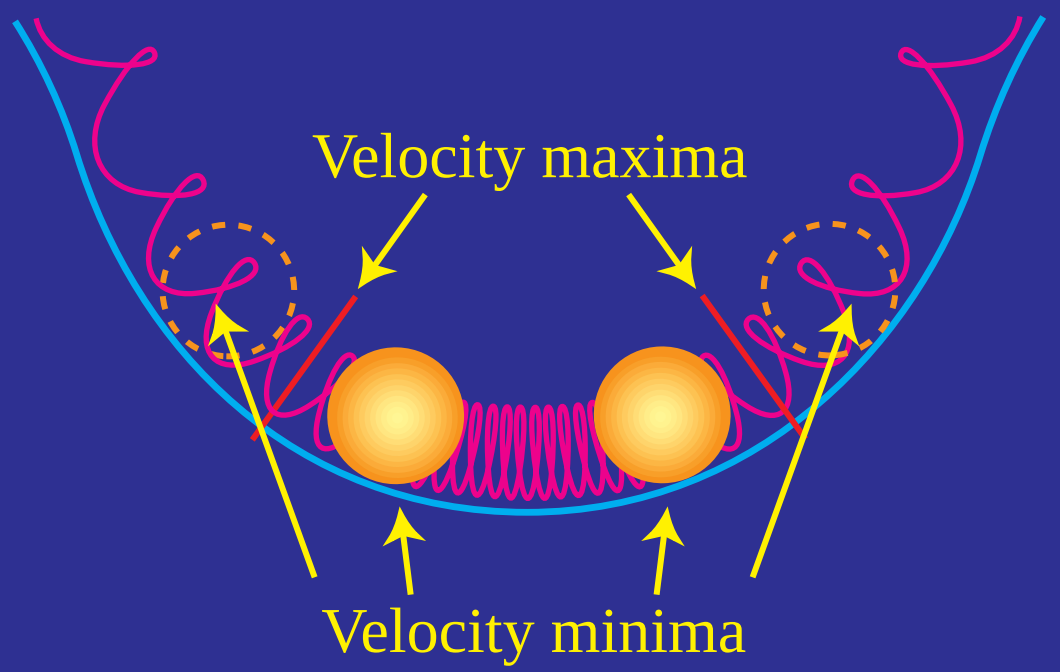
The Outtakes

- CMB Transfer Function
- Testing Inflation
- Weighing Neutrinos
- Decaying Neutrinos
- Testing Λ
- Testing Quintessence
- Polarization Sensitivity
- SDSS Complementarity
- Secondary Anisotropies
- Doppler Effect
- Vishniac Effect
- Patchy Reionization
- Sunyaev-Zel'dovich Effect
- Rees-Sciama & Lensing
- Foregrounds
- Doppler Peaks?
- SNIa Complementarity
- Polarization Primer
- Gamma Approximation
- ISW Effect

Back to Talk

Doppler Effect

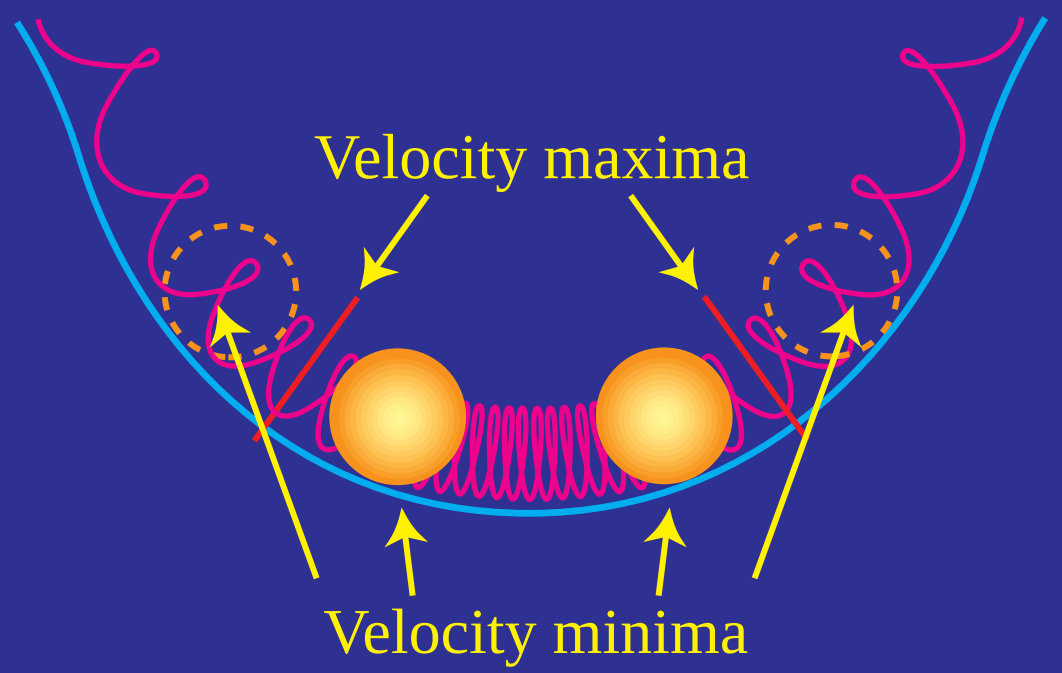
- Relative velocity of fluid and observer
- Extrema of oscillations are turning points or velocity zero points
- Velocity $\pi/2$ out of phase with temperature

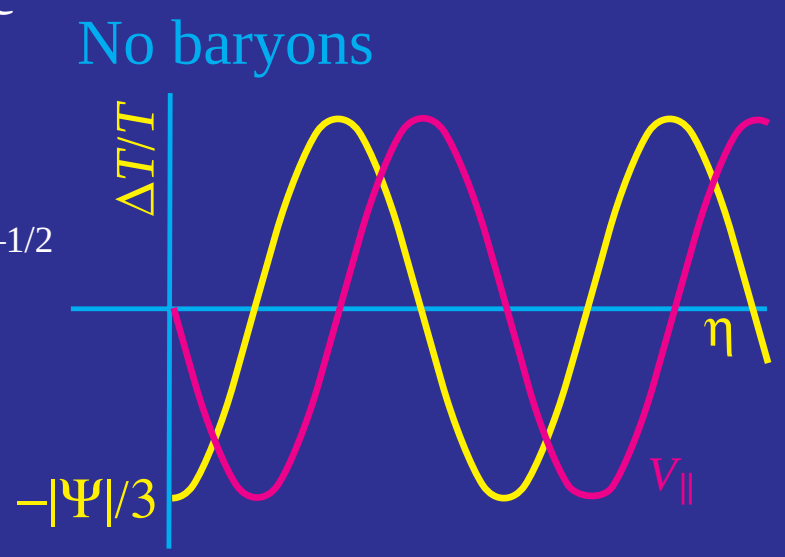


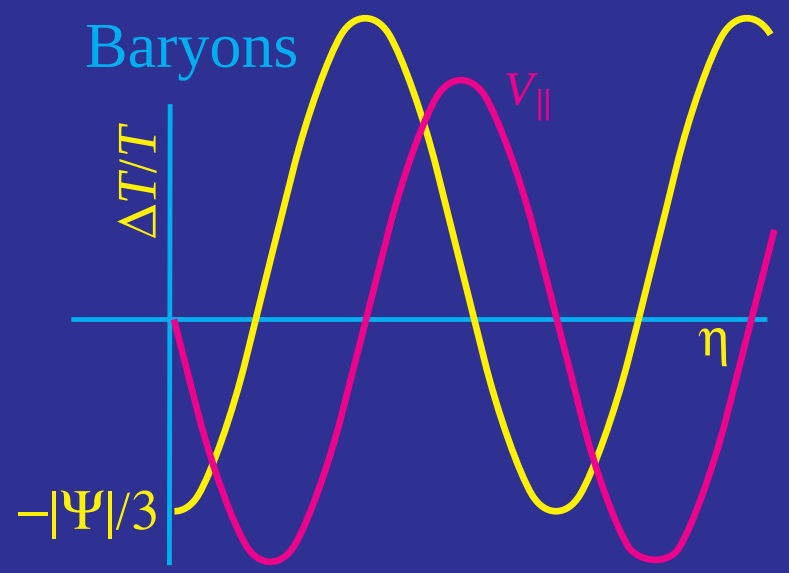
Doppler Effect

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

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

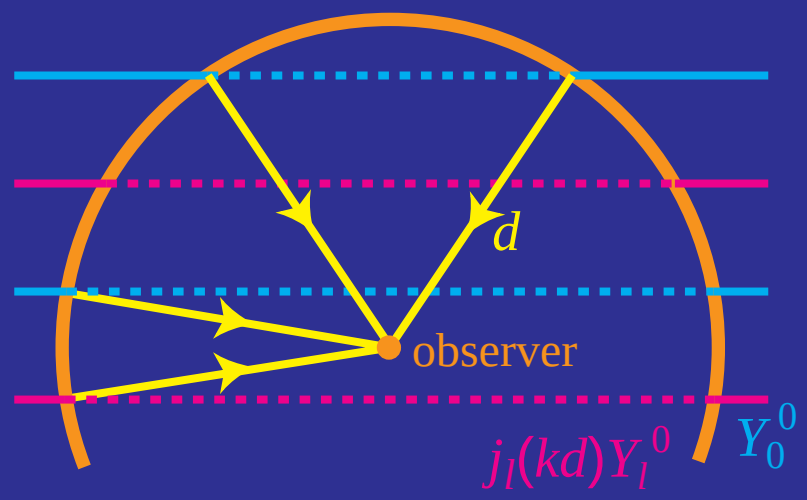


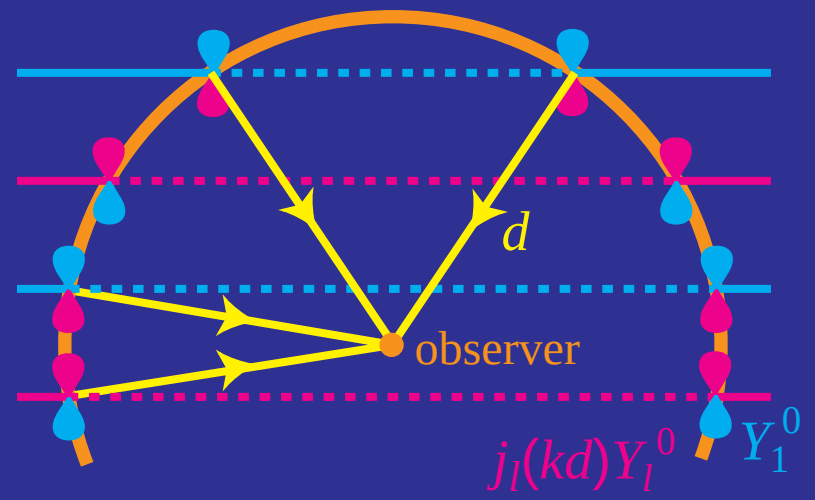


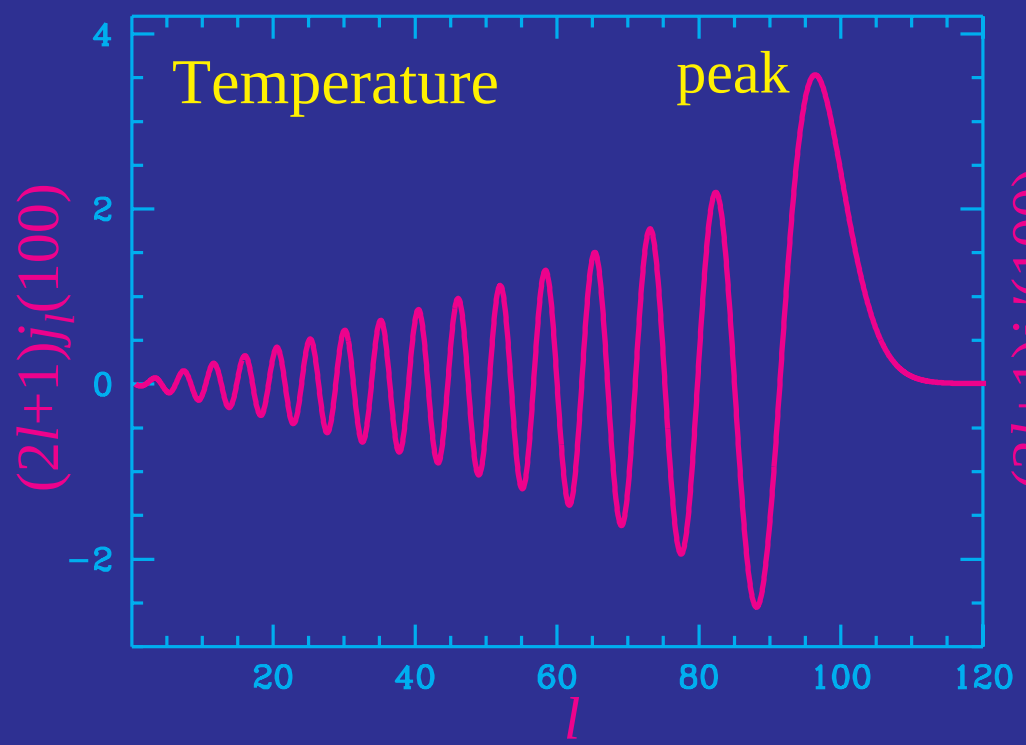


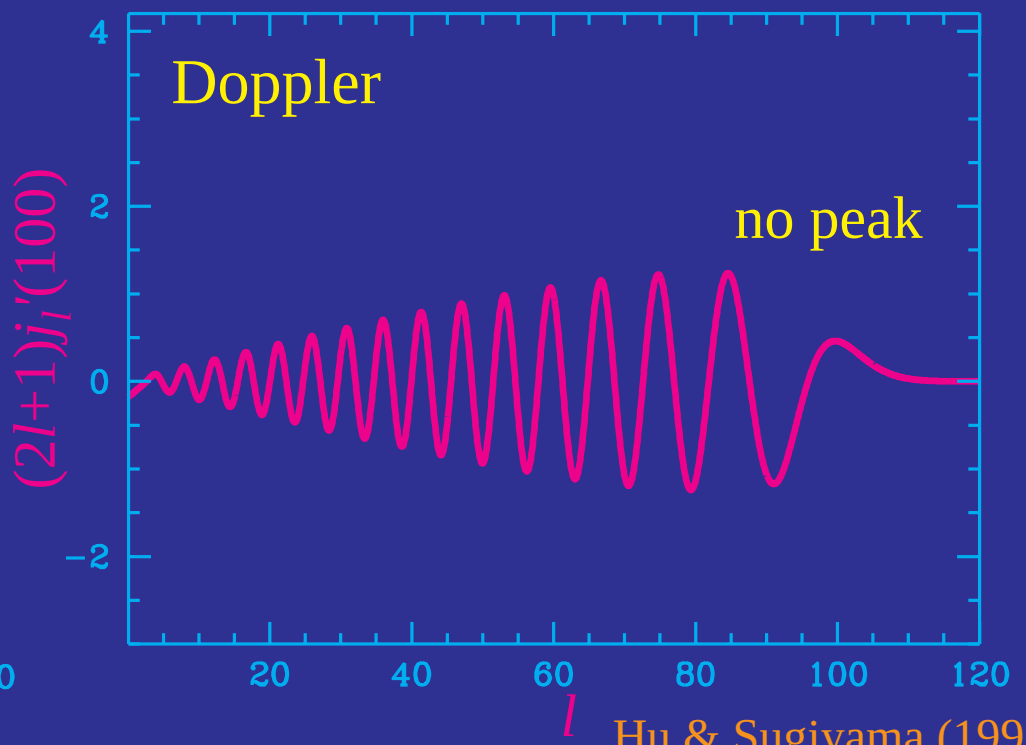
Doppler Peaks?

- Doppler effect has lower amplitude and weak features from projection



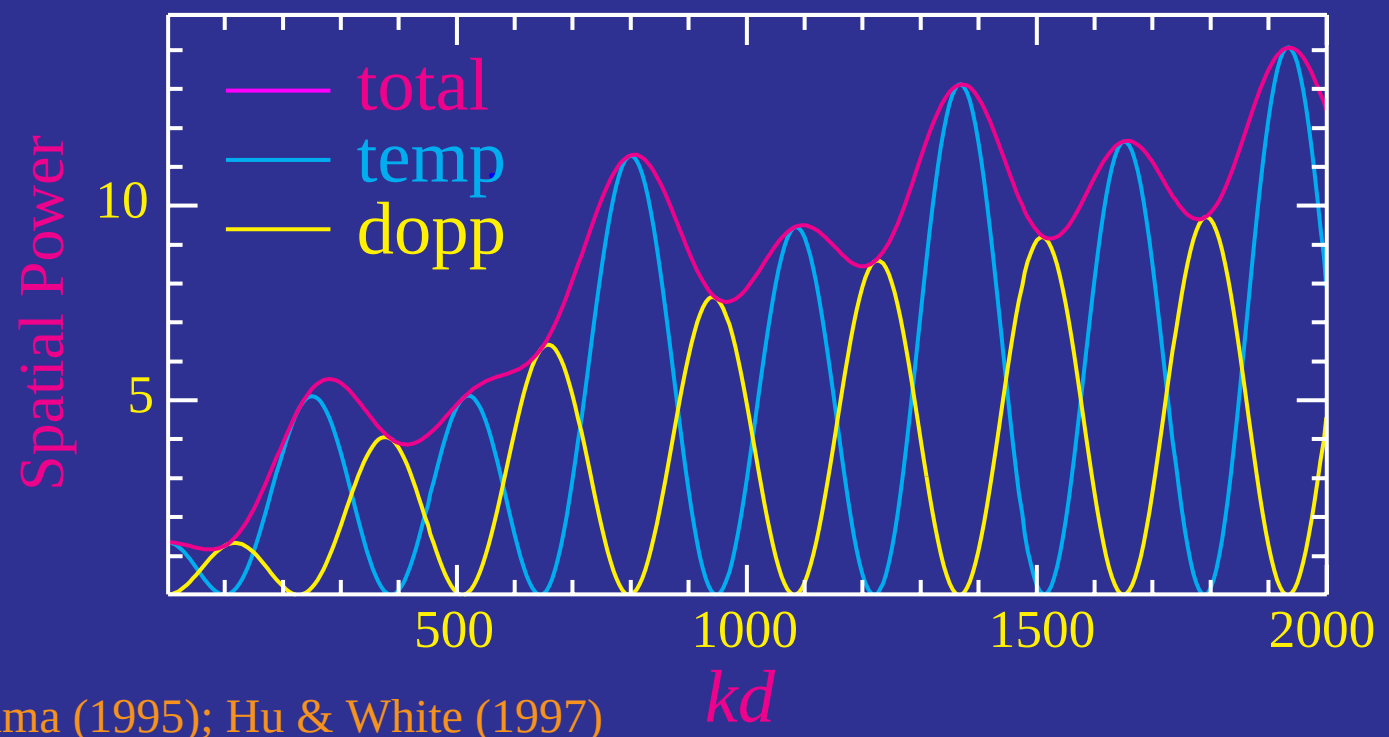






Hu & Sugiyama (1995)

Relative Contributions



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

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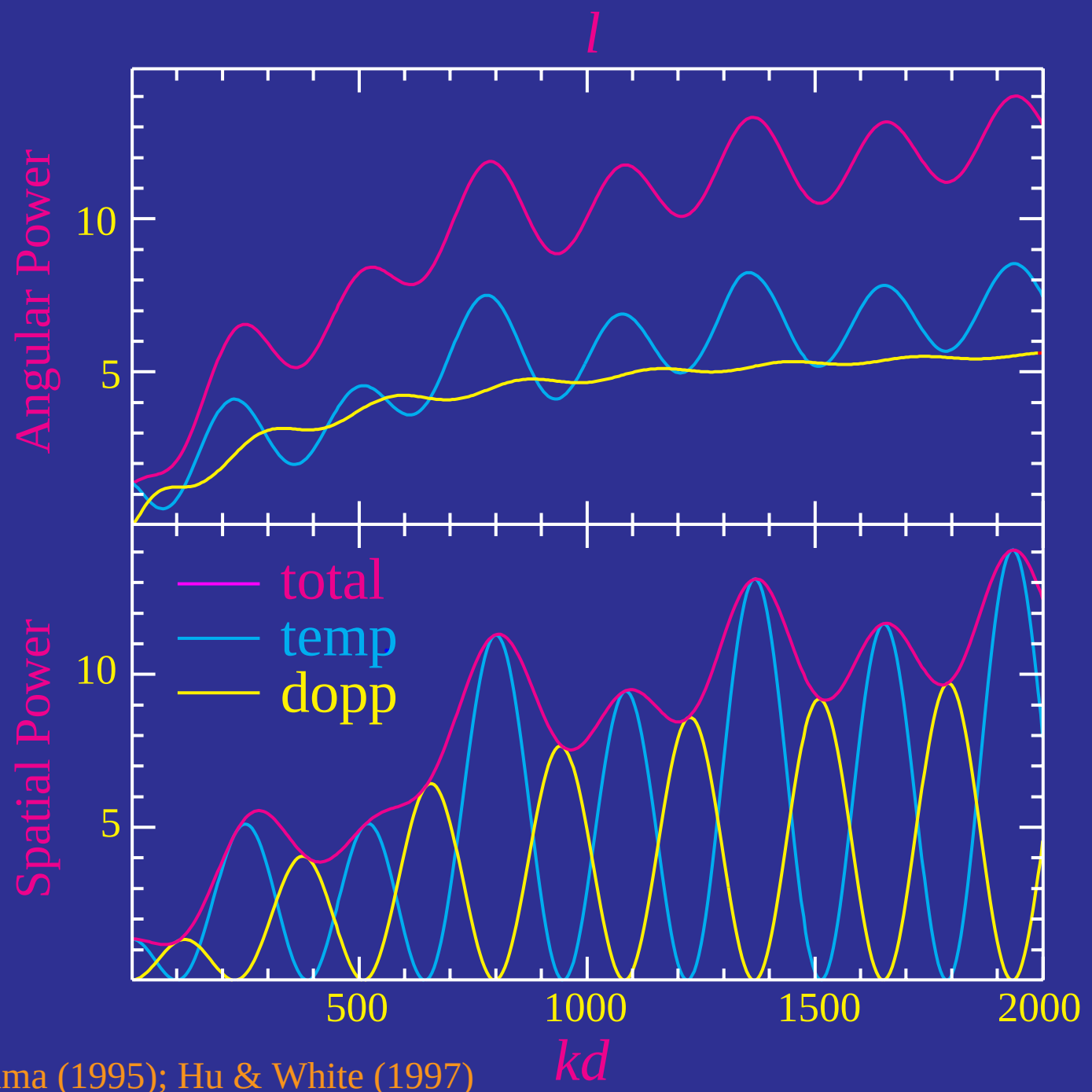
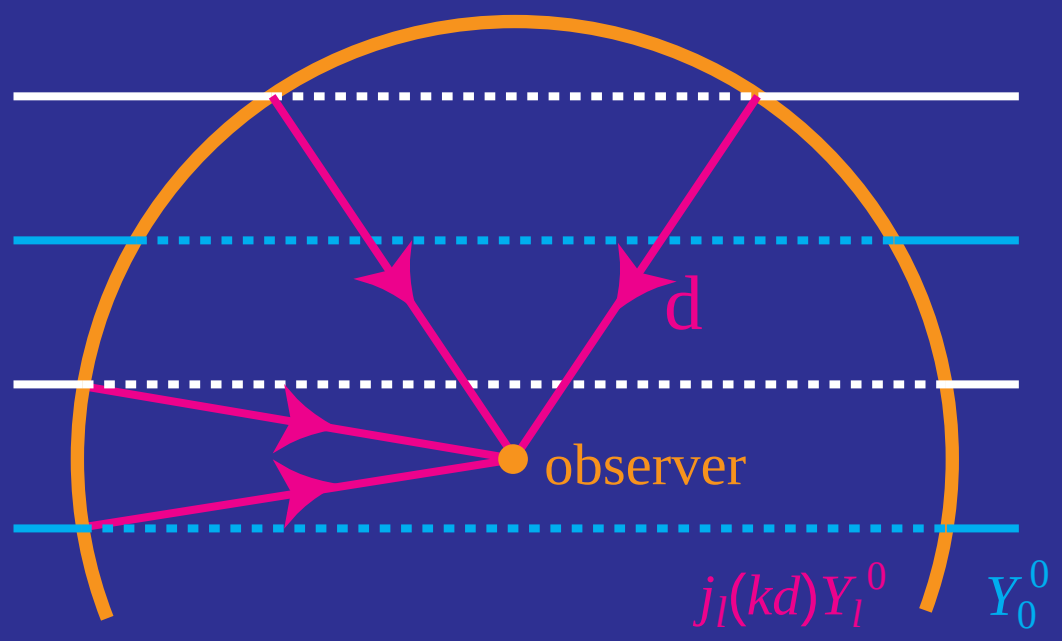


