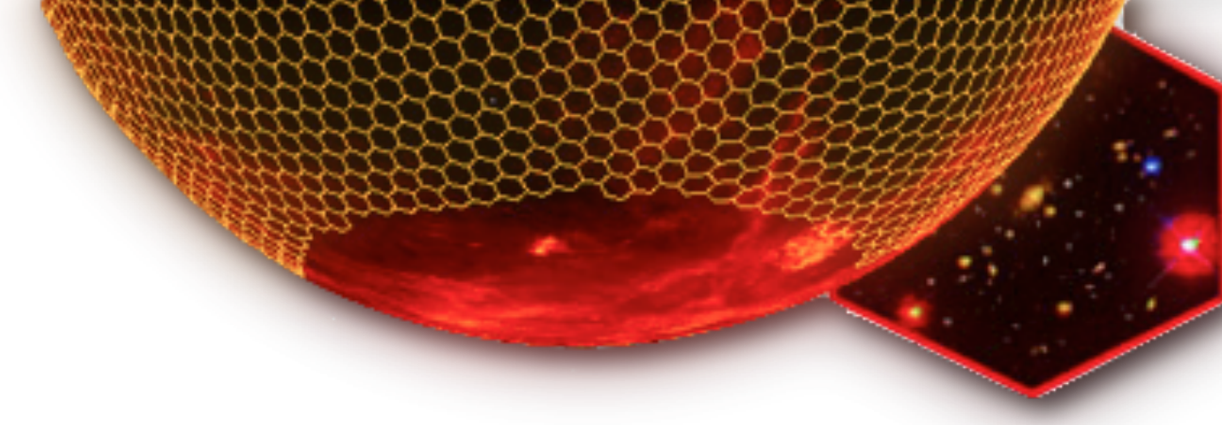

Strong Gravitational Lensing in the Dark Energy Survey

New Discoveries and Search Techniques

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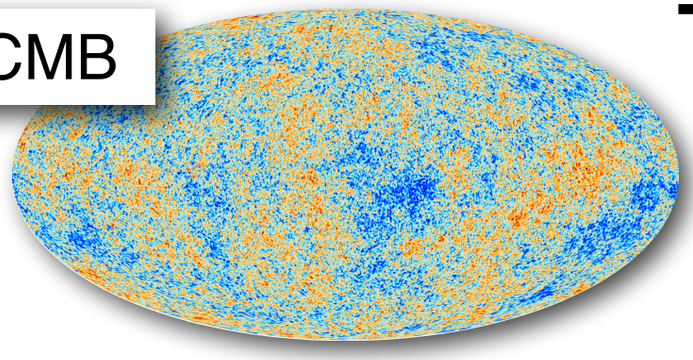
@iamstarnord

Sneak Preview

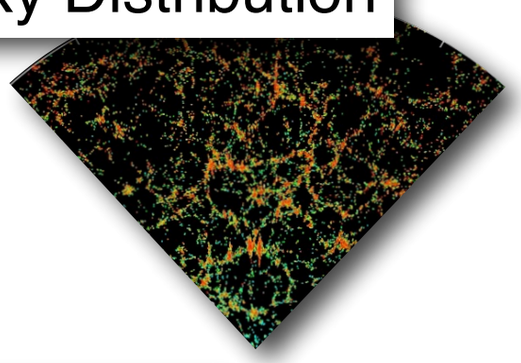
- Dark Energy Survey
- Strong Gravitational Lensing as a cosmological probe
- How to discover a lens: recent finds in DES
- New techniques for finding lenses

