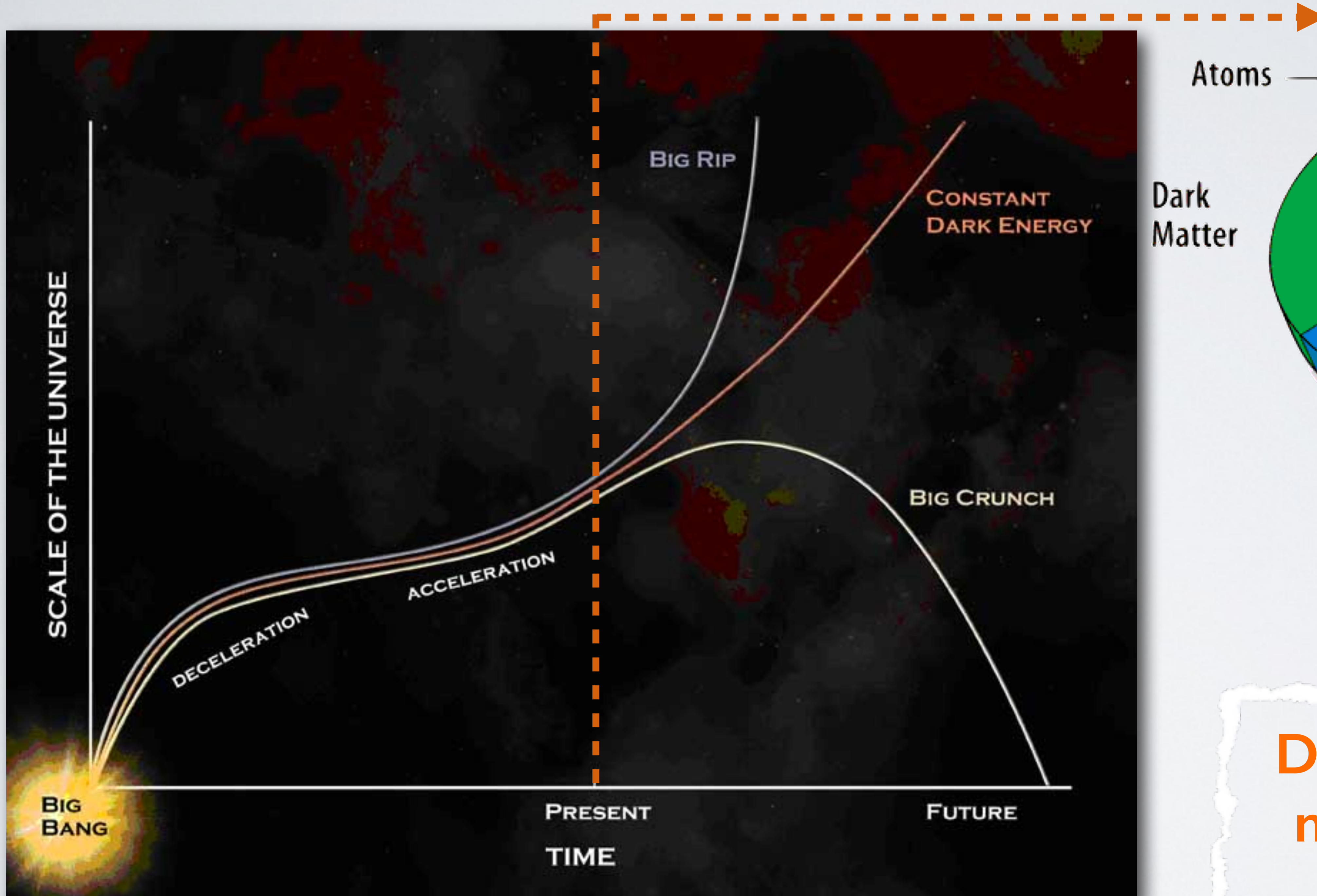
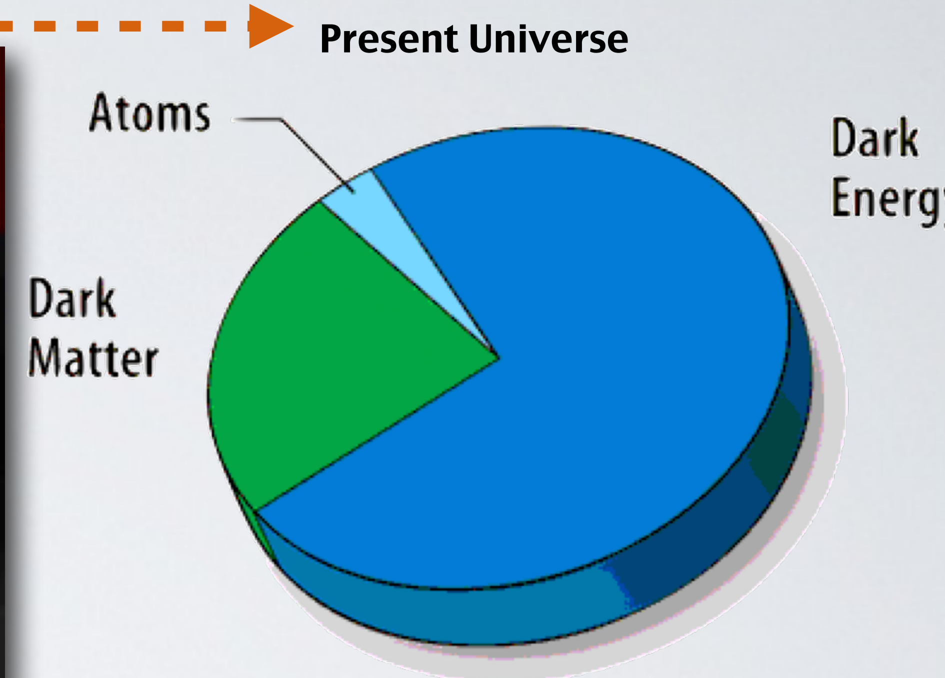
DARK ENERGY SURVEY

Marcelle Soares-Santos
Fermilab
DES Collaboration

PASCOS — July 12, 2016

DARK ENERGY & ACCELERATED EXPANSION



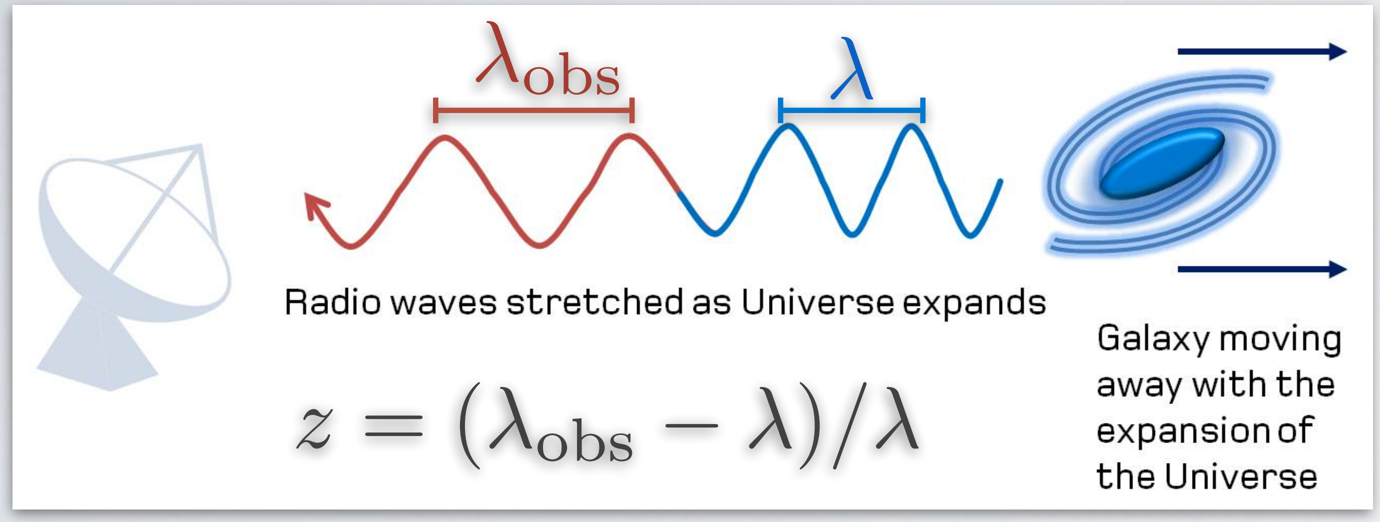


$$\Omega_m \simeq 1/3$$

$$\Omega_\Lambda \simeq 2/3$$

Dominance of new physics!

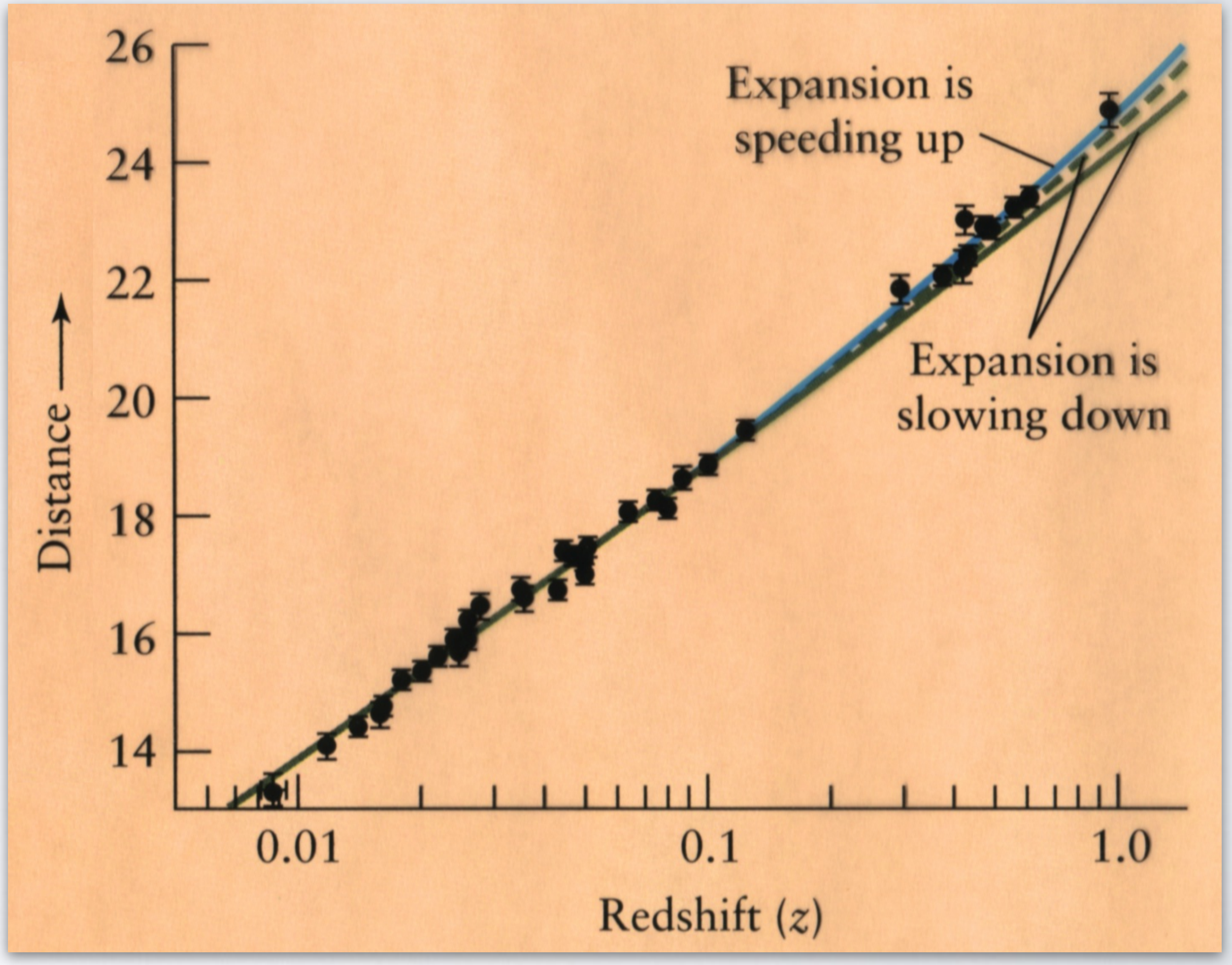
DISTANCE–REDSHIFT RELATION



Redshift (**z**) is an observable effect of the expansion of the Universe.

Faraway sources are more affected then nearby ones.

We can measure the rate of expansion using the **distance–redshift** relation!

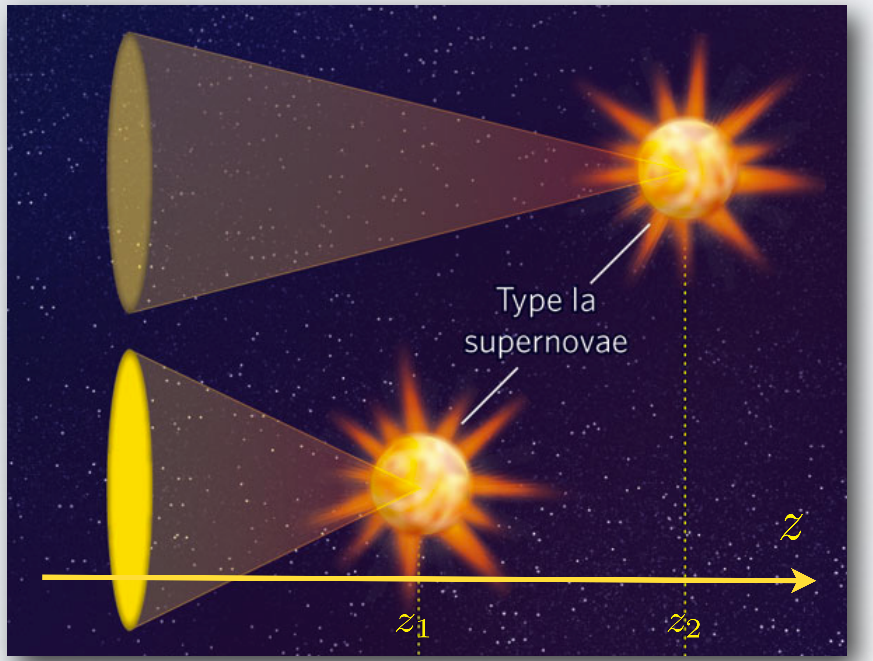


ASTROPHYSICAL OBSERVABLES

Luminosity distance:

standard candle

1. supernovae (SNe)



DES is sensitive to Dark Energy via 4 probes.

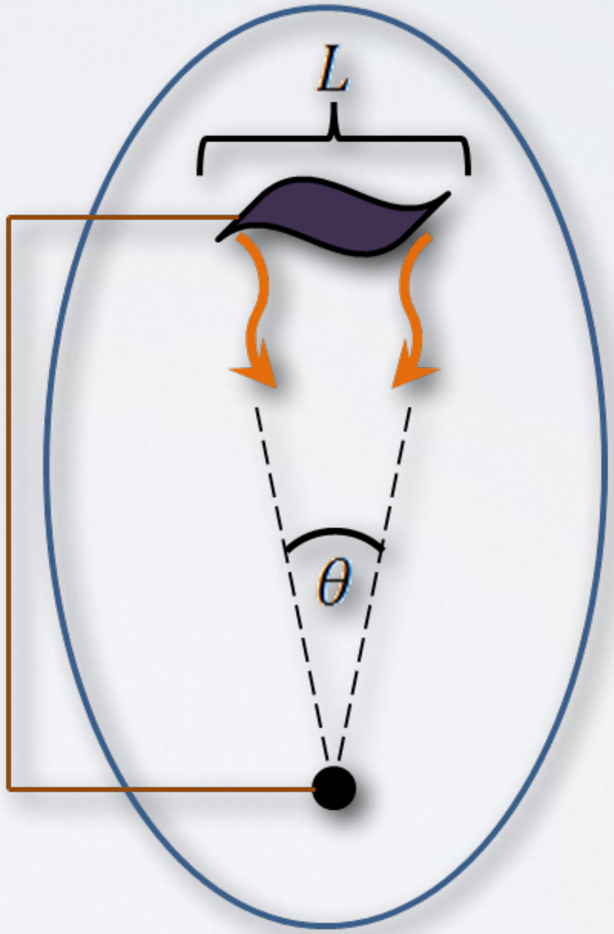
***CMB results from Planck are used in DES analyses.**

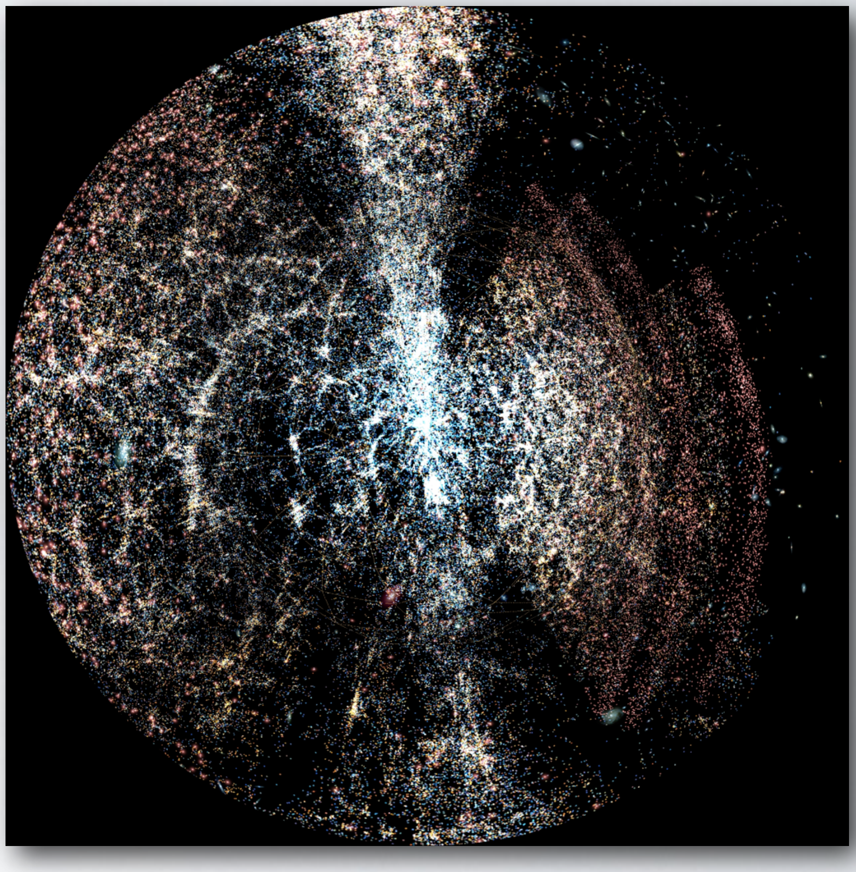
Angular diameter distance:

standard ruler

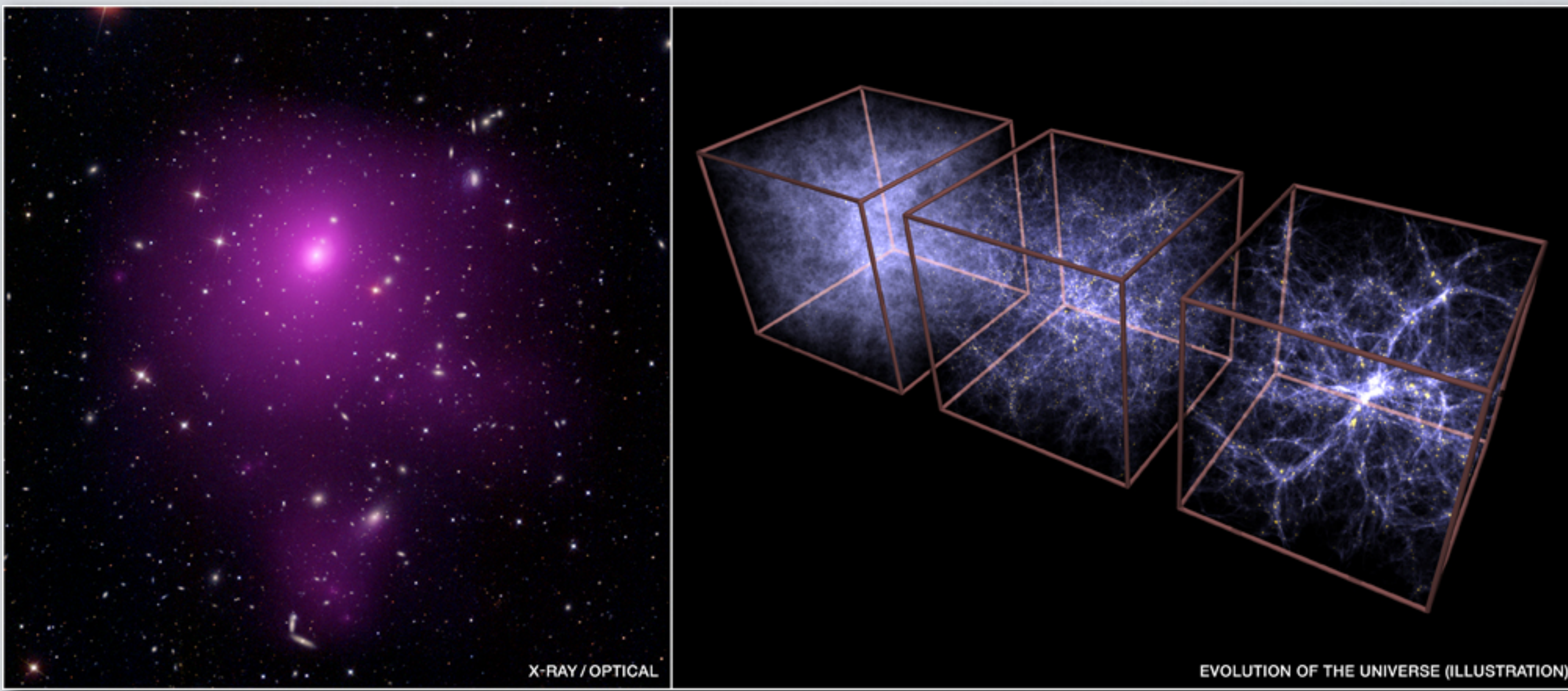
***cosmic microwave background (CMB)**

2. baryon acoustic oscillations (BAO)





GROWTH OF STRUCTURE



The **growth** of the largest structures in the universe, **clusters of galaxies**, is inhibited by **dark energy**.

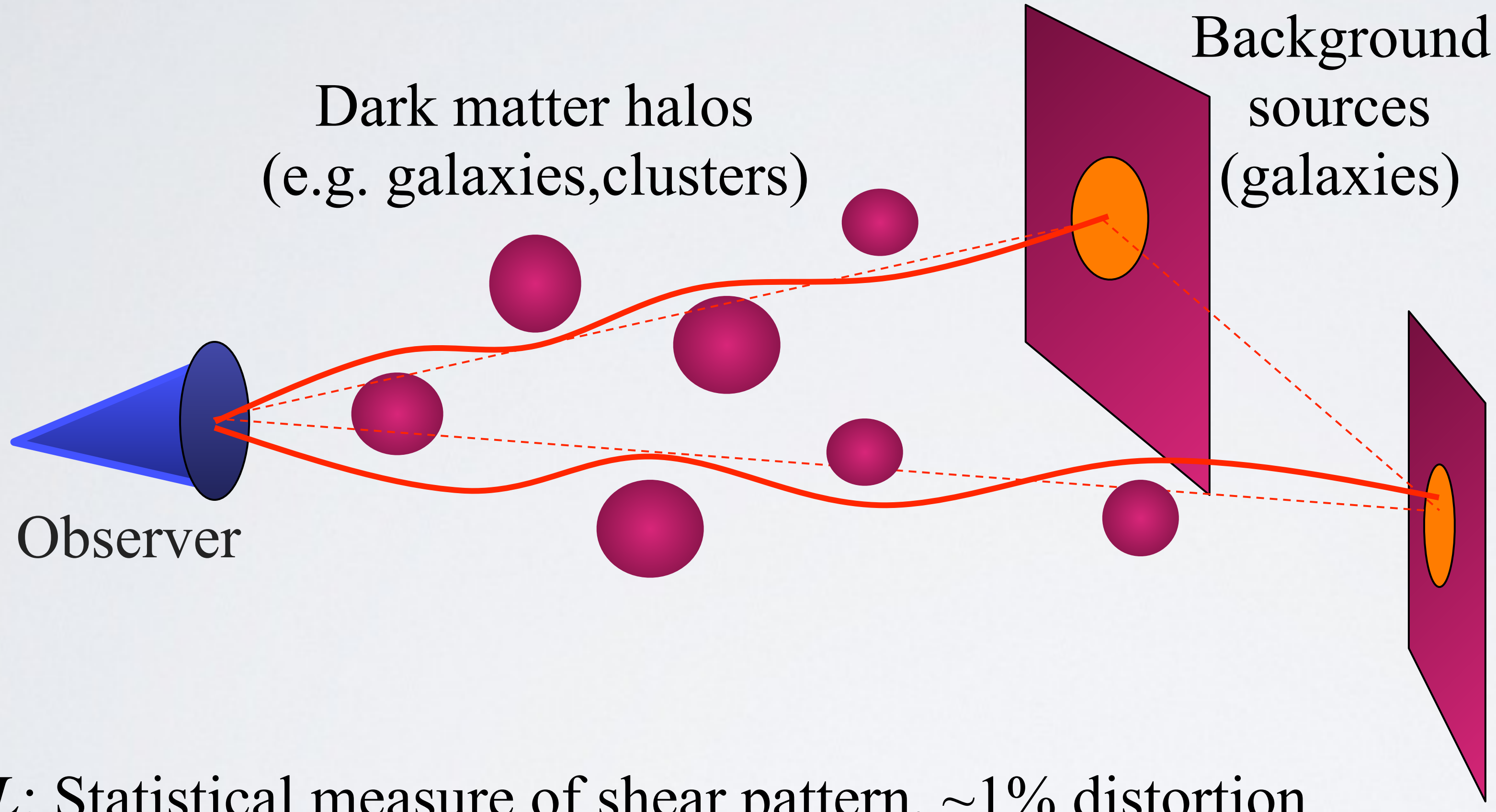
ASTROPHYSICAL OBSERVABLES

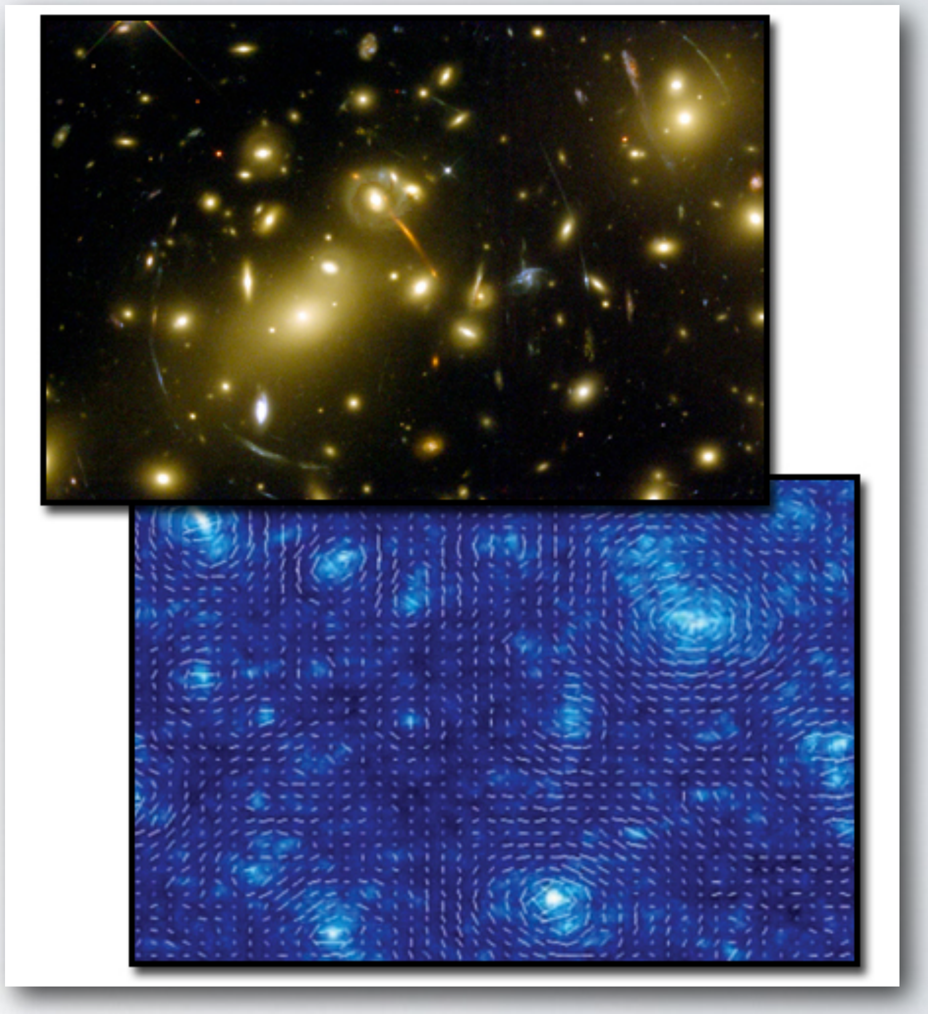
DES is sensitive to
Dark Energy via 4 probes.

WL, Clusters are also sensitive
to angular diameter distance.

