



# The Dark Energy Survey



Sarah Bridle (University College London)  
DES Weak Lensing Working Group Co-Coordinator



# The Dark Energy Survey

- Dark Energy
- DES Collaboration
- DES Science
- DECam
- Survey Strategy
- Data Management
- Status





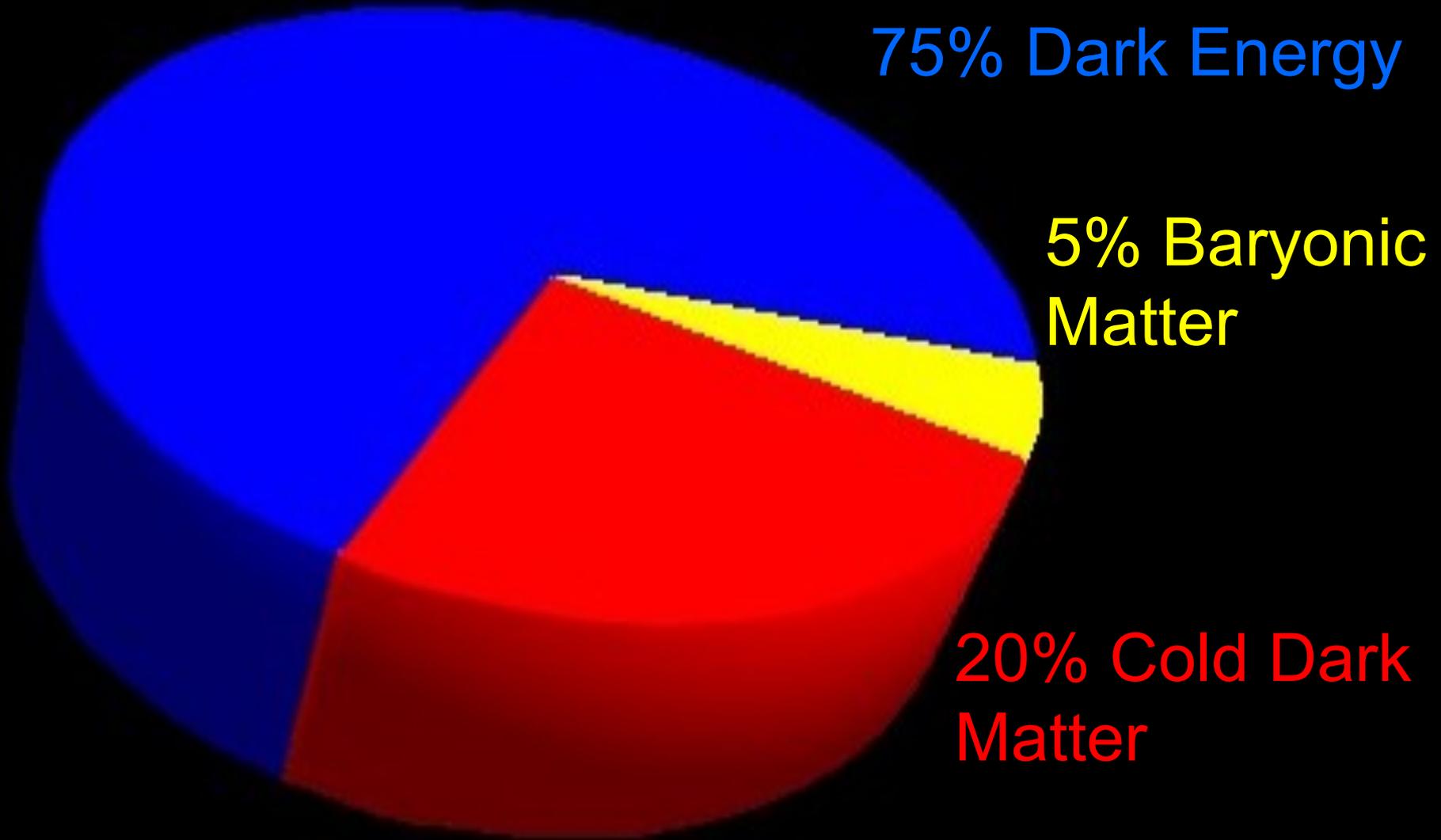
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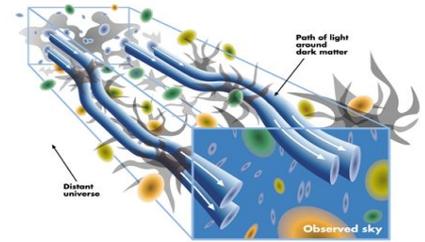
# Concordance Model



# Probes of Dark Energy

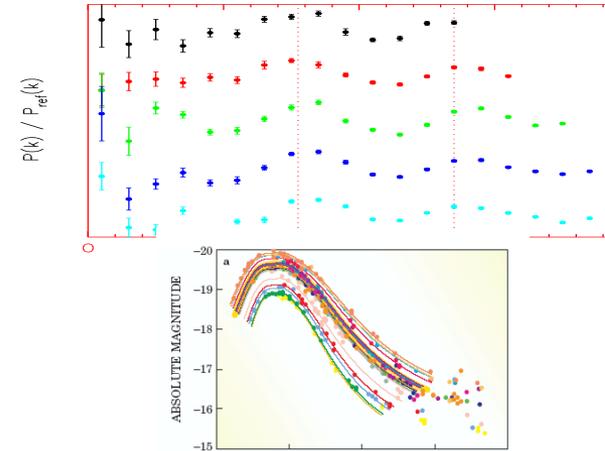
## Cosmic Shear

Evolution of dark matter perturbations  
Angular diameter distance  
Growth rate of structure



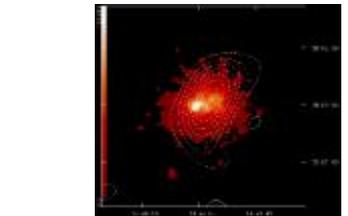
## Baryon Wiggles

Standard ruler  
Angular diameter distance



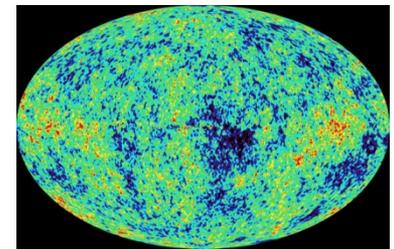
## Supernovae

Standard candle  
Luminosity distance



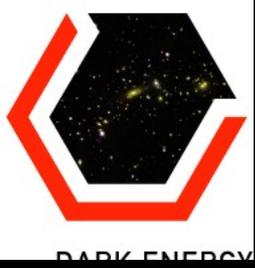
## Cluster counts

Evolution of dark matter perturbations  
Angular diameter distance  
Growth rate of structure



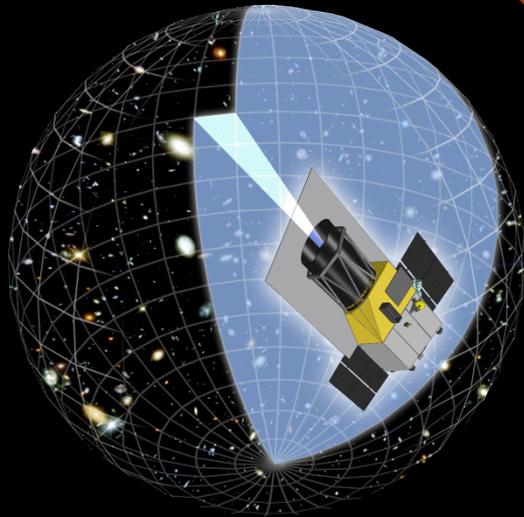
## CMB

Snapshot at  $\sim 400,000$  yr, viewed from  $z=0$   
Angular diameter distance to  $z \sim 1000$   
Growth rate of structure (from ISW)



# Future Dark Energy Surveys

The Dark Energy Survey



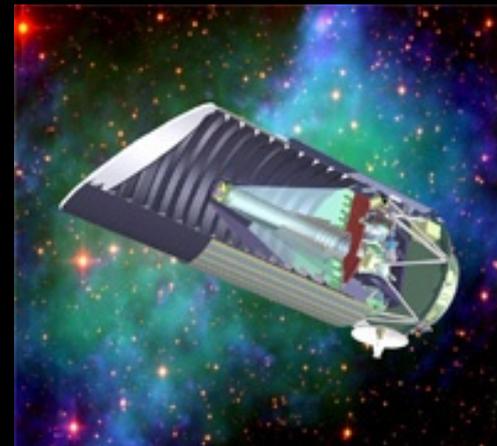
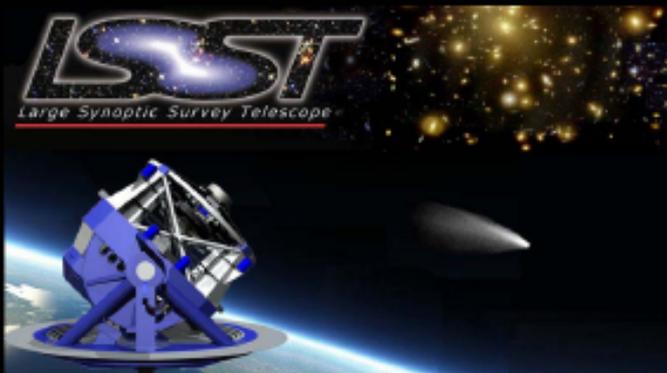
EUCLID



SuMIRe Project

Subaru Measurement of Images and Redshifts

FIRST - 最先端研究開発支援プログラム -



WFIRST





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# The Dark Energy Survey

- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg<sup>2</sup> *grizY* to 24th mag
  - 30 deg<sup>2</sup> repeat (SNe)
- Build new 3 deg<sup>2</sup> FOV camera and Data management system
  - Survey 2012-2017 (525 nights)
  - Facility instrument for Blanco





# The DES Collaboration



Fermilab

University of Illinois at Urbana-Champaign/NCSA

University of Chicago

Lawrence Berkeley National Lab

NOAO/CTIO

DES Spain Consortium

DES United Kingdom Consortium

University of Michigan

Ohio State University

University of Pennsylvania

DES Brazil Consortium

Argonne National Laboratory

SLAC-Stanford-Santa Cruz Consortium

Universitats-Sternwarte Munchen

Texas A&M University

plus Associate members at:

Brookhaven National Lab, U. North Dakota, Paris, Taiwan

Over 120 members  
plus students &  
postdocs

Funding: DOE, NSF;  
UK: STFC, SRIF;  
Spain Ministry of  
Science, Brazil:  
FINEP, Ministry of  
Science, FAPERJ;  
Germany: Excellence  
Cluster; collaborating  
institutions





# The DES Collaboration (Oct 2010)





**Joint Oversight Group**  
DOE, NSF

**DES Council**  
Fermilab, NCSA, NOAO

**DES Project Office**  
J. Frieman, Director  
R. Kron, Deputy Director  
J. Annis, Project Scientist  
D. Tucker, Calibration Scientist  
D. Finley, Schedule & Shipping

**Executive Committee**  
Proj. Director, Chair  
Dep. Director, Vice Chair  
DECam PM  
DES DM PM  
CFIP PM  
NOAO Instrument Scientist  
DES Project Scientist  
Science Committee Chair

**Management Committee**  
Institutional representatives  
Director is Chair

**Systems Interface Working Group**  
Deputy Director is Chair

**CFIP**  
T. Abbott, PM  
A. Walker, NOAO Instrument Scientist

**DECam**  
B. Flaugher, PM  
D. DePoy, Project Scientist

**DES DM**  
D. Petravick, PM  
J. Mohr, Project Scientist

**Science Committee**  
O. Lahav, Chair



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# DES Science Committee

- SC Chair: O. Lahav
- Large Scale Structure: E. Gaztanaga & W. Percival
- Weak Lensing: S. Bridle & B. Jain
- Clusters: T. McKay & J. Mohr
- SN Ia: J. Marriner & B. Nichol
- Photo-z: F. Castander & H. Lin
- Simulations: G. Evrard & A. Kravtsov
- Galaxy Evolution: D. Thomas & R. Wechsler
- QSO: P. Martini & R. McMahon
- Strong Lensing: L. Buckley-Geer & M. Makler
- Milky Way: B. Santiago & B. Yanny
- Theory & Combined Probes: W. Hu & J. Weller



# DES Science Summary

## Four Probes of Dark Energy

### • Galaxy Clusters

- ~100,000 clusters to  $z > 1$
- Synergy with SPT
- Sensitive to growth of structure and geometry

### • Weak Lensing

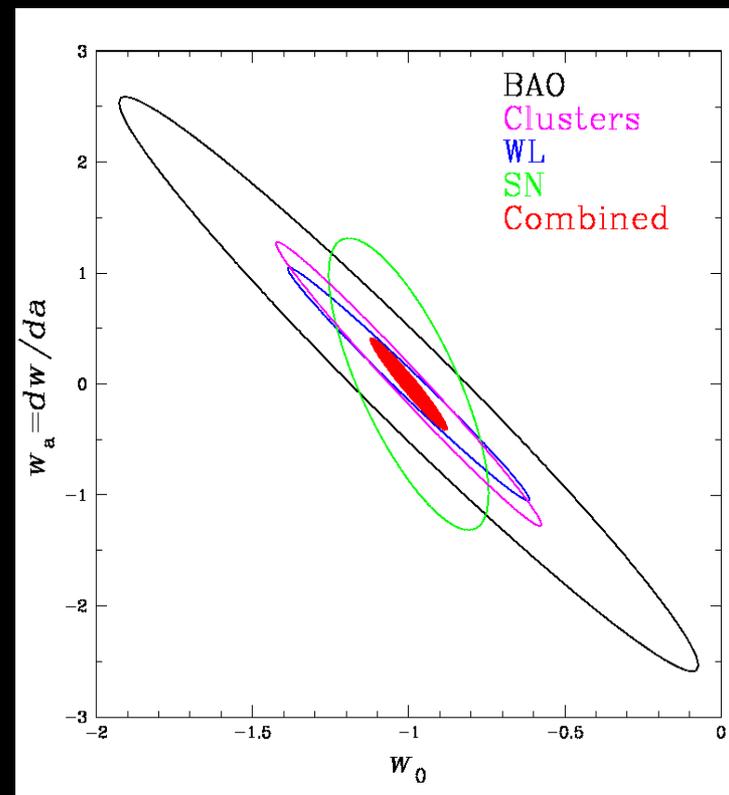
- Shape measurements of 300 million galaxies
- Sensitive to growth of structure and geometry

