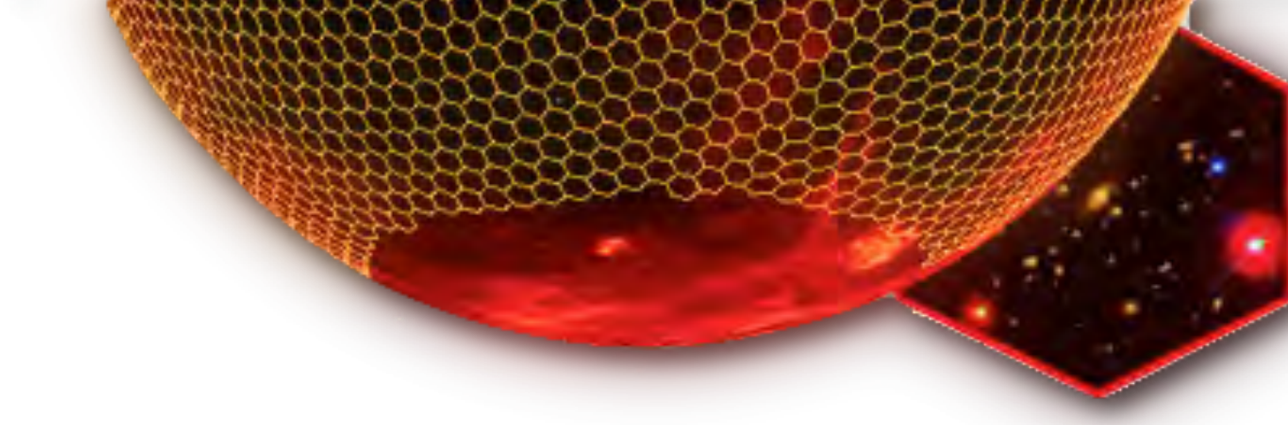

The **D**ark **E**nergy **S**urvey: Early Results

Brian Nord for the DES Collaboration
Fermilab

UCLA Dark Matter 2016
February 17, 2016

Sneak Preview

- The Dark Energy Survey (DES)
  - Instrument: *Dark Energy Camera*
  - Footprint and Survey Progress
- Recent results from early DES data
  - Strong lens discoveries
  - Mapping dark matter with weak lensing
  - Galaxy cluster observations

Sneak Preview

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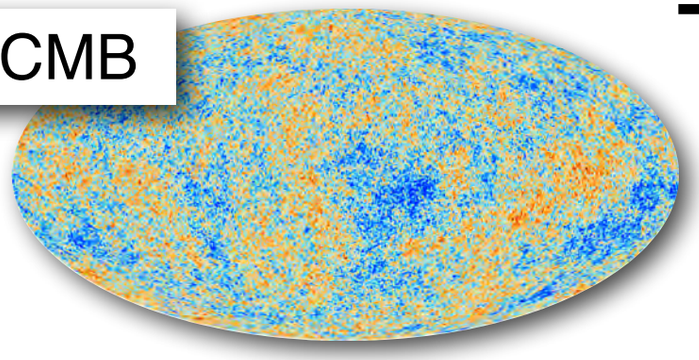
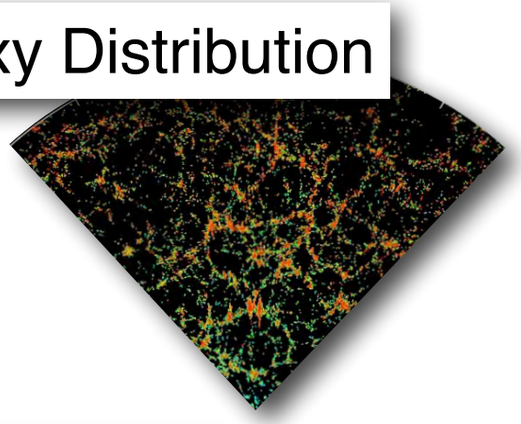
50 billion years
in the future

A Tug of War:
Complementary Probes

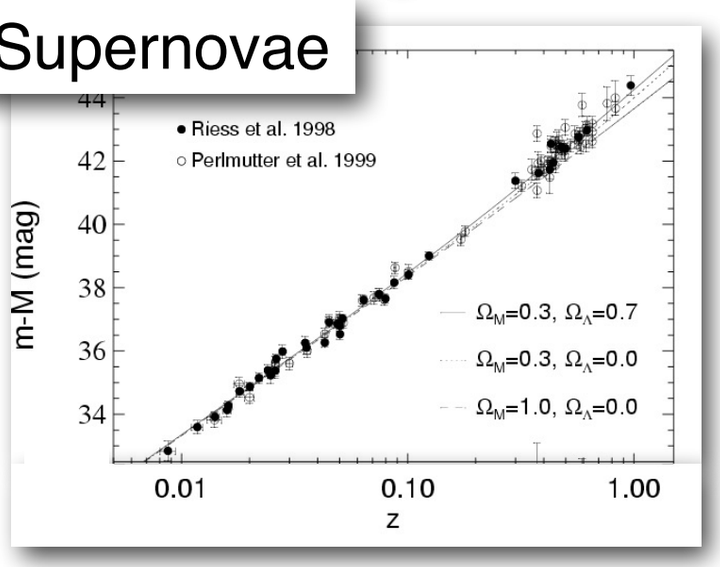
CMB



Galaxy Distribution



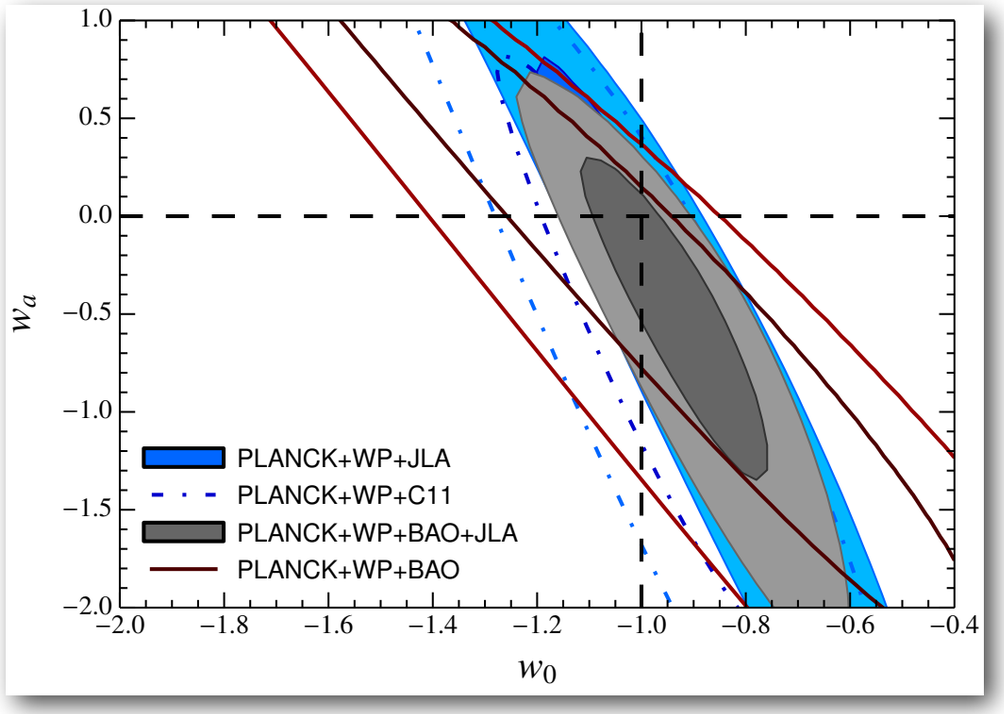
Supernovae



Geometry
+
Expansion
+
Structure
Growth

Evolving DE equation of state:

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

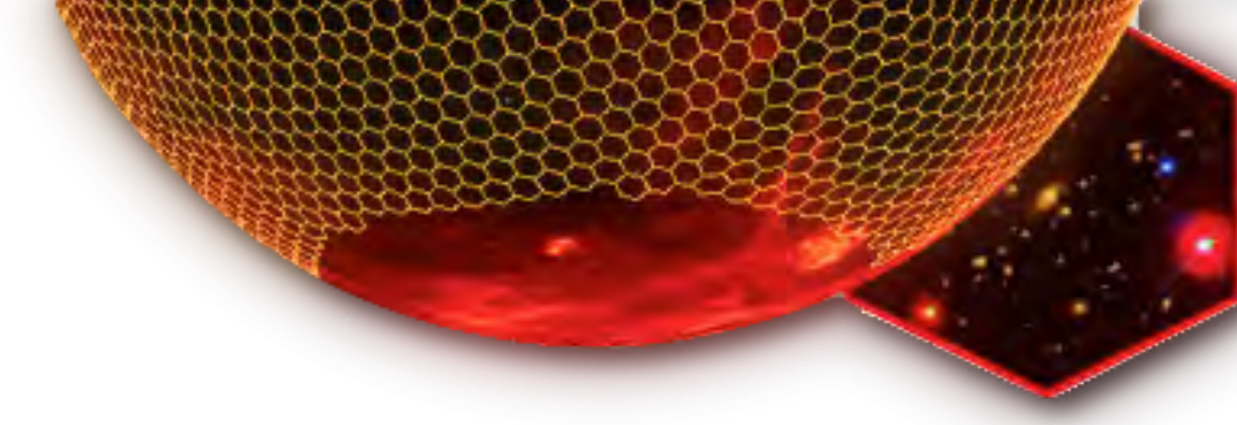


State of the art constraints:

w_0 = -0.957 ± 0.124 (~13%)

w_a = -0.336 ± 0.552 (~164%)

Betoule++2014



Dark **E**nergy **S**urvey

Hello from the dark siiiide

Expansion and Structure Growth

Multiple Probes, One Experiment

- *<u>Weak Lensing:</u> (structure)*
  - 200 million galaxy shapes
- *<u>Galaxy Clusters:</u> (structure)*
  - ~10,000s clusters to z>1
- *<u>Supernovae:</u> (expansion)*
  - ~3000 well-sampled SNe Ia to z ~1
- *<u>Large-scale galaxy distribution:</u> (expansion)*
  - 300 million galaxies to z > 1

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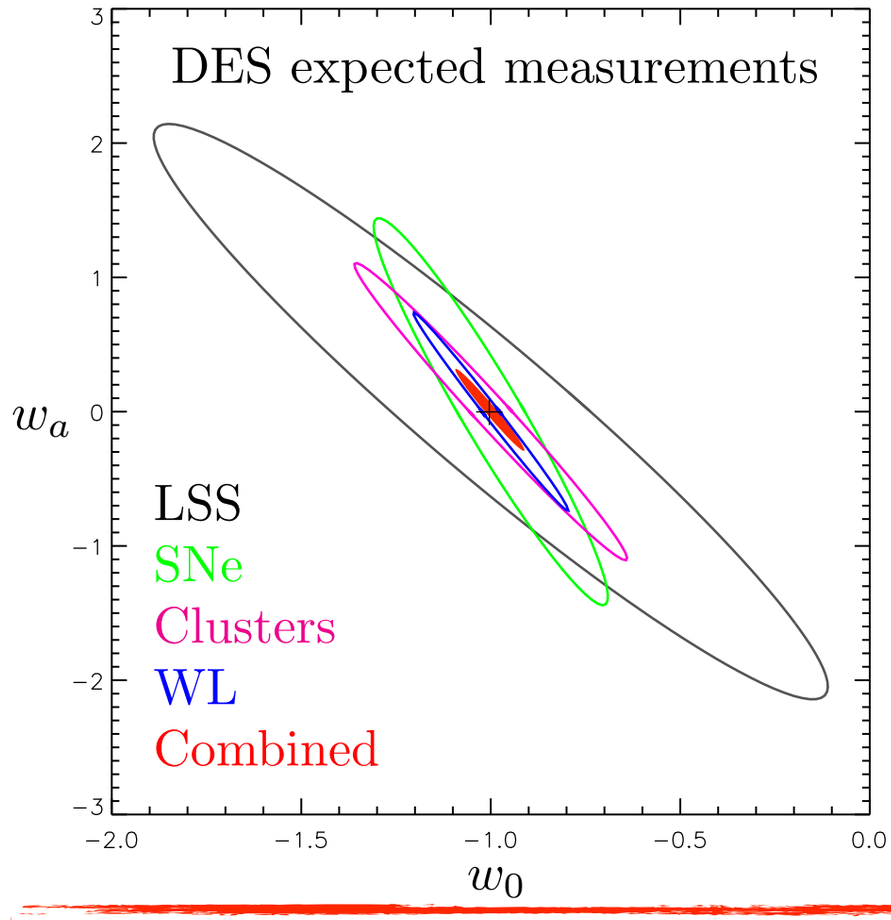

<u>Predicted DES Constraints:</u>

w_0 to ~5%

w_a to ~30%

Expansion and Structure Growth

Multiple Probes, One Experiment

- *Strong Lensing:* *(structure and expansion)*
  - ~2,000 galaxy-/cluster-scale lenses
- *Weak Lensing:* *(structure)*
  - 200 million galaxy shapes
- *Galaxy Clusters:* *(structure)*
  - ~10,000s clusters to z>1
- *Supernovae:* *(expansion)*
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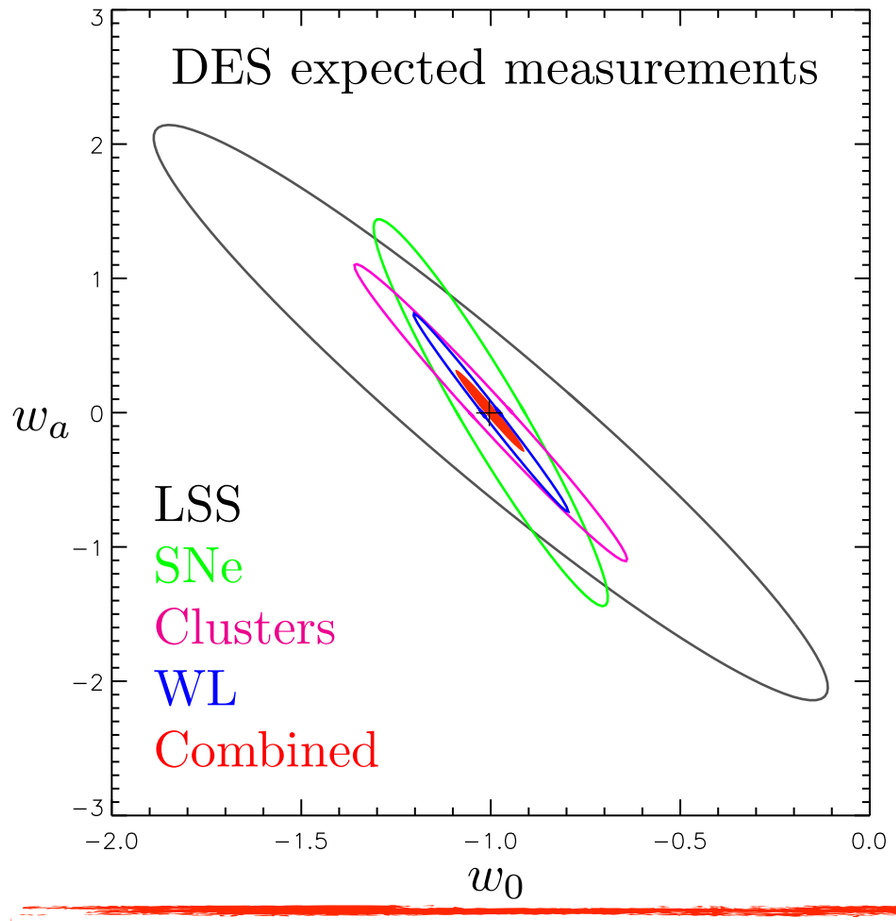

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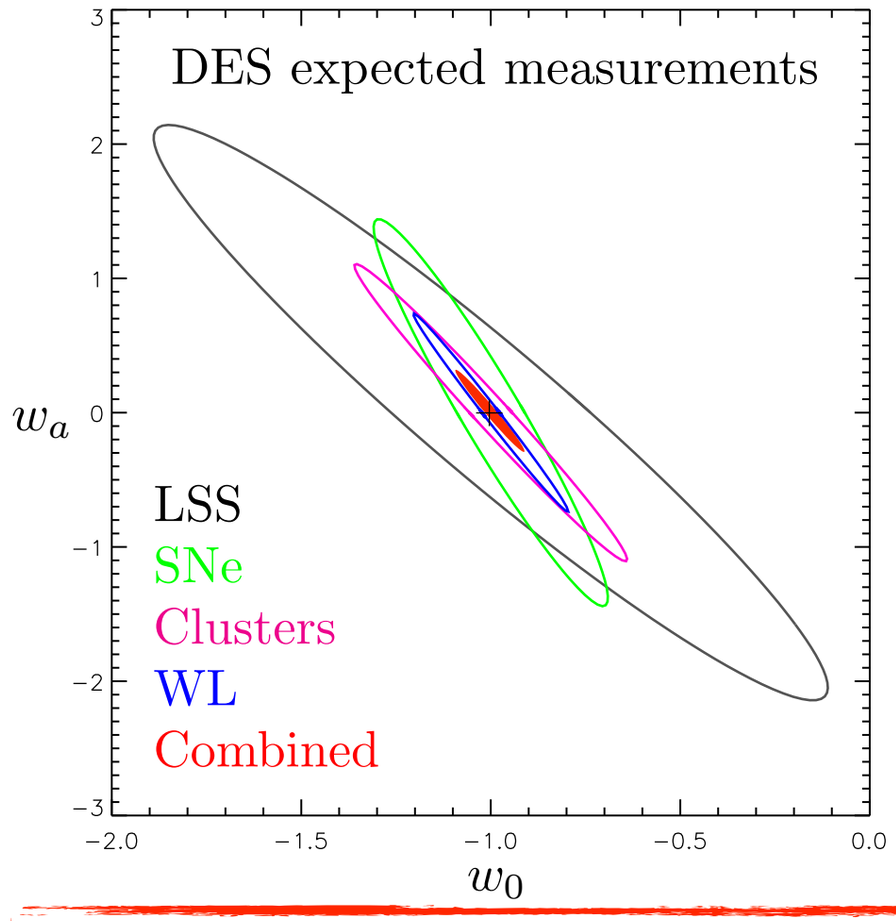

