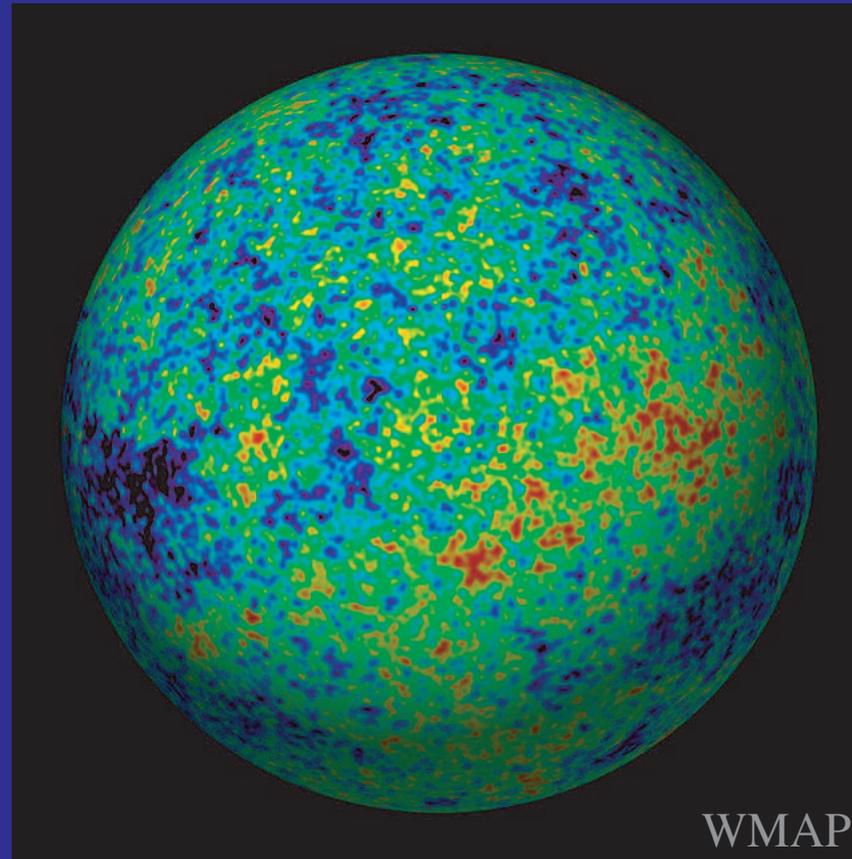


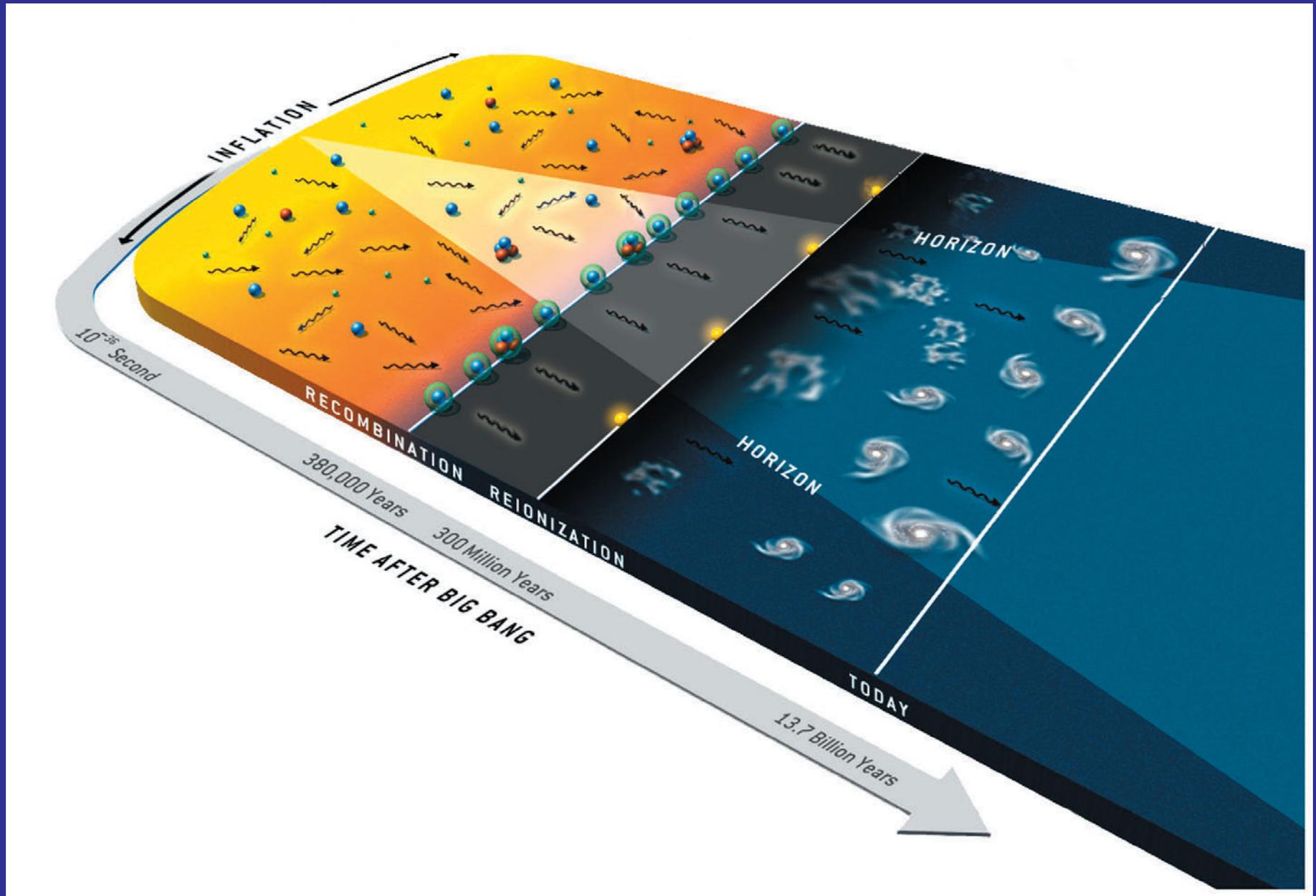
# CMB Movement I: Cosmic Tonality



Big Bang and Beyond  
Planetarium Short Course

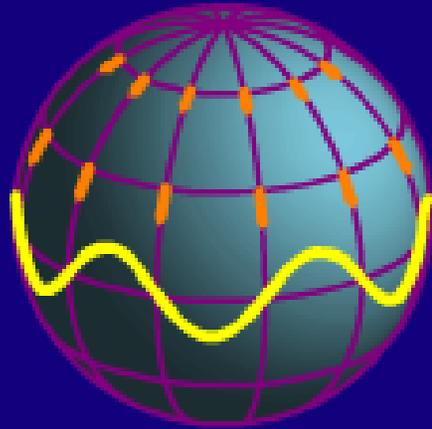
*Wayne Hu*  
KICP, September 2005

# In the Beginning... Dividing Light from Darkness

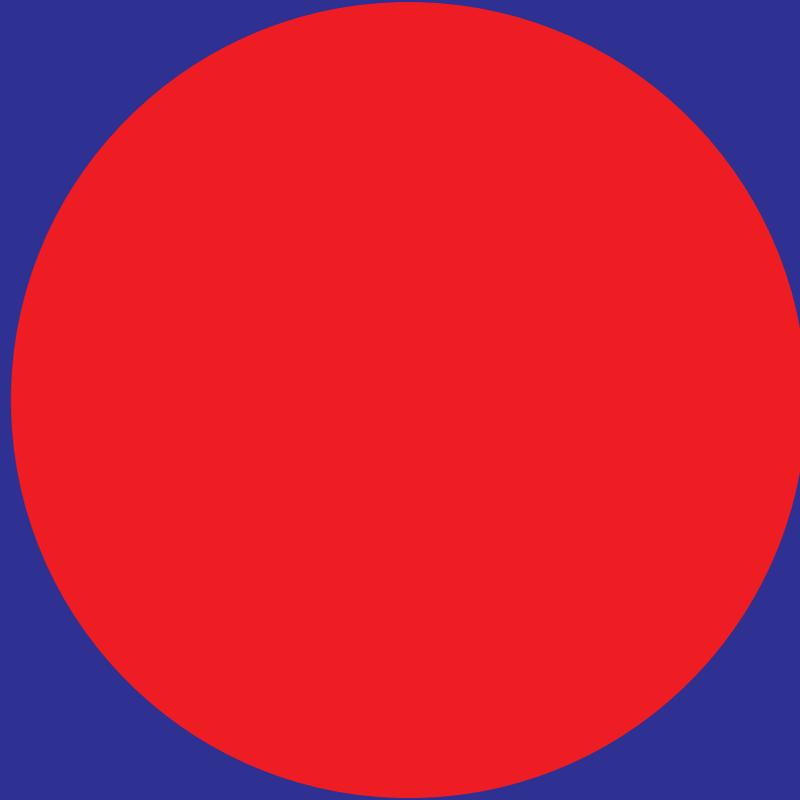


Hu & White (2004); artist: B. Christie/SciAm; available at <http://background.uchicago.edu>

