<u>*Probing Dark Energy from Ground and Space*</u>

"You can see a lot by looking."

– Y. Berra

Rocky Kolb

La Thuile 2006

How We "Know" There Is Dark Energy

- Assume model cosmology:
  - Friedmann equation ($G_{00} = 8\pi G\, T_{00}$): $H^2 + k/a^2 = 8\pi G\rho / 3$
  - Energy (and pressure) content: $\rho = \rho_M + \rho_R + \rho_\Lambda + \ldots$
  - Input or integrate over cosmological parameters: H_0, *etc*.
- Calculate observables $d_L(z)$, $d_A(z)$, …
- Compare to observations
- Model cosmology fits with ρ_Λ, but not without ρ_Λ
- All evidence for dark energy is *indirect*: observed $H(z)$ is *not* described by $H(z)$ calculated from the Einstein-de Sitter model (Friedmann-Lemaître-Robertson-Walker model with $k = 0$; $\rho = \rho_M$)

Evolution of $H(z)$ Is a Key Quantity

Robertson–Walker metric

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Many observables based on the comoving distance $r(z)$

$$\int_0^{r(z)} \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^t \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')}$$

- Physical distance

$$D(z) \propto r(z)$$

- Luminosity distance
  Flux = Luminosity / $4\pi d_L^2$

$$d_L(z) \propto r(z)(1+z)$$

- Angular diameter distance
  Angular diameter = Physical size / d_A

$$d_A(z) \propto r(z)/(1+z)$$

- Number counts in a volume $dV(z)$

$$dV(z) \propto \left[r^2(z)/H(z)\right] dz\, d\Omega$$

- Age of the universe

$$t(z) \propto \int_0^z \frac{dz'}{(1+z')H(z')}$$

Growth of structure

Growth of structure in FLRW:

$$\ddot{\delta}_i + 2H\dot{\delta}_i = 4\pi G\rho_0 \sum_j \frac{\rho_j}{\rho_0}\delta_j + ?$$

- $H = H$(dark energy)
- Modified gravity: additional term on r.h.s.

Phenomenology

- Model expansion rate of the Universe with ($\Sigma\, \Omega_i = 1$)
  - Matter: $\rho_M \propto a^{-3}$ Ω_M
  - Radiation: $\rho_R \propto a^{-4}$ Ω_R
  - Dark Energy: $\rho_{DE} \propto a^{-3[1+w(z)]}$ Ω_{DE} ($?{-1} \leq w \leq -1/3$)
  - Curvature: $\rho_k \propto a^{-2}$ $\Omega_k = 1 - \Omega_{DE} - \Omega_M - \Omega_R$
- In typical model cosmology there are something like 8 cosmological parameters.

  Dark energy: $w(z) = w_0 + w_a(1-a) = w_0 + w_a\, z/(1+z)$ and Ω_{DE}
- All parameterizations of $w(z)$ are quirky
- Cosmological constant: $w_0 = -1$ and $w_a = 0$
- Theory predictions dense in w_0 and w_a
- No magic goal (say w_0 to 1% or w_a to 3%).

DETF Science Goals

The goal of dark-energy science is to determine the very nature of the dark energy that causes the Universe to accelerate and seems to comprise most of the mass-energy of the Universe.

1. Exclude ΛCDM ($w_0 = -1$ and $w_a = 0$), *i.e.,* a null hypothesis test
2. If it is not due to a constant, probe the underlying dynamics by measuring as well as possible the time evolution of dark energy, for example by measuring $w(a)$.
3. Search for a possible failure of GR through comparison of cosmic expansion with growth of structure.
4. Precise determination of Ω_Λ is not that crucial.*

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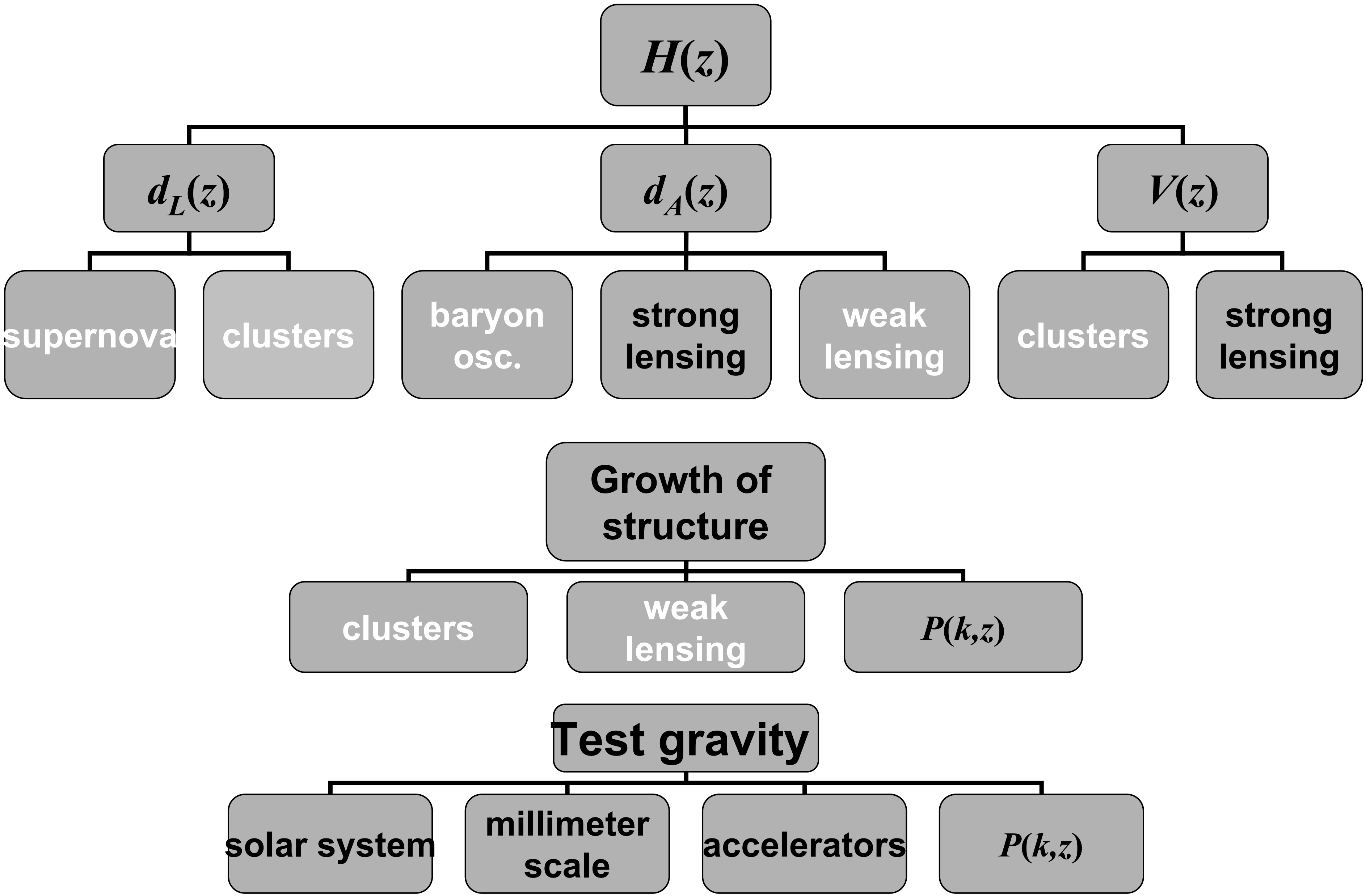
* Present theoretical predictions for Ω_Λ are off by 120 orders-of-magnitude, so don't require much precision.

