Dark Energy Survey (DES)

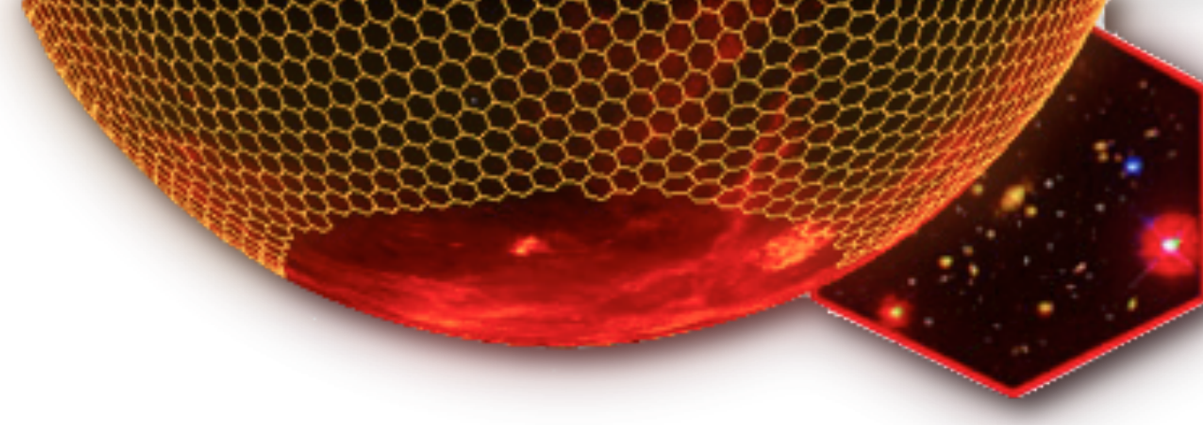
Bob Nichol on behalf of DES collaborators

@robertcnichol

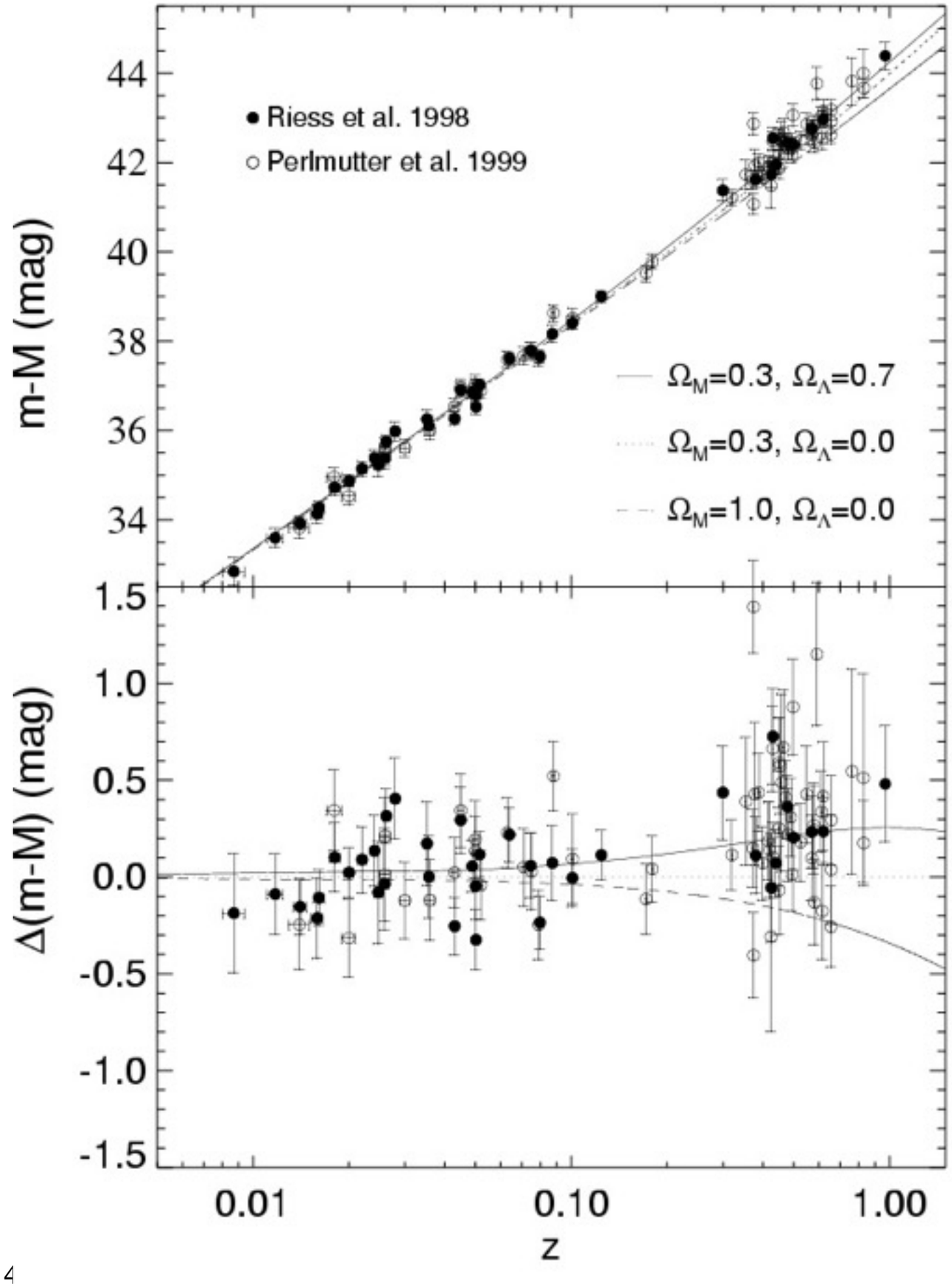
The DES Collaboration

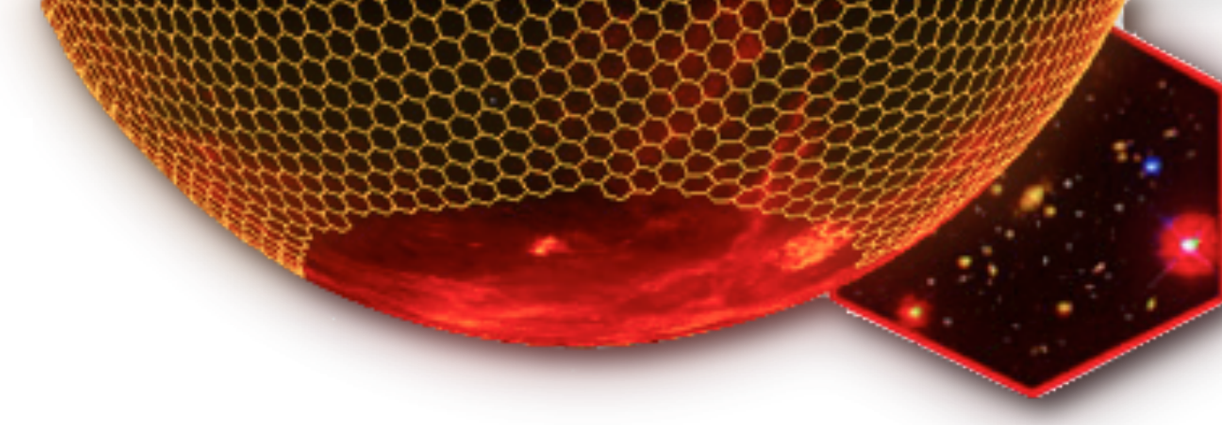
~400 Scientists from
~30 Institutions
7 Countries

- Fermi National Accelerator Laboratory
- Lawrence Berkeley National Laboratory
- Argonne National Laboratory
- National Optical Astronomy Observatory
- Chicago
- Ohio State
- Texas A&M
- Michigan
- Pennsylvania
- Santa Cruz-SLAC-Stanford DES Consortium
- Illinois at Urbana-Champaign
- National Center for Supercomputing Applications
- Ludwig-Maximilians Universität
- Excellence Cluster Universe
- College London
- Cambridge
- Edinburgh
- Portsmouth (joined in 2004)
- Sussex
- Nottingham
- Institut d'Estudis Espacials de Catalunya
- Consejo Superior de Investigaciones Científicas
- Institut de Fisica d'Altes Energies
- CIEMAT
- DES-Brazil Consortium
- ETH-Zurich
- Australian Universities and Observatories



Era of discovery (2000 - 2010)

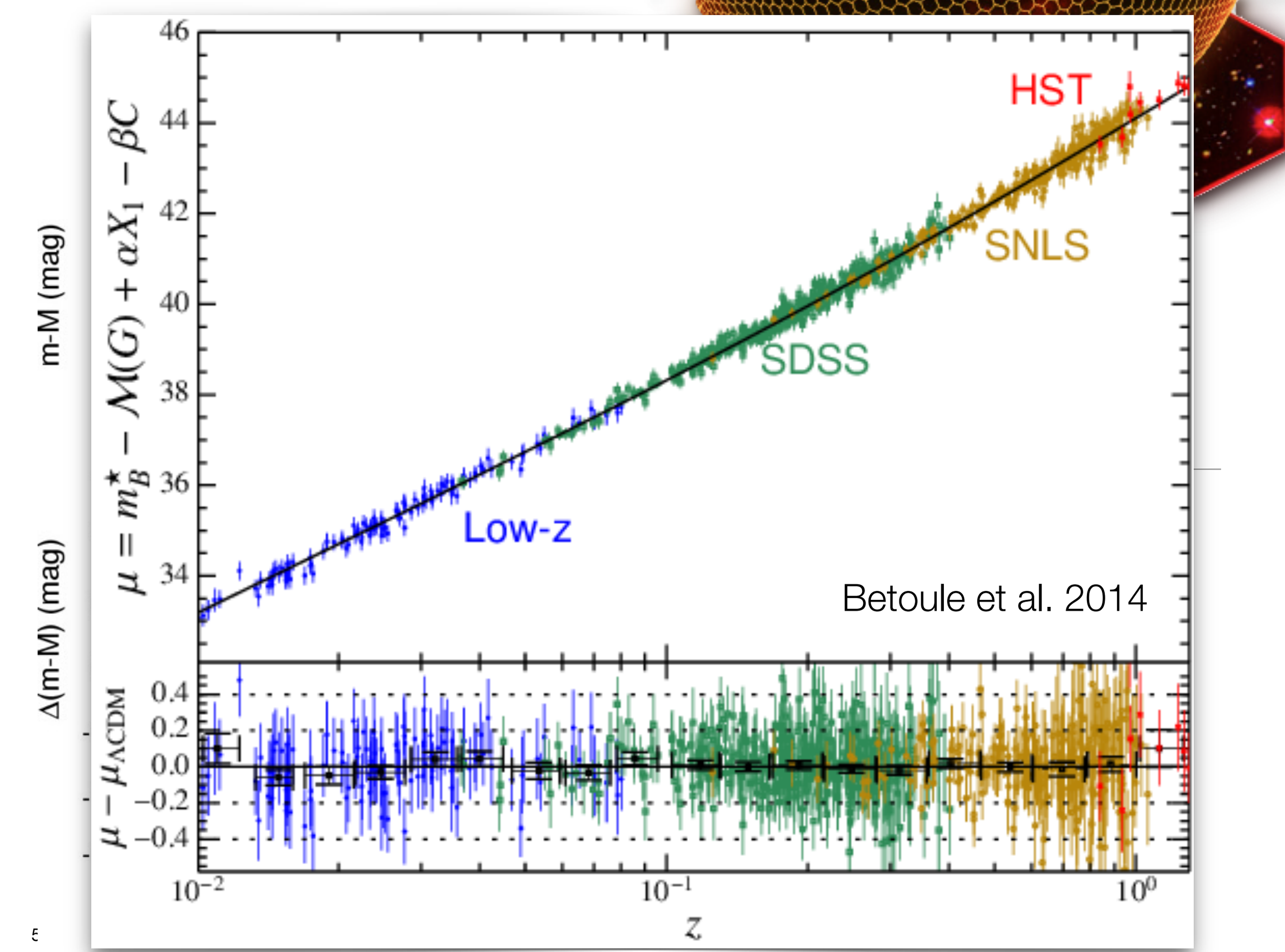




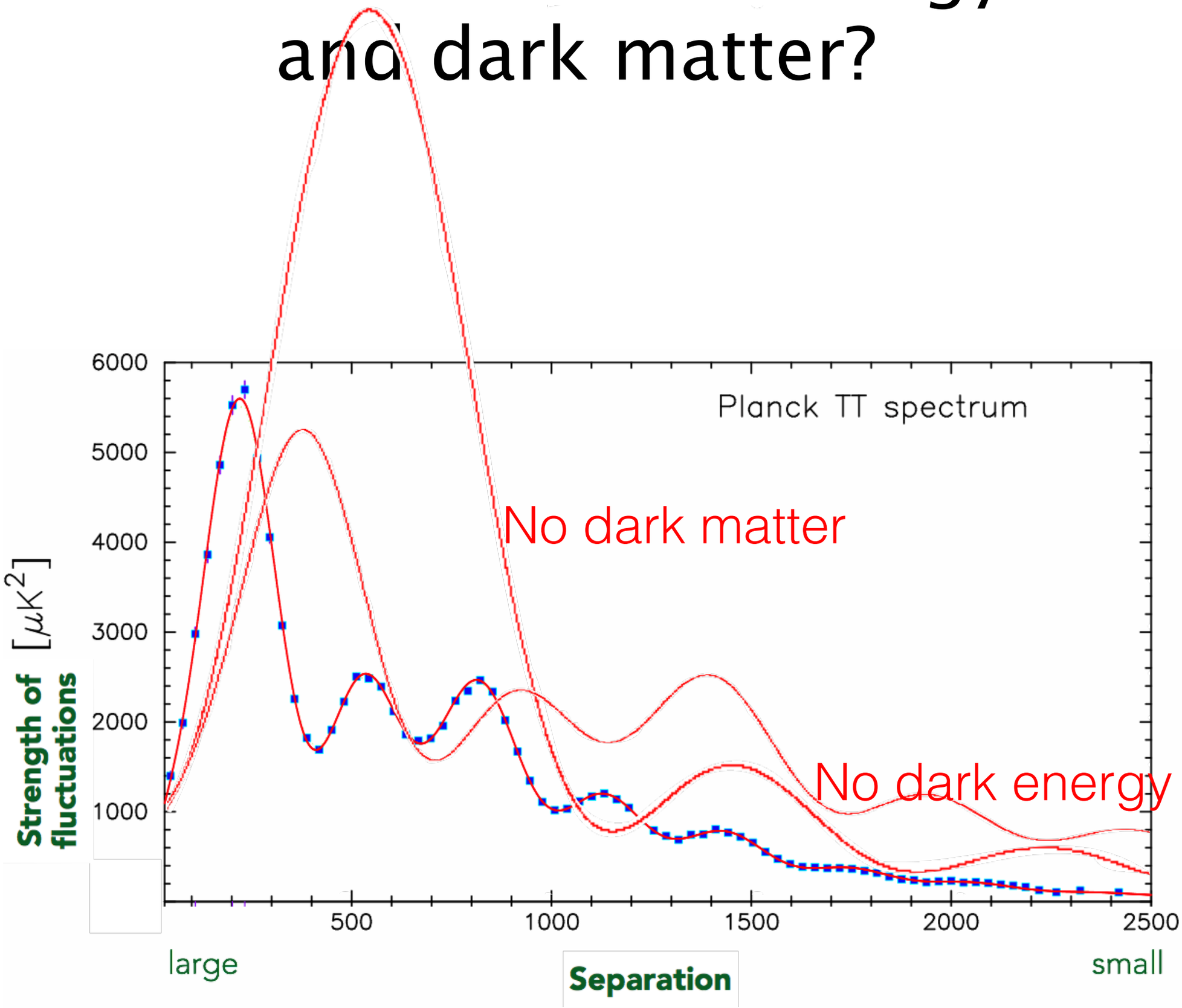
Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

(Nobel Prize 2011)

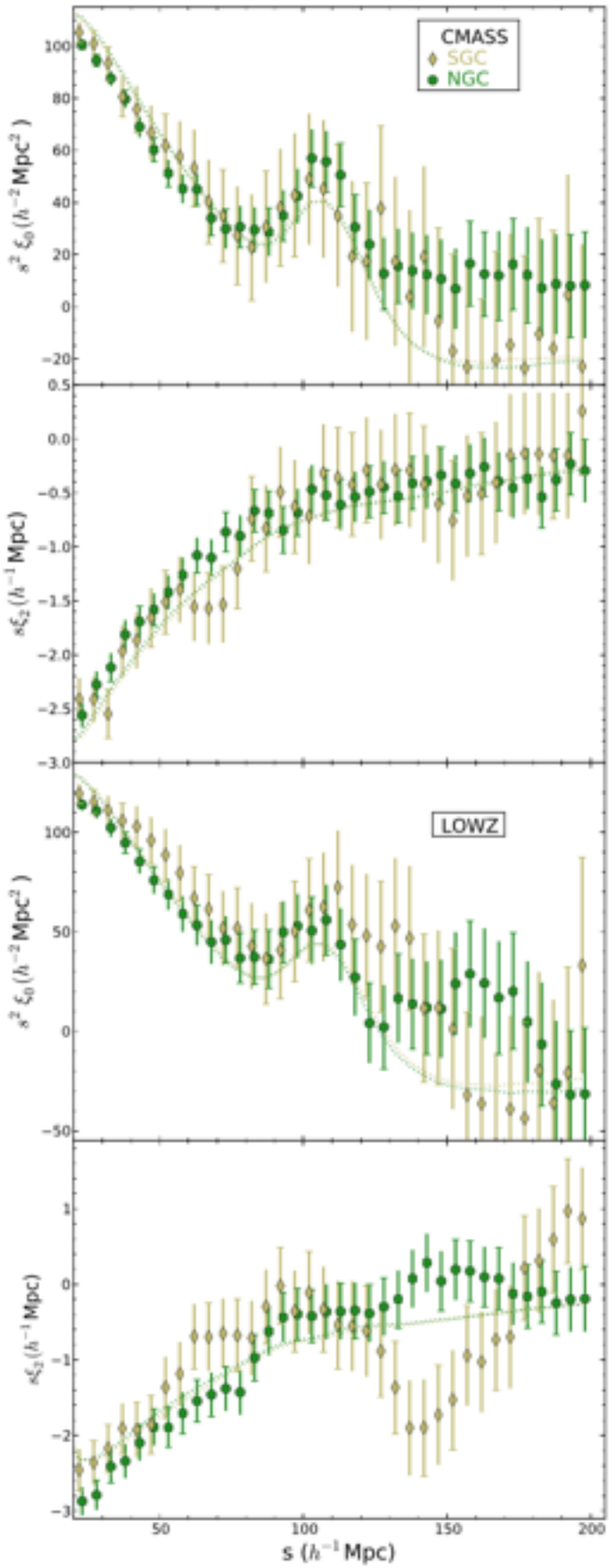
$(\Omega_M, \Omega_\Lambda)$
(0.3, 0.7)
(0.3, 0.0)
(1.0, 0.0)


m-M (mag)
$\mu = m_B^\star - \mathcal{M}(G) + \alpha X_1 - \beta C$
46
44
42
40
38
36
34
HST
SNLS
SDSS
Low-z
Betoule et al. 2014
Δ(m-M) (mag)
$\mu - \mu_{\Lambda CDM}$
0.4
0.2
0.0
−0.2
−0.4
10^{-2}
10^{-1}
10^{0}
z

Do we need dark energy and dark matter?

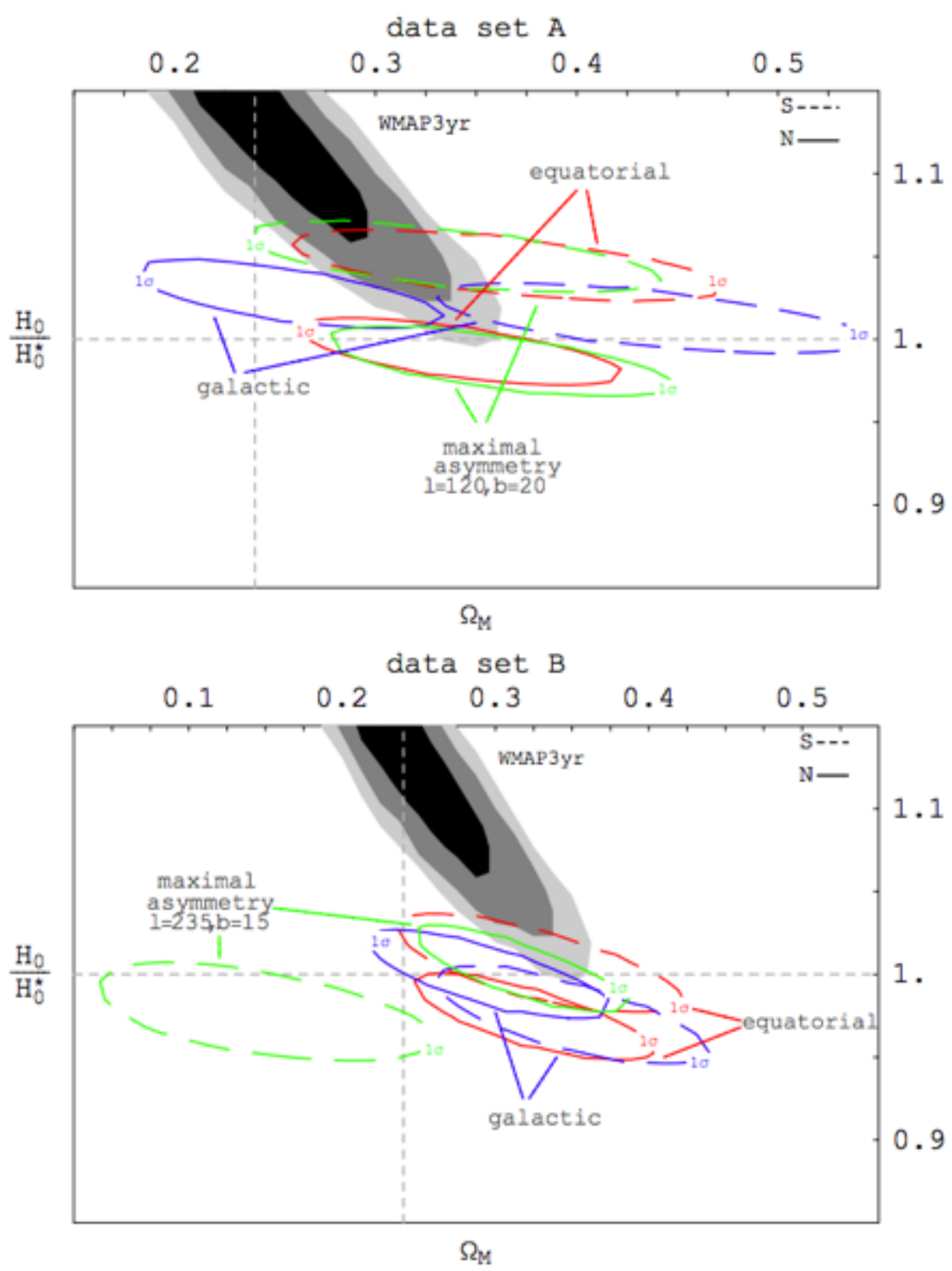


Credit: Chris Lidman



Ross et al. 2017 (BOSS)

Figure 7. The clustering of BOSS CMASS (top two panels) and LOWZ (bottom two panels) galaxies, for the two contiguous regions within the SGC and NGC hemispheres. The dotted lines denote the mean of the QPM mock samples.



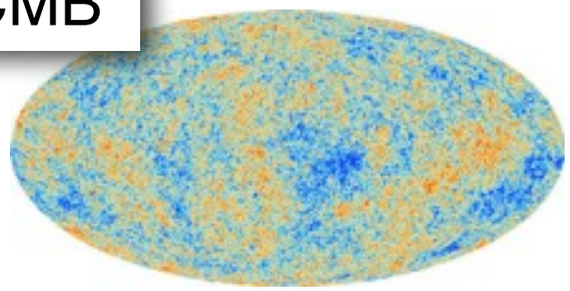
Schwarz et al. 2007 (SNe)

Fig. 7. North (full lines) and South (dashed lines) confidence contours and best-fit values for galactic, equatorial and maximum asymmetry hemispheres for the ΛCDM fit. These fits should be compared to the full-sky fits of figure 6. We do not show results for data set C, as the pencil beam geometry of that data set is not suitable for our test.

