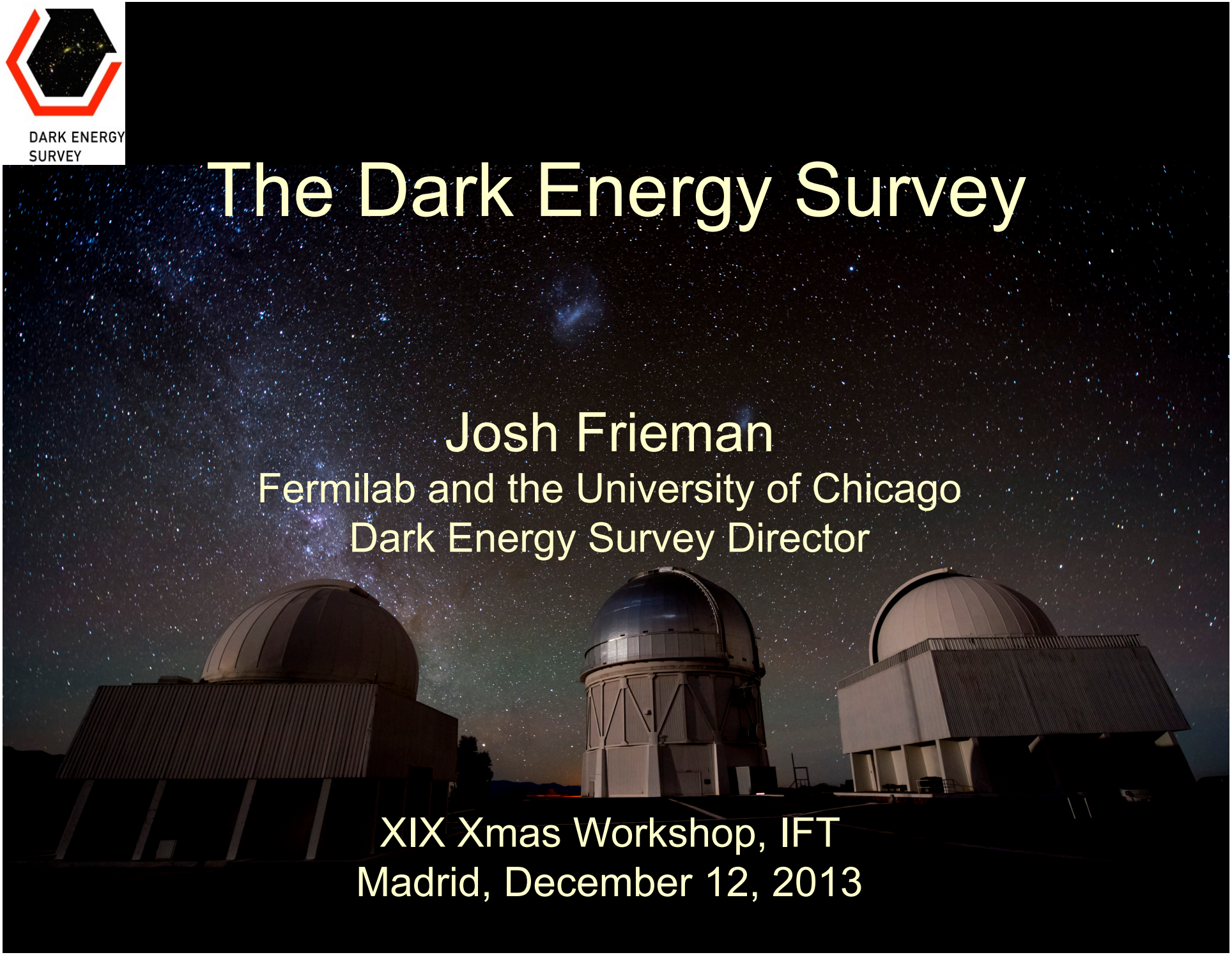
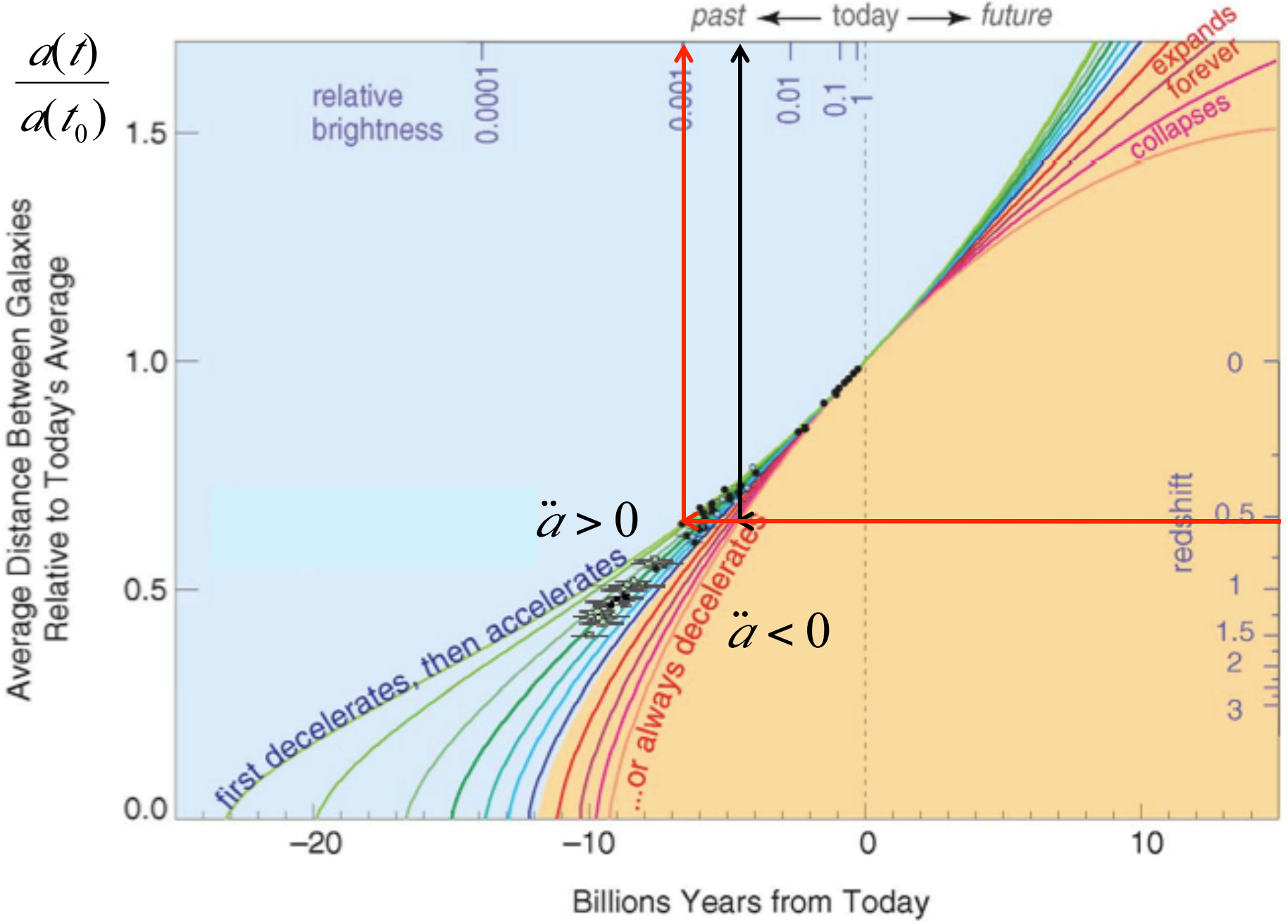


The Dark Energy Survey

Josh Frieman
Fermilab and the University of Chicago
Dark Energy Survey Director

XIX Xmas Workshop, IFT
Madrid, December 12, 2013

Supernova Data (1998)



Cosmological Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \rho_i\left(1+3w_i\right)$$

Friedmann Equation from GR

Equation of state parameter: $w_i = p_i / \rho_i c^2$

Non-relativistic matter: $p_m \sim \rho_m \mathrm{v}^2, \quad w \approx 0$

Relativistic particles: $p_r = \rho_r c^2 / 3, \qquad w = 1/3$

Acceleration ($\ddot{a} > 0$) requires component with negative pressure:

Dark Energy: $w_{DE} < -1/3$

or Replace GR dynamics with another gravity theory

Cosmological Constant and Acceleration

Einstein:

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Lemaitre:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$$\equiv 8\pi G\left(T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{vacuum})\right)$$

Vacuum Energy:

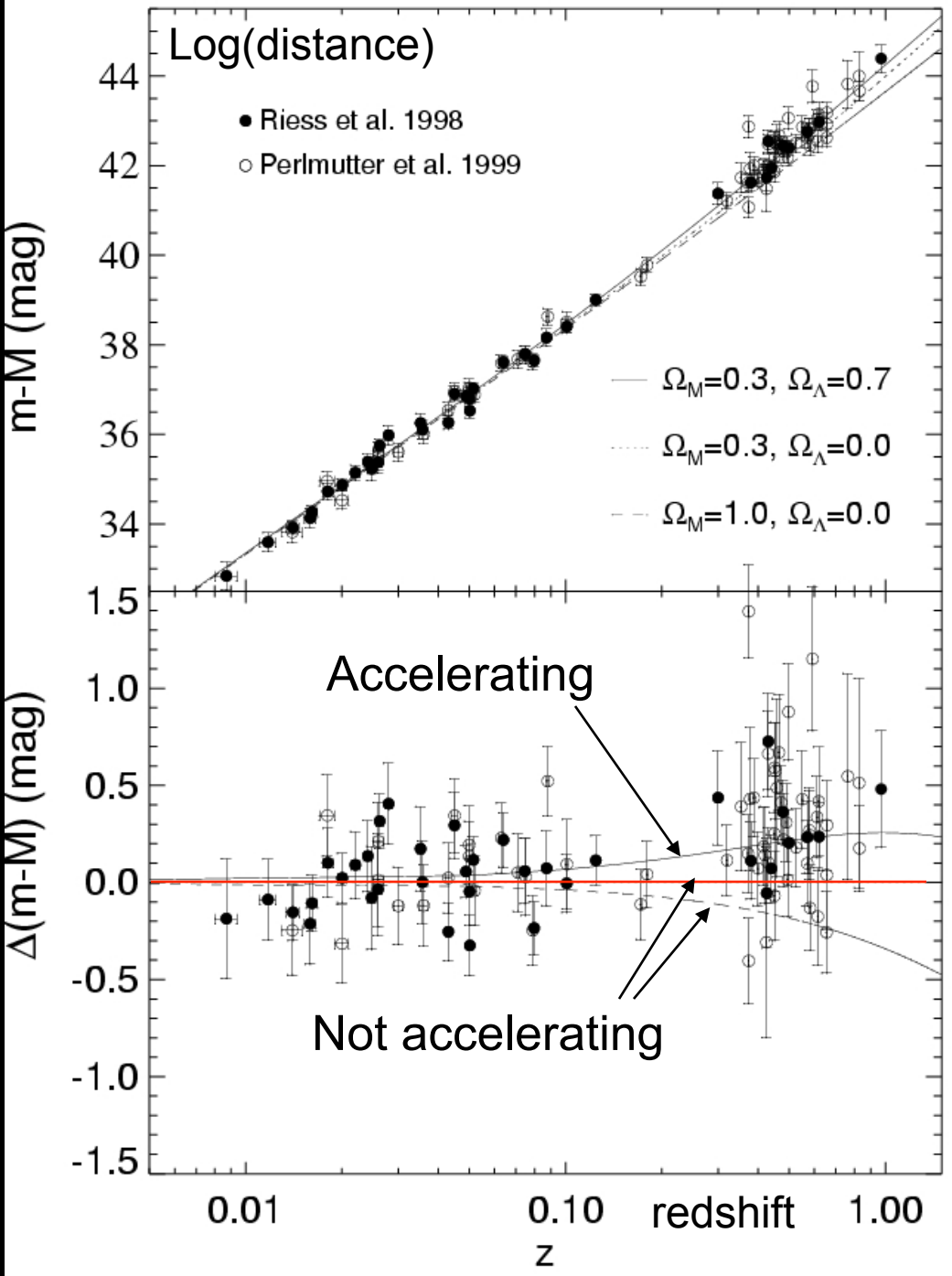
$$T_{\mu\nu}(\text{vac}) = \frac{\Lambda}{8\pi \text{G}} g_{\mu\nu}$$

$$\rho_{\text{vac}} = T_{00} = \frac{\Lambda}{8\pi \text{G}}, \quad p_{\text{vac}} = T_{ii} = -\frac{\Lambda}{8\pi \text{G}}$$

$$w_{\text{vac}} = -1 \Rightarrow \frac{\dot{a}}{a} = \text{constant} \Rightarrow a(t) \propto \exp(Ht)$$

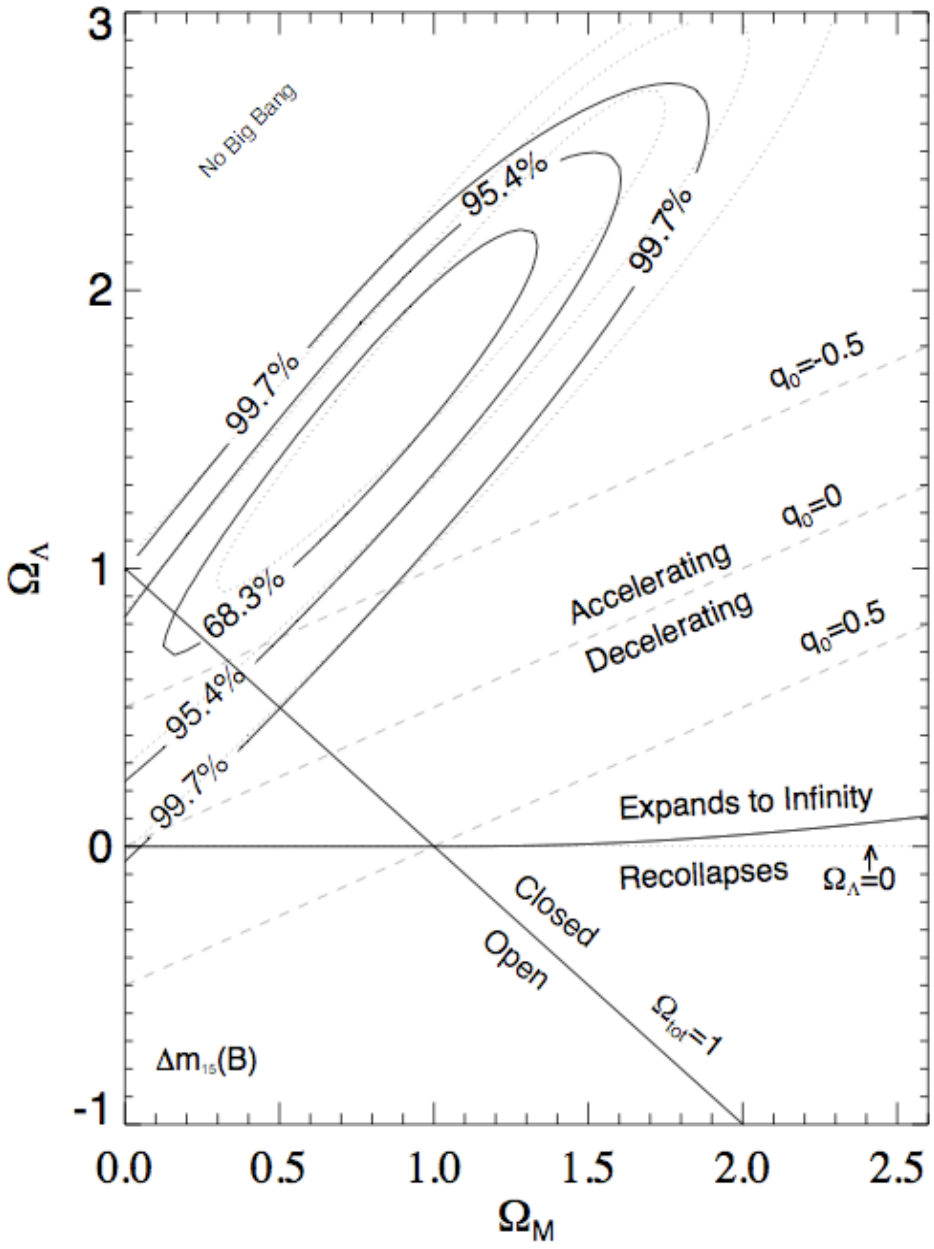
Discovery of Cosmic Acceleration from High-redshift Supernovae

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

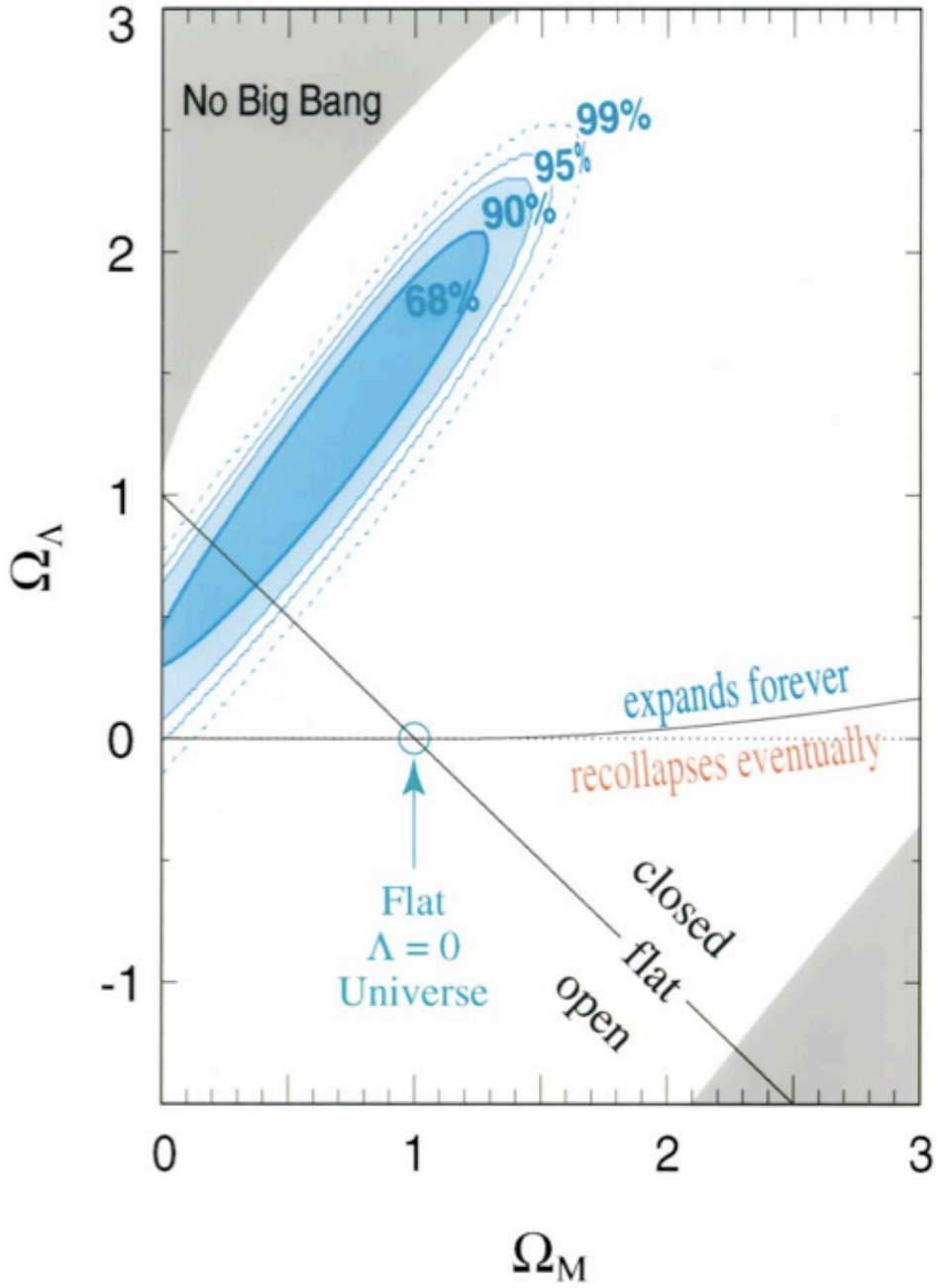


$\Omega_\Lambda = 0.7$
$\Omega_\Lambda = 0.$
$\Omega_m = 1.$

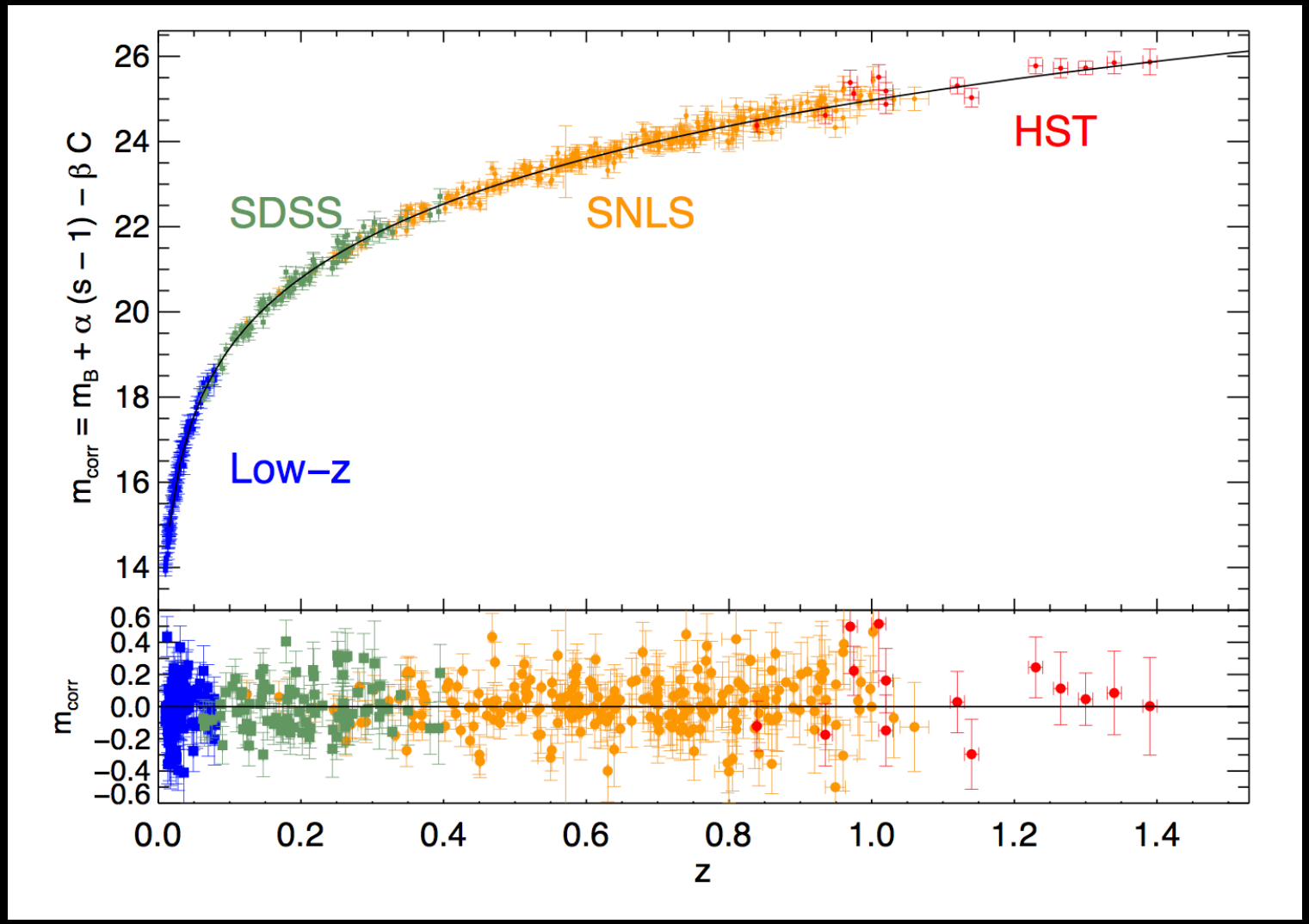
Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)

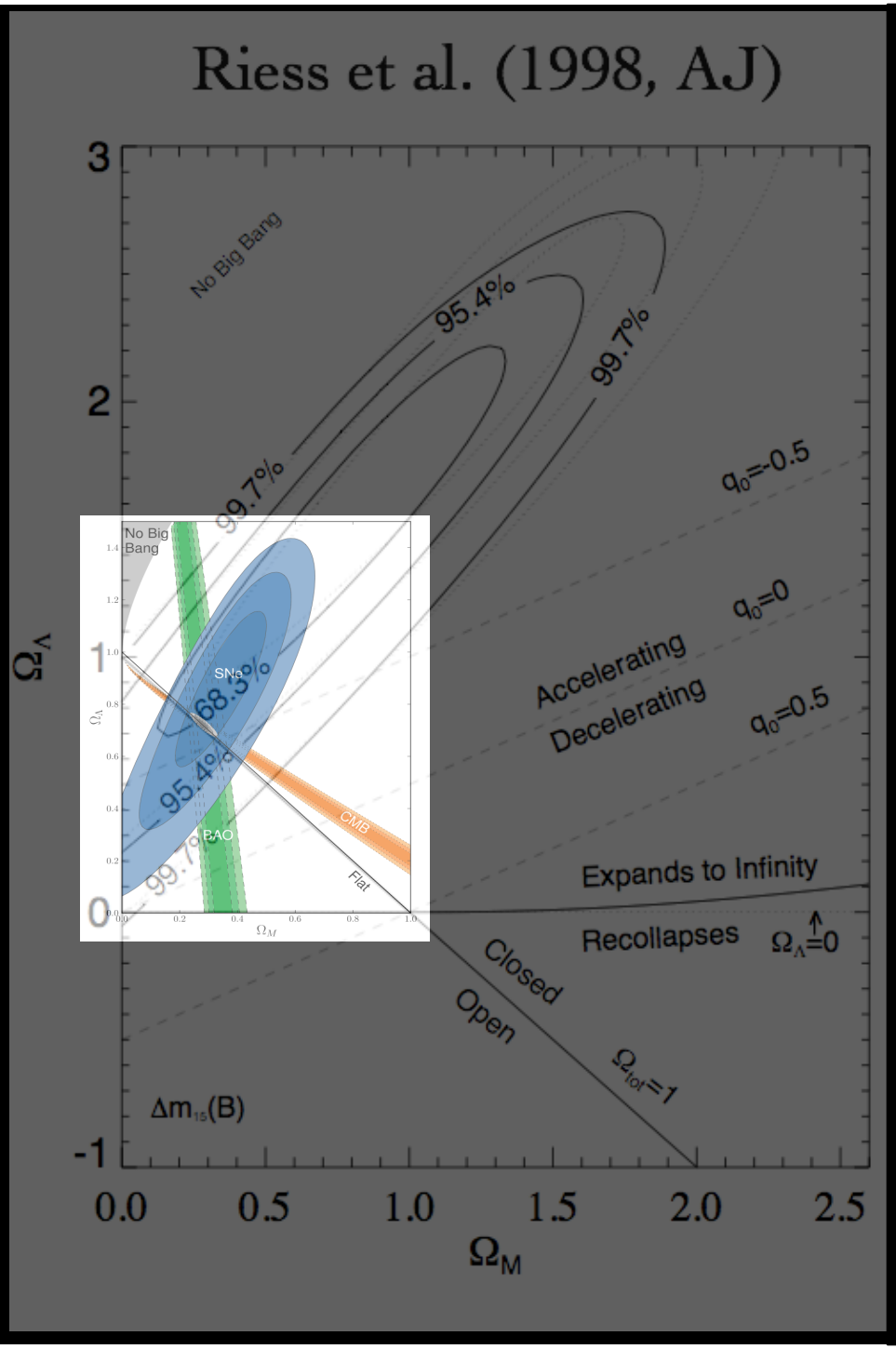


Recent SN Hubble Diagram



Conley etal 2011

Progres
s over
the last
15 years



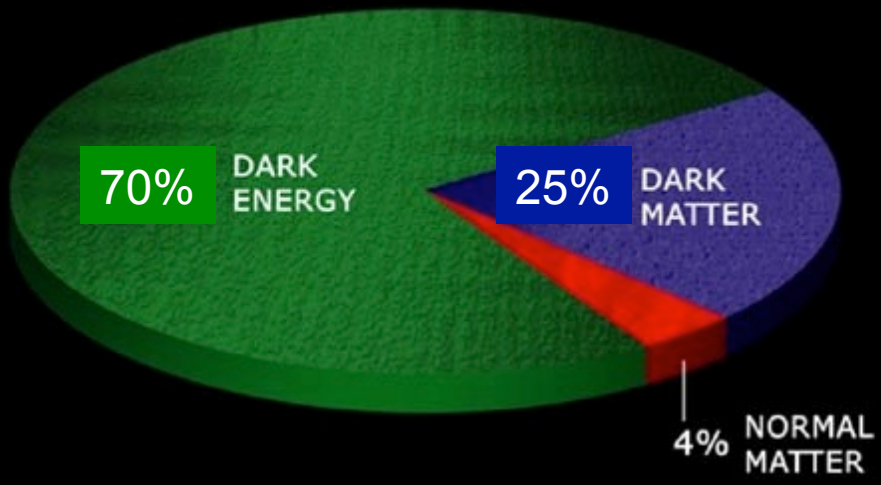
Supernovae

Baryon Acoustic Oscillations

Cosmic Microwave Background

From Discovery to Physics

- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - what is the DE equation of state parameter *w* and (how) does it evolve?