Growth of structure:

3. weak gravitational lensing (WL)
4. galaxy cluster abundance (Clusters)





- ***WL***: Statistical measure of shear pattern, ~1% distortion
- ***Clusters***: Number density vs. Mass vs. redshift
- Radial distances depend on ***geometry*** of Universe
- Mass distribution depends on ***growth*** of structure

BASIC OBSERVABLES

Positions on the sky (RA, Dec)

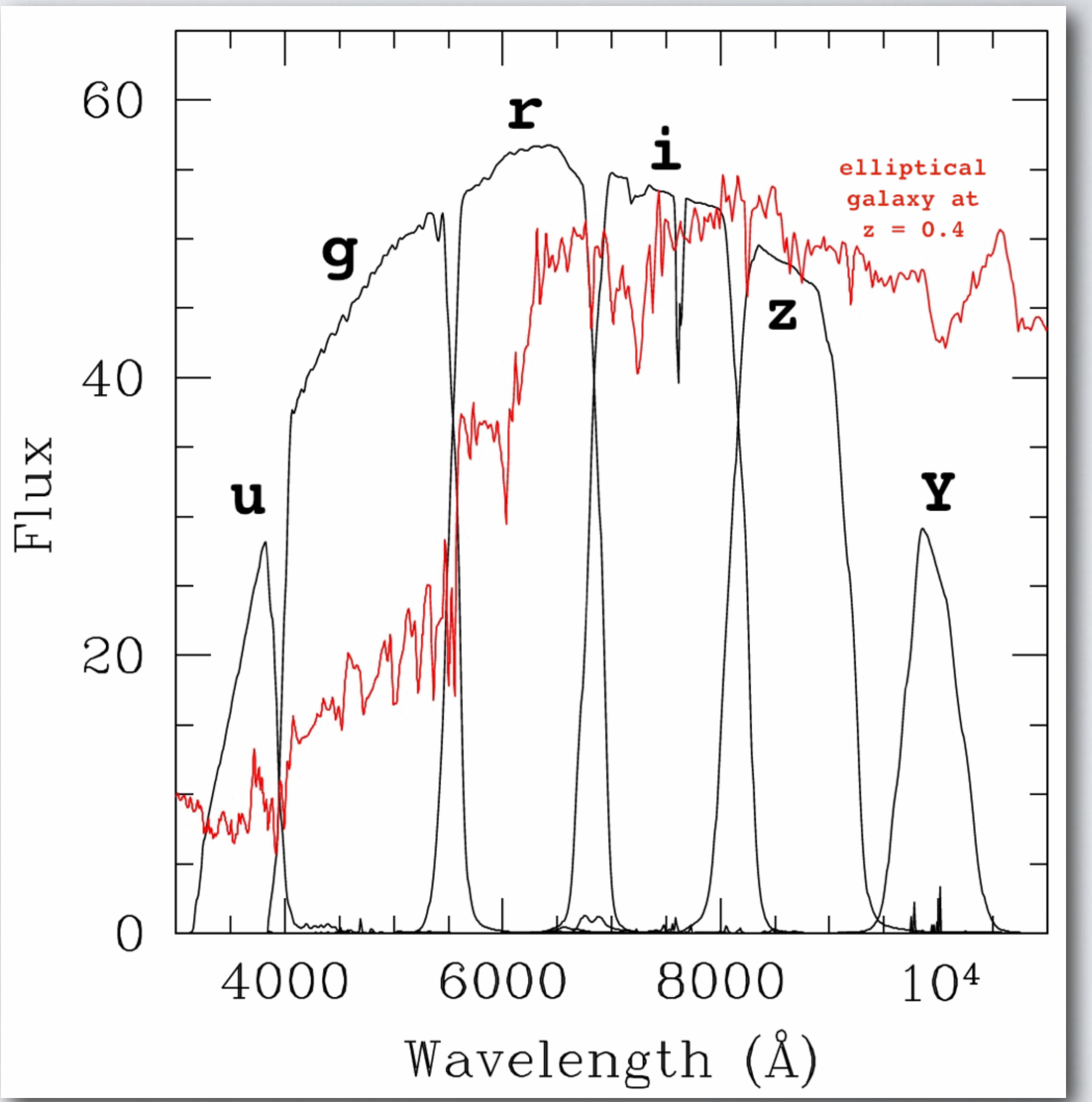
correct for distortions

Fluxes (counts/pix/sec)

take spectra, or images in **broadband filters**

calibrate from instrumental units to physical units

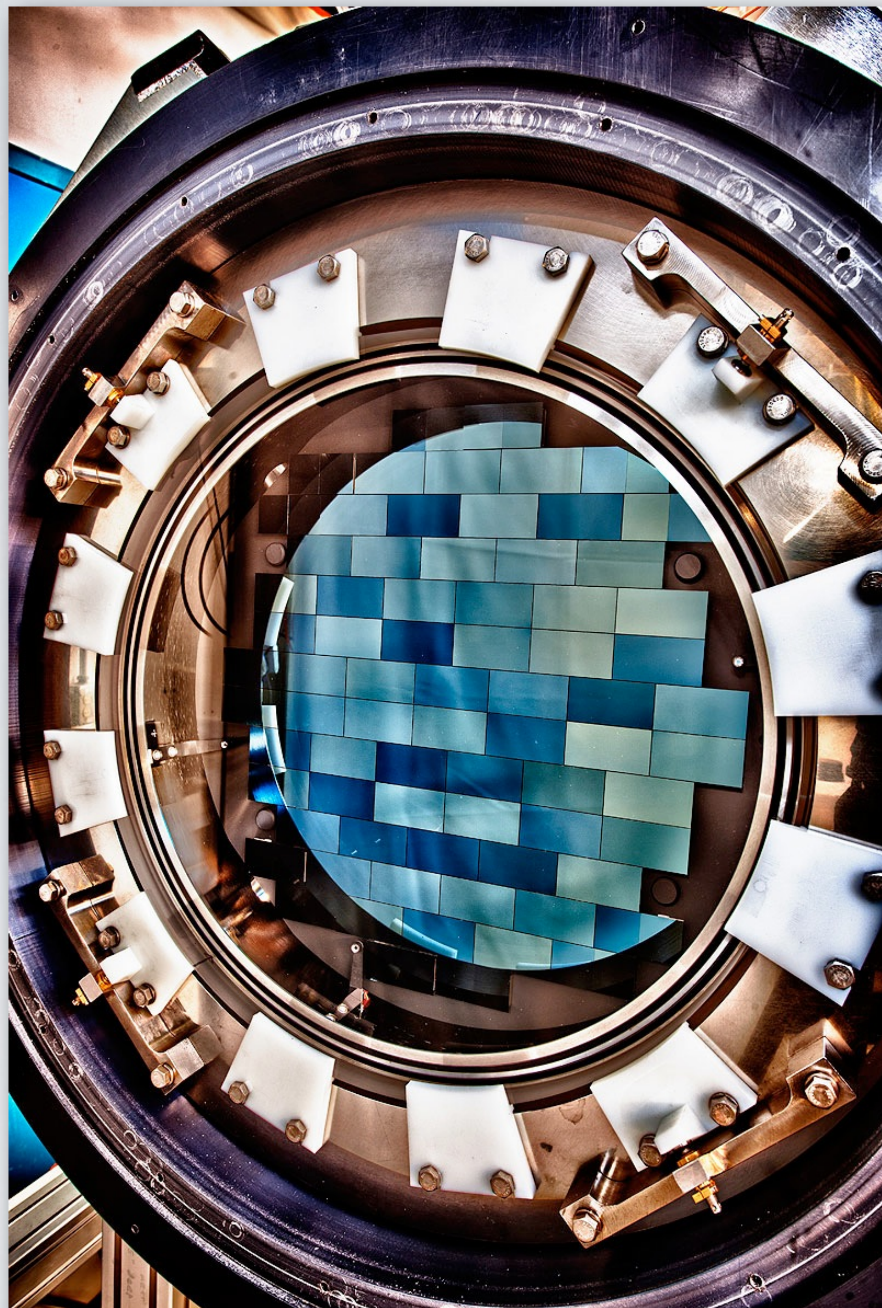
compute (photometric) redshifts

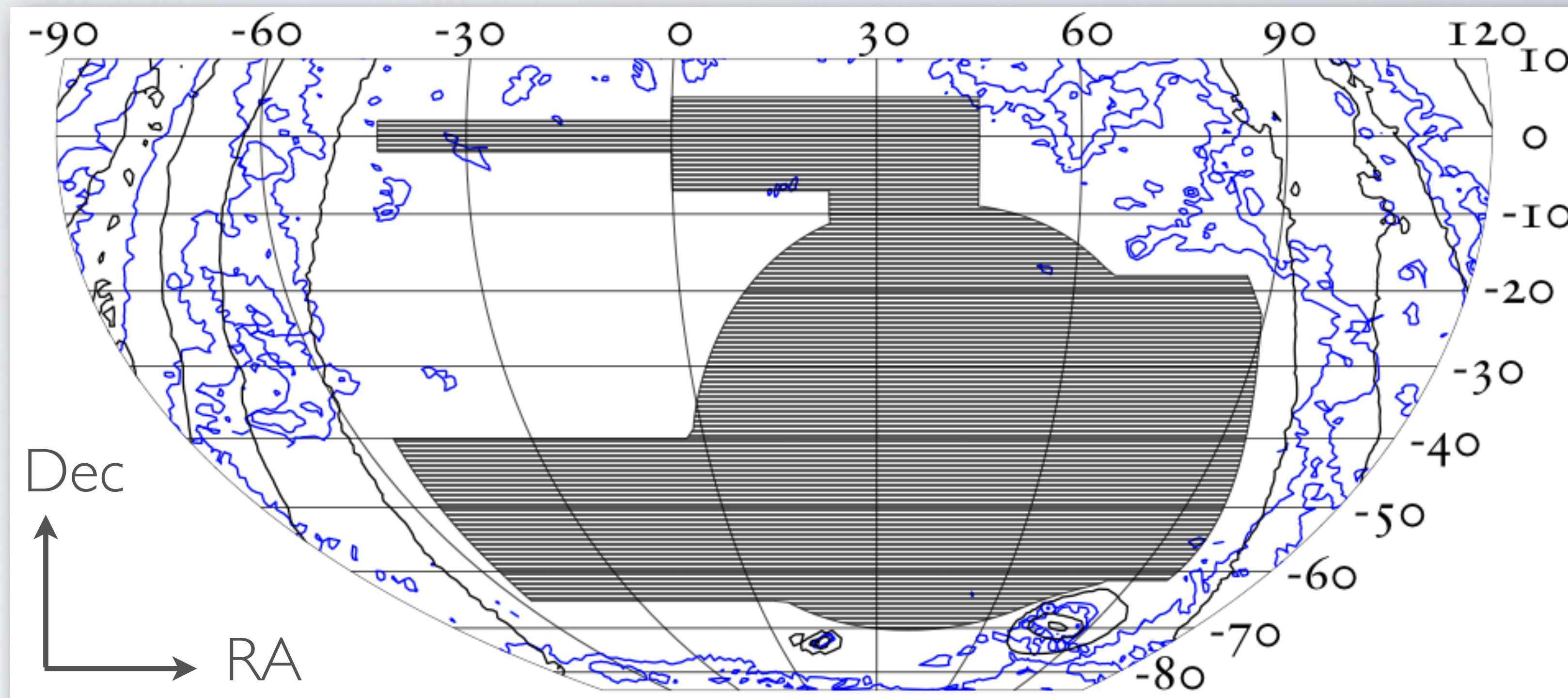


Shapes (ellipticity, size)

correct for distortions

DARK ENERGY SURVEY





DEcam

3 sq deg FOV, **570 Mpix** optical CCD camera

Facility instrument at **CTIO Blanco 4-m telescope in Chile**

First light: Sep 2012

Survey

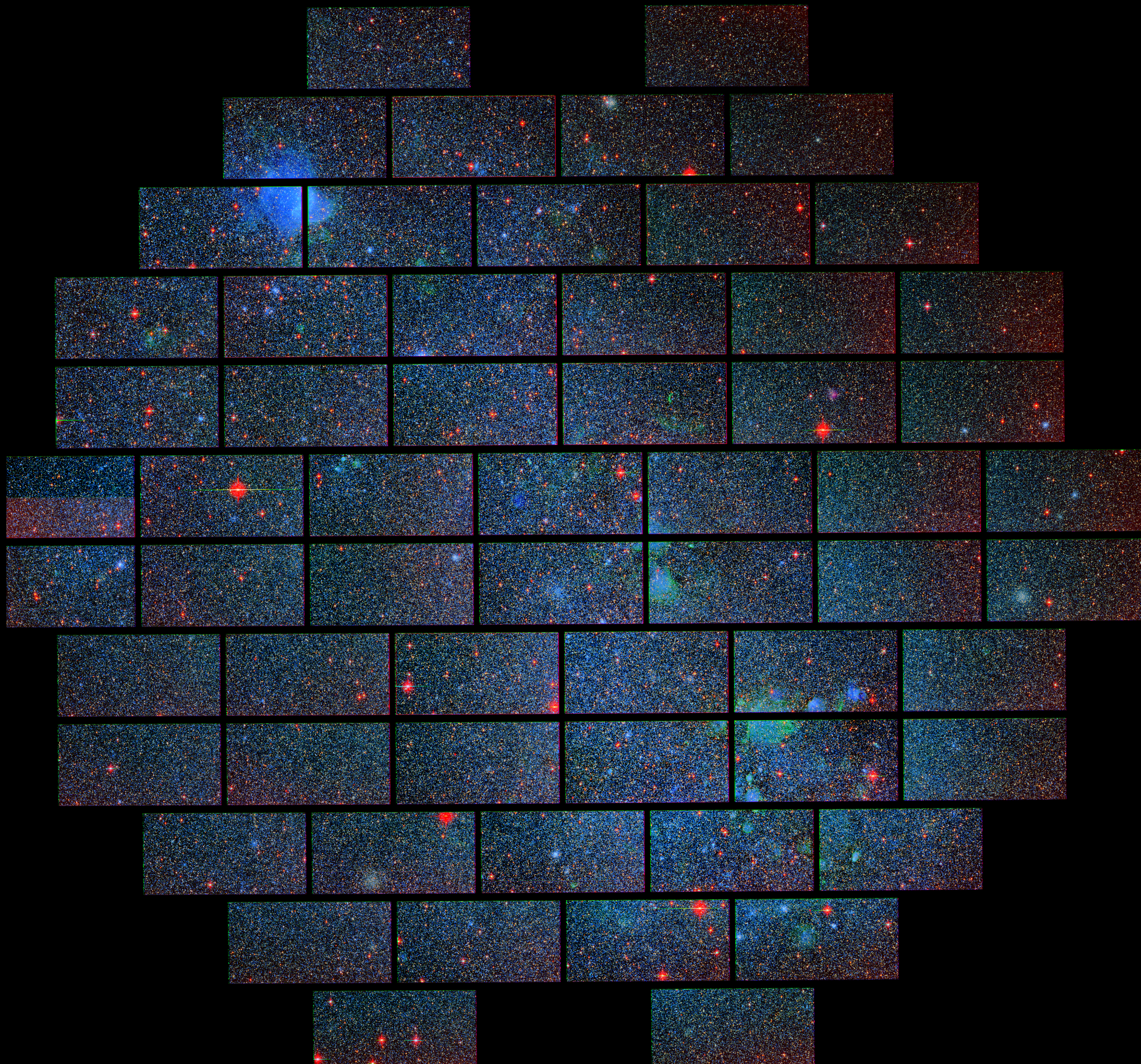
5000 sq deg grizY to **24th mag** overlaping with SPT and VISTA

30 sq deg SNe survey
0.9 arcseconds seeing

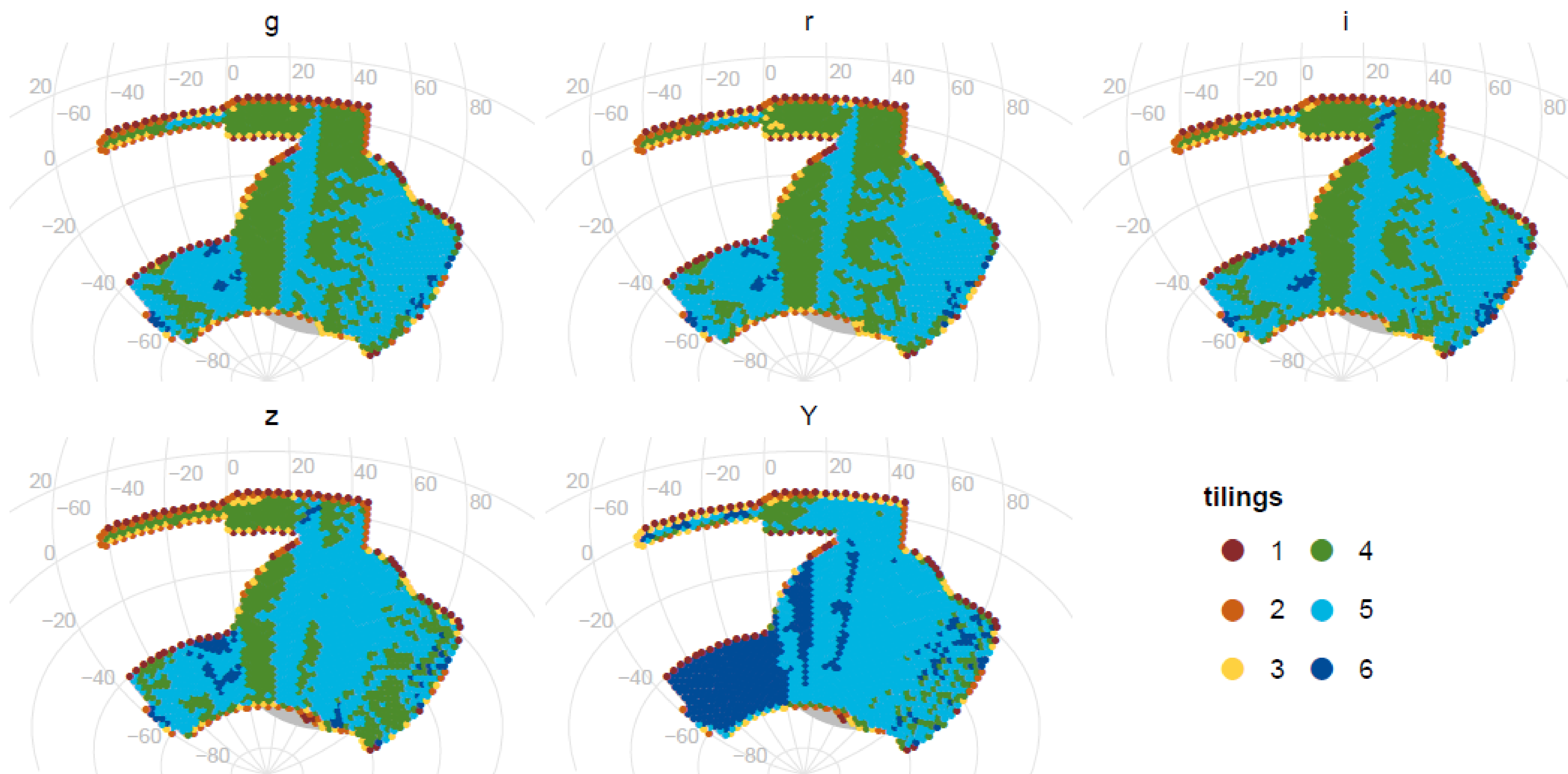
525 nights: 2013-2018

DES SITE: CERRO TOLOLO, CHILE

The Small Magellanic Cloud, DES 1st light image, Sep 12 2012



DES — STATUS AS OF FEB 2016



DES — SCIENCE RESULTS

DES has published over 70 papers based on the data taken so far.

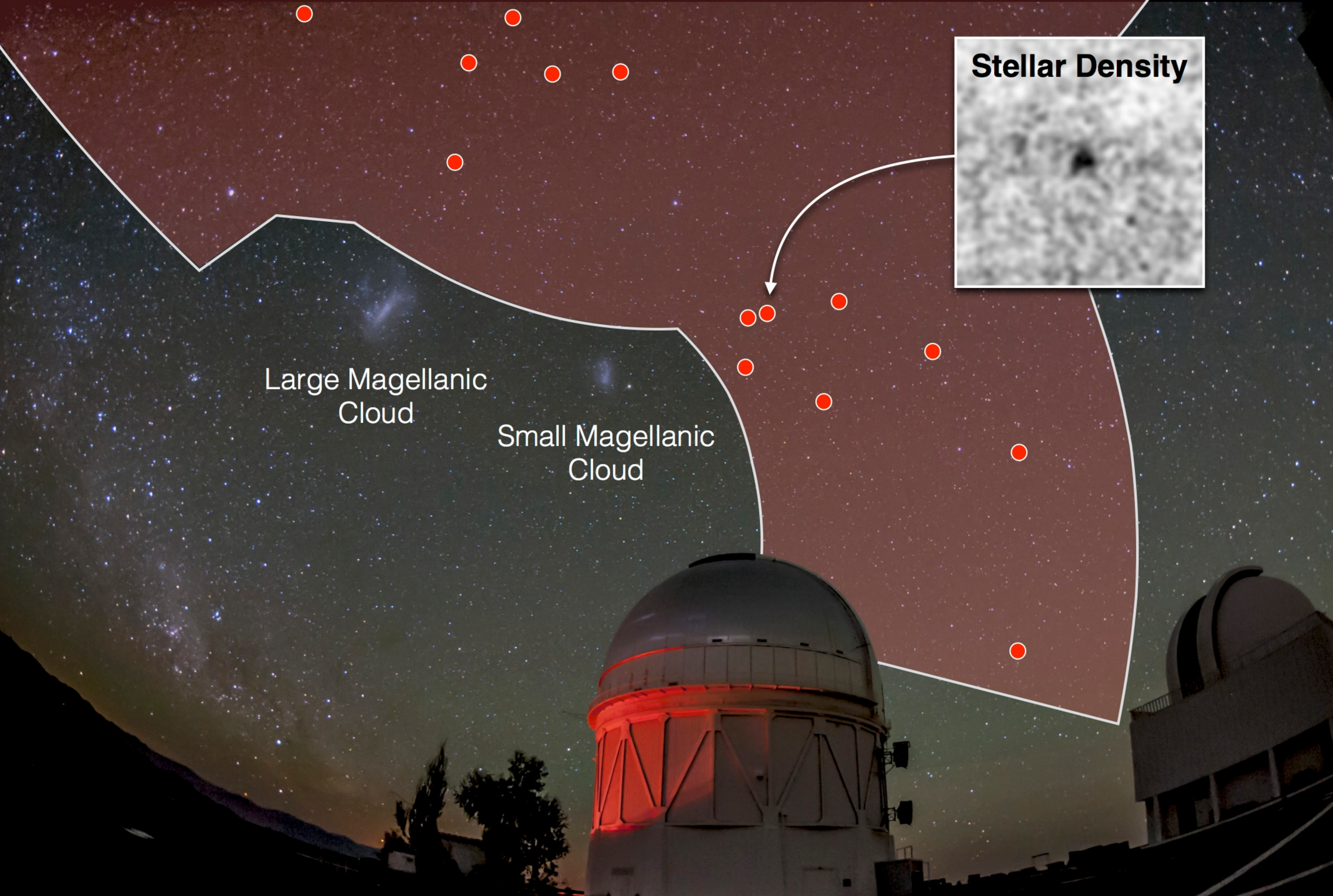
Most of them are **astrophysics results building towards cosmology measurements** (which are coming soon).

We also have **results that go beyond the traditional dark energy probes**, e.g.:

— New dwarf galaxies that enable **dark matter** searches

— Searches for optical signatures of **gravitational wave** events that might result in a new observable for cosmology.

In this talk I present a selection of recent DES results.

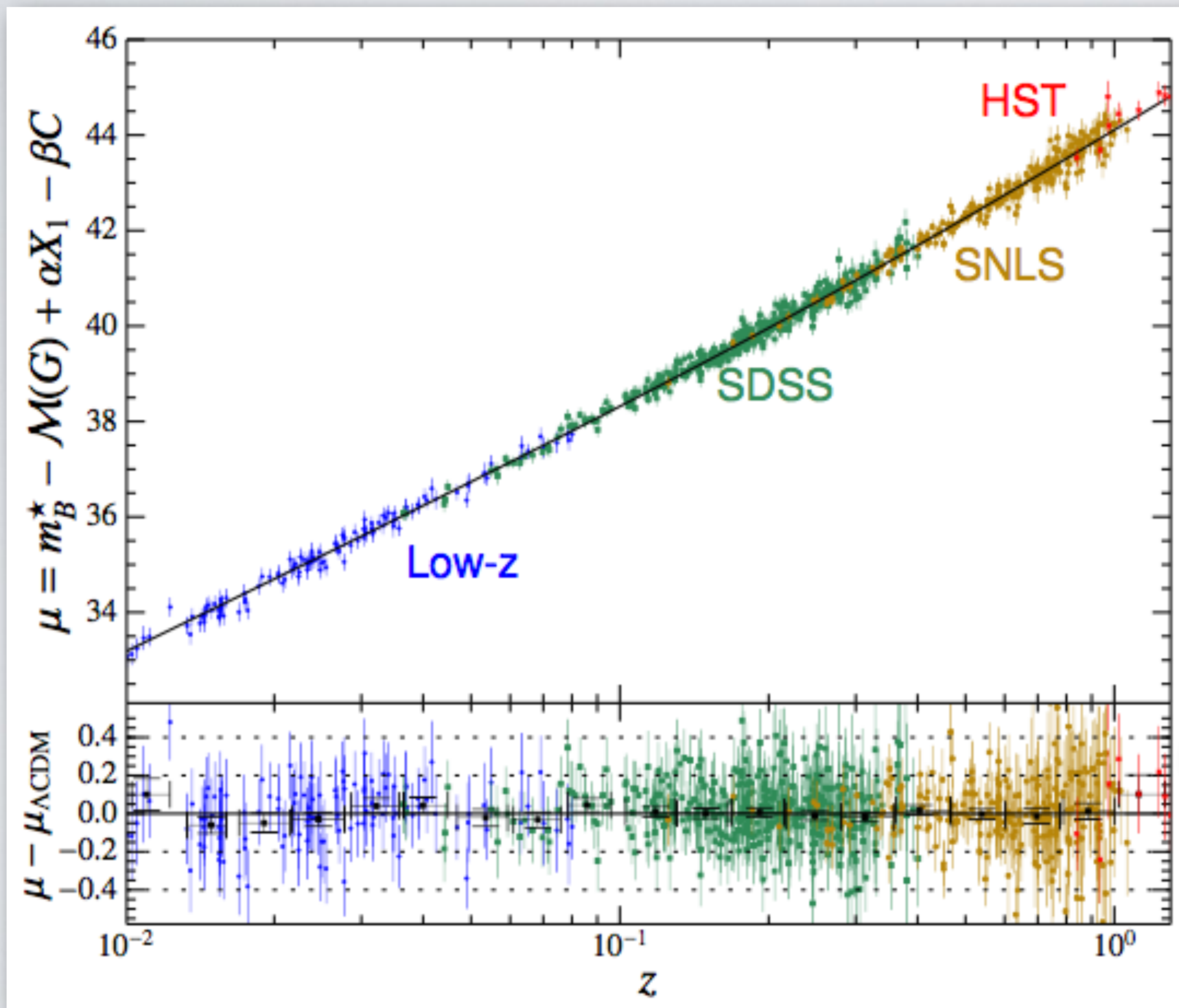


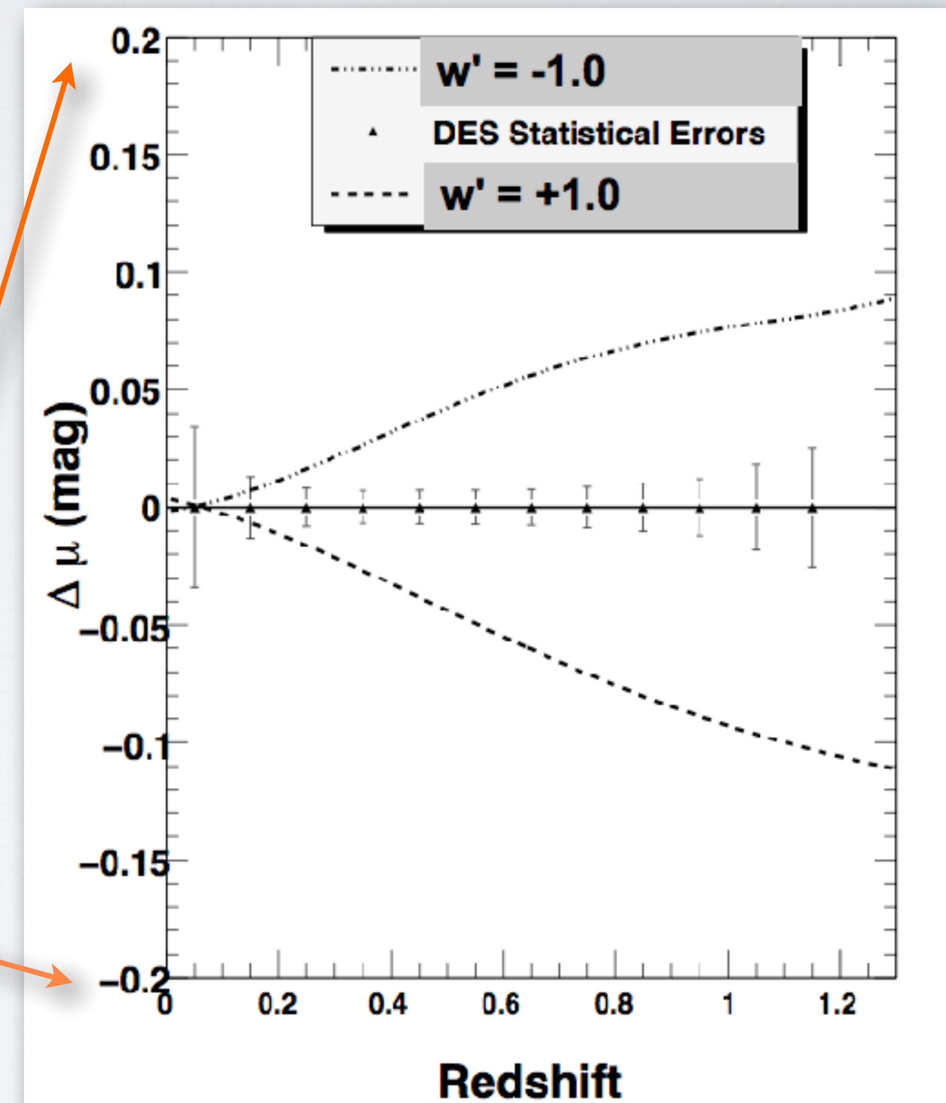
DES discovers new neighbors (dwarf galaxies)

DES SCIENCE: SN

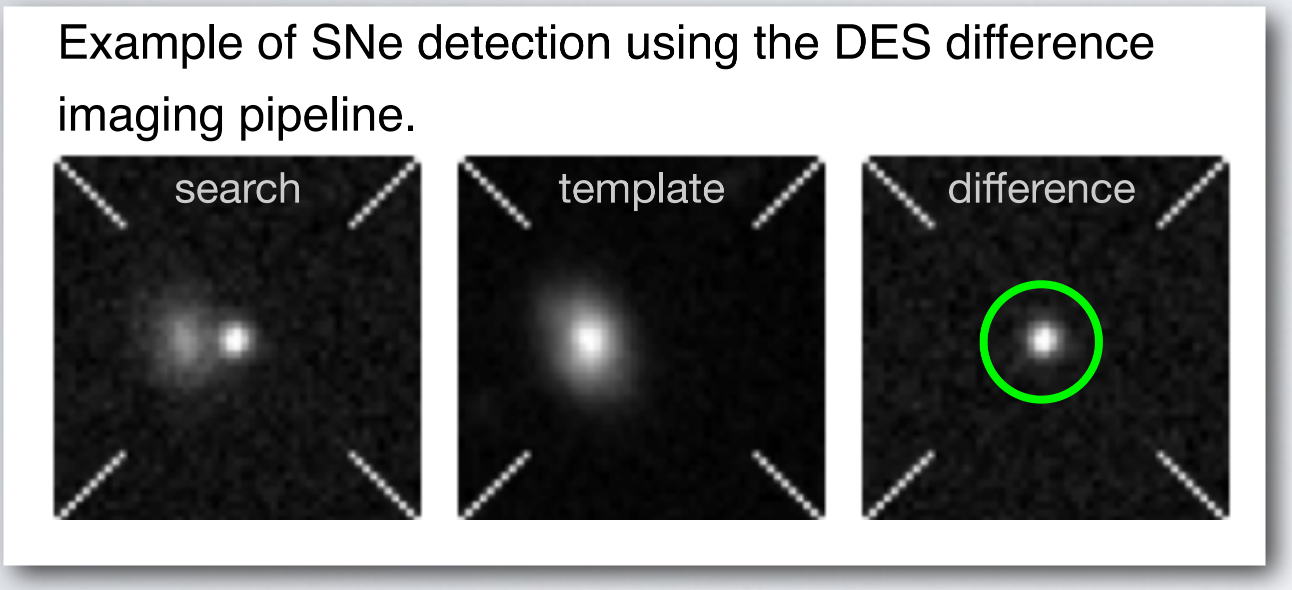
DES expected sensitivity, based on simulations.
3500 photometrically selected Type Ia SNe up to z = 1.2 in 30 sq-deg.

