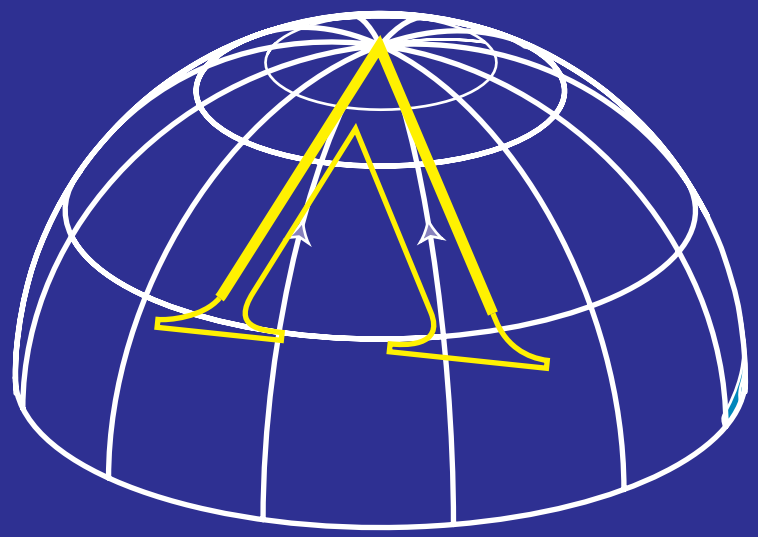
# Dark Energy in Light of the CMB



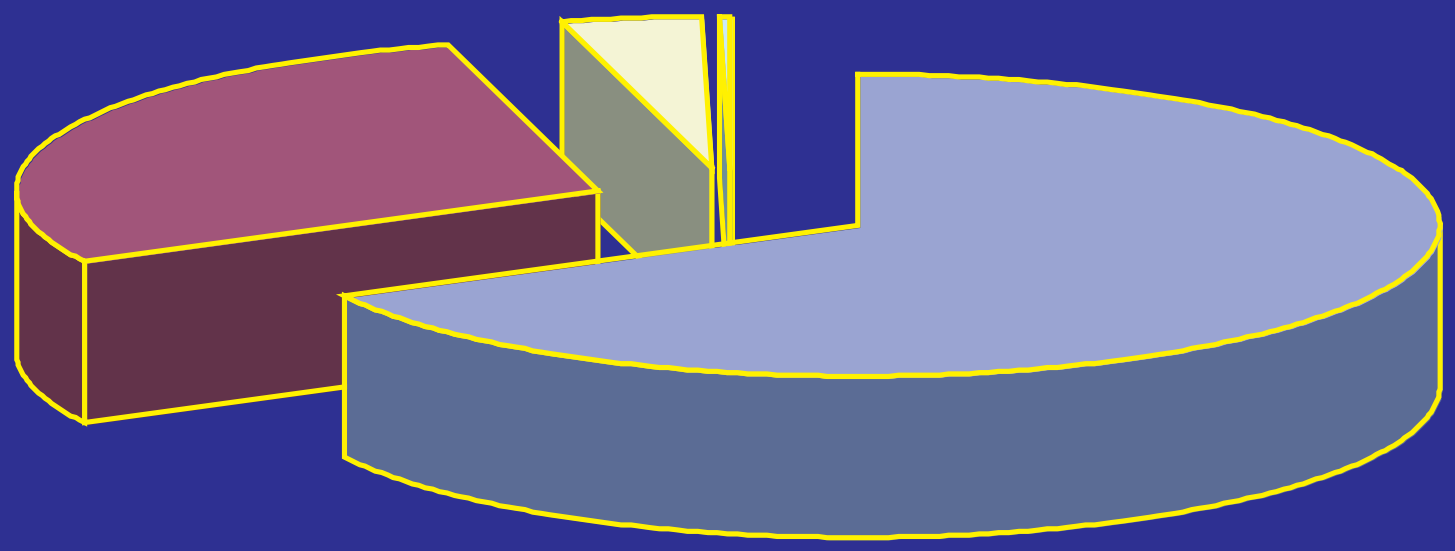
## (or why $H_0$ is the Dark Energy)

*Wayne Hu*

February 2006, NRAO, VA

# If its not dark, it doesn't matter!

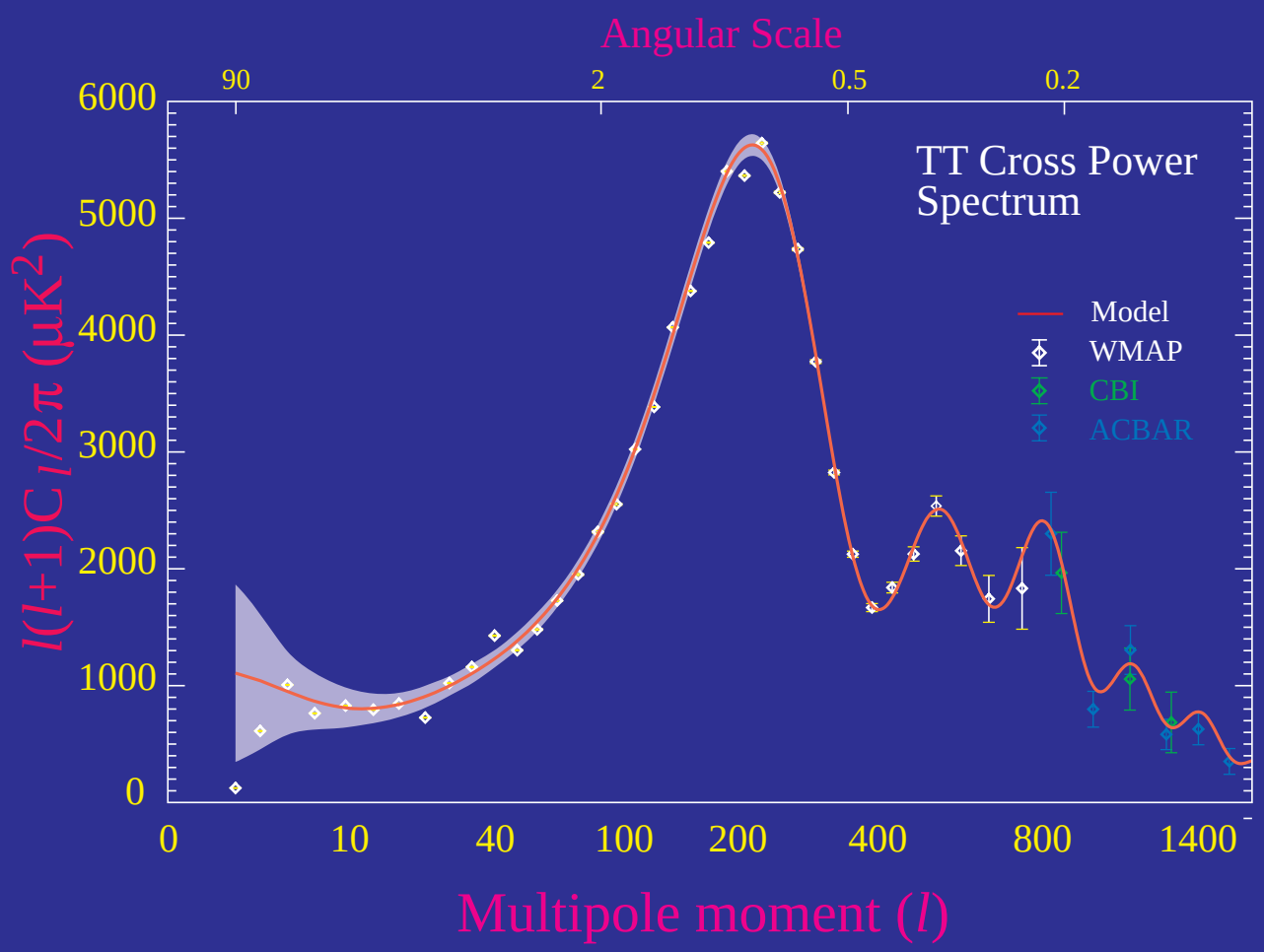
- Cosmic matter-energy budget:



Dark Energy
Dark Matter
Dark Baryons
Visible Matter
Dark Neutrinos

# CMB Cornerstone

- CMB temperature and polarization measures provide the high redshift cornerstone to cosmological inferences on the dark matter and dark energy




WMAP: Bennett et al (2003)

# Is $H_0$ Interesting?

- WMAP infers that in a flat $\Lambda$ cosmology $H_0=72\pm5$
- Key project measures $H_0=72\pm8$
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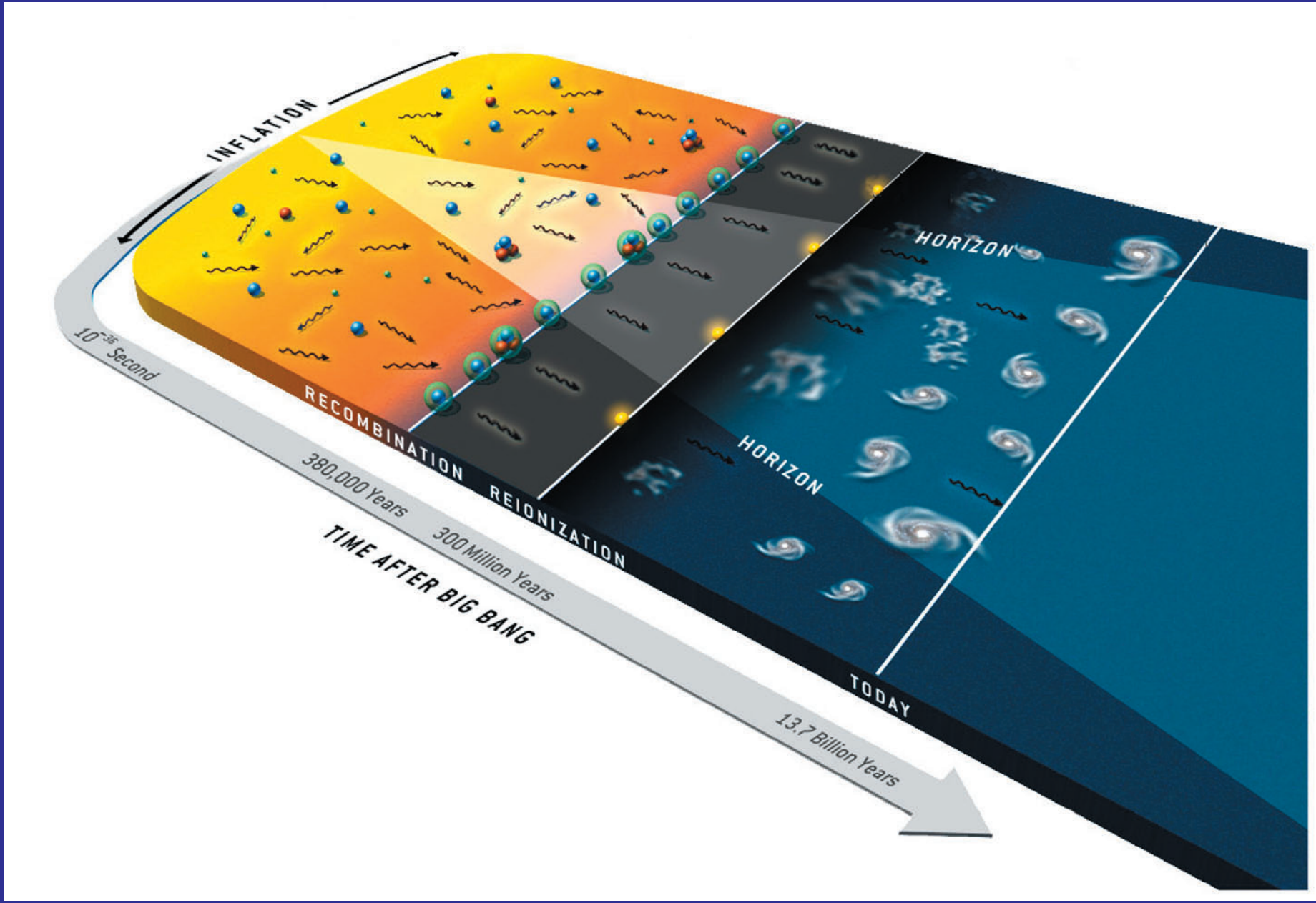
- CMB observables then predict $H_0$ for a given hypothesis about the dark energy (e.g. flat $\Lambda$)
- Consistency with measured value is strong evidence for dark energy and in the future can reveal properties such as its equation of state *if* $H_0$ *can be measured to percent precision*

# CMB Acoustic Oscillations

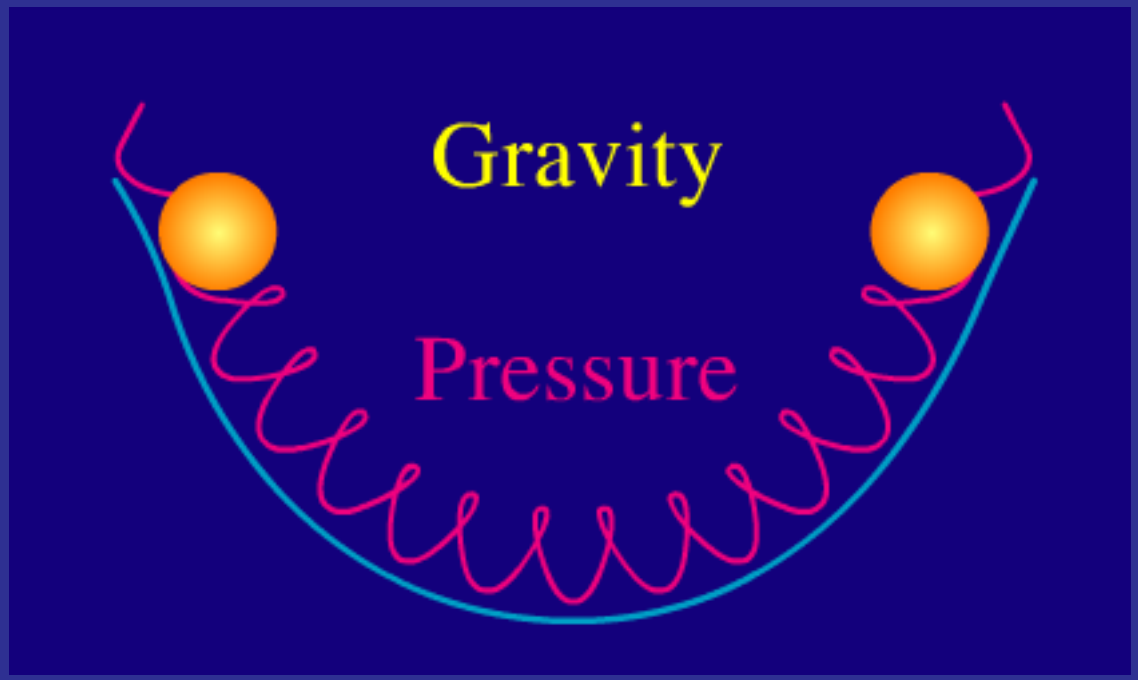
# In the Beginning...




Hu & White (2004); artist:B. Christie/SciAm

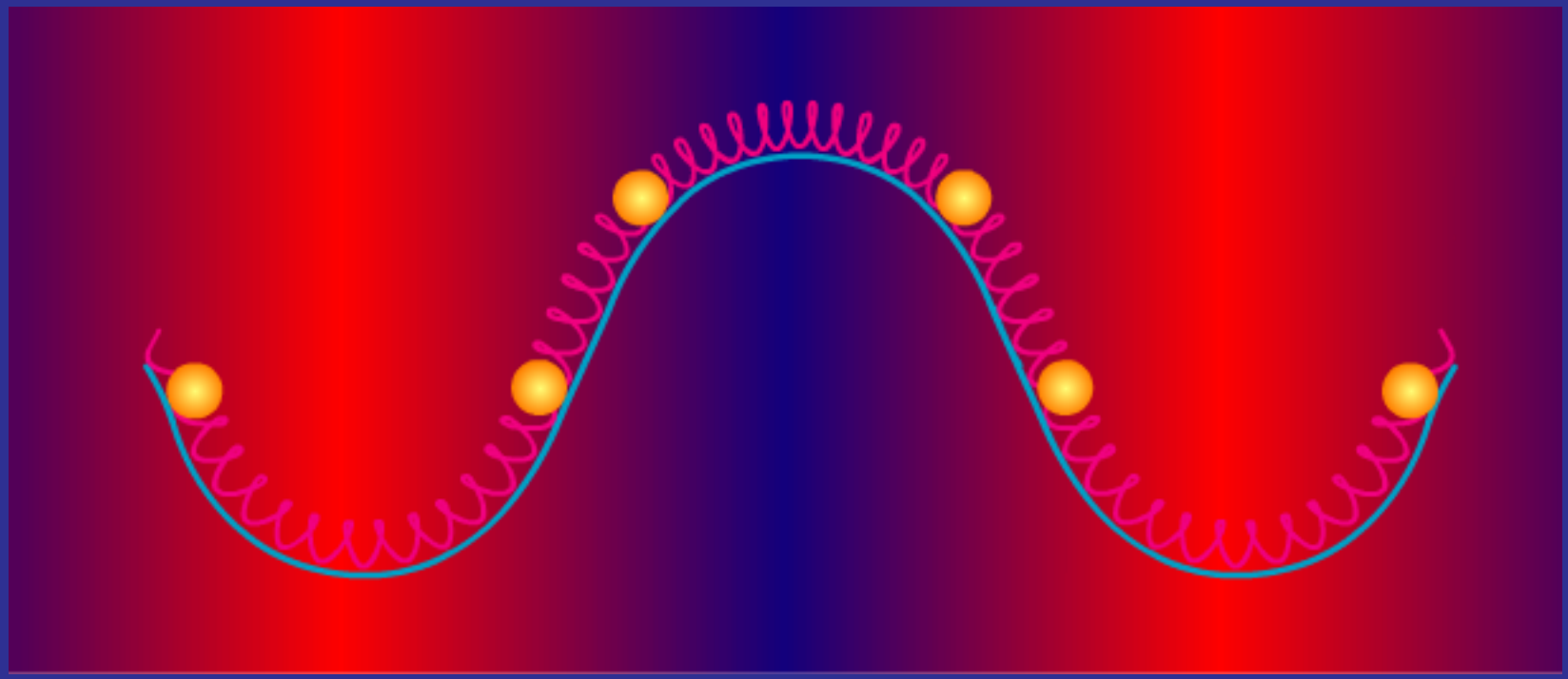
# Gravitational Ringing

- Potential wells = inflationary seeds of structure
- Fluid falls into wells, pressure resists: acoustic oscillations