A Tug of War:
Complementary Probes

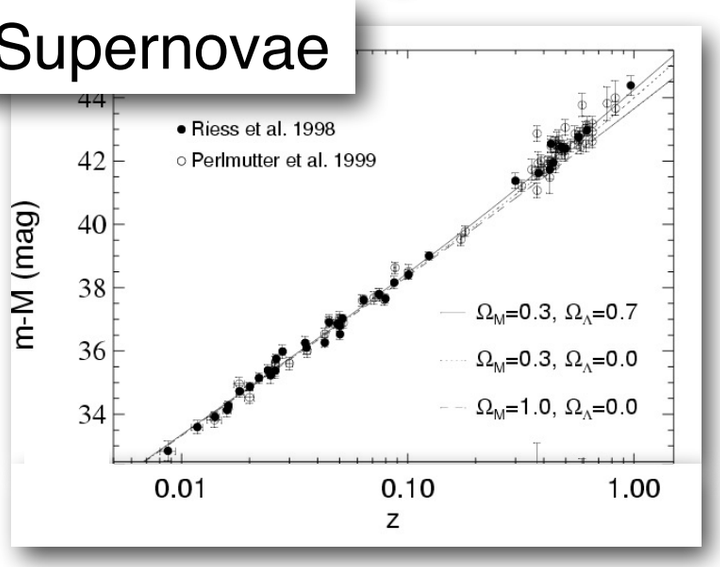
CMB



Galaxy Distribution

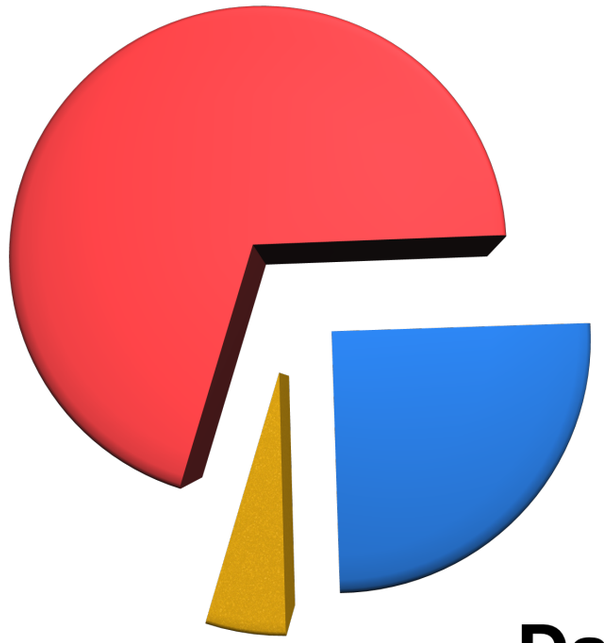


Supernovae



Geometry
+
Structure
Growth
+
Expansion

Dark Energy
70%

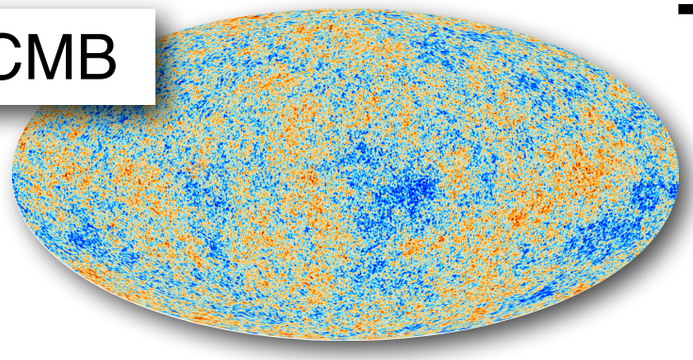


Baryons
5%

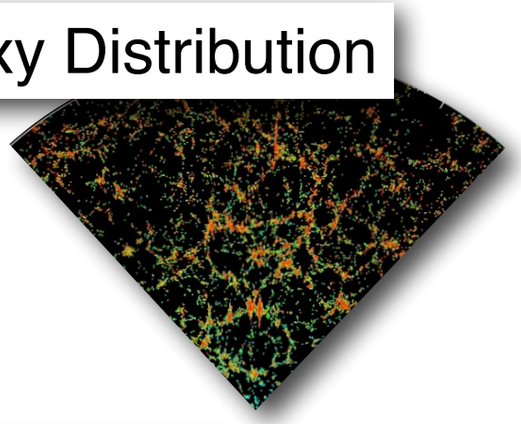
Dark Matter
25%

A Tug of War:
Complementary Probes

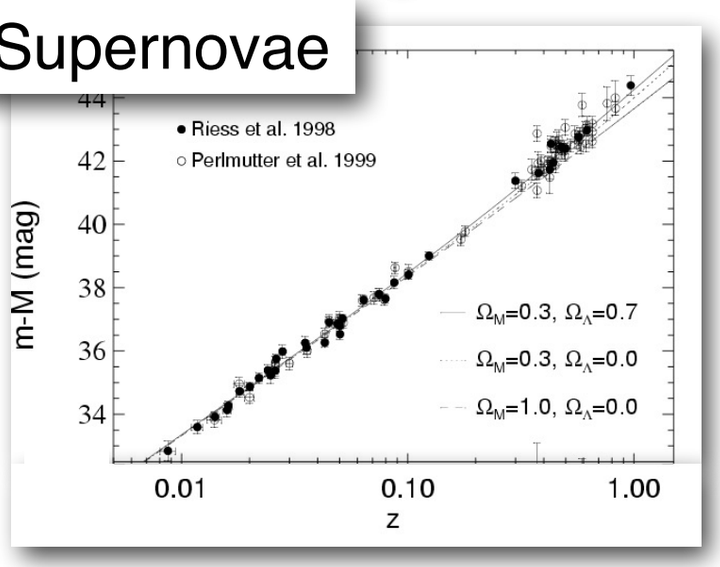
CMB



Galaxy Distribution



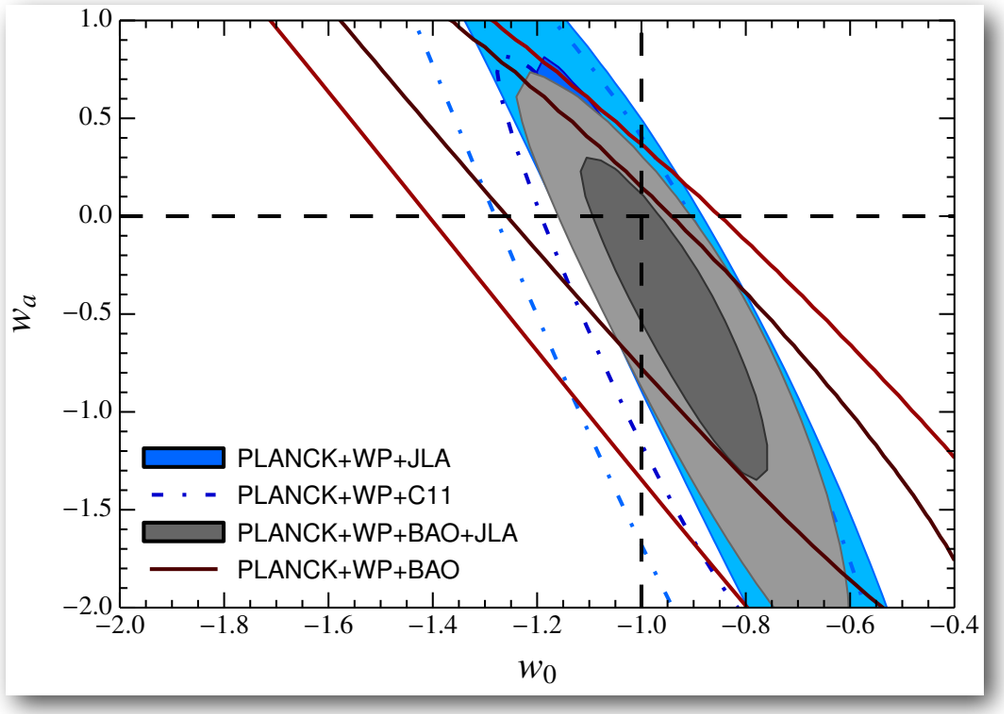
Supernovae



Geometry
+
Structure Growth
+
Expansion

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

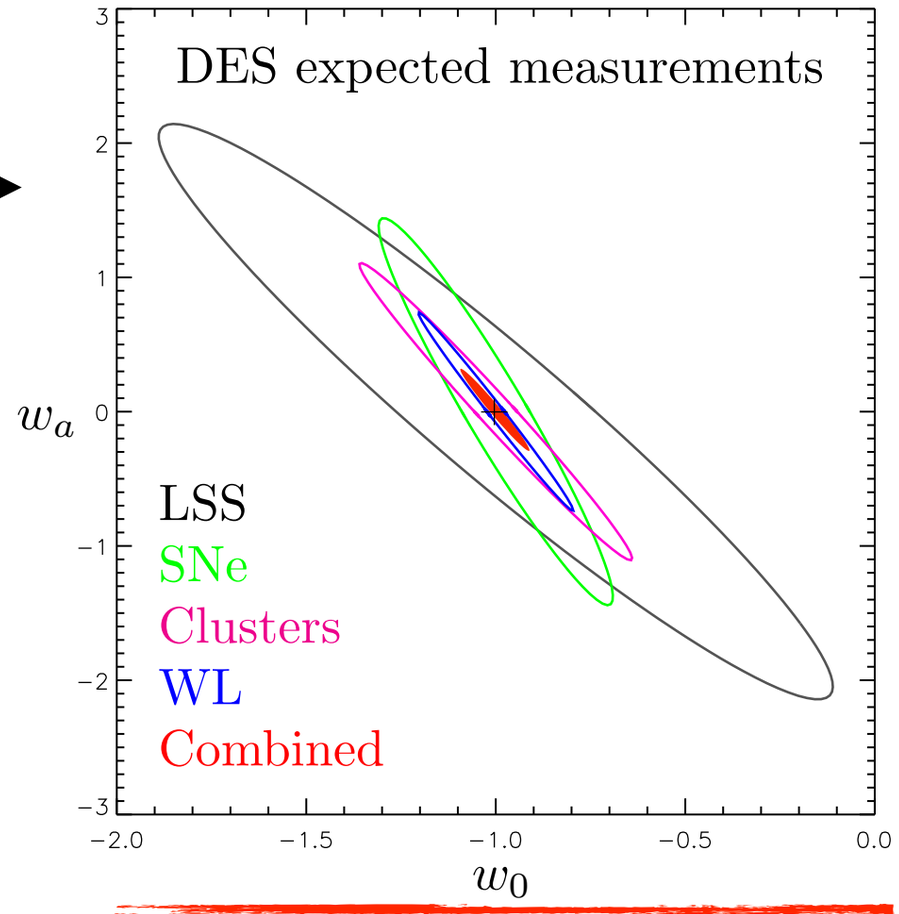
Expansion and Structure Growth

Multiple Probes, One Experiment

- ***Weak Lensing:*** *(structure)*
  - 200 million galaxy shapes
- ***Supernovae:*** *(expansion)*
  - ~3000 well-sampled SNe Ia to z ~1
- ***Galaxy Clusters:*** *(structure)*
  - ~10,000s clusters to z>1
- ***Large-scale galaxy distribution:*** *(expansion)*
  - 300 million galaxies to z > 1
- ***Strong Lensing:*** *(structure and expansion)*
  - ~2,000 galaxy-/cluster-scale lenses
- *As the size lens populations increases and diversifies, strong lensing has the potential to provide important complementary cosmological constraints.*

