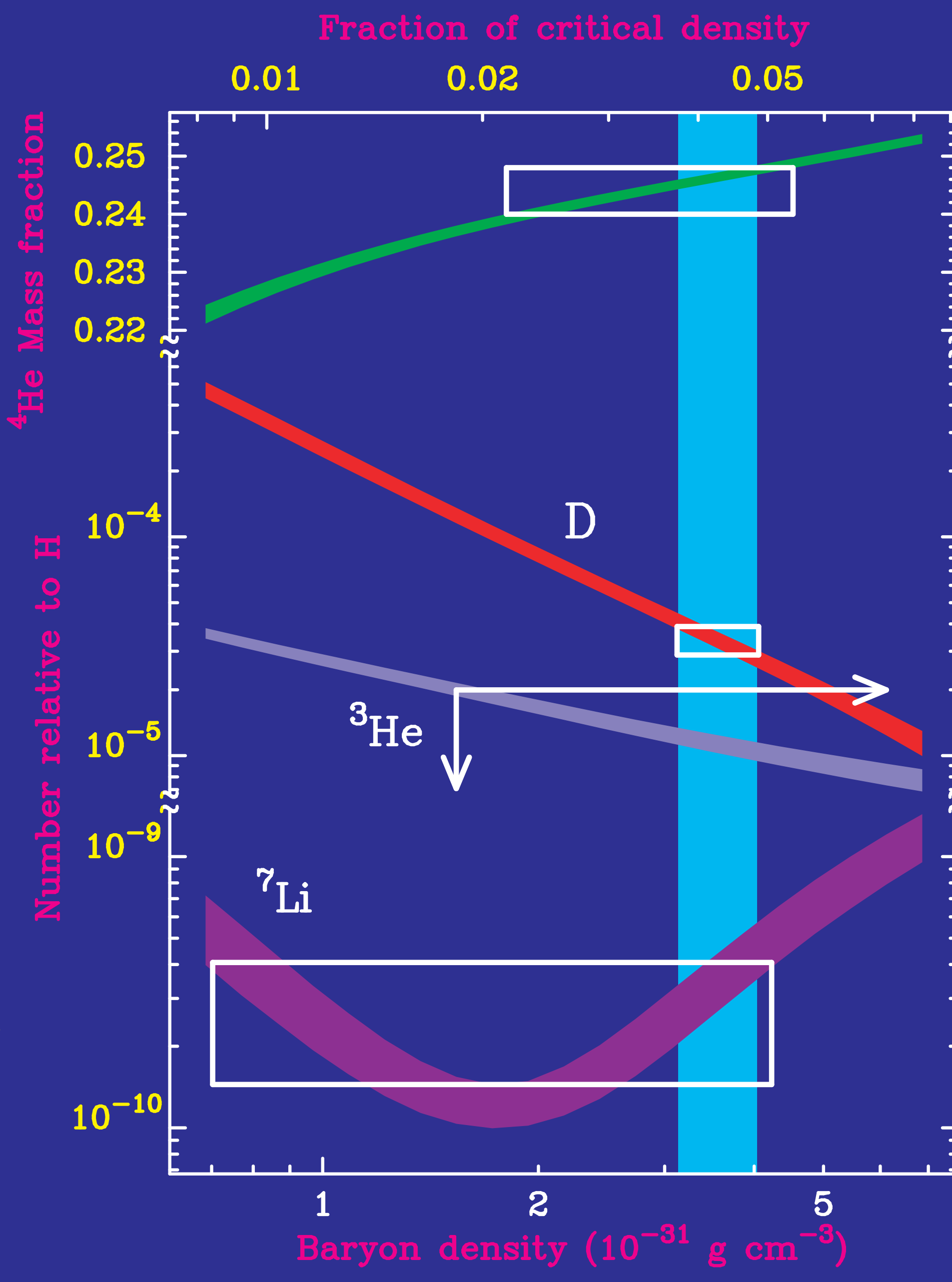
Predicting the CMB: Nucleosynthesis

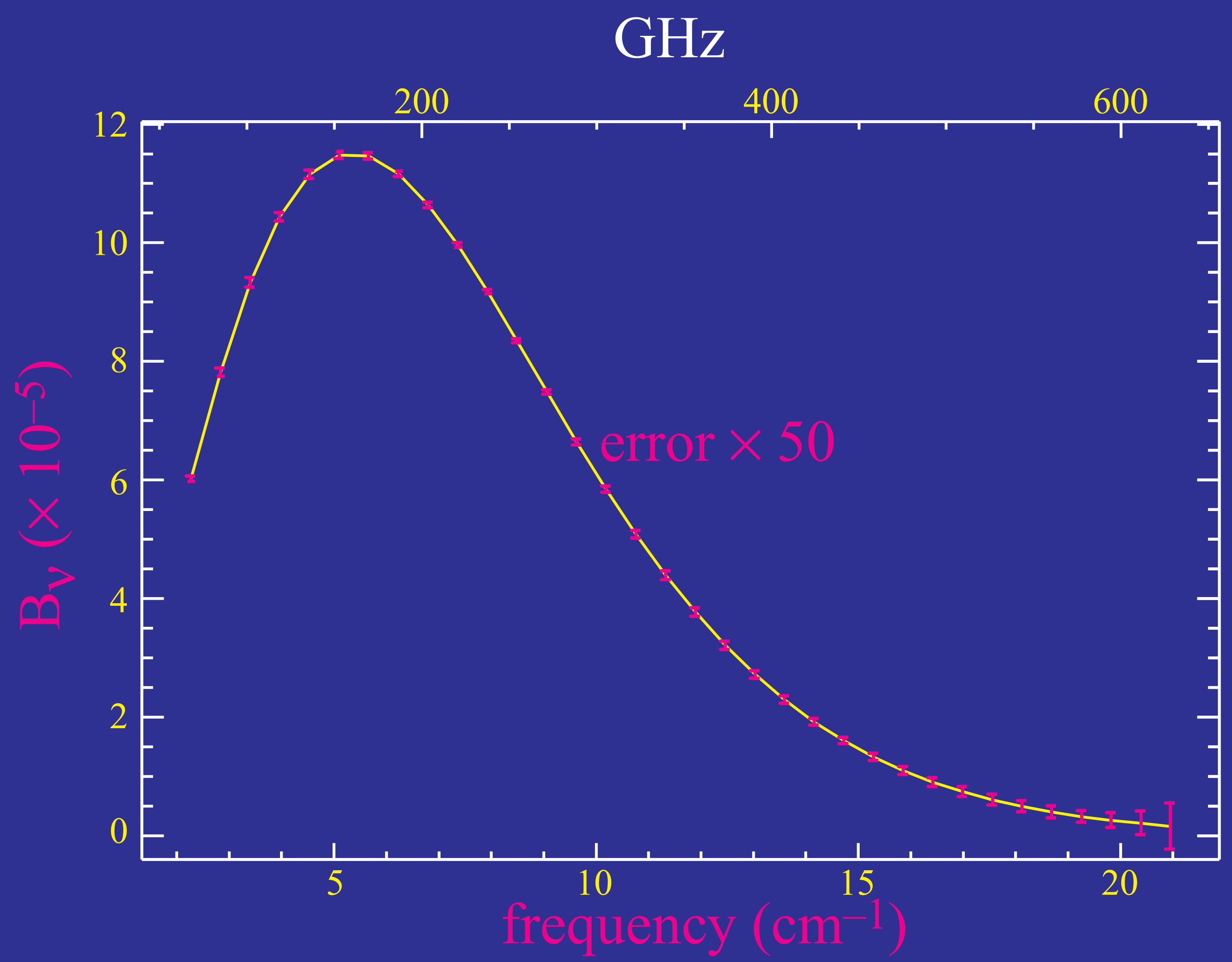
- Light element abundance depends on baryon/photon ratio
- Existence and temperature of CMB originally predicted (Gamow 1948) by light elements + visible baryons
- With the CMB photon number density fixed by the temperature light elements imply dark baryons
- Peaks say that photon-baryon ratio at MeV and eV scales are same



Burles, Nollett, Turner (1999)

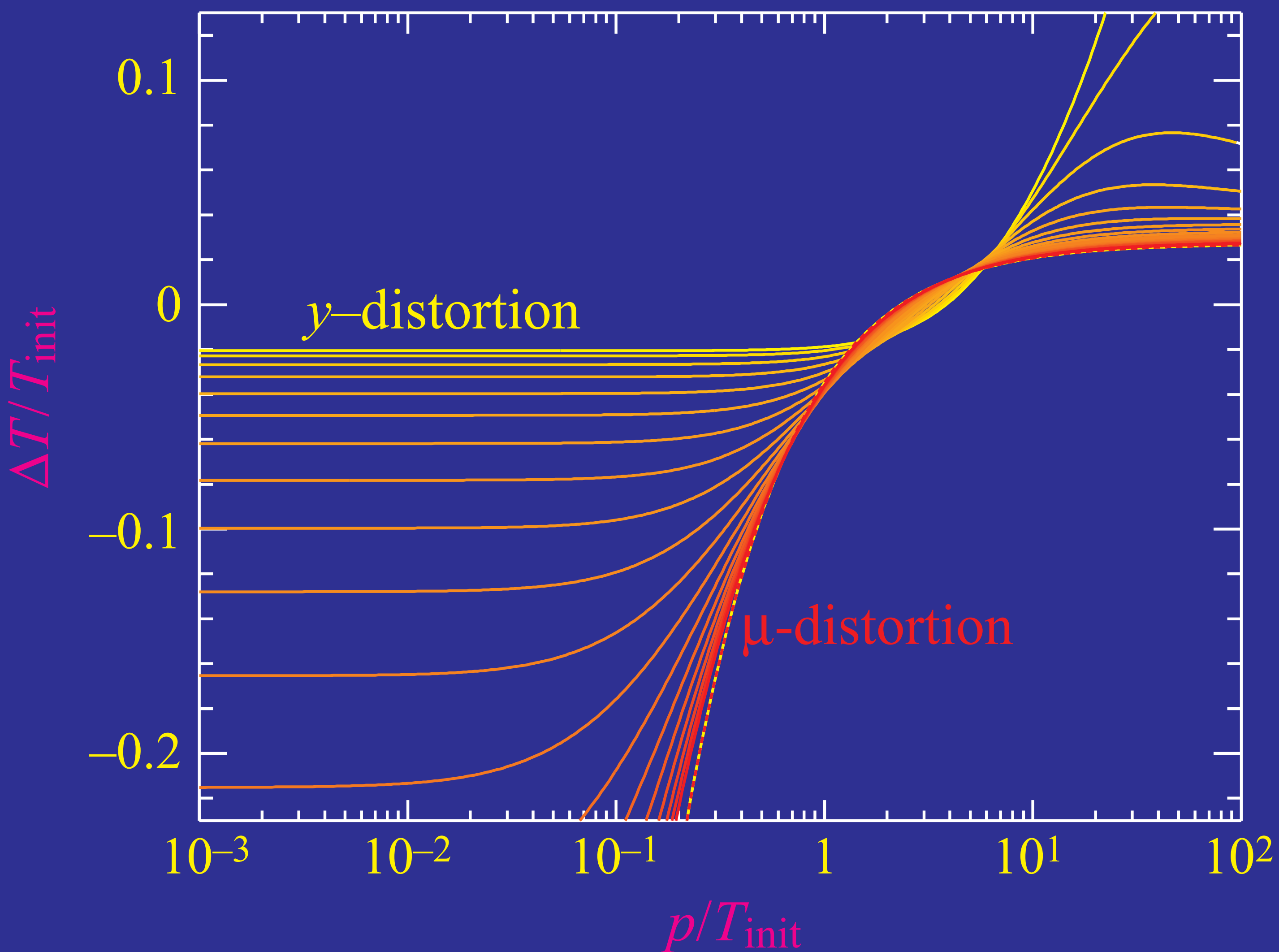
Spectrum

- FIRAS Spectrum
- Perfect Blackbody – μ=0 (t=1yr equilibrium)



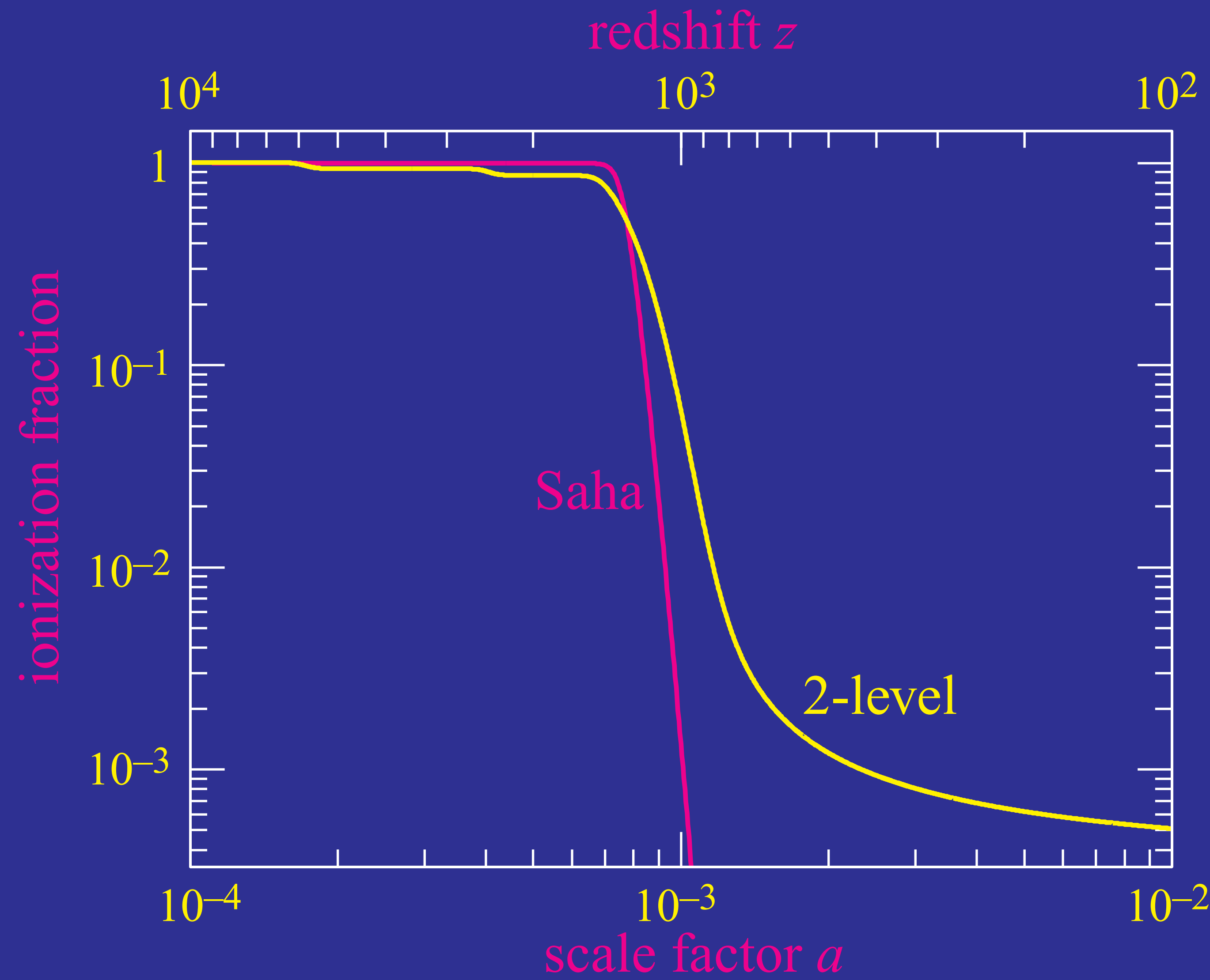
Comptonization

- Compton upscattering: *y*–distortion - seen in Galaxy clusters
- Redistribution: μ-distortion



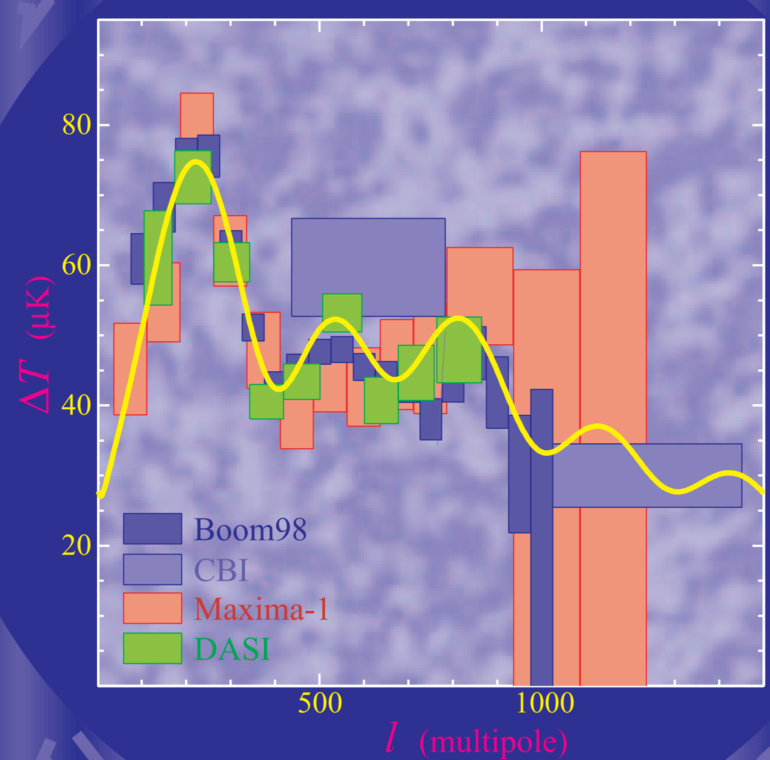
Recombination

- Hung up by Lyα opacity (2γ forbidden transition + redshifting)
- Frozen out with a finite residual ionization fraction



CMB Anisotropies:

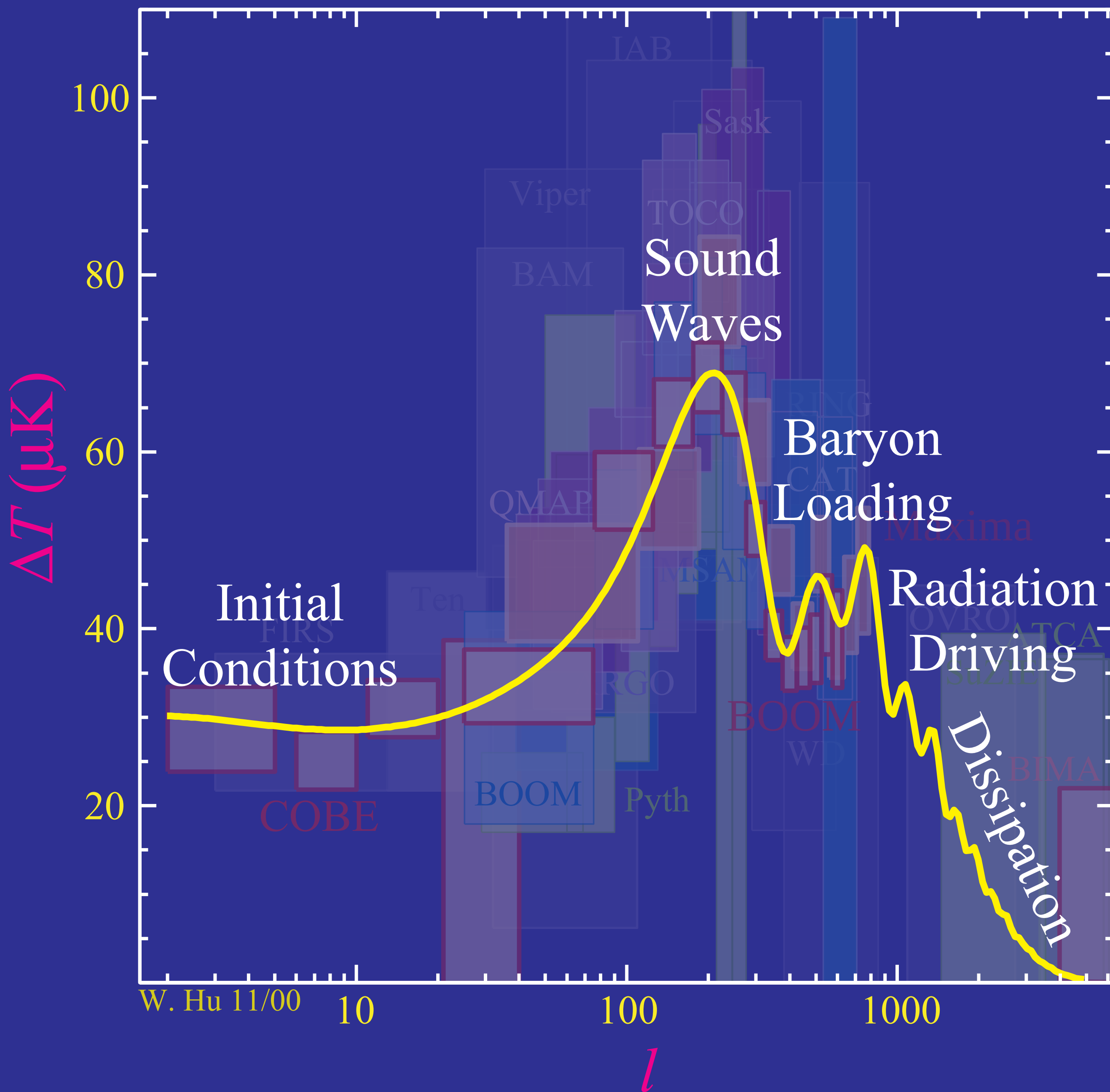
The Acoustic Peaks



Astro 282, Spring 2006

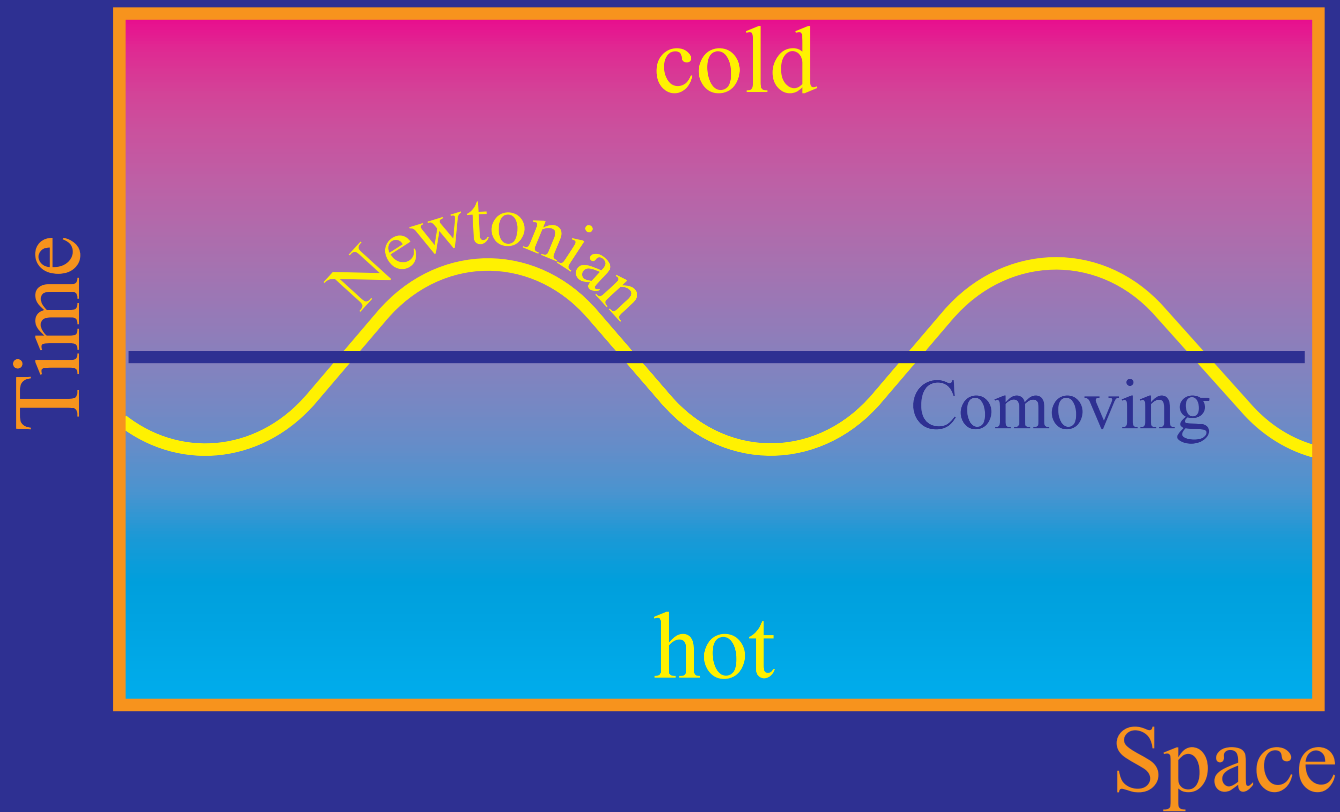
Wayne Hu

Physical Landscape



Inflation and the Initial Conditions

- Inflation: (nearly) scale-invariant curvature (potential) perturbations
- Superluminal expansion → superhorizon scales → "initial conditions"
- Accompanying temperture perturbations due to cosmological redshift



- Potential perturbation Ψ = time-time metric perturbation

$$\delta t/t = \Psi \quad \rightarrow \quad \delta T/T = -\delta a/a = -2/3\,\delta t/t = -2/3\,\Psi$$

Sachs & Wolfe (1967); White & Hu (1997)

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

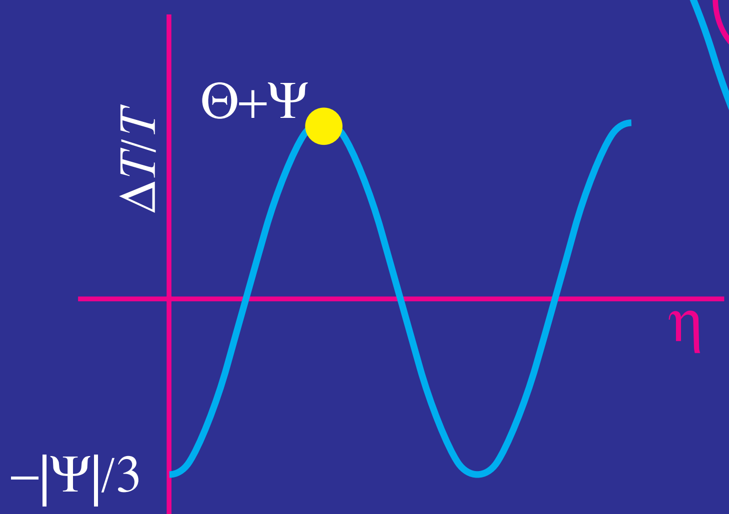
- Frequency proportional to wavenumber: $\omega = kc_s$
- Twice the wavenumber = twice the frequency of oscillation

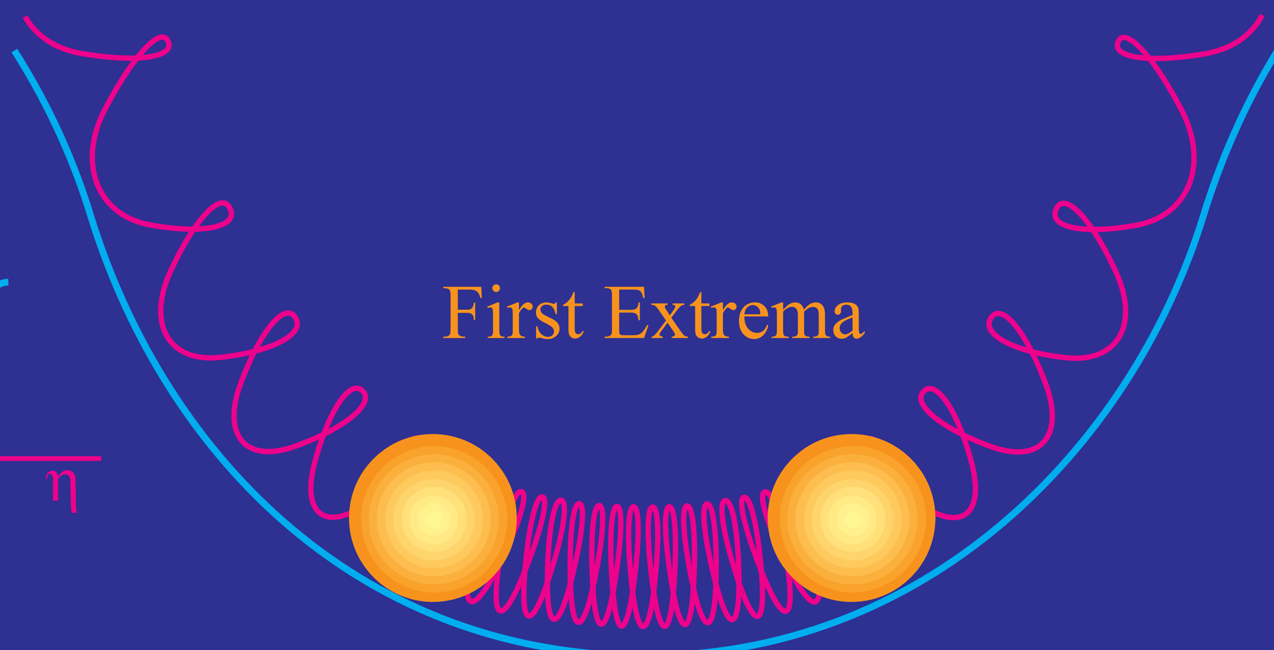
Seeing Sound

- Oscillations frozen at recombination
- Compression=hot spots, Rarefaction=cold spots

Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations
- Gravity displaces zero point
  $\Theta \equiv \delta T/T = -\Psi$
- Oscillation amplitude = initial displacement from zero pt.
  $\Theta - (-\Psi) = 1/3\Psi$
- Gravitational redshift: observed
  $(\delta T/T)_{\mathrm{obs}} = \Theta + \Psi$
  oscillates around zero





Peebles & Yu (1970)

Hu & Sugyama (1995); Hu, Sugiyama & Silk (1997)

Acoustic Oscillations

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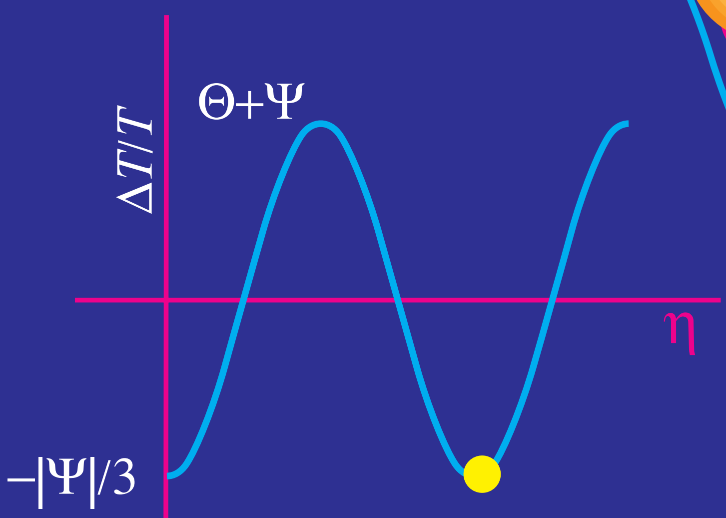
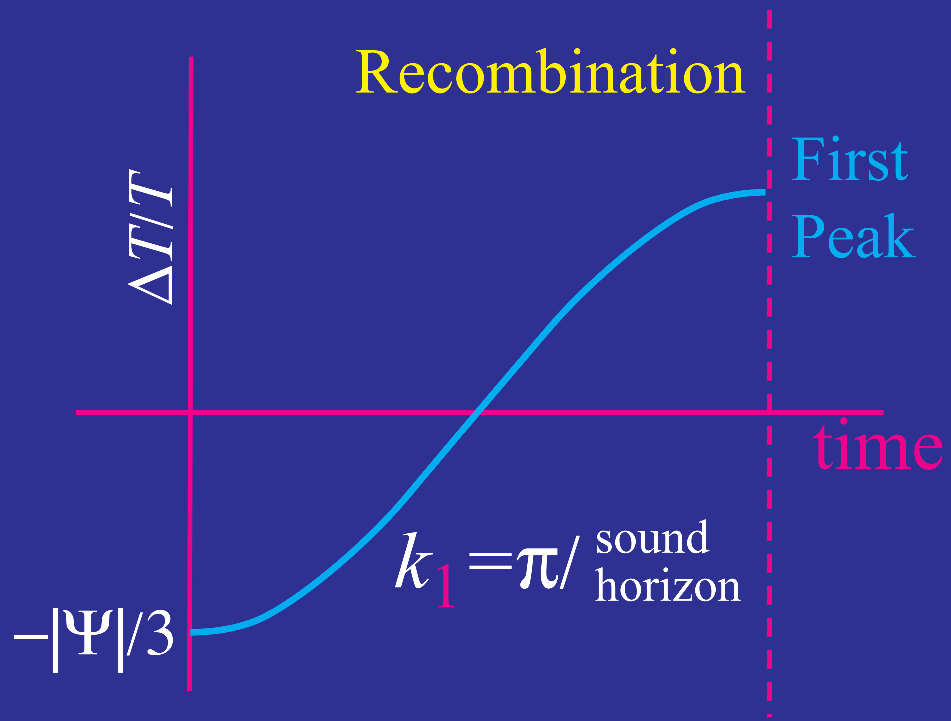


Peebles & Yu (1970)

Hu & Sugyama (1995); Hu, Sugiyama & Silk (1997)