# Fade to ~~Black~~ Microwave



# The Microwave Sky

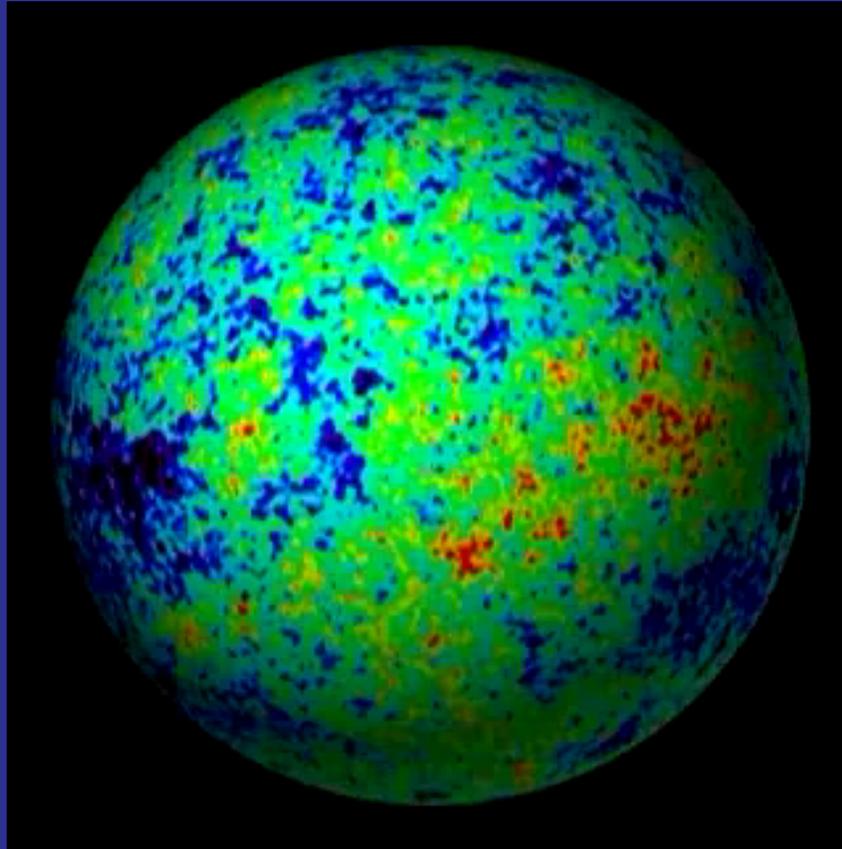


Uniform Emission



Penzias & Wilson 1965

# The Microwave Sky

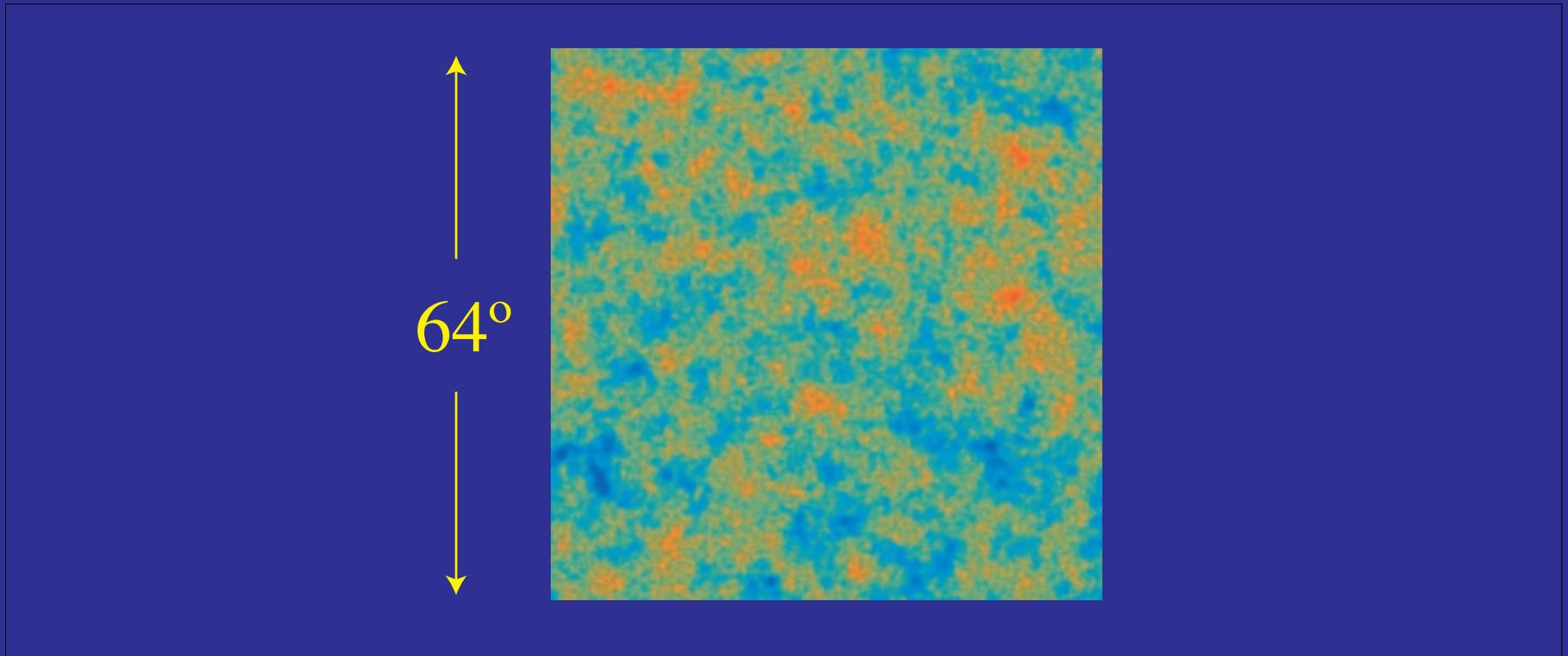


Nigel: but it goes up to 11  