Observational program



Supernova Type IA

Inverse-square law: Flux = Luminosity / $4\pi\, d_L^{\,2}$ $\qquad d_L(z) \propto r(z)(1+z)$

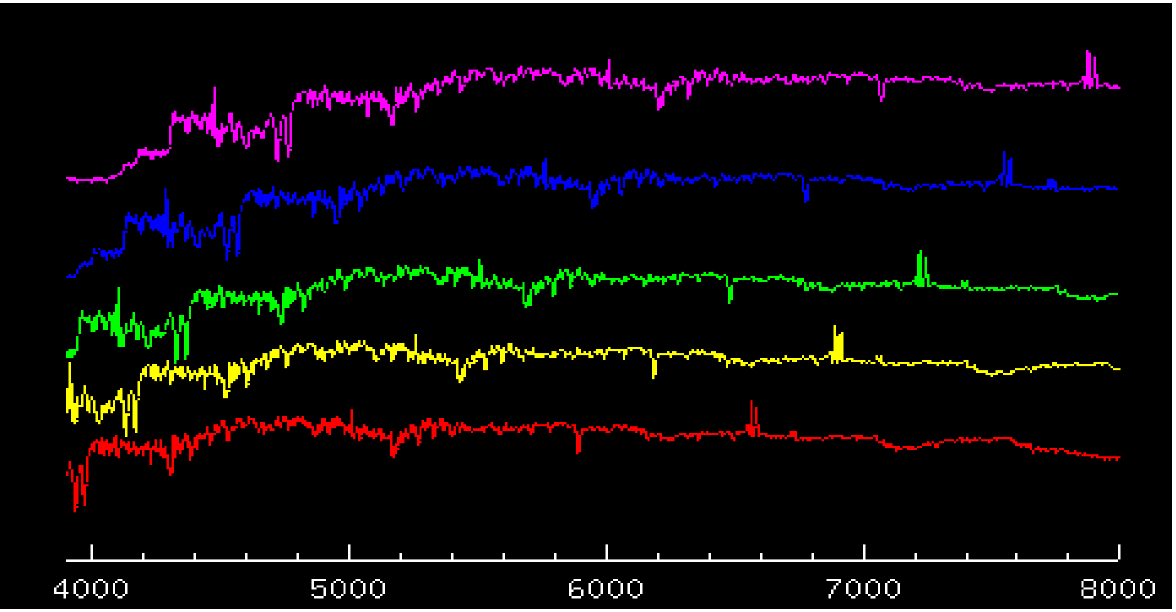
$r(z)$ determined from $\displaystyle\int_0^{r(z)} \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^{z} \frac{dz'}{H(z')}$

$$H^2(z) = H_0^2(z)\left[\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{DE} (1+z)^{3[1+w(z)]}\right]$$

$$\Omega_M + \Omega_k + \Omega_{DE} = 1$$

- Have to measure redshift and intensity as fn. of time (light curve)
- Systematics (dust, evolution, intrinsic luminosity dispersion, etc.)
- Present procedure:
  - Discover SNe by wide-area survey (the “easy” part)
  - Follow up with spectroscopy (the “hard” part) (requires a lot of time on 8m-class telescopes)
  - Photometric redshifts?
- A lot of information per supervova
- Well developed and practiced