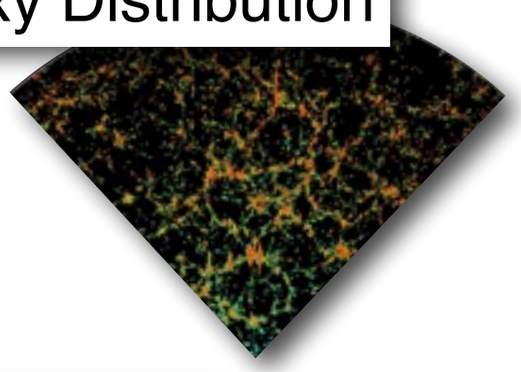
Searching for Meaning

Observational driven as theory offers little at present

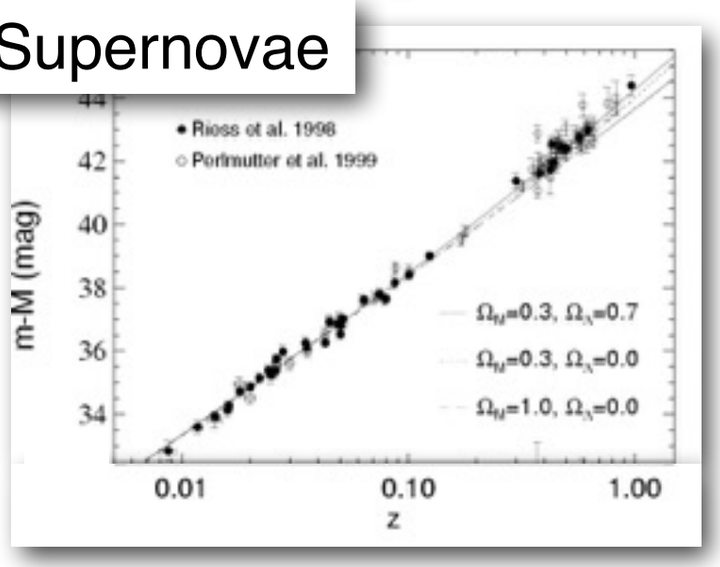
CMB



Galaxy Distribution



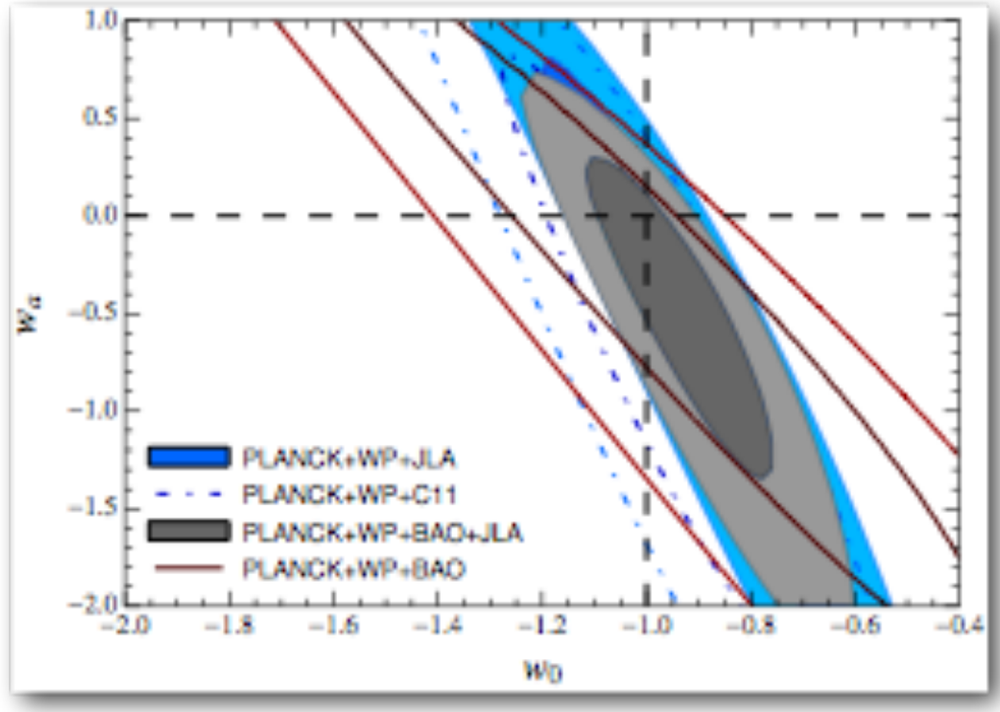
Supernovae



Geometry
+
Expansion
+
Structure
Growth

w = pressure / density

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



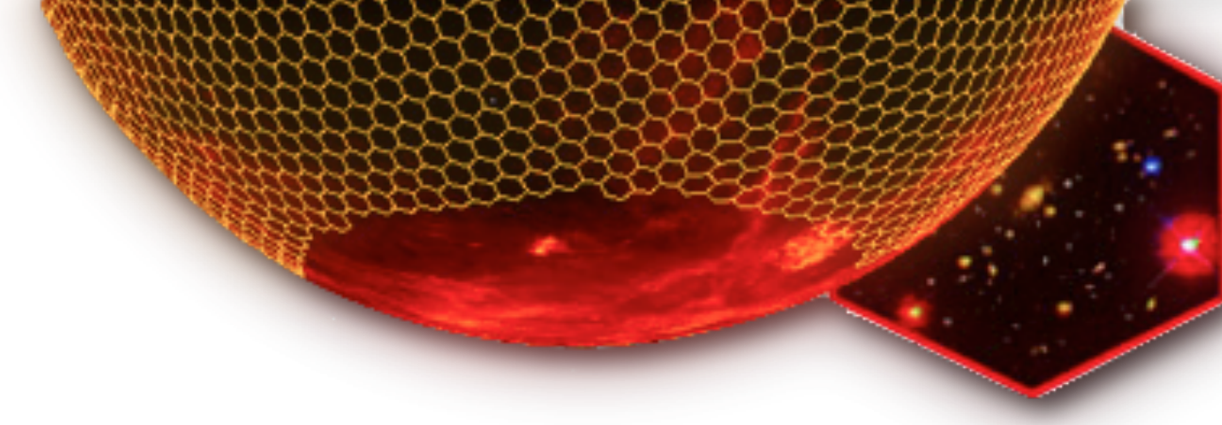
State of the art constraints:

w_0 = -0.957 ± 0.124 (~13%)

w_a = -0.336 ± 0.552 (~164%)

Betoule++2014

w_0 = -1 and w_a = 0 consistent vacuum energy



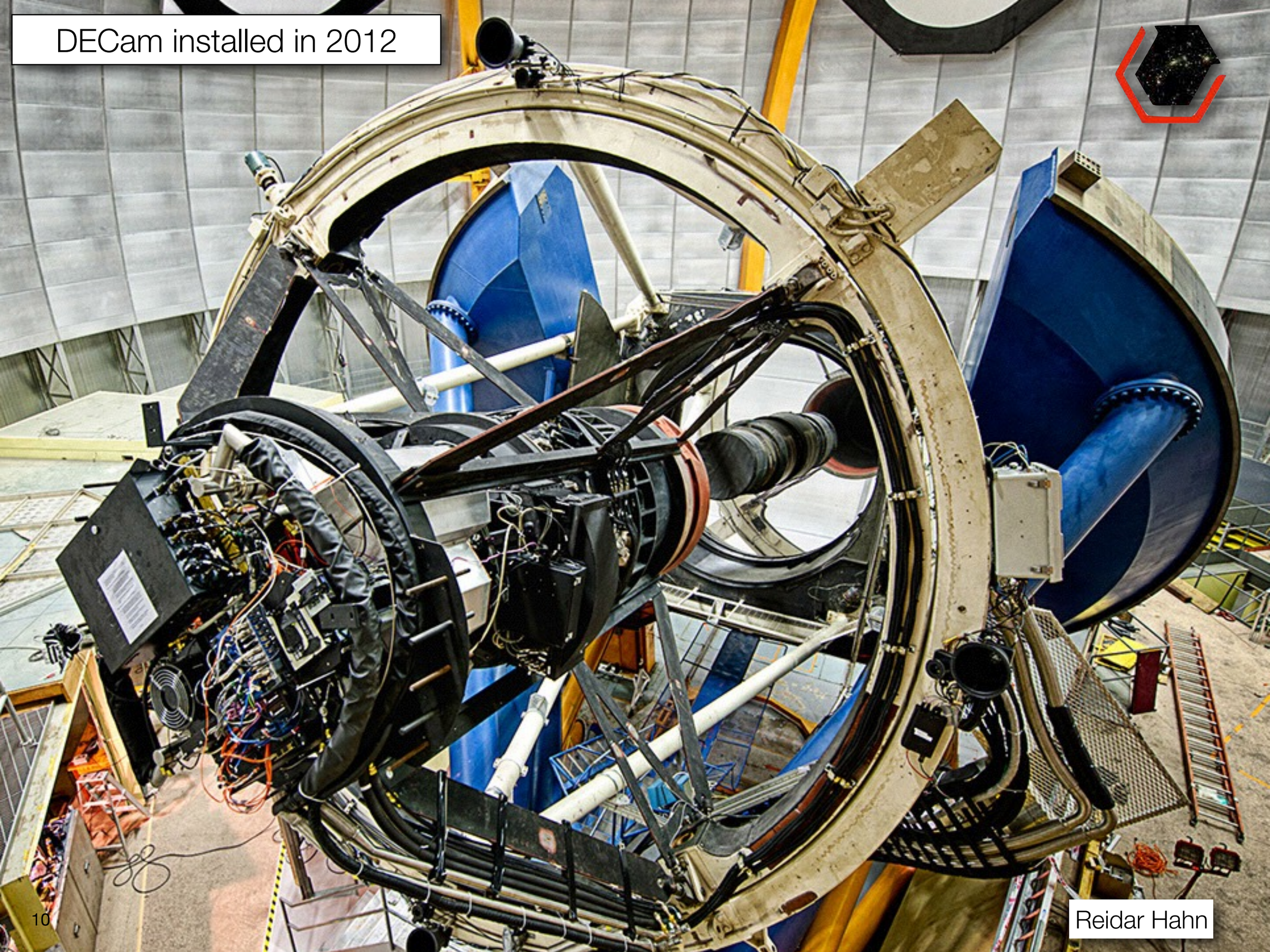
“Stage 3” era of systematics (2010 - 2020)

Table 11. Contribution of various source of measurement uncertainties to the uncertainty in Ω_m.

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

Notes. For the computation of $\sigma_{\rm stat}(\Omega_m)$, we include the diagonal terms of Eq. (13) in $C_{\rm stat}$.[(a)] We discuss an alternative model for the environmental dependence of the SN luminosity in Sect. 6.3.

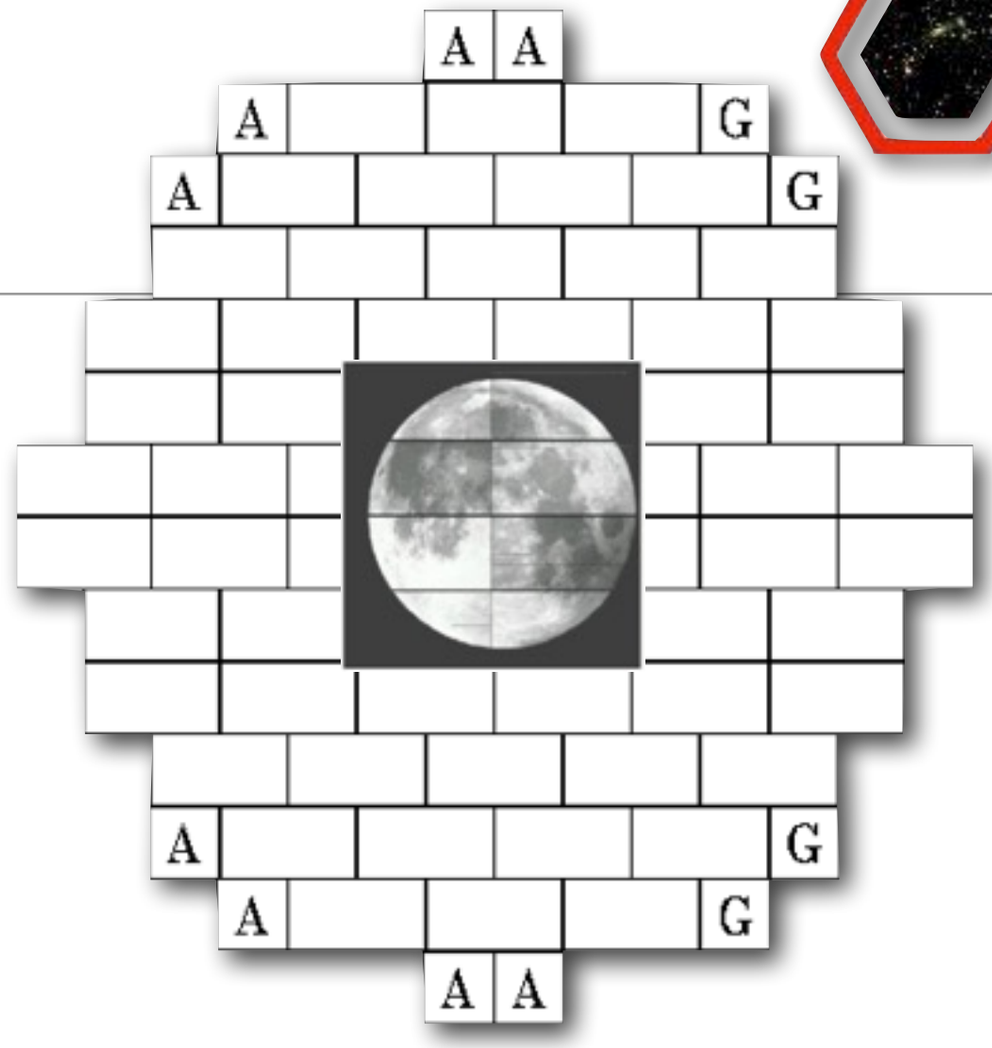
DECam installed in 2012

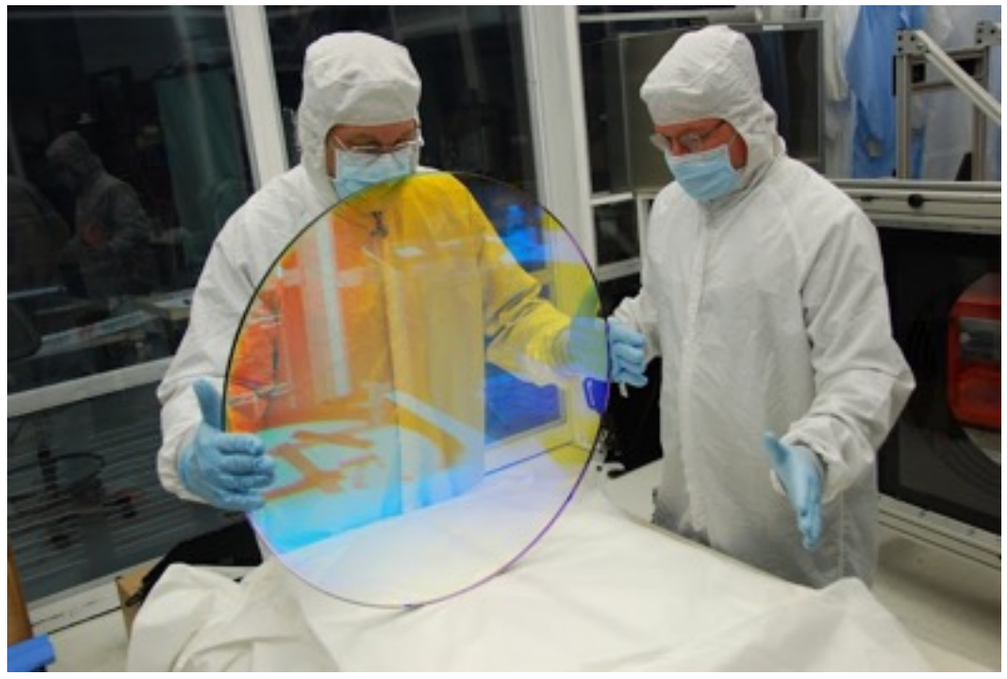


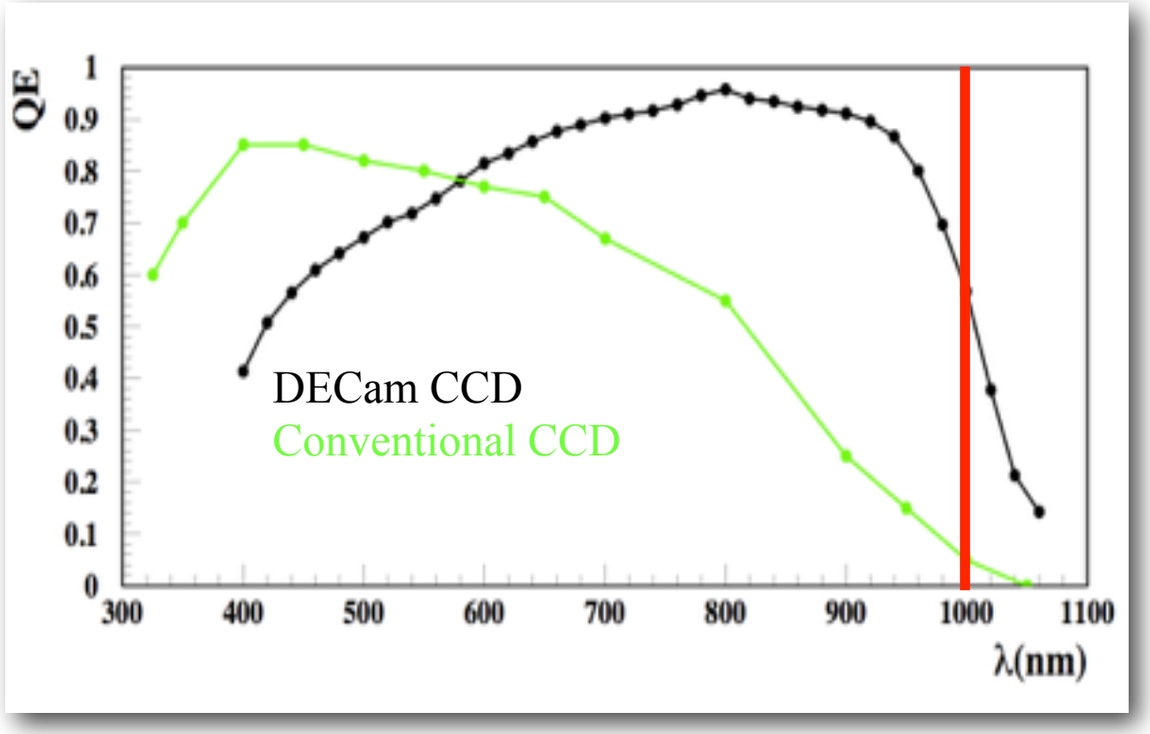
Reidar Hahn

Dark Energy Camera

- Imager
  - 74 Chips, 570 Megapixels
  - 3 sq. deg. FoV, 0.27''/pixel
  - Red-sensitive: QE > 50% @ 1000nm
- Filters
  - *grizY* bands: similar to SDSS
  - largest broadband filters for an astronomical instrument



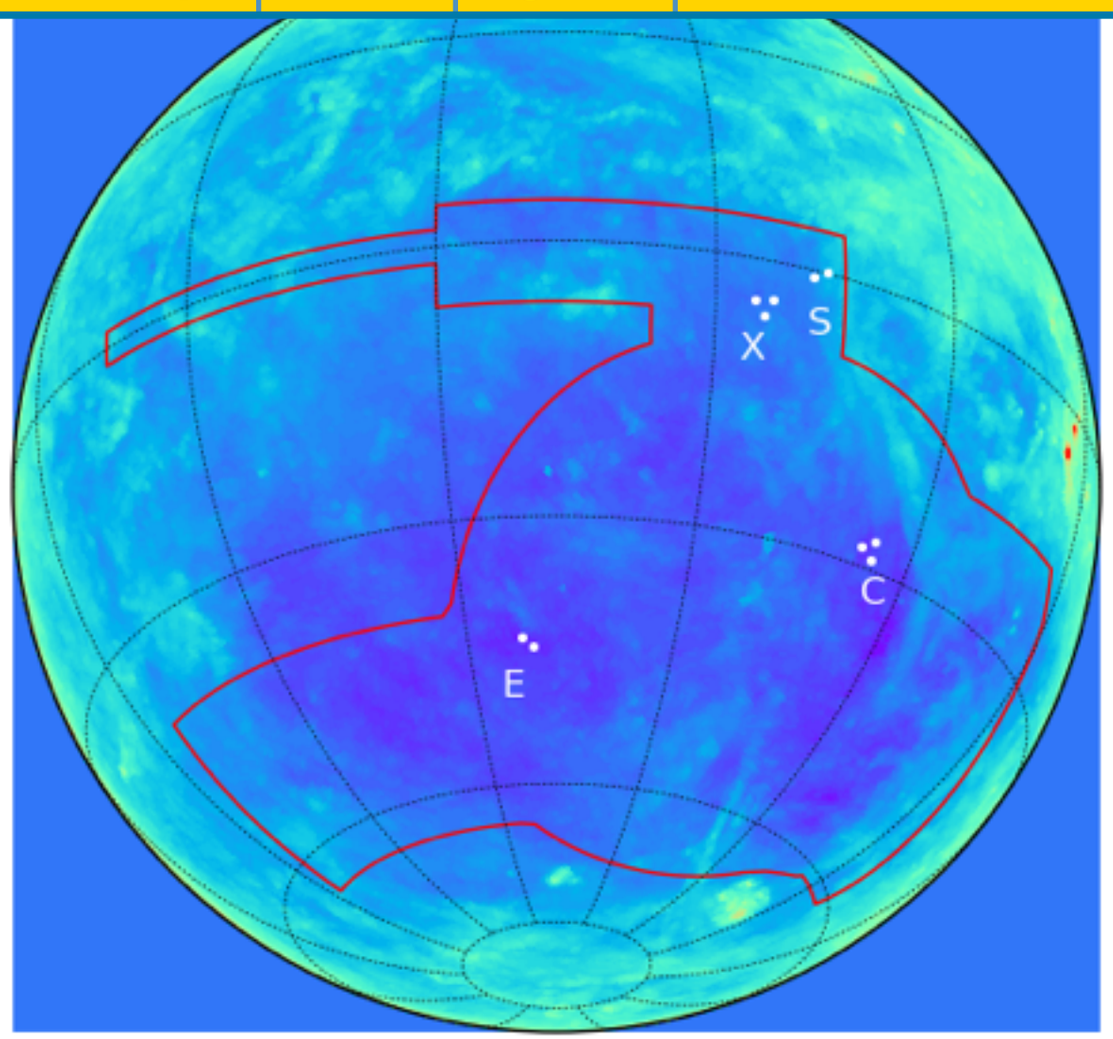


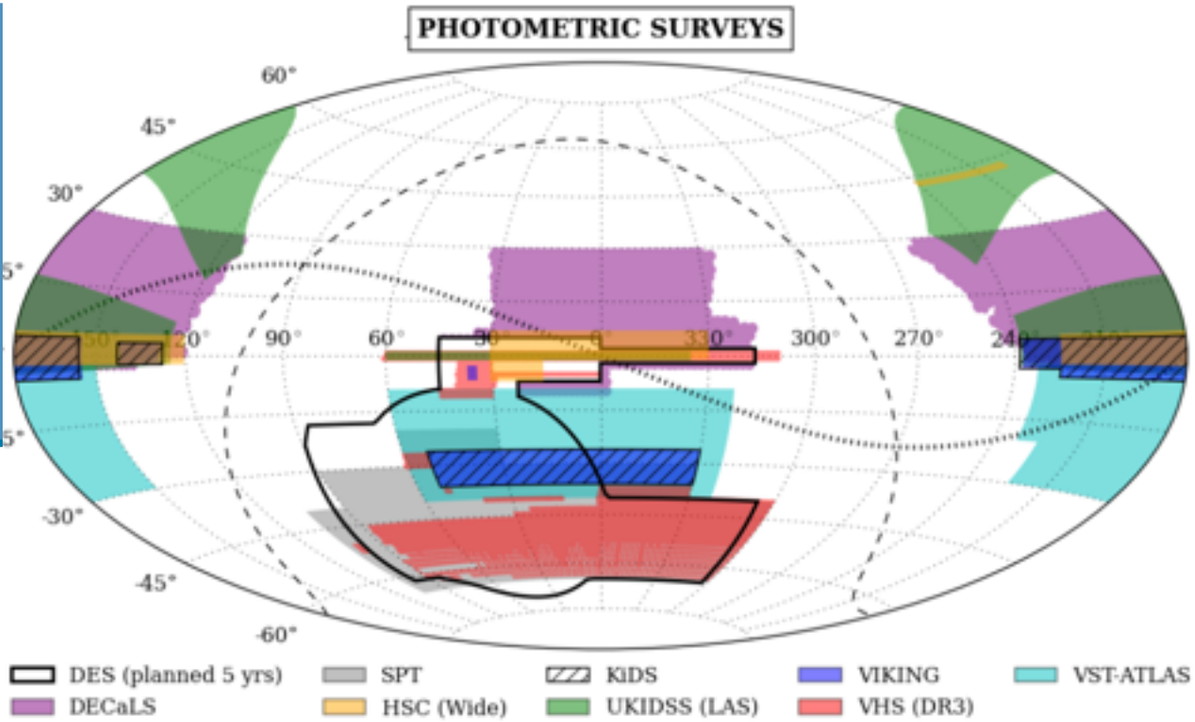


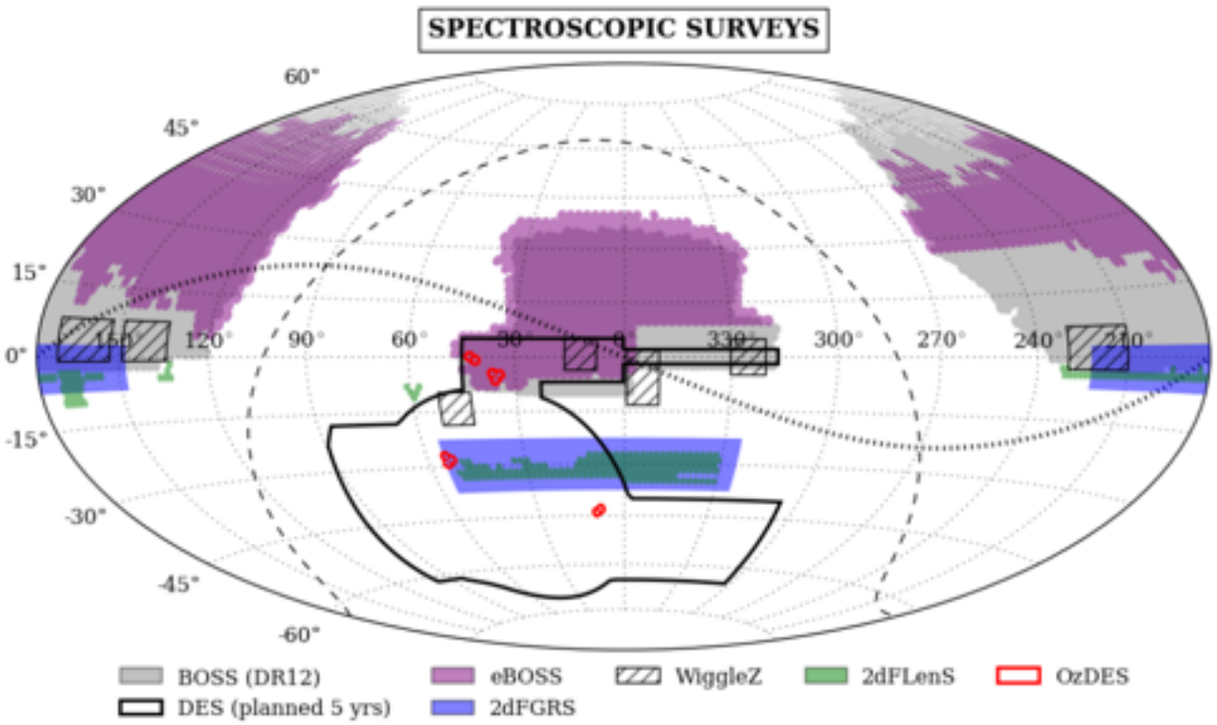
Survey Footprint

(525 nights at CTIO)

	area (deg^2)	filters	exposure time/visit (seconds)
Wide	5000	*grizY*	90/90/90/90/45
SN Shallow	24	*griz*	175/150/200/400
SN Deep	6	*griz*	600/1200/1800/3630







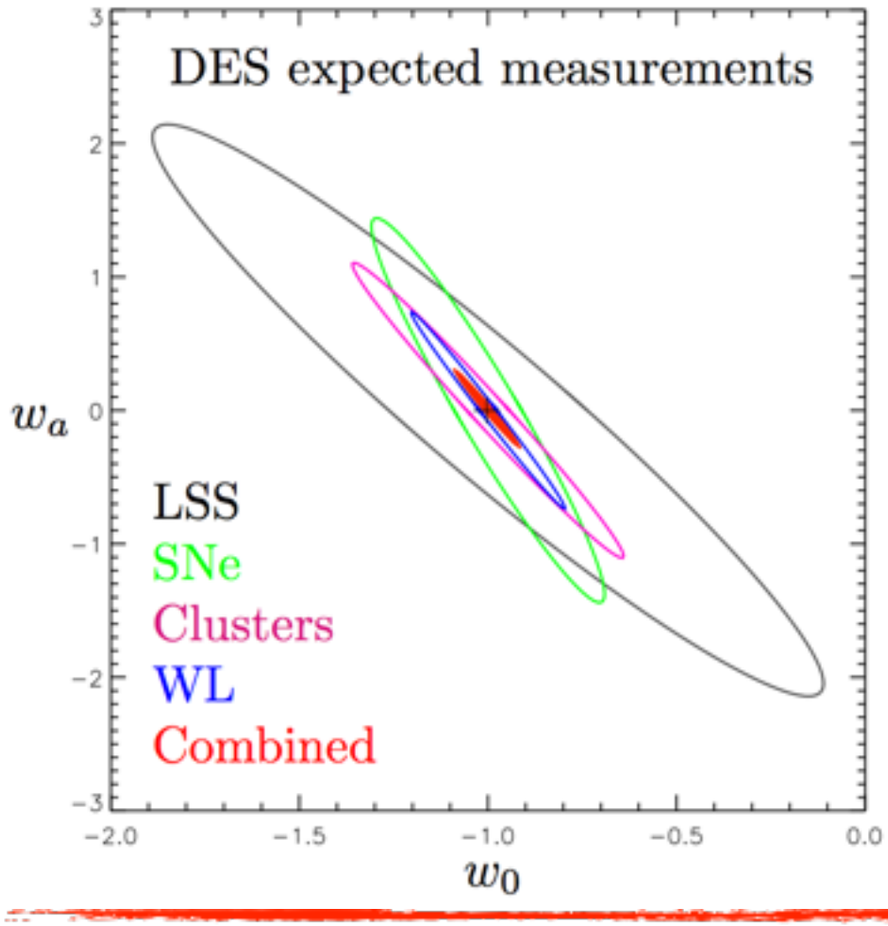
Expansion and Structure Growth

Multiple Probes, One Experiment

- *Weak Lensing:*
  - 200 million galaxy shapes
- *Galaxy Clusters:*
  - ~10,000 clusters to z>1
- *Supernovae:*
  - ~3000 well-sampled SNe Ia to z ~1
- *Large-scale galaxy distribution:*
  - 300 million galaxies to z > 1