Joint SDSS-II and SNLS results: Hubble diagram using 740 spectroscopically selected SNe (Betoule et al. 2014).



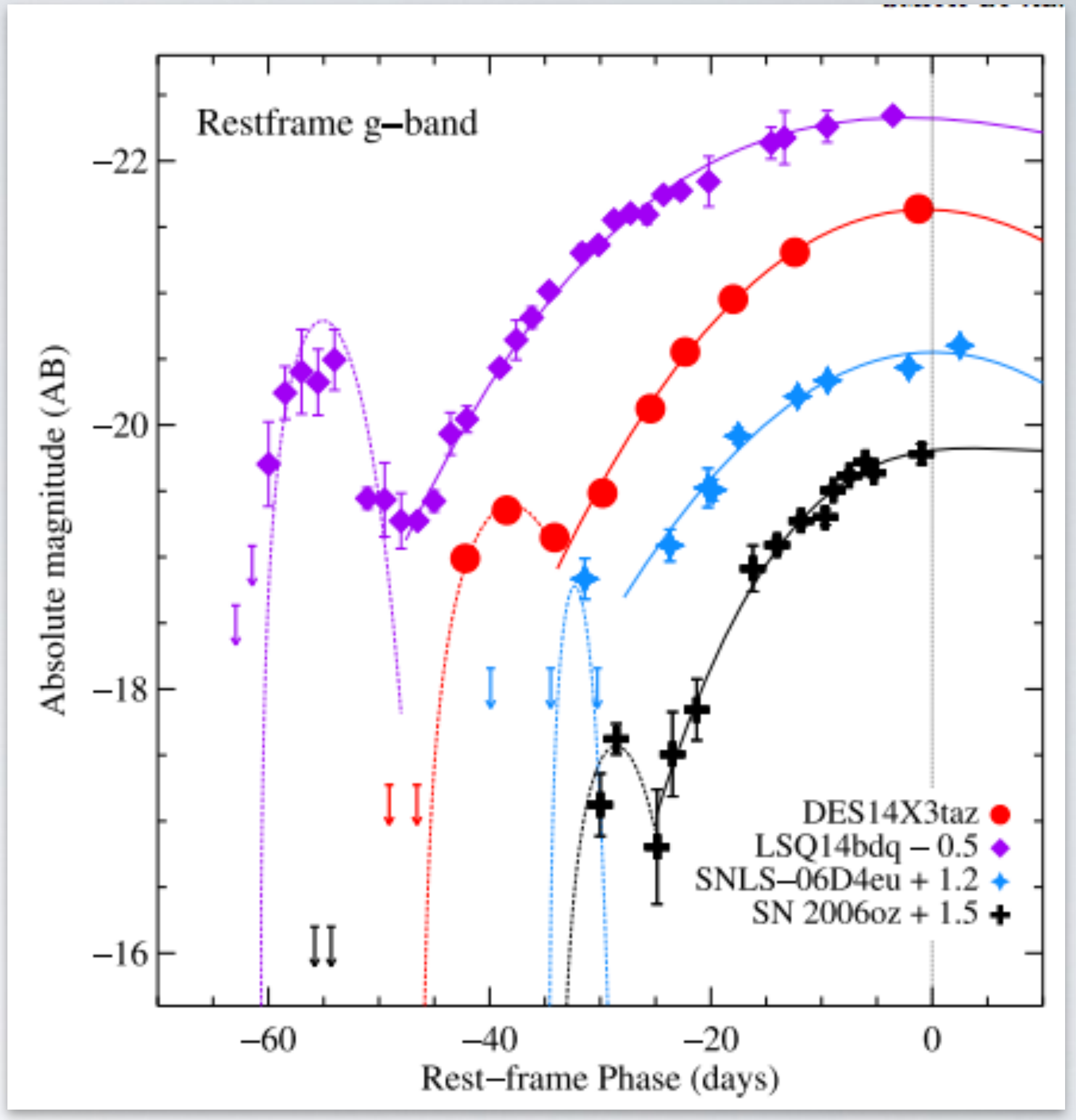


DES SCIENCE: SN



The Difference Imaging Pipeline for the Transient Search in the Dark Energy Survey

Kessler, et al. 2015, AJ, 150, 172



DES14X3taz: A Type I Superluminous Supernova Showing a Luminous, Rapidly Cooling Initial Pre-peak Bump

Smith, M. et al. 2016, ApJ, 818, 8

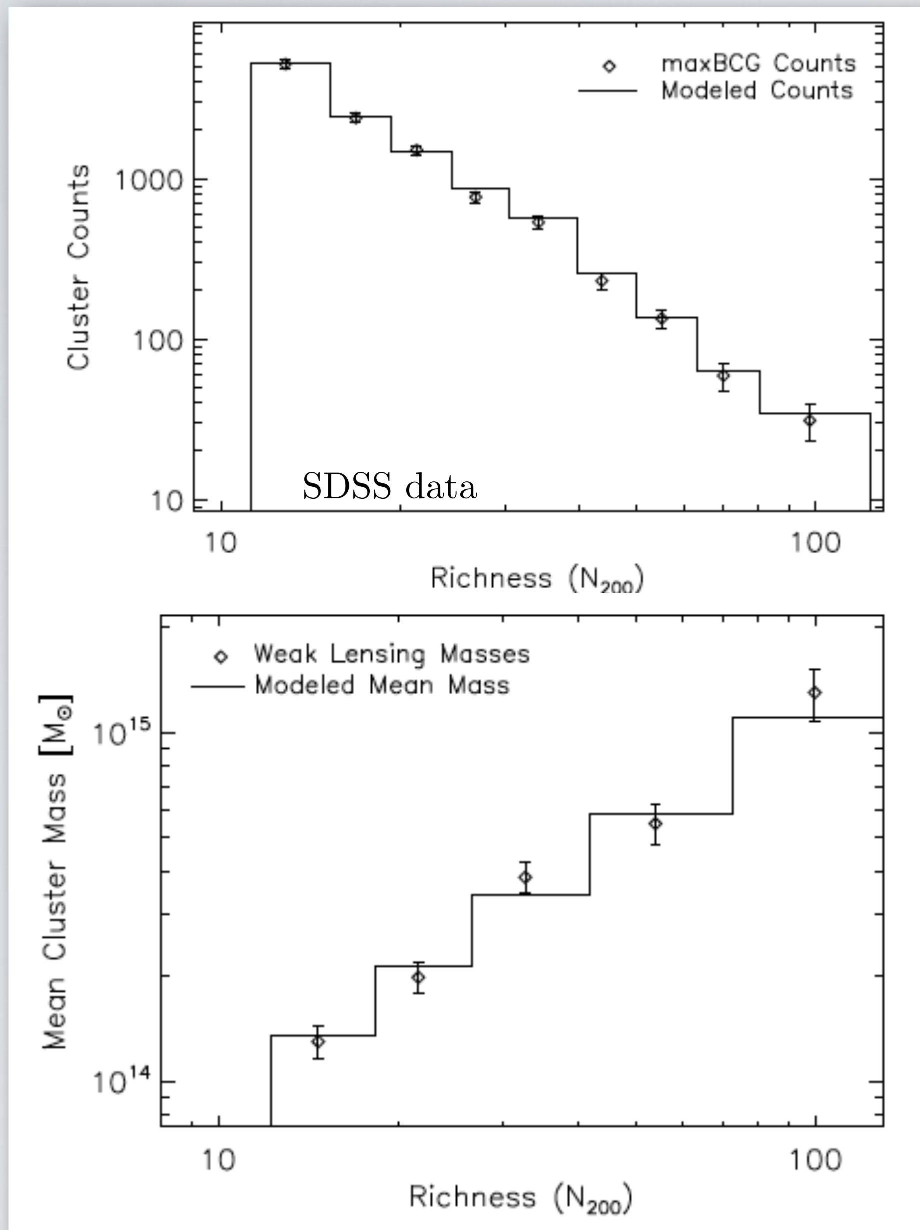
Over 200 type Ia SNe spectroscopically confirmed.

Photometrically selected sample 5x larger.

Cosmology results using type Ia SNe coming soon.

Also discovered many other types of supernova, including rare superluminous SNe.

DES SCIENCE: CLUSTERS

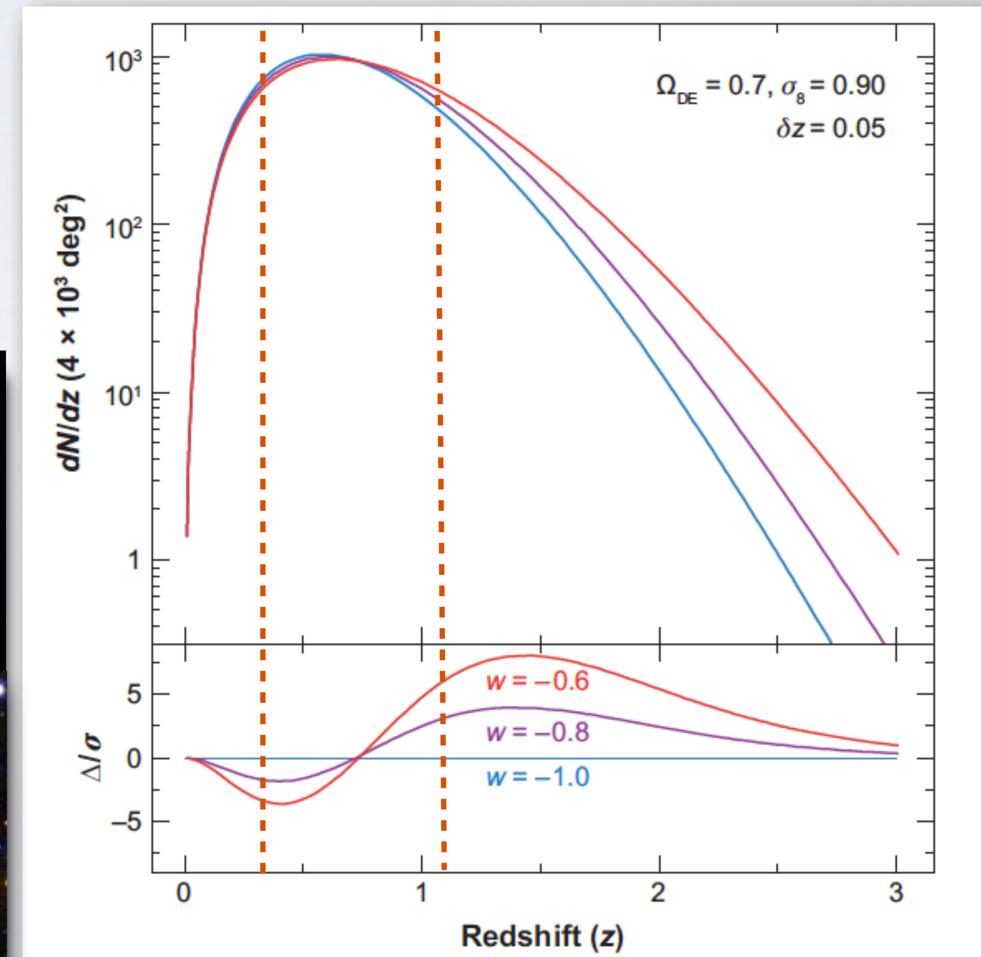


Results from 6000 SDSS clusters, z ~0.35 (Rozo et al. 2010)

DES image of the Bullet Cluster
arXiv:1405.4285

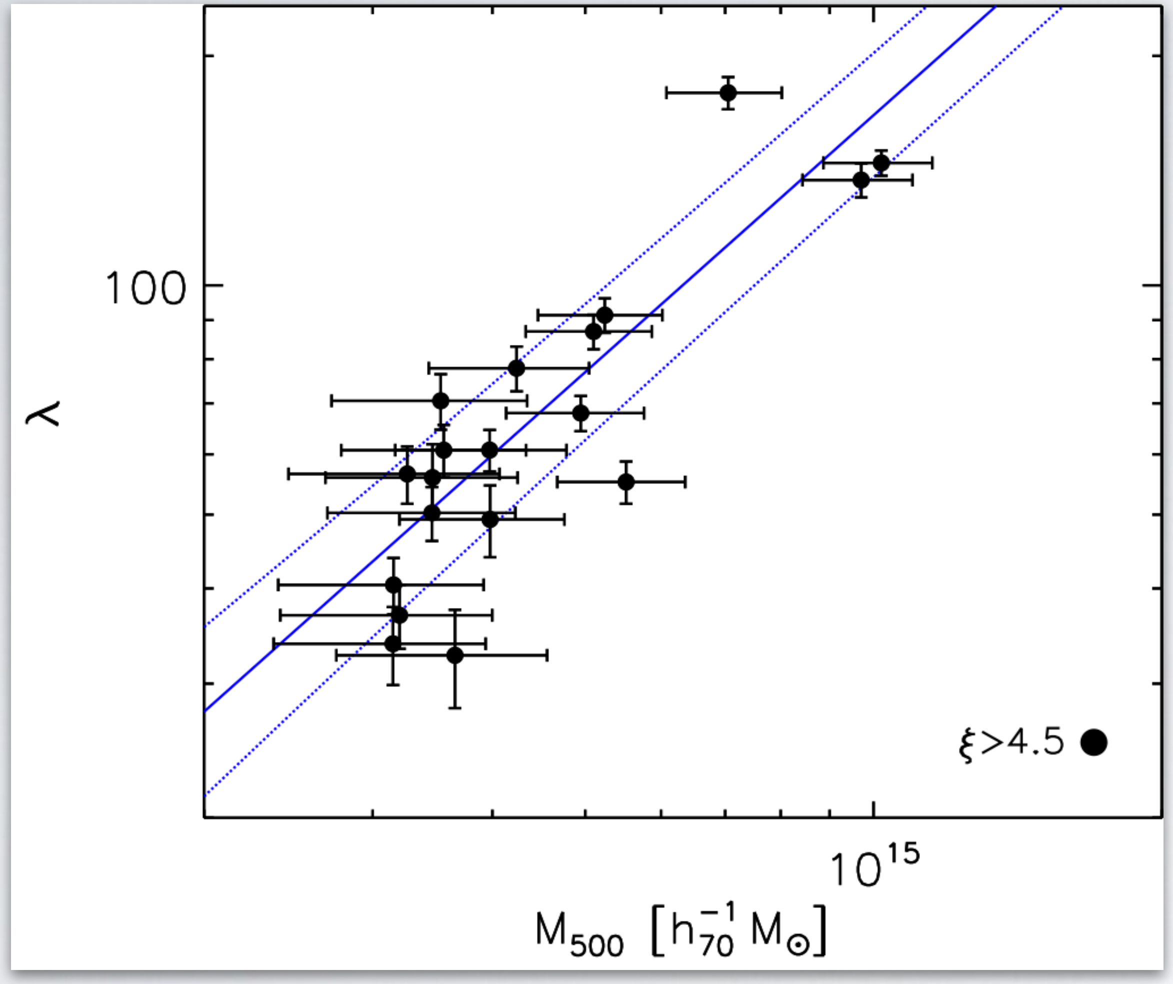
SDSS sample:
up to z ~ 0.3

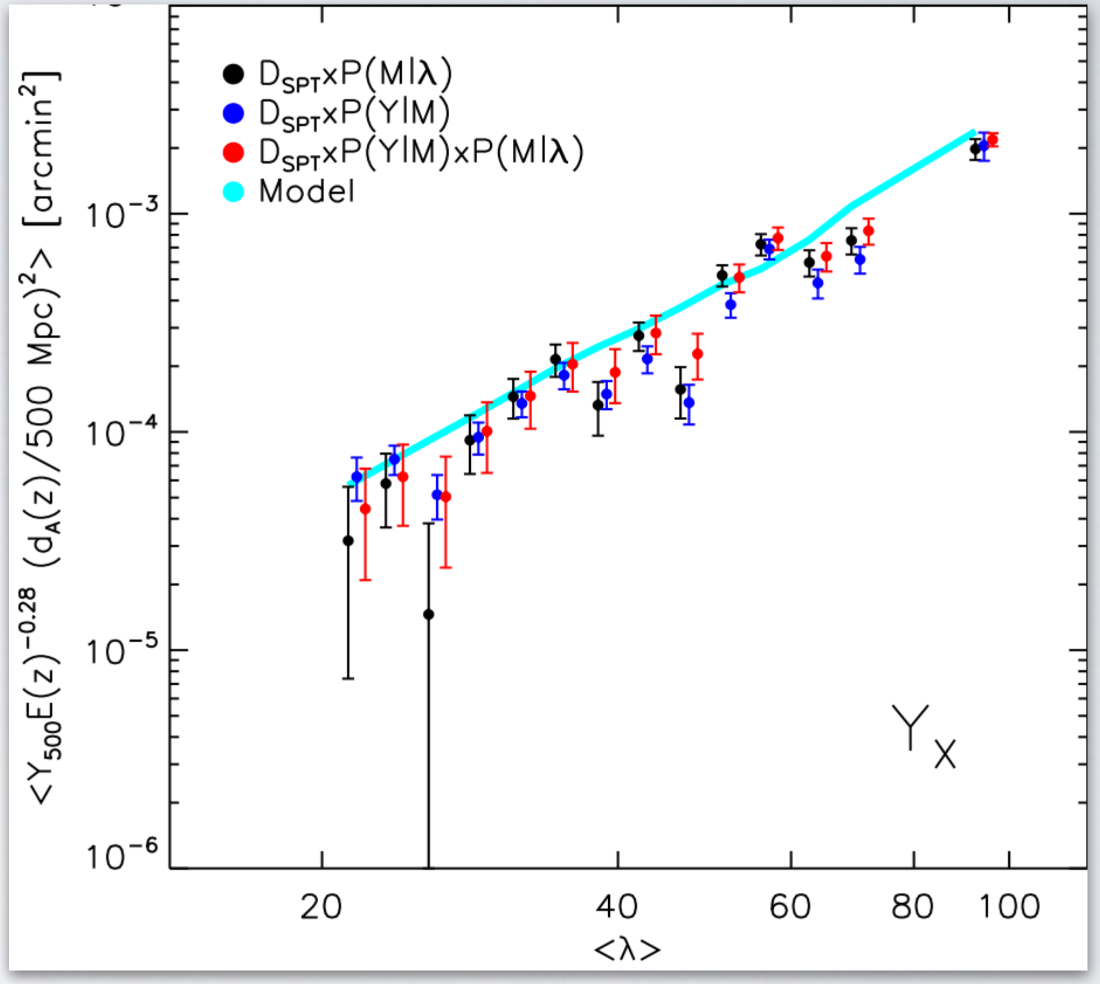
DES sample:
up to z ~ 1



Number of clusters above $10^{14.5}$ solar masses as a function of z, for a 4000 sq-deg survey in 3 different cosmologies.

DES SCIENCE: CLUSTERS





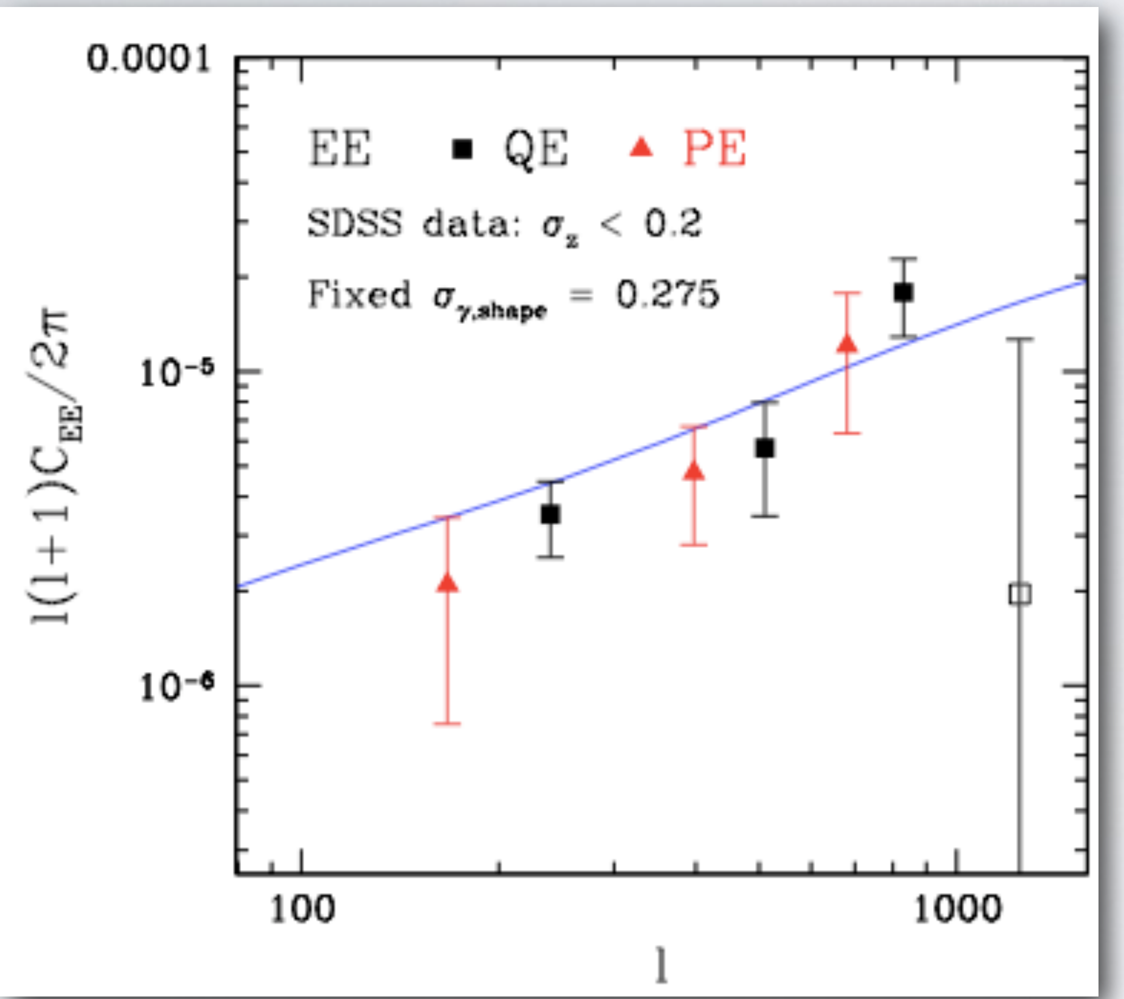
Constraints on the richness-mass relation and the optical-SZE positional offset distribution for SZE-selected clusters.

Saro, et al. 2015, MNRAS, 454, 2305

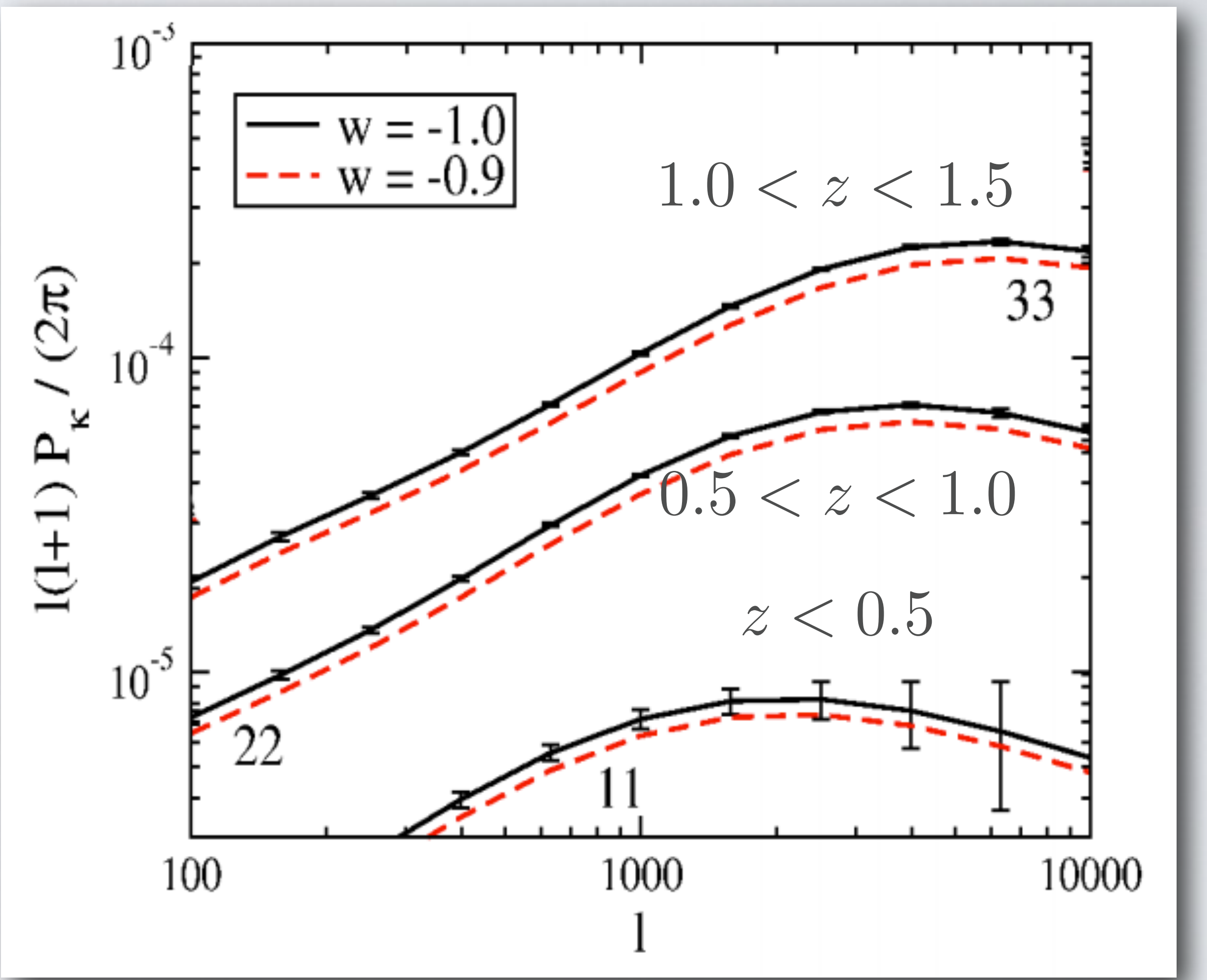
Optical-SZE Scaling Relations for DES Optically Selected Clusters within the SPT-SZ Survey

Saro, et al. 2016, arXiv:1605.08770

DES SCIENCE: WL

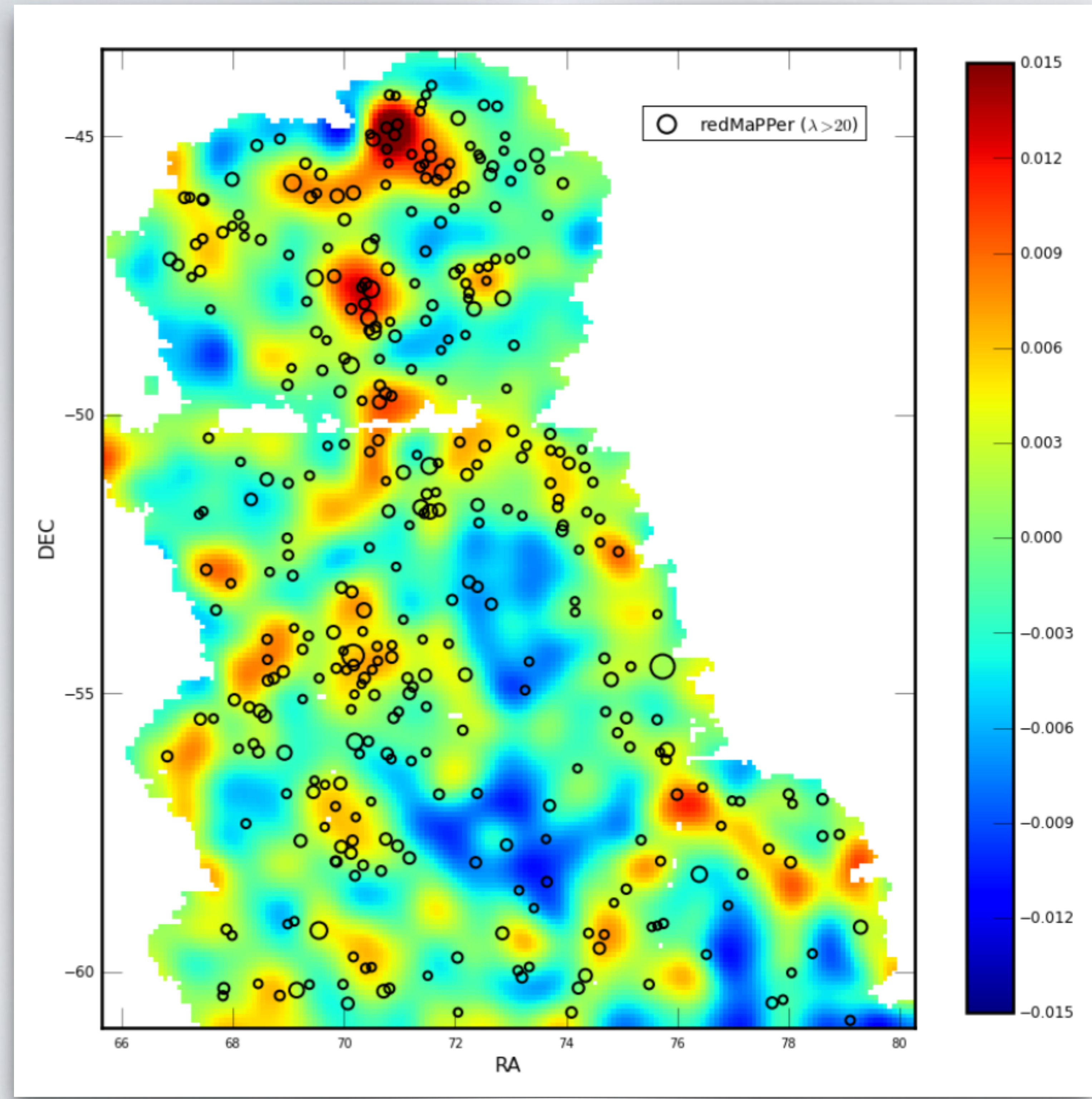


Results based on SDSS data:
275 sq deg, 24th mag, z<0.7
(Lin et al. 2012)



