DISCOVERING A NEW APPROACH TO COSMOLOGY WITH THE DARK ENERGY SURVEY AND GRAVITATIONAL WAVES

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Fermilab
DES Collaboration

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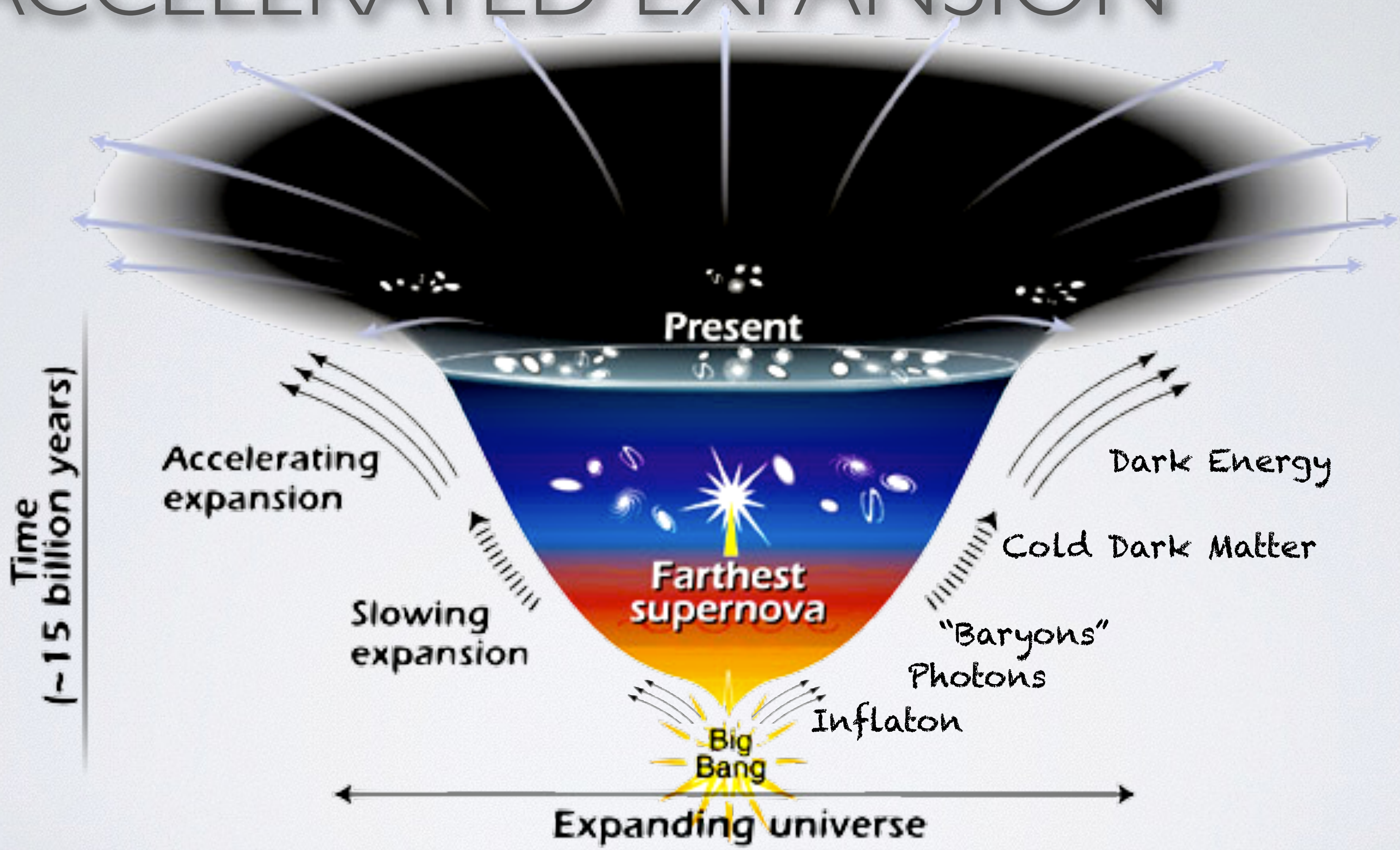
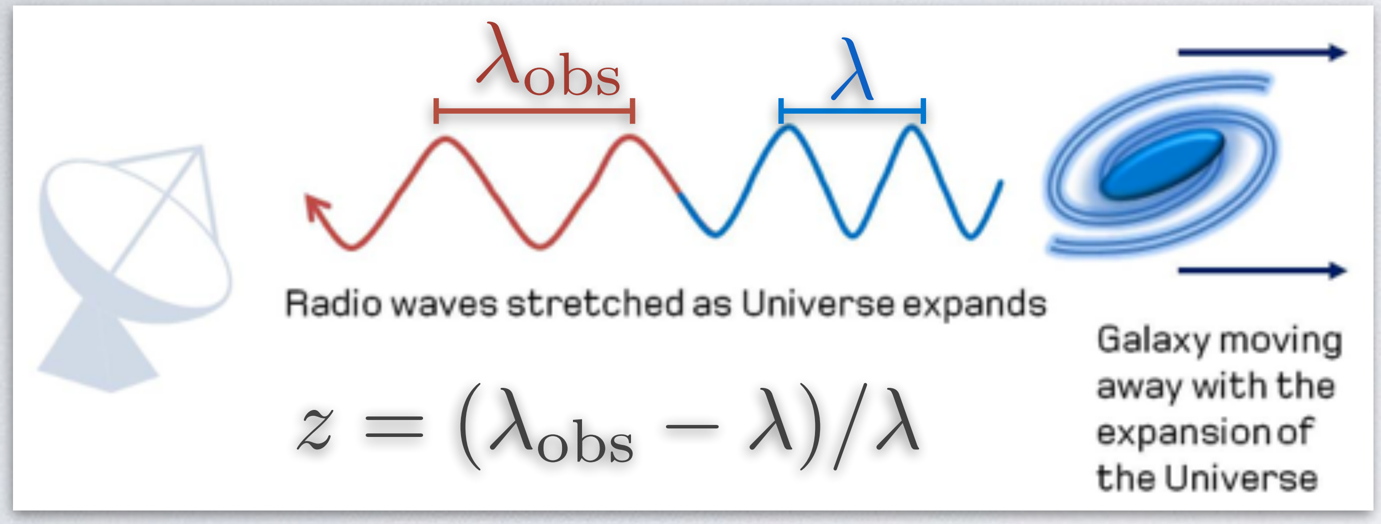
DARK ENERGY & ACCELERATED EXPANSION



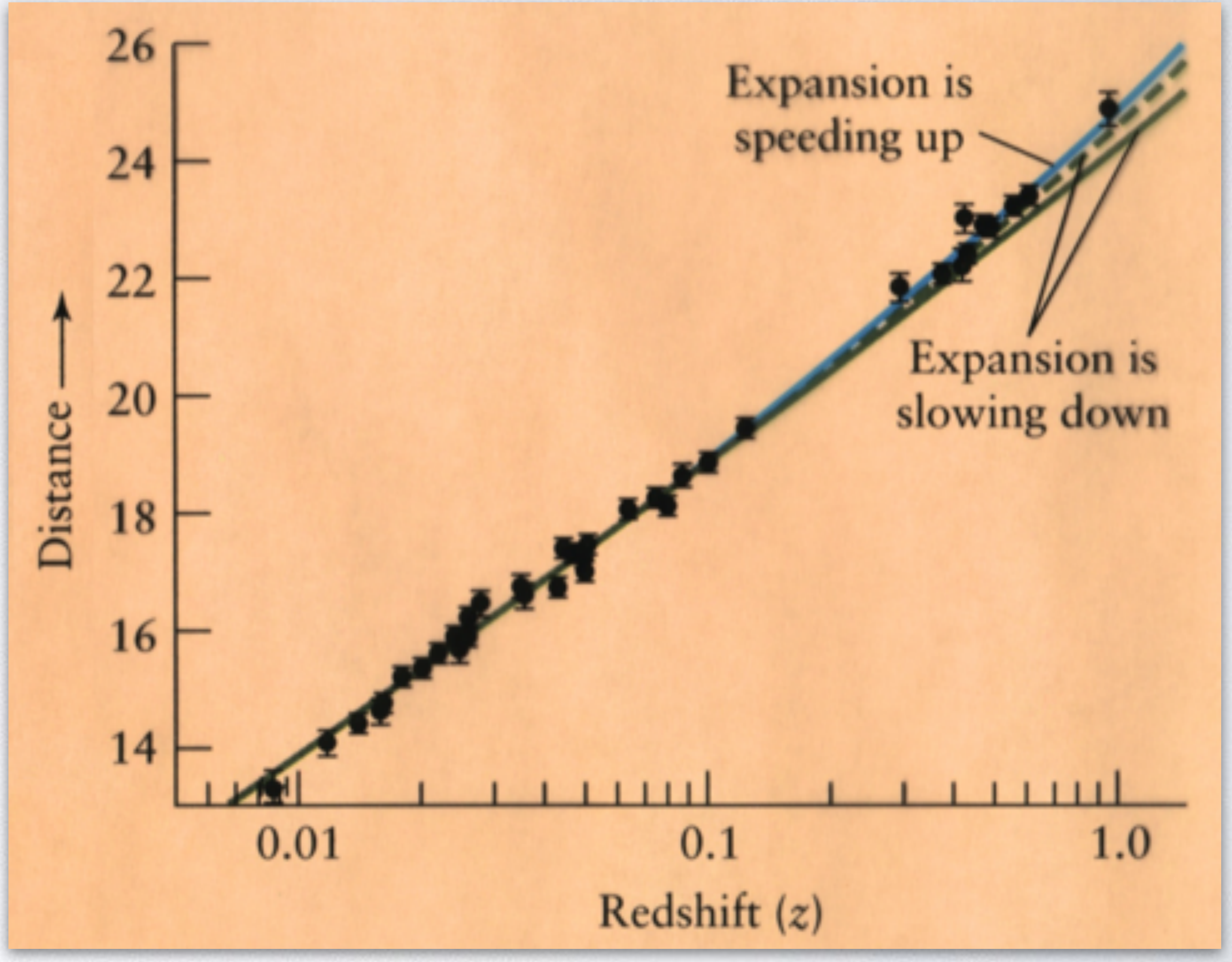
DISTANCE–REDSHIFT RELATION



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!

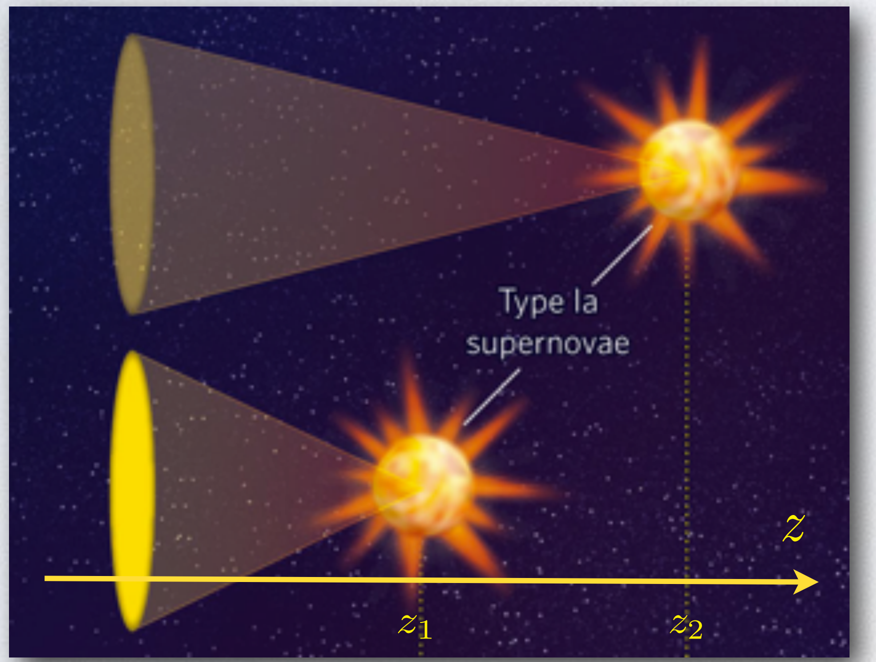


ASTROPHYSICAL OBSERVABLES

Luminosity distance:

standard candle

1. supernovae (SNe)



DES is sensitive to Dark Energy via multiple probes.

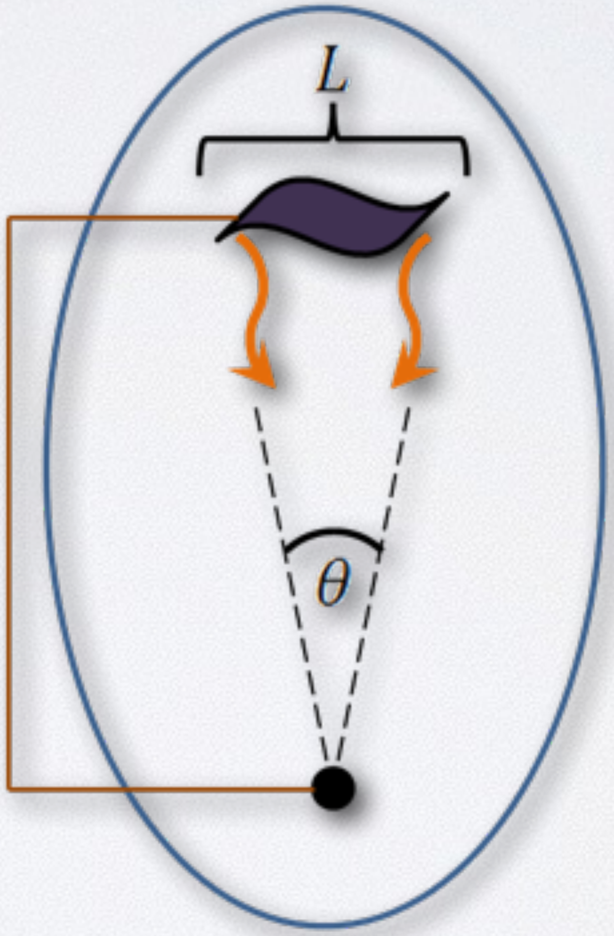
*CMB results from Planck are often used as priors in DES analyses.

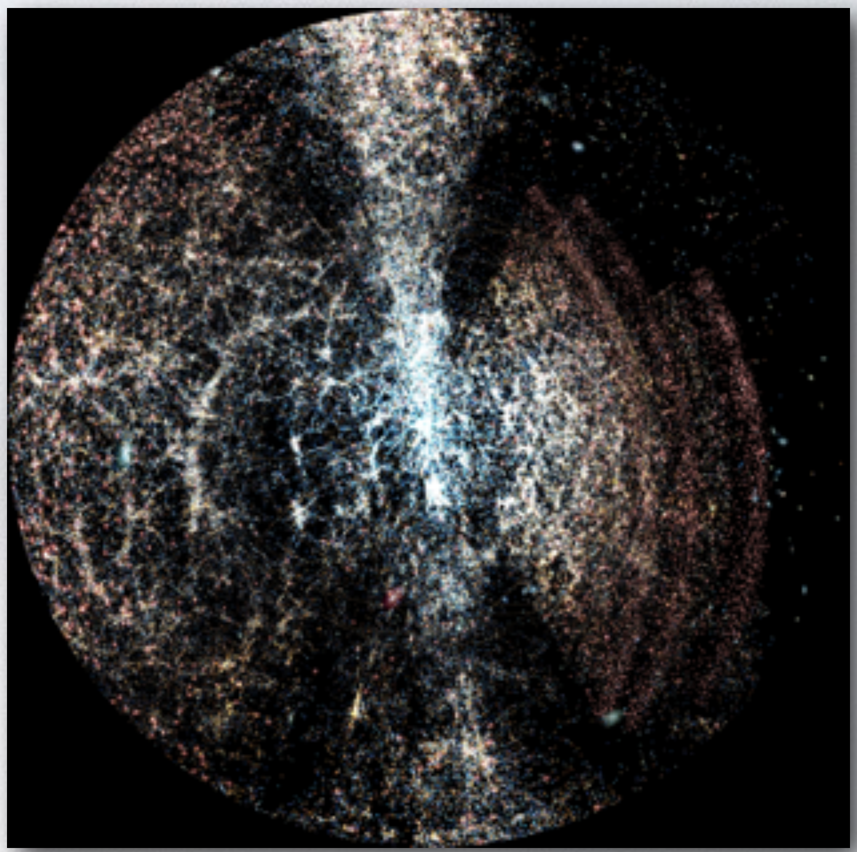
Angular diameter distance:

standard ruler

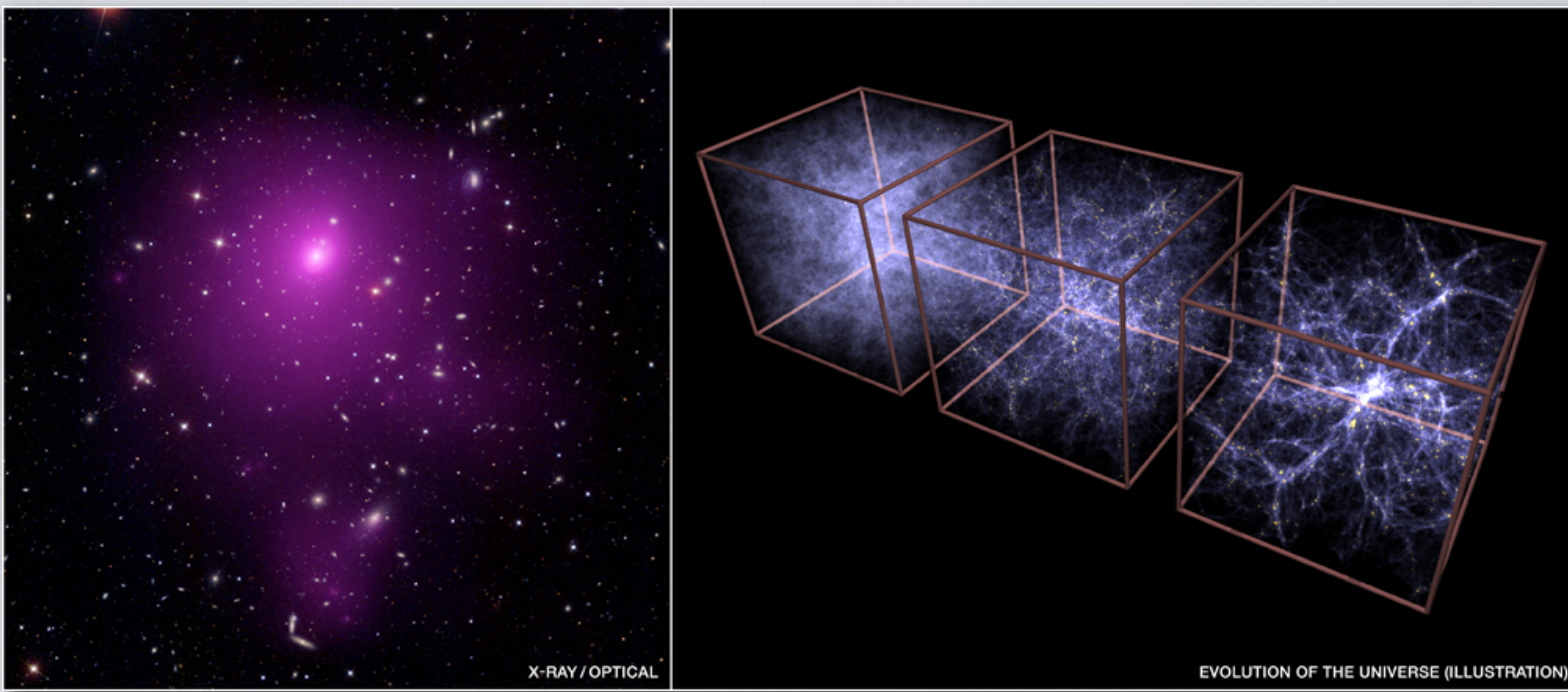
*cosmic microwave background (CMB)

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**.