Evolving DE equation of state:

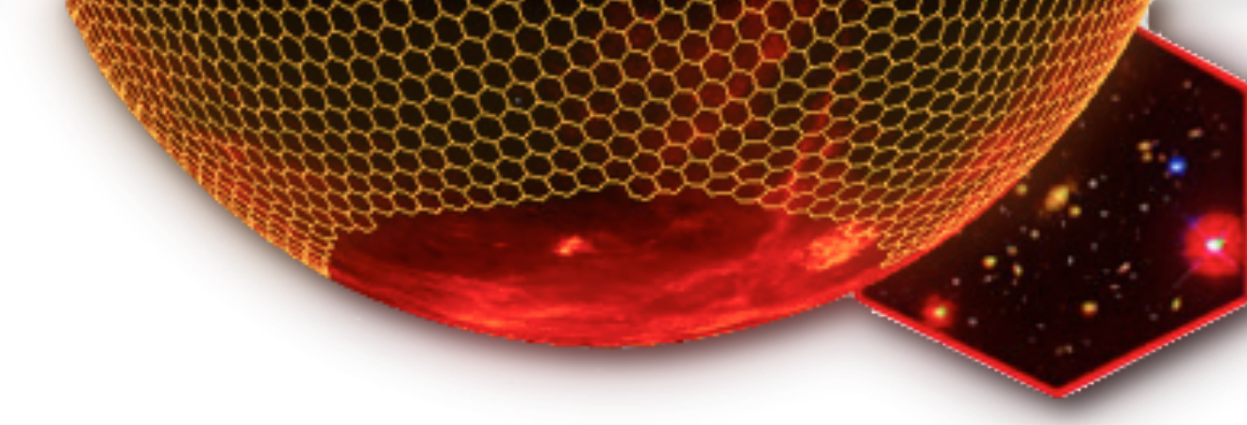
$$w(a) = w_0 + (1 - a)w_a$$



Predicted DES Constraints:

w_0 to ~5% (13% today)

w_a to ~30% (over 100% today)

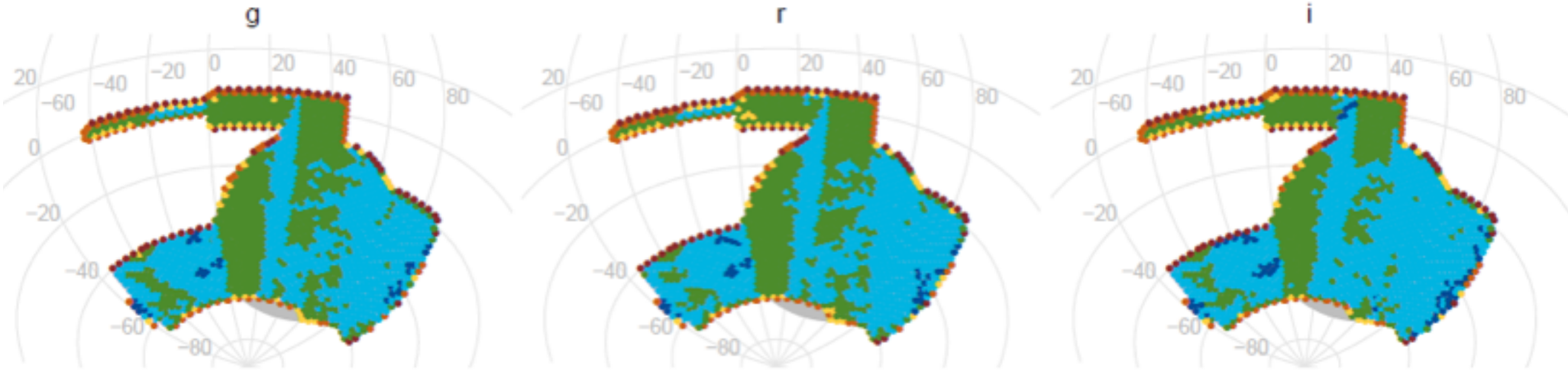


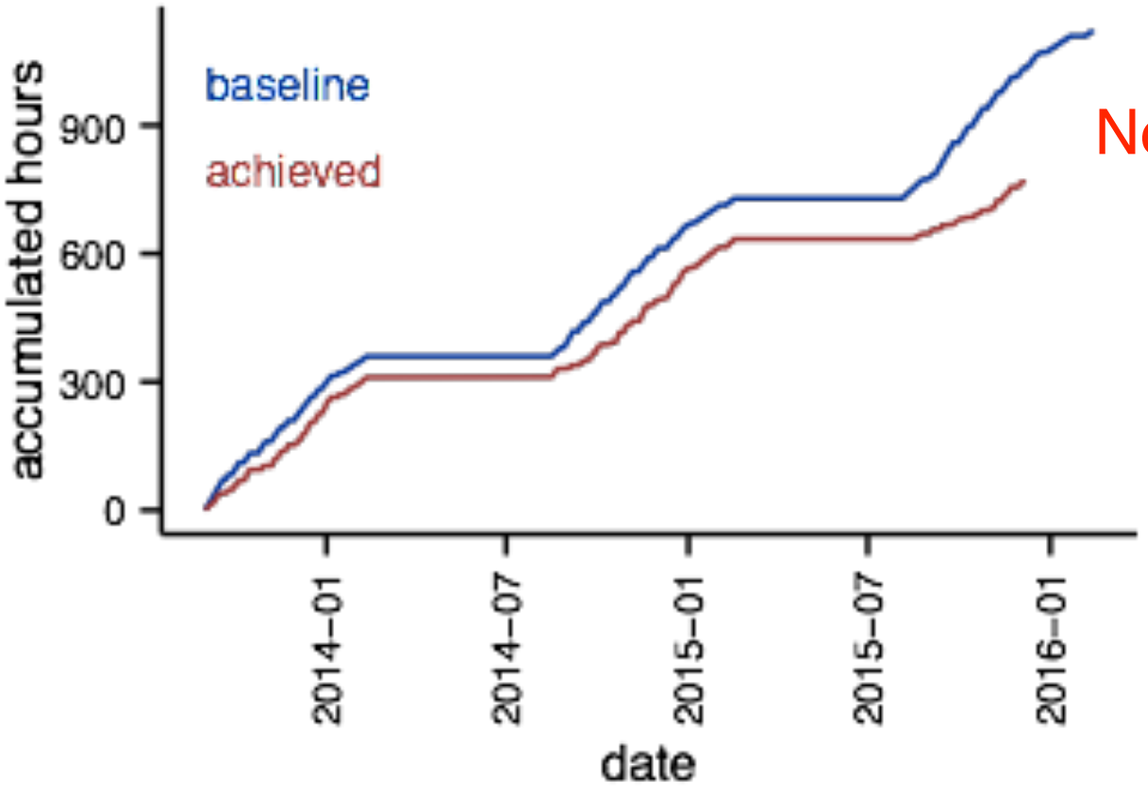
Survey Progress

Science Verification (SV) - 2012
Y1 - 2013/14 (Aug - Feb)
Y2 - 2014/15 (Aug - Feb)
Y3 - 2015/16 (Aug - Feb)
Y4 - 2016/17 (Aug - Feb)
Y5 - 2017/18 (Aug - Feb)
Y5.5?

Y1 through Y3

Tiling=One 90 sec exposure over entire footprint

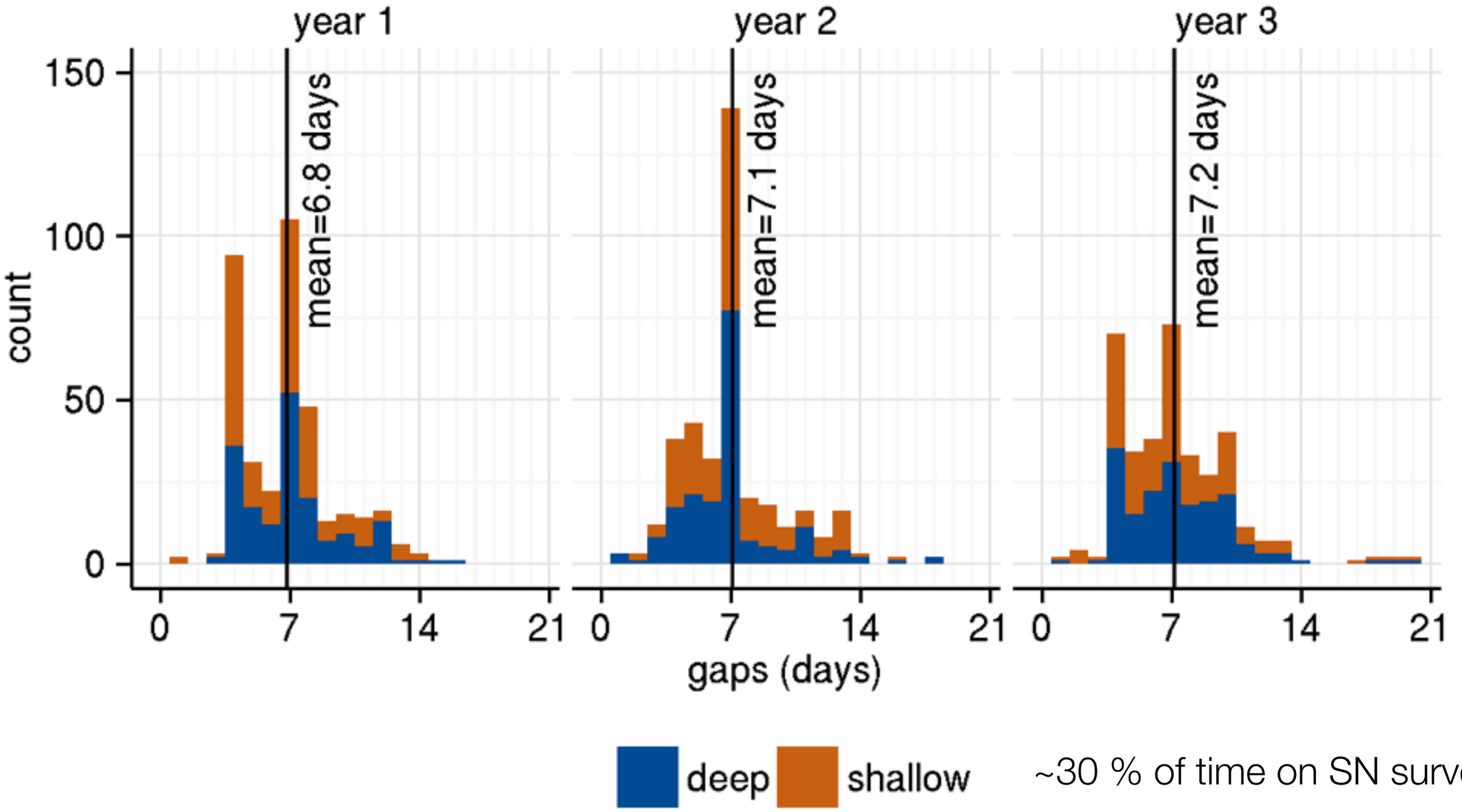




Need for Y6

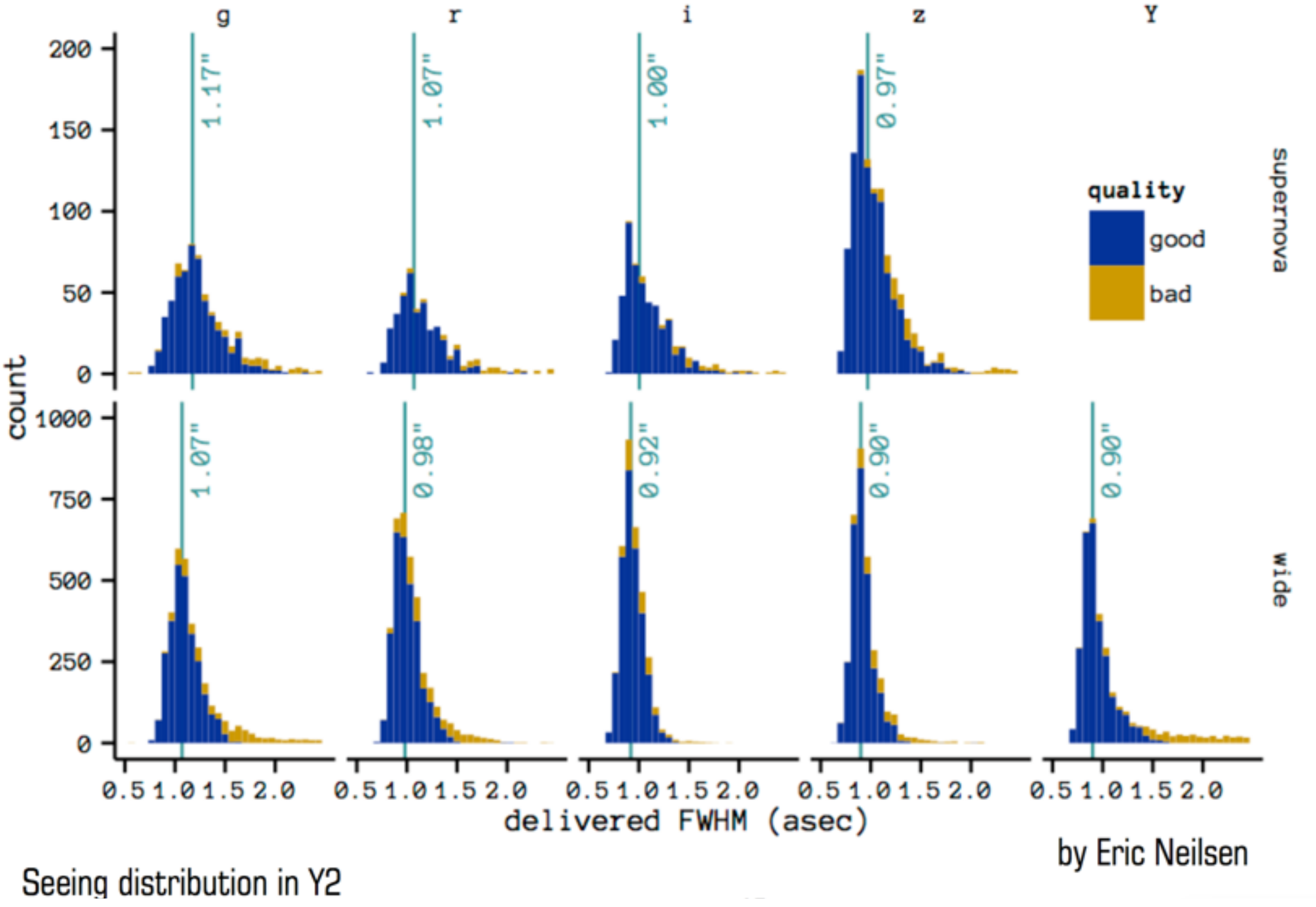
4-6 tilings in all bands over whole survey. No holes but slightly behind schedule because of El Nino). Planning for Y6

SN Cadence



~30 % of time on SN survey

Seeing



Delivering at science requirements

Astrometry

[Bernstein++2017; arXiv:1703.01679]

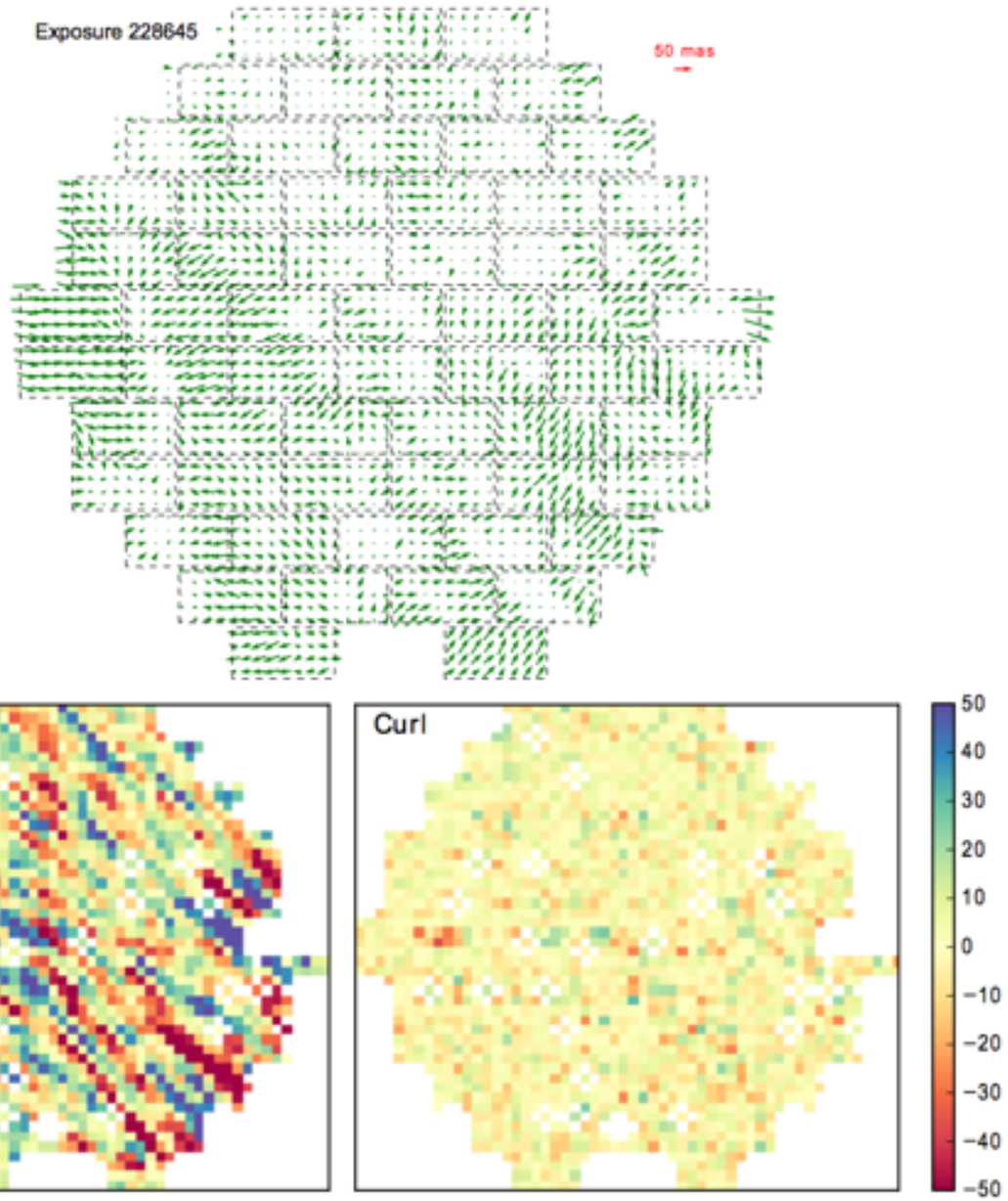
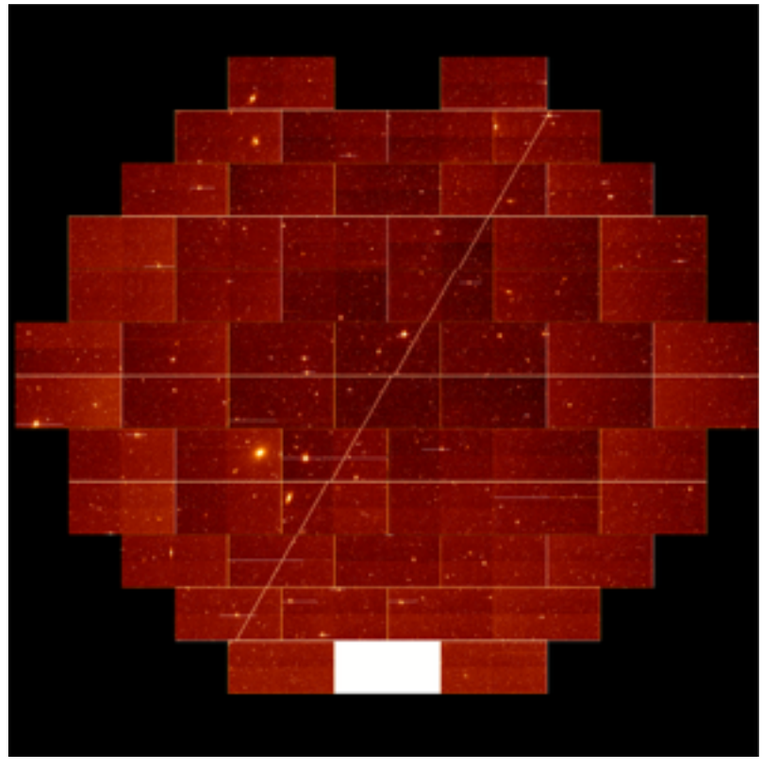


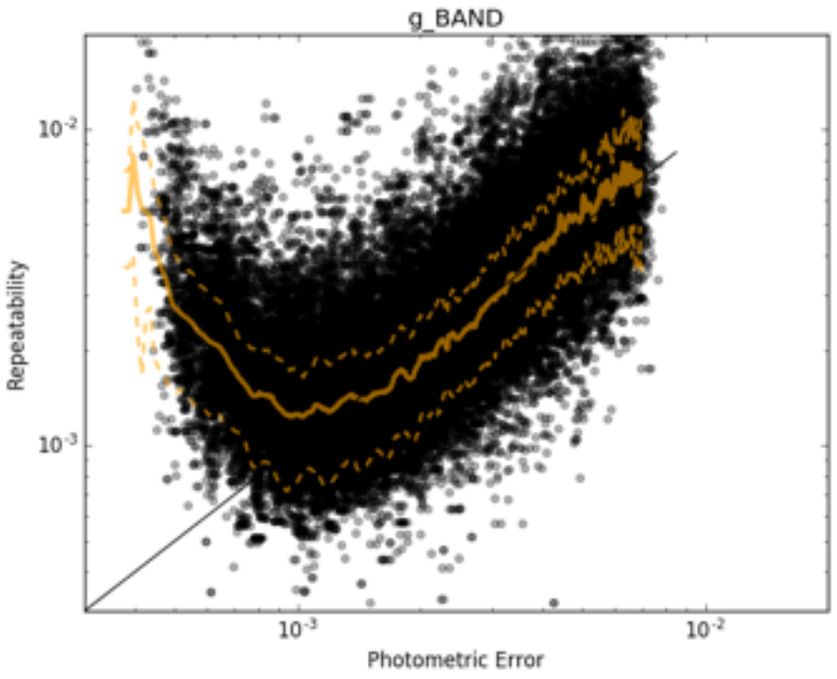
Fig. 10.— At top are the astrometric residuals of detections in a representative exposure (228645, z band), averaged in bins of focal-plane position. Below are the divergence and curl of this vector field, plotted on a common scale. The continuity of the vector field across chip boundaries, the curl-free nature of the field, and the streaky pattern of divergence strongly support the hypothesis that these distortions arise from atmospheric turbulence.