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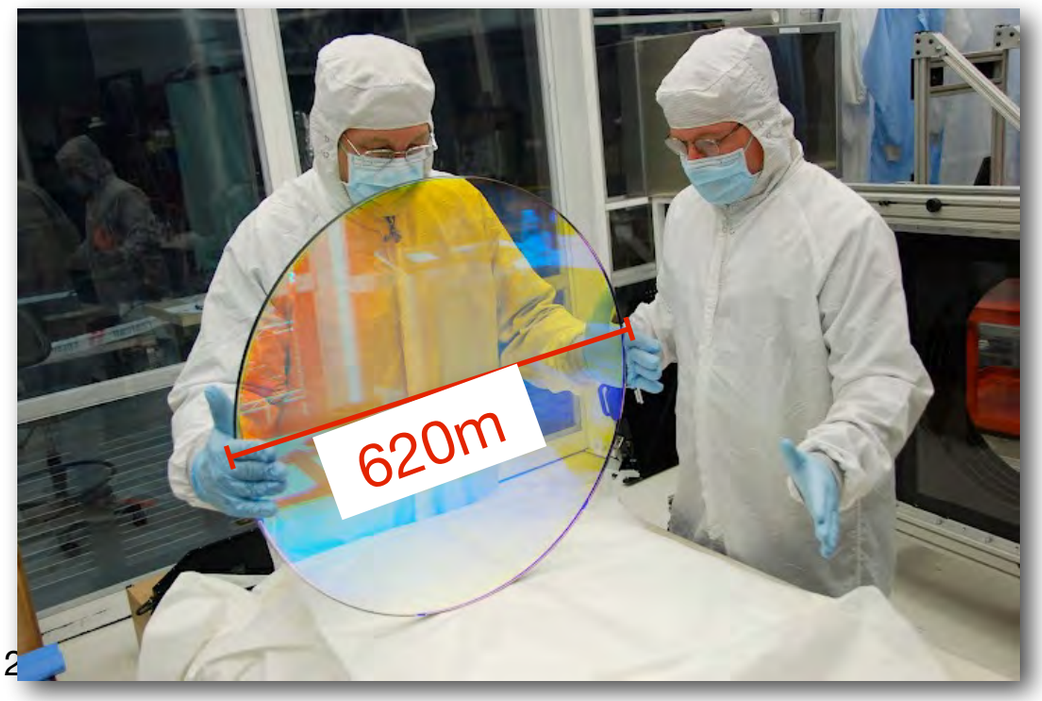
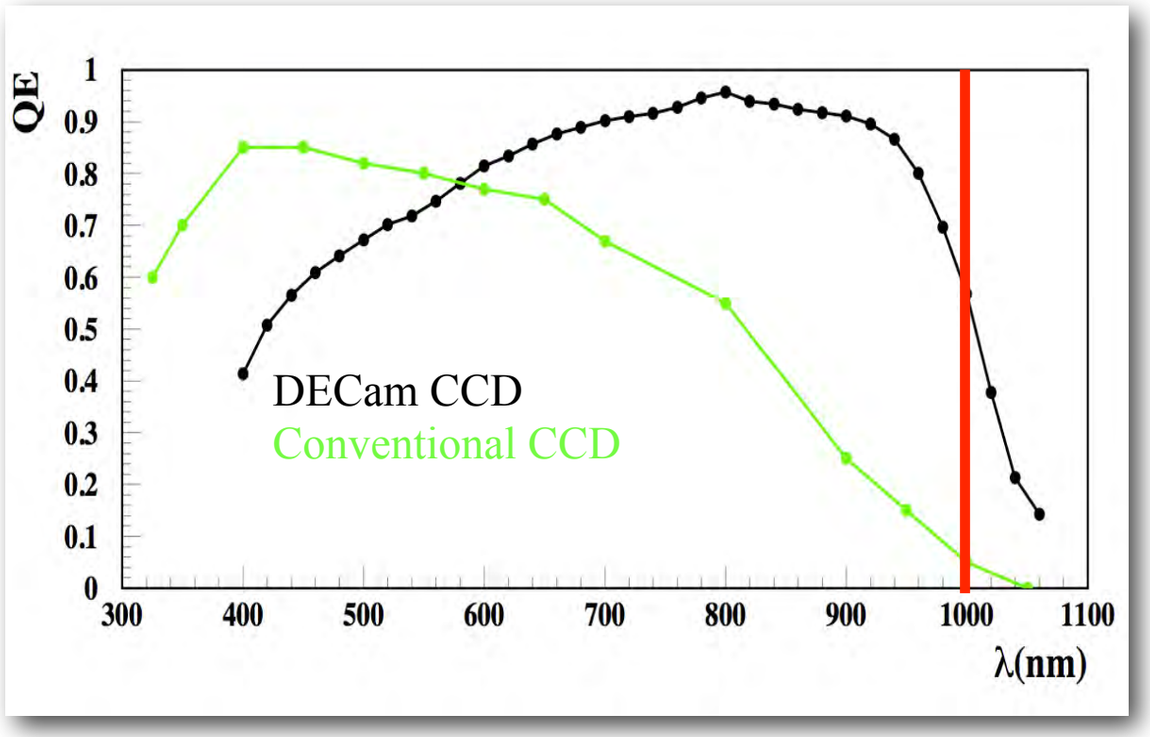
DECam installed in 2012

courtesy 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





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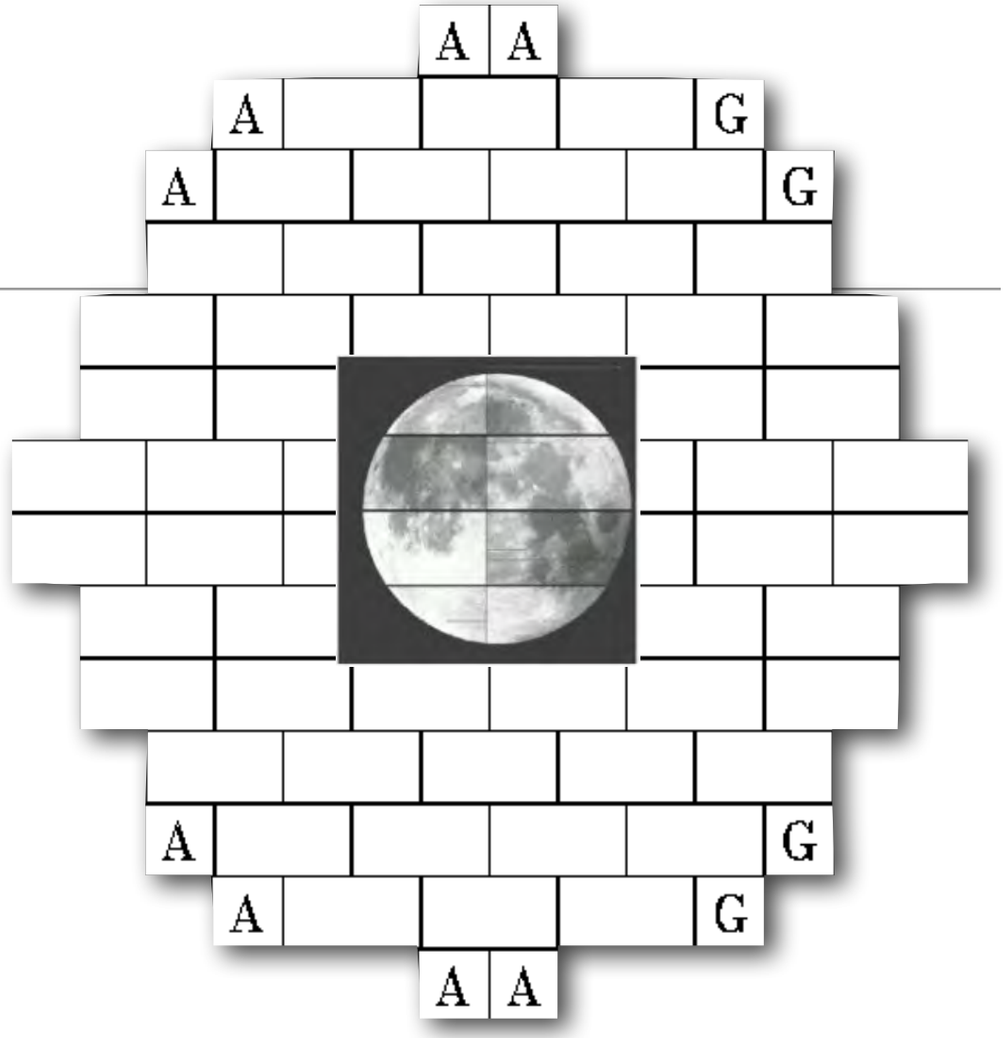
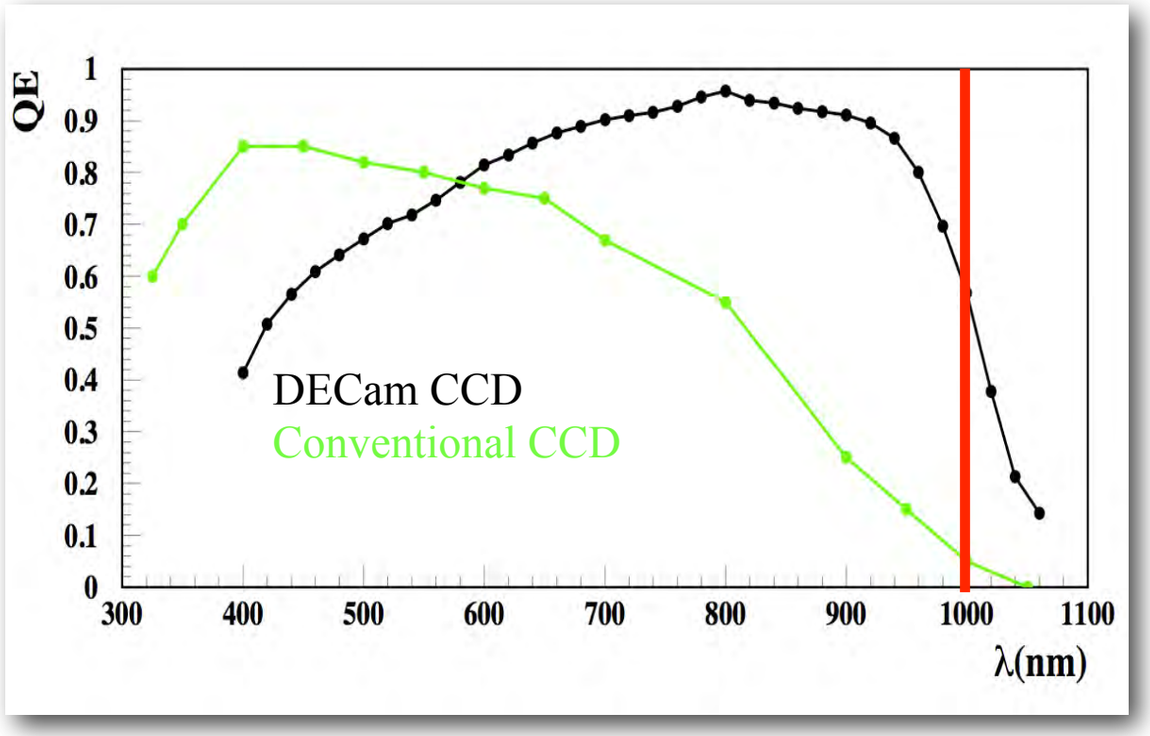
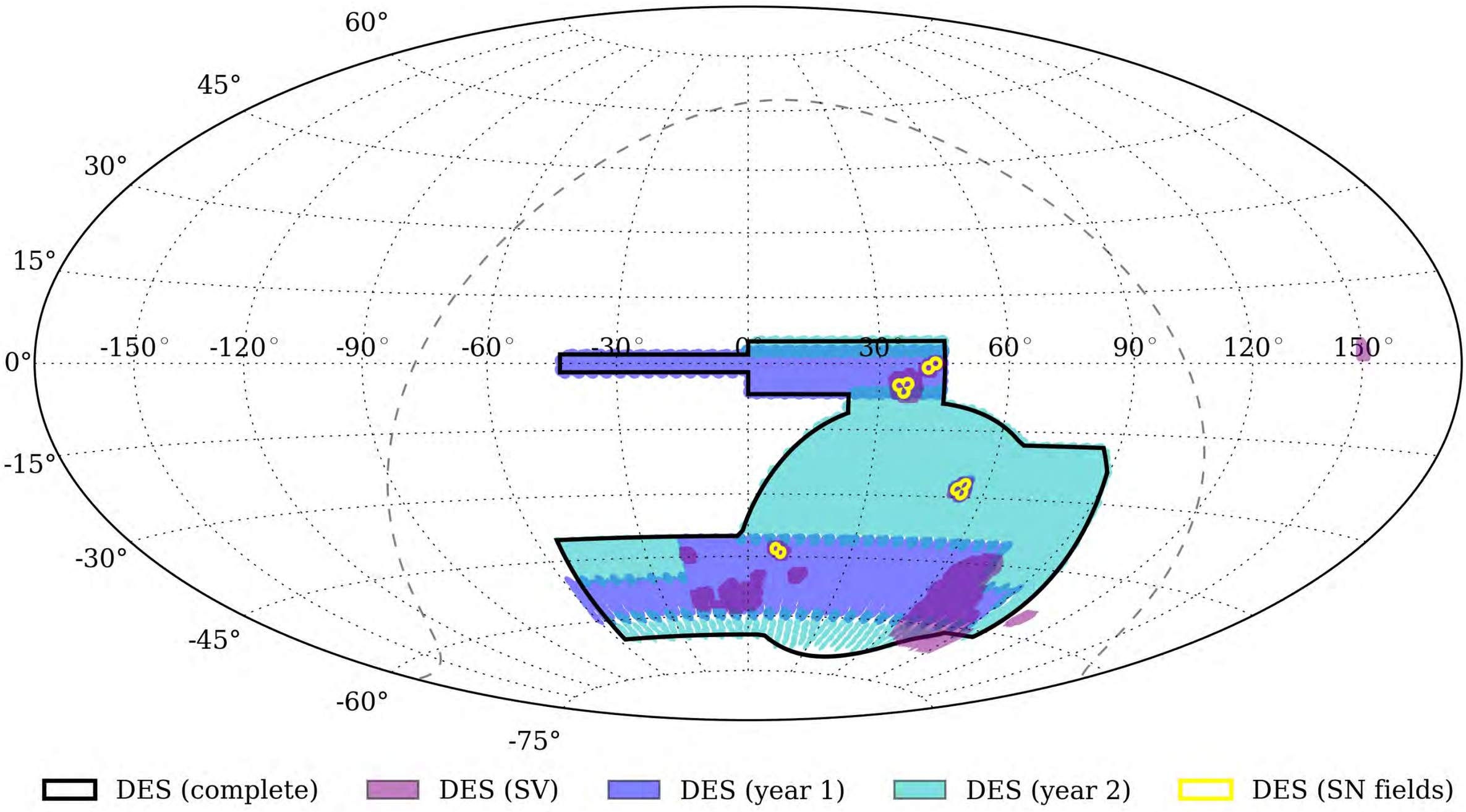




Survey Footprint

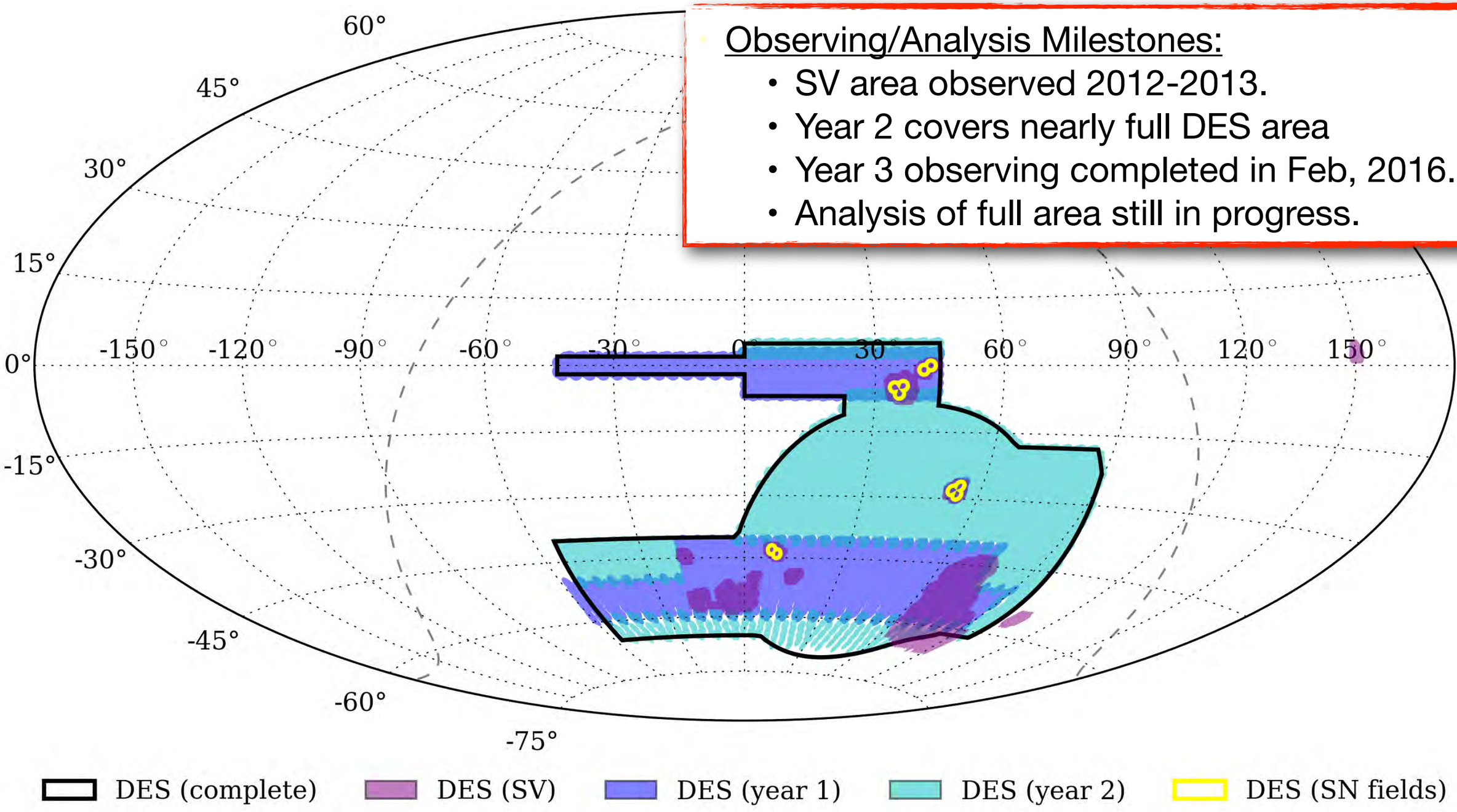
- ***250 sq. deg.:*** **Science Verification (SV)**
- ***5000 sq. deg.:*** **Total area**