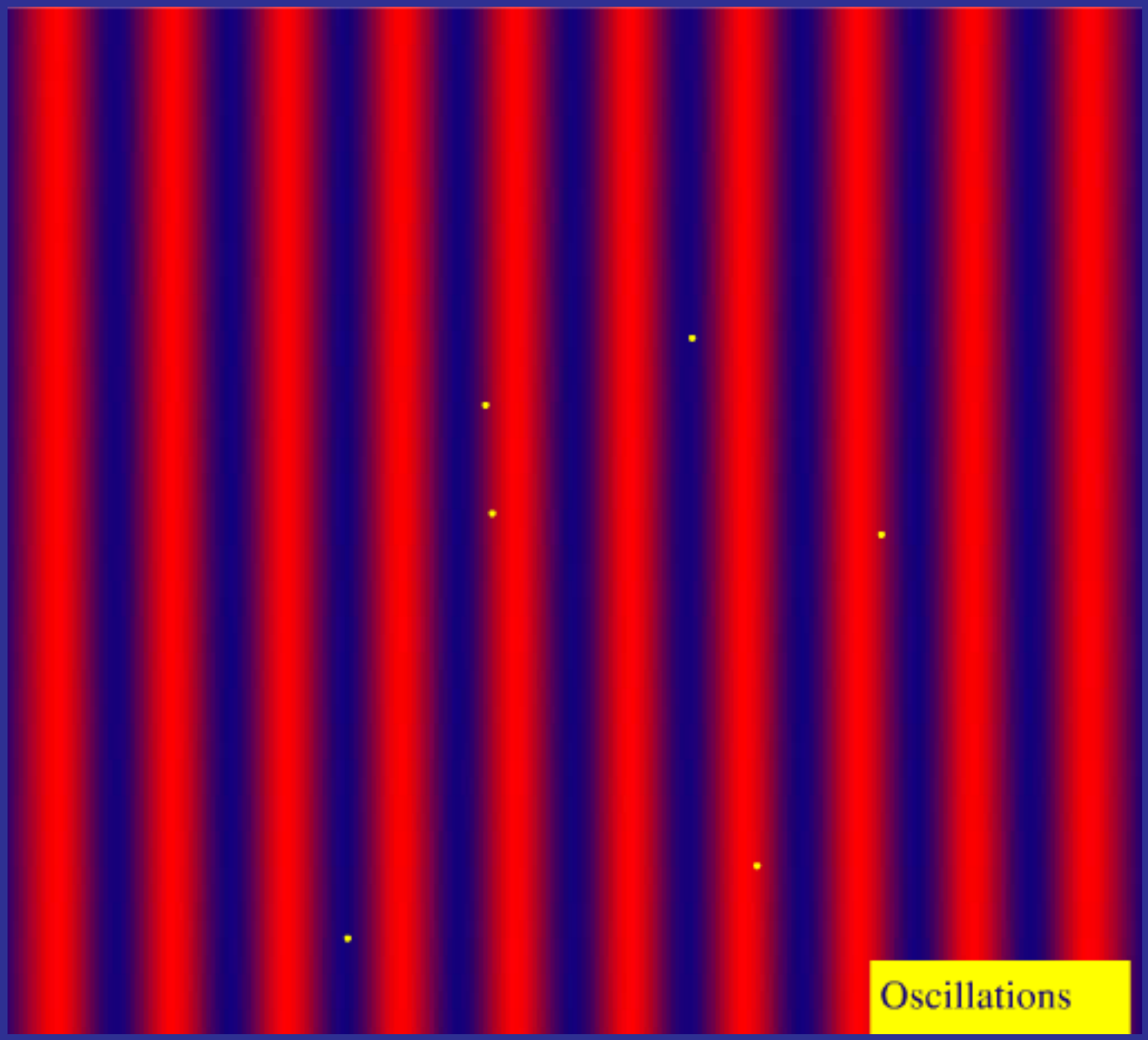
# Seeing Sound

- Oscillations frozen at recombination
- Compression=hot spots, Rarefaction=cold spots



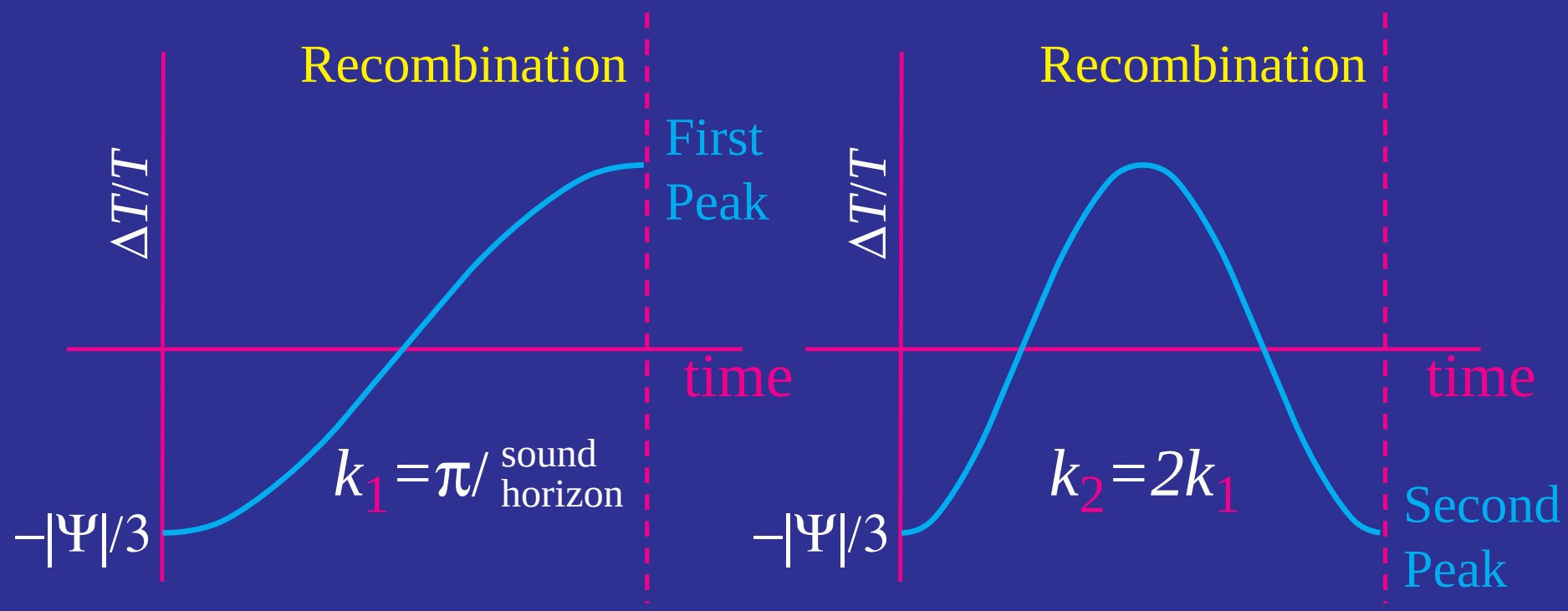
# Peaks in Angular Power

- The Anisotropy Formation Process



# Extrema=Peaks

- First peak = mode that just compresses
- Second peak = mode that compresses then rarefies
- Third peak = mode that compresses then rarefies then compresses



# Peak Location

- Fundmental physical scale, the distance sound travels, becomes an angular scale by simple projection according to the angular diameter distance $D_A$

$$\begin{aligned} \theta_A &= \lambda_A / D_A \\ \ell_A &= k_A D_A \end{aligned}$$

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- In a flat universe, the distance is simply $D_A = D \equiv \eta_0 - \eta_* \approx \eta_0$, the horizon distance, and $k_A = \pi / s_* = \sqrt{3}\pi / \eta_*$ so

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- In a matter-dominated universe $\eta \propto a^{1/2}$ so $\theta_A \approx 1/30 \approx 2^\circ$ or

$$\ell_A \approx 200$$

# CMB & the Dark Energy

- Universe is neither fully matter dominated at recombination nor at the present due to radiation and dark energy
- Given a recombination epoch $a_*$ (depends mainly on temperature and atomic physics) calculate the sound horizon

$$s_* \equiv \int c_s d\eta = \int_0^{a_*} da \frac{c_s}{a^2 H}$$

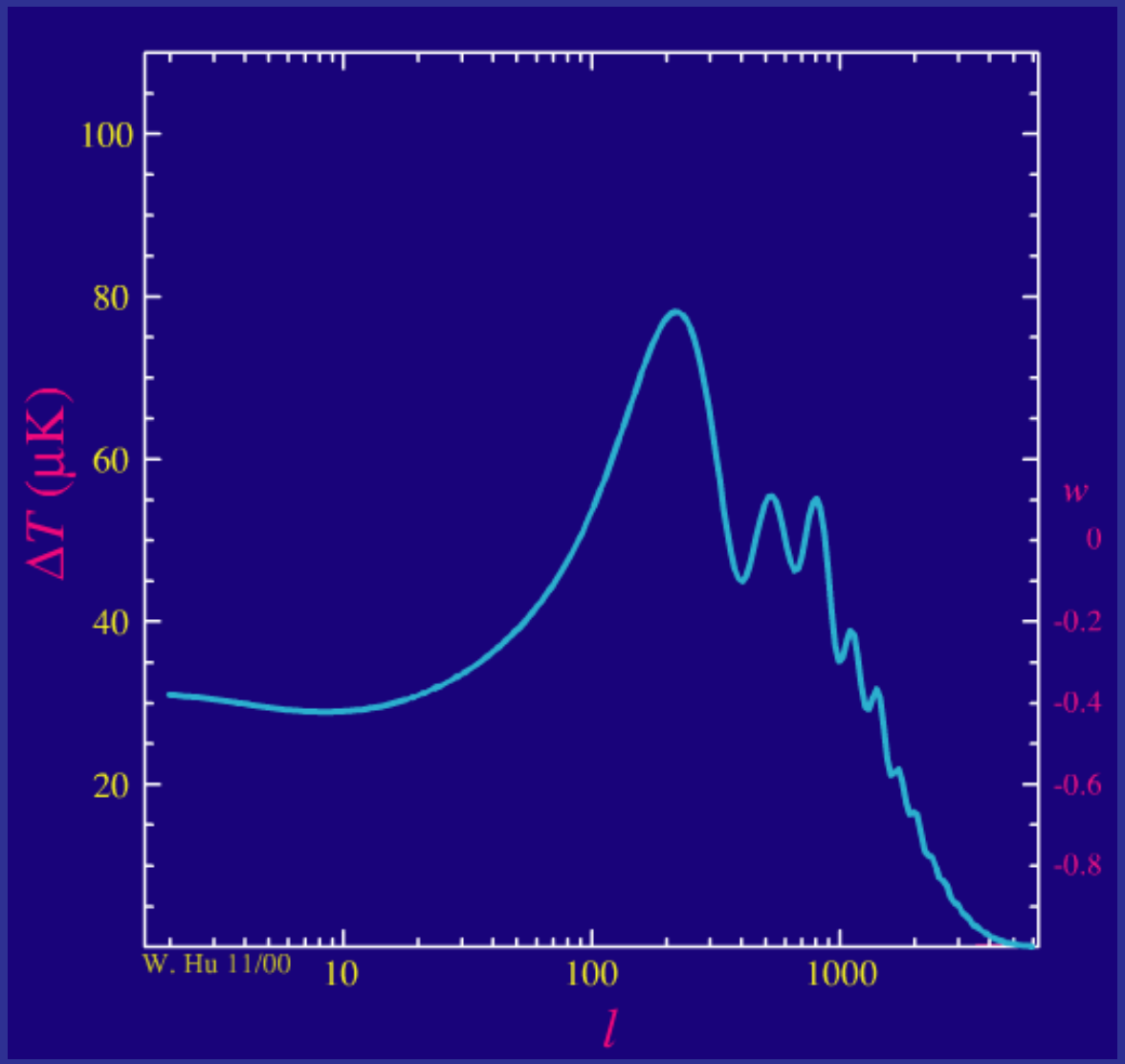
  note that this depends mainly on the expansion rate $H$ at $a_*$, i.e. the matter-radiation ratio and secondarily on the baryon-photon ratio.
- Given a dark energy model, calculate the comoving distance to $a_*$

$$D = \int_{a_*}^{1} da \frac{1}{a^2 H}$$

- Given a curvature calculate the angular diameter distance $D_A = R \sin(D/R)$

# Dark Energy in the Power Spectrum

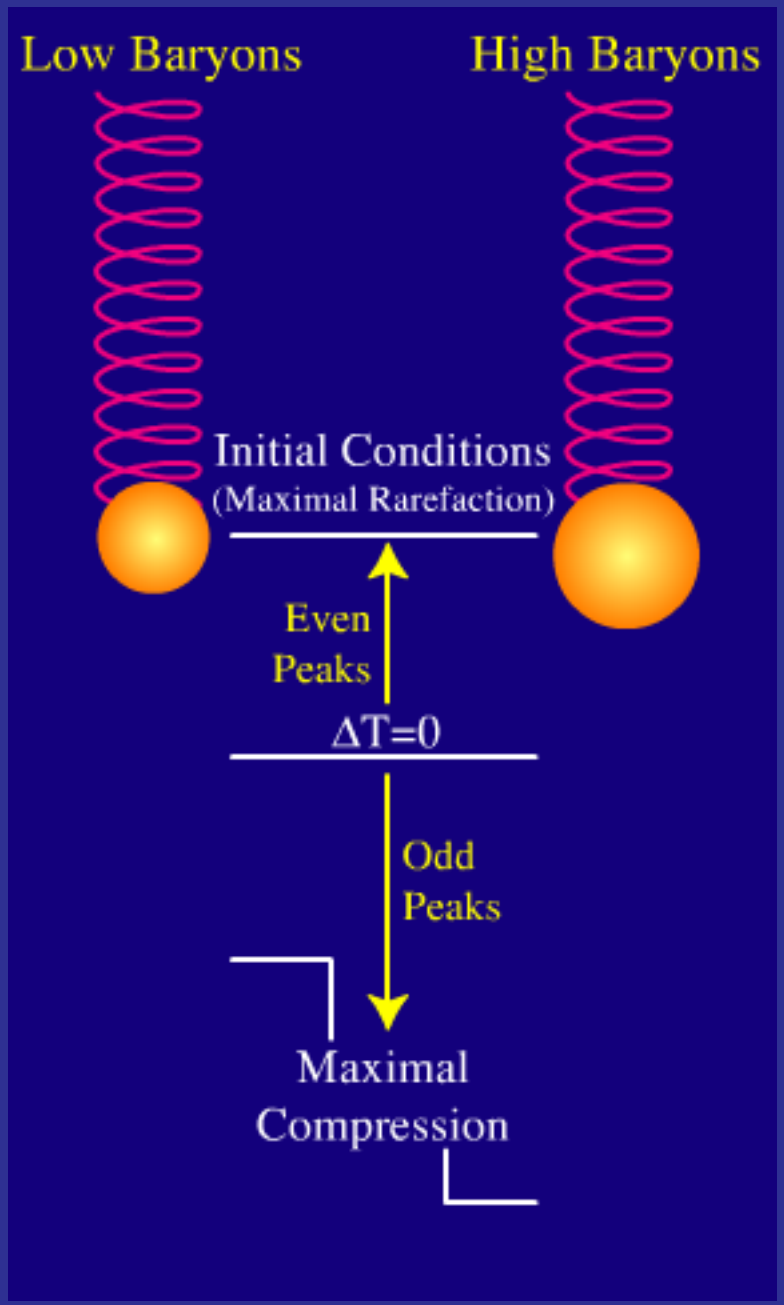
- Features scale with angular diameter distance
- Small shift but angle already measured to <1%



# Calibrating Standard Ruler

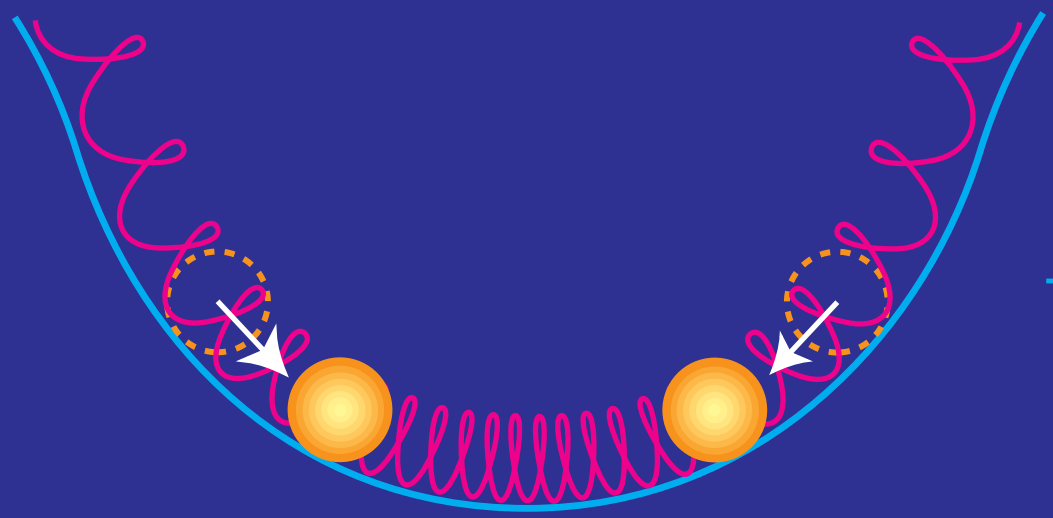
# Baryon & Inertia

- Baryons add inertia to the fluid
- Equivalent to adding mass on a spring
- Same initial conditions
- Same null in fluctuations
- Unequal amplitudes of extrema