no make that 100,000

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

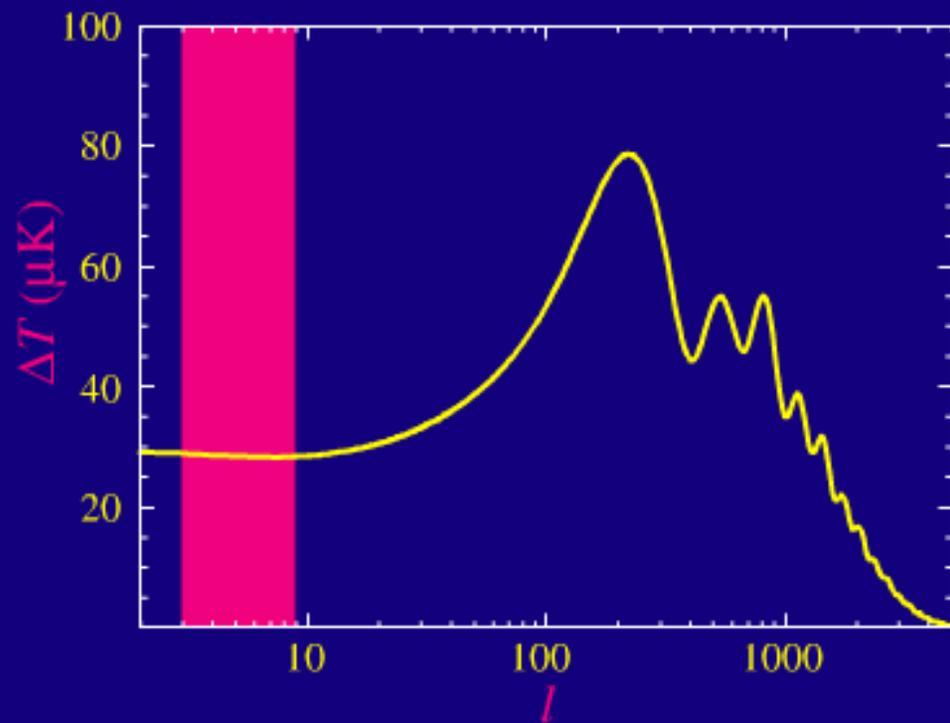
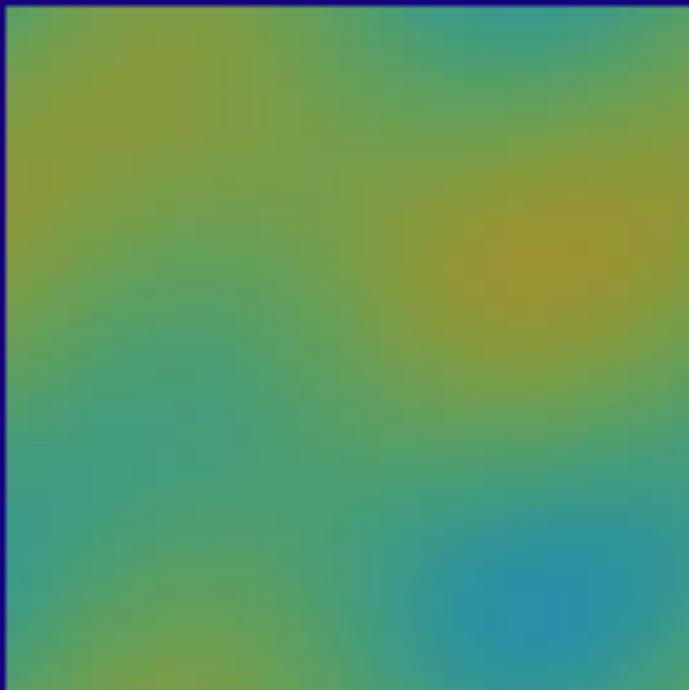
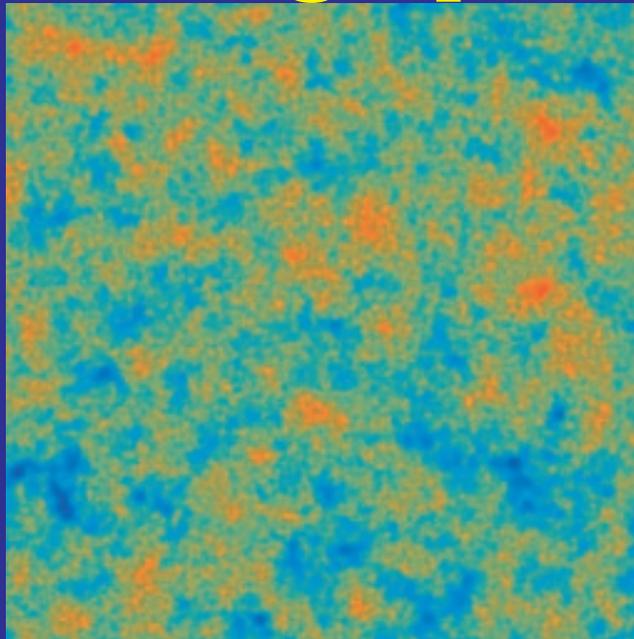
# Seeing Spots