Extrema=Peaks

- First peak = mode that just compresses



N.B.: "compression" short for

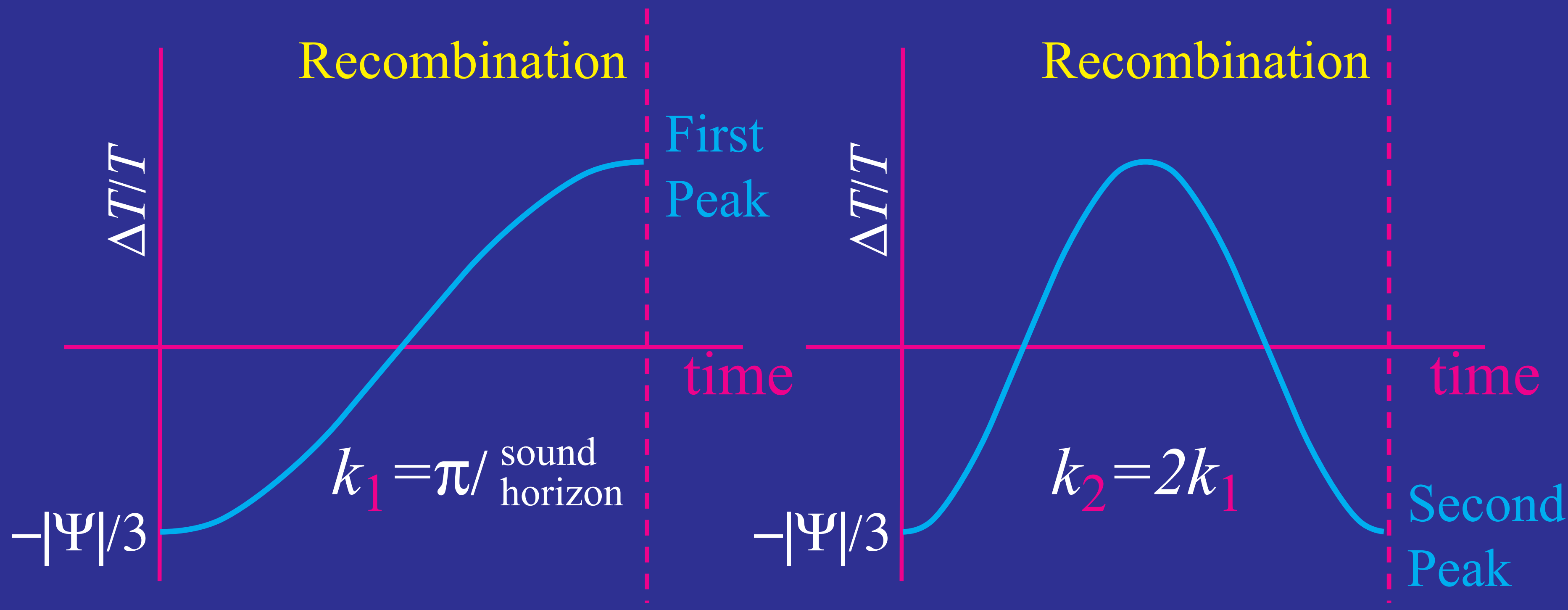
compression inside *potential wells*

and

rarefaction inside *potential hills*

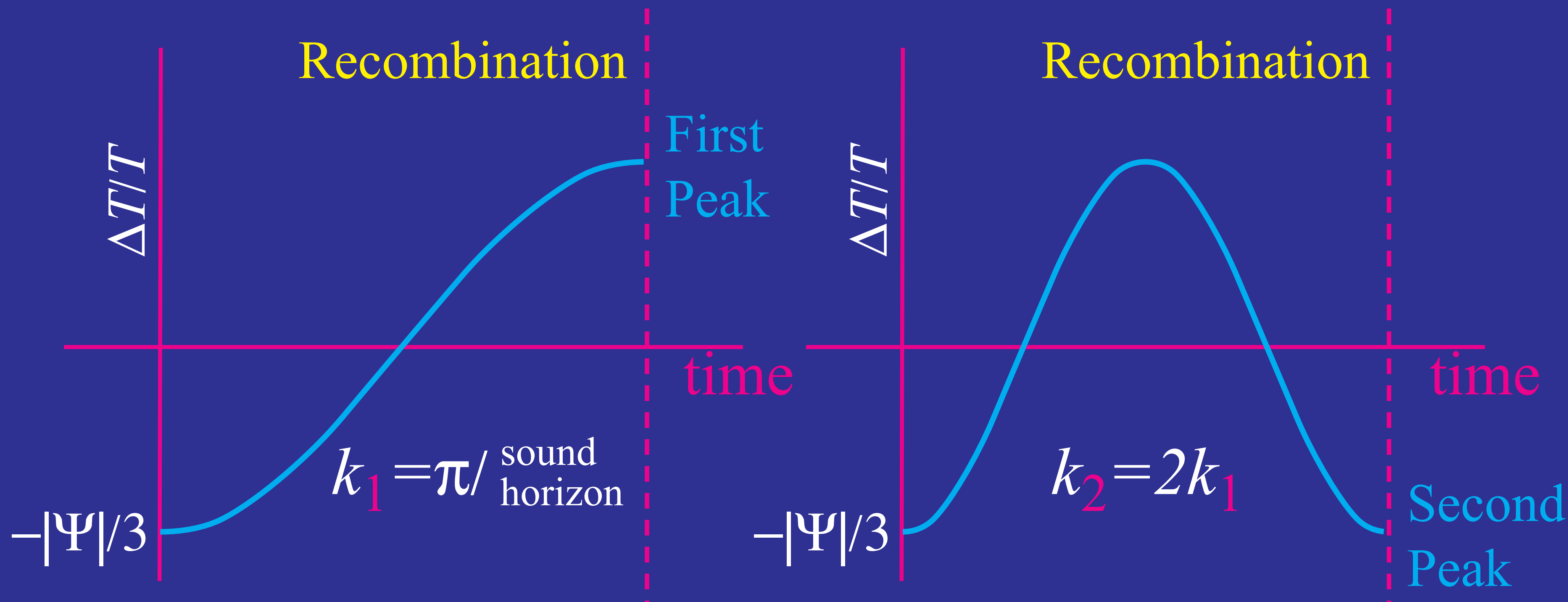
Extrema=Peaks

- First peak = mode that just compresses
- Second peak = mode that compresses then rarefies: twice the wavenumber



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



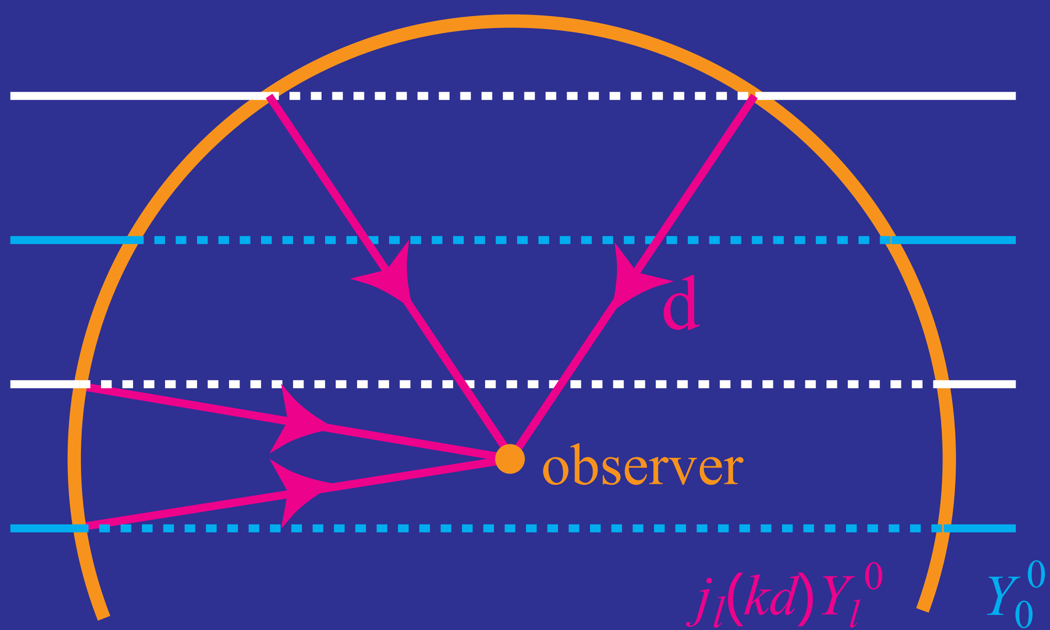
Angular Peaks

Peaks in Angular Power

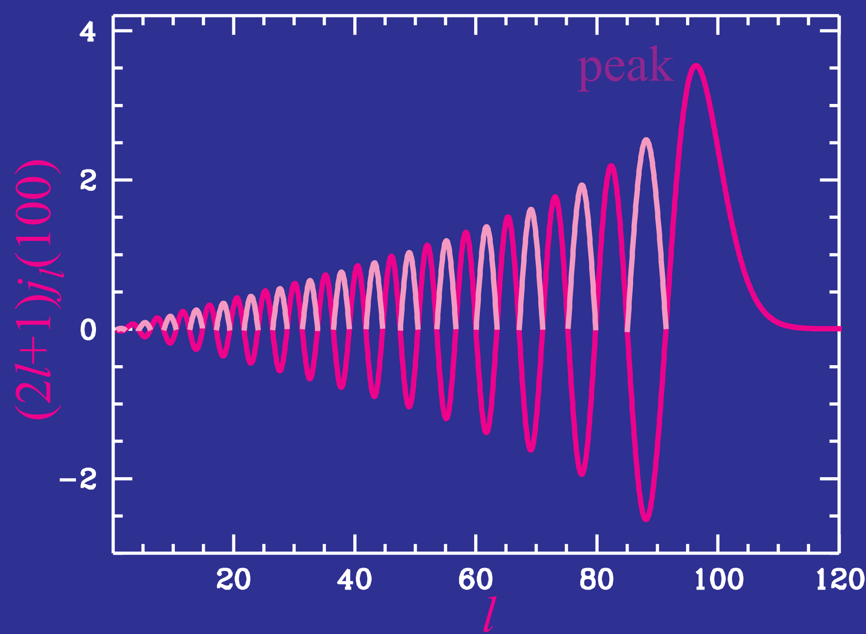
- The Anisotropy Formation Process

Projection into Angular Peaks

- Peaks in spatial power spectrum
- Projection on sphere
- Spherical harmonic decomposition
- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- Described by spherical bessel function $j_l(kd)$



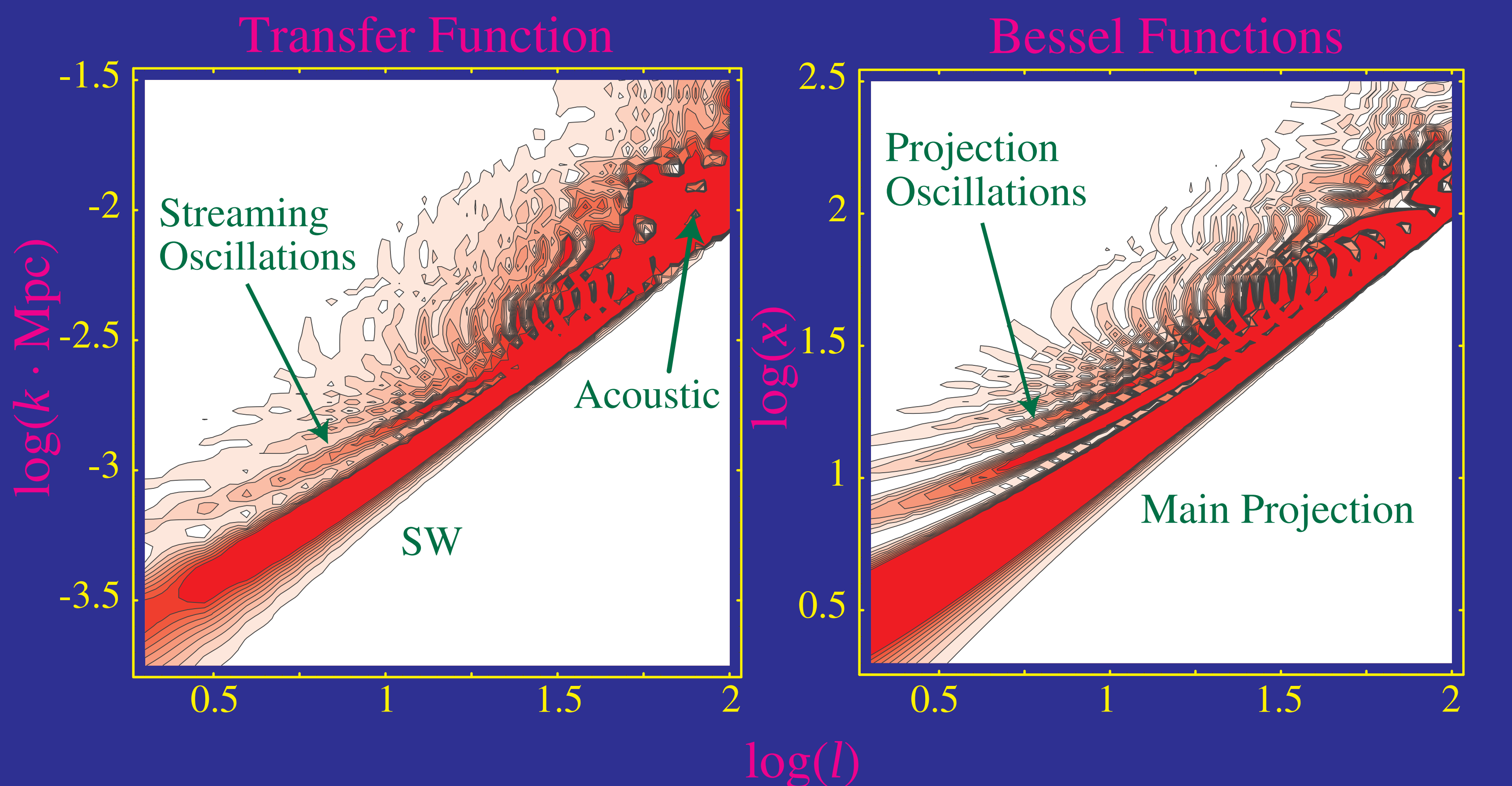
Bond & Efstathiou (1987)



Hu & Sugiyama (1995); Hu & White (1997)

Projection into Angular Peaks

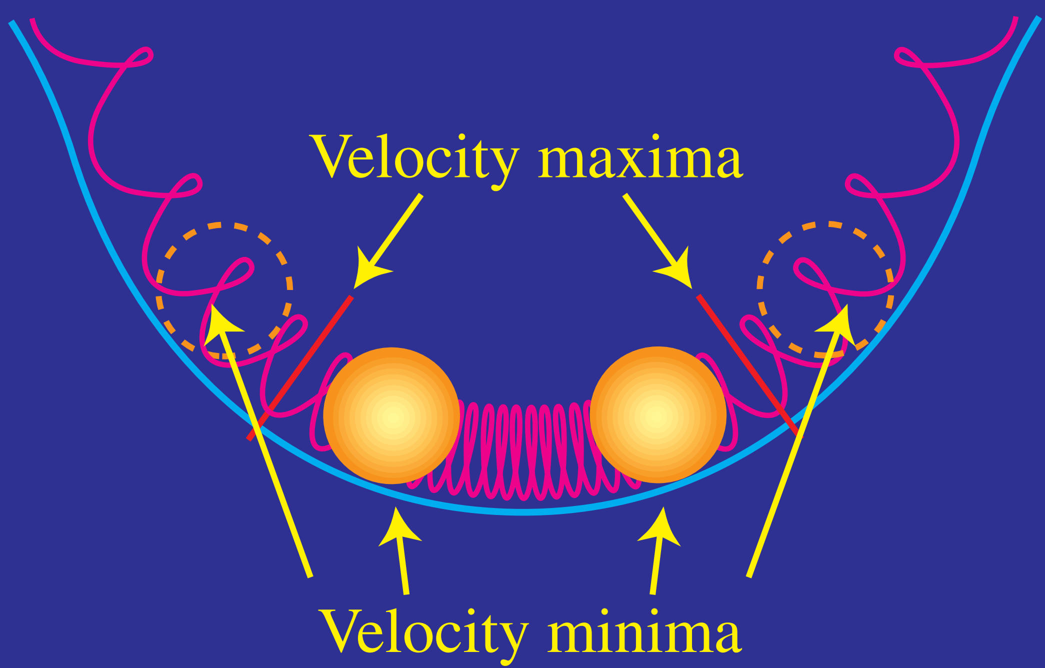
- Peaks in spatial power spectrum
- Projection on sphere
- Spherical harmonic decomposition
- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- 2D Transfer Function
  $T^2(k,l) \sim (2l+1)^2\,[\Delta T/T]^2\, j_l^2(kd)$



Hu & Sugiyama (1995)

Doppler Effect

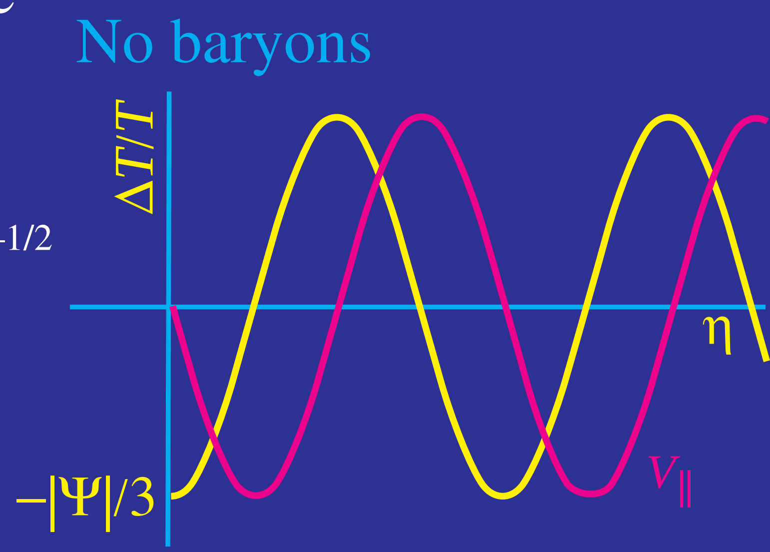
- Relative velocity of fluid and observer
- Extrema of oscillations are turning points or velocity zero points
- Velocity $\pi/2$ out of phase with temperature

