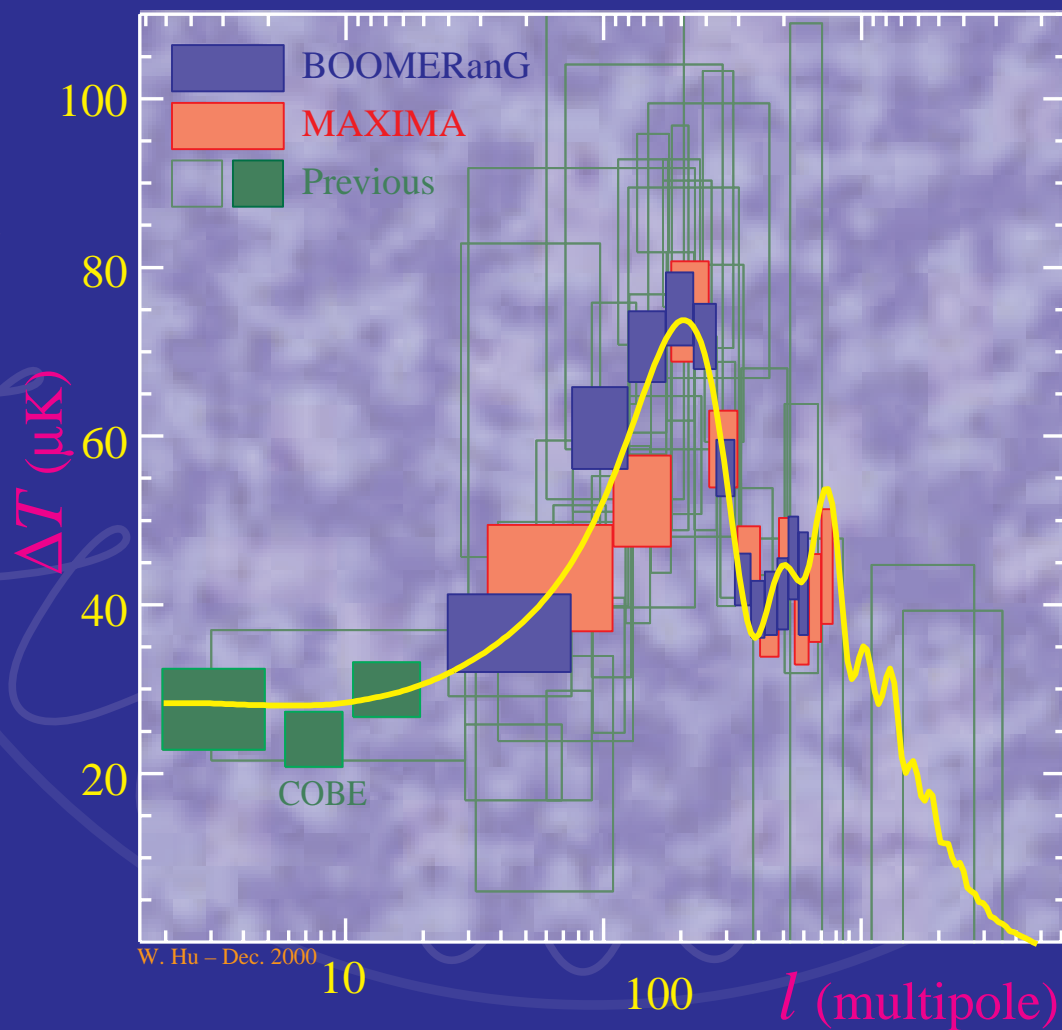


The Physics of CMB Anisotropies

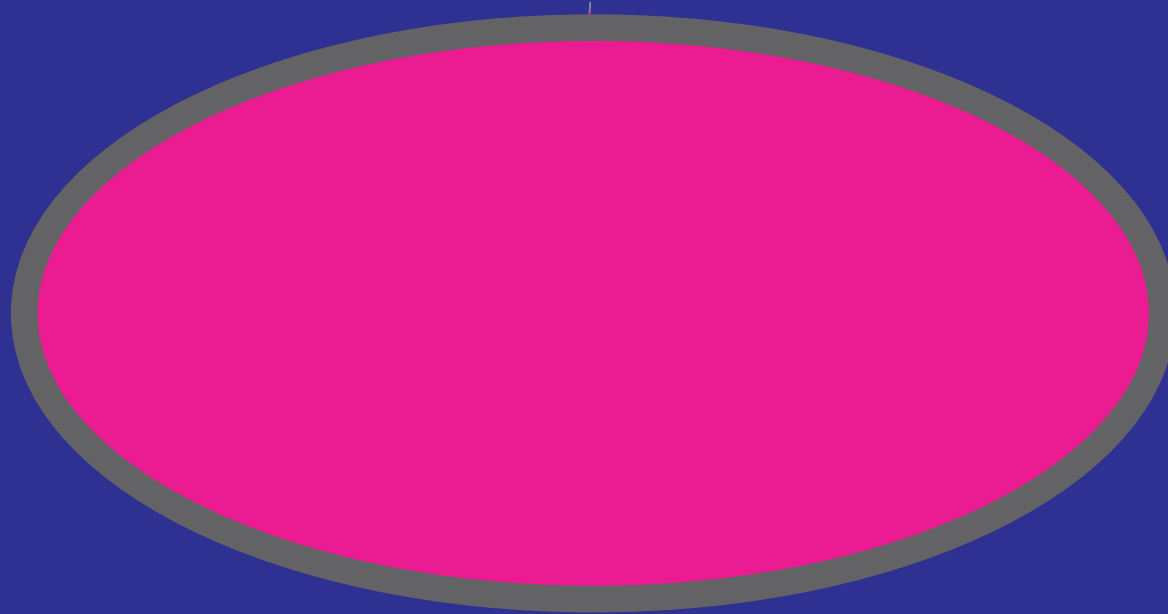


and their

Cosmological Implications

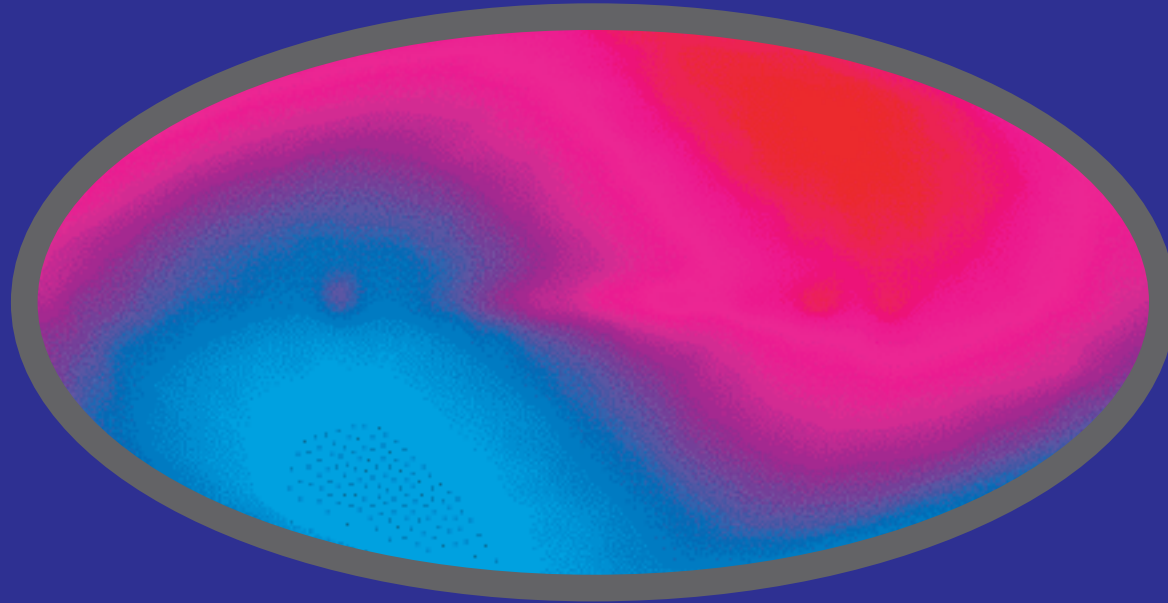
Wayne Hu

CMB Isotropy



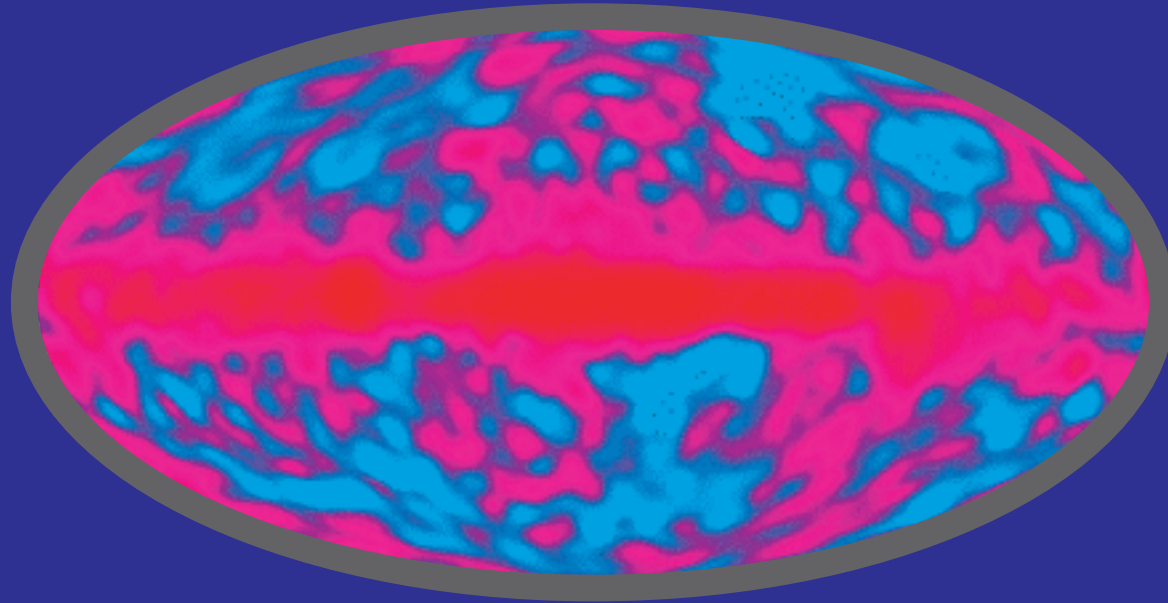
Actual Temperature Data

Dipole Anisotropy



our motion
1 part in 1000

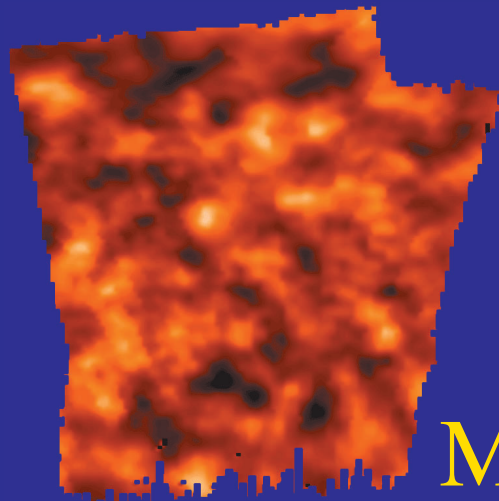
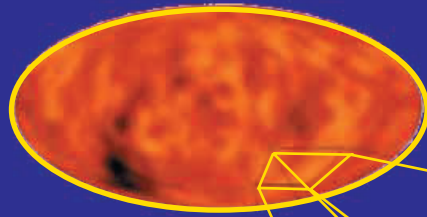
Large-Angle Anisotropies



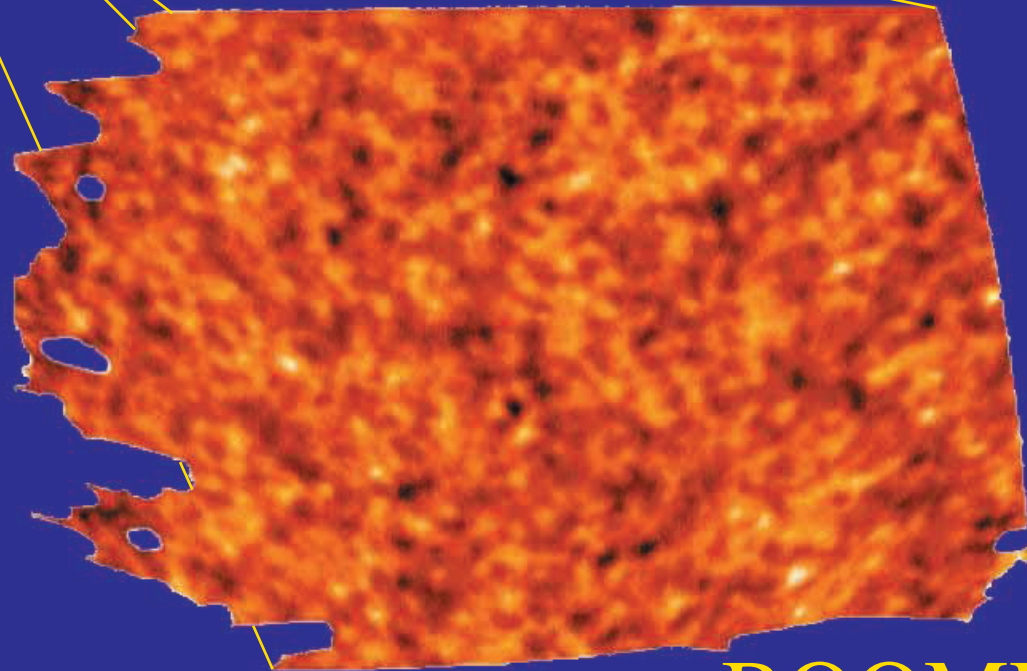
10° – 90° anisotropy
1 part in 100000

Precision Cosmology

COBE

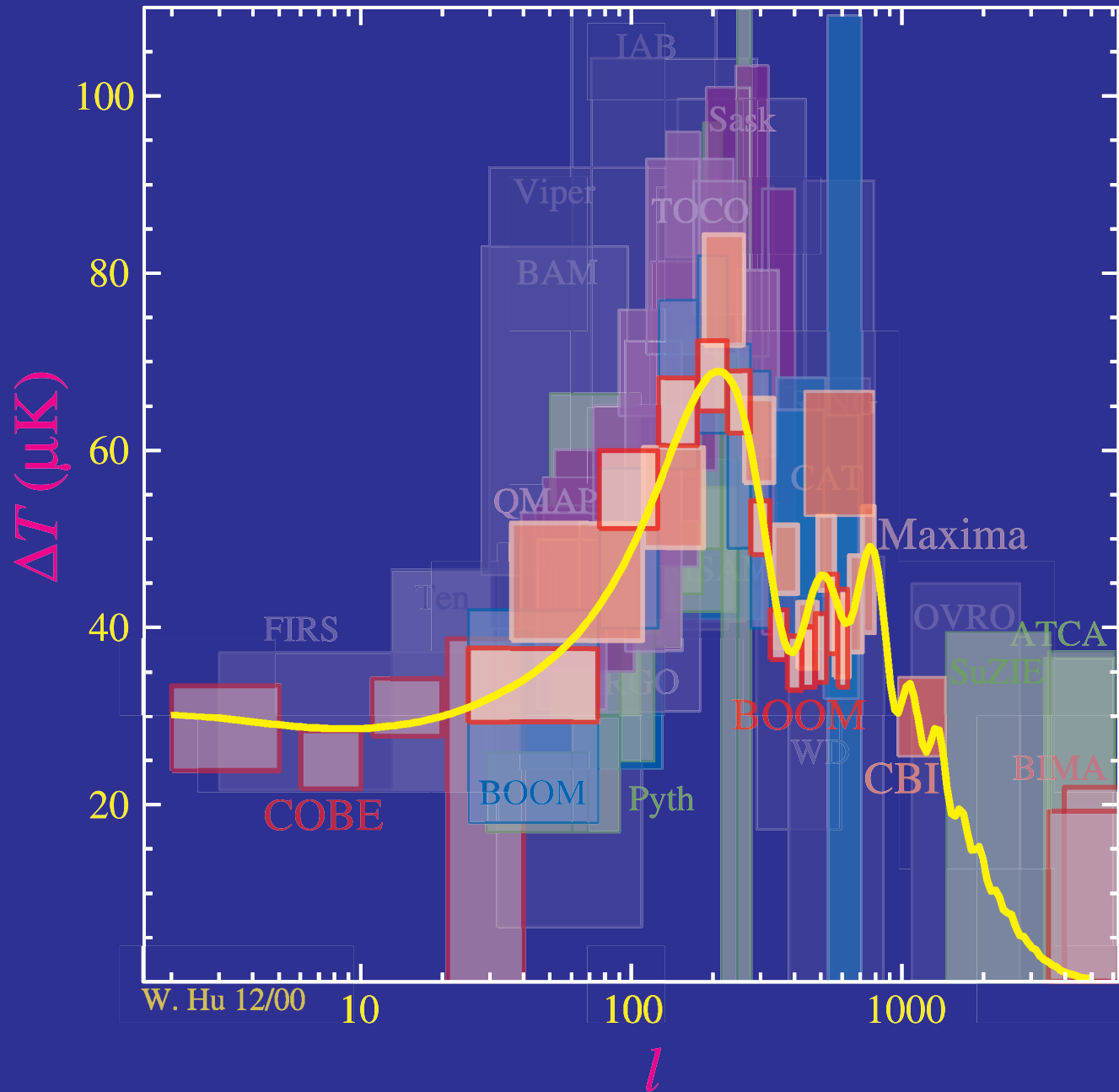


Maxima



BOOMERanG

Ringings in the New Cosmology



A diagram illustrating acoustic oscillations in a semi-circular cavity. The cavity is bounded by a curved bottom and two vertical walls. Two circular pistons are positioned at the top of the walls, connected to the walls by thin lines. A wavy line representing an acoustic wave is shown inside the cavity, oscillating between the two walls. The text "Acoustic Oscillations" is centered in the cavity in a yellow serif font.

