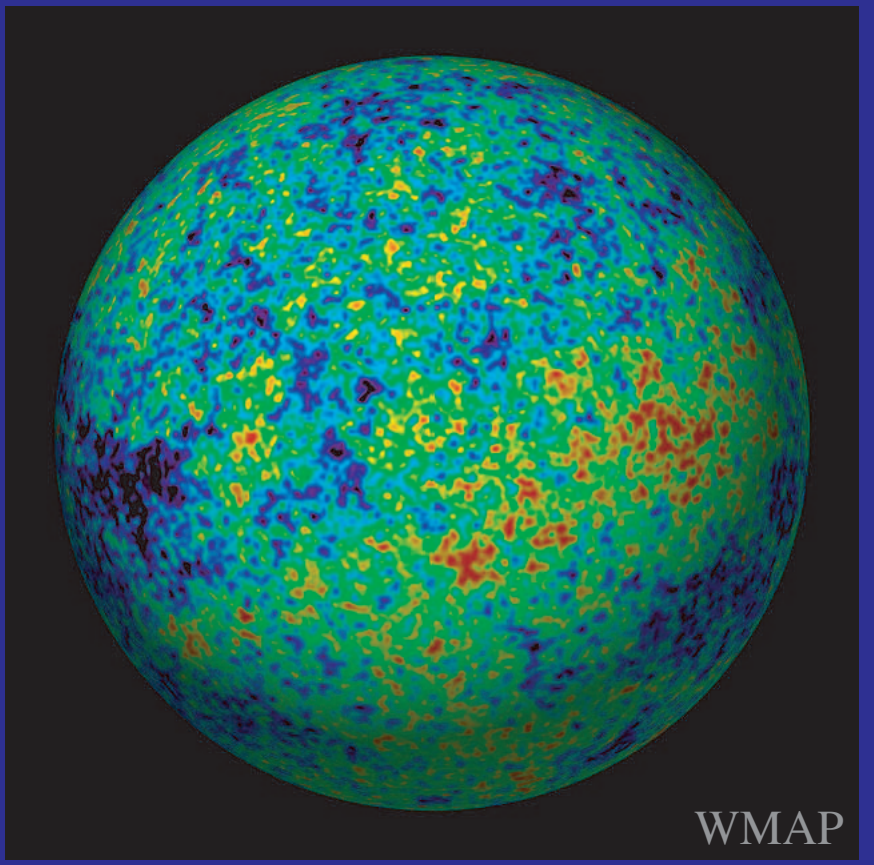
The Cosmic Microwave Background:

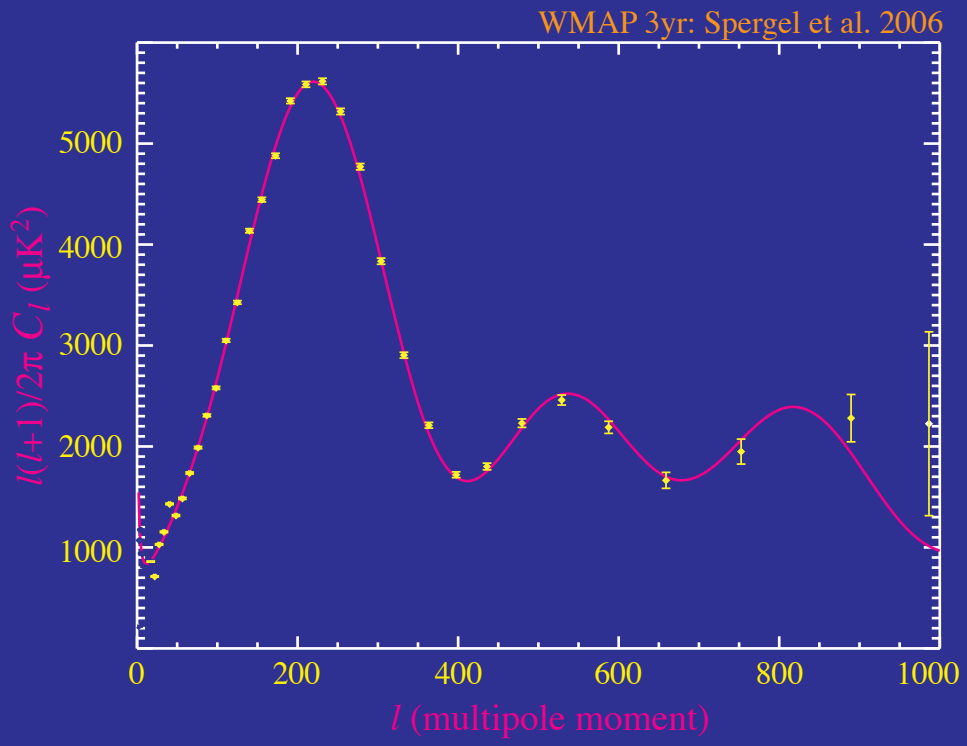


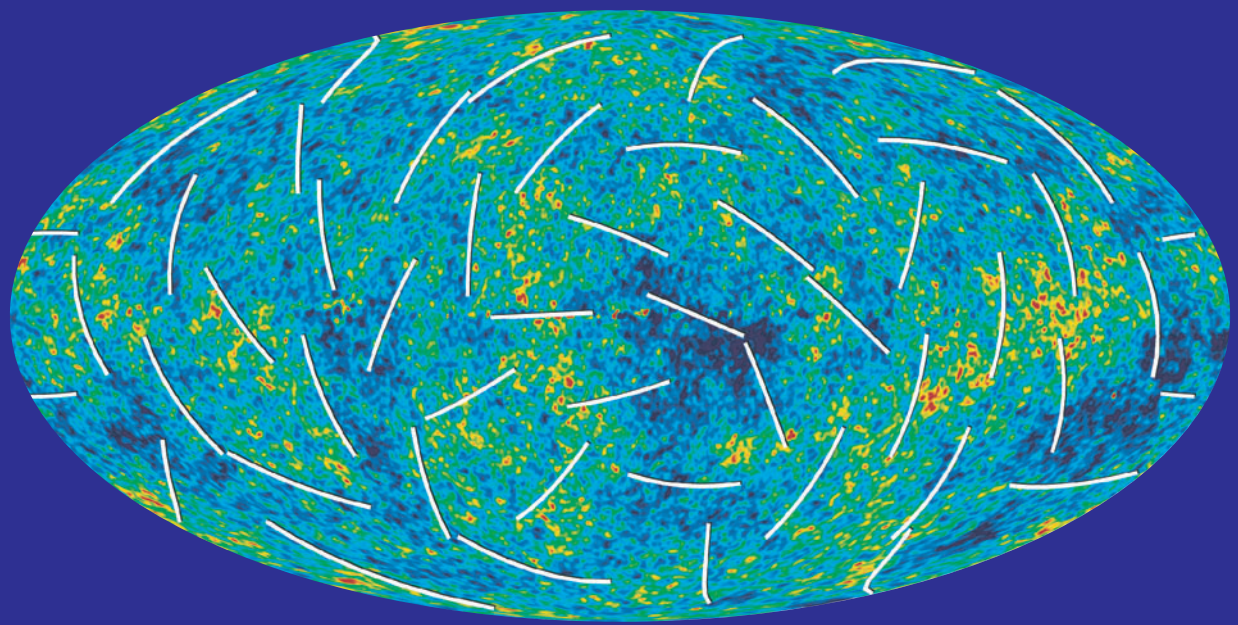
Ringing in the New Cosmology

Wayne Hu

Astro 282

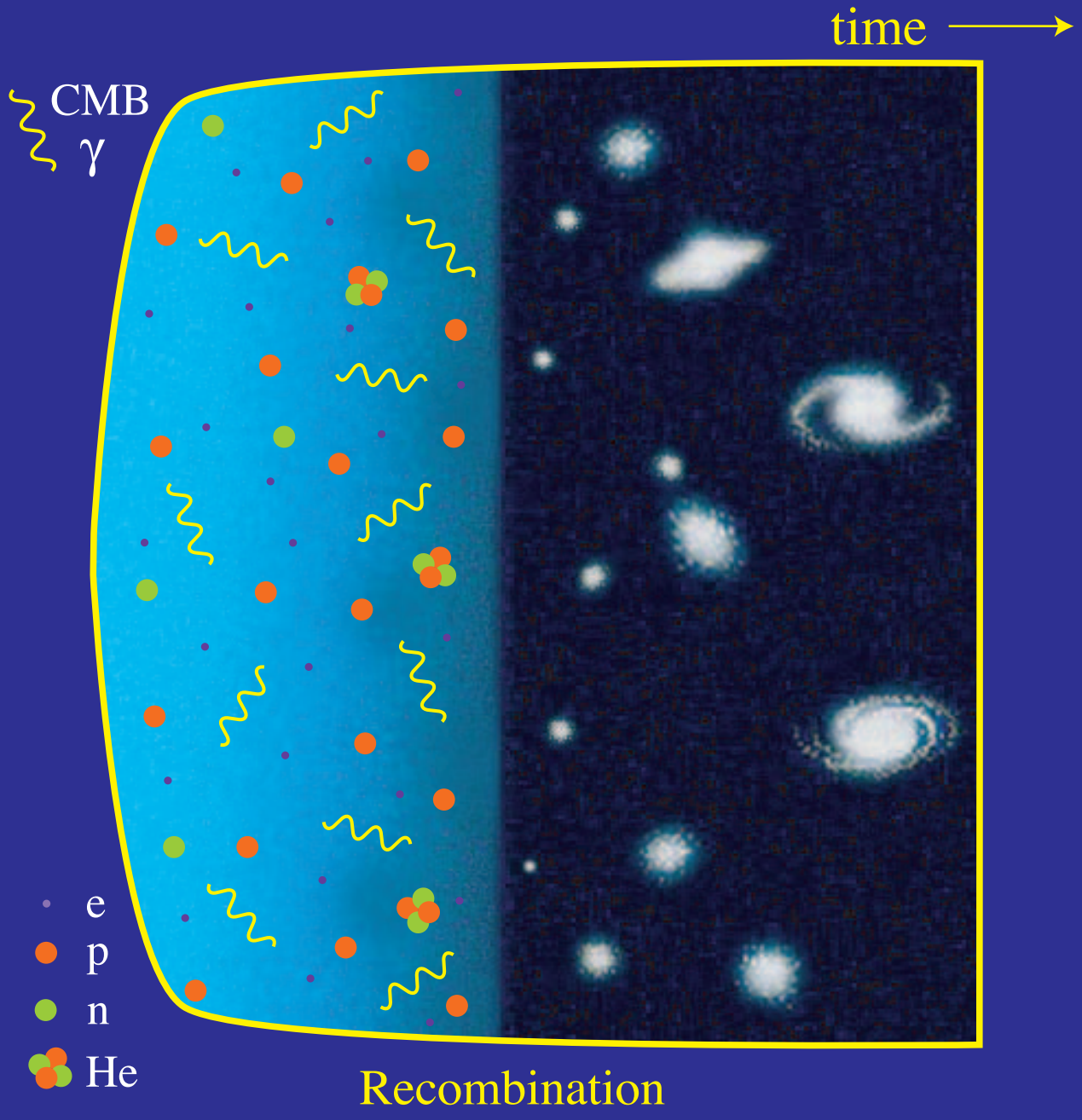
WMAP 3yr Data



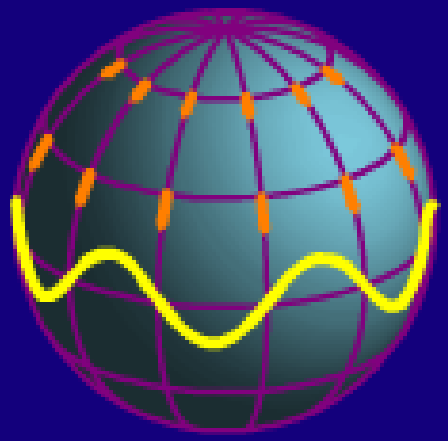


In the Beginning...

There Was Light



Fade to ~~Black~~ Microwave

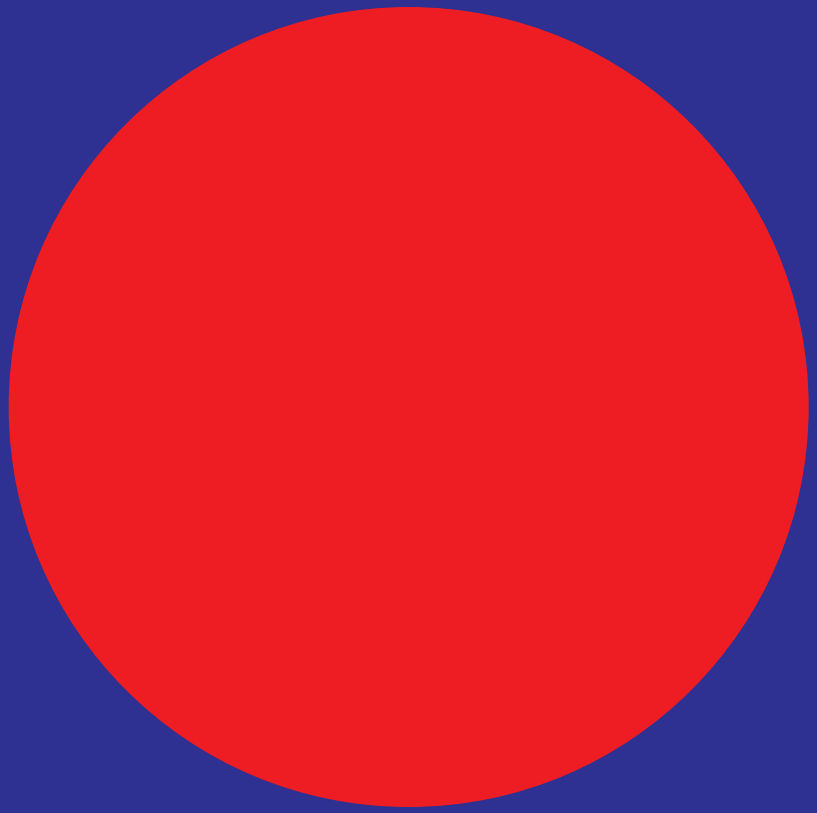


Turn on, Tune in, Drop out

- CMB photons have dropped out of the visible spectrum into the microwaves; a temperature 3 degrees above absolute zero
- Wavelengths in the mm-cm regime, comparable to radio and TV wavelengths

- Tune a TV between channels and about 1% of the static is from the CMB
- Tune a microwave receiver to the peak frequency of CMB photons and they dominate the night sky and come from everywhere at a rate of 10 trillion photons per second per square cm.