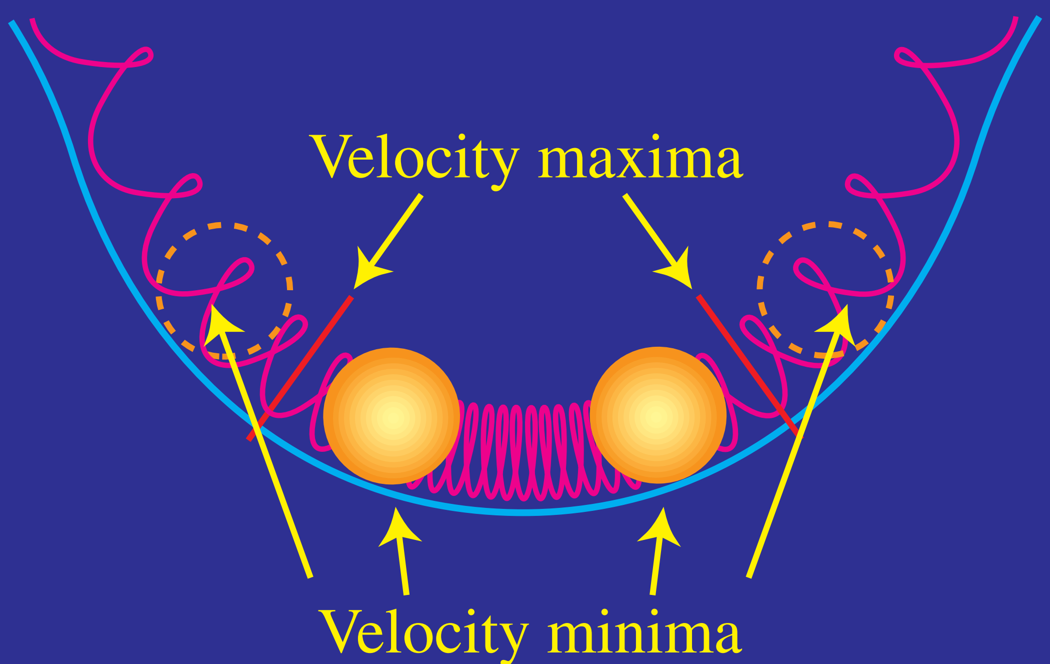


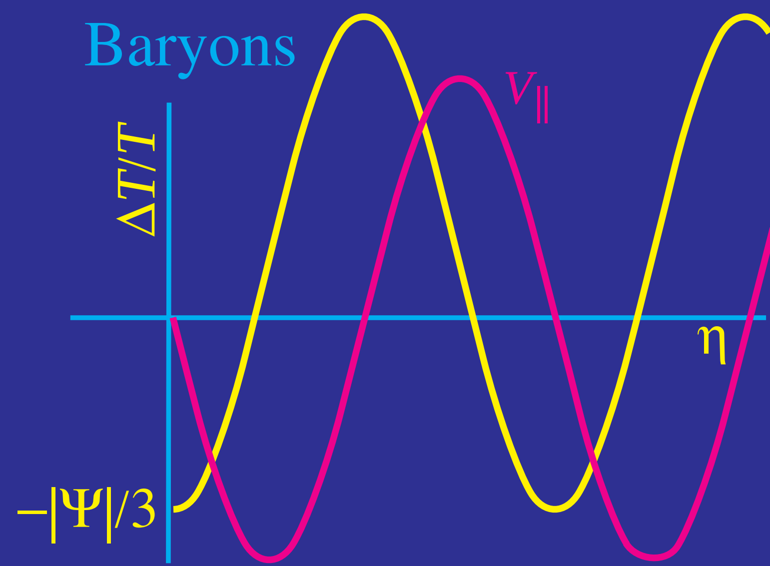
Doppler Effect

- Relative velocity of fluid and observer
- Extrema of oscillations are turning points or velocity zero points
- Velocity $\pi/2$ out of phase with temperature
- Zero point not shifted by baryon drag
- Increased baryon inertia decreases effect

$$m_{\rm eff} V^2 = \text{const.} \qquad V \propto m_{\rm eff}^{-1/2} = (1+R)^{-1/2}$$

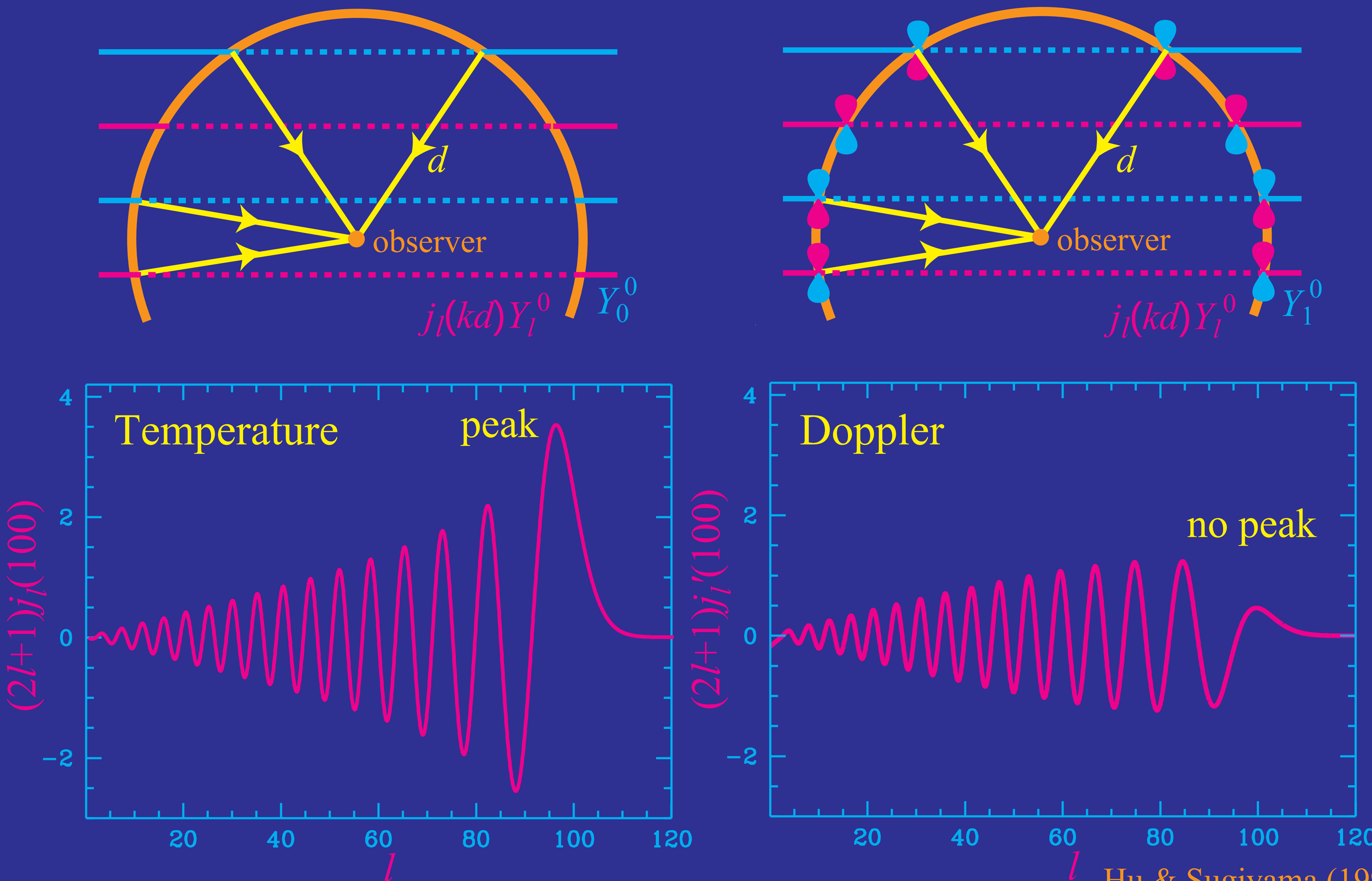






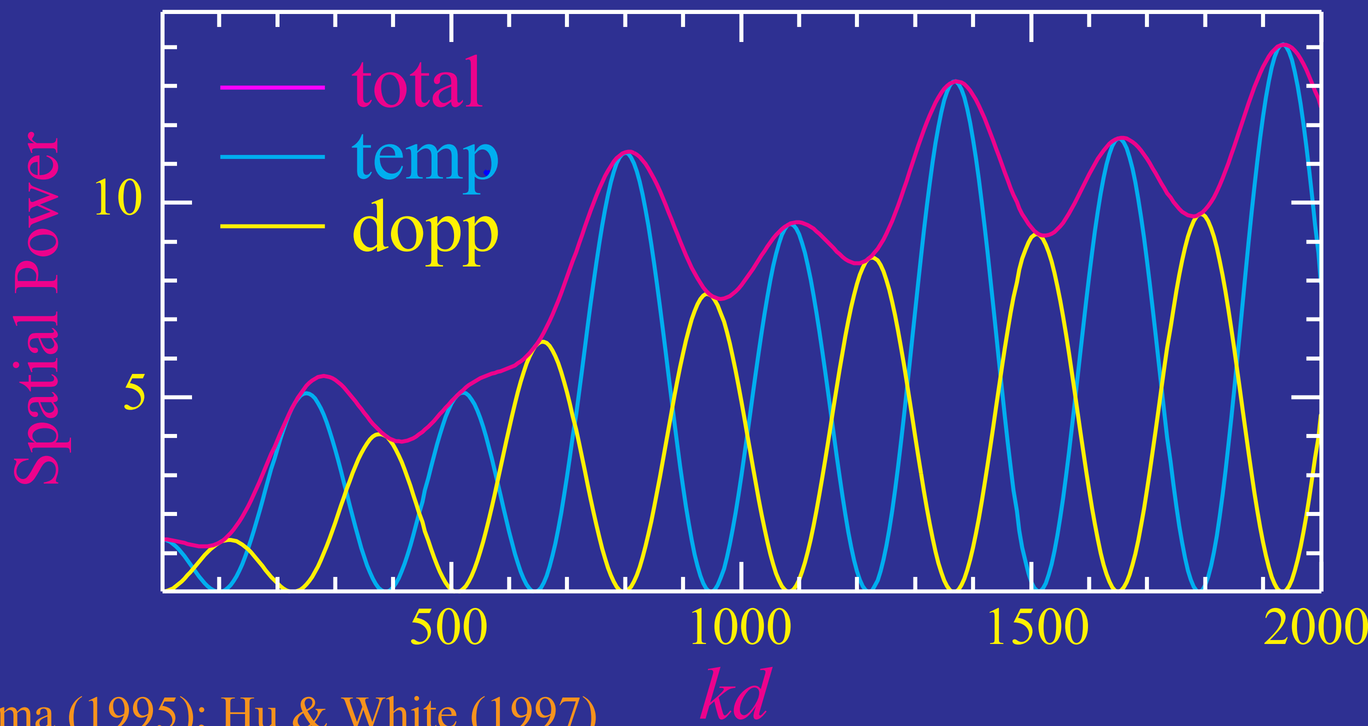
Doppler Peaks?

- Doppler effect has lower amplitude and weak features from projection



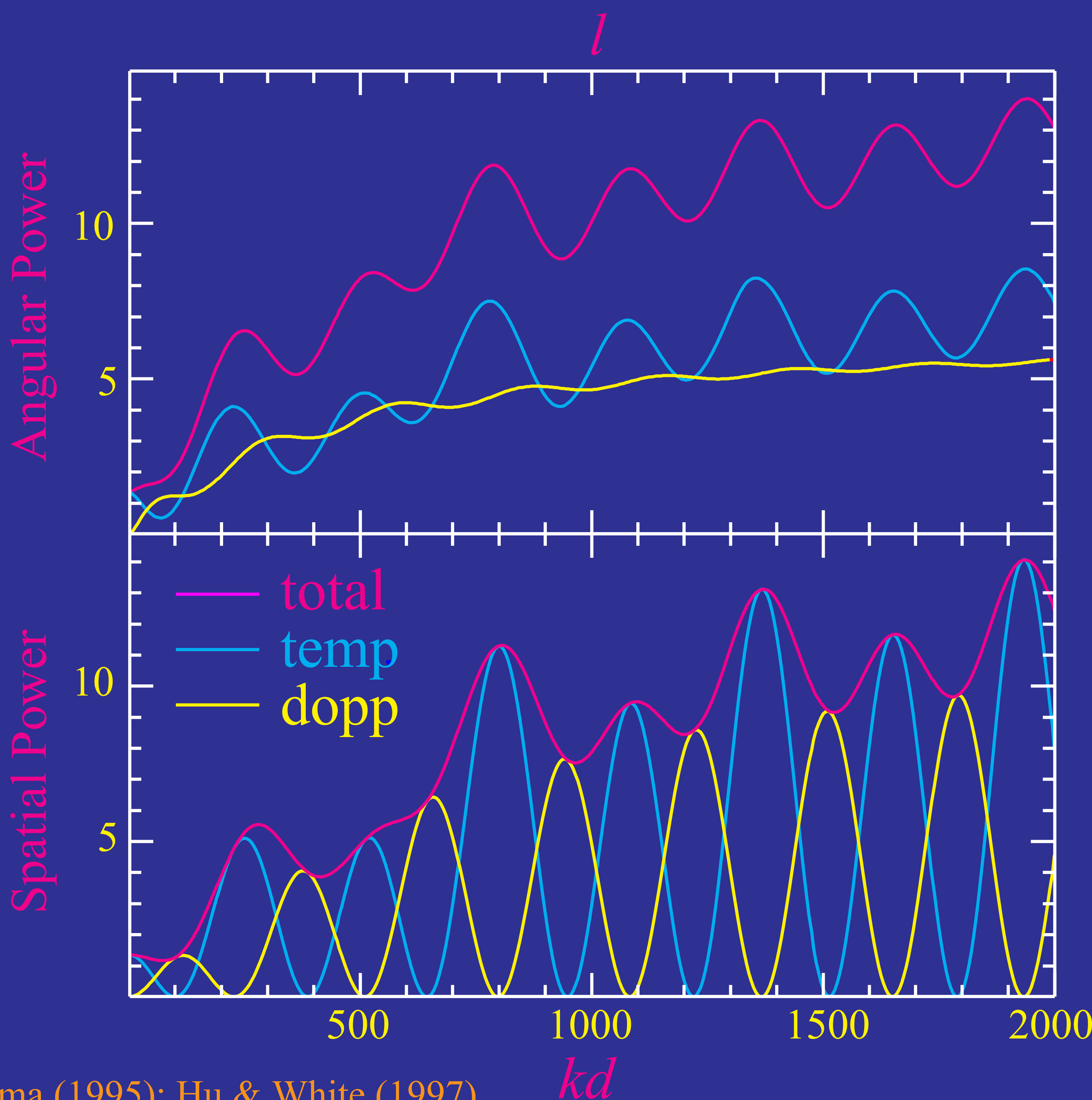
Hu & Sugiyama (1995)

Relative Contributions



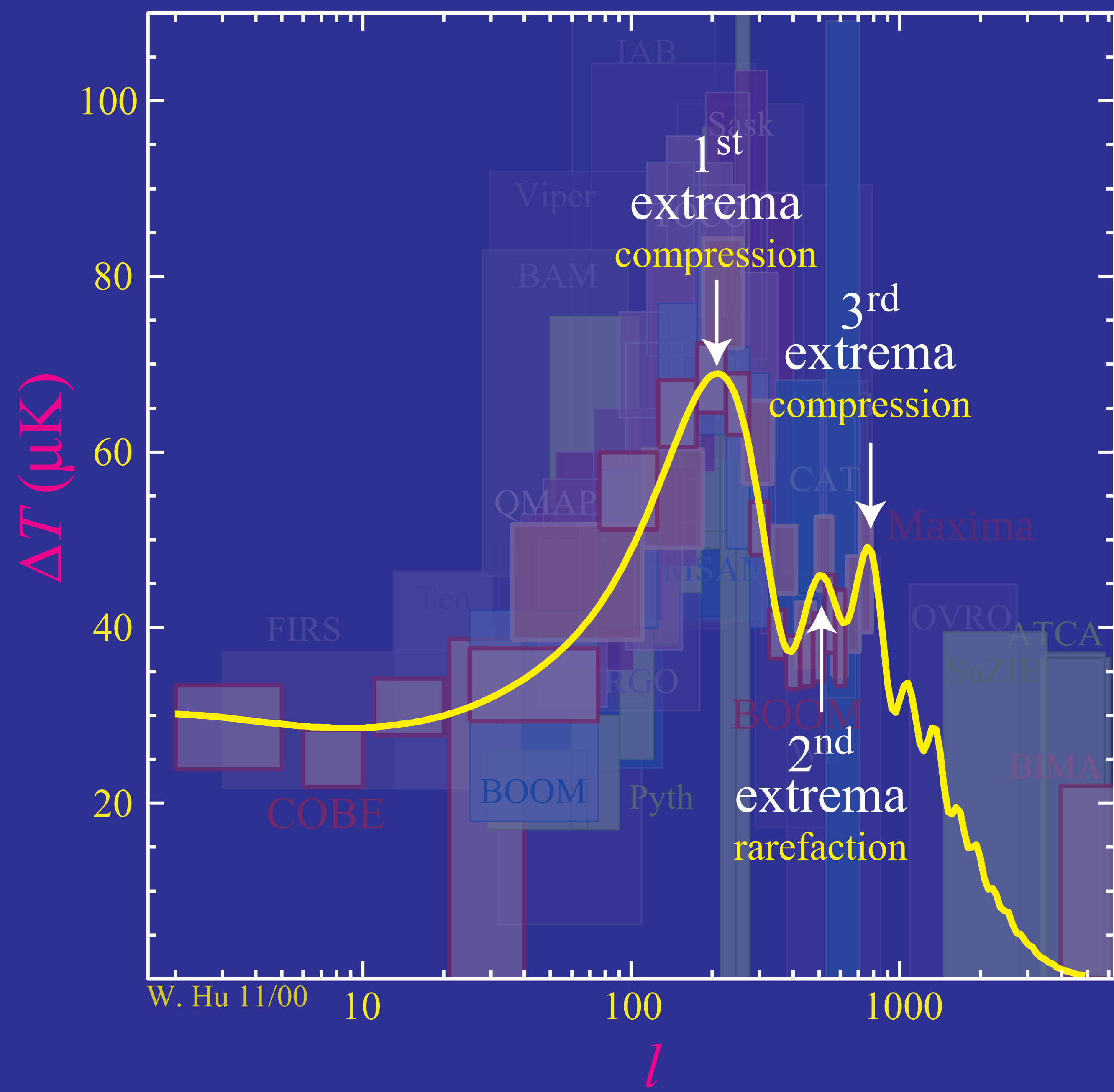
Hu & Sugiyama (1995); Hu & White (1997)

Relative Contributions



Hu & Sugiyama (1995); Hu & White (1997)