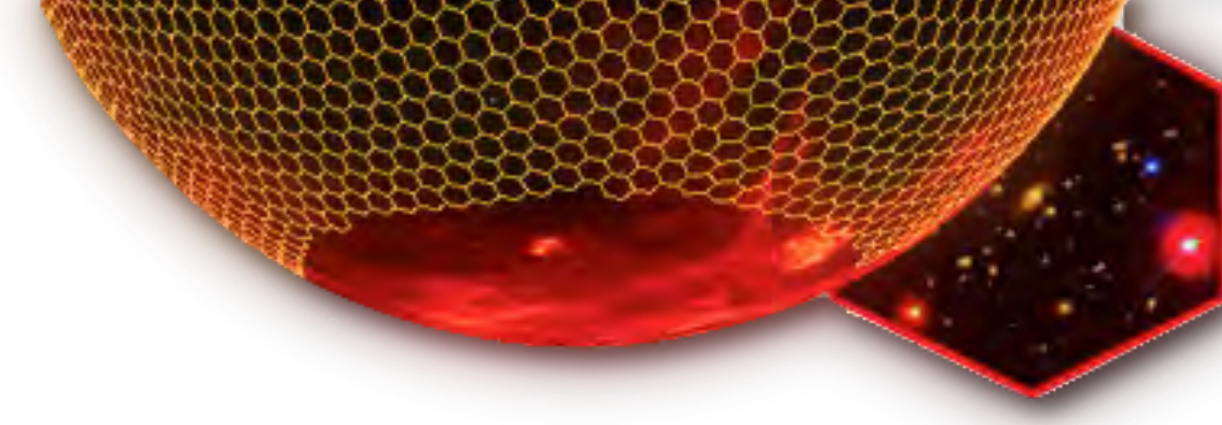


Survey Footprint

- ***250 sq. deg.:*** **Science Verification (SV)**
- ***5000 sq. deg.:*** **Total area**

- <u>Observing/Analysis Milestones:</u>
  - SV area observed 2012-2013.
  - Year 2 covers nearly full DES area
  - Year 3 observing completed in Feb, 2016.
  - Analysis of full area still in progress.





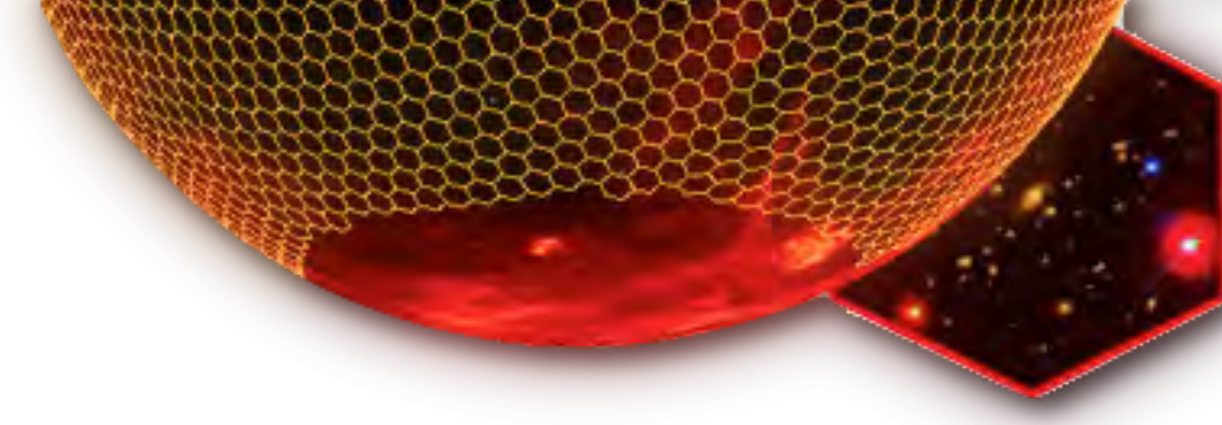
Early Results from Science Verification Season

Strong Lensing
Weak Lensing
Galaxy Clusters

It takes a (big) village

~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
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



Early Results from Science Verification Season

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Weak Lensing
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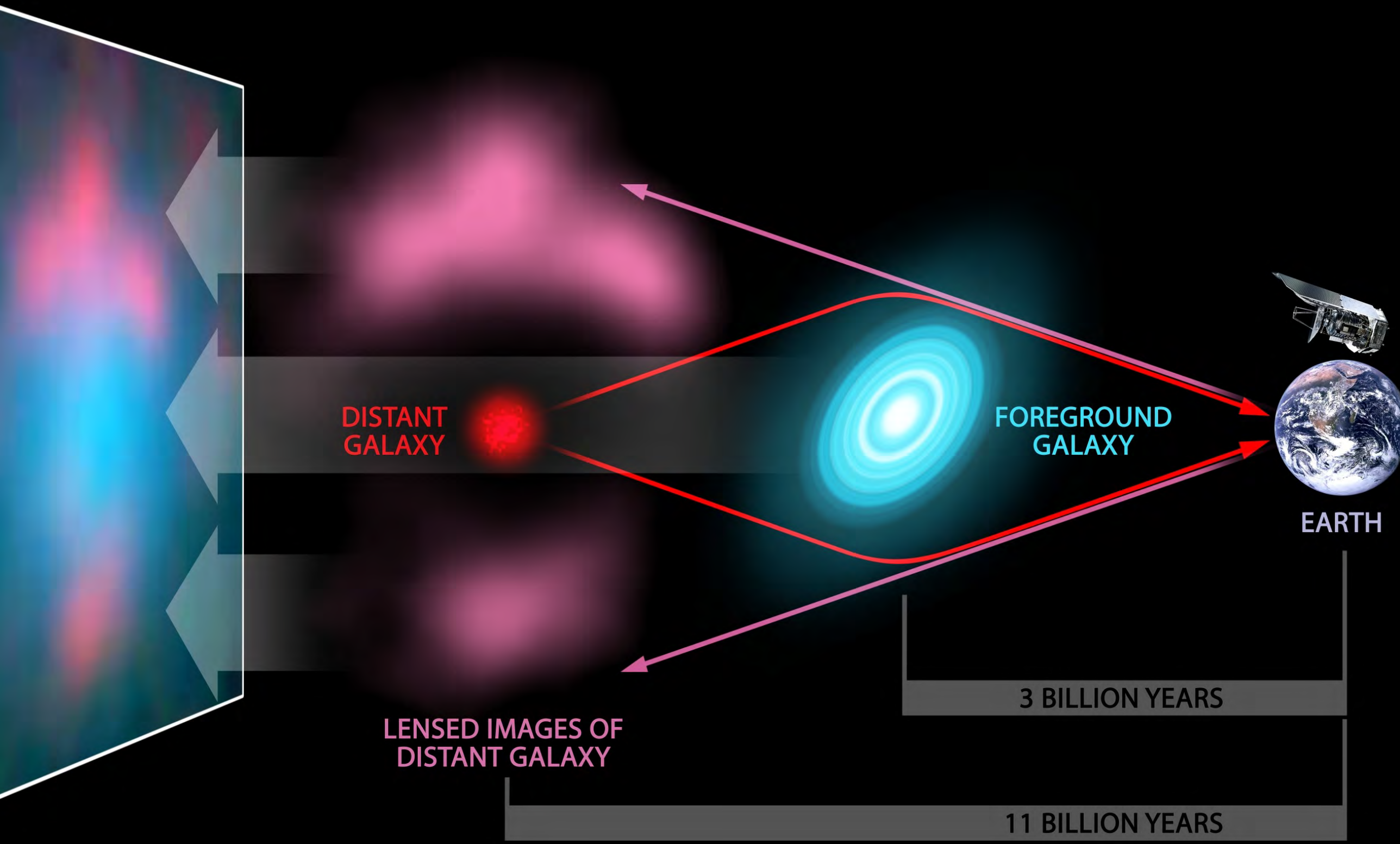
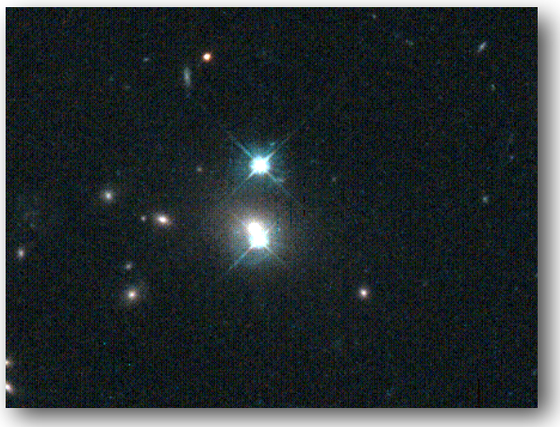
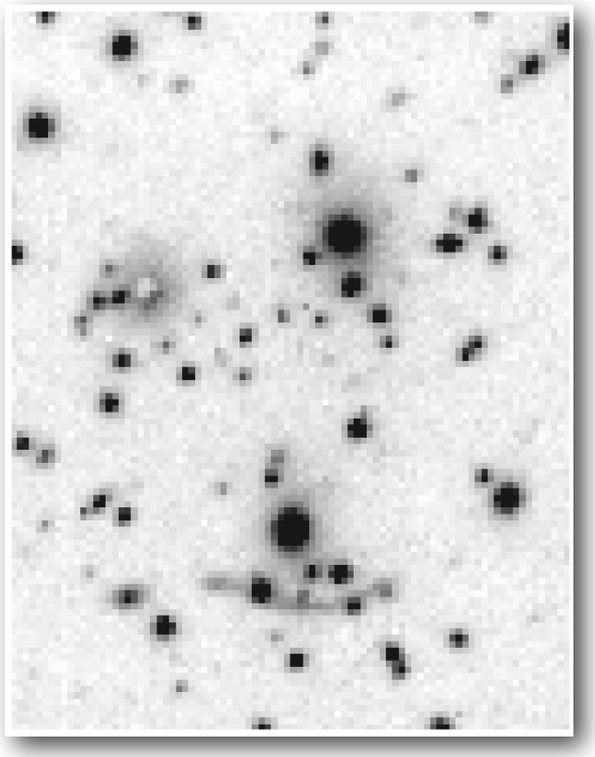

DISTANT GALAXY
FOREGROUND GALAXY
EARTH
3 BILLION YEARS
LENSED IMAGES OF DISTANT GALAXY
11 BILLION YEARS

Strong Lens Forecasts for DES

- 1979: First lensed system



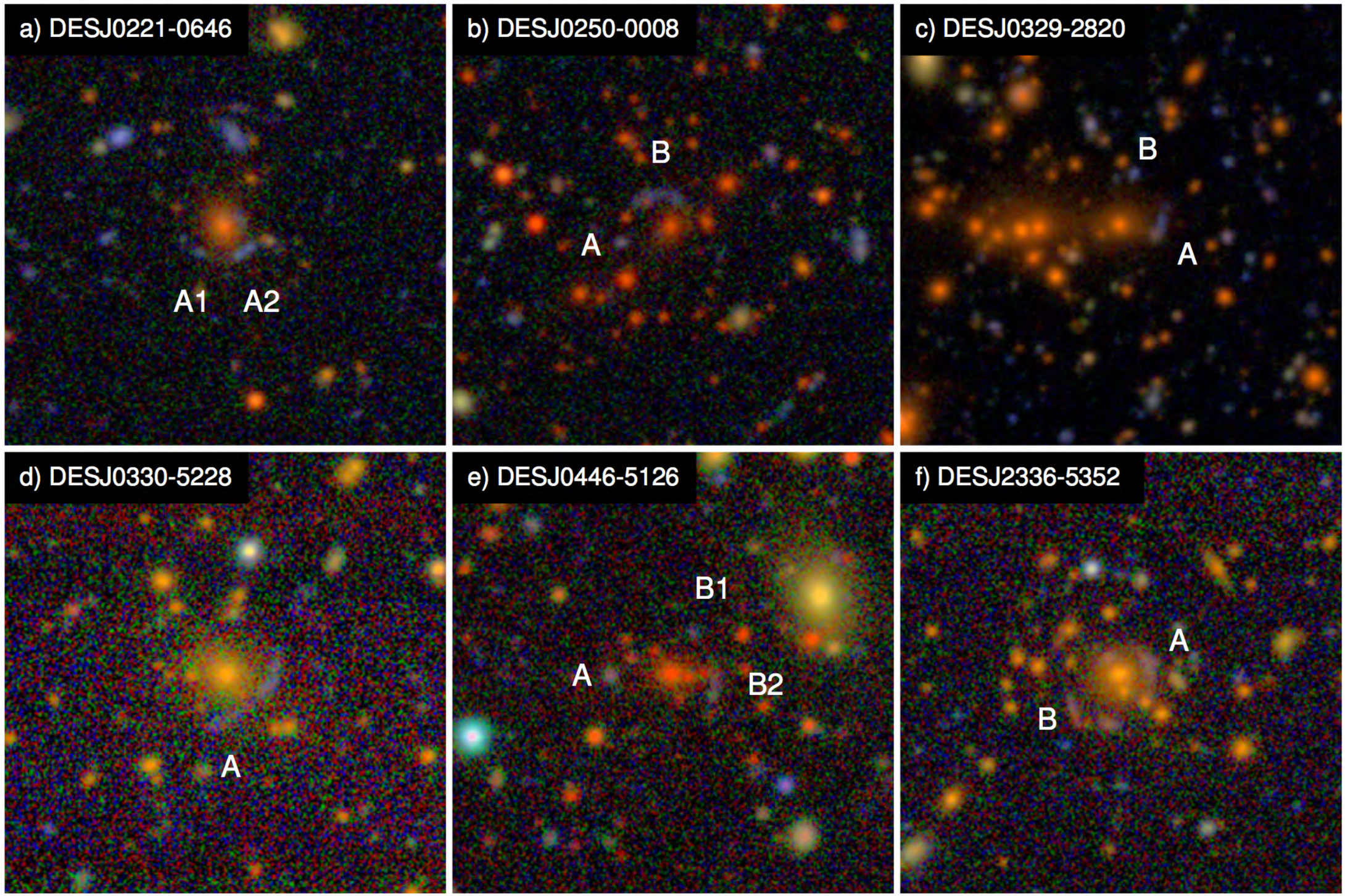
- 1986: First lensed galaxy (arcs)



- Census
  - In history, across all wavebands, **~1000** strongly lensed systems have been discovered.
  - About half of those come from optical searches.
- Current predictions for DES discovery
  - **~2000 lenses** (galaxy- to cluster-scale)
  - **~120 lensed quasars and < 10 lensed supernovae** (Oguri & Marshall, 2010)
  - Made possible by red-sensitive DECam CCDs
- Potential for Cosmology
  - Dark matter halo mass profiles
  - Measure cosmology with a single system

Confirmed Lensing Systems in DES SV

[Nord++,2015; arXiv:1512.03062]