DES expected WL power spectrum assuming 5000 sq-deg, in 3 bins of photot-z width 0.5 out to z = 1.5

DES SCIENCE: WL, AND CLUSTERS



DES map of projected mass for z < 0.5

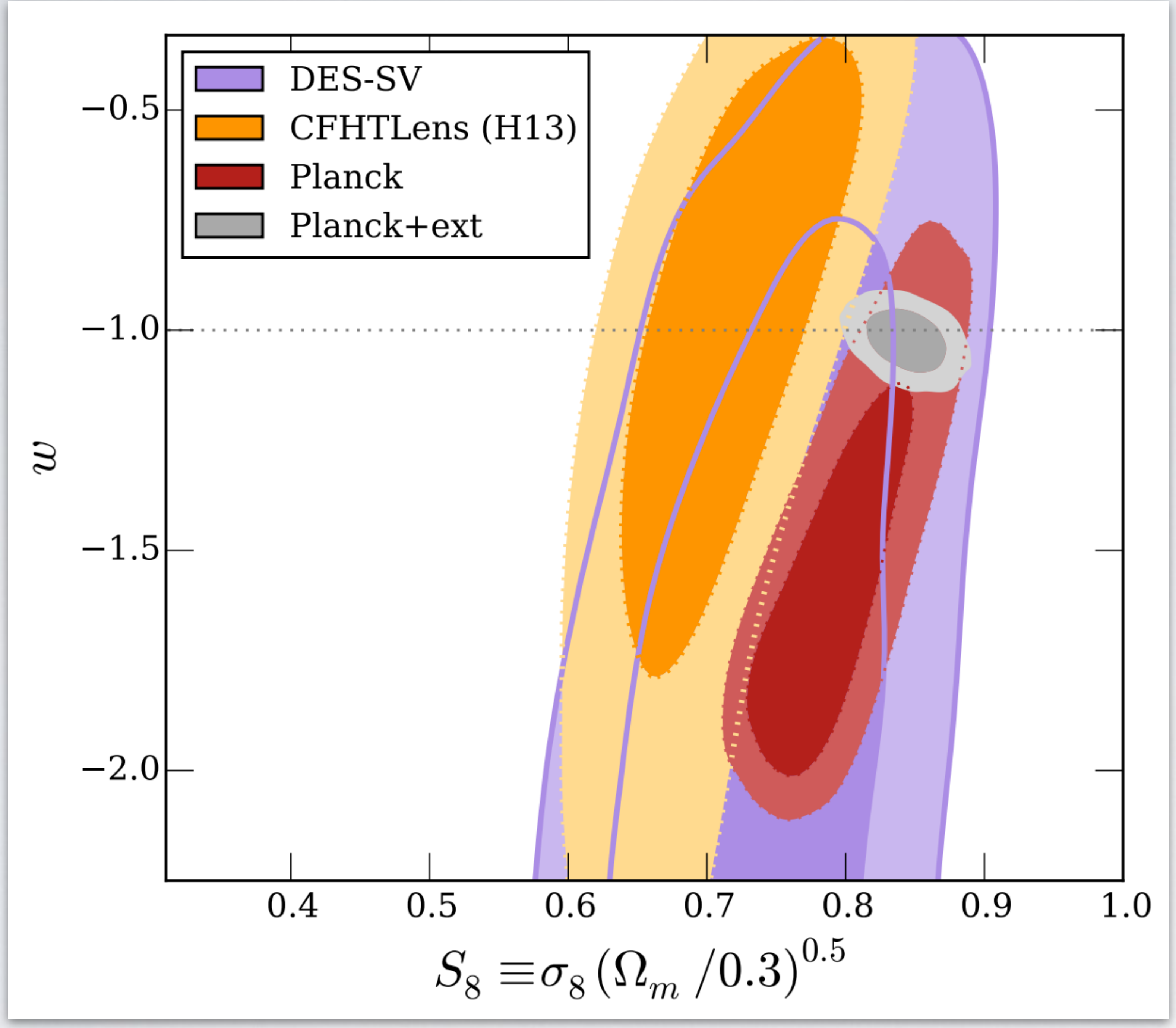
Hot (red) regions are more massive than cold (blue) regions.

Circles: galaxy clusters

Clusters are correlated with "hot" regions!

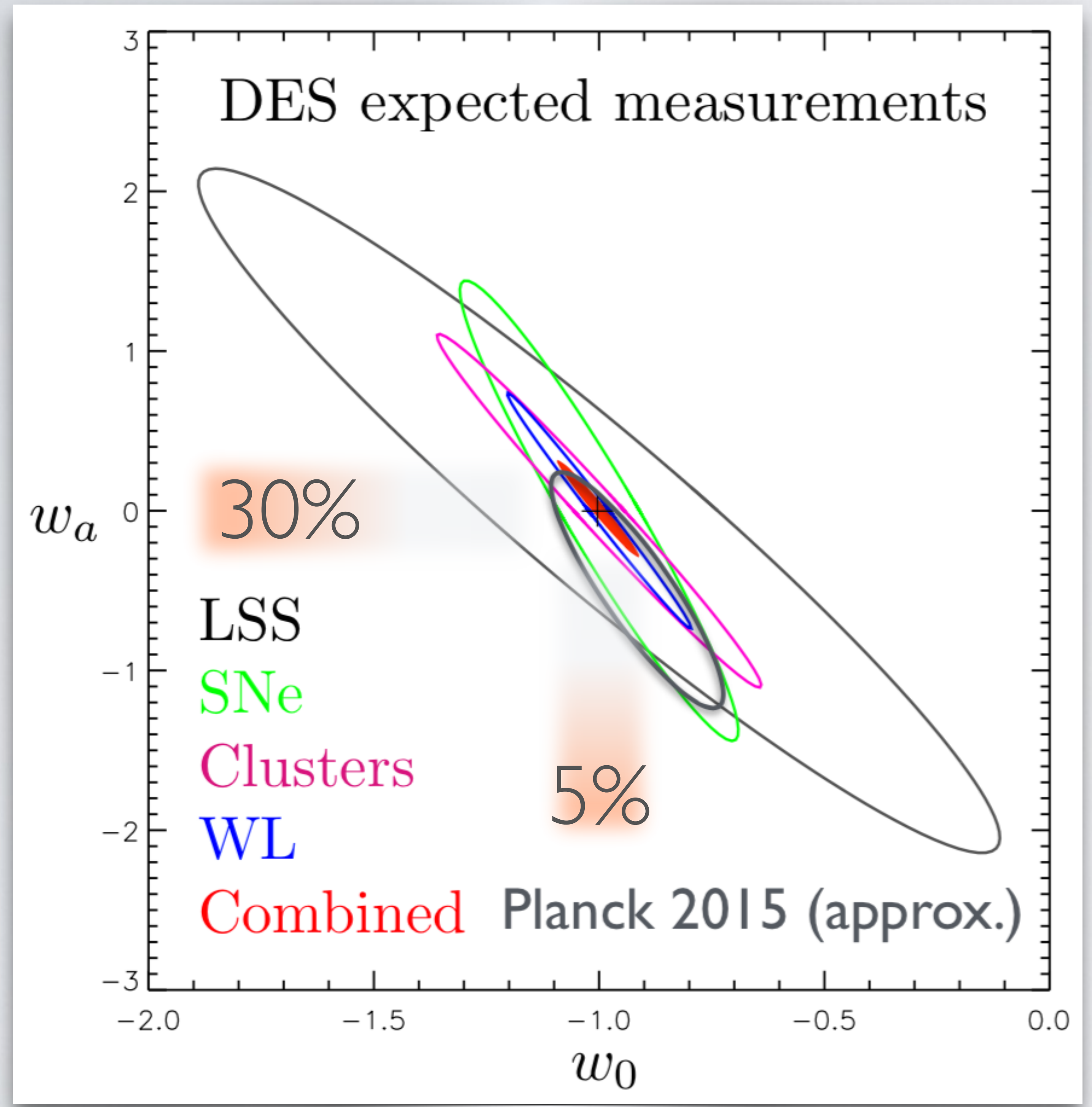
arXiv:1504.03002

DES SCIENCE: WL



arXiv:1507.05552

DES PROJECTIONS



5000 deg^2, 0.9'' seeing, 24th mag (redshift~1.4)

300M galaxies, shapes, 100K clusters, 4K SNe

4 combined probes

3-5x improved Dark Energy measurement

Can we add another DE probe to this picture?

GW+EM OPPORTUNITIES

Astrophysics

First detections of NS-NS, NS-BH mergers
Evolution of binary systems
Origin of r-process elements in the Universe
Neutron Star equation of state

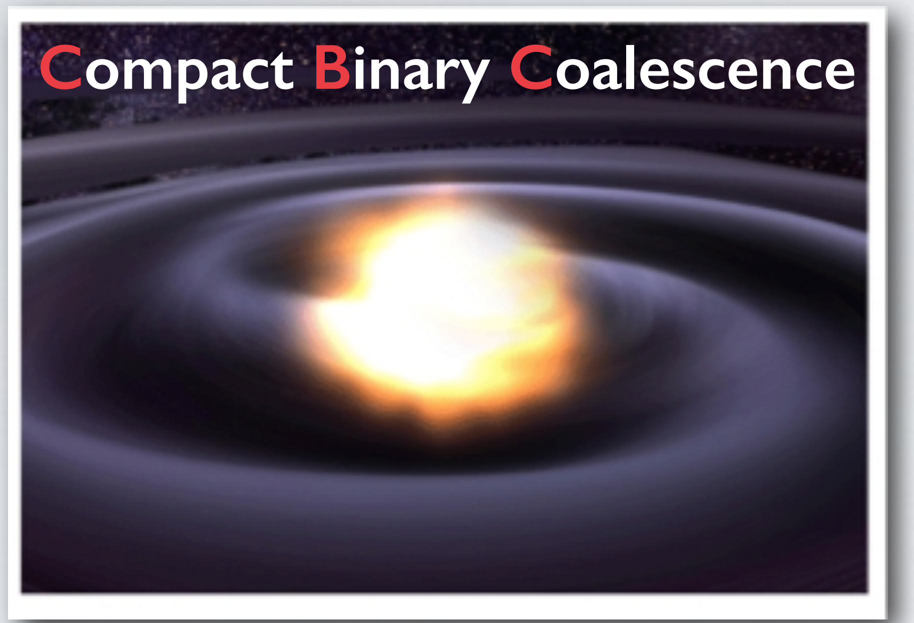
Cosmology

Standard sirens (the GW-equivalent of standard candles)

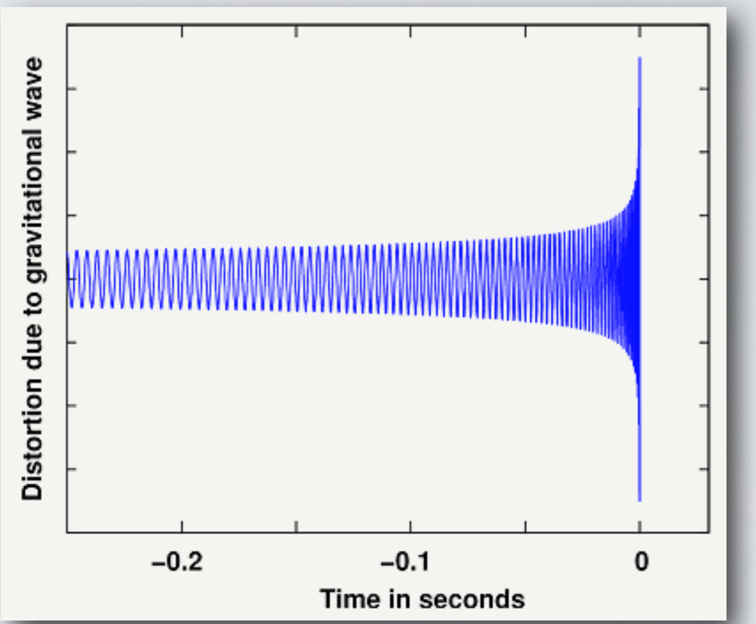
Physics of space-time

Time of flight experiments (including neutrinos?)
Tests of General Relativity

STANDARD SIRENS

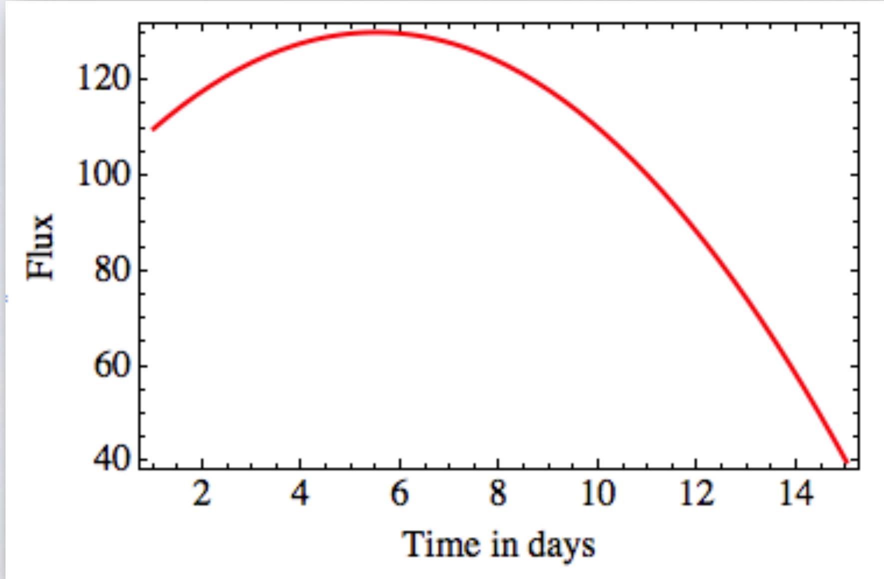


GW →

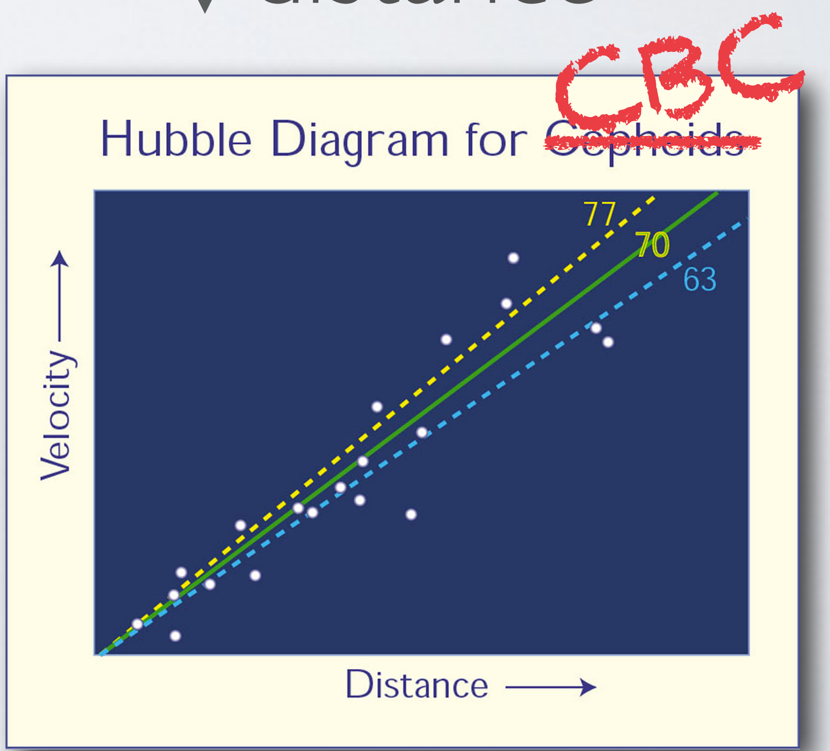


↓ EM

↓ distance



redshift →



GRAVITATIONAL WAVES

A DECam Search for an Optical Counterpart to the LIGO Gravitational Wave Event GW151226

Cowperthwaite, et al. 2016, submitted to ApJL

A Dark Energy Camera Search for Missing Supergiants in the LMC after the Advanced LIGO Gravitational-wave Event GW150914

Annis, et al. 2016, ApJL, 823, 34

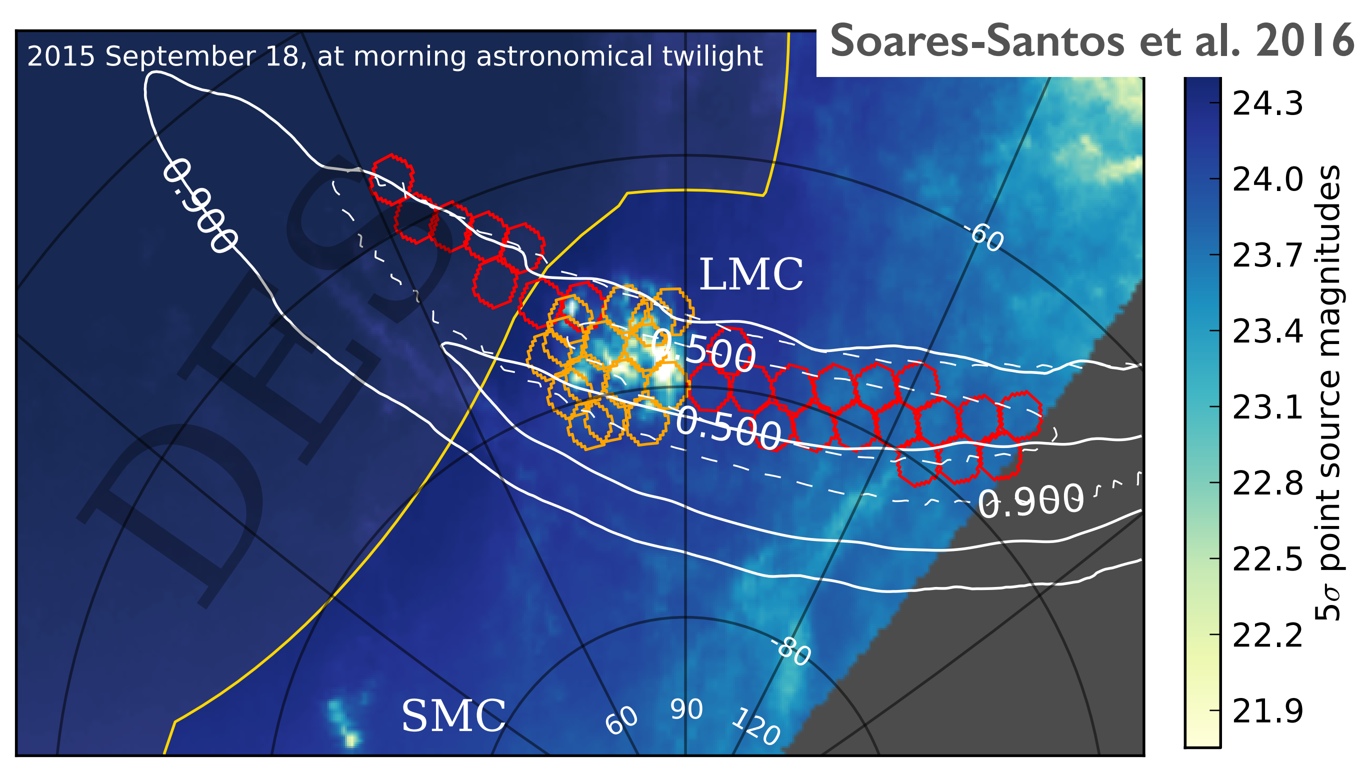
A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

Soares-Santos, et al. 2016, ApJL, 816, 98

Funding:

LDRD (FY15, FY16), Chicago SCI (FY17)

Potentially a new cosmological probe!



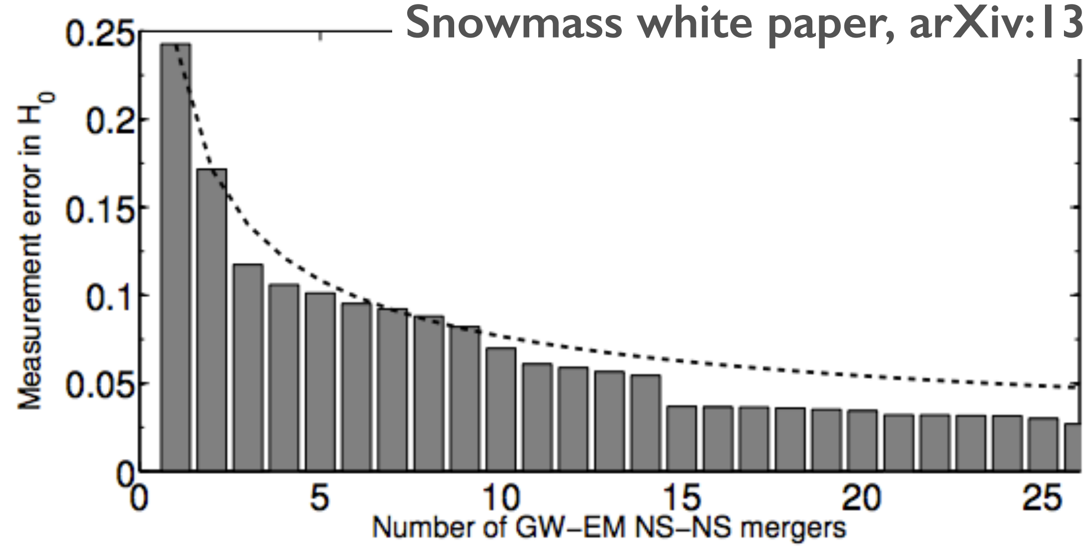
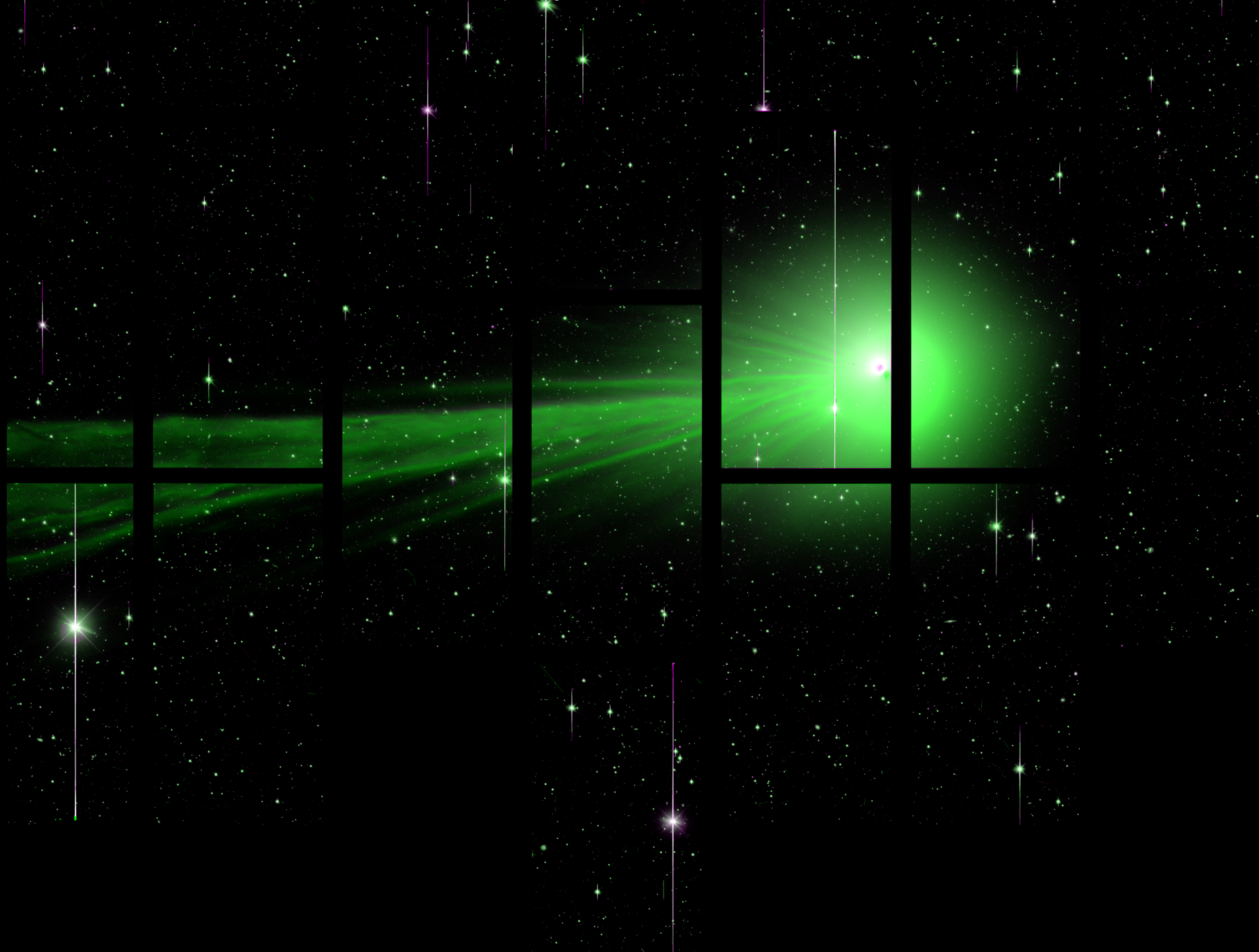


Figure 8: H_0 measurement uncertainty as a function of the number of multi-messenger (GW+EM) double neutron star merger events observed by an advanced LIGO-Virgo network. The dashed line shows Gaussian convergence.

These are exciting times for **Dark Energy** science, and more, with DES. Stay tuned for more results soon!



Comet Lovejoy, DES image, 27-12-2014

BACKUP SLIDES

DES-GW

Can we take advantage of this new way to observe the universe, with Gravitational Waves, to add a new Dark Energy probe to our repertoire and beat down the systematics?

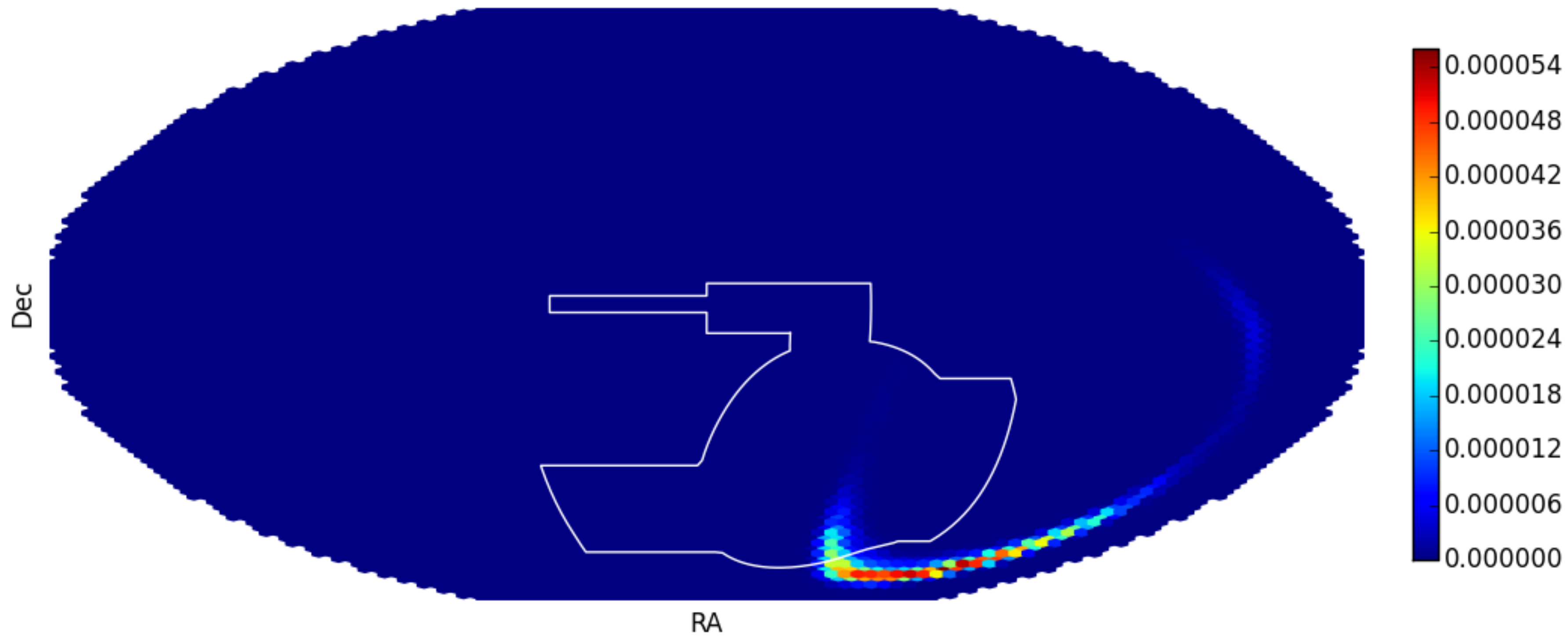
With this motivation, we launched the DESGW project in 2013. We established a joint effort that includes LIGO members (Holz et al.) and non-DES DECam users (Berger et al.)

