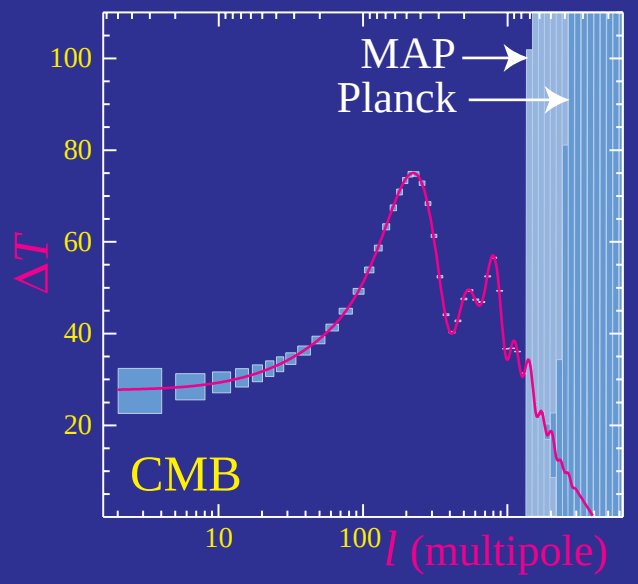
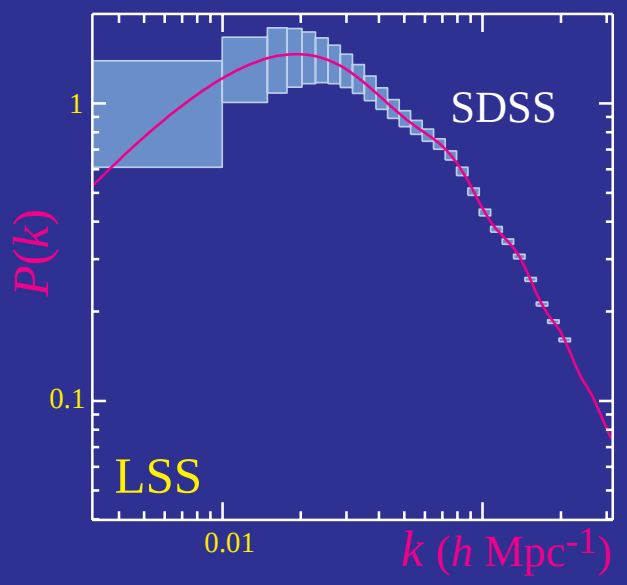
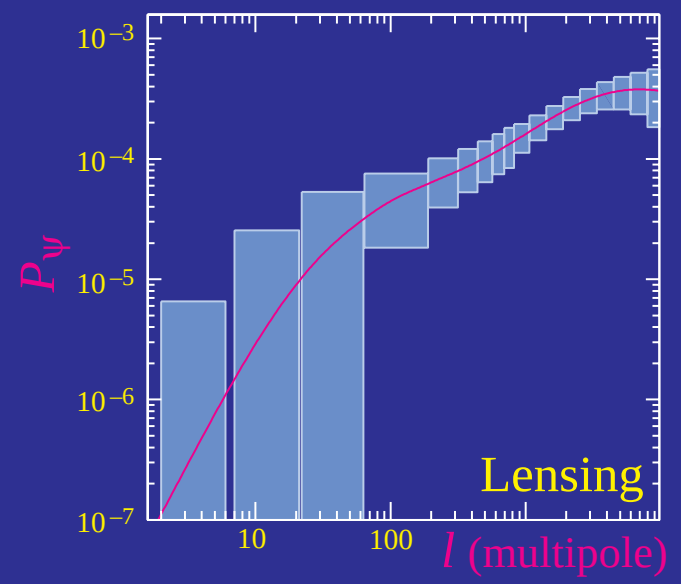
Probing the Dark Side







of

Structure Formation

Wayne Hu

The Dark Side of Structure Formation

- The Dark Side

  All components that contributes to the expansion rate that do not couple to ordinary matter at the present

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- The Usual Suspects

  Cold dark matter, dark baryons, cosmological constant, spatial curvature

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- Other Shady Characters

  Massive neutrinos, scalar fields, decaying dark matter, background neutrinos...

  - Observationally testing the properties of the dark sector combining low and high redshift information

Collaborators
Past & Present

- Microwave Background
  - Emory Bunn
  - Asantha Cooray
  - Andrei Gruzinov
  - Douglas Scott
  - Uros Seljak
  - Joe Silk
  - Naoshi Sugiyama
  - Martin White
  - Matias Zaldarriaga
- Large-Scale Structure
  - Rupert Croft
  - Romeel Dave
  - Daniel Eisenstein
  - Jim Peebles
  - Alex Szalay
  - Max Tegmark

http://www.sns.ias.edu/~whu/yukawa.pdf

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  - Alex Szalay
  - Max Tegmark
- Presentation

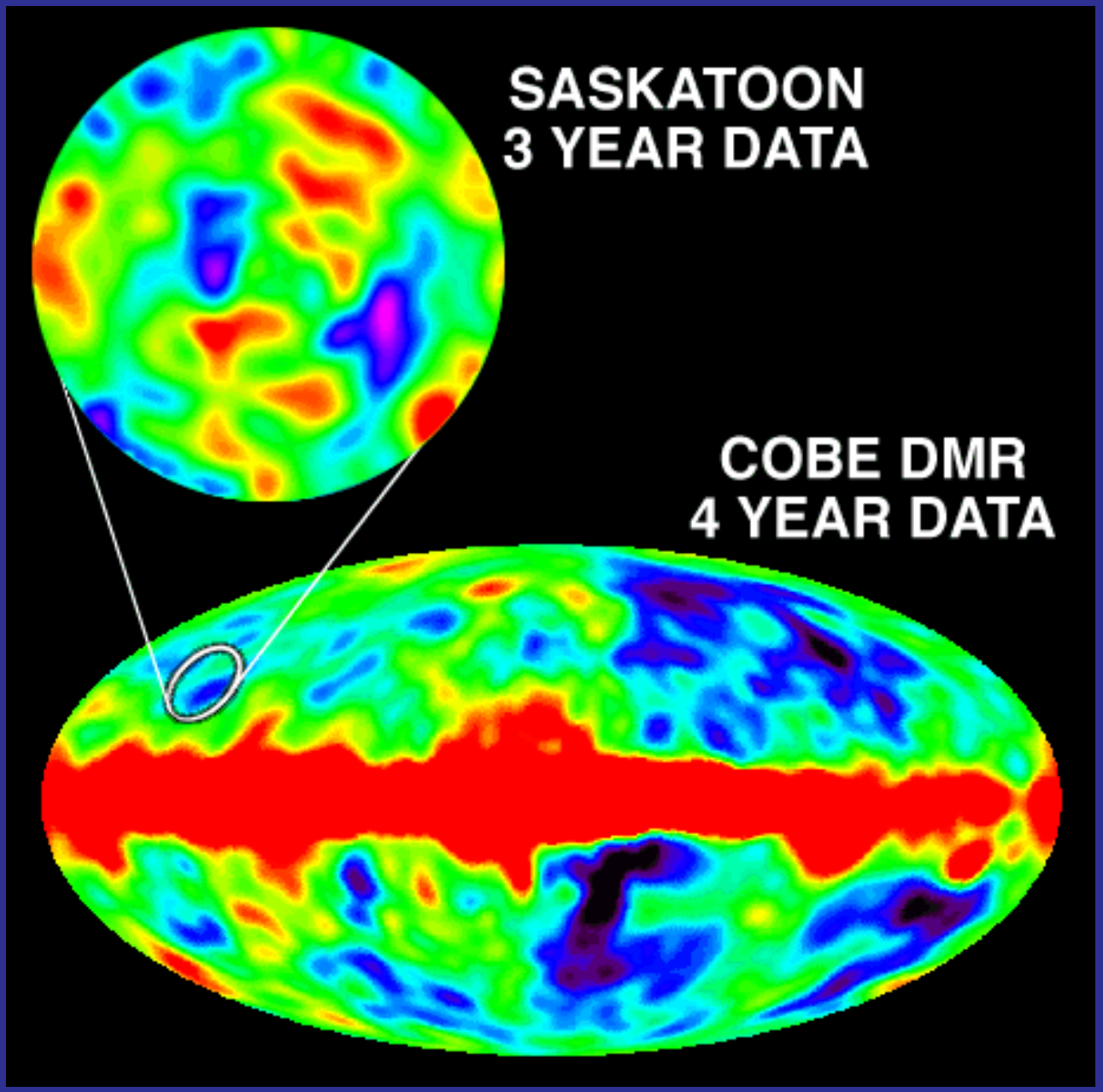
http://www.sns.ias.edu/~whu/yukawa.pdf

Part I:
Establishing the Cosmological Framework

Begin with the CMB because...

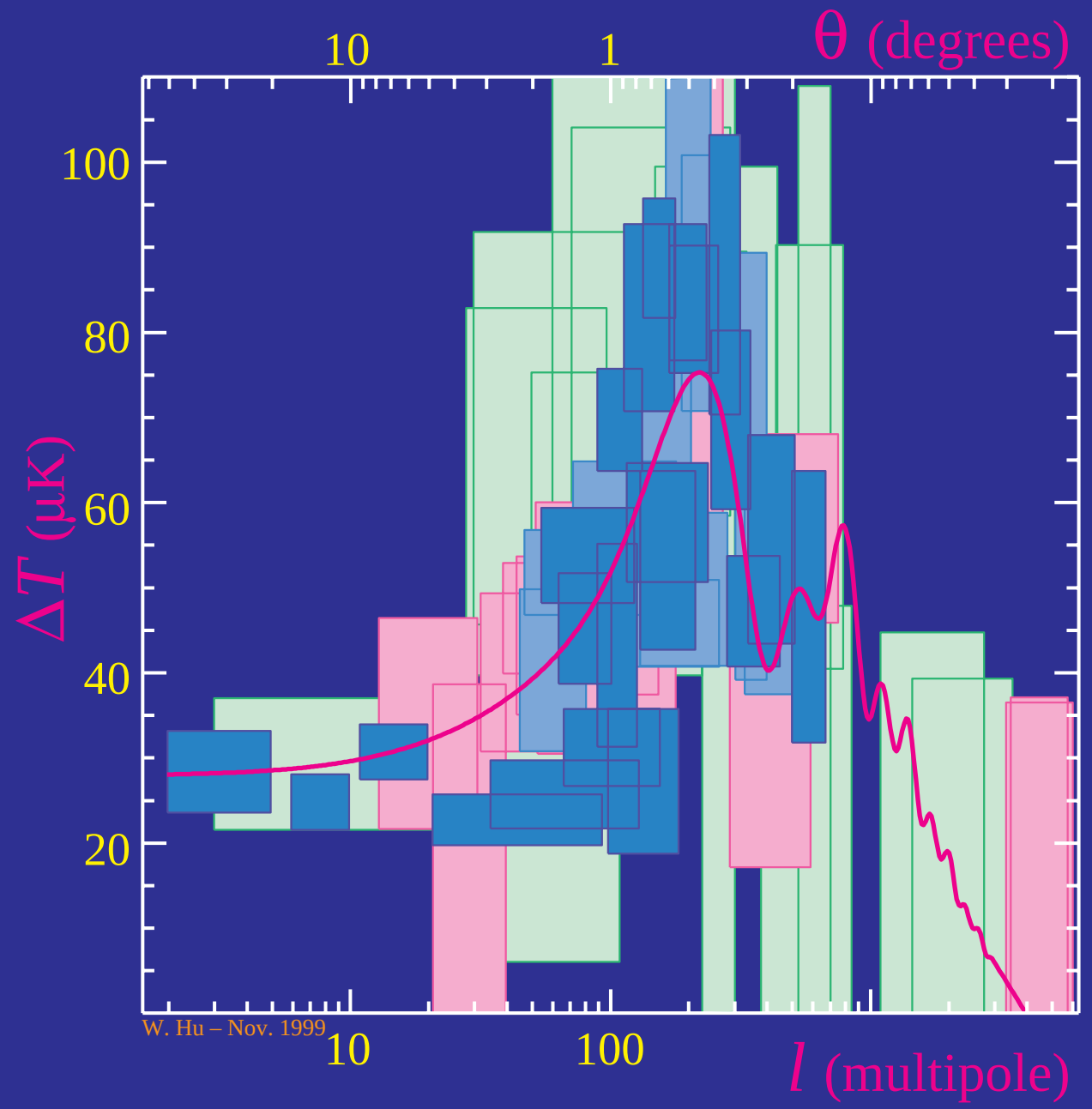
- Linearity observed: $\Delta T/T \sim 10^{-5}$
- Simple Physics
  - Gravity
  - Fluid Dynamics
  - Geometry
- Rich Features
  - Acoustic Peaks

CMB Anisotropies

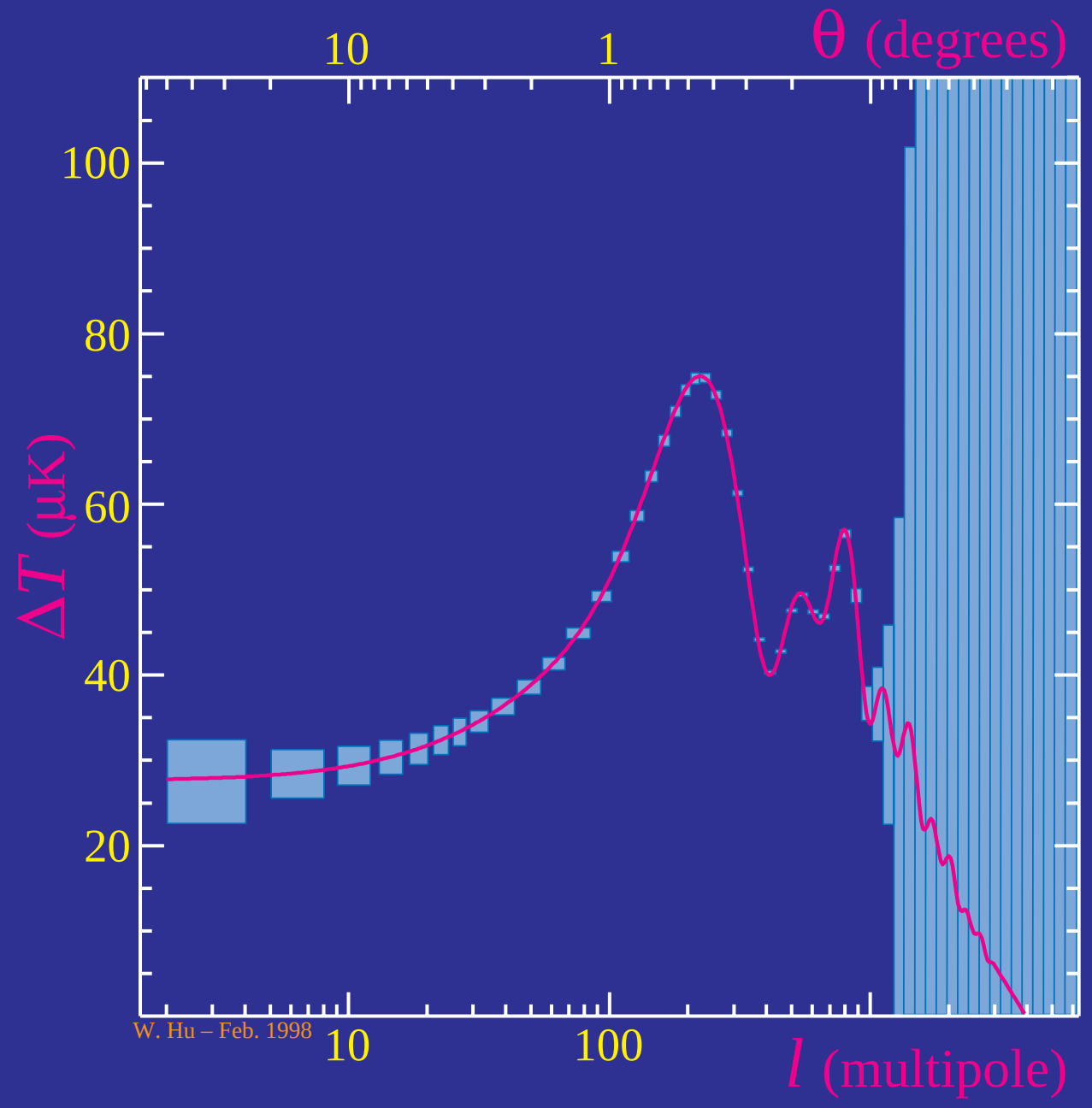


Tegmark, de Oliviera Costa, Devlin, Netterfield, & Page (1996)

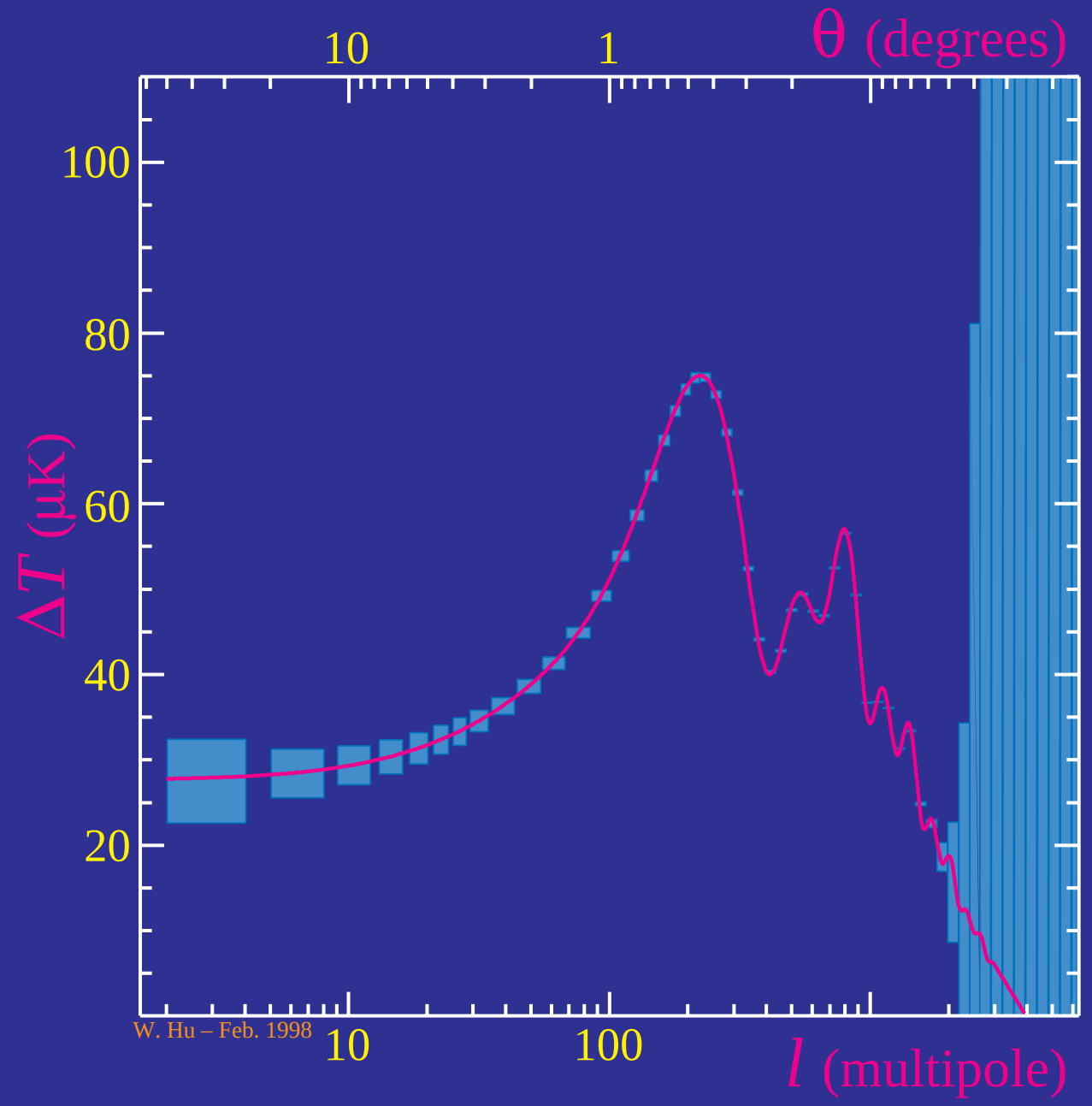
Current CMB Quilt



Projected MAP Errors



Projected Planck Errors



Thermal History

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

  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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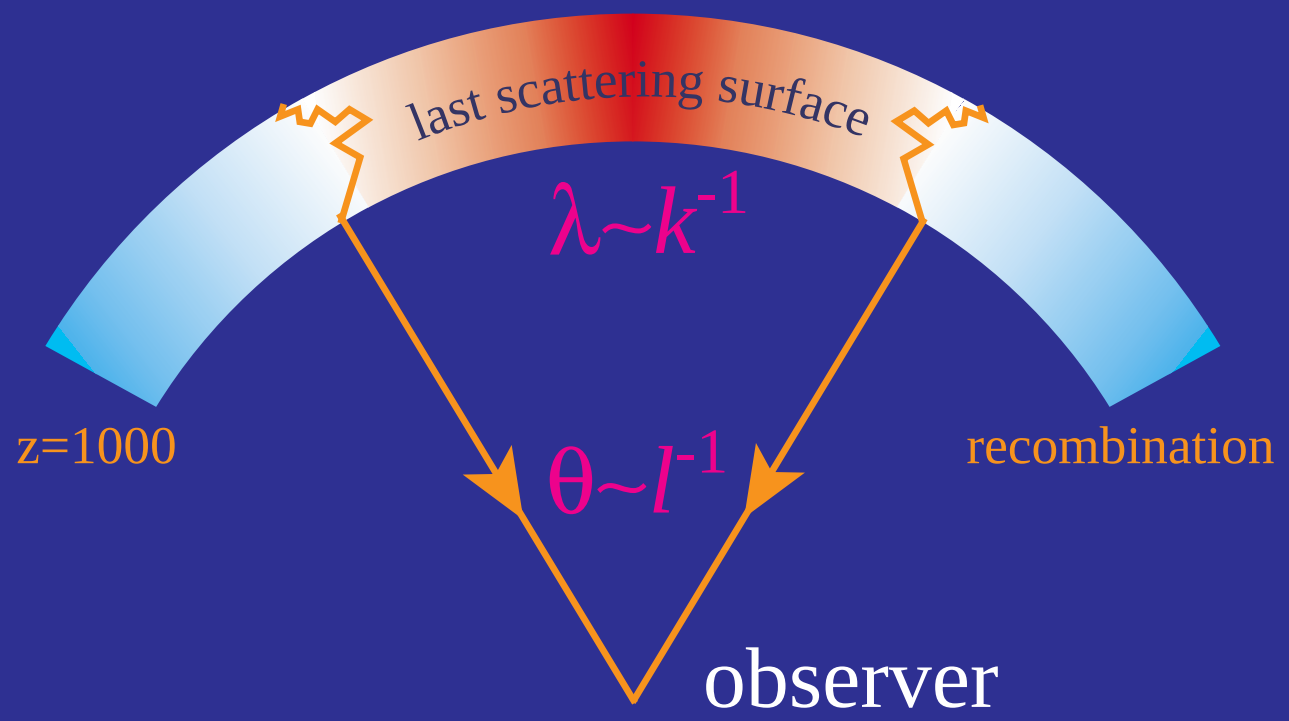
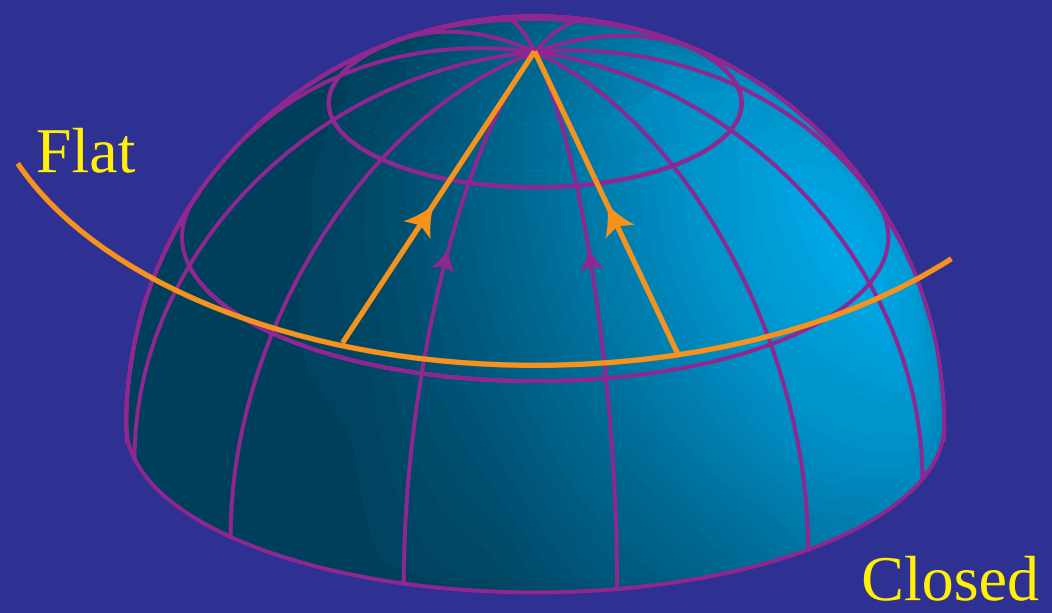
  Photon–baryon fluid
  Potential wells that later form structure

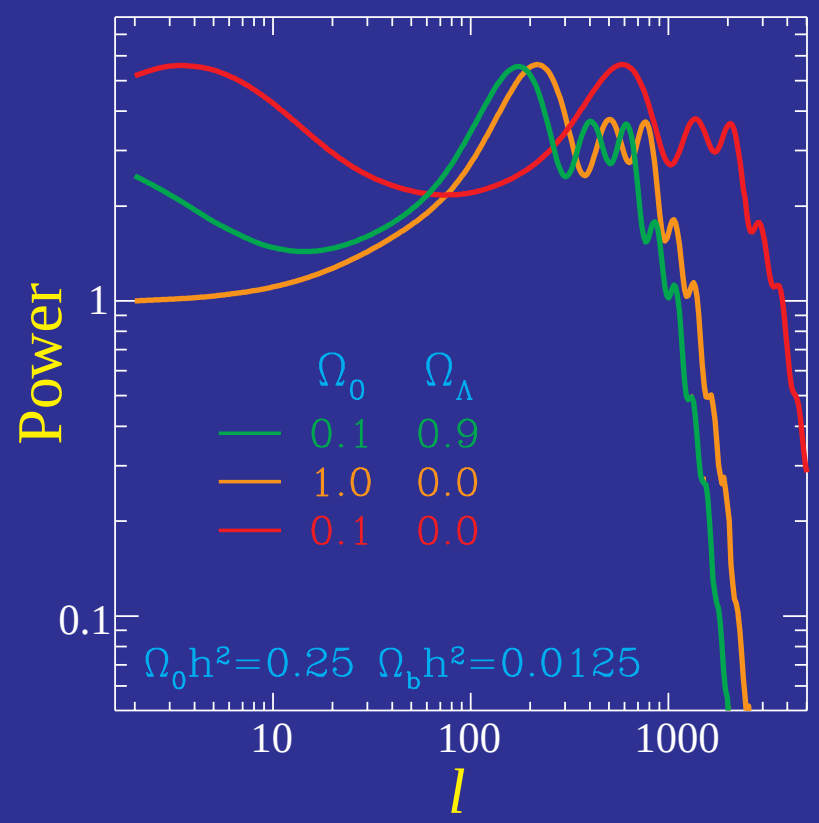
- $z \sim 1000$; $T_\gamma \sim 3000K$
  Recombination
  Fluid breakdown
- $z < 1000$; $T_\gamma < 3000K$
  Gravitational redshifts & lensing
  Reionization; rescattering