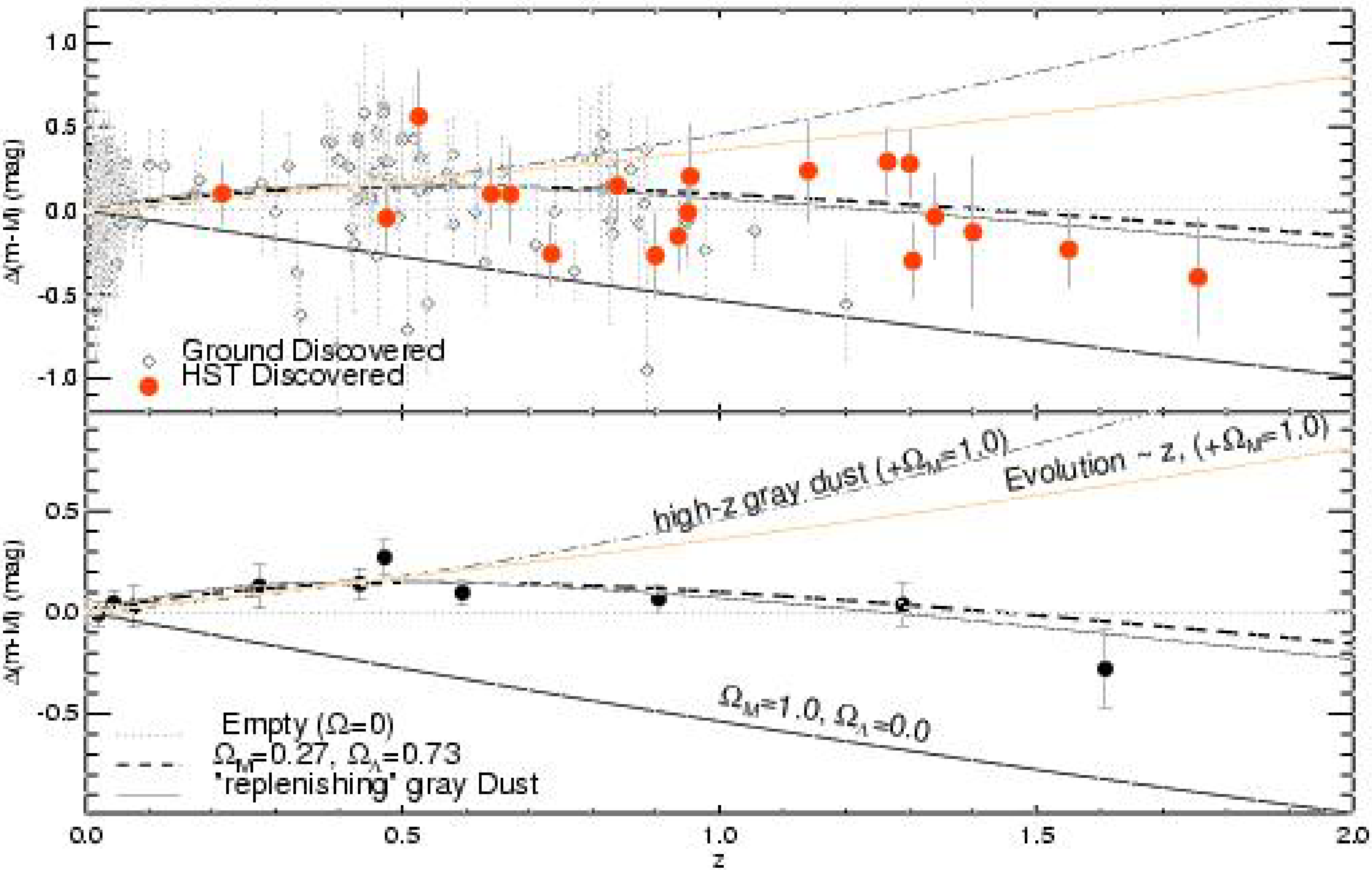
Photometric redshifts



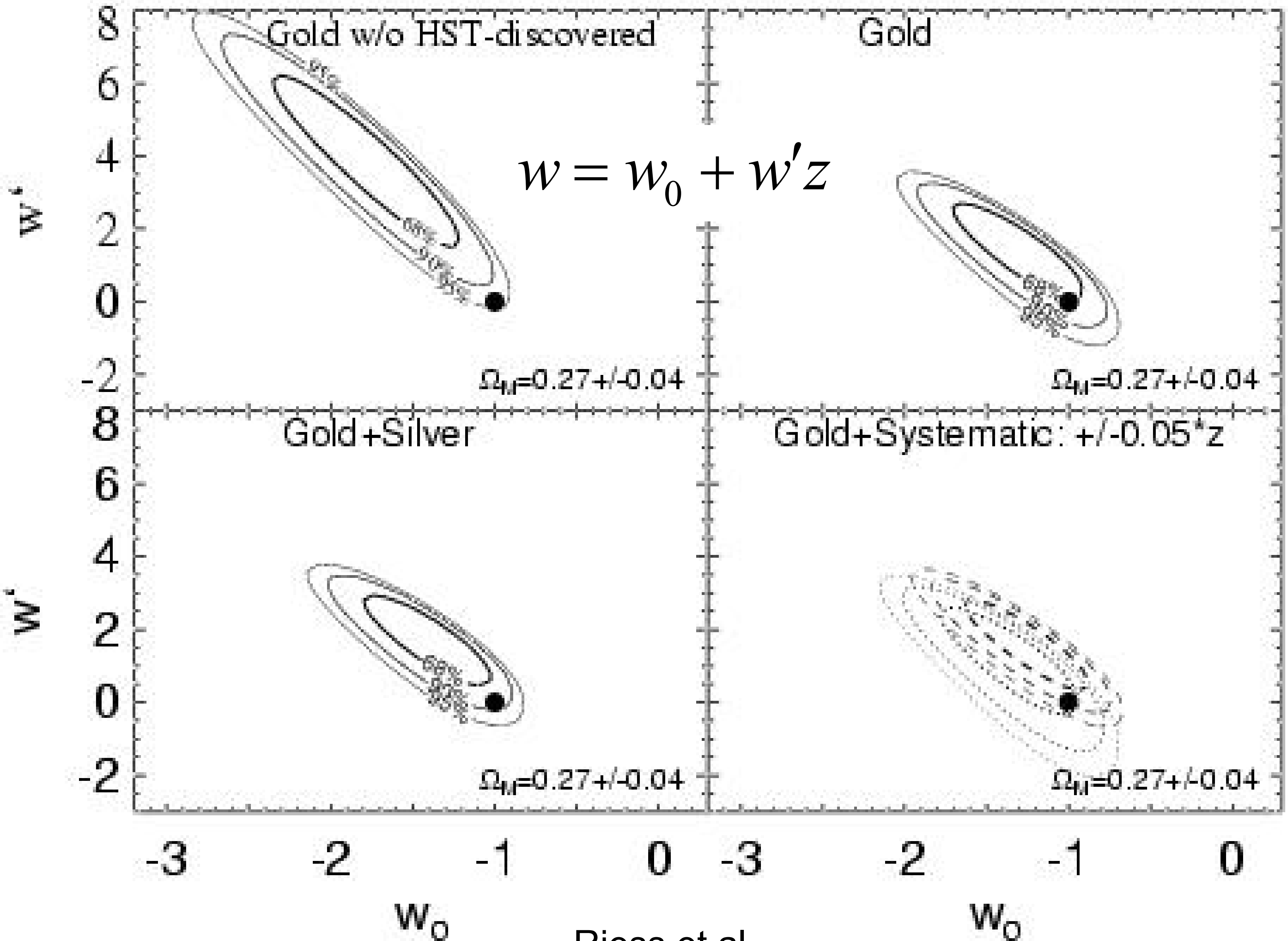
Traditional redshift from spectroscopy

Photometric redshift from multicolor photometry

Supernova Type IA



Riess et al. **Astrophys.J.607:665-687,2004**



$$w = w_0 + w'z$$

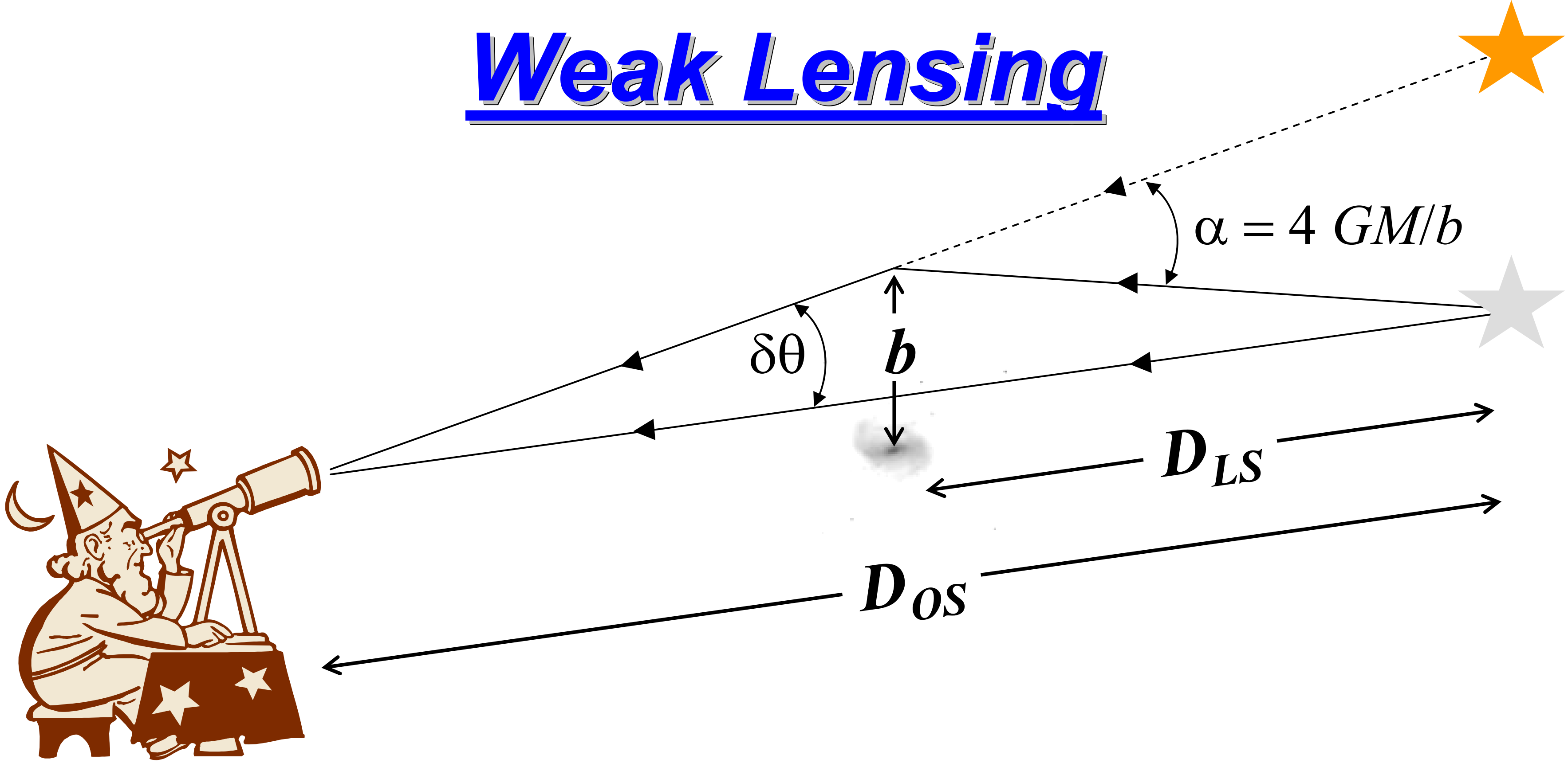
Riess et al.

