Gravitational Lenses of the Dark Universe

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Outline

1. Introduction to Gravitational Lensing

2. Current Big Questions in Cosmology

3. The Dark Universe with Gravitational Lensing

4. Weak Lensing Experiments: Past, Present and Future

Gravitational Lensing

History of Light Bending

Dyson, Eddington & Davidson 1919

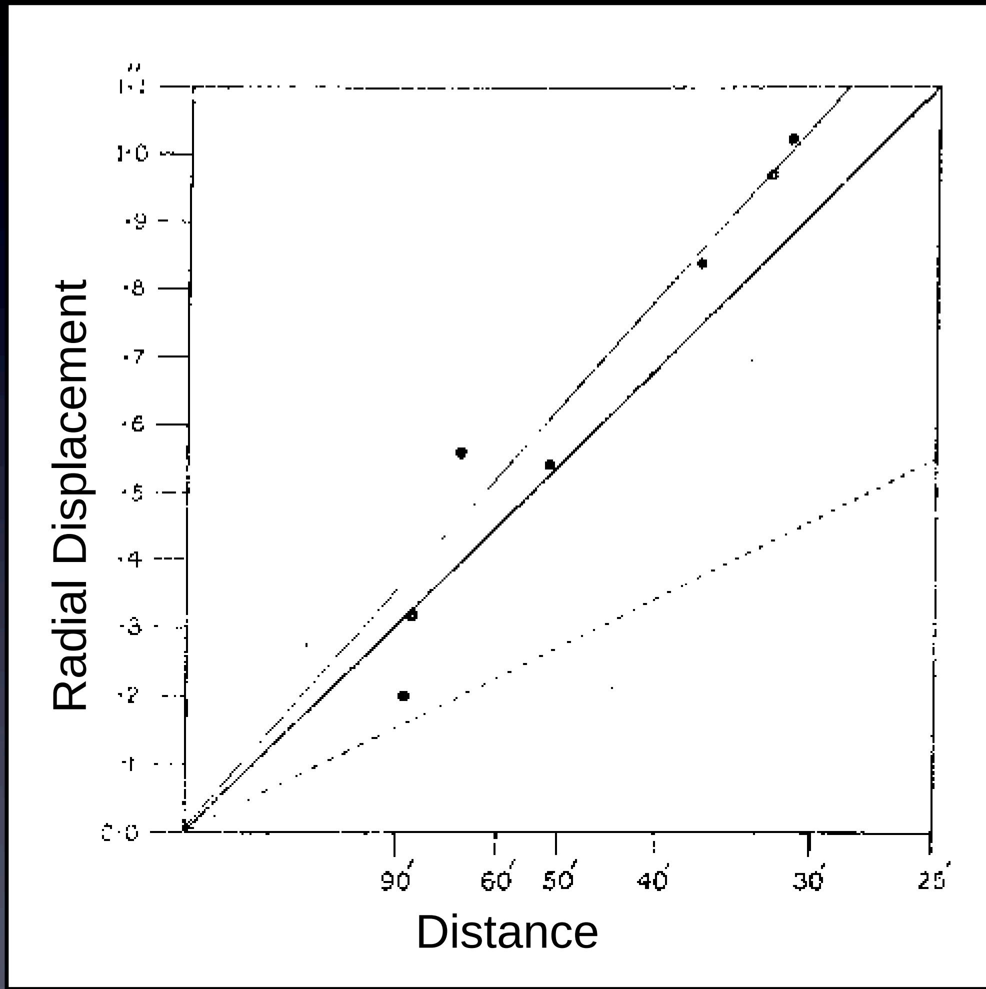
1915: General Relativity

1919: Eclipse Experiment

1937: Galaxies as Lens (*Zwicky*)

1979: First Galaxy Lens

$$\alpha = \frac{4G}{c^2}\frac{M}{r}$$



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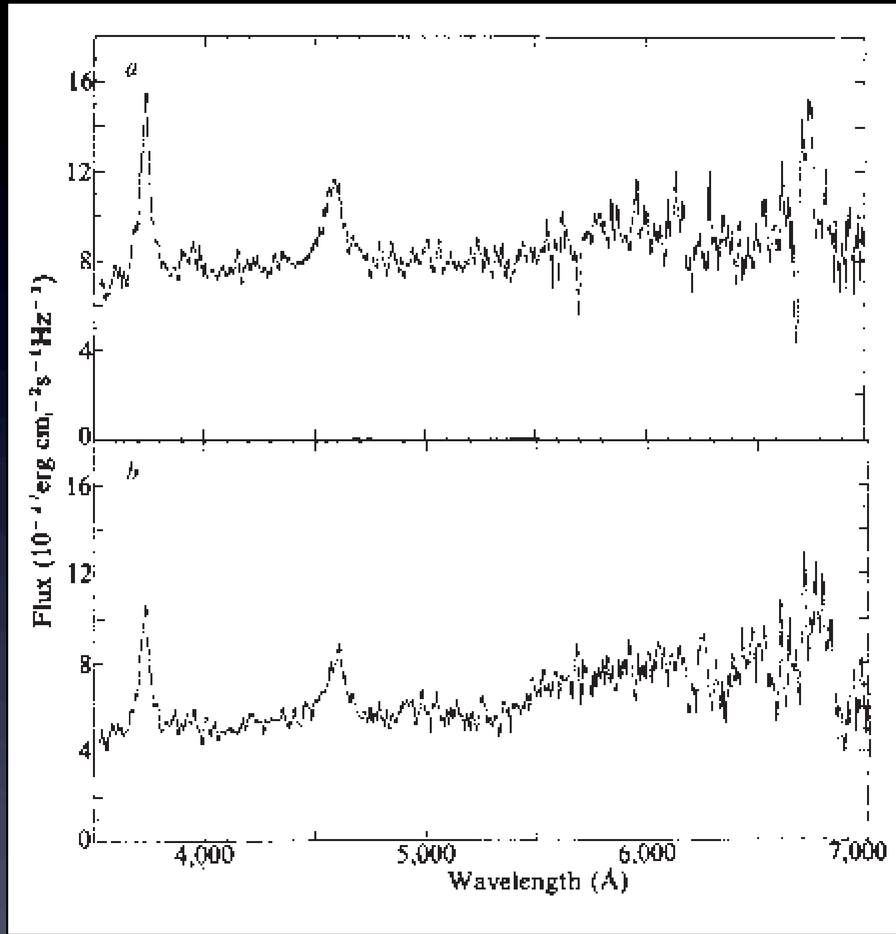


$$\alpha = \frac{4G}{c^2}\frac{M}{r}$$

- Separated by ~6"
- Both QSOs
- Redshift ~ 1.40

Lens Equations

- Depend on 'Lensing Potential' (ψ)

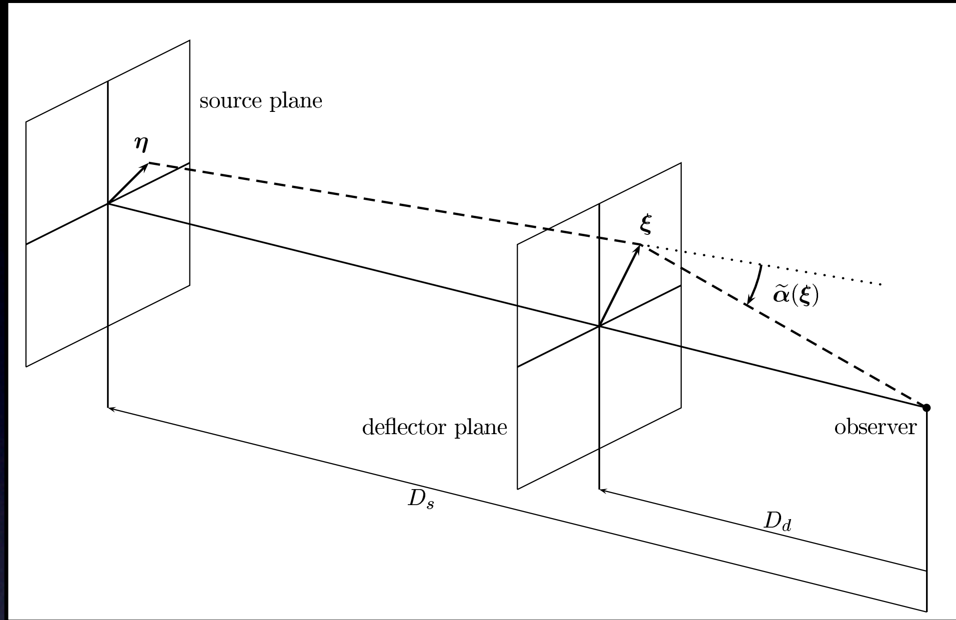
$$\nabla^2\psi(\theta) = 2\kappa(\theta)$$

- Convergence (κ) given by

$$\kappa(\theta) = \frac{4\pi G}{c^2}\frac{D_L D_{LS}}{D_S}\Sigma(\theta)$$

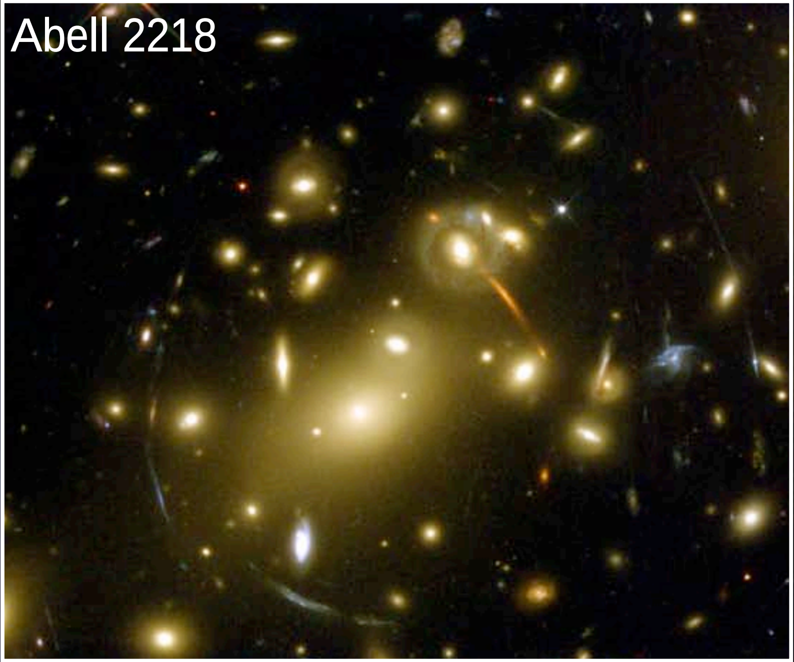
- Lensing depends on

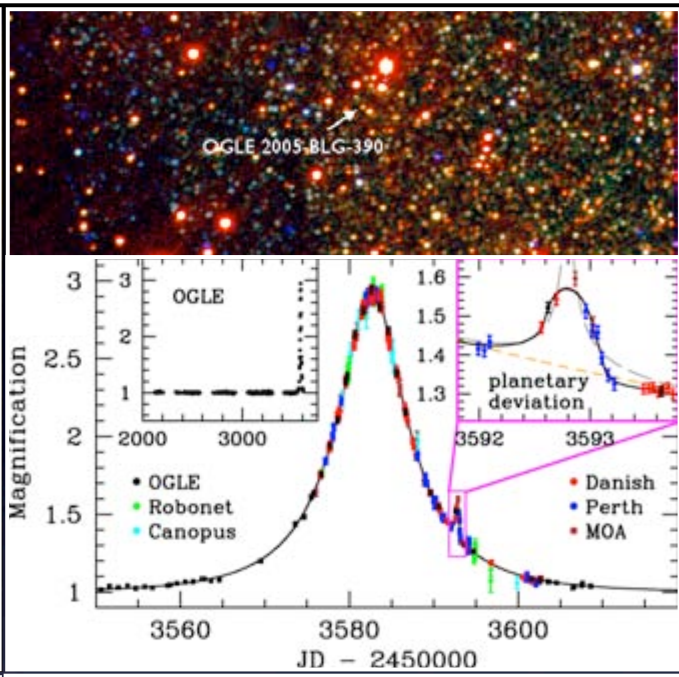
1. Masses
2. Impact parameter
3. Distances along line of sight

