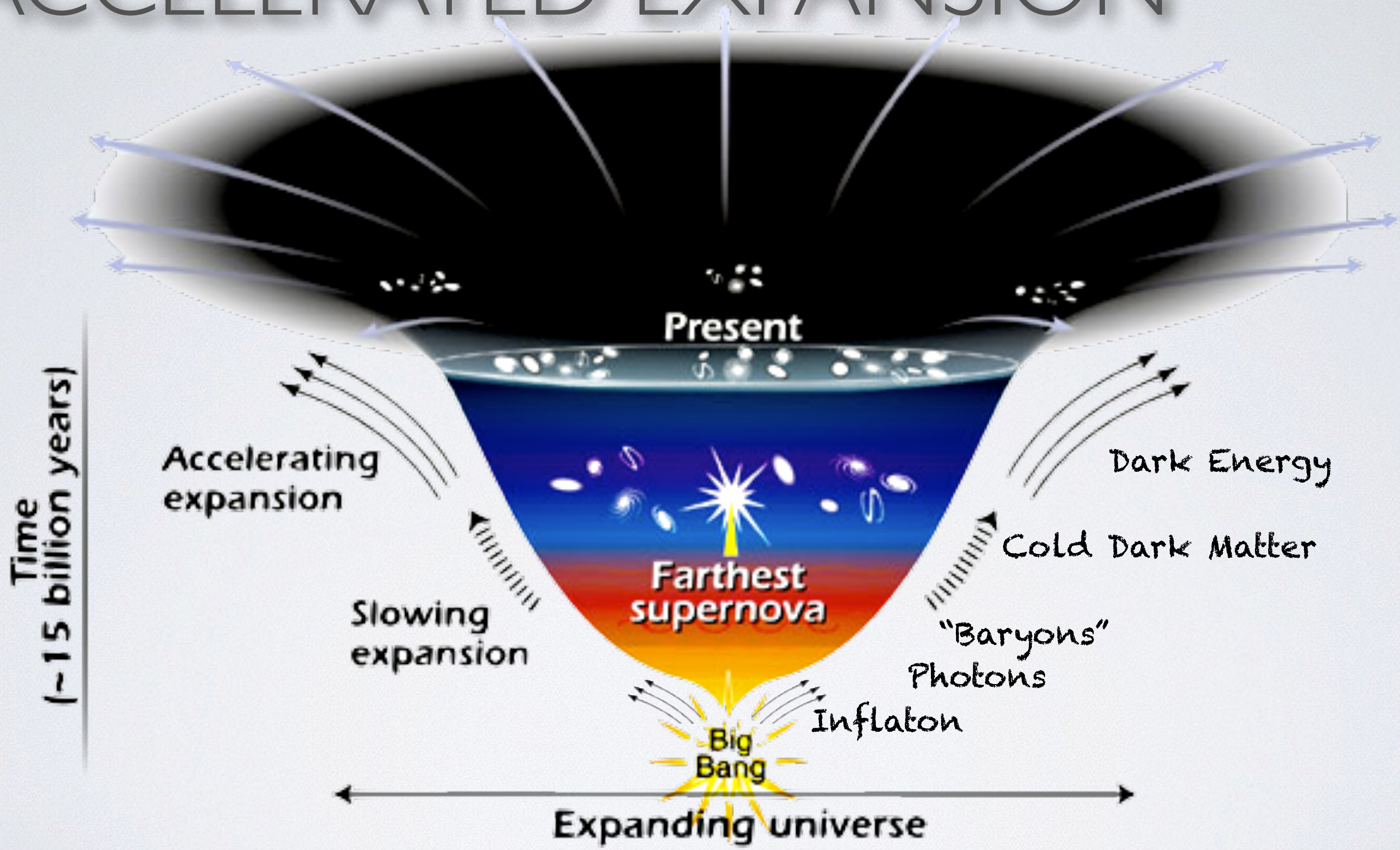
THE DARK ENERGY SURVEY AND GRAVITATIONAL WAVES

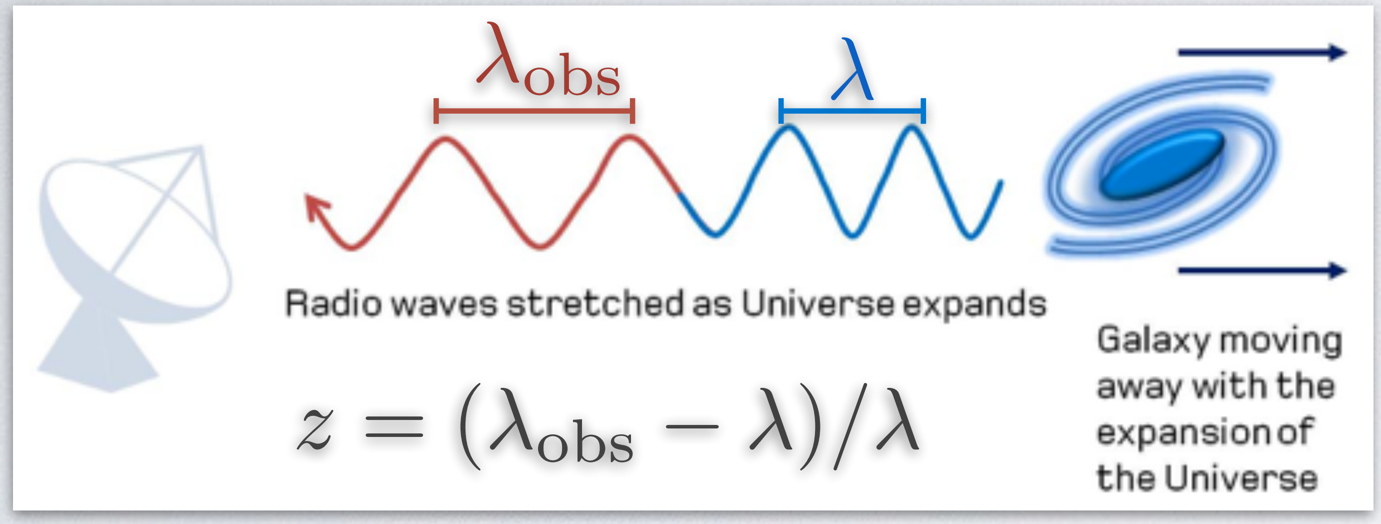
Marcelle Soares-Santos
Fermilab
DES Collaboration

U. Chicago KICP Colloquium — Oct 12, 2016

DARK ENERGY & ACCELERATED EXPANSION



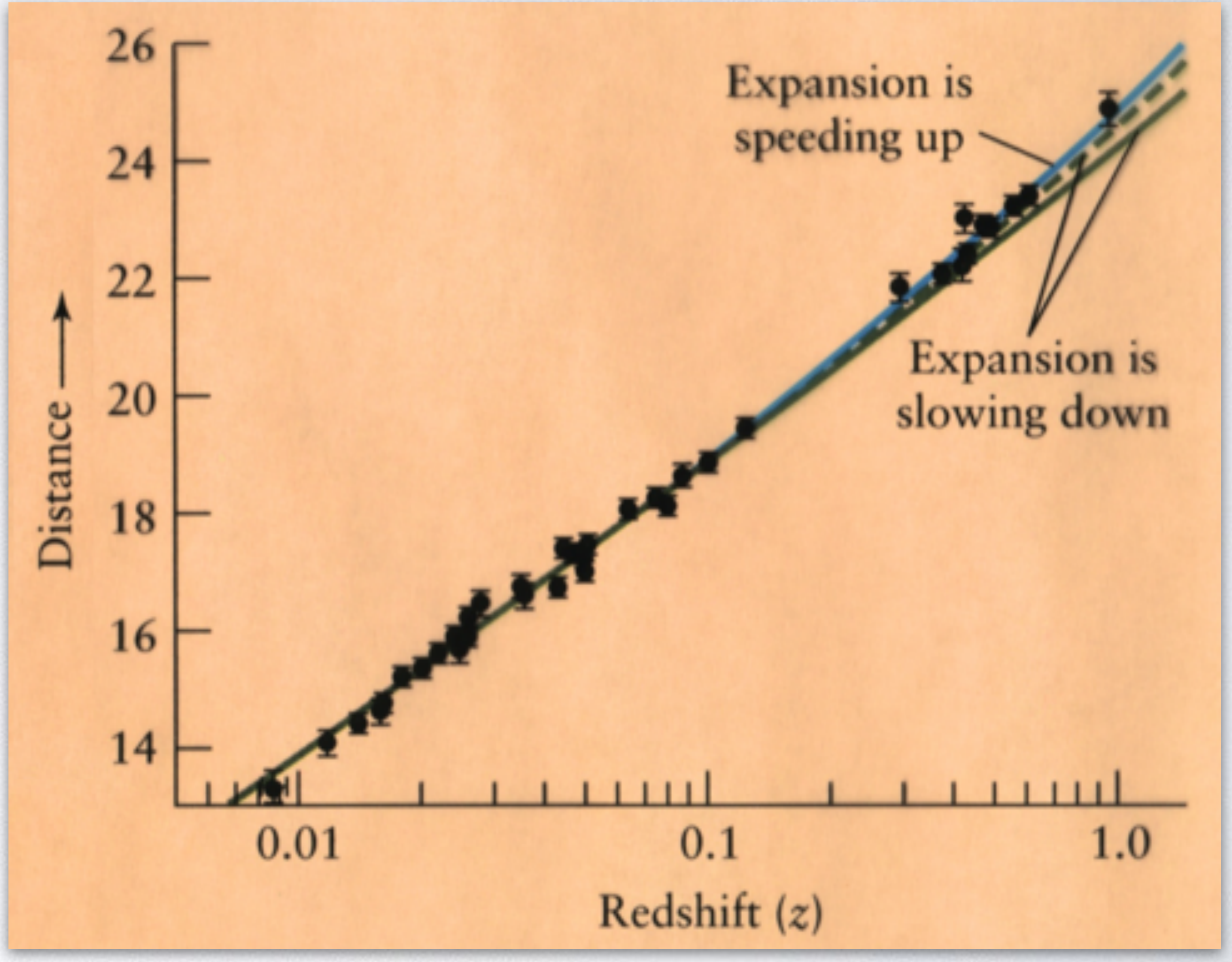
DISTANCE–REDSHIFT RELATION



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!

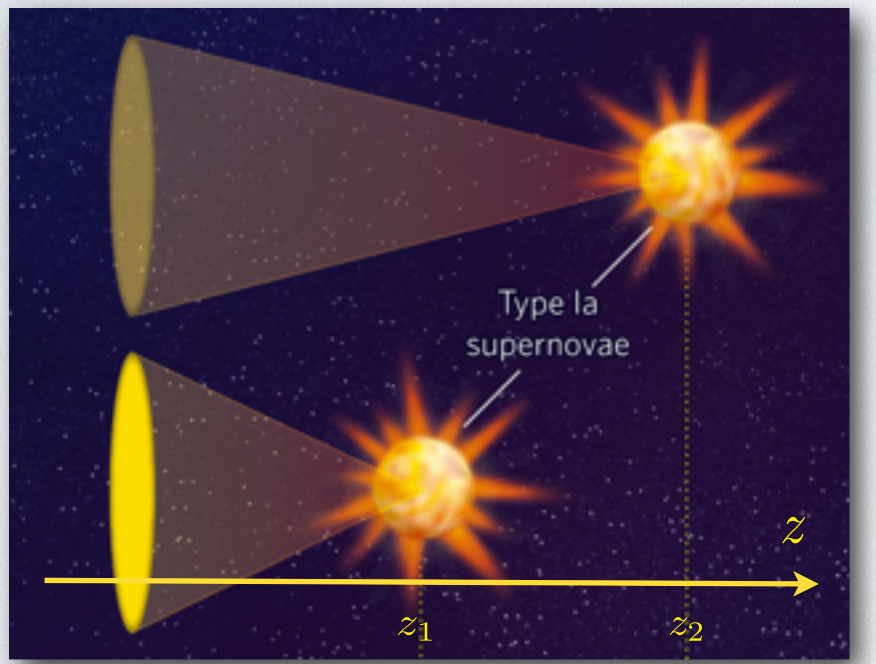


ASTROPHYSICAL OBSERVABLES

Luminosity distance:

standard candle

1. supernovae (SNe)



DES is sensitive to Dark Energy via 4 probes.