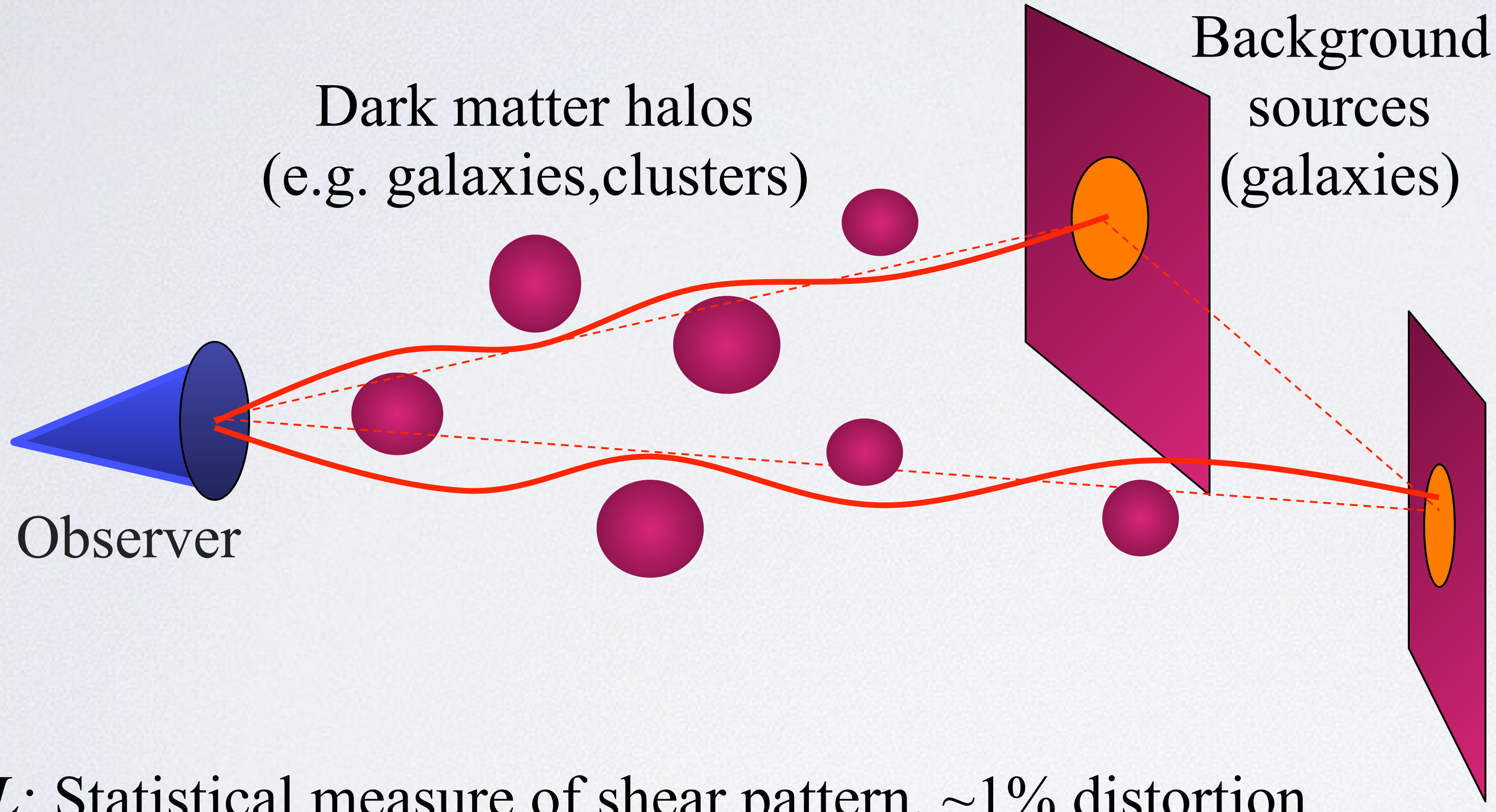
ASTROPHYSICAL OBSERVABLES

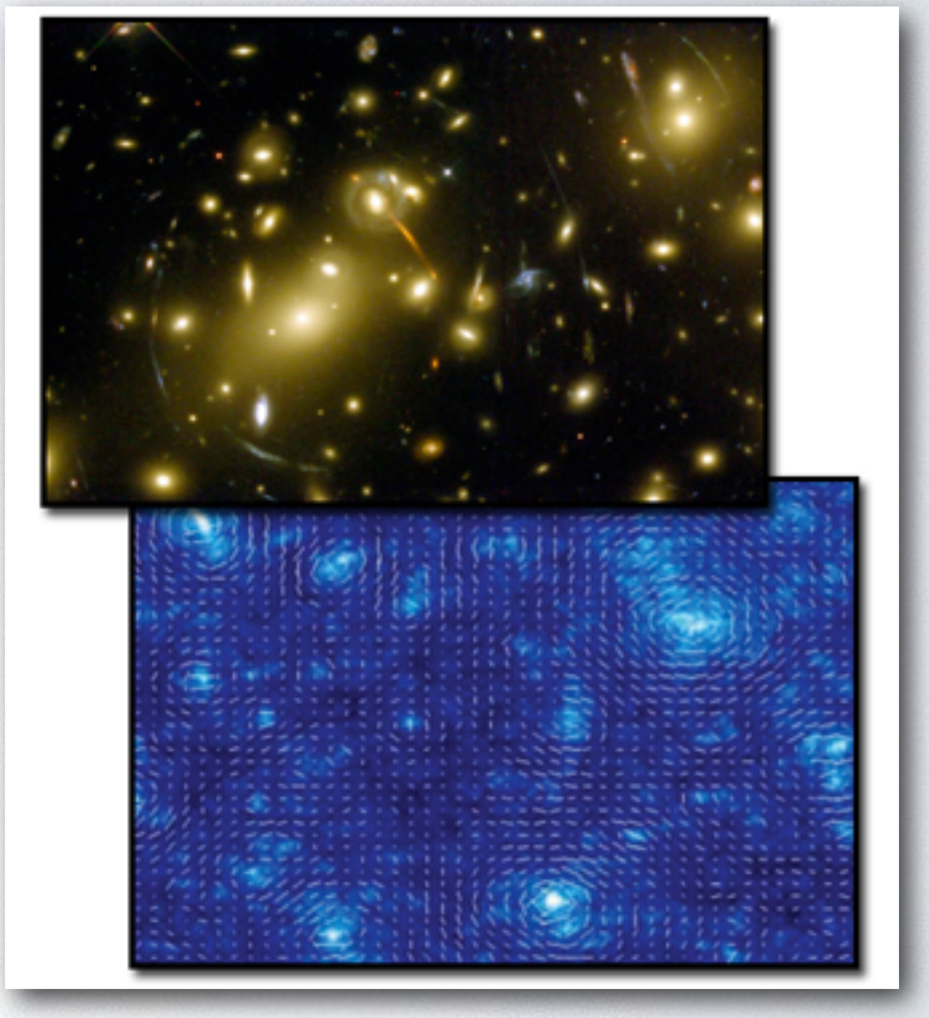
DES is sensitive to
Dark Energy via 4 probes.

WL, Clusters are also sensitive
to angular diameter distance.

Growth of structure:

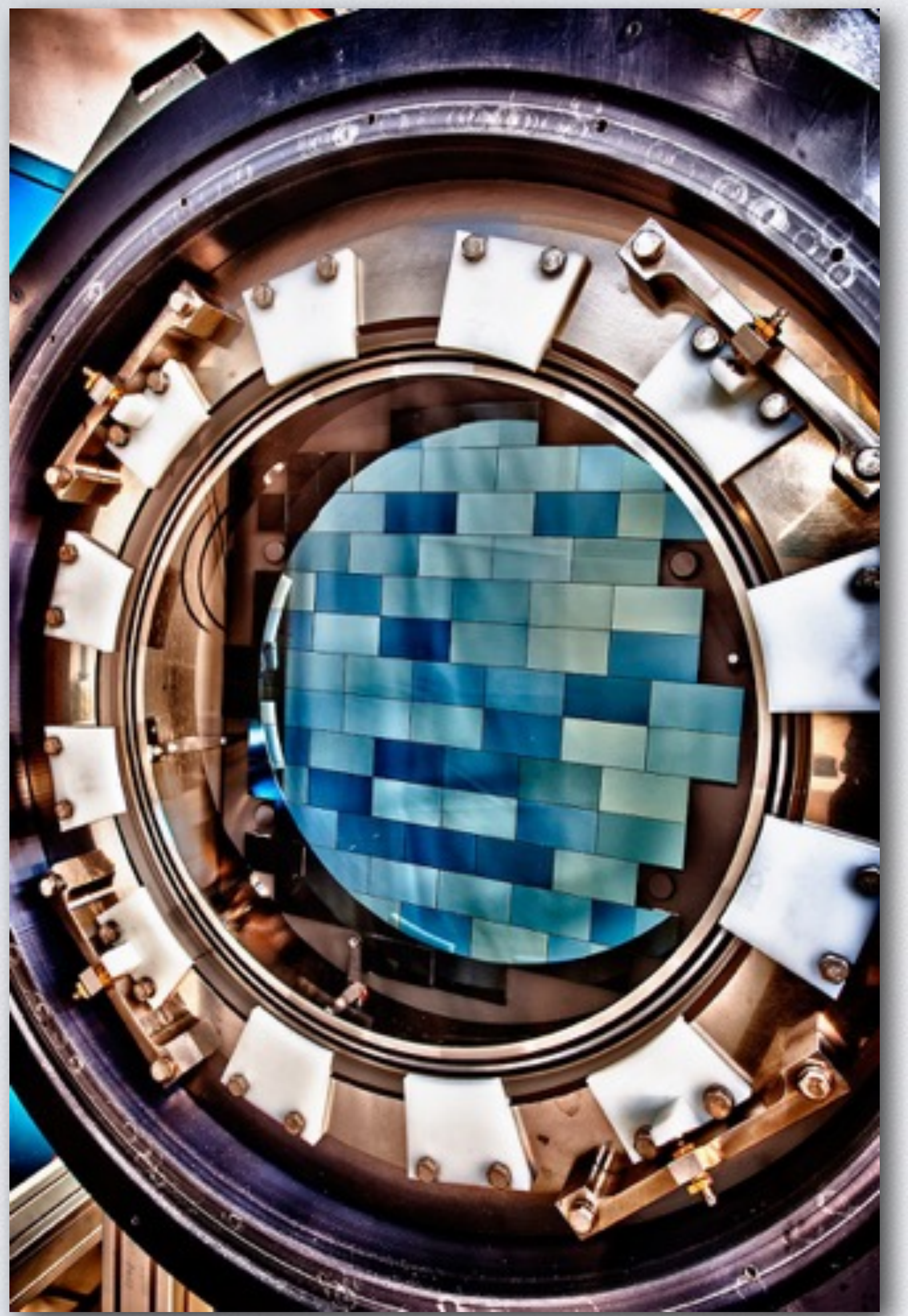
3. weak gravitational lensing (WL)
4. galaxy cluster abundance (Clusters)

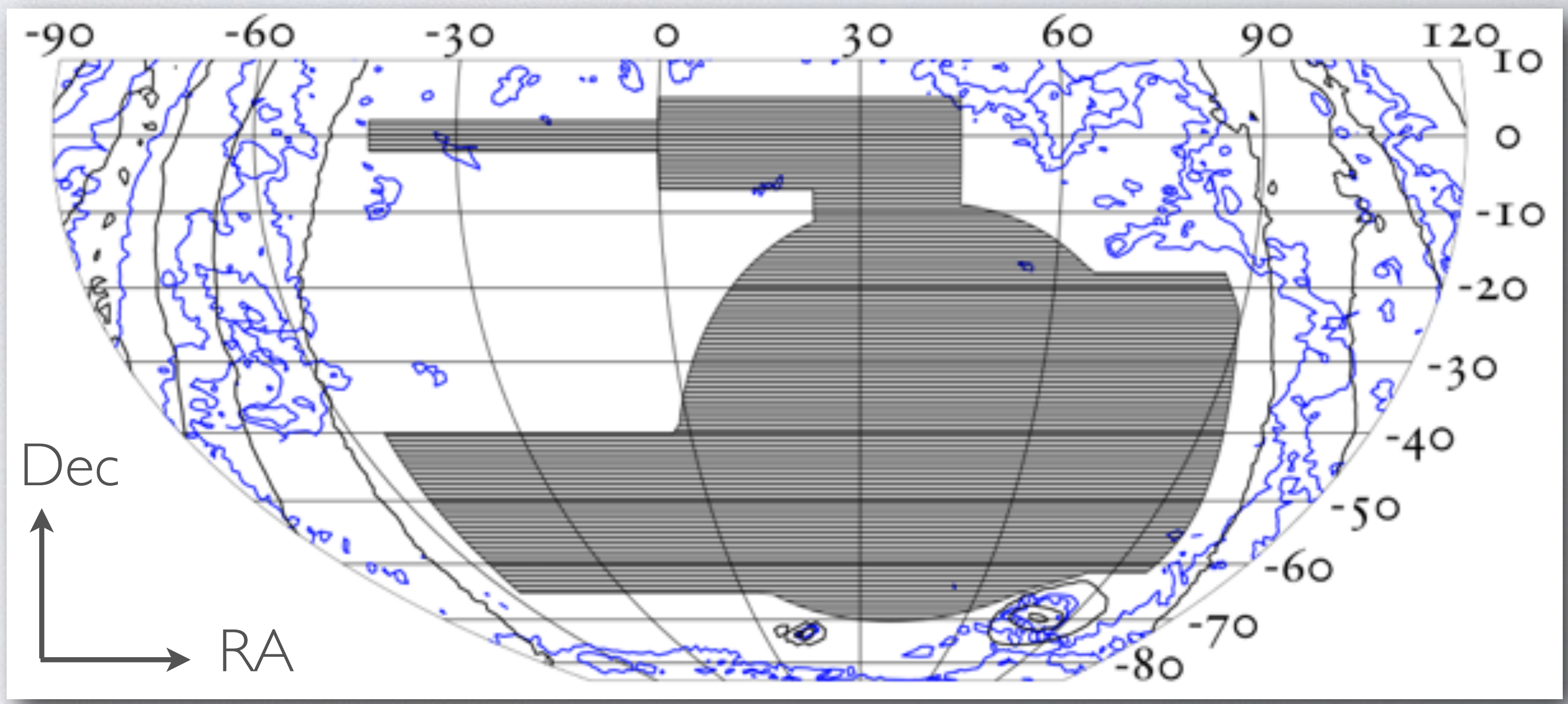




- ***WL***: Statistical measure of shear pattern, ~1% distortion
- ***Clusters***: Number density vs. Mass vs. redshift
- Radial distances depend on ***geometry*** of Universe
- Mass distribution depends on ***growth*** of structure