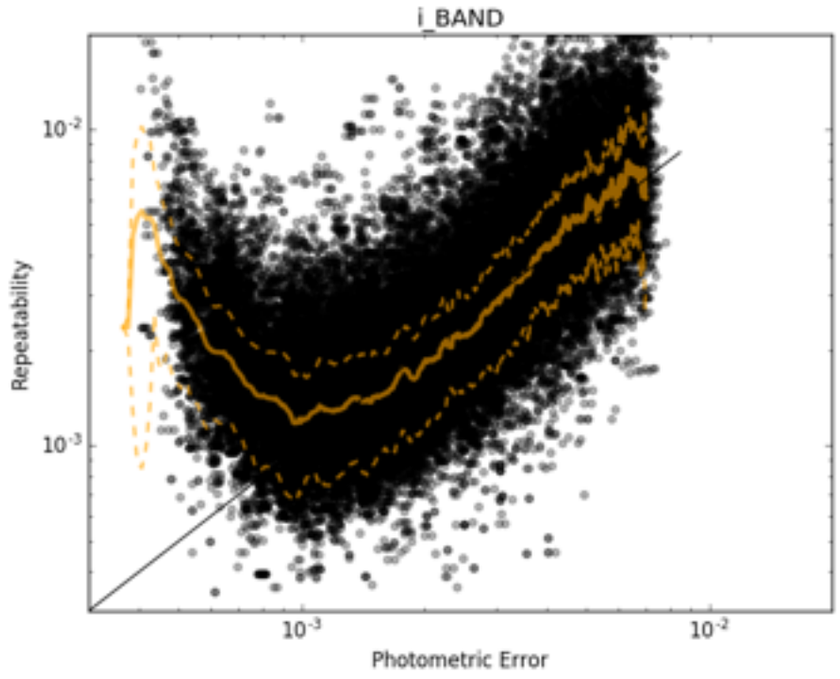


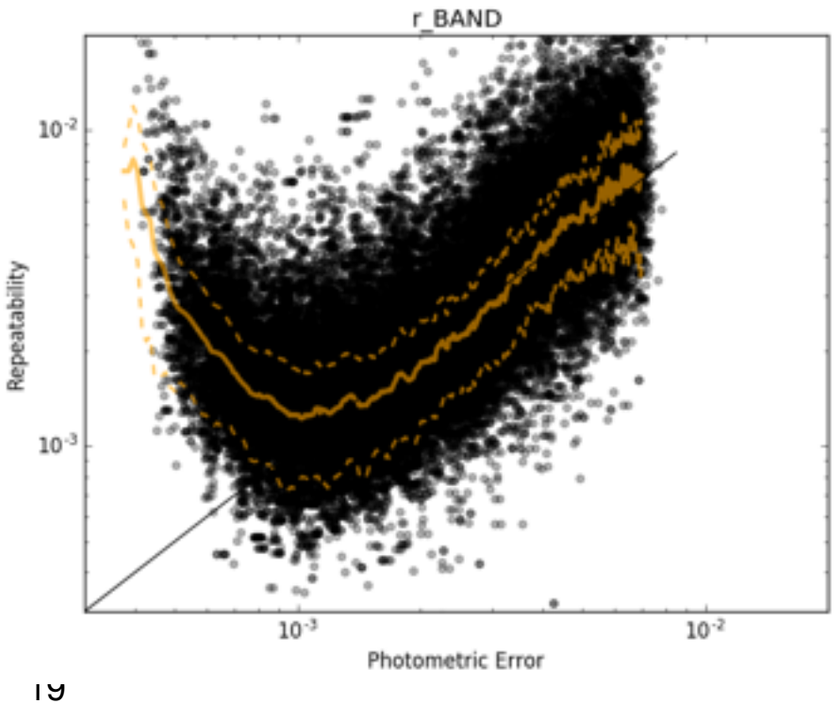
3-6 mas (0.02 pixel) in a single exposure

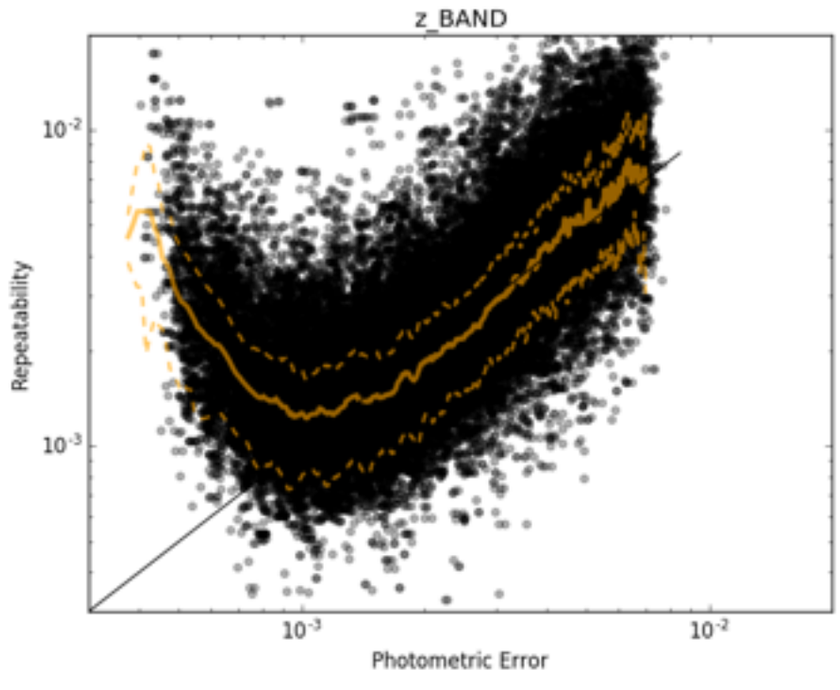
Photometry

[Brout, Lasker, Scolnic]





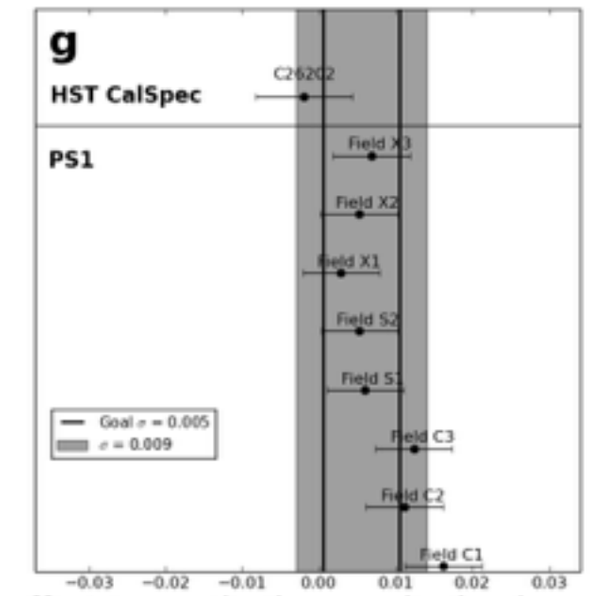


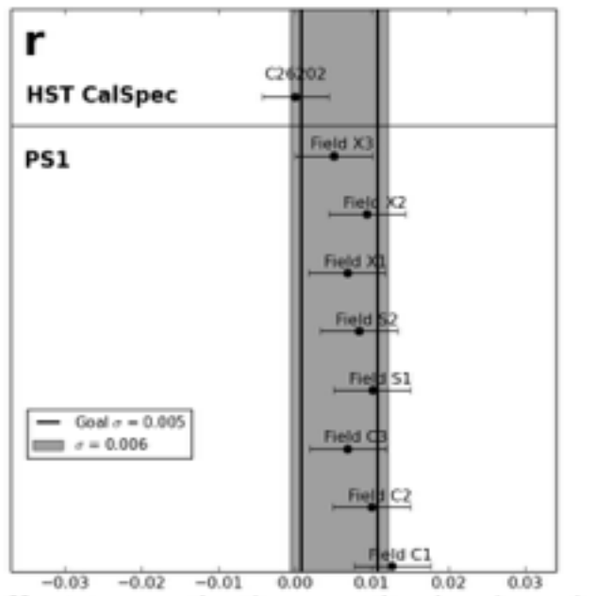


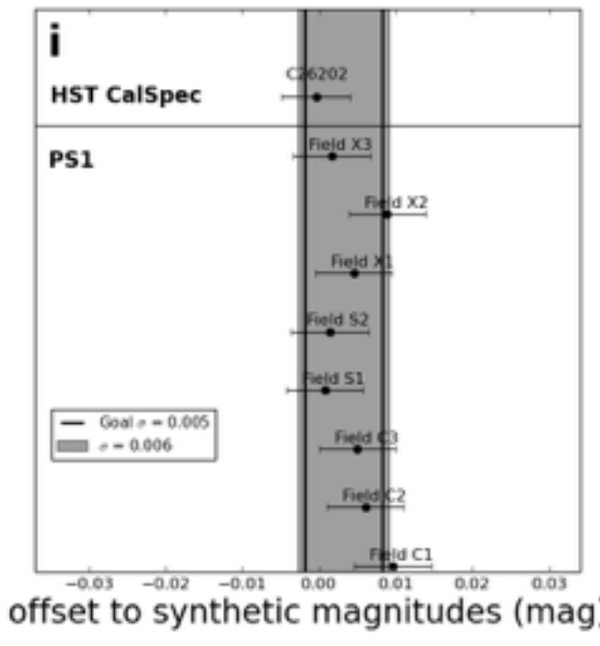
Relative
(millimag repeatability)

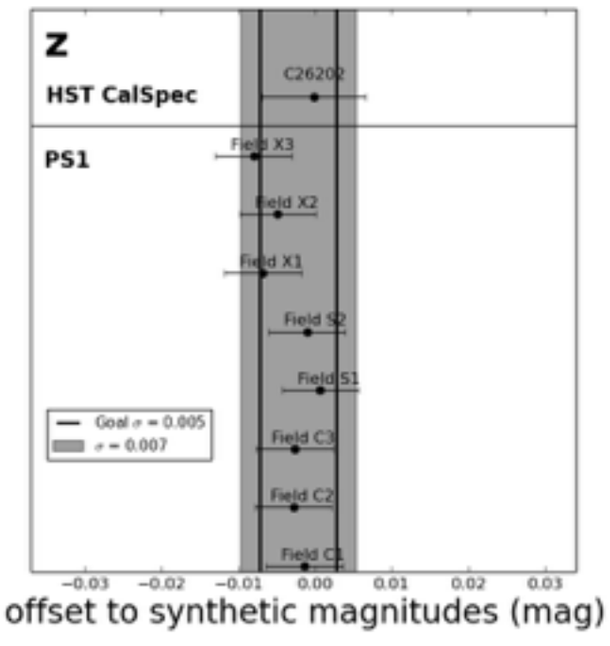
Photometry

[Brout, Lasker, Scolnic]

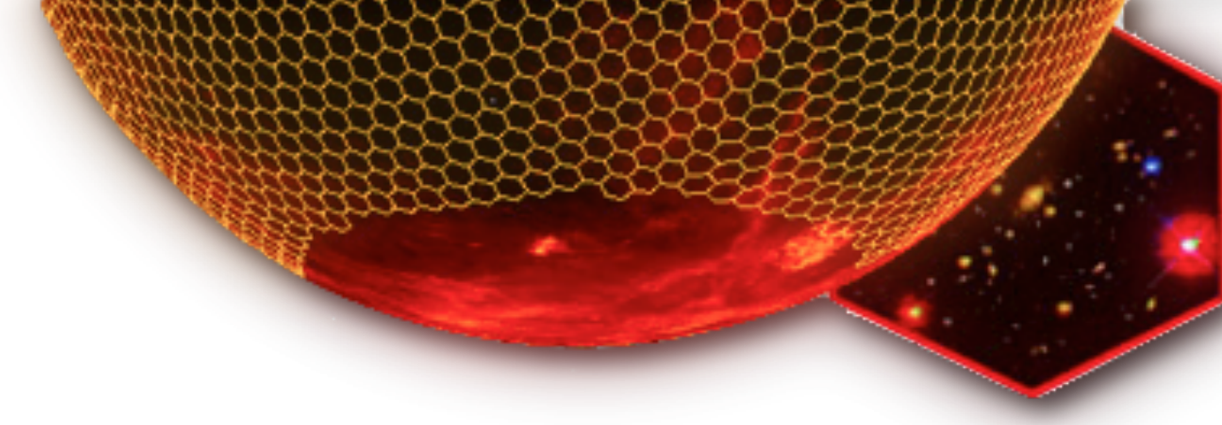








Absolute
(millimag cross-calibration)



Early Results from DES

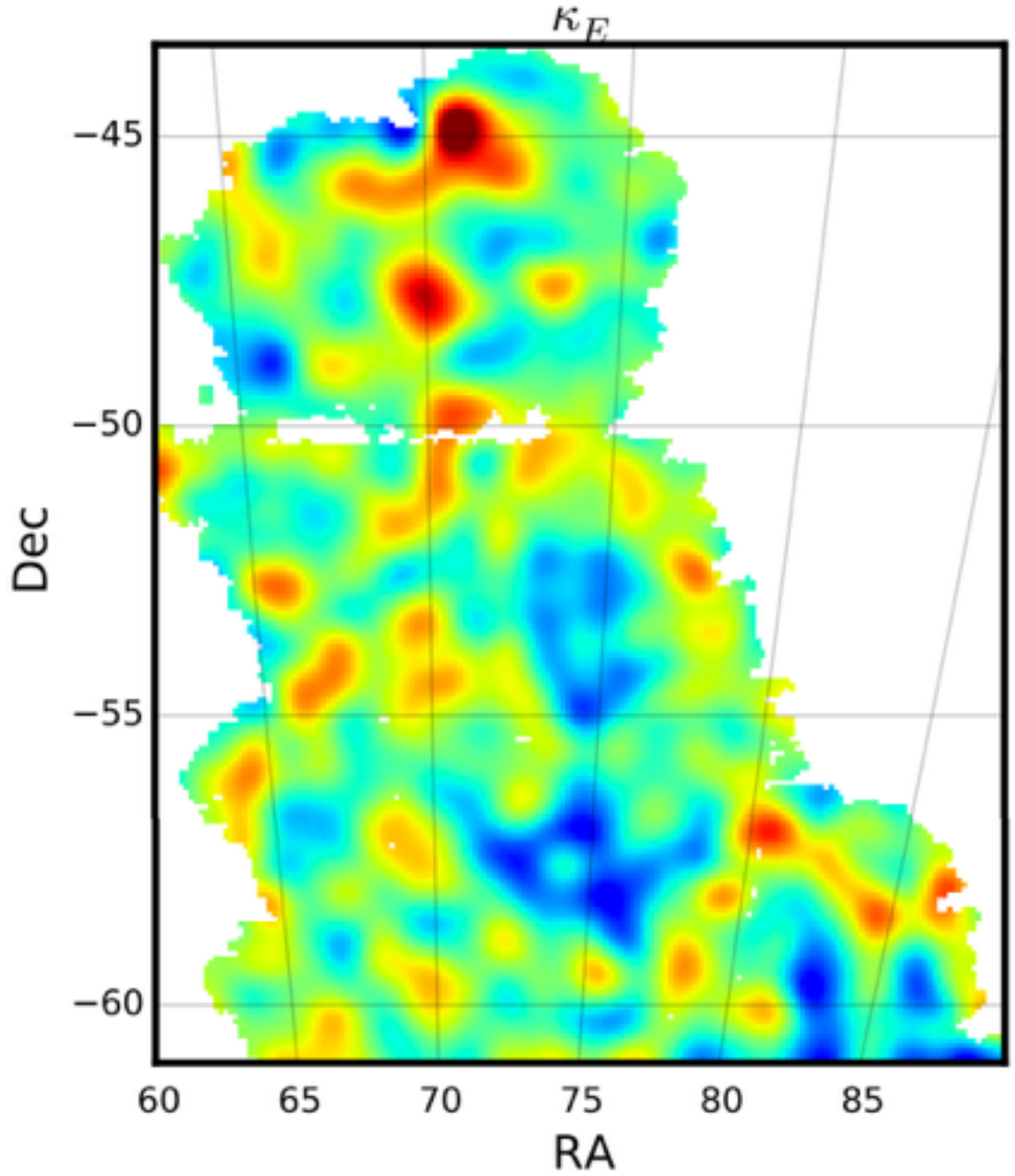
Weak Lensing
Galaxy Clustering
Strong Lensing
Supernova

Mapping dark matter with SV data

[Vikram++2015; arXiv:1504.03002]

- redder = higher matter density, higher lensing signal
- bluer = voids

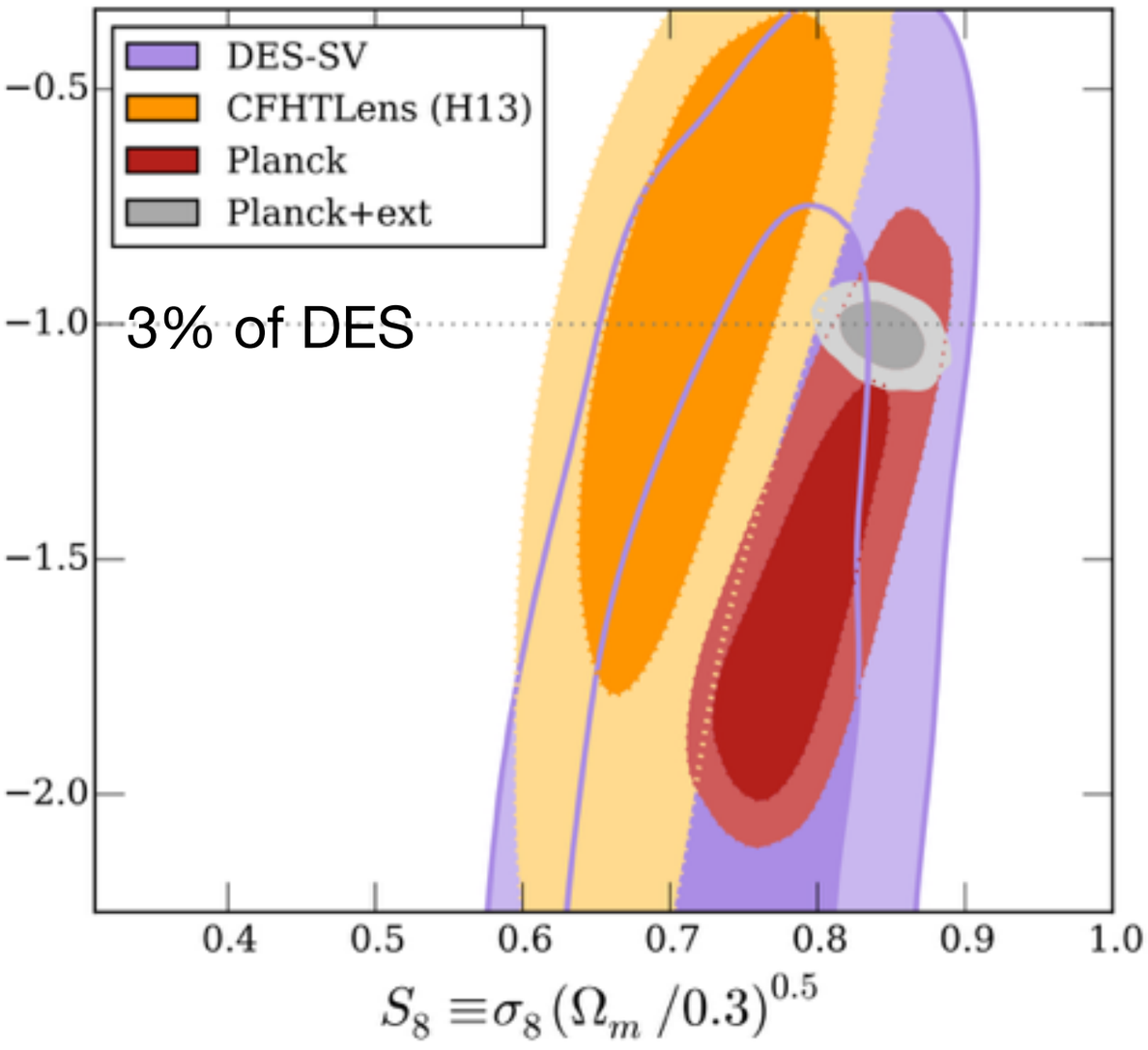
- <u>One of the largest contiguous map of dark matter ever created</u>
  - 139 sq. degs (only 3% of DES area)
  - 3 million galaxies with shape measurements
  - 6.8 sigma correlation with galaxies
- <u>Analysis:</u>
  - compare with CMB lensing and DE evolution [Kirk++2015, arXiv: 1512.04535]
  - 2-point correlation functions of shear measure the large-scale structure in the region of the foreground lensing galaxies:

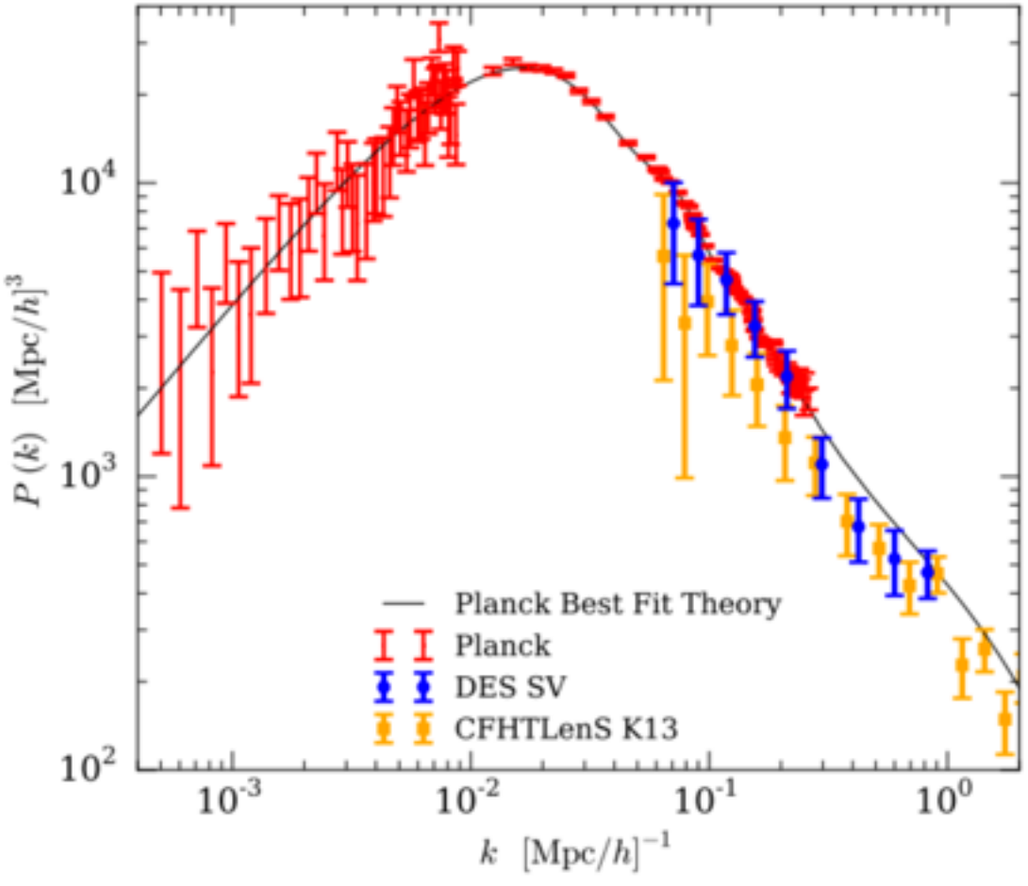


Cosmological Constraints from Shear

[DES Collaboration, 2015 arXiv:1507.05552]

- current constraints on dark energy
  - **CFHTLenS: deep galaxy survey 154 sq. deg, ~7.5 million galaxies, 6 redshift bins**
  - **Planck**
  - **DES: 139 sq. deg. ~3 million galaxies, 3 redshift bins**





$$S_8 = 0.81 \pm 0.06$$

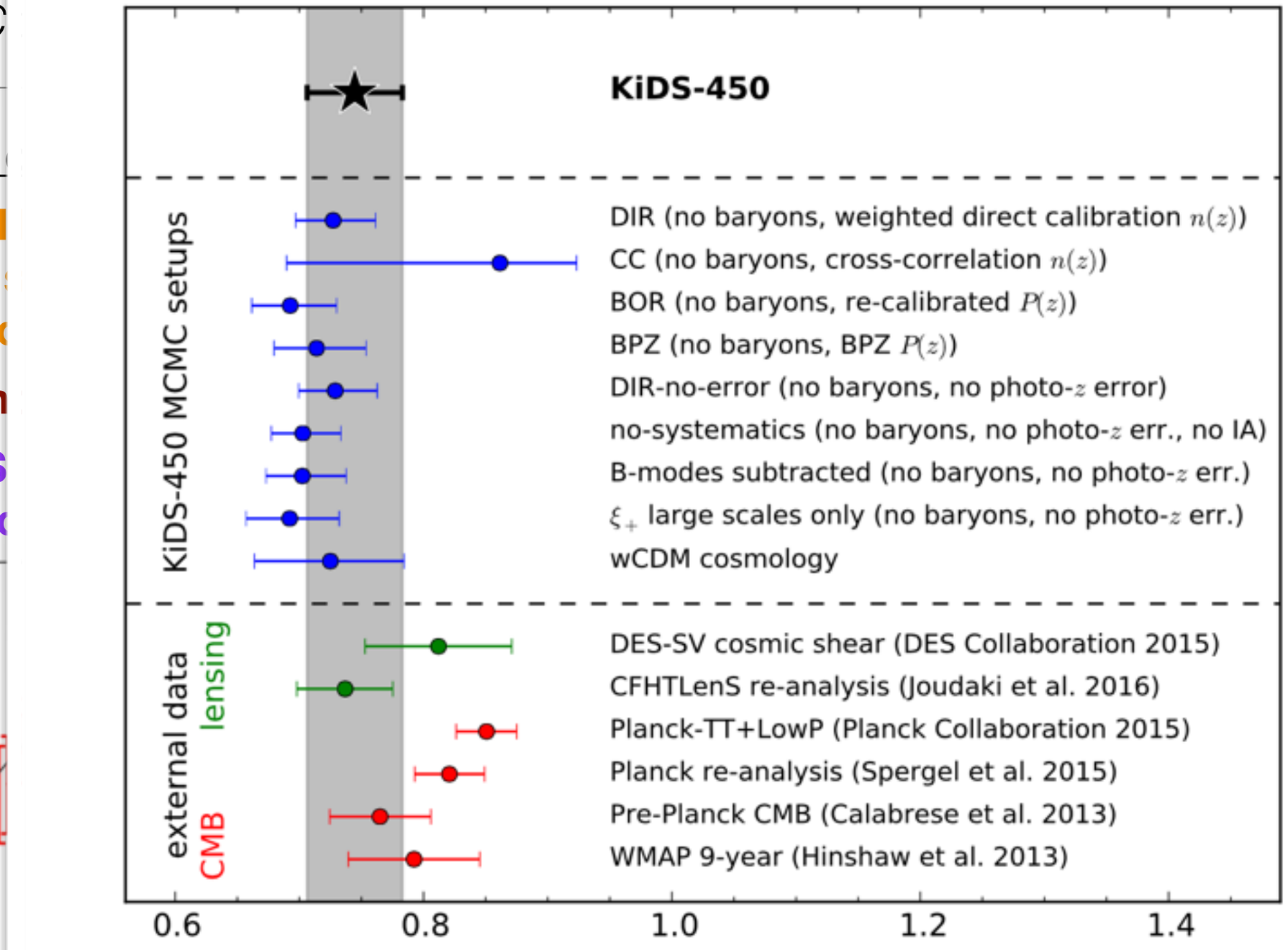
Marginalised over nuisance: shear calibration, photo-z calibration, intrinsic alignment, non-linear matter power p(k)

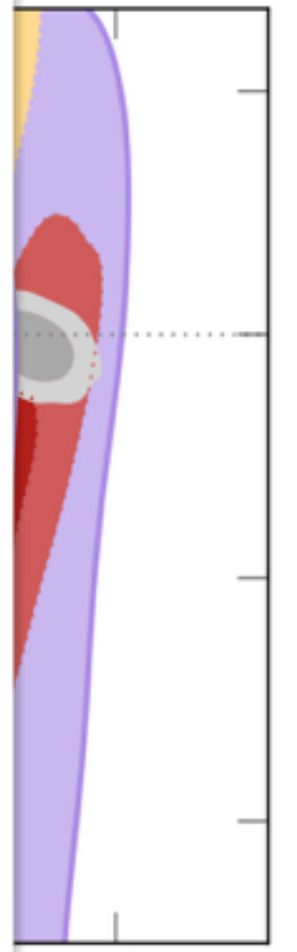
Marginalised over three cosmological parameters

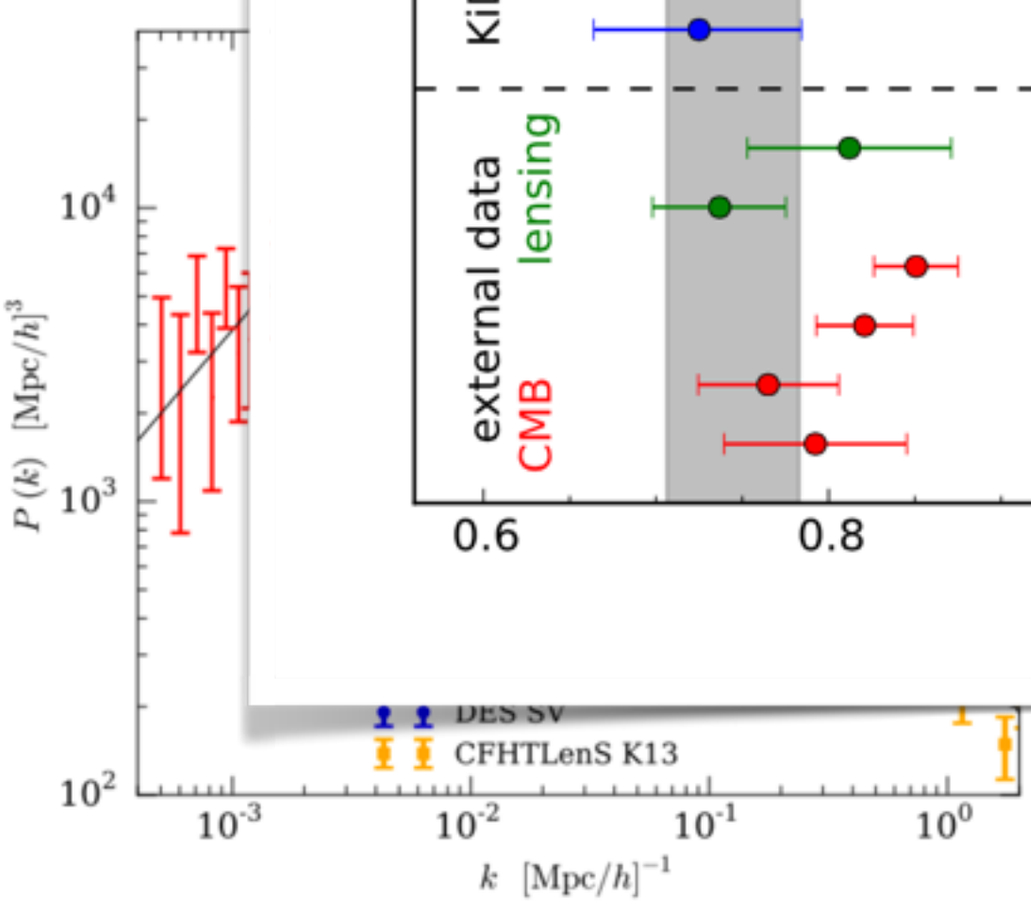
Cosmological Constraints from Shear

[DES C

- current
  - **CFH**
    154
    6 rec
  - **Plan**
  - **DES**
    3 rec







Hildebrandt et al. 2016

$\pm$ 0.06

Marginalised over nuisance: shear calibration, photo-z calibration, intrinsic alignment, non-linear matter power p(k)

