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CMB Episode II:

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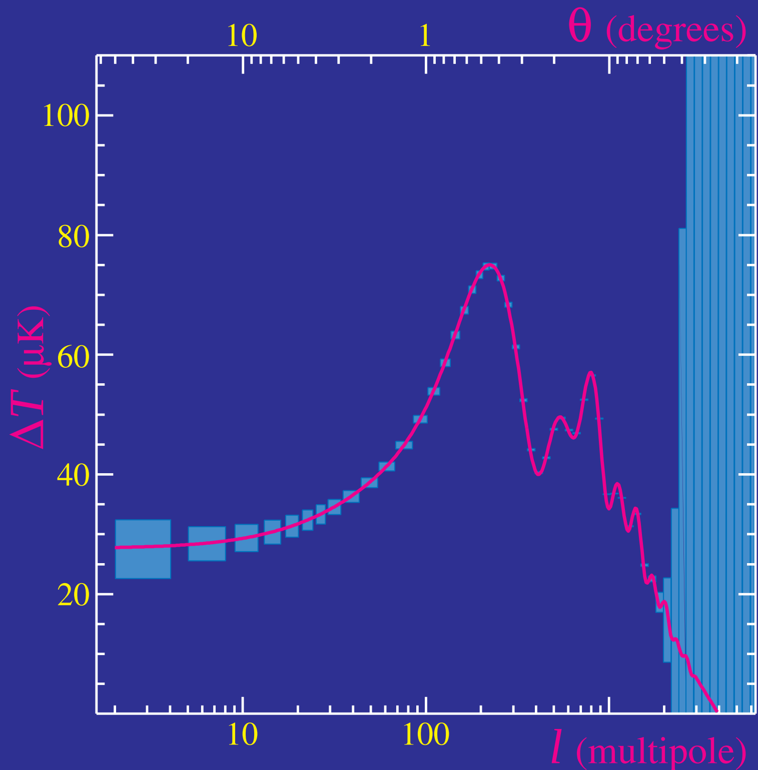
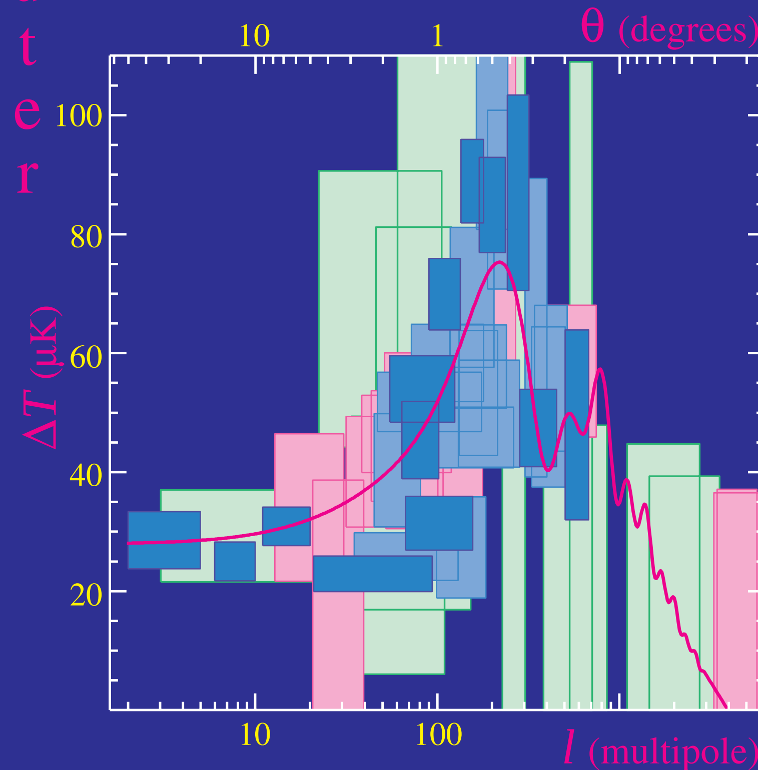
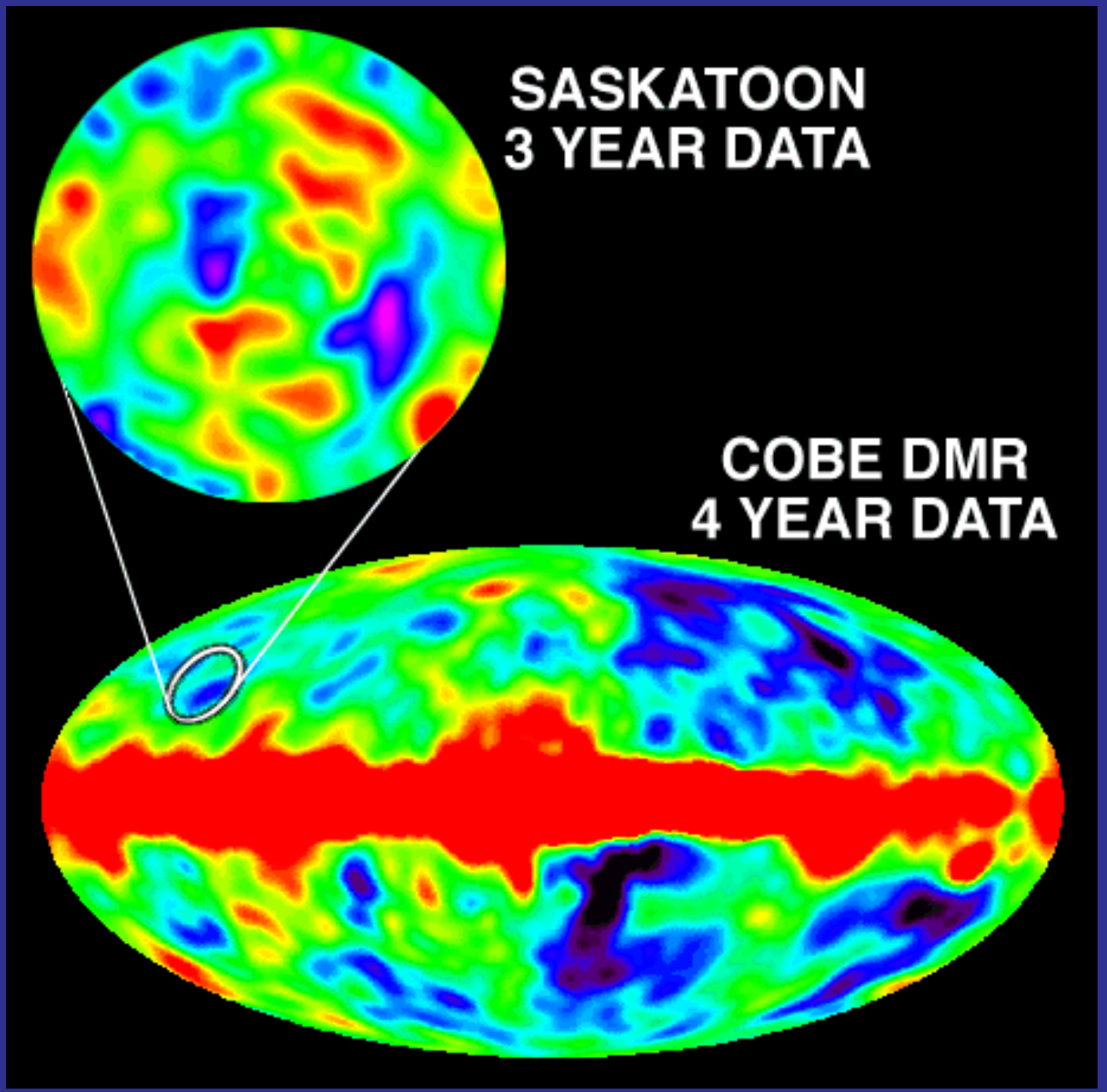




Theory or Reality?

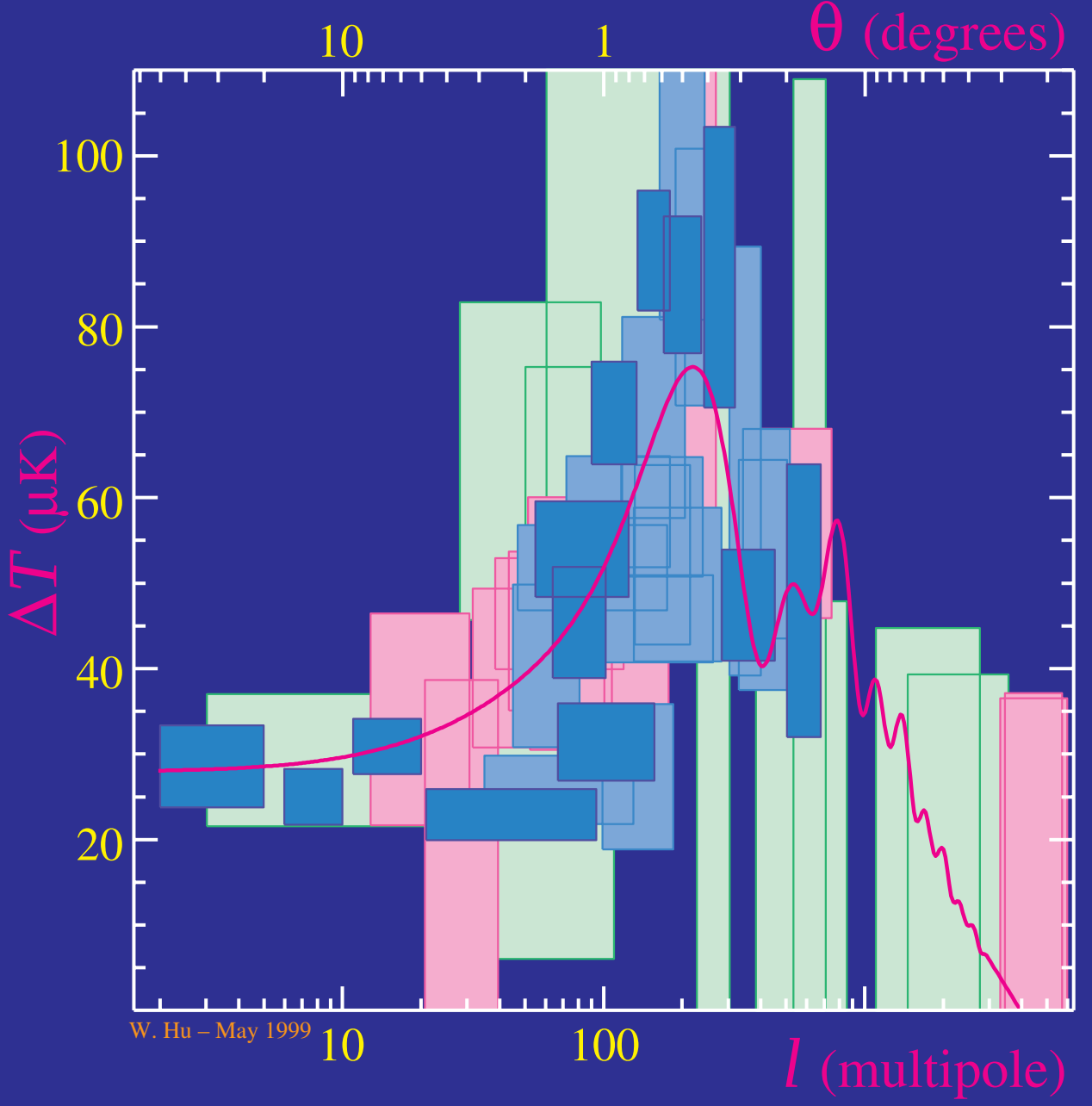
Wayne Hu

CMB Anisotropies

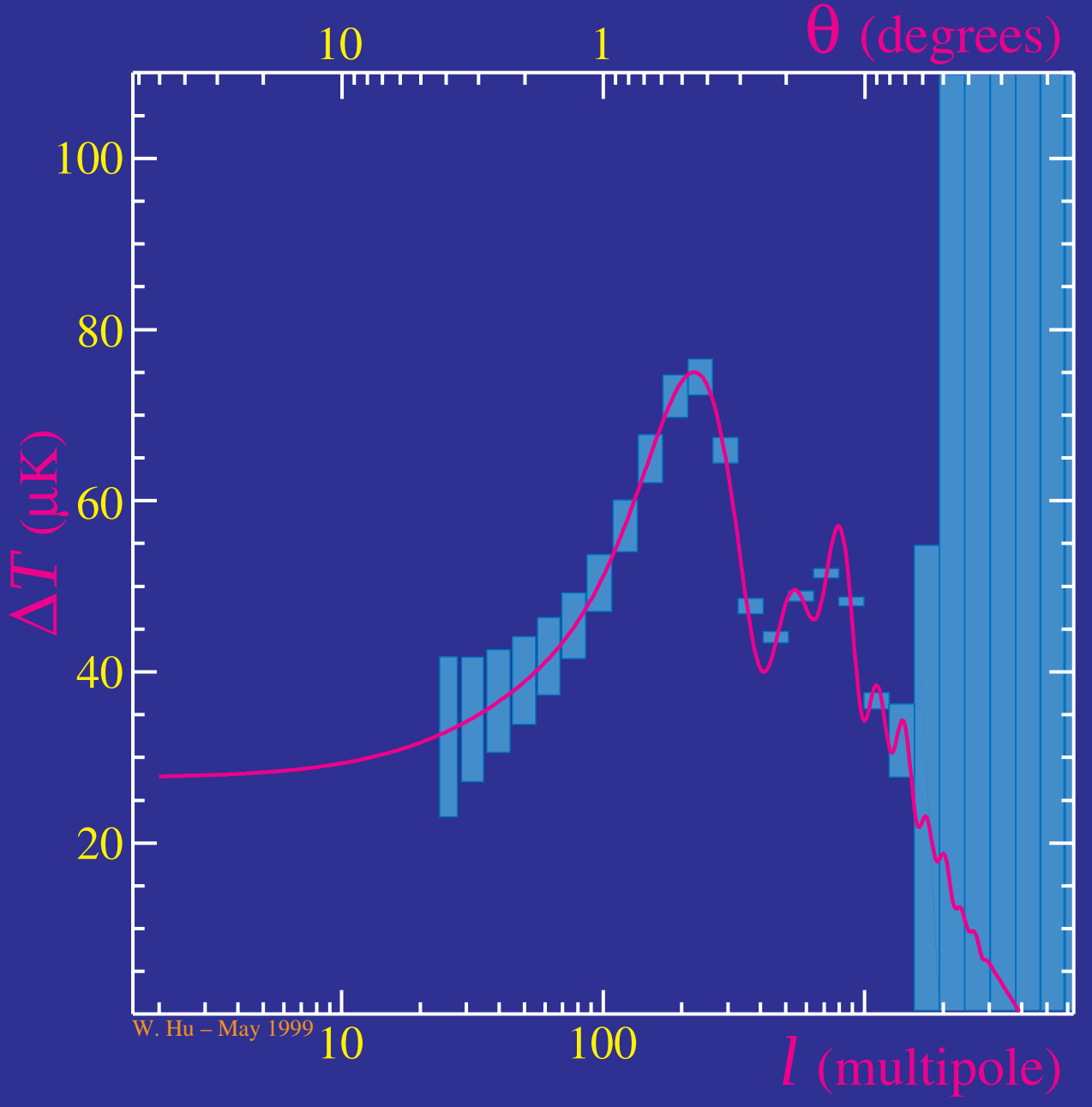


Tegmark, de Oliviera Costa, Devlin, Netterfield, & Page (1996)

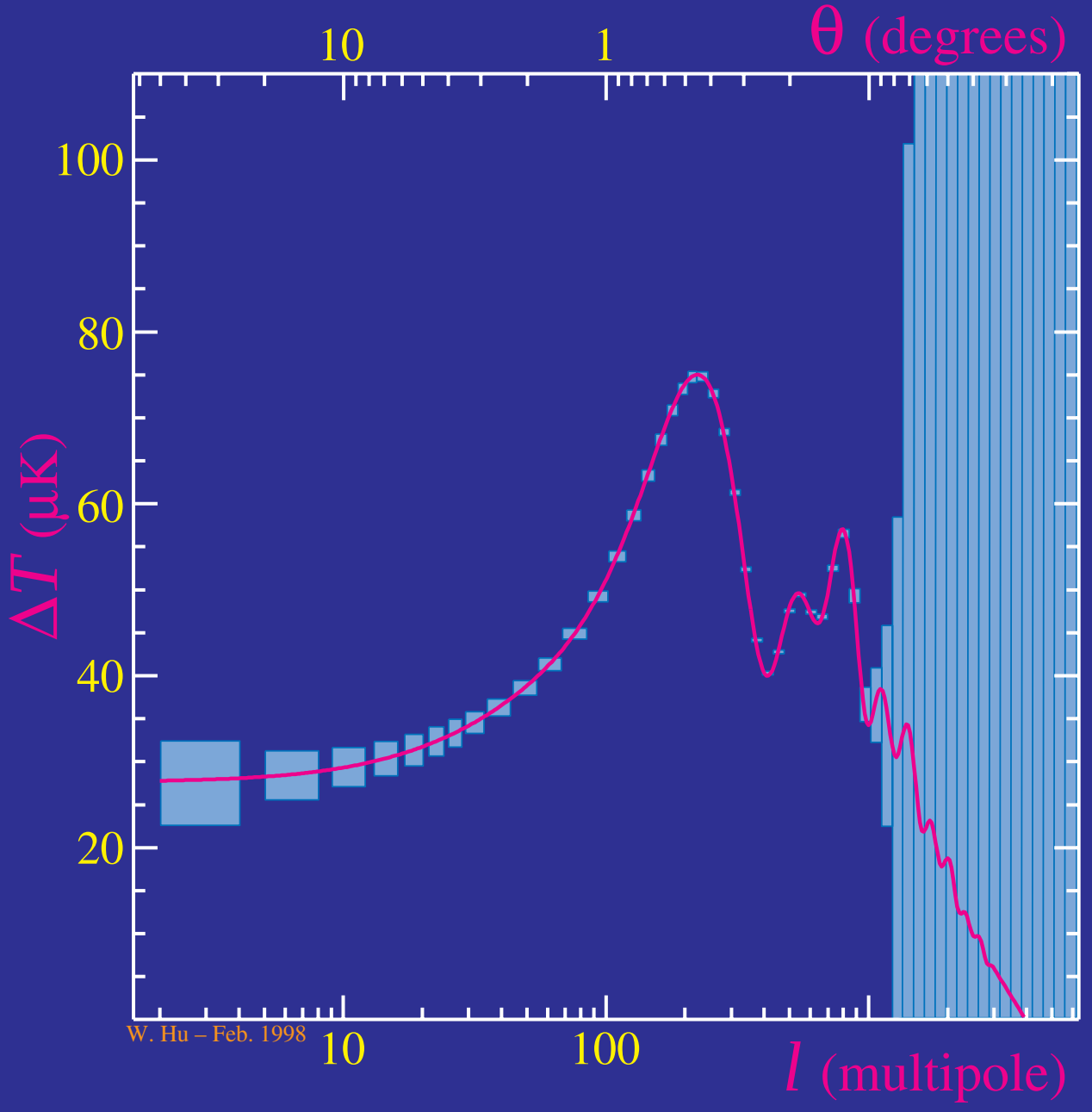
Current CMB Quilt



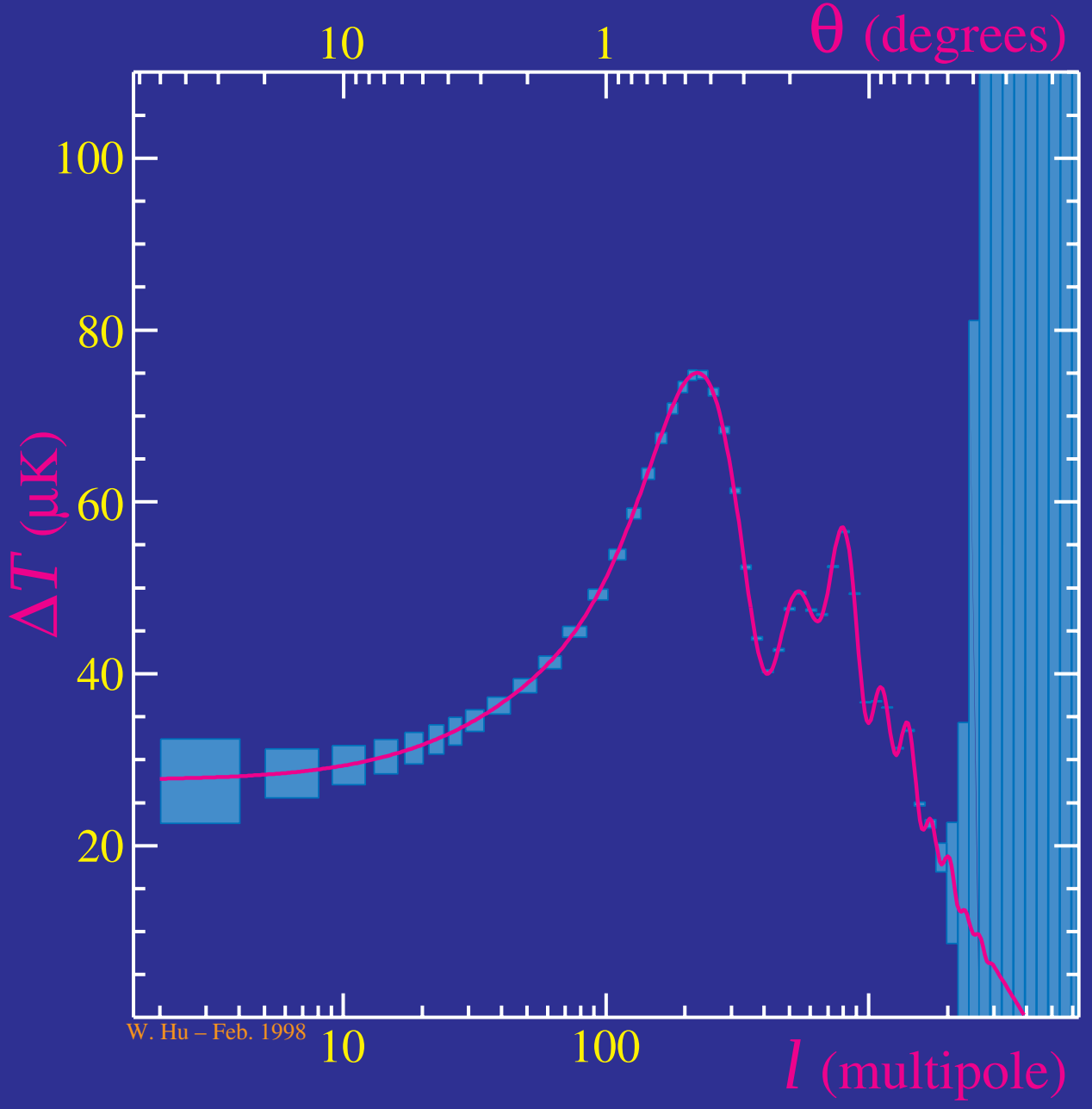
Projected Boomerang Errors



Projected MAP Errors



Projected Planck Errors



CMB Today

?

