Early results from the Dark Energy Survey (E939)

NGC 253
(DECam 90s g,r,i)
Year 2 DES

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Fermilab Joint Experimental-Theoretical Physics Seminar
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Thanks to J Frieman, A Ross, HT Diehl, DES for slide content

Outline of talk:

- A brief survey of the contents of the expanding universe.
- A remarkable discovery, a fundamental puzzle.
- The Dark Energy Survey (DES)
- DES lays the groundwork
- Exciting early DES Science
- More exciting, early DES Science

Contents of the Expanding Universe:

The universe consists of a large amount of stuff of various types separated by space which is currently expanding at an enormous rate (parameterized by the Hubble 'constant'):

$$H_0 = 70 km s^{-1} Mpc^{-1} = (13.8 Gyr)^{-1}$$

Thanks to Einstein's General Theory of Relativity (100th anniversary this year!), we know how to relate 'stuff' to the expansion of space.

<u>Types of stuff:</u>

1. Ordinary Matter (stars, rocks, air)
2. Radiation (photons)
3. Dark Matter
4. Did we miss anything?

A sketch of the Friedmann-Robertson-Walker-Lemaitre cosmology:

- Start with Einstein's 1915 equations of General Relativity:

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu},$$

The curvature (think: acceleration) of space-time (LHS) is equated to the amount of 'stuff' in the stress-energy tensor (RHS). To simplify 10 eqns, assume isotropy and homogenity: then the metric is a function of a(t), the `size' of the universe with time.

$$ds^2 = a(t)^2 \, ds_3^2 - c^2 \, dt^2$$

Now, we (Friedmann) can reduce Einstein's eqns to two equations for the three unknowns: a(t), p, and density:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho.$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p).$$

If we can relate density and pressure, we can solve for the expansion history of the universe! So.....

Equation of State: The importance of 'w'

If we can determine the equation of state (which relates pressure to density) for each type of stuff then we can break the degeneracy and solve the expansion equation a(t), using our knowledge of the relative amounts of each component.

$$p = w\rho c^2$$

$$T^{\alpha\beta} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Consider each of our content types:

1. Ordinary Matter (stars, rocks, air) $$p = w\rho c^2$$

Recall your freshman chemistry, ideal gas equation of state:

$$pV = nRT, p \sim \rho kT \sim \rho v^2$$

But ordinary matter moves at low speeds, typically one one-thousandth the speed of light or less, therefore w=0 and one can determine expansion rate vs. time using H eqn:

$$w = \frac{\rho v^2}{\rho c^2} \sim 0, v << c$$

$$\boxed{w_{OM} \sim 0, a_{OM}(t) \sim t^{2/3}}$$

$$p = w\rho c^2$$

2. Radiation (photons, neutrinos)

Here the speed is relativistic (not << c), so there is a significant pressure component at all densities:

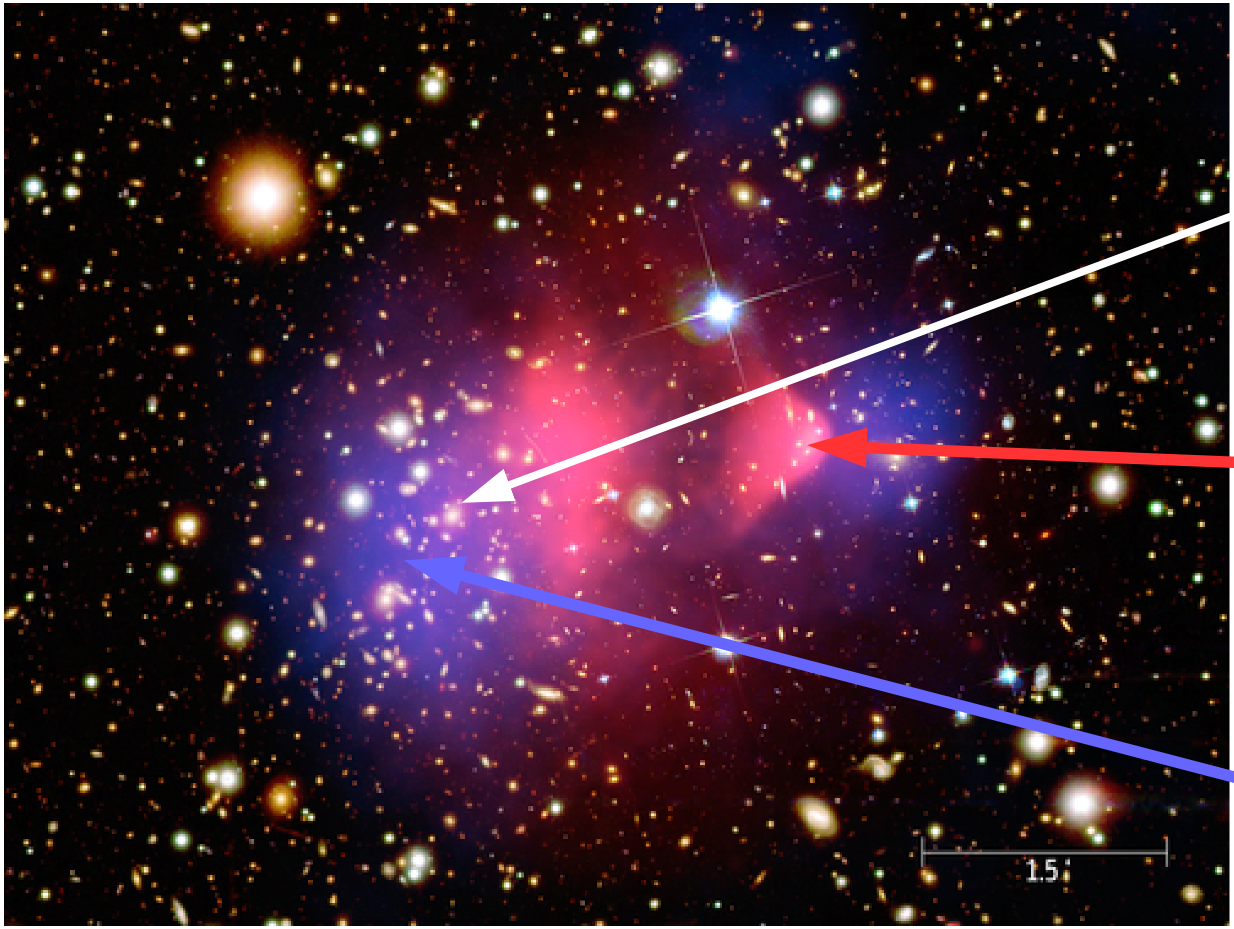
$$\boxed{w_{\gamma,\nu} = \frac{1}{3}, a_{\gamma,\nu}(t) \sim t^{1/2}}$$

Where does the 1/3 factor come from:

$$V = 4/3\pi r^3, A = 4\pi r^2, P = \frac{dE/cdt}{A}$$

$$p = w\rho c^2$$

3. Dark Matter: Observations show
it attracts and clumps like ordinary matter,
Therefore, it's cold, and thus w is the same as for baryons:



Galaxies (White): Ordinary Matter (non-dissipative)

X-ray gas (Red): Ordinary Matter (dissipative)

Weak-lensing shear (Blue): (non-dissipative)

Cold Dark Matter, v<<c:

$$w_{DM} \sim 0, a_{DM}(t) \sim t^{2/3}$$

A remarkable discovery – a fundamental puzzle

The three types of substance considered so far all gravitationally attract and cause an overall **deceleration** of the expansion of space as time increases.