Evolving DE equation of state:

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



Predicted DES Constraints:

w_0 to ~5%

w_a to ~30%

DECam installed in 2012

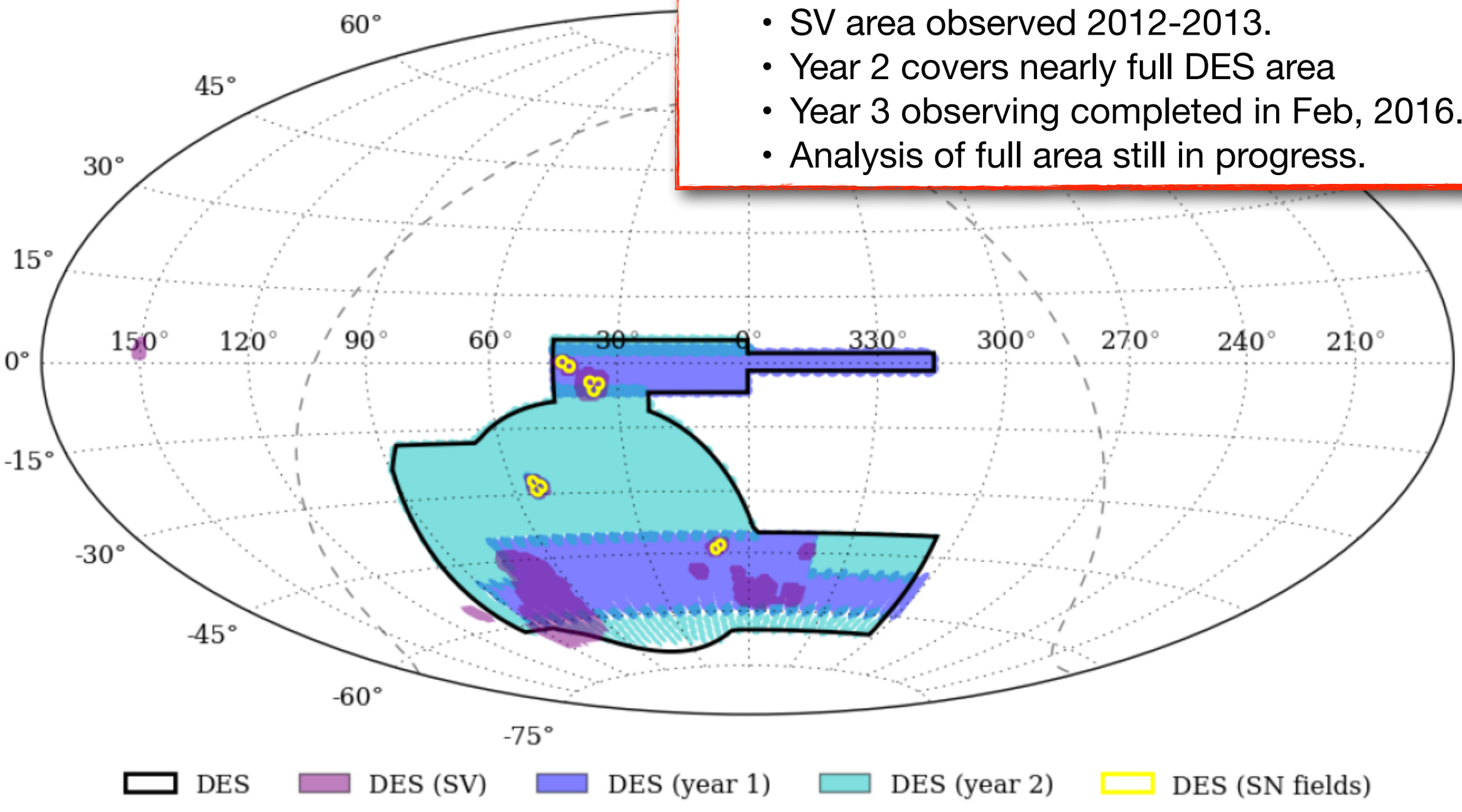
~500 Scientists from
~30 Institutions
7 Countries