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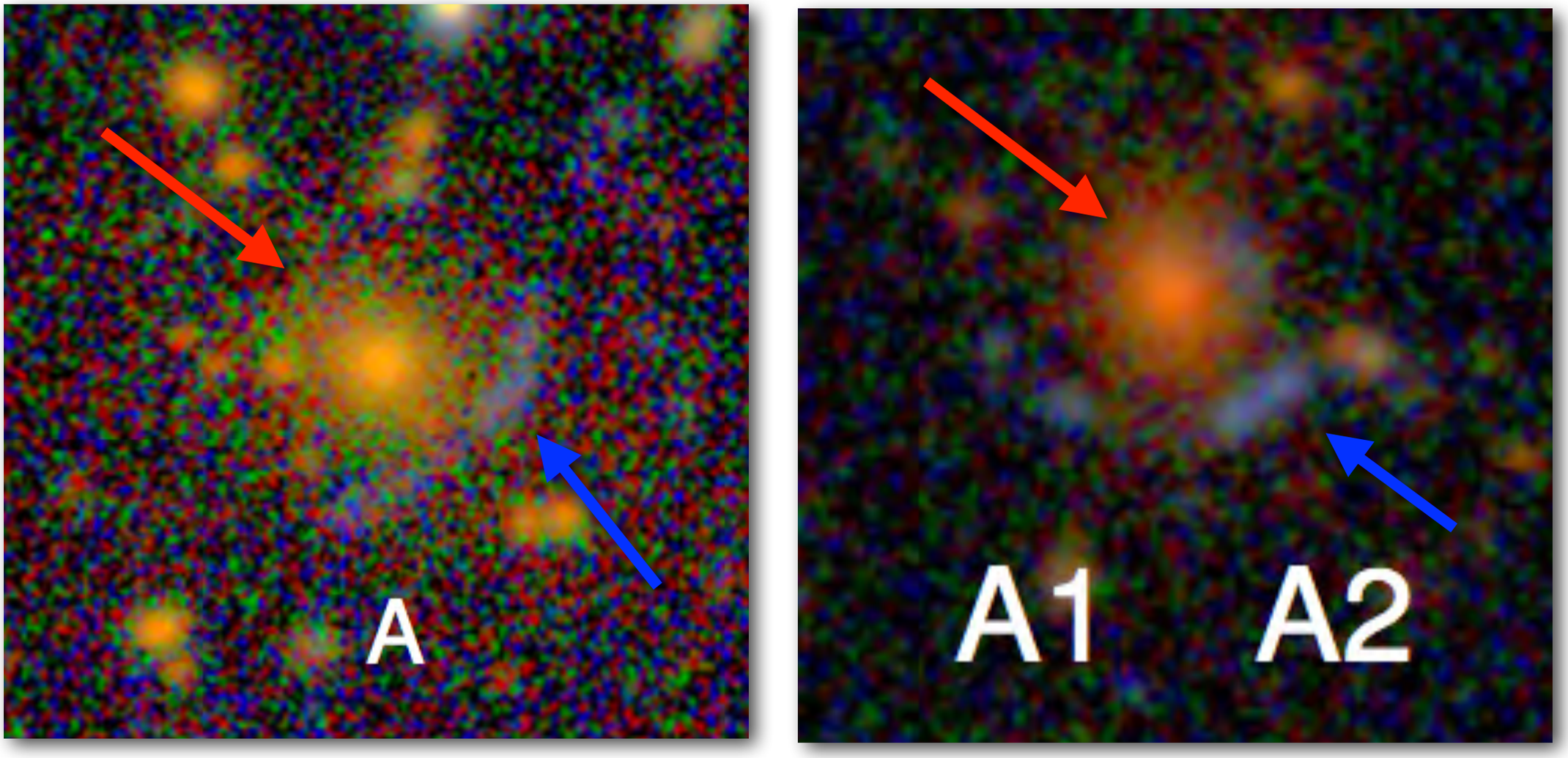
Lens

Source

Image



- Larger-radii systems are easier to detect in DES
- We are now searching Y1 data for more that are useful for cosmology and dark matter profile studies

Confirmed Lensing Systems in DES SV

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Lens

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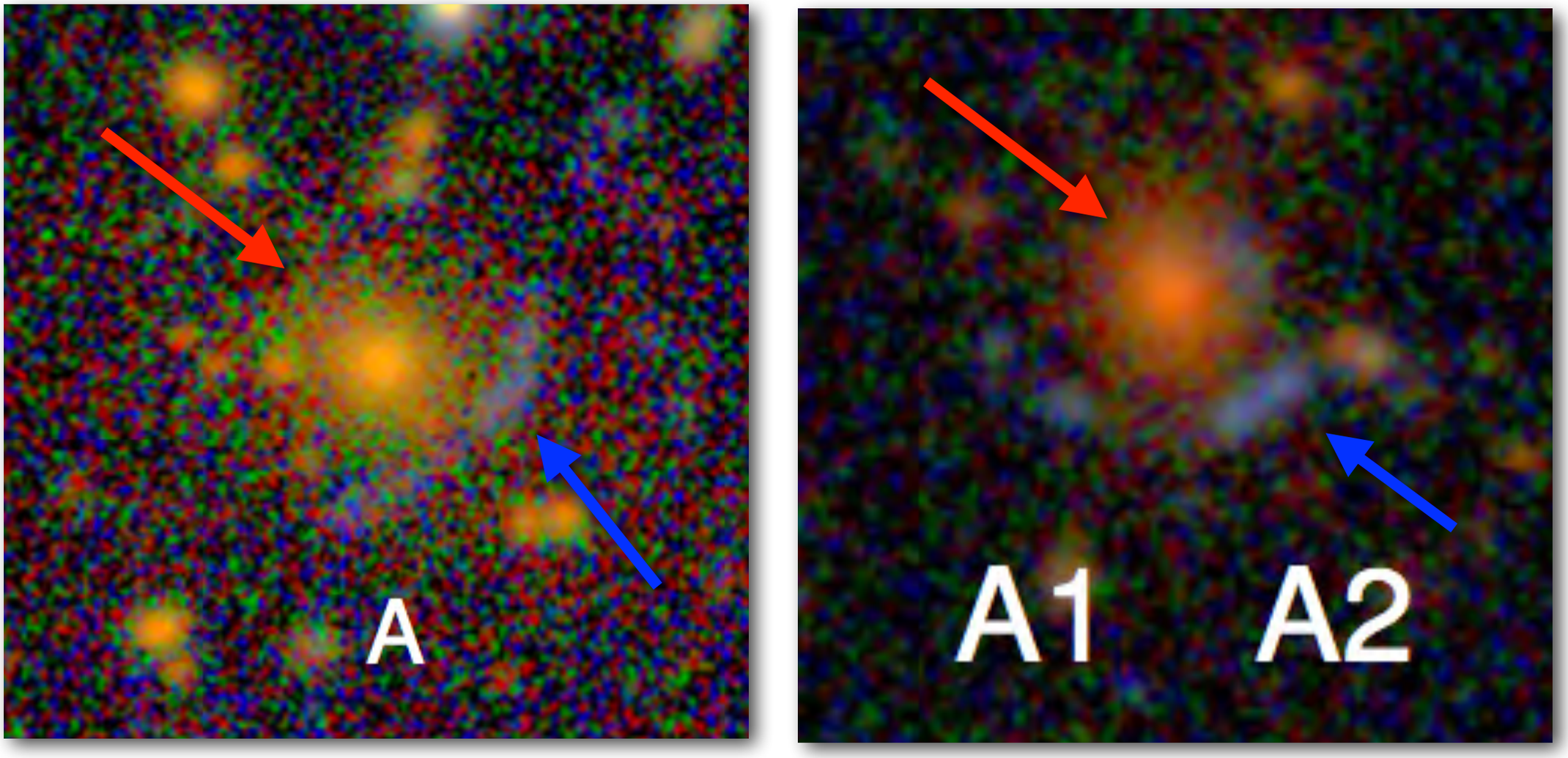
Image



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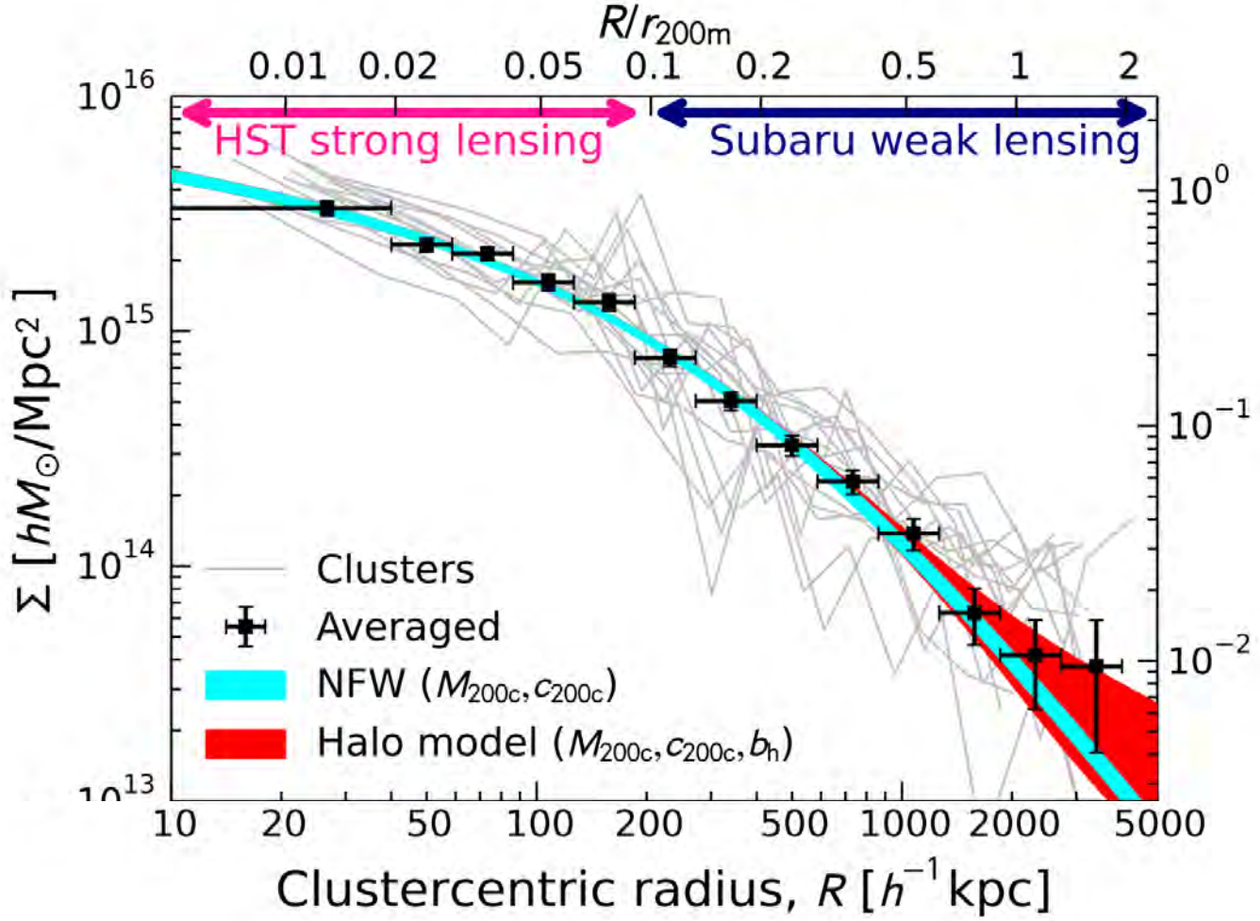
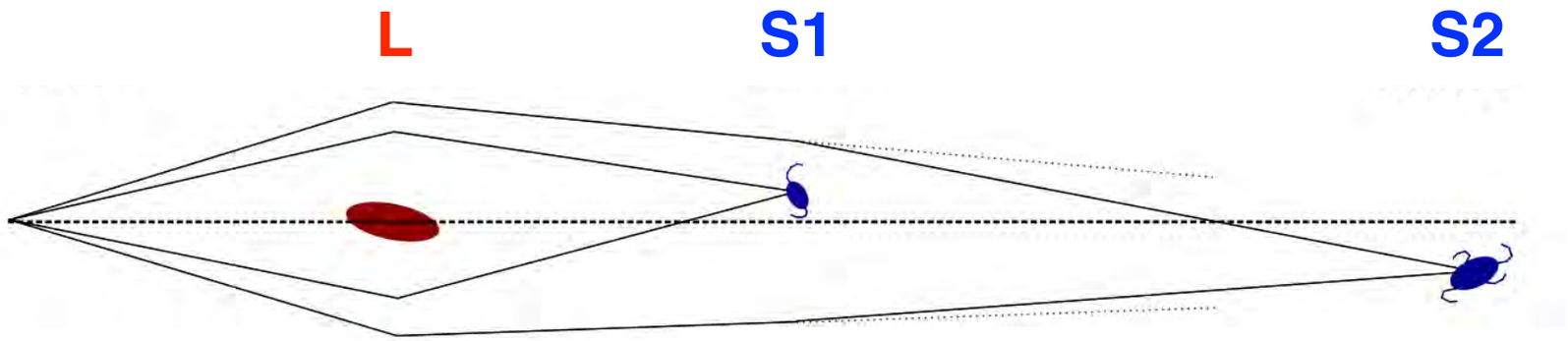
Lenses for Cosmology
Dark matter halo profiles

- Combining weak and strong lensing allows measurements of cluster density profiles over a large dynamic range.
- Strong and weak lensing probe inner and outer radii, respectively
- <u>16 stacked clusters</u>
  - profiles are well fit by canonical NFW model, *not* by power laws
  - concentration-mass relation shows agreement with LCDM
  - strong lensing is key for these studies.



Umetsu++2015

Lenses for Cosmology
Double-source systems



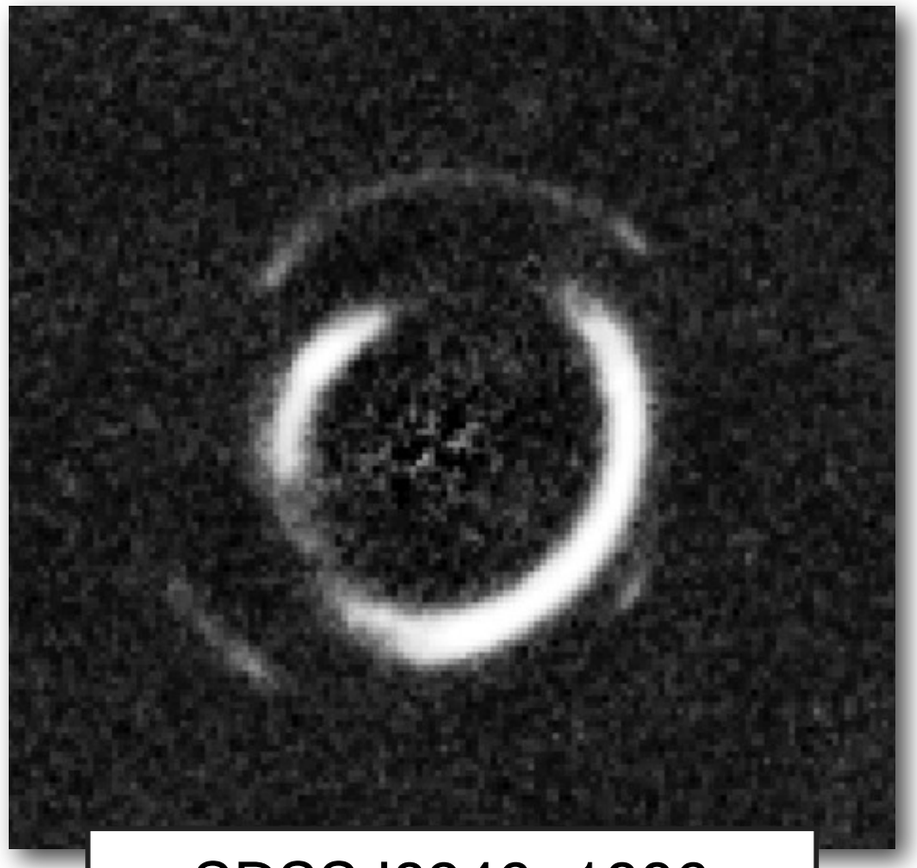
- Distance is a function Hubble parameter and matter and dark energy densities:

$$D_{ij}(\, z_L,\, z_s\, ;\, H_0,\, \Omega_M,\, \Omega_\Lambda,\, w\,)$$

- The ratio of distances, ***D***, provides constraints $\boldsymbol{\Omega_M}$, $\boldsymbol{\Omega_\Lambda}$, $\boldsymbol{w}$ independent of H_0

$$\Xi(z_{\rm lens}, z_1, z_2; \Omega_M, \Omega_\Lambda, w) = \frac{D_{\rm LS}(z_1)}{D_{\rm S}(z_1)} \frac{D_{\rm S}(z_2)}{D_{\rm LS}(z_2)}$$

- To date, only one has been found.
- We expect ~10 in DES (Gavazzi++2008)



SDSSJ0946+1006

Lenses for Cosmology
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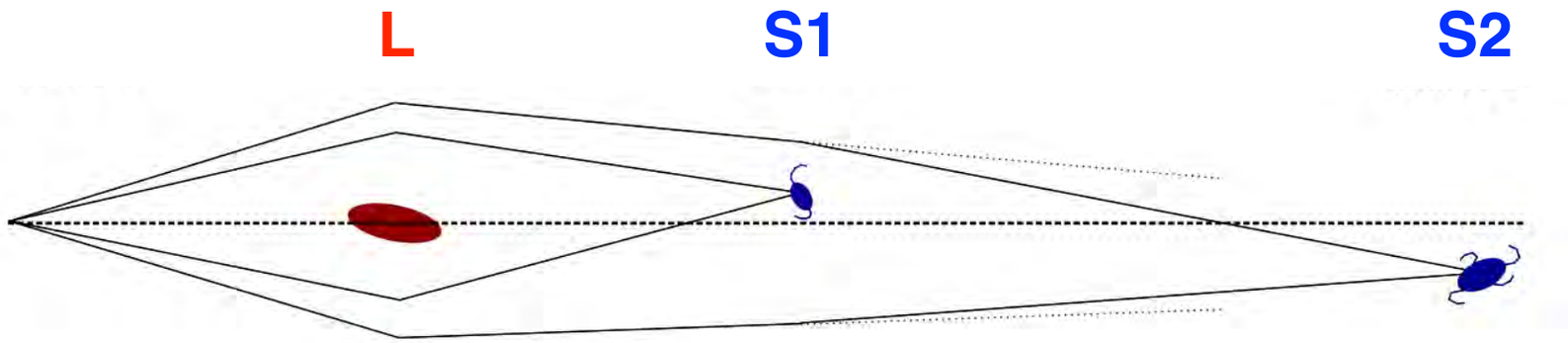