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

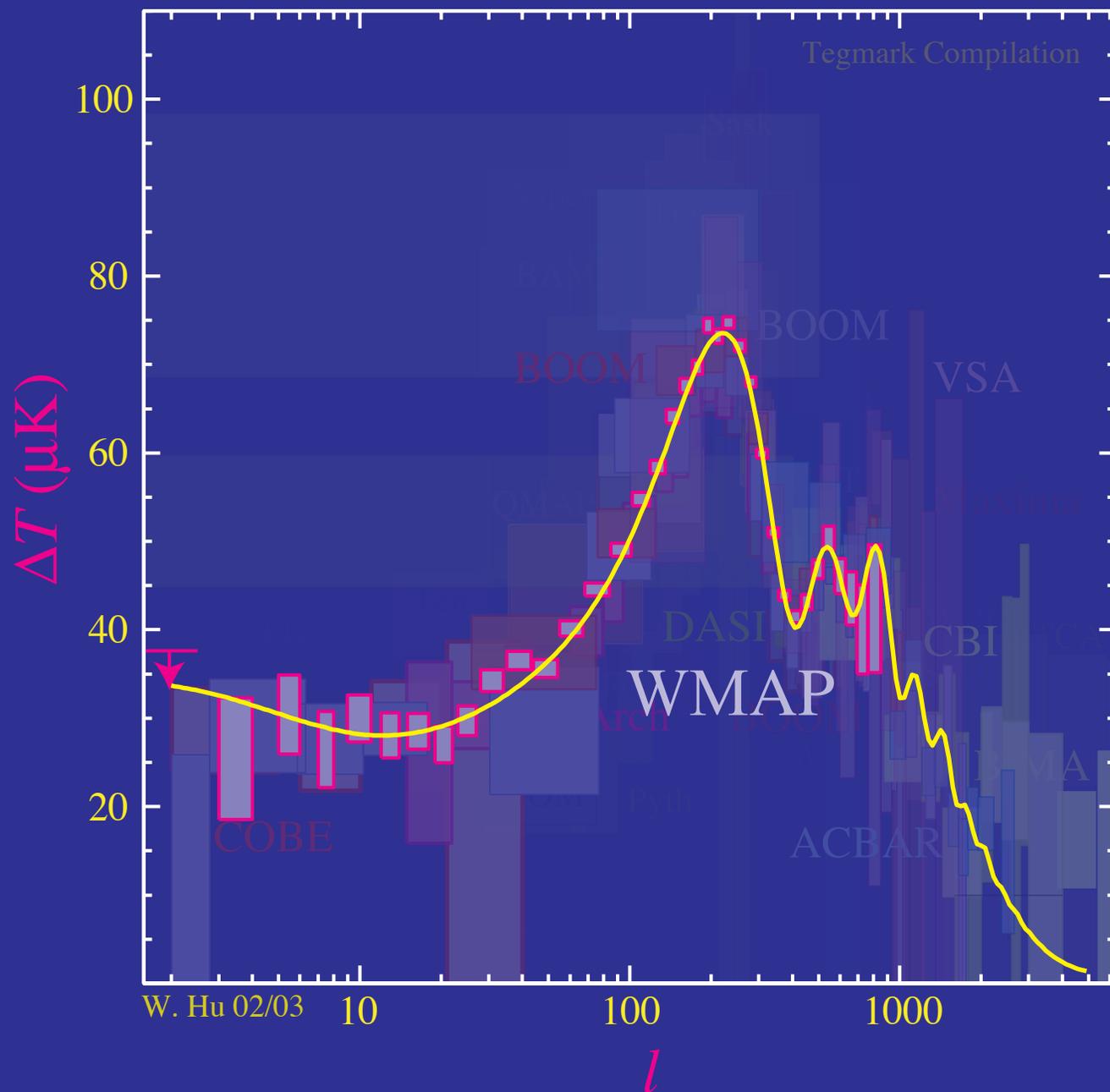


- Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

# 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

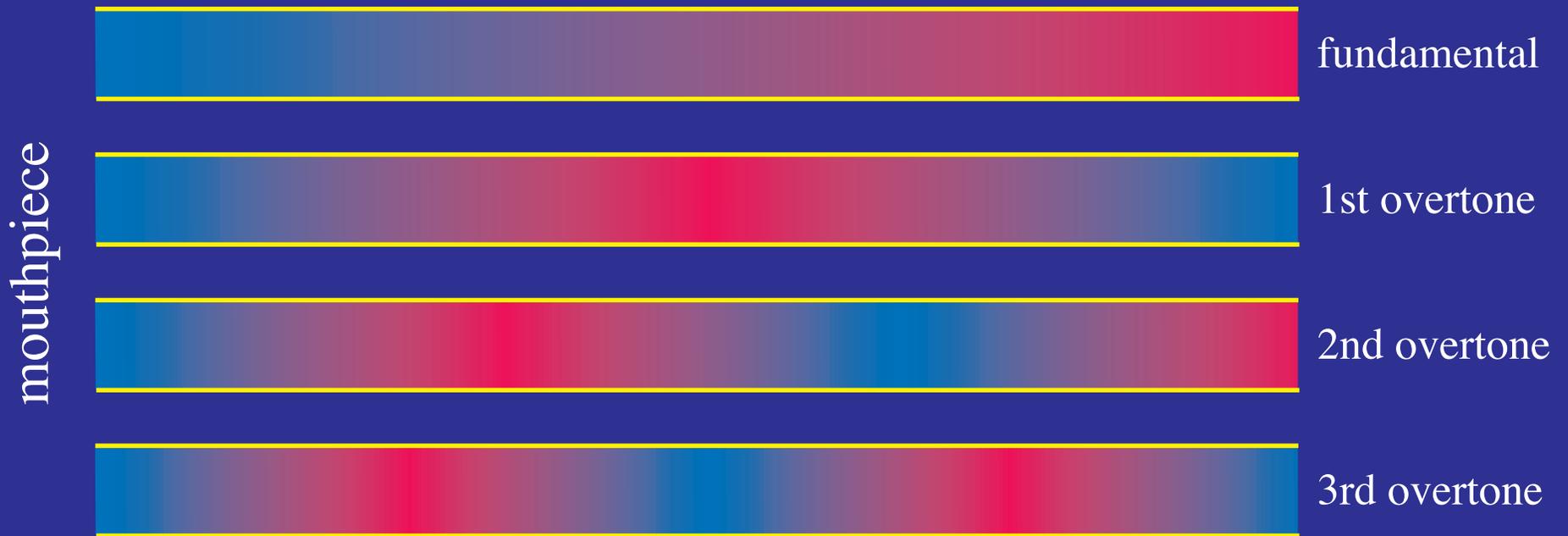
- Colliding **electrons**, **protons** and **photons** forms a **plasma**
- Acts as **gas** just like molecules in the **air**
- **Compressional disturbance** propagates in the gas through **particle collisions**
- In the air we experience this as **sound** hitting the **eardrum**