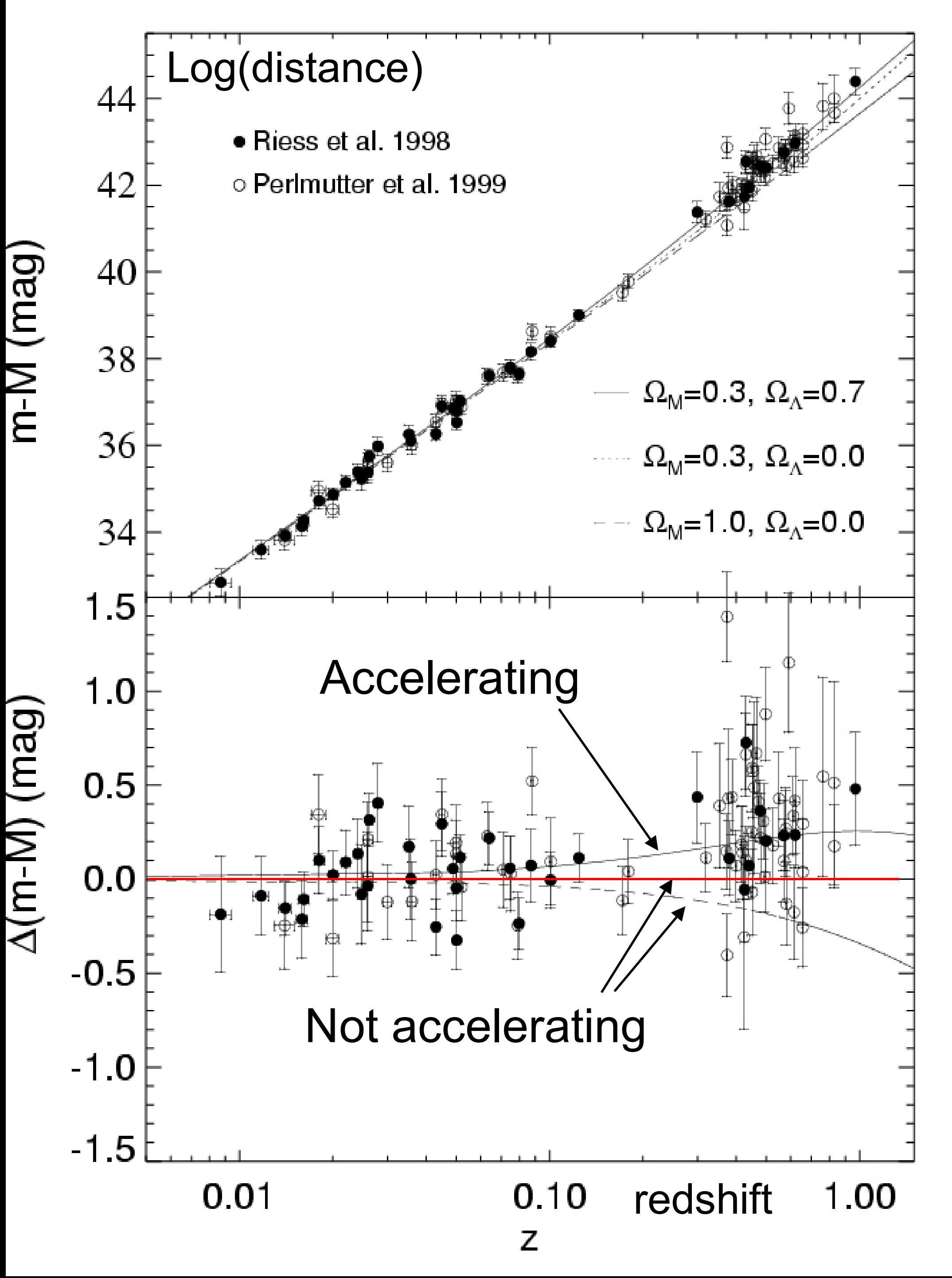
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p).$$

But then, in 1998, came the results of two supernovae surveys, with the surprising, but highly-significant conclusion that the universe was not decelerating, but rather **accelerating** its expansion.

Discovery of Cosmic Acceleration from High-redshift Supernovae

2011 Nobel Prize

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



$\Omega_\Lambda = 0.7$

$\Omega_\Lambda = 0.$

$\Omega_m = 1.$

4. Dark Energy:

Einstein's equations allow for a 'constant of integration' term. However, it has the effect of adding 'real' curvature to the metric, along with some other odd properties....

the reciprocal of the metric tensor is simply

$$g^{\alpha\beta} = \begin{pmatrix} -c^{-2} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

and the stress–energy tensor is a diagonal matrix

$$T^{\alpha\beta} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}.$$

Here, $\rho = -p = \Lambda$

$$\rho + 3p = -2\rho < 0$$

and thus (setting c=1):

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p).$$

Sign changes from deceleration to acceleration when w < -1/3!!