- Very early reionization
- Simplest isocurvature models

Griffiths et al. (1999); Hu, Bunn & Sugiyama (1995);
Pen, Seljak & Turok (1997)

CMB Today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- Very early reionization
- Simplest isocurvature models
- "Missing Energy" in curvature
  $\Omega_K \lesssim 0.5$ (95%CL) if $\Omega_\Lambda=0$
- Baryon Content
  $0.015 < \Omega_b h^2 < 0.087$ (68%CL)

- Constraints on $(\Omega_m,\Omega_\Lambda)$ when combined with SNIa, age...
  $\Omega_\Lambda > 0.5$ (95%CL)

Lineweaver (1998); Bond & Jaffe (1998); White (1998); Efstathiou et al (1999); Tegmark (1999)

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CMB Forecast


?

- Percent Level Constraints on
  $\Omega_b h^2$, $\Omega_m h^2$, d_A (mainly Ω_K)
- Inflationary/adiabatic initial conditions

Jungman et al. (1996); Hu & White (1996)

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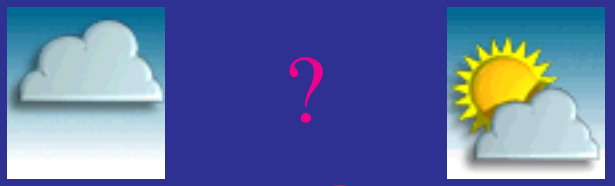
- Tensors / Inflationary dynamics
  $T/S < 0.4$ (MAP); 0.024 (Planck)
- Dark Matter/Energy:
  $m_\nu < 0.2$ eV (Planck + 10° Lensing)
  $1+w_Q < 0.07$ (Planck + SDSS)

Zaldarriaga et al. (1997); Eisenstein et al. (1999)
Hu & Tegmark (1999); Hu et al. (1999)

CMB Today



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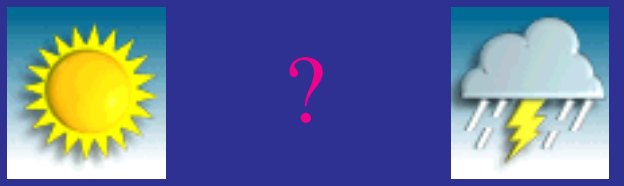
CMB Forecast



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  $1+w_Q < 0.07$ (Planck + SDSS)
- Caveat: Microwave Foregrounds

Tegmark & Efstathiou (1996); Dodelson (1996); Knox (1999); Bouchet & Gispert (1999); Tegmark et al. (1999)

Forecasts & Results:
Are They Believable?

- Yes!

  Statements based on acoustic peaks once they are confirmed by the observation of at least 2 of them

- Maybe...

  Statements based on combining anisotropies with polarization and other cosmological data sets: systematic effects!

Thermal History

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

  Hydrogen ionized

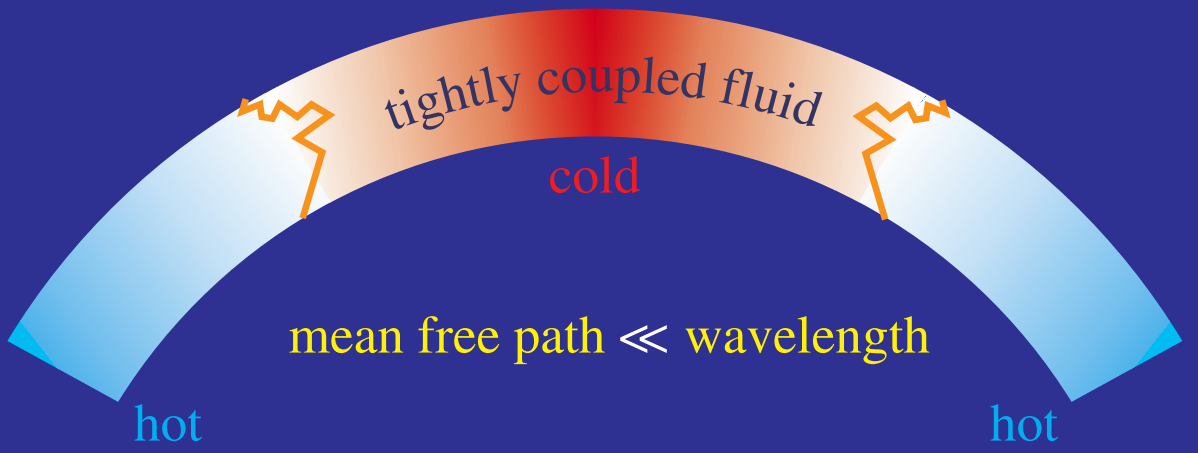
  Free electrons glue photons to baryons

  γ ~~~~ e– ~~~~ p

  compton scattering coulomb interactions

  Photon–baryon fluid

  Potential wells that later form structure



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  Hydrogen ionized
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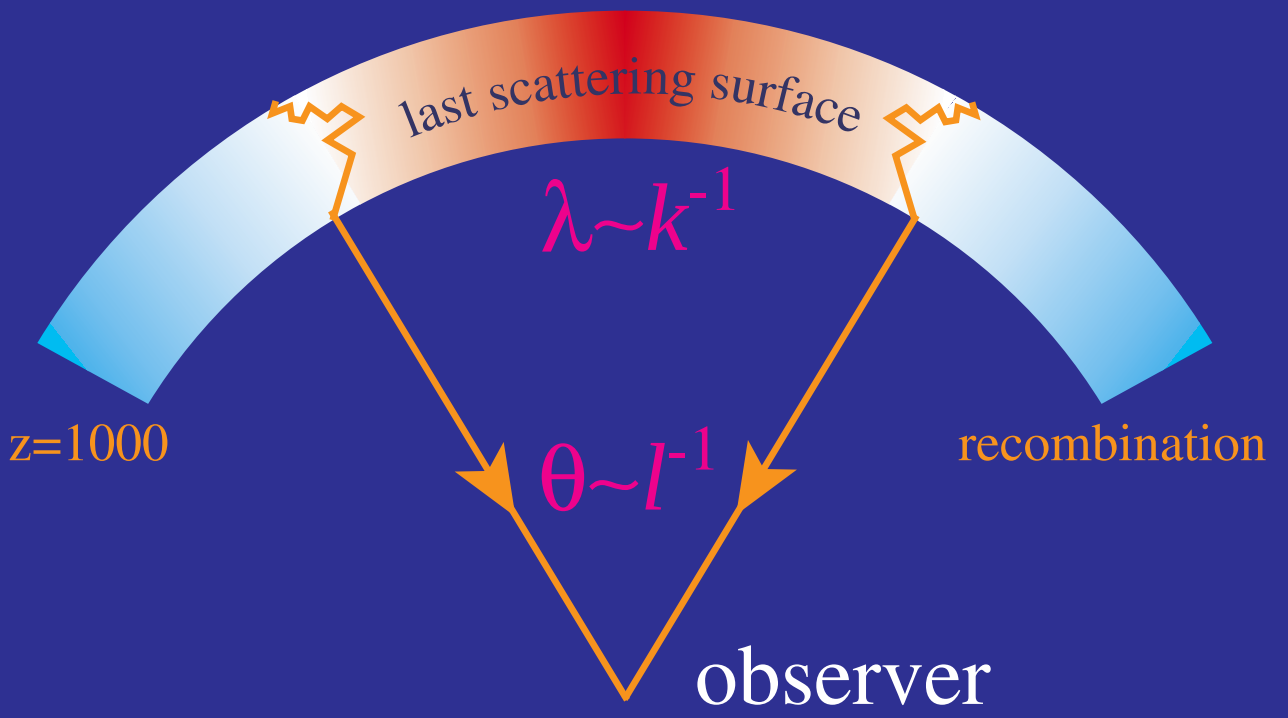
  γ ~~~~~ e– ~~~~~ p

  compton scattering coulomb interactions

  Photon–baryon fluid
  Potential wells that later form structure

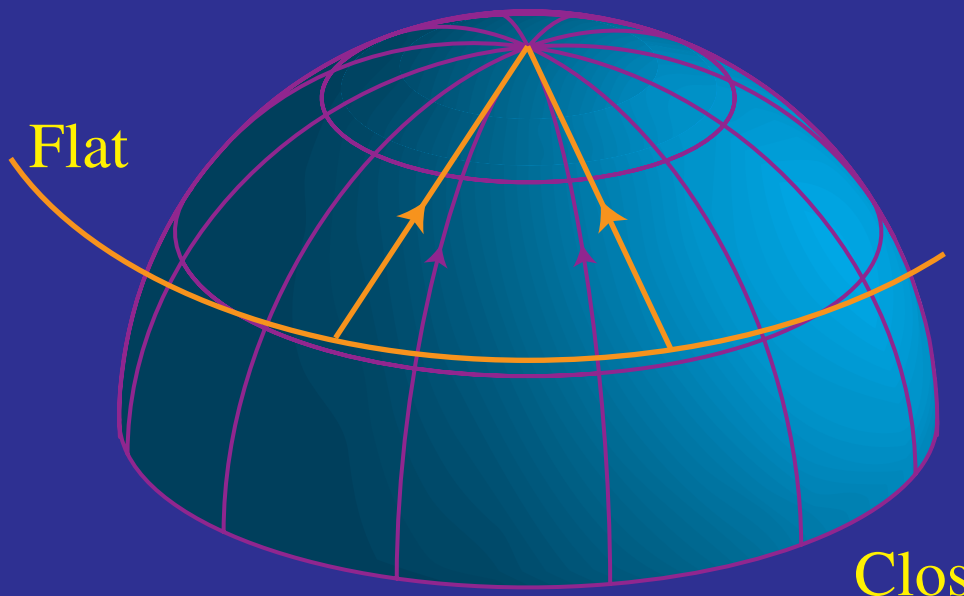
- $z \sim 1000$; $T_\gamma \sim 3000$K
  Recombination
  Fluid breakdown
- $z < 1000$; $T_\gamma < 3000$K
  Gravitational redshifts & lensing
  Reionization; rescattering

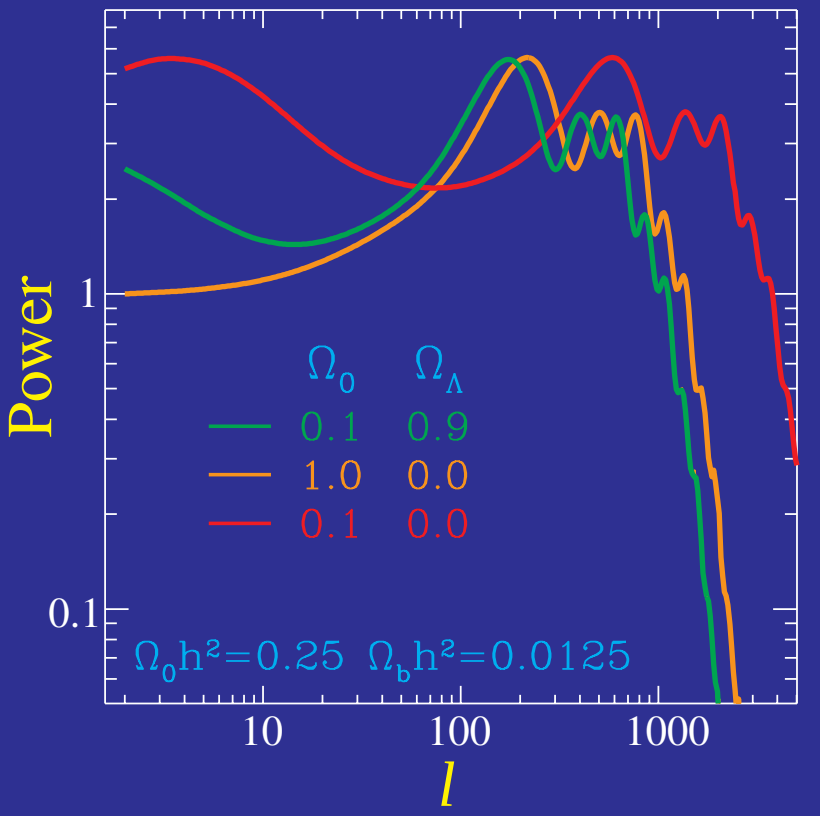


Angular Diameter Distance

- **Spatial Curvature**
  - Standardized ruler
  - Measure angular extent
  - Ruler & comoving distance scale
    (except for Λ)
  - Infer curvature

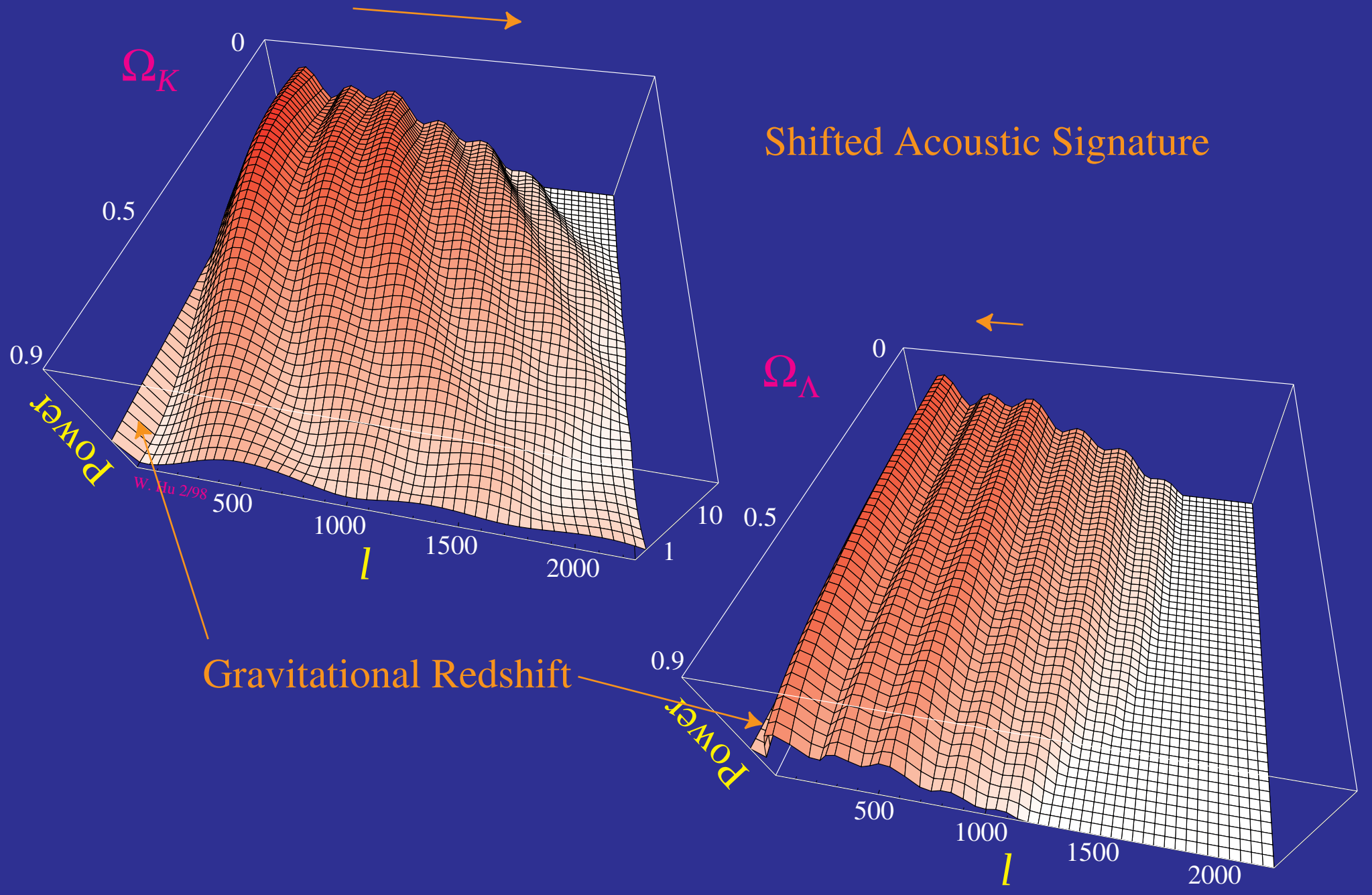
- **Robust Physical Scales**
  - Sound horizon → Peak spacing
  - Diffusion scale → Damping tail





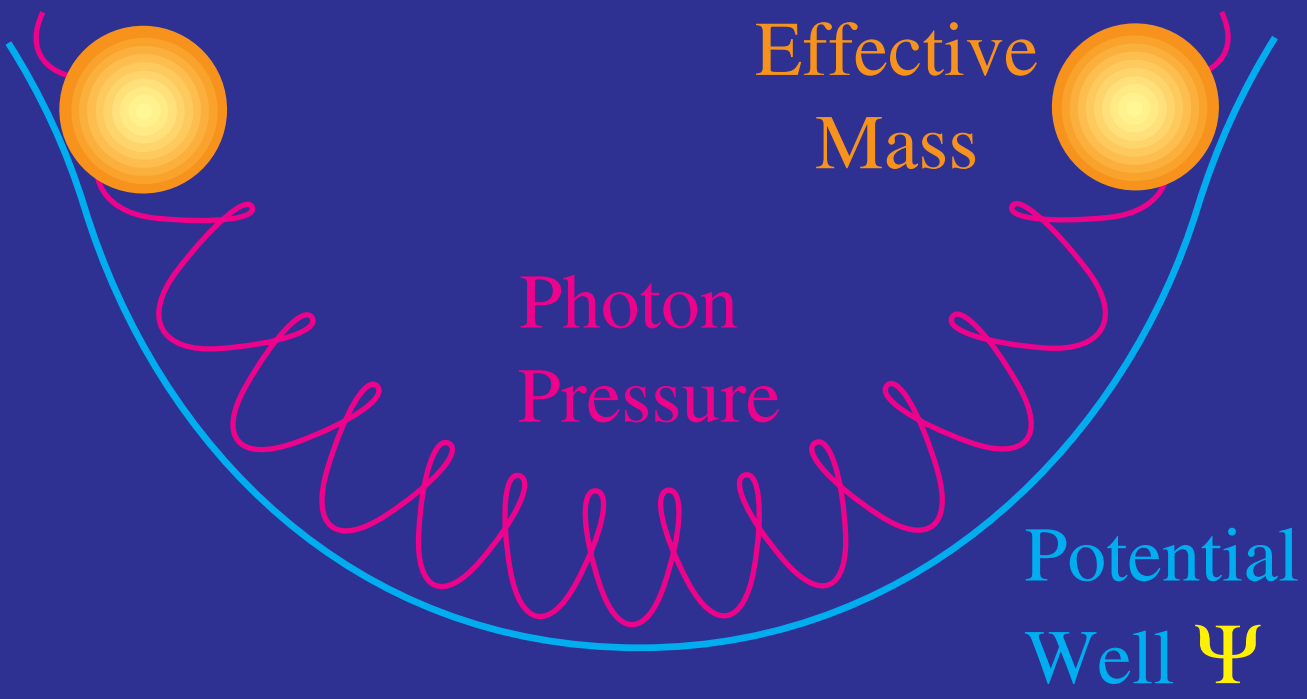
Kamionkowski, Spergel & Sugiyama (1994)
Hu & White (1996)

