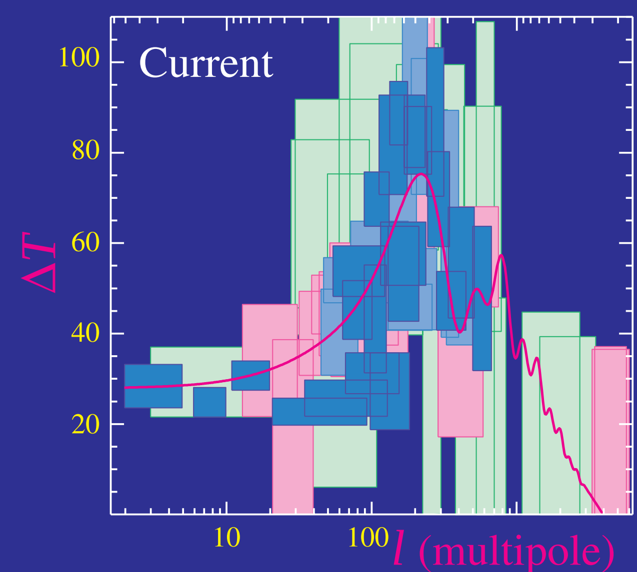
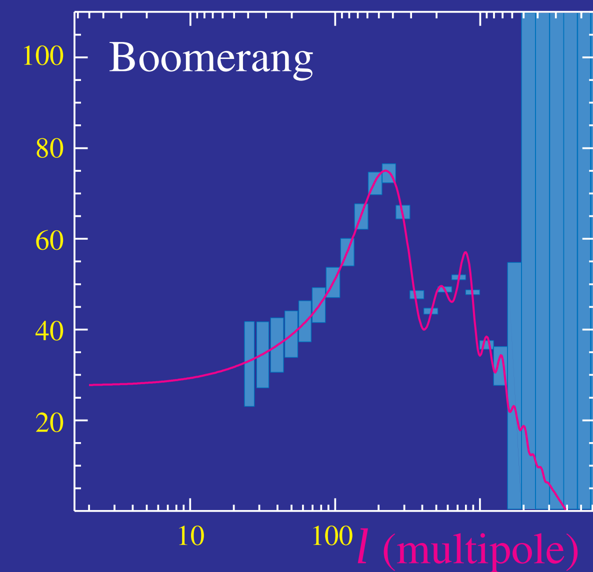
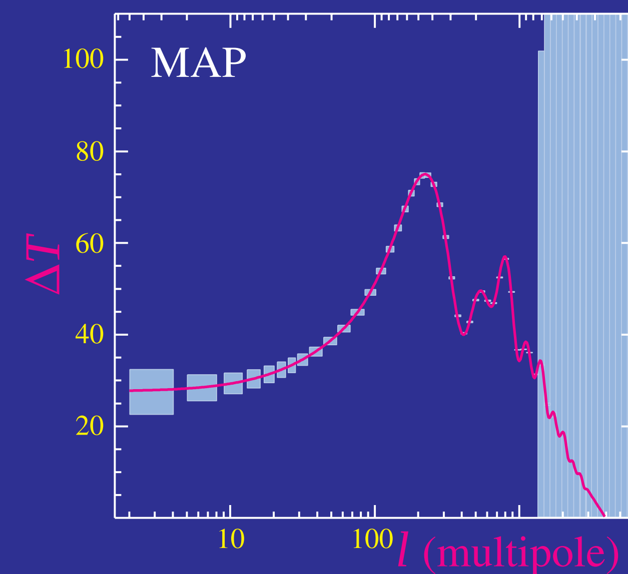
¥2.7K



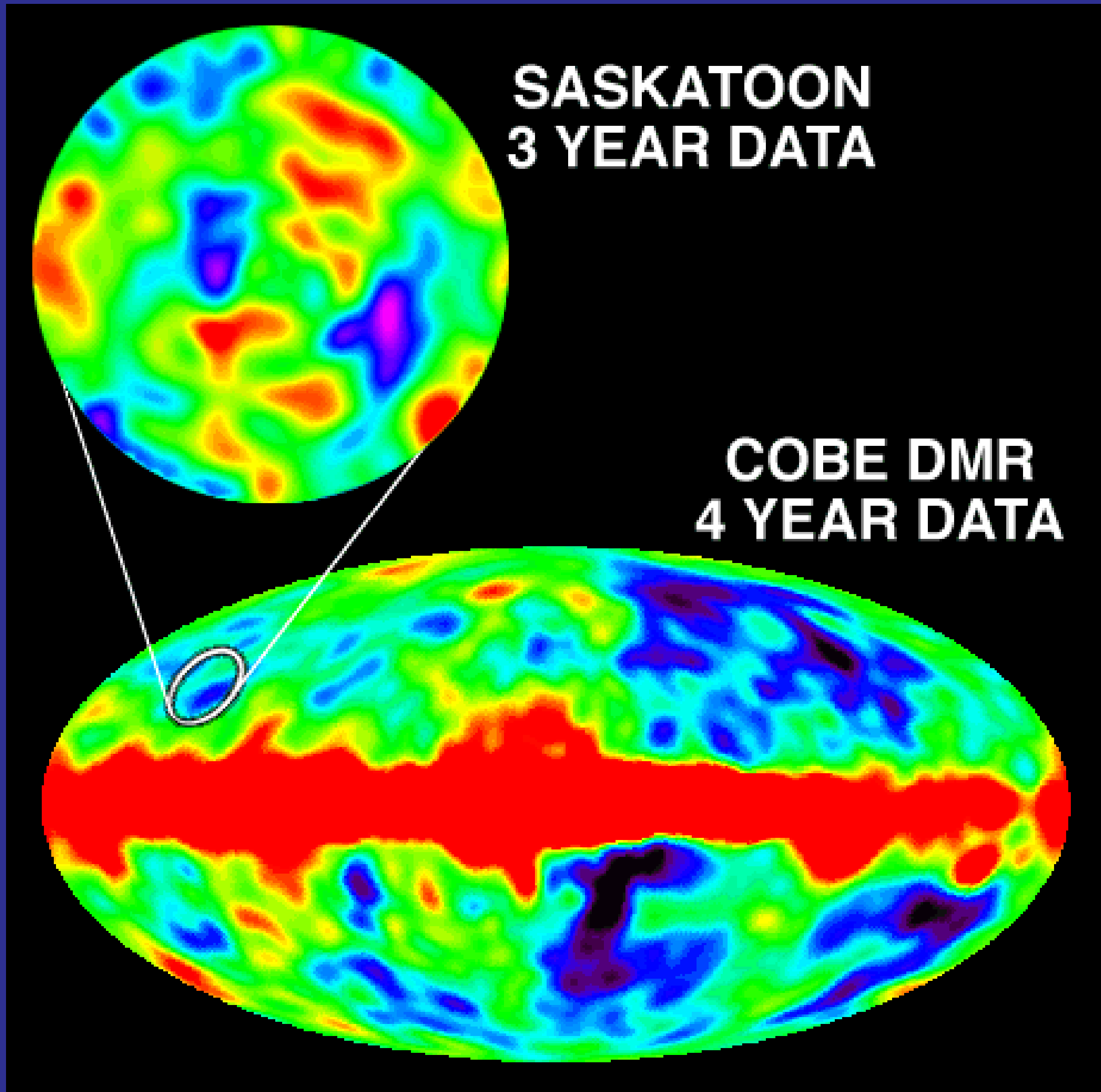




RESCEU 1999

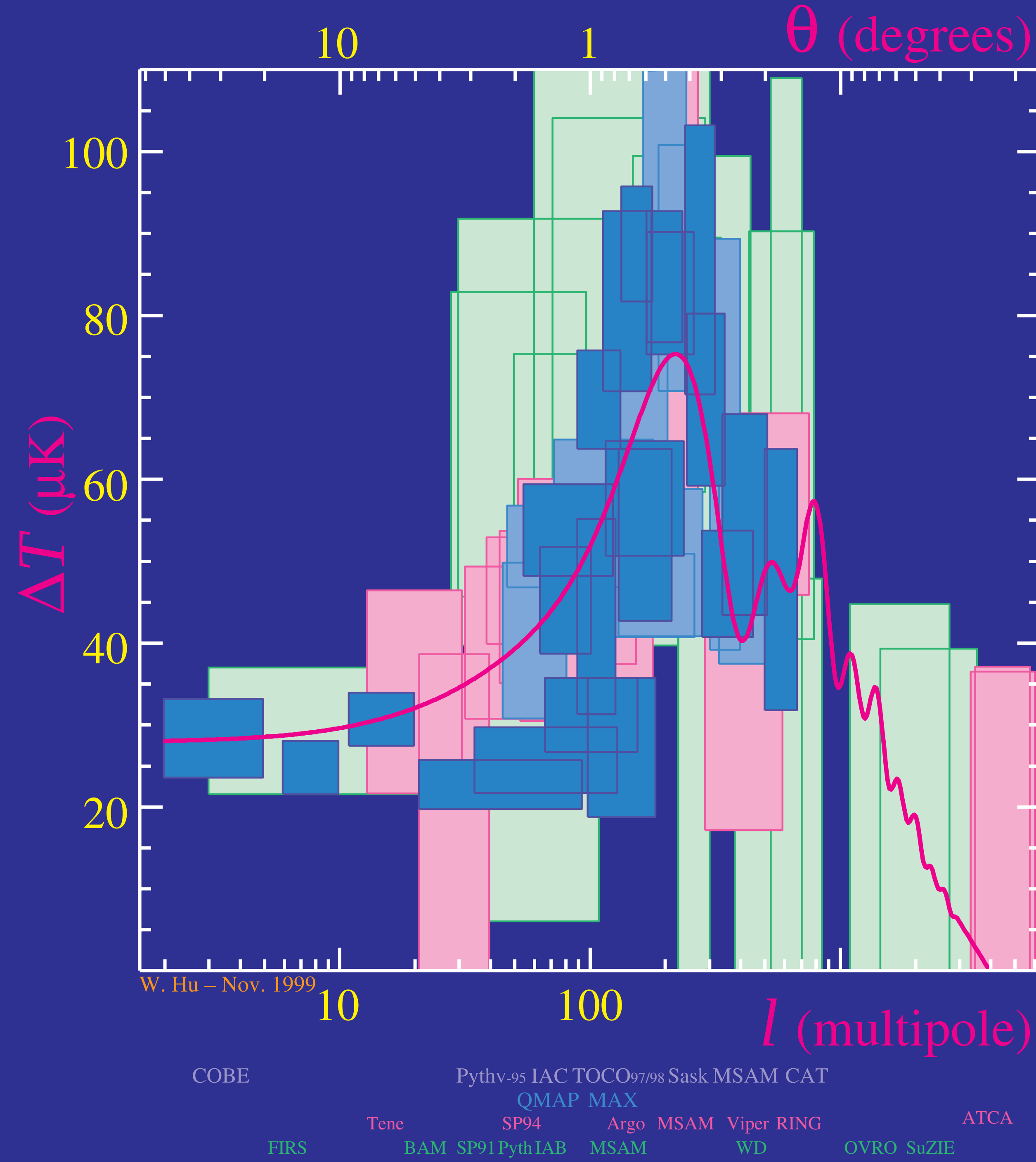
Wayne Hu

CMB Anisotropies

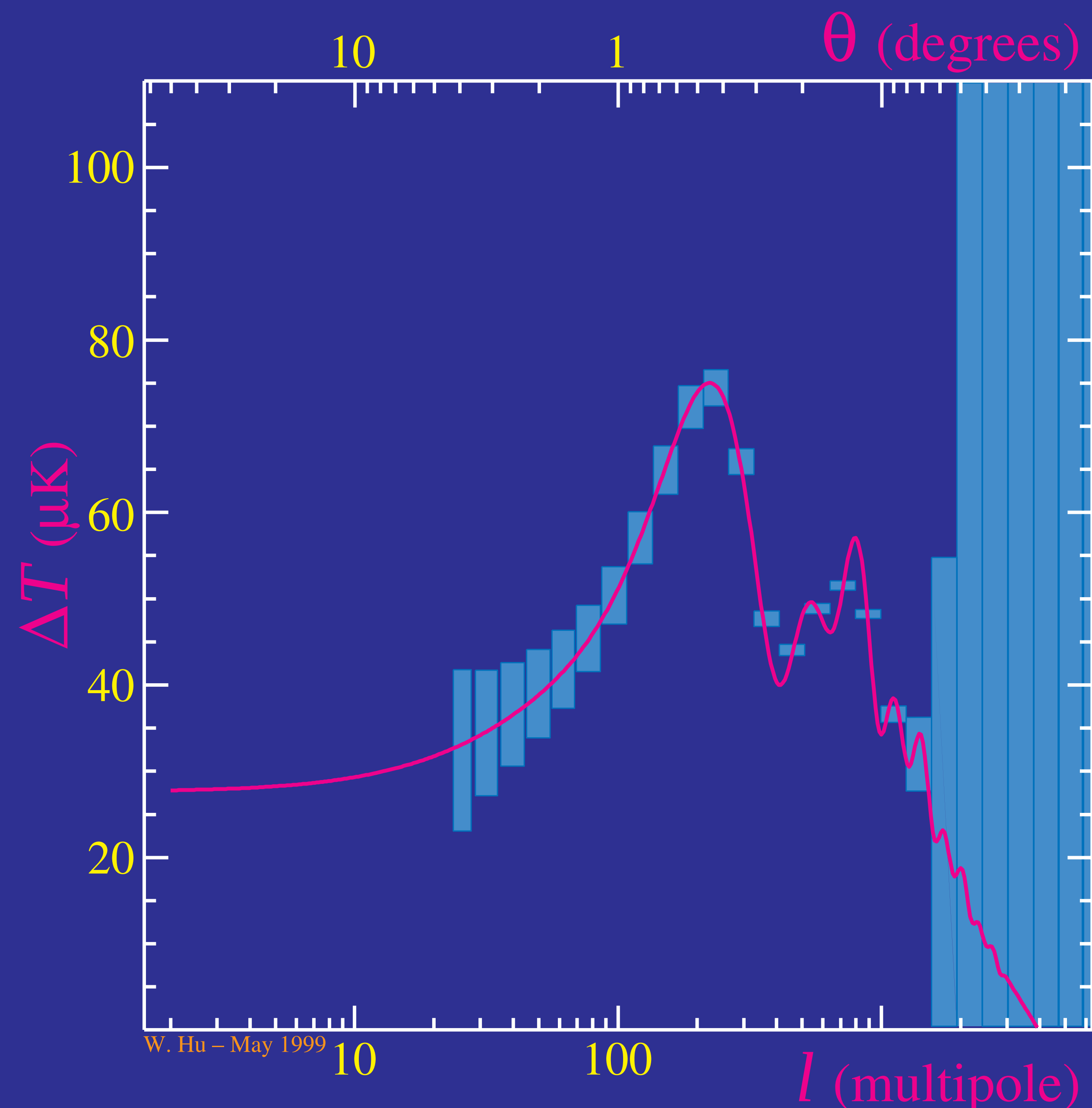


Tegmark, de Oliviera Costa, Devlin, Netterfield, & Page (1996)