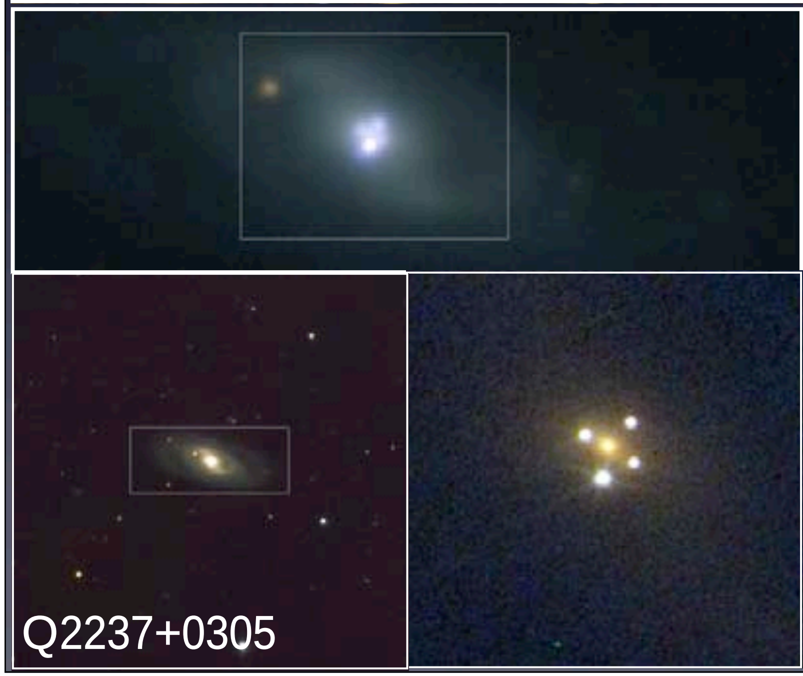


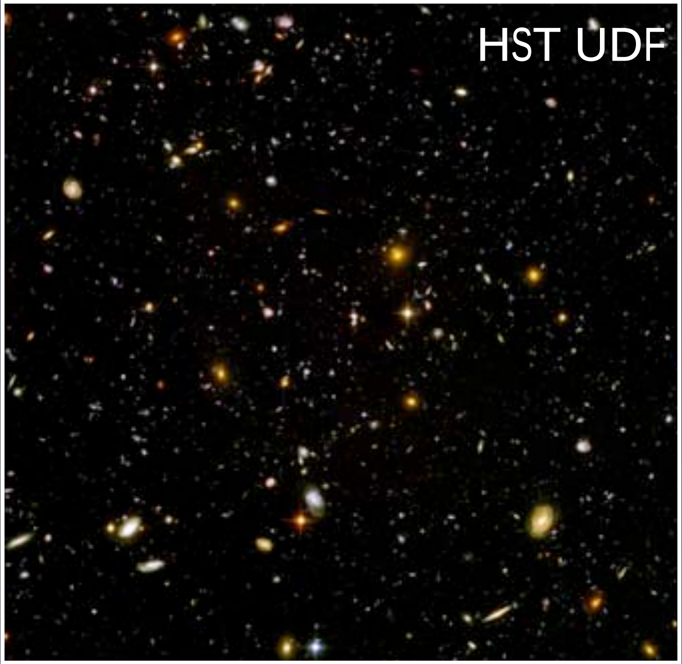
Deflection	$\overrightarrow{\Delta\theta}(\vec{\theta}) = \nabla\psi(\vec{\theta})$
Shear	$\gamma_1(\vec{\theta}) = \frac{1}{2}\left(\frac{\partial^2\psi}{\partial\theta_i^2} - \frac{\partial^2\psi}{\partial\theta_j^2}\right)$
	$\gamma_2(\vec{\theta}) = \left(\frac{\partial^2\psi}{\partial\theta_i\partial\theta_j}\right)$
Magnification	$\mu = \frac{1}{(1-\kappa)^2-\vert\gamma\vert^2}$

Examples of Gravitational Lenses









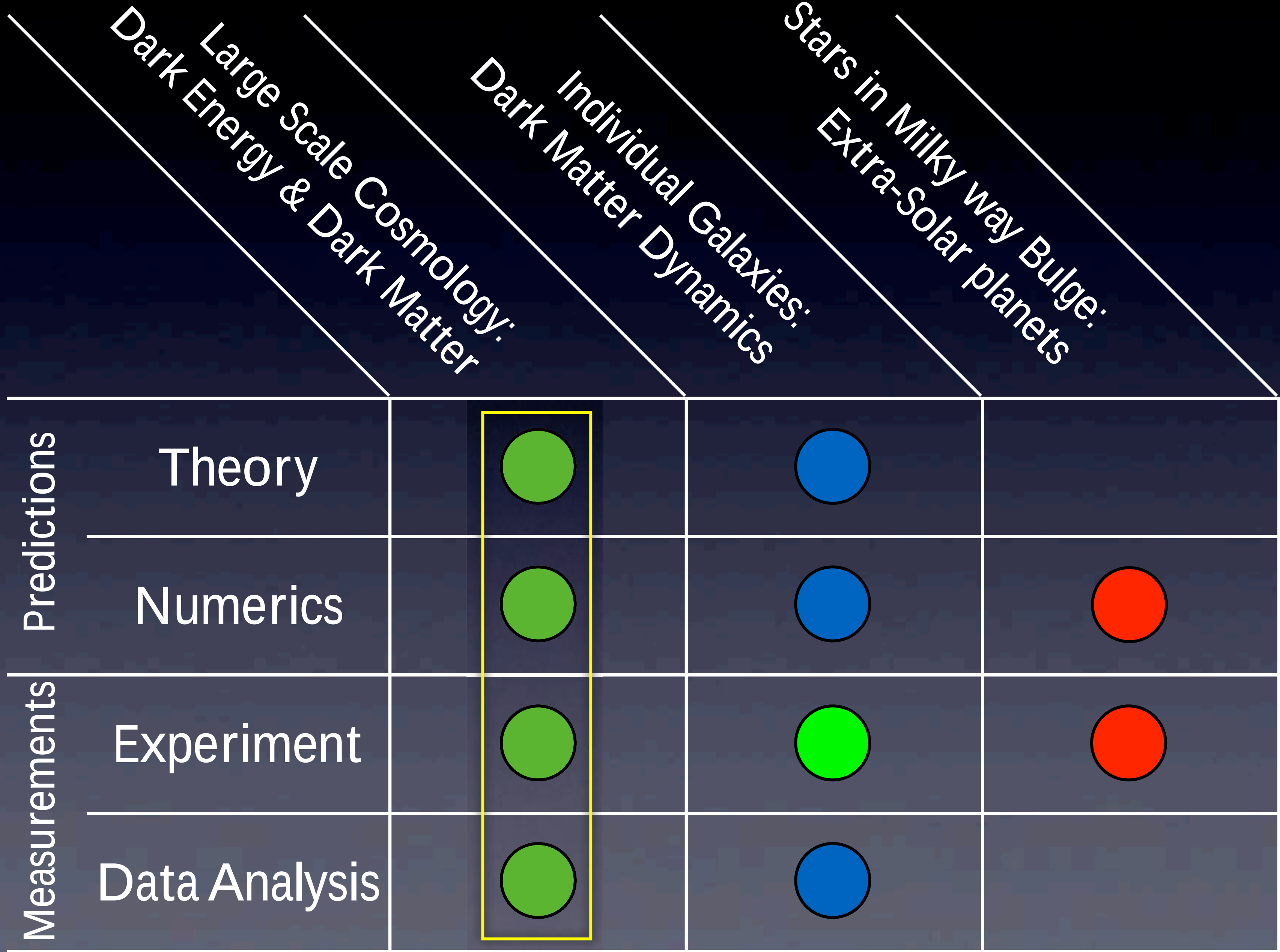
Mass Scales

Abell 2218
~ few x10^{14} M_S

OGLE-2005-BLG-390
~ 5 M_E (2 x 10^{-6} M_S)

Total Mass range:10^{20}

Multiple Purpose Tool for Astronomy



Big Questions in Cosmology: 'Dark Energy'

Physics thrives on crisis.

Perhaps it is for want of other crises…that interest is increasingly centered on one veritable crisis…expectations for the cosmological constant exceed observational limits by some 120 orders of magnitude.

- Weinberg 1989

Evidence for ‘Dark Energy’