Angular Diameter Distance

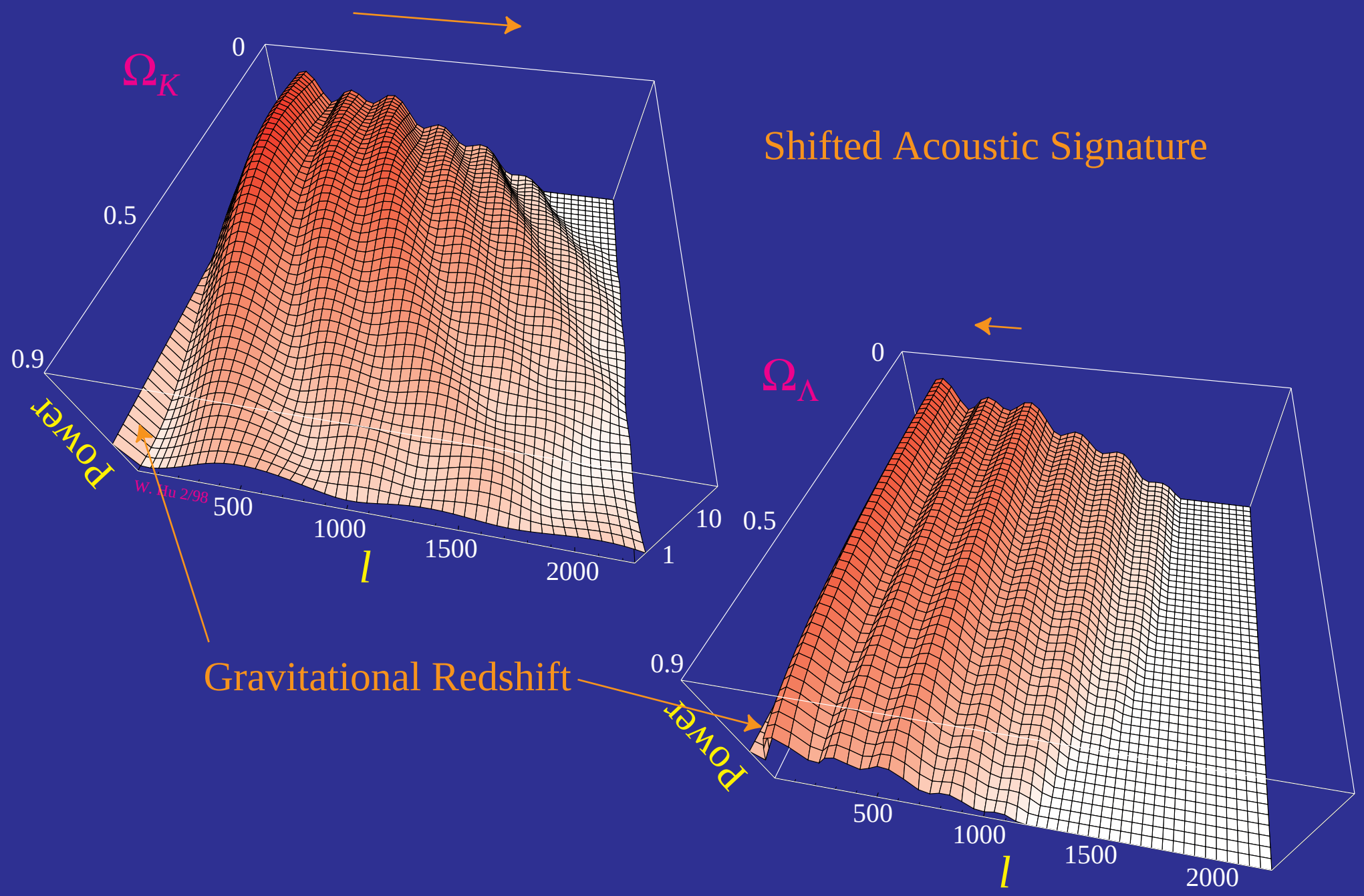
- Spatial Curvature
  - Standardized ruler
  - Measure angular extent
  - Ruler & comoving distance scale (except for Λ)
  - Infer curvature
- Robust Physical Scales
  - Sound horizon → Peak spacing
  - Diffusion scale → Damping tail





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

Curvature and the Cosmological Constant

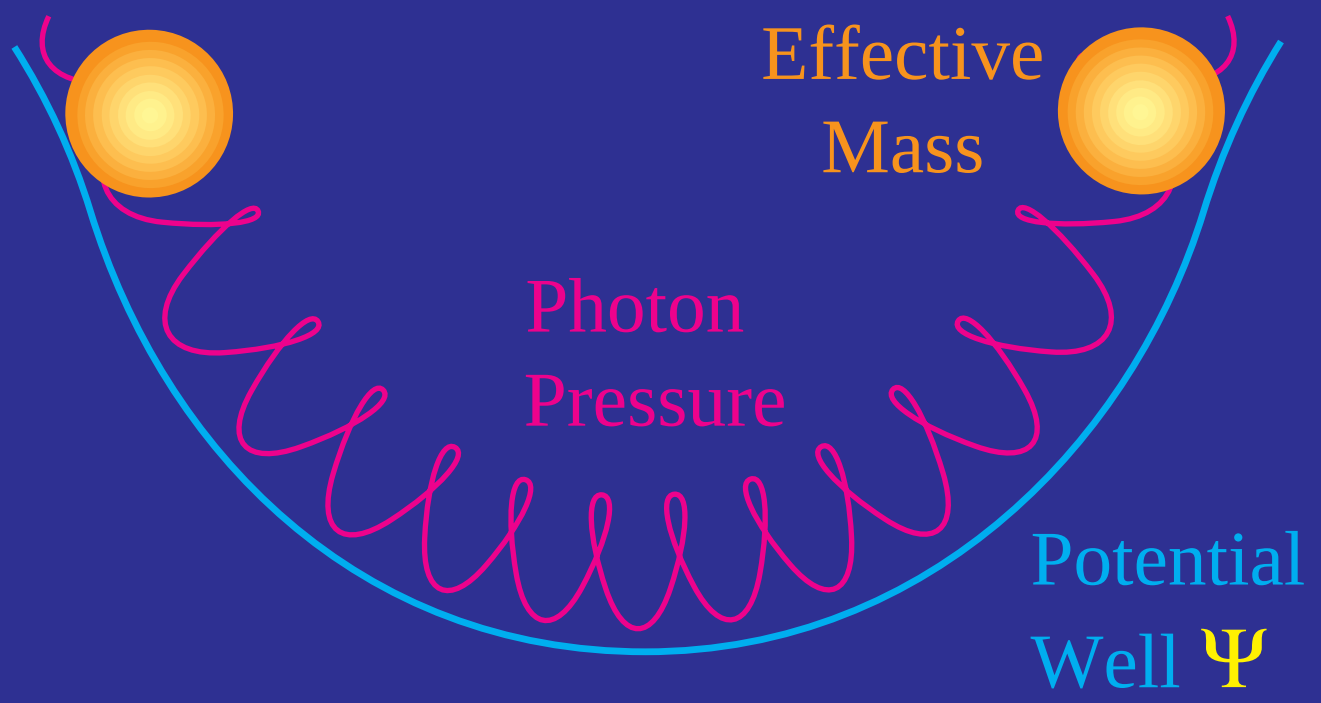


The
Acoustic Peaks

- Acoustic Oscillations
- Peak Positions
- Baryon Drag
- Radiation Driving
- Diffusion Damping

Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations



Peebles & Yu (1970)

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

Acoustic Oscillations

- Photon pressure resists compression in potential wells
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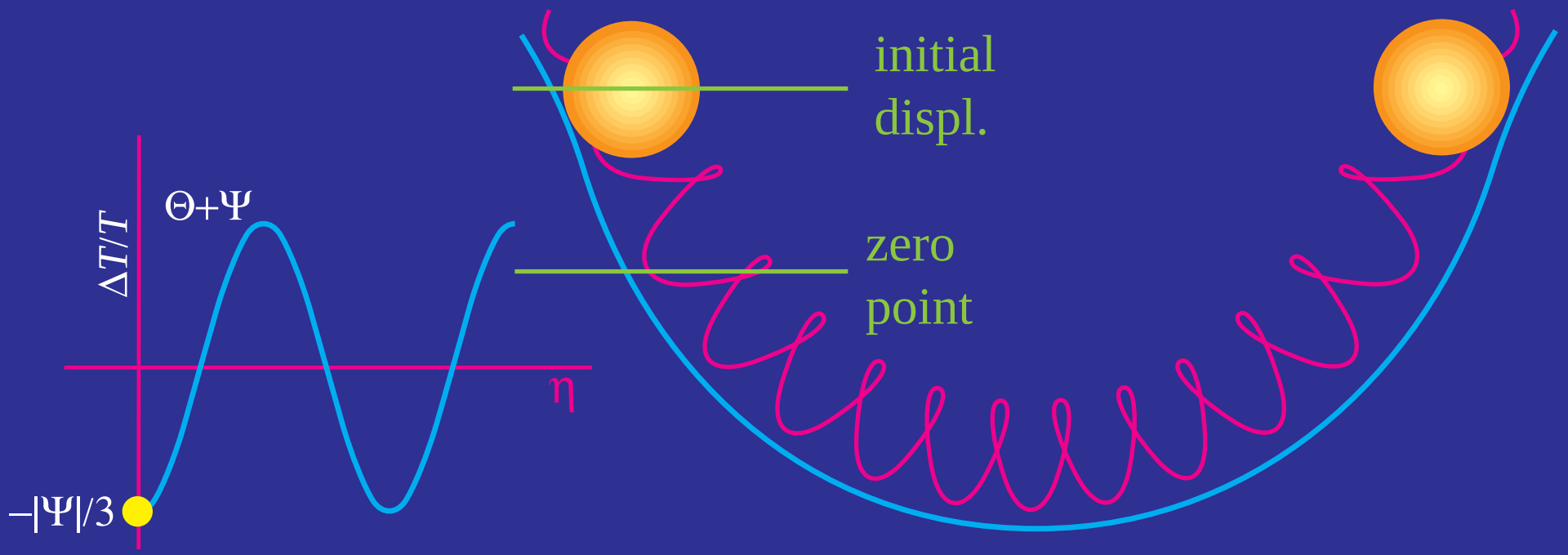
- Gravity displaces zero point
  $\Theta \equiv \delta T/T = -\Psi$

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



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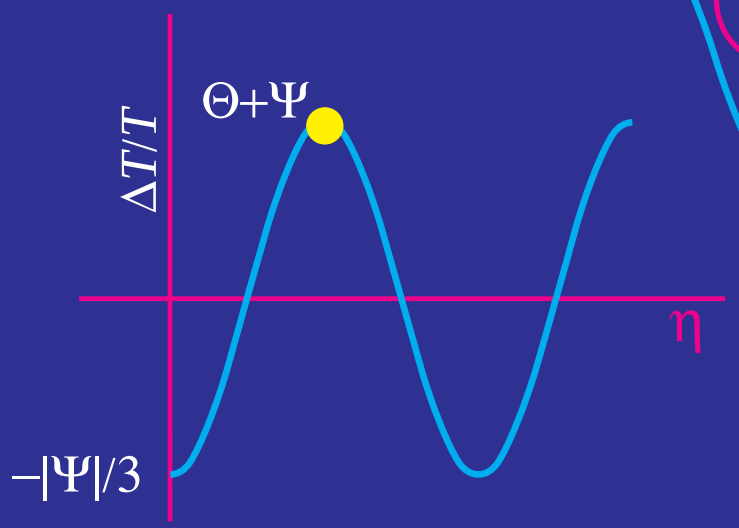

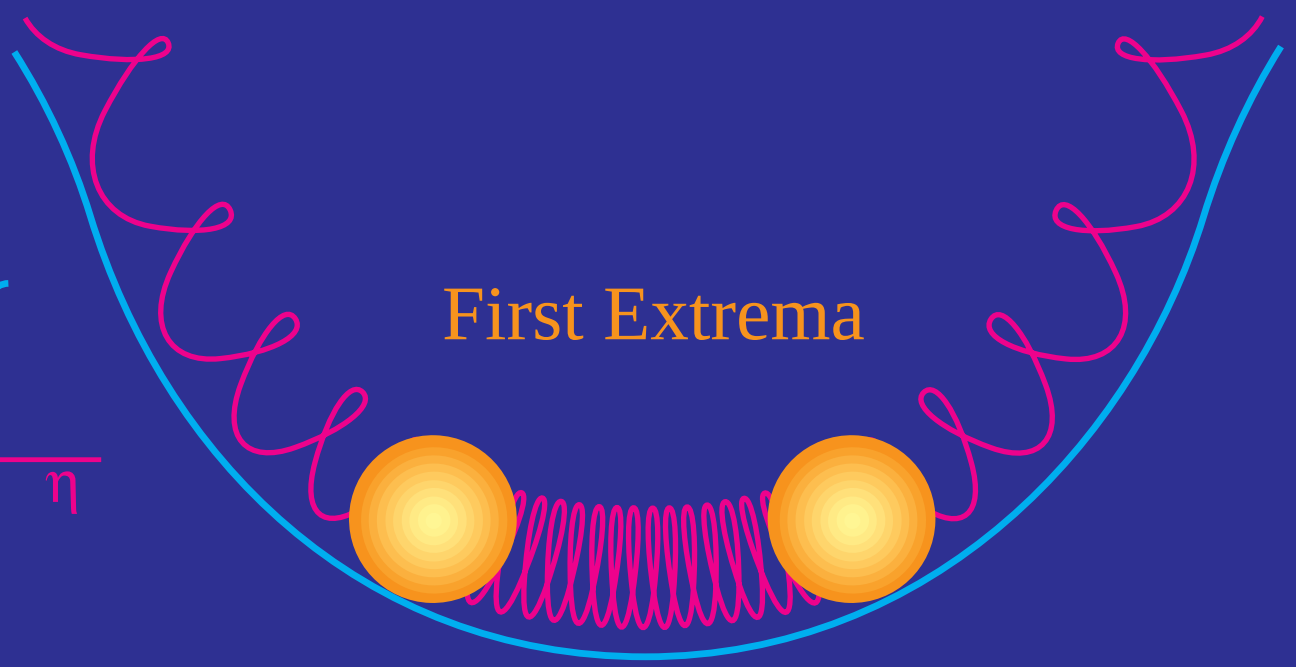

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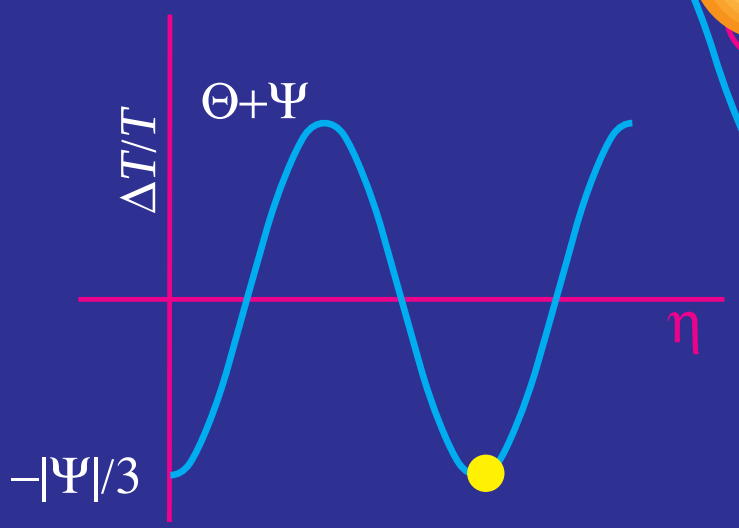

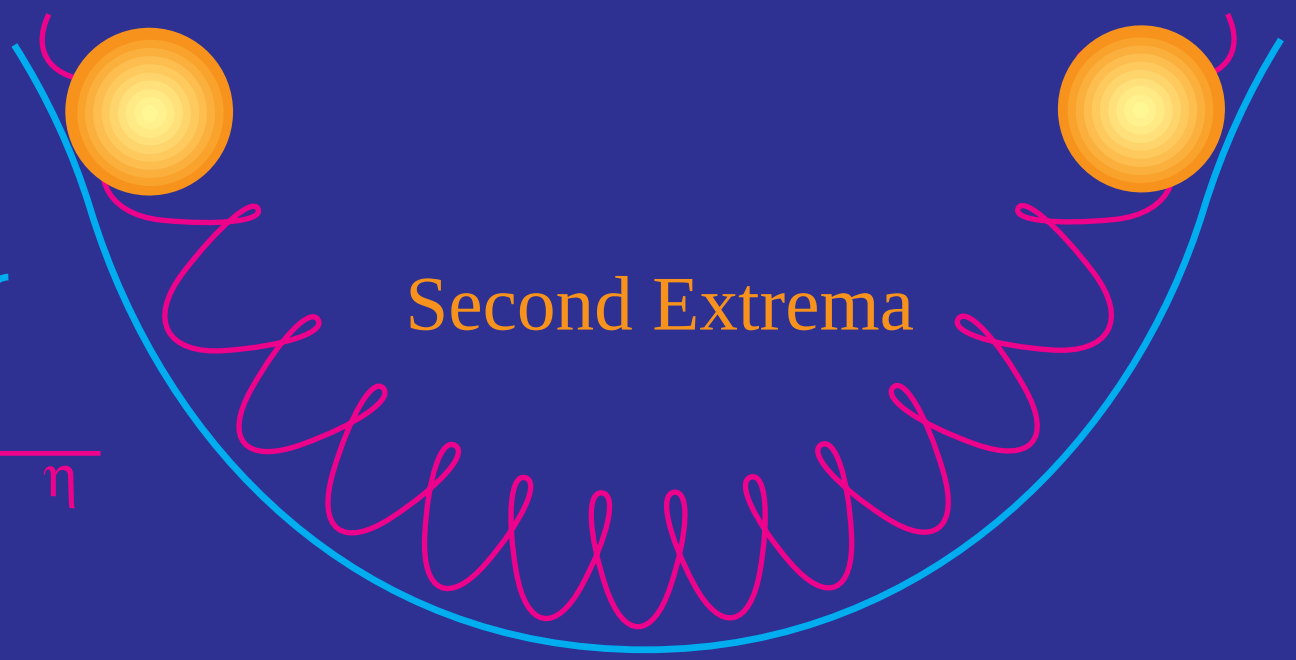

Peebles & Yu (1970)

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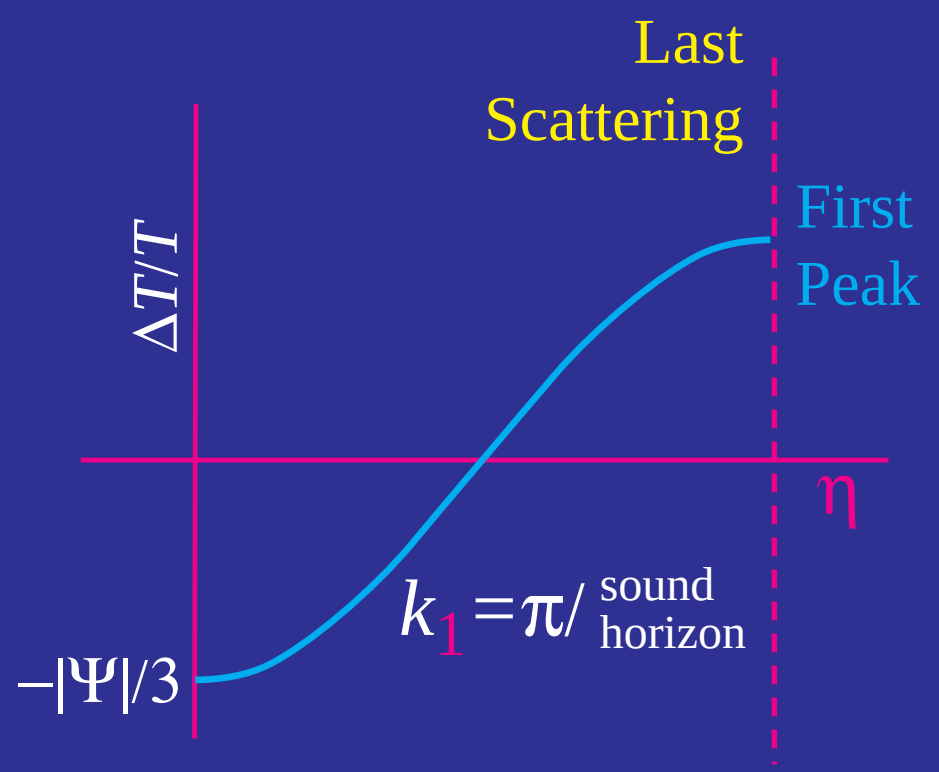
Harmonic Peaks

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



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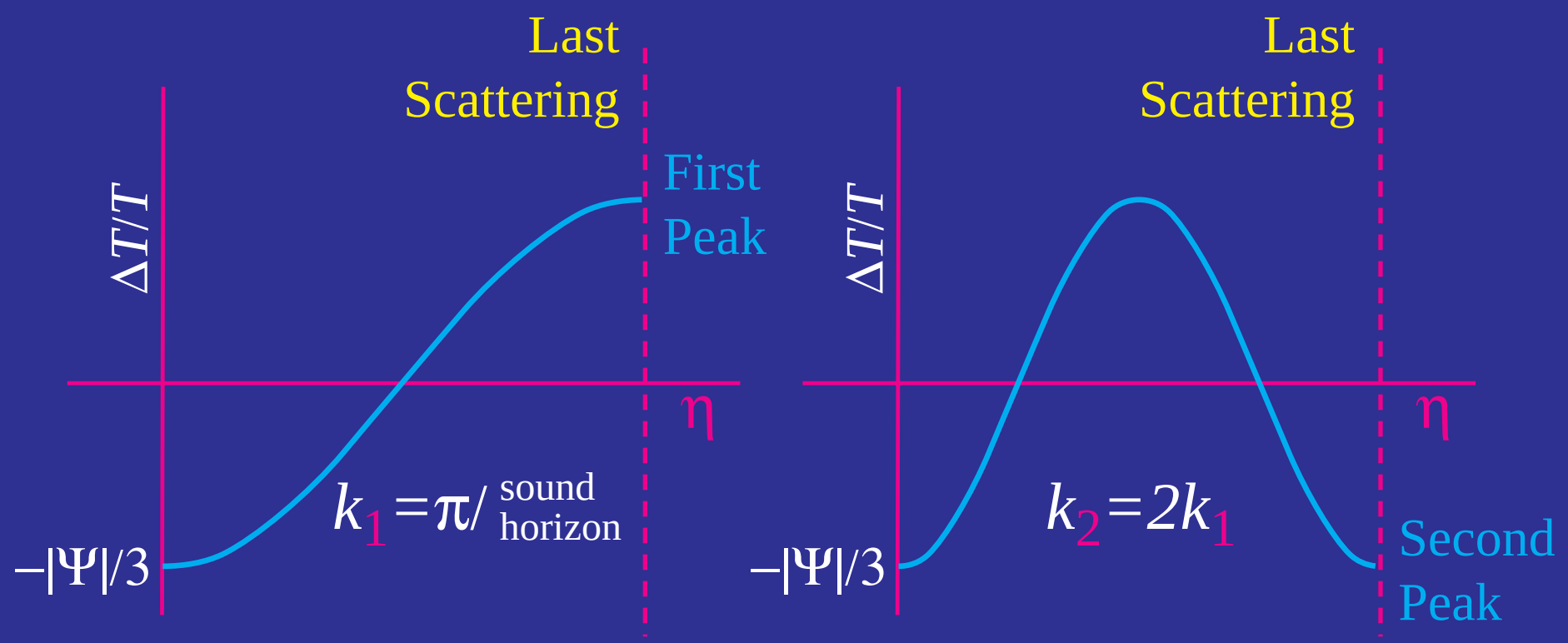
- Frequency $\omega = kc_s$; conformal time η
- Phase $\propto k$; $\phi = \int_0^{\text{last scattering}} d\eta\, \omega = k\, \text{sound horizon}$
- Harmonic series in sound horizon $\phi_n = n\pi \rightarrow k_n = n\pi/\text{sound horizon}$

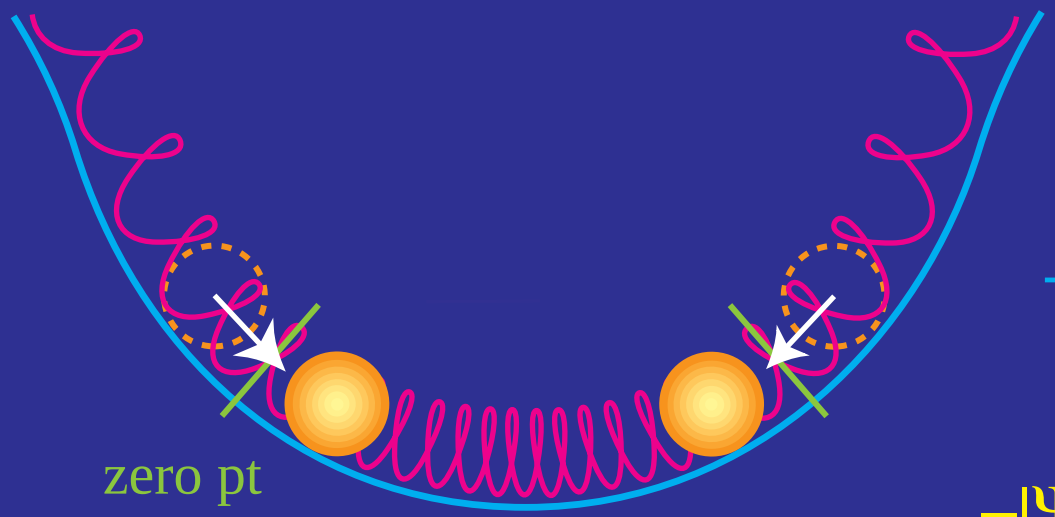


Hu & Sugyama (1995); Hu, Sugiyama & Silk (1997)

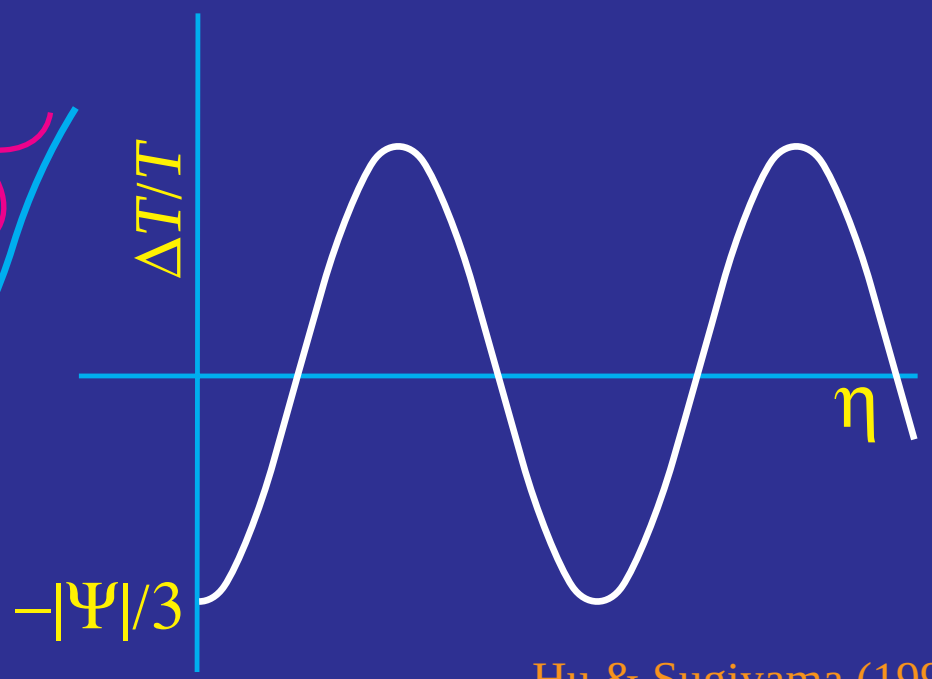
Baryon Drag

- 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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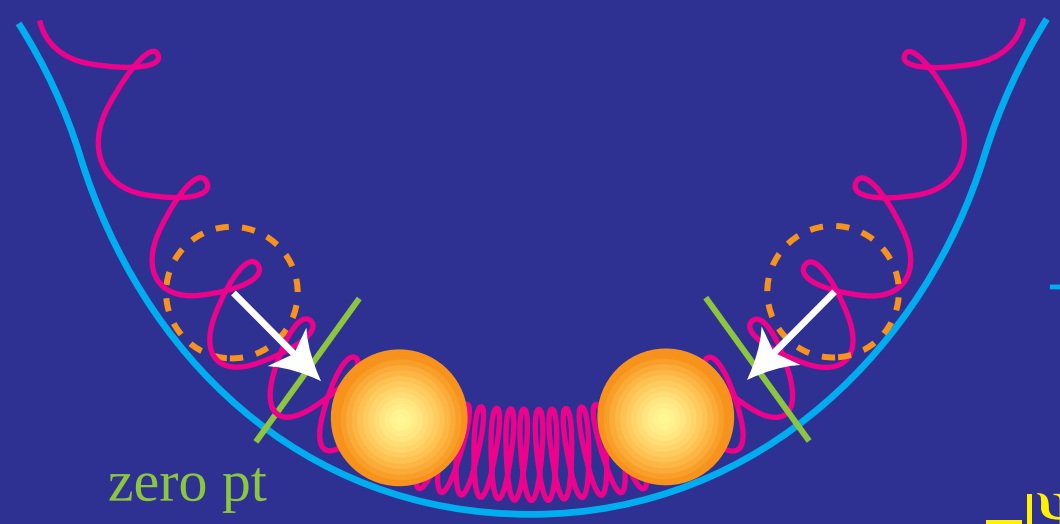
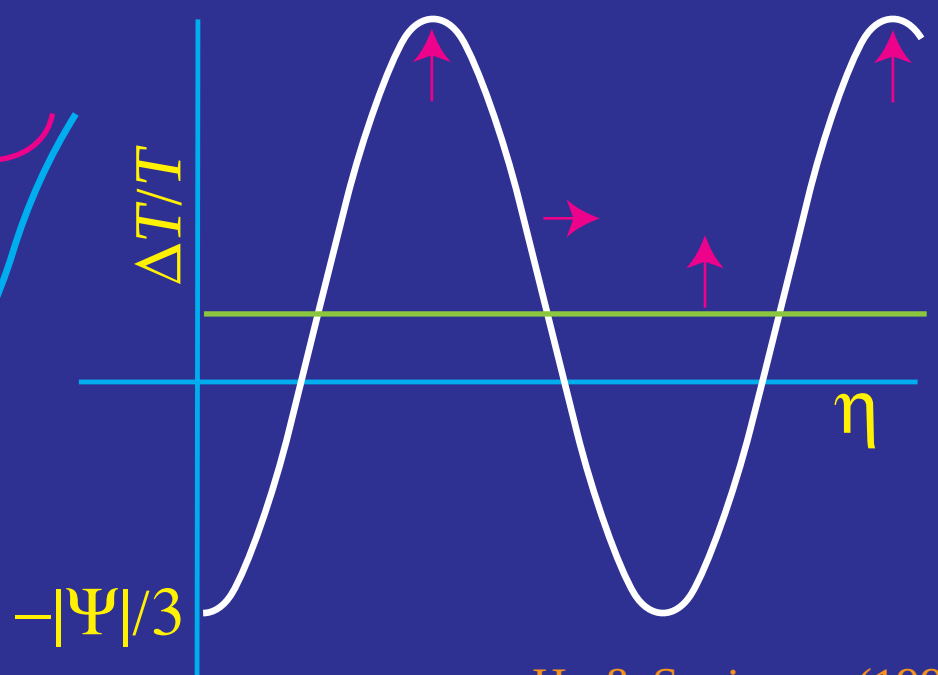
- Baryons drag photons into potential wells $\rightarrow$ zero point $\uparrow$
- Amplitude $\uparrow$
- Frequency $\downarrow$ $(\omega \propto m_{eff}^{-1/2})$