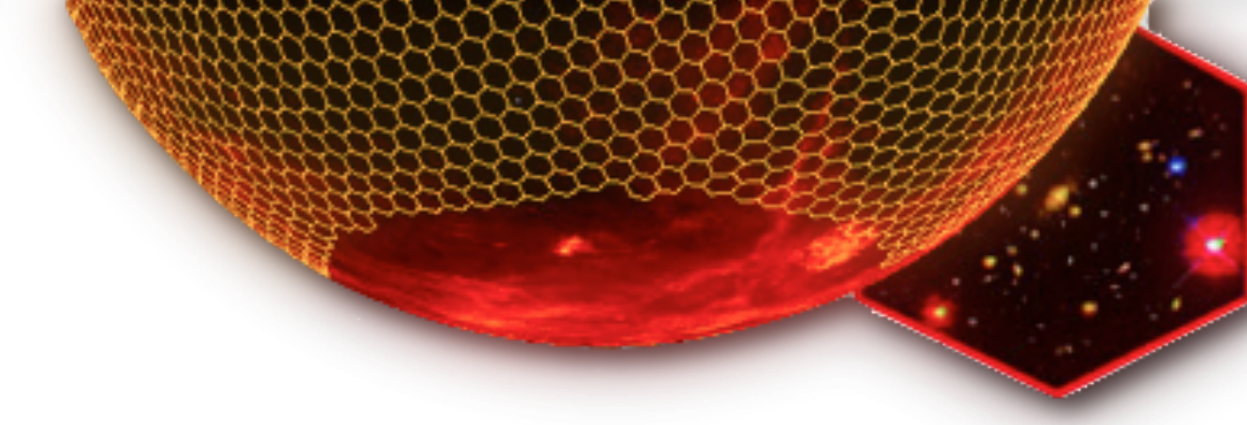
image by Reidar Hahn (FNAL)

Survey Footprint

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

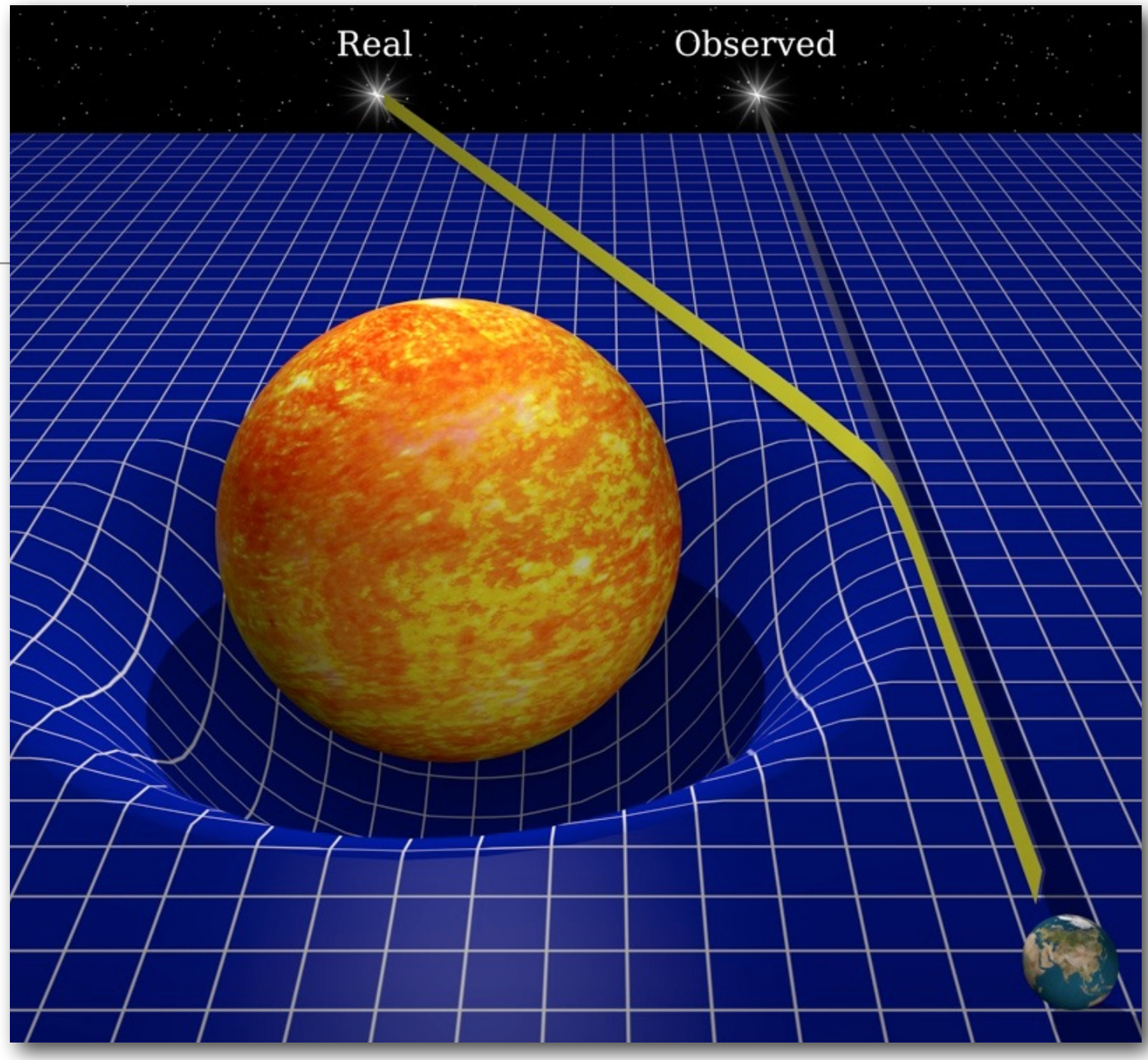
- <u>Observing/Analysis Milestones:</u>
  - SV area observed 2012-2013.
  - Year 2 covers nearly full DES area
  - Year 3 observing completed in Feb, 2016.
  - Analysis of full area still in progress.