### • Baryon Acoustic Oscillations

- 300 million galaxies to  $z = 1$  and beyond
- Sensitive to geometry

### • Supernovae

- 30 sq deg time-domain survey
- ~4000 well-sampled SNe Ia to  $z \sim 1$
- Sensitive to geometry



**Factor 3-5 improvement over Stage II DETF Figure of Merit**



# Cluster counts

- Elements of the Method:

- Clusters are proxies for massive halos and can be identified optically to redshifts  $z > 1$

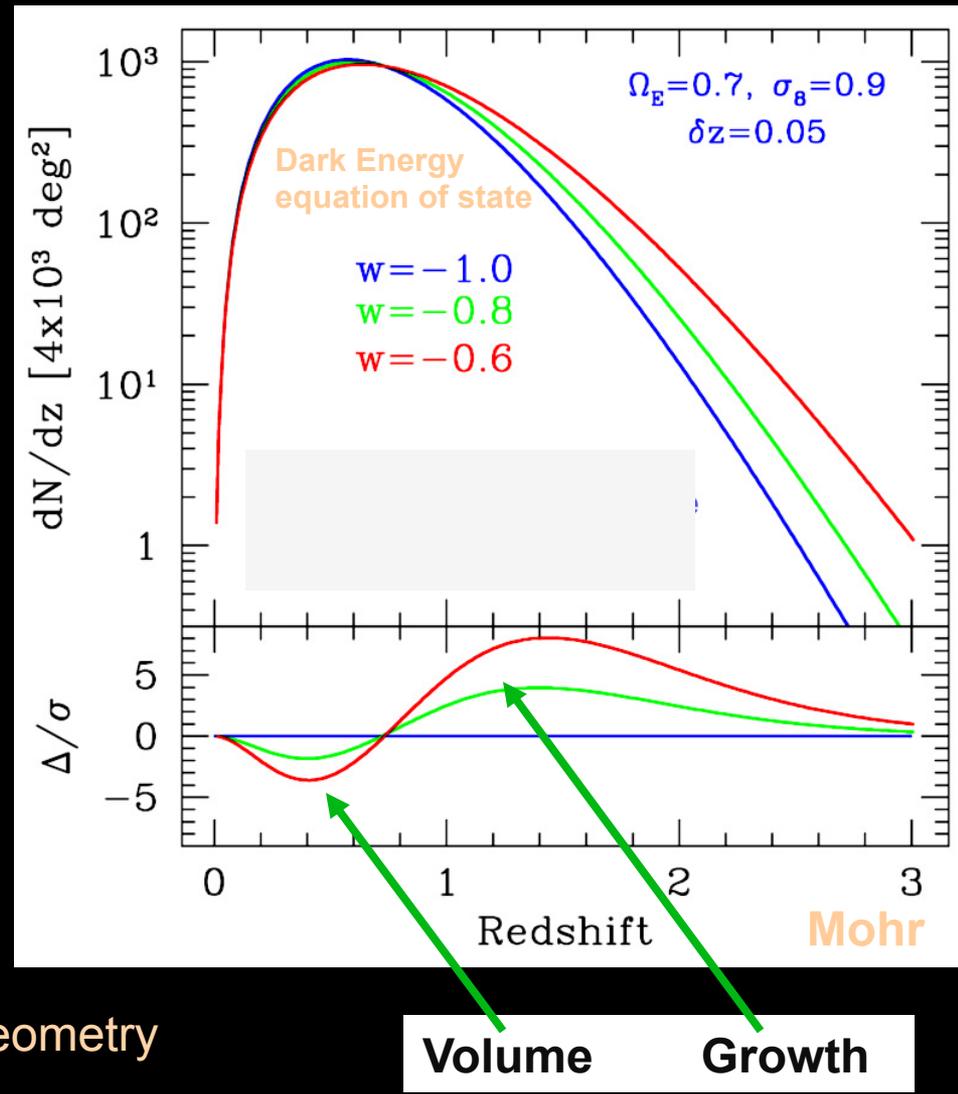
- Galaxy colors provide photometric redshift estimates for each cluster

- Observable proxies for cluster mass: optical richness (DES), SZ flux decrement (SPT), weak lensing mass (DES), X-ray flux (eRosita)

- Cluster spatial correlations help calibrate mass estimates

- ~100,000 clusters to  $z > 1$
- Synergy with SPT
- Sensitive to growth of structure and geometry

## Number of clusters above mass threshold

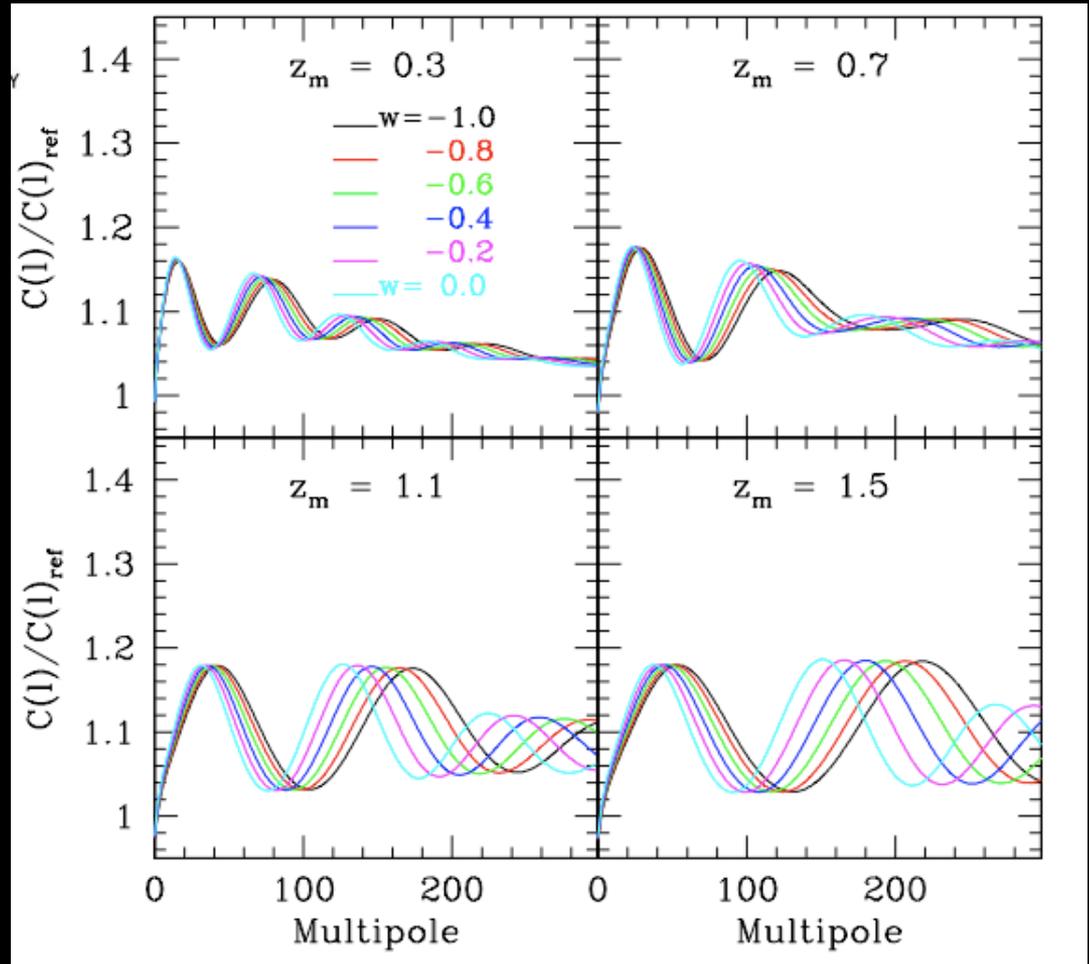




# Large Scale Structure

**Galaxy Angular  
Correlation Function  
in Photo-z bins  
-> baryon acoustic  
oscillations**

**Systematics:  
photo-zs,  
correlated  
photometric  
errors, non-  
linearity, scale-  
dependent bias**



- 300 million galaxies to  $z = 1$  and beyond
- Sensitive to geometry

Fosalba & Gaztanaga



# Total Neutrino Mass

## DES+Planck vs. KATRIN

$M_\nu < 0.1 \text{ eV}$        $M_\nu < 0.6 \text{ eV}$

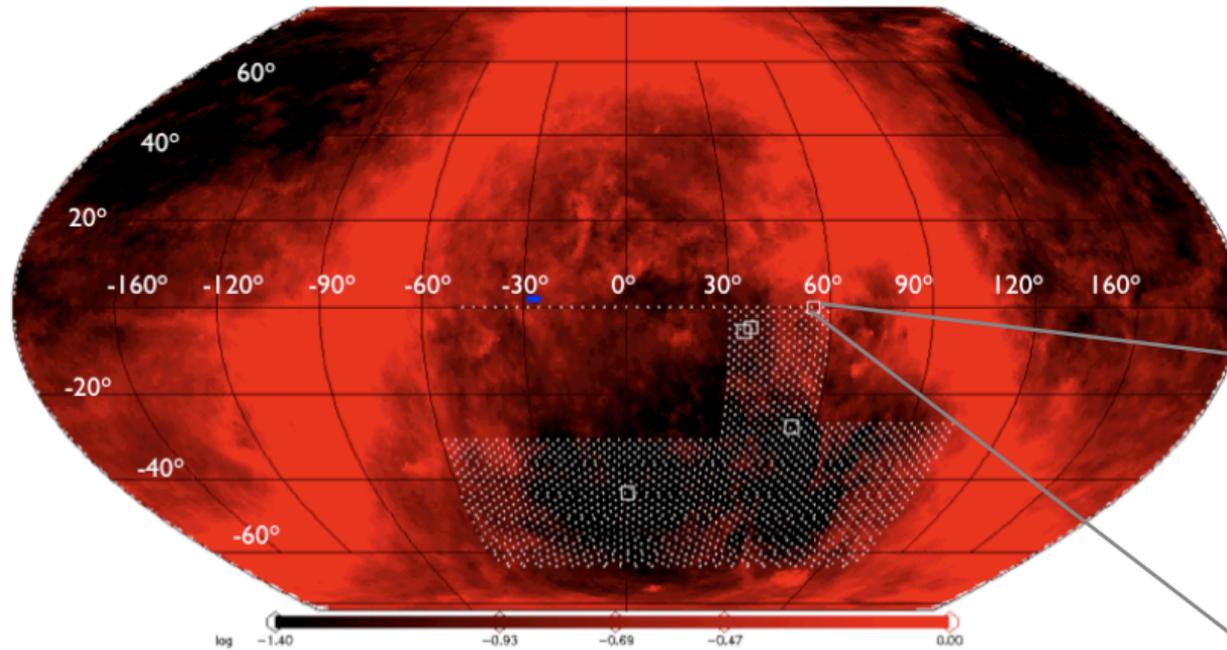


Lahav, Kiakotou, Abdalla and Blake (2010) 0910.4714

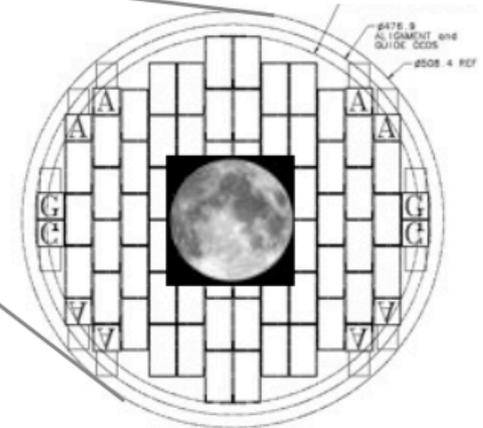


DARK ENERGY SURVEY

# DES SN Survey



Fields to overlap with existing and near-future deep imaging (e.g., CDF-S, SNLS, VIDEO) and spectroscopic surveys (DEEP2, VIPERS, VVDS, WiggleZ, GAMA I/II).



## 10 DES fields

Visit once every ~4 days.

2 deep + 8 shallow (30 deg<sup>2</sup>)

deep: 6600 sec per visit (*griz*)

shallow: 800 sec per visit (*griz*)

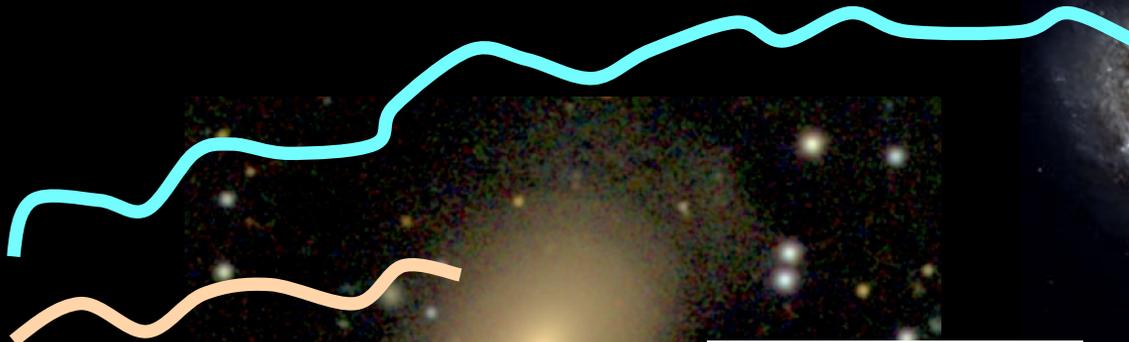
good z-band efficiency (~4x higher than CFHT/MegaCam) and target high-z SN Ia

→ good rest-frame g-band light curves of z~1 SN Ia.

