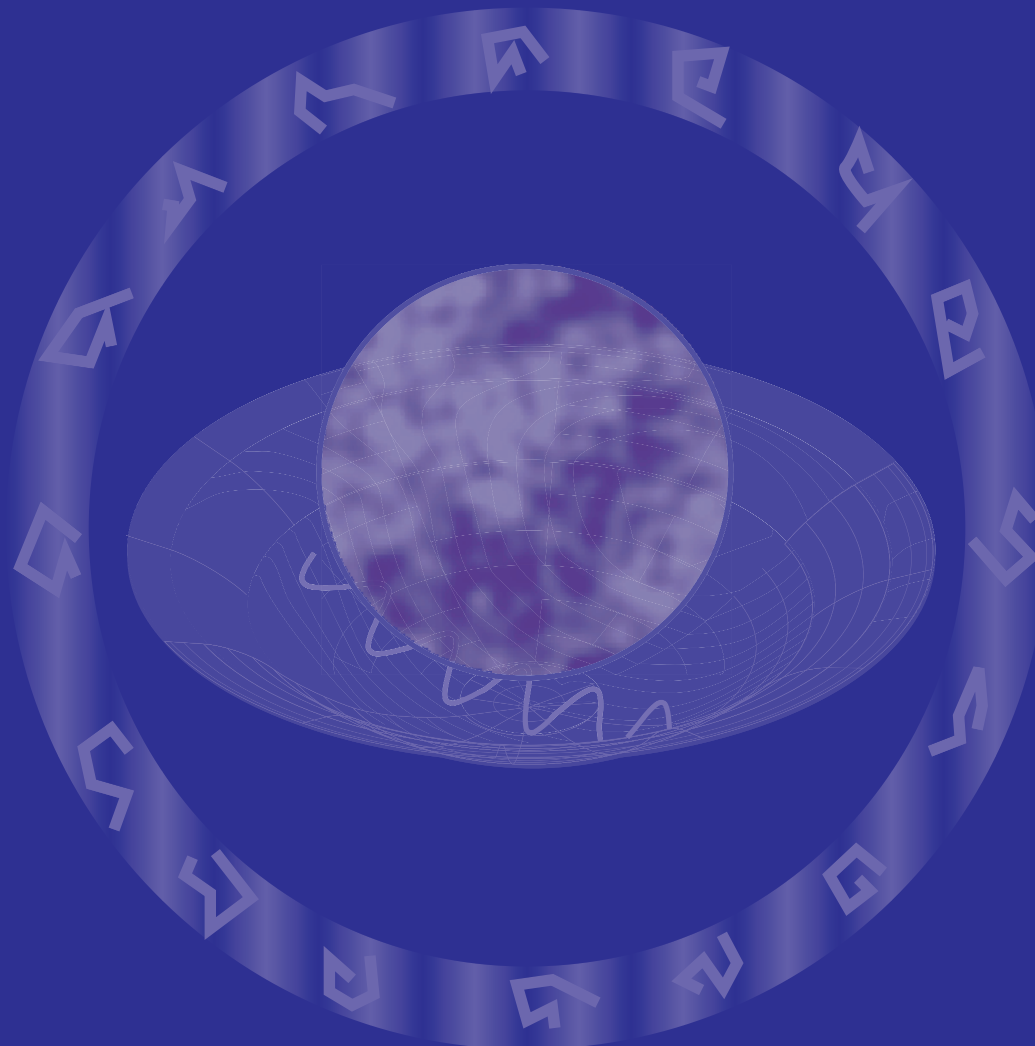
Dark Energy in the CMB



Dec. 2001, CfCP

Wayne Hu

Outline

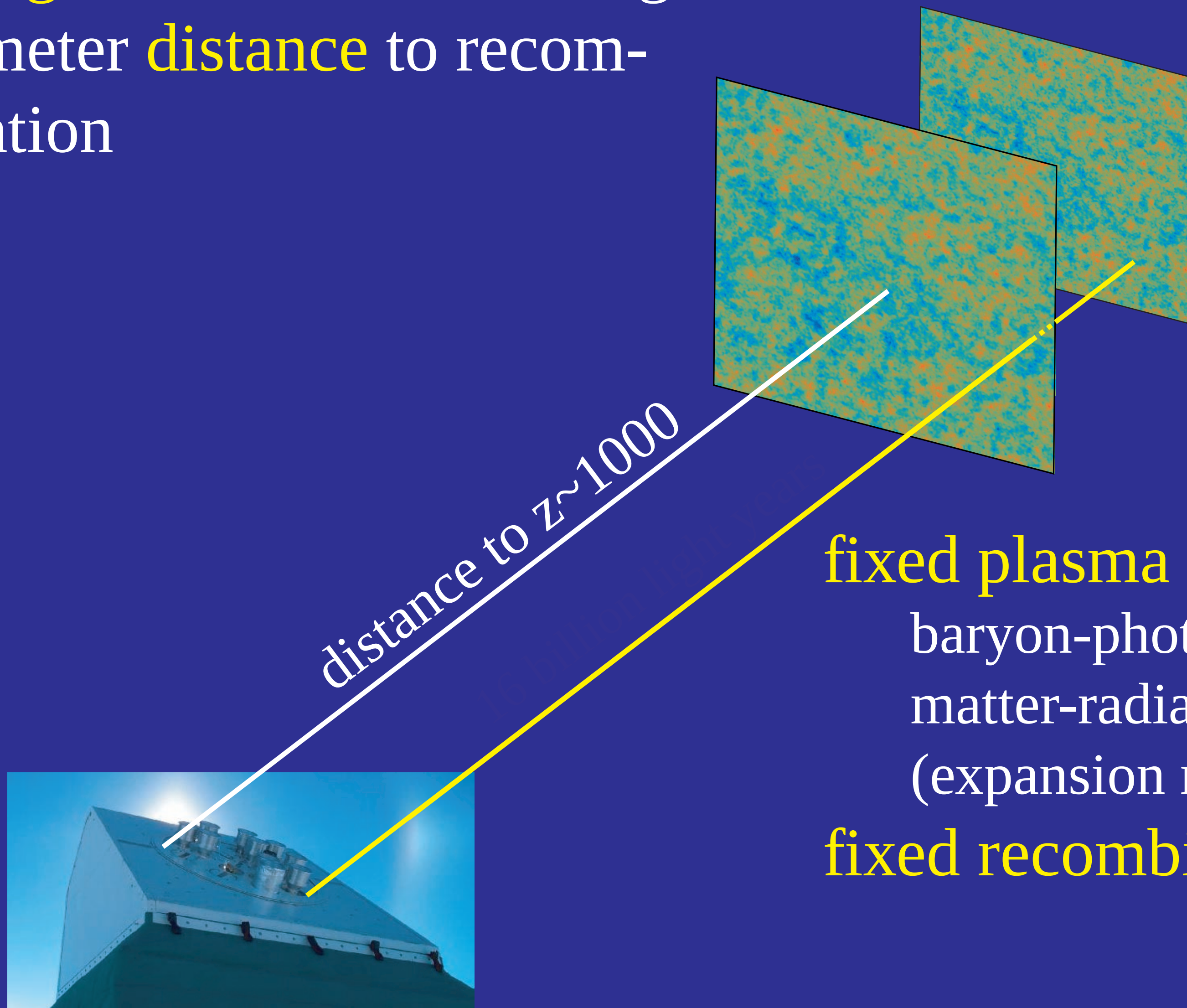
- Angular Diameter Distance
  - Location of peaks
  - Degeneracy
- Integrated Sachs-Wolfe (ISW) Effect
  - Breaks degeneracy
  - Measures dark energy smoothness
  - Cosmic variance
- CMB lensing
  - Reconstruct large-scale potential
  - Cross correlate with CMB
  - Test dark energy particle properties
- Collaborators
  - Daniel Eisenstein
  - Takemi Okamoto
  - Max Tegmark
  - Matias Zaldarriaga
- Presentation

http://background.uchicago.edu/~whu/Presentations/darke.pdf

Angular Diameter Distance

Angular Diameter Distance

- Temperature (and polarization) patterns shift in and out in angular scale with the angular diameter distance to recom-bination



fixed plasma conditions

baryon-photon ratio: $\Omega_b h^2$

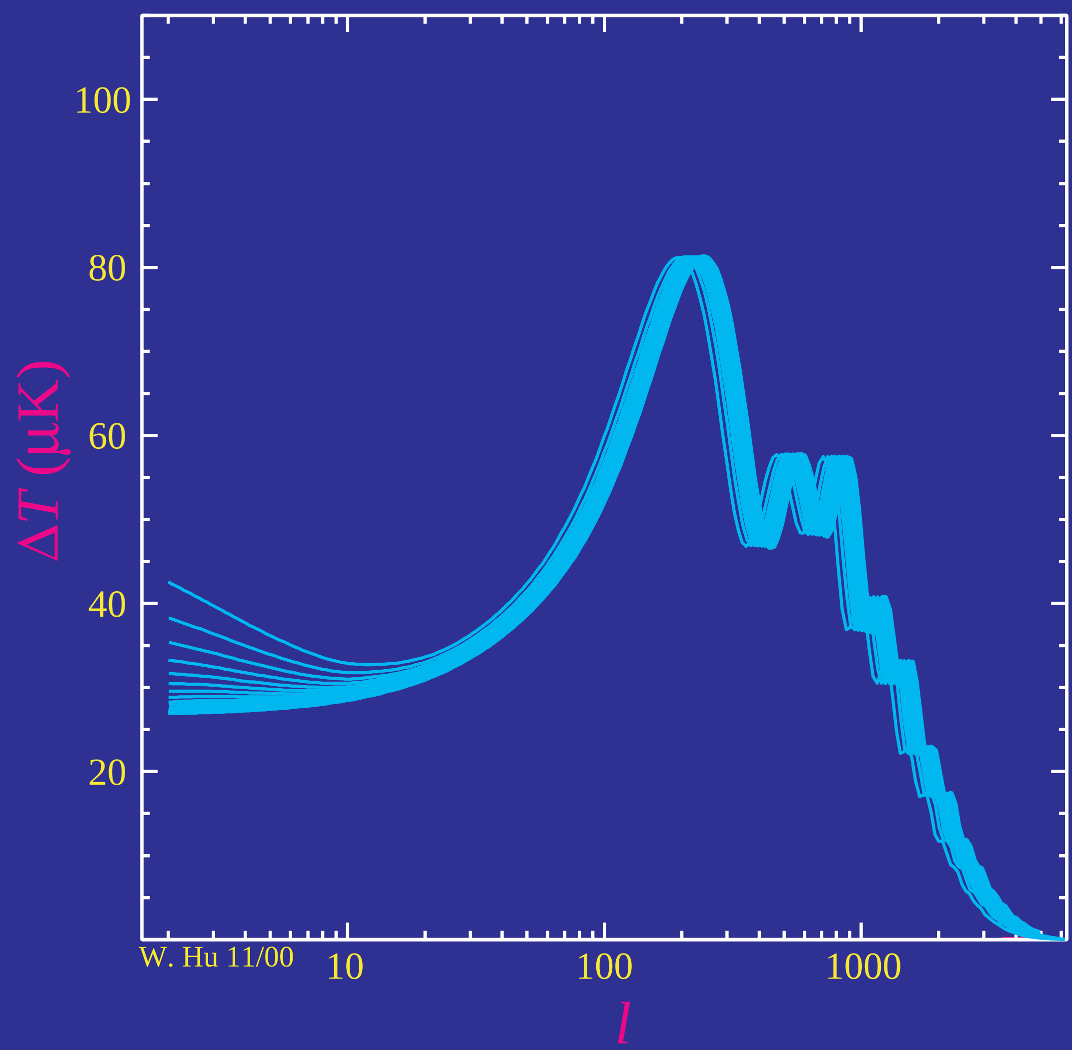
matter-radiation ratio: $\Omega_m h^2$

(expansion rate)