Theory?

- No consensus model for Dark Energy or Modified Gravity
- Theoretical prejudice in favor of cosmological constant (vacuum energy) with $w=-1$ was probably wrong once (Cf. inflation): not a strong argument for it being correct now
- Cosmological constant problem (why is vacuum energy density not 120 orders of magnitude larger?) is not necessarily informative for model-building
- Some alternatives to Λ (Cf. quintessence) rely on notion that a very light degree of freedom can take ~current Hubble time to reach its ground state.

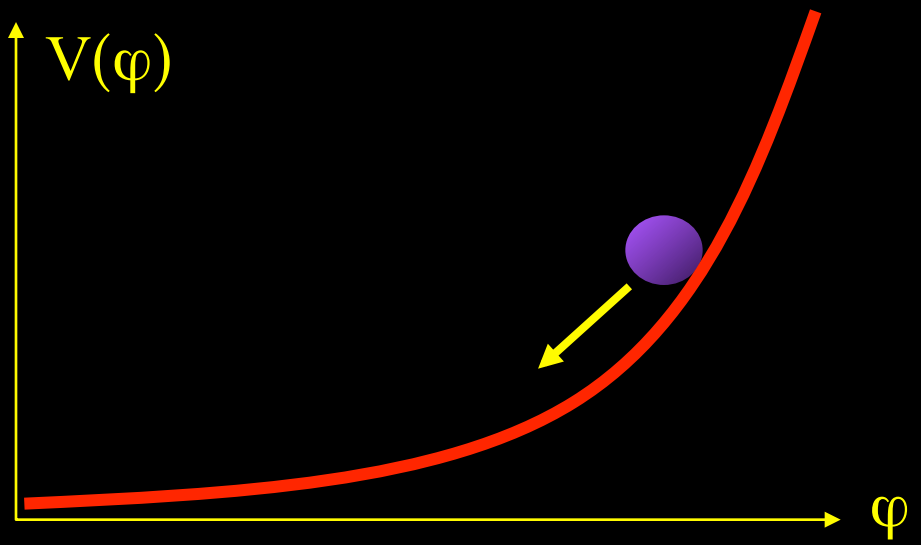
Scalar Field Dark Energy
(aka quintessence)

- Dark Energy could be due to a very light scalar field φ, slowly evolving in a potential, V(φ):

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV}{d\varphi} = 0$$

- Density & pressure:

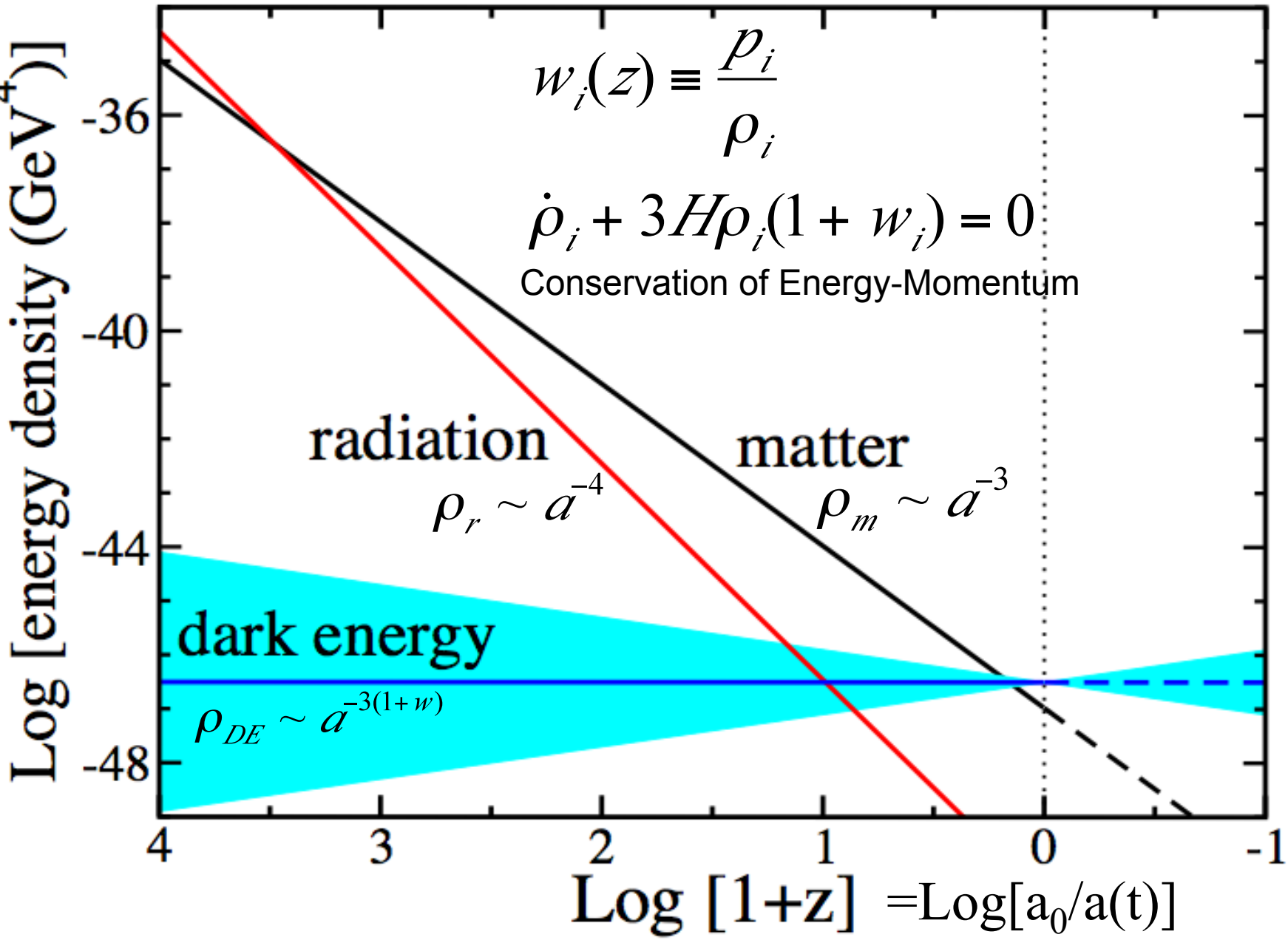
$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$



- Slow roll:

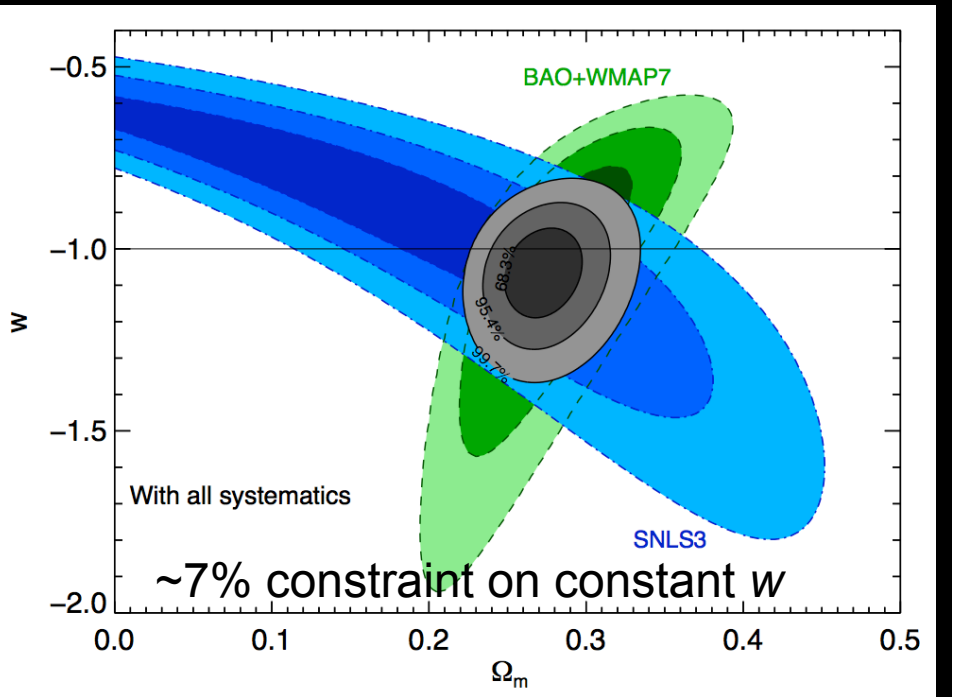
$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Rightarrow P < 0 \Leftrightarrow w < 0 \text{ and time - dependent}$$

Equation of State parameter *w* determines Cosmic Evolution



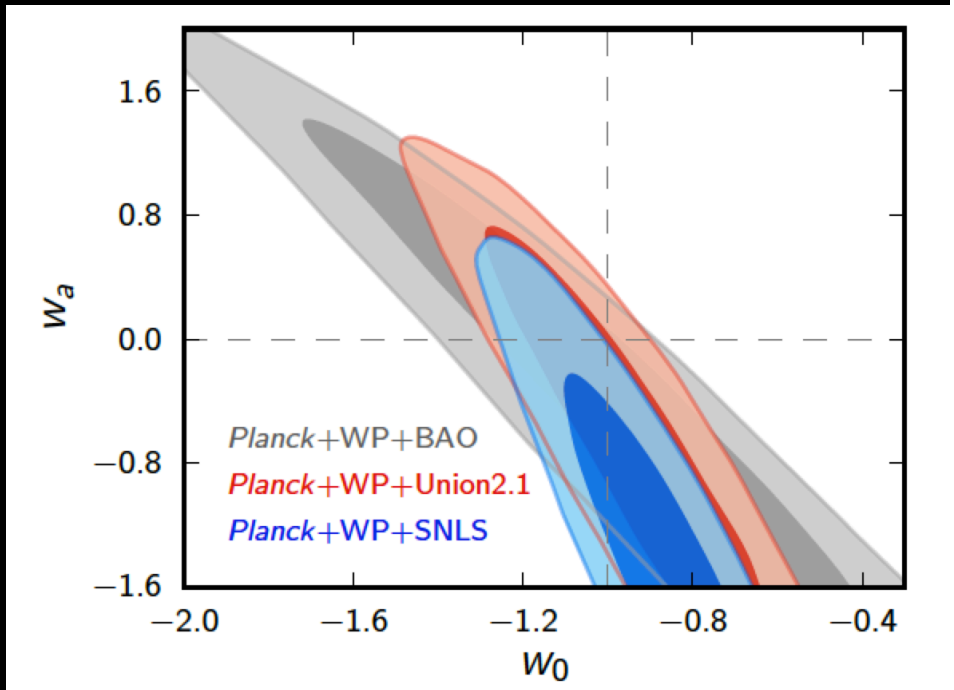
Recent Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*



Sullivan etal 2011

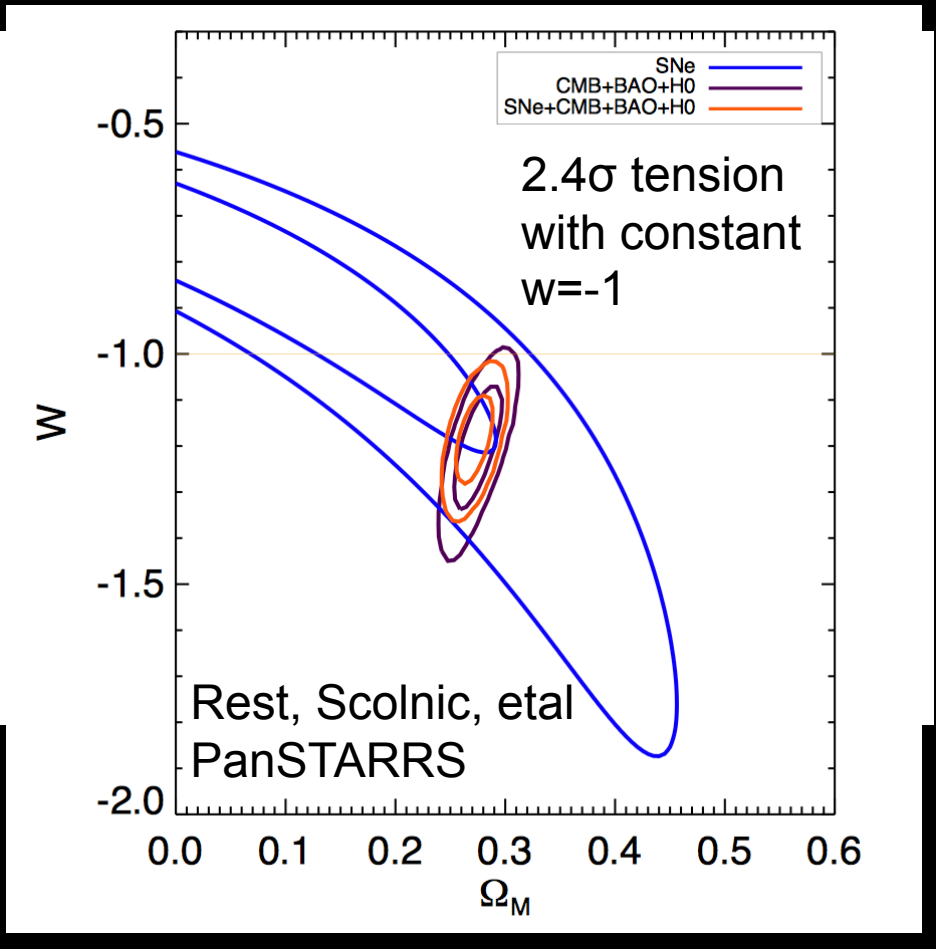
Assuming $w=w_0+w_a(1-a)$



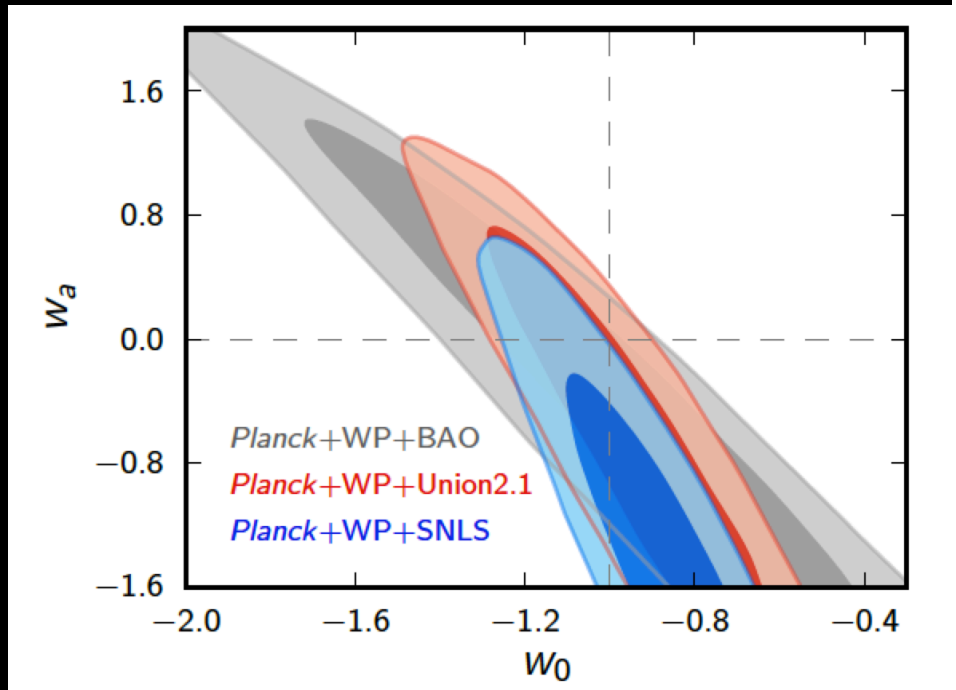
Ade etal 2013

Recent Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*



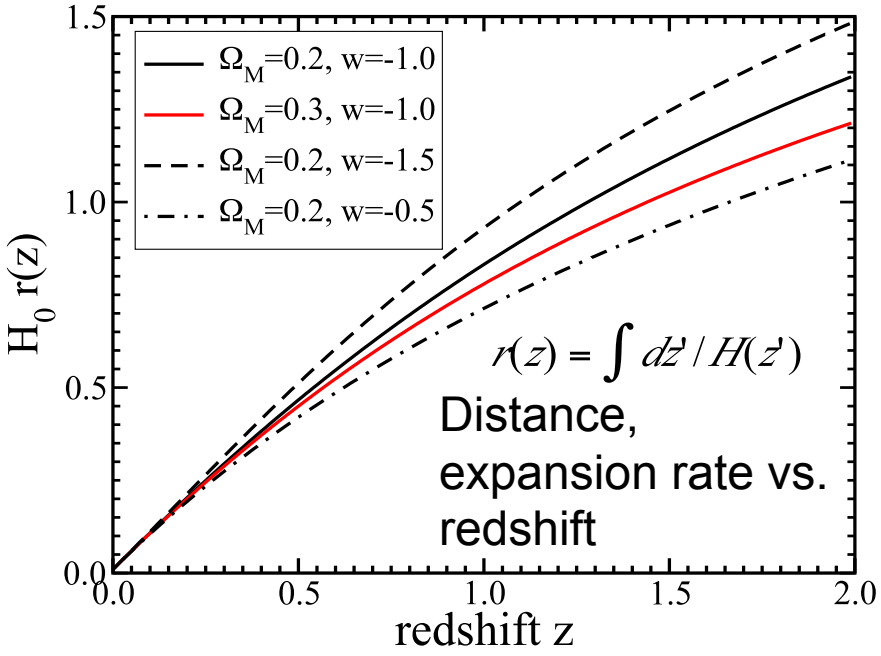
Assuming $w=w_0+w_a(1-a)$

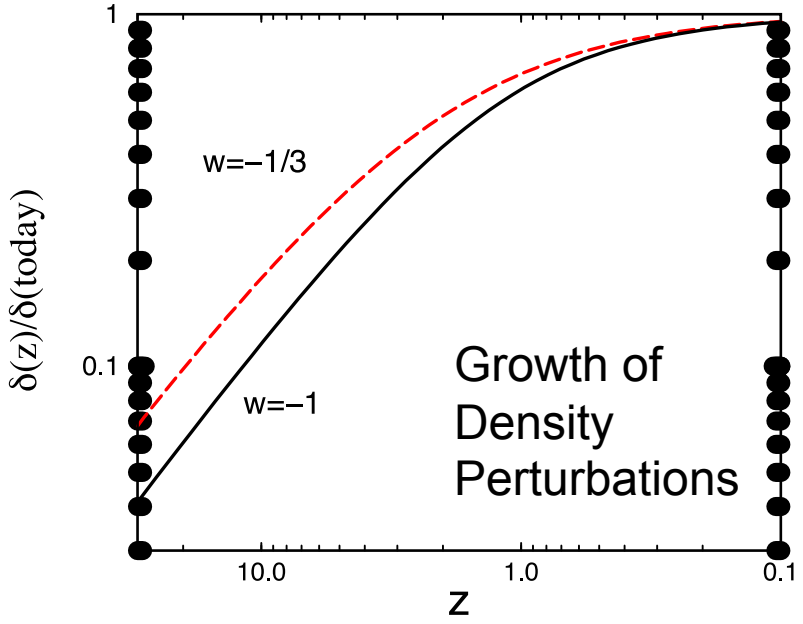


SDSS+SNLS joint analysis due out soon

What can we probe?

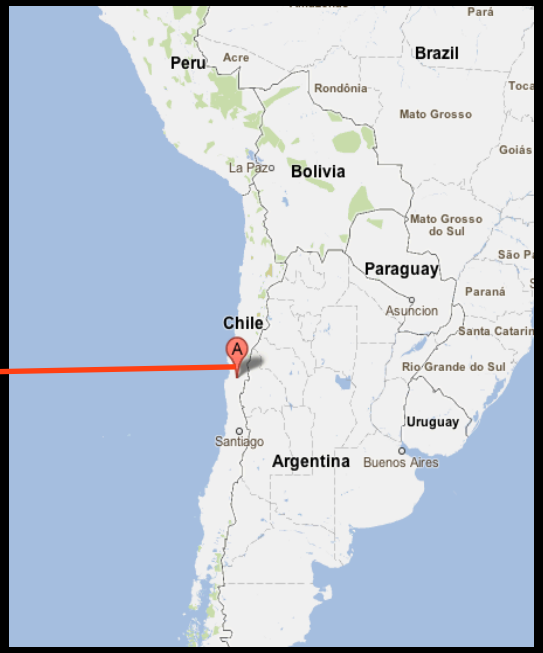
Require both to disentangle Dark Energy from Modified Gravity





- Weak Lensing cosmic shear — Distances+growth
- Supernovae — Distances
- Baryon Acoustic Oscillations — Distances and H(z)
- Cluster counts — Distances+growth
- Redshift Distortions — Growth

Cerro Tololo Inter-American Observatory

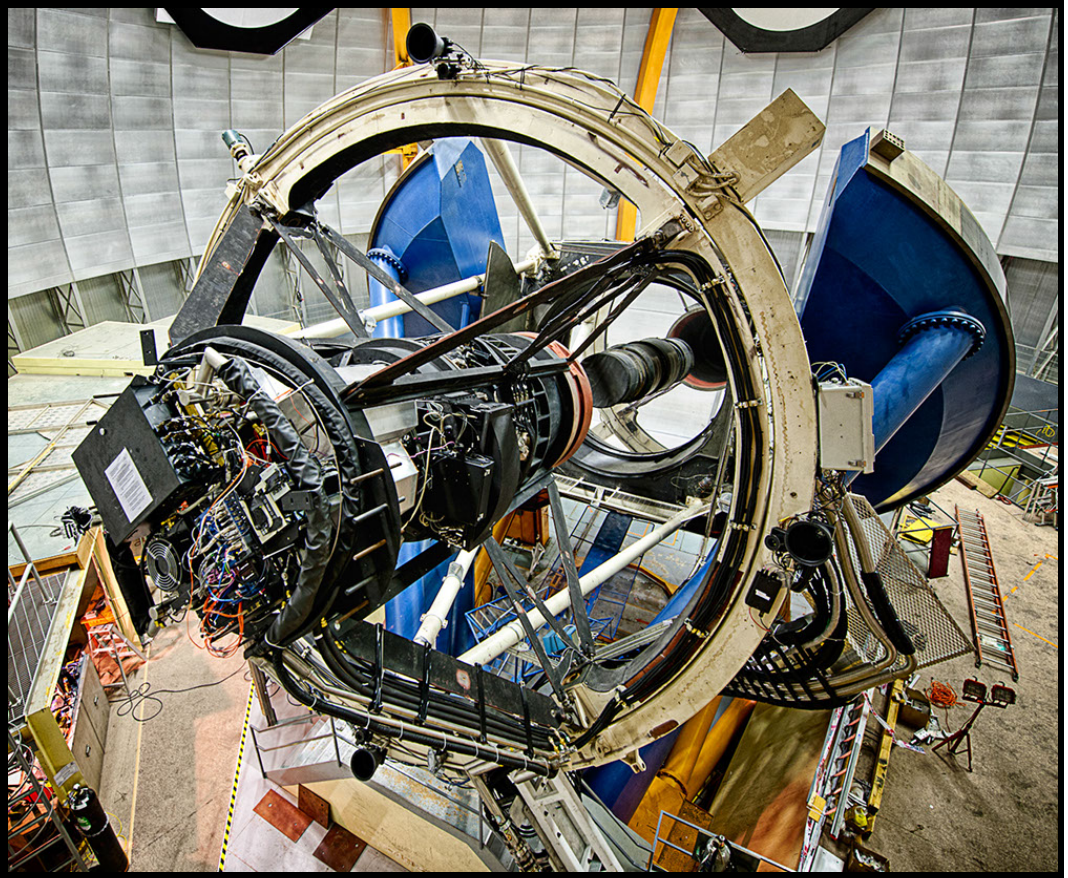


- Excellent astronomical site in Chilean Andes:
  - good seeing: ~0.75” median for site
  - high, dry: high percentage of clear, photometric nights
- Late 2003: NOAO Announcement of Opportunity for new facility instrument on the Blanco 4-meter telescope
- DES collaboration formed to build Dark Energy Camera and carry out Dark Energy Survey

The Dark Energy Survey

- Probe Dark Energy and the origin of Cosmic Acceleration:
  - History of cosmic expansion
  - Growth of structure
- Two multicolor surveys:
  - 300 M galaxies over 1/8 sky
  - 4000 supernovae (30 sq deg)
- Using new camera on the Blanco
- Five-year Survey started Aug. 31, 2013
  - 525 nights (Sept.-Feb.)

DECam on the Blanco

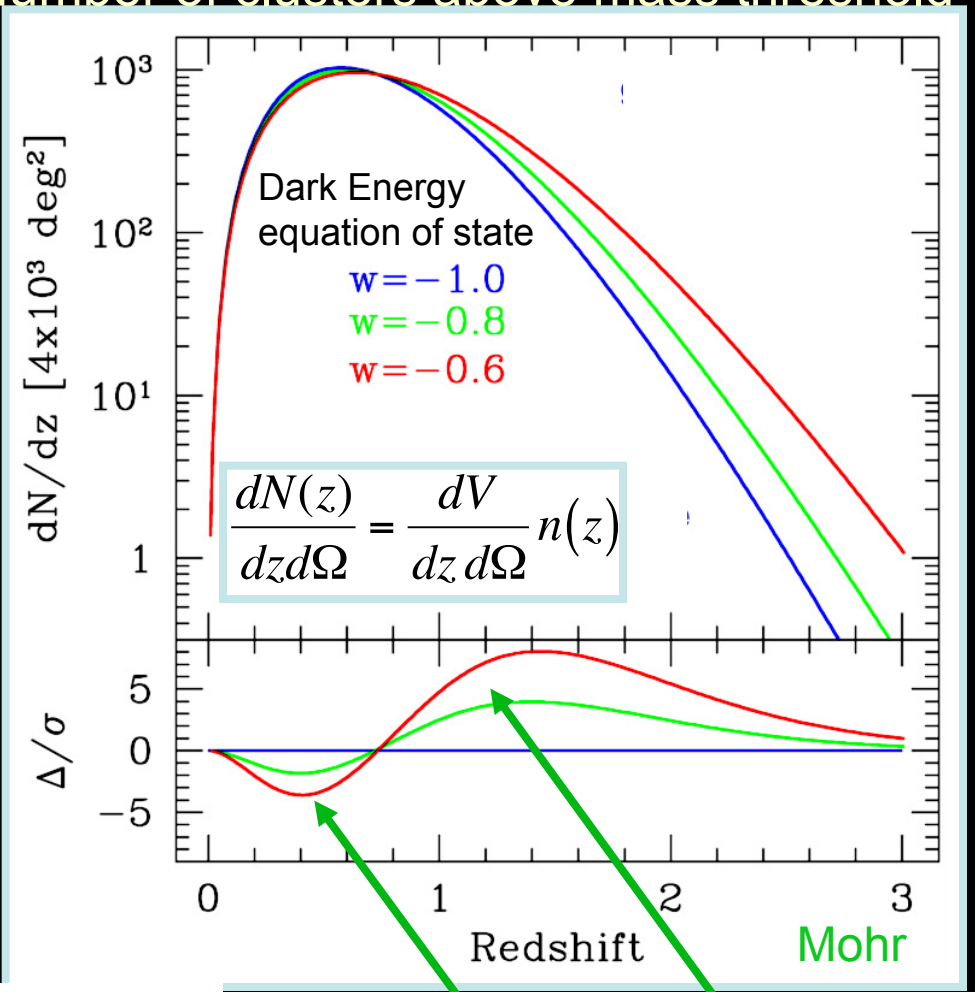


www.darkenergysurvey.org
www.darkenergydetectives.org

I. Clusters

- Clusters are proxies for massive halos and can be identified to redshifts z>1
- Galaxy colors provide photometric redshift estimates for each cluster, σ(z)~0.01
- Challenge: determine mass-observable relation *p(O|M,z)* with sufficient precision
- Multiple observable proxies *O* for cluster mass: optical richness (DES), SZ flux (SPT), weak lensing mass (DES), X-ray flux