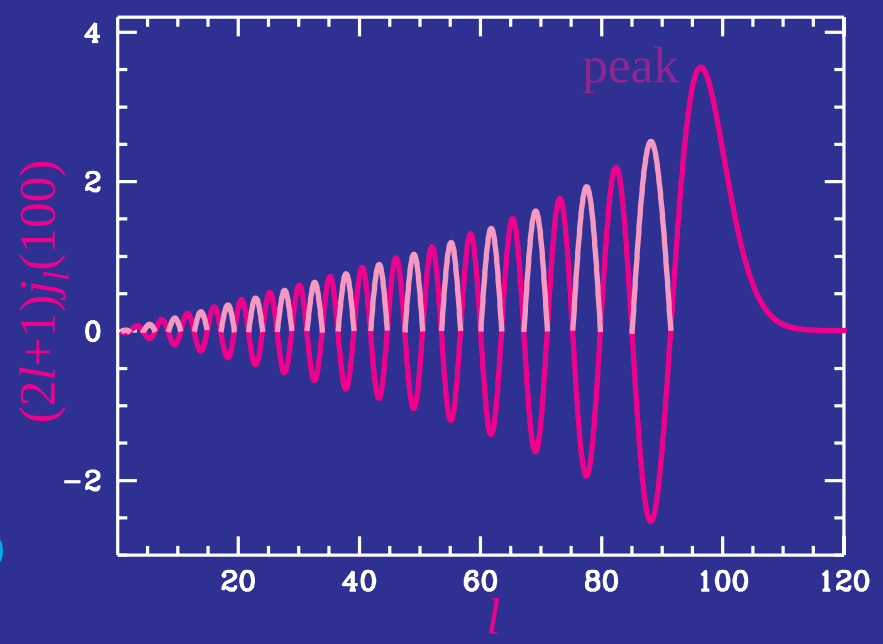
Hu & Sugiyama (1995); Hu & White (1997)

Projection into Angular Peaks

- Peaks in spatial power spectrum
- Projection on sphere
- Spherical harmonic decomposition

- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- Described by spherical bessel function $j_l(kd)$





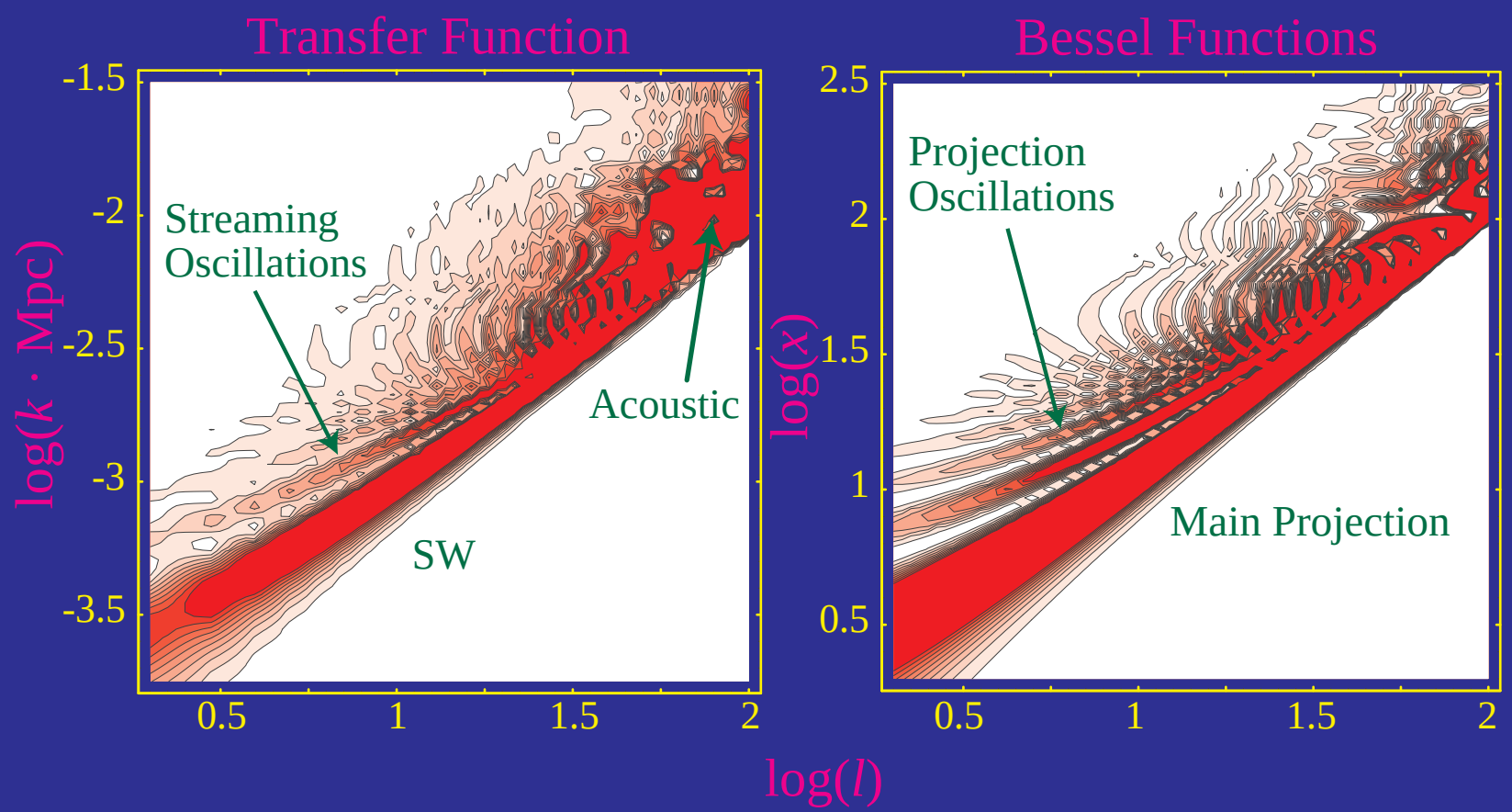
Bond & Efstathiou (1987)

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

Projection into Angular Peaks

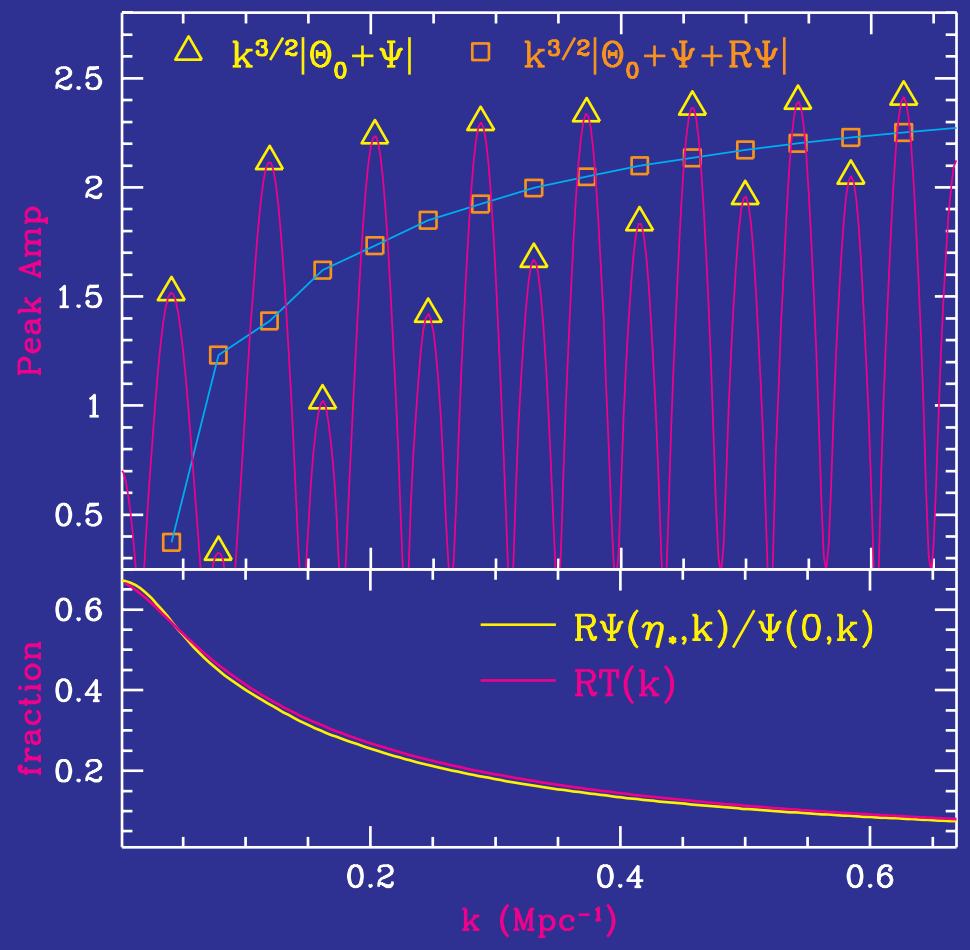
- Peaks in spatial power spectrum
- Projection on sphere
- Spherical harmonic decomposition

- Maximum power at $l = kd$
- Extended tail to $l \ll kd$
- 2D Transfer Function
  $T^2(k,l) \sim (2l+1)^2 \, [\Delta T/T]^2 \, j_l^2(kd)$



Hu & Sugiyama (1995)

Measuring the Potential



- Remove smooth damping (independent of perturbations)
- Measure relative peak heights
- Relate to $R\Psi$ at last scattering
- Compare with large scale structure Ψ today
- Residual is smooth potential envelope and measures matter–radiation ratio

Hu & White (1996)

Uses of Acoustic Oscillations

- Distinct features
- Presence/absence unmistakenable
- Sensitive to background parameters through fluid parameters
- Sensitive to perturbations through gravitational potential wells which later form structure

- Robust measures of

  Angular diameter distance (curvature)
  Baryon–photon ratio

Uses of Baryon Drag

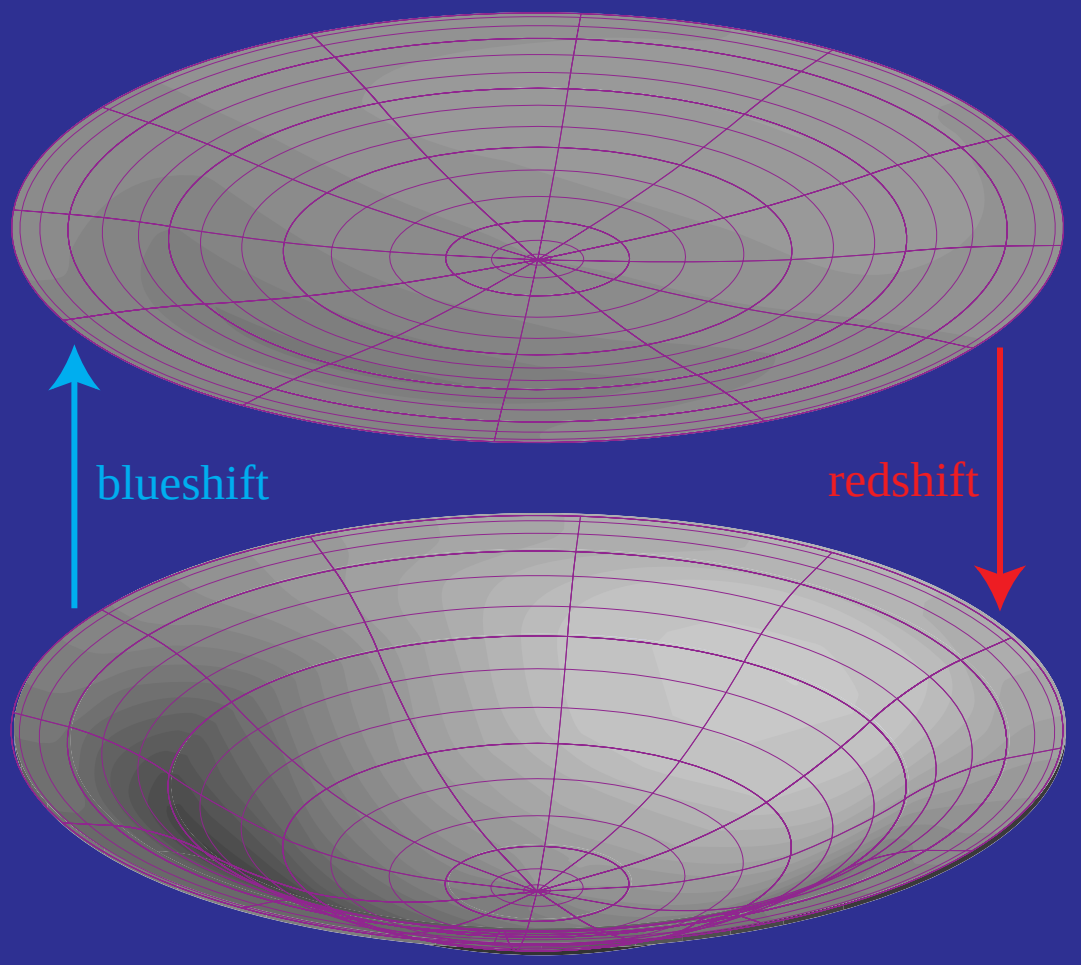
- Measures baryon–photon ratio at last scattering + $z_{\text{last scattering}}$ + T_{CMB} $\rightarrow \Omega_b h^2$
- Measures potential wells at last scattering (compare with large–scale structure today)
- Removes phase ambiguity by distinguishing compression from rarefaction peaks (separates inflation from causal seed models)

Uses of Damping

- Sensitive to thermal history and baryon content
- Independent of (robust to changes in) perturbation spectrum
- Robust physical scale for angular diameter distance test (Ω_K, Ω_Λ)

Integrated Sachs–Wolfe Effect

- Potential redshift: $g_{00}=-(1+\Psi)^2\,\delta_{ij}$



Kofman & Starobinskii (1985)

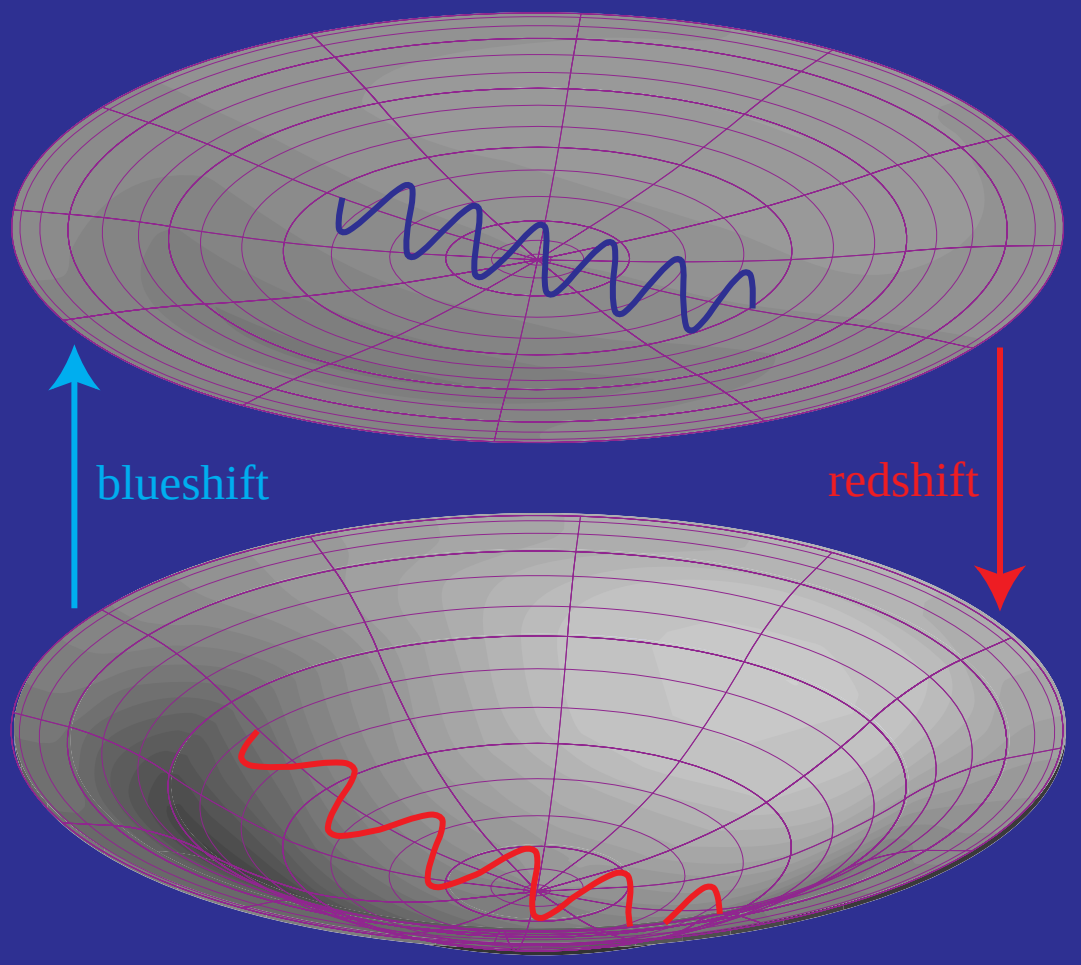
Hu & Sugiyama (1994)

Integrated Sachs–Wolfe Effect

- Potential redshift: $g_{00}=-(1+\Psi)^2\,\delta_{ij}$
- Perturbed cosmological redshift

  $g_{ij}=a^2(1+\Psi)^2\,\delta_{ij}$

  $\delta T/T = -\delta a/a = \Psi$



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- Perturbed cosmological redshift

  $g_{ij}=a^2(1+\Psi)^2\,\delta_{ij}$

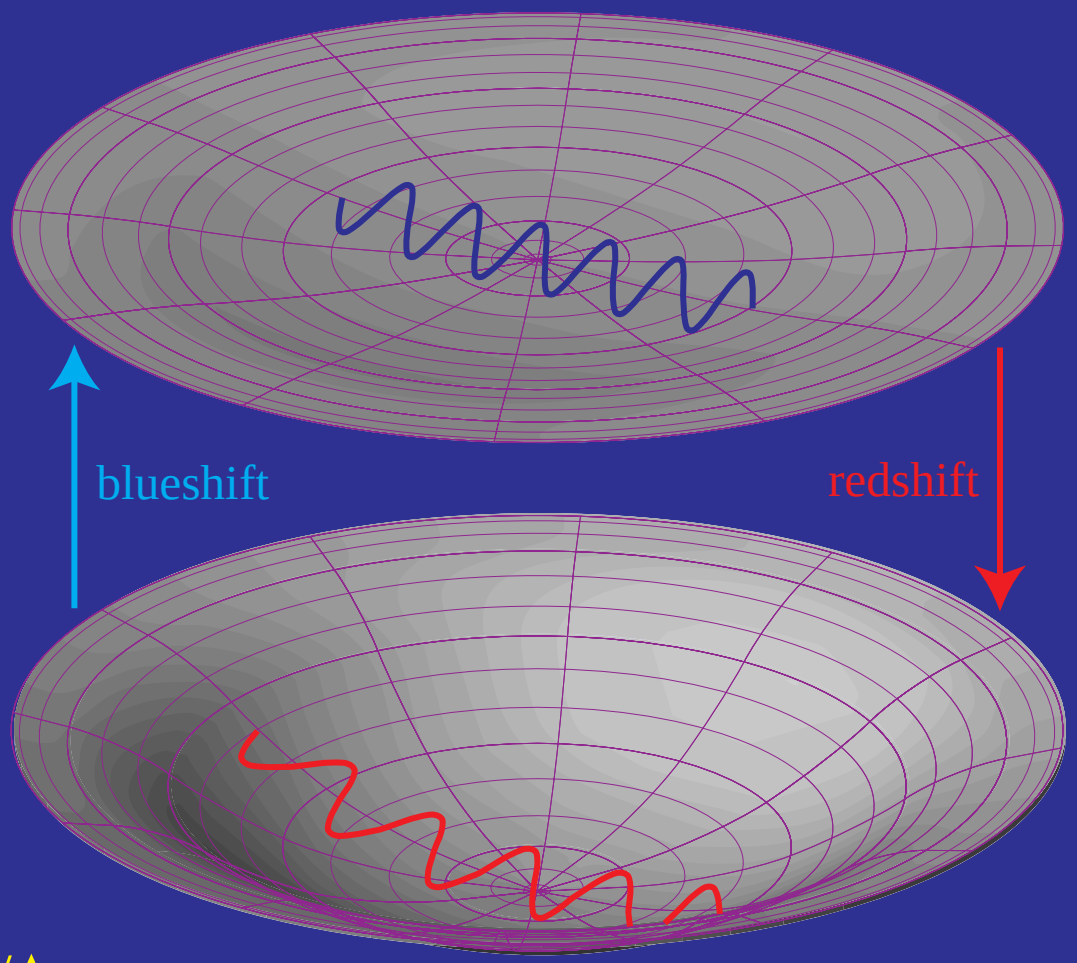
  $\delta T/T = -\delta a/a = \Psi$
- Time–varying potential

