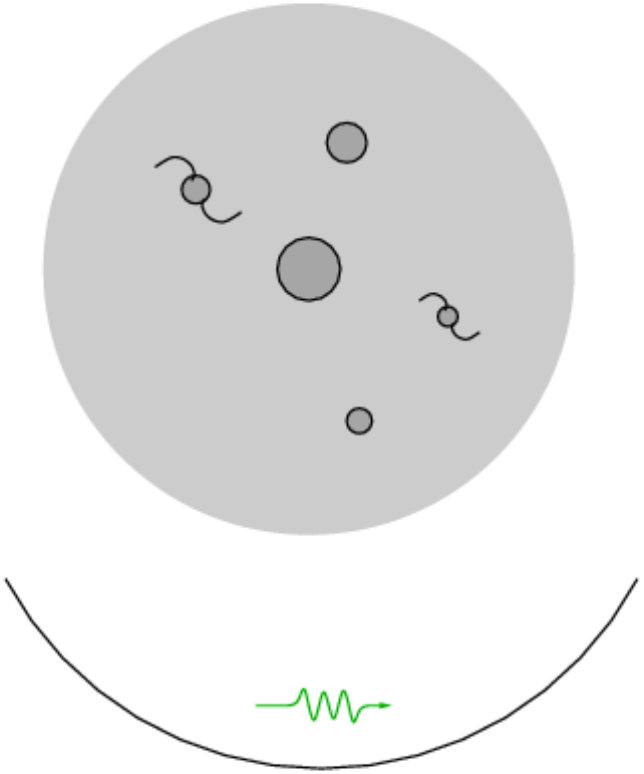


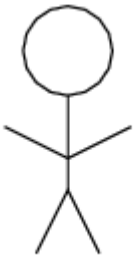
Integrated Sachs-Wolfe



Integrated Sachs-Wolfe

When Λ starts to influence expansion, potential wells can evolve during transit!

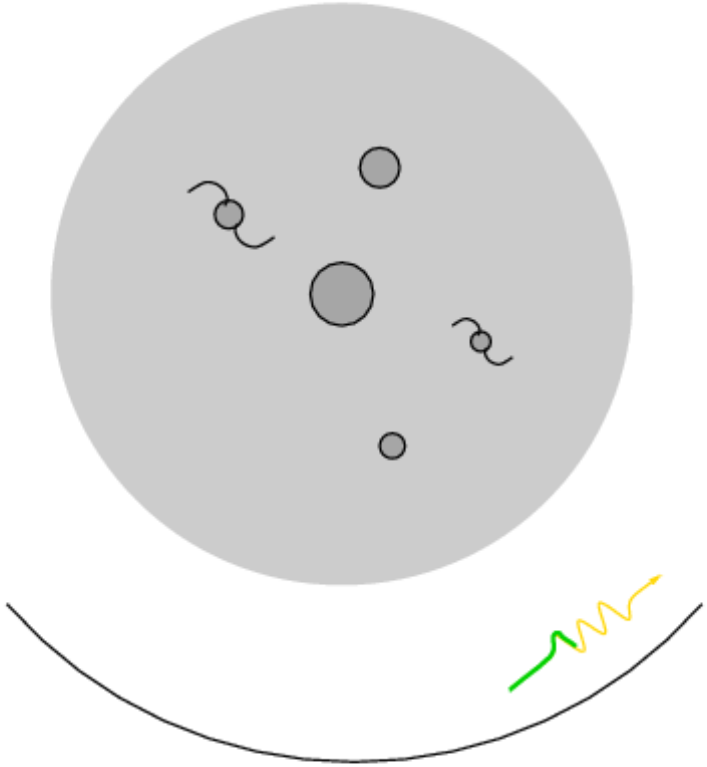




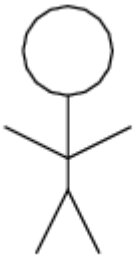
T = 3 Gyr

Integrated Sachs-Wolfe

When Λ starts to influence expansion, potential wells can evolve during transit!

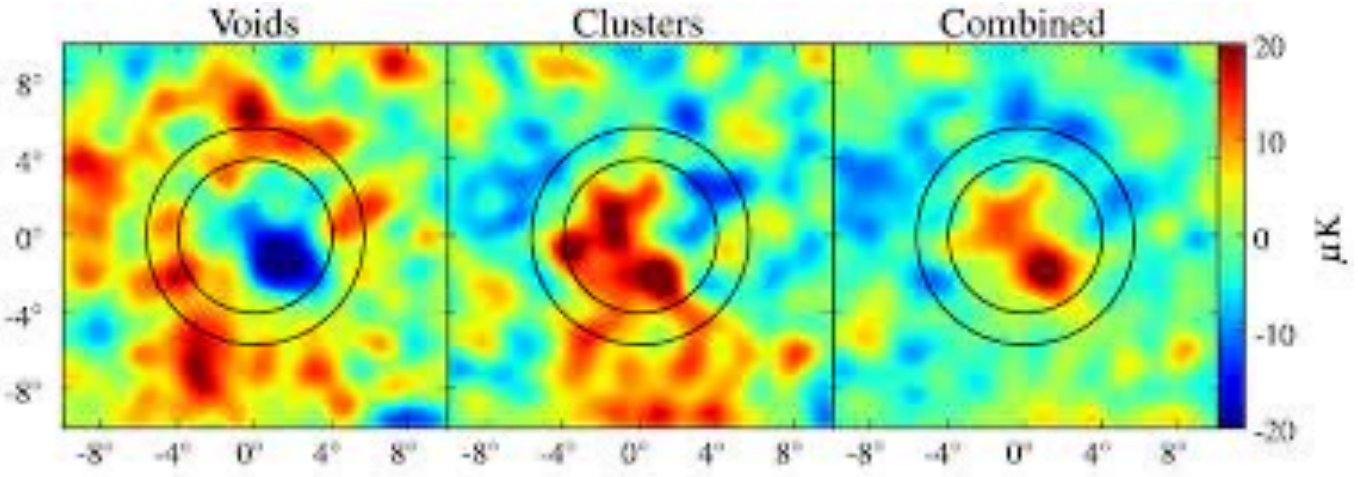


T = 4 Gyr

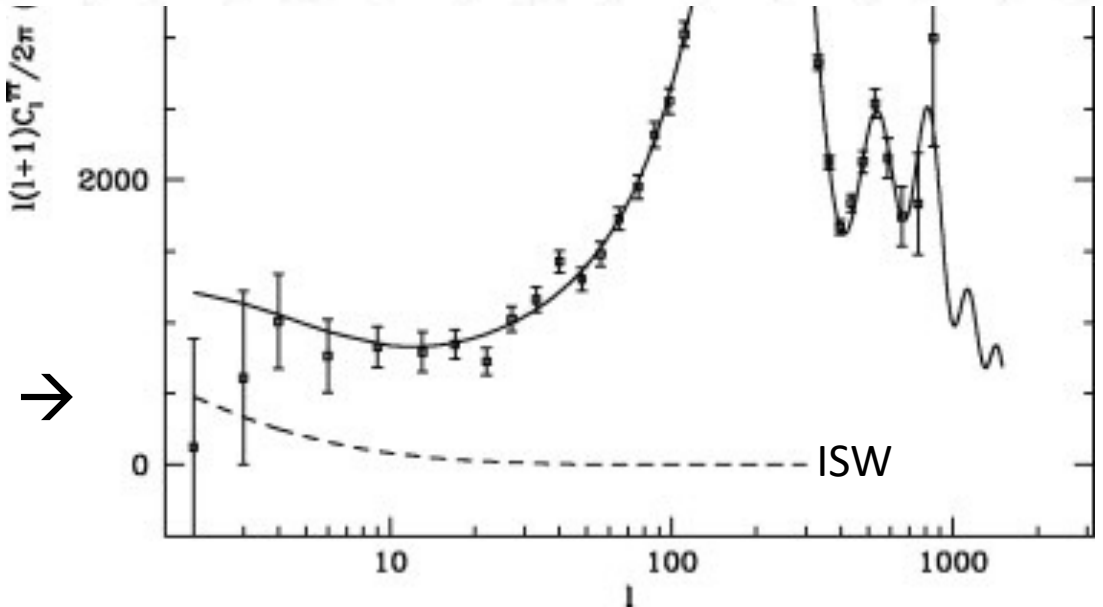


Integrated Sachs-Wolfe

Can see in CMB stacks!