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

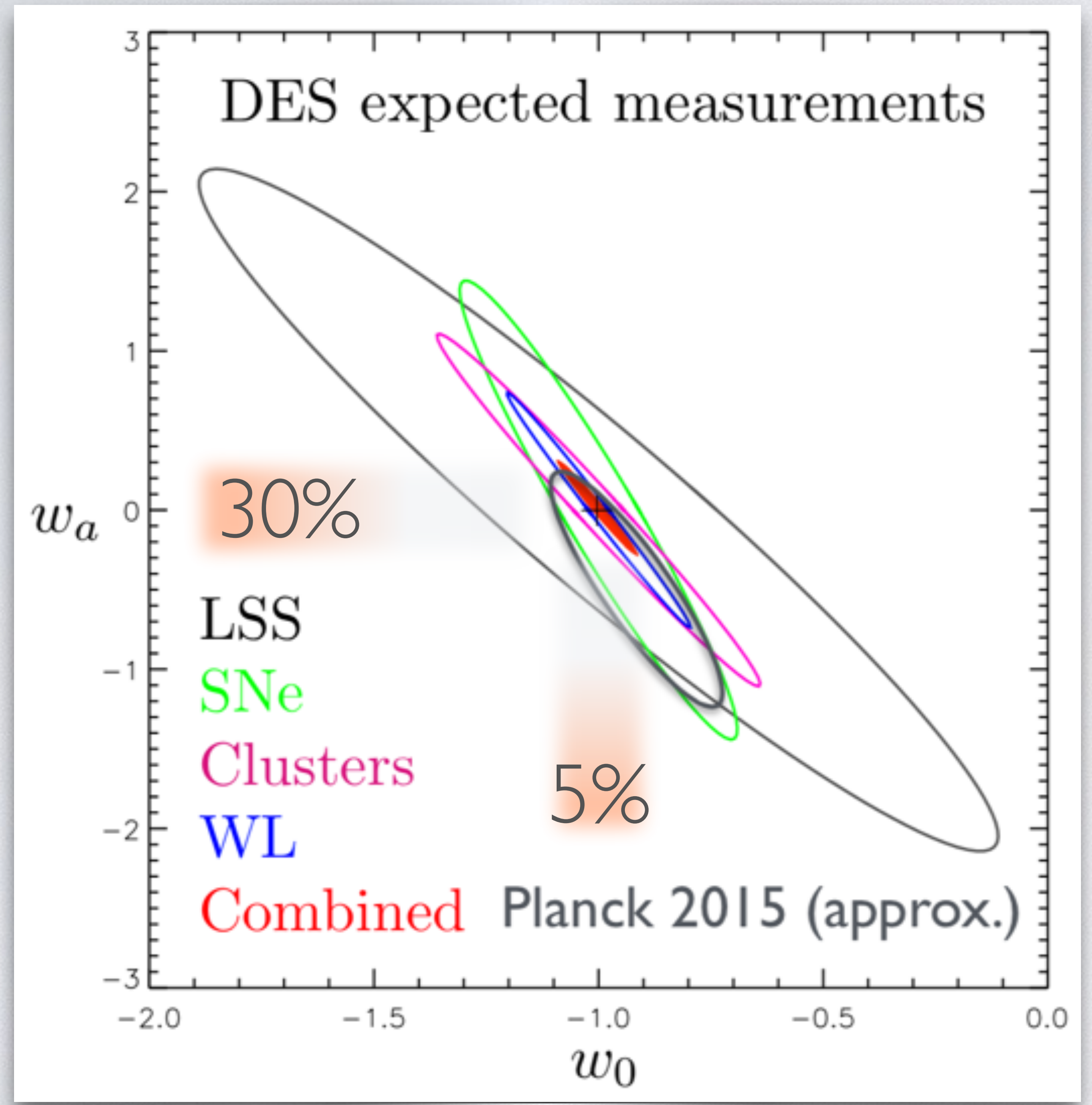
5000 sq deg grizY to **24th mag** overlapping with SPT

30 sq deg SNe survey
0.9 arcseconds seeing

525 nights: 2013-2018

DES SITE: CERRO TOLOLO, CHILE

DES PROJECTIONS (5 YEARS)



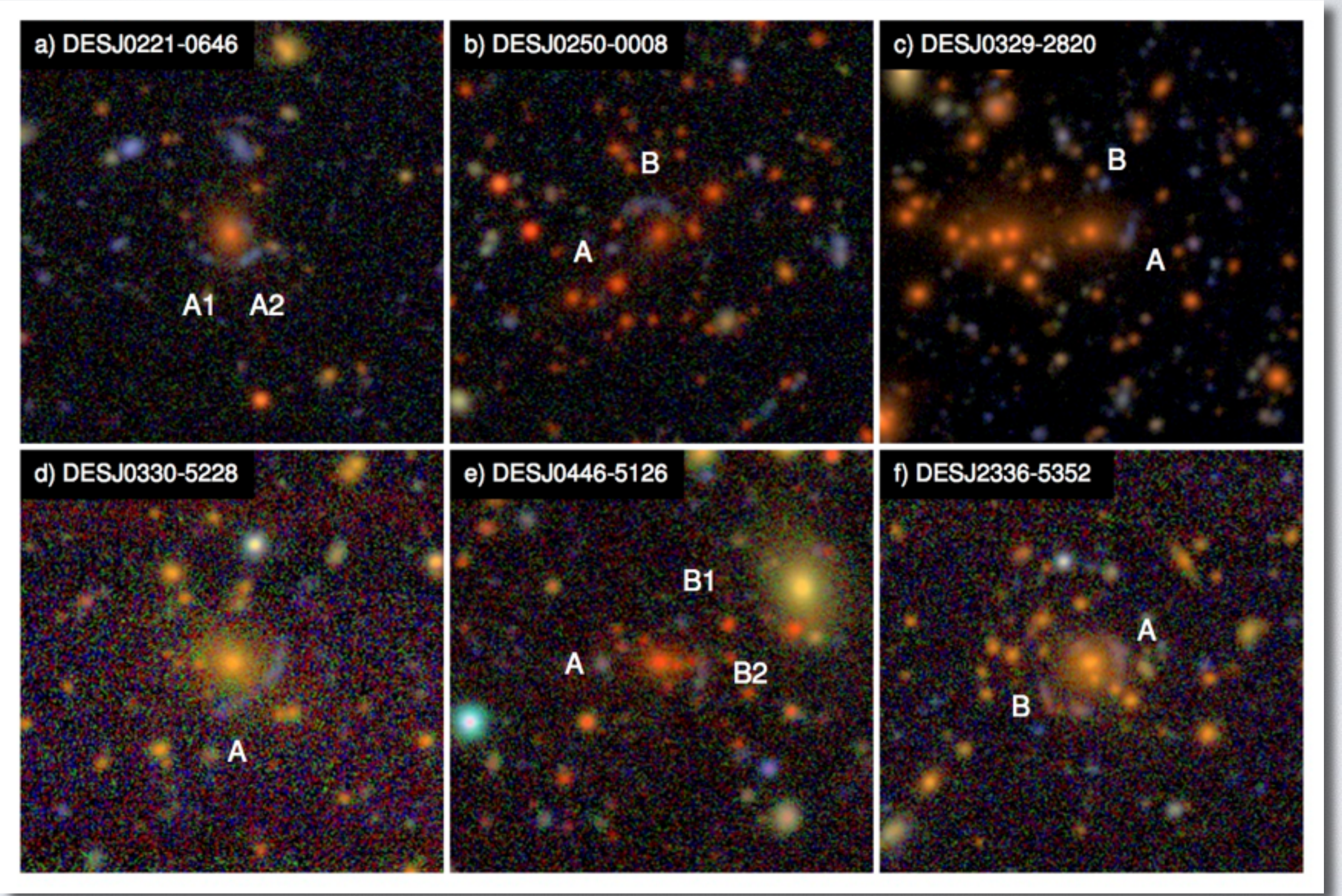
5000 deg^2, 0.9'' seeing, 24th mag (redshift~1.4)

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

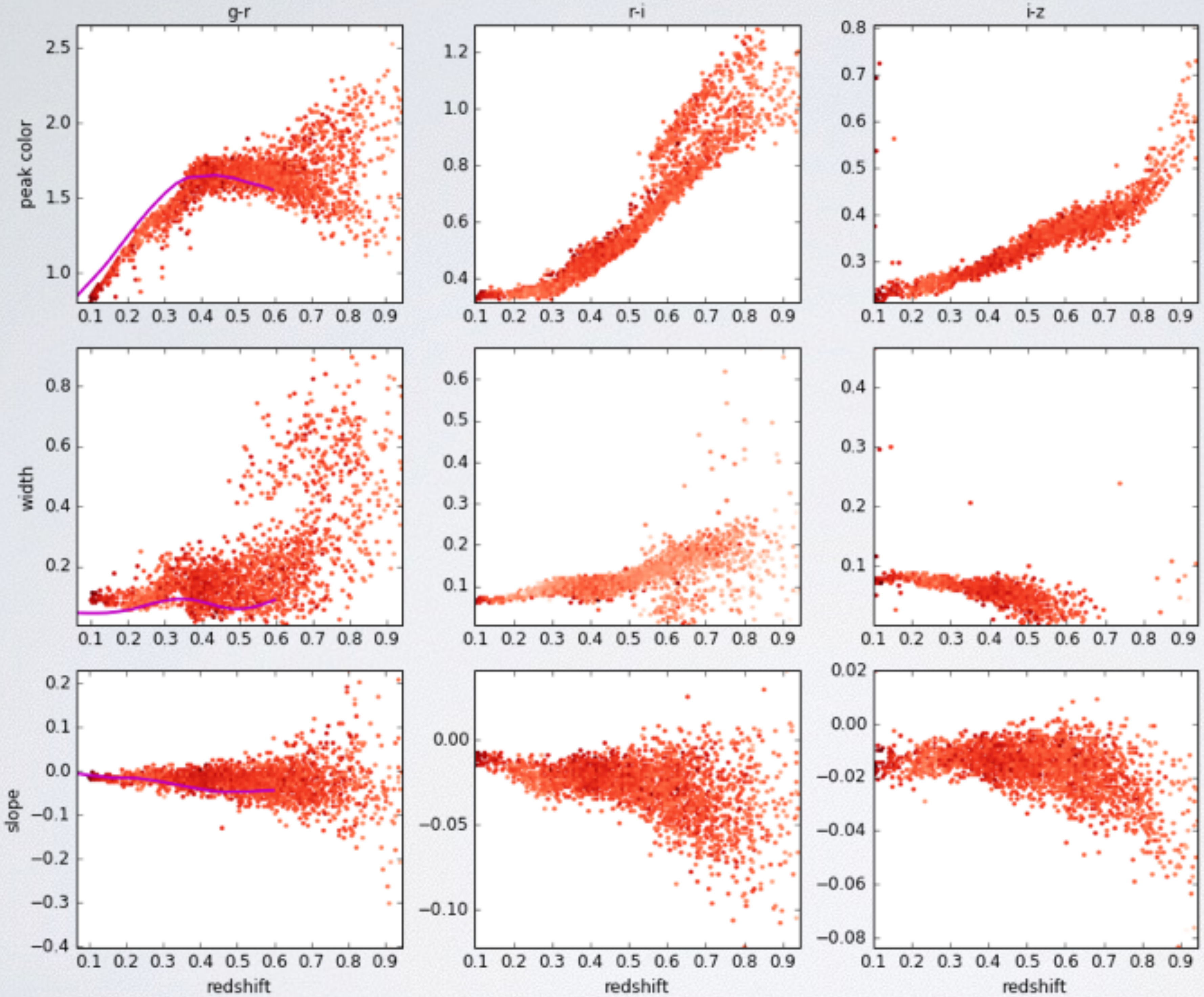
4 combined probes

3-5x improved Dark Energy measurement

GALAXY CLUSTERS



THE RED SEQUENCE



Brian Welch, Antonella Palmese, et al. in prep

~10,000 clusters from DES

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.:

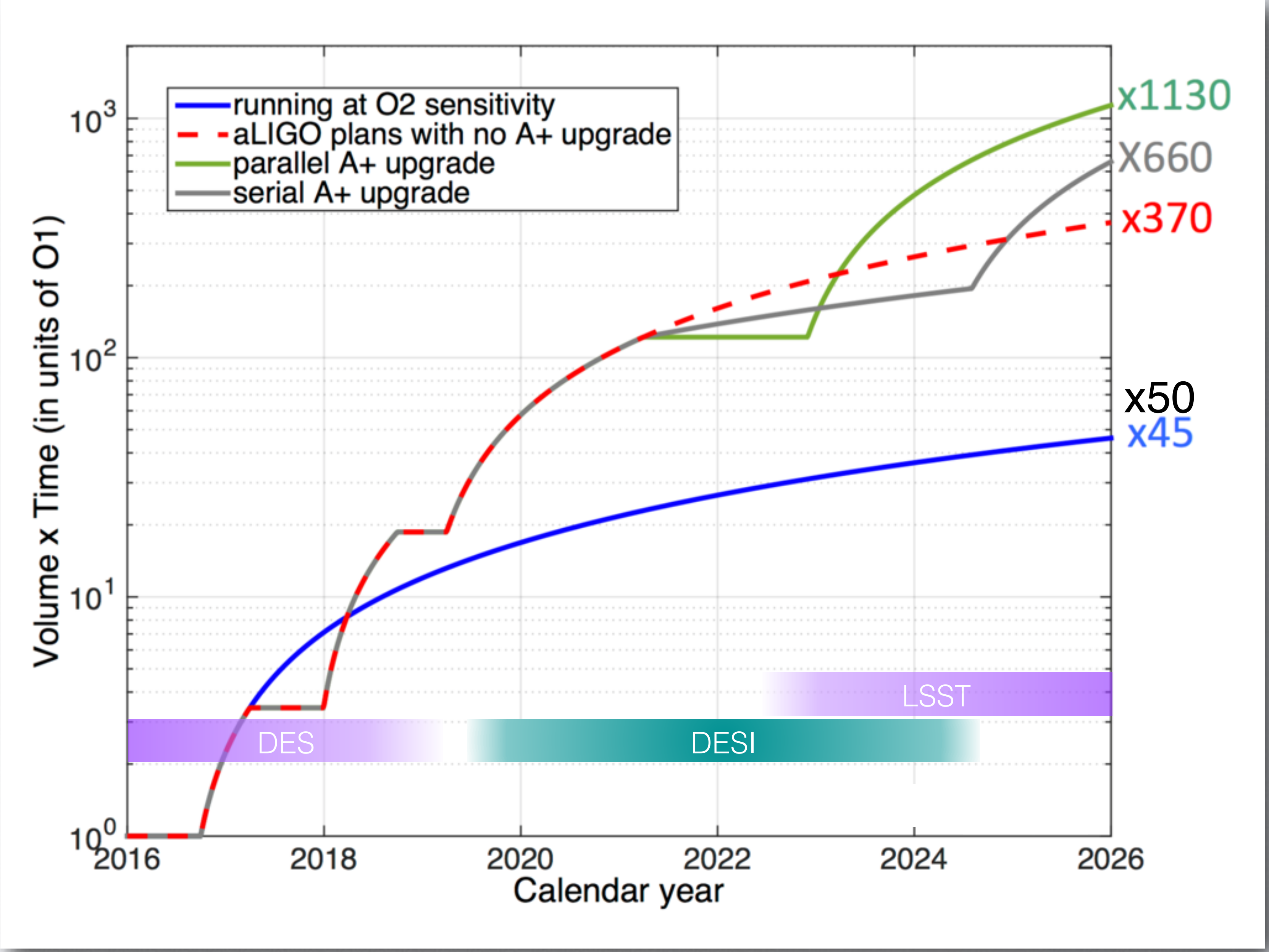
— Searches for electromagnetic signatures, in optical wavelengths, of gravitational wave sources.

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

THE ERA OF GW ASTRONOMY

The outstanding LIGO results from the first observing run (O1) have inaugurated a new era of gravitational wave astronomy:
2 black hole mergers!

Many more detections are expected in the coming years. That's a very exciting prospect!



Plot from the DAWN-2016 workshop report.

GW+EM OPPORTUNITIES

Astrophysics

First observations of NS-NS, NS-BH mergers
Evolution of binary systems and their environment
Origin of r-process elements in the Universe
Neutron Star equation of state
Potential for discovery of new astrophysical phenomena

Cosmology

Standard sirens (the GW-equivalent of standard candles)*****

Physics of space-time

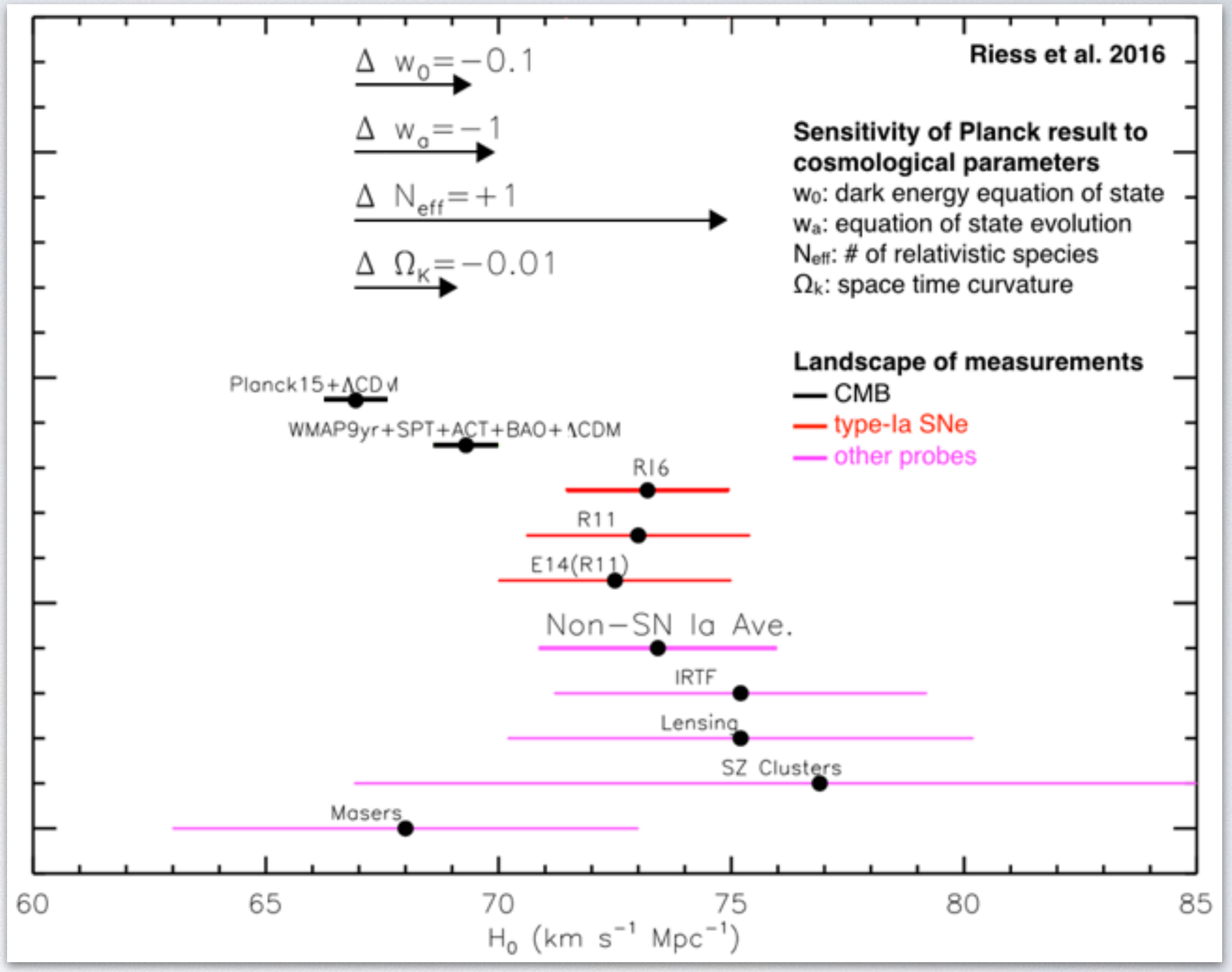
Time of flight experiments (including neutrinos)
Tests of General Relativity