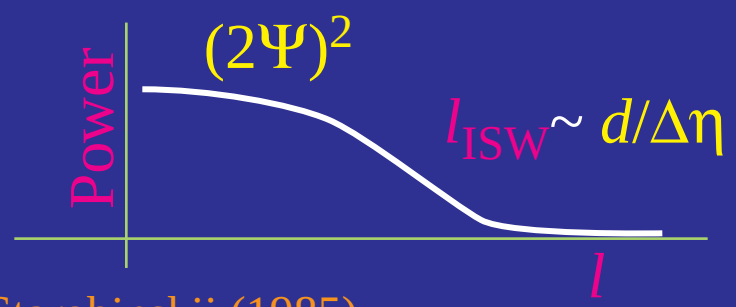
  Rapid compared with λ/c

  $\delta T/T = -2\Delta\Psi$

  Slow compared with λ/c

  redshift–blueshift cancel
- Imprint characteristic time scale of decay in angular spectrum



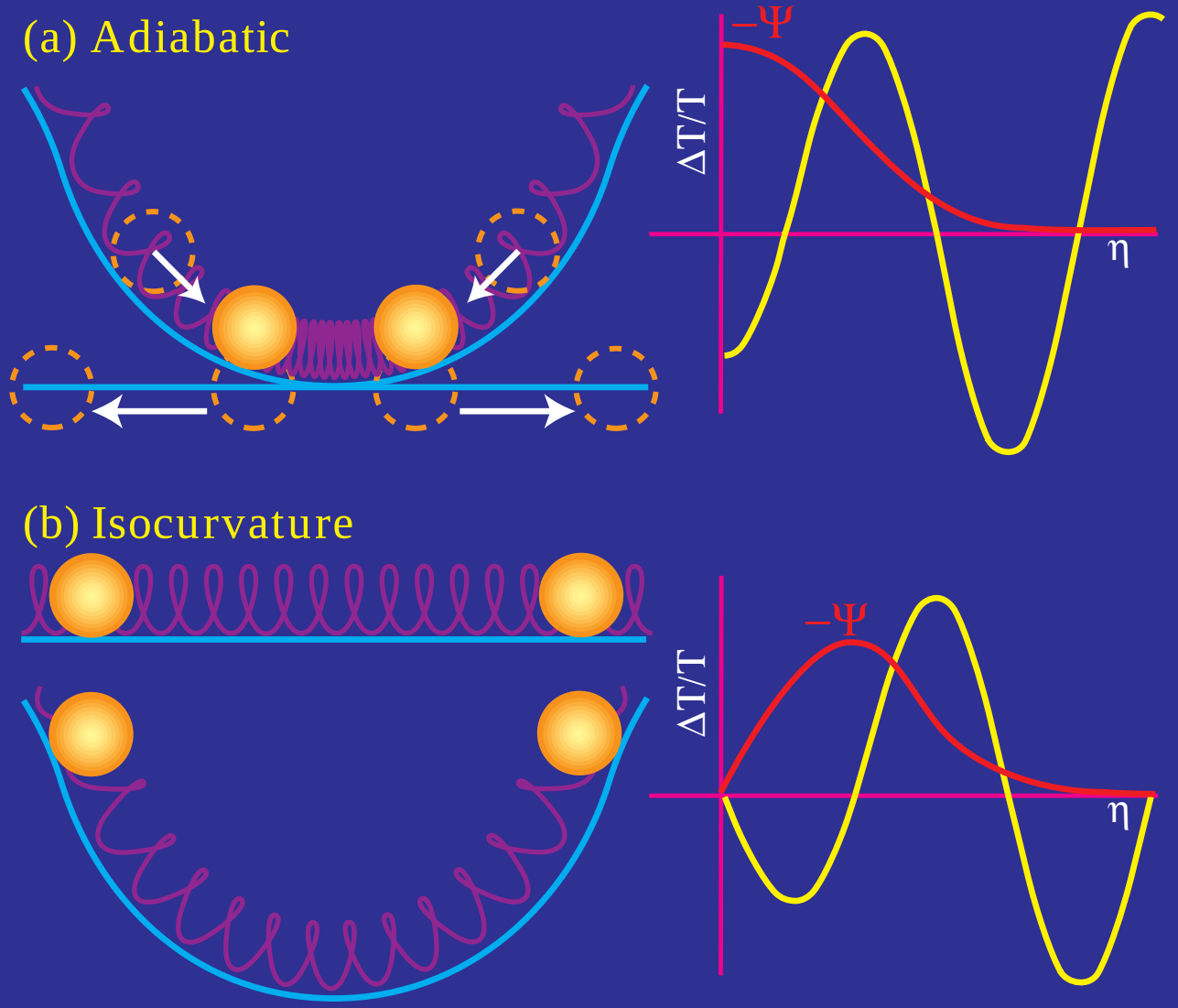


Kofman & Starobinskii (1985)

Hu & Sugiyama (1994)

Testing Inflation / Initial Conditions

- 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)

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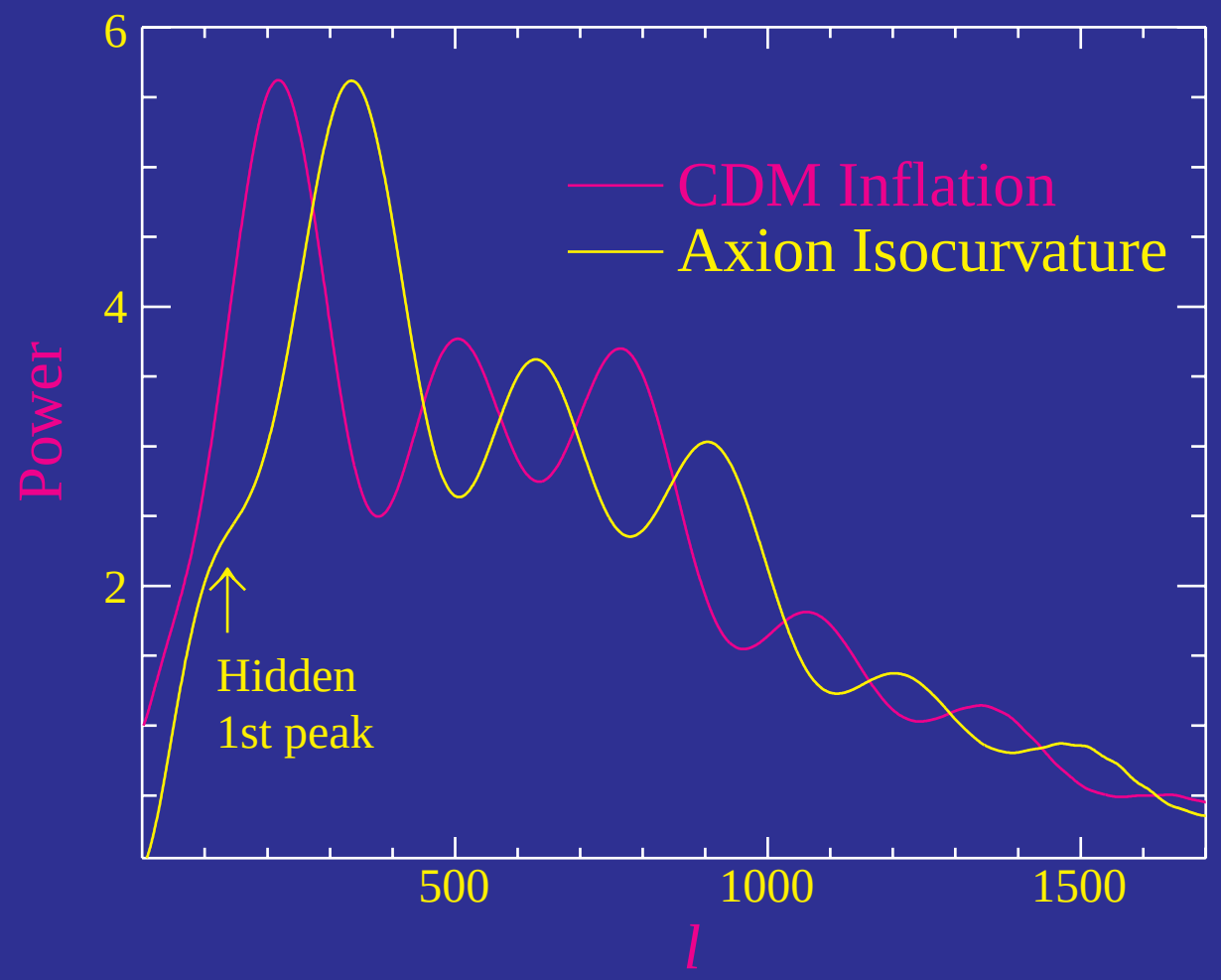
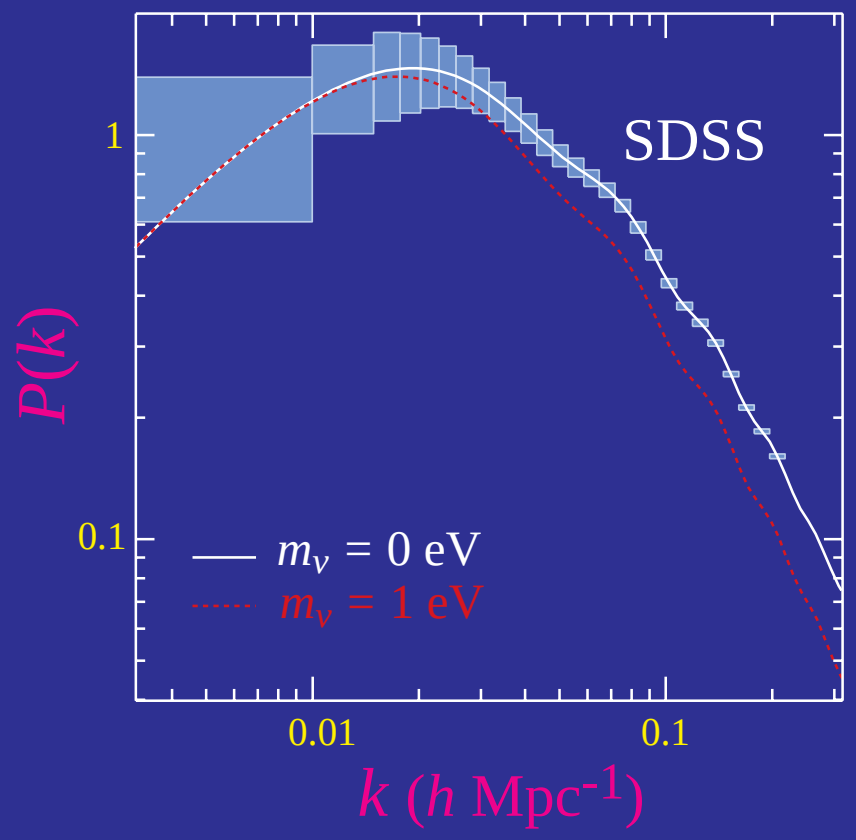


Hu & White (1996)

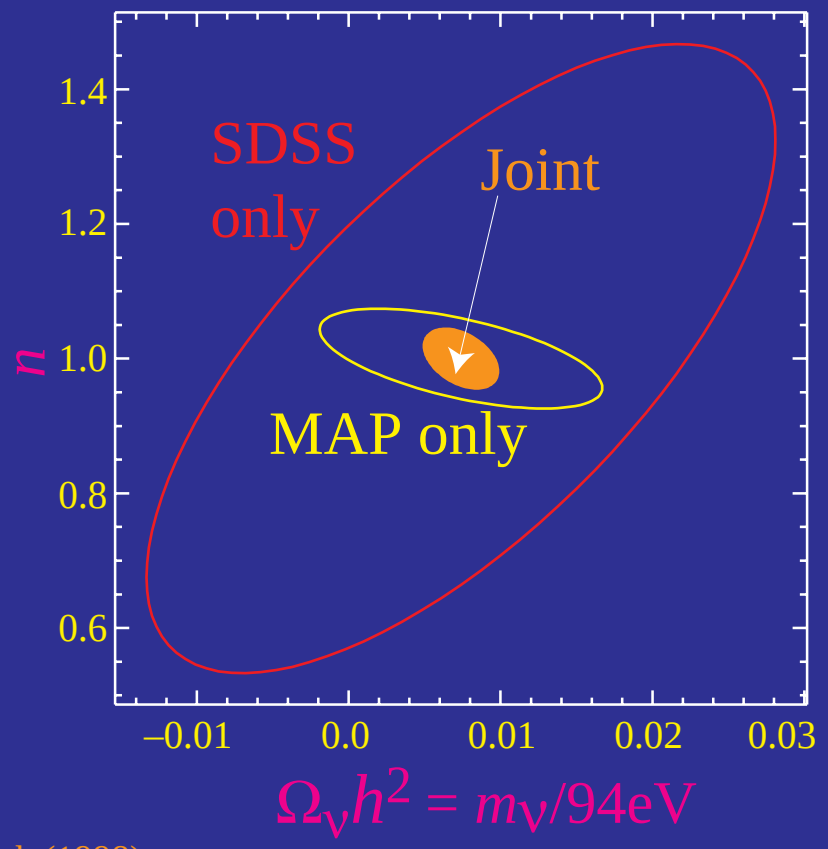
Weighing Neutrinos

- Massive neutrinos suppress power strongly on small scales [$\Delta P/P \approx -8\Omega_\nu/\Omega_m$]: well modeled by [$c_{eff}^2 = w_g$, $c_{vis}^2 = w_g$, w_g: $1/3 \rightarrow 1$]
- Degenerate with other effects [tilt n, $\Omega_m h^2$...]
- CMB signal small but breaks degeneracies
- 2σ Detection: 0.3eV [Map (pol) + SDSS]

Power Suppression

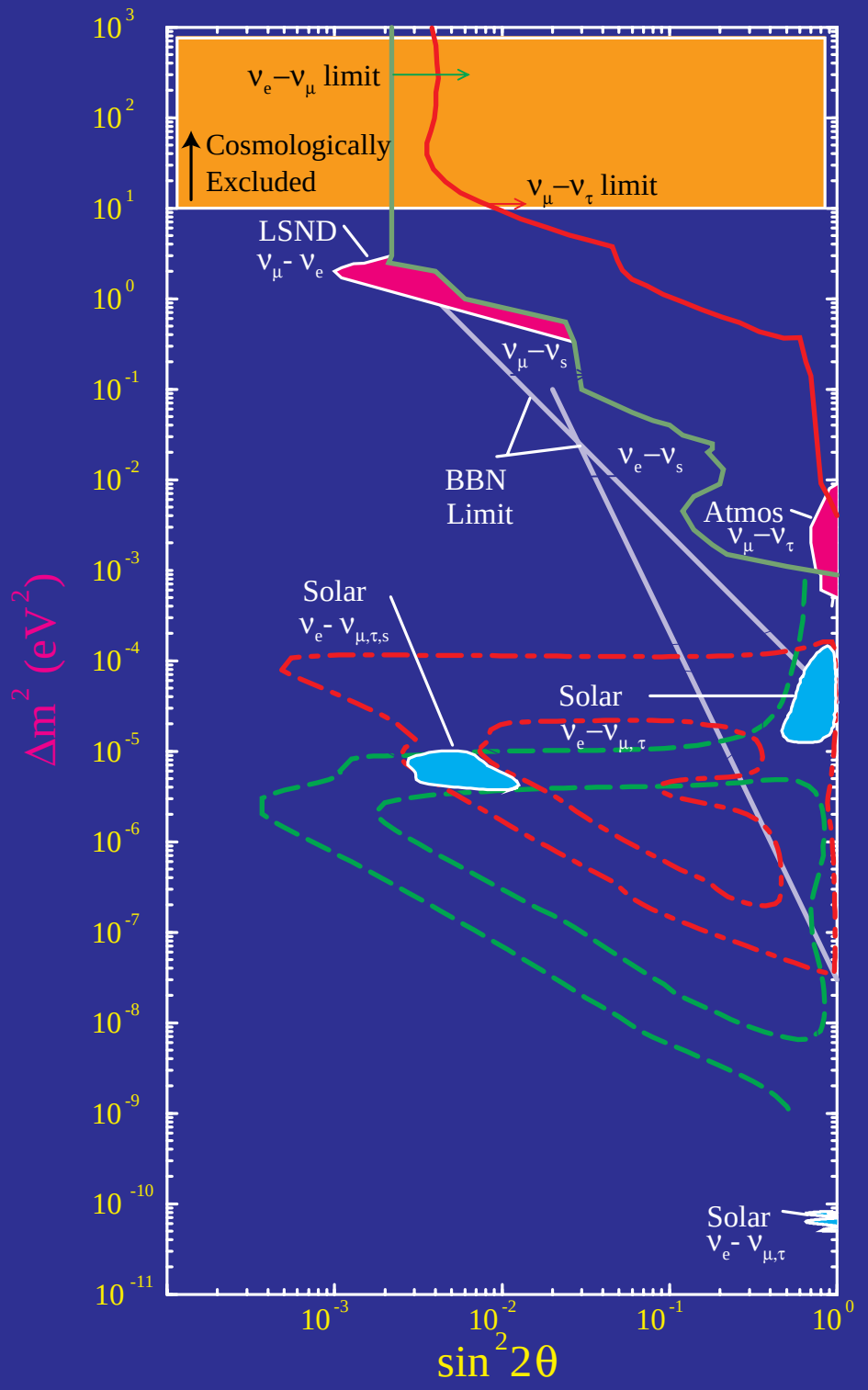


Complementarity



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

Cosmology and the Neutrino Anomalies



Hata (1998)

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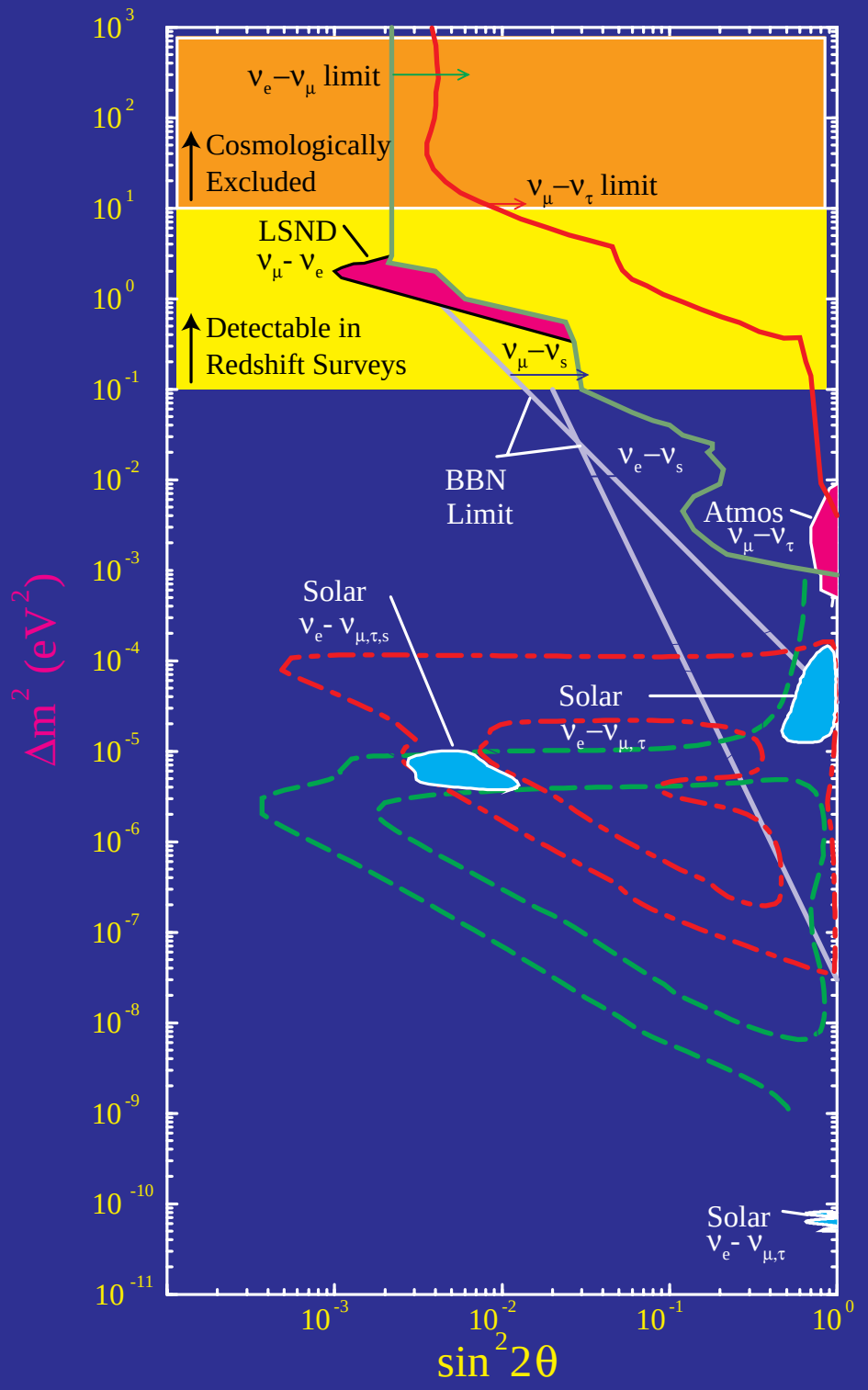

Hata (1998)
Hu, Eisenstein & Tegmark (1998)