$$w_{DE} = -1, a_{DE}(t) \sim e^{Ht}$$

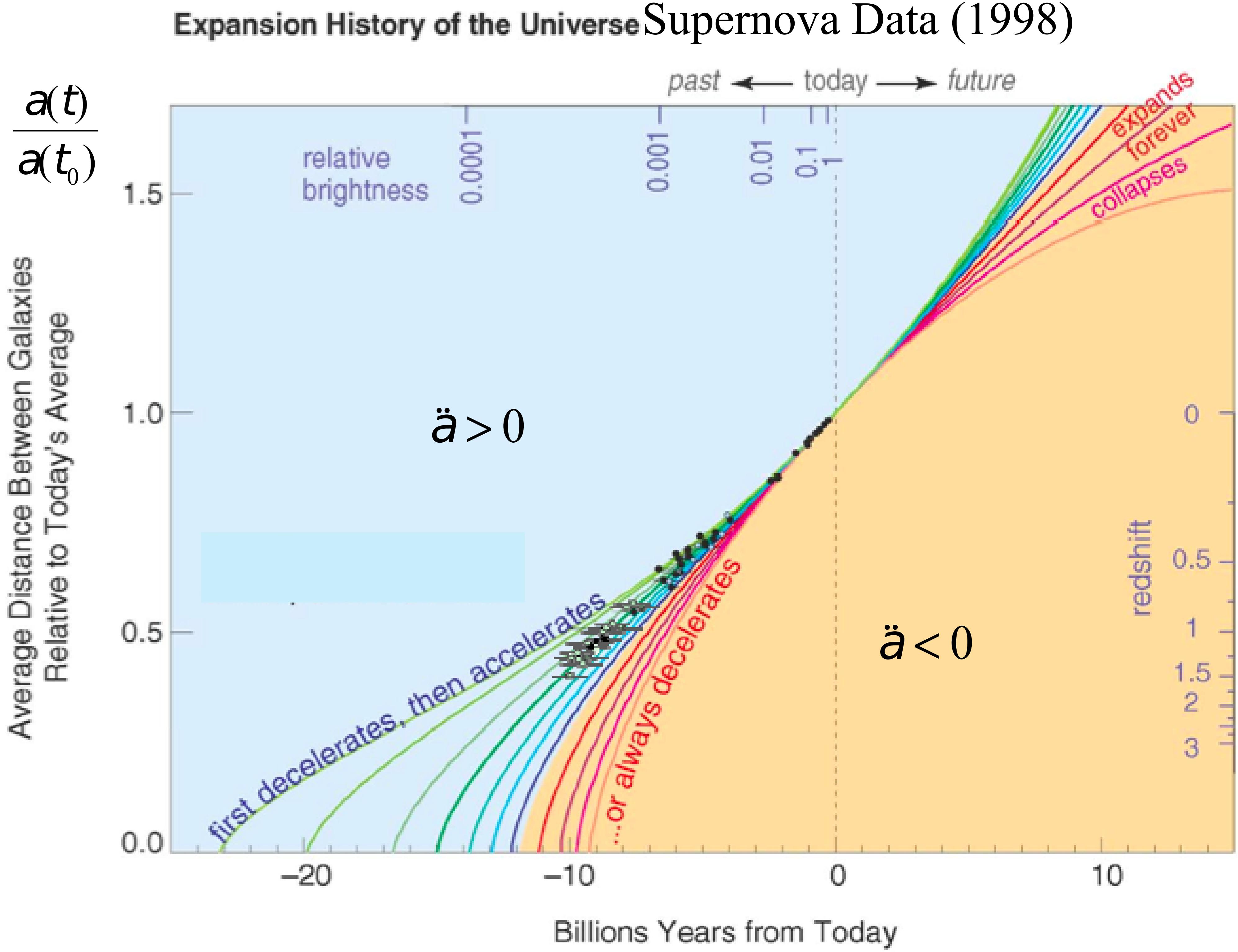
The overall expansion rate of the universe at any time is given by combining the relative amounts of ordinary matter, radiation, Dark Matter and Dark Energy in their relative proportions at that moment.

Though Dark Energy (~70%) and Dark Matter (~26%) are the dominant components (OM 4%, radiation < 1%), if one is to constrain w(DE) to the level of a few percent, one must know the amount of the other components present, especially the Dark Matter component.

Knowledge of the amount and distribution of Dark Matter(t) is a prerequisite to doing precision Dark Energy Science!

$$\Omega_\Lambda = 0.7 \quad \Omega_{(OM+DM)} \sim 0.3$$

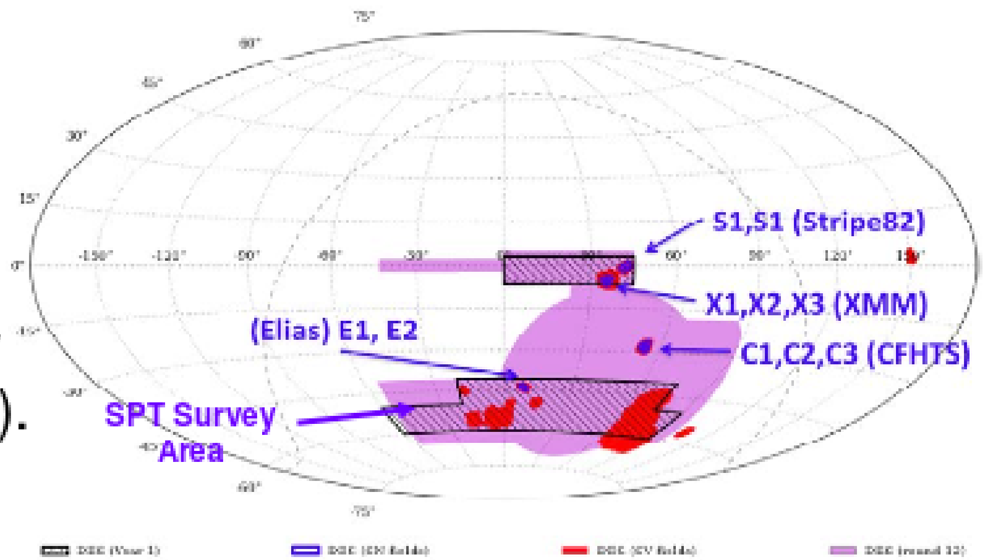
Supernova Data (1998)

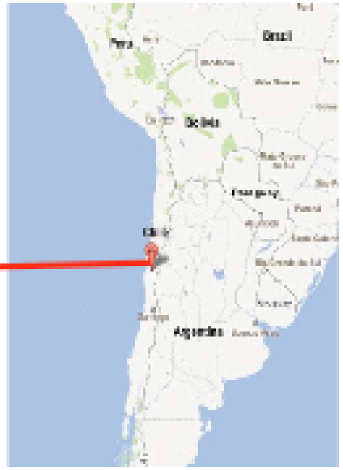


The Dark Energy Survey

DARK ENERGY SURVEY

- DES Built DECam, a 3 deg^2 FOV camera for the Blanco 4m telescope at CTIO
  - Survey 2013-2018 (525 nights)
  - Facility instrument for astronomy community (DES uses 30% time).
- DES uses 4 complementary techniques to measure acceleration of the Universe
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure (BAO)
  - IV. Supernovae
- Two multiband imaging surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat *griz* (SNe)





The Dark Energy Survey Collaboration

DARK ENERGY SURVEY

~300 scientists
US support from DOE+NSF

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

The DES science plan:

To confirm or deny to high precision (few % level) that the Dark Energy component of the universe really behaves like a cosmological constant:

$$w(DE) = -1.00 \,? \quad dw(DE)/dt = 0 \,?$$

We do this in part by obtaining many points on the (t,a(t)) diagram, and compare with models of w(t) as it impacts a(t):