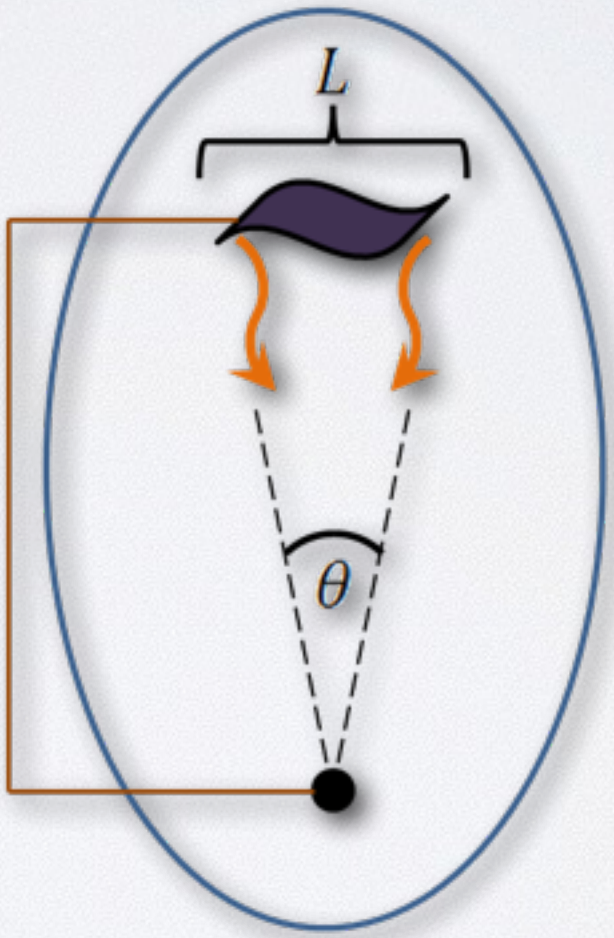
***CMB results from Planck are used in DES analyses.**

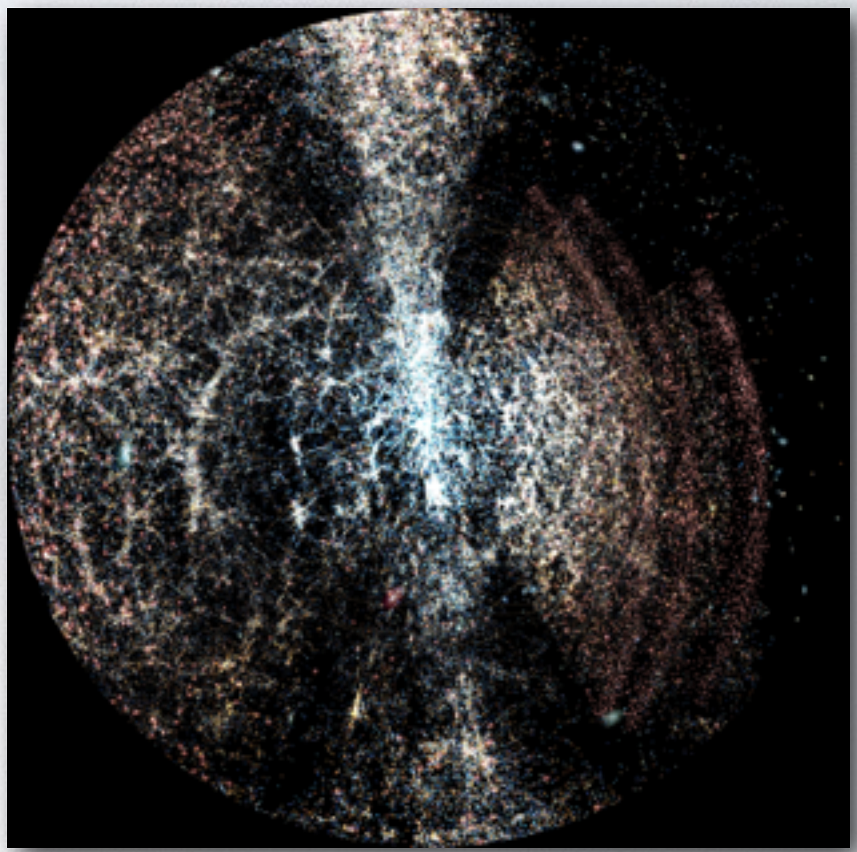
Angular diameter distance:

standard ruler

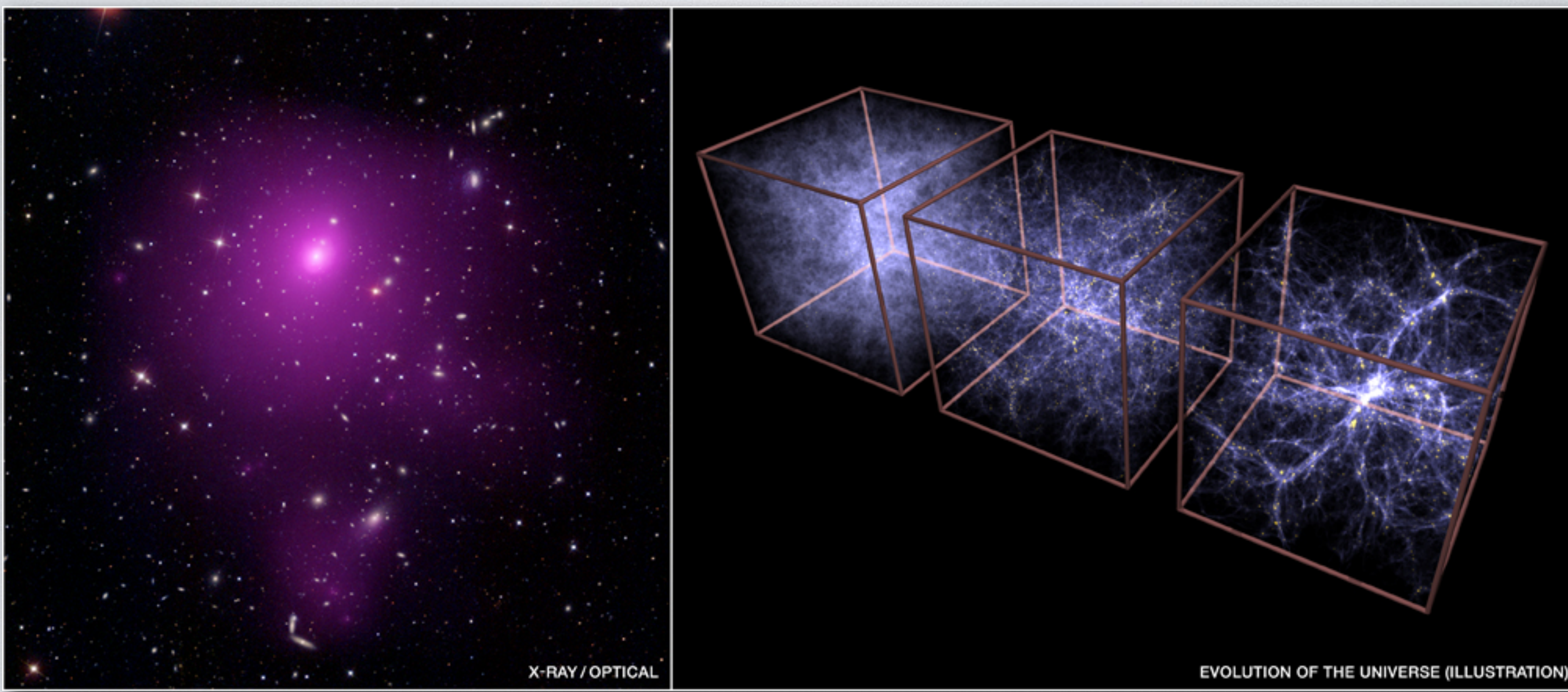
***cosmic microwave background (CMB)**

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**.

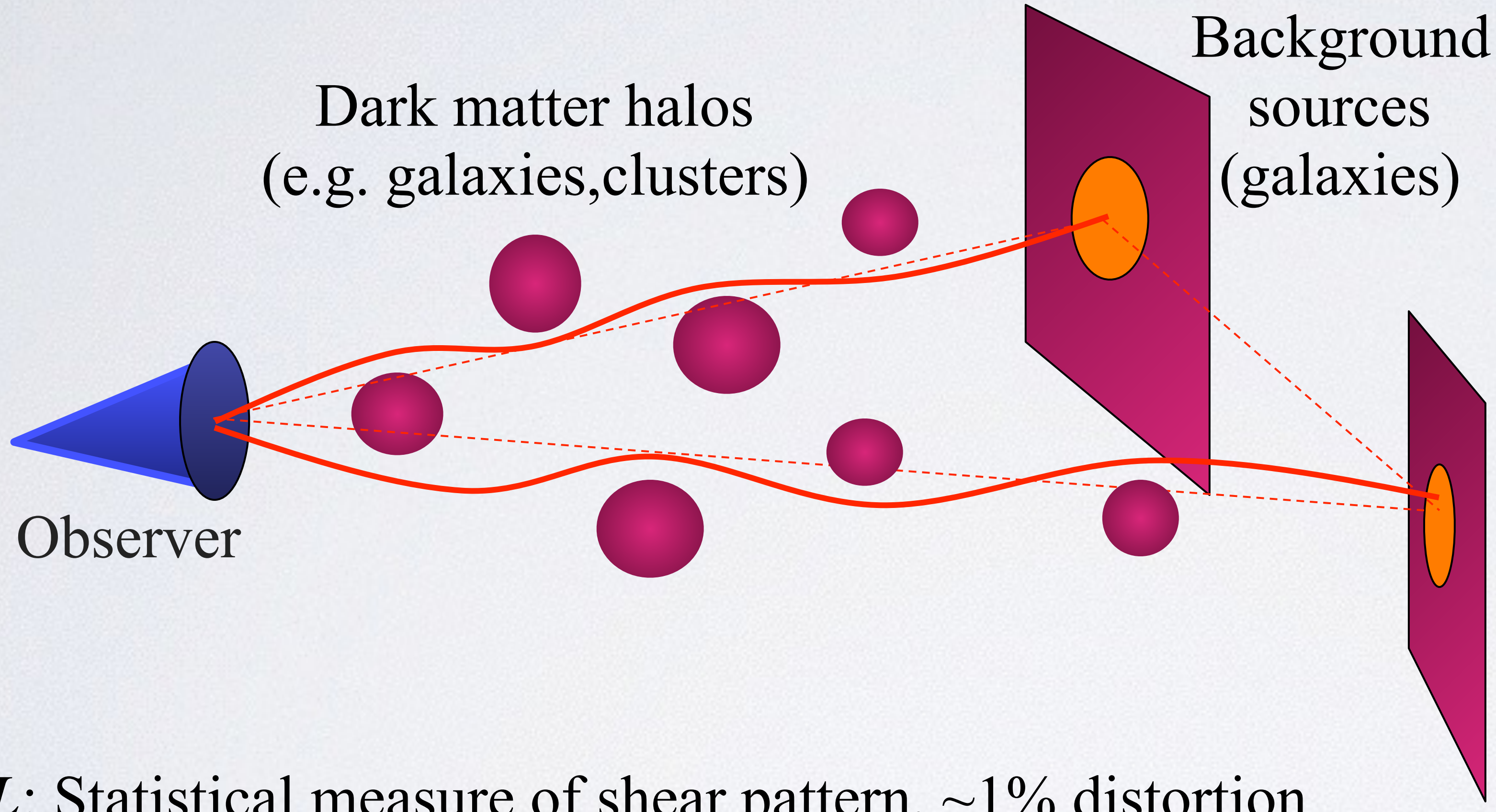
ASTROPHYSICAL OBSERVABLES

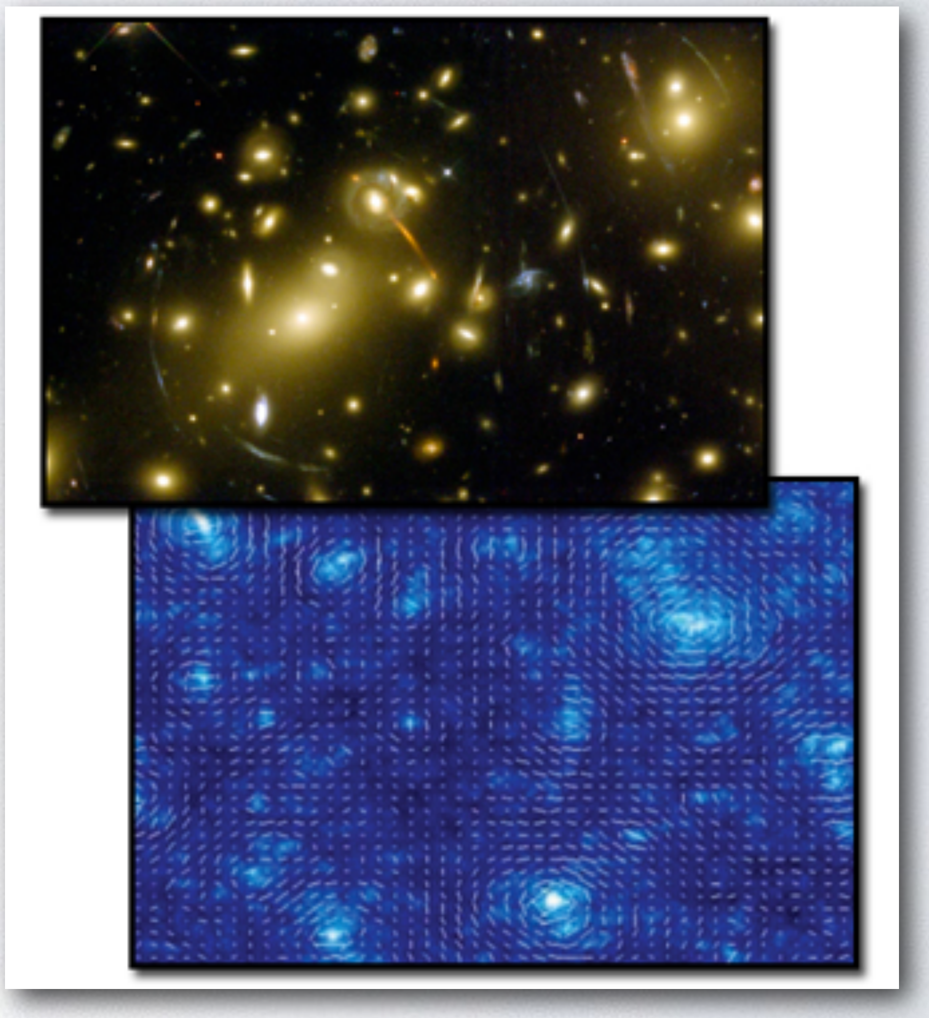
DES is sensitive to
Dark Energy via 4 probes.

