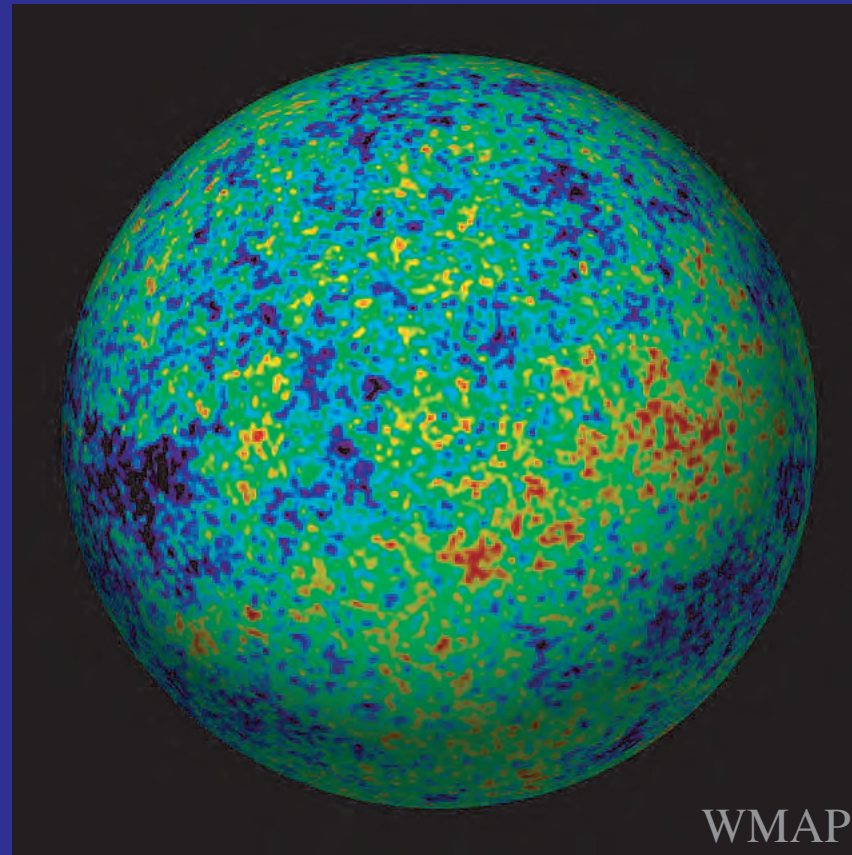


# The Cosmic Microwave Background:



## Ringing in the New Cosmology

*Wayne Hu*

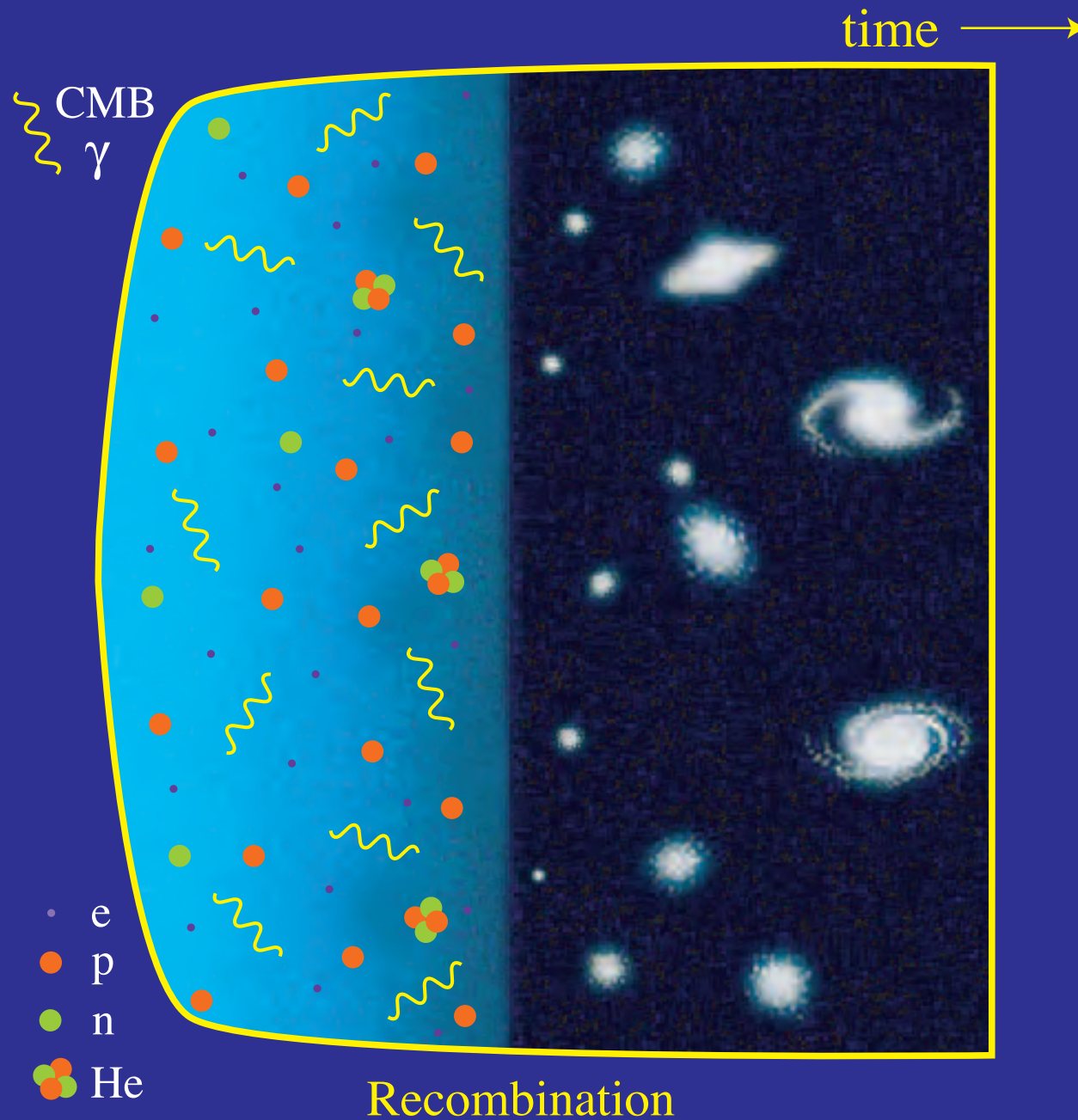
Planetarium Short Course

Center for Cosmological Physics, September 2003

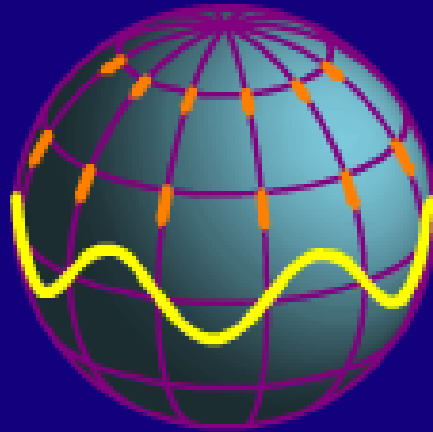
In the Beginning...



