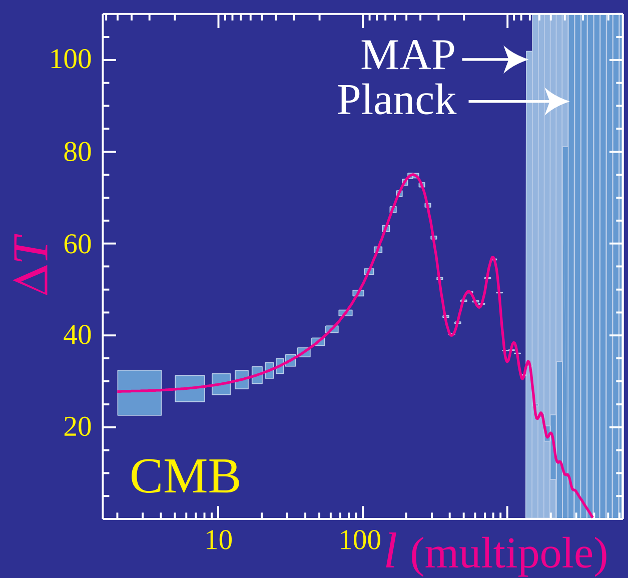
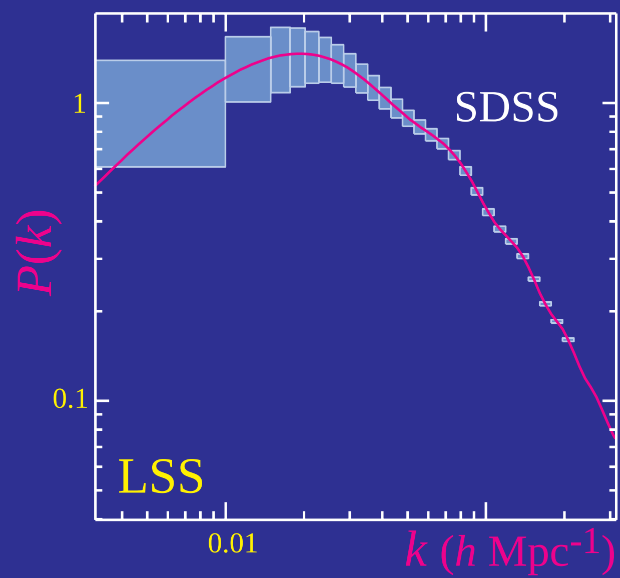
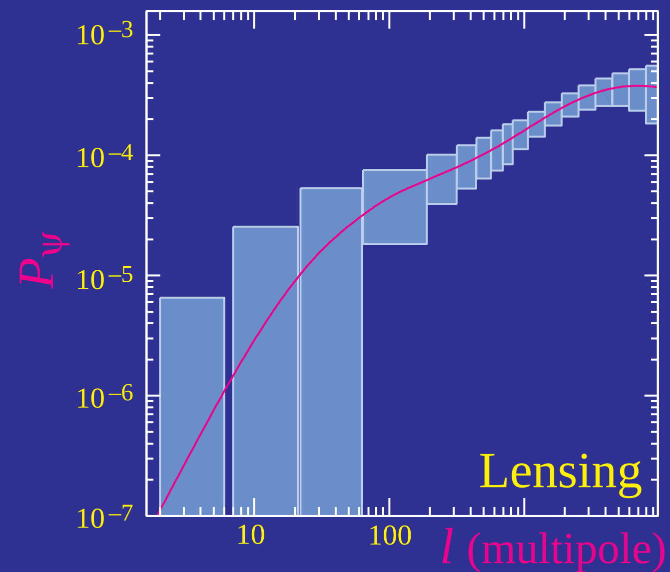
Probing the Dark Side







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

  - Establishing the basic cosmological framework at high redshifts through sub–degree scale CMB anisotropies
  - Achieving precision with large-scale structure from galaxy surveys, lensing...
  - Constructing consistency tests between these measures, distance measures...

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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
  Douglas Scott
  Uros Seljak
  Joe Silk
  Naoshi Sugiyama
  Martin White
  Matias Zaldarriaga

- Large-Scale Structure
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- Presentation

Microsoft

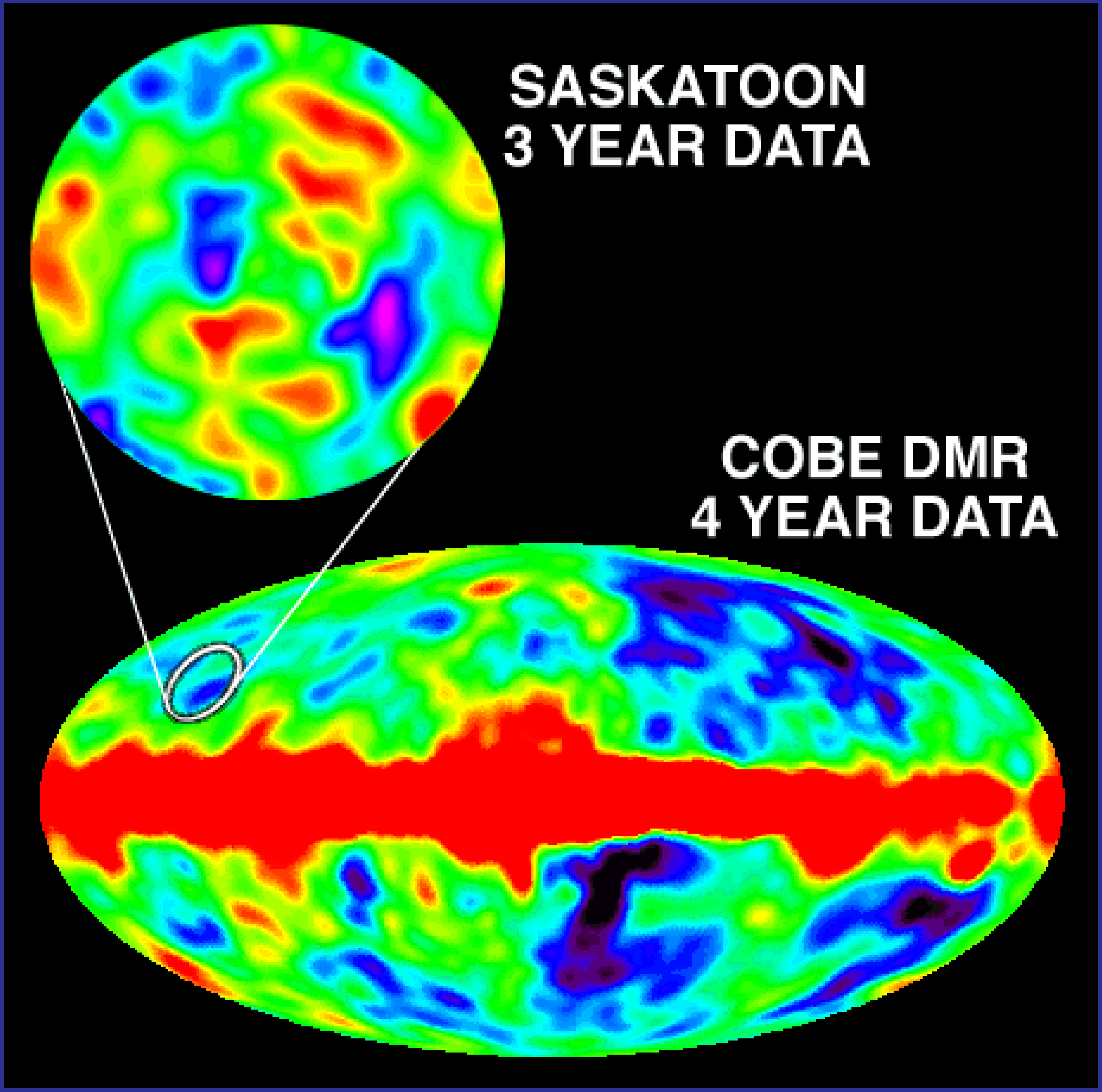
http://www.sns.ias.edu/~whu/dark.pdf

Part I:
Establishing the Cosmological Framework

Begin with the CMB because...

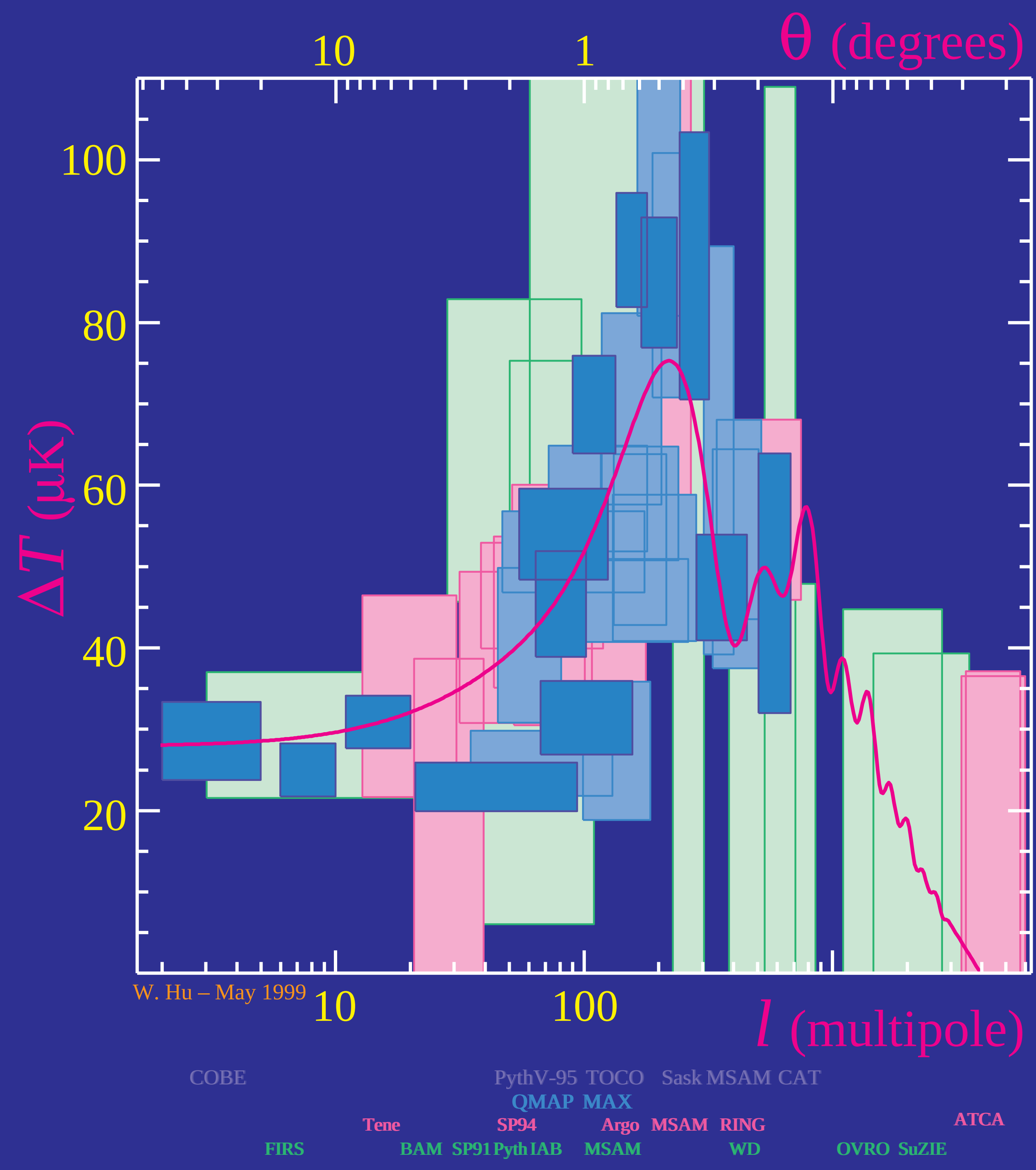
- Linearity observed: $\Delta T/T \sim 10^{-5}$
- Simple Physics
  - Gravity
  - Fluid Dynamics
  - Geometry
- Rich Features
  - Acoustic Peaks

CMB Anisotropies

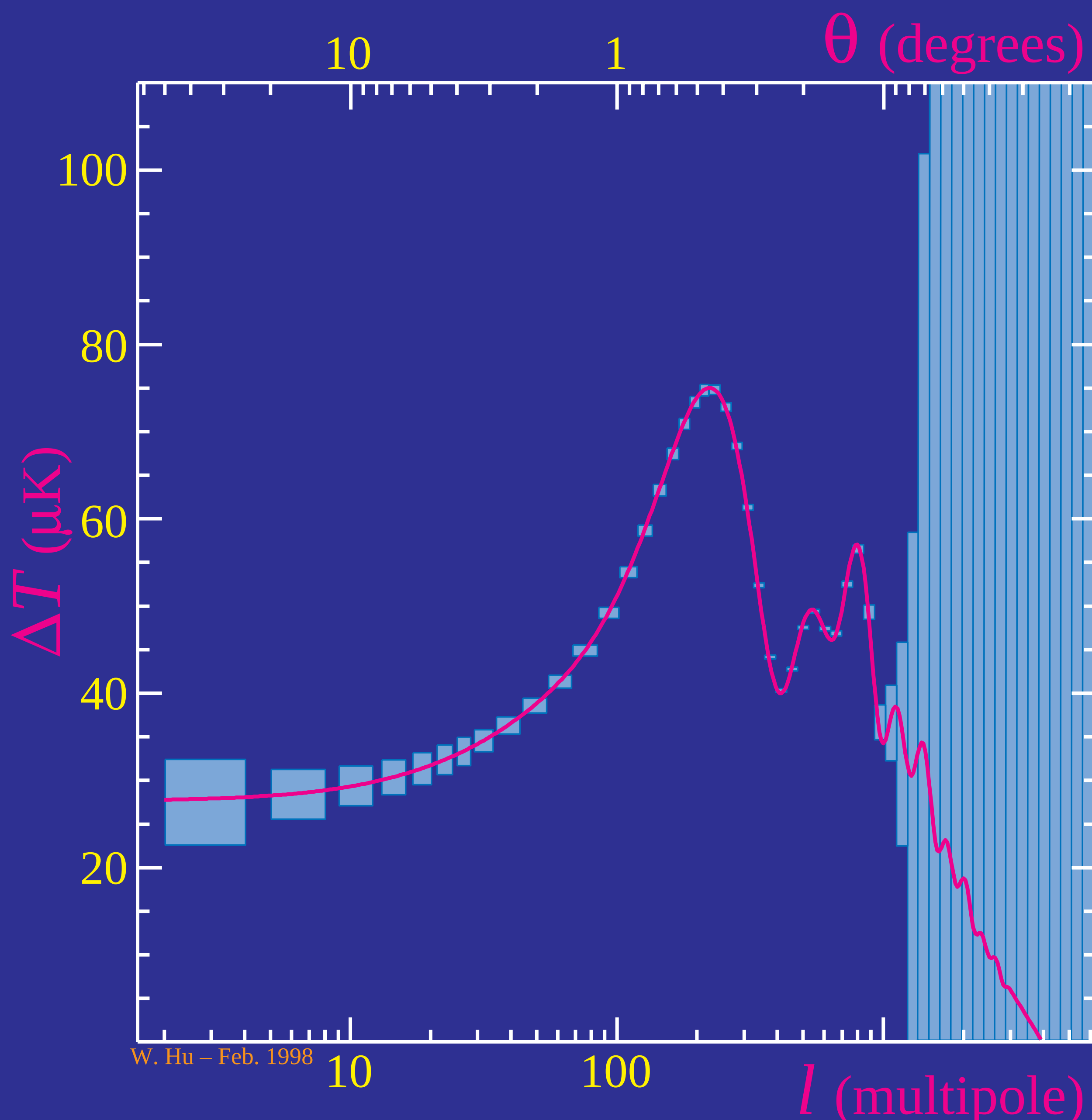


Tegmark, de Oliviera Costa, Devlin, Netterfield, & Page (1996)

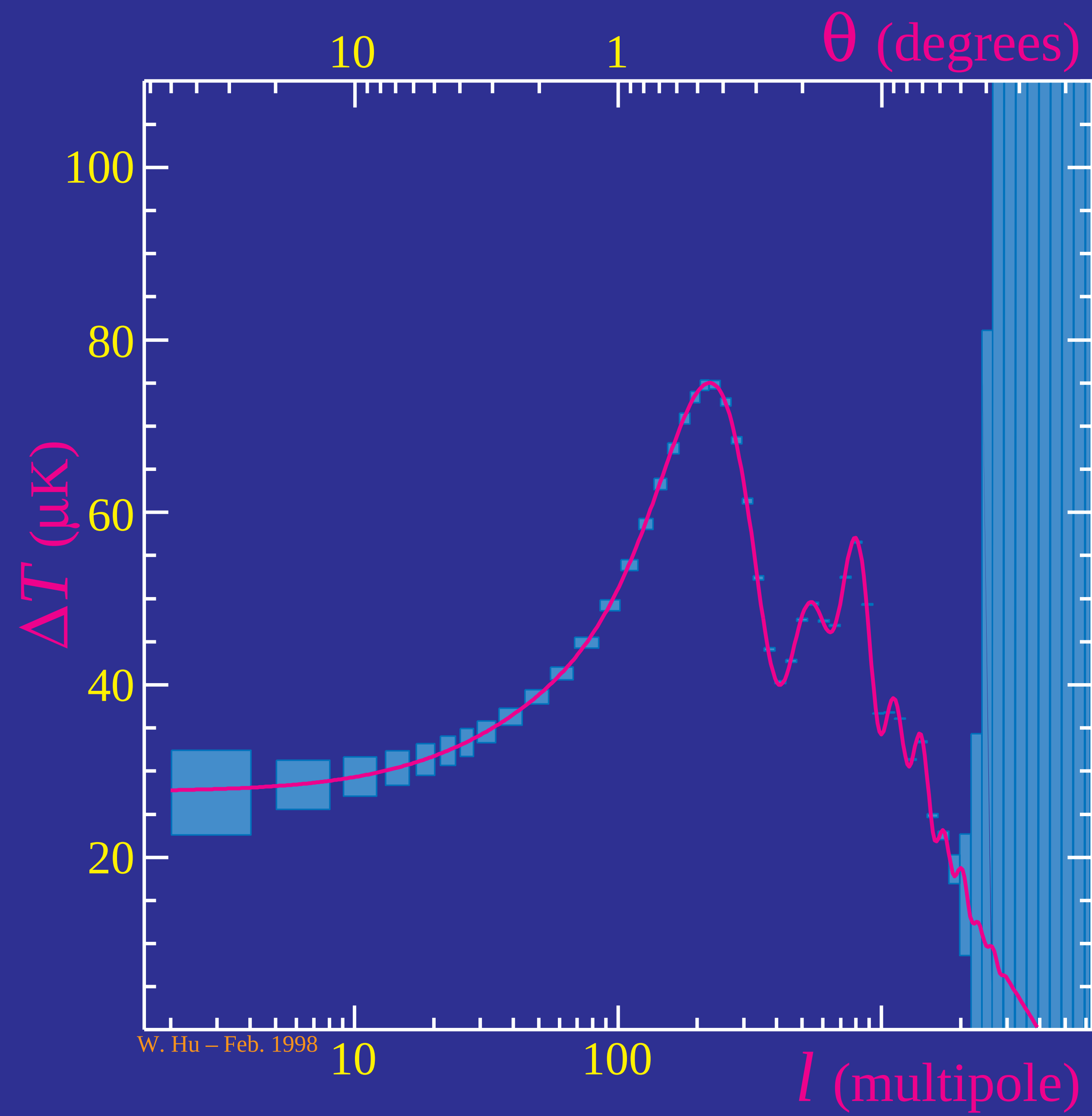
Current CMB Quilt



Projected MAP Errors



Projected Planck Errors



Thermal History

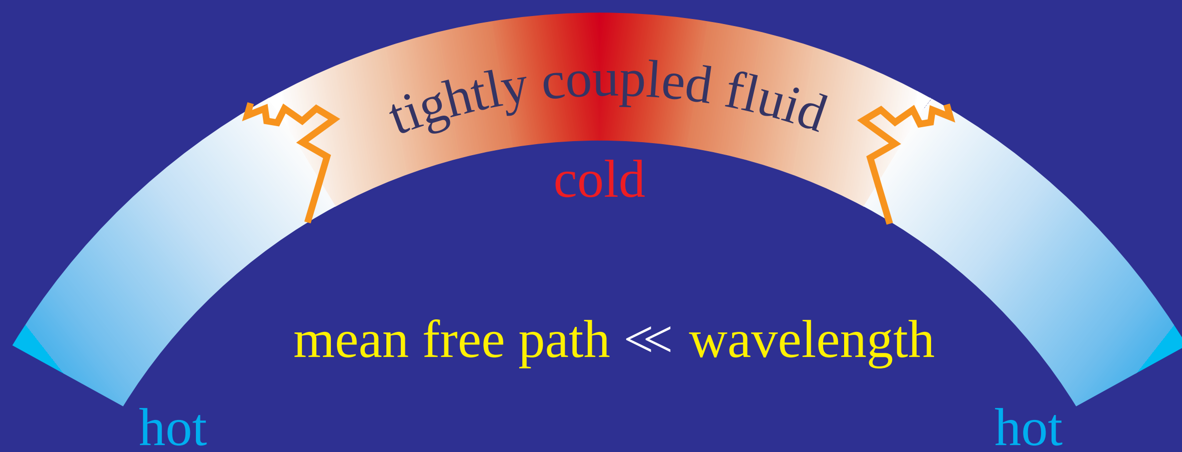
- $z > 1000$; $T_\gamma > 3000K$

  Hydrogen ionized

  Free electrons glue photons to baryons

  Photon–baryon fluid

  Potential wells that later form structure



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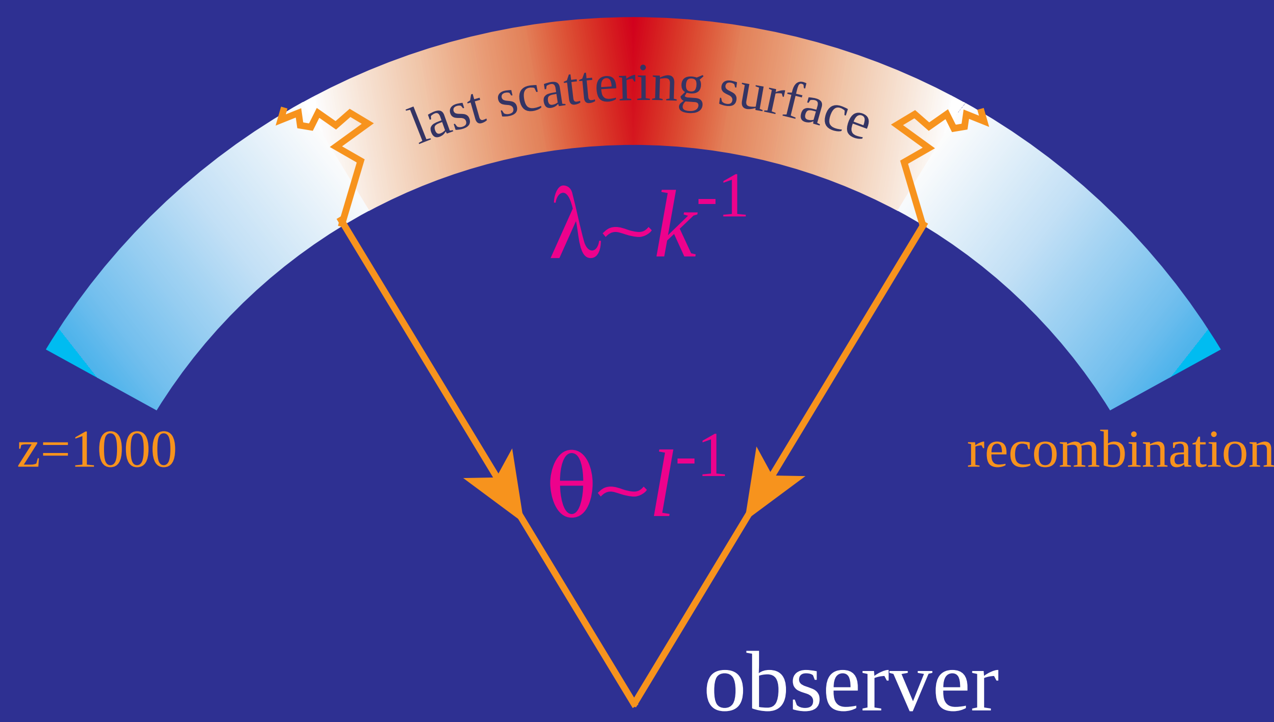
  - Hydrogen ionized
  - Free electrons glue photons to baryons

γ — compton scattering — e^- — coulomb interactions — p

  - 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

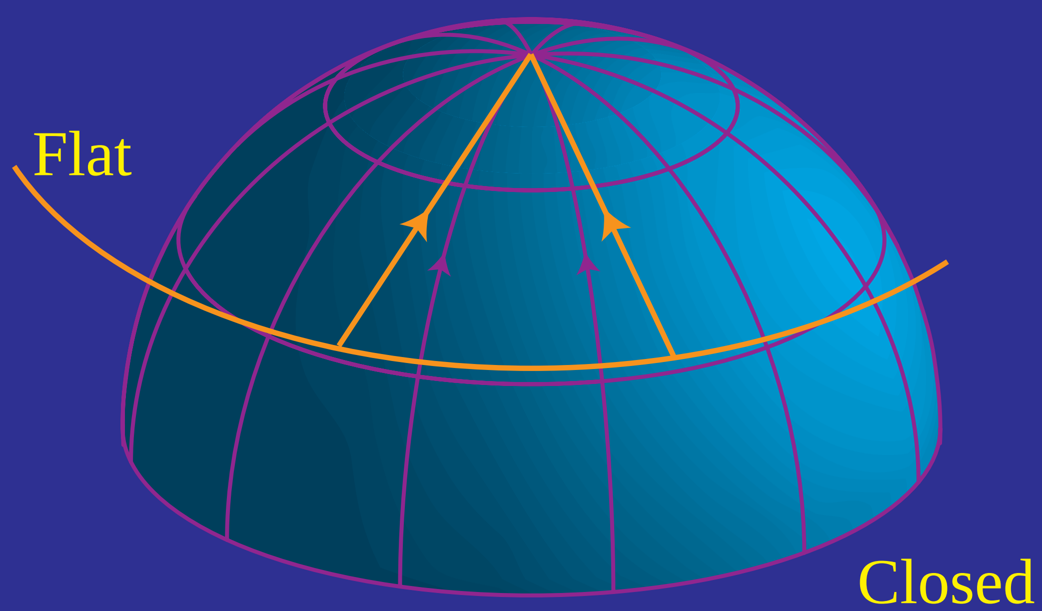
  (except for Λ)