WL, Clusters are also sensitive
to angular diameter distance.

Growth of structure:

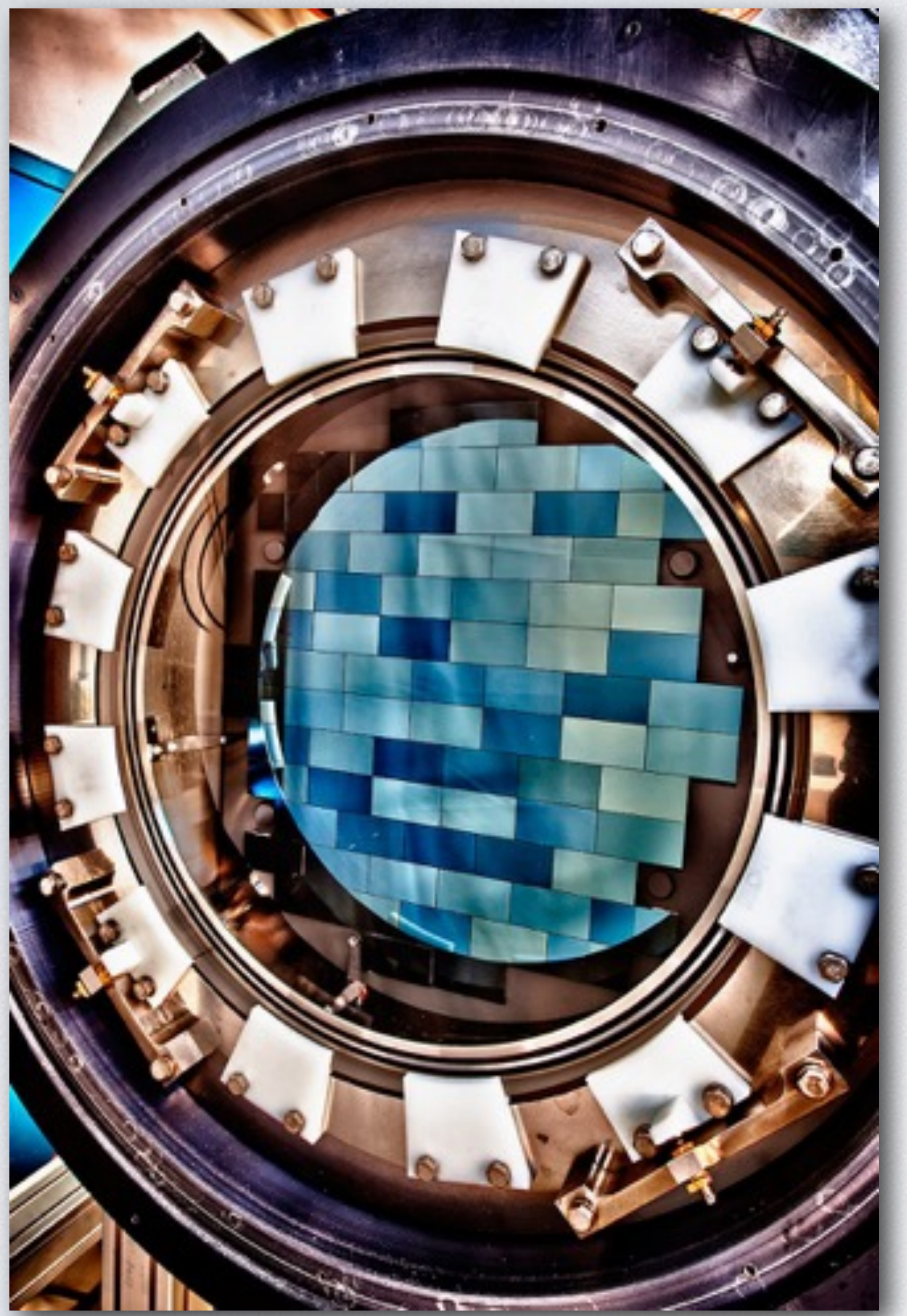
3. weak gravitational lensing (WL)
4. galaxy cluster abundance (Clusters)

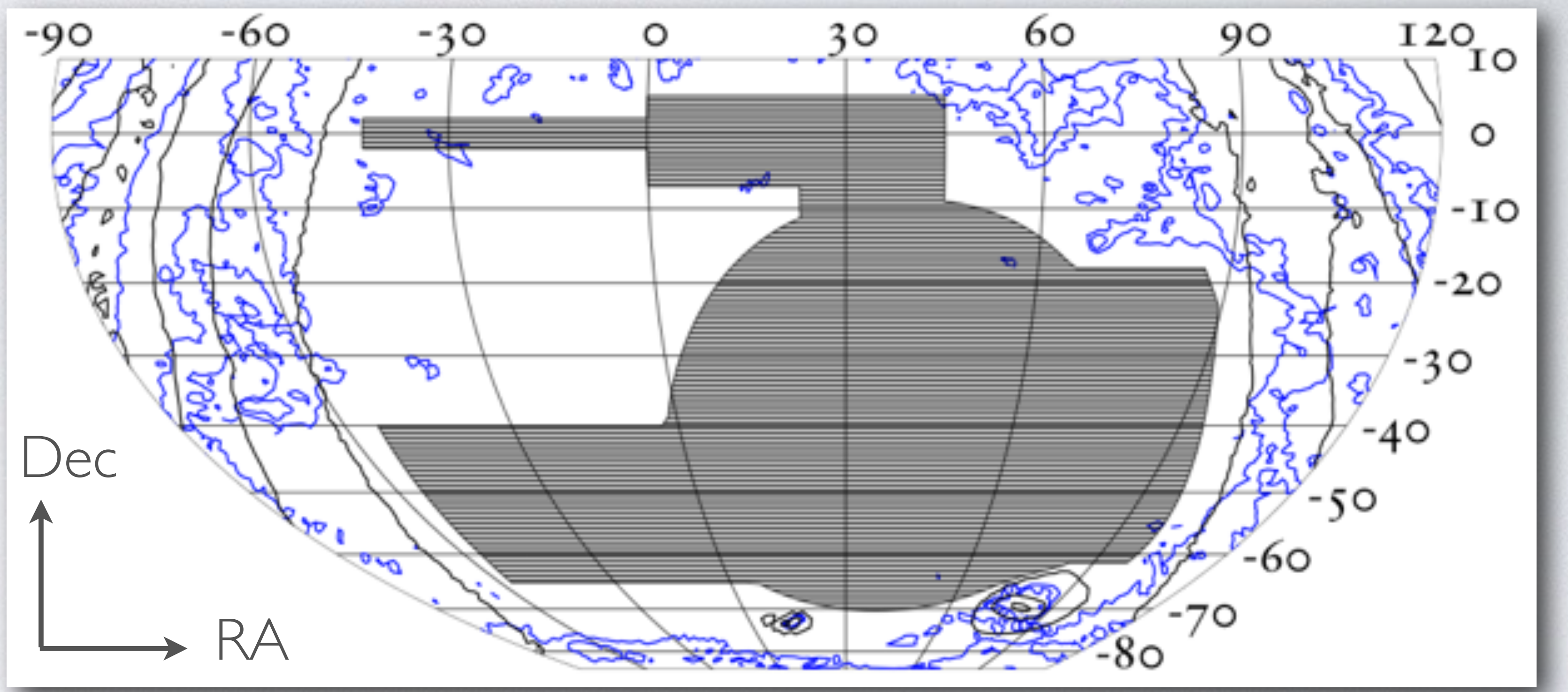




- ***WL***: Statistical measure of shear pattern, ~1% distortion
- ***Clusters***: Number density vs. Mass vs. redshift
- Radial distances depend on ***geometry*** of Universe
- Mass distribution depends on ***growth*** of structure

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

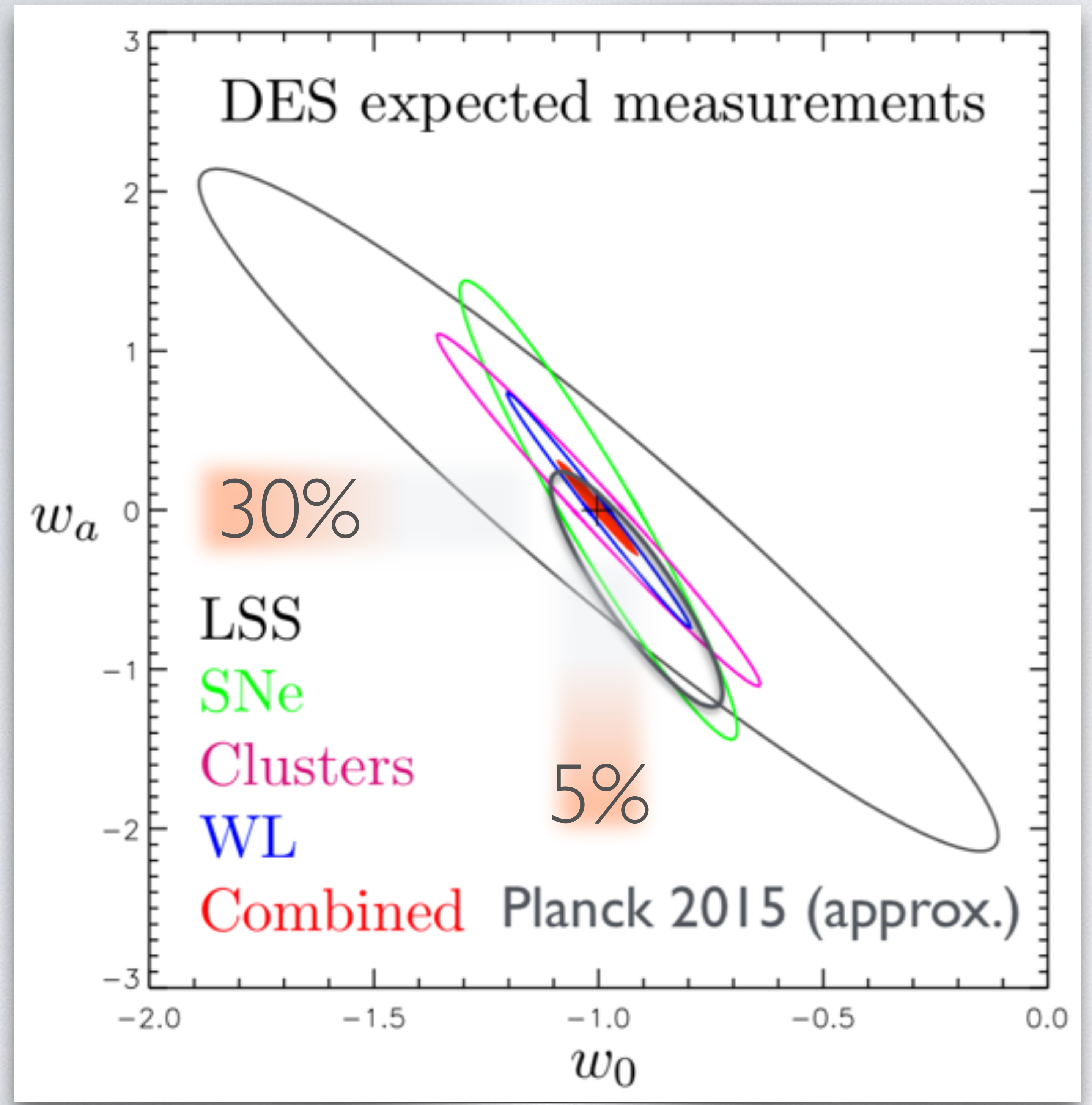
5000 sq deg grizY to **24th mag** overlapping with SPT

30 sq deg SNe survey
0.9 arcseconds seeing

525 nights: 2013-2018

DES SITE: CERRO TOLOLO, CHILE

DES PROJECTIONS (5 YEARS)



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

DES — SCIENCE RESULTS

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

Most 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.:

> **— 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.