Acoustic Oscillations

A Brief Thermal History

- CMB photons **hotter** at **high redshift** z
- At $z \sim 1000$, $T \sim 3000\text{K}$: photons **ionize hydrogen**

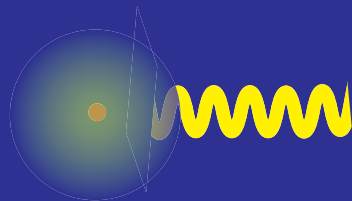
Microwaves



Cosmological
Redshift



Recombination
 $z \sim 1000$; $T \sim 3000\text{K}$

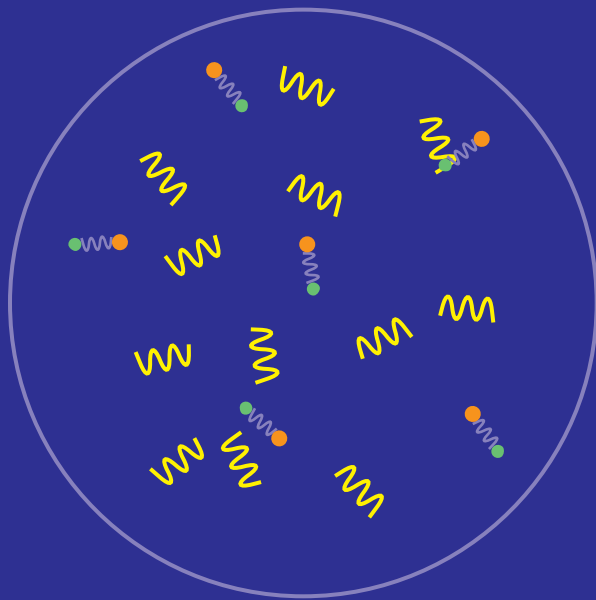


Photon-Baryon
Plasma



A Brief Thermal History

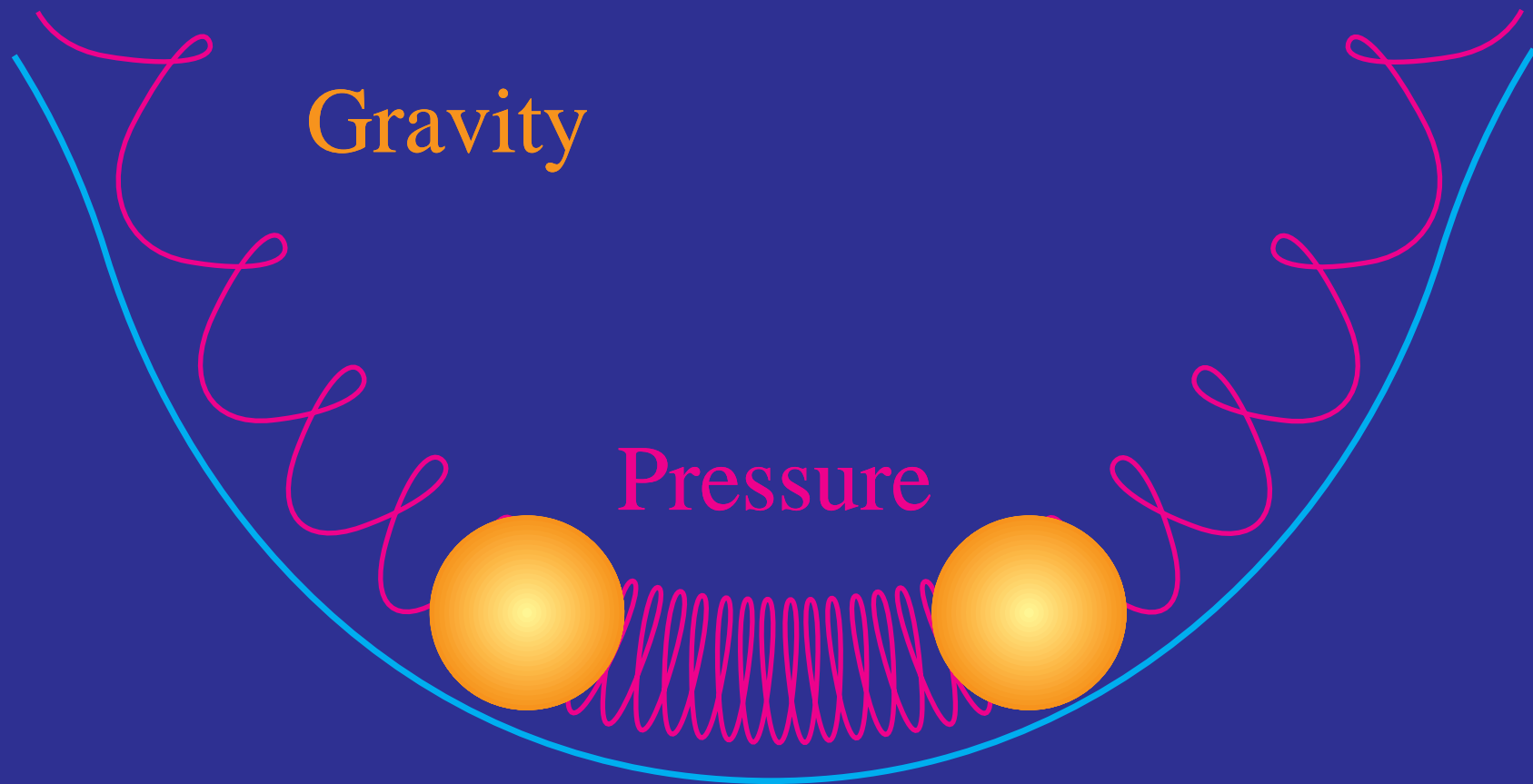
- At $z > 1000$, photon-baryon plasma: perfect fluid
- Photons provide pressure; baryons add inertia



Perfect Fluid

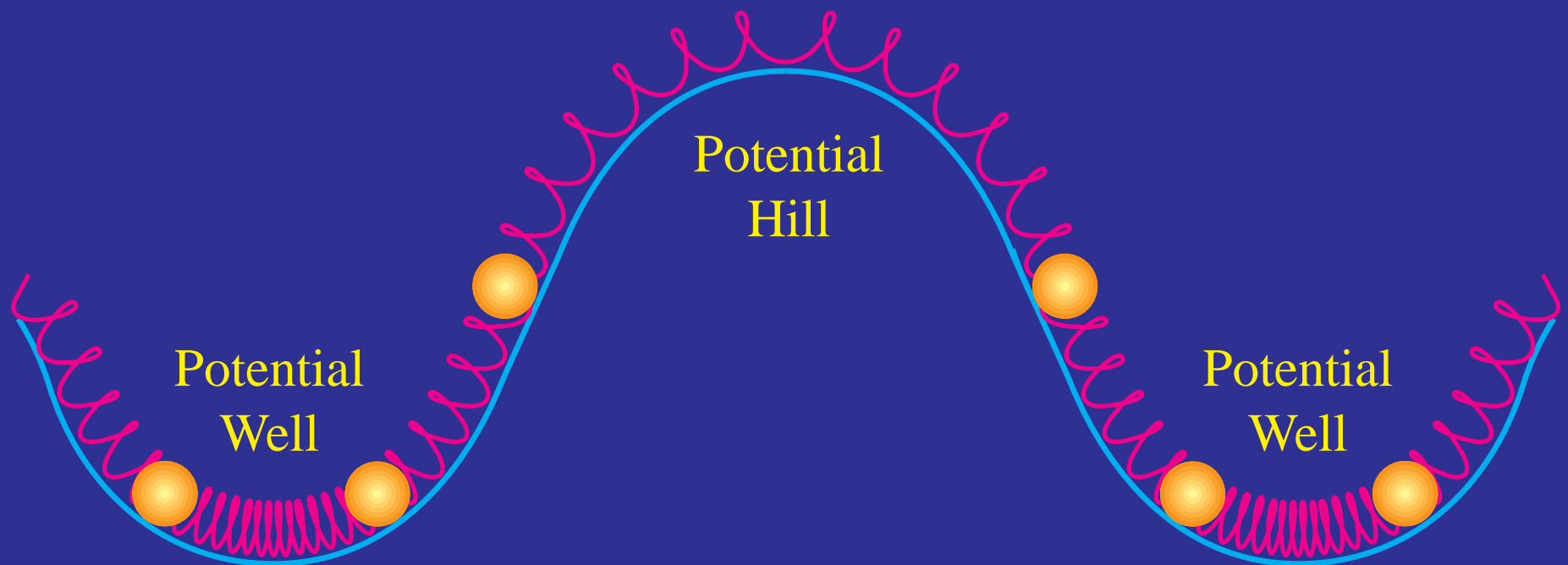
Gravitational Ringing

- Potential wells = inflationary seeds of structure
- Fluid falls into wells, pressure resists: acoustic oscillations



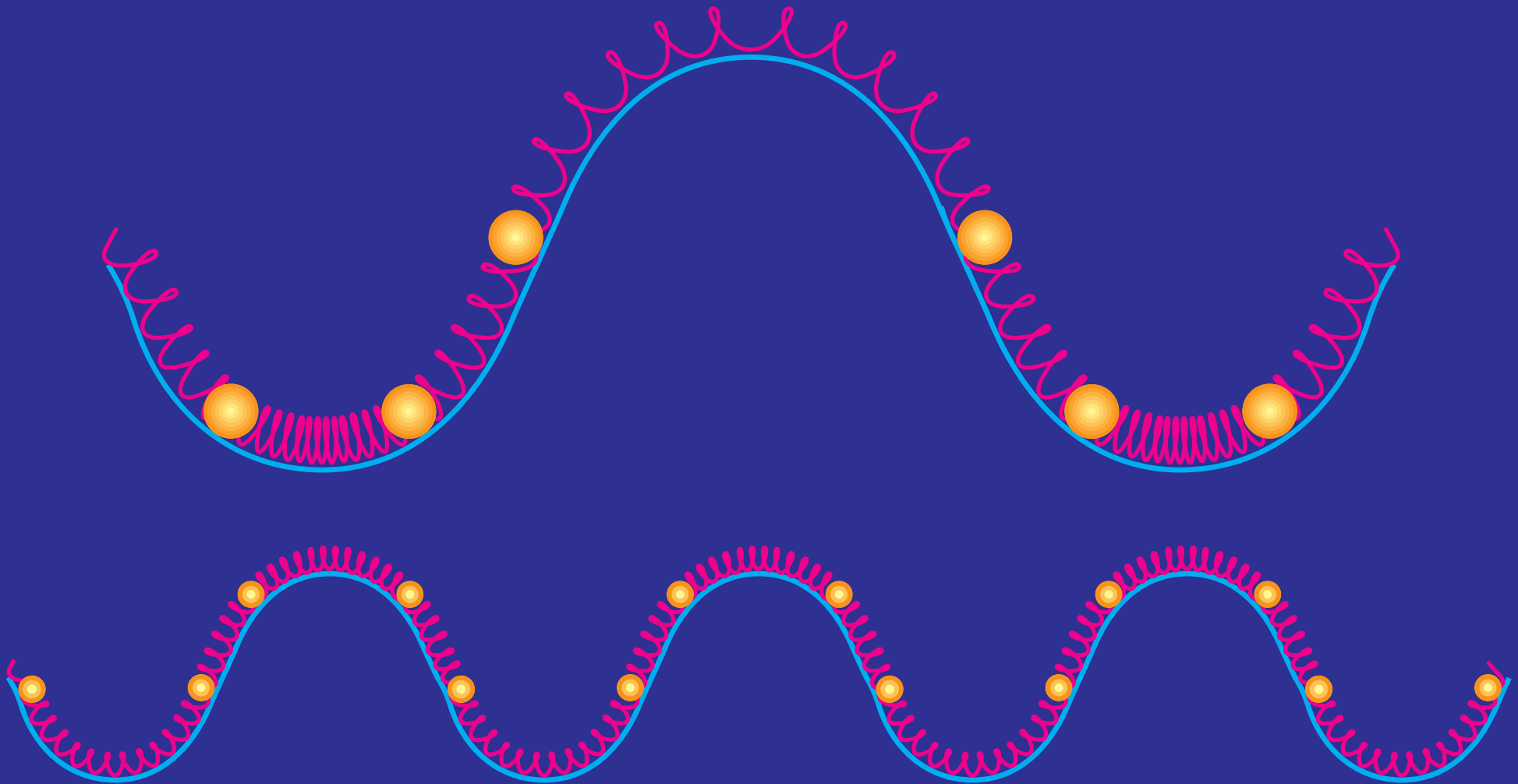
Plane Waves

- Potential wells: part of a fluctuation spectrum
- Plane wave decomposition



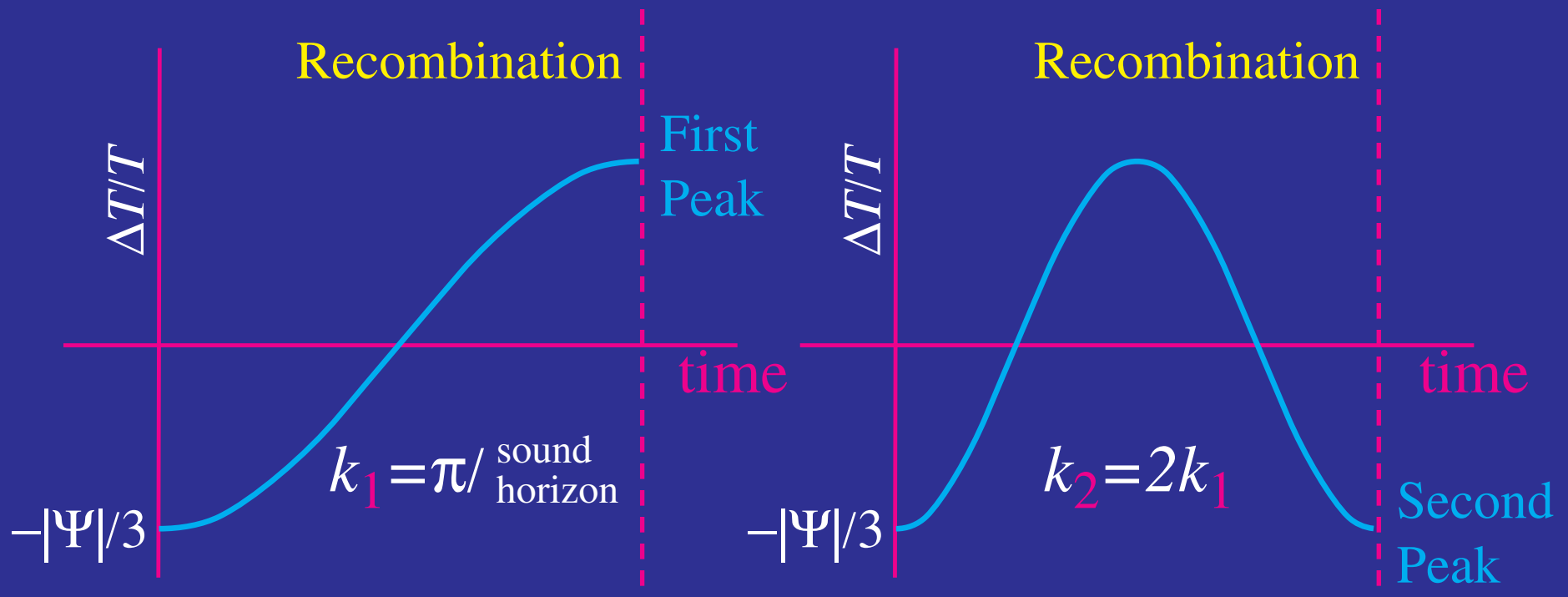
Harmonic Modes

- Frequency proportional to wavenumber: $\omega = kc_s$
- Twice the wavenumber = twice the frequency of oscillation



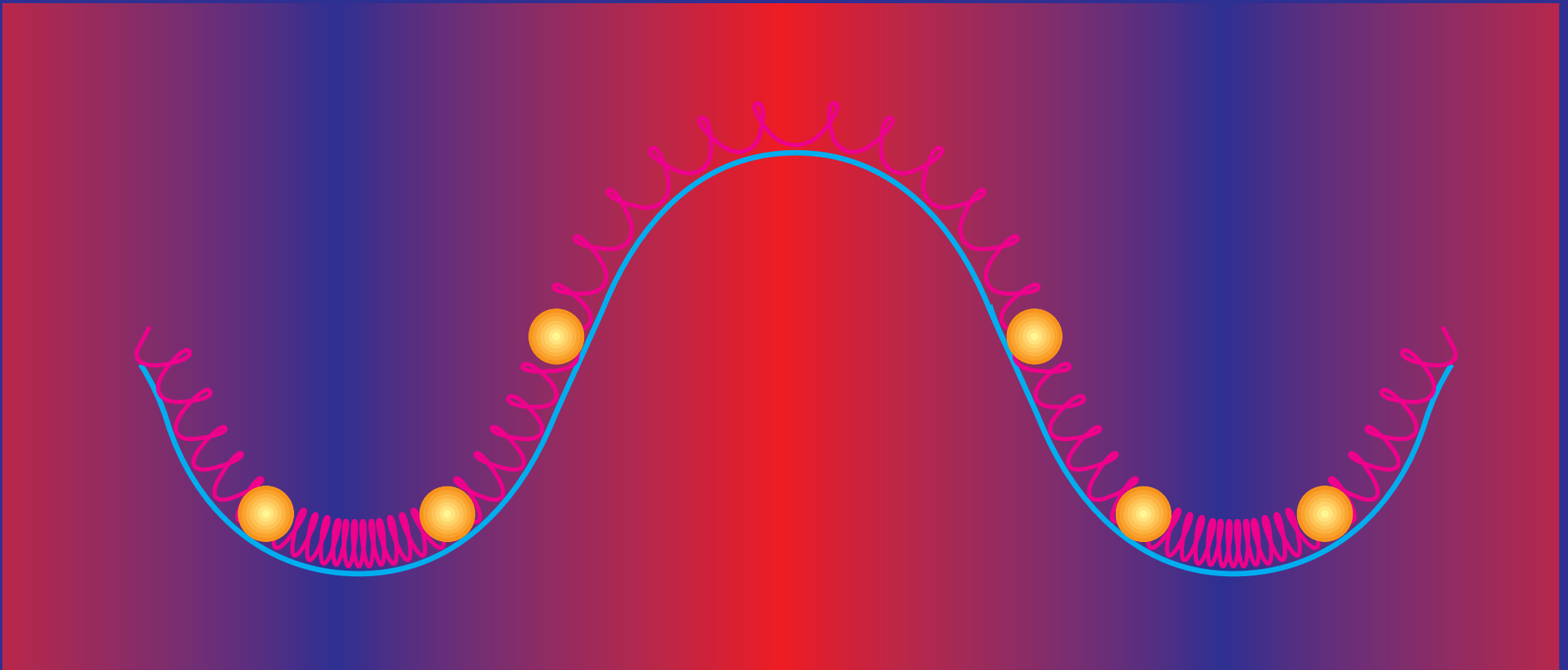
Extrema=Peaks

- First peak = mode that just compresses
- Second peak = mode that compresses then rarefies: twice the wavenumber
- Harmonic peaks: 1:2:3 in wavenumber