Caution in Interpretation

Always read the fine print:

- Astrophysical systematic errors
- What are the model assumptions?
  - w = constant? w', w_a
  - assume a value for Ω_Λ?
- What are the priors?
  - Ω_M, Ω_B, H_0, …, $\Omega_{\mathrm{TOTAL}} = 1$?

Weak Lensing



observe deflection angle

$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$

dark energy affects geometric distance factors

dark energy affects growth rate of M

Weak Lensing

The signal from any single galaxy is *very* small,
but there are a *lot* of galaxies! Require photo-z's?

Systematic errors:

- Dominant source is PSF of atmosphere and telescope
  - use stars to correct
- Errors in photometric redshifts
  - biases in the estimated z
  - catastrophic errors in z
- Lensing from space
  - Better resolution, helps PSF
  - NIR improved photo-z's
  - deeper?
  - stable platform
- What area/aperture of space survey beats ground large-area large-aperture

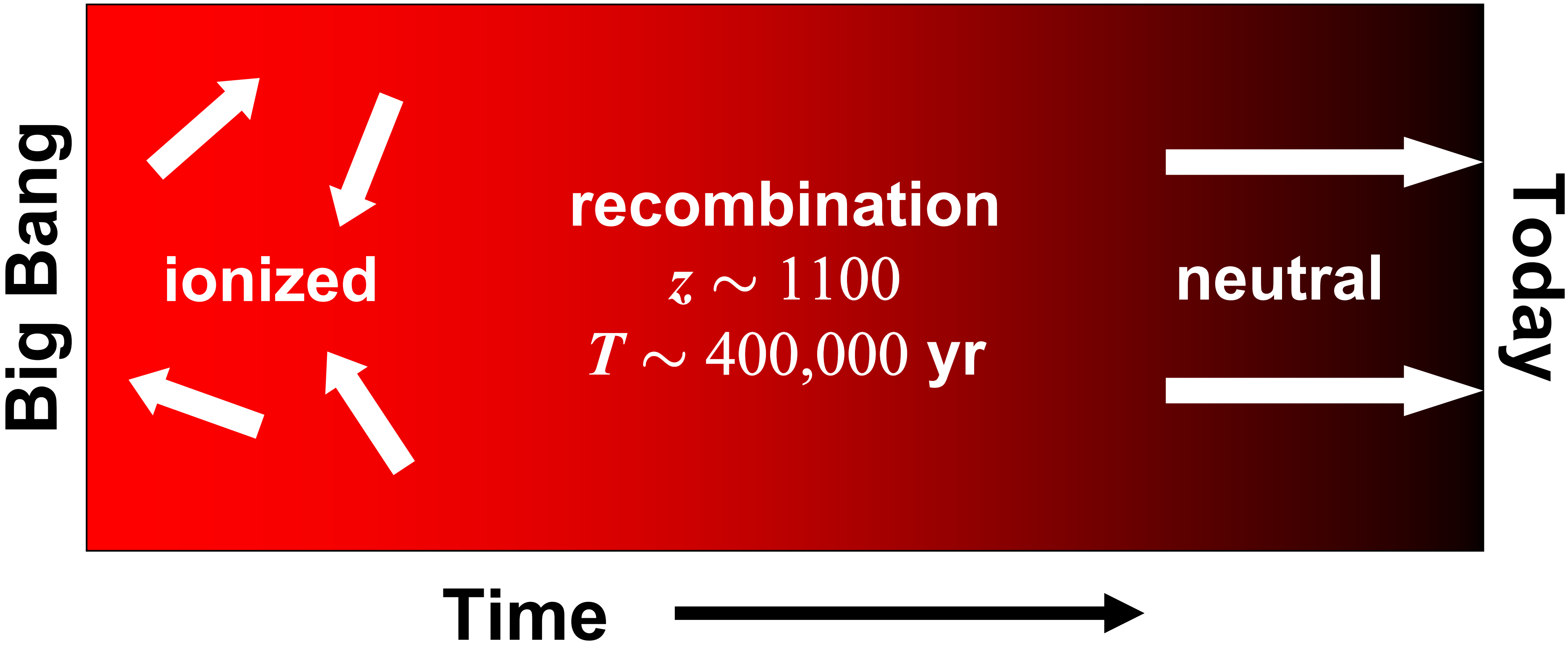
The Landscape:

- Current projects
  - 100's of sq. degs. deep multicolor data
  - 1000's of sq. degs. shallow 2-color data
- DES (2009)
  - 1000's of sq. degs. deep multicolor data
- LSST (201?)
  - full hemisphere, very deep 6 colors
- JDEM (201?)

Baryon Acoustic Oscillations

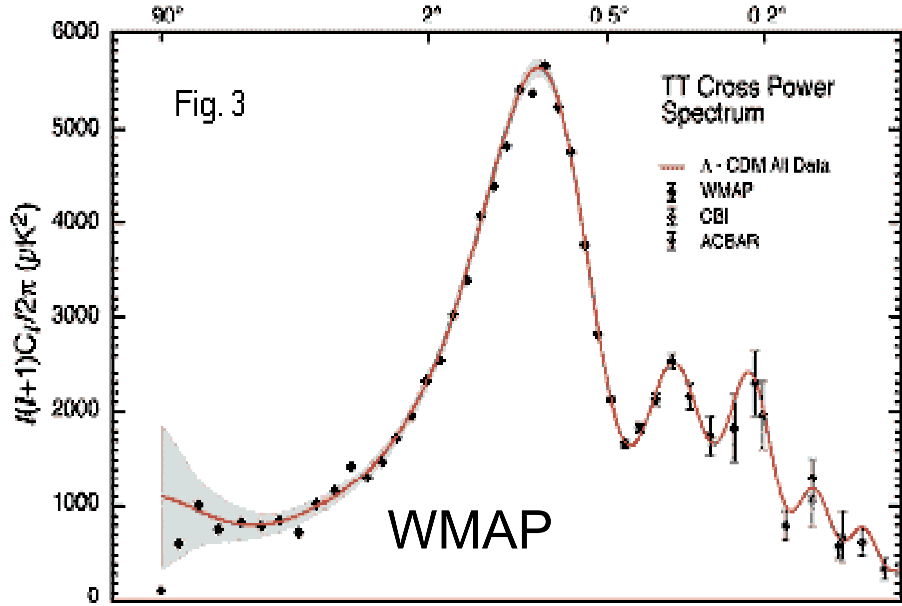
Pre-recombination
- universe ionized
- photons provide enormous pressure and restoring force
- perturbations oscillate (acoustic waves)

Post-recombination
- universe neutral
- photons travel freely (decouple from baryons)
- perturbations grow (structure formation)