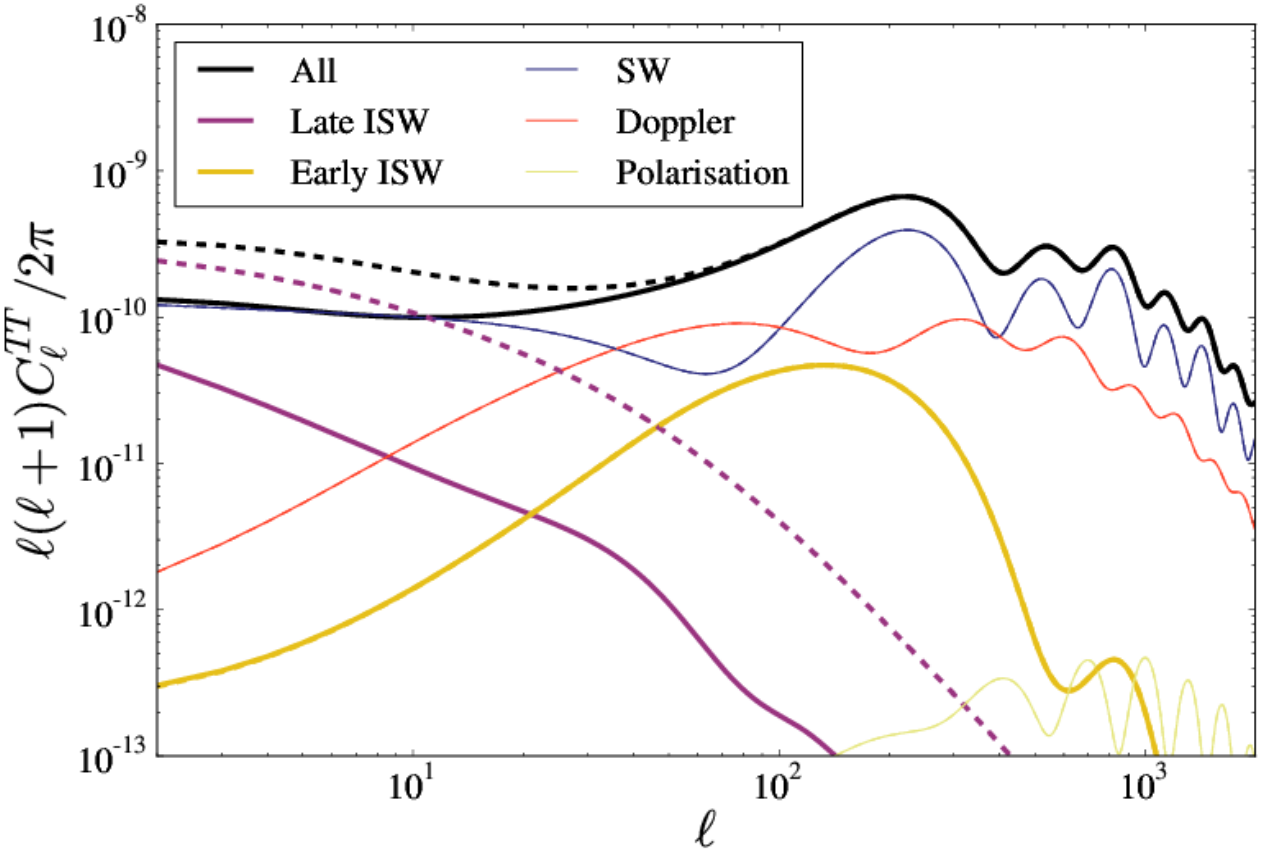


ISW at largest scales →

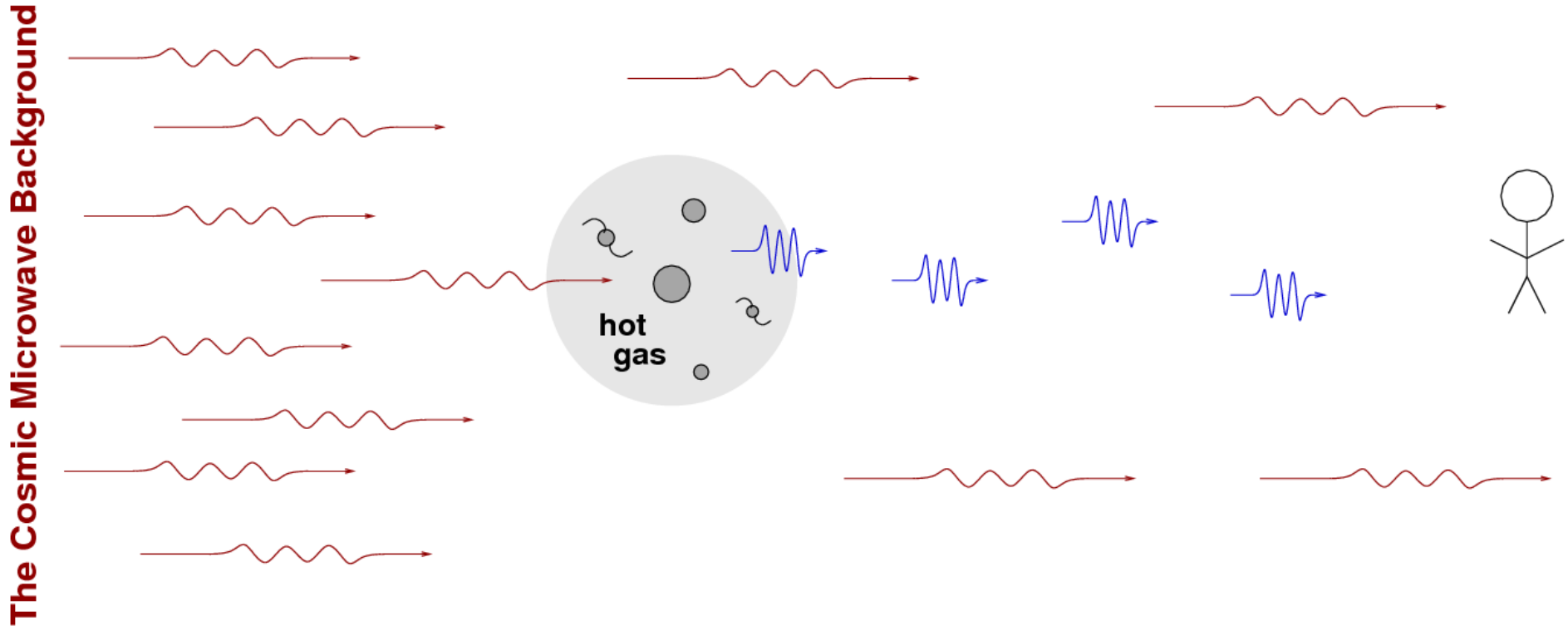


Early ISW

Anything other than pure Matter-domination means potential wells can evolve during transit.
During last scattering, radiation still mattered enough.