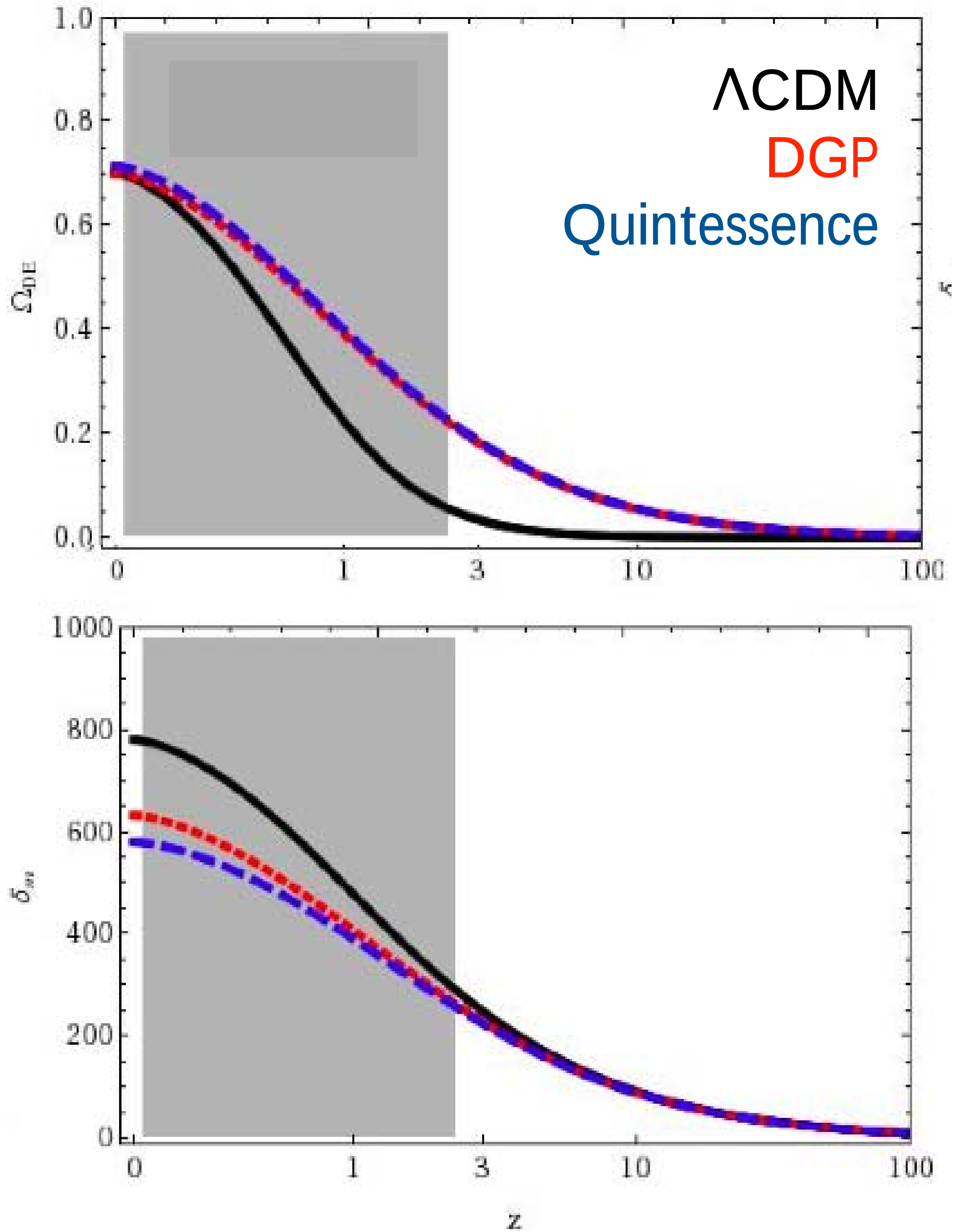
- Inflation: Spatially flat with $\Omega = 1$
  (Guth 1981)
- Low Ω_m points to smooth component (DE)
  (Peebles 1984, Turner+ 1984)
- ΛCDM better fit to LSS than $\Omega_m = 1$
  (Efstathiou+ 1990, Turner 1991)
- COBE data ruled out $\Omega_m = 1$ CDM model
  (1992)
- Cosmological constant
  (Frieman+1995, Krauss & Turner 1995, Ostriker & Steinhart 1995)
- Measurement of supernova light curves
  (Riess+ 1998, Perlmutter+ 1999)

Growing evidence of ΛCDM from many measurements

Impact of 'Dark Energy'

Dark Energy Effects:

- Background Expansion
- Growth of Structure



Euclid Yellow Book (2010)

Expansion History

Hubble parameter: $H = \frac{\dot{a}}{a}$

Friedmann equation:

$$H^2(a) = H_0^2 \left(\frac{\Omega_k}{a^2} + \frac{\Omega_m}{a^3} + \Omega_\Lambda \right)$$

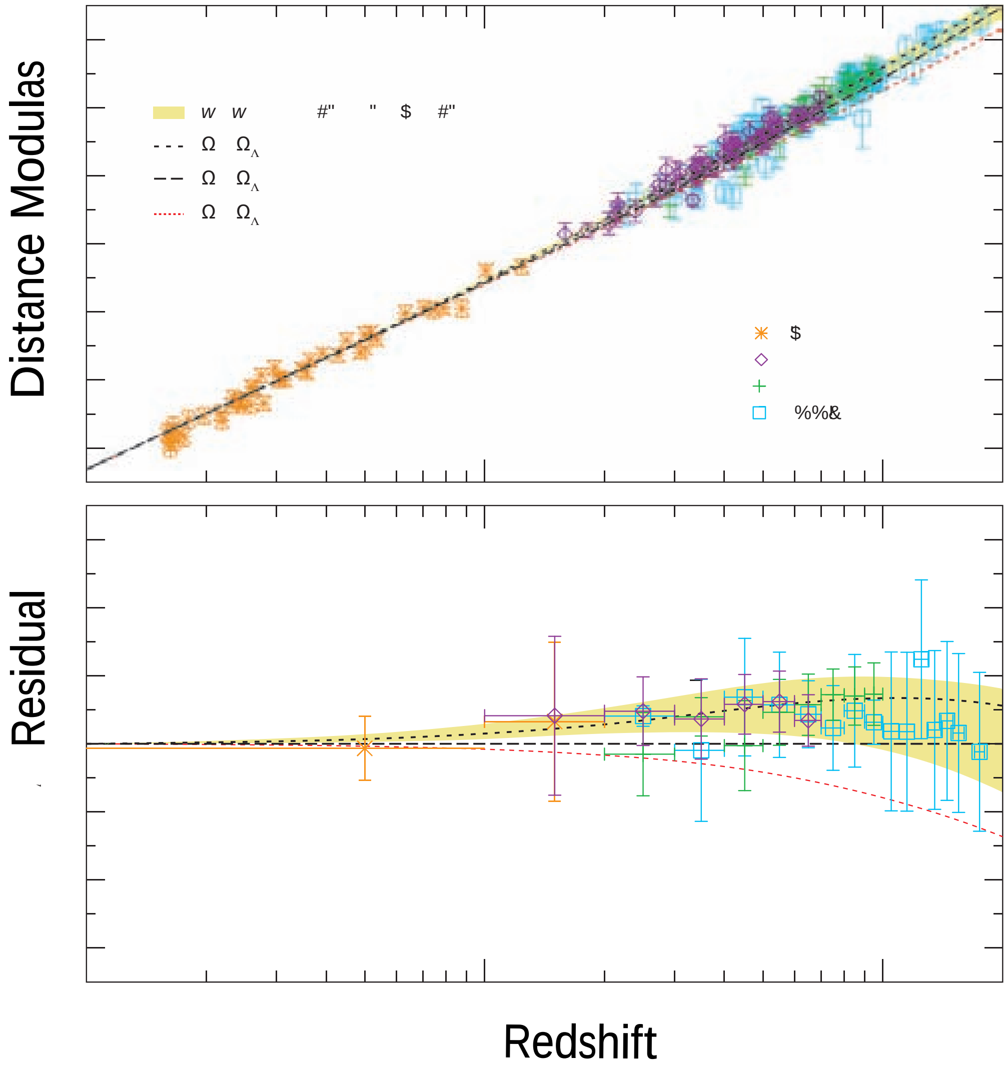
Deceleration: $\dot{a} \downarrow$, as t $\uparrow$ (i.e. a $\uparrow$)

$$\Omega_m = 1, \ \dot{a} = H_0/\sqrt{a}$$

Acceleration: $\dot{a} \uparrow$, as t $\uparrow$ (i.e. a $\uparrow$)

$$\Omega_\Lambda = 1, \ \dot{a} = H_0 a$$

Frieman+ 2008



What is Dark Energy?

- Accelerated expansion
  - Modified G. R.
    - F(R) Gravity
    - Brane World (e.g. DGP)
    - Scalar-Tensor Theory
  - Within G. R.
    - Large Scale Void
    - Coupled Dark Energy
    - Chaplin Gas
    - Back Reaction
    - Topological Defects
    - Phantom Energy
    - Quintessence Field
    - Vacuum Energy
    - Constant of Nature (Λ)

Reviews:

Durrer & Maartens 2008

Copeland, Sami & Tsujikawa 2006

Peebles 2006

Weinberg 1989

What is Dark Energy?

Equation of State: $w = p/\rho$

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

- Is there a better parametrisation?
- 'Figure of Merit' for dark energy experiments

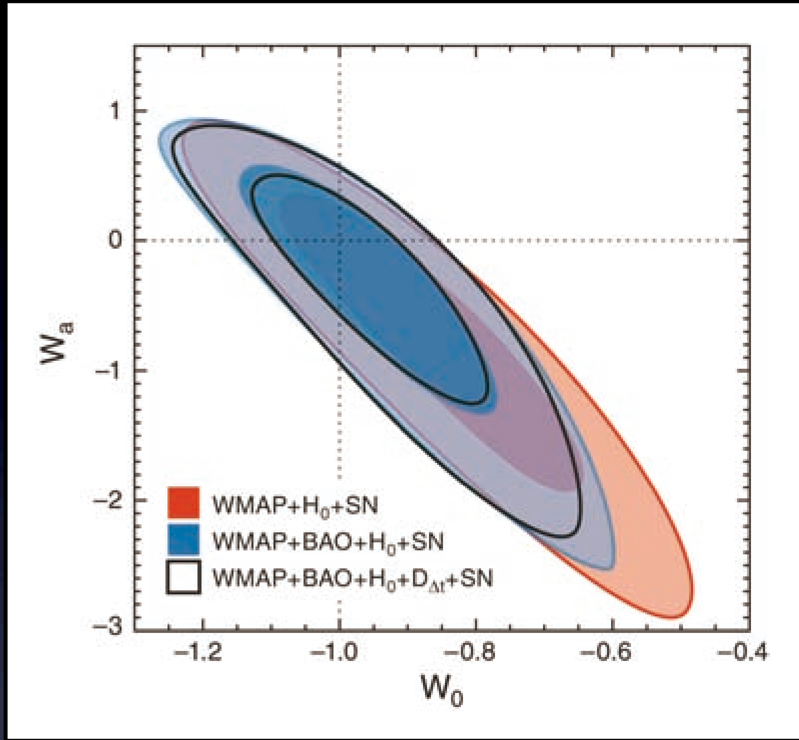
  FoM = $1/(\Delta w_n \times \Delta w_a)$

Amara+ 2010
Albrecht+ (FoMSWG) 2008
Albrecht+ (DETF) 2007

State of the Art Today

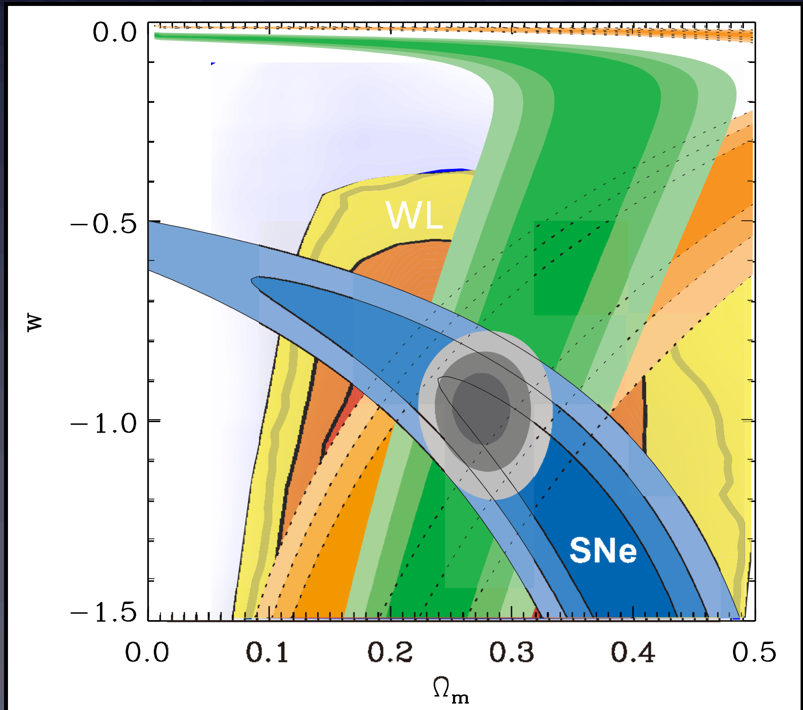
Four established measures of dark energy