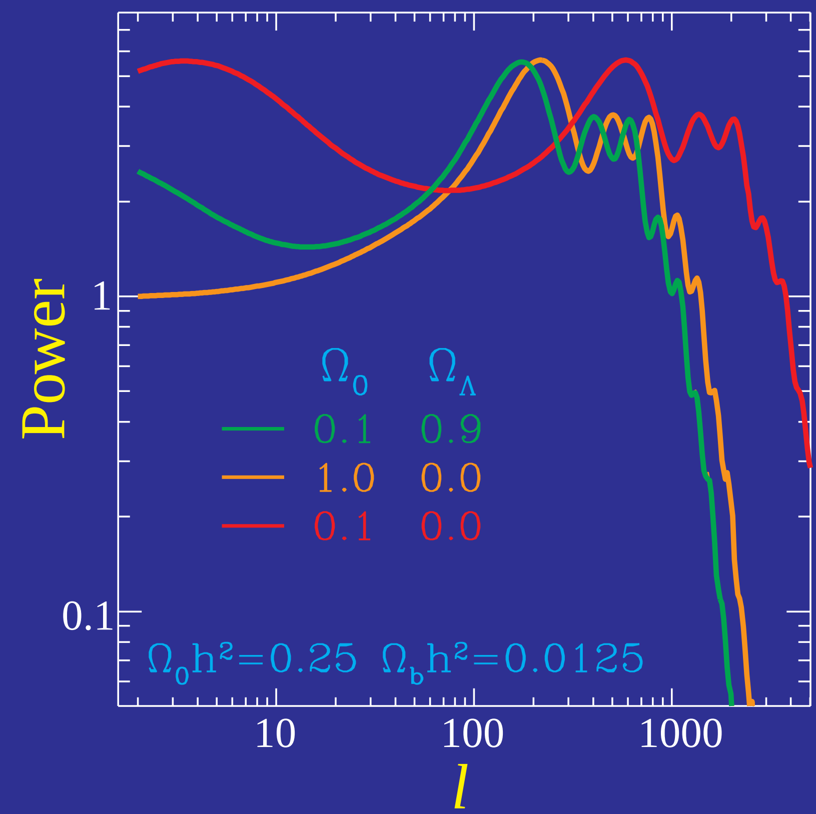
  Infer curvature

- Robust Physical Scales

  Sound horizon → Peak spacing

  Diffusion scale → Damping tail

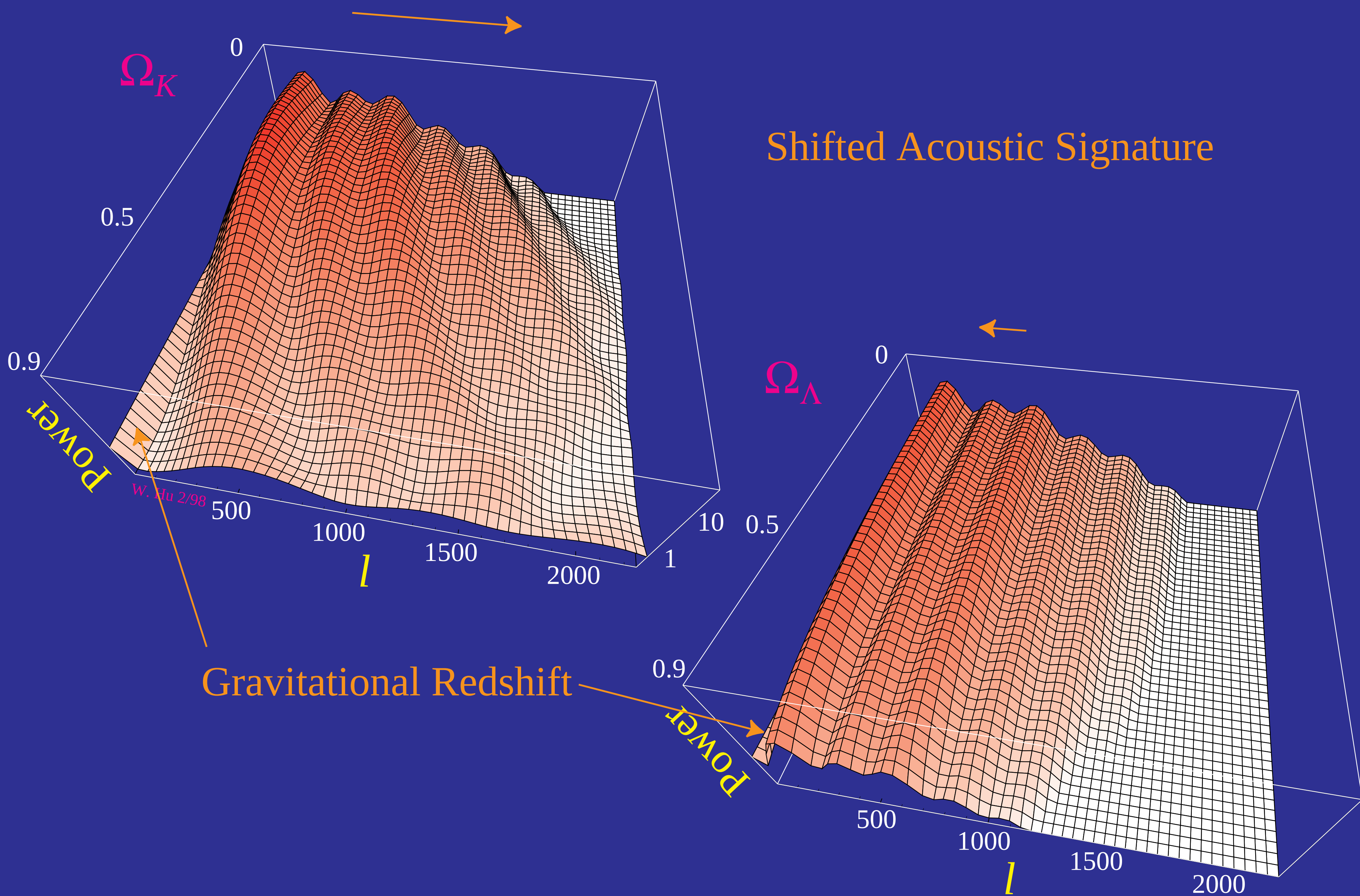




Kamionkowski, Spergel & Sugiyama (1994)

Hu & White (1996)

Curvature and the Cosmological Constant

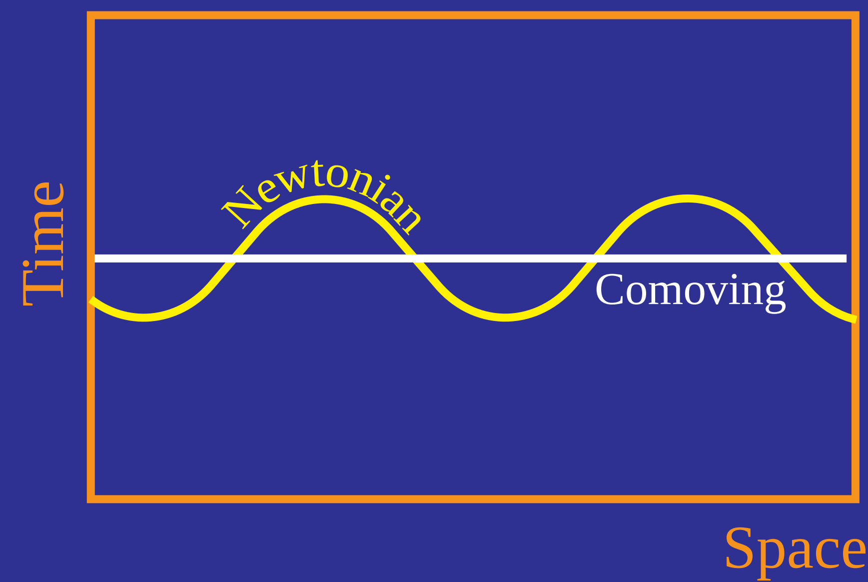


The
Acoustic Peaks

- Initial Conditions
  and the Sachs–Wolfe Effect
- Acoustic Oscillations
- Peak Positions
- Baryon Drag
- Radiation Driving
- Diffusion Damping

Initial Conditions & the Sachs-Wolfe Effect

- Initial temperature perturbation
- Observed temperature perturbation
  Gravitational redshift: Ψ
  + Initial temperature: $+\ \Theta$
- Potential = time-time metric perturbations $\Psi = \delta t/t$



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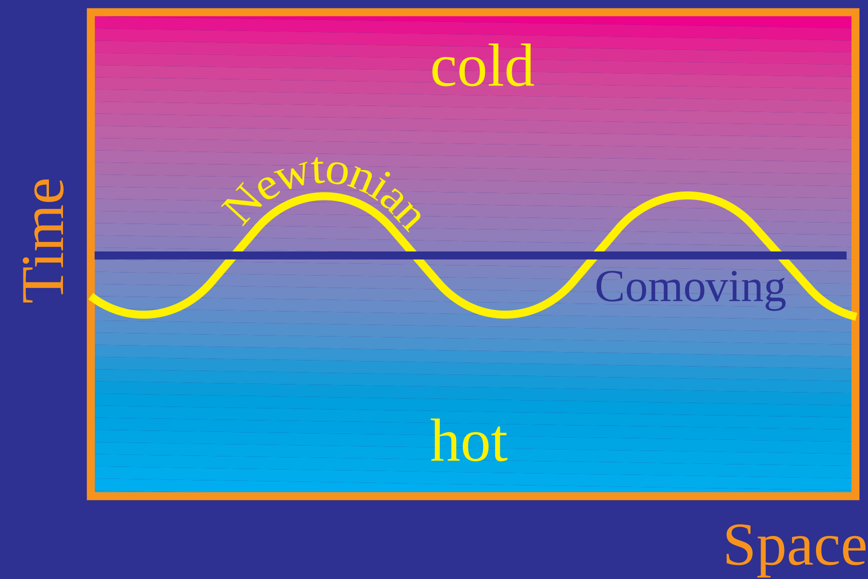
- Temperature falls as: $T \propto a^{-1}$
- Temperature fluctuation: $\delta T/T = -\delta a/a$



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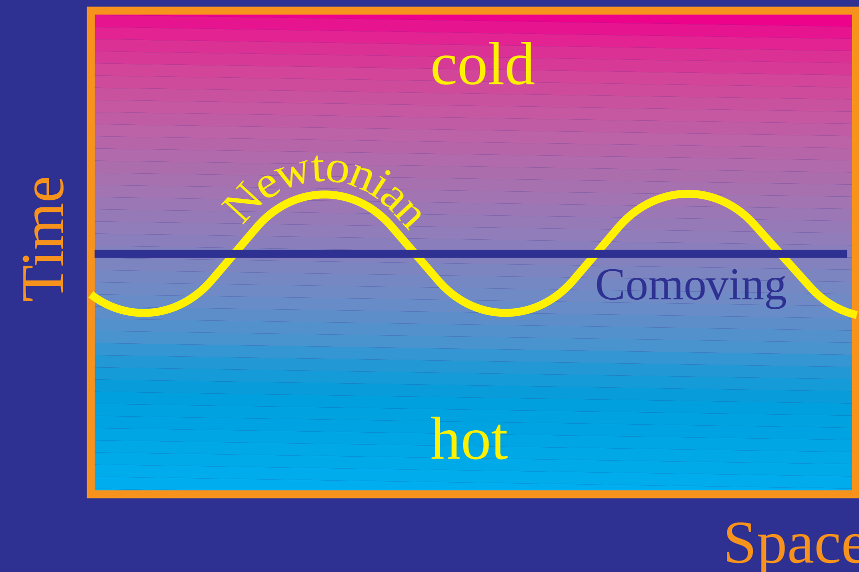

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- Temperature falls as: $T \propto a^{-1}$
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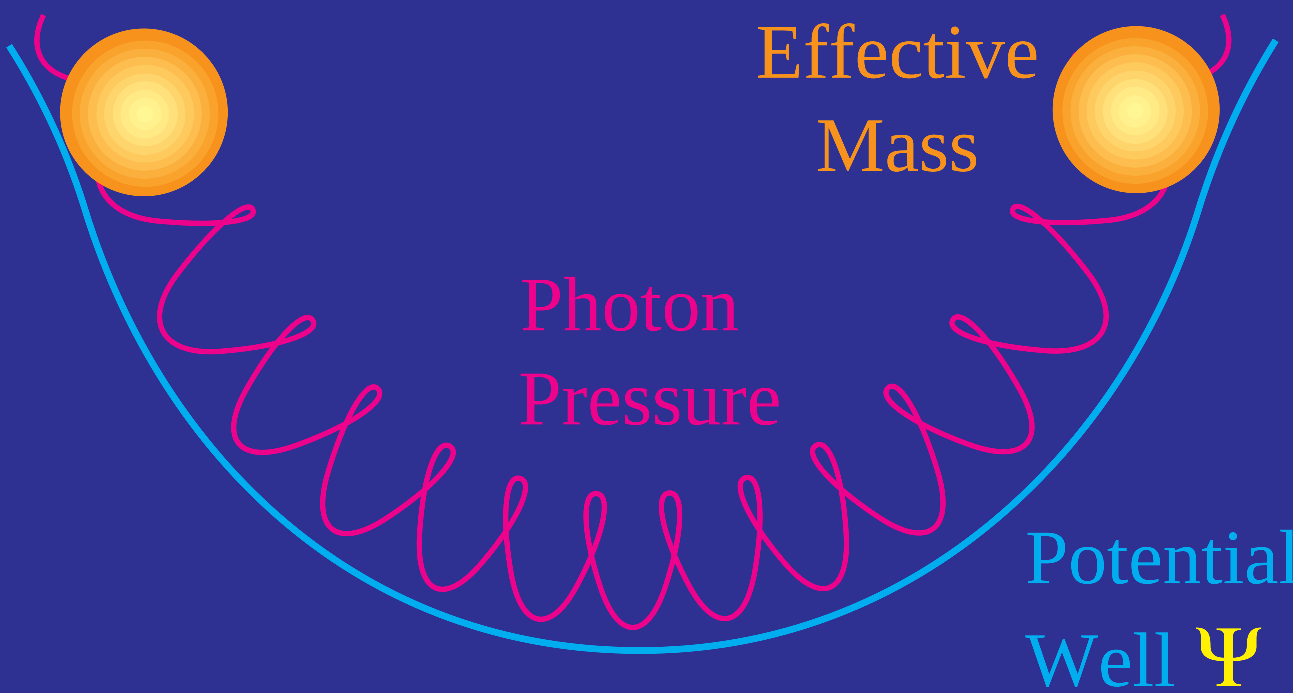
- Result
  Initial temperature perturbation: $\Theta \equiv \delta T/T = -\delta a/a = -2/3\,\delta t/t$
  $= -2/3\,\Psi$

  Observed temperature perturbation: $(\delta T/T)_{obs} = \Theta + \Psi = 1/3\,\Psi$

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

Acoustic Oscillations

- Photon pressure resists compression in potential wells
- Acoustic oscillations



Peebles & Yu (1970)

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

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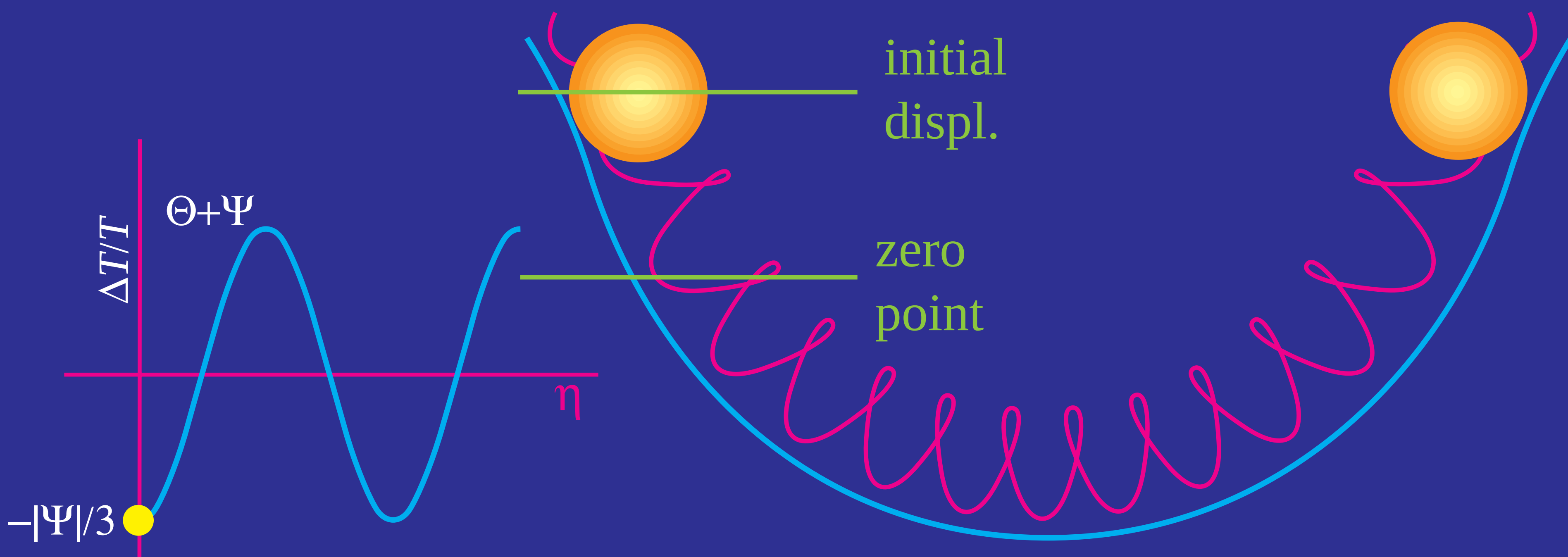

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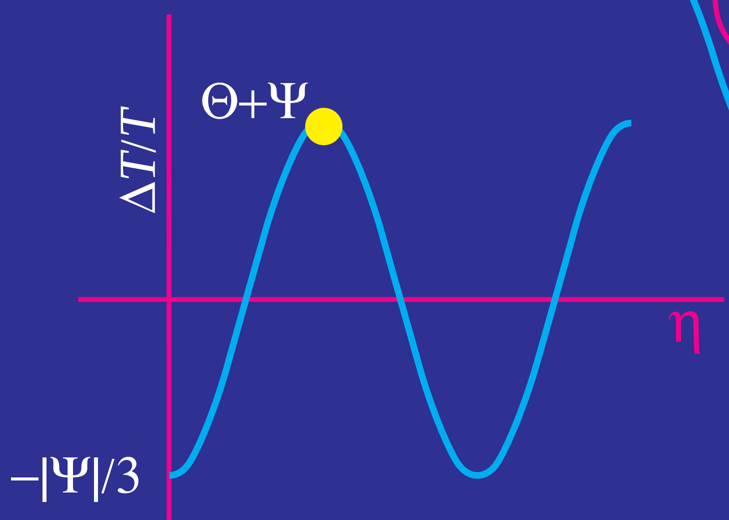
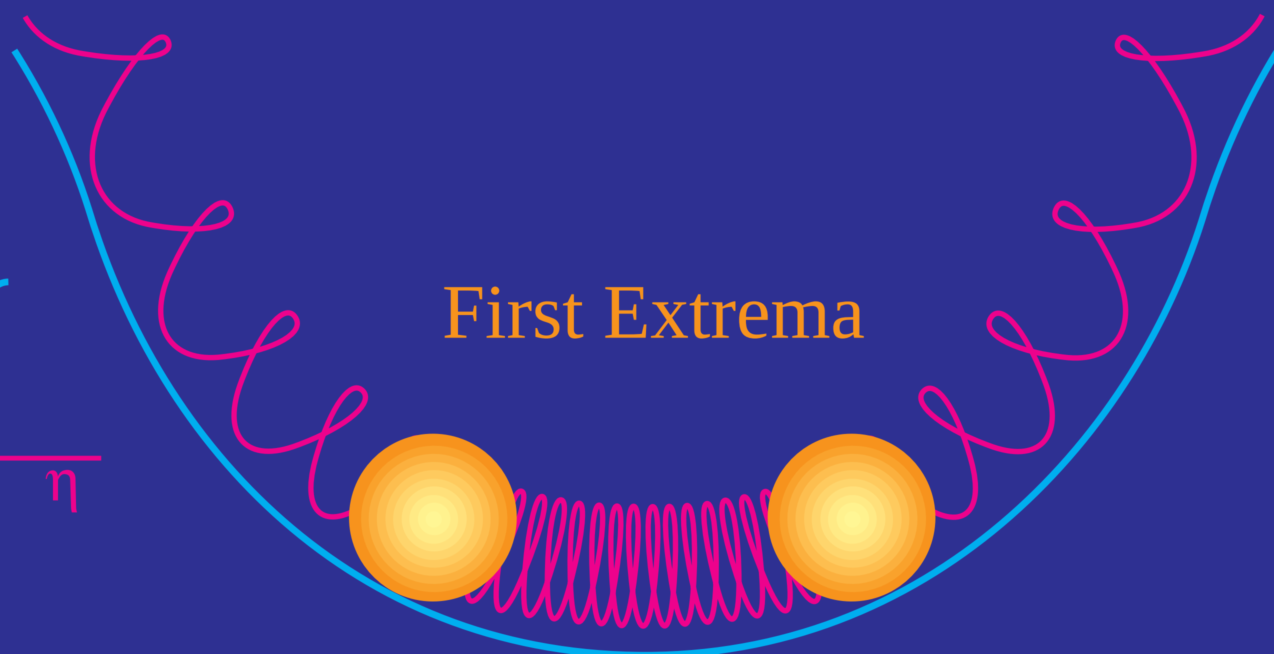
  oscillates around zero





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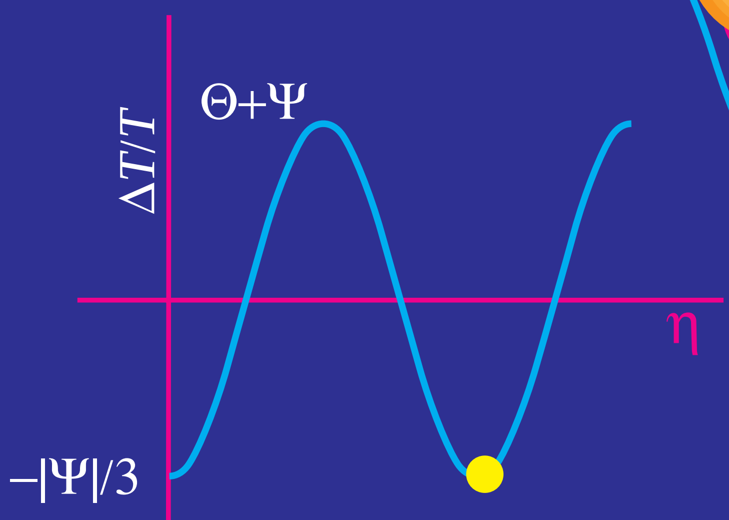

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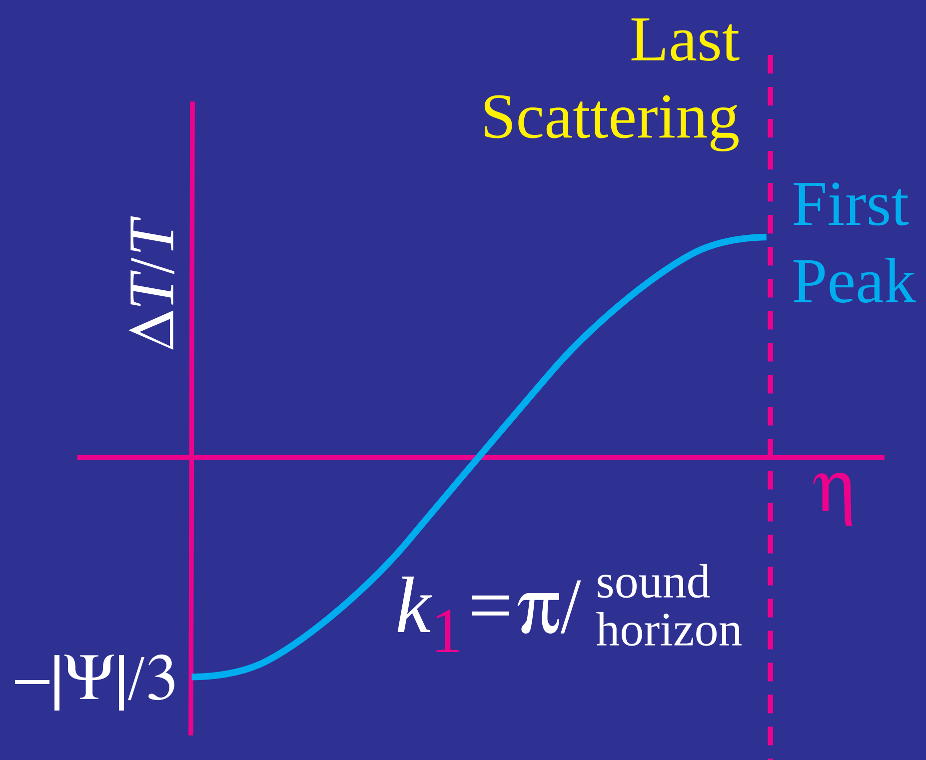
Harmonic Peaks