*** In this talk.**

COSMOLOGY MOTIVATION

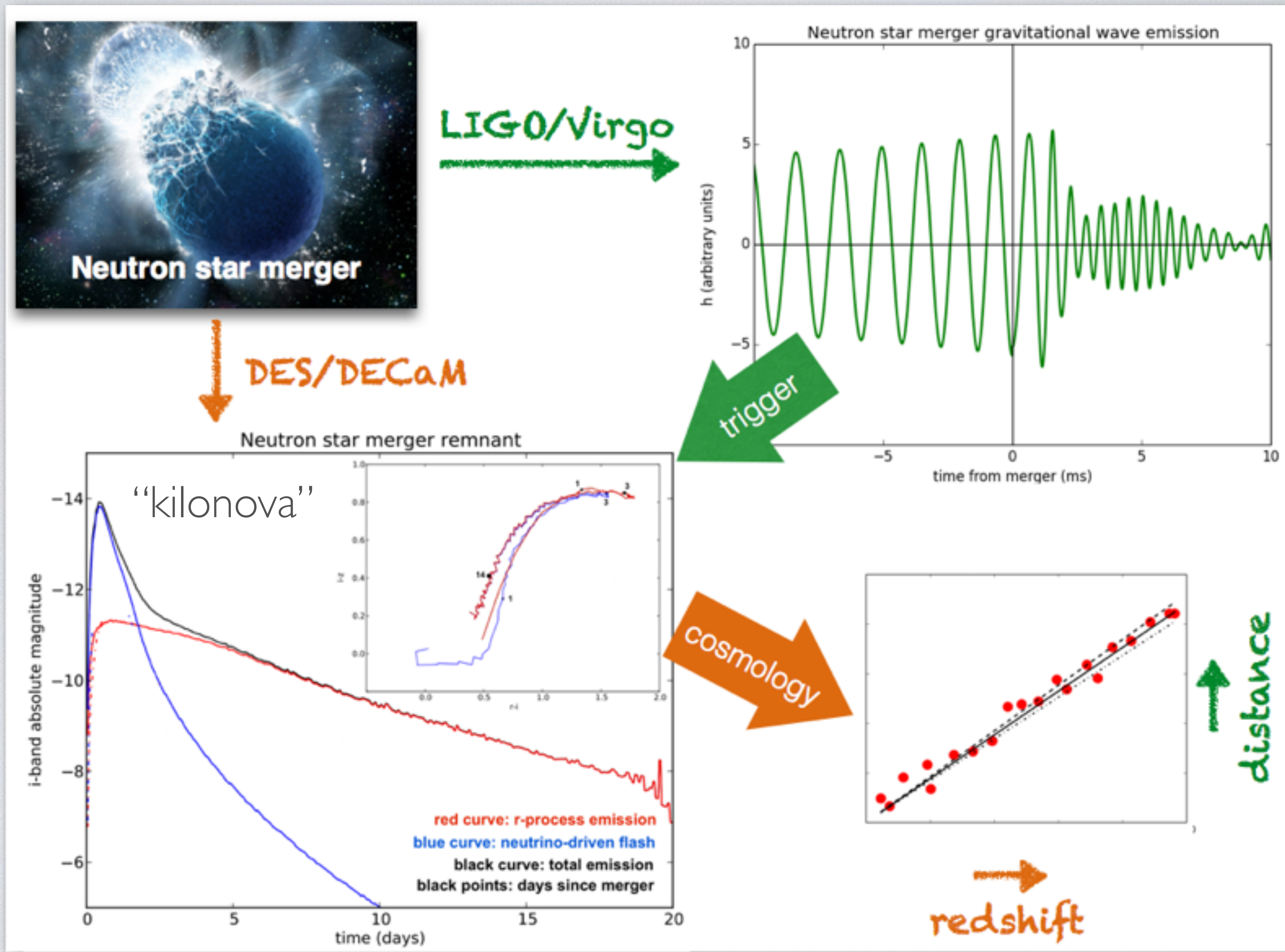
Growing discrepancy between SNe and CMB-based measurements of the current rate of expansion: systematic effects, or new physics?

A new, independent, measurement will be most helpful here!



$$H \equiv \dot{a}/a \text{ , where } a = 1/(1+z)$$
$$H(z) = H_0 \cdot f(z; \Omega_m, \Omega_k, \Omega_{DE}, w_0, w_a)$$

STANDARD SIRENS



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 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 in 2015-2016 run. 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: DECam nights (3 in 2015B, 5 in 2016B, 13 in 2017A).

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

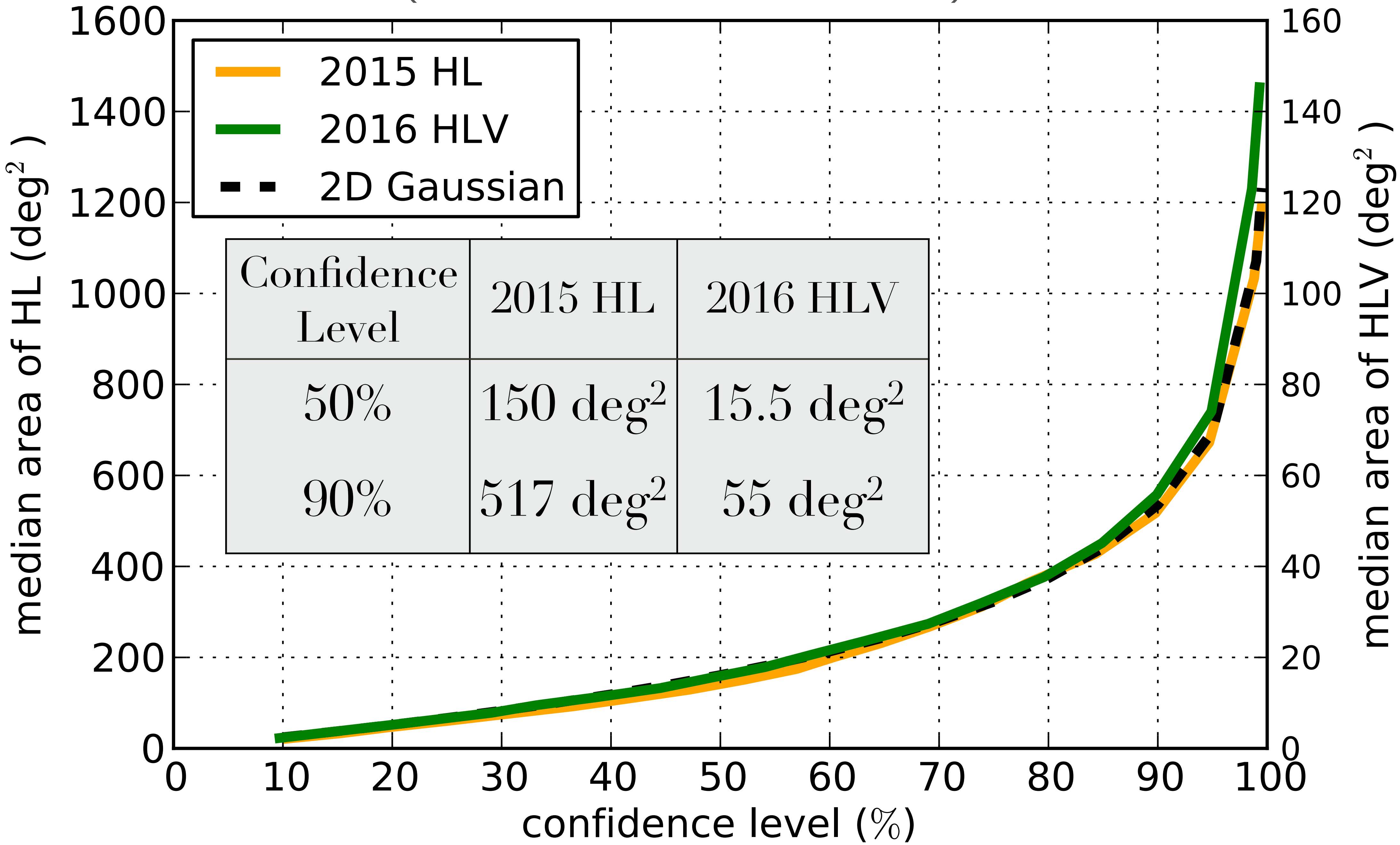
	Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
aLigo	2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
aLigo	2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 –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

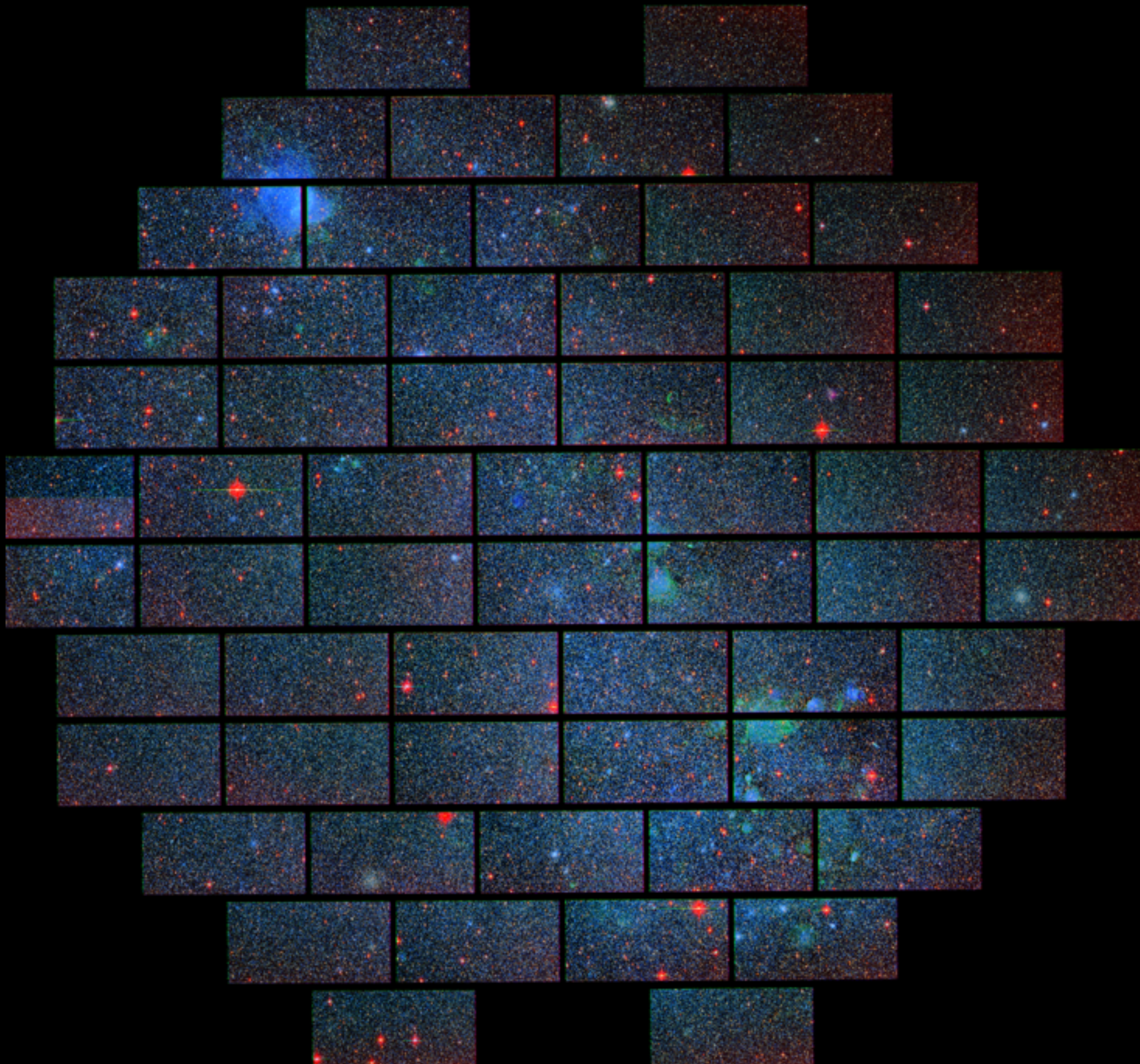
(Chen & Holz 2015)



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

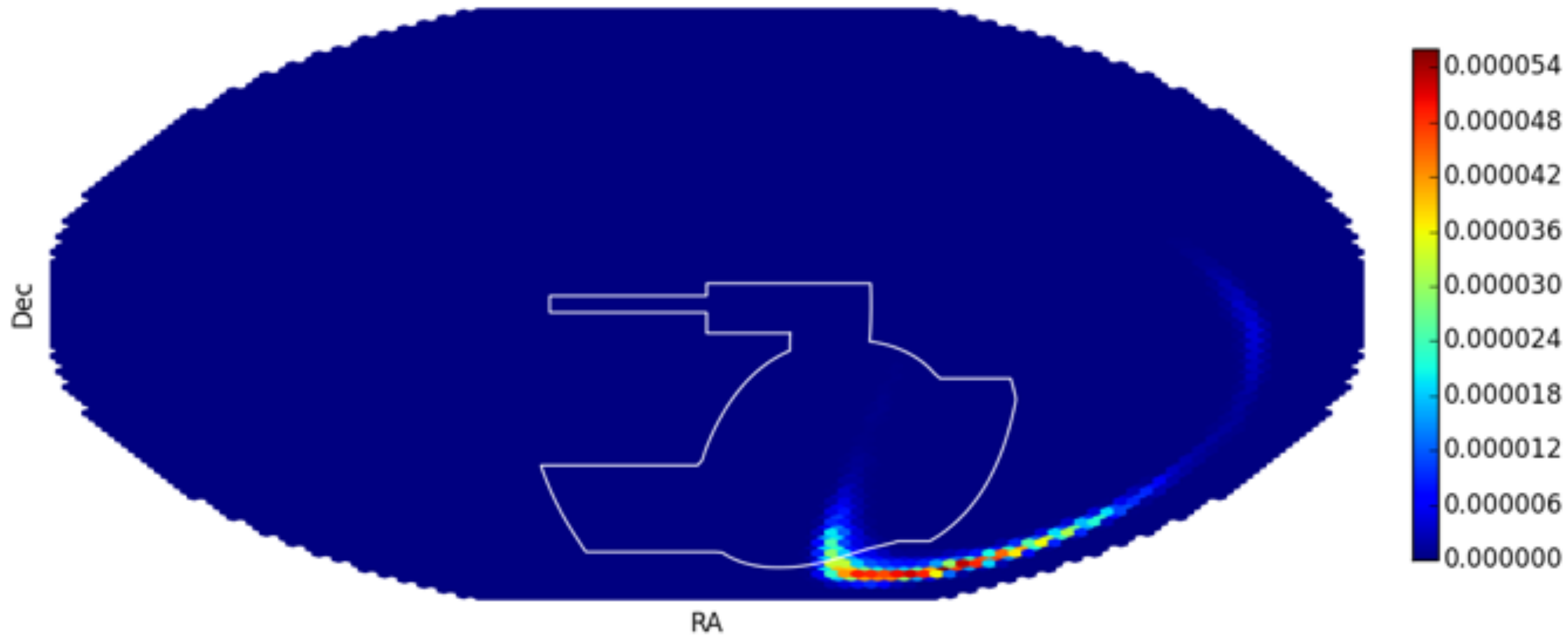
THE PROGRAM IN ACTION

The 1st Event:

GW150914

GW150914

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

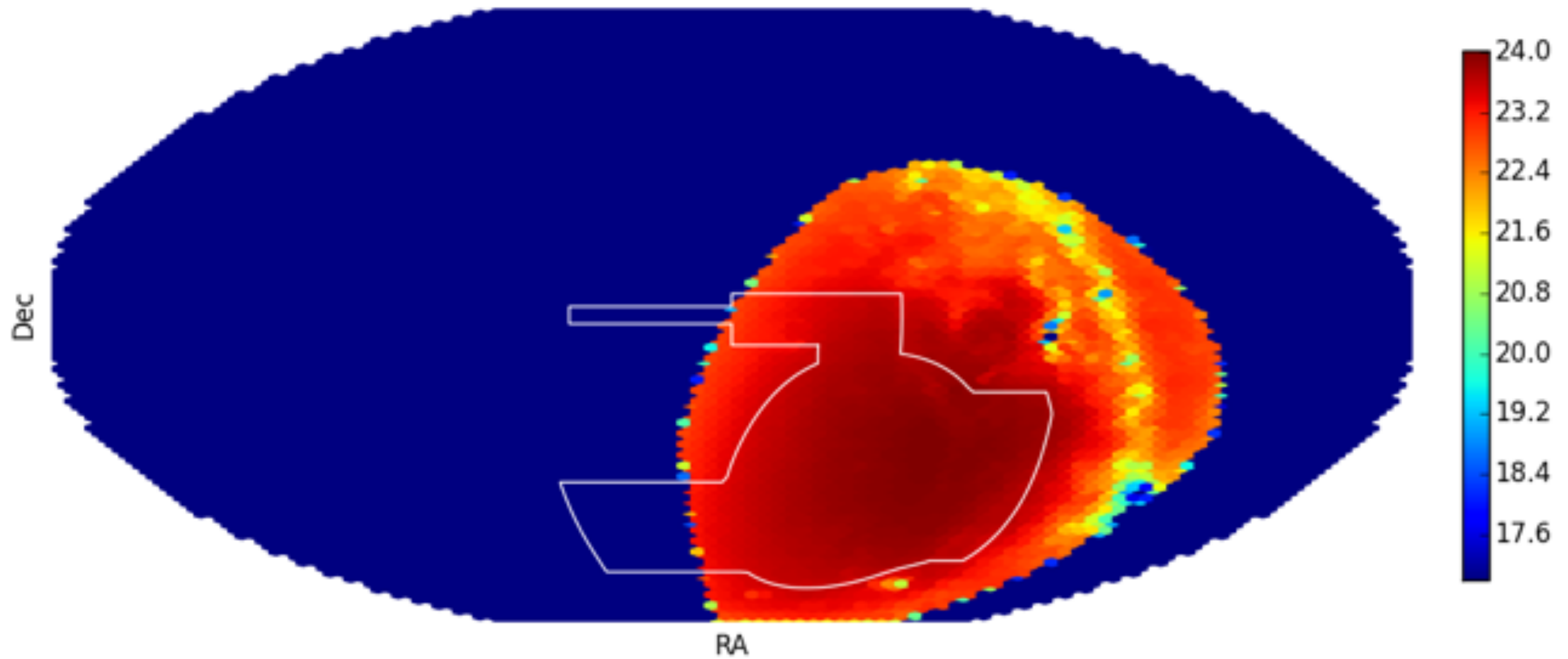


LVC sky localization probability map (final)

