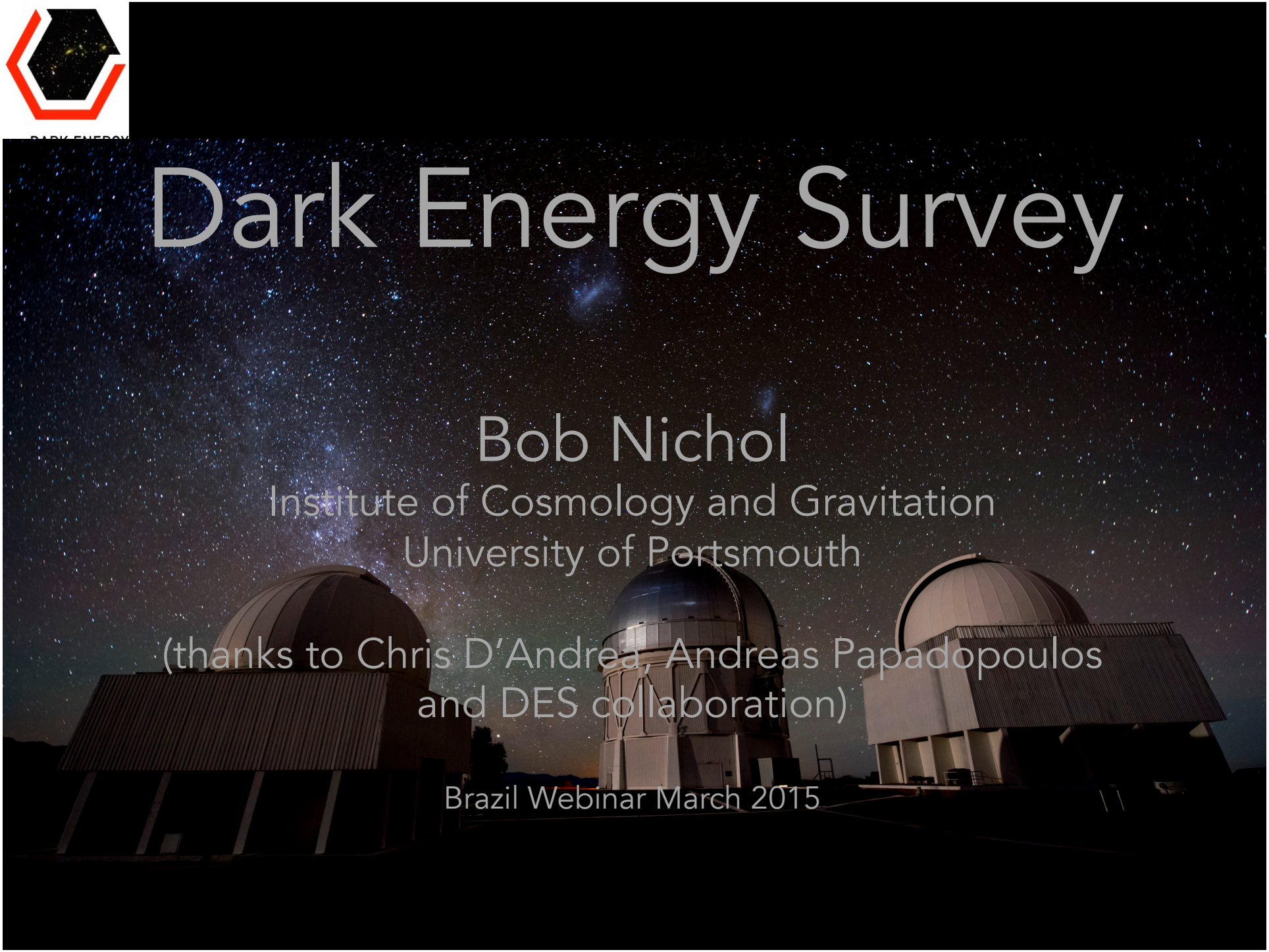


Dark Energy Survey

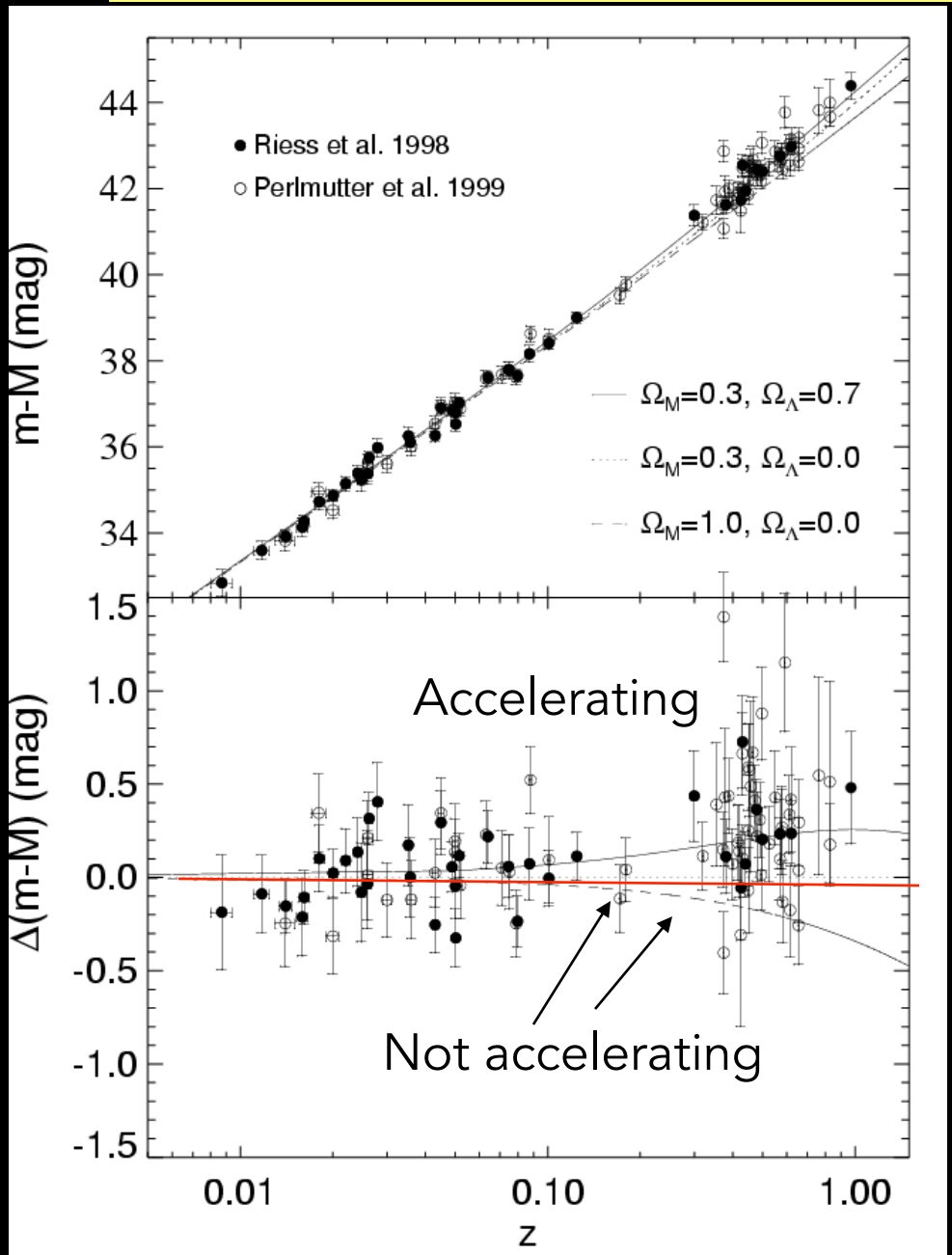
Bob Nichol

Institute of Cosmology and Gravitation
University of Portsmouth

(thanks to Chris D'Andrea, Andreas Papadopoulos and DES collaboration)

Brazil Webinar March 2015

Discovery of Cosmic Acceleration

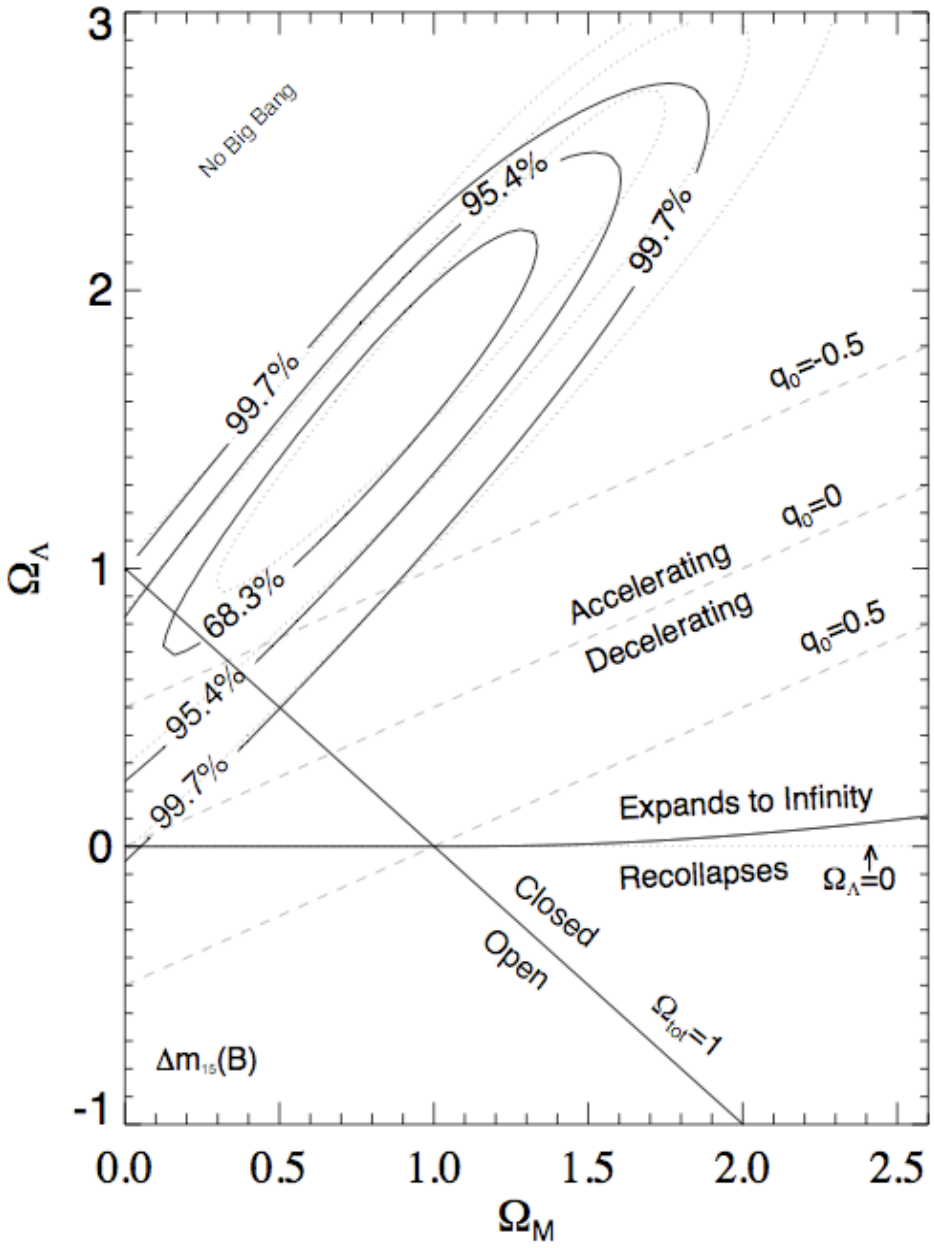


Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

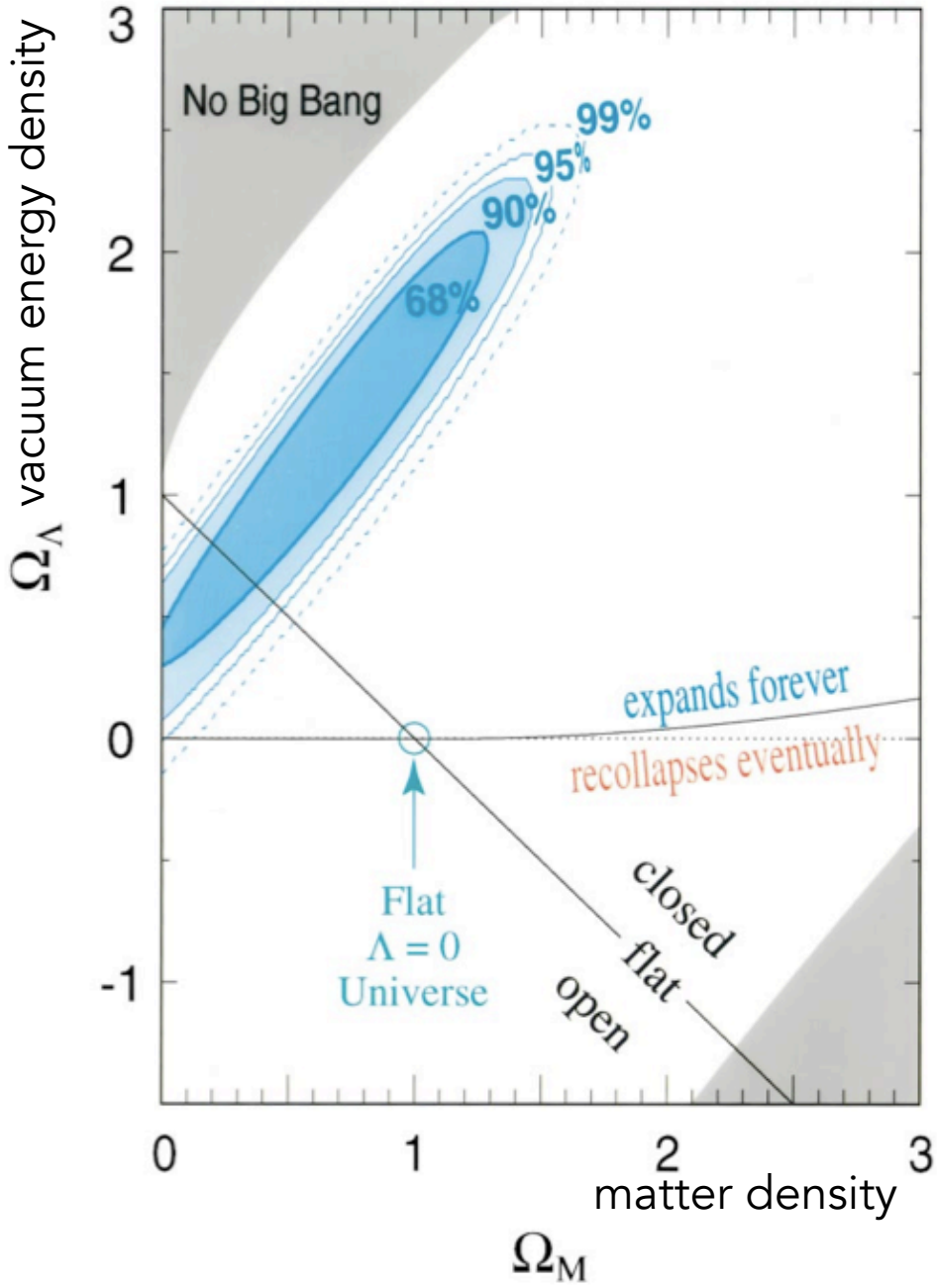
$(\Omega_M, \Omega_\Lambda)$
(0.3, 0.7)
(0.3, 0.0)
(1.0, 0.0)

2011 Nobel Prize in Physics

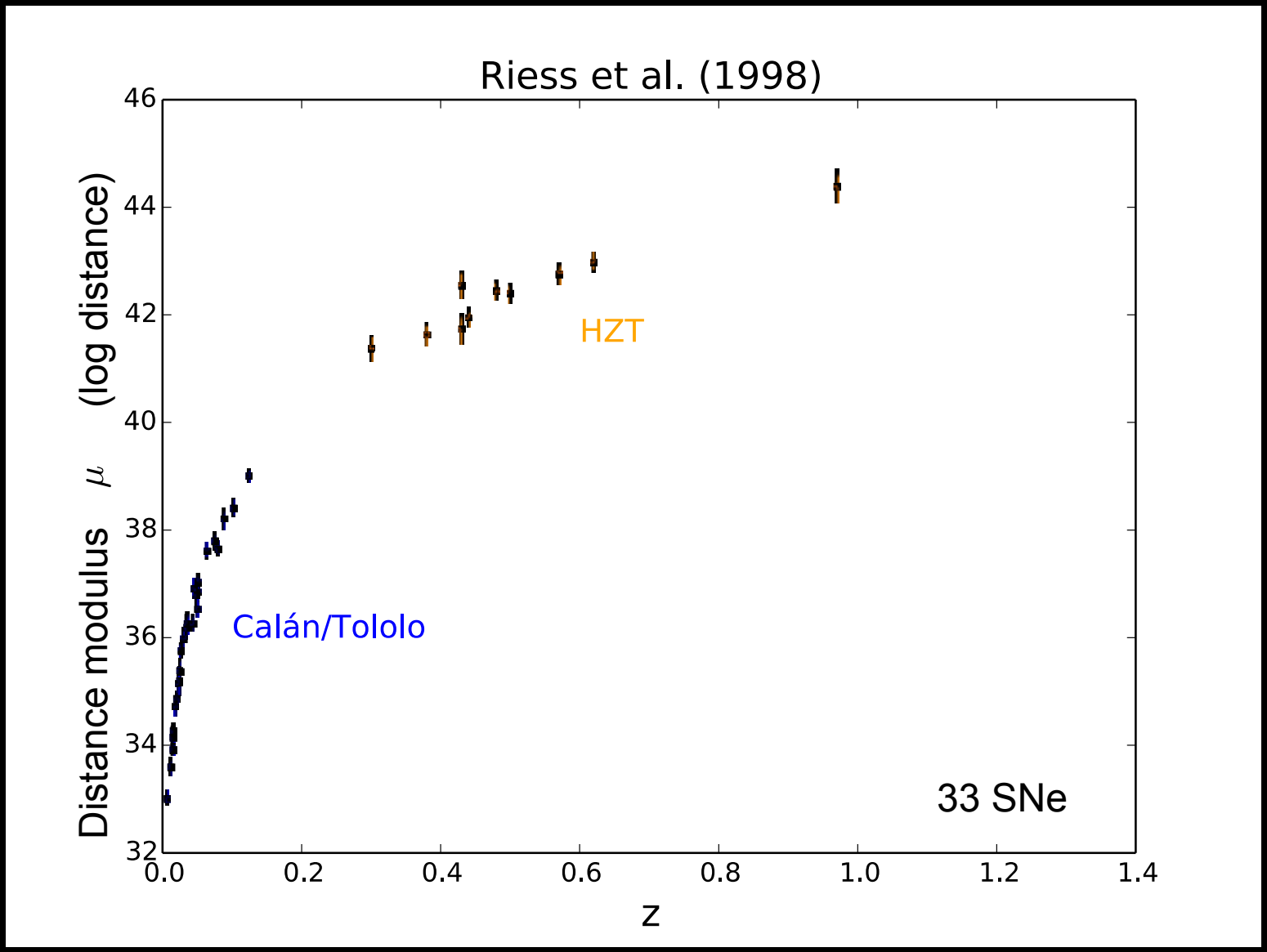
Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)

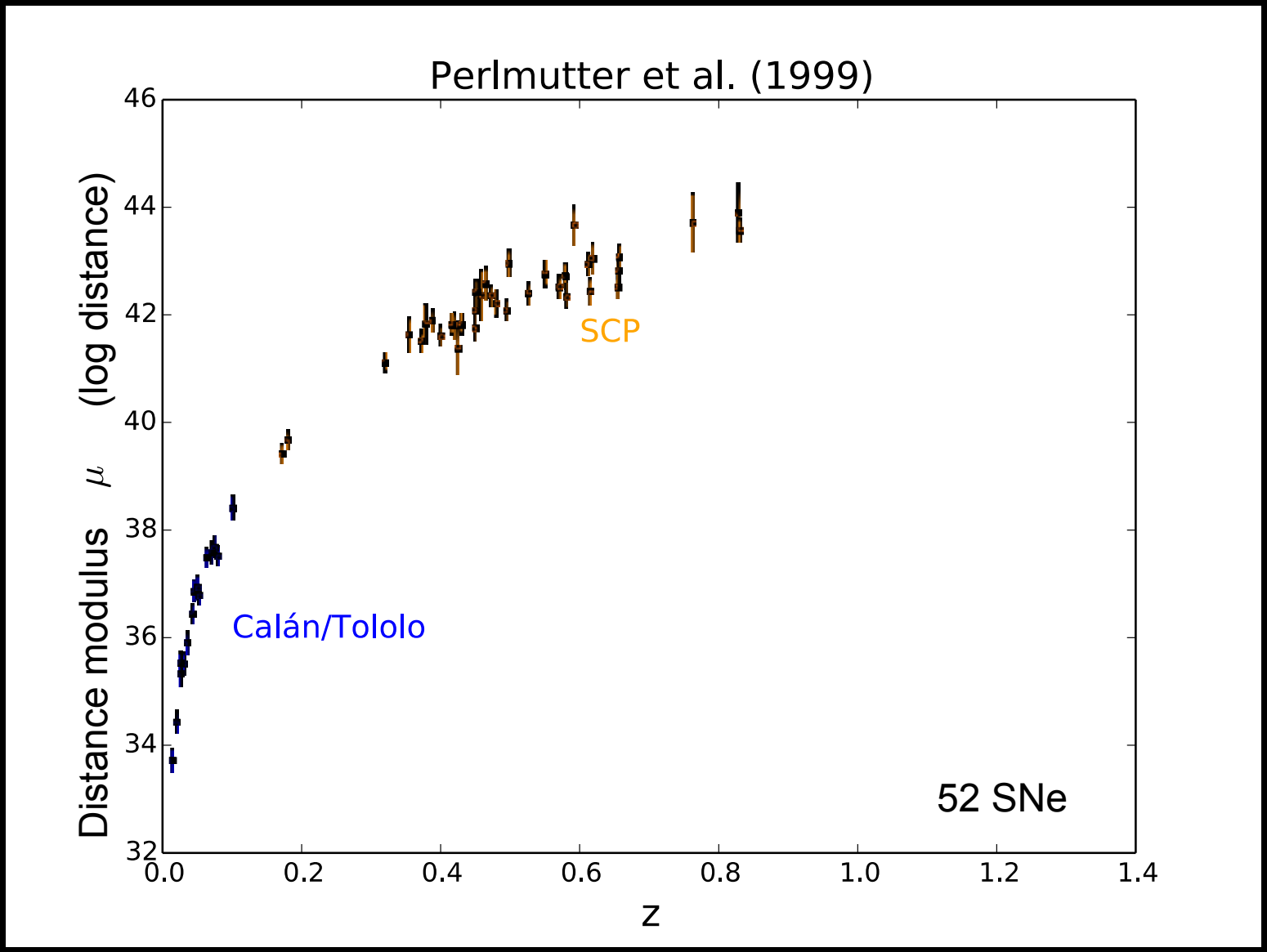


SUPERNOVA IA HUBBLE DIAGRAM

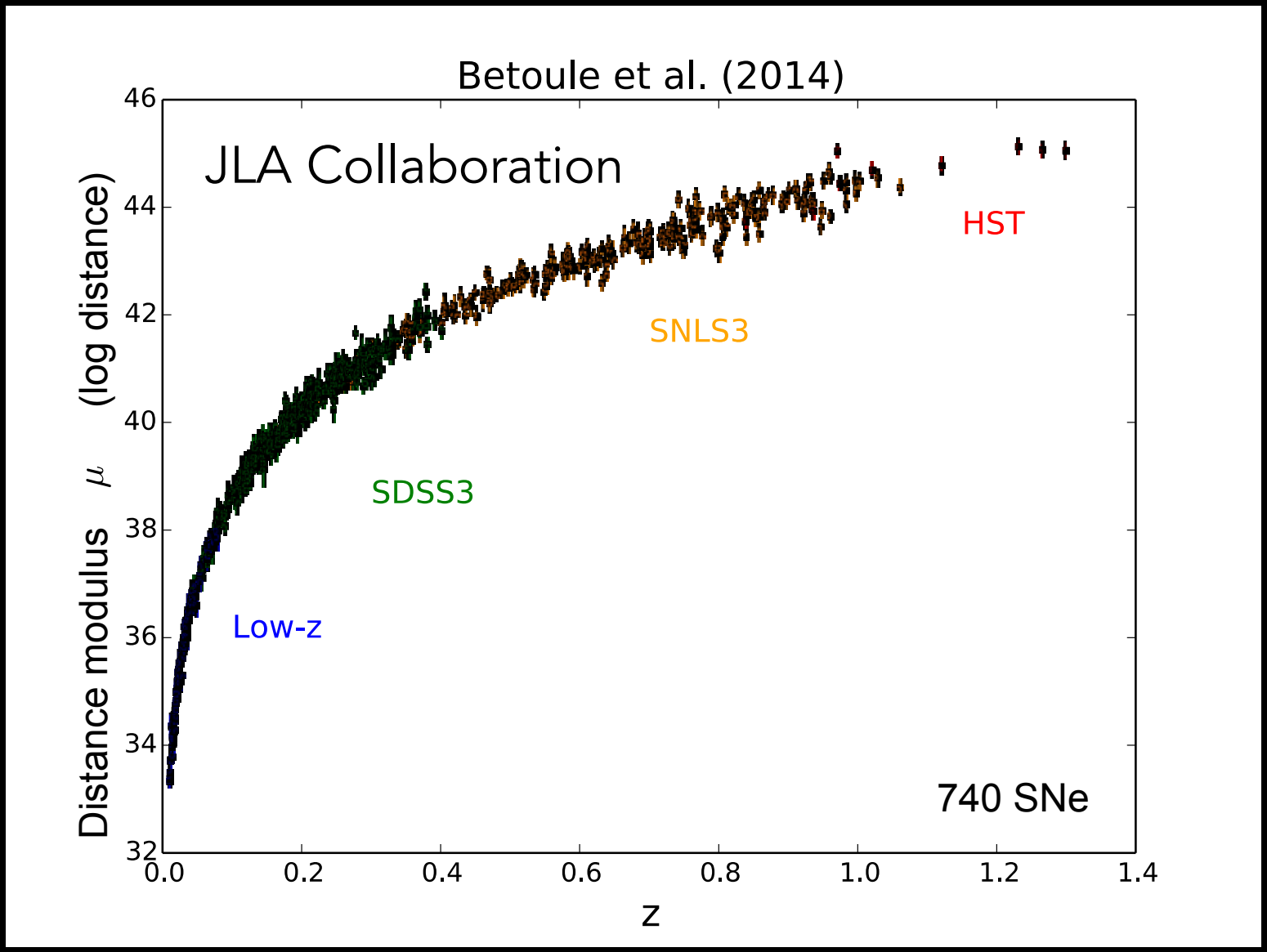


figures by A. Conley

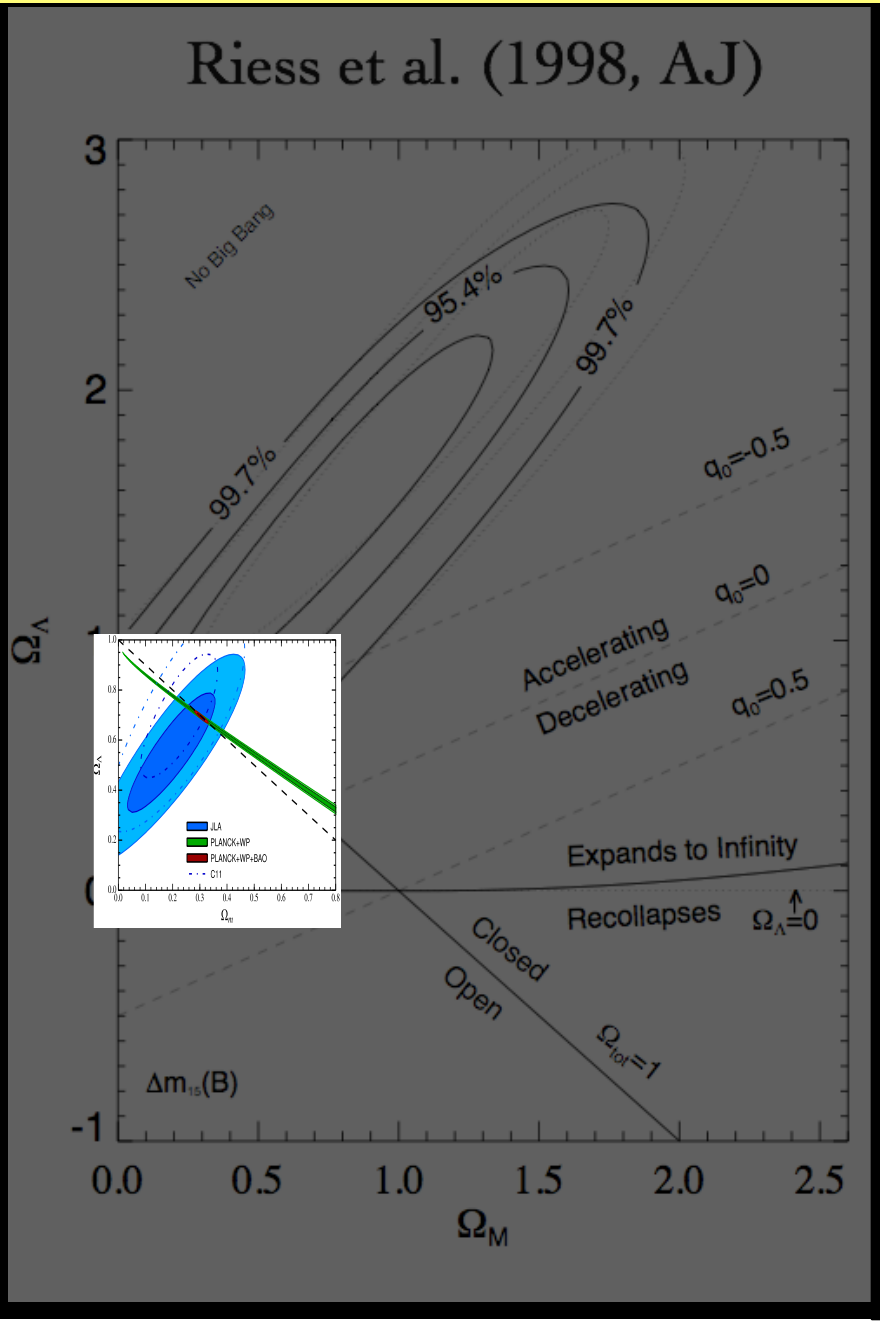
Supernova Ia Hubble Diagram



Supernova Ia Hubble Diagram



PROGRESS OVER THE PAST 15 YEARS



Supernovae

Cosmic Microwave Background (Planck, WMAP)