# 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

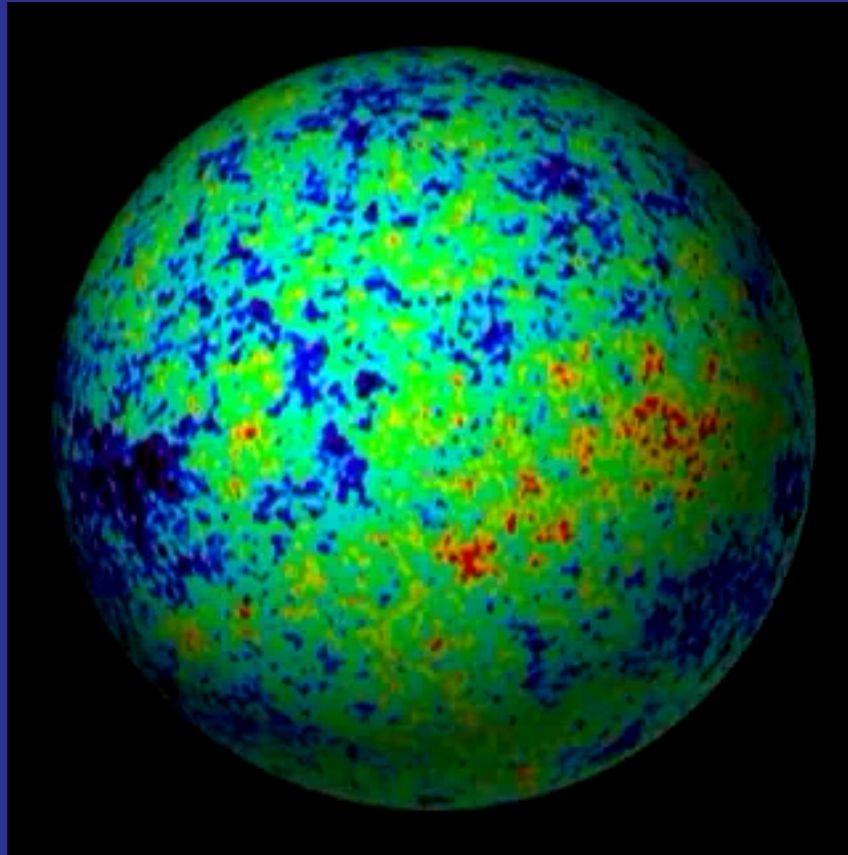


Uniform Emission



Penzias & Wilson 1965

# The Microwave Sky

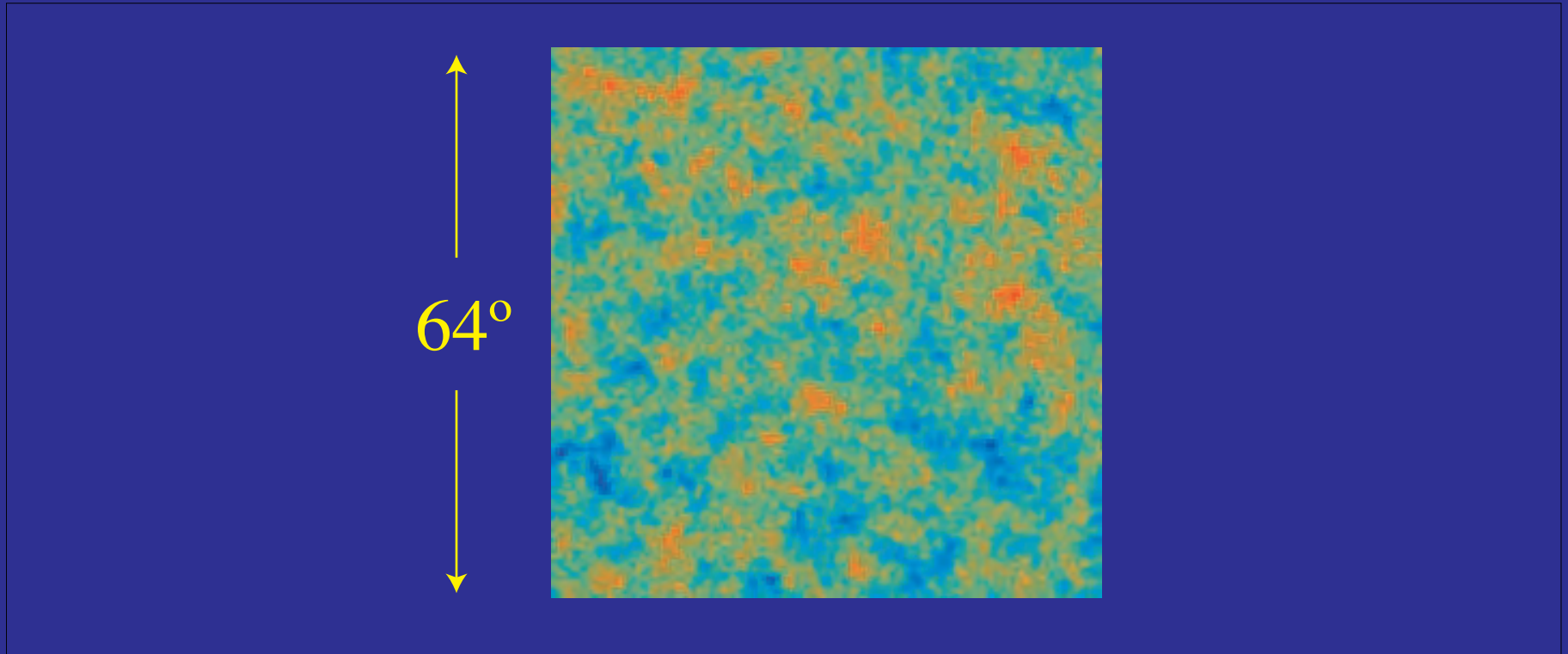


Nigel: but it goes up to 11  
no make that 100,000

<http://map.gsfc.nasa.gov>

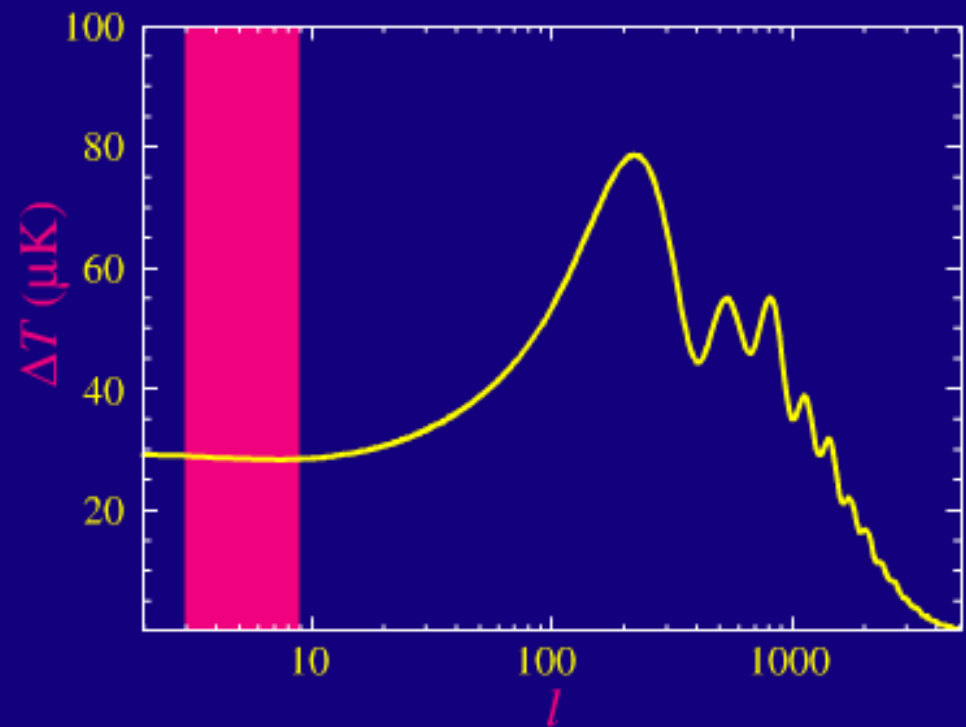
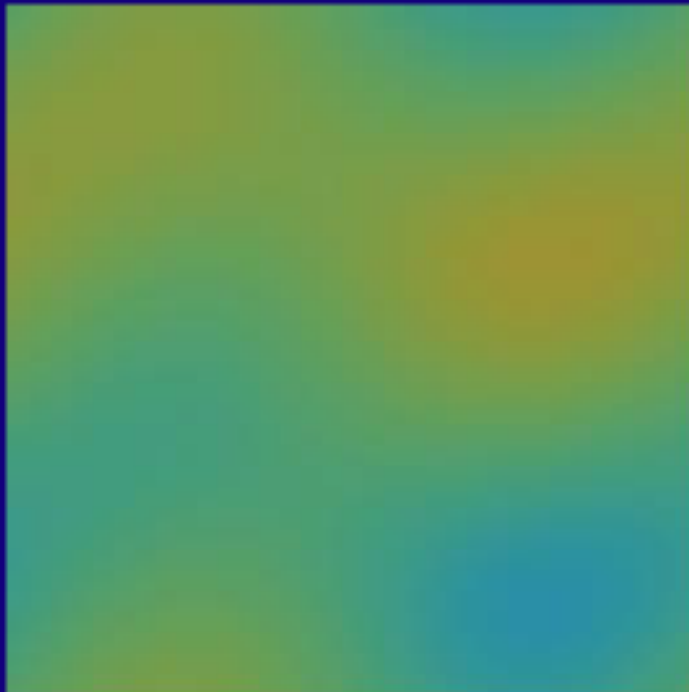
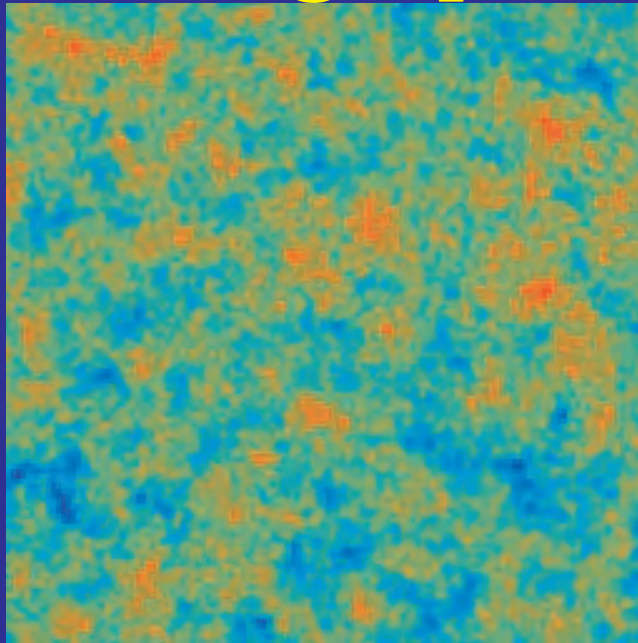
# Seeing Spots