Marginalised over three cosmological parameters

Cross-correlations in DES

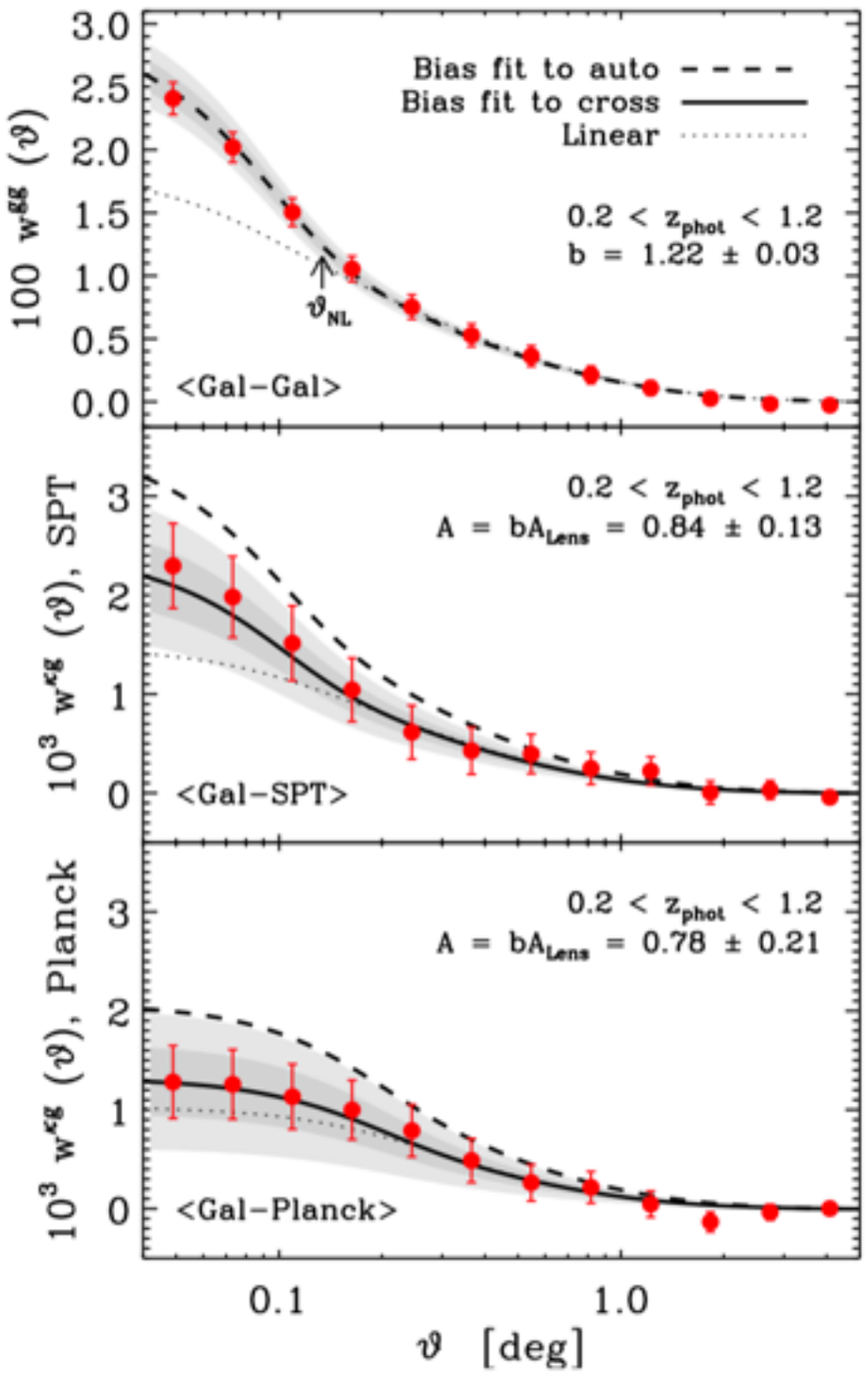
[Giannantonio++2015 arXiv:1507.05551]

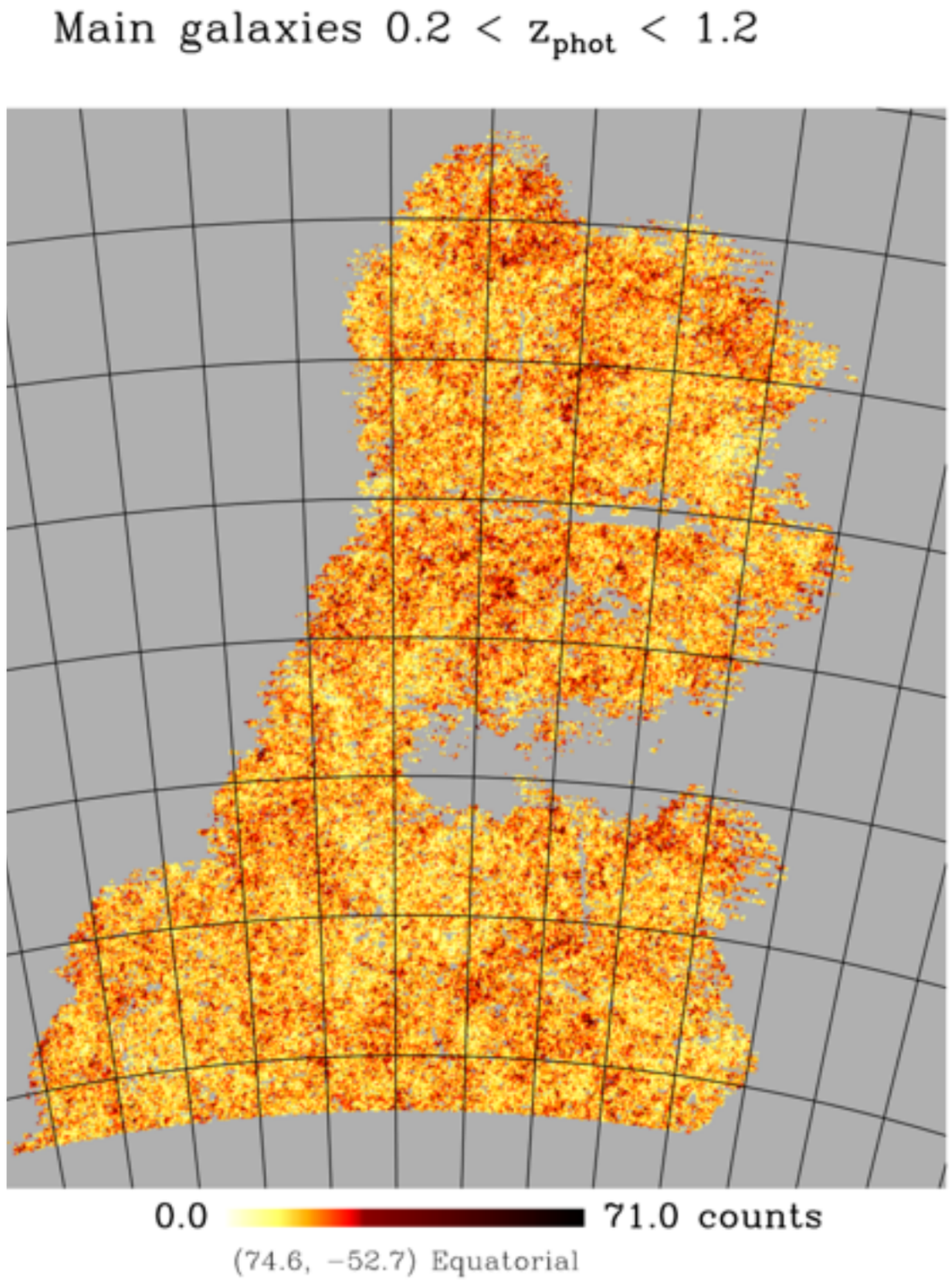
<u>SV data</u>

Gal-Gal

Gal-SPT
(6 sigma)

Gal-Planck
(4 sigma)





Cross-correlations in DES

[Giannantonio++2015 arXiv:1507.05551]

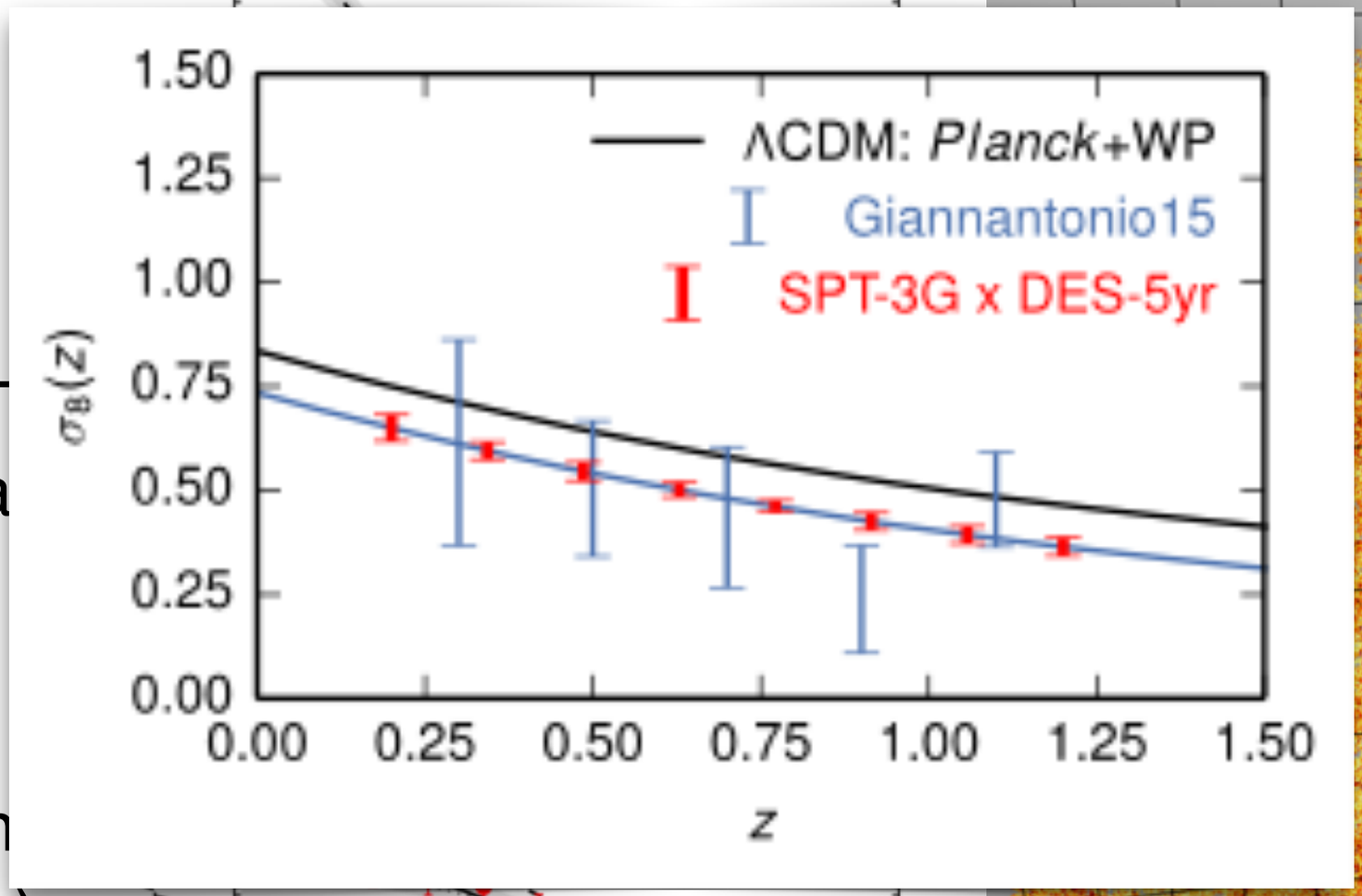
Lower growth than predicted by Planck?

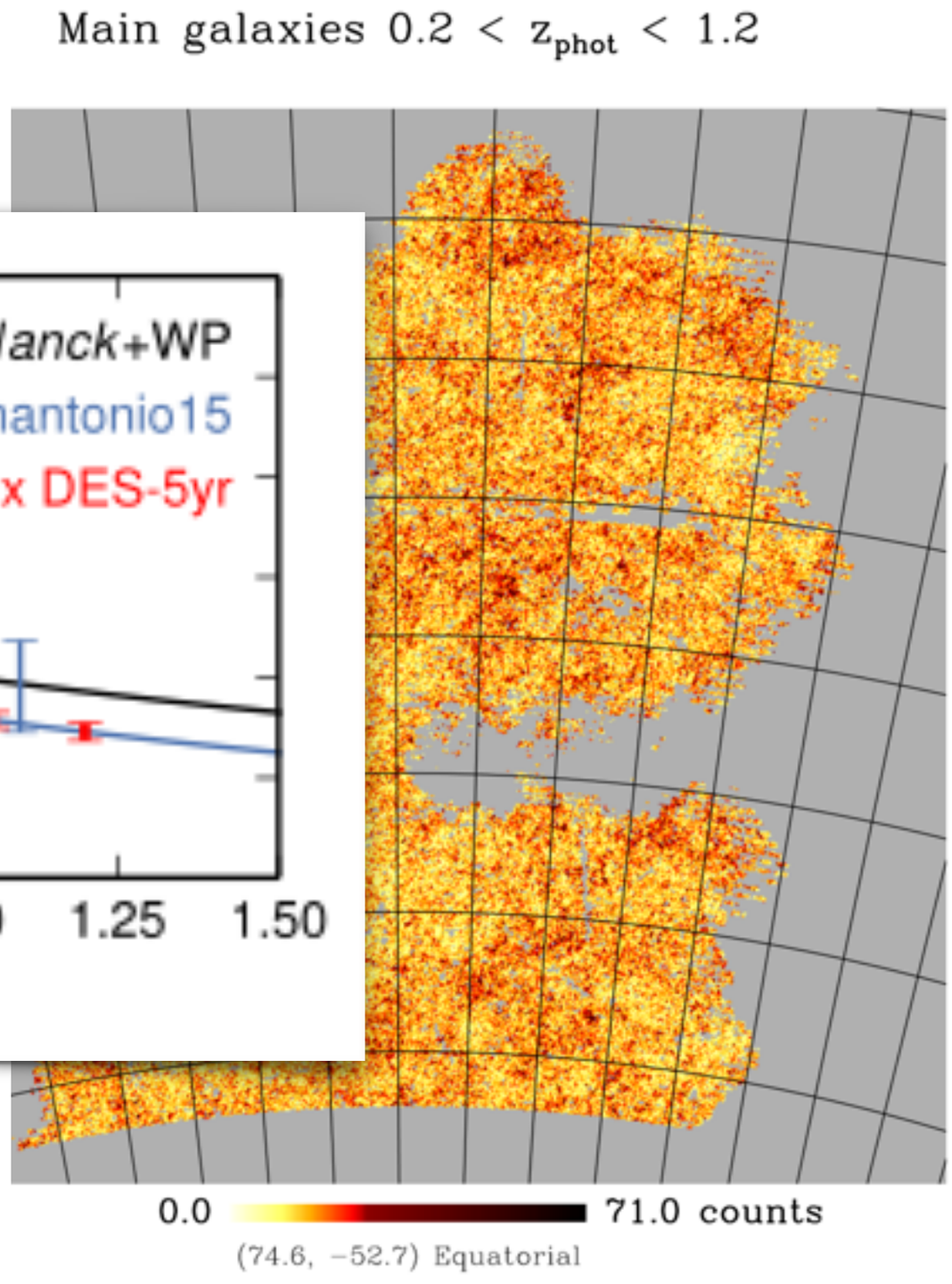
<u>SV data</u>

Gal-Gal

Gal-SPT
(6 sigma

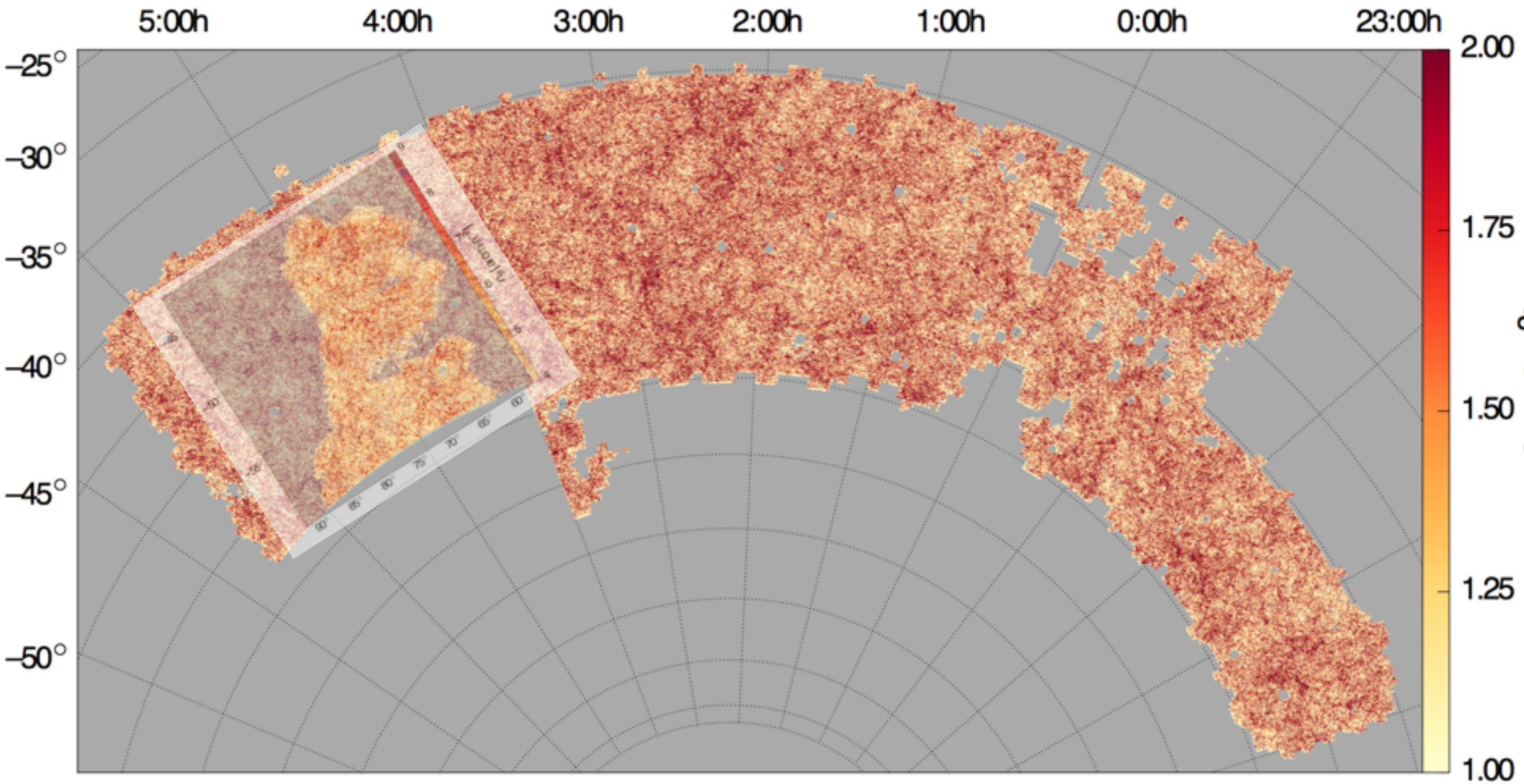
Gal-Plan
(4 sigma)





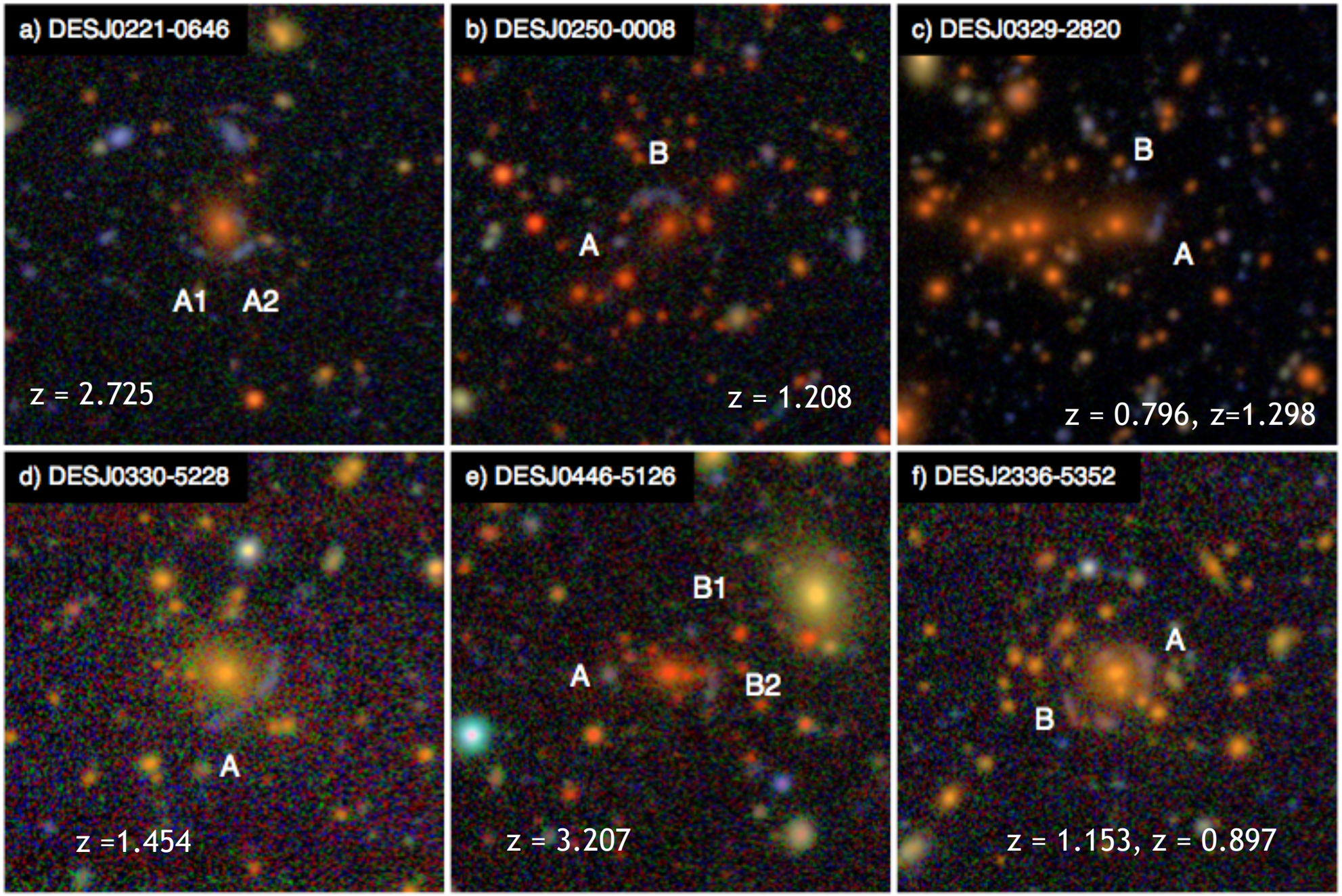
Y1 results soon (1500 deg^2)

First data release



Confirmed Lensing Systems in DES SV

[Nord++,2015; arXiv:1512.03062]



~2000 lenses (galaxy- to cluster-scale), **~120 lensed QSO and ~ few lensed SNe**

Cusp or Merger?

[Collett++,2017;submitted]

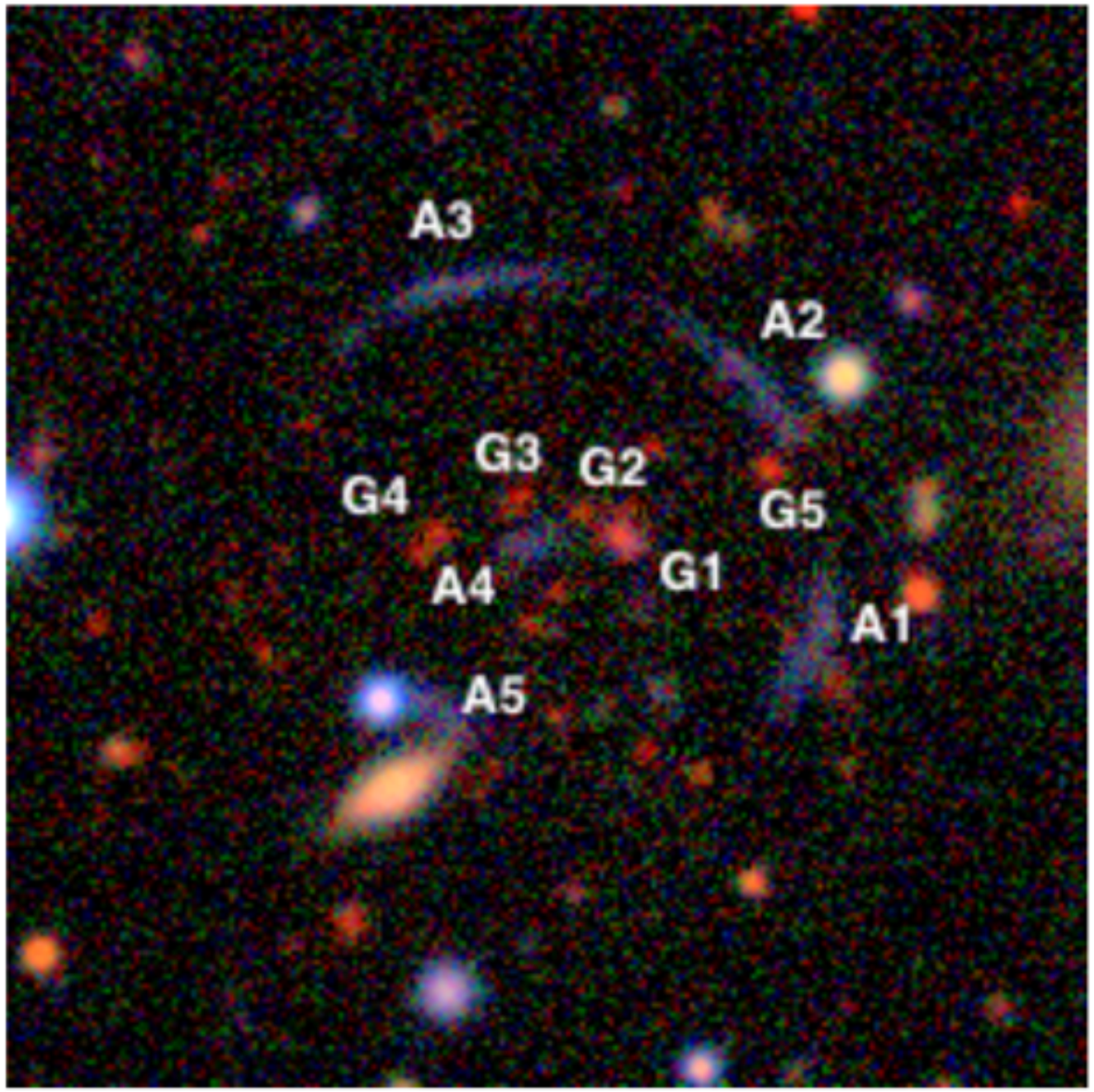


FIG. 1.— Pseudo-colour *gri* composite image of the lens J2011, taken from the first three years of operation of DES. The image is 1 arcminute on a side.