fixed recombination

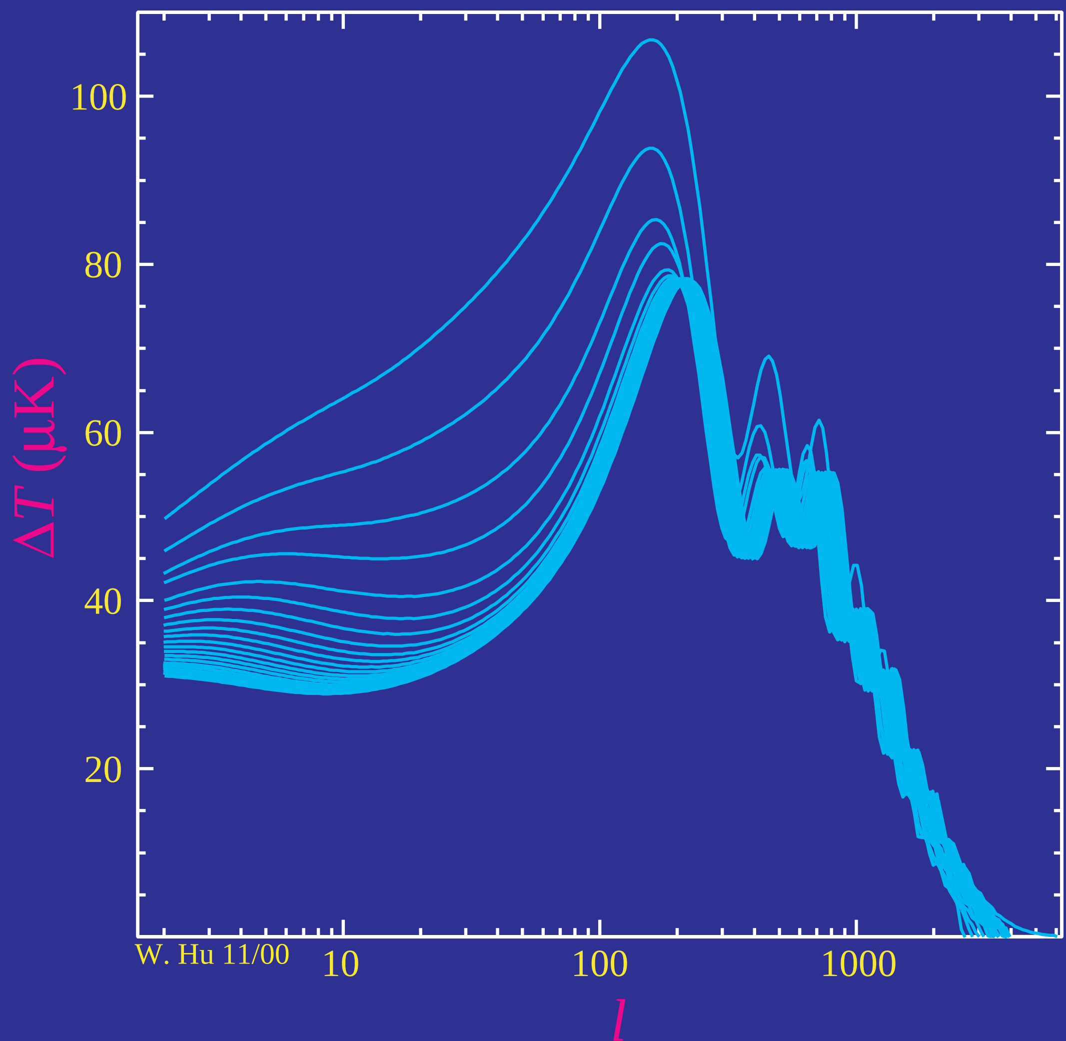
Location of the Peaks

- Peaks shift to lower multipoles as the dark energy density increases



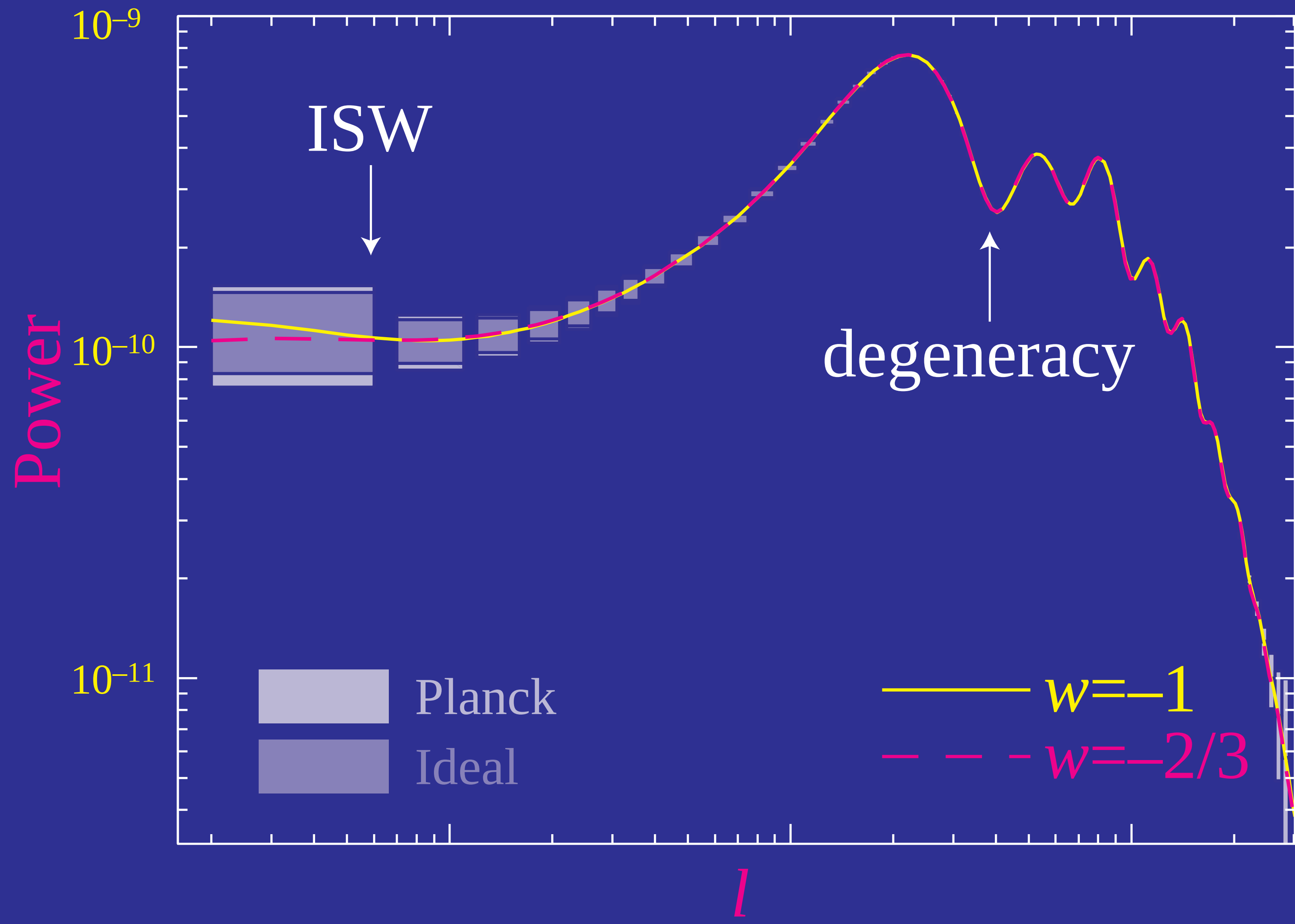
Location of the Peaks

- But raising the equation of state w=p/ρ has the same effect



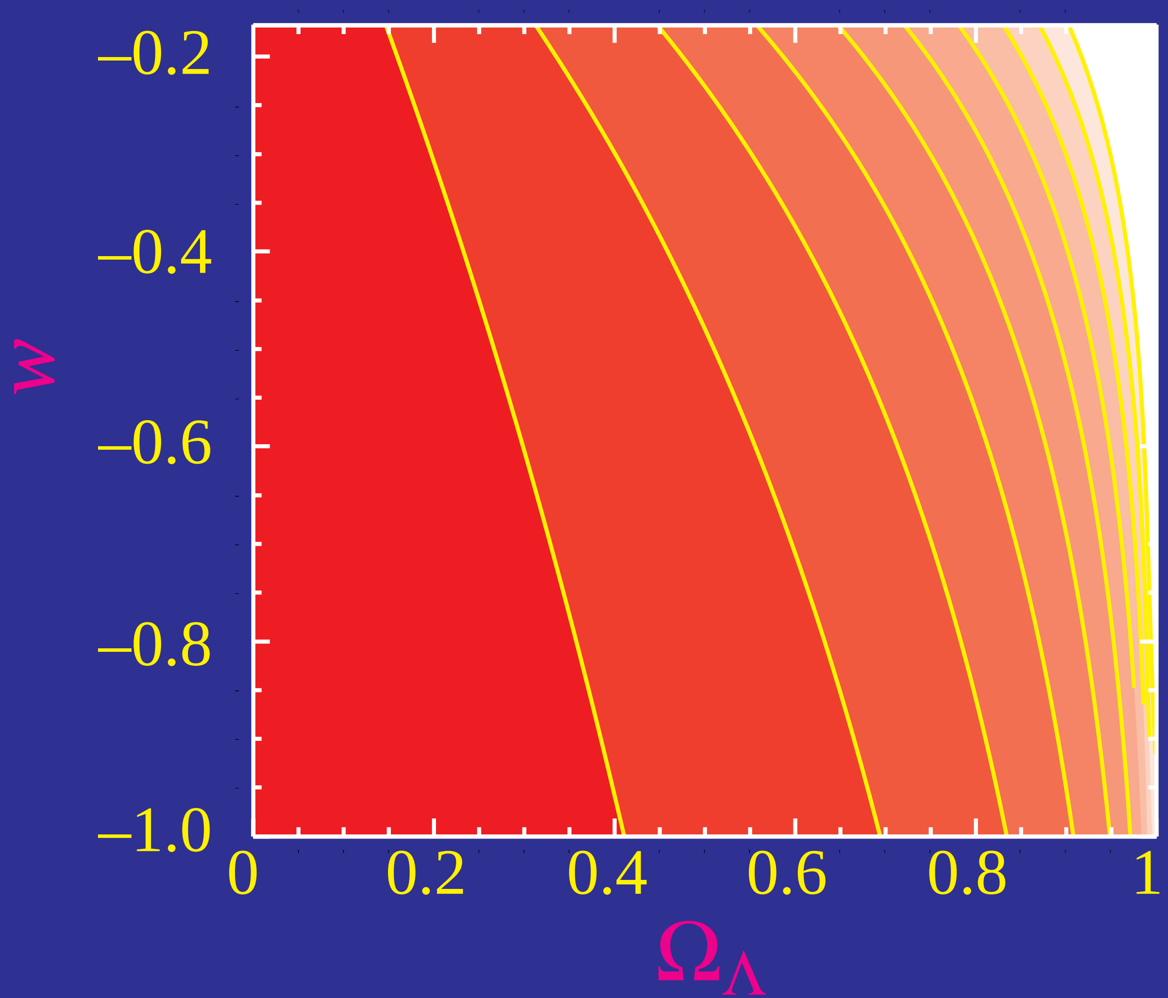
Degeneracy of the Peak Locations

- But raising the equation of state w=p/ρ has the same effect



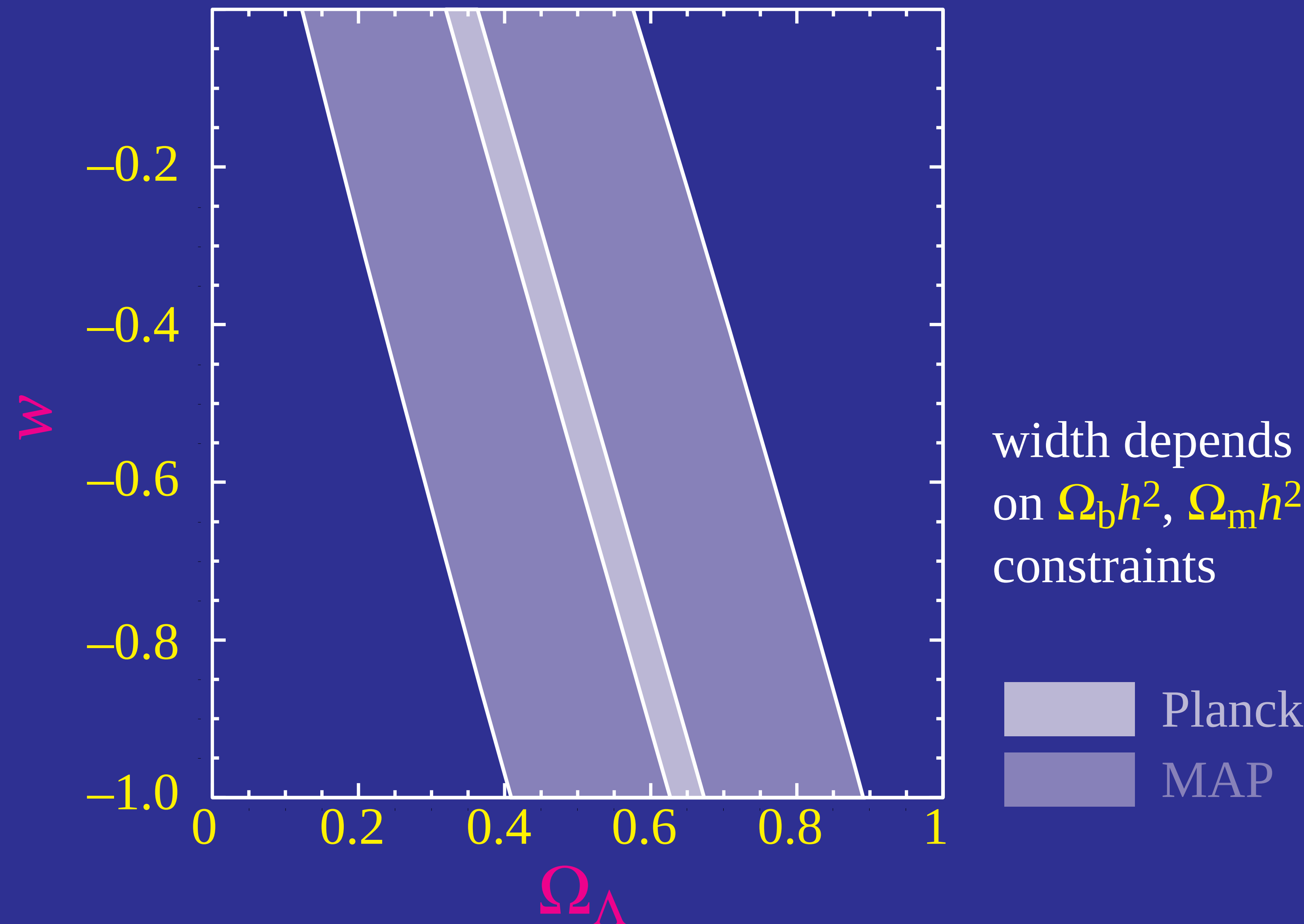
Degeneracy of the Peak Locations