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

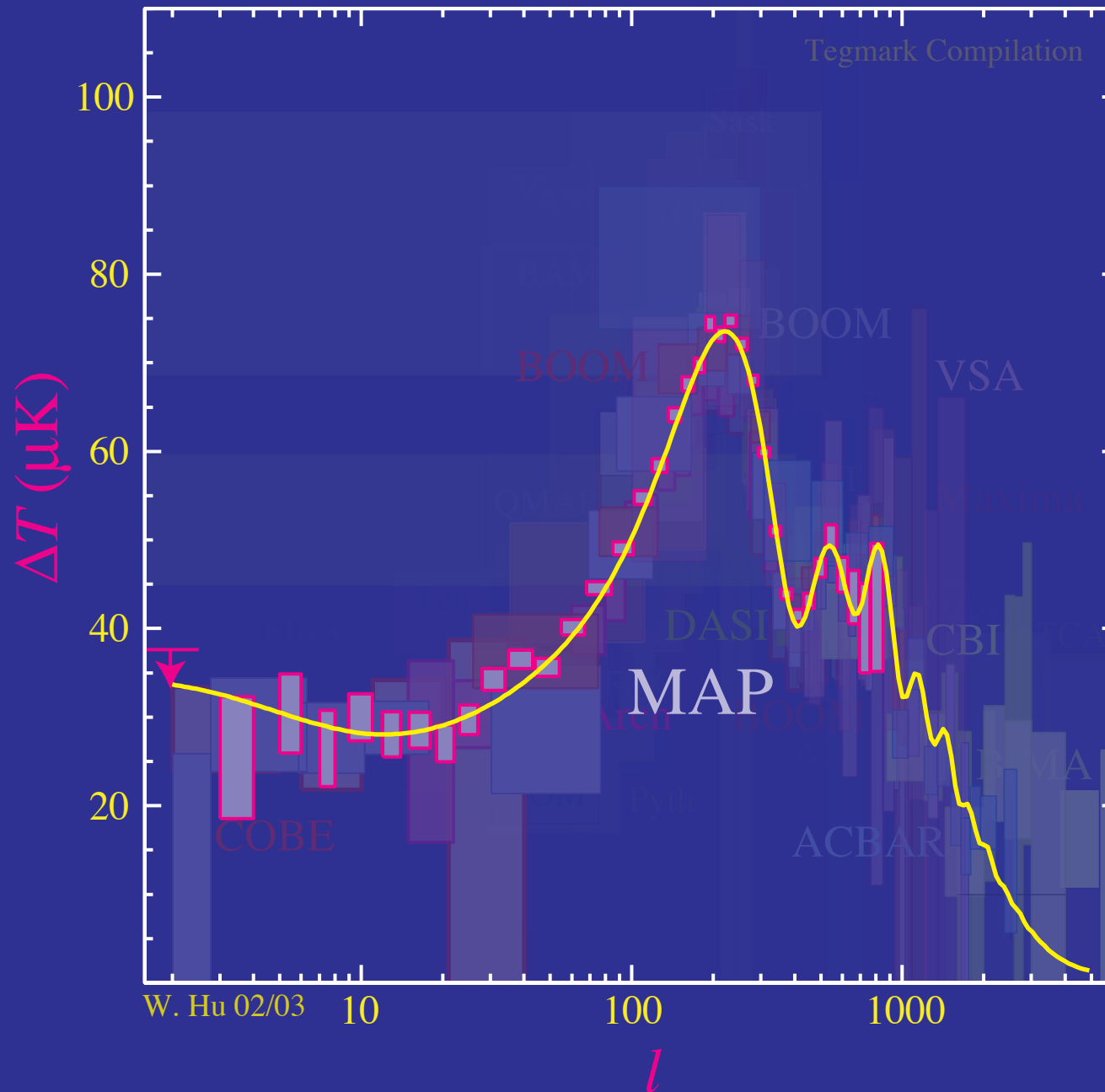


- Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

# Seeing Spots



# Observed Power Spectrum

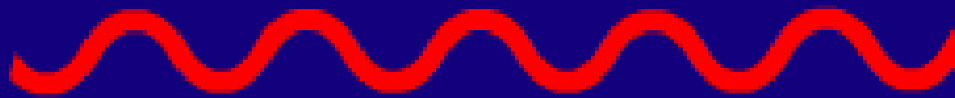




# Sounding Out Origins

# 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 disintegrate atoms into electrons and protons.



Blueshift

# 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**

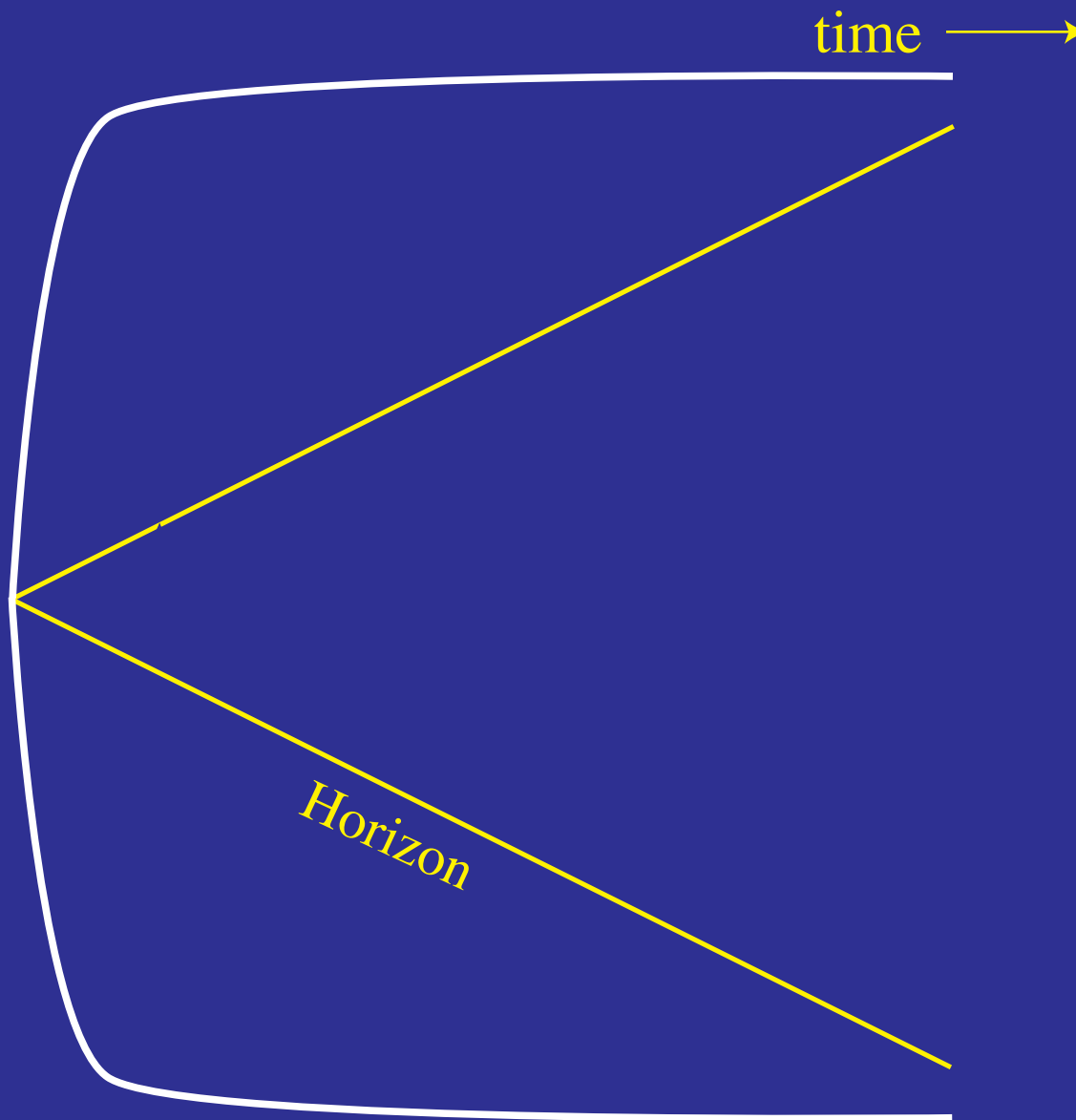


- Unlike sound in the air, we **see** the **sound** in the CMB
- **Compression heats** the gas resulting in a **hot spot** in the CMB