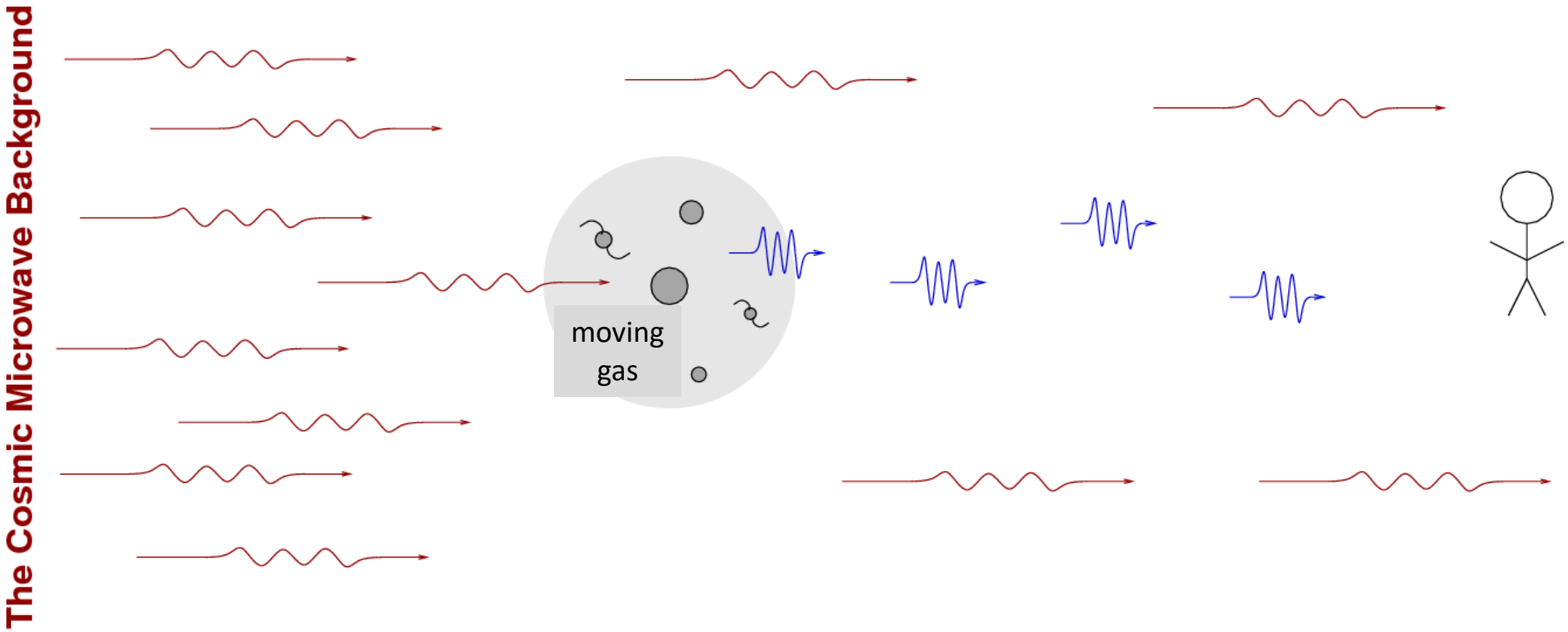


(Thermal) Sunyaev-Zel'Dovich (tSZ) Effect



CMB Photons inverse Thompson scatter off hot electrons.
Gain energy and shift spectrum

(Kinetic) Sunyaev-Zel'Dovich (kSZ) Effect

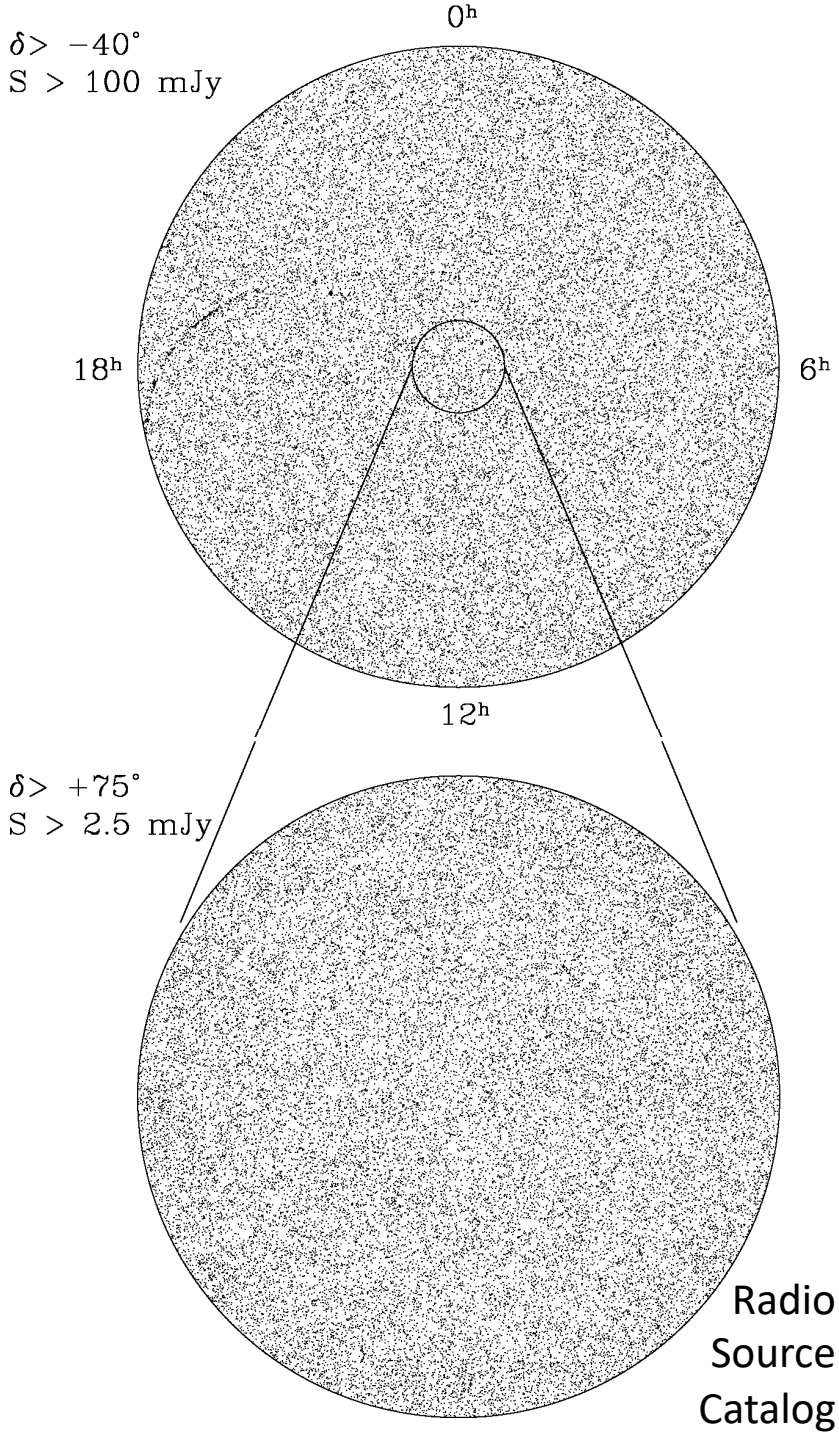


CMB Photons Thompson scatter off gas with peculiar motion.
Doppler red-/blue-shift.