- 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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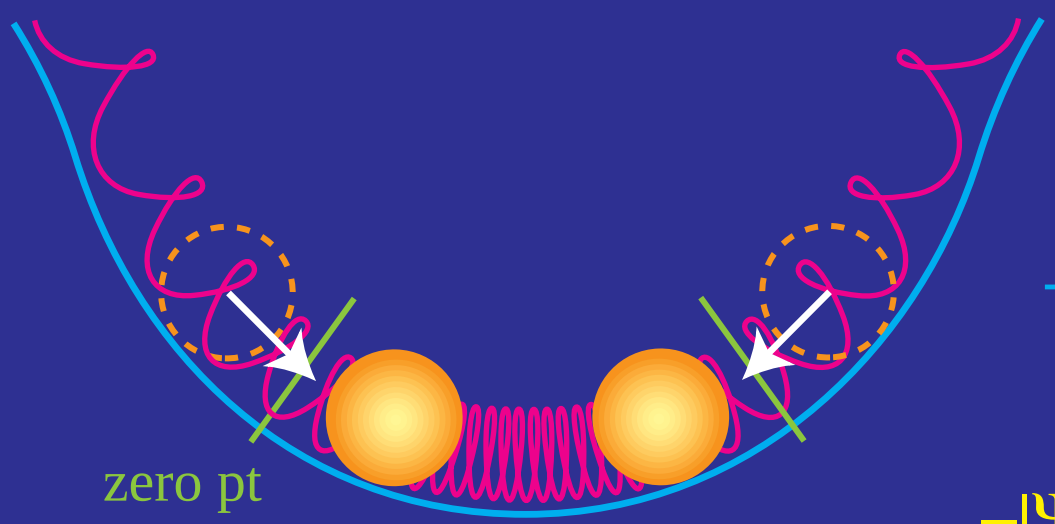
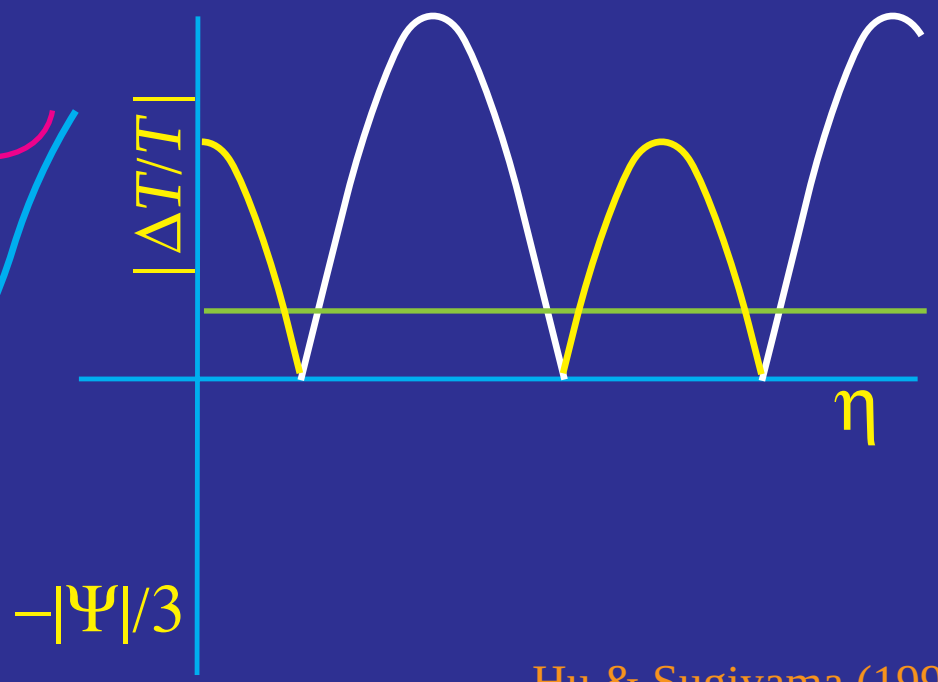
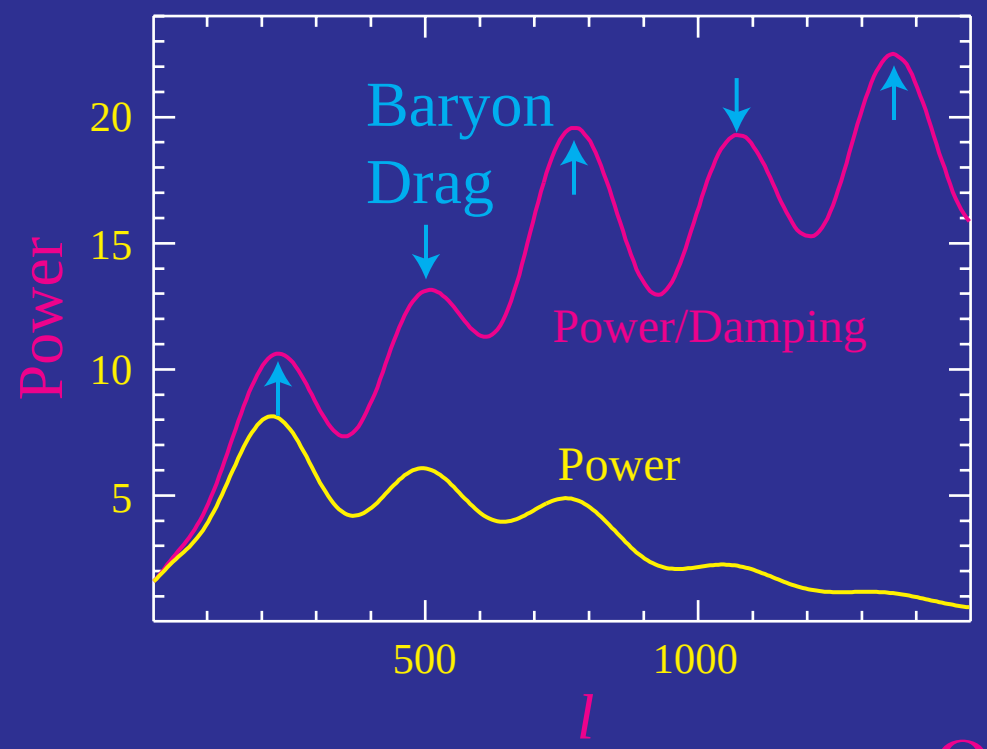


Alternating Peak Heights



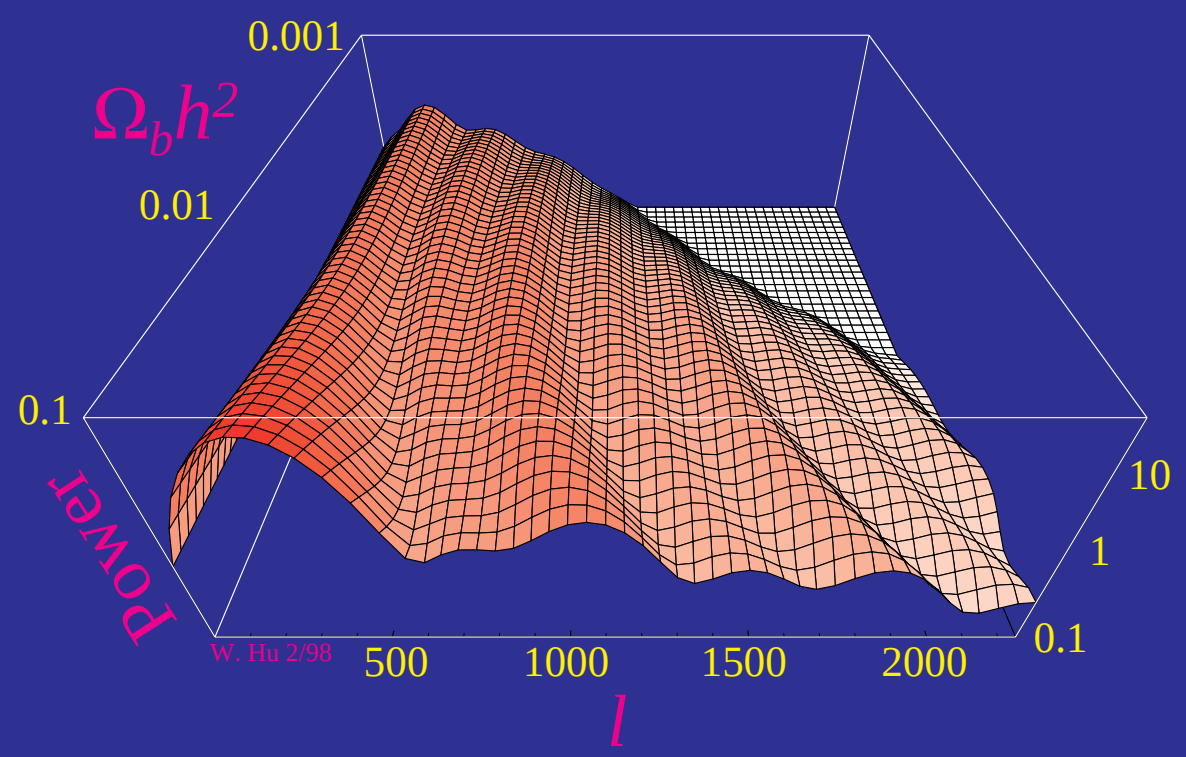
Hu & Sugiyama (1995)

Baryons in the CMB



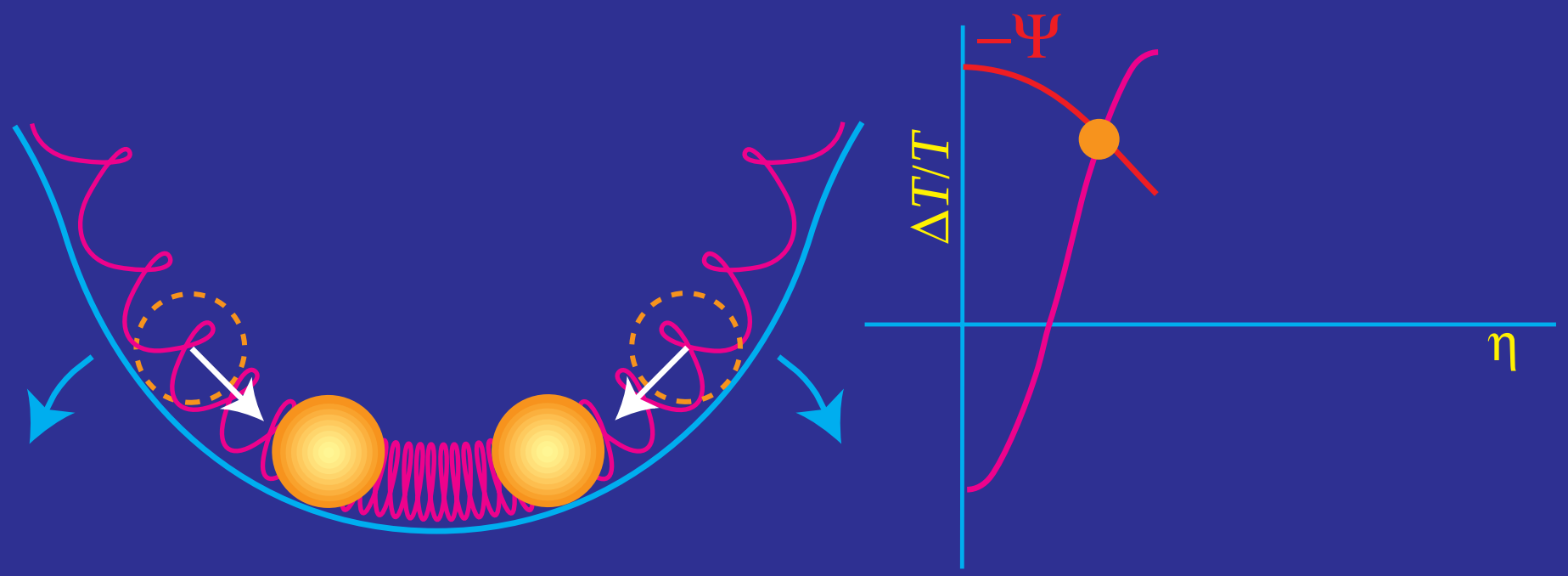
- High odd peaks

- 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



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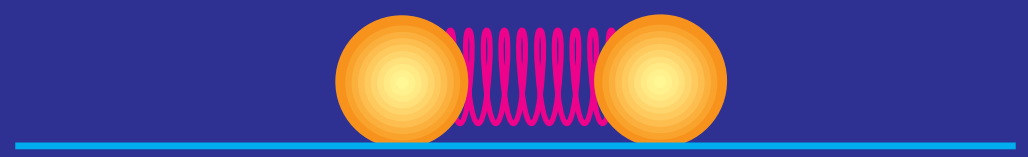
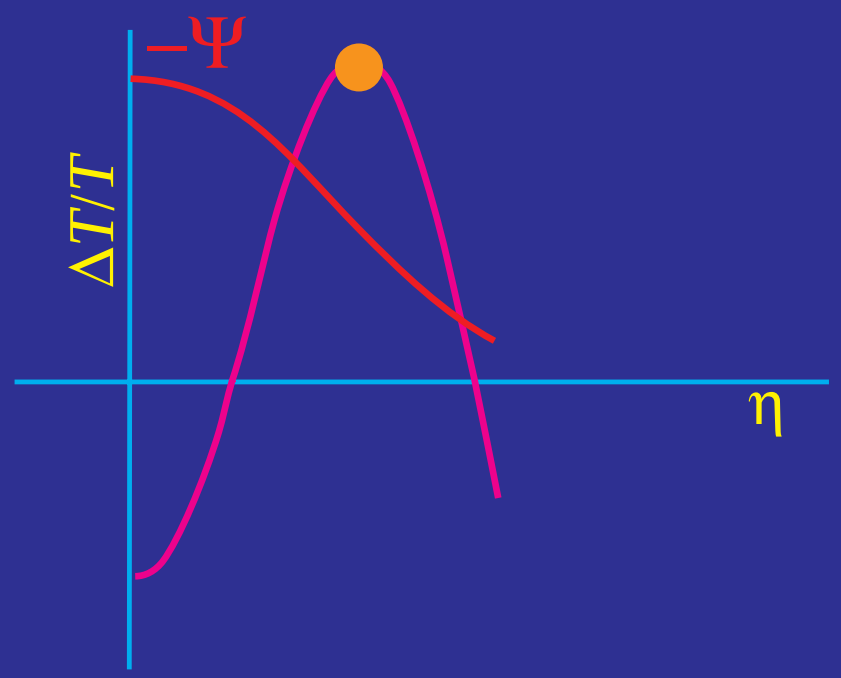
  $-2\Psi + (1/3)\Psi = -(5/3)\Psi \rightarrow$ 5x boost
- Feedback stops at matter domination





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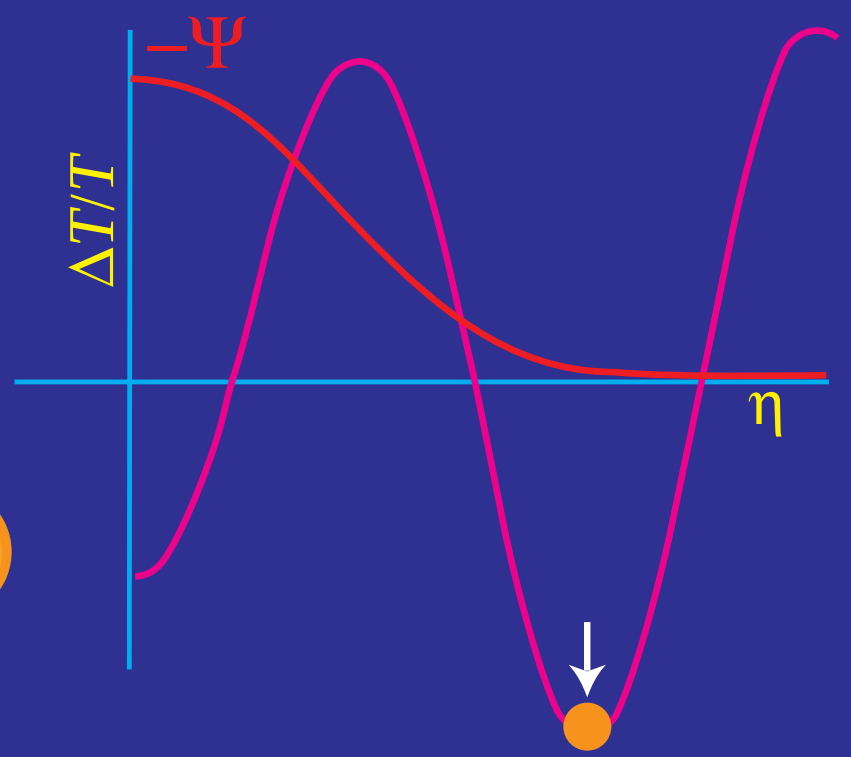
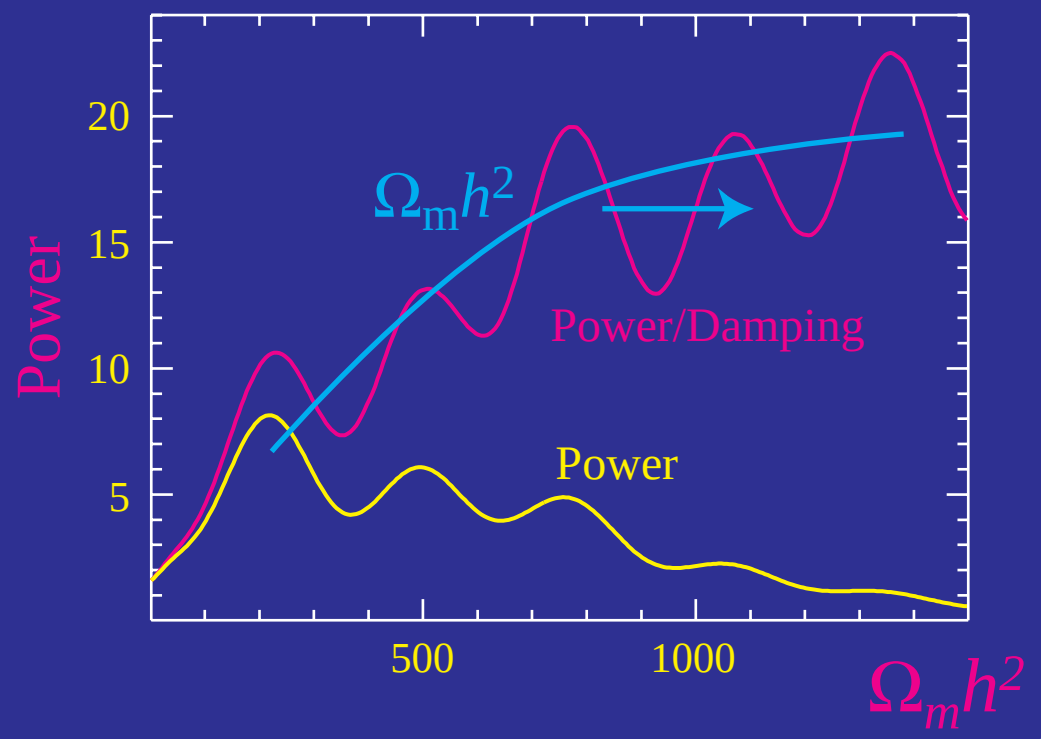
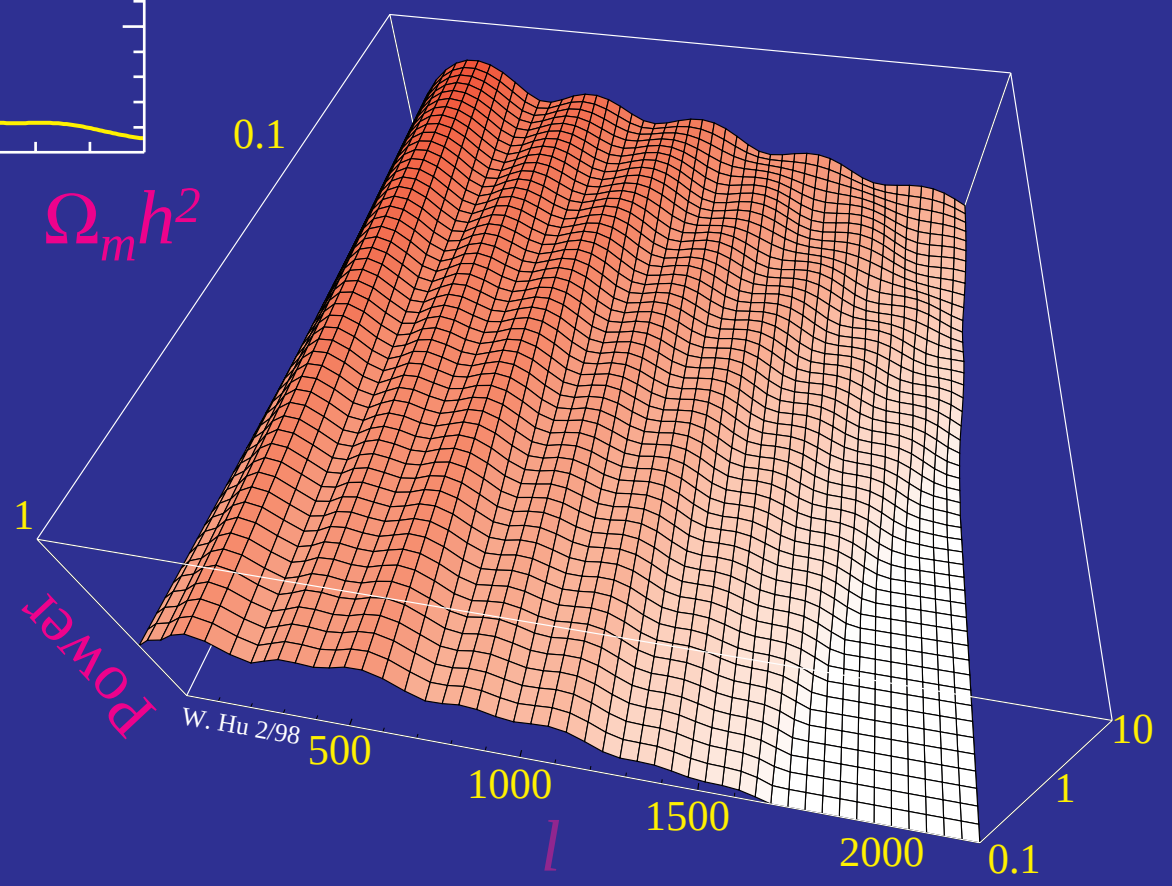


Hu & Sugiyama (1995)

Matter Density in the CMB



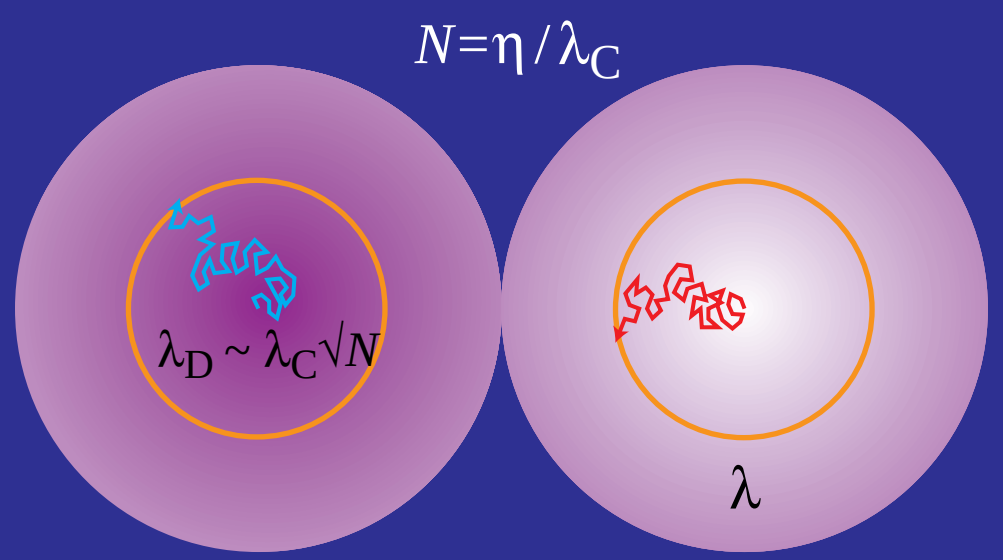
- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history

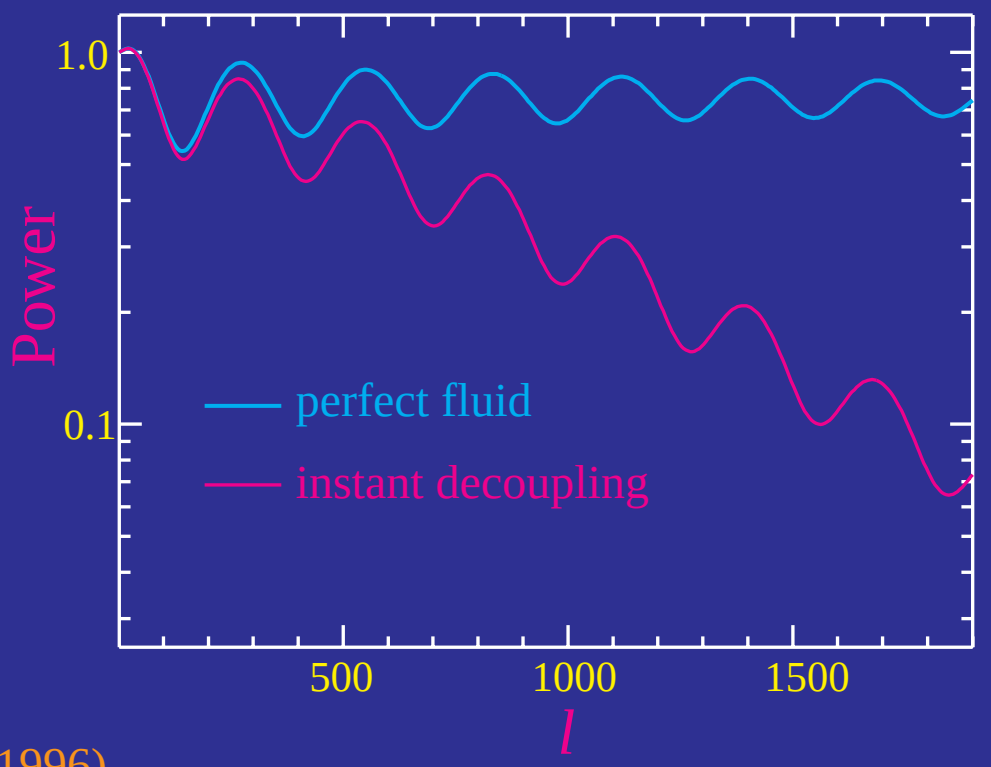


- Measure $\Omega_m h^2$ from peak heights

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 $R>1$

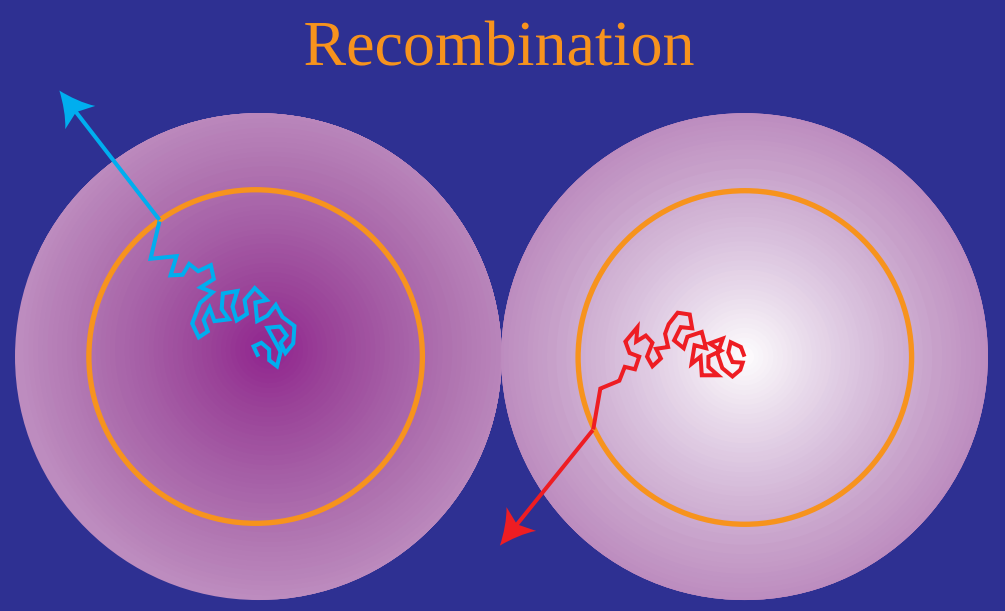


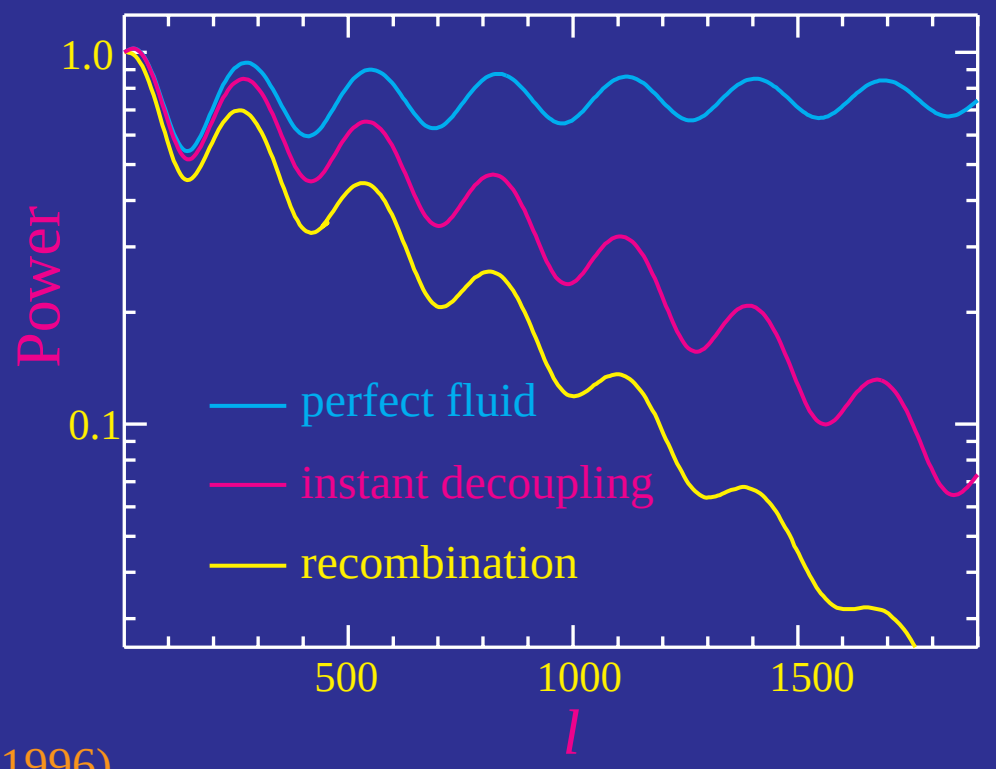


Silk (1968); Hu & Sugiyama (1995); Hu & White (1996)