- Supernovae
- BAO
- Galaxy Clusters
- Weak Lensing



Current Error Bars

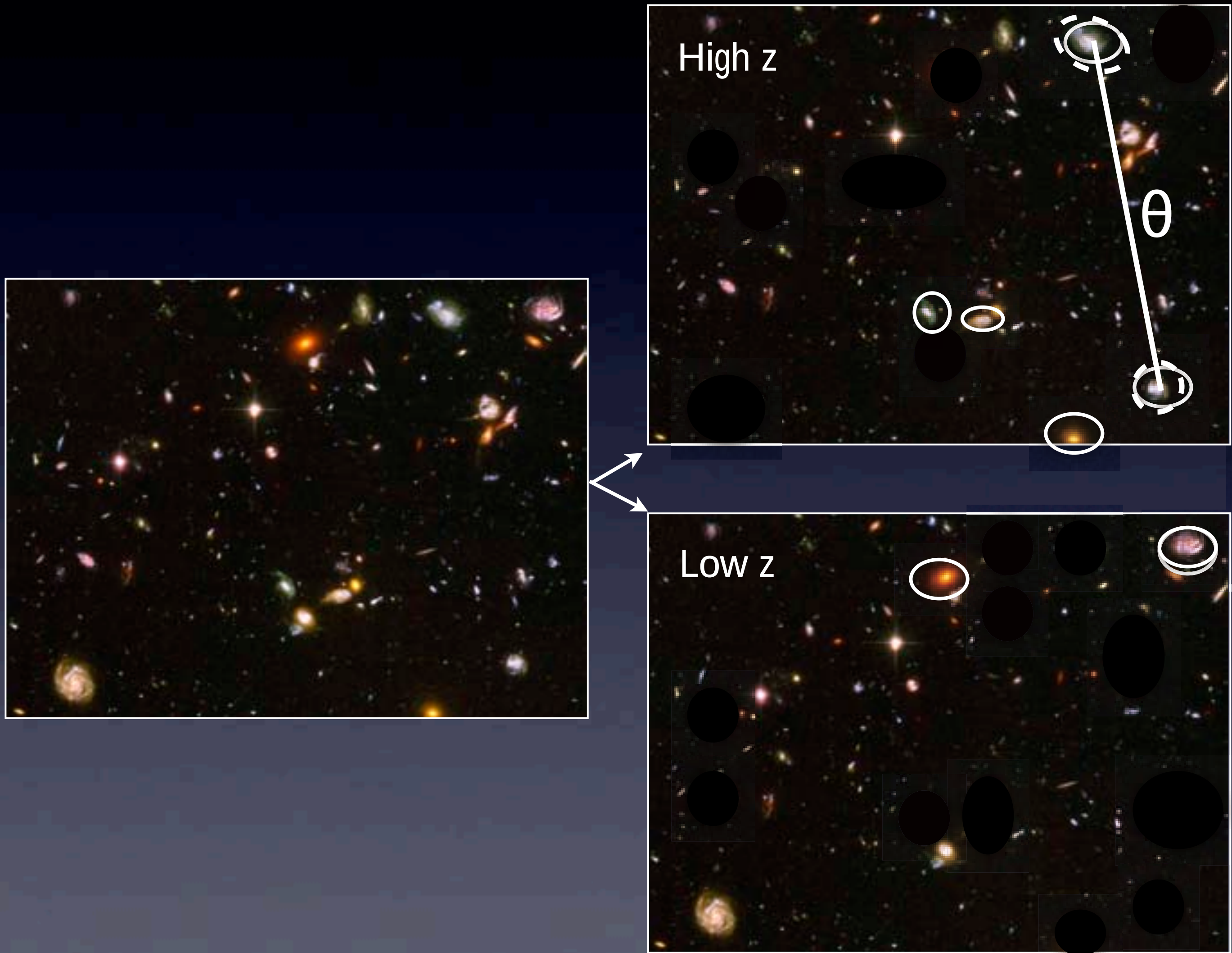
- per method w_0 error weak
- $w_0 \sim -1 \pm 0.2$
- w_a unconstrained

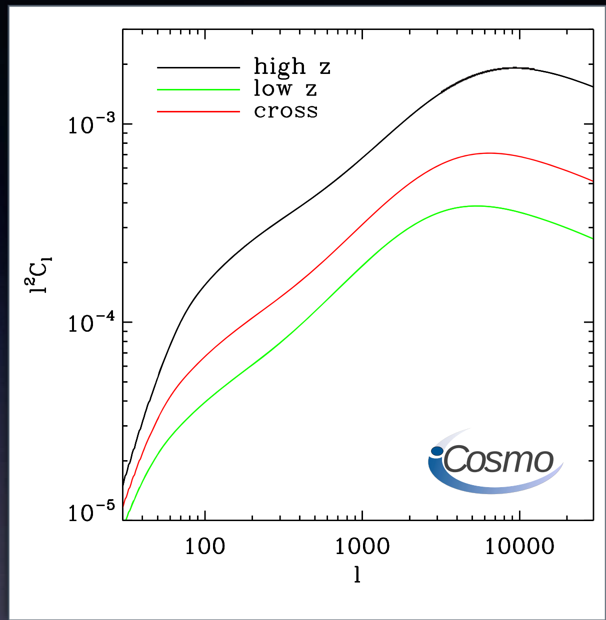


Schrabback+ 2010
Hoekstra+ 2006
Kowalski+ 2008

The Dark Universe with Gravitational Lensing

Lensing Tomography





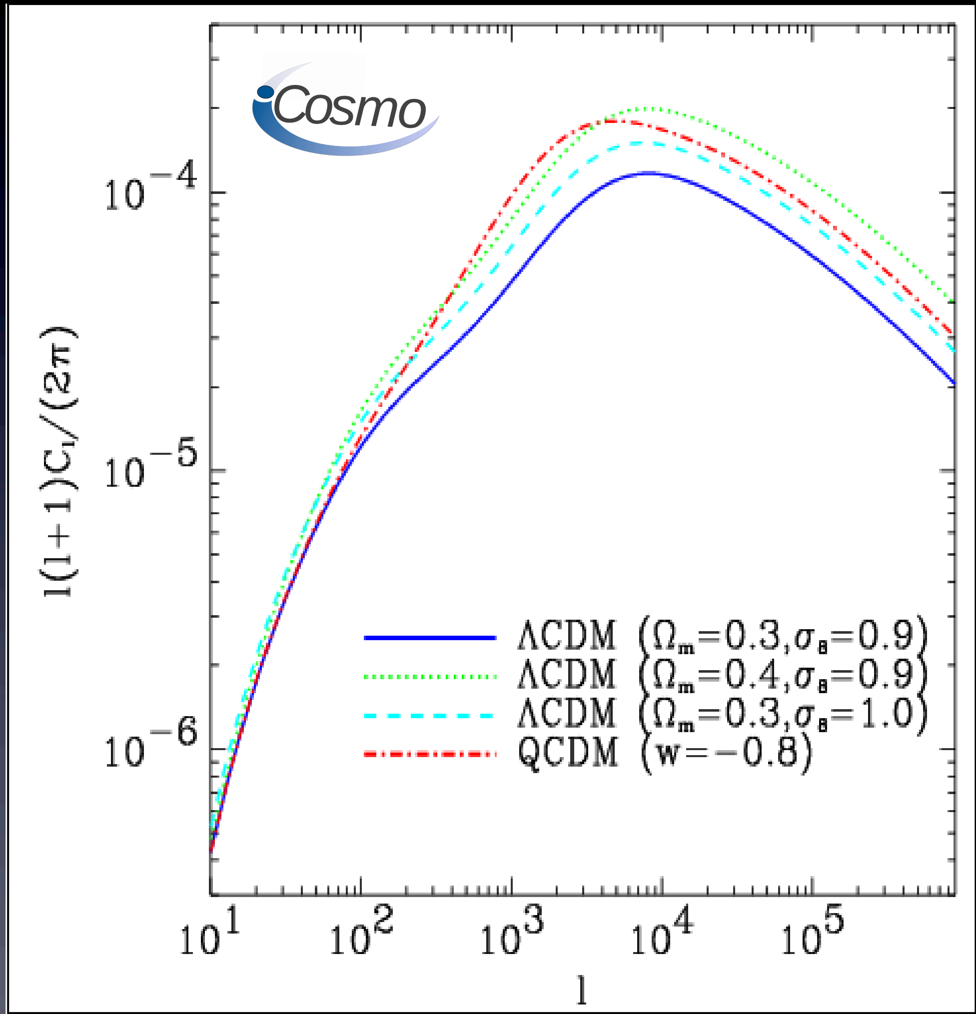
Lensing Correlations and Cosmology

- Lensing Correlation Function

$$C_\ell = \int \frac{q_i(\chi) q_j(\chi)}{\chi^2} P_\delta(k;\chi) d\chi$$

- Weight Function

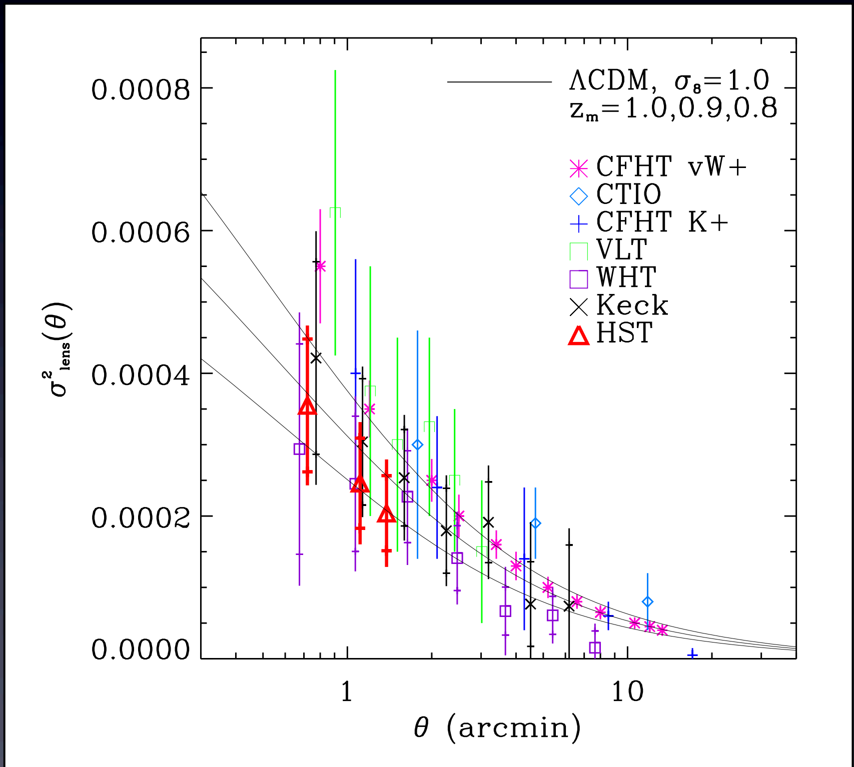
$$q(\chi) \propto \frac{\Omega_m}{a} \int n(\chi_s) \frac{(\chi_s - \chi)\chi}{\chi_s} d\chi_s$$