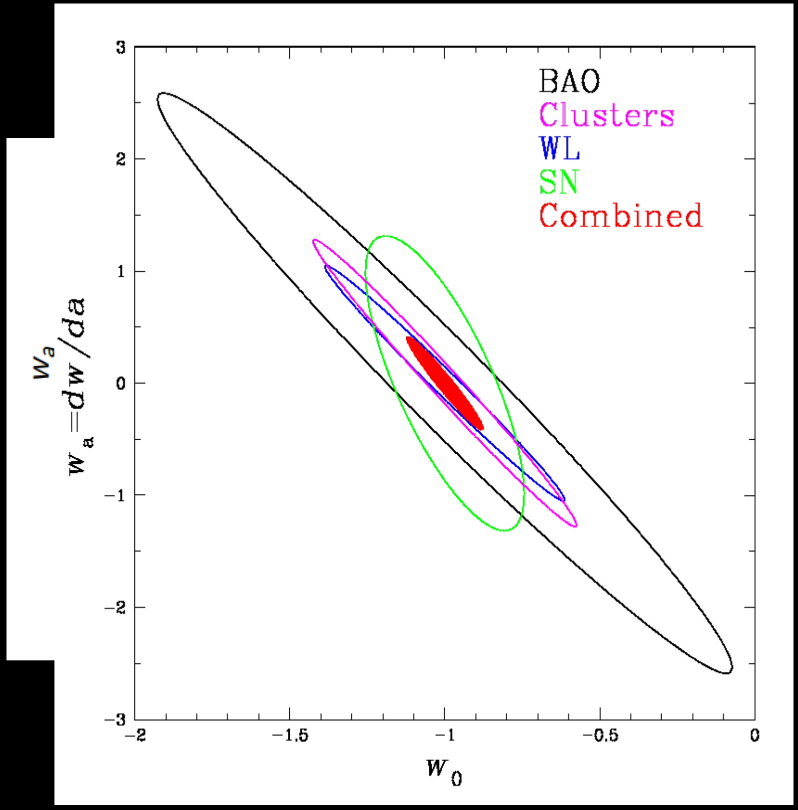
t: cosmic time can be inferred by integrating a model a(t) backward from the present and forward from the Big Bang to get an observable distance or angle. Standard candles (SNIa) or standard rulers (BAO scale) are generally required.

a: a(t) = 1/(1+z), where z is redshift, Thus a(t) comes from the direct astrophysical observable redshift.

DES Science Summary

Constraints on DE Equation of State

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

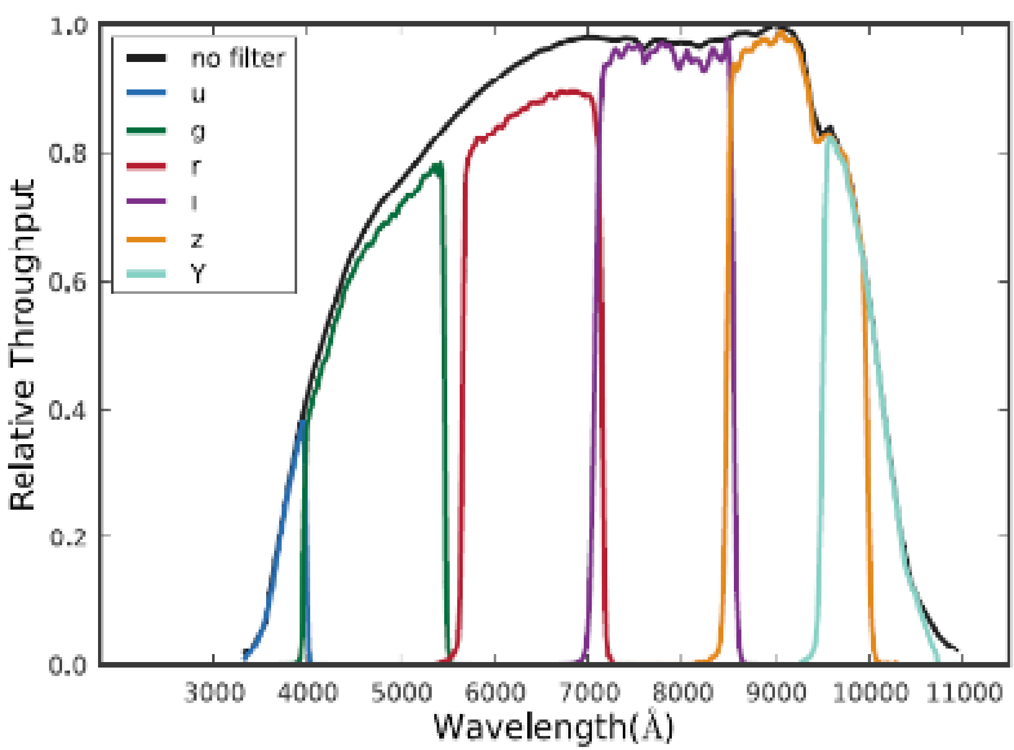


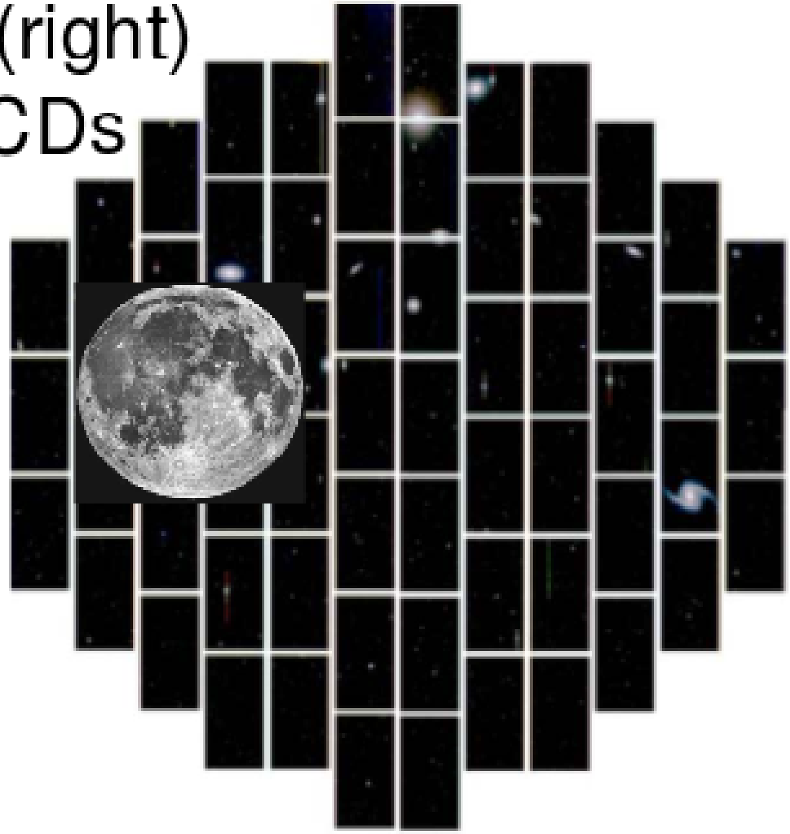
Four Probes of Dark Energy

- **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
  - ~3000 well-sampled SNe Ia to z ~1

DECam Strengths

- Wide FoV (2.2 deg), 3 sq-deg (right)
- Fully-depleted red-sensitive CCDs
- Telescope w/ 4-m primary
- Excellent site conditions