**~4000 well-sampled SNe Ia to z ~1**

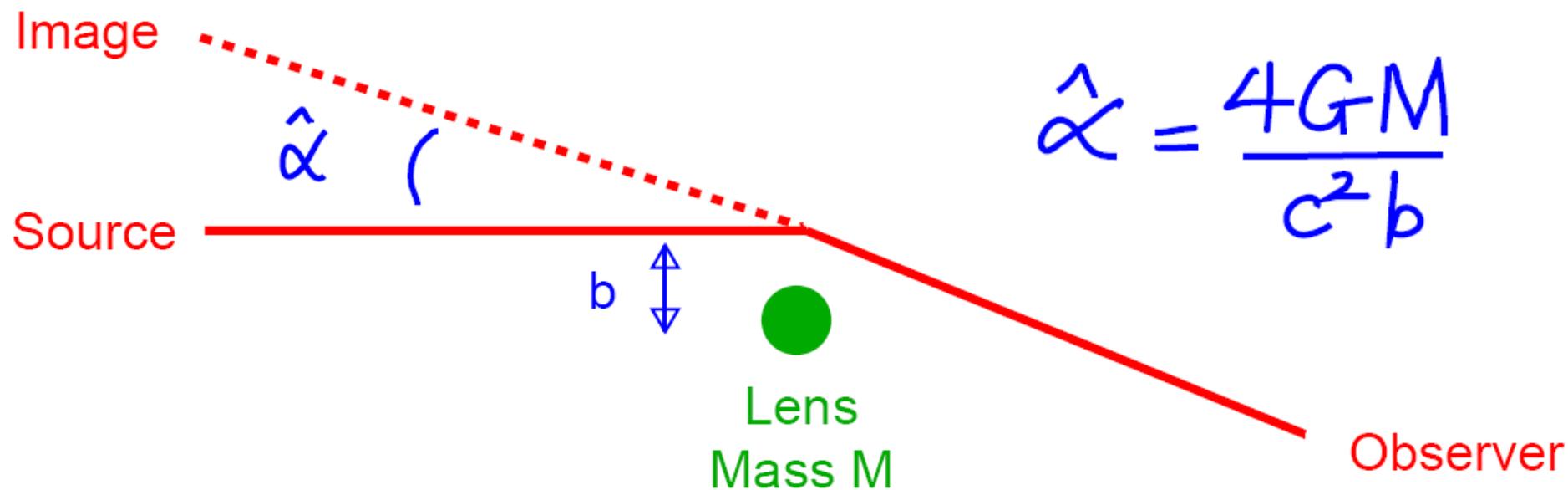


# Weak Lensing





# Just one Equation from General Relativity





**Galaxy Cluster Abell 2218**  
Hubble Space Telescope • WFPC2



DARK ENERGY  
SURVEY



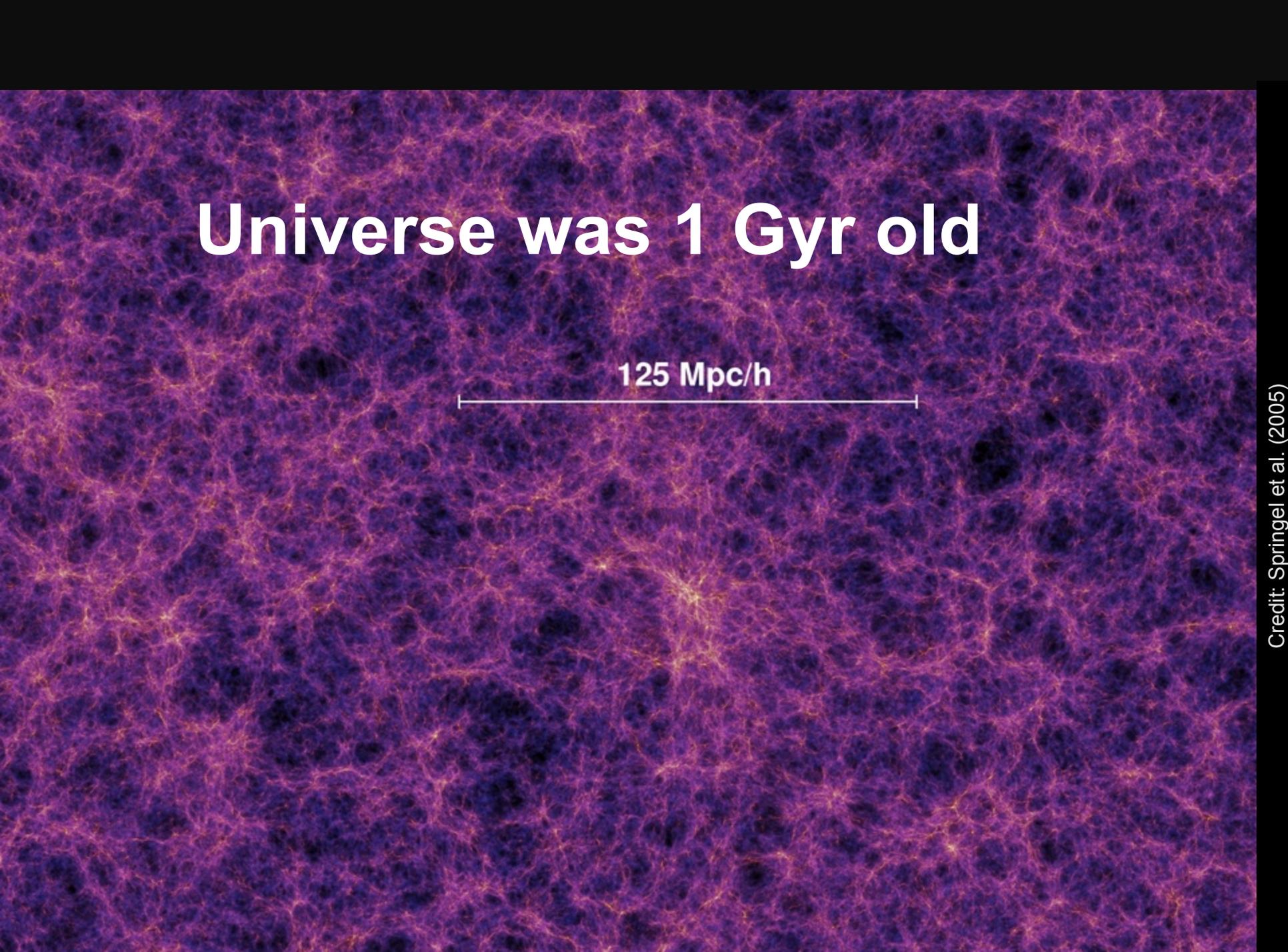
# Universe was 0.2 Gyr old

125 Mpc/h



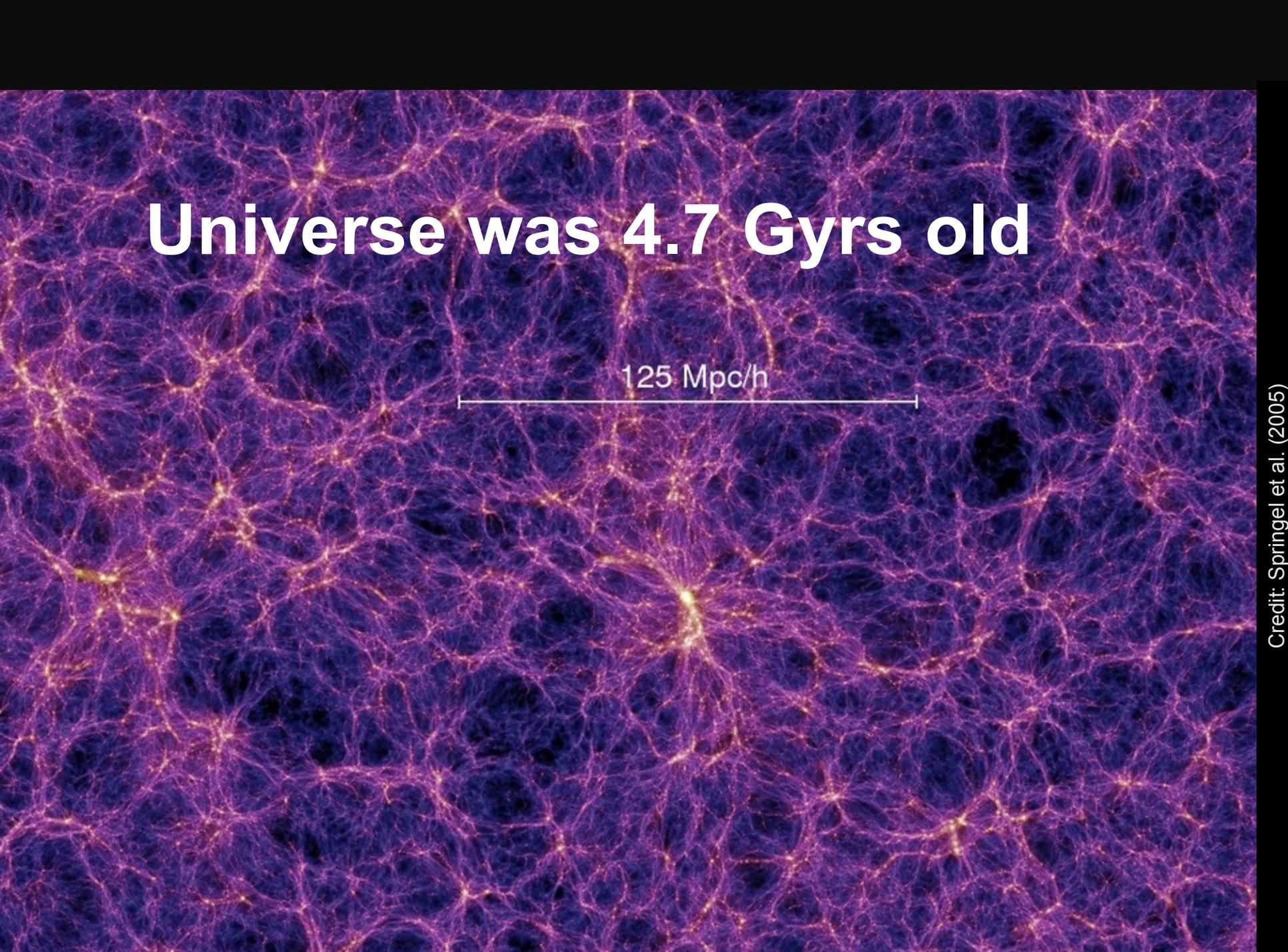
# Universe was 1 Gyr old

125 Mpc/h



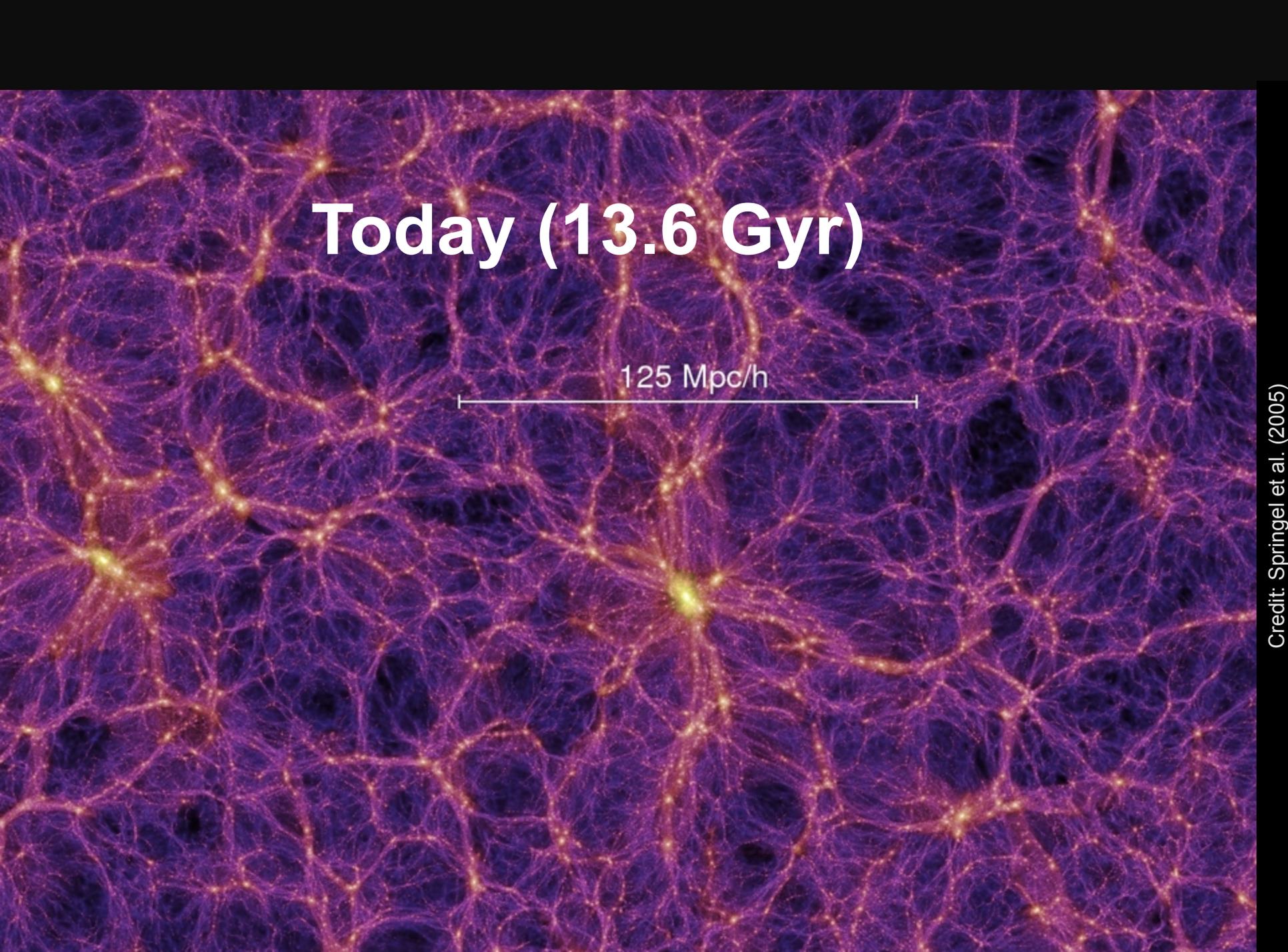
# Universe was 4.7 Gyrs old

125 Mpc/h

A visualization of the cosmic web at 4.7 Gyrs old. The image shows a complex network of dark purple filaments and nodes, representing the distribution of matter in the universe. The filaments are interconnected, forming a web-like structure. The nodes are brighter, indicating regions of higher density. A scale bar is present in the center, labeled '125 Mpc/h', indicating the distance between two points on the web.

