

SEARCHES FOR OPTICAL SIGNATURES OF GRAVITATIONAL WAVE EVENTS IN THE DARK ENERGY SURVEY

Marcelle Soares-Santos

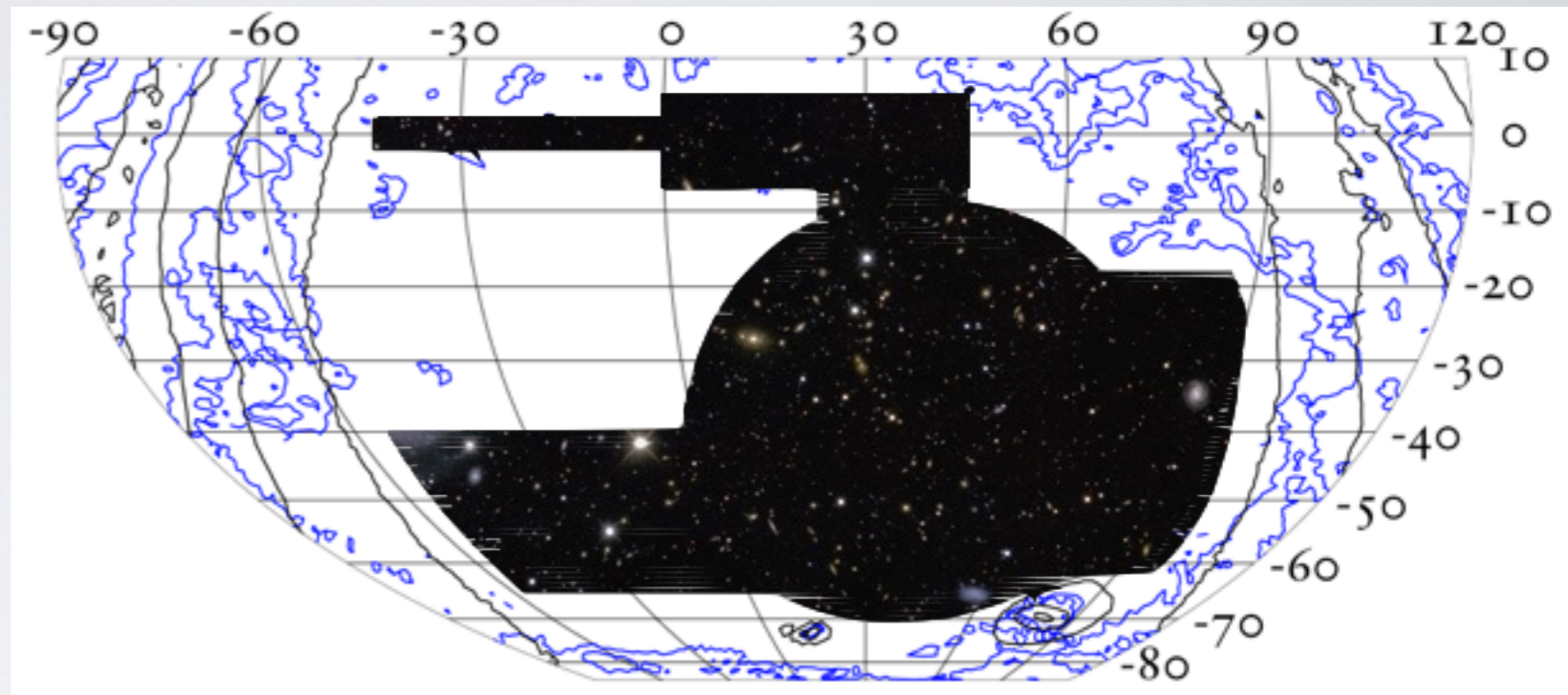
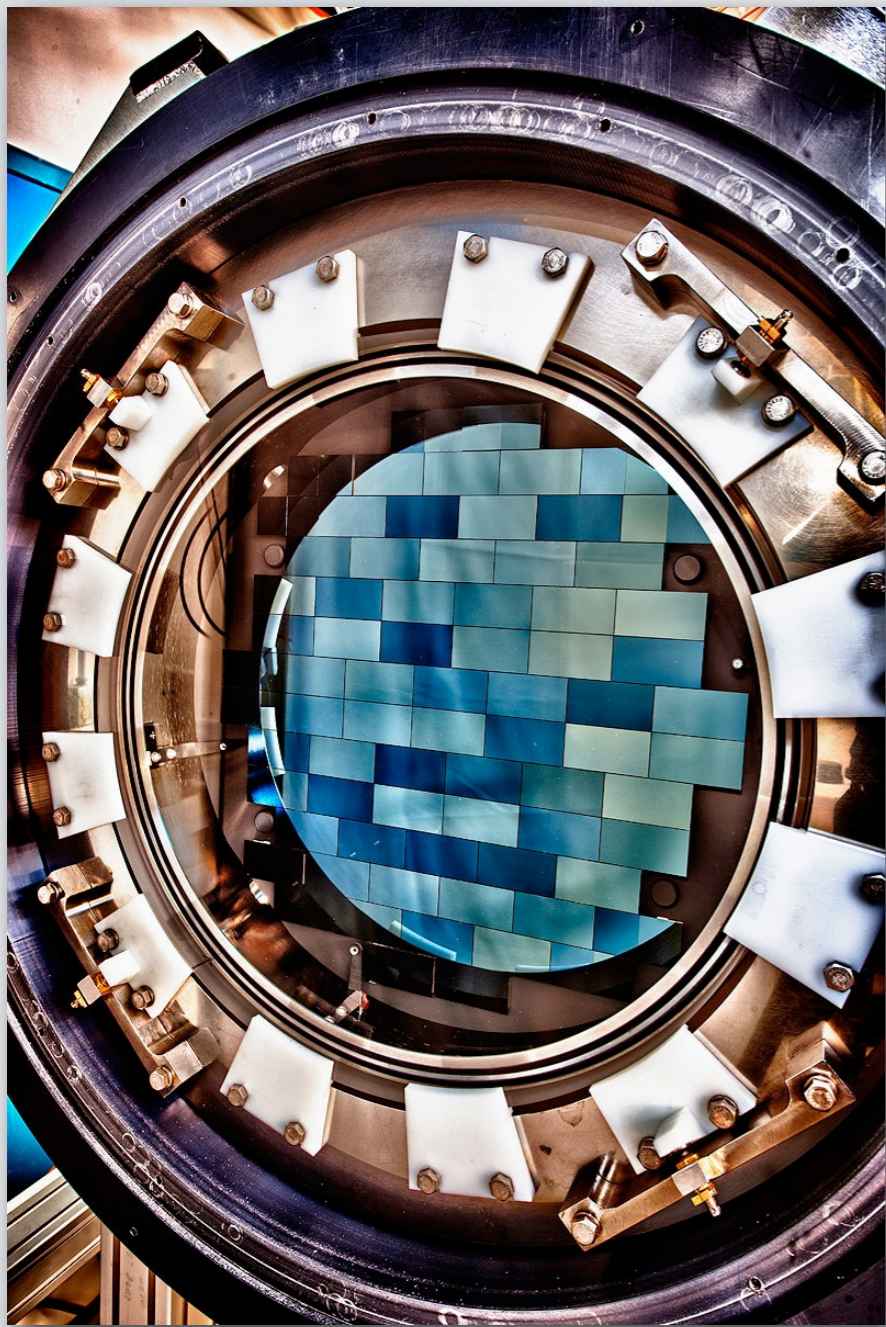
Fermilab

DES Collaboration

Site of DES,
in Chile.

THE DARK ENERGY SURVEY

300+ collaborators, 70+ publications
in this talk: 3 DESGW papers



DECam

3 sq deg FOV

570 Mpix optical camera

Facility instrument at
CTIO Blanco 4-m
telescope in Chile

First light: Sep 2012

Survey

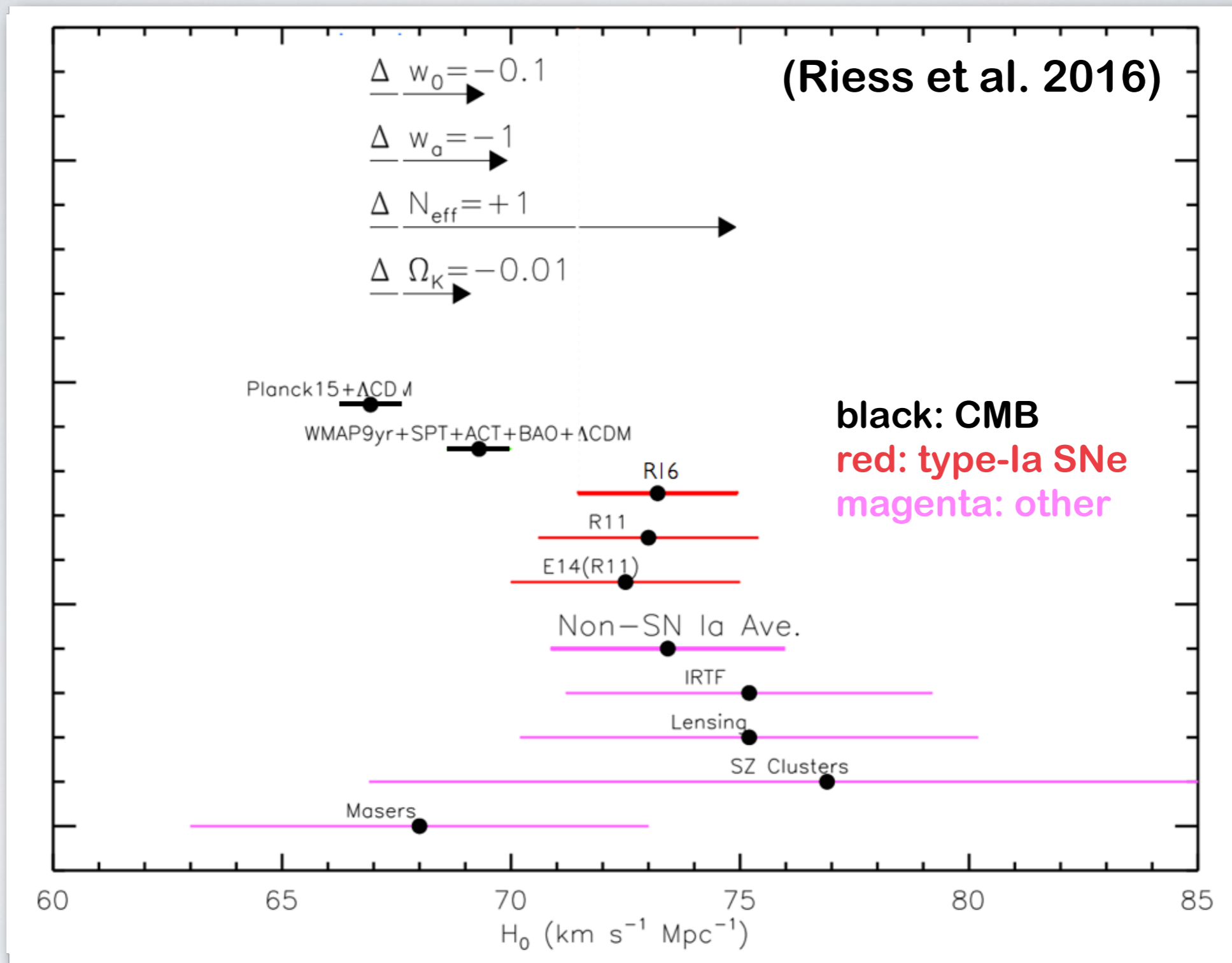
5000 sq deg grizY to 24th mag

0.9 arcseconds seeing

30 sq deg SNe survey

525 nights: 2013-2018

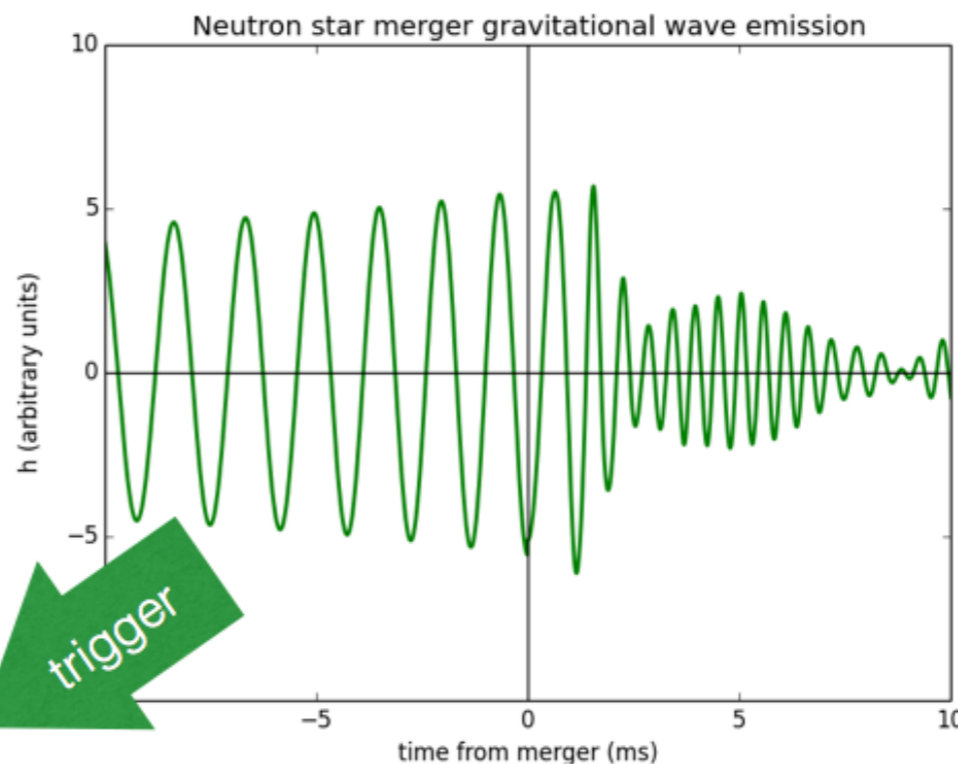
SYSTEMATICS OR NEW PHYSICS?