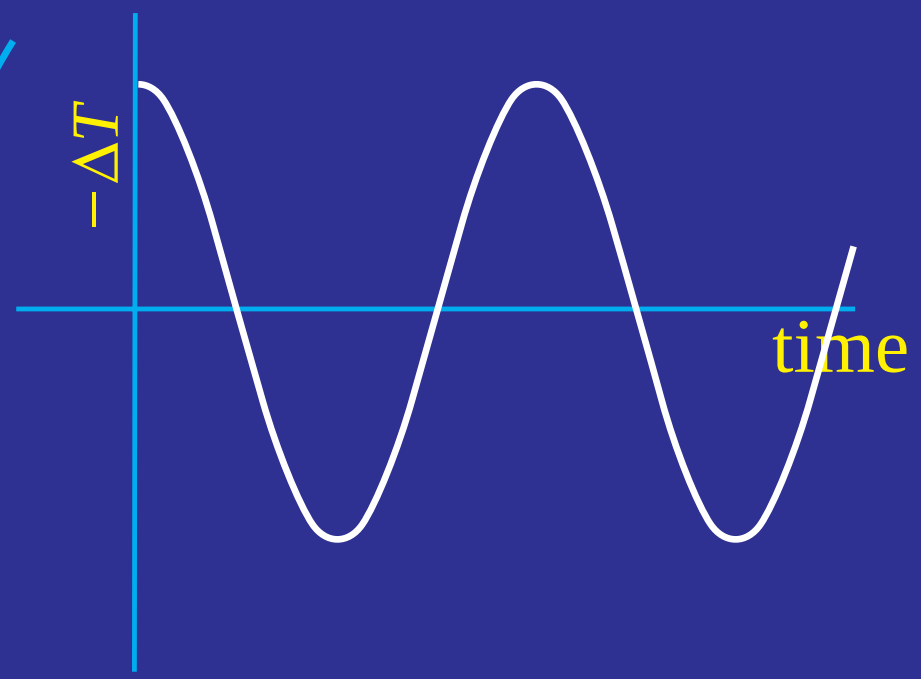


# A Baryon-meter

- Low baryons: symmetric compressions and rarefactions

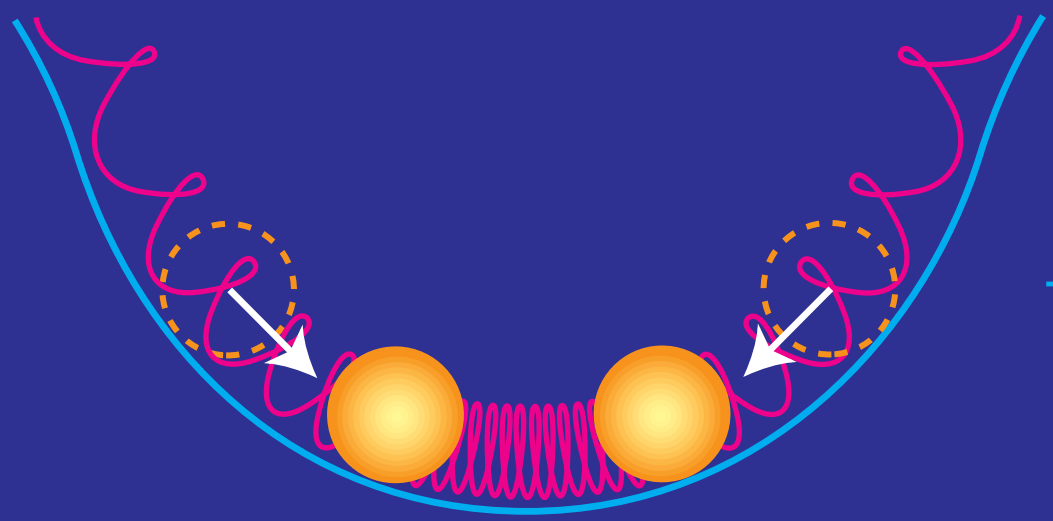


Low Baryons

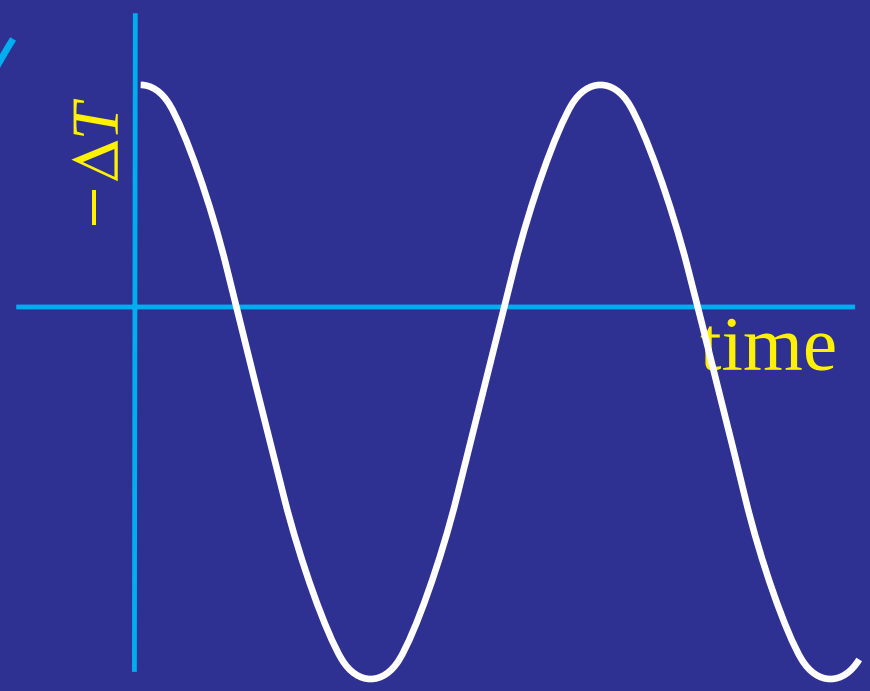


# A Baryon-meter

- Load the fluid adding to gravitational force
- Enhance compressional peaks (odd) over rarefaction peaks (even)



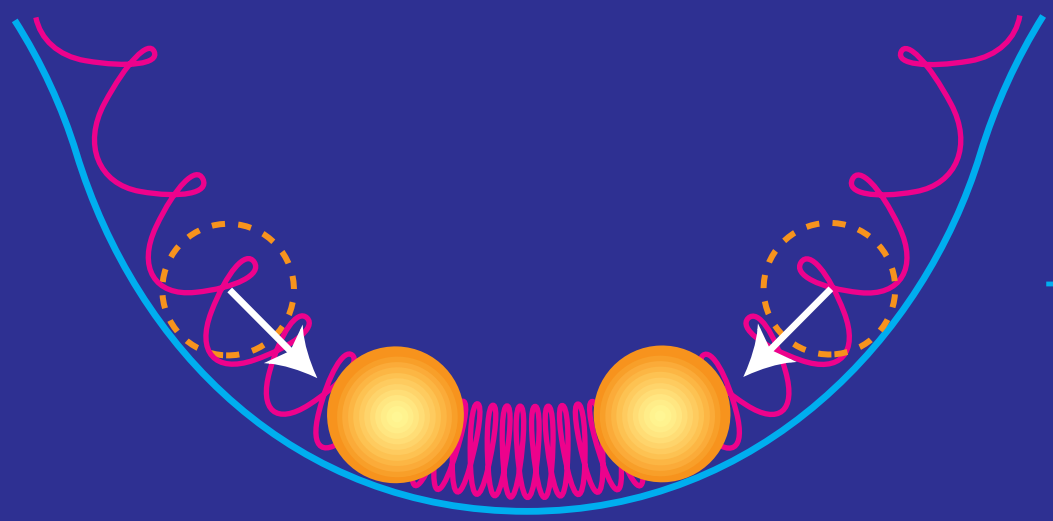
Baryon Loading

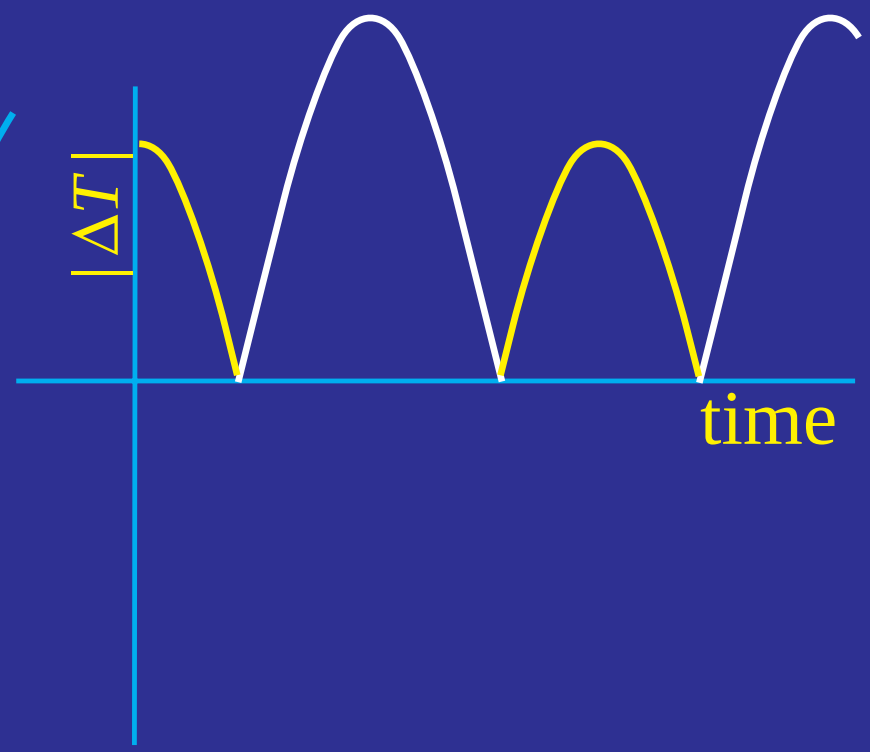


# A Baryon-meter

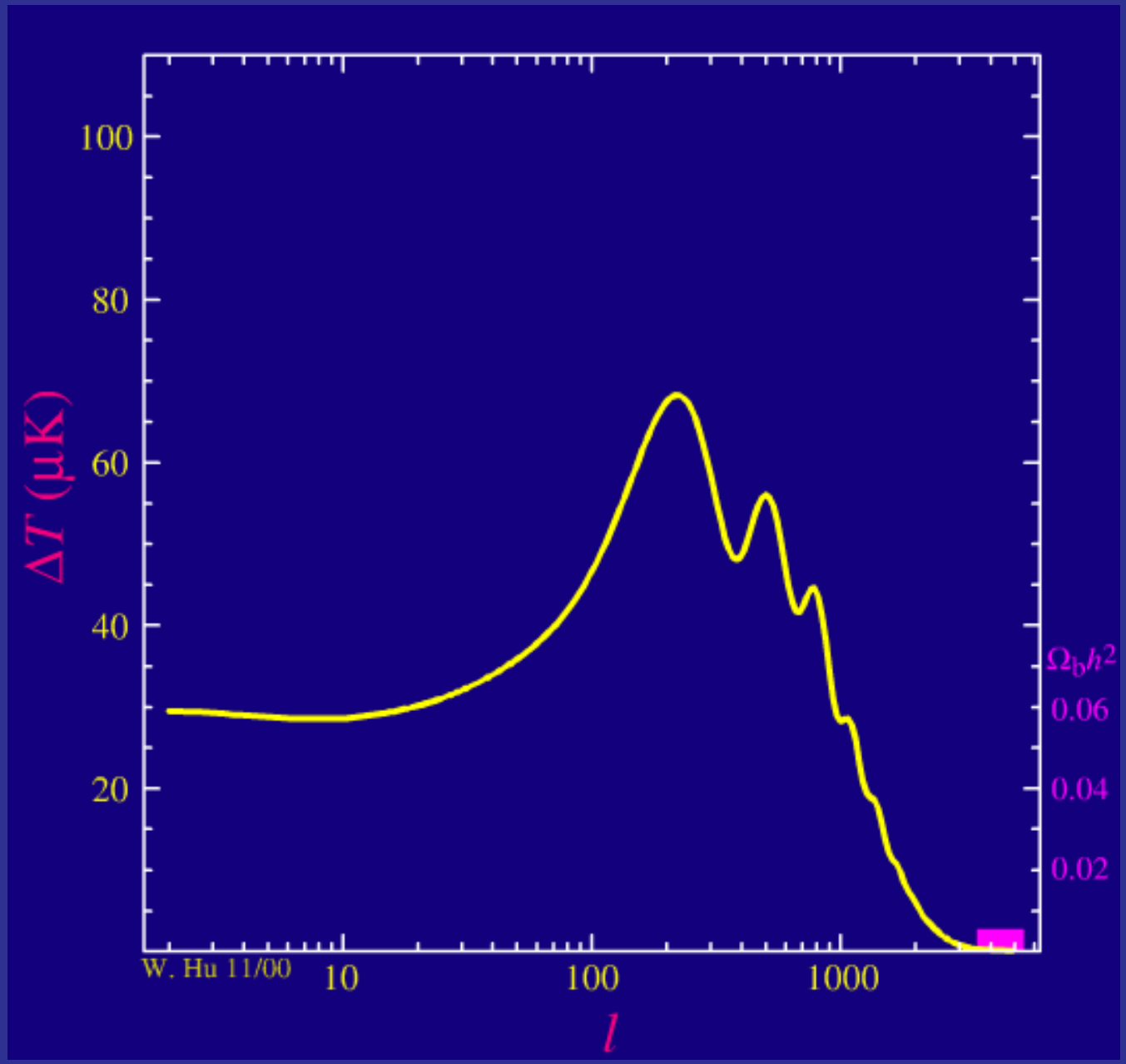
- Enhance compressional peaks (odd) over rarefaction peaks (even)