- Contours of angular diameter distance $H_0 D_A$ at constant $\Omega_b h^2$, $\Omega_m h^2$ (peak locations and morphology)



Degeneracy of the Peak Locations

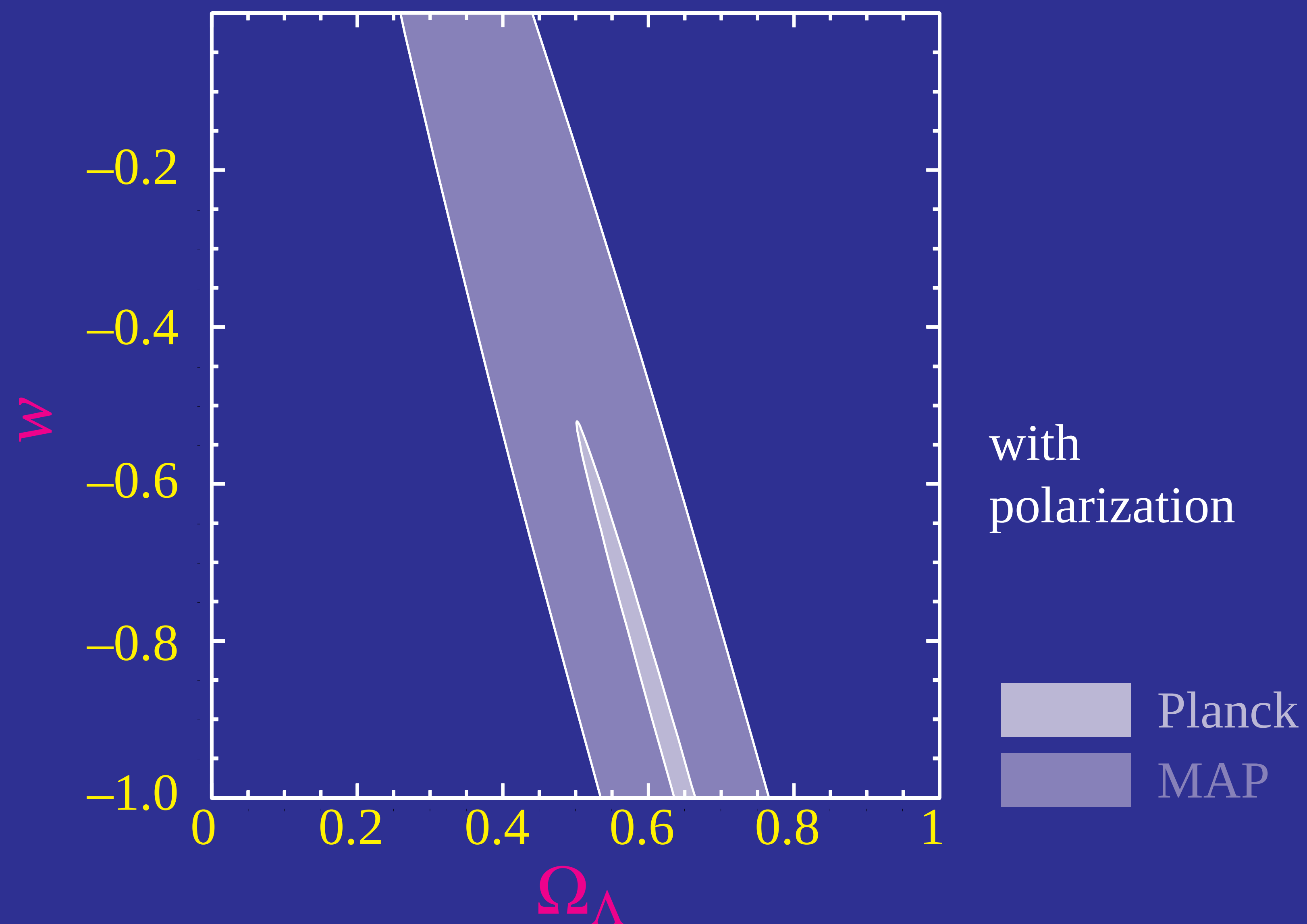
- Fisher (local) approximation to statistical errors



width depends on $\Omega_b h^2$, $\Omega_m h^2$ constraints

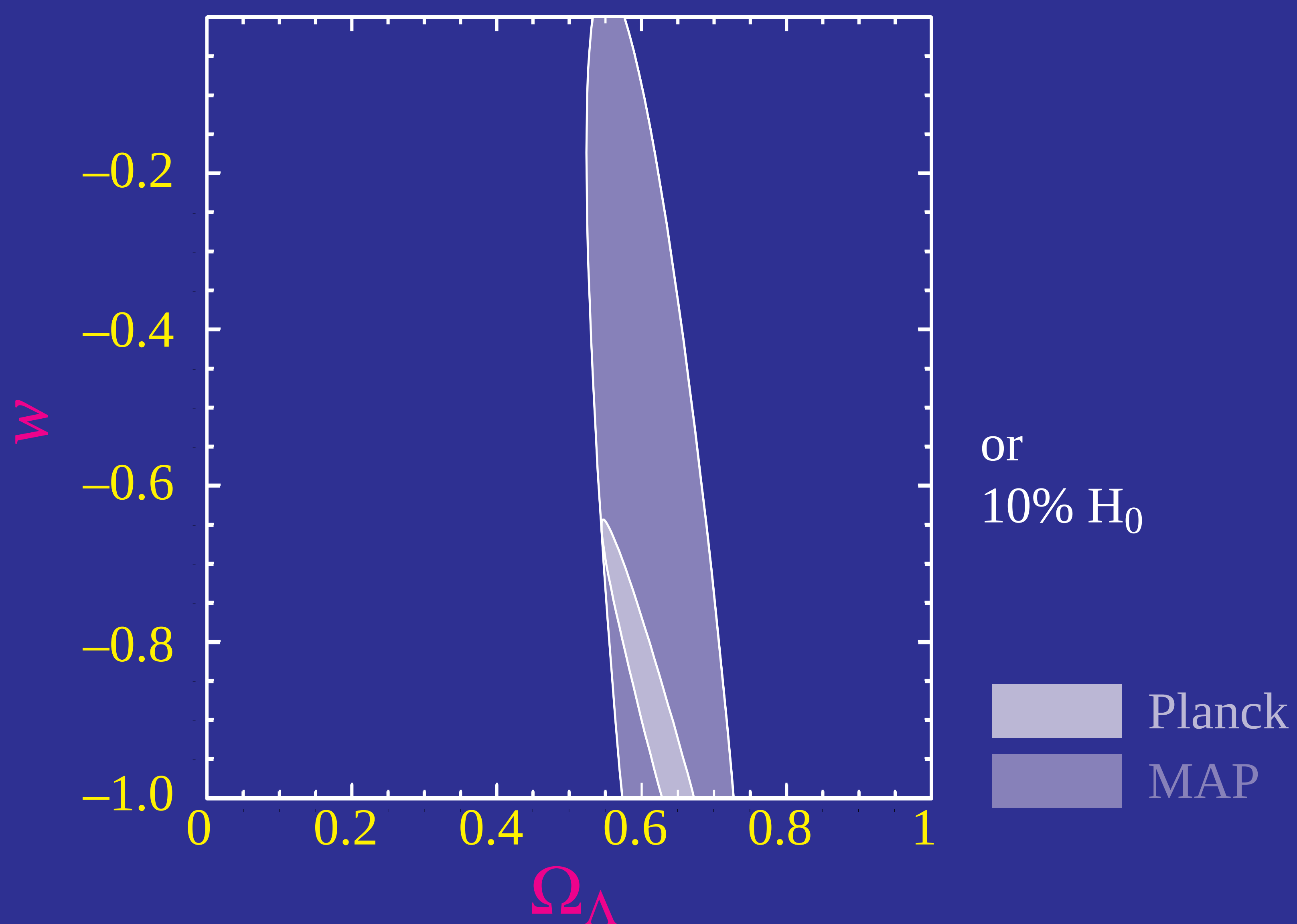
Degeneracy of the Peak Locations

- Polarization adds info on $\Omega_b h^2$, $\Omega_m h^2$ (and τ, T/S)