CMB+BAO

Here assuming $w = -1$

Betoule et al. 2014

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

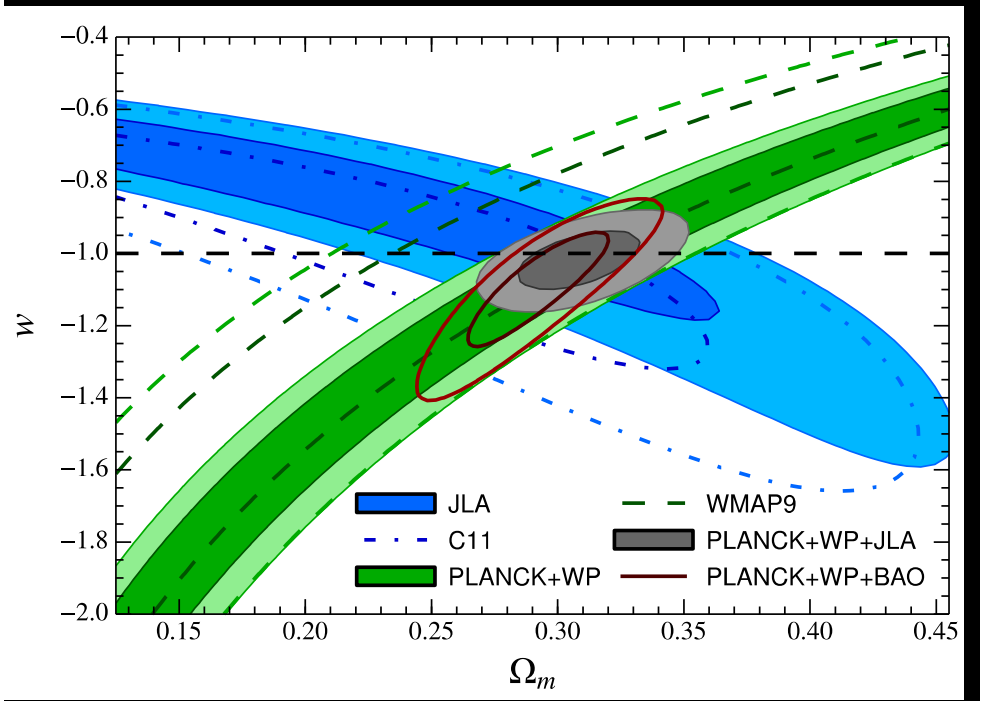
Cosmological Constant: $w_\Lambda = -1$

or Replace GR dynamics with another gravity theory

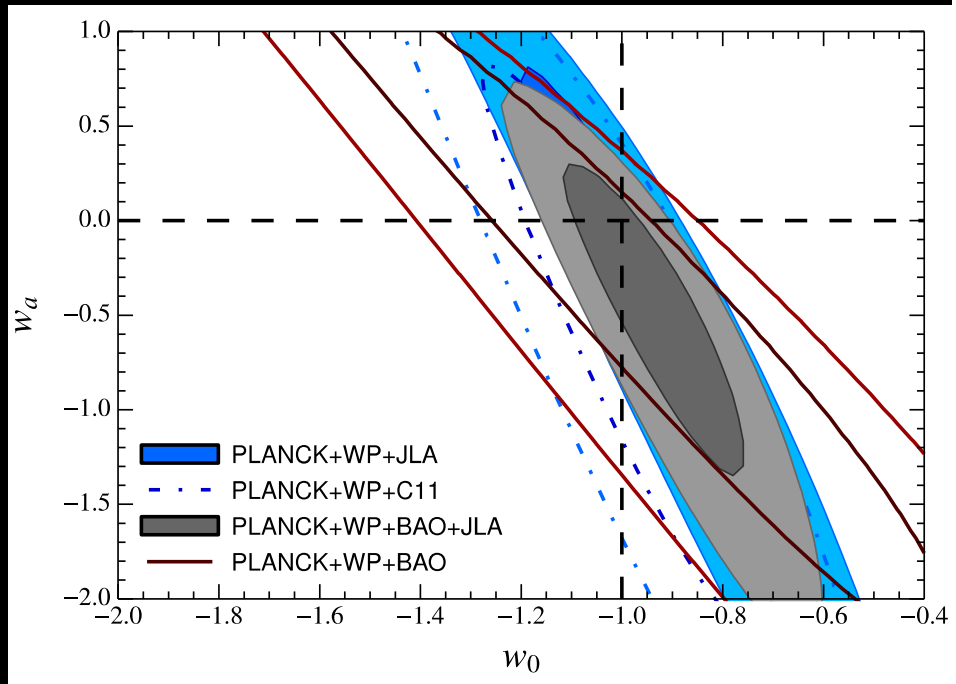
Current Dark Energy Constraints

Supernovae, CMB, and Large-Scale Structure

Assuming constant *w*



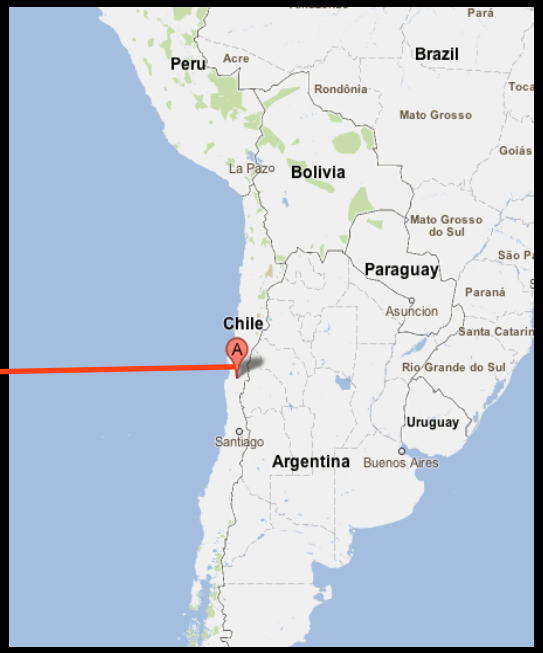
Assuming $w=w_0+w_a(1-a)$



Consistent with vacuum energy (Λ): $w_0=-1$, $w_a=0$

Betoule et. al (2014)

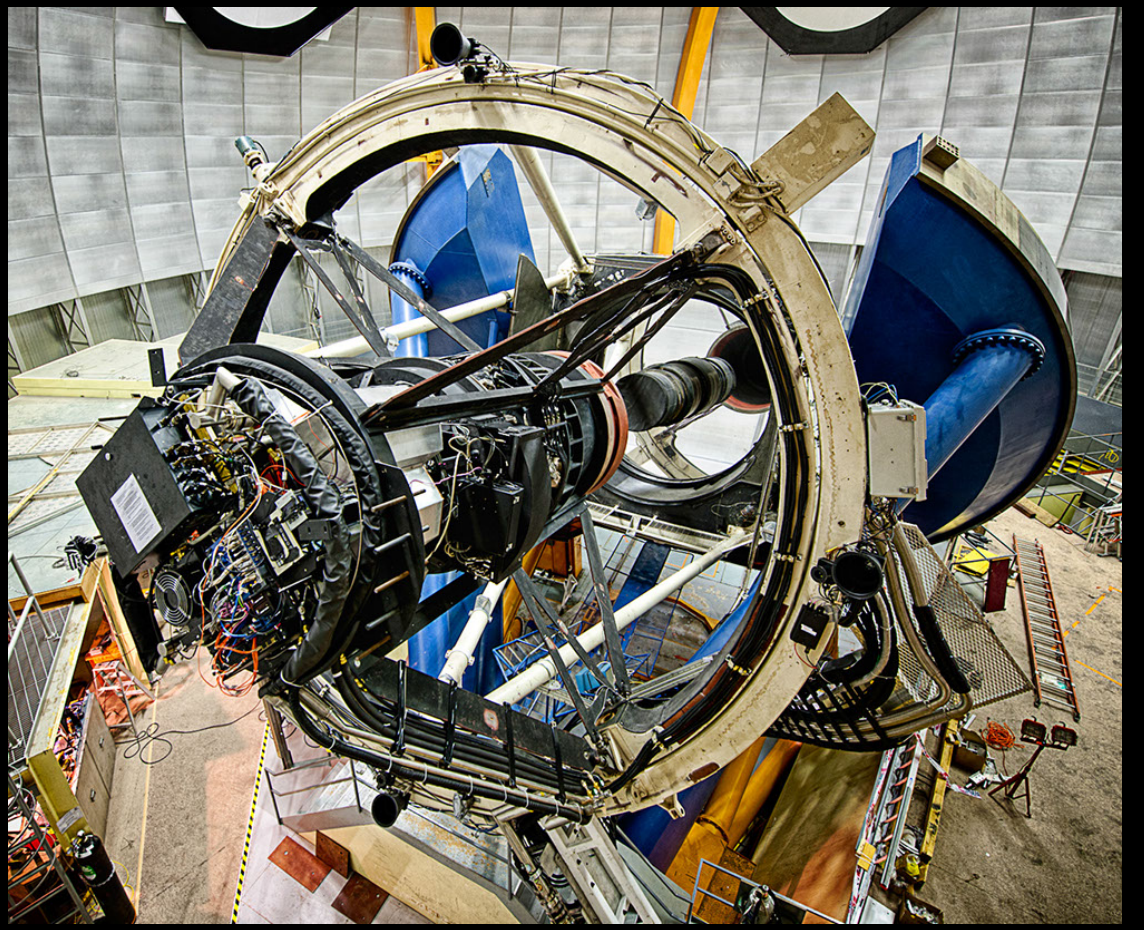
Origins of The Dark Energy Survey



- Late 2003: NOAO Announcement of Opportunity for new facility instrument on the Blanco 4-meter telescope
  - Cerro Tololo Inter-American Observatory
  - Good seeing: ~0.75" median for site
  - High percentage of clear, photometric nights
- 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
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:
  - 300 M galaxies over 1/8 sky
  - 3500 supernovae (30 deg^2)
- Built new camera for CTIO Blanco telescope
  - Facility instrument
- Five-year Survey
  - 525 nights (Aug - Feb)

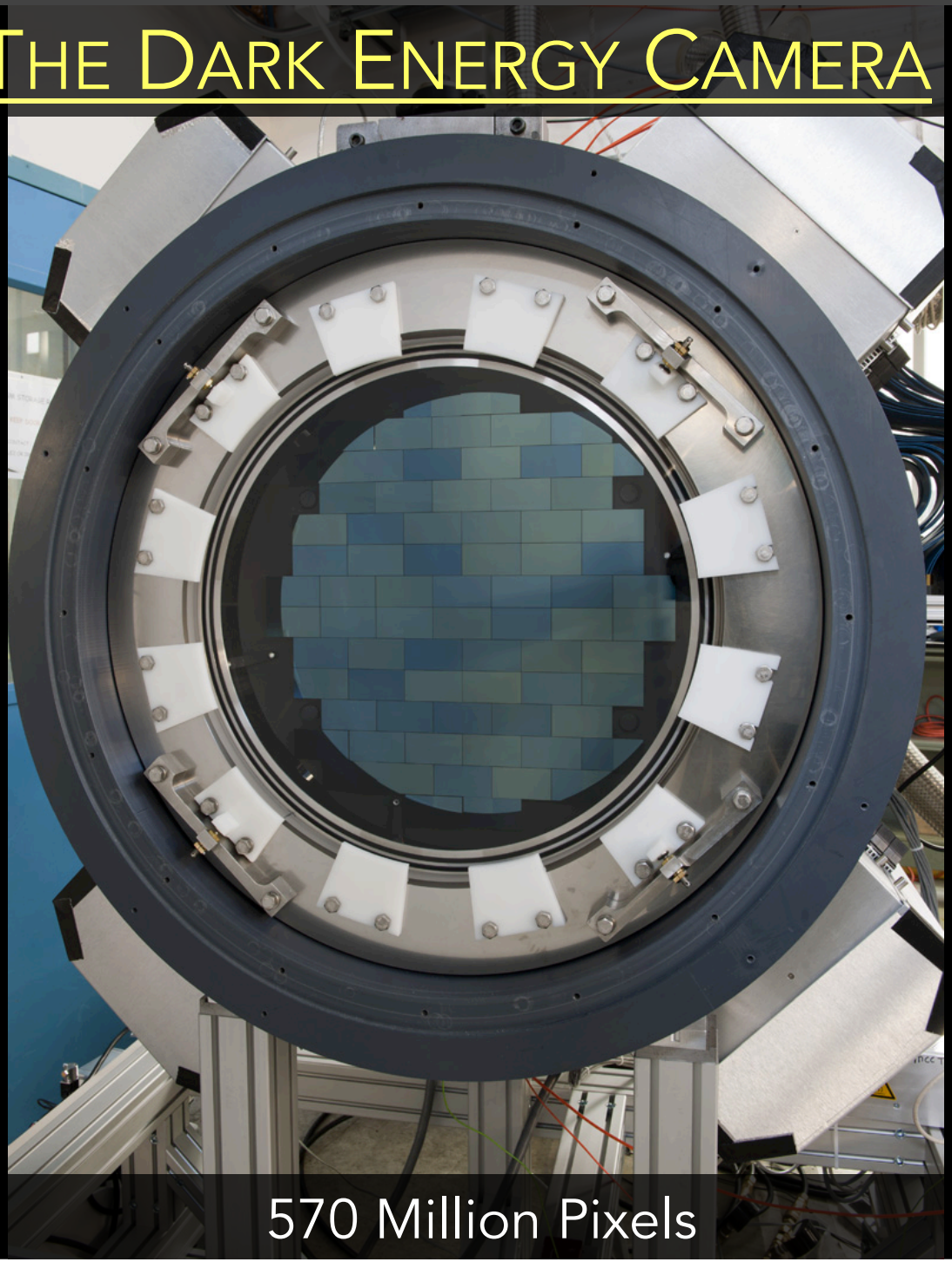


DARK ENERGY SURVEY COLLABORATION

~300 scientists

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

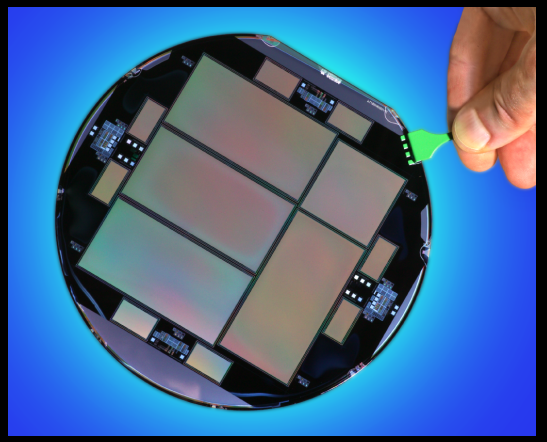
The Dark Energy Camera



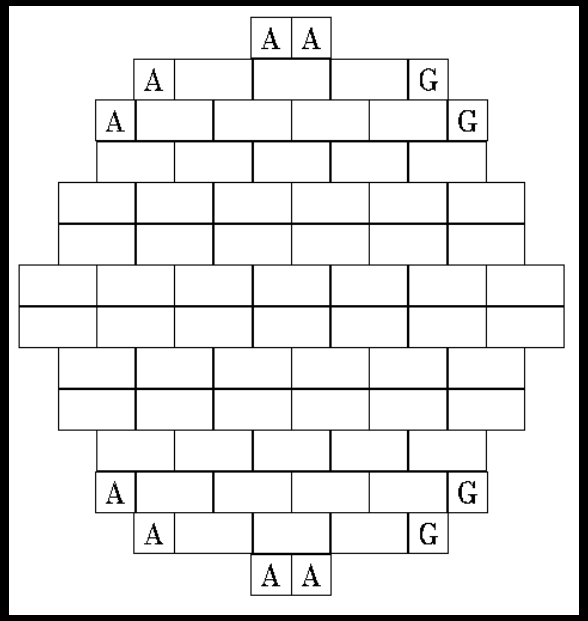
570 Million Pixels

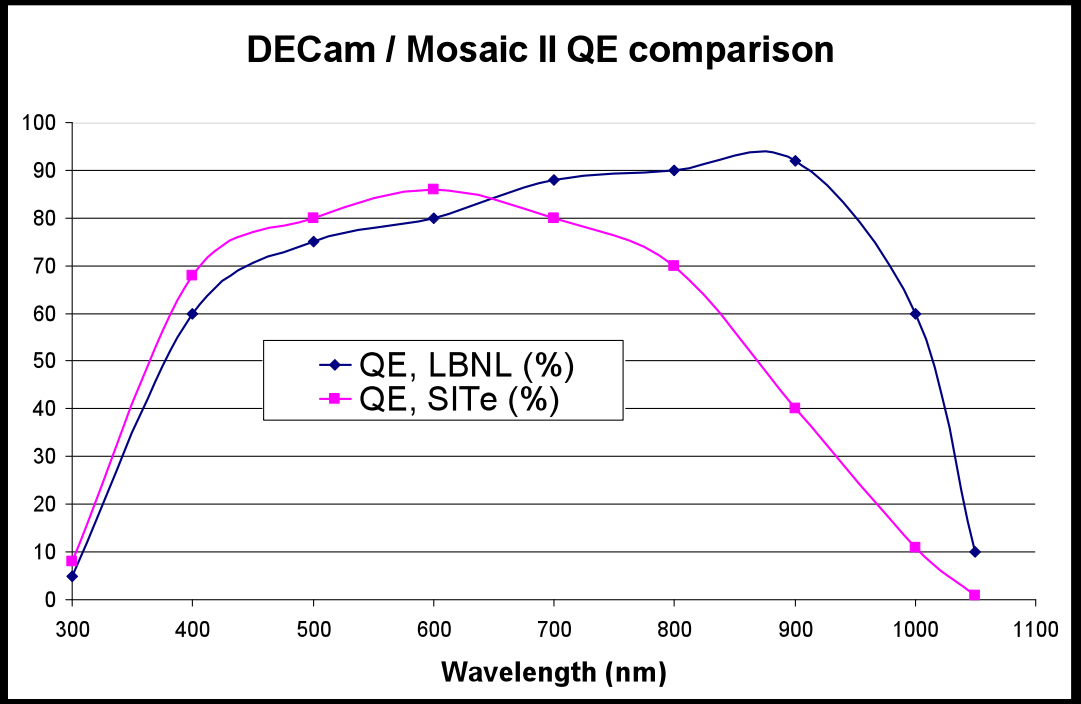
DARK ENERGY SURVEY

DECAM CCDS

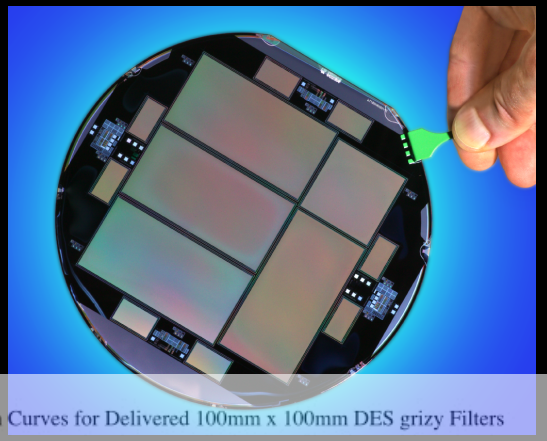


- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264") pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels

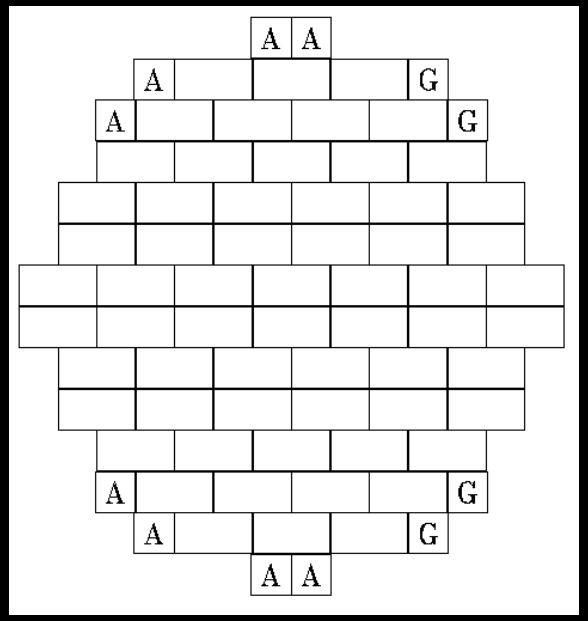


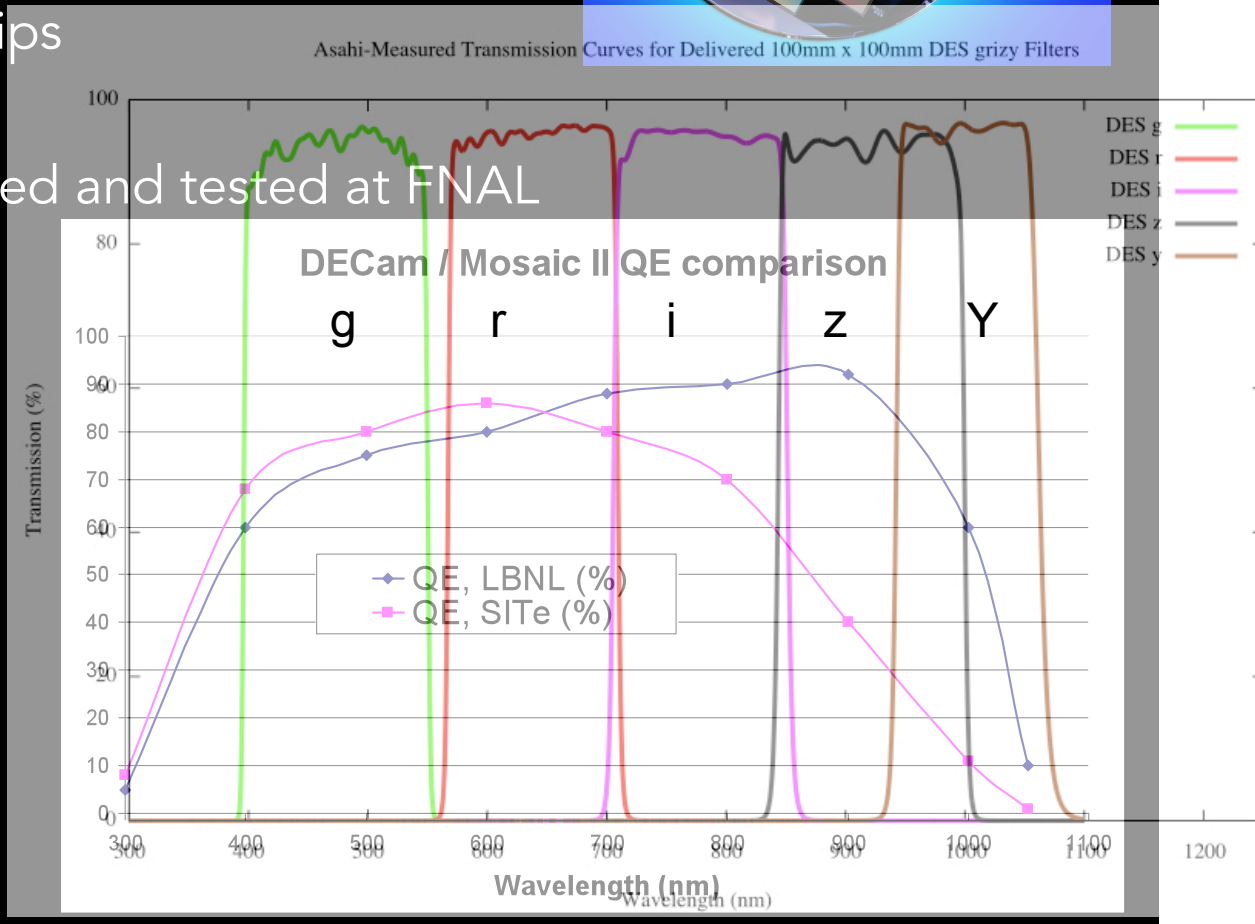


DECAM CCDS



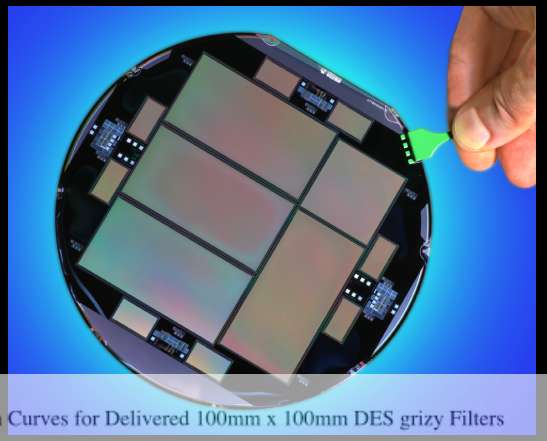
- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264") pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels



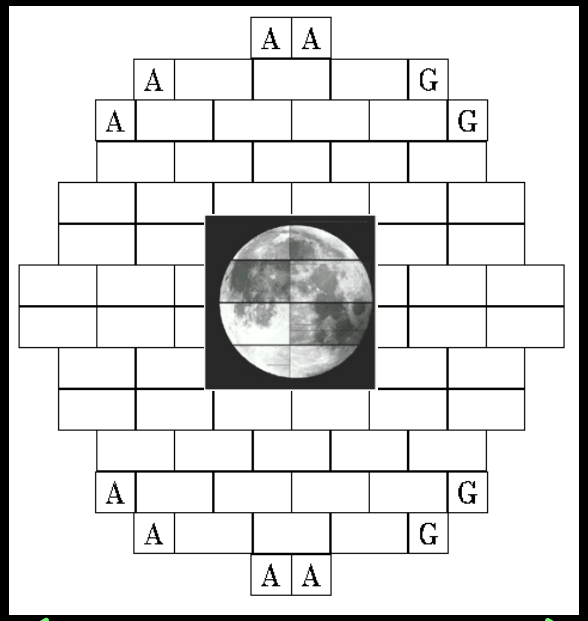


DES filters

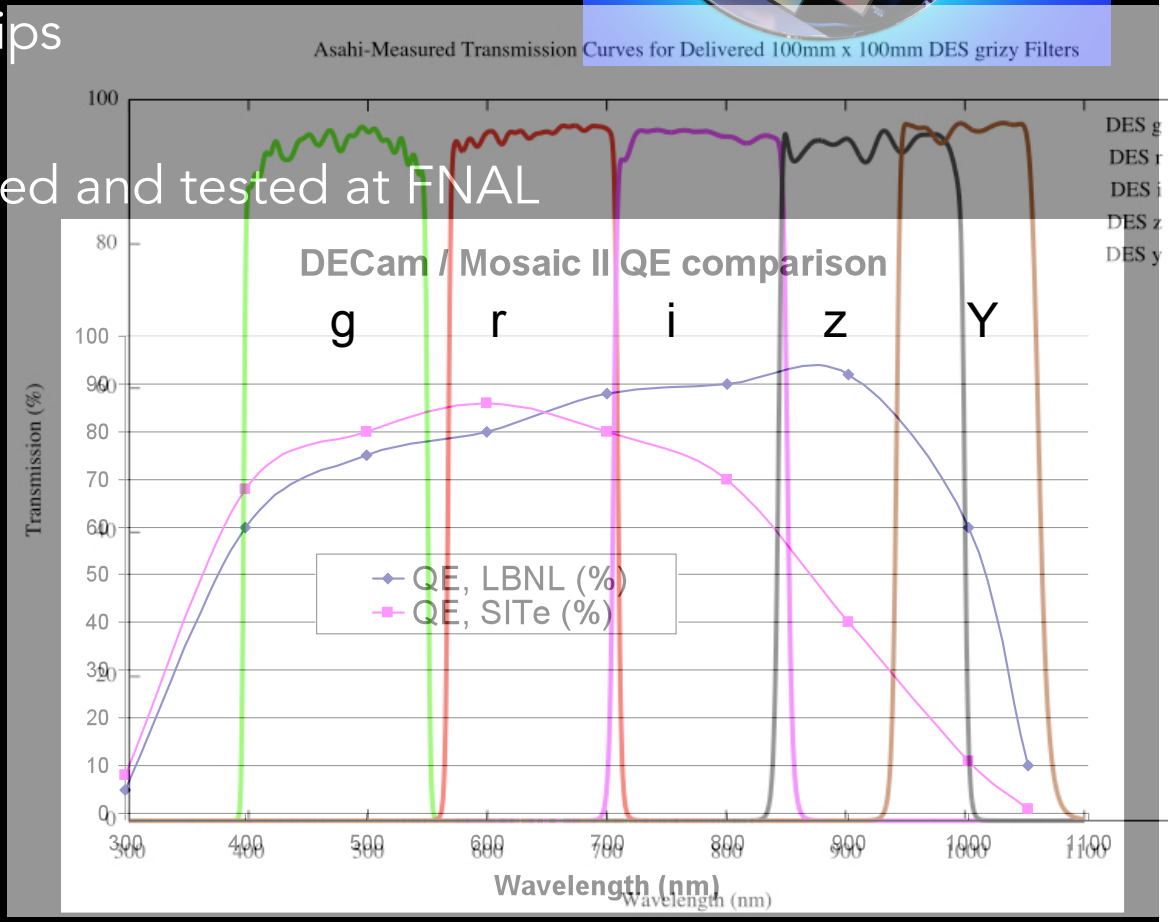
DECAM CCDS



- 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



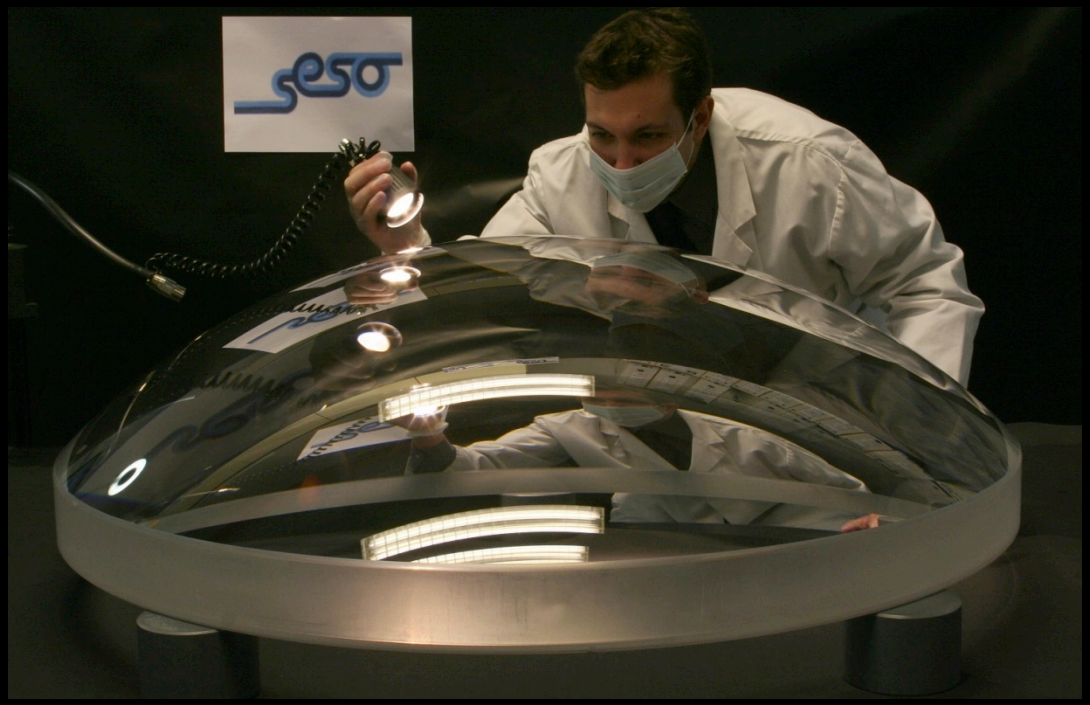
2.2 deg

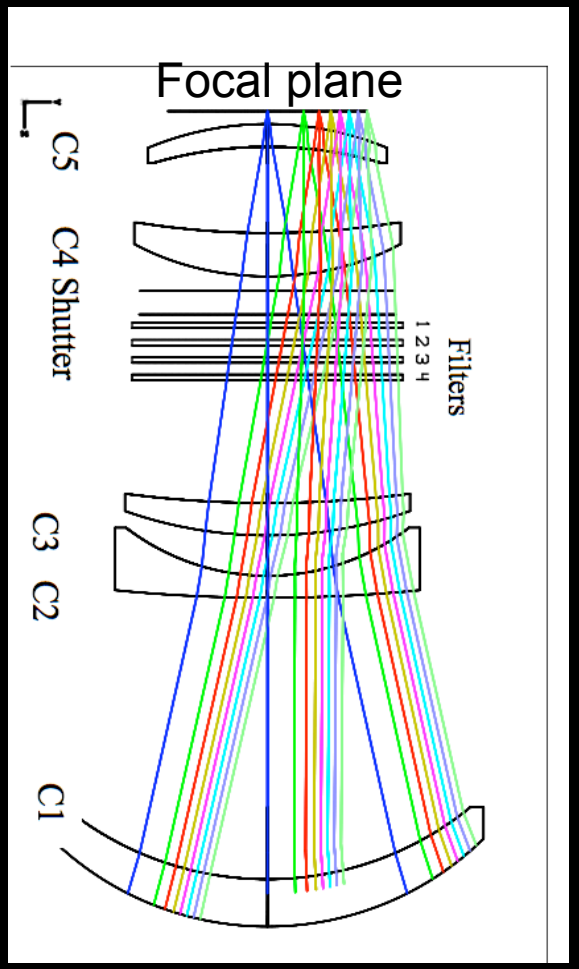


DES filters

Optical Corrector Lenses

- Field of view: 2.2 deg diameter
- Good image quality across FOV
- Optical elements aligned at UCL





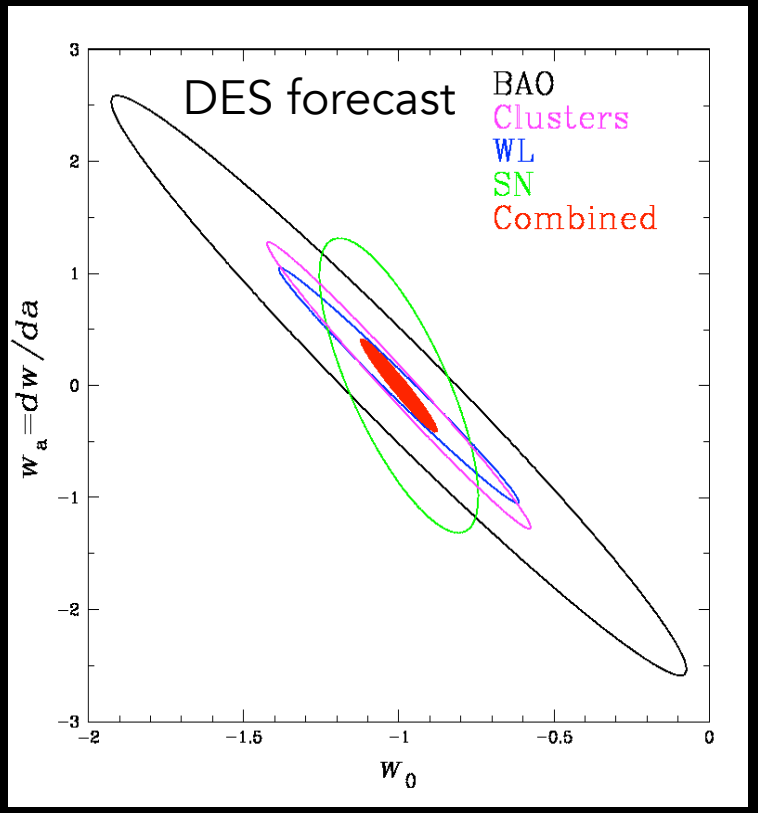
DES Science Performance

Four Probes of Dark Energy:

- Galaxy Clusters
  - Tens of thousands of 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
  - 3500 well-sampled SNe Ia to z ~1

Forecast Constraints on DE Equation of State

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



Focus here on supernovae (expansion history)

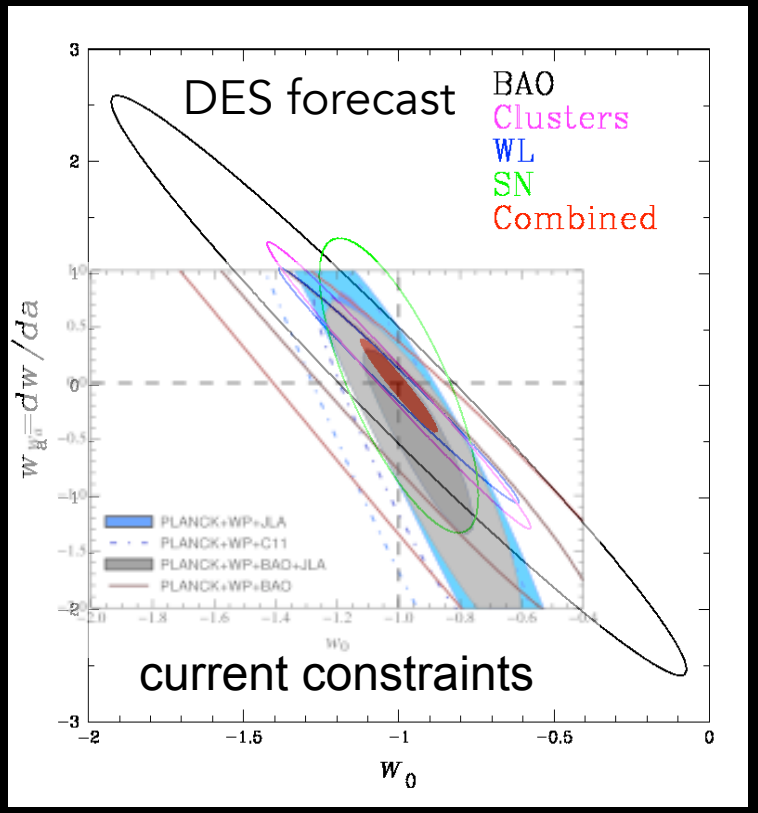
DES Science Performance

Four Probes of Dark Energy:

- Galaxy Clusters
  - Tens of thousands of 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
  - 3500 well-sampled SNe Ia to z ~1

Forecast Constraints on DE Equation of State

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



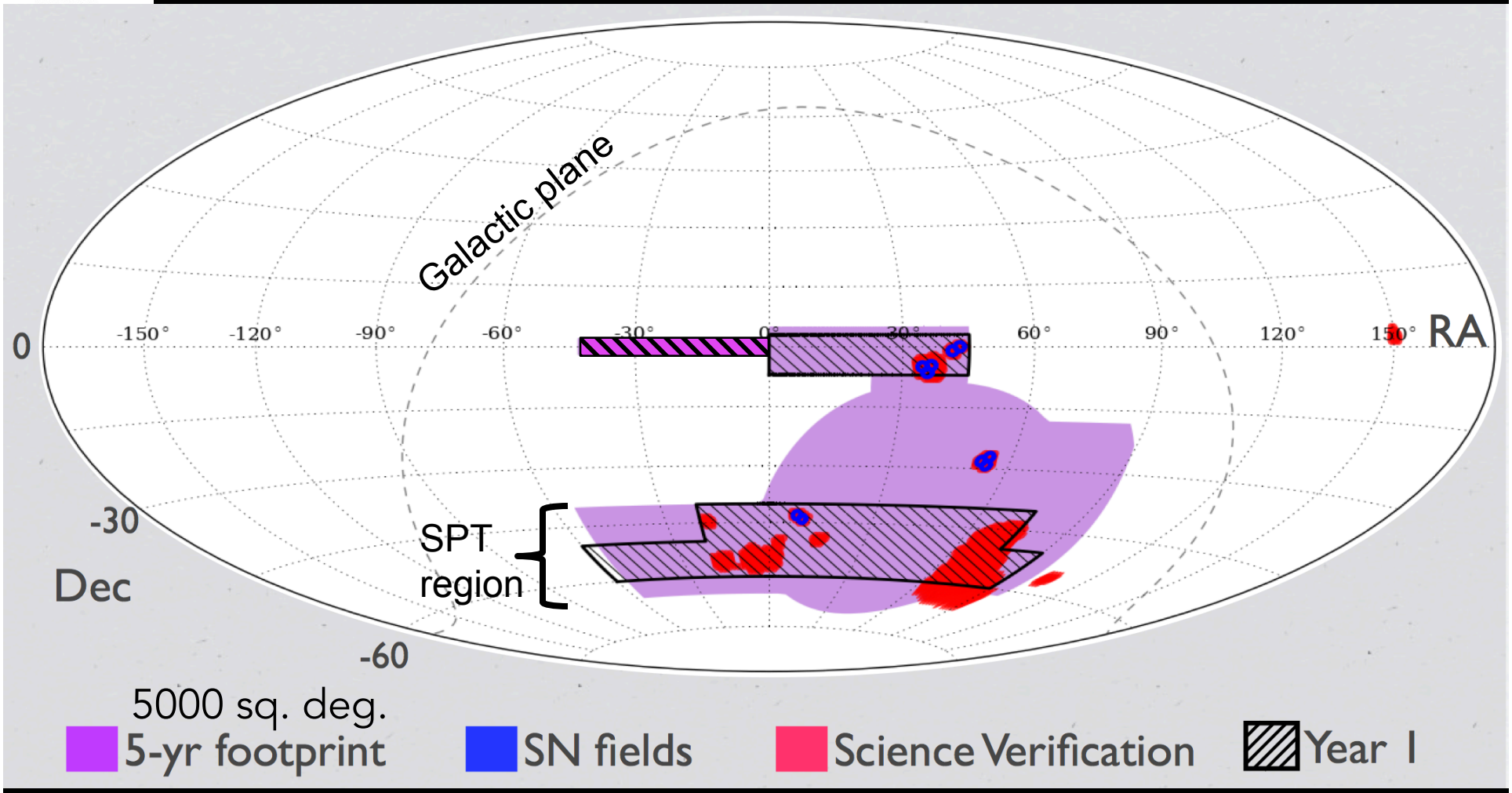
Focus here on supernovae (expansion history)

DES Observing Strategy

- *Wide Survey:* 5000 sq deg
  10x90s in *griz;* 10x45 s in *Y*
- Redder (bluer) bands in bright (dark) time
- Multiple overlapping exposures for photometric calibration ("ubercal")
- *Supernova Survey:* 10 fields
  ~5 day cadence
  (8) shallow: 175/150/200/400s
  (2) deep: 600/1200/1800/3600s
- Wide/SN trigger based on seeing and SN gaps

- Overlap with SPT, OzDES, VHS, SDSS, eBOSS, ACT, …
- Footprint overhead Aug – Feb
- DES members do all observing

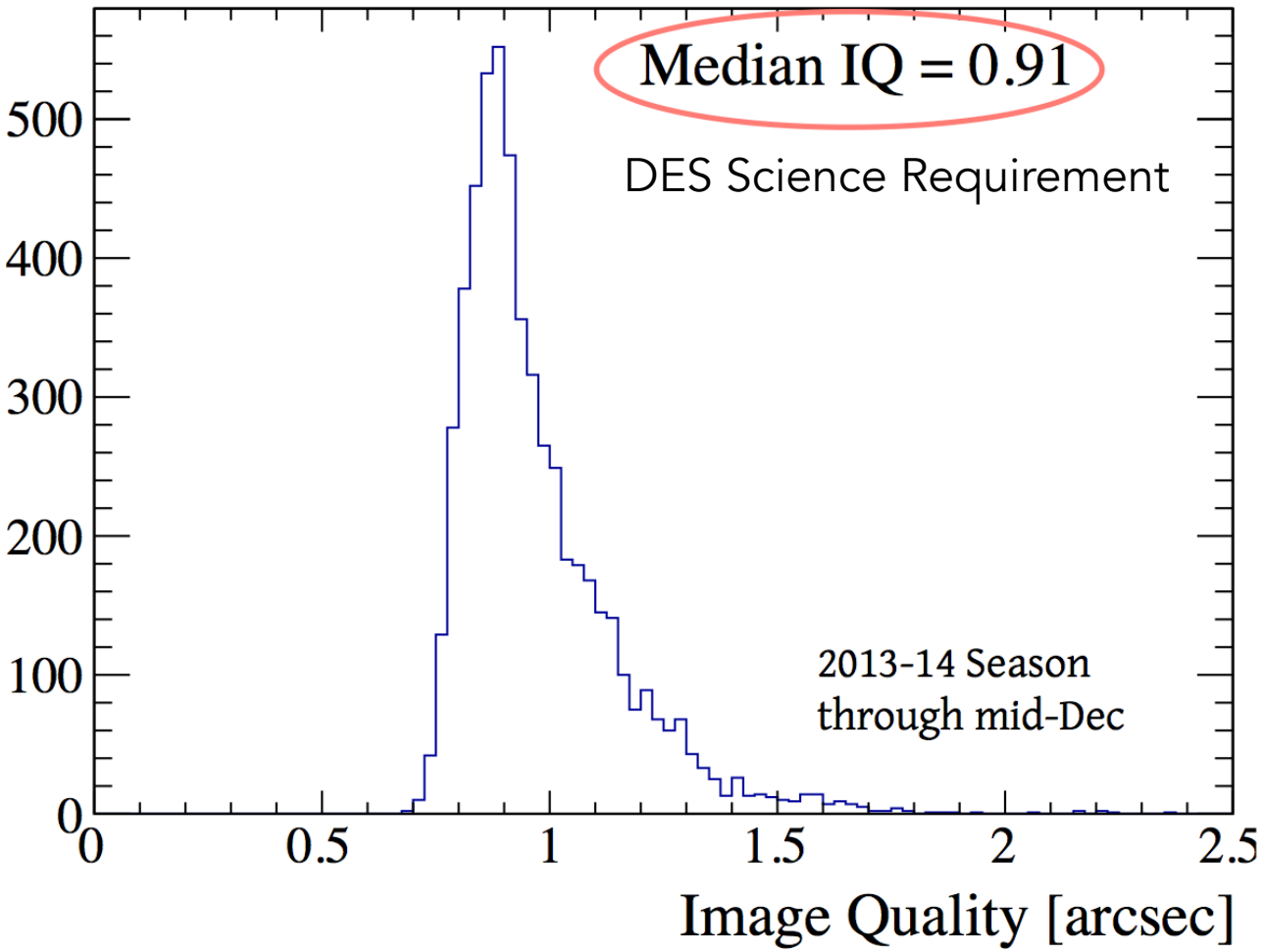
DES Survey Footprint



- Science Verification (SV): ~250 sq. deg. to ~full depth; 45 M objects
- Year 1 (Y1): ~2000 sq. deg; overlap SPT, SDSS: 4/10 tilings; 140 M objects