# Today (13.6 Gyr)

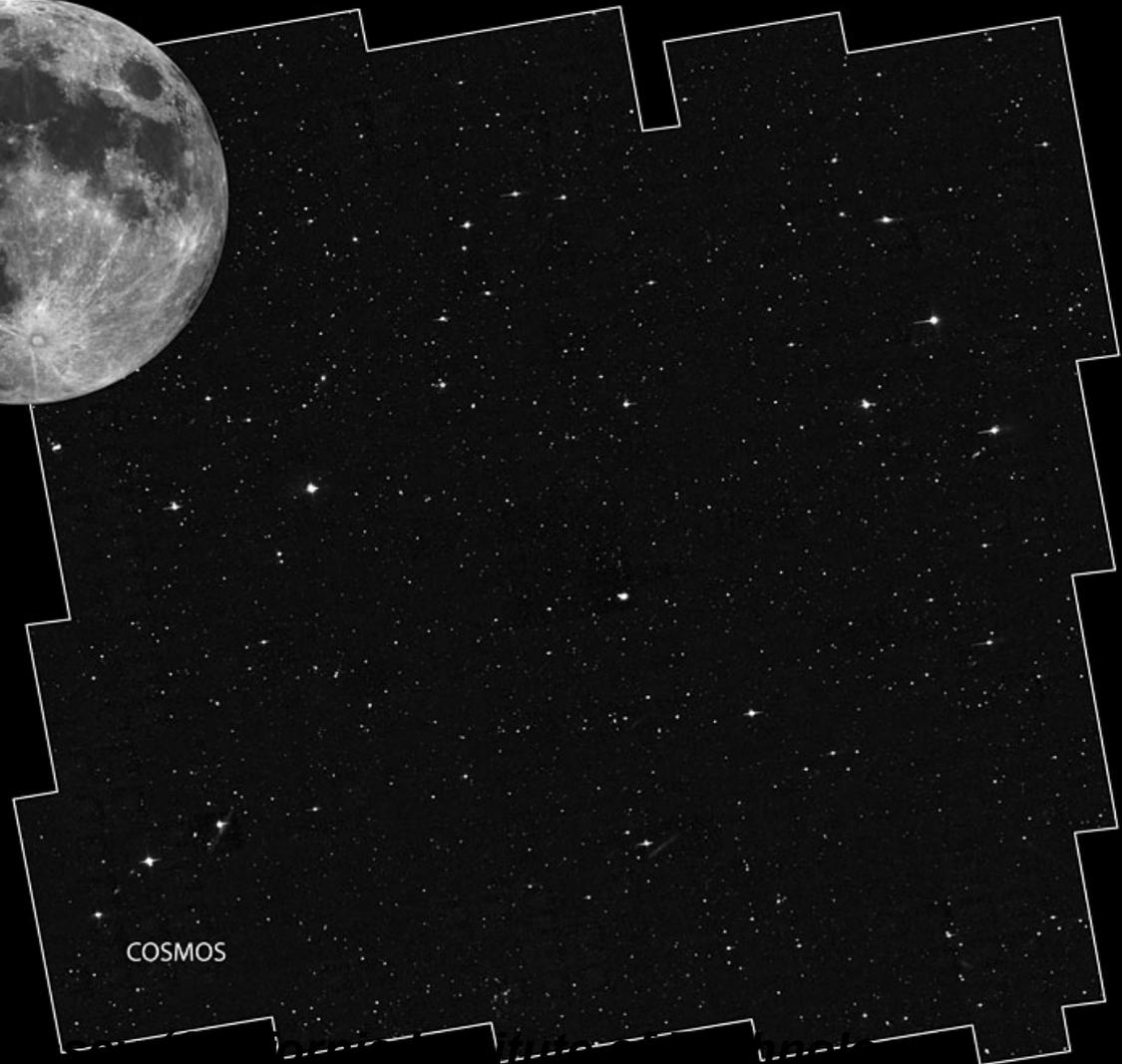
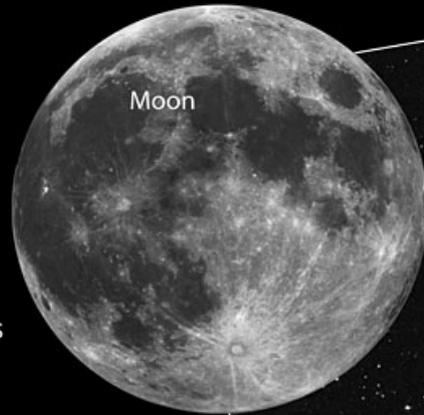
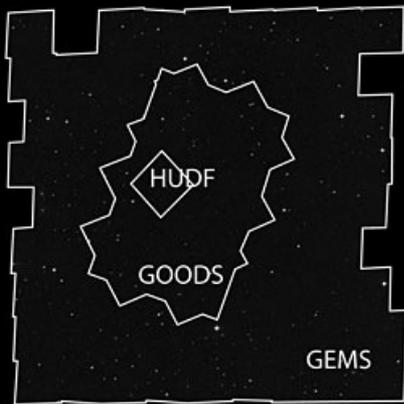
125 Mpc/h

A visualization of the cosmic web at 13.6 Gyr. The image shows a complex network of dark purple filaments and nodes, with bright yellow and orange spots representing galaxy clusters and individual galaxies. A horizontal scale bar is located in the center, labeled "125 Mpc/h".

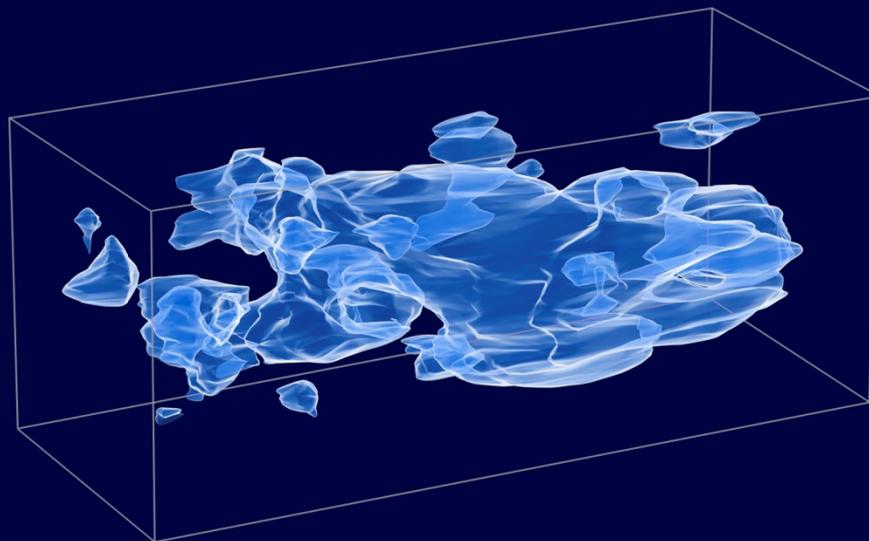
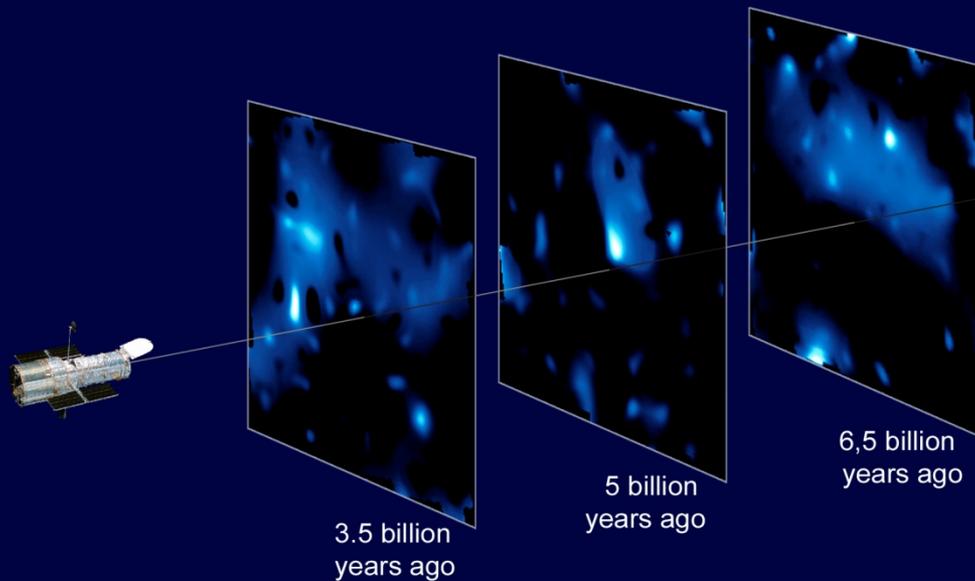


# COSMOS: The Largest ever Survey with HST

Relative Sizes of *HST* ACS Surveys



# In 3 Dimensions

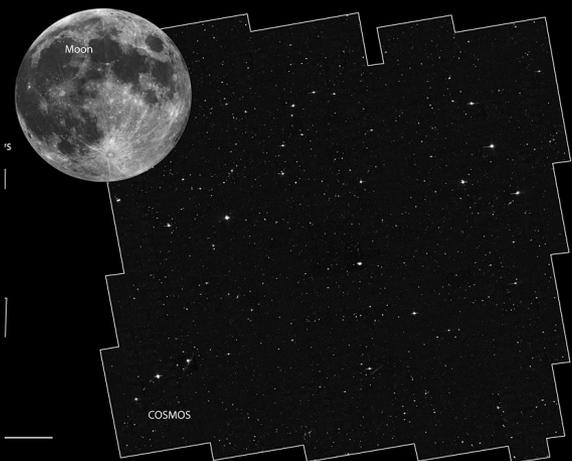




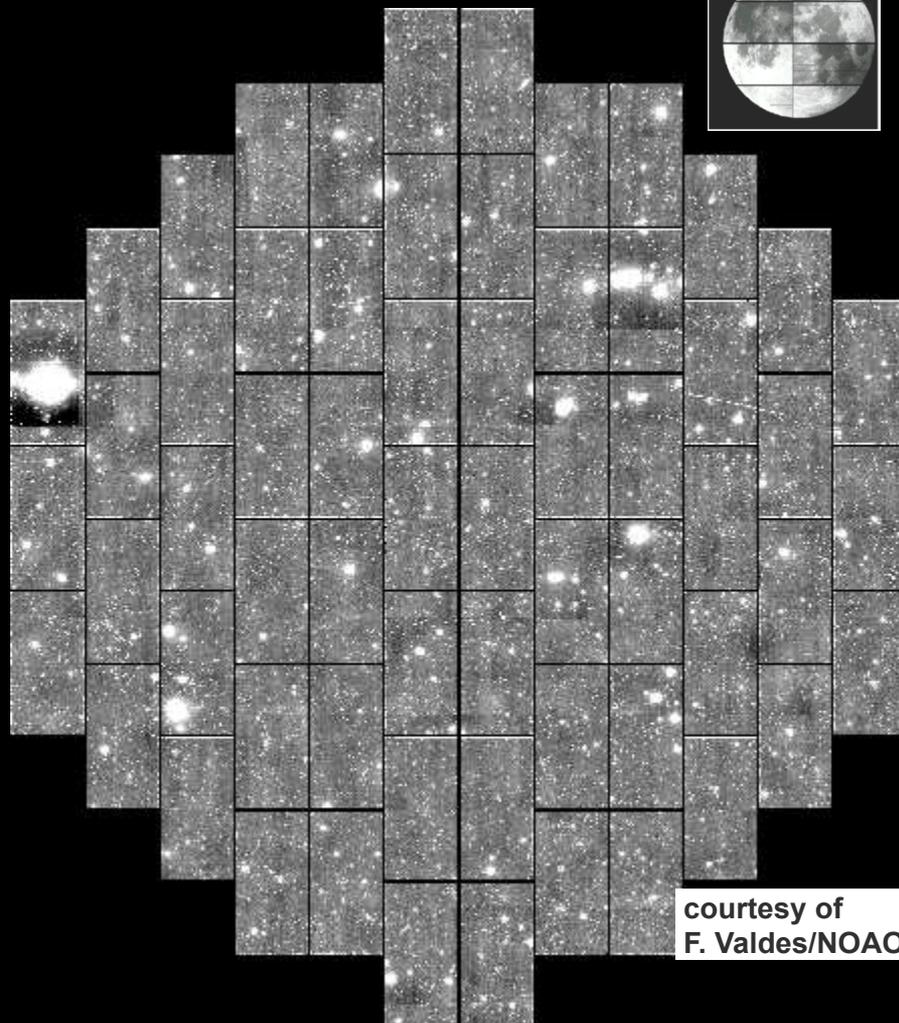
COSMOS



DES



COSMOS



courtesy of  
F. Valdes/NOAO

One DES image (3 sq deg)  
Cf whole DES survey 5000 sq deg



# DES Science Summary

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- ~100,000 clusters to  $z > 1$
- Synergy with SPT
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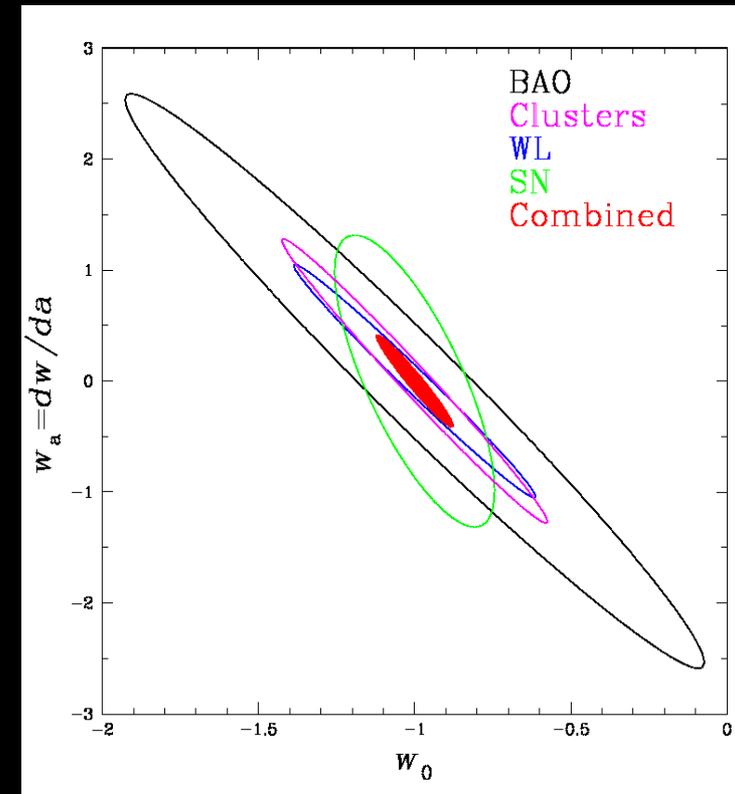
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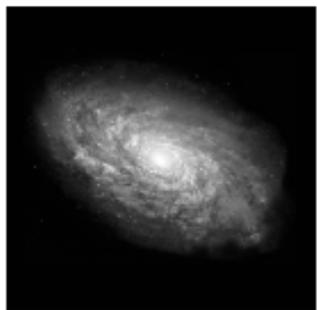
**Factor 3-5 improvement over Stage II DETF Figure of Merit**