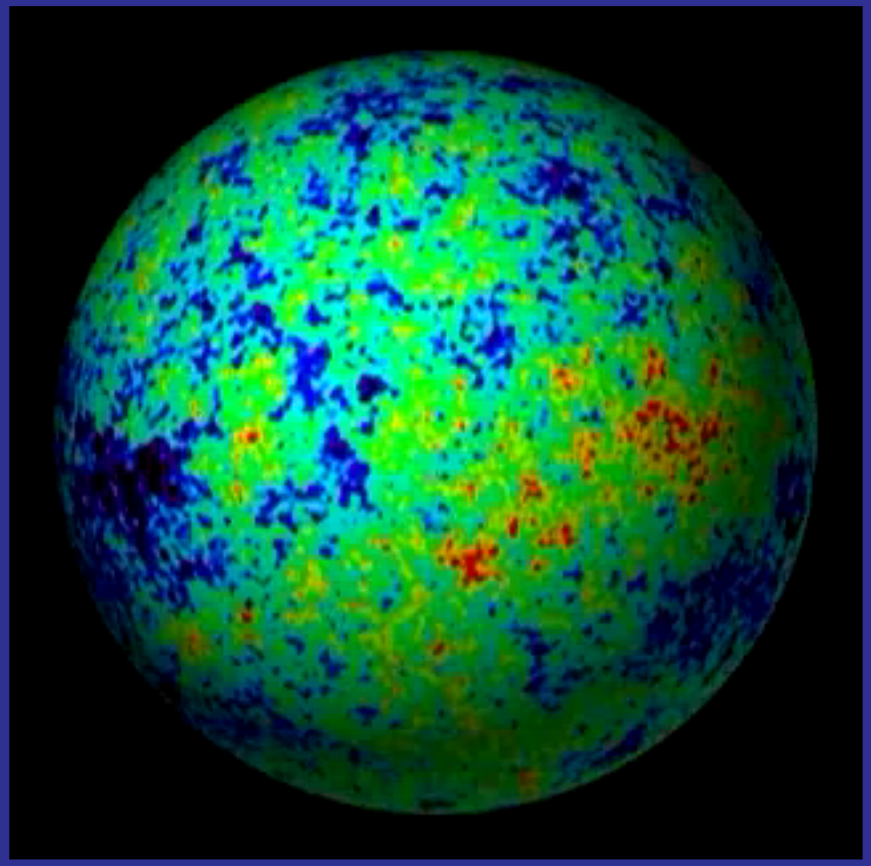
The Microwave Sky



Uniform Emission

Penzias & Wilson 1965

The Microwave Sky

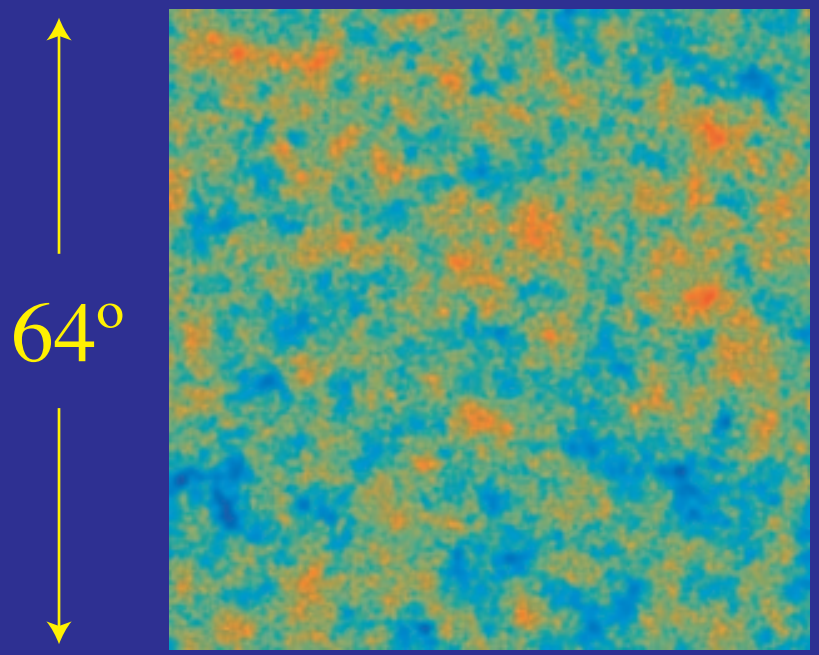


Nigel: but it goes up to 11
no make that 100,000

http://map.gsfc.nasa.gov

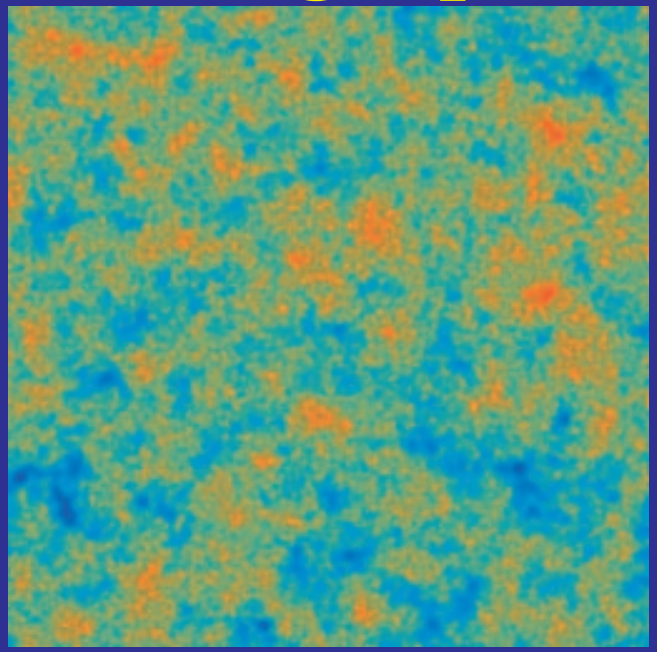
Seeing Spots

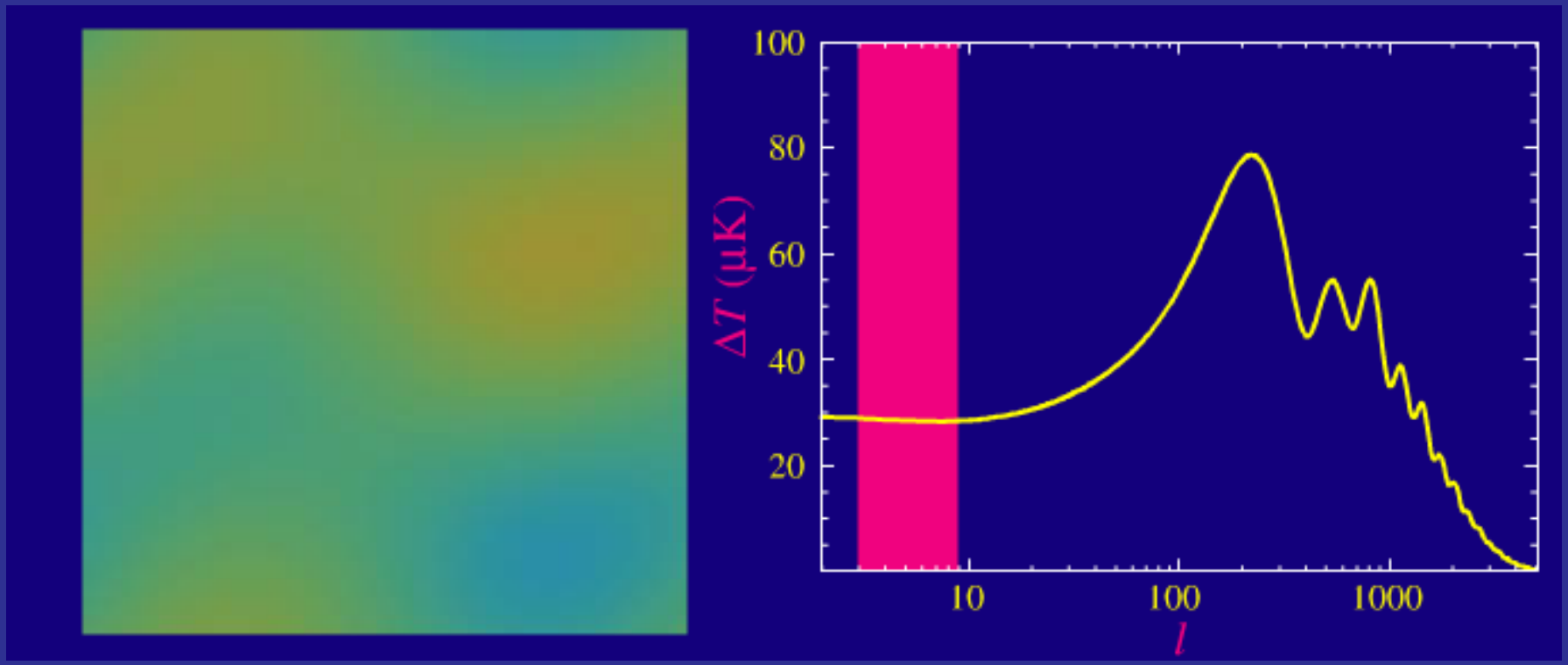
- 1 part in 100000 variations in temperature
- Spot sizes ranging from a fraction of a degree to 180 degrees



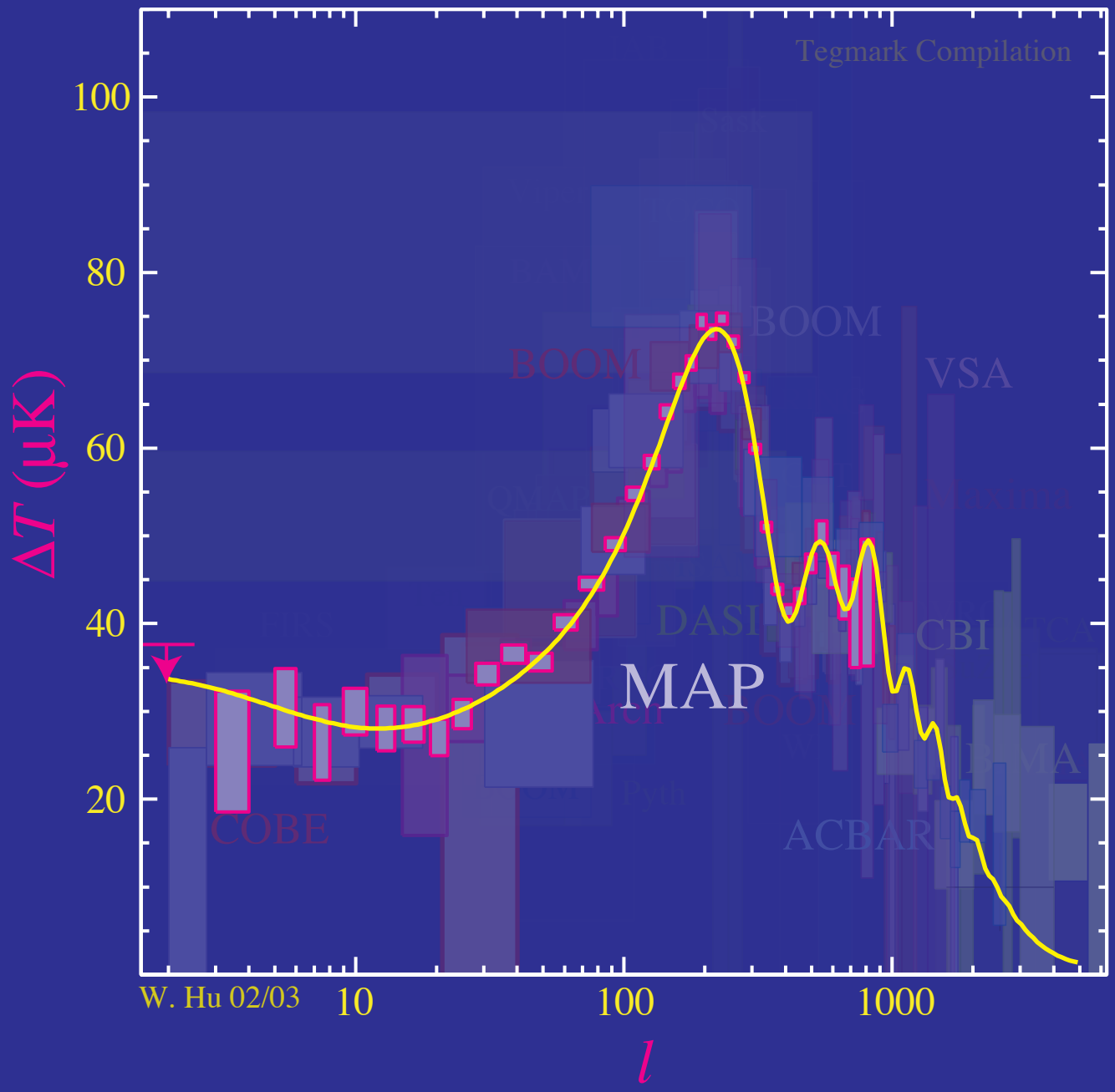
- Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