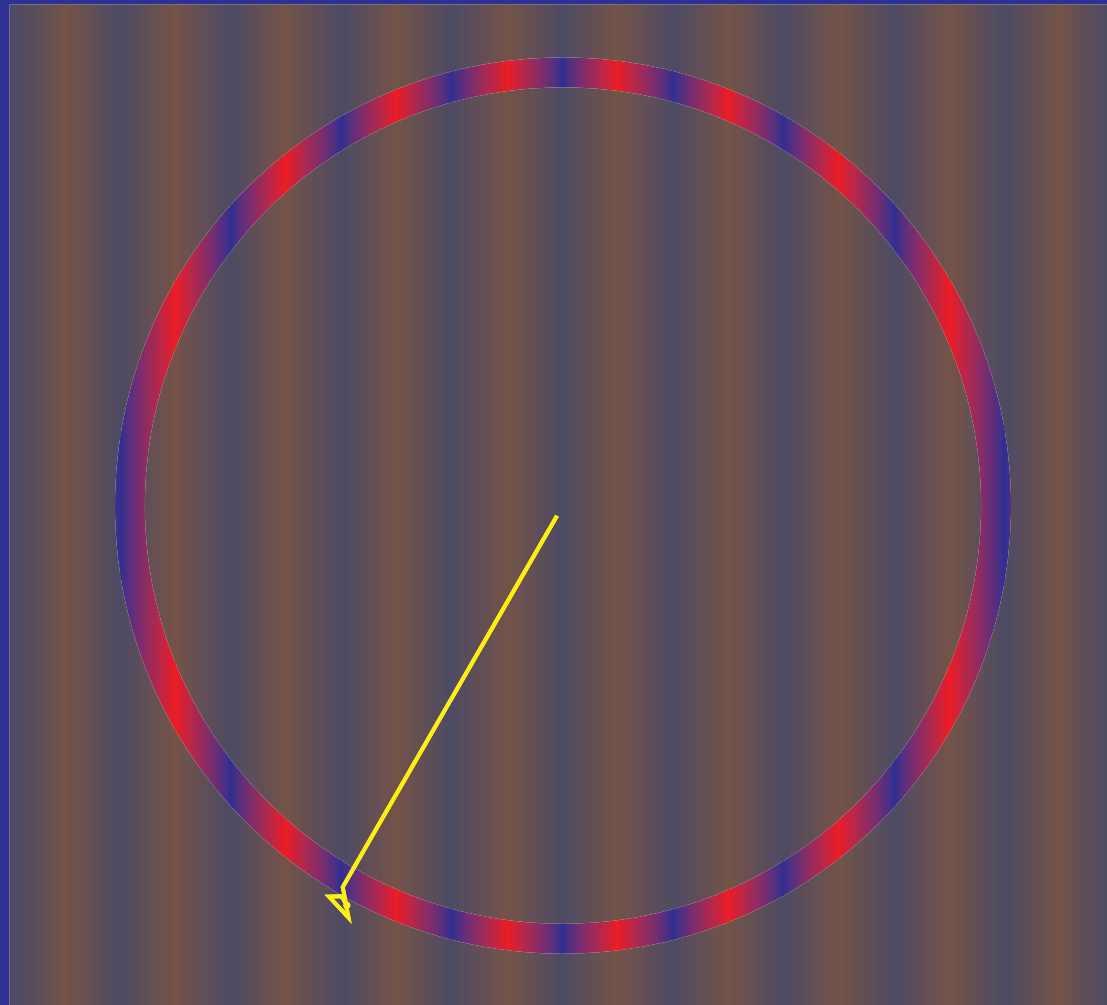
Seeing Sound

- Oscillations **frozen** at recombination
- Compression=**hot** spots, Rarefaction=**cold** spots
- Extrema are **harmonics** of distance sound travels

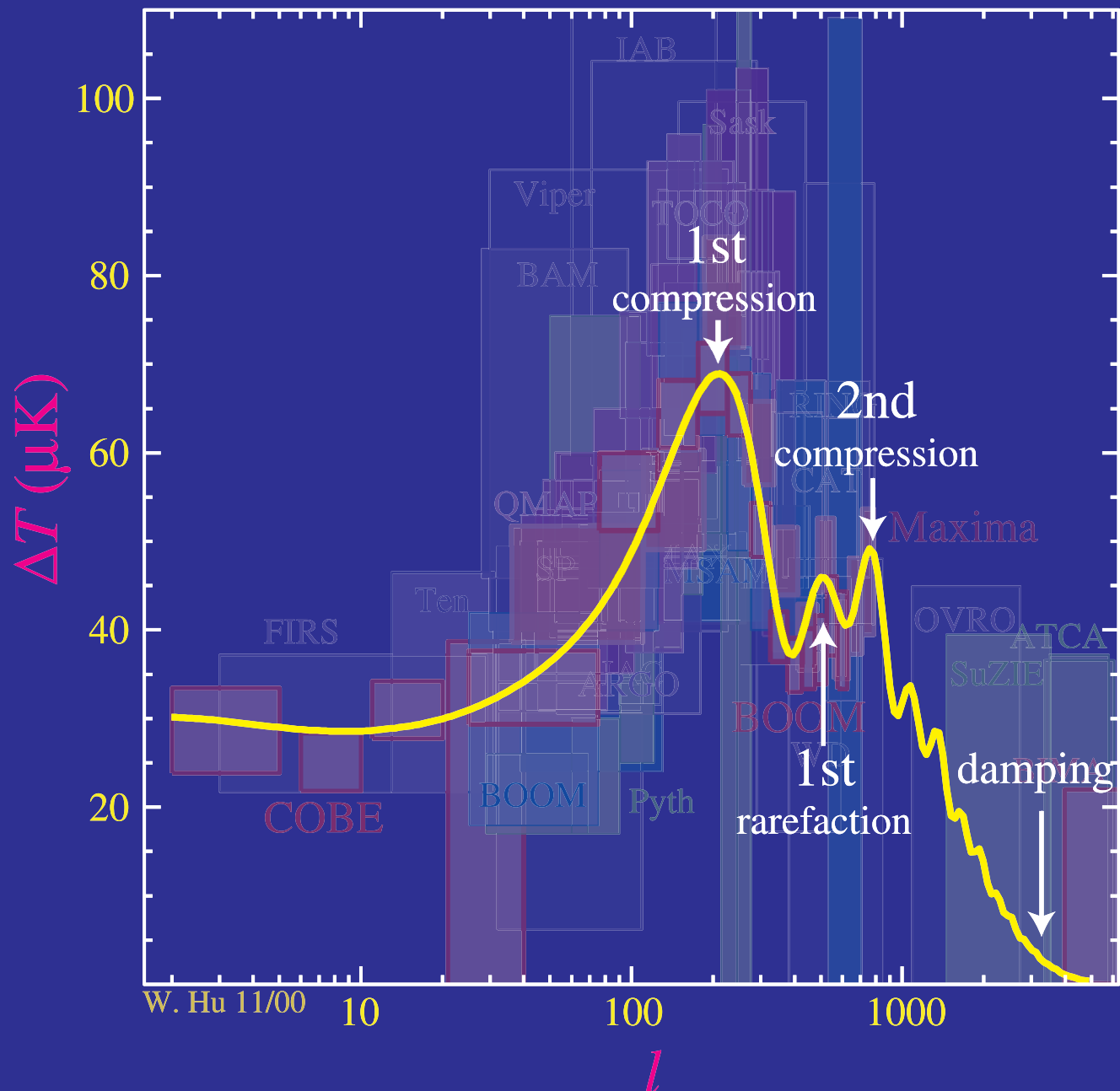


Peaks in Angular Power

- Oscillations frozen at **recombination**
- **Distant** hot and cold spots appear as temperature anisotropies



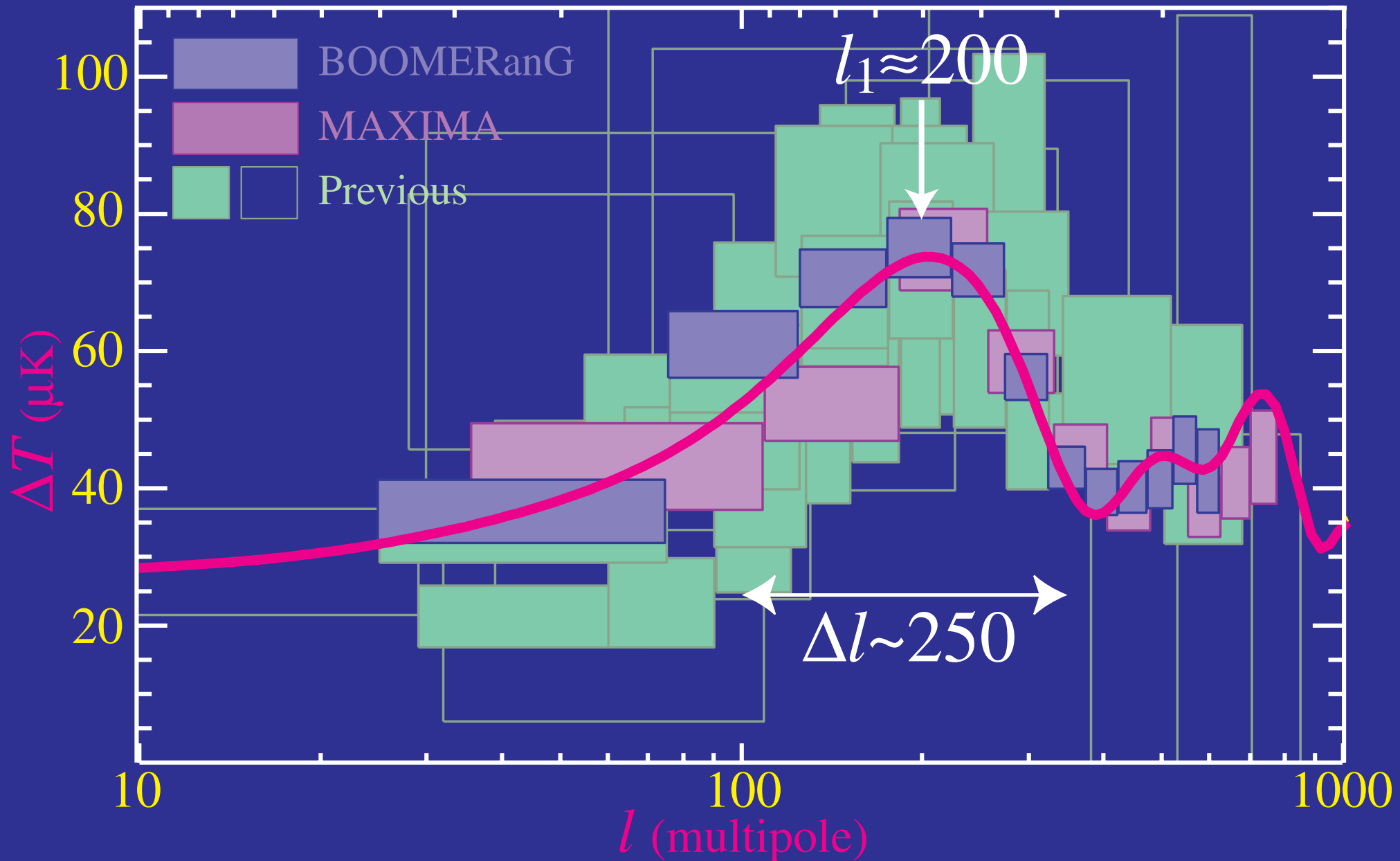
Basic Structure



A wireframe dome structure, resembling a geodesic dome or a dome with a grid of lines, is centered on a solid blue background. The dome is composed of several curved lines that meet at a central point at the top, creating a series of triangular and quadrilateral facets. The lines are light blue and semi-transparent, allowing the blue background to show through.

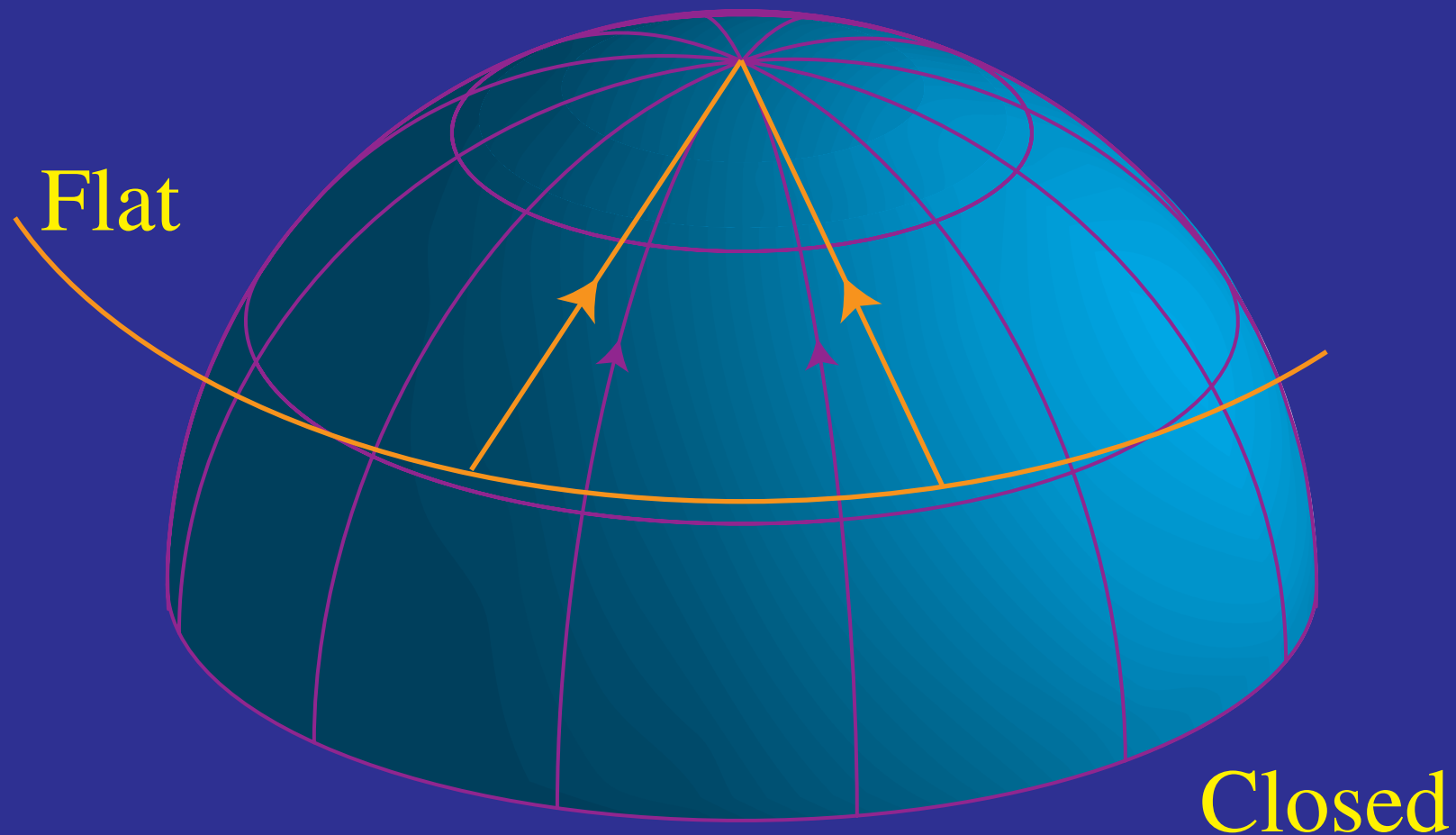
The First Peak

First Peak Precisely Measured



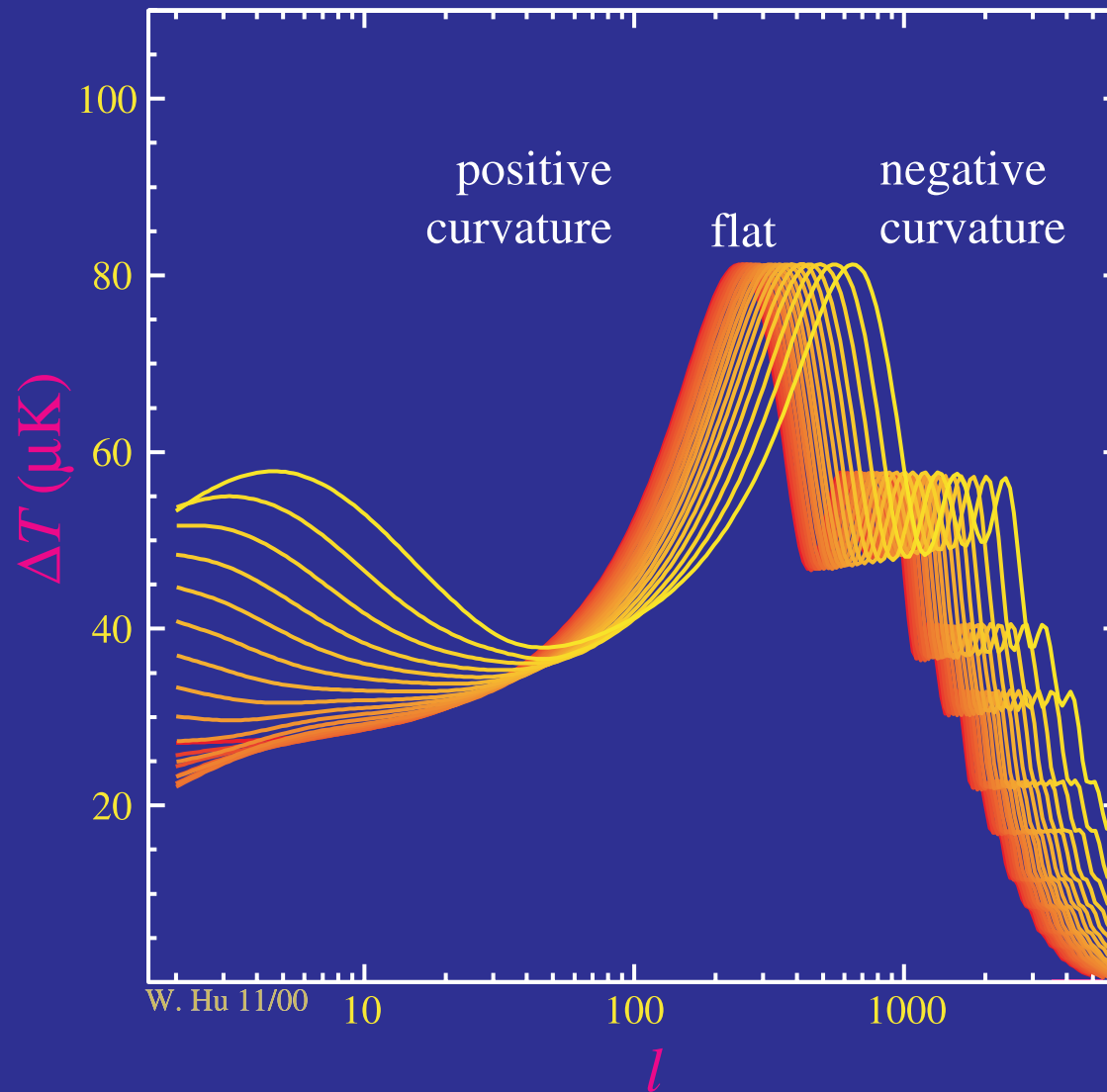
Spatial Curvature

- Physical scale of peak = distance sound travels
- Angular scale measured: comoving angular diameter distance test for curvature