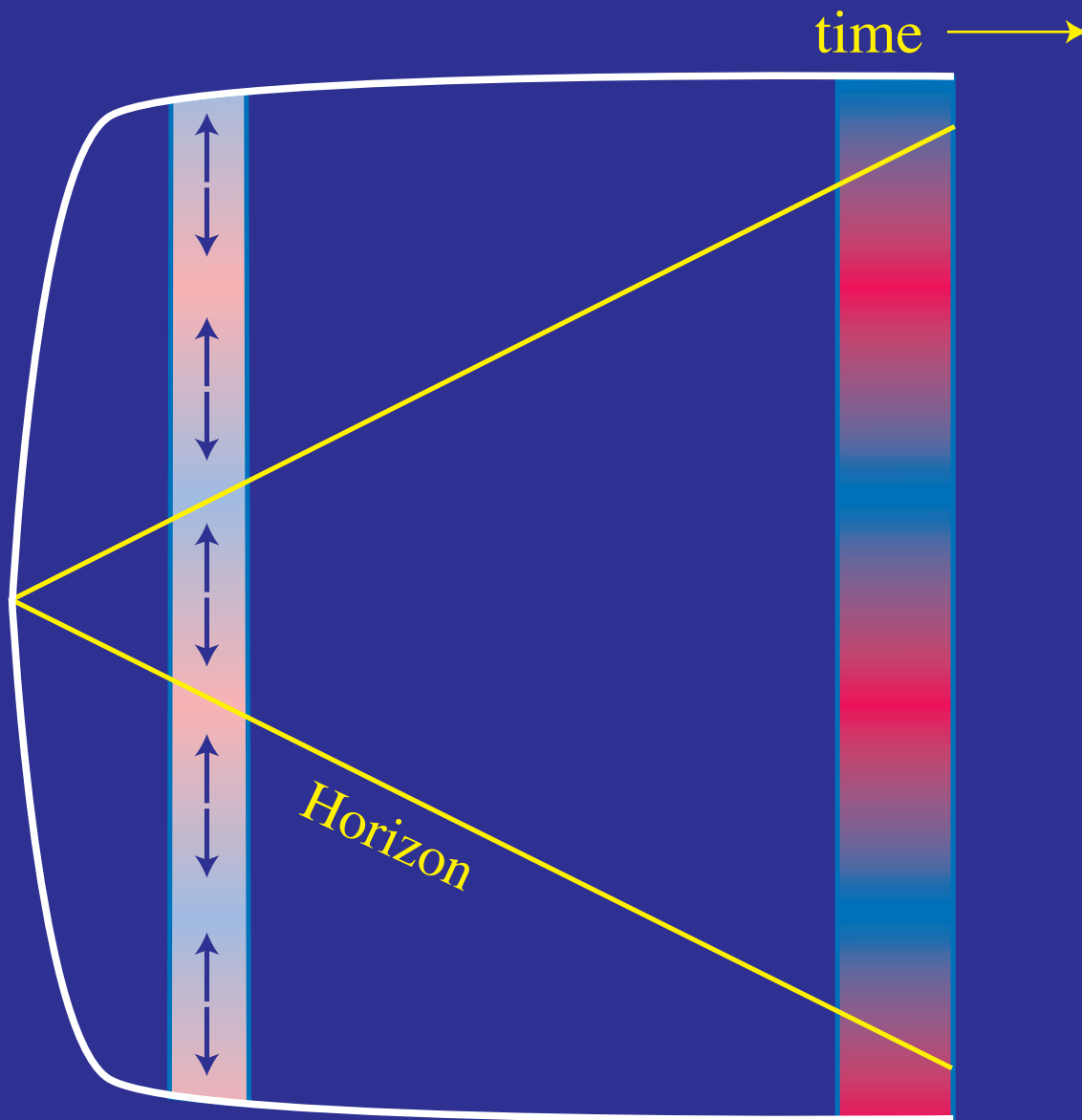
# Gravitational Formation of Structure

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

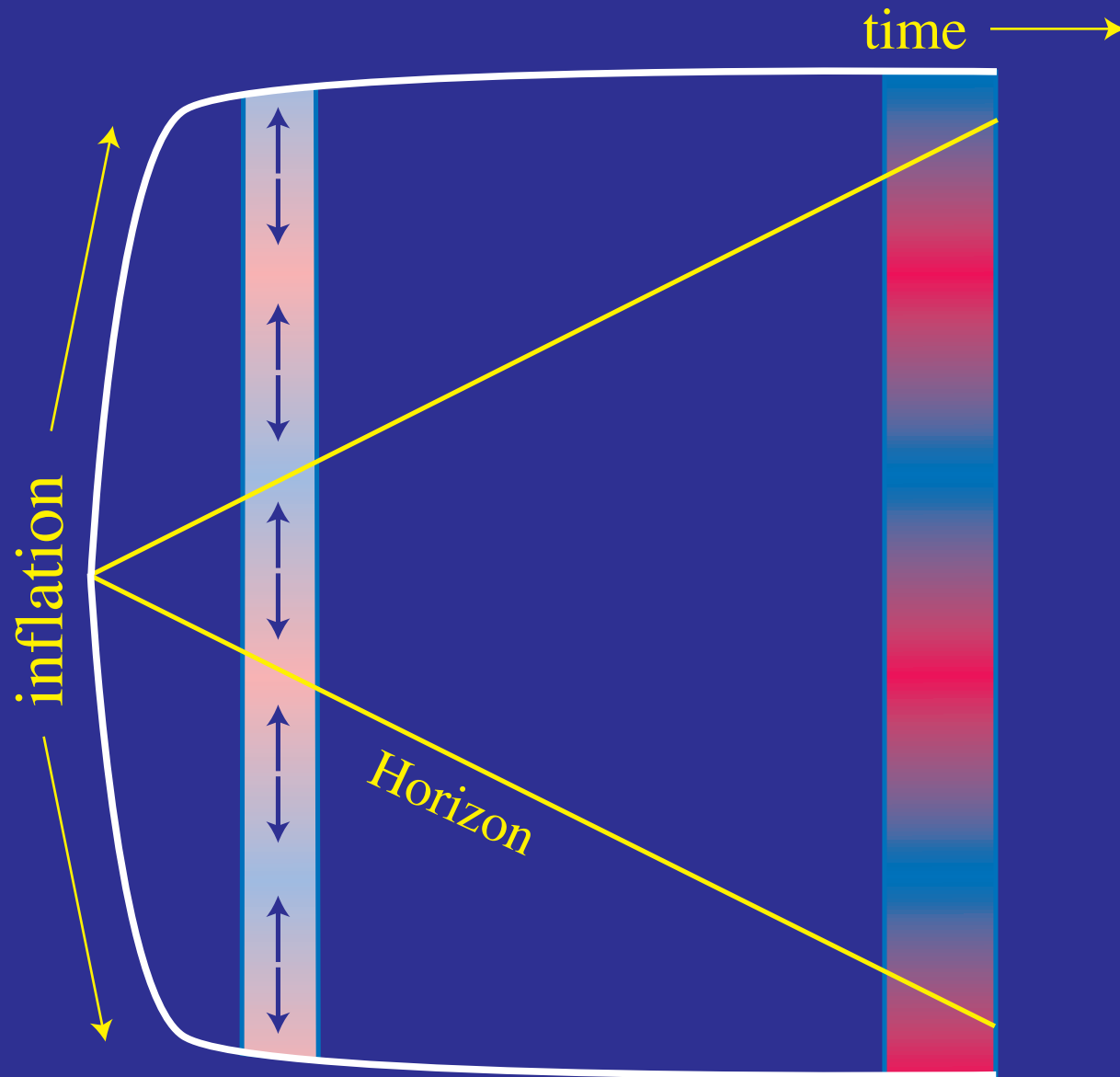
# Prime Mover



# Prime Mover



# Prime Mover



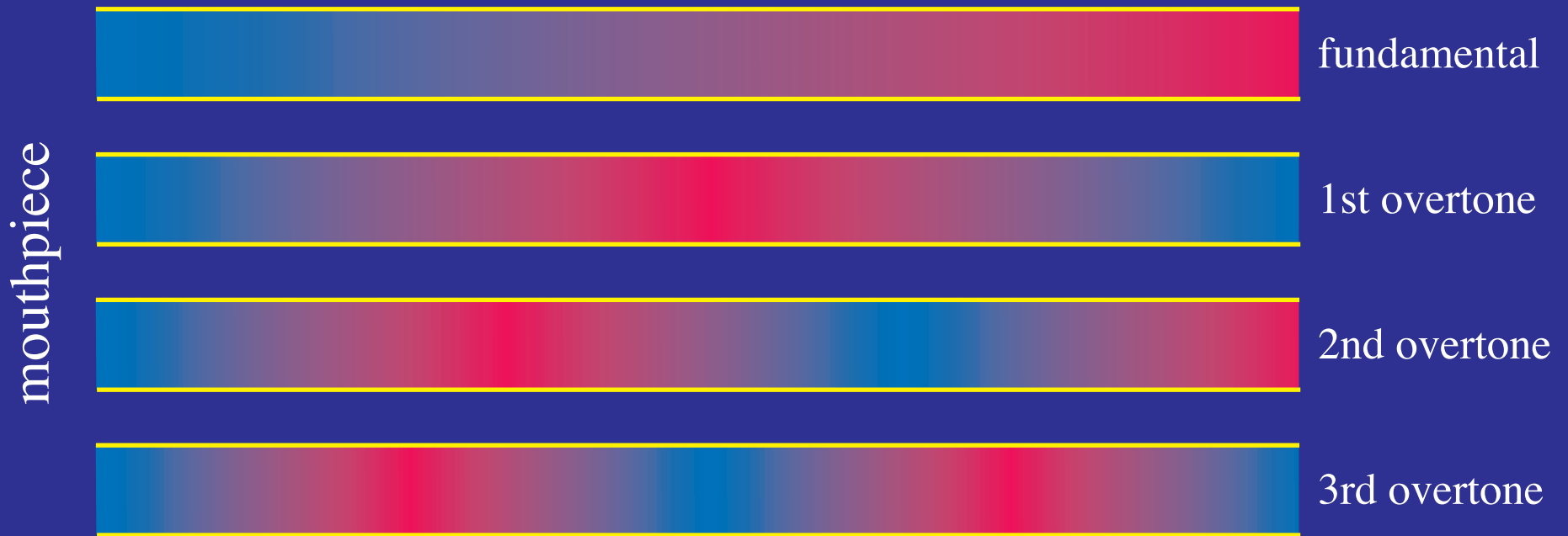
# Inflation as Prime Mover

- 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?