We developed an analysis that is sensitive to NS-NS, BH-NS mergers out to 200Mpc — and didn't see an optical counterpart. It turned out this event did not have a NS in it, but prospects for future are good!

DESGW is supported by Fermilab's LDRD program in FY14, FY15

GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

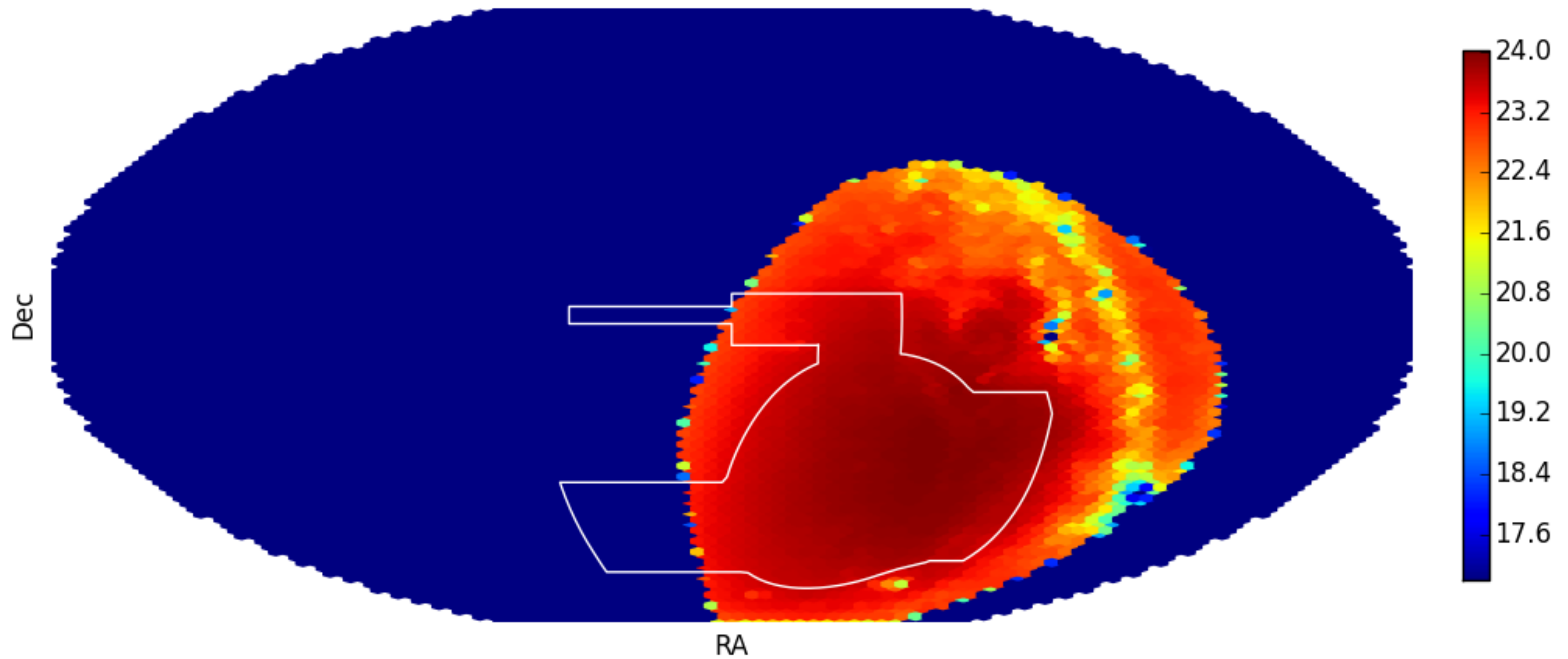


LVC sky localization probability map (final)

GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)

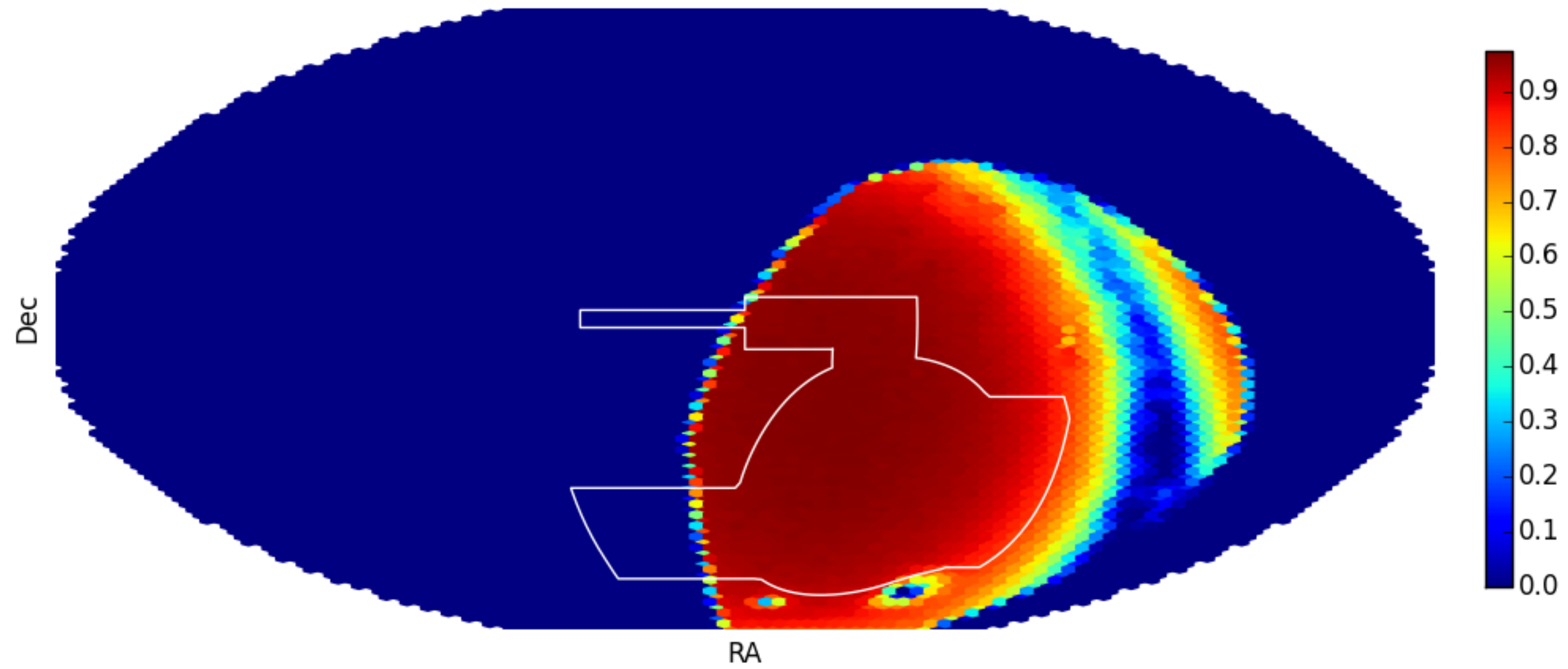


DES mag limit model

GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)

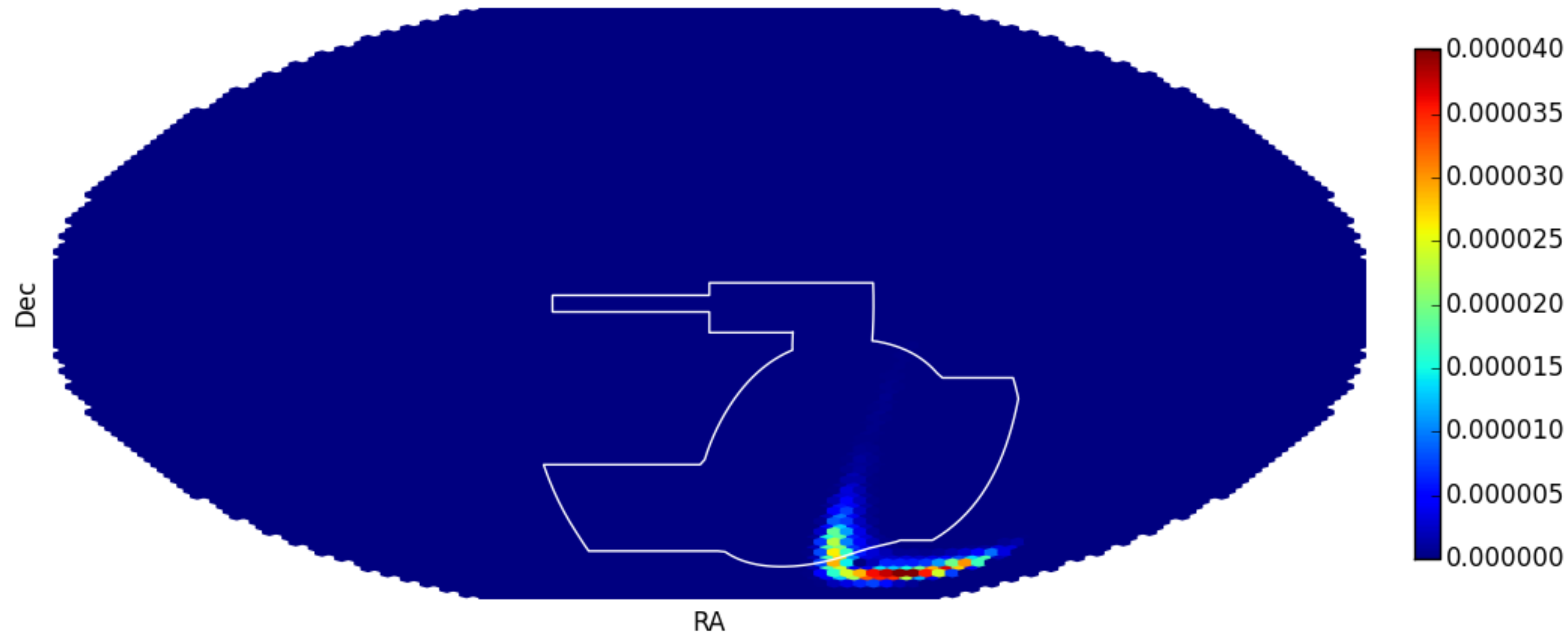


DES source detection probability map

GW150914

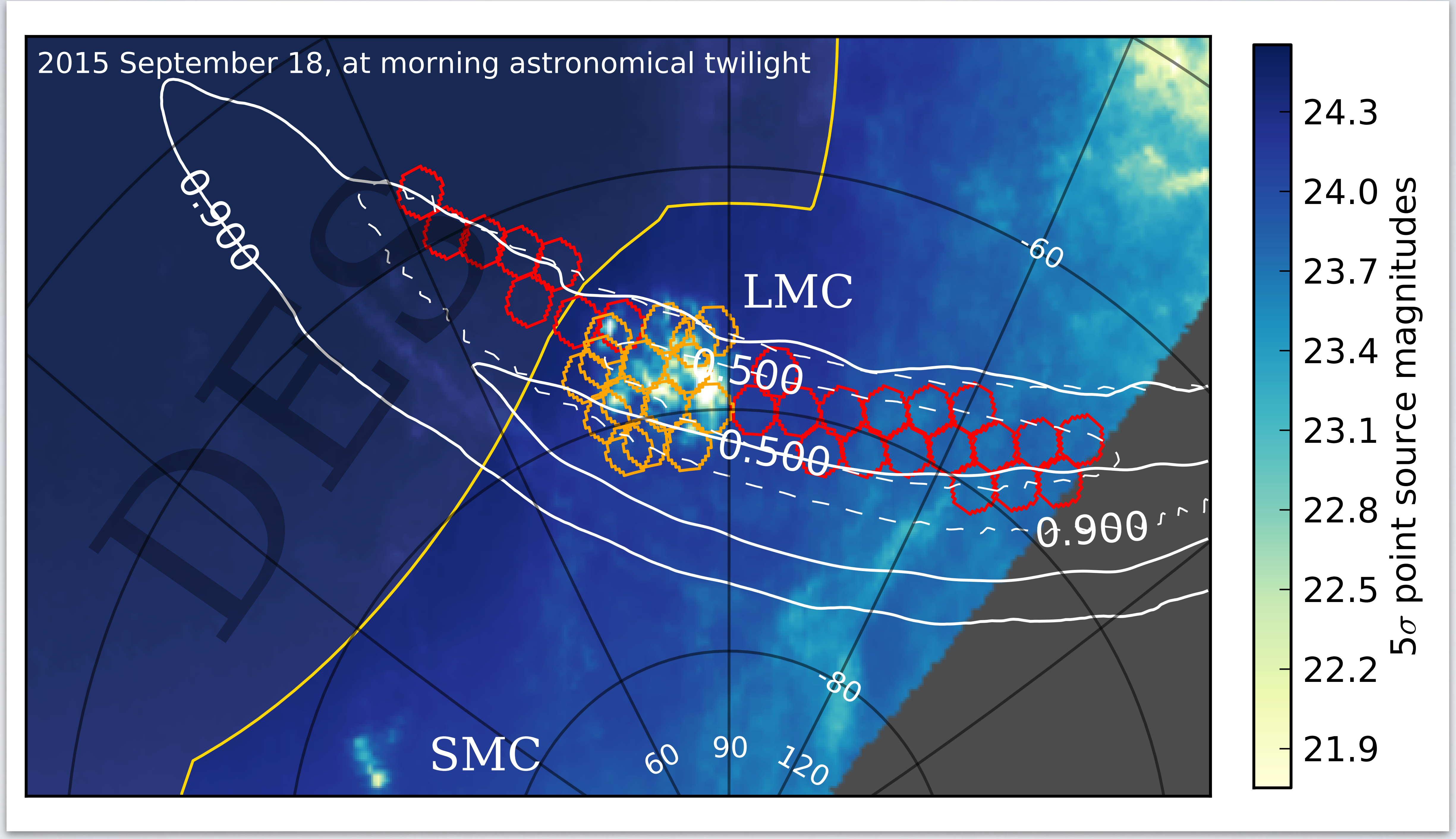
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

Obs time: 2015 Sep 18
(end of the night)



DES source detection probability map

DATA


2015 September 18, at morning astronomical twilight
LMC
SMC
DES
0.900
0.500
0.500
0.900
-60
-80
60
90
120
24.3
24.0
23.7
23.4
23.1
22.8
22.5
22.2
21.9
5σ point source magnitudes

DATA

28 fields, izz bands, 90 sec (11 in footprint, 17 outside)

20 fields, izz bands, 5 sec (LMC area)

Program	Night	MJD	Δt^a (days)	$\langle PSF(FWHM_i)\rangle$ (arcsec)	$\langle airmass\rangle$	$\langle depth_i\rangle$ (mag)	$\langle depth_z\rangle$ (mag)	$A_{eff}{}^b$ (deg^2)
Main, 1st epoch	2015-09-17	57383	3.88	1.38	1.50	22.71	22.00	52.8
	2015-09-18	57384	4.97	1.35	1.46	22.82	22.12	14.4
Main, 2nd epoch	2015-09-20	57286	6.86	2.17	1.51	22.18	21.48	67.2
Main, 3rd epoch	2015-10-07	57303	23.84	1.46	1.40	22.33	21.63	67.2
LMC, initial	2015-09-17	57383	3.98	1.14	1.30	21.32	20.62	14.4
LMC, extension	2015-09-26	57292	12.96	1.21	1.28	20.91	20.21	33.6

IMAGE PROCESSING

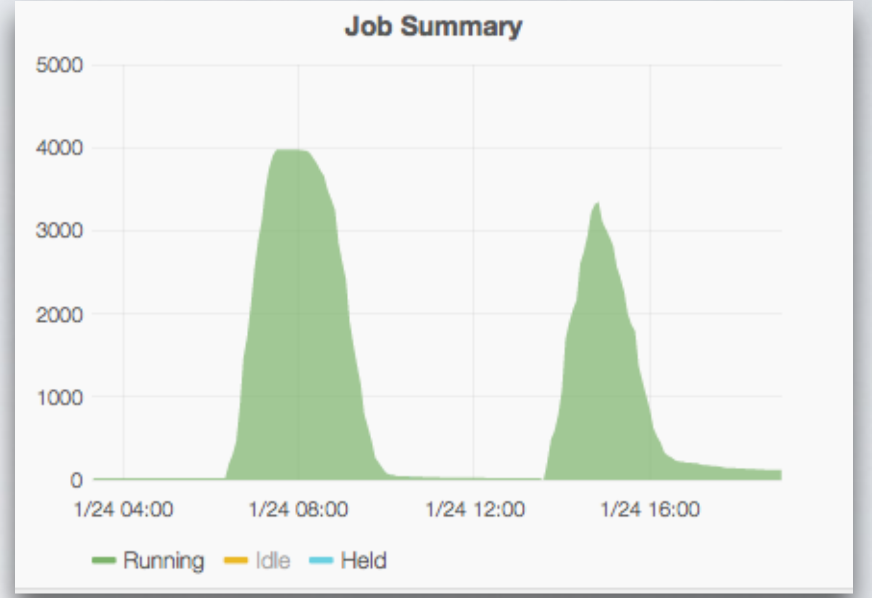
Each search image and template run through ***single epoch*** processing (few hours each)

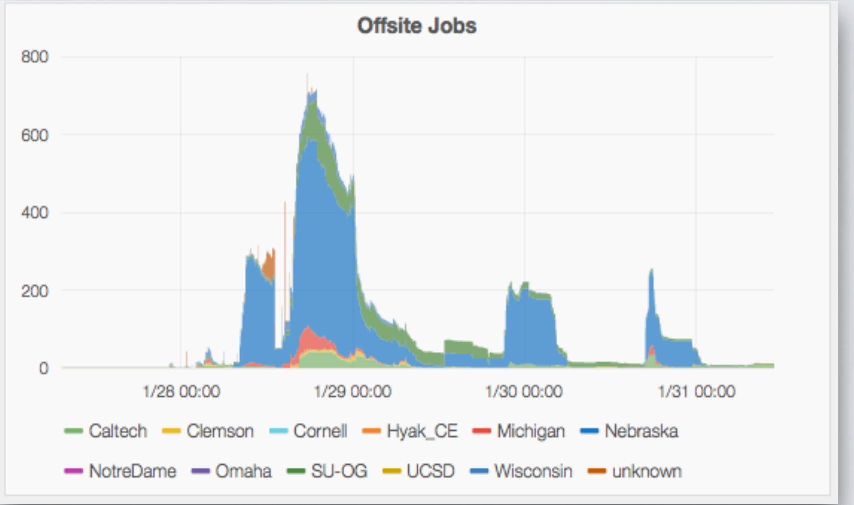
Then each CCD in each search image goes through ***difference imaging*** pipeline in parallel, copying in needed templates (~1hr/job)

Challenge: **raw images to plots in < 24 hrs**

A productive collaboration involving **PPD, SCD**.

Completely automated job submission immediately after search image available.





http://fifemon.fnal.gov/

Able to run dozens of images in parallel using Fermilab and OSG grid resources, with support from SCD — *thank you!*

ANALYSIS I

Search for a decaying transient (Soares-Santos et al. 2016)

Area (square degrees)
Total observed: 102
Excluding LMC: 84
Considering fill-factor: 67
Good after diffimg: 40
(~30% loss due to missing templates)

Sample selection
(all cuts in i and z bands)
0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

Efficiency estimates from simulated events
decay rate: 0.3 mag/day
50% recovery rate depth:

color: (i-z) ~ 1	i = 21.5
color: (i-z) ~ 0	i = 21.1
color: (i-z) ~-1	i = 20.1

Sensitive to typical NS-NS mergers out to 200Mpc.

ANALYSIS I

Search for a decaying transient (Soares-Santos et al. 2016)

Result

Zero candidates pass our selection criteria. No optical signatures are predicted for BBH events, so this is not surprising.

NUMBER OF SELECTED EVENTS

mag(i)	raw	cut 1	cut 2	cut 3
18.0–18.5	84	1	0	0
18.5–19.0	177	1	0	0
19.0–19.5	291	2	0	0
19.5–20.0	227	2	1	0
20.0–20.5	156	17	2	0
20.5–21.0	225	42	3	0
21.0–21.5	334	84	2	0
21.5–22.0	756	159	1	0
22.0–22.5	1099	183	0	0
total	2349	491	9	0

Sample selection
(all cuts in i and z bands)

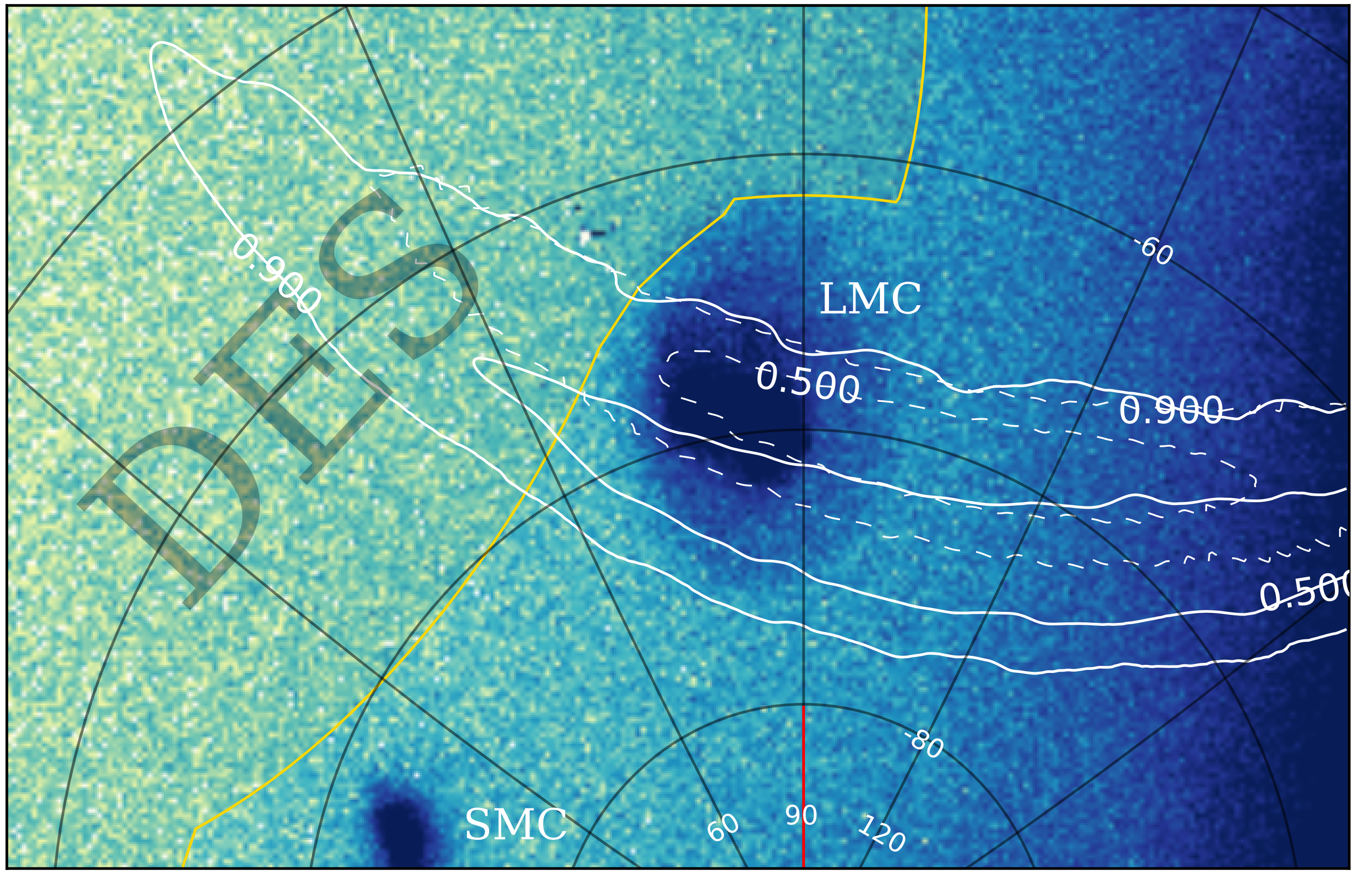
0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

This type of search is a starting point for future NS-NS merger searches.

ANALYSIS 2

Search for disappearing stars in the LMC (Annis et al. 2016)

GW150914 was *initially* thought to be a burst event, and could be due to a core-collapse (CC) nearby.



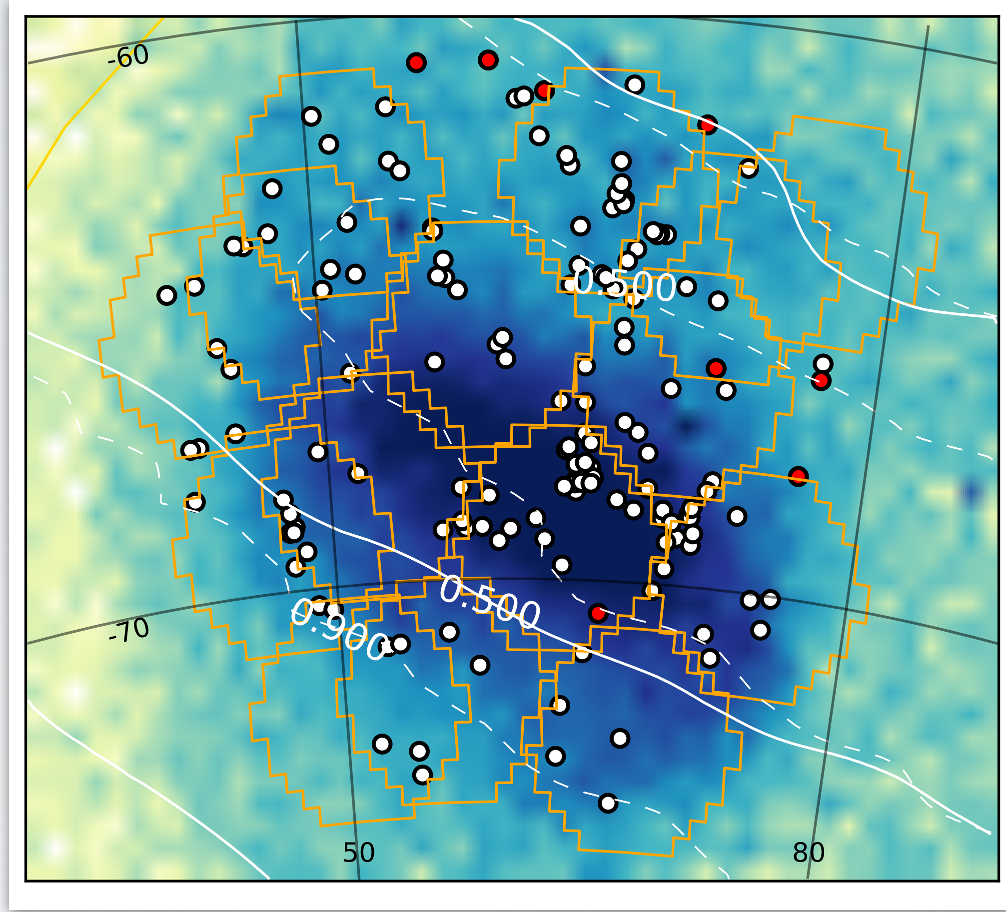
CC's often result in supernova explosions (e.g. 1987A), but none were reported in the LMC at the time.

~ 20% of the CC's are expected to fail to produce supernovae.
Could GW150914 be associated with a failed SNe?

ANALYSIS 2

Search for disappearing stars in the LMC (Annis et al. 2016)

We take possible progenitors (152 red supergiants) catalogued in the literature, and search for them via visual inspection. 144 were in the observed area; all accounted for.

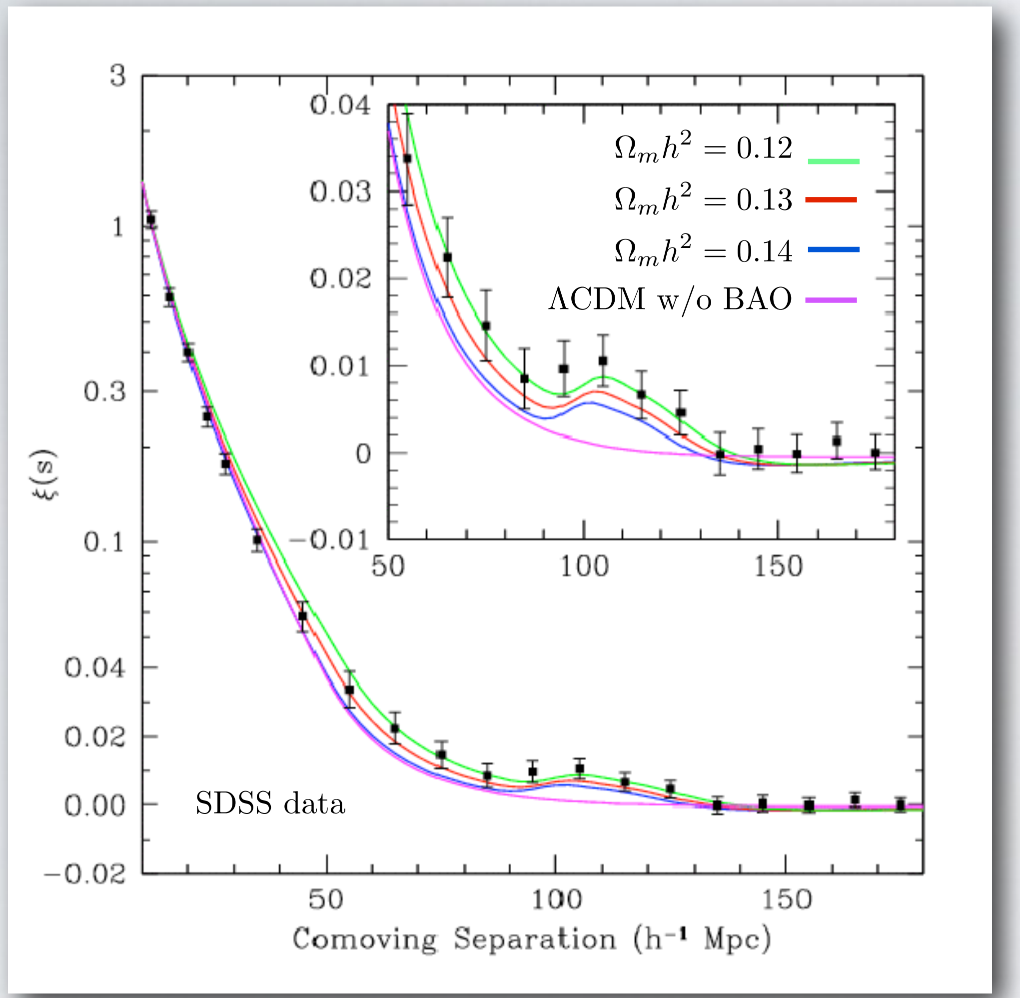


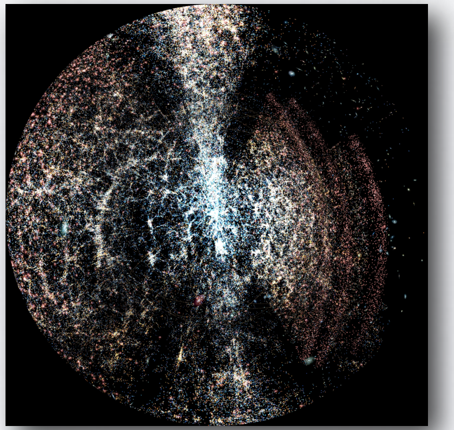
We concluded that the GW event was unlikely to arise from a failed SNe.