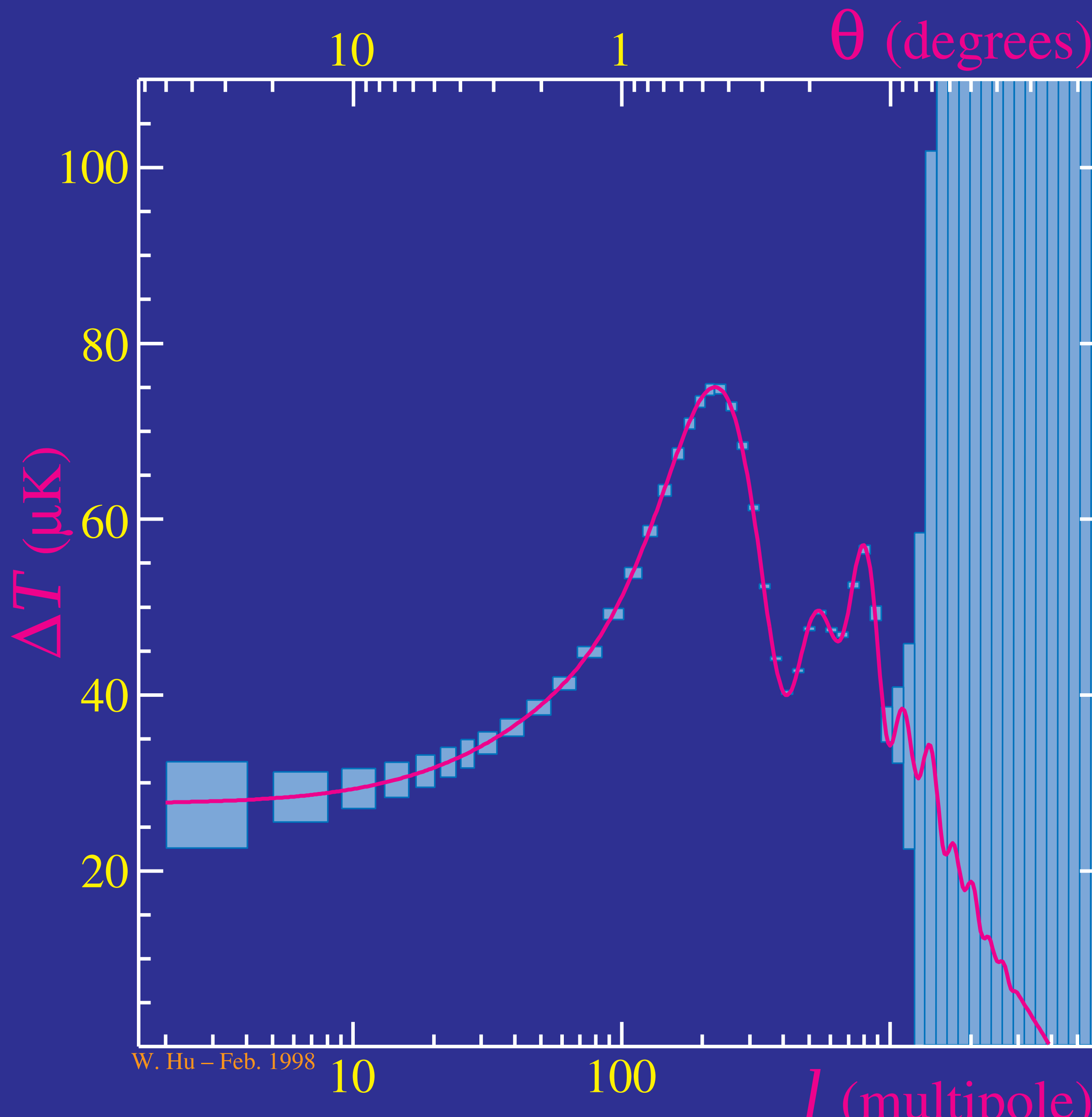
Current CMB Quilt



Projected Boomerang Errors



Projected MAP Errors



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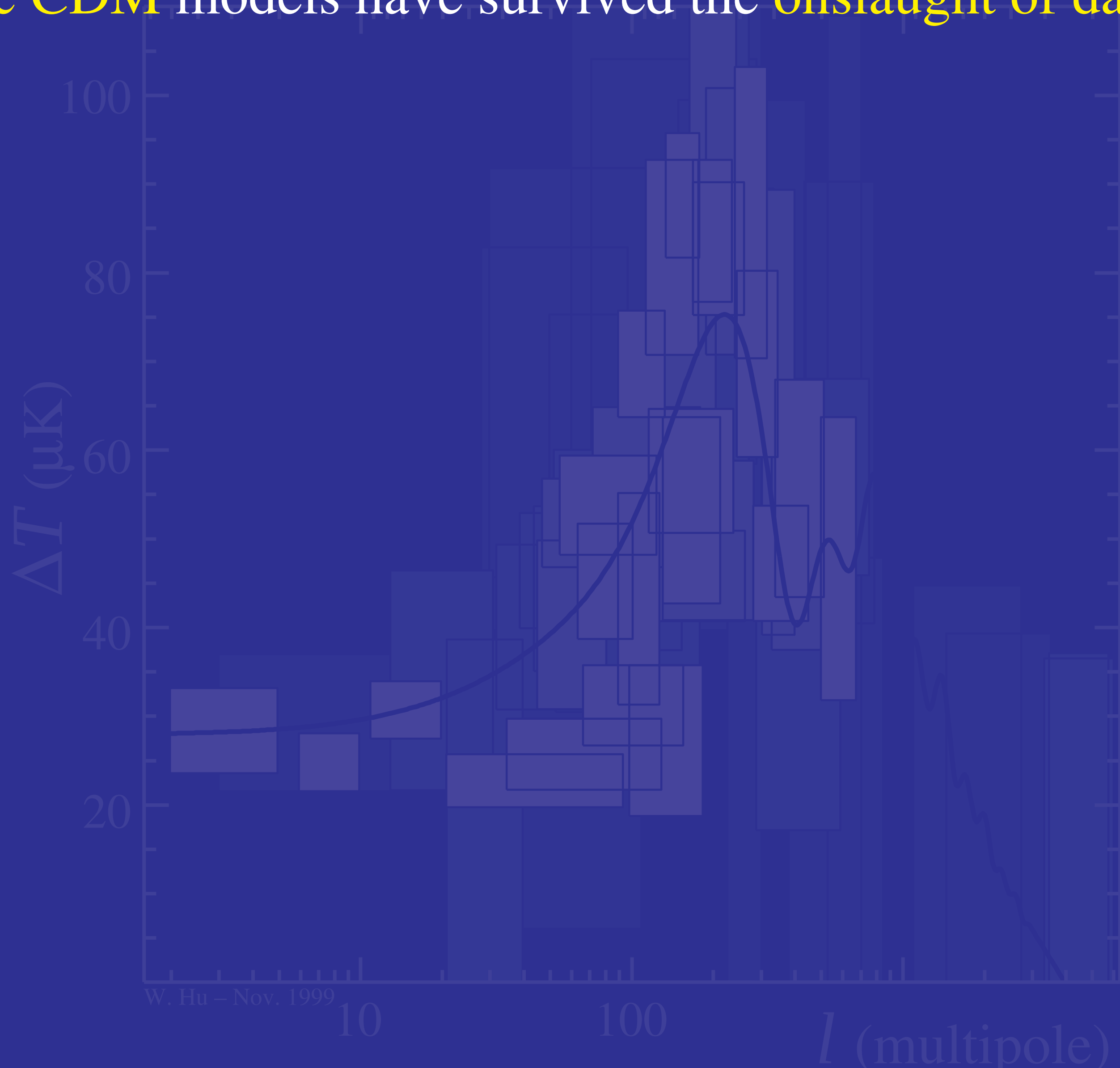

Lineweaver (1998); Bond & Jaffe (1998); Dodelson & Knox (1999); Tegmark & Zaldarriaga (1999)

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  Optically thin during reionization $\tau \lesssim 0.5$

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- Consistent with LSS, cluster abundance, SNIa, BBN, h

Lineweaver (1998); Bond & Jaffe (1998); Dodelson & Knox (1999); Tegmark & Zaldarriaga (1999)

Acoustic Peak Preliminaries

Thermal History

- $z > 1000$; $T_\gamma > 3000$K

  Hydrogen ionized

  Free electrons glue photons to baryons

  Photon–baryon fluid

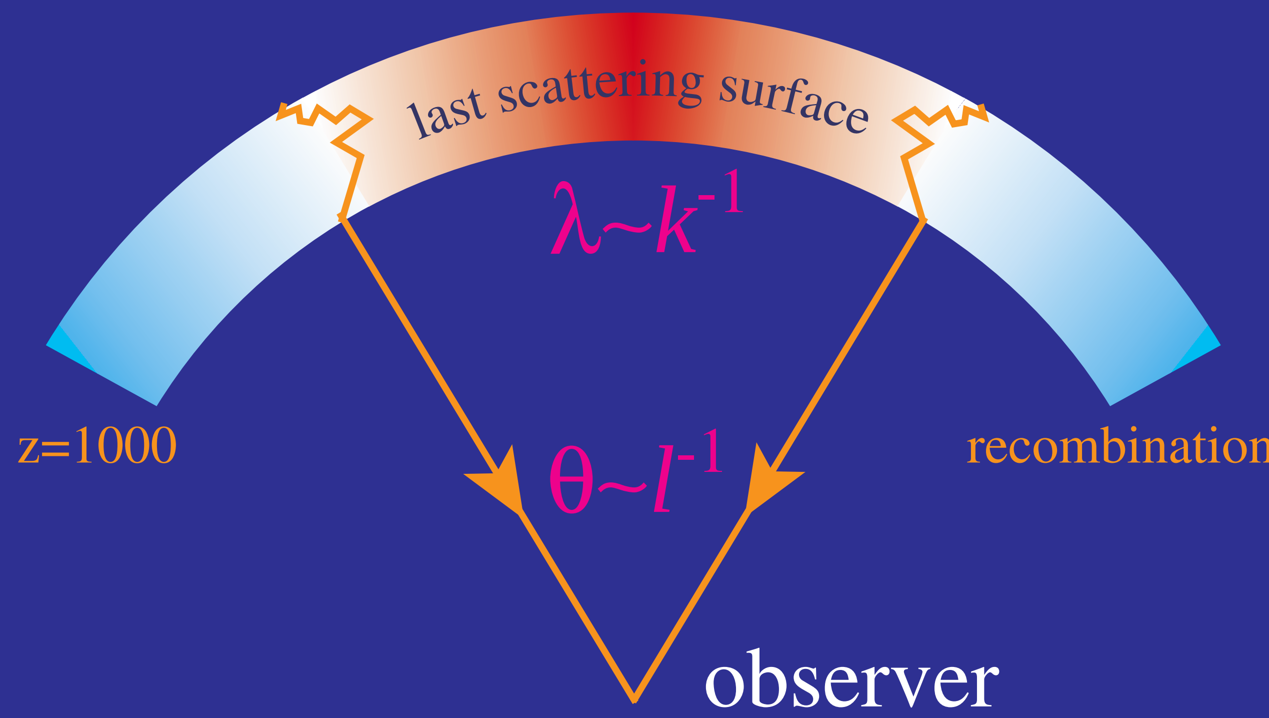
  Potential wells that later form structure

Thermal History

- $z > 1000$; $T_\gamma > 3000K$
  - Hydrogen ionized
  - Free electrons glue photons to baryons

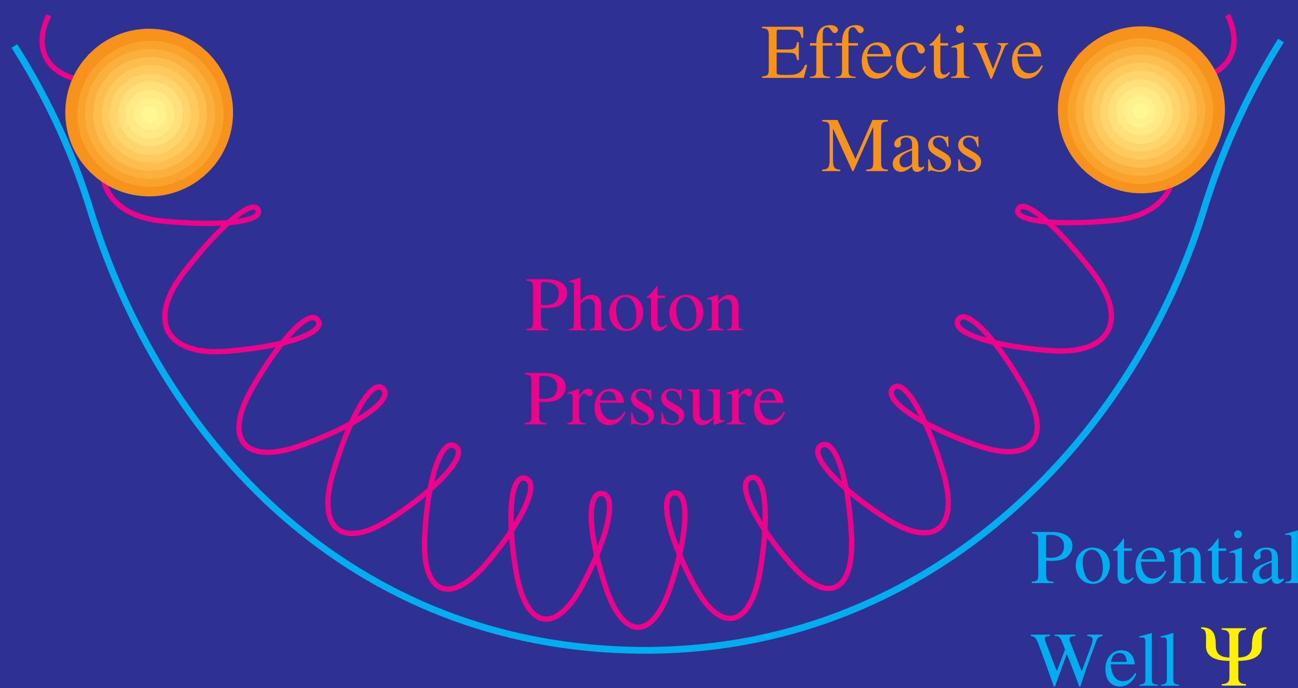
  - Photon–baryon fluid
  - Potential wells that later form structure

- $z \sim 1000$; $T_\gamma \sim 3000K$
  - Recombination
  - Fluid breakdown
- $z < 1000$; $T_\gamma < 3000K$
  - Gravitational redshifts & lensing
  - Reionization; rescattering



Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations



Peebles & Yu (1970)

Hu & Sugyama (1995)

Acoustic Oscillations

- Photon pressure resists compression in potential wells
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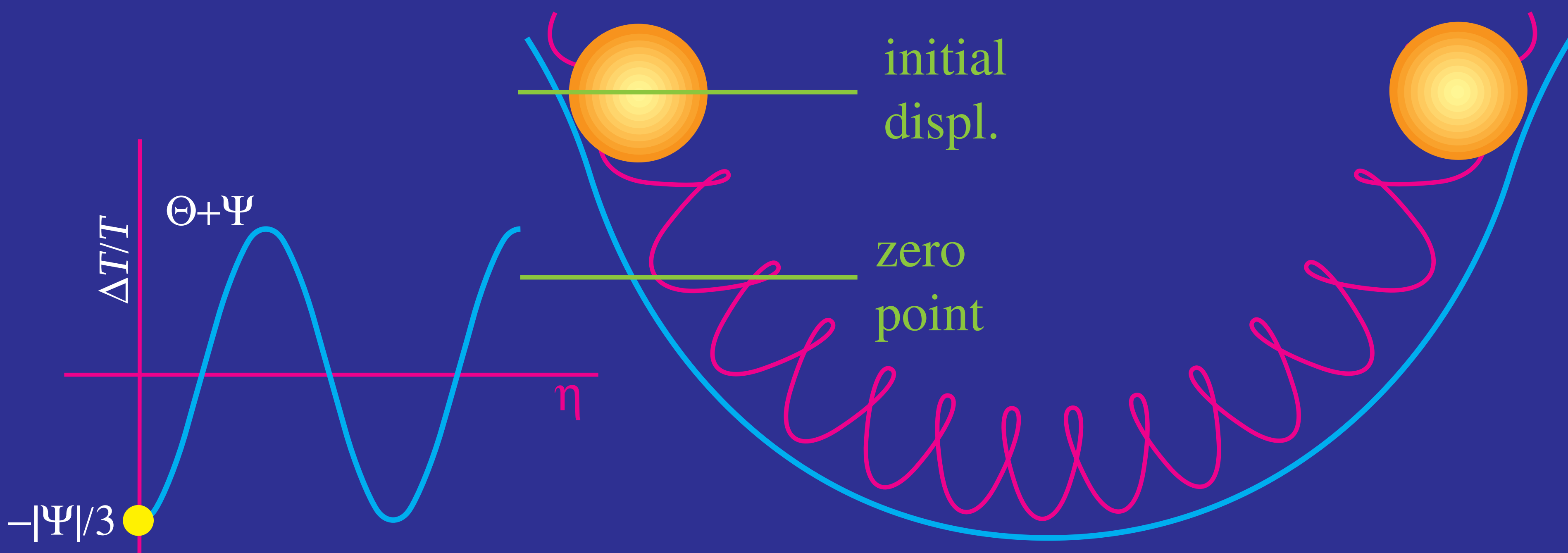
- Gravity displaces zero point
  $\Theta \equiv \delta T/T = -\Psi$
- Oscillation amplitude = initial displacement from zero pt.
  $\Theta - (-\Psi) = 1/3\Psi$



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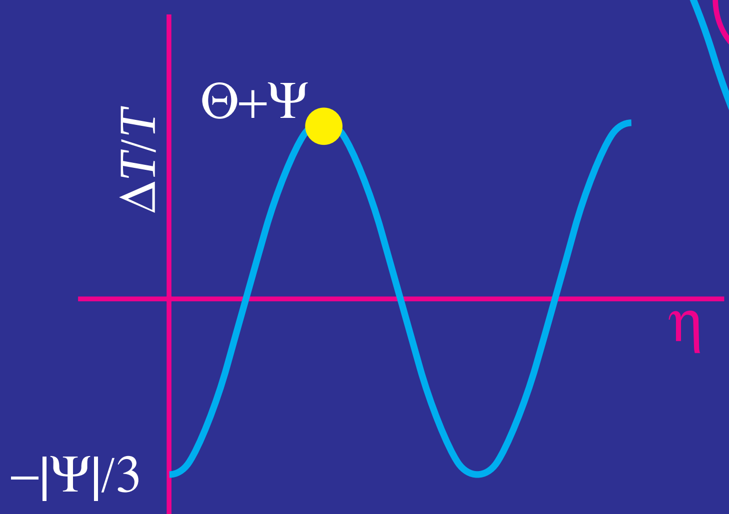

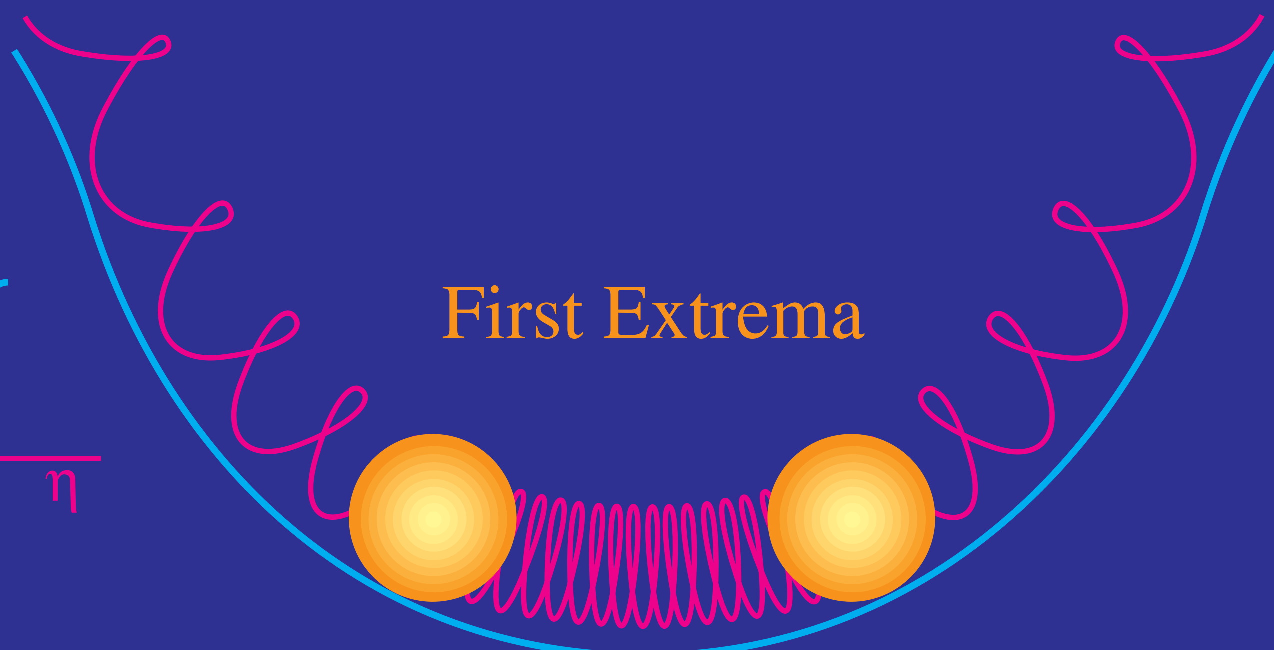

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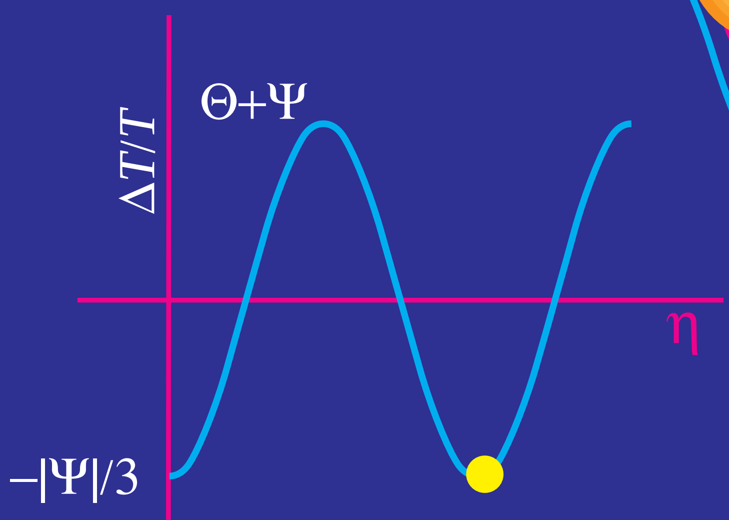

Peebles & Yu (1970)