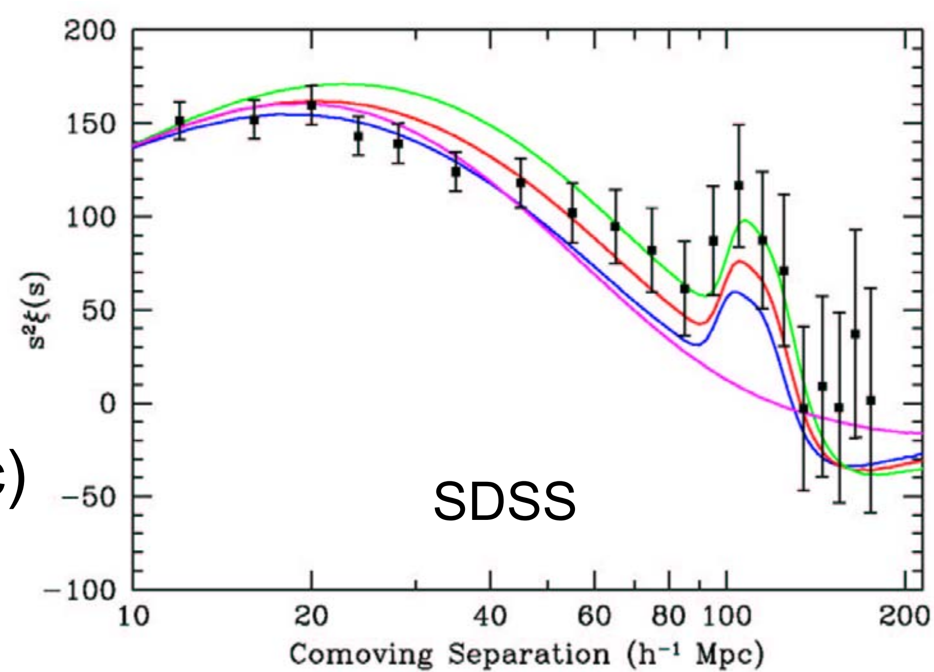


Baryon Acoustic Oscillations

- Each overdense region is an overpressure that launches a spherical sound wave
- Wave travels outward at $0.57c$
- Photons decouple, travel to us and observable as CMB acoustic peaks

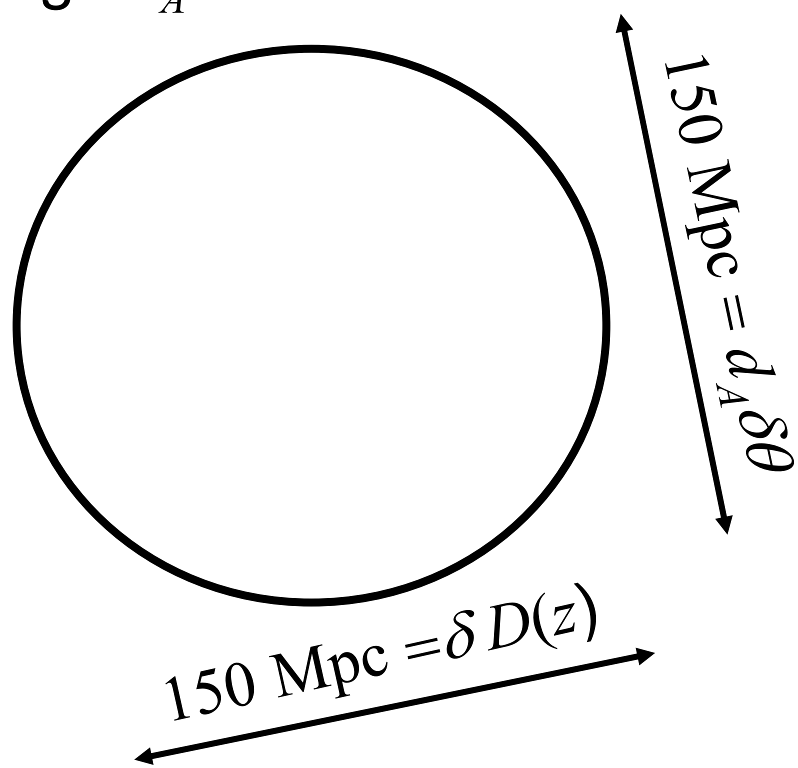


- Sound speed plummets, wave stalls
- Total distance traveled (150 Mpc) imprinted on power spectrum



Baryon Acoustic Oscillations

- Acoustic oscillation scale depends on $\Omega_M h^2$ and $\Omega_B h^2$ (set by CMB acoustic oscillations)
- It is a small effect ($\Omega_B h^2 \ll \Omega_M h^2$)
- Dark energy enters through d_A and H

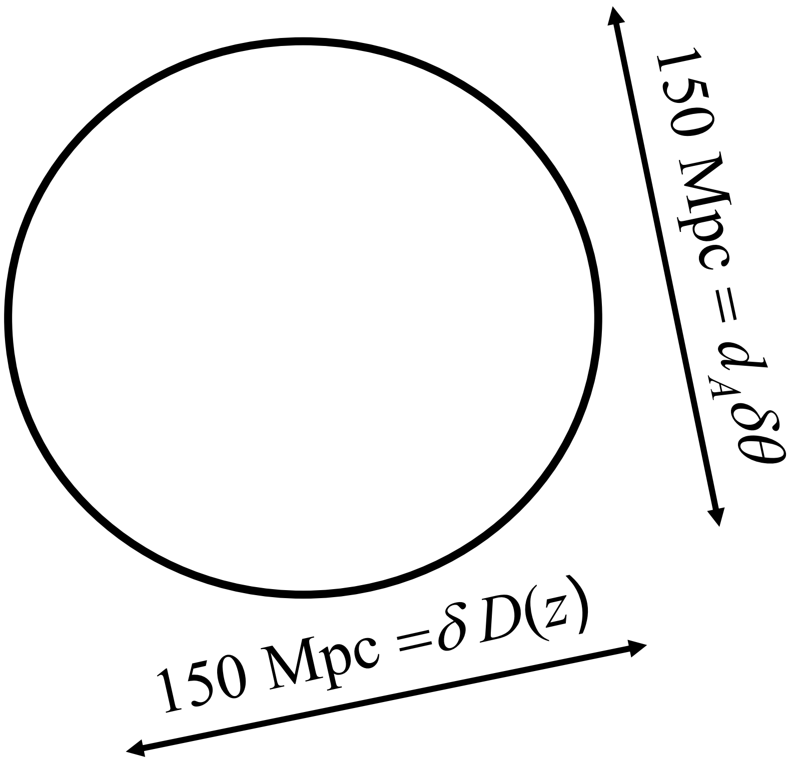


Baryon Acoustic Oscillations

- Virtues: pure geometry. Systematic effects should be small.

- Problems: Amplitude small, require large scales, huge volumes.

- Photometric redshifts?



Clusters

Cluster redshift surveys measure

- cluster redshift distribution
- cluster mass distribution as function of z
- spatial clustering of clusters

Sensitivity to dark energy

- volume-redshift relation
- angular-diameter distance–redshift relation
- growth rate of structure
- power spectrum shape (transfer fn.)