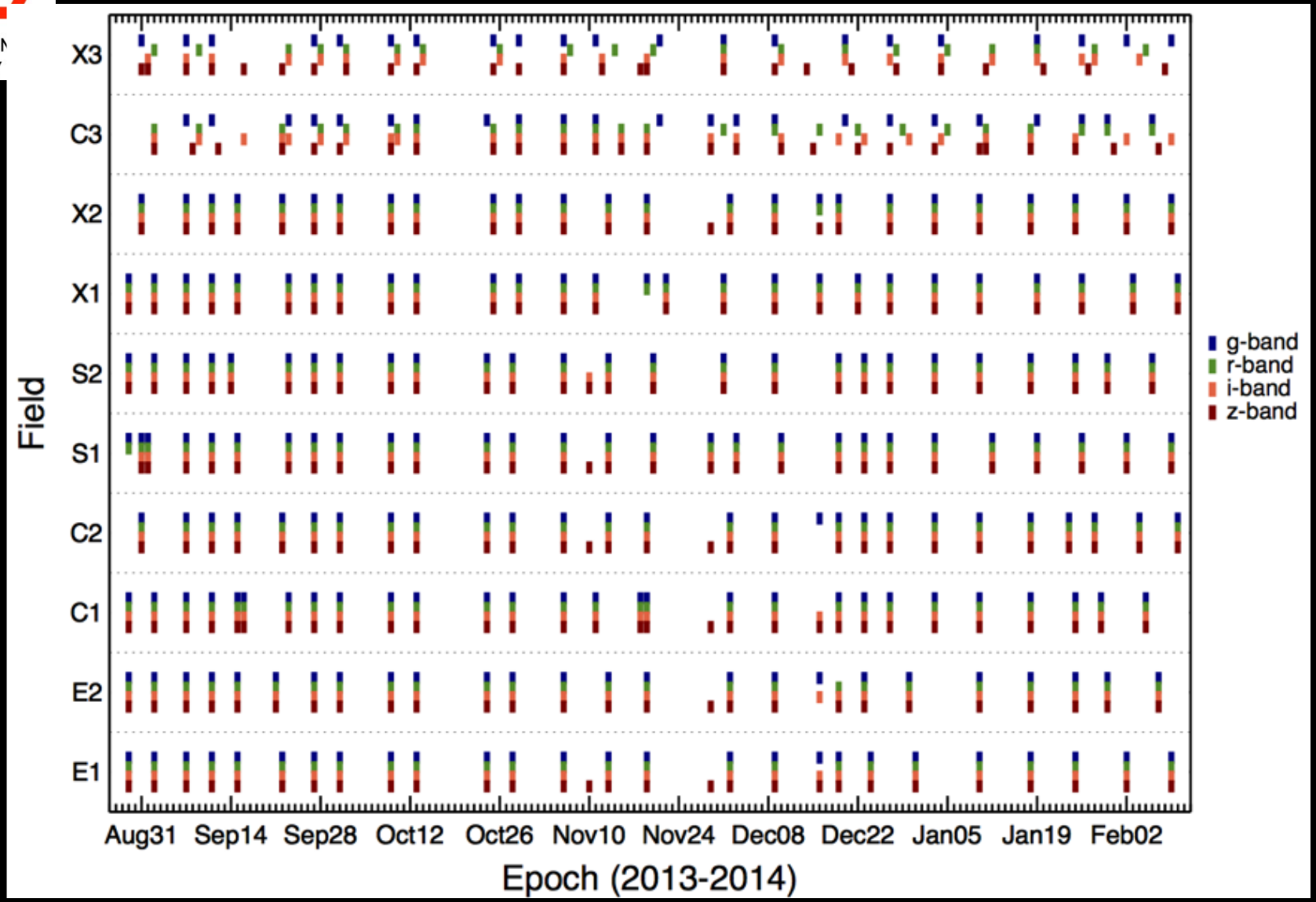
DES Delivered Image Quality

PSF FWHM for r,i,z band wide field images



DARK EN
SURVEY

DES Y1

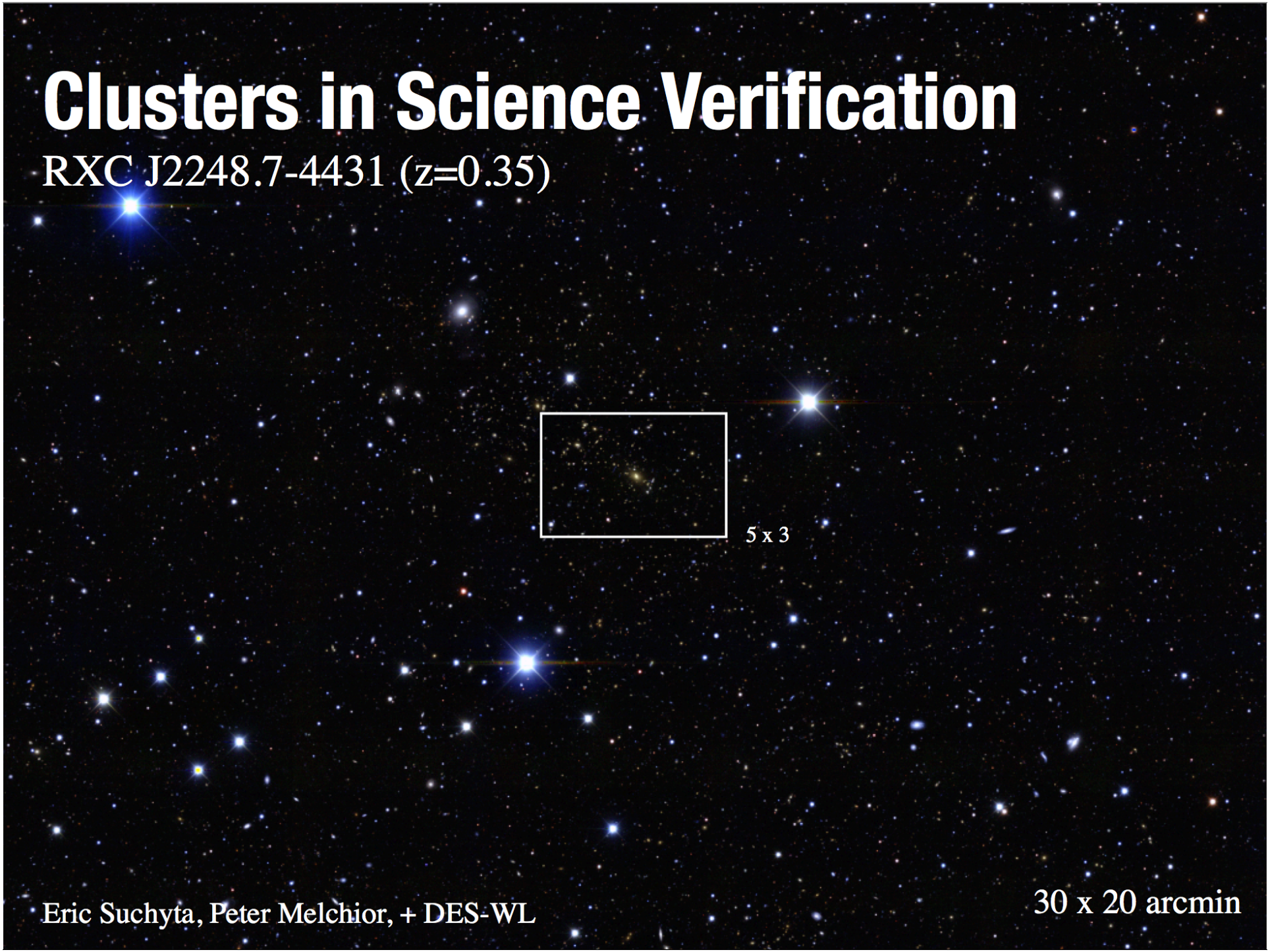


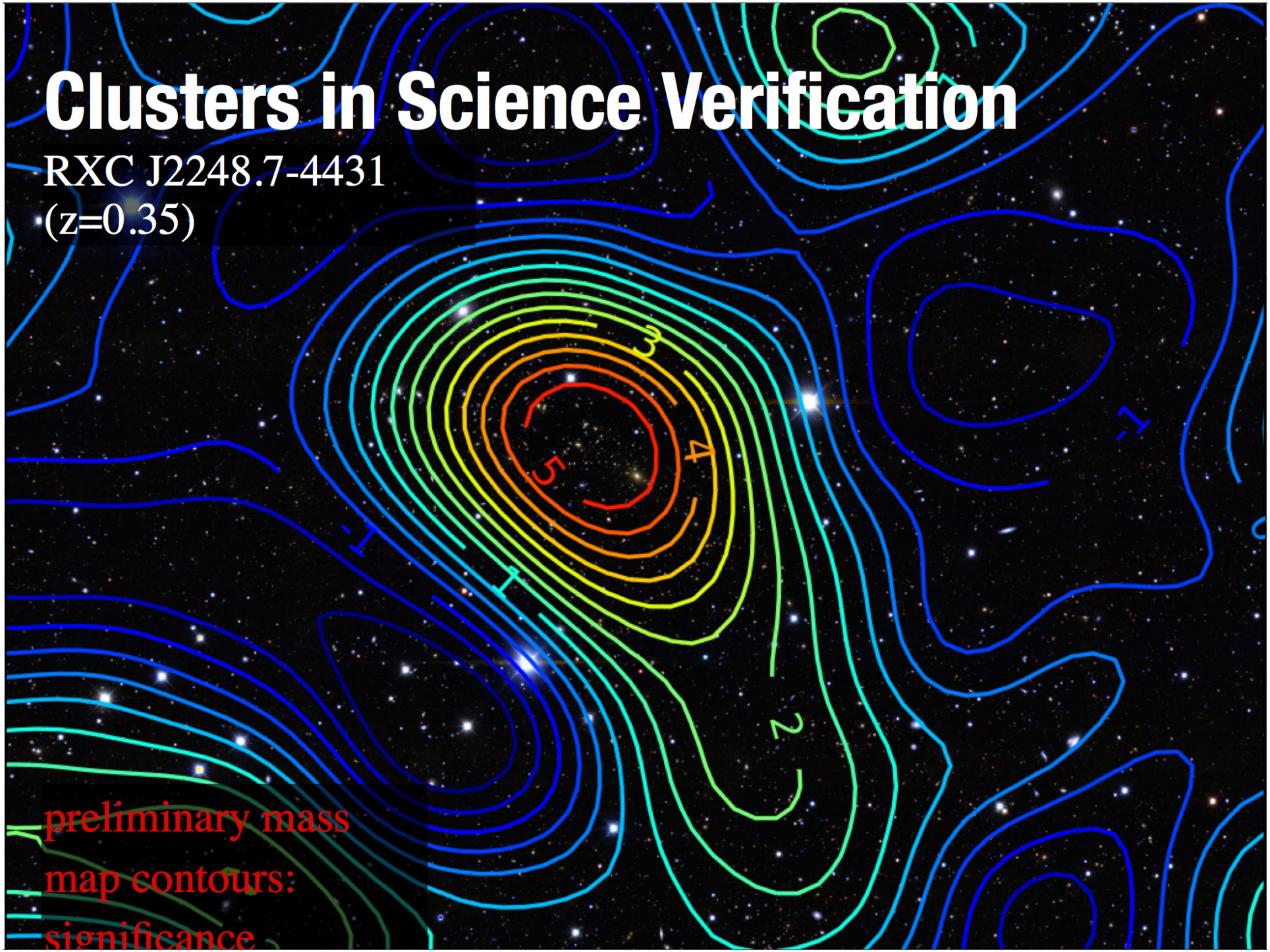
~6 day average cadence

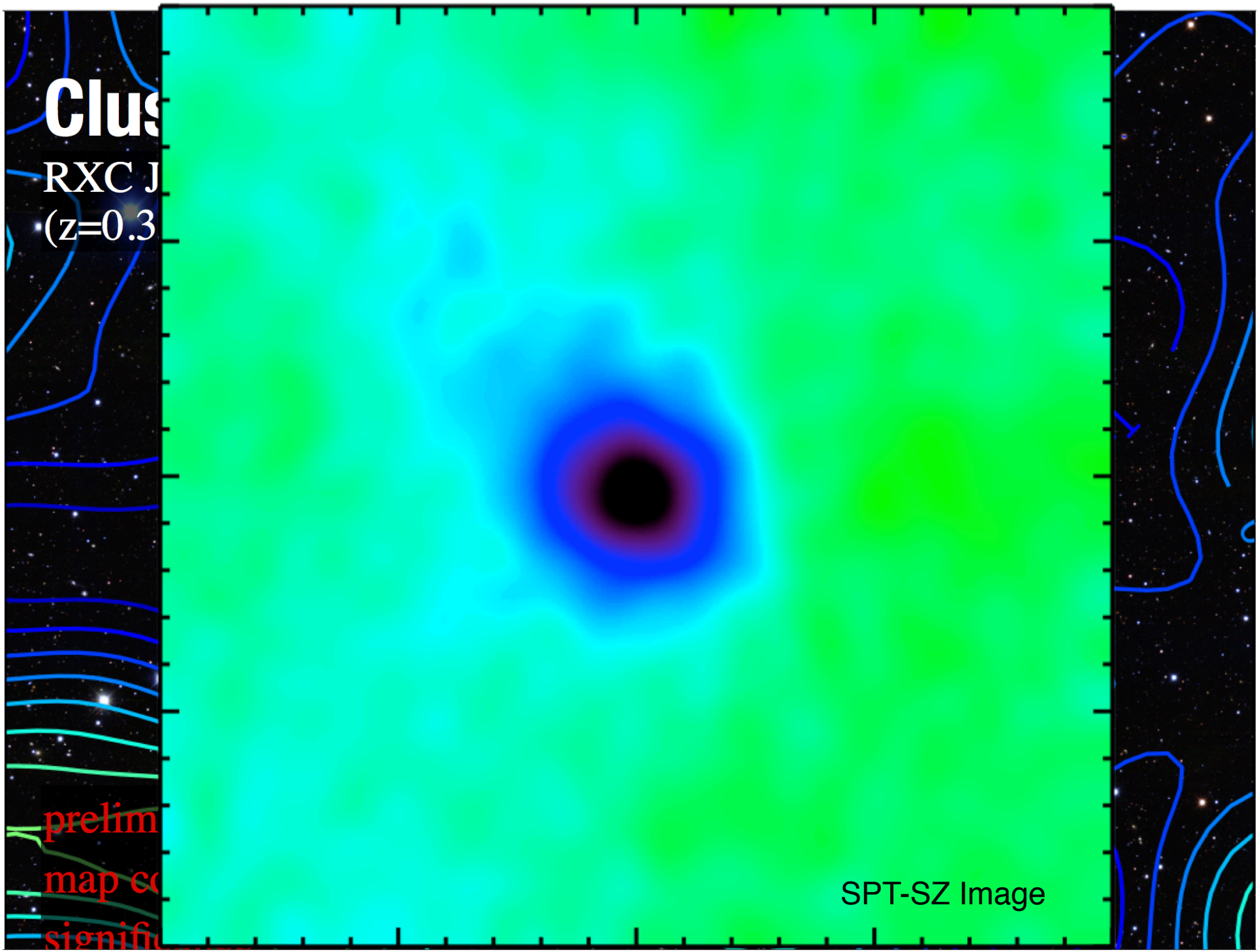
All DES results in this talk are (mostly)

PRELIMINARY


Clusters in Science Verification
RXC J2248.7-4431 (z=0.35)
Eric Suchyta, Peter Melchior, + DES-WL
5 x 3

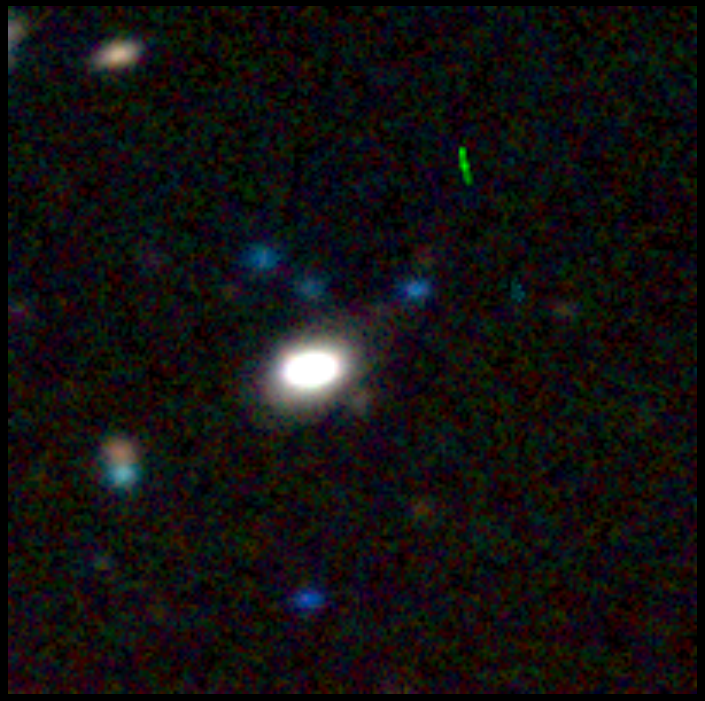

Clusters in Science Verification
RXC J2248.7-4431 (z=0.35)
5 x 3
Eric Suchyta, Peter Melchior, + DES-WL
30 x 20 arcmin


Clusters in Science Verification
RXC J2248.7-4431
(z=0.35)
3
4
5
-1
-1
2
preliminary mass
map contours:
significance