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)





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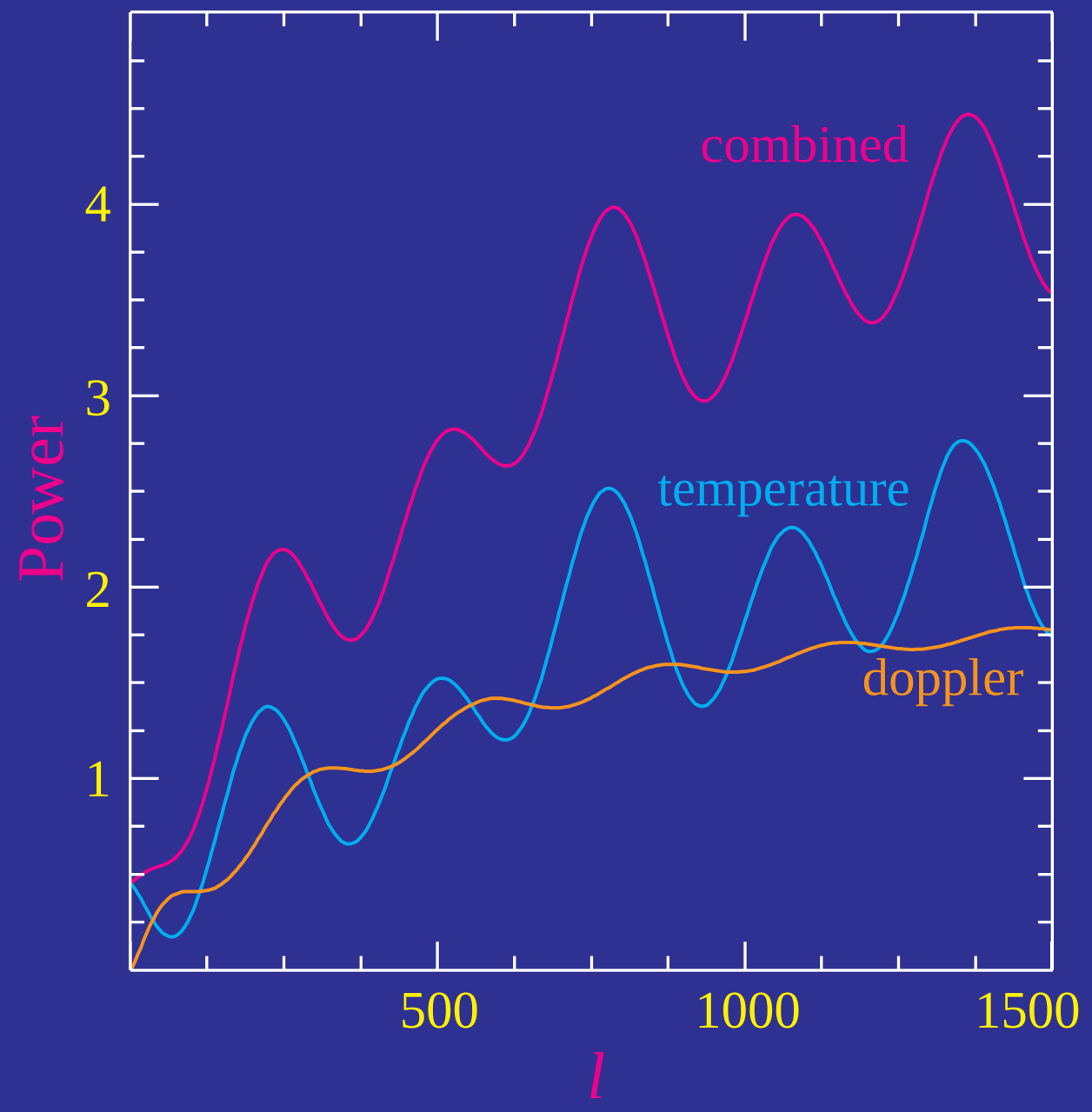
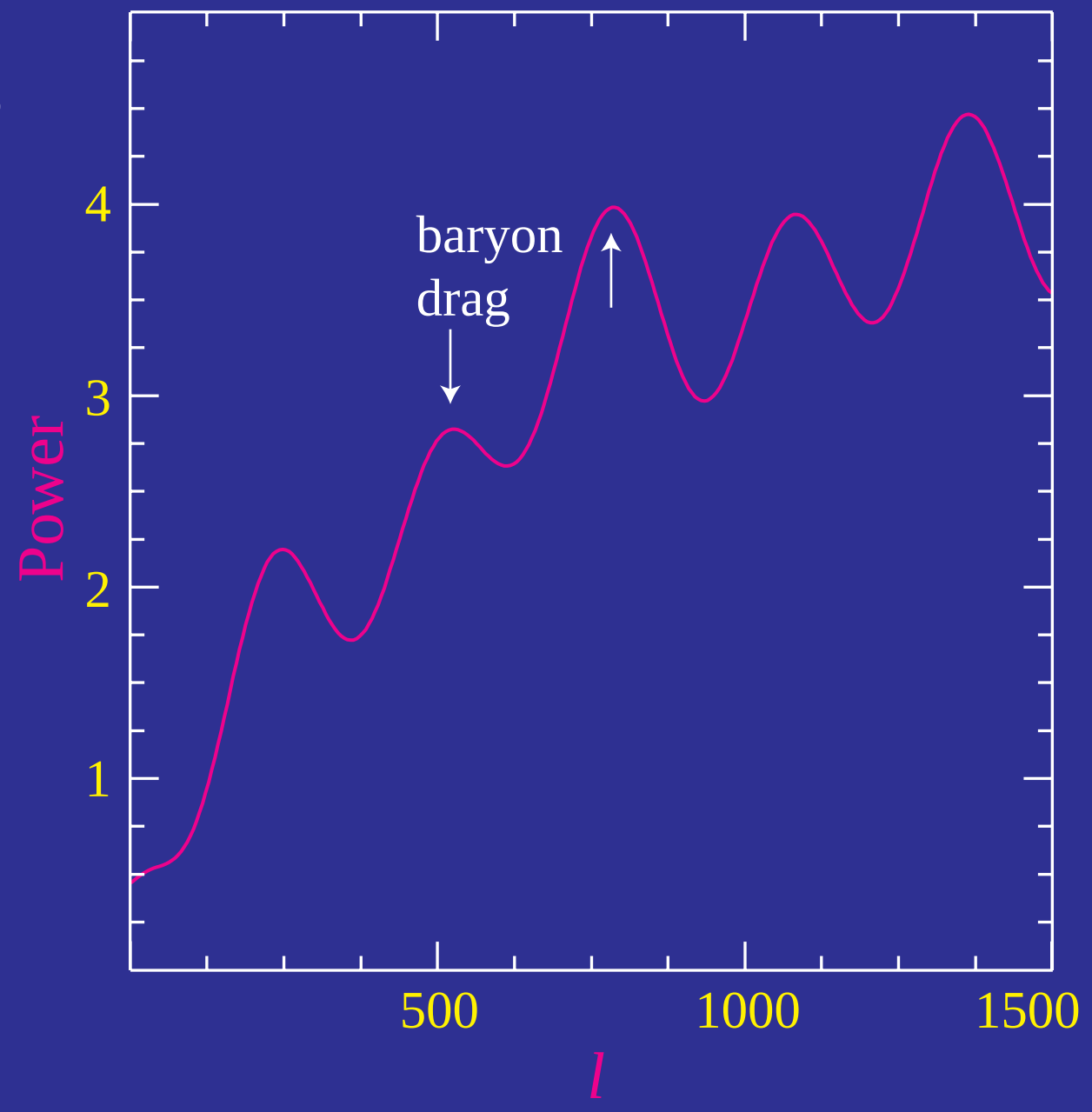
Physical Decomposition & Information



Physical Decomposition & Information

- Fluid + Gravity
  - → alternating peaks
  - → photon-baryon ratio
  - → $\Omega_b h^2$



Physical Decomposition & Information

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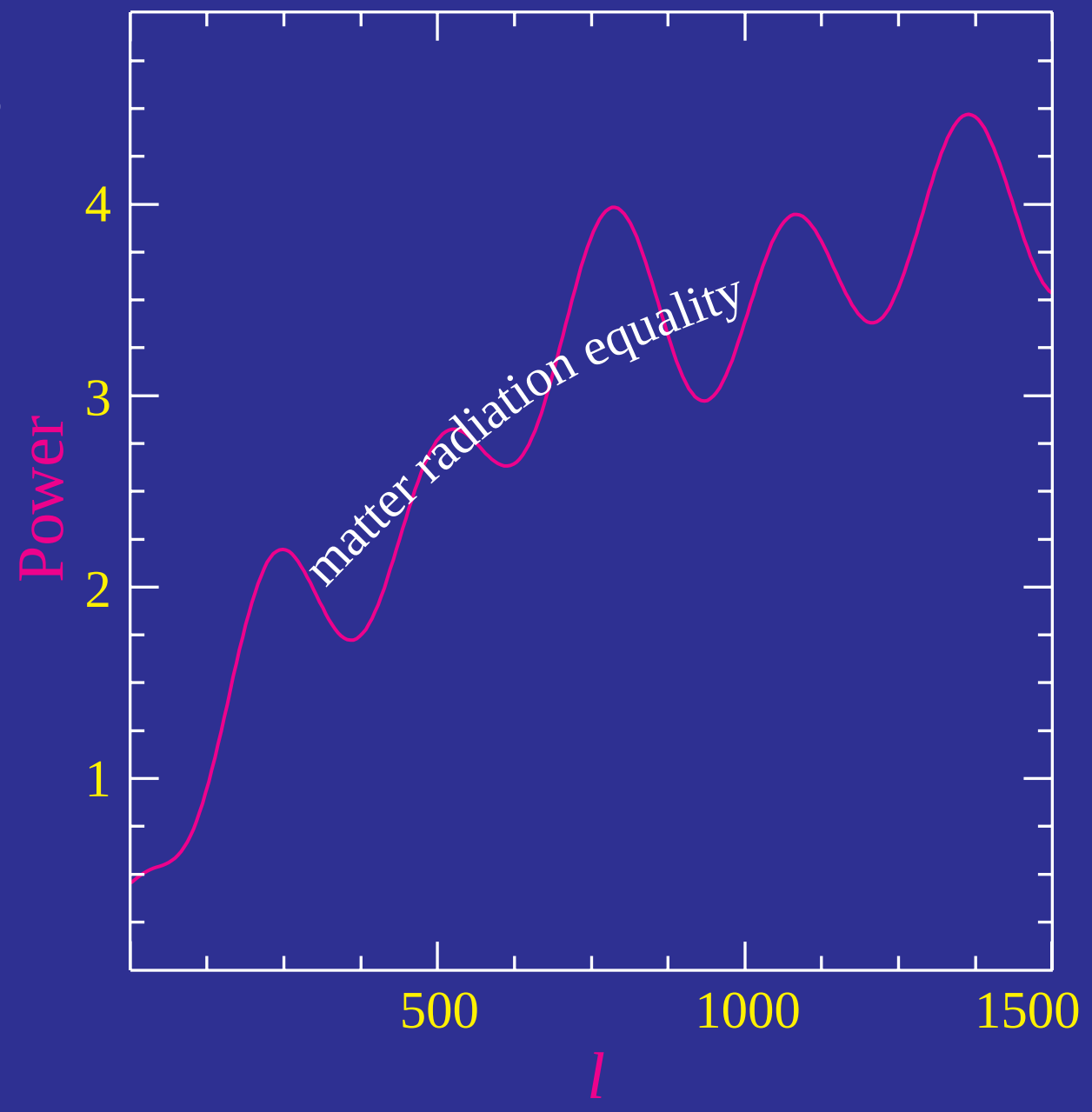
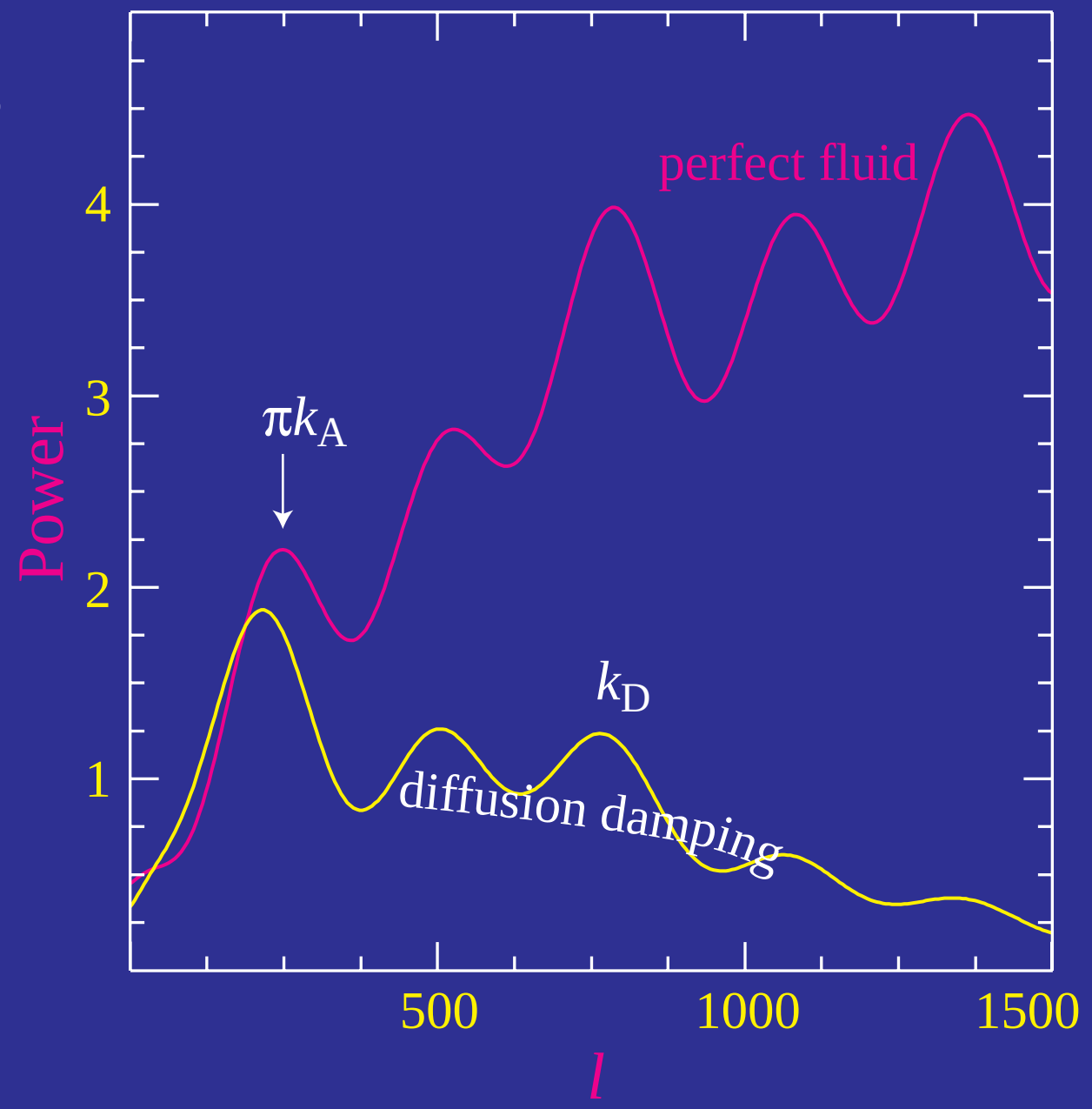
  - → driven oscillations
  - → matter–radiation ratio
  - → $\Omega_m h^2$



Physical Decomposition & Information

- Fluid + Gravity
  - → alternating peaks
  - → photon-baryon ratio
  - → $\Omega_b h^2$
  - → driven oscillations
  - → matter–radiation ratio
  - → $\Omega_m h^2$
- Fluid Rulers
  - → sound horizon
  - → damping scale



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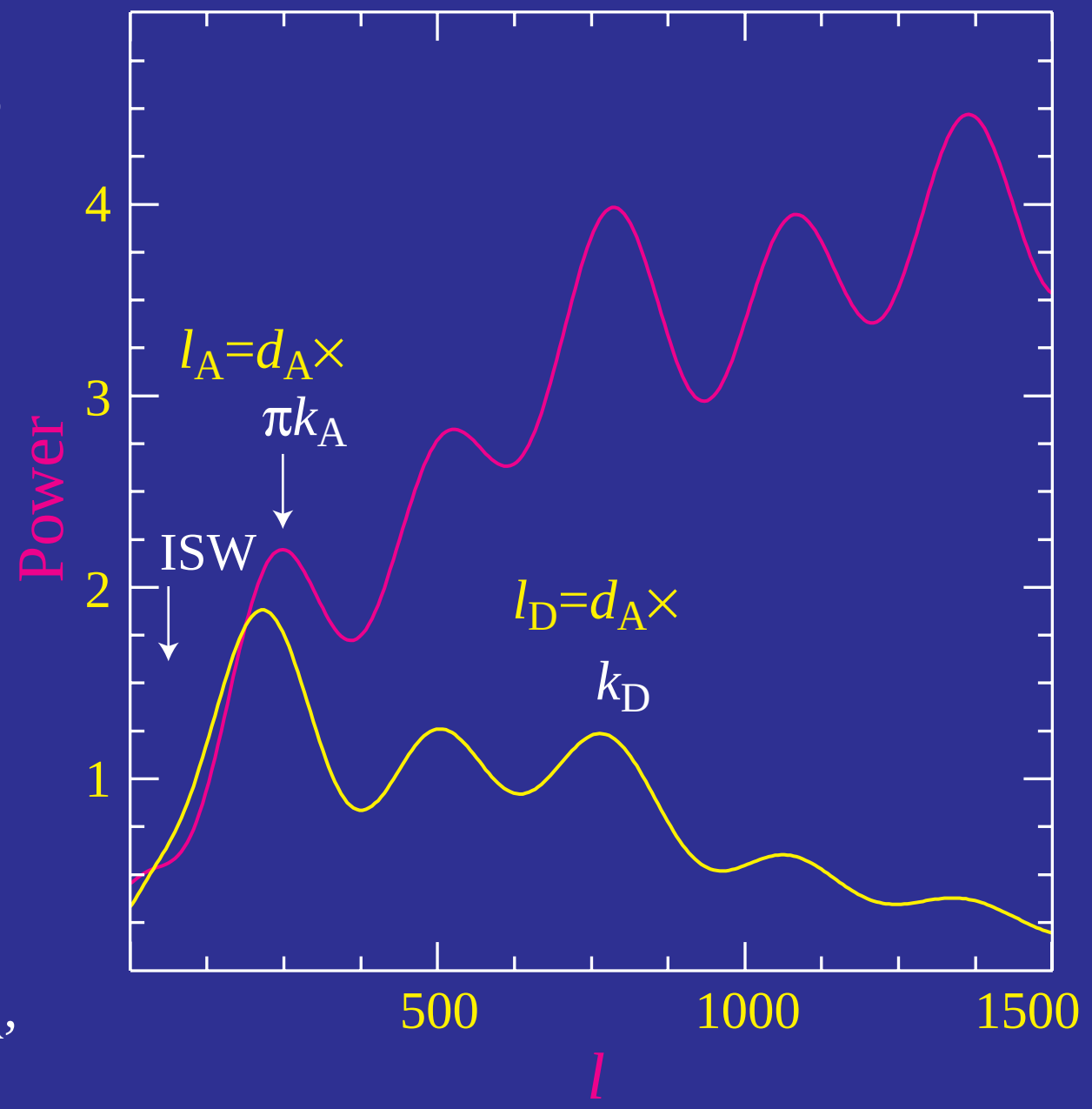
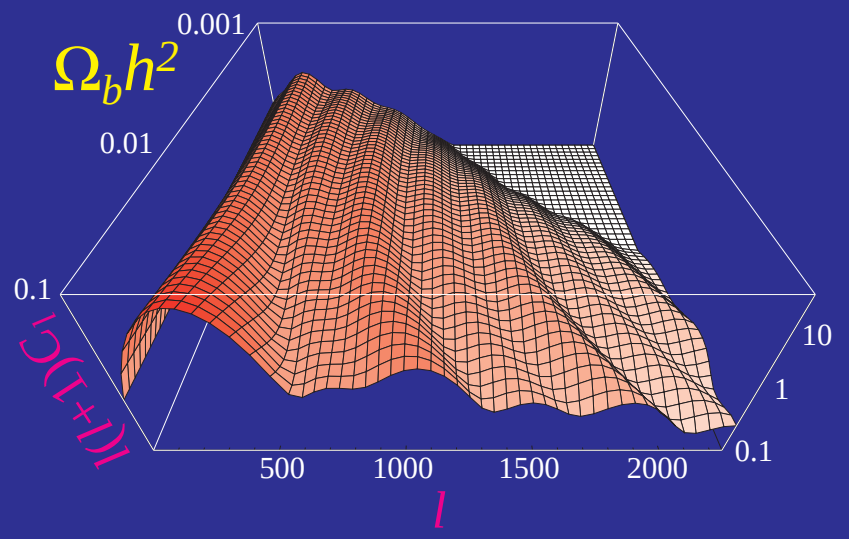
  - → driven oscillations
  - → matter–radiation ratio
  - → $\Omega_m h^2$
- Fluid Rulers
  - → sound horizon
  - → damping scale
- Geometry
  - → angular diameter distance $f(\Omega_\Lambda,\Omega_K)$ + flatness or no Ω_Λ,
  - → Ω_Λ or Ω_K