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

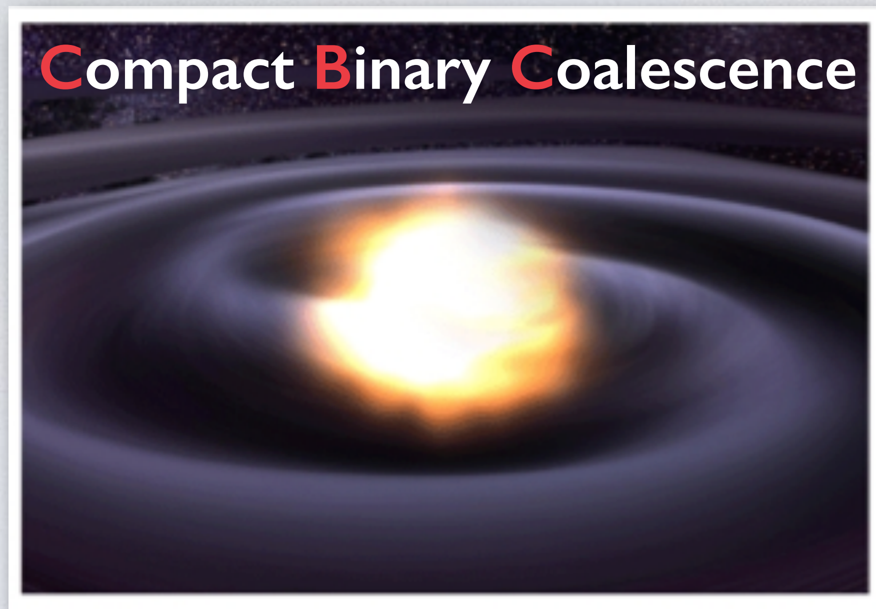
Cosmology

Standard sirens (the GW-equivalent of standard candles)

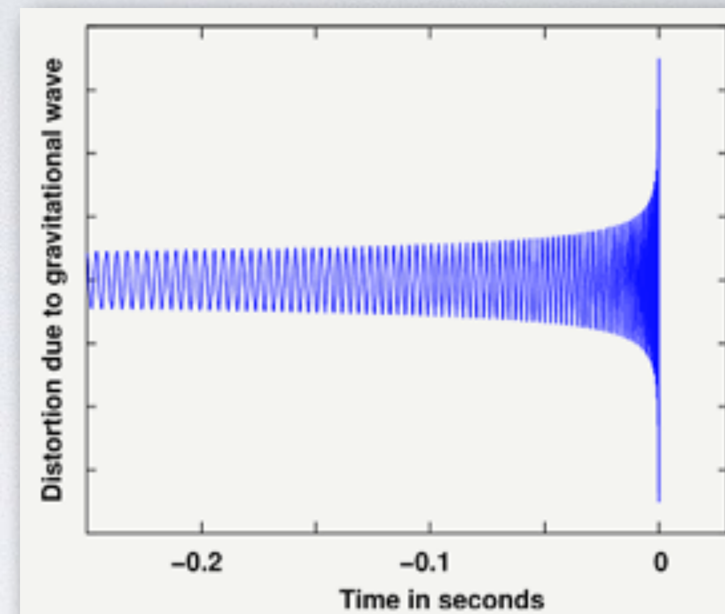
Physics of space-time

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

STANDARD SIRENS

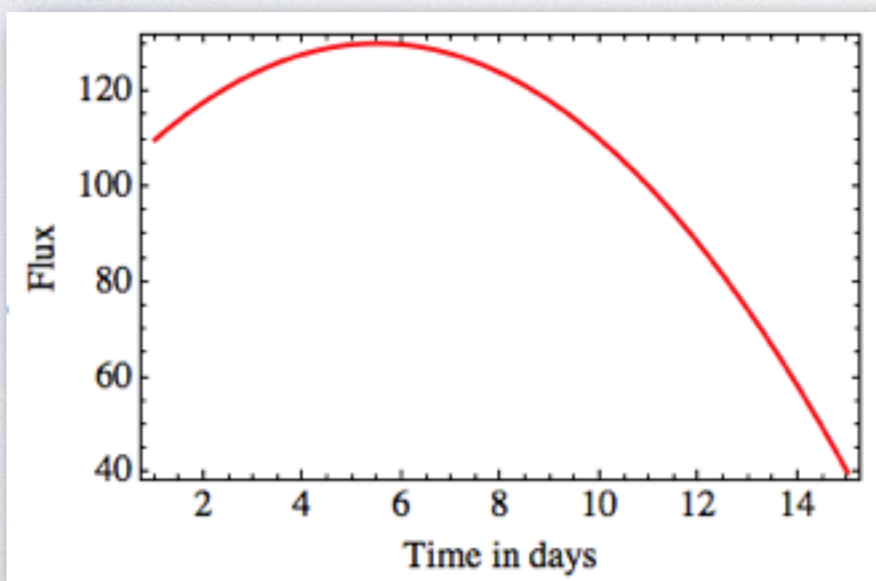


GW

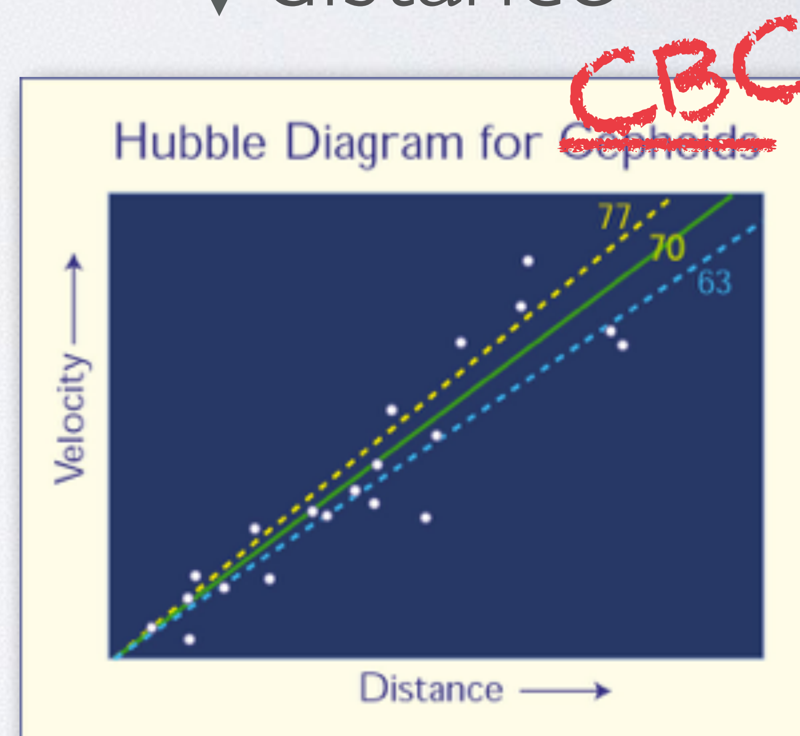


distance

EM



redshift



DES SCIENCE: 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 obtained strong support from the DES Collaboration — *thank you, Josh!* — including experts from the SNe group (Kessler, Sako, Brout, Scolnic, Frieman, et al.).

We established a joint effort with LIGO members (Holz, Chen, Doctor, Farr) and non-DES DECam users (Berger, Cowperthwaite 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 the first events did not have a NS in them, but prospects for future are good!

Funding: Fermilab LDRD (FY15, FY16), UChicago SCI grant (FY17).
Telescope time: Blanco/DECam nights (3 in 2015B, 5 in 2016B; PI: Berger).

THE PROGRAM

GW trigger
time stamp
sky region
distance
event type

~24h

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

LIGO: arXiv:1304.0670

We are here!

O1

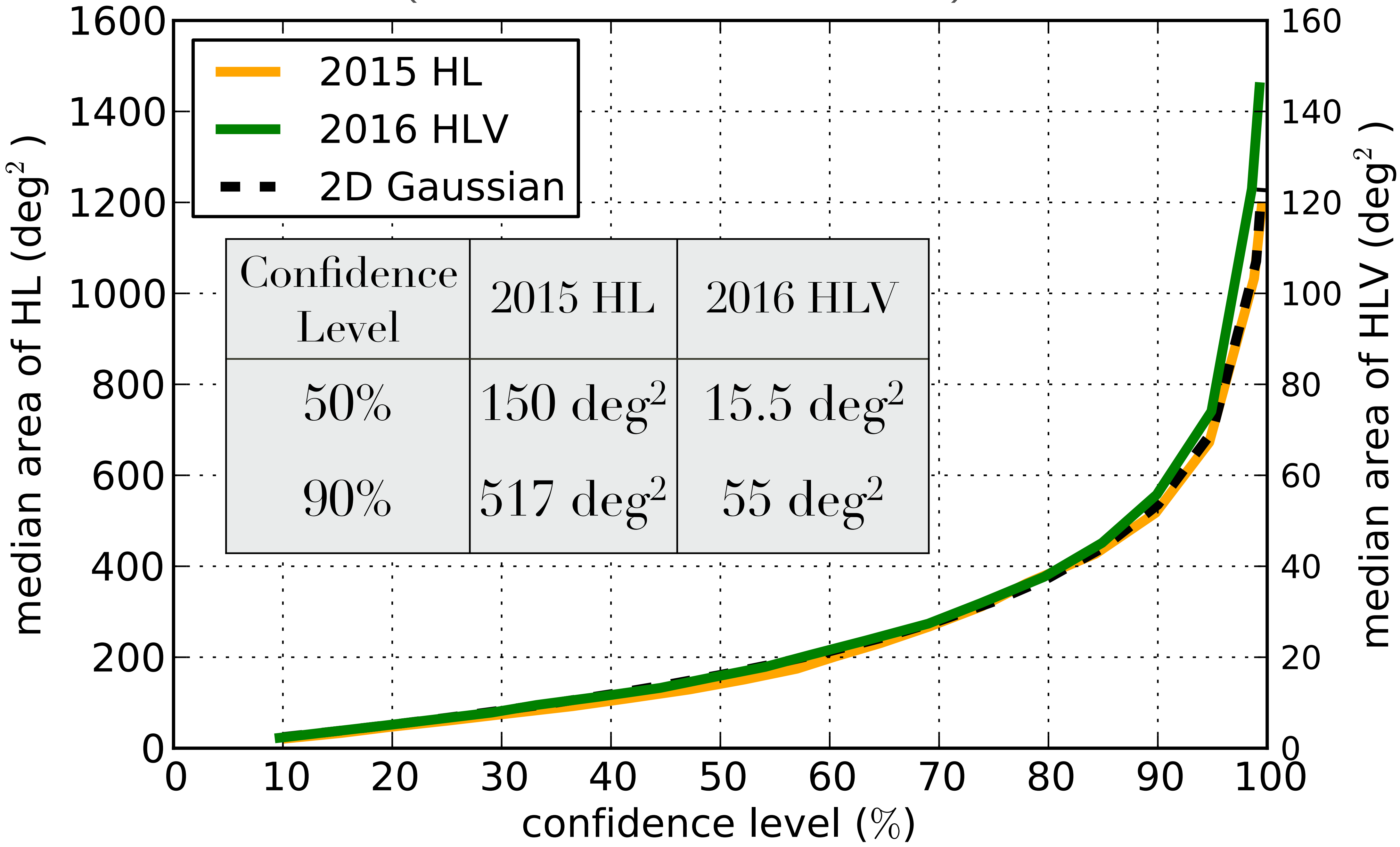
	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 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

DES observations (Sep-Feb months)

LSST era!