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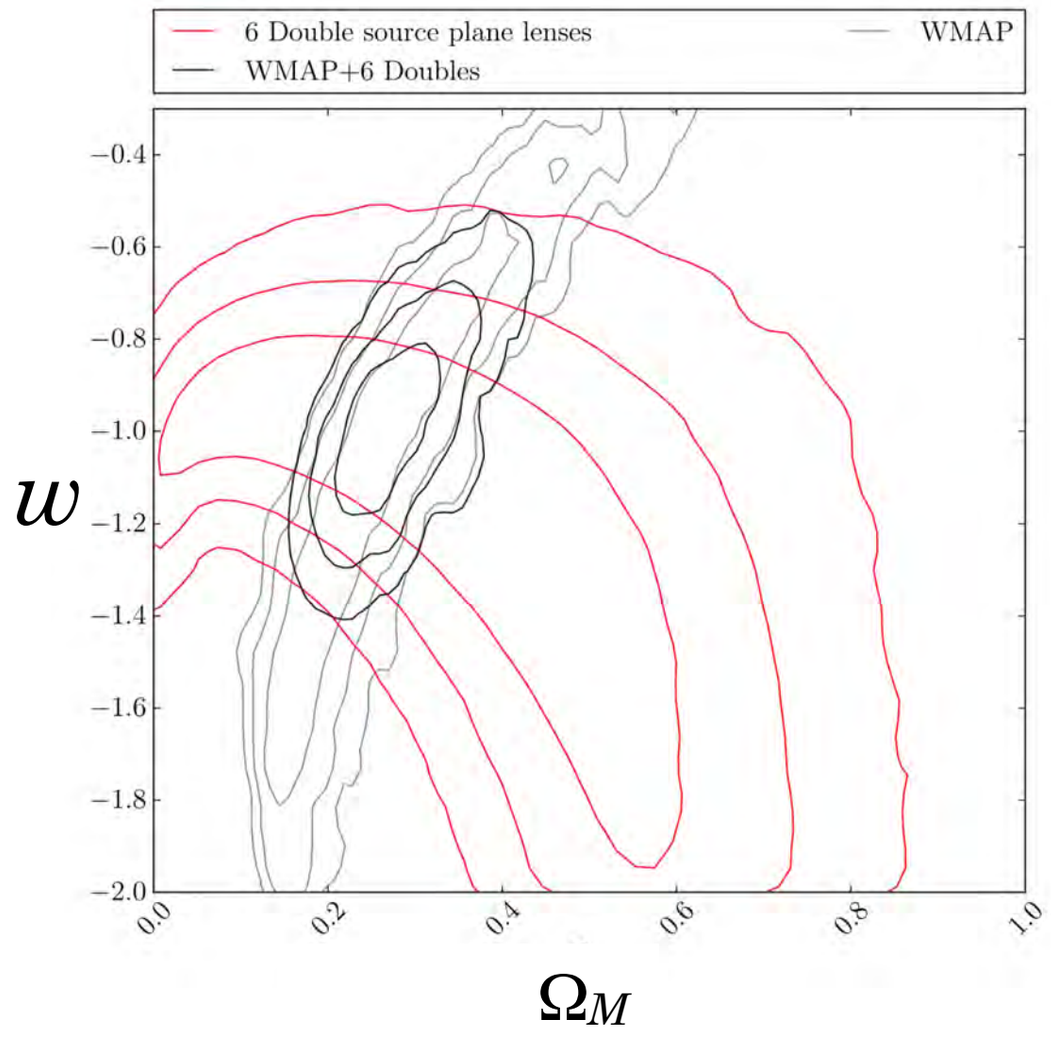


Lenses for Cosmology
Time delays

- The time delay between different light paths is proportional to the Hubble constant, H_0 (Refsdal, 1964)
- Systematics: quasar samples and mass modeling
- Complementary to CMB and SNe, improving dark energy constraints by over 50%
- STRIDES:
  STRong lensing **I**nsights into **D**ark **E**nergy **S**urvey (collaboration with external partners, led by T. Treu)

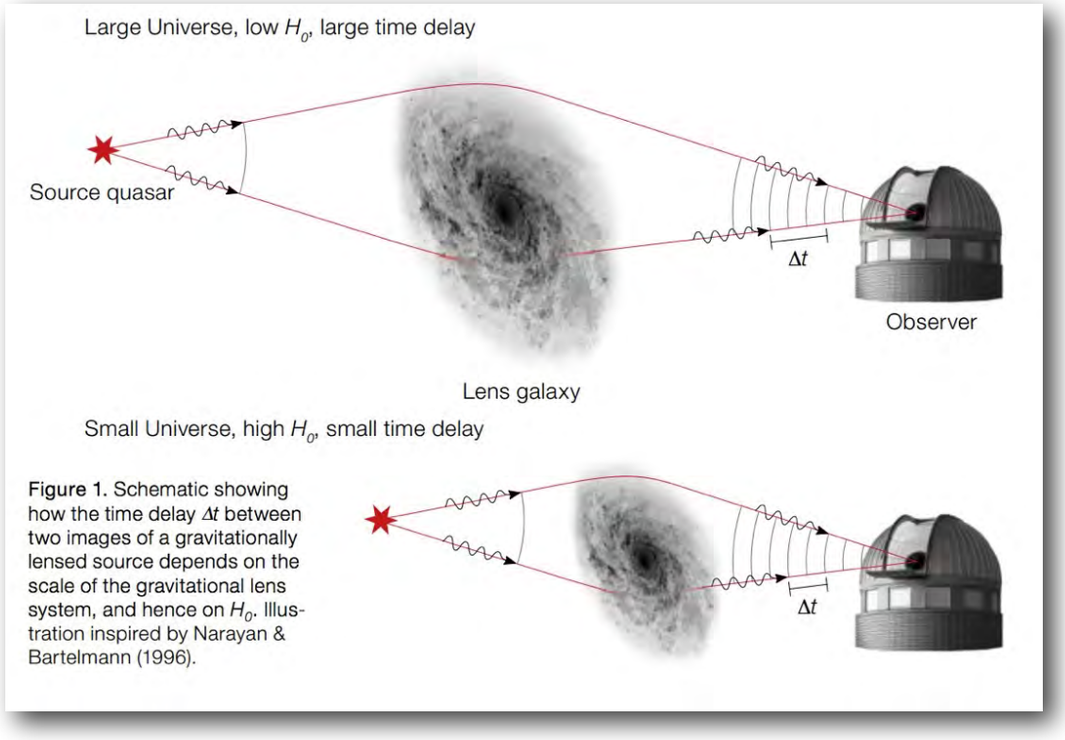
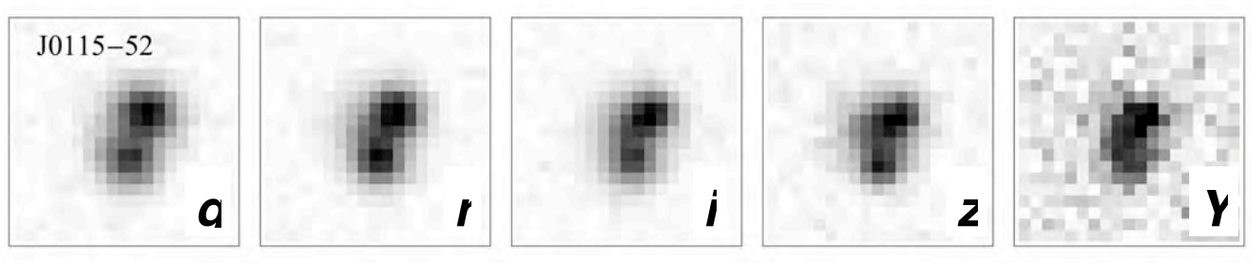


Figure 1. Schematic showing how the time delay Δt between two images of a gravitationally lensed source depends on the scale of the gravitational lens system, and hence on H_0. Illustration inspired by Narayan & Bartelmann (1996).



[Agnello++,2015; arXiv:1508.01203]

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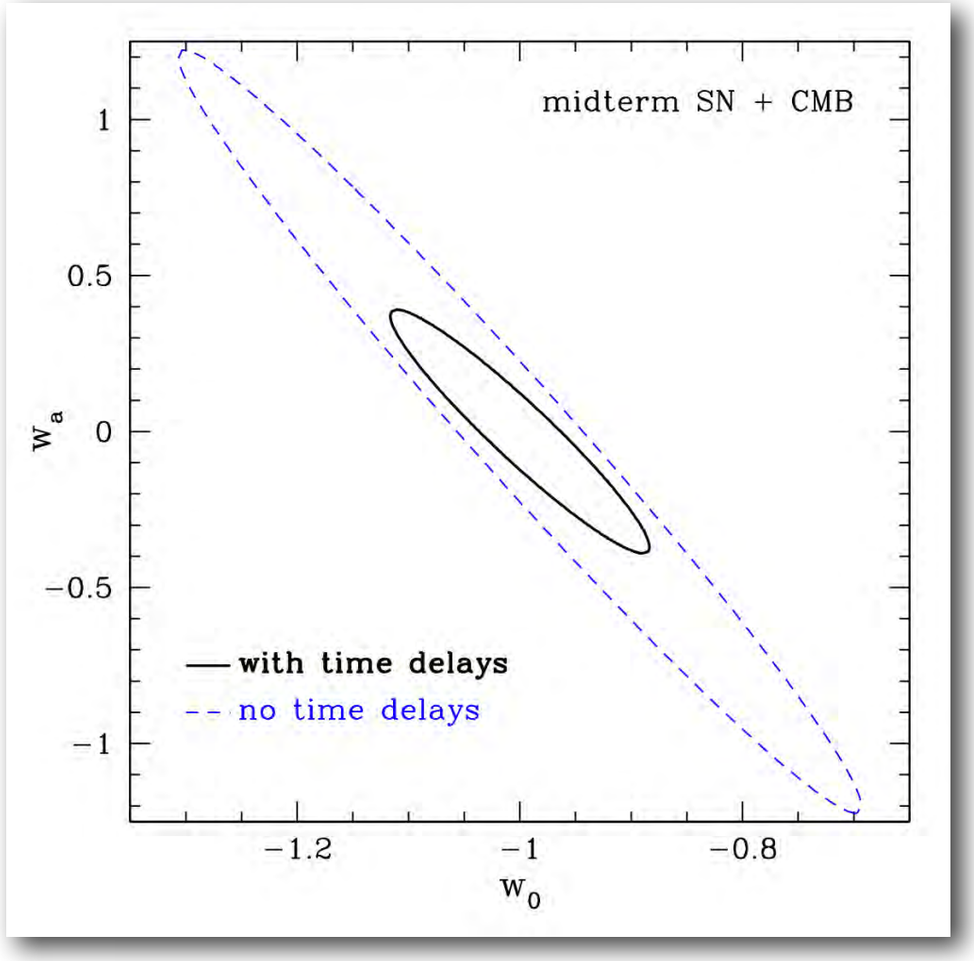

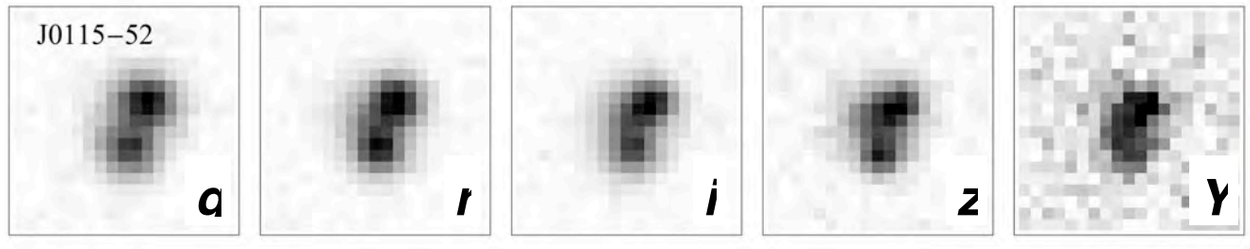

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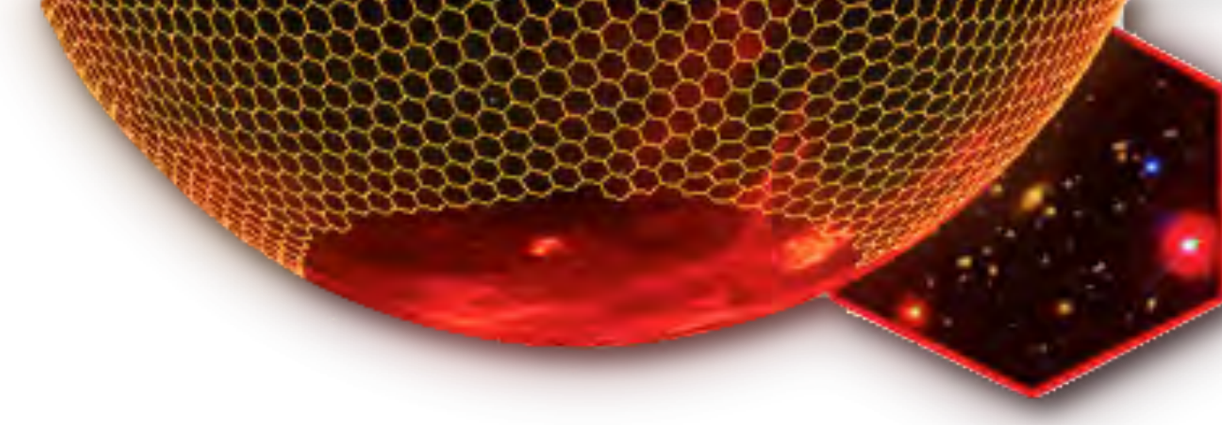
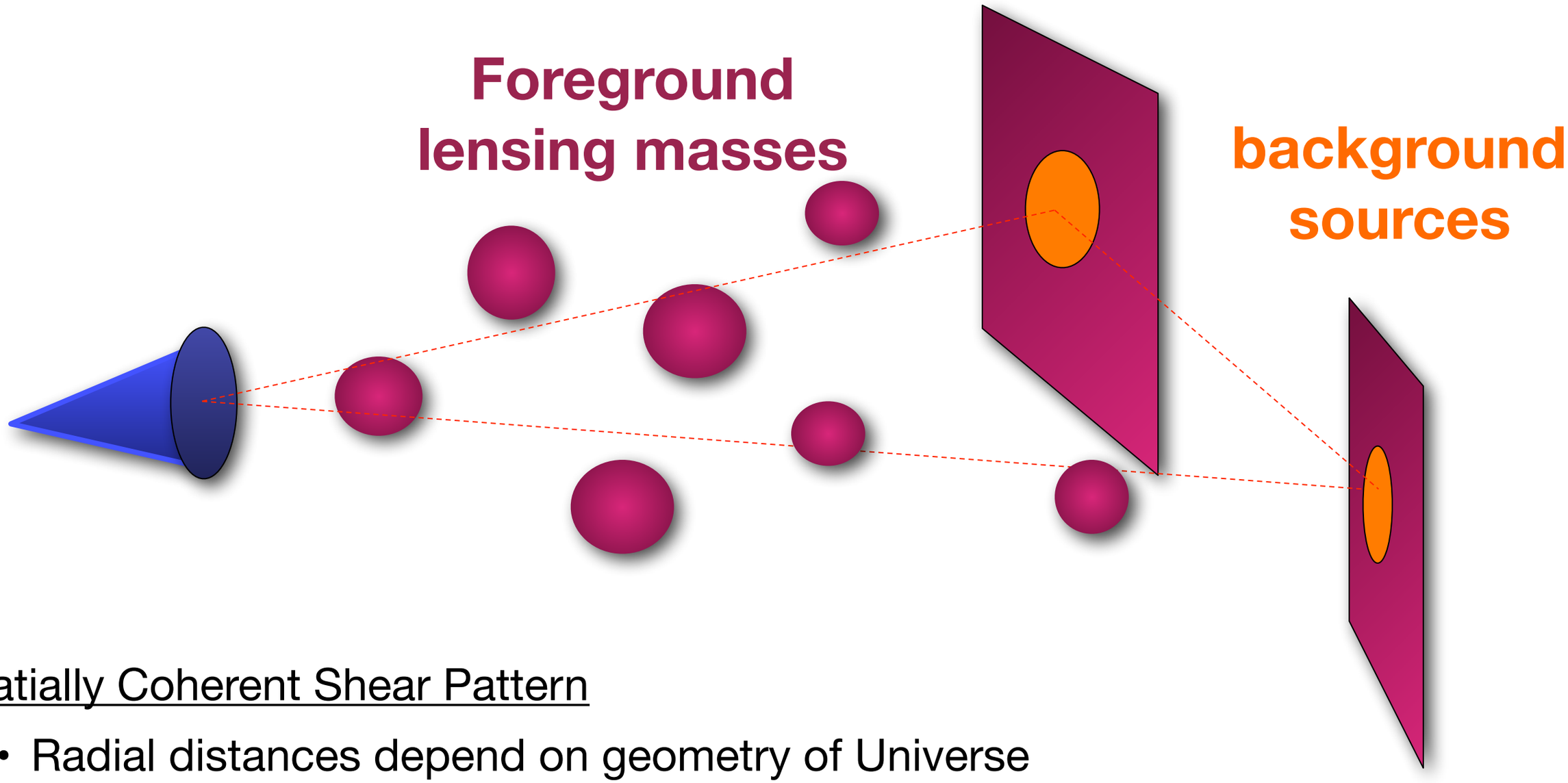