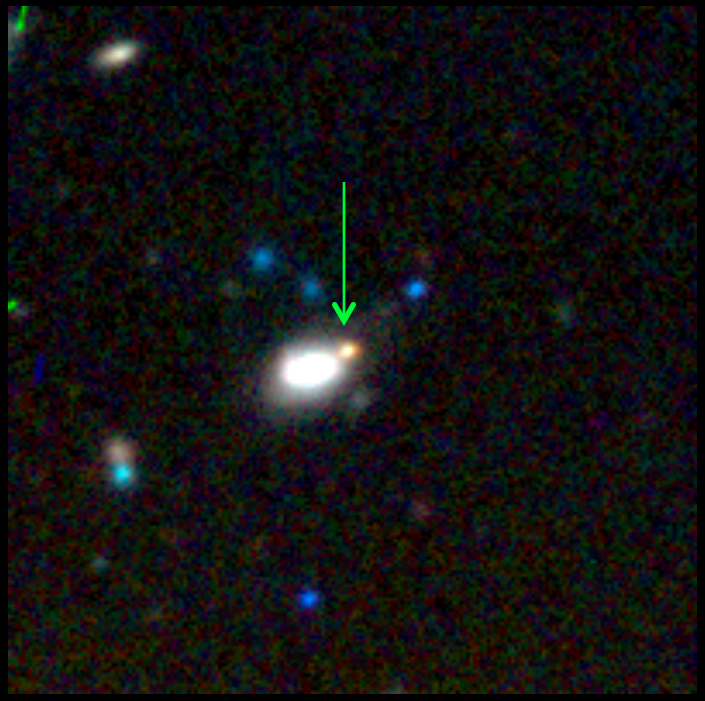

Clus
RXC J
(z=0.3
prelim
map c
signifi
SPT-SZ Image

DARK ENERGY SURVEY

SUPERNOVAE

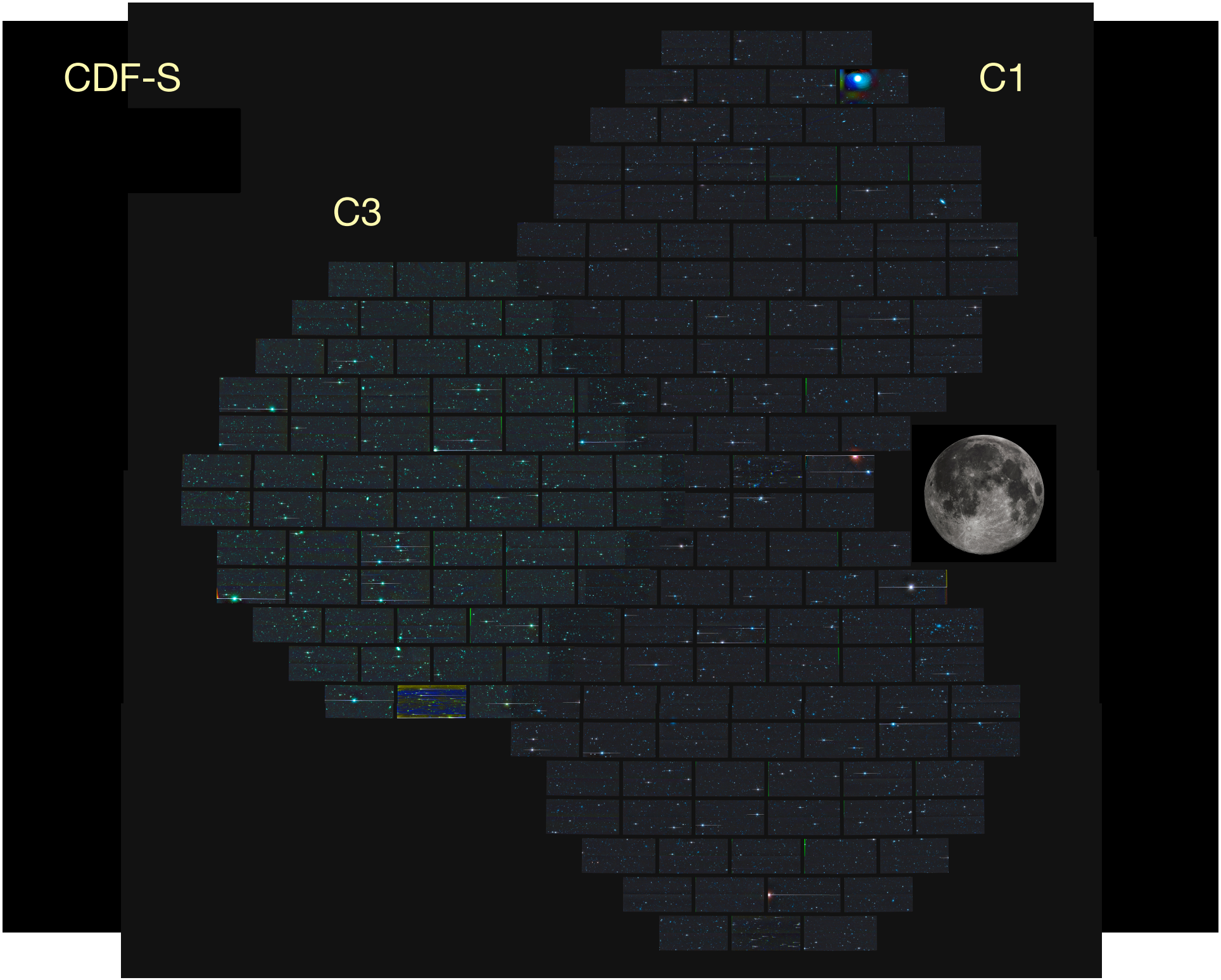


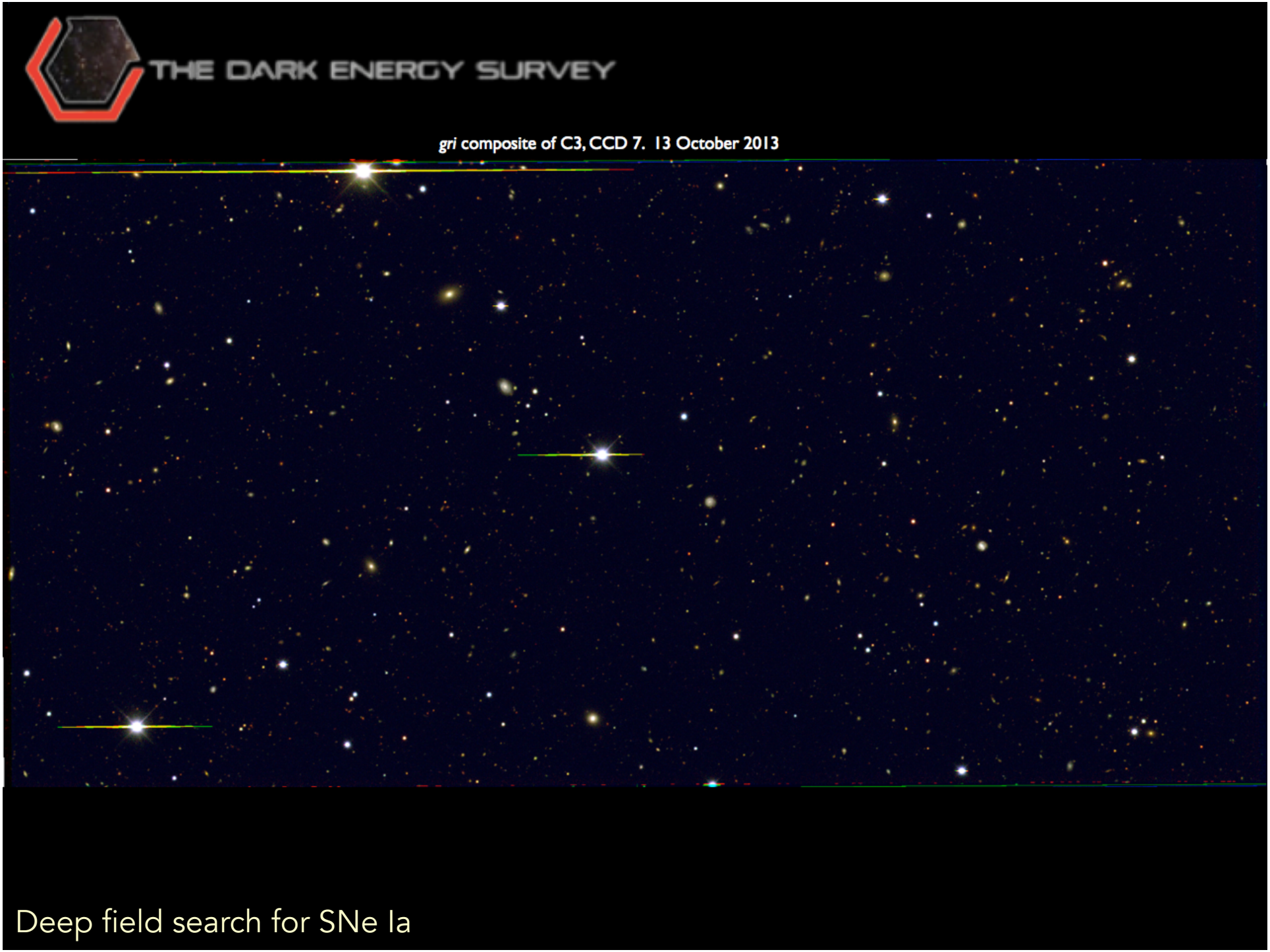
Nov. 7, 2012



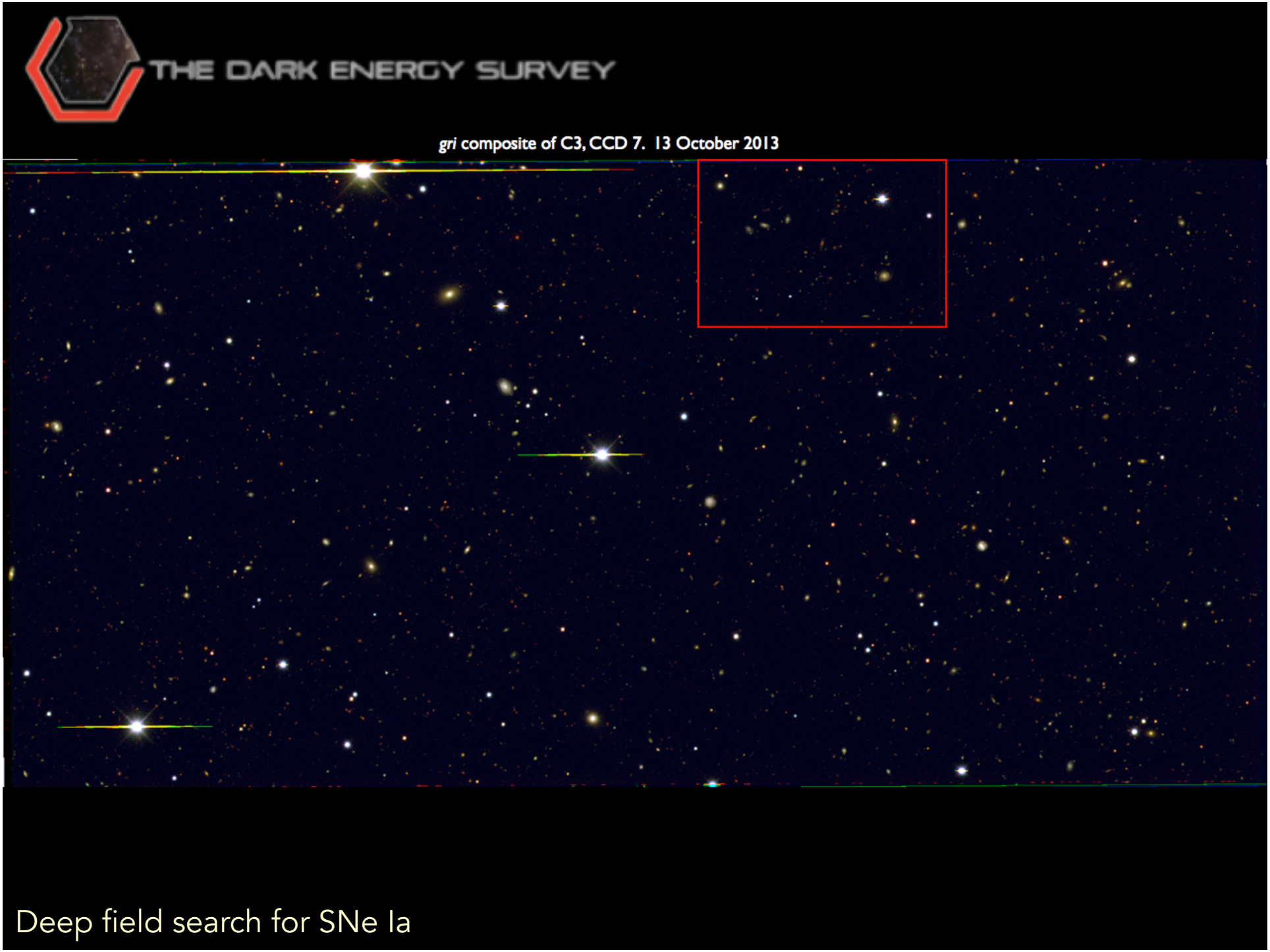
Dec. 15, 2012

SN Ia at z=0.2 confirmed at AAO

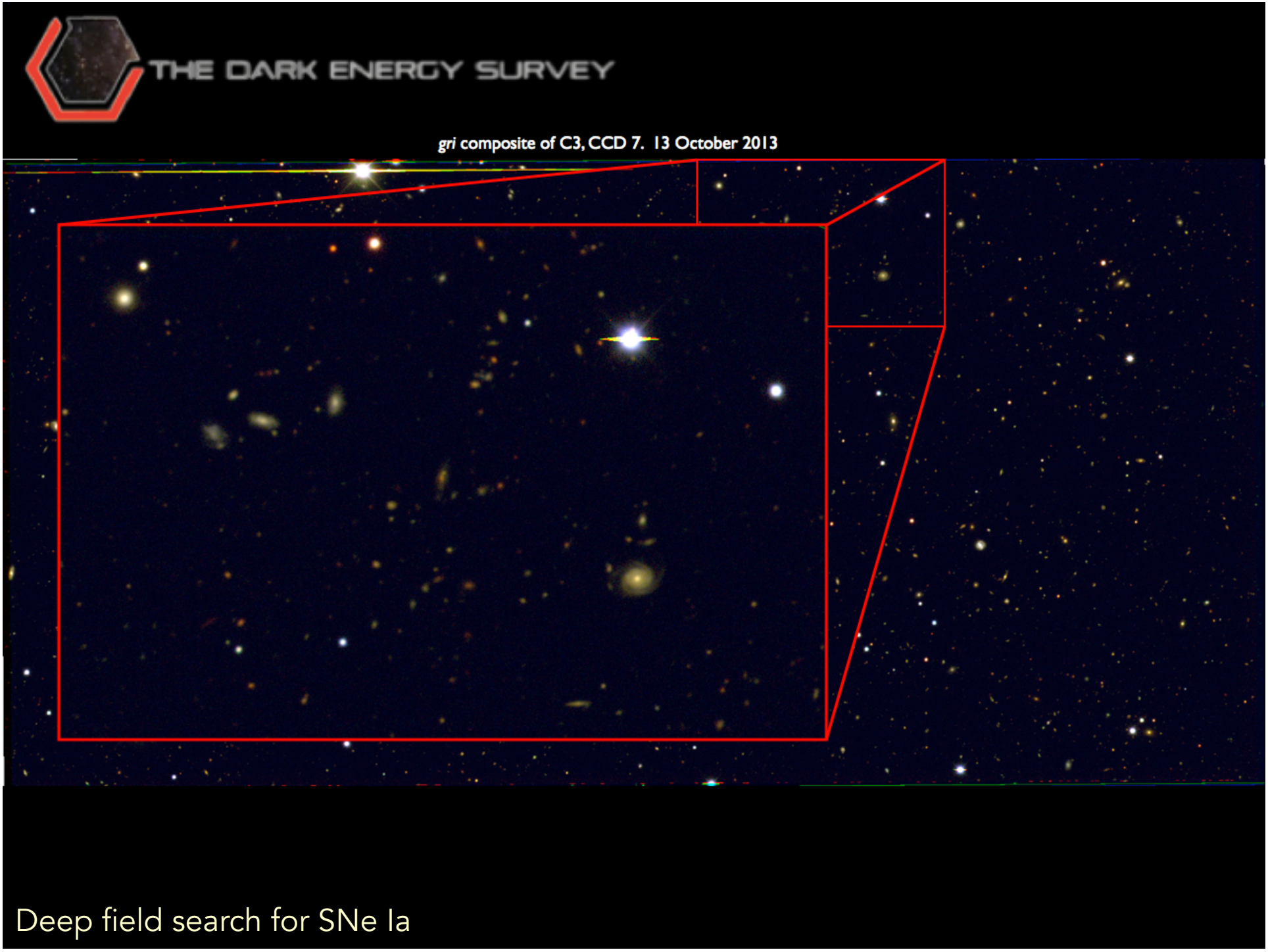

CDF-S
C1
C3



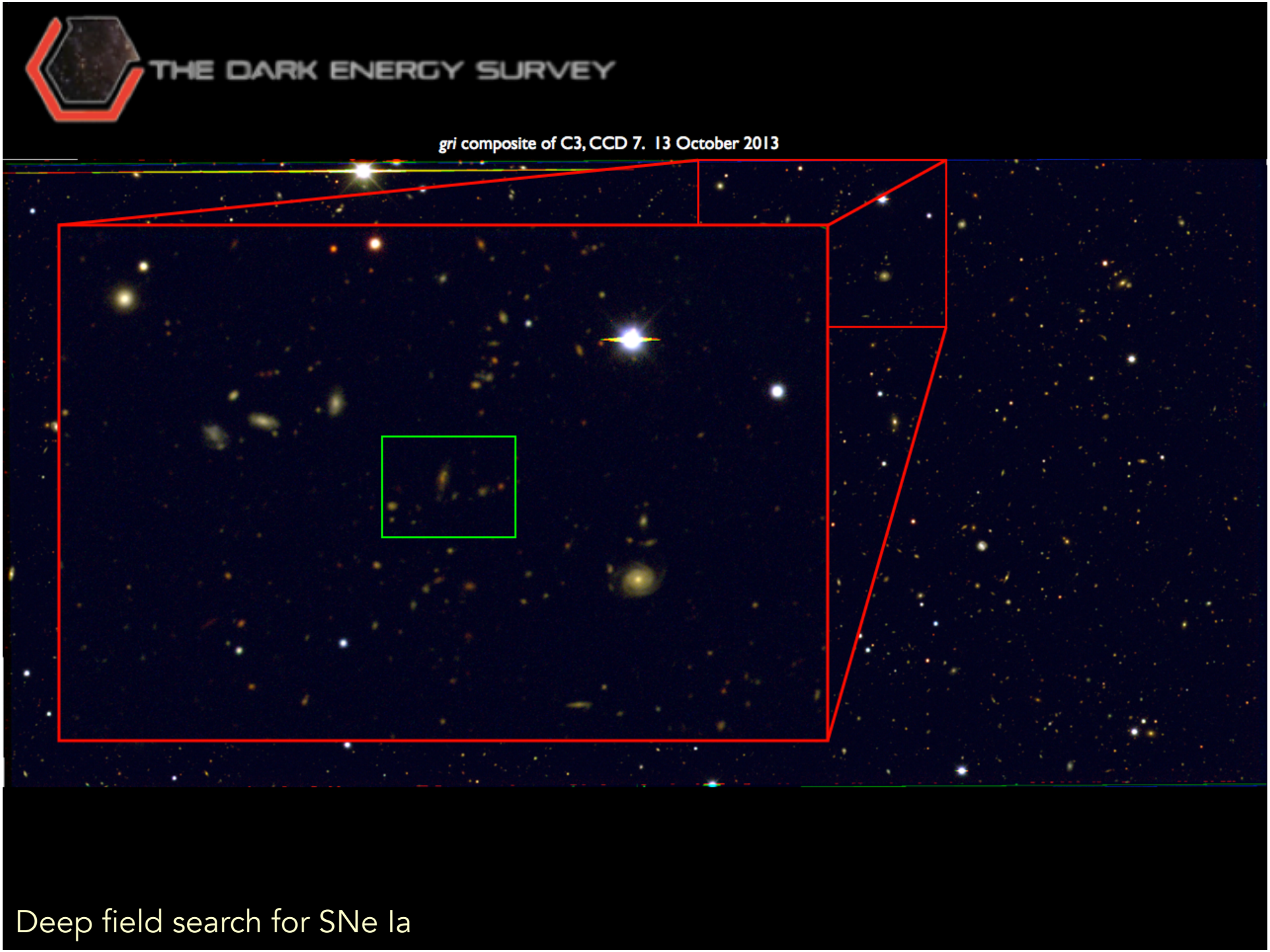
Deep field search for SNe Ia



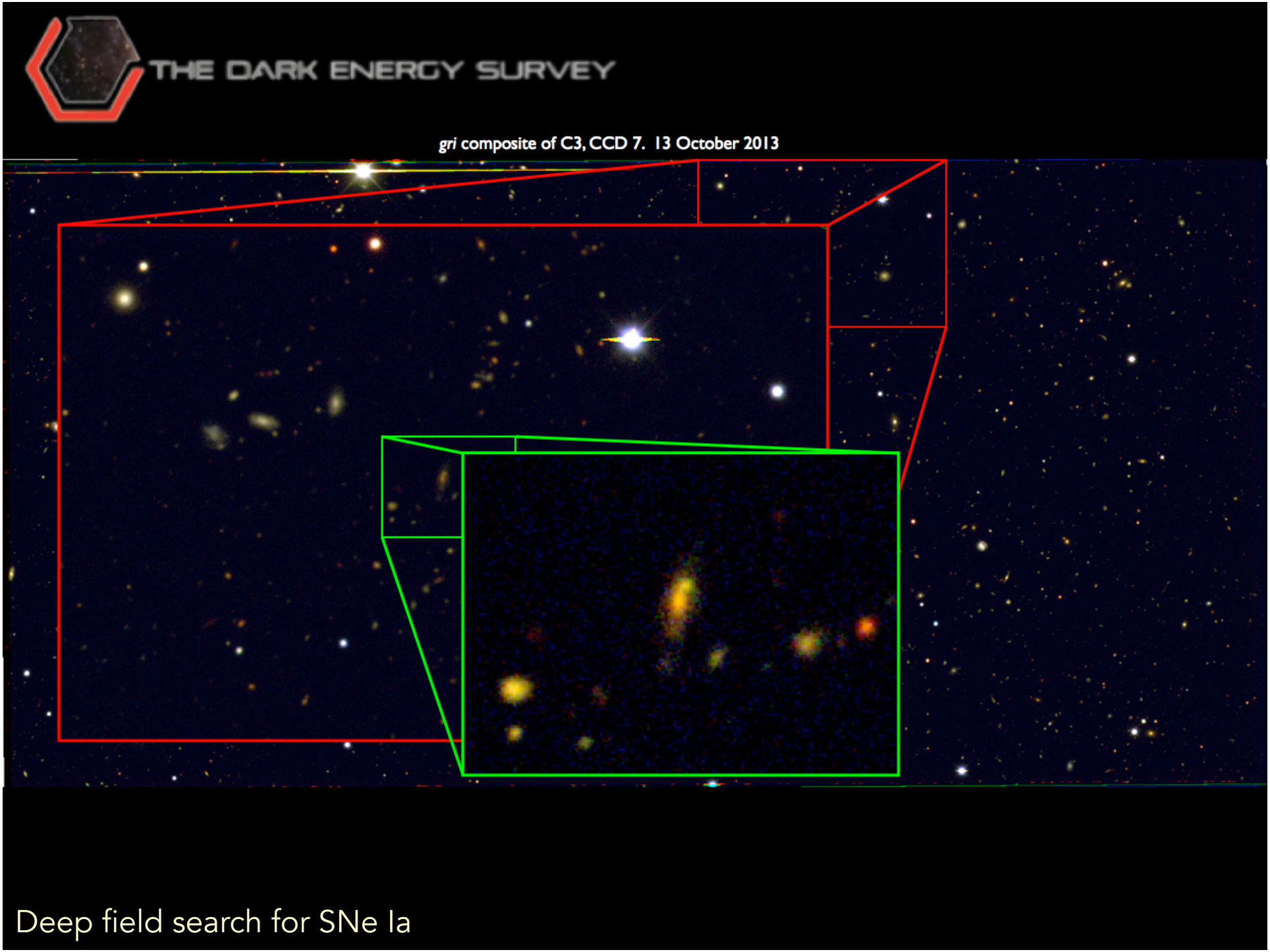
Deep field search for SNe Ia



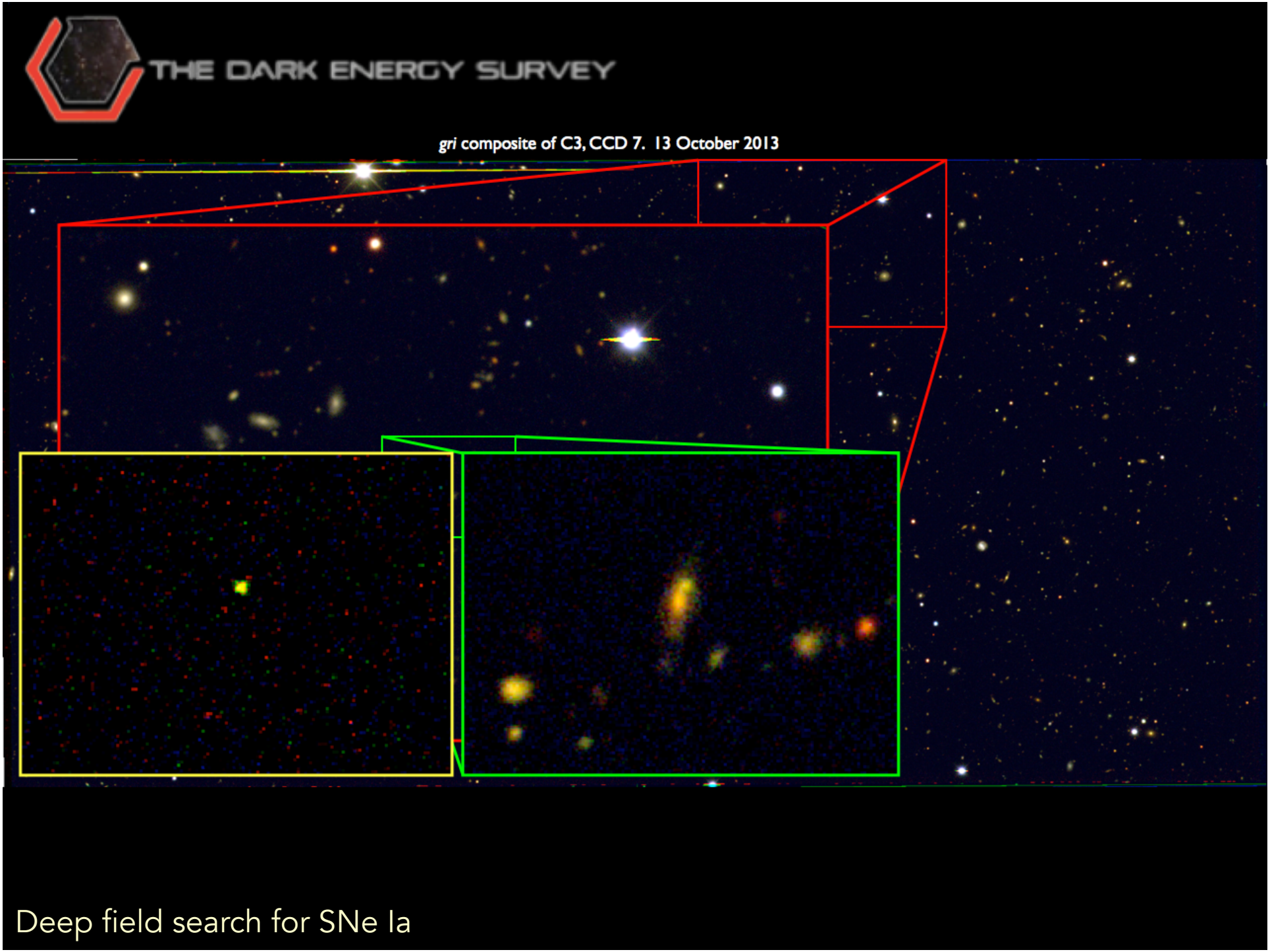
Deep field search for SNe Ia



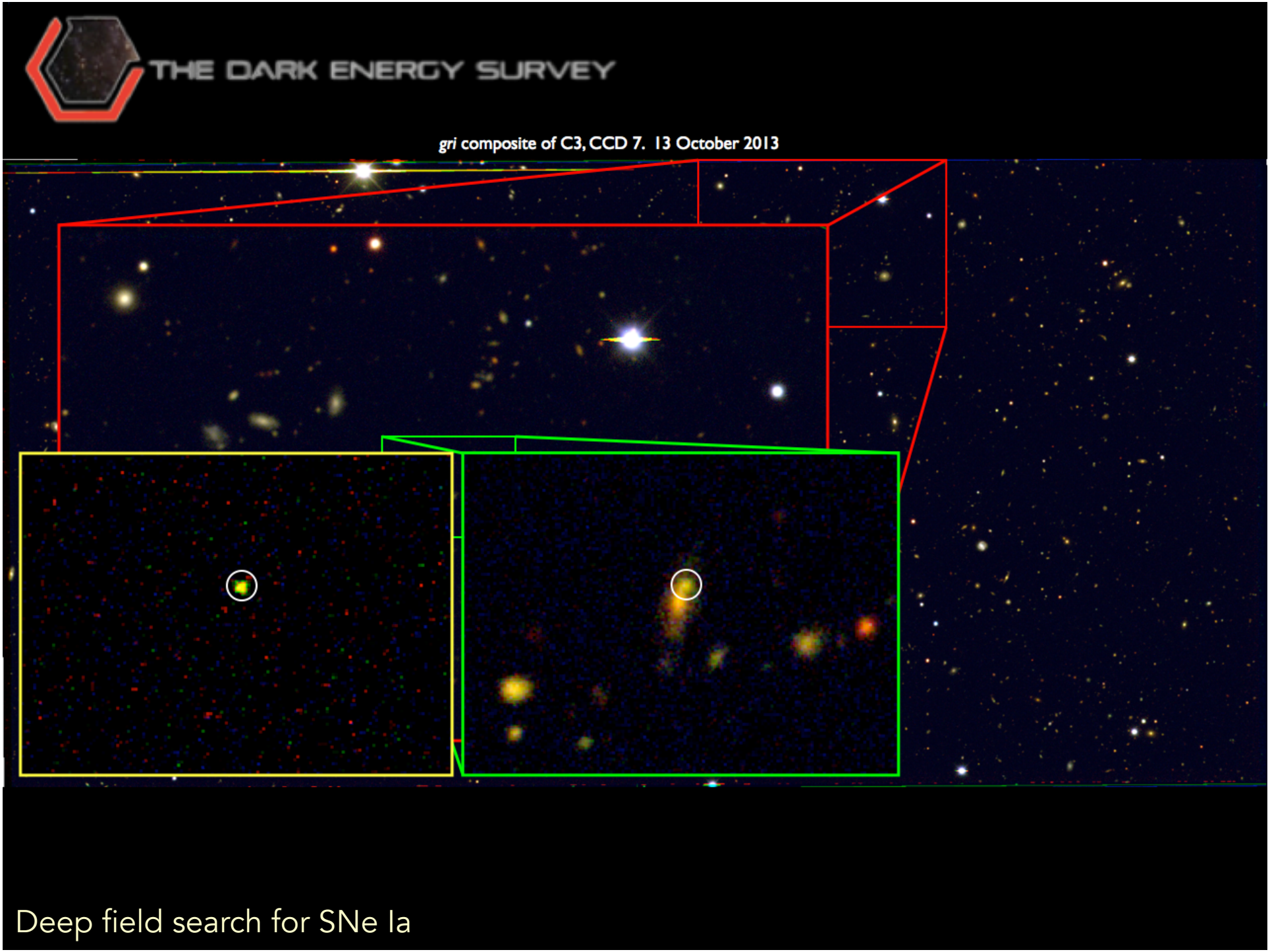
Deep field search for SNe Ia



Deep field search for SNe Ia



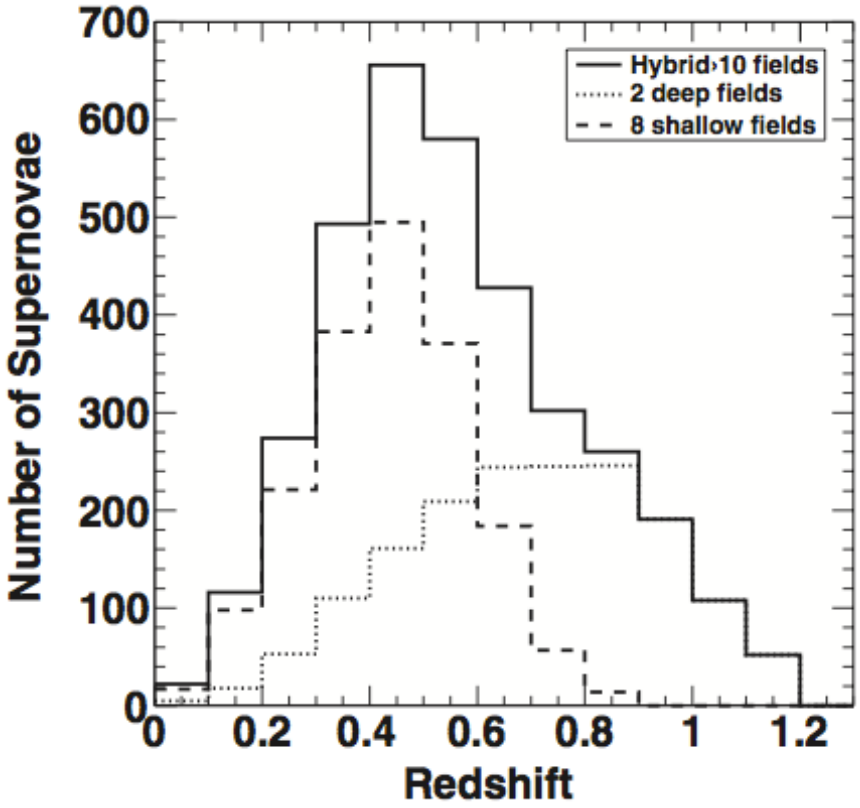
Deep field search for SNe Ia



Deep field search for SNe Ia

DES Supernova Survey

Filter	Shallow Field Exposure Time (s)	Shallow Field Limiting Mag	Deep Field Exposure Time (s)	Deep Field Limiting Mag
g	175	24.9	600	25.6
r	150	24.3	1200	25.4
i	200	23.9	1800	25.1
z	400	23.8	3630	24.8



Pathway to Cosmology

FoM=120

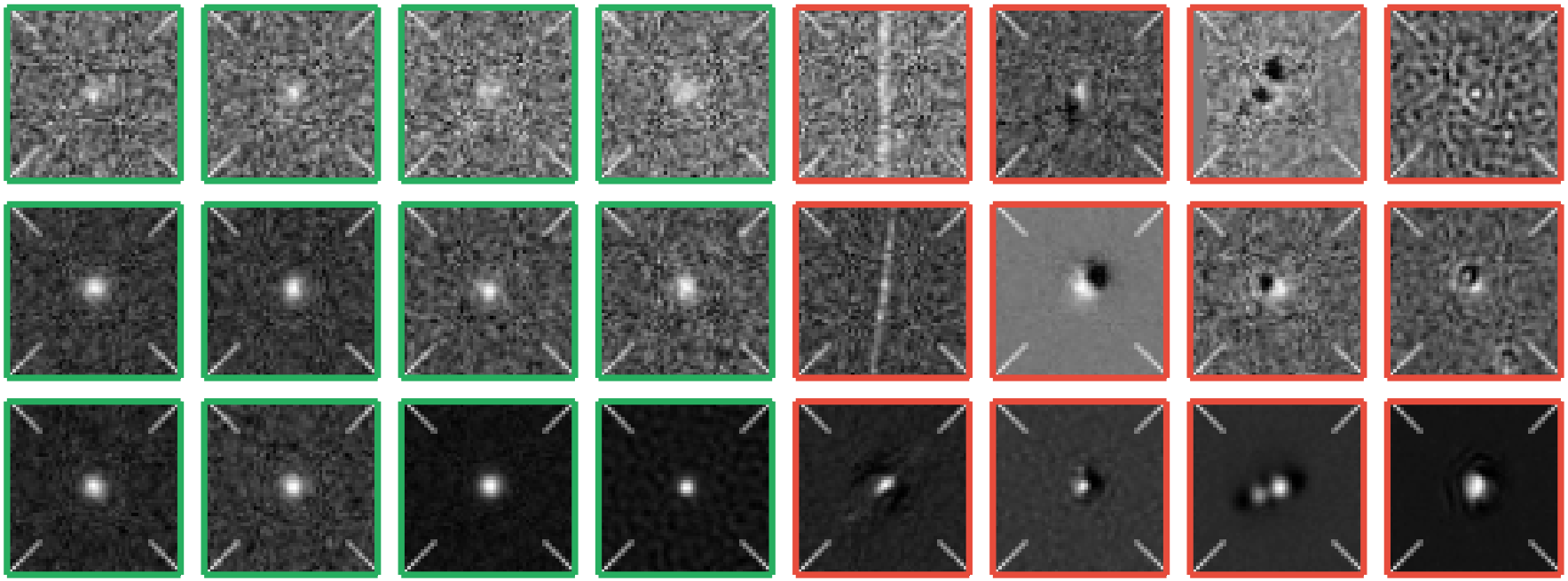
- SN-like transients
- Classification
- Photometry (not today)

"Supernova Simulations and Strategies For the Dark Energy Survey"

Bernstein et al., 2012, ApJ, 753, 152

Goldstein et al.

Real or Artifact?

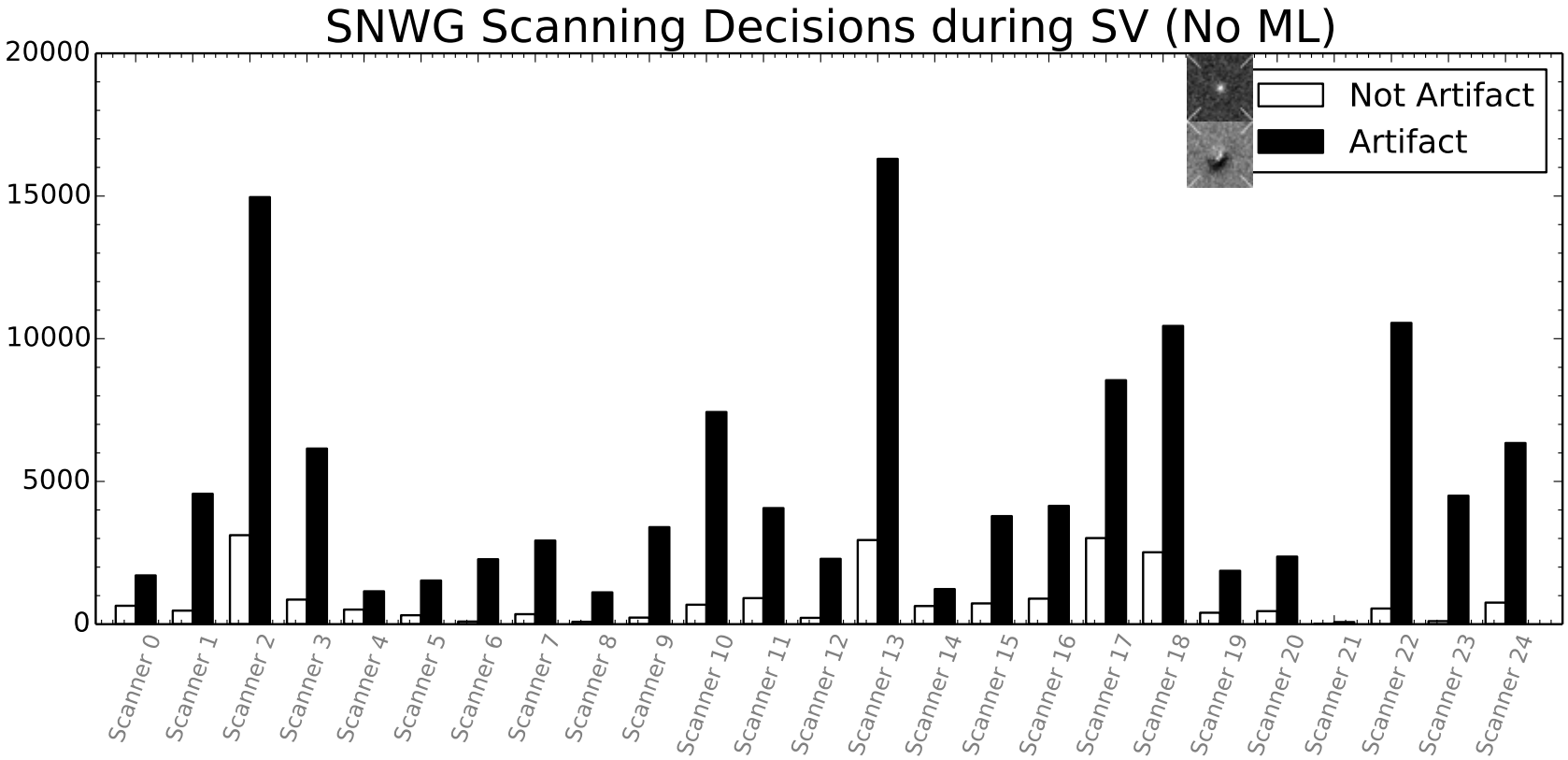


Consistently approximate a PSF

Dipoles, Streaks, Ripples, Holes…

Goldstein et al.

Quantifying the Scanning Load

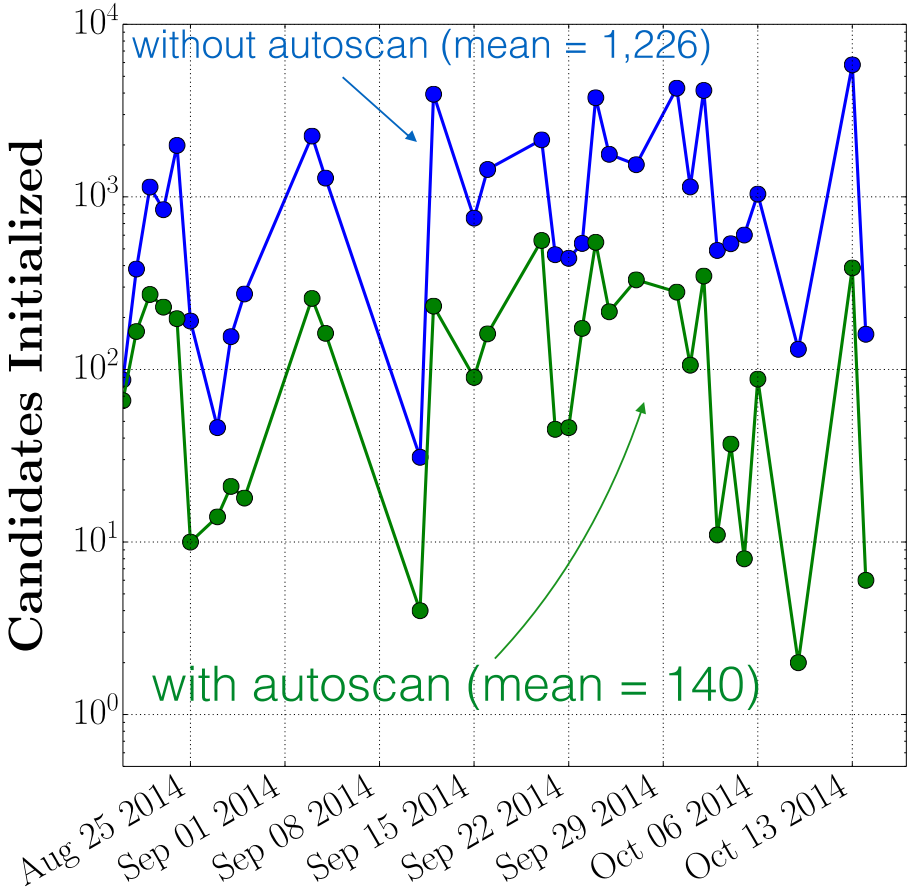


Data rate: ~1.5 x 10^3 new scannable candidates / night, after requiring two detections.

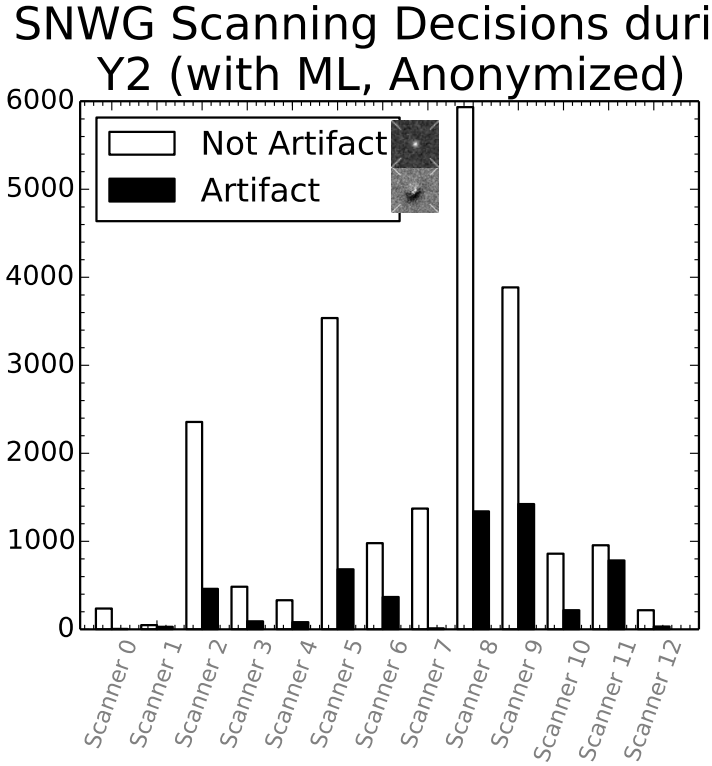
False positives: ~85% of scanned detections are artifacts.

Goldstein et al.

Y2 with autoScan



8.2x fewer new candidates created / night with ML.

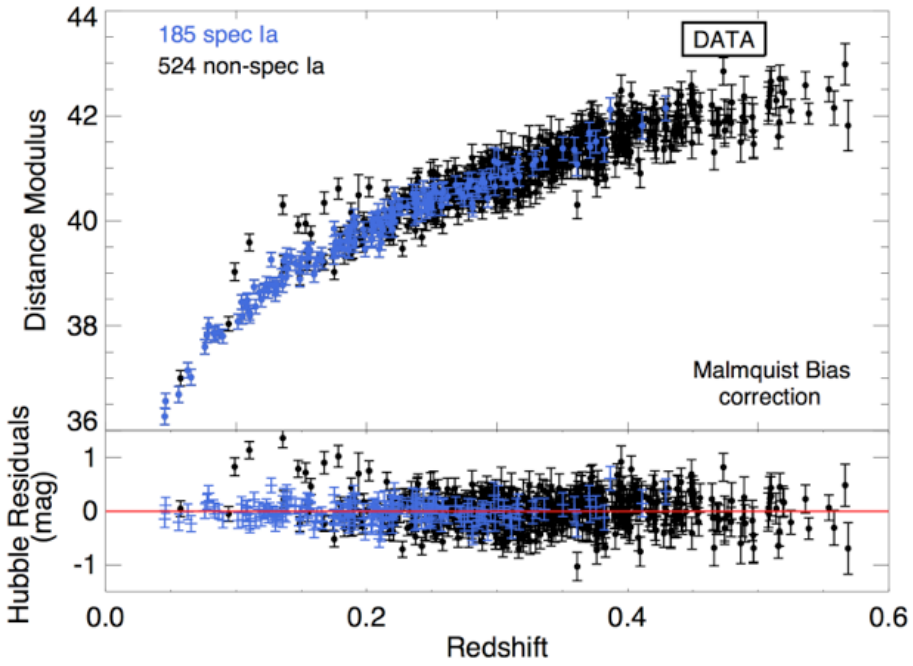


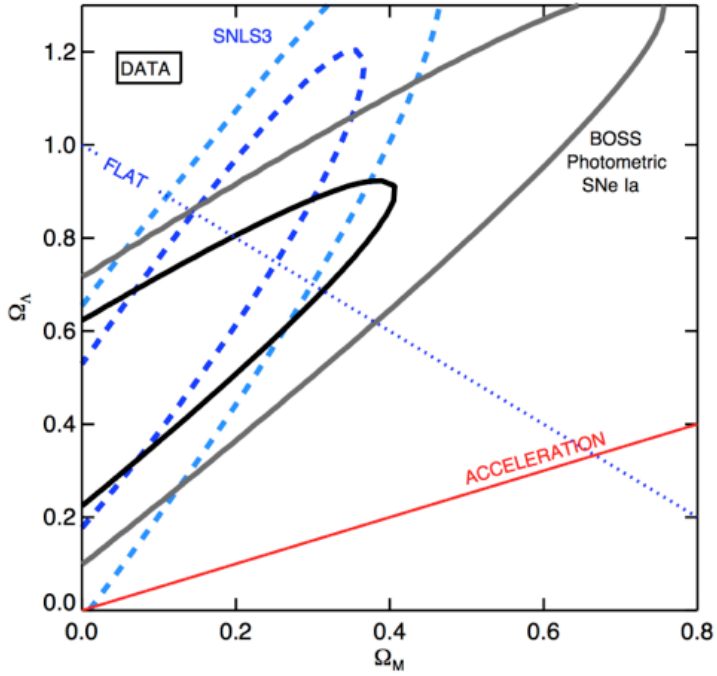
Detection-level purity up by ~25x.

Number of scanners down by factor of 2 from SV in comparable period.