Curvature and the Cosmological Constant



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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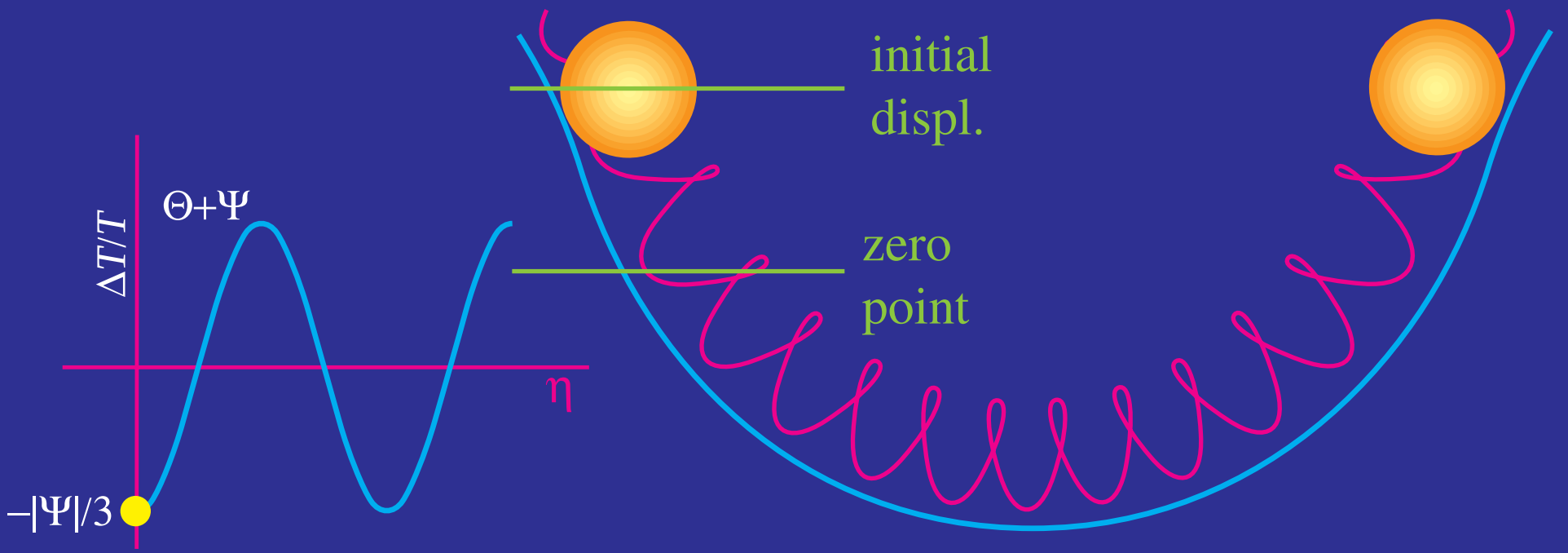
- Gravity displaces zero point
  $\Theta \equiv \delta T/T = -\Psi$

- Oscillation amplitude = initial displacement from zero pt.
  $\Theta - (-\Psi) = 1/3\Psi$



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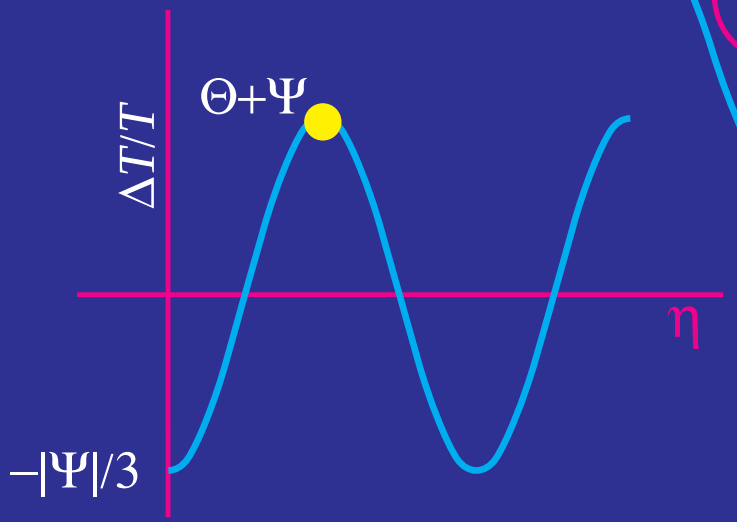
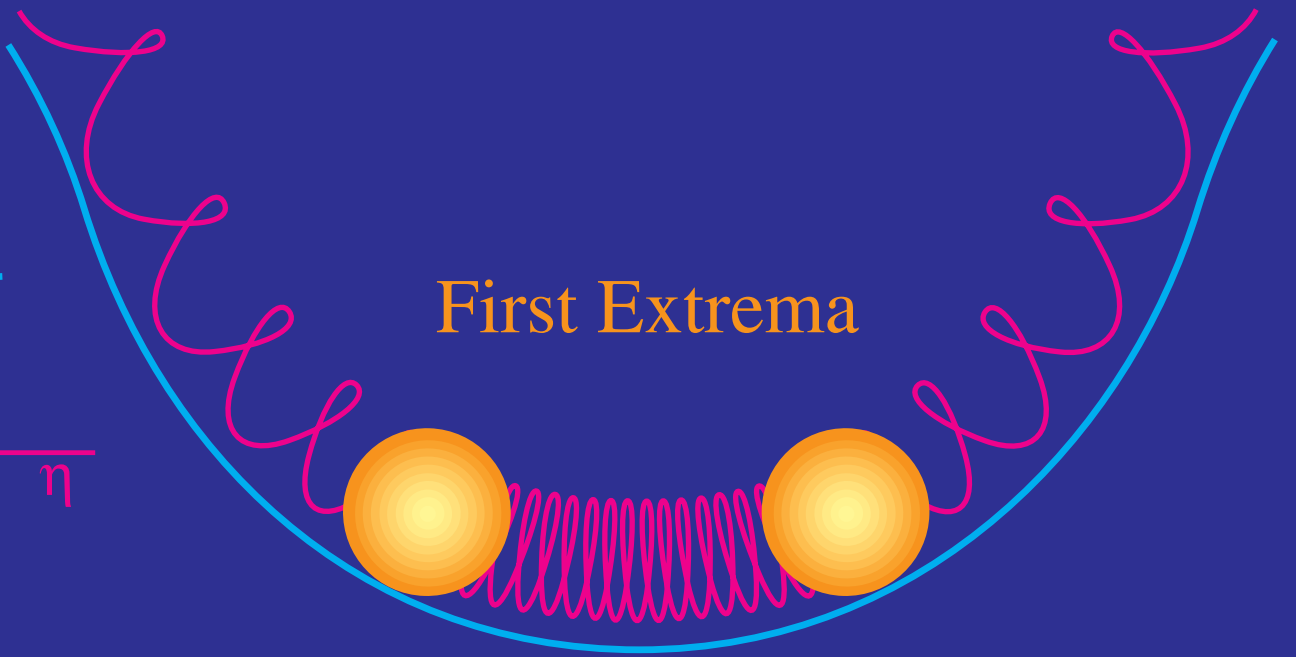
  $(\delta T/T)_{obs} = \Theta + \Psi$
  oscillates around zero





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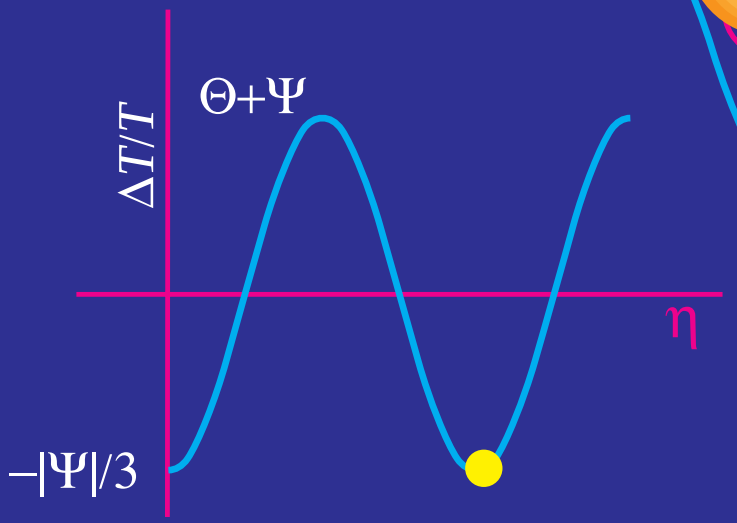

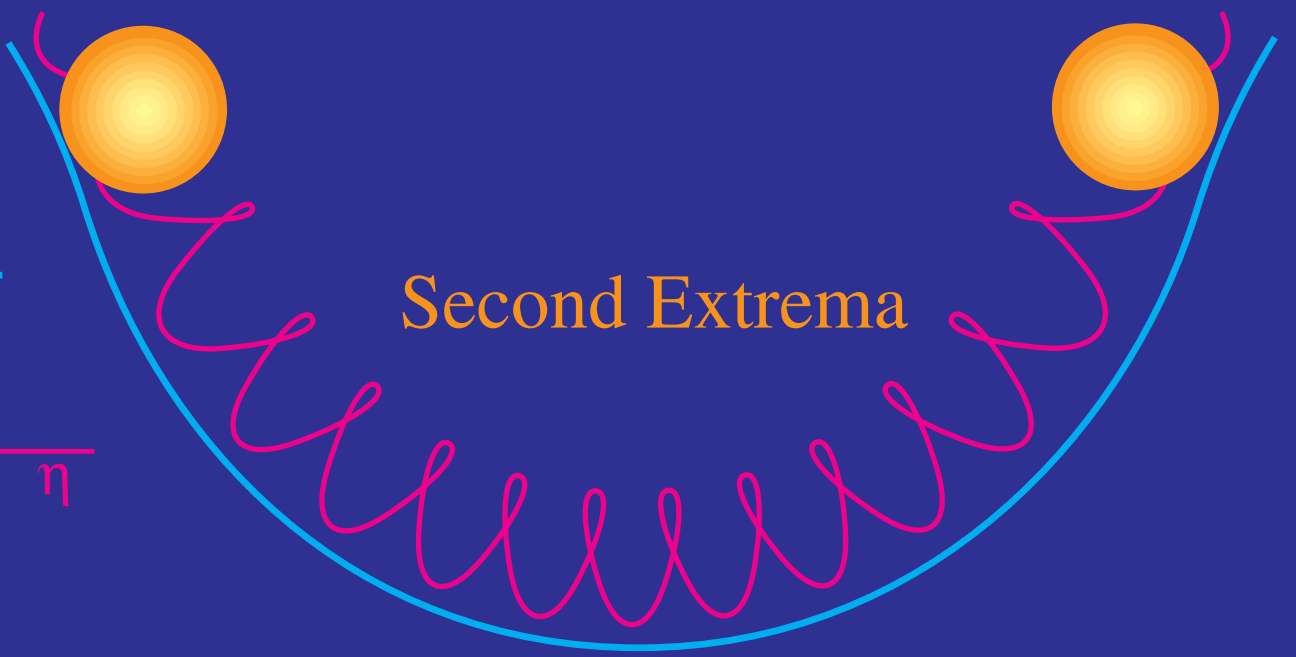

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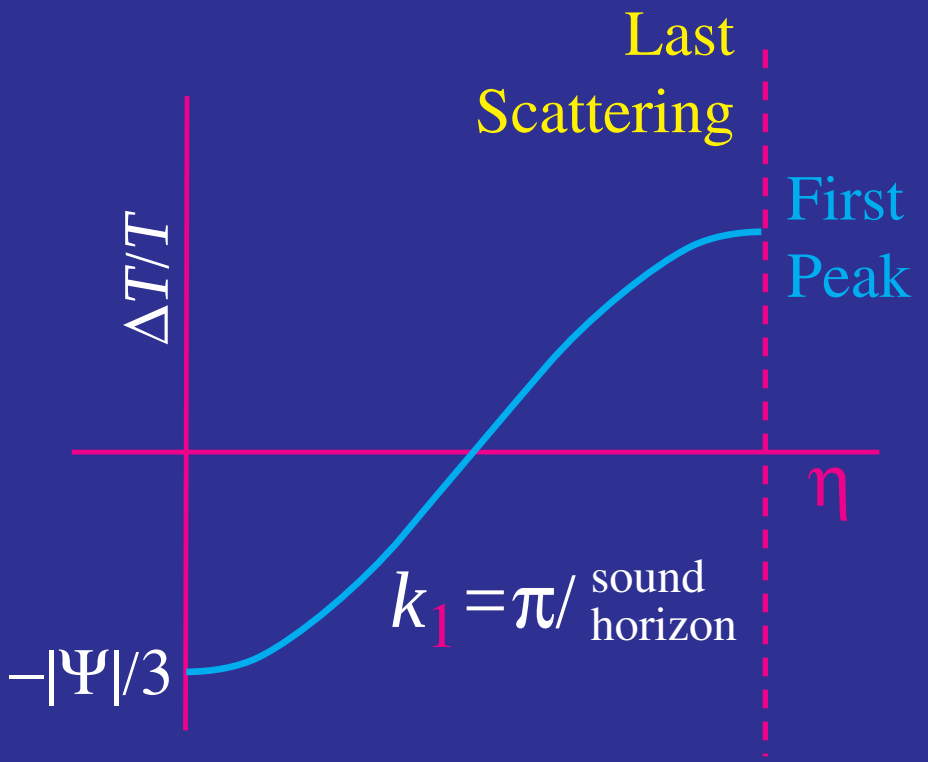
Harmonic Peaks

- 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
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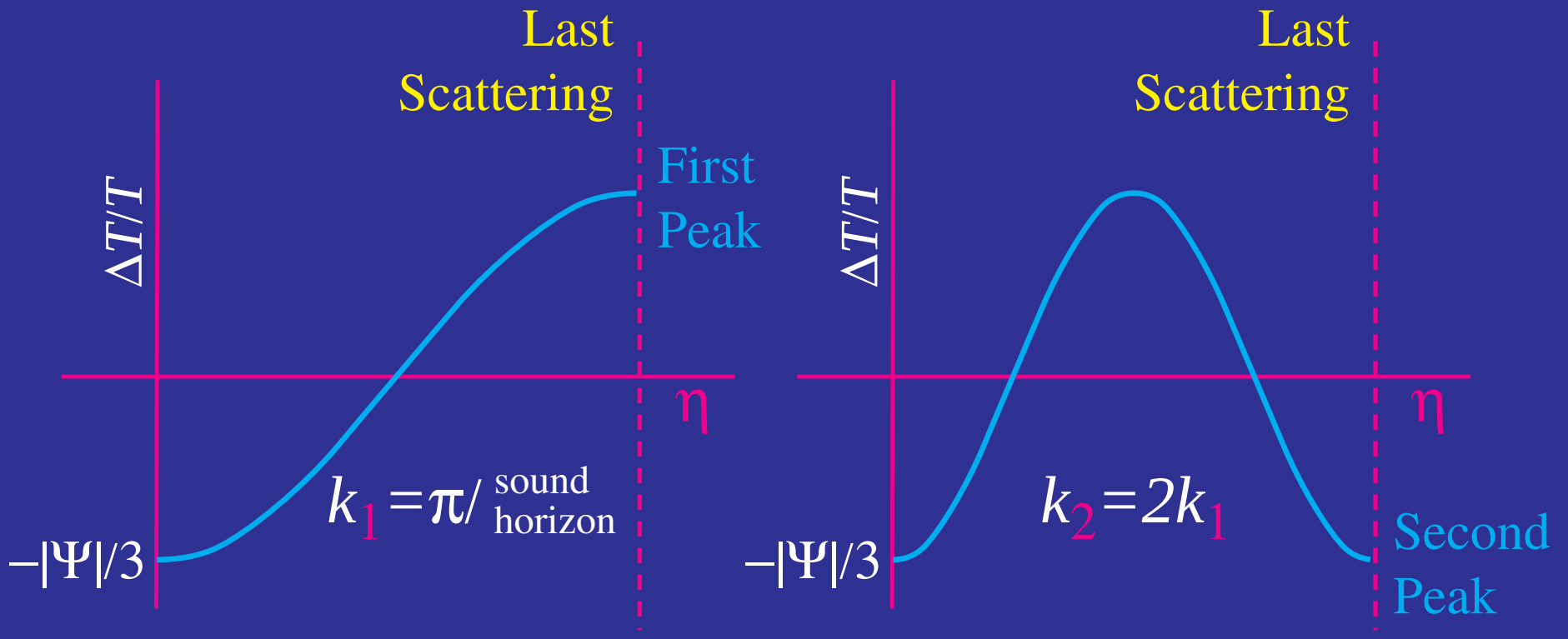
- Sound speed c_s

- Frequency $\omega = kc_s$; conformal time η
- Phase $\propto k$; $\phi = \int_0^{\text{last scattering}} d\eta\ \omega = k\ {}^{\text{sound}}_{\text{horizon}}$
- Harmonic series in sound horizon
  $\phi_n = n\pi \rightarrow k_n = n\pi/{}^{\text{sound}}_{\text{horizon}}$



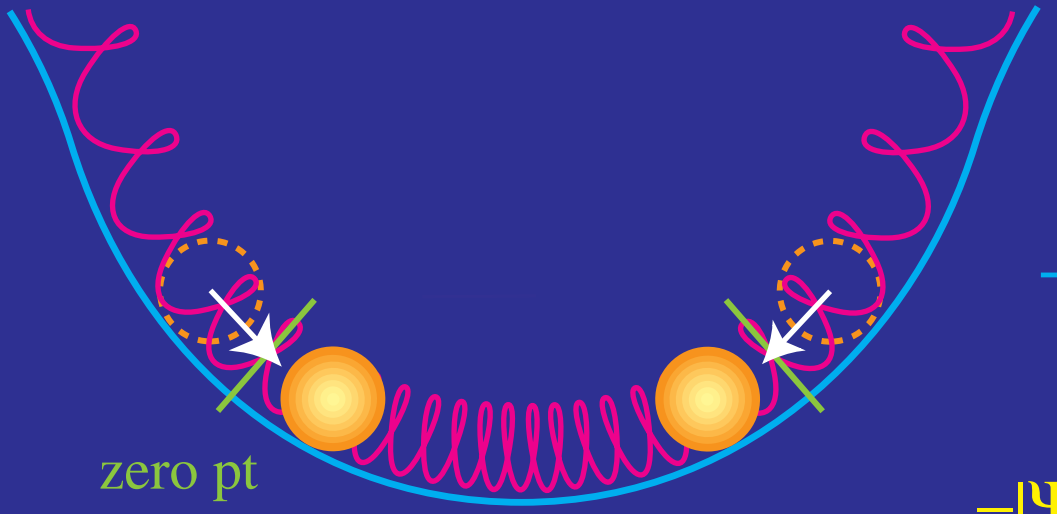
Doroshkevich, Zel'dovich & Sunyaev (1978); Bond & Efstathiou (1984); Hu & Sugiyama (1995)