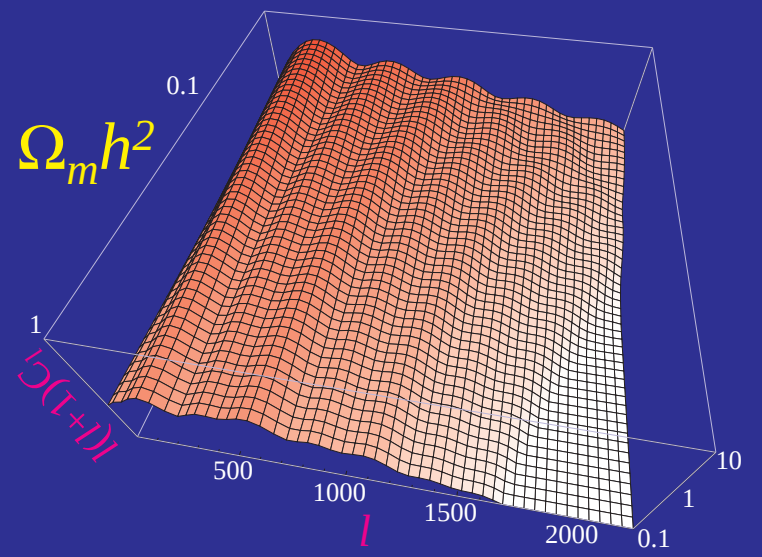


Cosmological Parameters in the CMB

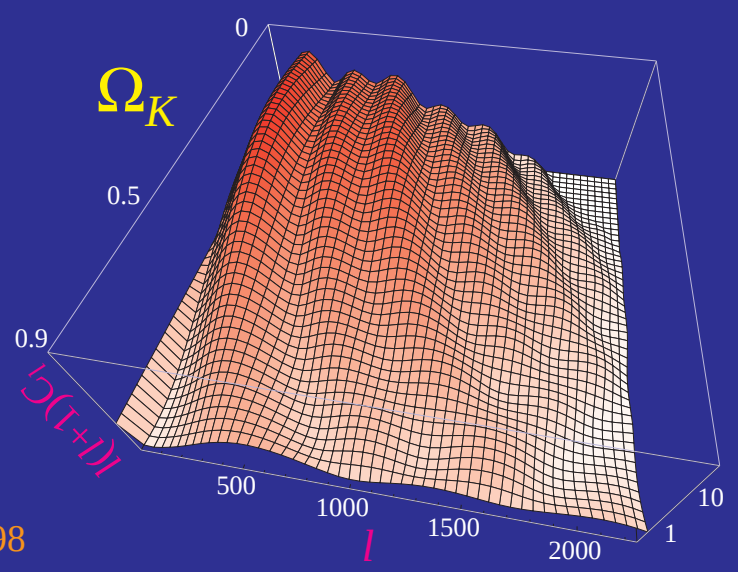
Baryon–Photon Ratio



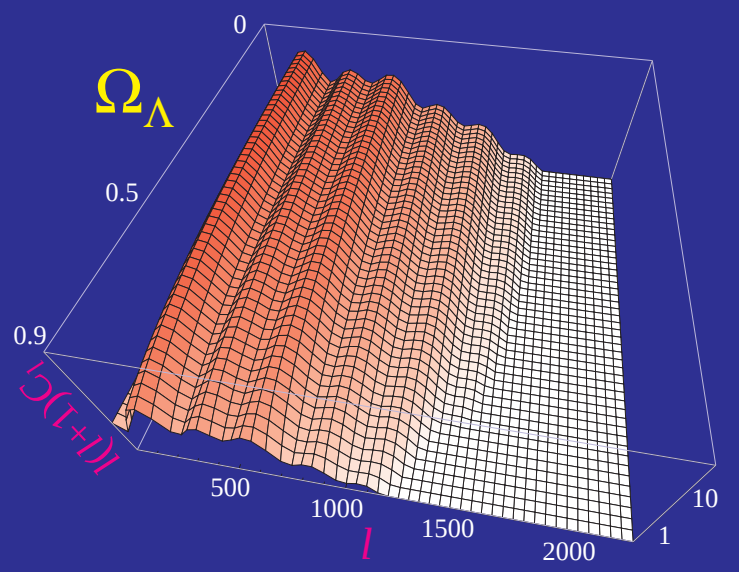
Matter–Radiation Ratio



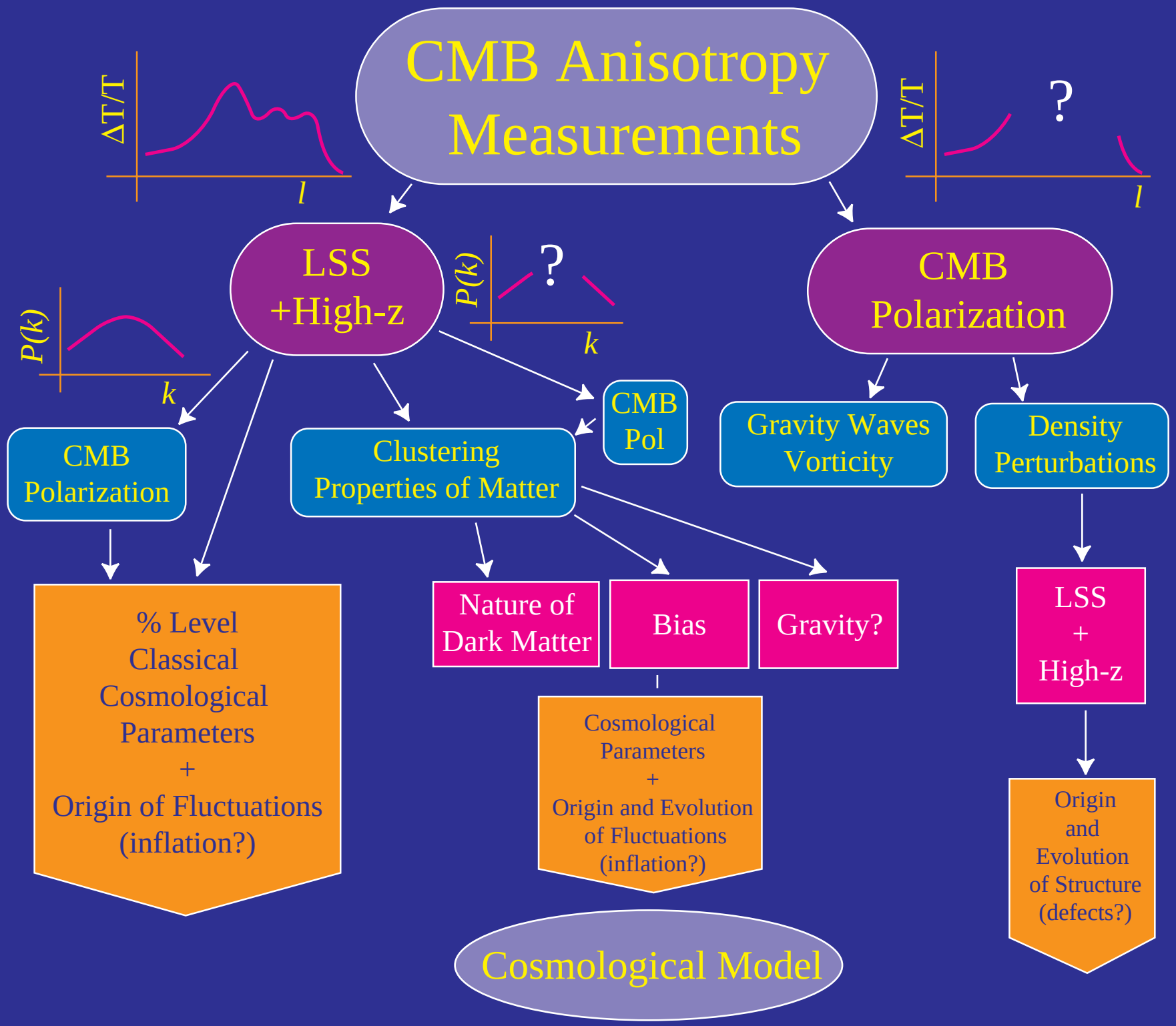
Curvature



Cosmological Constant



W.Hu 2/98

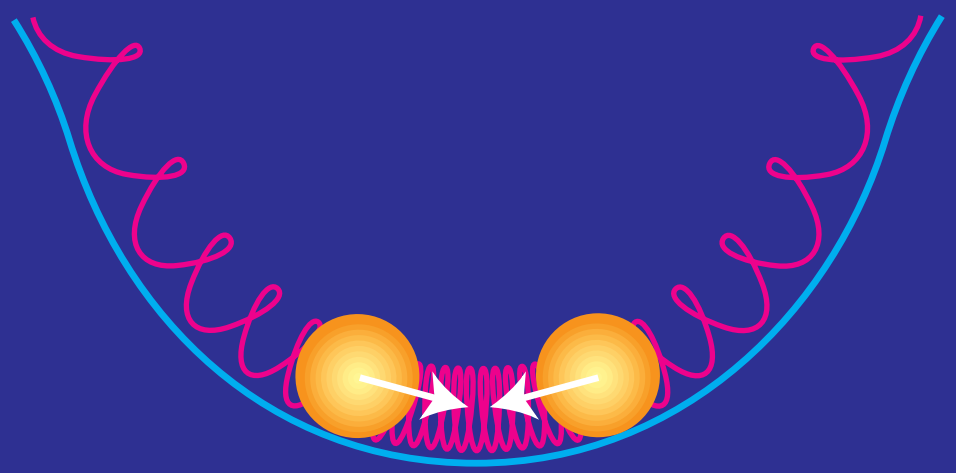

CMB Anisotropy Measurements
ΔT/T
l
ΔT/T
?
l
LSS +High-z
P(k)
?
k
P(k)
k
CMB Polarization
CMB Pol
Clustering Properties of Matter
CMB Polarization
Gravity Waves Vorticity
Density Perturbations
% Level Classical Cosmological Parameters + Origin of Fluctuations (inflation?)
Nature of Dark Matter
Bias
Gravity?
Cosmological Parameters + Origin and Evolution of Fluctuations (inflation?)
LSS + High-z
Origin and Evolution of Structure (defects?)
Cosmological Model

Part II:
Complementarity: Achieving Precision through Large Scale Structure

- Acoustic oscillations in the matter power spectrum
- Isolating classical cosmological parameters
- Weak lensing by large scale structure
- Measuring the growth rate of perturbations

Acoustic Peaks in the Matter

- Baryon density & velocity oscillates with CMB
- Baryons decouple at $\tau / R \sim 1$, the end of Compton drag epoch
- Decoupling: $\delta_b(\text{drag}) \sim V_b(\text{drag})$, but not frozen



End of Drag Epoch

Hu & Sugiyama (1996)

Acoustic Peaks in the Matter

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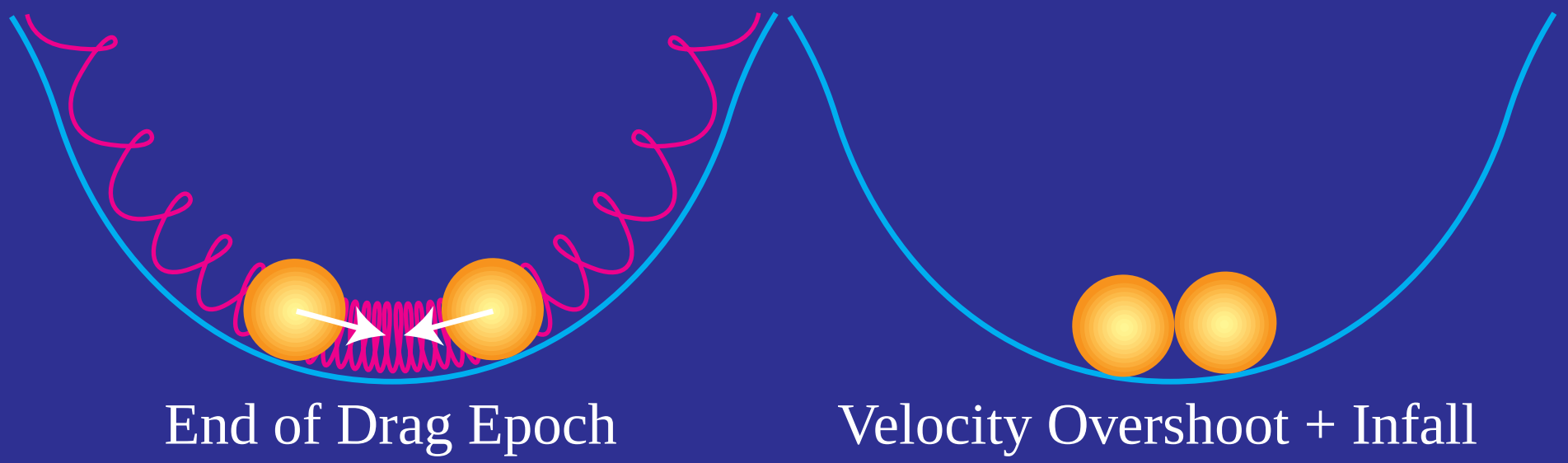
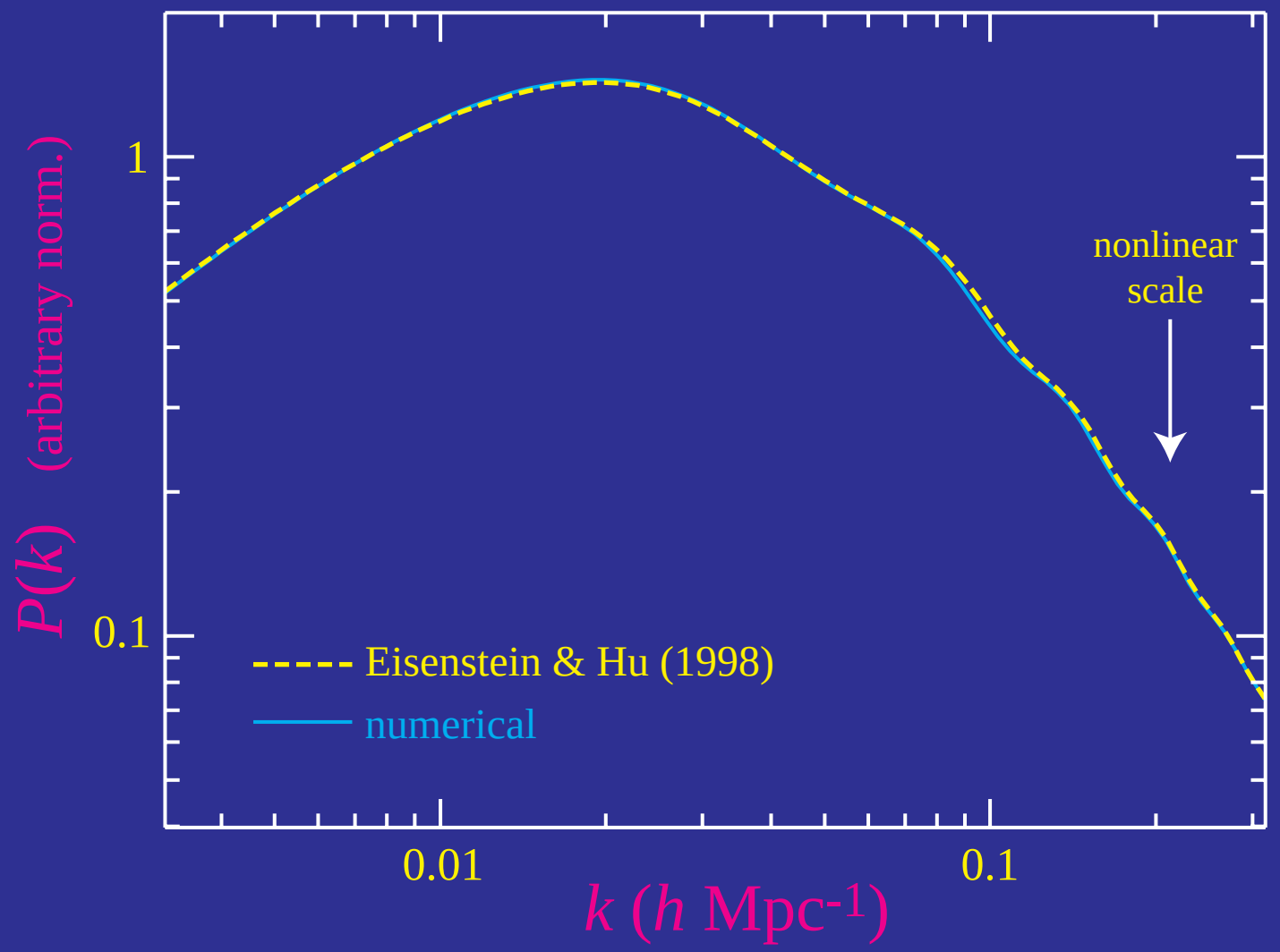
- Decoupling: $\delta_b(\text{drag}) \sim V_b(\text{drag})$, but not frozen
- Continuity: $\dot{\delta}_b = -kV_b$
- Velocity Overshoot Dominates: $\delta_b \sim V_b(\text{drag})\, k\eta \gg \delta_b(\text{drag})$
- Oscillations $\pi/2$ out of phase with CMB
- Infall into potential wells (DC component)



Hu & Sugiyama (1996)

Features in the Power Spectrum

- Features in the linear power spectrum
- Break at sound horizon
- Oscillations at small scales; washed out by nonlinearities



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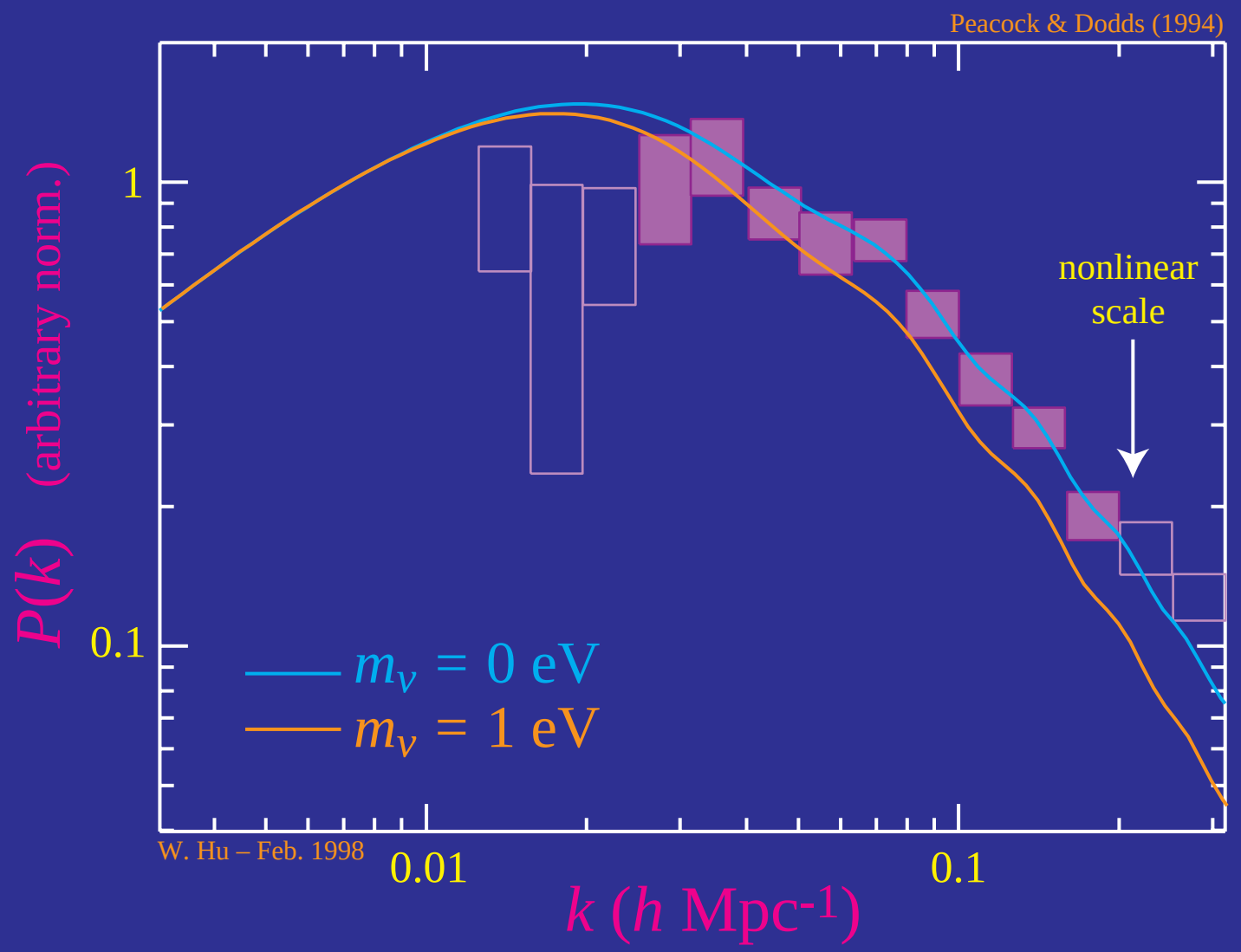

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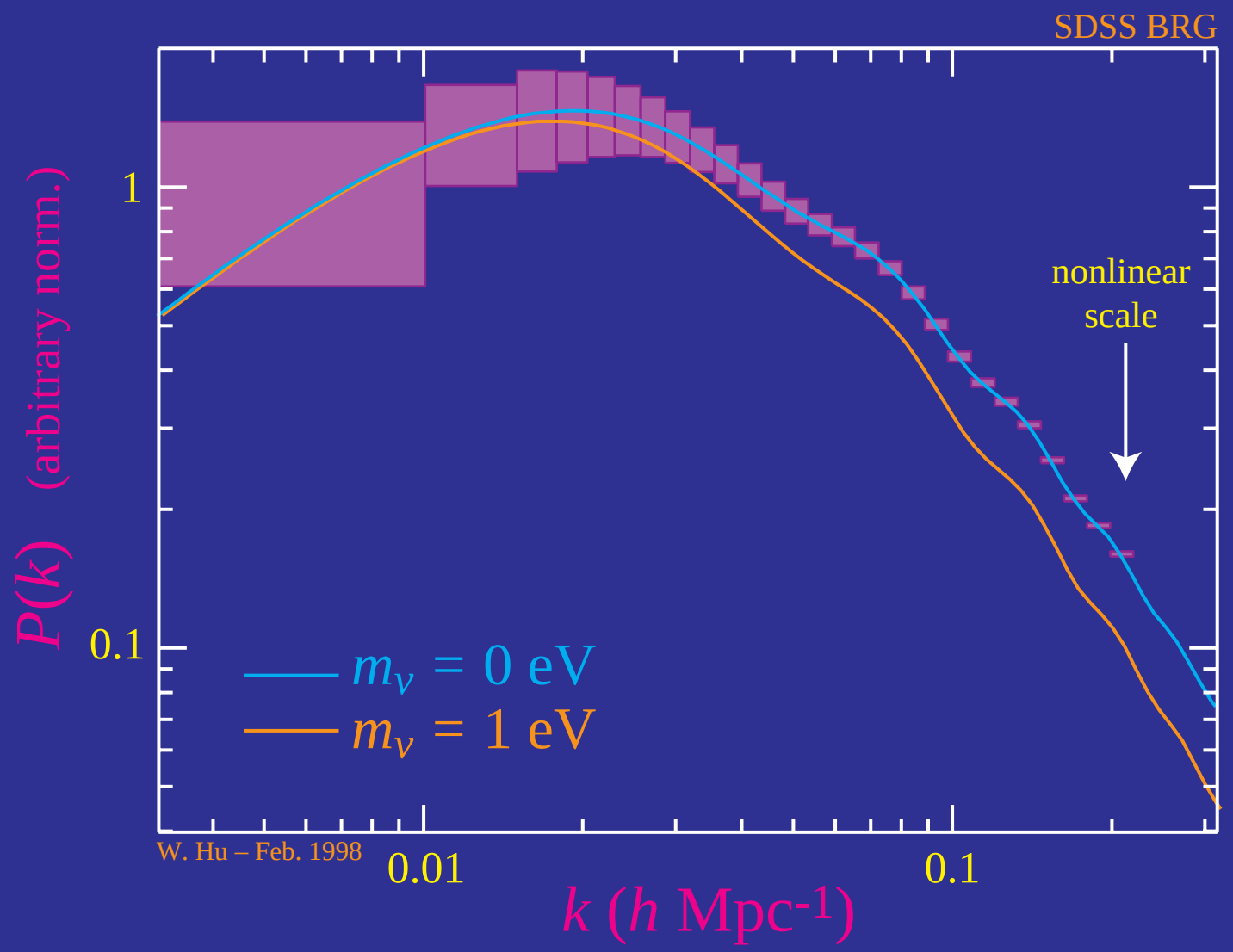
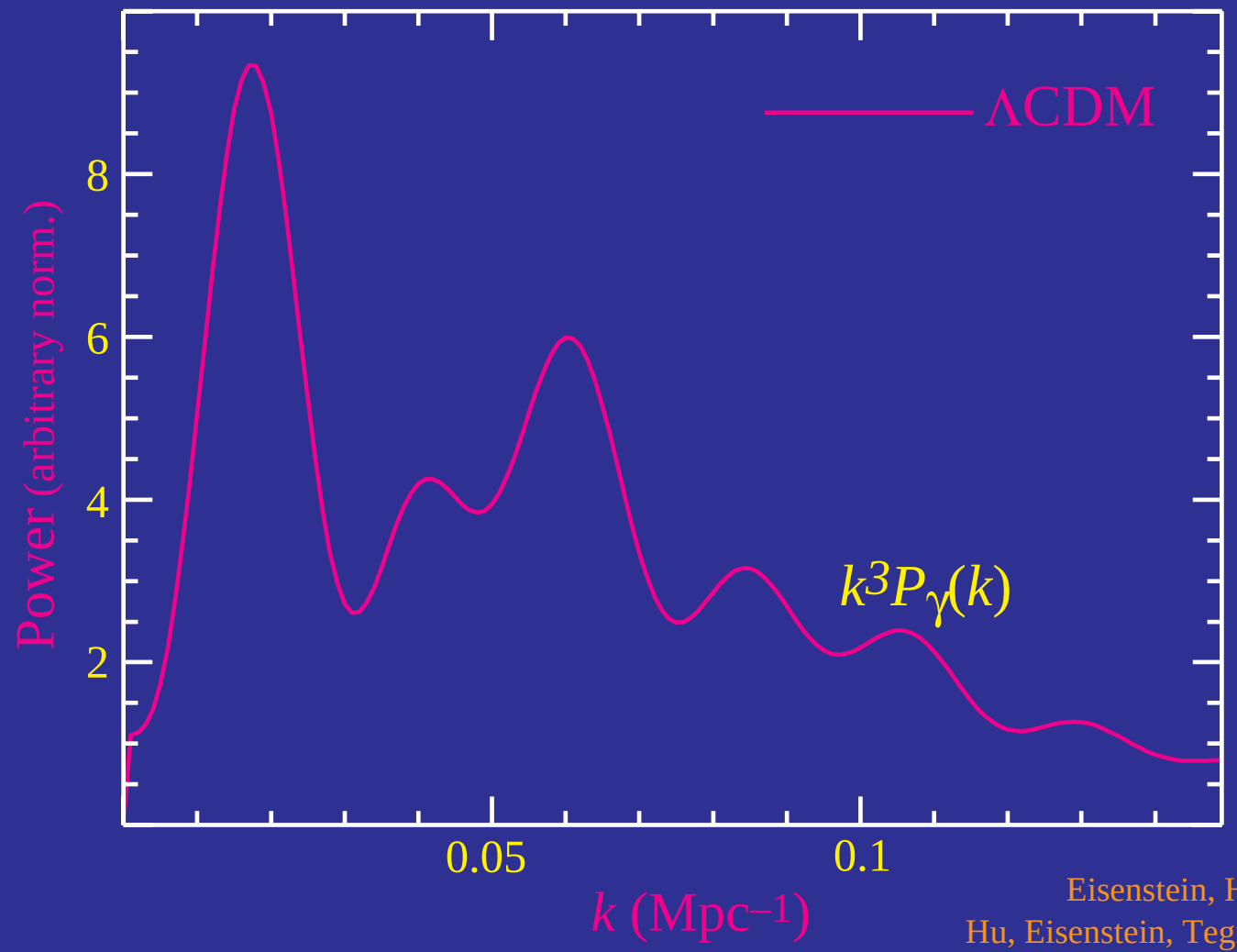


Combining Features in LSS + CMB

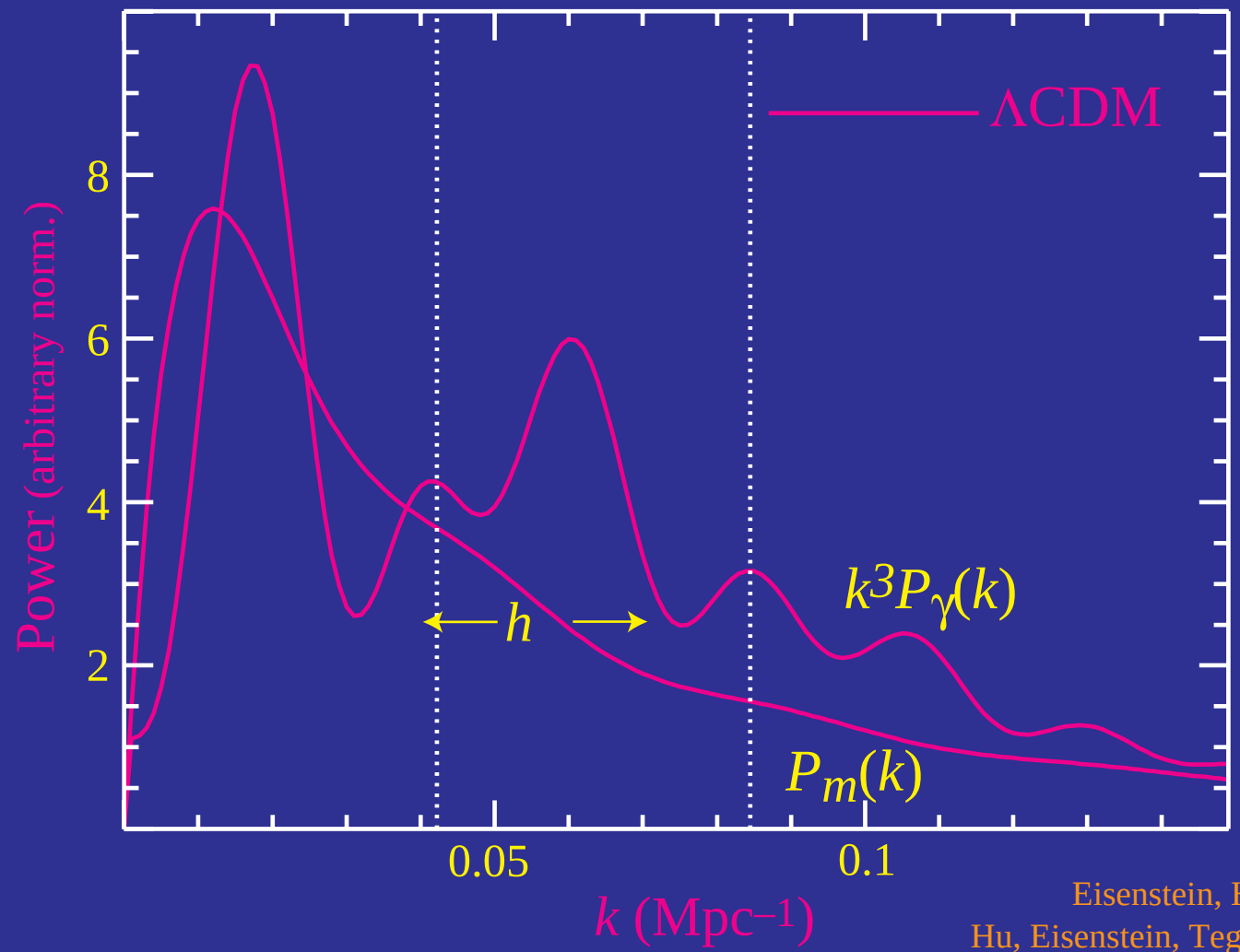
- Consistency check on thermal history and photon–baryon ratio
- Infer physical scale l_{peak}(CMB) $\rightarrow$ k_{peak}(LSS) in Mpc^{-1}



Eisenstein, Hu & Tegmark (1998)
Hu, Eisenstein, Tegmark & White (1998)

Combining Features in LSS + CMB

- Consistency check on thermal history and photon–baryon ratio
- Infer physical scale $l_{\mathrm{peak}}(\mathrm{CMB}) \rightarrow k_{\mathrm{peak}}(\mathrm{LSS})$ in Mpc^{-1}
- Measure in redshift survey $k_{\mathrm{peak}}(\mathrm{LSS})$ in $h\ \mathrm{Mpc}^{-1} \rightarrow h$