Photometric Classification

Sloan Digital Sky Survey - Supernova II





Campbell et al. (2013)

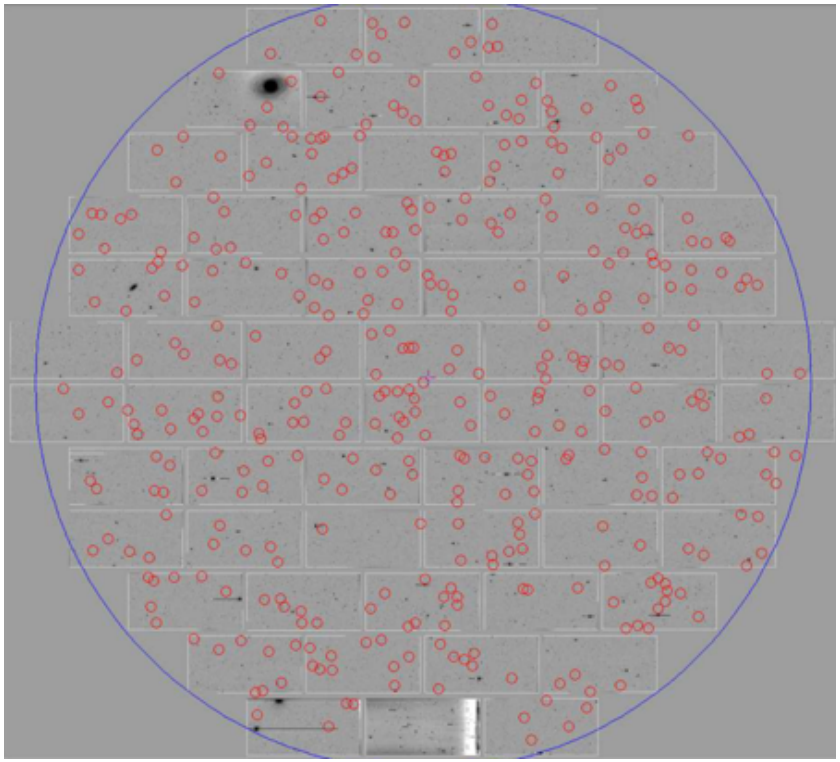
Photometric Classification

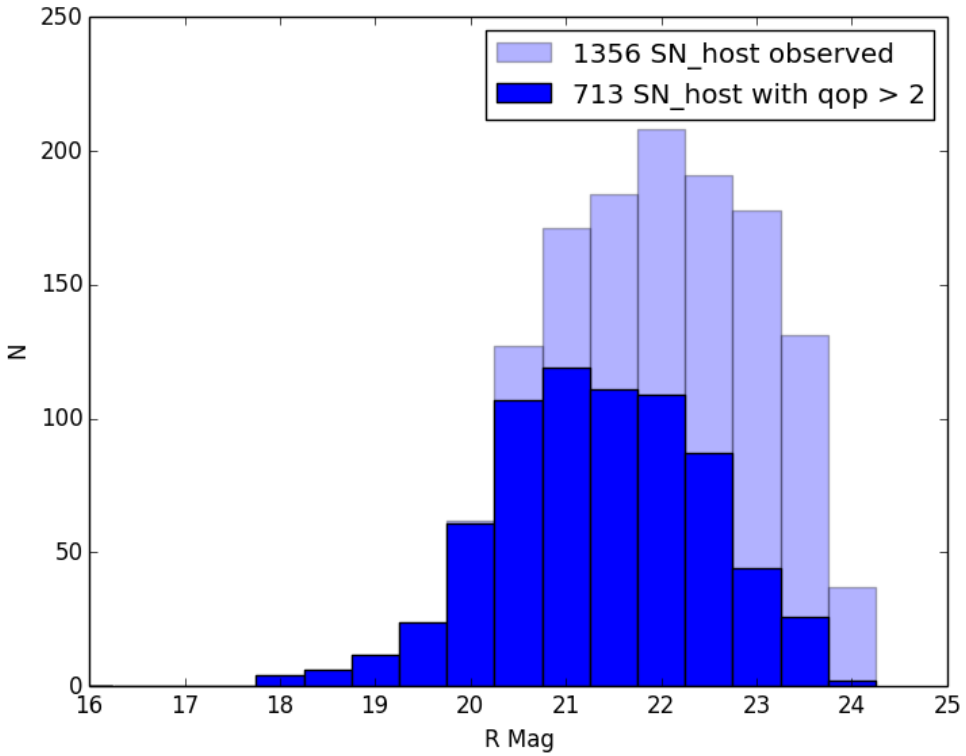
Too many, too faint for spectroscopic followup

Problems: Purity; loss of spectral information

Benefits: Numbers; selection biases

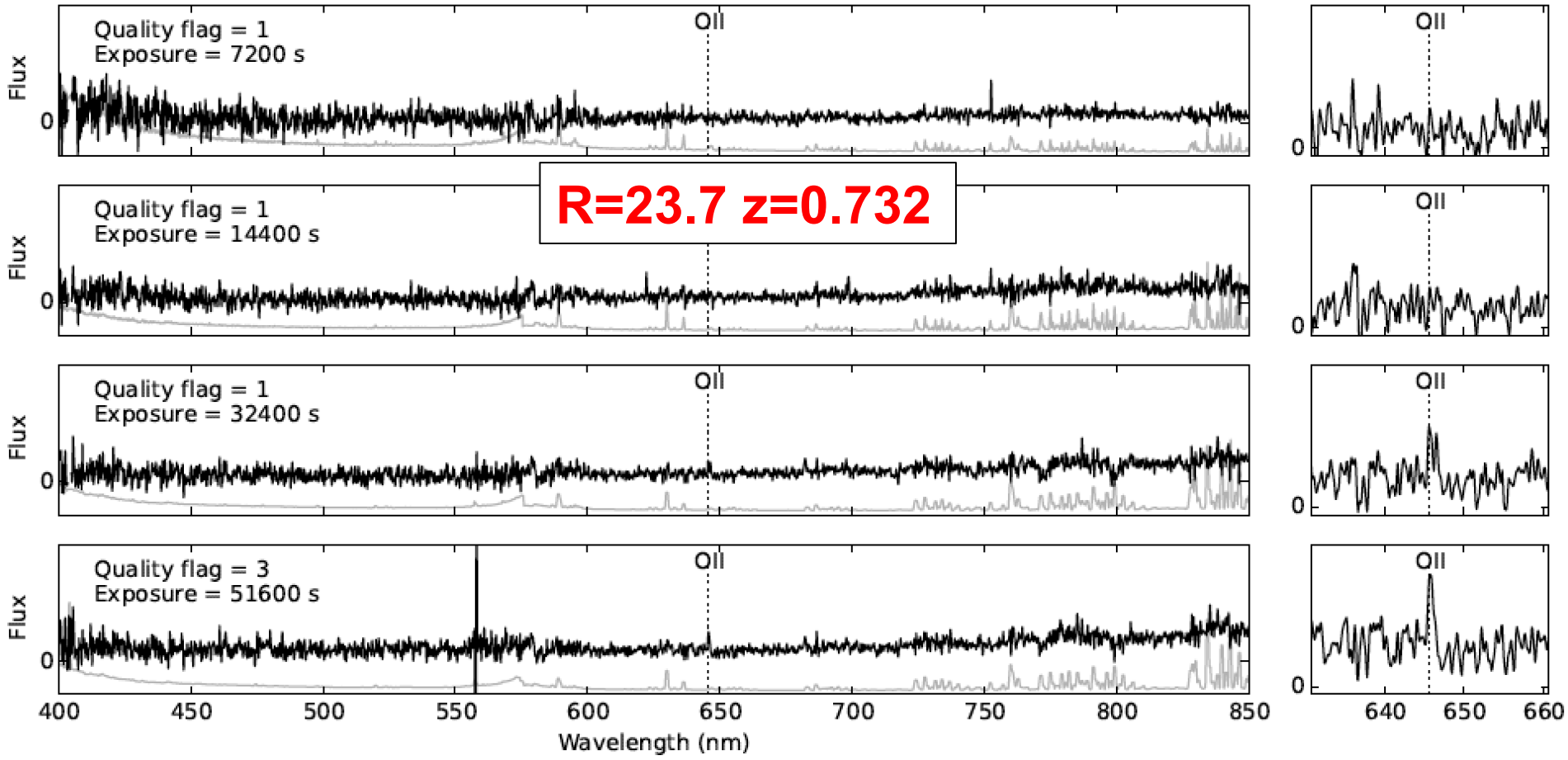
- AAOmega/2dF on AAT: perfect overlap with DECam FoV
- SN Host Galaxies targeted repeatedly to build depth
- Fibers placed on live SNe (r < 21)
- **100 nights over 5 years**



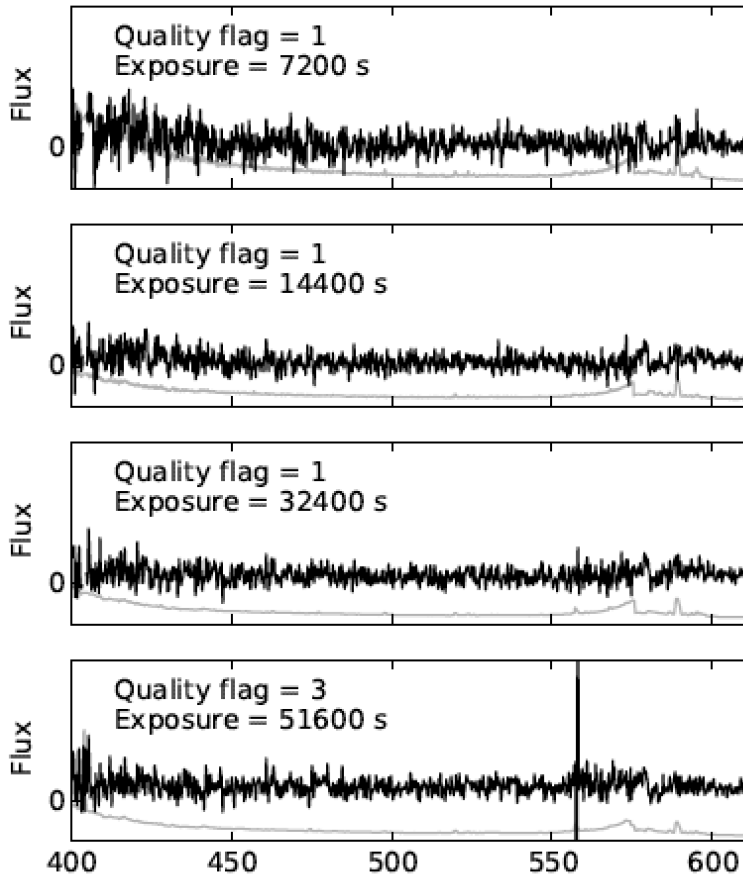


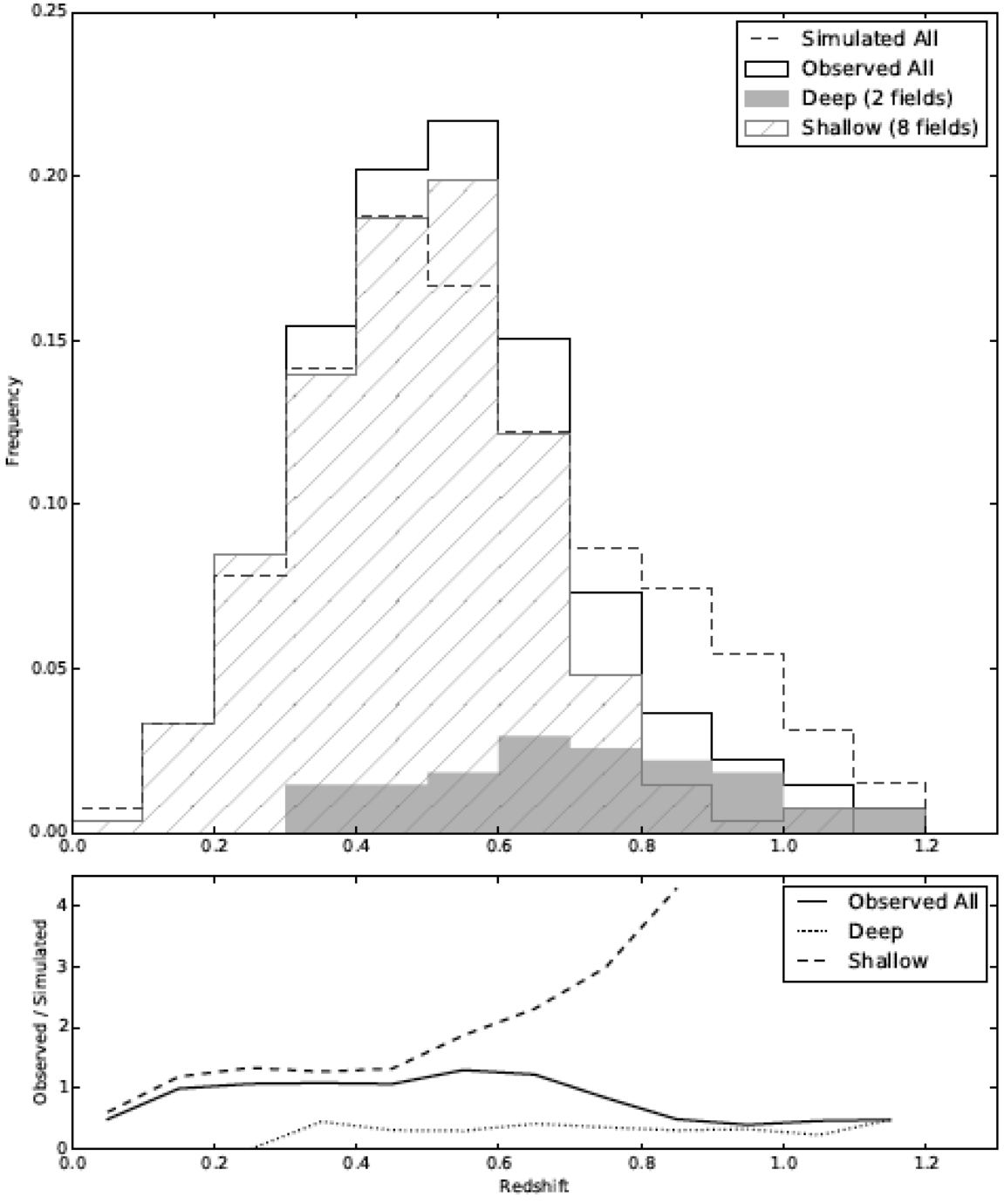
DES SV + Y1: fitprob_ia > 0.0001, p_bayes_ia > 0.9

- AAOmega/2dF on AAT: perfect overlap with DECam FoV
- SN Host Galaxies targeted repeatedly to build depth
- Fibers placed on live SNe (r < 21)
- **100 nights over 5 years**




zDES


Quality flag = 1
Exposure = 7200 s
Quality flag = 1
Exposure = 14400 s
Quality flag = 1
Exposure = 32400 s
Quality flag = 3
Exposure = 51600 s
Flux
0
400
450
500
550
600
Wavelength (nm)


Simulated All
Observed All
Deep (2 fields)
Shallow (8 fields)
Frequency
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Observed All
Deep
Shallow
Observed / Simulated
0
1
2
3
4
Redshift

The goal is to select targets for spectroscopic follow-up observations such that the final spectroscopic sample provides the maximal improvement to our final cosmological measurements.

1. Spectroscopically complete sample to z < 0.2

We are complete to r = -13.7/14.4. This will get nearly every SN. But will result in ~140 SNe Ia and 210 CC SNe over the full survey... this is a lot of follow-up

2. Magnitude-limited sample for r_peak < 21

Will guarantee getting all low-z SNe and will reduce bias. Overlaps with #1.

3. Representative "flat" sample for systematics

Randomly selected, weighted by Ia and z probability

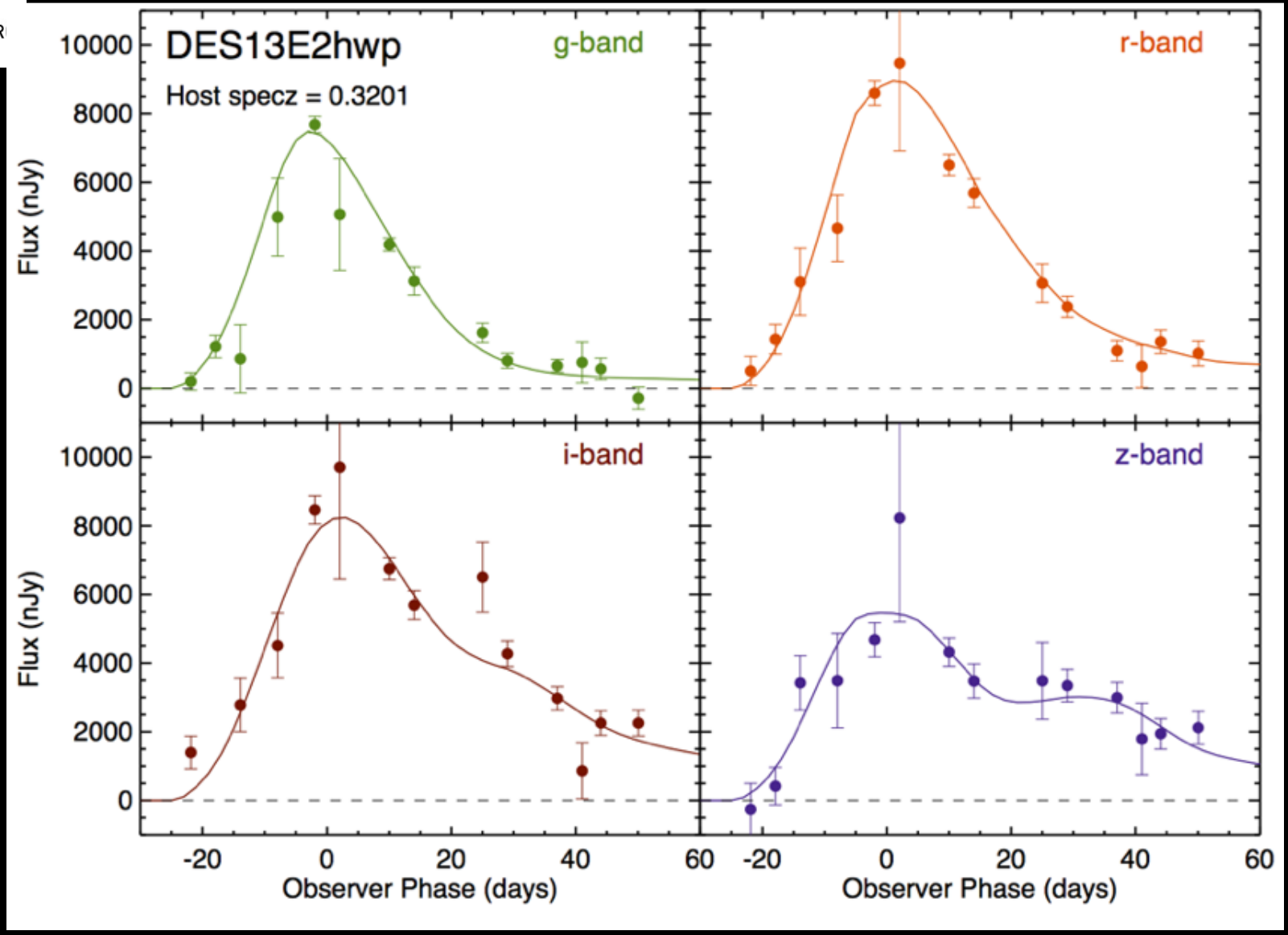
Ryan Foley

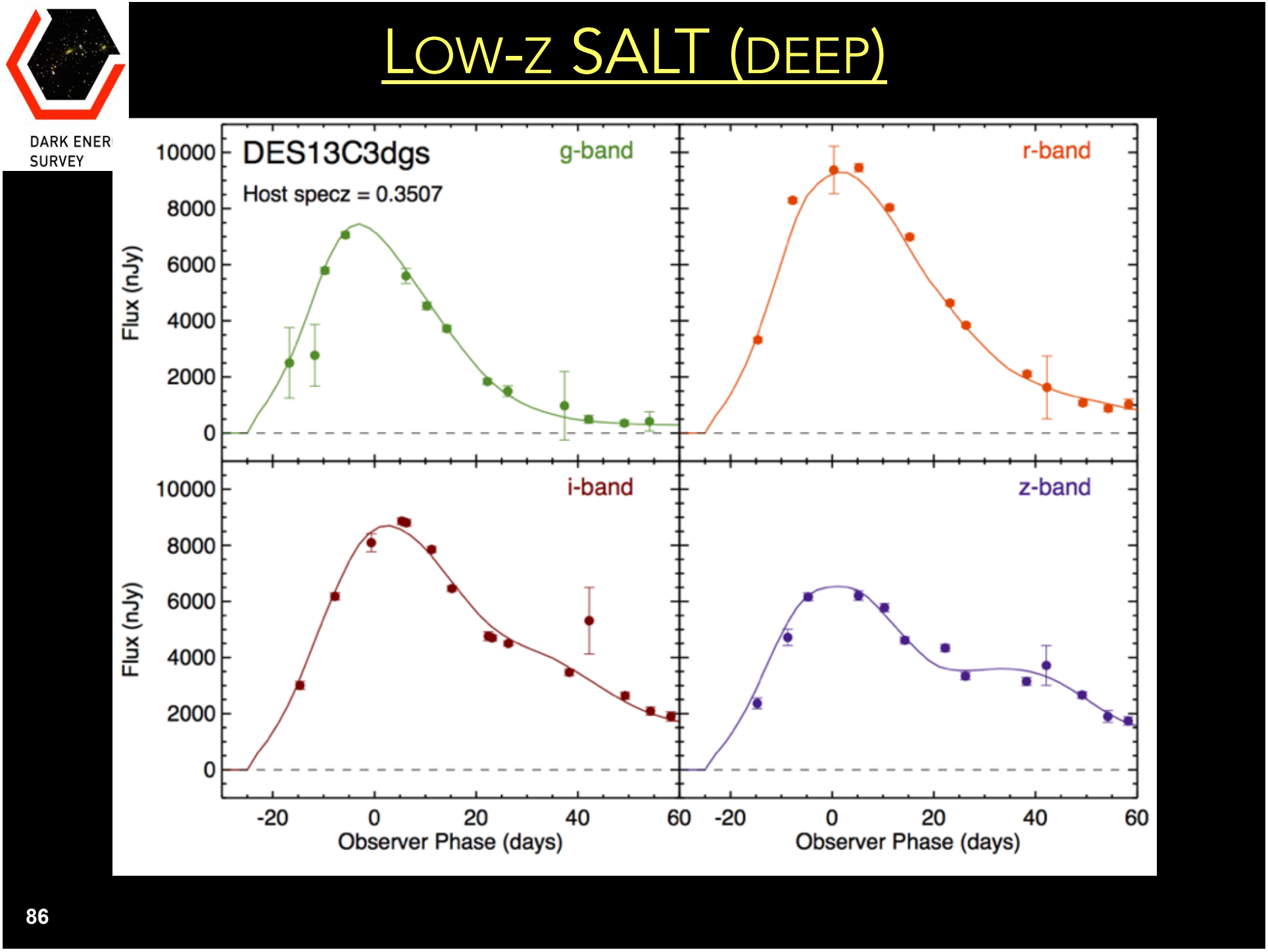
Other telescopes for live transients (2014)

Telescope	Time (2014-15)
VLT (Sullivan)	7 nights
GTC (Castander)	13hrs (ToO)
MMT/Magellan (Kirshner)	9.5 nights
Keck (Nugent)	5.5 nights + 8hrs ToO
Magellan (Kessler)	0.5 nights
SALT (Smith)	10.5 hrs

DARK ENER
SURVEY

LOW-Z SALT FITS (SHALLOW)

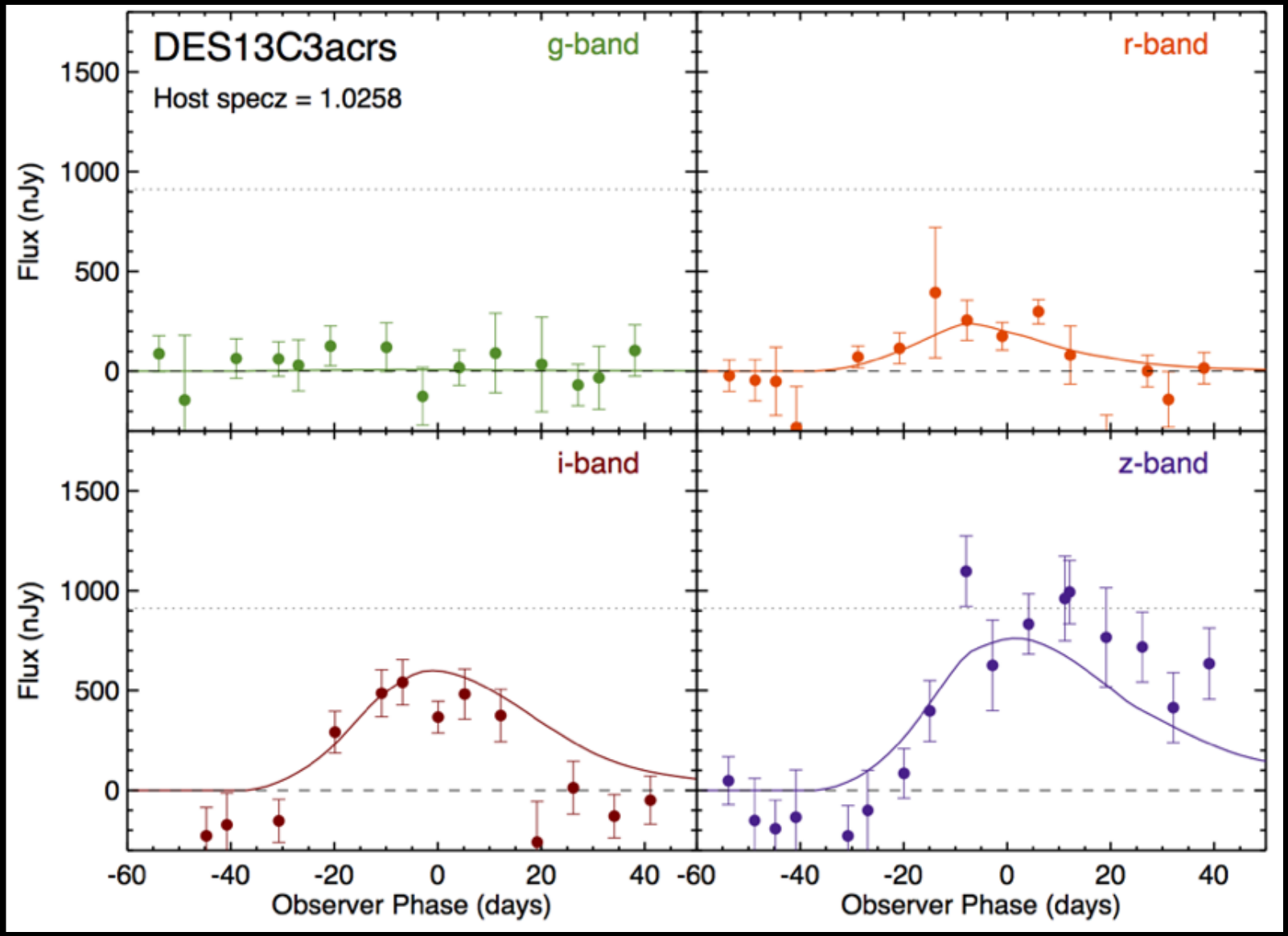


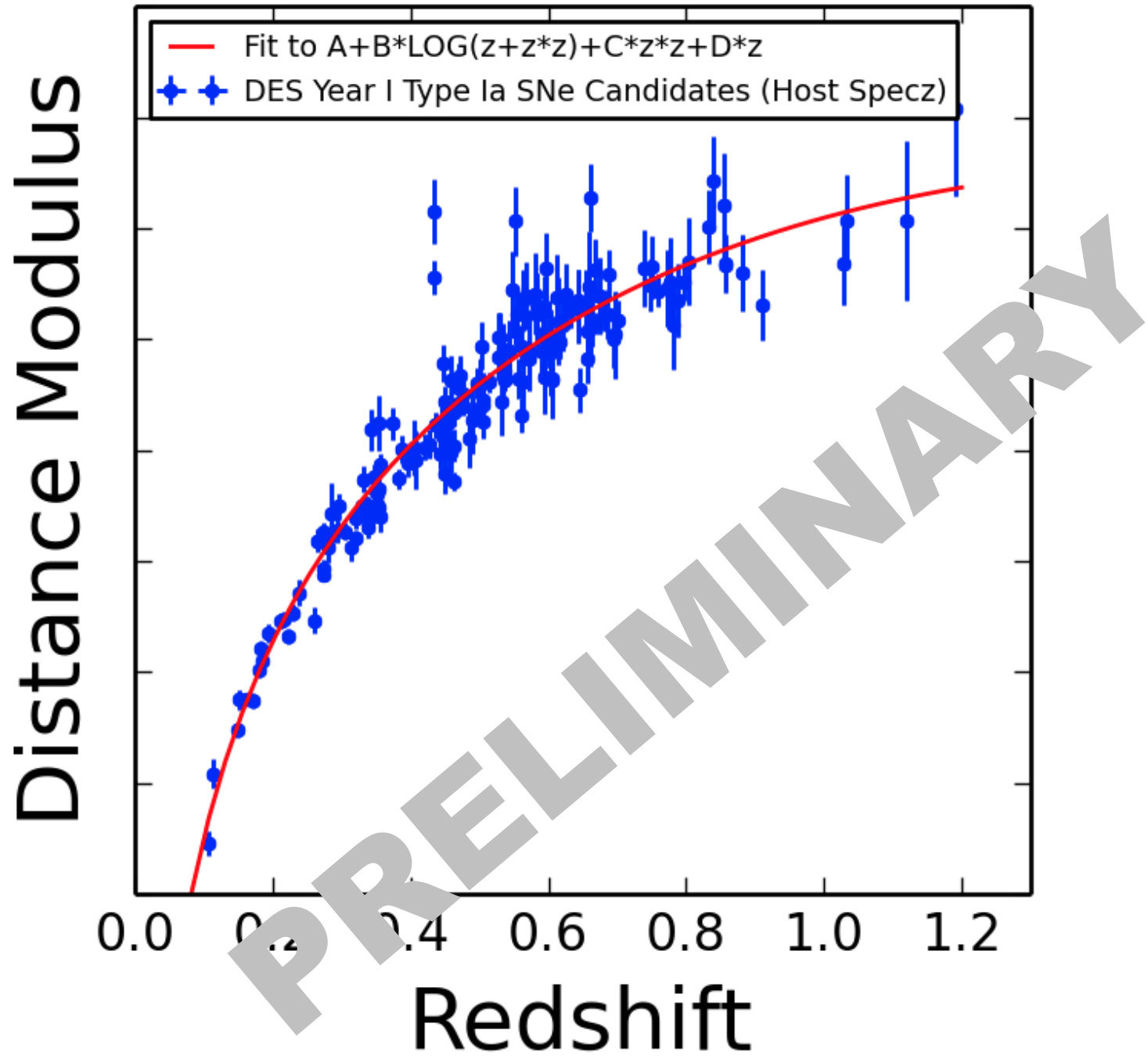


DARK ENER
SURVEY

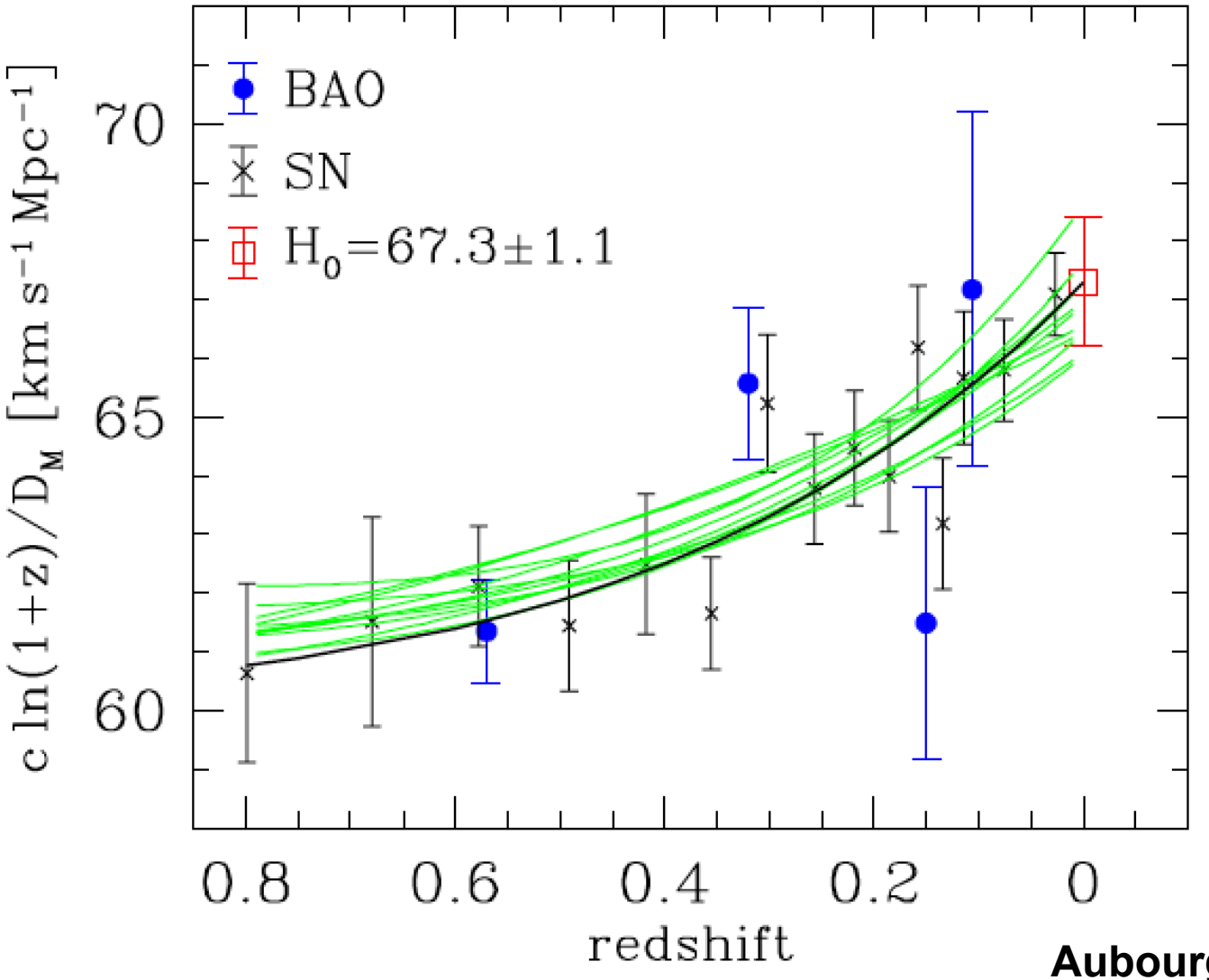
LOW-Z SALT (DEEP)