Number of clusters above mass threshold



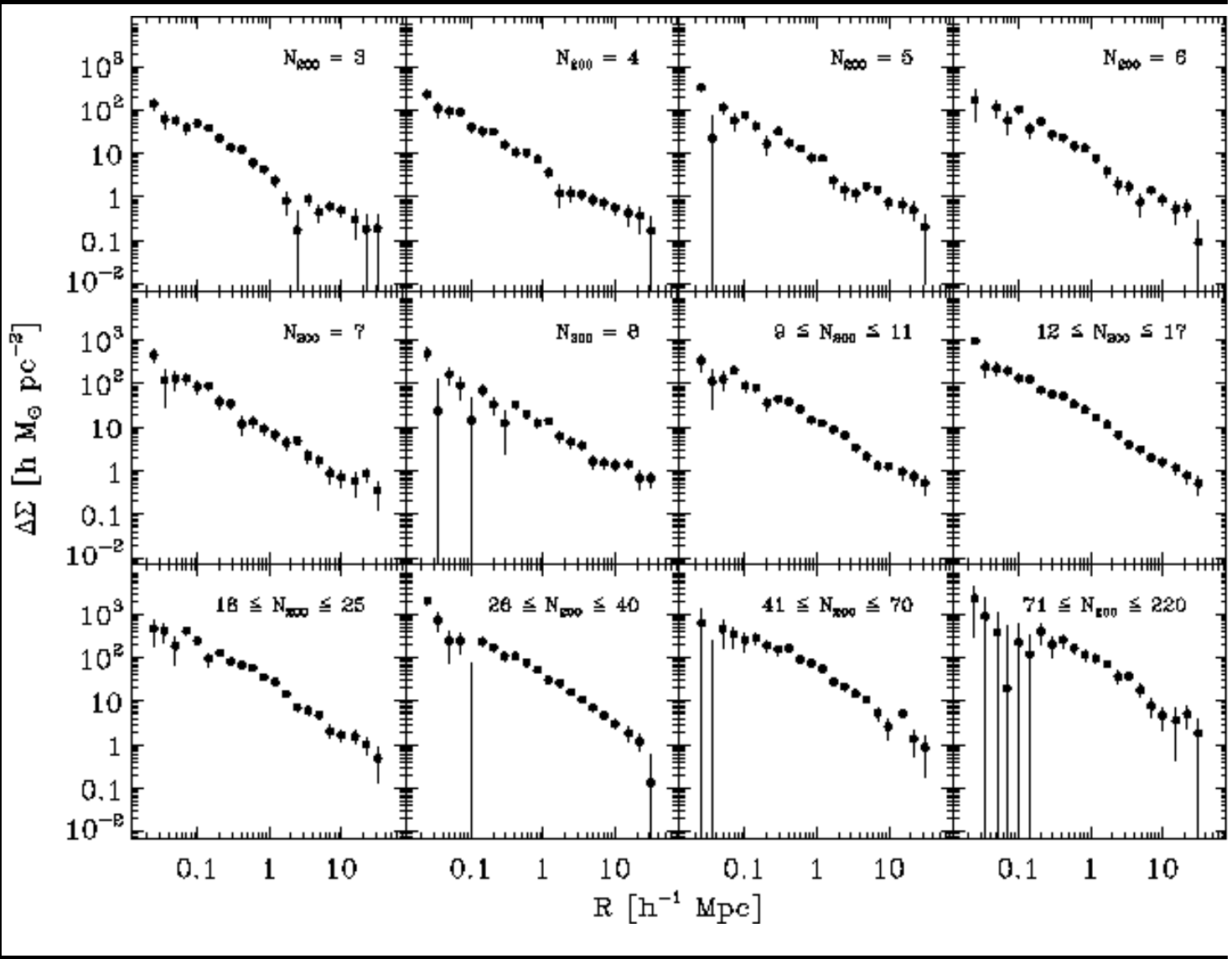
$$\frac{d^2N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z) dO \int p(O \mid M,z) \frac{dn(z)}{dM} dM$$

Volume Growth

Statistical Weak Lensing by Galaxy Clusters

Mean Tangential Shear Profile in Optical Richness (N_{gal}) Bins to 30 h^{-1}Mpc

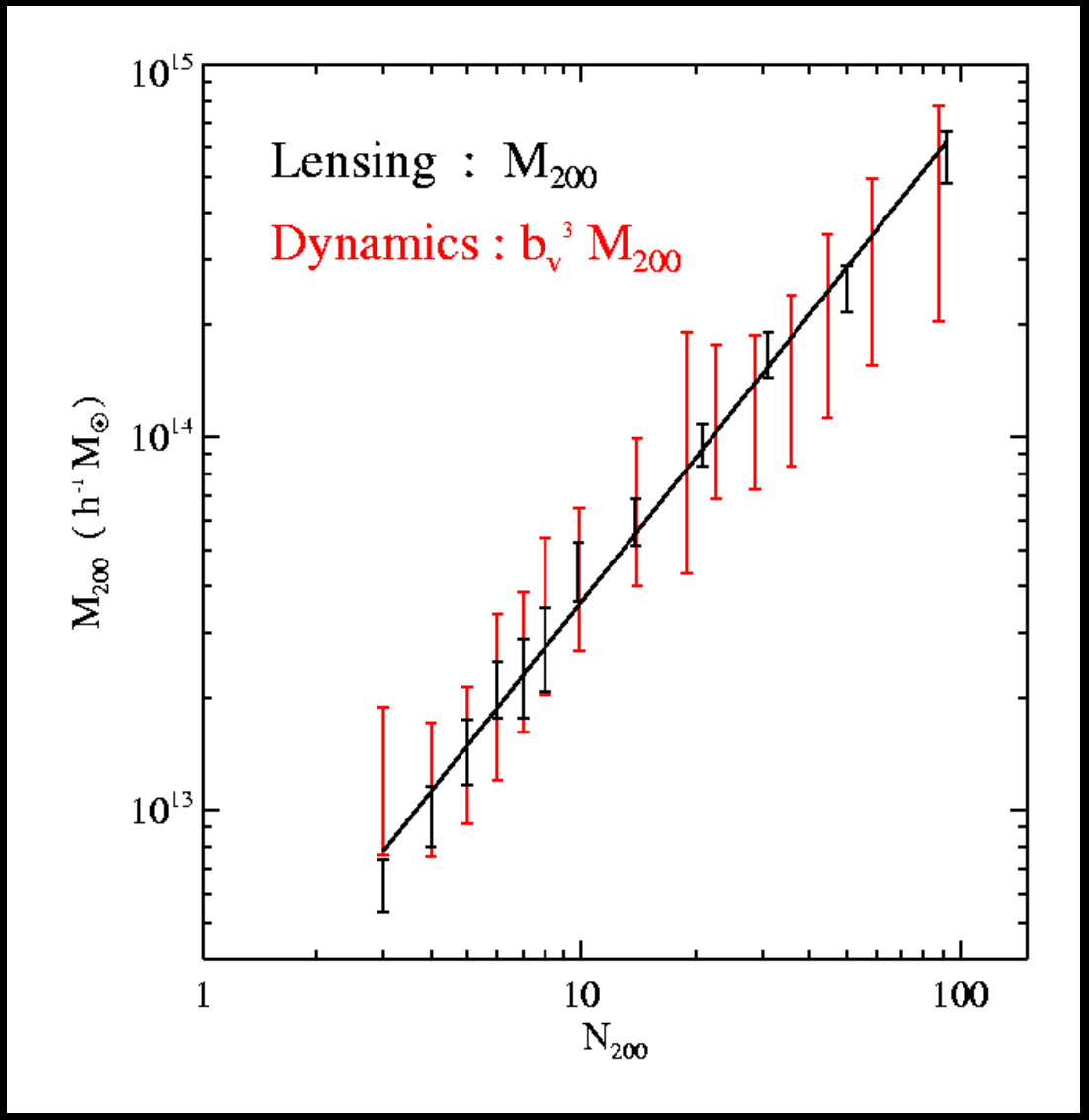
Sheldon, Johnston, etal SDSS



Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

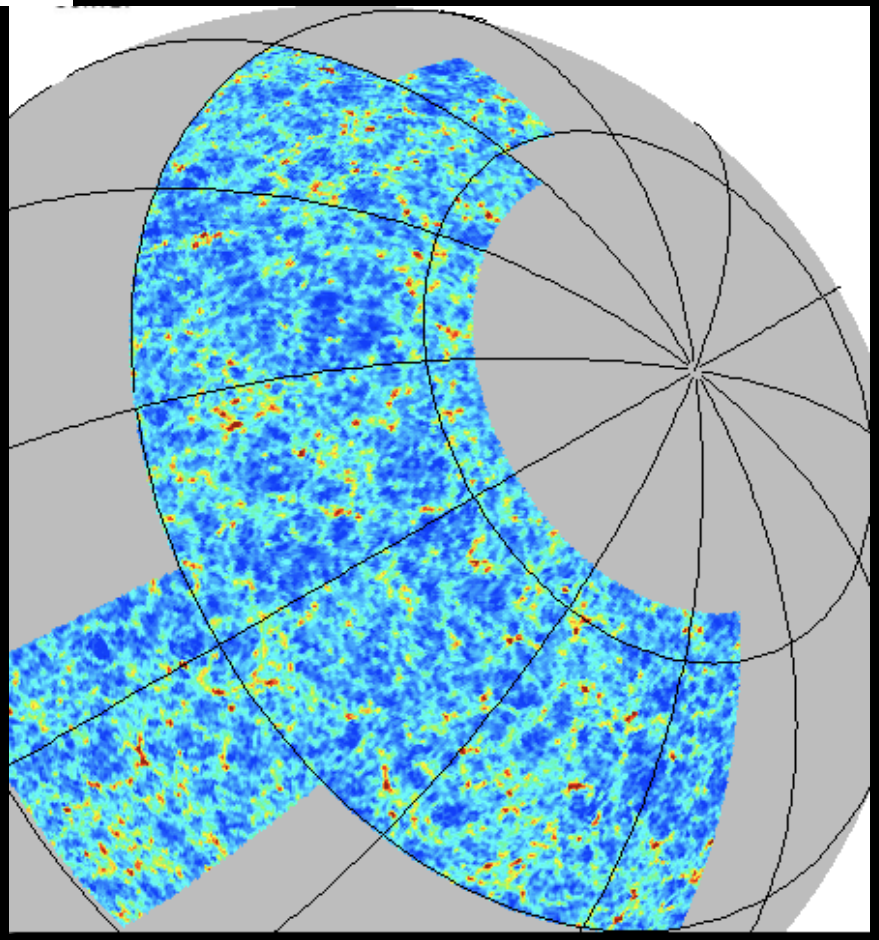
Cluster Mass vs. Number of galaxies they contain (richness) from SDSS

Johnston, Sheldon, etal



Synergy with South Pole Telescope

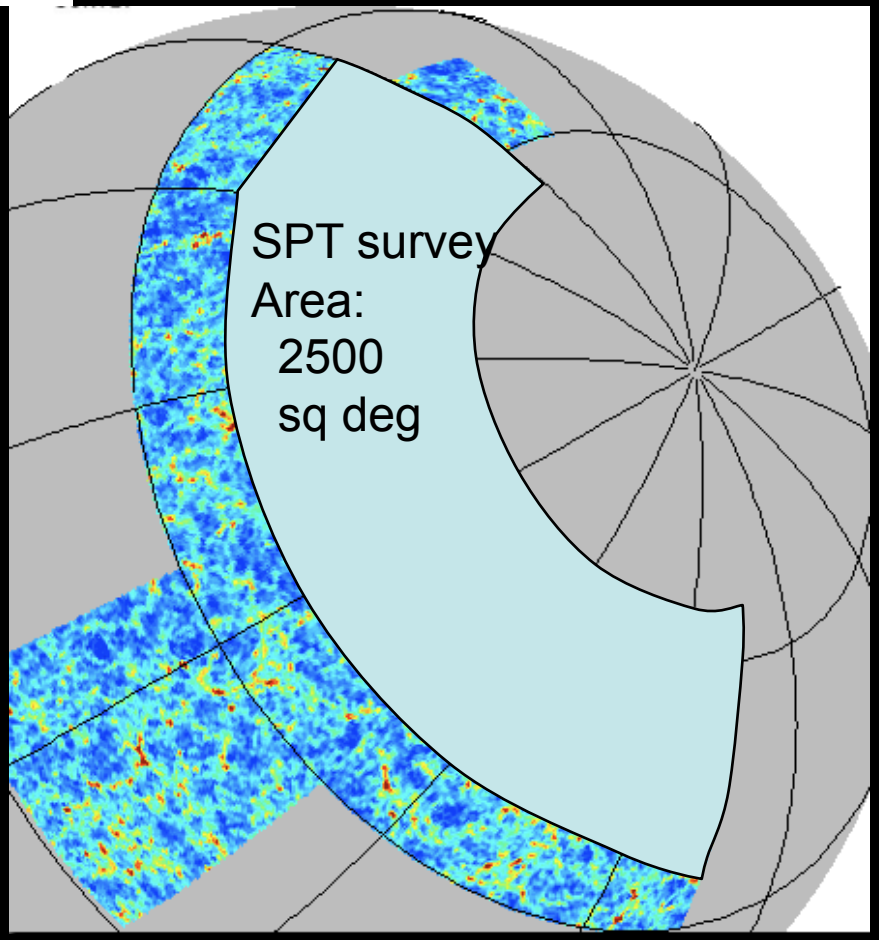
DES footprint: 5000 sq deg



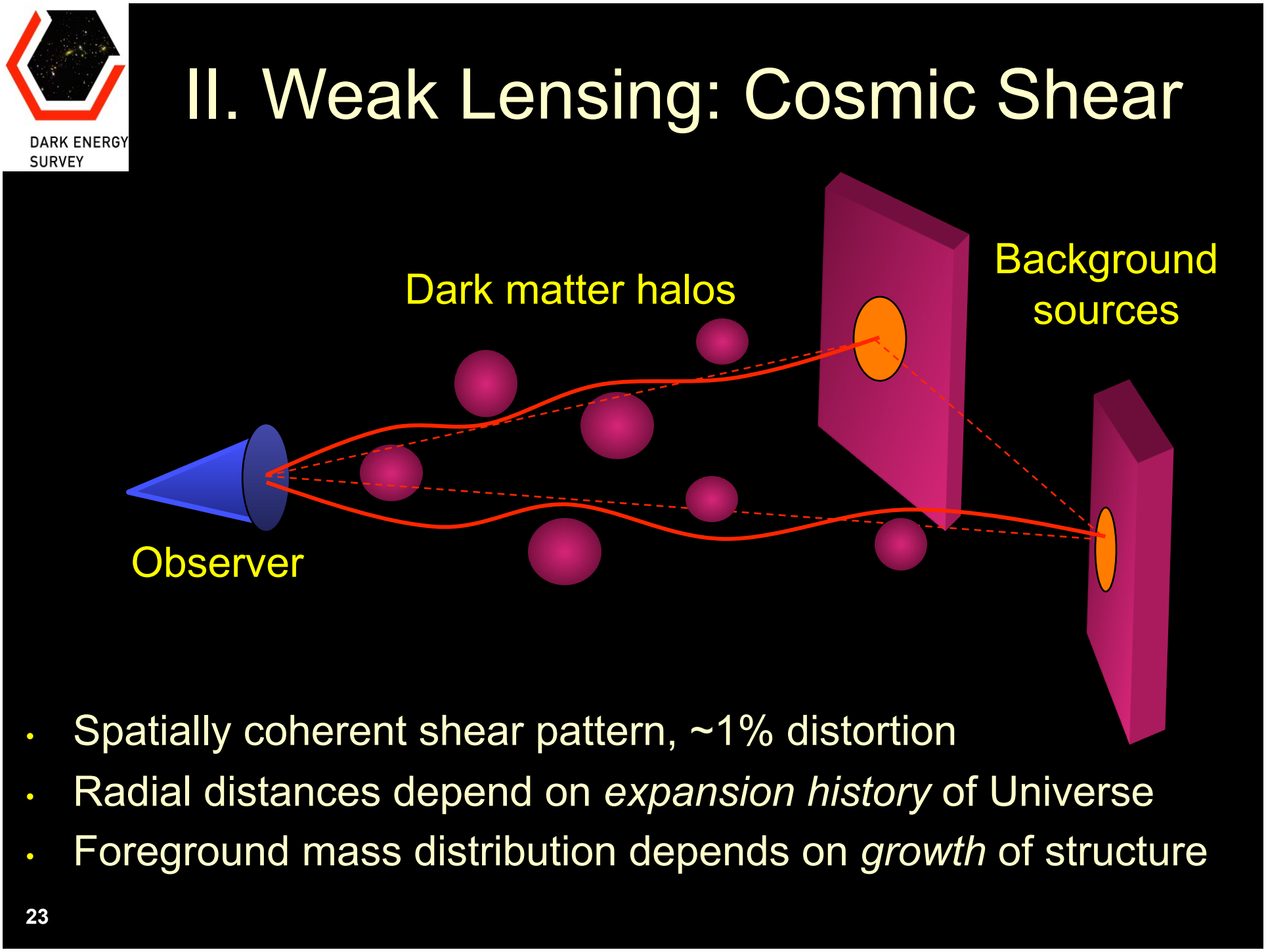
DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

Synergy with South Pole Telescope

DES footprint: 5000 sq deg



DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey
SZ flux correlates with cluster halo mass with ~10% scatter



II. Weak Lensing: Cosmic Shear

- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

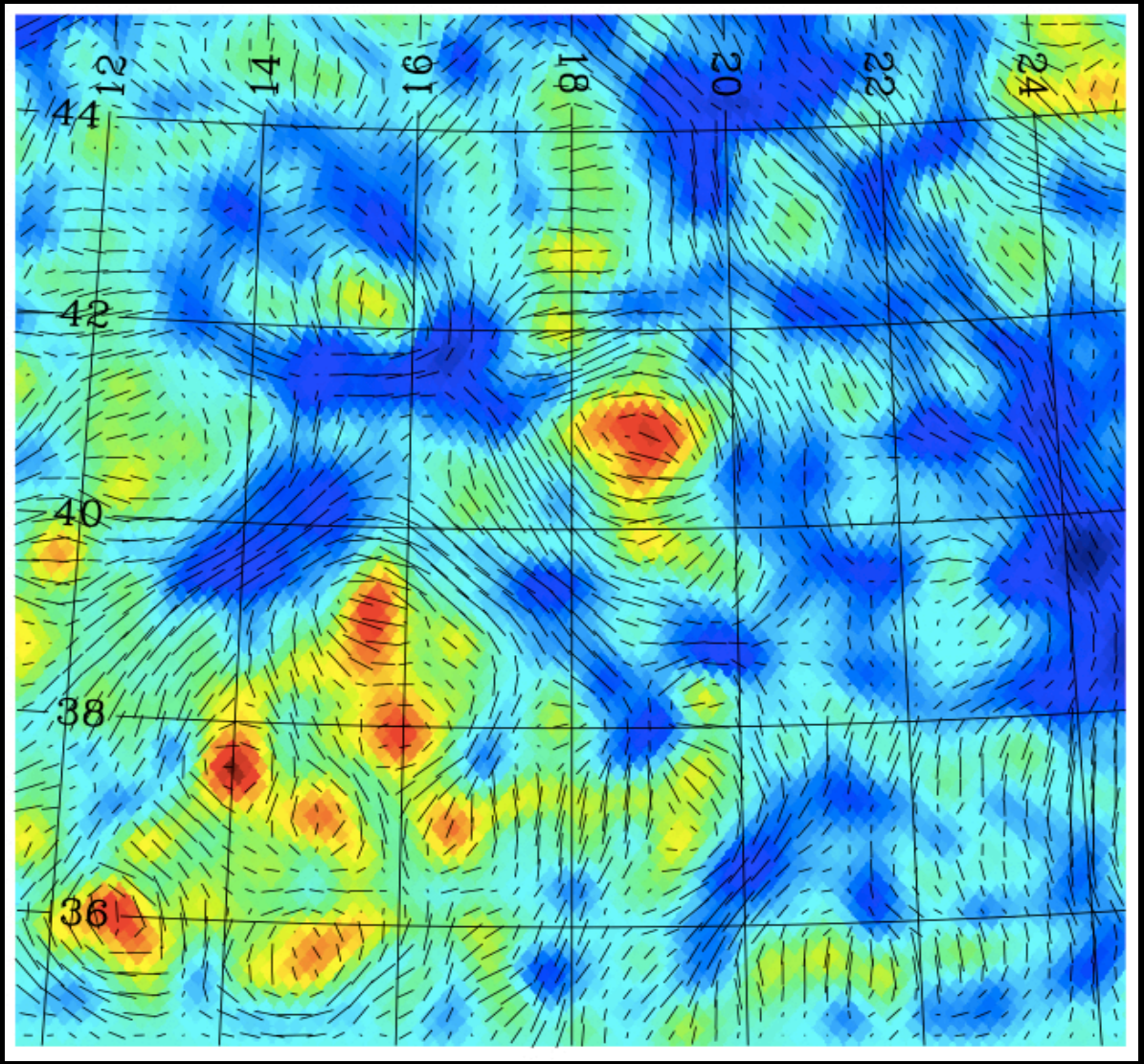
Weak Lensing Mass and Shear

DES Simulation

Tick marks: shear

Colors: projected mass density

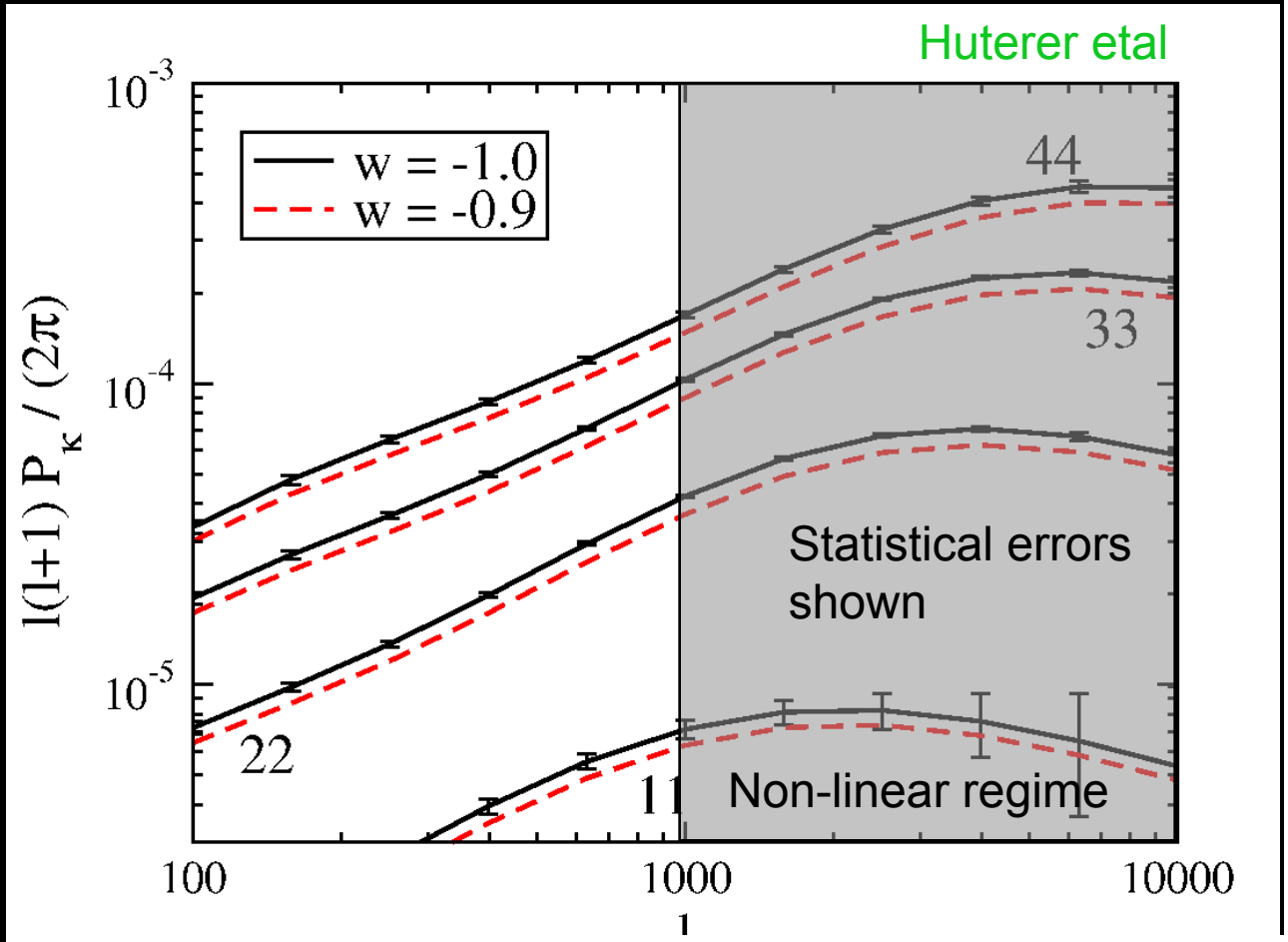
Becker, Kravtsov, etal



Weak Lensing Tomography

DARK ENERGY SURVEY

- Cosmic Shear Angular Power Spectrum in 4 Photo-z Slices
- Shapes of ~200 million well-resolved galaxies, $\langle z \rangle = 0.7$
- Systematics Challenges: photo-z's, intrinsic alignments, PSF anisotropy, shear calibration, nonlinear +baryon *P(k)* effects



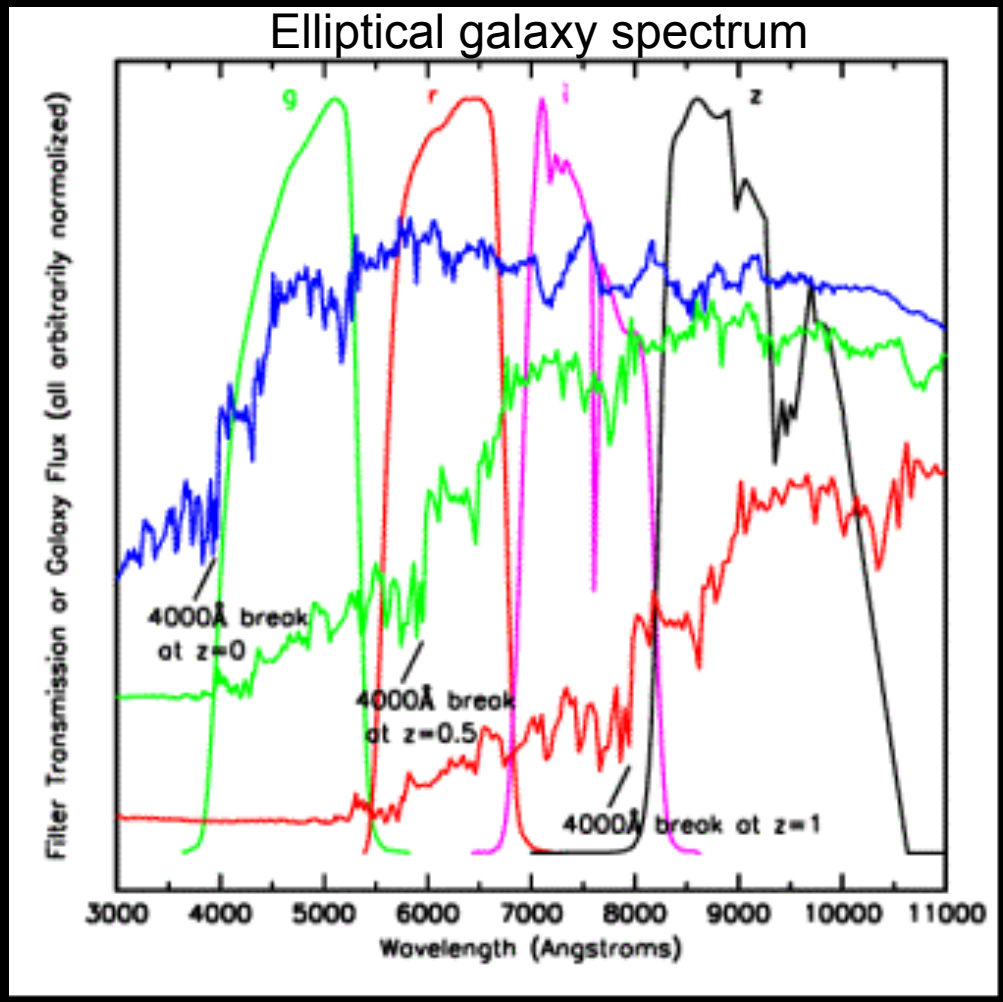
$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

DARK ENERGY SURVEY

Photometric Redshifts

- Measure relative flux in multiple filters (colors)
- Fit colors to template spectra or use spectroscopic data to train empirical z=f(colors) relation.
- Estimate galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.01 for clusters)
- Precision is sufficient for Dark Energy probes, *provided* error distributions well measured.
- Challenge: spectroscopic data not complete to depth of survey