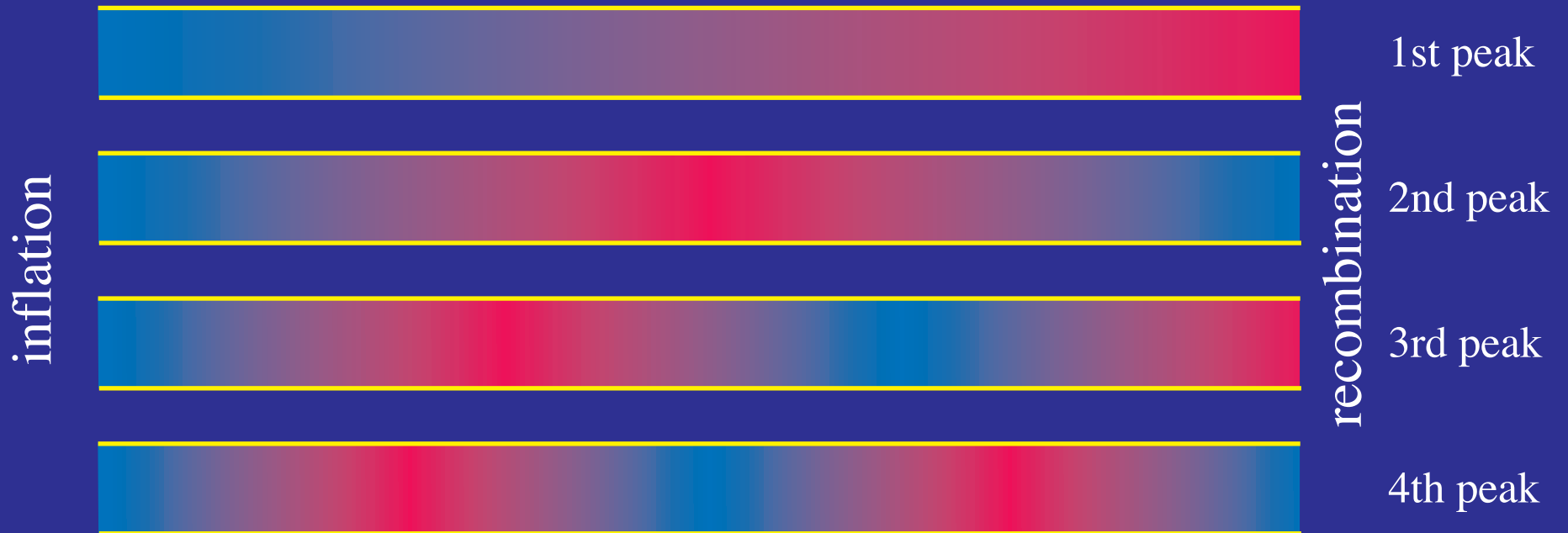
# Piper at the Gates of Dawn

- 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**



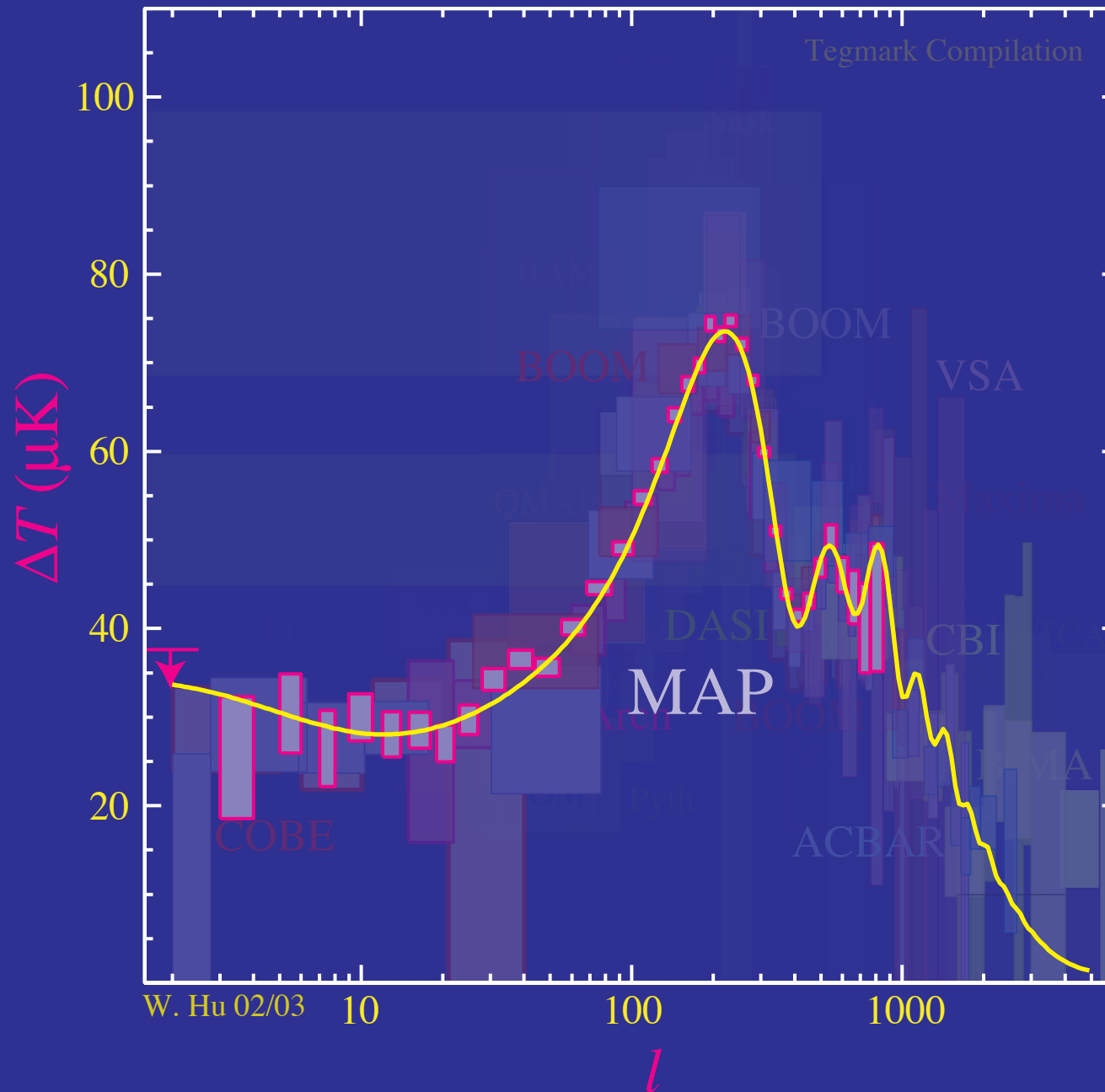
# Harmonic Signature

- 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  **$\sim 4\%$**

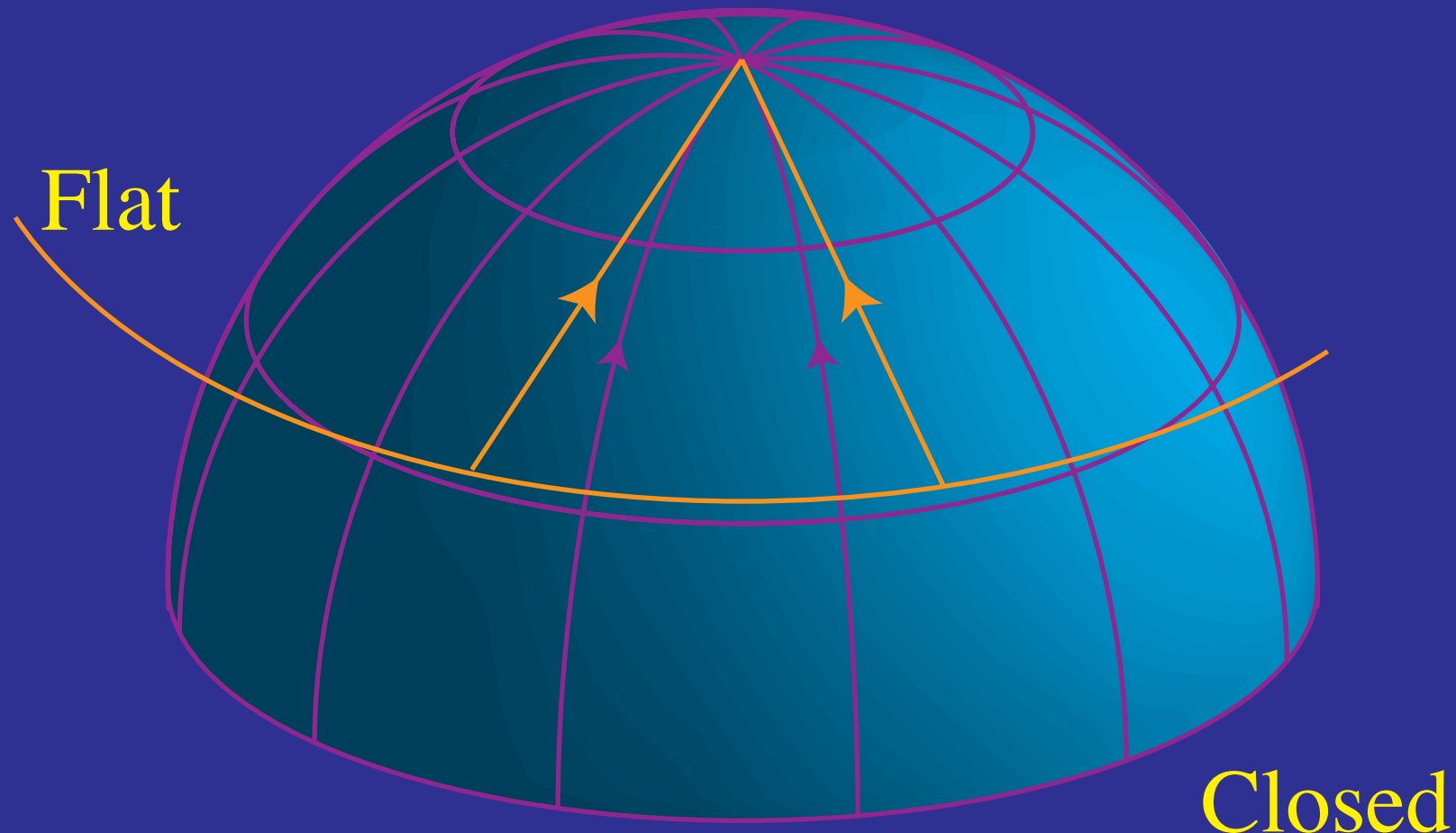
# Observed Power Spectrum



# Harmonic Composition

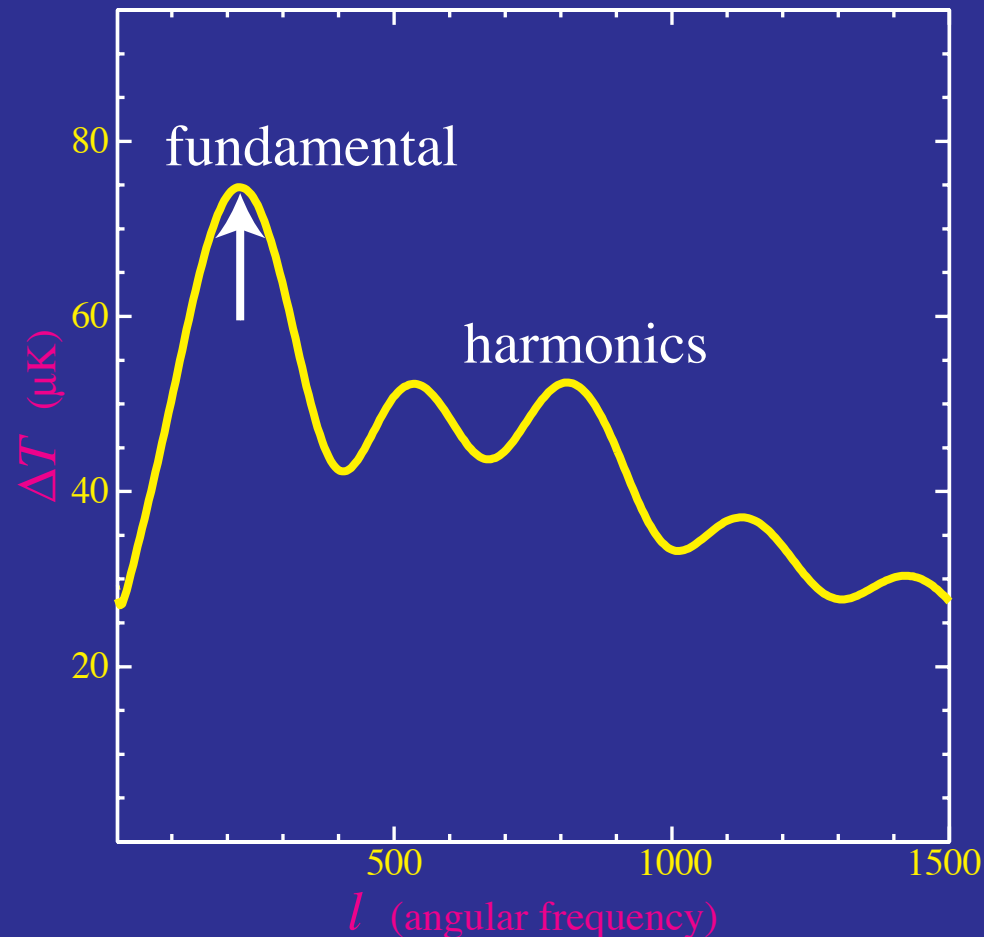
# Fundamental: Weighing the Universe

- 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