Degeneracy of the Peak Locations

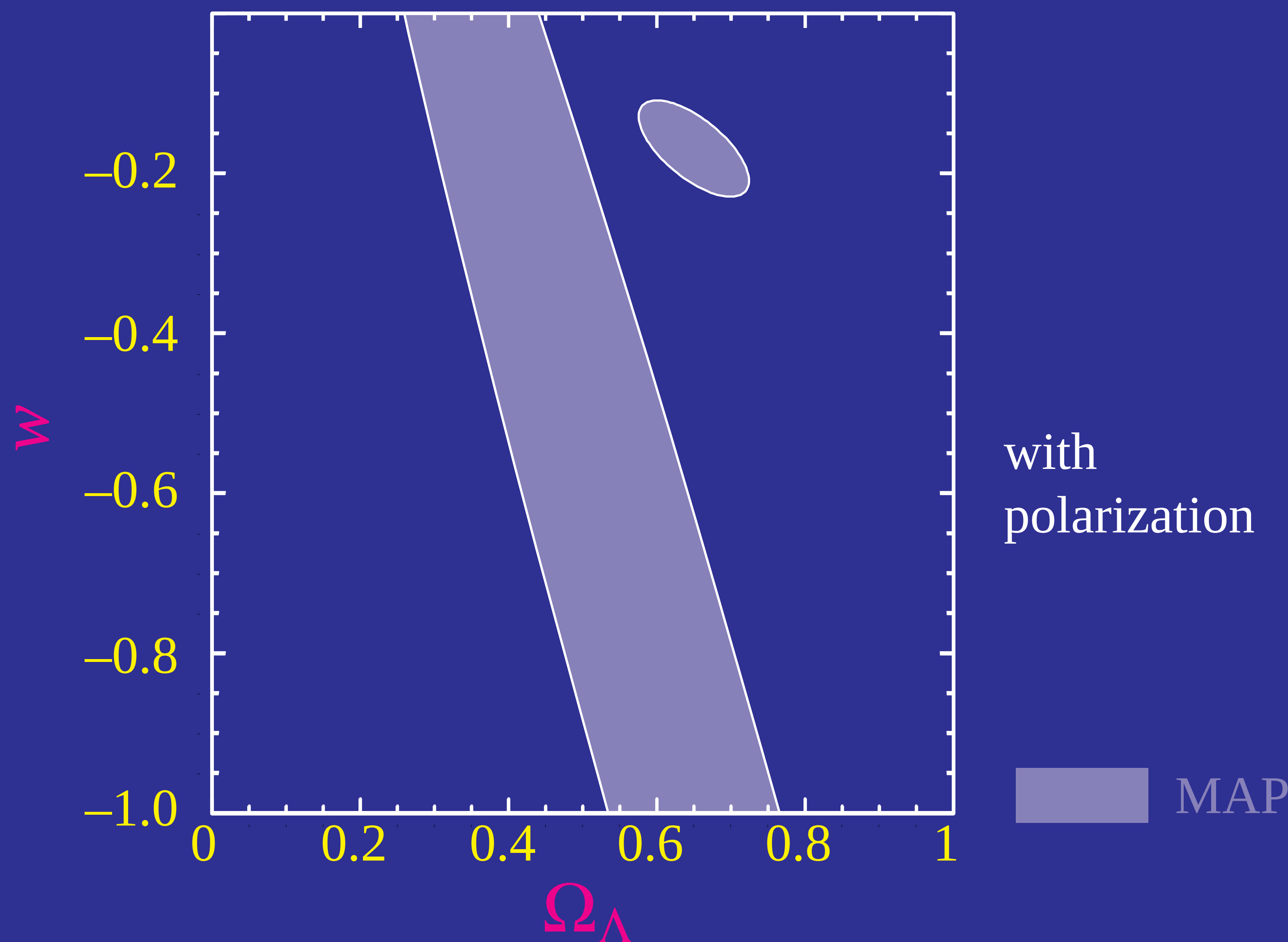
- External information, especially H_0 (or acceleration) helps



Hu et al. (1998); Hu (2001)

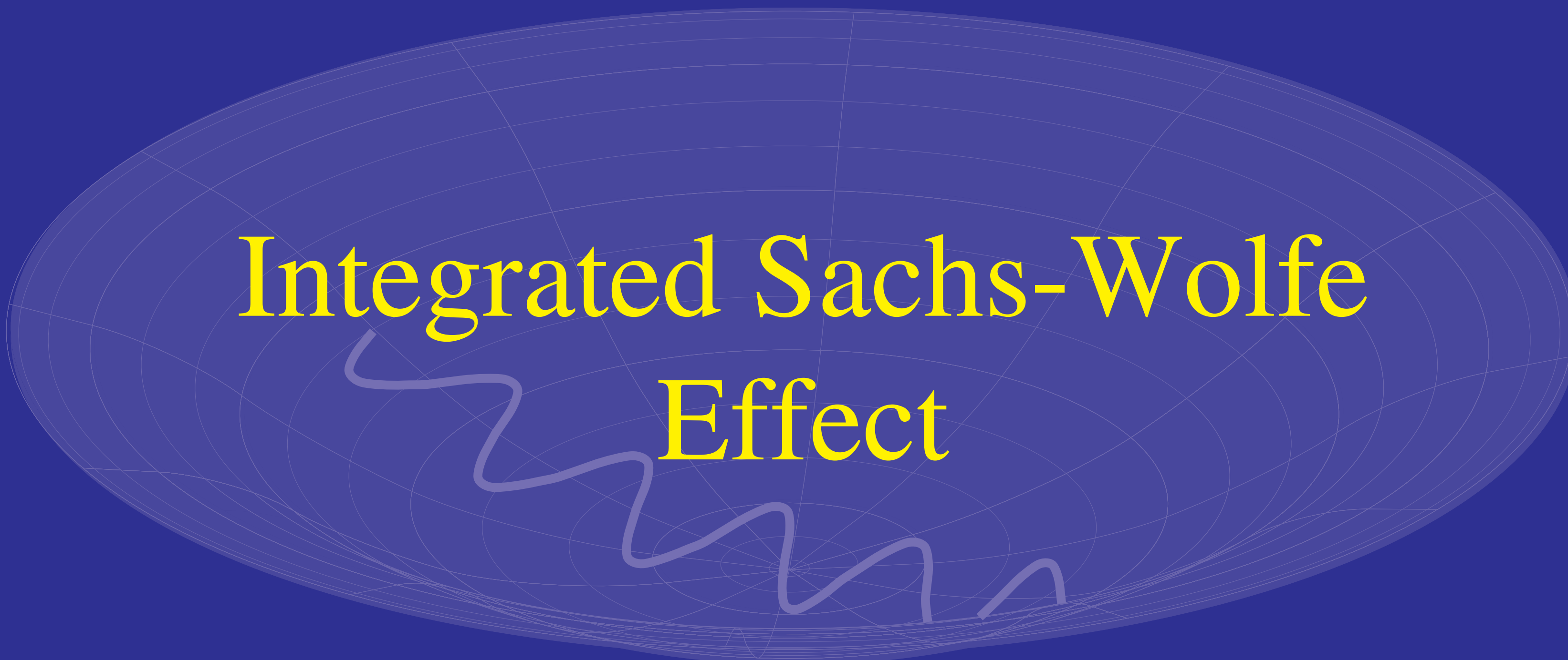
Inadequacy of the Fisher Approximation

- At higher w, degeneracy is broken by the ISW effect



Hu et al. (1998)

Integrated Sachs-Wolfe Effect



Smooth Energy Density & Potential Decay

- Regardless of the equation of state an energy component that clusters preserves an approximately constant gravitational potential (formally Bardeen curvature ζ)
- A smooth component contributes

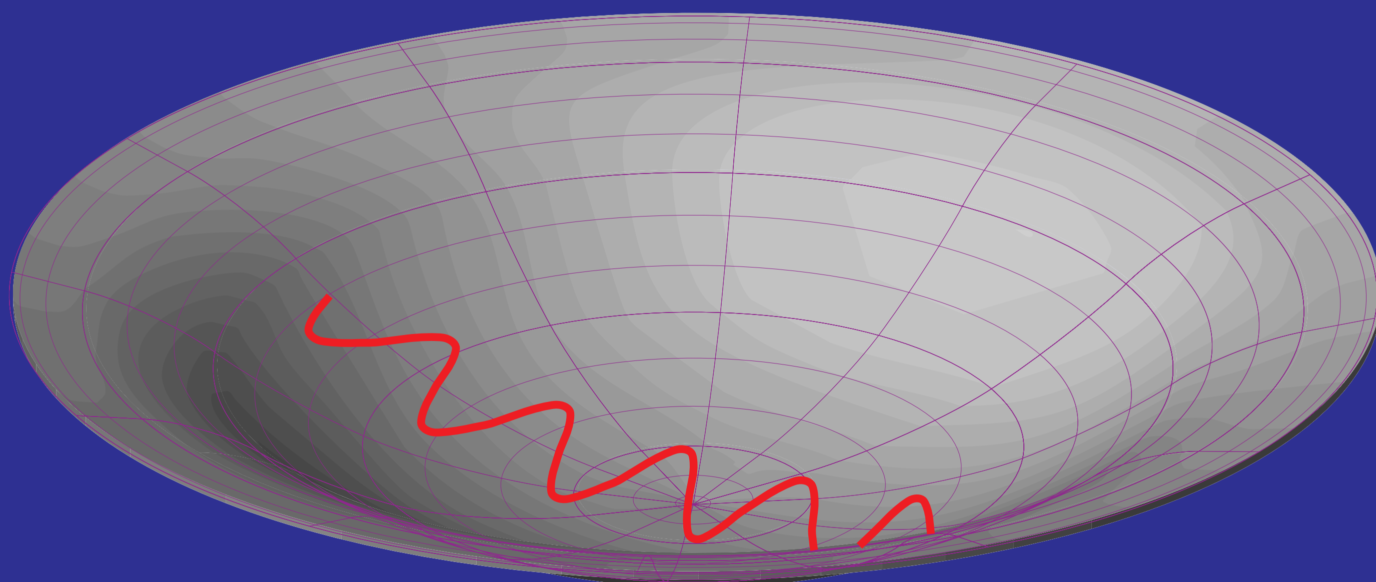
  density ρ to the expansion

  but not

  density fluctuation $\delta\rho$ to the Poisson equation
- Imbalance causes potential to decay once smooth component dominates the expansion
- Scalar field dark energy (quintessence) is smooth out to the horizon scale (sound speed c_s=1)
- Potential decay measures the clustering properties and hence the particle properties of the dark energy

ISW Effect

- Gravitational blueshift on infall does not cancel redshift on climbing out
- Contraction of spatial metric doubles the effect: $\Delta T/T = 2\Delta\Phi$
- Effect from potential hills and wells cancel on small scales