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

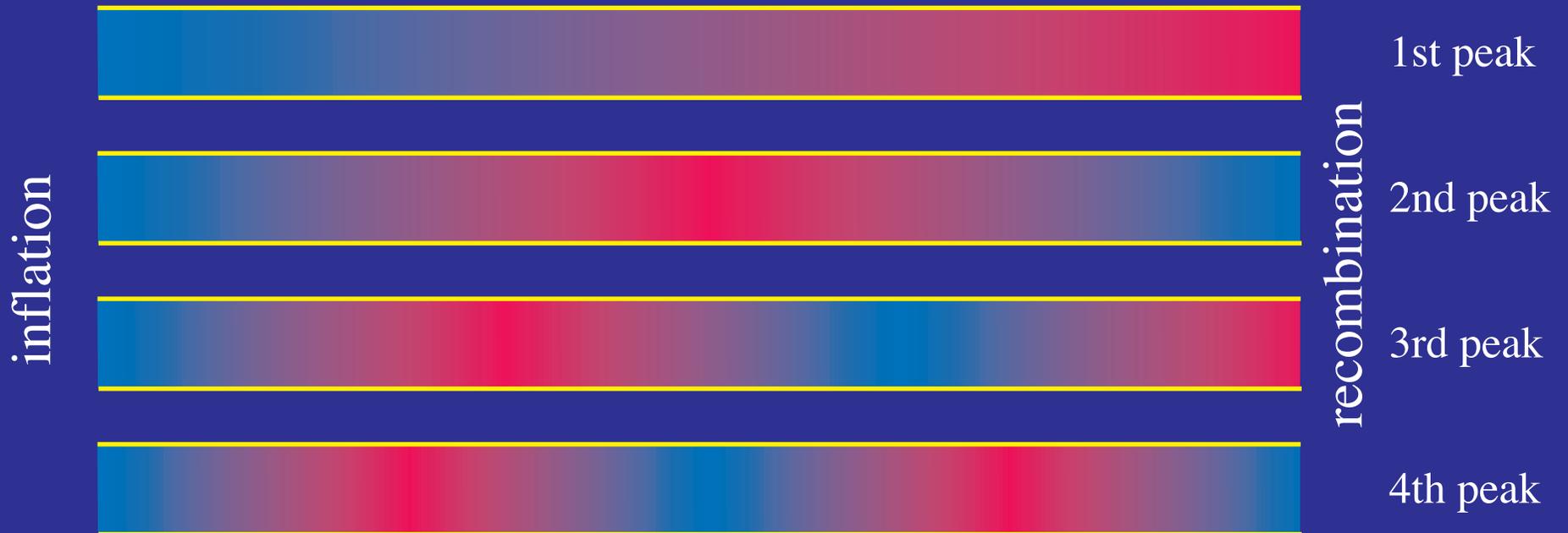
# Piper at the Gates of Dawn

- 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**

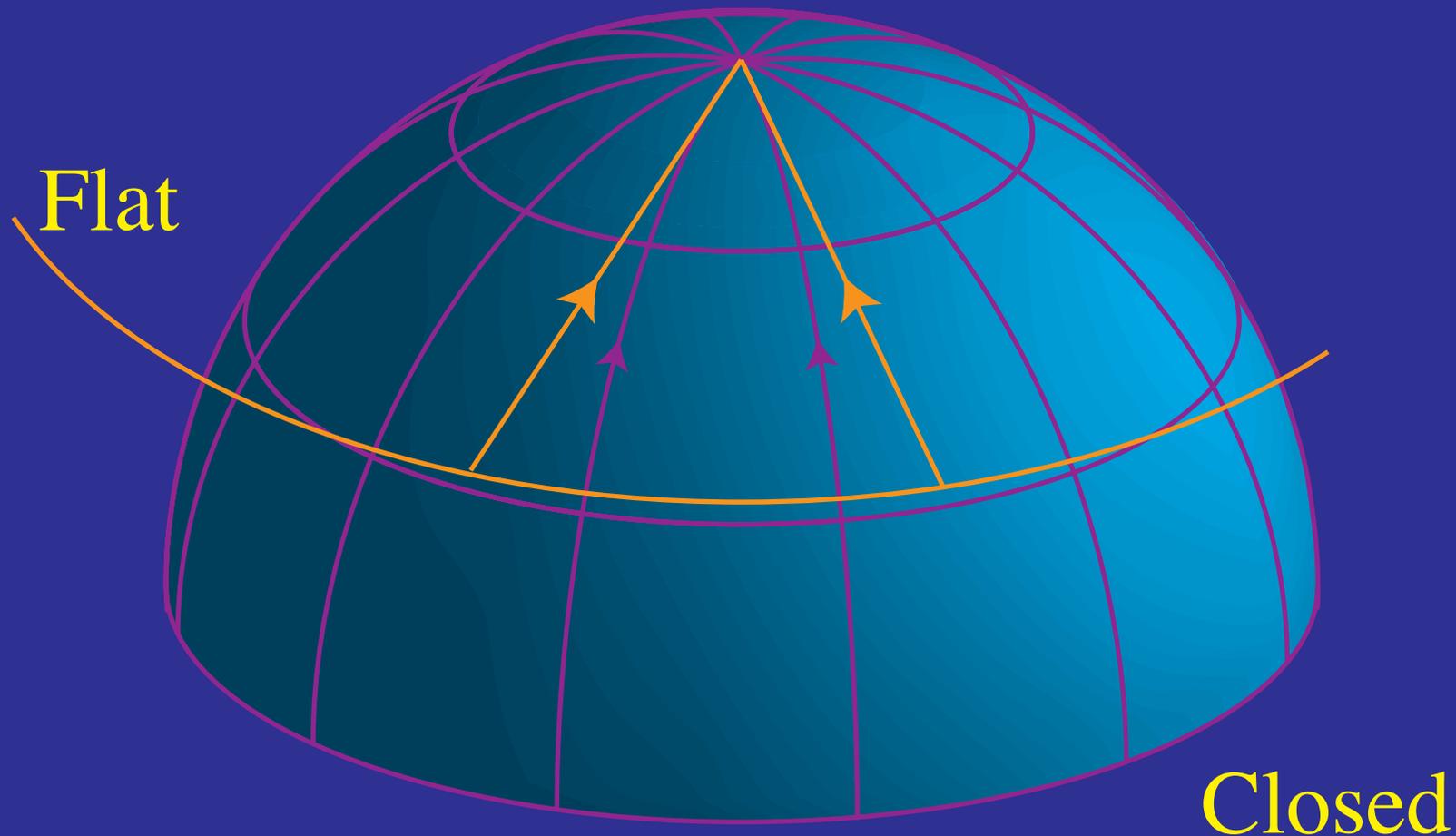
(stay tuned for Scott Dodelson's **talk**)