STANDARD SIRENS



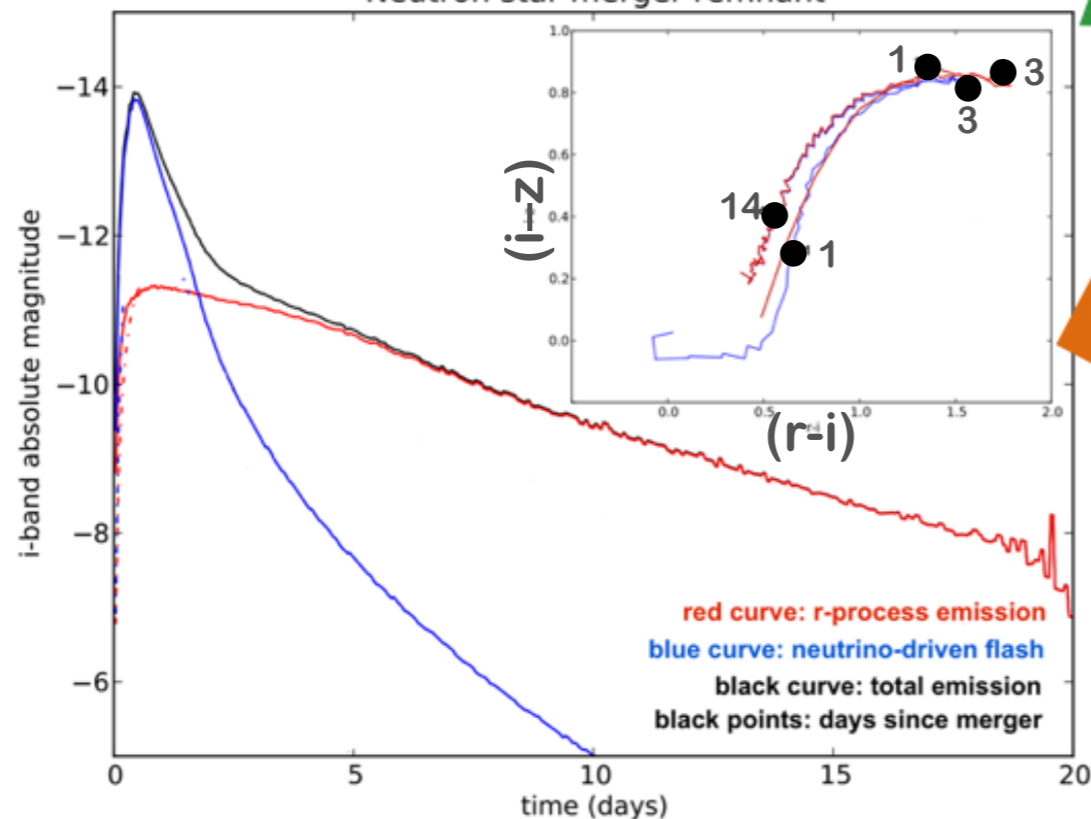
LIGO/Virgo



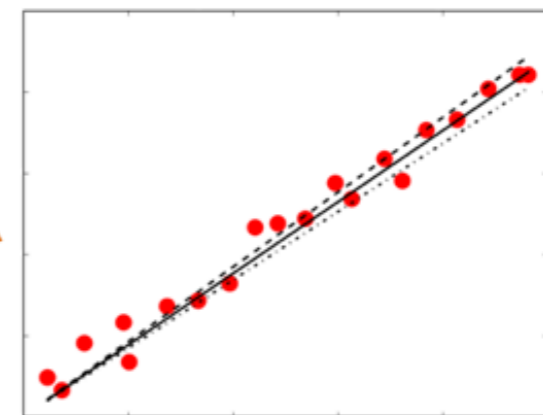
trigger

DES/DECaM

Neutron star merger remnant



cosmology

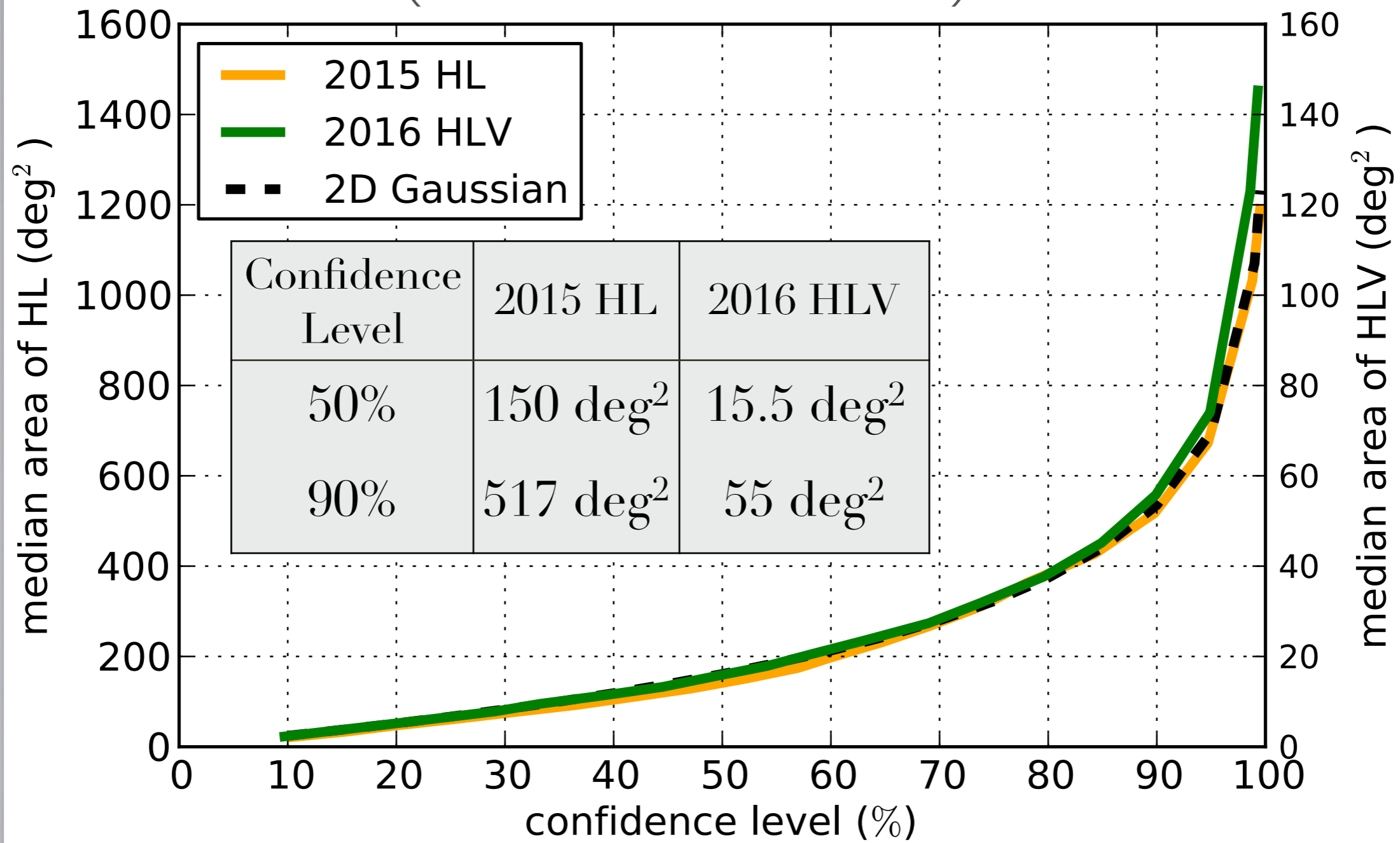


distance

redshift

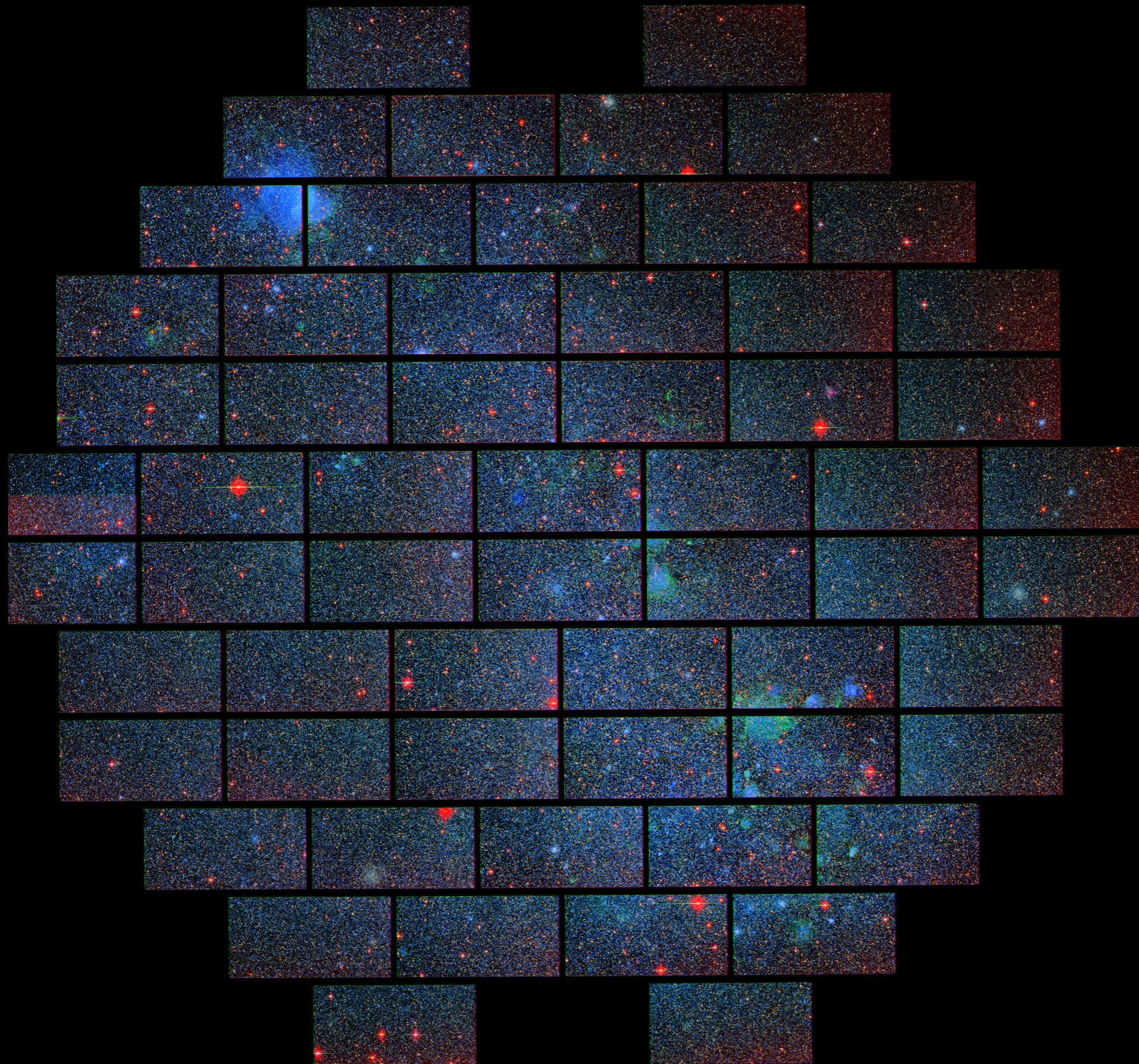
CHALLENGING SEARCH AREAS

(Chen & Holz 2015)