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

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FAR: 1/203k yr
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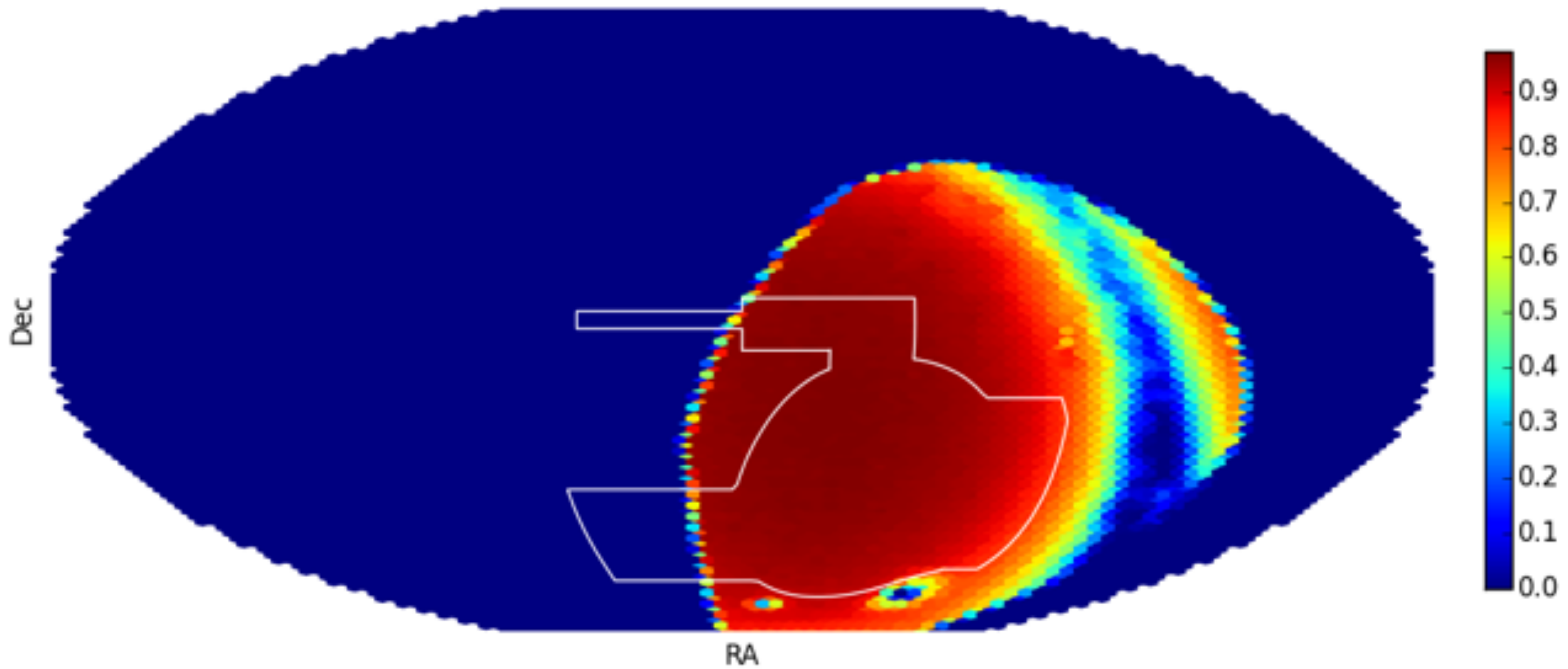
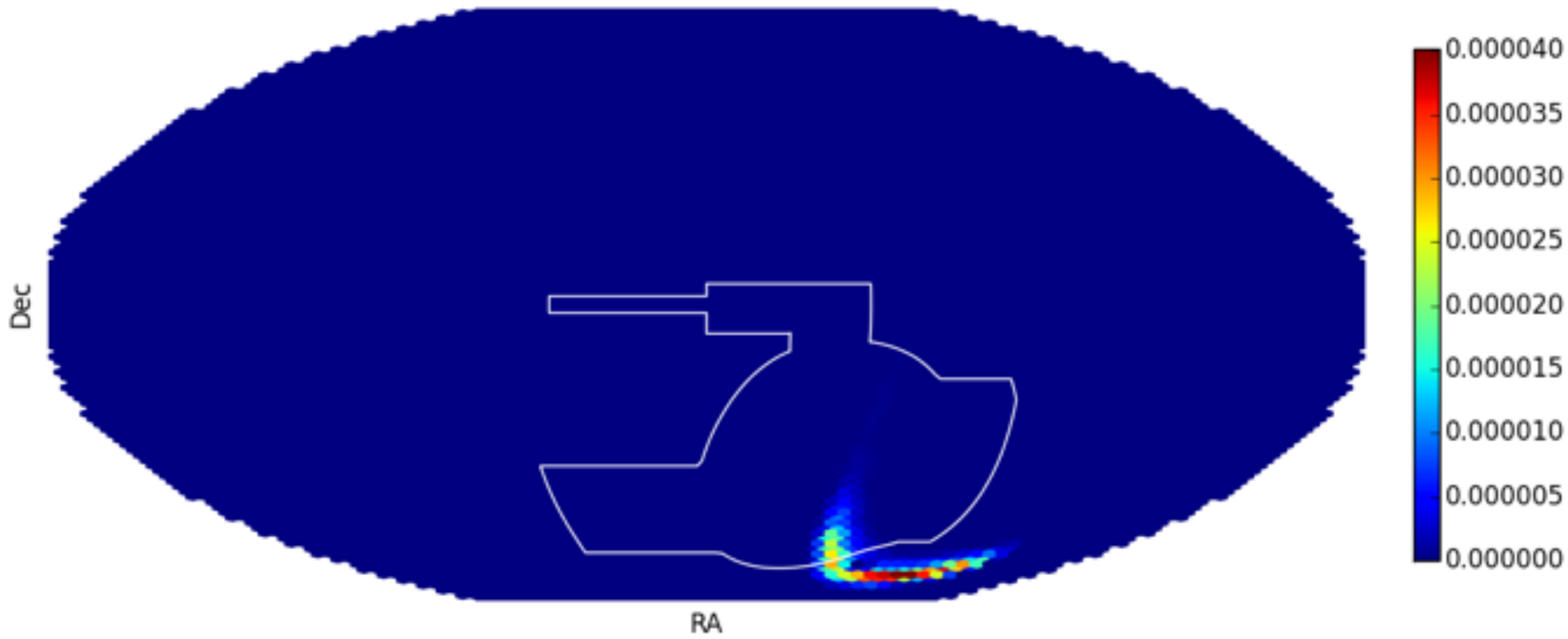


DES source detection probability map

GW150914

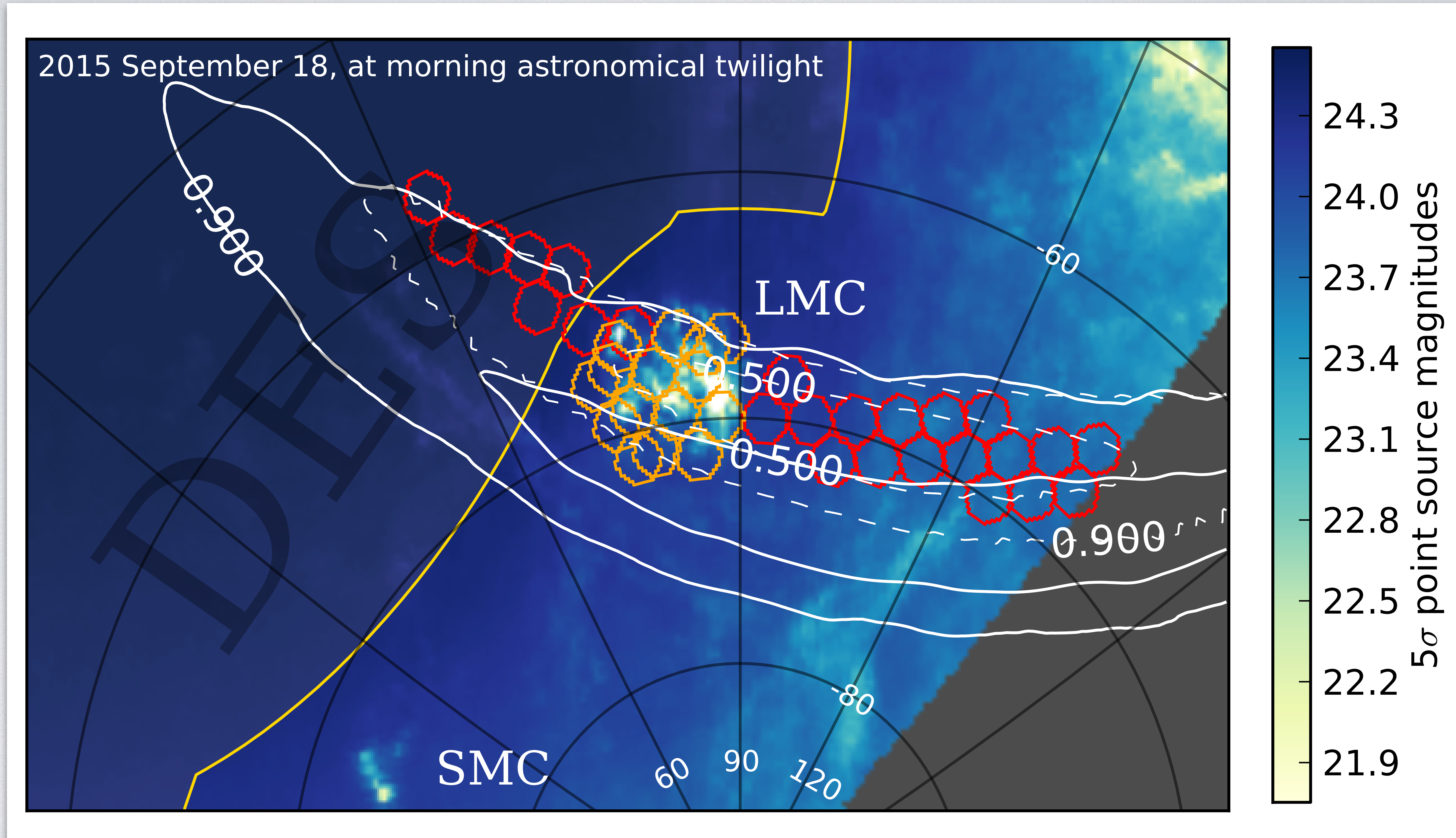
Time: Sep 14, 2015 09:50:41
FAR: 1/203k yr
Distance: 410Mpc
Type: BBH merger

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



DESxLIGO source detection probability map

DATA



2015 September 18, at morning astronomical twilight
0.900
0.500
0.500
0.900
LMC
SMC
DES
-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)	$A_{\text{eff}}{}^{b}$ (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

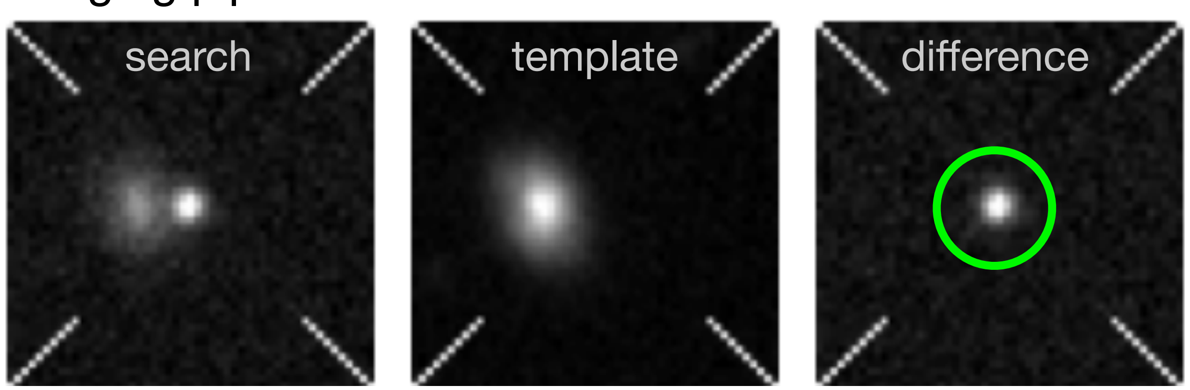
DIFFERENCE IMAGING

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

Then each CCD in each search image goes through ***difference imaging*** in parallel (~1hr/job)

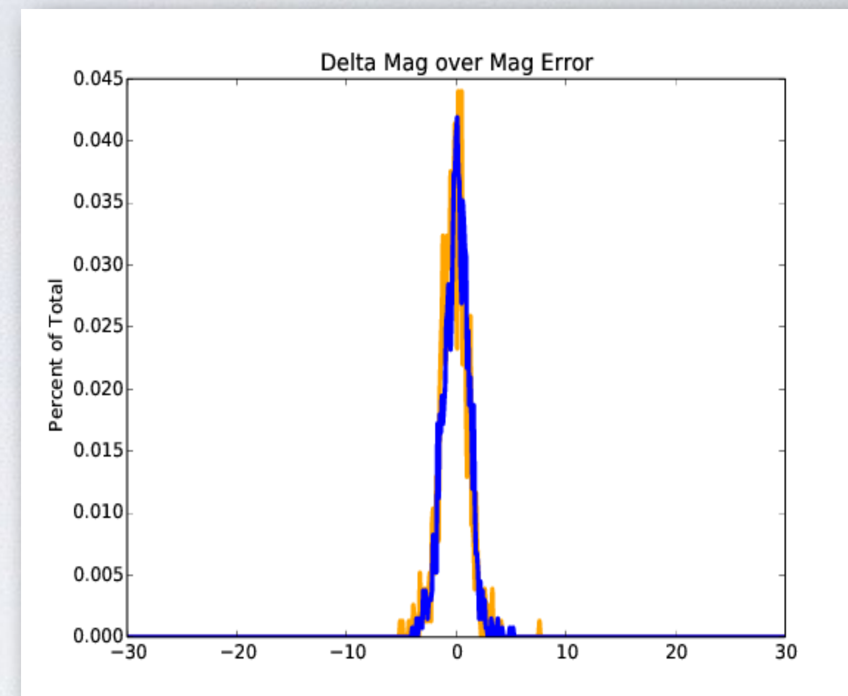
Finally ***post-processing*** does assessment of outputs and creates the candidates list.

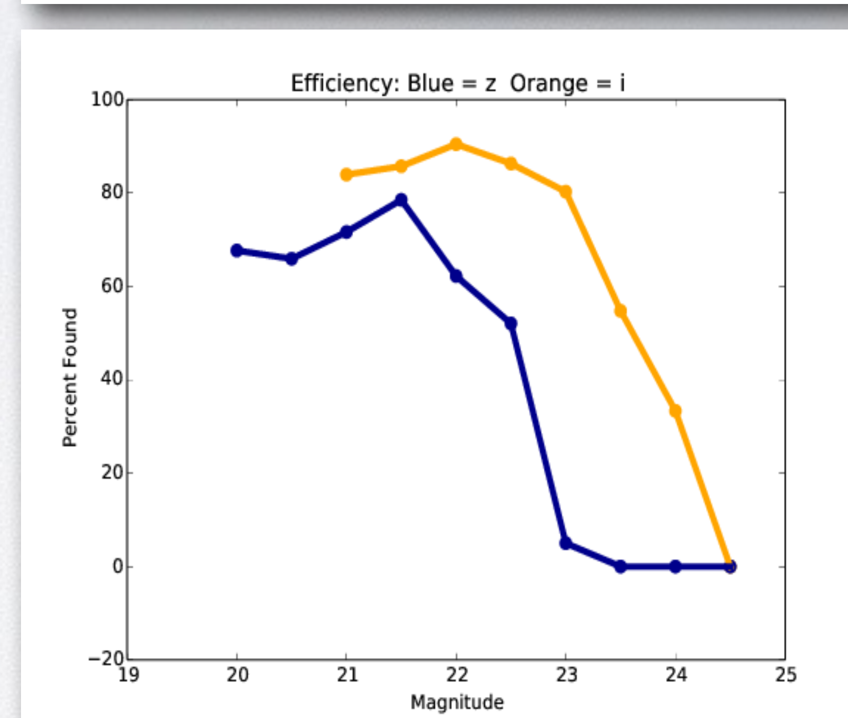
Example of SNe detection using the DES difference imaging pipeline.