Seeing Spots





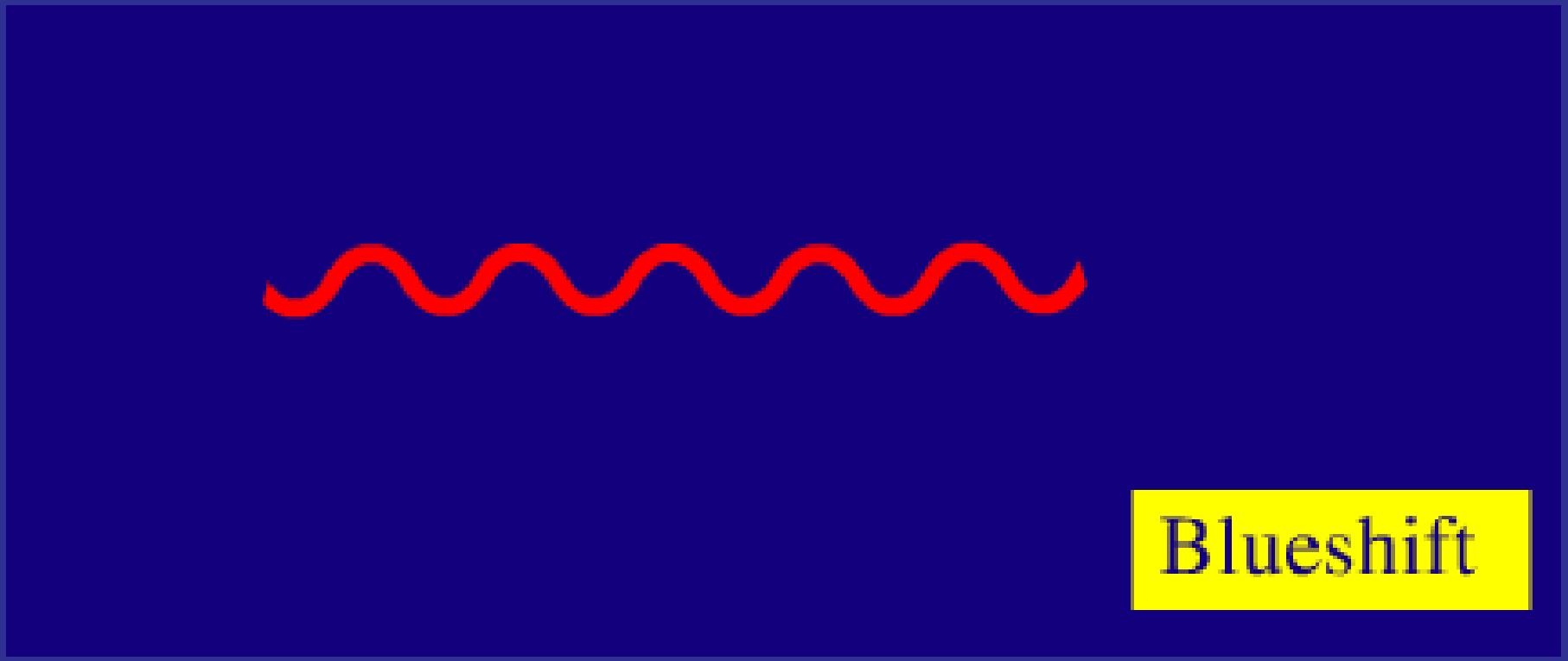
Observed Power Spectrum



Sounding Out Origins

Darkness from Light: Recombination

- Reversing the expansion, CMB photons got hotter and hotter into the past
- When the universe was 1000 times smaller and the CMB photons were at 3000K they were energetic enough disintingrate atoms into electrons and protons.



Seeing Sound

- Colliding electrons, protons and photons forms a plasma
- Acts as gas just like molecules in the air
- Compressional disturbance propagates in the gas through particle collisions
- In the air we experience this as sound hitting the eardrum

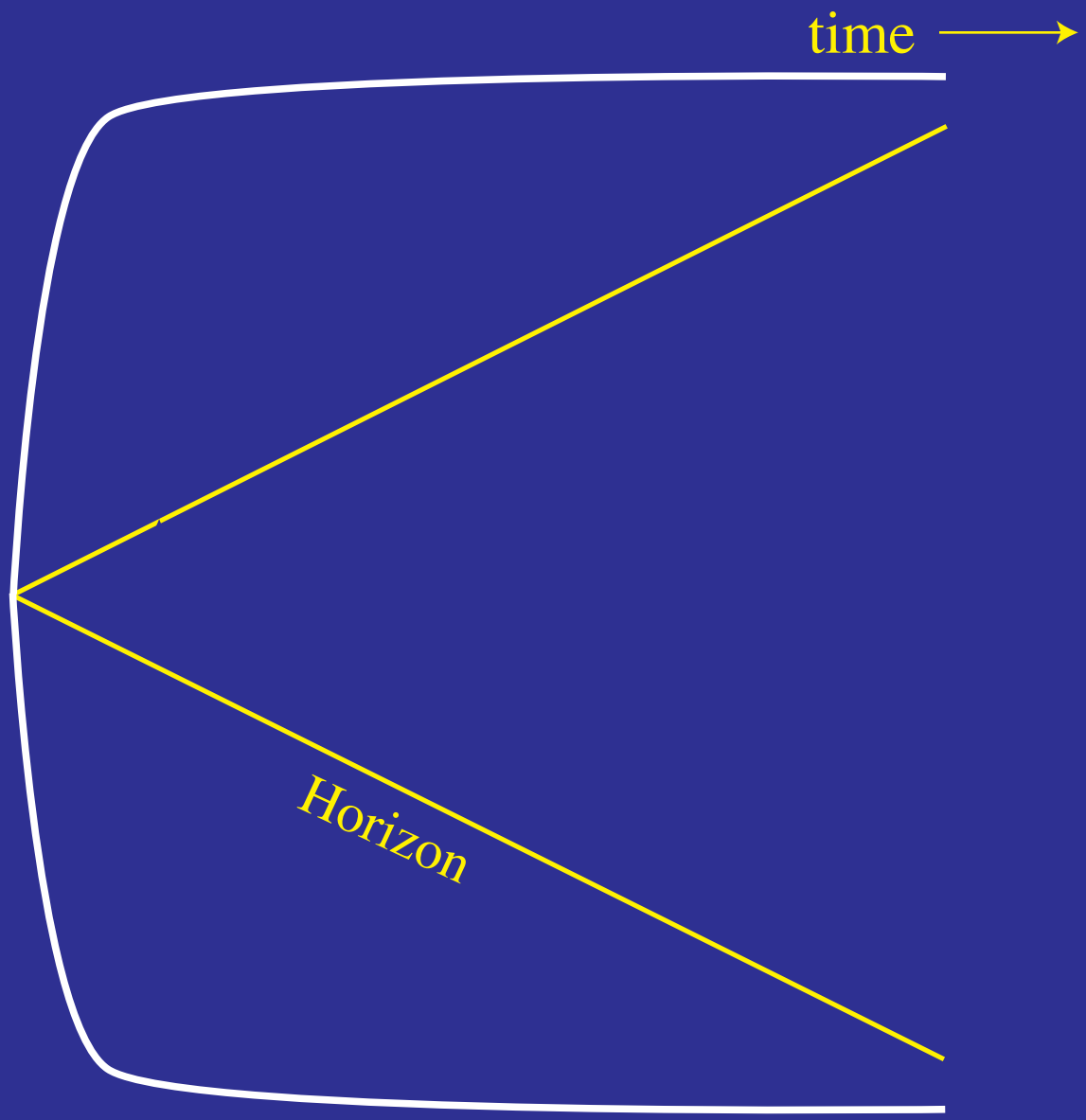
- Unlike sound in the air, we see the sound in the CMB
- Compression heats the gas resulting in a hot spot in the CMB