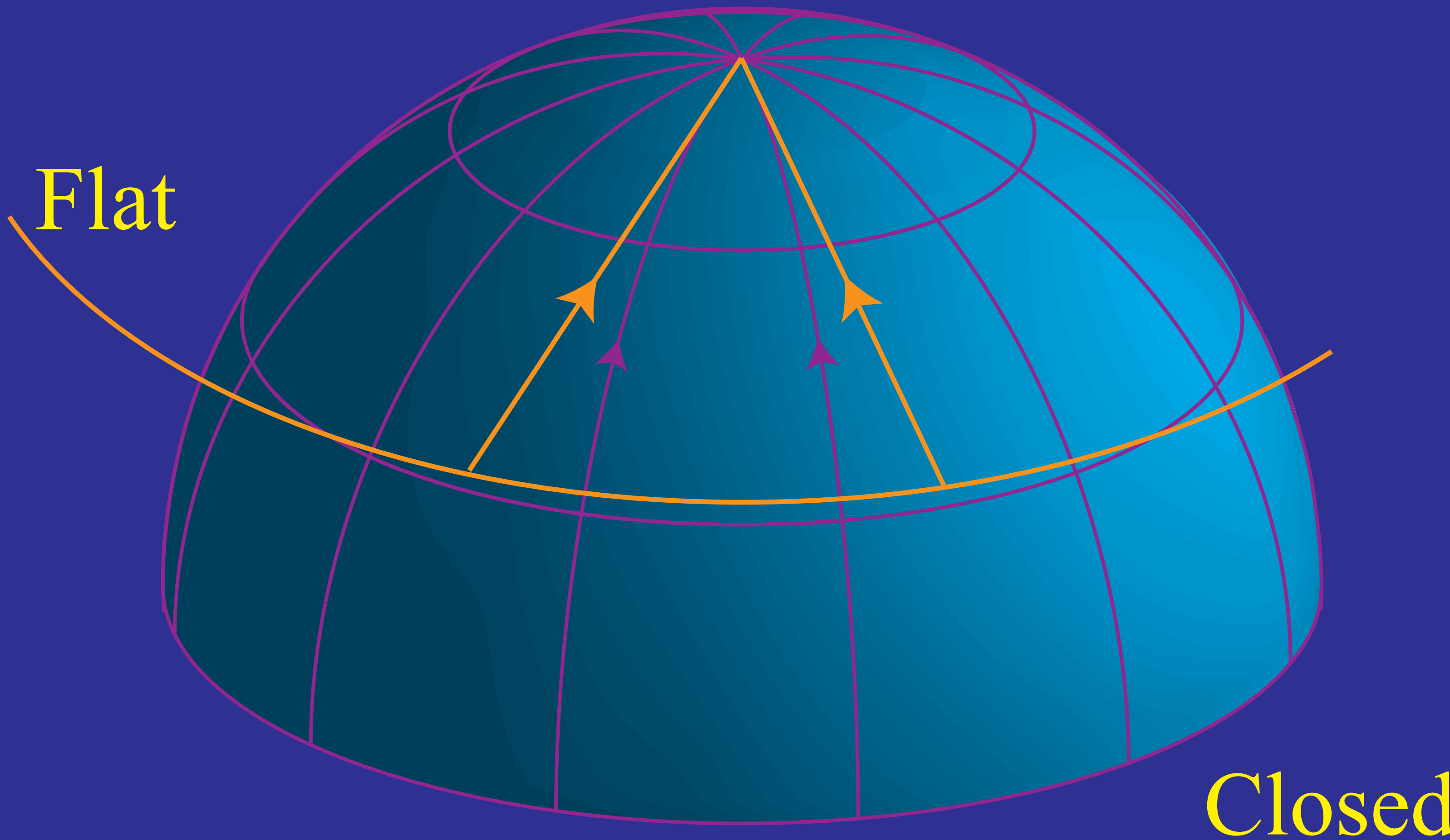
Acoustic Landscape



The First Peak

Spatial Curvature

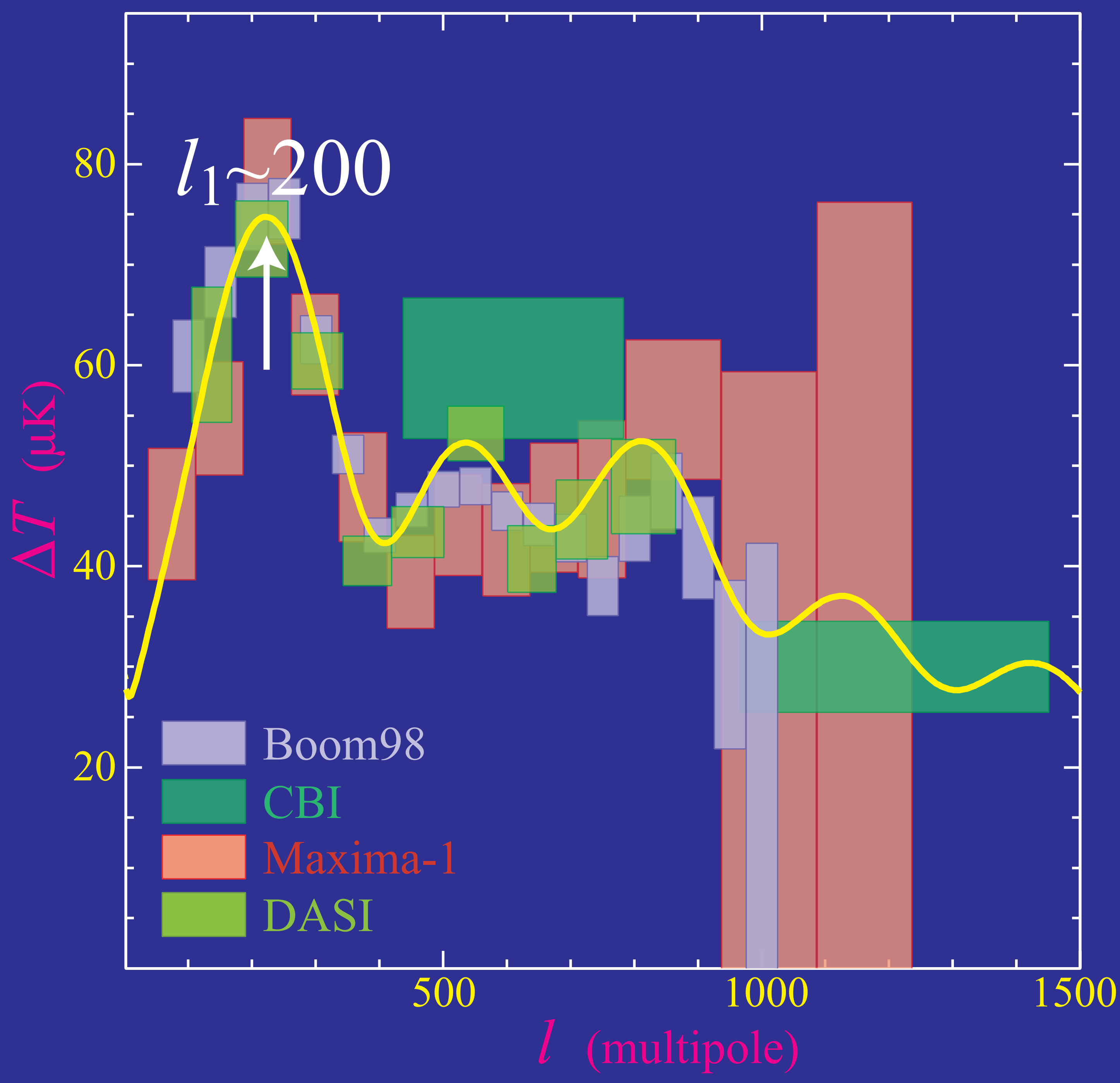
- Physical scale of peak = distance sound travels
- Angular scale measured: comoving angular diameter distance test for curvature



Curvature in the Power Spectrum

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

First Peak Precisely Measured



Standard Rulers

- Calibrating the Standard Rulers

- Sound Horizon

- Damping Scale

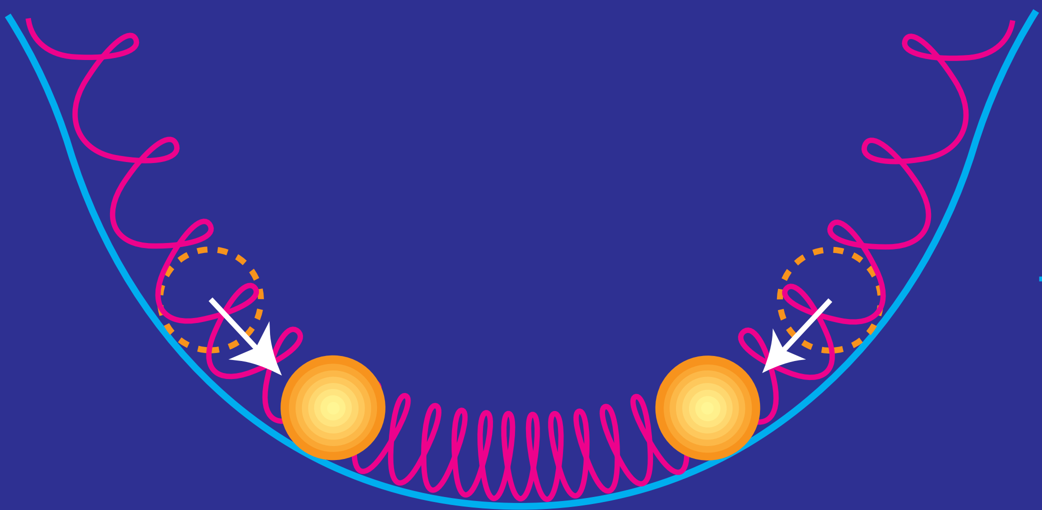
The Second Peak

Baryon & Inertia

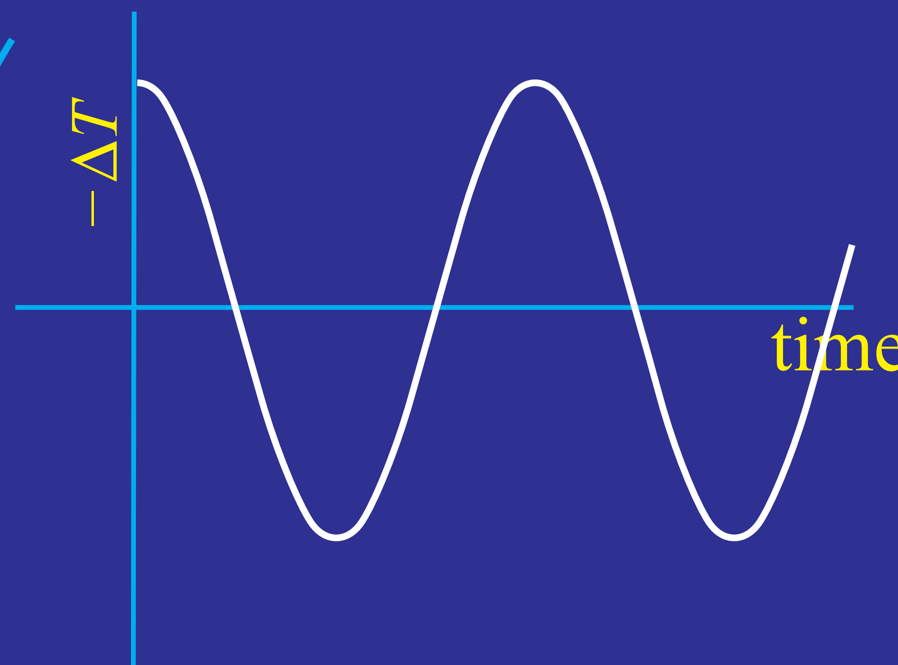
- Baryons add inertia to the fluid
- Equivalent to adding mass on a spring
- Same initial conditions
- Same null in fluctuations
- Unequal amplitudes of extrema

A Baryon-meter

- Low baryons: symmetric compressions and rarefactions

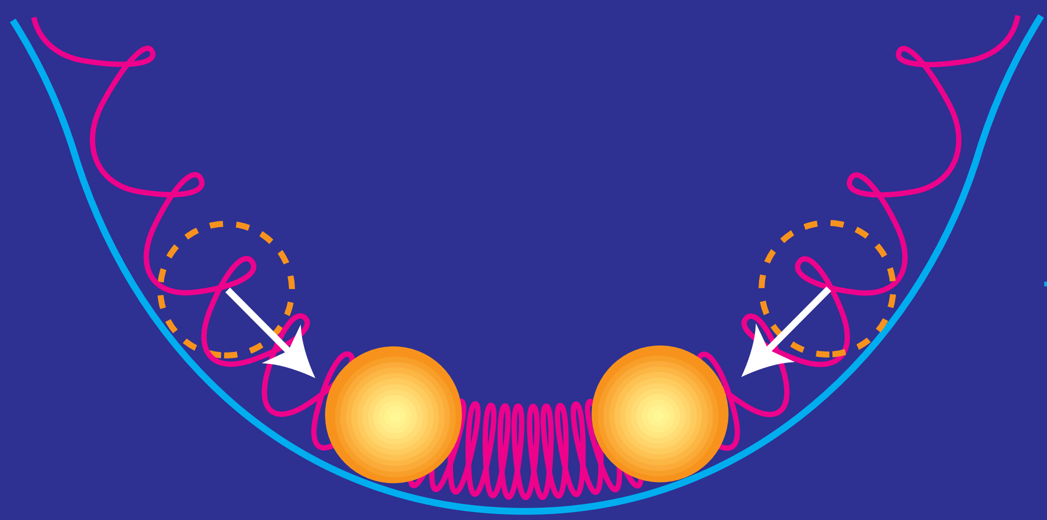


Low Baryons

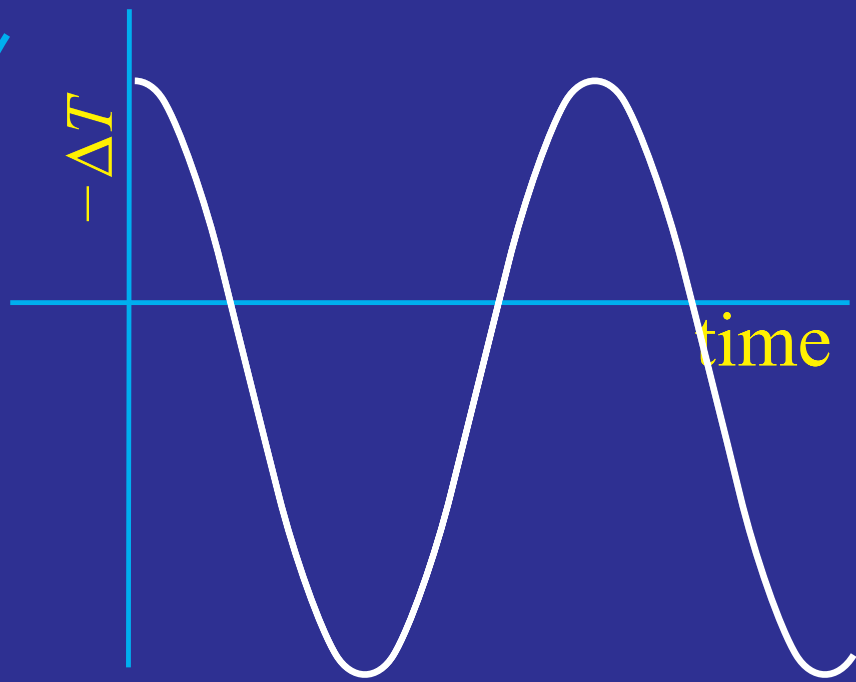


A Baryon-meter

- Load the fluid adding to gravitational force
- Enhance compressional peaks (odd) over rarefaction peaks (even)



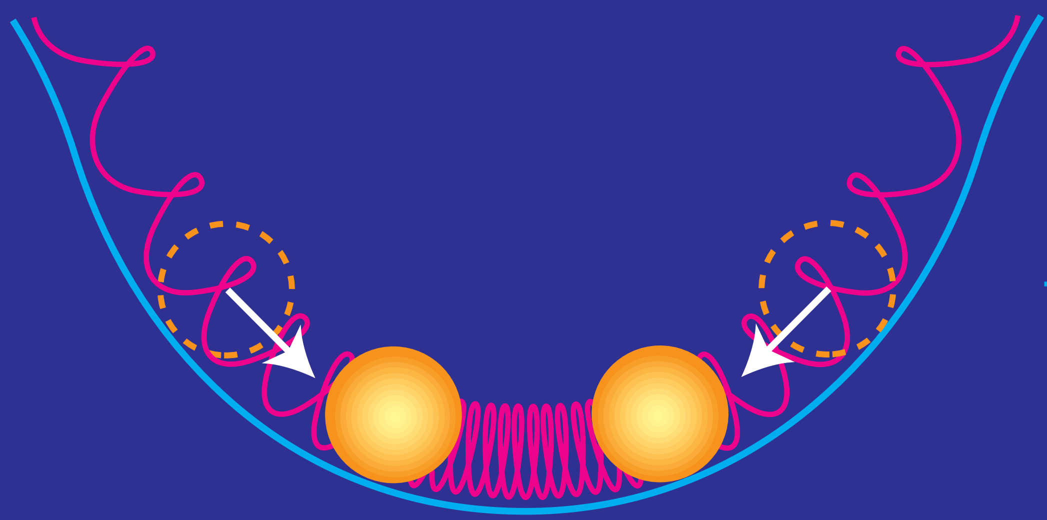
Baryon Loading

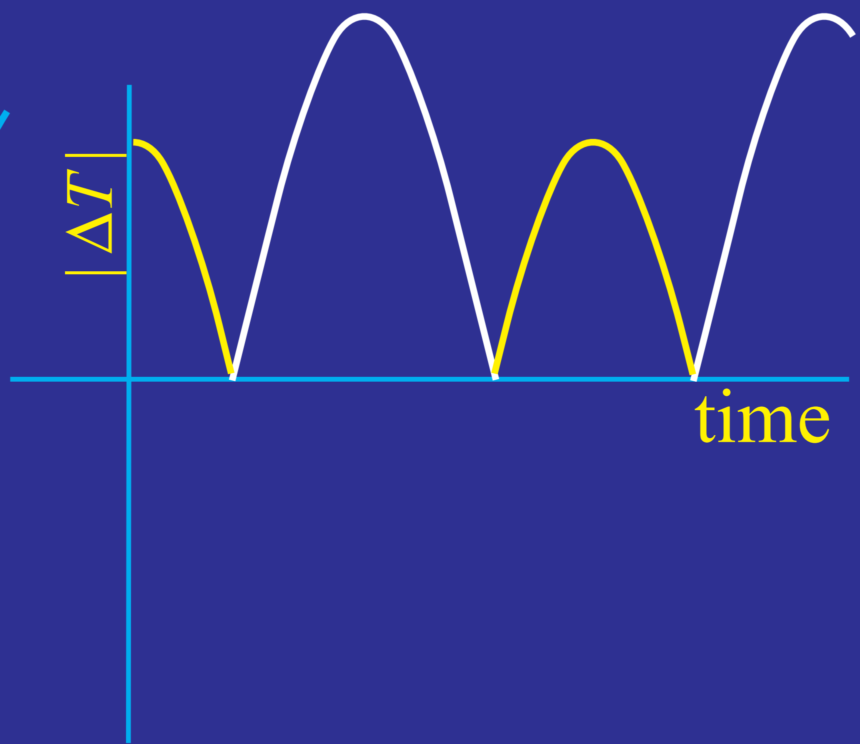


A Baryon-meter

- Enhance compressional peaks (odd) over rarefaction peaks (even)