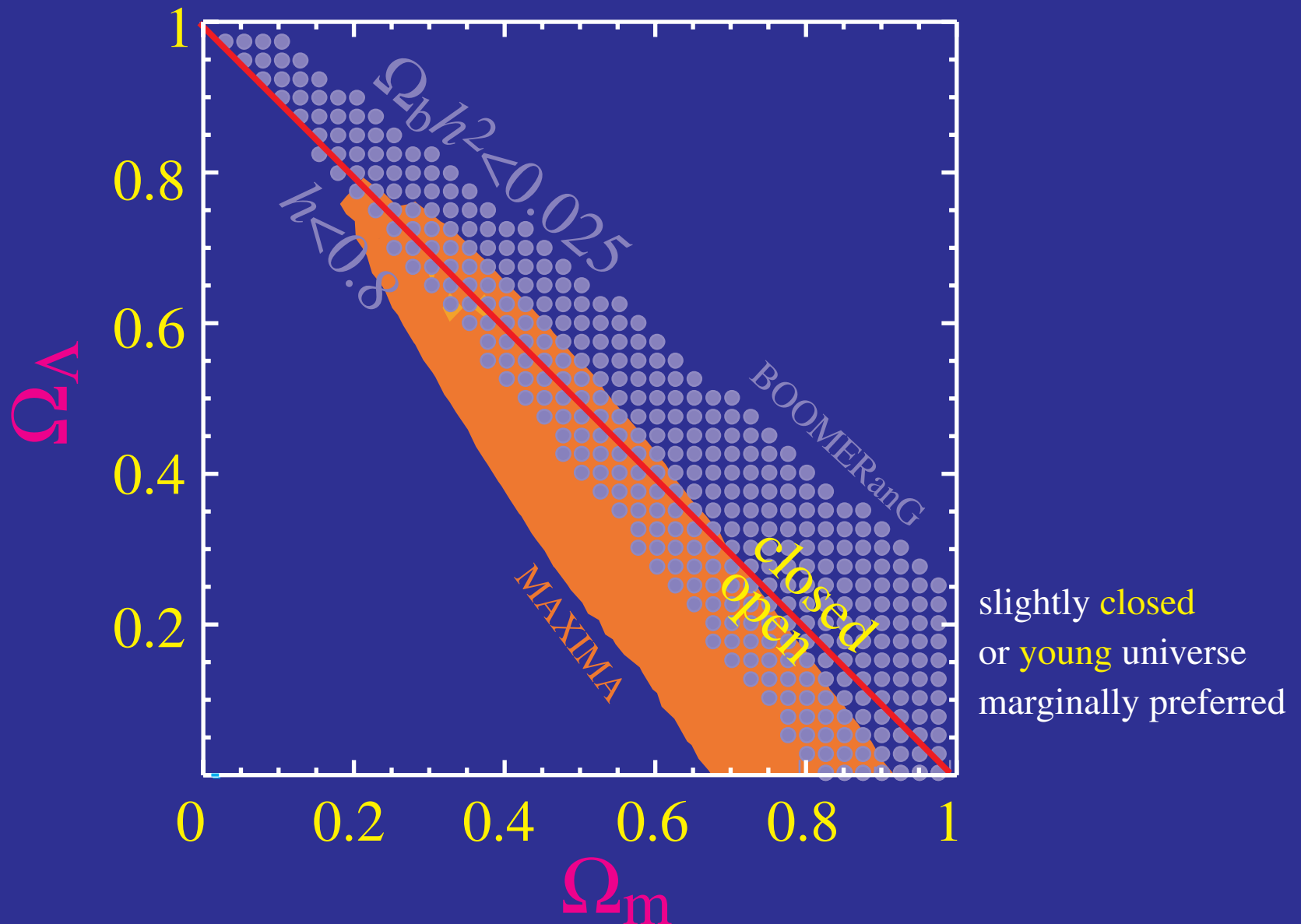


Curvature in the Power Spectrum

- Features scale with angular diameter distance
- Angular location of the first peak

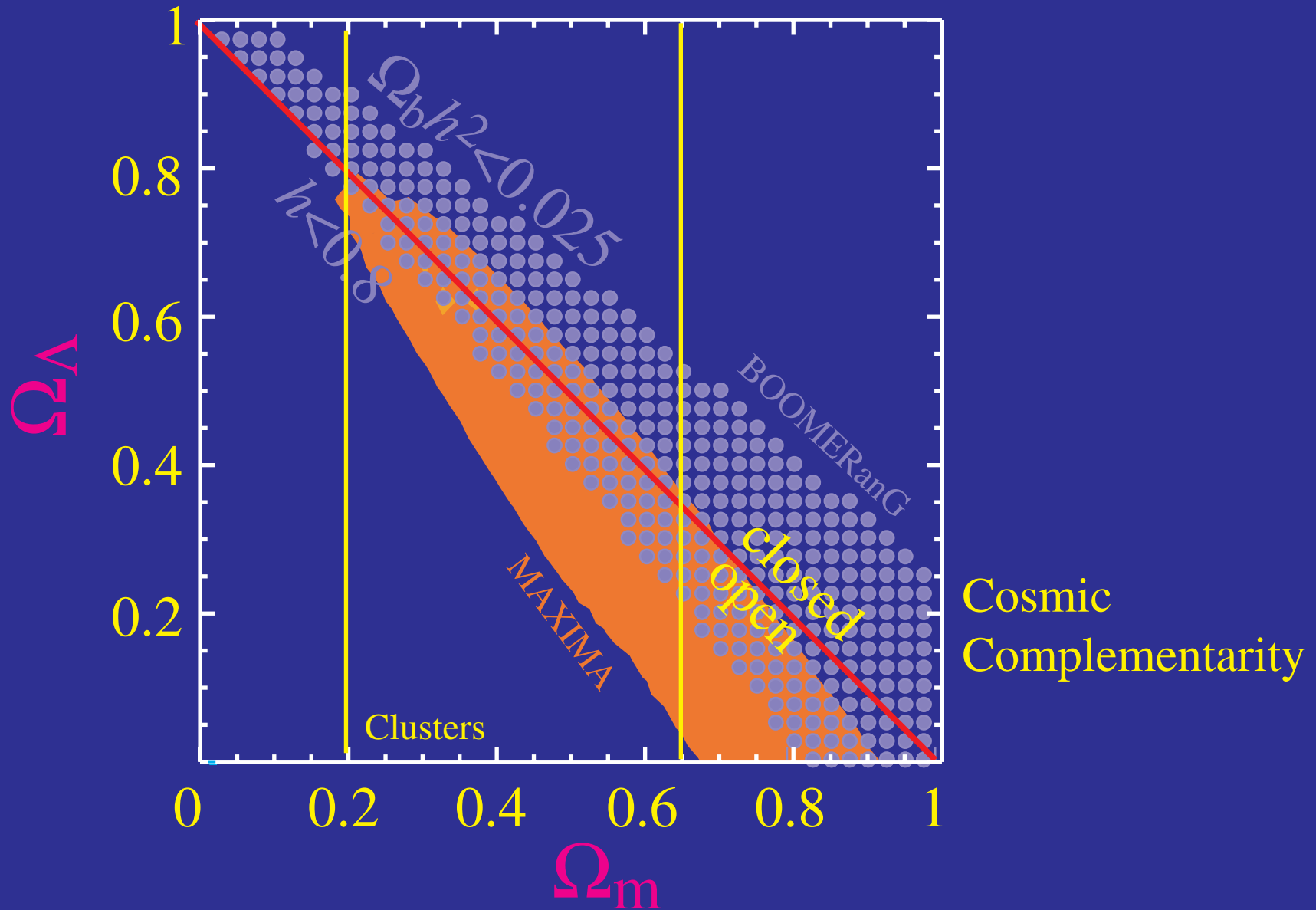


A (Nearly?!) Flat Universe



- Hubble constant! Baryons: calibrate rulers

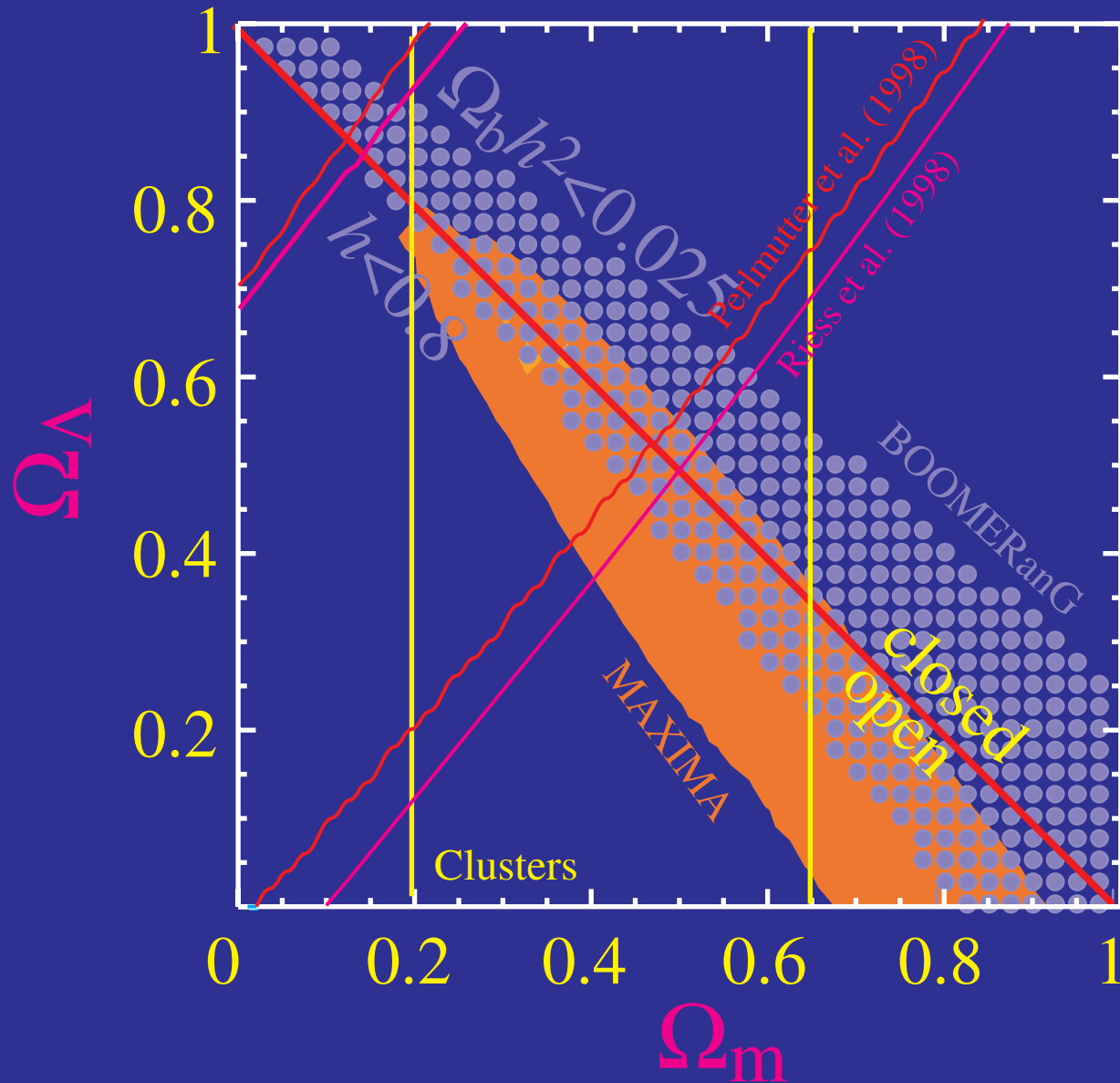
What Makes It Flat?



- Info on H_0 , Ω_m , or Ω_Λ breaks degeneracy

H_0 : currently by assuming flatness, future by measuring $\Omega_m h^2$

Concordance!?



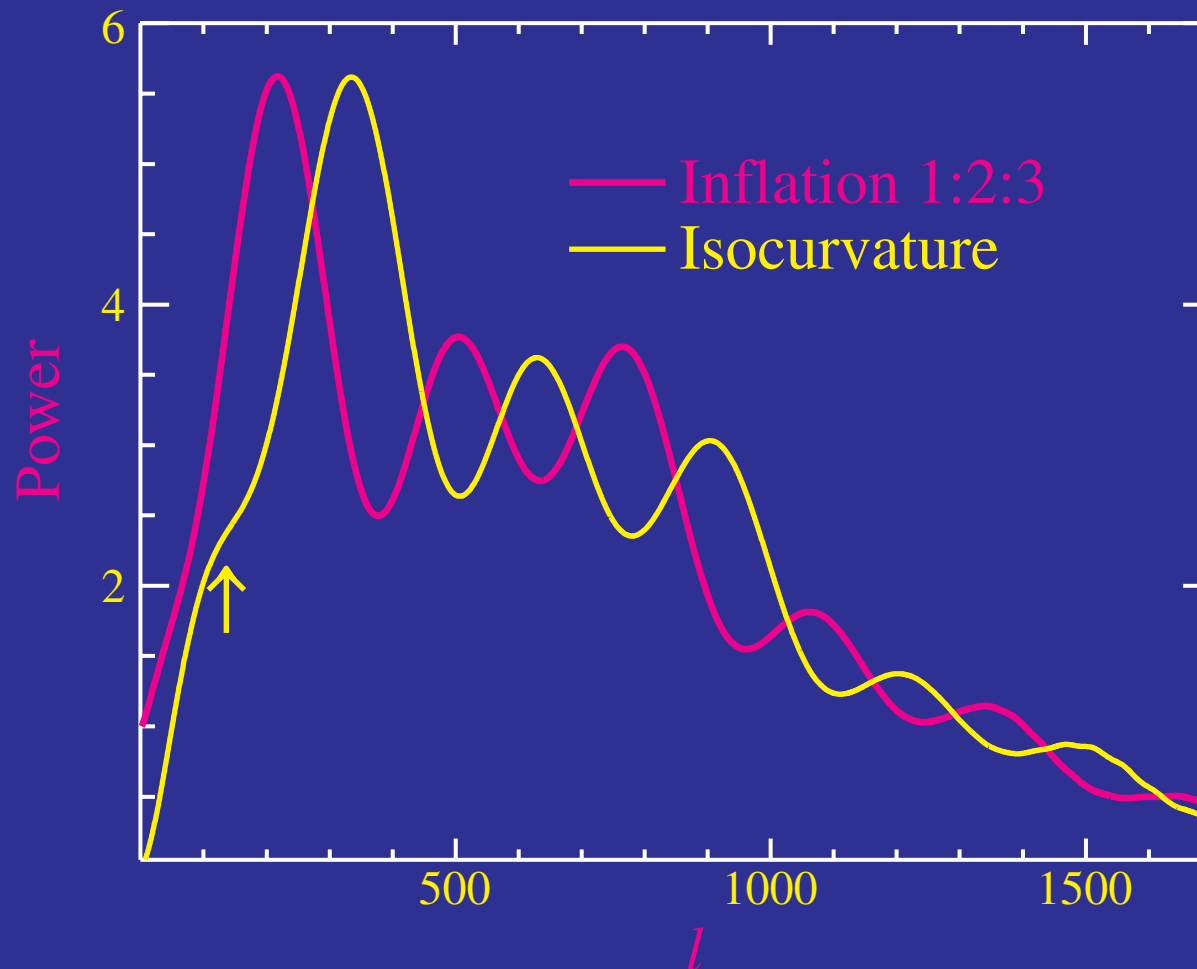
- Consistent and requires missing “dark” energy