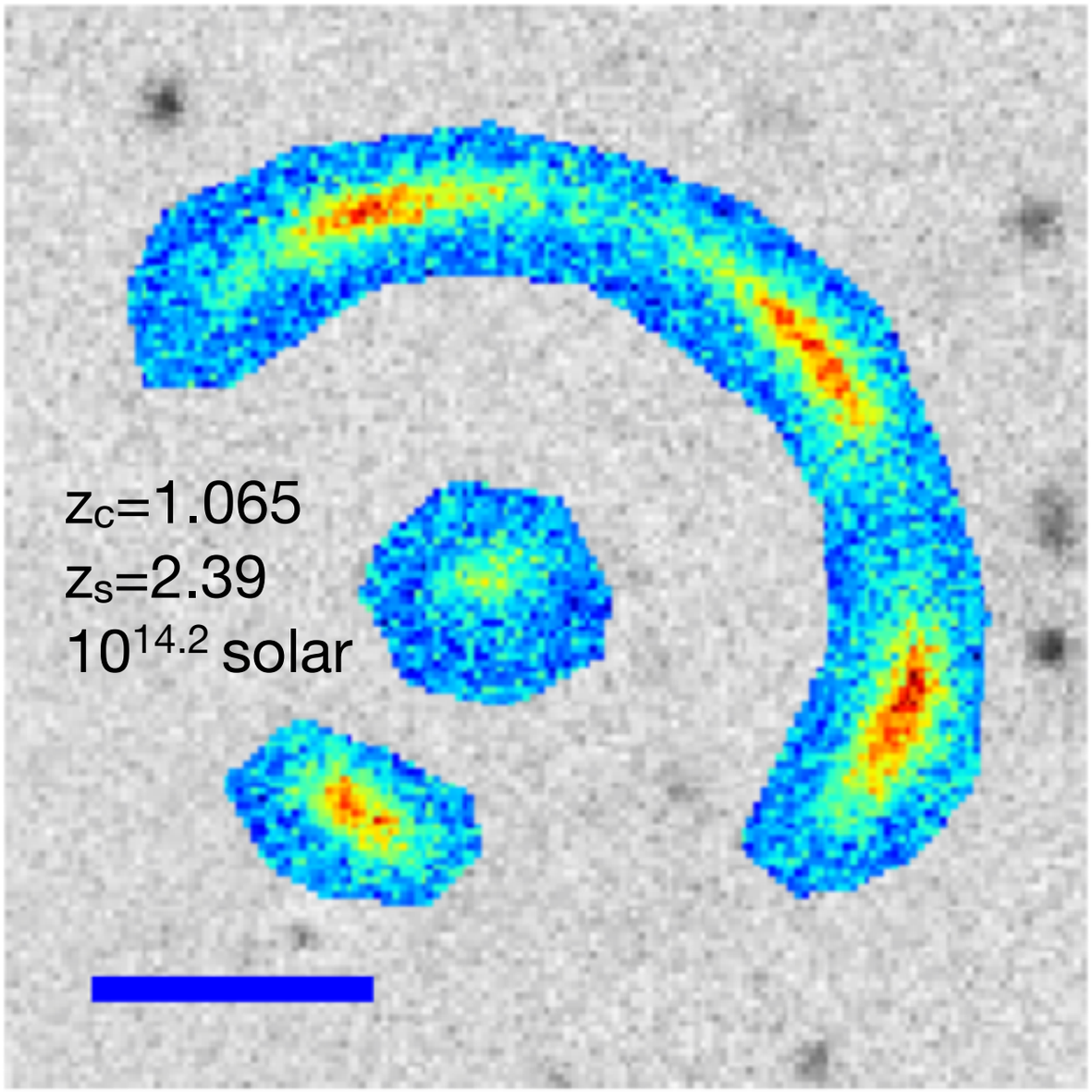
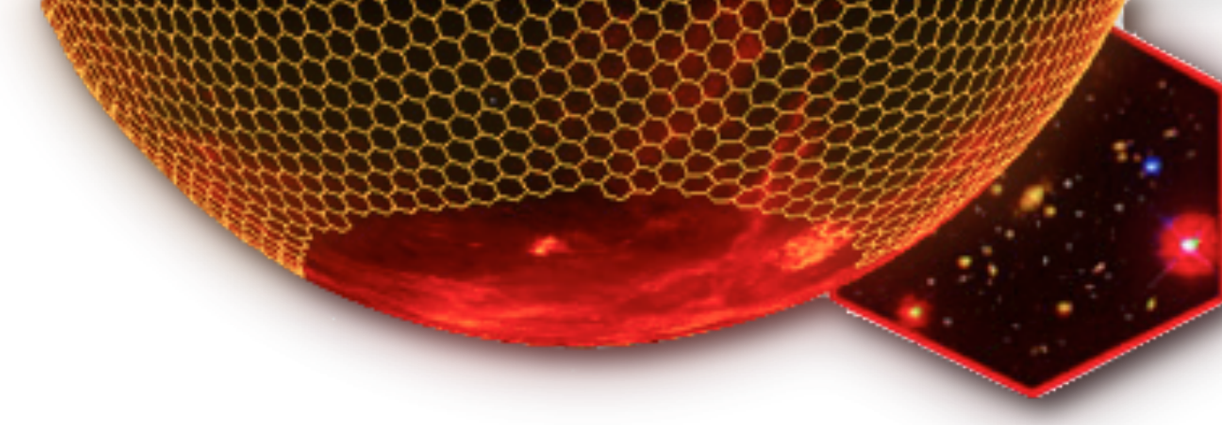


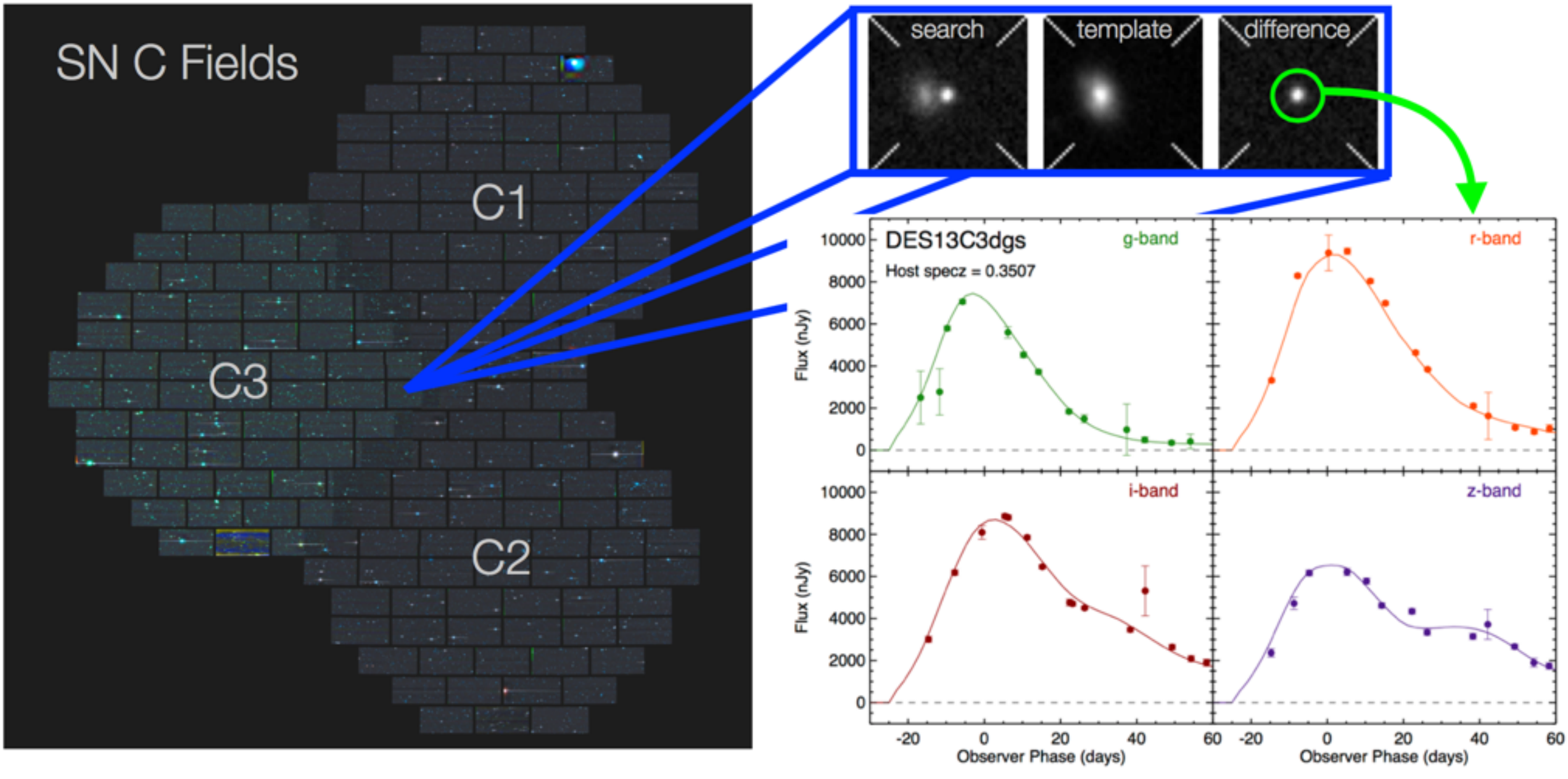
FIG. 2.— *g* band image of the arcs and central image, after subtracting foregrounds. Only the coloured pixels are included in the lens modelling of Section 3. The blue bar shows a ten arcsecond scale.



Supernovae in DES

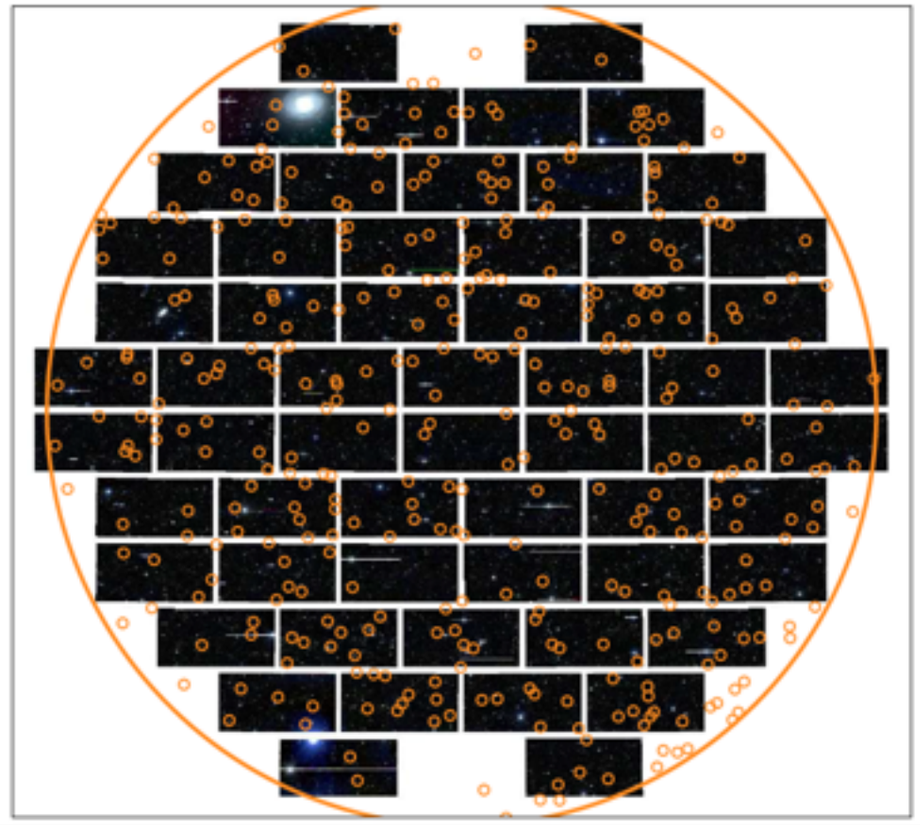
Supernovae

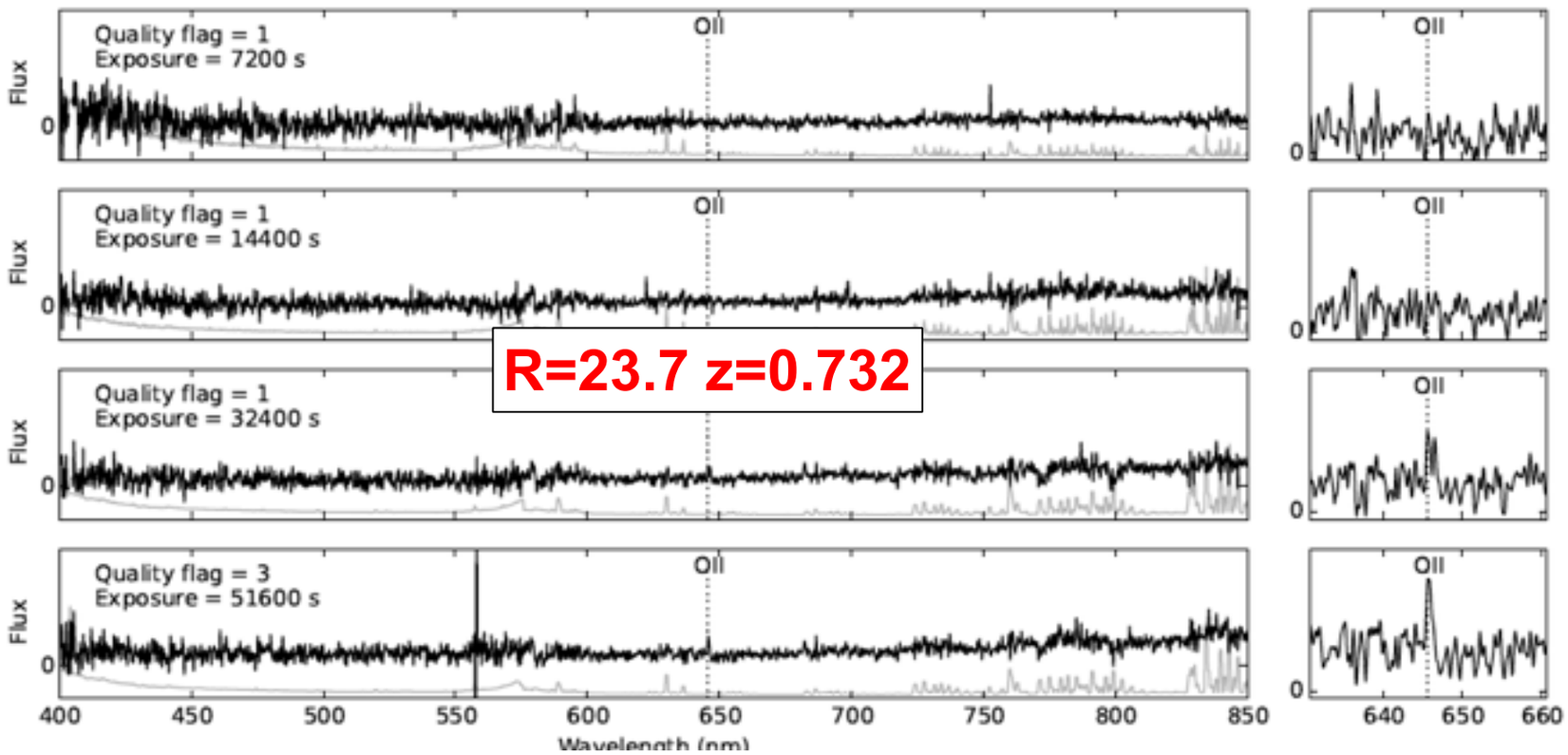
Fields monitored for ~5 months
each week for last 4 years



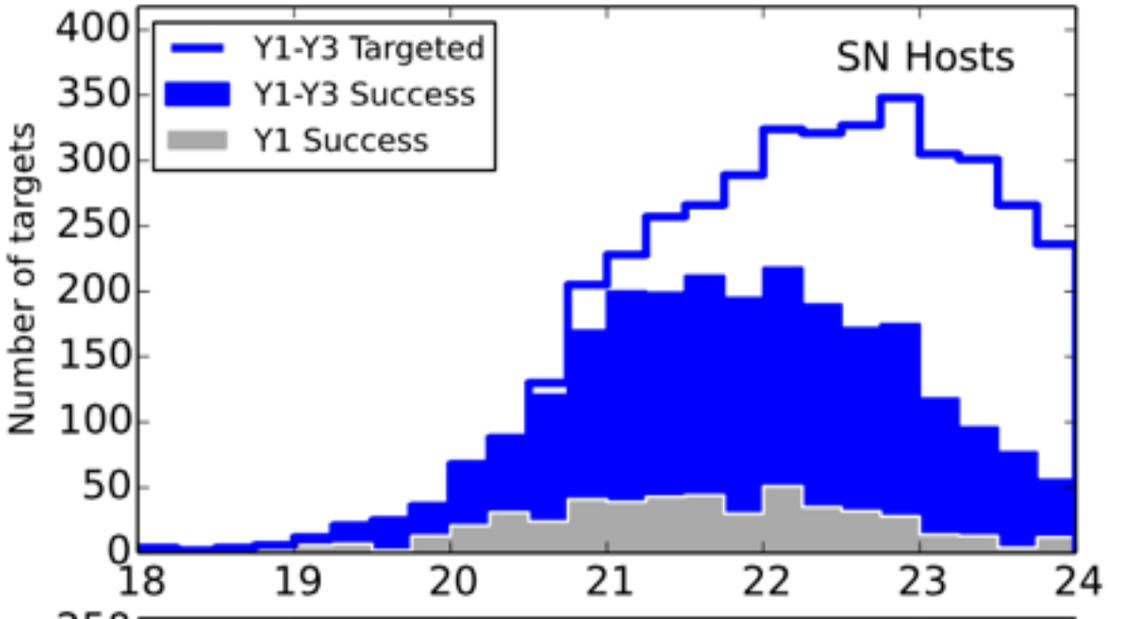
Thousands of Supernovae

[Yuan++,2015, Childress++,2017]





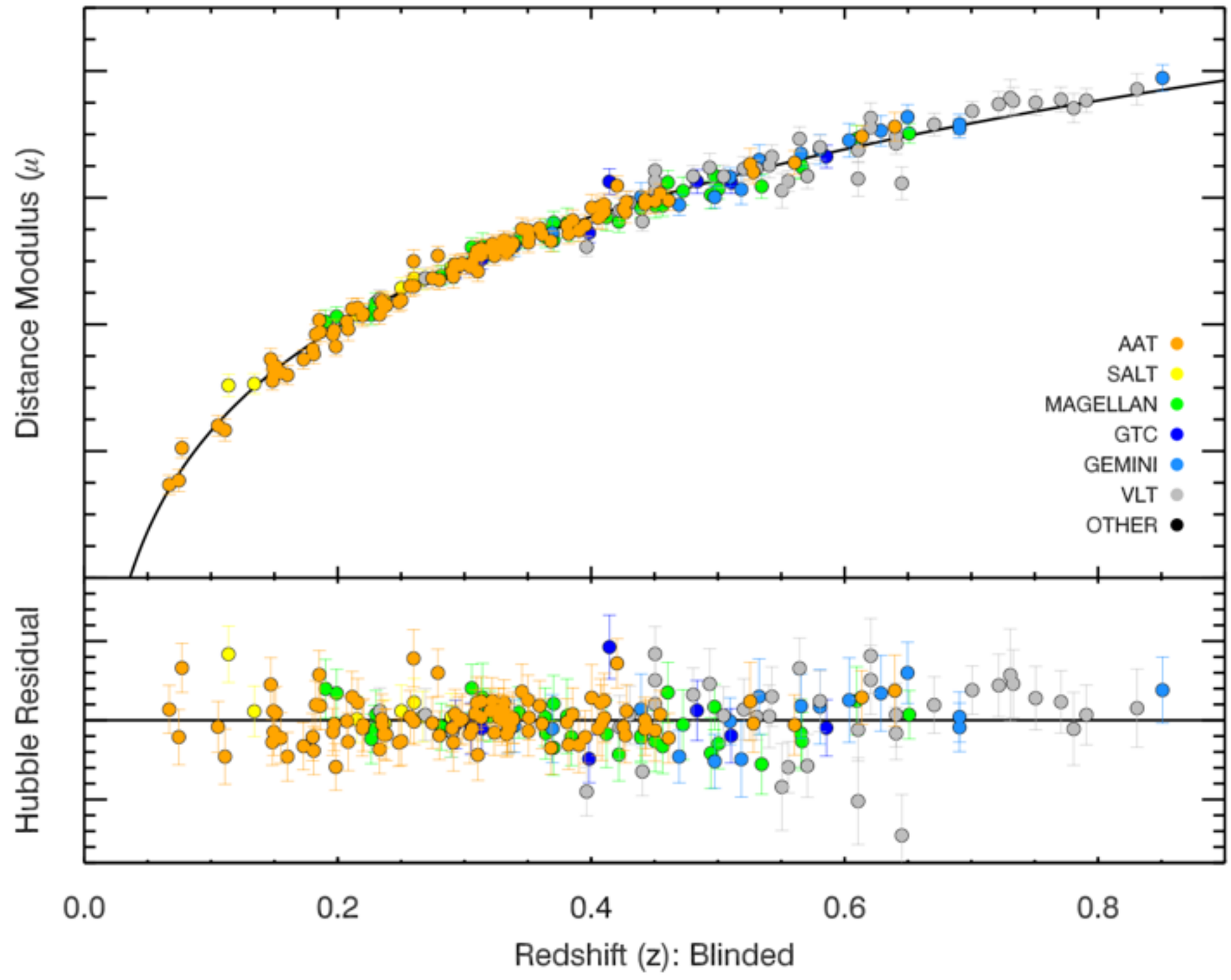
- <u>100 nights on AAT</u>
  - Repeat observations builds up S/N
  - 68 nights done (end of Y4)
  - 4200 SN host redshifts already
  - ~80% of all hosts to r~24
  - Remainder with 8m telescopes (VLT)



Spectroscopic Hubble Diagram

[D'Andrea++,2017 in prep]

AAT, SALT, VLT, Magellan, Gemini,
Keck, MMT, GTC, SOAR



SNe Ia by Year

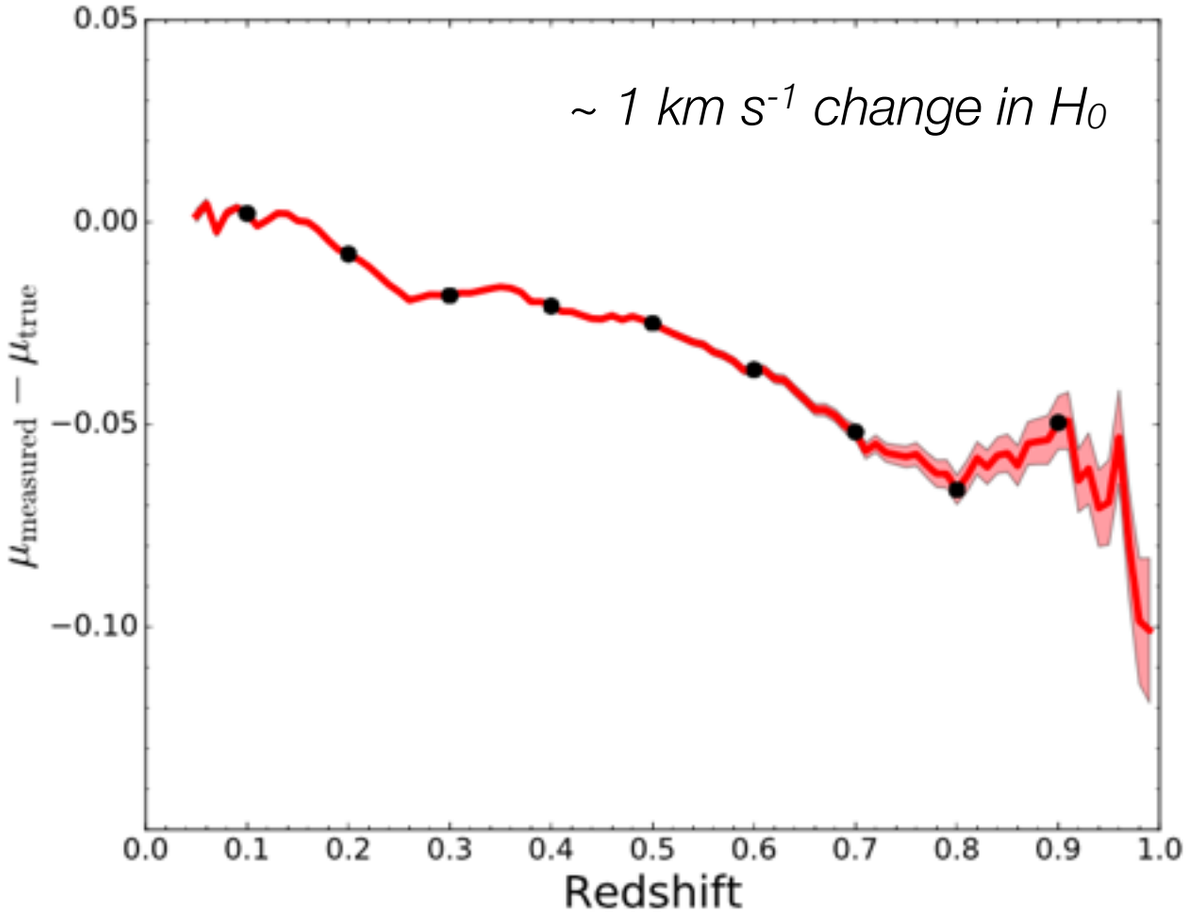
Year	# Confirmed
1	24
2	75
3	129

SNe by Type

SN Type	# Confirmed
Ia	228
II	33
Ib/c	10
IIb	1
SLSN	13

First cosmology

[Macauley++ 2017, in prep]