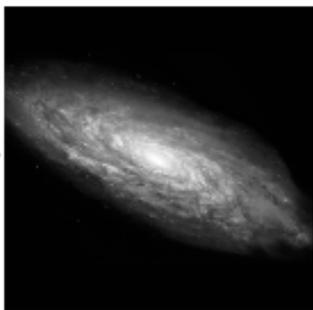
# The Shear Measurement Problem

## The Forward Process.

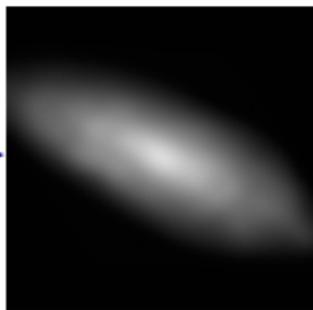
**Galaxies:** Intrinsic galaxy shapes to measured image:



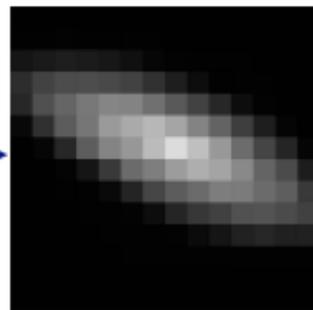
Intrinsic galaxy  
(shape unknown)



Gravitational lensing  
causes a **shear ( $g$ )**



Atmosphere and telescope  
cause a convolution



Detectors measure  
a pixelated image

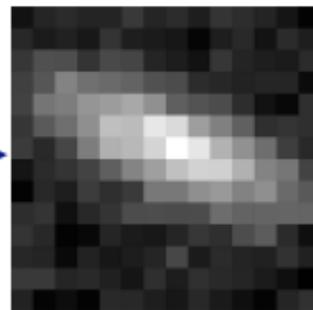
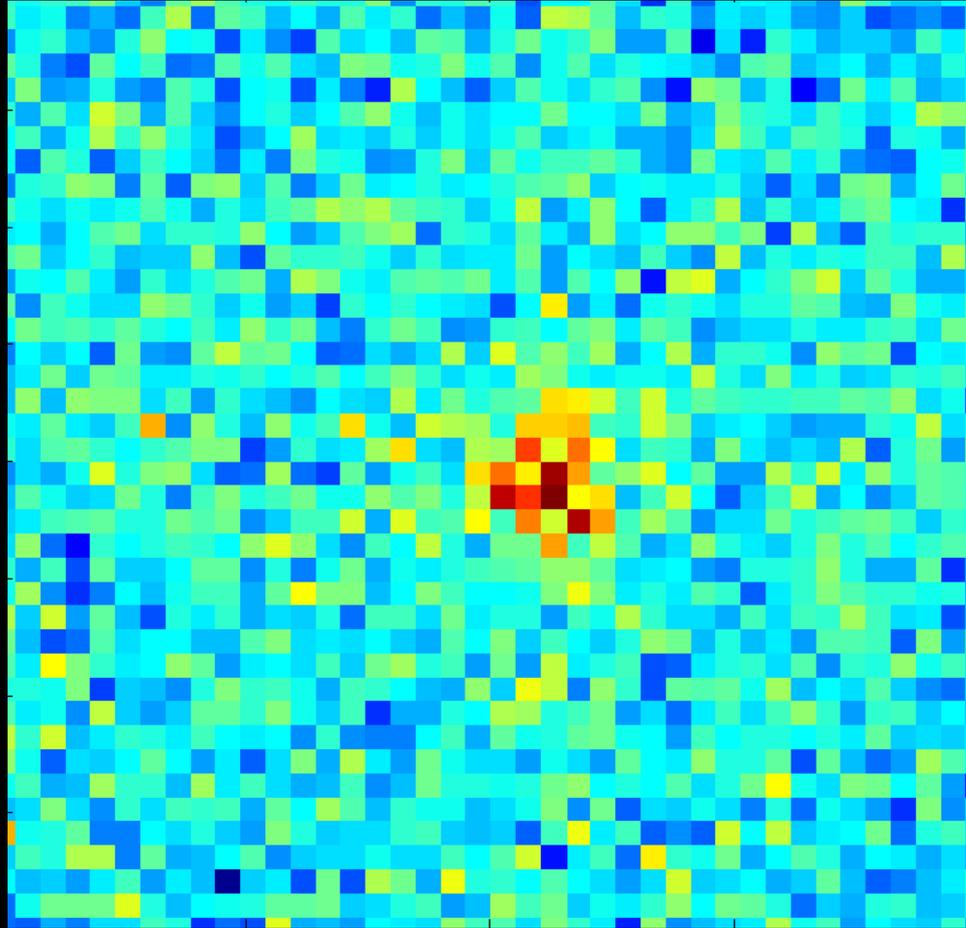


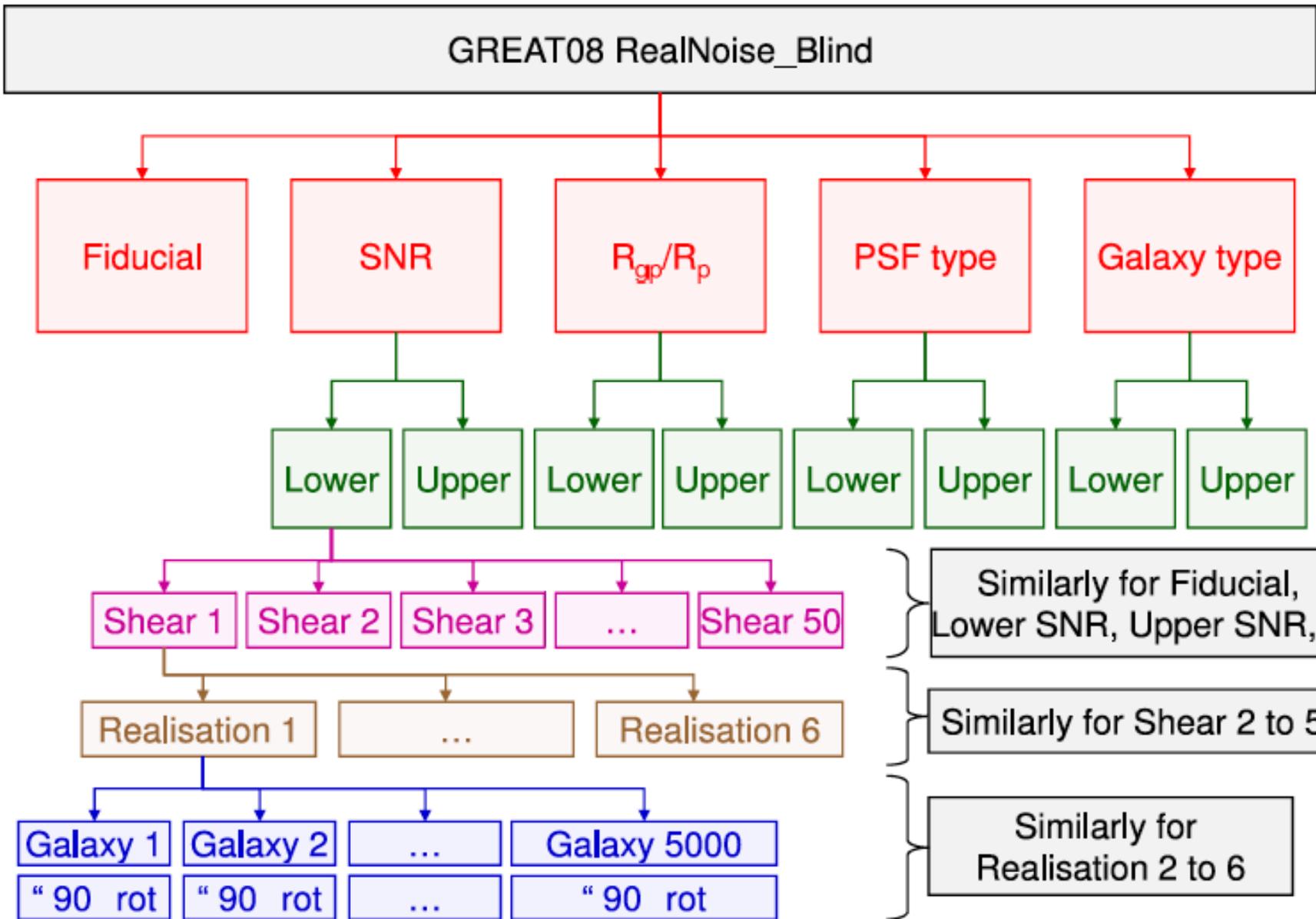
Image also  
contains noise



# A Typical Galaxy



Results of the GREAT08 Challenge (Bridle et al. 2010)



**Results of the GREAT08 Challenge (Bridle et al. 2010)**



DARK ENERGY  
SURVEY

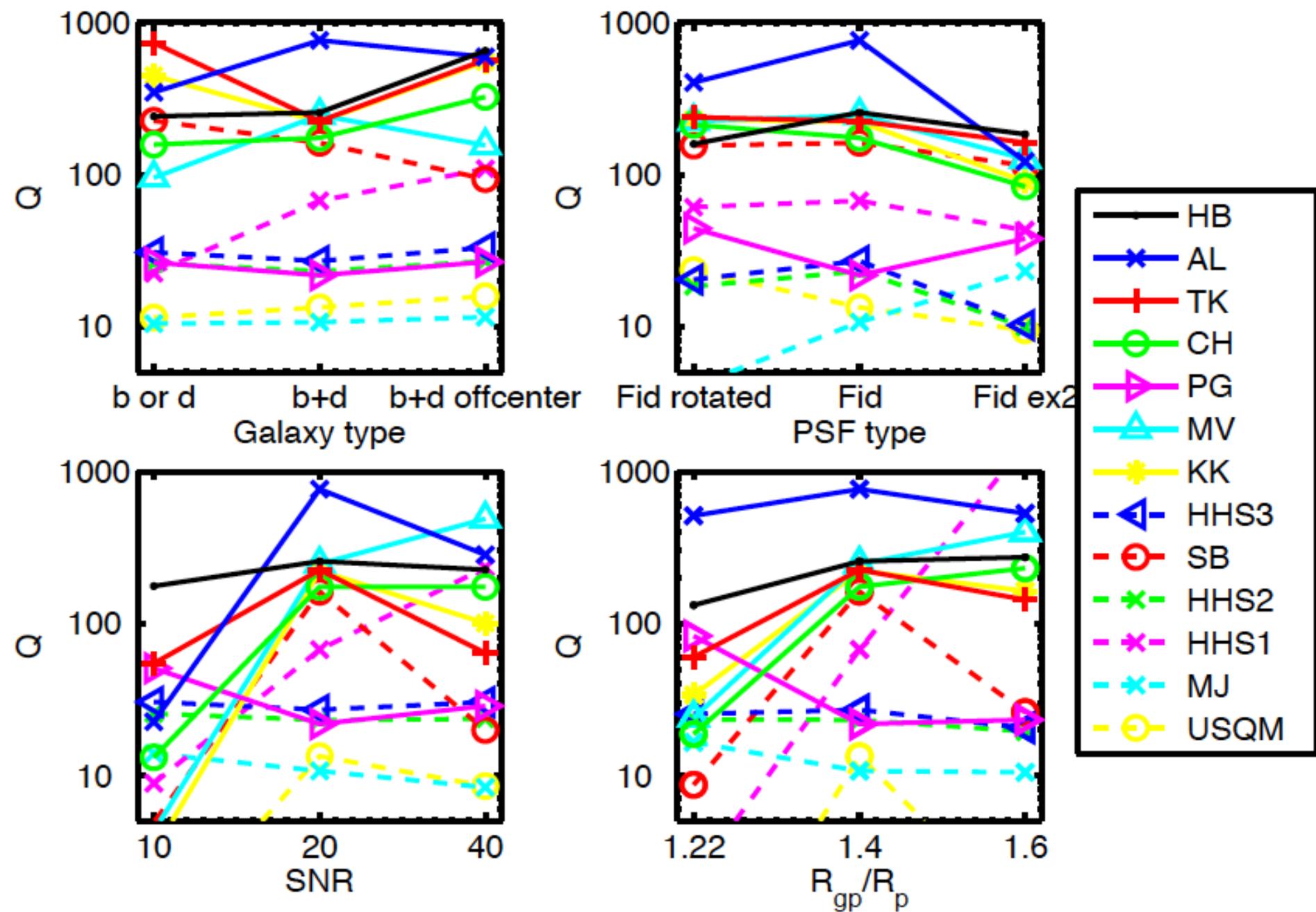
Participant(s)	Key	Action 1	Action 2	Action 3
Hosseini, Bethge	HB	Estimate power spectrum	Average power spectra	Fit elliptical model * PSF
Lewis	AL	Estimate centroids	Average images	Fit elliptical model * PSF
Kitching	TK <sup>†</sup>	Fit elliptical model * PSF	Combine ellipticity PDFs	Calculate shear
Heymans	CH <sup>†</sup>	Measure weighted quadrupole moments	Correct for weight and PSF	Average shear estimates
Paulin, Gentile	PG	Fit elliptical model * PSF		Average shear estimates
Velander	MV	Fit flexed elliptical model * PSF		Average shear estimates
Kuijken	KK <sup>†</sup>	Fit elliptical model * PSF		Average shear estimates
Harmeling, Hirsch, Schölkopf	HHS3	Estimate centroids	Average good images	Fit elliptical model * PSF
Bridle	SB <sup>†</sup>	Fit elliptical model * PSF		Average shear estimates
Harmeling, Hirsch, Schölkopf	HHS2	Estimate centroids	Average images	Fit elliptical model * PSF
Harmeling, Hirsch, Schölkopf	HHS1	Fit elliptical Gaussian	Correct for model and PSF	Average shear estimates
Jarvis	MJ <sup>†</sup>	Fit “elliptical” model * PSF		Average shear estimates
Bridle, Schrabback	USQM <sup>†</sup>	Measure quadrupole moments - PSF	Average quadrupole moments	Calculate shear

**Results of the GREAT08 Challenge (Bridle et al. 2010)**



Rank	Author	Method	Q
1	HB	CVN Fourier	211
2	AL	KK99	131
3	TK	Lensfit	119
4	CH	KSBf90	52.3
5	PG	gfit	32.0
6	MV	KKshapelets with flexion	28.6
7	KK	KKshapelets	23.0
8	HHS3	GaussStackForwardGaussCleaned	22.4
9	SB	im2shape	20.1
10	HHS2	GaussStackForwardGauss	19.9
11	HHS1	Gauss	12.8
12	MJ	BJ02 deconvolved shapelets	9.80
13	USQM	USQM	1.22

Results of the GREAT08 Challenge (Bridle et al. 2010)



Results of the GREAT08 Challenge (Bridle et al. 2010)

News : [Mirror Site Now Available for Download](#)

Welcome to GREAT10, a simulation challenge that aims to improve image analysis algorithms for cosmic gravitational lensing. You are invited to participate in the Galaxy Challenge and the Star Challenge, for more information follow the links below and read the [Challenge Handbook](#). We also provide a brief explanation below.