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



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Harmonic Peaks

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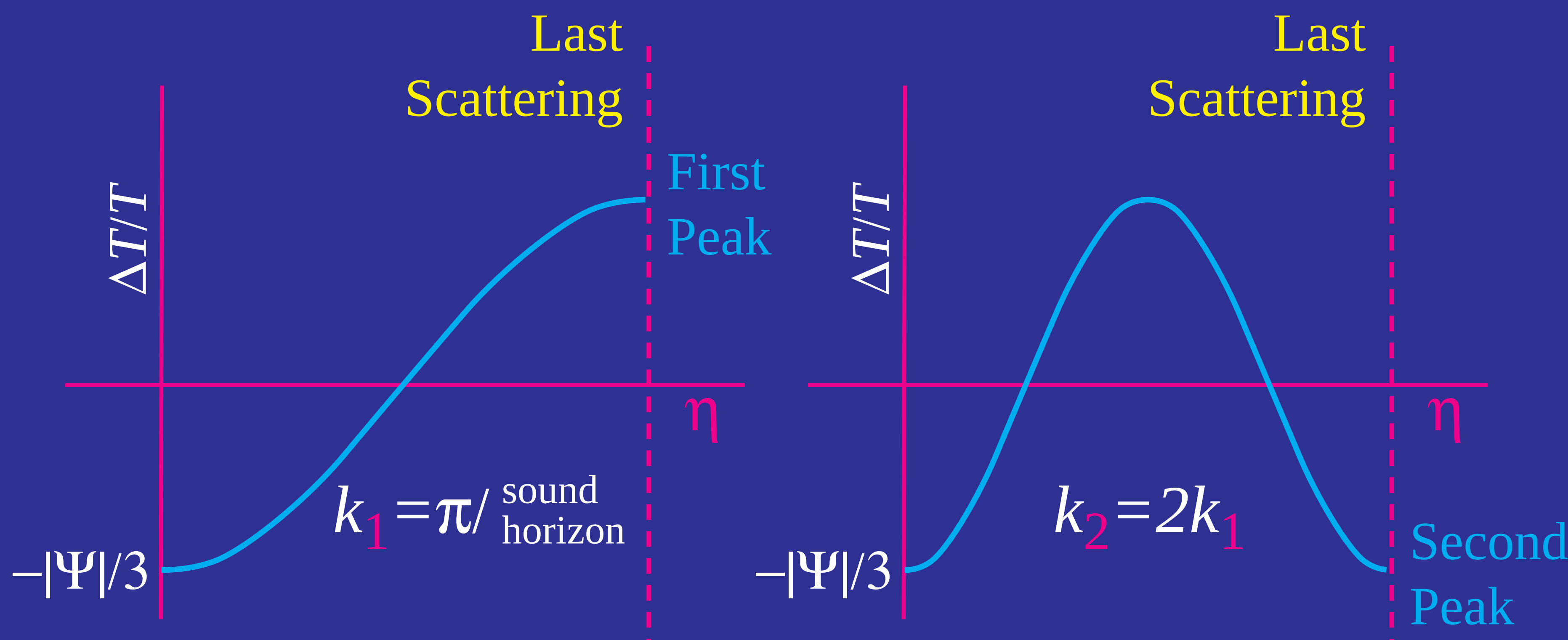
- Sound speed c_s

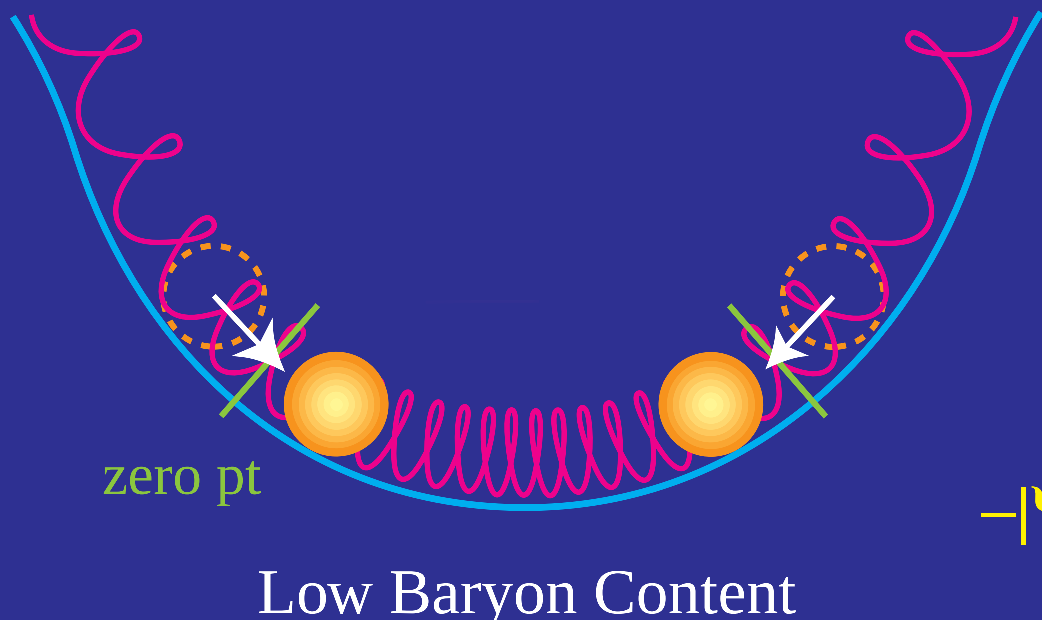
- Frequency $\omega = kc_s$; conformal time η
- Phase $\propto k$; $\phi = \int_0^{\text{last scattering}} d\eta\, \omega = k$ sound horizon
- Harmonic series in sound horizon
  $\phi_n = n\pi \rightarrow k_n = n\pi/$ sound horizon

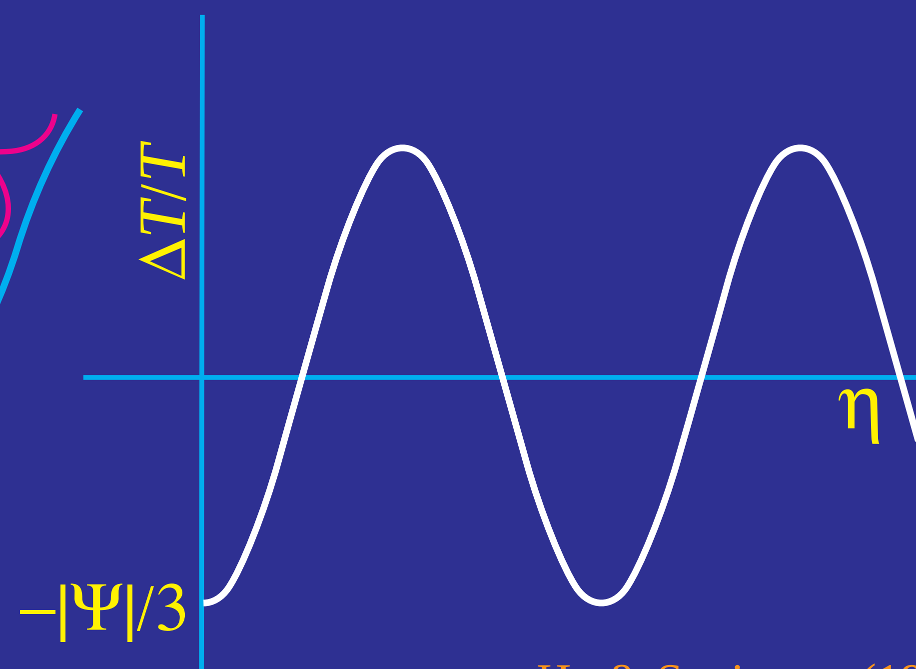


Hu & Sugyama (1995); Hu, Sugiyama & Silk (1997)

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





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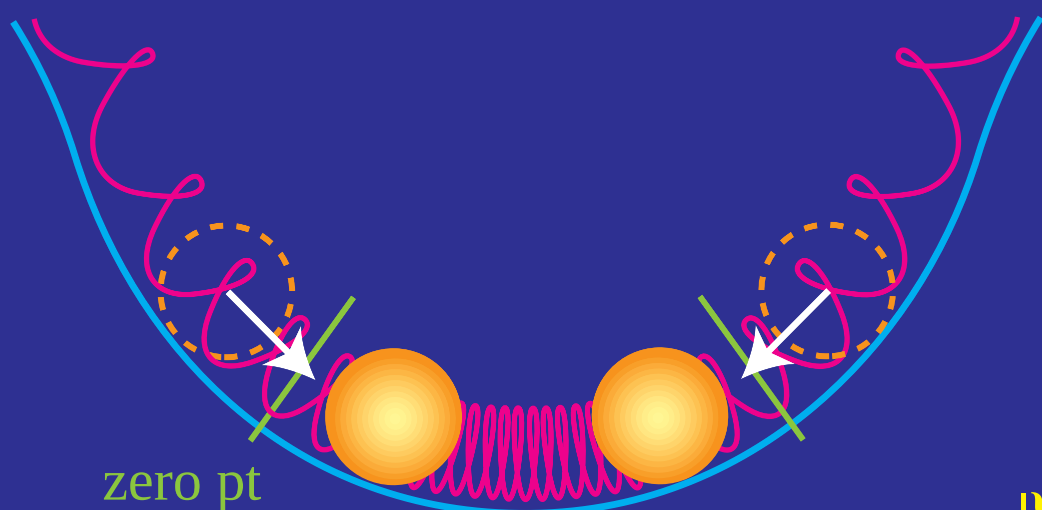
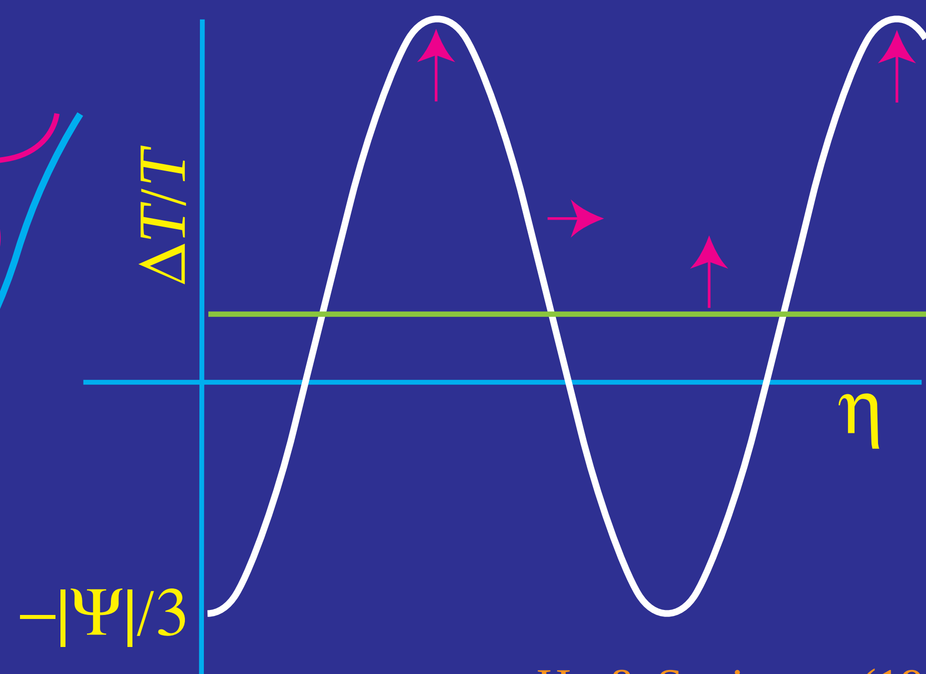
- Baryons drag photons into potential wells → zero point ↑
- Amplitude ↑
- Frequency ↓ $(\omega \propto m_{\rm eff}^{-1/2})$
- Constant R, Ψ: $(1+R)\ddot{\Theta} + (k^2/3)\Theta = -(1+R)(k^2/3)\Psi$

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



High Baryon Content



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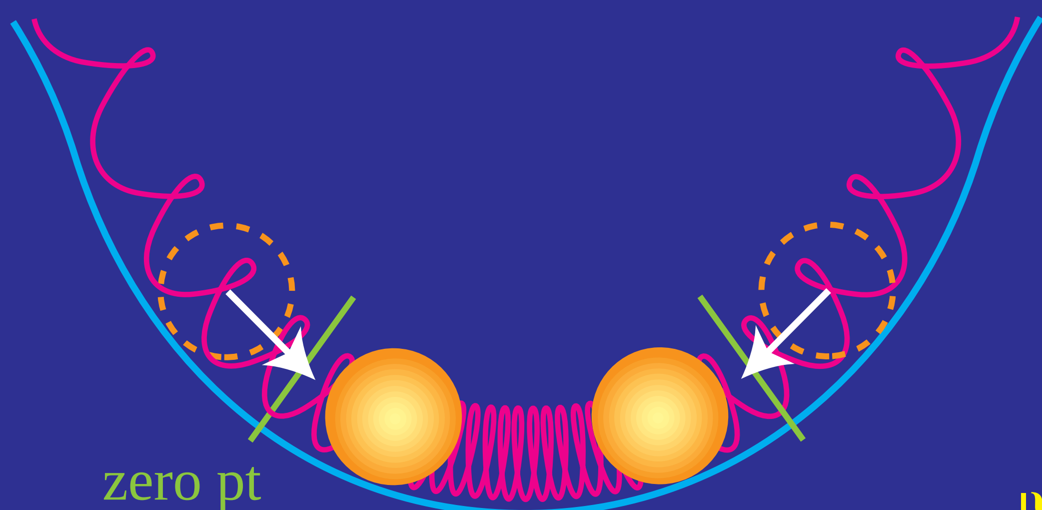
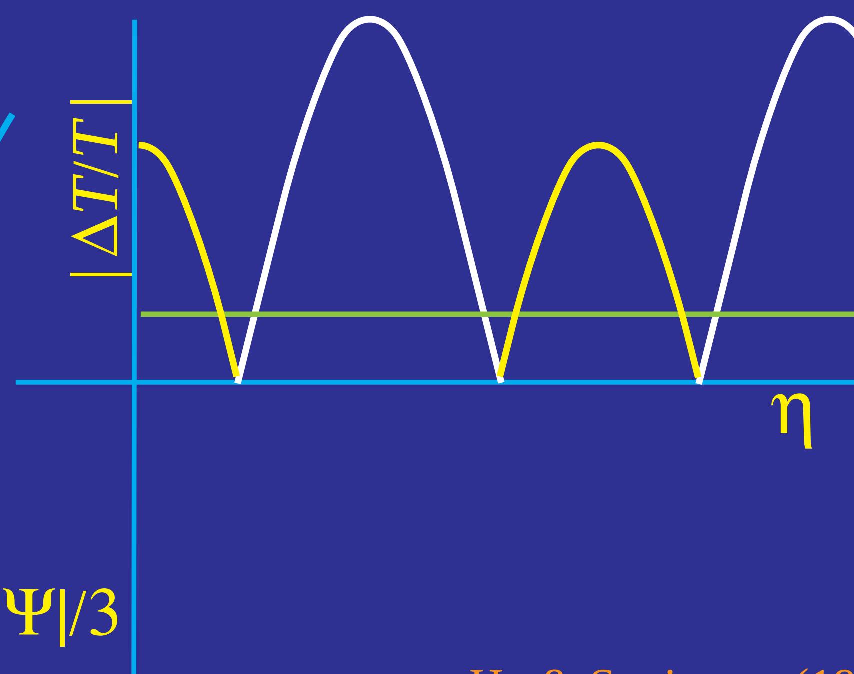
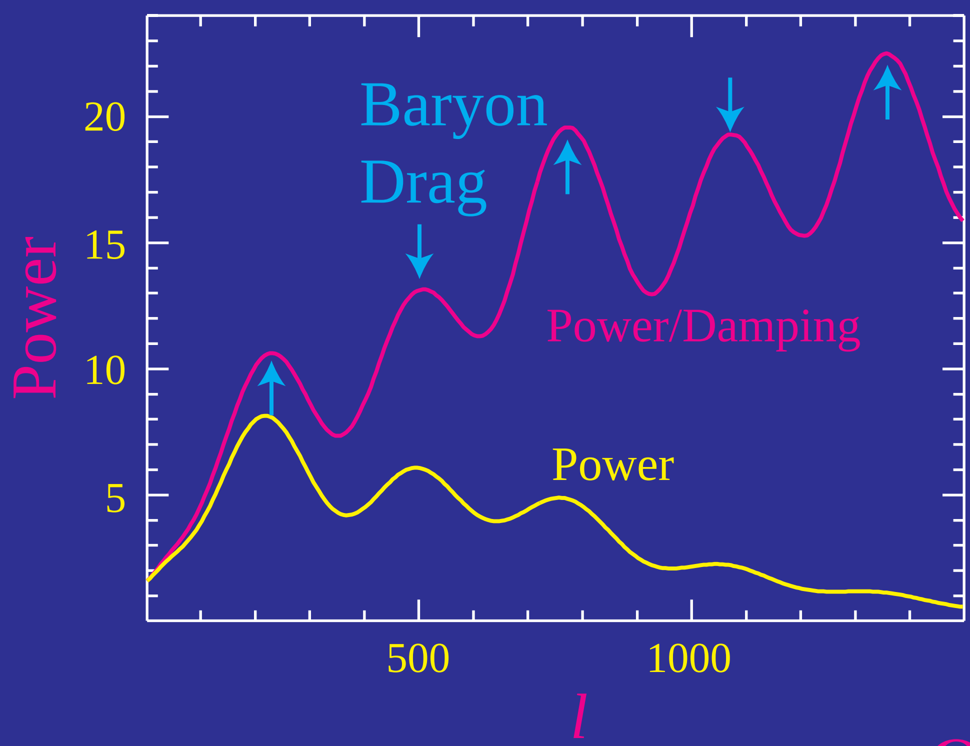


Alternating Peak Heights

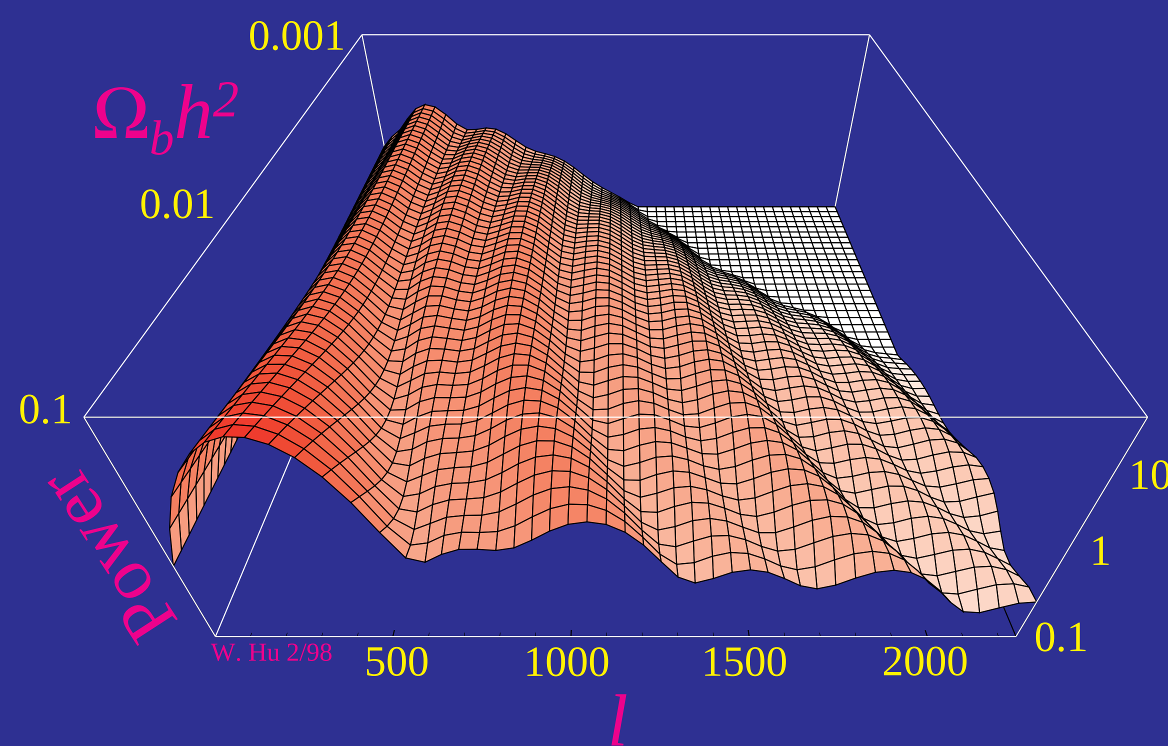


Hu & Sugiyama (1995)

Baryons in the CMB



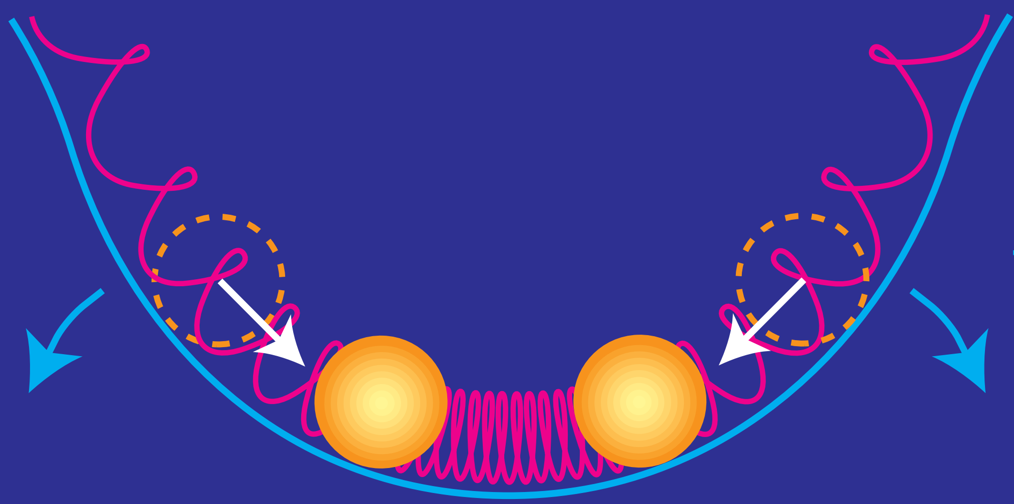
- High odd peaks

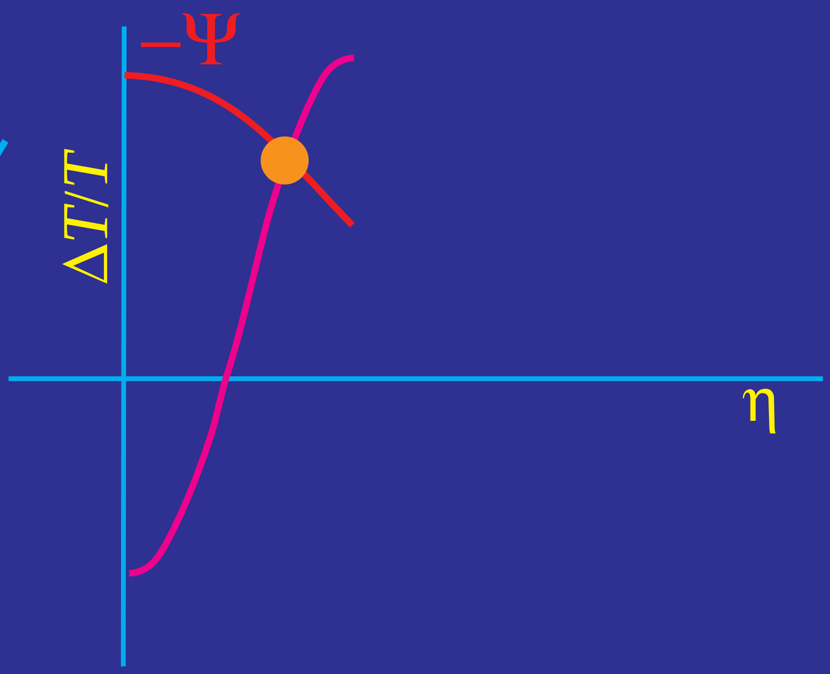


- Additional Effects
  - Time–varying potential
  - Dissipation/Fluid imperfections