High-z SALT Fits (deep)




Fit to A+B*LOG(z+z*z)+C*z*z+D*z
DES Year I Type Ia SNe Candidates (Host Specz)
Distance Modulus
Redshift
0.0
0.4
0.6
0.8
1.0
1.2
PRELIMINARY

Inverse Hubble Diagram



Aubourg et al. 2015

Superluminous SNe (SLSNe)

<u>Superluminous:</u>

- $M_{absolute}$ < -21
- ~50 times brighter

<u>Light-curves:</u>

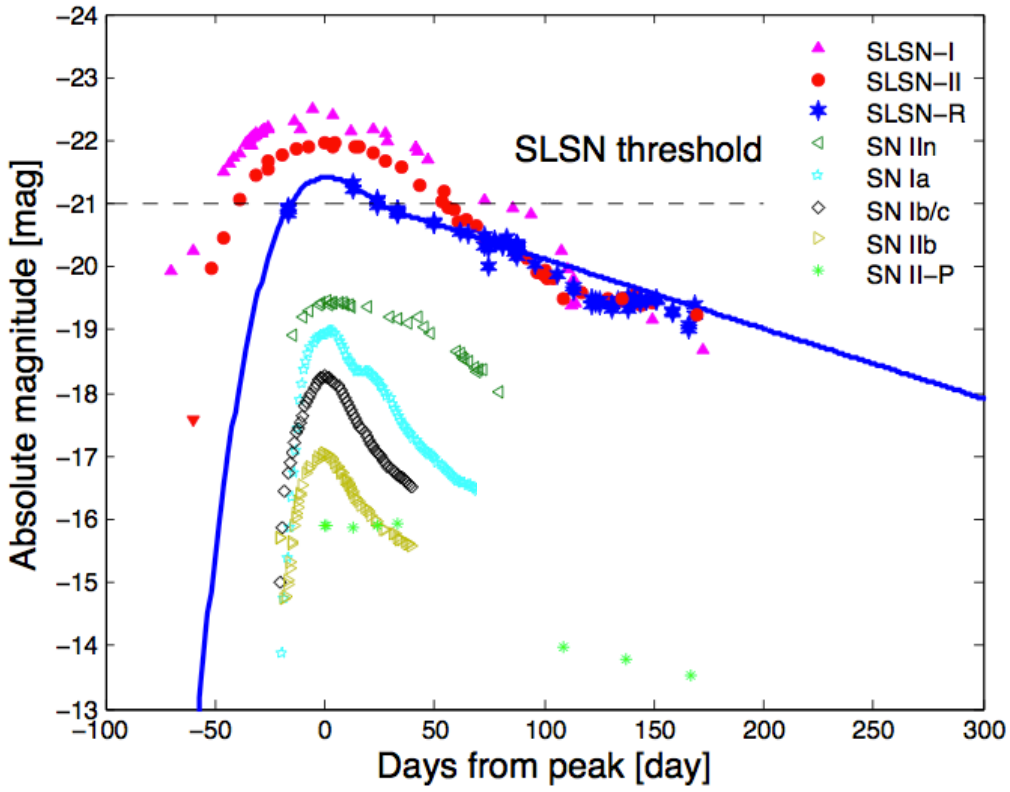
- 100s of days
- long rise/fall timescales

<u>Rare events:</u>

- ~50 discovered up to date
- 0.01% of SNe Ia rates
  - local Universe
- *15 increase @ z>1
  - SNLS, Cooke et al. 2012

<u>High-z:</u>

- SN 1000+0216 @ z=3.9 , Cooke et al. 2012



Andreas.Papadopoulos@port.ac.uk

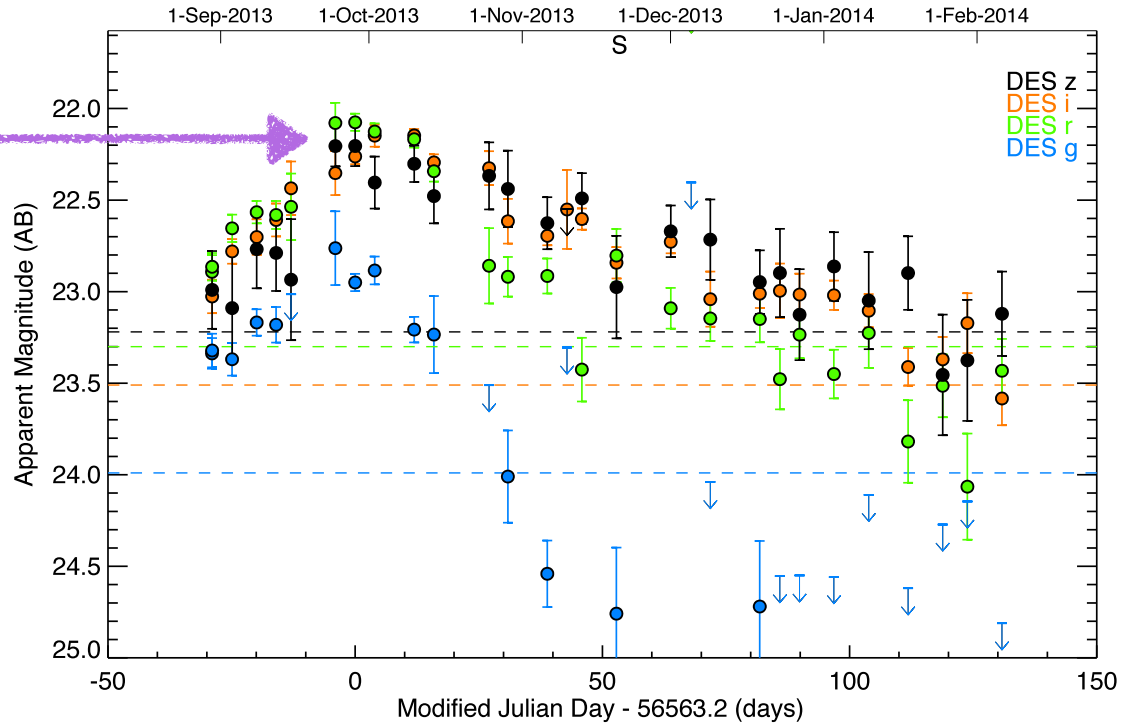
DES13S2cmm - DES Y1

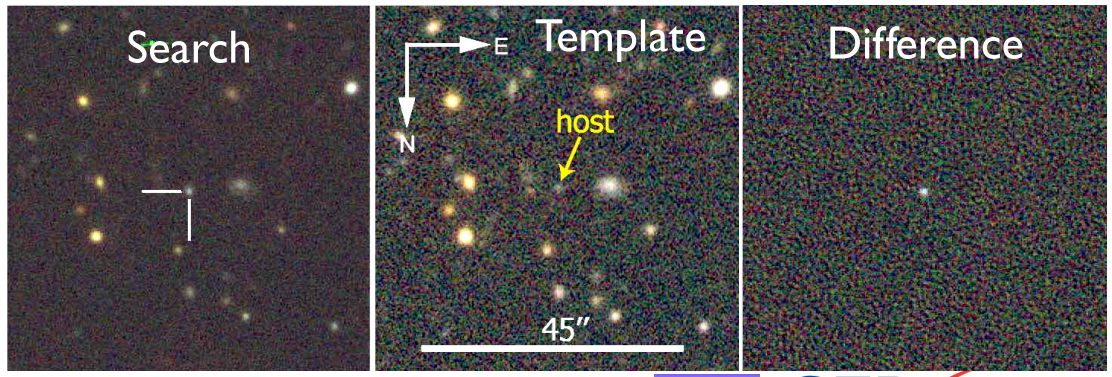
Peak Brightness:

- 28-September-2013

SLSNe type-I:

- VLT(ESO) spectrum
- z = 0.663 ± 0.003
- M_U = -21.0
- ATel #5603

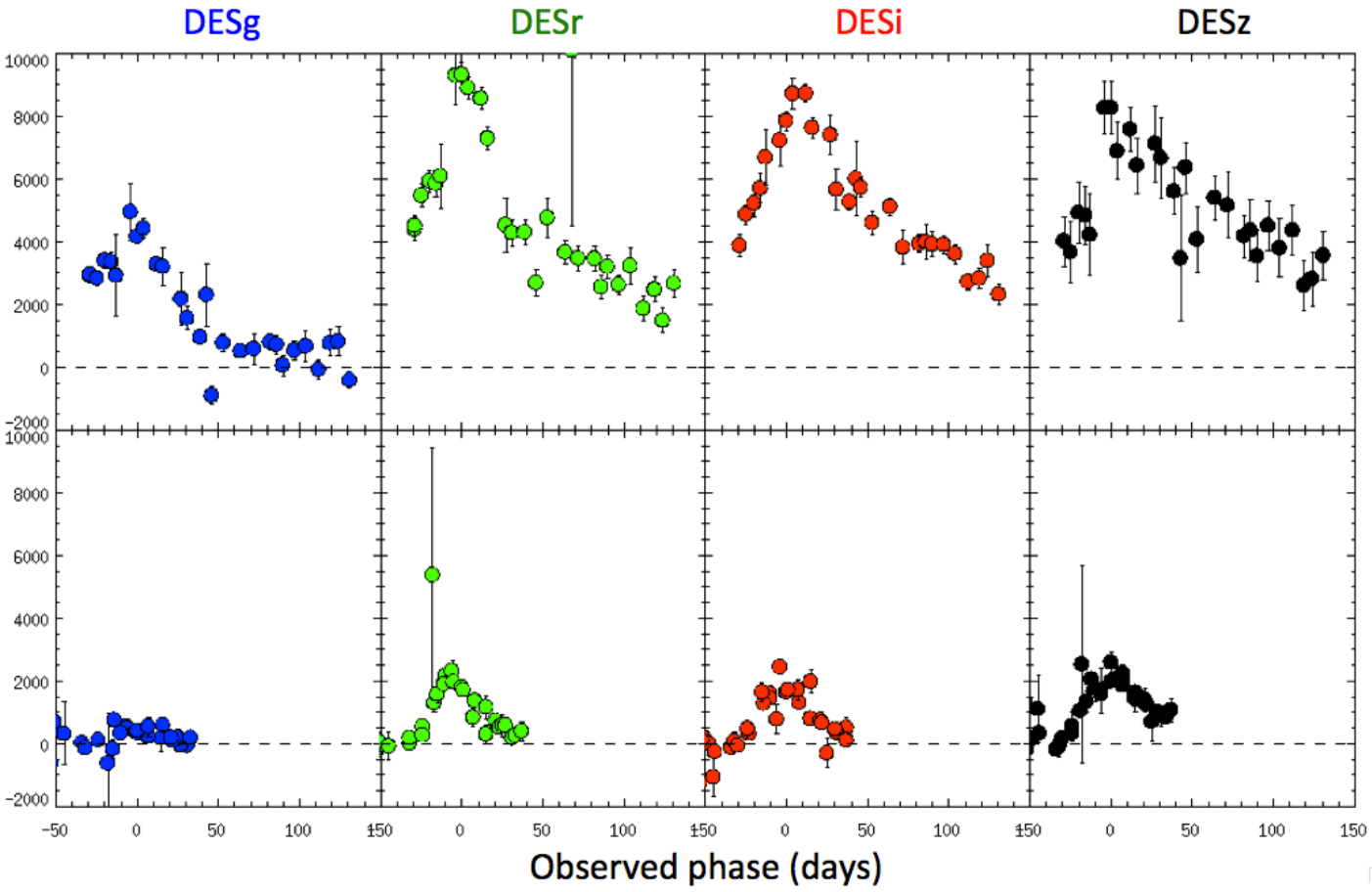




University of Portsmouth

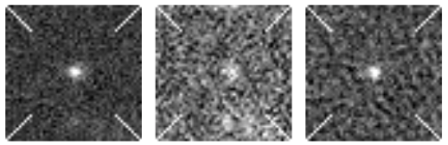
Andreas.Papadopoulos@port.ac.uk

DES13S2cmm Vs SNe type Ia



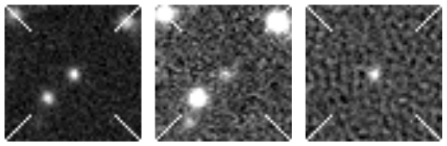
DES13S2cmm:

- VLT
  - z = 0.663
- SLSN-I

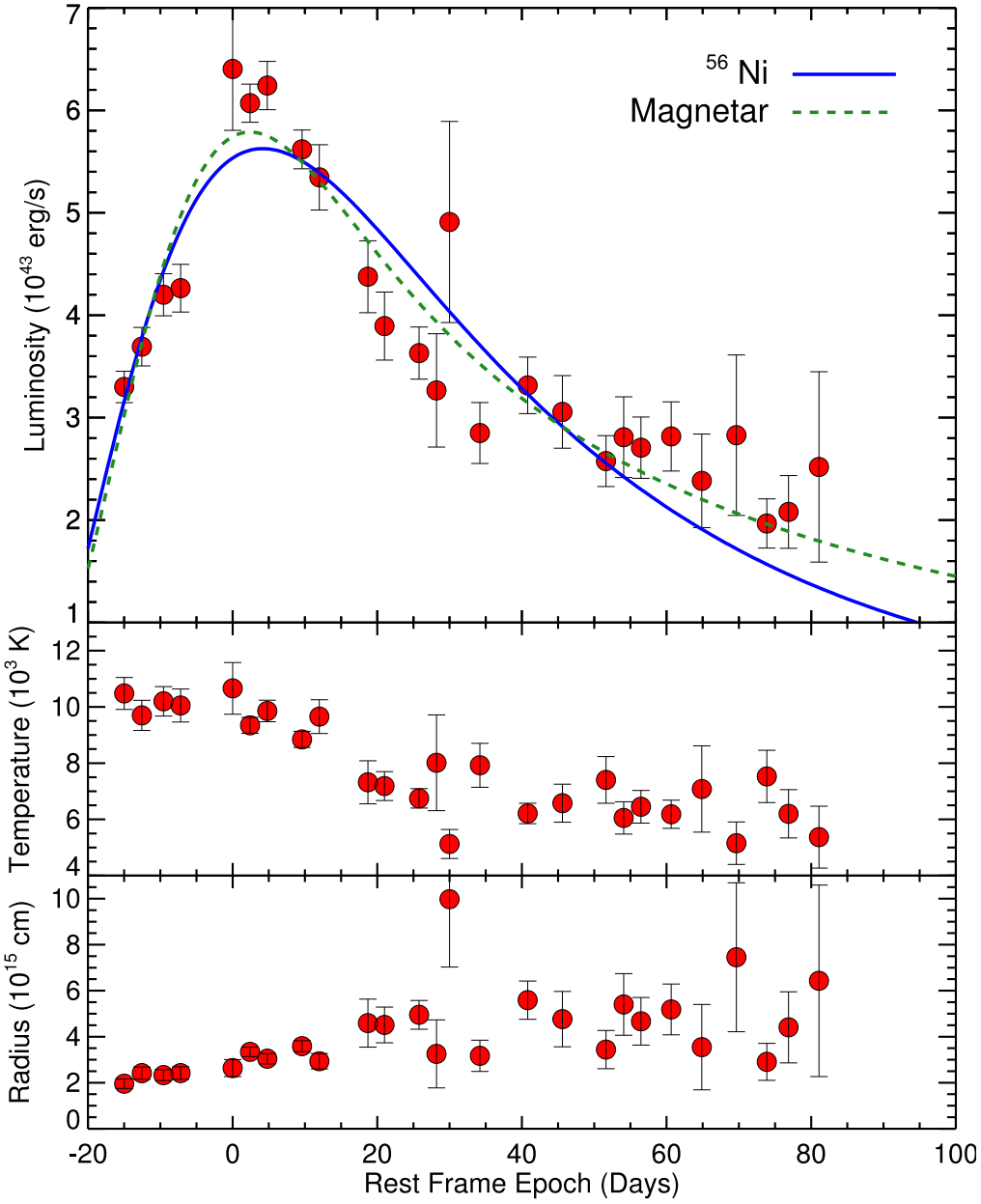


DES13C3abht:

- Gemini-South
  - z = 0.690
- type Ia



Understanding SLSNe



DES14X2byo - confirmed

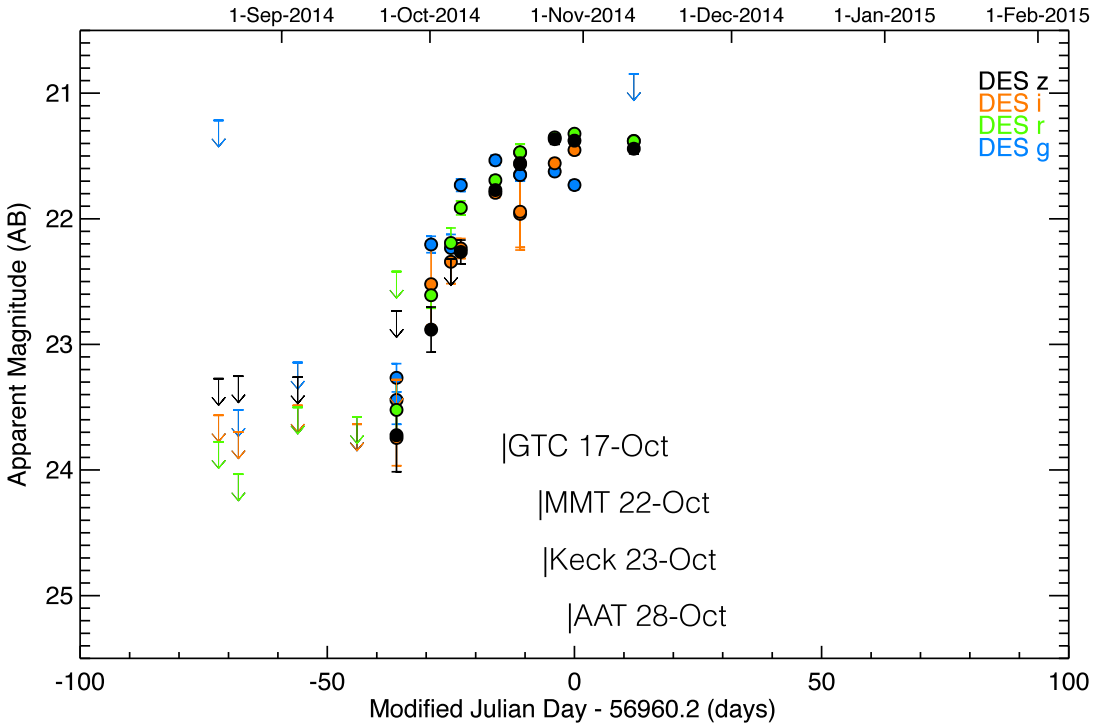
Detection:
- Auto-SNe: 22-Sep
- As SLSNe: 17-Oct

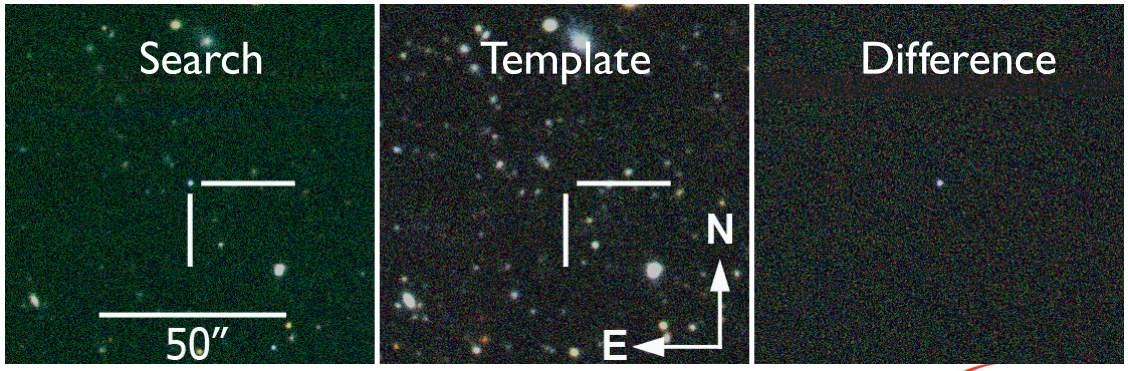
Spectra:
- 17-Oct - GTC -F.Gastander
- 22-Oct - MMT -R.Foley
- 23-Oct - Keck -P.Nugent
- 28-Oct - AAT - OzDES

- MgII 2800 absorption
- Fe II 2600 absorption
- O II 3727 emission
- SLSNe type-I @ z=0.869

Peak Brightness:
- ~29-Oct-2014
- Mr = -22.4 @ z=0.869

ATel#6635
- http://www.astronomerstelegram.org/?read=6635

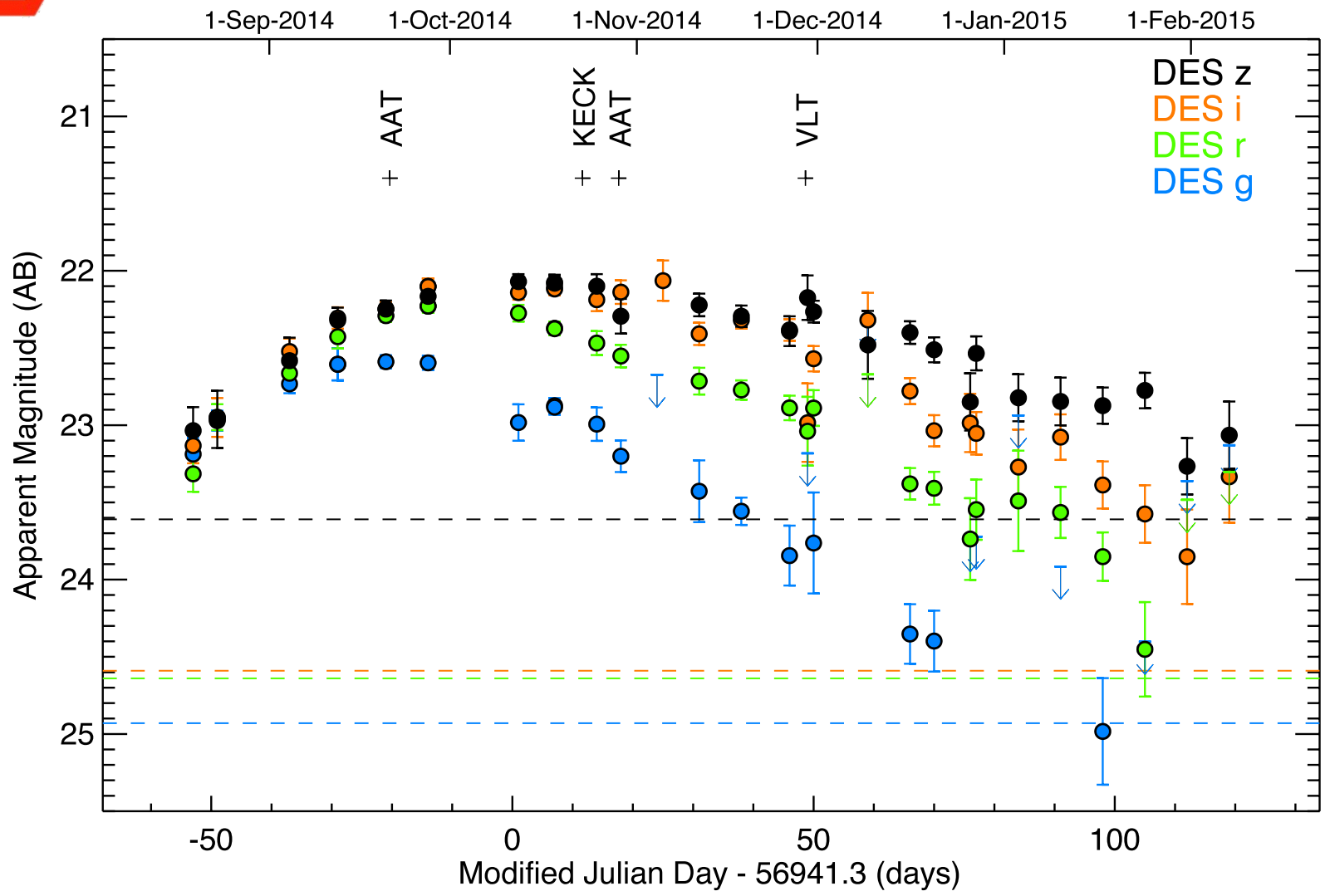




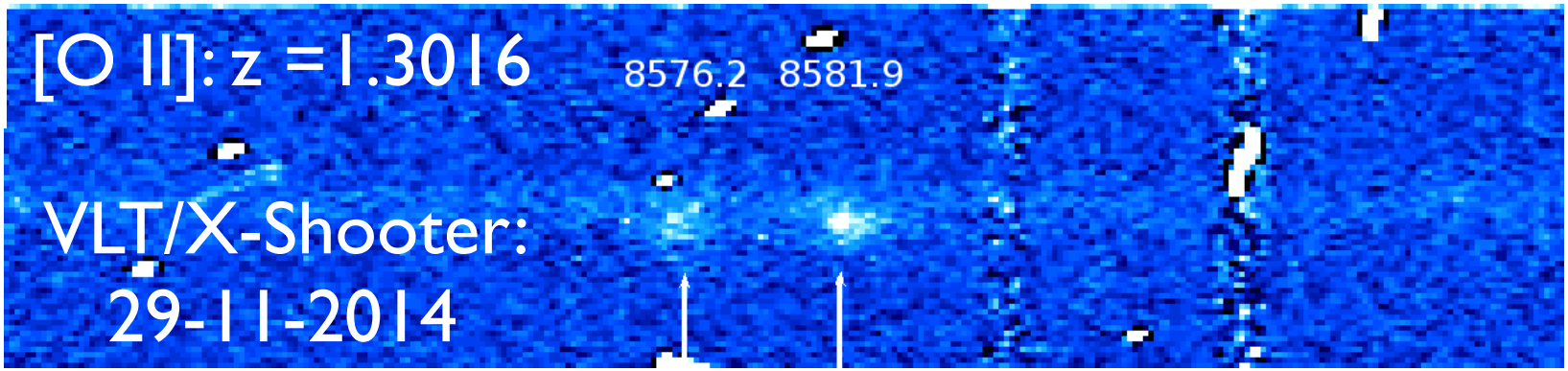
University of Portsmouth
Andreas.Papadopoulos@port.ac.uk
ICG Portsmouth
SEPnet South East Physics Network