e.g. relative suppression of second peak



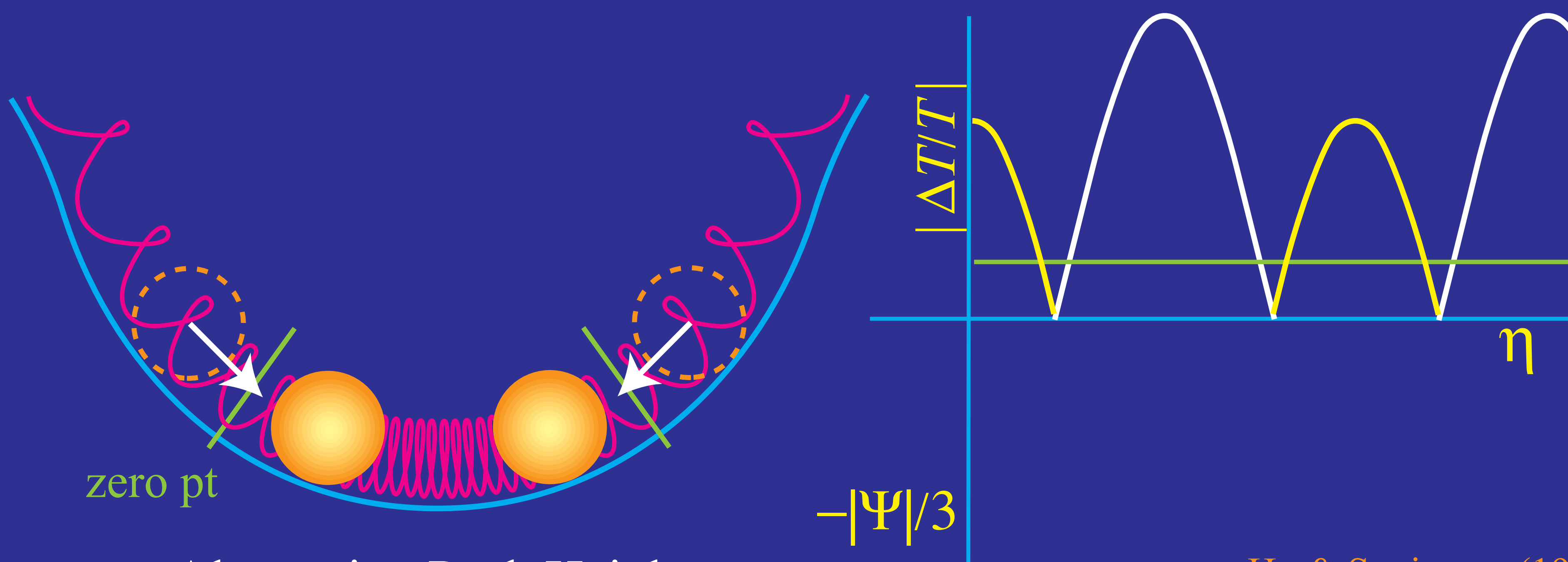


Baryon Loading

- Baryons provide inertia
- Relative momentum density

  $R = (\rho_b + p_b)V_b \, / \, (\rho_\gamma + p_\gamma)V_\gamma \propto \Omega_b h^2$
- Effective mass $m_{\rm eff} = (1 + R)$
- Baryons drag photons into potential wells $\rightarrow$ zero point $\uparrow$
- Amplitude $\uparrow$
- Frequency $\downarrow$ $(\omega \propto m_{\rm eff}^{-1/2})$
- Constant R, Ψ: $(1+R)\ddot{\Theta} + (k^2/3)\Theta = -(1+R)(k^2/3)\Psi$

$$\Theta + \Psi = [\Theta(0) + (1+R)\Psi(0)] \cos [\, k\eta/\sqrt{3(1+R)}] - R\Psi$$

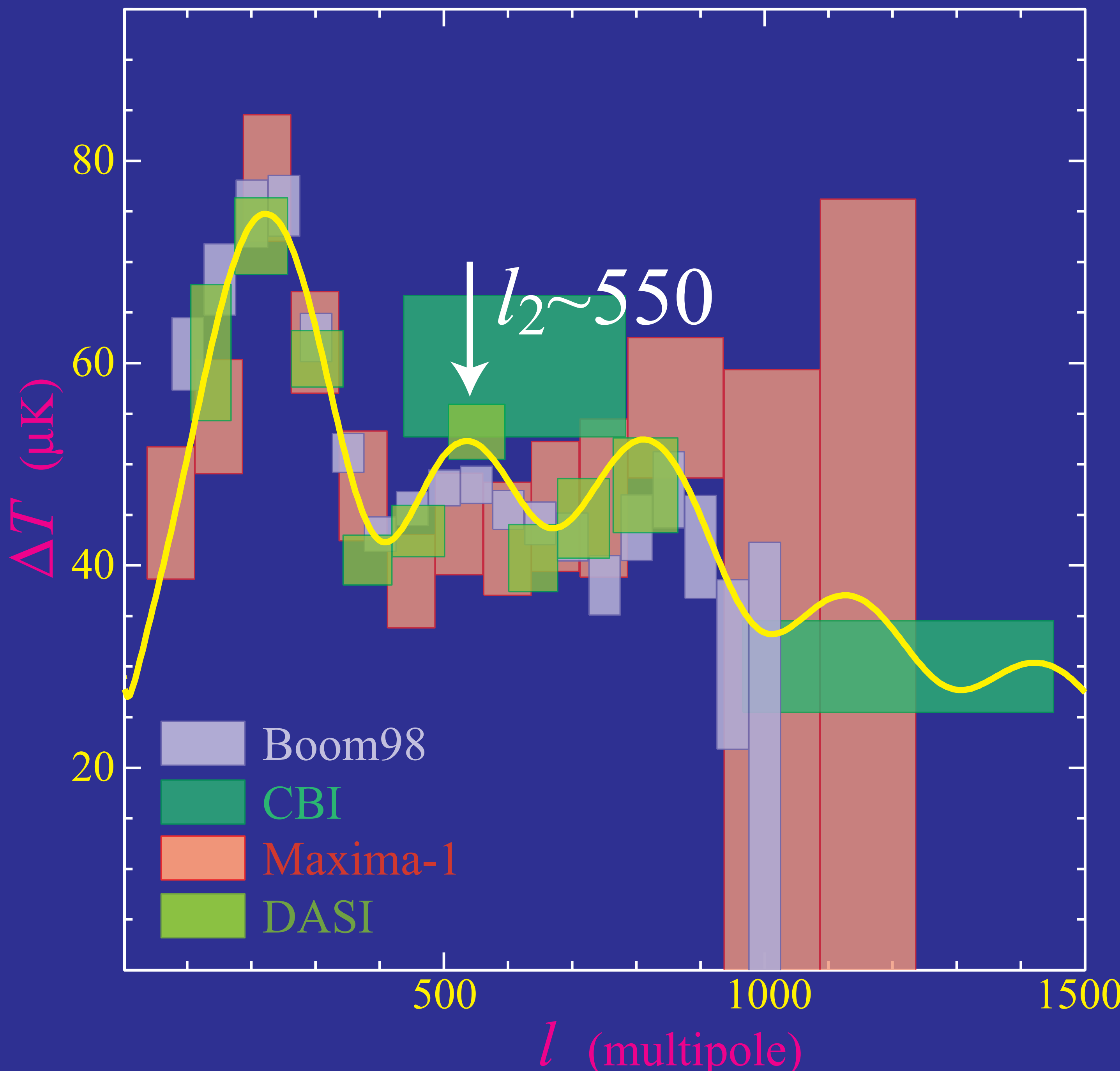


Alternating Peak Heights

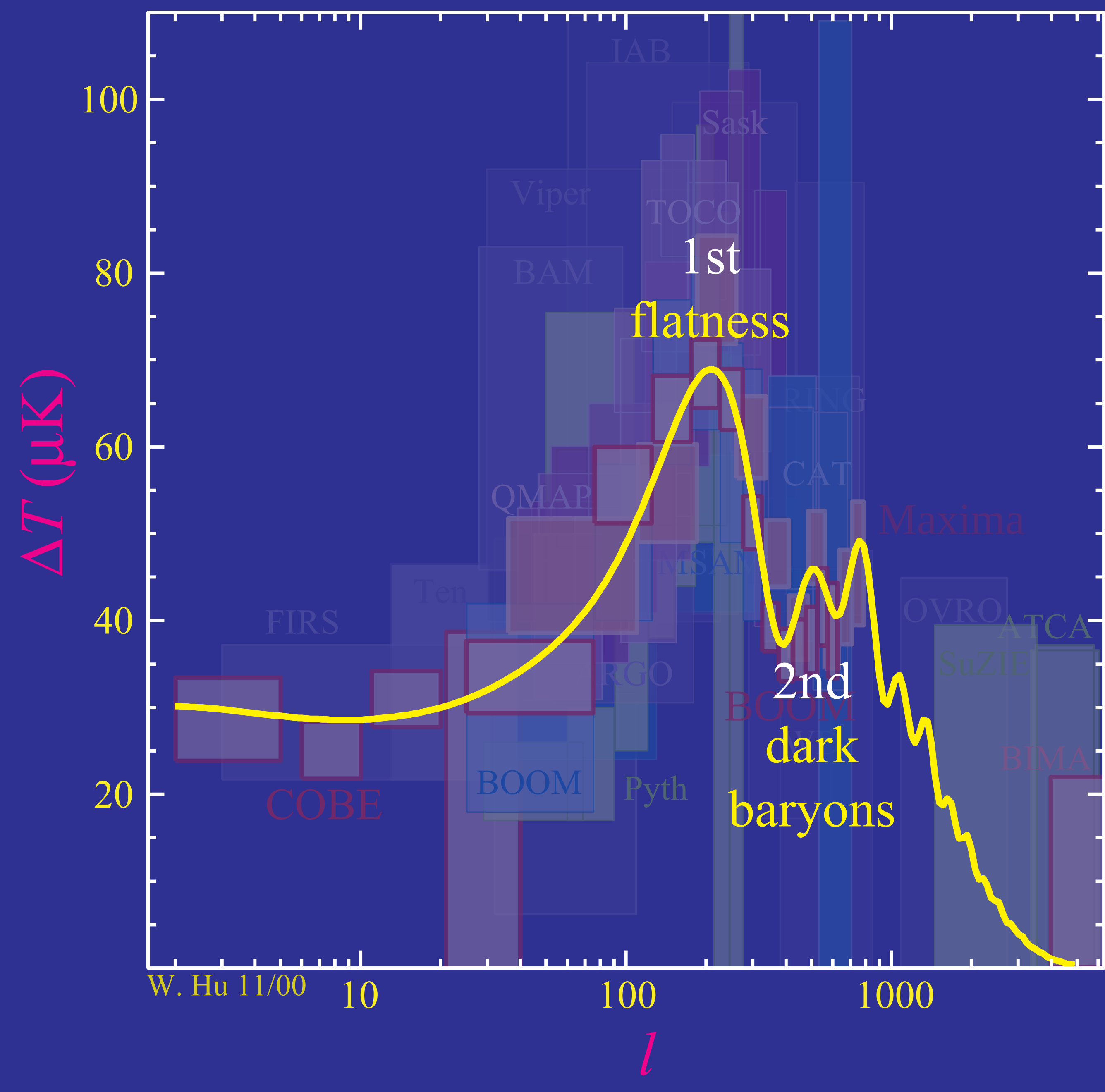
Hu & Sugiyama (1995)

Baryons in the Power Spectrum

Second Peak Detected



Score Card



100
80
60
40
20
ΔT (μK)
10
100
1000
l
W. Hu 11/00
1st
flatness
2nd
dark
baryons
IAB
Sask
Viper
TOCO
BAM
RING
CAT
QMAP
Maxima
MSAM
Ten
FIRS
OVRO
ATCA
SuZIE
ARGO
BOOM
BIMA
COBE
Pyth

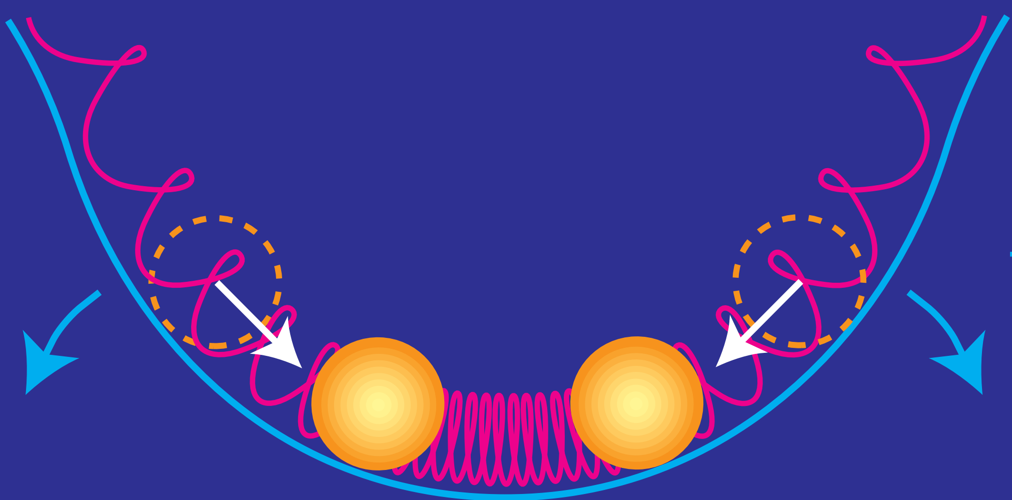
Third Peak

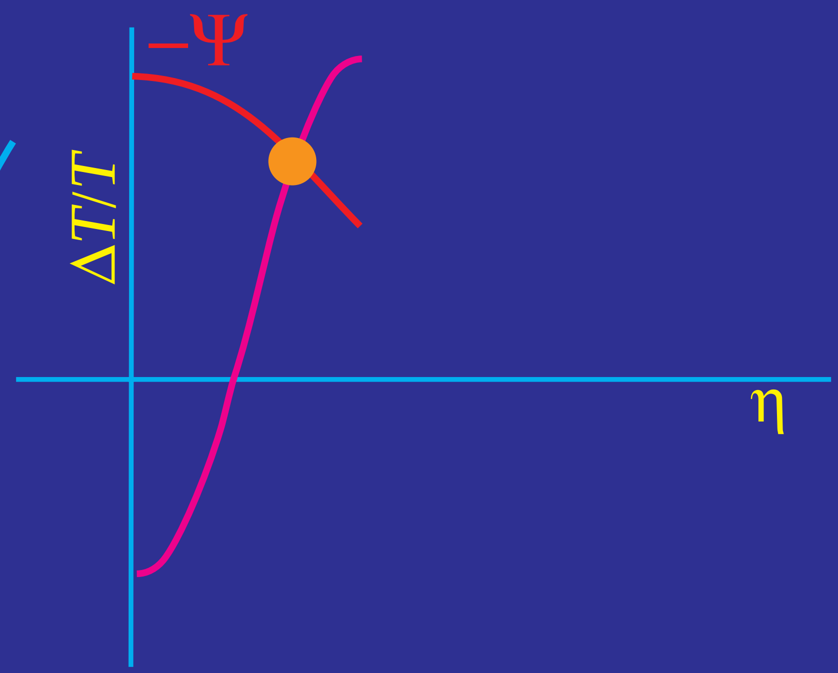
Radiation and Dark Matter

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

Driving Effects and Matter/Radiation

- Potential perturbation: $k^2\Psi = -4\pi G a^2 \delta\rho$ generated by radiation
- Radiation $\to$ Potential: inside sound horizon $\delta\rho/\rho$ pressure supported $\delta\rho$ hence Ψ decays with expansion





Hu & Sugiyama (1995)