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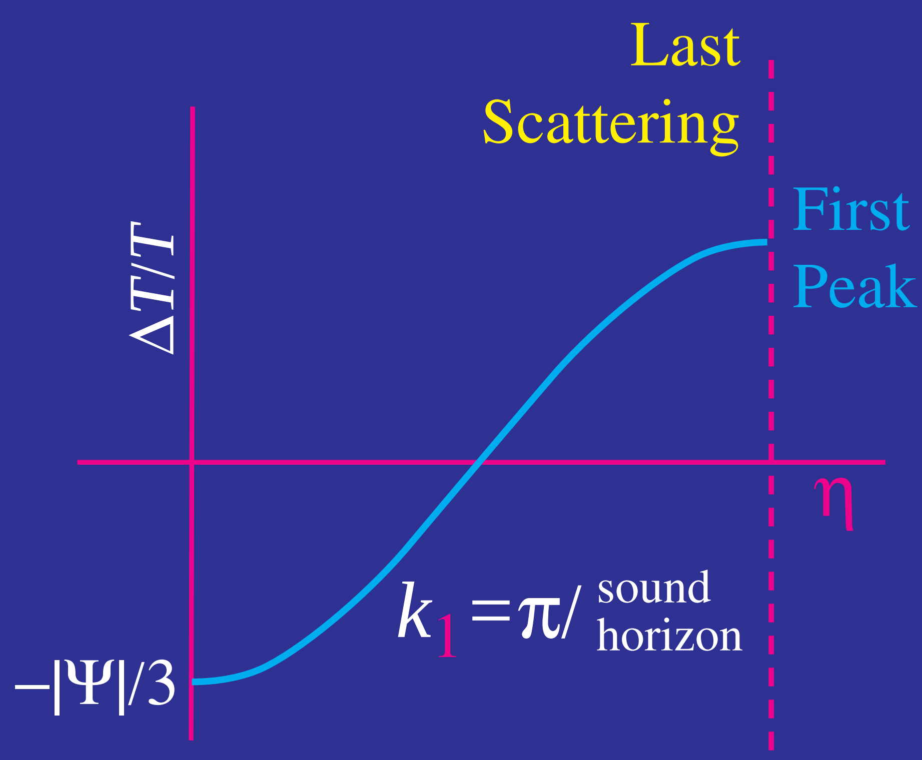
Harmonic Peaks

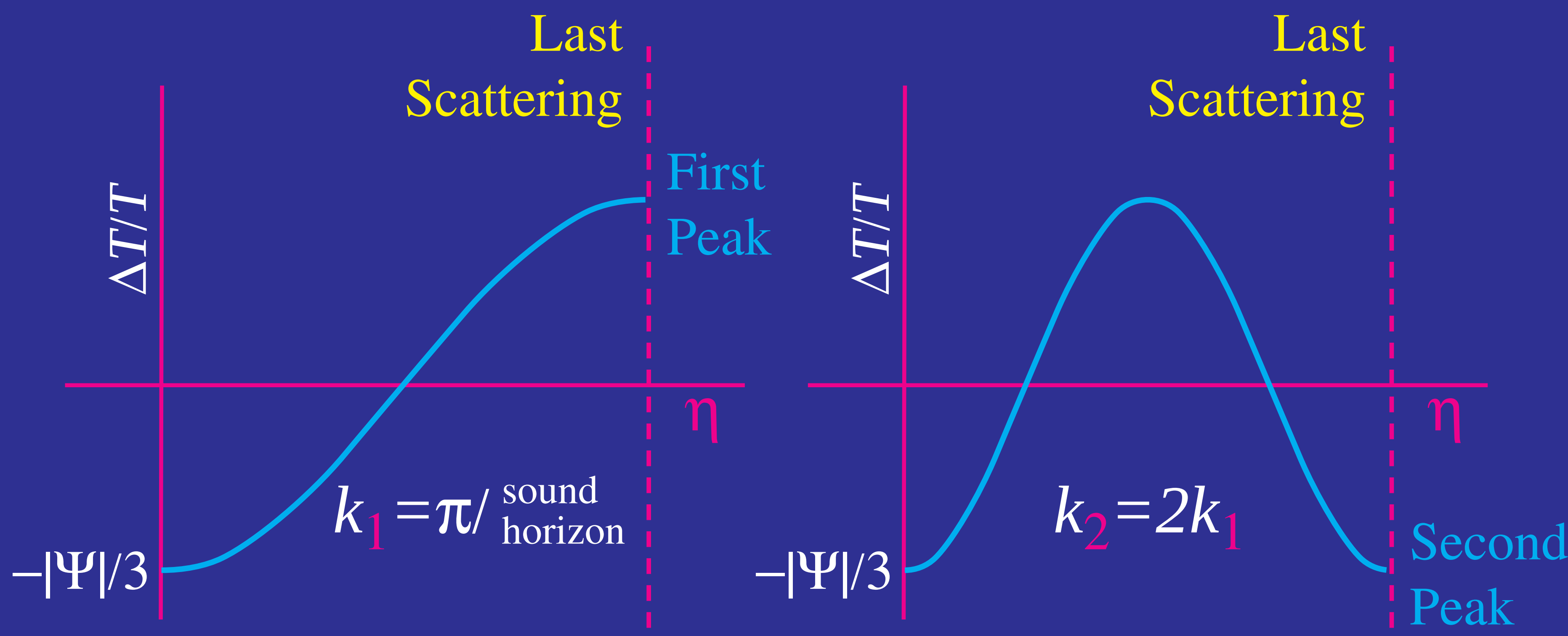
- Oscillations frozen at last scattering
- Wavenumbers at extrema = peaks
- Sound speed c_s



Doroshkevich, Zel'dovich & Sunyaev (1978); Bond & Efstathiou (1984); Hu & Sugiyama (1995)

Harmonic Peaks

- Oscillations frozen at last scattering
- Wavenumbers at extrema = peaks
- Sound speed c_s
- Frequency $\omega = k c_s$; conformal time η
- Phase $\propto k$; $\phi = \int_0^{\text{last scattering}} d\eta \, \omega = k \text{ sound horizon}$
- Harmonic series in sound horizon
  $\phi_n = n\pi \rightarrow k_n = n\pi / \text{sound horizon}$



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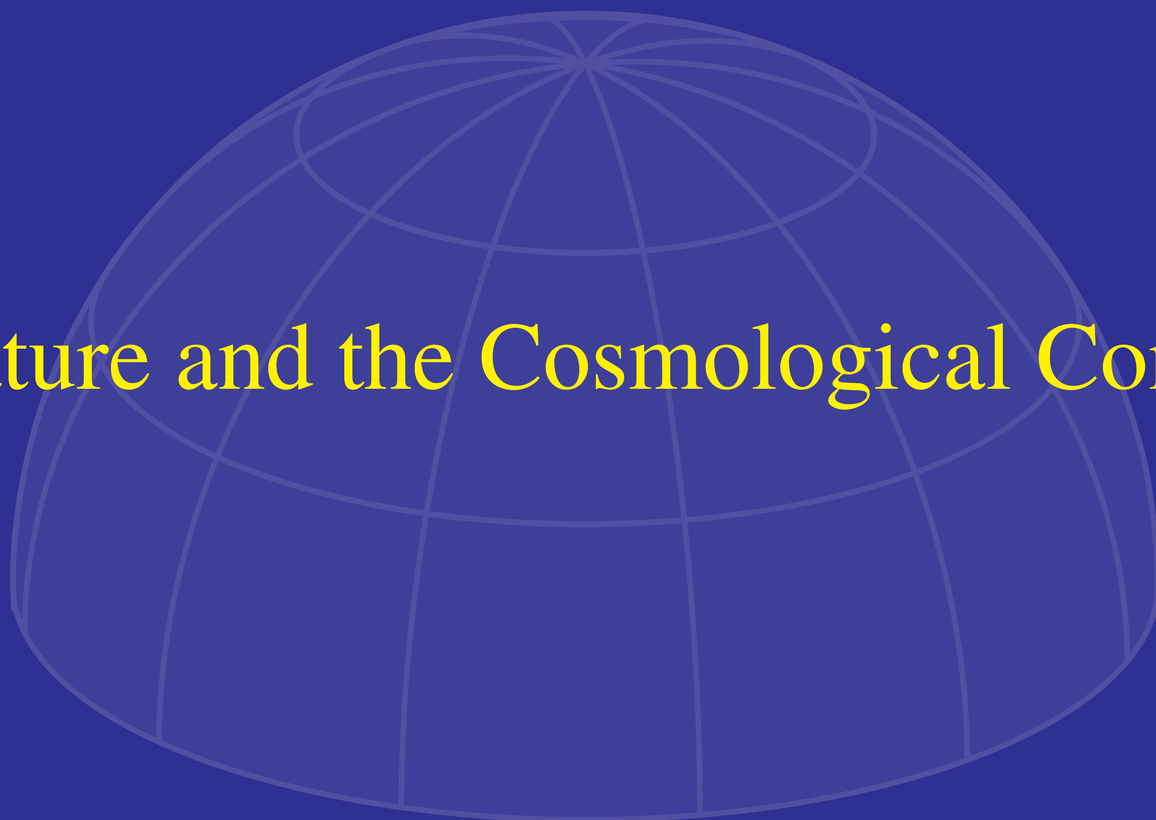
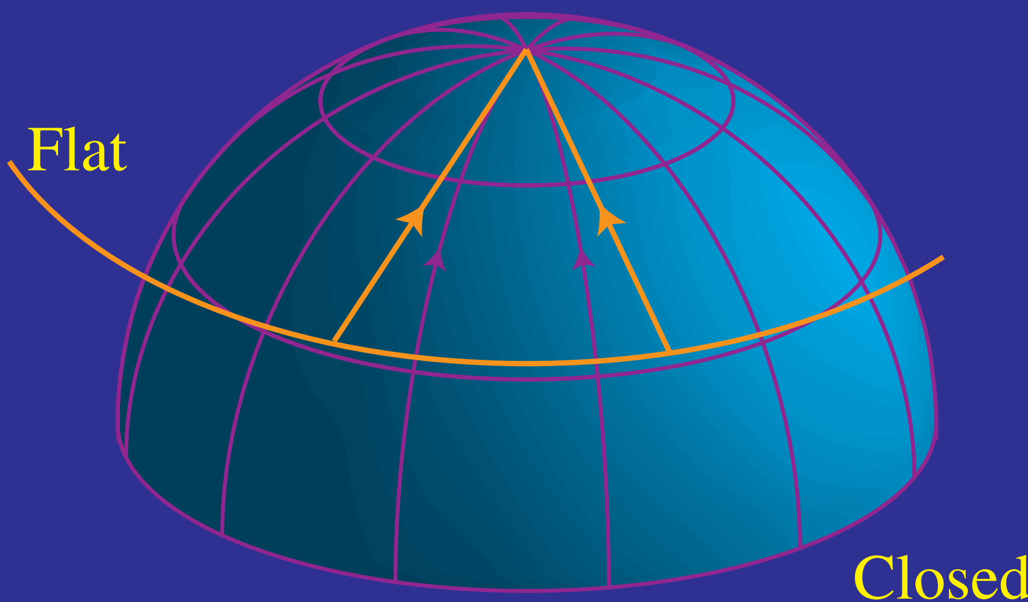
Curvature and the Cosmological Constant

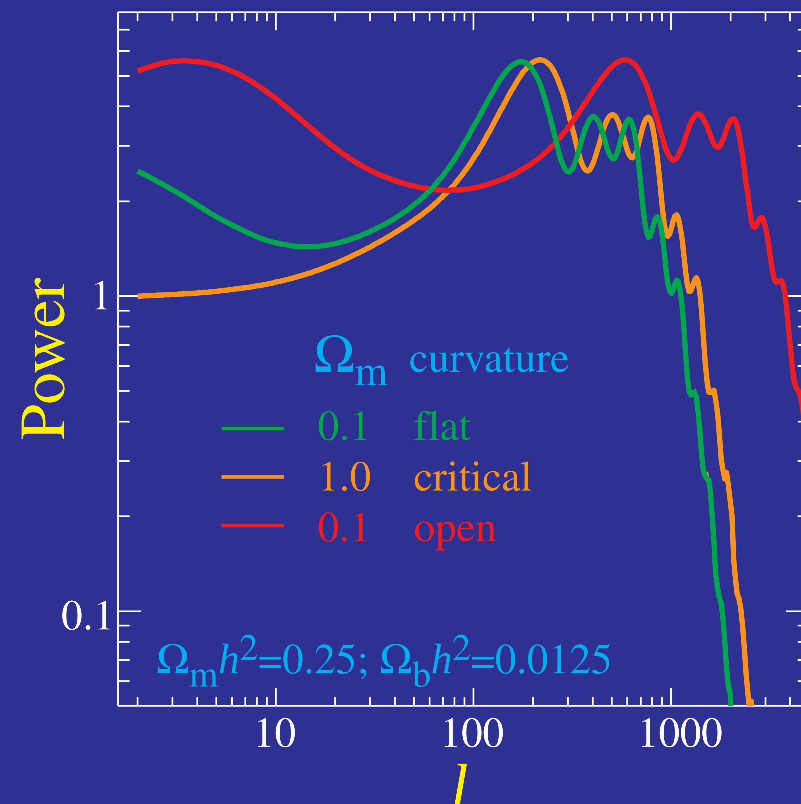


Angular Diameter Distance

- A Classical Test
  - Standard(ized) comoving ruler
  - Measure angular extent
  - Absolute scale drops out
  - Infer curvature
- Upper limit 1st Peak Scale (Horizon)
  Upper limit on Curvature
- Calibrate 2 Physical Scales
  - Sound horizon (peak spacing)] $\Omega_m h^2$
  - Diffusion scale (damping tail)] $\Omega_b h^2$

  IC's





Kamionkowski, Spergel & Sugiyama (1994)
Hu & White (1996)

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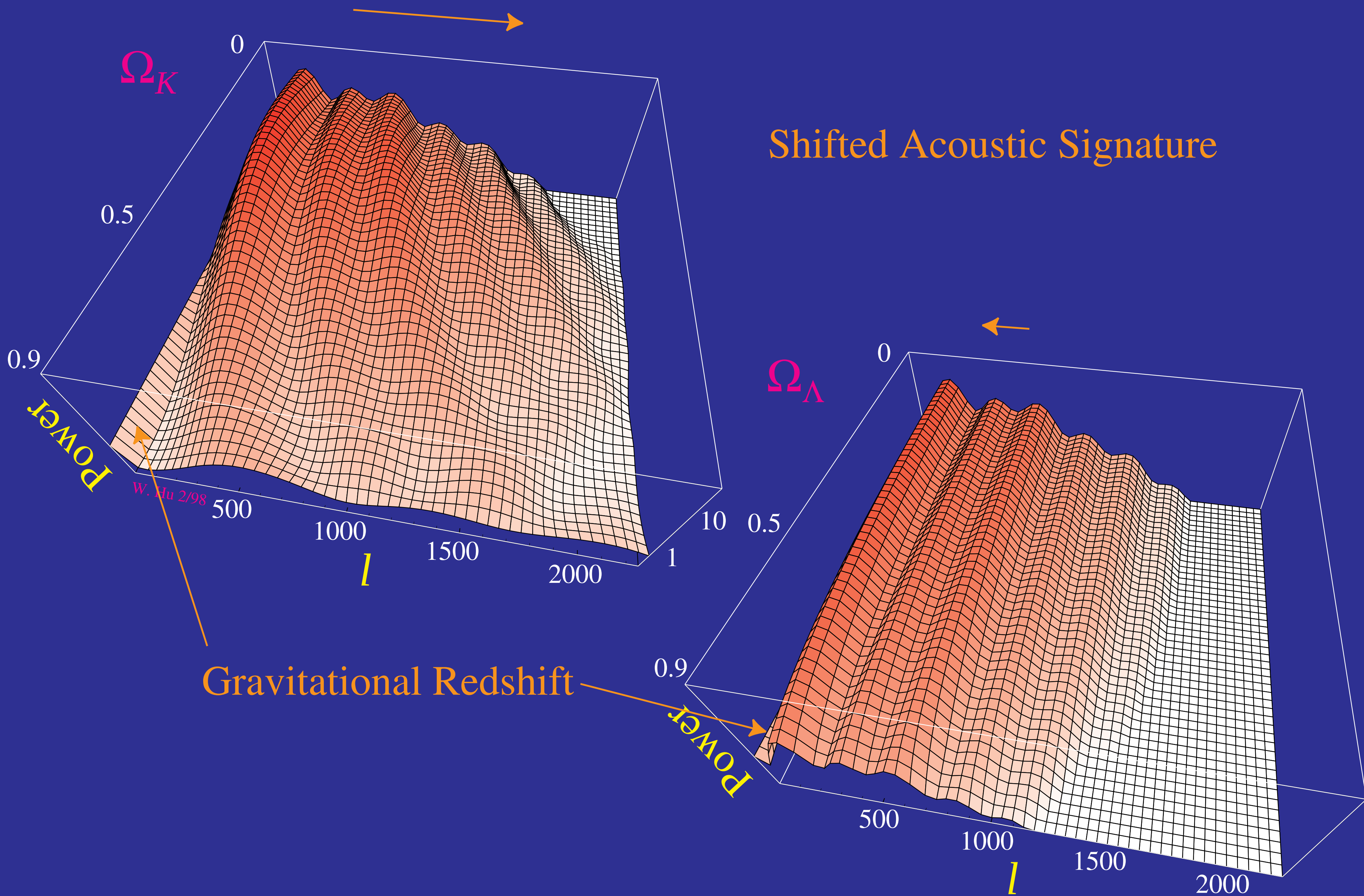
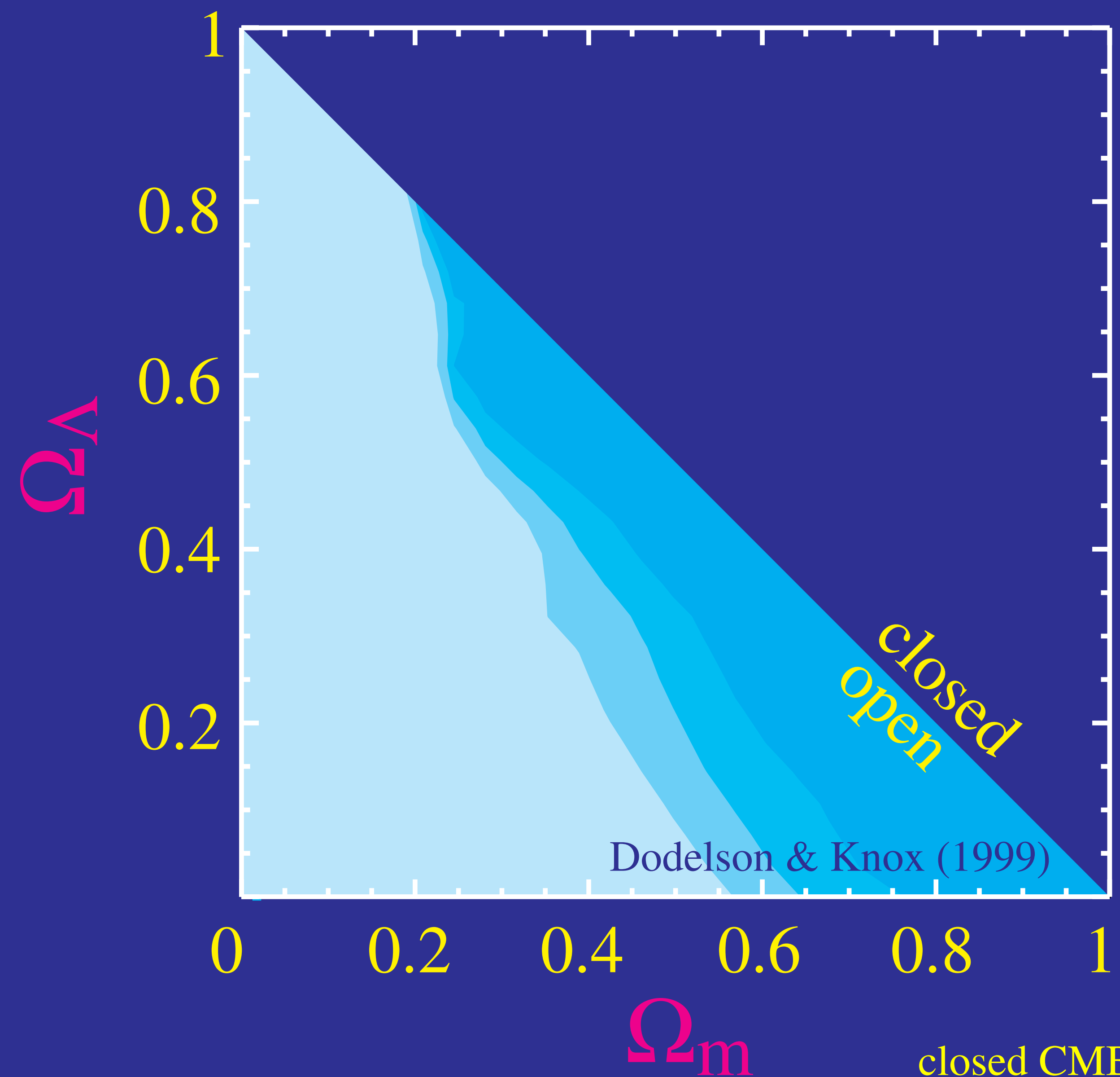
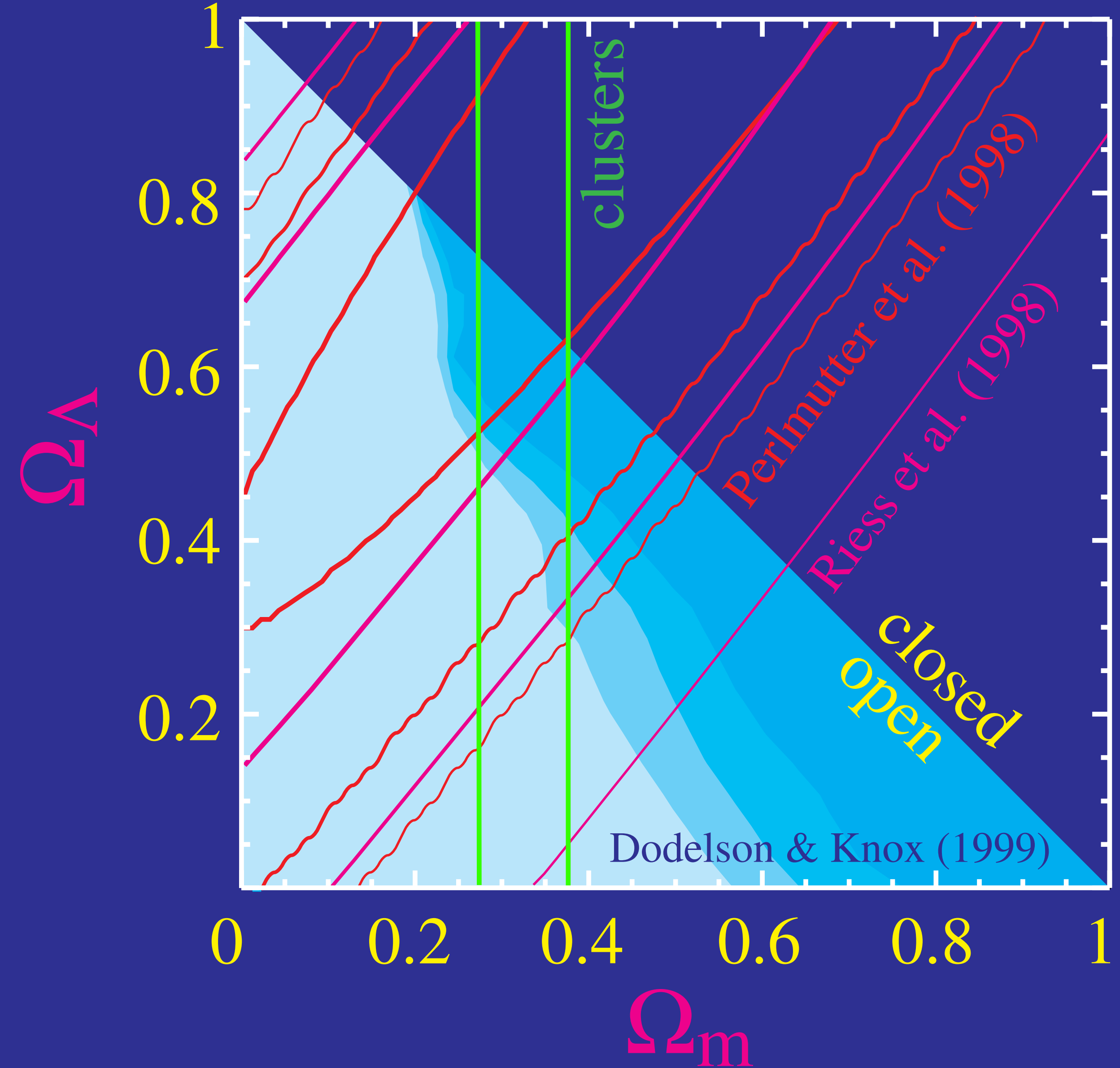