Early Results from Science Verification Season

Strong Lensing
Weak Lensing
Galaxy Clusters

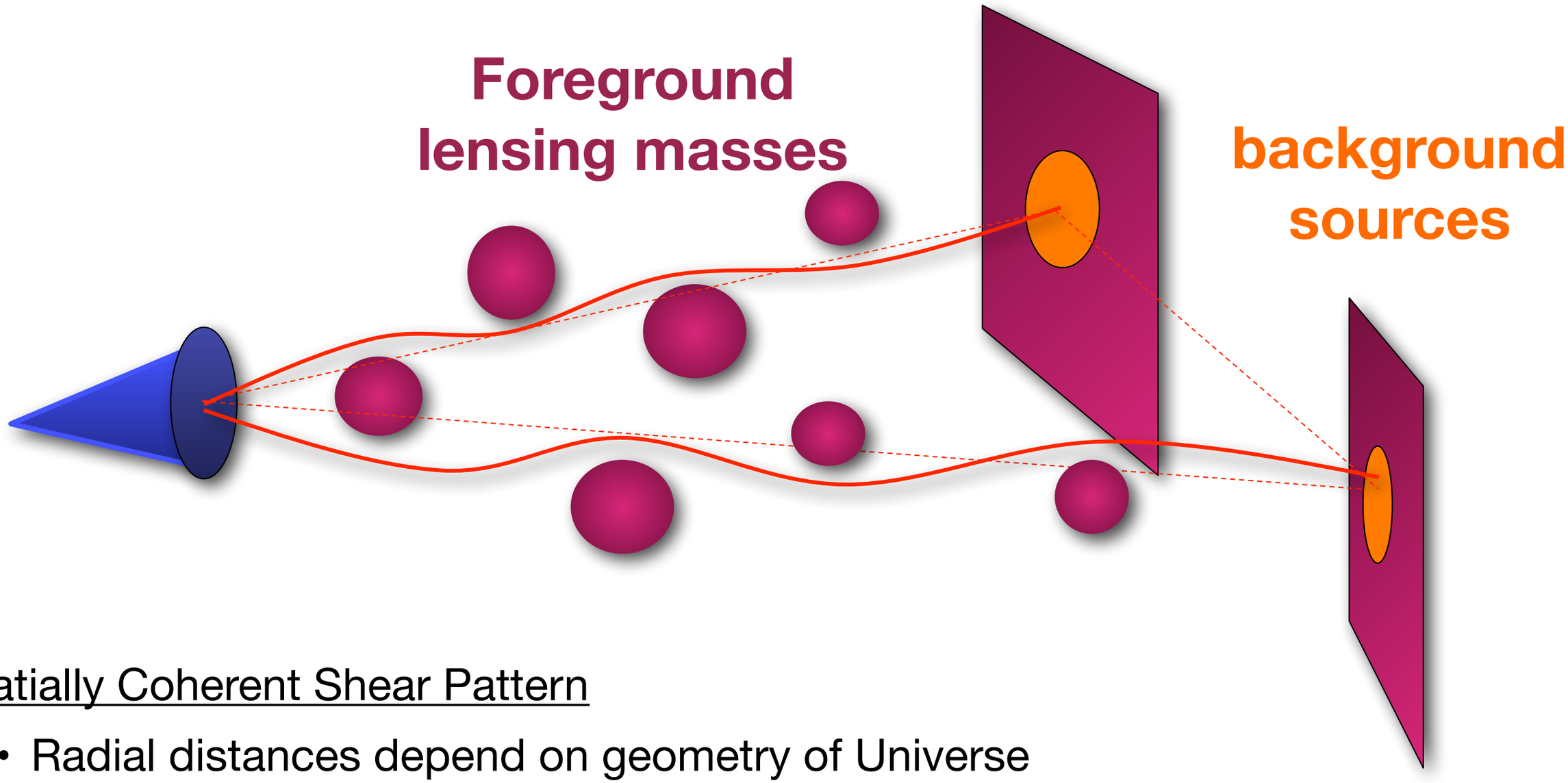
Structure Formation:
Cosmic Lensing



Spatially Coherent Shear Pattern

- Radial distances depend on geometry of Universe
- Foreground mass distribution depends on growth of structure
- **only ~1% distortion of galaxy shapes**

Structure Formation:
Cosmic Lensing



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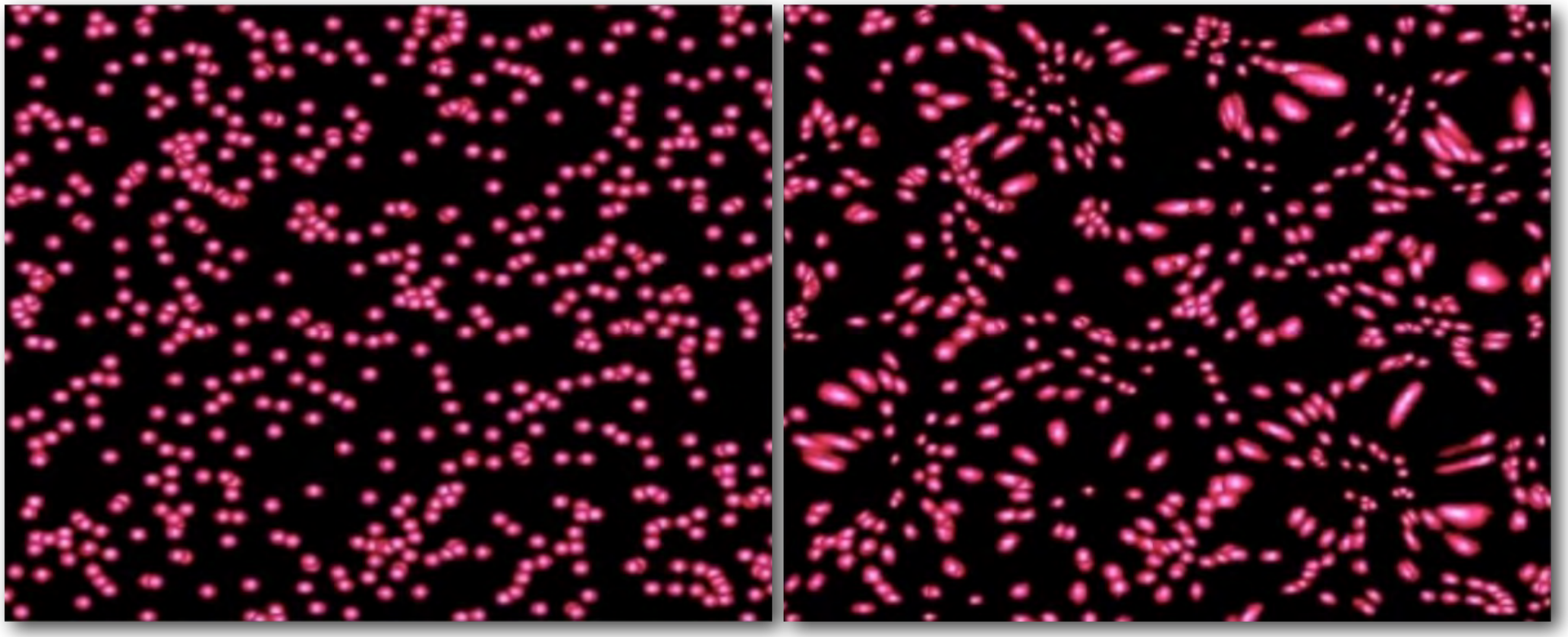

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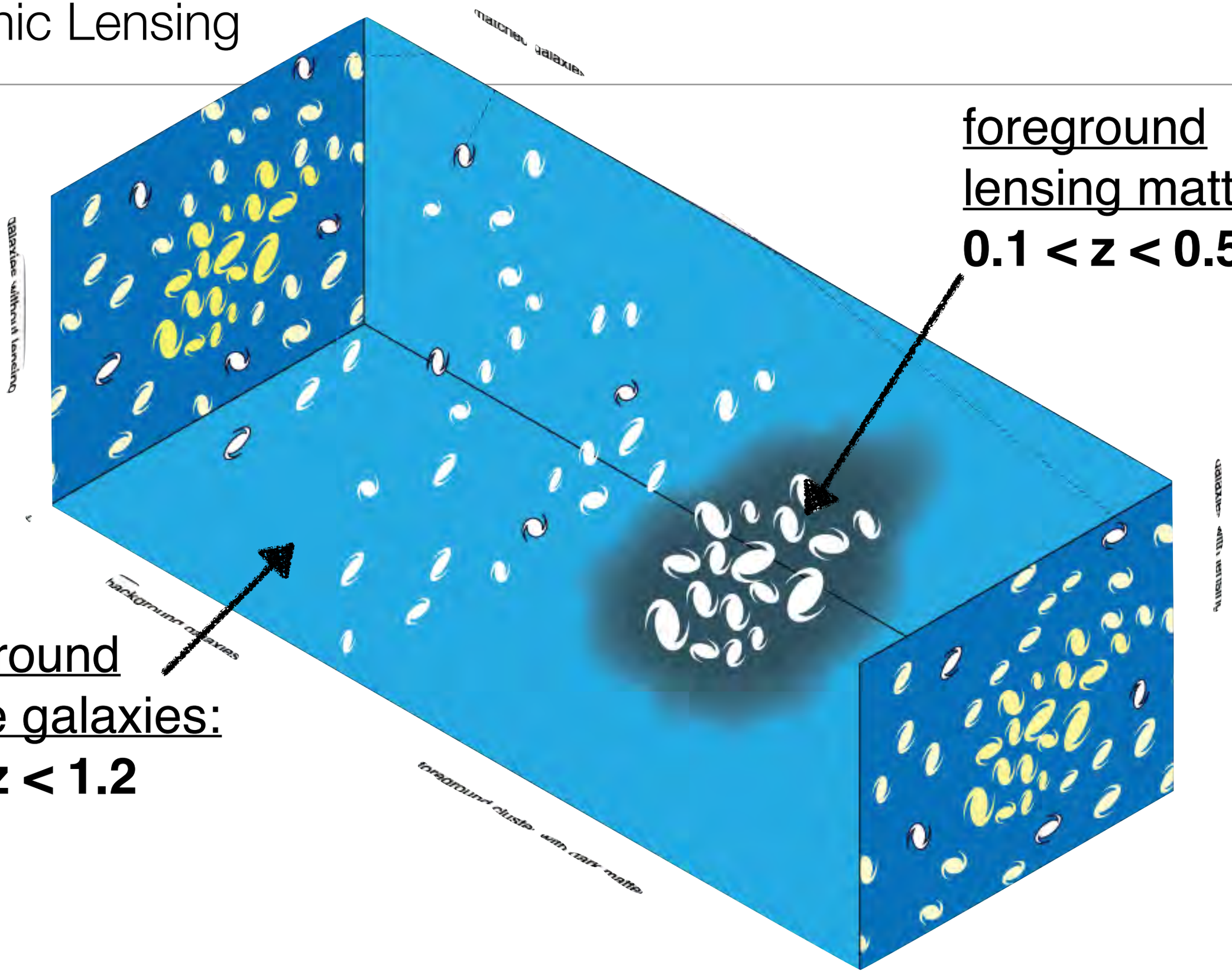


foreground
lensing matter
0.1 < z < 0.5

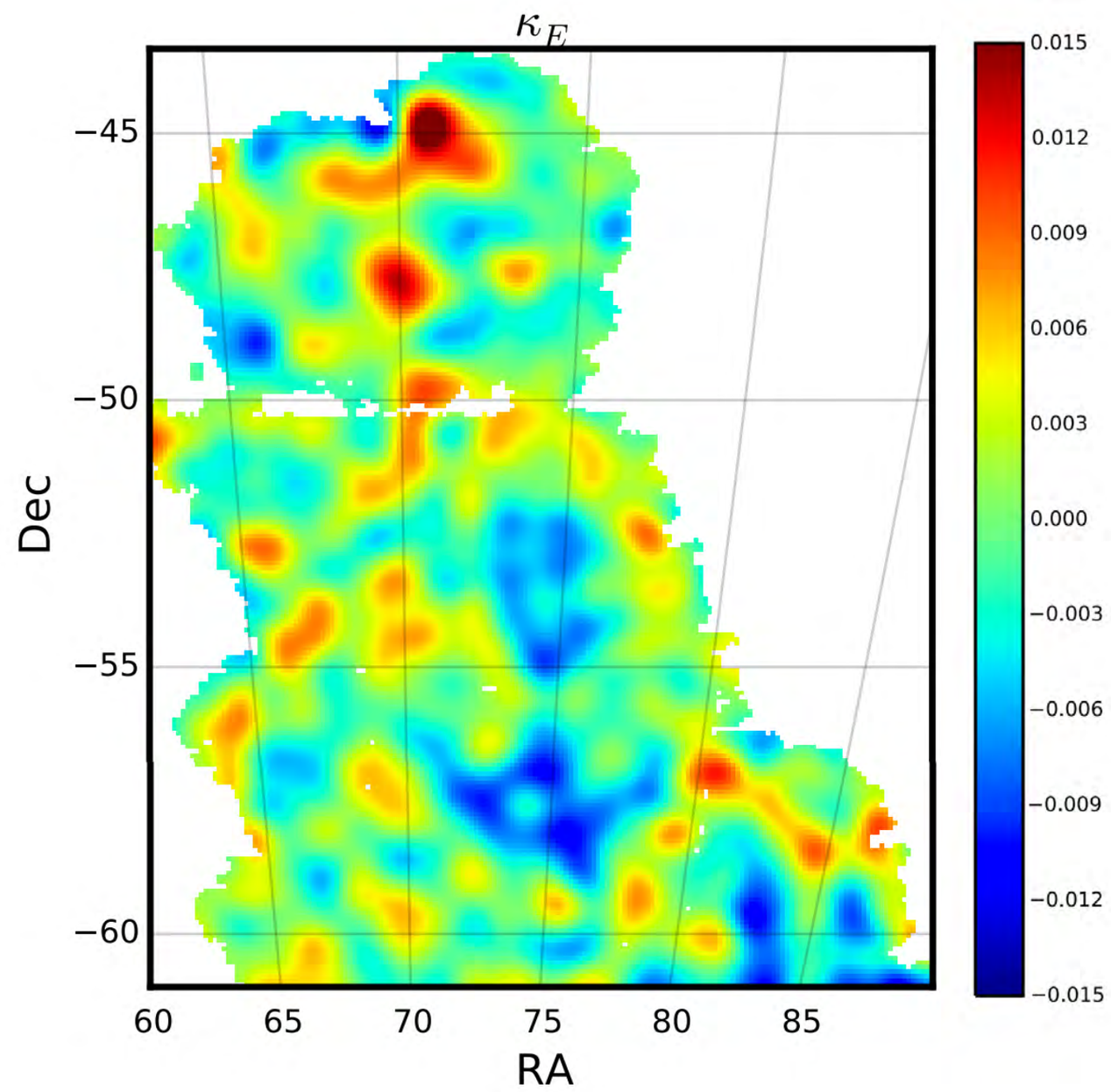
background
source galaxies:
0.6 < z < 1.2

Mapping dark matter with SV data

[Vikram, Chang++2015; arXiv:1504.03002]

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

- <u>Largest contiguous map of dark matter ever created</u>
  - shear signal: a galaxy stretched by 1-2%
  - *shape noise ~20%:* need many galaxies to overcome intrinsic unknown ellipticity
- <u>Motivation:</u>
  - compare with light maps
    - e.g., 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*:
    - mean matter density, Ω_M
    - spatial variation, σ_8

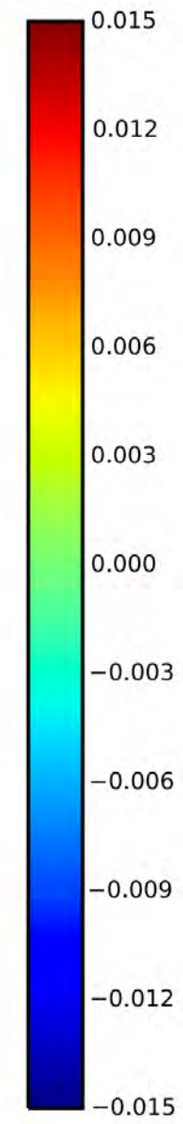


- 139 sq. deg (<3% full area)
- ~3 million galaxies (shapes)

Mapping dark matter with SV data

[Vikram, Chang++2015; arXiv:1504.03002]

- <u>Largest contiguous map of dark matter ever created</u>
  - shear signal: a galaxy stretched by 1-2%
  - *shape noise ~20%:* need many galaxies to overcome intrinsic unknown ellipticity
- <u>Motivation:</u>
  - compare with light maps
    - e.g., 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*:
    - mean matter density, Ω_M
    - spatial variation, σ_8