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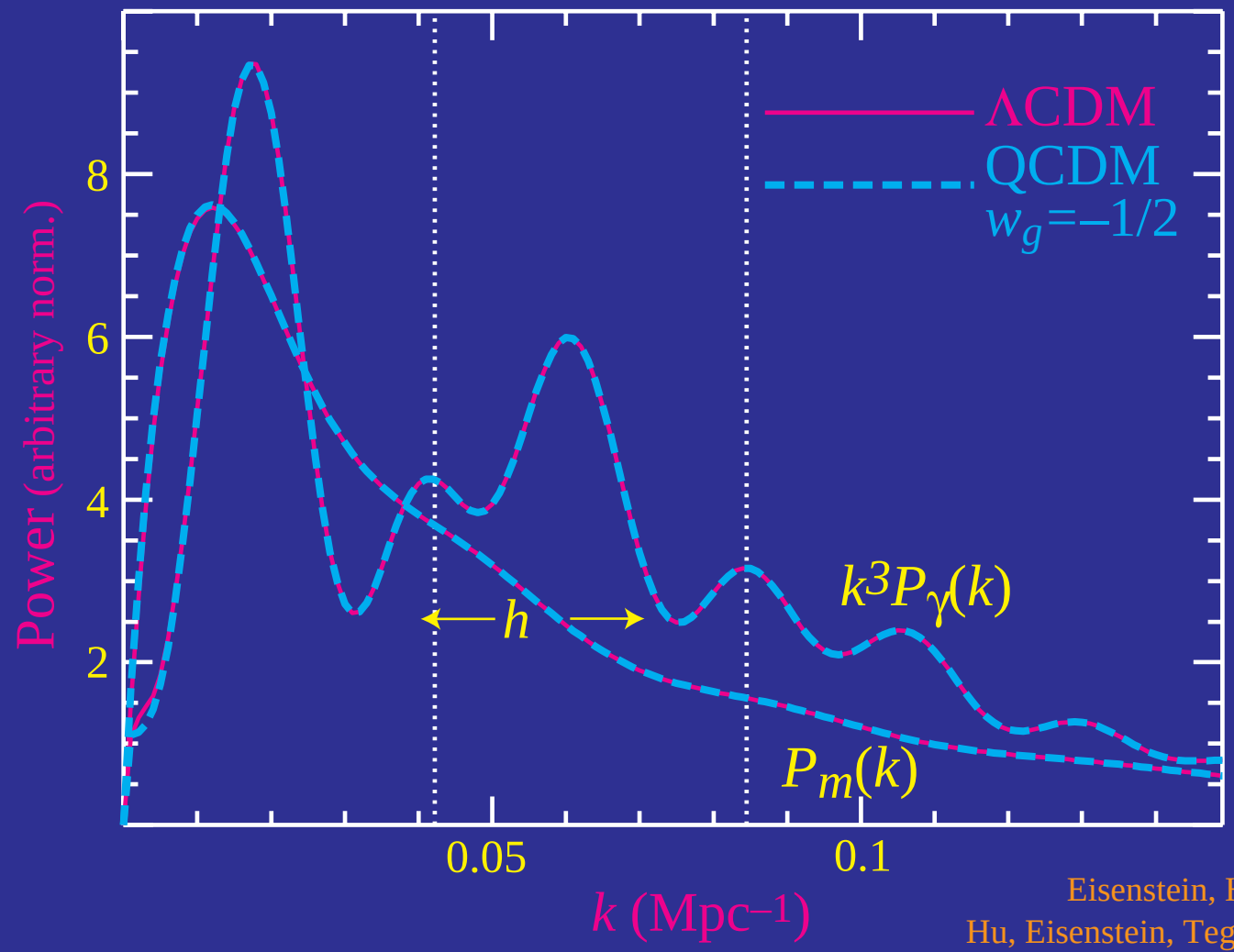
- Infer physical scale $l_{\rm peak}$(CMB) $\rightarrow$ $k_{\rm peak}$(LSS) in Mpc^{-1}
- Measure in redshift survey $k_{\rm peak}$(LSS) in h Mpc^{-1} $\rightarrow$ h
- Robust to low redshift physics (e.g. quintessence, GDM)

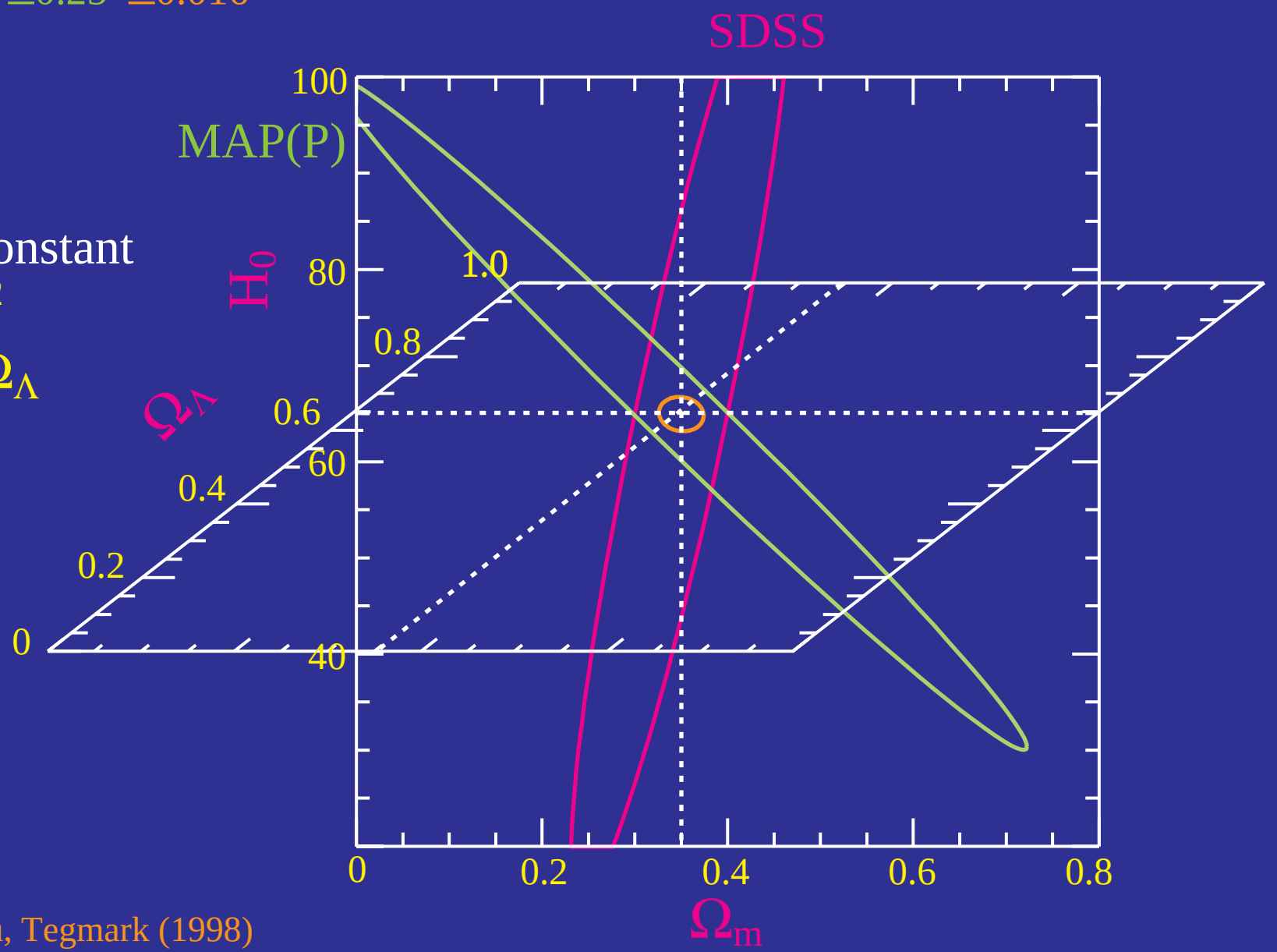


Eisenstein, Hu & Tegmark (1998)
Hu, Eisenstein, Tegmark & White (1998)

Classical Cosmology

	MAP	+P	+SDSS
H_0	±130	±23	±1.2
Ω_m	±1.4	±0.25	±0.016

CMB:
~line of constant
$\Omega_m H_0^2$
$\Omega_m + \Omega_\Lambda$



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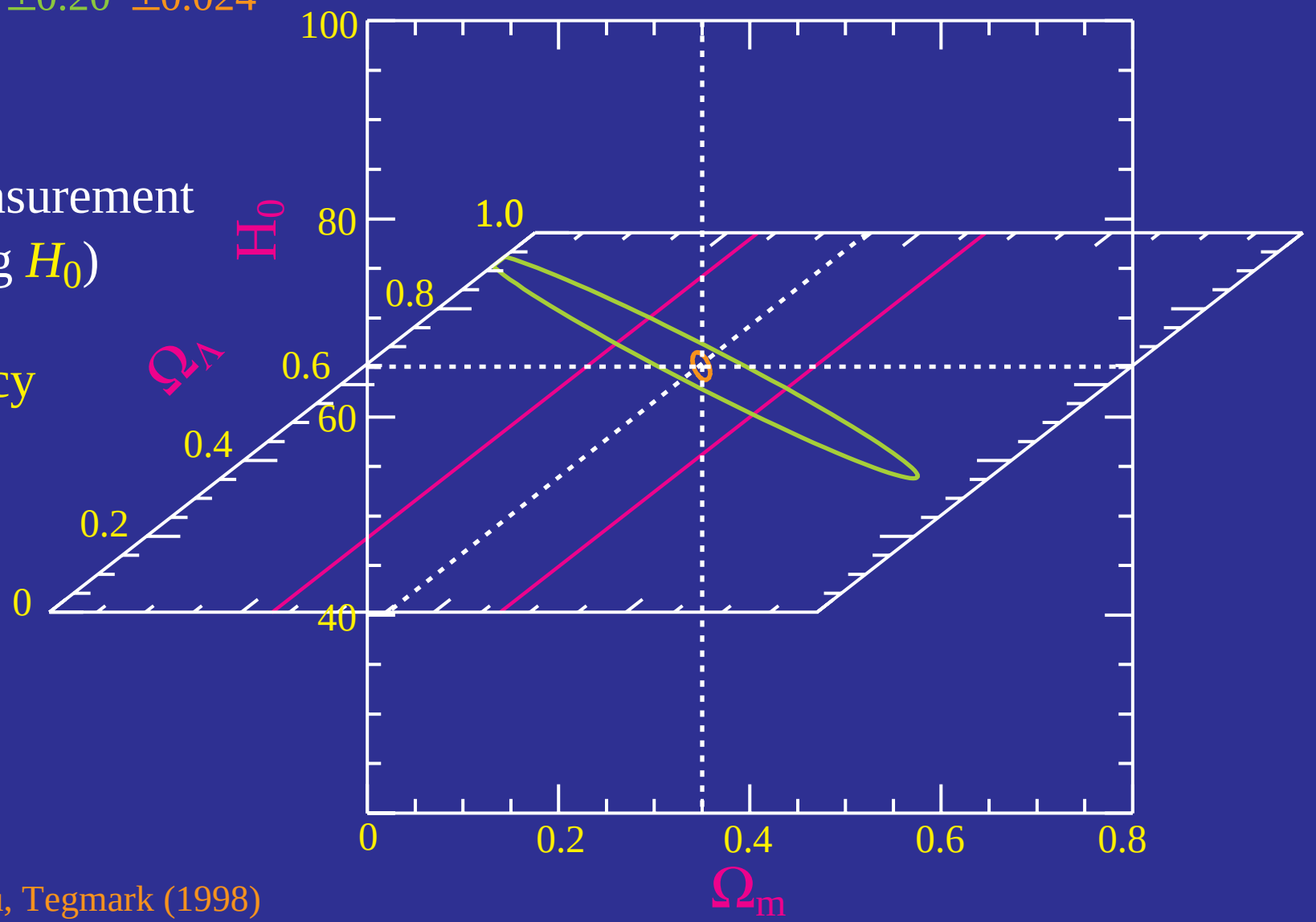
H_0	±130	±23	±1.2
Ω_m	±1.4	±0.25	±0.016
Ω_Λ	±1.1	±0.20	±0.024

Any other measurement (including H_0) breaks degeneracy



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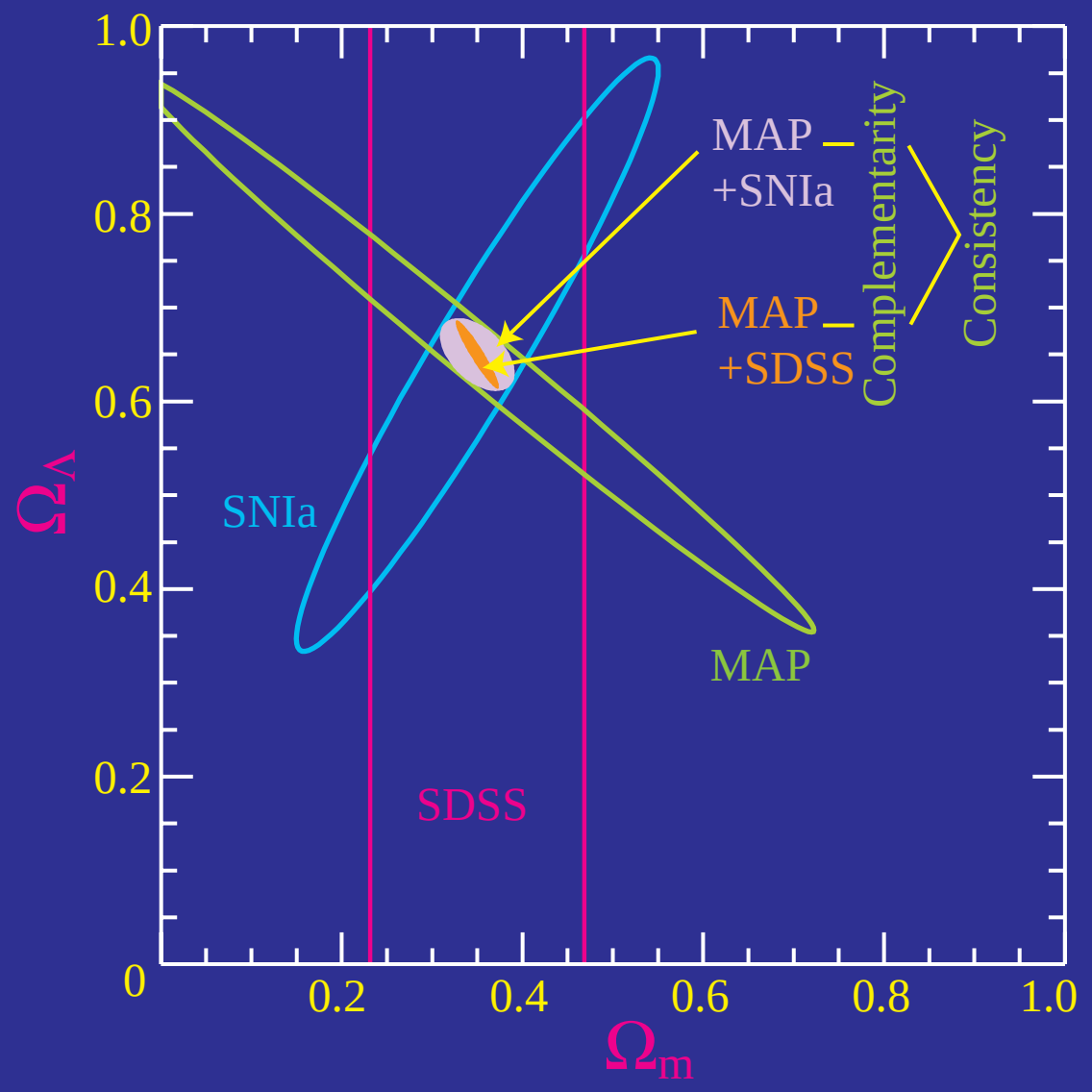
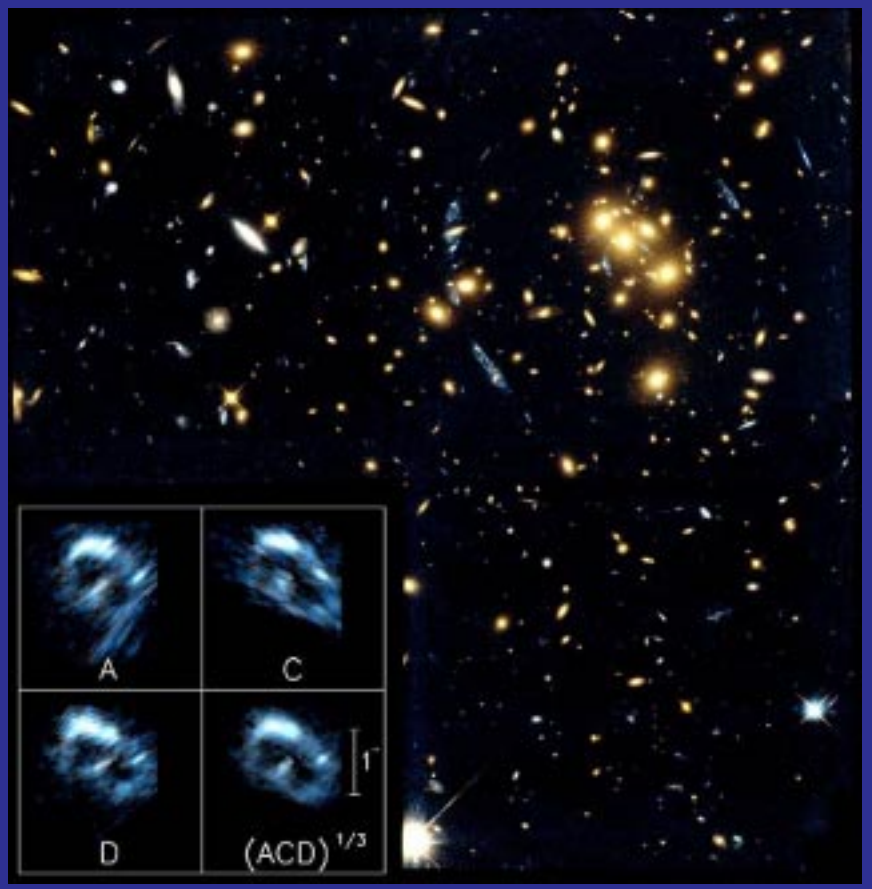
Many opportunities for consistency checks! (e.g. high-z SNIa)



Eisenstein, Hu, Tegmark (1998)

Gravitational Lensing by LSS

- Shearing of galaxy images reliably detected in clusters
- Main systematic effects are instrumental rather than astrophysical

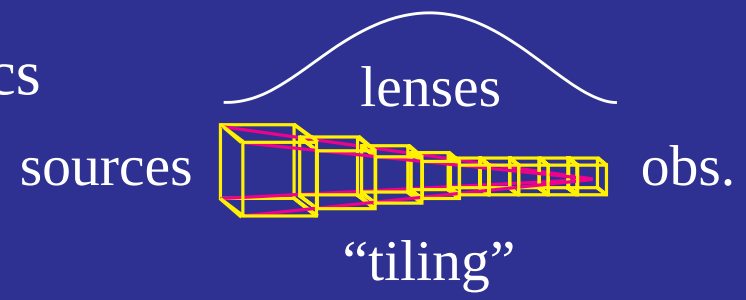


Cluster (Strong) Lensing: 0024+1654

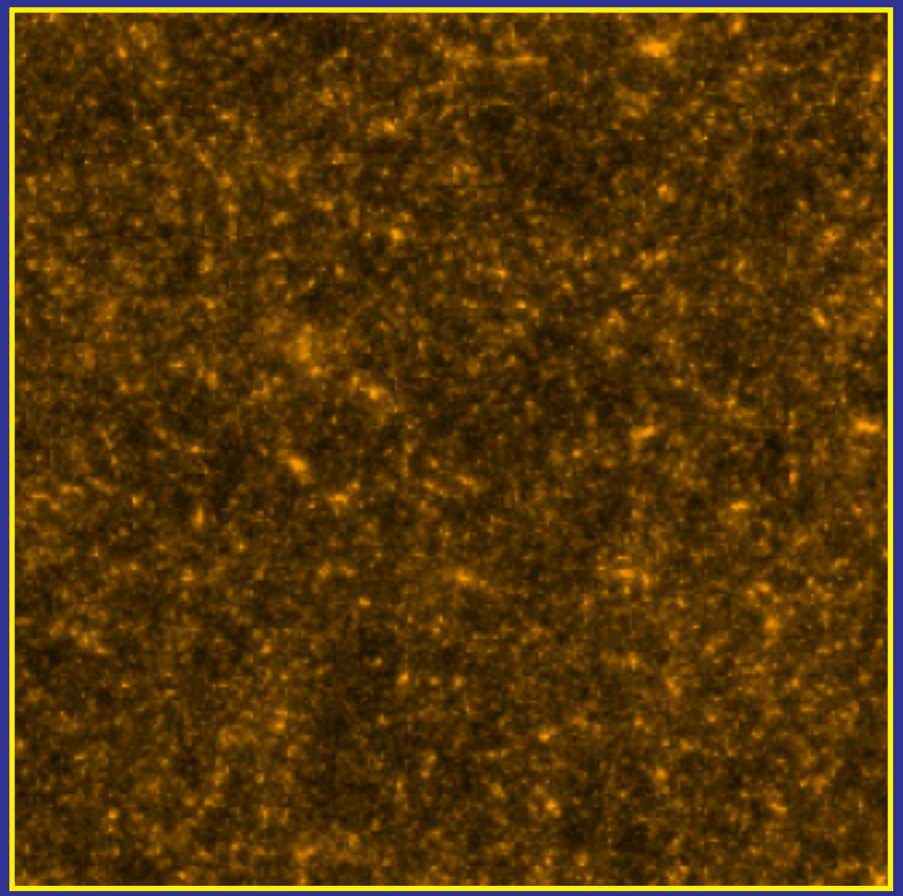
Colley, Turner, & Tyson (1996)

Statistics of Weak Lensing by LSS

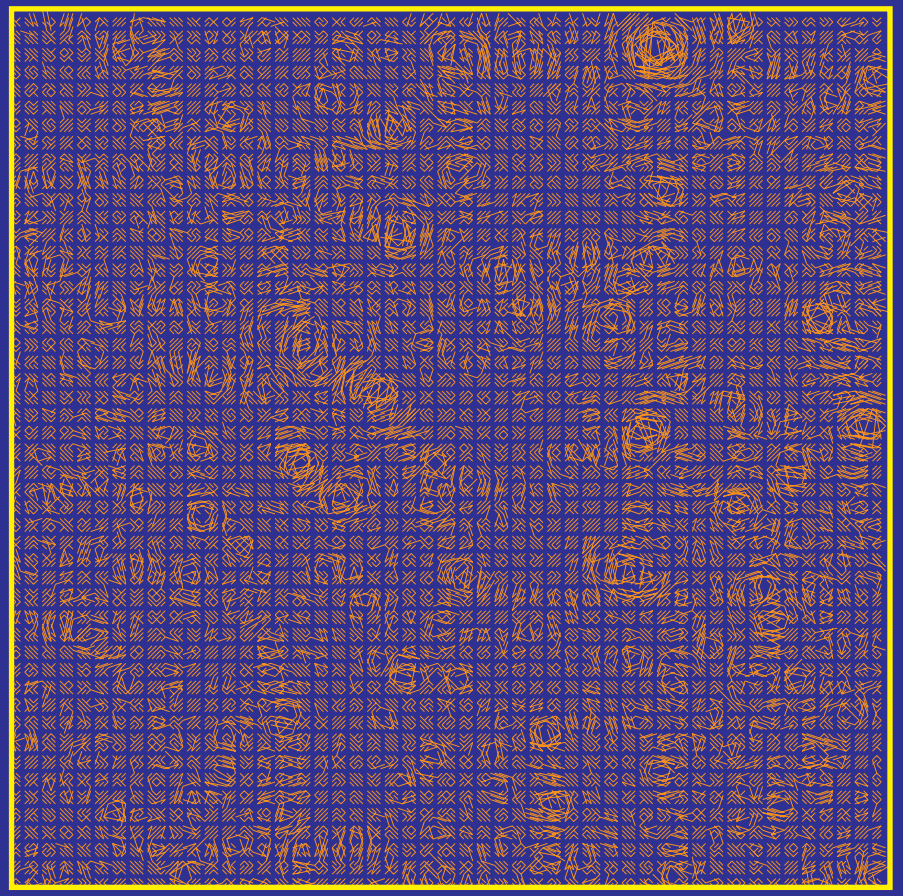
- Efficient PM simulations to build statistics
- Tiling of hundreds of independent simulations



Convergence



Shear

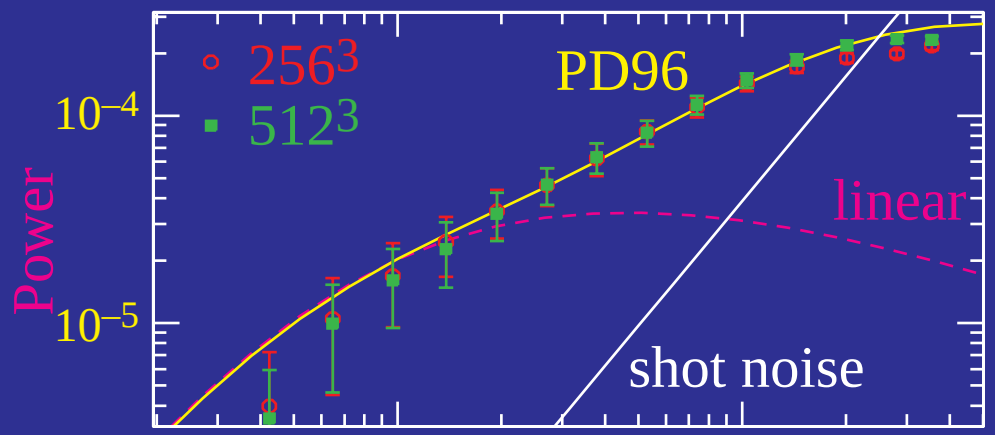


$6° \times 6°$ FOV; 2' Res.; 245–75 h^{-1}Mpc box; 480–145 h^{-1}kpc mesh; 2–70 10^9 $M_\odot$

White & Hu (1999)

Weak Lensing: Power Spectrum

- Convergence power spectrum
- Sub-degree scale power from non-linear regime ($l \gtrsim 100$)



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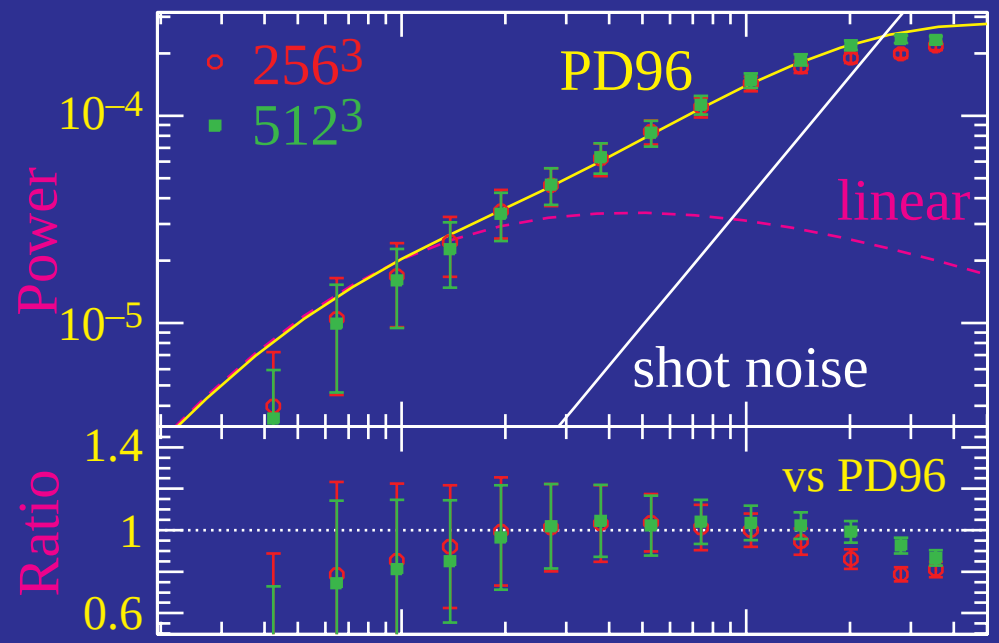