CHALLENGING SEARCH AREAS

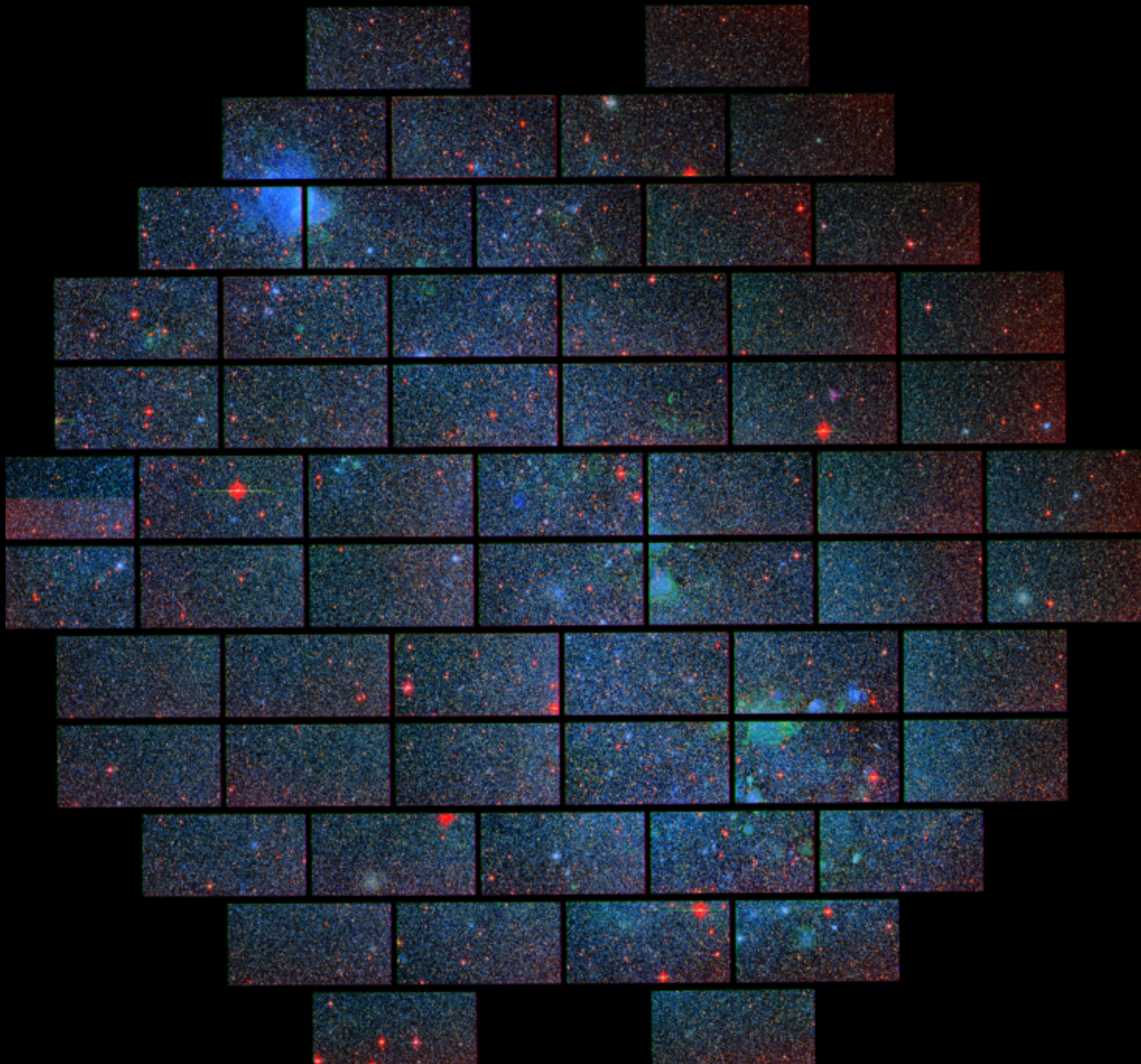
(Chen & Holz 2015)



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

BUT WE HAVE THE RIGHT INSTRUMENT…

3 square degree FOV on a 4-meter telescope!



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

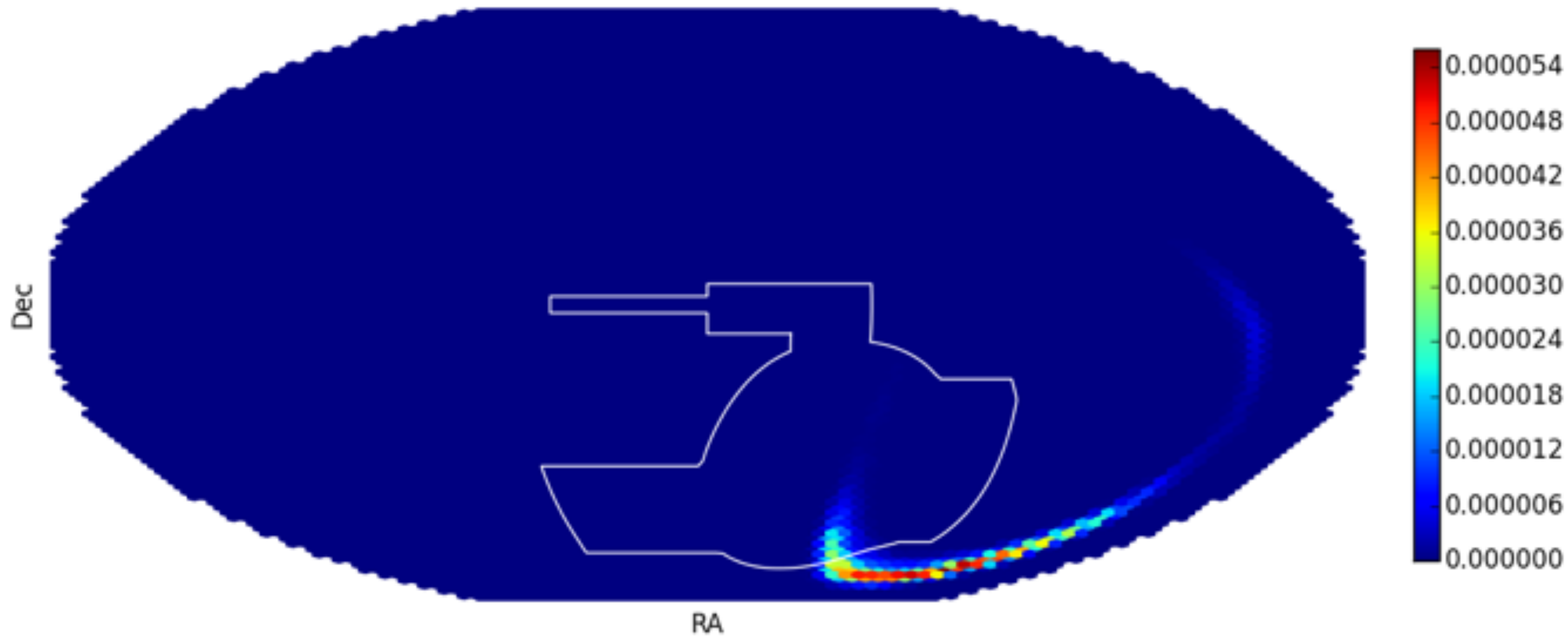
THE PROGRAM IN ACTION

The 1st Event:

GW150914

GW150914

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

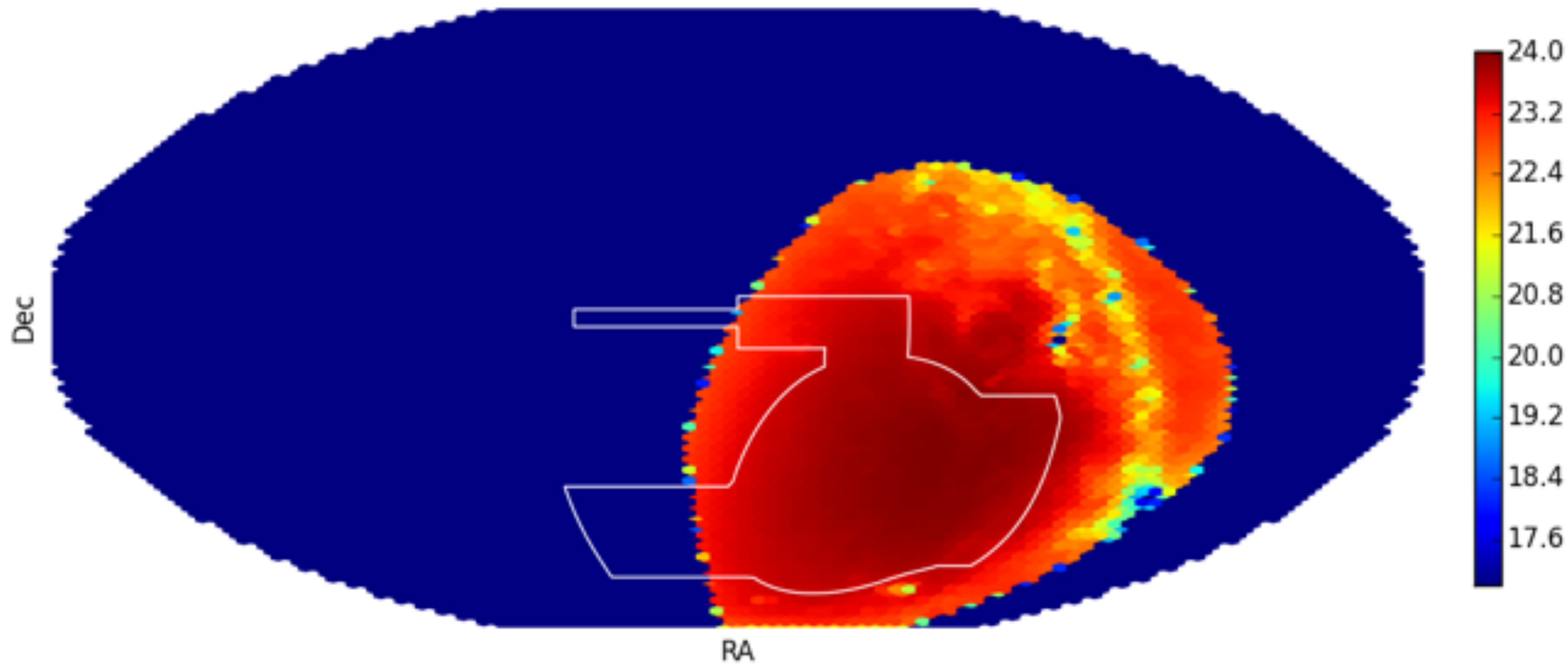


LVC sky localization probability map (final)

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)

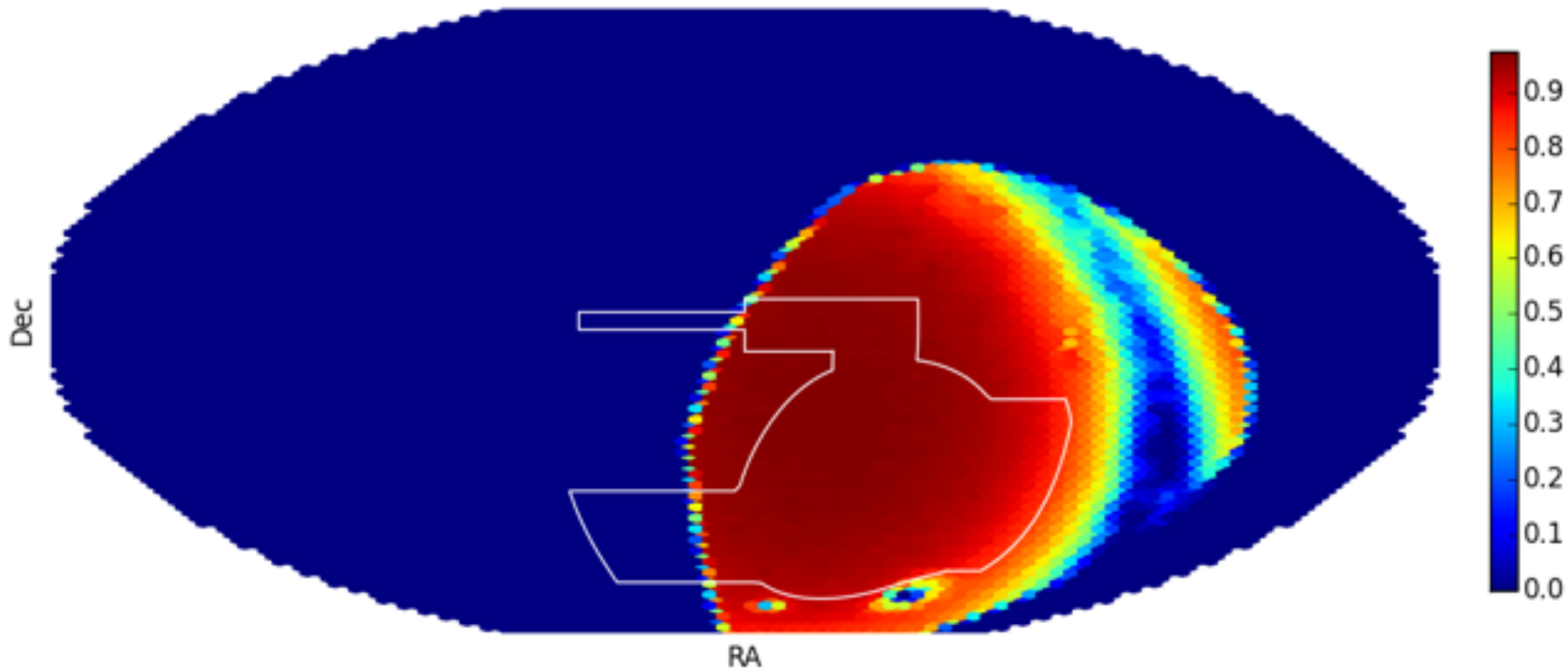


DES mag limit model

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)