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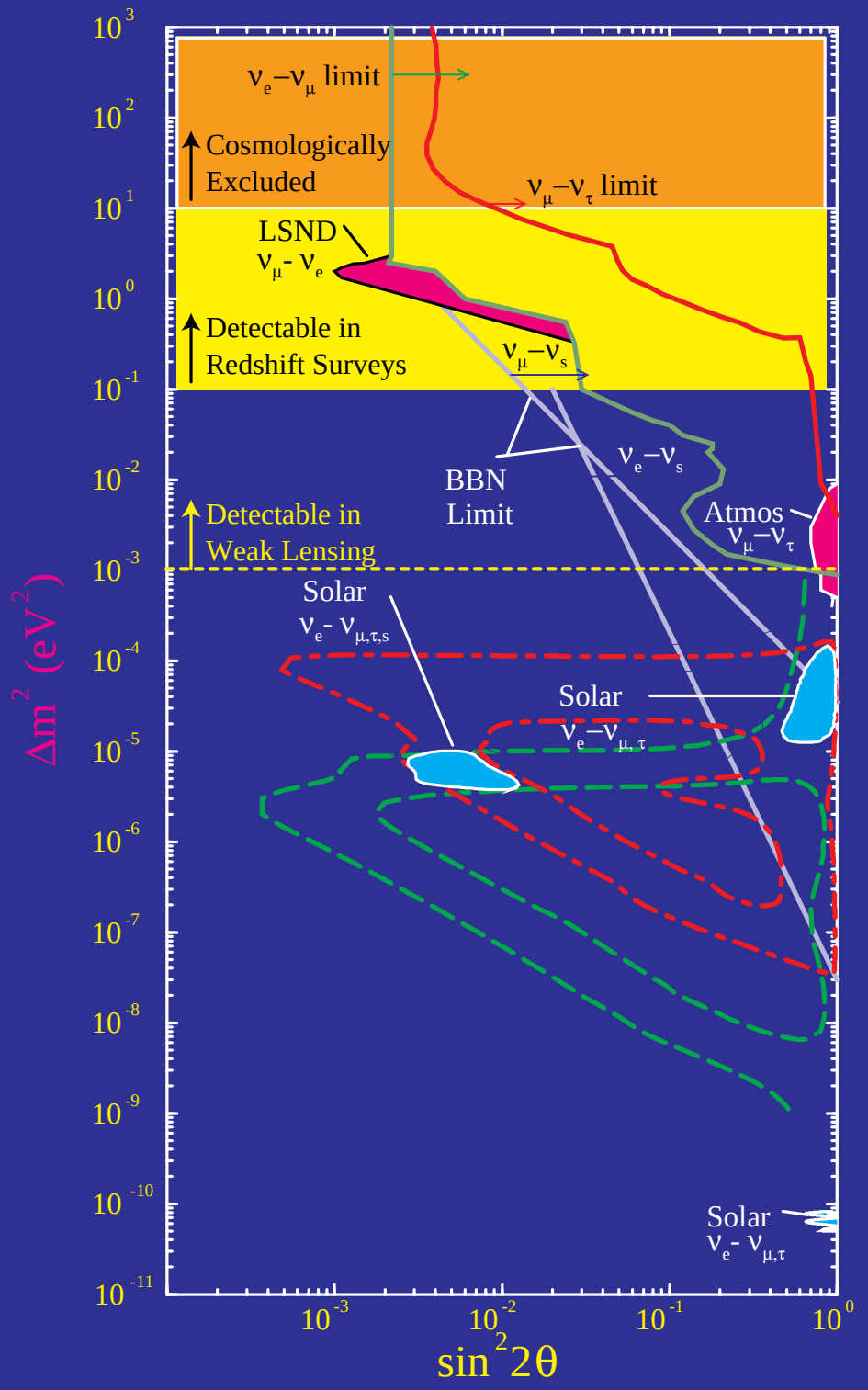
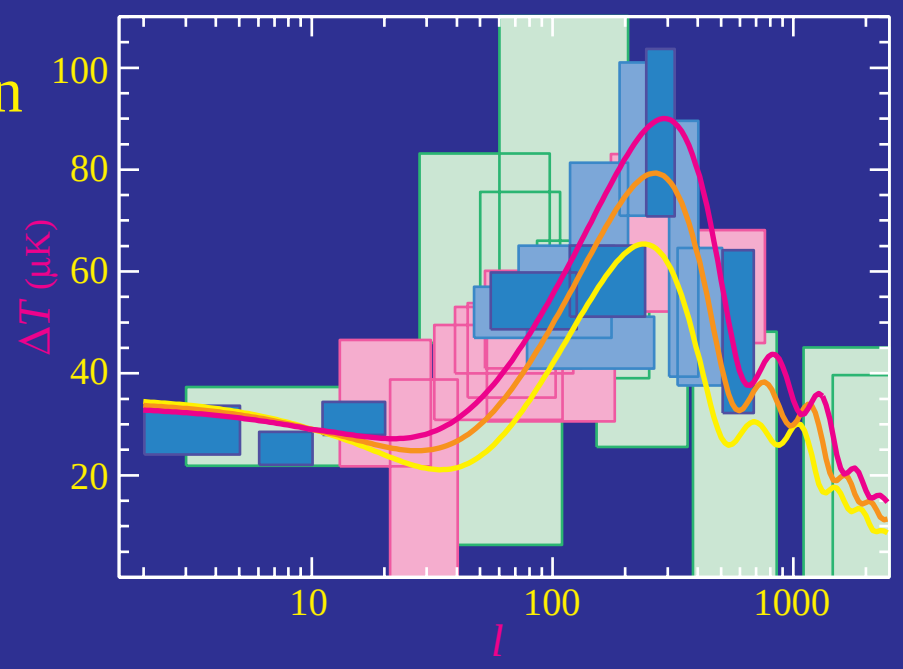
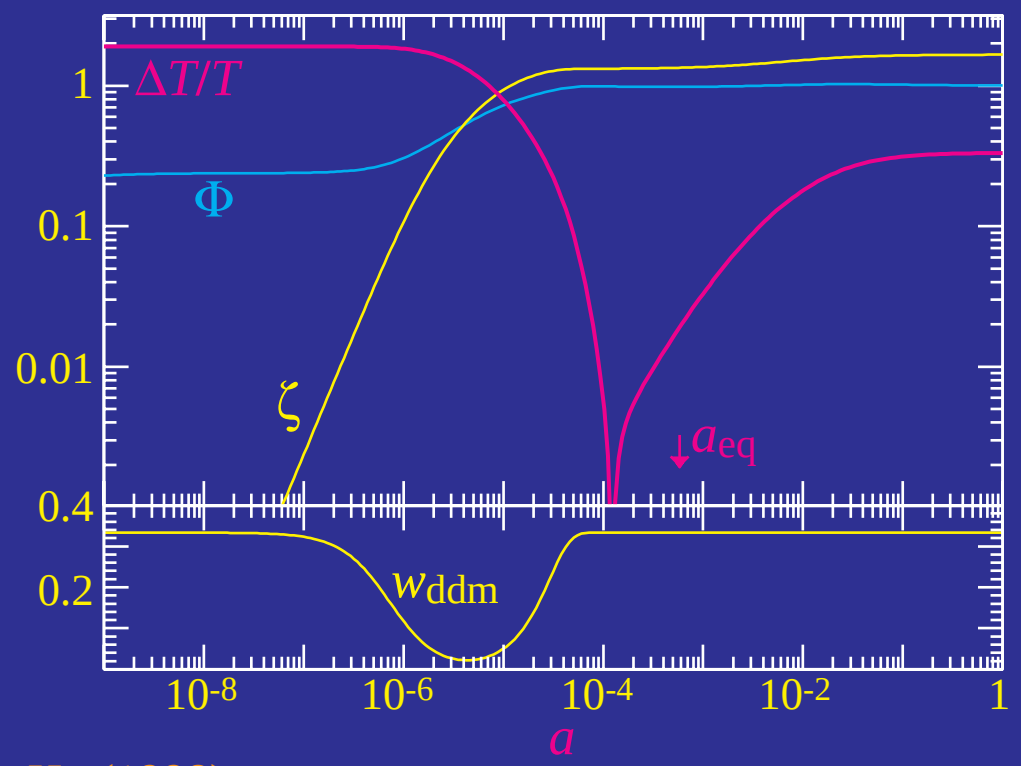


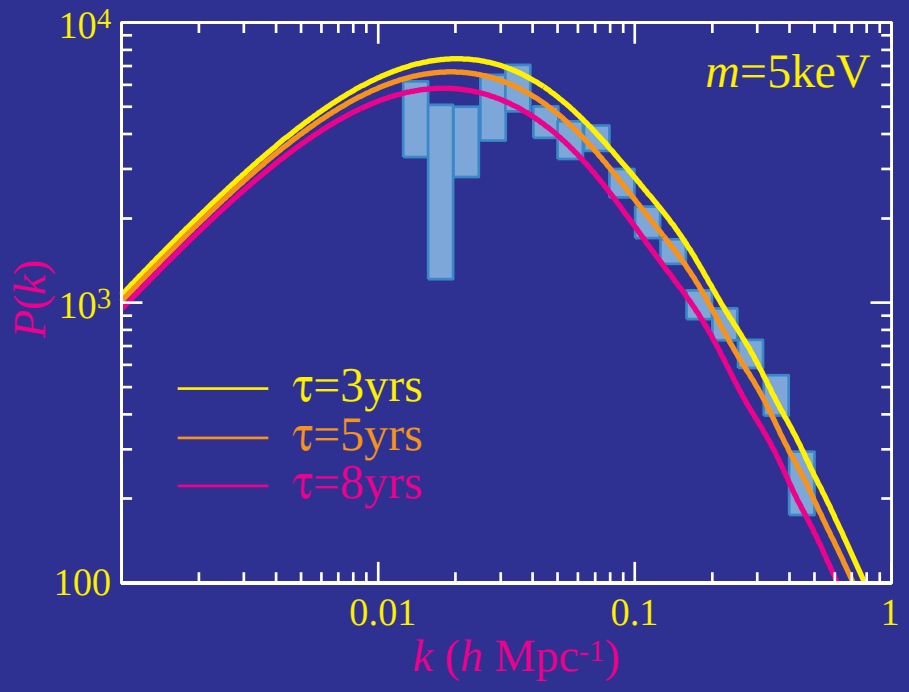
Hata (1998)
Hu, Eisenstein & Tegmark (1998)
Hu & Tegmark (1998)

Decaying Dark Matter

- Example: relativistic matter goes non-relativistic, decays back into radiation
- Model decay and decay products as a single component of dark matter
- Novel consequences: scale–invariant curvature perturbation from scale–invariant isocurvature perturbations





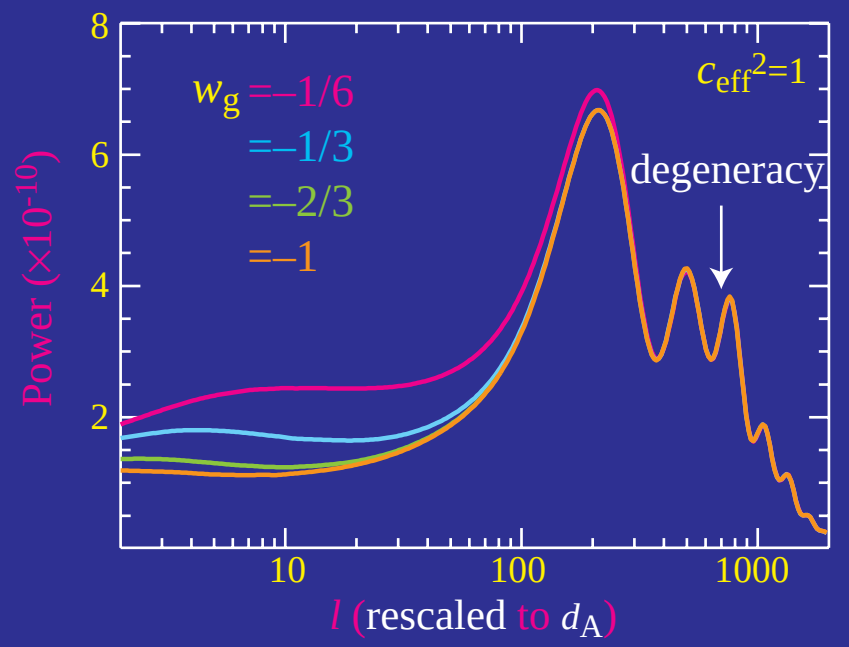


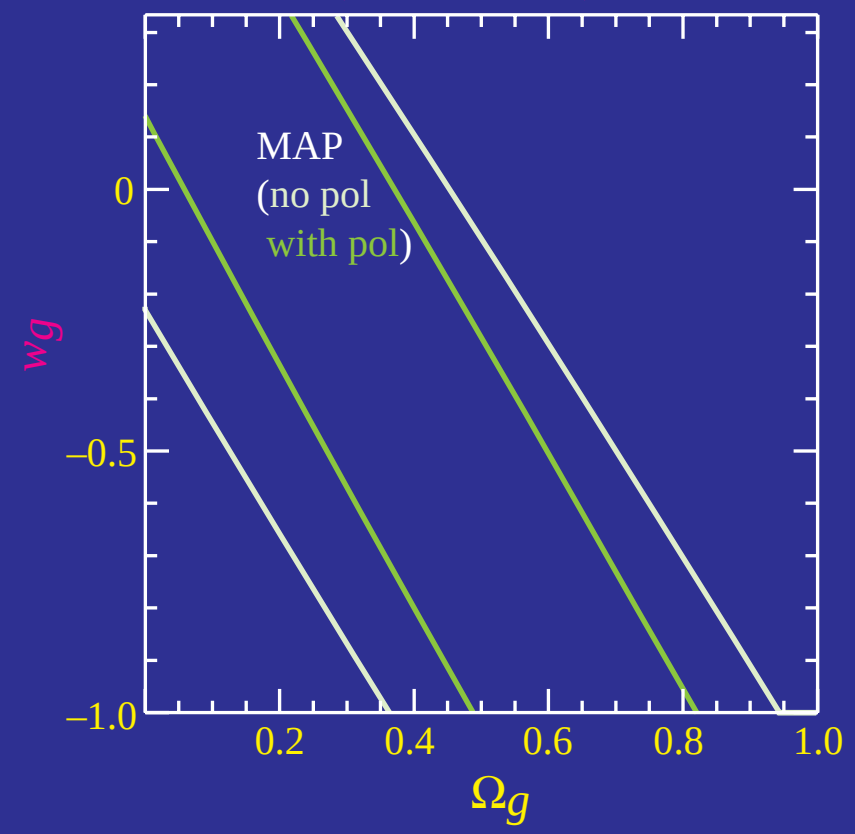
Hu (1998)

Testing Λ

- If $w_g<0$, GDM has no effect on acoustic dynamics → (k_{peaks}, heights) independent of w_g, Ω_g, c_{eff}, c_{vis}

- CMB sensitive to GDM/Λ mainly through angular diameter distance [$d_A = f(w_g, \Omega_g ...)$]





Hu, Eisenstein, Tegmark & White (1998)

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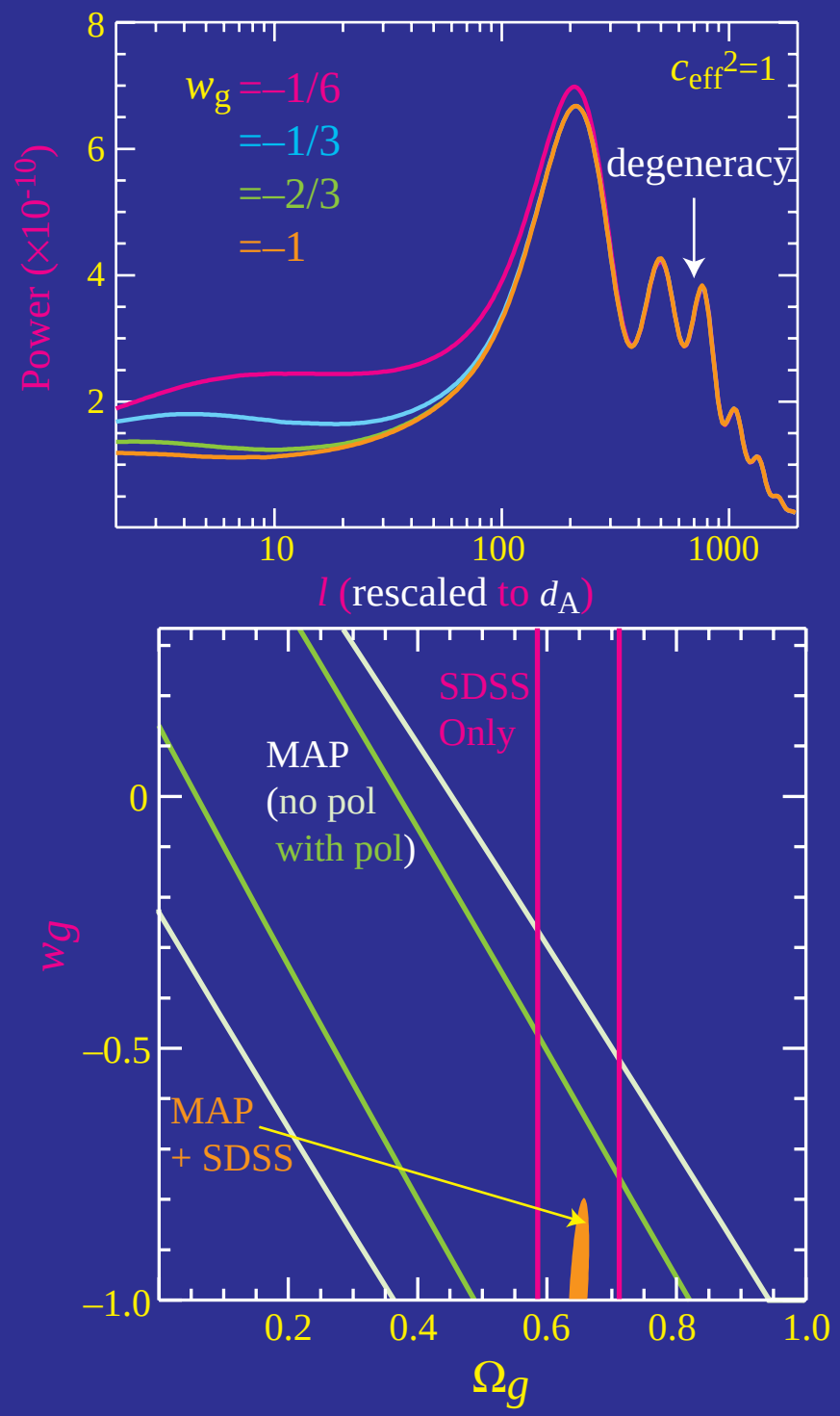
- Galaxy surveys determines h
- CMB determines $\Omega_m h^2 \rightarrow \Omega_m$
- Flatness $\Omega_g = 1 - \Omega_m$



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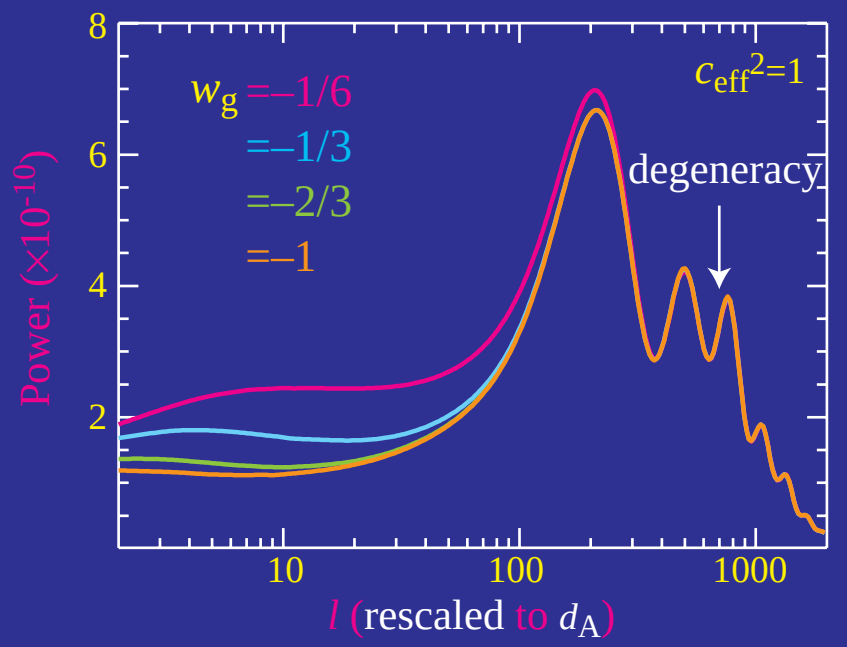
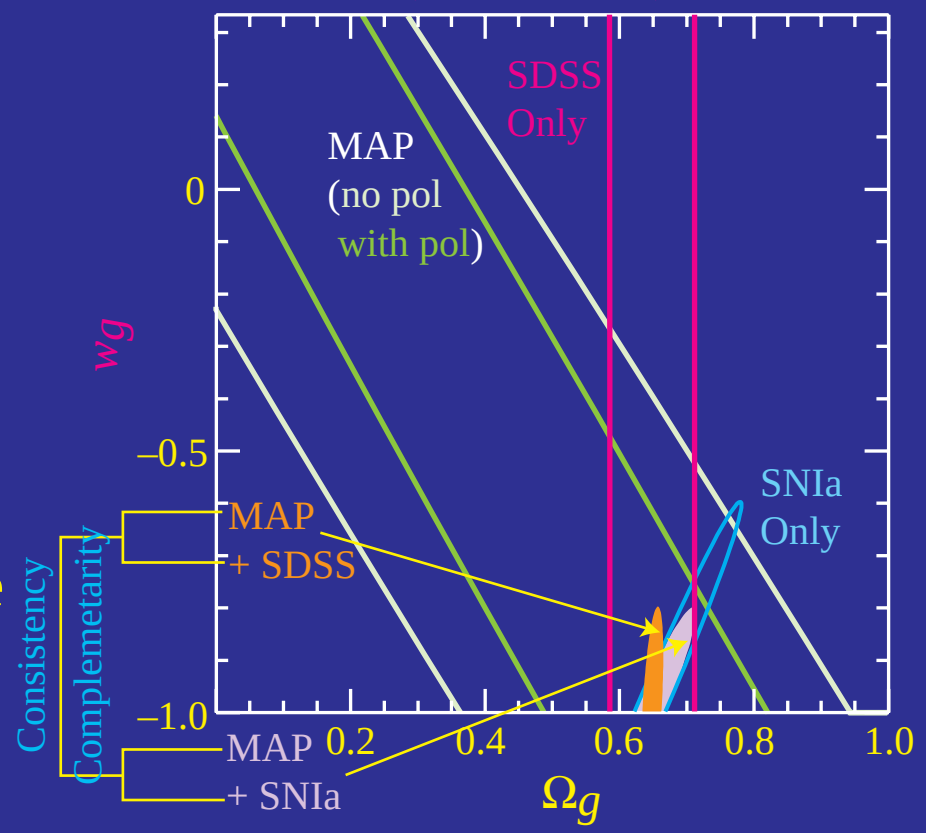
- SNIa determines luminosity distance [$d_L = f(w_g, \Omega_g)$]