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

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





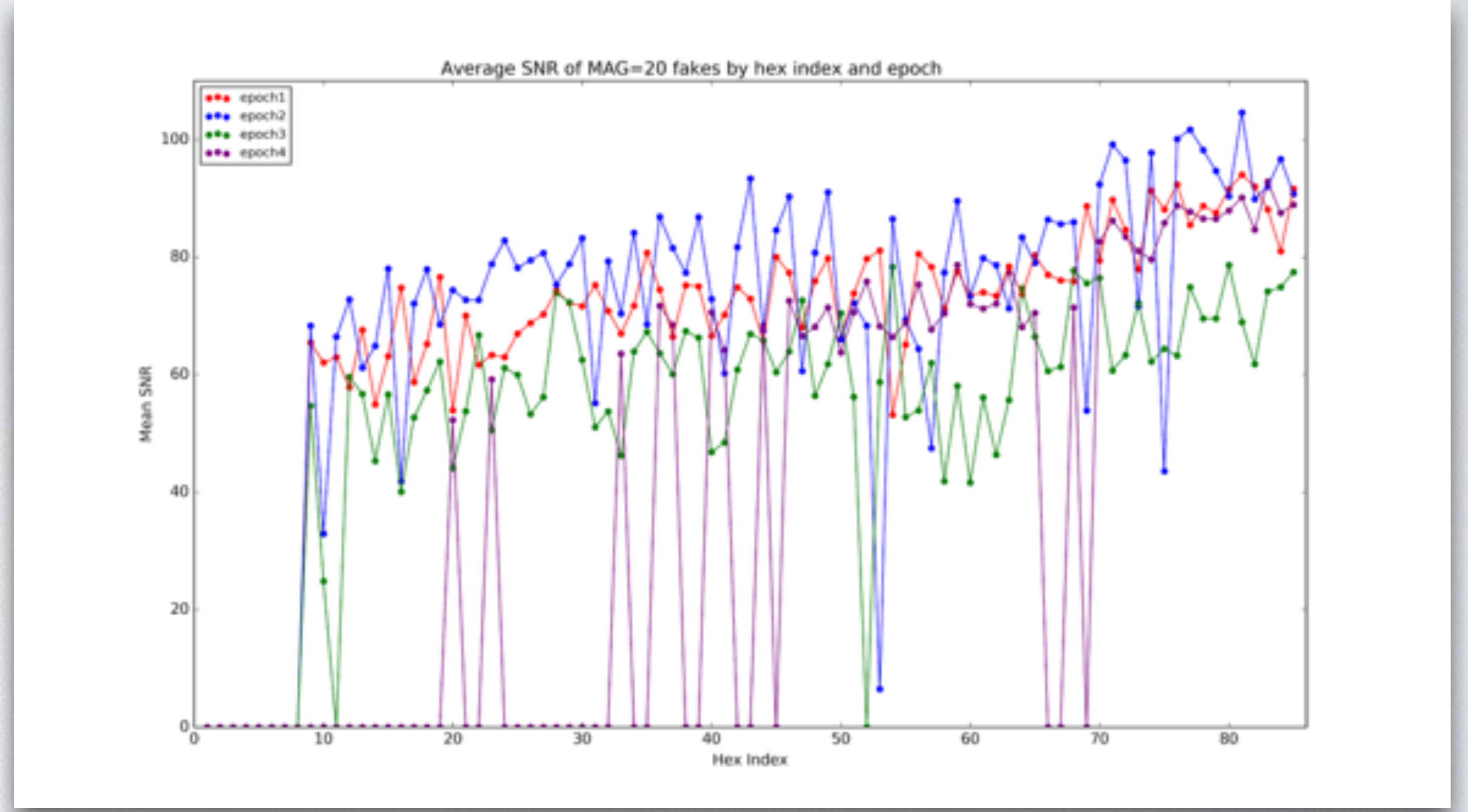
Plots by Tim Osborn, summer intern.

IMAGE PROCESSING PIPELINE

Completely automated job submission immediately after search image available.

Able to run dozens of images in parallel using Fermilab and Open Science Grid.

Team includes senior scientists, PhD students, and undergraduate interns.



Plot by Bobby Butler, undergraduate student intern.

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)

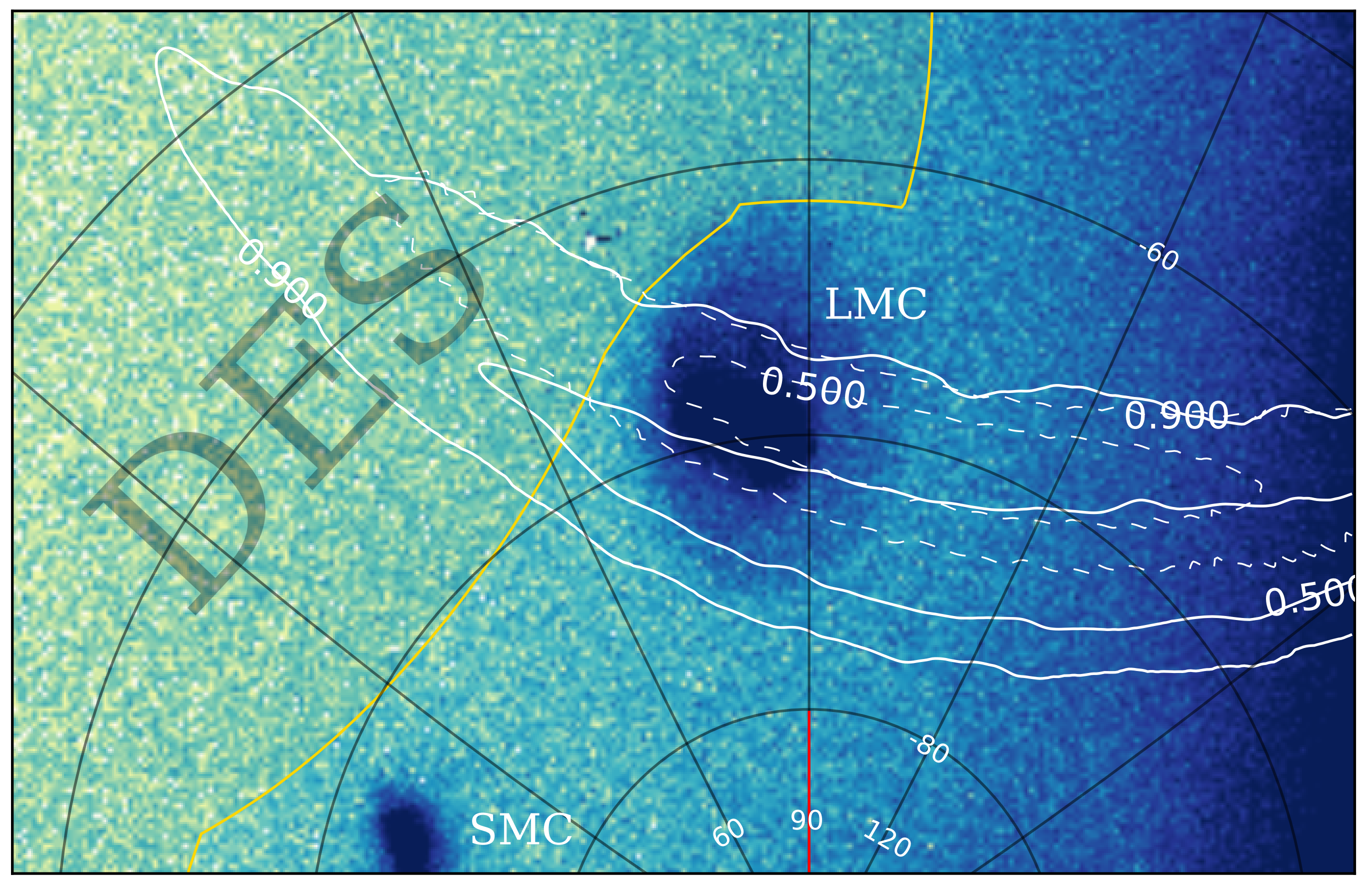
0) Good detection in 1st epoch
1) 2nd epoch S/N>2
2) 3+ sigma 1st to 2nd epoch flux decline
3) S/N < 3 sigma in the 3rd epoch

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.



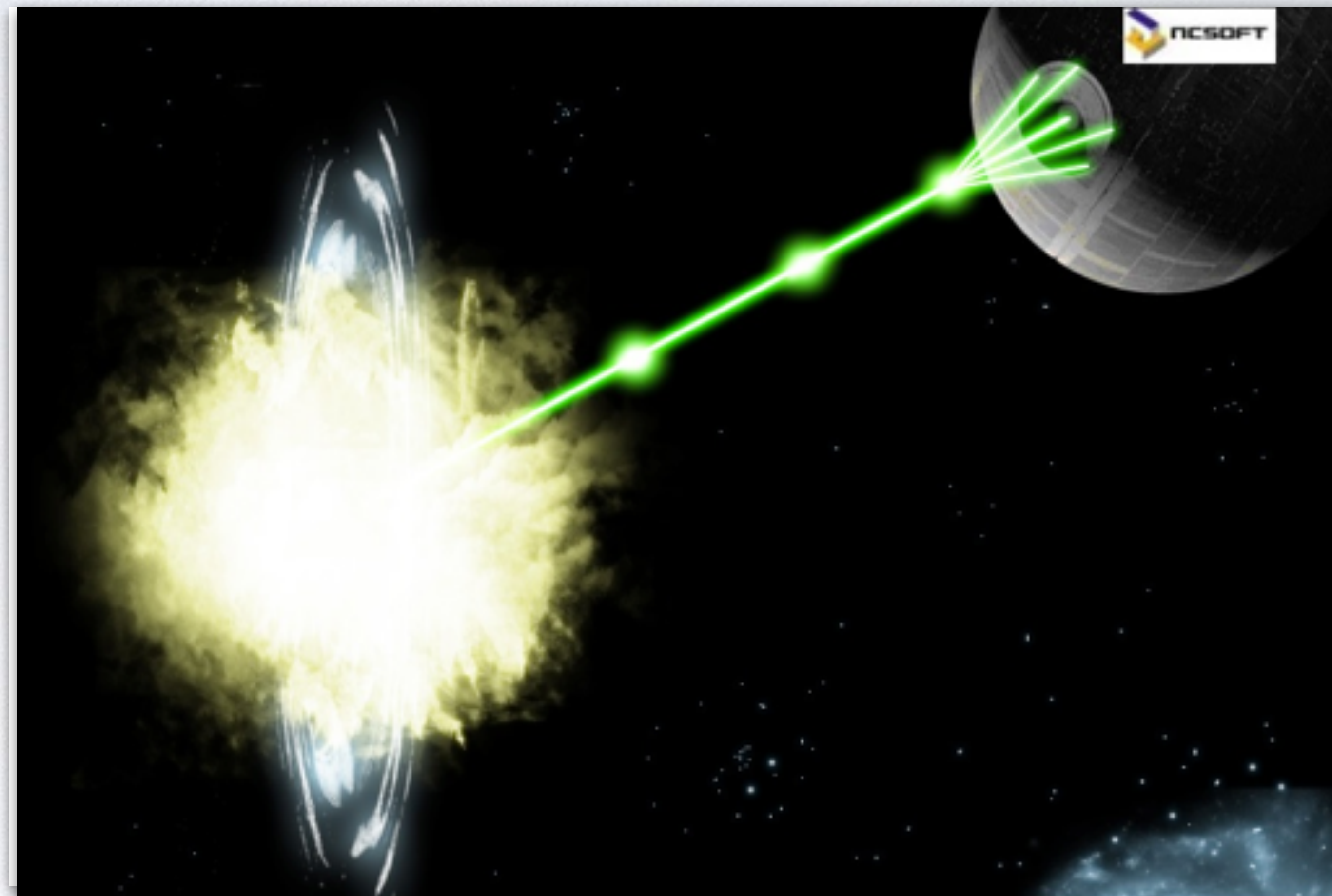
CC's often result in supernova explosions (e.g. 1987A), but none were reported in the LMC at the time.

~ 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)



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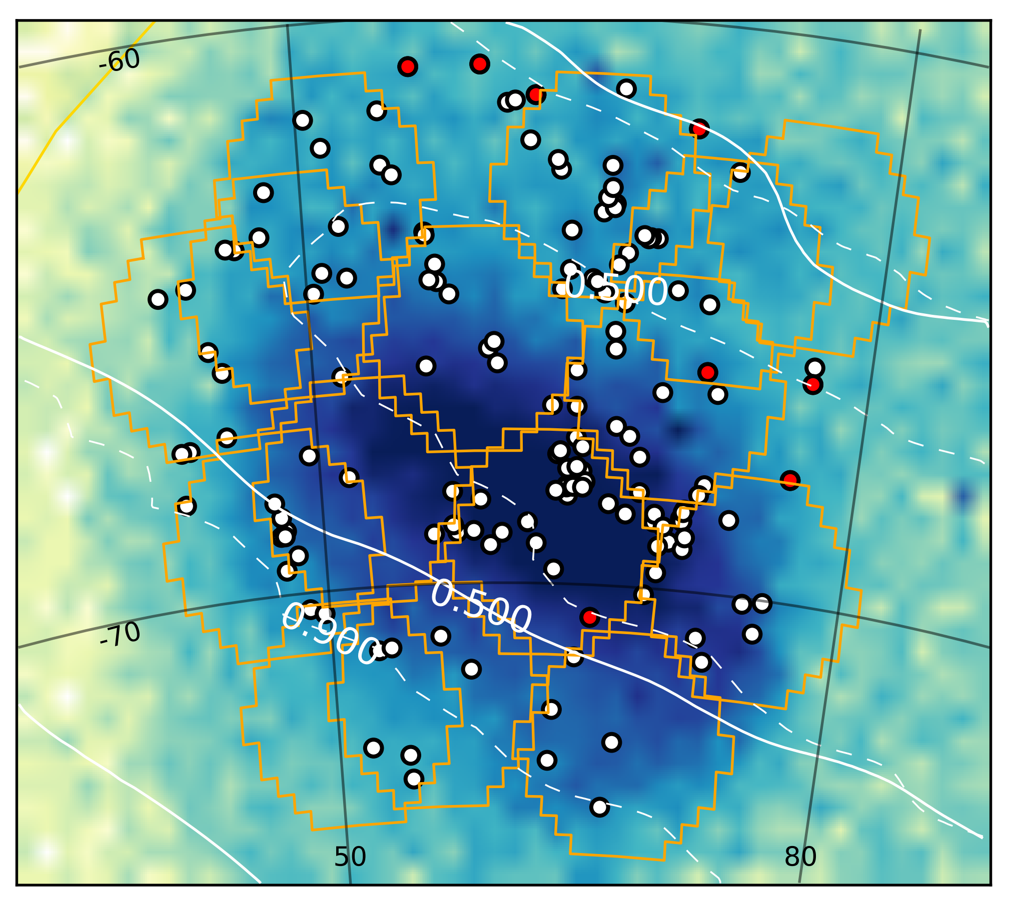
Could GW150914 be associated with a failed SNe?

ANALYSIS 2

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

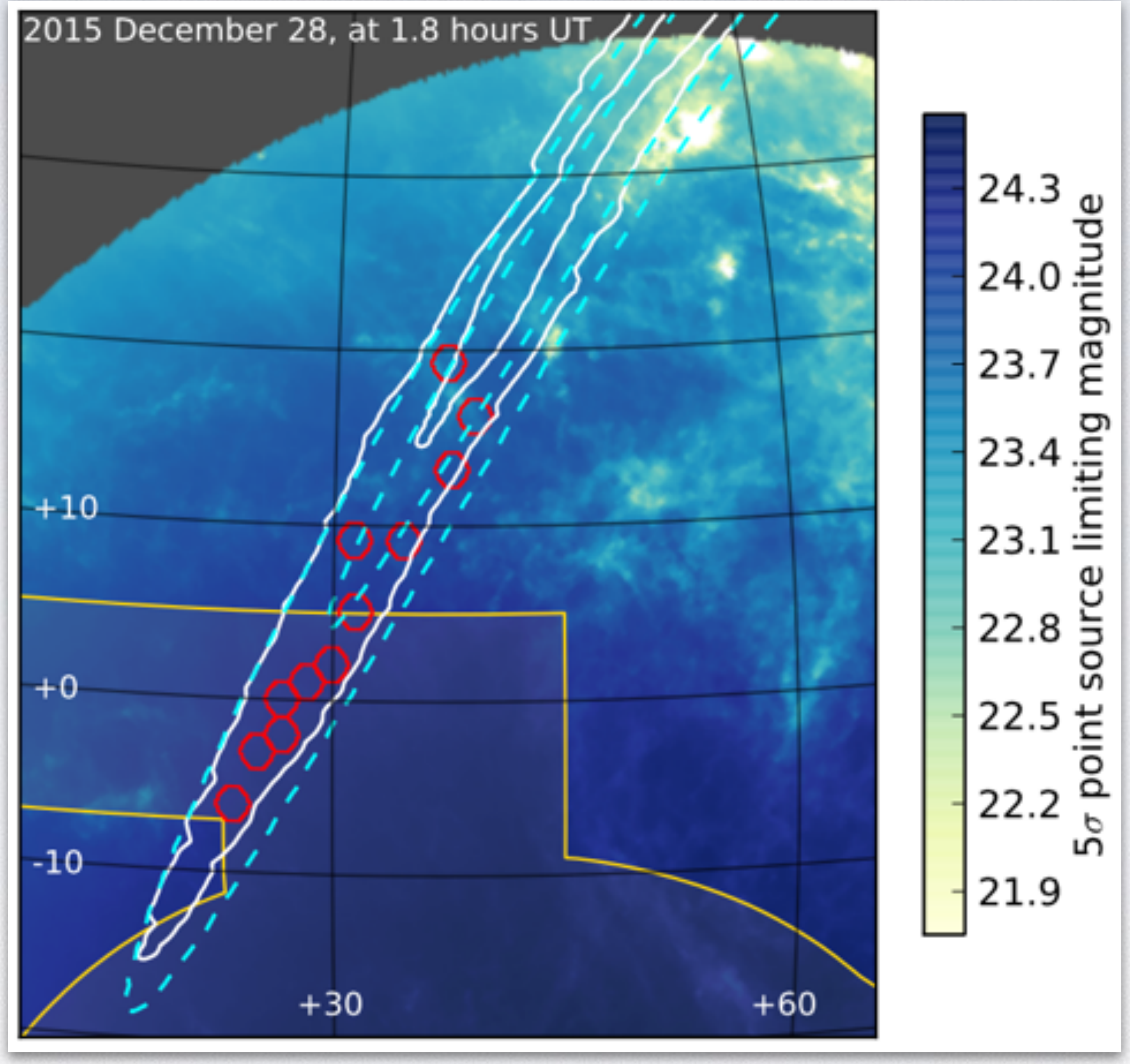
We take possible progenitors (152 red supergiants) catalogued in the literature, and search for them via visual inspection. 144 were in the observed area; all accounted for.