LIGO's result published yesterday show we learned that G150914 was a BBH merger. **This type of search is a template for future GW events, specifically those likely to be a CC event.**

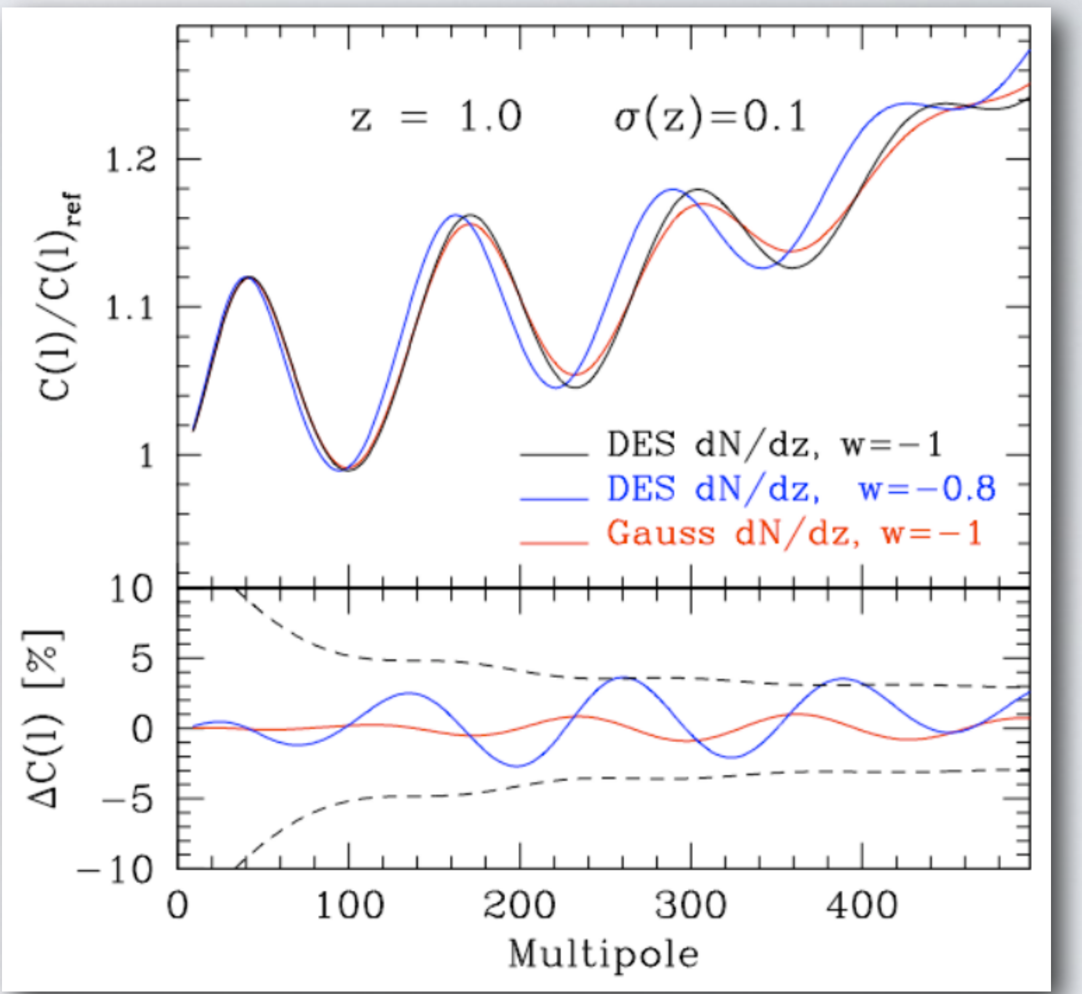
DES SCIENCE: BAO

real space





Fourier space



SDSS: mean spectroscopic redshift ~ 0.35. (Eisenstein et al. 2005)

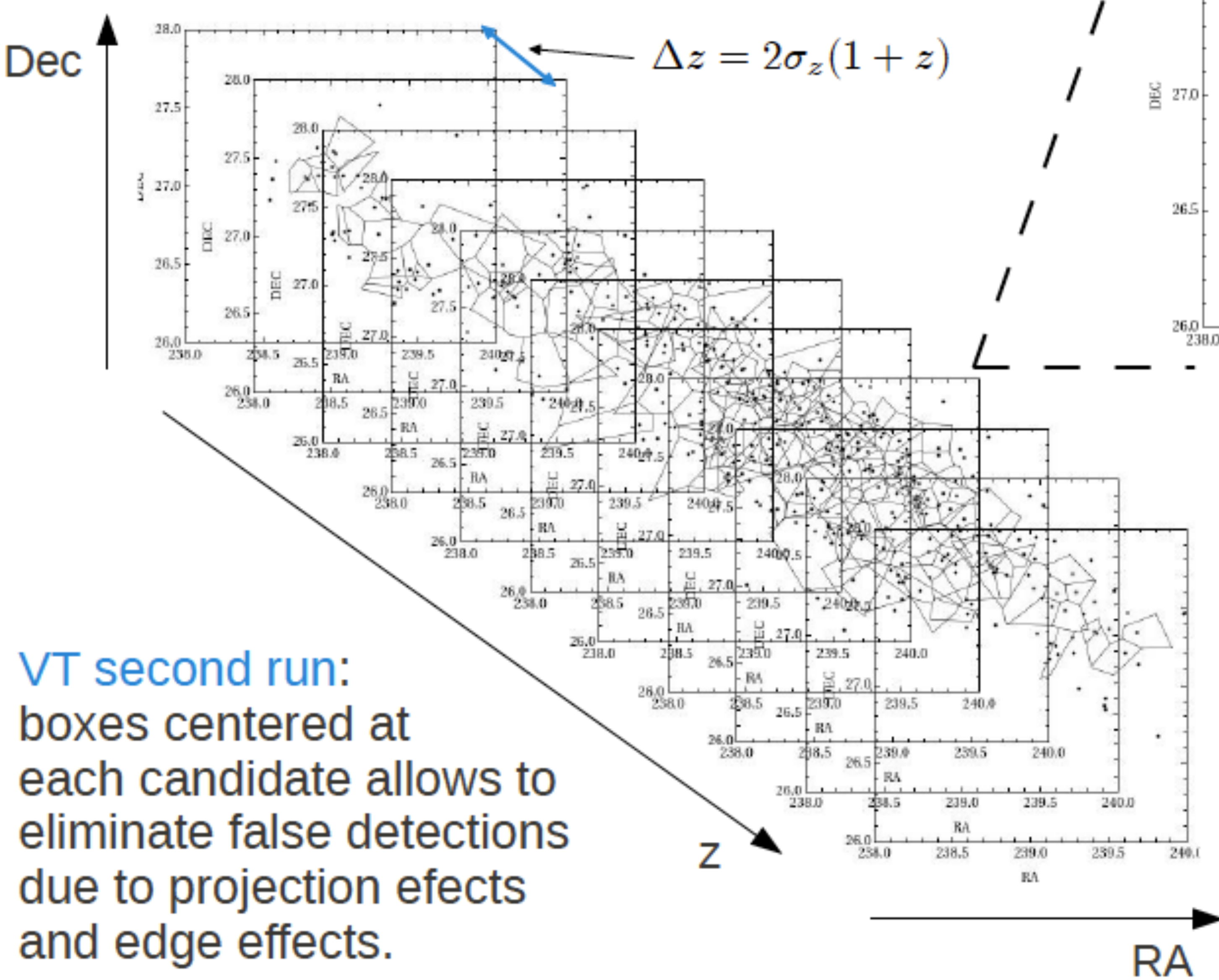
DES expected sensitivity. Can measure w by probing deeper and slicing in z.

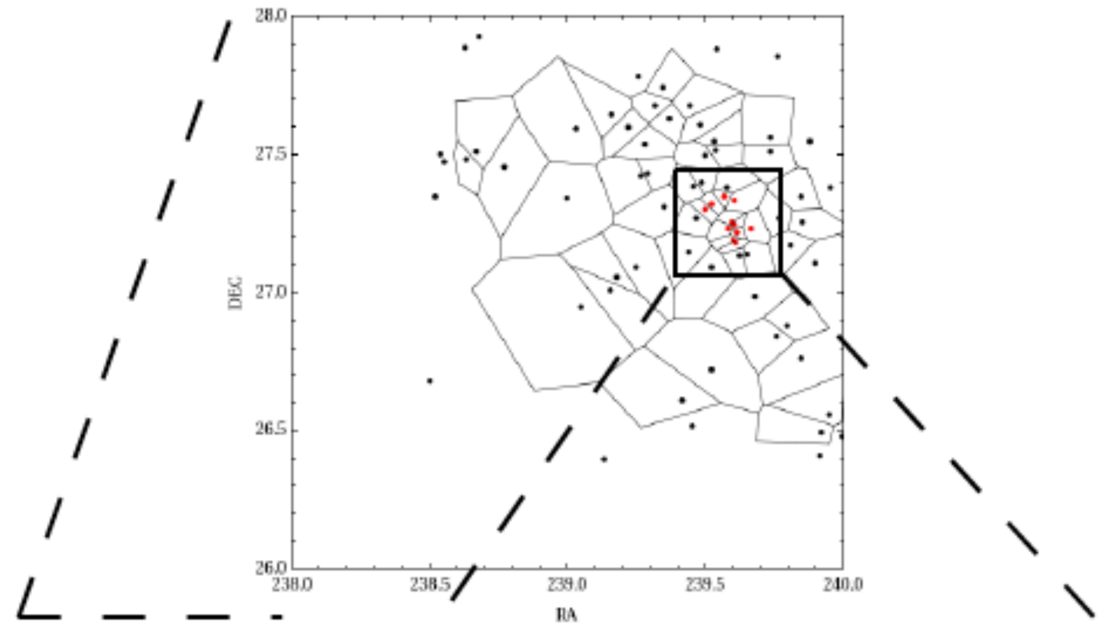
NGC1365: DES FIRST LIGHT IMAGE

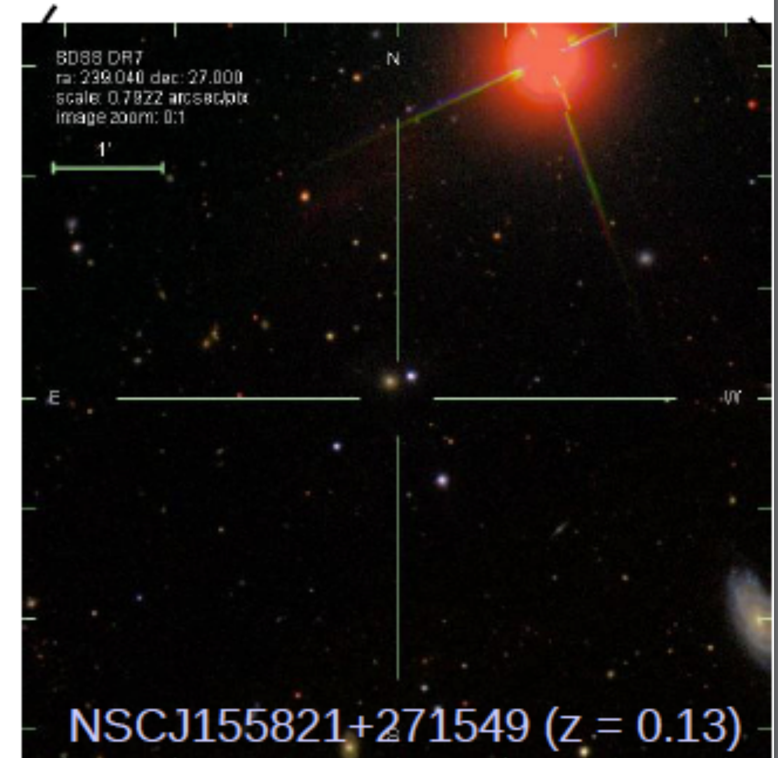
CLUSTER FINDER

VT cluster finder in 2+1D

VT first run: cluster candidates detected in photo-z shells



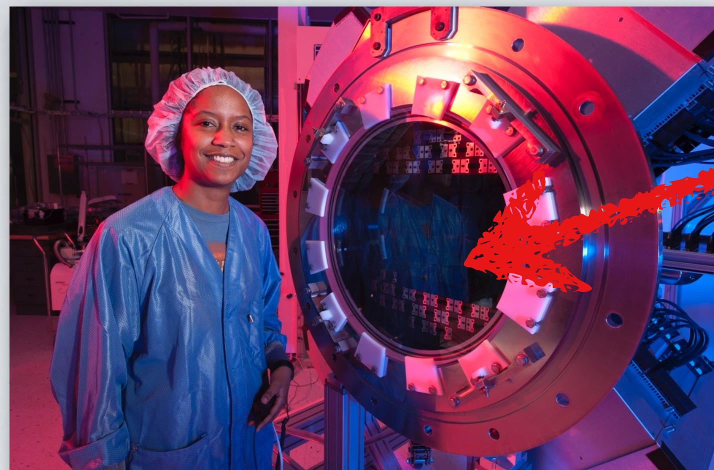


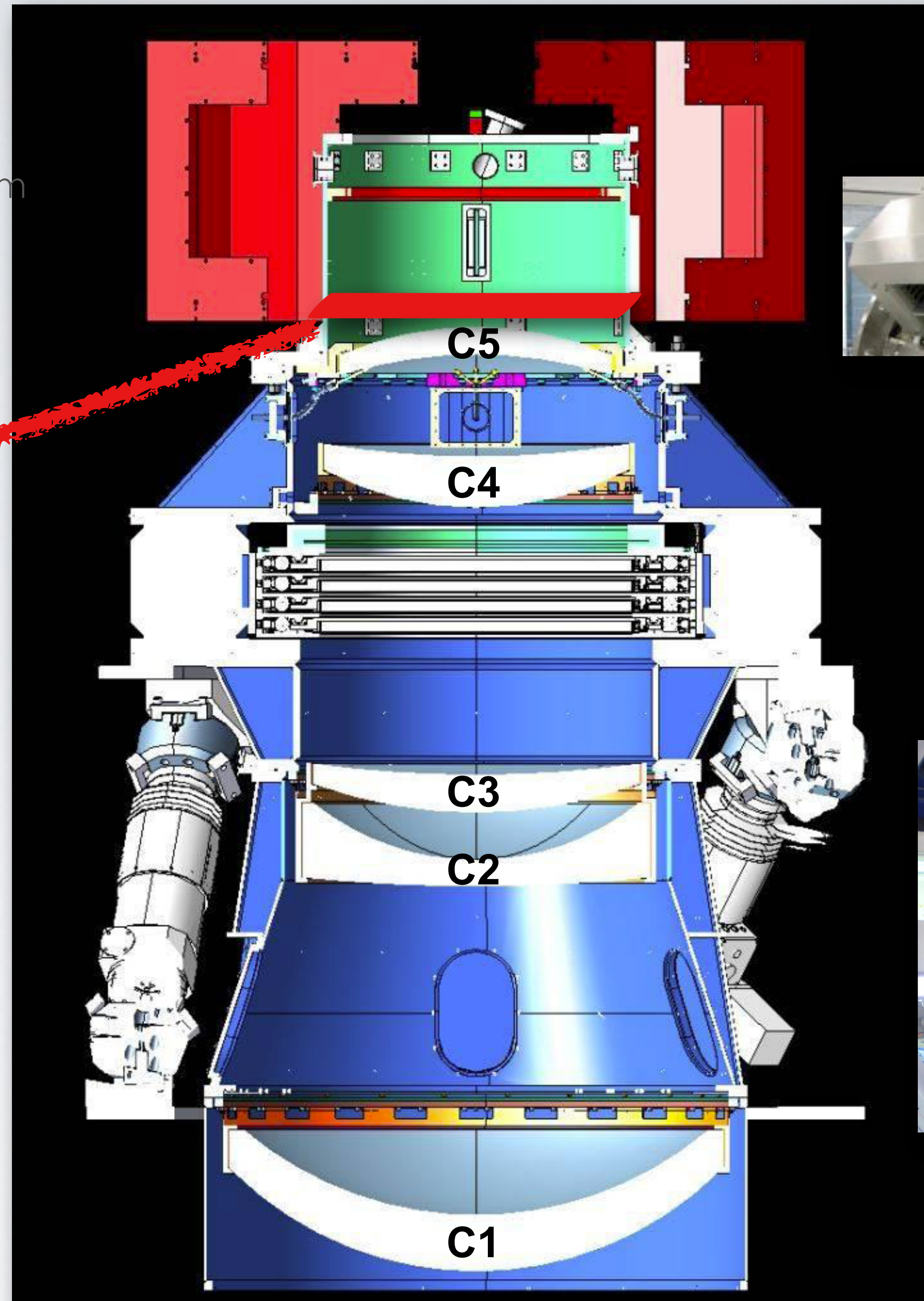


VT second run: boxes centered at each candidate allows to eliminate false detections due to projection efects and edge effects.

DECAM

CCD focal plane is housed in a vacuum vessel (**the imager**)





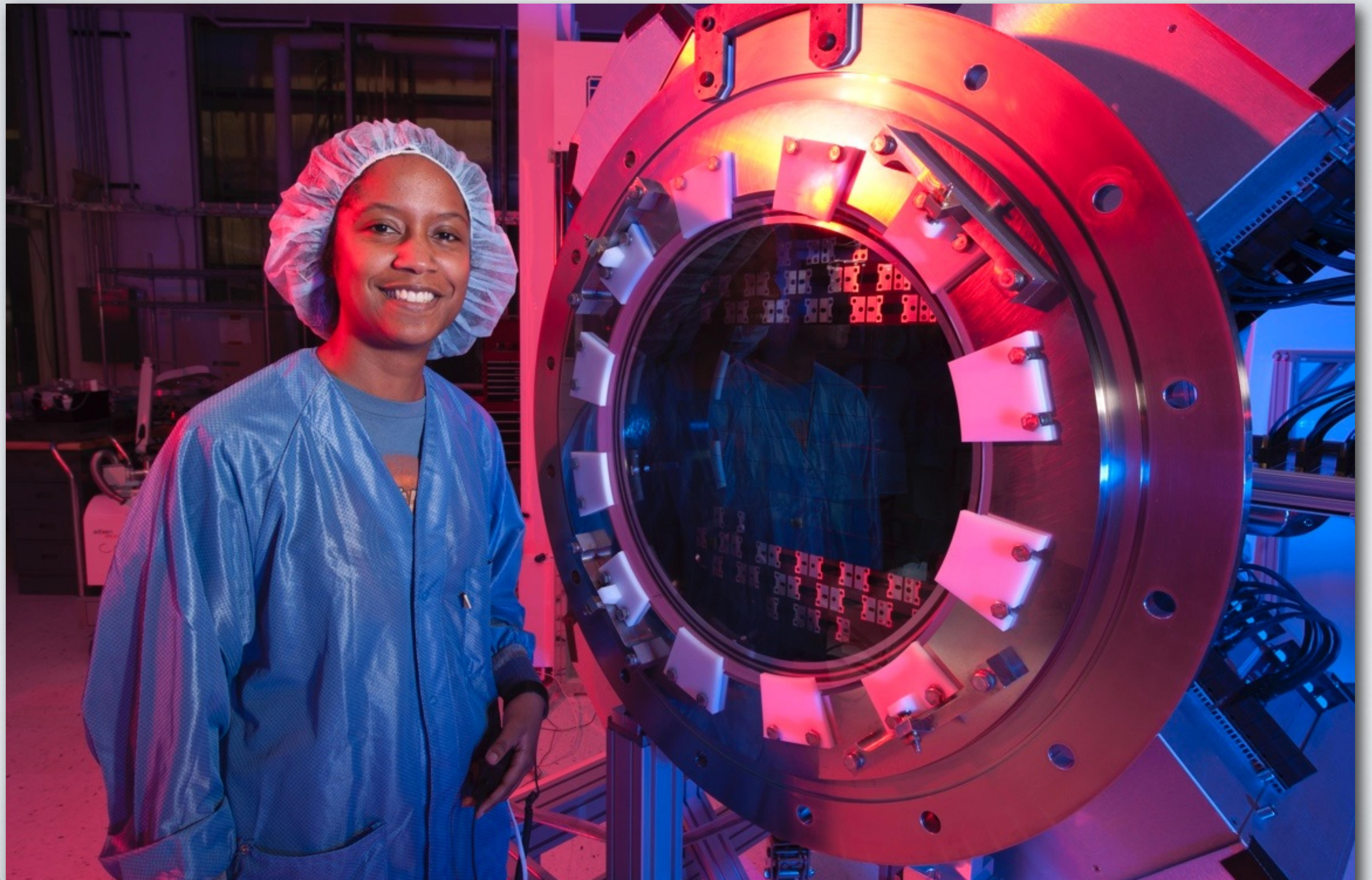
CCD readout electronic crates are actively cooled to eliminate thermal plumes

Hexapod provides focus and lateral alignment capability for the corrector-imager system

Barrel supports the **5 lenses** and imager

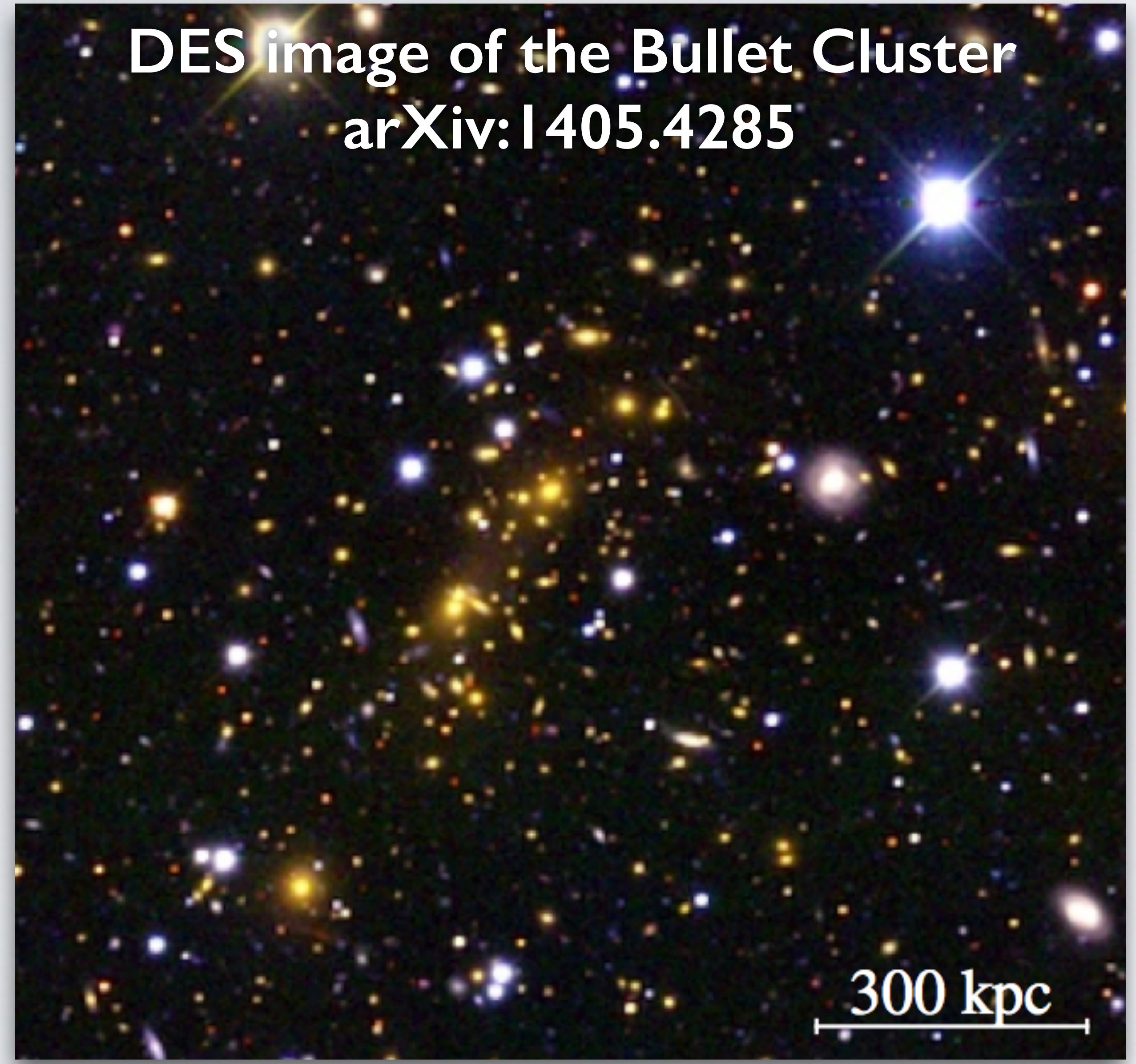
Filter changer with 8 filter capacity and **shutter** fit between lenses **C3** and **C4**

LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C



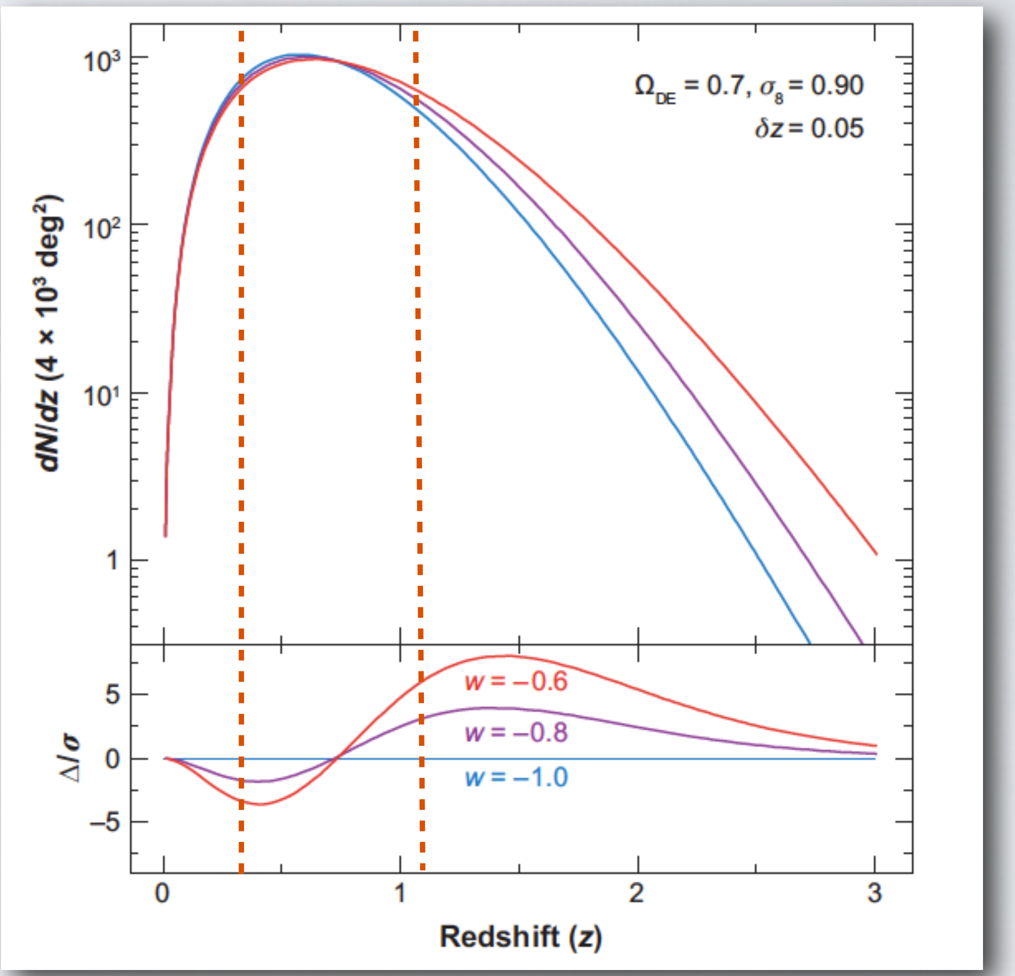
DES SITE: CERRO TOLOLO, CHILE

DES SCIENCE: CLUSTERS



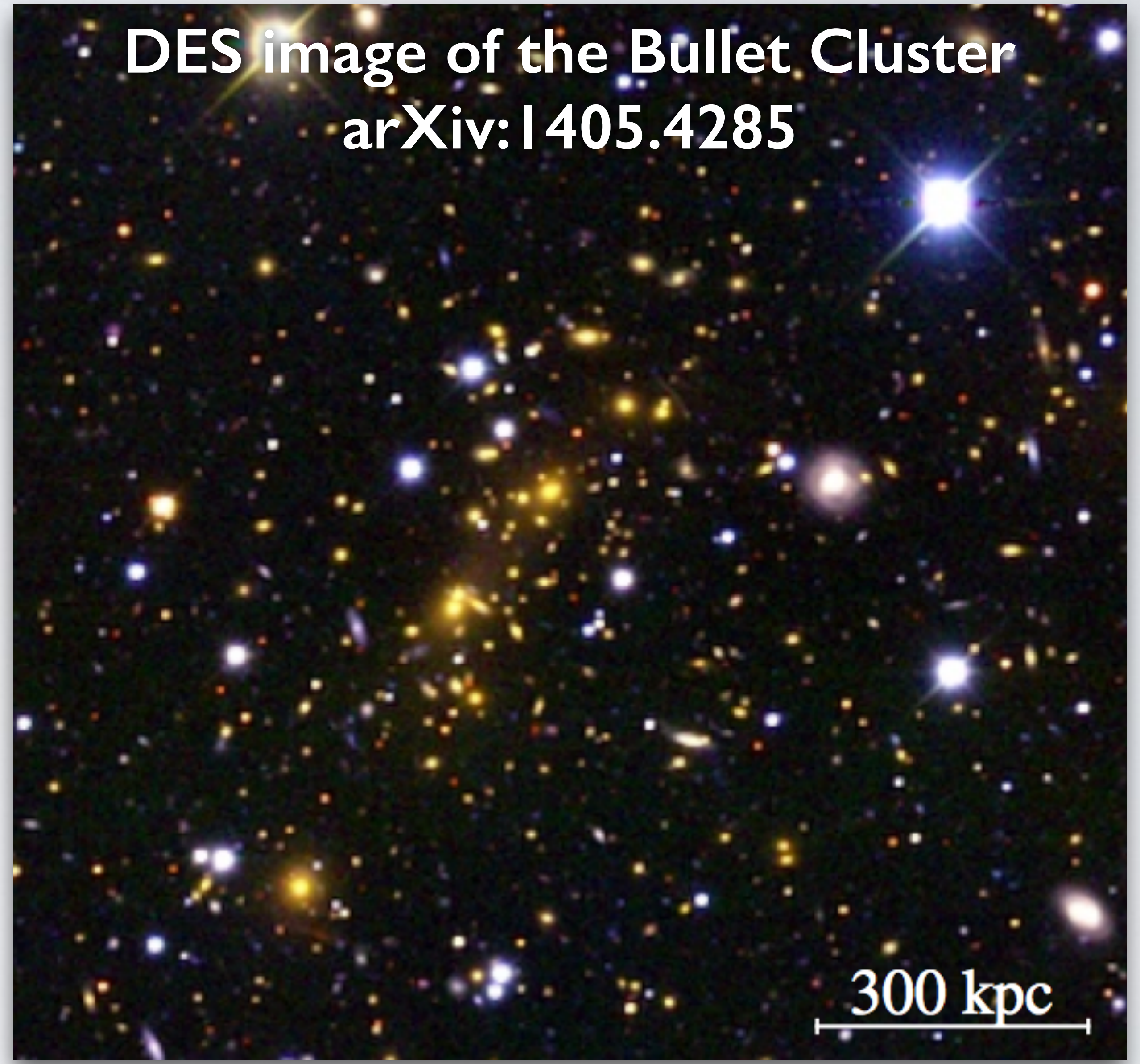
SDSS sample: up to z ~ 0.3

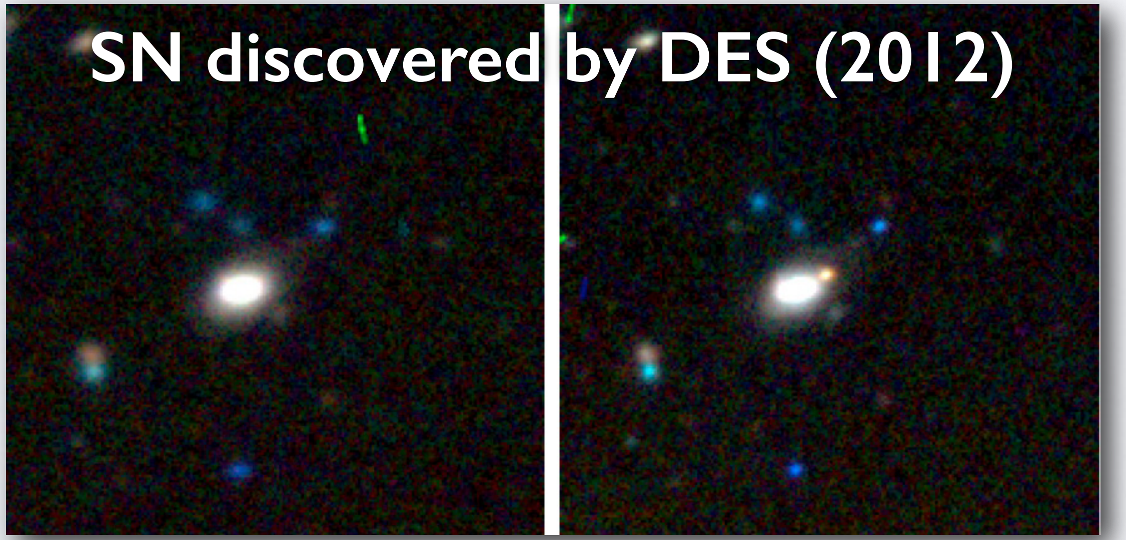
DES sample: up to z ~ 1



Number of clusters above $10^{14.5}$ solar masses as a function of z, for a 4000 sq-deg survey in 3 different cosmologies.