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

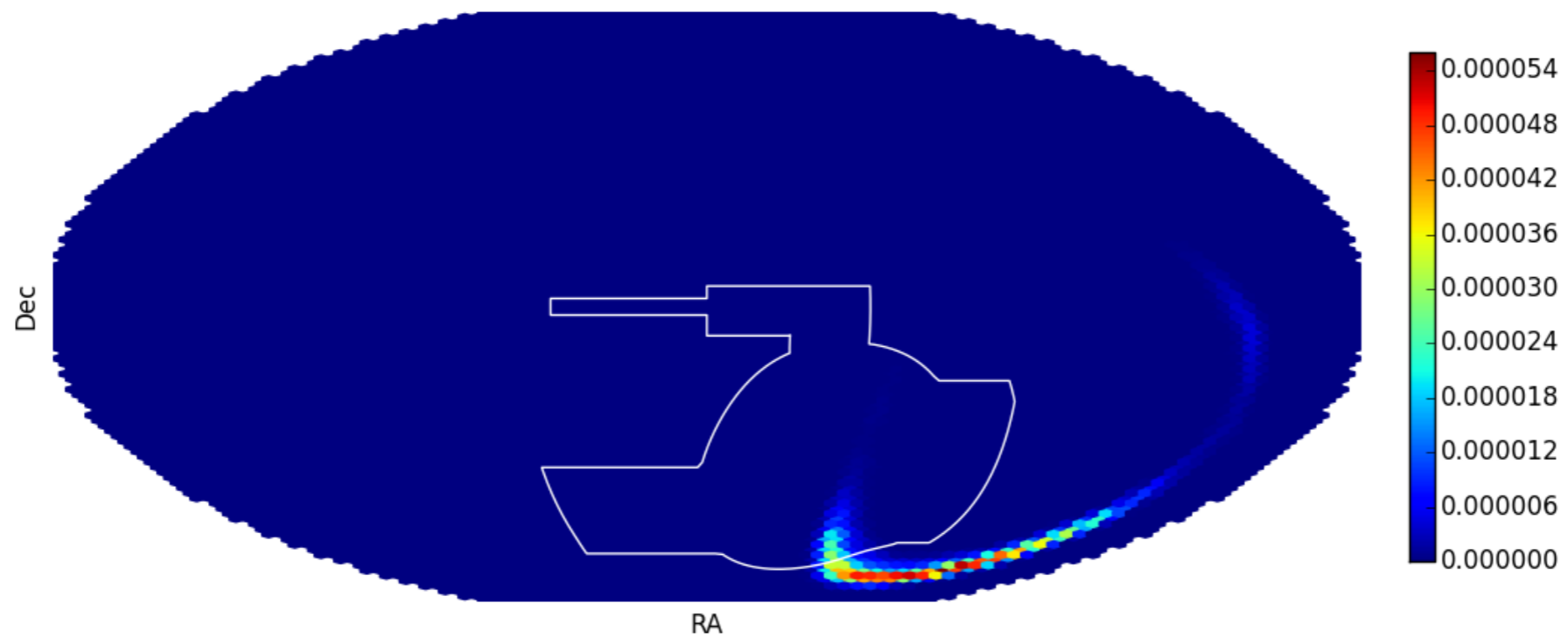
GW150914

Time: Sep 14, 2015 09:50:41

FAR: 1/203k yr

Distance: 410Mpc

Type: BBH merger

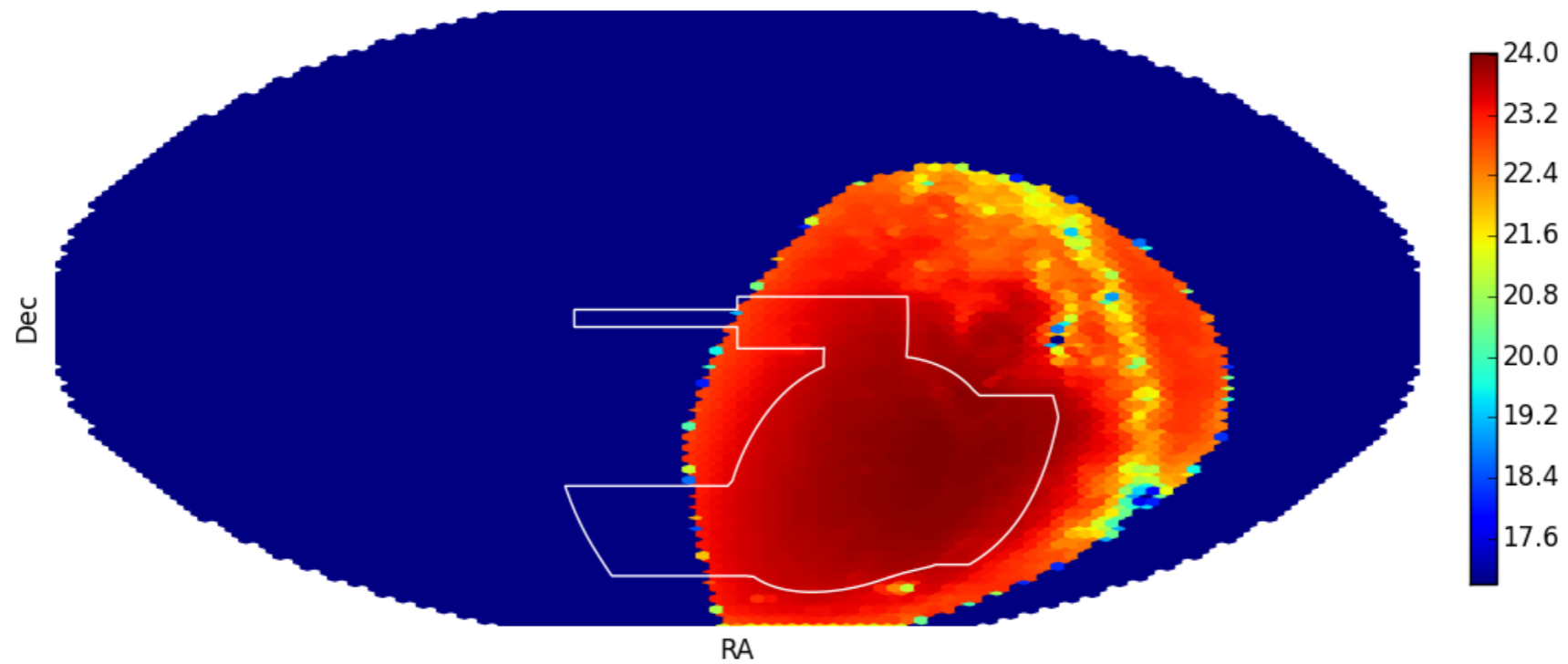


LVC sky localization probability map (final)

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)

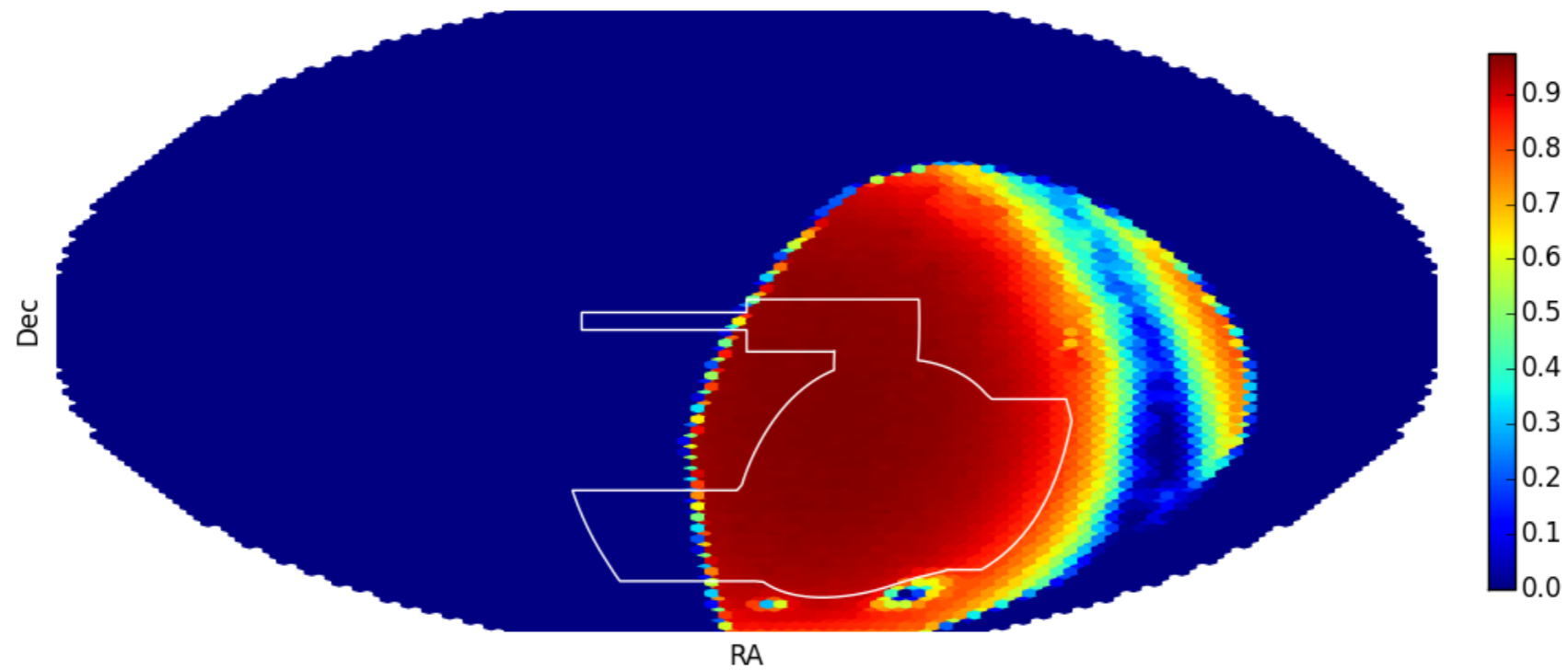


DES mag limit model

GW150914

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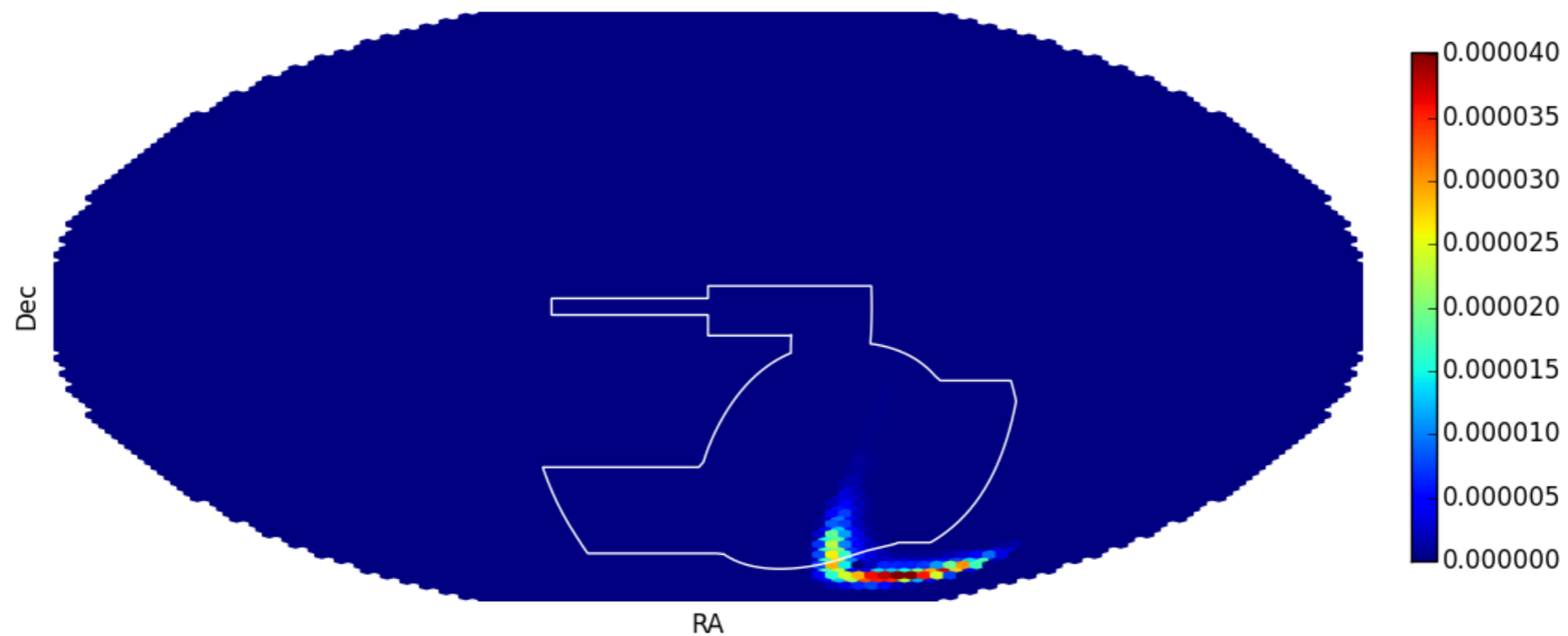


DES source detection probability map

GW150914

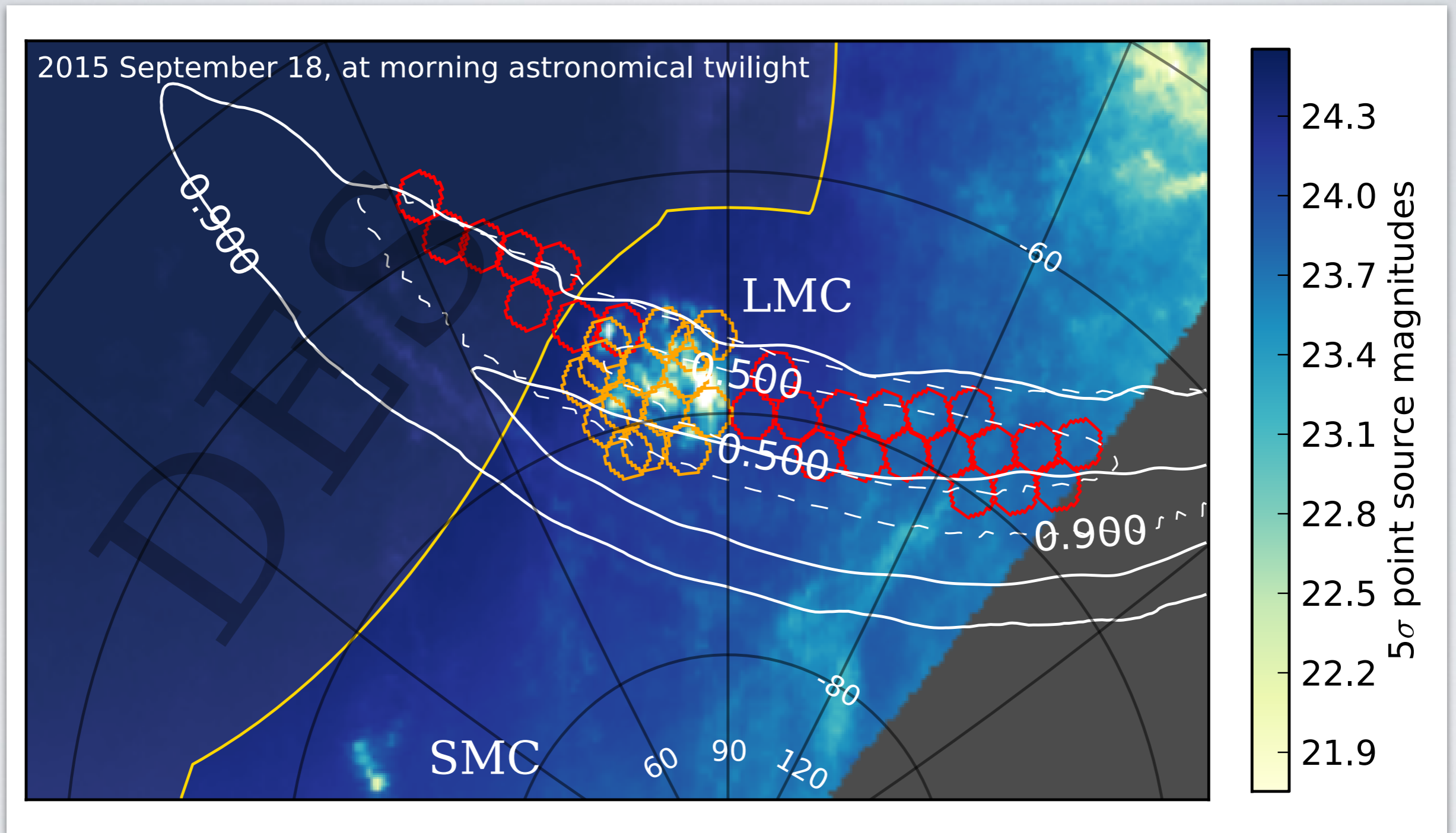
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