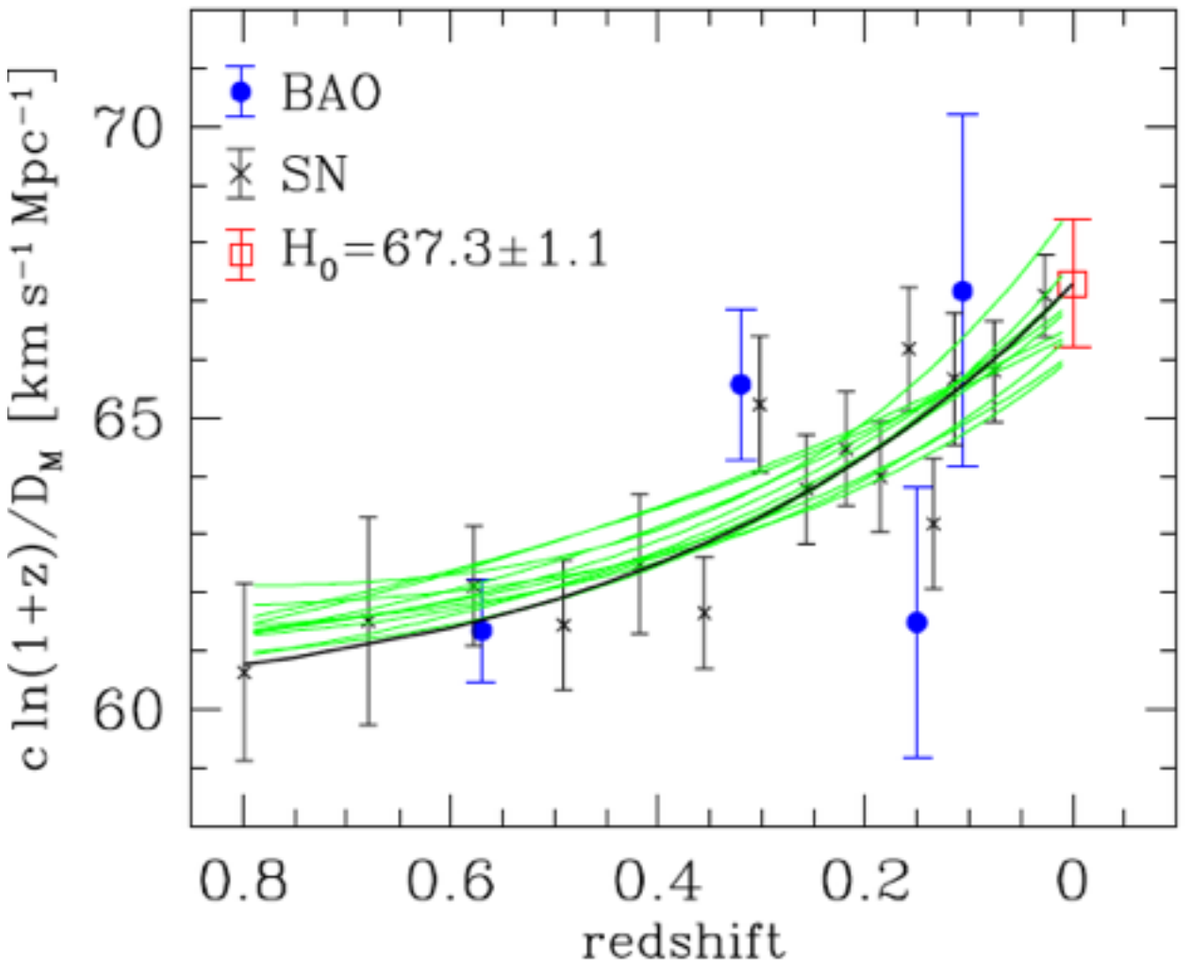
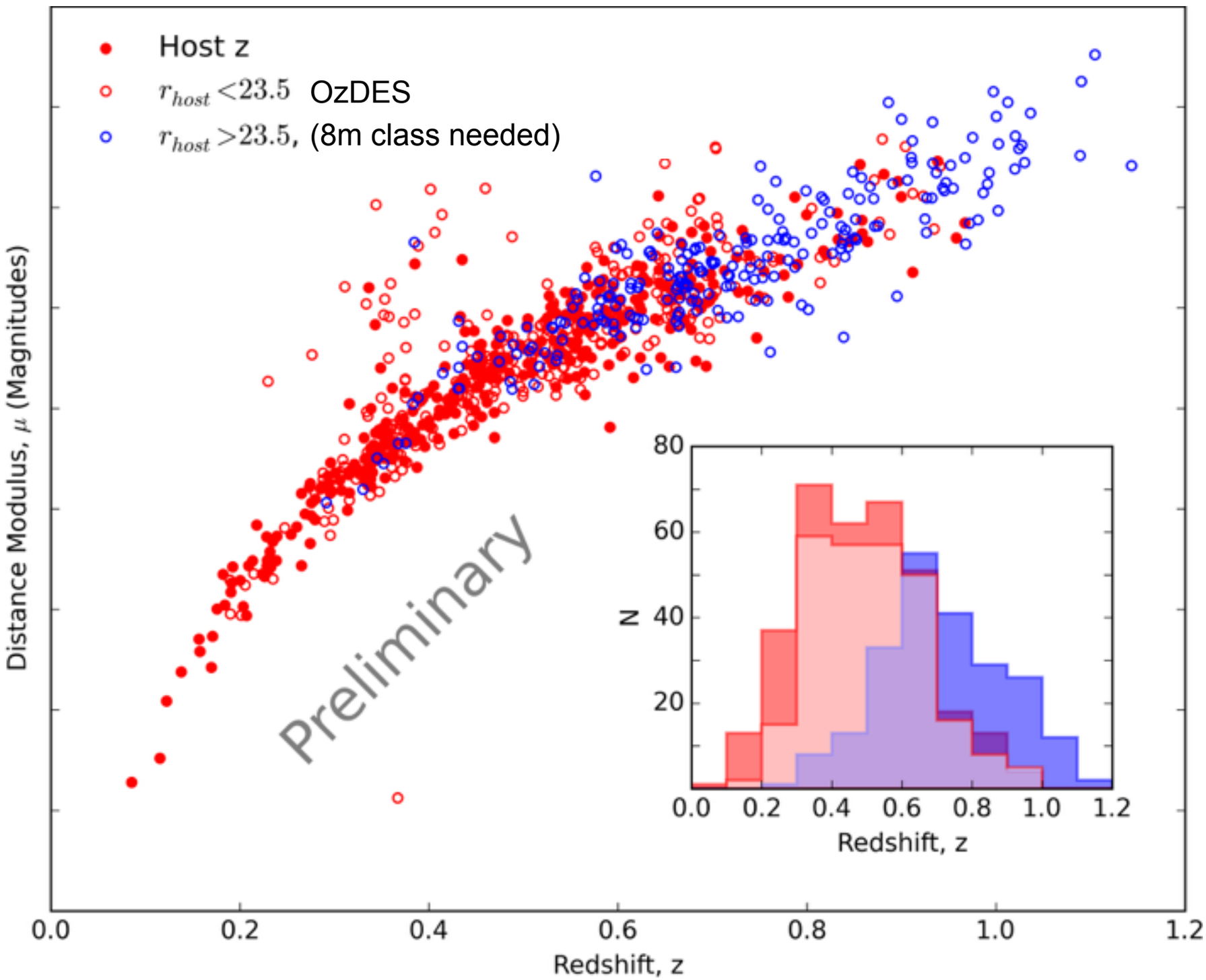


Figure 12. Redshift dependent bias in measured values of μ.

Photometric Hubble Diagram

With host galaxy redshifts

Campbell++ 2013
Olmstead++ 2015
Jones++ 2017
Roberts++ 2017

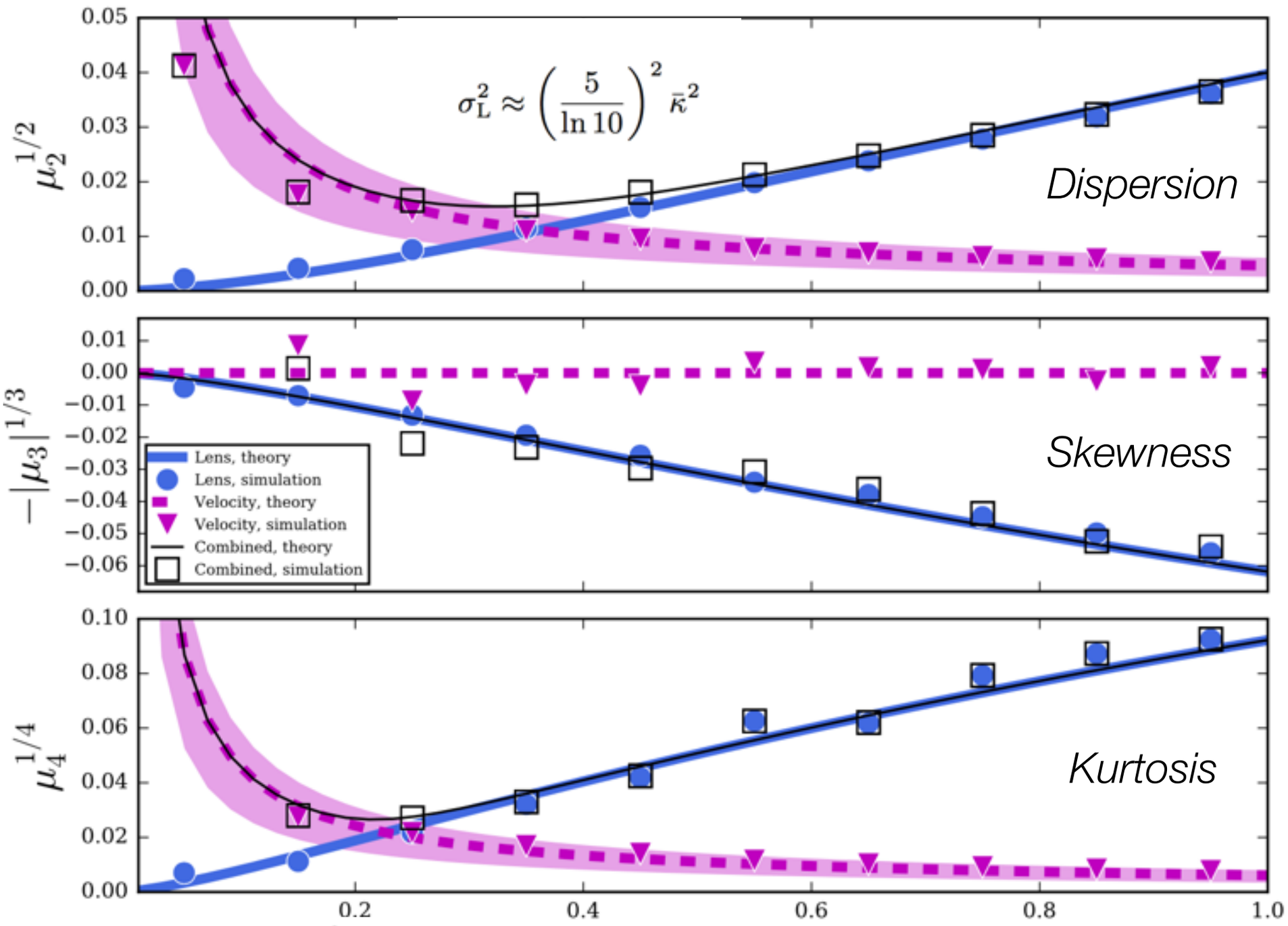


Over 2500 high-quality SNeIa by end of decade

SN lensing

Constraining growth of structure and p(k)

Marra++ 2013
Macaulay ++ 2017

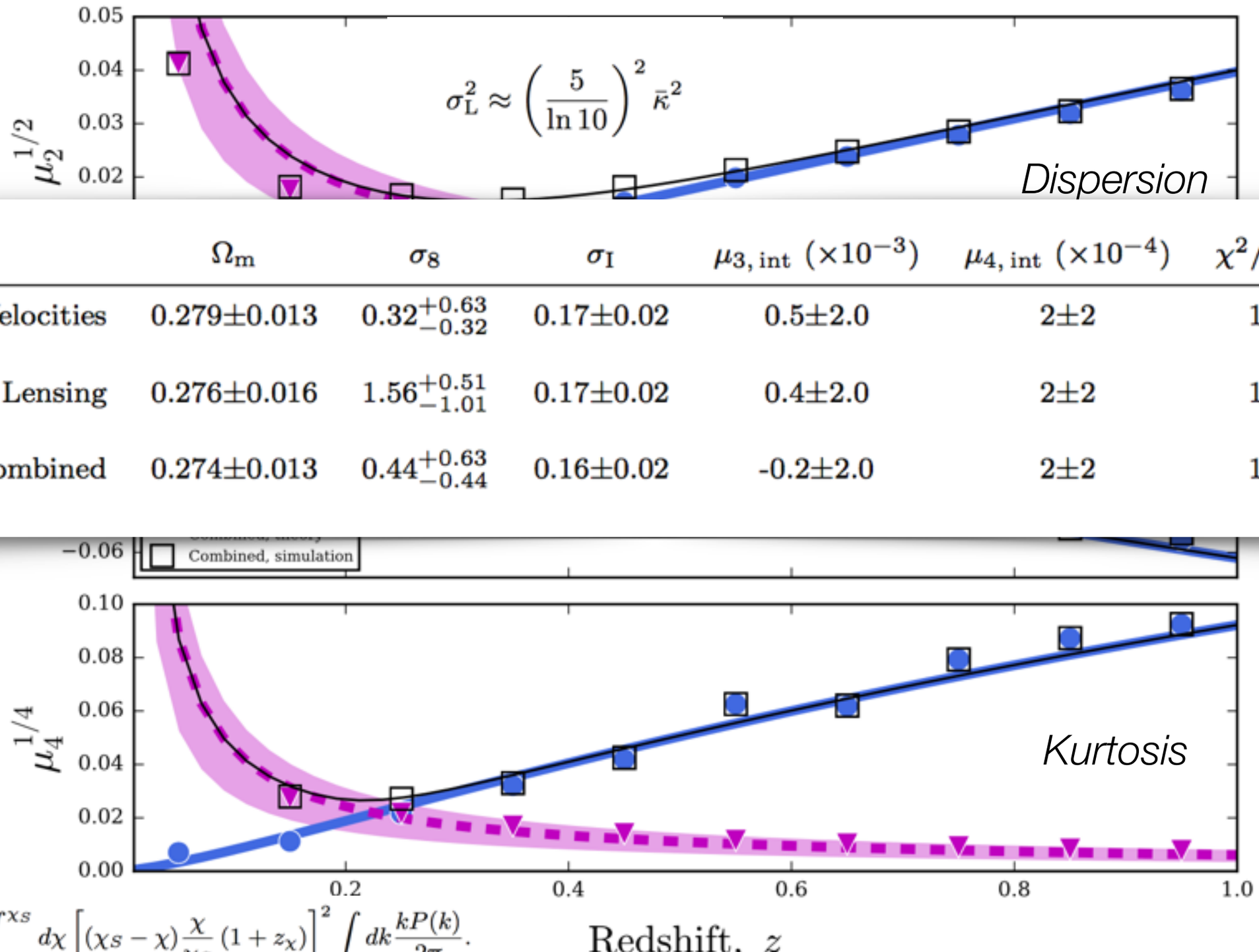


$$\bar{\kappa}^2 = \frac{9\Omega_m^2 H_0^4}{4c^4} \int_0^{\chi_S} d\chi \left[(\chi_S - \chi)\frac{\chi}{\chi_S}(1+z_\chi)\right]^2 \int dk \frac{kP(k)}{2\pi}.$$

SN lensing

Constraining growth of structure and p(k)

Marra++ 2013
Macaulay ++ 2017



	$\Omega_{\rm m}$	σ_8	$\sigma_{\rm I}$	$\mu_{3,\,\rm int}$ $(\times 10^{-3})$	$\mu_{4,\,\rm int}$ $(\times 10^{-4})$	χ^2/ DoF
Velocities	0.279±0.013	$0.32^{+0.63}_{-0.32}$	0.17±0.02	0.5±2.0	2±2	1.14
Lensing	0.276±0.016	$1.56^{+0.51}_{-1.01}$	0.17±0.02	0.4±2.0	2±2	1.20
Combined	0.274±0.013	$0.44^{+0.63}_{-0.44}$	0.16±0.02	-0.2±2.0	2±2	1.14

$$\bar{\kappa}^2 = \frac{9\Omega_{\rm m}^2 H_0^4}{4c^4} \int_0^{\chi_S} d\chi \left[(\chi_S - \chi)\frac{\chi}{\chi_S}(1+z_\chi)\right]^2 \int dk \frac{kP(k)}{2\pi}.$$

SN lensing

Expectations for DES

Quartin++ 2014
Scovacricchi++ 2017

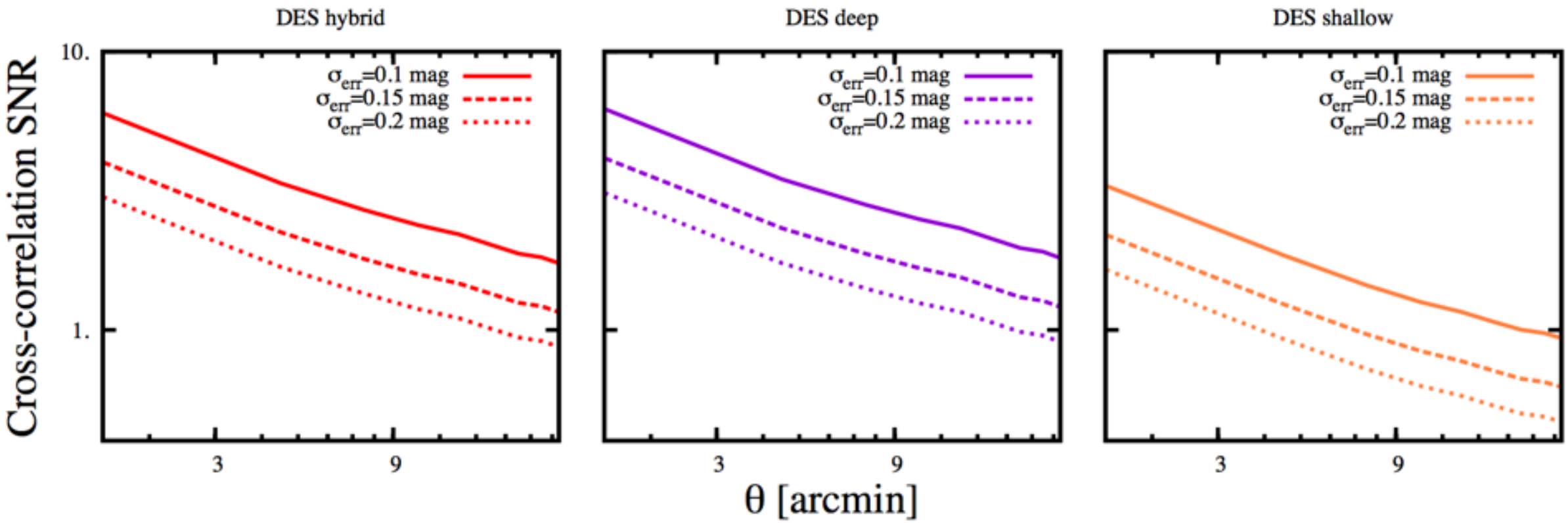
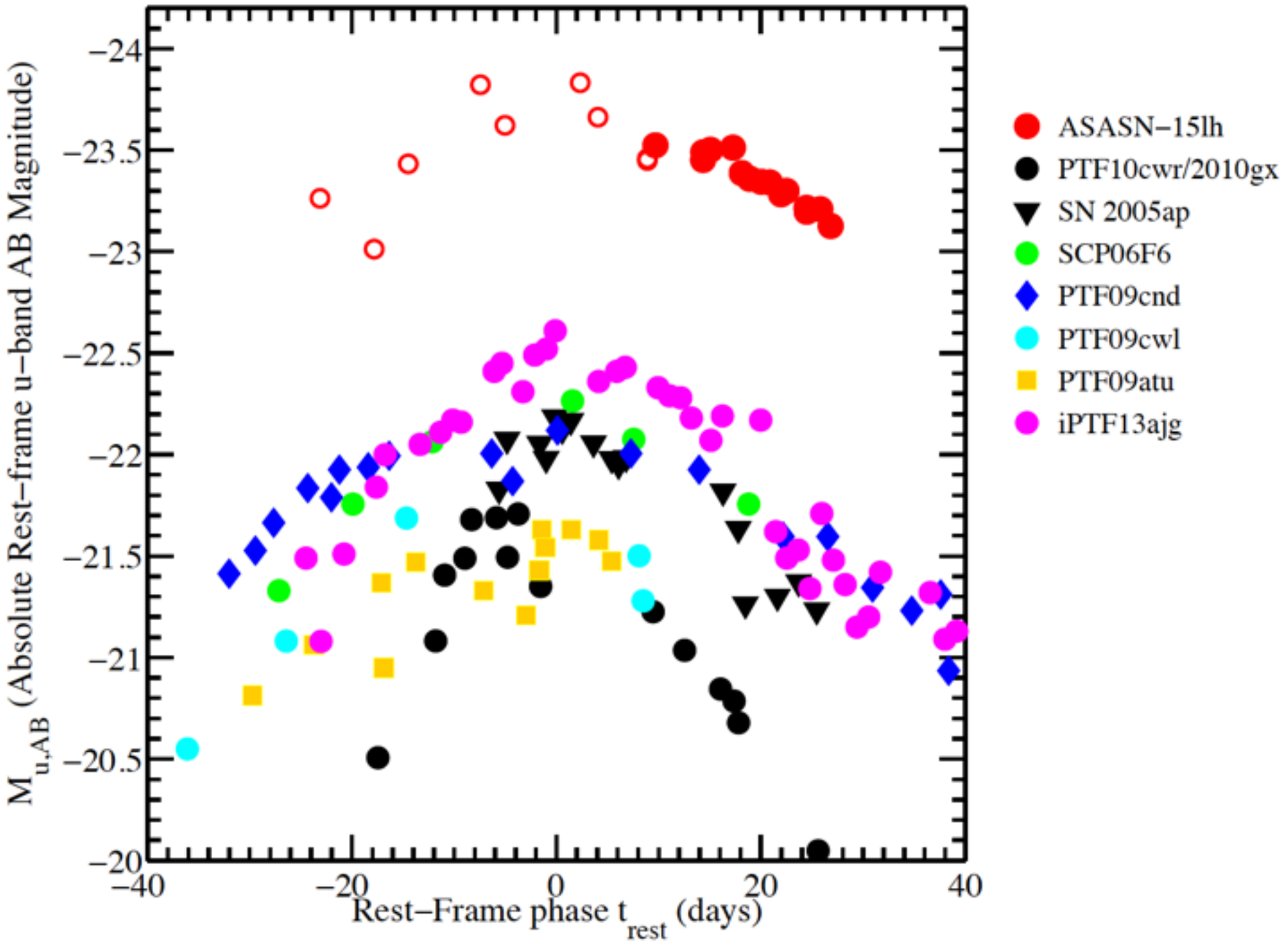


Figure 2. The binned signal-to-noise predictions for DES cross-correlation function (bin size is 3 arcminutes) as a function of survey configuration, total number of SNe Ia and value of $\sigma_{\rm err}$ (see Table 1 for details).

Total S/N ~ 15 (below 30 arcmins)

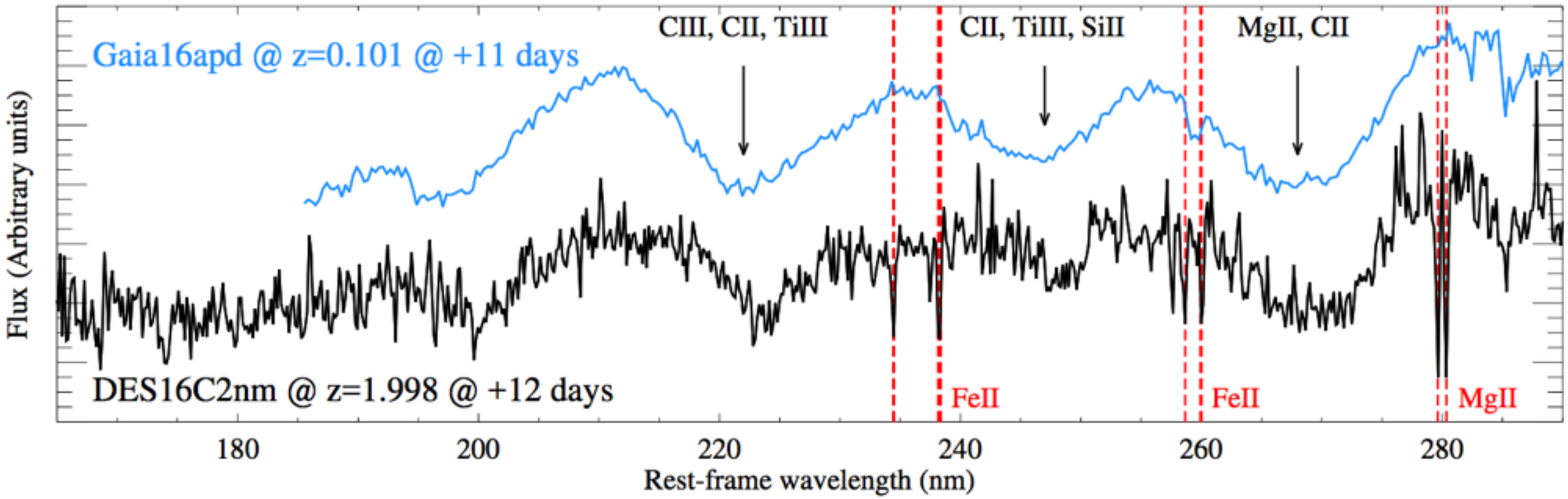
Superluminous Supernovae

[Gal-Yam 2012, Dong++ 2015]