The Second Peak

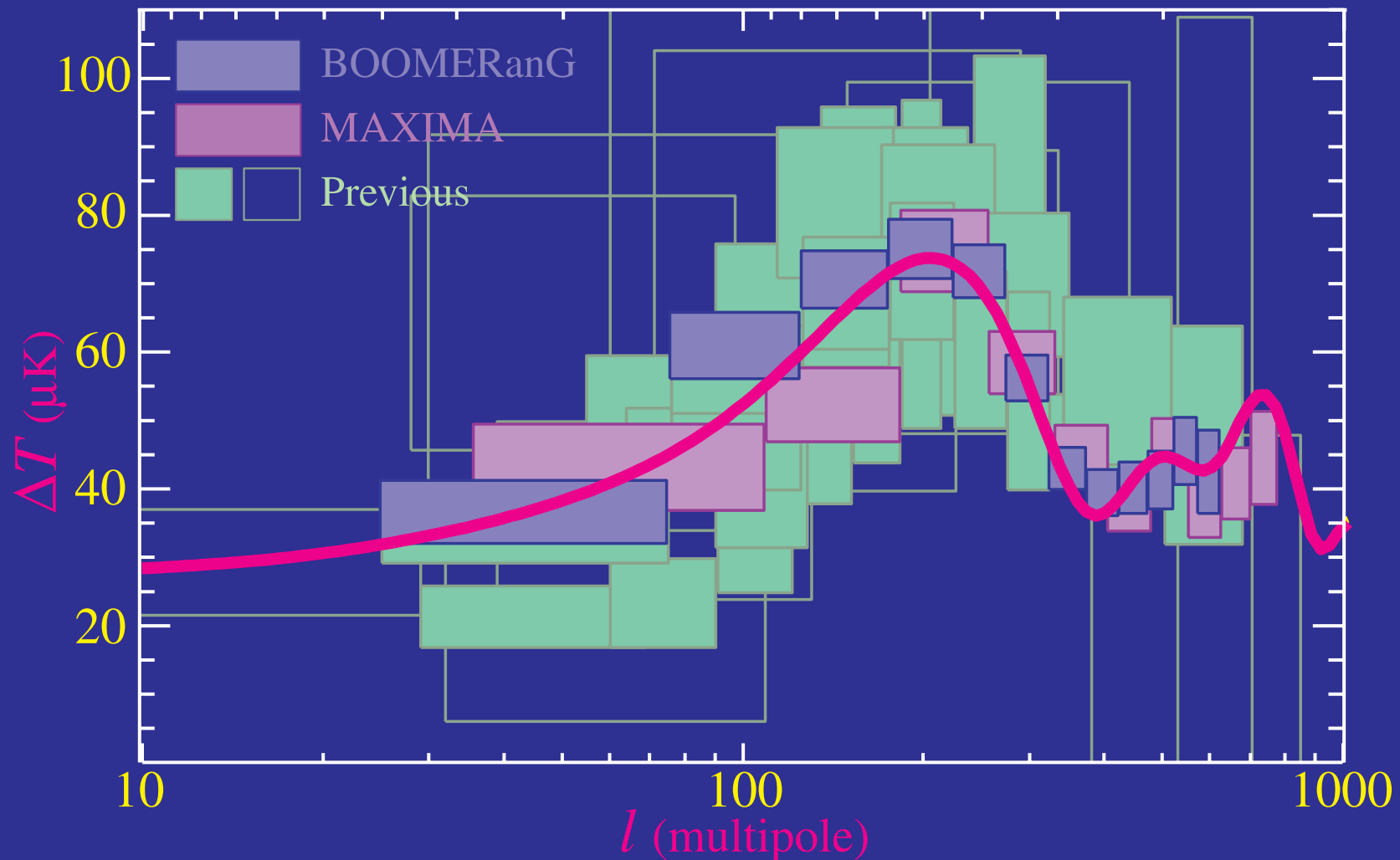
What is it Good For

- **Acoustic nature:** beyond reasonable doubt
- **Inflation:** superhorizon potential perturbations
defects already strongly disfavored: narrow first peak



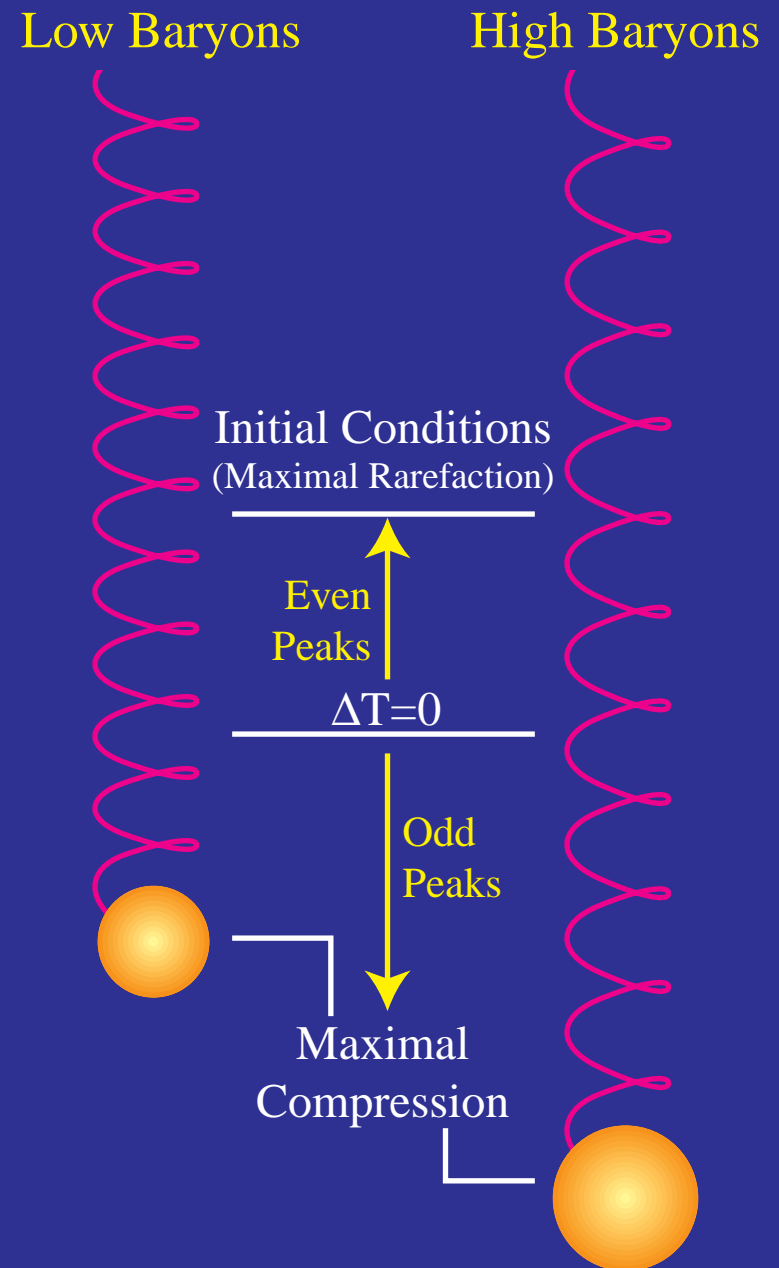
What is it Good For

- **Current:** second peak unresolved
- **Amplitude:** constrained to be low



Baryon & Inertia

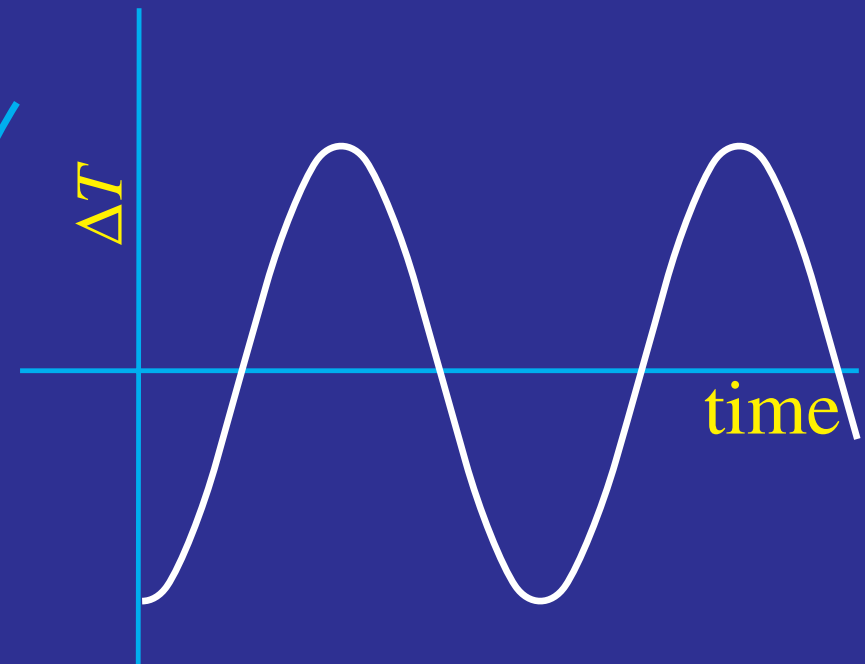
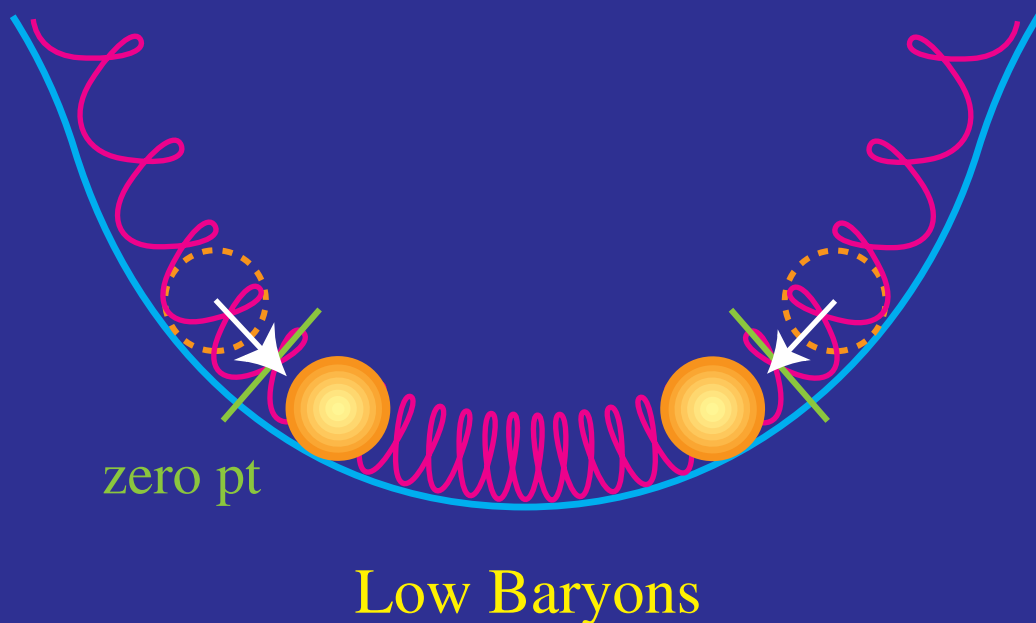
- **Baryons** add inertia to the fluid
- Equivalent to adding **mass** on a **spring**
- Same **initial conditions**
- Same **null in fluctuations**
- **Unequal** amplitudes of extrema



A Baryon-meter

- Baryons drag the fluid into potential wells
- Enhance compressional peaks (odd) over rarefaction peaks (even)

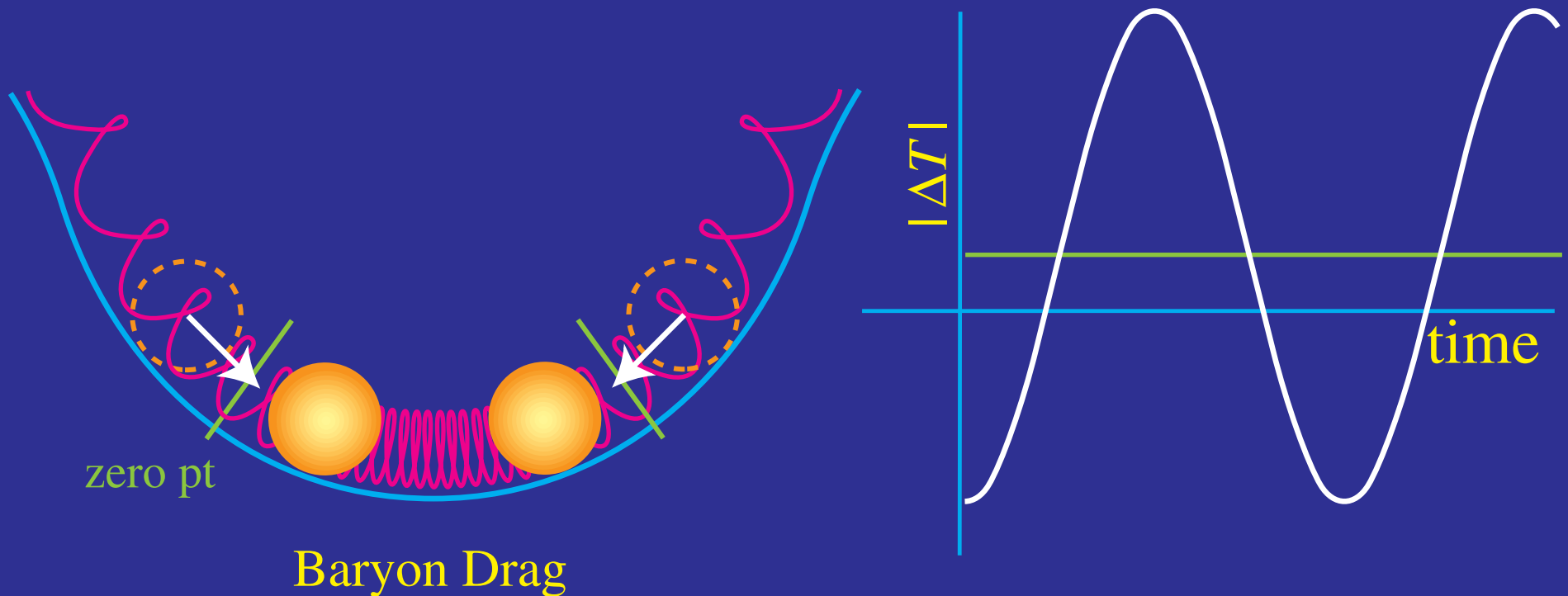
e.g. suppression of second peak



A Baryon-meter

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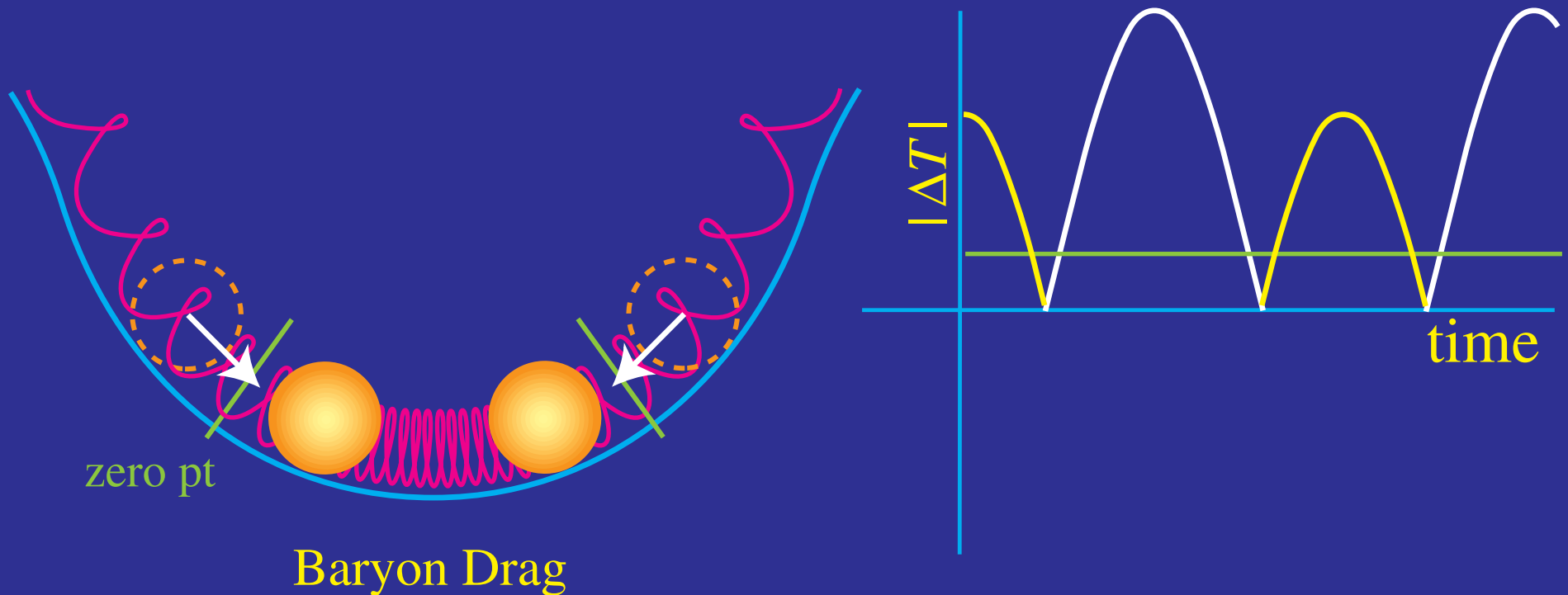
e.g. suppression of second peak



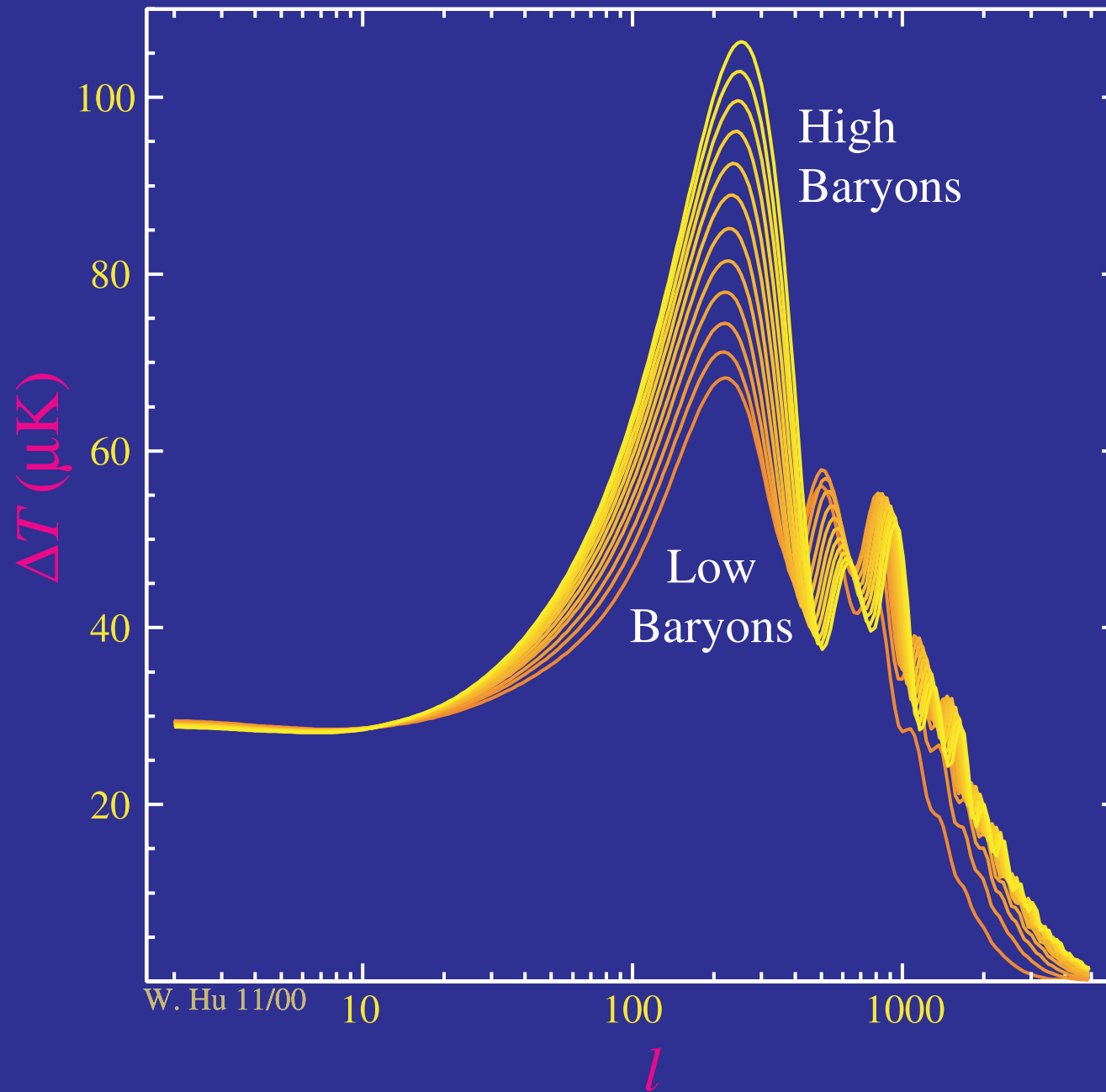
A Baryon-meter

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e.g. suppression of second peak