Gravitational Formation of Structure

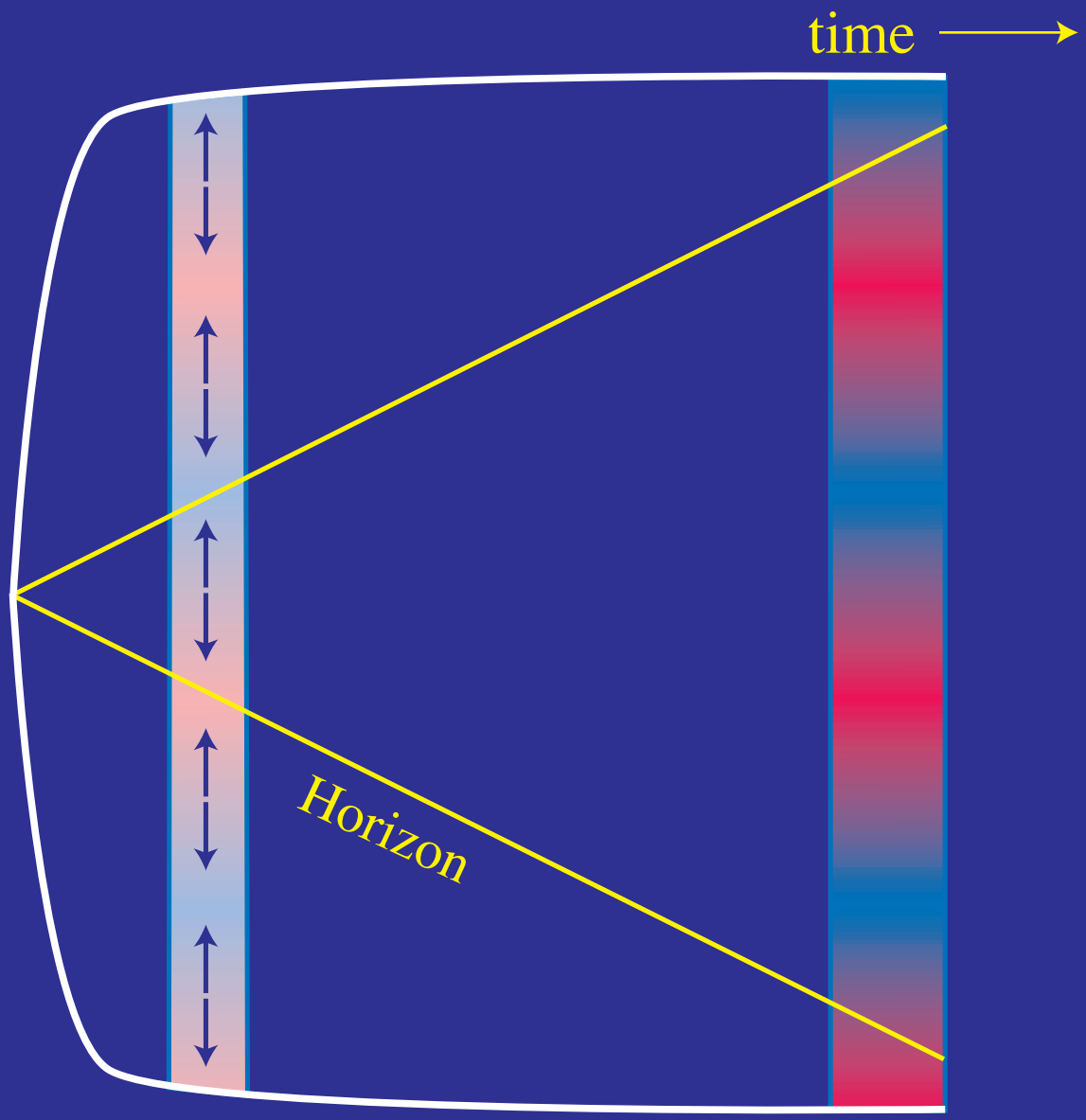
- After recombination, CMB photons stop interacting with matter
- Matter fluctuation collapses due to graviational self-attraction
- Grows into the large scale structure of the universe in 14 billion yrs

A. Kravtsov

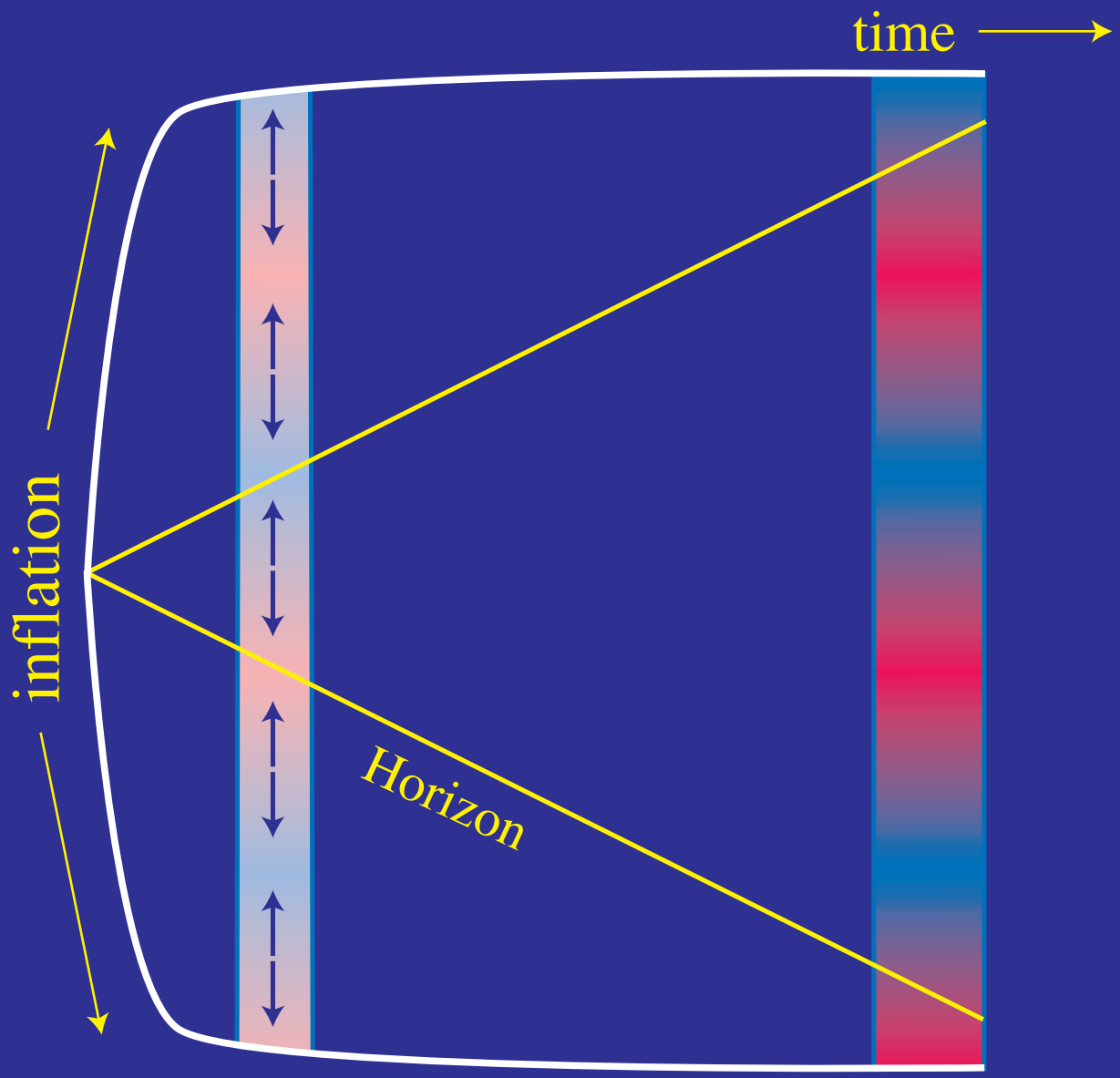
Prime Mover



Prime Mover



Prime Mover



Inflation as Prime Mover

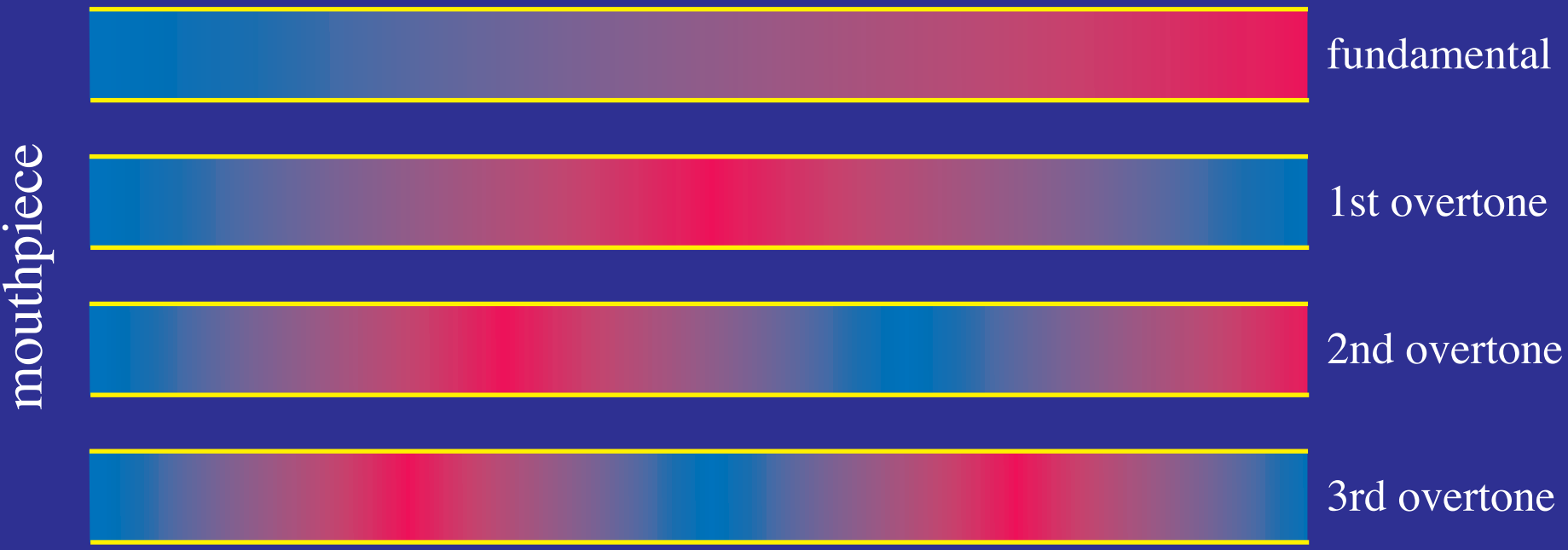
- Searching backwards in time for the origin of structure, eventually the size of a given structure becomes larger than the horizon
- Since information cannot travel faster than light, no causal process can then originate the structure under a normal expansion

- Inflation is a period of superluminal expansion that takes microphysical scales into cosmological scales
- Driven by a hypothetical form of matter called the inflaton
- Quantum mechanical fluctuations due to the uncertainty principle become the seeds of structure today

- Can structure originate at intermediate times and provide a loophole?