Baryon Drag

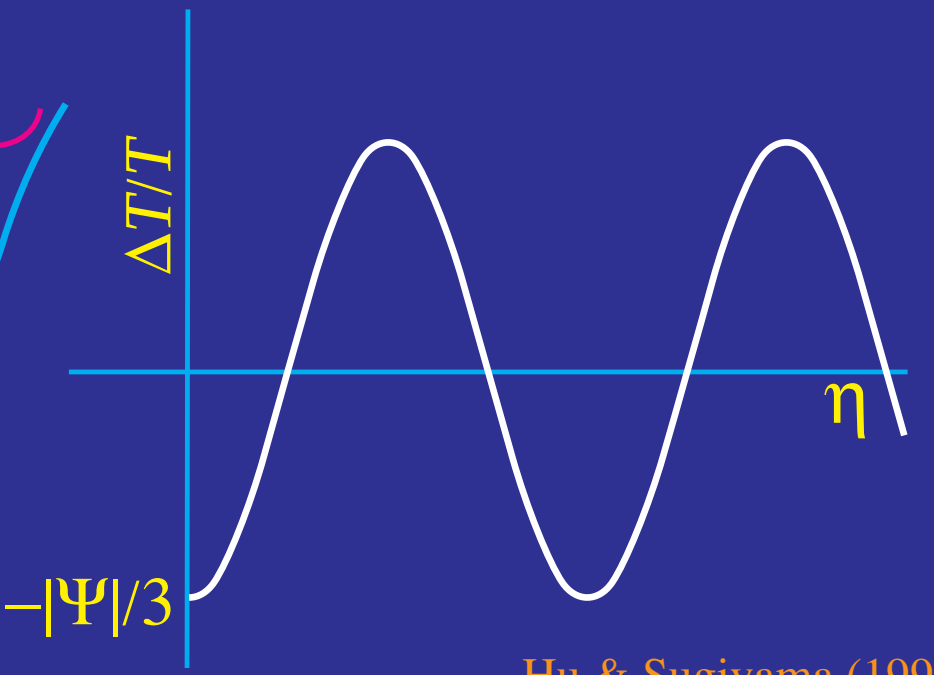
- Baryons provide inertia
- Relative momentum density

$$R = (\rho_b + p_b)V_b / (\rho_\gamma + p_\gamma)V_\gamma \propto \Omega_b h^2$$

- Effective mass $m_{eff} = (1 + R)$



Low Baryon Content



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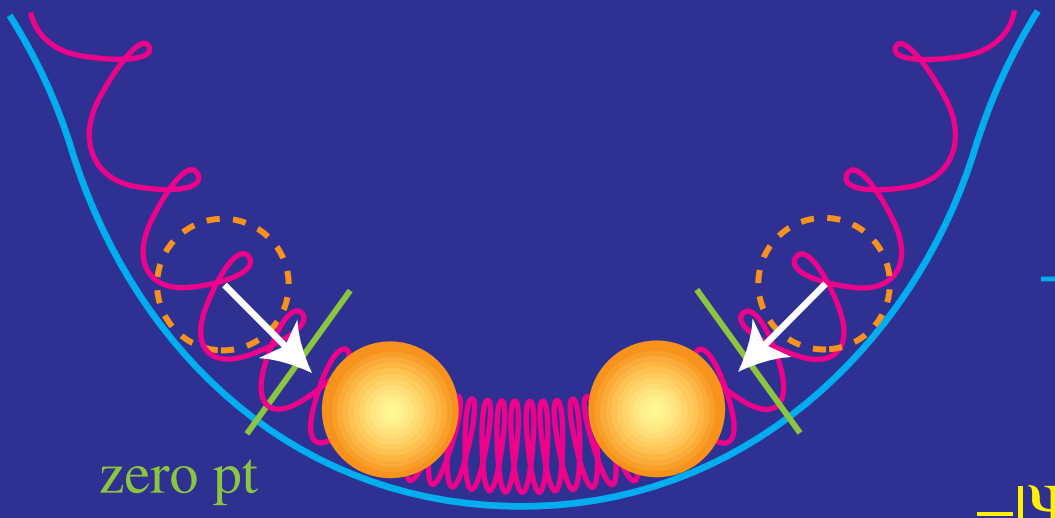
- Amplitude $\uparrow$
- Frequency $\downarrow$ $(\omega \propto m_{\rm eff}^{-1/2})$

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

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



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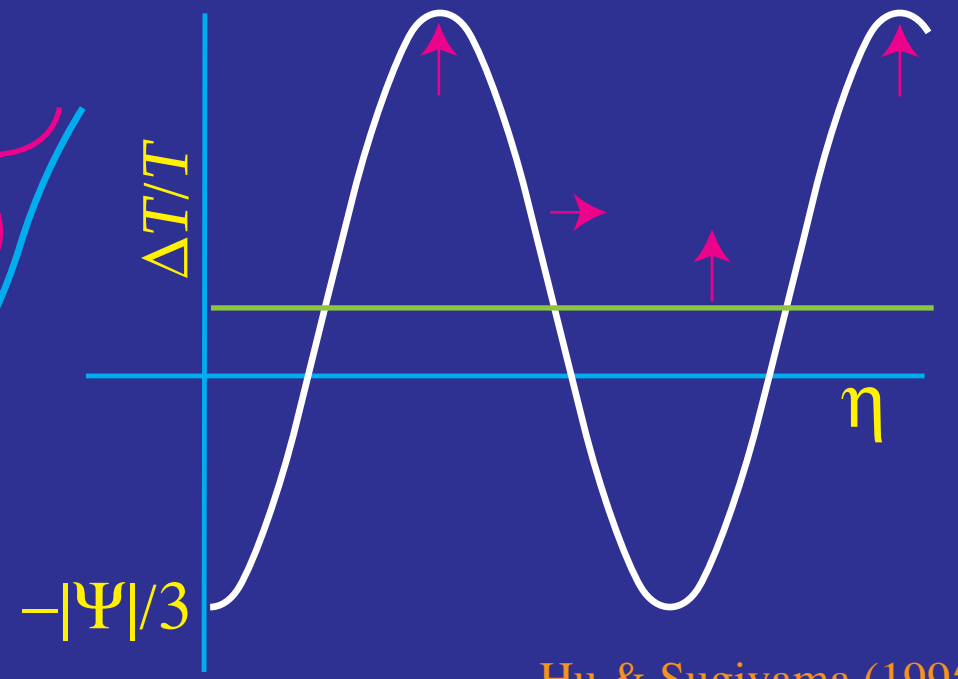

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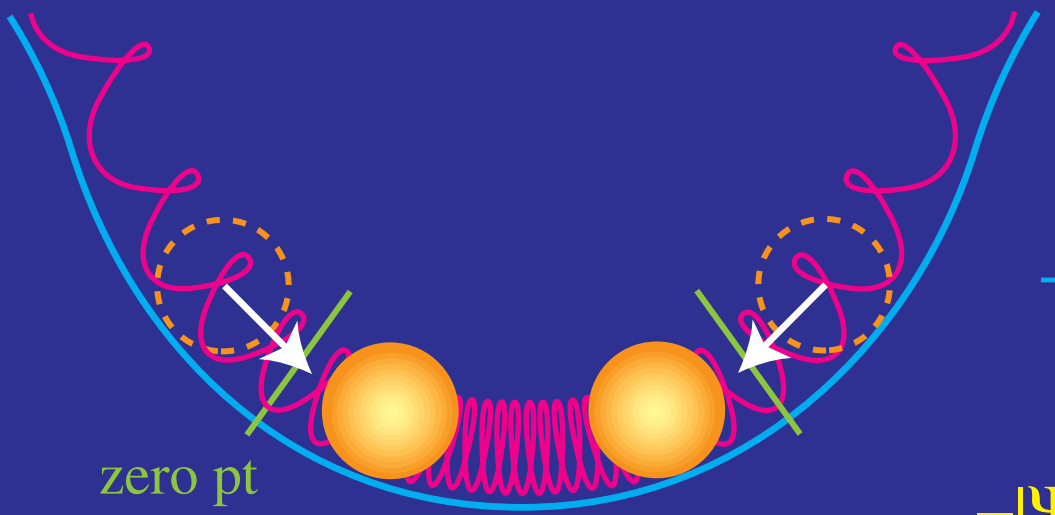
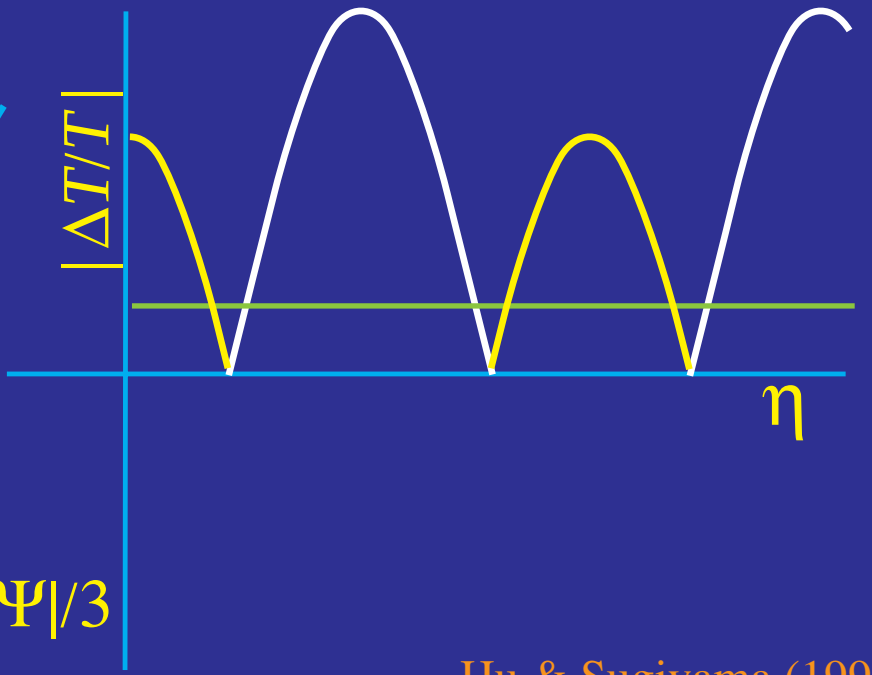
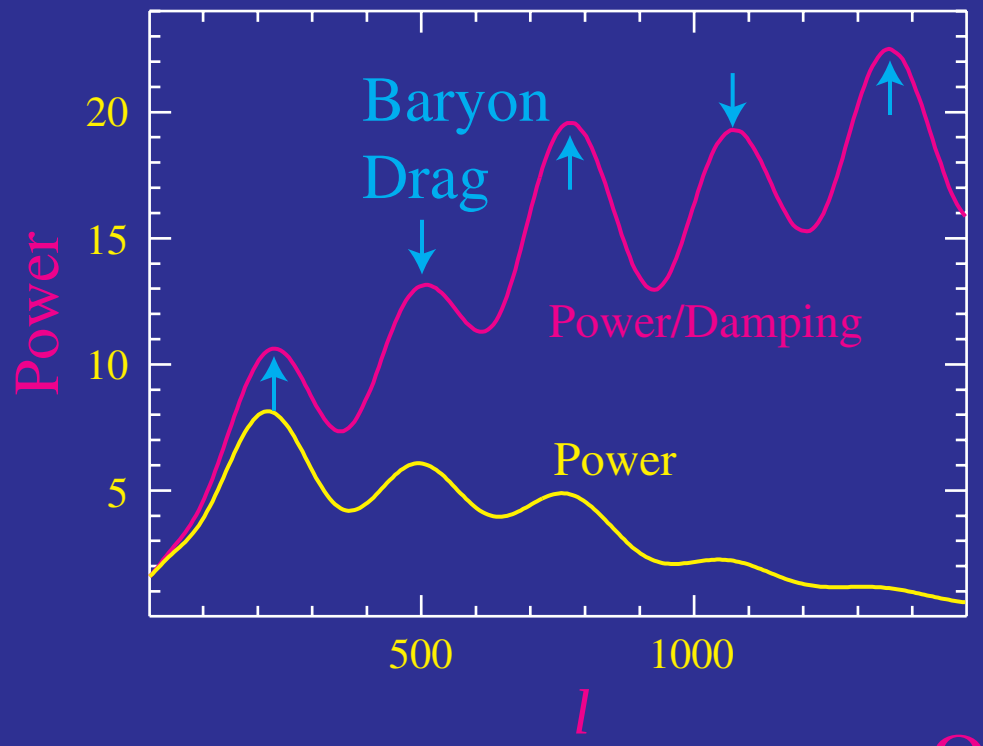


Alternating Peak Heights



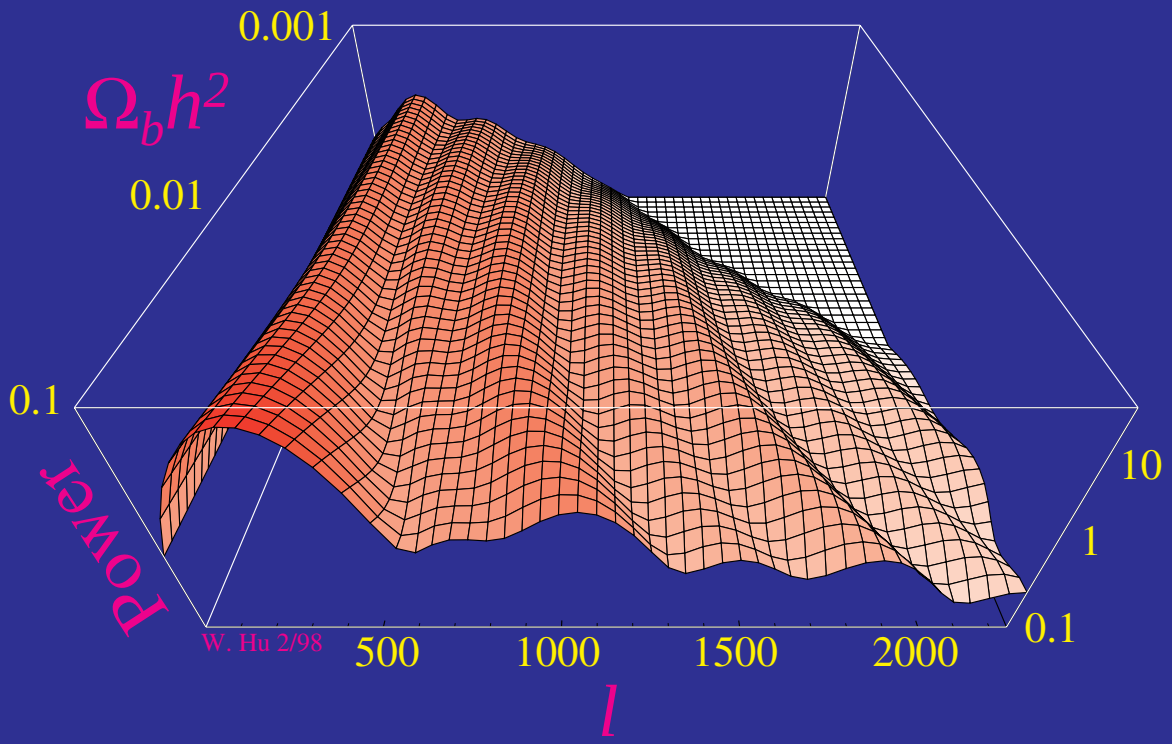
Hu & Sugiyama (1995)

Baryons in the CMB



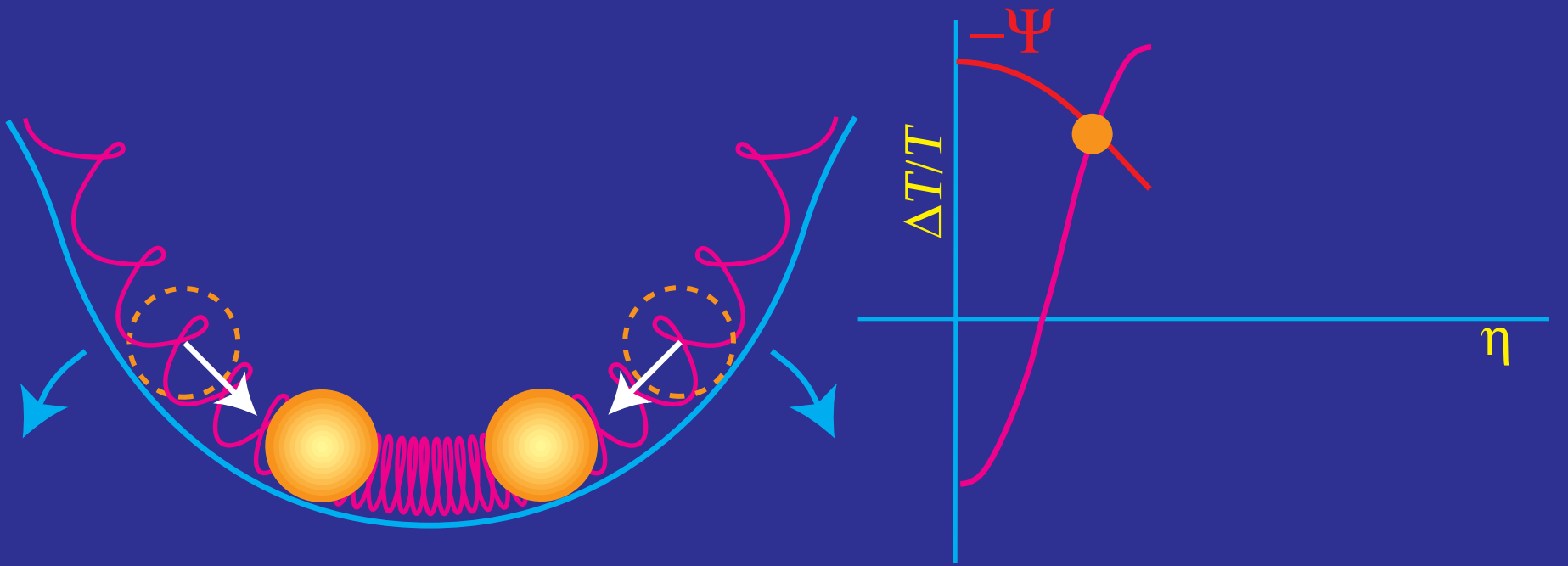
- High odd peaks

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



Driving Effects and Matter/Radiation

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



Hu & Sugiyama (1995)

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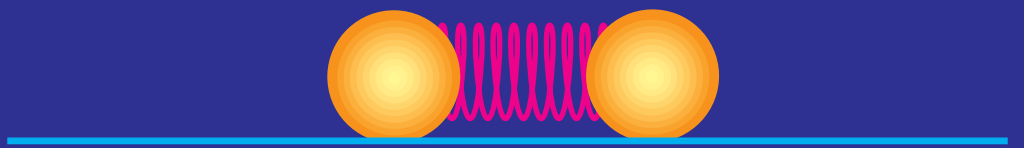
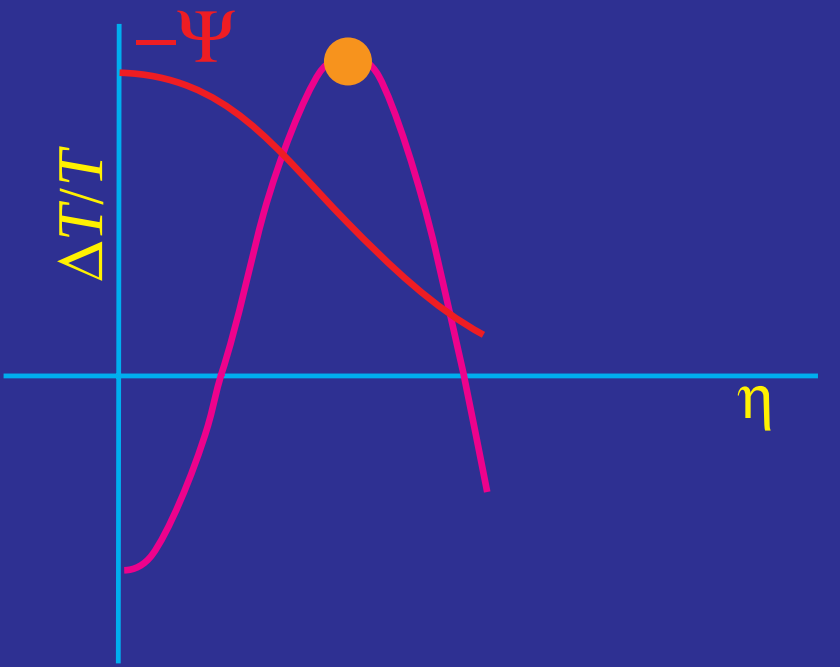
  $-2\Psi + (1/3)\Psi = -(5/3)\Psi$ → 5x boost
- Feedback stops at matter domination