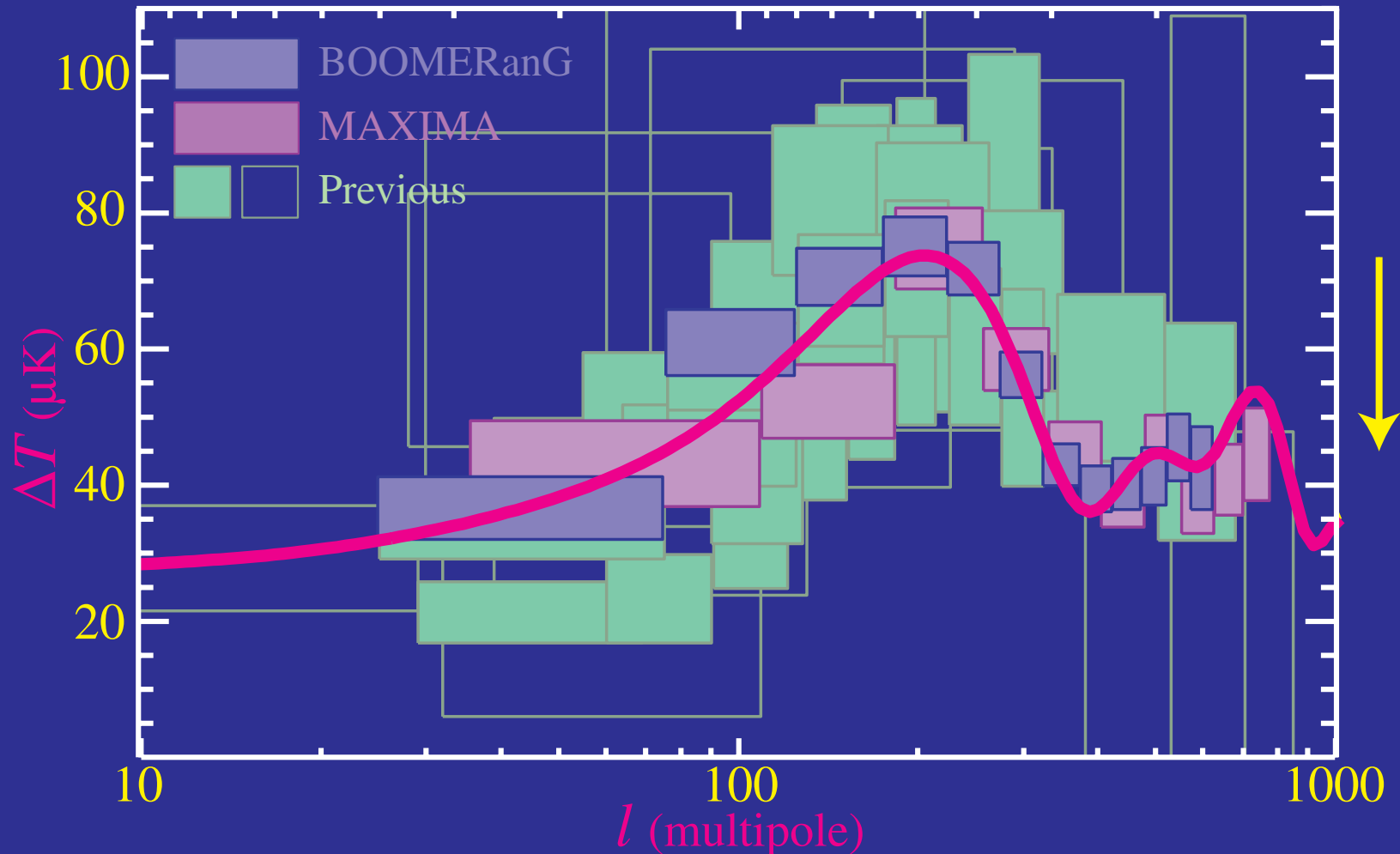


Baryons in the Power Spectrum

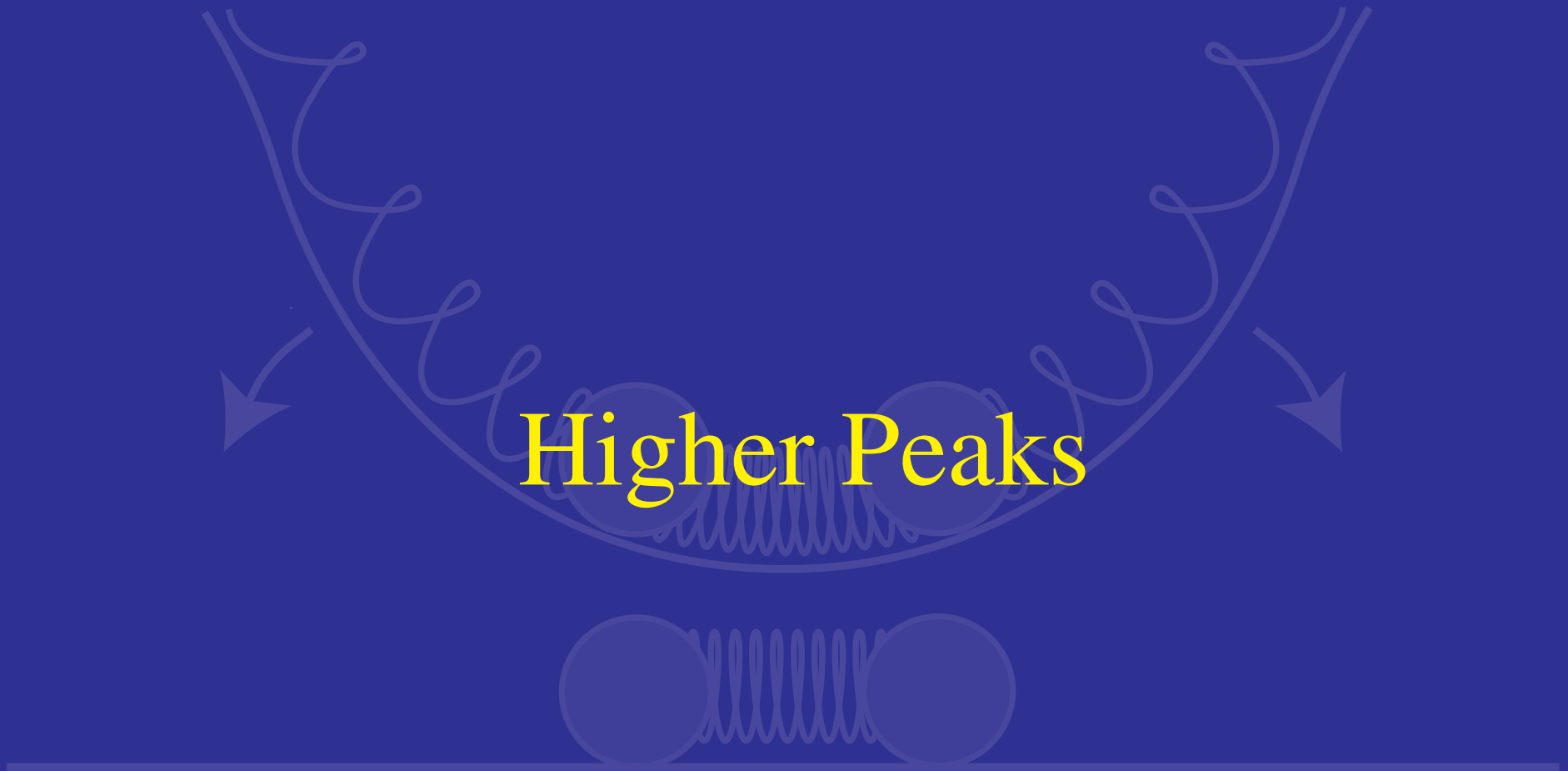


Second Peak

- Second peak is (too?) suppressed
- At least as many **baryons** as **nucleosynthesis**
(50% more preferred
BBN consistent at 95% CL including variations in other parameters, e.g. spectrum tilt)

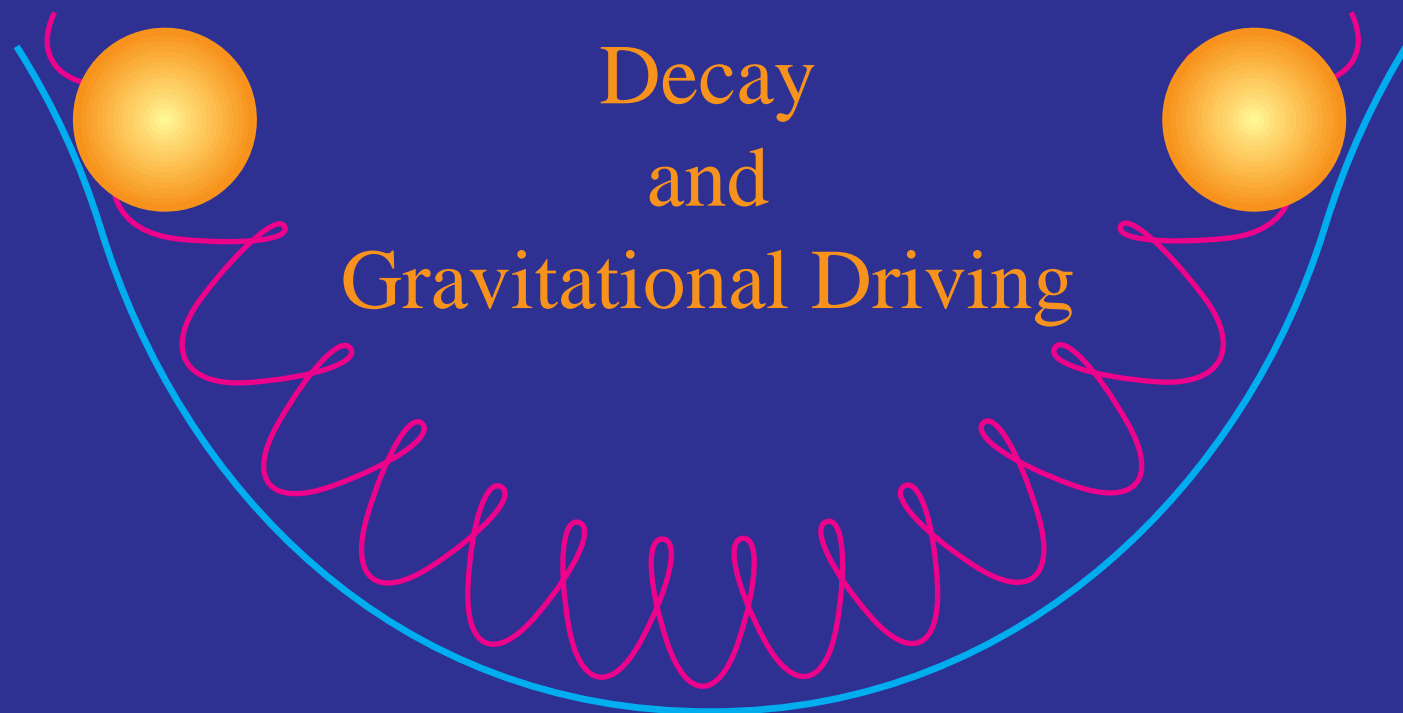


Higher Peaks



Radiation and Dark Matter

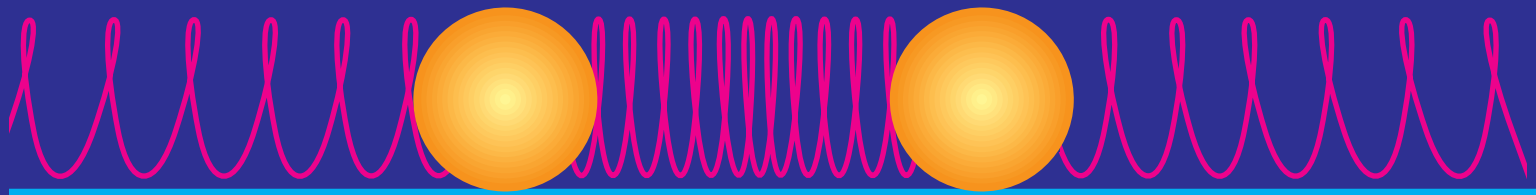
- Radiation domination:
potential wells created by CMB itself
- Pressure support \Rightarrow potential decay \Rightarrow driving
- Heights measures when dark matter dominates



Radiation and Dark Matter

- Radiation domination:
potential wells created by CMB itself
- Pressure support \Rightarrow potential decay \Rightarrow driving
- Heights measures when dark matter dominates

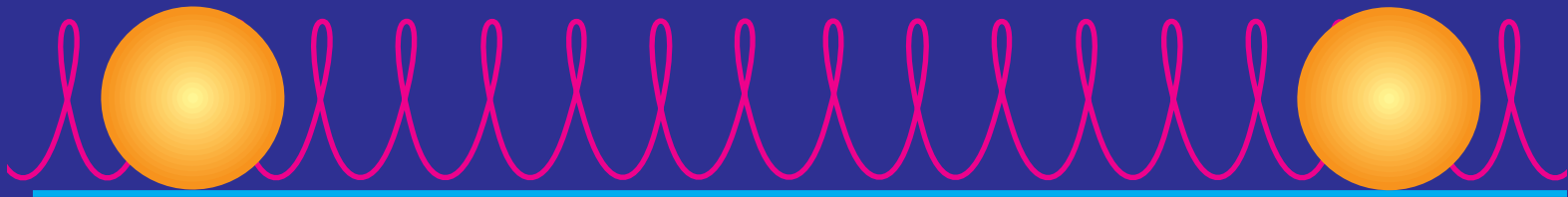
Decay
and
Gravitational Driving



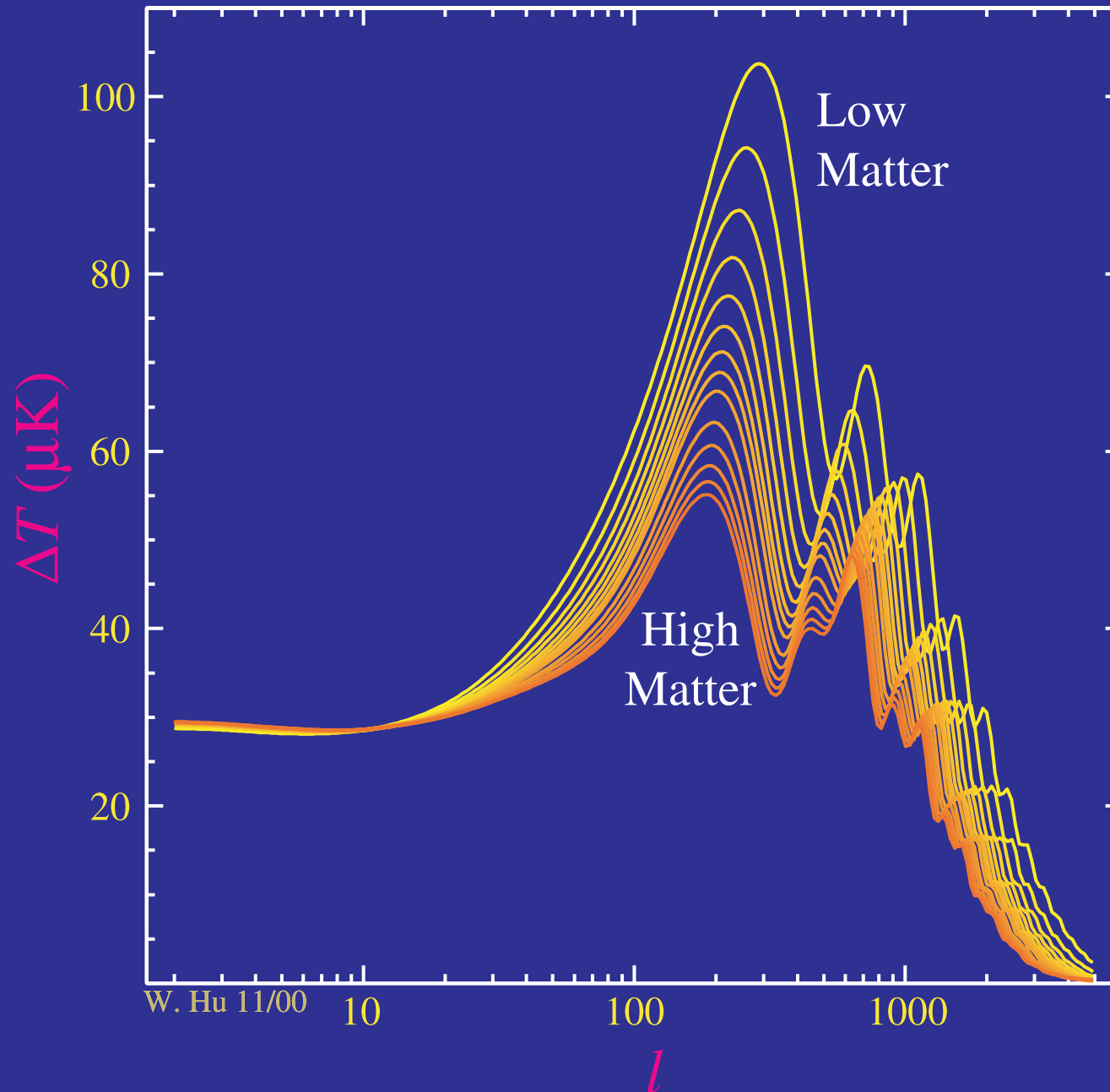
Radiation and Dark Matter

- Radiation domination:
potential wells created by CMB itself
- Pressure support \Rightarrow potential decay \Rightarrow driving
- Heights measures when dark matter dominates