Curvature & Λ: Constraints

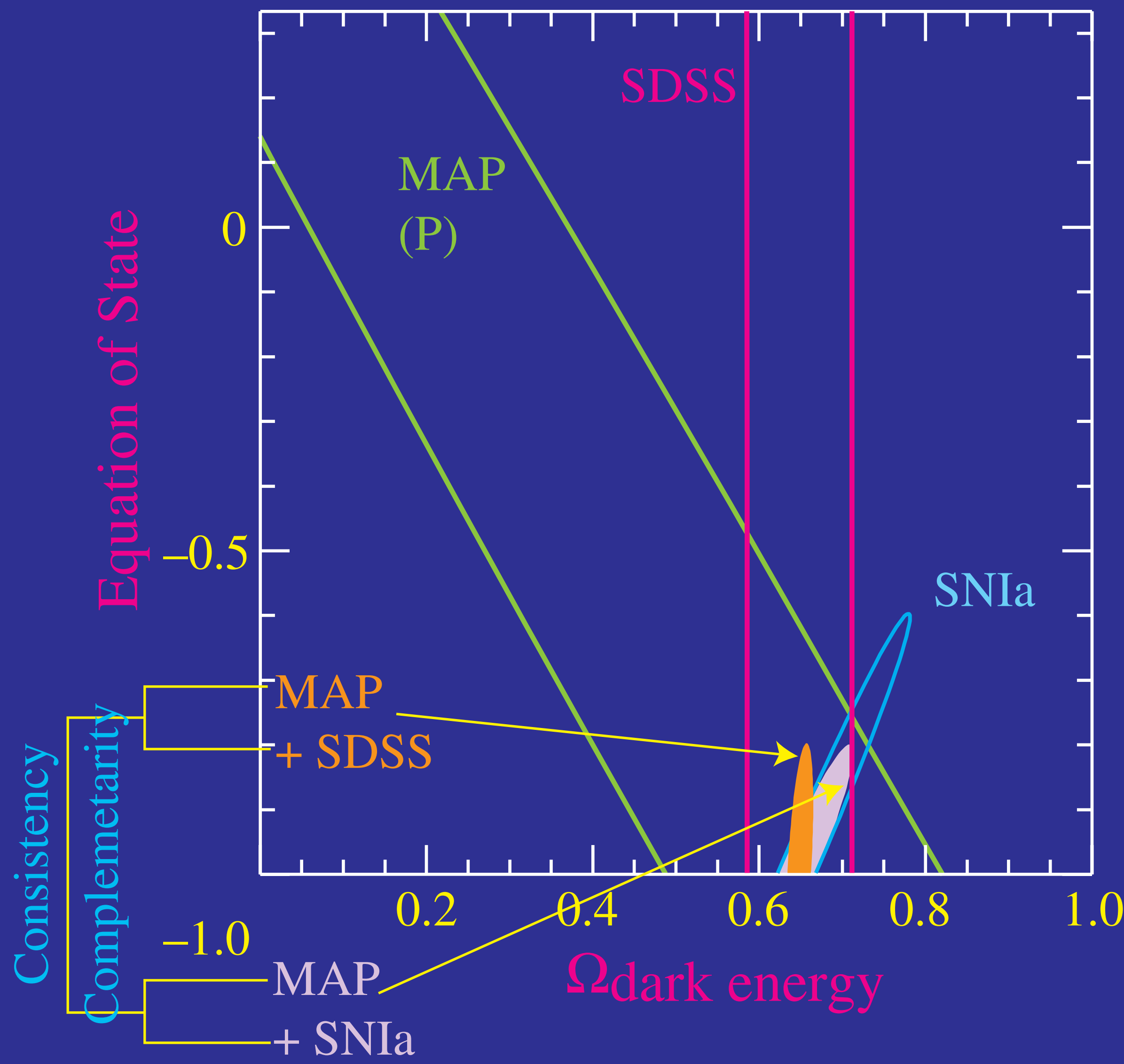


closed CMBFast available!

Curvature & Λ: Constraints



Dark Energy: Future Prospects



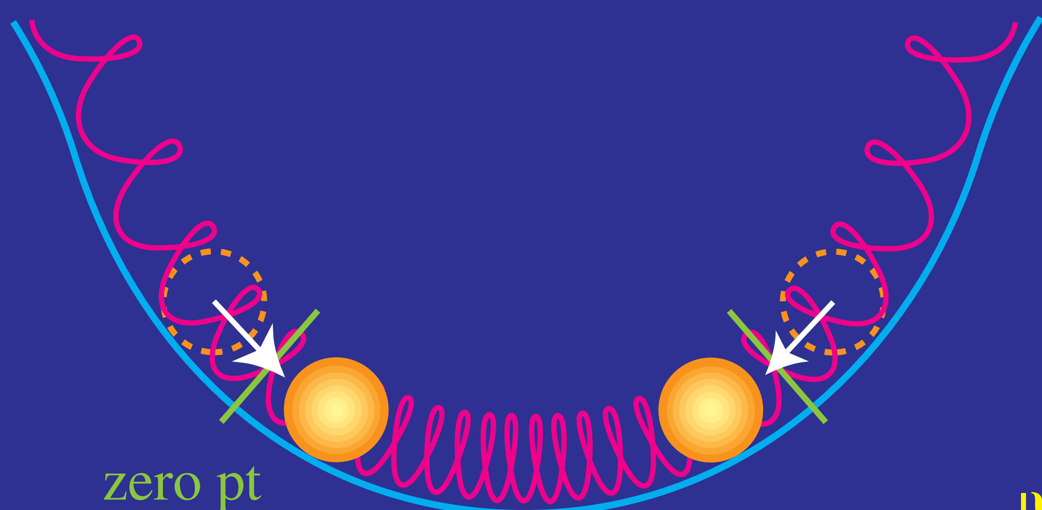
Hu, Eisenstein, Tegmark & White (1998)

Current: Garnavich et al. (1999)

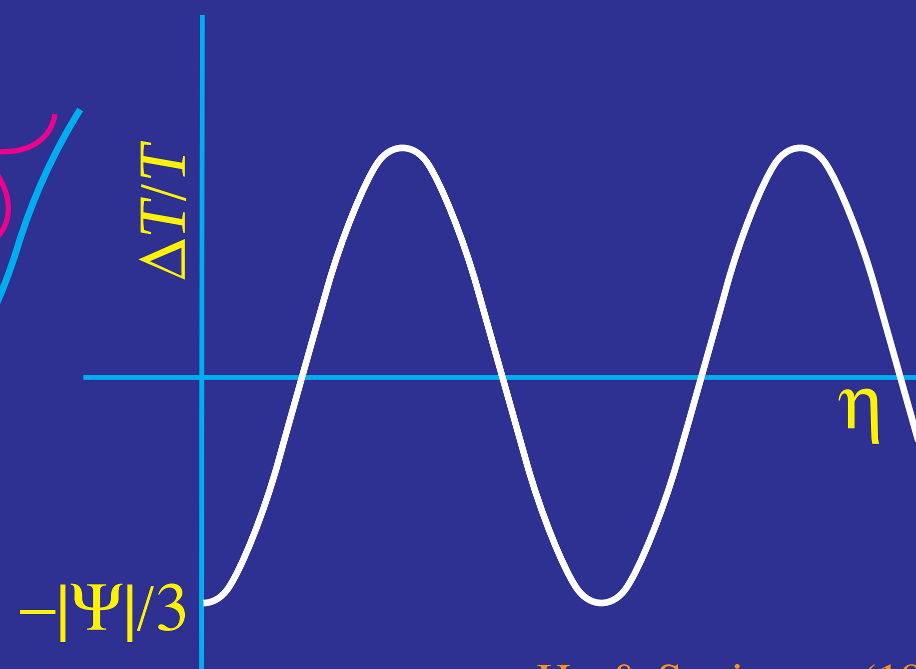
Dark Baryons

Baryon Drag

- 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 $m_{\rm eff} = (1 + R)$



Low Baryon Content



Hu & Sugiyama (1995)

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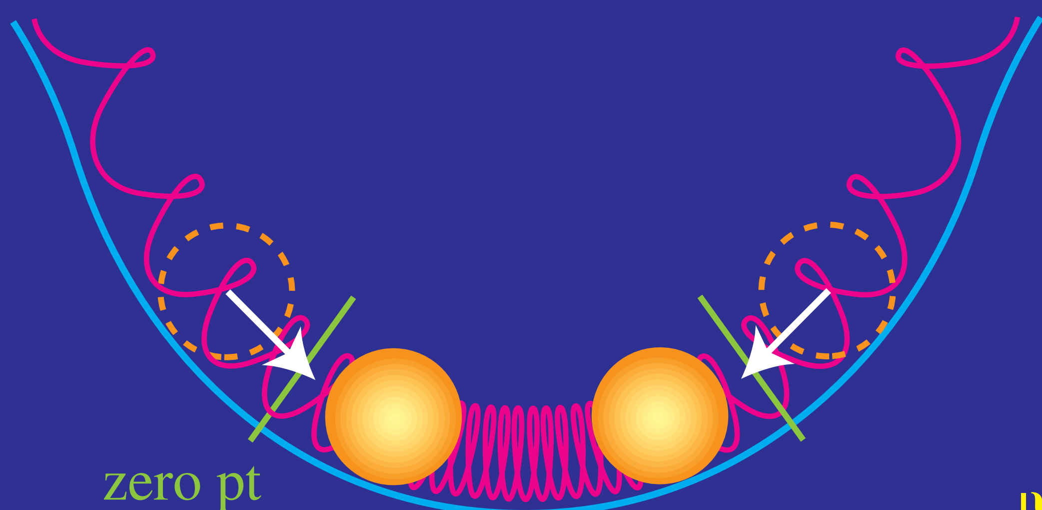
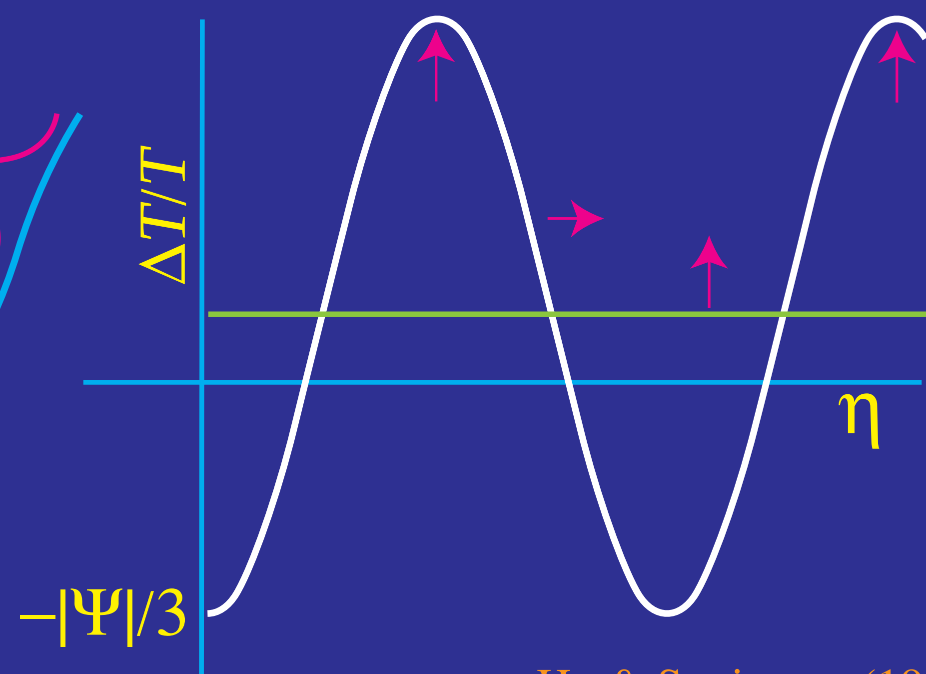
- Effective mass $m_{\rm eff} = (1 + R)$
- Baryons drag photons into potential wells → zero point ↑
- Amplitude ↑
- Frequency ↓ $(\omega \propto m_{\rm eff}^{-1/2})$

- Constant R, Ψ: $(1+R)\ddot{\Theta} + (k^2/3)\Theta = -(1+R)(k^2/3)\Psi$

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



High Baryon Content



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- Amplitude $\uparrow$
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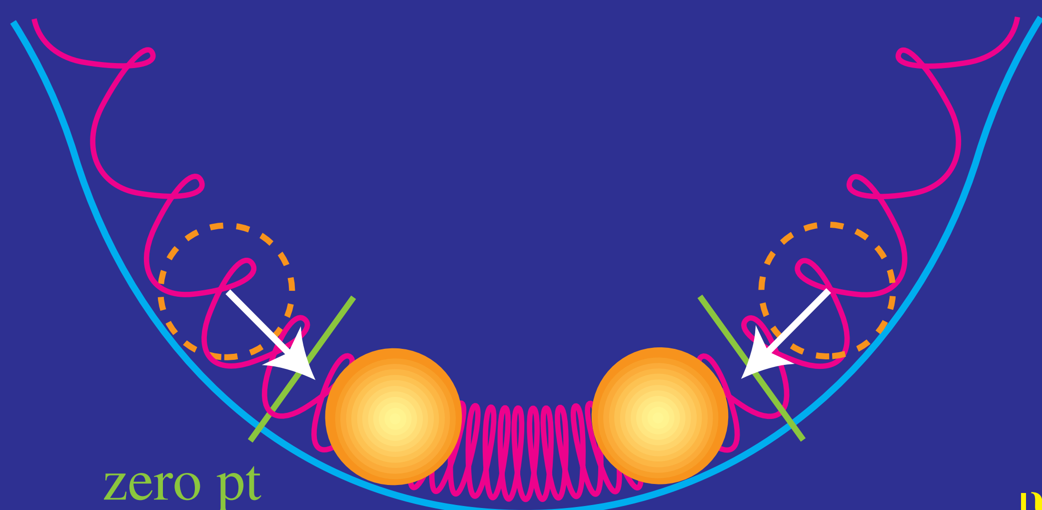
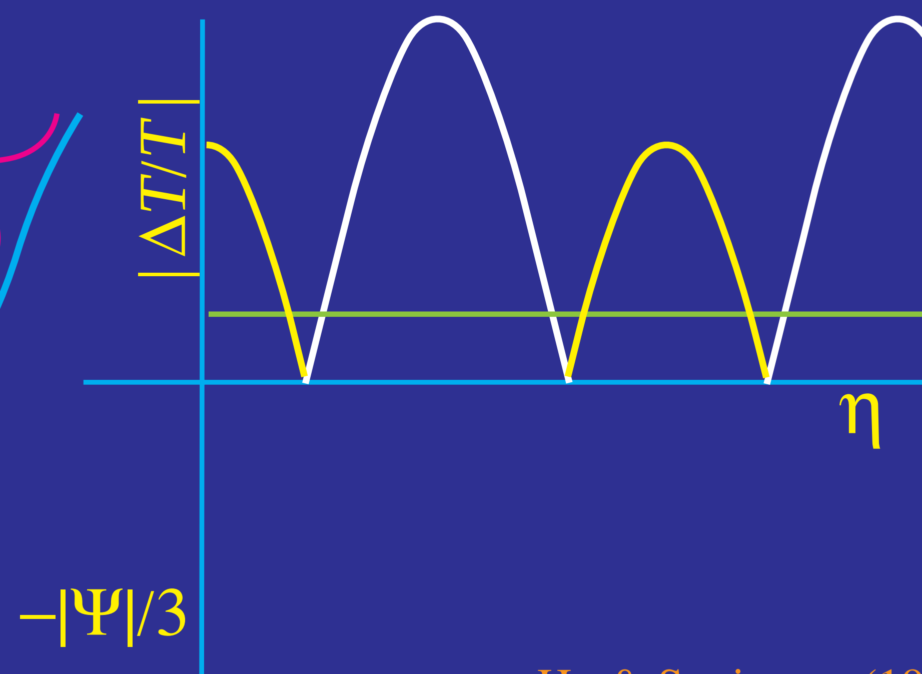