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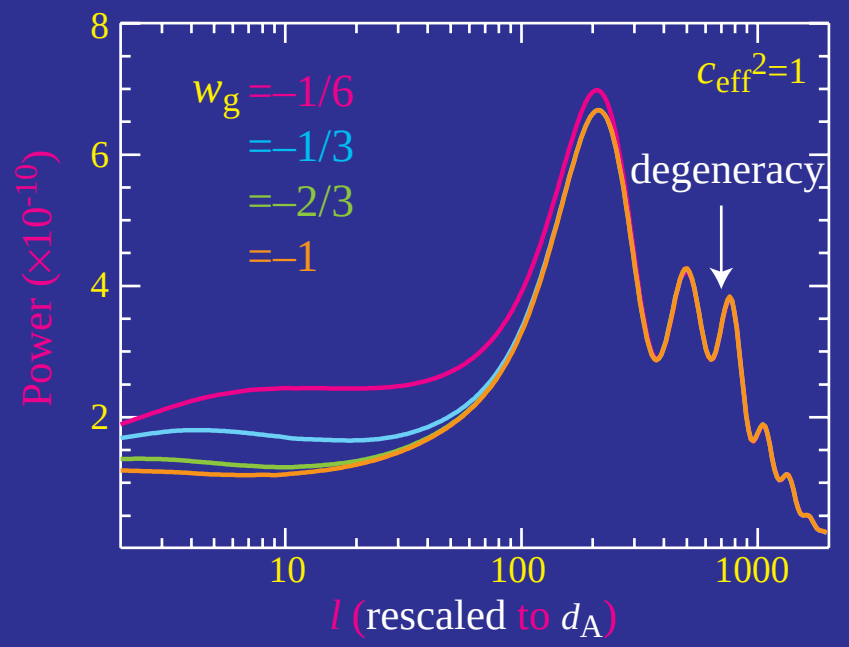
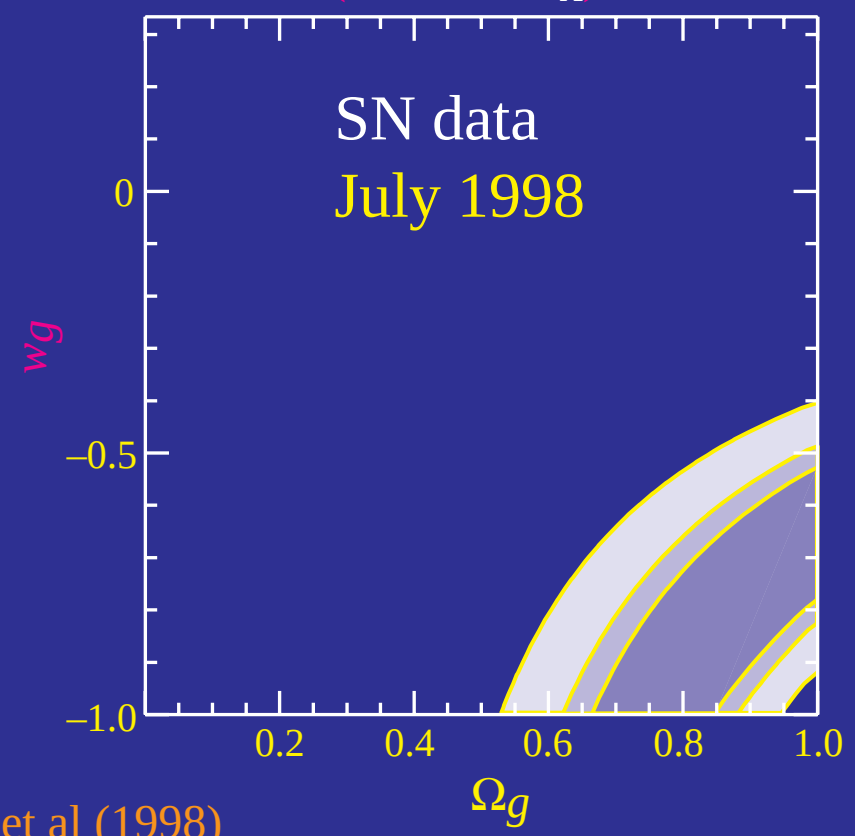


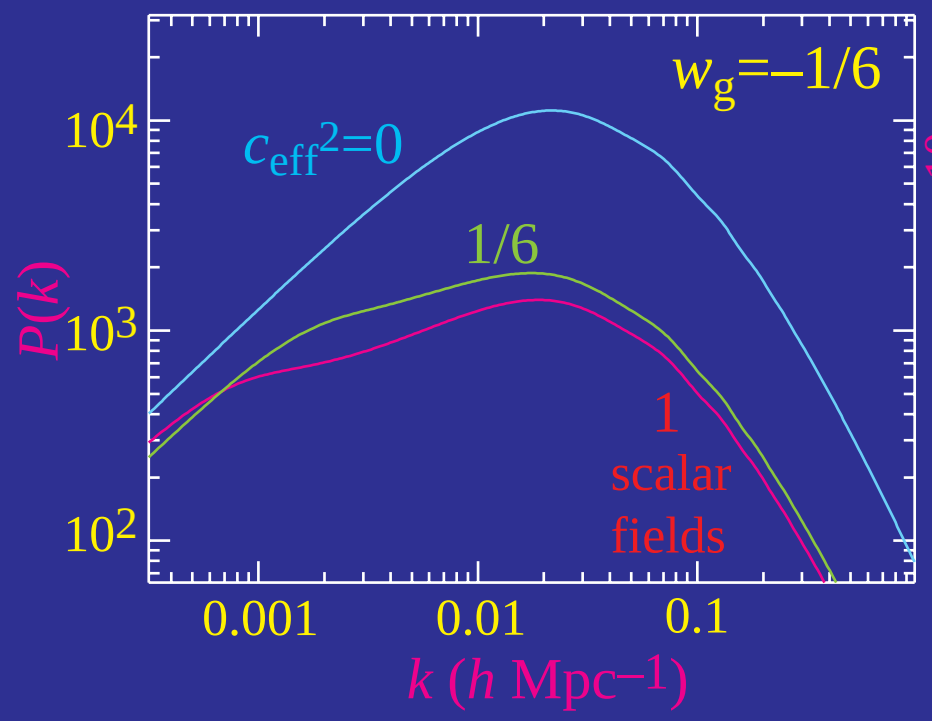


Garnavich et al (1998); Riess et al (1998); Perlmutter et al (1998)

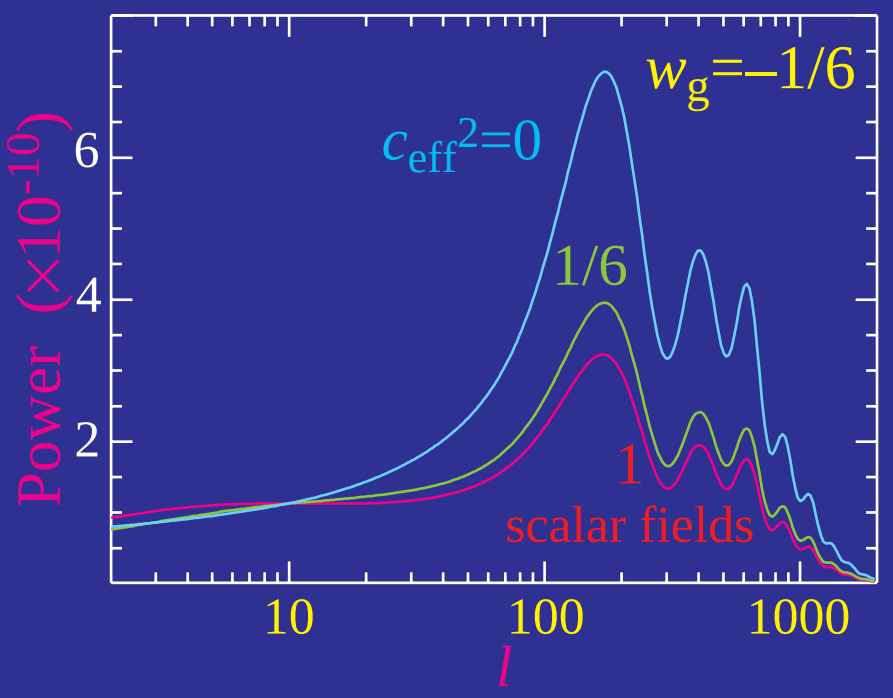
Is the Missing Energy a Scalar Field?

- Scalar Fields have maximal sound speed [$c_{\rm eff}$ =1, speed of light]
- CMB+LSS → Lower limit on $c_{\rm eff}$>0.6 at $w_{\rm g}$=–1/6
  [2.7σ: MAP+SDSS; 7.7σ: Planck+SDSS]
  [in 10d parameter space, including bias, tensors]
- Strong constraints for $w_{\rm g}$ > –1/2

Large Scale Structure



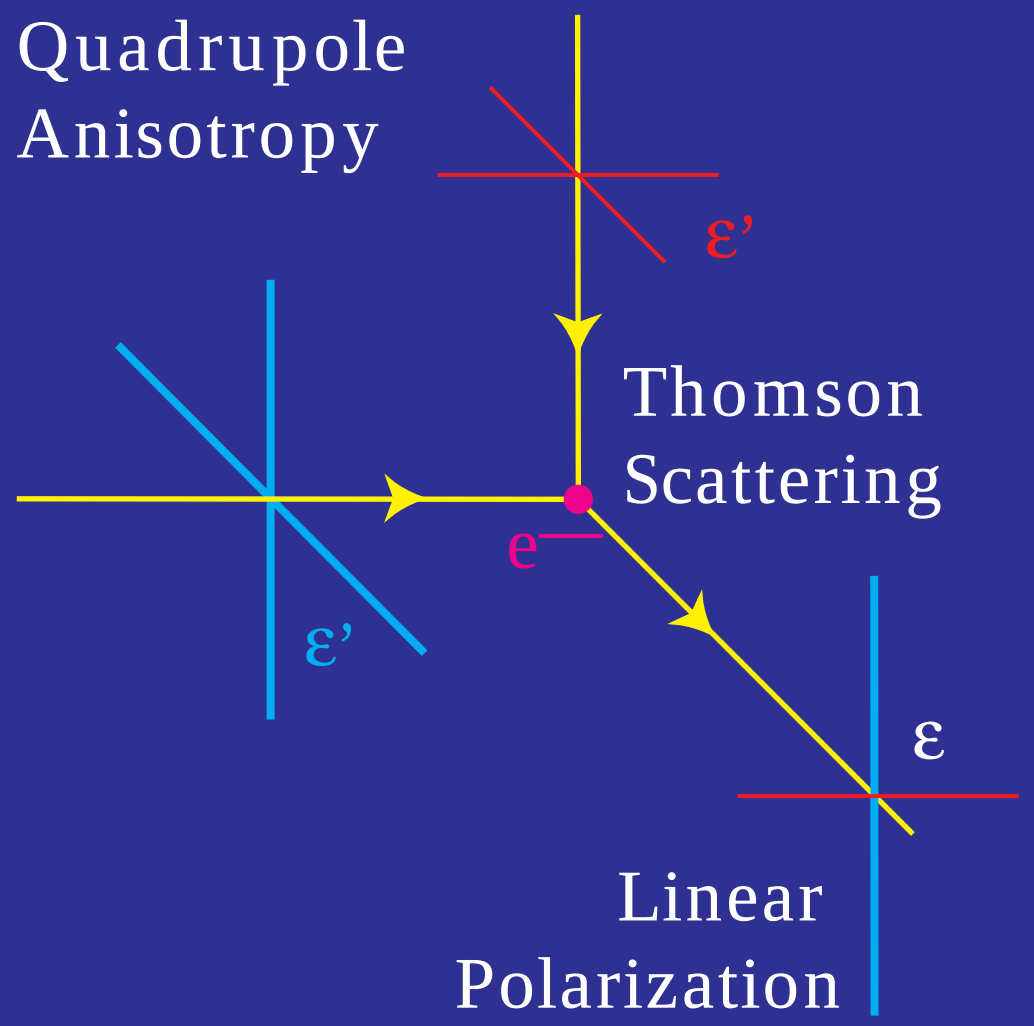
CMB Anisotropies



Hu, Eisenstein, Tegmark & White (1998)

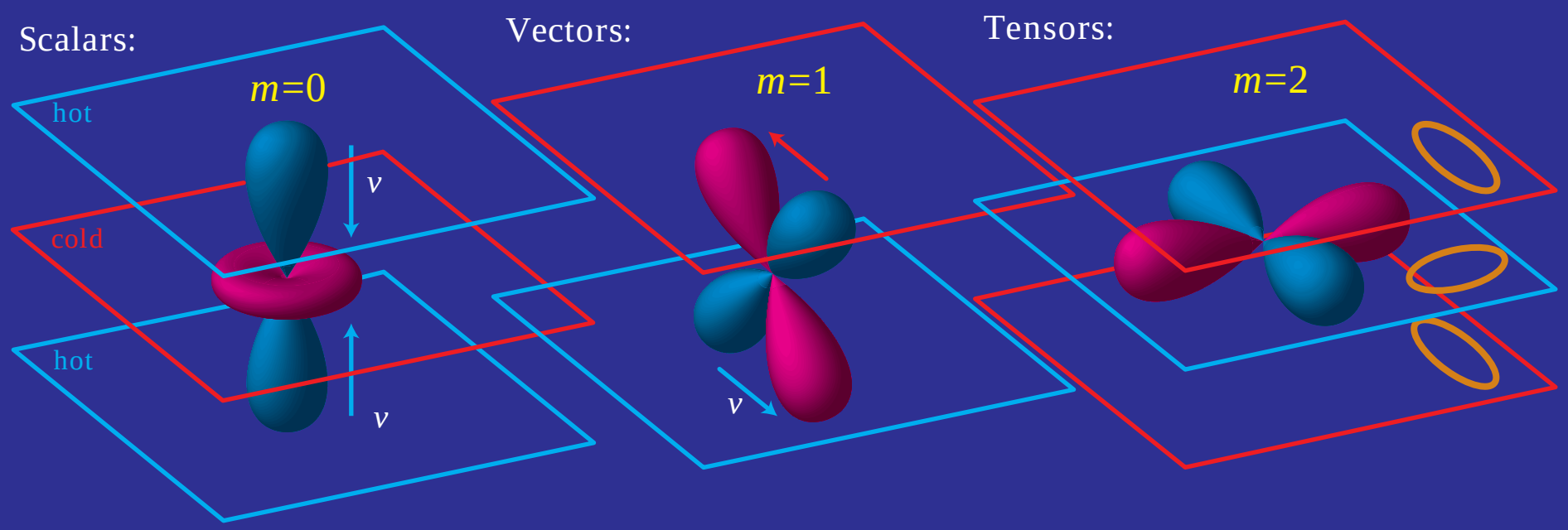
Polarization from Thomson Scattering

- Thomson scattering of anisotropic radiation → linear polarization
- Polarization aligned with cold lobe of the quadrupole anisotropy



Perturbations & Their Quadrupoles

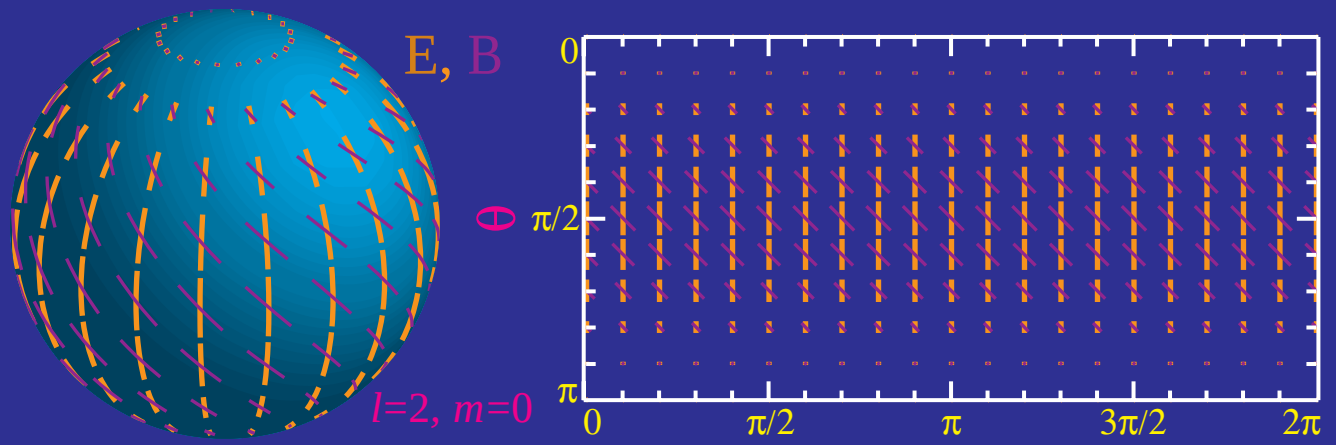
- Orientation of quadrupole relative to wave (**k**) determines pattern
- Scalars (density) m=0
- Vectors (vorticity) m=±1
- Tensors (gravity waves) m=±2



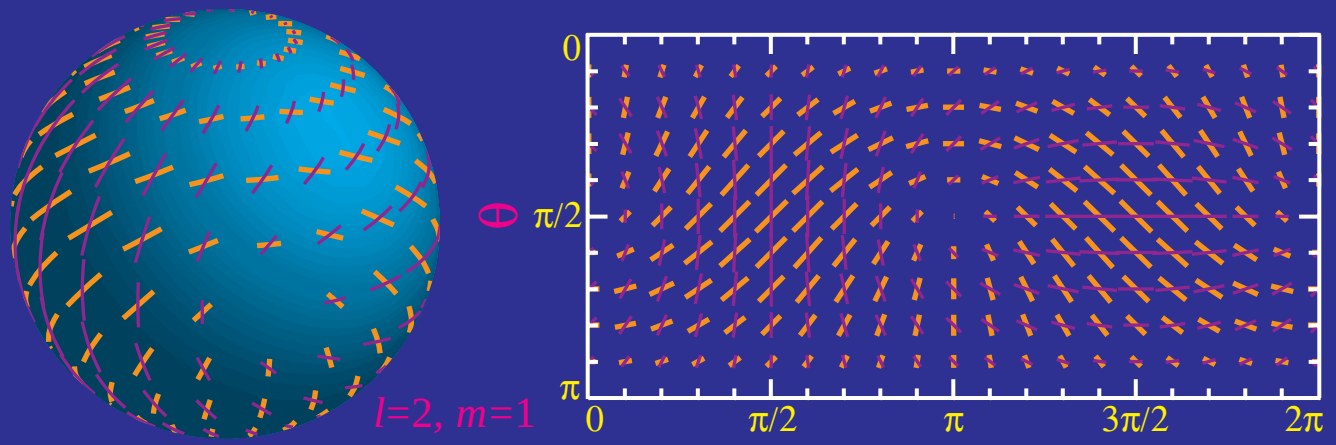
Hu & White (1997)