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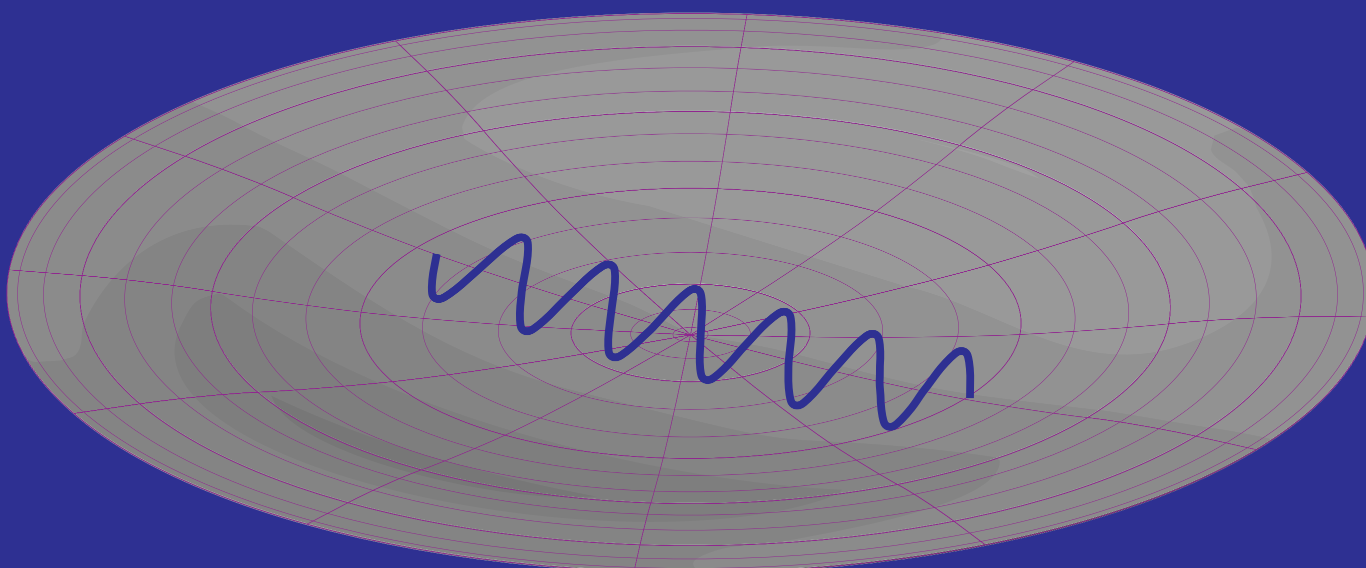
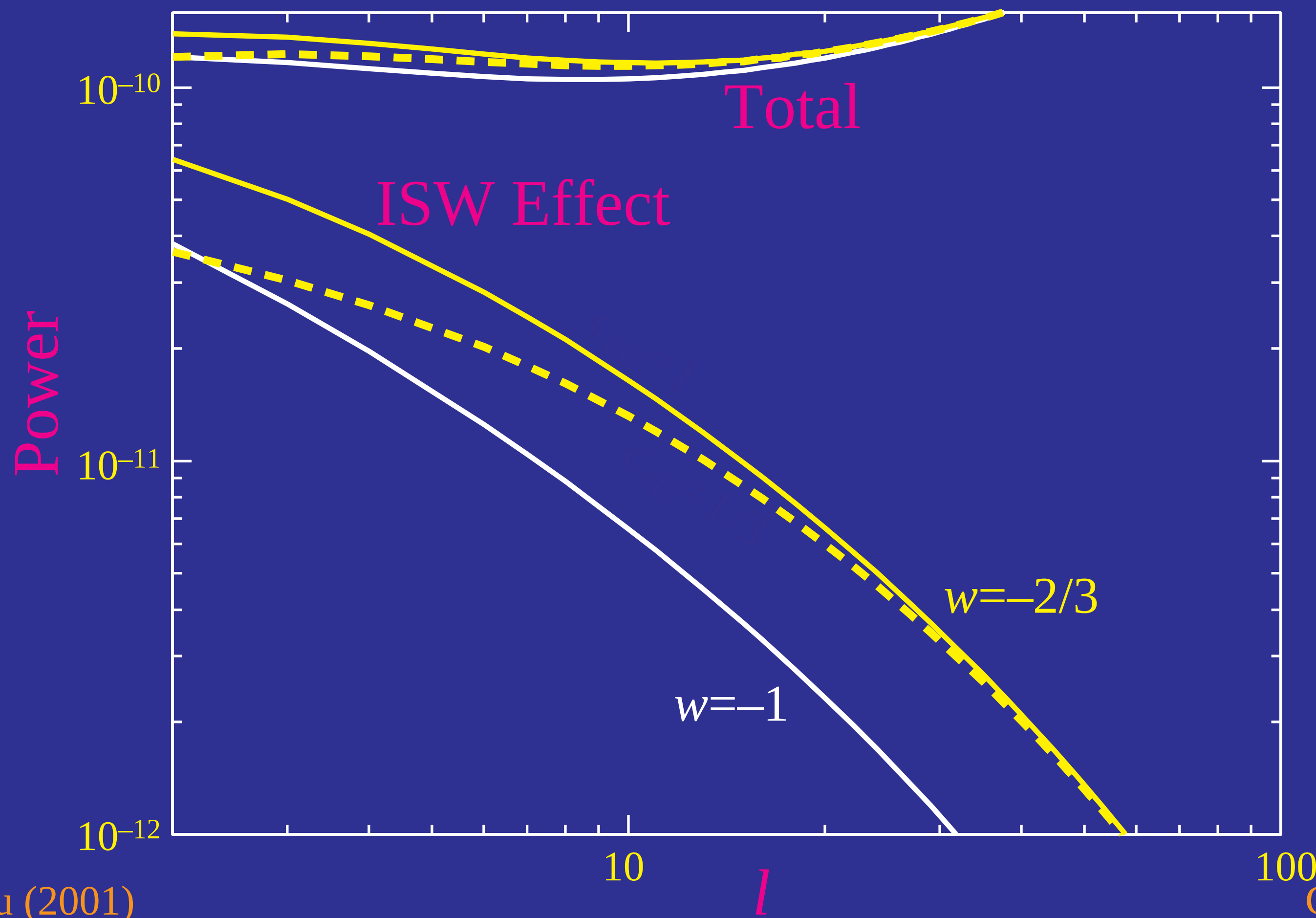


ISW Effect and Dark Energy

- Raising equation of state increases redshift of dark energy domination and raises the ISW effect
- Lowering the sound speed increases clustering and reduces ISW effect at large angles

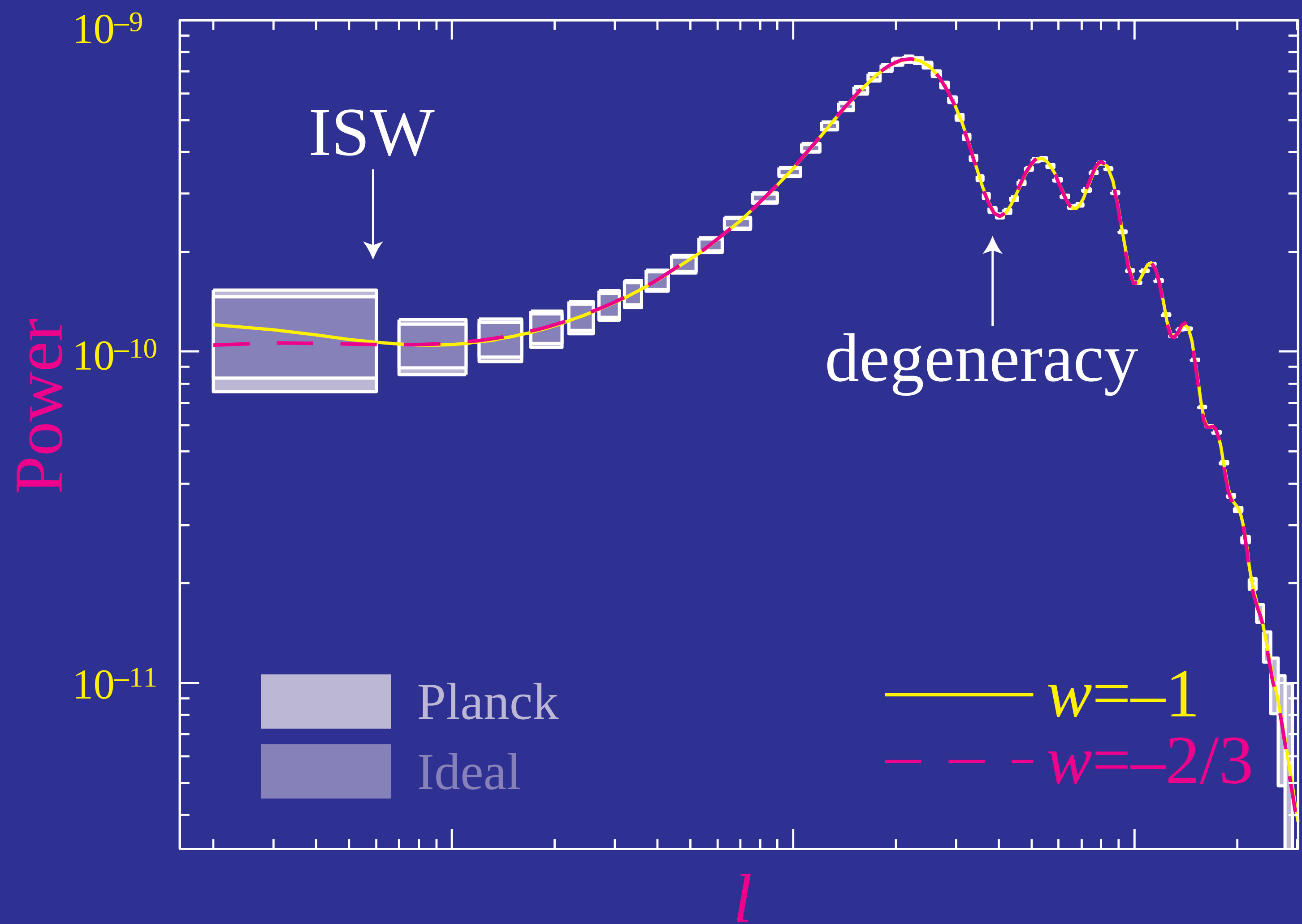


Hu (1998); Hu (2001)

Coble et al. (1997)
Caldwell et al. (1998)

Cosmic Variance Problem

- Power spectrum sampling errors = $[(l+1/2)f_{\rm sky}]^{-1/2}$
- Low multipole effects severely cosmic variance limited



Solution?

- Cross correlation with other tracers of gravitational potential
- Requires:
  Large fraction of sky f_{sky}> few percent
  Redshift sensitivity when dark energy dominates: z~0.5-1
- Possibilities:
  X-ray surveys
  Radio surveys
  (issues of bias, evolution) Crittenden et al.

  Cosmic shear surveys
  (intrinsically small shear signals above degree scale)

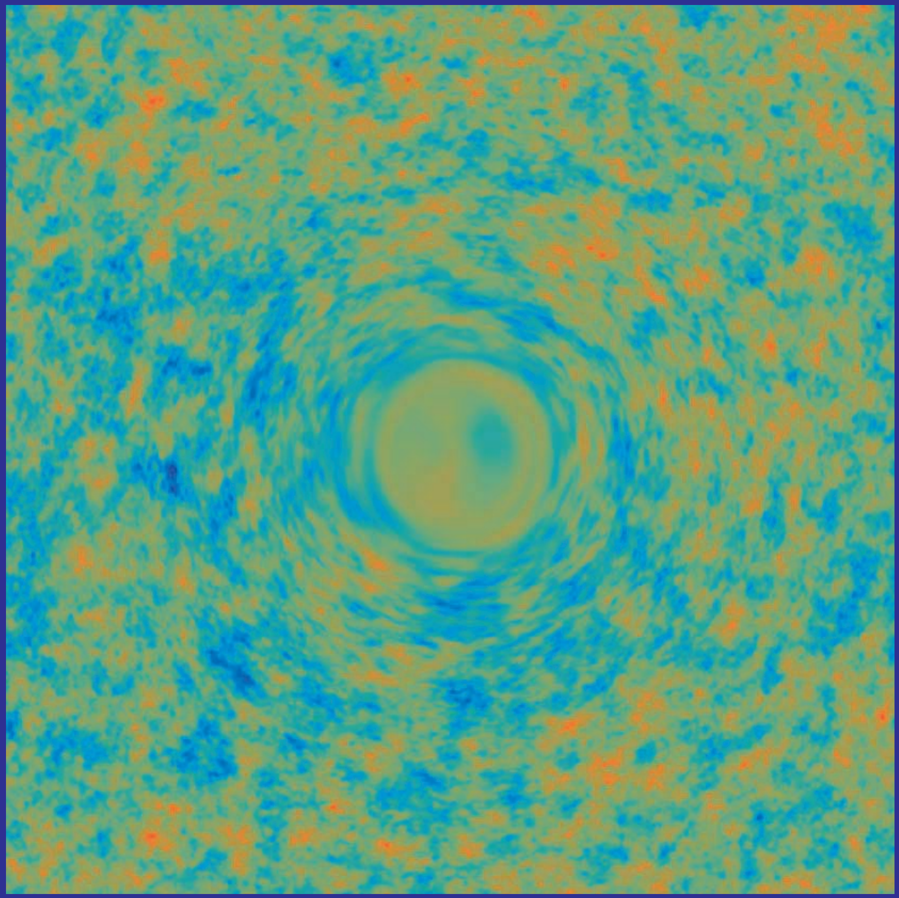
  Hu (2001)