Decay
and
Gravitational Driving

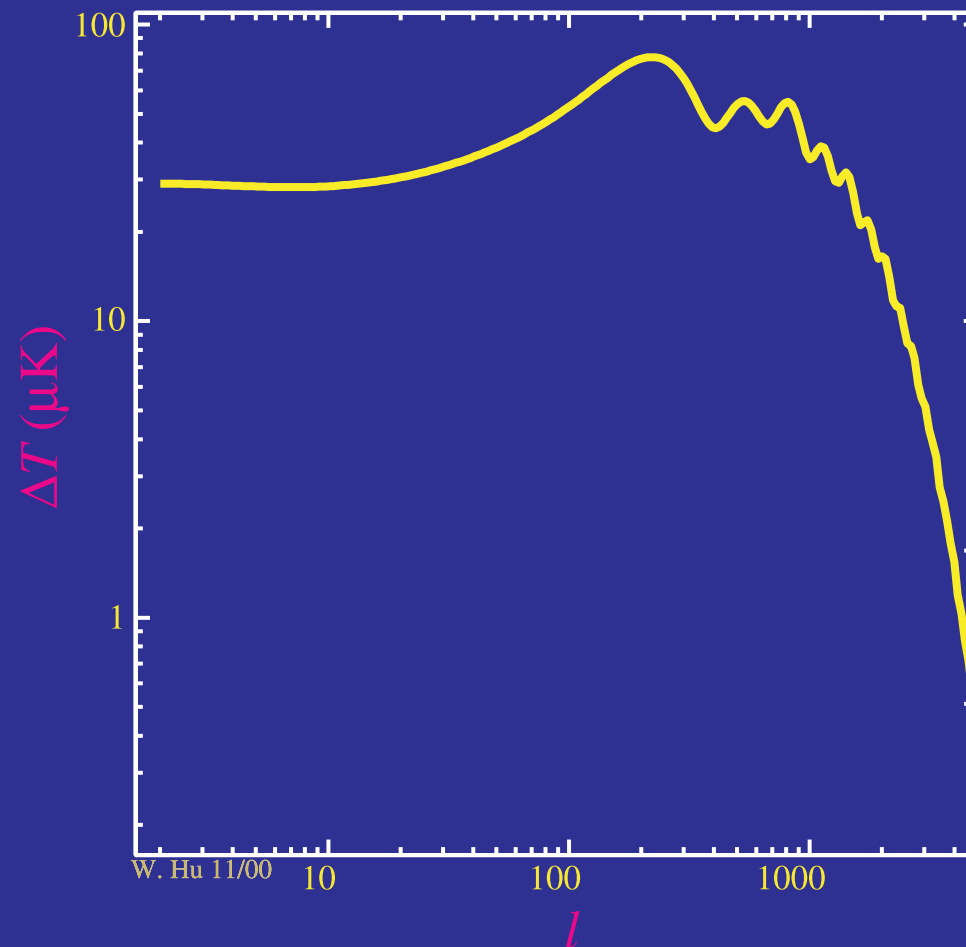


Dark Matter in the Power Spectrum



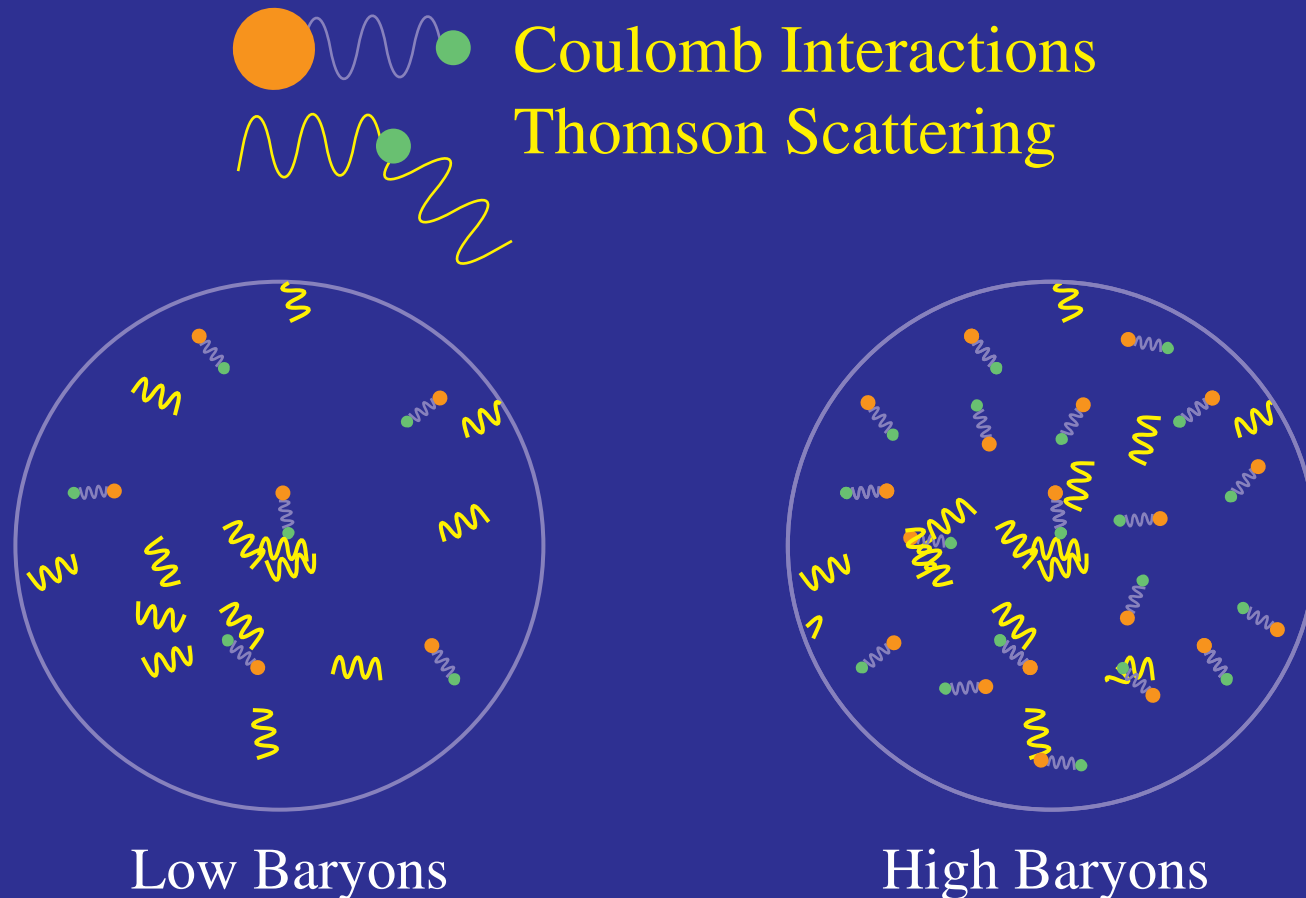
Damping Tail in the Power Spectrum

- Photon diffusion exponentially damps oscillations
- Calibrate the standard rulers in curvature test



Diffusion Damping

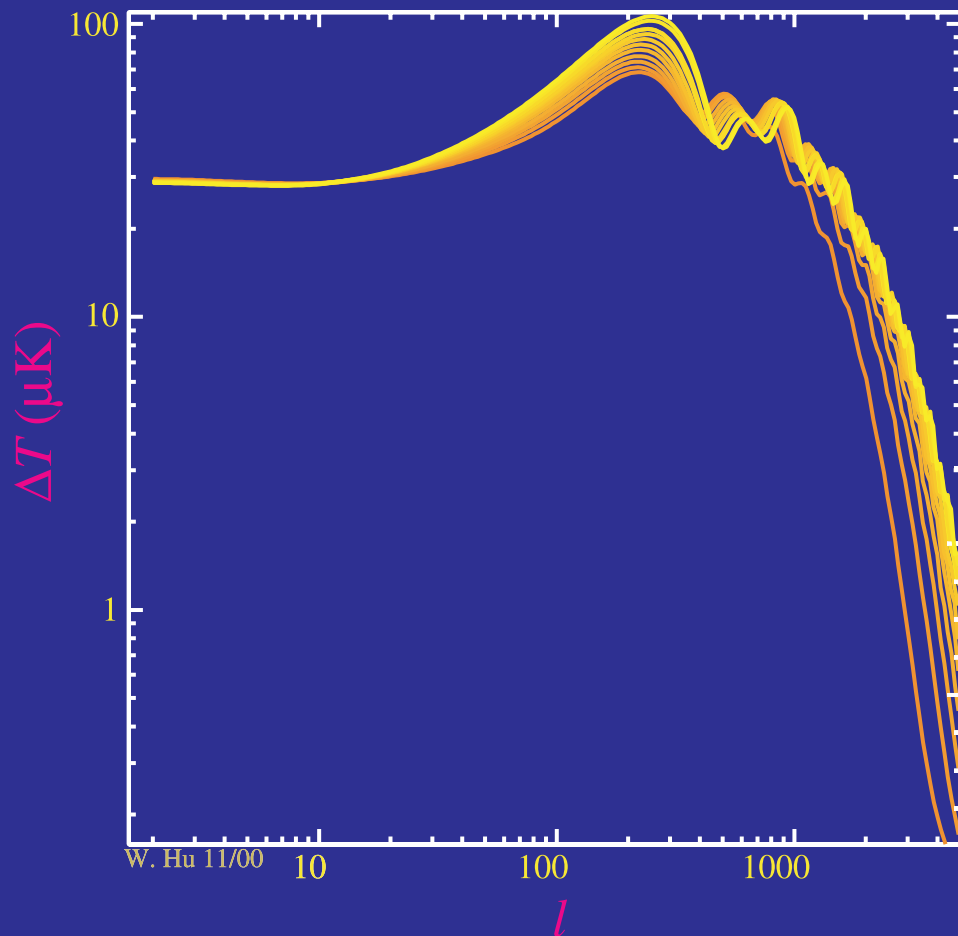
- Diffusion inhibited by baryons
- Random walk length scale depends on time to diffuse: horizon scale at recombination



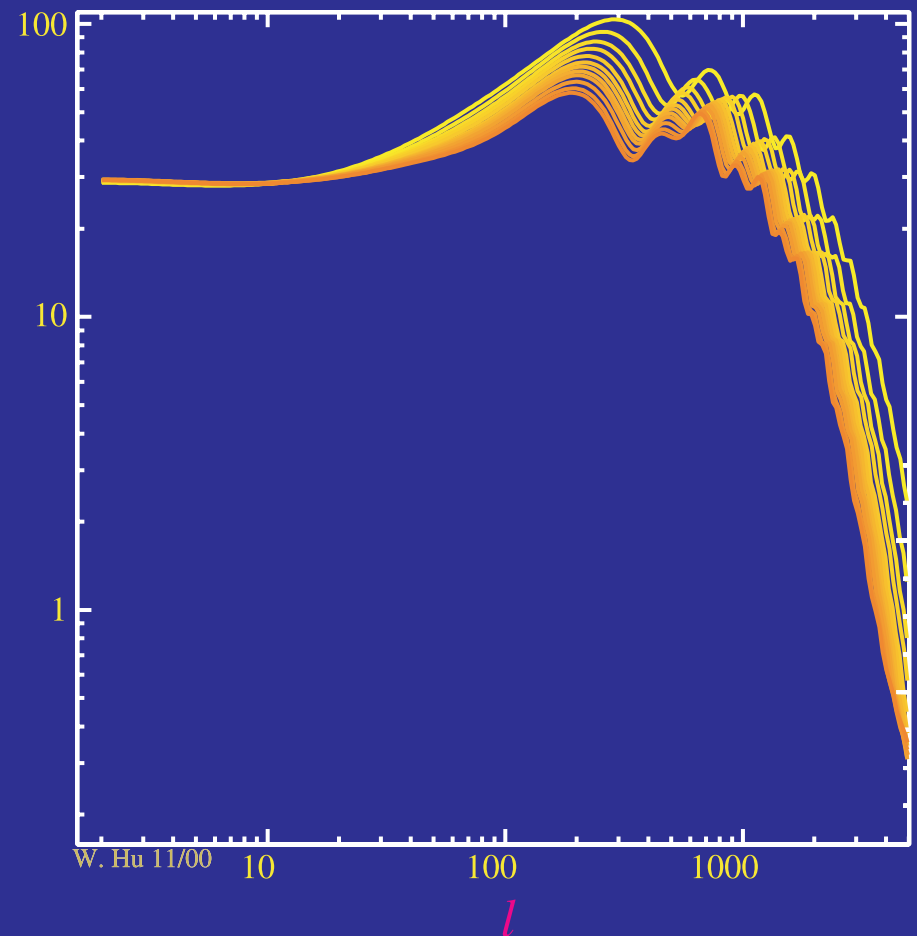
Damping Consistency Tests

- Additional measure of **baryons** and **dark matter**

Baryons



Dark Matter

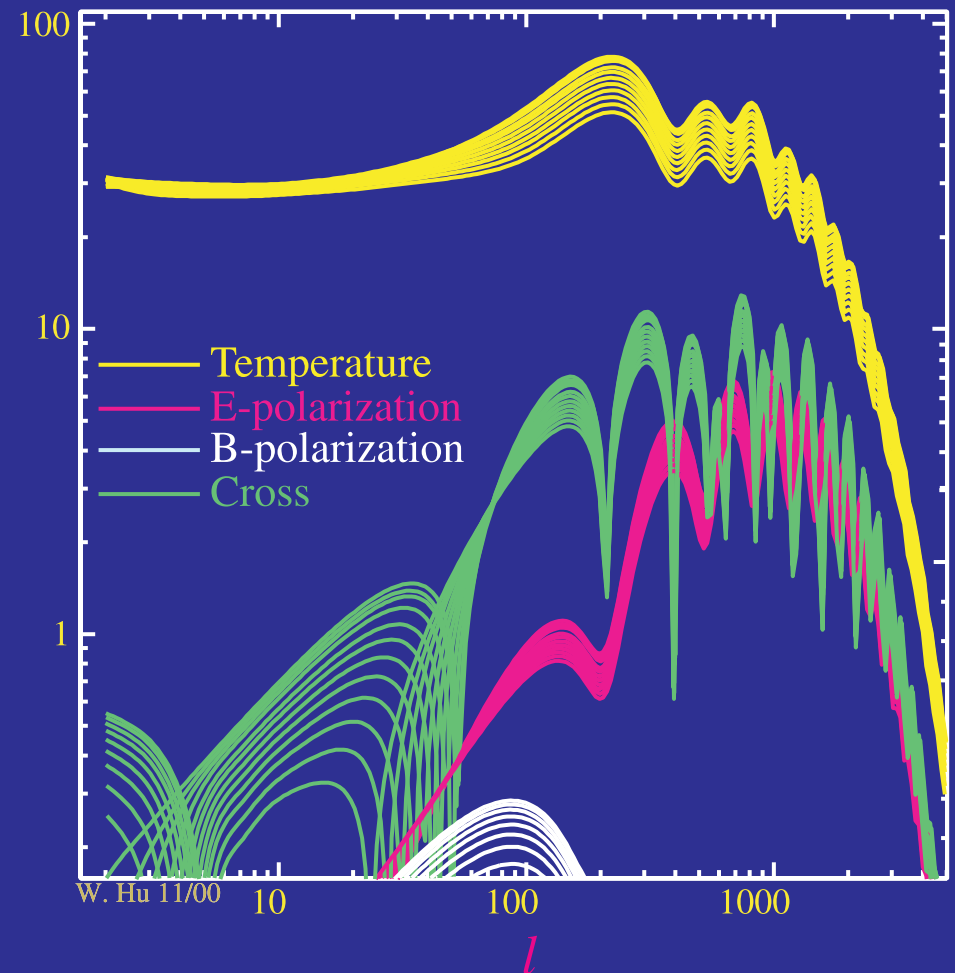
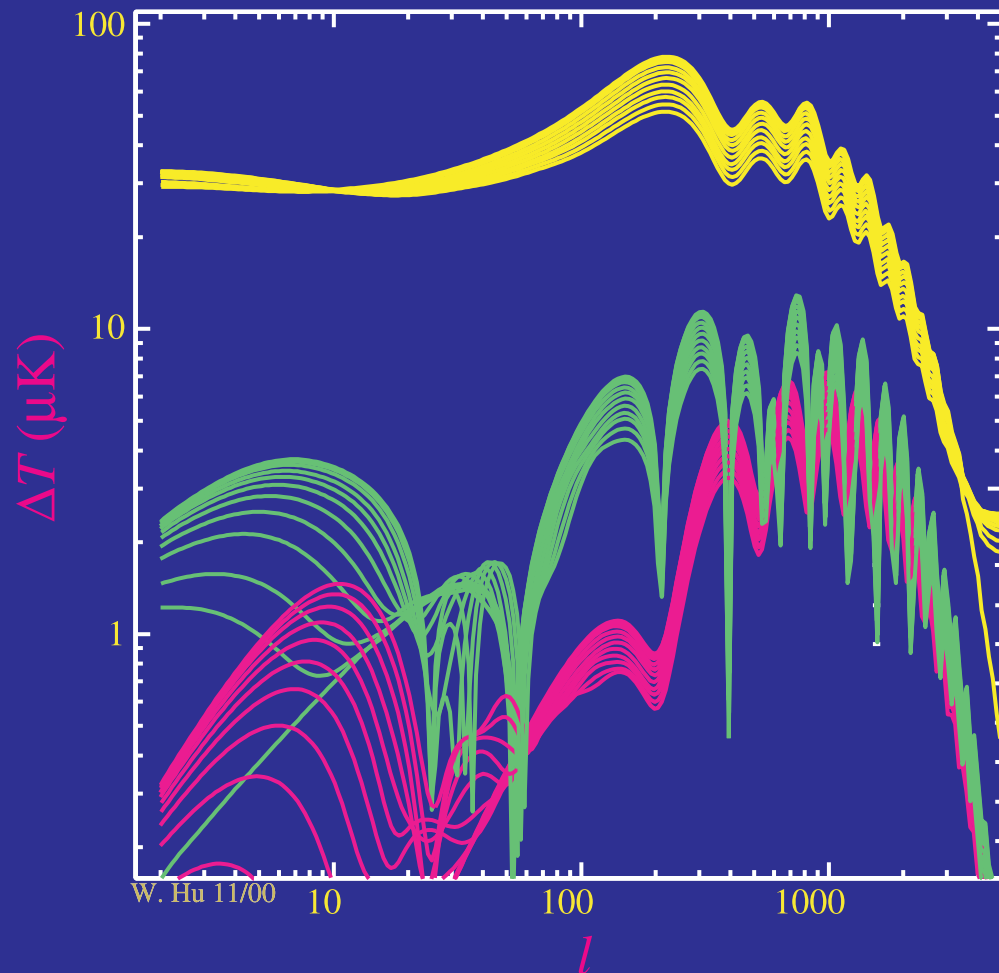