- Detailed examination of the **overtones**, reveals the **composition** of the universe

# Harmonic Composition

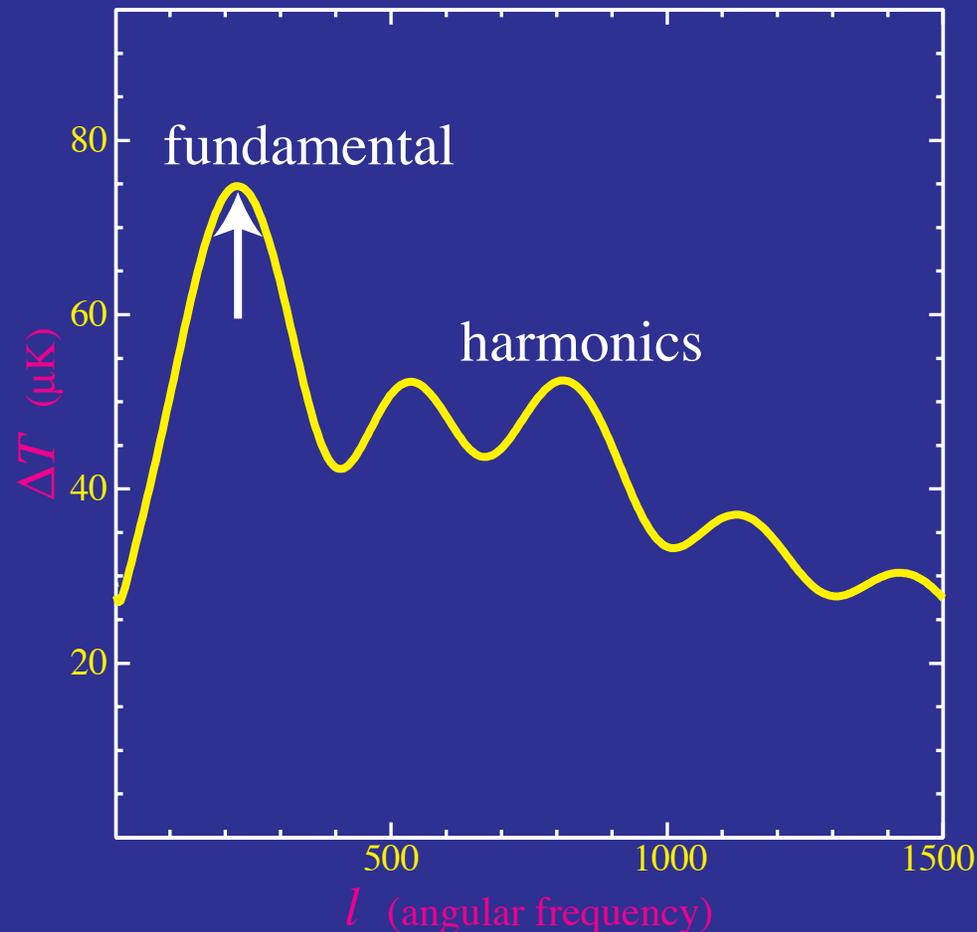
# Fundamental: Weighing the Universe

- 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

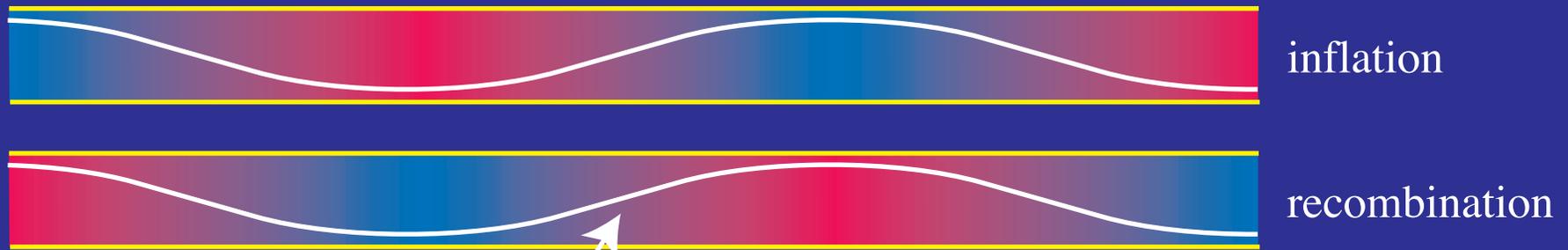
- Spectrum of sound shows harmonics at integer ratios of the fundamental
- Other models that generate structure causally at intermediate times would not have these harmonics