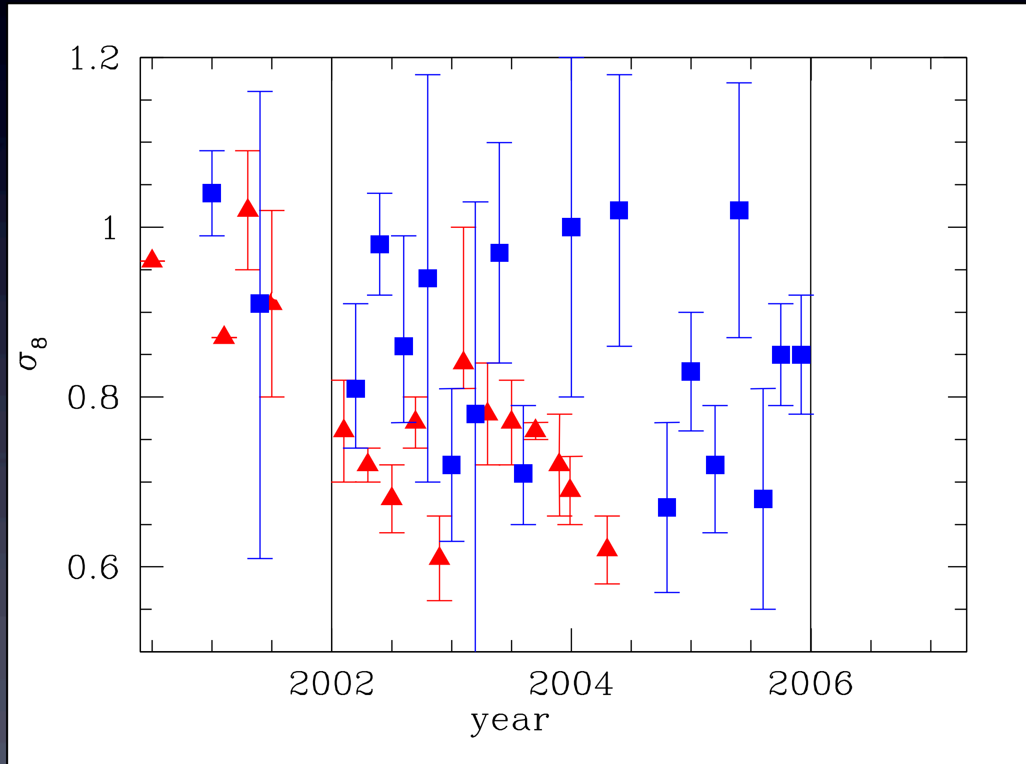


Early Years of Weak Lensing

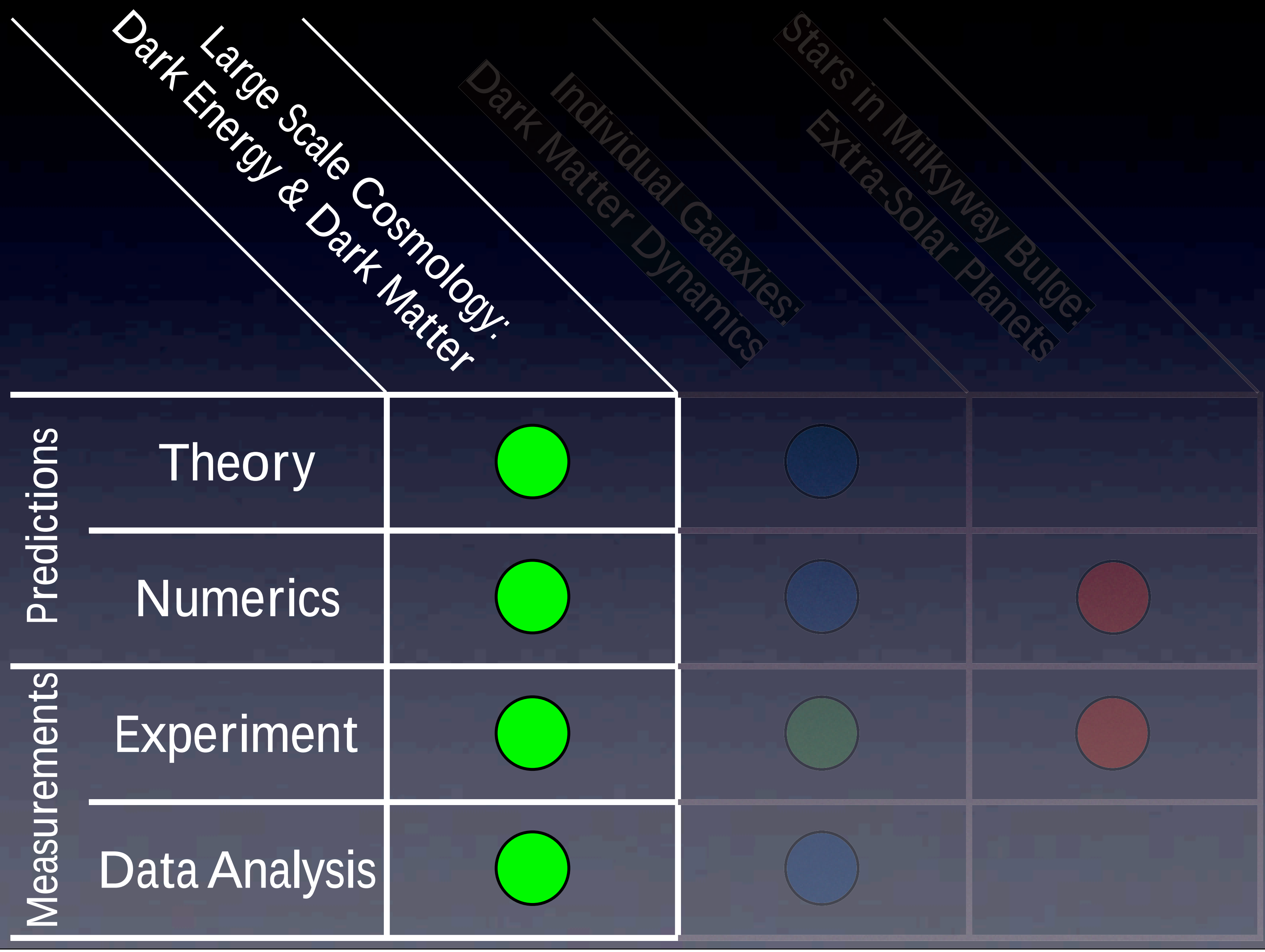
Refregier 2003

Hetterscheidt+ 2007



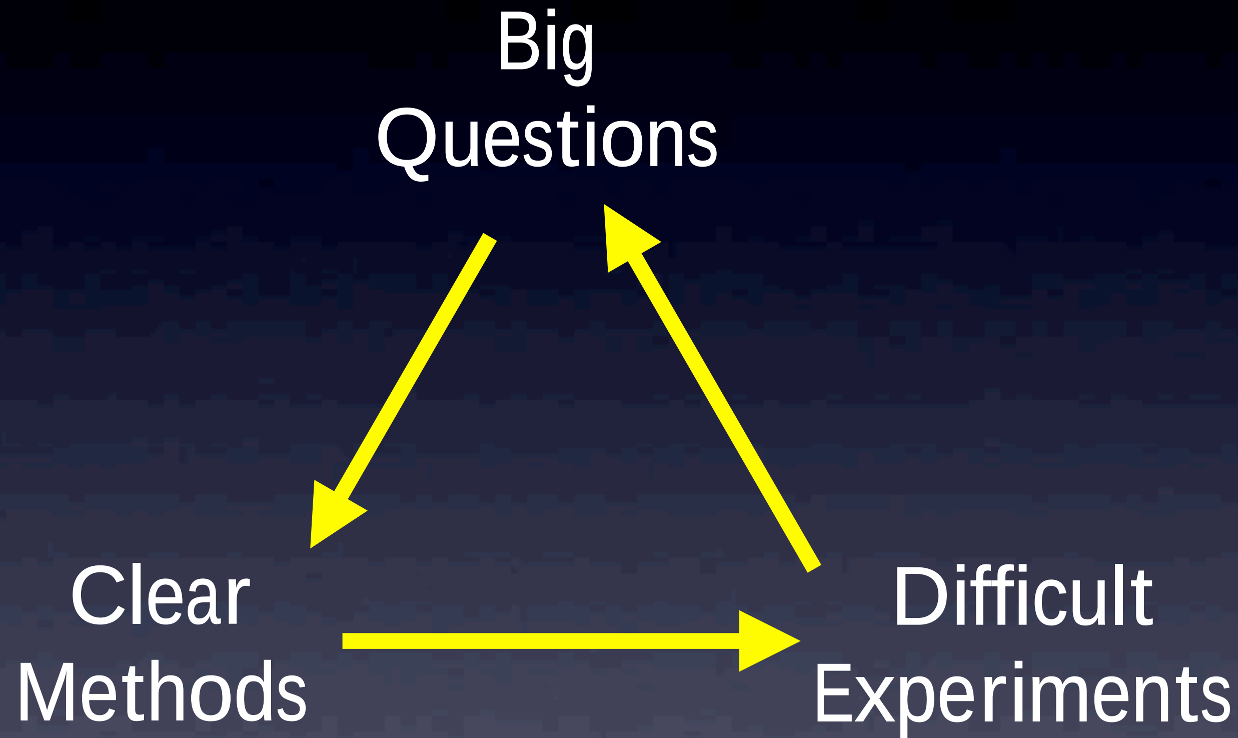


Main Challenges for Weak Lensing



What Physicists are Good at

Impact of dark energy on dynamics and structure formation in the Universe



Weak Lensing Statistics

Euclid/WFIRST/LSST

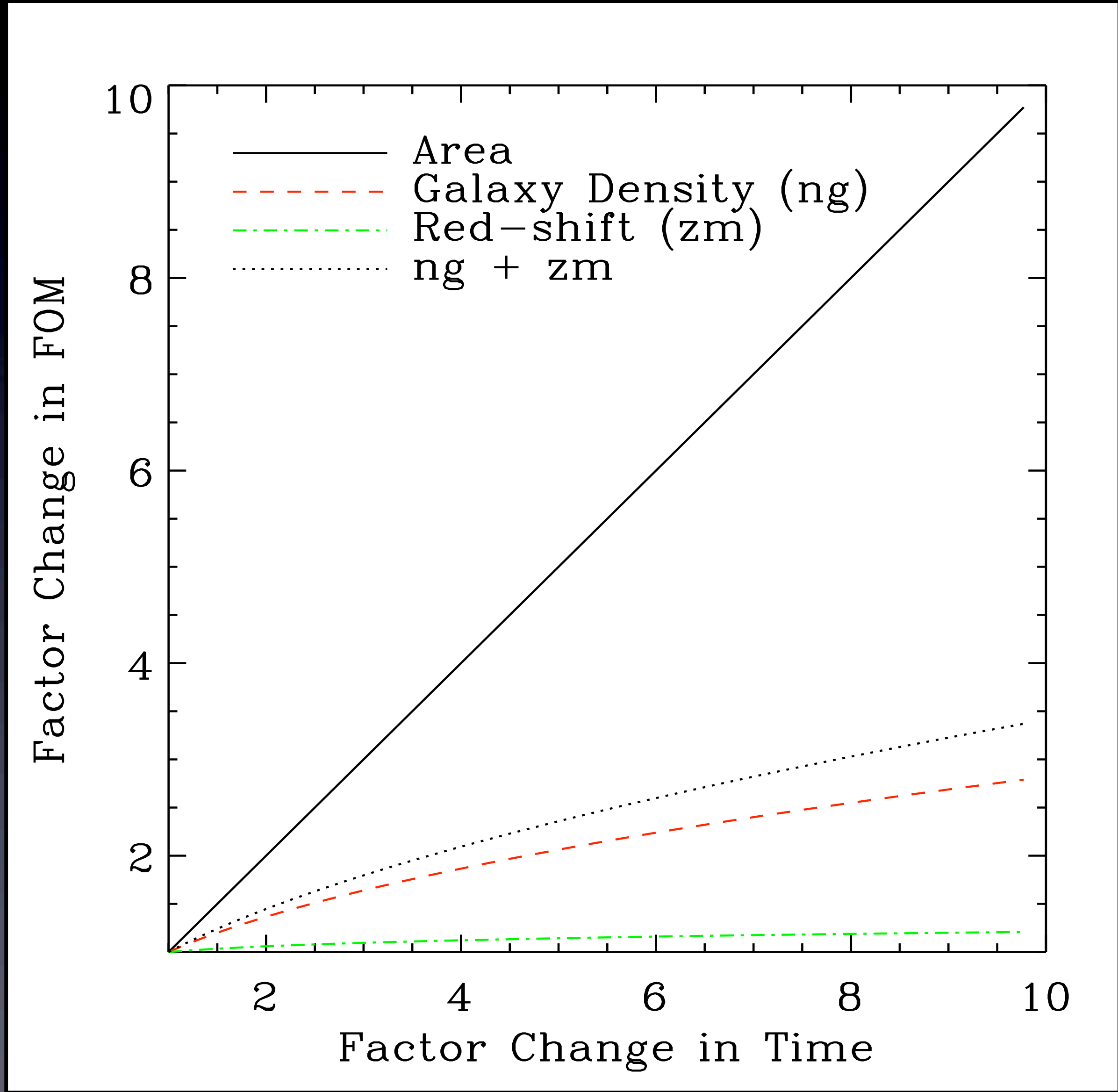
Completing this loop takes a long term investment

Gravitational Lensing Experiments

Designing the Best Lensing Experiment

Amara & Refregier (2007)

- Surveys have three basic properties:
  - Area (A_s)
  - Median redshift (z_m)
  - Number of galaxies (n_g)
- Choice: Area vs. Depth
- Dark Energy Figure of Merit:
  - FOM=$1/(\delta w_n \delta w_a)$



Current and Planned Experiments

Survey	Start (rough dates)
COSMOS	2003
CFHTLS	2003

Above atmosphere:

Current and Planned Experiments

Survey	Start (rough dates)
COSMOS	2003
CFHTLS	2003
Pan-STARRS1	**2009**
KIDS	**2011**
DES	**2012**
HSC	**2012**
HALO (balloon)	**2014**

Above atmosphere:

Current and Planned Experiments

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COSMOS	2003
CFHTLS	2003
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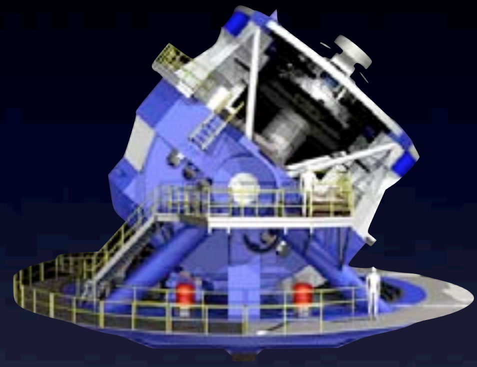
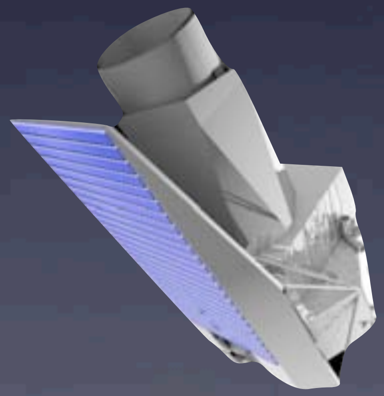
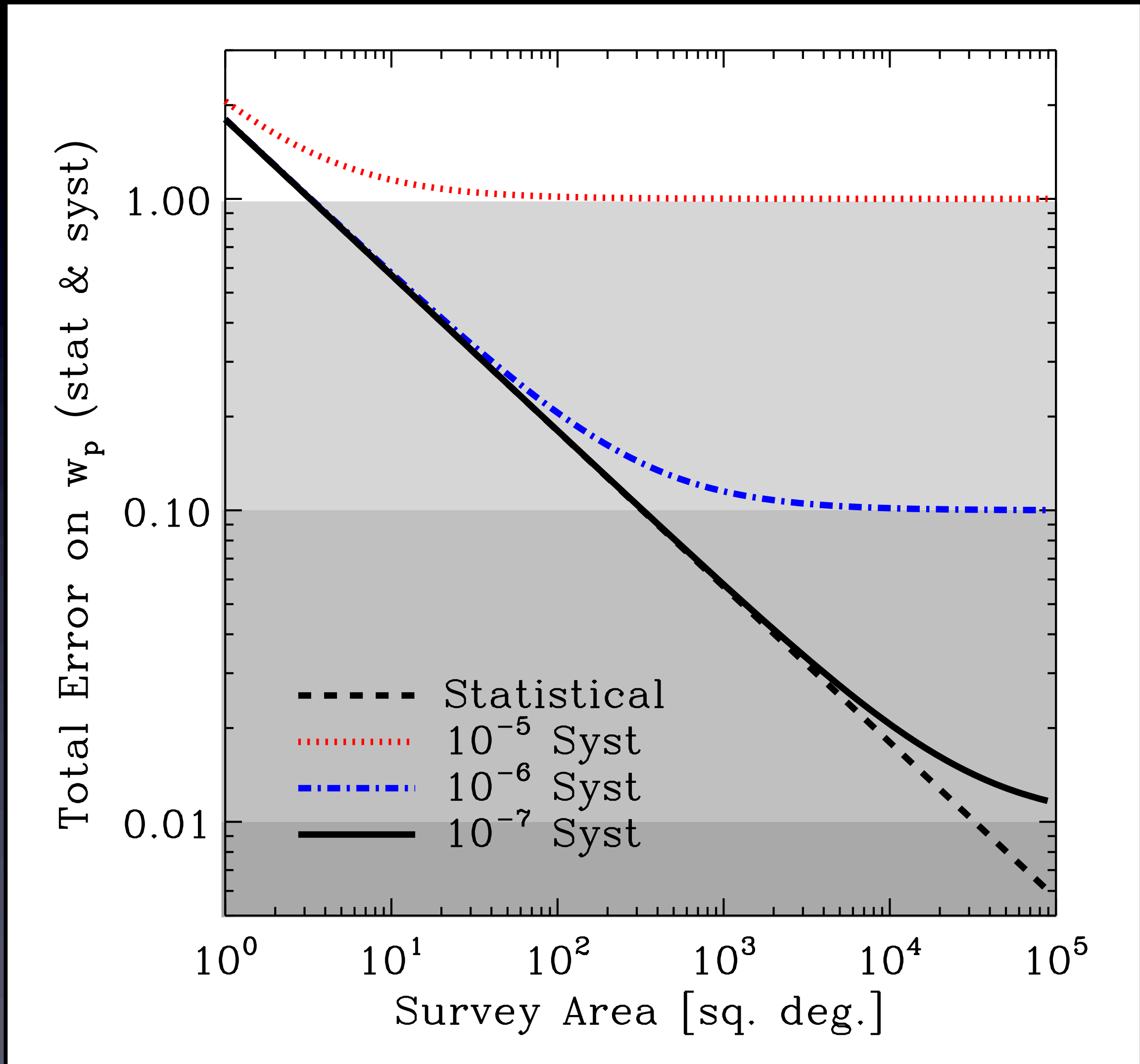
KIDS	2011
DES	2012
HSC	2012
HALO (balloon)	2014
LSST	**2018**
Euclid	**2018**
WFIRST	**?**