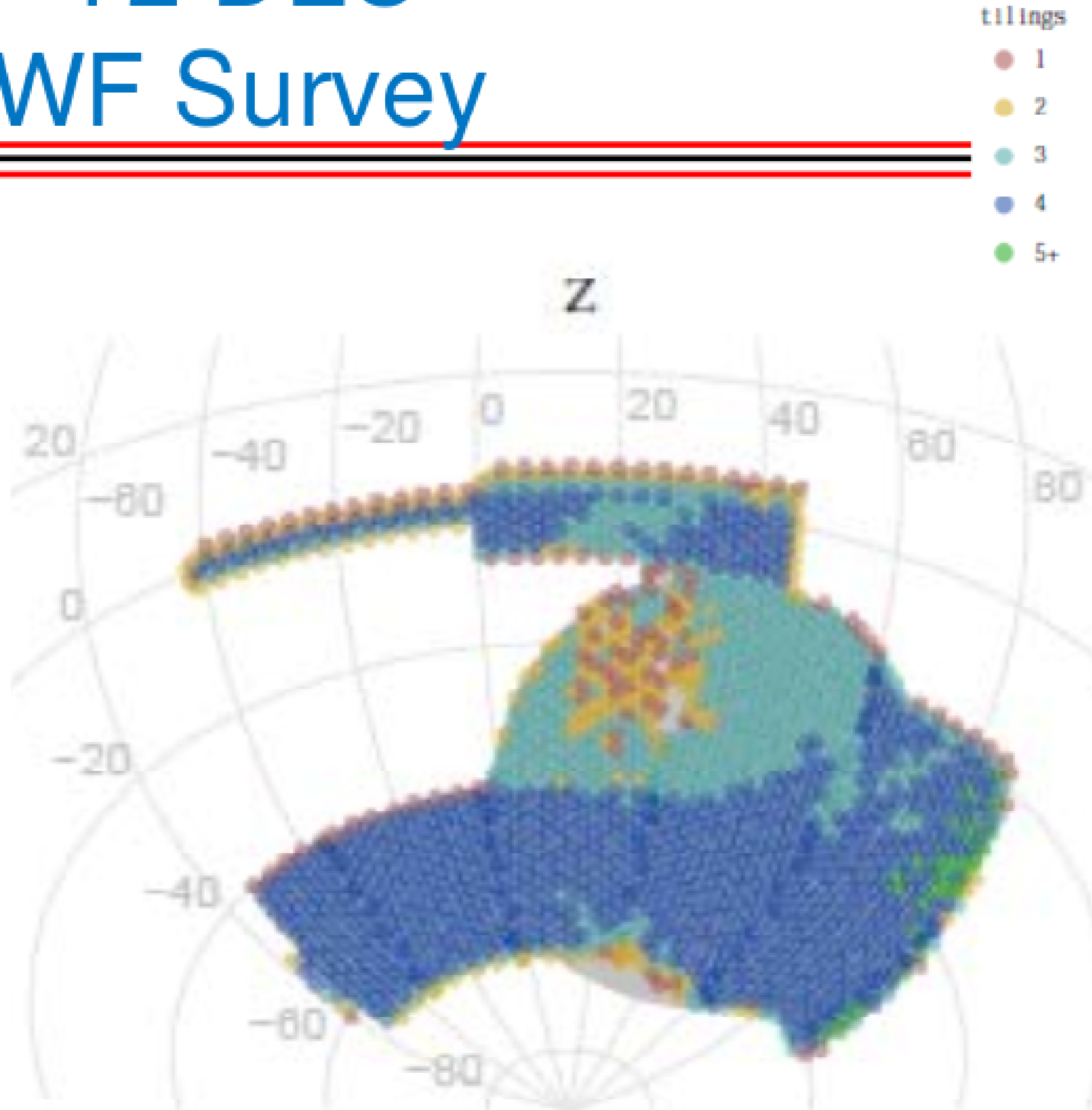


- (left) camera throughput vs λ

DES Status after Year 2

Y2 DES WF Survey

- Goal for Y2 was to finish the survey field 4 tiles in 5 filters.
- Plot on RHS shows what we got:
  - 14447 “good” images
  - z-band (right) is typical of the result by the end of Y2 observations
  - 3 or 4+ tile coverage except an area at RA ~20
  - After Y2 we have observed 90% of our original Y1 + Y2 goal.



Early DES results:

- The DECam technical paper – arXiv:1504.02900
- Simulations – arXiv: 1504:02778
- Photometric redshift calibration
  (technique to get redshifts with DECam photometry
  alone) – arXiv:1504.03039
- Dark Energy preliminaries
  - Clusters – arXiv:1504.02983
  - Weak Lensing – arXiv:1504.03002
  - Supernovae setup – arXiv:1504.02996, 1504.03264
- Redshift 6.10 quasar – arXiv:1504.03264
- Dwarf Galaxies – ...

Laying the groundwork – redshifts

DES is an imaging survey, and so a primary way to obtain redshifts is to use the 'photometric redshift' technique and the power of billions of detections in several colors to estimate redshifts for faint galaxies. This technique must be calibrated with actual spectroscopic data. Additionally, the supernovae standard candles need redshifts measured. For these we rely on our collaborators in the land of Oz...