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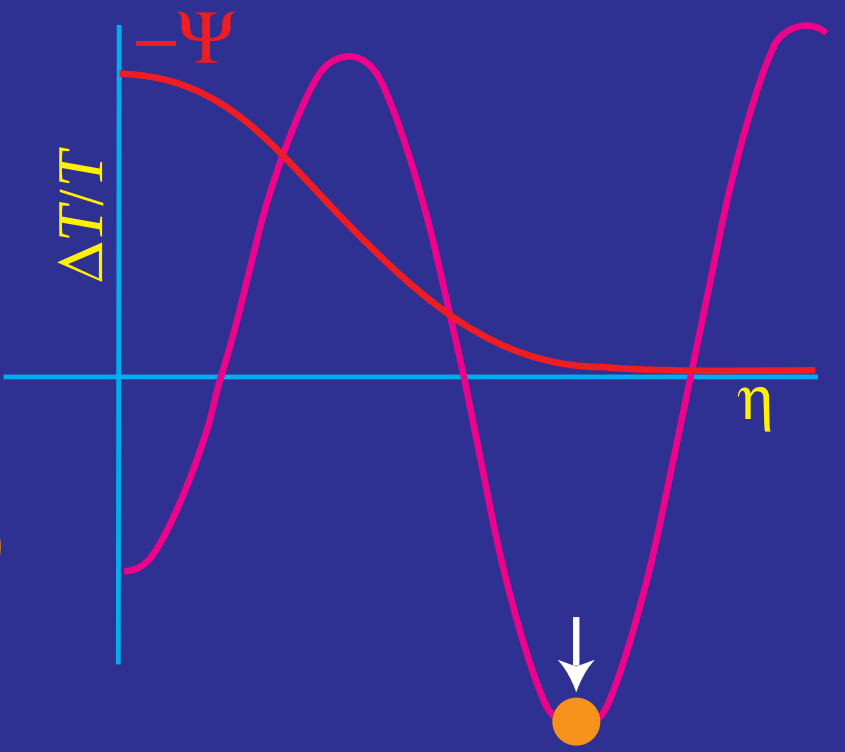
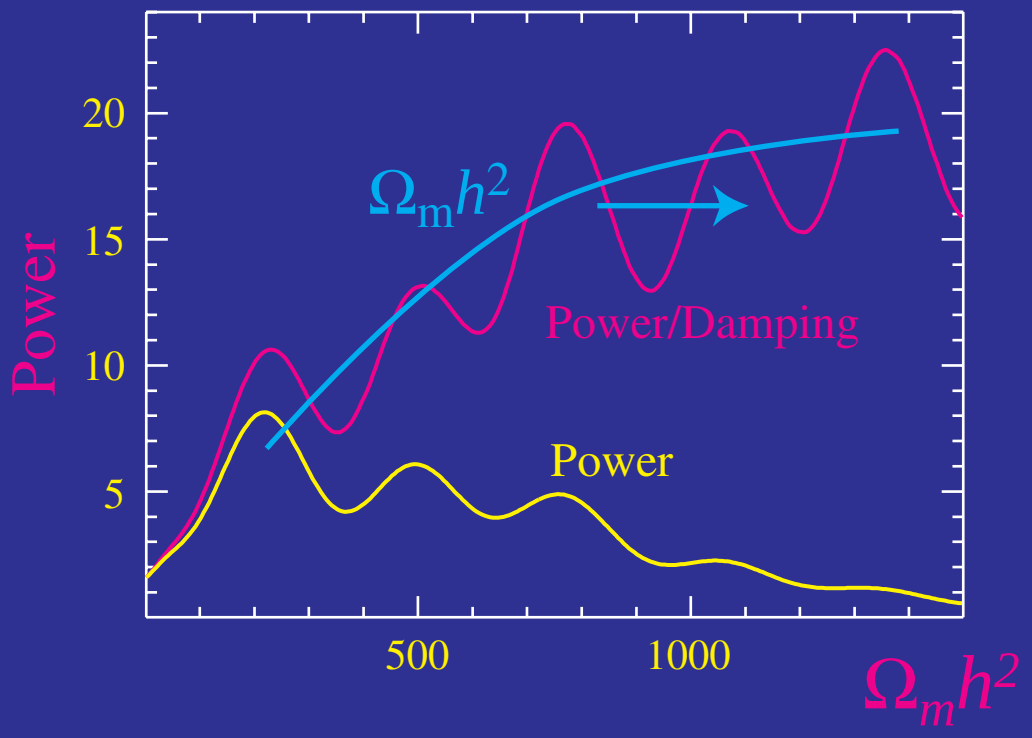


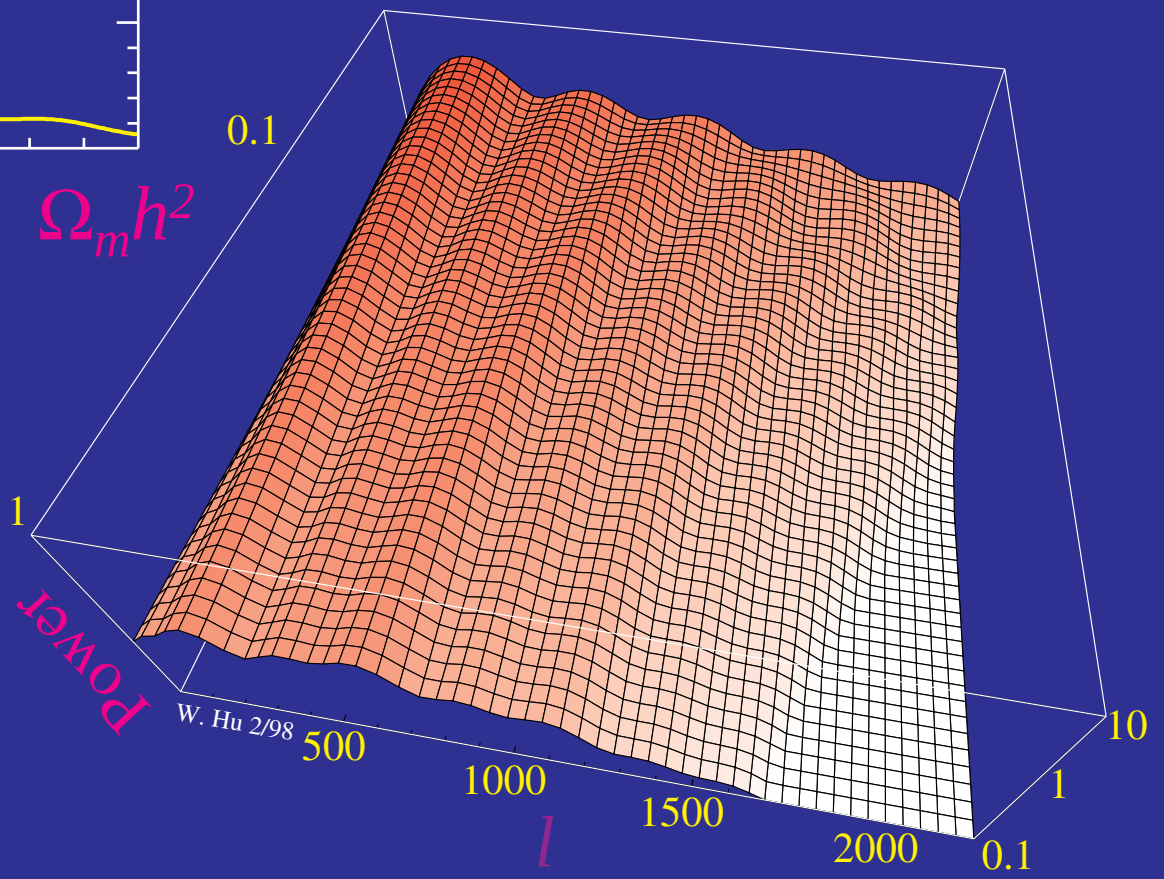
Hu & Sugiyama (1995)

Matter Density in the CMB



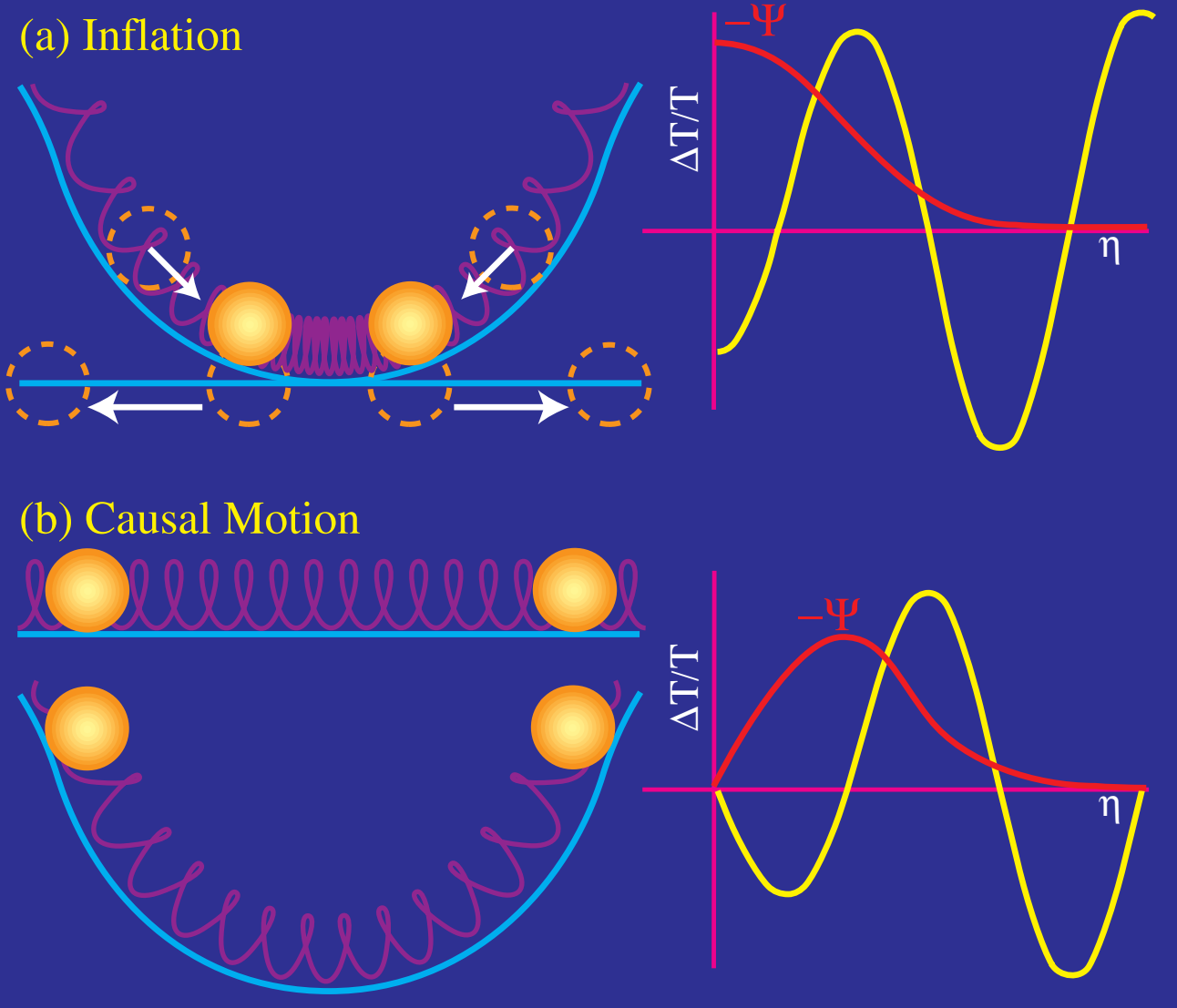
- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history

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



Inflation as Source of Perturbations

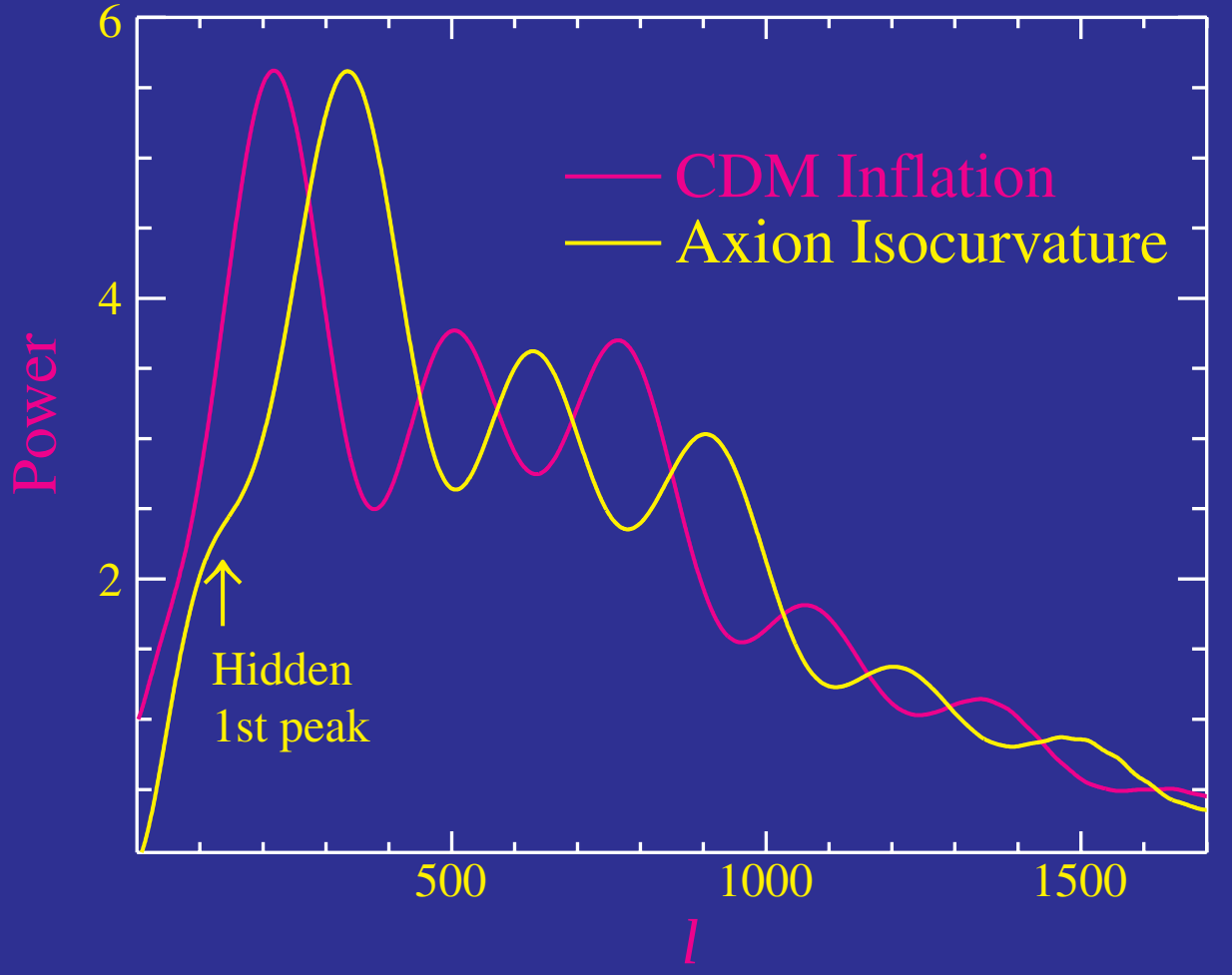
- Superluminal expansion (inflation) required to generate superhorizon curvature (density) perturbations
- Else perturbations are isocurvature initially with matter moving causally
- Curvature (potential) perturbations drive acoustic oscillations
- Ratio of peak locations
- Harmonic series:
  curvature 1:2:3...
  isocurvature 1:3:5...



Hu & White (1996)

Inflation as Source of Perturbations

- Superluminal expansion (inflation) required to generate superhorizon curvature (density) perturbations
- Else perturbations are isocurvature initially with matter moving causally
- Curvature (potential) perturbations drive acoustic oscillations
- Ratio of peak locations
- Harmonic series:
  curvature 1:2:3...
  isocurvature 1:3:5...



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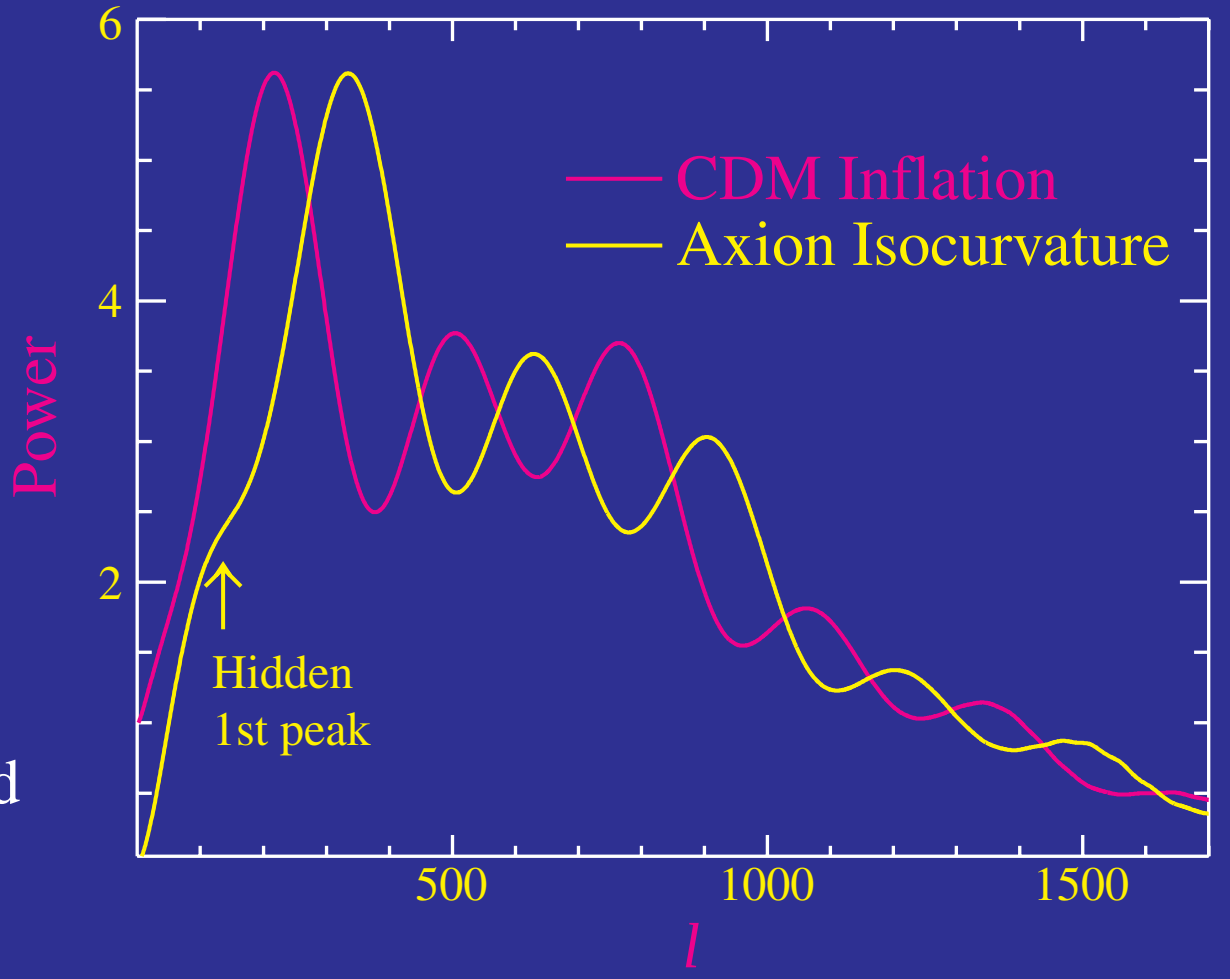
- Random Forcing: washed out peaks