  e.g. relative suppression of second peak



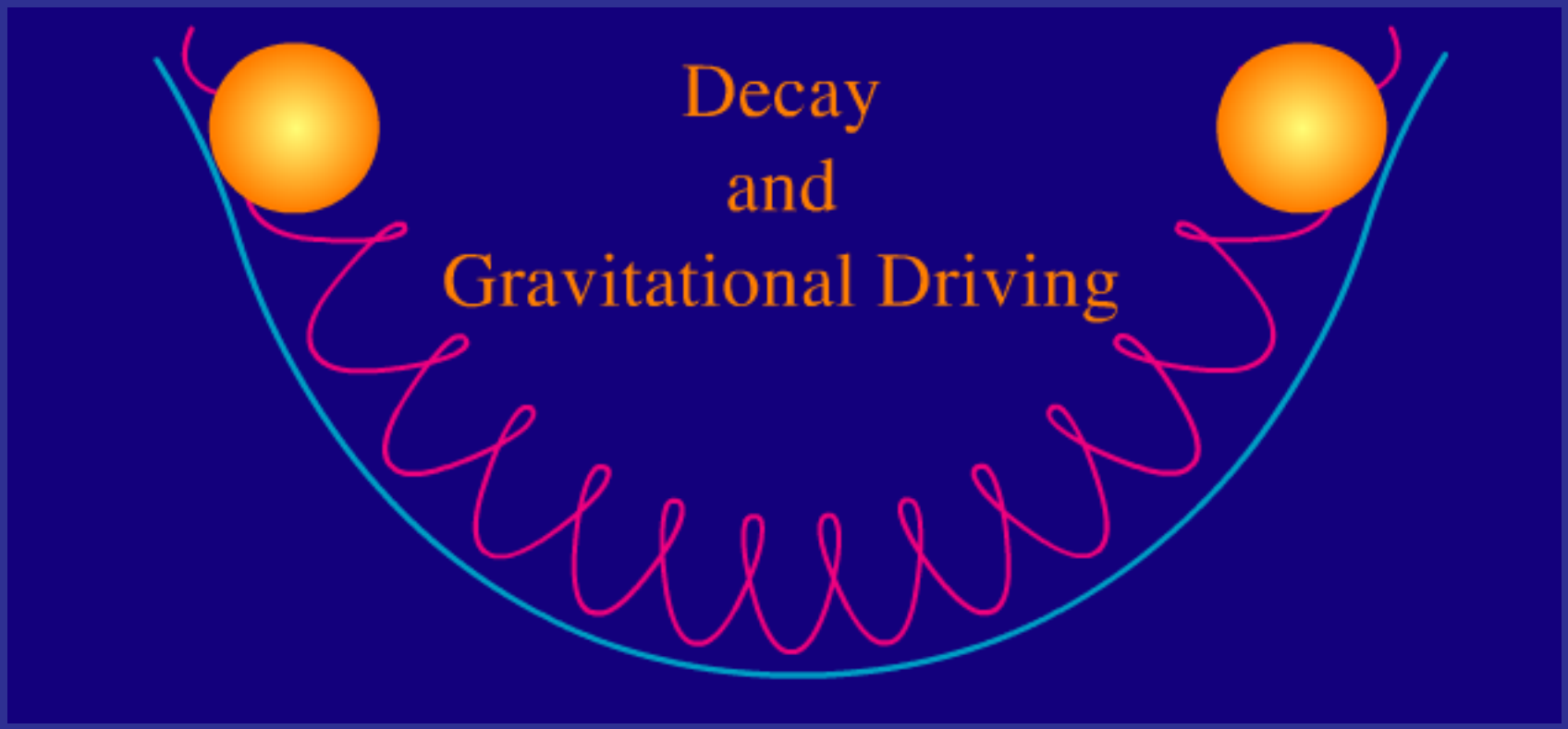


# Baryons in the Power Spectrum



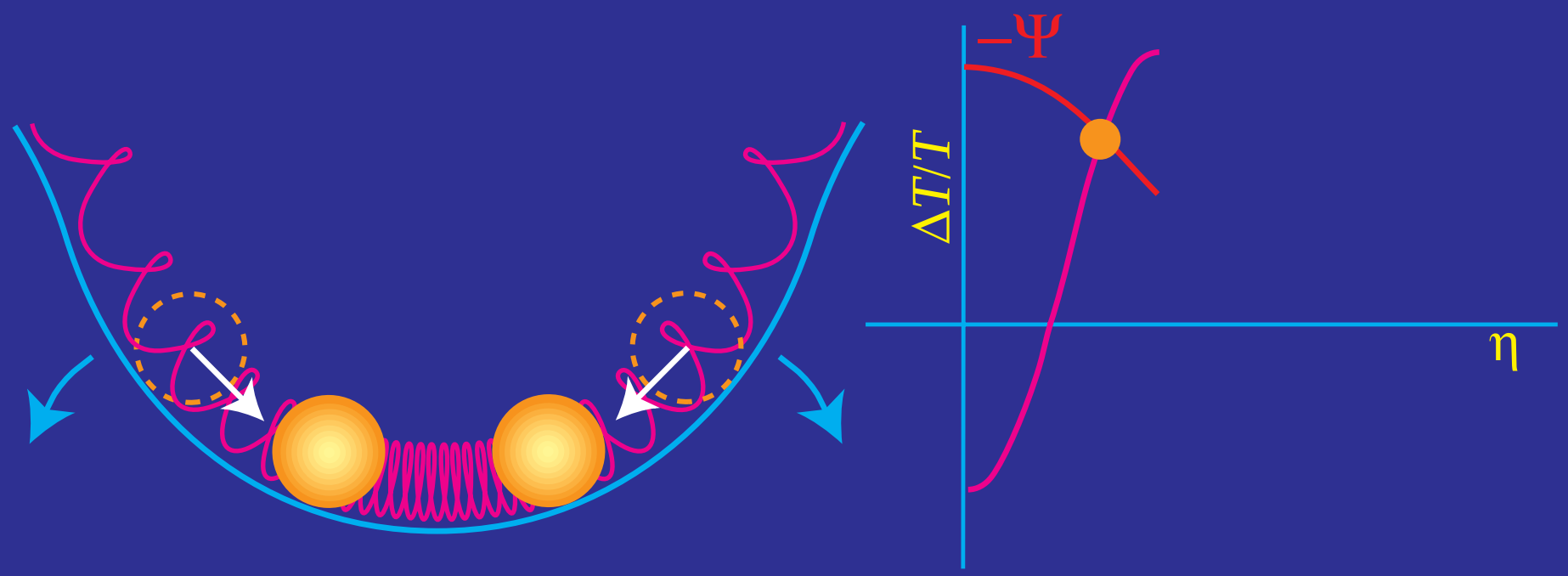
# Radiation and Dark Matter

- Radiation domination:
  potential wells created by CMB itself
- Pressure support ⇒ potential decay ⇒ driving
- Heights measures when dark matter dominates



# 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 $\Psi$ decays with expansion




Hu & Sugiyama (1995)

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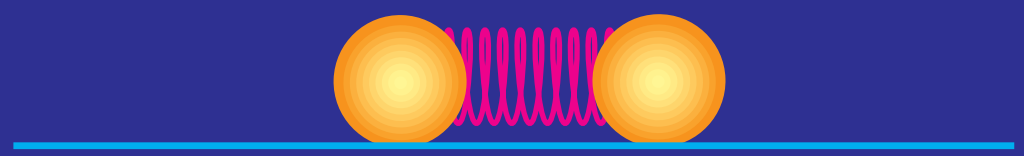
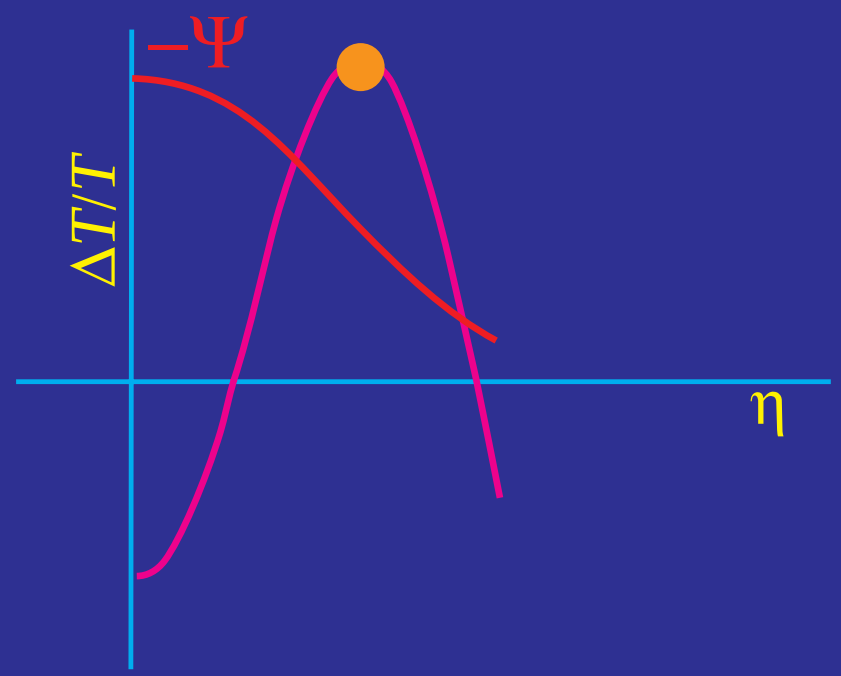
- Feedback stops at matter domination



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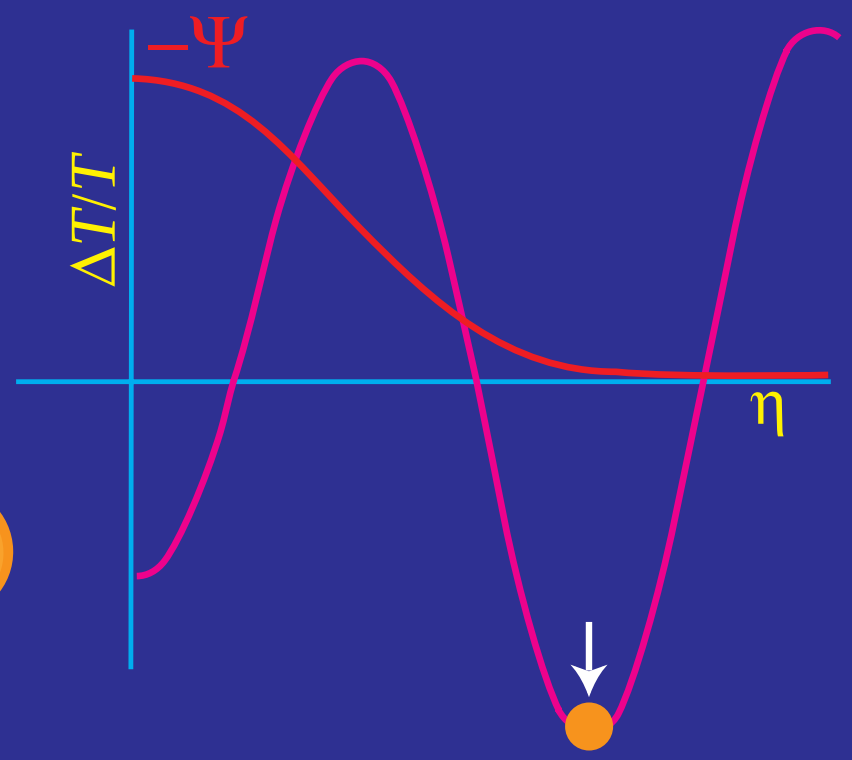


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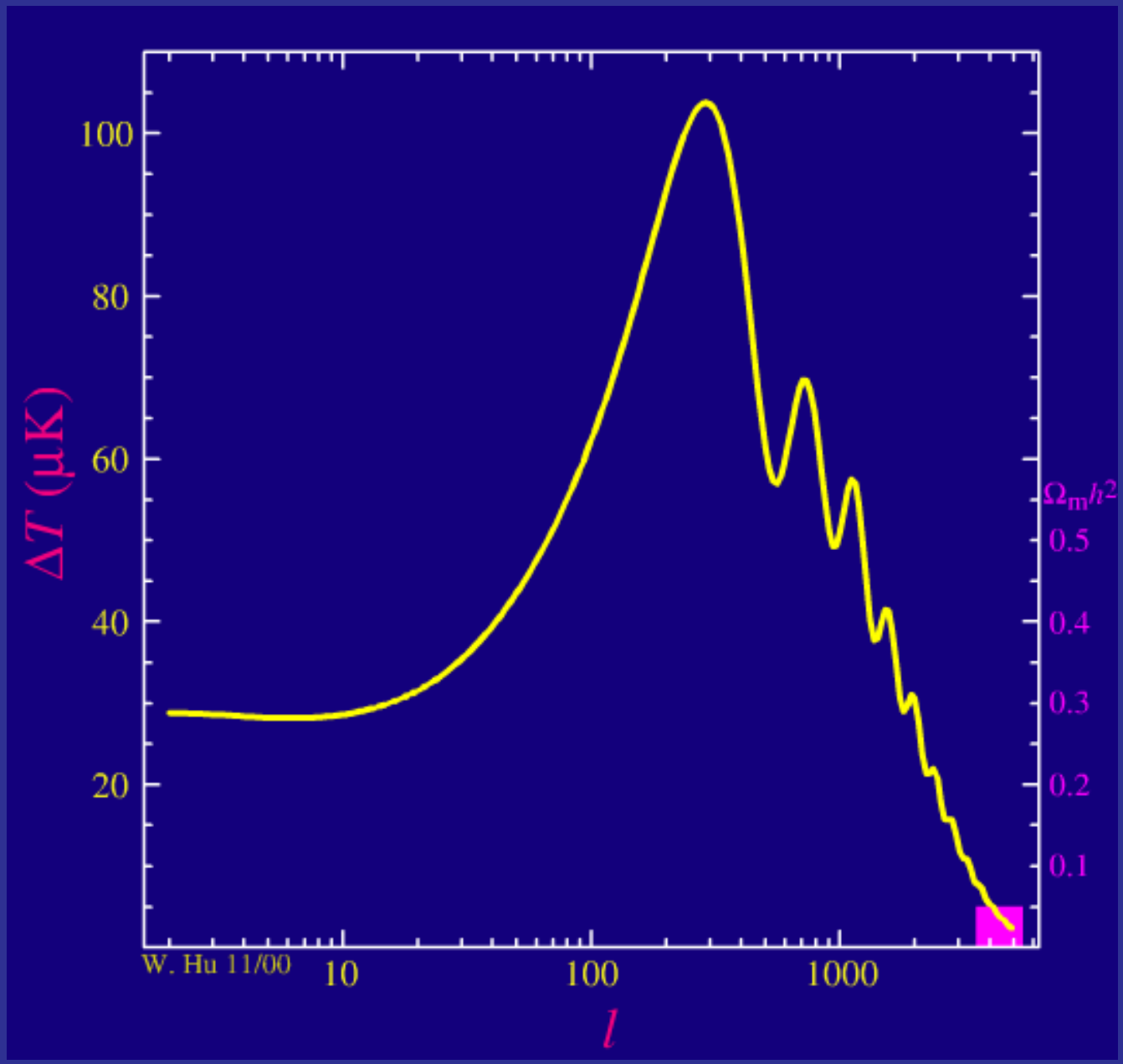
# Dark Matter in the Power Spectrum



# Fixing the Past; Changing the Future

# Fixed Deceleration Epoch

- CMB determination of matter density controls all determinations in the deceleration (matter dominated) epoch
- Current status: $\Omega_m h^2 = 0.14 \pm 0.01 \rightarrow 7\%$
- Distance to recombination $D_*$ determined to $\frac{1}{4}7\% \approx 2\%$
- Expansion rate during any redshift in the deceleration epoch determined to 7%
- Distance to any redshift in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- Volumes determined by a combination $dV = D_A^2 d\Omega dz/H(z)$
- Structure also determined by growth of fluctuations from $z_*$
- $\Omega_m h^2$ can be determined to $\sim 1\%$ in the future.

# Value of Local Measurements

- With high redshifts fixed, the largest deviations from the dark energy appear at low redshift $z \sim 0$
- By the Friedman equation $H^2 \propto \rho$ and difference between $H(z)$ extrapolated from the CMB $H_0 = 37$ and $72$ is entirely due to the dark energy in a flat universe
- With the dark energy density fixed by $H_0$, the deviation from the CMB observed $D_*$ from the $\Lambda$CDM prediction measures the equation of state (or evolution of the dark energy density)

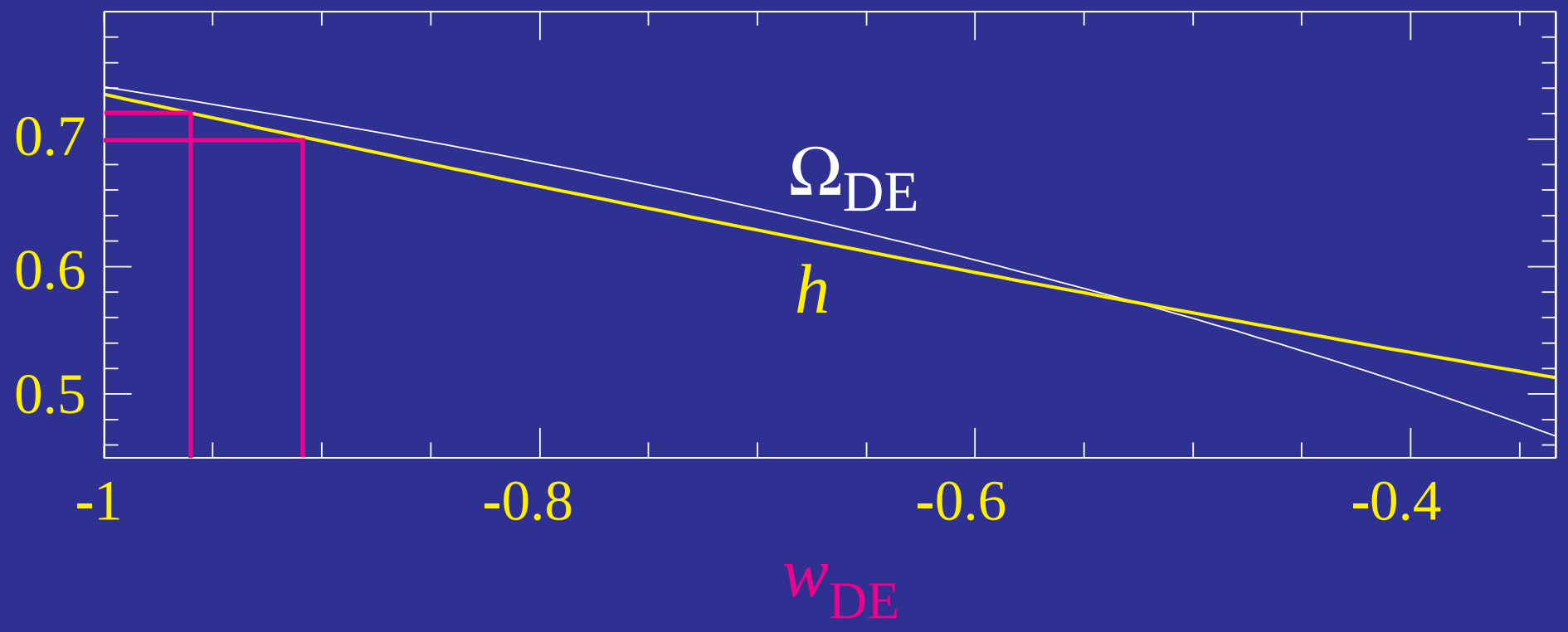
$$p_{\rm DE} = w \rho_{\rm DE}$$

- Intermediate redshift dark energy probes can then test flatness assumption and the evolution of the equation of state: e.g.