  CMB Lensing Goldberg & Spergel (1999); Zaldarriaga & Seljak (1999)
  Hu (2001)

CMB
Temperature & Polarization
Lensing

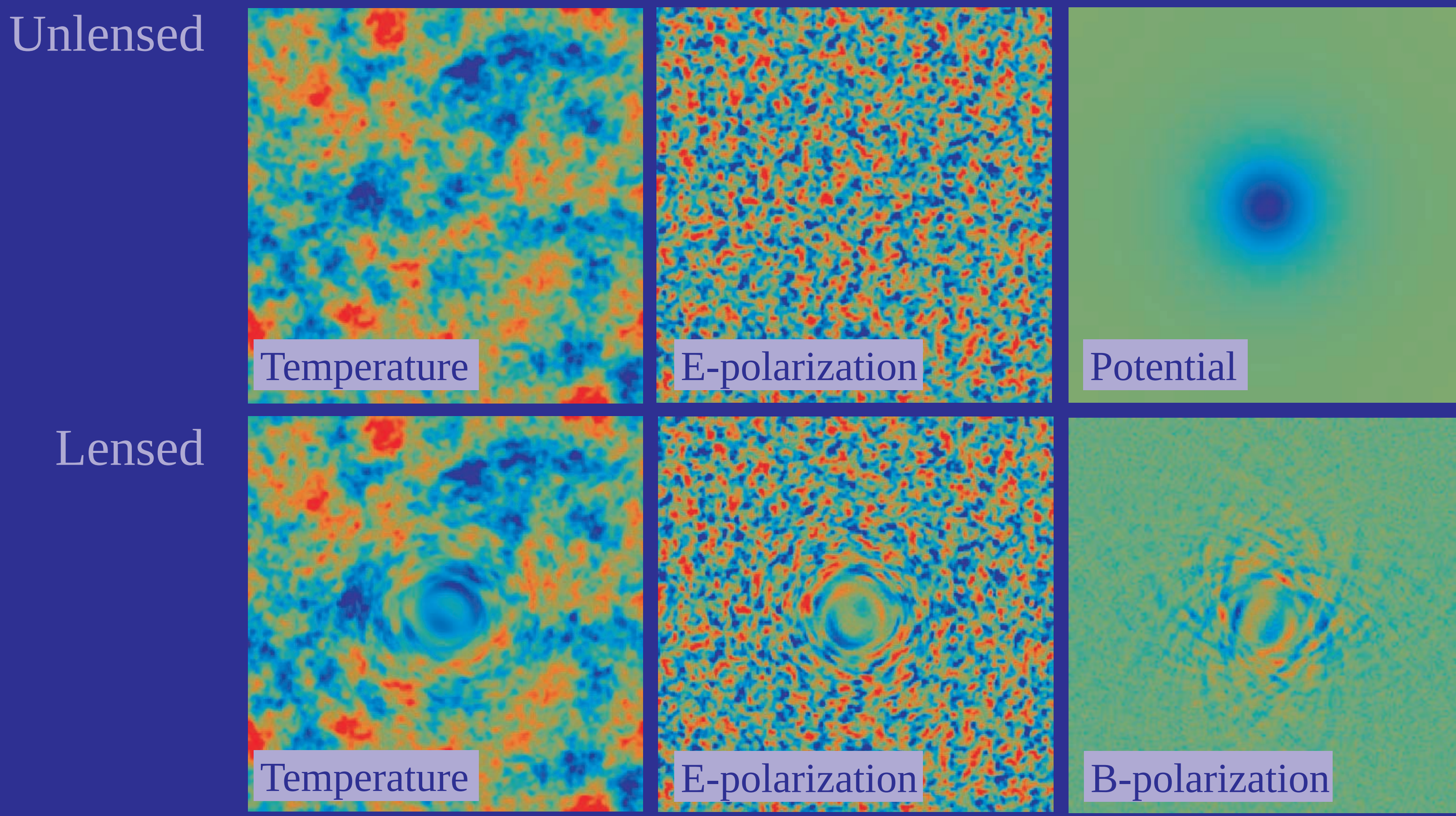
Lensing of a Gaussian Random Field

- CMB temperature and polarization anisotropies are Gaussian random fields – unlike galaxy weak lensing
- Average over many noisy images – like galaxy weak lensing



Temperature & Polarization

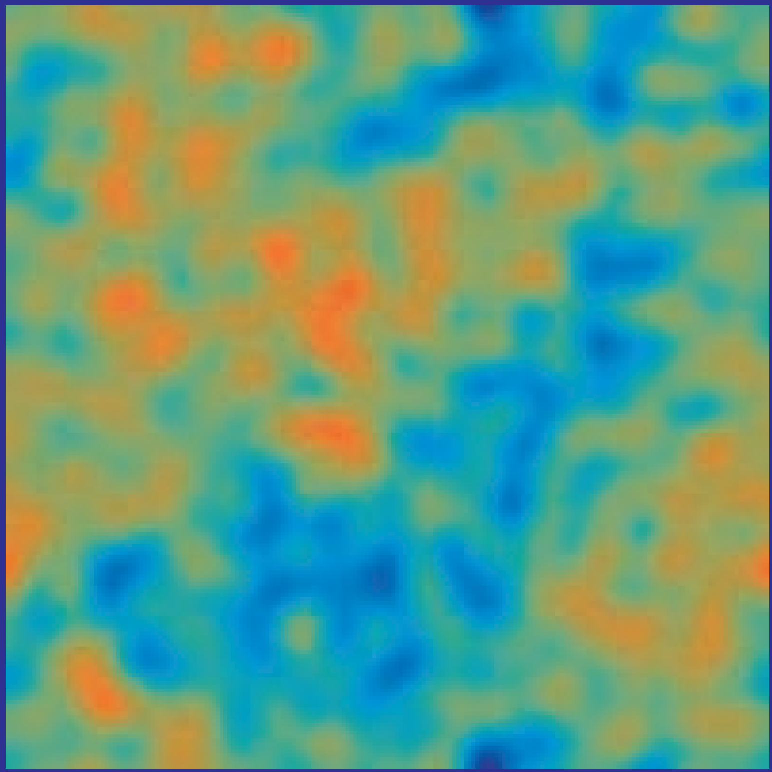
- Mass distribution at large angles and high redshift in in the linear regime (100 sq. deg.)



Hu & Okamoto (2001)

Lensing by a Gaussian Random Field

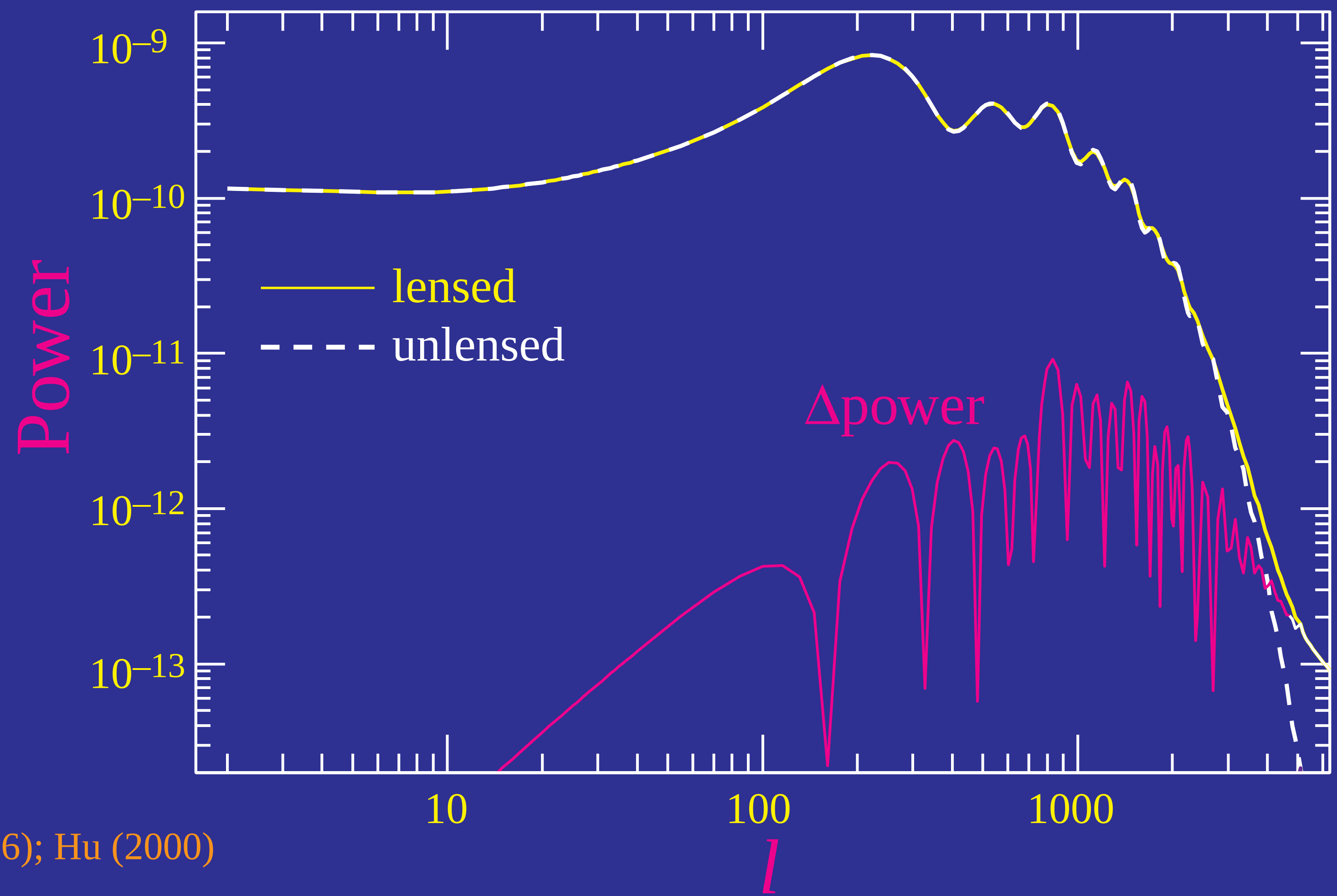
- Mass distribution at large angles and high redshift in in the linear regime
- Projected mass distribution (low pass filtered reflecting deflection angles): 1000 sq. deg



rms deflection
2.6'
deflection coherence
10°

Lensing in the Power Spectrum

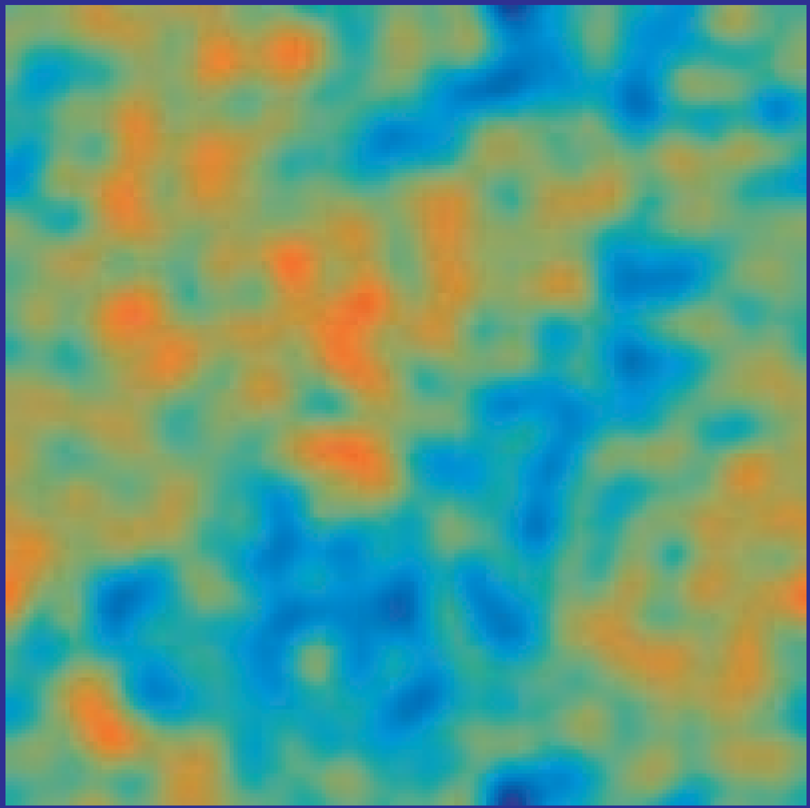
- Lensing smooths the power spectrum with a width $\Delta l \sim 60$
- Convolution with specific kernel: higher order correlations between multipole moments – not apparent in power