Warped Perspective

Energy tells space how to curve, and space tells energy how to move.



DISTANT GALAXY

FOREGROUND GALAXY

EARTH

3 BILLION YEARS

LENSED IMAGES OF DISTANT GALAXY

11 BILLION YEARS

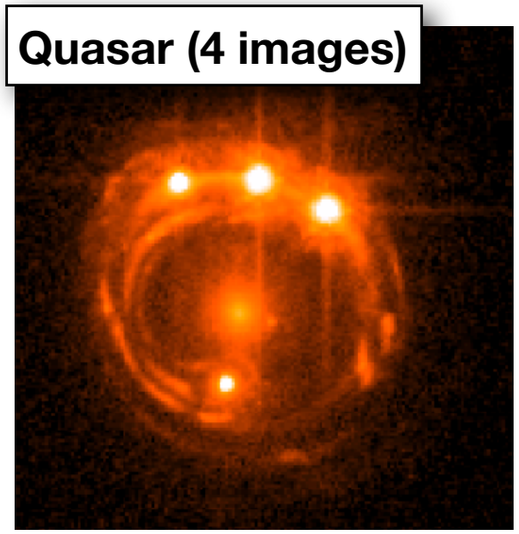
Strong Lens Forecasts for DES

- Census of literature
  - Variety of techniques and wavelengths, from radio to optical.
  - **~1000 strongly lensed systems** have been discovered to date.

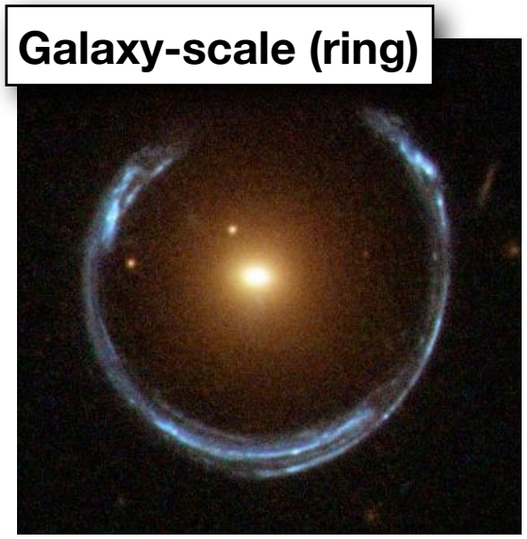
- Current predictions for DES discovery:
  - **~2000 lenses** galaxy- to cluster-scale (Nord+2015, Collett+2015)
  - **~120 lensed quasars and < 10 lensed supernovae** (Oguri & Marshall, 2010)

- *Large populations in DES made possible by red-sensitive DECam CCDs, which allow depth of survey.*