<p><b>GREAT10</b> Leader-boards</p>	<p><b>Galaxy Challenge</b></p> <p>Download Participate</p>  <p>Information FAQs</p>	<p><b>Star Challenge</b></p> <p>Download Participate</p>  <p>Information FAQs</p>	<p><b>HELP!</b> Email the <a href="#">helpdesk</a></p>
---	--	--	--

Challenge Closes In

2nd September **77:07:48:10**

Days Hours Mins Secs



Subscribe to GREAT10 Emails

Win a Gadget (~\$1000) and an expenses paid visit to NASA/JPL



**The Star Challenge** : Is to the reconstruct the Point Spread Function, or convolution kernel, in astronomical images, which occurs because of the slight blurring effects of the telescope and atmosphere. The PSF varies across each image and is only *sparsely sampled* by stars,



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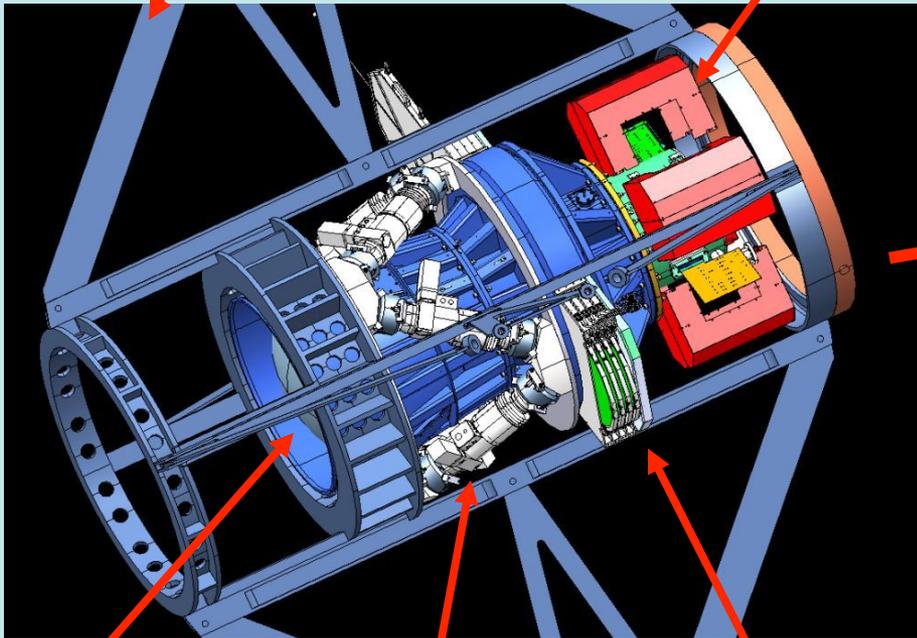




# Dark Energy Camera

**Mechanical Interface of  
DECam Project to the  
Blanco**

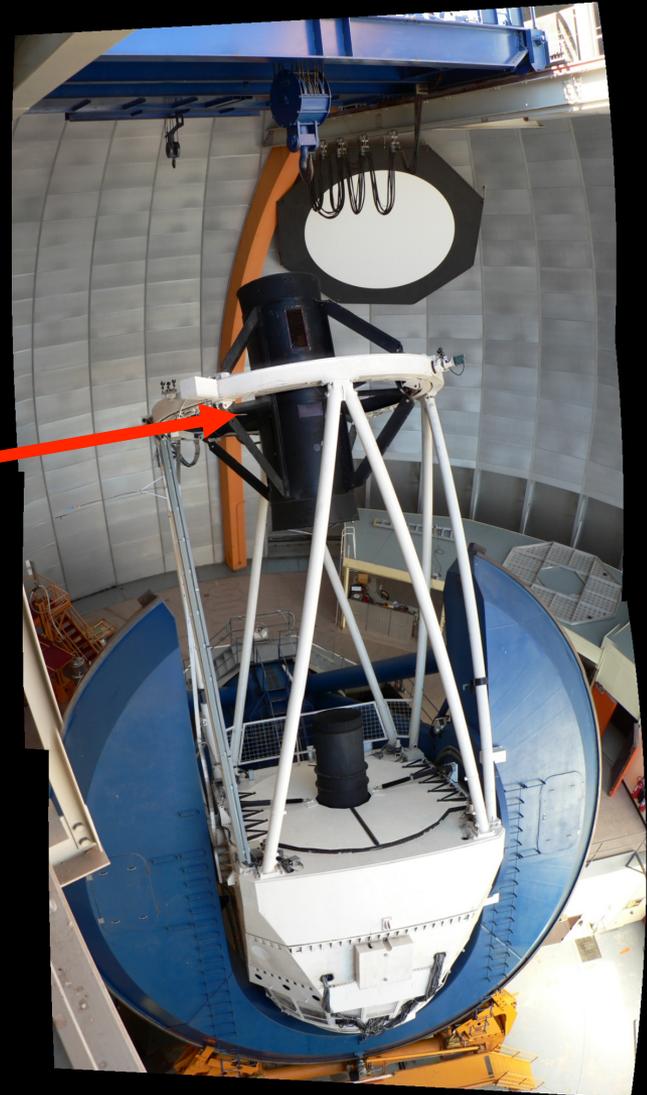
**CCD  
Readout**



**Optical  
Corrector  
Lenses**

**Hexapod:  
optical  
alignment**

**Filters &  
Shutter**



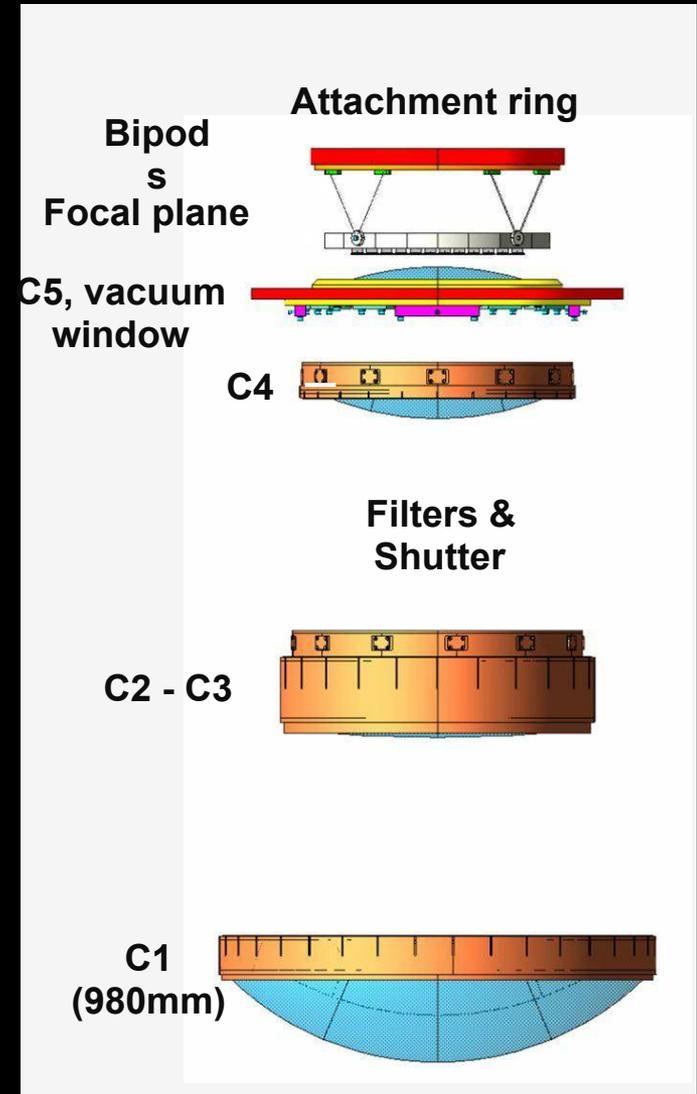


# Optics

- Field of view: 2.2° diameter
- Good image quality across FOV
- Optical elements being aligned in barrel at UCL, will ship to CTIO Aug/Sept



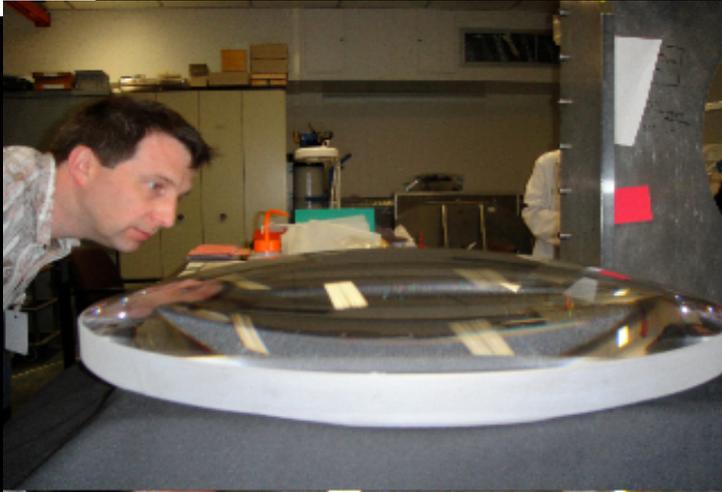
S. Kent (FNAL)





# The 5 lenses are nearly ready

C3



C1

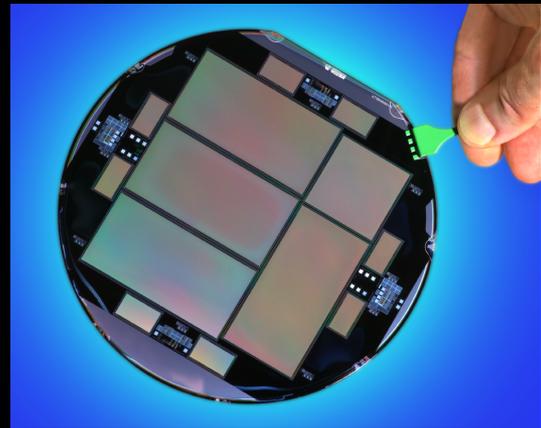


Polishing & coating coordinated  
by UCL (with 1.7M STFC funding)





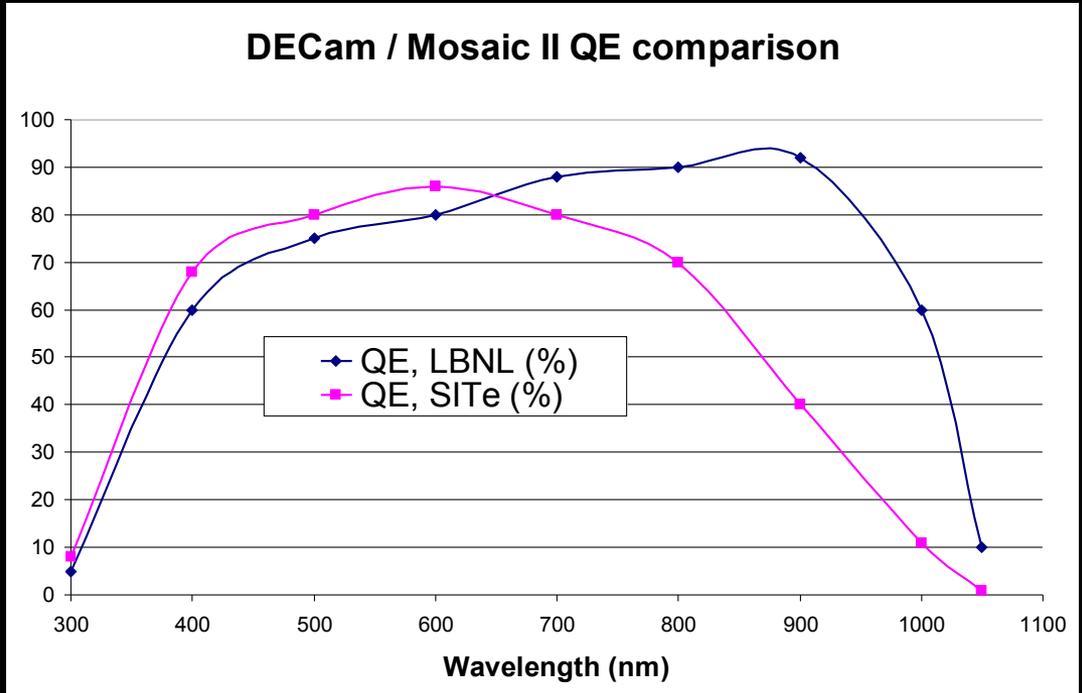
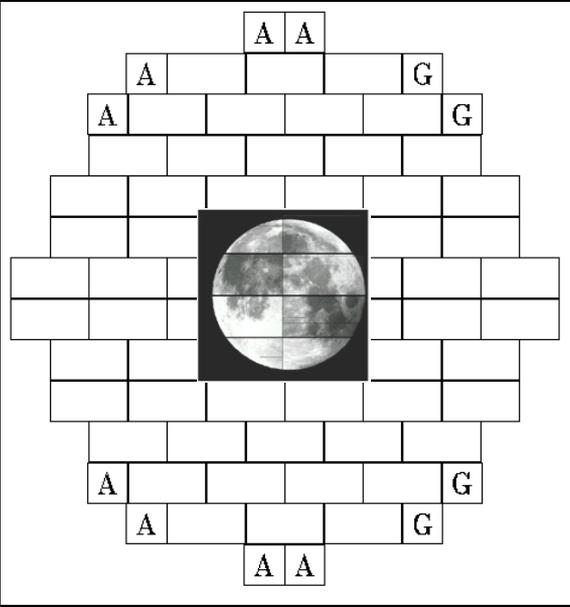
# DECam CCDs



Developed by LBNL

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.27") pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Roughly twice the number of science-grade CCDs packaged