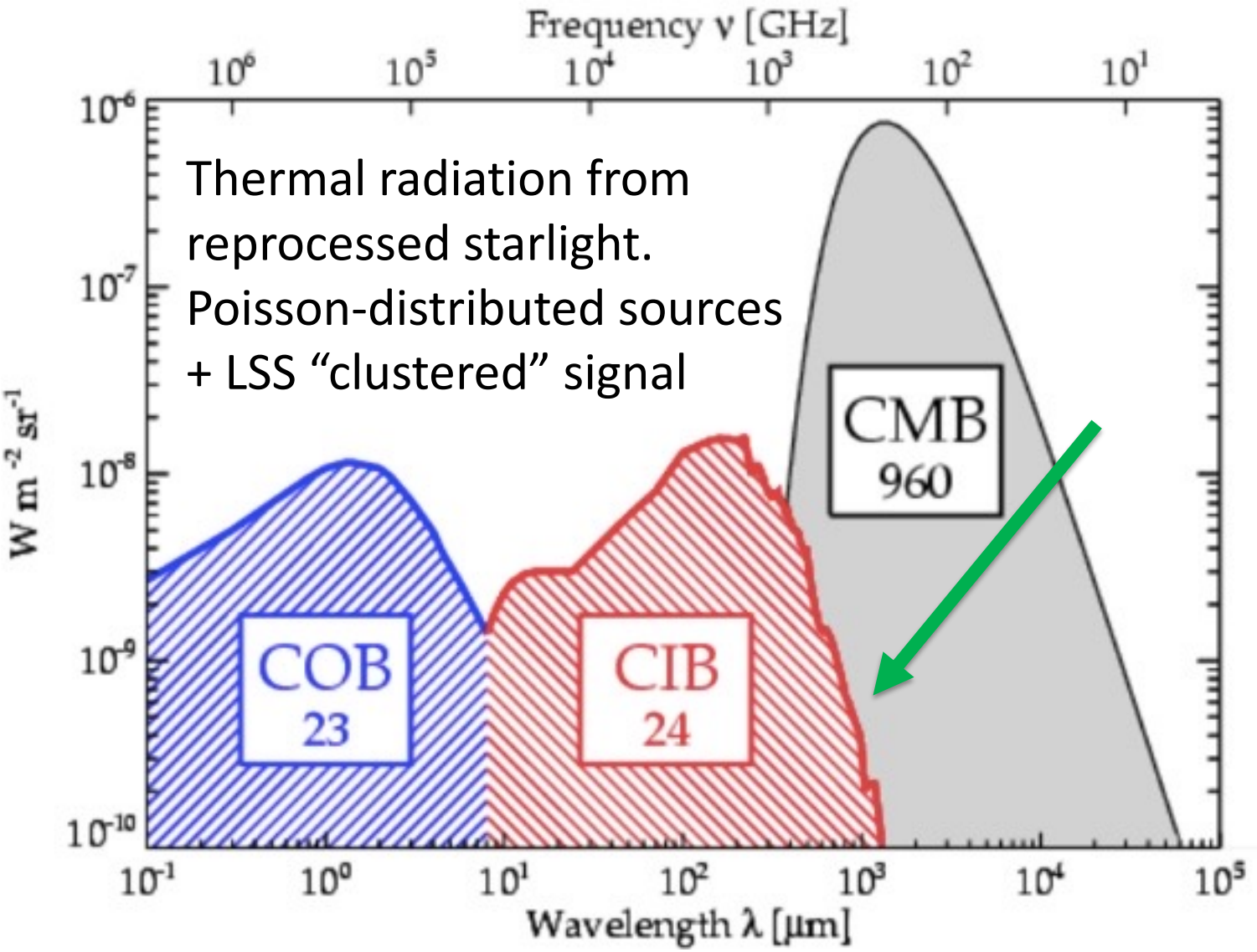
Radio Galaxies

Unresolved AGN and synchrotron radiation.
Poisson Distributed

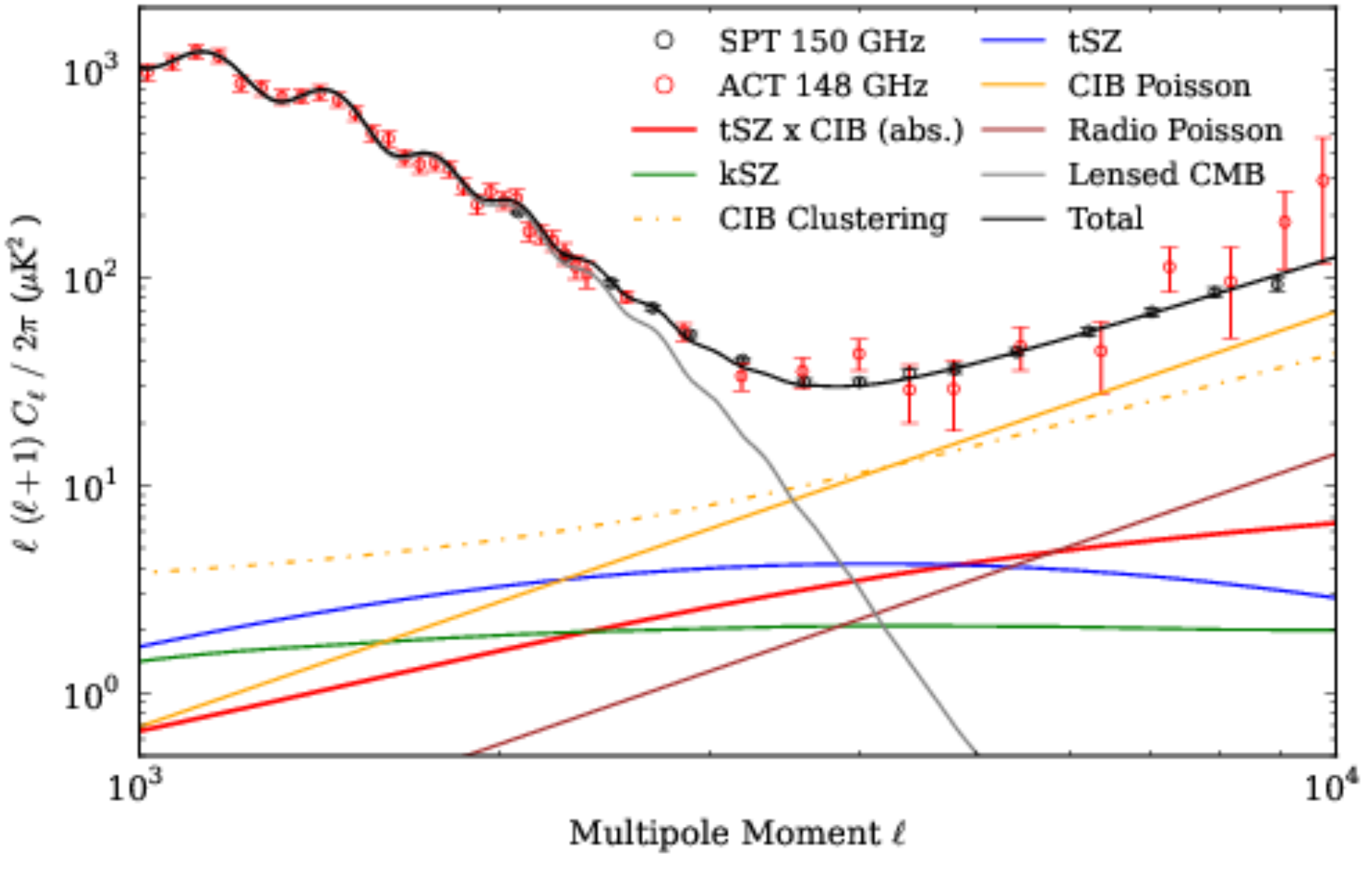
→ flat in C_l



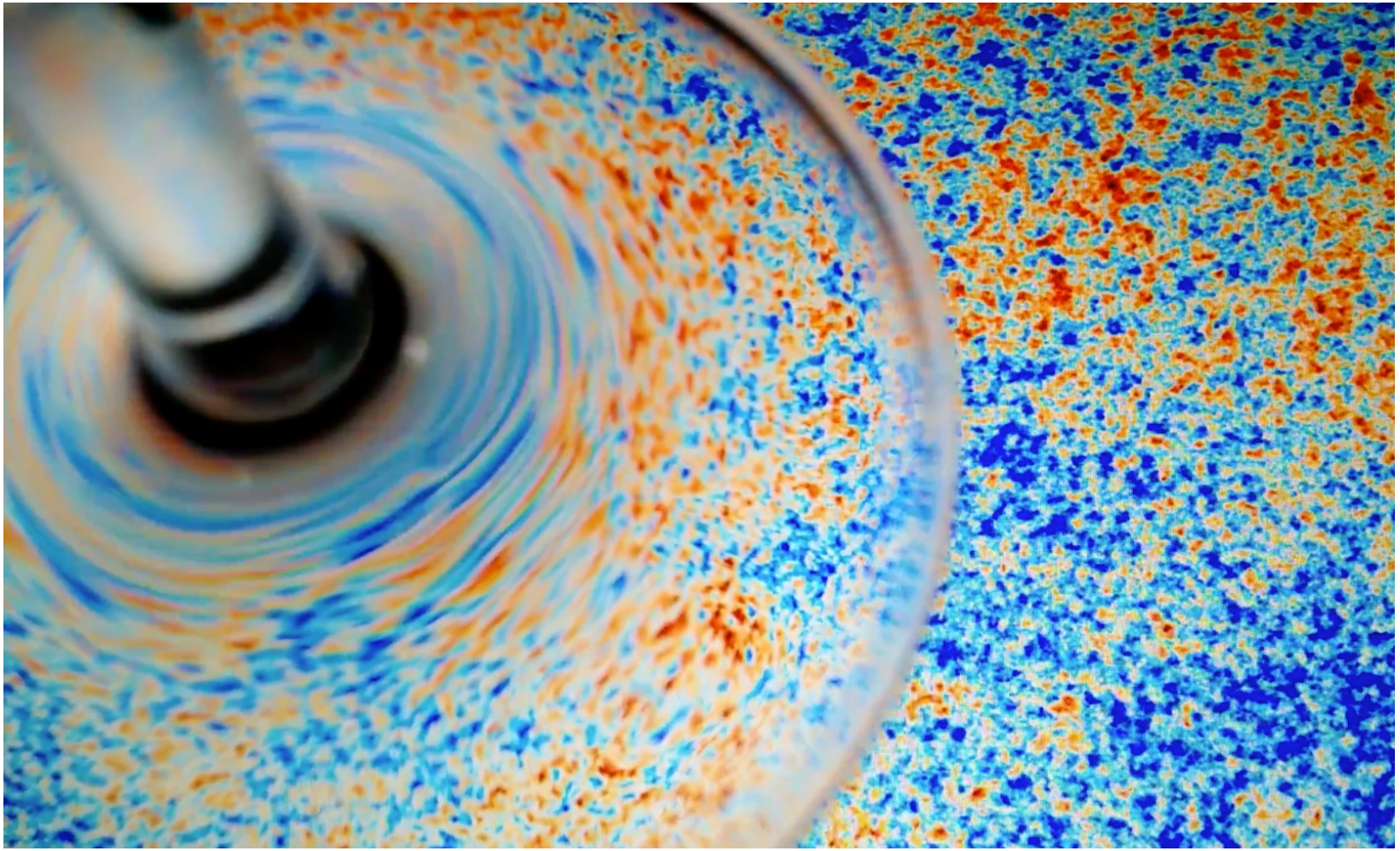