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



DESxLIGO source detection probability map

DATA



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: $(i-z) \sim 1$ $i = 21.5$

color: $(i-z) \sim 0$ $i = 21.1$

color: $(i-z) \sim -1$ $i = 20.1$

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.**

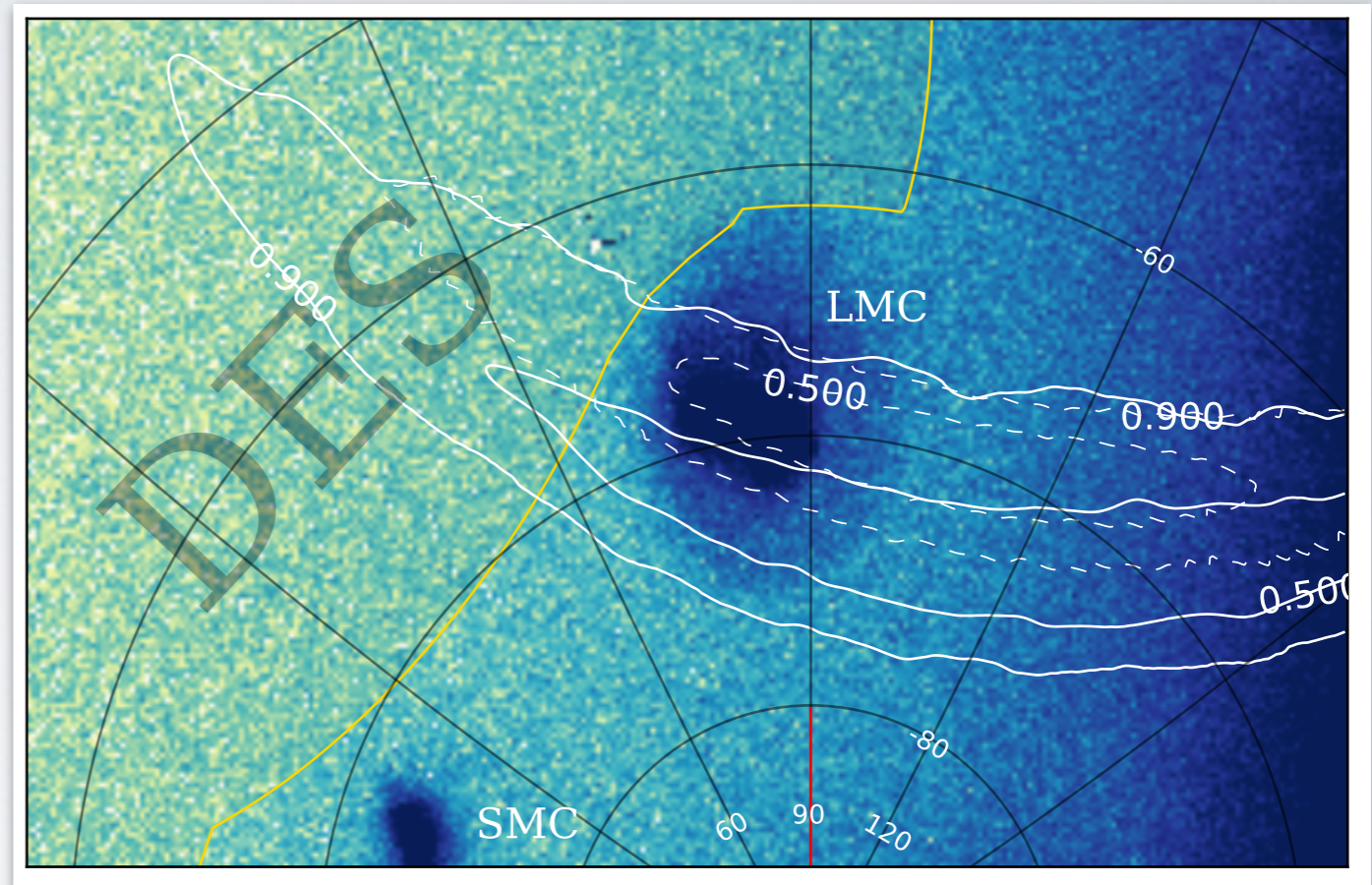
ANALYSIS 2

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?



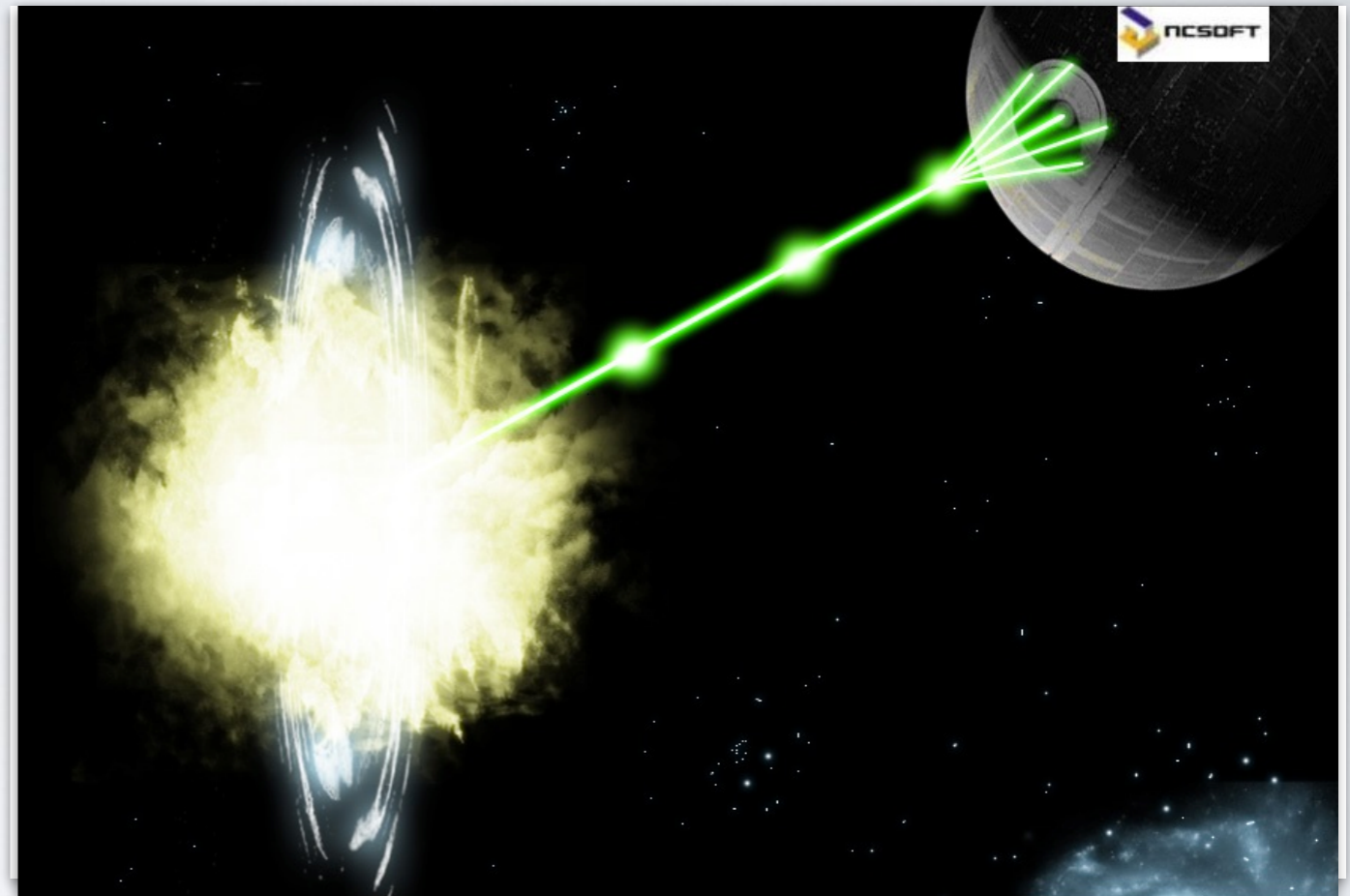
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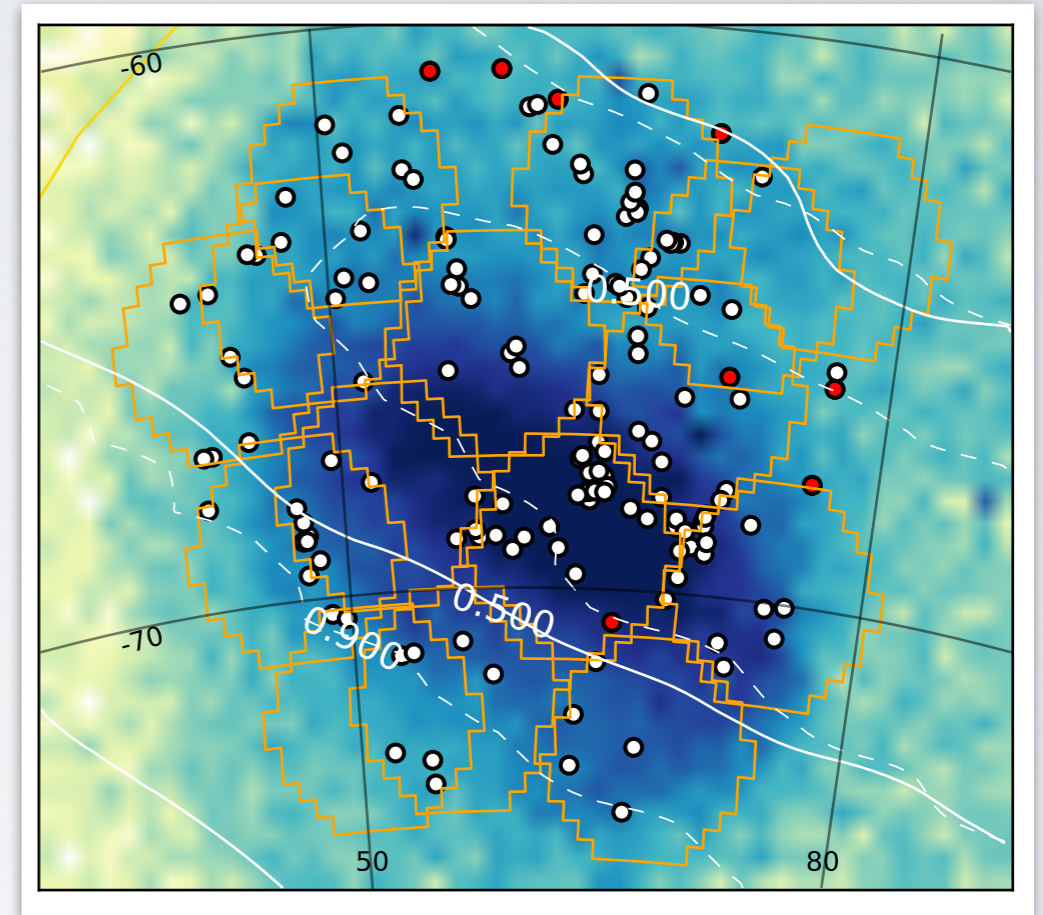
ANALYSIS 2

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

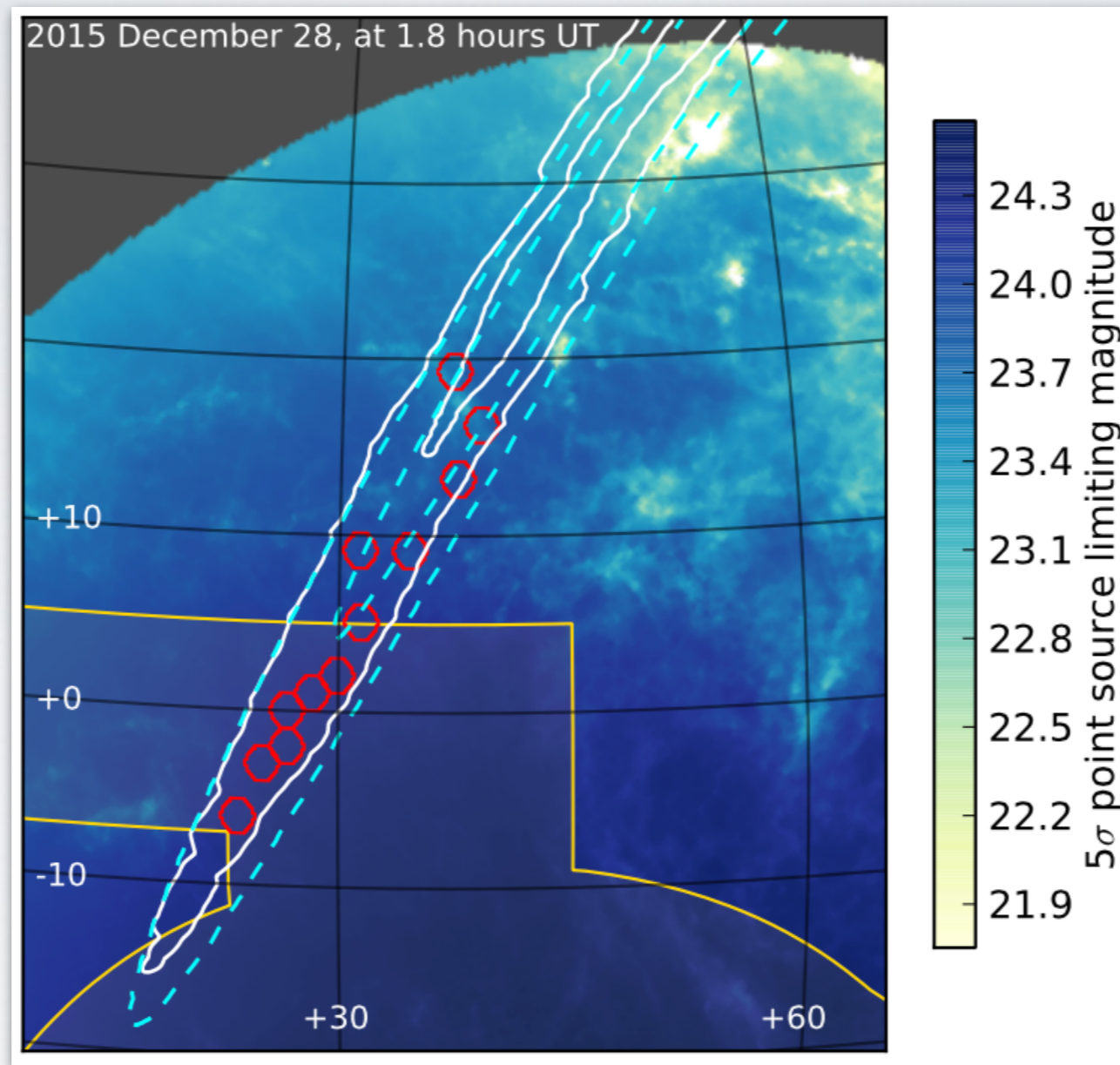
We take possible progenitors (red supergiants) catalogued in the literature, and search for them via visual inspection; all accounted for.