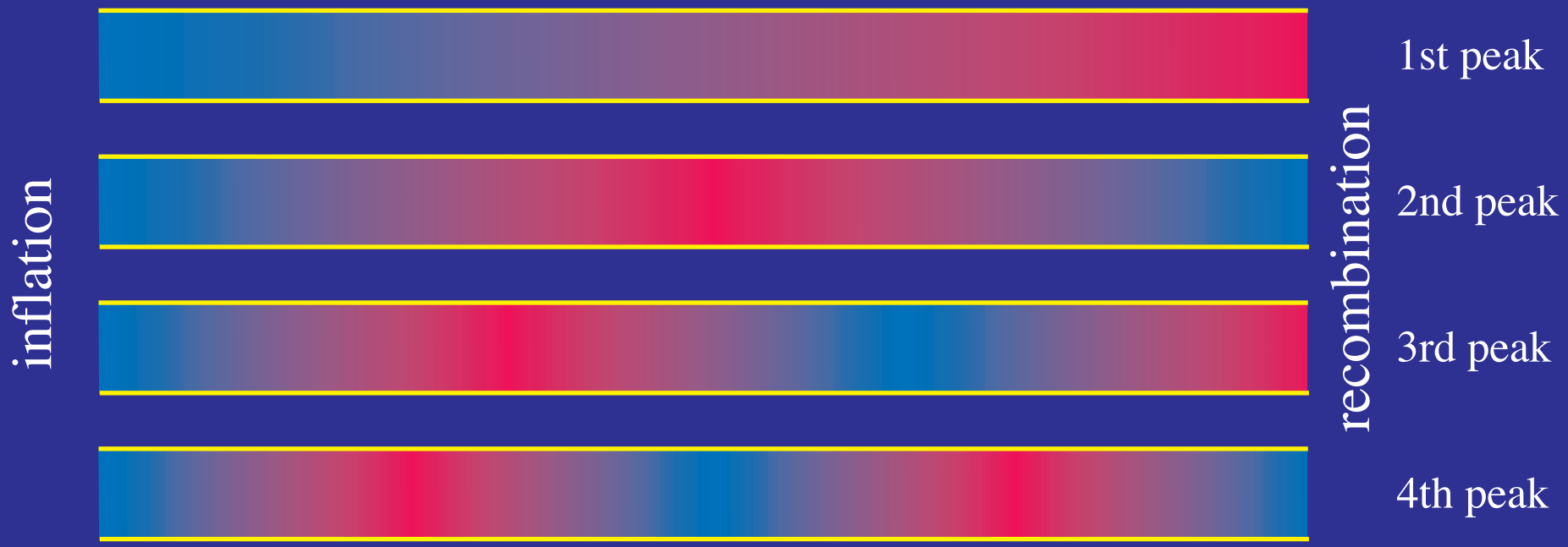
Piper at the Gates of Dawn

- Blow into a flute or an open pipe
- Spectrum of sound contains a fundamental frequency and harmonic overtones



Piper at the Gates of Dawn

- Inflation is the source of sound waves at the beginning of time
- Sound waves are frozen at recombination, yielding a harmonic spectrum of frequencies that reach maximum displacement



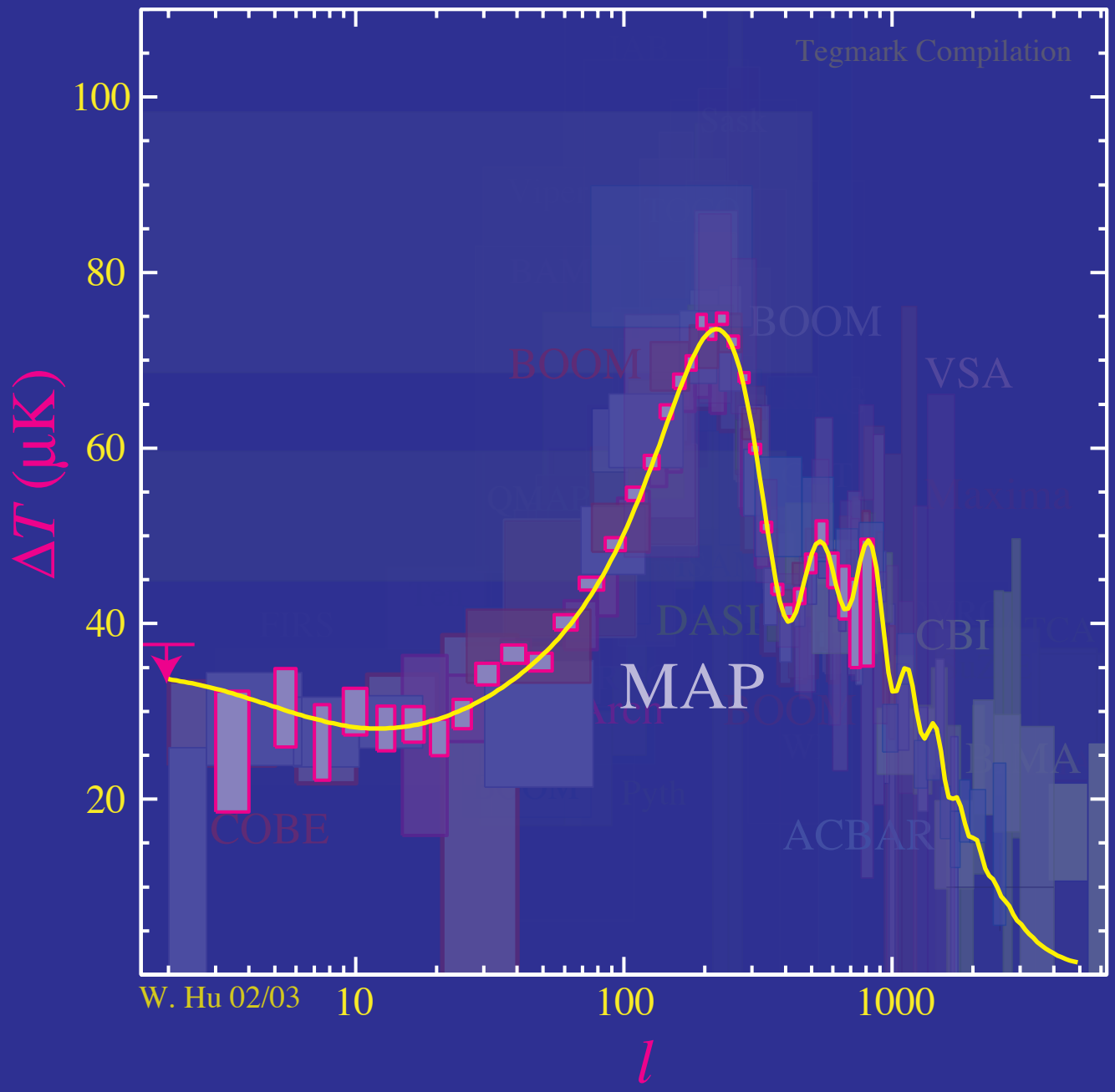
Harmonic Signature

- Much like a musical instrument, identify construction through the pattern of overtones on the fundamental frequency
- Without inflation, fluctuations must be generated at intermediate times
- Like drilling holes in the pipe and blowing in random places, harmonic structure of peaks destroyed
- Observed frequency spectrum consistent with inflationary origin
- Detailed examination of the overtones, reveals the composition of the universe
- But first...