DES EARLY RESULTS





PROSPECTS FOR COSMIC SIRENS

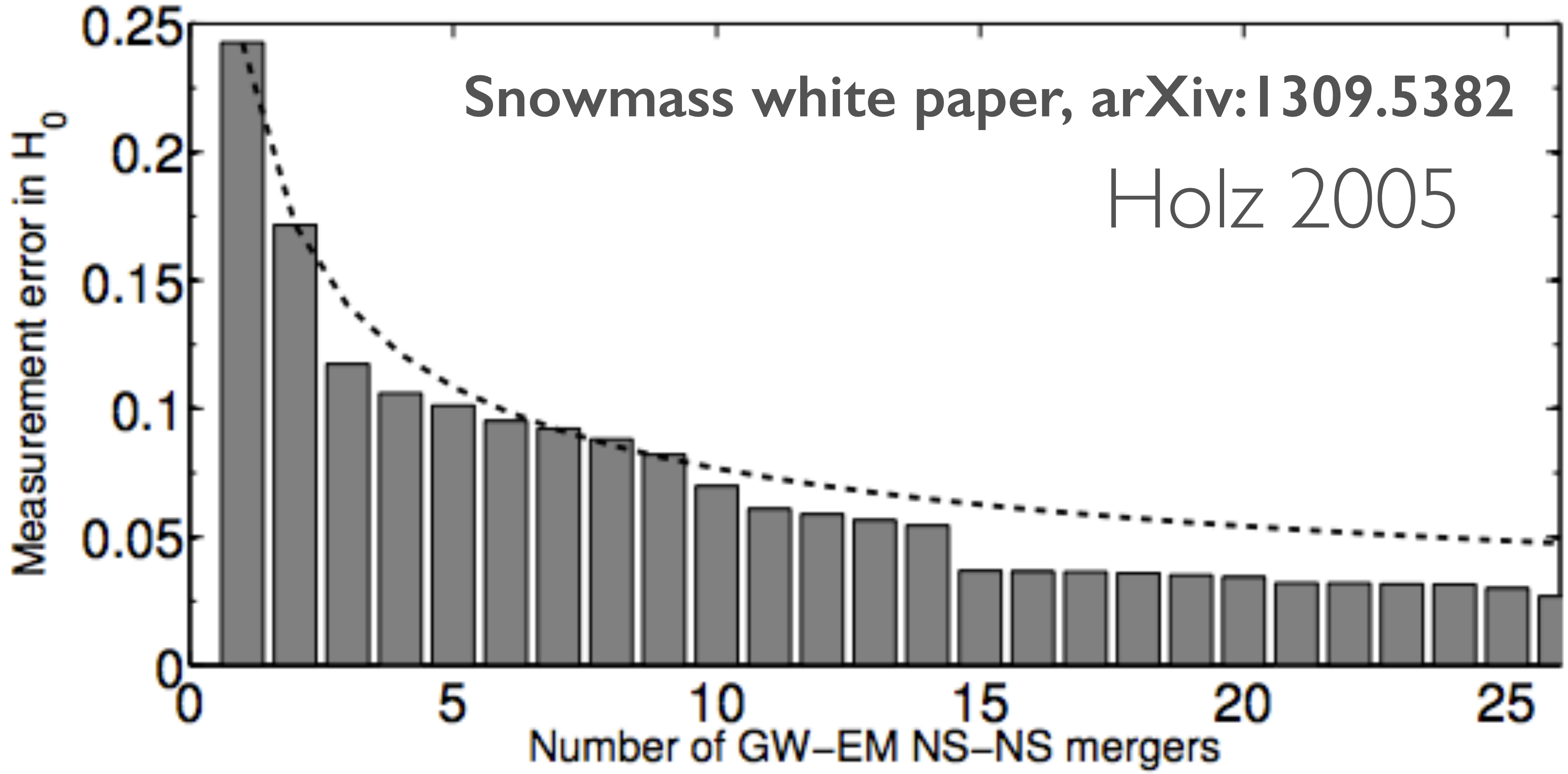
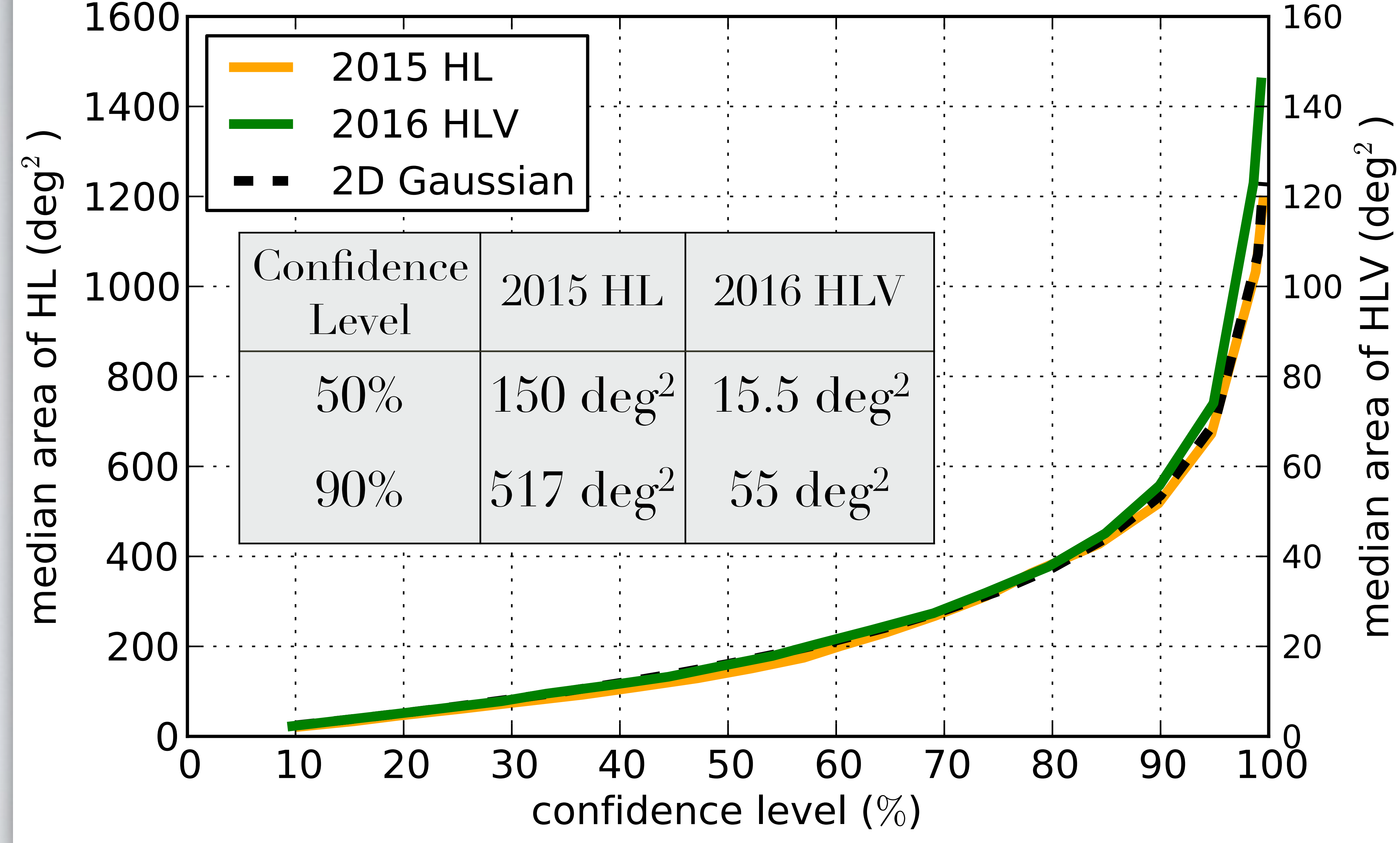


Figure 8: H_0 measurement uncertainty as a function of the number of multi-messenger (GW+EM) double neutron star merger events observed by an advanced LIGO-Virgo network. The dashed line shows Gaussian convergence.

MEDIAN LOCALIZATION AREA

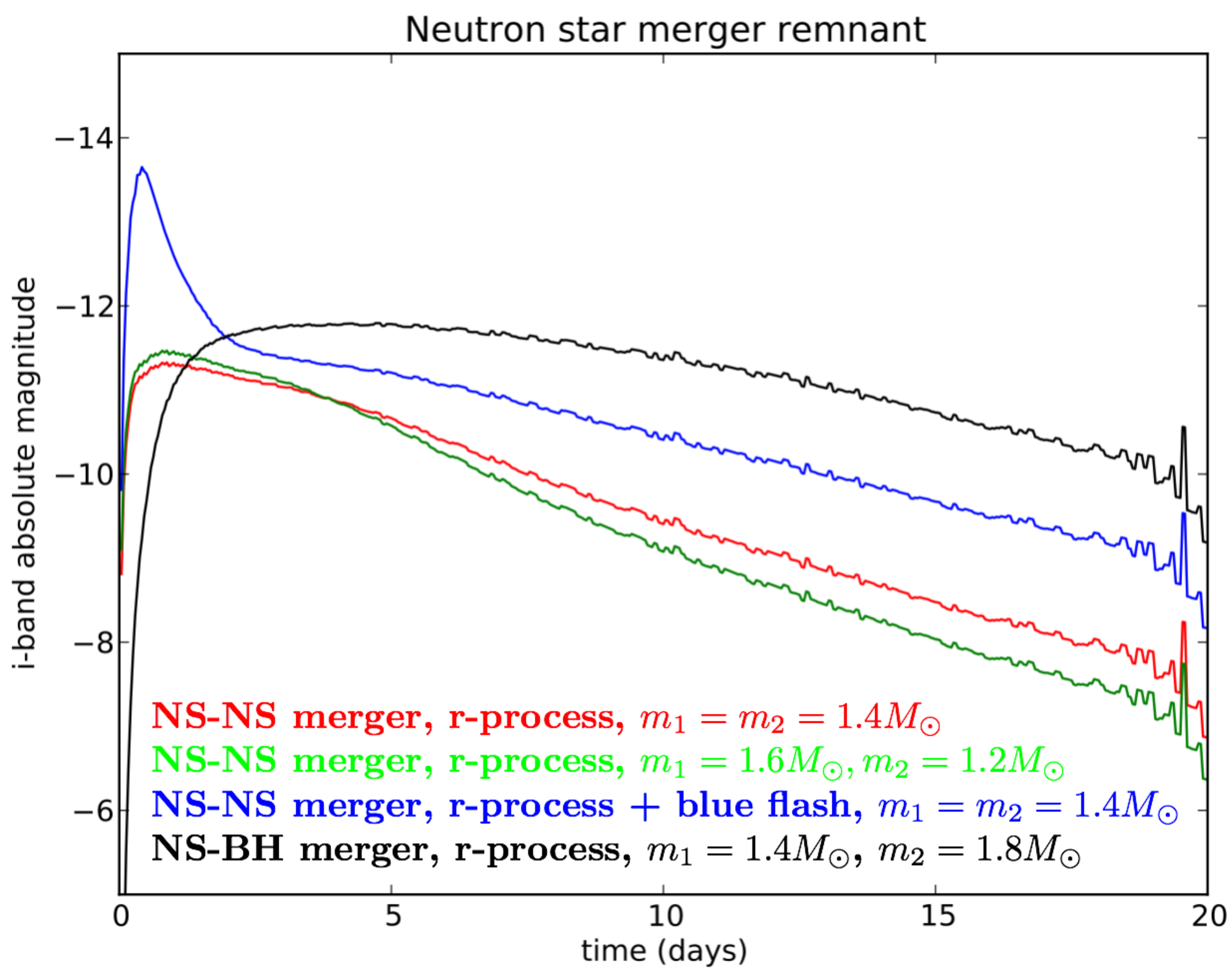
(Chen & Holz 2015)

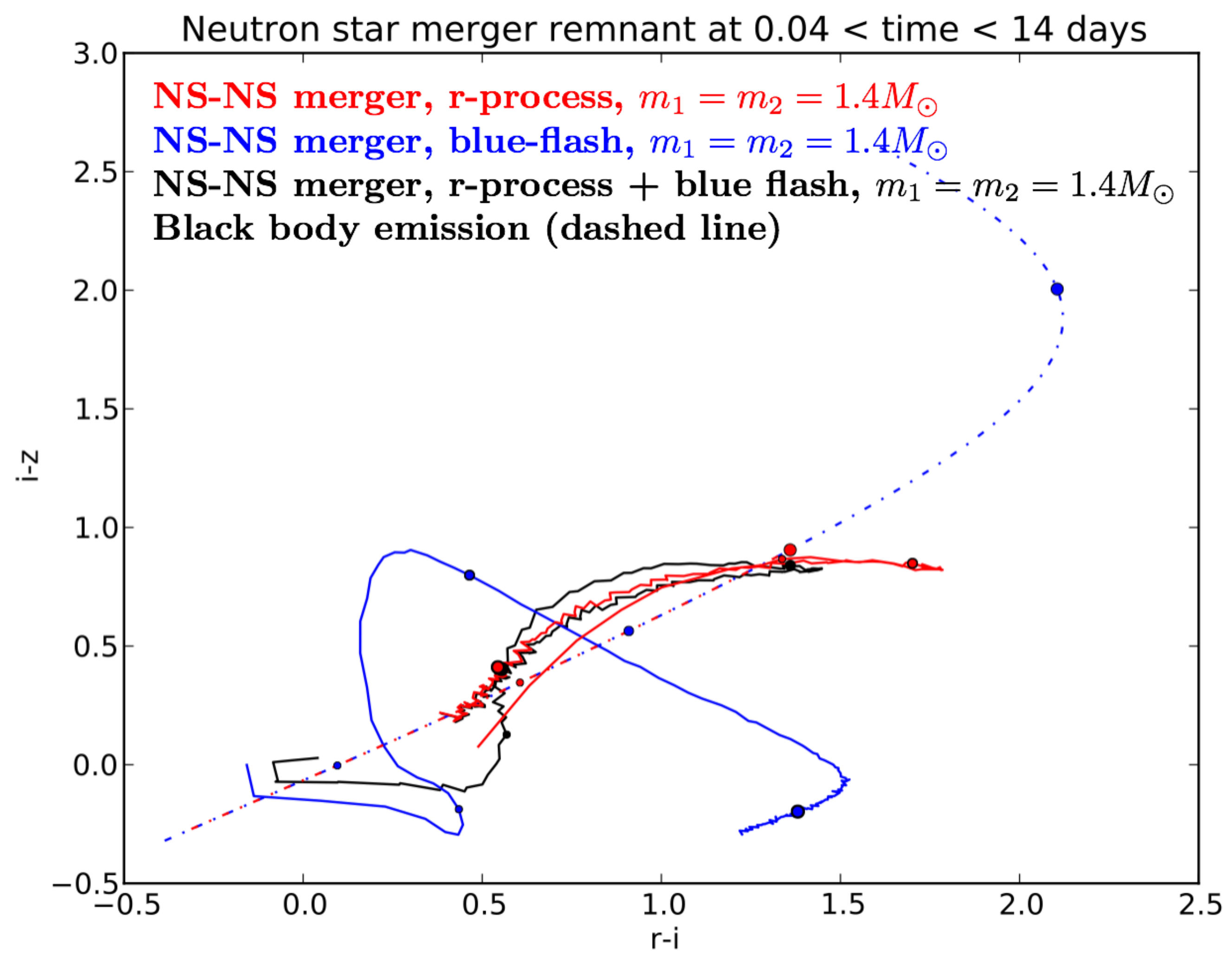


Confidence Level	2015 HL	2016 HLV
50%	150 deg^2	15.5 deg^2
90%	517 deg^2	55 deg^2

KILONOVA MODELS

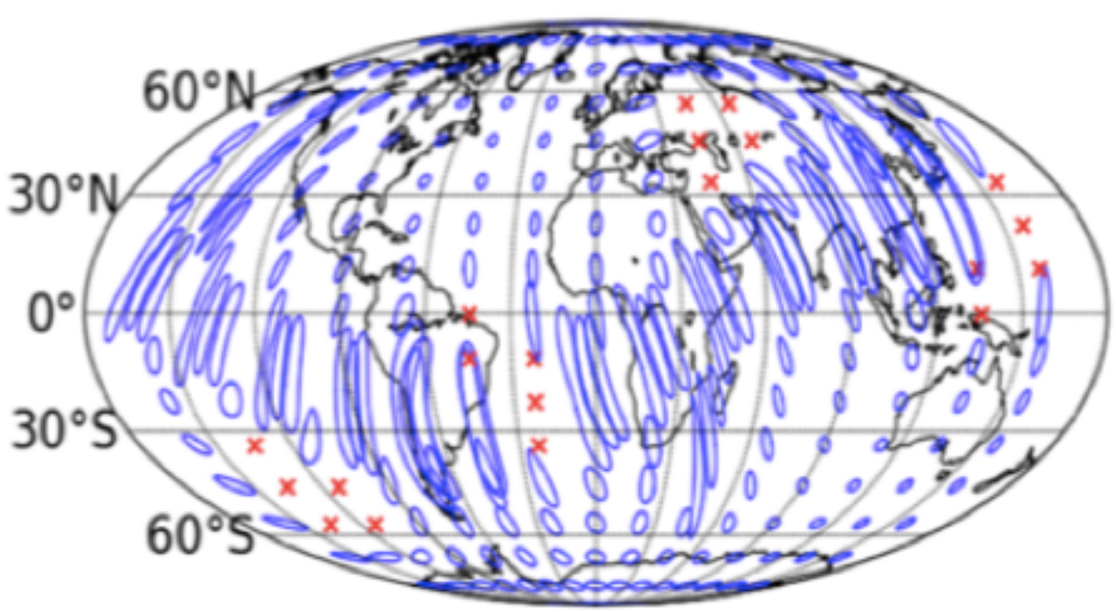
For NS-NS mergers or BH-NS mergers, a red faint transient with decay timescales of about 10 days is predicted.



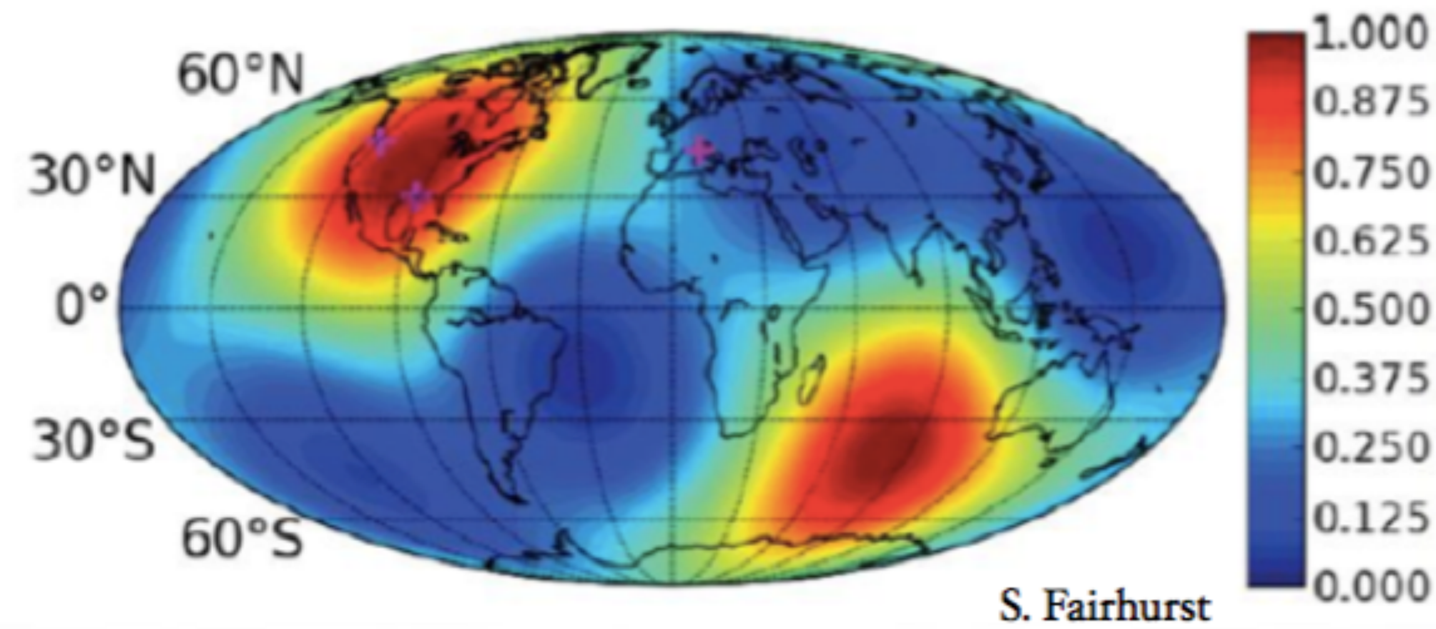


LIGO saw a BH-BH merger (with no predicted optical counterpart). This information came along only after we performed our followup observations.

GW+EM: LOCALIZATION CHALLENGE (2015-2016)



LIGO: arXiv:1304.0670



Position localizations

Detection rates

GW events happening during <u>CTIO day time</u> are more likely and have better localization information. <u>8-12 hours</u> later, their region of interest will be overhead during the night for DES observations.

DESGW PROGRAM

GW trigger
- time stamp
- sky region
- distance

~24h

DECam search system
- prepare template images
- schedule observations
- take new images
- perform image subtraction
- detect, model counterpart

LIGO: arXiv:1304.0670

	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
aVirgo + aLigo	2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
aVirgo + aLigo	2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
	2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

We are here!

DES observations (Sep-Feb months)

LSST era!

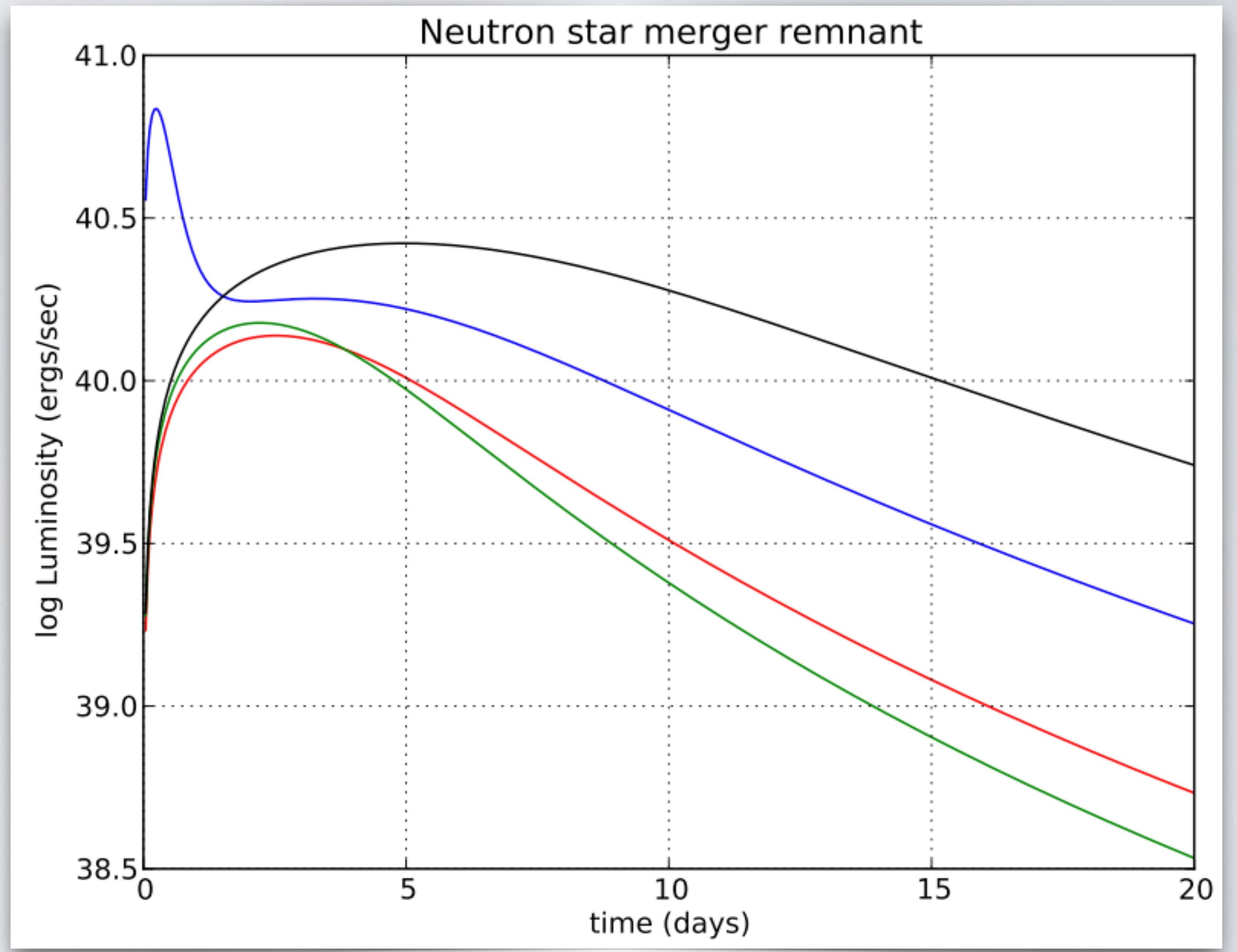
POSSIBLE EM SIGNAL: KILONOVA

Semi-analytic models tuned with simulations (based on Grossman et al. 2014)

The red curve peaks at absolute mag ***M* = *-11*** in i-band.

Very red transient: ***i-z ~ 0.8*** in all cases except for blue flash.

Red: Equal mass NS-NS merger
Green: Unequal mass NS-NS merger
Black: NS-BH merger
Blue: Neutron-driven wind (blue flash)



THE OPPORTUNITY

LIGO-VIRGO advanced GW detectors are ramping up over the next ~5 yrs (first run to start September 14, 2015).

DECam is one of the few imagers capable of timely 24th mag searches over large regions (unique in the southern hemisphere).