$$w(a) = w_0 + (1-a) w_a$$

# $H_0$ = Dark Energy

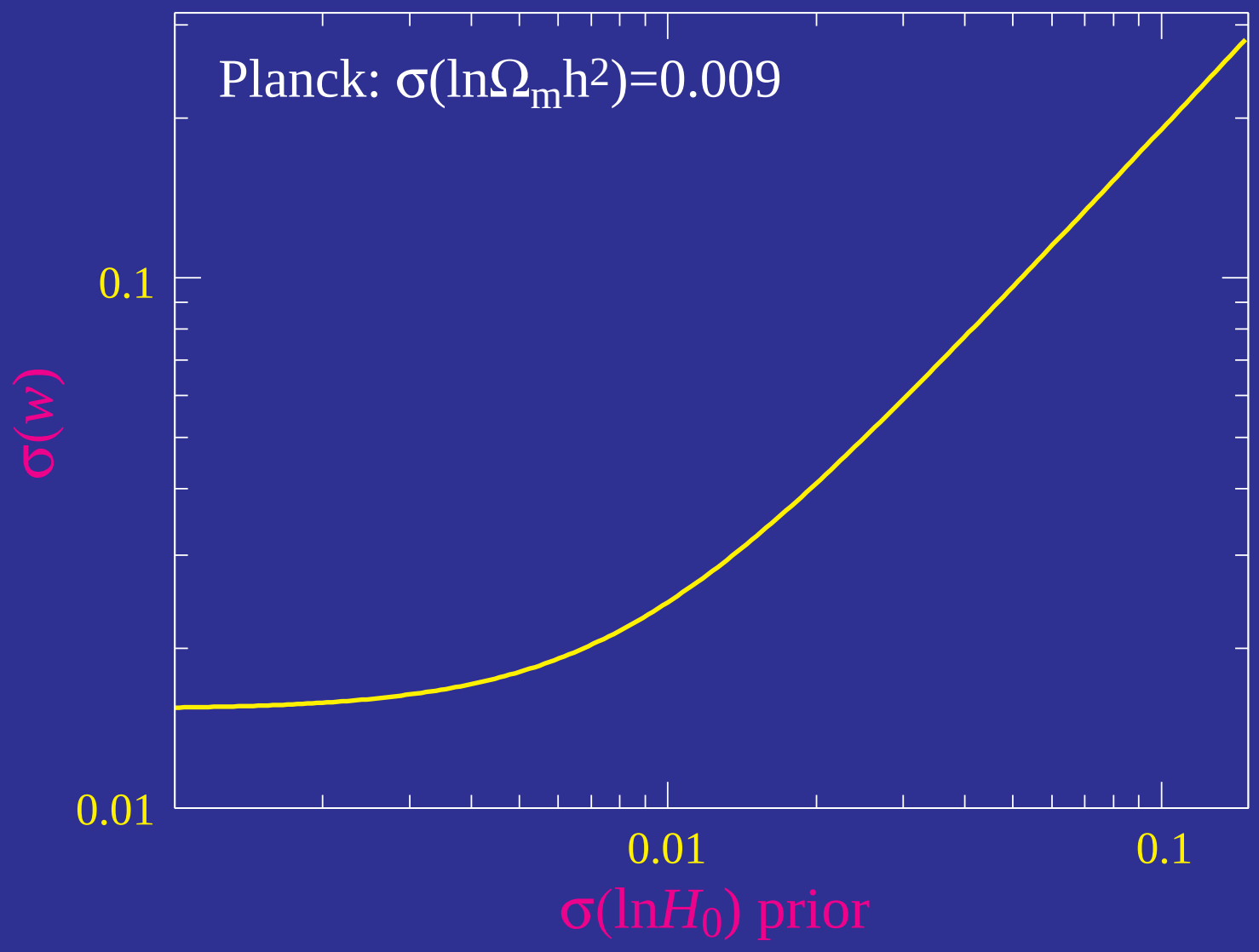
- Flat constant *w* dark energy model
- Determination of Hubble constant gives *w* to comparable precision




- For evolving *w*, equal precision on average or pivot *w*, equally useful for testing a cosmological constant

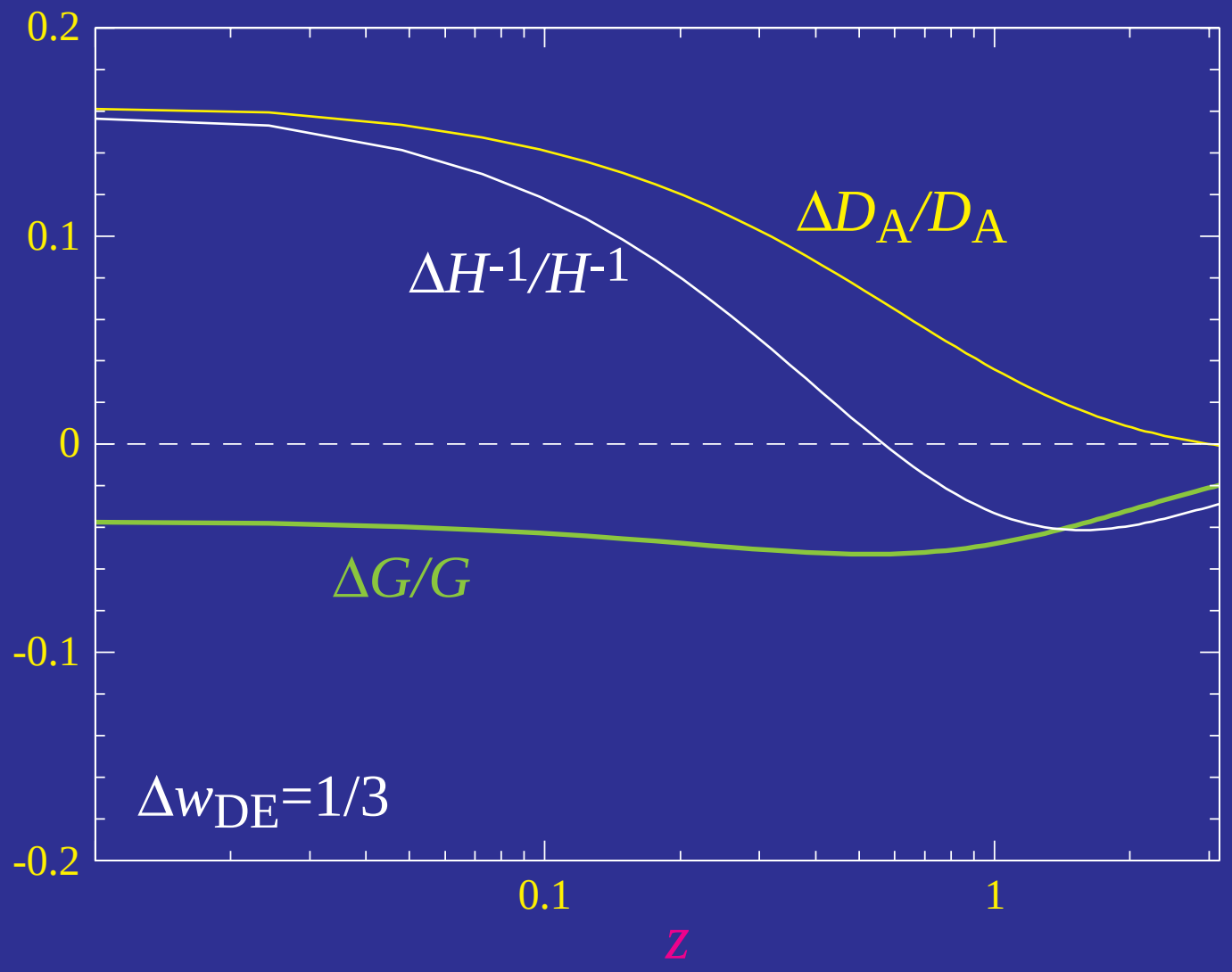
# Forecasts for CMB+$H_0$

- To complement CMB observations with $\Omega_m h^2$ to 1%, an $H_0$ of ~1% enables constant $w$ measurement to ~2% in a flat universe



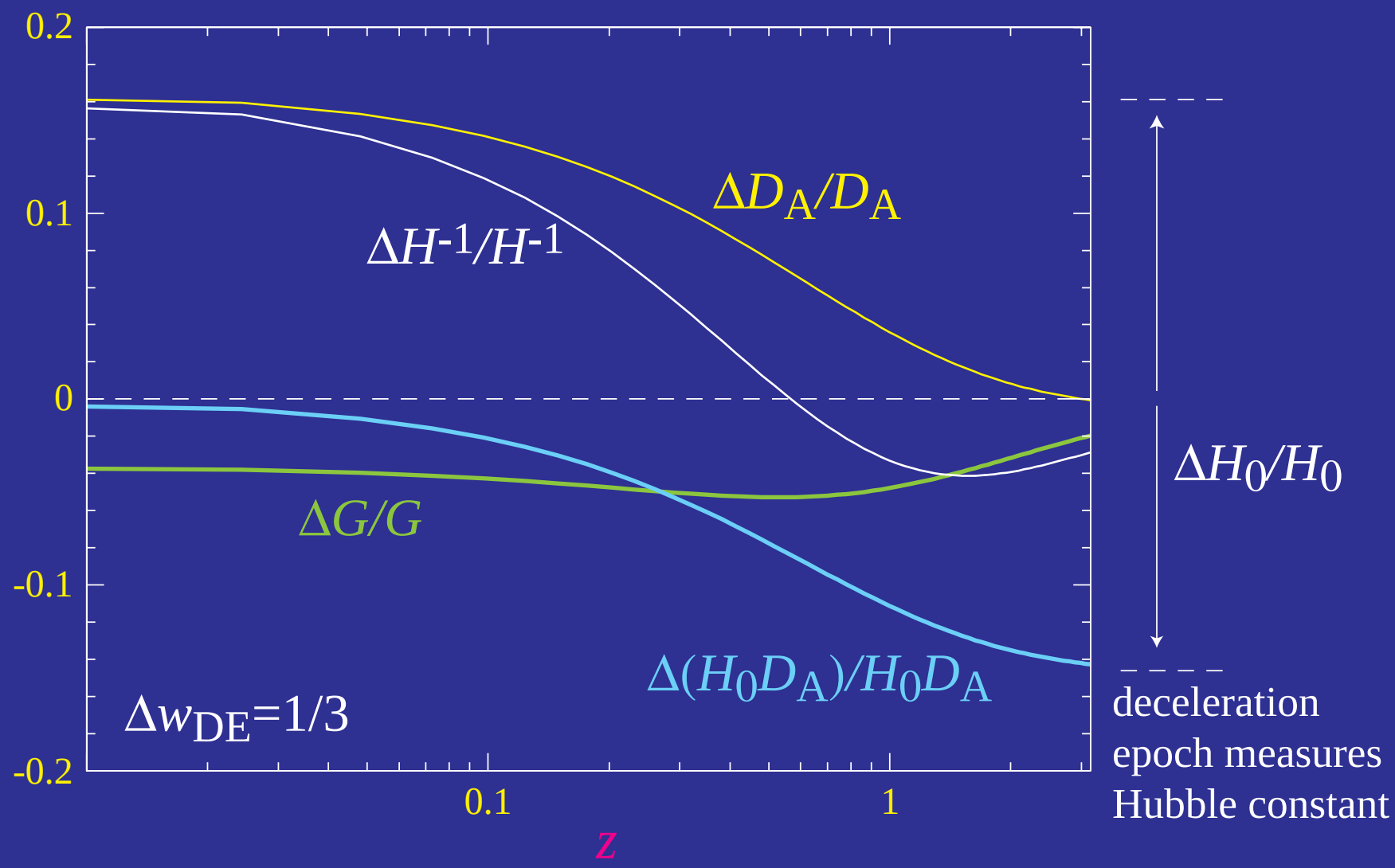
# Sensitivity in Redshift

- Fixed distance to recombination $D_A(z{\sim}1100)$
- Fixed initial fluctuation $G(z{\sim}1100)$
- Constant $w=w_{DE}$; ($\Omega_{DE}$ adjusted - one parameter family of curves)



# Sensitivity in Redshift

- SNIa high-z distance useful because it fixes the Hubble constant!



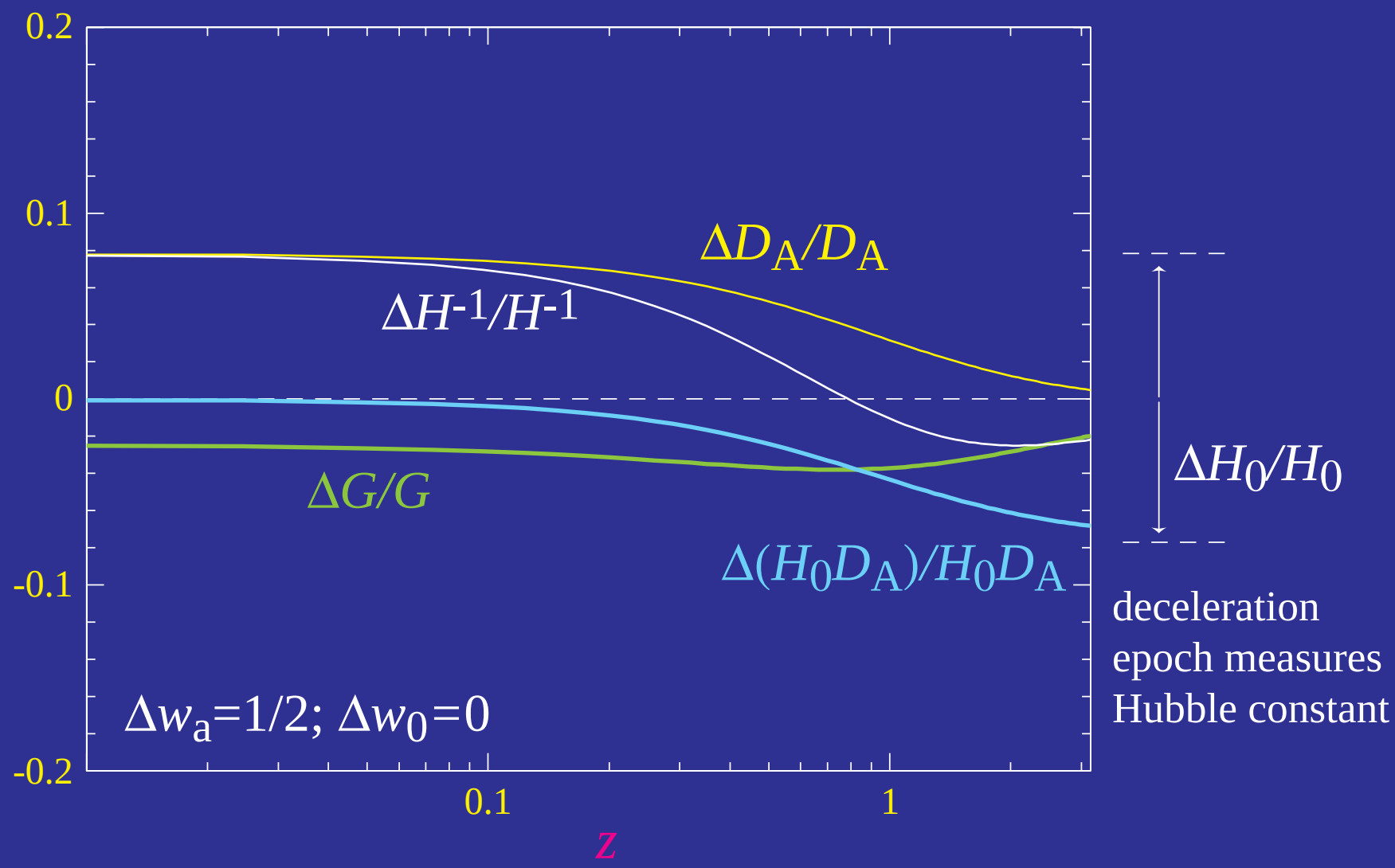
# Evolution of the Dark Energy

# Beyond Testing $\Lambda$

- In the context of testing a cosmological constant, constraining a constant $w$ in a flat universe is the most important first test.
- CMB measurements are best complemented by $H_0$.
- A deviation between the CMB predicted $H_0$ and its measured value in the form of a constant $w \neq 1$ is evidence against a flat $\Lambda$CDM model.
- However it does not necessarily indicate a constant $w \neq 1$ flat model is correct! $w$ is measured as its average or pivot value, a small spatial curvature can change the expansion rate.
- A positive detection of deviations from $\Lambda$CDM will require more than $H_0$ to determine its physical origin.
- Investigate the role of $H_0$ planning for success...