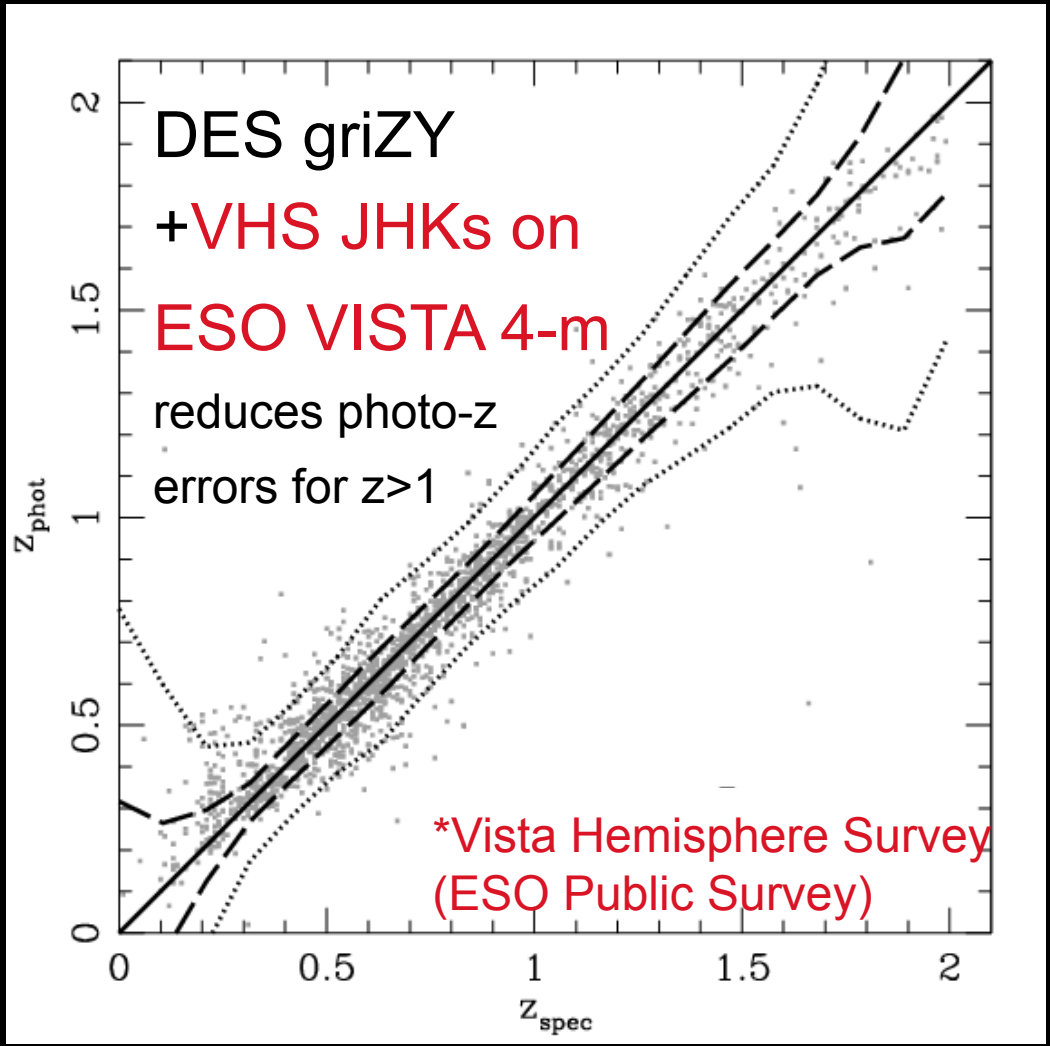
Galaxy Photo-z Simulations

DES +VHS*

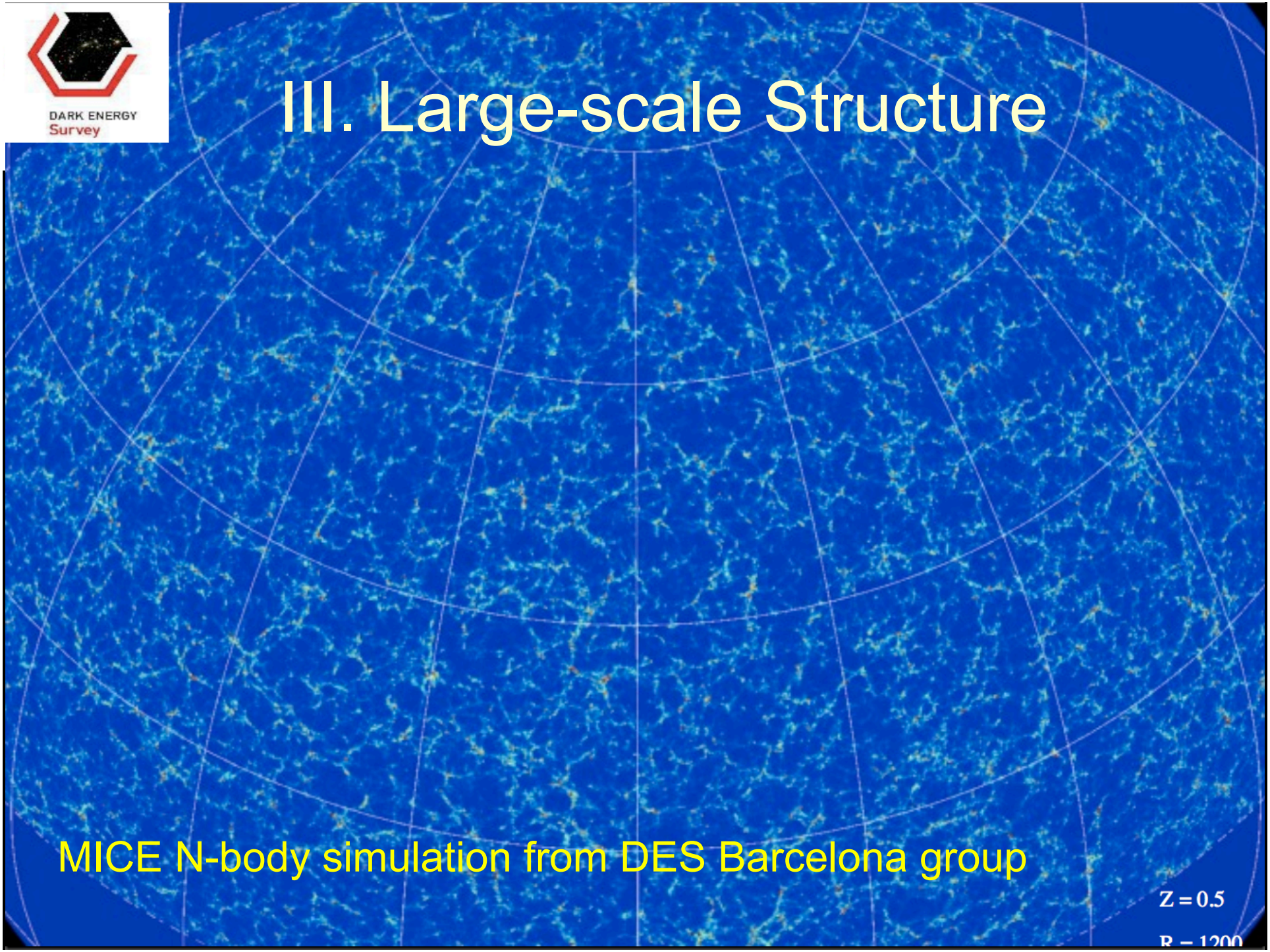
10σ Limiting Magnitudes

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



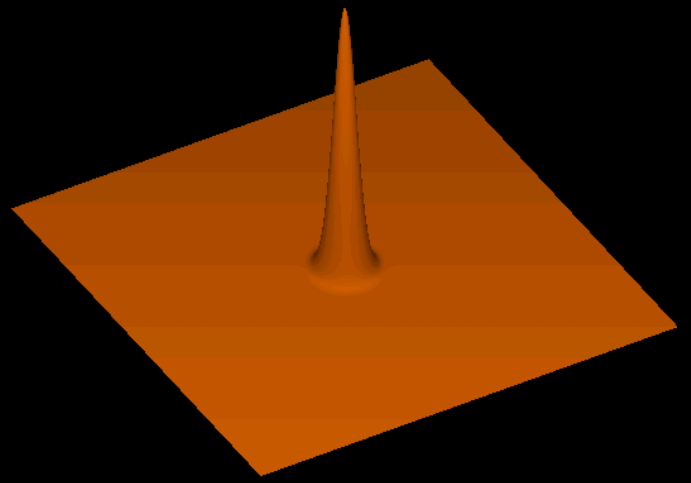
III. Large-scale Structure

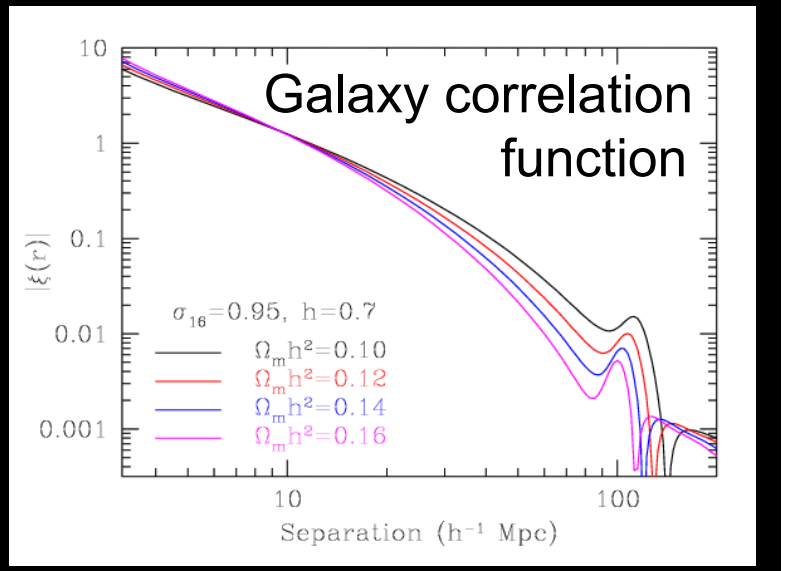


MICE N-body simulation from DES Barcelona group

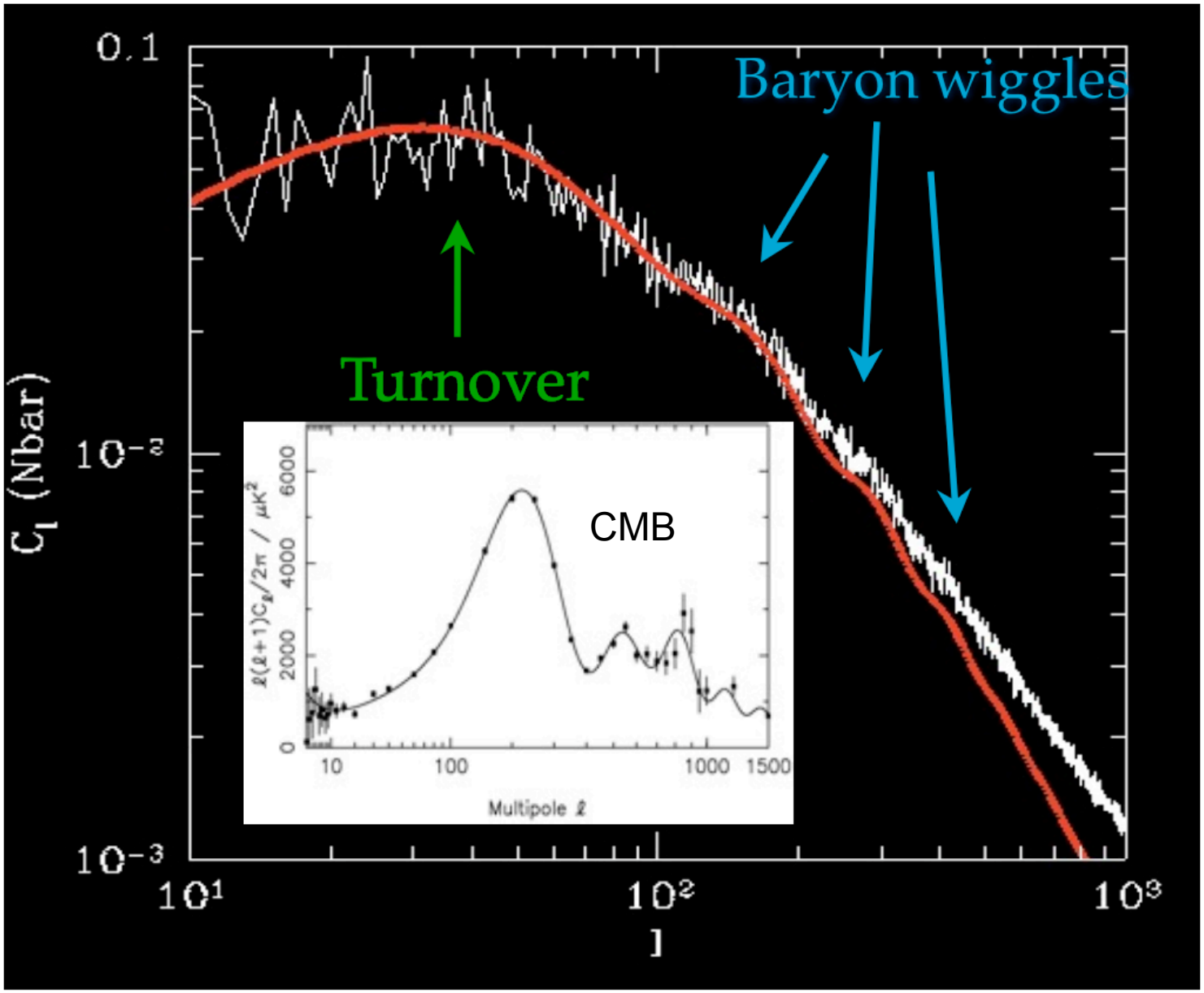
Baryon Acoustic Oscillations

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.





Eisenstein



DARK ENERGY Survey

Galaxy Angular Spectrum

For single redshift slice:

z =0.9-1.0

Out of MICE Simulation

www.ice.cat/mice

Slide from E. Gaztanaga, DES Spain

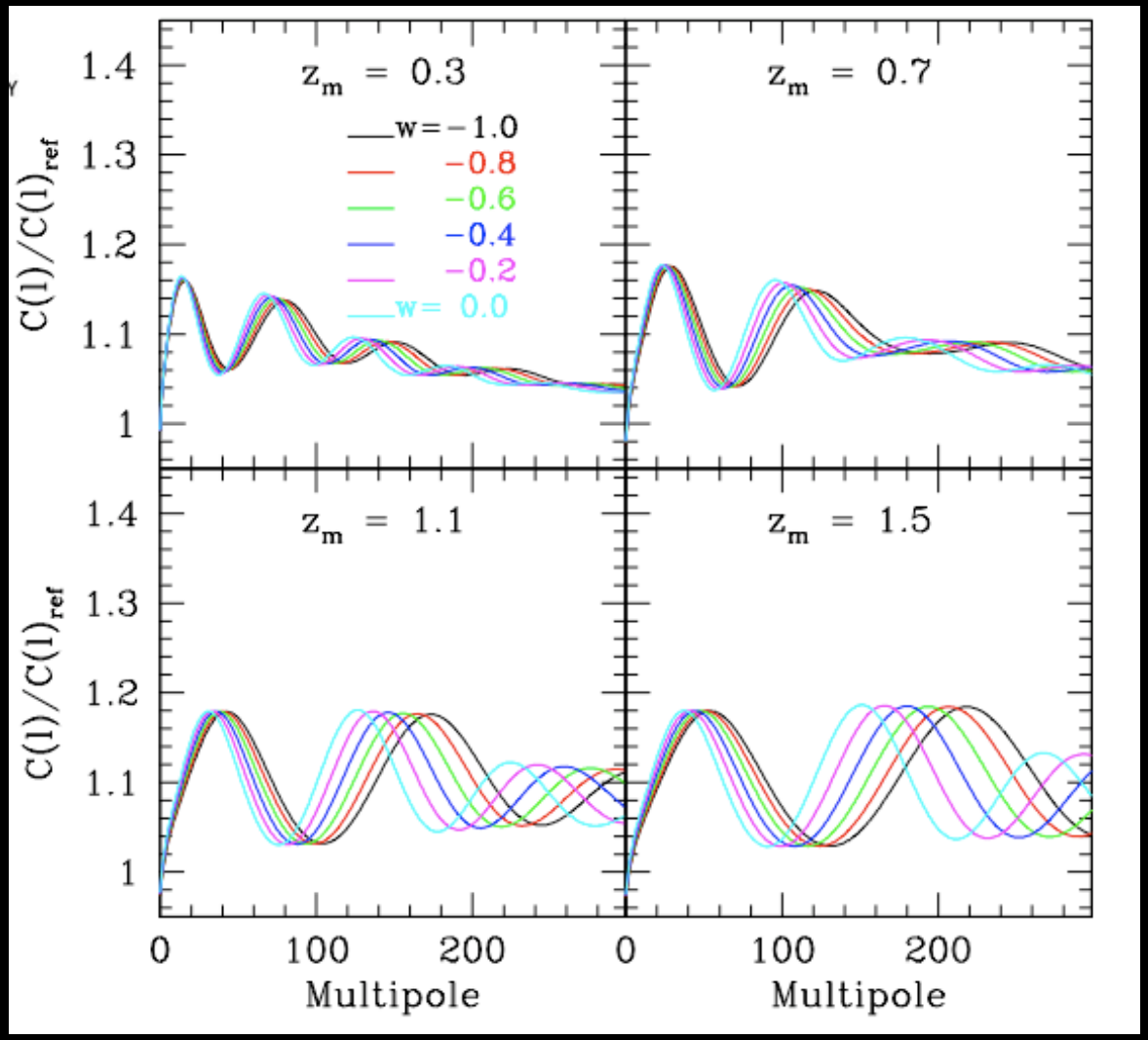
Measurements can provide both with:
1. BAO scale (DM & Baryon density)
2. distance to BAO scale (DE)

$$c\Delta z_{BAO} = r_{BAO} H(z) \qquad \Delta\theta_{BAO} = \frac{r_{BAO}}{d_A(z)}$$

Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins (relative to model without BAO)

Photometric surveys provide this angular measure



Fosalba & Gaztanaga

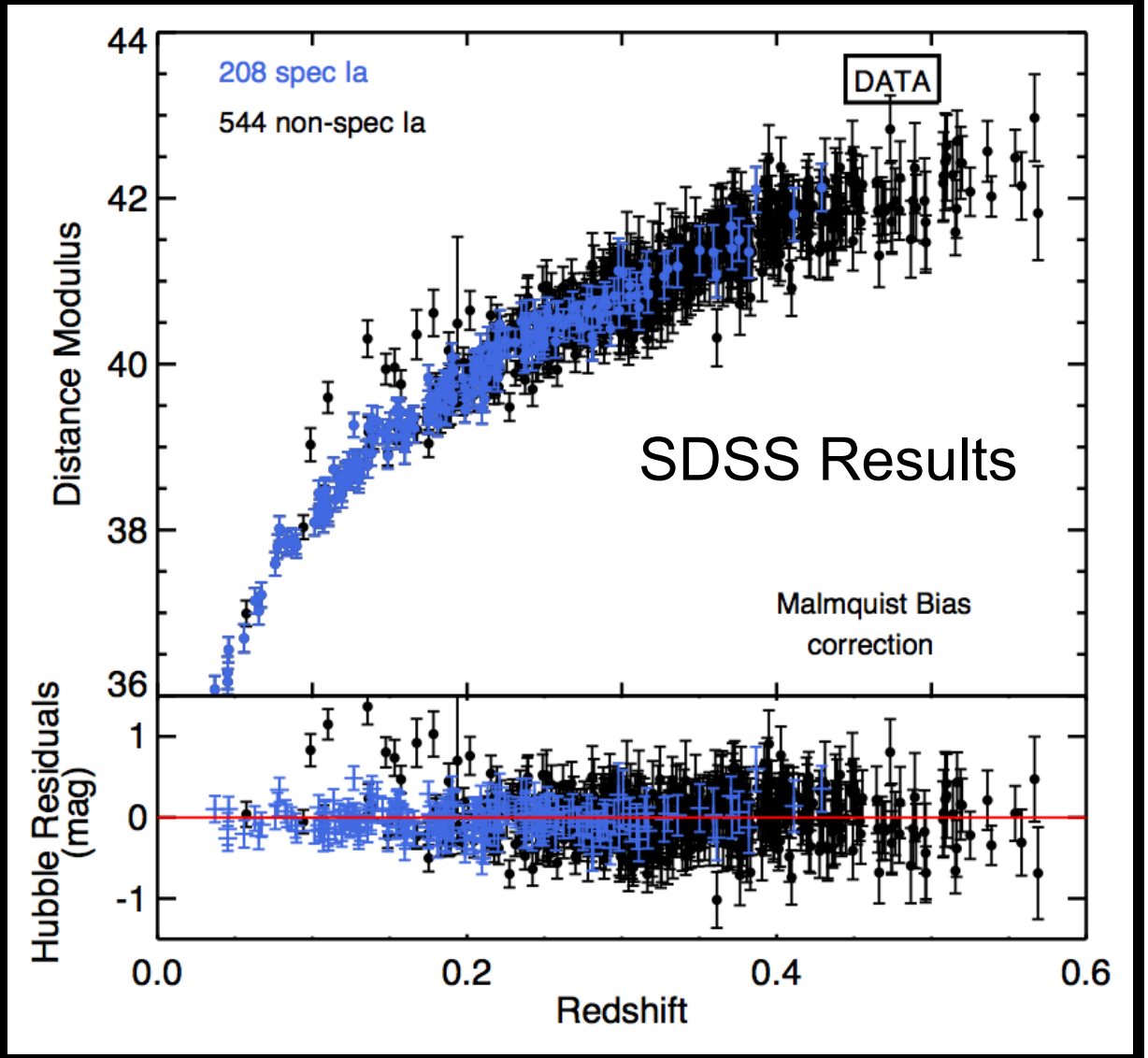
IV. Supernovae

B. Dilday

SDSS-II: 500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III

Photometric SN Cosmology

- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts
- DES will have host redshifts, plus SN spectra for a subsample



Campbell, etal

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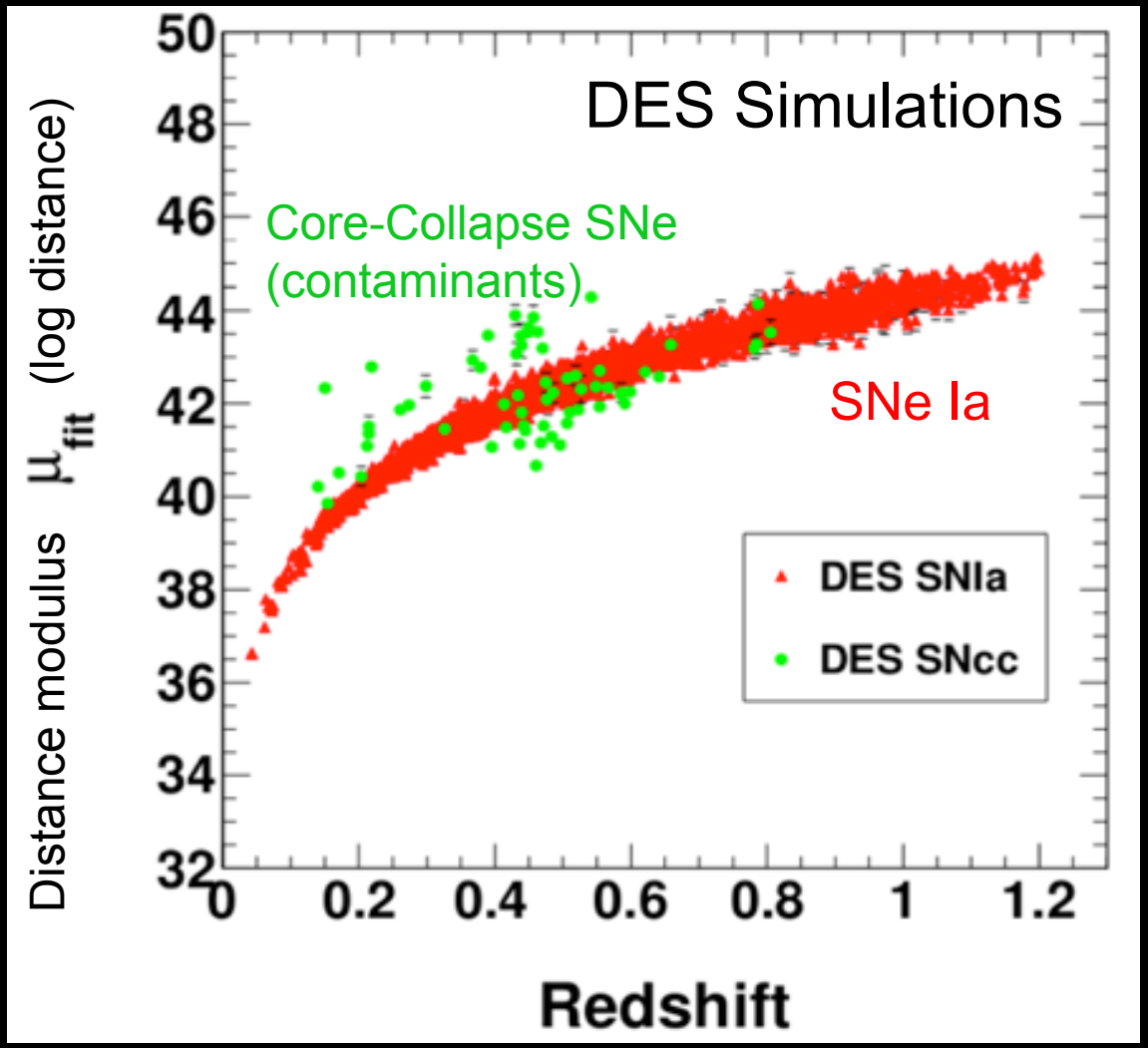


Bernstein, etal

DES Science Summary

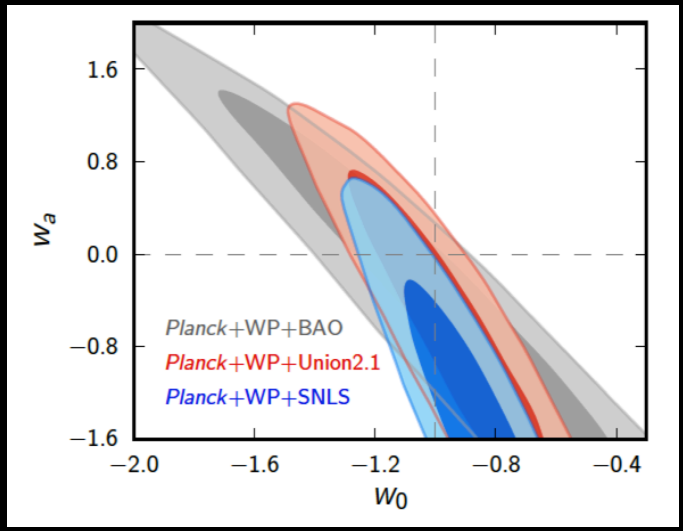
DARK ENERGY SURVEY

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
- Weak Lensing
  - Shape and magnification measurements of 200 million galaxies
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1

Current Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



Ade, etal

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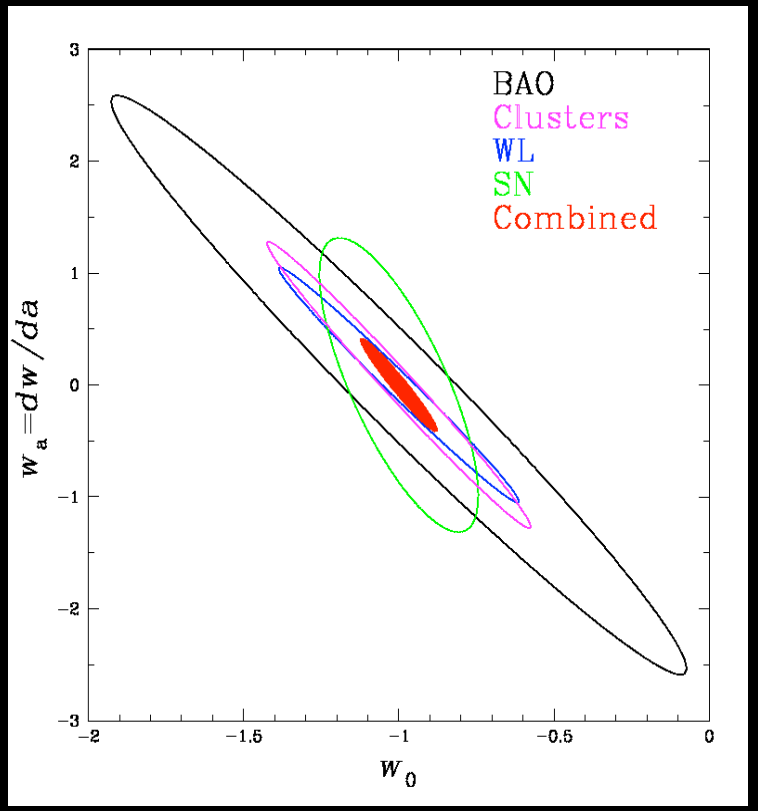
Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



DES forecast

DES Science Summary

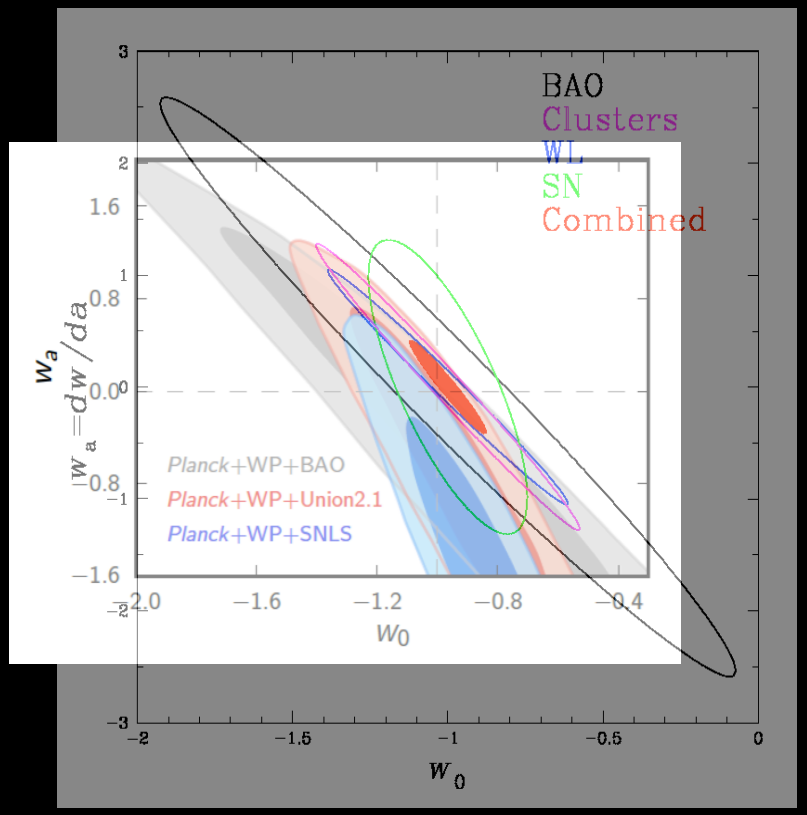
DARK ENERGY SURVEY

Four Probes of Dark Energy

- **Galaxy Clusters**
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
- **Weak Lensing**
  - Shape and magnification measurements of 200 million galaxies
- **Baryon Acoustic Oscillations**
  - 300 million galaxies to z = 1 and beyond
- **Supernovae**
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1