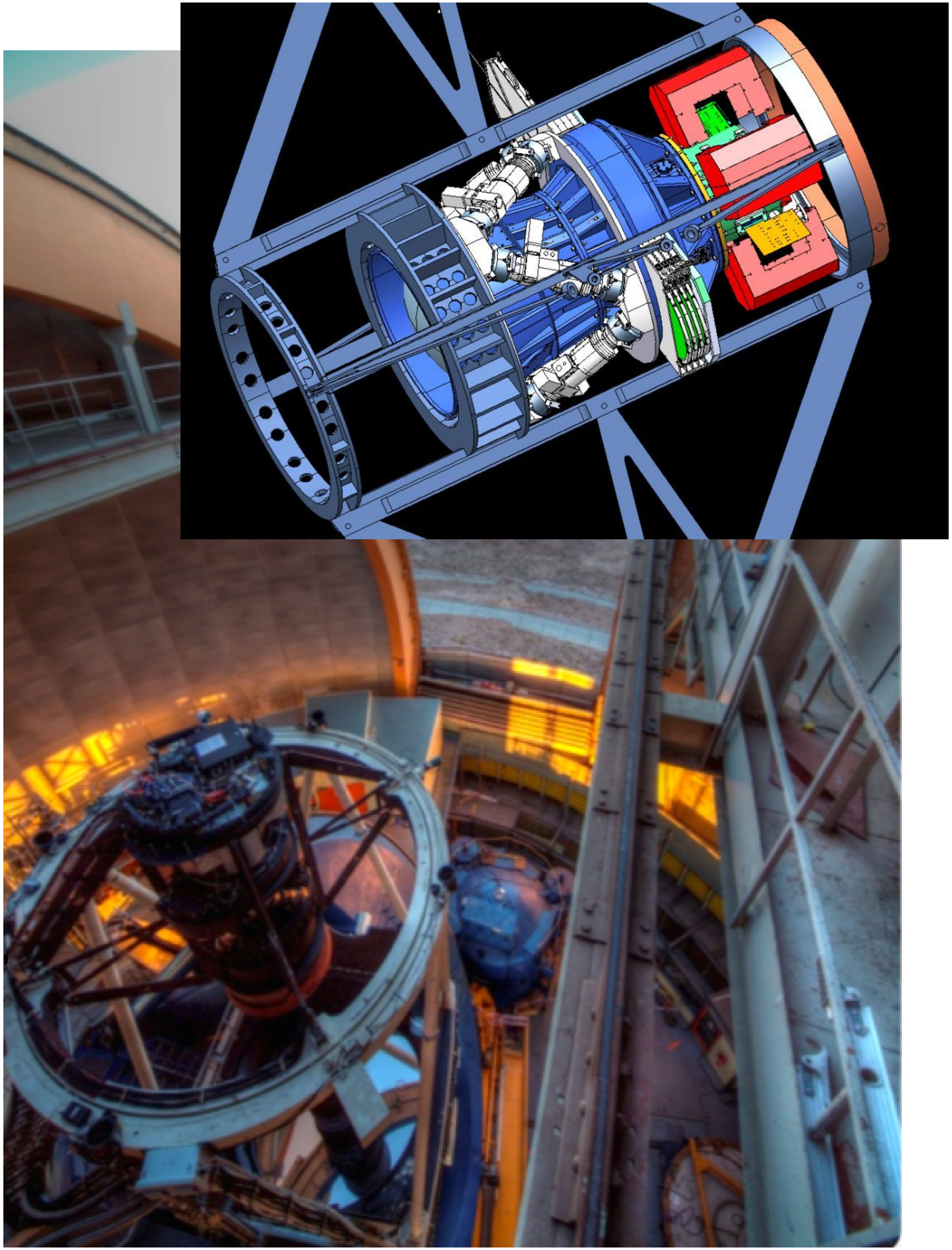
] 13 Apr 2015

OzDES multi-fibre spectroscopy for the Dark Energy Survey: first-year operation and results

Fang Yuan,[1,2⋆] C. Lidman[2,3], T. M. Davis[2,4], M. Childress[1,2], F. B. Abdalla[5], M. Banerji[6,7], E. Buckley-Geer[8], A. Carnero Rosell[9,10], D. Carollo[11,12], F. J. Castander[13], C. B. D'Andrea[14], H. T. Diehl[8], C. E Cunha[15], R. J. Foley[16,17], J. Frieman[8,18], K. Glazebrook[19], J. Gschwend[9,10], S. Hinton[2,4], S. Jouvel[5], R. Kessler[18], A. G. Kim[20], A. L. King[4,21], K. Kuehn[3], S. Kuhlmann[22], G. F. Lewis[23], H. Lin[8], P. Martini[24,25], R. G. McMahon[6,7], J. Mould[19],

- The DECam technical paper – arXiv:1504.02900

- Describes the specs and workings of the 540Mpix camera



Led by Flaugher, Diehl, with
Annis, Alvarez, Angstadt,
Buckley-Geer, Campa, Cease,
Chappa, Chi, Derylo, Drlica-Wagner,
Estrada, Finley, Flores, Frieman,
Gutierrez, Hao, Holm, Huffman,
Jackson, Jonas, Kent, Kuk, Lathrop,
Mandrichenko, Merritt, Nielsen, Nord,
Olsen, Peoples, Rauch, Schmitt, Schultz
Scott, Shaw, Soares-Santos Stefanik
Stuermer, Tucker, Watson, Wester,
Woods, Yanny, +

Key Fermilab effort at every stage!

Two of the ways DES proposes to constrain the w(DE) parameter are:

1. Counts and Mass calibration of Galaxy Clusters (z)

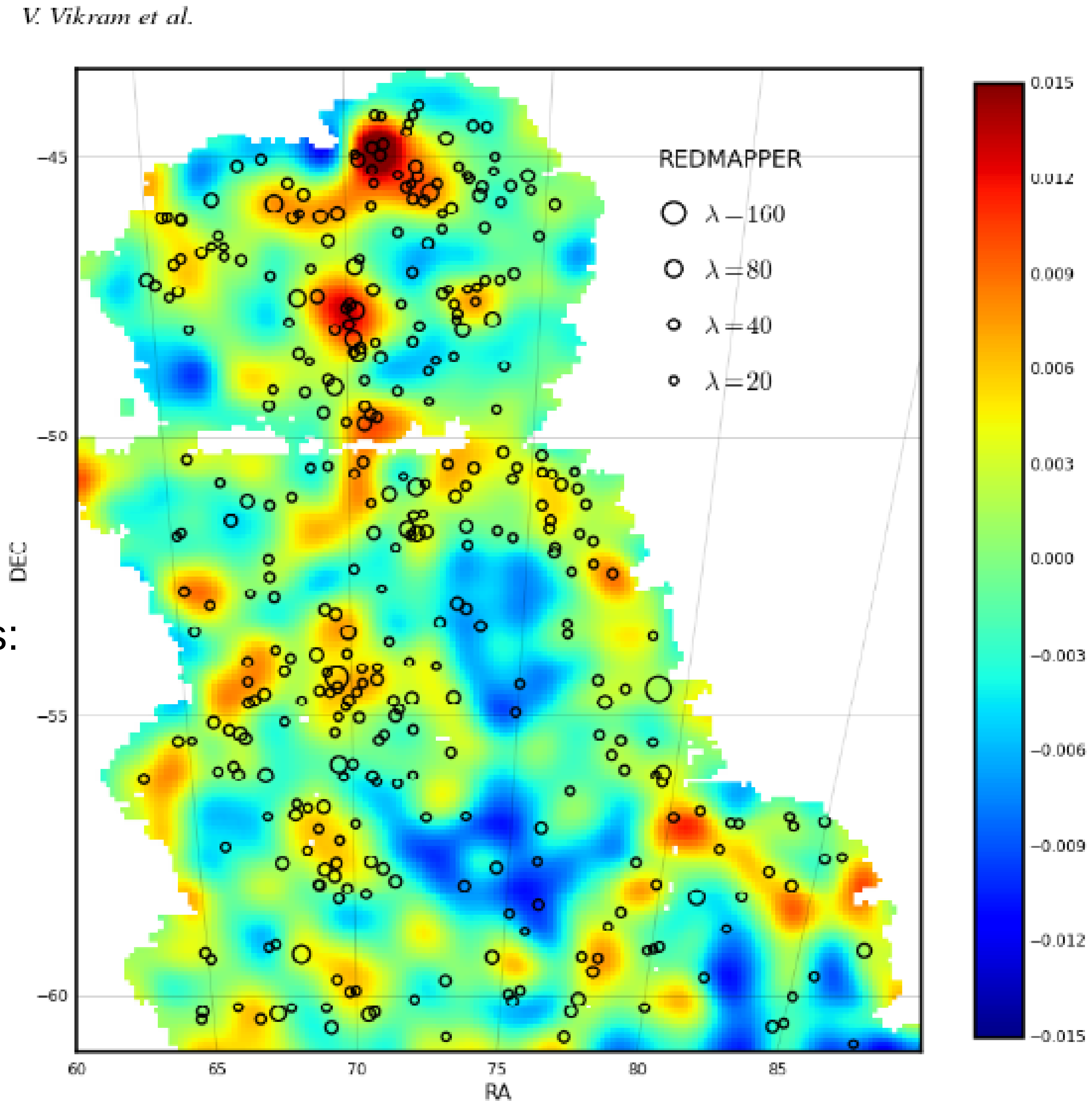
2. Weak gravitational lensing measurements over large areas to determine locations of mass concentrations

If these two methods are to help, they should 'see' the same amount of matter in the same direction on the sky.