Driving Effects and Matter/Radiation

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





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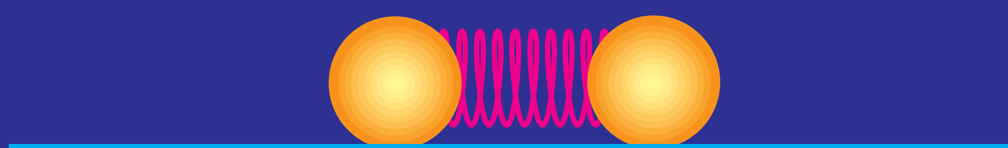
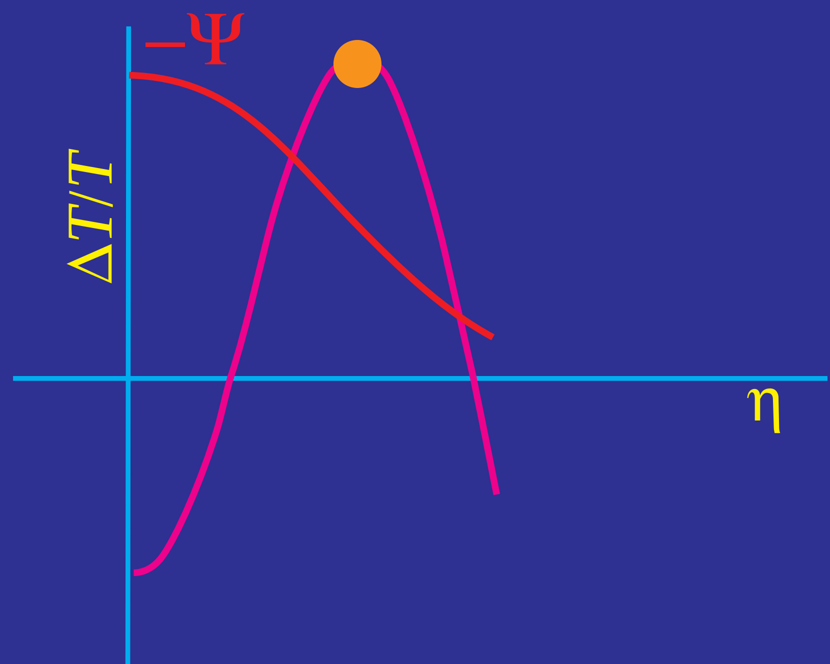
  $-2\Psi + (1/3)\Psi = -(5/3)\Psi \rightarrow$ 5x boost
- Feedback stops at matter domination





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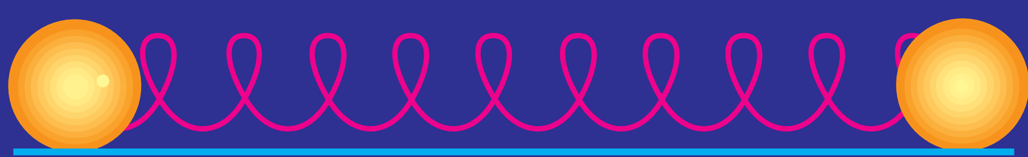
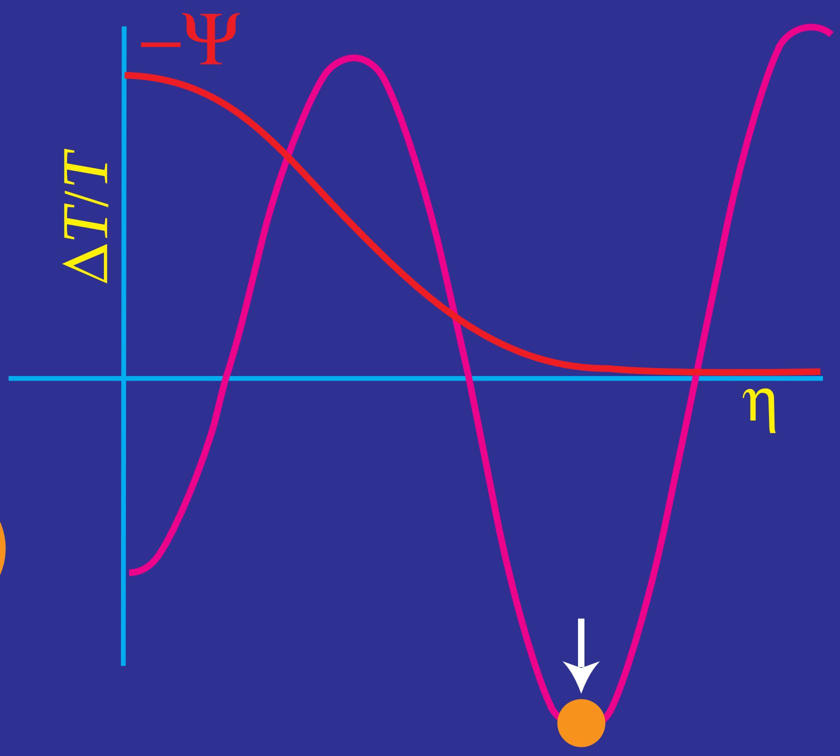
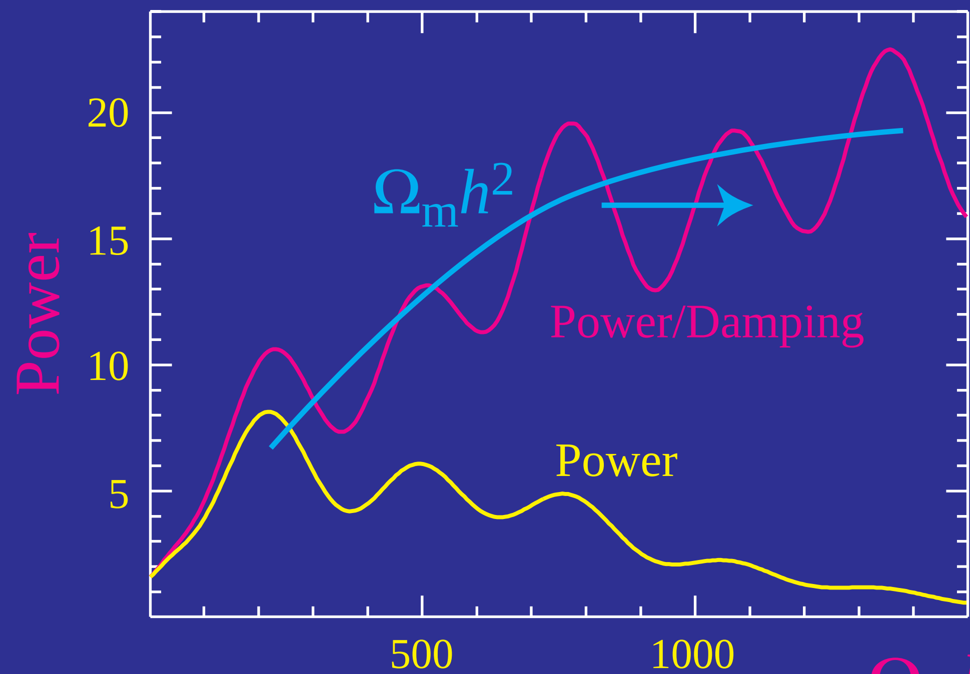


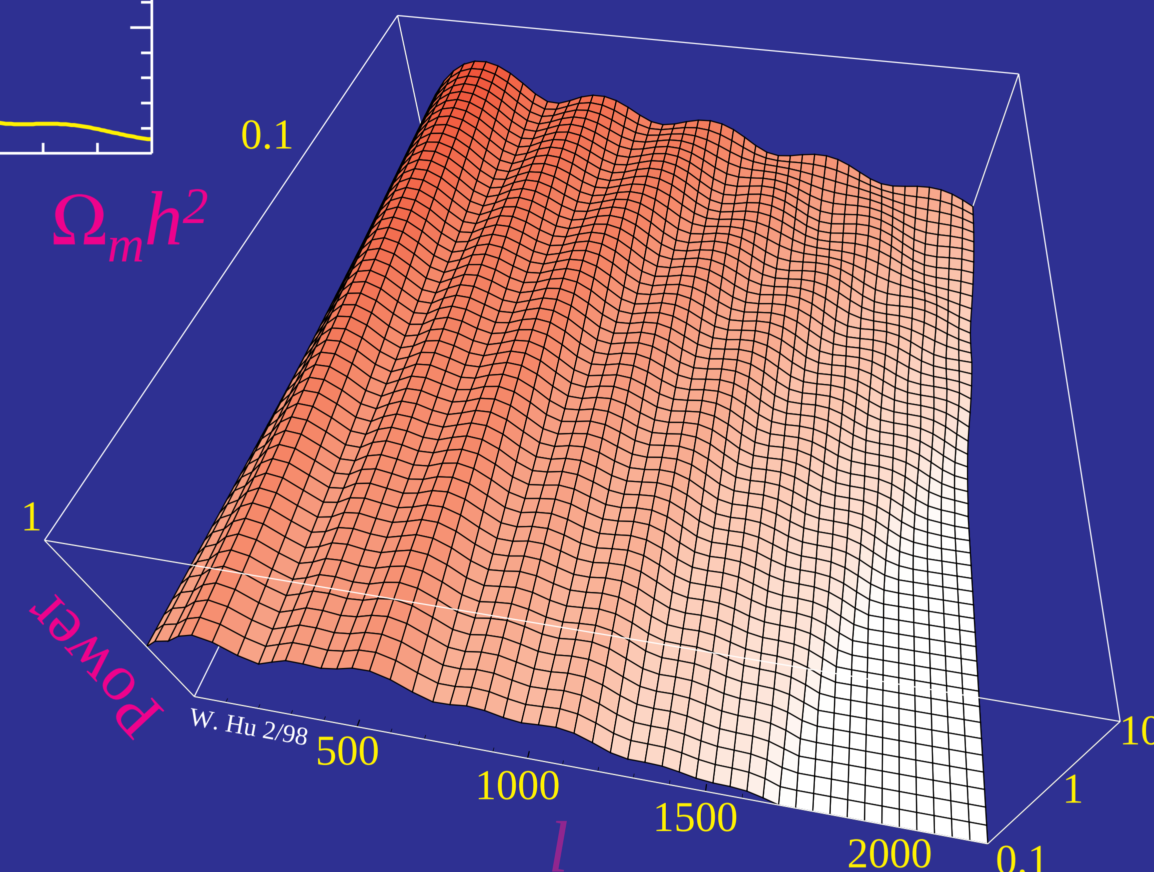


Hu & Sugiyama (1995)

Matter Density in the CMB



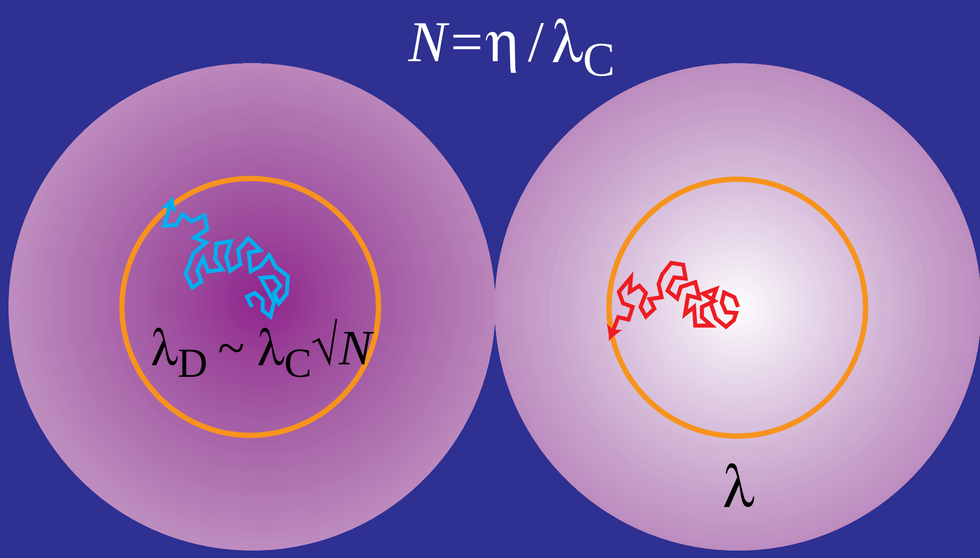
- Amplitude ramp across matter–radiation equality
- Radiation density fixed by CMB temperature & thermal history

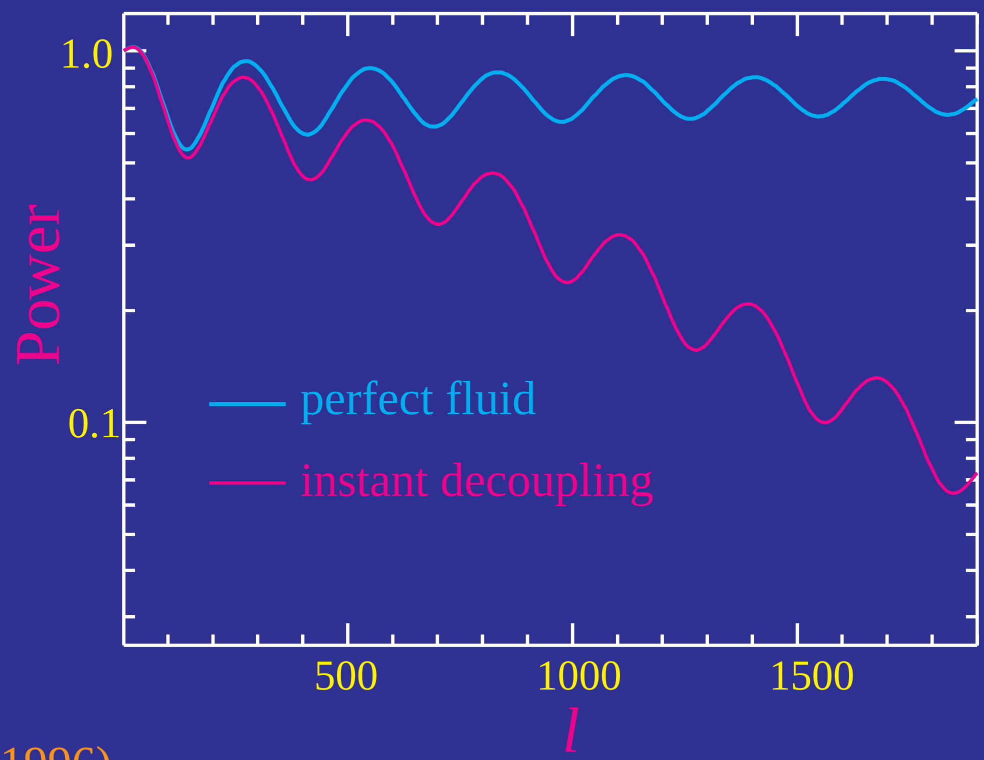


- Measure $\Omega_m h^2$ from peak heights

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 $R>1$

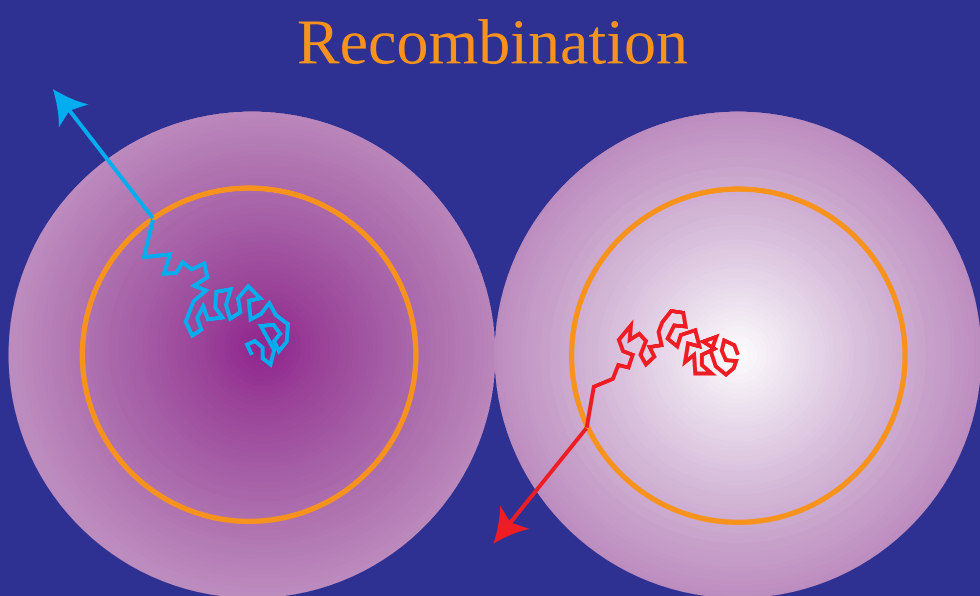


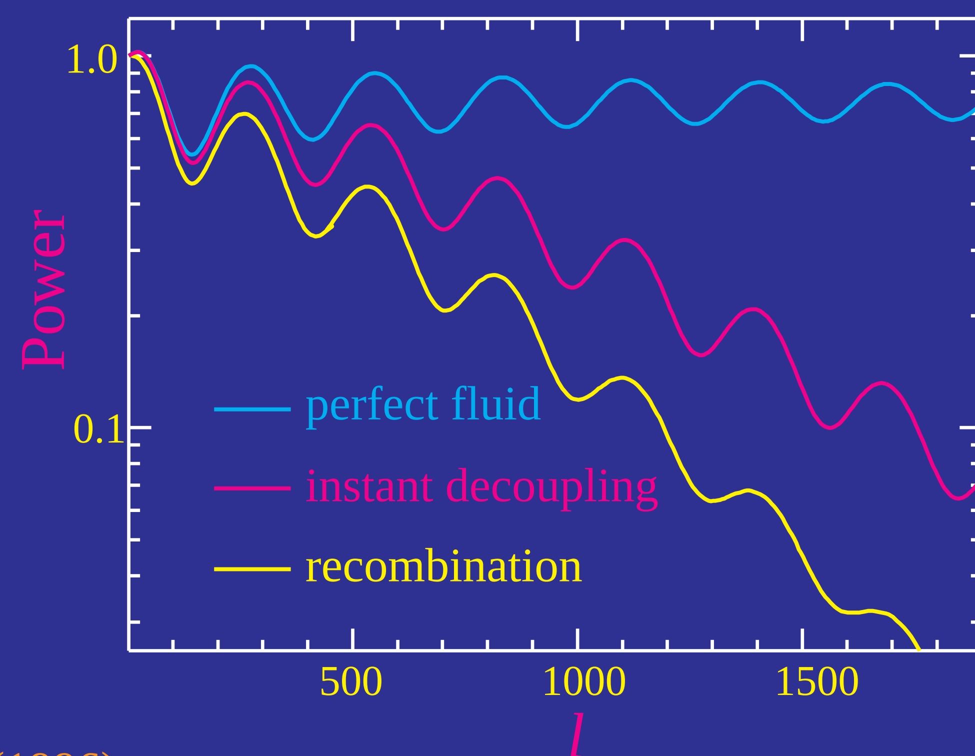


Silk (1968); Hu & Sugiyama (1995); Hu & White (1996)

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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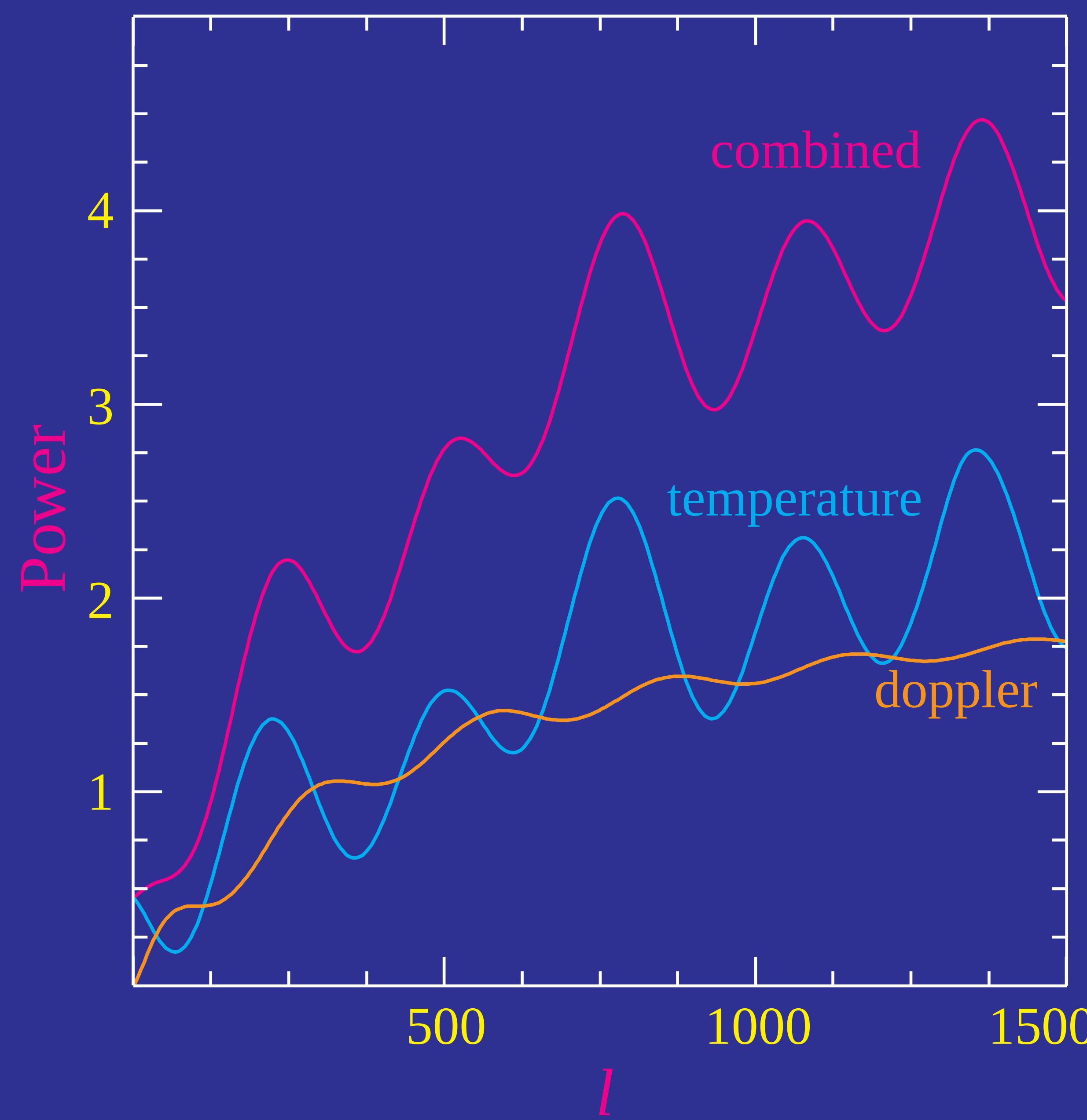
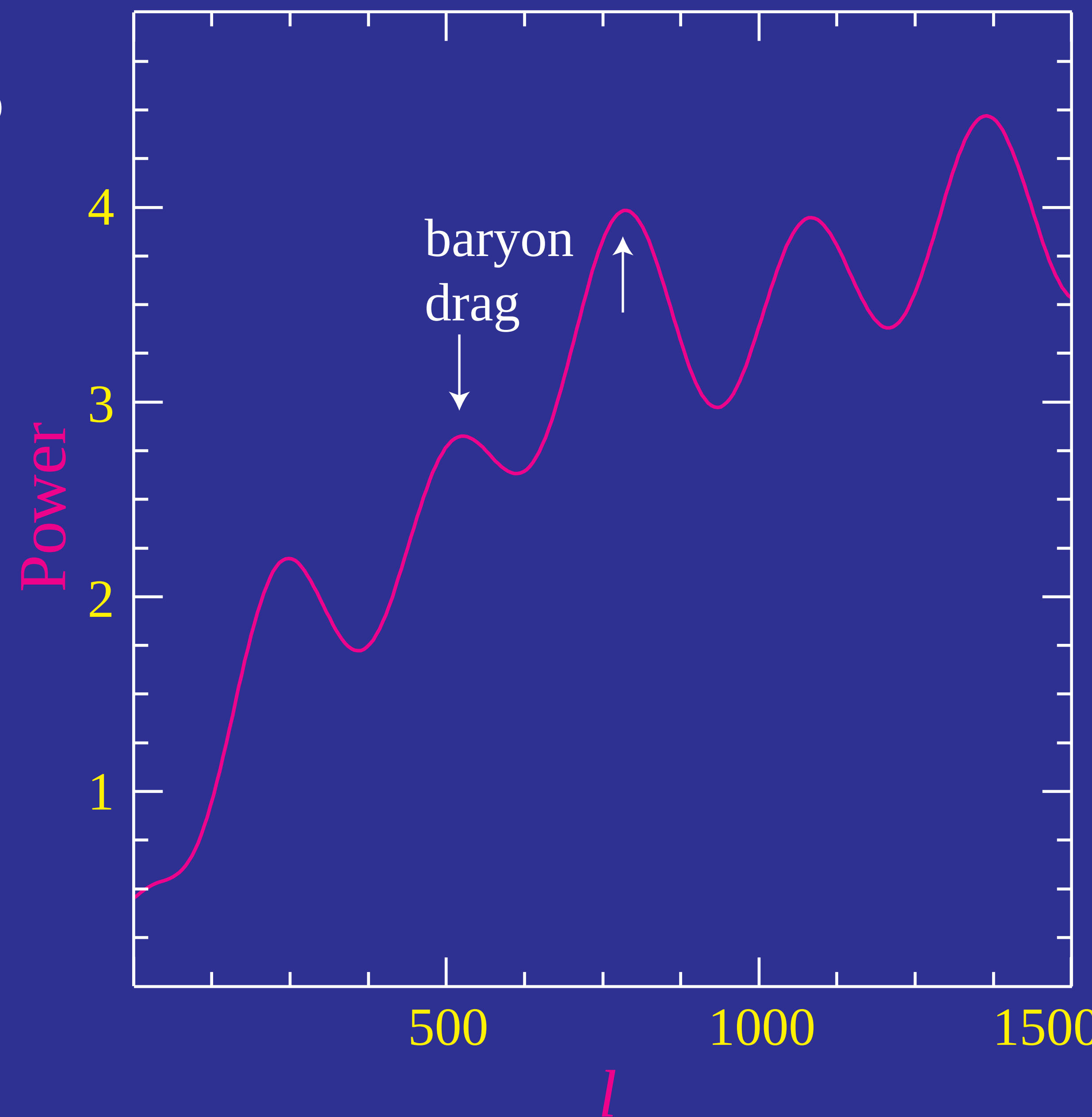
Physical Decomposition & Information