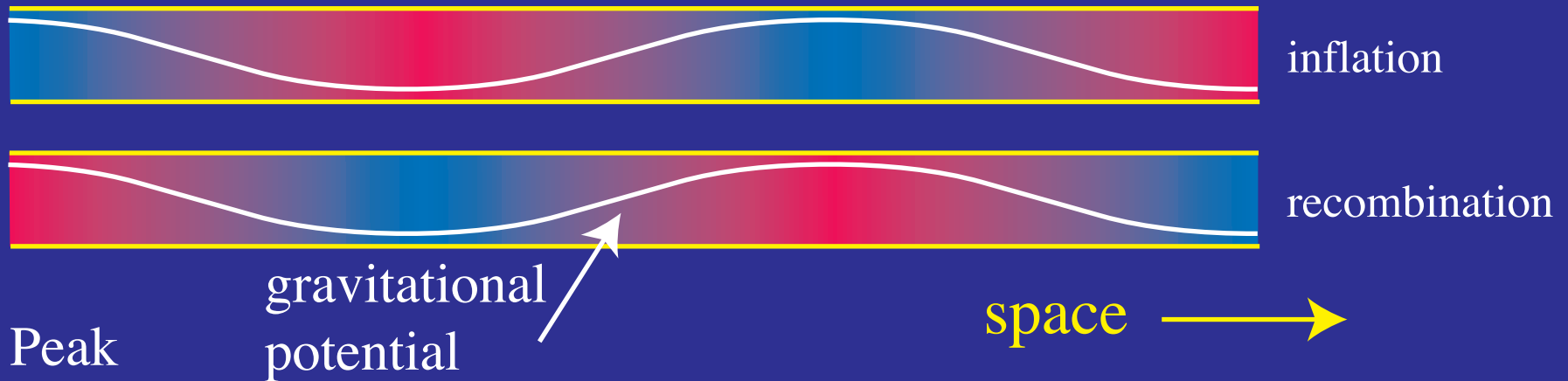




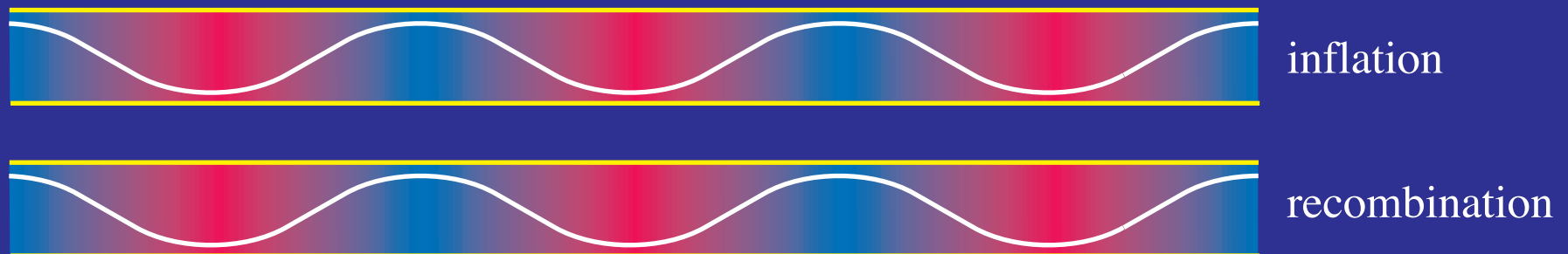
# Harmonics: Ordinary Matter

- 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

Fundamental

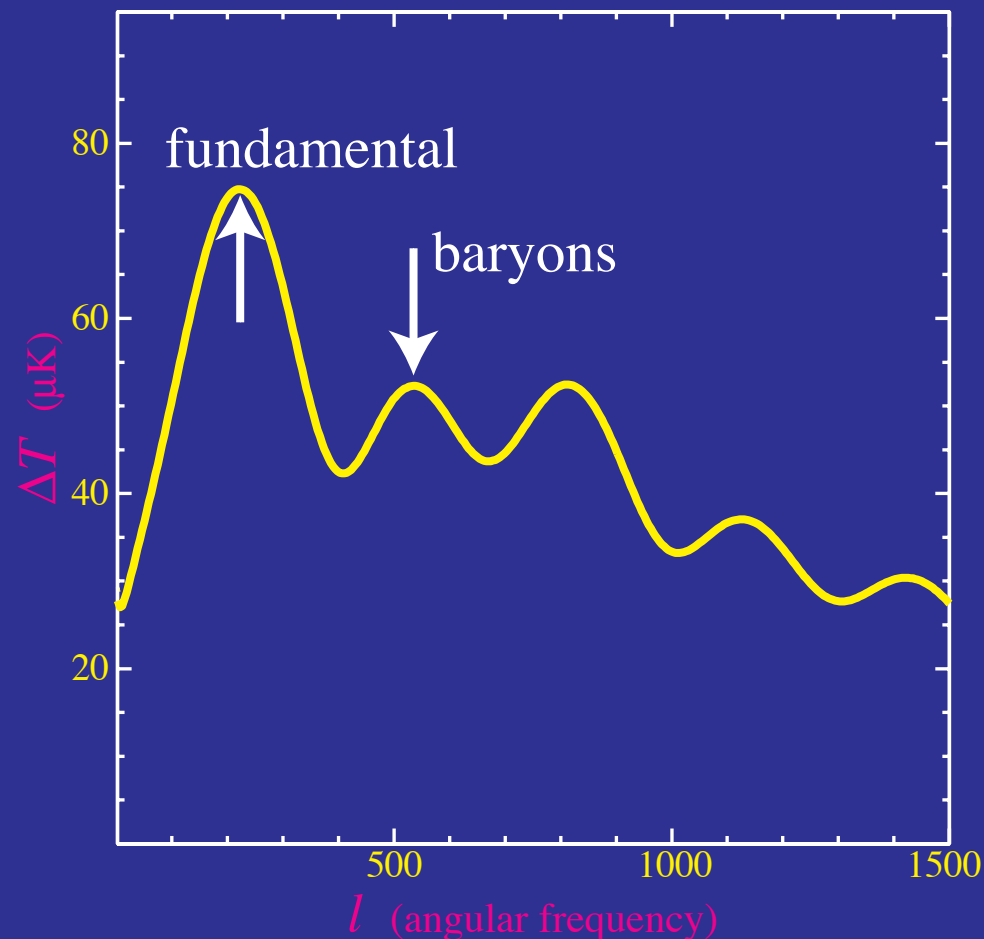


2nd Peak



# Ordinary Matter

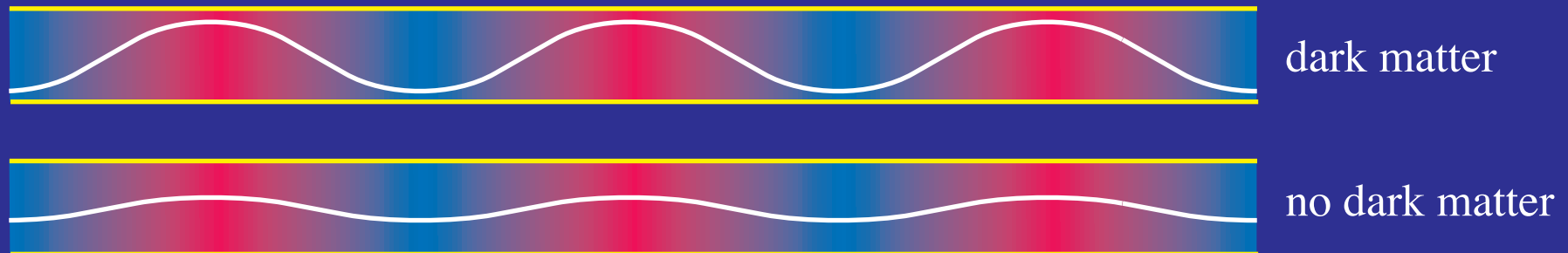
- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of  $\sim 5\%$  of the critical density today