In Space No One Can Hear You Scream

- Inflation predicts equal amplitude initial fluctuations on all scales since universe looks the same as it expands
- Observed fluctuations bear the imprint of sonic processing
- Most dramatically: fluctuations beyond the third peak or 10 arcminutes are exponentially damped
- Sound propagates through the collision of particles
- In air, molecules can only travel 10^{-5} cm before colliding
- In the "empty space" before recombination photons travel 10^{4} light years before colliding!
- Sound waves of shorter wavelength cannot propagate and are damped
- Accounting for this, variation in the initial fluctuations over a decade in scale no more than ~4%

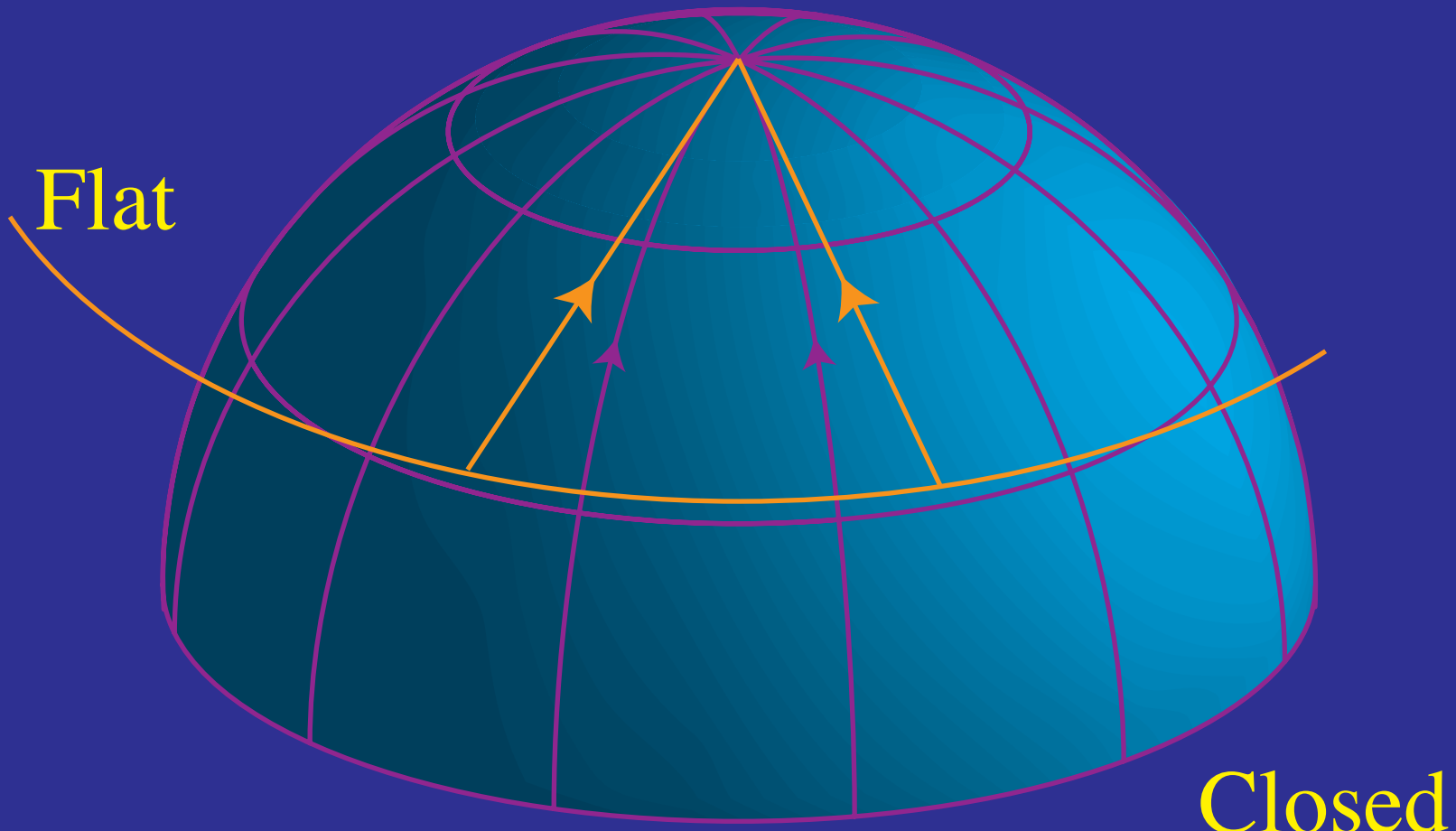
Observed Power Spectrum



Harmonic Composition

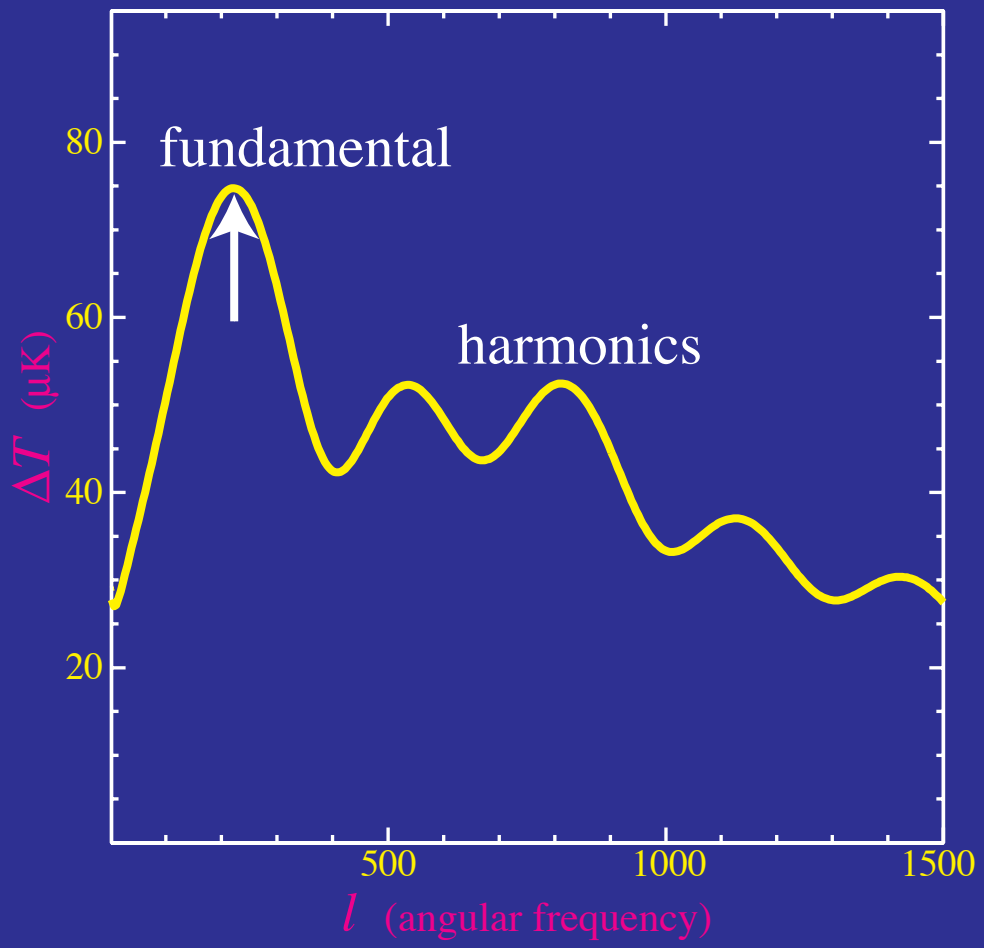
Fundamental: Weighing the Universe

- Measuring the angular extent of the fundamental wavelength (spot size) yields the curvature - universe is spatially flat
- Einstein says matter-energy density curves space: universe is at the critical density



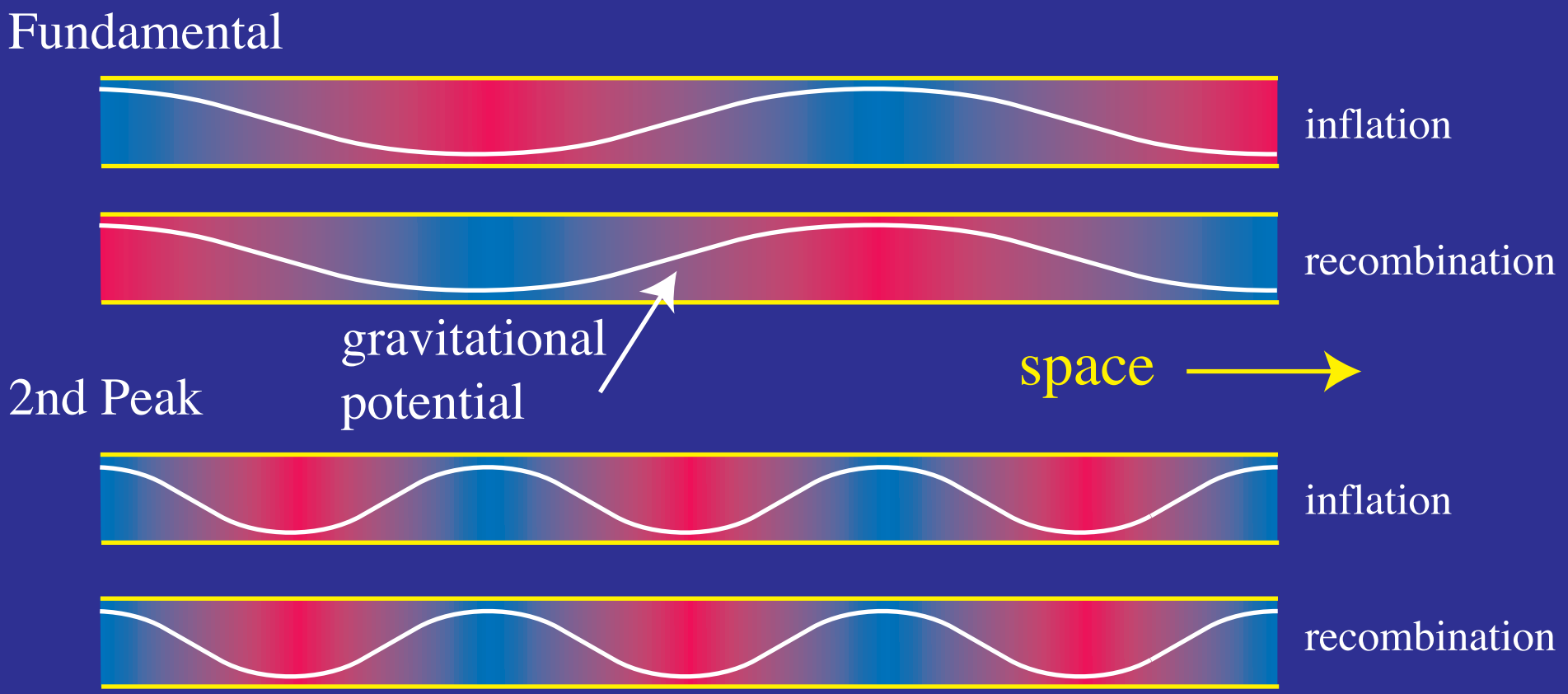
Sound Spectrum

- Spectrum of sound shows harmonics at integer ratios of the fundamental
- Other models that generate structure causally at intermediate times would not have these harmonics