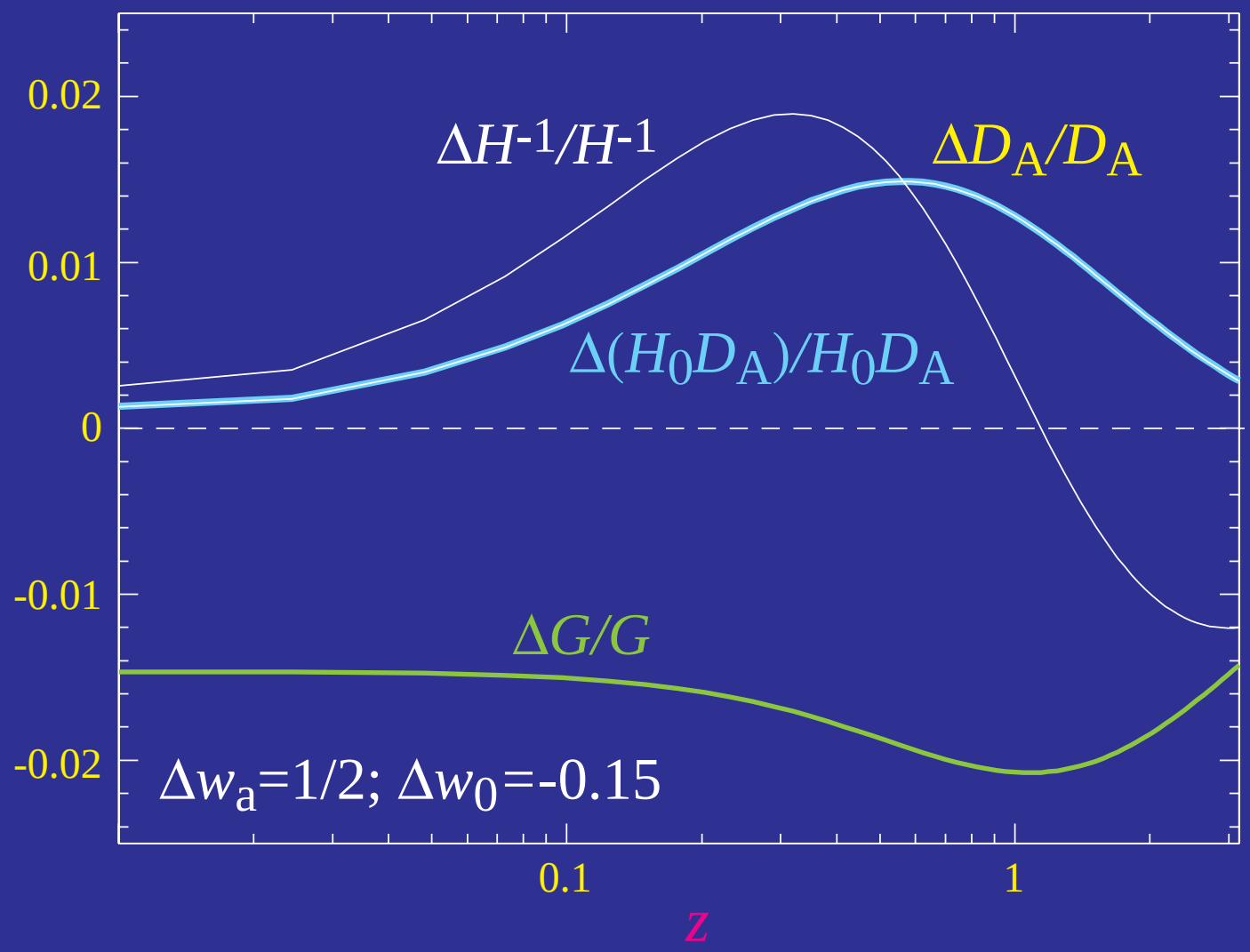
# Sensitivity in Redshift

- Three parameter dark energy model: $w(z=0)=w_0$; $w_a=-dw/da$; $\Omega_{DE}$
- $w_a$ sensitivity; (fixed $w_0 = -1$; $\Omega_{DE}$ adjusted)



# Dark Energy Sensitivity

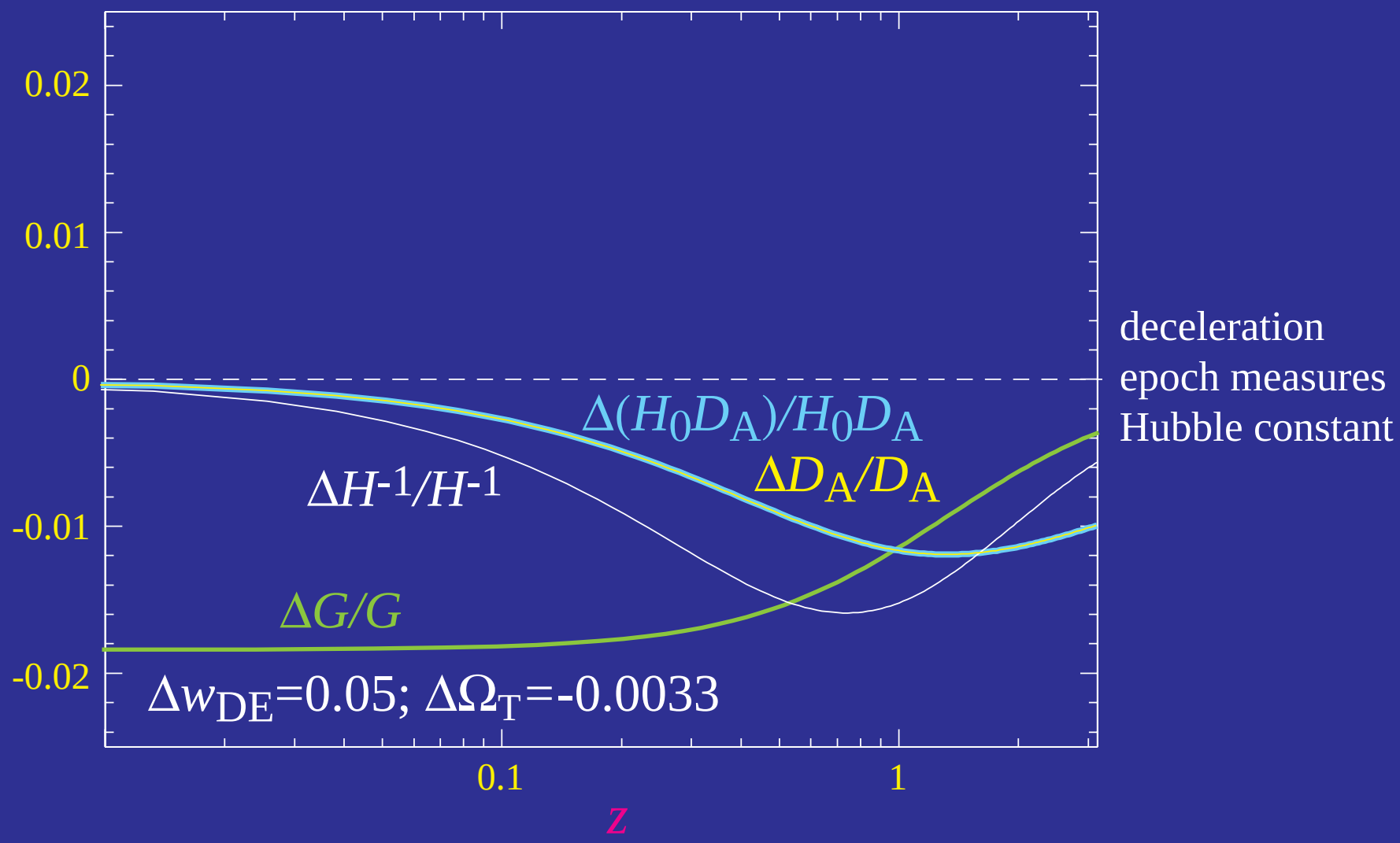
- Three parameter dark energy model: $w(z=0)=w_0$; $w_a=-dw/da$; $\Omega_{DE}$
- $H_0$ fixed (or $\Omega_{DE}$); remaining $w_0$-$w_a$ degeneracy
- Note: degeneracy does not preclude ruling out $\Lambda$ ($w(z)\neq-1$ at some $z$)




deceleration epoch measures Hubble constant

# Dark Energy Sensitivity

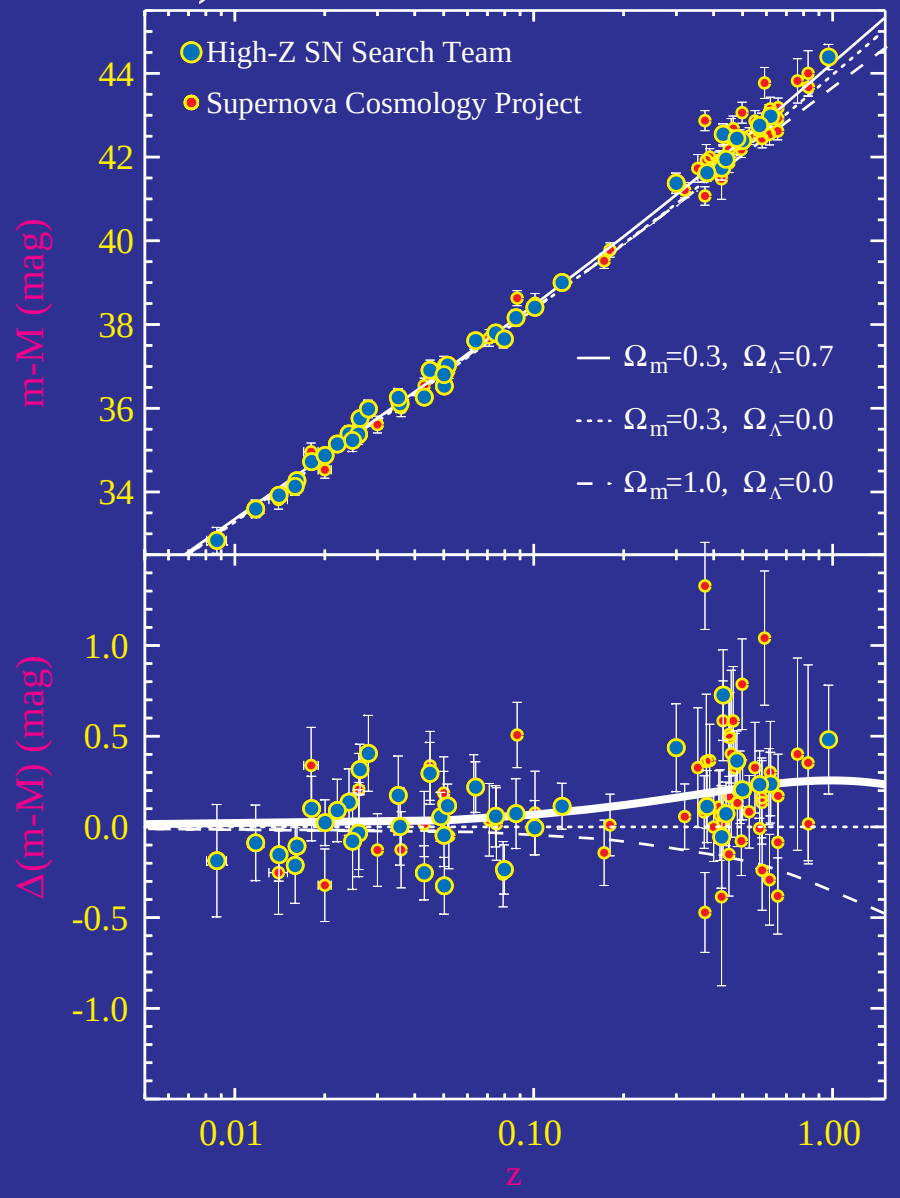
- $H_0$ fixed (or $\Omega_{DE}$); remaining $w_{DE}$-$\Omega_T$ spatial curvature degeneracy
- Growth rate breaks the degeneracy anywhere in the acceleration regime including local measurements!



# Supernovae

# Discovery of Acceleration

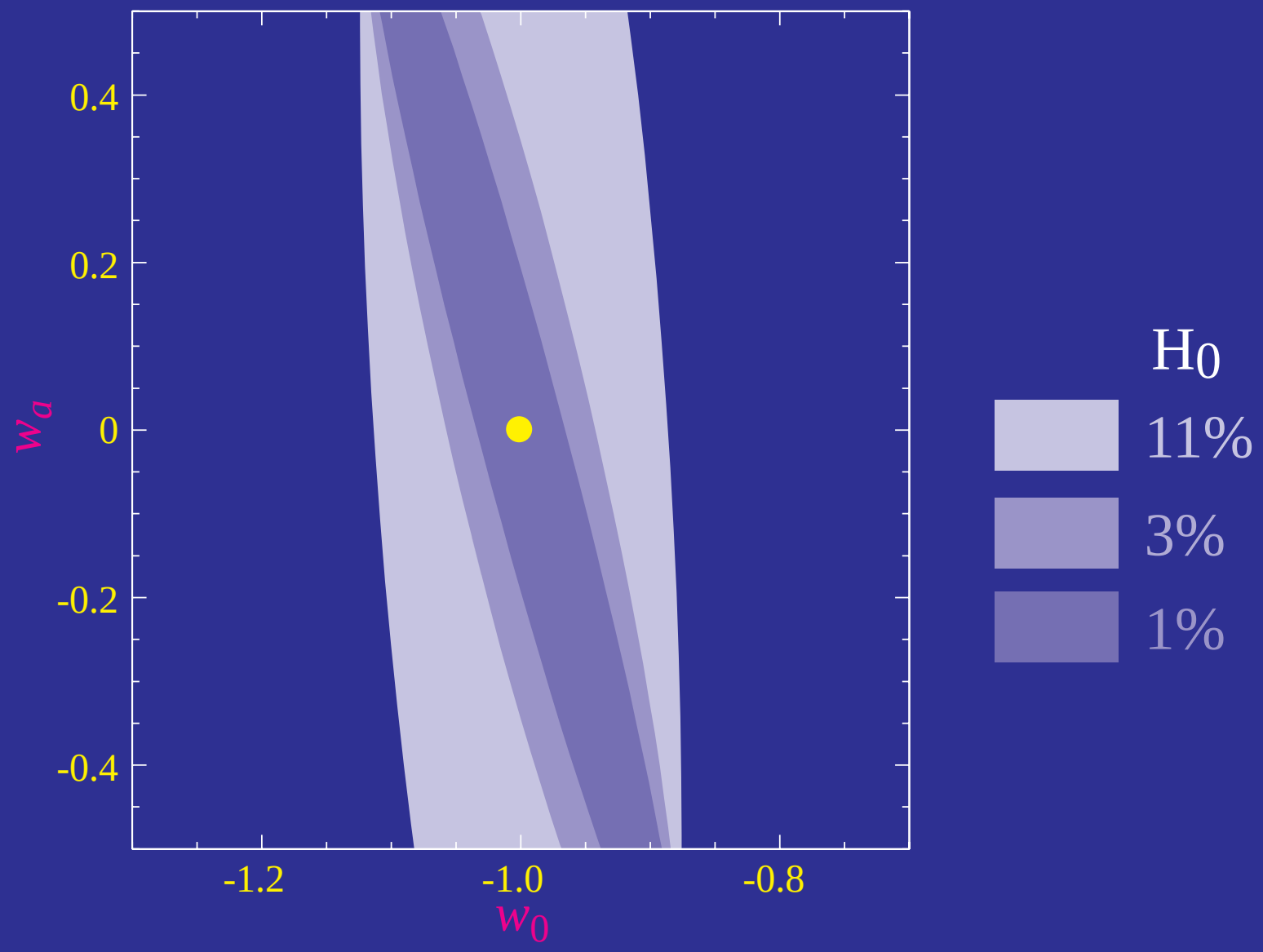
- Distance-redshift to supernovae Ia indicates cosmological dimming (acceleration)




compilation from High-z team

# Forecasts for CMB+$H_0$+SNIa

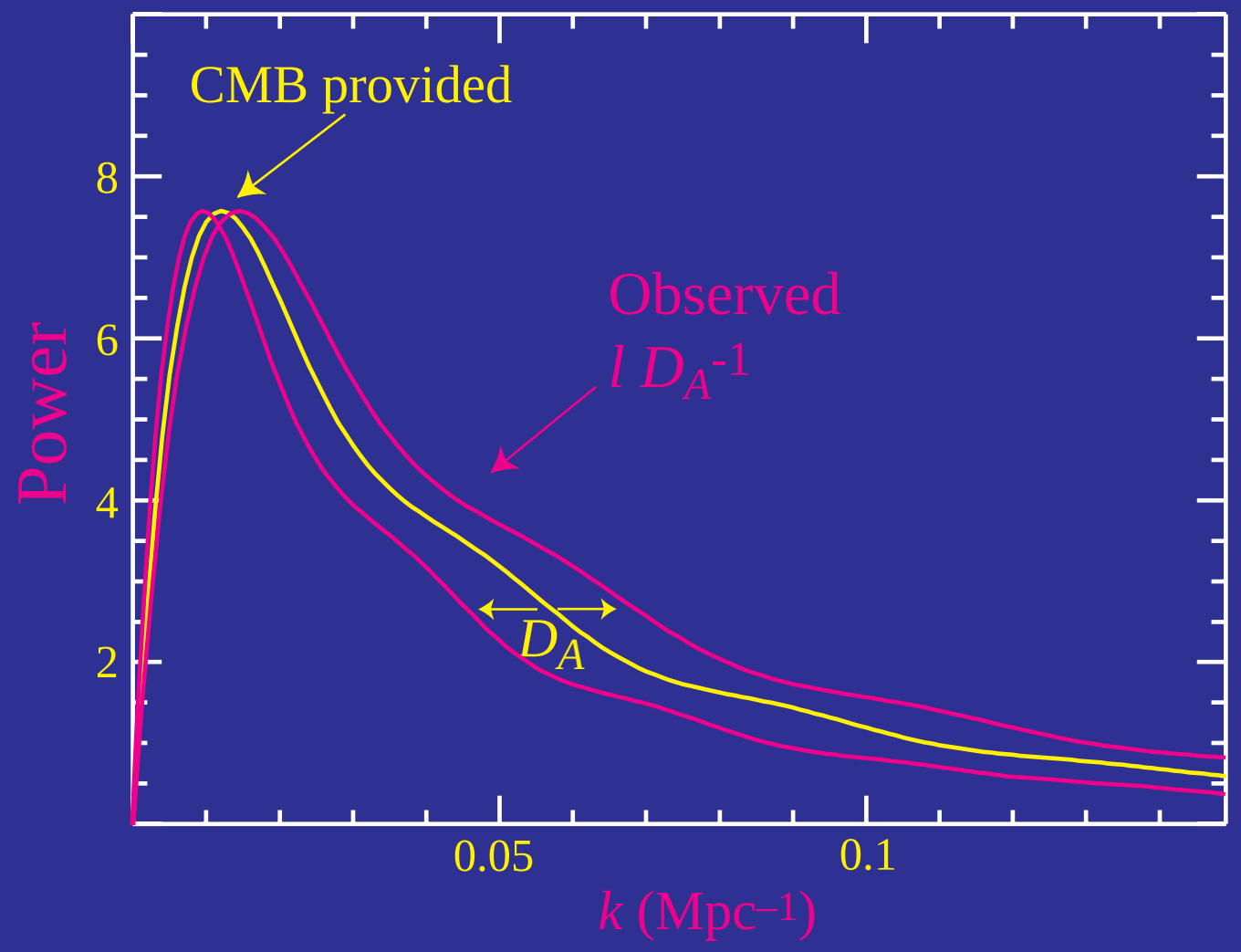
- Supernova Ia (2000 out to z=1) with curvature marginalized statistical errors only