Cosmic Infrared Background

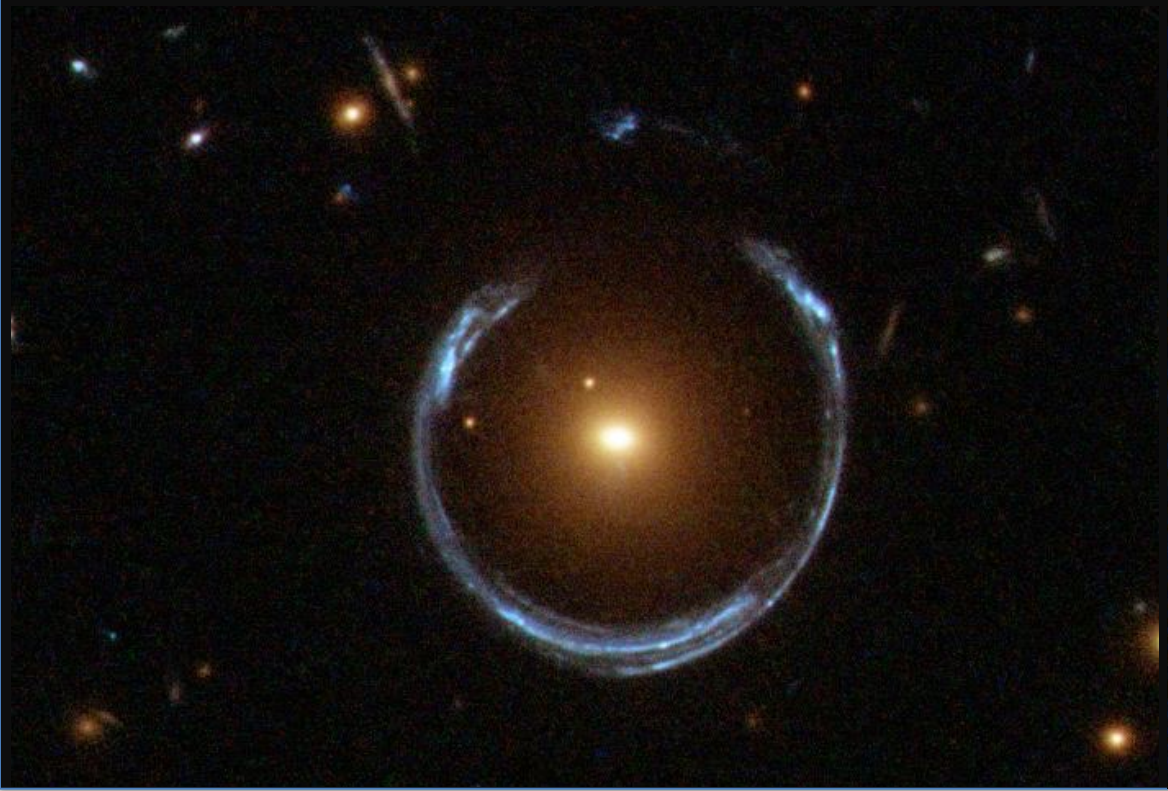


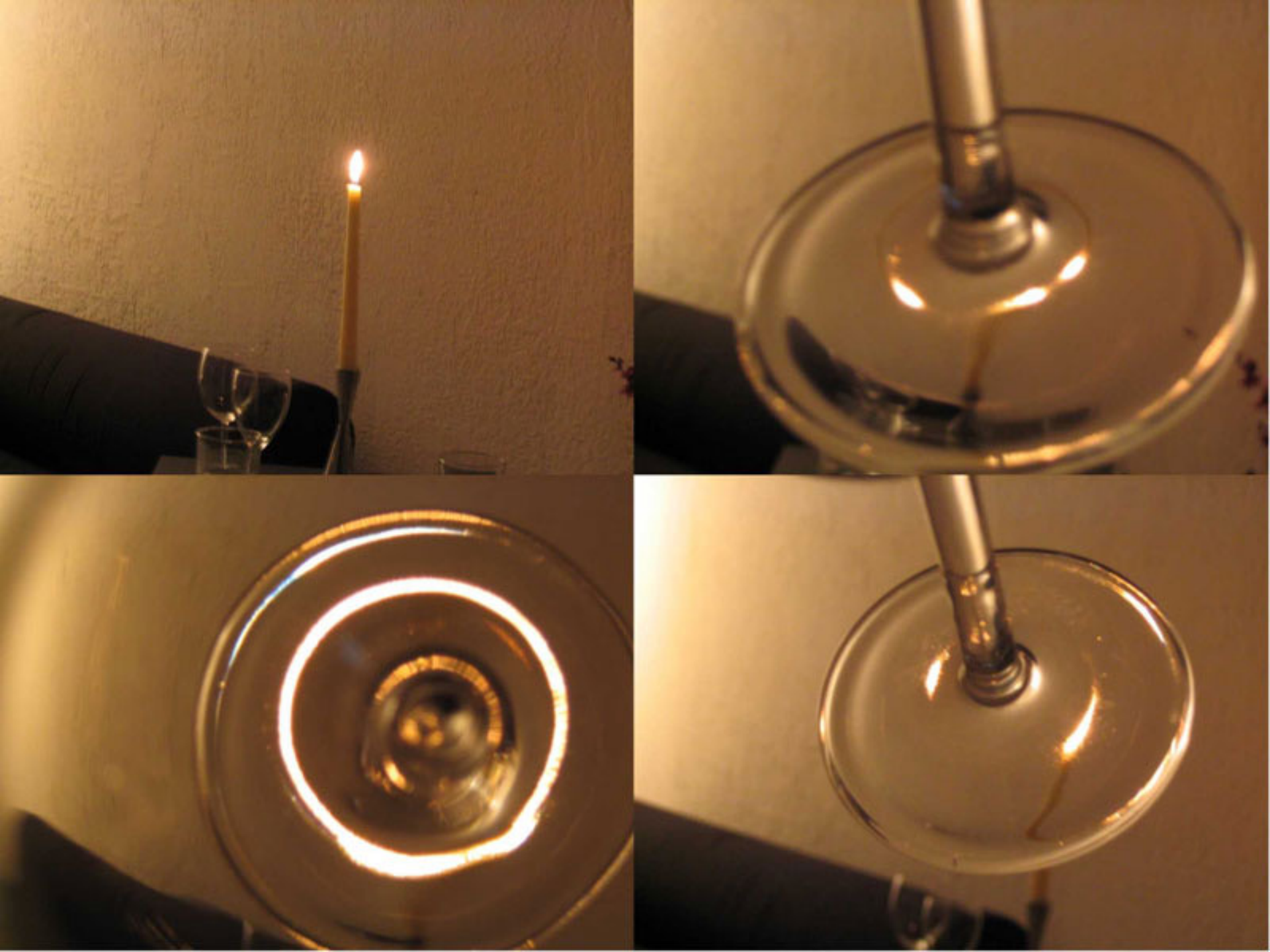
The Secondary CMB



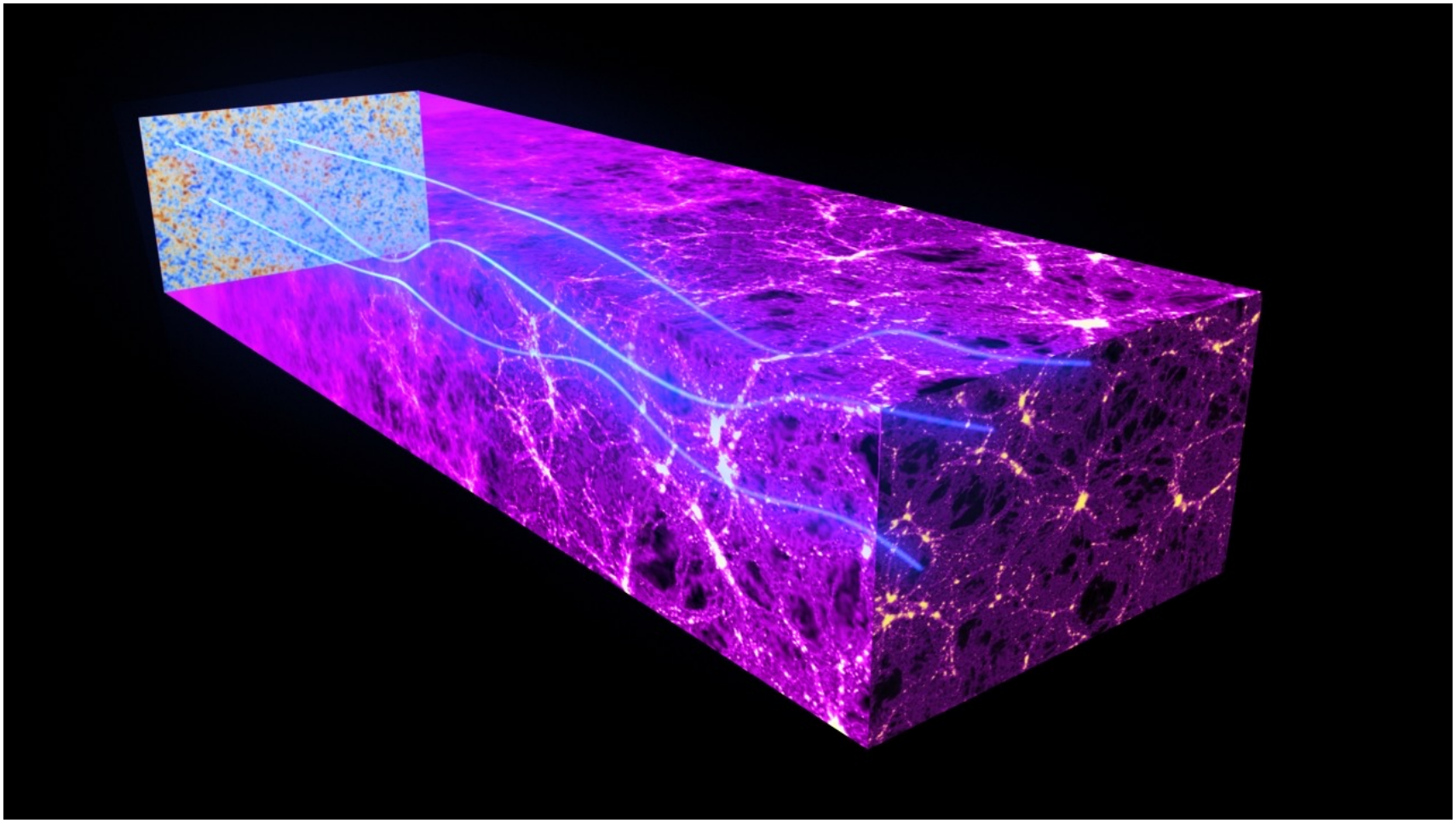
Lensing