Alternating Peak Heights

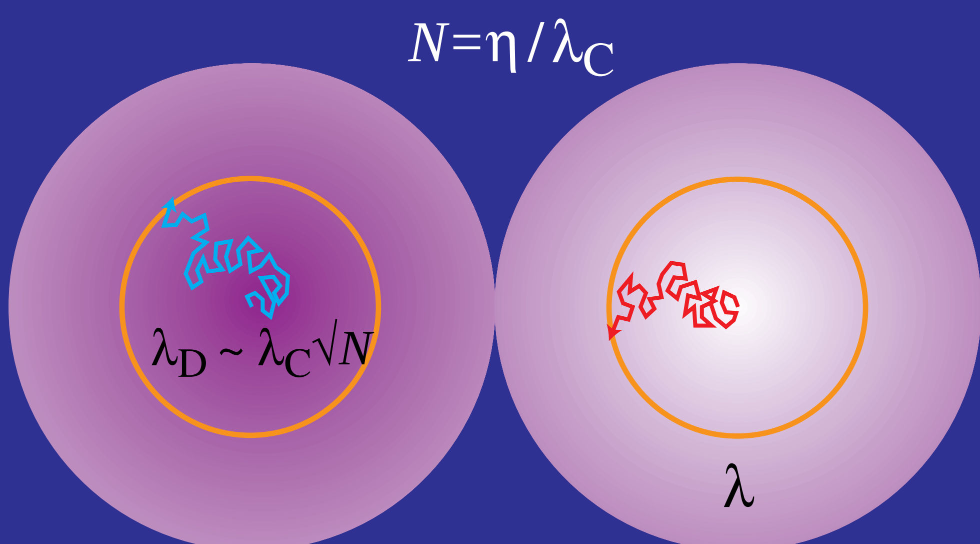


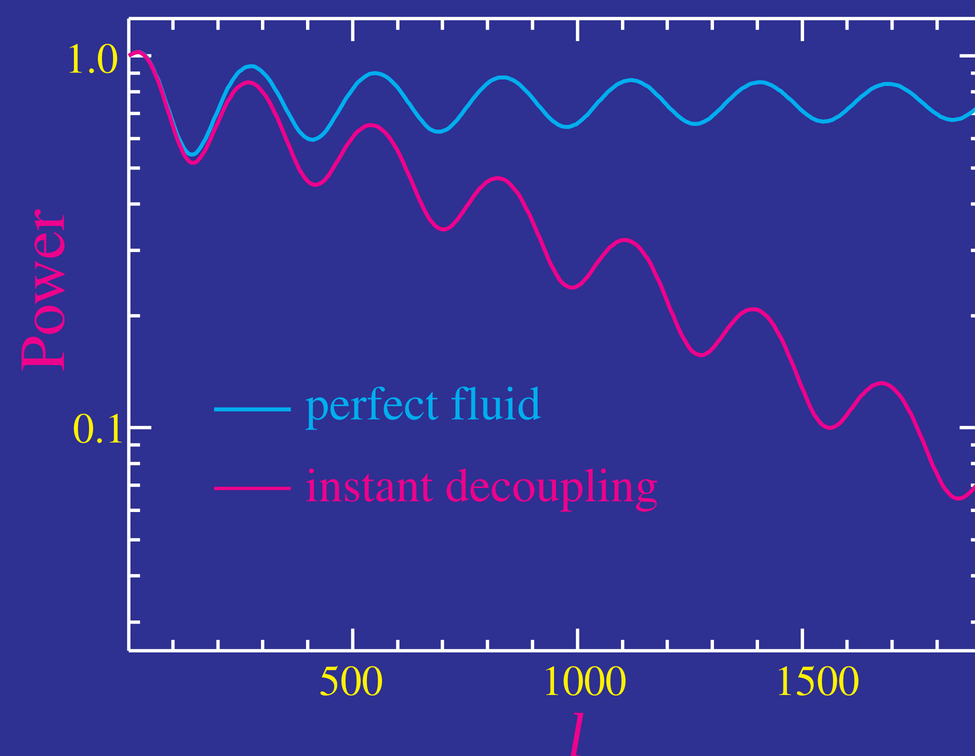
Hu & Sugiyama (1995)

Dissipation / Diffusion Damping

- Imperfections in the coupled fluid → mean free path λ_C in the baryons
- Random walk over diffusion scale: $\lambda_D \sim \lambda_C \sqrt{N} \sim \sqrt{\lambda_C \eta} \gg \lambda_C$

viscous damping for $R<1$; heat conduction damping for $R>1$





Silk (1968)

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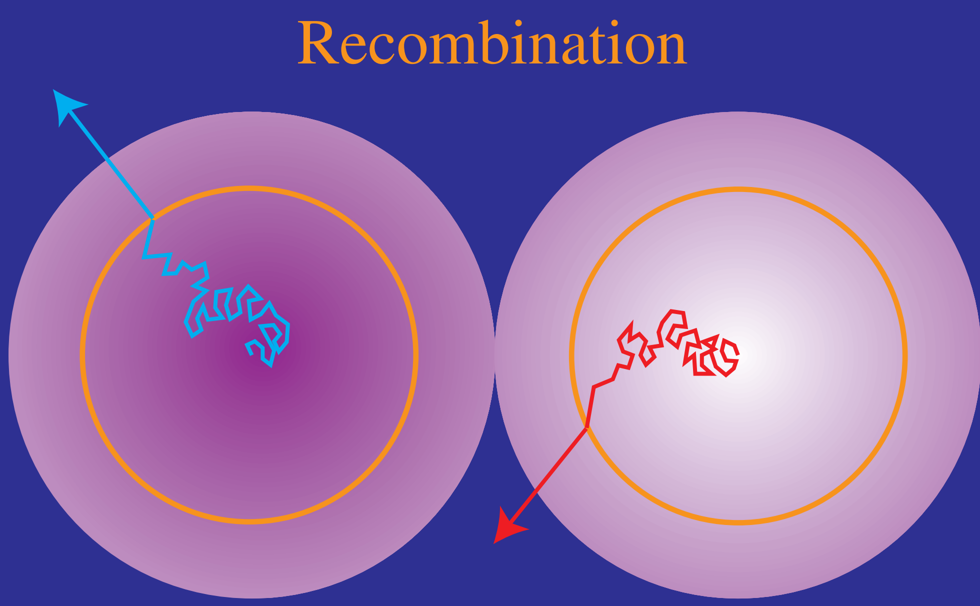
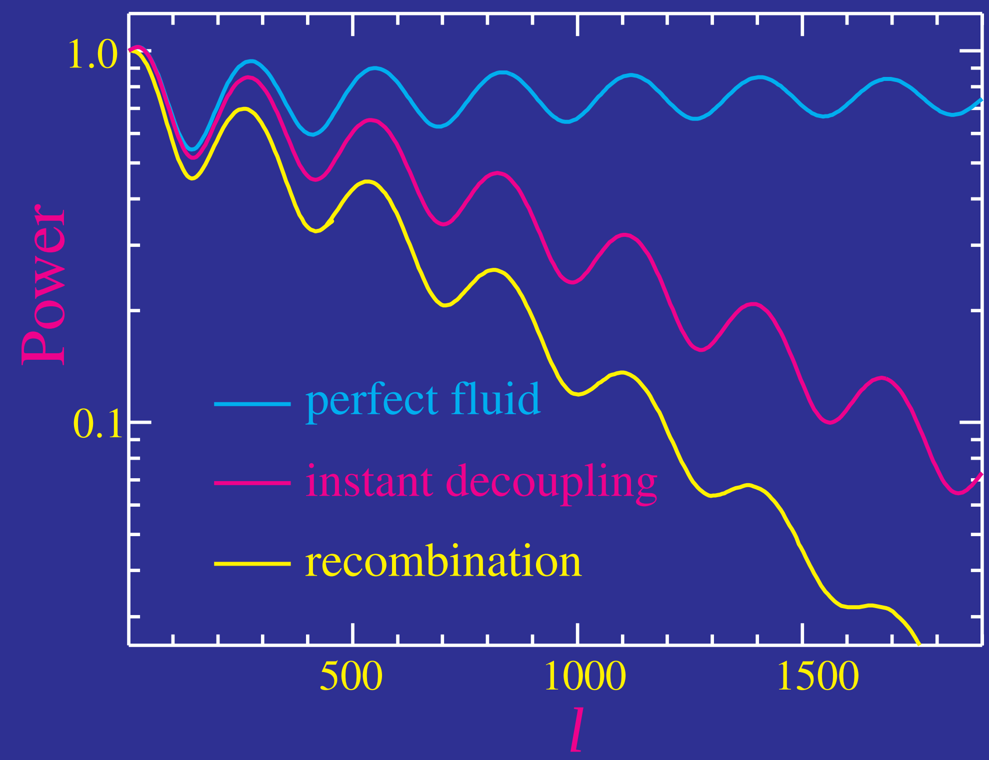
- Rapid increase at recombination as mfp ↑

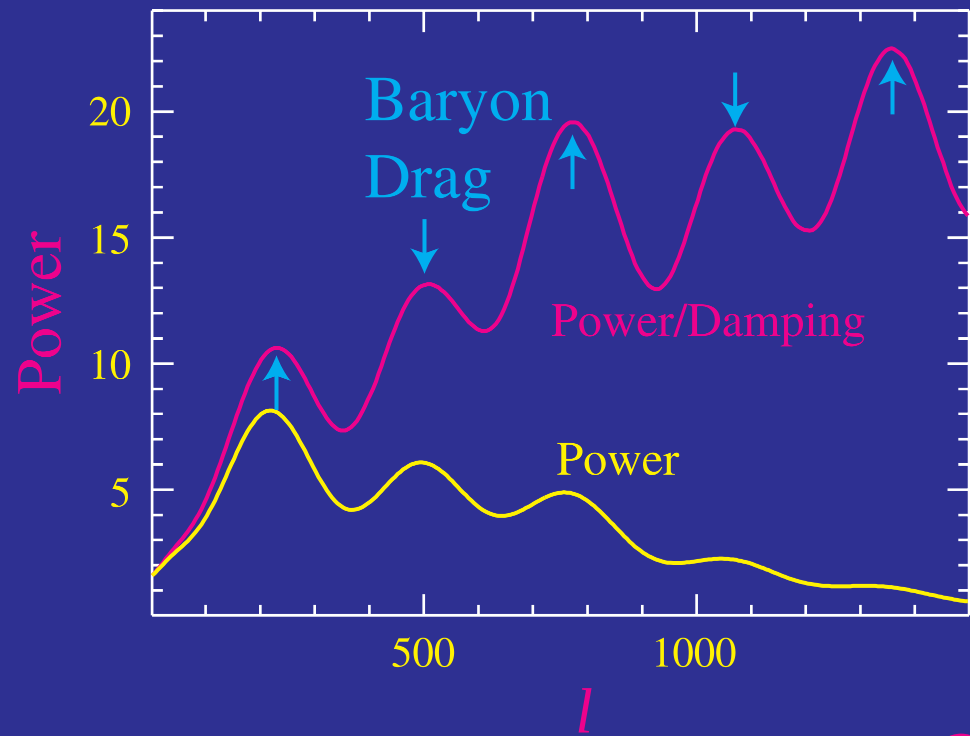
- Peak/Damping angular scale: calibrate $\Omega_b h^2$ or test recombination
- Robust physical scale for angular diameter distance test (Ω_K, Ω_Λ)





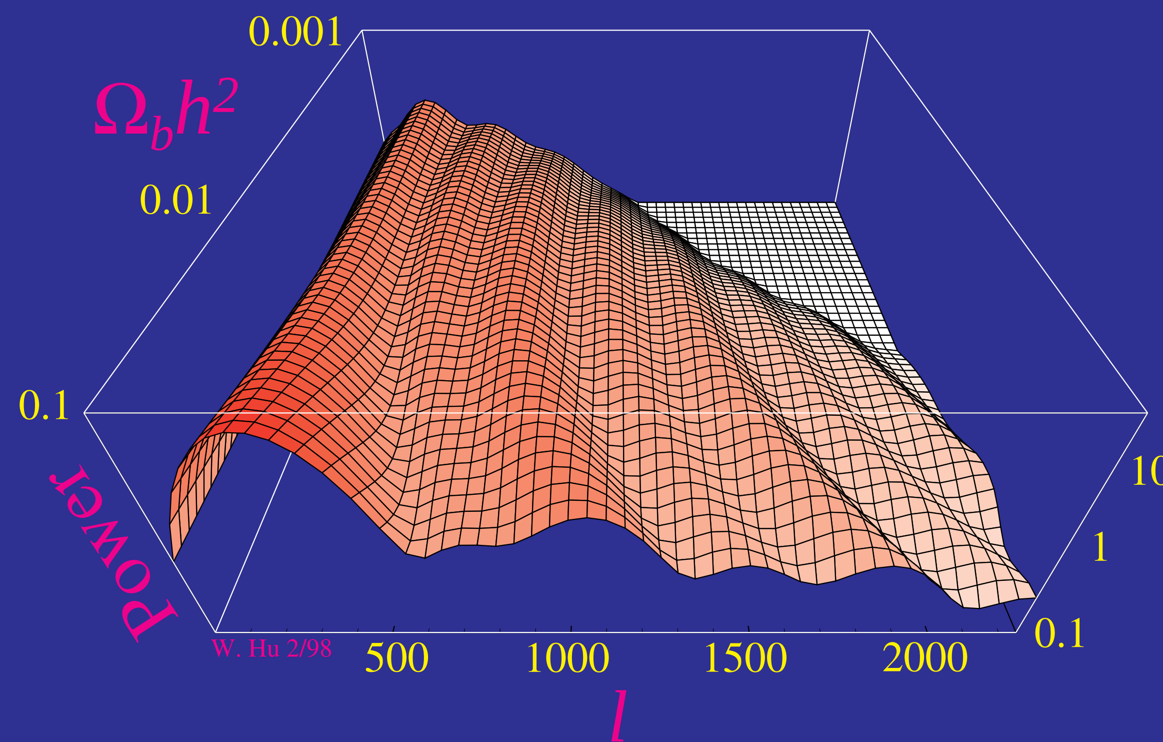
Silk (1968); Hu & White (1996)

Baryons in the CMB

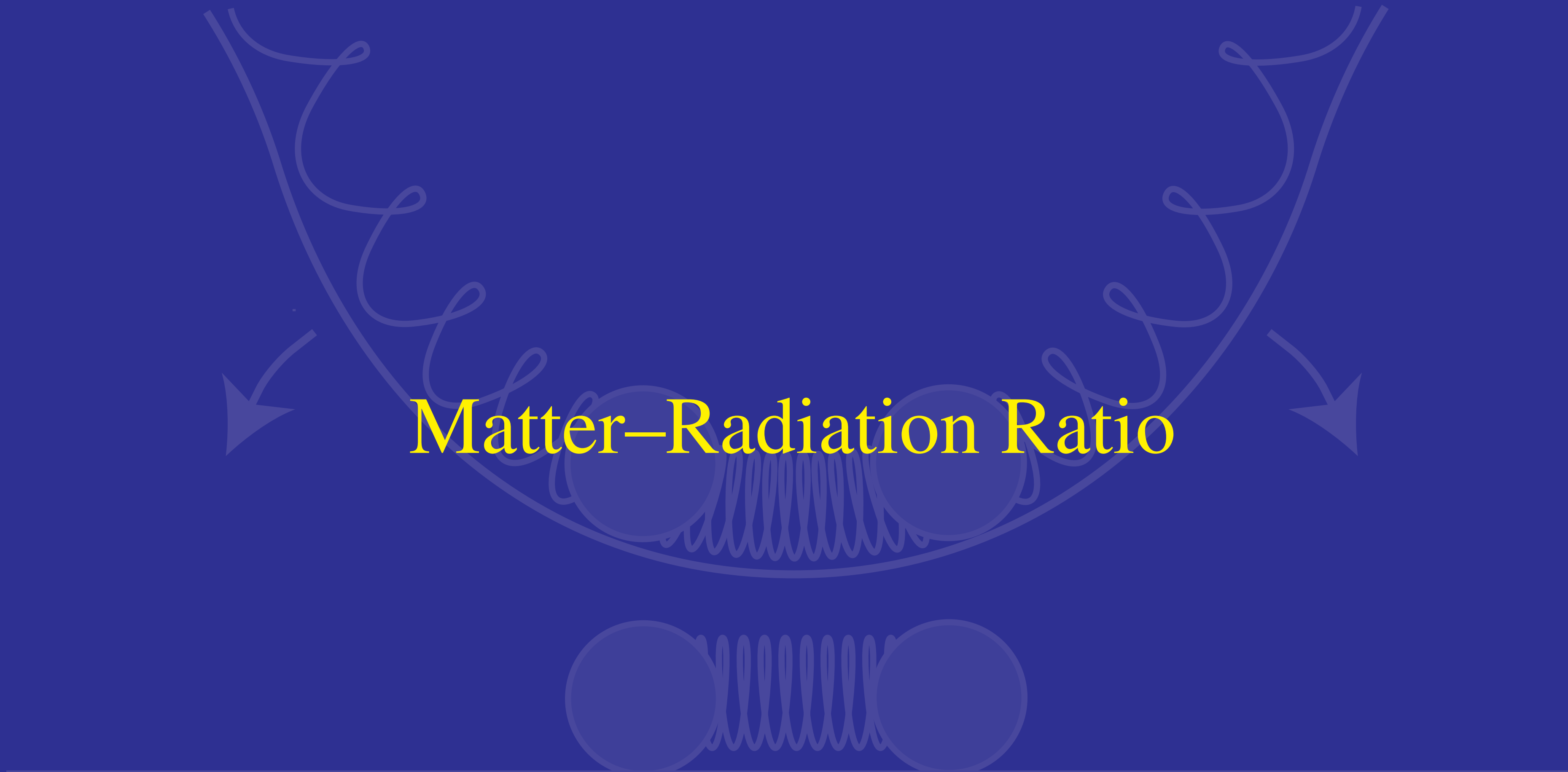


- High odd peaks

- Additional Effects
  - Time–varying potential
  - Dissipation/Fluid imperfections