Physical Decomposition & Information

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



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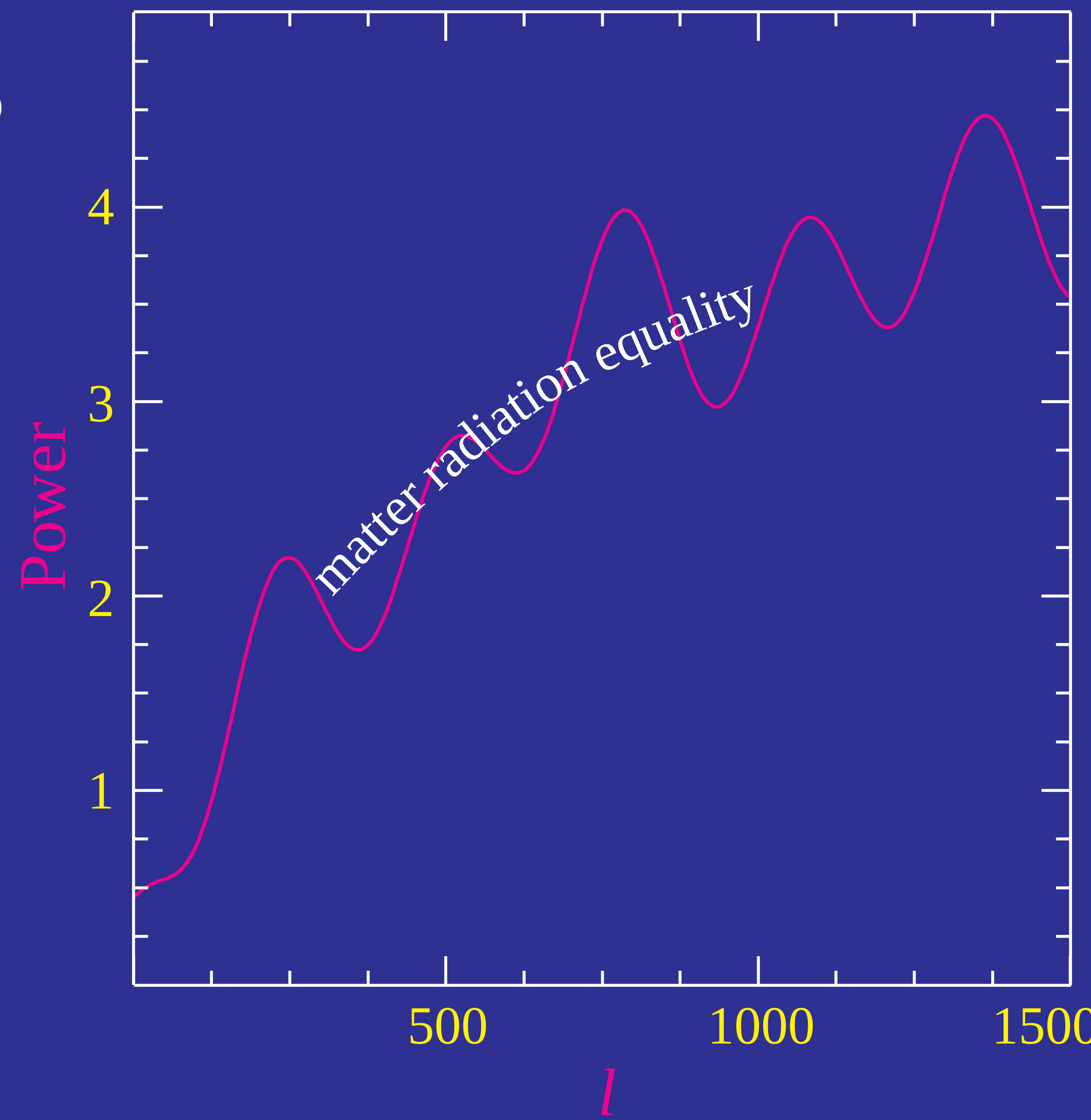
  - → photon-baryon ratio
  - → $\Omega_b h^2$
  - → driven oscillations
  - → matter–radiation ratio
  - → $\Omega_m h^2$



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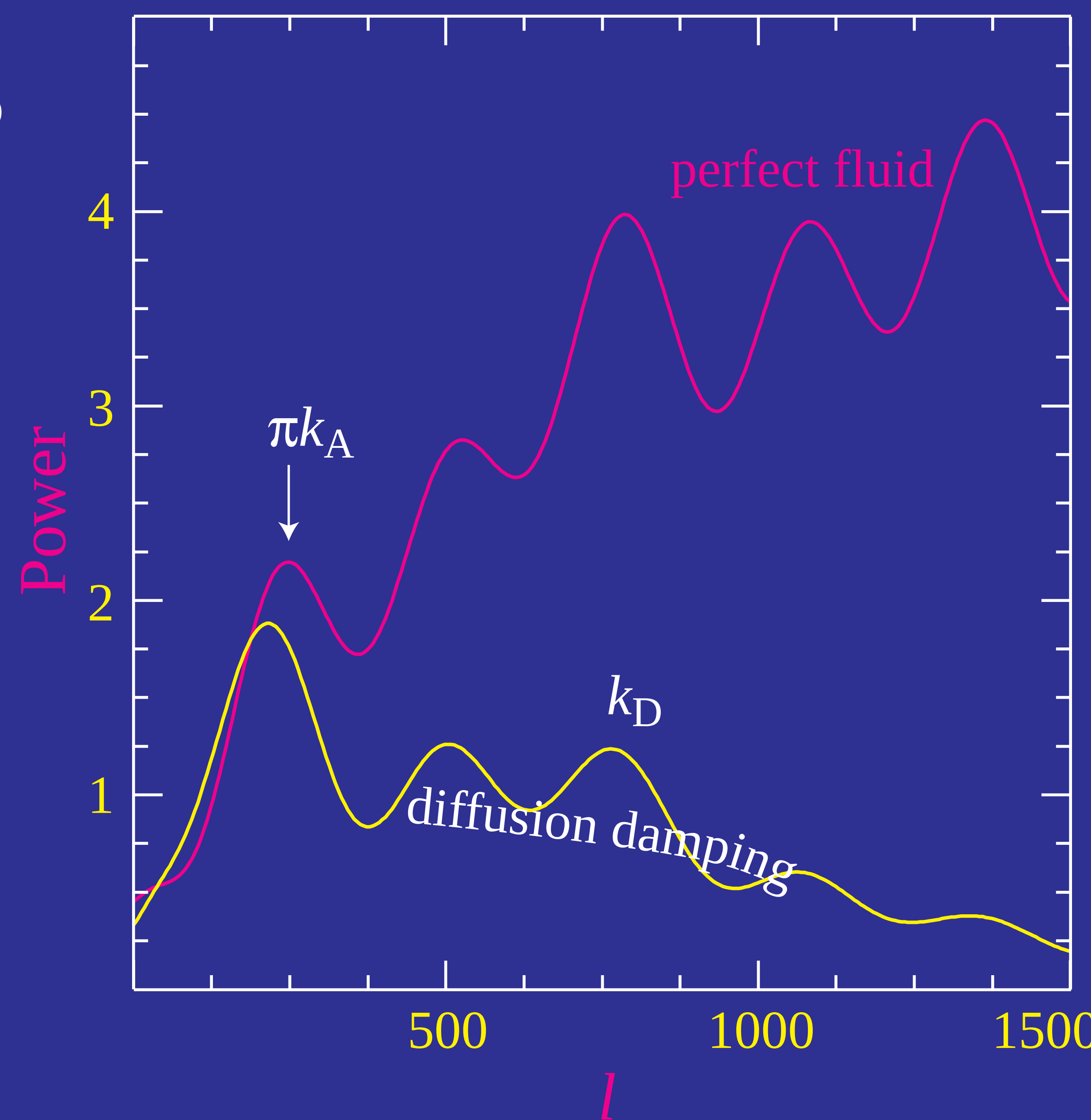
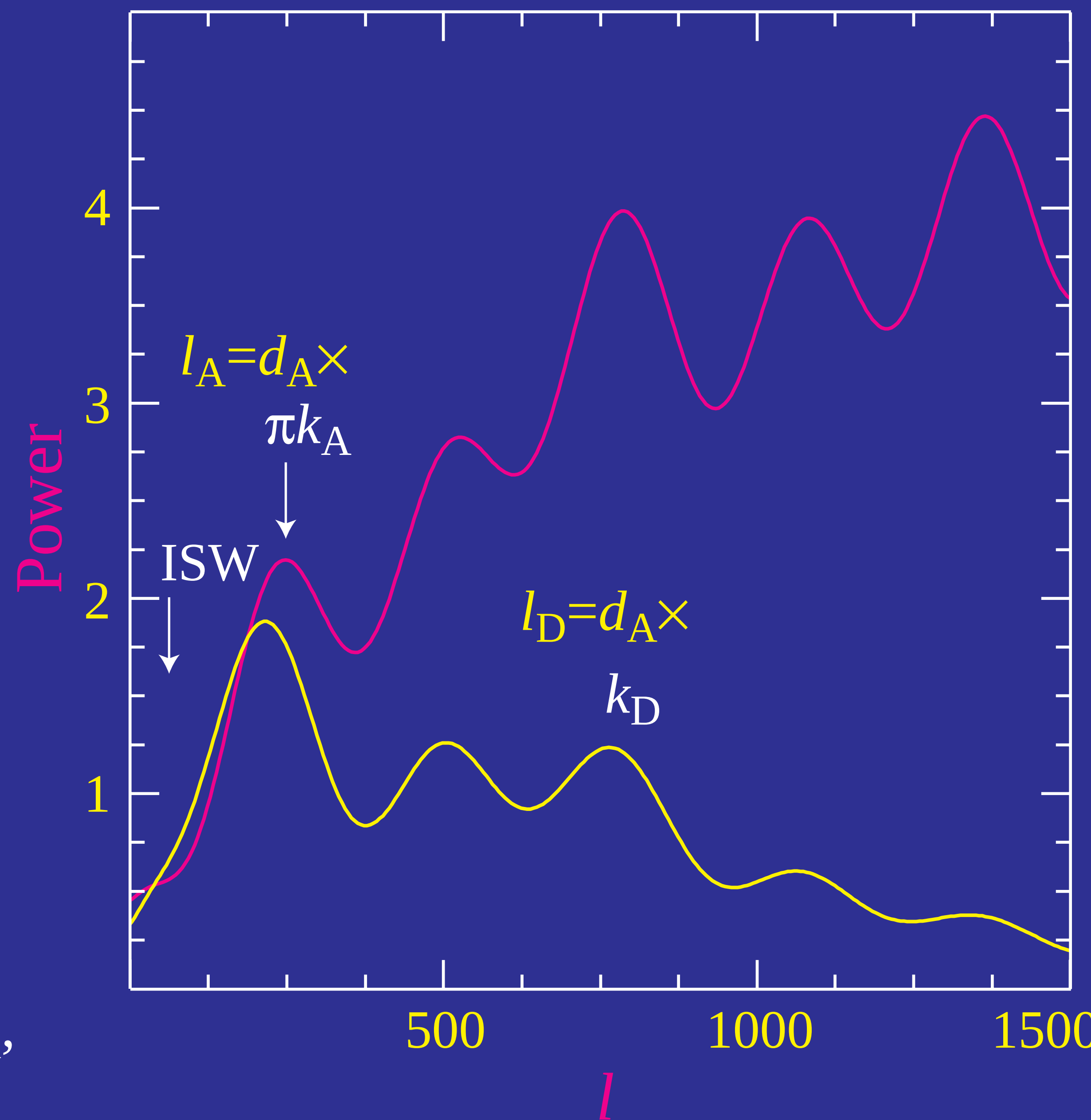
  - → $\Omega_b h^2$
  - → driven oscillations
  - → matter–radiation ratio
  - → $\Omega_m h^2$
- Fluid Rulers
  - → sound horizon
  - → damping scale

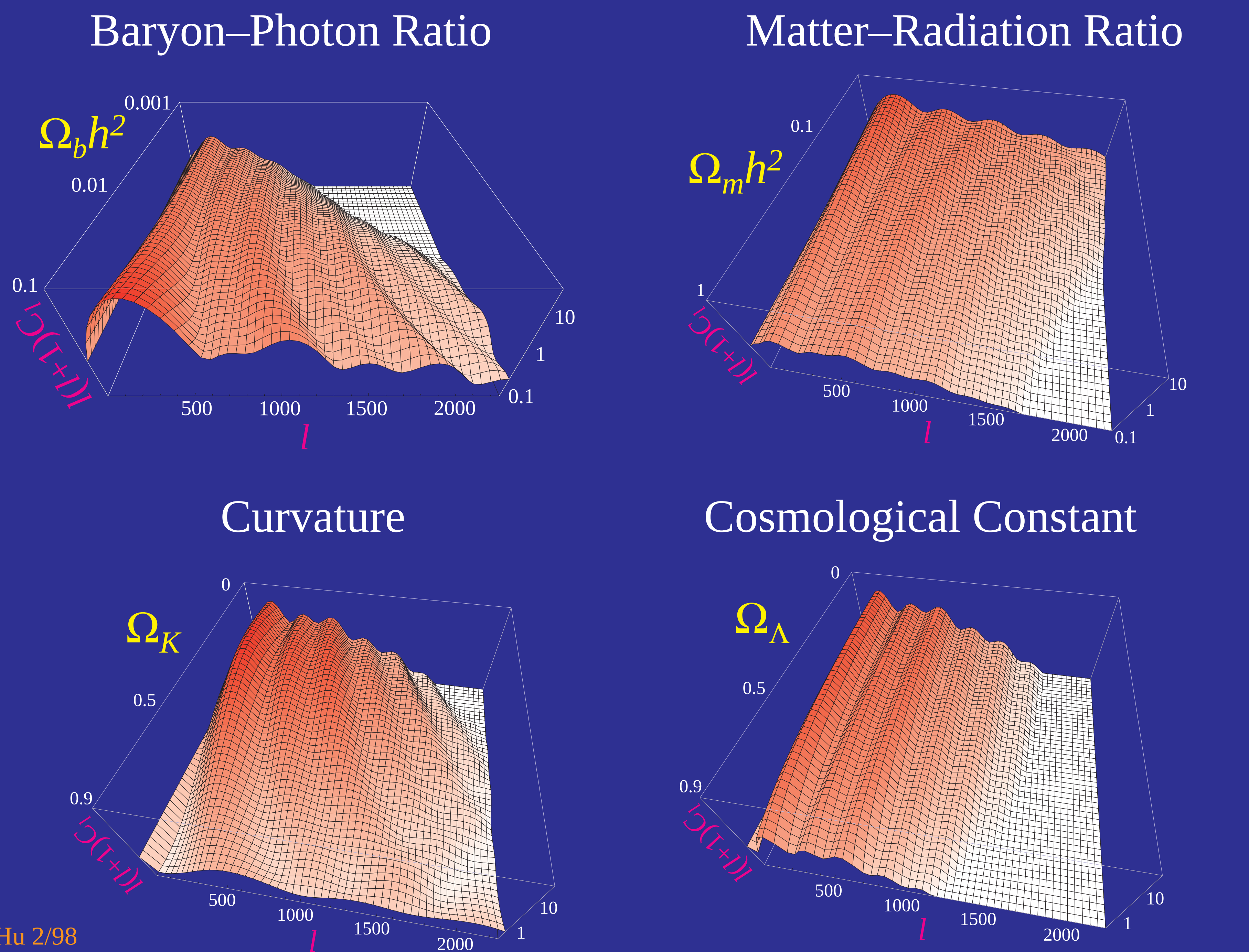


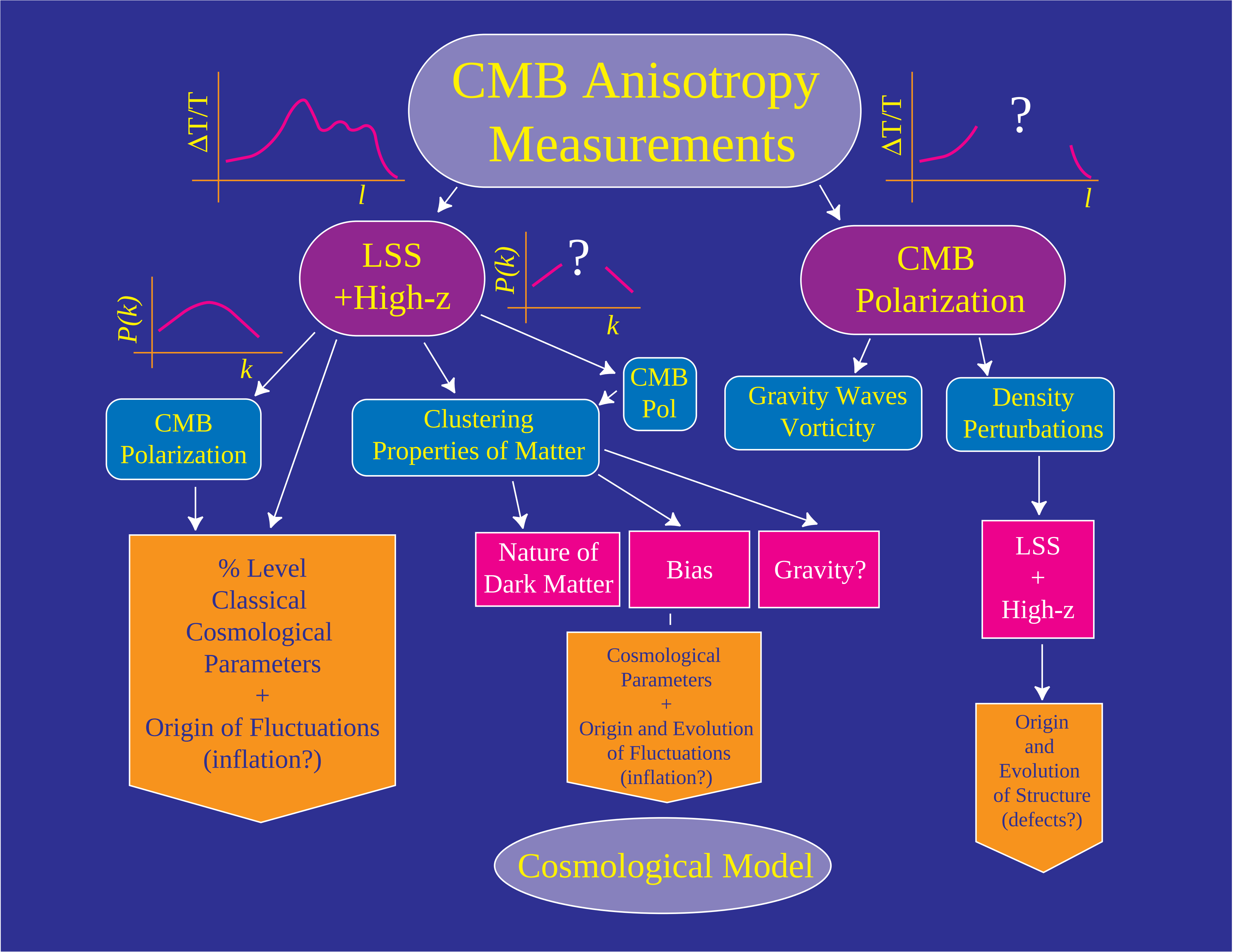
Physical Decomposition & Information

- 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
- Geometry
  - → angular diameter distance $f(\Omega_\Lambda, \Omega_K)$ + flatness or no Ω_Λ,
  - → Ω_Λ or Ω_K



Cosmological Parameters in the CMB





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

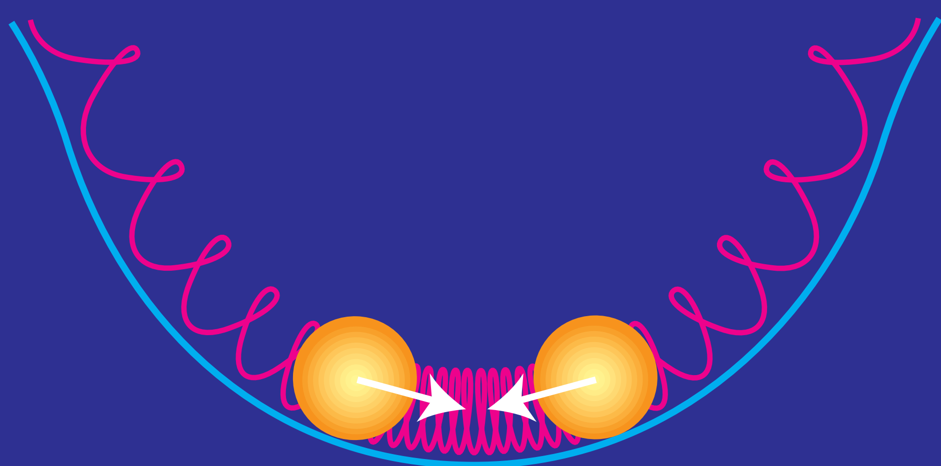
Part II:

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: δ_b(drag) $\sim V_b$(drag), but not frozen

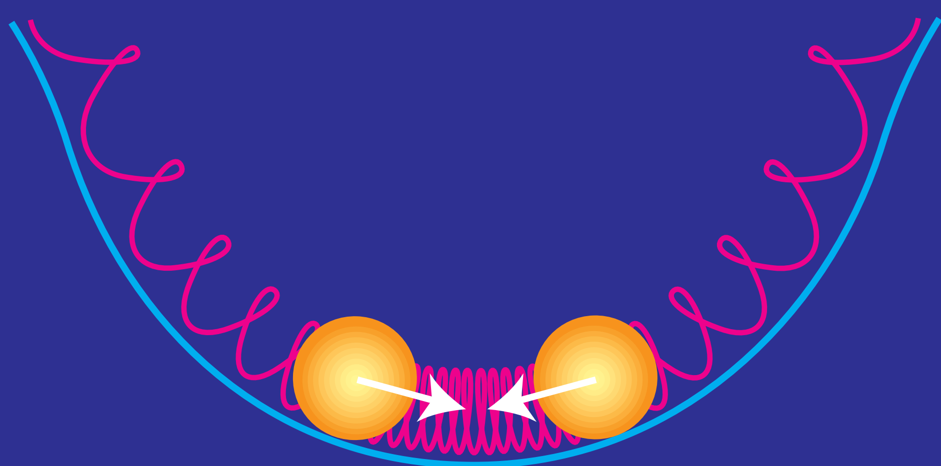


End of Drag Epoch

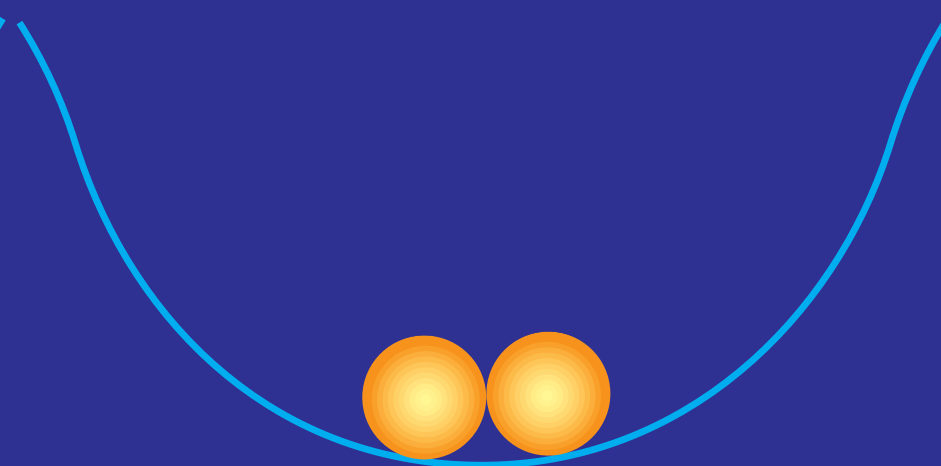
Hu & Sugiyama (1996)

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
- 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)