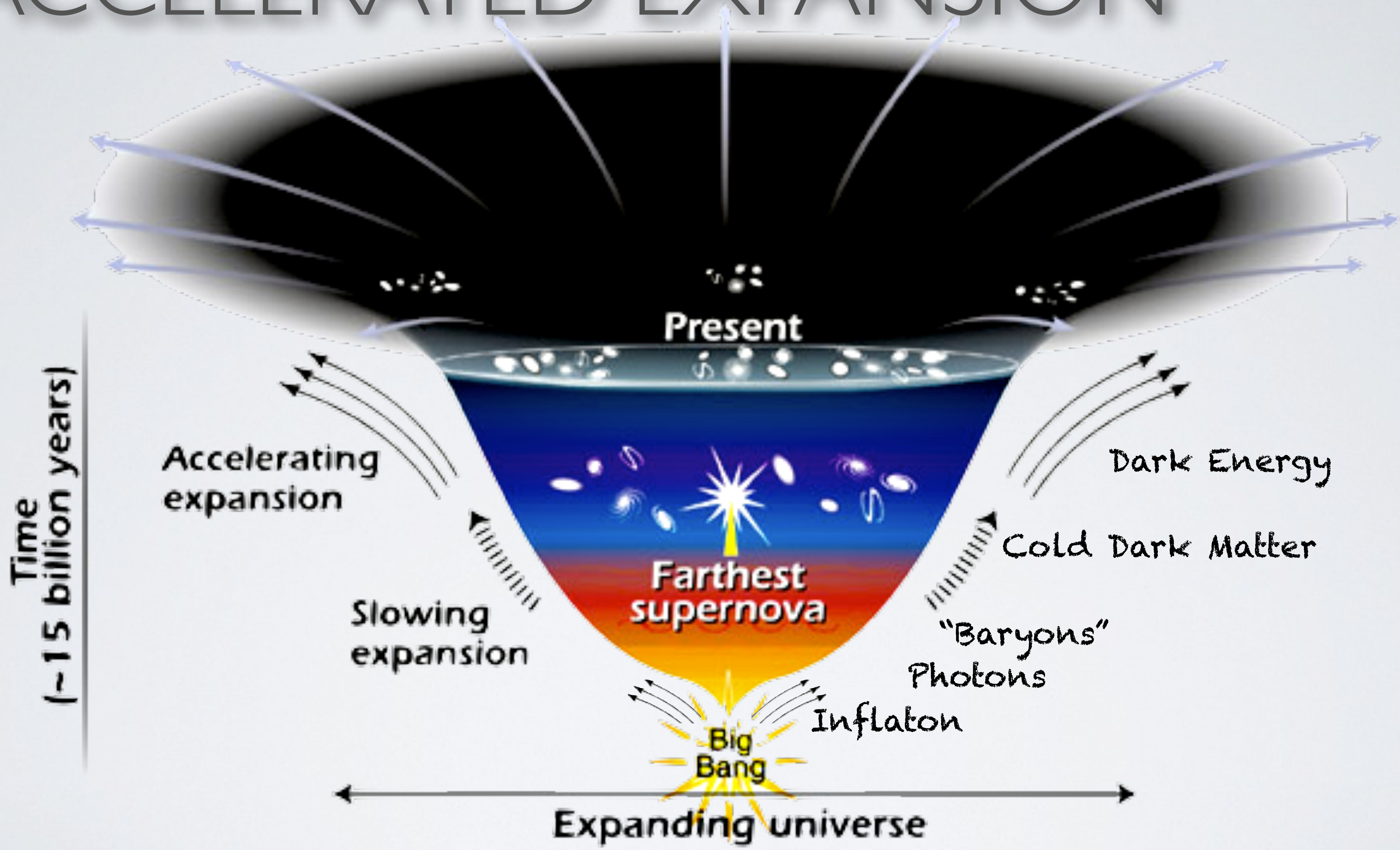
DECam community already has "templates" for thousands of sq-deg.

DES is on sky 2/3 of the time in B semesters through 2018.

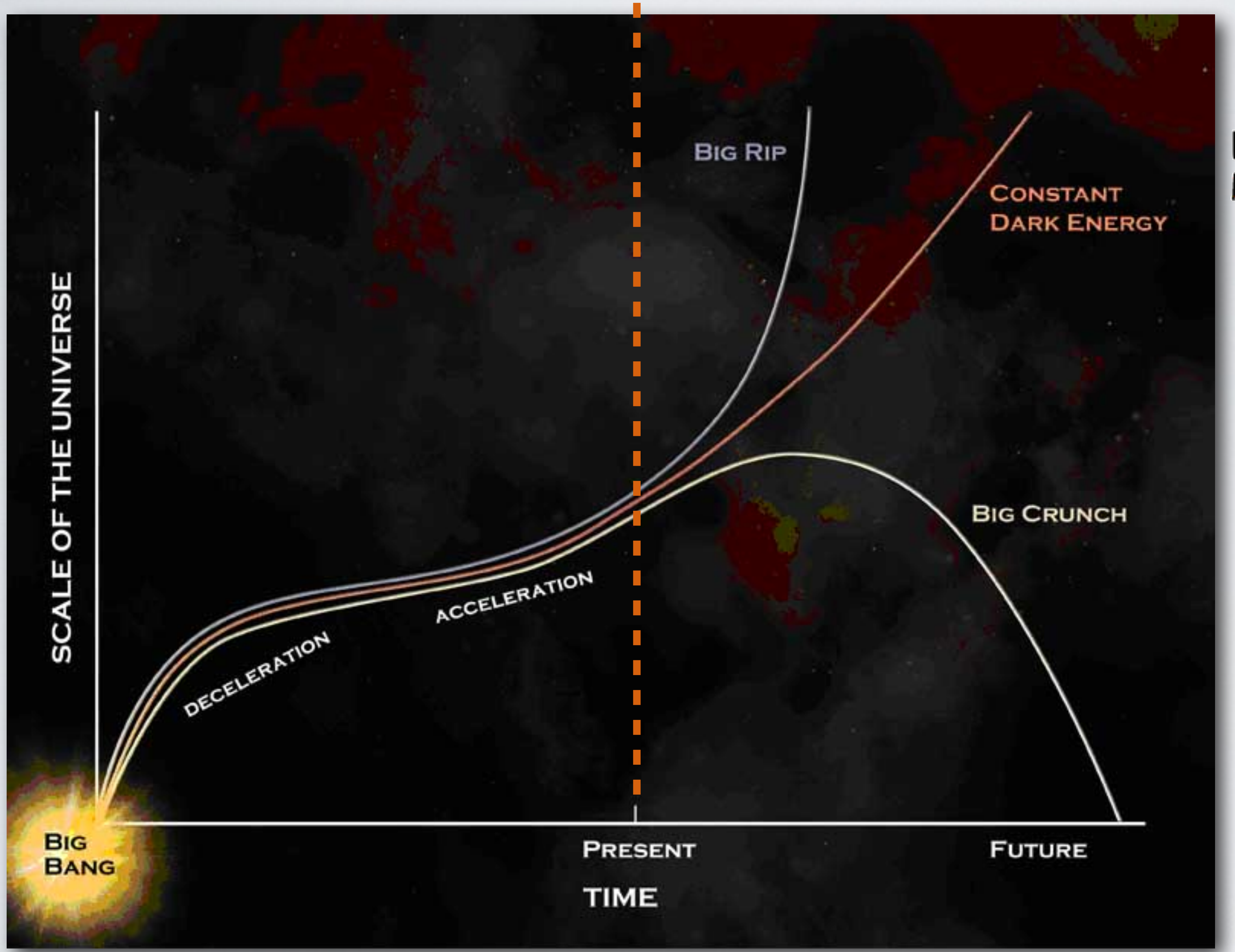
DES has a transient detection pipeline and experience in adaptive scheduling observations.

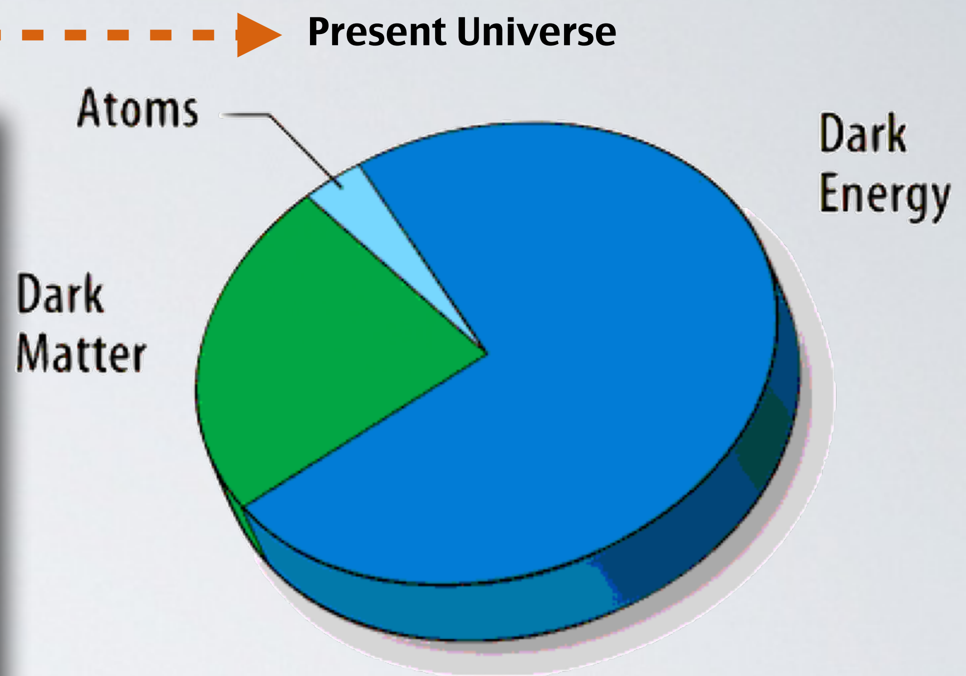
Ideal opportunity to pioneer a Standard Sirens program!

DARK ENERGY & ACCELERATED EXPANSION



FATE OF THE UNIVERSE?





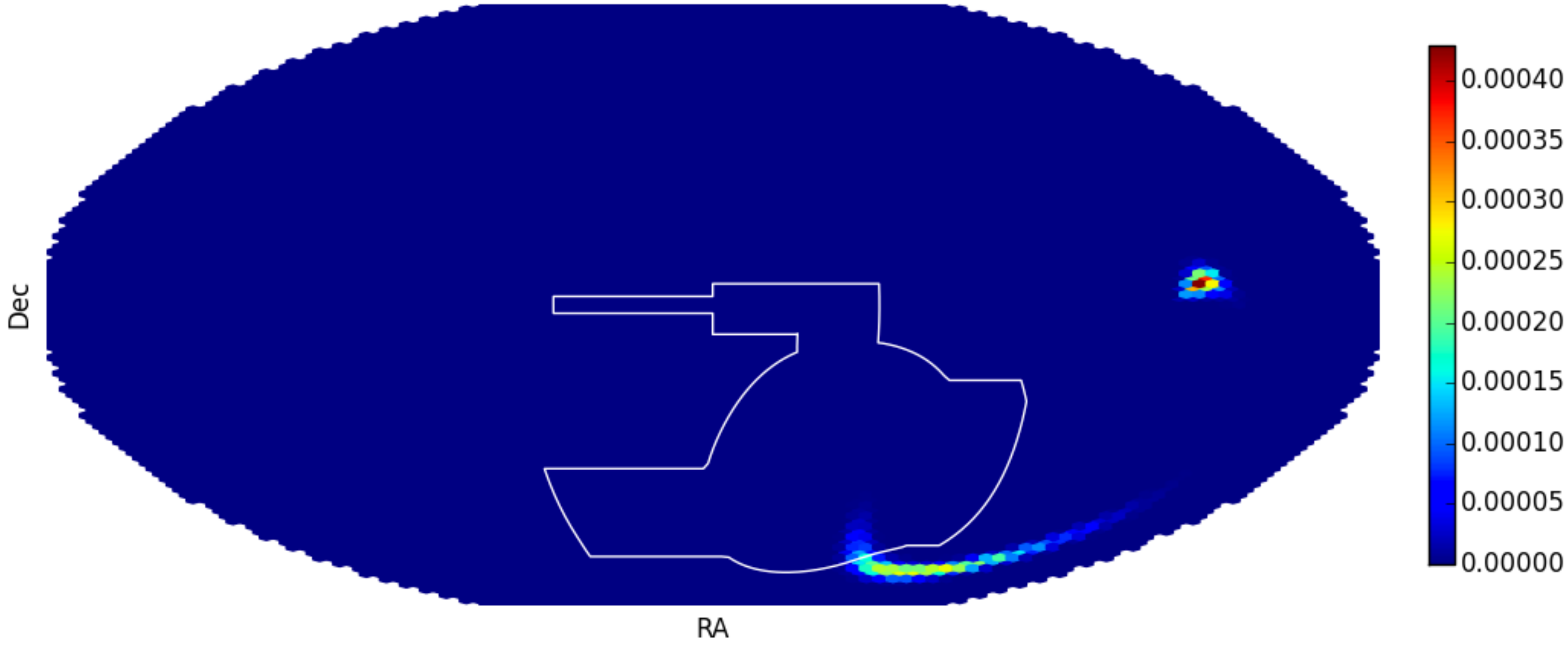
$$\Omega_m \simeq 1/3$$

$$\Omega_\Lambda \simeq 2/3$$

Dominance of new physics!

GW150914

Time: Sep 14, 2015 09:50:41
FAR: 1/203k-yr
Distance: 410Mpc
Type: BBH merger



LVC sky localization probability map (initial)

FORMING A COLLABORATION

Initiated in June 2013 by MSS and Annis (in response to the LIGO–Virgo Collaboration open call for LOIs).

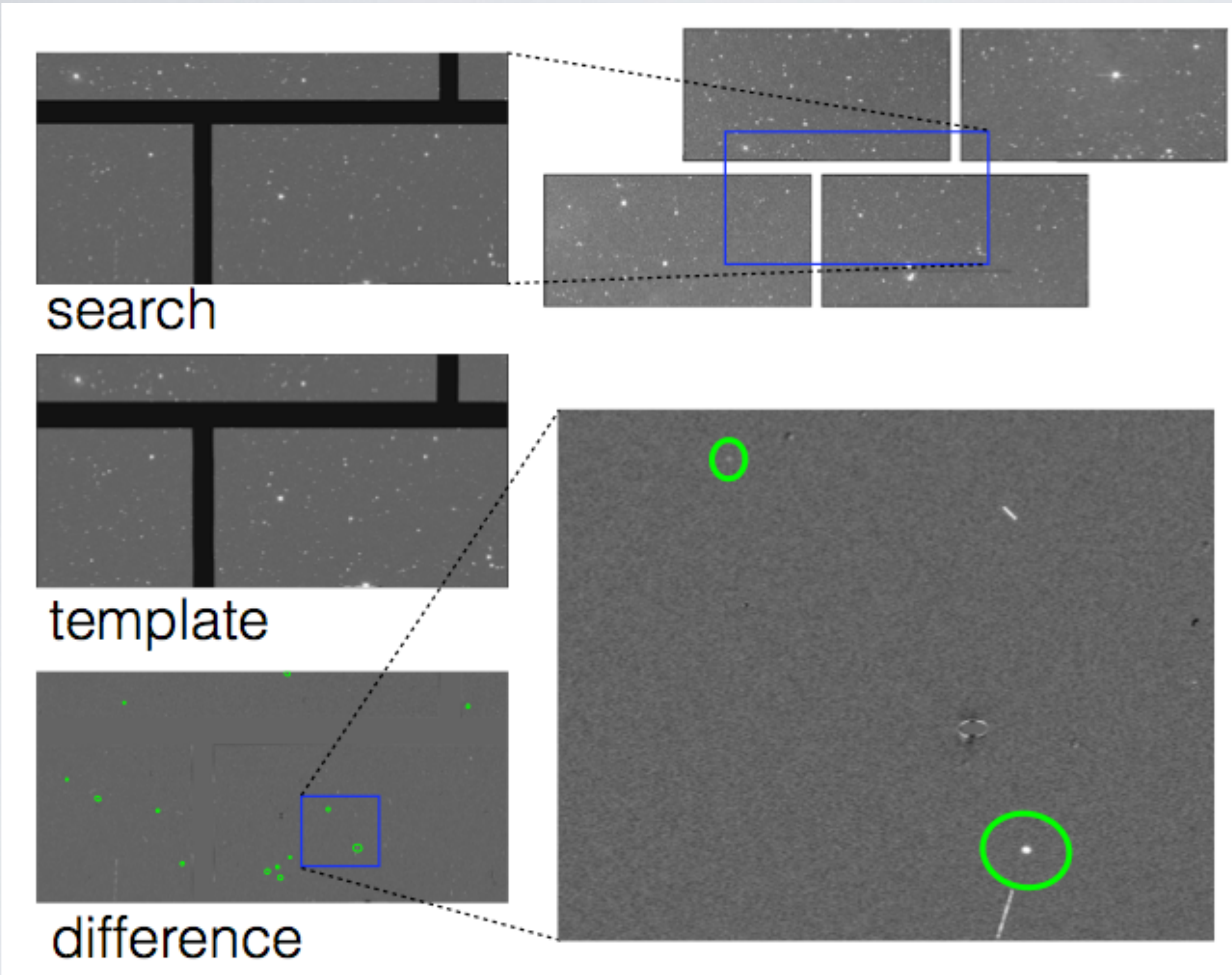
In collaboration with U Chicago LIGO group (led by Daniel Holz) since Aug 2013.

Obtained funding from Fermilab's LDRD grant program (FY15 and FY16).

Obtained 3 additional DECam nights for this TOO program, in collaboration with Edo Berger from Harvard.

Preparing to start observations on September 14 2015.

DIFFERENCE IMAGING



Example of DiffIm
on the wide field survey.

90 sec i-band exposures
Sep 28,29 2013

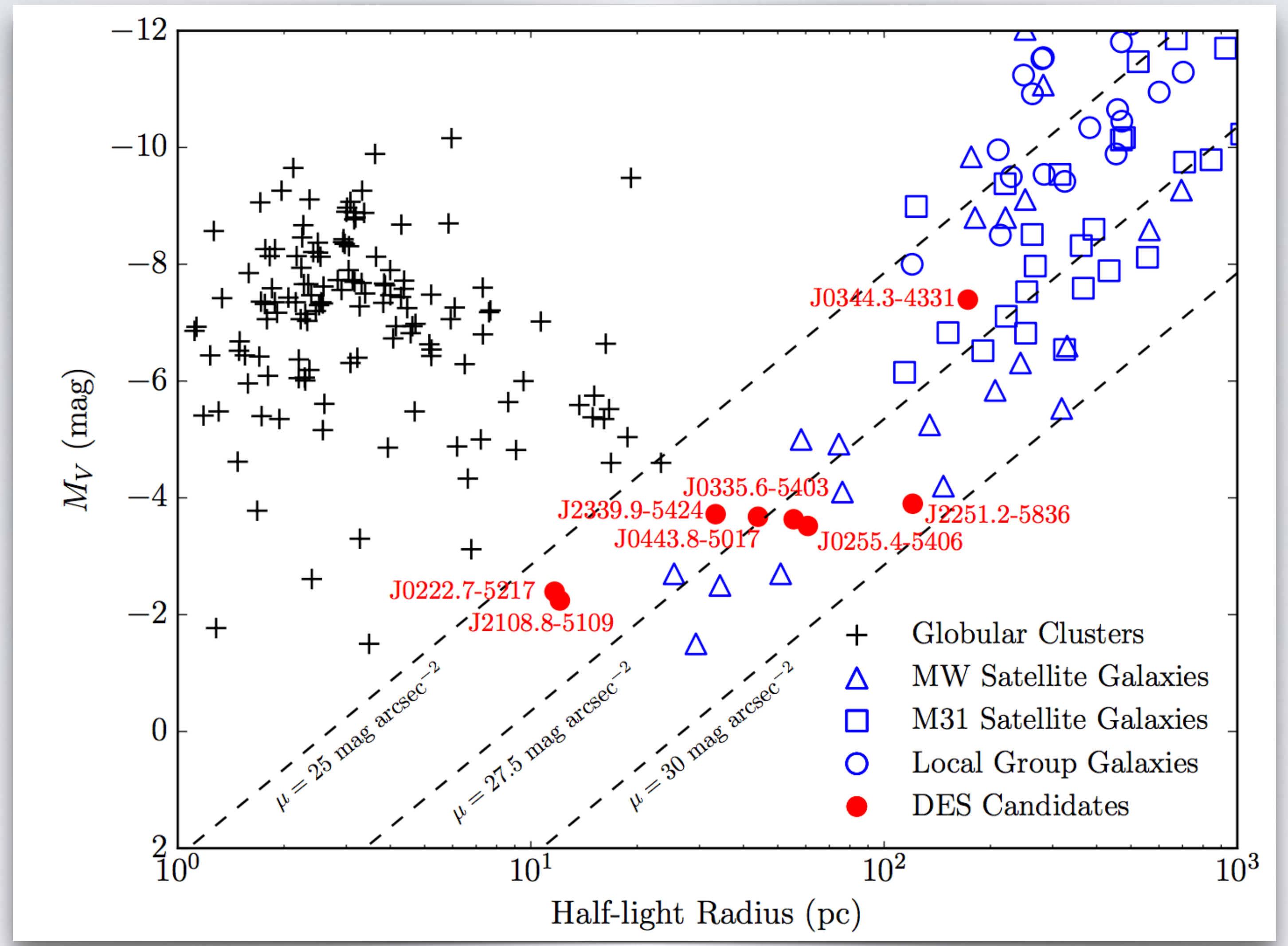
2 candidates:
i = 23.3 and i = 20.2

- Test on SNe fields OK.
- Deploying production software now.

M. Sako

DES & DARK MATTER

arXiv:1503.02584, 1503.02632

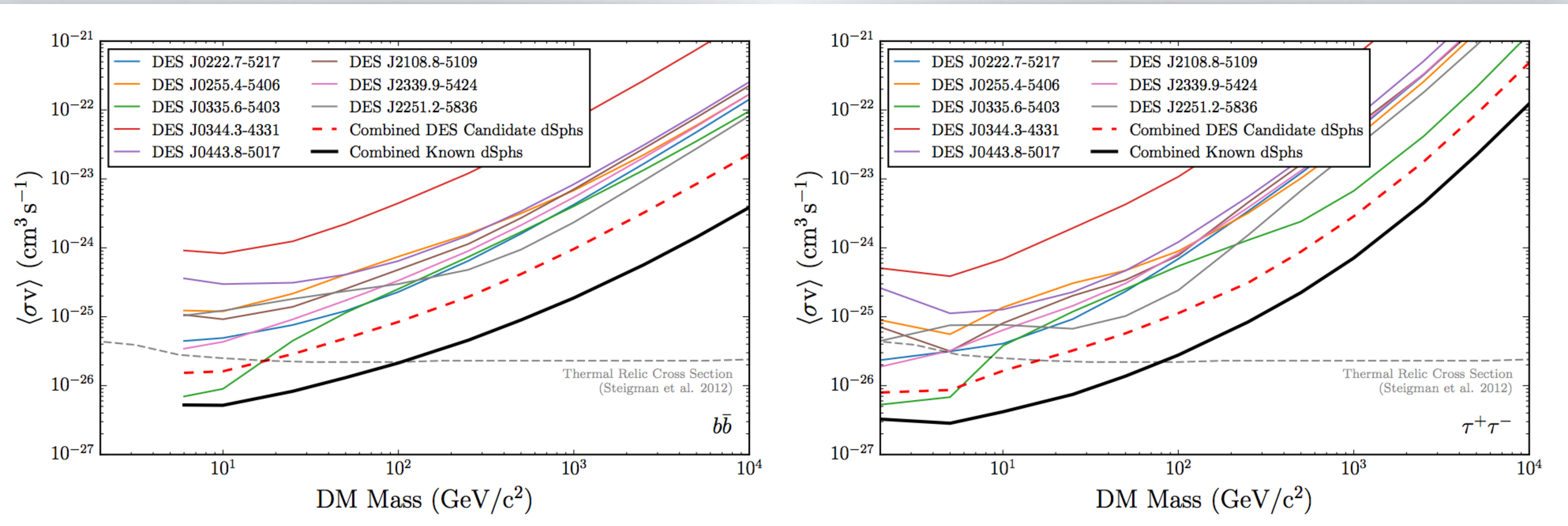


8 new dwarf galaxies satellites of the Milky Way

DES & DARK MATTER

arXiv:1503.02584, 1503.02632

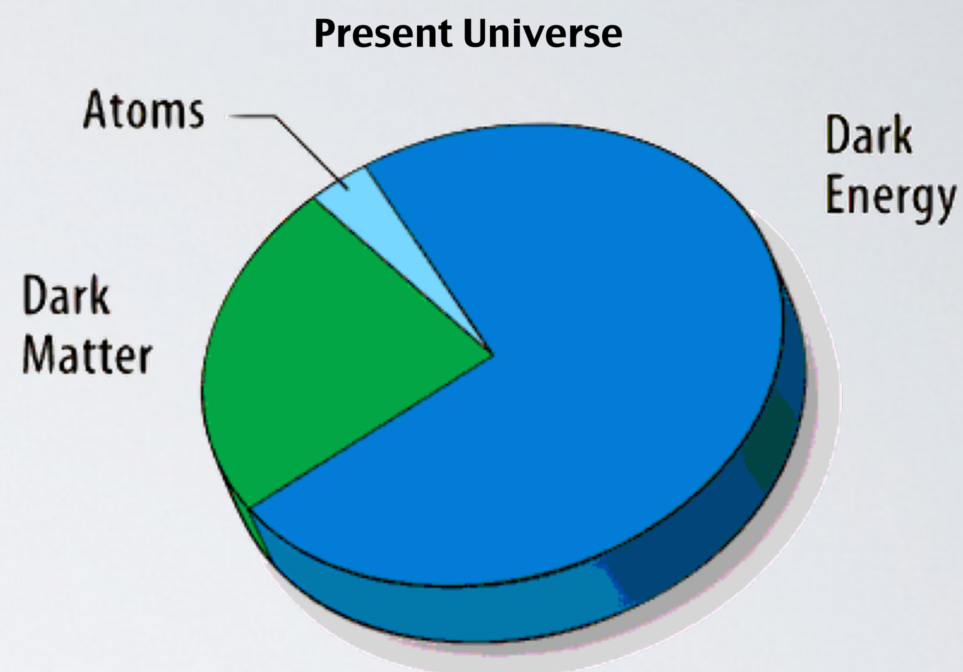
(Joint DES Fermi-LAT analysis)

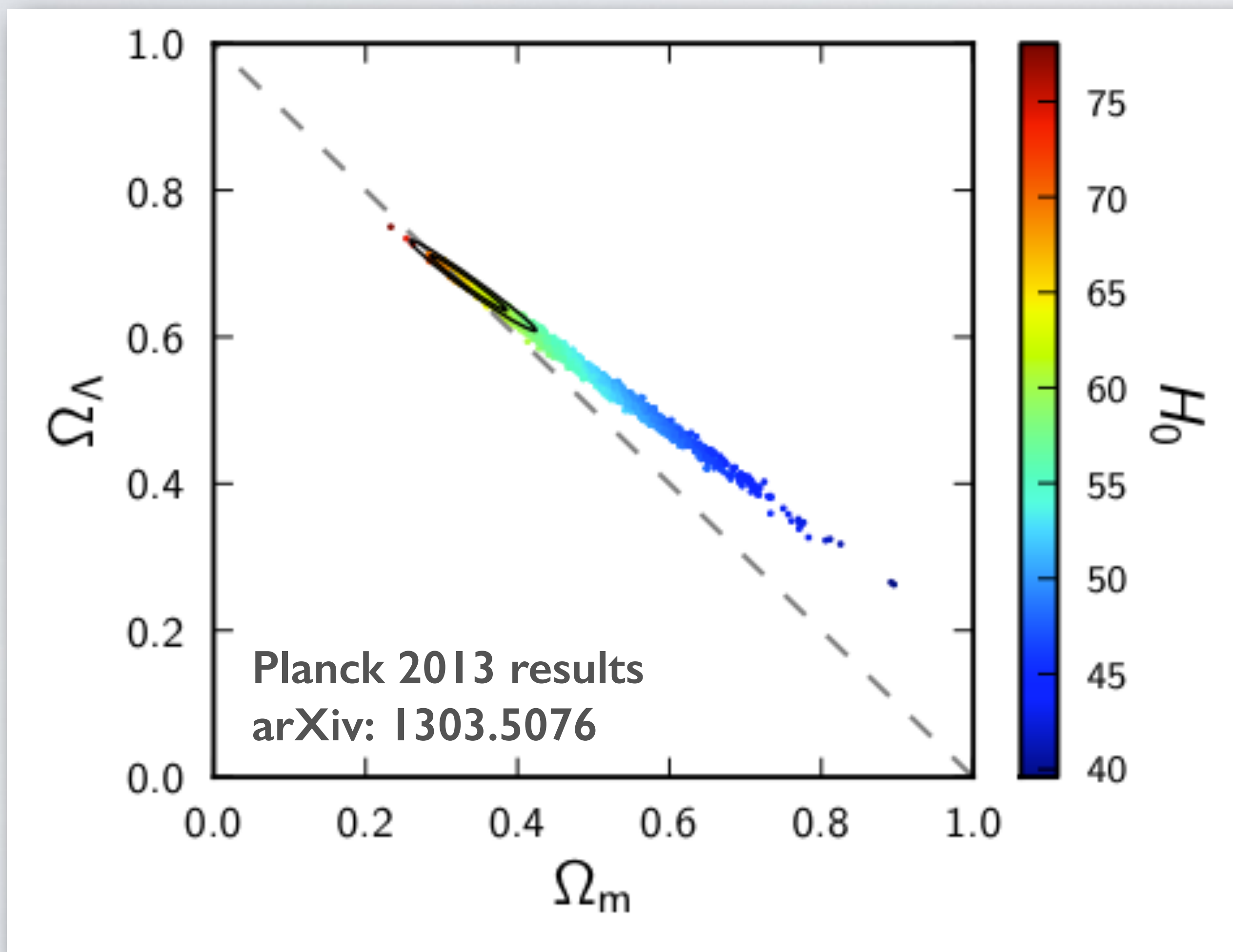


Limits on DM cross-section, mass parameter space from 8 new dwarf galaxies satellites of the Milky Way

DOMINANCE OF NEW PHYSICS

2/3 of today's Universe is Dark Energy
(most of the remaining 1/3 is Dark Matter)





$$\Omega_m \simeq 1/3$$

$$\Omega_\Lambda \simeq 2/3$$

$H_0 \longrightarrow$ **Current expansion rate**

$$h \equiv H_0/100$$