Current Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$

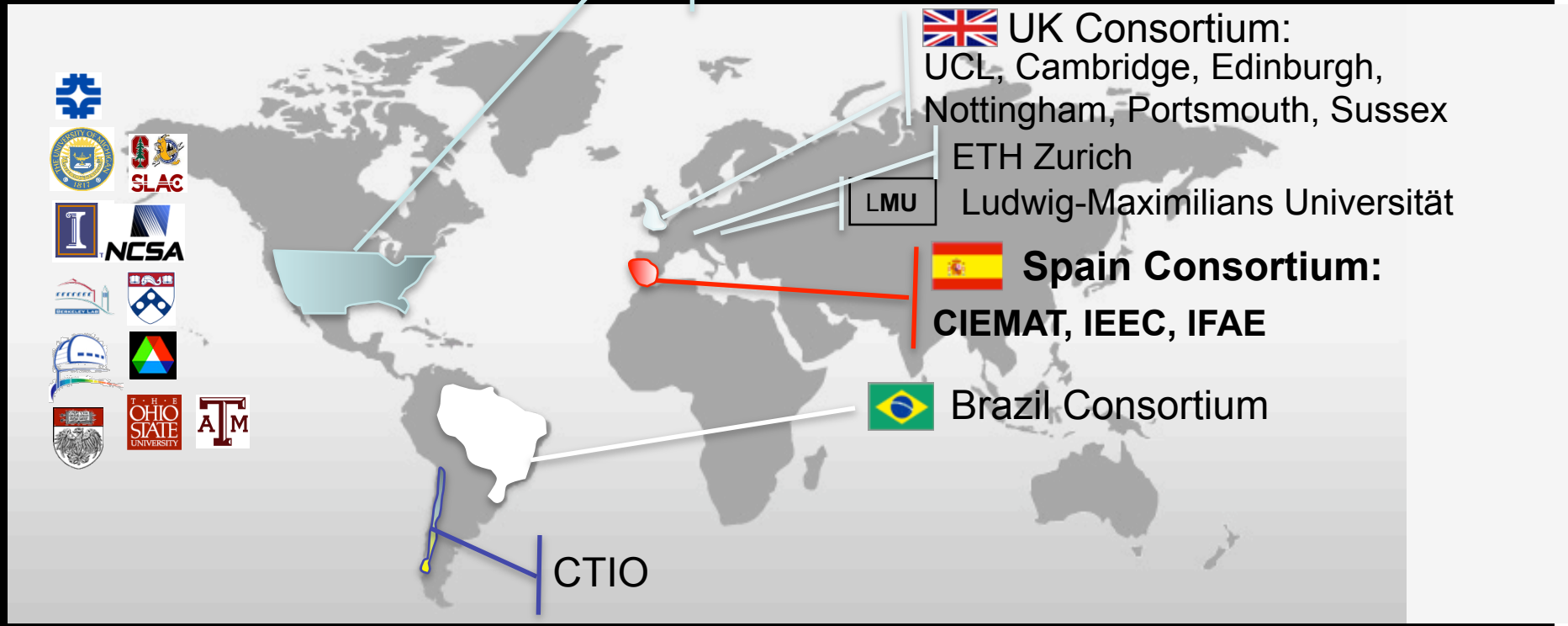


DES forecast

Dark Energy Survey Collaboration

~300 scientists from around the world

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M



DES Group in Madrid

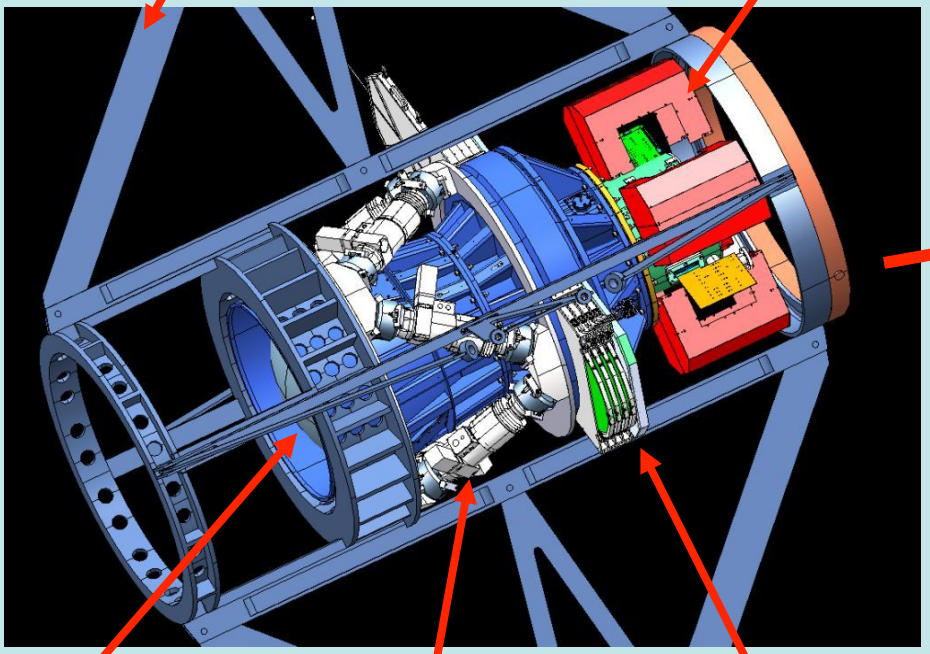
- Eusebio Sanchez
- Juan Garcia-Bellido
- Ignacio Sevilla
- Juan de Vicente
- Savvas Nesseris
- Rafael Ponce
- Javier Sanchez
- Ana Salvador
- Santiago Avila

- CIEMAT and UAM
- DES contributions from Spanish Ministry of Science and Education

Dark Energy Camera

Mechanical Interface of DECam Project to the Blanco

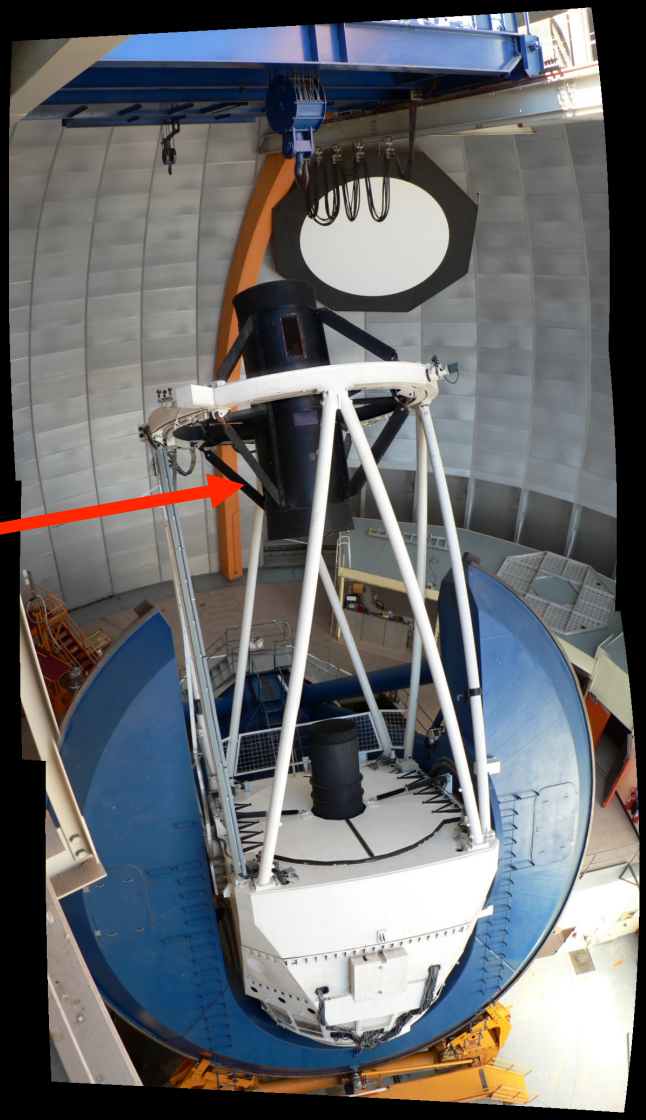
CCD Readout



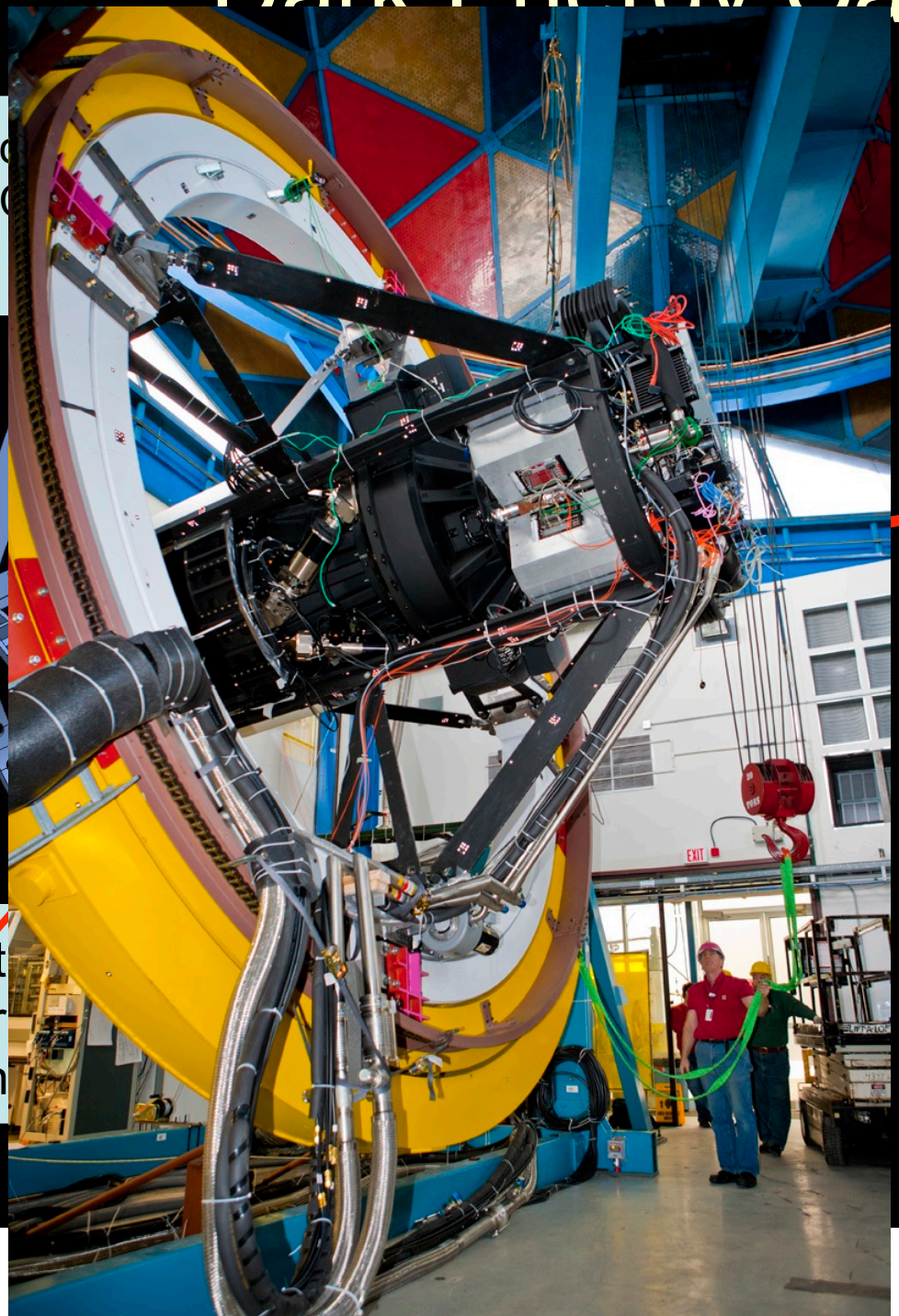
Optical Corrector Lenses

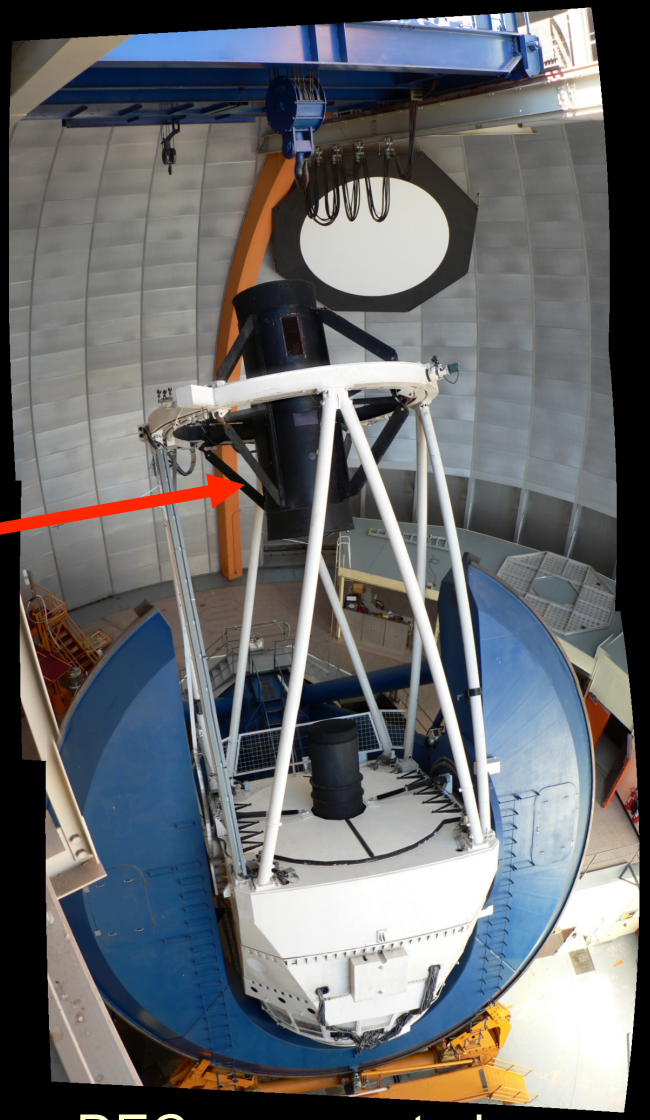
Hexapod: optical alignment

Filters & Shutter



Dark Energy Camera

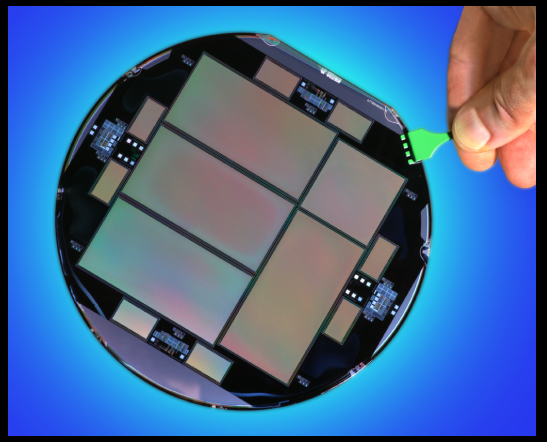




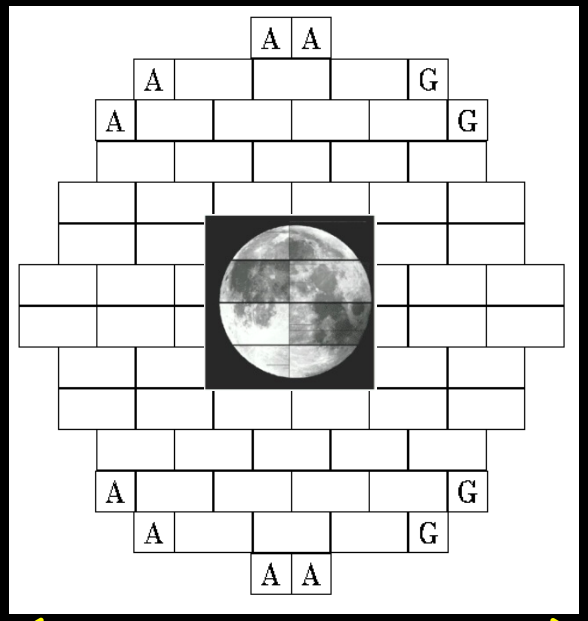
DECam mounted on
Telescope Simulator
at Fermilab in early 2011

DARK ENERGY SURVEY

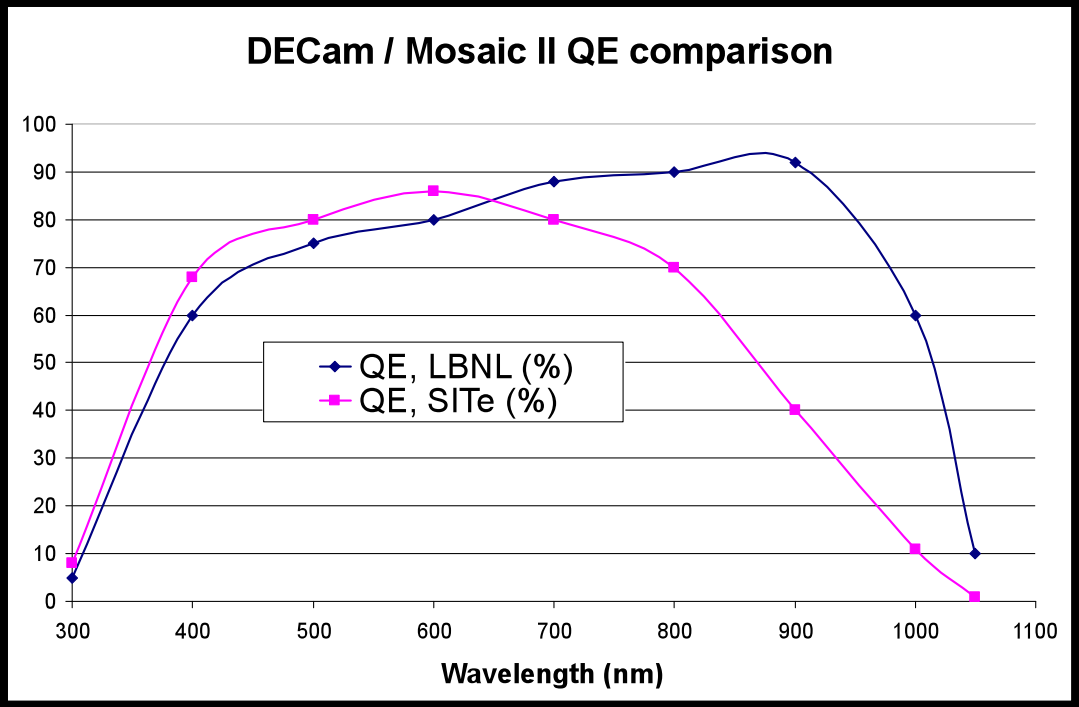
DECam CCDs



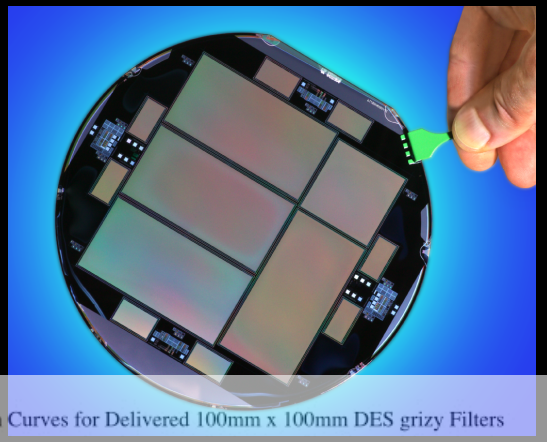
- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels



2.2 deg



DECam CCDs



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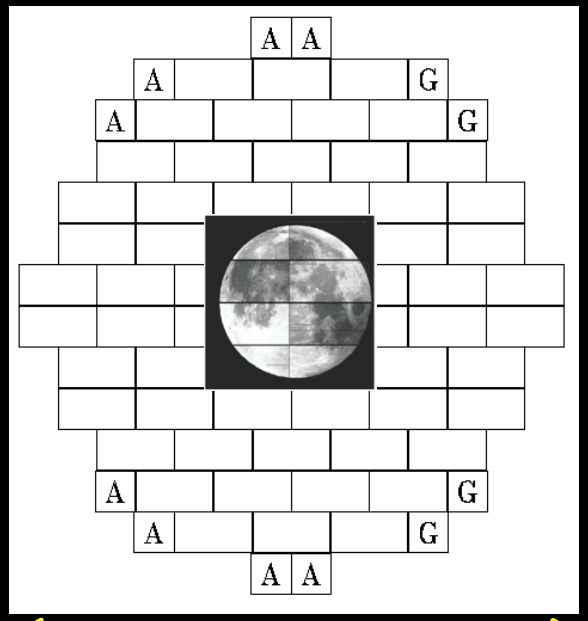
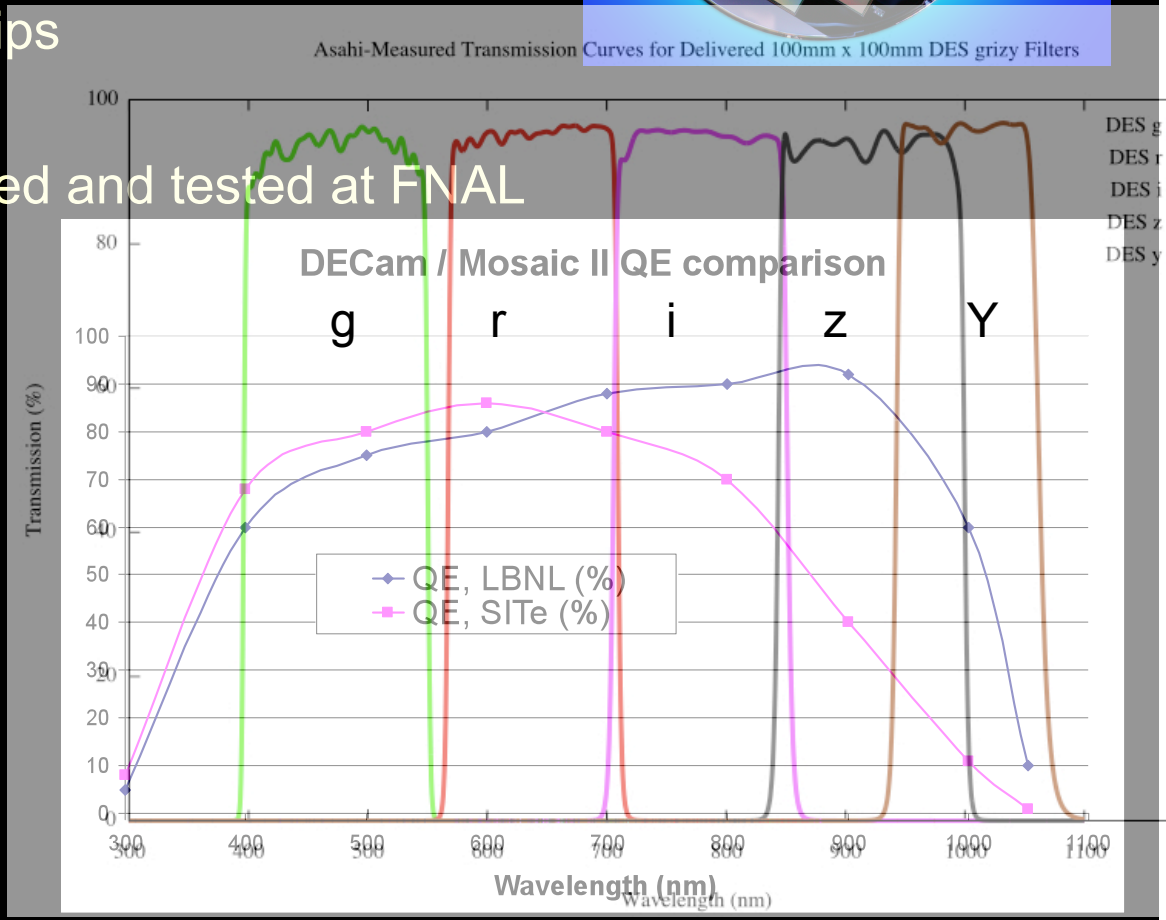


2.2 deg

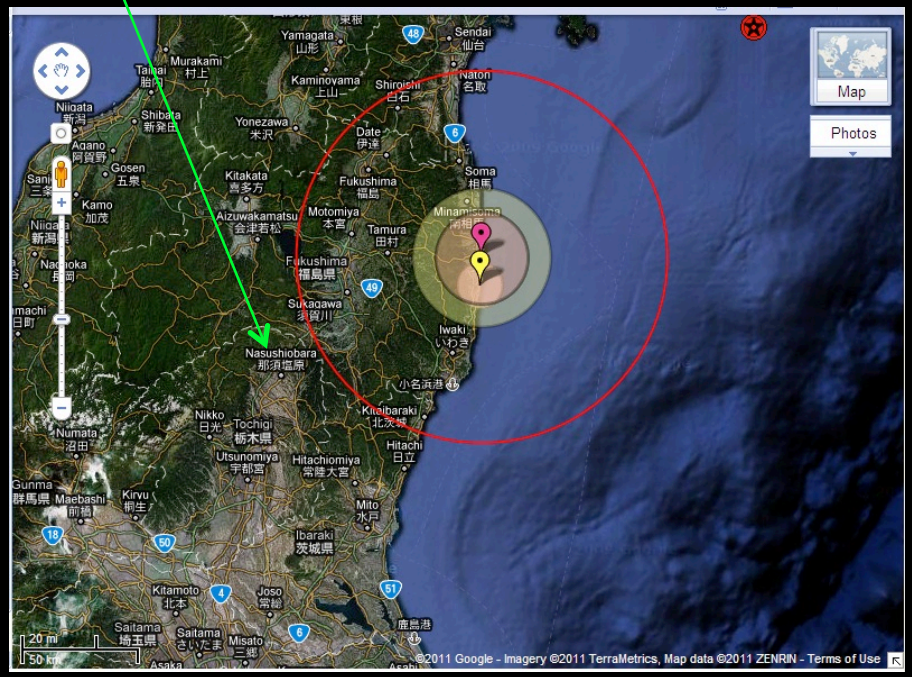


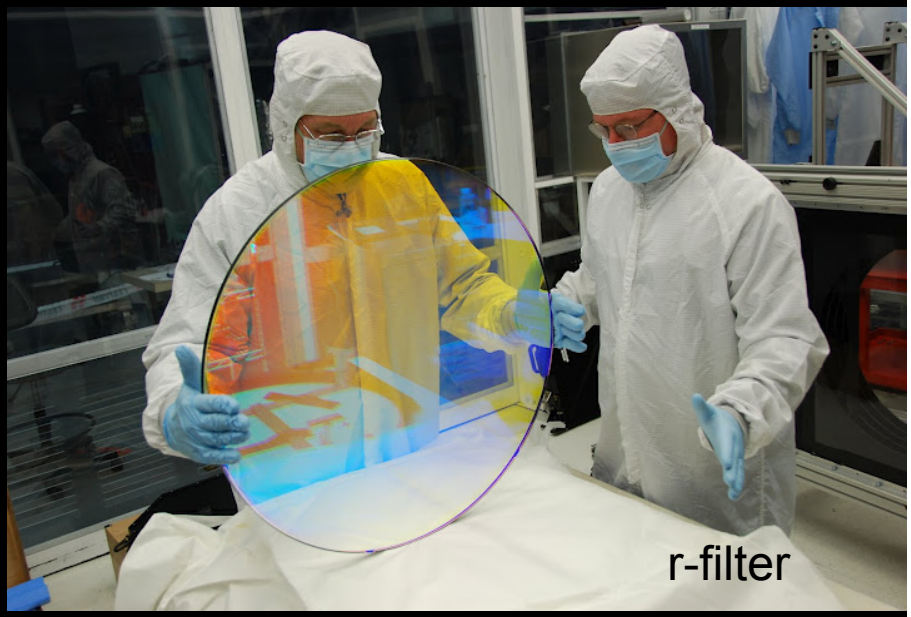
DES filters

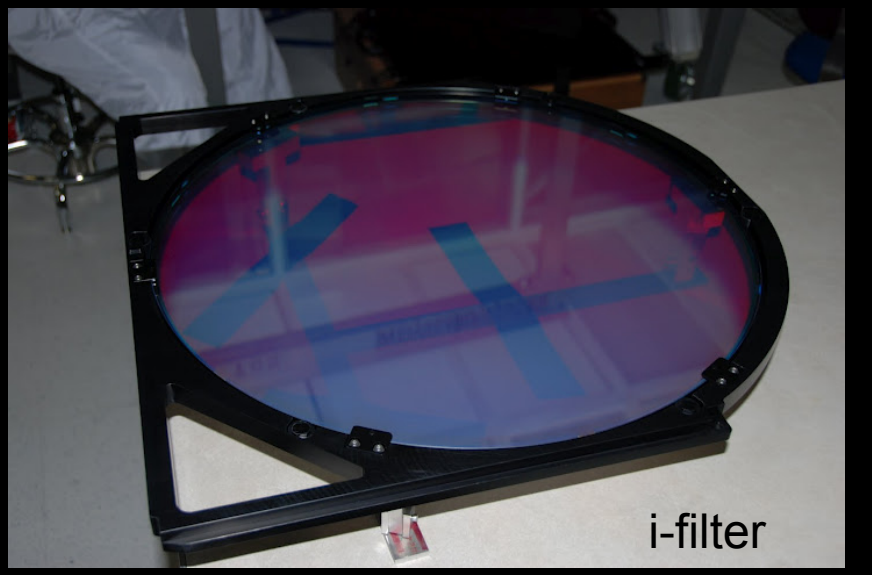
DARK ENERGY SURVEY

Filters

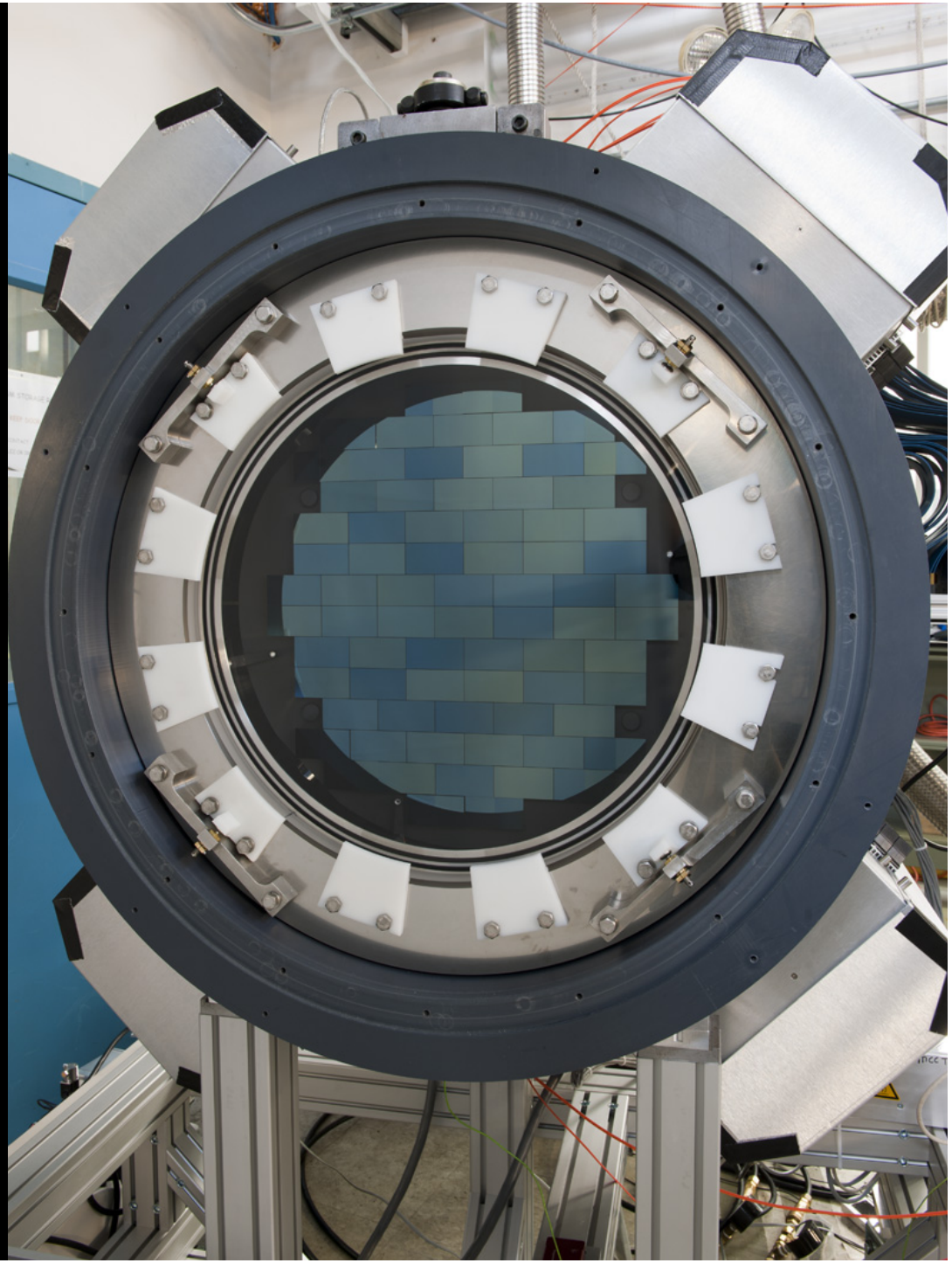
- 600 mm clear aperture, tight uniformity constraints, excellent throughput.
- Fabrication completed by Asahi within months of the tsunami in Japan.