# Baryon Acoustic Oscillations

# Cosmological Distances

- Modes perpendicular to line of sight measure angular diameter distance

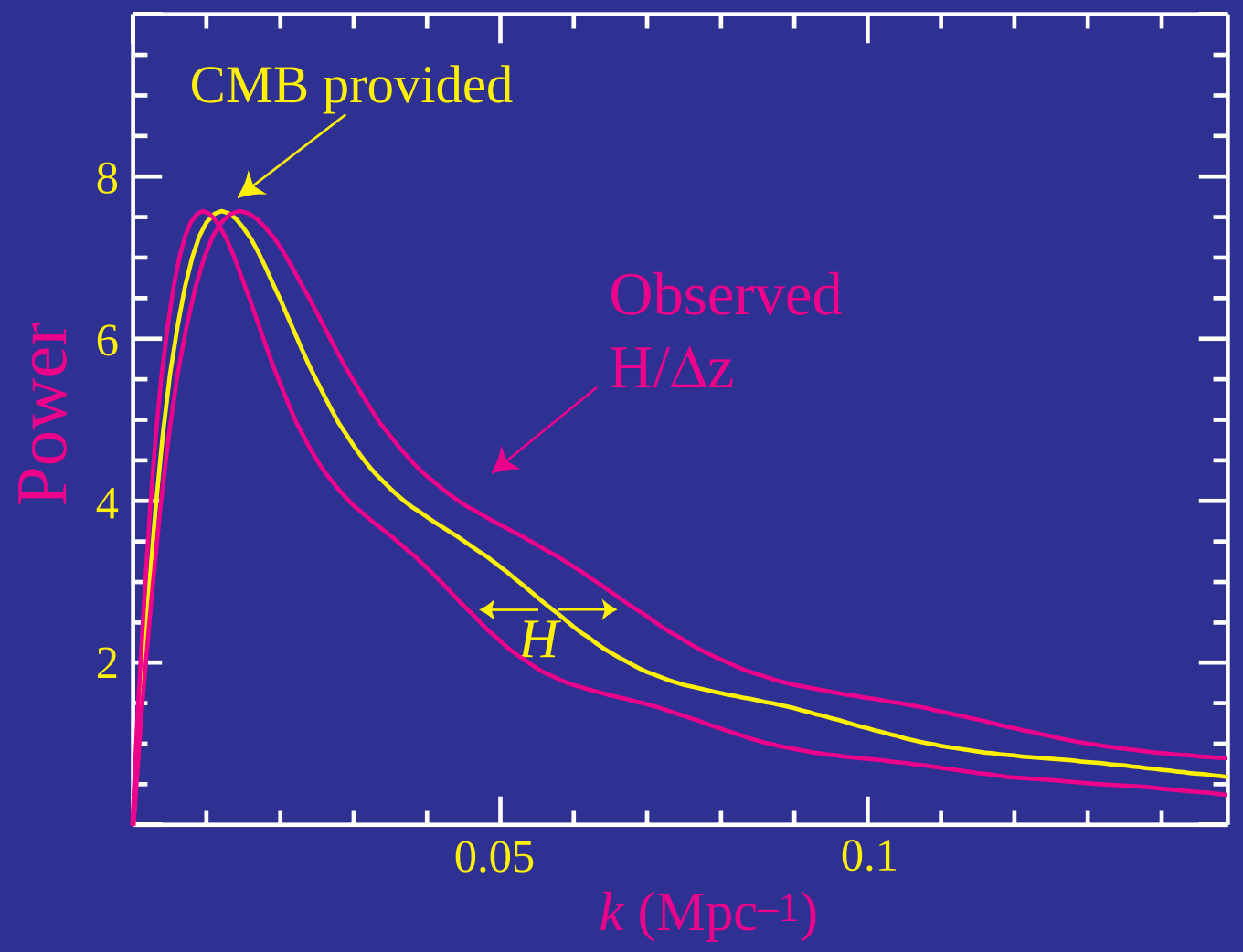



Local: Eisenstein, Hu, Tegmark (1998)

Cosmological: Cooray, Hu, Huterer, Joffre (2001)

# Cosmological Distances

- Modes parallel to line of sight measure the Hubble parameter

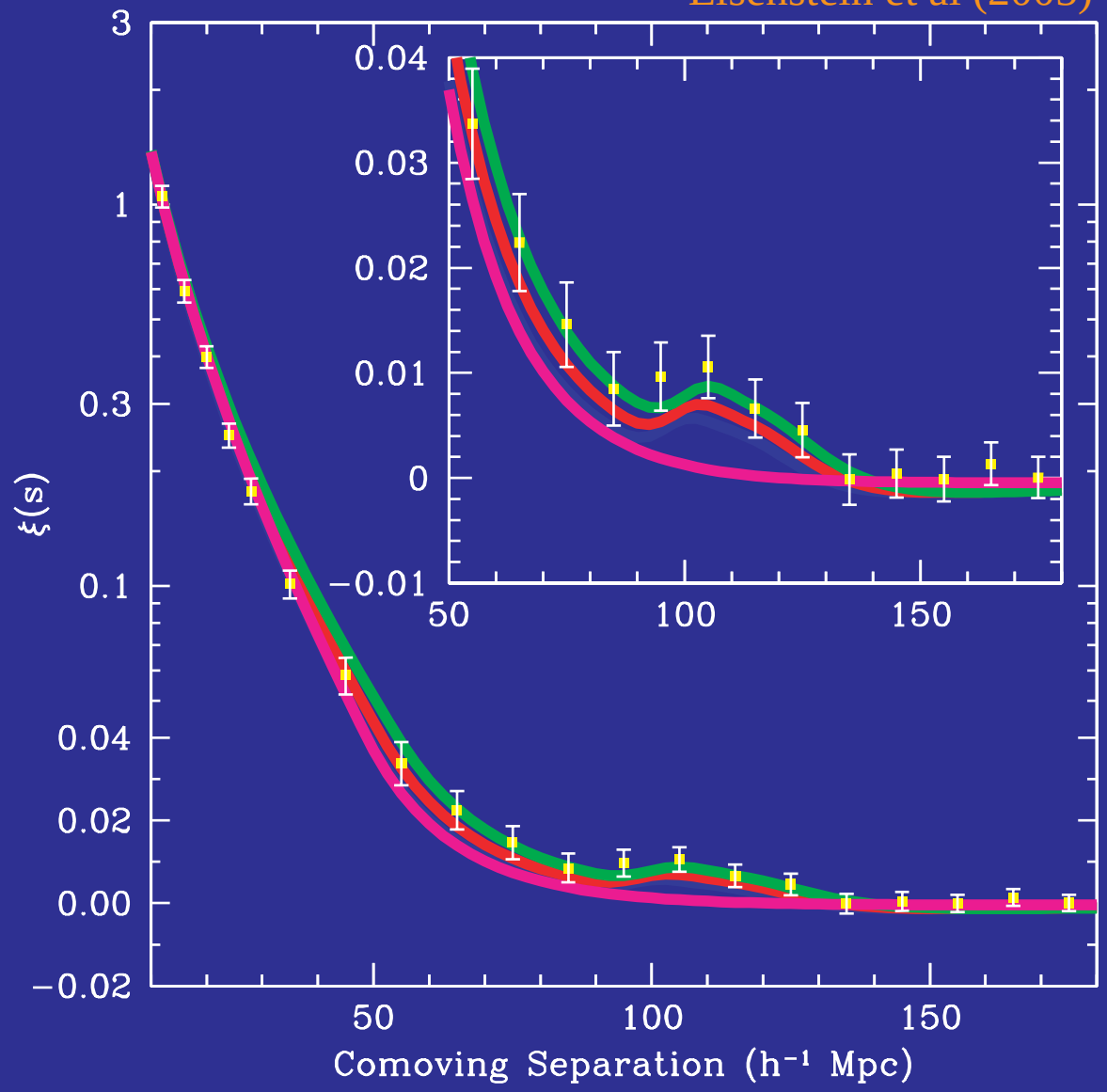



Eisenstein (2003); Blake & Glazebrook (2003); Hu & Haiman (2003); Seo & Eisenstein (2003)

# BAO Detection in SDSS

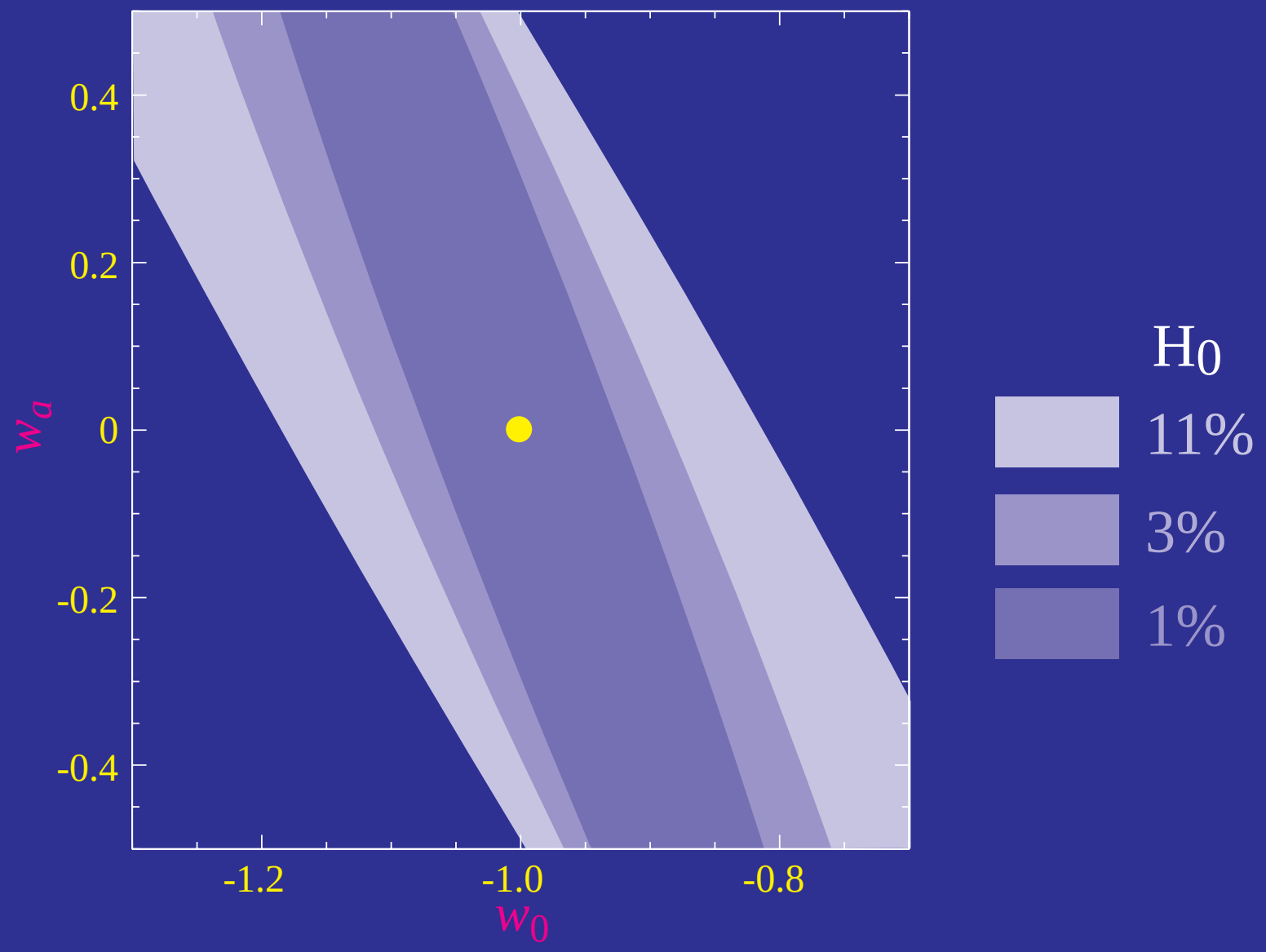
- Baryon oscillations detected in 2-pt correlation function

Eisenstein et al (2005)



# Forecasts for CMB+$H_0$+BAO

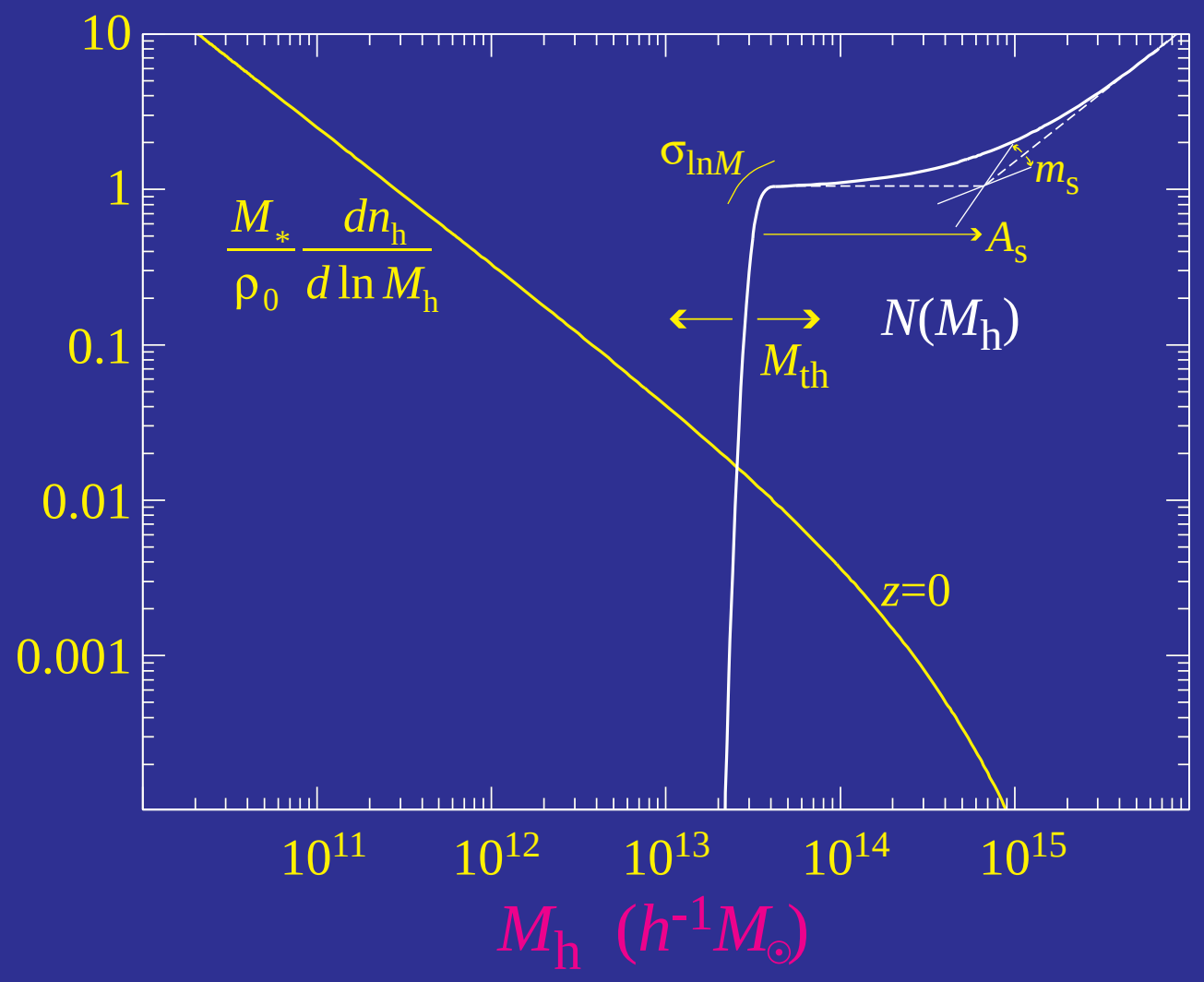
- Baryon oscillations (2000deg$^2$ out to $z$=1.3 with spectroscopy) with curvature marginalized statistical errors only



# Cluster Abundance

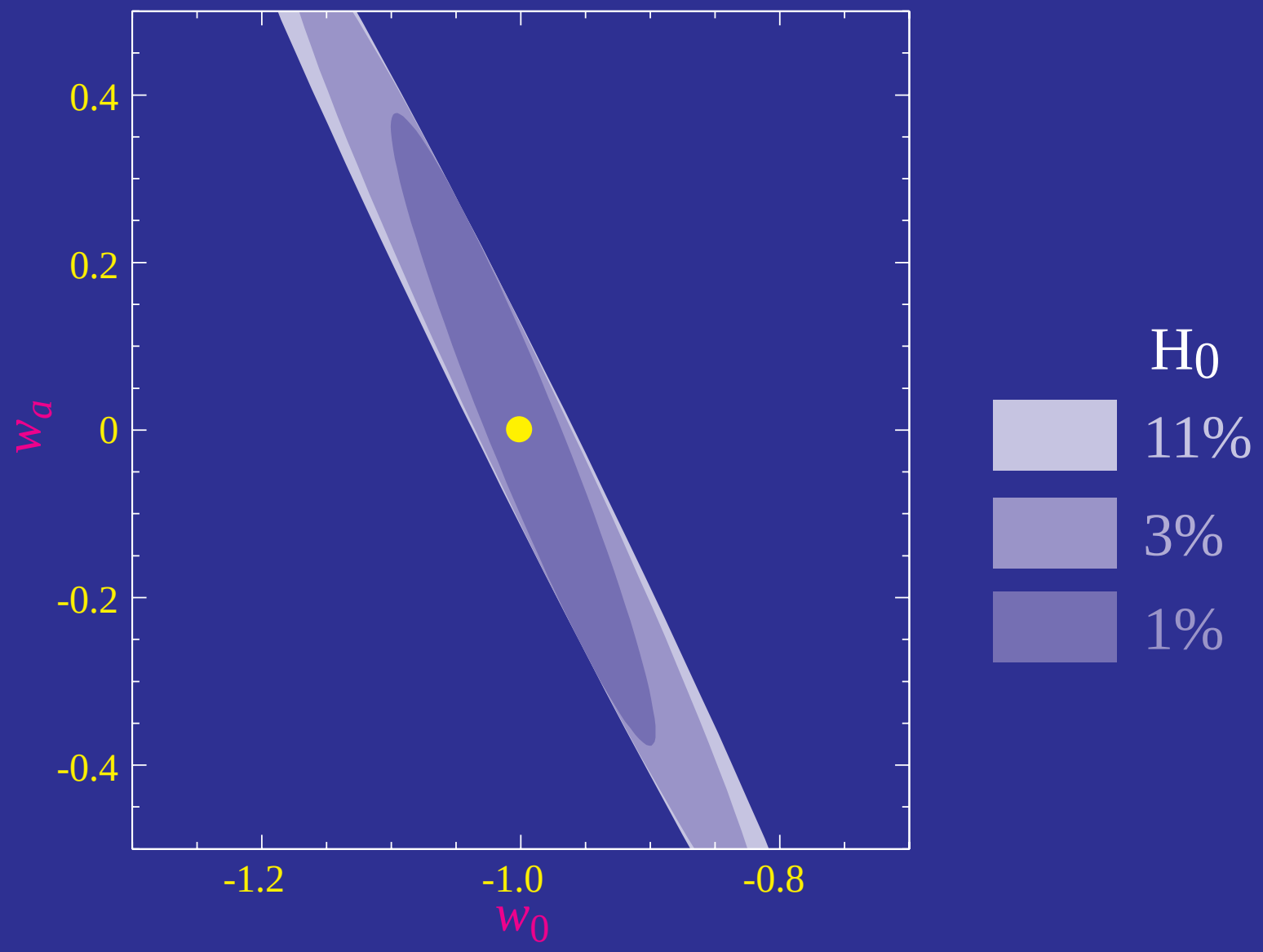
# Cluster Abundance

- Abundance of rare massive dark matter halos exponentially sensitive to the growth of structure
- Dark energy constraints if clusters can be mapped onto halos