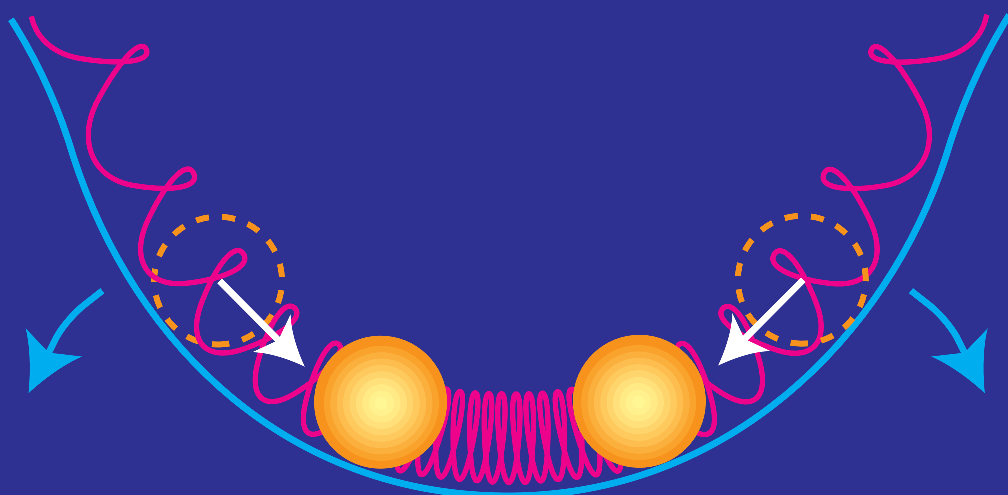


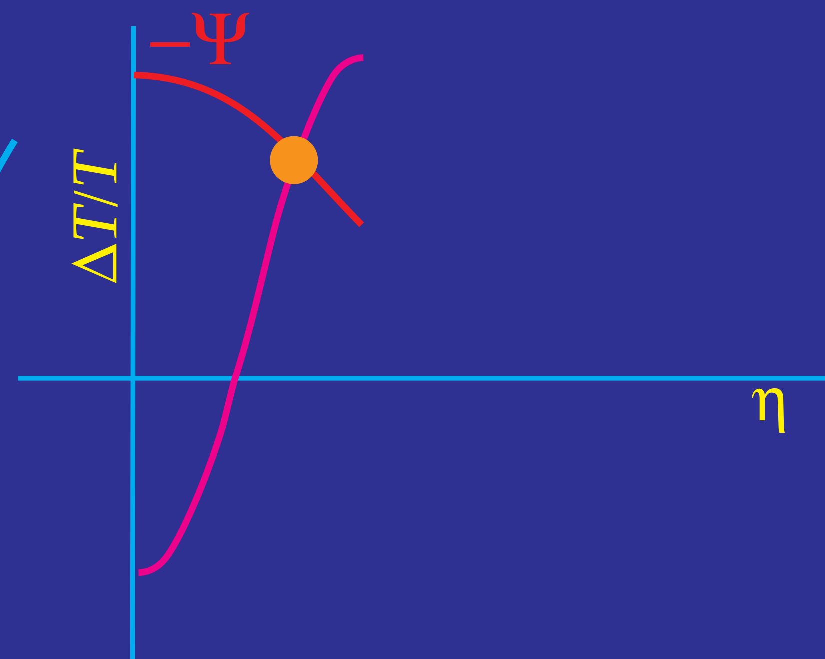
Matter–Radiation Ratio



Driving Effects and Matter/Radiation

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





Hu & Sugiyama (1995)

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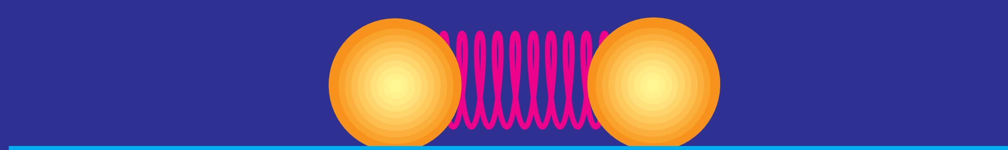
- Feedback stops at matter domination



Hu & Sugiyama (1995)

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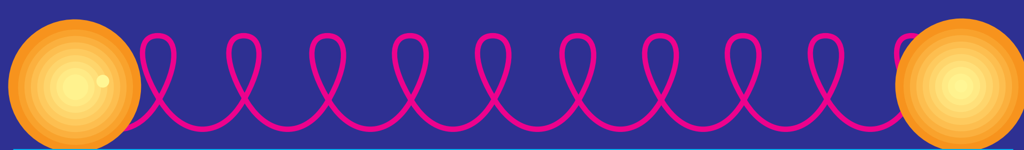
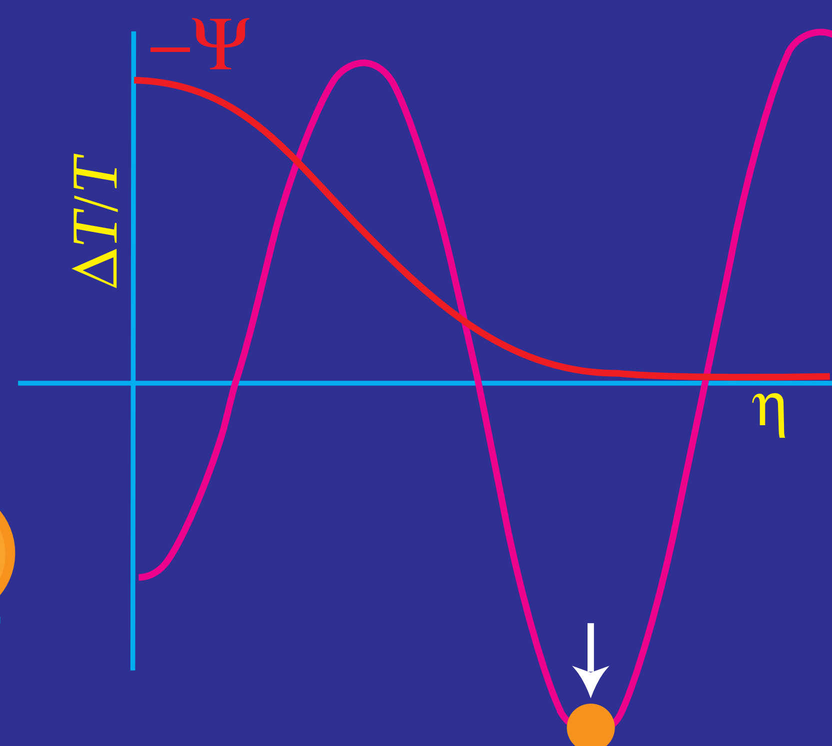
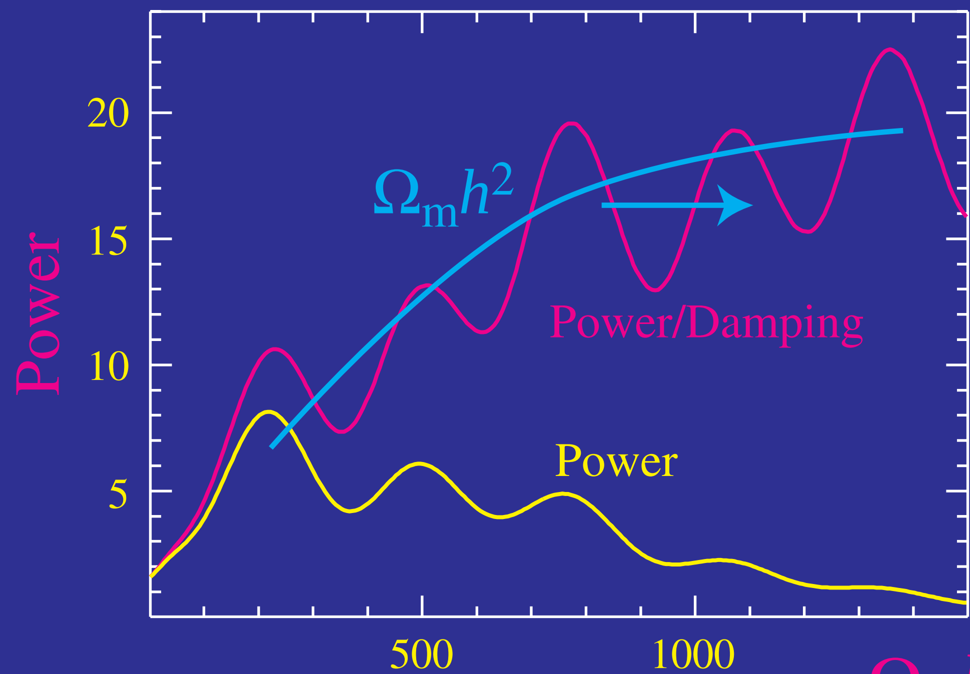


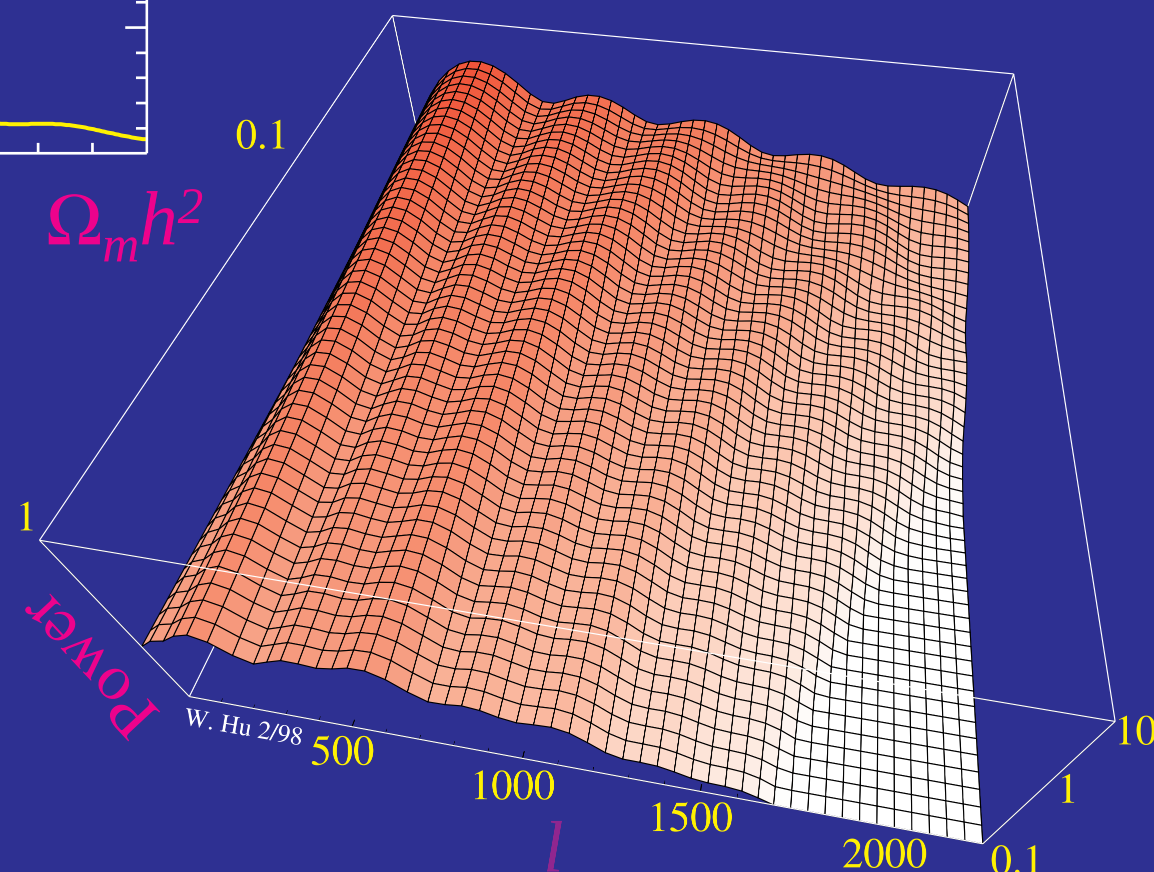


Hu & Sugiyama (1995)

Matter Density in the CMB



- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history



- Measure $\Omega_m h^2$ from peak heights

1.2.3

Inflation
&
The Origin of Perturbations

Inflation as Source of Perturbations

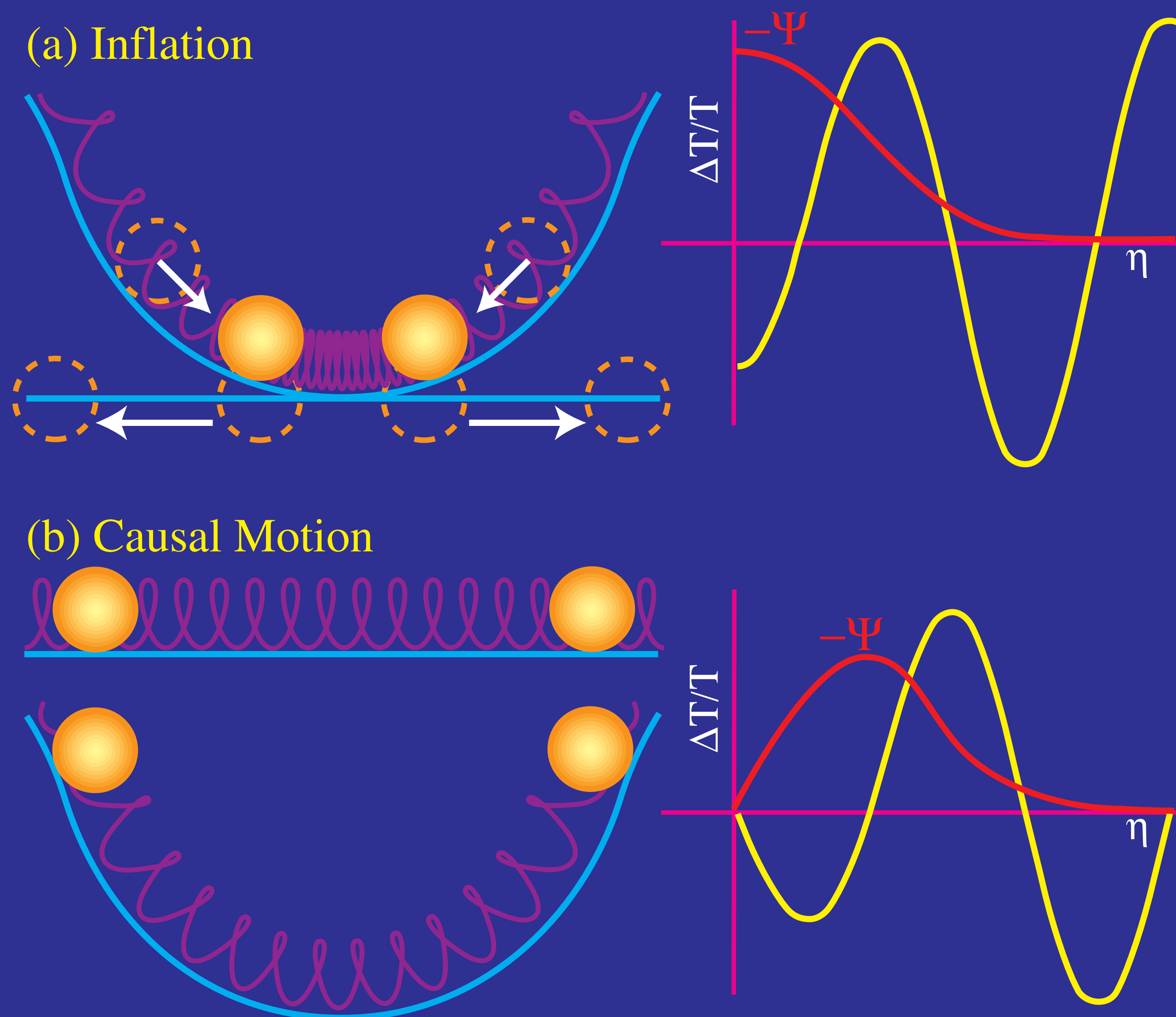
- Superluminal expansion (inflation) required to generate superhorizon potential (density) perturbations
- Potential perturbations drive oscillations
- (Nearly) unique prediction for phase
- Ratio of peak locations

ving causally

inflation: 1:2:3...

passive causal
  models: 1:3:5...

active causal
  models: no peaks



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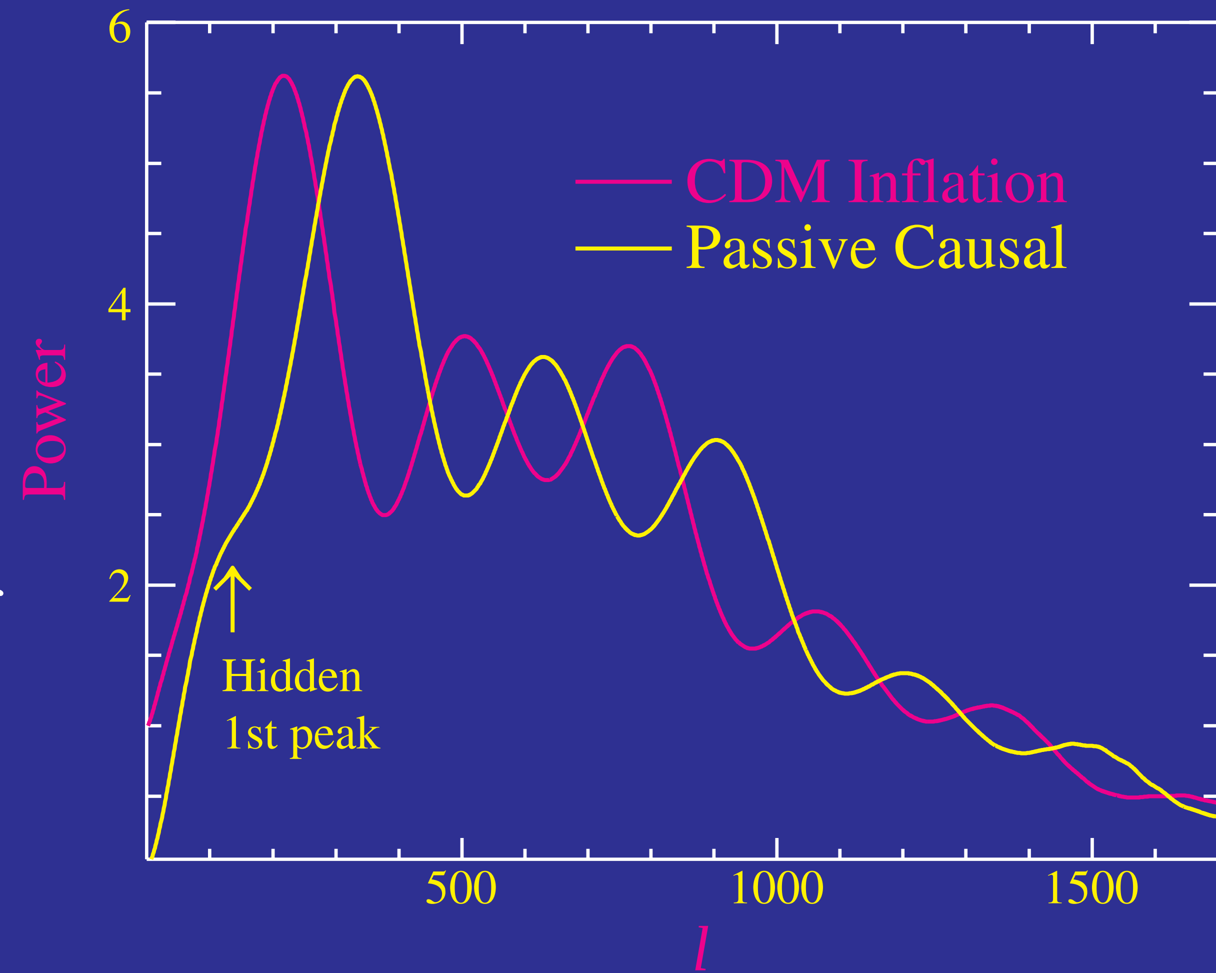
- Ratio of peak locations