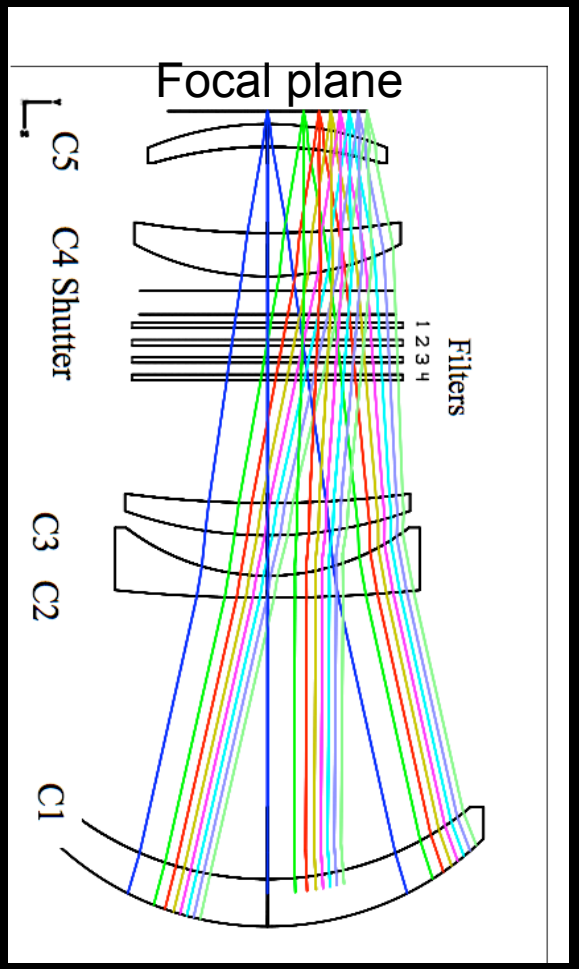
570-Million pixel Dark Energy Camera



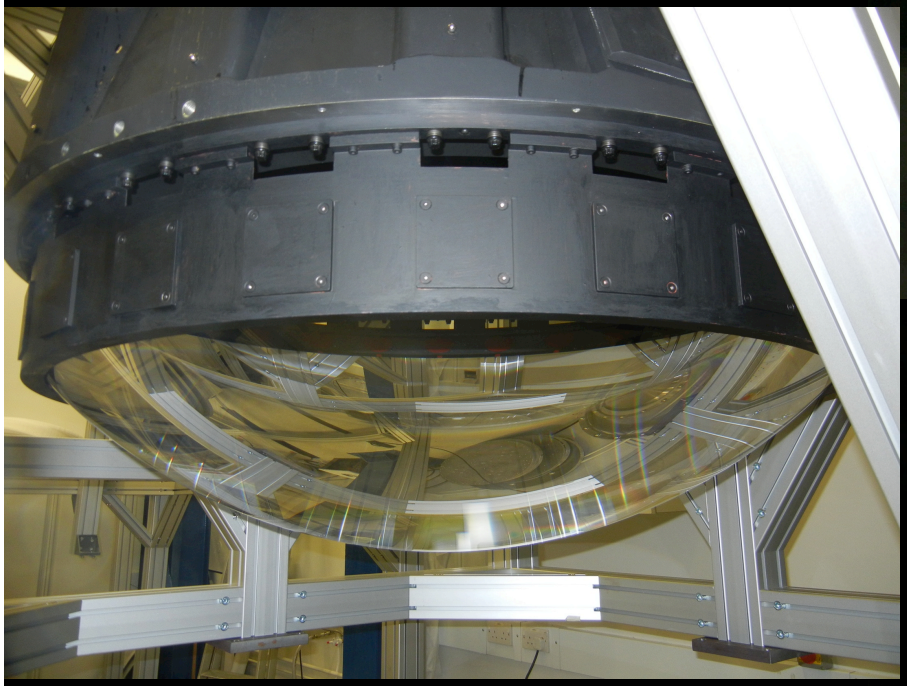
Optical Corrector Lenses

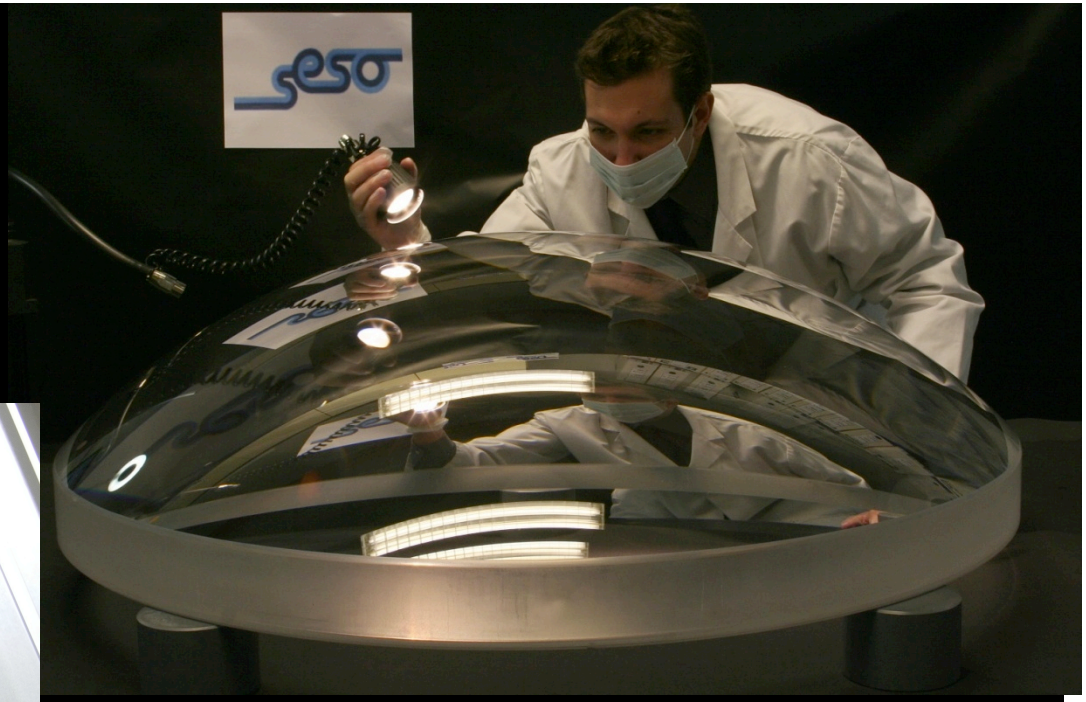
- Field of view: 2.2^{o} diameter
- Good image quality across FOV
- Optical elements aligned at UCL

S. Kent (Fermilab)



DARK ENERGY SURVEY

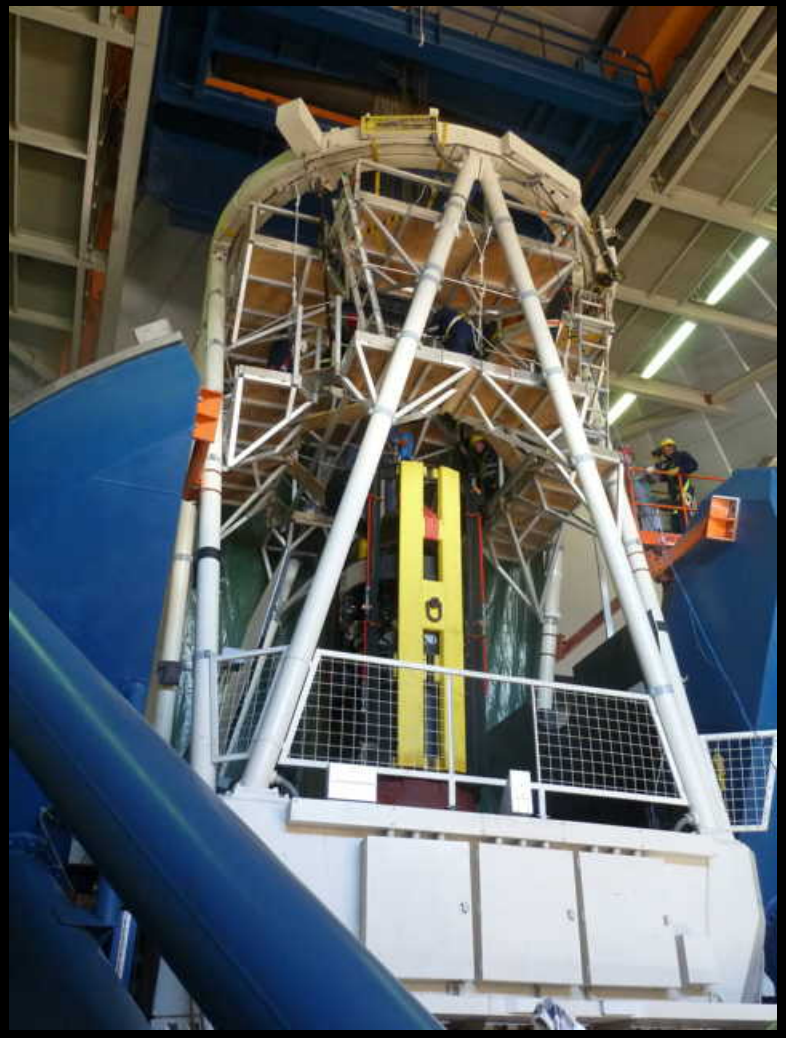




Biggest Lens
(out of 5 lenses)

DARK ENERGY
SURVEY

DARK ENERGY
SURVEY

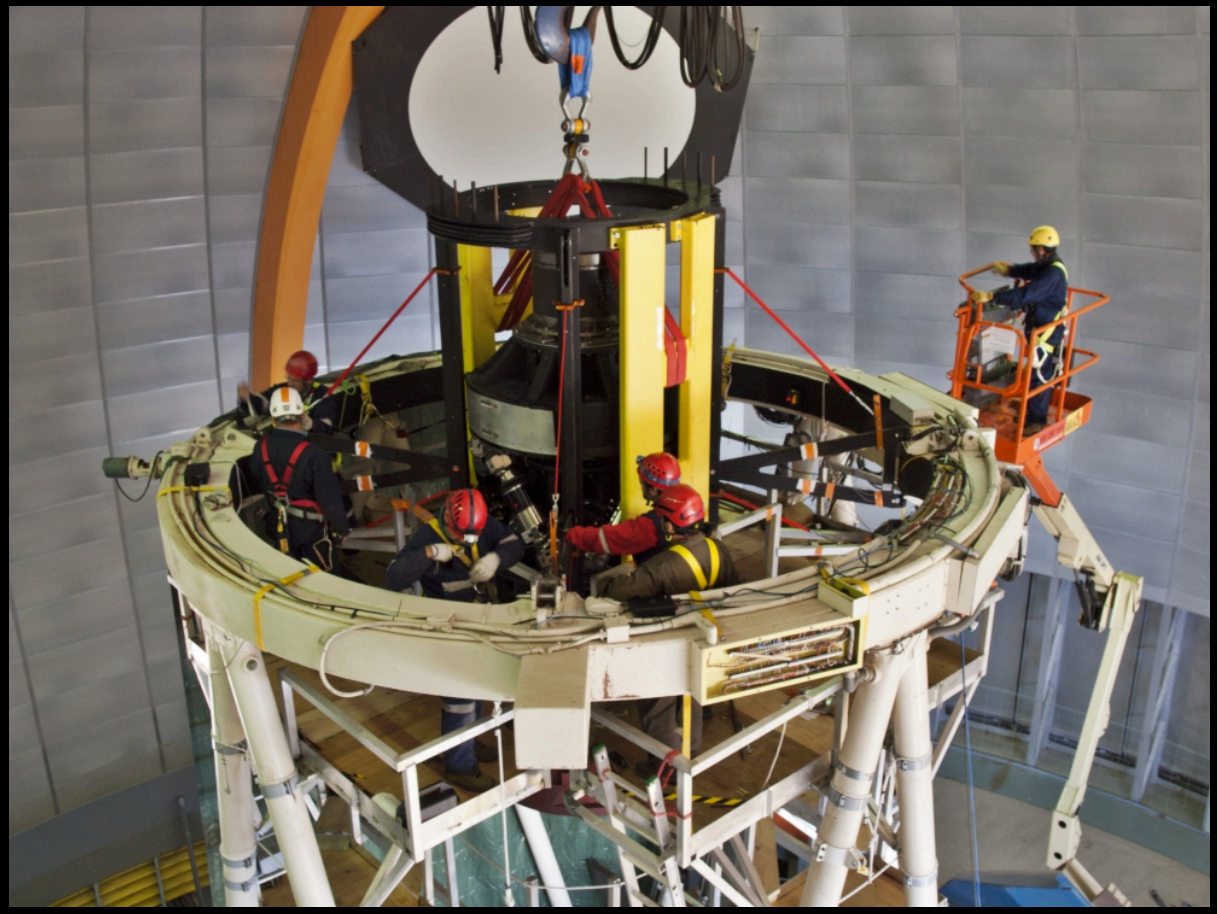


DARK ENERGY
SURVEY

DARK ENERGY
SURVEY

DARK ENERGY SURVEY

DECam Prime Focus Cage Installed



early May 2012

DARK ENERGY SURVEY

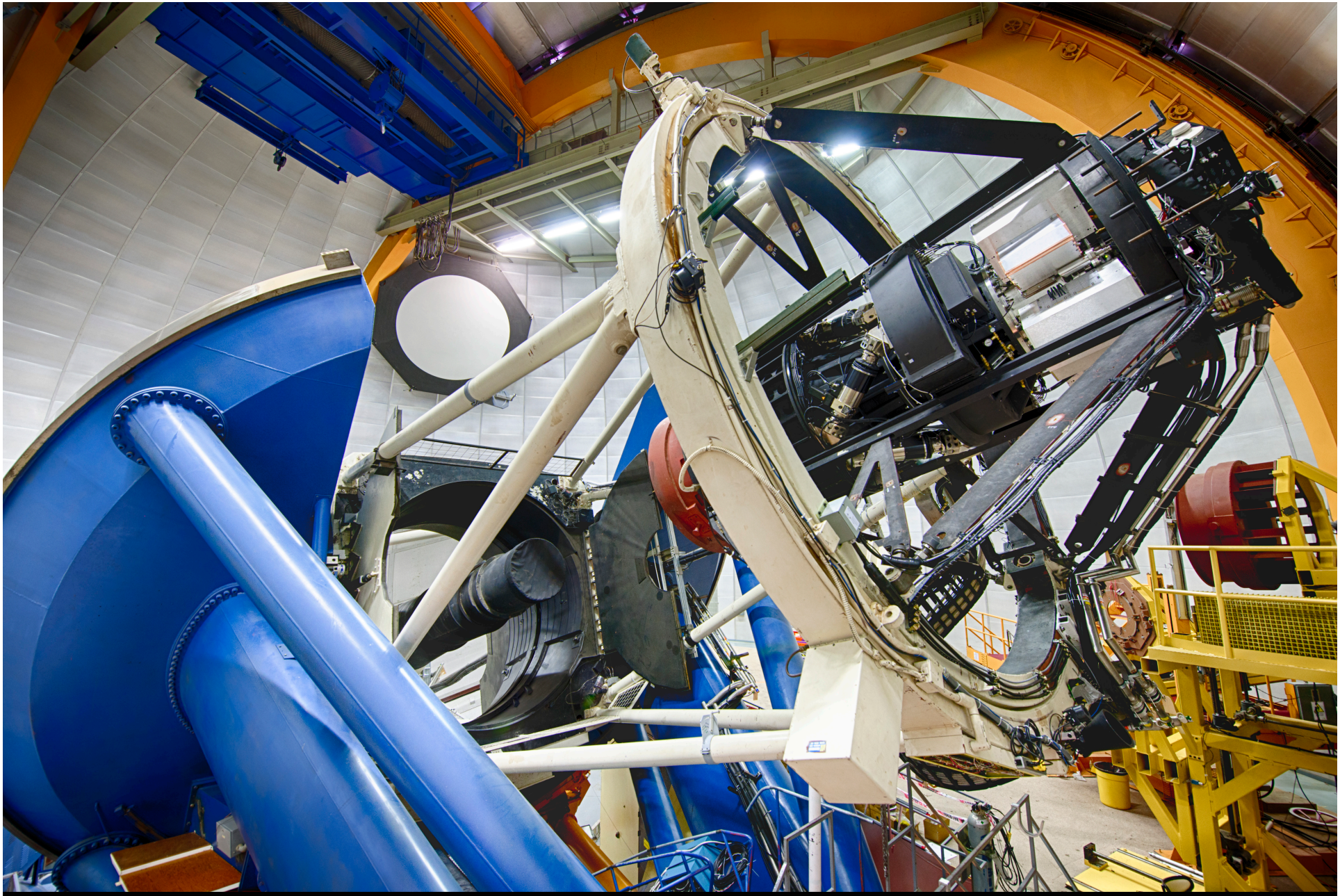
Imager Installation

August 2012

DARK ENERGY SURVEY

Imager Installation

August 2012



Dark Energy Camera on the Blanco Telescope

DARK ENERGY SURVEY

First Images

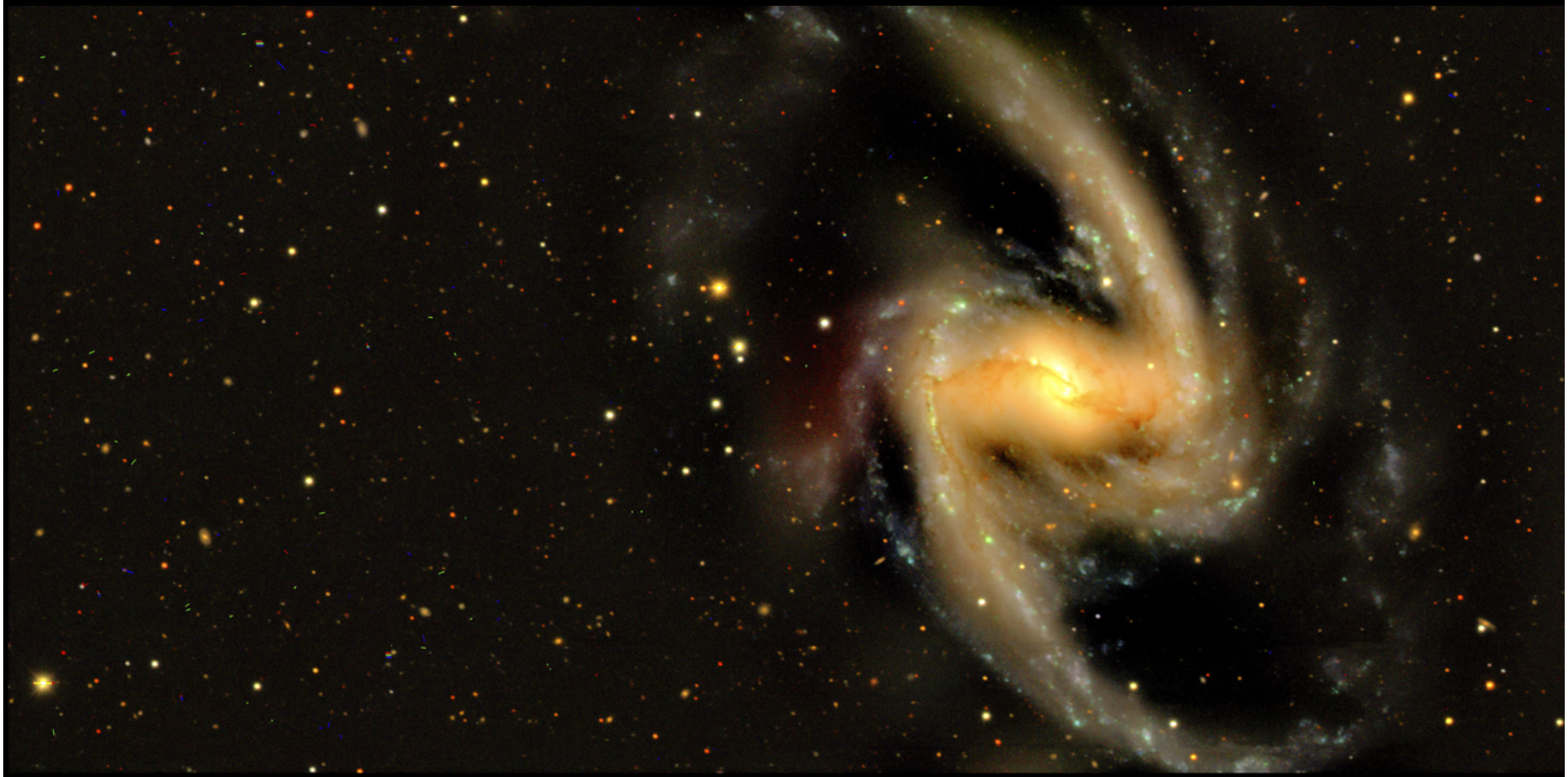
Fornax Cluster of Galaxies

First Light on Sept. 12, 2012

covered in 258 publications in 35 countries

DARK ENERGY SURVEY

First Images



Galaxy NGC 1365 in Fornax image from a single CCD

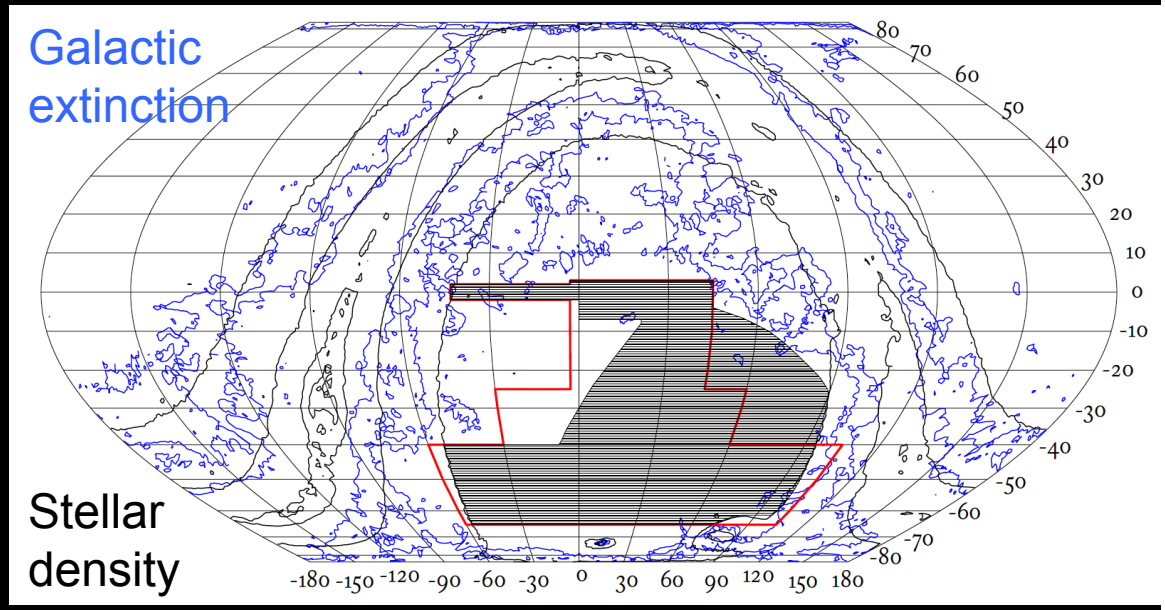
Early Image taken with the Dark Energy Camera


DARK ENERGY
SURVEY
Orion nebula

DES Observing Strategy

- 10x90 sec exposures in *griz*, 10x45 sec in *Y* for wide-area survey, longer exposures in SN fields
- Bluer (redder) bands in bright (dark) time (the moon is blue)
- Multiple overlapping exposures for photometric calibration
- 2 exposures/filter/year over entire survey footprint, except in first 2 years
- Do supernova fields when seeing is worse or when they haven't been recently observed

DES Footprint: (grey)



- Total area: 5000 sq. deg
- 10 Supernova fields (2 deep, 8 shallow), distributed within wide-area footprint
- Footprint is overhead at night from Sept.-Feb.