Cluster selection must be well understood

- “by eye” in optical samples
- ICM properties (x-ray, SZE effect)
- weak lensing shear
- best probably x-ray or SZE with optical confirmation
- need photo-z’s

Clusters

Things to learn

- photo-z's
- proxy for cluster mass
- spatial clustering of clusters
- "self-calibration"
- numerical simulations of structure formation

Things to work on

- theory of structure formation/halo mass fn. and evolution
- cluster selection
- cluster mass proxy

What's Ahead

2006 2010 2015

Lensing: CFHTLS SUBARU DES, VISTA DUNE LSST SKA
DLS SDSS ATLAS KIDS Hyper suprime Pan-STARRS JDEM

BAO: FMOS LAMOST DES, VISTA,VIRUS WFMOS LSST SKA
SDSS ATLAS Hyper suprime Pan-STARRS JDEM

SNe: CFHT CSP ESSENCE DES LSST
SDSS CFHTLS Pan-STARRS JDEM

Clusters: AMI APEX SPT DES
XCS SZA AMIBA ACT

CMB: WMAP 2/3 WMAP 6 yr
Planck Planck 4yr

2005 2010 2015

Large Resources

Not all on same cost basis
My estimate of costs

DES	$18M
Darkcam	$18M
PanSTARRS	$70M
HETDEX	$25M
HyperSuprime	$20M
WFMOS	$60M
Total	$211M

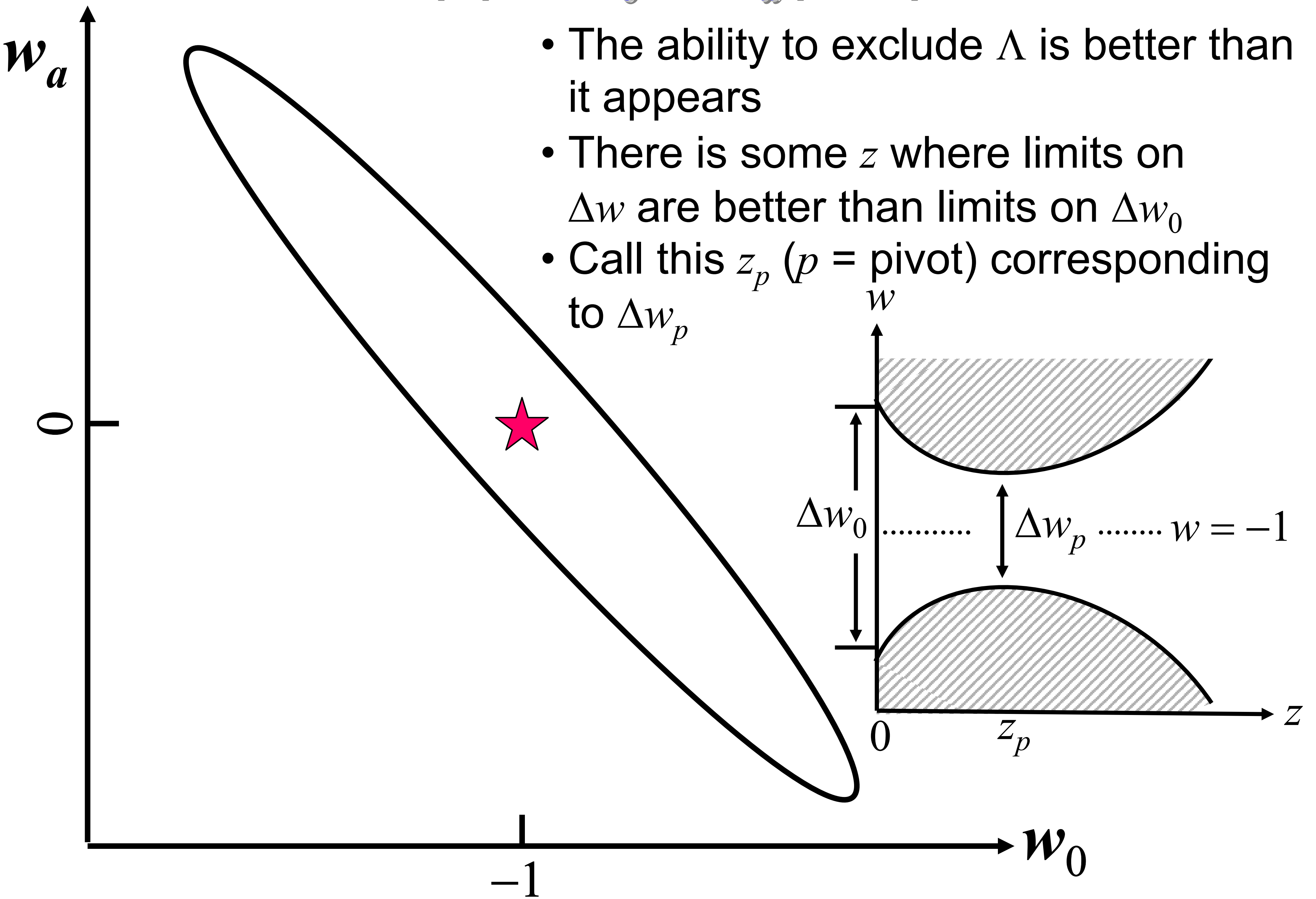
and later……..