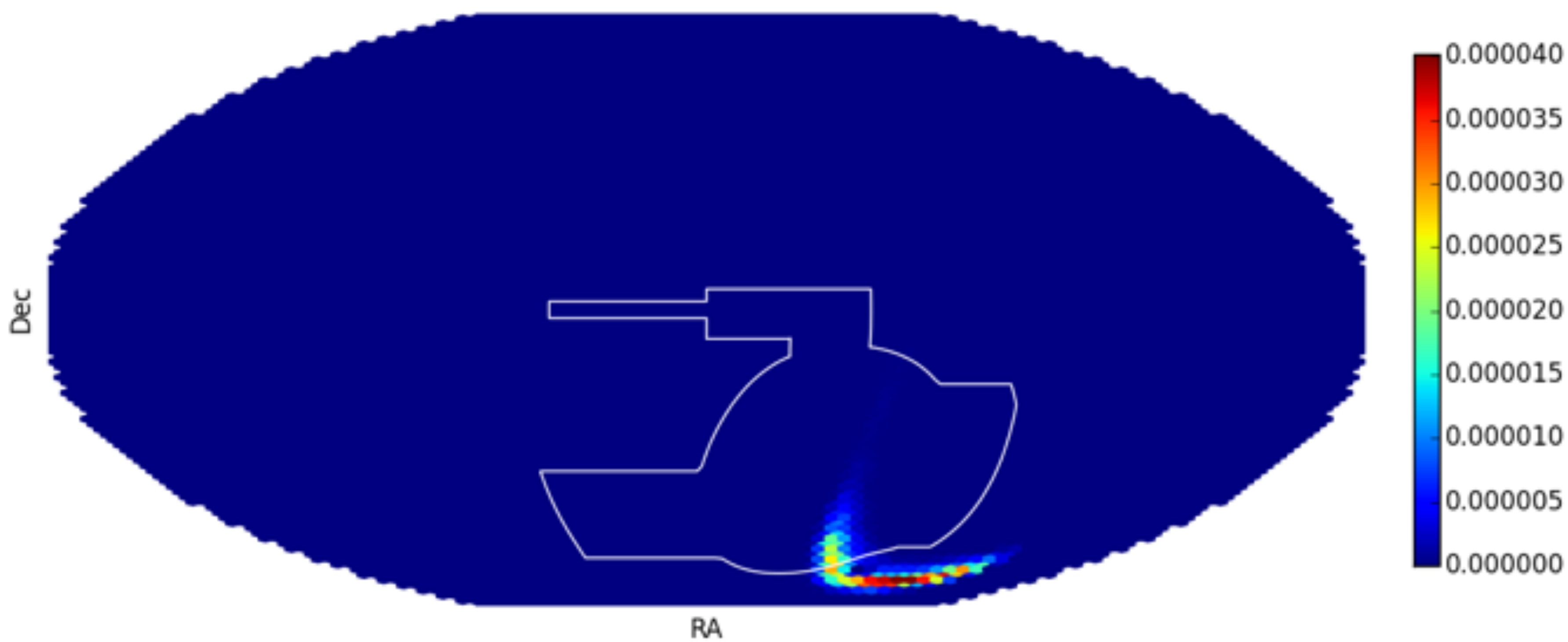


DES source detection probability map

GW150914

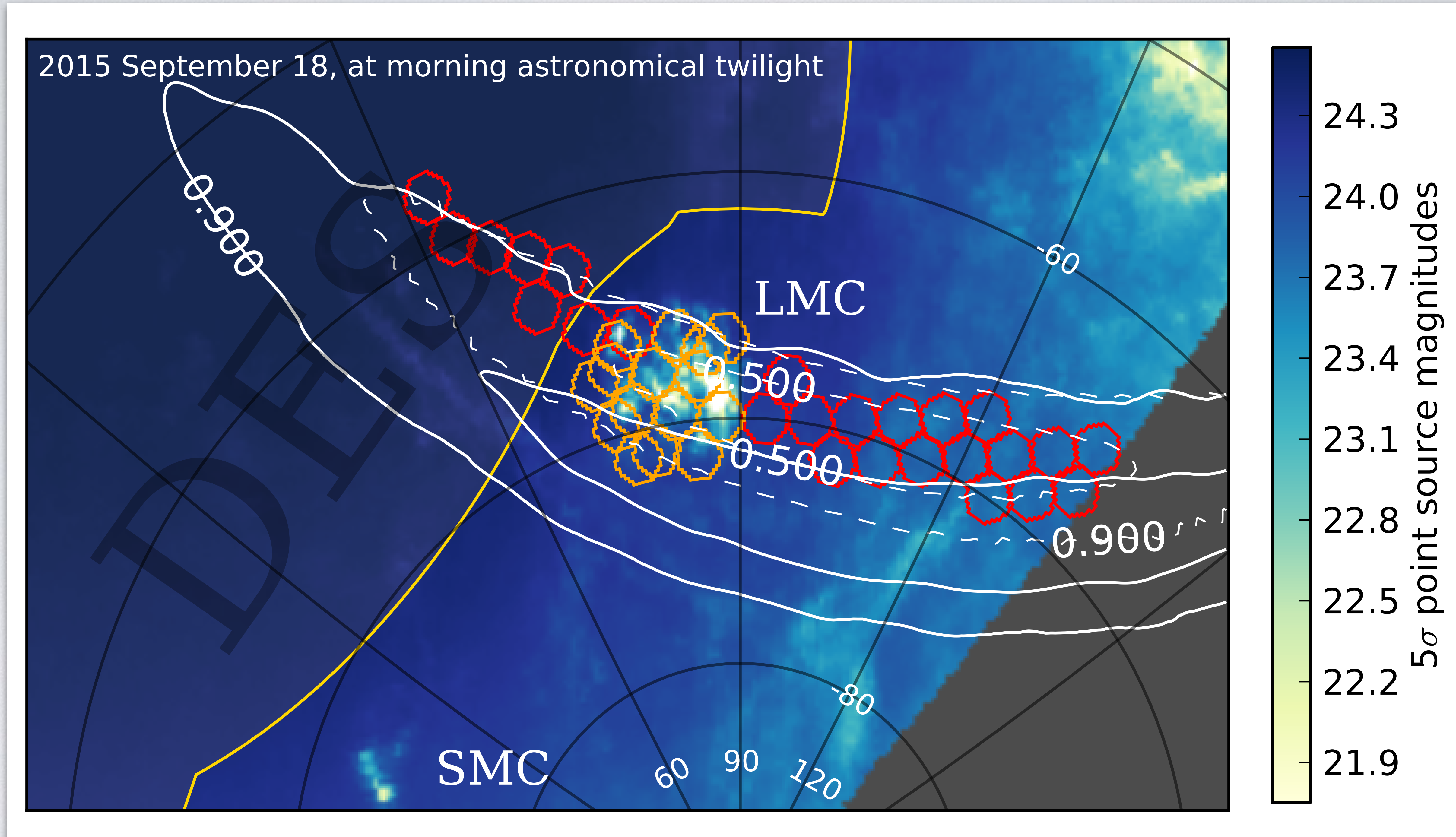
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

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



DESxLIGO source detection probability map

DATA



2015 September 18, at morning astronomical twilight
0.900
DES
LMC
0.500
0.500
0.900
SMC
-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

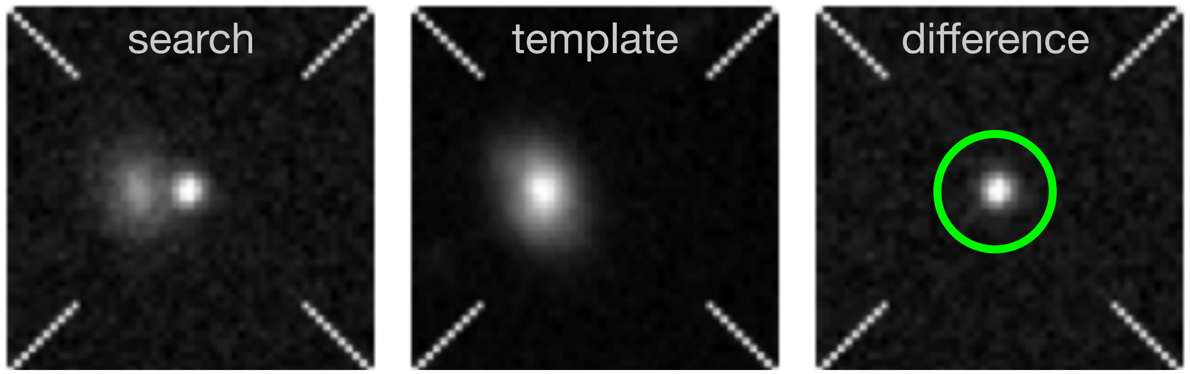
28 fields, izz bands, 90 sec (11 in footprint, 17 outside)

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)	$A_{\rm eff}$ [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

SYNERGIES WITH SN SURVEY

Example of SNe detection using the DES difference imaging pipeline.



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

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

<u>Status of DES SN Survey:</u>

Over 200 spectroscopically confirmed type Ia SNe (photometrically selected sample is about 5x larger)

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

Cosmology results using spectroscopically selected type Ia SNe coming soon.

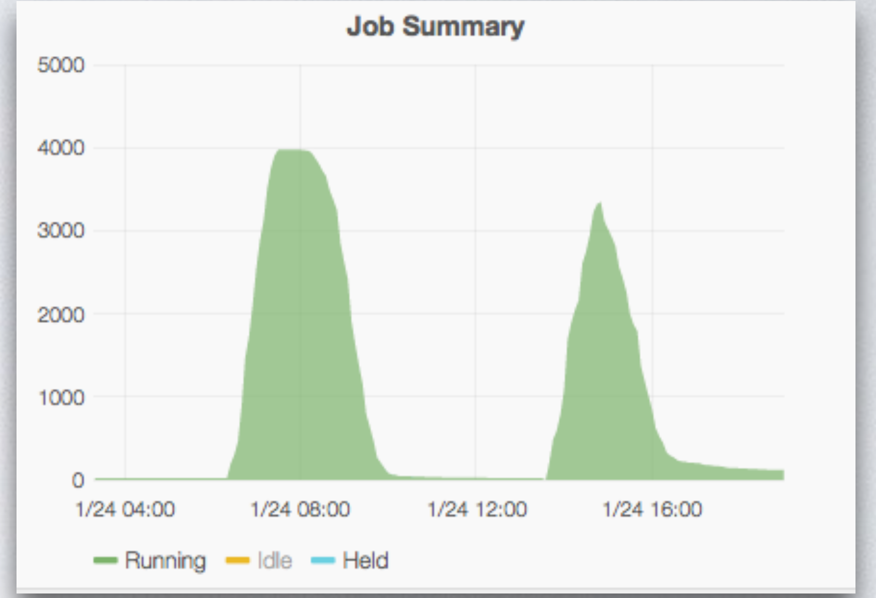
IMAGE PROCESSING

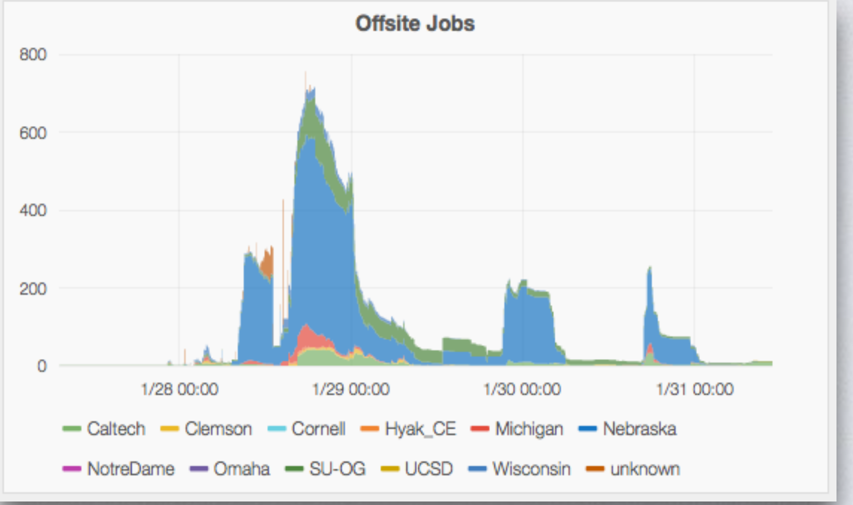
Each search image and template run through ***single epoch*** processing (few hours each)

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**

Completely automated job submission immediately after search image available. Able to run dozens of images in parallel using Fermilab and Open Science Grid resources.





http://fifemon.fnal.gov/

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.