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

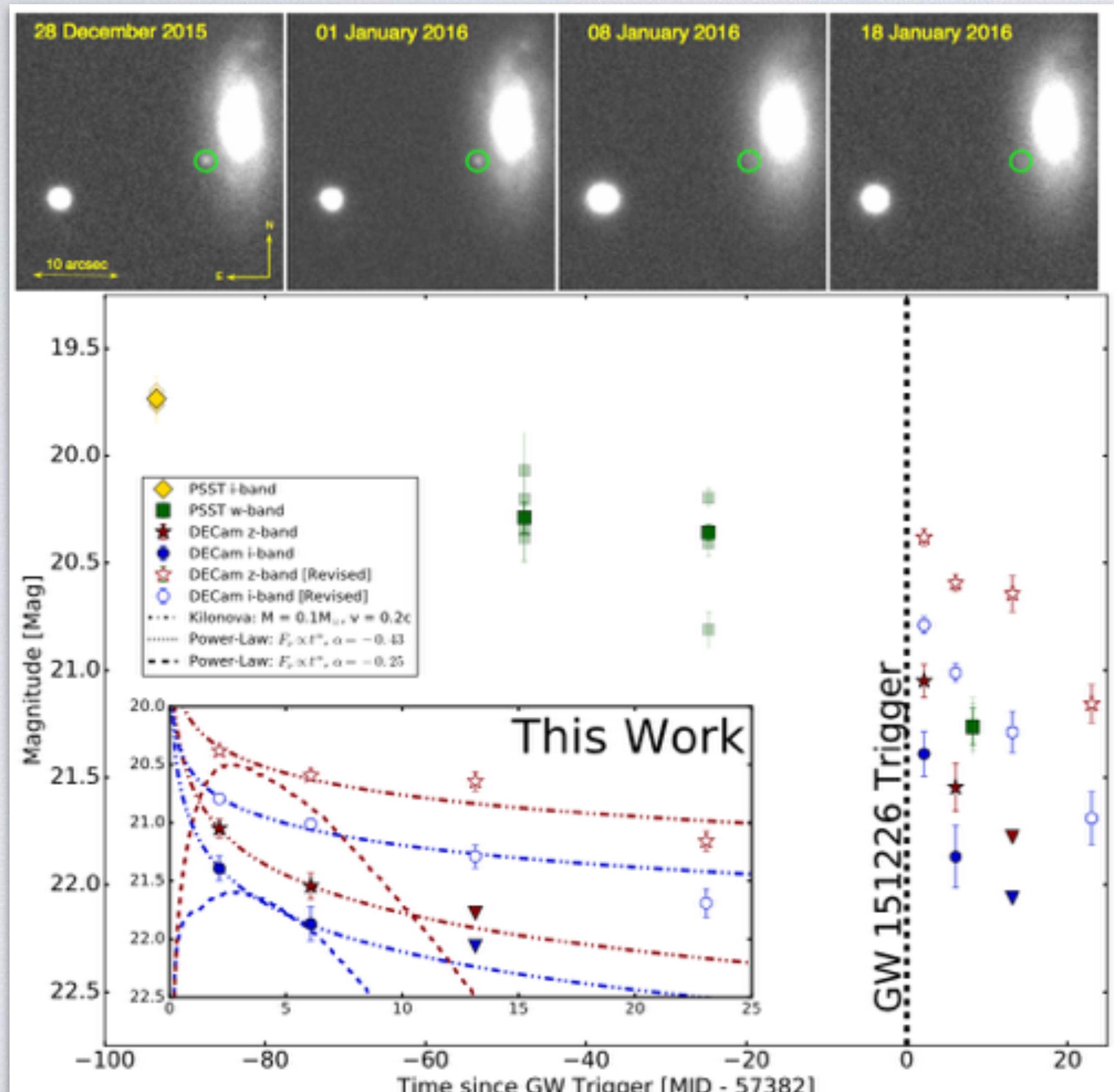
After LIGO's result became public we learned that G150914 was a BBH merger. **This type of search is a template for future GW events, specifically those likely to be a CC event.**

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!

UN-TRIGGERED KN SEARCH

Only a few kilonova (KN) candidates have been observed to date
— all of them as a result of followup observations triggered by gamma-ray burst events.

They are intrinsically rare, and faint, events.

We performed the very first un-triggered KN search ever
— using the DES data taken in the SN fields (deep observations, with ~1 week cadence).

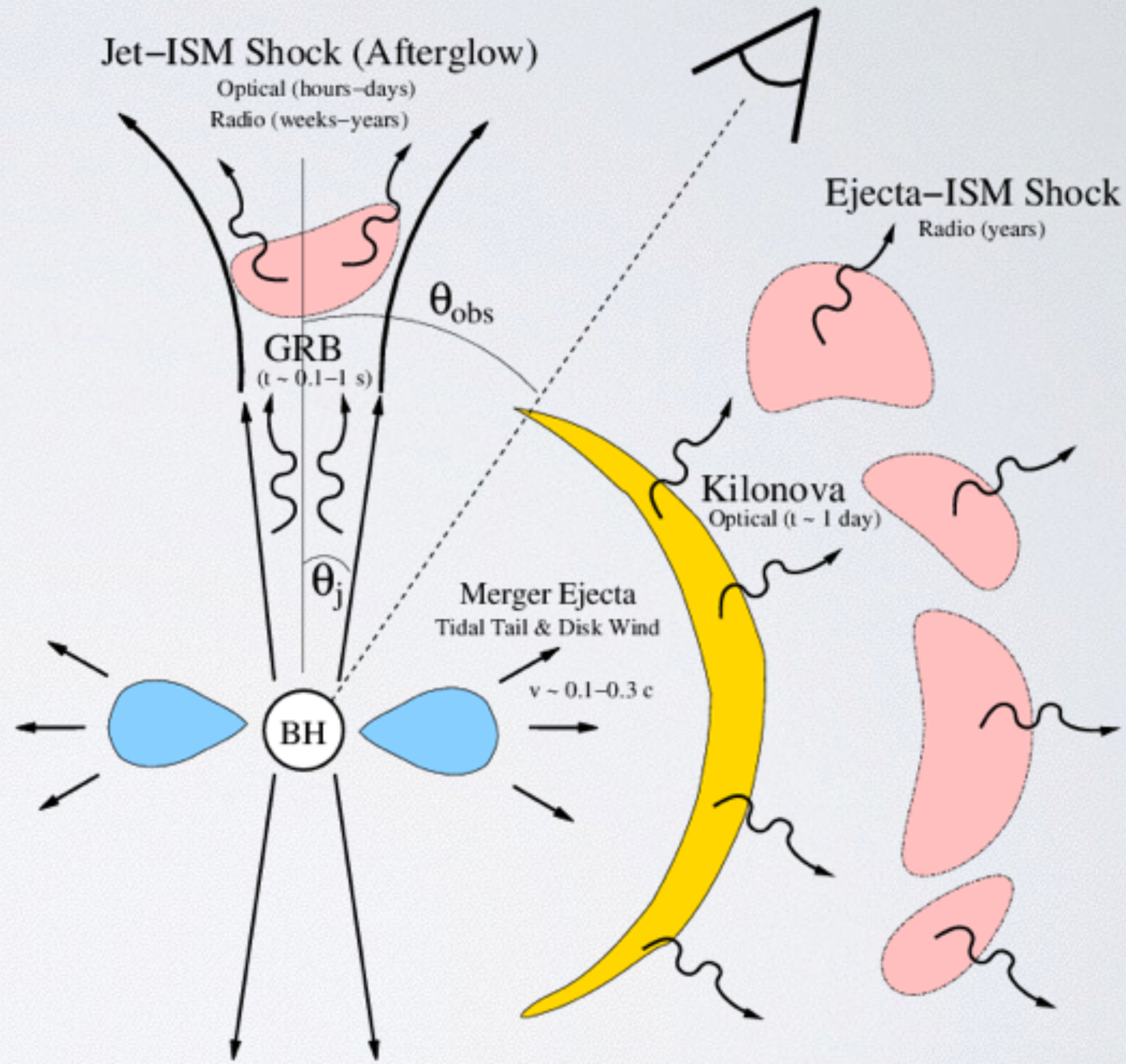
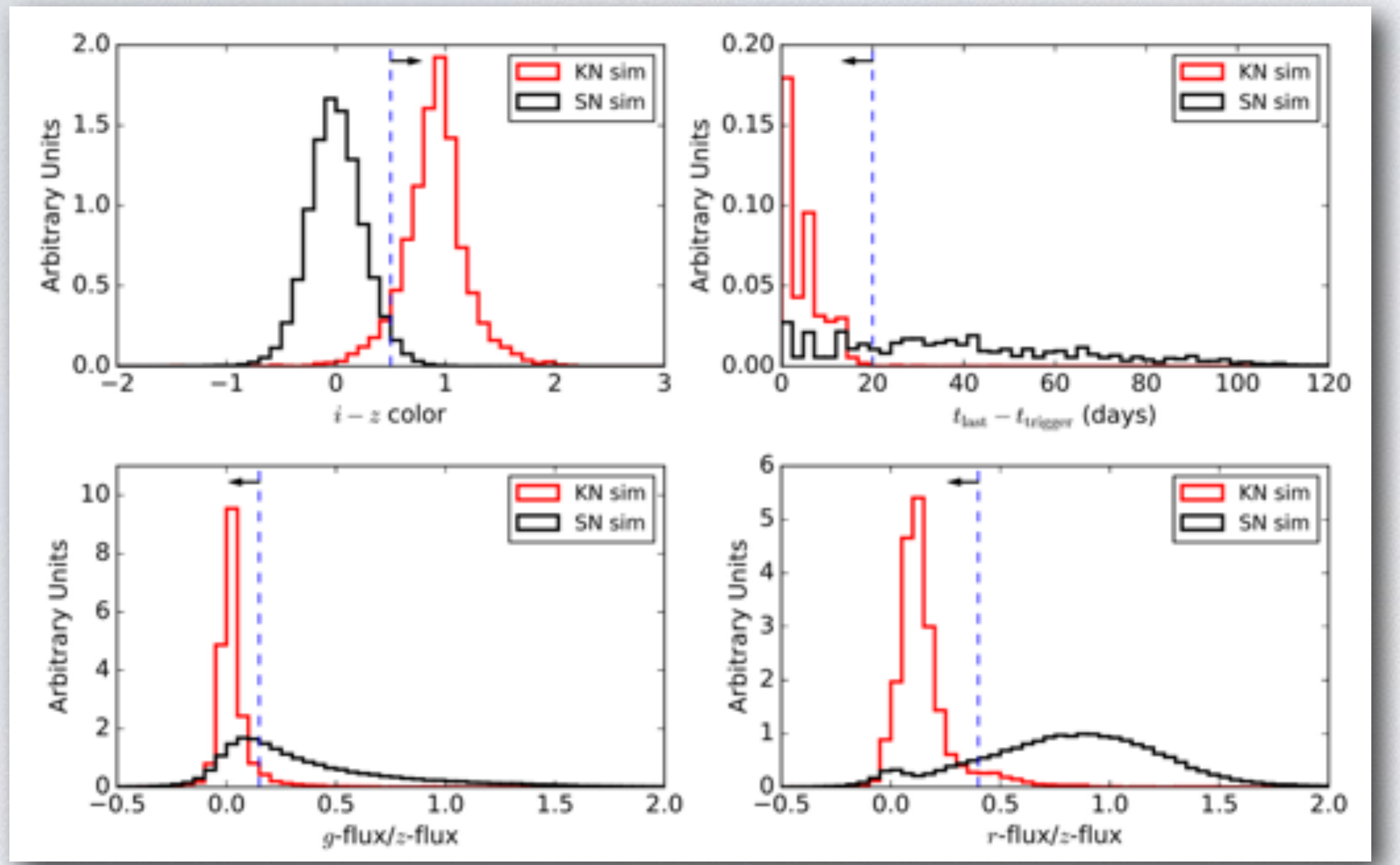
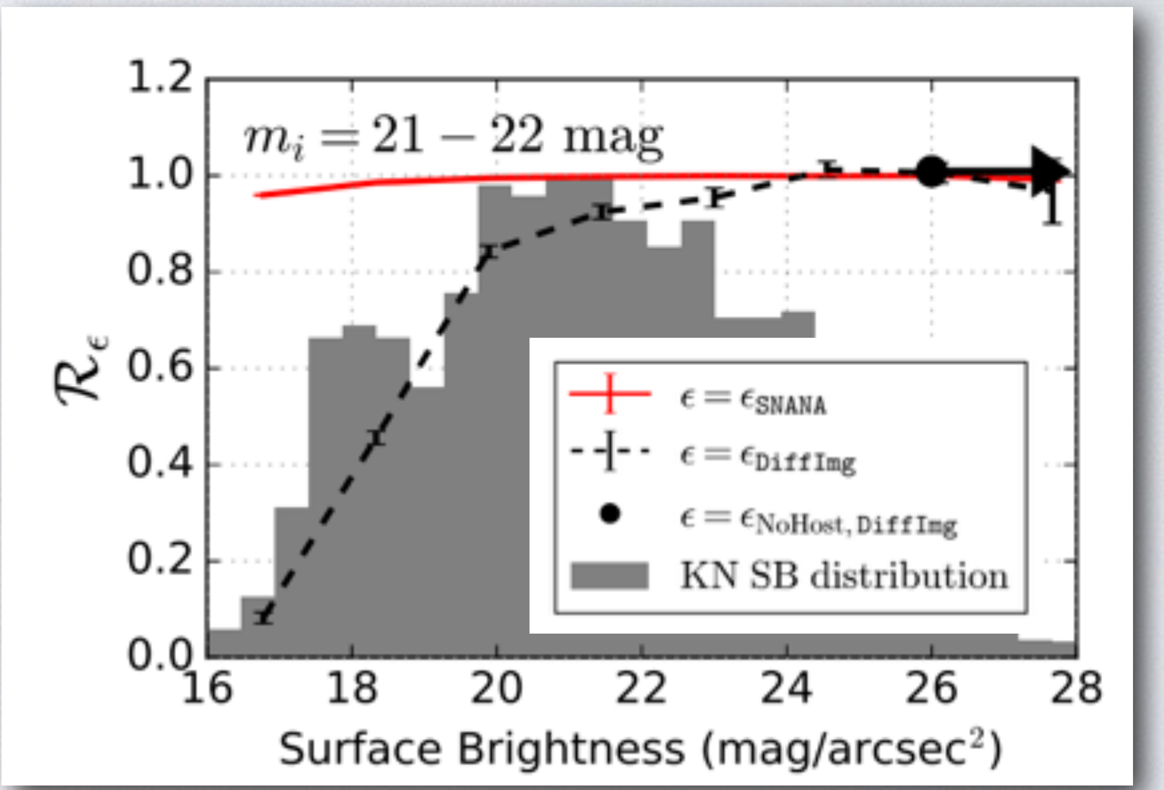


Figure: Metzger & Berger (arXiv: 1108.6056)

ANALYSIS 4

Search for Kilonovae in DES (Doctor et al. 2017)

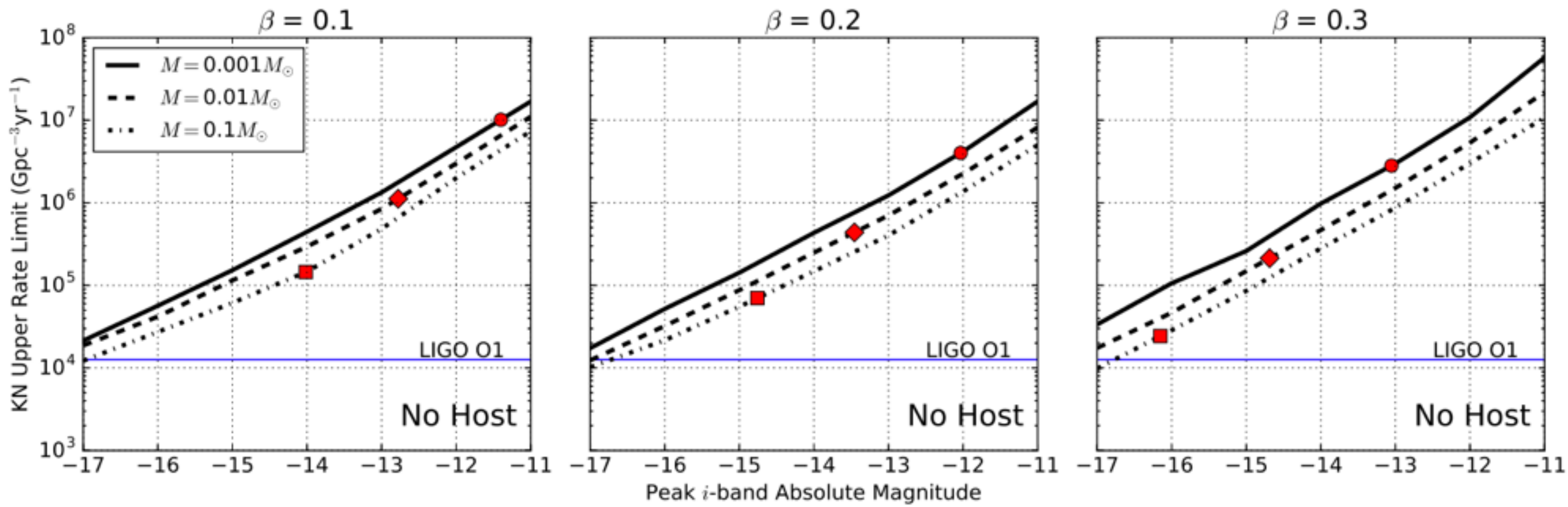




We developed cuts, and studied the efficiency of the search, using simulations. We learned that difference imaging close to bright galaxies is an issue.

ANALYSIS 4

Search for Kilonovae in DES (Doctor et al. 2017)



Results for nine values of the parameters (M, \beta) from Barnes & Kasen 2013 (BK13). The points show results fixing the absolute magnitude parameter to BK13's best fit values. The lines show the results varying the absolute magnitude parameter.