LSST	$500M
SKA	$700m
JDEM	$600M–$1B
Total	$1.8B–$2.2B

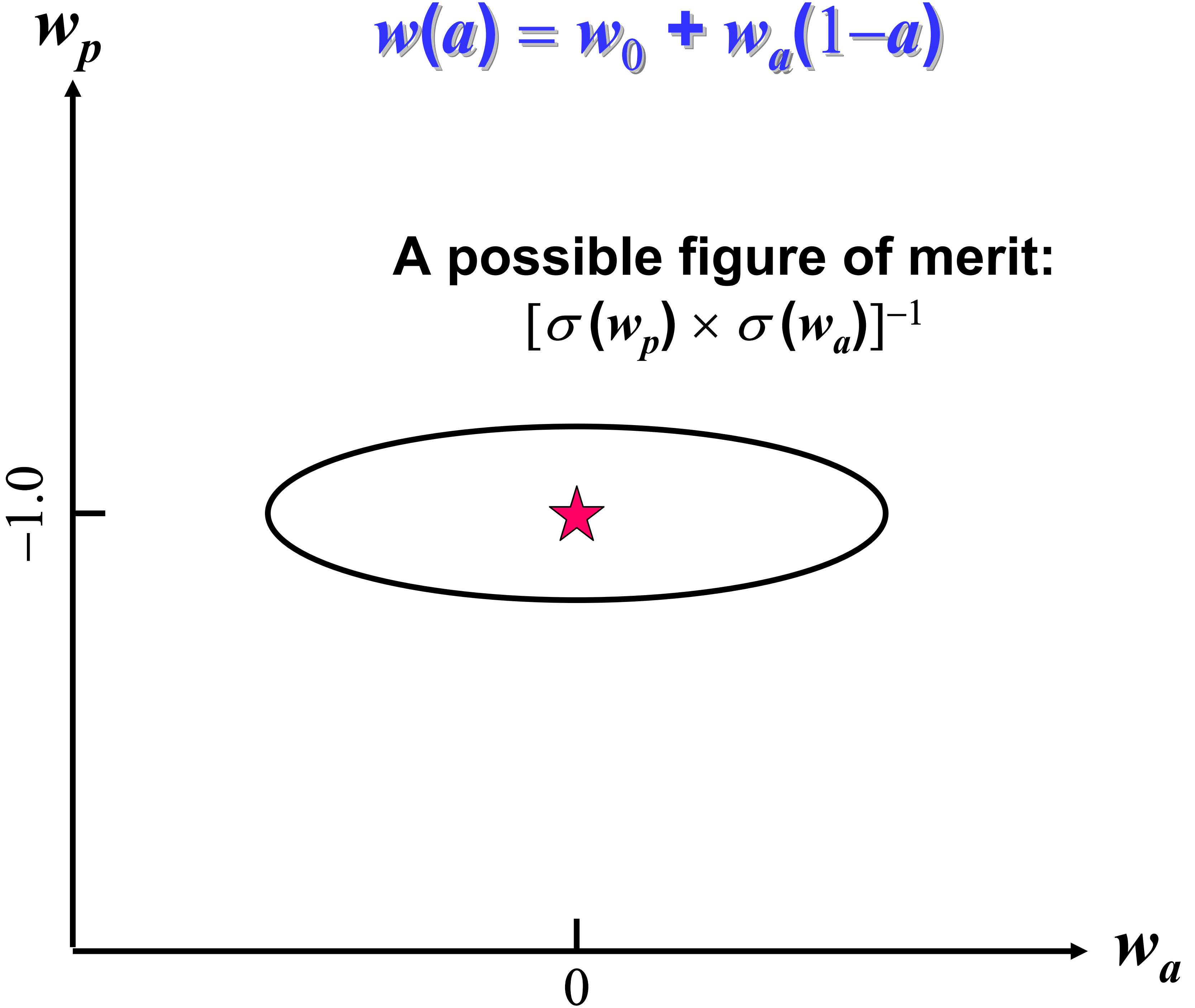
Grand total	$2B–$2.4B

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

- The ability to exclude Λ is better than it appears
- There is some z where limits on Δw are better than limits on Δw_0
- Call this z_p (p = pivot) corresponding to Δw_p