# Forecasts for CMB+$H_0$+Clusters

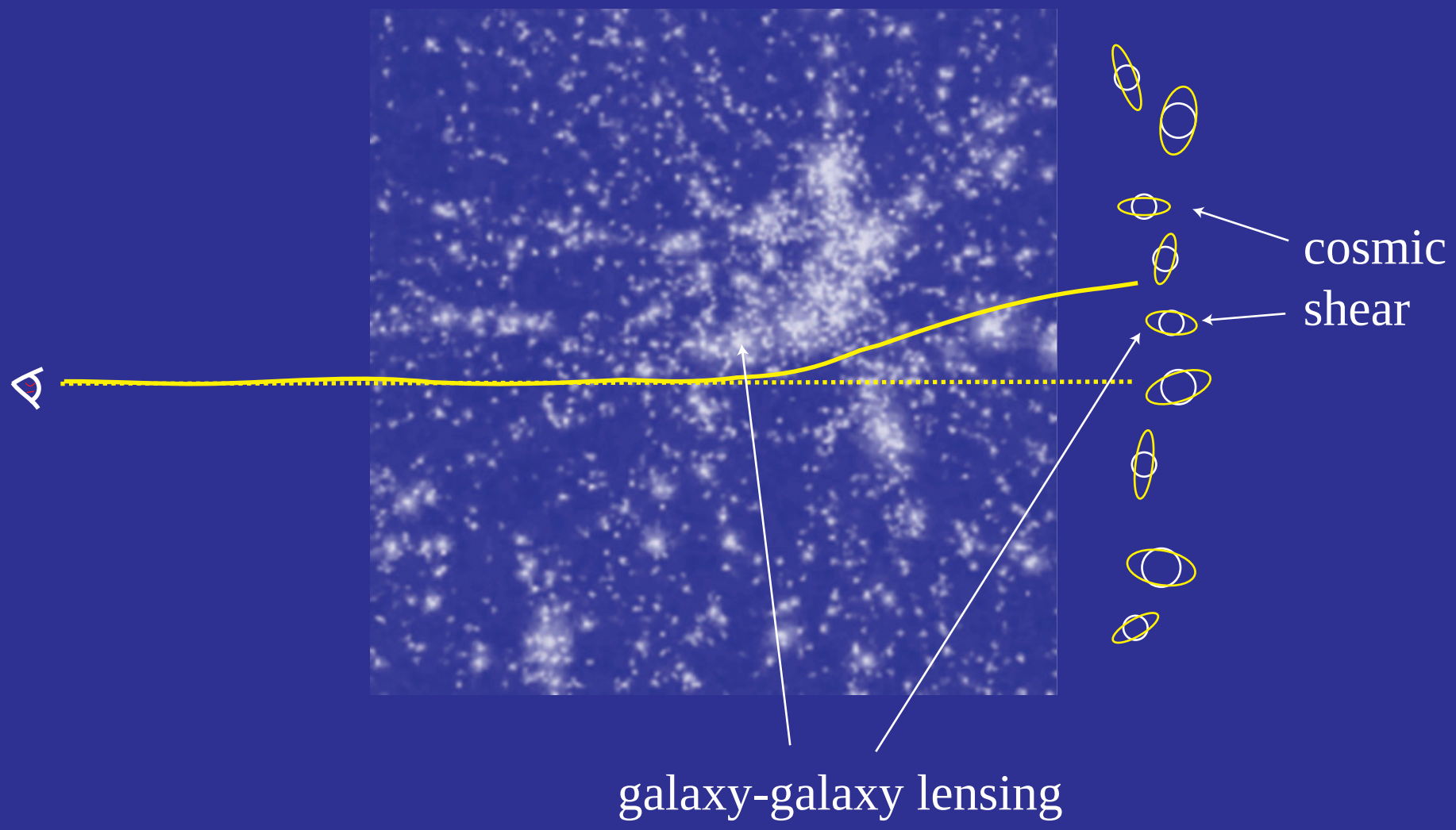
- Galaxy clusters (4000deg$^2$ out to $z$=2 with photometric redshifts) with curvature marginalized statistical errors only



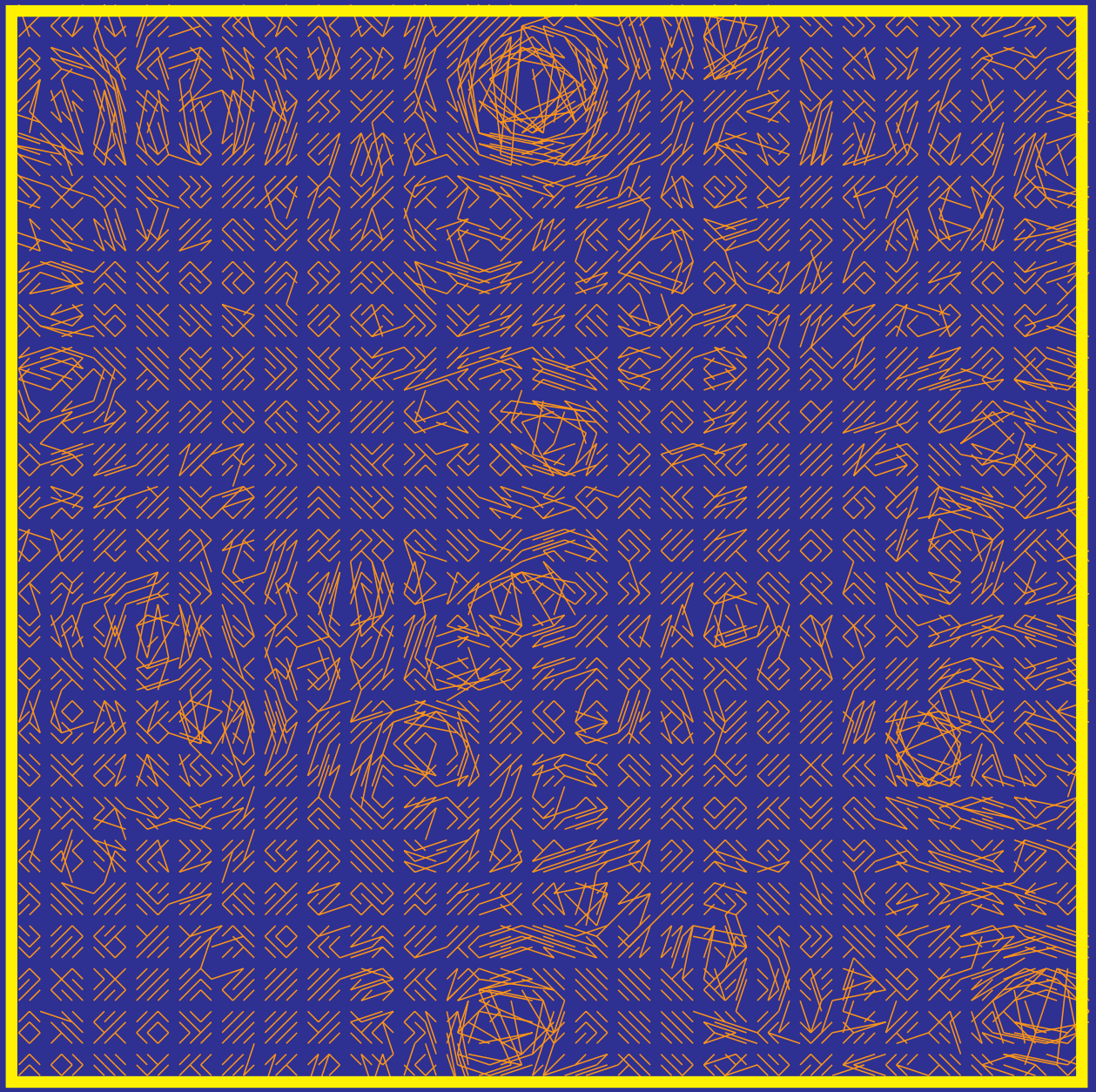
# Weak Gravitational Lensing

# Lensing Observables

- Correlation of shear distortion of background images: cosmic shear
- Cross correlation between foreground lens tracers and shear: galaxy-galaxy lensing

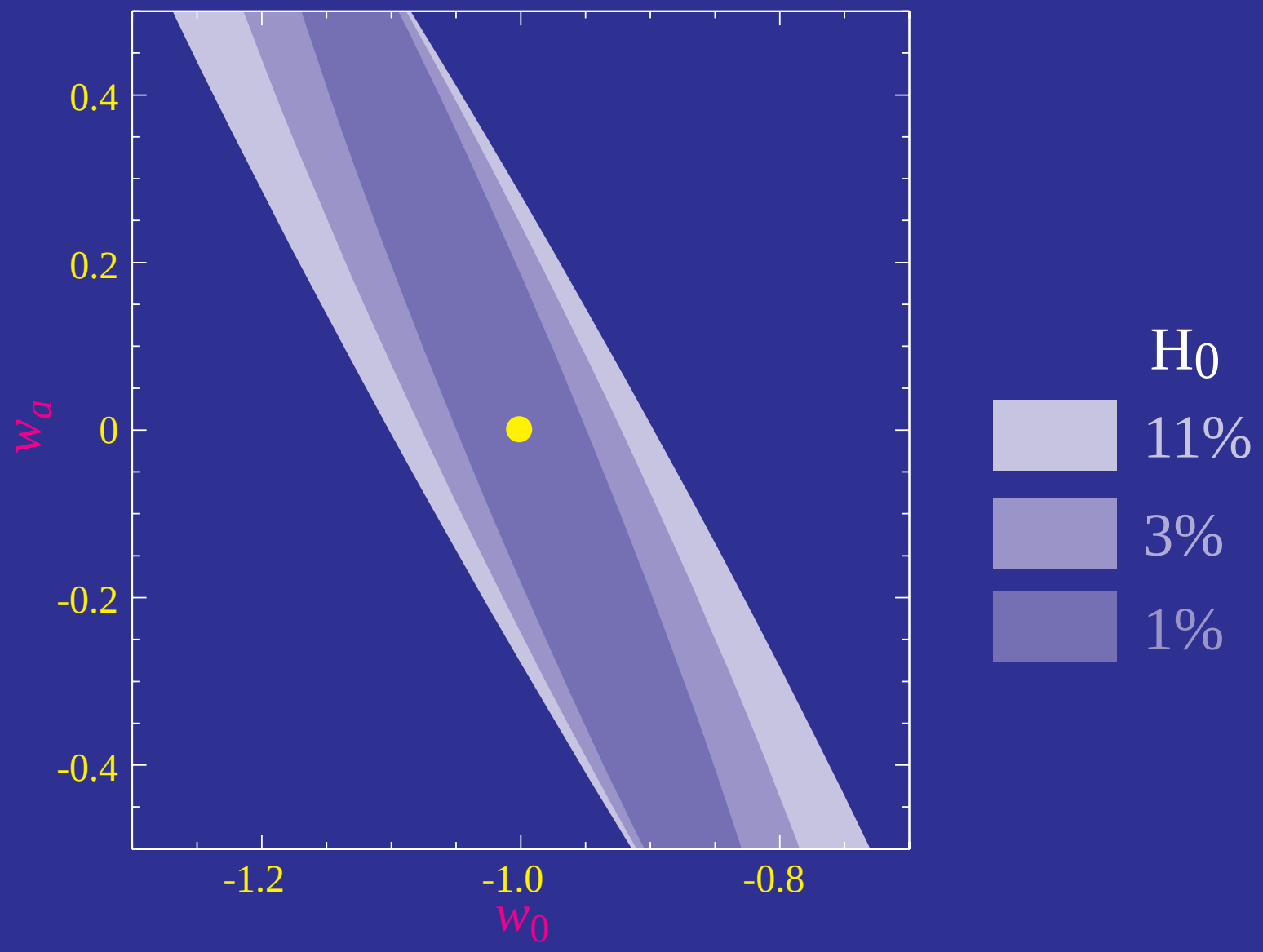


# Halos and Shear



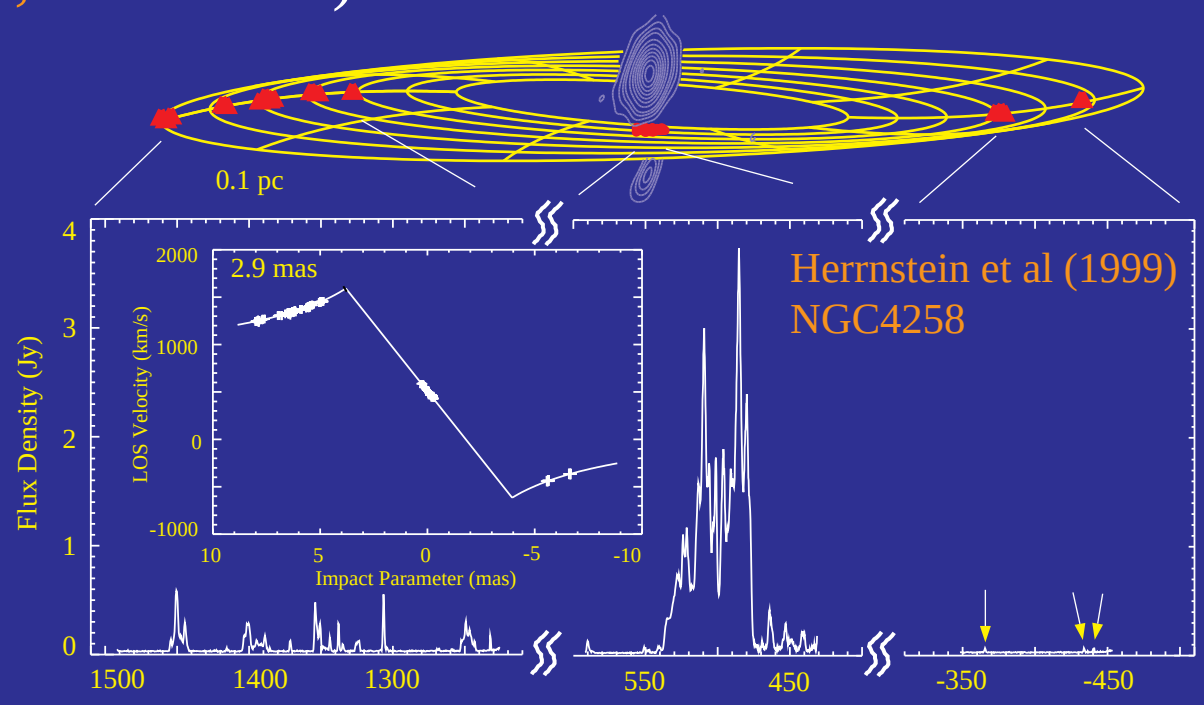
# Forecasts for CMB+$H_0$+Lensing

- Weak lensing (4000deg$^2$ out to $z_{med}$=1 with photometric redshifts) with curvature marginalized



# Prospects for Percent $H_0$

- Improving the distance ladder with SNIa (~3%, Riess 2005)
- Water maser proper motion, acceleration (~3%, VLBA Condon & Lo 2005; ~1% SKA, Greenhill 2004)




- Gravity wave sirens (~2% - 3x Adv. LIGO + GRB sat, Dalal et al 2006)
- Combination of dark energy tests: e.g. SNIa relative distances: $H_0 D(z)$ and baryon acoustic oscillations $D(z)$

# Summary

- CMB fixes energy densities, expansion rate and distances in the deceleration epoch
- Strongest deviations due to the dark energy appear locally at z=0

- The single best complement to the CMB observables is $H_0$ for a flat cosmology in determining deviations in the equation of state from a cosmological constant
- Precision in $H_0$ equal to CMB $\Omega_m h^2$ optimal: 1% (masers, gw,..?)

- $H_0$ also improves the ability of any single intermediate redshift dark energy probe (SNIa, BAO, Clusters, WL) to measure the evolution in the equation of state even in the SNAP/LST era
- Combinations of dark energy probes can themselves indirectly determine $H_0$