DES GW RESULTS SUMMARY

A search for Kilonovae in the Dark Energy Survey

Doctor, et al. arXiv:1611.08052, ApJ in review

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

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

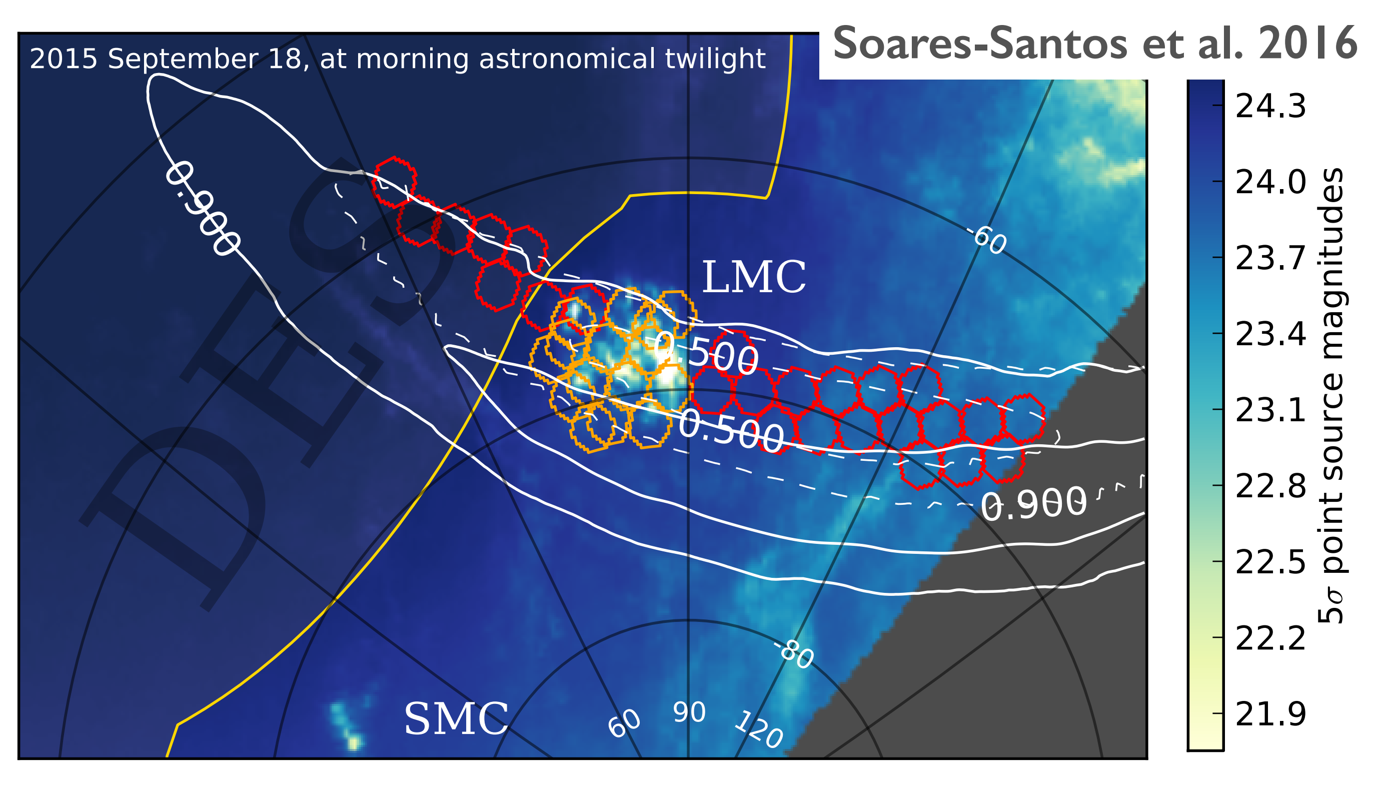
A Dark Energy Camera Search for Missing Supergiants in the LMC after the Advanced LIGO Gravitational Wave Event GW150914

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

Potentially a new cosmological probe!



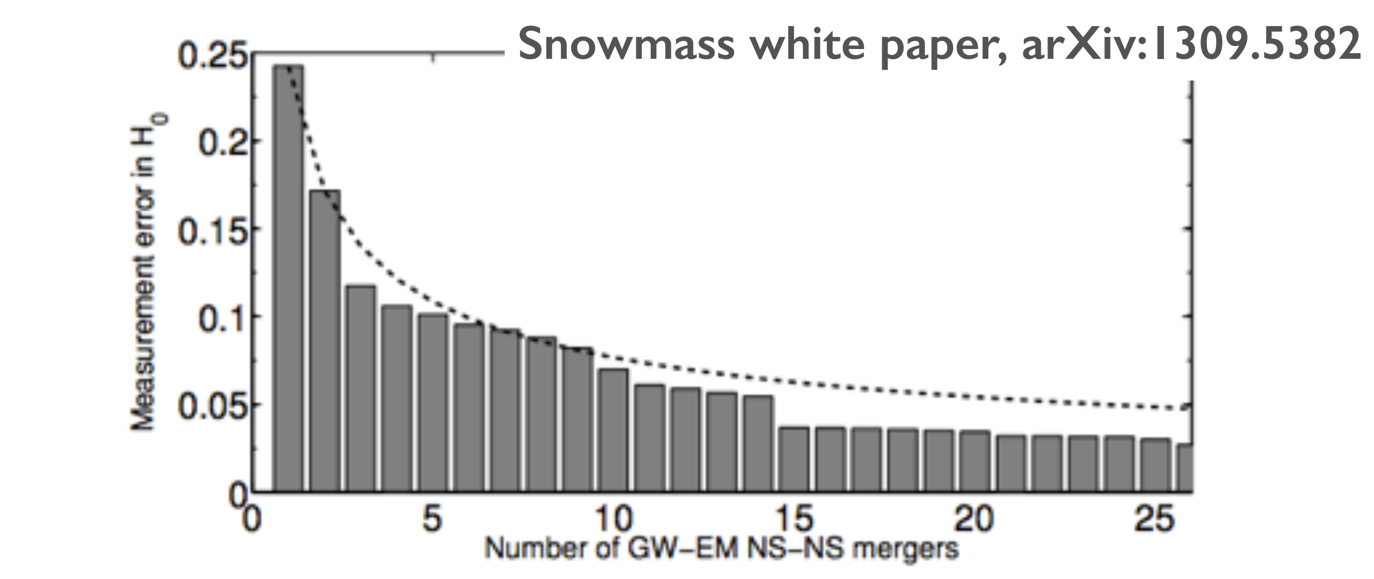


Figure 8: H_0 measurement uncertainty as a function of the number of multi-messenger (GW+EM) double neutron star merger events observed by an advanced LIGO-Virgo network. The dashed line shows Gaussian convergence.

MIND THE GAPS!

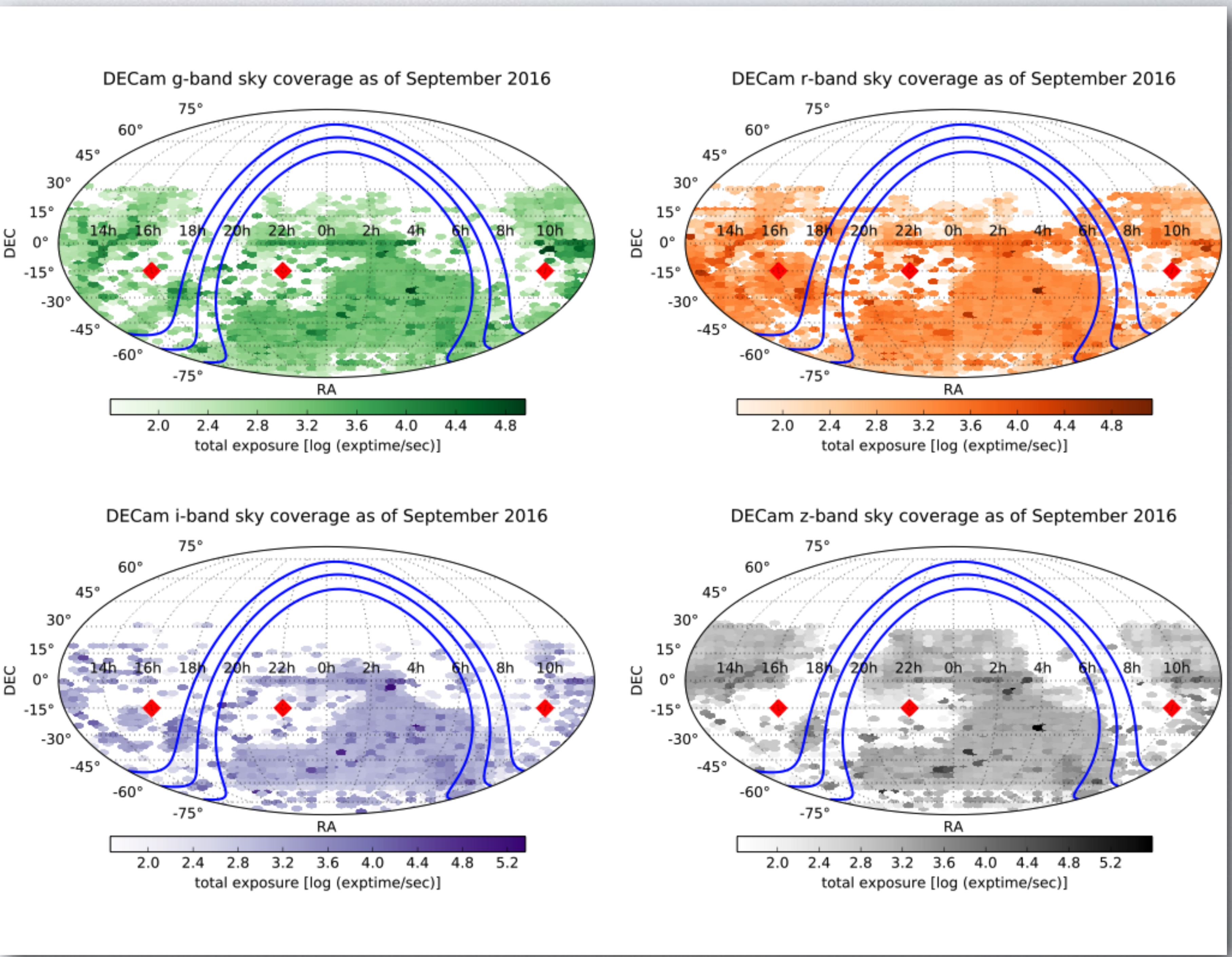
Blanco Images of the Southern Sky (BLISS)

Designed to complete the accessible sky coverage before LSST.

Science cases:

— GW
— Dwarf galaxies
— Planet 9

Pilot program: 10^3deg^2
11.5 nights in 2017A
(PI: Soares-Santos)



UPGRADES, PROSPECTS

Developed separate ***observing strategies*** for
— ***bright*** sirens (mergers with at least one neutron star)
— ***dark*** sirens (e.g. binary black holes, for which we have no EM model)

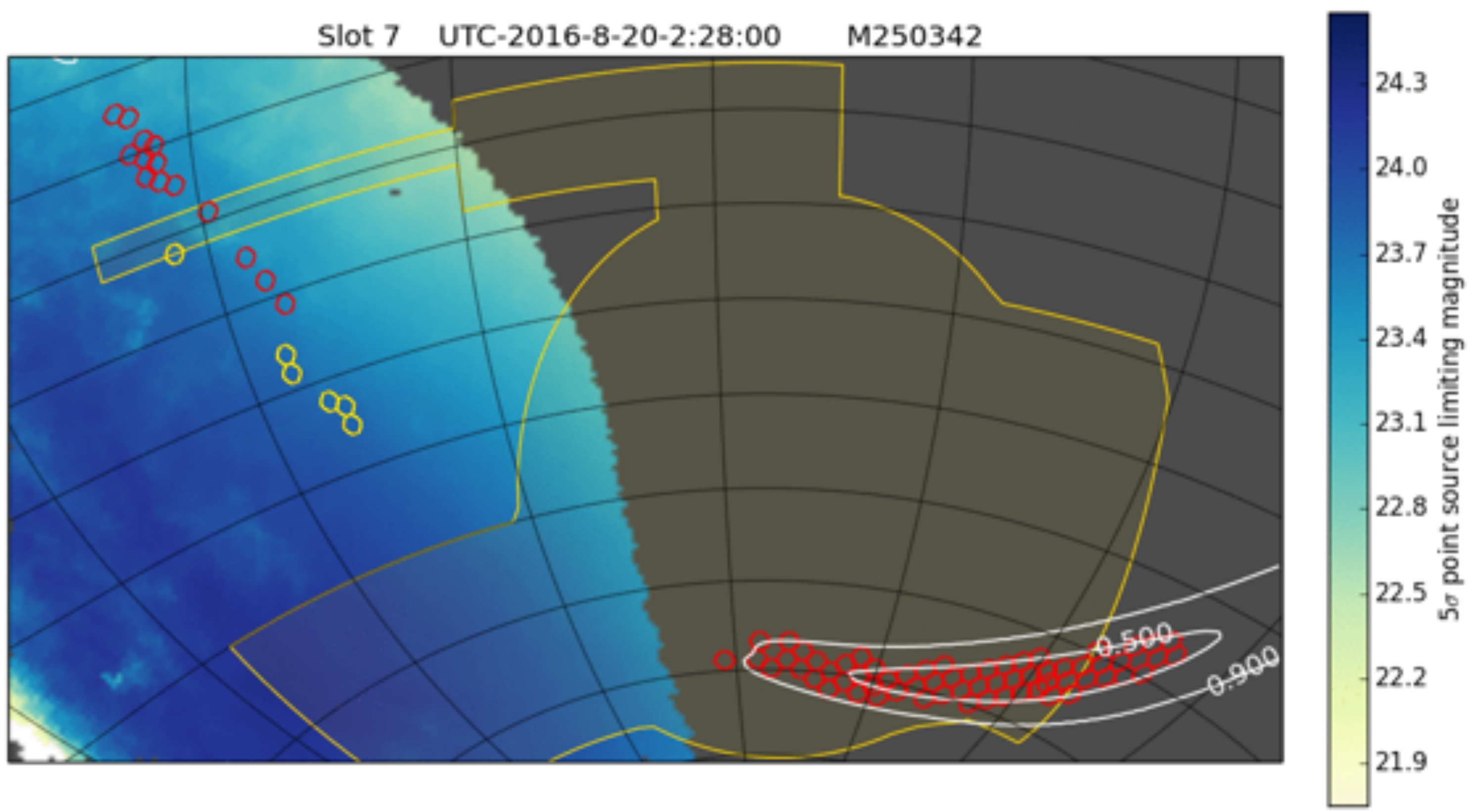
We are improving our ***processing times*** to ~24h and prepared to engage ***spectroscopic*** and ***multi-wavelength*** resources to confirm candidates.

We will start gathering ***more templates***, with ***BLISS***.

If nature continues to be so kind, soon we expect to have
— First limits on optical emission for binary black hole mergers
— First searches for a merger involving a neutron star

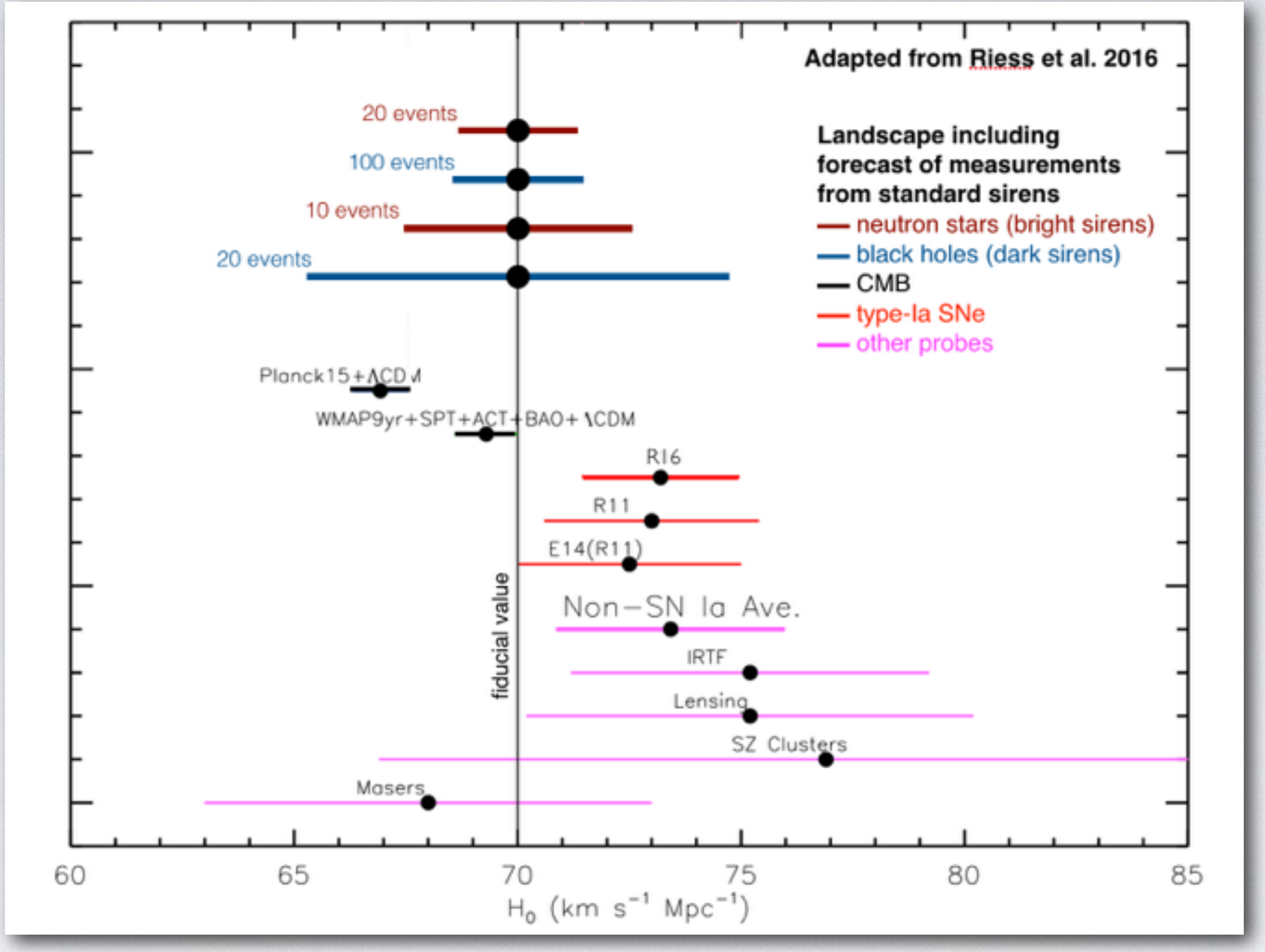
In the long run, we want to combine ~20 good detections to obtain a measurement with 3% uncertainty.
— That will allow us to contribute to the Hubble parameter debate and set the stage for percent-level precision with LSST in the 2022 and beyond!

SIMULATED O2 EVENT



We have improved the visualization tools too!

COSMOLOGY MOTIVATION



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

The second observing run is ongoing. Stay tuned for more exciting results coming soon!