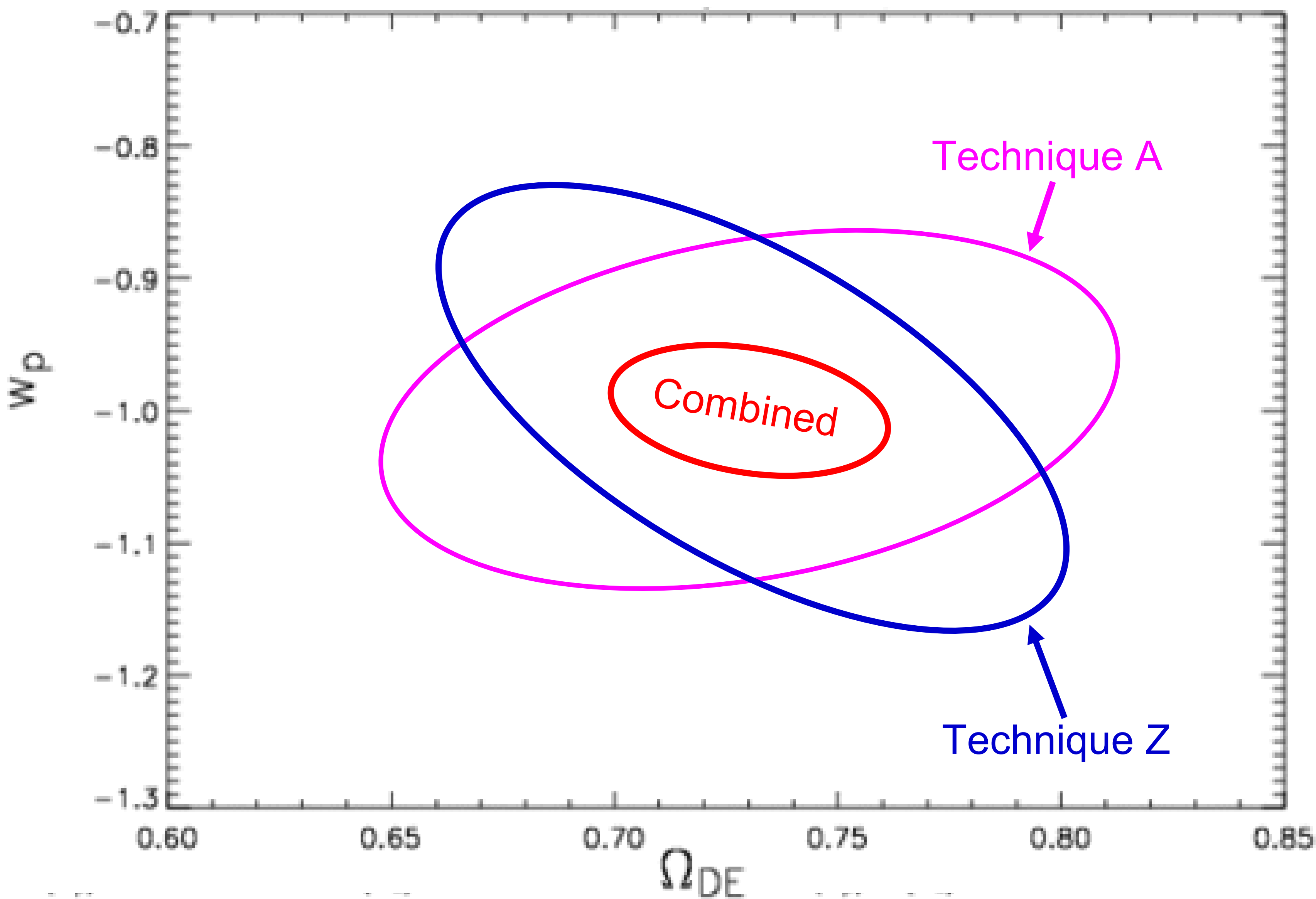


$$w(a) = w_0 + w_a(1-a)$$



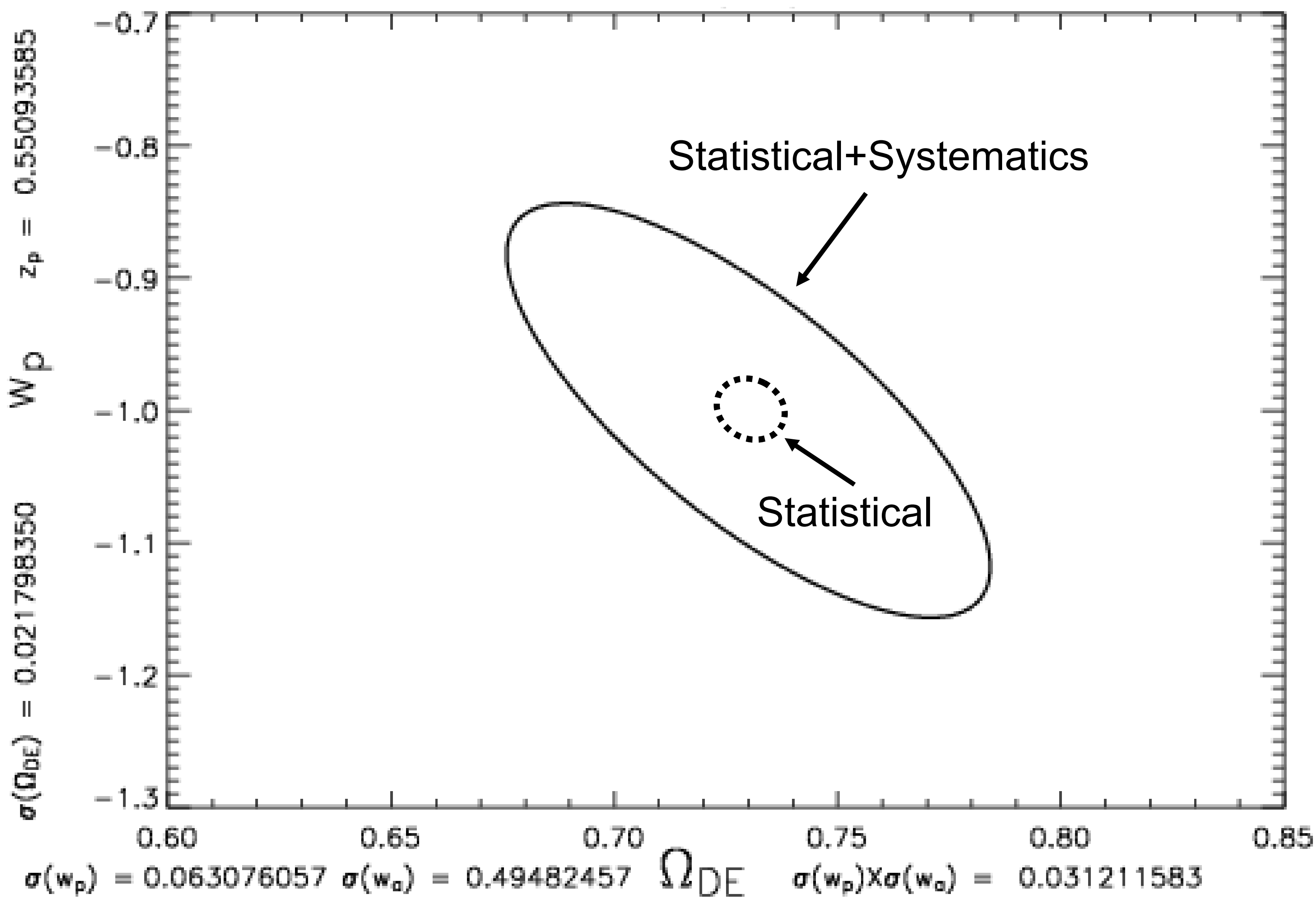
The Power of Two (or Three, or Four)

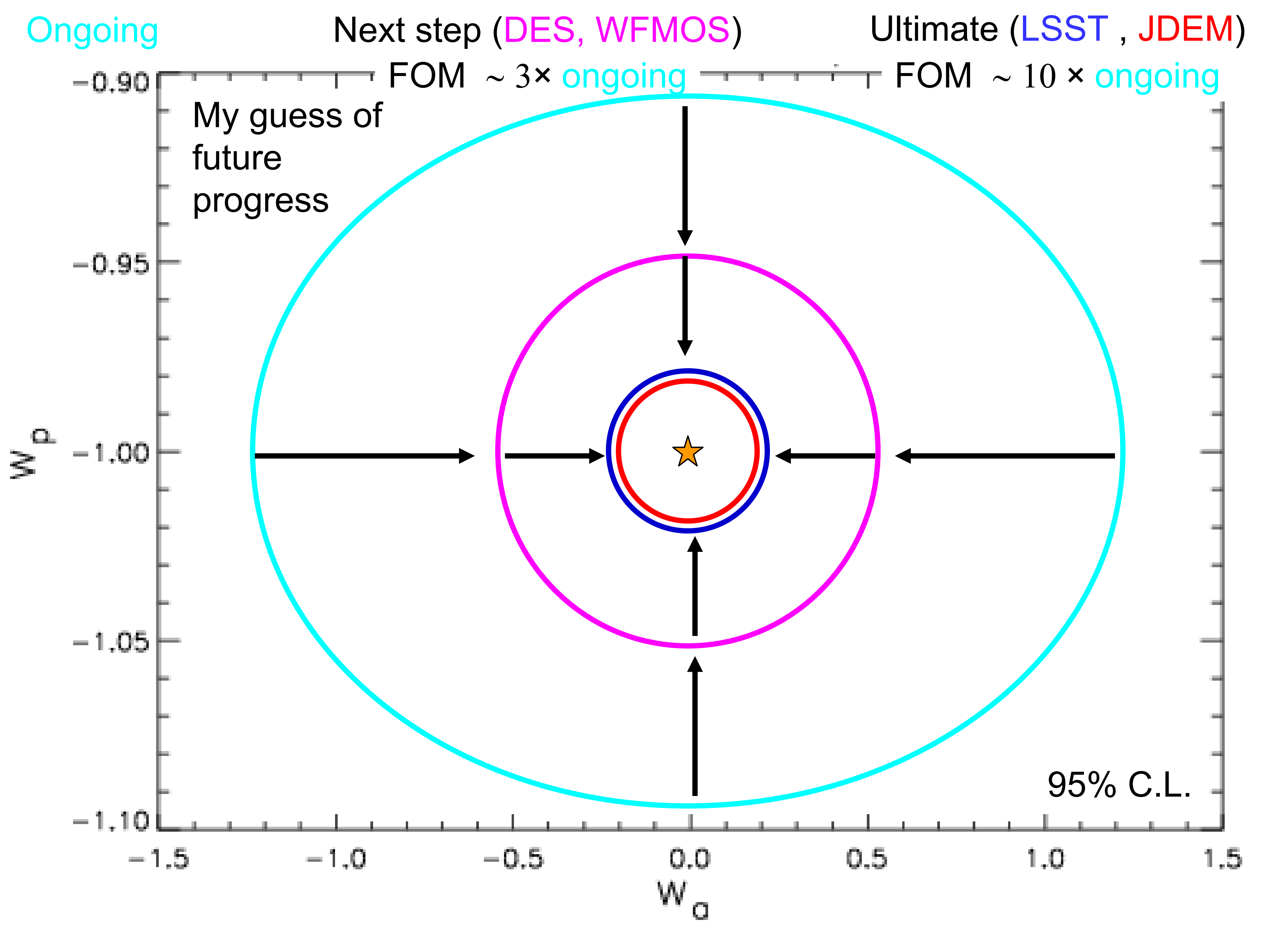
$\sigma(w_p) \times \sigma(w_a) = 0.04$ $\sigma(w_p) \times \sigma(w_a) = 0.009$ $\sigma(w_p) \times \sigma(w_a) = 0.05$



Systematics, Systematics, Systematics

A sample WL fiducial model




Ongoing
Next step (DES, WFMOS)
Ultimate (LSST , JDEM)
FOM ~ 3× ongoing
FOM ~ 10 × ongoing
My guess of future progress
95% C.L.
−0.90
−0.95
−1.00
−1.05
−1.10
w p
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
w a

Conclusions

The expansion history of the universe, $H(z)$, is not described by Einstein-de Sitter. Evidence:

1. Well established: Supernova Ia
2. Circumstantial: subtraction, age, structure formation, …
3. Emergent techniques: baryon acoustic oscillations, clusters, weak lensing

Explanations:

1. Dark energy
   - "constant" vacuum energy "Λ"
   - time varying vacuum energy (low-mass scalar fields)
2. Modification of GR
   - growth rate of structure modified
3. Standard cosmological model (FLRW) not applicable
   - Should make predictions for cosmological observables: effective $H(z)$

Phenomenology:

1. $w(z)$: w_0, w_a
2. Figure of merit: $w_0 \times w_a$
3. Order of magnitude improvement in figure of merit feasible

Probing Dark Energy from Ground and Space

"You can see a lot by looking."

– *Y. Berra*

Rocky Kolb

La Thuile 2006