End of Drag Epoch

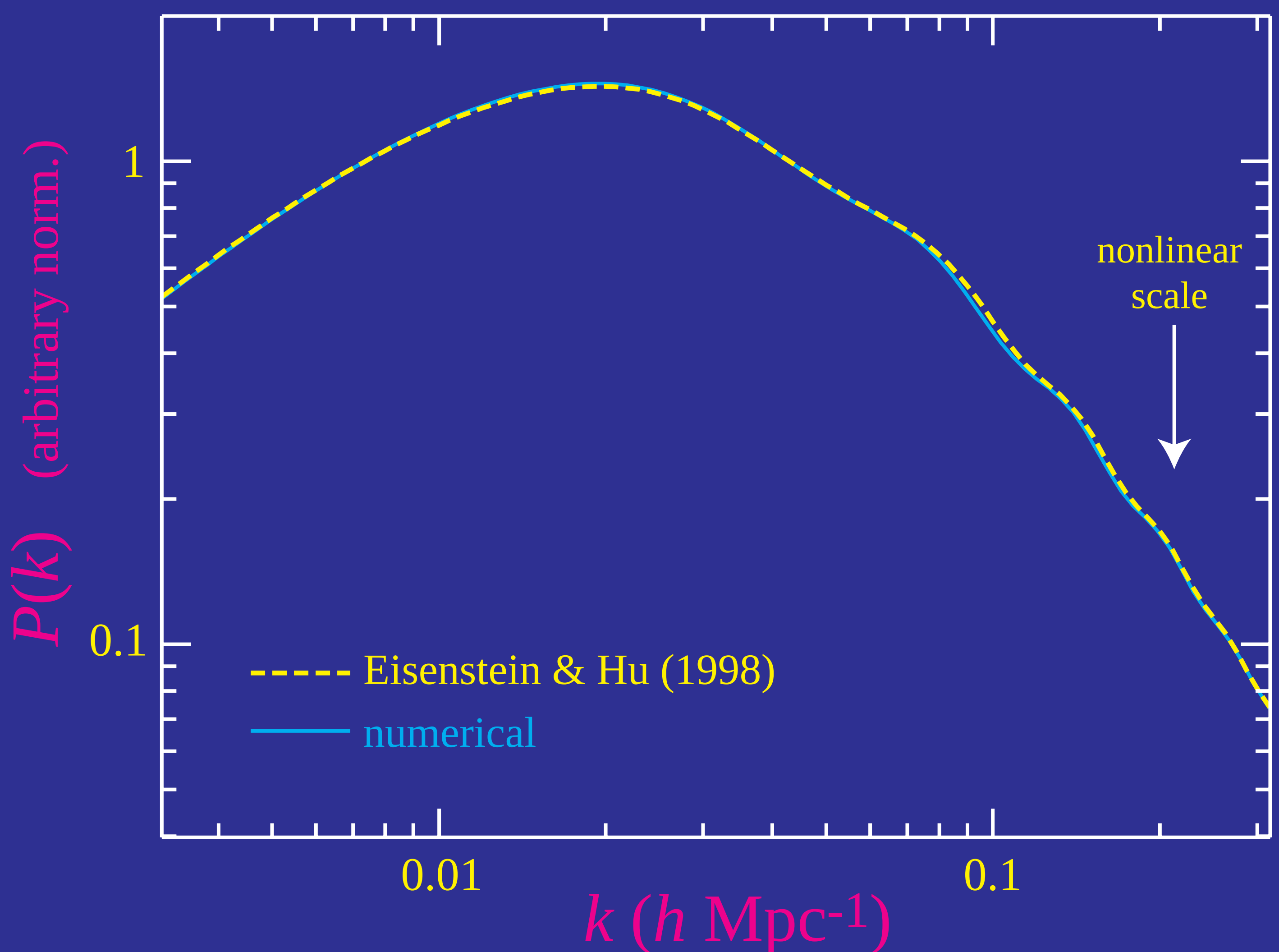


Velocity Overshoot + Infall

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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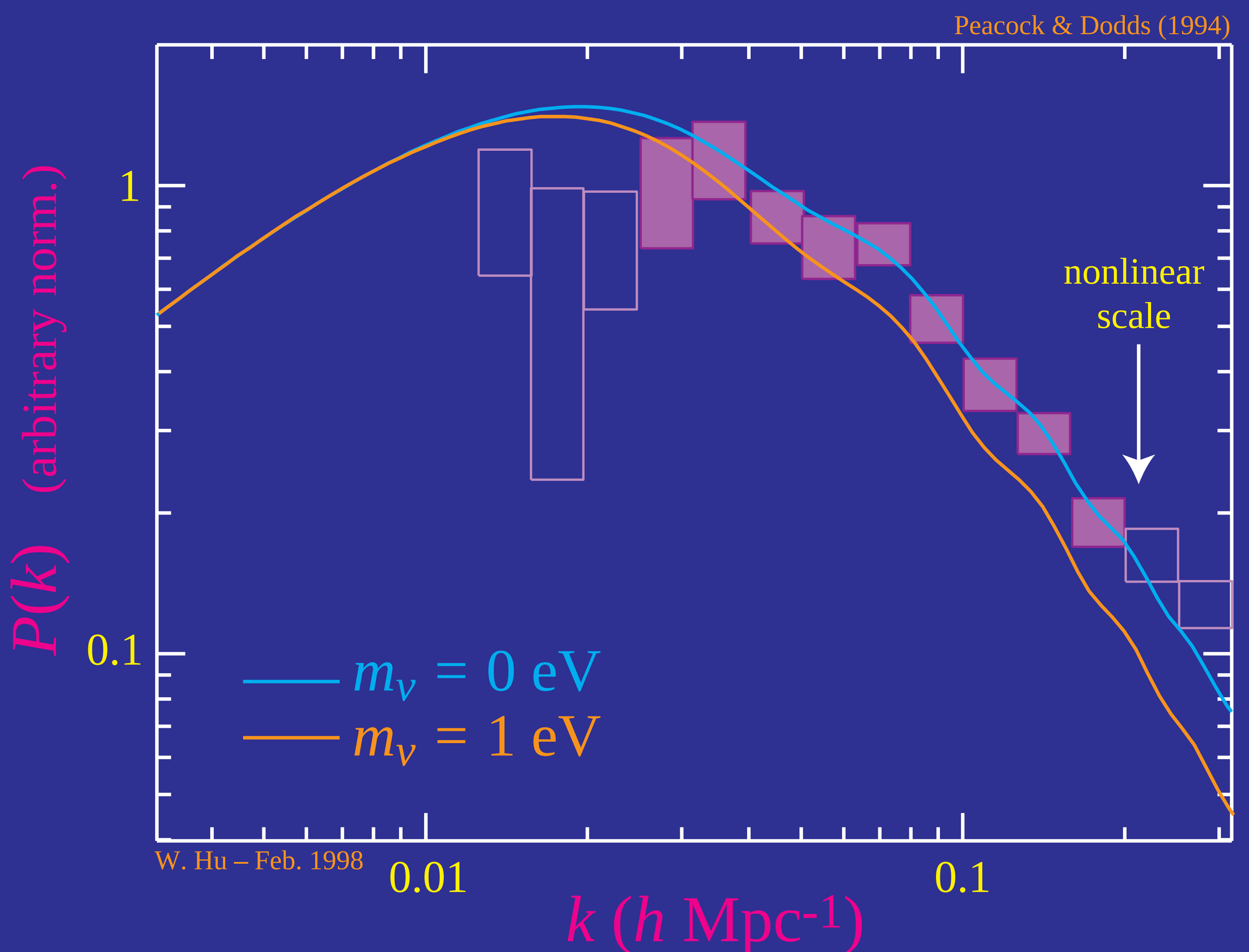

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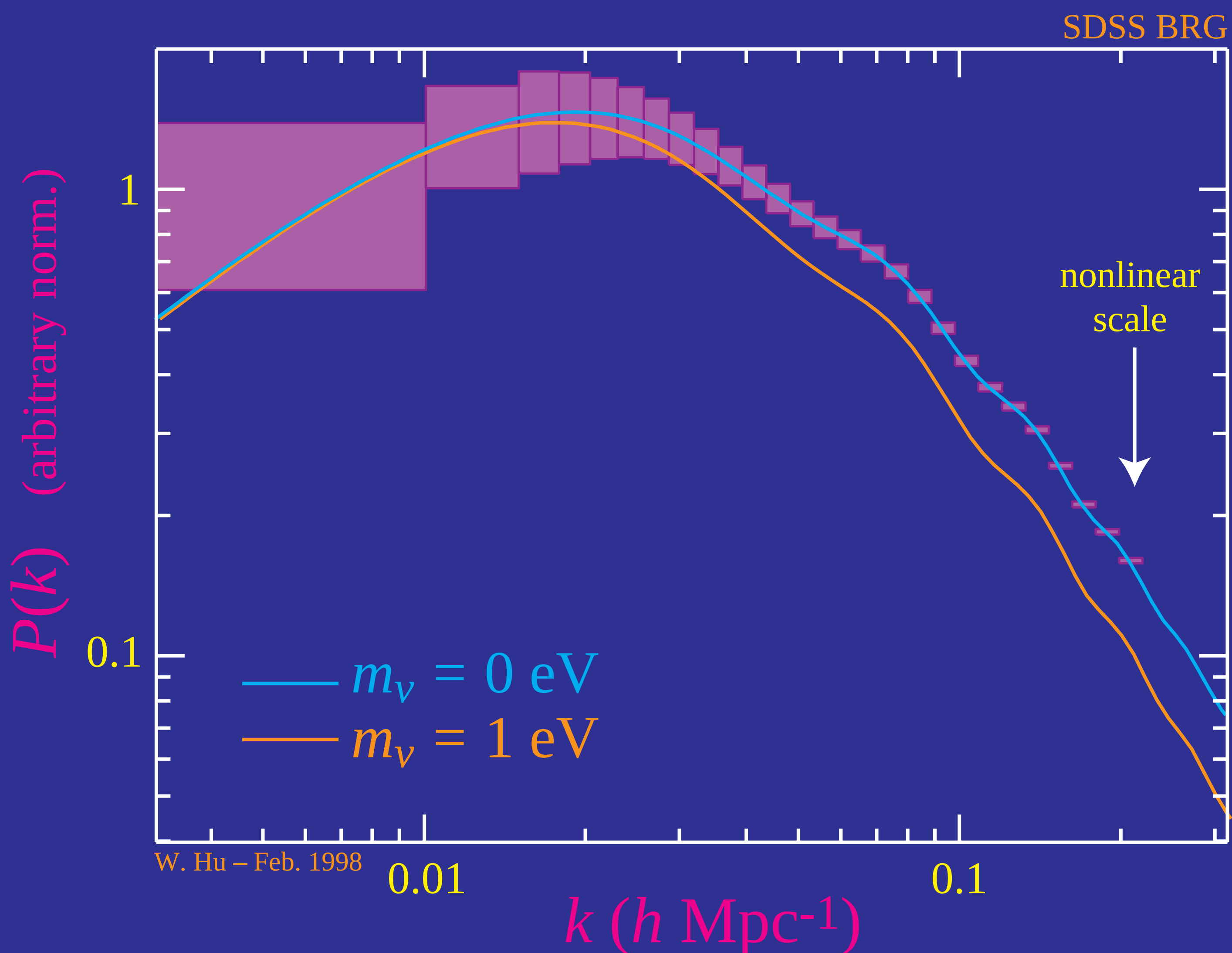
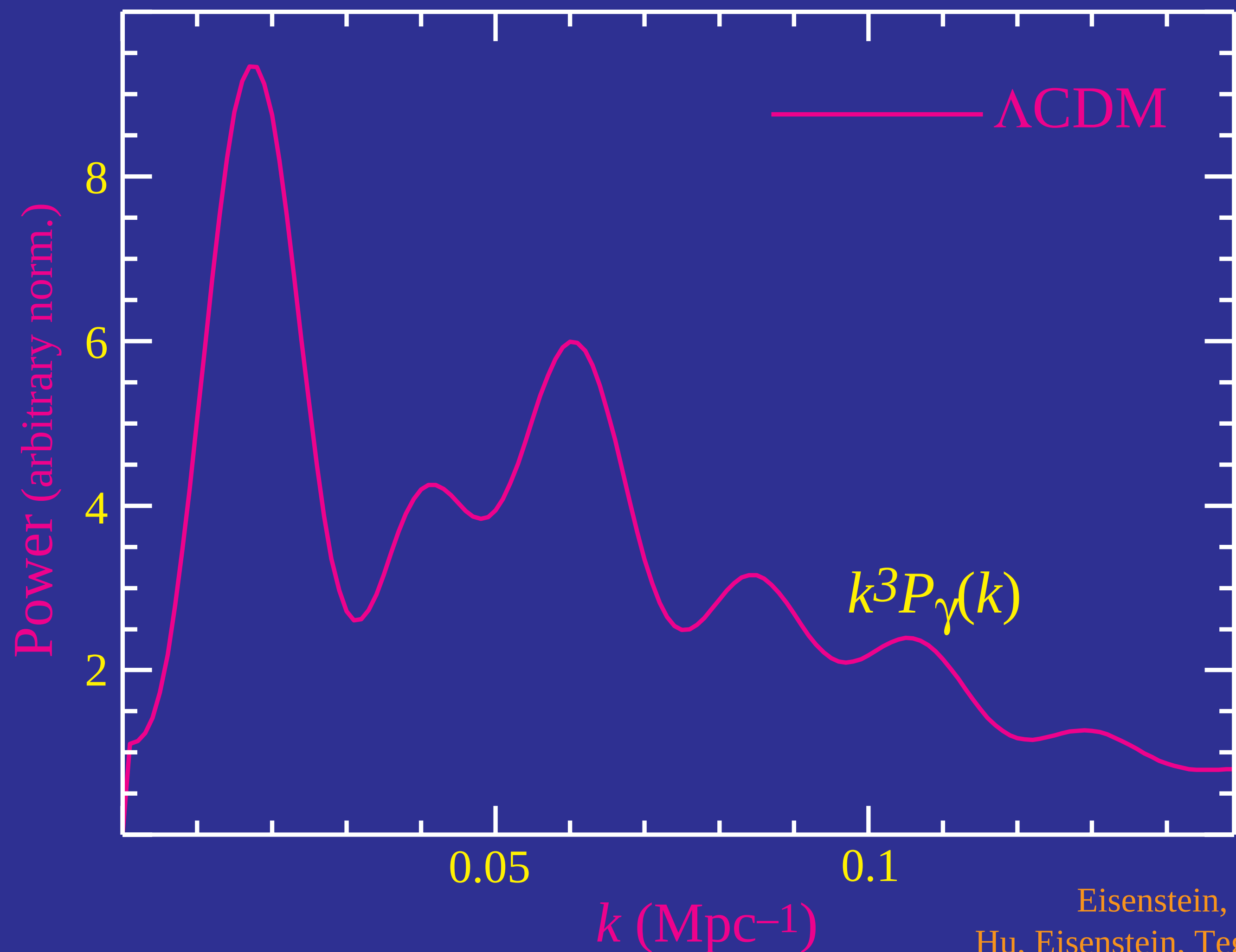


Combining Features in LSS + CMB

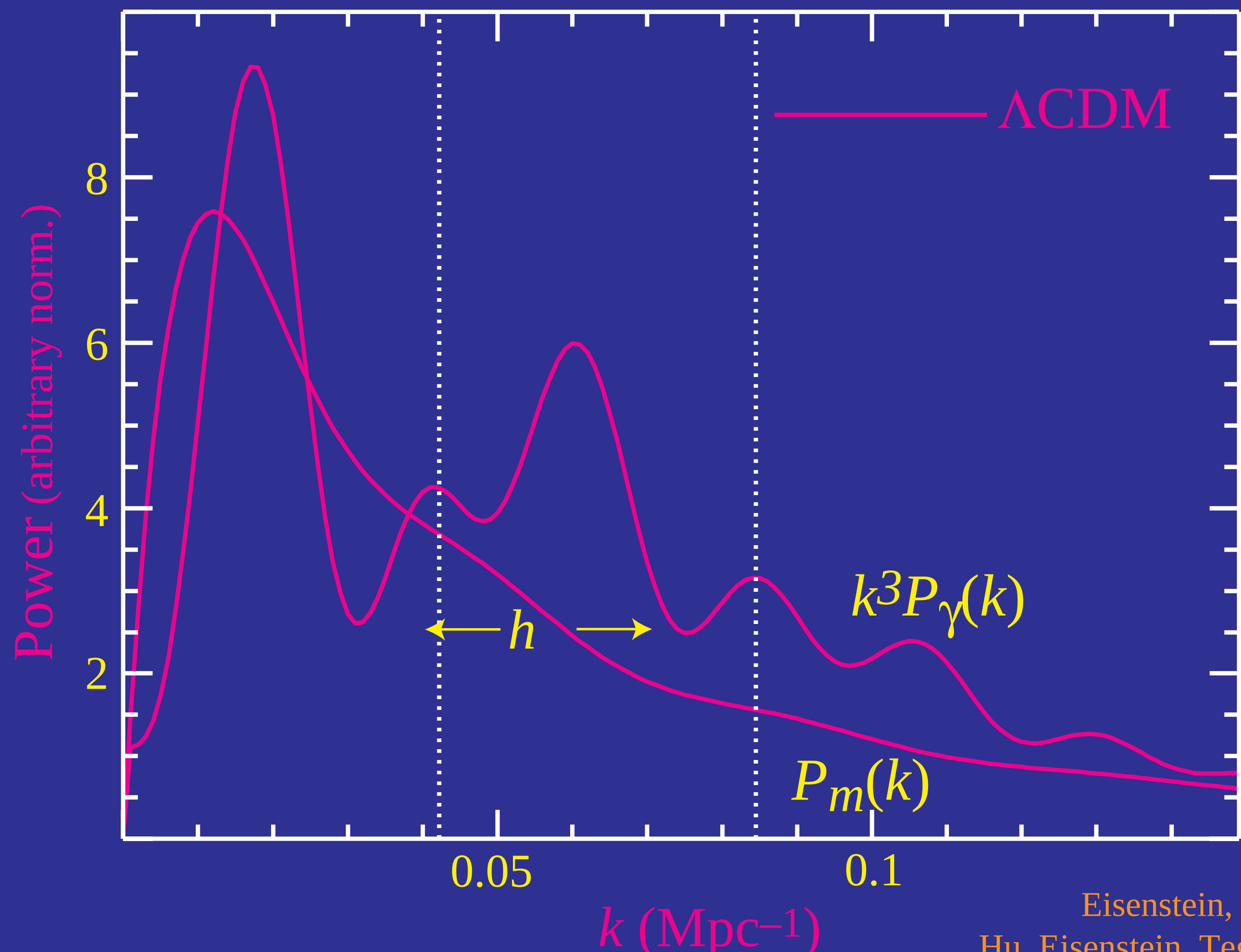
- Consistency check on thermal history and photon–baryon ratio
- Infer physical scale l_{peak}(CMB) → k_{peak}(LSS) in Mpc^{-1}



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_{peak}(CMB) → k_{peak}(LSS) in Mpc^{-1}
- Measure in redshift survey k_{peak}(LSS) in h Mpc^{-1} → h



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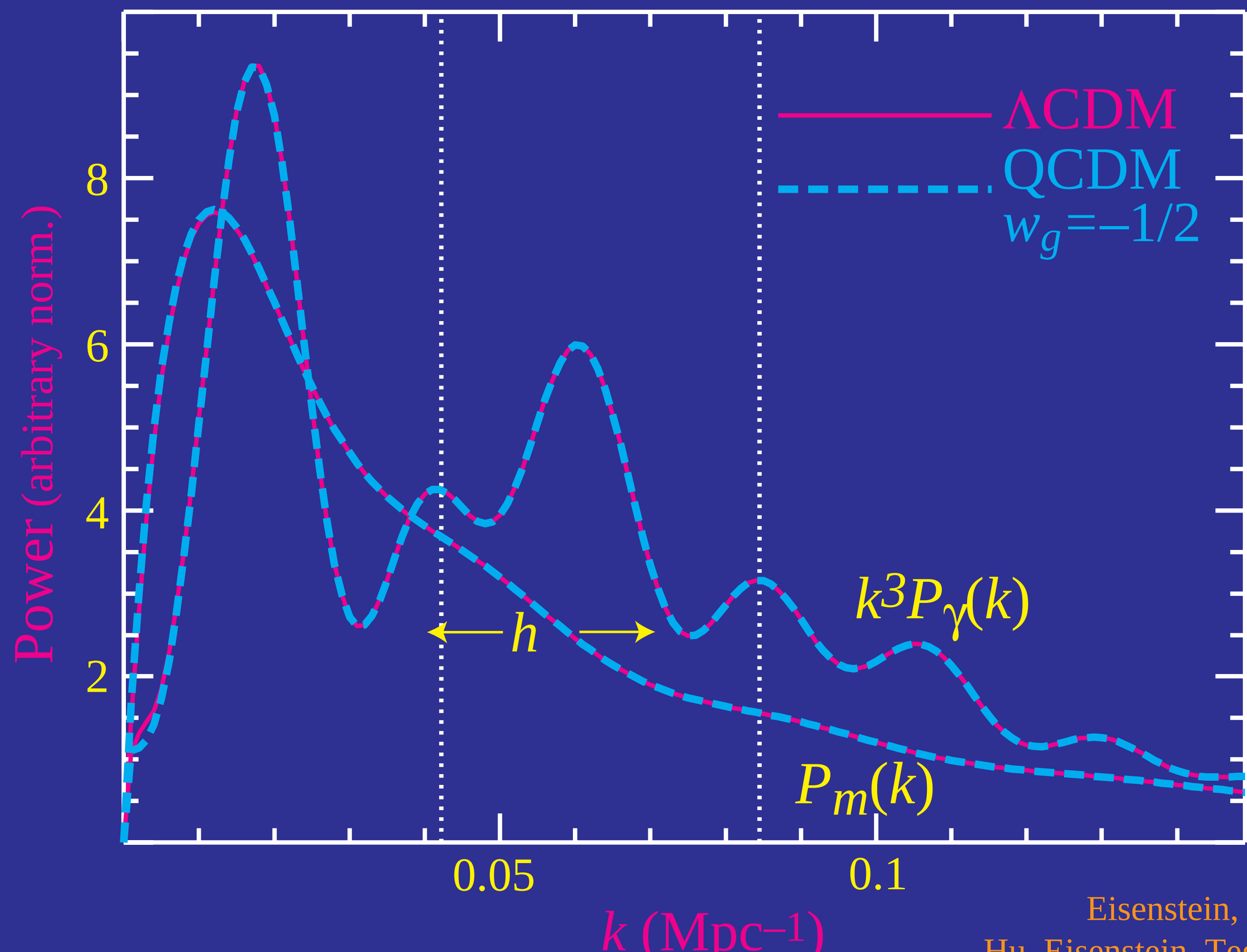
- Infer physical scale $l_{\rm peak}$(CMB) $\rightarrow$ $k_{\rm peak}$(LSS) in Mpc^{-1}
- Measure in redshift survey $k_{\rm peak}$(LSS) in h Mpc^{-1} $\rightarrow$ h
- Robust to low redshift physics (e.g. quintessence, GDM)



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

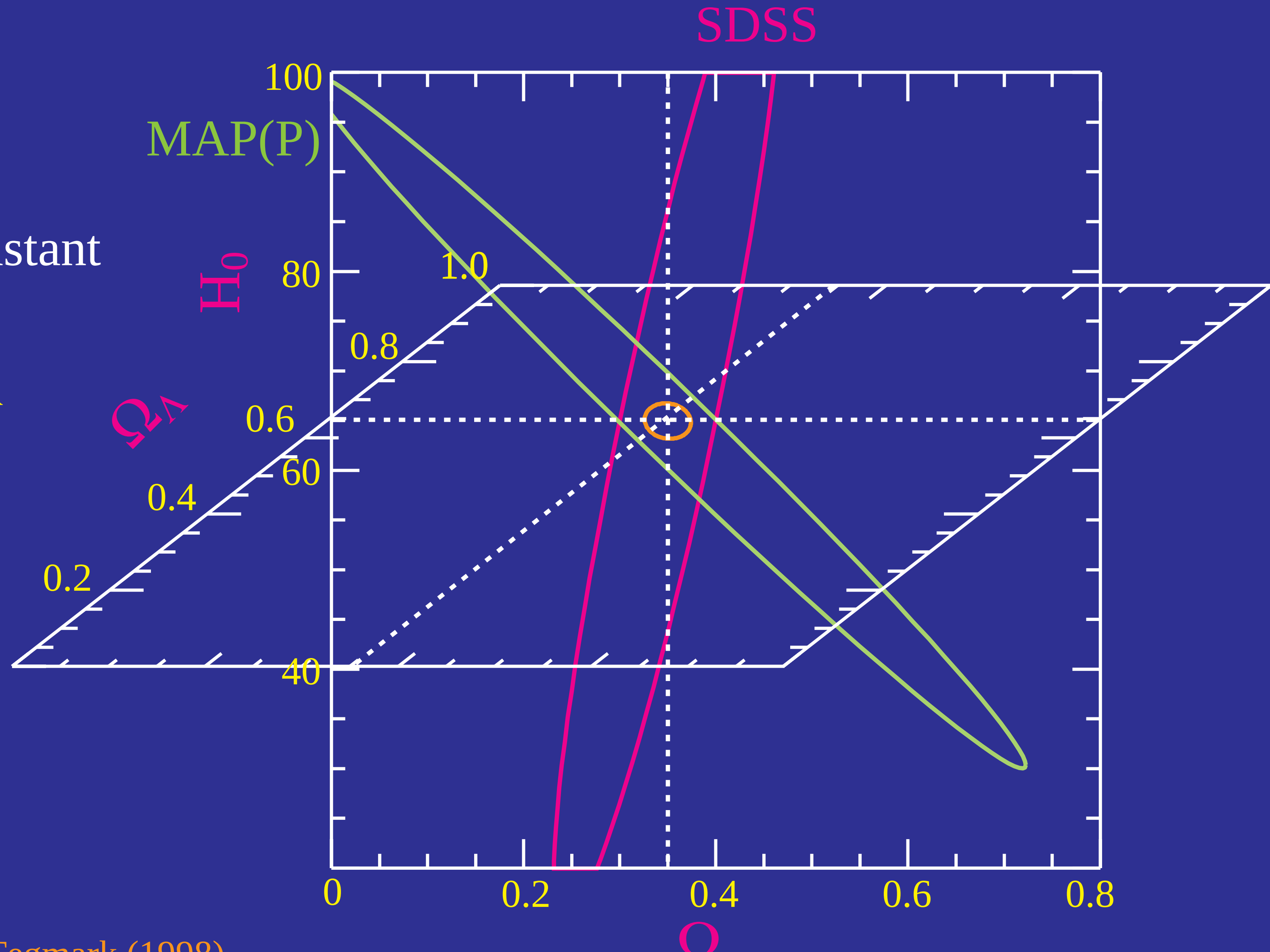
Classical Cosmology

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

CMB:
~line of constant

$\Omega_m H_0^2$

$\Omega_m + \Omega_\Lambda$

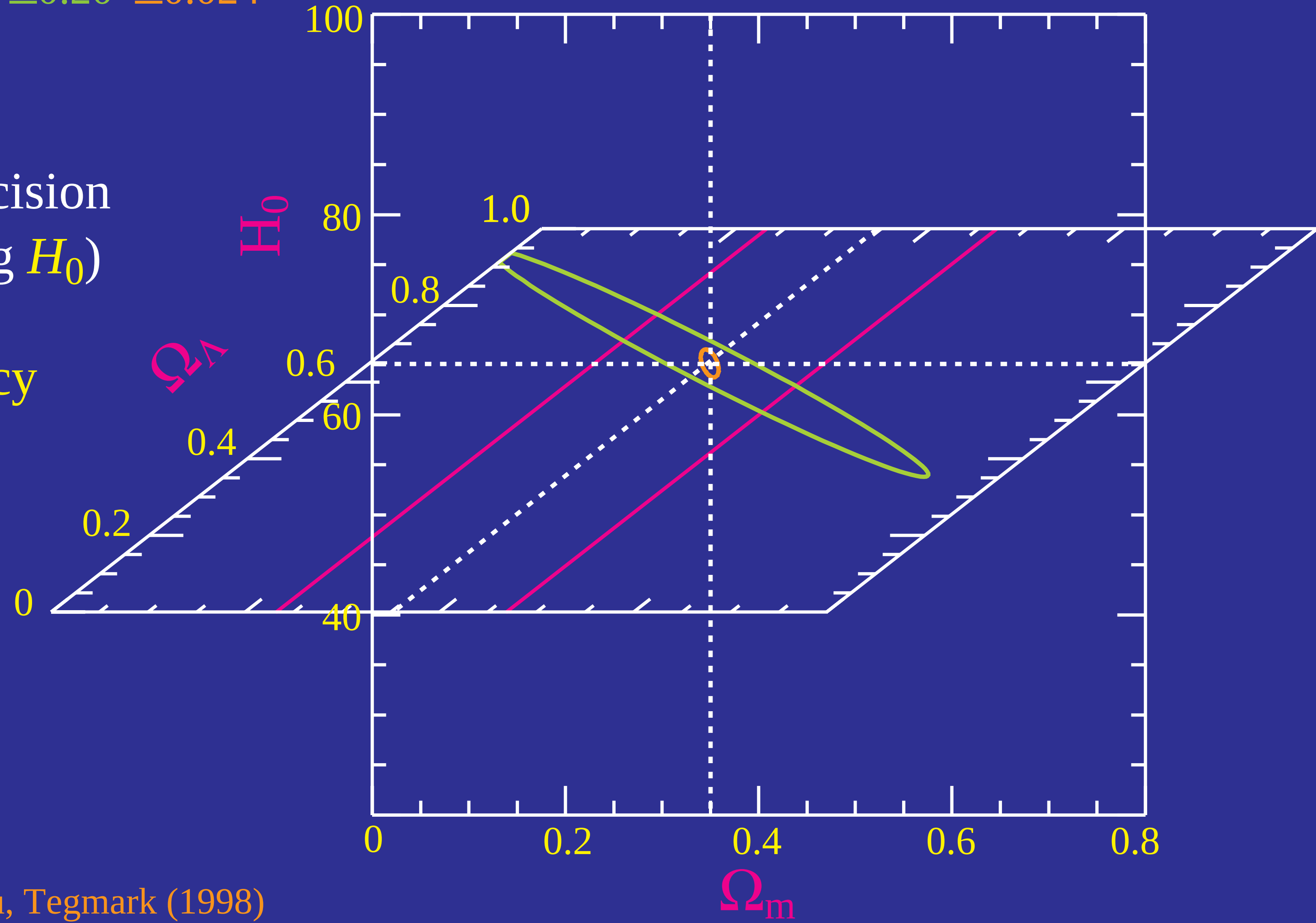


Eisenstein, Hu, Tegmark (1998)