Beyond the Peaks

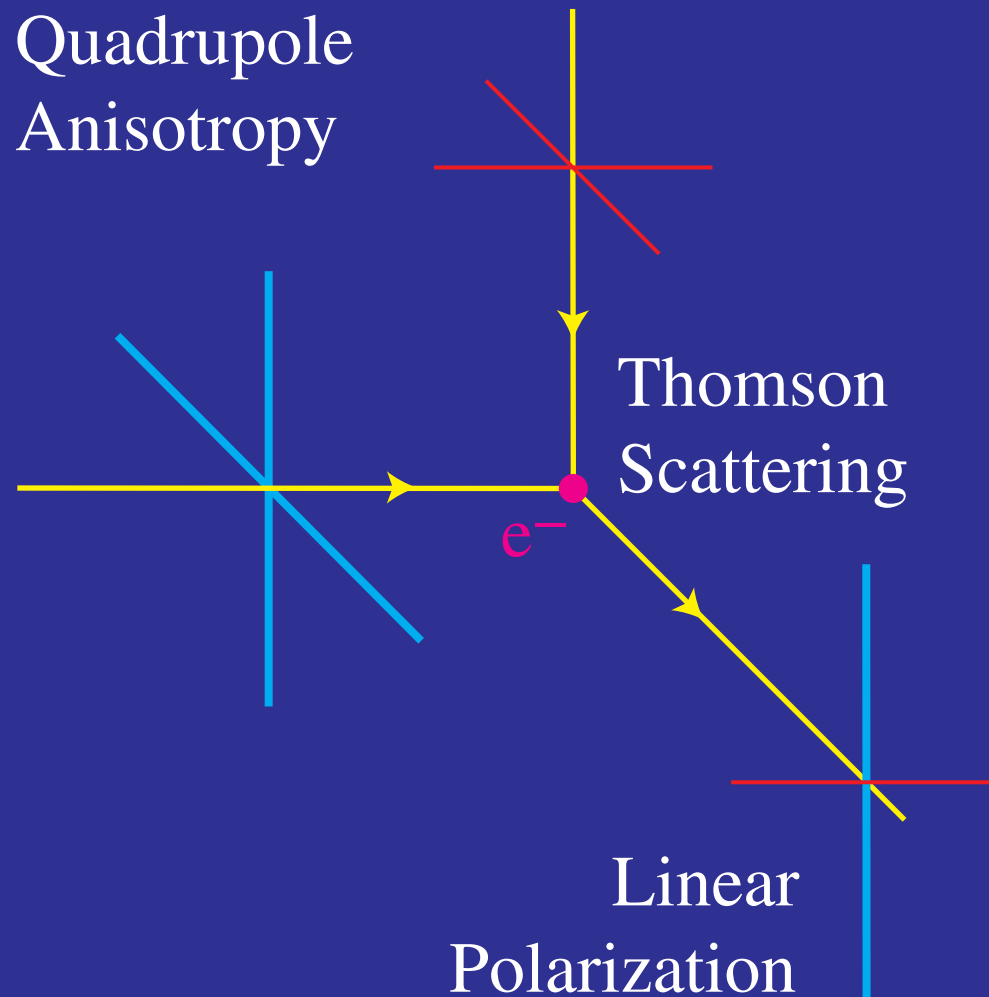
Degeneracies

- Multiple cosmological parameters have (nearly) degenerate effects on the power spectrum
- Example: reionization and gravity waves



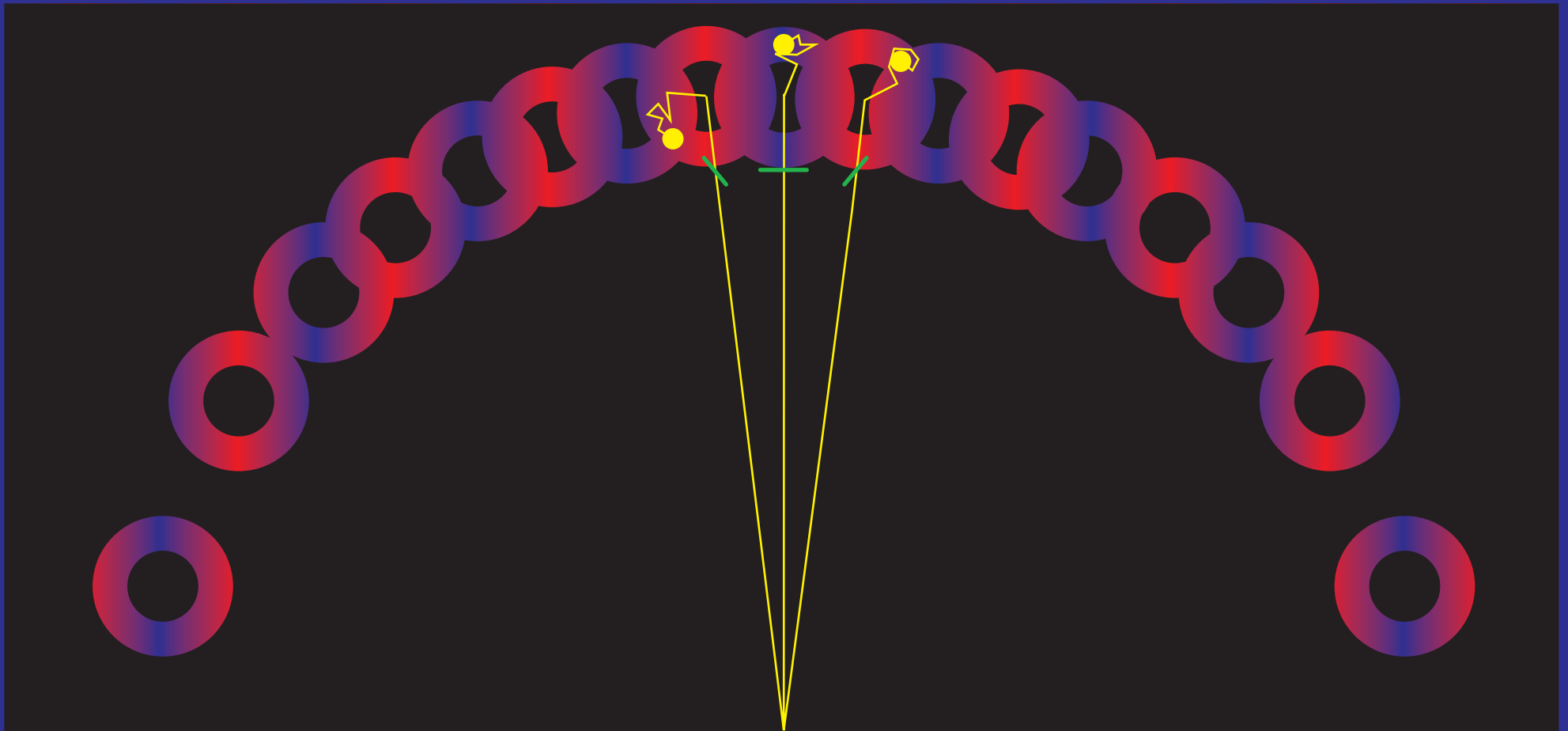
Polarization

- Thomson of quadrupole temperature anisotropy
- Linear polarization:



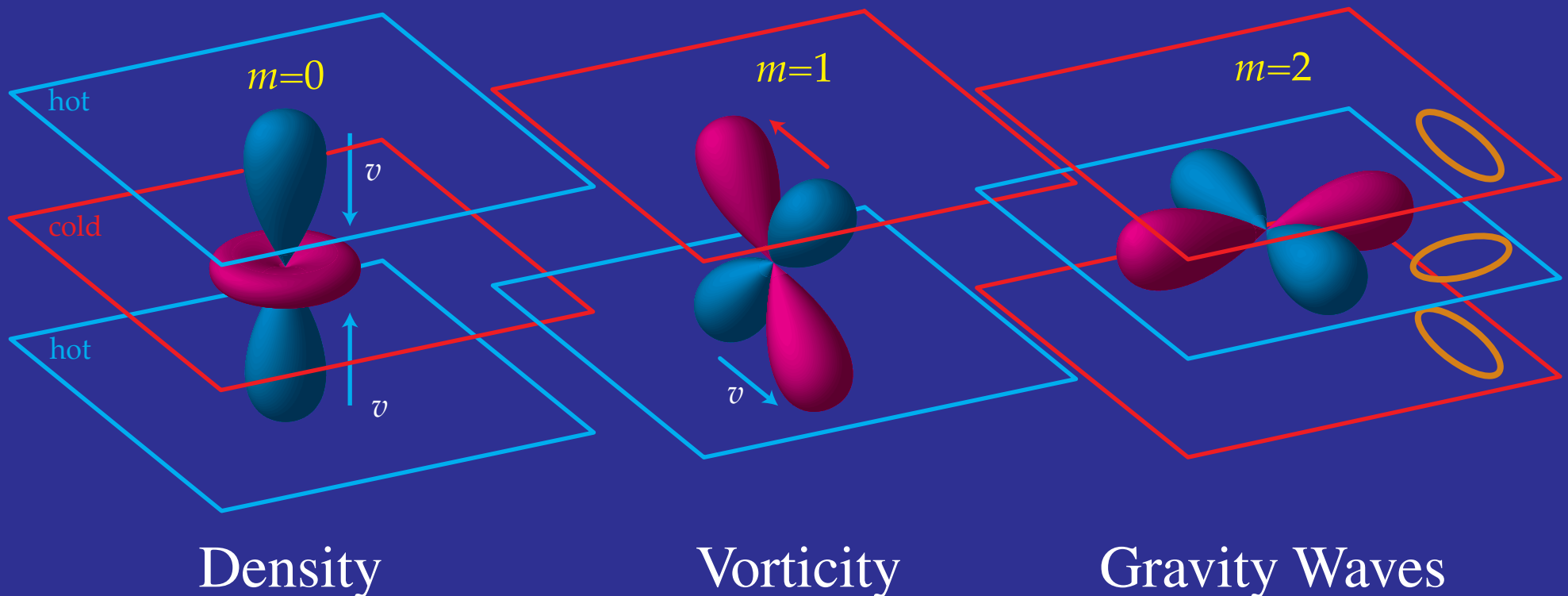
Polarization Generation

- Quadrupole anisotropies generated in optically thin regime
- Anisotropies $< 10\%$ polarized



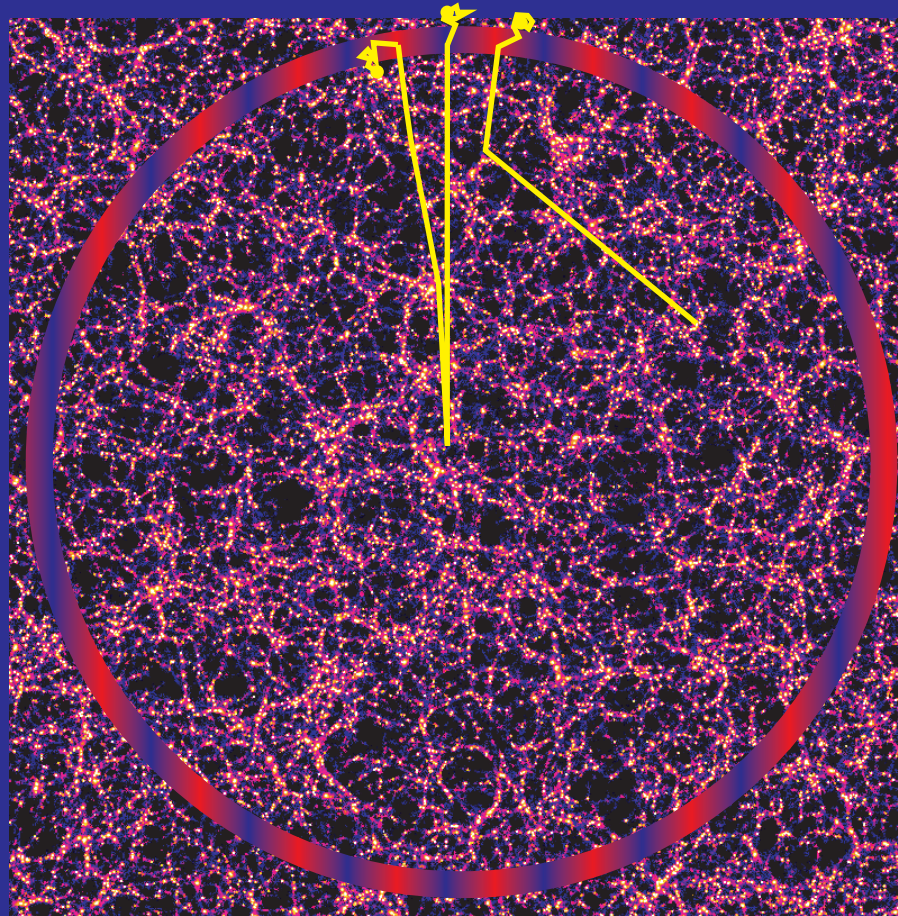
Polarization Patterns

- Pattern reflects the **projection** of quadrupole anisotropies
- **Three types**: density, vorticity, gravity waves
- Potential to **isolate gravity waves**



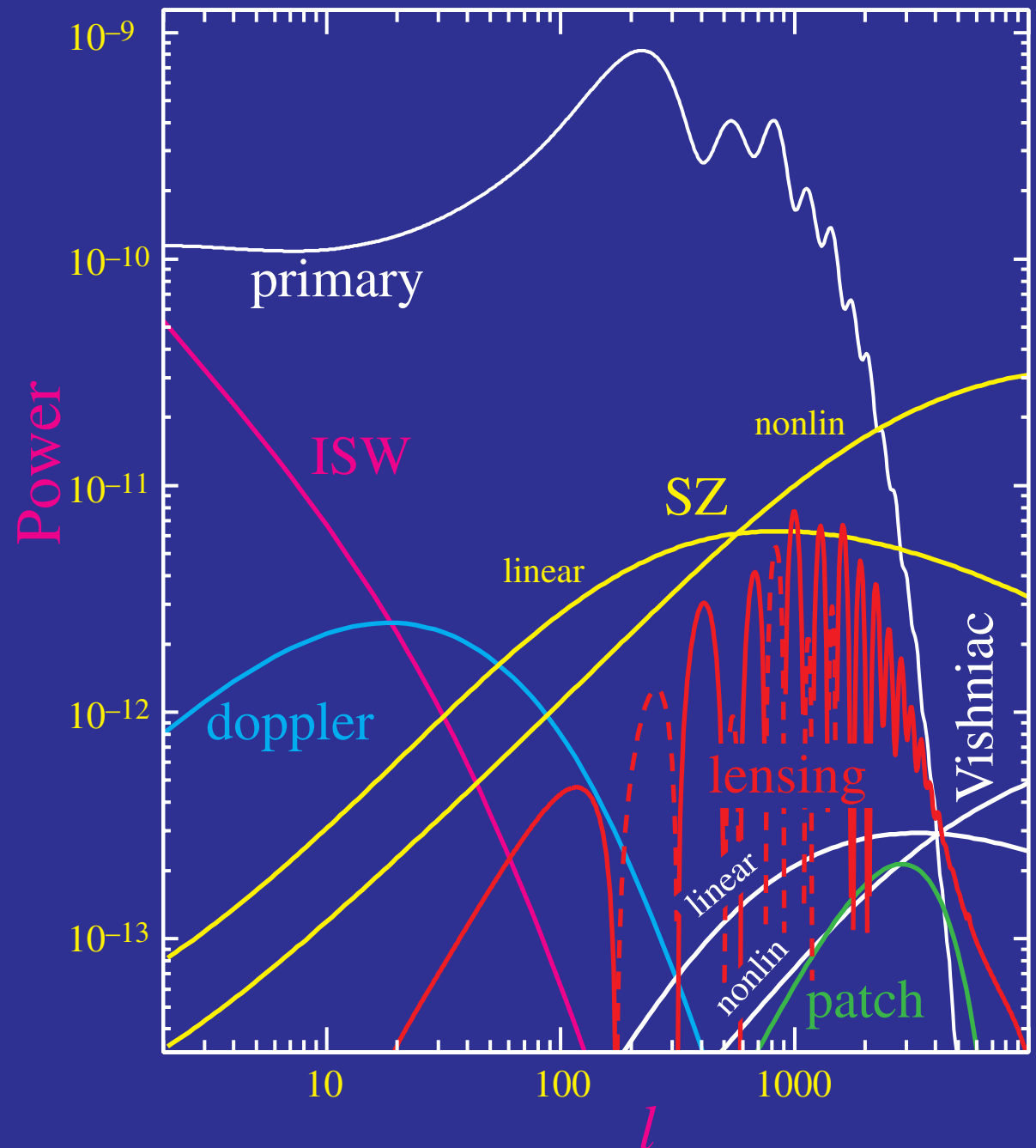
Secondary Anisotropies

- CMB photons **traverse** the **large-scale structure** of the universe
- **Scattering** (\sim few%), gravitational **redshift**, **lensing**



Power in Secondaries

- Gravitational
ISW (redshift) Effect
Weak Lensing
- Scattering
Doppler Effect
Vishniac Effect
Kinetic SZ Effect
Patchy Reionization
Thermal SZ Effect
- Separation
Arcminute Scales
Spectrum
Non-Gaussianity



Summary

- Age of precision cosmology
- Sound waves: inflationary/initial perturbations
- First peak nailed: (nearly?) flat universe
(11 Gyr young universe preferred)
- Second peak constrained: baryonic dark matter
(50% more baryons preferred)
- Degeneracies and ambiguities:
 - dark energy: complementary measures
 - dark matter: higher peaks
 - gravity waves: polarization
 - reionization: polarization & secondaries