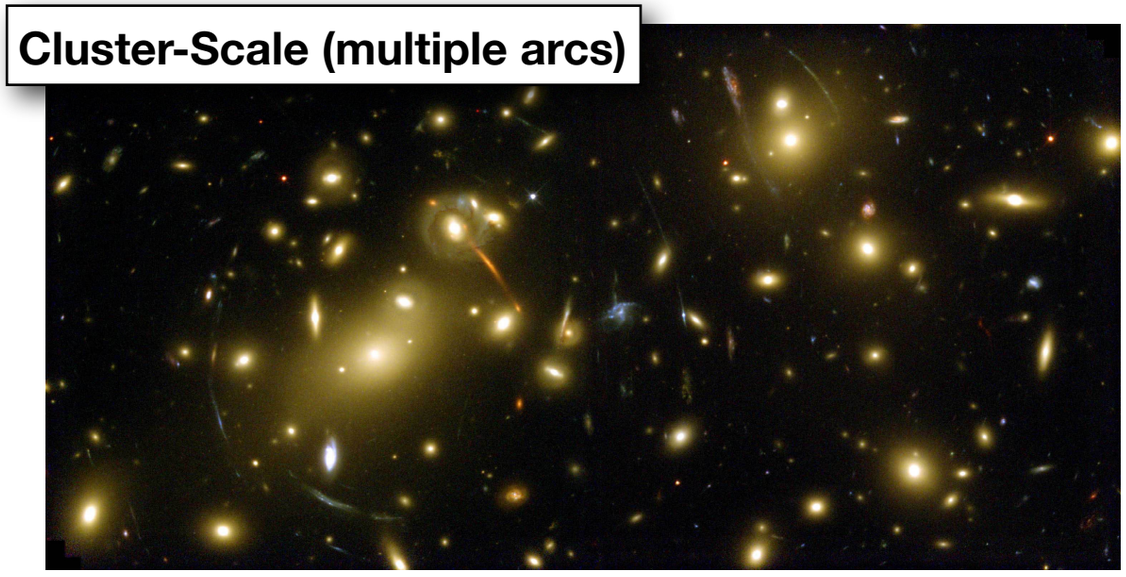
Famous Lenses from Literature



RXJ1131-123



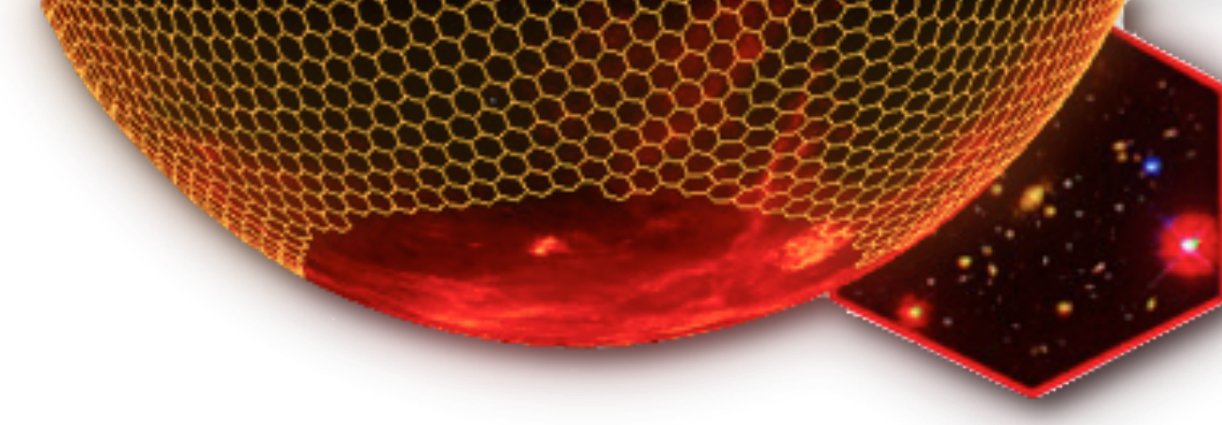
Cosmic Horseshoe
(SDSS J114833.14+193003.2)