Polarization Patterns

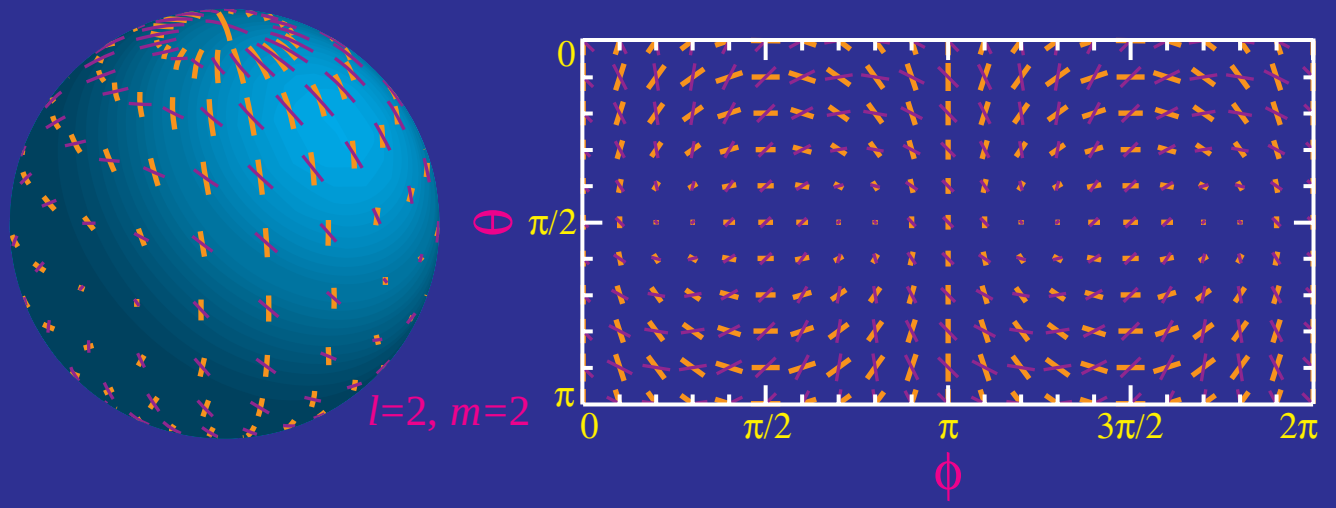
Scalars



Vectors

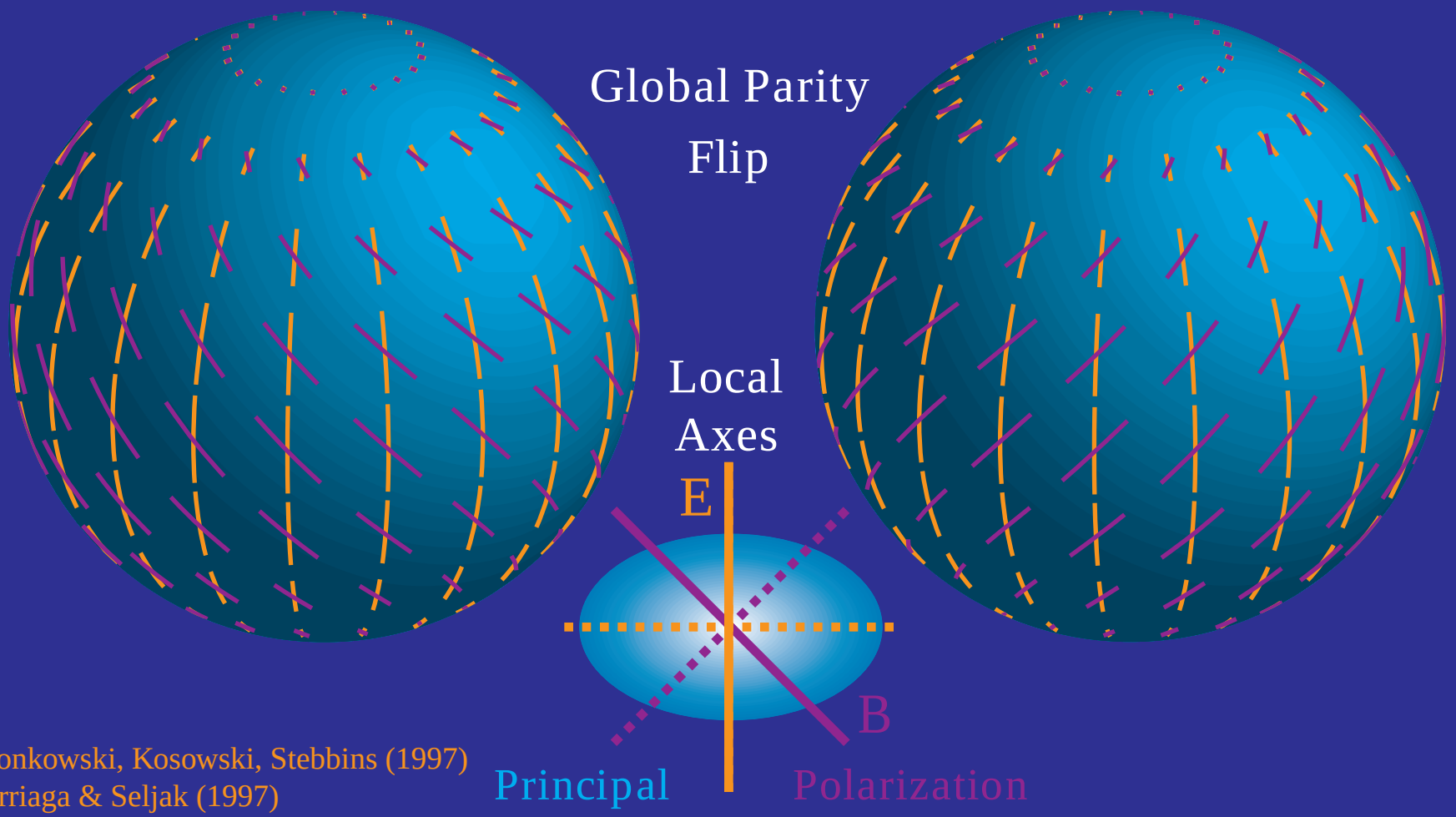


Tensors



Electric & Magnetic Patterns

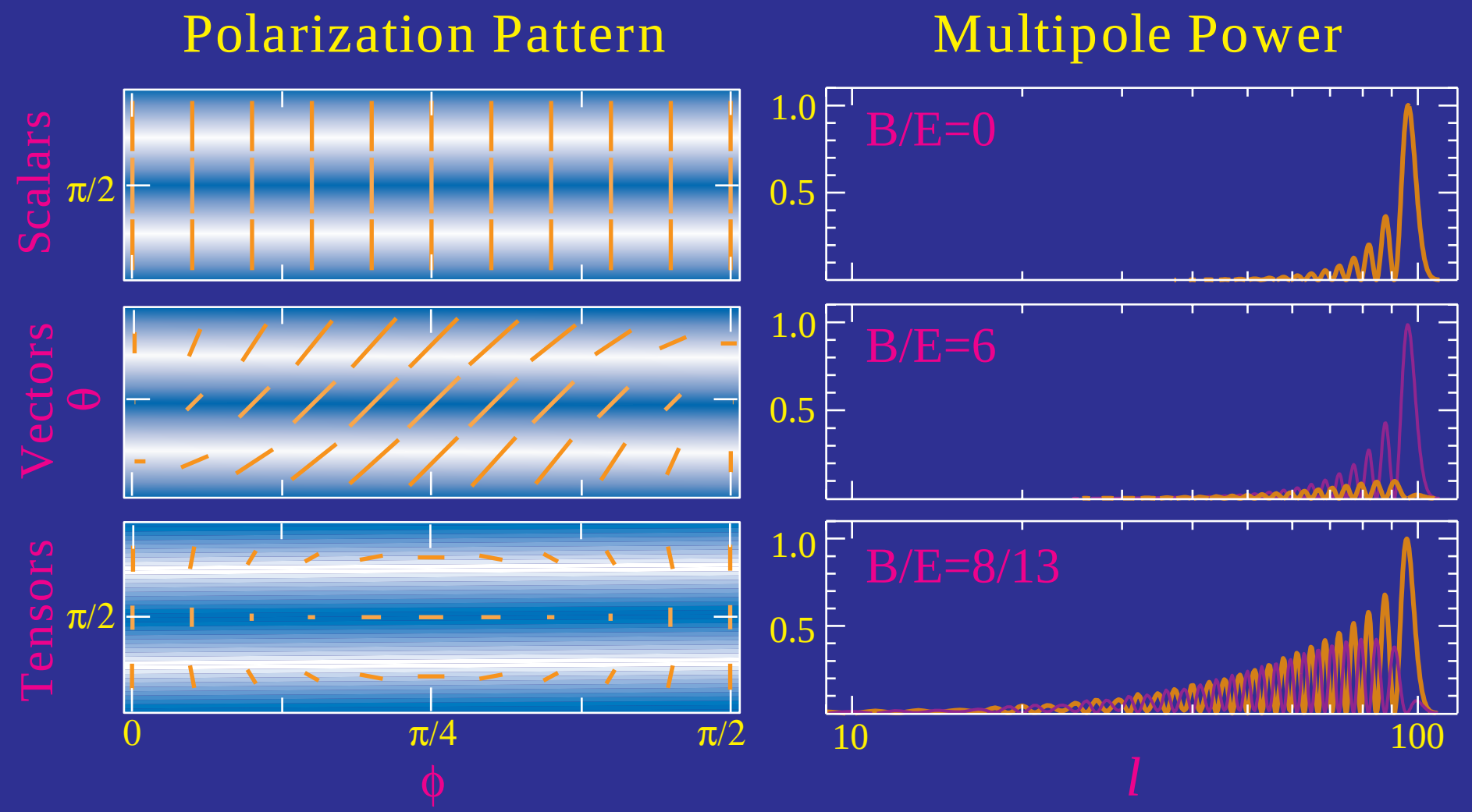
- Global view: behavior under parity
- Local view: alignment of principle vs. polarization axes



Kamionkowski, Kosowski, Stebbins (1997)
Zaldarriaga & Seljak (1997)
Hu & White (1997)

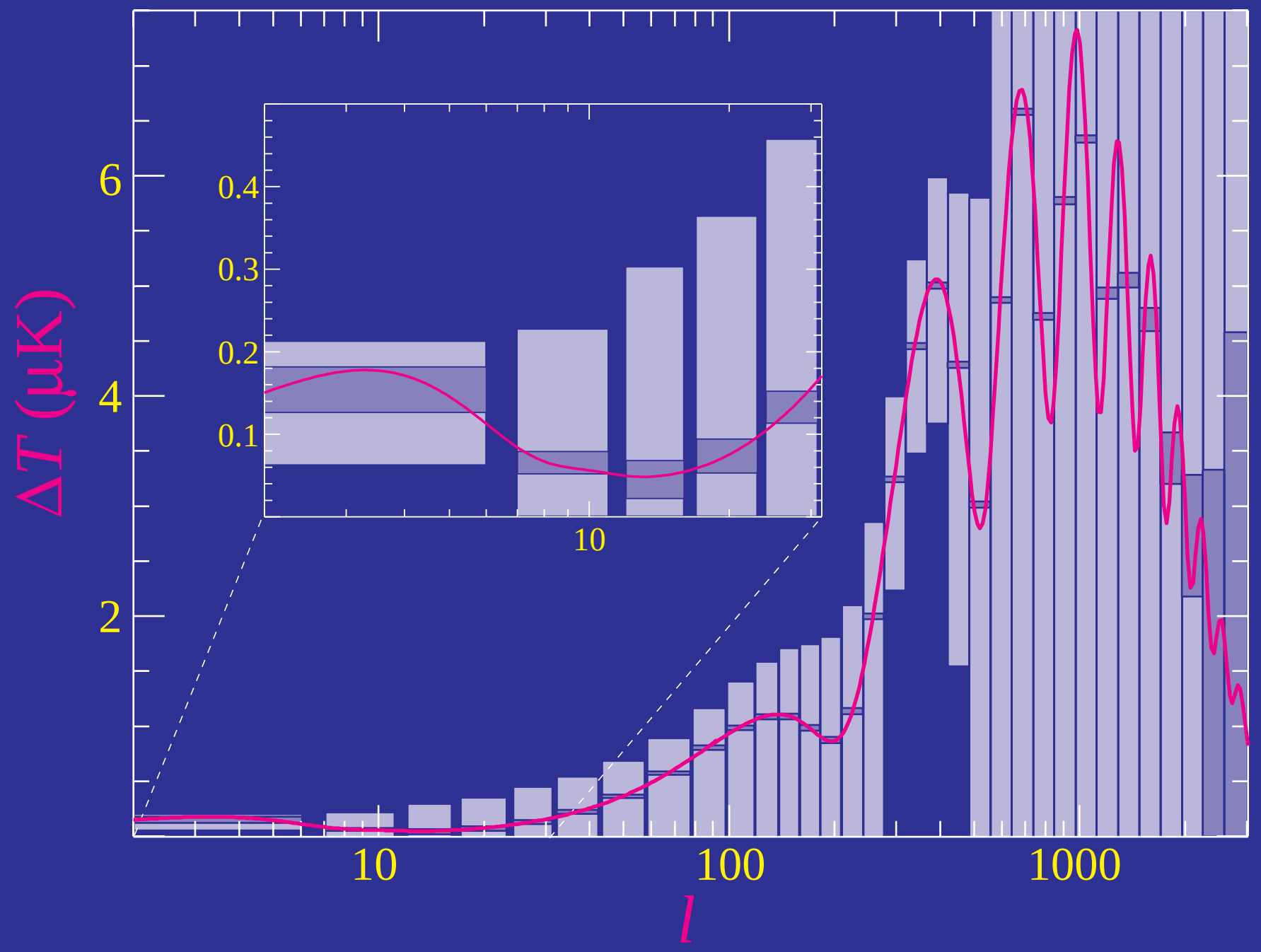
Patterns and Perturbation Types

- Amplitude modulated by plane wave → Principle axis
- Direction detemined by perturbation type → Polarization axis

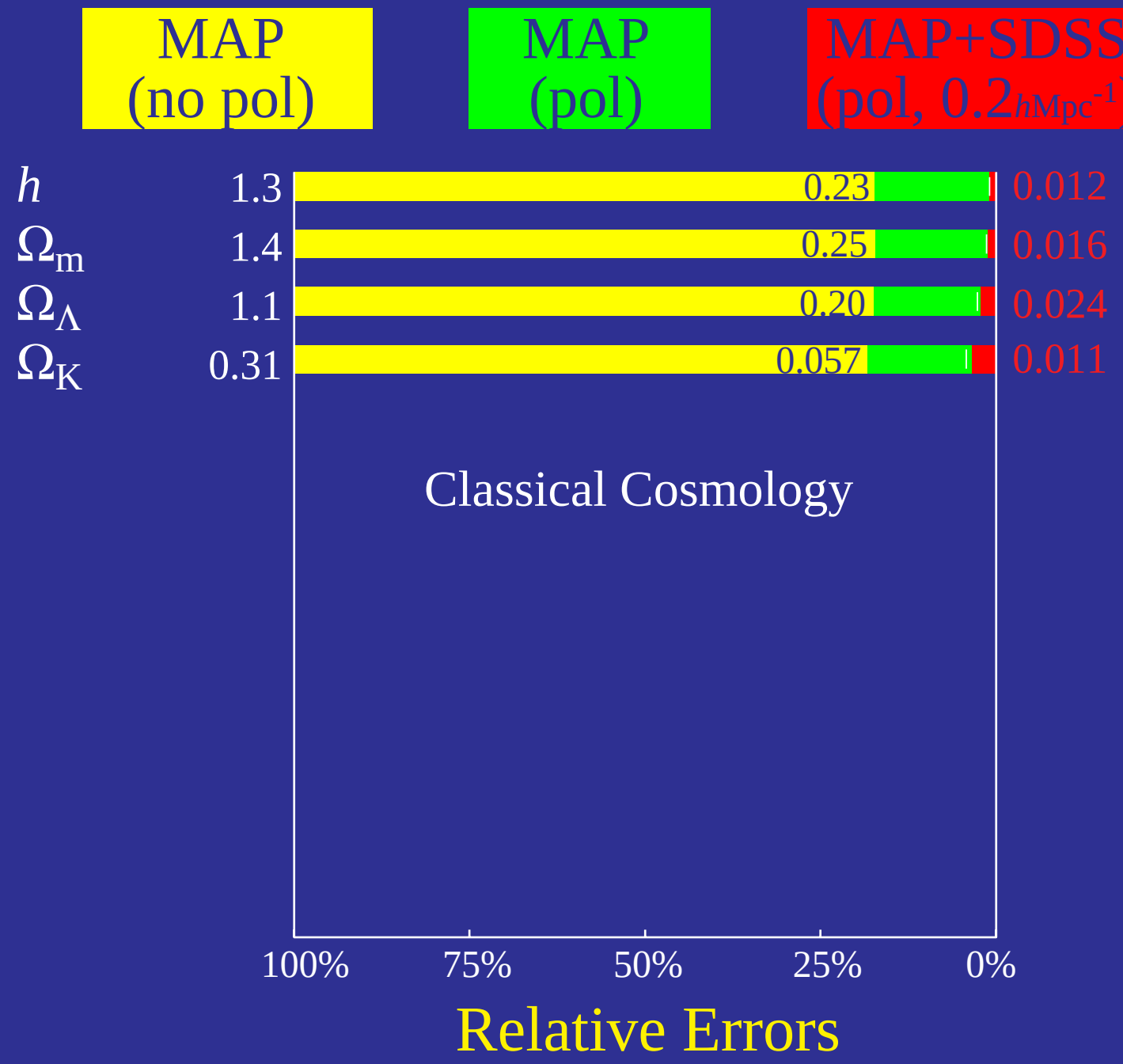


Kamionkowski, Kosowski, Stebbins (1997); Zaldarriaga & Seljak (1997); Hu & White (1997)

Polarization Raw Sensitivity

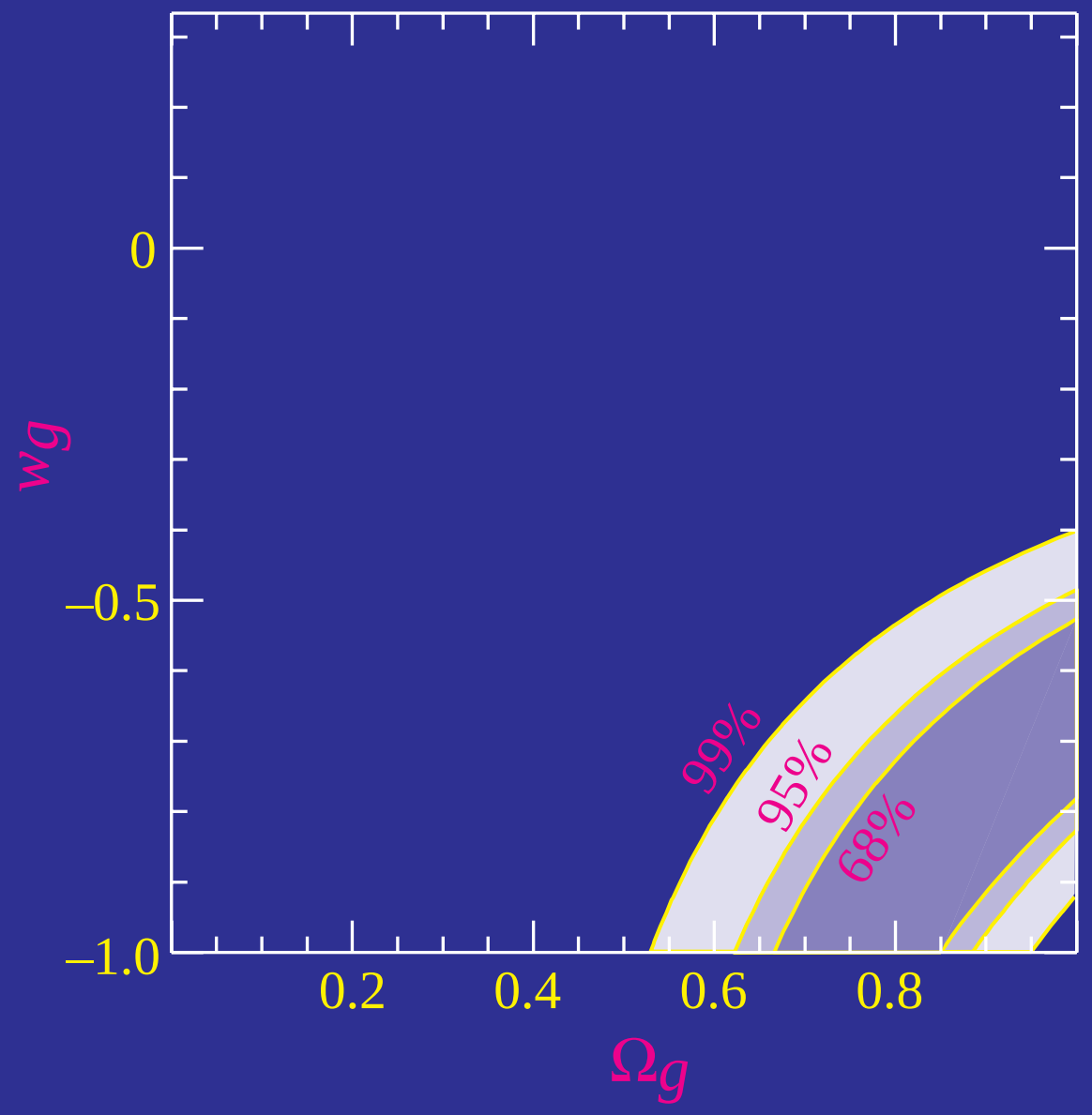


SDSS: Improving Parameter Estimation



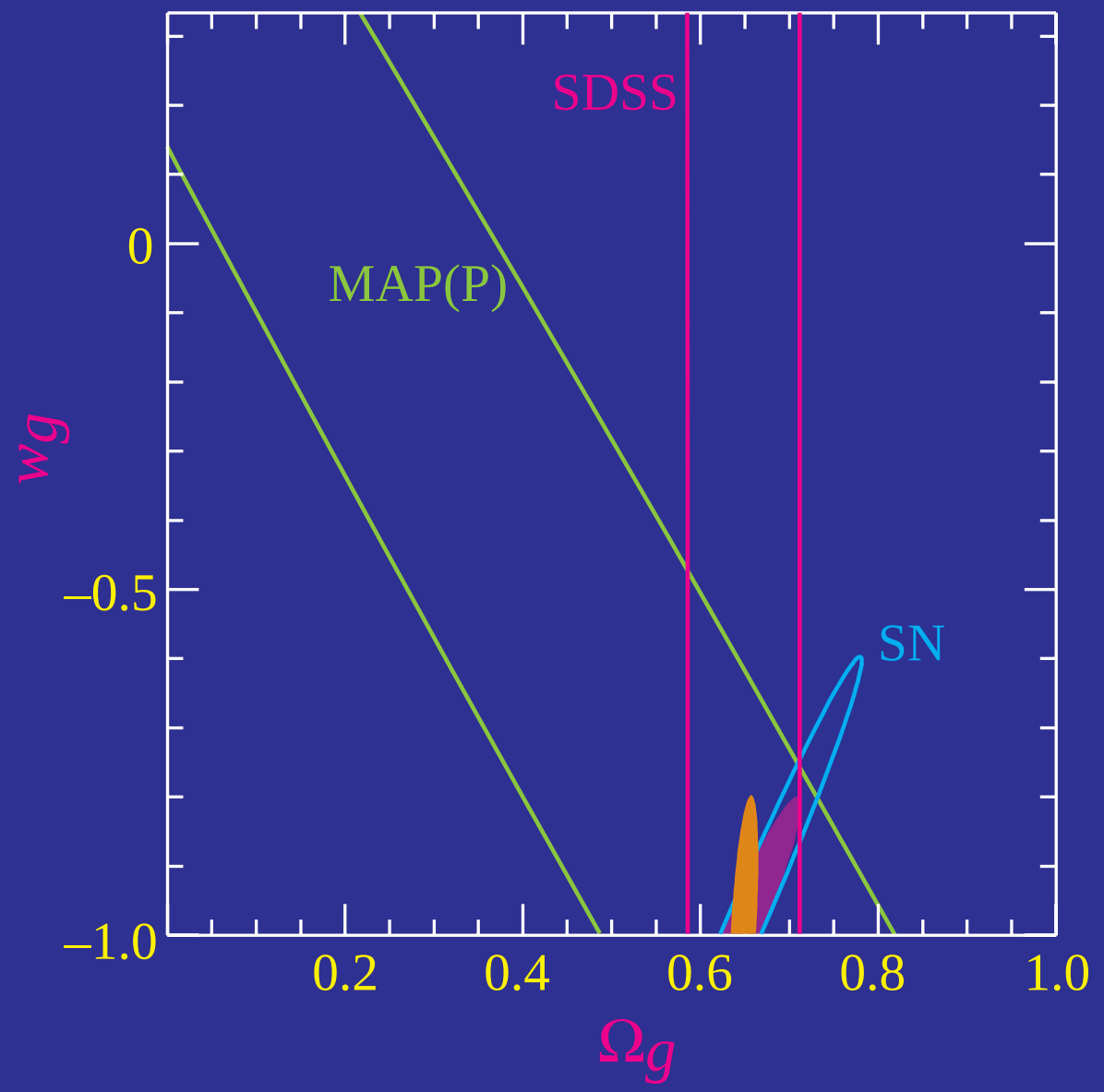
Eisenstein, Hu & Tegmark (1998)