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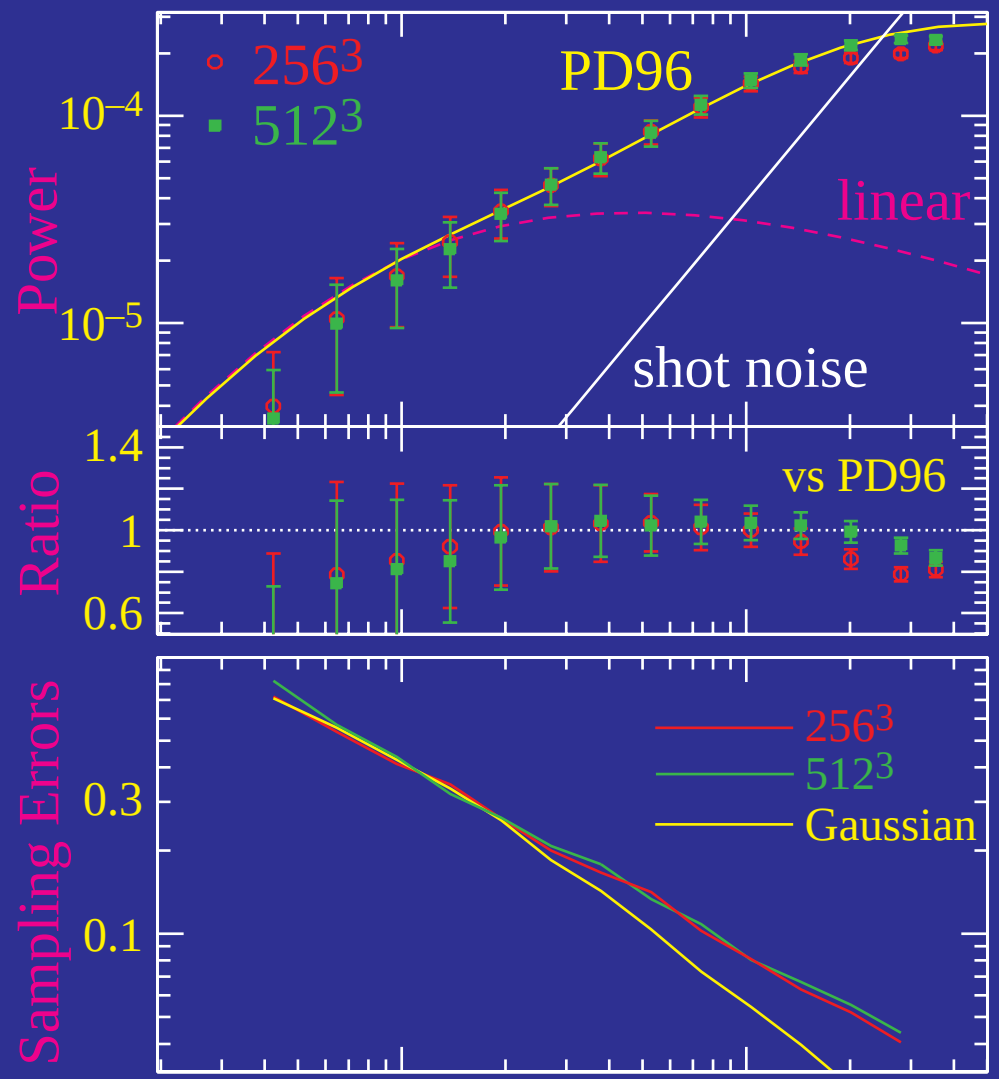
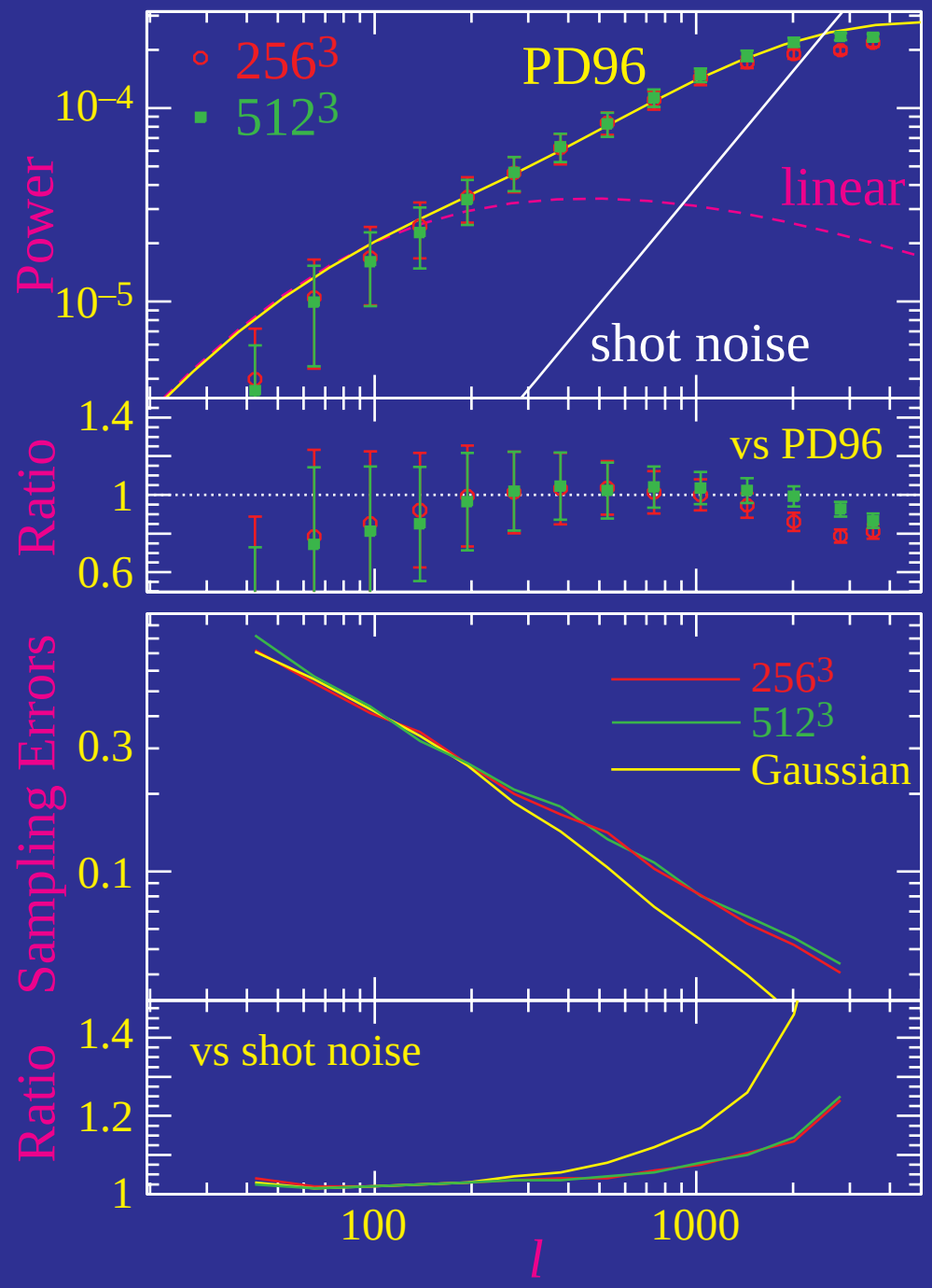


White & Hu (1999)

Weak Lensing: Power Spectrum

- Convergence power spectrum
- Sub-degree scale power from non-linear regime ($l \gtrsim 100$)
- Mean power matches density scaling prediction (PD96)
- Sample variance near Gaussian until $l \sim 1000$
- Shot noise from intrinsic ellipticities takes over for $l \gtrsim 1000$ ($\gamma_{rms}=0.4$; $2\times10^5 \mathrm{deg}^{-1}$)
- Gaussian approximation reasonable for estimation purposes



White & Hu (1999)

Weak Lensing:
Power Spectrum & Cosmological Parameters

- Potentially as precise as the CMB
- Systematic effects are under control at the sub% level in shear
- The Good News: Depends on most (8) cosmological parameters

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- The Good News: Depends on most (8) cosmological parameters
- The Bad News: Depends on most (8) cosmological parameters

Blandford et al. (1991); Miralda-Escude (1991); Kaiser (1992)

Degeneracies!

- Solutions:

  Large sky coverage
  Tomography on source distribution
  Combination with CMB measurements
  Nongaussianity

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Degeneracies!

- Solutions:

  Large sky coverage
  Tomography on source distribution
  Combination with CMB measurements
  Nongaussianity

Weak Lensing: Power Spectrum & Cosmological Parameters

- Large sky coverage
- Comparable precision to CMB per area of sky

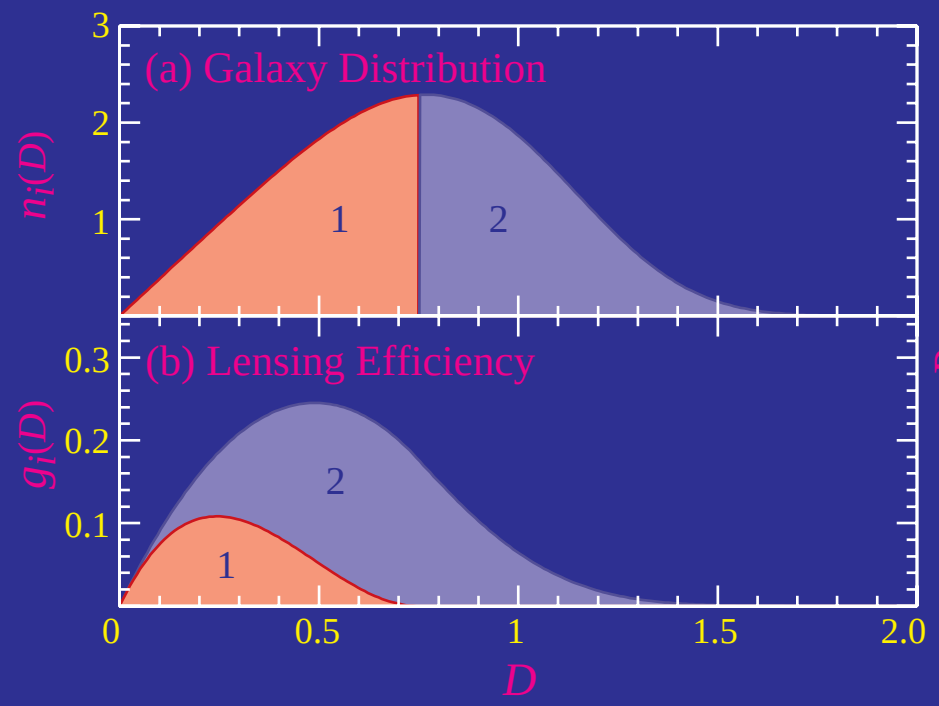
11D CDM Space

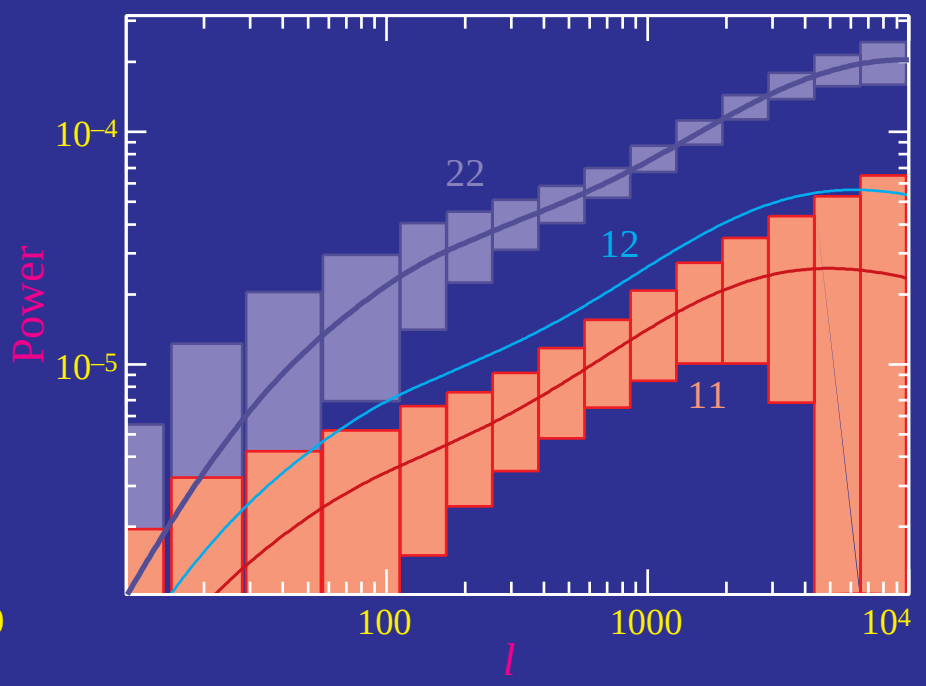
	WL$\sqrt{f_{sky}}$	MAP(T)	Planck(T+P)
$\sigma(\Omega_m h^2)$	0.024	0.029	0.0027
$\sigma(\Omega_b h^2)$	0.0092	0.0029	0.0002
$\sigma(m_\nu)$	0.29	0.77	0.25
$\sigma(\Omega_\Lambda)$	0.079	1.0	0.11
$\sigma(\Omega_K)$	0.096	0.29	0.030
$\sigma(n_s)$	0.066	0.1	0.009
$\sigma(\ln A)$	0.28	1.21	0.045
$\sigma(z_s)$	0.047	(1)	(1)
$\sigma(\tau)$	–	0.63	0.004
$\sigma(T/S)$	–	0.45	0.012
$\sigma(Y_p)$	(0.02)	(0.02)	0.01

Hu & Tegmark (1999)

Weak Lensing: Power Spectrum & Cosmological Parameters

- Divide sample by photometric redshifts
- Cross correlate samples



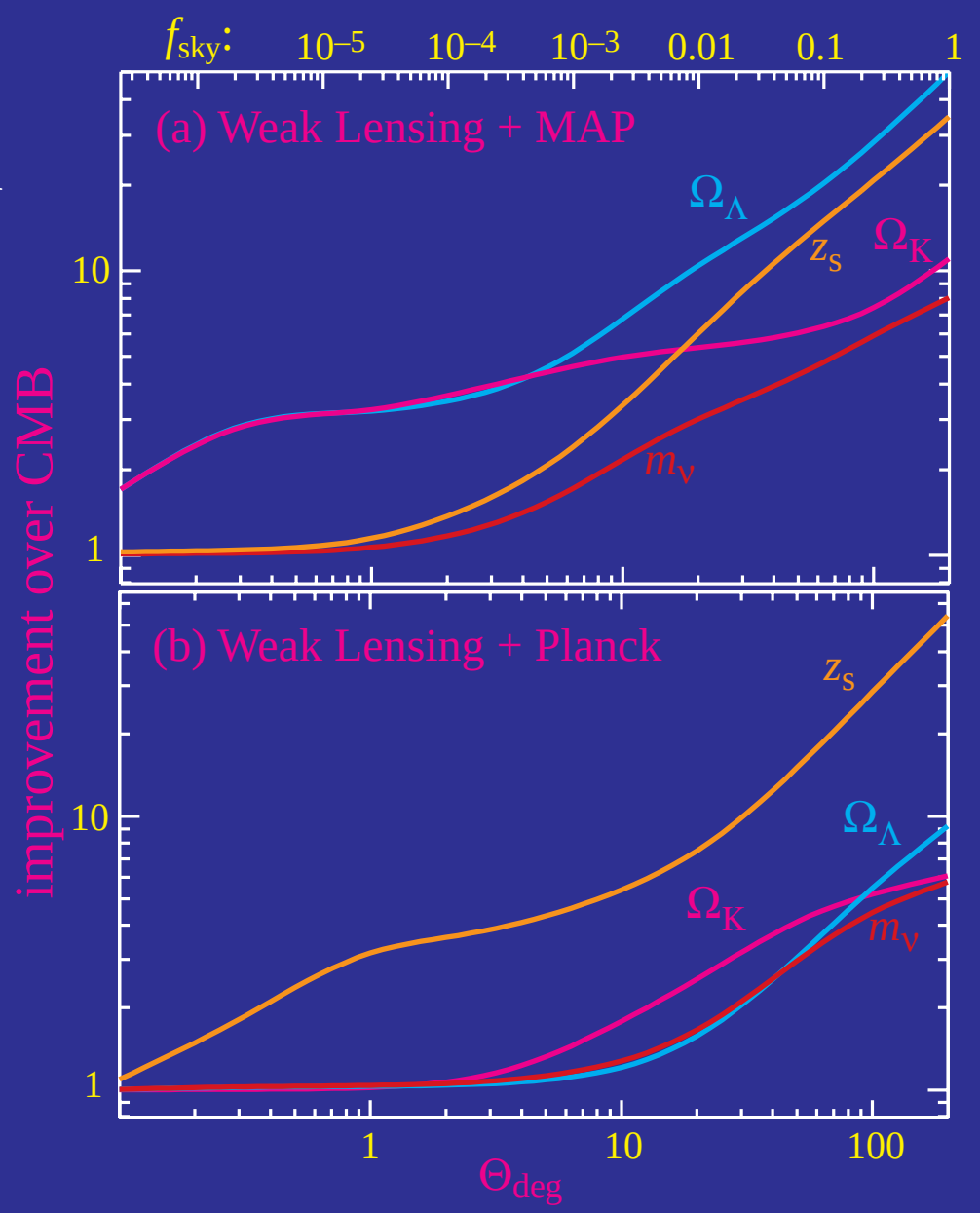


- Order of magnitude increase in precision, e.g. Ω_Λ

Hu (1999)

Weak Lensing: Power Spectrum & Cosmological Parameters

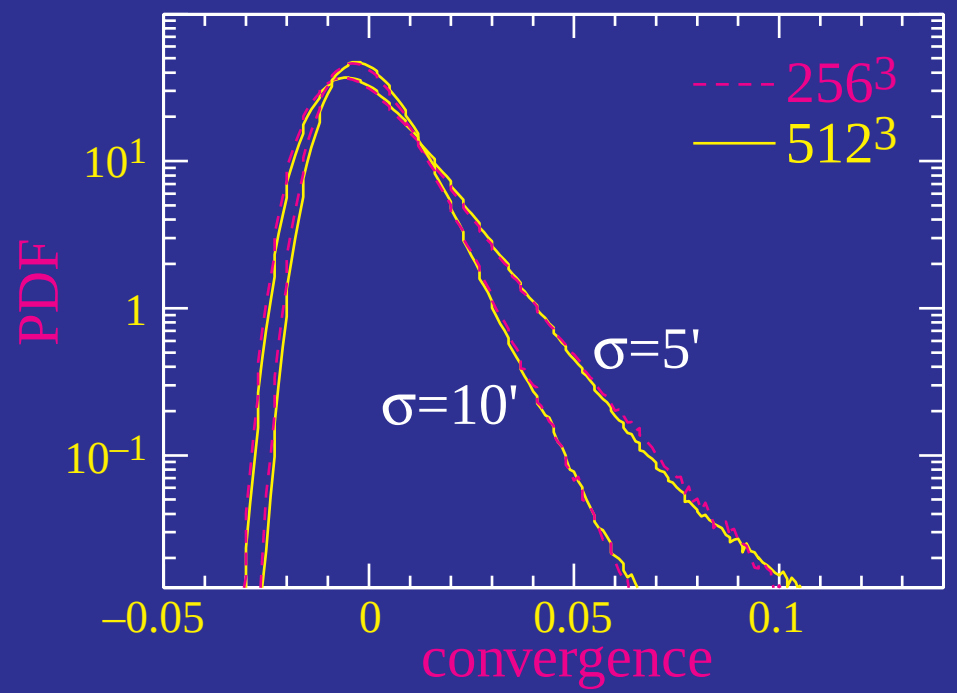
- Combine with CMB
- Degeneracy breaking even with 1° FOV (acheivable today)
- Order of magnitude gains for > 10° FOV
- Opportunity to probe the detailed nature of dark energy

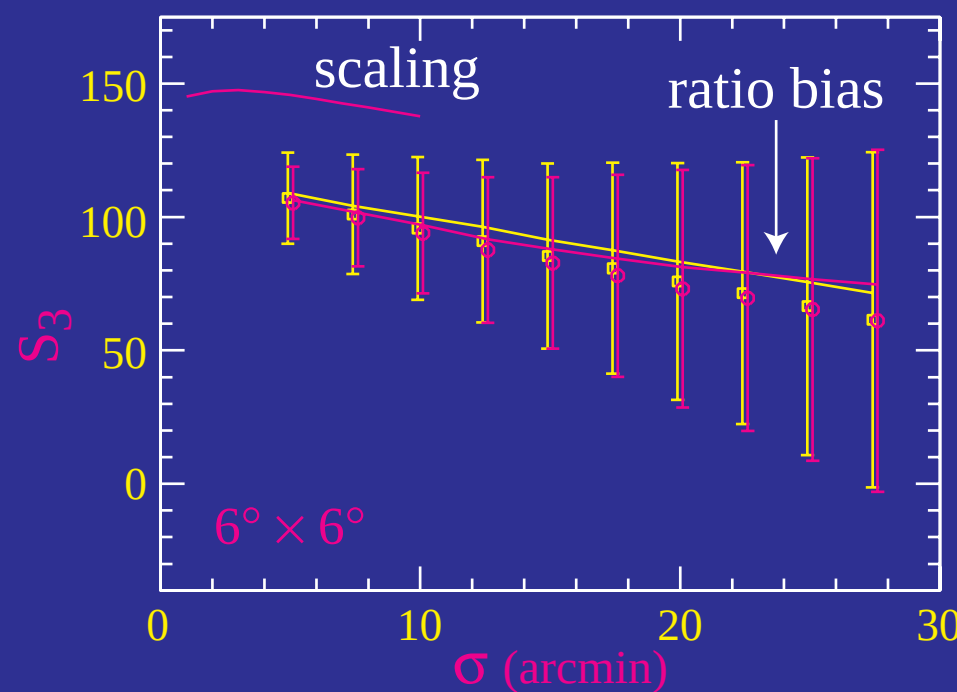


Hu & Tegmark (1999)

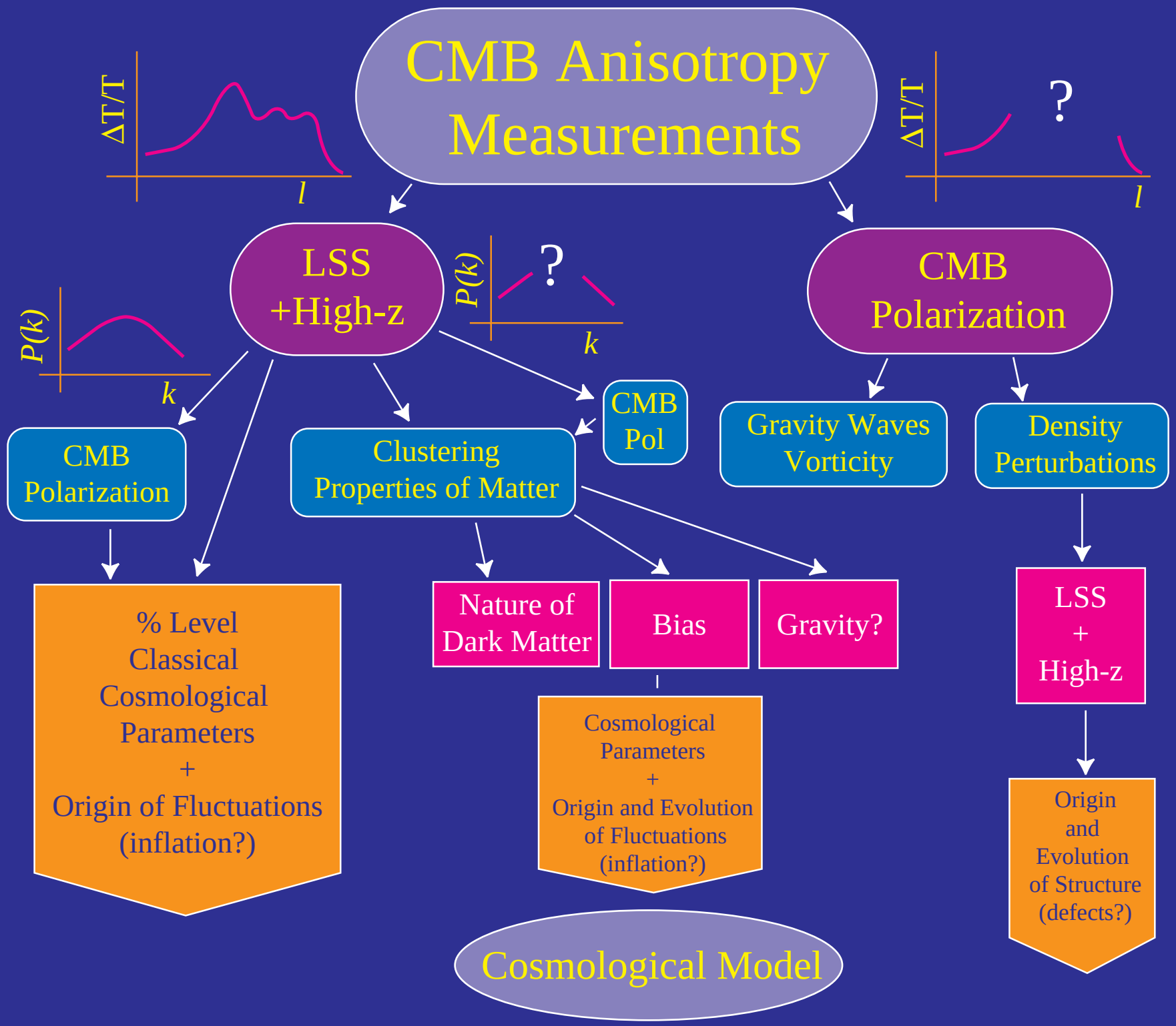
Weak Lensing: Skewness

- Skewness of the convergence
- Sensitive to Ω_m, Ω_G
  (Bernardeau *et al.* 1997, Hui 1999; Jain, Seljak & White 1999)
- But depends on:
  degree of non-linearity
  shape of power spectrum
- Hierarchical scaling ansatz only applies on deeply-nonlinear, shot noise limited scales (<1')
- Severely limited by sample variance (>1')





White & Hu (1999)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Cosmological Model

Part III:
Determining the Properties of the Dark Sector

- Inconsistent precision measures?
- Generalized dark matter
- Examples:

  massive neutrinos, scalar fields, decaying dark matter, neutrino background radiation

Inconsistent Precision Measures ?

- Expect precision results from CMB, galaxy surveys, SNIa, weak lensing...
- May turn out inconsistent with even the large adiabatic CDM parameter space (11–15 parameters)

Inconsistent Precision Measures ?

- Expect precision results from CMB, galaxy surveys, SNIa, weak lensing...
- May turn out inconsistent with even the large adiabatic CDM parameter space (11–15 parameters)

What If

- CMB shows sub–degree scale structure, but not necessarily the peaks of adiabatic CDM
  - Nature of the initial fluctuations
    isocurvature vs. adiabatic
    inflation vs. ordinary causal mechanisms
  - Clustering properties of matter
    scale & time dependent bias
    gravity on large scales
    dark matter properties

Beyond Cold Dark Matter

- Parameter estimation and likelihood analysis is only as good as the model space considered

- Even if we do live in CDM space one should observationally prove
  dark matter is CDM
  and
  missing energy is Λ or scalar field quintessence

- Need to parameterize the possibilities continuously from CDM to more exotic possibilities

Generalized Dark Matter

- An extention of X-matter (Chiba, Sugiyama & Nakamura 1997) based on gauge invariant variables (Kodama & Sasaki 1984)

Generalized Dark Matter

- Arbitrary Stress–Energy Tensor $T_{\mu\nu}$ 16 Components
- Local Lorentz Invariance $\rightarrow$ Symmetric $T_{\mu\nu}$ 10 Components

Hu (1998)

Generalized Dark Matter

- Arbitrary Stress–Energy Tensor $T_{\mu\nu}$ — 16 Components
- Local Lorentz Invariance $\rightarrow$ Symmetric $T_{\mu\nu}$ — 10 Components
- Energy–Momentum Conservation — 4 Constraints
  - 1 Pressure
  - 5 Anisotropic stresses

Hu (1998)

Generalized Dark Matter

- Arbitrary Stress–Energy Tensor $T_{\mu\nu}$ — 16 Components
- Local Lorentz Invariance $\rightarrow$ Symmetric $T_{\mu\nu}$ — 10 Components
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  - 1 Pressure
  - 5 Anisotropic stresses
- Linear Perturbations scalar, vector, tensor
  - 1 Pressure (scalar)
  - 1 Scalar anisotropic stress
  - 2 vorticities — 2 Vector anisotropic stress
  - 2 gravity wave pol. — 2 Tensor anisotropic stress
- Homogeneity & Isotropy + Gravitational Instability
  - 1 Background pressure
  - 1 Pressure fluctuation
  - 1 Scalar anisotropic stress fluctuation

Hu (1998)

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- Homogeneity & Isotropy + Gravitational Instability — 1 Background pressure; 1 Pressure fluctuation; 1 Scalar anisotropic stress fluctuation
- Model as Equations of State
- Gauge Invariance
  - $w = p/\rho$ — 1 Equation of State
  - $c_{\mathrm{eff}}^2 = (\delta p/\delta\rho)_{\mathrm{comov}}$ — 1 Sound Speed
  - $c_{\mathrm{vis}}^2 =$ (viscosity coefficient) — 1 Anisotropic Stress

Hu (1998)

Dark Components

Prototypes:

- Cold dark matter
  (WIMPs)
- Hot dark matter
  (light neutrinos)
- Cosmological constant
  (vacuum energy)

equation of state w_g	sound speed c_{eff}^2	viscosity c_{vis}^2
0	0	0
	$1/3 \rightarrow 0$	
–1	arbitrary	arbitrary

Dark Components

	equation of state w_g	sound speed c_{eff}^2	viscosity c_{vis}^2
Prototypes:			
• Cold dark matter (WIMPs)	0	0	0
• Hot dark matter (light neutrinos)	$1/3 \rightarrow 0$		
• Cosmological constant (vacuum energy)	–1	arbitrary	arbitrary
Exotica:			
• Quintessence (slowly-rolling scalar field)	variable	1	0
• Decaying dark matter (massive neutrinos)	$1/3 \rightarrow 0 \rightarrow 1/3$		
• Radiation backgrounds (rapidly-rolling scalar field, NBR)	1/3	1/3	$0 \rightarrow 1/3$

Exotic Dark Matter: Examples

- Two examples

  (1) Dark Energy (accelerating component)

  (2) Relativistic Dark Matter

  (a) alternate model for the seeds of fluctuations

  (b) neutrino background radiation
  (number, anisotropies?)