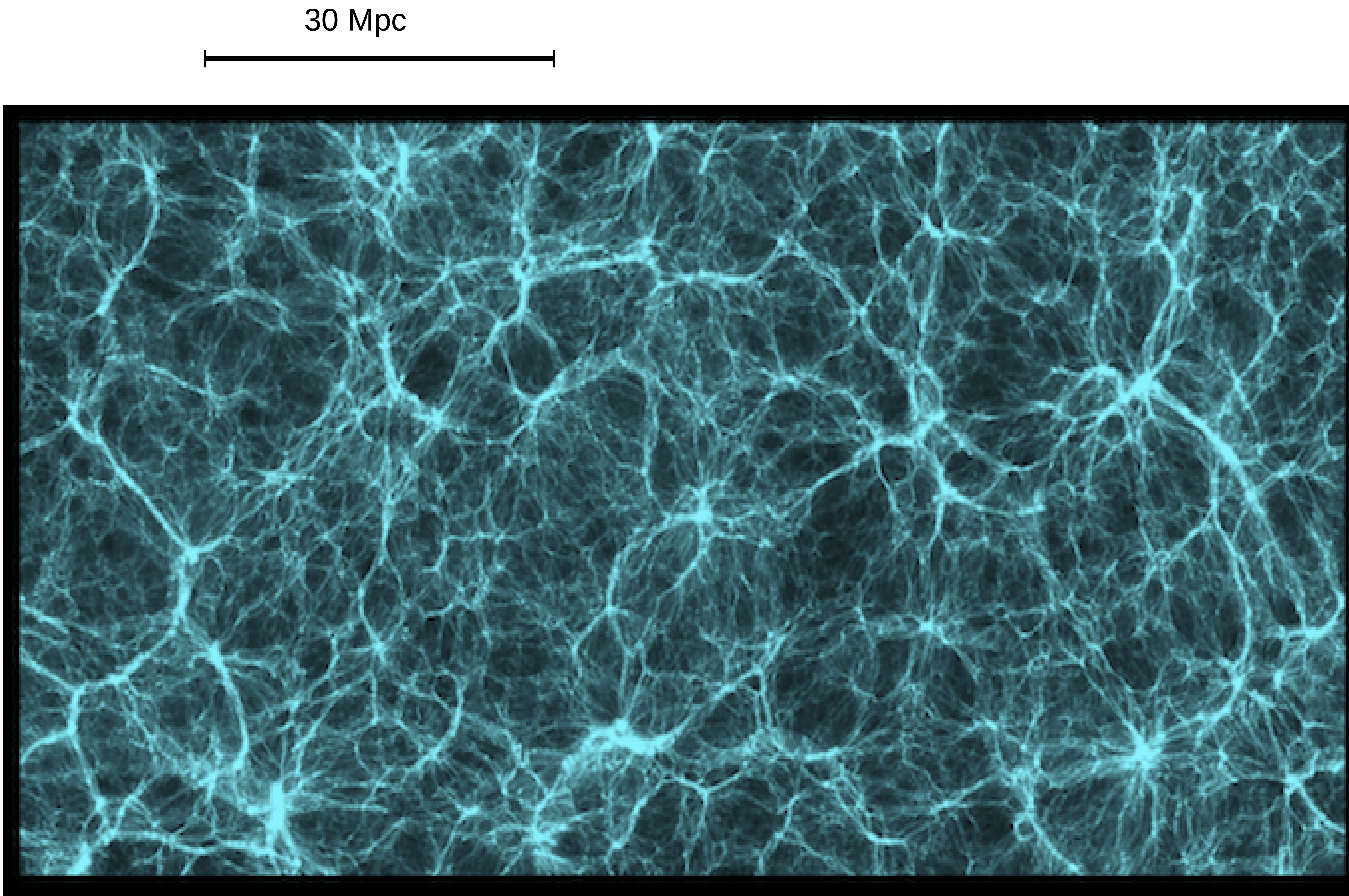
This is the topic of: arXiv:1504.03002
Vikram, …, Lin, Buckley-Geer, Diehl, Estrada, Kent, Kuropatkin, Merritt, Nord et al...

Black Circles:
Galaxy Clusters

Colored contours:
Weak Lensing
Shear excess
showing
Dark Matter
overdensities



A. Berlind (LasDamas Dark Matter simulation)



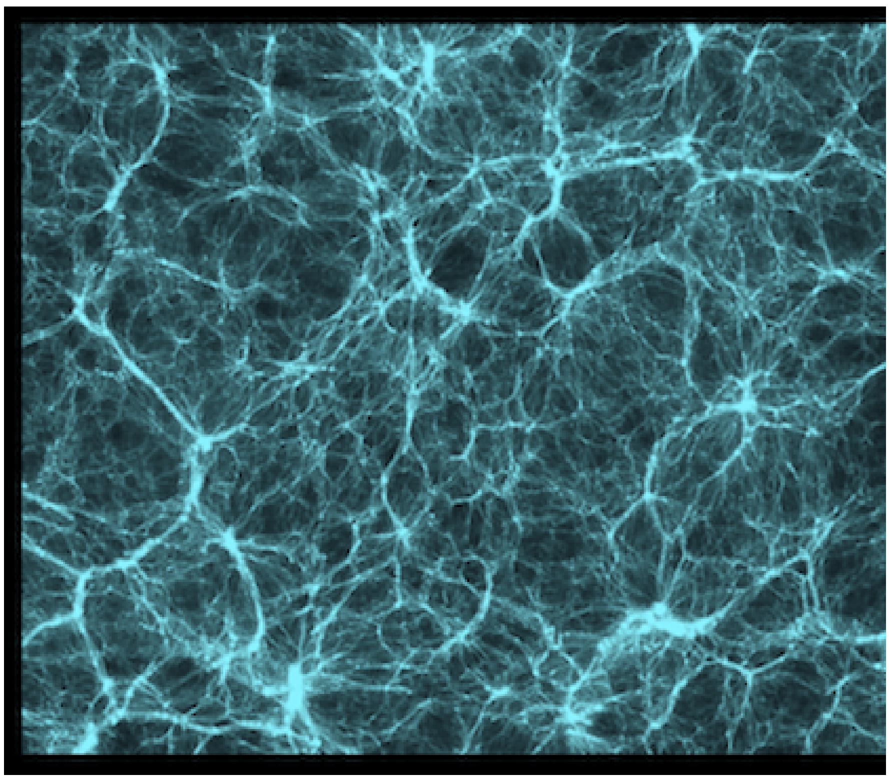
What's new:

http://arxiv.org/abs/1504.03002
Vikram+

Large Scale of the data,
Making visible the dark
matter large scale cosmic
structure web, prev. sims only.