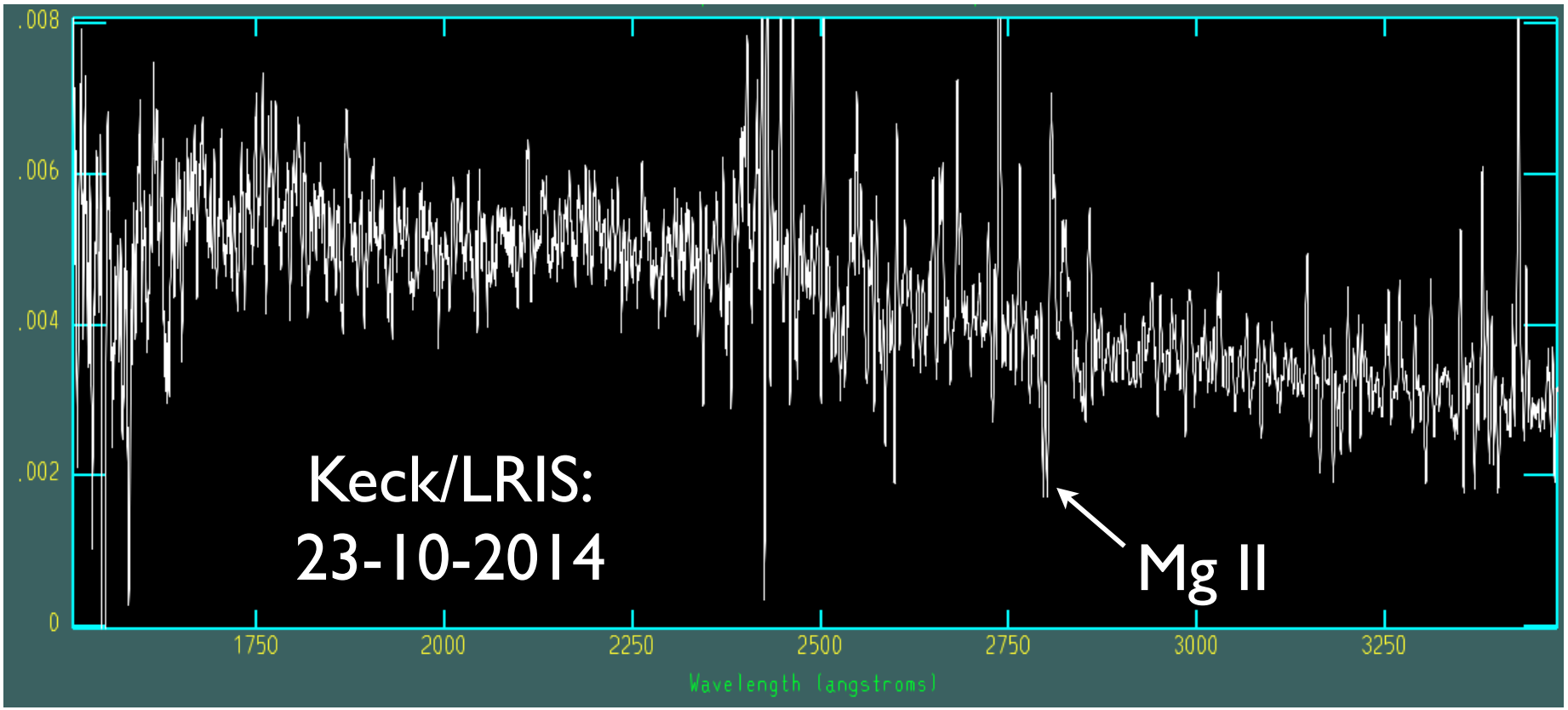
DES14C1fi

$M_{U,peak} \sim -22.5$

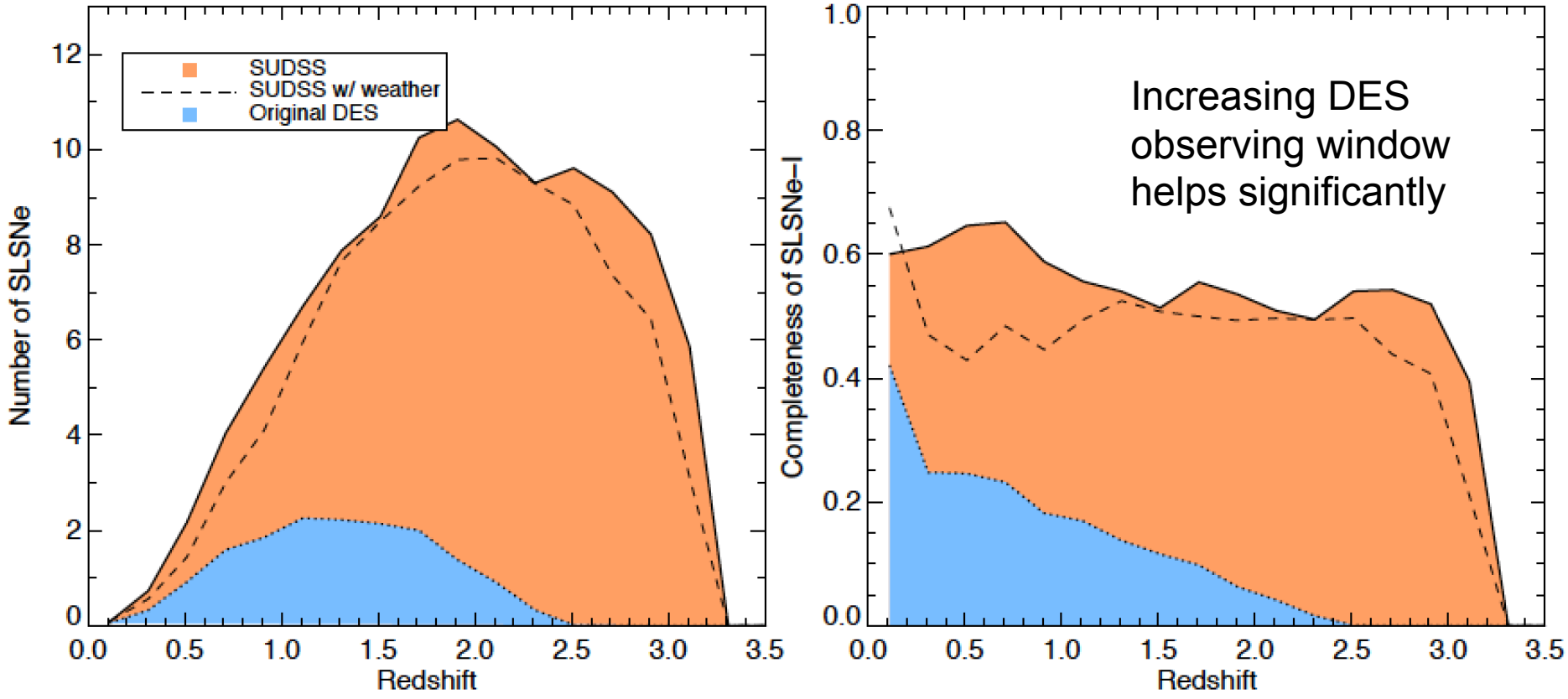


DES14C1fi

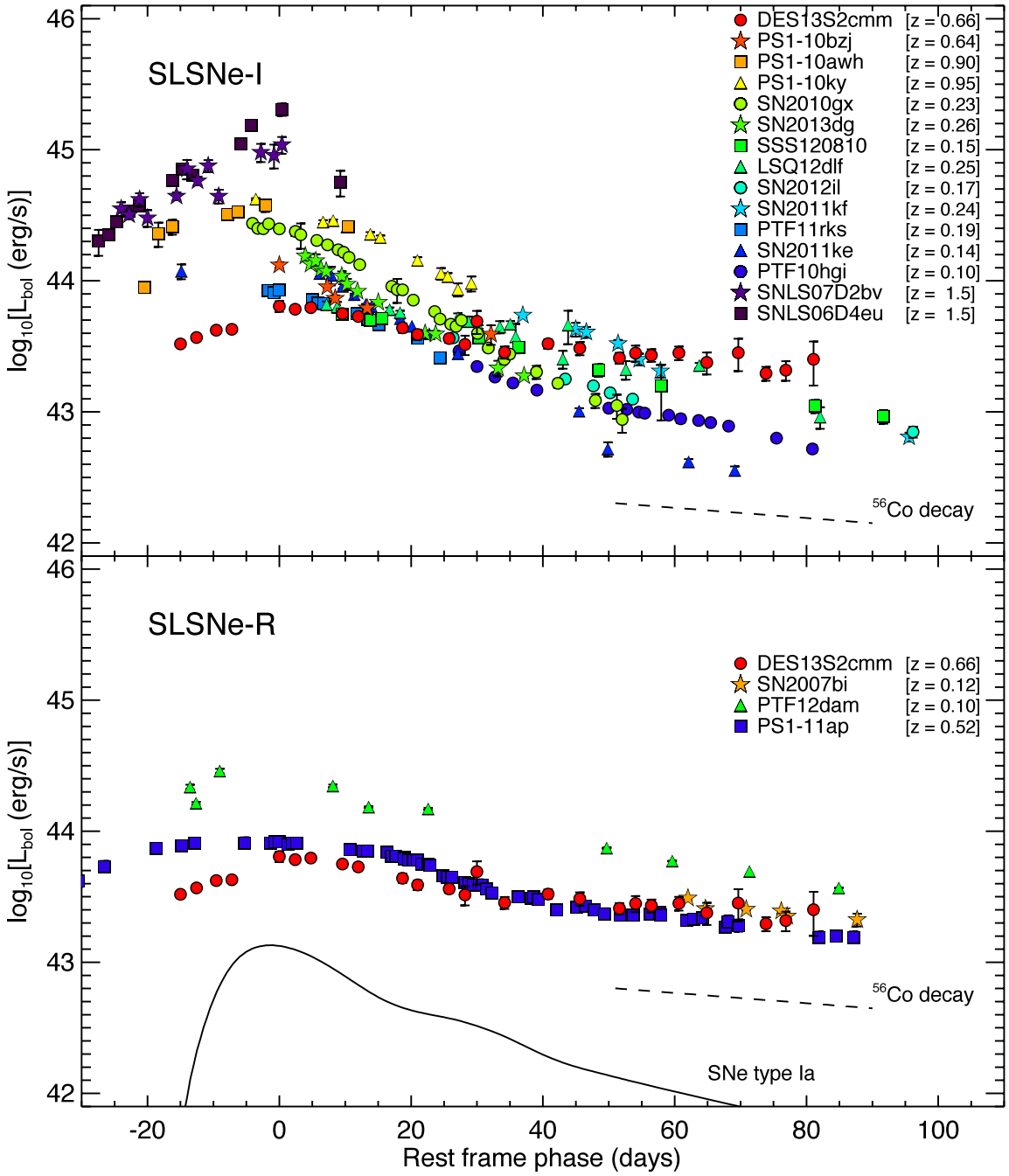

[O II]: z = 1.3016
8576.2
8581.9
VLT/X-Shooter:
29-11-2014

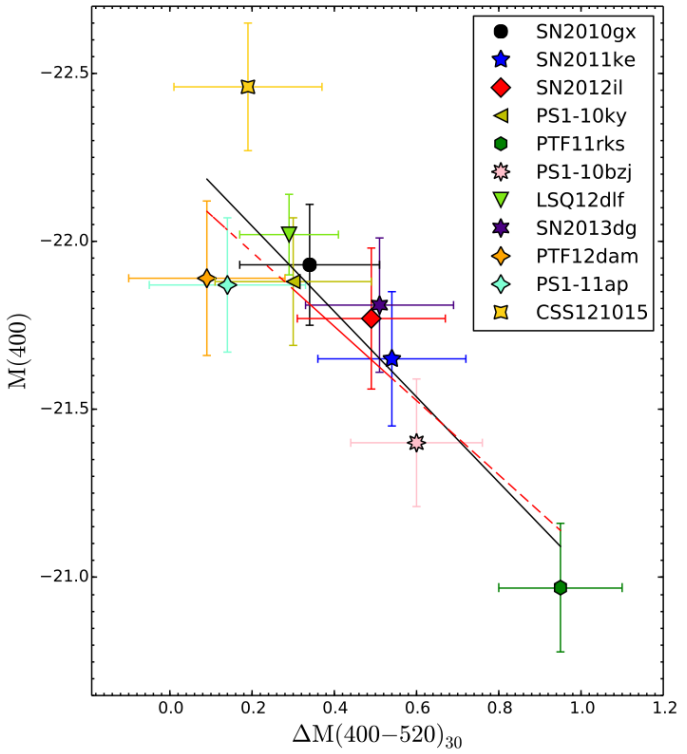

.008
.006
.004
.002
0
1750
2000
2250
2500
2750
3000
3250
Wavelength (angstroms)
Keck/LRIS:
23-10-2014
Mg II

Survey Using DECam for Superluminous Supernovae



24 deg^2 at ~14 day cadence for ~7 months to twice depth of DES shallow fields



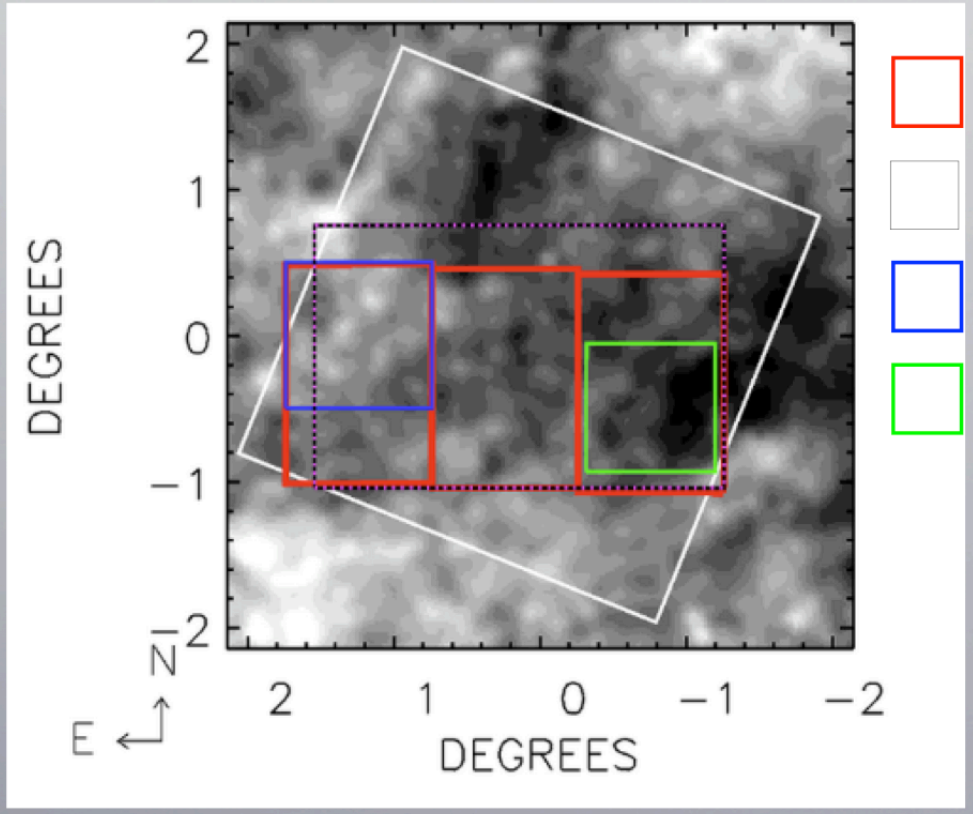


DES + SUDSS will find ~100, improving the DES cosmology by at least 25%. LSST will find 20,000 of these events!

The VIDEO Survey

VISTA Deep Extragalactic Observations

(*Jarvis et al. 2013*)



VIDEO

Spitzer SWIRE

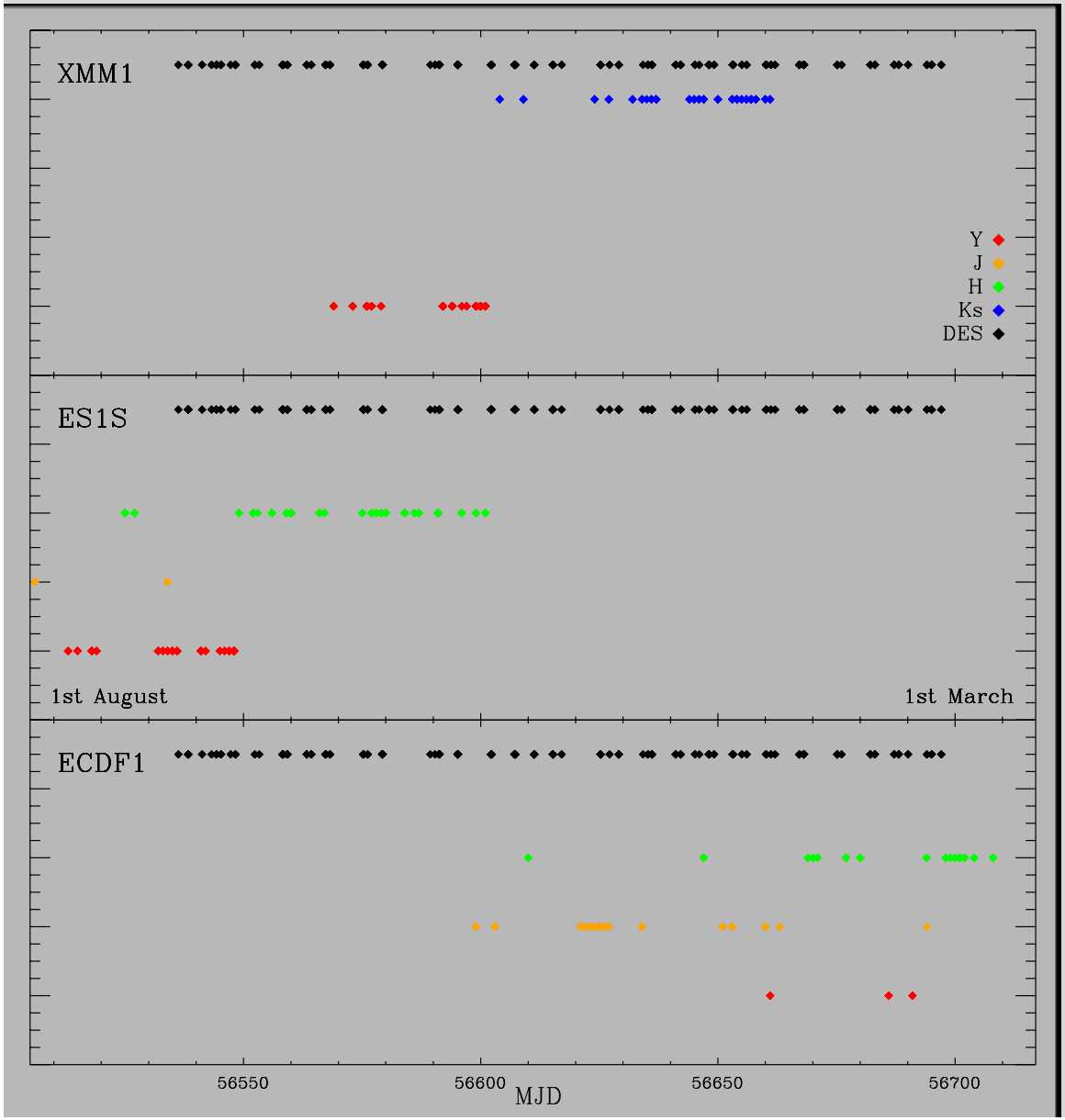
CFHTLS-D1

UKIDSS-UDS

- 12 deg^2
- (NIR): ***Z, Y, J, H, K_s***
- Visible: **ugriz** (CFHTLS)
- $z_{phot} < 4.0$
- z_{phot} *obtained from LePhare*

Y = 24.5, J = 24.4, H = 24.1 and K_s = 23.8

DES & VIDEO Overlap

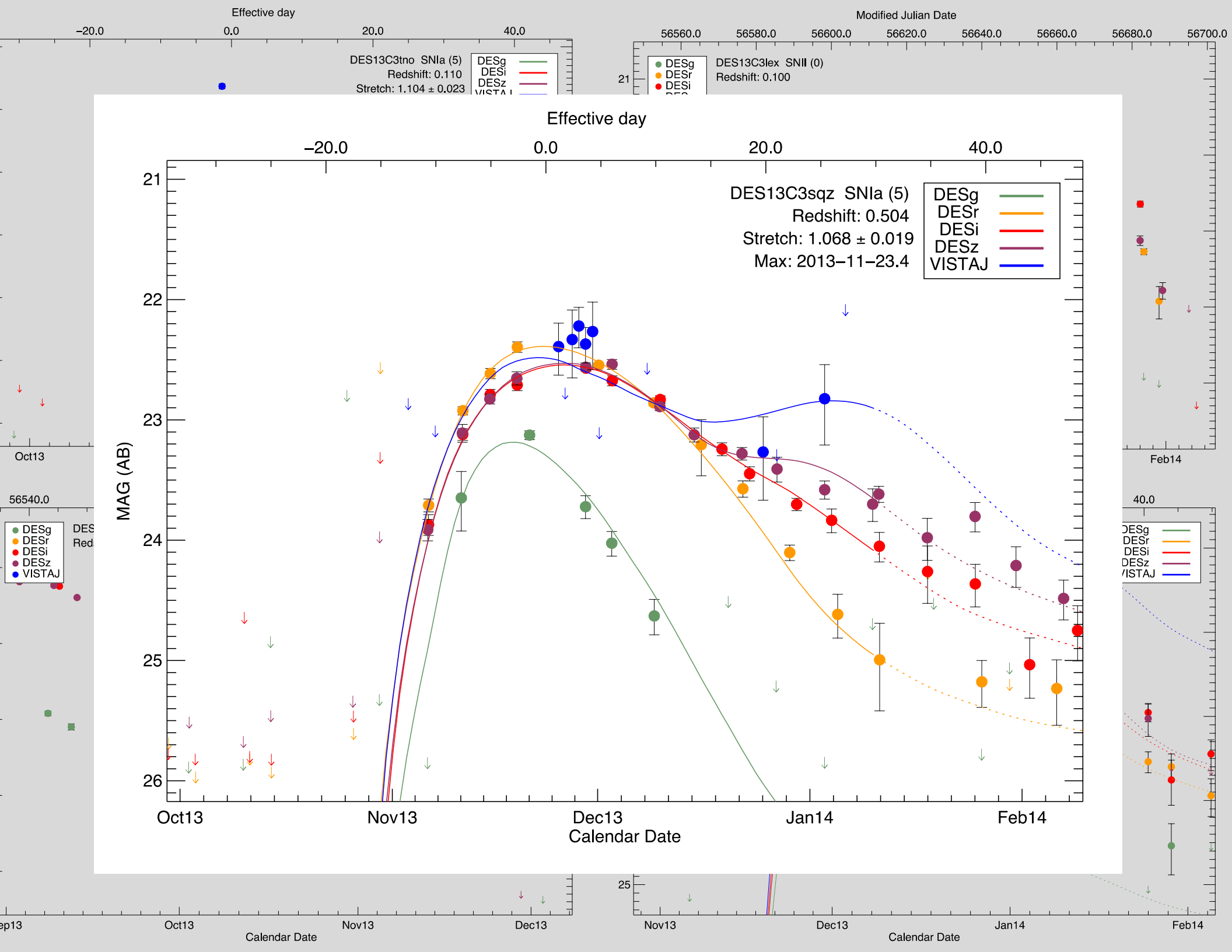


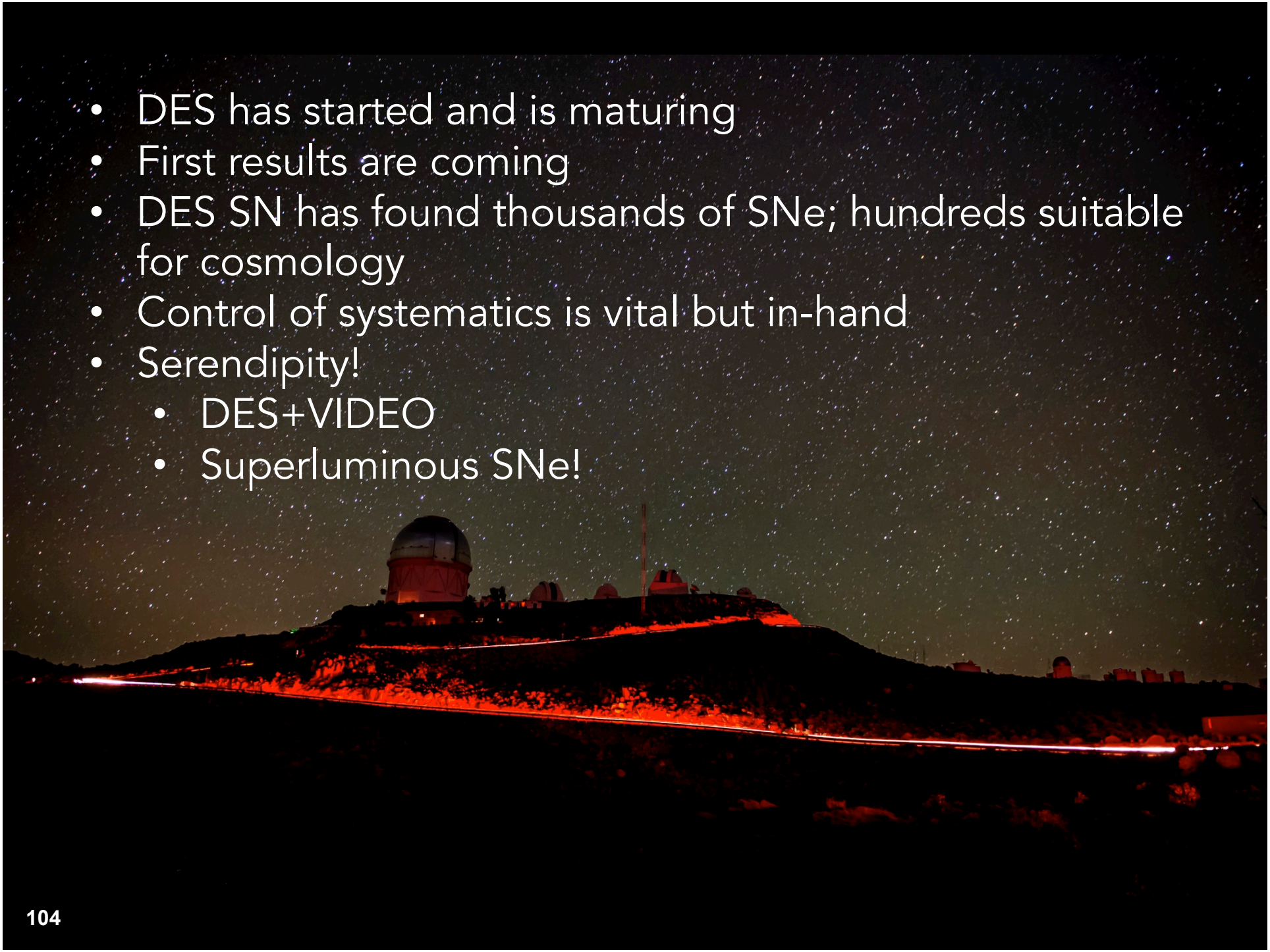
The VIDEO footprint overlaps with the DES X, C and E fields

Observations will coincide with DES SV, Y1 & Y2

Potential overlap in Y, J, H & K (invaluable for host galaxy prop)

Can we produce NIR light-curves of DES SNe….


Effective day
−20.0
0.0
20.0
40.0
DES13C3sqz SNIa (5)
Redshift: 0.504
Stretch: 1.068 ± 0.019
Max: 2013−11−23.4
DESg
DESr
DESi
DESz
VISTAJ
MAG (AB)
21
22
23
24
25
26
Oct13
Nov13
Dec13
Jan14
Feb14
Calendar Date
Modified Julian Date
56560.0
56580.0
56600.0
56620.0
56640.0
56660.0
56680.0
56700.0
DES13C3tno SNIa (5)
Redshift: 0.110
Stretch: 1.104 ± 0.023
DES13C3lex SNII (0)
Redshift: 0.100
56540.0
40.0


• DES has started and is maturing
• First results are coming
• DES SN has found thousands of SNe; hundreds suitable for cosmology
• Control of systematics is vital but in-hand
• Serendipity!
• DES+VIDEO
• Superluminous SNe!

DES Timeline

• 2003	Project begins
• 2004 – 2008	R&D
• 2008 – 2011	DECam construction
• 2012	Installation
• Sept 2012	First light
• Sept – Oct 2012	Commissioning
• Nov 2012 – Feb 2013	Science verification (SV)
• 31 Aug 2013 – 9 Feb 2014	First season (Year 1)
• 15 Aug 2014	Year 2 begins
• Feb 2018	Nominal end of survey operations