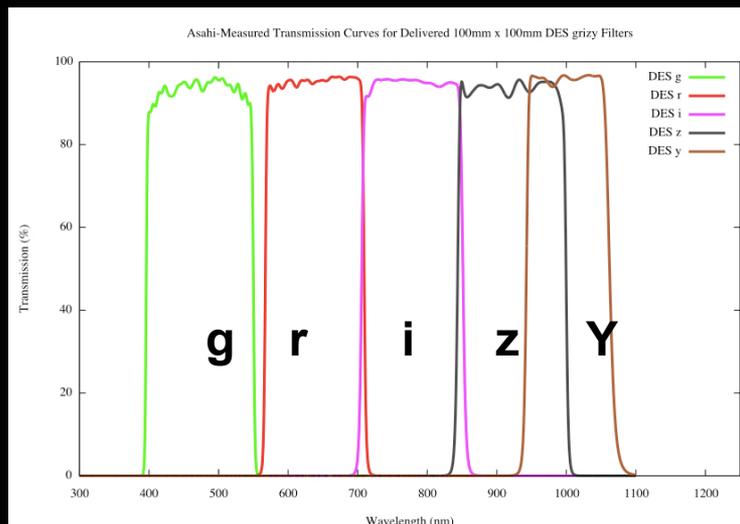
47 now installed





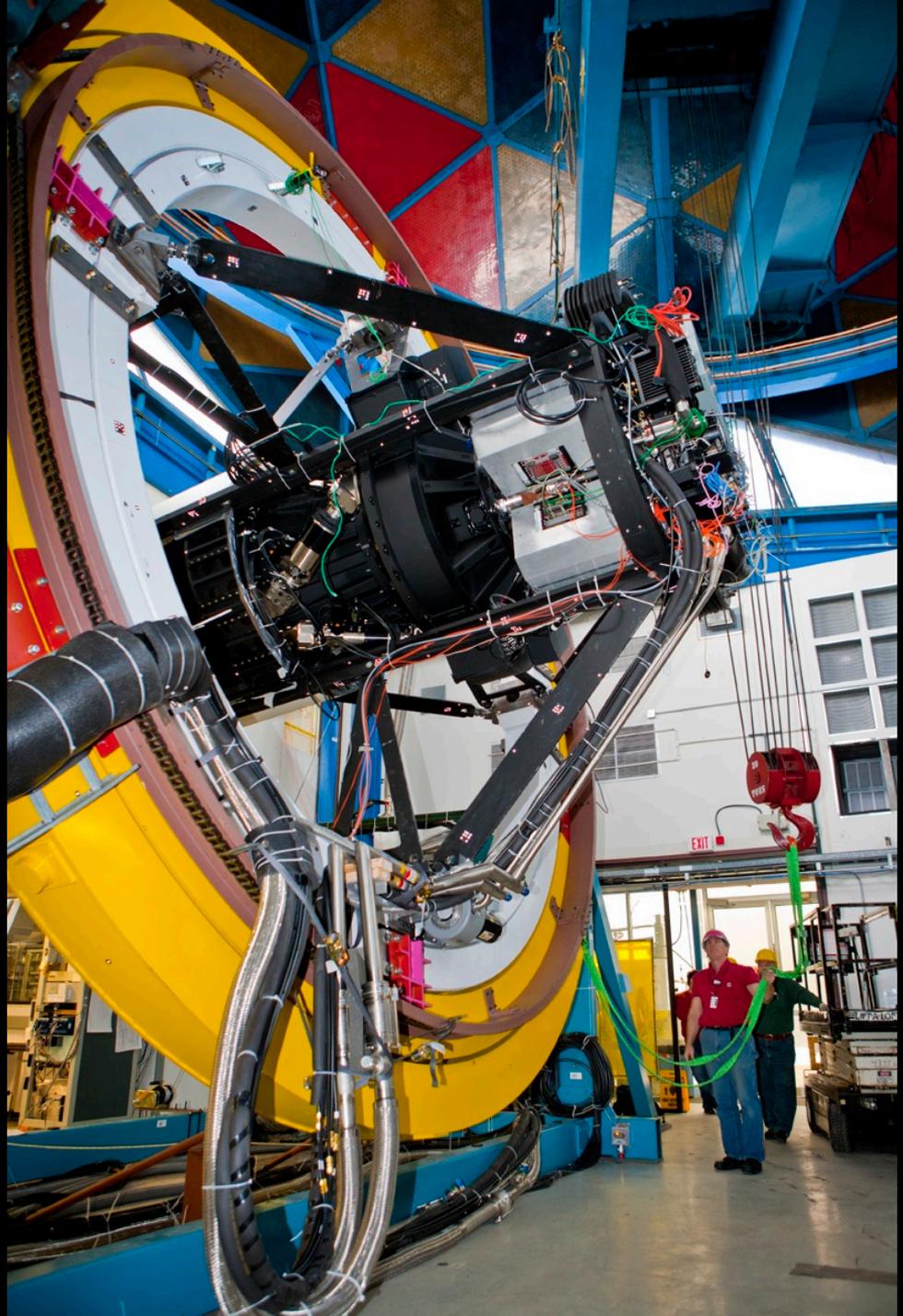
# Filters

- Filter contract awarded to Asahi in 2009
- 620mm substrate, 600mm clear aperture
- Asahi has built and commissioned a huge coating chamber as well as custom cleaning, polishing and testing equipment
- i and z filters completed and about to ship to Chile. 1 side of Y done





- DECam mounted on Telescope Simulator at Fermilab in early 2011
- DECam both DES survey instrument and CTIO facility instrument
- The CTIO Director has scheduled the telescope shutdown to start on Nov. 8.





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# DES Observing Strategy

Sept-Feb observing seasons

80-100 sec exposures

2 filters per pointing  
(typically)

*gr* in dark time

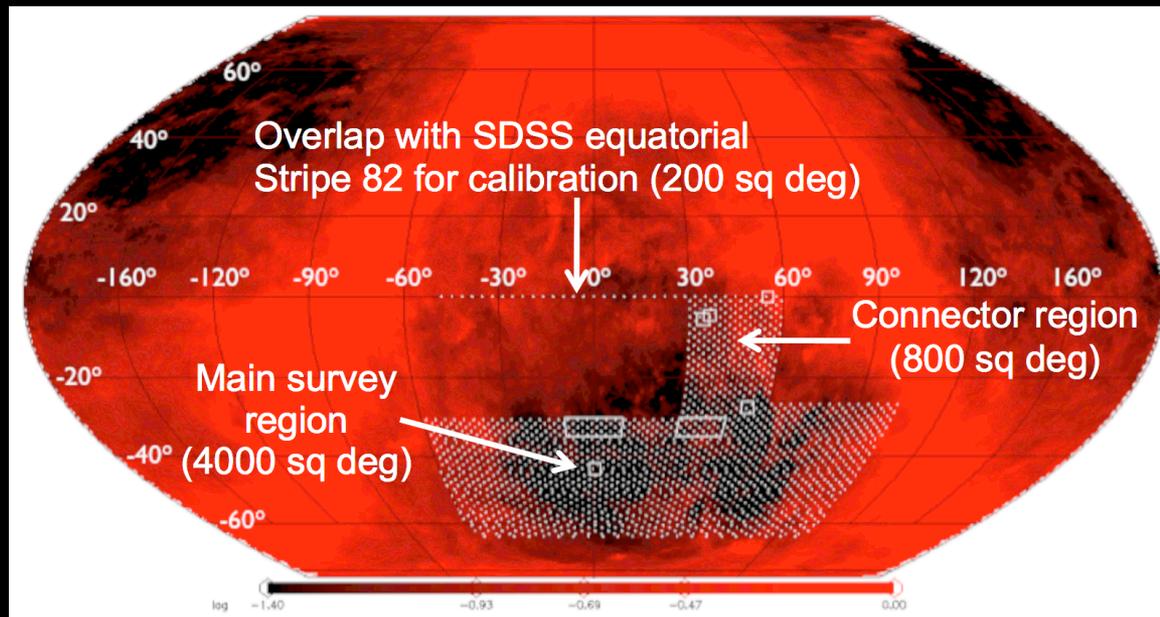
*izy* in bright/grey time

Photometric calibration:  
overlap tilings, standard  
stars, spectrophotometric  
calibration system, preCAM

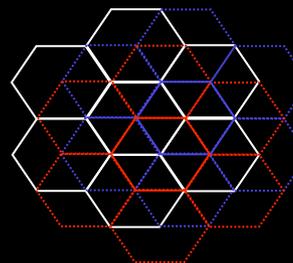
2 survey tilings/filter/year

Interleave 10 SN fields in  
*griz* if non-photometric or  
bad seeing or time gap (aim  
for ~5 day cadence)

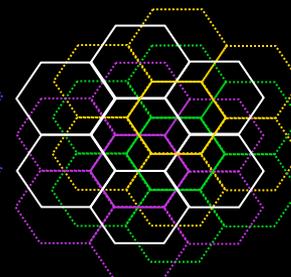
**Survey Area 5000 sq deg**



**2 tilings**

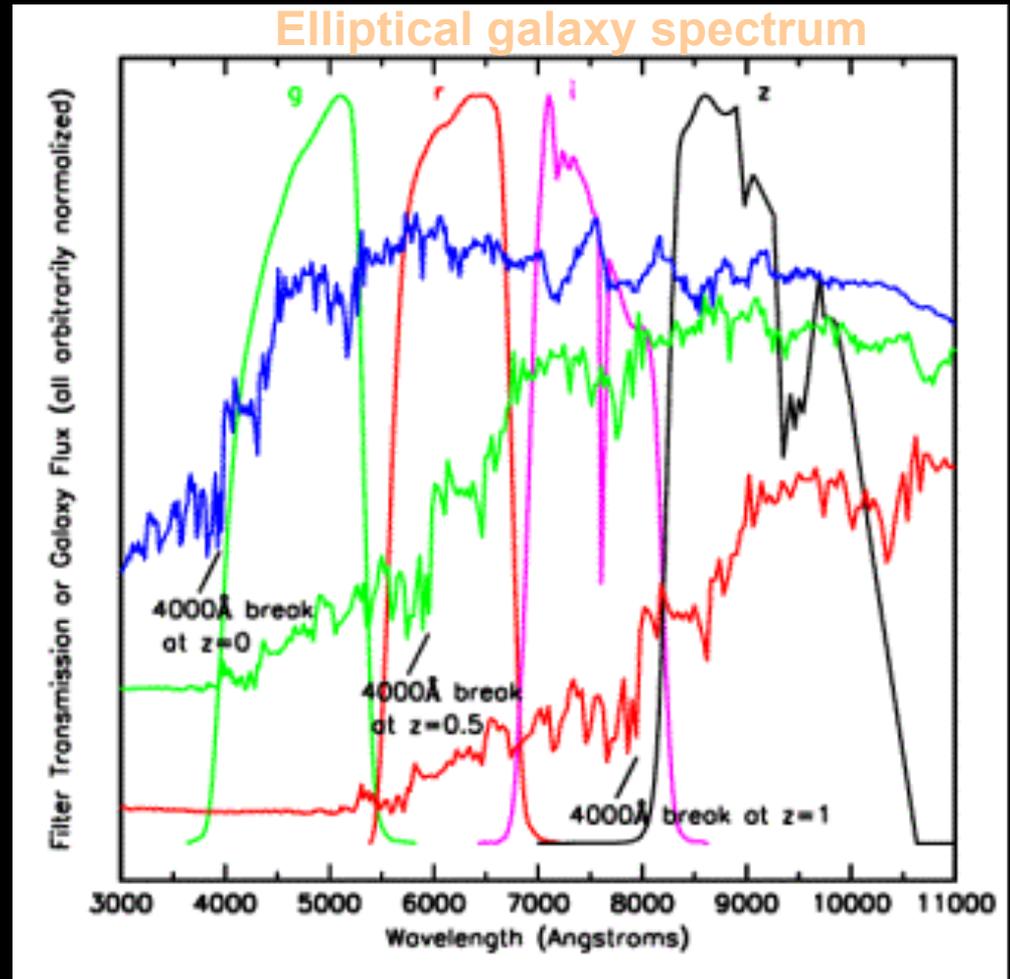


**3 tilings**

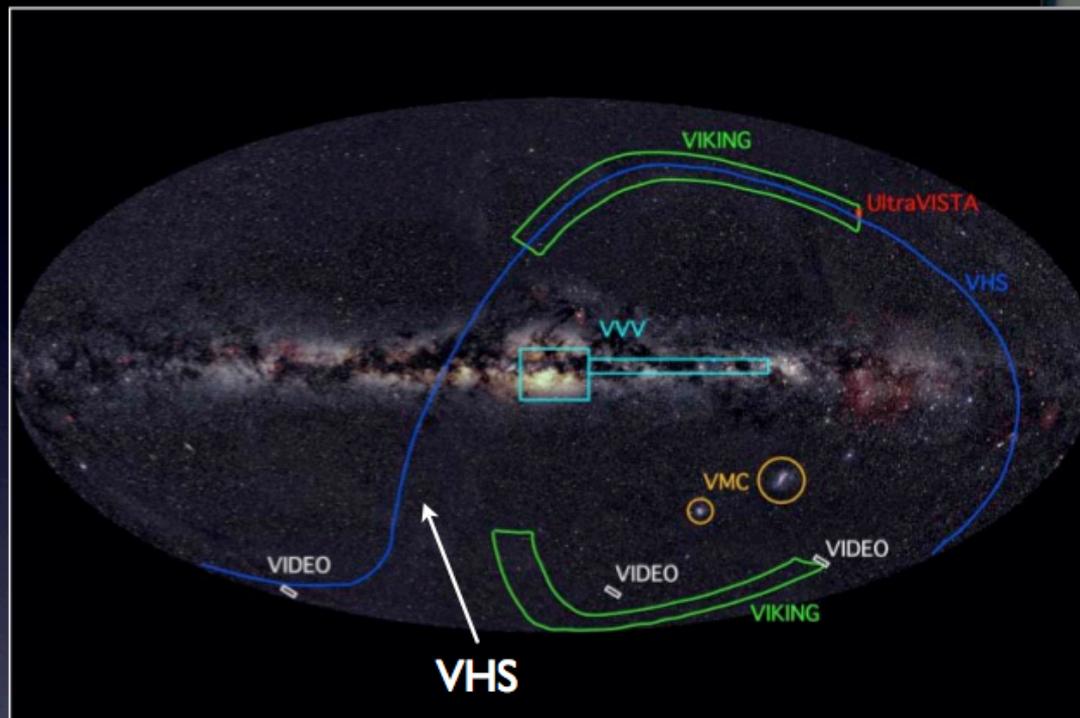


# Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 Å break
- Estimate individual galaxy redshifts with accuracy  $\sigma(z) < 0.1$  ( $\sim 0.02$  for clusters)
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.