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

We later learned that G150914 was a BBH merger. **This type of search is a template for future GW sources from CC events.**

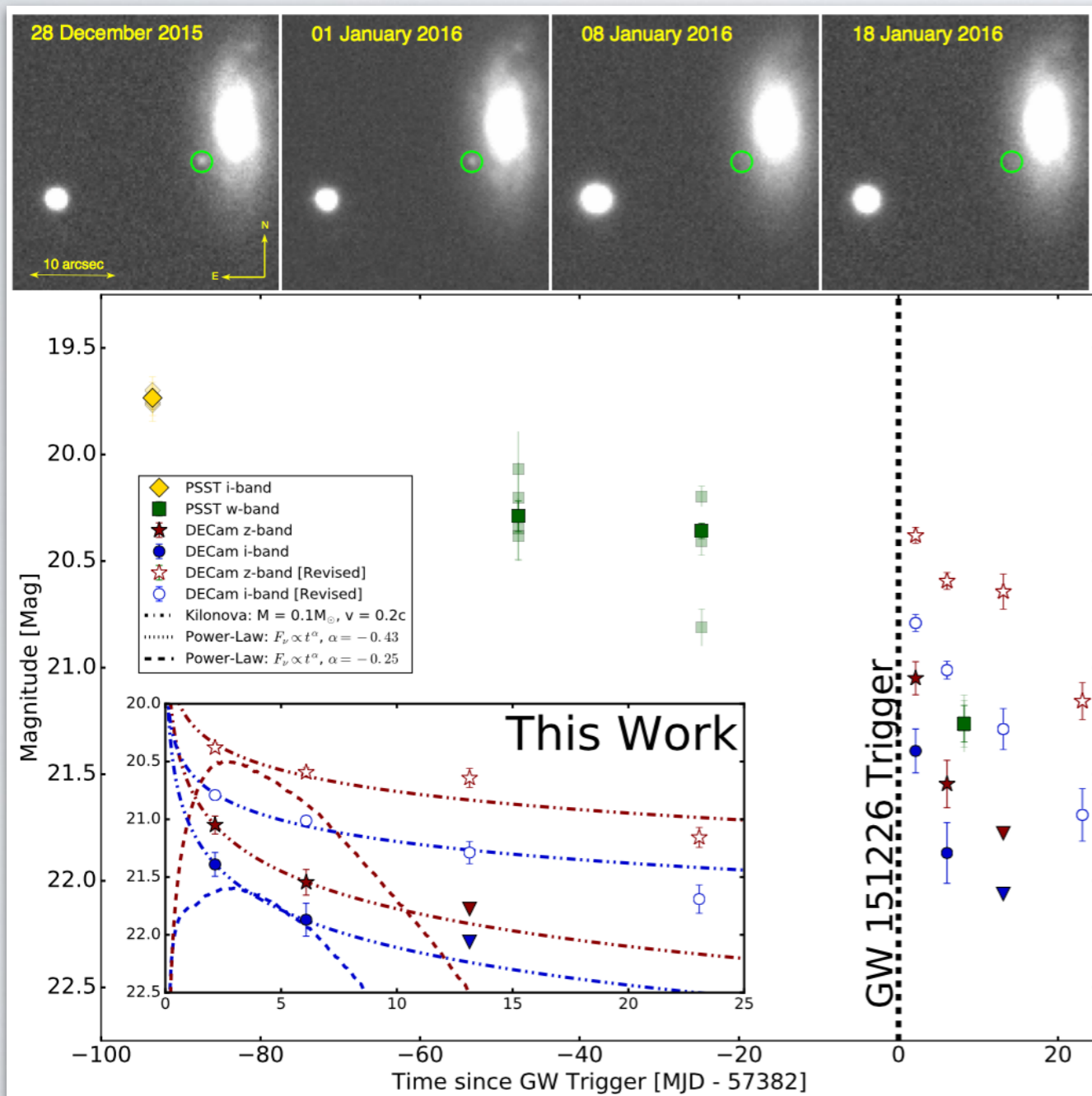


EVENT #2 – GW151226



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; or
Rising portion of light curve
would have helped reject those:

- Need to increase template sample
- Need to observe ASAP after trigger

DESGW 1ST CAMPAIGN RESULTS

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

Cowperthwaite, et al. 2016, ApJL, 826, 29

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

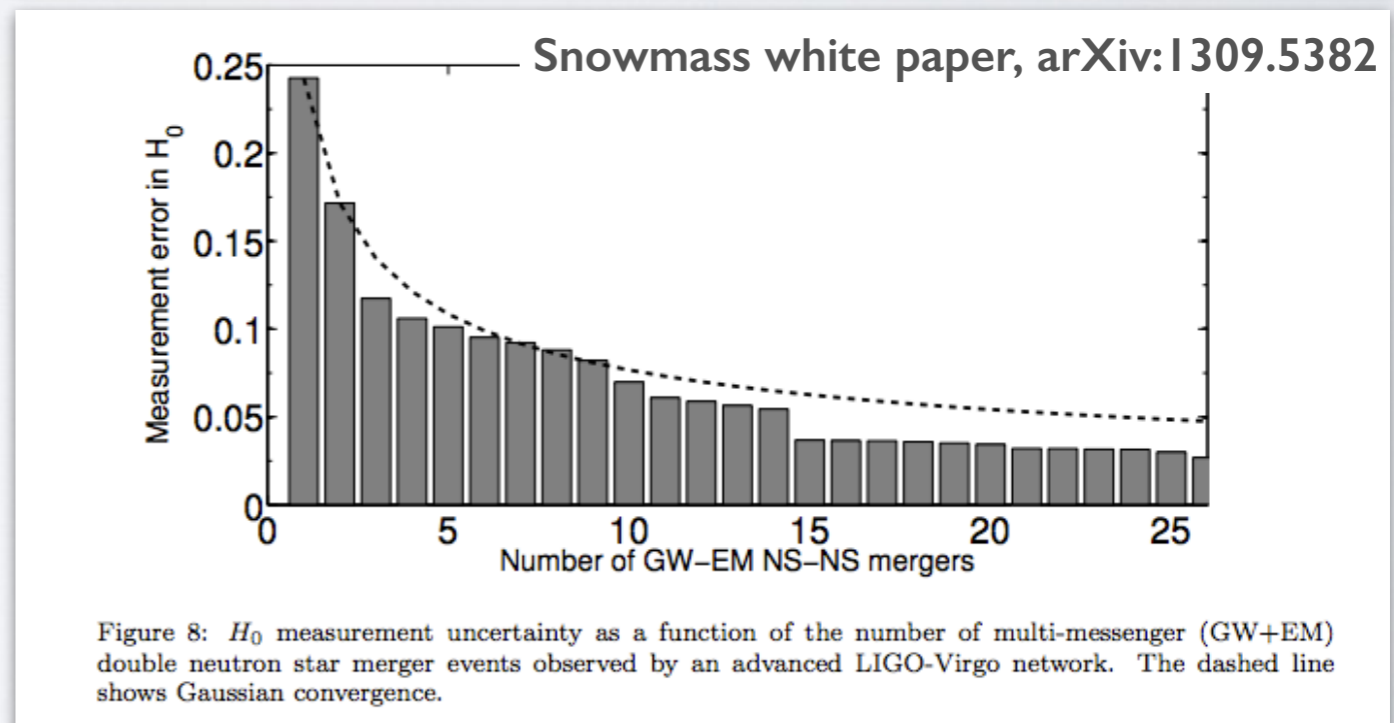
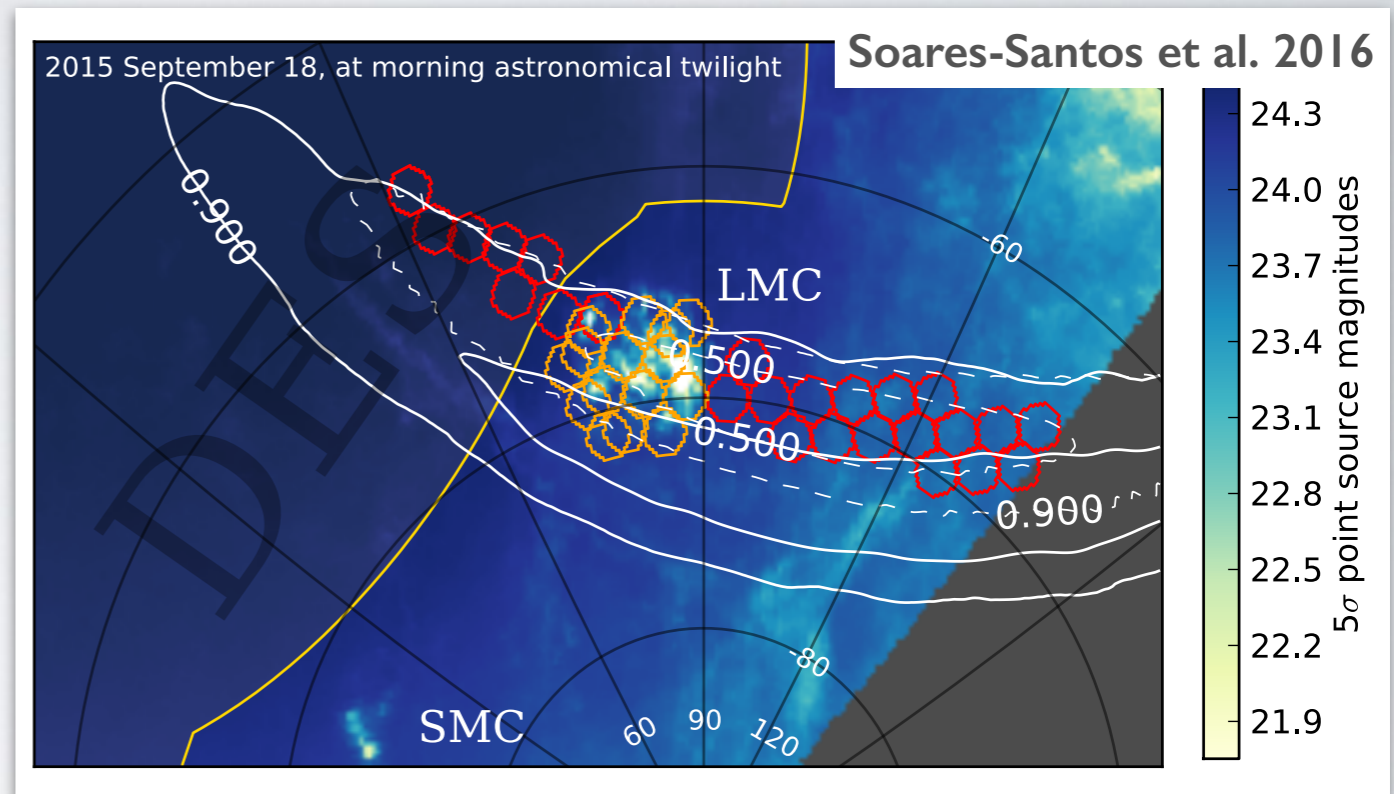
A Dark Energy Camera Search for an Optical Counterpart to the First Advanced LIGO Gravitational Wave Event GW150914

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

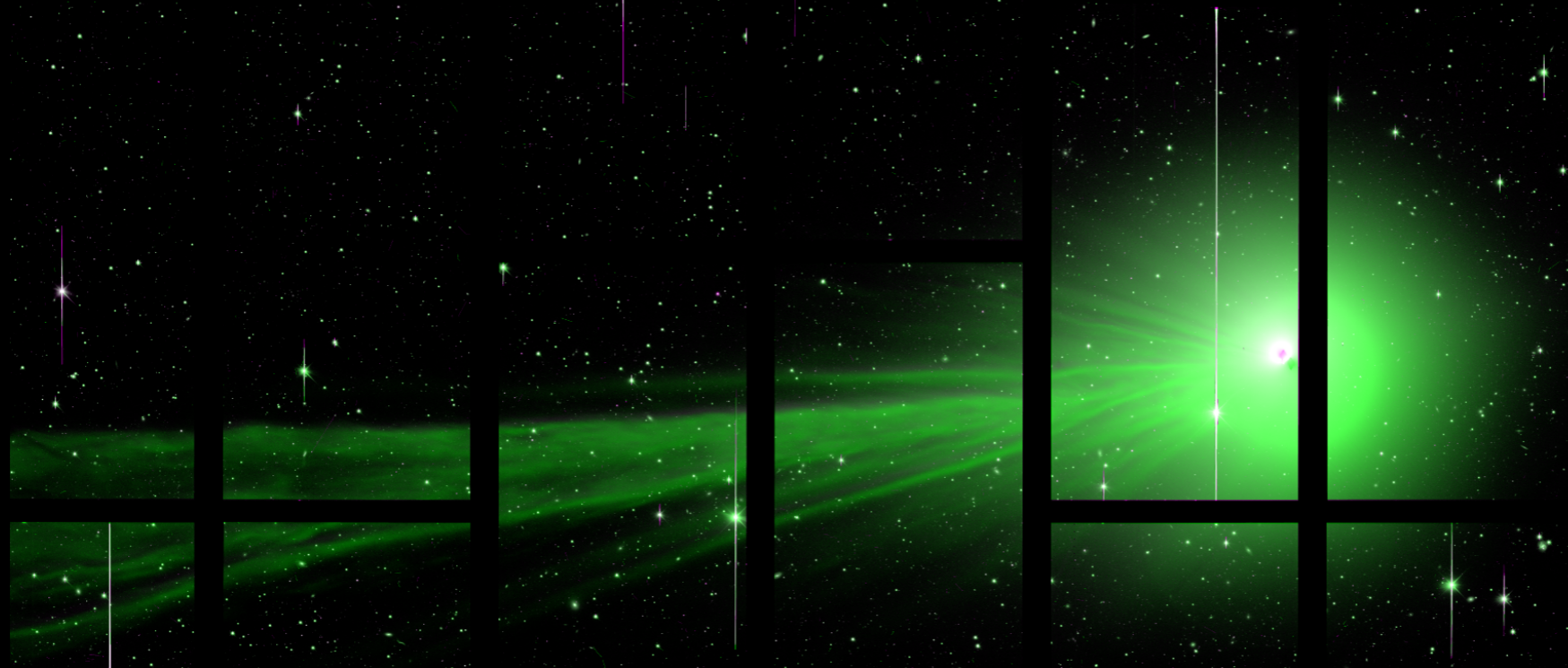
Funding:

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

Potentially a new cosmological probe!