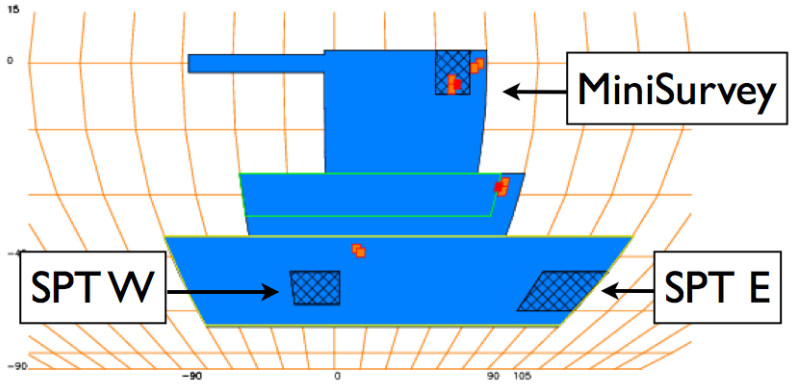
DARK ENERGY SURVEY

Science Verification Observations

Nov. 2012-Feb. 2013

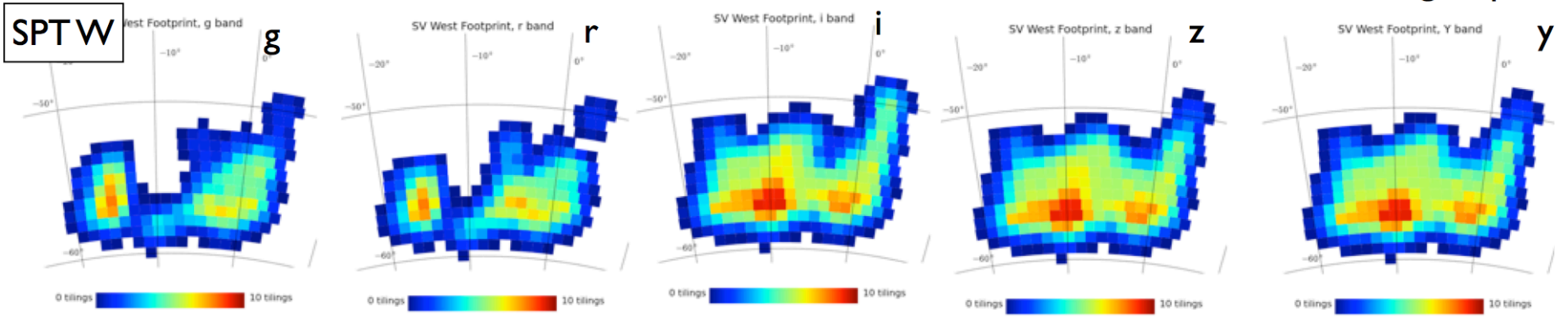
Field	Exposures	Deg²	Tilings	Notes
Minisurvey	244	~30	~3	Inhomogeneous, poor IQ
SPT-W	322	~60	~3	Inhomogenous, mostly izY.
SPT-E	2537	~157	10	Homogeneous depth, all exposures <1.3" FWHM

SV report (docdb 6985)

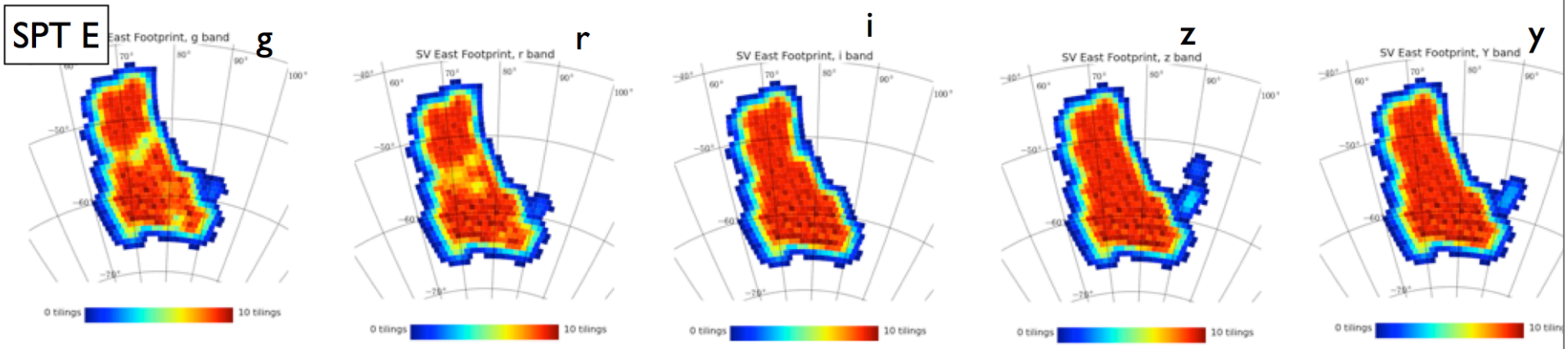


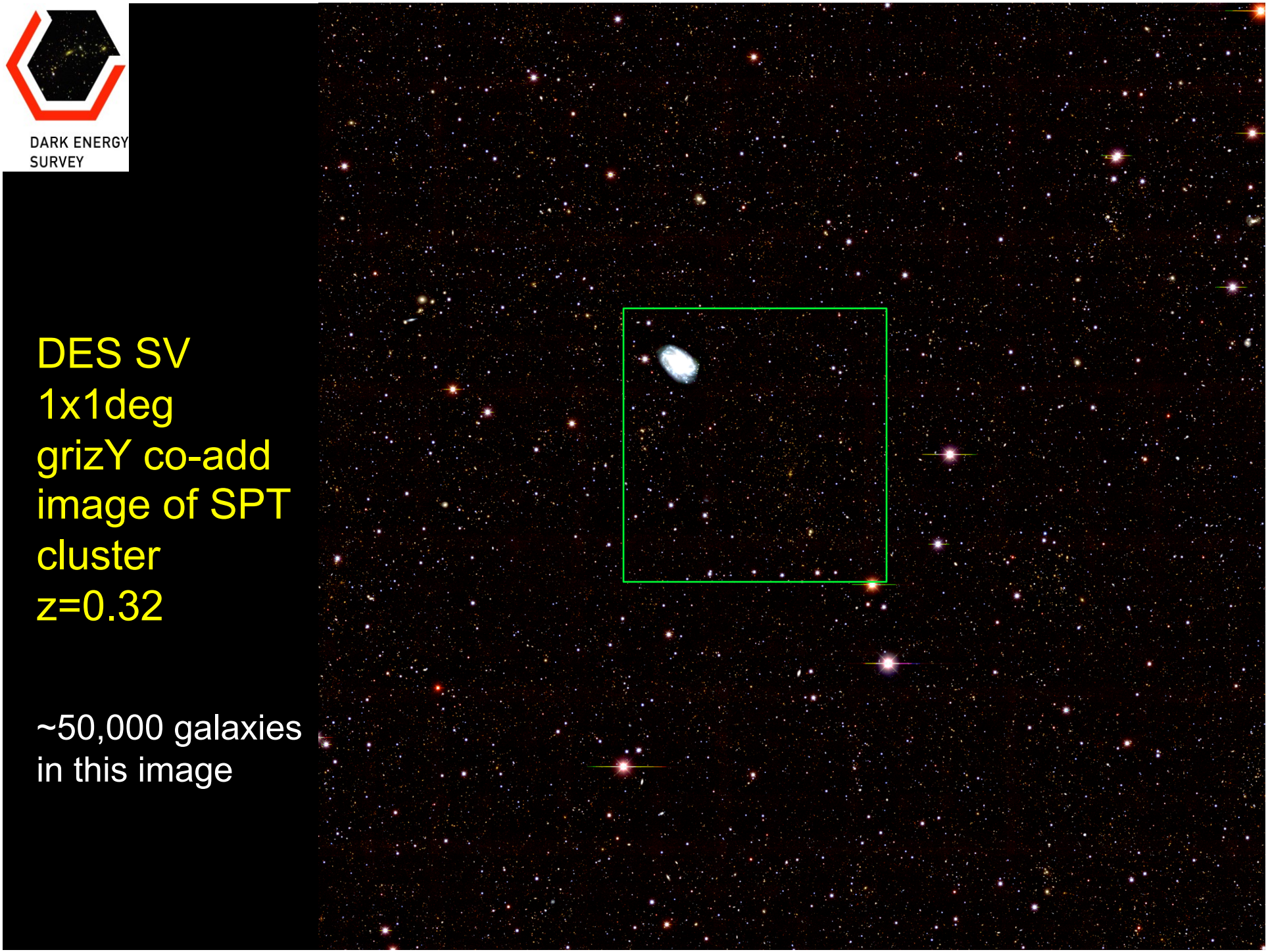
Number of tiling maps

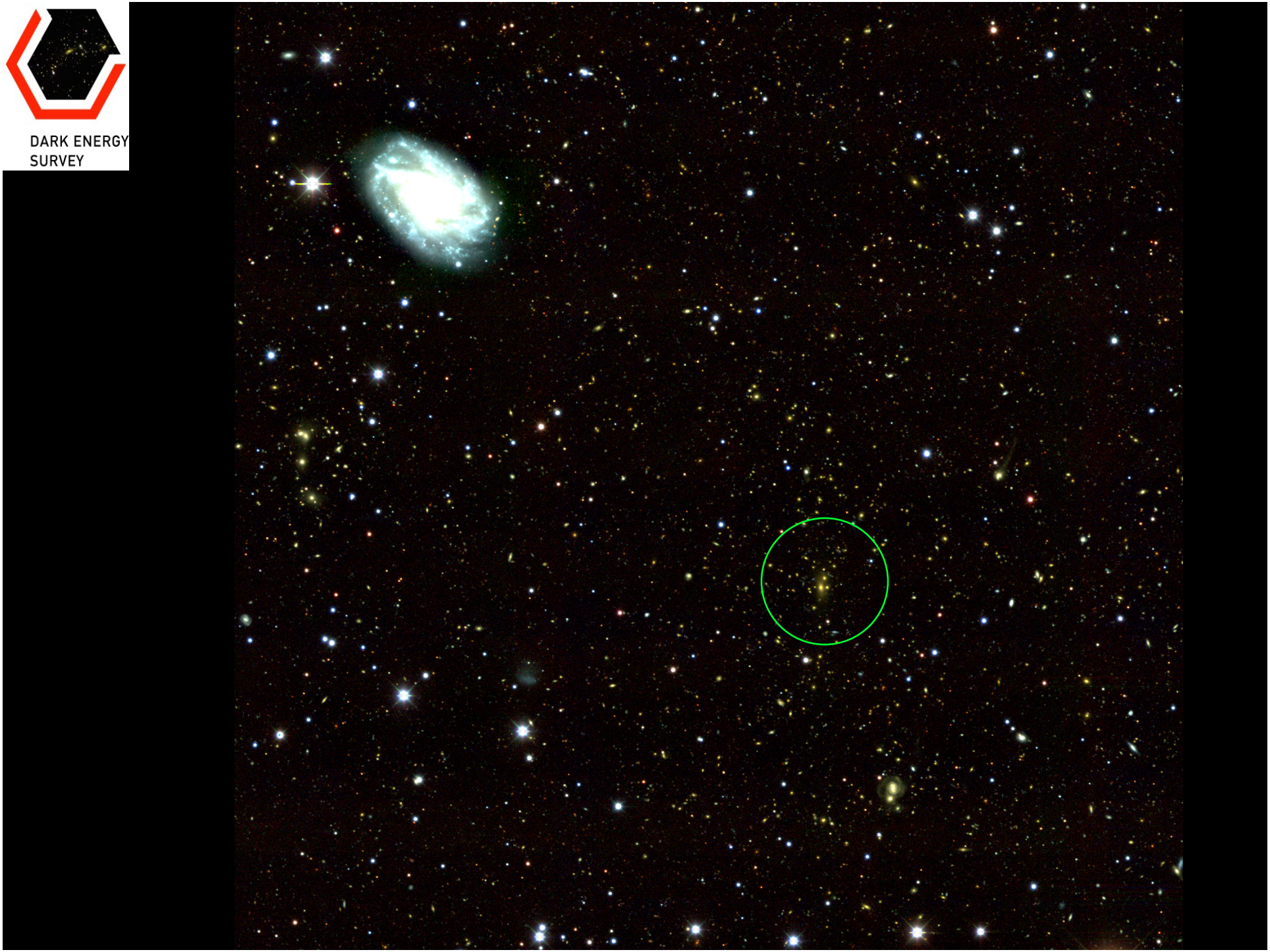
SPT W

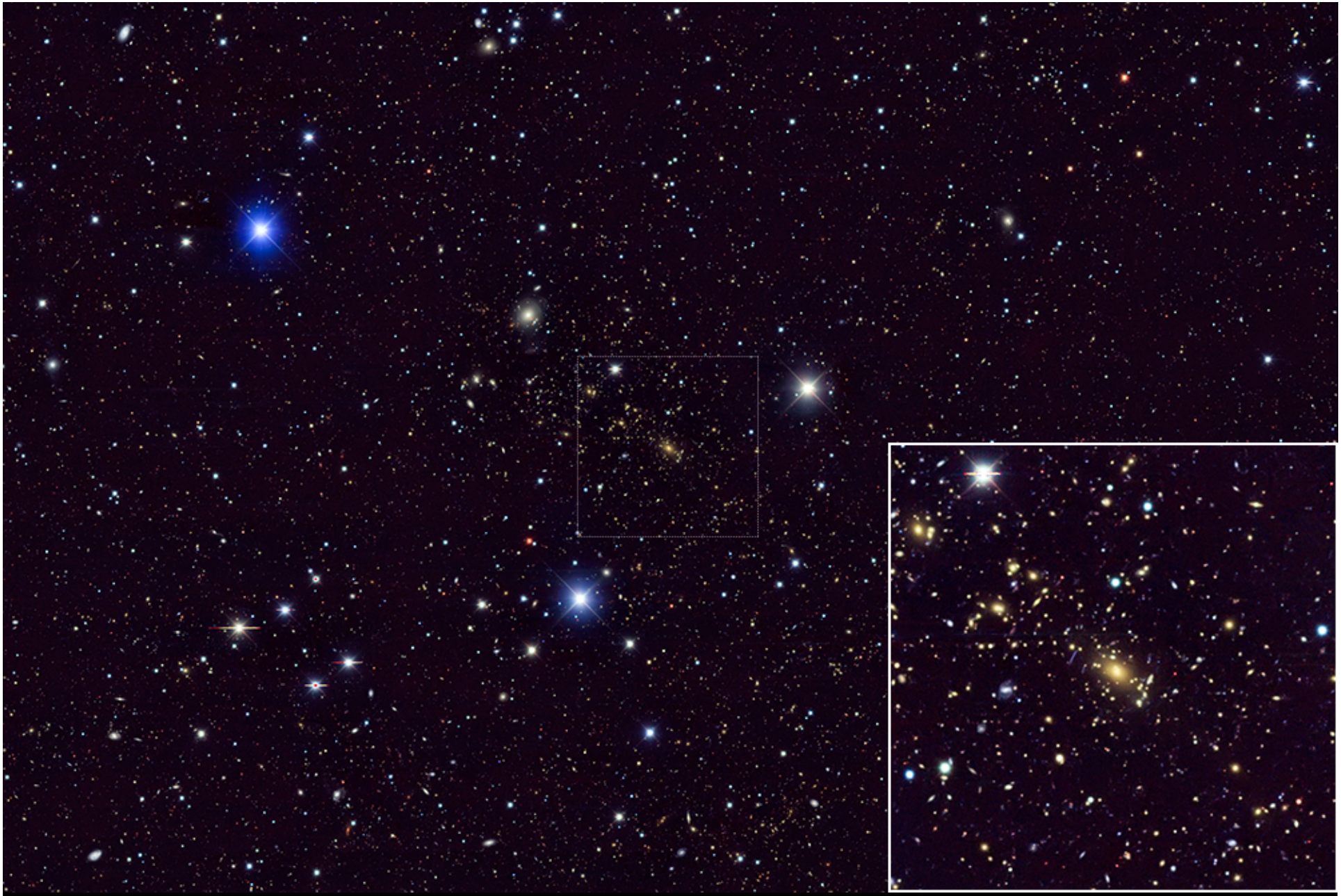


SPT E




DARK ENERGY
SURVEY
DES SV
1x1deg
grizY co-add
image of SPT
cluster
z=0.32
~50,000 galaxies
in this image

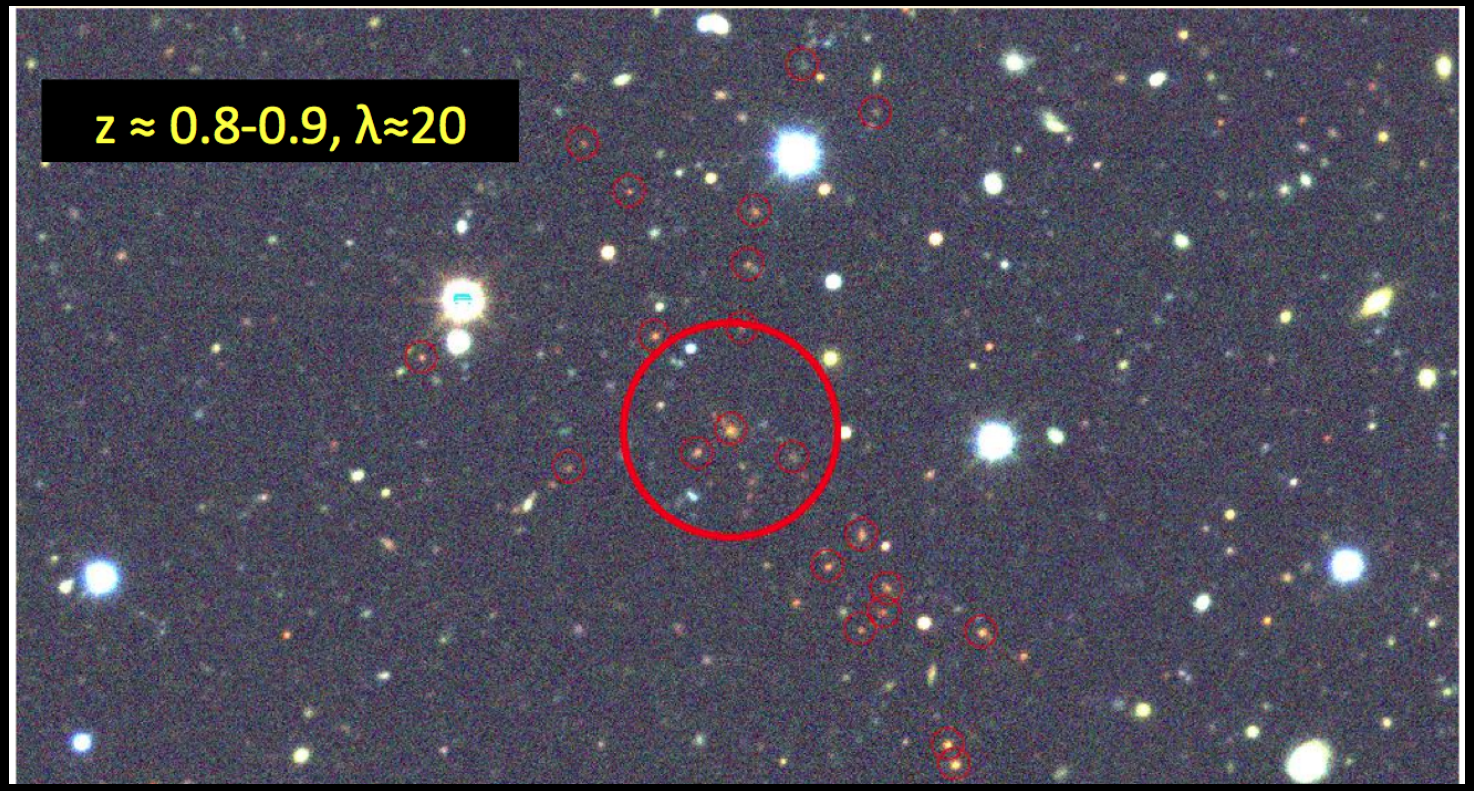

DARK ENERGY
SURVEY



Another Cluster of Galaxies

DARK ENERGY SURVEY

High Redshift Cluster Discovered by DES

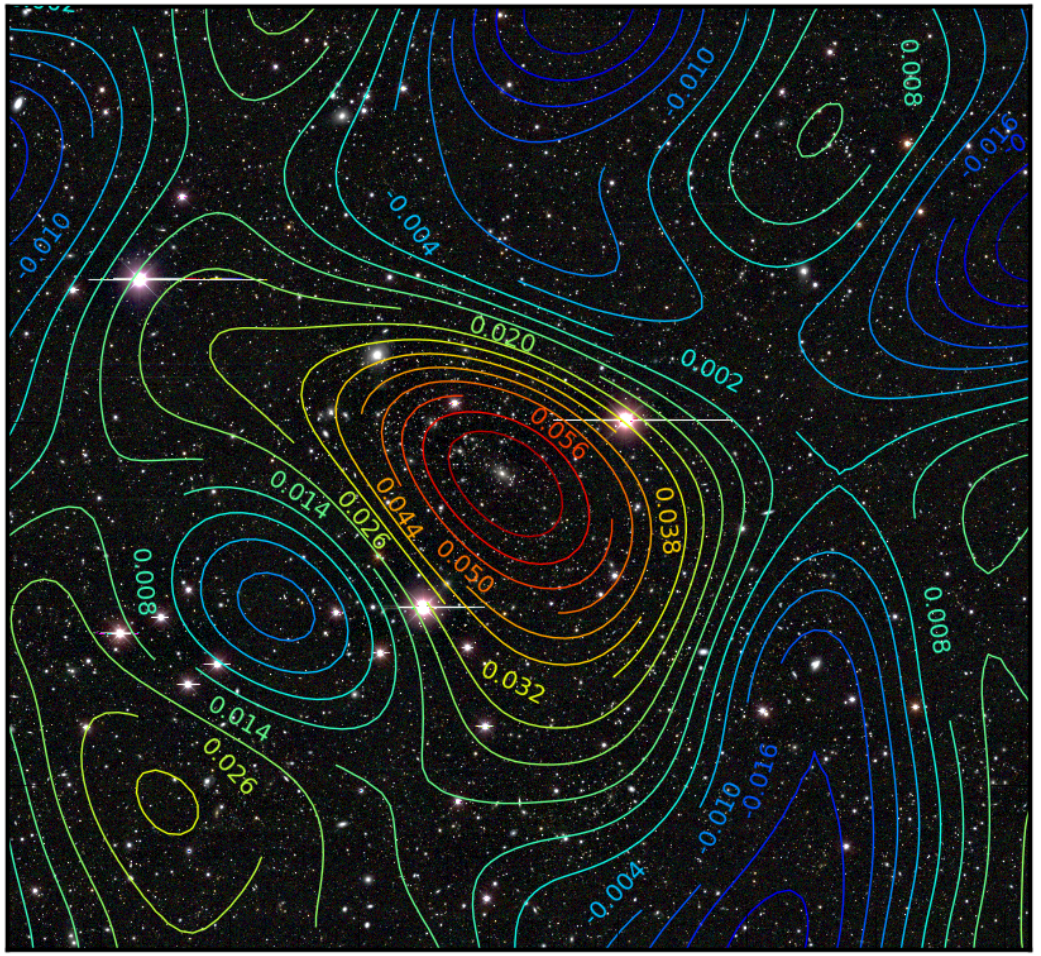


from DES Science Verification data in November 2012

DARK ENERGY SURVEY

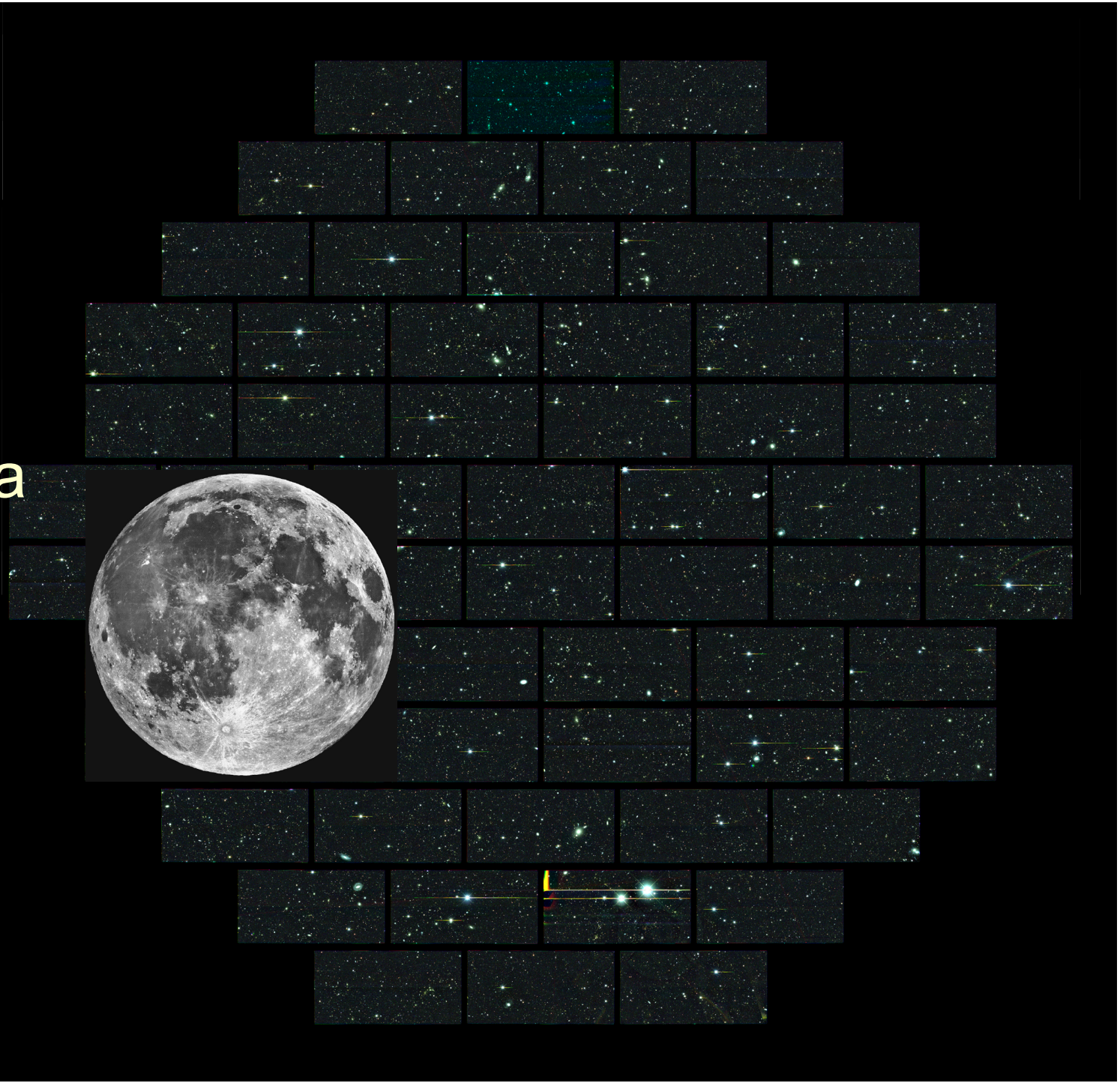
Cluster Weak Lensing: `Seeing' Dark Matter

- Image: light from a cluster of galaxies
- Contours: inferred dark matter distribution in the cluster from gravitational lensing
- DES SV data