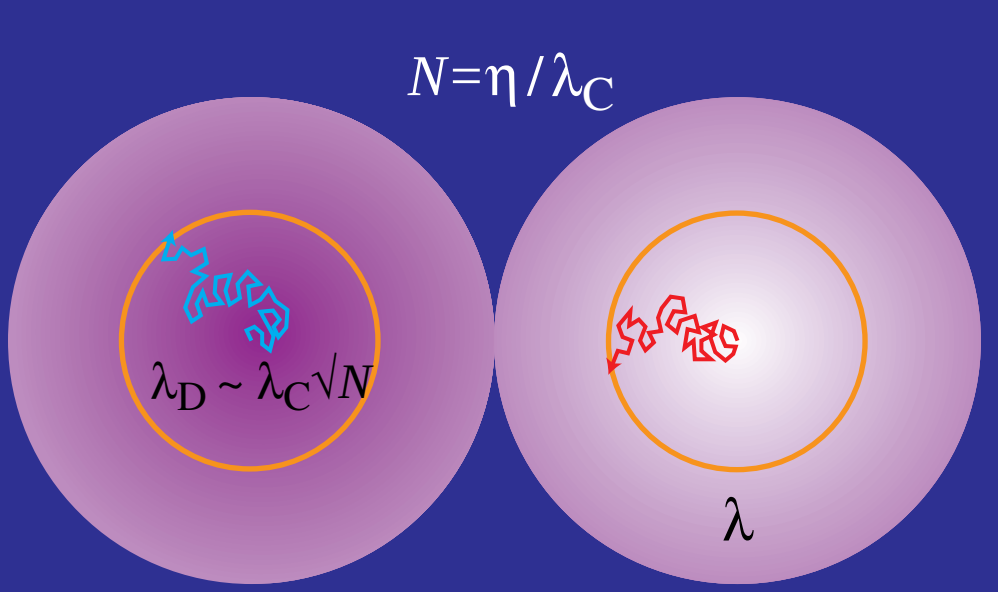


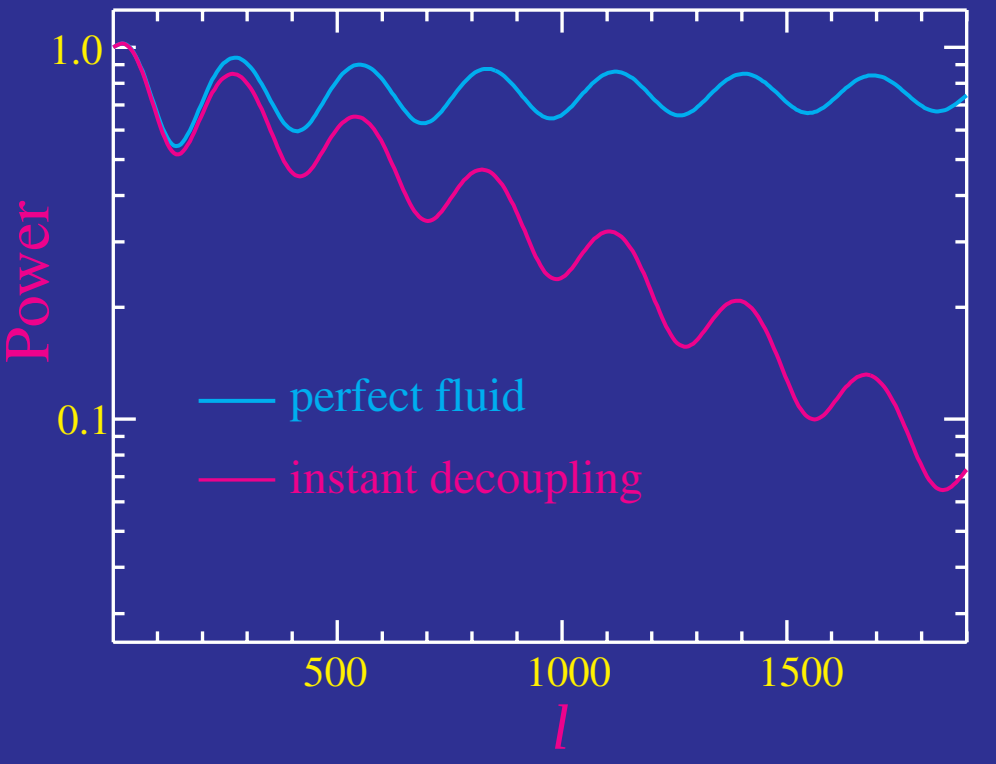
Hu & White (1996); Albrecht et al. (1996)

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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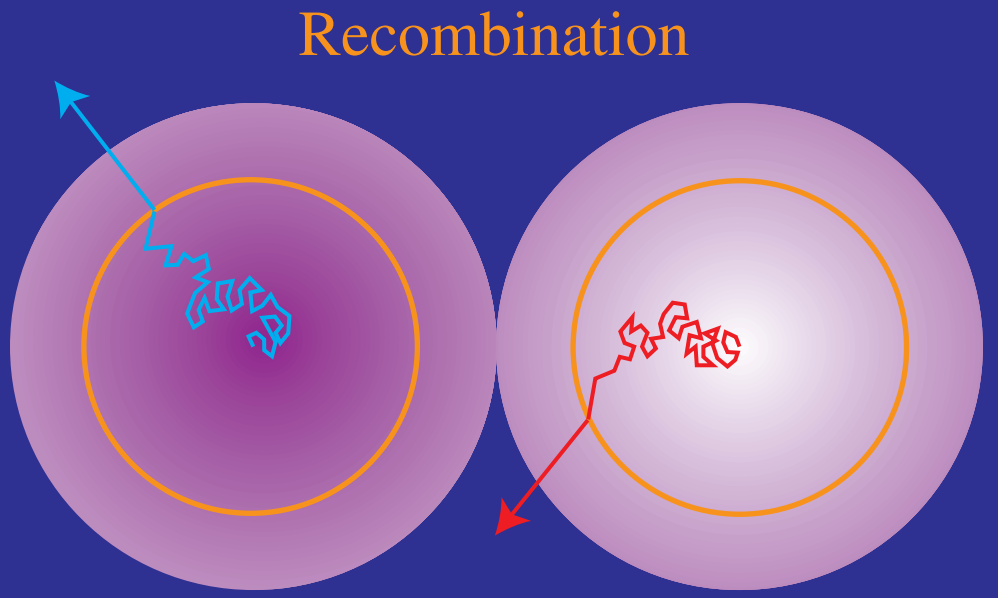
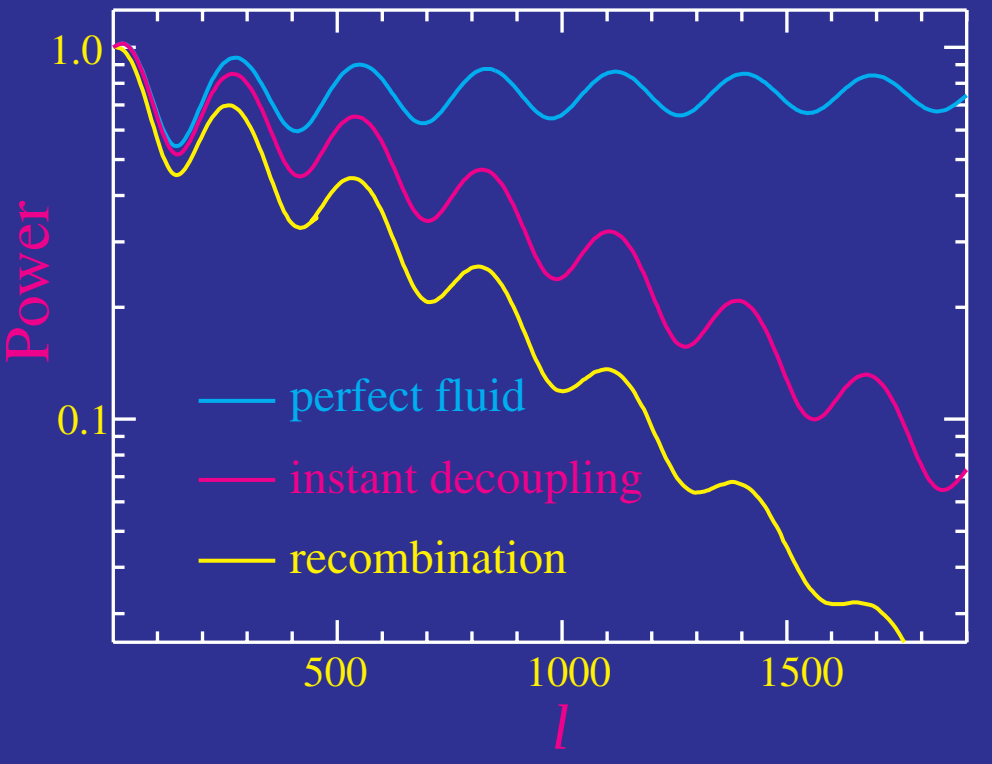
- Rapid increase at recombination as mfp ↑

- Robust physical scale for angular diameter distance test (Ω_K, Ω_Λ)





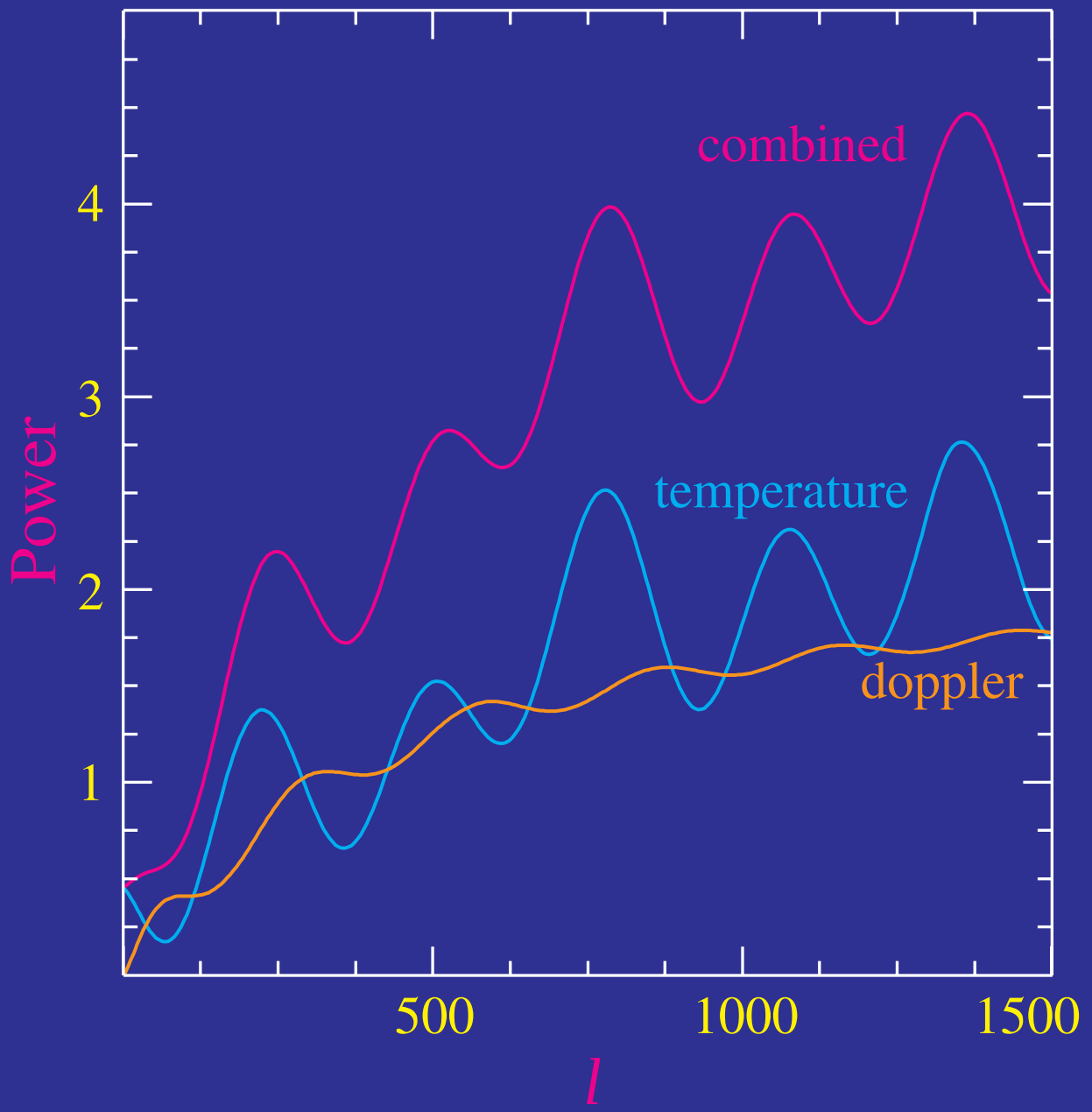
Silk (1968); Hu & White (1996)

Physical Decomposition & Information

- Fluid + Gravity

  → harmonic series:

  inflationary origin



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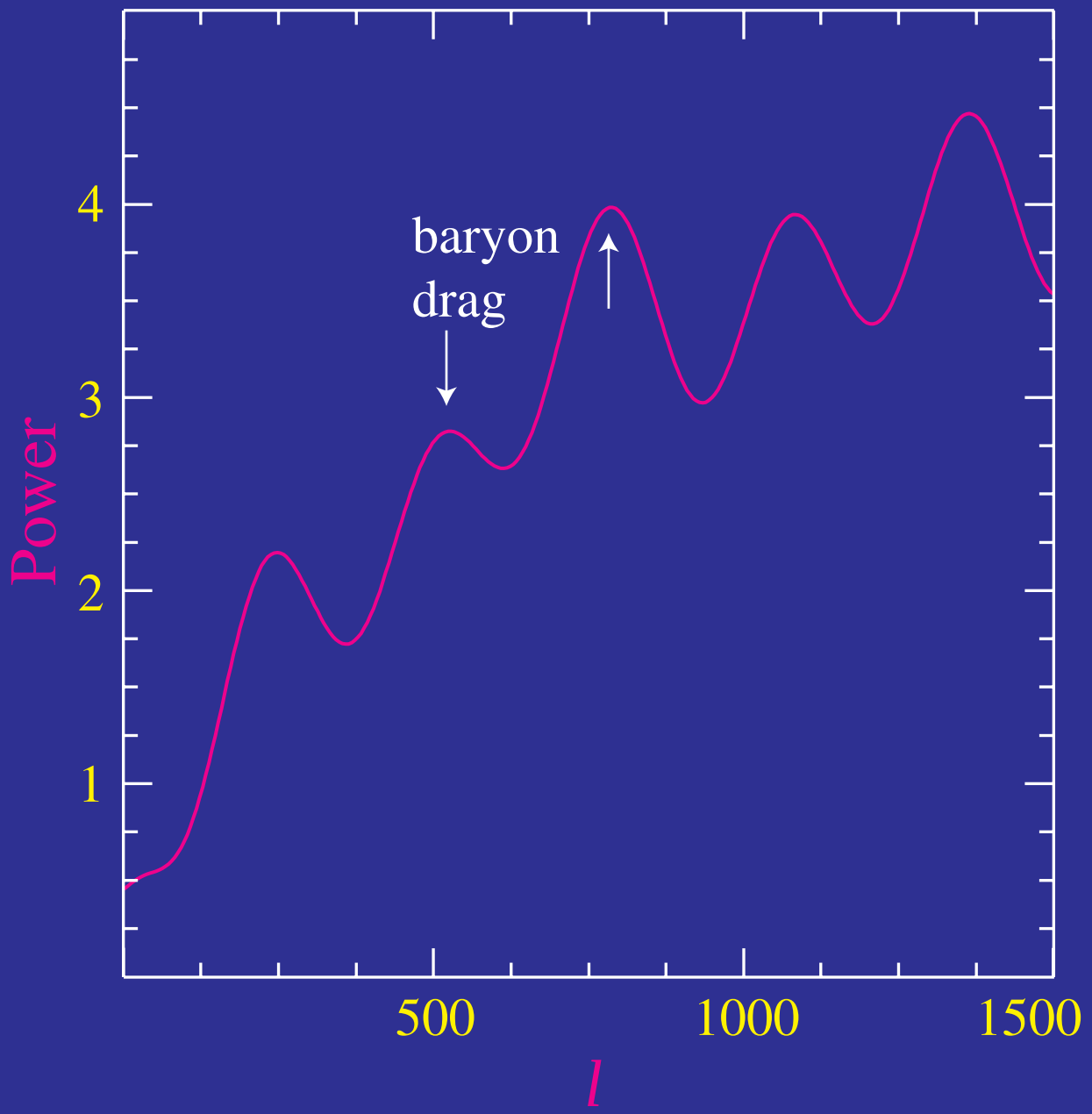
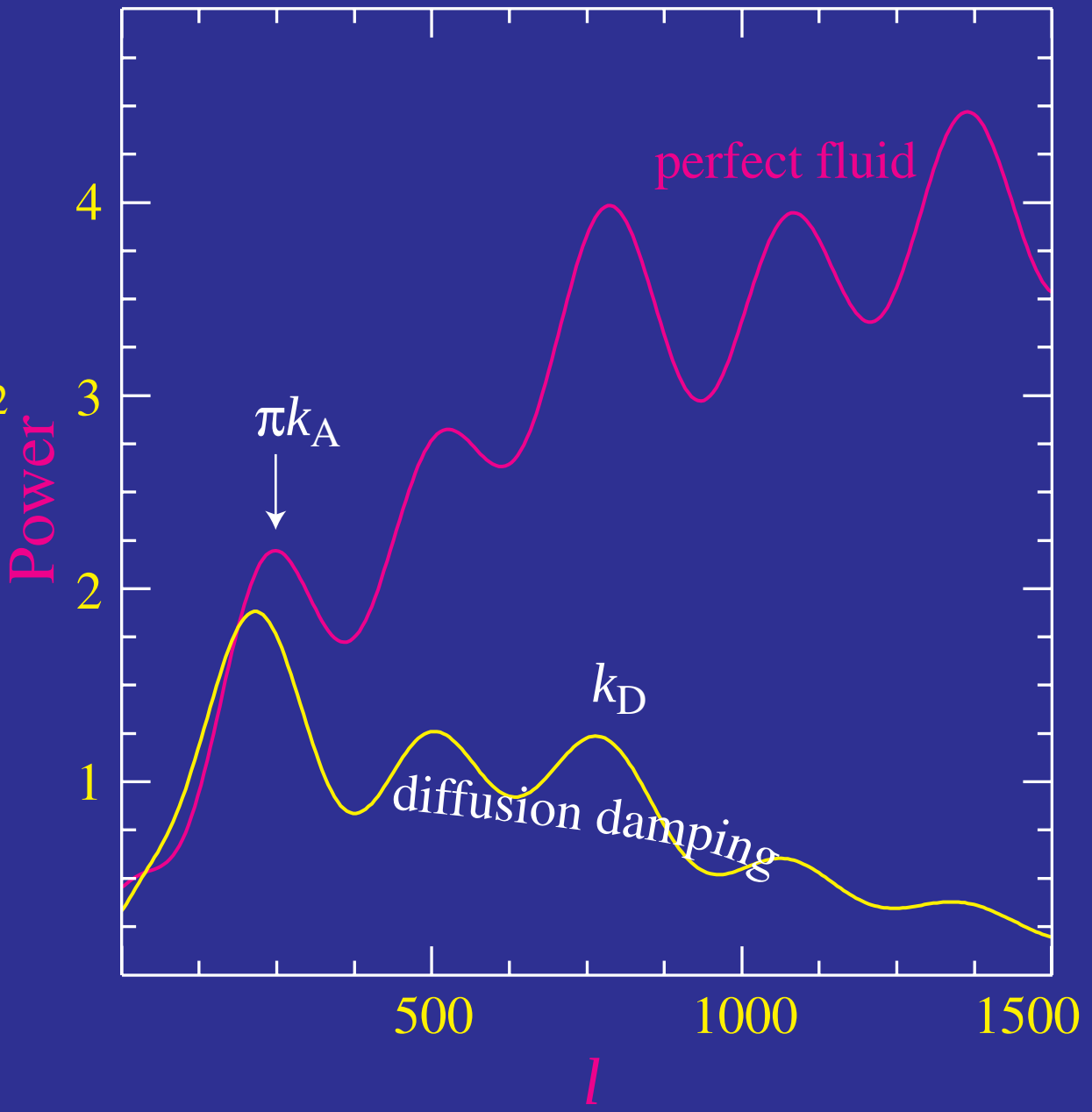
  → alternating peaks:

  photon/baryon $\Omega_b h^2$



Physical Decomposition & Information

- 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



Physical Decomposition & Information

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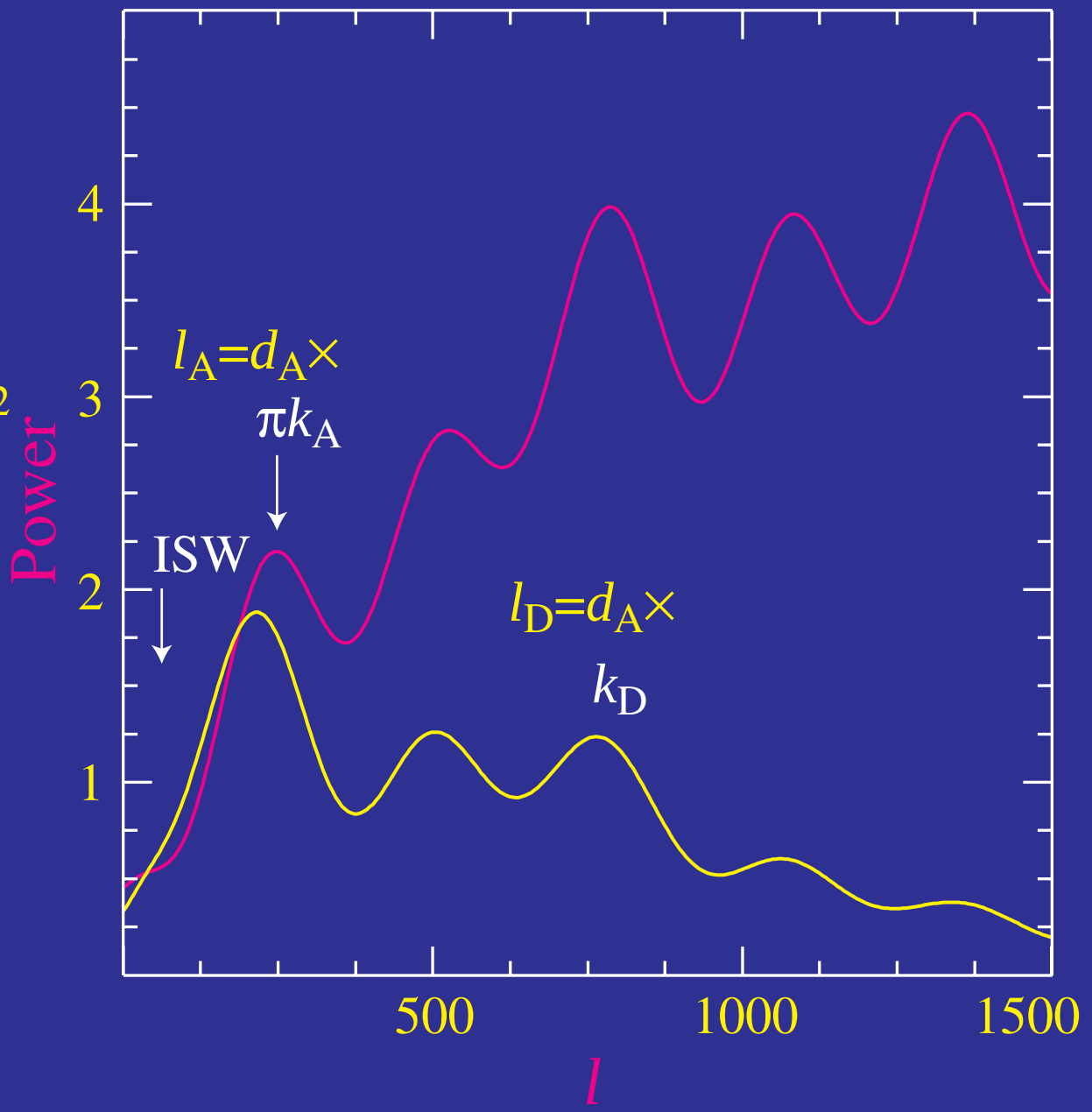
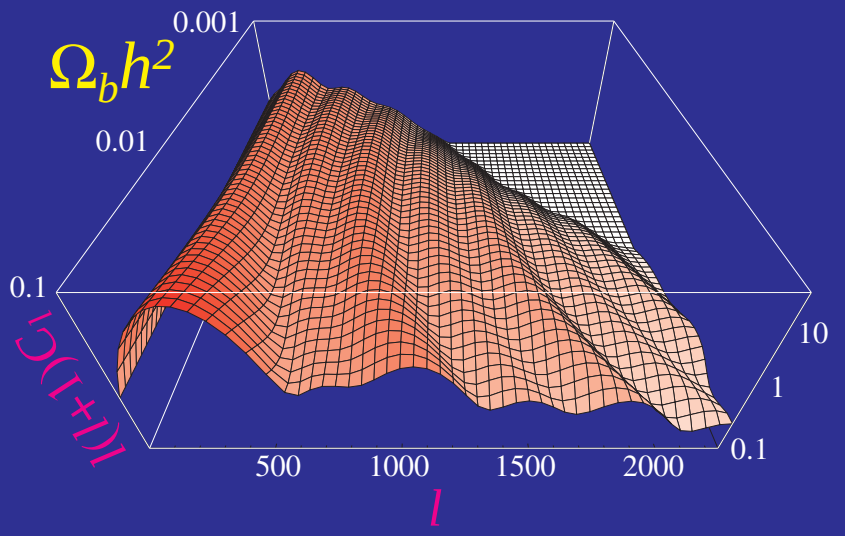
- Ruler Calibration
  - → sound horizon
  - → damping scale
- Geometry
  - → angular diameter distance $f(\Omega_\Lambda,\Omega_K)$ + flatness or no Ω_Λ,
  - → Ω_Λ or Ω_K

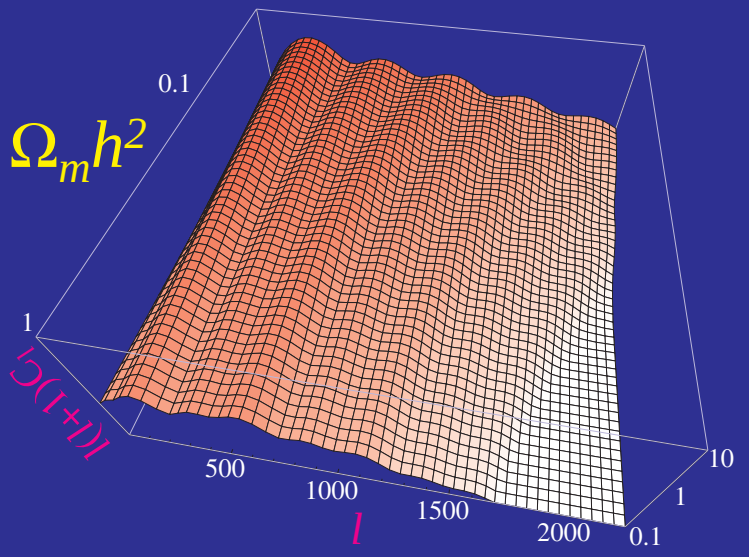


Neoclassical Cosmology & the CMB

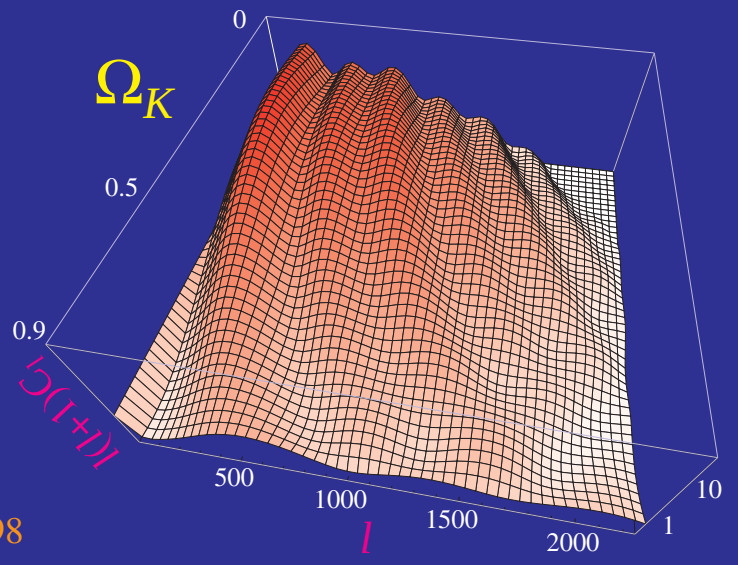
Baryon–Photon Ratio



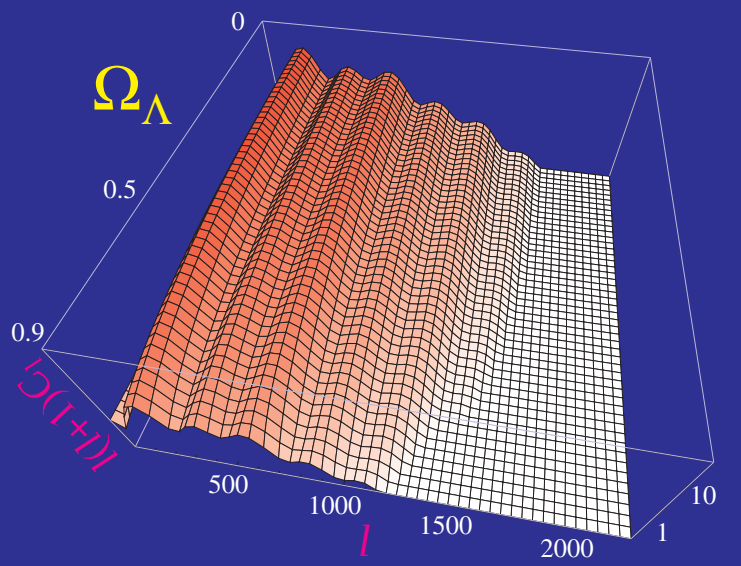
Matter–Radiation Ratio



Curvature



Cosmological Constant

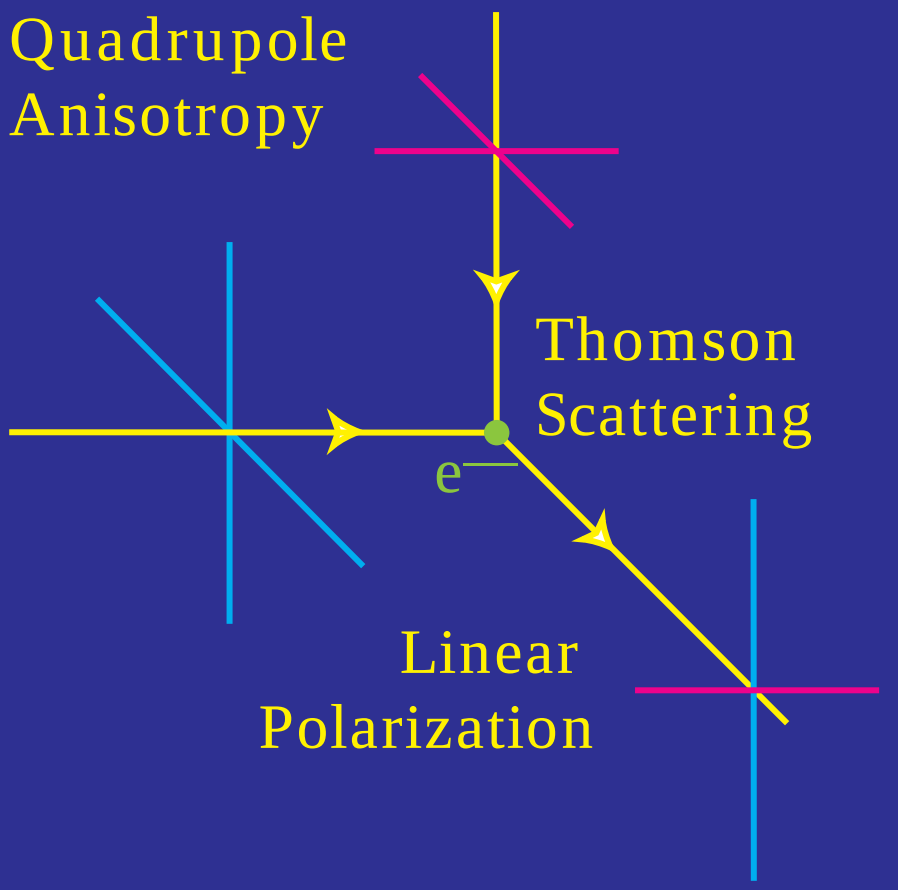


W.Hu 2/98

Beyond the Acoustic Peaks

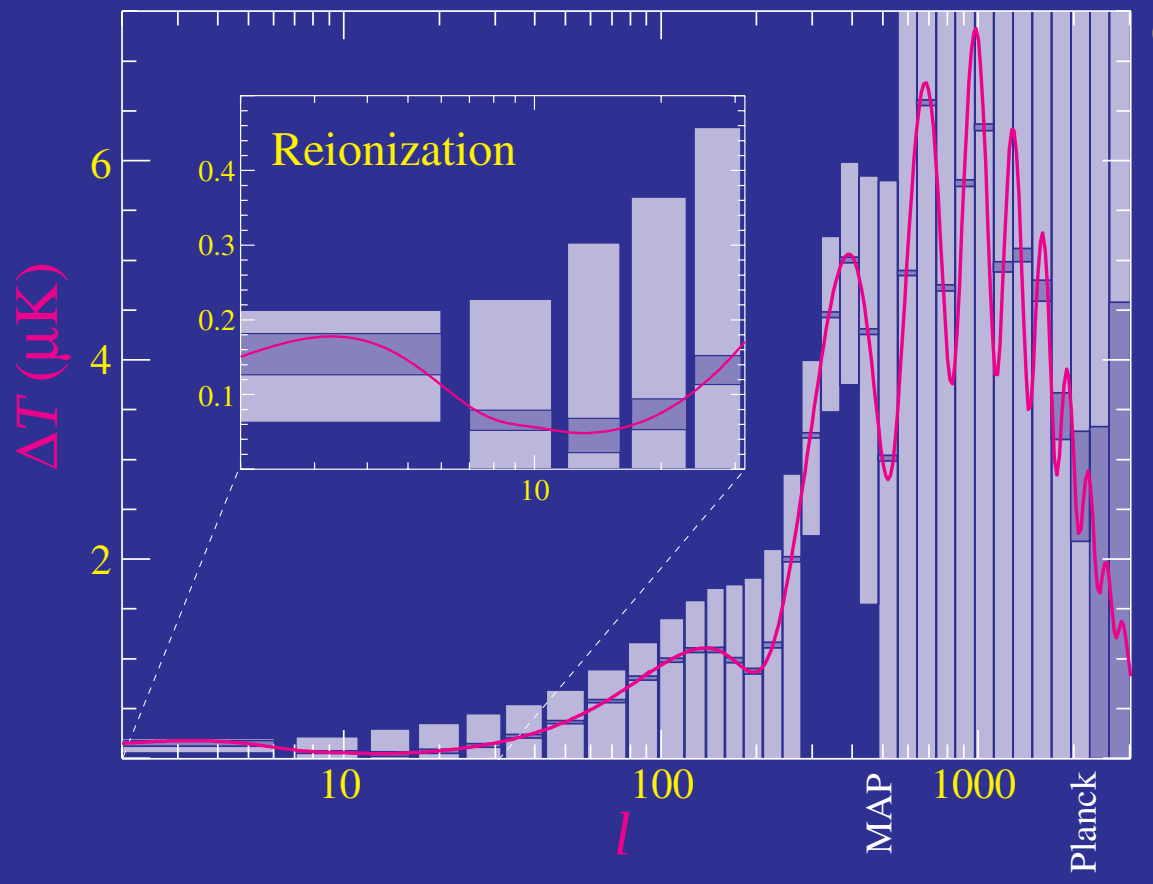
Polarization Diagnostics

- CMB polarization generated by scattering of quadrupole anisotropies



Polarization Diagnostics

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

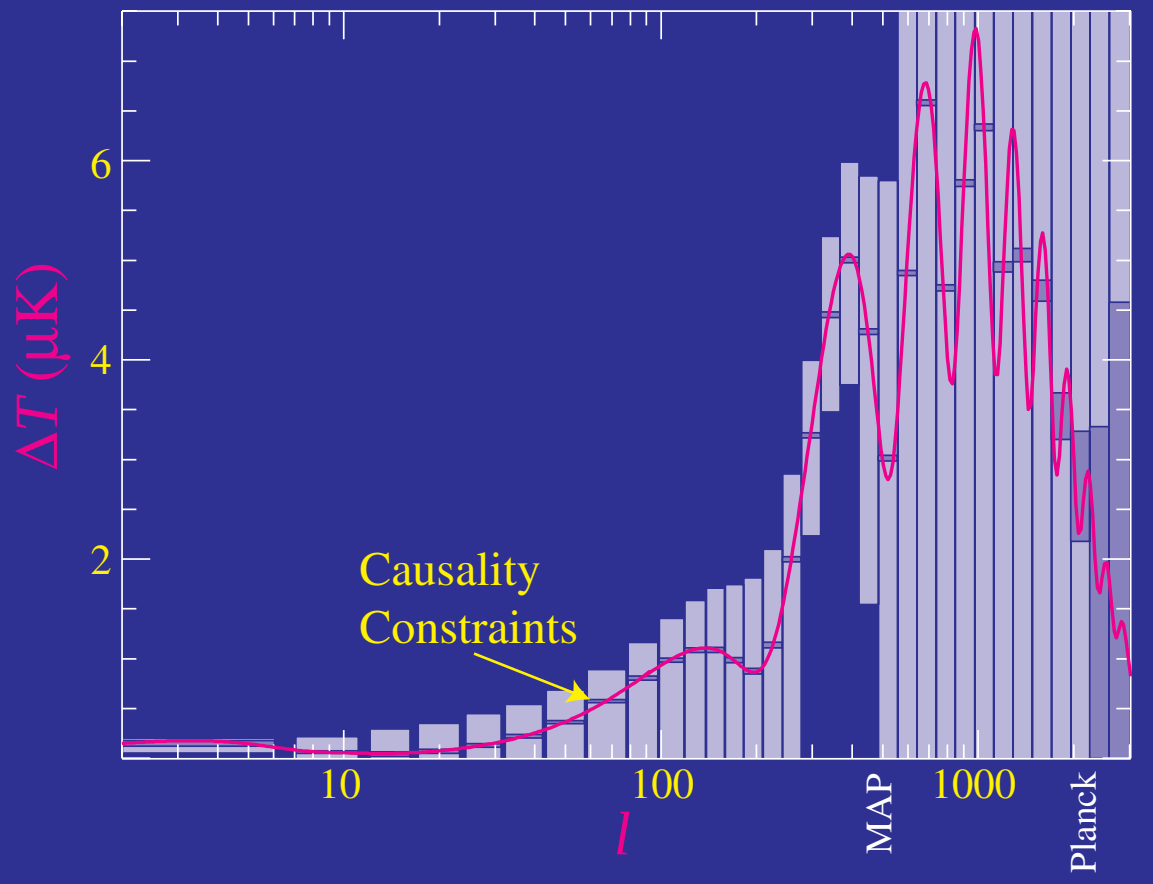


Current Constraints
< 20–40μK
Saskatoon
TOCO

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

Polarization Diagnostics

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



Current Constraints
< 20–40μK
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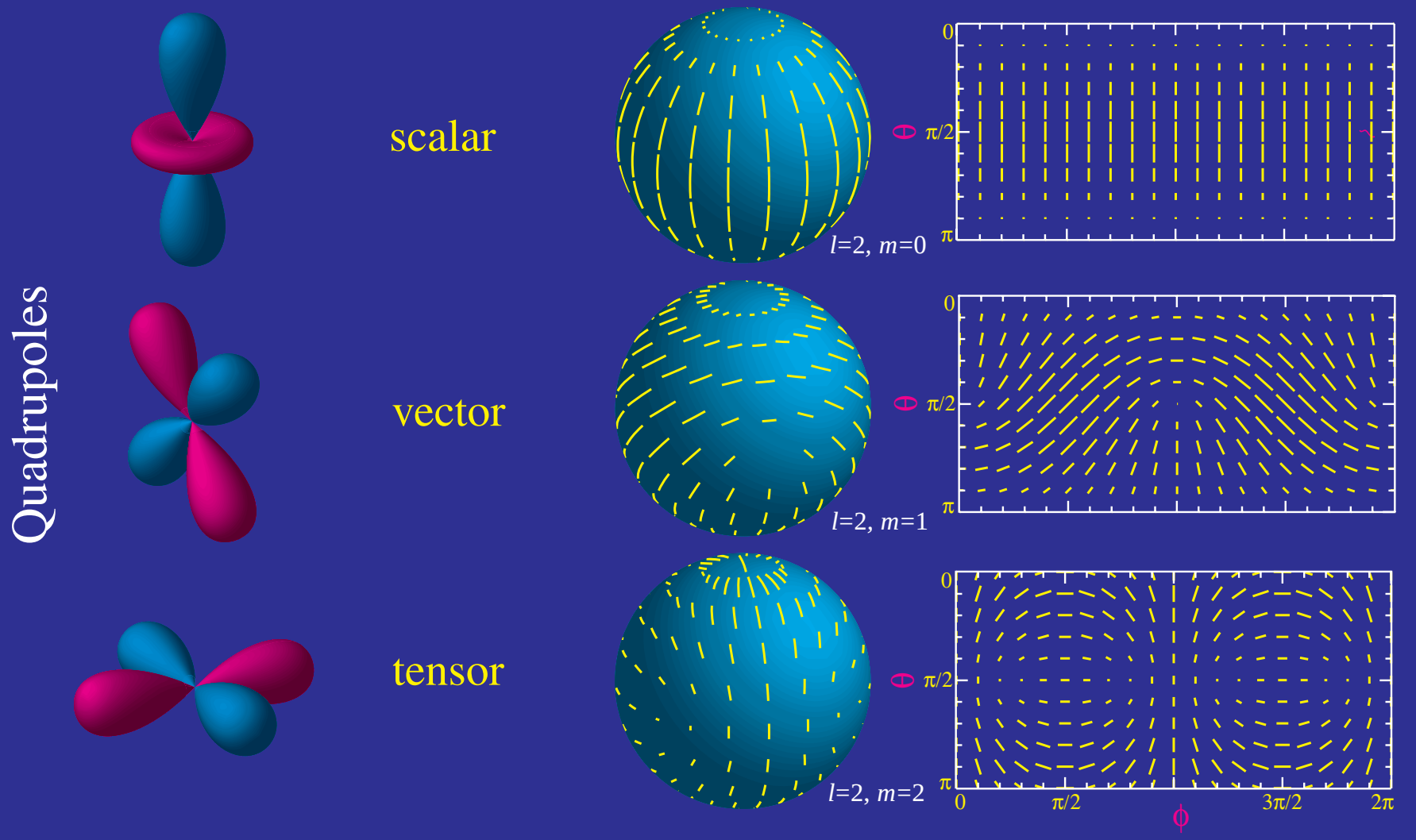
TOCO