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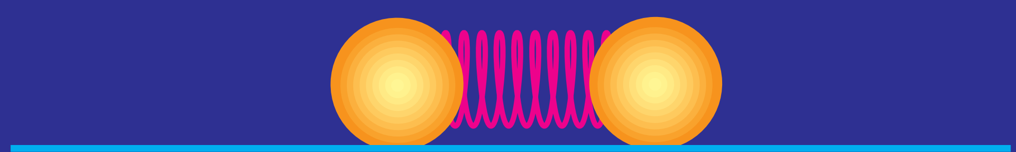
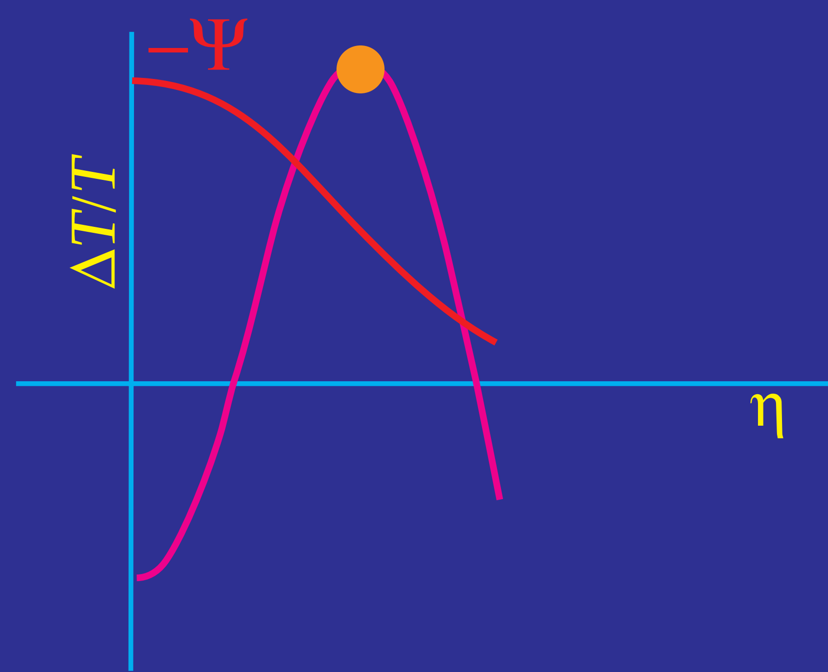
- Feedback stops at matter domination





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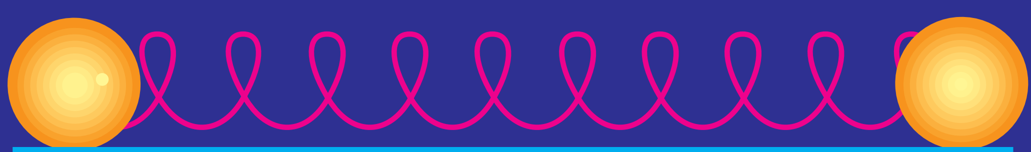
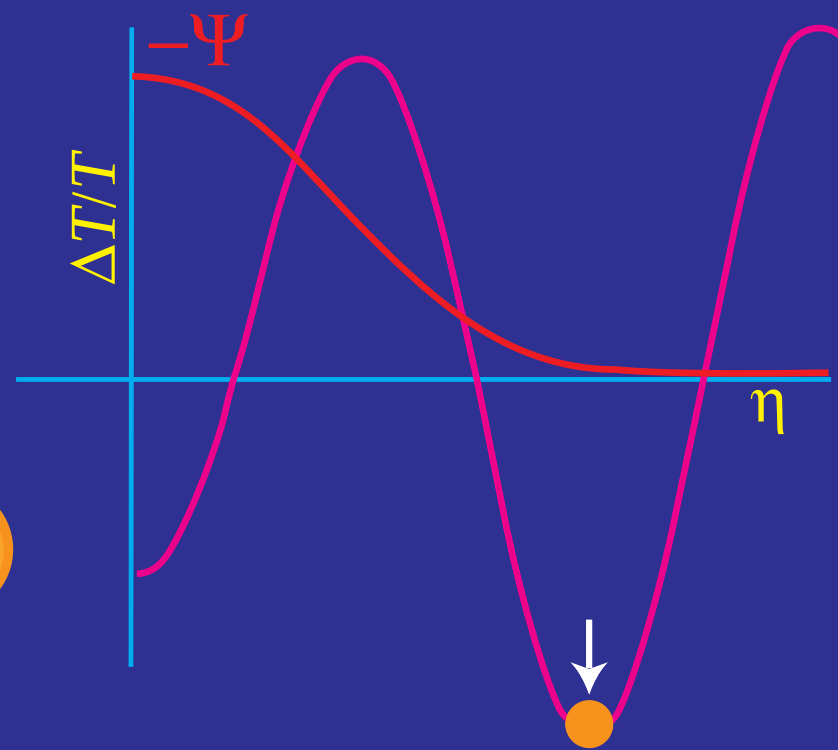
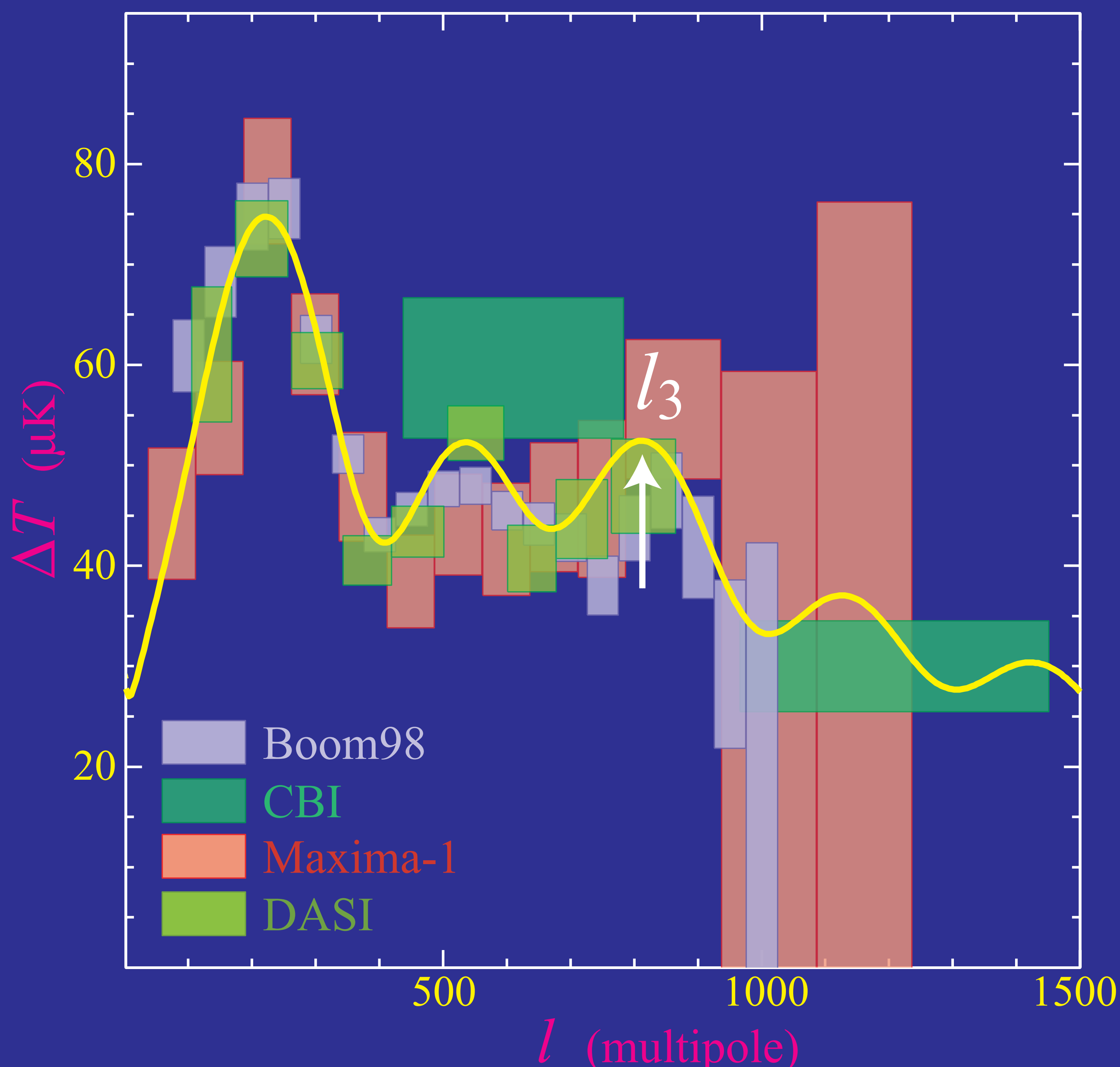




Hu & Sugiyama (1995)

Dark Matter in the Power Spectrum

Third Peak Constrained



Clean Laundry: Standard Rulers

- Calibrated the Standard Rulers

- Sound Horizon

← Baryons

Matter/Radiation →

- Baryon drag & Radiation driving

Damping Tail

Diffusion Damping

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

Diffusion Damping

- Random walk during recombination
- Dissipation as hot meets cold
- Physical scale for standard ruler or calibration

Damping

- Perfect fluid: no anisotropic stresses due to scattering isotropization; baryons and photons move as single fluid

Damping

- Perfect fluid: no anisotropic stresses due to scattering isotropization; baryons and photons move as single fluid
- Fluid imperfections are related to the mean free path of the photons in the baryons

$$\lambda_C = \dot{\tau}^{-1} \quad \text{where} \quad \dot{\tau} = n_e \sigma_T a$$

is the conformal opacity to Thomson scattering

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- Dissipation is related to the diffusion length: random walk approximation

$$\lambda_D = \sqrt{N}\lambda_C = \sqrt{\eta/\lambda_C}\,\lambda_C = \sqrt{\eta\lambda_C}$$

  the geometric mean between the horizon and mean free path

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  $$\lambda_D = \sqrt{N}\lambda_C = \sqrt{\eta/\lambda_C}\,\lambda_C = \sqrt{\eta\lambda_C}$$

  the geometric mean between the horizon and mean free path
- $\lambda_D/\eta_* \sim$ few %, so expect the peaks $>$ 3rd to be affected by dissipation

Equations of Motion

- Continuity

$$\dot{\Theta} = -\frac{k}{3} v_\gamma \,, \quad \dot{\delta}_b = -k v_b$$

where gravitational effects ignored and $\Theta \equiv \Delta T/T$.

- Euler

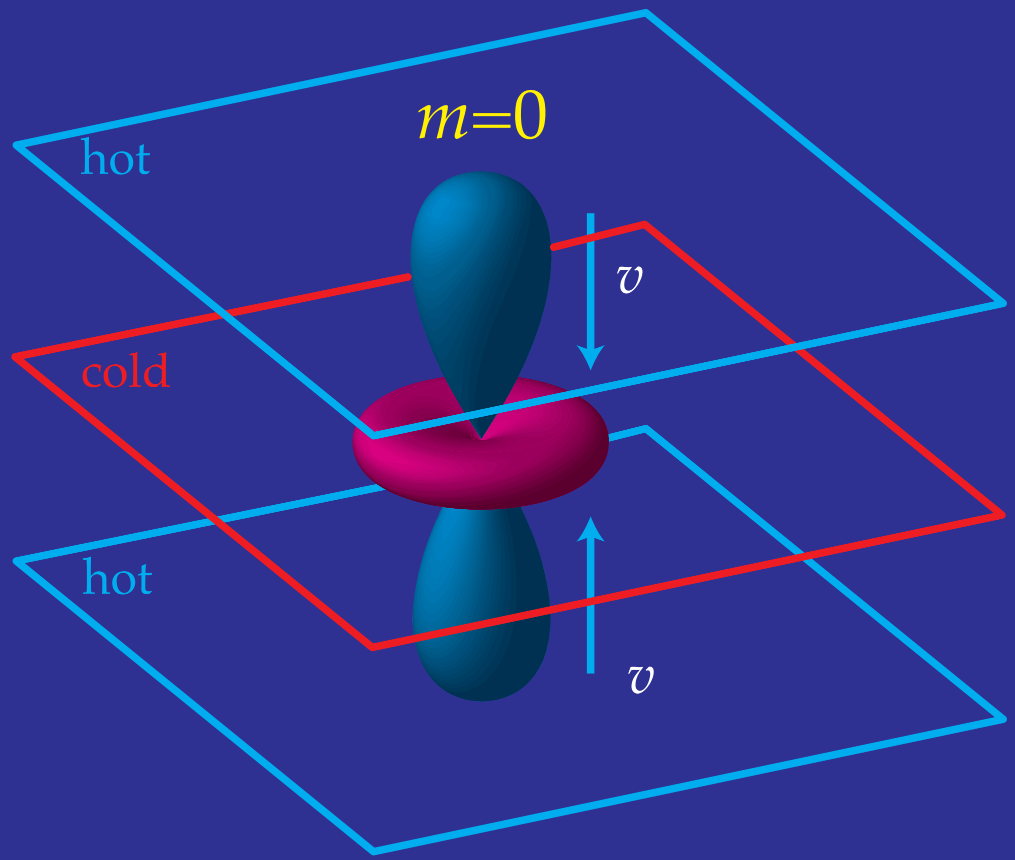
$$\dot{v}_\gamma = k\Theta - \frac{k}{6}\pi_\gamma - \dot{\tau}(v_\gamma - v_b)$$

$$\dot{v}_b = -\frac{\dot{a}}{a} v_b + \dot{\tau}(v_\gamma - v_b)/R$$

where $k\Theta$ is the pressure gradient term, $k\pi_\gamma$ is the viscous stress term, and $v_\gamma - v_b$ is the momentum exchange term with $R \equiv 3\rho_b/4\rho_\gamma$ the baryon-photon momentum ratio.

Viscosity & Heat Conduction

- Both fluid imperfections are related to the gradient of the velocity kv_γ by opacity $\dot\tau$: slippage of fluids $v_\gamma - v_b$.
- Viscosity is an anisotropic stress or quadrupole moment formed by radiation streaming from hot to cold regions



Damping Term

- Oscillator equation contains a $\dot{\Theta}$ damping term

$$\ddot{\Theta} + \frac{k^2}{\dot{\tau}} A_{\rm d} \dot{\Theta} + k^2 c_s^2 \Theta = 0$$

- Solve in the adiabatic approximation

$$\Theta \propto \exp(i \int \omega d\eta)$$

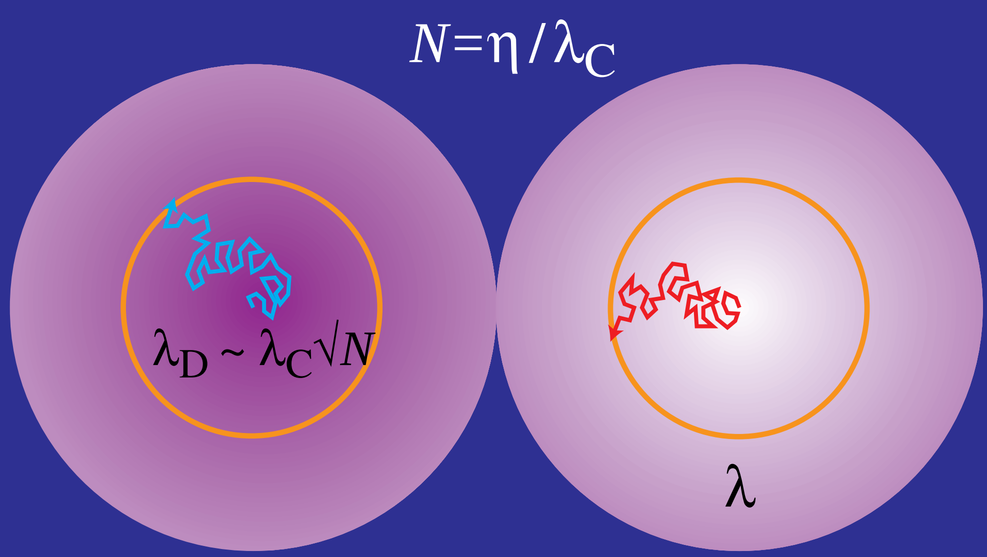
$$\exp(i \int \omega d\eta) = e^{\pm ik \int c_s d\eta} \exp[-(k/k_D)^2]$$

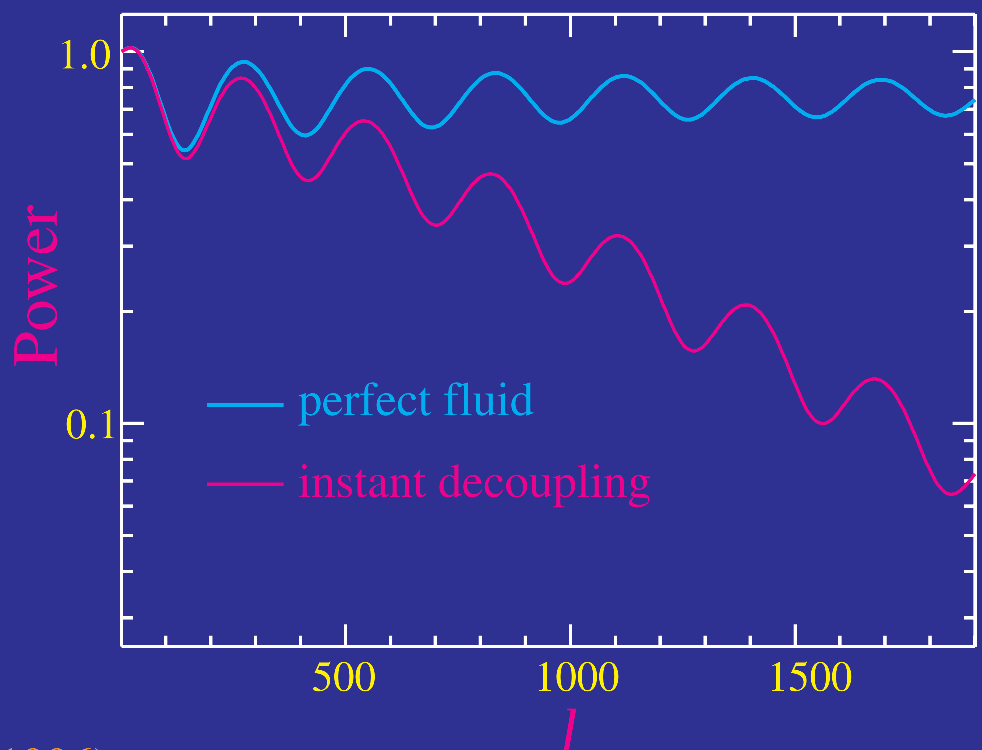
- Diffusion wavenumber, geometric mean between horizon and mfp:

$$k_D^{-2} = \frac{1}{2} \int \frac{d\eta}{\dot{\tau}} A_{\rm d} \sim \frac{\eta}{\dot{\tau}}$$