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!

extra slides

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!

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within		
		LIGO	Virgo	LIGO	Virgo		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	

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)	$\langle \text{PSF}(\text{FWHM}_i) \rangle$ (arcsec)	$\langle \text{airmass} \rangle$	$\langle \text{depth}_i \rangle$ (mag)	$\langle \text{depth}_z \rangle$ (mag)	A_{eff}^b (deg ²)
Main, 1 st 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, 2 nd epoch	2015-09-20	57286	6.86	2.17	1.51	22.18	21.48	67.2
Main, 3 rd 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

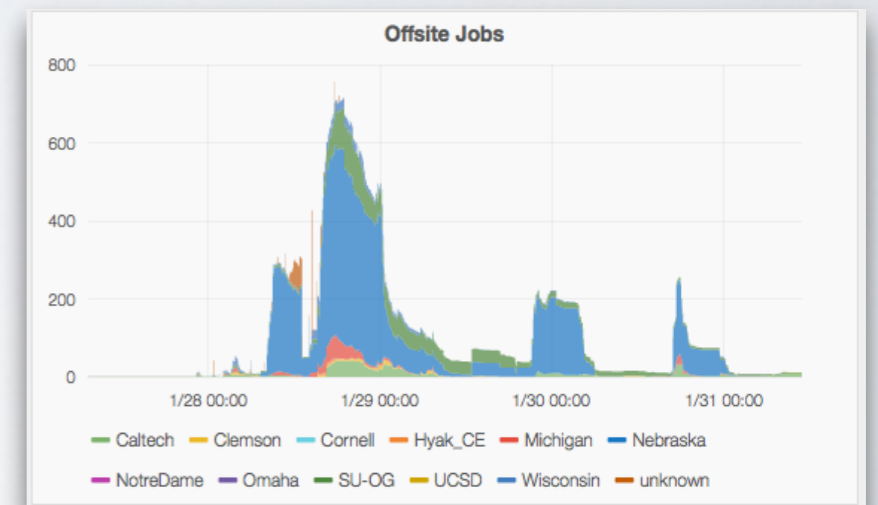
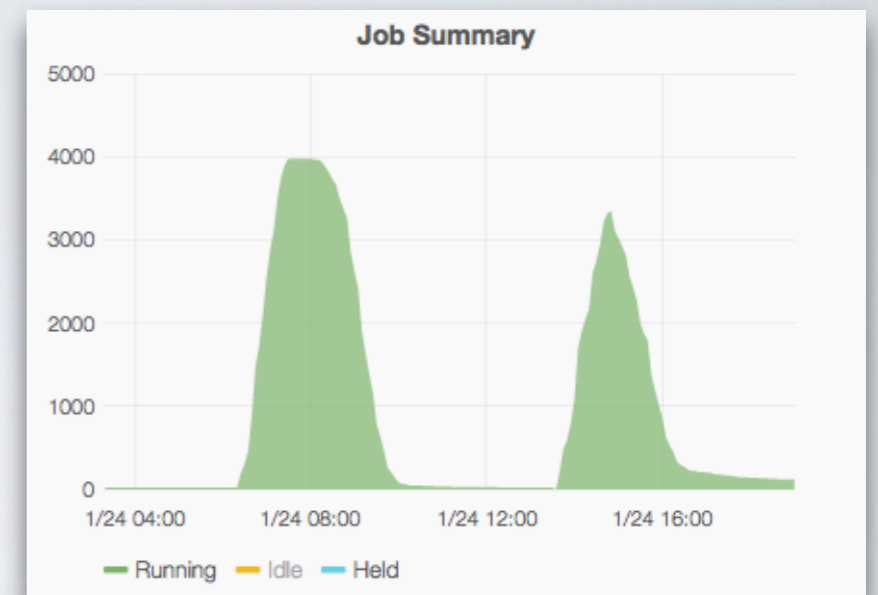
IMAGE PROCESSING

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 (~1 hr/job)

Challenge: raw images to plots in < 24 hrs

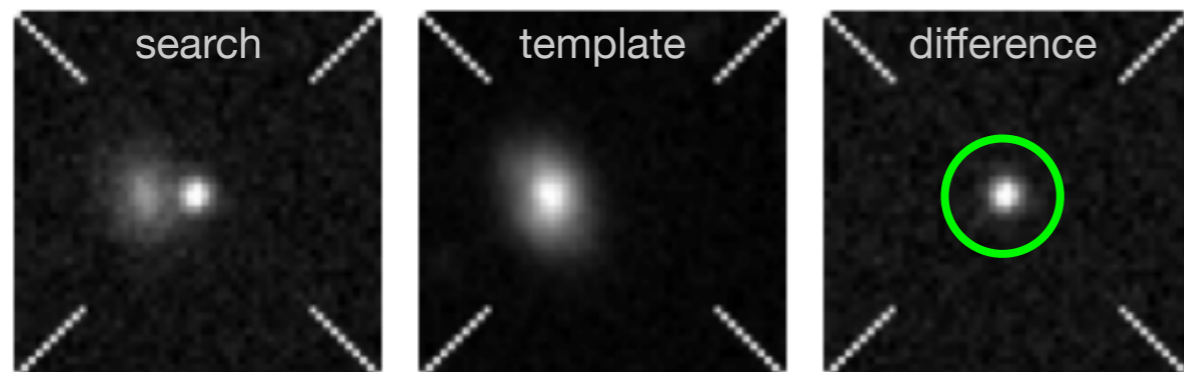
Completely automated job submission immediately after search image available. Able to run dozens of images in parallel using Fermilab and Open Science Grid resources.



<http://fifemon.fnal.gov/>

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

Status of DES SN Survey:

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.

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

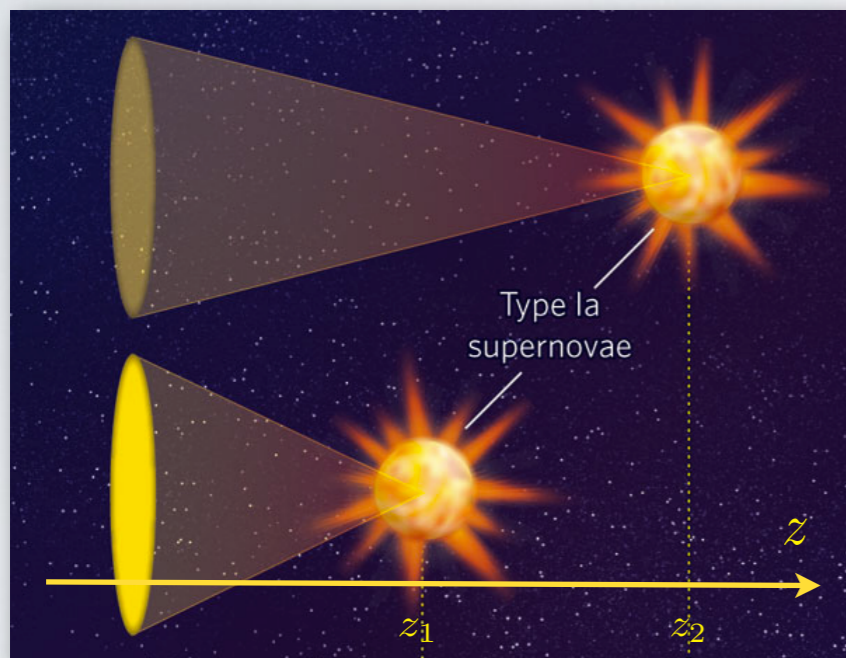
Time of flight experiments (including neutrinos)

Tests of General Relativity

ASTROPHYSICAL OBSERVABLES

Luminosity distance:
standard candle

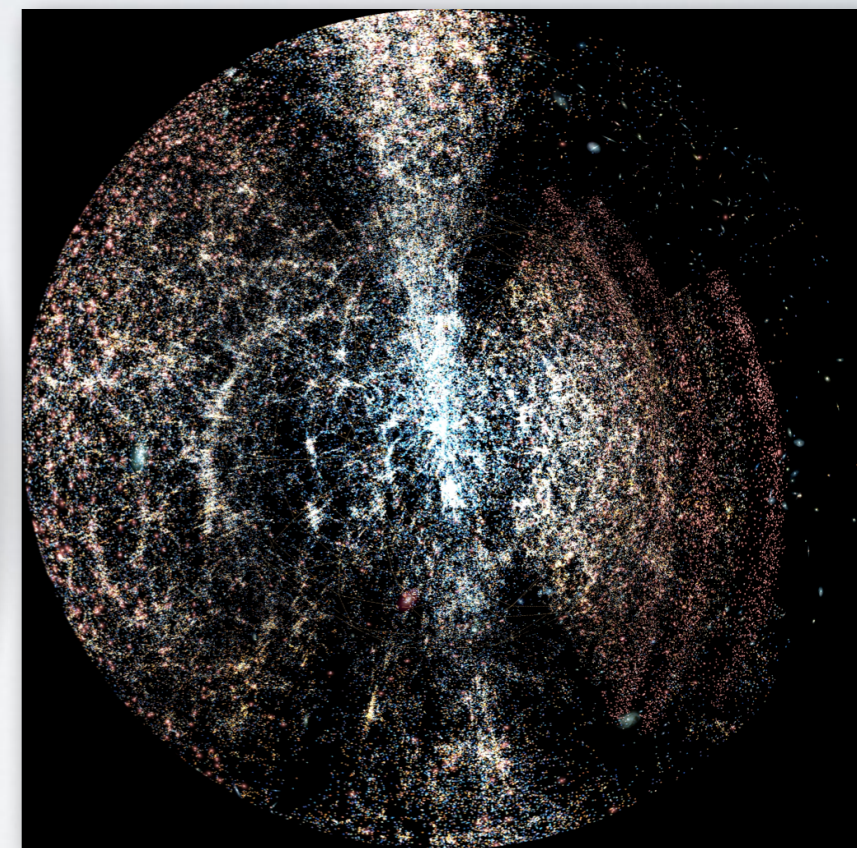
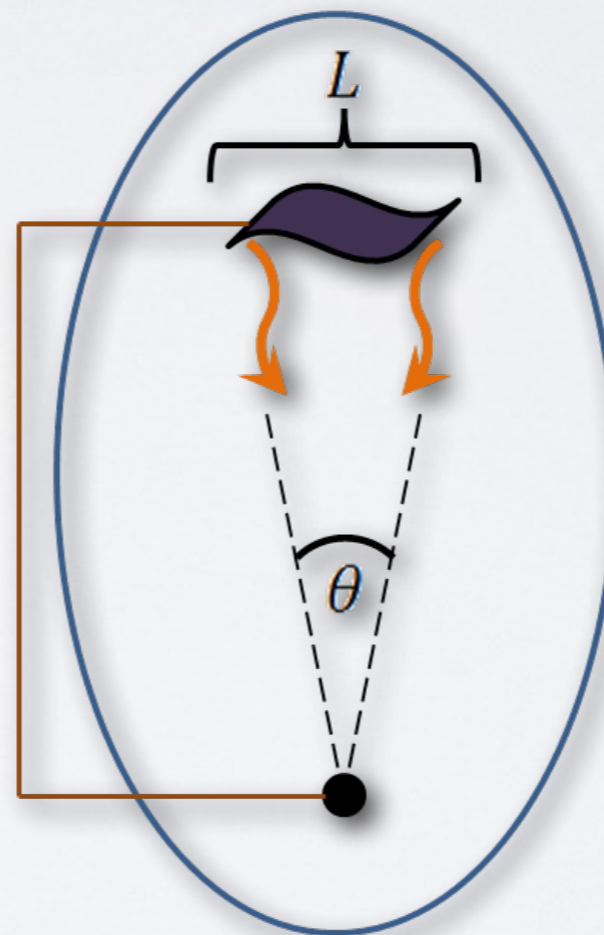
Supernovae (SNe)



Angular diameter distance:
standard ruler

Cosmic microwave background (CMB)

Baryon acoustic oscillations (BAO)