Supernovae Type Ia
July 1998



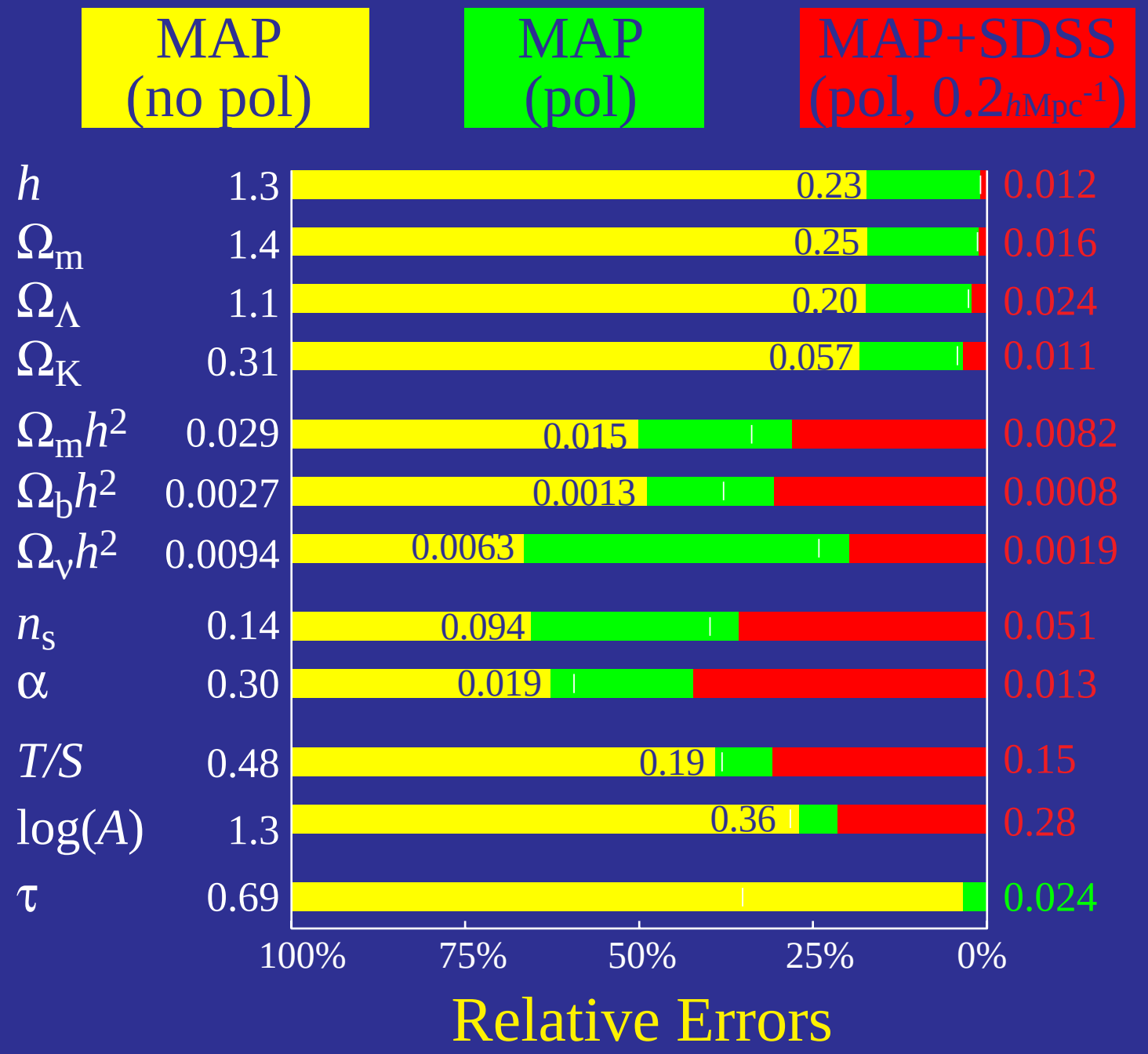
Garnavich et al. (1998); Riess et al. (1998); Perlmutter et al. (1998)
Figure: Hu, Eisenstein, Tegmark, White (1998)

Supernovae Type Ia, CMB & LSS Projection



Hu, Eisenstein, Tegmark, White (1998)

SDSS: Improving Parameter Estimation

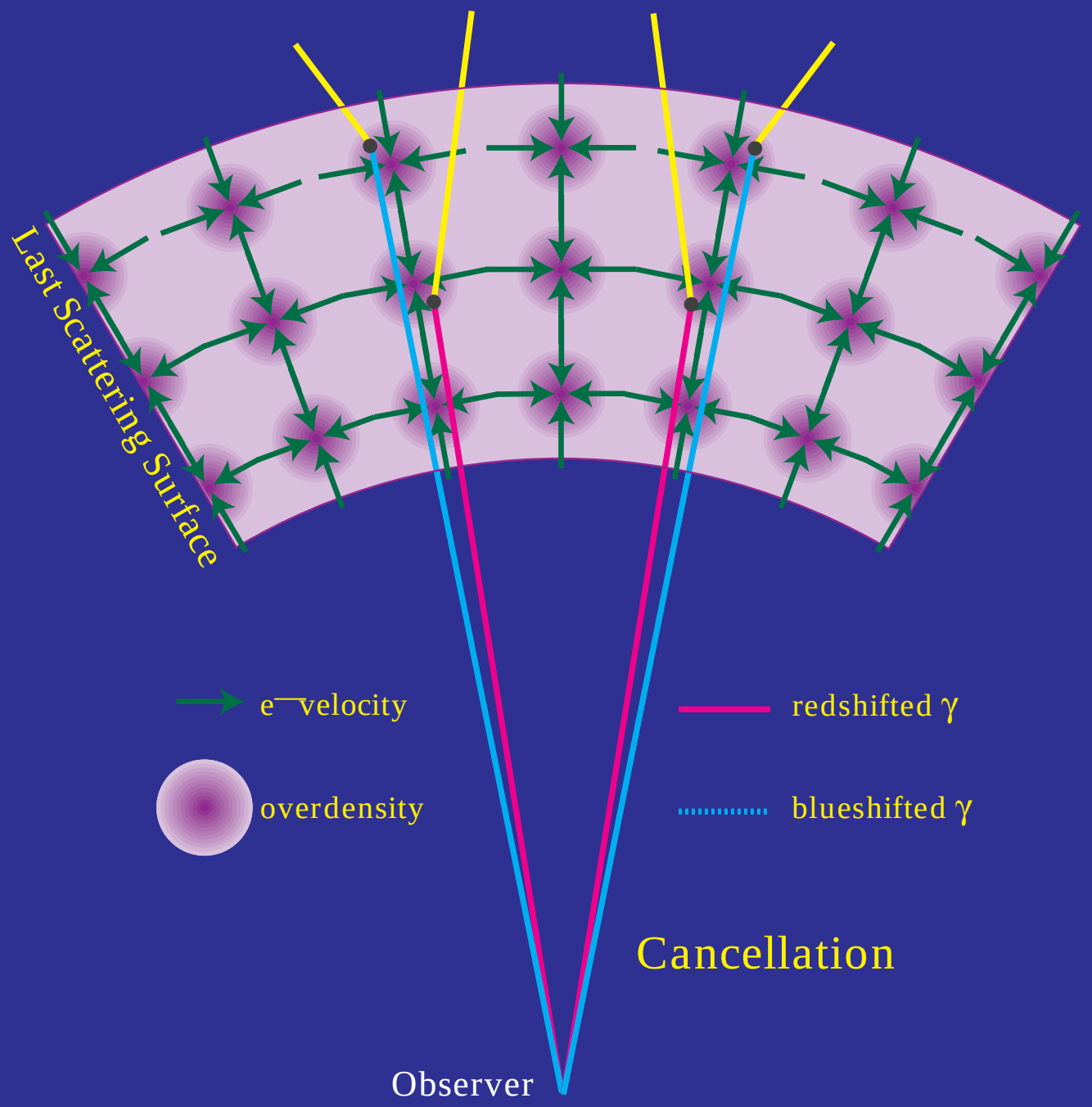


Eisenstein, Hu & Tegmark (1998)

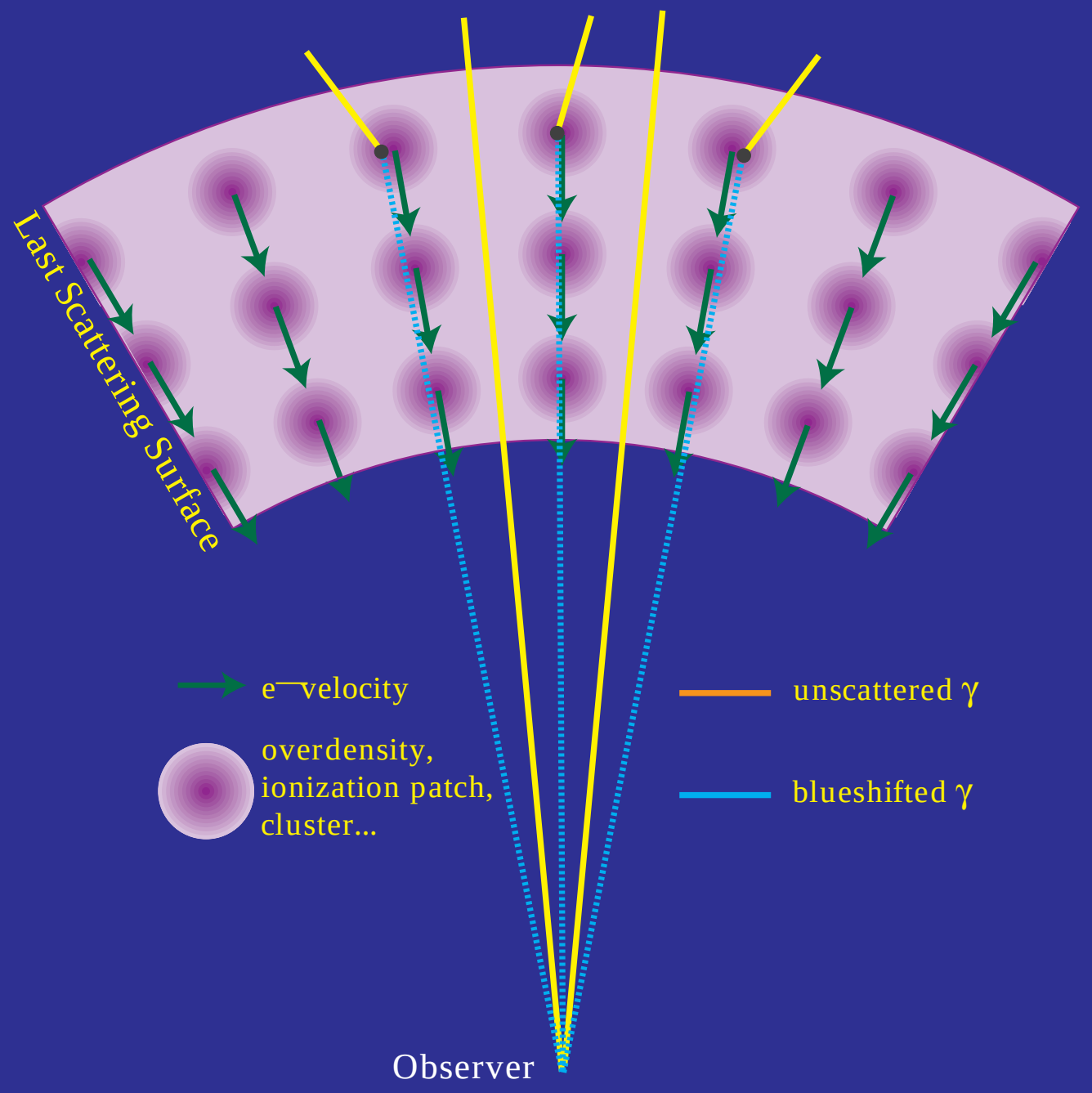
Secondary Anisotropies

- Temperature and polarization anisotropies imprinted in the CMB after z=1000
- Rescattering Effects
  - Linear Doppler Effect (cancelled)
  - Modulated Doppler Effects (non–linear)
    - by linear density perturbations → Ostriker–Vishniac Effect
    - by ionization fraction → Inhomogeneous Reionization
    - by clusters → thermal & kinetic Sunyaev–Zel'dovich Effects
- Gravitational Effects
  - Gravitational Redshifts
    - by cessation of linear growth → Integrated Sachs–Wolfe Effect
    - by non–linear growth → Rees–Sciama Effect
  - Gravitational Lensing

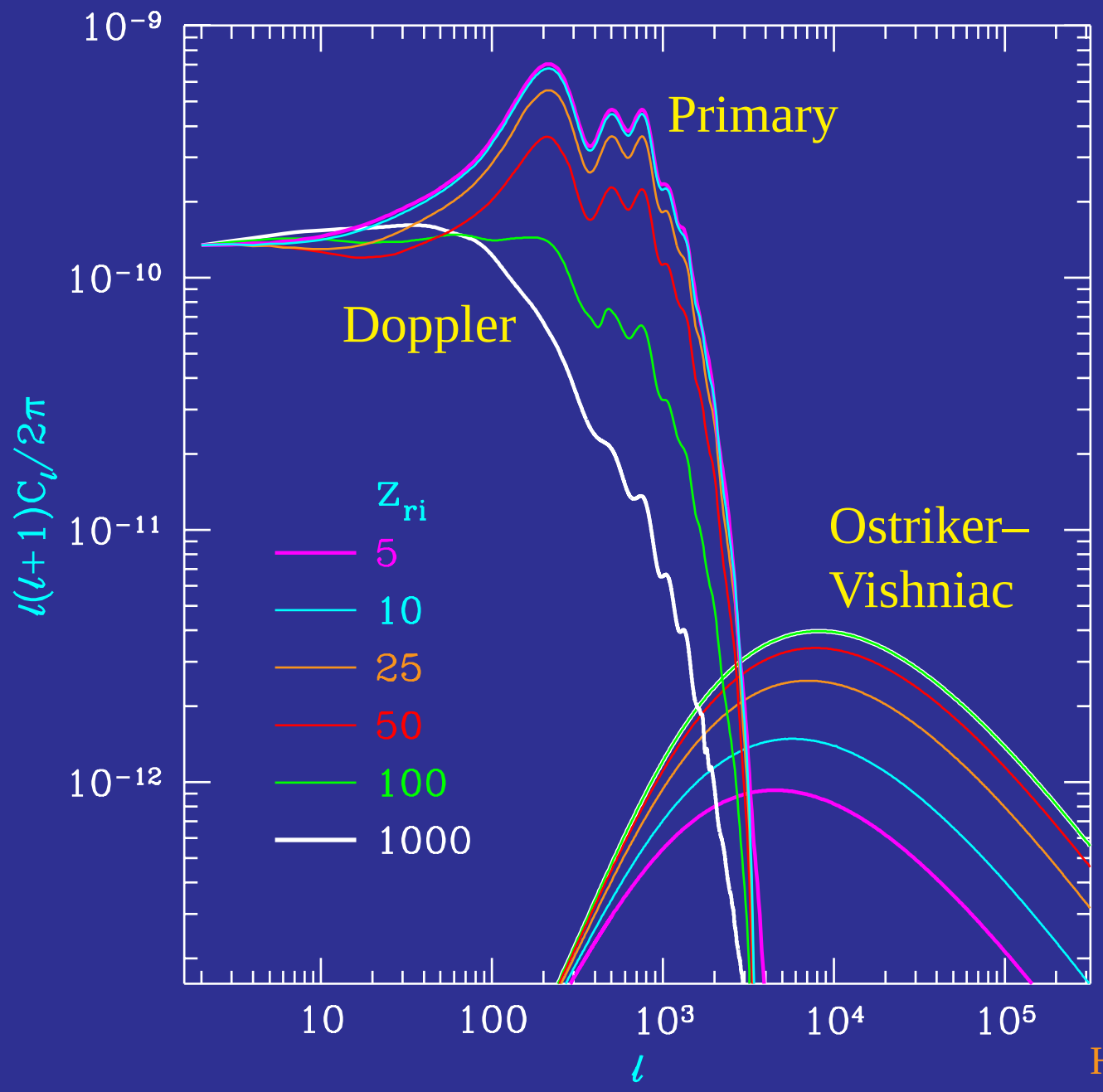
Cancellation of the Linear Effect



Modulated Doppler Effect



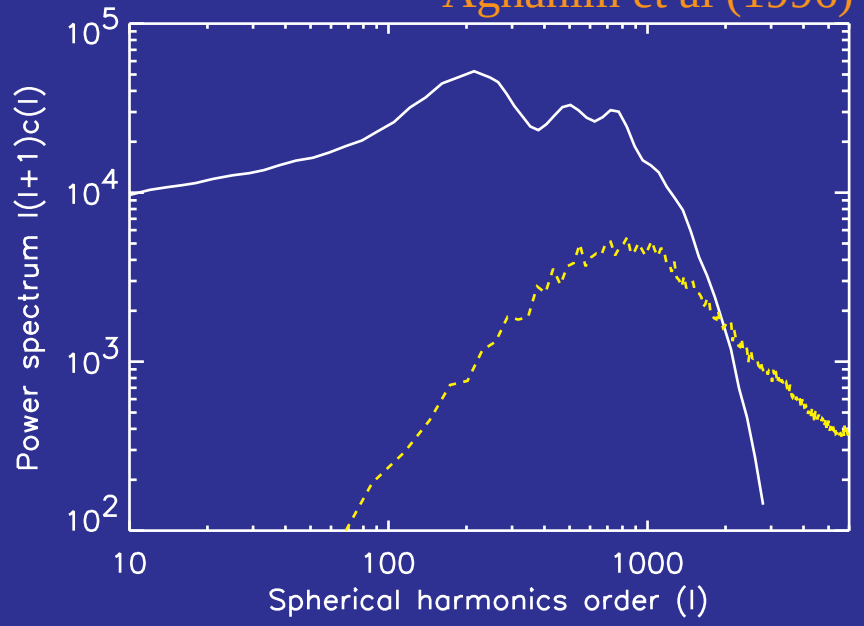
Ostriker–Vishniac Effect



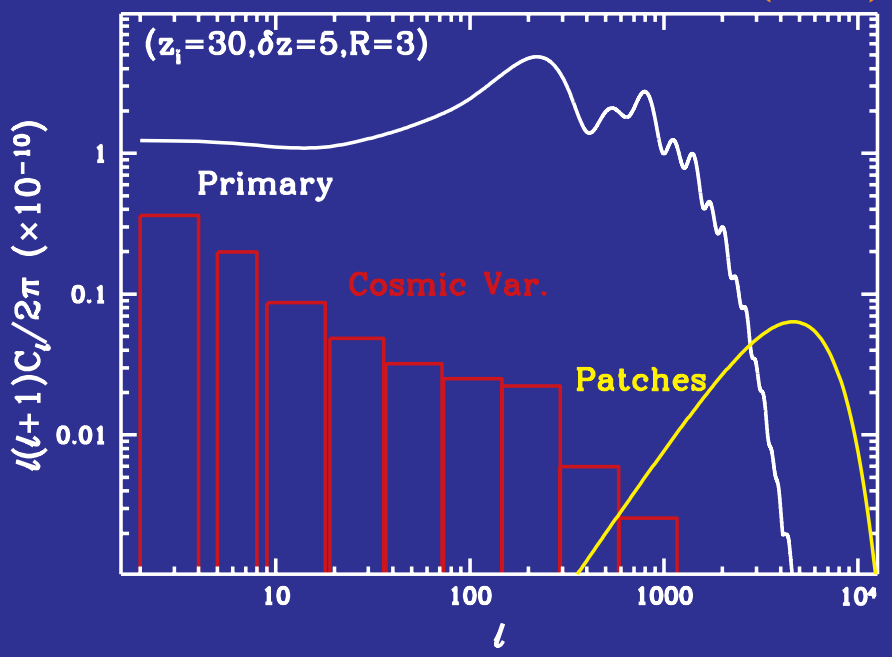
Hu & White (1996)

Patchy Reionization

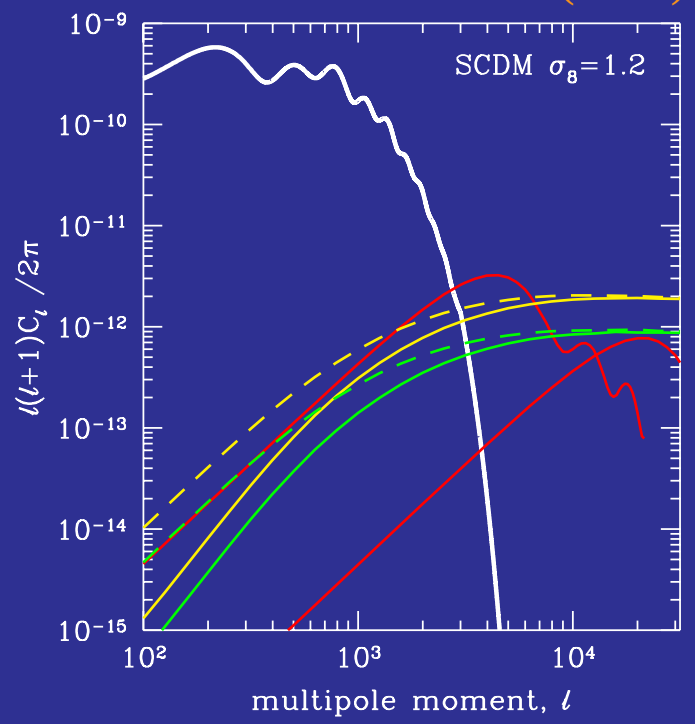
Aghanim et al (1996)