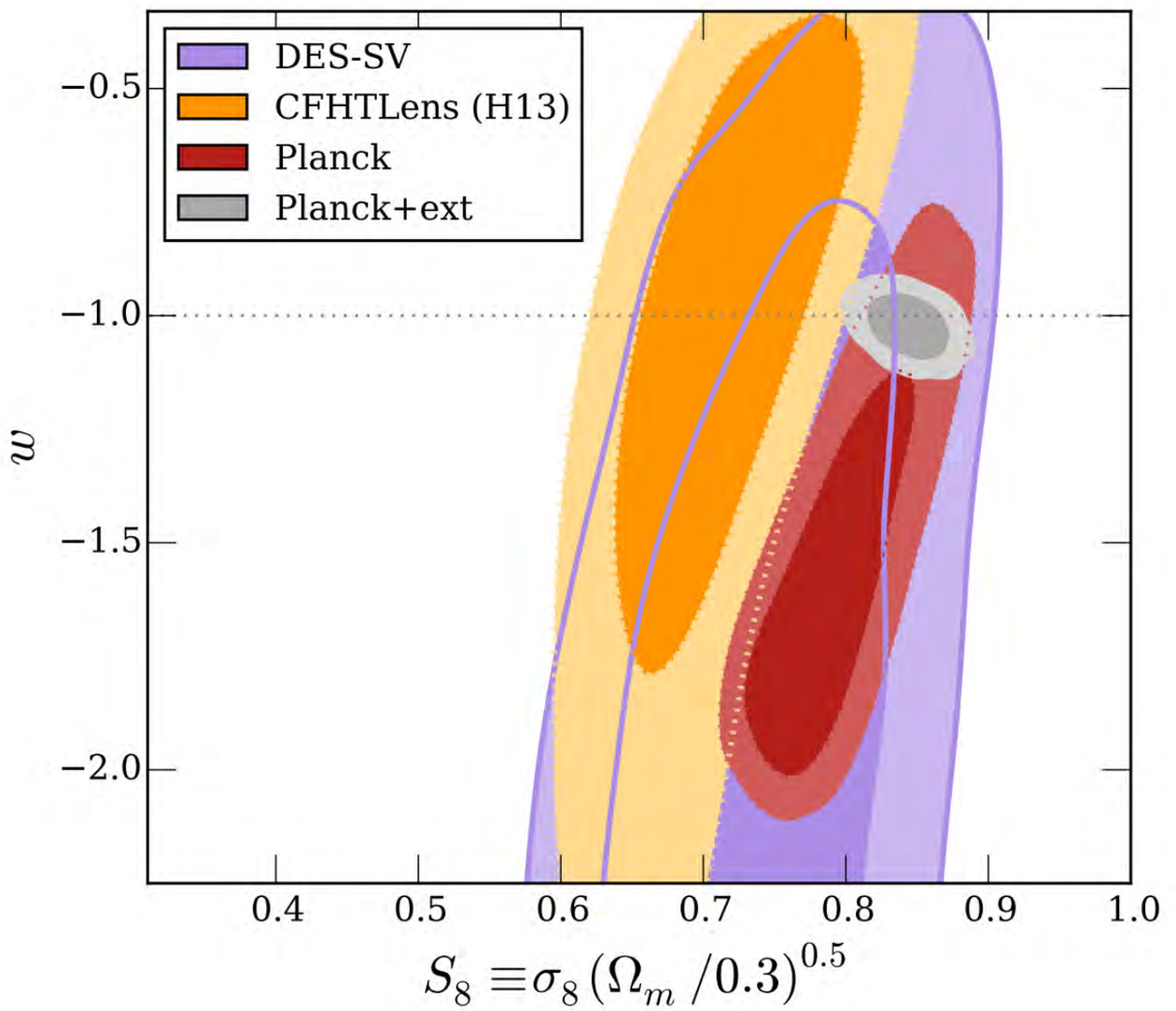


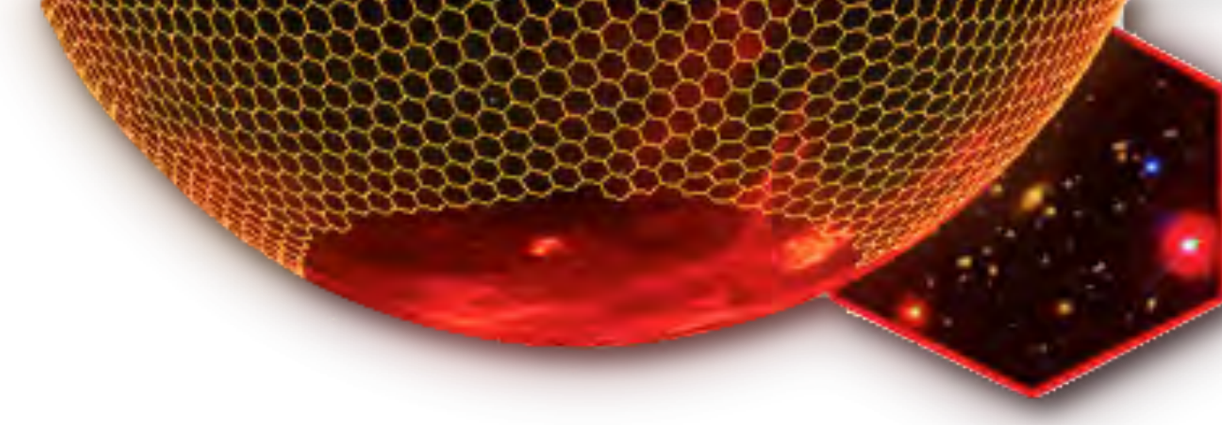
- 139 sq. deg (<3% full area)
- ~3 million galaxies (shapes)

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**
- Future
  - DES uncertainties *30% larger* due to *lower number density* of shear catalog
  - This only 3% of DES full area.





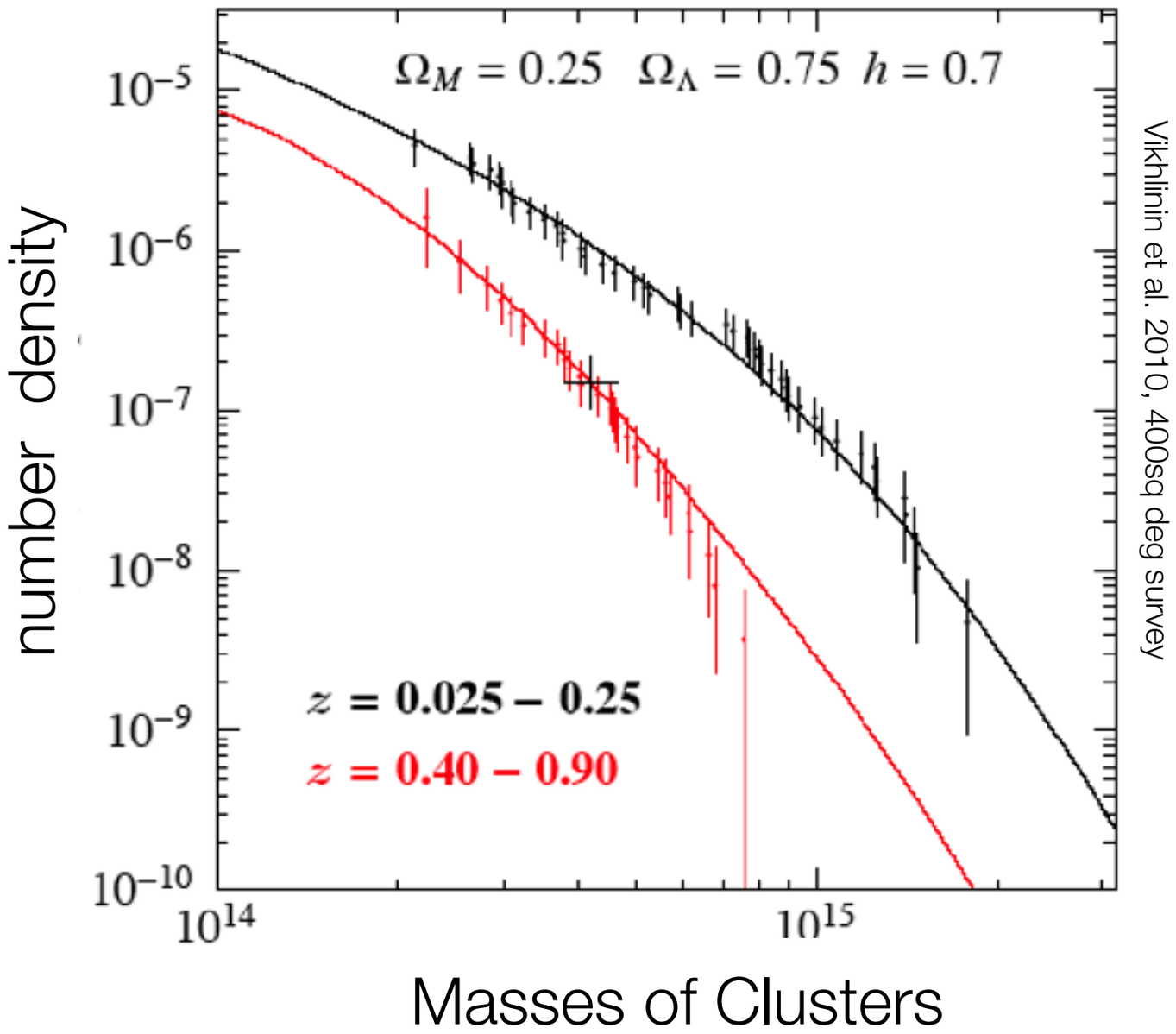
Early Results from Science Verification Season

Strong Lensing
Weak Lensing
Galaxy Clusters

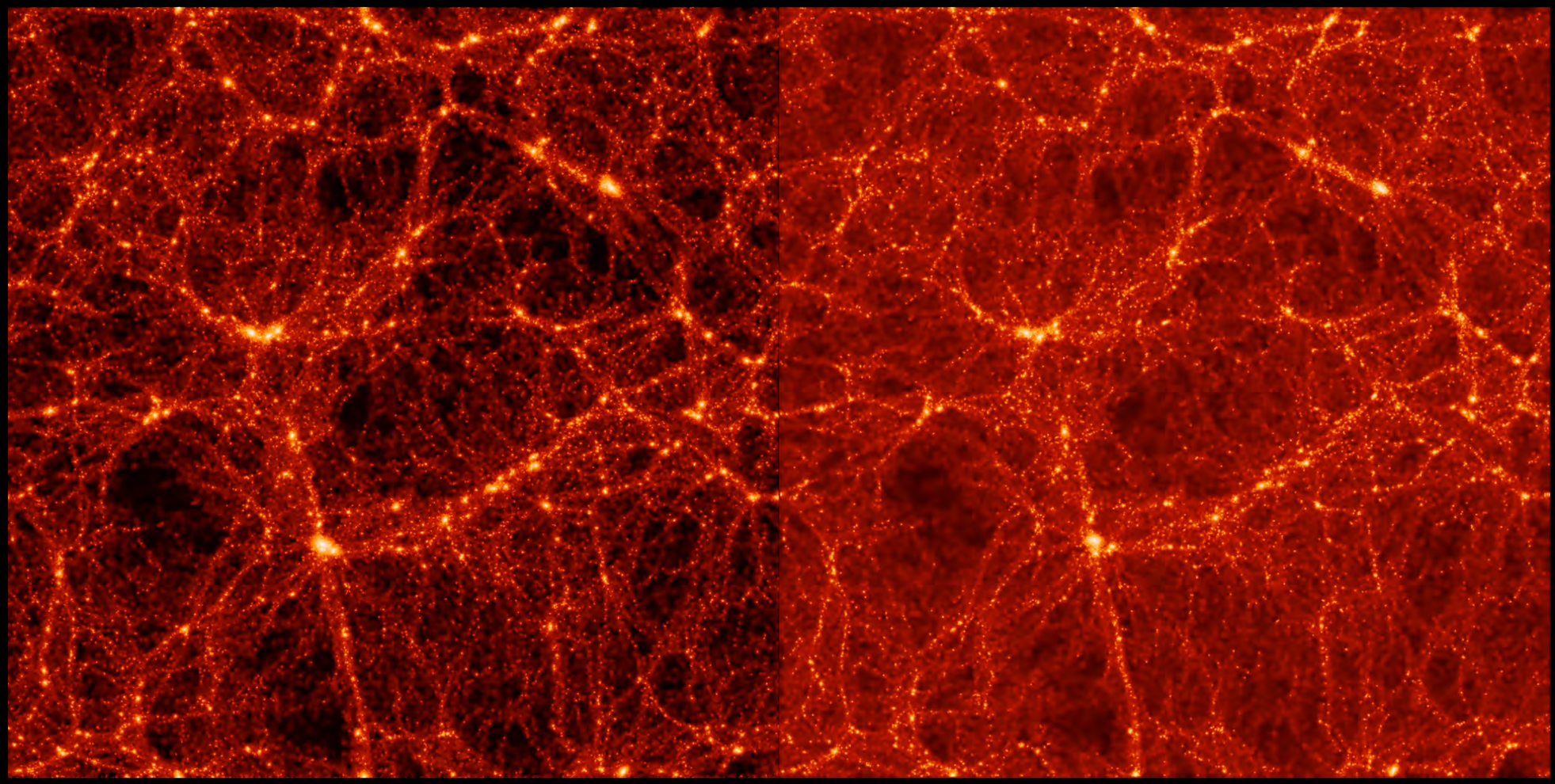
Halo Mass Function

- Halo Abundance =
  How many haloes are there as a function of mass and redshift
- This depends acutely on the growth rate of structure, which is influenced by both the dark energy and matter densities.
- Multiple ways to observe galaxy clusters, each probing something different: X-rays, optical, sub-mm

number density vs. mass



Simulations of the Cosmic Web

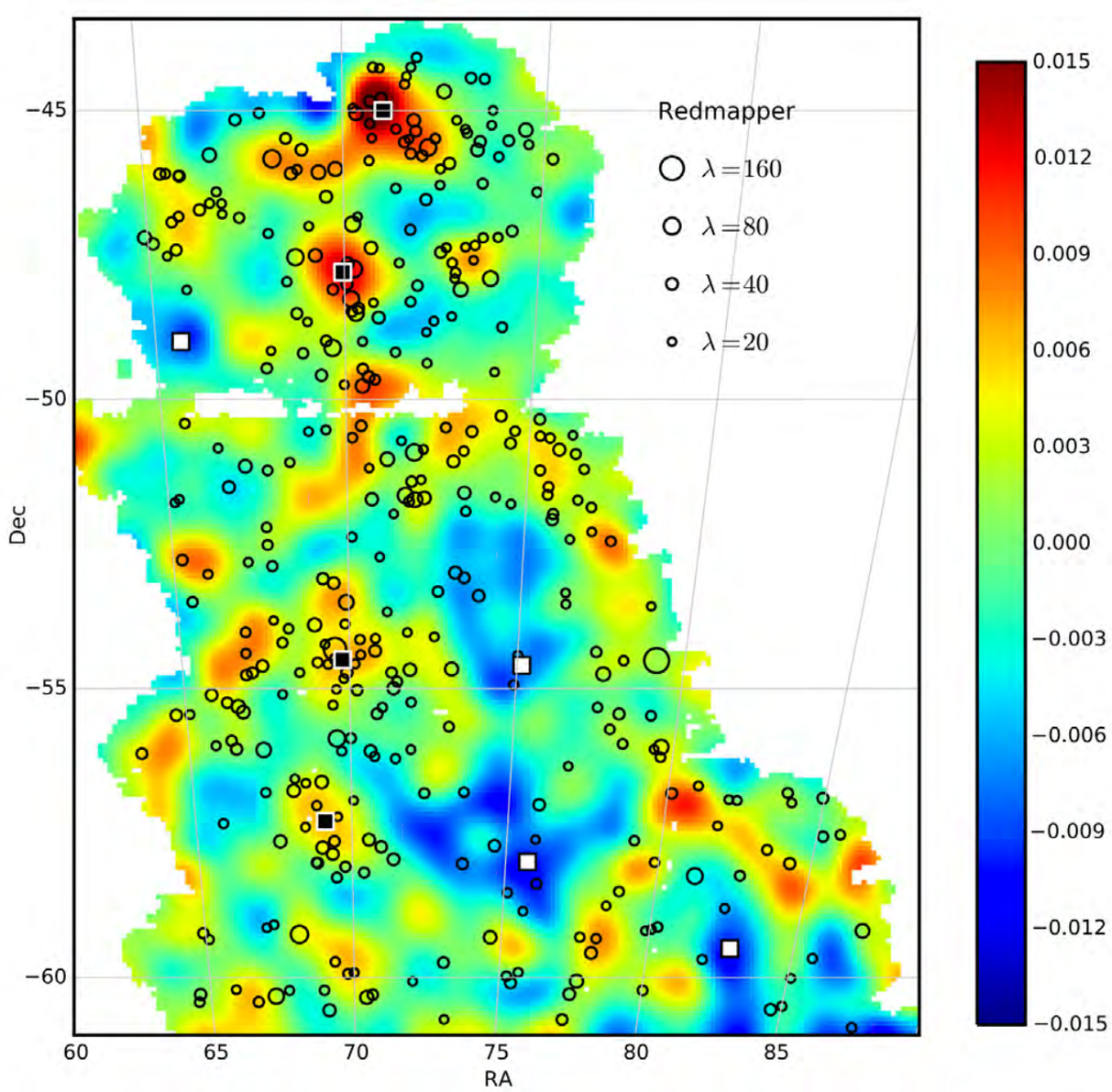


Discovering Clusters in DES

[Rykoff++2016 arXiv:1601.00621]

○ open circles represent known galaxy clusters

- *redMaPPer* Optical Cluster-finder
  - optical “red sequence” finder
  - ~1500 clusters
  - $0.2 < z < 0.9$
  - SDSS cluster sample goes to $z < 0.4$
- Many ways to measure clusters
  - only 1% of mass in **galaxies**
  - Hot intra-cluster plasma emits **X-rays**
  - plasma scatters CMB photons, giving a **sub-mm** signature
  - **weak lensing** is the most direct measurement of the total halo mass

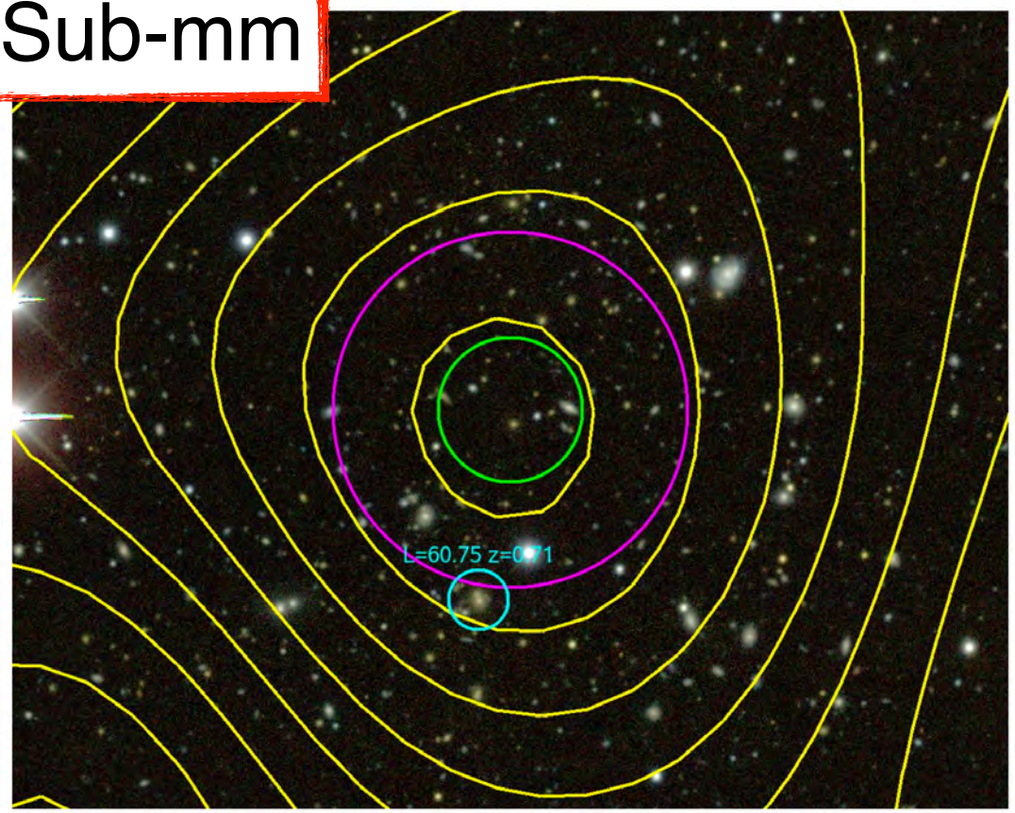


Each signature measures a different part of a cluster. All are needed for precise, self-consistent measure of mass.