Impact of Systematics

Amara & Refregier 2008



Future Targets

$\sigma^2_{sys} < 10^{-7}$

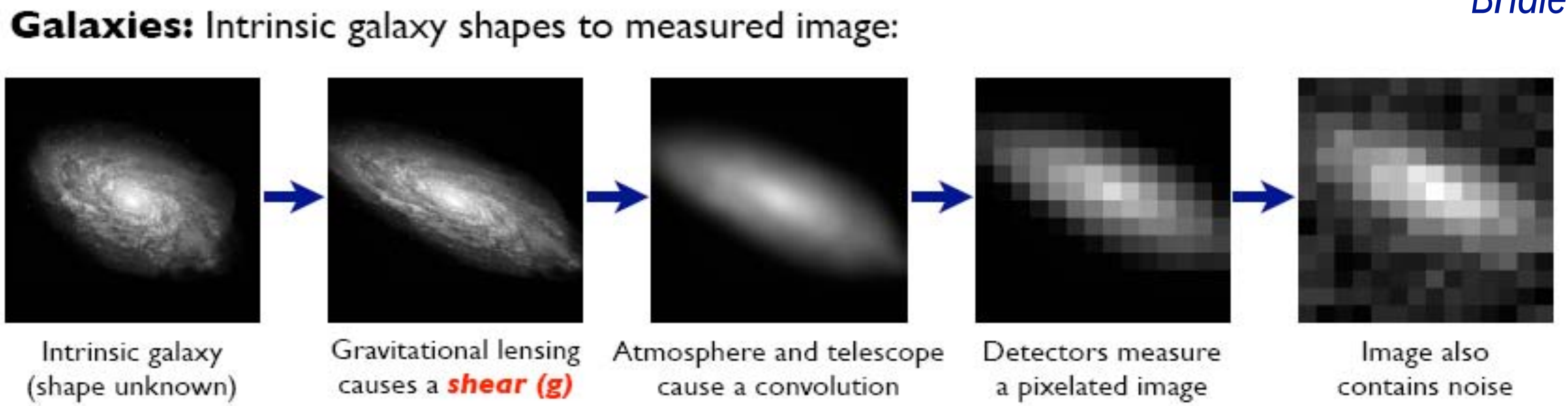
Applies

1) Shape measurement

2) Redshift measurement

Galaxy Shapes

Bridle+ 2008

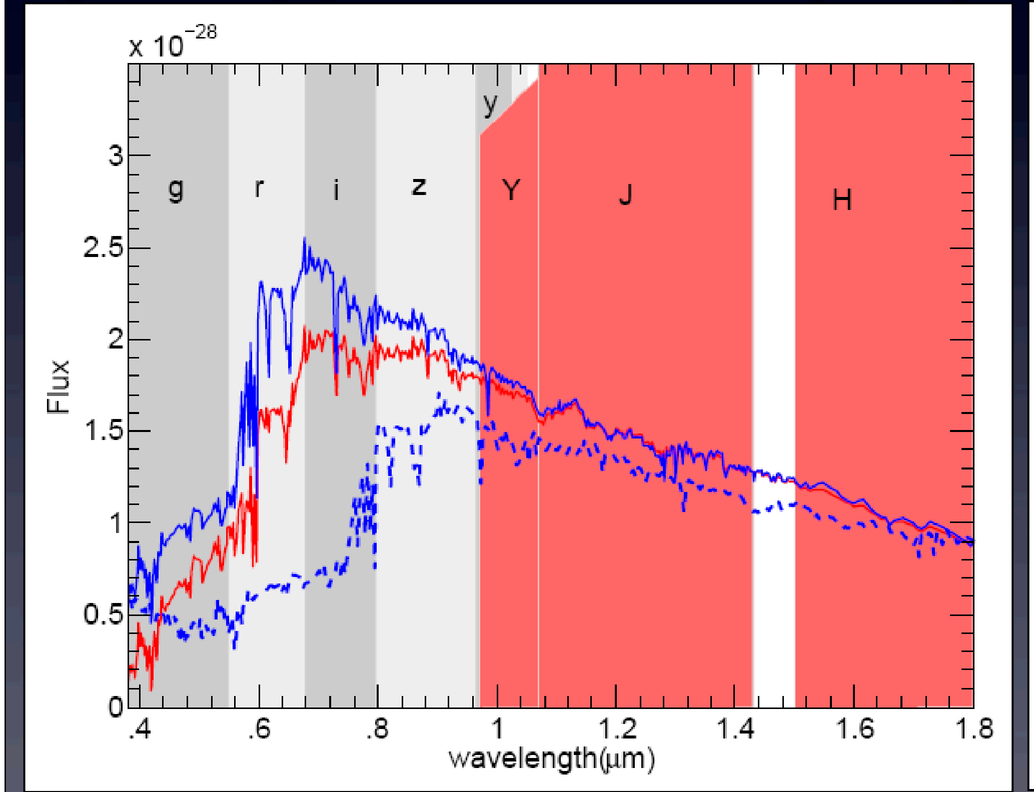


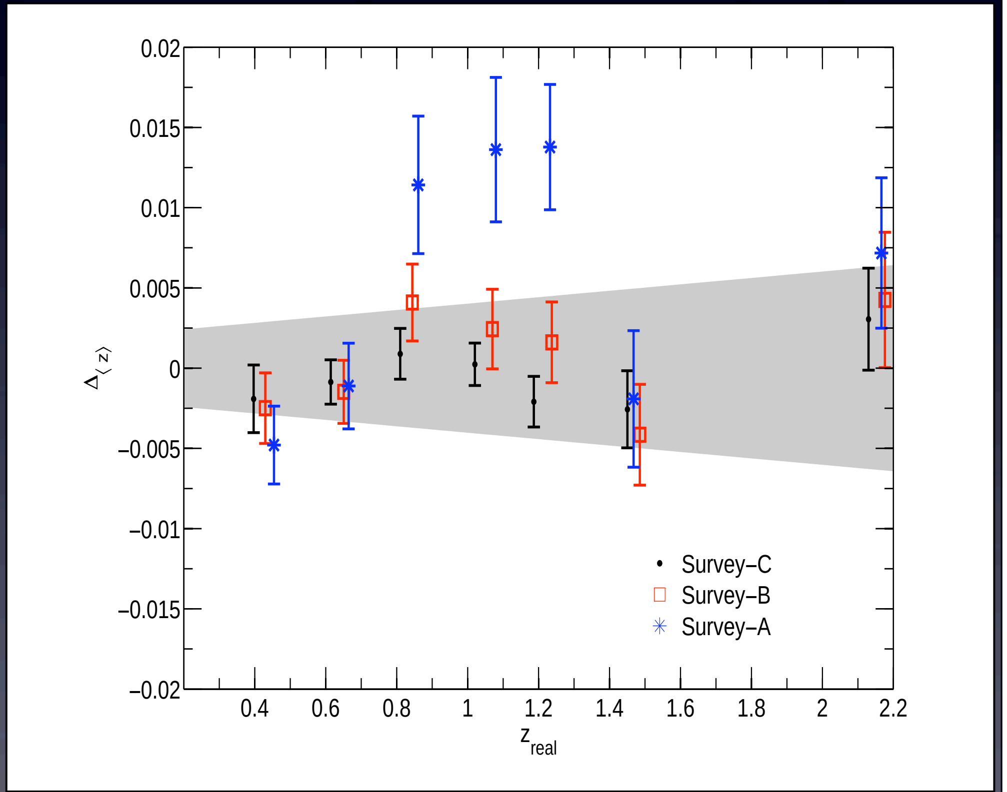
- Key to precision lensing is a well-behaved PSF
- Best achieved in Space.

Amara+ 2010
Cypriano+ 2010
Paulin-Henriksson, Refregier & Amara 2009
Paulin-Henriksson+ 2008

Photometric Redshifts

Amara & Refregier 2007
Abdalla+ 2008
Bordoloi, Amara & Lilly 2010





A Road Map to Precision Lensing

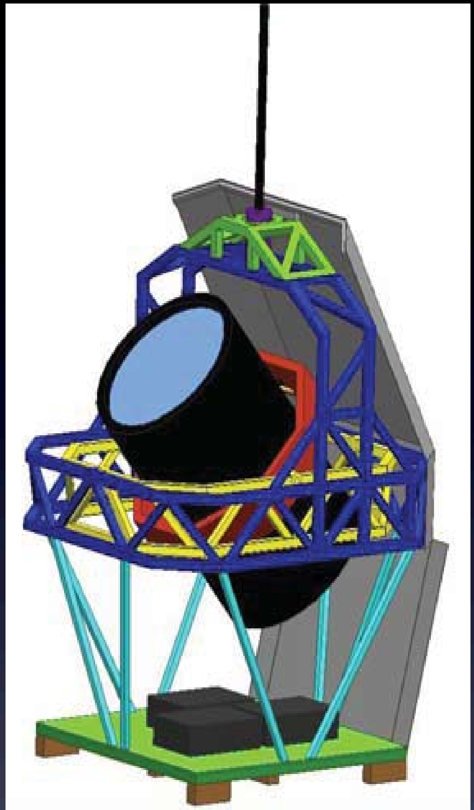
Current: e.g. COSMOS	2 sq. deg.	2003 - Ongoing
Next Generation: e.g. HALO	2,000 sq. deg.	2013 - 2018
Long Term: Euclid/WFIRST/LSST	20,000 sq. deg.	2018 - 2025

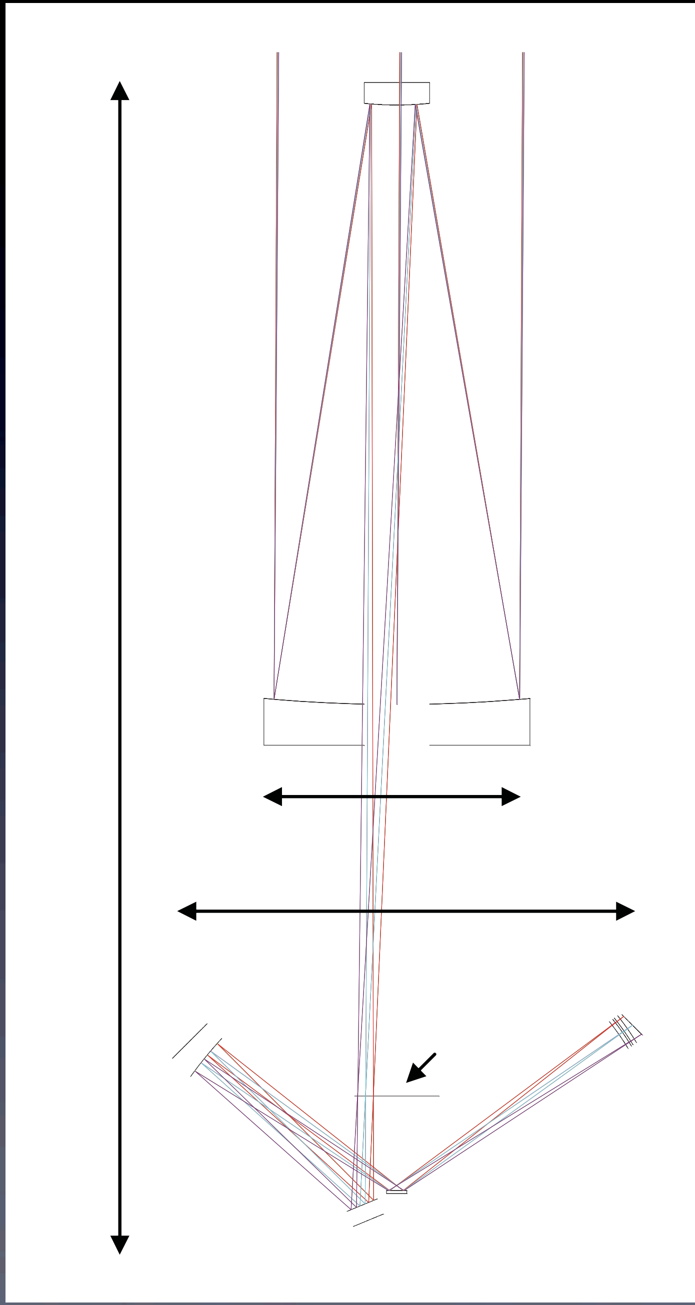
HALO in More Detail

PI: Jason Rhodes (+11 Co-I)

Swiss Role Through ETH:

1. Design optimal survey for dark energy
2. Set the requirements on for the experiment
3. Procure hexapod focusing mechanism
4. Setup a weak lensing data analysis pipeline

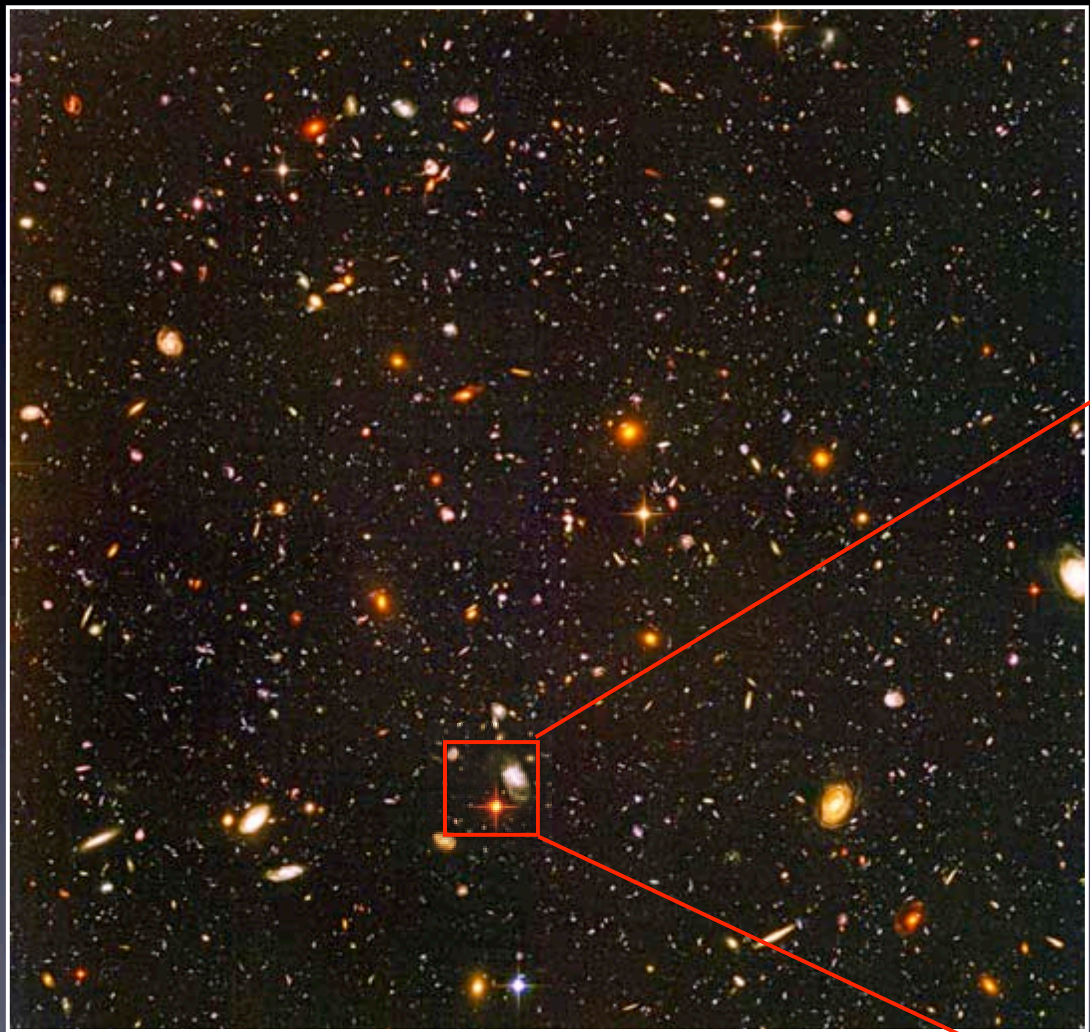




Collaboration:

USA- JPL, Caltech, IPAC, WFF
Switzerland- ETH Zurich
Japan- NAOJ (Satoshi Miyazaki)
UK- U. Edinburgh, U. Durham
France- CEA Saclay

Hubble Ultra Deep Field

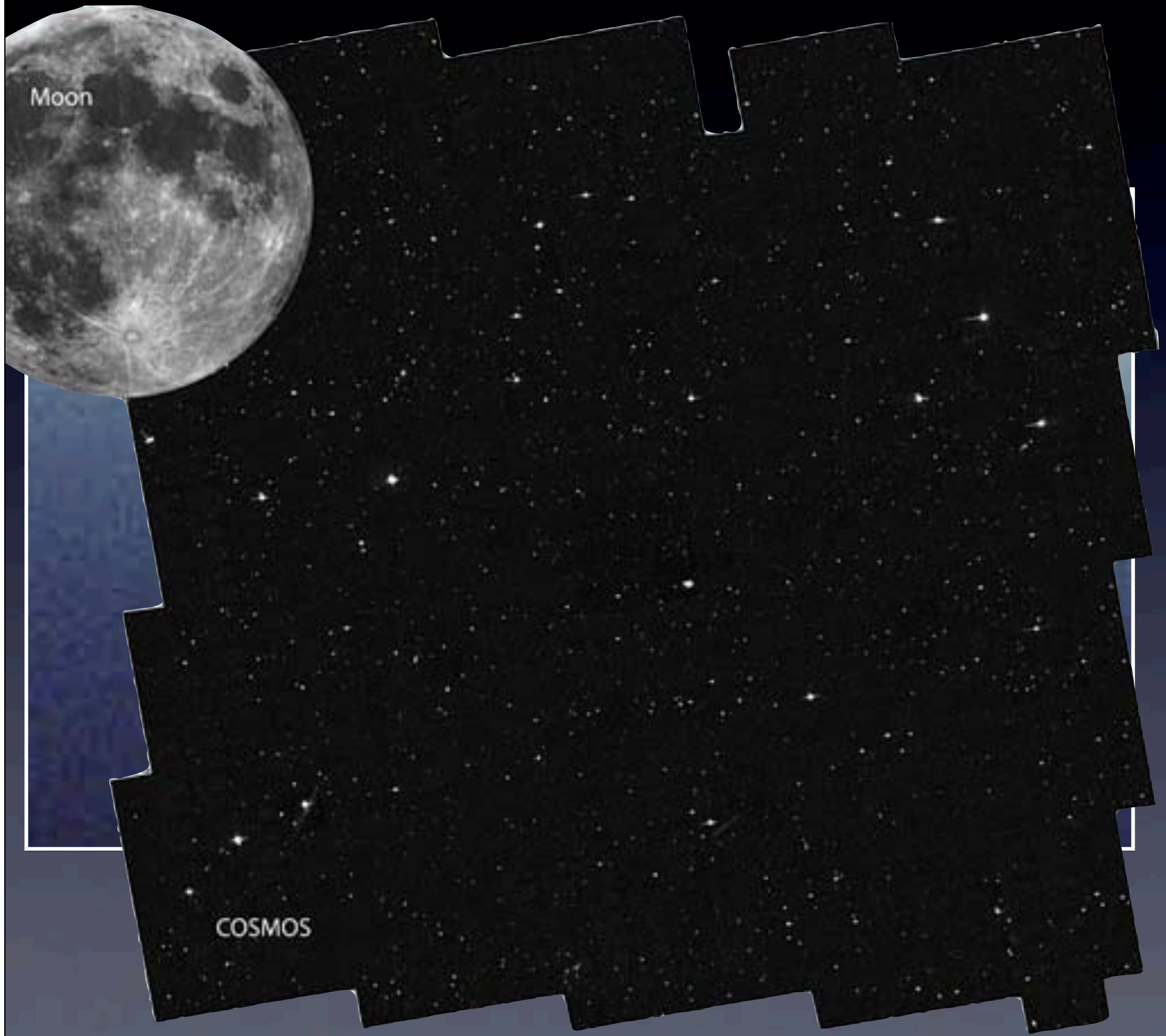


- Over 10,000 Objects
- 0.05'' Resolution

COSMOS

- Largest HST Survey
- 0.5 M Lensed Galaxies
- w < -0.4 (error ~ unity)

HALO



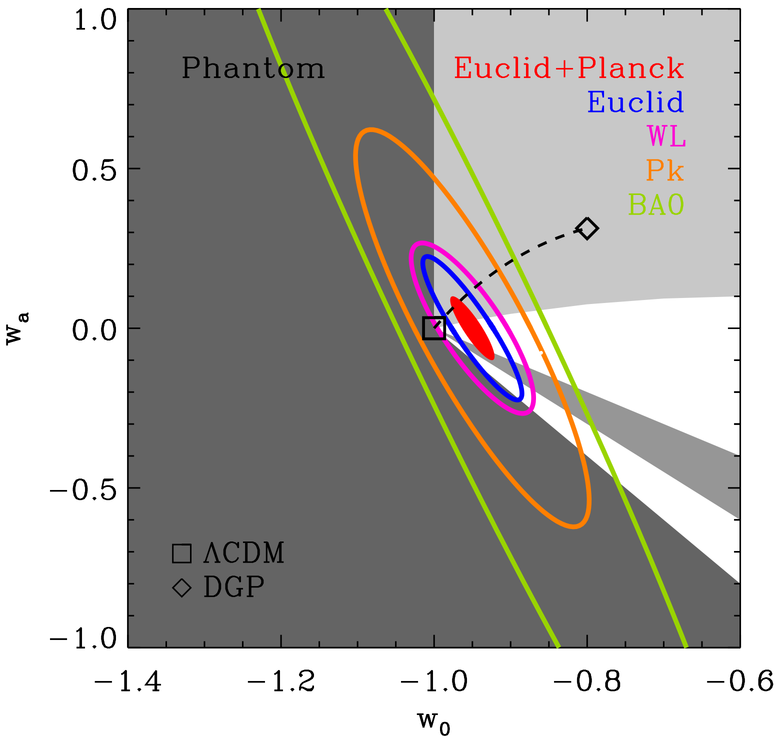
- 2000 Square Degrees
- 100 M Lensed Galaxies
- <10% error on w (alone)

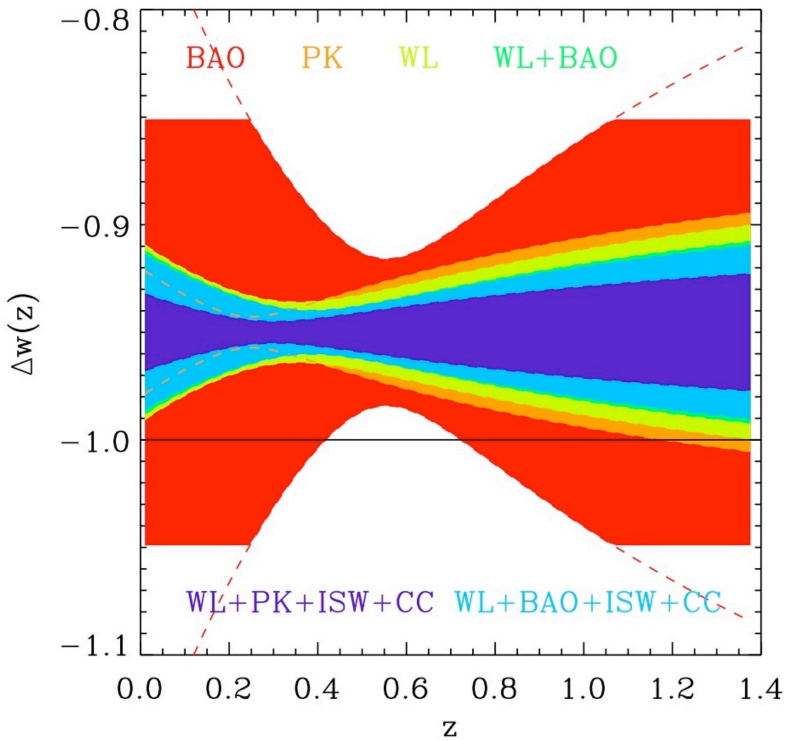
Euclid / WFRIST / LSST

- 20,000 Square Degrees
- 2 B Lensed Galaxies
- 1% error on w

Future Parameter Constraints

	Dark Energy		Densities			Initial Conditions		Hubble	DE FoM[2]
	Δw_p	Δw_a	$\Delta\Omega_m$	$\Delta\Omega_\Lambda$	$\Delta\Omega_b$	$\Delta\sigma_8$	Δn_s	Δh	
Current +WMAP[3]	0.13	-	0.01	0.015	0.0015	0.026	0.013	0.013	**~10**
Planck	-	-	0.008	-	0.0007	0.05	0.005	0.007	**-**
Euclid Req.	0.018	0.15	0.004	0.012	0.006	0.004	0.007	0.022	**400**
Euclid Goal	0.016	0.13	0.003	0.012	0.005	0.003	0.006	0.020	**500**
Euclid +Planck	0.010	0.066	0.0008	0.003	0.0004	0.0015	0.003	0.002	**1500**
Factor gain on Current	**13**	**> 15**	**13**	**5**	**4**	**17**	**4**	**7**	**150**





Concluding Remarks

- Gravitational Lensing: Powerful Tool for Astronomy, Cosmology & Physics
  - Theory is simple
  - Depends on mass regardless of state
  - Relevant on all astronomical scales
- Dark Energy is one of the most compelling open questions in Physics
  - Many competing theories
  - Experimental data on its nature only now becoming available
  - Cosmology is a unique laboratory for testing fundamental physics
- The main challenges in lensing are experimental
  - Very high image quality (& stable PSF) very important
  - We now know how to build such experiments
  - To be a pioneer in this requires a long term investment