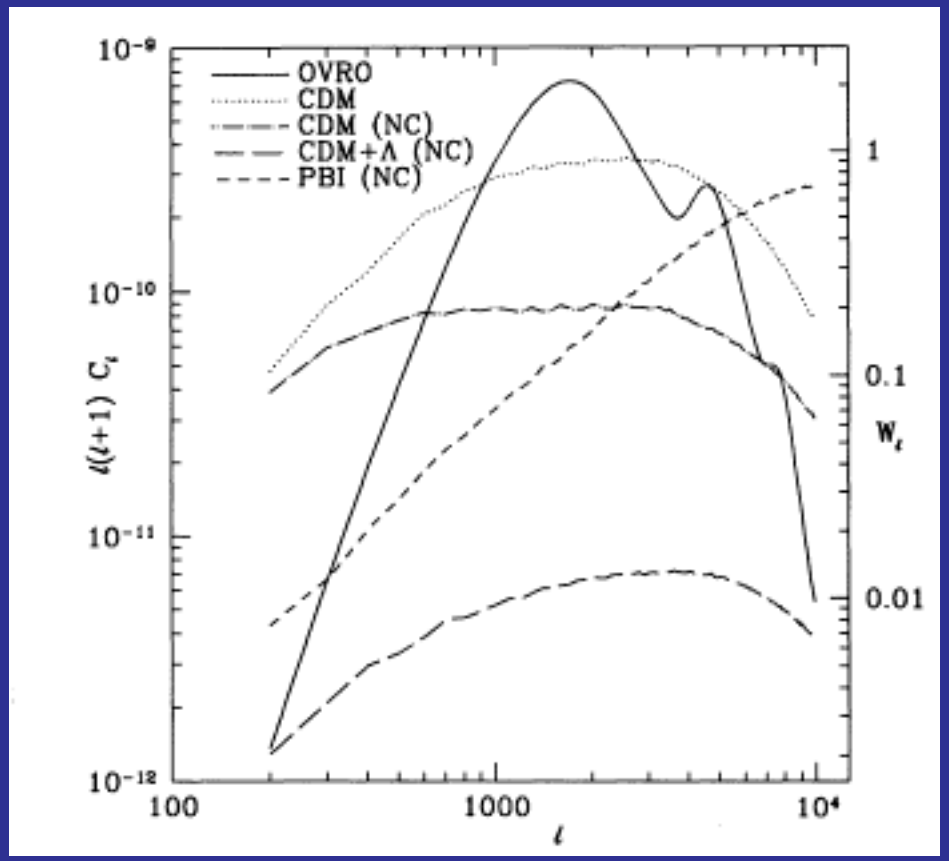
Gruzinov & Hu (1998)

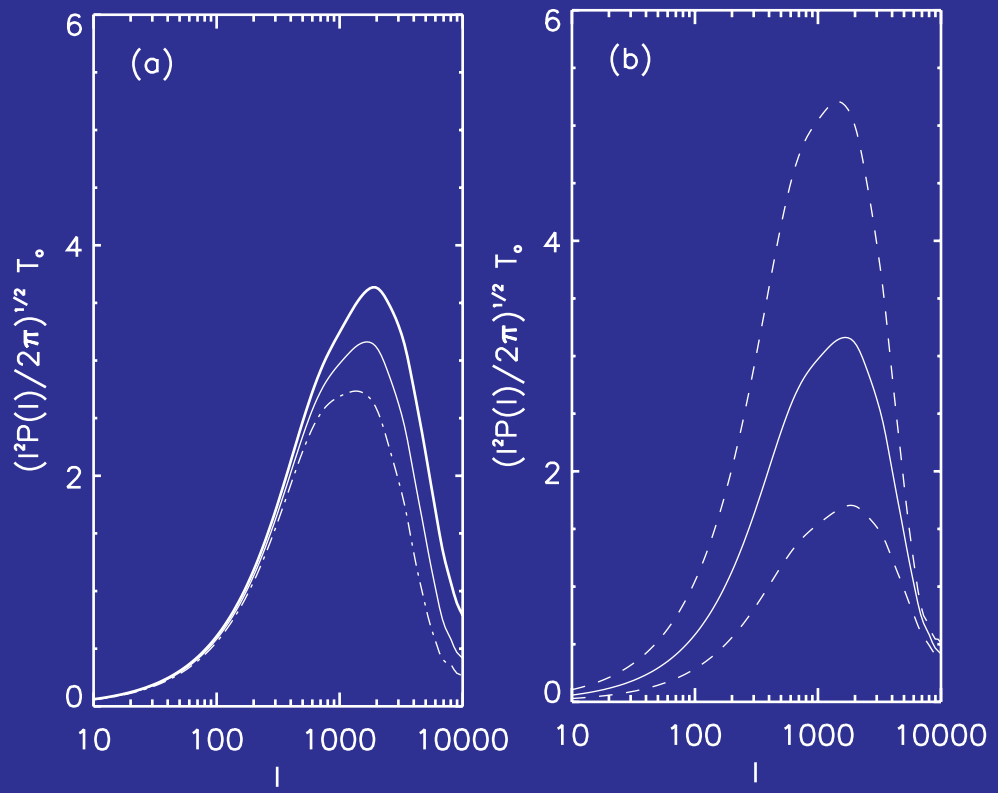


Knox, Scocciomarro & Dodelson (1998)



Thermal SZ Effect

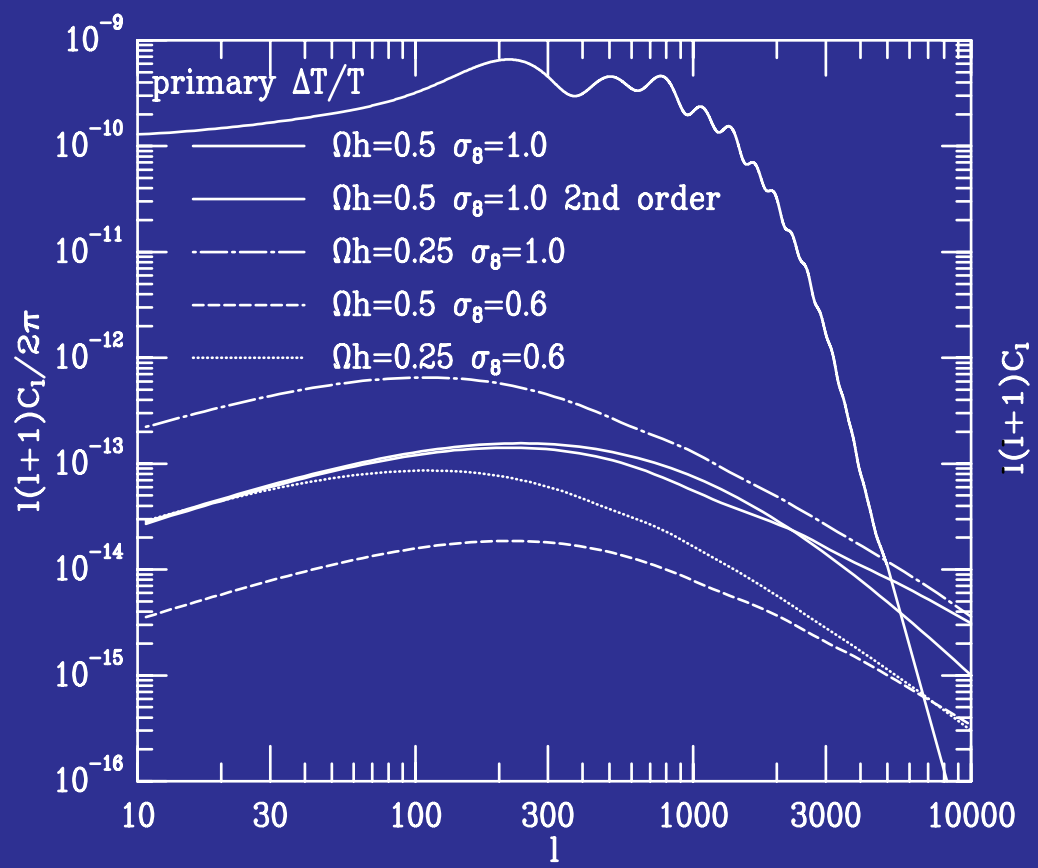




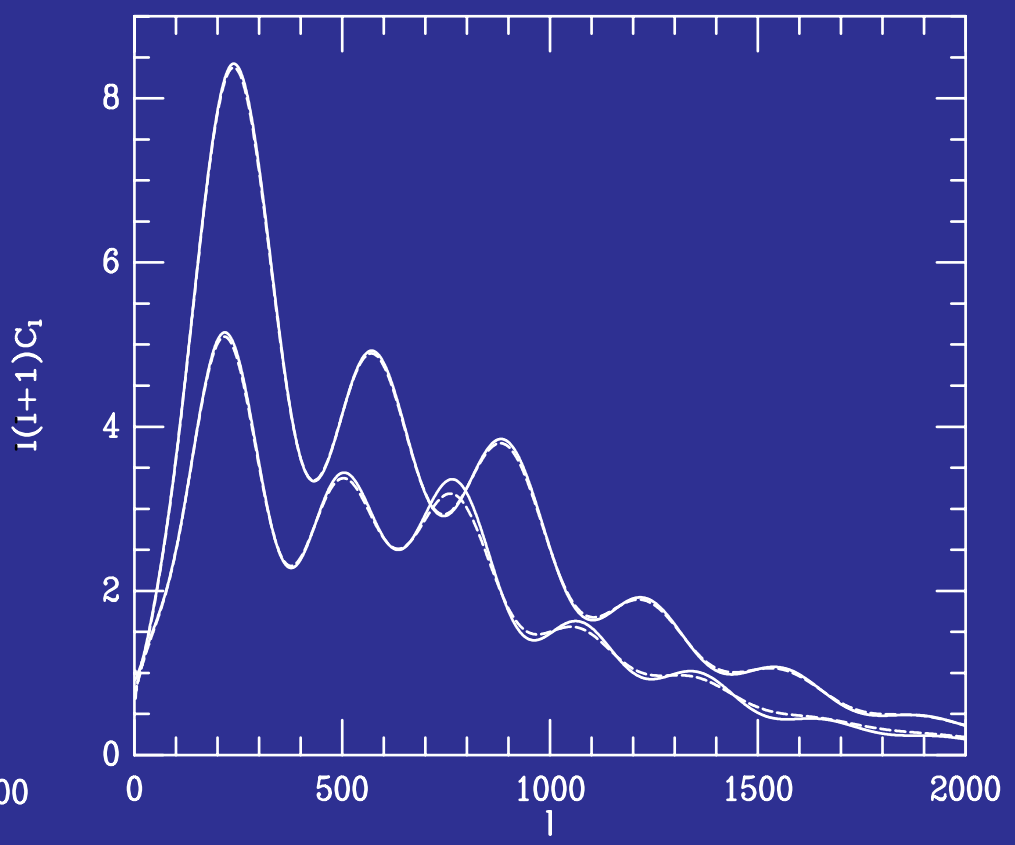
Persi et al. (1995)

Atrio–Barandela & Muecket (1998)

Rees–Sciama Effect

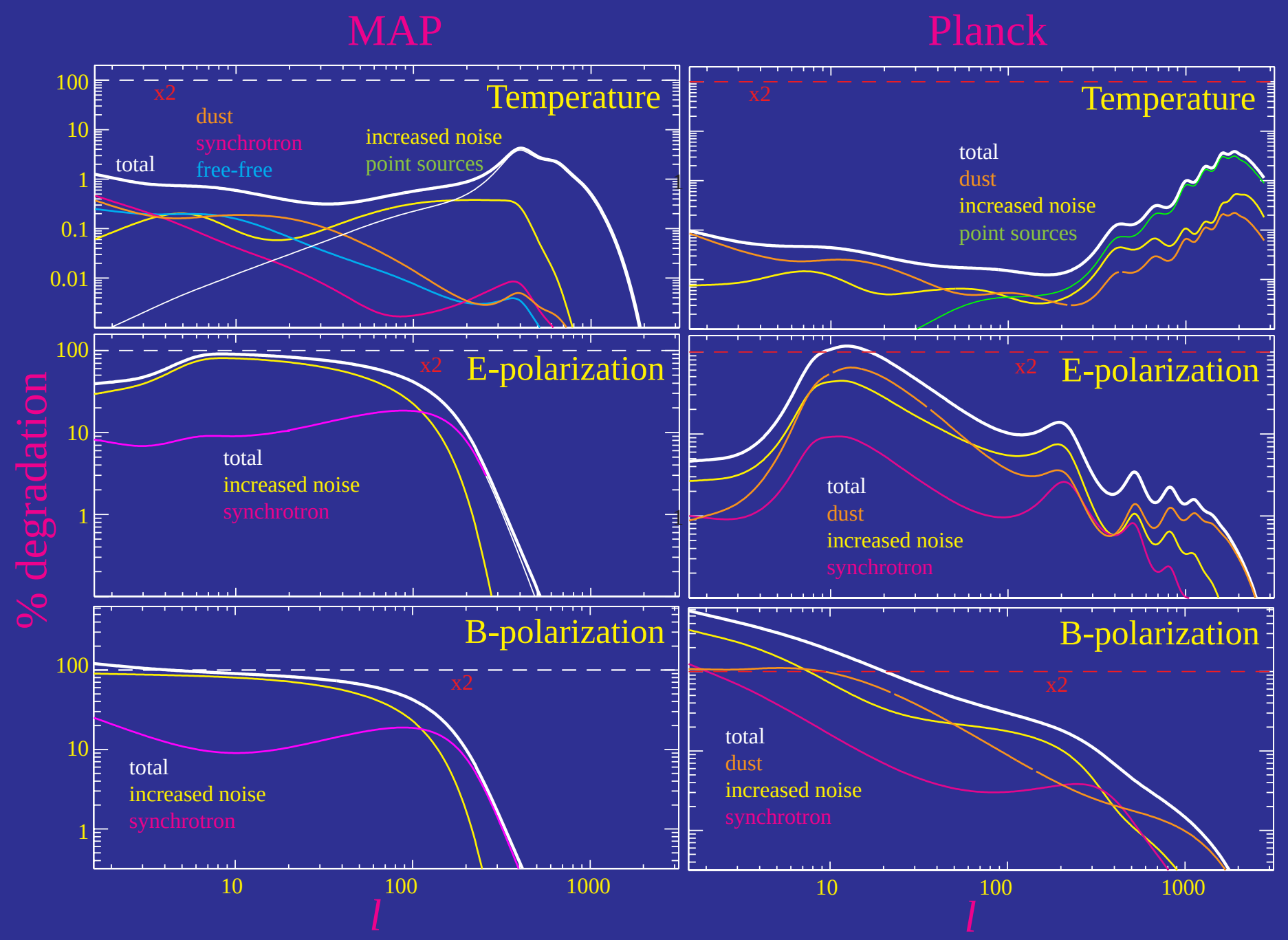


Gravitational Lensing

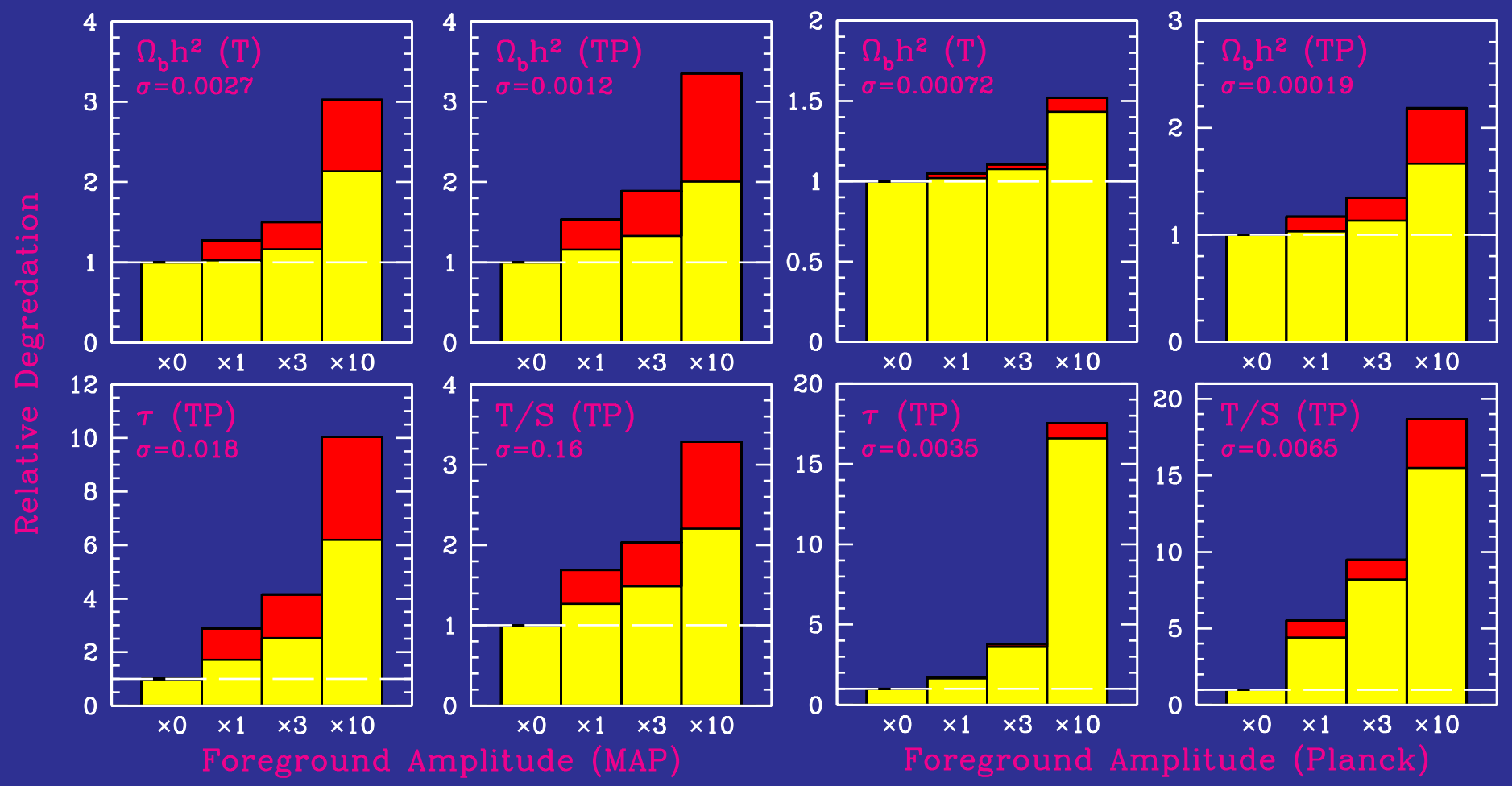


Seljak (1996a,b)

Residual Foreground Effects



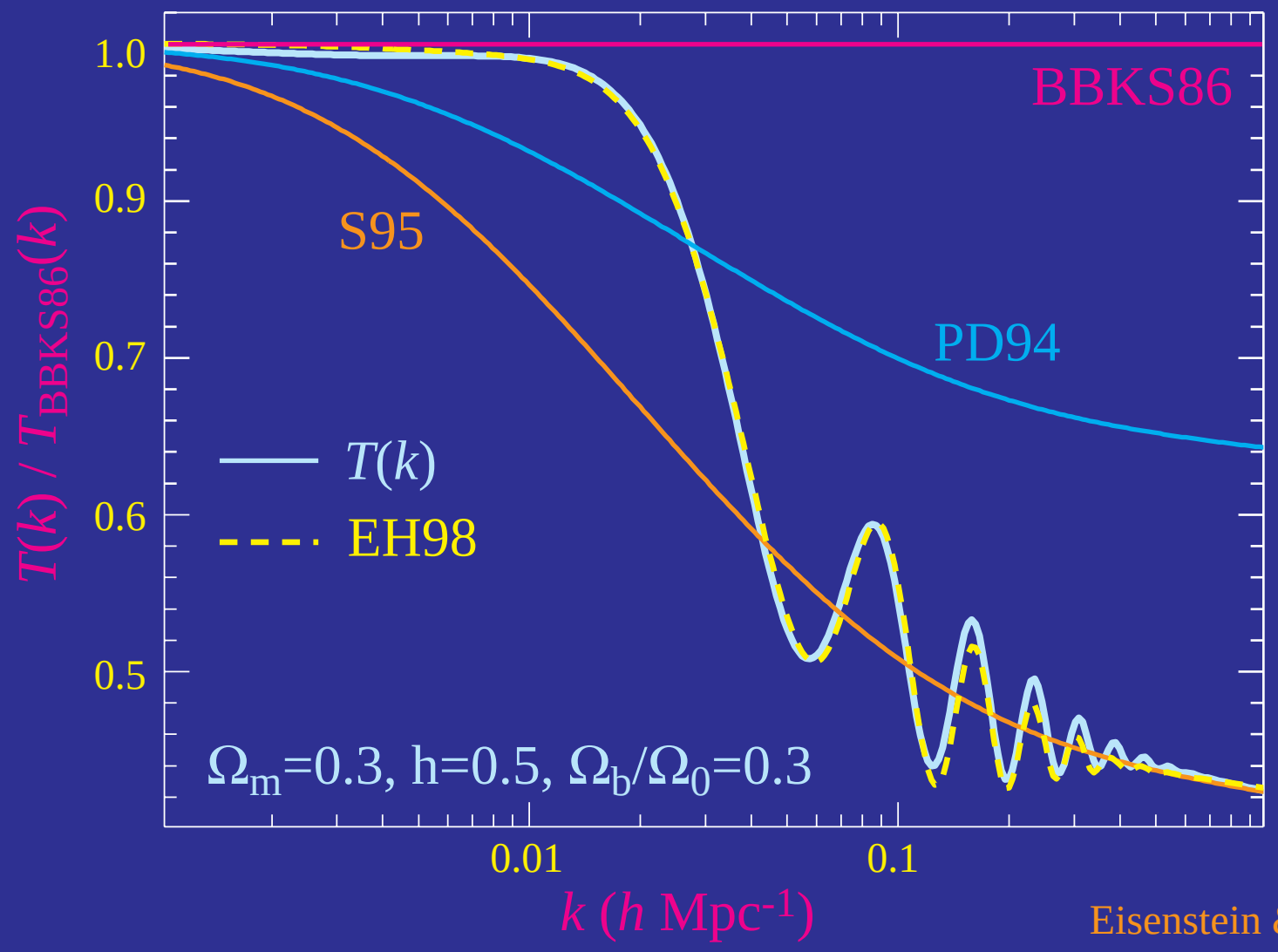
Foregrounds & Parameter Estimation



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

Features in the Transfer Function

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



Eisenstein & Hu (1998)