Dissipation / Diffusion Damping

- Imperfections in the coupled fluid → mean free path λ_C in the baryons
- Random walk over diffusion scale: geometric mean of mfp & horizon
  $\lambda_D \sim \lambda_C \sqrt{N} \sim \sqrt{\lambda_C \eta} \gg \lambda_C$
- Overtake wavelength: $\lambda_D \sim \lambda$; second order in λ_C/λ
- Viscous damping for $R<1$; heat conduction damping for $R>1$

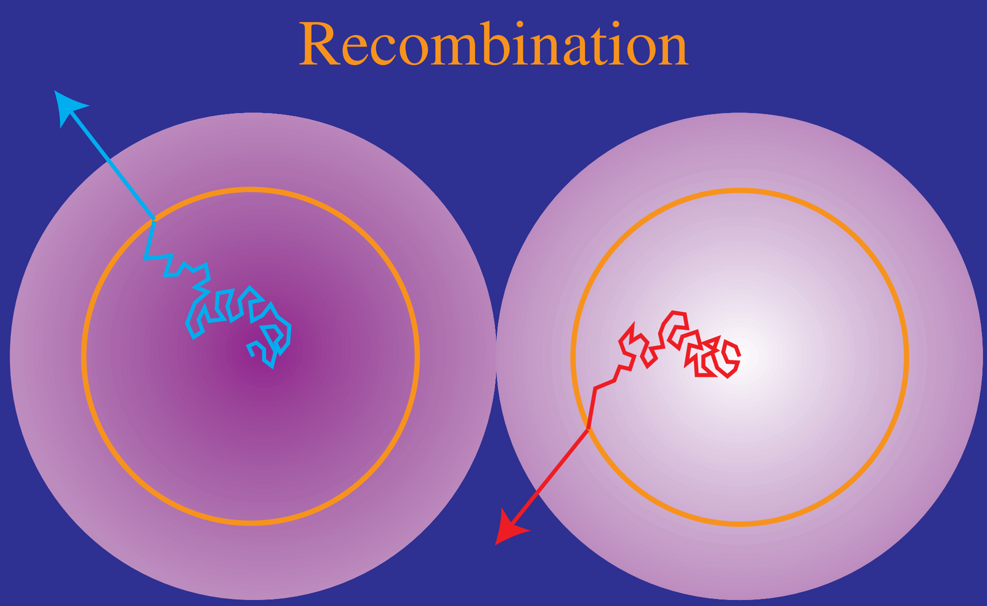


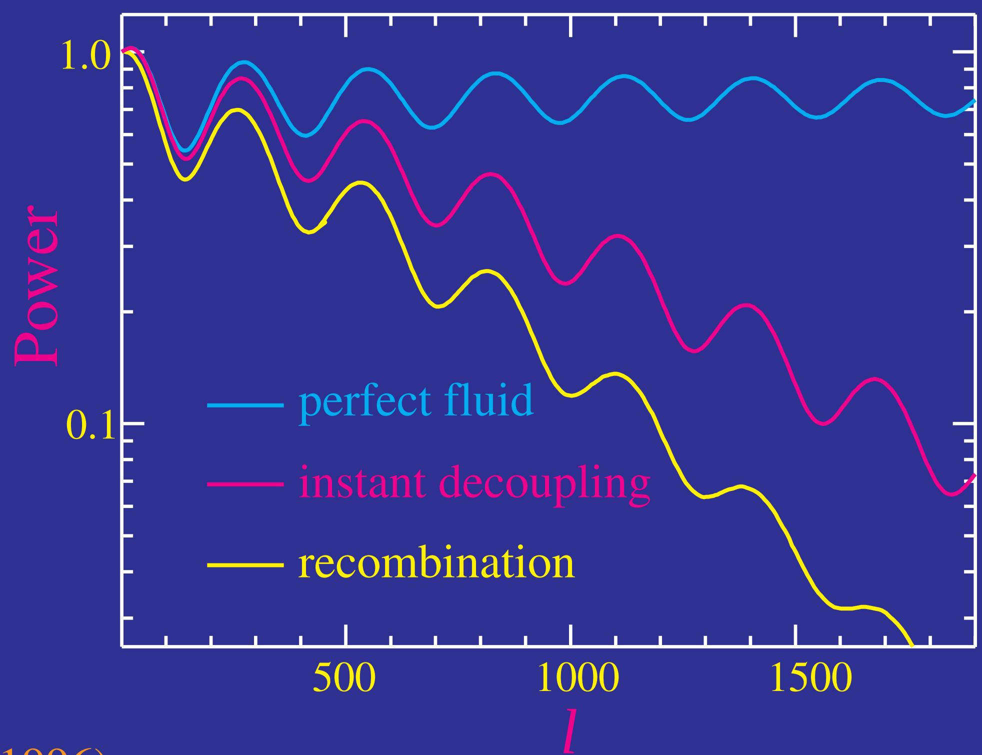


Silk (1968); Hu & Sugiyama (1995); Hu & White (1996)

Dissipation / Diffusion Damping

- Rapid increase at recombination as mfp ↑
- Independent of (robust to changes in) perturbation spectrum
- Robust physical scale for angular diameter distance test (Ω_K, Ω_Λ)





Silk (1968); Hu & Sugiyama (1995); Hu & White (1996)

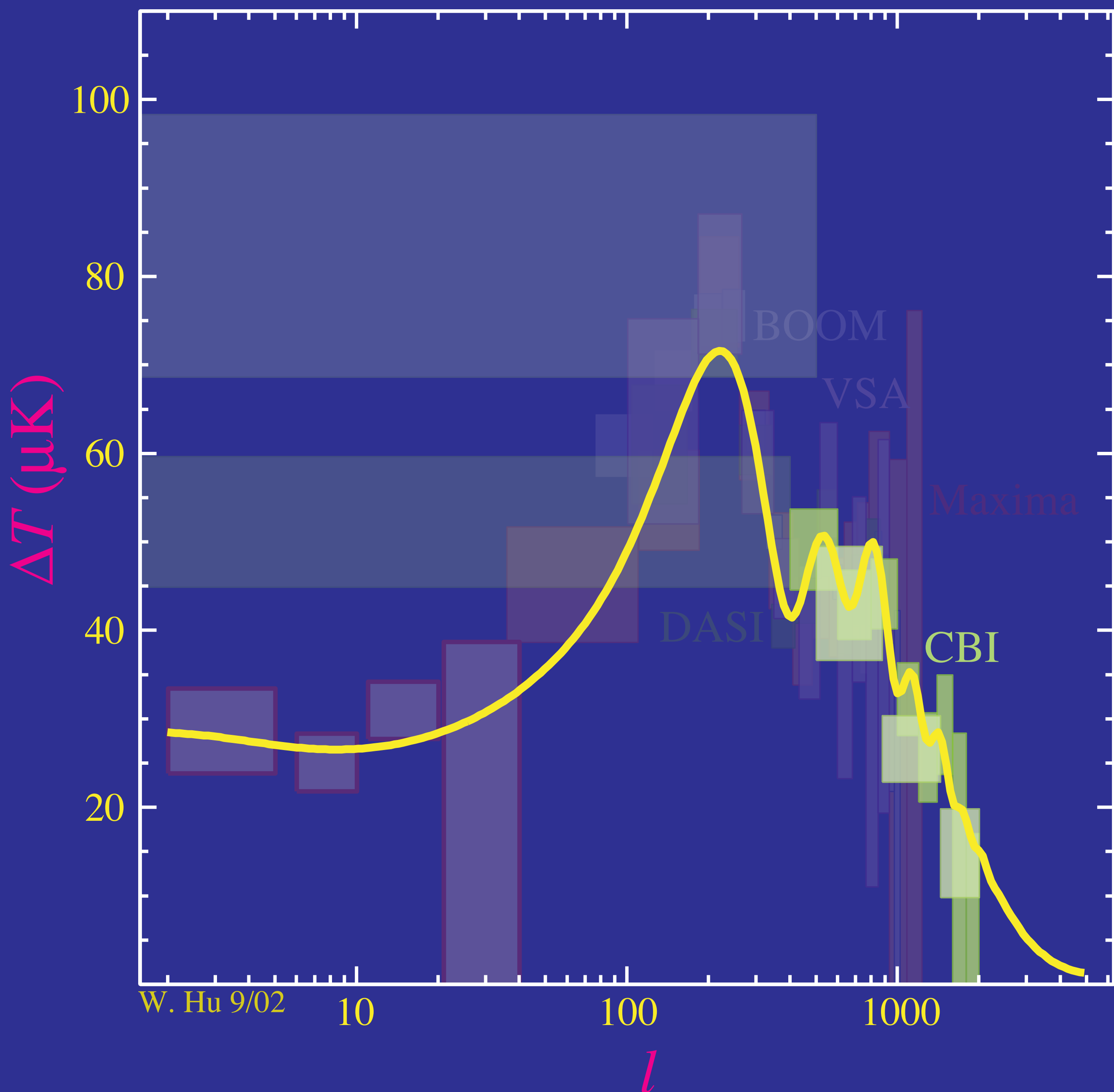
Standard Ruler

- Damping length is a fixed physical scale given properties at recombination
- Gemoetric mean of mean free path and horizon: depends on baryon-photon ratio and matter-radiation ratio

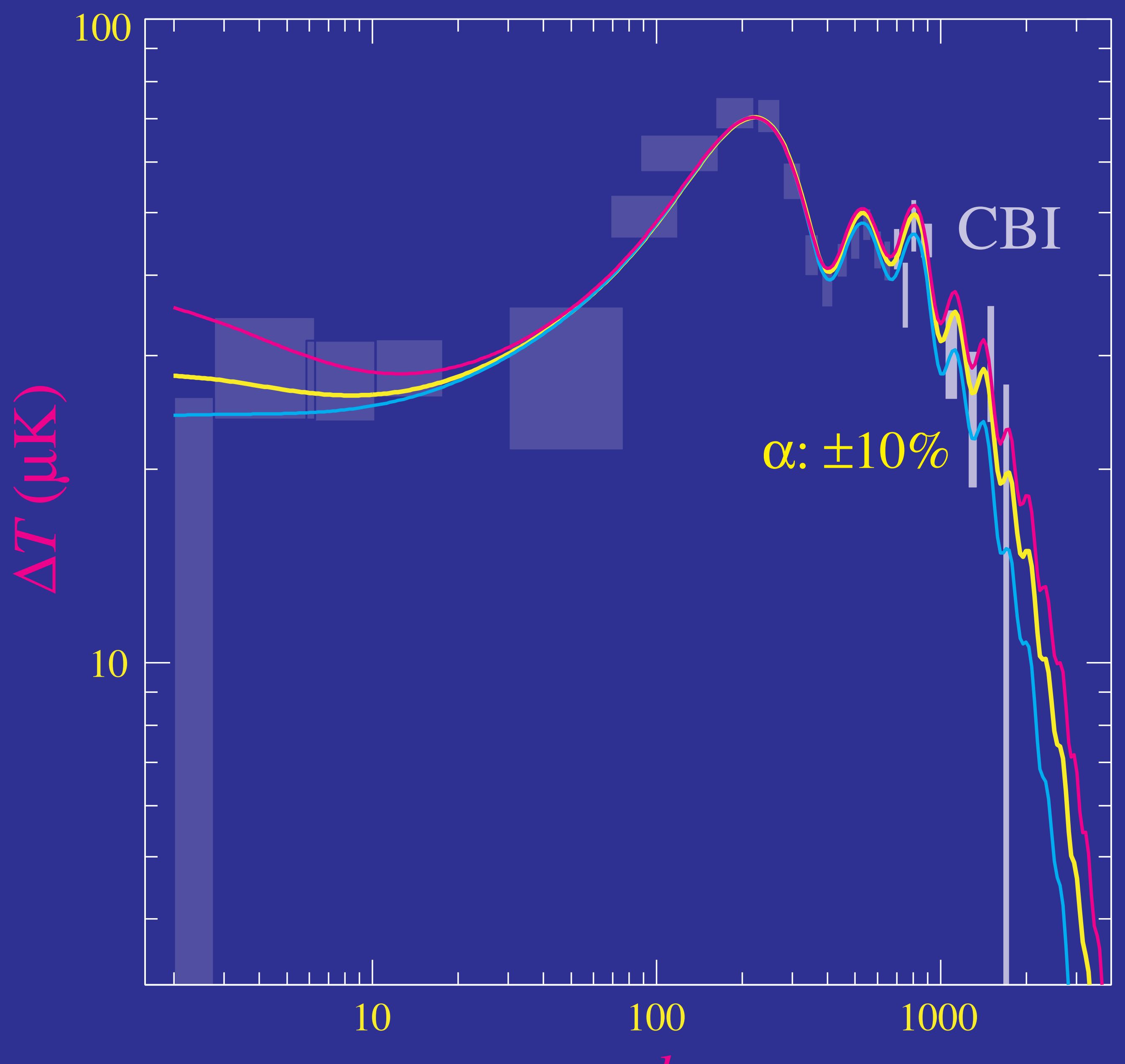
Curvature

- Calibration from lower peaks of $\Omega_b h^2$ and $\Omega_m h^2$ allows measurement of curvature from damping scale
- Independently of peak scale, confirms flat geometry

Damping Tail Measured



Beyond the Standard Model



fixed l_A, ρ_b/ρ_γ, ρ_m/ρ_r

Implications of Damping

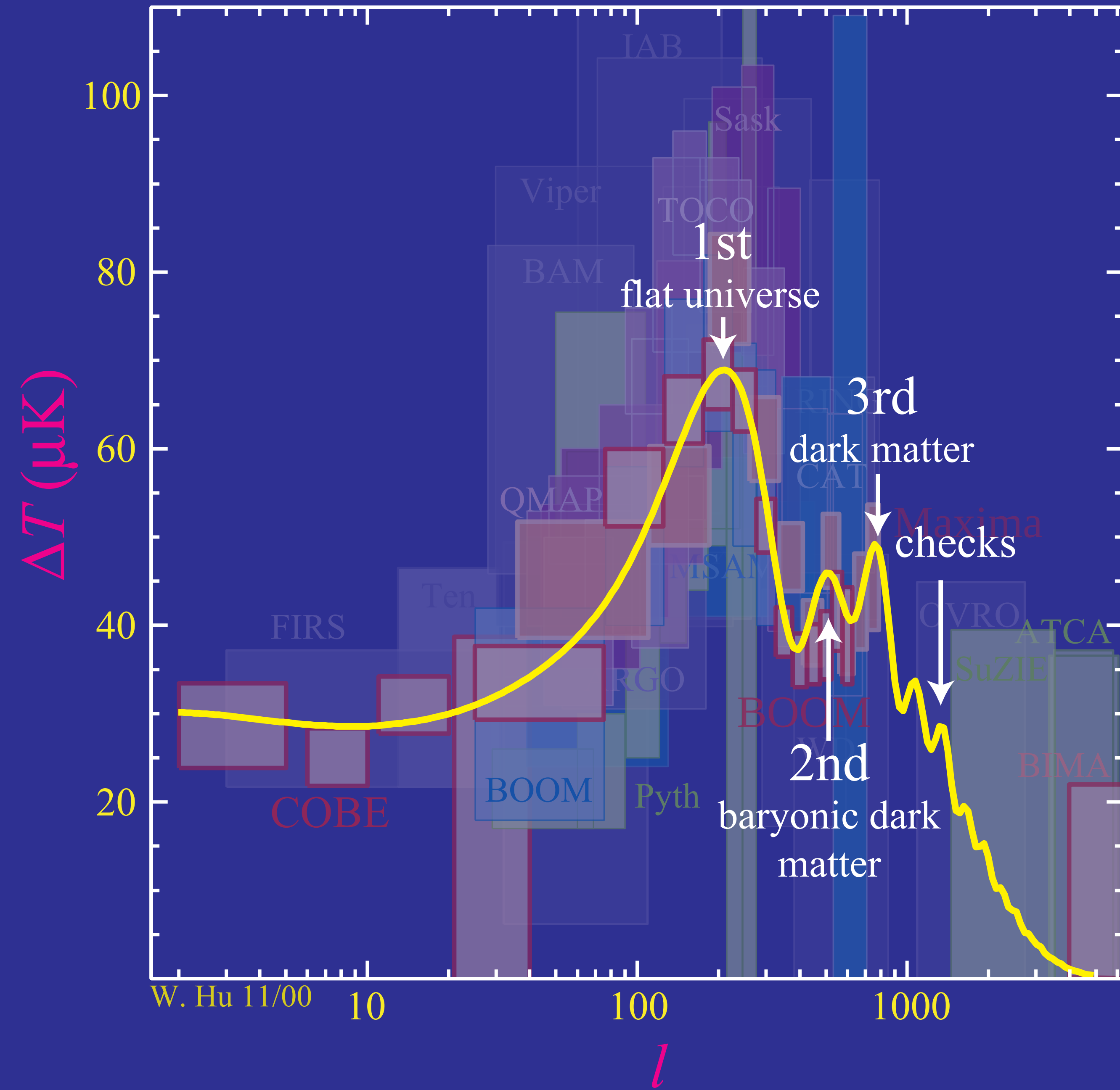
- CMB anisotropies ~10% polarized

  dissipation –> viscosity –> quadrupole anisotropy –> linear polarization

- Secondary anisotropies are observable

  dissipation –> exponential suppression of primary anisotropy –> uncovery of secondary anisotropy

The Peaks



100
80
60
40
20
ΔT (μK)
10
100
1000
l
W. Hu 11/00
1st
flat universe
2nd
baryonic dark
matter
3rd
dark matter
checks
COBE
FIRS
Ten
BOOM
Pyth
RGO
QMAP
BAM
Viper
TOCO
IAB
Sask
CAT
MSAM
BOOM
Maxima
CVRO
ATCA
SuZIE
BIMA

Summary

- Precision cosmology has arrived
- Sound physics seen (pun intended)
- Consistent with inflationary initial conditions

- First peak nailed: nearly flat universe
- Second determined: baryonic dark matter
  (consistent with Big Bang Nucleosynthesis)
- Third measured: cold dark matter required
  but does not add up to critical: dark energy

- Damping detected: consistency checks passed