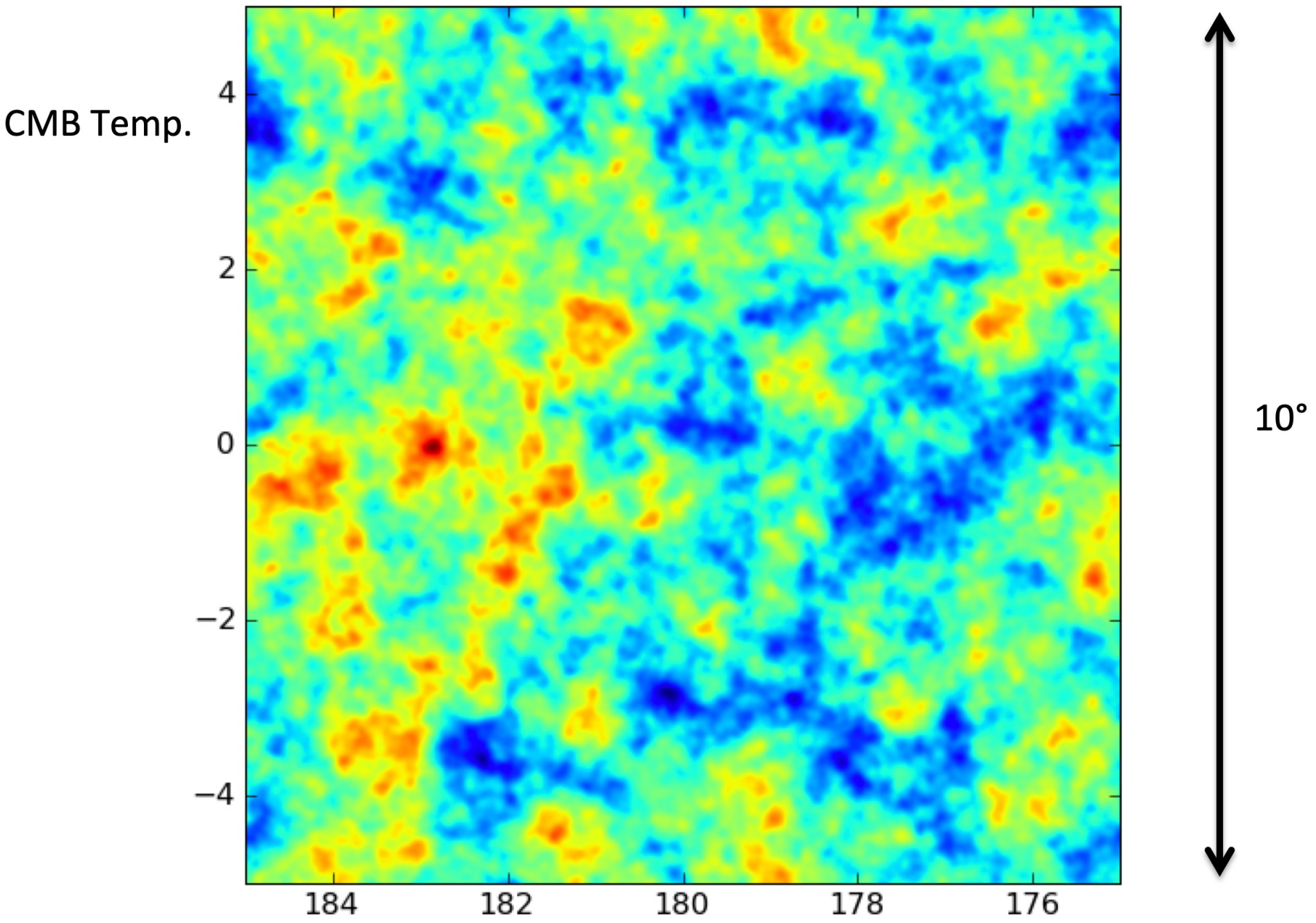




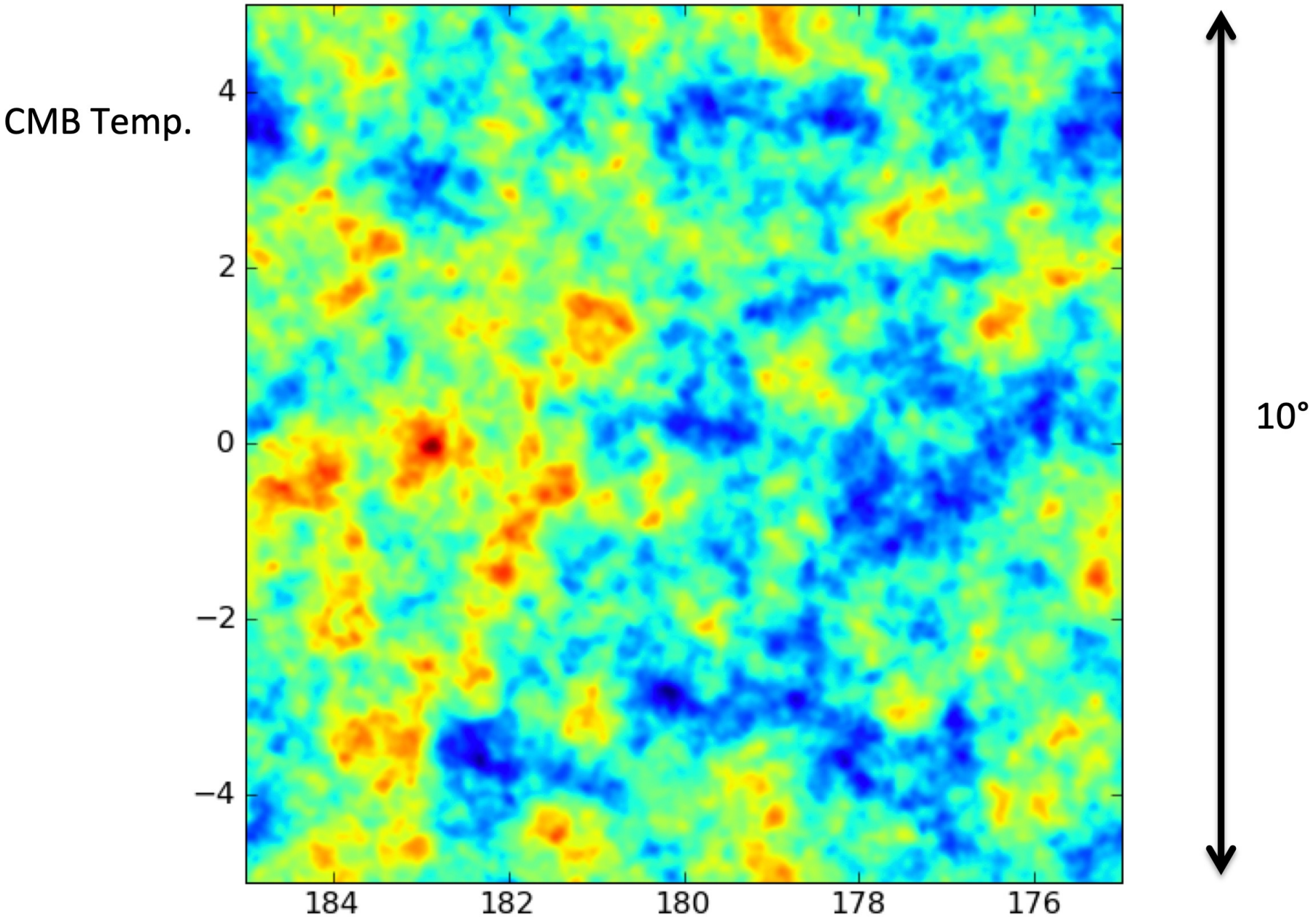
CMB Lensing

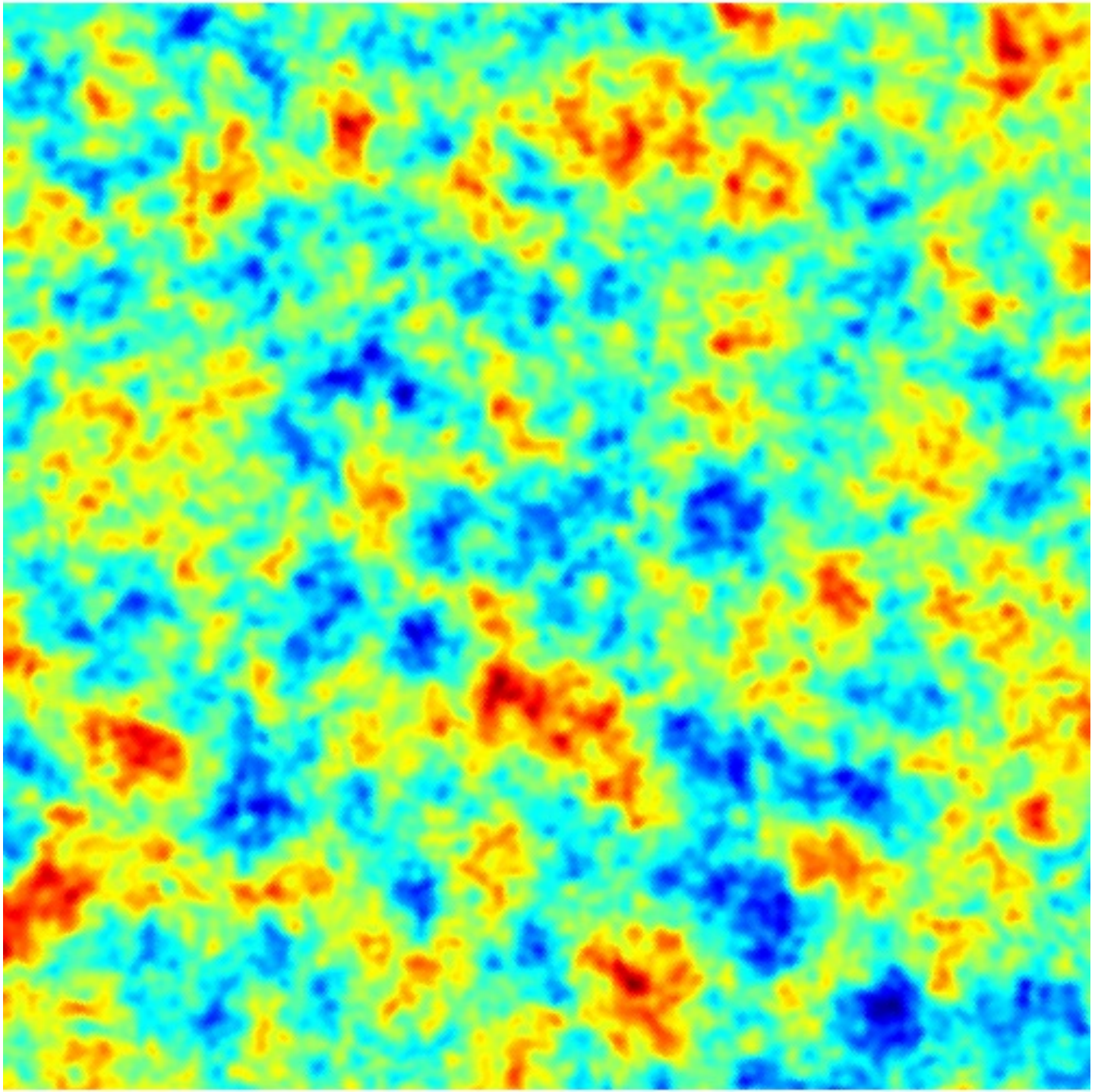


Unlensed CMB



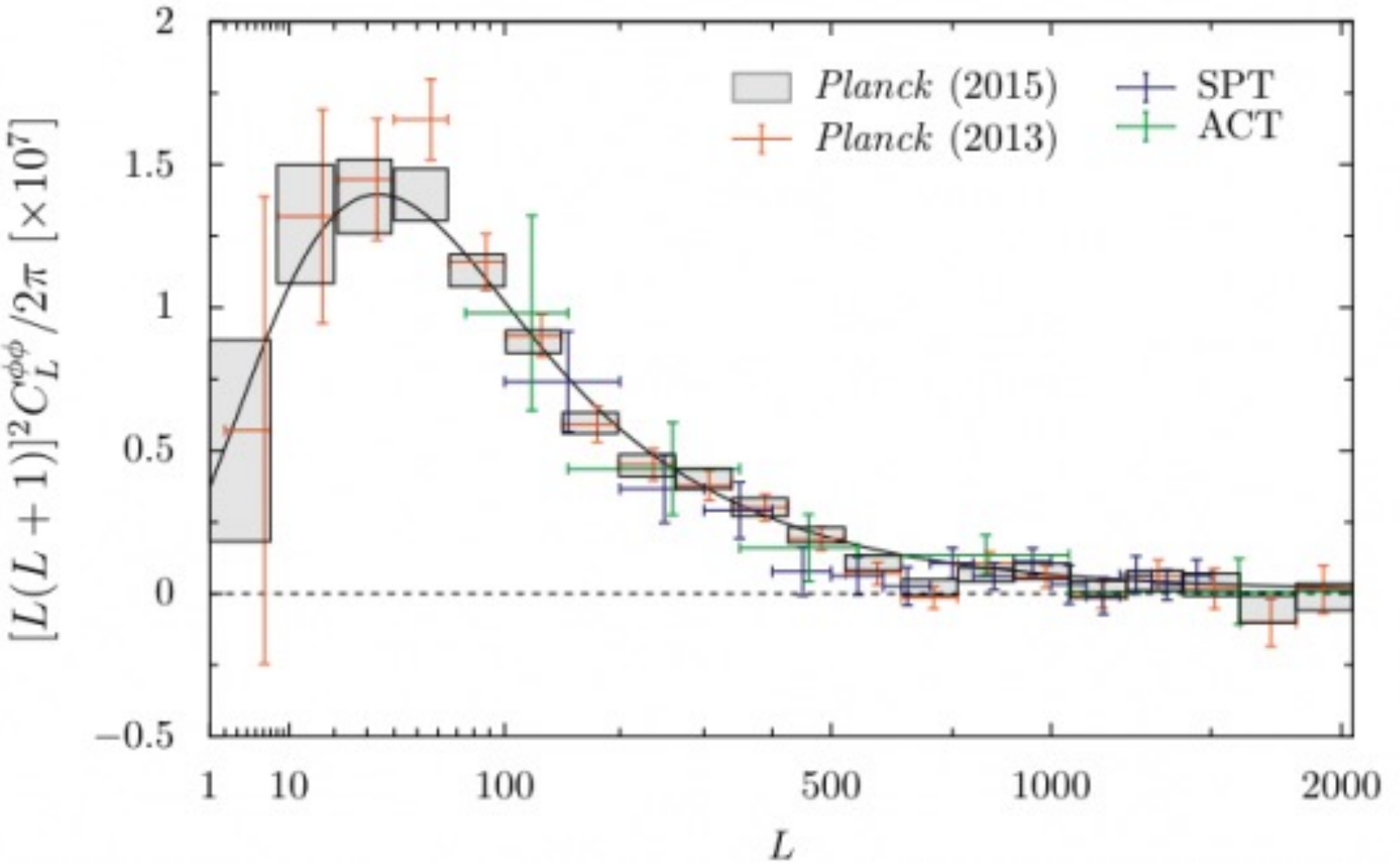