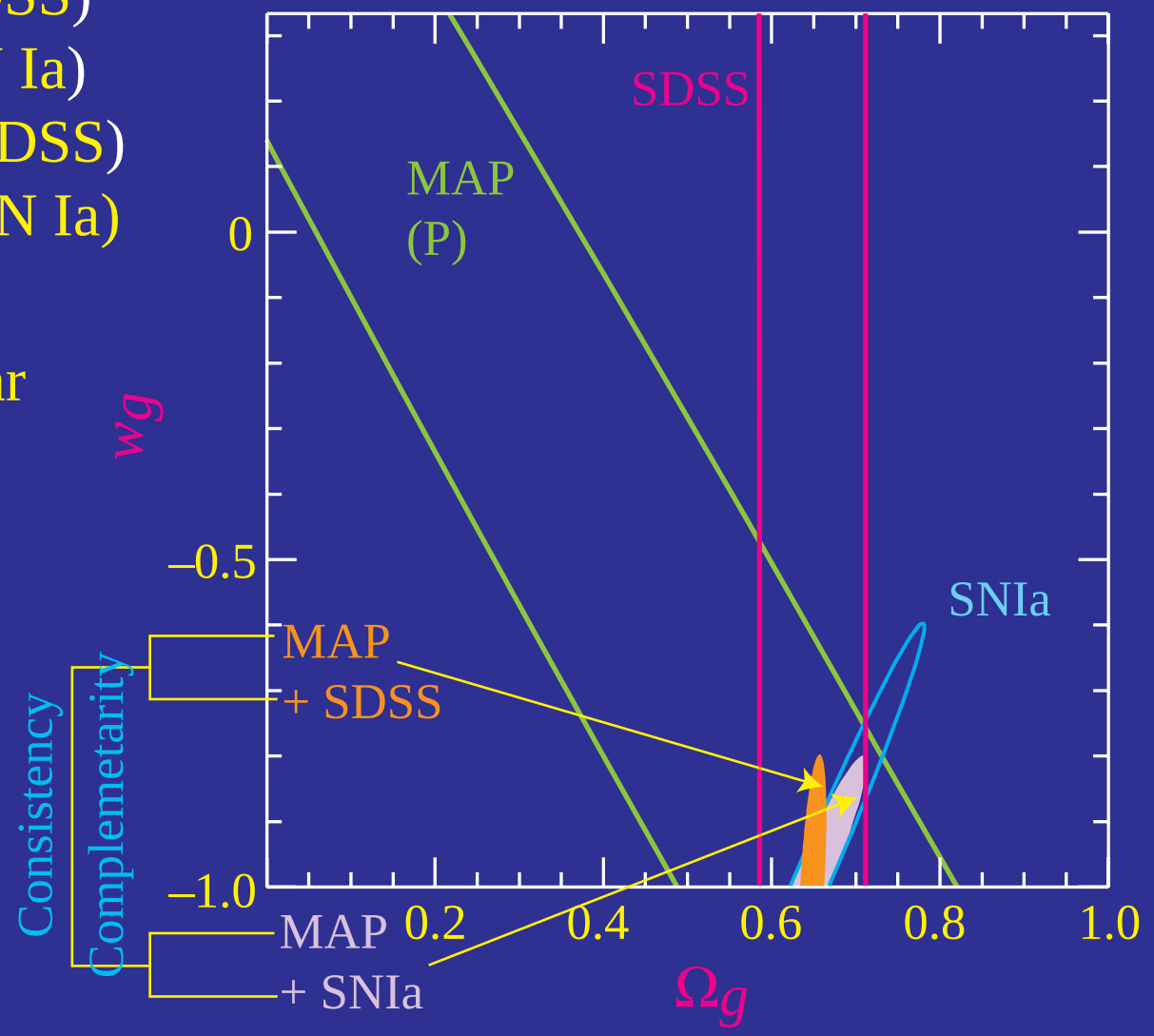
Determining the Accelerating Component

- Is a cosmological constant responsible for the acceleration?

  $\sigma(w_g)=0.13$ (MAP+SDSS)
  $\sigma(w_g)=0.13$ (MAP+SN Ia)
  $\sigma(w_g)=0.03$ (Planck+SDSS)
  $\sigma(w_g)=0.03$ (Planck+SN Ia)

- If not ($-1<w_g<0$), is a scalar field responsible?

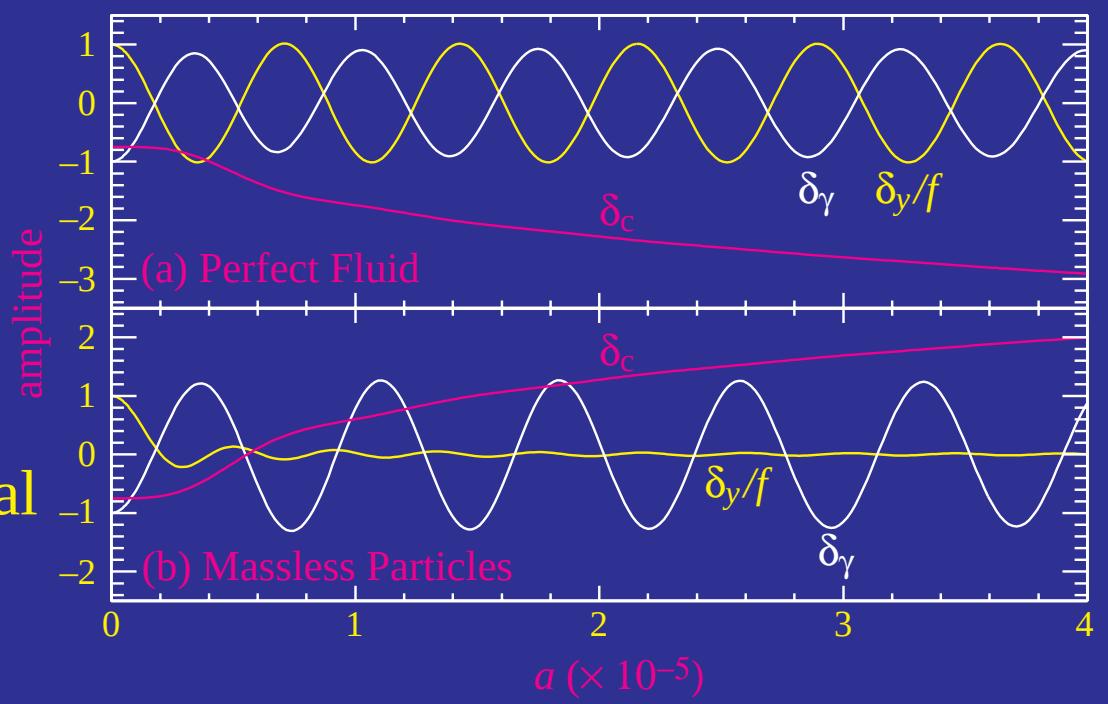
  sound speed constrained if $w_g > -1/2$



Hu, Eisenstein, Tegmark & White (1998)

Relativistic Dark Matter: Model

- Defining Elements:
  - Additional species of dark matter: relativistic ideal fluid ρ_y
  - Scale-invariant isocurvature fluctuations
    - $\delta\rho_y = -(\delta\rho_\gamma + \delta\rho_\nu + \delta\rho_c)$; $k^3 P_y(k) = \text{const.}$
  - Adiabatic relation in the usual components: $\delta_\gamma = \delta_\nu = 4\delta_c/3$
- Phenomenological Consequences:
  - Scale–invariant series of
    - Acoustic Peaks
  - Correct CMB/LSS power
    - ($\Delta T/T = -\Phi/3$)
- Early–Universe Pedigree:
  - Scalar field rapidly
    - rolling in quartic potential
  - Gravitationally produced
    - during inflation



Hu & Peebles (1999)

Relativistic Dark Matter: Consequences

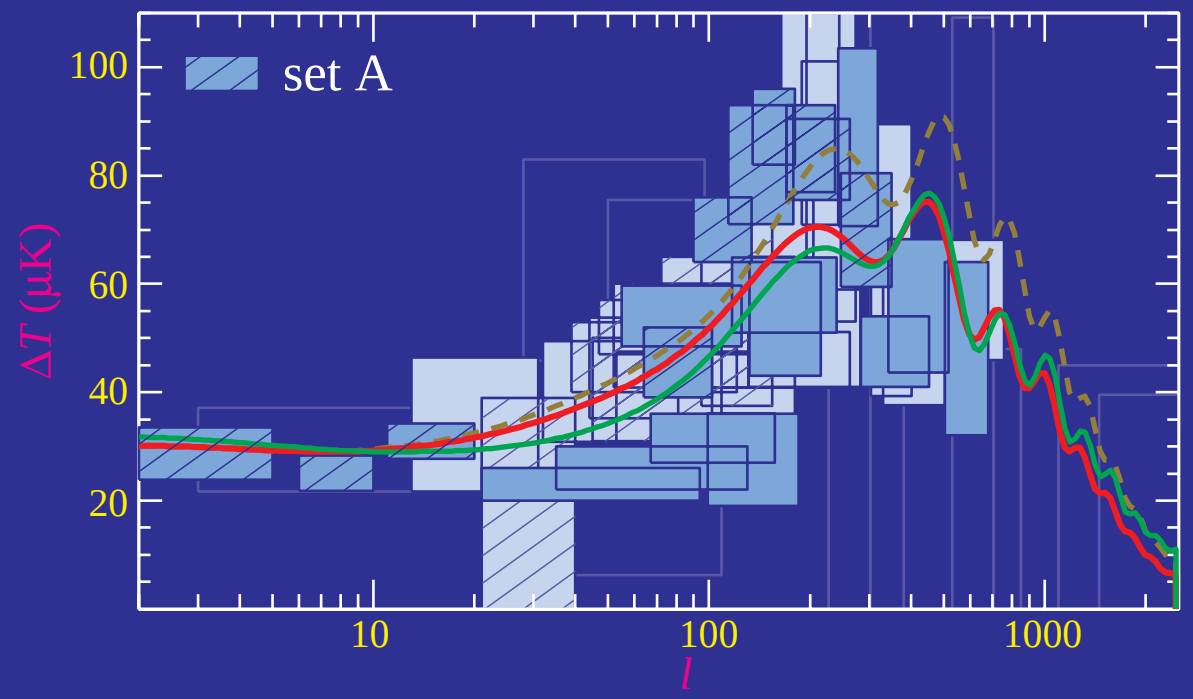
- Differs from ΛCDM by ~10% to l=200

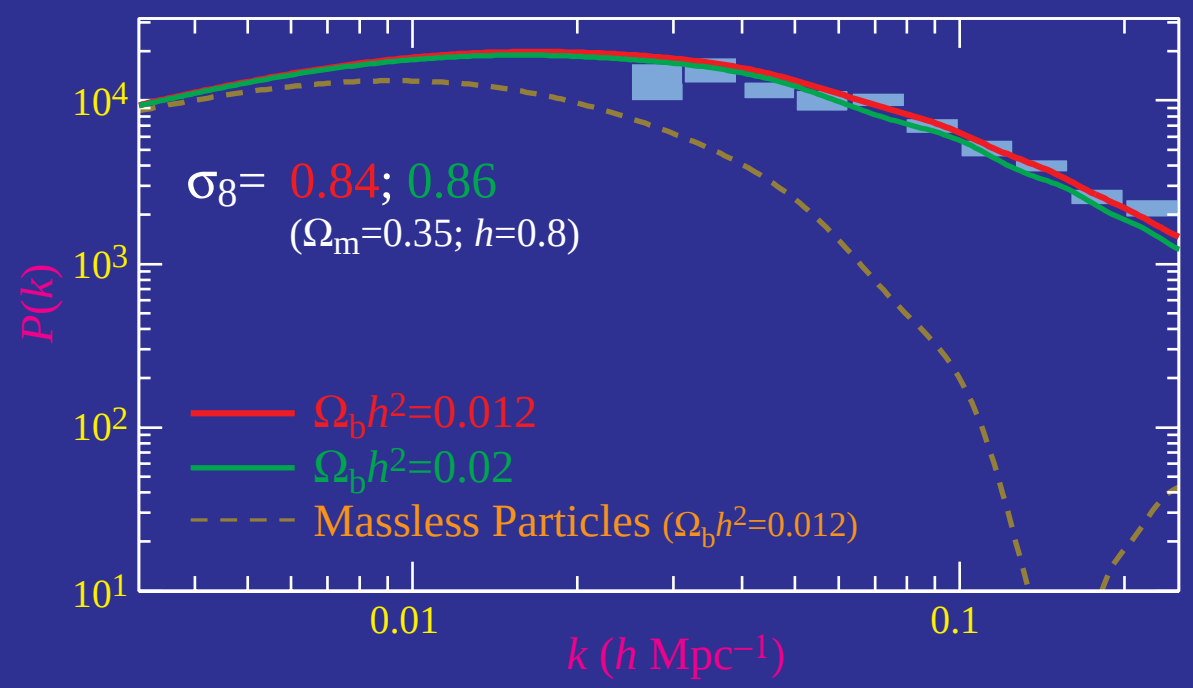
Approximate χ^2/ν

Model	All	A	B
	2.6	1.5	1.3
	2.7	2.0	1.3
ΛCDM	2.5	1.2	1.4

- Peak heights opposite to ΛCDM for $\Omega_b h^2$ for $\Omega_m h^2$

- Large scale structure sensitive to rel. dark matter dynamics: c^2_{vis} = 0 vs 1/3

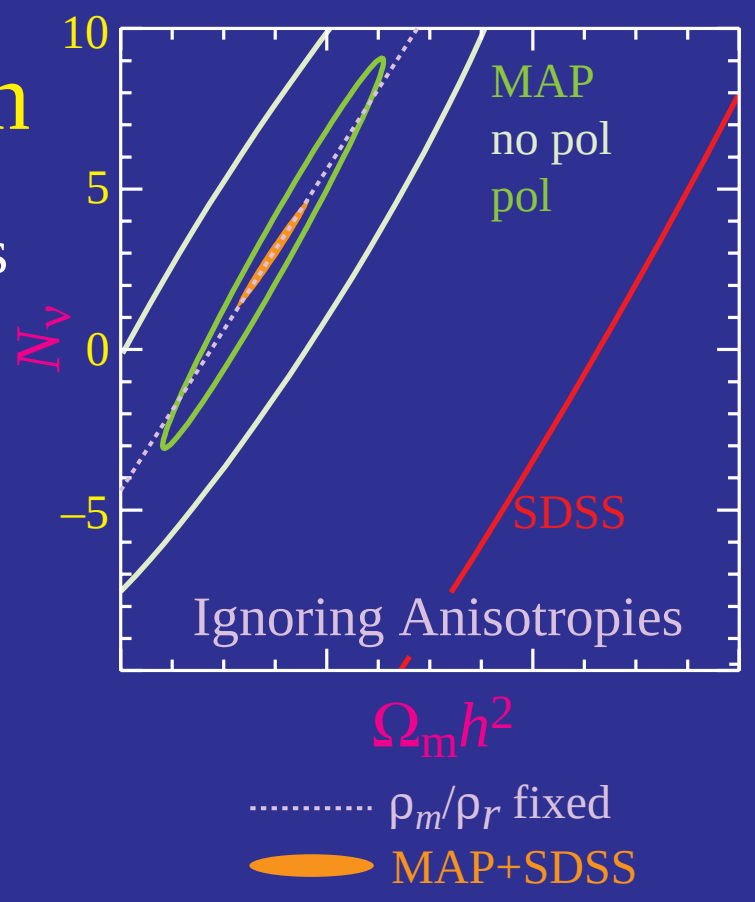




Hu & Peebles (1999)

Detecting the Neutrino Background Radiation

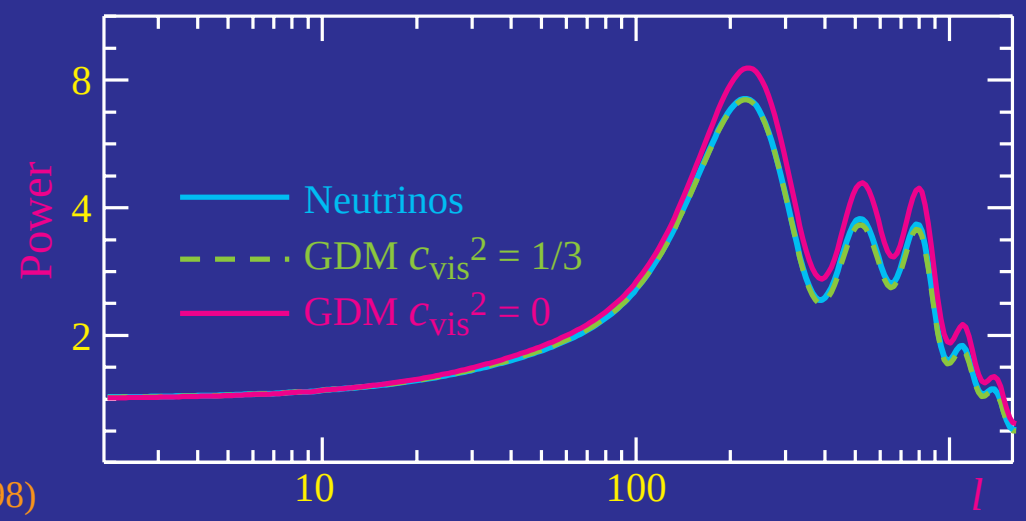
- Neutrino number N_ν or temperature T_ν alters the matter–radiation ratio
- Degenerate with matter density $\Omega_m h^2$
- Break degeneracy with NBR anisotropies

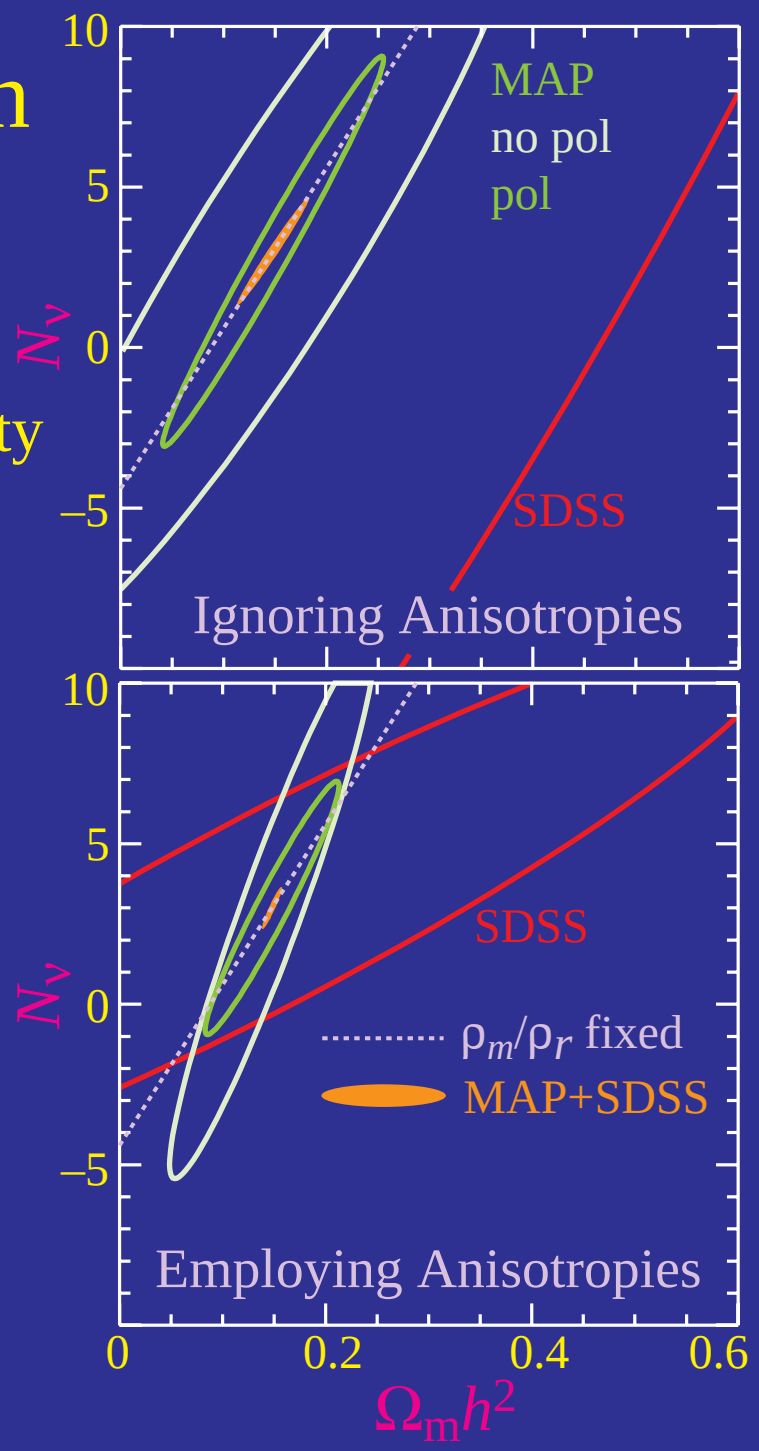


Hu, Eisenstein, Tegmark & White (1998)

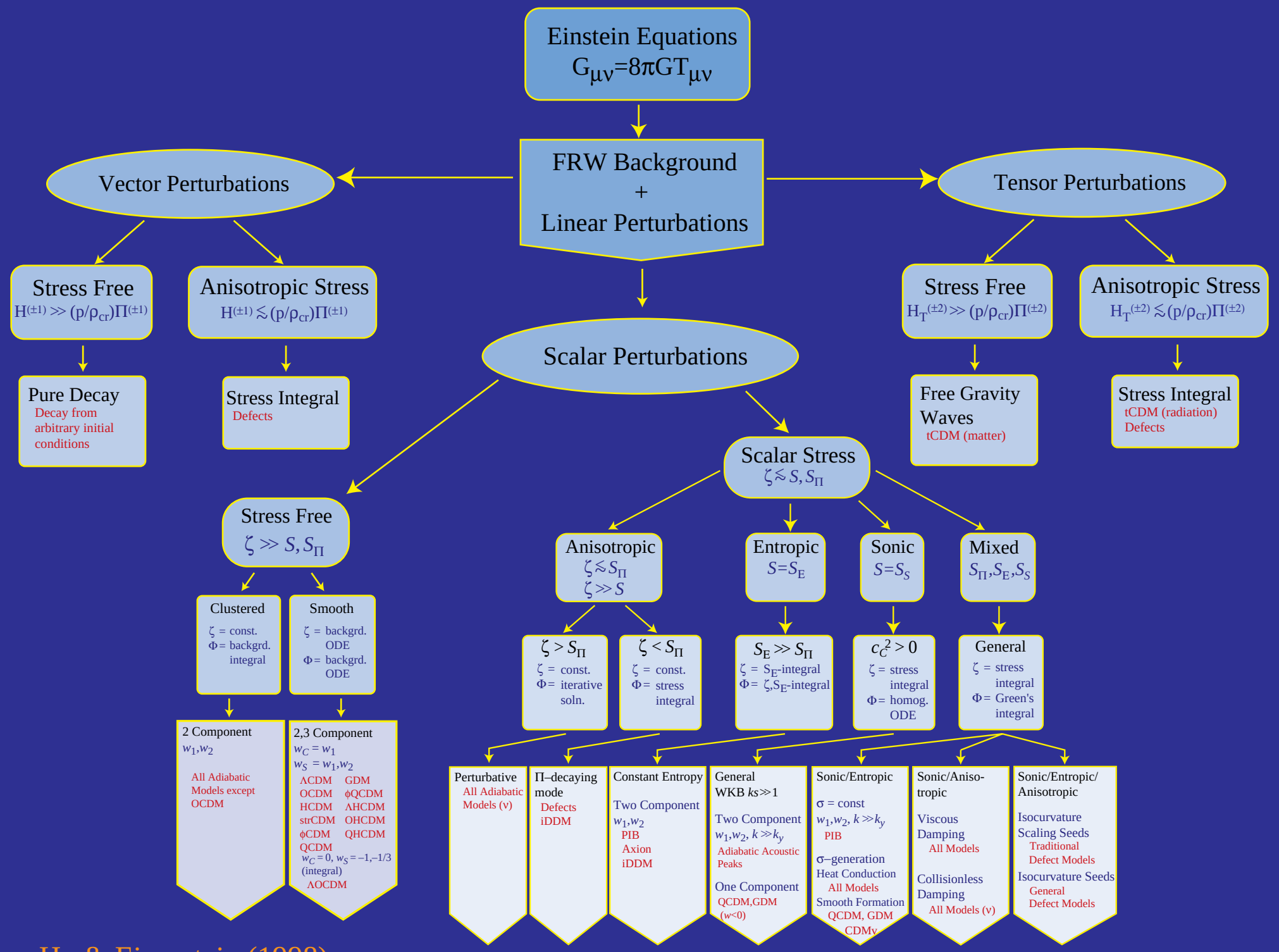
Anisotropies in the Neutrino Background Radiation

- Neutrino quadrupole anisotropies alter Ψ and drive acoustic oscillations
- Anisotropies well modeled by GDM viscosity $c_{vis}^2 = 1/3$ but largely degenerate
- Detectability: 1σ, MAP (pol); 3.5σ, MAP+SDSS; 7.2σ, Planck (pol); 8.7σ, Planck+SDSS





Hu (1998)
Hu, Eisenstein, Tegmark & White (1998)



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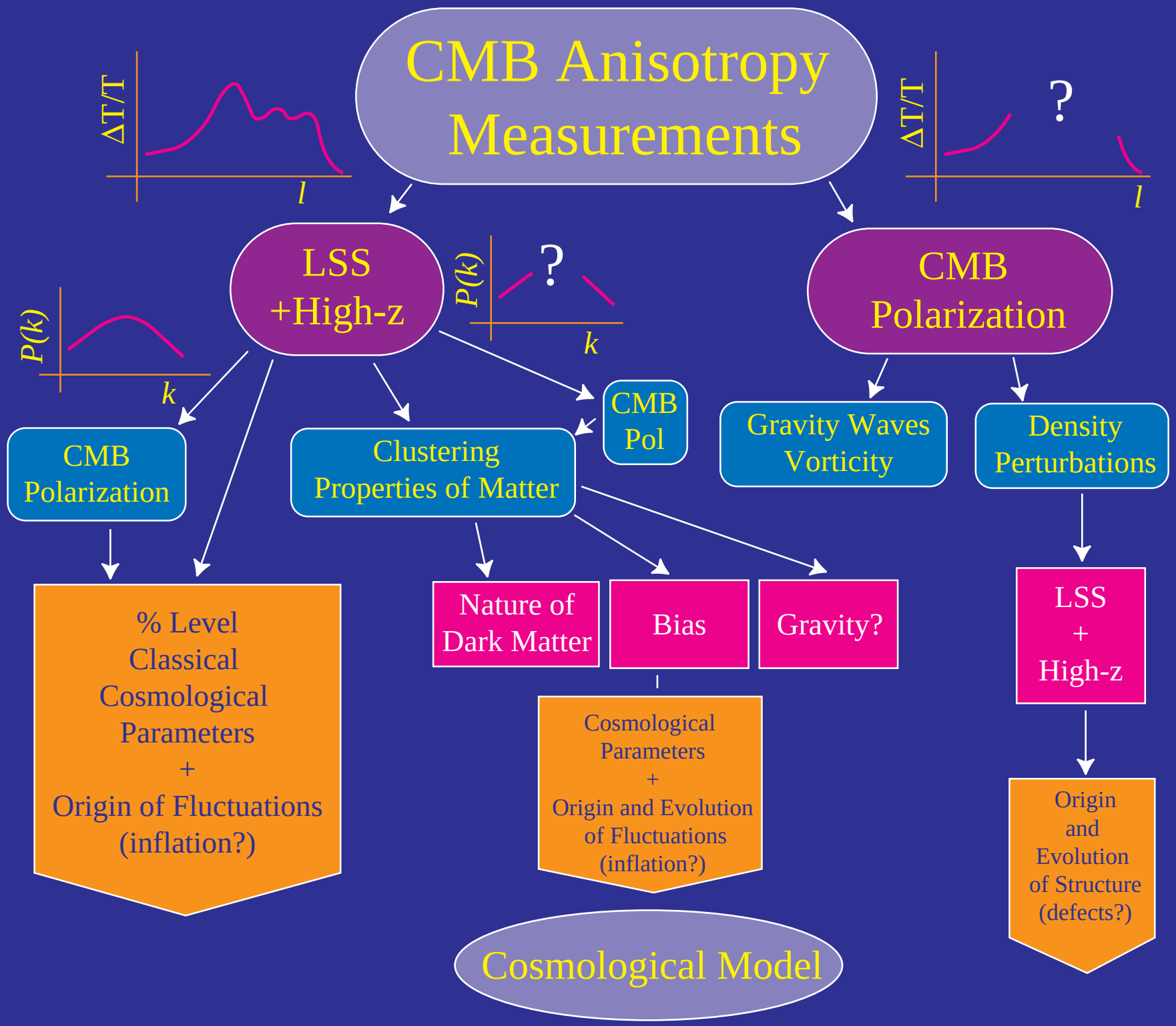
CMB Anisotropy Measurements
ΔT/T
l
ΔT/T
?
l
LSS +High-z
P(k)
?
k
P(k)
k
CMB Polarization
CMB Pol
Clustering Properties of Matter
CMB Polarization
Gravity Waves Vorticity
Density Perturbations
% Level Classical Cosmological Parameters + Origin of Fluctuations (inflation?)
Nature of Dark Matter
Bias
Gravity?
Cosmological Parameters + Origin and Evolution of Fluctuations (inflation?)
LSS + High-z
Origin and Evolution of Structure (defects?)
Cosmological Model

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angular diameter distance	Ω_Λ or Ω_K

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- If acoustic structures are not found at sub–degree scales, we need to to reexamine basic assumptions and use all diagnostics to reconstruct the cosmological model, e.g CMB polarization

Index