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

Polarization Diagnostics

- CMB polarization generated by scattering of quadrupole anisotropies
- Robust ratios of the two parity patterns: scalar (0), vector (6), tensor (0.6)



Zaldarriaga & Seljak (1997)
Kamionkowski, Kosowsky & Stebbins (1997)

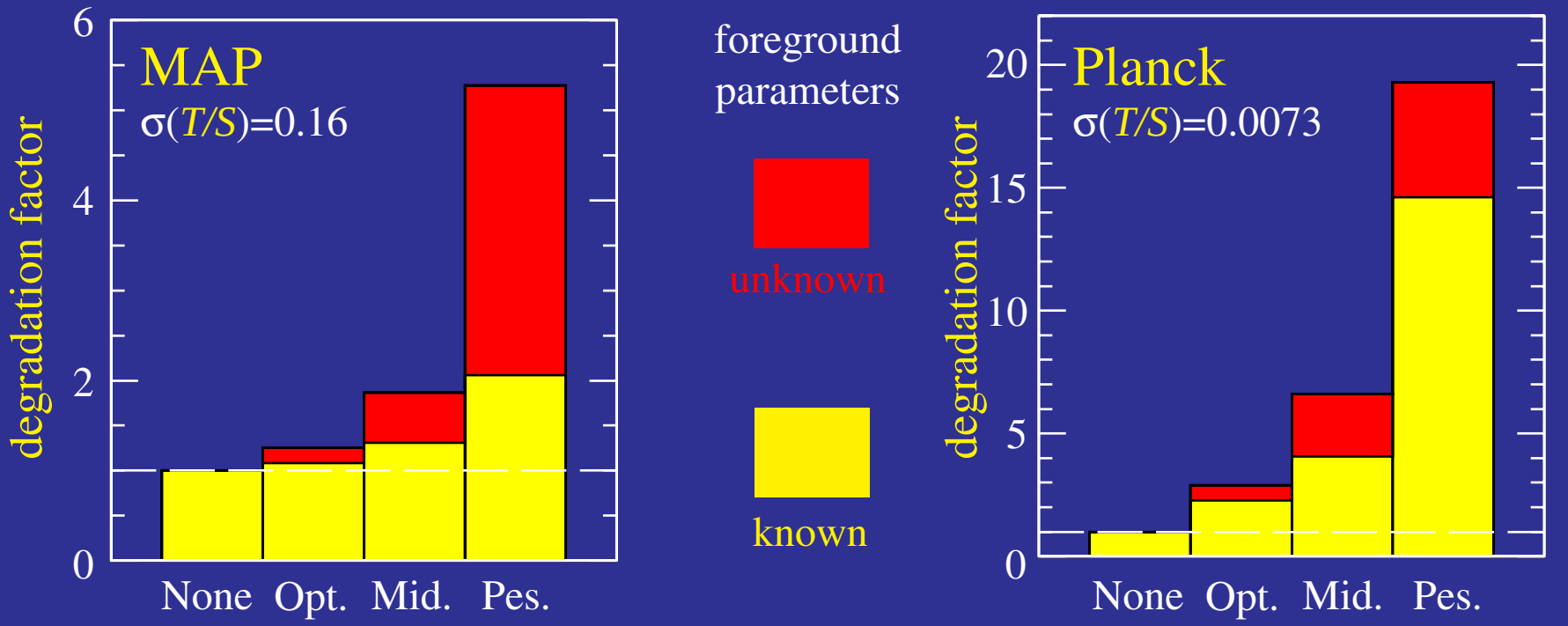
Hu & White (1997)

Tensors & Inflation

- Tensor Amplitude $\propto$ V (inflaton potential)
- Current upper limits: inflationary energy scale $< 2 \times 10^{16}$ GeV
- Tensor / Scalar amplitude $\propto (V'/V)^2$
  Tensor slope $\propto (V'/V)^2$
- Consistency Relation – test of slow-roll inflation

- Meaningful test by Planck only possible if T/S close to current limits
- Next next-generation satellite dedicated to polarization?

Foregrounds and Tensors



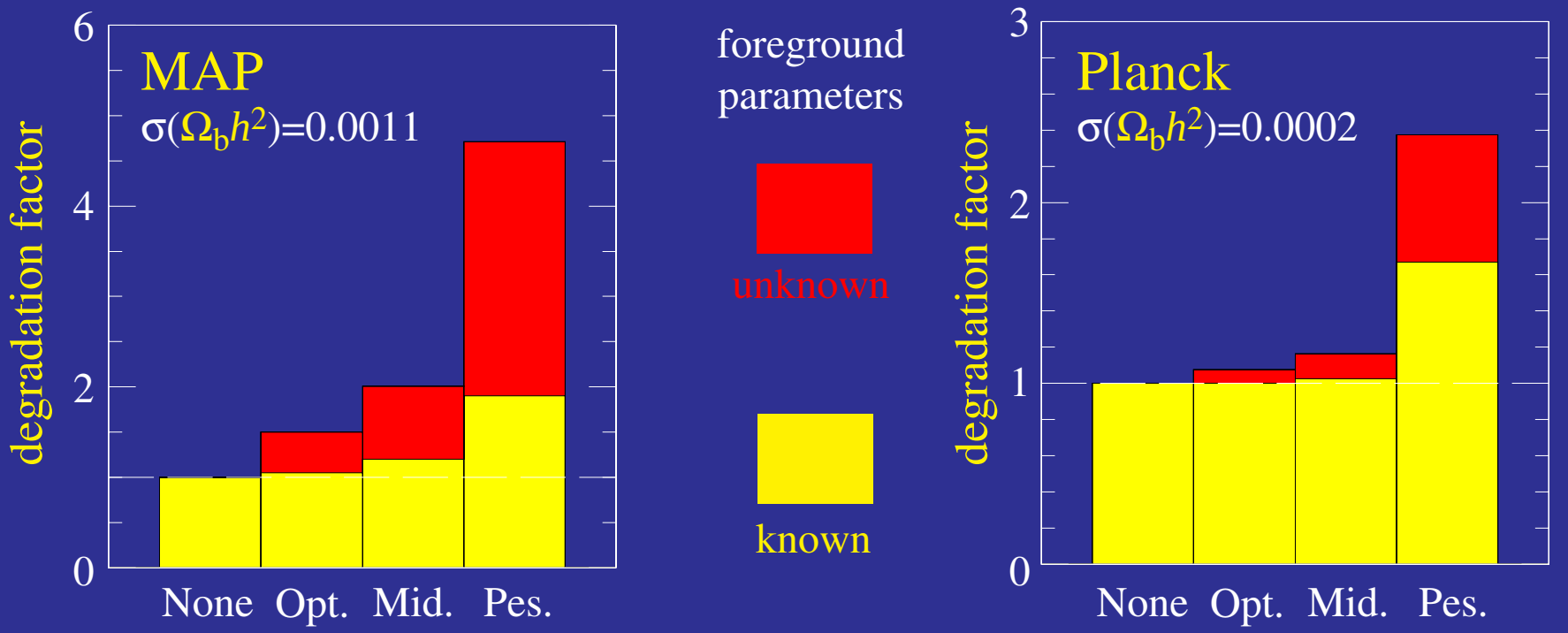
- 257–561 Foreground Parameters Simultaneously Estimated
- Foreground power spectra, frequency dependence, frequency coherence

  free-free, synchrotron, vibrating dust, rotating dust, thermal SZ, radio point sources, IR point sources
- 10 Cosmological Parameters
- Potentially significant degradation: better prior knowledge; more frequencies

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

Bouchet & Gispert (1999); Knox (1999)

Foregrounds and Baryons



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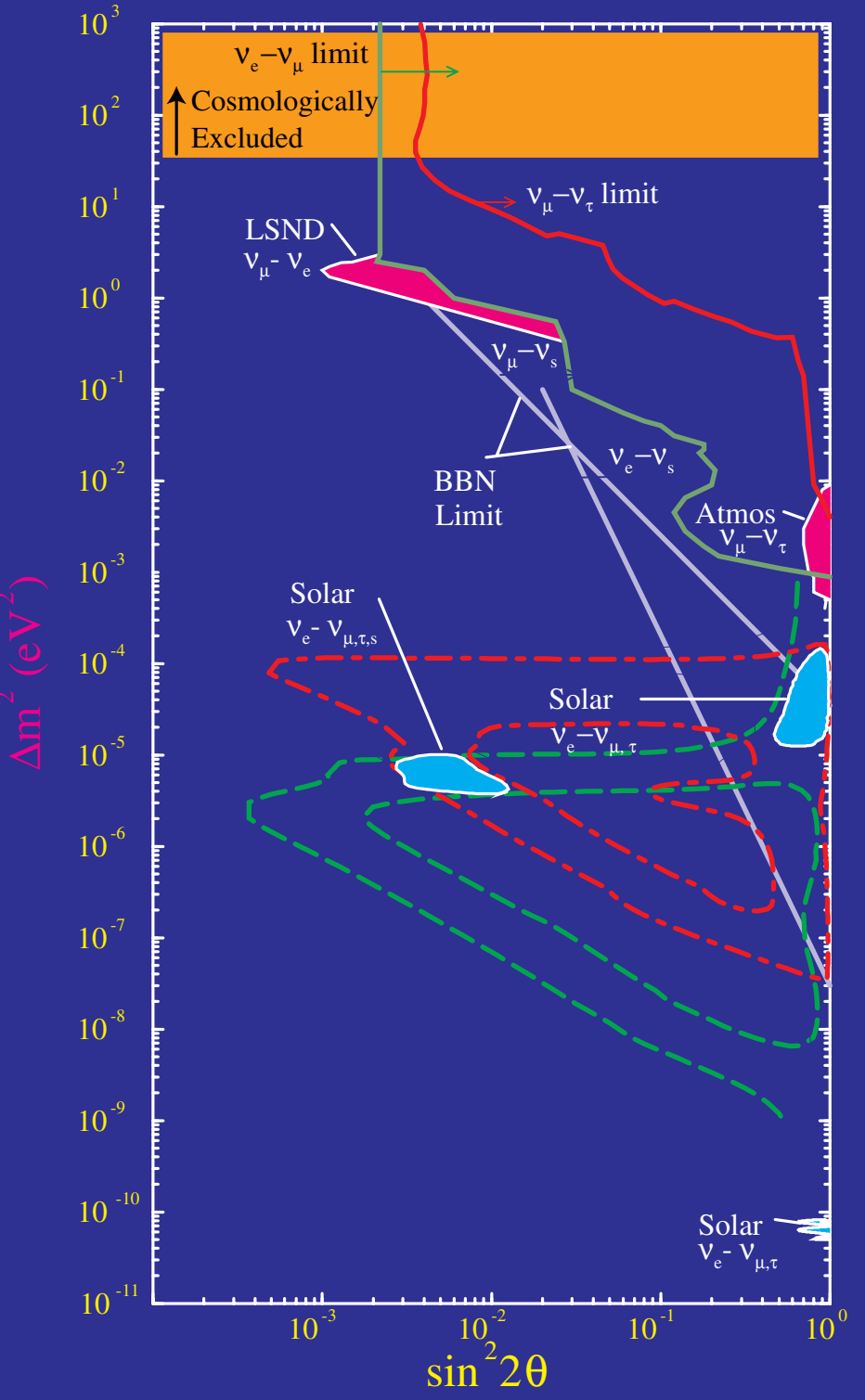
- 10 Cosmological Parameters
- Degradation of less than 2 in errors

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

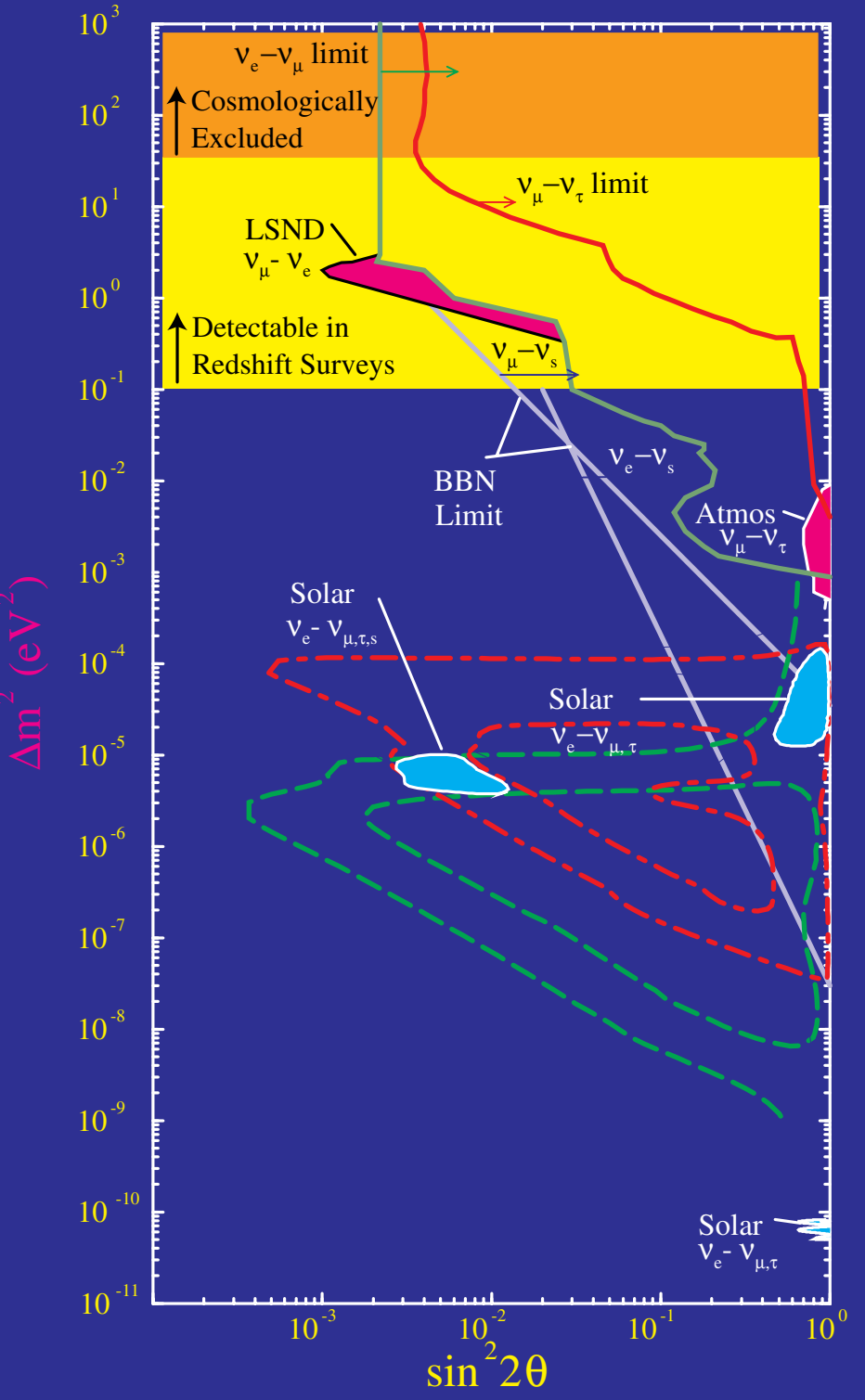
Cosmology and the Neutrino Anomalies



Anomalies: Hata (1998)

Croft, Hu & Davé (1999)

Cosmology and the Neutrino Anomalies



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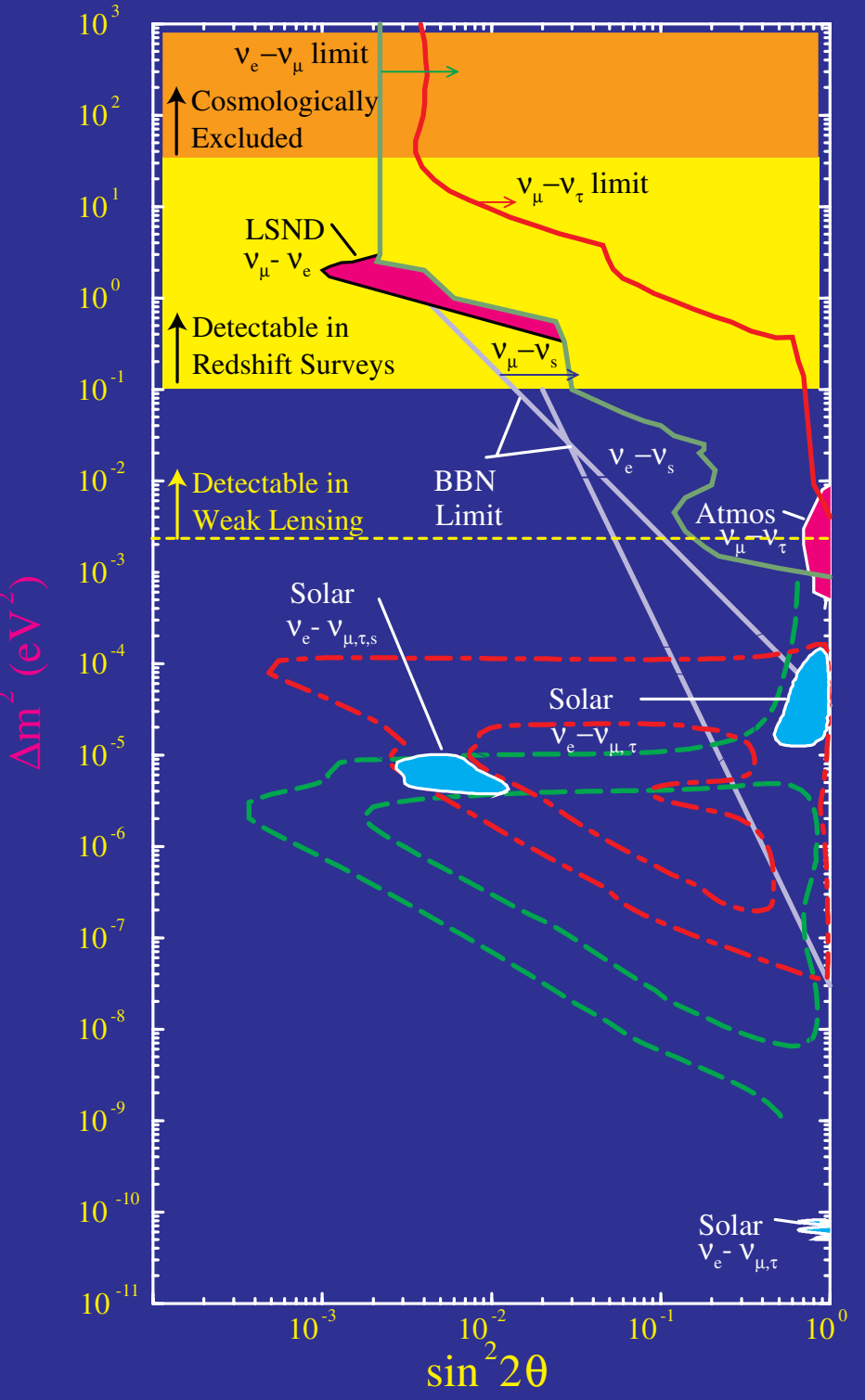

Anomalies: Hata (1998)

Croft, Hu & Davé (1999)
Hu, Eisenstein & Tegmark (1998)
Hu & Tegmark / Hu (1999)

Conclusions: Cautious Optimism

- Simple adiabatic CDM models have survived the onslaught of data to date
- Three parameters: $\Omega_b h^2$, $\Omega_m h^2$, combination of Ω_K, Ω_Λ already interestingly constrained
- Precision parameter estimation on these satellites are robust to all but pathological foregrounds

- Precision constraints on gravity waves and dark energy/matter possible
- Requires CMB polarization and complementary information from other cosmological measures
- May require more detailed modelling of foregrounds and/or a next-generation CMB satellite mission

Index

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

Outtakes