Lensed CMB



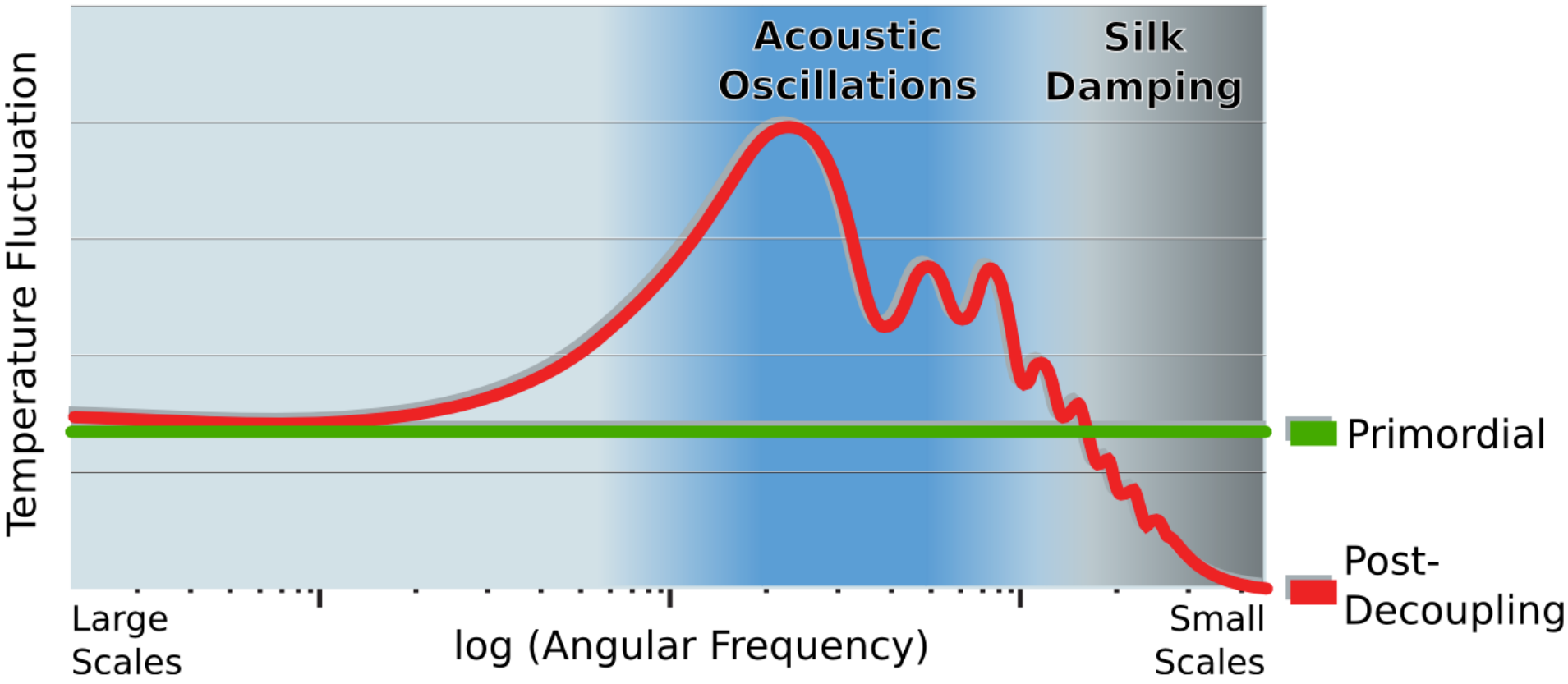


CMB Lensing

L ≈ how much power is mixed between C_l's separated by $\Delta l = L$



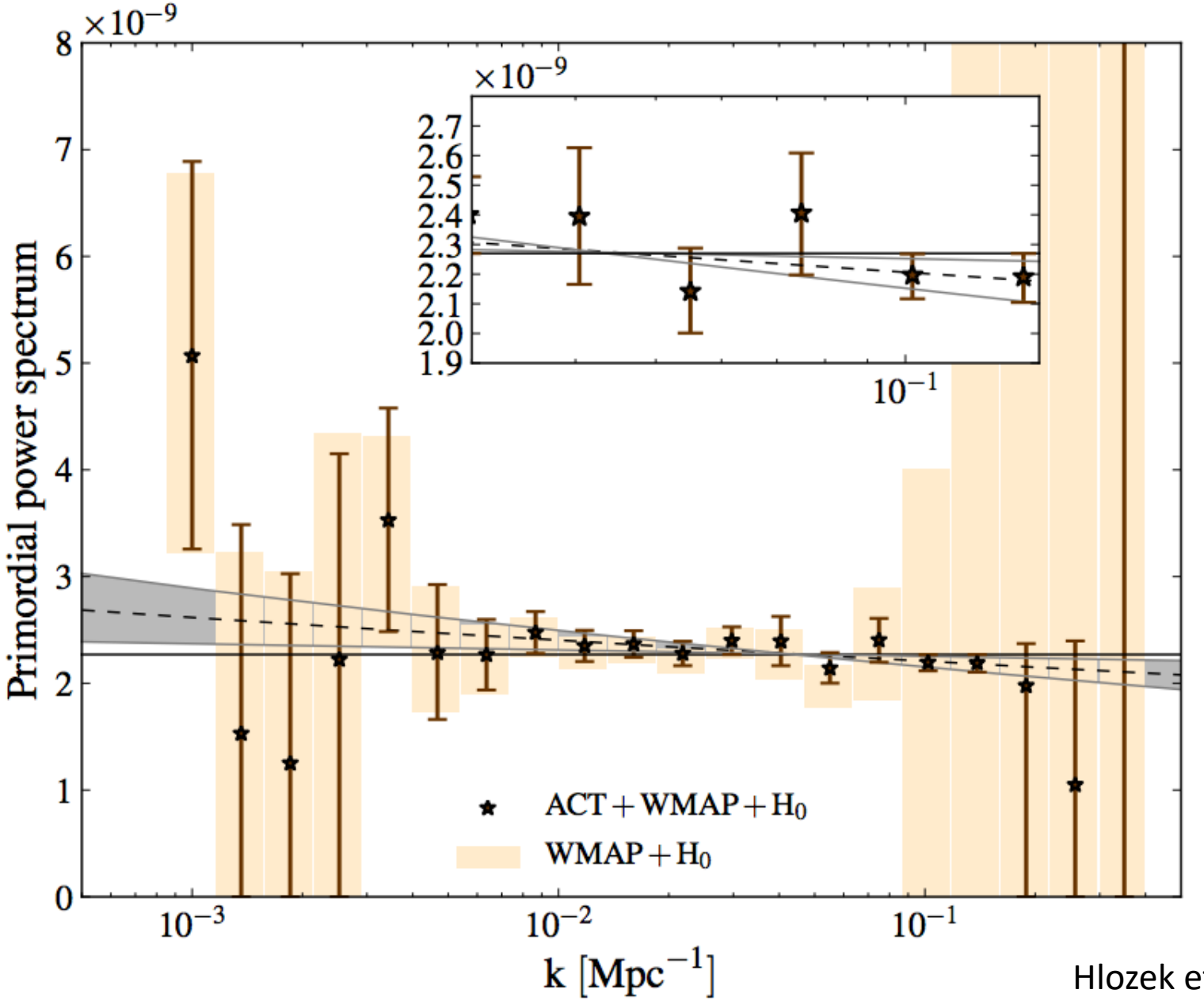
CMB Angular Power Spectrum



Primordial spectrum is predicted by inflation!

(Slope, ratio of amplitudes in different perturbation modes, …)

The Primordial Spectrum



Hlozek et al., 2011

Next Time:

Polarization!

(+ Review)