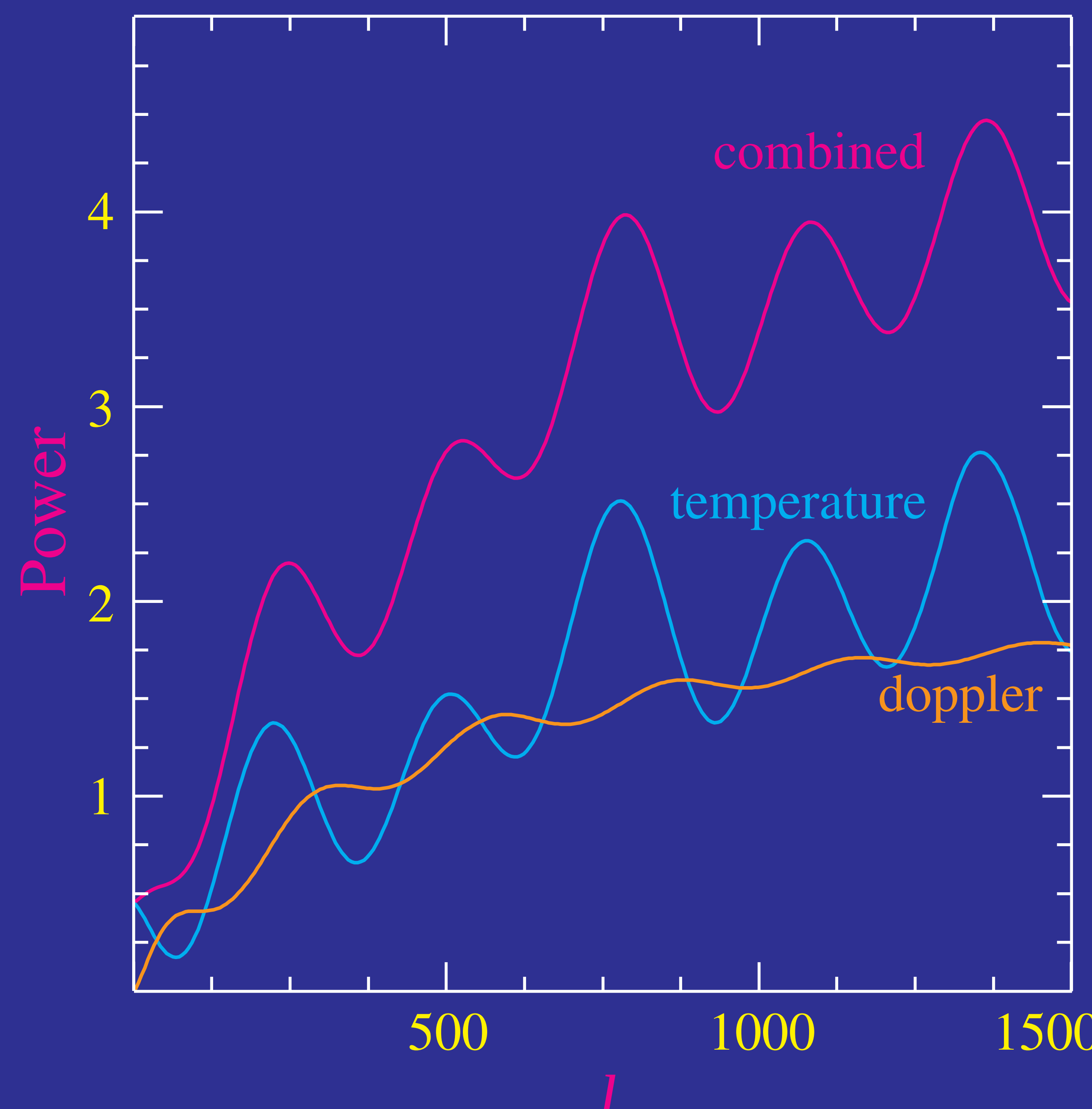
1:2:3 strongly suggests inflation but not necessarily the adiabatic or isocurvature nature of initial conditions



(Hu 1998; Hu & Peebles 1999)

Summary of Acoustic Phenomenology

- Fluid + Gravity
  - → harmonic series:
    inflationary origin



Summary of Acoustic Phenomenology

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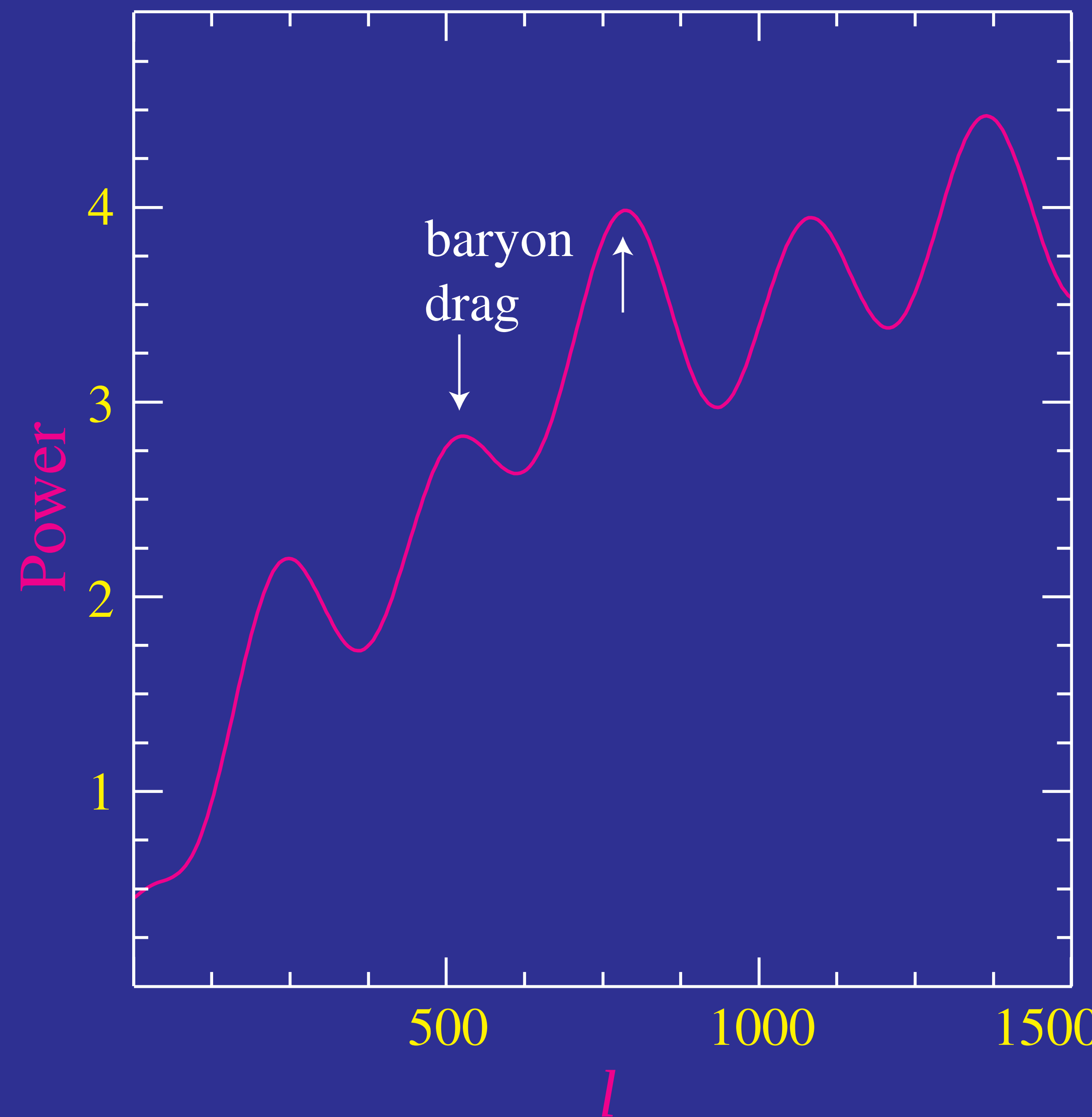

Summary of Acoustic Phenomenology

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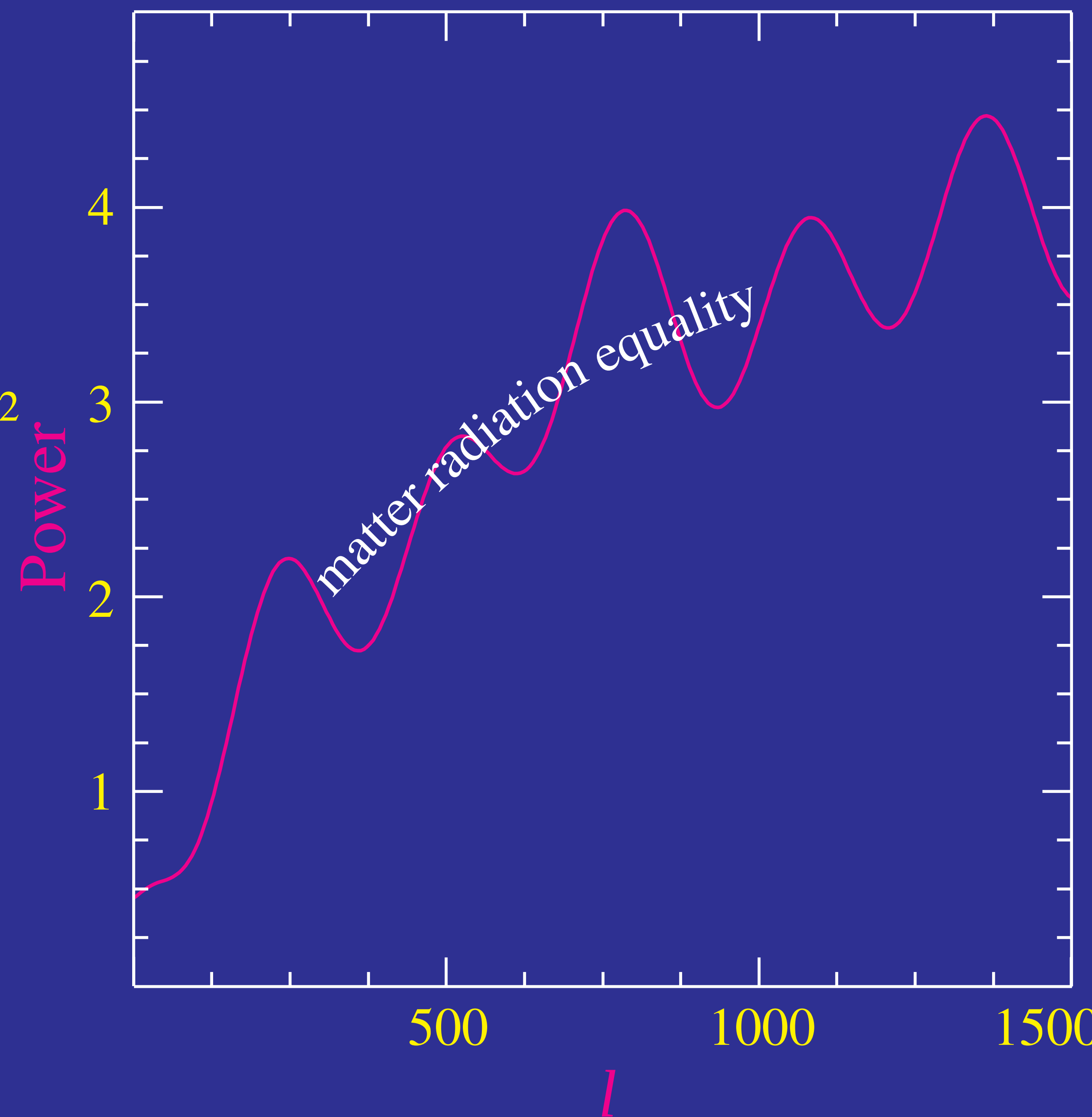
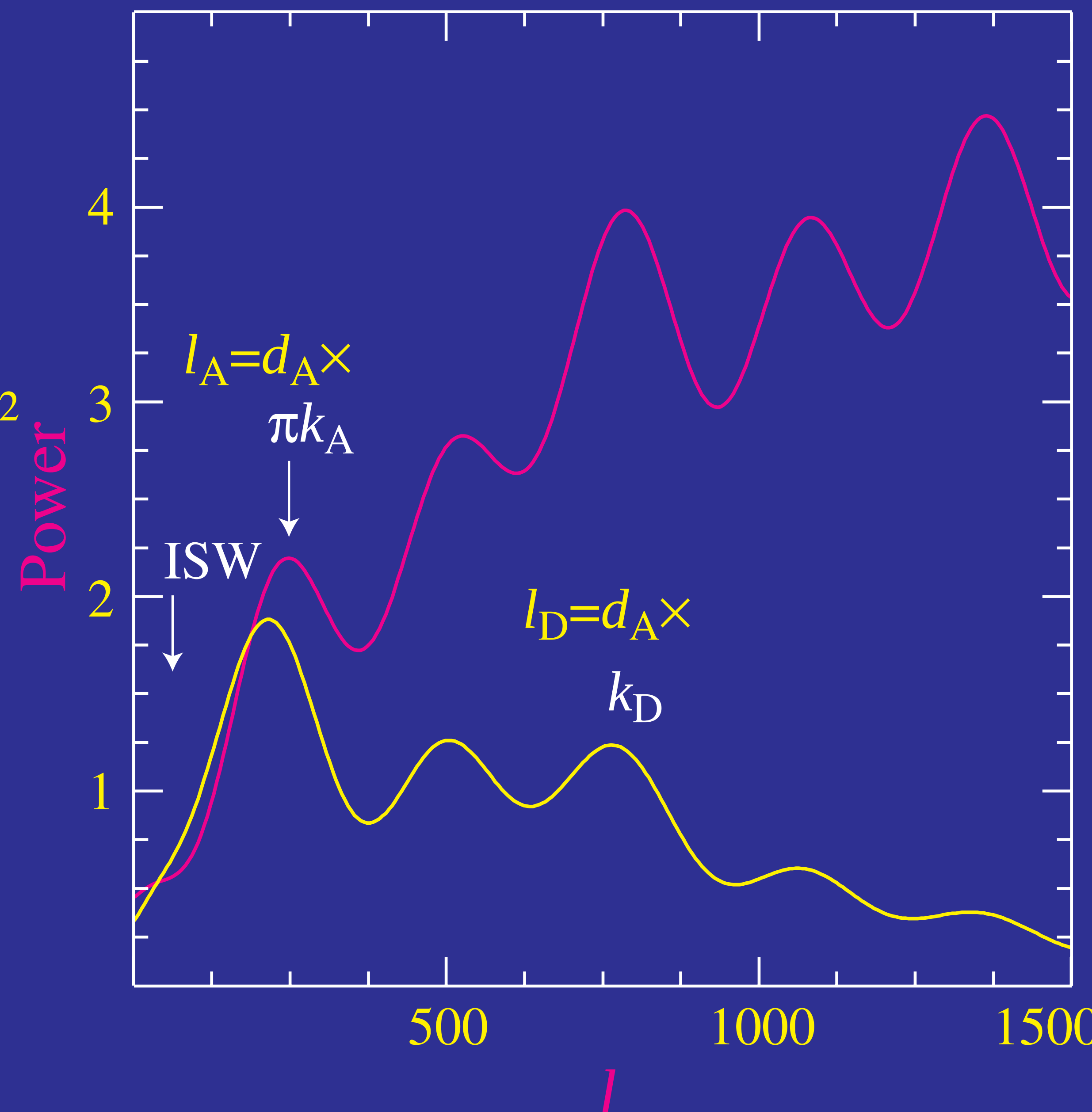


Summary of Acoustic Phenomenology

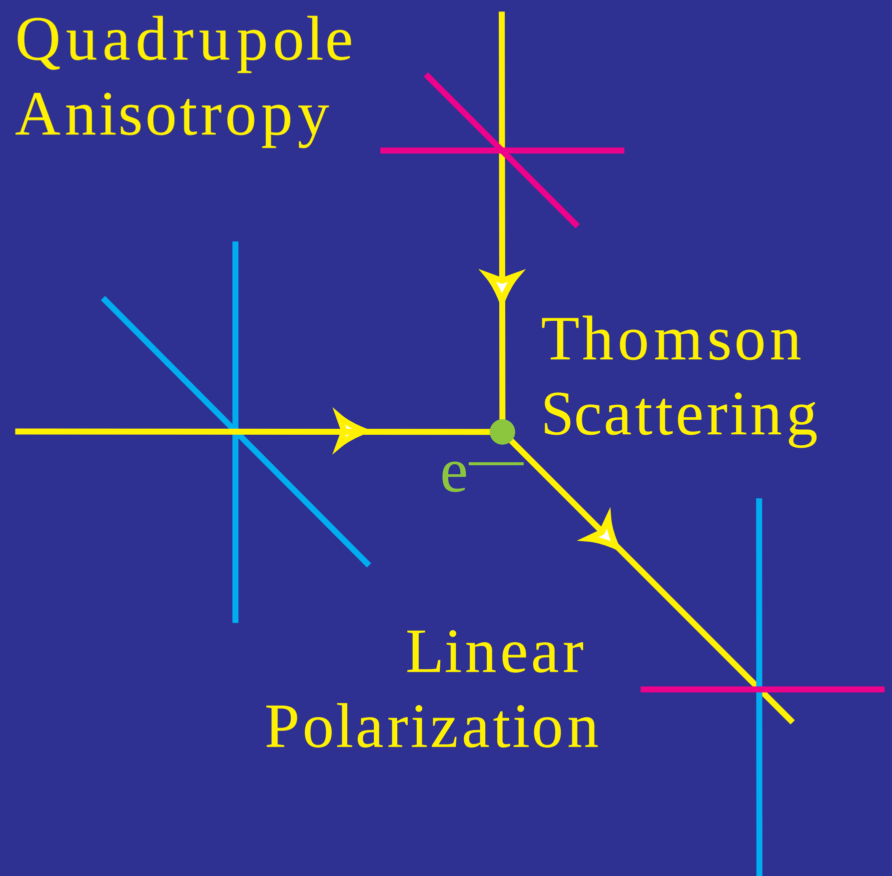
- Fluid + Gravity
  - → harmonic series: inflationary origin
  - → alternating peaks: photon/baryon $\Omega_b h^2$
  - → driven oscillations: matter/radiation $\Omega_m h^2$
- Ruler Calibration
  - → sound horizon
  - → damping scale
- Geometry
  - → angular diameter distance $f(\Omega_\Lambda,\Omega_K)$ + flatness or no Ω_Λ,
  - → Ω_Λ or Ω_K