Superluminous Supernovae

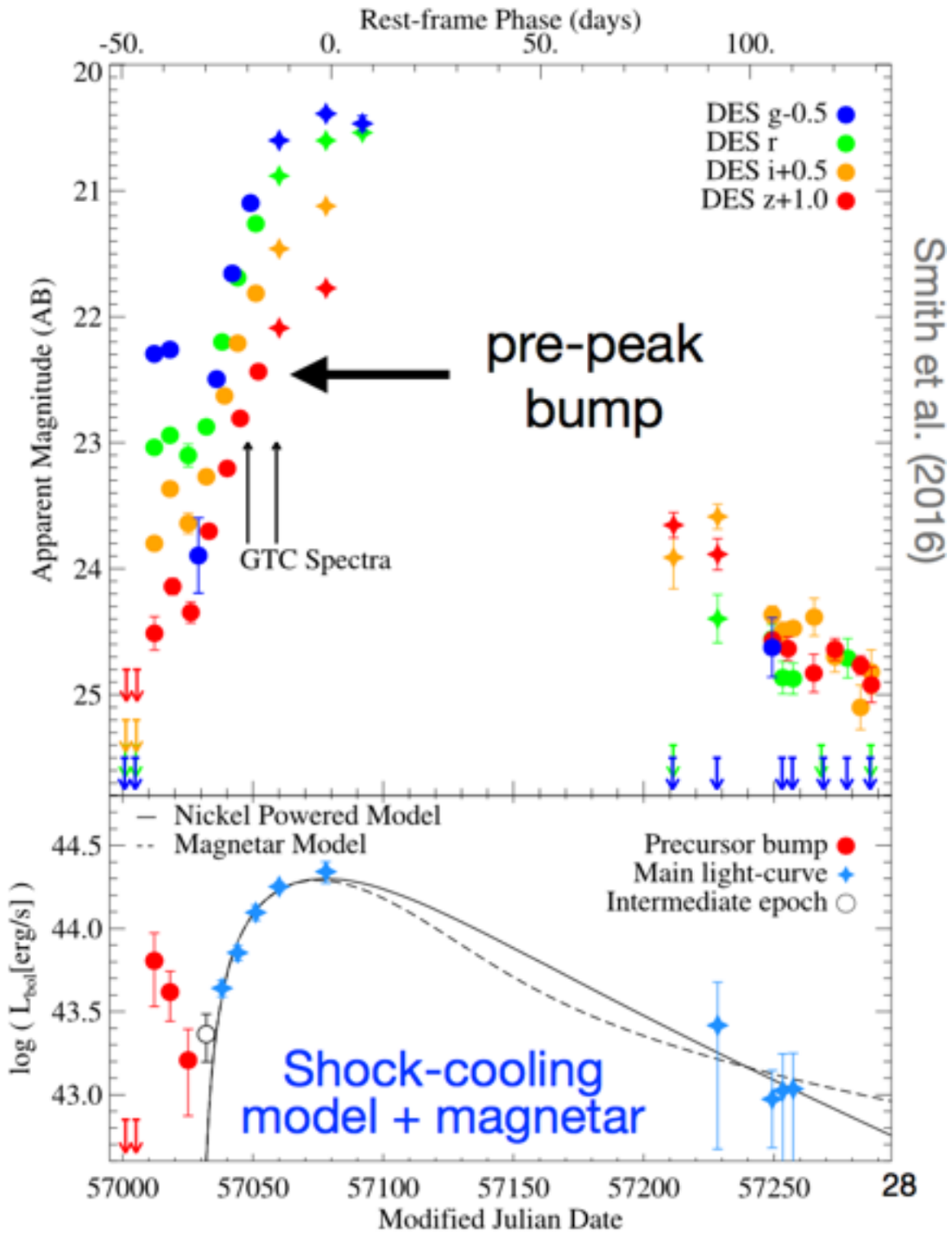
[Papadopoulos++,2015, Smith++, 2016, 2017]

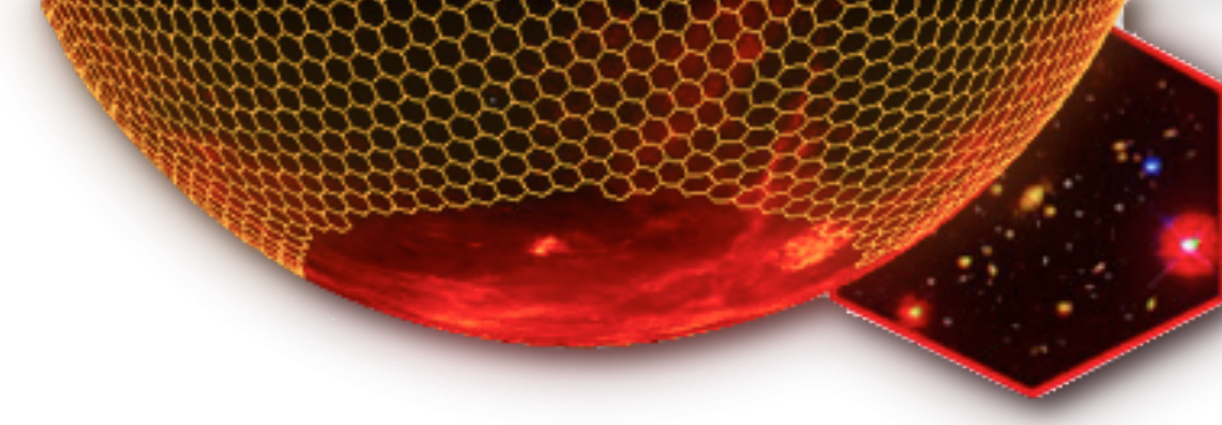


DES16C2nm is the brightest, most distant SN ever confirmed

Superluminous Supernovae

[Smith++, 2016]



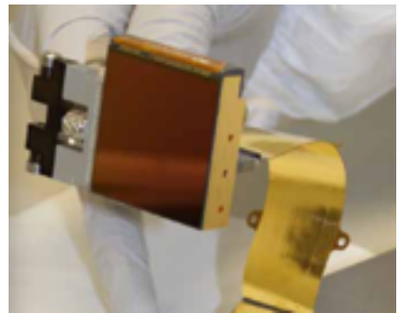


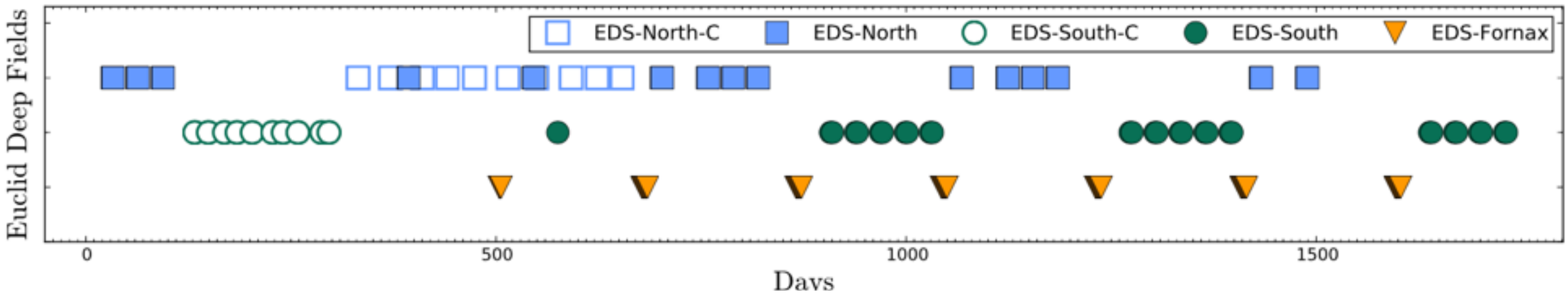
Near Future (2020 - 2030)

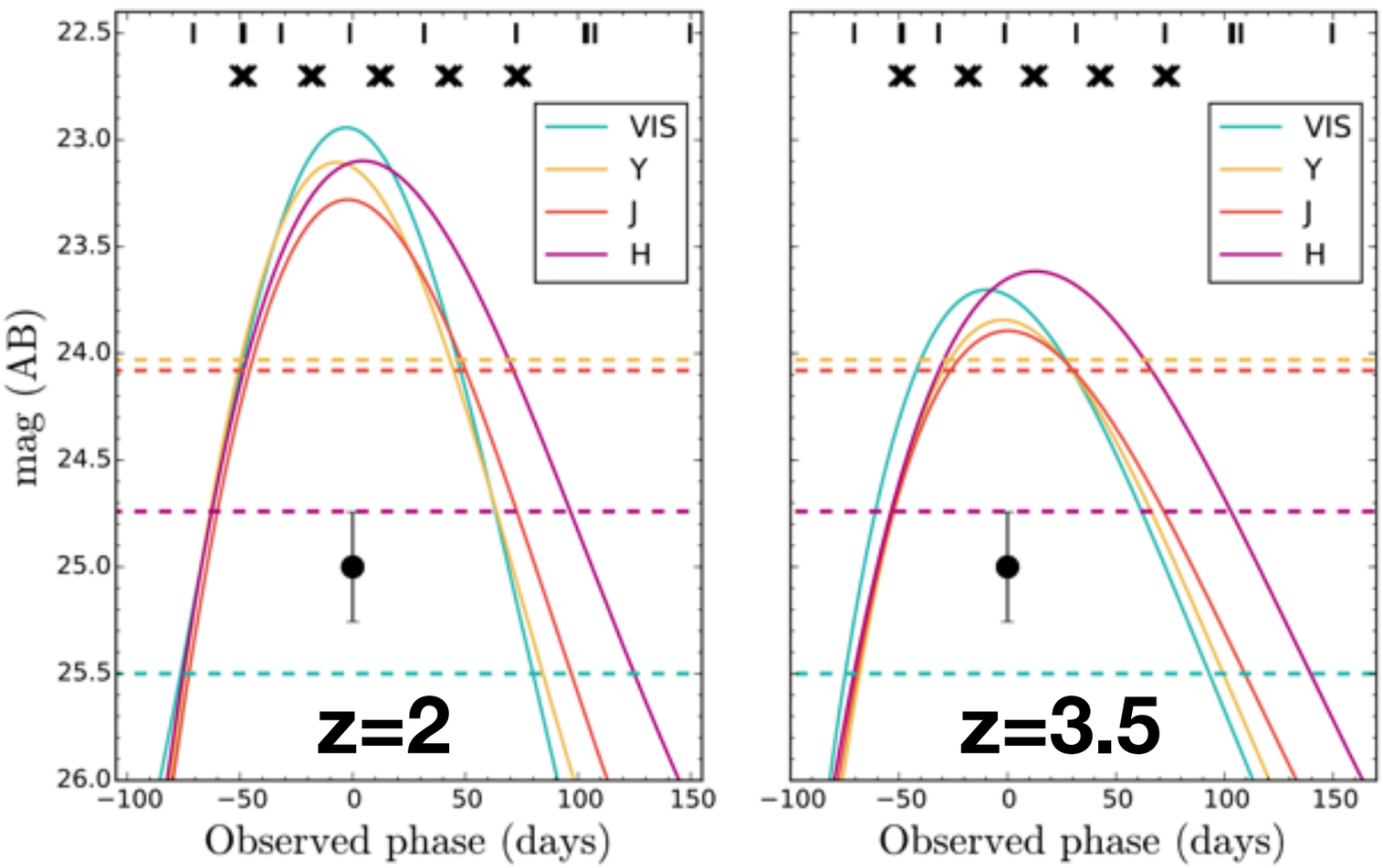
DESI, Euclid, WFIRST, LSST, 4MOST

Euclid

Hundreds of SLSNe to z~4 for free

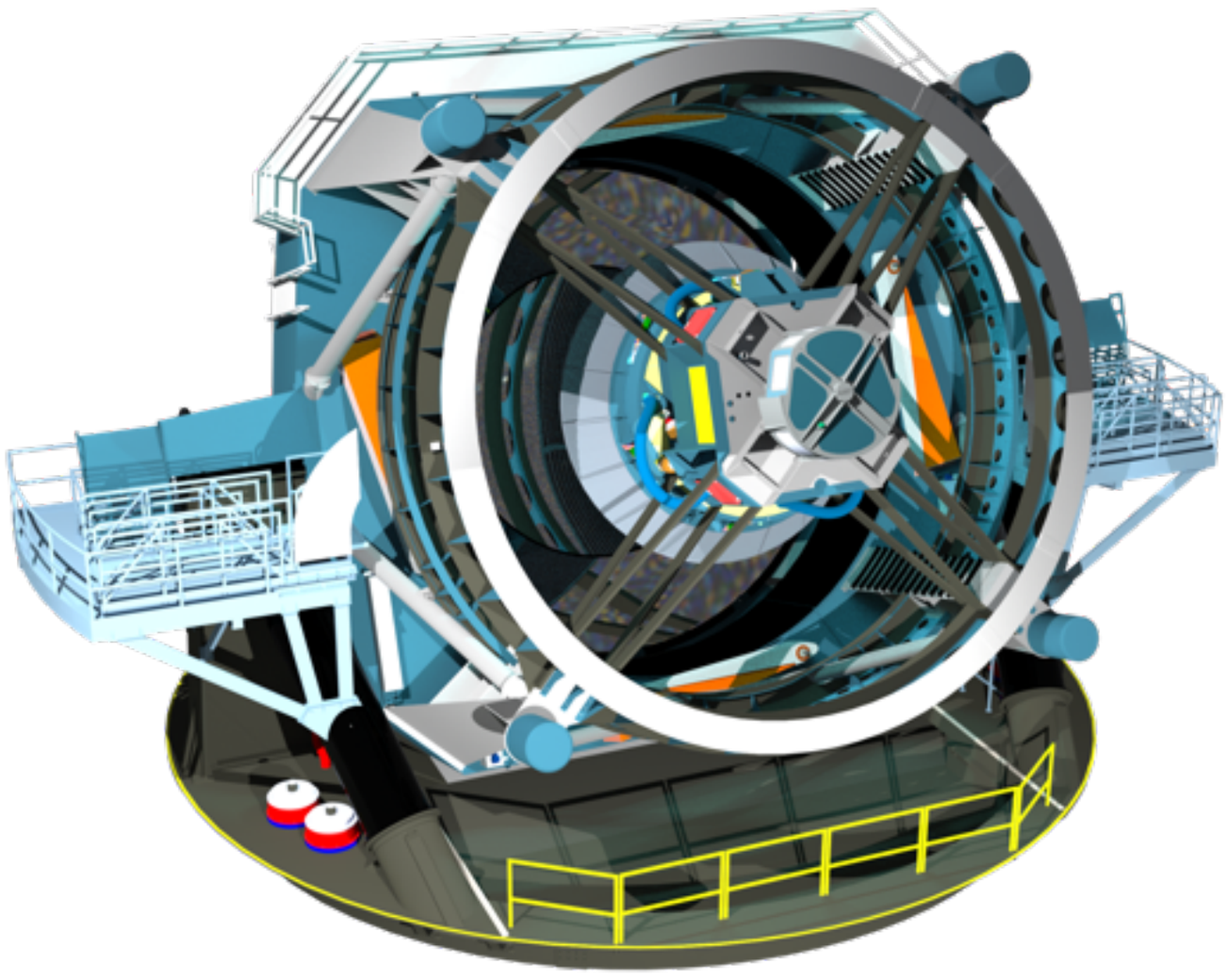






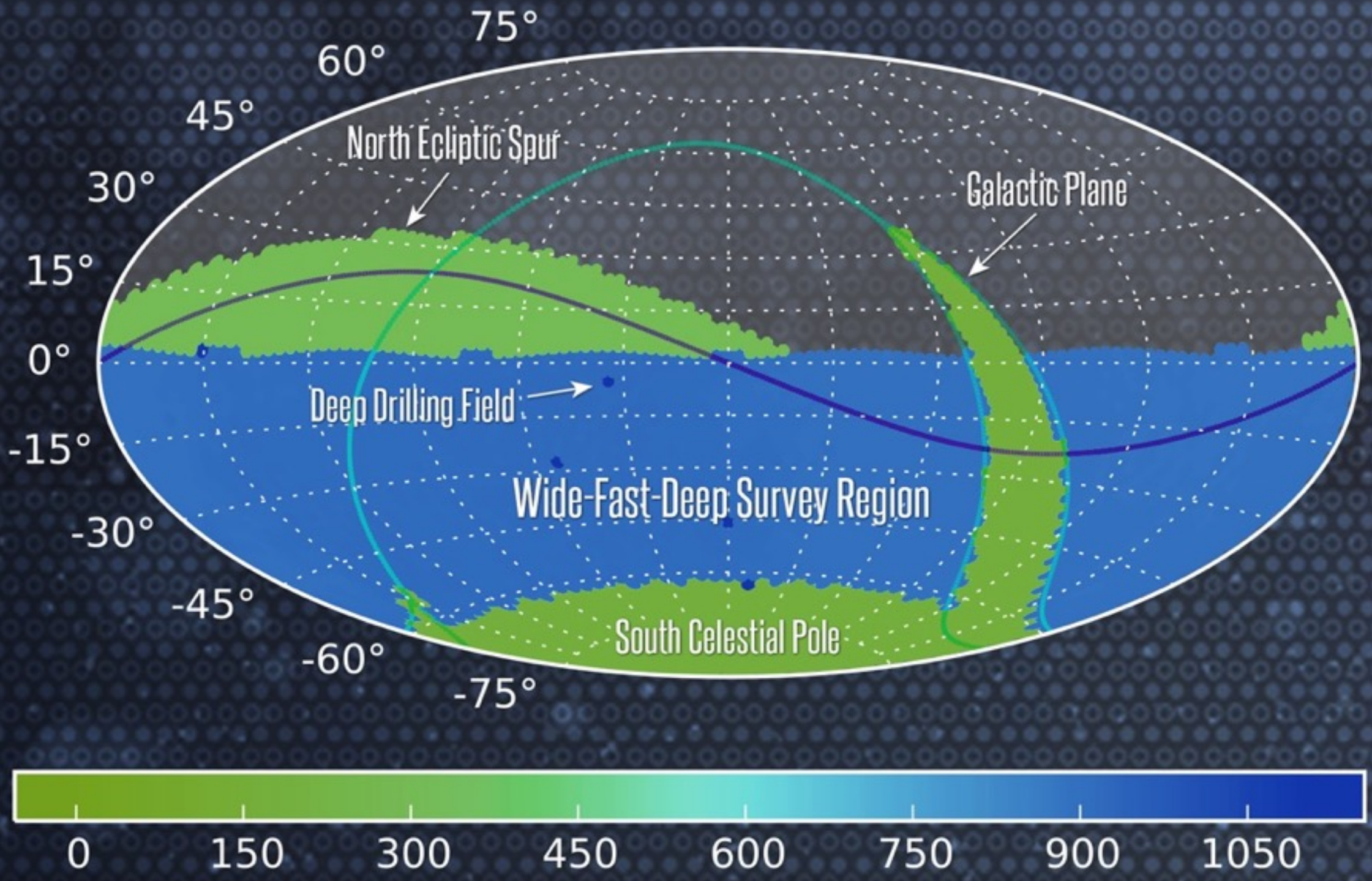
LSST

Millions of SNe; thousands of SLSNe



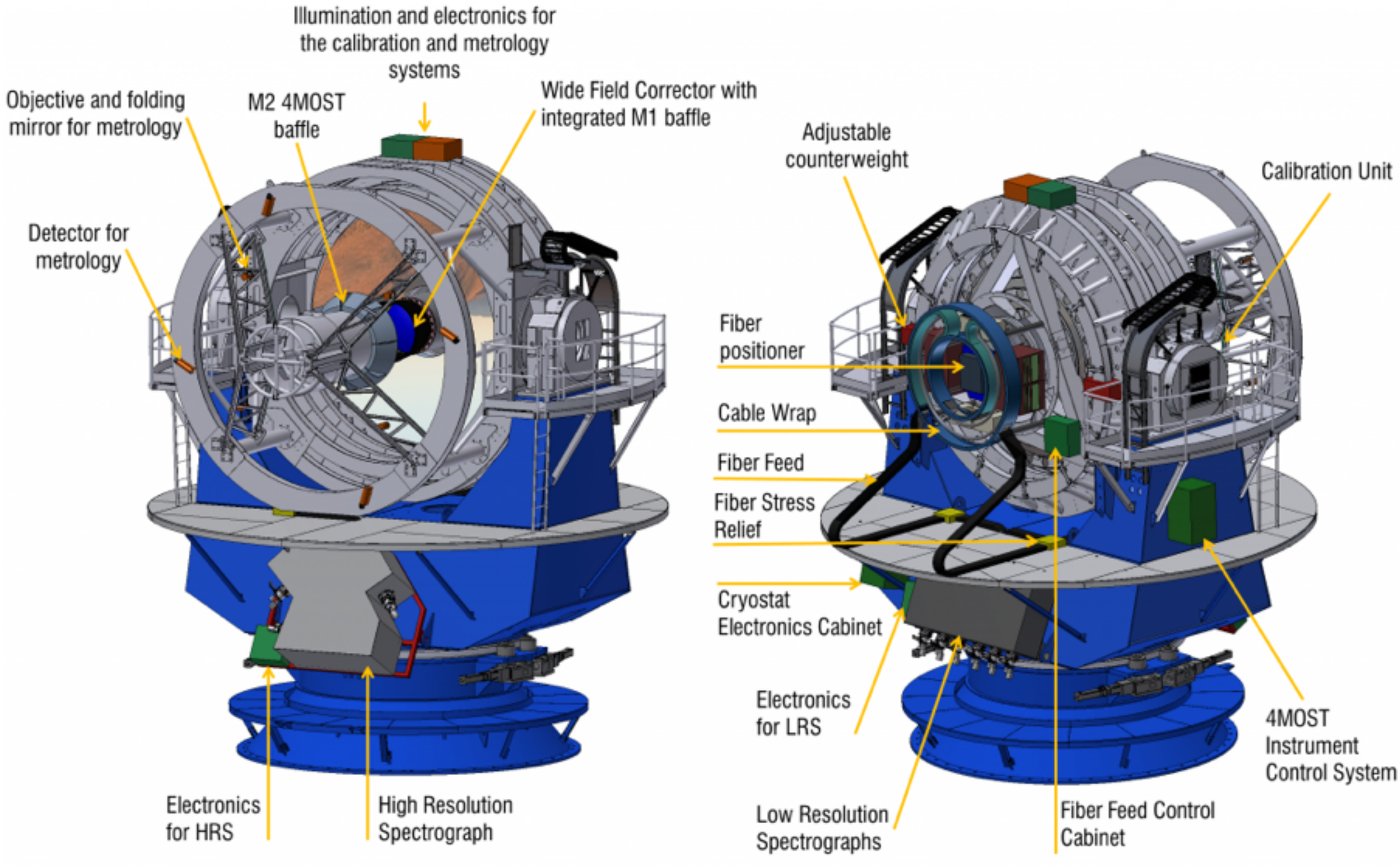
Number of Visits

(all-band, 10 years)



TiDES @ ESO 4MOST

250,000 SN and host galaxies



LSST SN lensing

Quartin++ 2014
Scovacricchi++ 2017

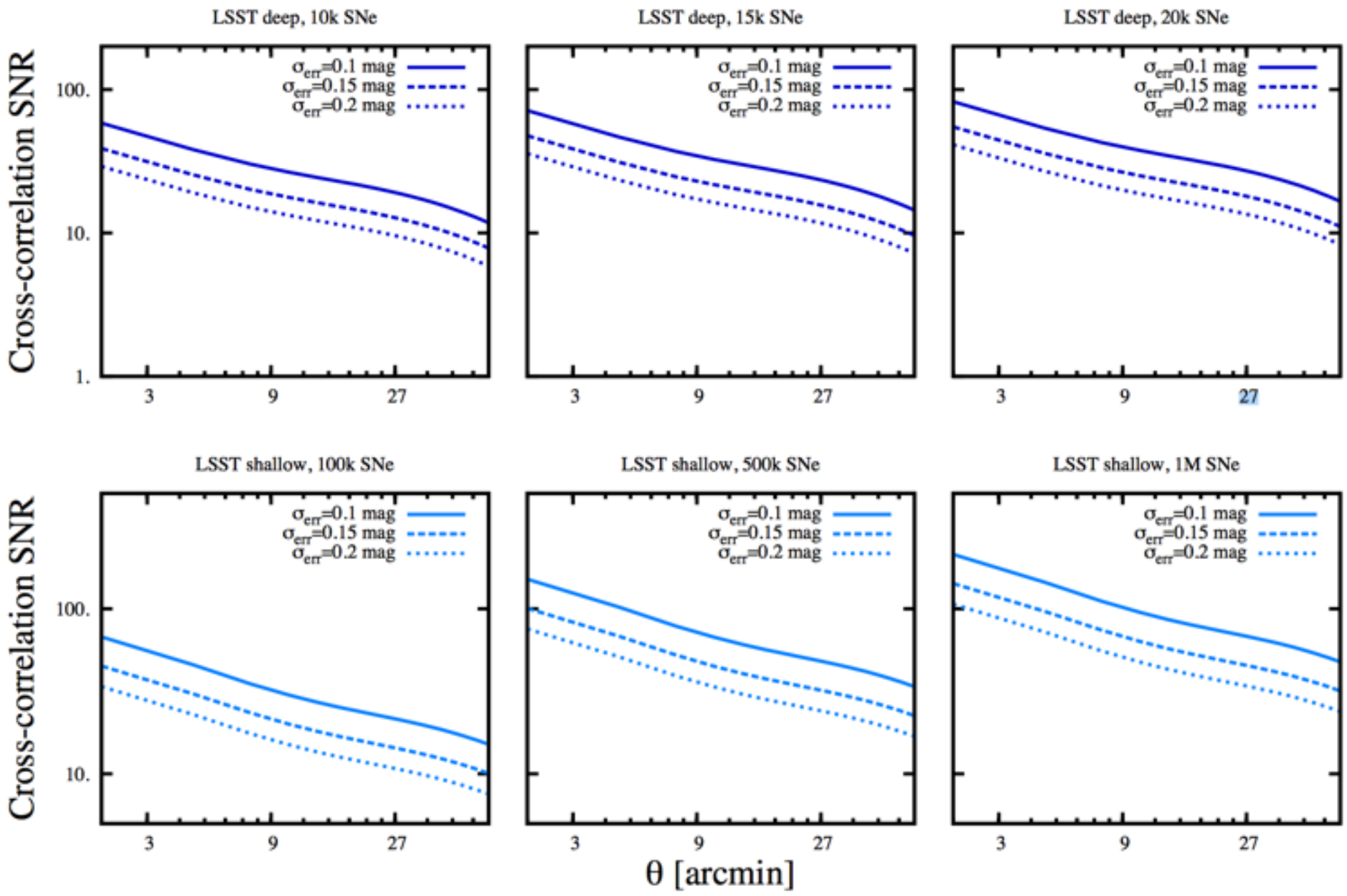
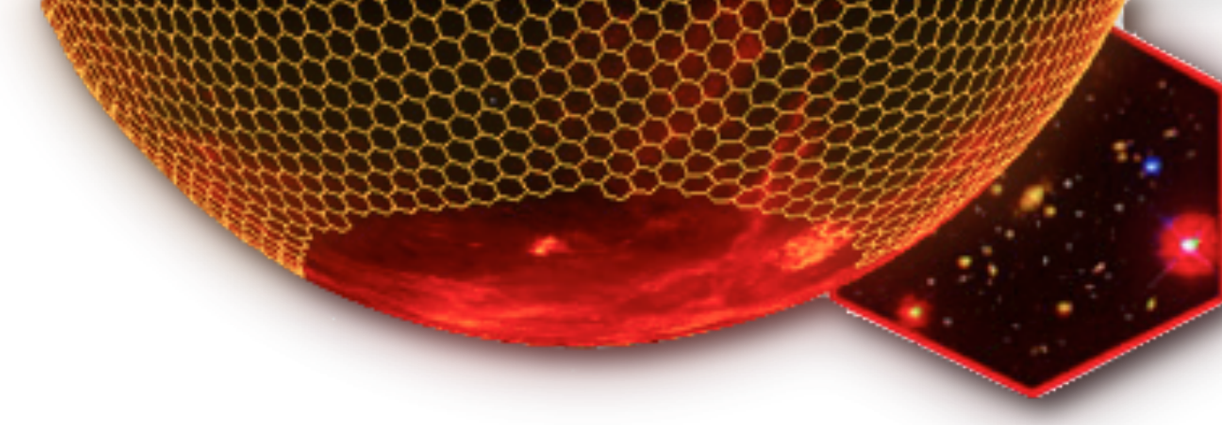


Figure 4. The binned signal-to-noise predictions for LSST cross-correlation function (bin size is 3 arcminutes) as a function of survey configuration, total number of SNe Ia and value of $\sigma_{\rm err}$ (see Table 1 for details).



Summary

Dark Energy Survey has reached maturity - *lots of results to come in next year, which should shed some light on systematics and maybe the nature of dark energy.*

Good time (data-rich) to be studying cosmology - *especially with projects like LSST, DESI and Euclid on horizon*