Seljak (1996); Hu (2000)

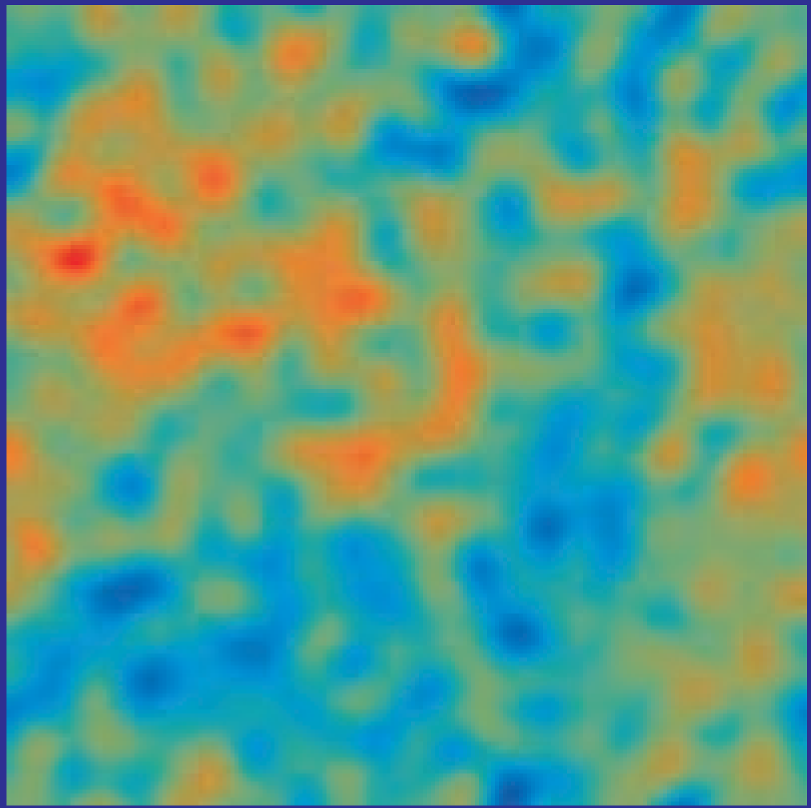
Quadratic Reconstruction

- Matched filter (minimum variance) averaging over pairs of multipole moments
- Real space: divergence of a temperature-weighted gradient



original

potential map (1000sq. deg)



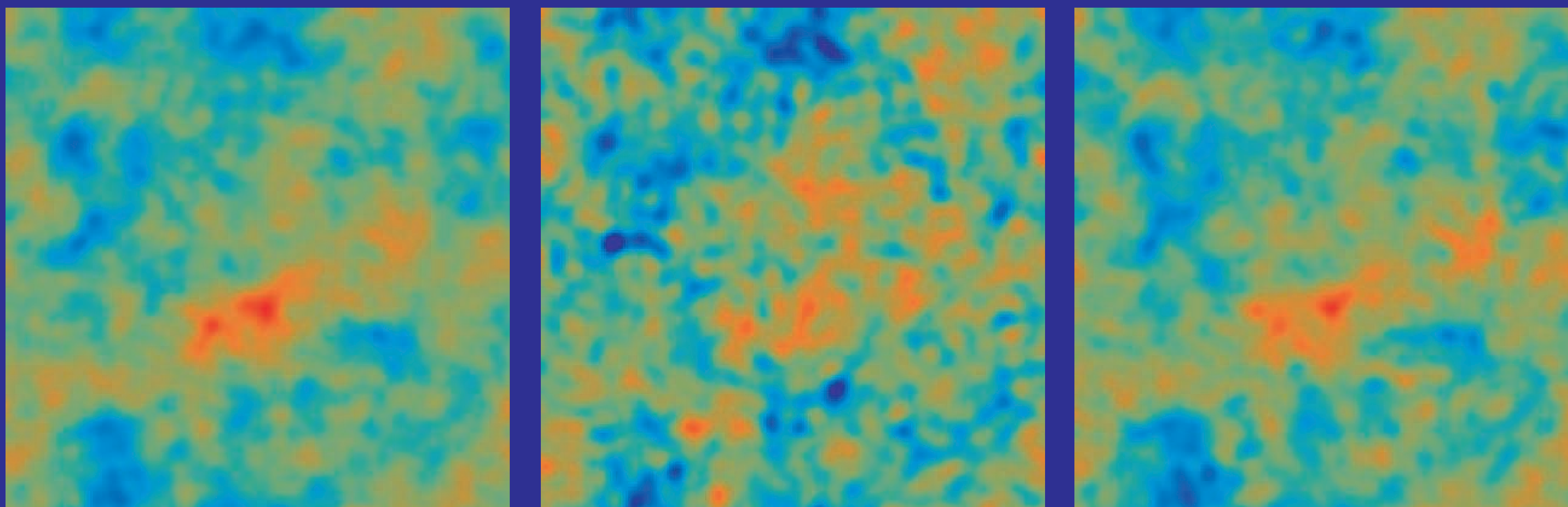
reconstructed

1.5' beam; 27μK-arcmin noise

Hu (2001)

Ultimate (Cosmic Variance) Limit

- Cosmic variance of CMB fields sets ultimate limit
- Polarization allows mapping to finer scales (~10')



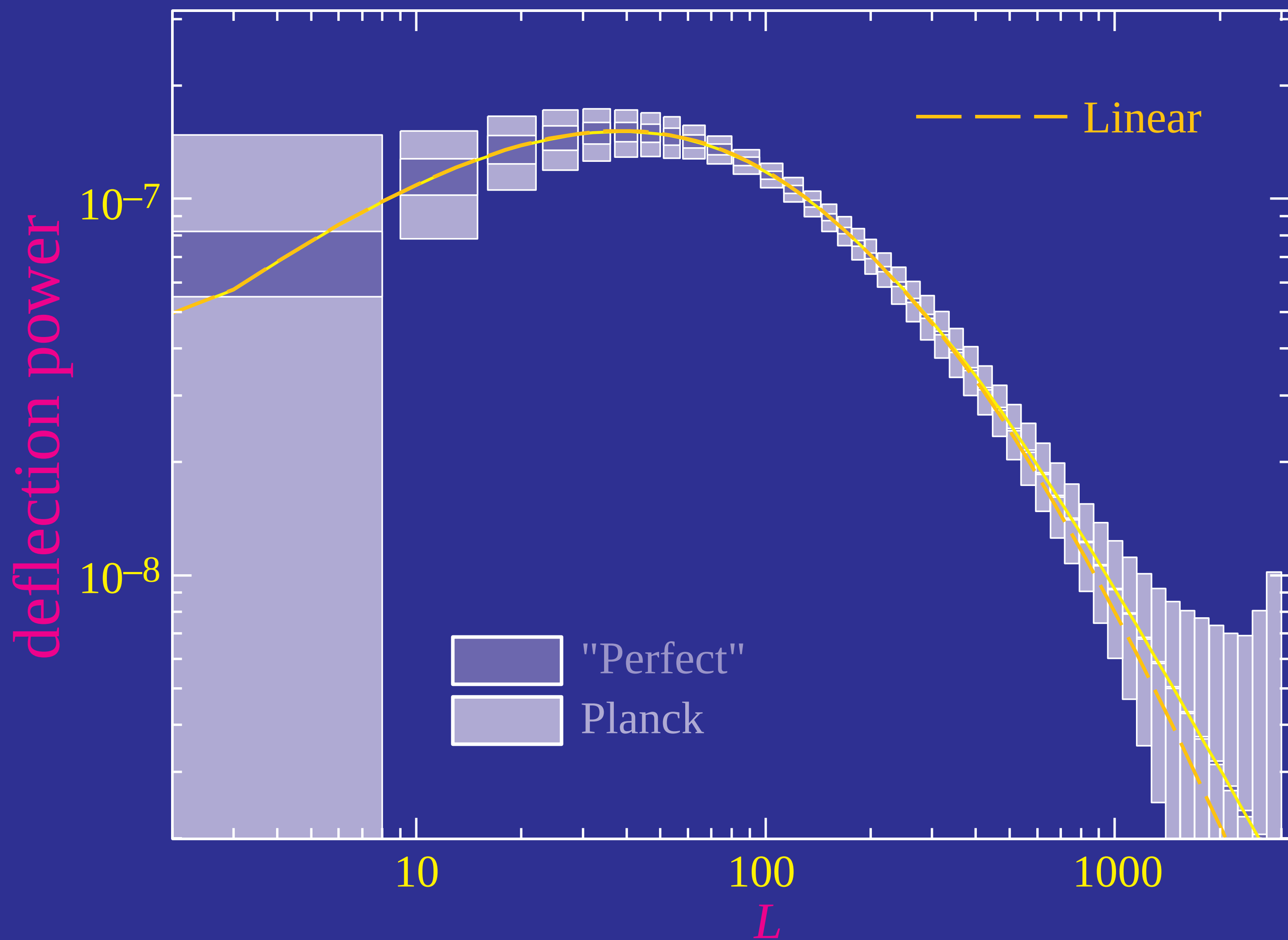
mass | temp. reconstruction | EB pol. reconstruction

100 sq. deg; 4' beam; 1μK-arcmin

Hu & Okamoto (2001)