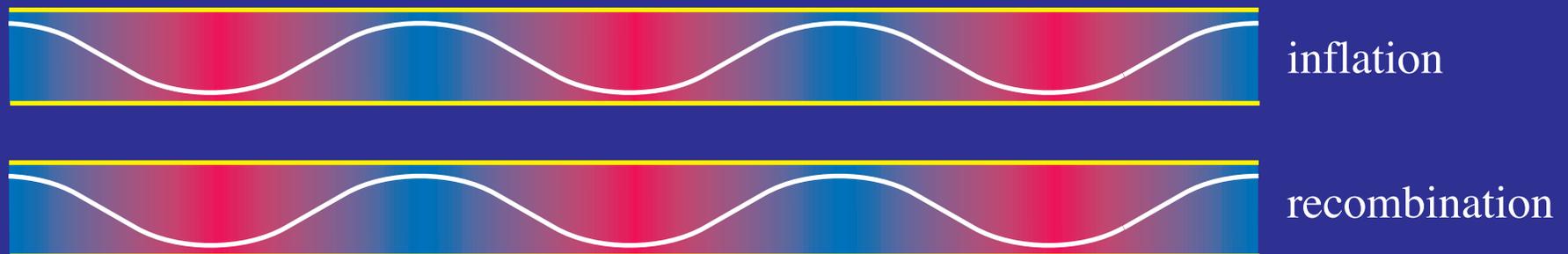
# Harmonics: Ordinary Matter

- 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

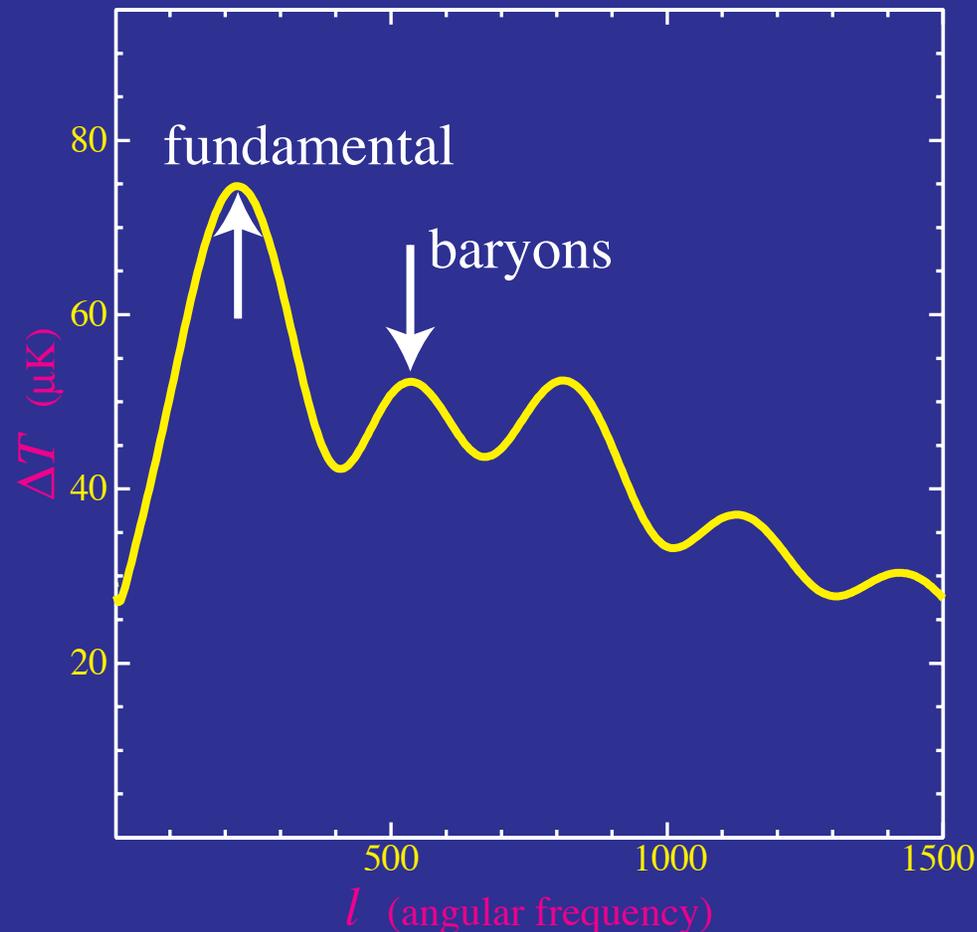


2nd Peak



# Ordinary Matter

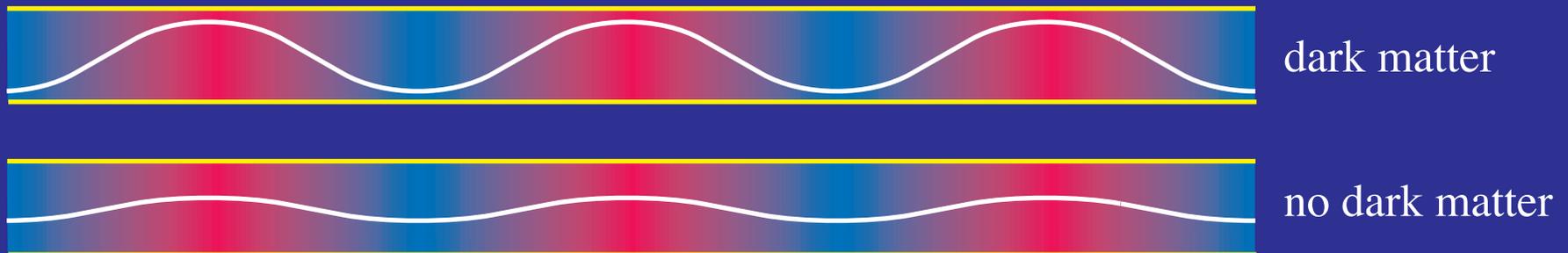
- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of  $\sim 5\%$  of the critical density today