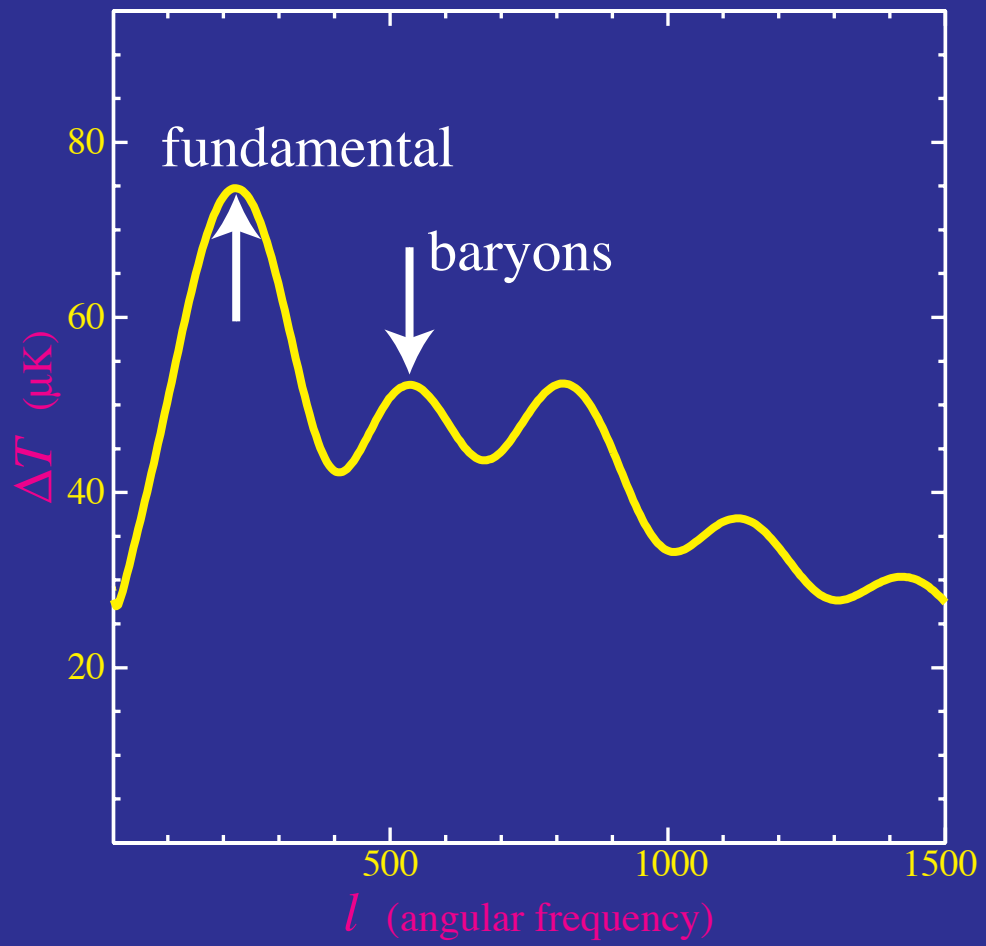
Harmonics: Ordinary Matter

- Competition between gravity and pressure depends on phase of oscillation
- At the fundamental (and odd frequency multiples) gravity assists sonic motion; at second peak (and even multiples) gravity fights sonic motion



Ordinary Matter

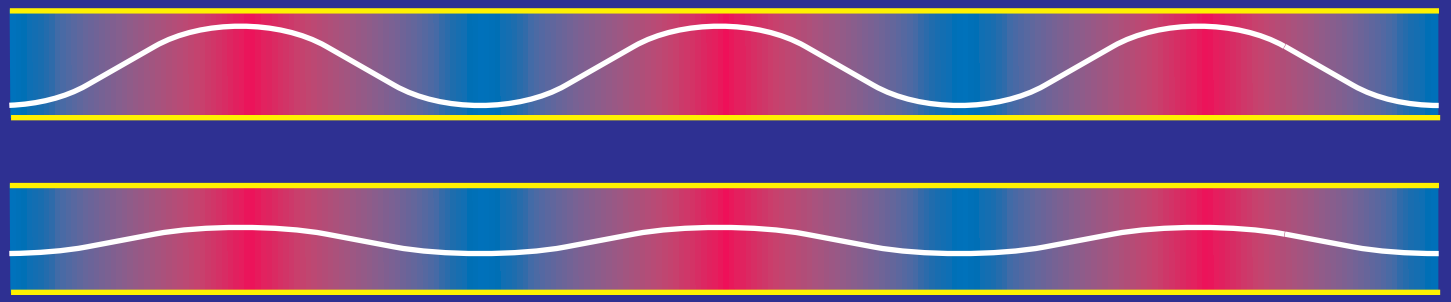
- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of ~5% of the critical density today



Harmonics: Dark Matter

- What maintains the gravitational potential if the ordinary matter oscillates as a stable sound wave?
- Without matter that does not interact with photons/light or dark matter, gravitational potentials decay once ordinary matter enters into oscillation
- Gravitational enhancement destroyed soon after 1st peak

Recombination

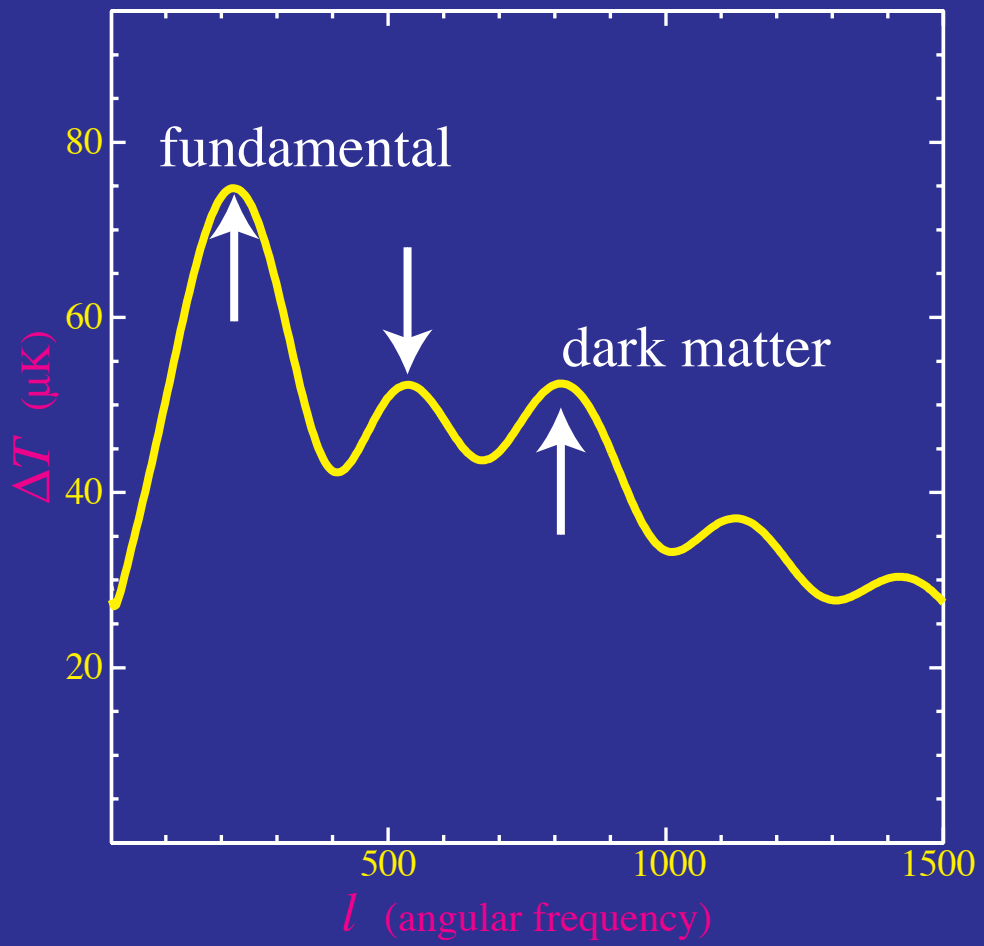


dark matter

no dark matter

Dark Matter

- A third peak comparable to second peak indicates a dark matter density ~5x that of ordinary matter
- Dark matter ~25% of the critical density



Missing Energy

- Ordinary matter and dark matter comprise ~25% of the total density as measured by the first peak
- ~75% of the universe unaccounted for
- Must have negligible contribution at recombination else else seen in the peaks
- New form of energy whose energy density decreases more slowly than matter as the universe expands

- Dub this new form of energy density:

Dark Energy