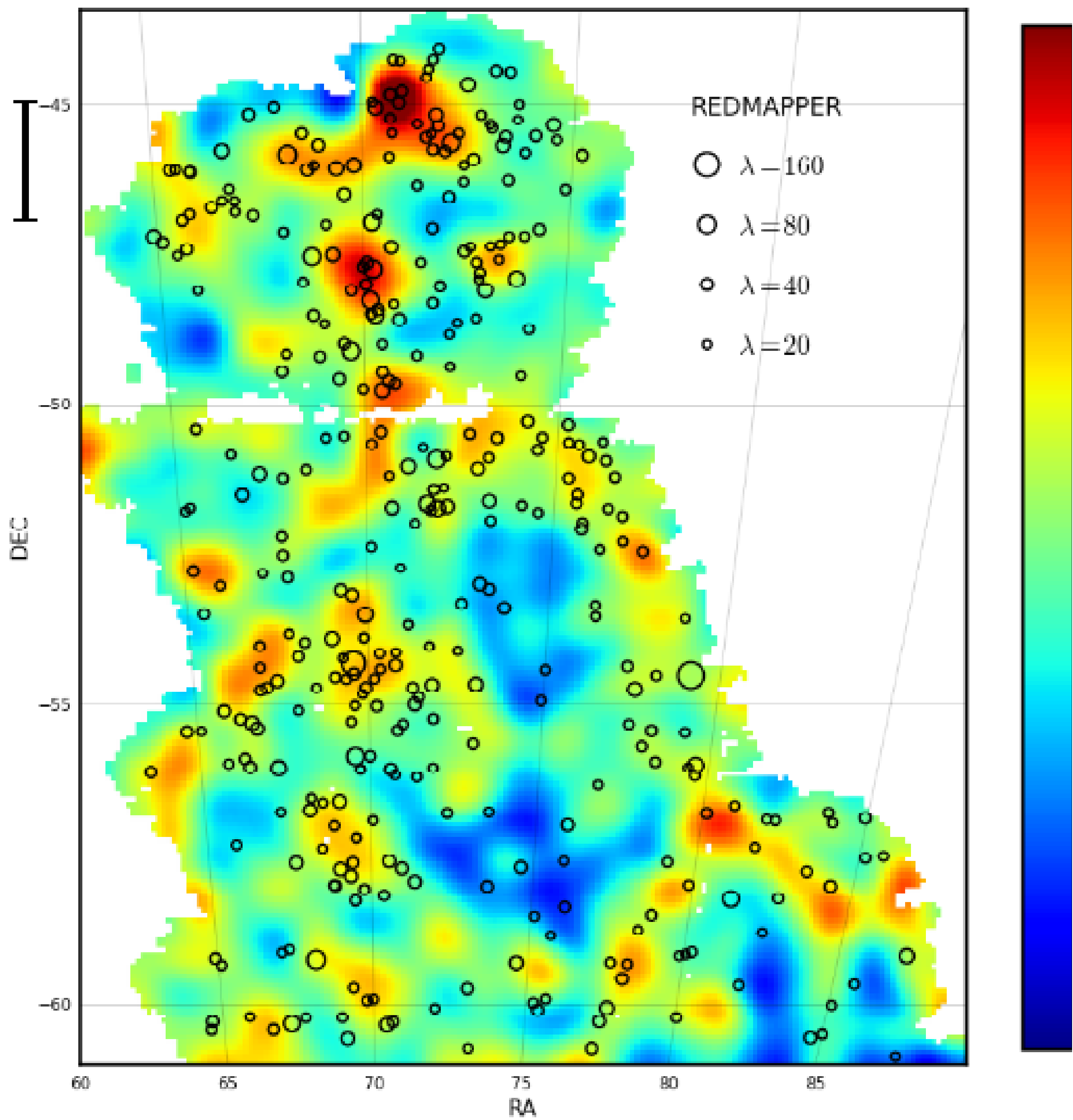
~30 Mpc

~30
Mpc



A. Berlind (LasDamas dark matter sim.)

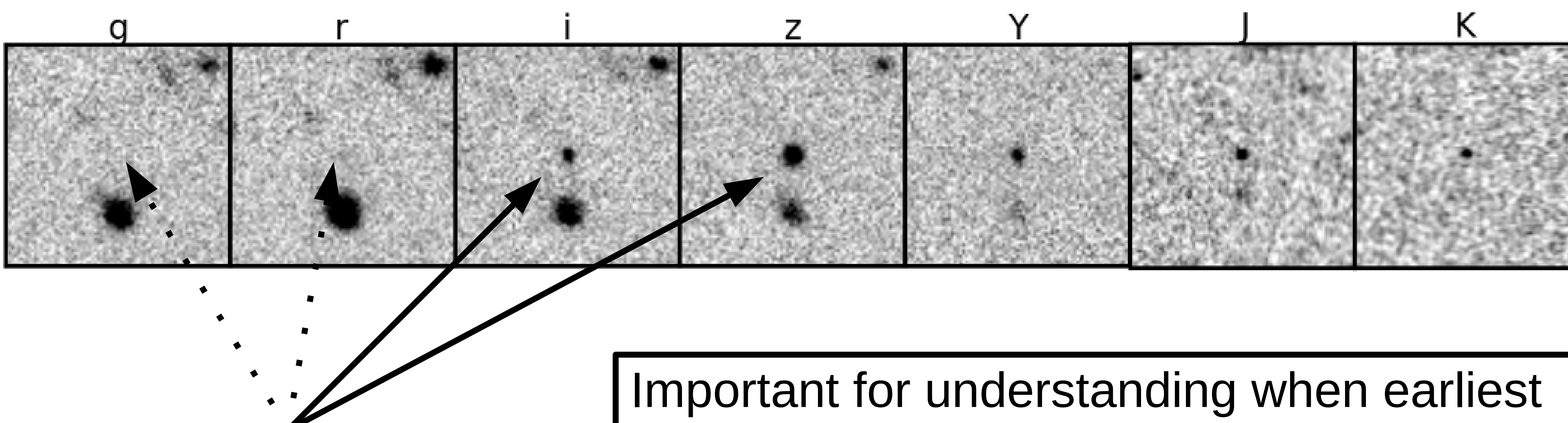
V. Vikram et al.



More early DES science (non-Dark Energy):

Very high redshift quasars disappear in bluer filters (g,r below) and are only visible in the infrared filters (I,z,Y,J,K). This quasar is at a redshift > 6; i.e. when the Universe was less than 1/(1+6) = 14% of it's current age.

Reed+ arXiv:1504.03264



Redshift 6.1 quasar image

Important for understanding when earliest structures formed in Universe.

One more recent DES result to discuss...