Multi-wavelength Observations

[Saro++,2015 arXiv:1506.07814v1]

Sub-mm



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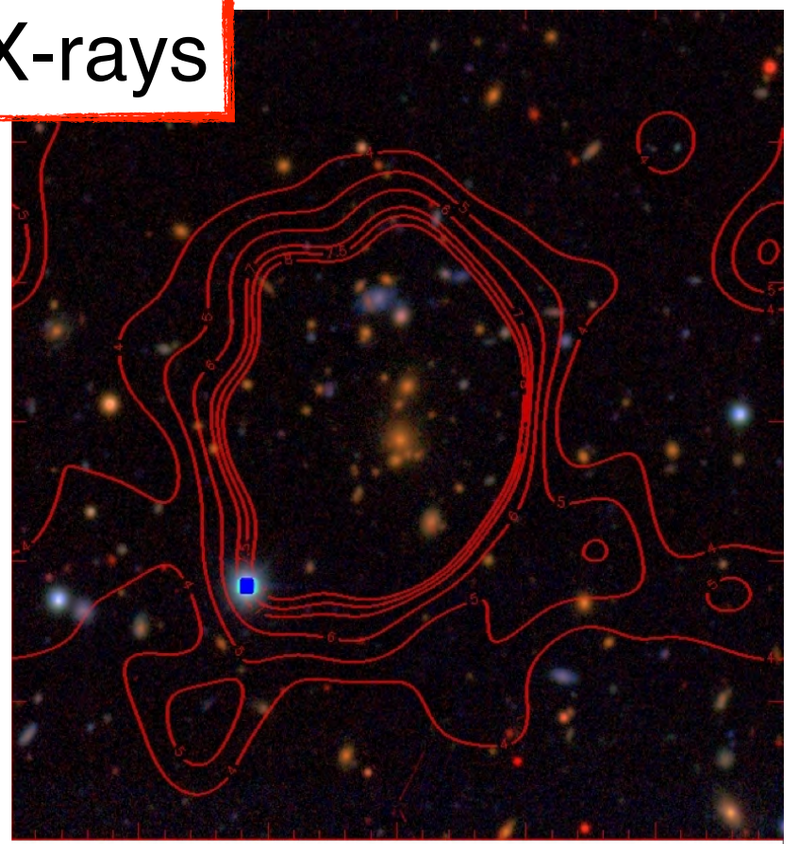
X-rays

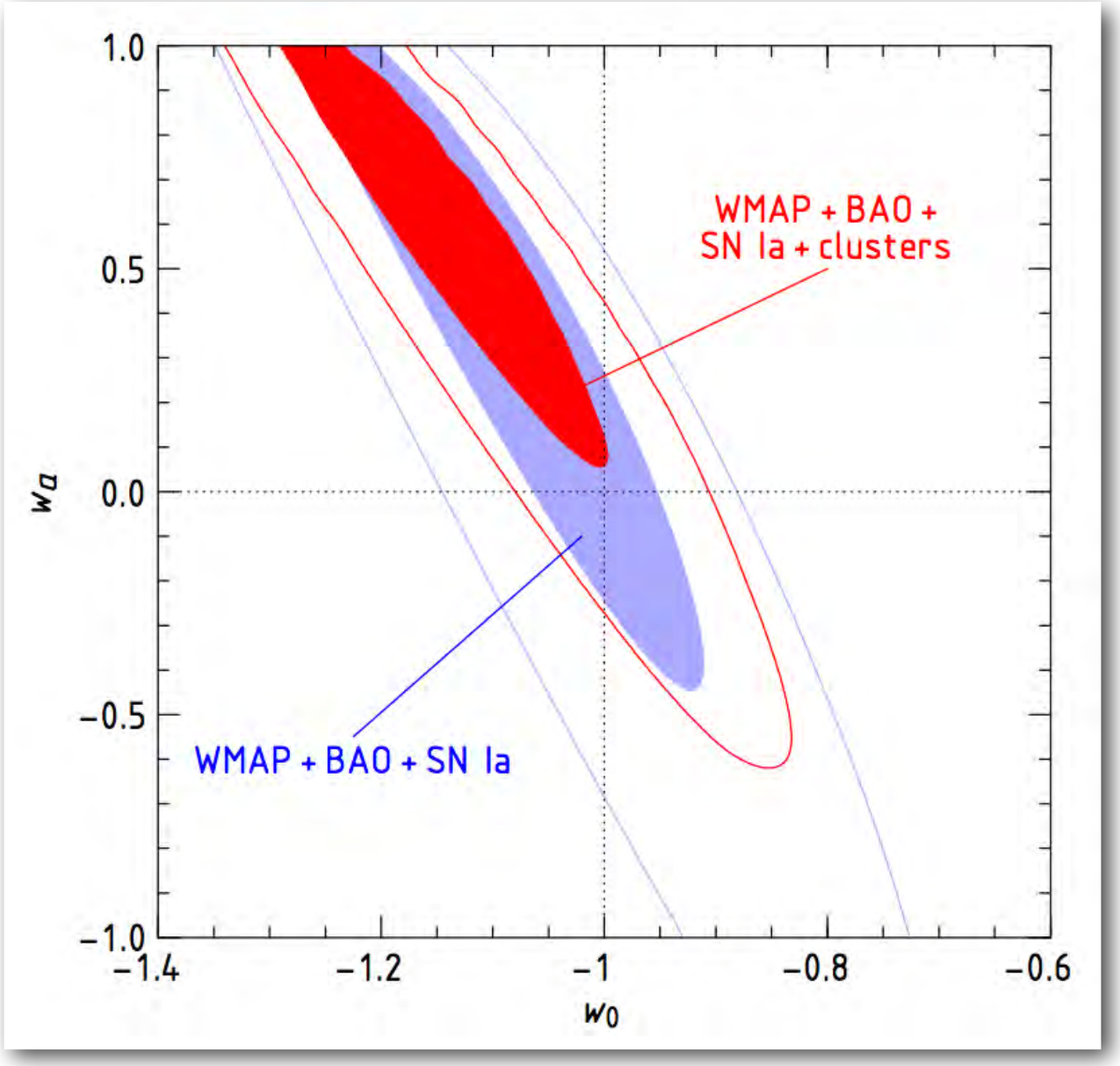


XMMXCSJ234231.5-562106.8

- Weak lensing + Sub-mm:
  20% scatter: most precise correlation yet between mass and galaxy count
- Optical + sub-mm + X-ray:
  Large swaths of DES area overlap with other cluster surveys, creating one of the largest ever multi-wavelength samples of clusters

Cosmological Constraints from Clusters

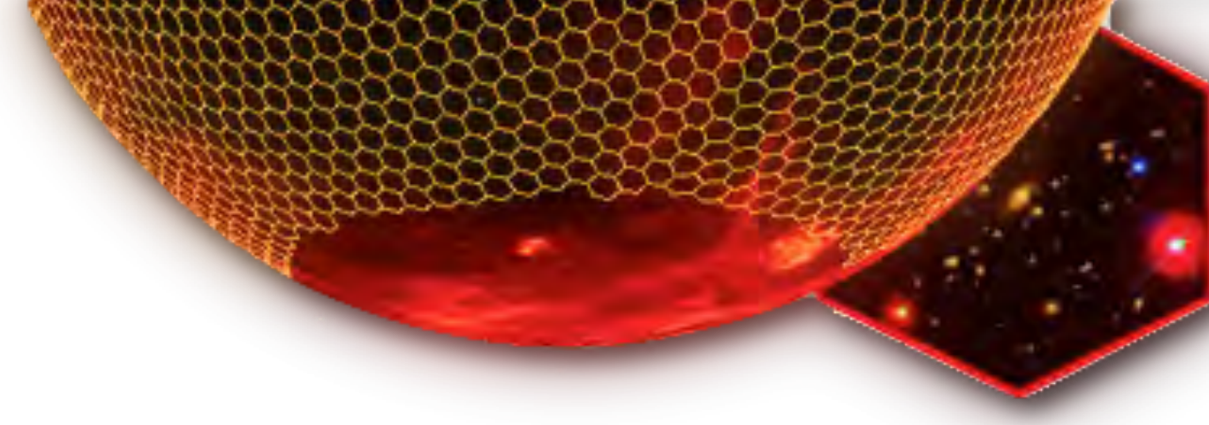
- Clusters complement other cosmological probes:
  - break degeneracies in constraints on w_0-w_a
  - improve constraints on w_a by ~50%
- But, their potential will be realized only when cluster masses are precisely calibrated, requiring multi-wavelength data set.



Vikhlinin++2009

Summary: @TheDESurvey

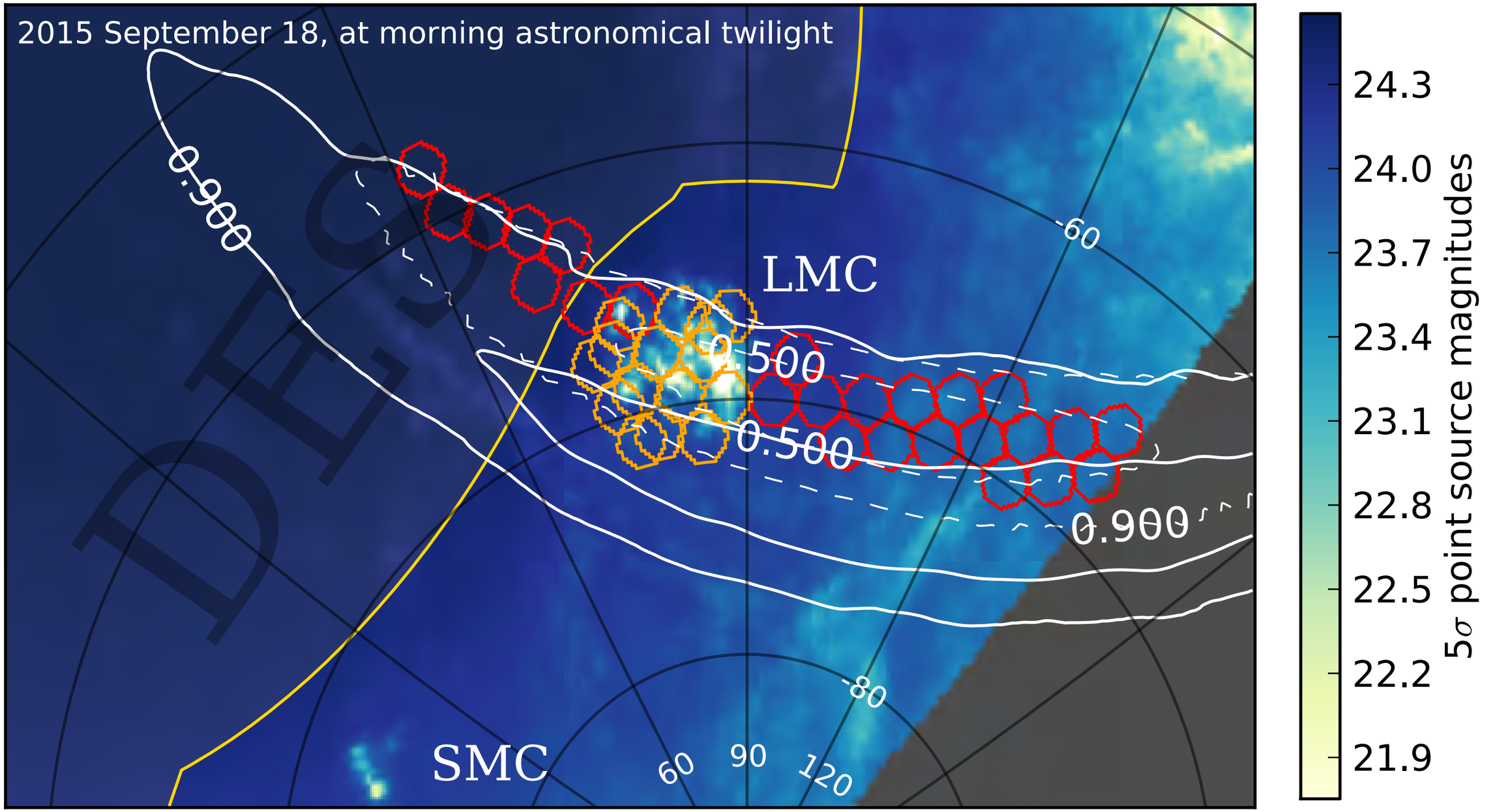
- **DES uses multiple signatures of structure growth and expansion to investigate dark energy and dark matter to new depths.**
- Recent Results:
  - ~50 Publications to date, mostly from SV data; calibrating systematics and testing analysis methods
  - DES has just finished Year 3 of observing
    - We are following up LIGO gravitational wave candidates
- Future
  - Constraints on DE and DM from full survey area (Y1 and Y2 data) *are slated for release* some time next year
- Data Releases:
  - *raw* images from Y1, Y2 is currently available; processed images from Y1; recent release of value-added data from SV (object catalogs and more)
- See Alex Drlica-Wagner's talk at 8am on Thursday, "DES and Fermi results on dwarf galaxies"



And there’s more!

Gravitational Wave follow-up with DES

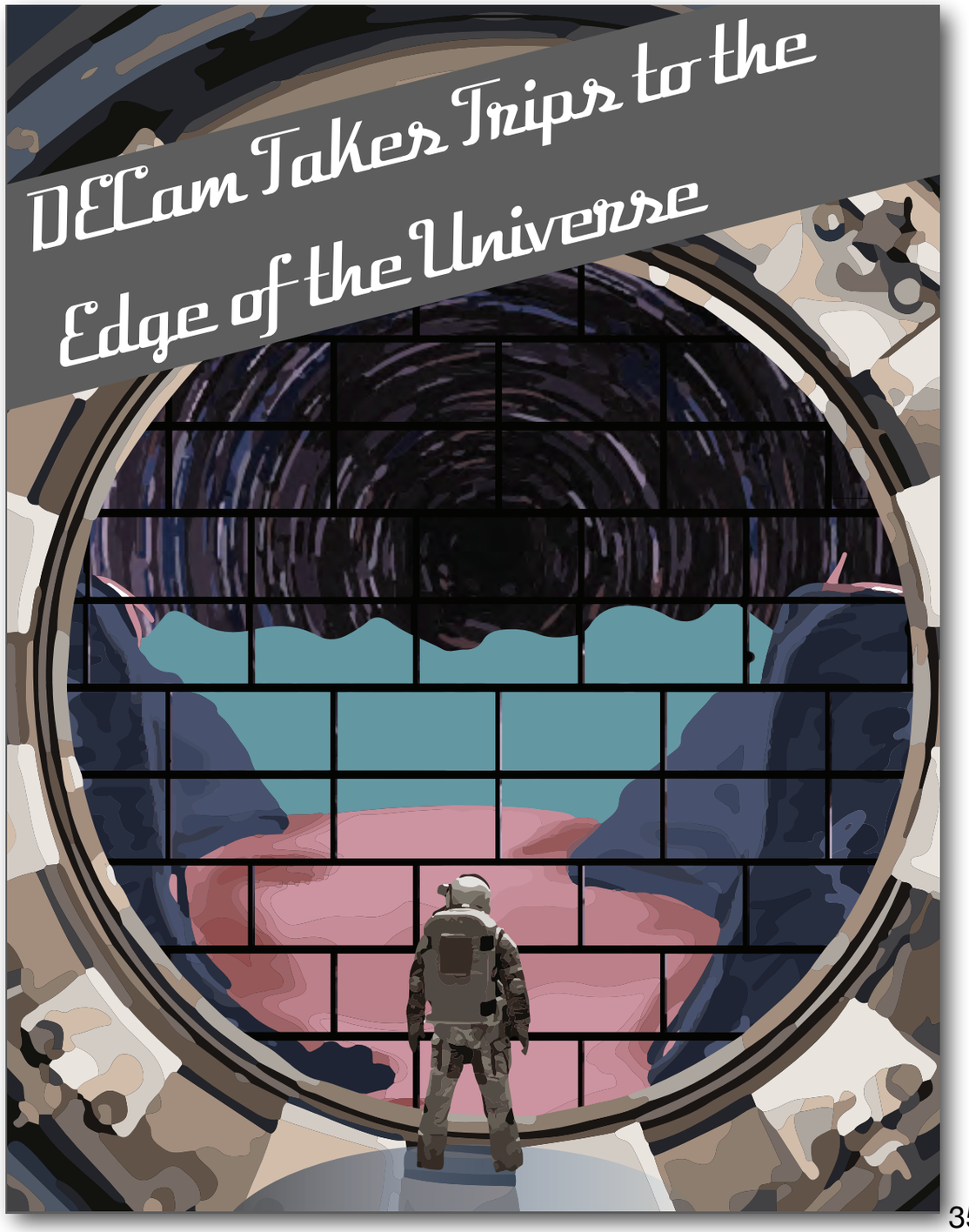
[Soares-santos++2016; Annis++2016]



DES Outreach:

- A simple vision:
  - Help all DES scientists participate in sharing their perspective on cosmology, so that members of the public can have as intimate and realistic view of science as possible.

- Programs:
  - Social Media (multiple languages)
  - Graphics
  - Arranging presentations/visits
  - Integrating public events with collaboration meetings



DES Outreach:

DarkEnergyDetectives.org

DArchives *DES Results in a Nutshell*

Scientist of the Week
(example: Gus Evrard, UofM)

Dark Bites: *quick facts in a big universe*