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

NUMBER OF SELECTED EVENTS

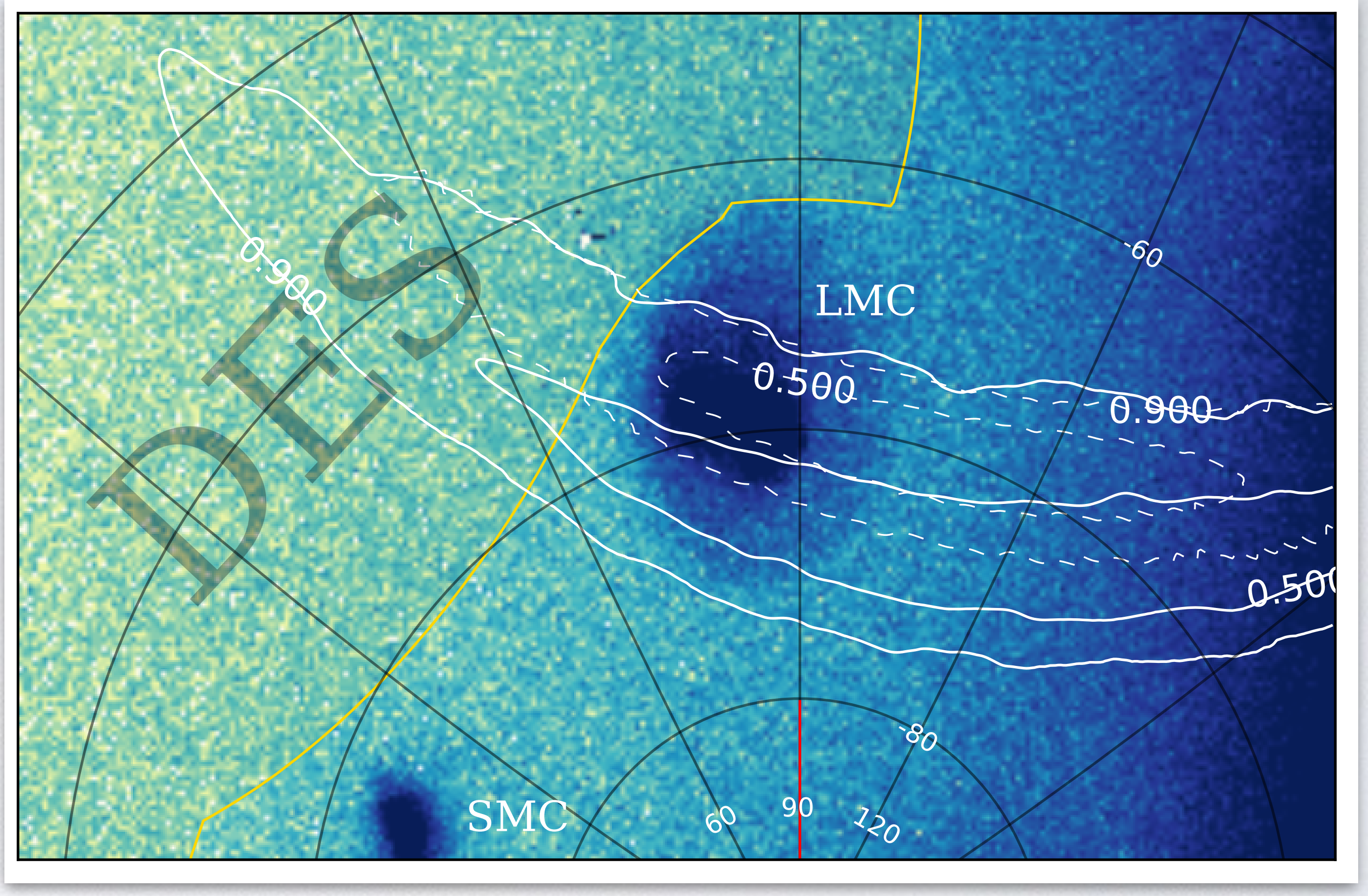
mag(i)	raw	cut 1	cut 2	cut 3
18.0–18.5	84	1	0	0
18.5–19.0	177	1	0	0
19.0–19.5	291	2	0	0
19.5–20.0	227	2	1	0
20.0–20.5	156	17	2	0
20.5–21.0	225	42	3	0
21.0–21.5	334	84	2	0
21.5–22.0	756	159	1	0
22.0–22.5	1099	183	0	0
total	2349	491	9	0

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.

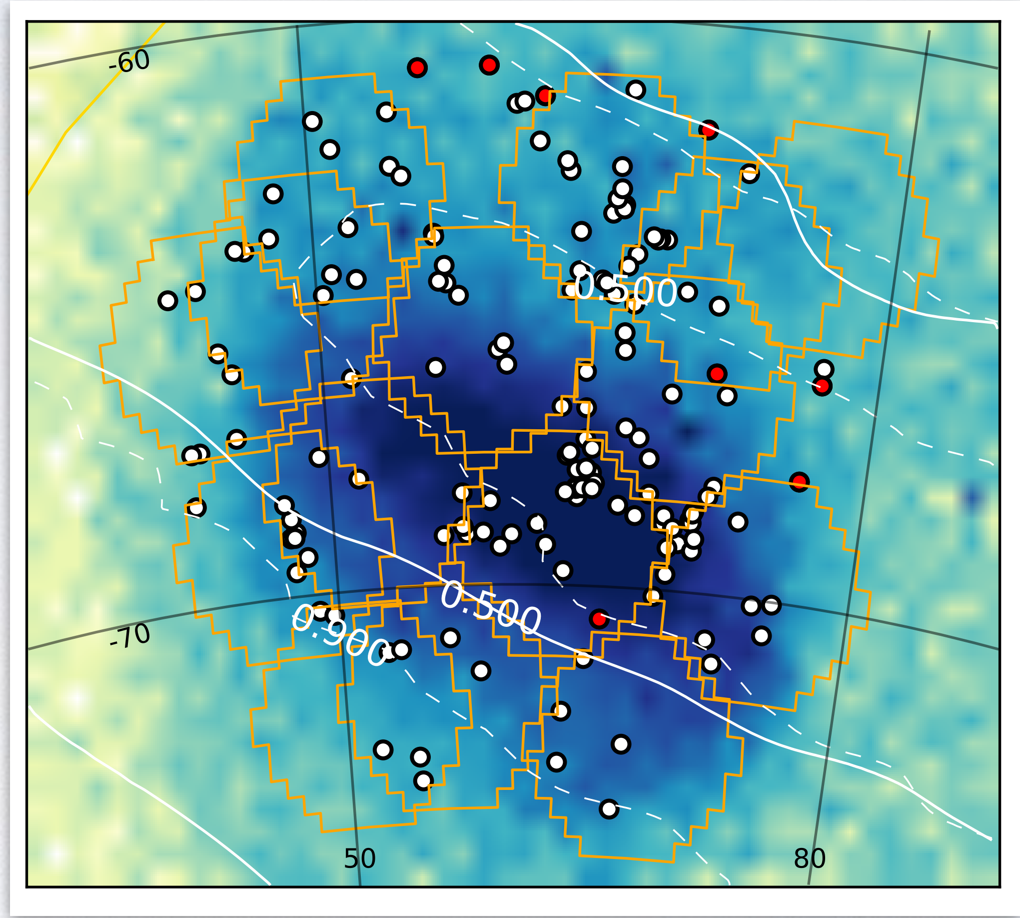
~ 20% of the CC's are expected to fail to produce supernovae.
Could GW150914 be associated with a failed SNe?

ANALYSIS 2

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

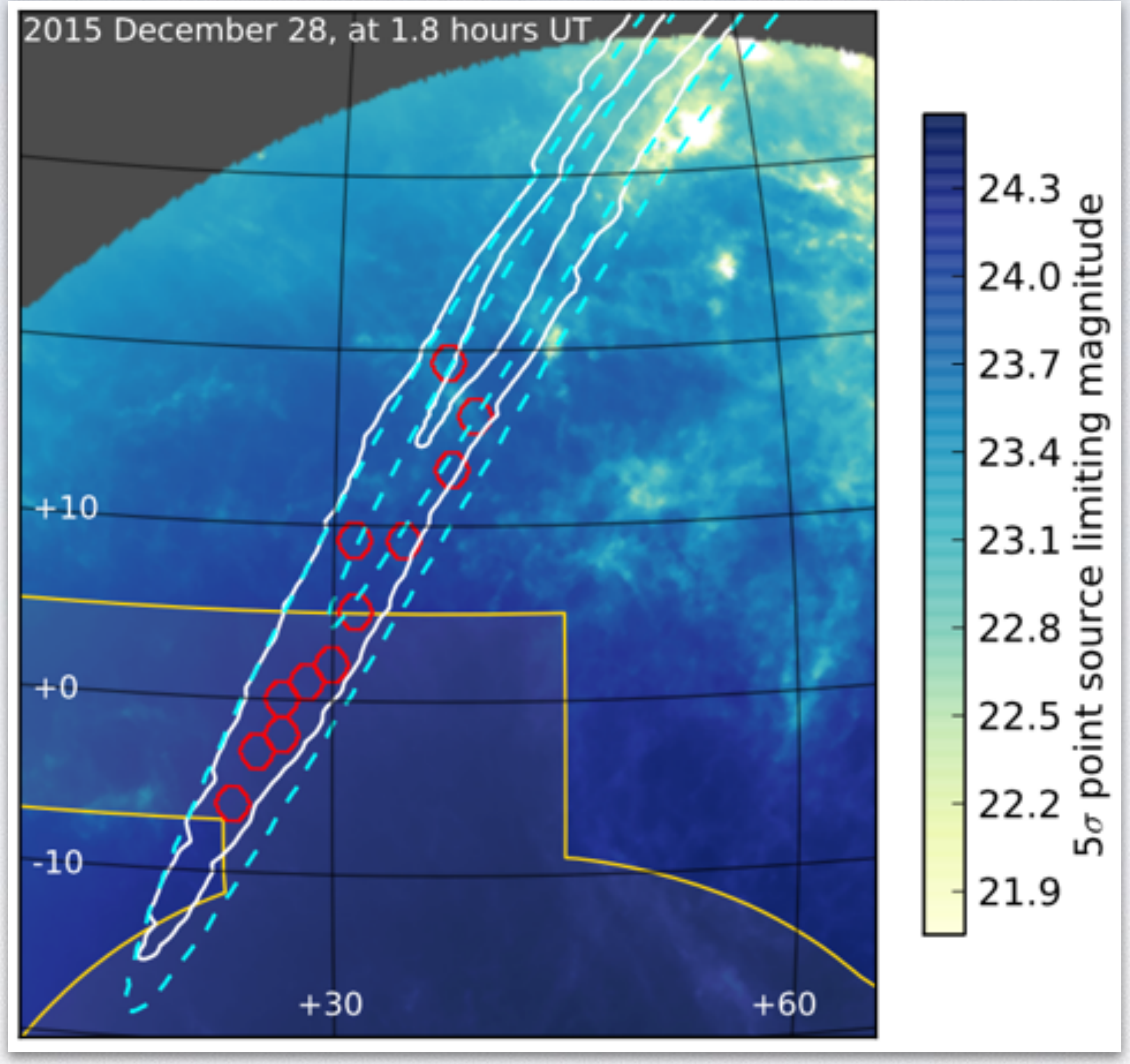
We take possible progenitors (152 <u>red supergiants</u>) catalogued in the literature, and search for them via visual inspection. 144 were in the observed area; <u>all accounted for.</u>

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



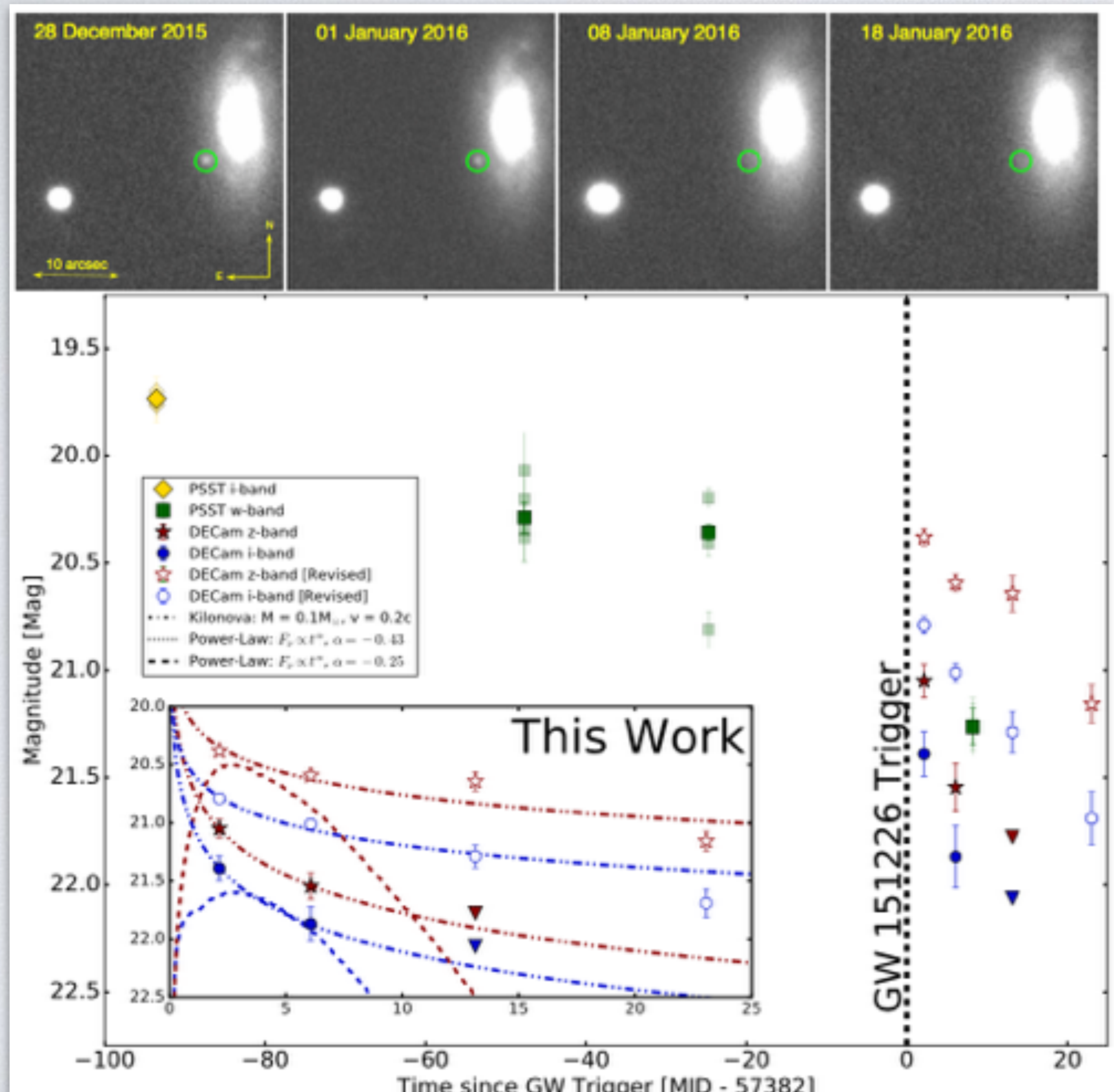
LIGO's result published yesterday show we learned that G150914 was a BBH merger. **This type of search is a template for future GW events, specifically those likely to be a CC event.**