# VISTA Hemisphere Survey



120 sec JHK exposures

## VISTA

4.1 m primary mirror  
1.5deg field of view  
16 2kx2k HgCdTe

## VHS

380 nights over 5 yrs  
120 sec JHK exposures  
Richard McMahon, PI

VHS limiting magnitudes

[AB system;  $5\sigma$ ]

	deg <sup>2</sup>	Y	J	H	K
VHS-DES	5000	21.9	21.2	20.8	20.2

DES collaborates with VHS: DES acquires Y imaging, VHS shares JHK data



# Galaxy Photo-z Simulations

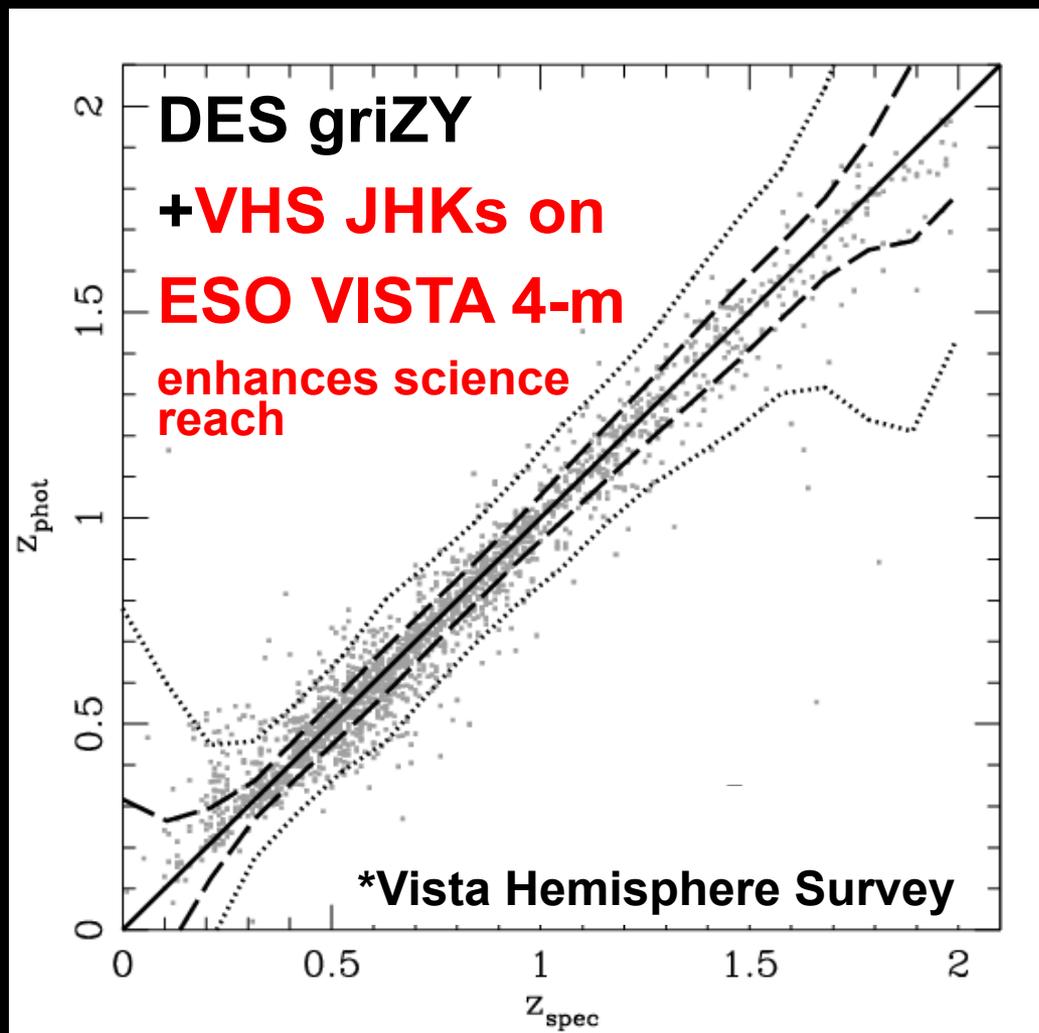
## DES+VHS\*

### 10 $\sigma$ Limiting Magnitudes

g	24.6		
r	24.1		
i	24.0	J	20.3
z	23.8	H	19.4
Y	21.6	Ks	18.3

+2% photometric calibration error added in quadrature

Spectroscopic training sets comparable to DES depth exist

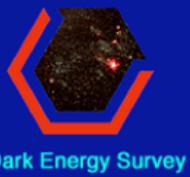




# The Dark Energy Survey

- Dark Energy
- DES Collaboration
- DES Science
- DECam
- Survey Strategy
- **Data Management**
- Status



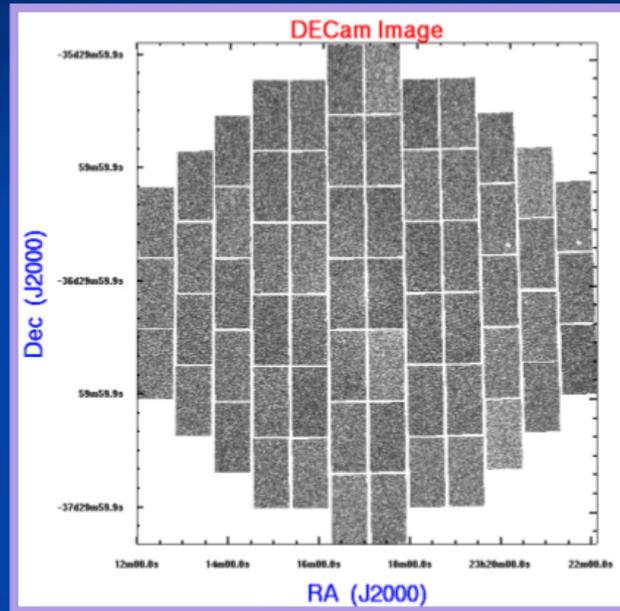


# DES Data Management

<http://cosmology.illinois.edu/DES/>

- The DESDM system:
  - Process DES data at NCSA
  - Archive DES data over the long term
    - ~4PB total, ~350TB database
  - Distribute data to Collaboration
  - Distribute data to public
    - Raw/reduced data after 1 yr
    - Co-adds/catalogs at midpoint and end of survey

NOAO  
NCSA



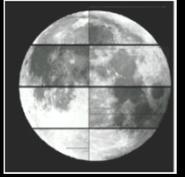
Exposure consists of 62  
2kX4k CCD images - 3deg<sup>2</sup>

Survey is ~150,000 exposures  
over 525 nights





# DECam Simulated Image



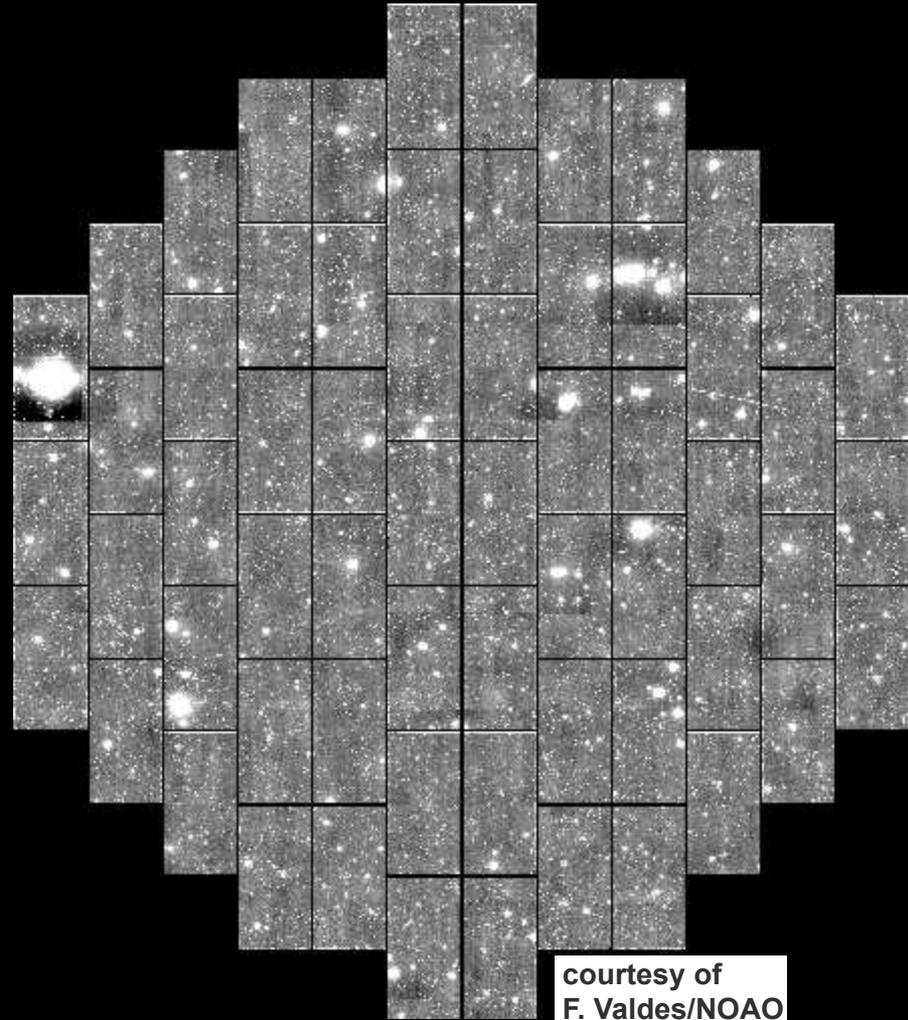
## Each image

- 3 sq. deg.
- ~ 20 Galaxy clusters
- ~ 200,000 Galaxies
- 520 Mega pixels (62 CCDs)

Each night ~ 300 GB of image data

We will use 500 nights for the Dark Energy Survey

The large field of view lets us cover the sky in a reasonable amount of time.



courtesy of  
F. Valdes/NOAO



# DECam Image Simulations

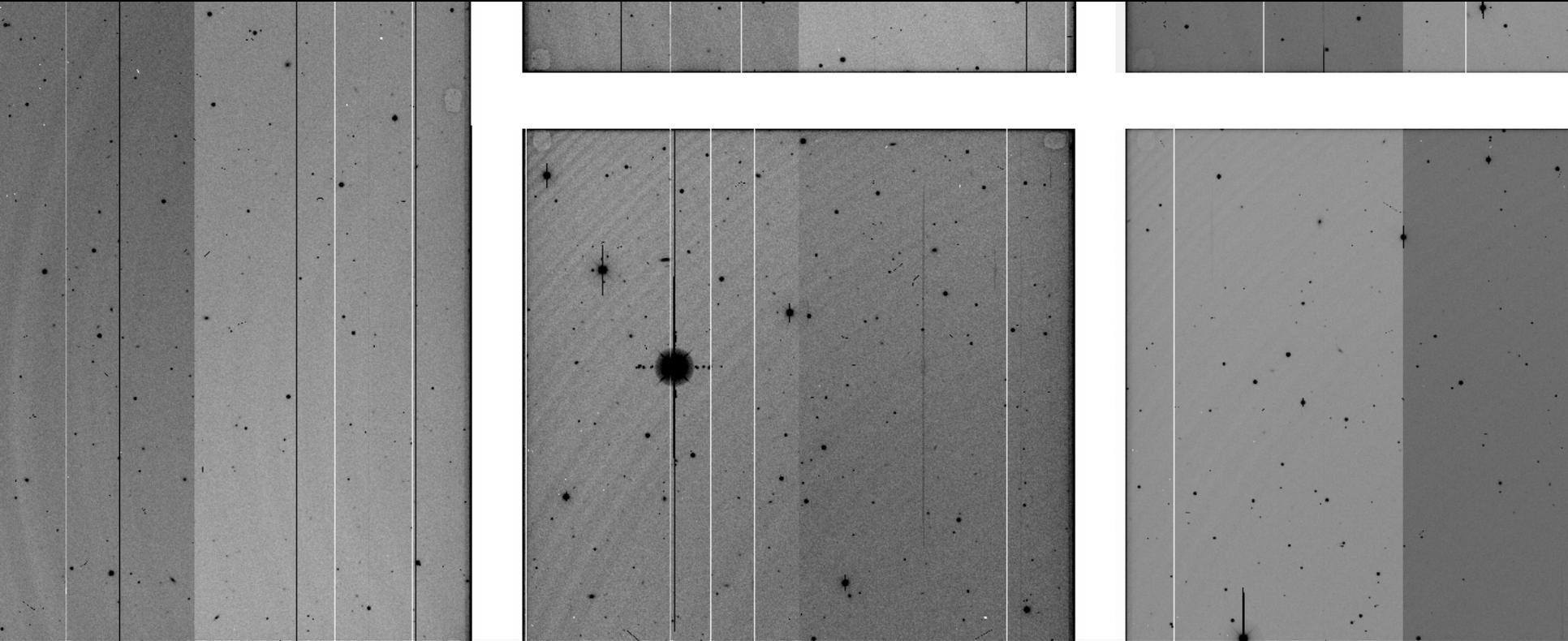


**Populate N-body sims w/ galaxies drawn from SDSS+evolution+shapes**



# DECam Image Simulations

Series of Data Challenges to test Data Management System



Note bright star artifacts, cosmic rays, cross talk, glowing edges, flatfield ("grind marks", tape bumps), bad columns, 2 amplifiers/CCD.



# The Dark Energy Survey

- Dark Energy
- DES Collaboration
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- Status





# Project Structure & Timeline

- **3 Construction Projects:**
  - **DECam (hosted by FNAL; DOE supported)**
  - **Data Management System (NCSA; NSF support)**
  - **CTIO Facilities Improvement Project (NSF/NOAO)**
    - NOAO Blanco Announcement of Opportunity 2003
    - DECam R&D 2004-8
    - Camera construction 2008-11
    - Final construction, testing, integration now on-going
    - Ship components to Chile this year
    - Installation of imager ~Nov/Dec 2011
    - First light on telescope: ~Jan 2012
    - Commissioning and Science Verification: Jan-April 2012
    - Survey operations begin: Sept 2012



# DESPEC: Spectroscopic follow up of DES

- Proposed Dark Energy Spectrometer (DESPEC)
- 4000–fibre instrument for the 4m Blanco telescope in Chile, using DES optics and spare CCDs
- 10 million galaxy spectra, target list from DES, powerful synergy of imaging and spectroscopy, starting 2017-18
- DES+DESPEC can improve DE FoM by 3-6, making it DETF Stage IV experiment
- DES+DESPEC can distinguish DE from ModGrav
- Participants: current international DES collaboration + new teams



# Project Structure & Timeline

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