	MAP	+P	+SDSS
H_0	±130	±23	±1.2
Ω_m	±1.4	±0.25	±0.016
Ω_Λ	±1.1	±0.20	±0.024

Classical Cosmology

Any
other precision
(including H_0)
breaks
degeneracy



Eisenstein, Hu, Tegmark (1998)

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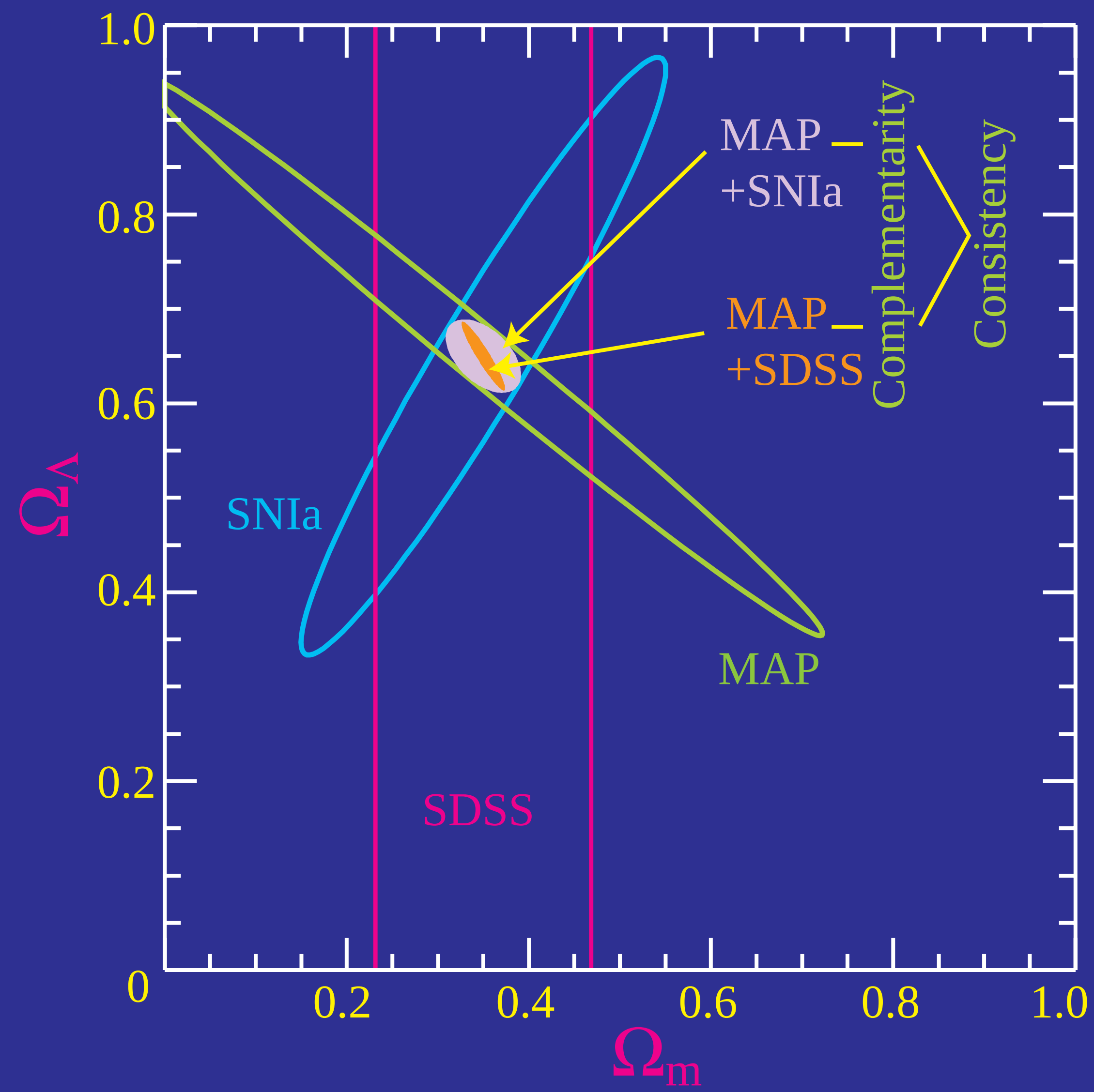
Ω_m	±1.4	±0.25	±0.016
Ω_Λ	±1.1	±0.20	±0.024

Classical Cosmology

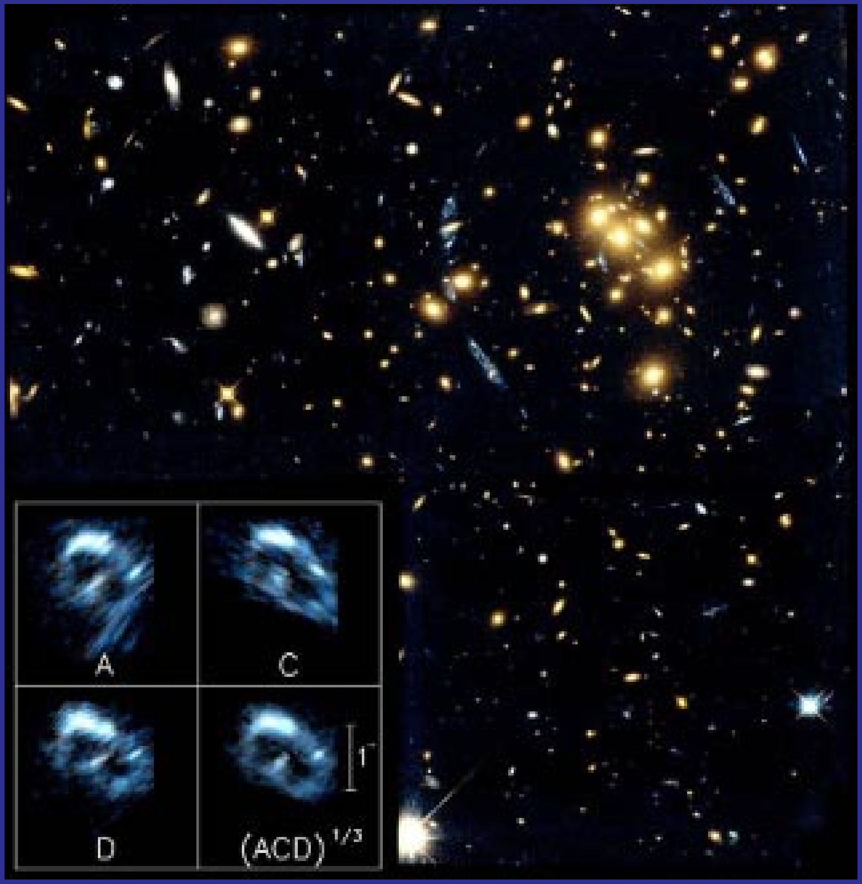
Many opportunities for consistency checks! (e.g. high-z SNIa)



Eisenstein, Hu, Tegmark (1998)

Weak Lensing:
Prospects for Measuring Cosmological Parameters

- Potentially as precise as the CMB
- Main systematic effects are instrumental rather than astrophysical



Cluster (Strong) Lensing: 0024+1654

Colley, Turner, & Tyson (1996)

Weak Lensing:
Prospects for Measuring Cosmological Parameters

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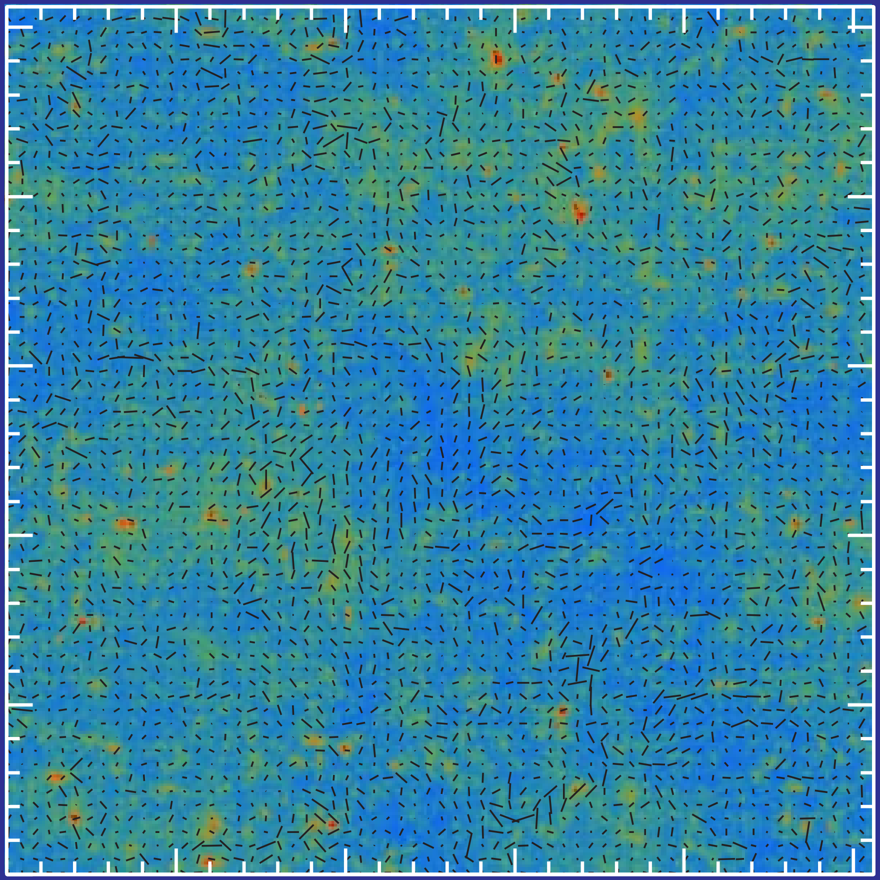


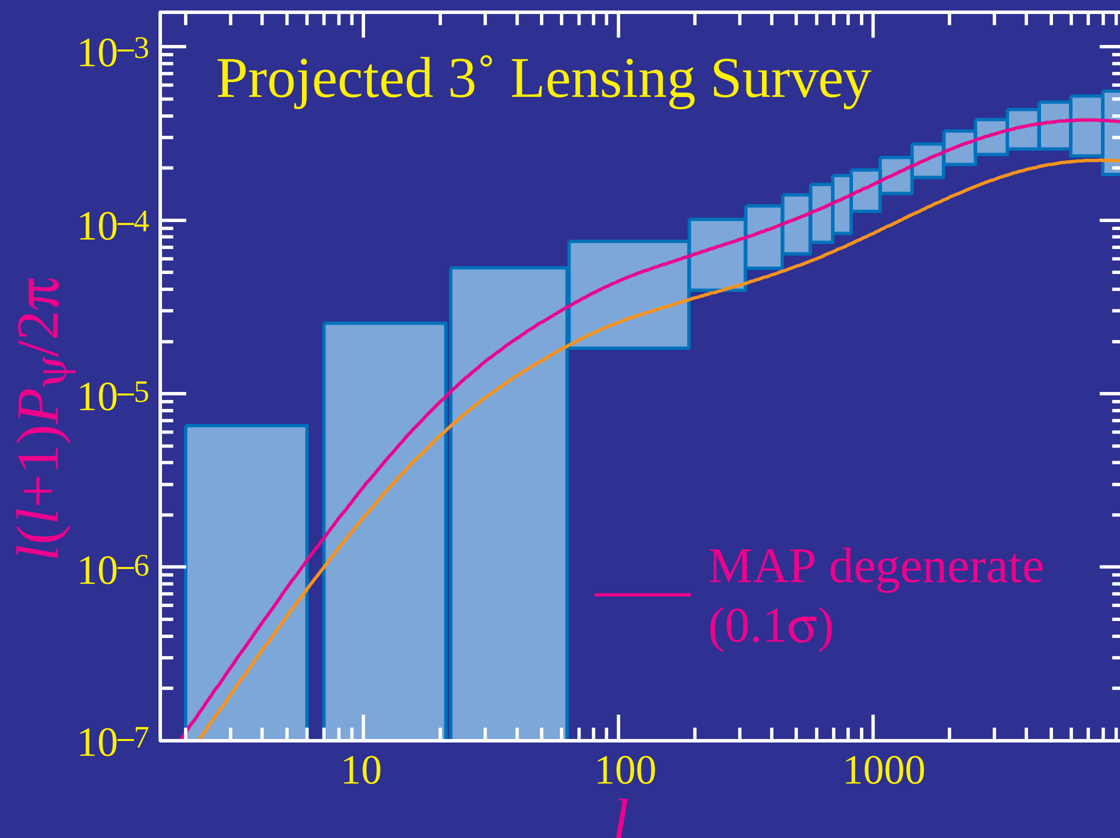
5 degree field

White & Hu (1999)

Weak Lensing:
Prospects for Measuring Cosmological Parameters

- Potentially as precise as the CMB
- Main systematic effects are instrumental rather than astrophysical
- The Bad News

  Depends on most (8)
  cosmological parameters



Hu & Tegmark (1998)

Weak Lensing: Prospects for Measuring Cosmological Parameters

- Potentially as precise as the CMB
- Main systematic effects are instrumental rather than astrophysical
- The Bad News
  Depends on most (8) cosmological parameters
- The Good News
  Depends on most (8) cosmological parameters
- $P(k)$
- Growth
- Distribution of faint galaxies

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 (1998)

Weak Lensing:
Prospects for Measuring Cosmological Parameters

- Potentially as precise as the CMB
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- The Bad News
  Depends on most (8) cosmological parameters
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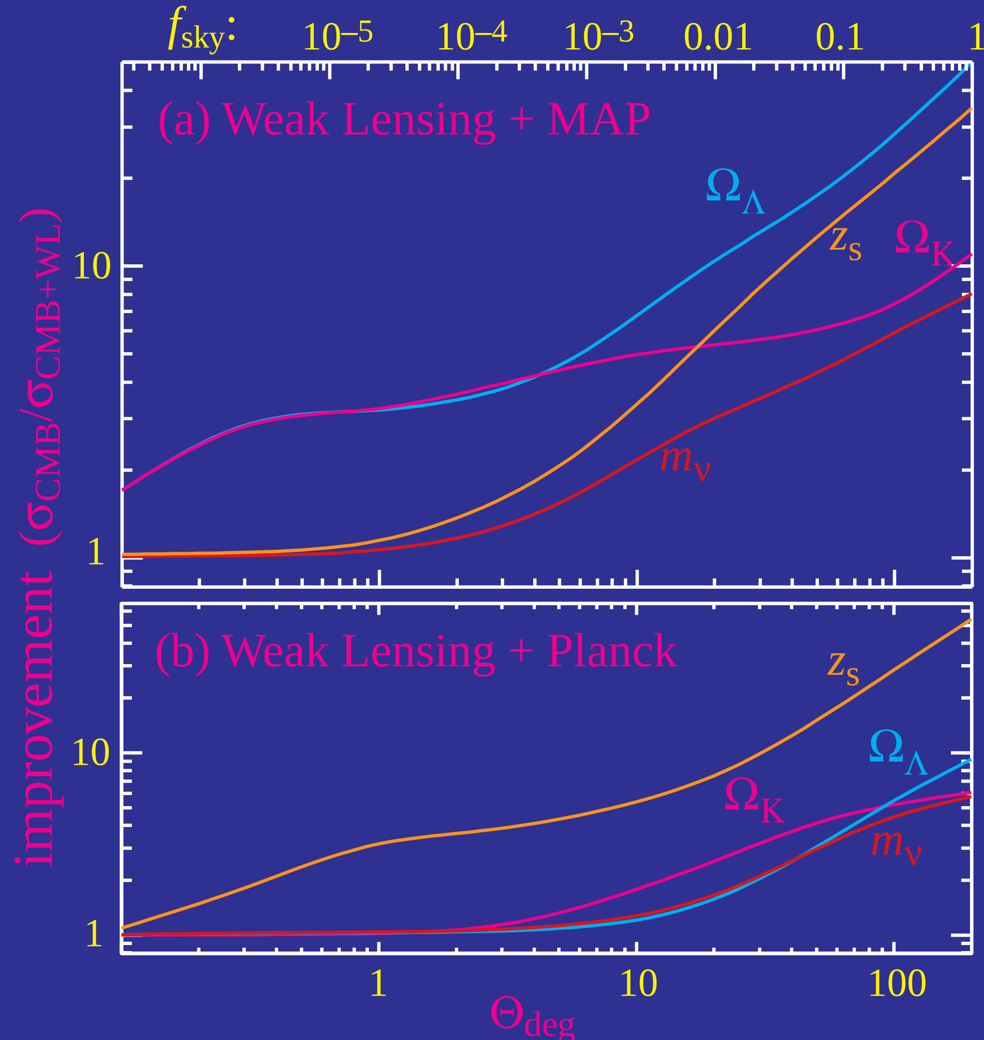
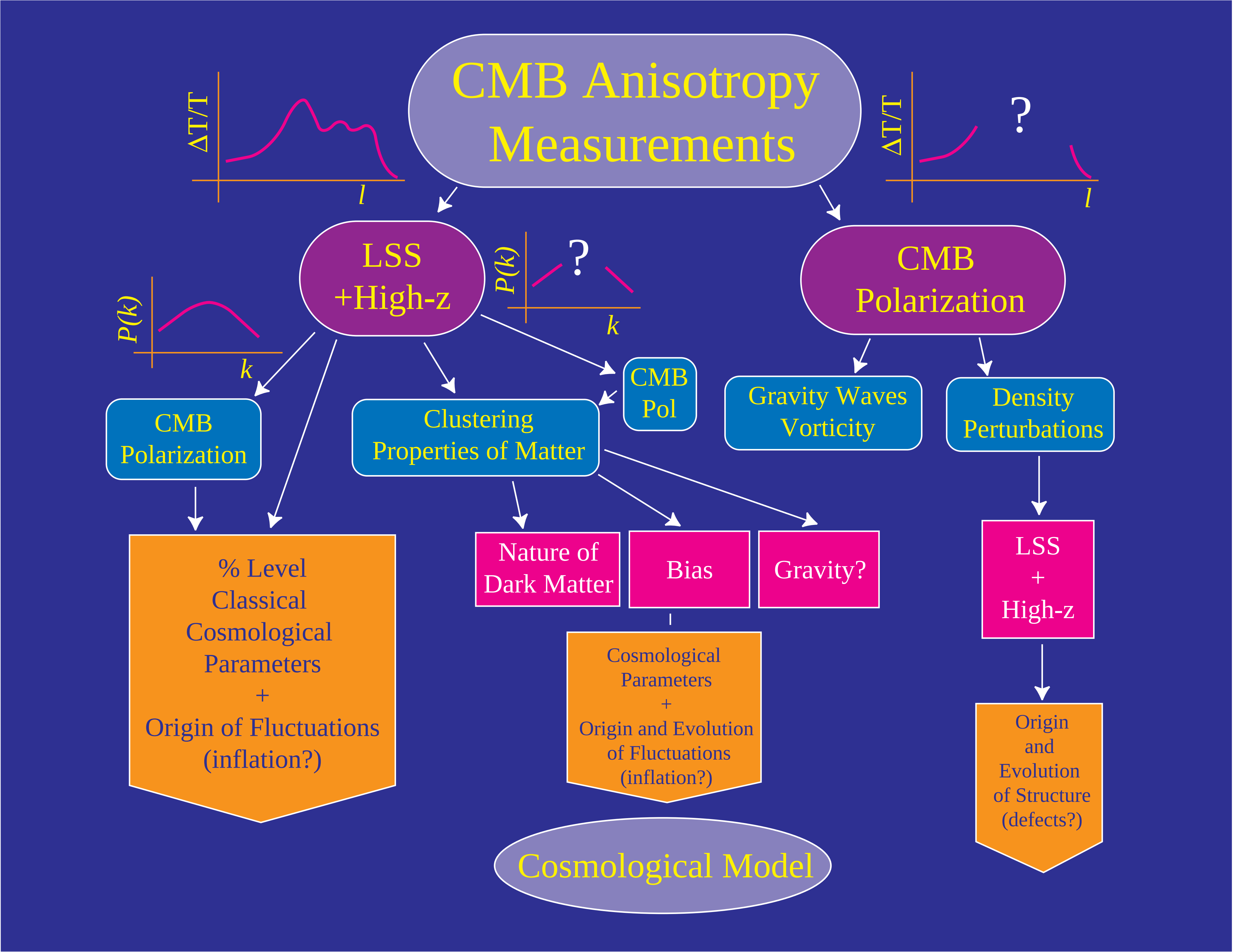


Hu & Tegmark (1998)



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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

Generalized Dark Matter

- Arbitrary Stress–Energy Tensor $T_{\mu\nu}$ — 16 Components
- Local Lorentz Invariance → 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 → Symmetric $T_{\mu\nu}$		10 Components
• Energy–Momentum Conservation	4 Constraints	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)

Generalized Dark Matter

- Arbitrary Stress–Energy Tensor $T_{\mu\nu}$ — 16 Components
- Local Lorentz Invariance → Symmetric $T_{\mu\nu}$ — 10 Components
- Energy–Momentum Conservation — 4 Constraints
  - 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
- Model as Equations of State
- Gauge Invariance
  - $w = p/\rho$ — 1 Equation of State
  - $c_{\rm eff}^2 = (\delta p/\delta\rho)_{\rm comov}$ — 1 Sound Speed
  - $c_{\rm vis}^2$ = (viscosity coefficient) — 1 Anisotropic Stress

Hu (1998)

Dark Components

Prototypes:

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

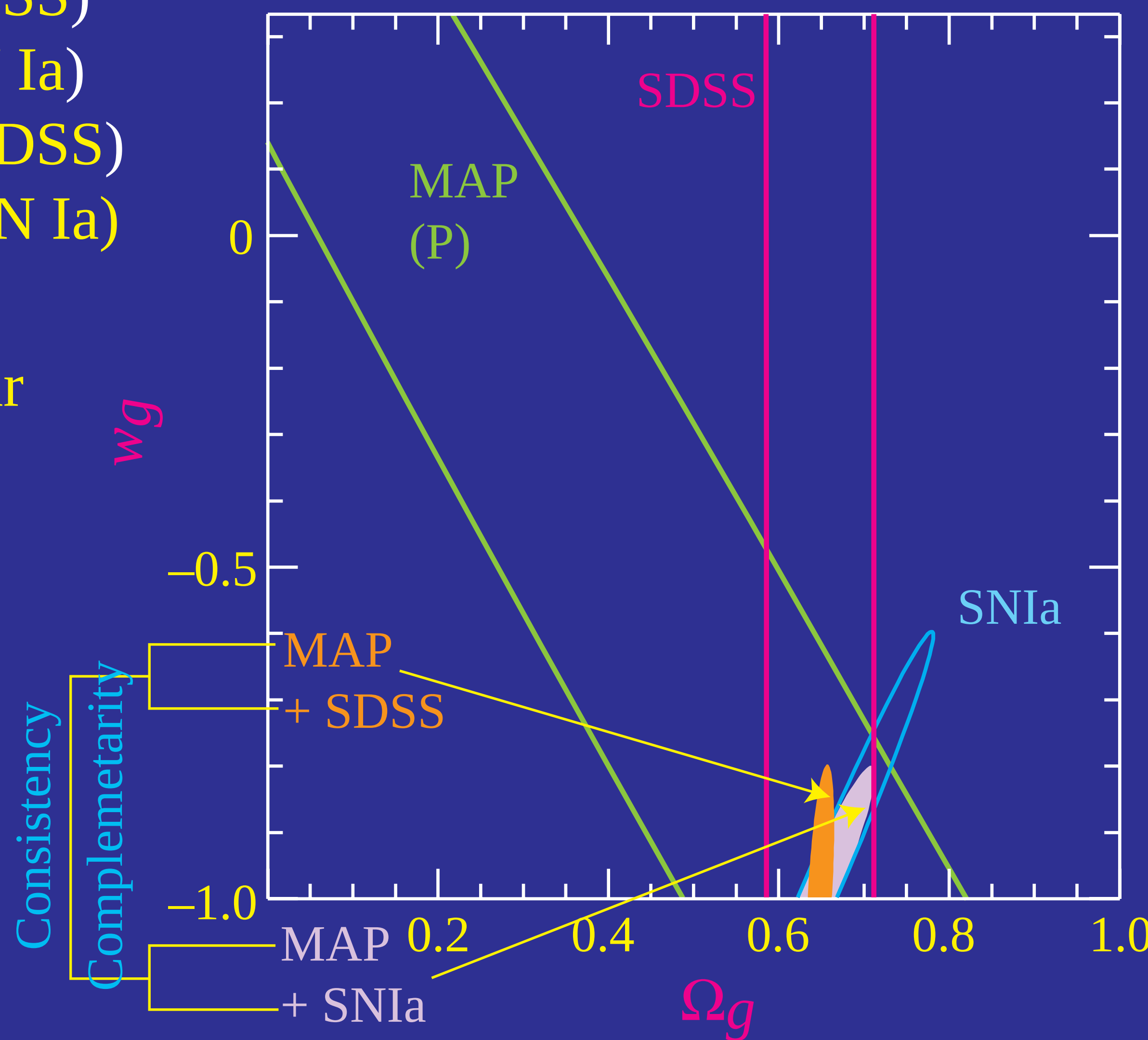
Determining the Accelerating Component

- 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?