Beyond
the
Acoustic Peaks

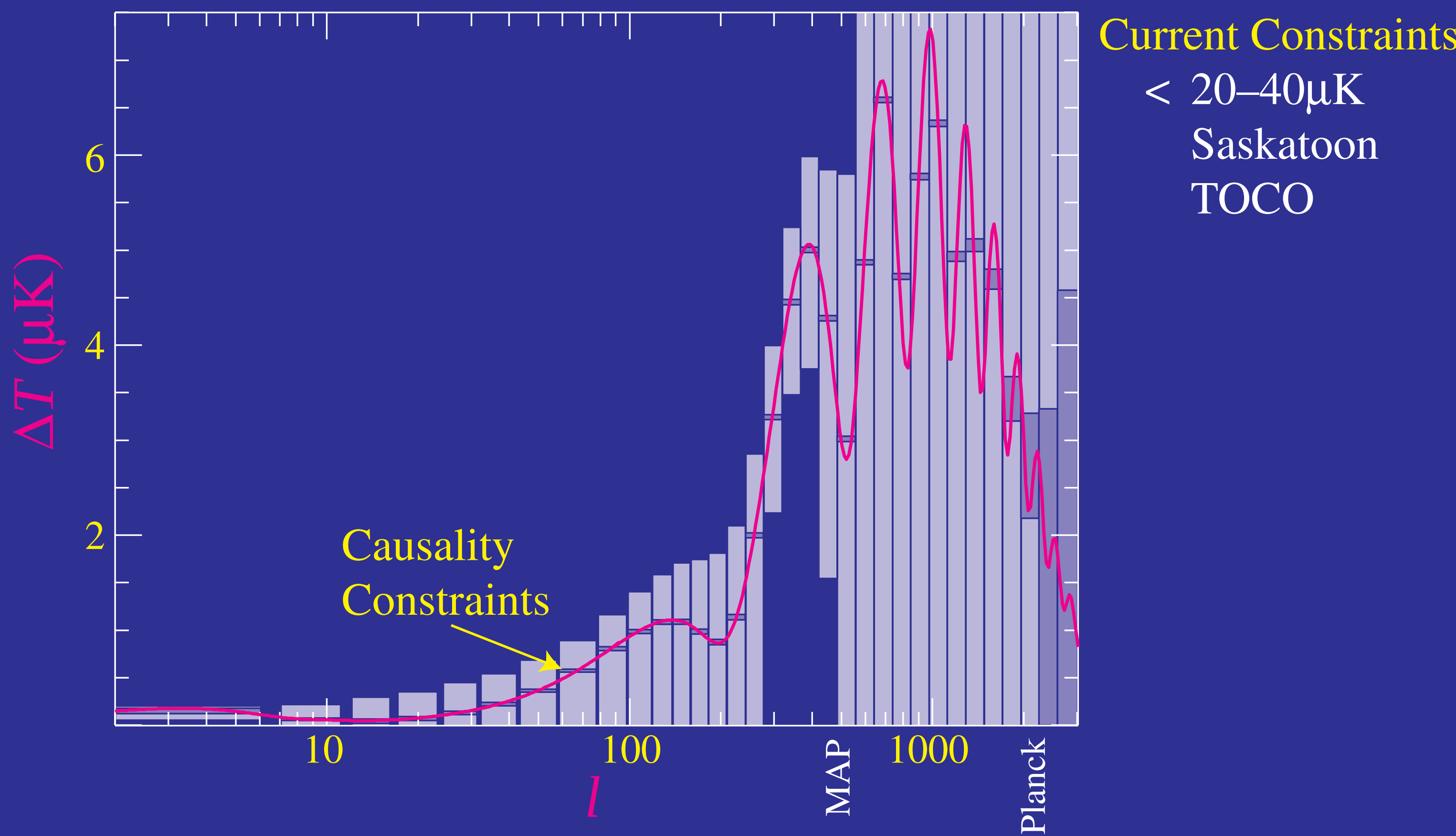
Polarization Diagnostics

- CMB polarization generated by scattering of quadrupole anisotropies



Polarization Diagnostics

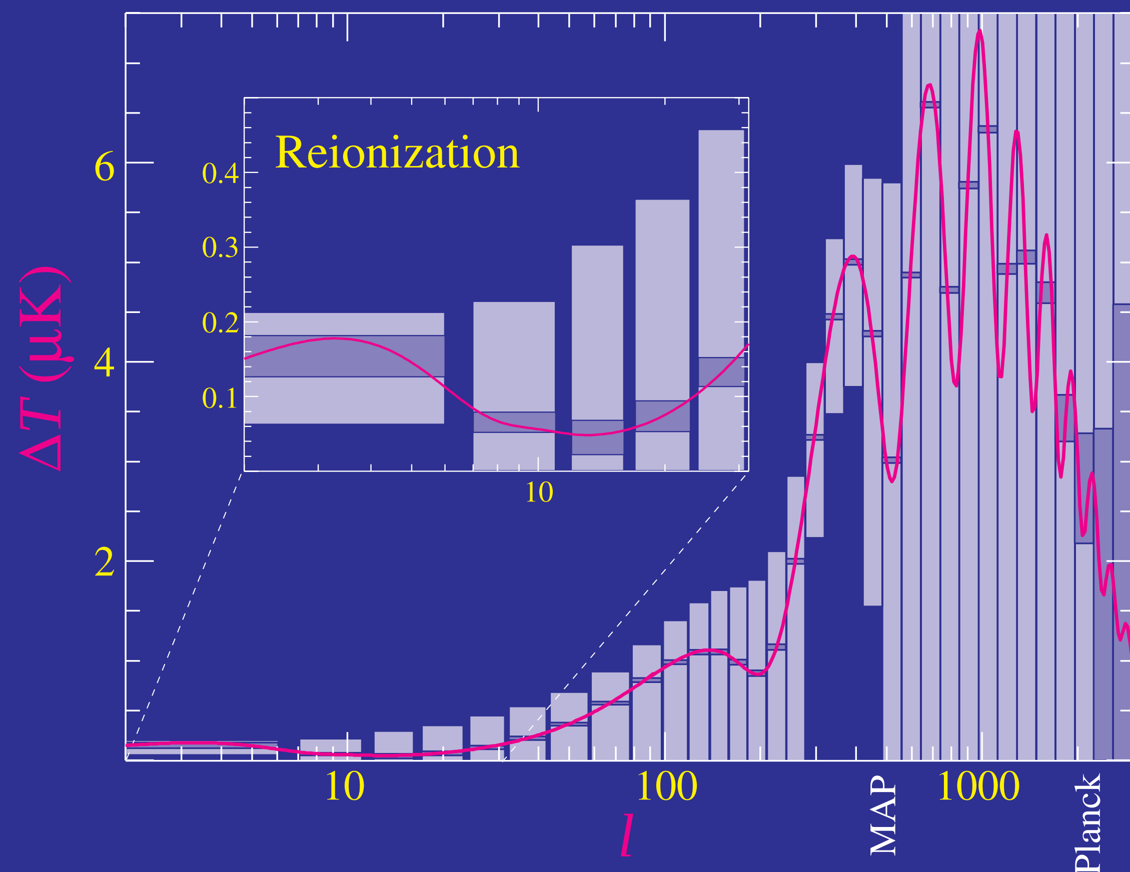
- CMB polarization generated by scattering of quadrupole anisotropies
- Isolates the last scattering surface
  → tests causal generation (inflation vs. defects)



Hu & White (1997)
Zaldarriaga & Spergel (1997)

Polarization Diagnostics

- CMB polarization generated by scattering of quadrupole anisotropies
- Isolates the last scattering surface
  → measures the reionization epoch / optical depth (first structures)

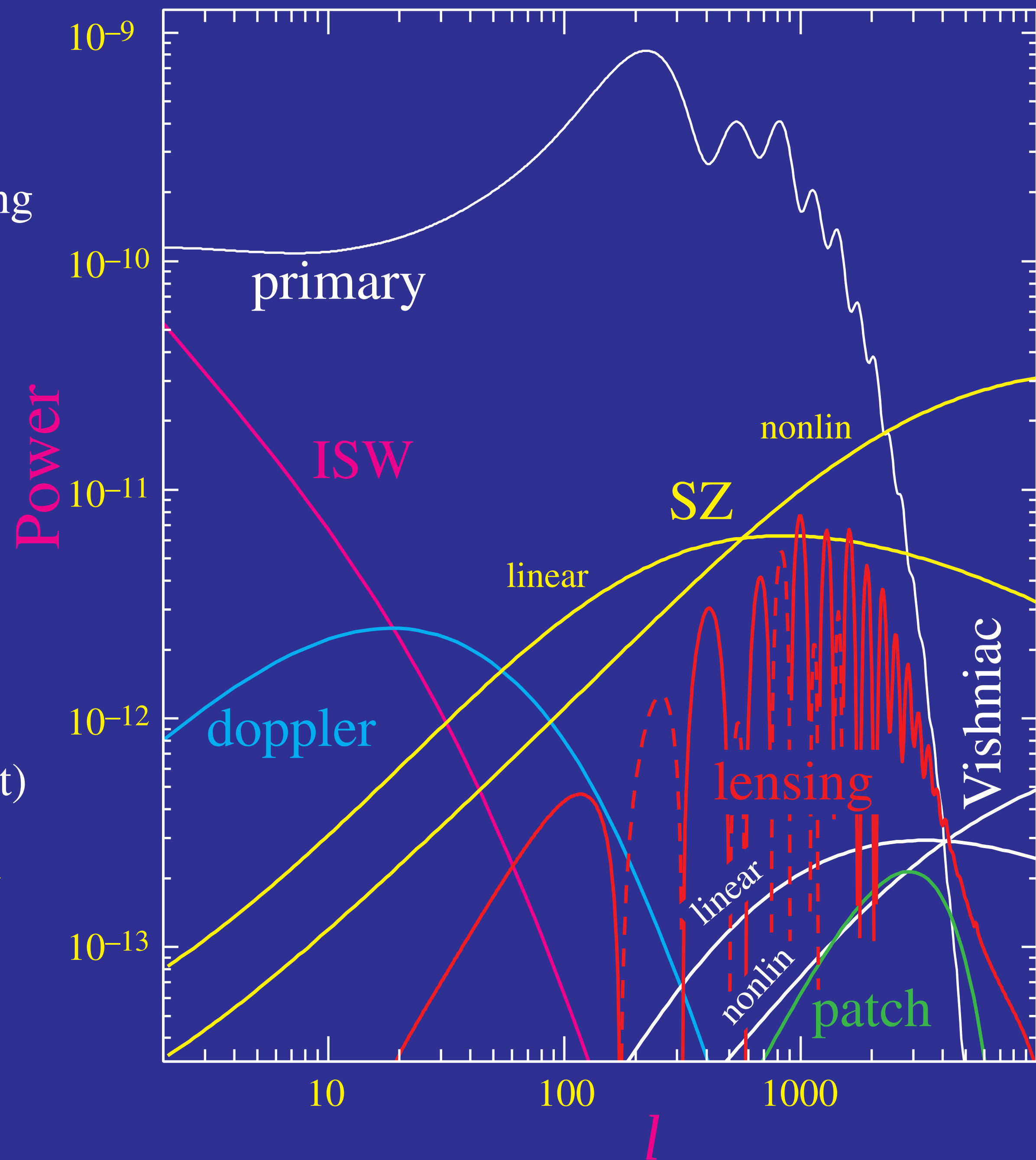


Current Constraints
< 20–40μK
Saskatoon
TOCO

Hogan, Kaiser, & Rees (1982)
Efstathiou & Bond (1987)

Secondary Anisotropies: Power Spectra

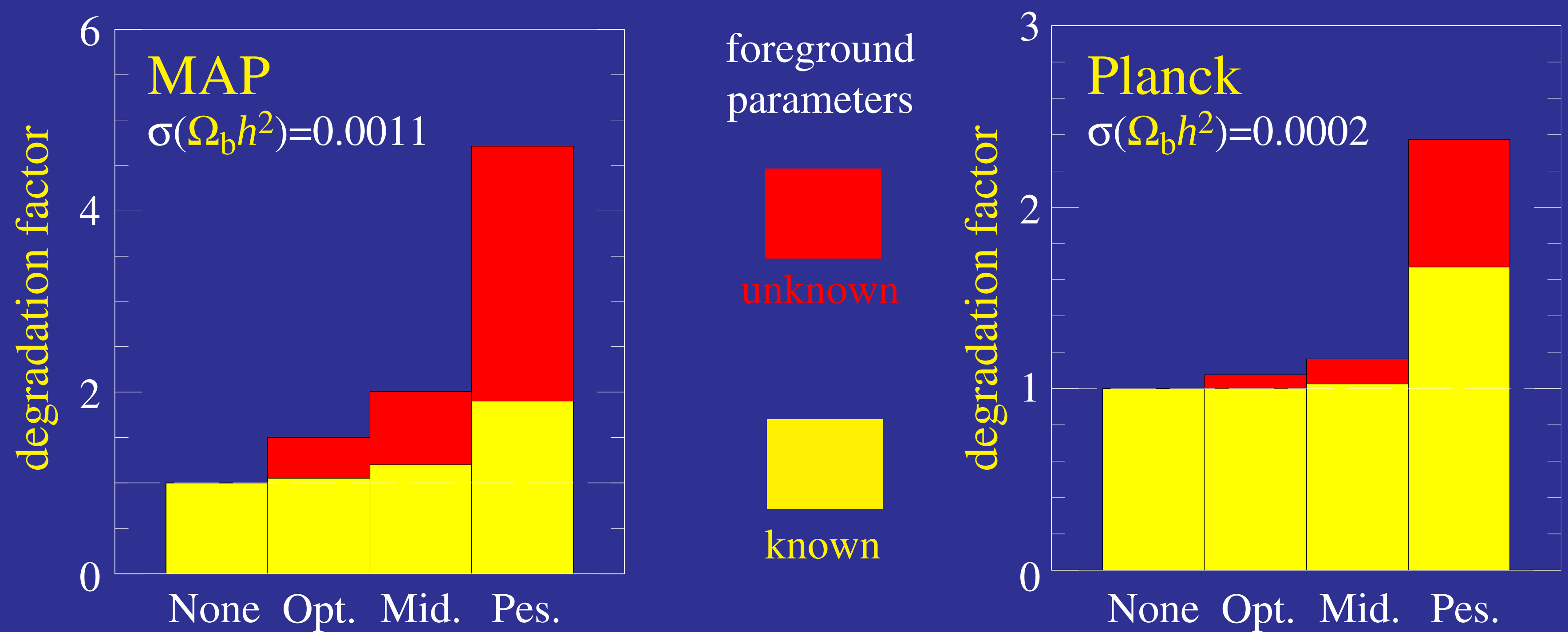
- Gravitational Effects
  - ISW Effect
    - (redshift from decaying potentials)
  - Weak Lensing
    - (smooths peaks and generates power <1')
- Scattering Effects
  - Doppler Effect
  - Vishniac Effect
    - (LSS kinetic SZ effect)
  - Patchy Reionization
  - SZ effect
    - (LSS thermal)



Recent Work on Isolating Secondary Anisotropies

- Subarcminute Power Spectrum
  - Vishniac Effect; Kinetic SZ Effect;
    - Patchy Reionization Hu (1999)
    - Sugiyama (next talk)
  - SZ in Radio Galaxies
    - Yamada, Sugiyama, Silk (1999)
- Polarization
  - Weak Lensing
    - Zaldarriaga & Seljak (1999)
  - Secondary Scattering
    - Hu (1999); Weller (1999)
- Frequency spectrum
  - SZ Effect
    - Bouchet & Gispert (1999)
    - Tegmark, Eisenstein, Hu & de Oliviera Costa (1999)
    - Cooray, Hu & Tegmark (1999)
- Non-Gaussianity
  - Weak Lensing & ISW:
    - 3pt function (bispectrum)
    - Goldberg & Spergel (1999),
    - Seljak & Zaldarriaga (1999)
  - Weak Lensing & Doppler
    - Effect; Vishniac Effect
    - Cooray & Hu (1999)
  - Weak Lensing: 4pt function
    - (trispectrum) Zaldarriaga (1999)
    - spot ellipticity & correlation
    - Van Waerbeke,Bernardeau & Benabed (1999)
  - SZ Effect: hydro-simulations
    - Refrigier et al. (1999) semi-analytic
    - Aghanim & Forni (1999)

Foregrounds and Baryons



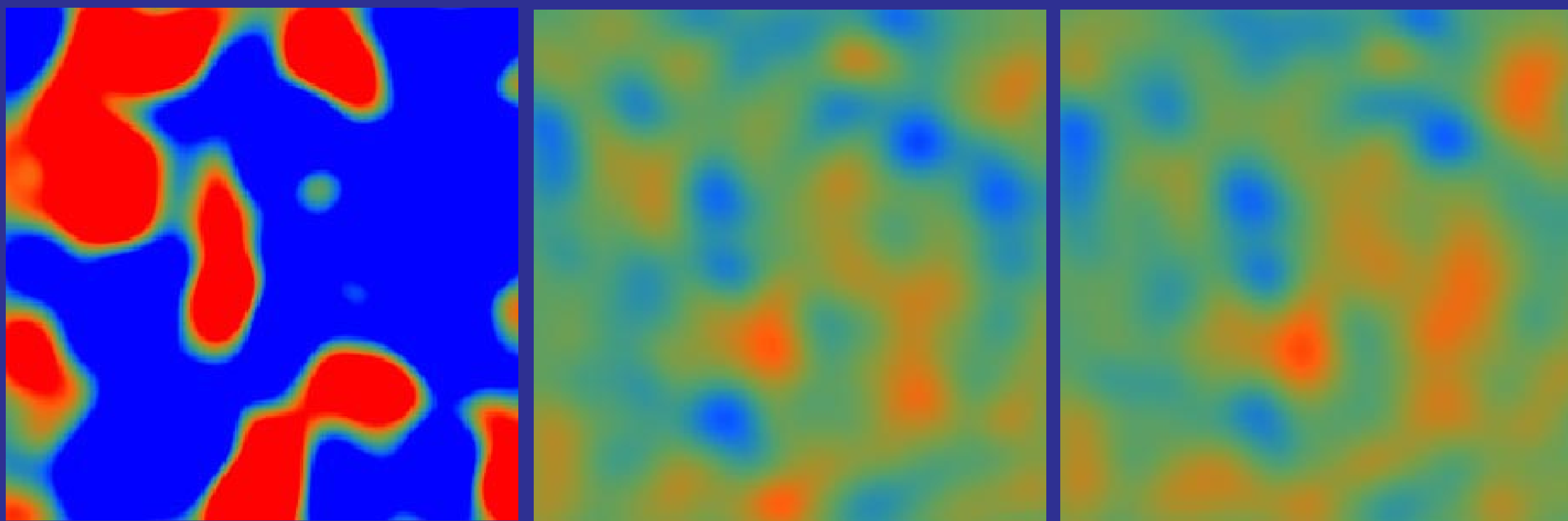
- 257–561 Foreground Parameters Simultaneously Estimated
- Foreground power spectra, frequency dependence, frequency coherence

  free-free, synchrotron, vibrating dust, rotating dust, thermal SZ, radio point sources, IR point sources
- 10 Cosmological Parameters
- Degradation of less than 2 in errors (but 10-20 for T/S from polariz.)

Tegmark, Eisenstein, Hu, de Oliviera-Costa (1999)

Extracting the SZ Foreground

- Multifrequency extraction of SZ signal in presence of foregrounds
- CMB itself is the primary ‘‘foreground’’
- Planck channels & sensitivity



Rayleigh-Jeans
CMB+Foregrounds

SZ Signal

Cleaned Map

- Toy SZ model: pressure a biased tracer of mass + PM simulations
  6° x 6° smoothed at 20'

Cooray, Hu & Tegmark (1999)

Summary

- Simple adiabatic CDM models have survived the onslaught of data to date
- The dark energy is not curvature
- Baryonic dark matter and low density cold dark matter indicated
- Origin of perturbations inconsistent with most non-inflationary models

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- First objects and reionization revealed by polarization and sub-arcminute scale anisotropy
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- Simple adiabatic CDM models have survived the onslaught of data to date
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- Foregrounds not expected to be a problem for power spectrum estimation in the acoustic regime but will be a serious issue for polarization, sub-arcminute anisotropy and non-Gaussianity.

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Complete Talk:
http://www.sns.ias.edu/~whu/resceu.pdf

Outtakes