# Harmonics: Dark Matter

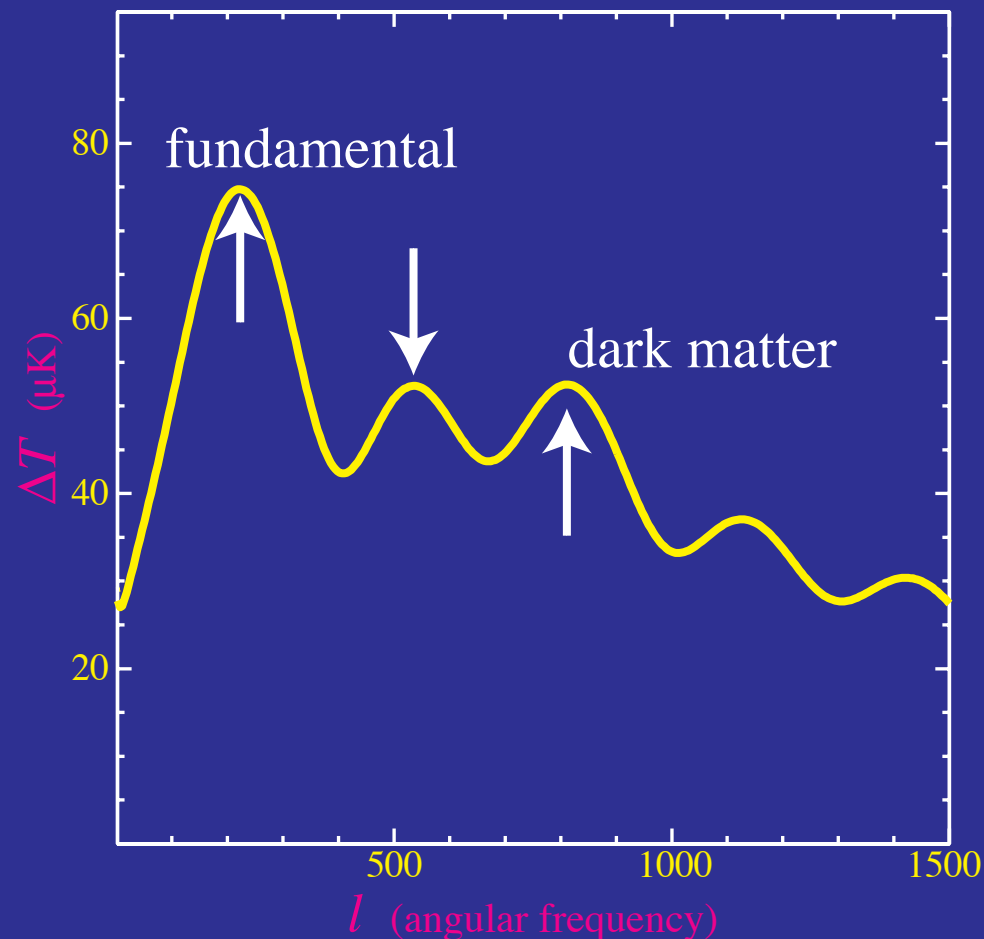
- What **maintains** the **gravitational potential** if the **ordinary matter** oscillates as a **stable** sound wave?
- Without matter that **does not interact** with photons/light or **dark matter**, gravitational **potentials decay** once ordinary matter enters into oscillation
- Gravitational **enhancement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

Recombination



# Dark Matter

- A third peak comparable to second peak indicates a dark matter density  $\sim 5\times$  that of ordinary matter
- Dark matter  $\sim 25\%$  of the critical density



# Missing Energy

- Ordinary matter and dark matter comprise  $\sim 30\%$  of the total density as measured by the first peak
- $\sim 70\%$  of the universe unaccounted for
- Must have negligible contribution at recombination 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

# Concord (and Discord?)

# Yeah, Right...

- An improbable conclusion? new forms of matter: inflaton, dark matter, dark energy
- Dark matter and dark energy densities must scale differently with the expansion and yet coincidentally have comparable densities today
- More than just a fanciful story
- Concordance with previously known cosmological facts
- Predicts phenomena that have now been observed
- Predictions will be sharply tested by new observations

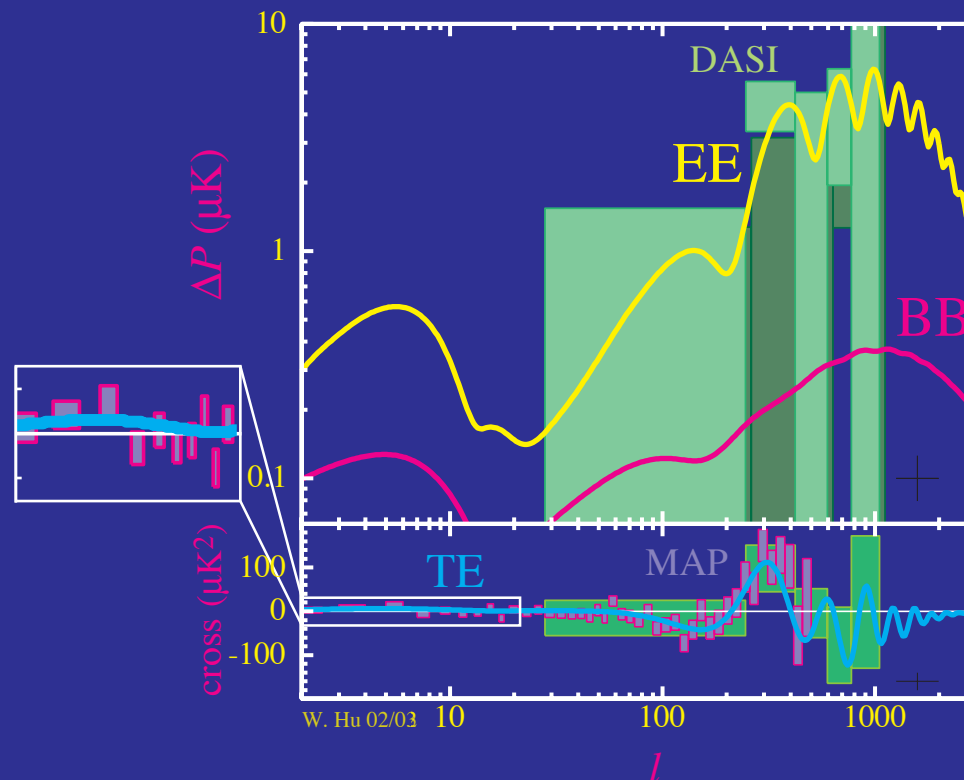
# CMB Chauvanist Anacronisms

- Dark matter originally introduced by Zwicky in 1930's to explain the mass density in clusters of galaxies
- Dark energy originally introduced by Einstein in 1917 to change the expansion rate; observational support from distant supernovae which show the universe is accelerating
- Inflation introduced to explain the lack of relics from the early universe
- Density of ordinary matter originally set to explain the observed abundance of light elements with big-bang nucleosynthesis
- CMB determinations beautifully consistent with these disparate observations
- Simplicity of the acoustic physics allows for the cleanest, most precise probes of these phenomena to date



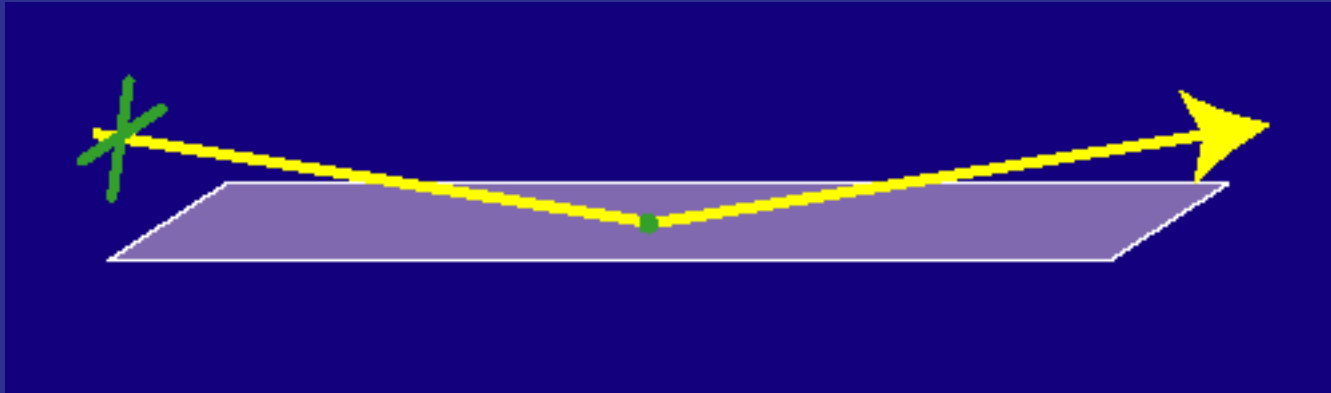
# Predictive Power

- Model **predicts** the precise form of the **damping** of sound waves: **observed**
- Model **predicts** that associated with the damping, the CMB becomes **polarized**: **observed**
- Model **predicts** that temperature fluctuations **correlated** with local structure due to the **dark energy**: **observed**