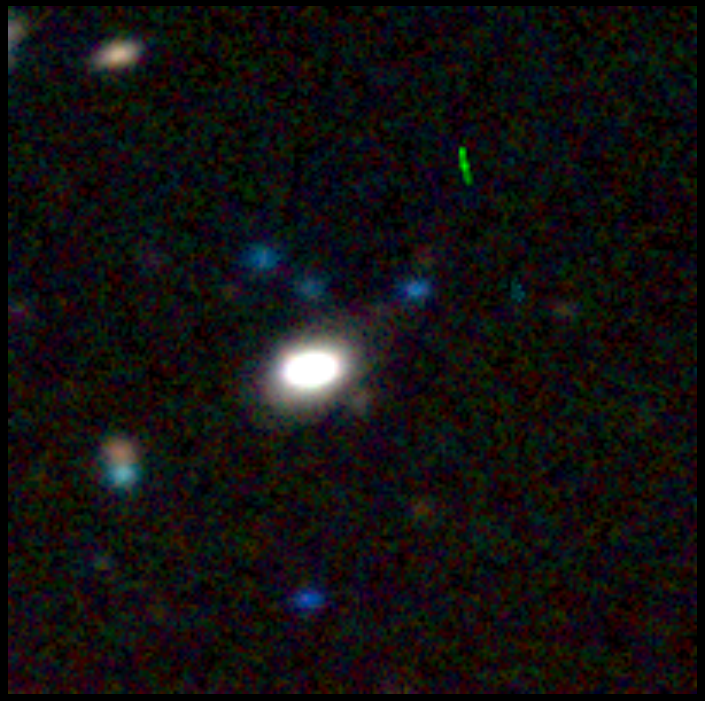
DARK ENERGY SURVEY

DES SV image of a deep SN field

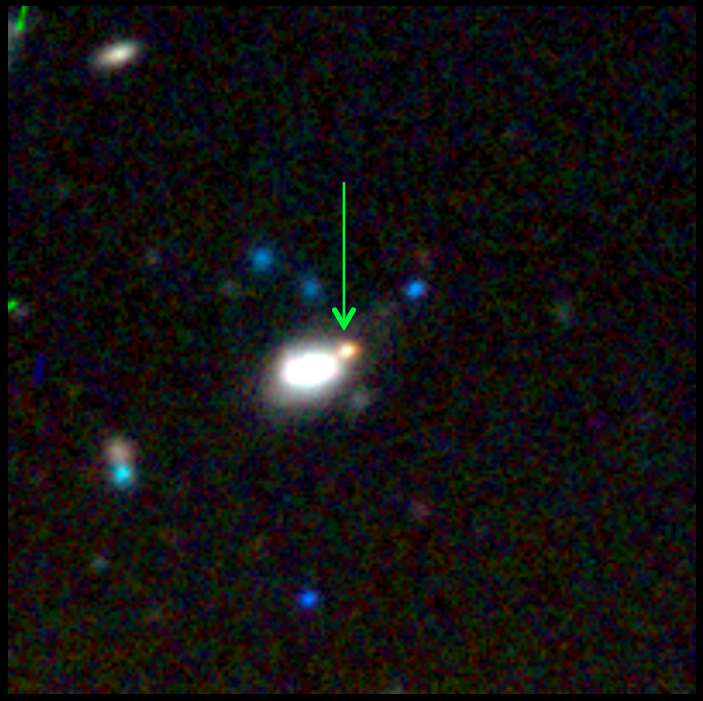


DARK ENERGY SURVEY

Discovering Supernovae



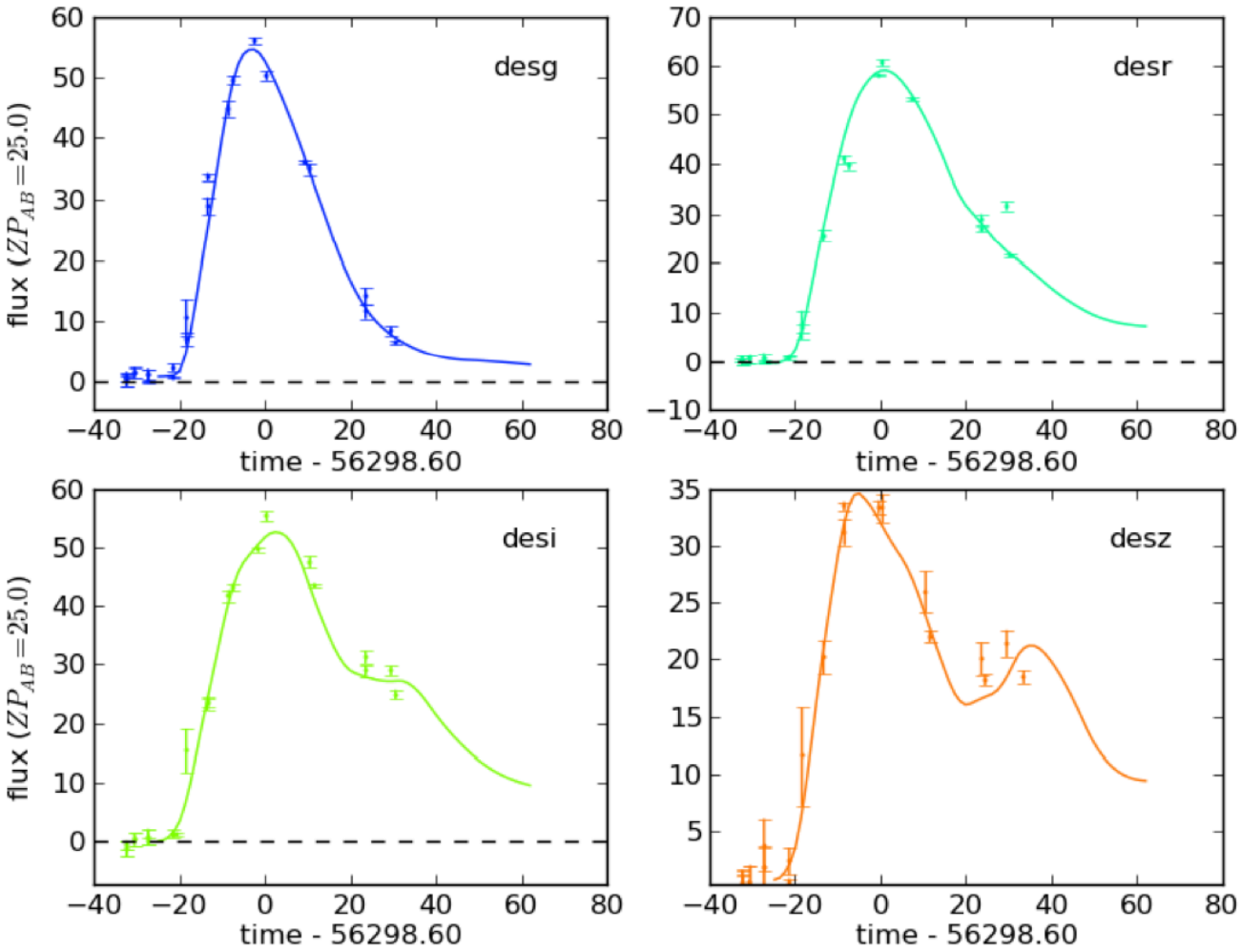
Nov. 7, 2012



Dec. 15, 2012

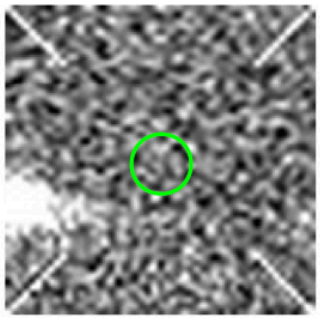
SN Ia at z=0.2 confirmed at AAO (OzDES: 100 spectroscopy nights over next 3 years)

Science Verification: Supernovae

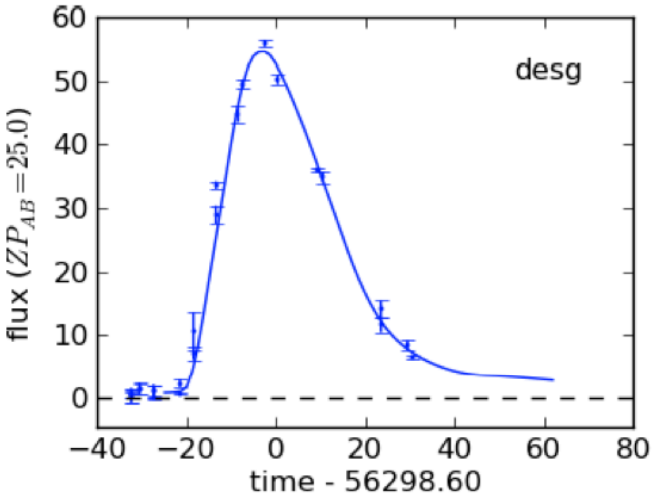


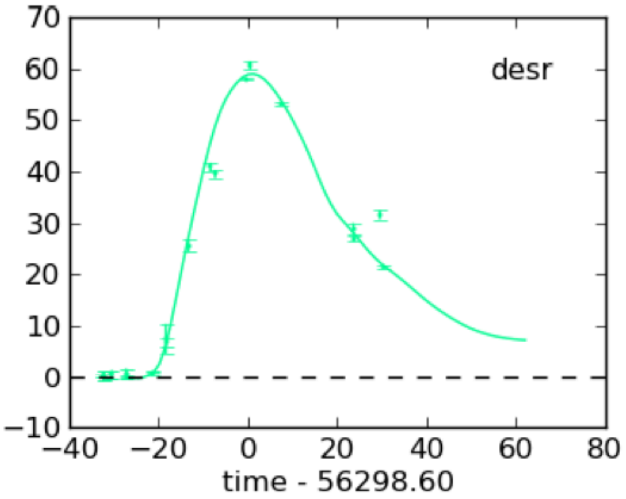
$z = 0.241$

DES12C3a
(642239)



Science Verification: Supernovae

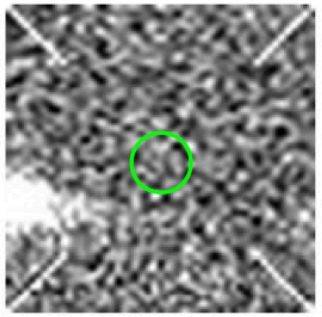


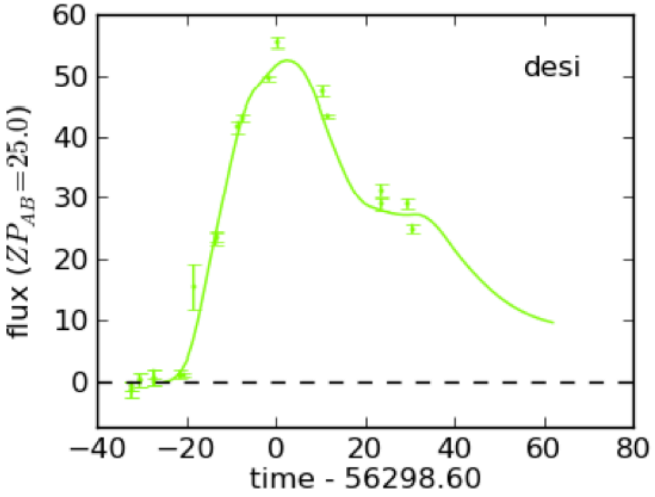


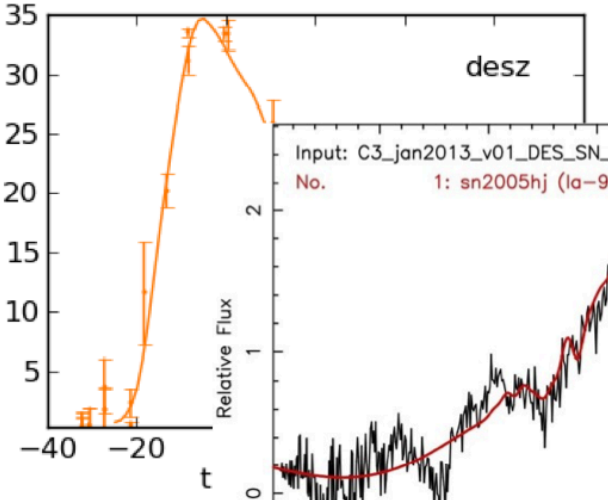
$z = 0.241$

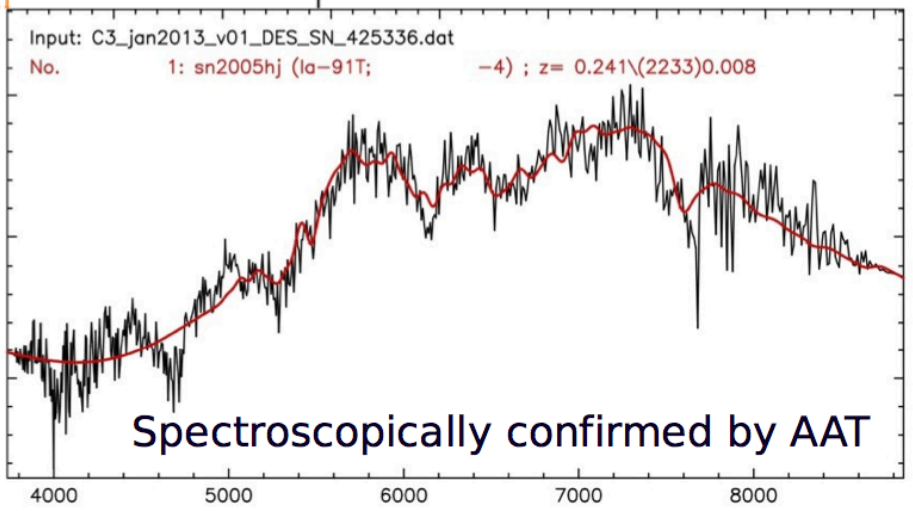
DES12C3a

(642239)

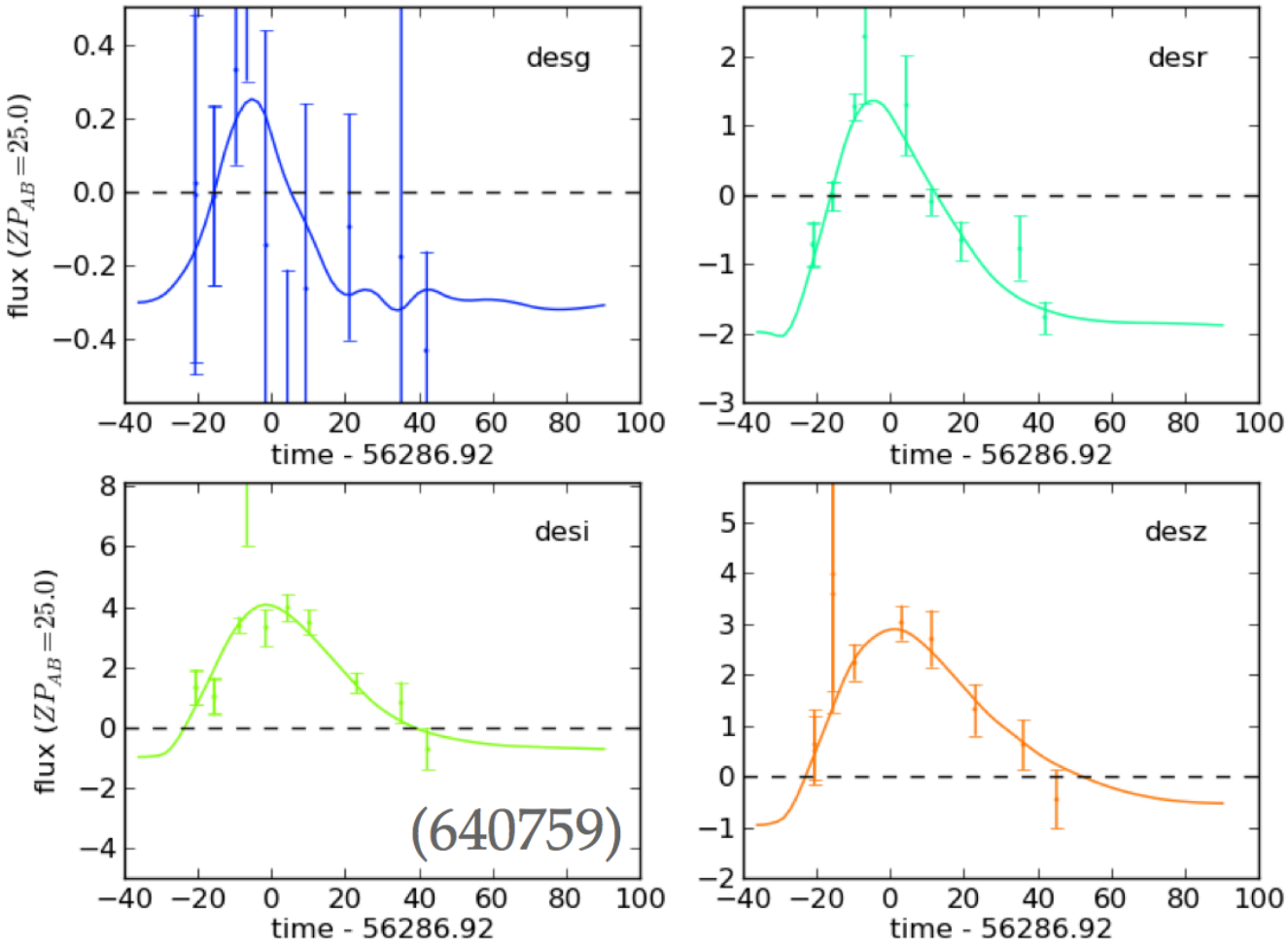




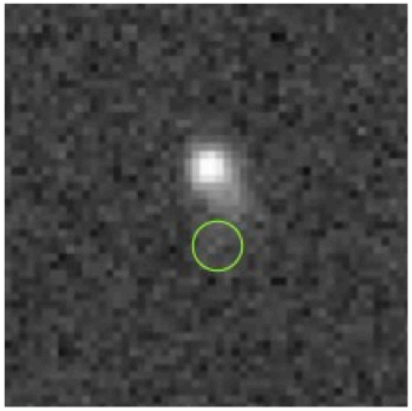




Science Verification: Supernovae

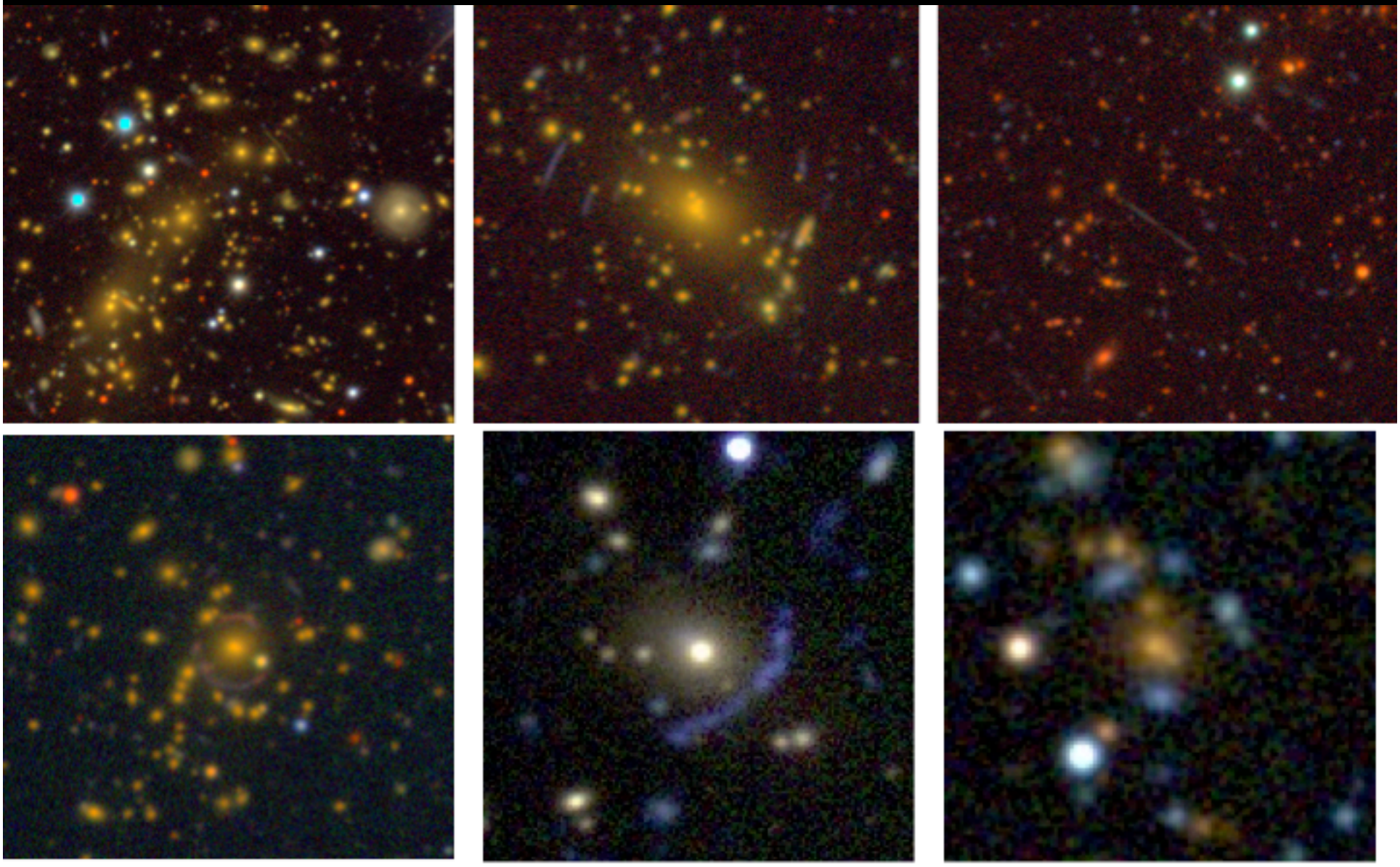


$z = 0.806$
from host spec-z
(VVDS)



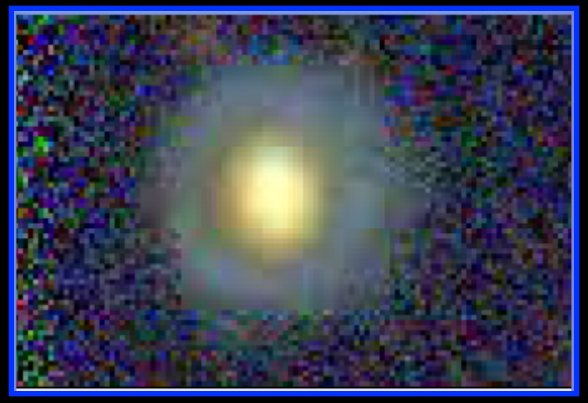
Strong Gravitational Lensing

foreground mass bends light from distant galaxies (SV images)

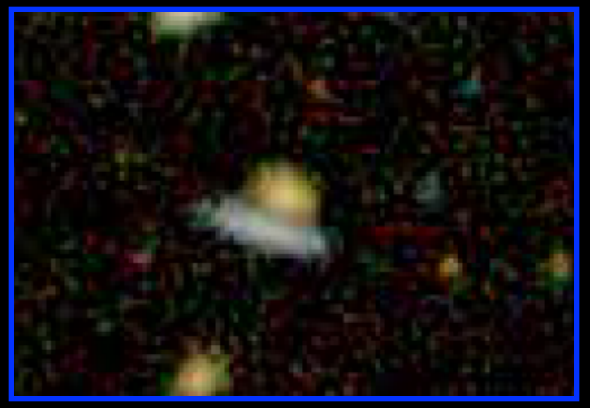


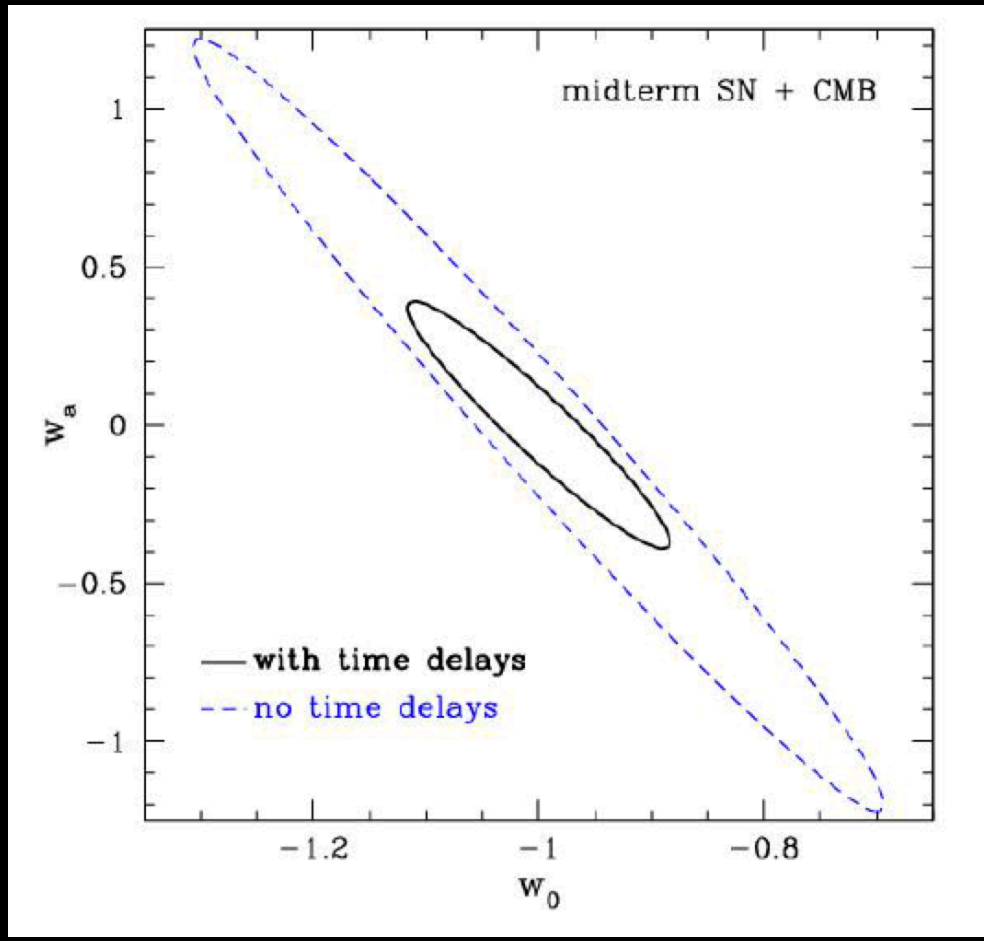
DARK ENERGY SURVEY

Strong Lens Time Delays: new/old probe of Dark Energy



Strong Lens Candidates in DES SV





Snowmass White Paper (Treu, etal).

DES started
Aug. 31, 2013

newsblog
Nature brings you breaking news from the world of science

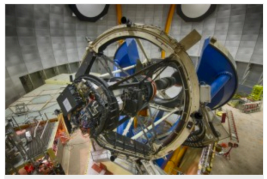
NATURE NEWS BLOG

Dark energy survey launches

03 Sep 2013 | 19:25 BST | Posted by Alexandra Witze | Category: Space and astronomy

High in the Chilean Andes, a massive project to probe the nature of dark energy has begun.

The Dark Energy Survey (DES) launched on 31 August at the 4-metre Blanco telescope at the Cerro Tololo Inter-American Observatory. It is one of several new pushes to explore the physical properties of dark energy, the mysterious force that is driving the Universe to expand at an ever faster rate.



The Dark Energy Camera photographs galaxies from its perch on the Blanco telescope in Chile.

Over the course of 5 years, the DES will map 300 million galaxies over one-eighth of the night sky. Its backbone is a 570-megapixel digital camera (pictured).

NATIONAL GEOGRAPHIC Daily News

Space Pictures This Week: Solar Storm, Spiral Galaxy

Majestic Spiral

Image courtesy Dark Energy Survey Collaboration

Like a ghostly pinwheel, a majestic spiral galaxy known as NGC 1398 shines in the Fornax constellation some 65 million light-years from Earth in a picture released September 3.

Stretching some 135,000 light-years across, the galaxy is just slightly bigger than our own Milky Way galaxy, but contains less than a tenth the amount of stars.

This deep-sky image is part of the Dark Energy Survey being conducted by the 4-meter Victor M. Blanco Telescope at the National Science Foundation's Cerro Tololo Inter-American Observatory in Chile.

Trending News

Rare White Giraffe Spotted in Africa
Stunning white animal is not a true albino but is merely a lighter color than the average giraffe.

Poachers Kill Hundreds of Vultures
Why are elephant poachers killing vultures? Because vultures circling in the sky alert wildlife authorities to the location of poachers' activities.

Indelible 9/11 Pictures
See iconic images of the tragedy, as chosen by National Geographic photo editors. *Warning: graphic content.*

Newsletters

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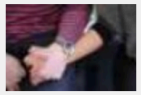
The Washington Post

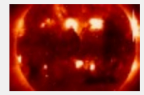
Health & Science

In the News Syria Lael Brainard Petrobras Diana Nyad '50 Shades' Serena Williams

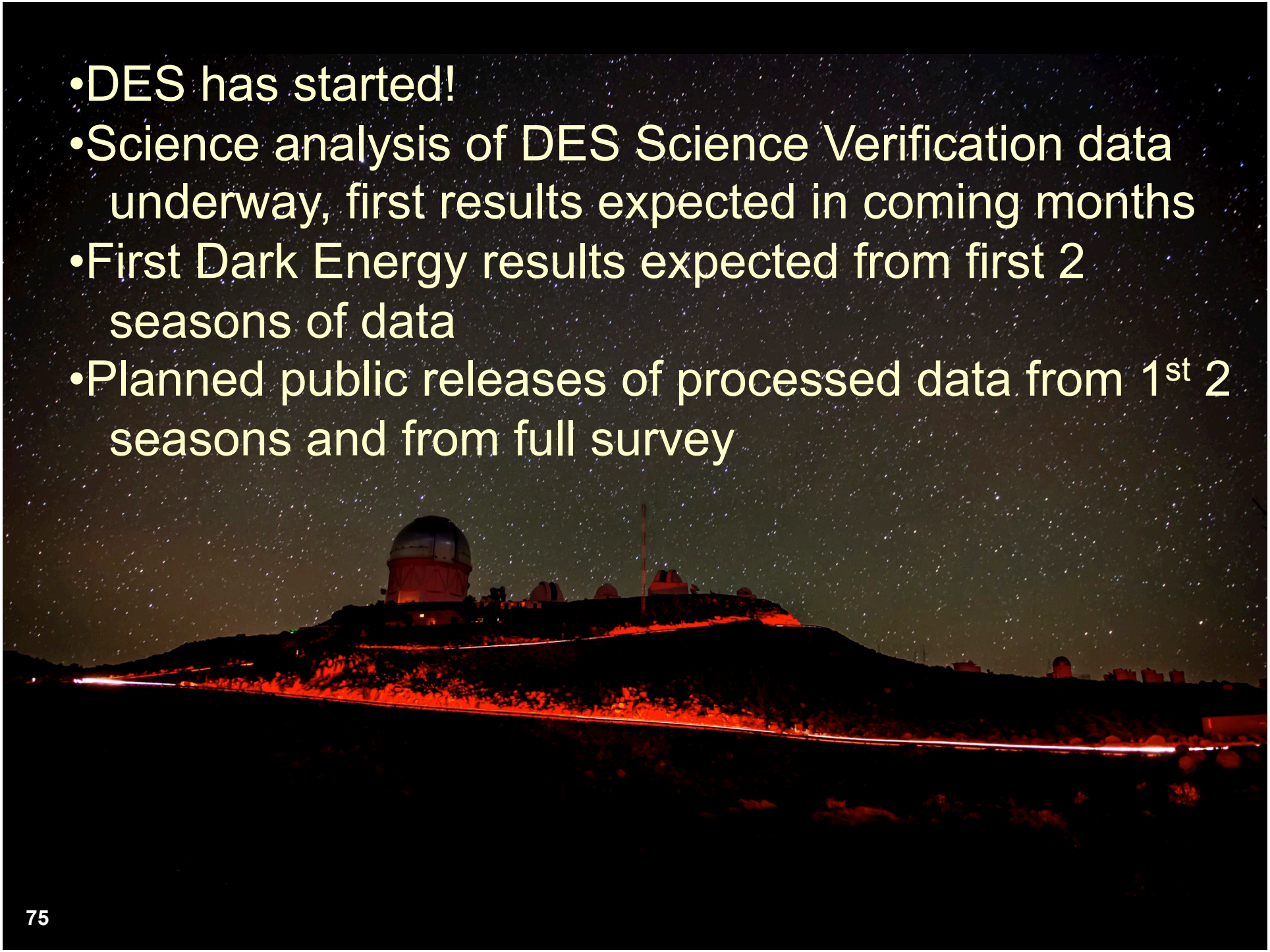
Homes for the taking: Liens, loss and profiteers



VIDEO | The ultimate dating experience



Giant digital camera probes cosmic 'dark energy,' the universe's deepest mystery


•DES has started!
•Science analysis of DES Science Verification data underway, first results expected in coming months
•First Dark Energy results expected from first 2 seasons of data
•Planned public releases of processed data from 1st 2 seasons and from full survey