Matter Power Spectrum

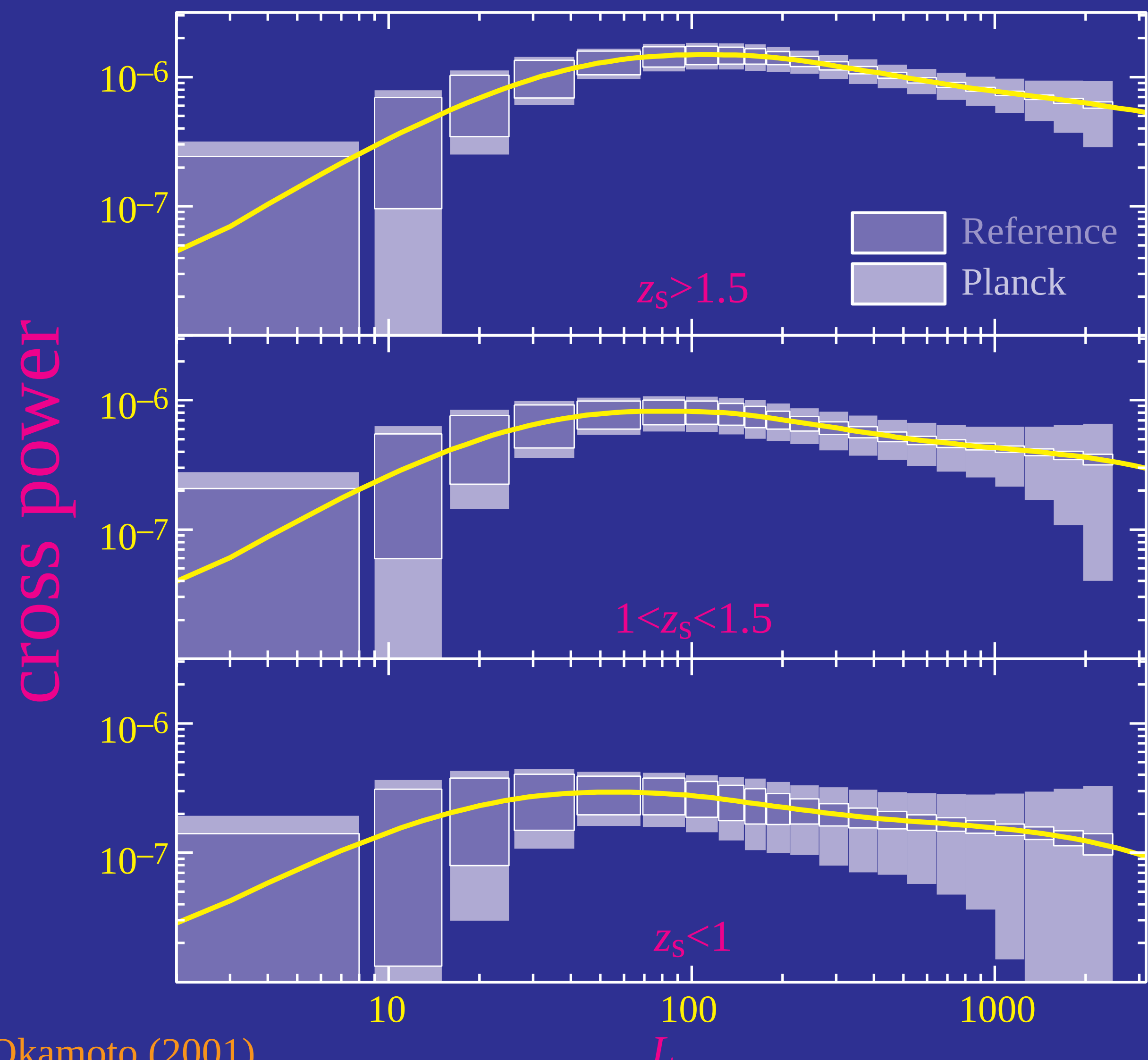
- Measuring projected matter power spectrum to cosmic variance limit across whole linear regime 0.002< k < 0.2 *h*/Mpc



Hu & Okamoto (2001)

Tomography & Growth Rate

- Cross correlation with cosmic shear – mass tomography anchor in the decelerating regime

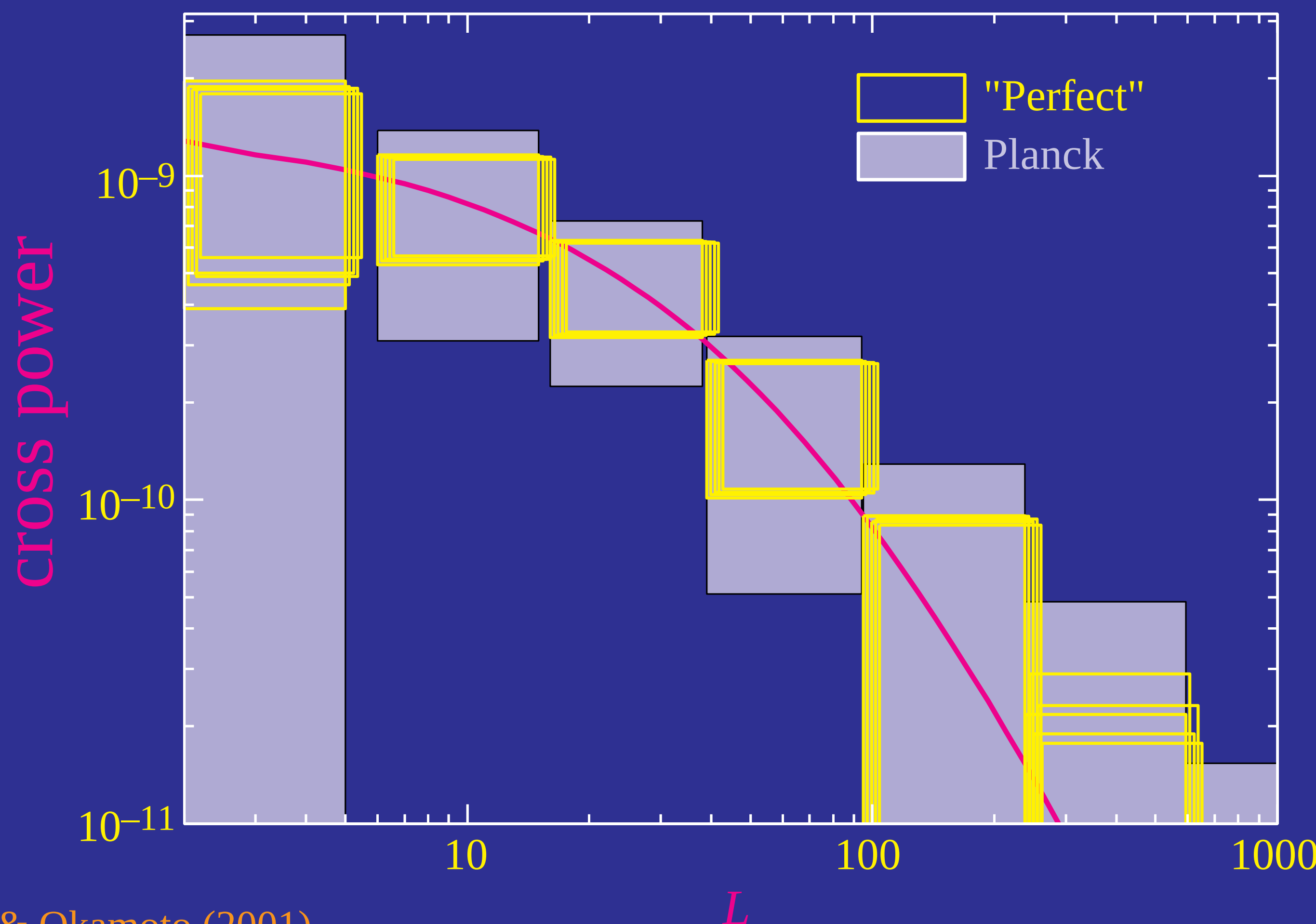


1000 sq. deg.

Hu (2001); Hu & Okamoto (2001)

Cross Correlation with Temperature

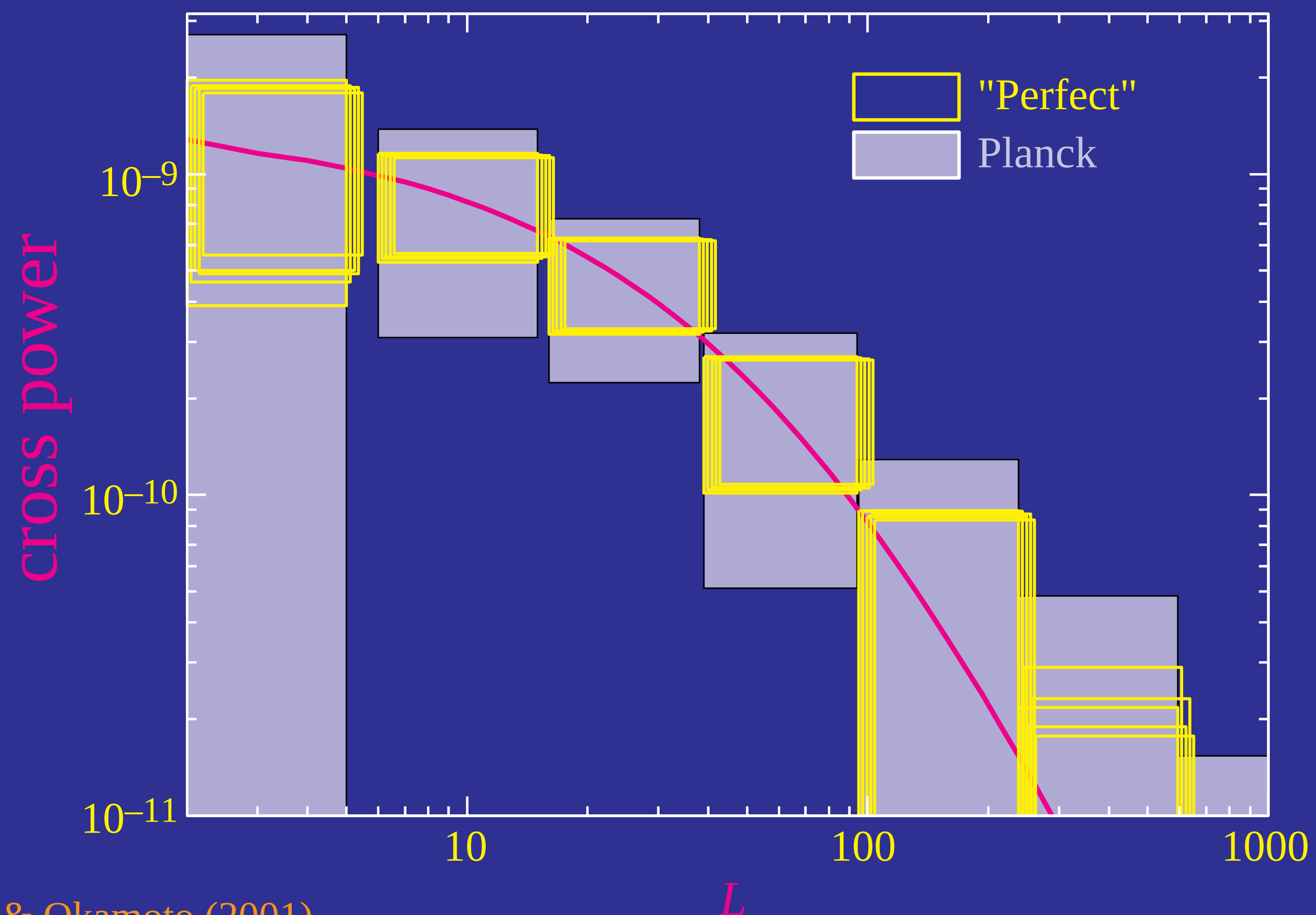
- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- 5 nearly independent measures in temperature & polarization



Hu (2001); Hu & Okamoto (2001)

Cross Correlation with Temperature

- Any correlation is a direct detection of a smooth energy density component through the ISW effect
- Show dark energy smooth >5-6 Gpc scale, test quintesence



Hu (2001); Hu & Okamoto (2001)

Summary

- Peaks measure the angular diameter distance to recombination, photon-baryon ratio, matter-radiation ratio
- Leaves a degenerate combination of dark energy density and equation of state in a flat universe
- Degeneracy is broken by H_0, acceleration, Ω_m
  ISW effect – strongly for high w
- ISW effect fundamentally measures dark energy smoothness
- Severely cosmic variance limited near w=–1
- Measure by cross correlation
- CMB lensing to reconstruct projected potential
- Can show that dark energy is smooth out to 5-6 Gpc