# Harmonics: Dark Matter

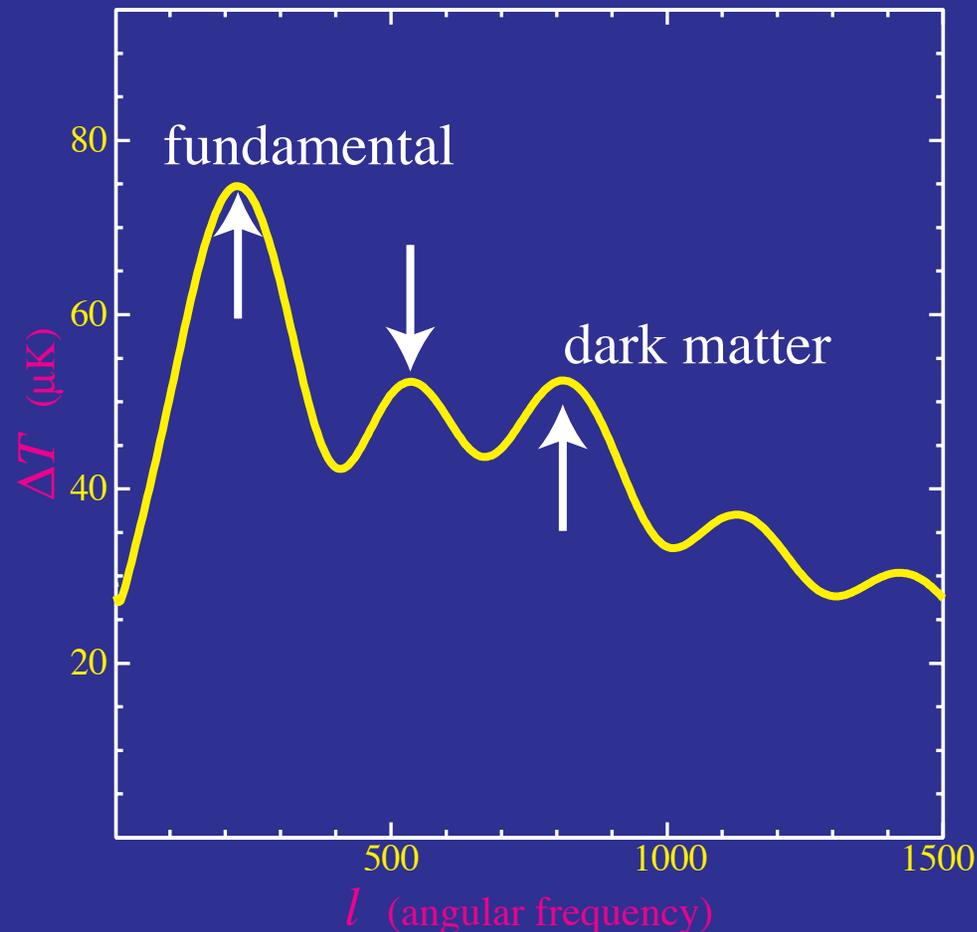
- What **maintains** the **gravitational potential** if the **ordinary matter** oscillates as a **stable** sound wave?
- Without matter that **does not interact** with photons/light or **dark matter**, gravitational **potentials decay** once ordinary matter enters into oscillation
- Gravitational **enhancement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

Recombination



# Dark Matter

- A third peak comparable to second peak indicates a dark matter density  $\sim 5x$  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 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

(stay tuned for Sean Carroll's talk)

# Notes of Discord?

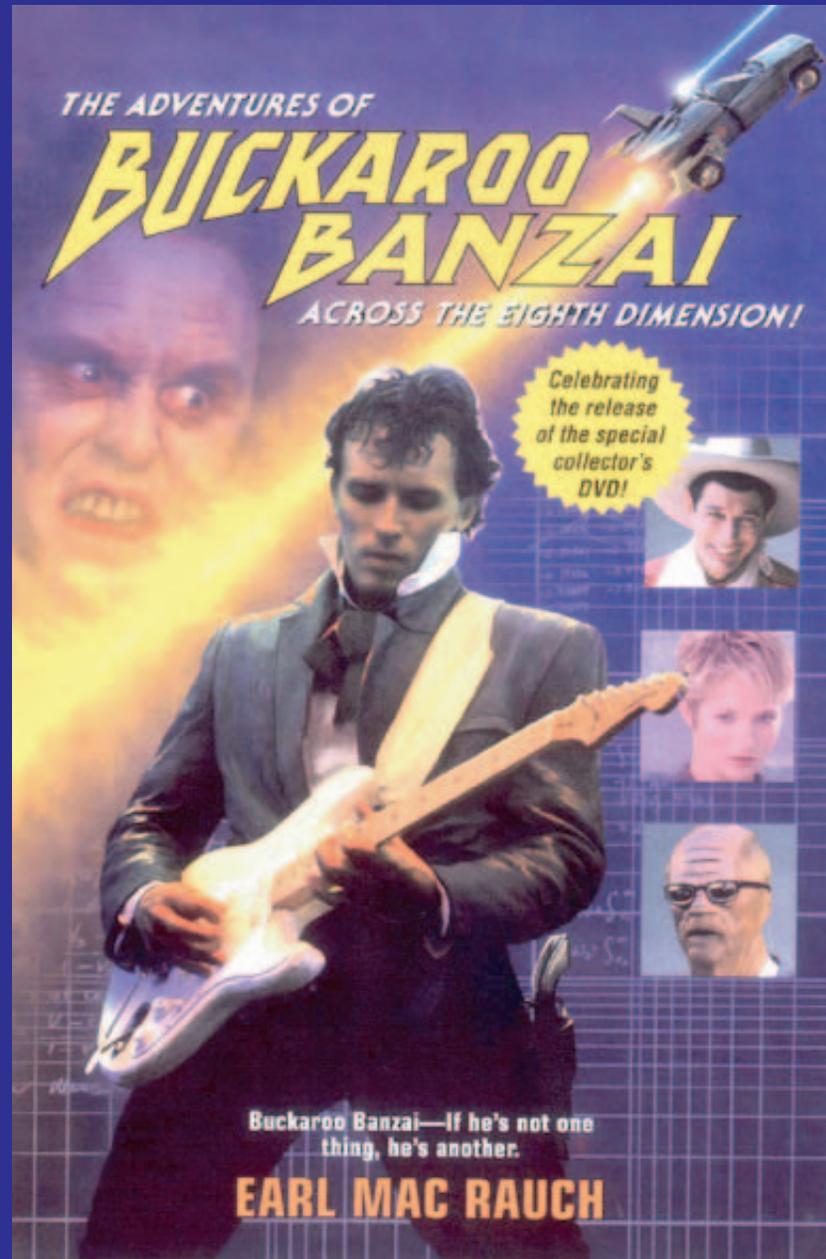
- **Polarization of CMB** in WMAP implies an early formation of stars - too early? [Stephan Meyer's talk]
- **Large angle** temperature fluctuations show curious  
    lack of power  
    alignment

Clues to **missing physics** associated with the early universe?  
dark energy? gravity? topology?

- Nevertheless: small scale **acoustic properties** of the CMB will remain robust determinations of **matter/energy content**: rests on well established **19th century physics...**

**which now gives way to...**

# Atonal Physics & Rock Star Physicists



*In my experience  
nothing is ever what  
it seems to be, but  
everything is exactly  
what it is.*

– Buckaroo Banzai