ASTROPHYSICAL OBSERVABLES

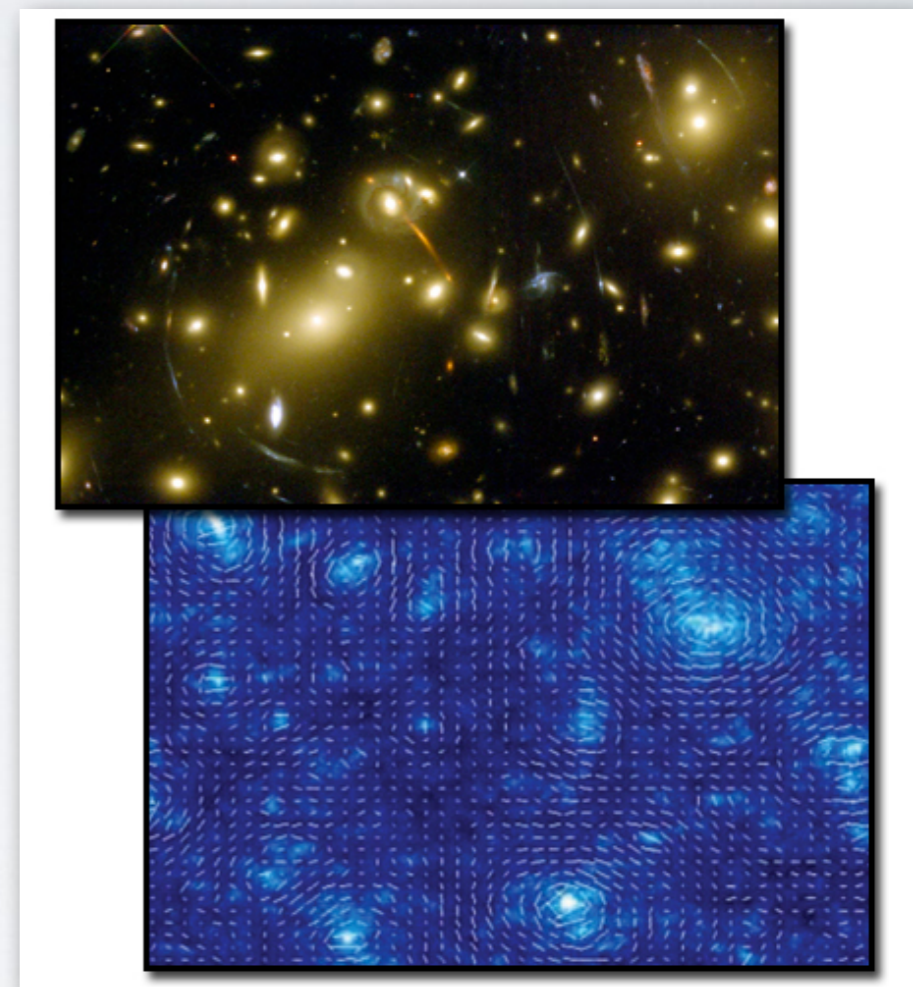
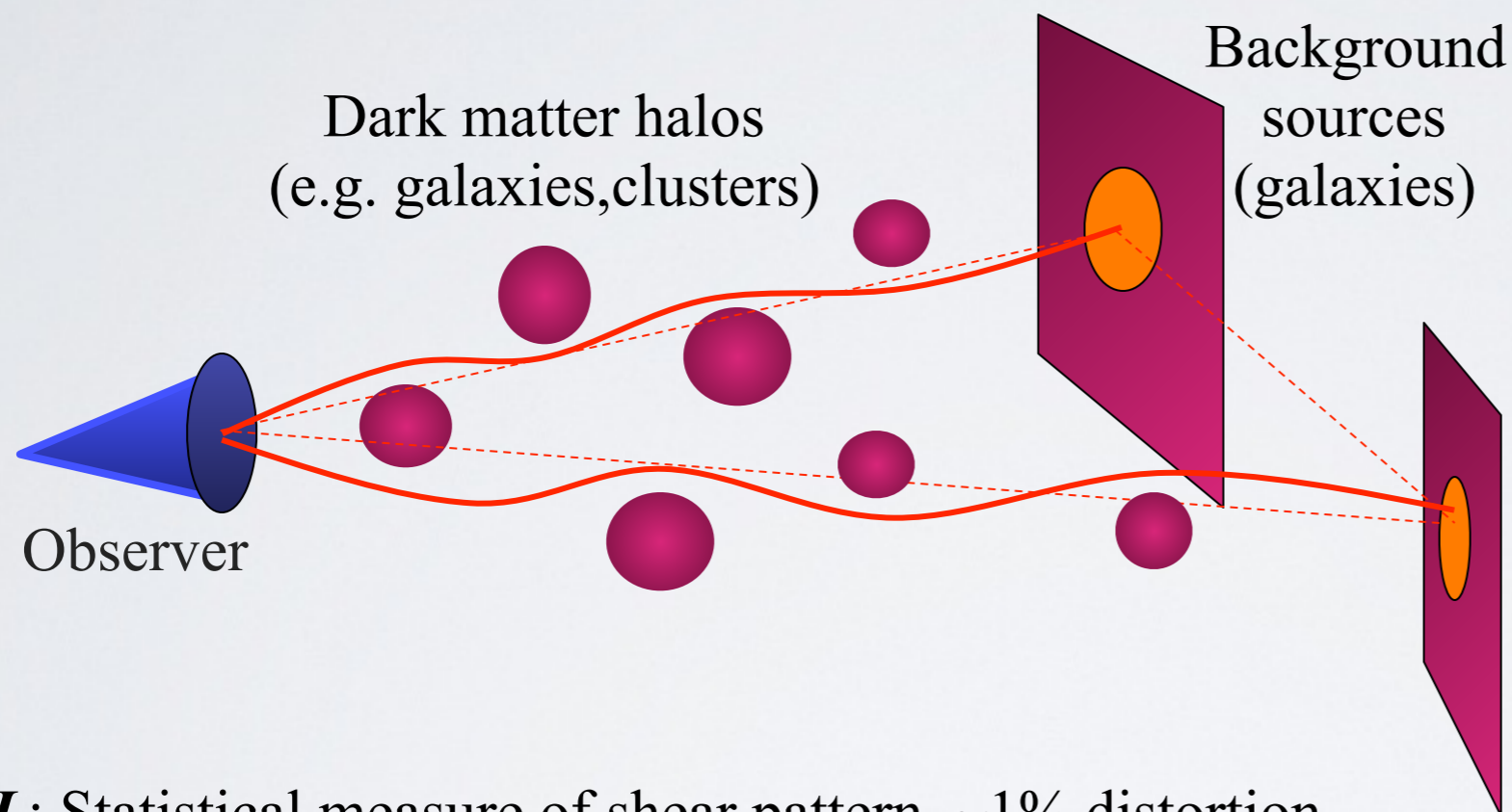
Growth of structure:

Weak gravitational lensing (WL)

Galaxy cluster abundance (Clusters)

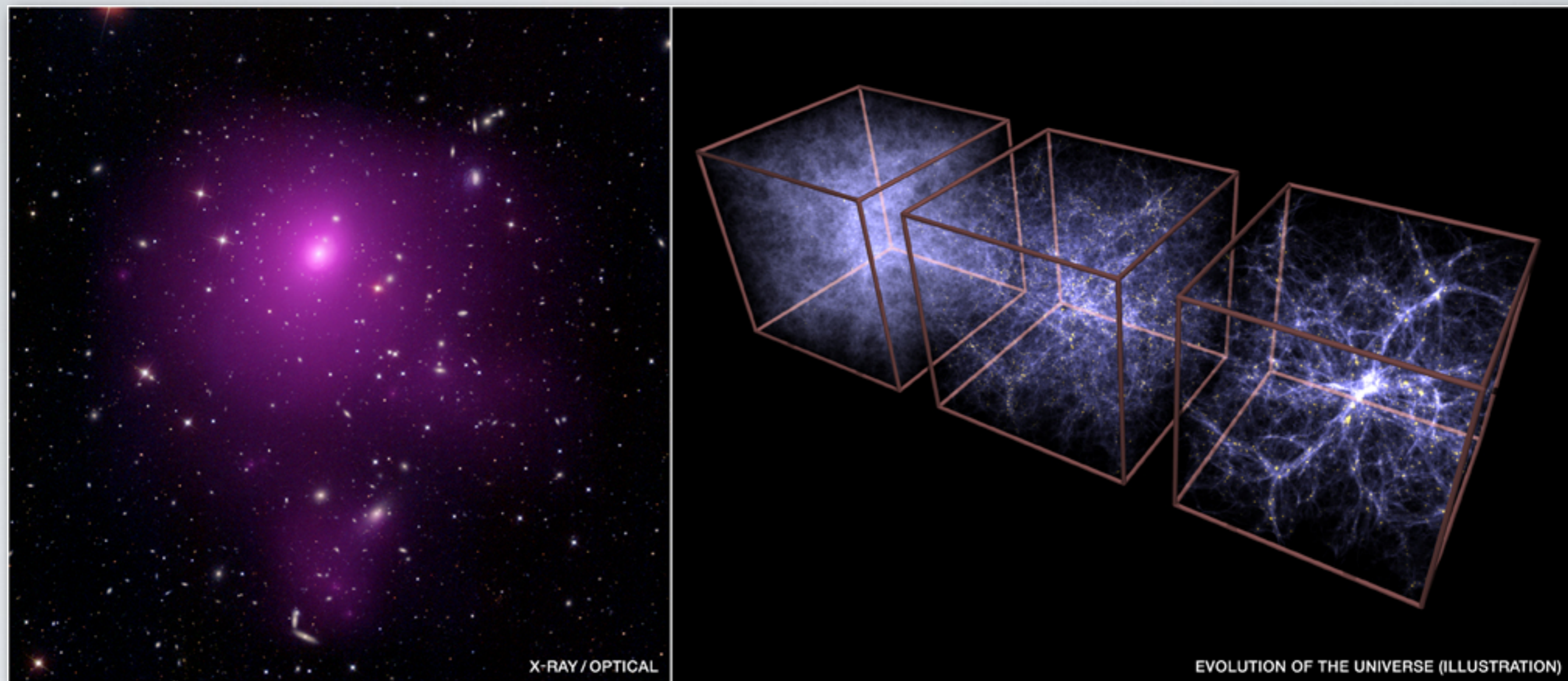
DES is sensitive to
Dark Energy via 4 probes.

WL, Clusters are also sensitive
to angular diameter distance.



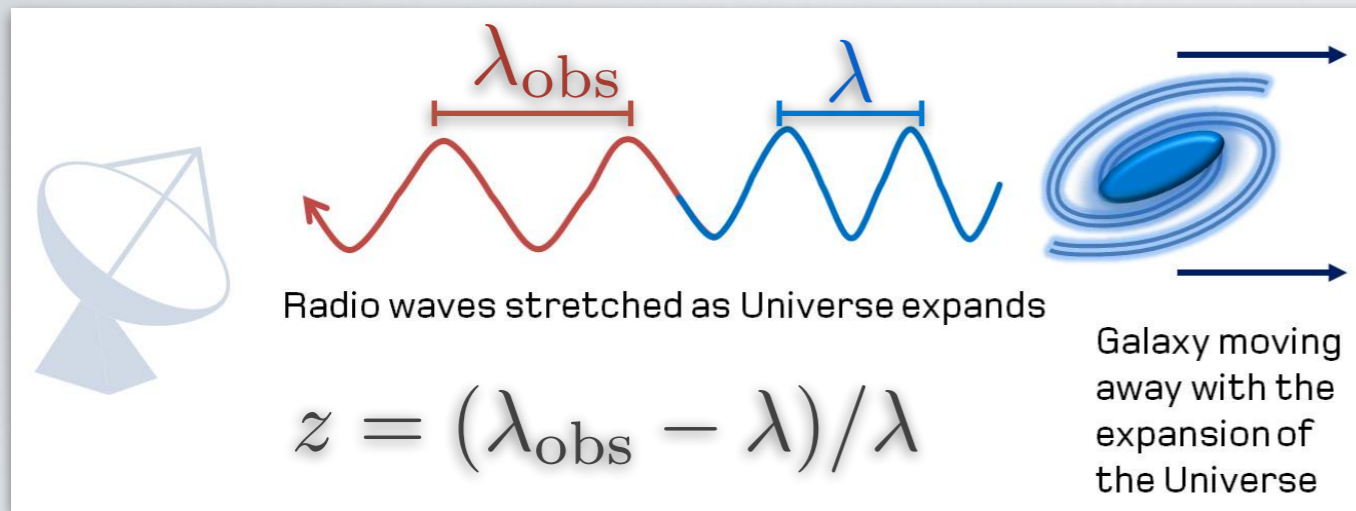
- **WL**: Statistical measure of shear pattern, $\sim 1\%$ distortion
- **Clusters**: Number density vs. Mass vs. redshift
- Radial distances depend on **geometry** of Universe
- Mass distribution depends on **growth** of structure