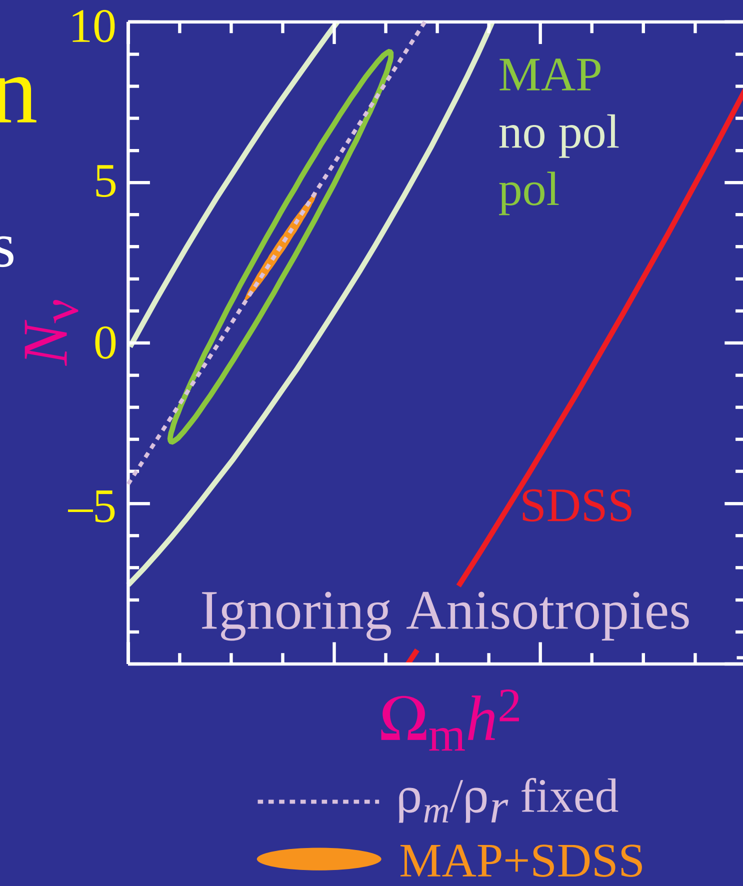
  sound speed constrained
  if $w_g > -1/2$



Hu, Eisenstein, Tegmark & White (1998)

Detecting the Neutrino Background Radiation

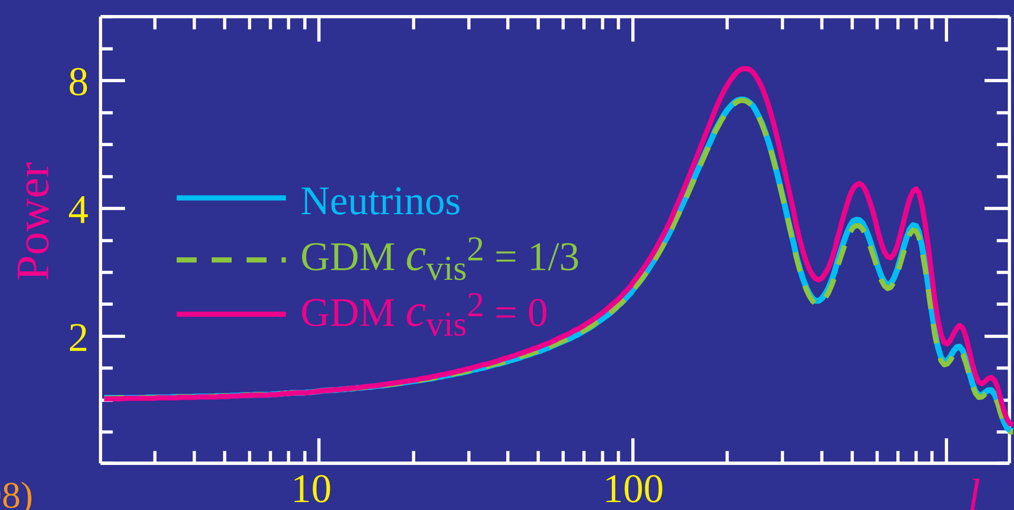
- Neutrino number N_ν or temperature T_ν alters the matter–radiation ratio
- Degenerate with matter density $\Omega_m h^2$
- Break degeneracy with NBR anisotropies

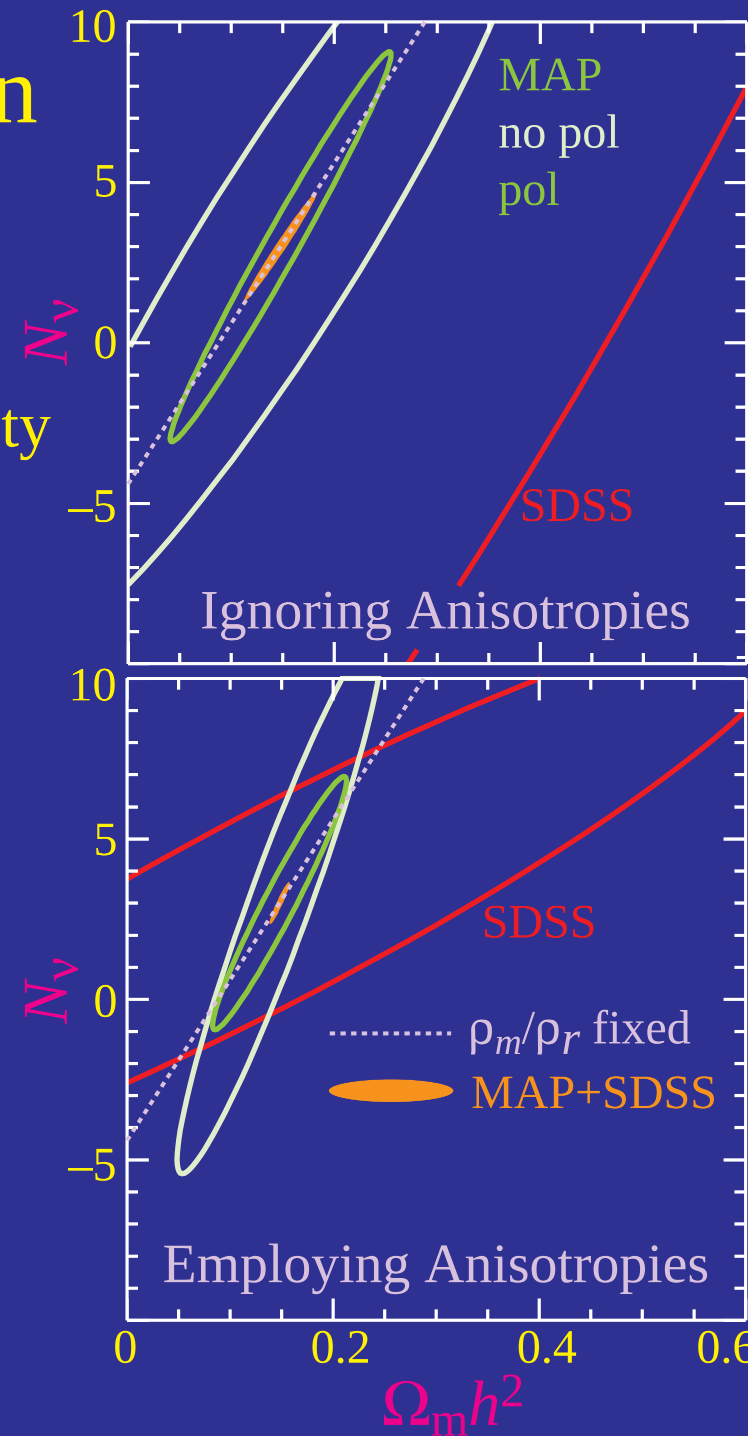


Hu, Eisenstein, Tegmark & White (1998)

Anisotropies in the Neutrino Background Radiation

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

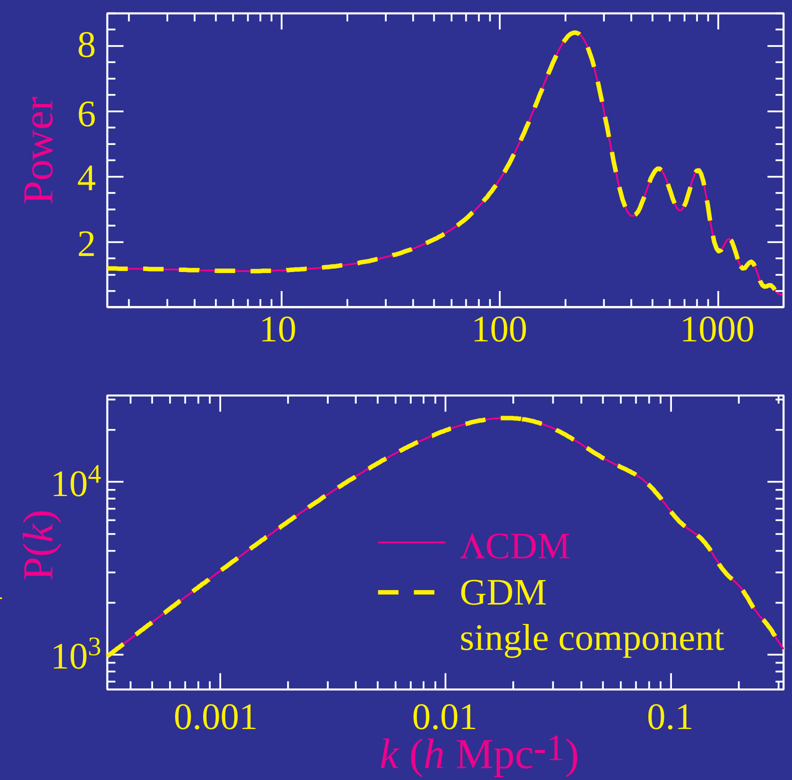




Hu (1998)
Hu, Eisenstein, Tegmark & White (1998)

Stressing the Dark Sector

- A structure formation model is completely defined by its stress history
- Stress properties of the ordinary/luminous matter are known
- Model is defined by the stress history of the dark sector
- Two models with exactly the same stress history are phenomenologically identical (ΛCDM vs. GDM with no CDM with right w_g and $c_{\rm eff}^2=0$, $c_{\rm vis}^2=0$)



Hu & Eisenstein (1998)

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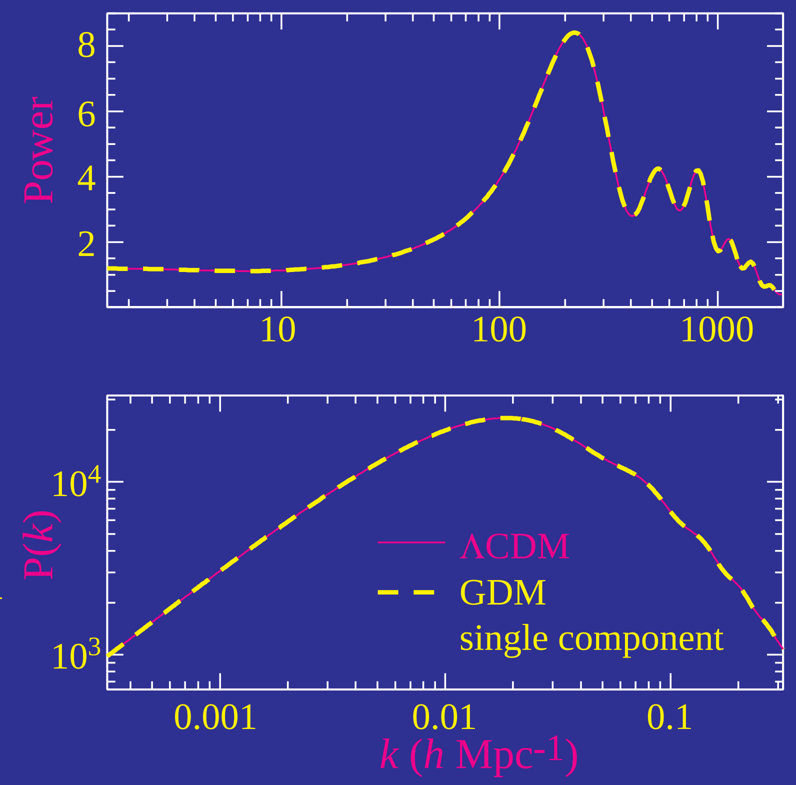
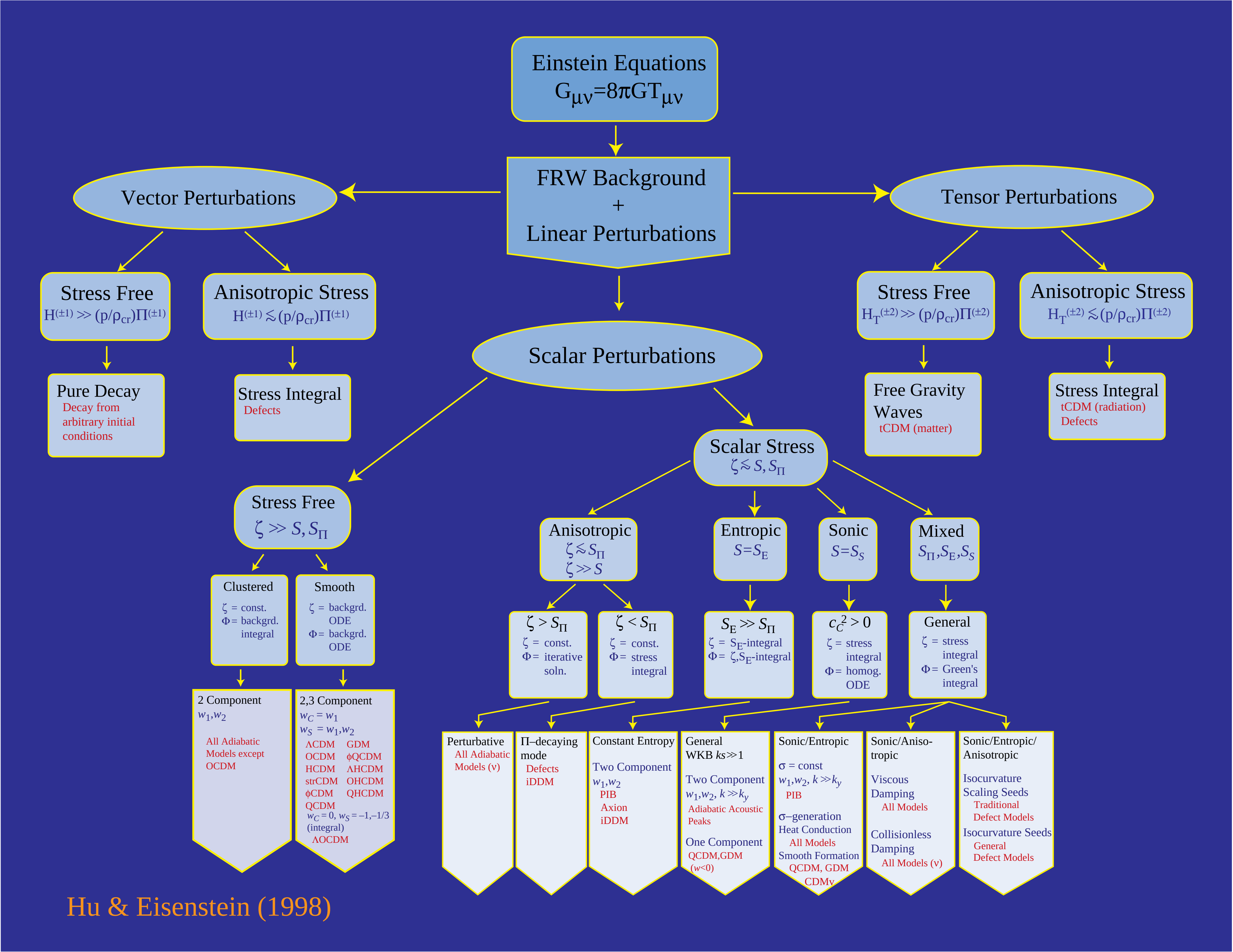
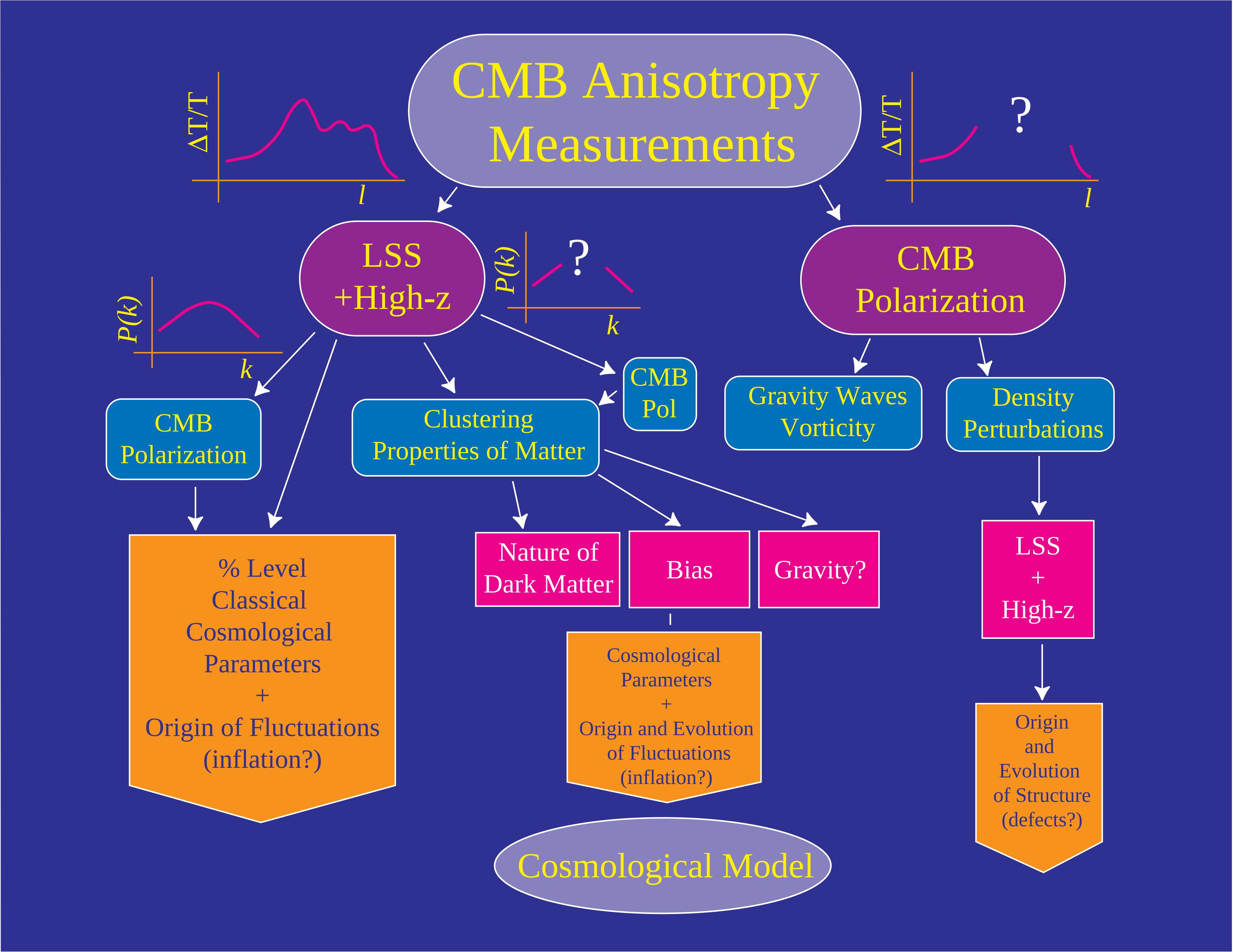


- GDM ansatz: stress history is defined by simple equations of state for stresses in the background and (separately) in the perturbations
- Reasonable if model phenomenology is similar to adiabatic CDM
- If not, must go beyond the GDM ansatz...

Hu & Eisenstein (1998)


Einstein Equations
$G_{\mu\nu}=8\pi G T_{\mu\nu}$
FRW Background
+
Linear Perturbations
Vector Perturbations
Tensor Perturbations
Scalar Perturbations
Stress Free
$H^{(\pm1)} \gg (p/\rho_{cr})\Pi^{(\pm1)}$
Anisotropic Stress
$H^{(\pm1)} \lesssim (p/\rho_{cr})\Pi^{(\pm1)}$
Pure Decay
Decay from arbitrary initial conditions
Stress Integral
Defects
Stress Free
$H_T^{(\pm2)} \gg (p/\rho_{cr})\Pi^{(\pm2)}$
Anisotropic Stress
$H_T^{(\pm2)} \lesssim (p/\rho_{cr})\Pi^{(\pm2)}$
Free Gravity Waves
tCDM (matter)
Stress Integral
tCDM (radiation)
Defects
Stress Free
$\zeta \gg S, S_\Pi$
Scalar Stress
$\zeta \lesssim S, S_\Pi$
Clustered
ζ = const.
Φ = backgrd. integral
Smooth
ζ = backgrd. ODE
Φ = backgrd. ODE
2 Component
w_1,w_2
All Adiabatic Models except OCDM
2,3 Component
$w_C = w_1$
$w_S = w_1,w_2$
ΛCDM GDM
OCDM ϕQCDM
HCDM ΛHCDM
strCDM OHCDM
ϕCDM QHCDM
QCDM
$w_C = 0,\ w_S = -1,-1/3$ (integral)
ΛOCDM
Anisotropic
$\zeta \lesssim S_\Pi$
$\zeta \gg S$
Entropic
$S = S_E$
Sonic
$S = S_S$
Mixed
S_Π, S_E, S_S
$\zeta > S_\Pi$
ζ = const.
Φ = iterative soln.
$\zeta < S_\Pi$
ζ = const.
Φ = stress integral
$S_E \gg S_\Pi$
ζ = S_E-integral
Φ = ζ,S_E-integral
$c_C^2 > 0$
ζ = stress integral
Φ = homog. ODE
General
ζ = stress integral
Φ = Green's integral
Perturbative
All Adiabatic Models (ν)
Π–decaying mode
Defects
iDDM
Constant Entropy
Two Component
w_1,w_2
PIB
Axion
iDDM
General WKB $ks \gg 1$
Two Component
$w_1,w_2,\ k \gg k_y$
Adiabatic Acoustic Peaks
One Component
QCDM,GDM
(w<0)
Sonic/Entropic
σ = const
$w_1,w_2,\ k \gg k_y$
PIB
σ–generation
Heat Conduction
All Models
Smooth Formation
QCDM, GDM
CDMν
Sonic/Aniso-tropic
Viscous Damping
All Models
Collisionless Damping
All Models (ν)
Sonic/Entropic/ Anisotropic
Isocurvature Scaling Seeds
Traditional Defect Models
Isocurvature Seeds
General Defect Models
Hu & Eisenstein (1998)



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Clustering Properties of Matter
CMB Pol
Gravity Waves Vorticity
Density Perturbations
% Level Classical Cosmological Parameters + Origin of Fluctuations (inflation?)
Nature of Dark Matter
Bias
Gravity?
LSS + High-z
Cosmological Parameters + Origin and Evolution of Fluctuations (inflation?)
Origin and Evolution of Structure (defects?)
Cosmological Model

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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

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