EVENT #2 – GW151226



ANALYSIS 3

Search for a decaying transient (Cowperthwaite et al. 2016)



36 square degrees observed
(28.8 if considering fill-factor)

4 epochs (last one is template)

4 "candidates" (3 AGNs, 1 SN)

Pre-existing templates would have helped reject those.
It is really important to have pre-existing templates!

Rising portion of light curve helps too.
Need to observe ASAP after a trigger!

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

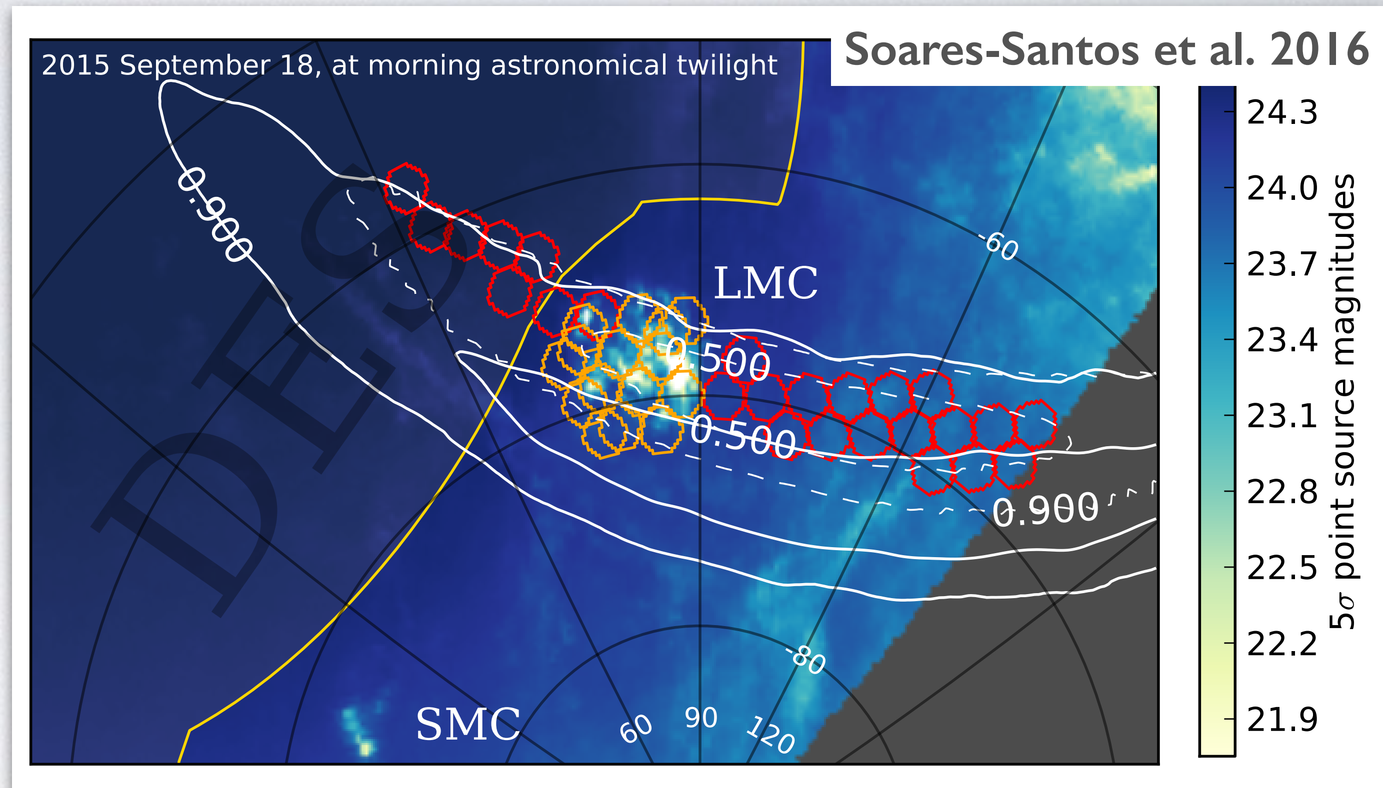
A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

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

Funding:

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

Potentially a new cosmological probe!



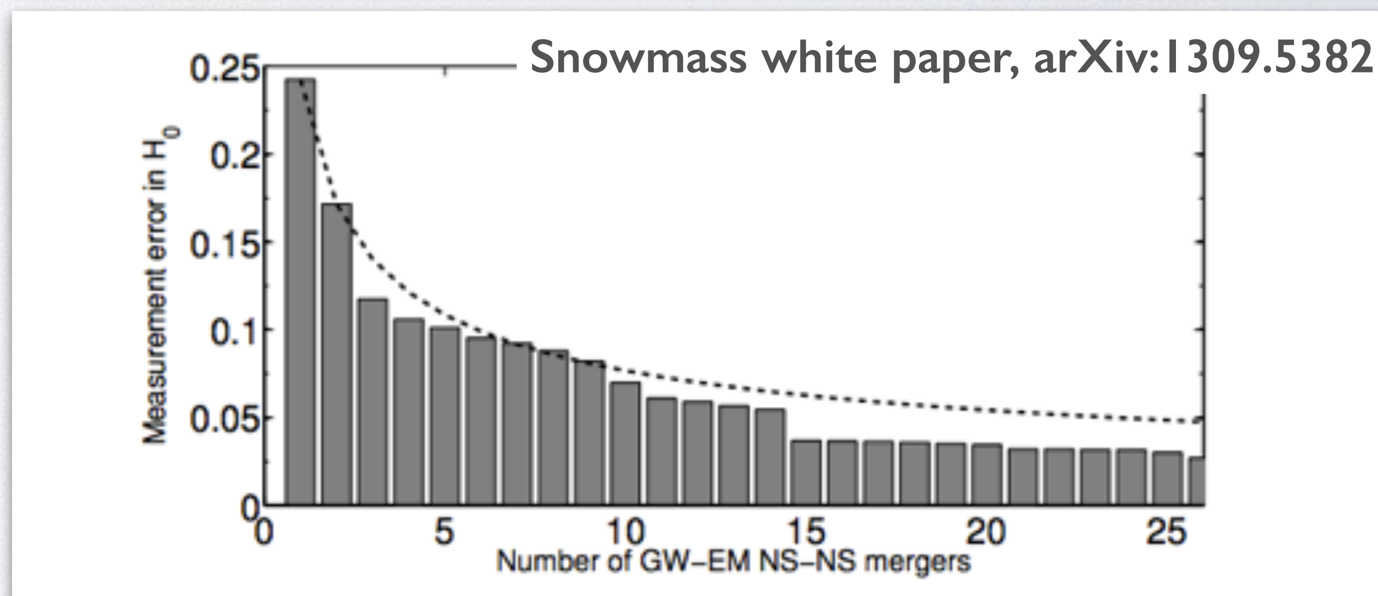
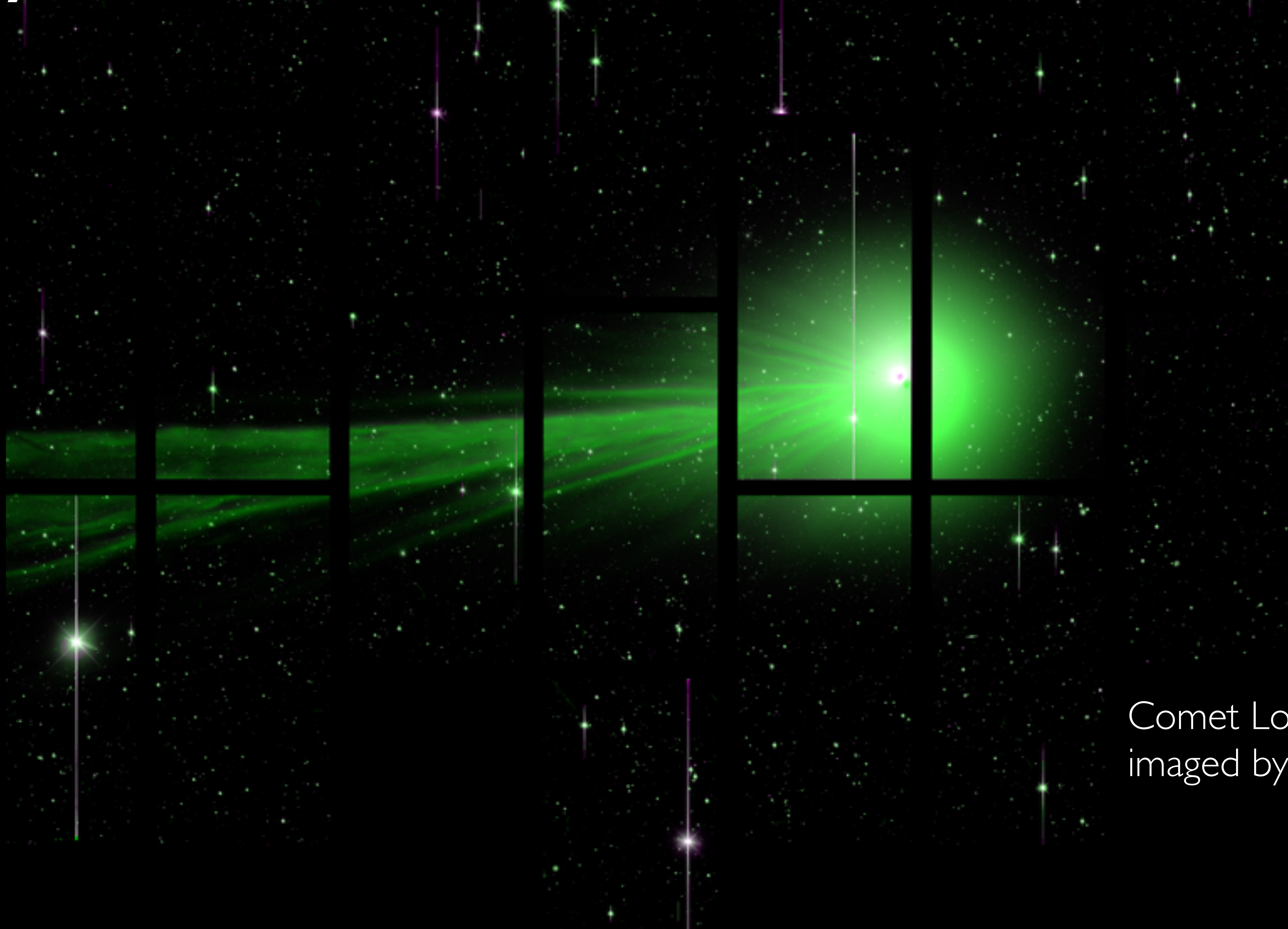


Figure 8: H_0 measurement uncertainty as a function of the number of multi-messenger (GW+EM) double neutron star merger events observed by an advanced LIGO-Virgo network. The dashed line shows Gaussian convergence.

These are exciting times for science with the **Dark Energy Survey** and **Gravitational Waves**. Last season was a blast!



Comet Lovejoy as imaged by DES.

We are now preparing for a second observing run. Stay tuned for exciting results coming soon!