# Why Polarization?

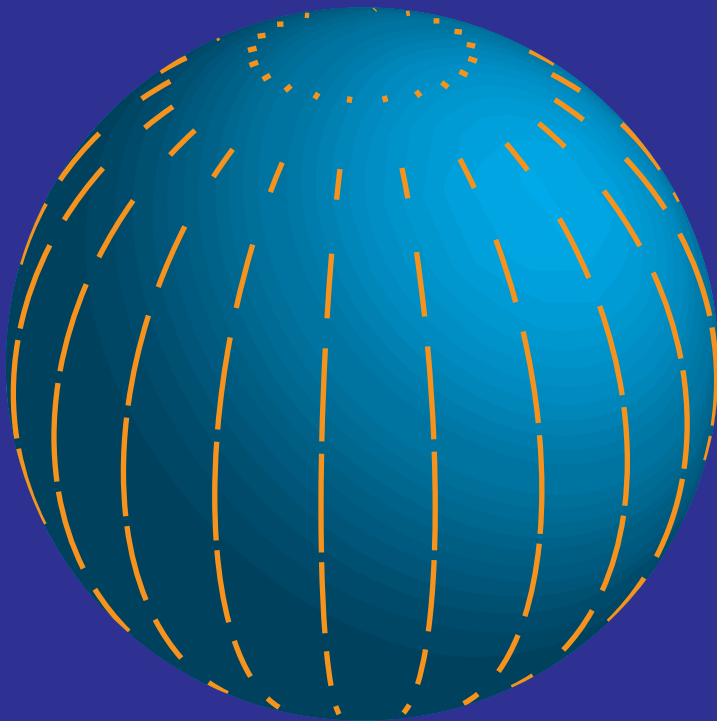
- Polarization arises from scattering of CMB photons just like reflection of sunlight off of a surface



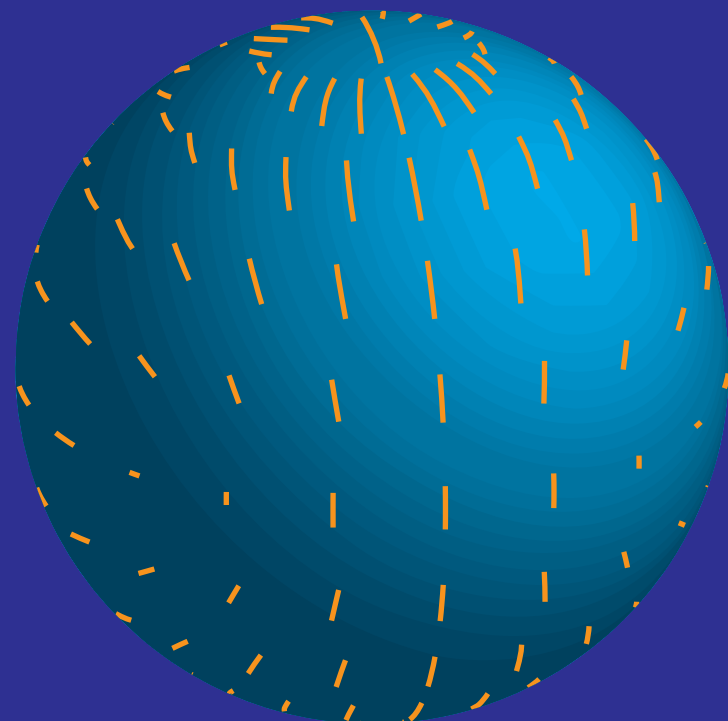
- Heuristically, photon electric field shakes the electron which emits light polarized in the direction of the shaking
- Polarization requires a preferred or special direction – absent if photon directions randomly changing because of rapid scattering
- Only on scales where the photons are streaming relatively unimpeded can a preferred direction arise and impart a polarization

# Polarization on the Sky

- Polarization retains directional information on temperature variations at recombination
- Distinguish between temperature variations from sound waves vs. gravitational waves (from anisotropic stretching of photon wavelengths)



sound wave



gravitational wave

# (Re)Scattering

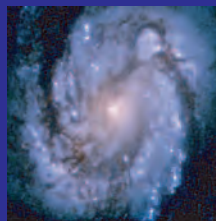
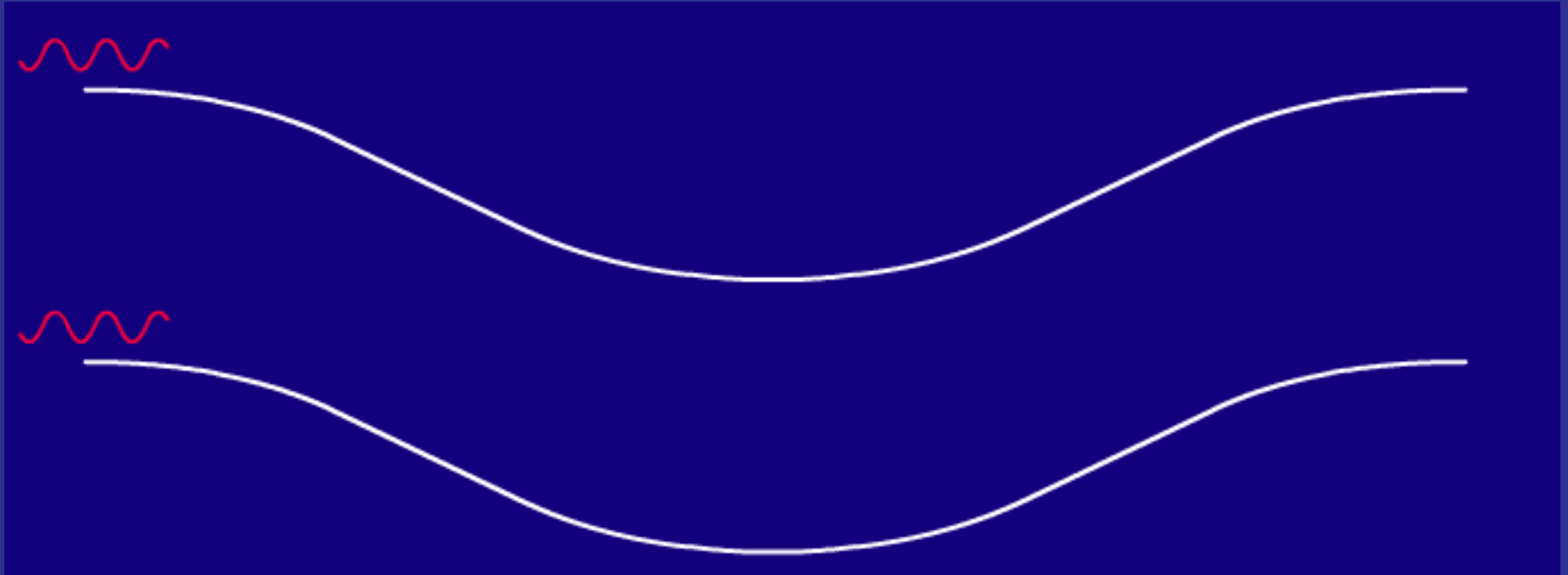
- Polarization requires a difference in the intensity of photons at 90 degree angles
- Rapid collisions randomize the directions of photons leading to no polarization
- Polarization only occurs on scales comparable to the distance between collisions
- During recombination this is the damping scale
- After recombination, this scale increases to the whole observable universe
- Large scale polarization of the CMB measures the amount of scattering after recombination
- WMAP Surprise: 20% of the photons have rescattered during a period of reionization

# Reionization and Inflationary Spectrum

- Reionization of the universe is a natural outcome of the gravitational instability model for structure formation
- Inflationary fluctuations on small scales collapse and eventually form the first stars; starlight then ionizes hydrogen
- Surprise is this event occurred relatively early: challenge for star formation models and may perhaps require larger fluctuations on small scales than simple inflationary models predict
- Conversely, hints of a deficit of power at intermediate scales (large scale structure) and the largest scales (CMB) increasing tension on theory
- Discord?

# Dark Energy & Gravitational Redshifts

- Accelerated expansion halts the growth of structure
- Gravitational potential decays - blueshift correlated with galaxies and the large scale structure of the universe



# Requiem? Not!

- CMB observations have helped establish a standard cosmological model based on
  - Inflationary Origin of Structure
  - Dark Matter
  - Dark Energywhich has predictive and explanatory power
- A phenomenological model that fails to answer deeper questions: what is the inflation, dark matter and dark energy
- Inflationary physics from spectrum of initial fluctuations and gravitational waves in the polarization of the CMB
- Dark matter and energy from using the CMB to backlight structure in the universe: scattering in clusters of galaxies and gravitational lensing

The Emperor of the South Sea was **Fast**, the Emperor of the North Sea **Furious**, the Emperor of the center was **Primordial Blob**. Fast and Furious were discussing how to repay Primordial Blob's bounty.

*All men have seven holes through which they look, listen, eat, breathe; he alone doesn't have any. Let's try boring them.*

Every day they bored one hole, and on the seventh day Primordial Blob died.

– Chuang-tzu (c. 350 BC)



Lecture based on **Scientific American** article in collaboration with **Martin White** (UC Berkeley) to appear 2004

Animations require the free **Acrobat 6** (or higher) and a computer with **multimedia capabilities**; best viewed on a Macintosh