GROWTH OF STRUCTURE



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

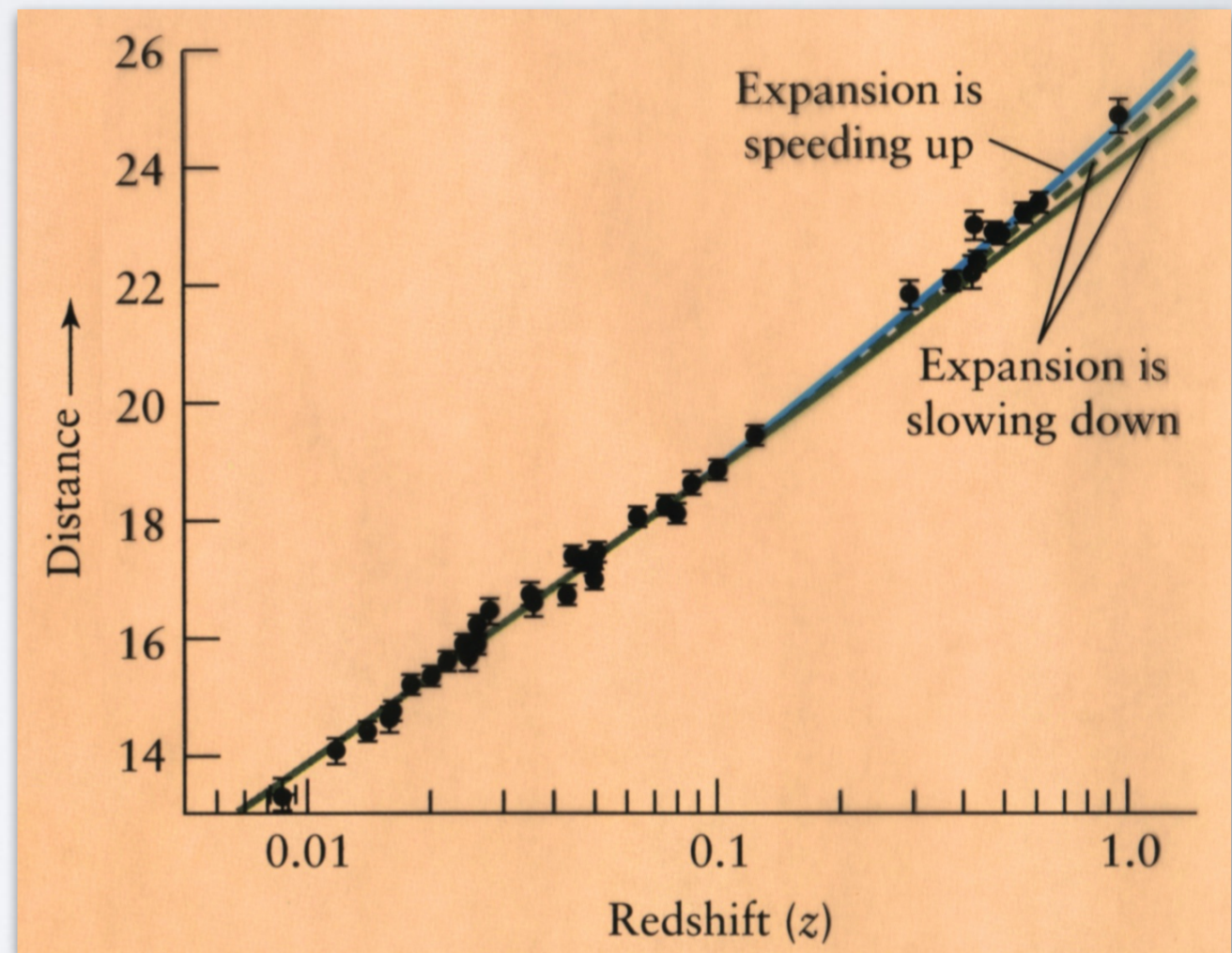
DISTANCE-REDSHIFT RELATION



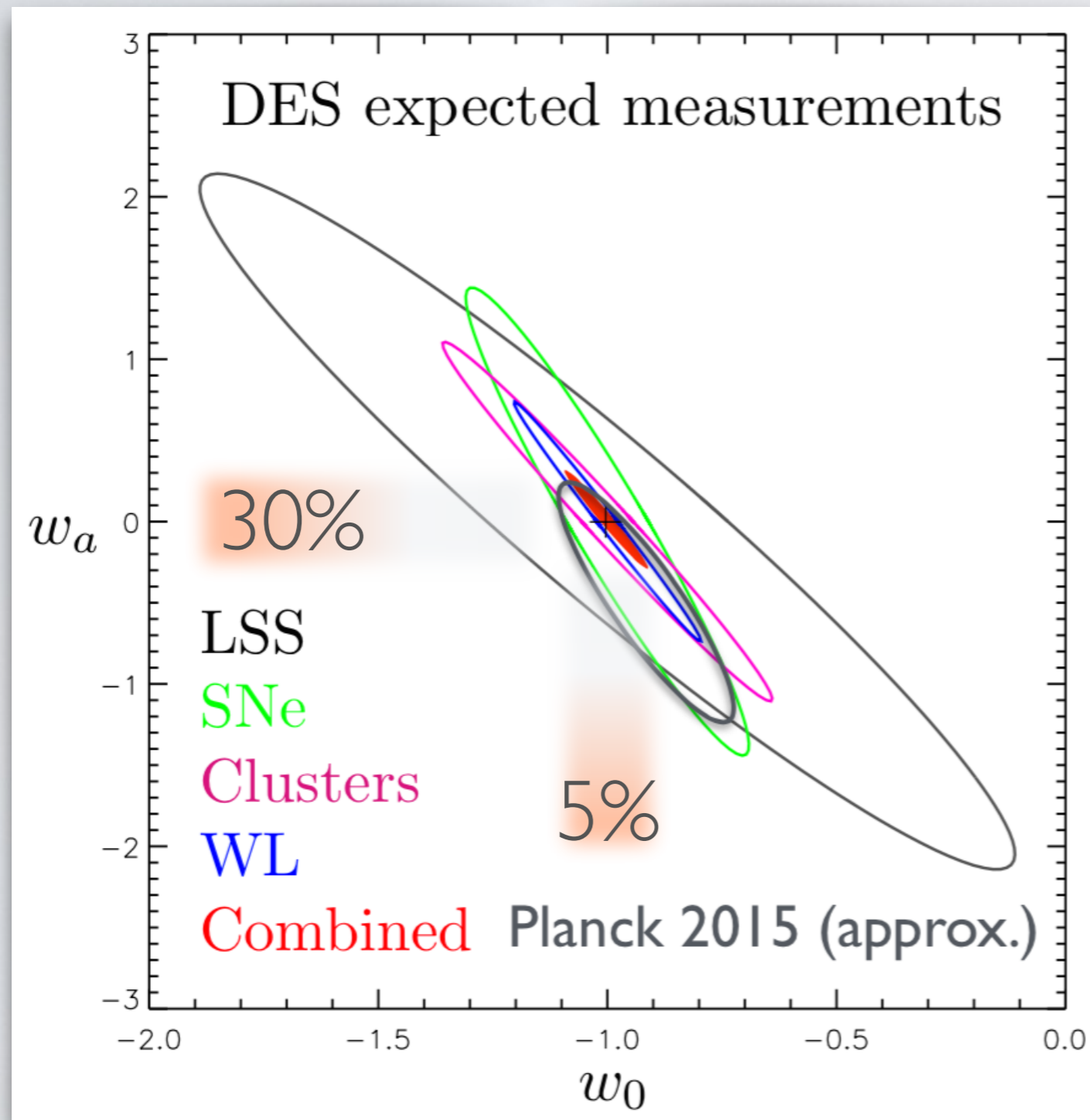
Redshift (z) is an observable effect of the expansion of the Universe.

Faraway sources are more affected than nearby ones.

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



DES PROJECTIONS (5 YEARS)



5000 deg², 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: 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.).

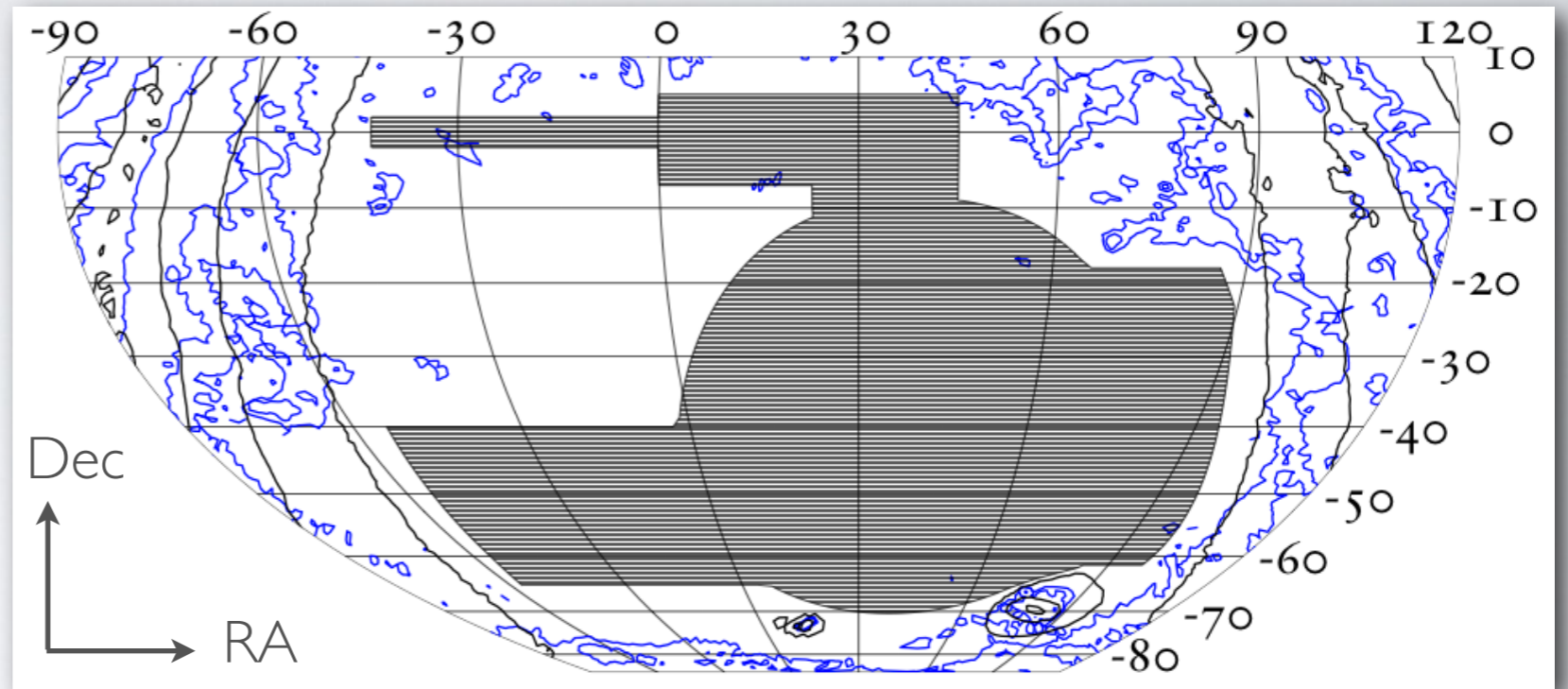
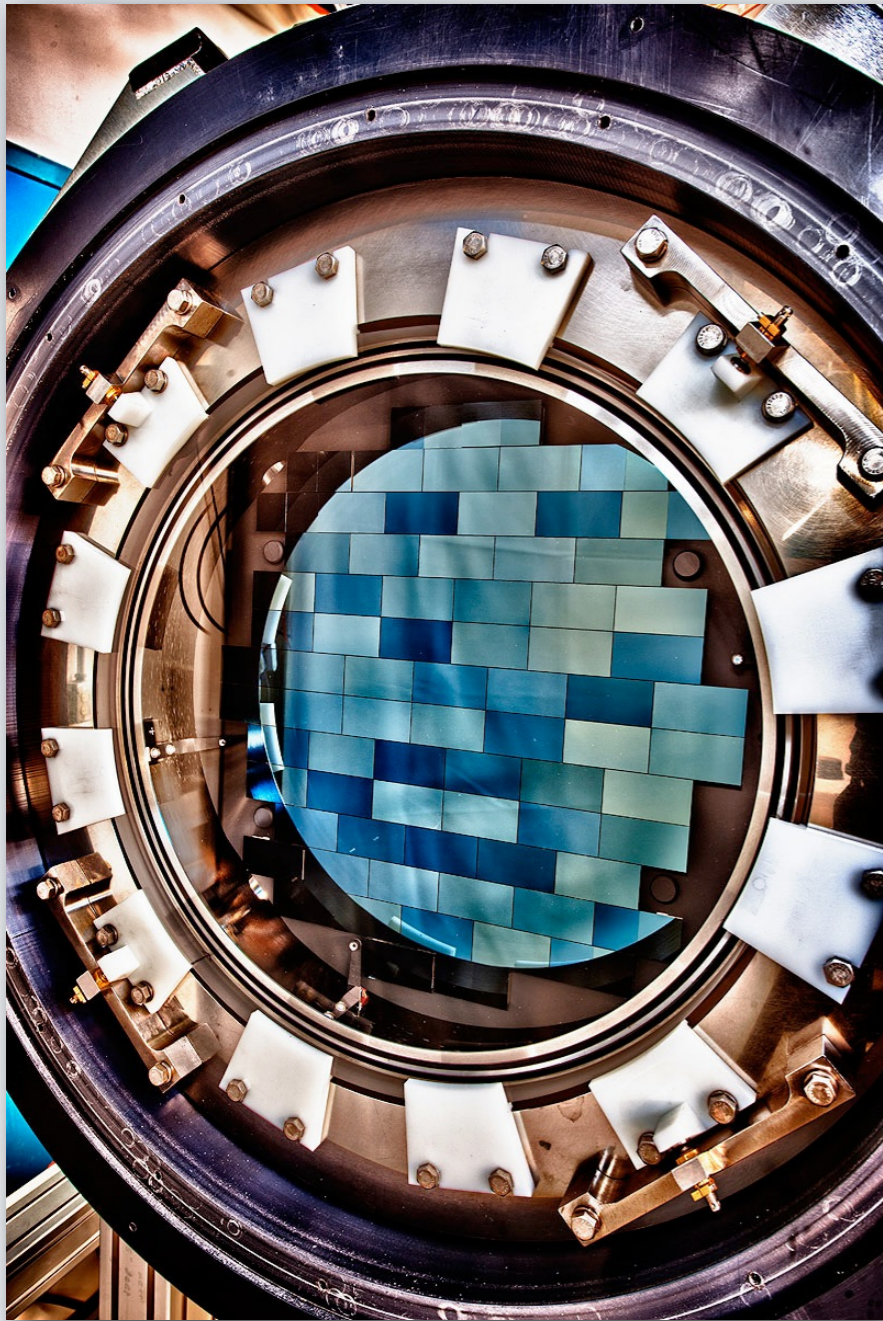
We established a joint effort with LIGO members (Holz, Chen, Doctor, Farr) and non-DES DECam users (Berger, Cowperthwaite et al.).

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 SCl grant (FY17).

Telescope time: Blanco/DECam nights (3 in 2015B, 5 in 2016B; PI: Berger).

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

0.9 arcseconds seeing

30 sq deg SNe survey

525 nights: 2013-2018

DES SCIENCE

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 DES results.

DES SCIENCE: GW

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Telescope time: NOAO CTIO Blanco/DECam nights (3 in 2015B, 5 in 2016B)

DARK ENERGY & ACCELERATED EXPANSION