Abell 2218

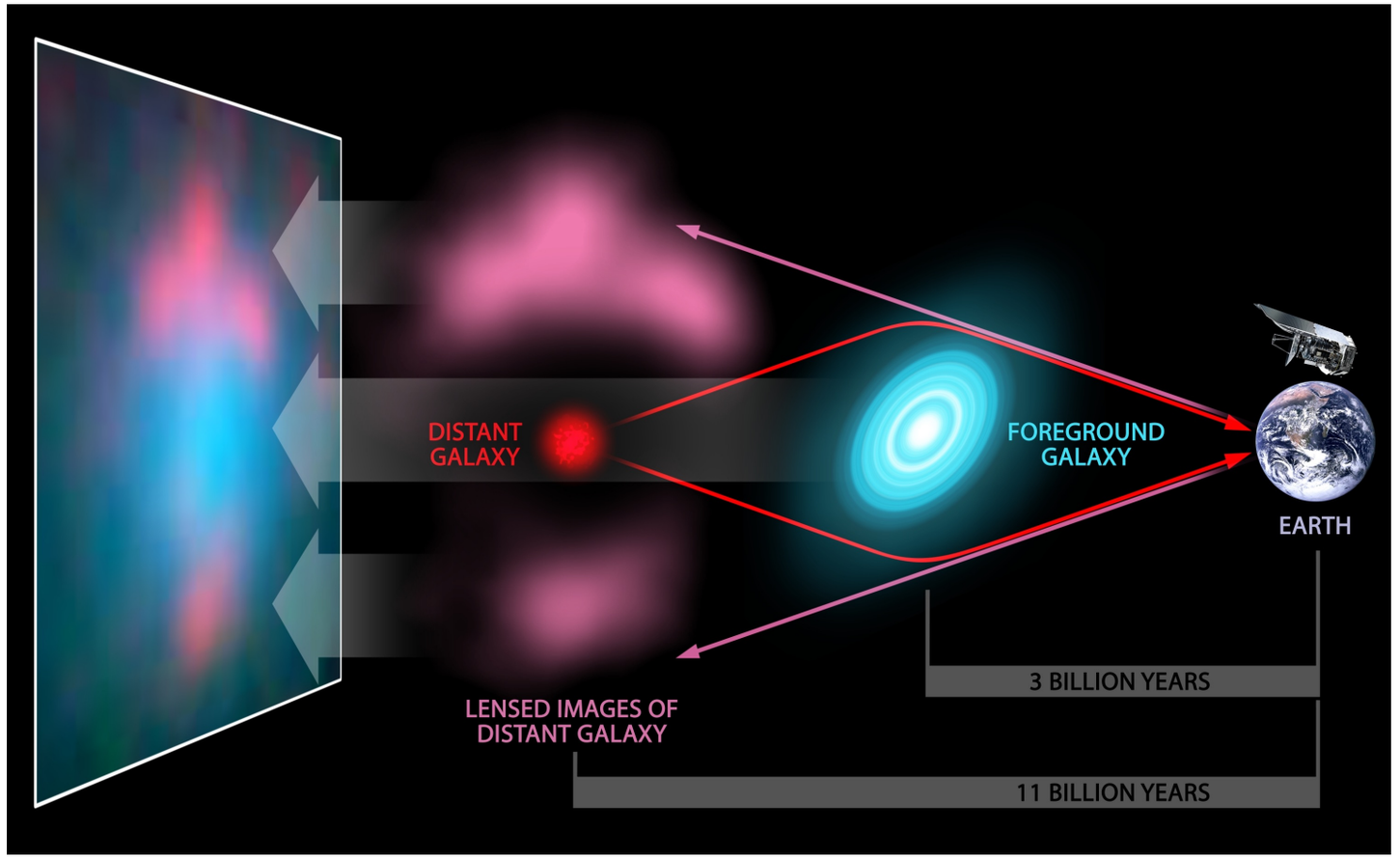
Chicago - Lensed

via GravLensHD by Eli Rykoff



DES Strong Lensing: *Search, Discovery and Science*

1. <u>Scan data:</u>
   Visual scan, arc-finding, catalog search
2. <u>Obtain precise distances</u>
   spectroscopic follow-up
3. <u>Science!</u>
   1. Model lensing mass
   2. Measure cosmological parameters

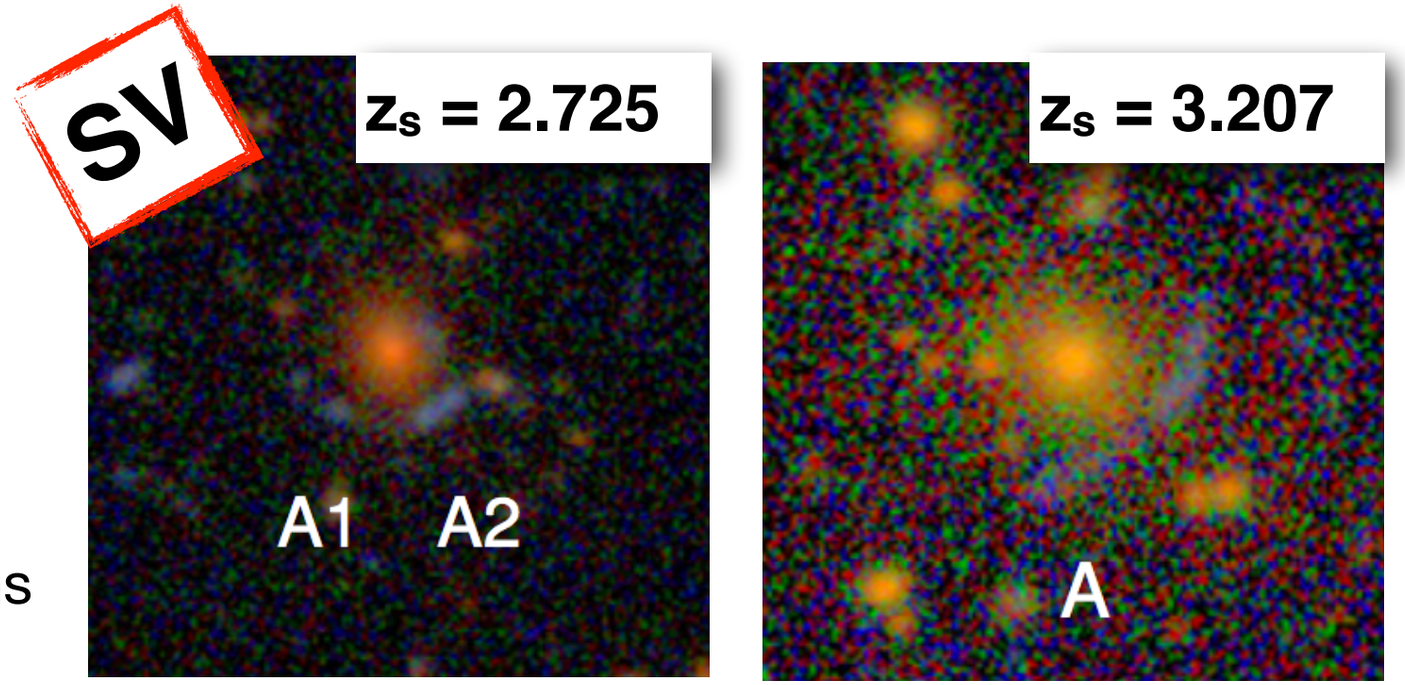


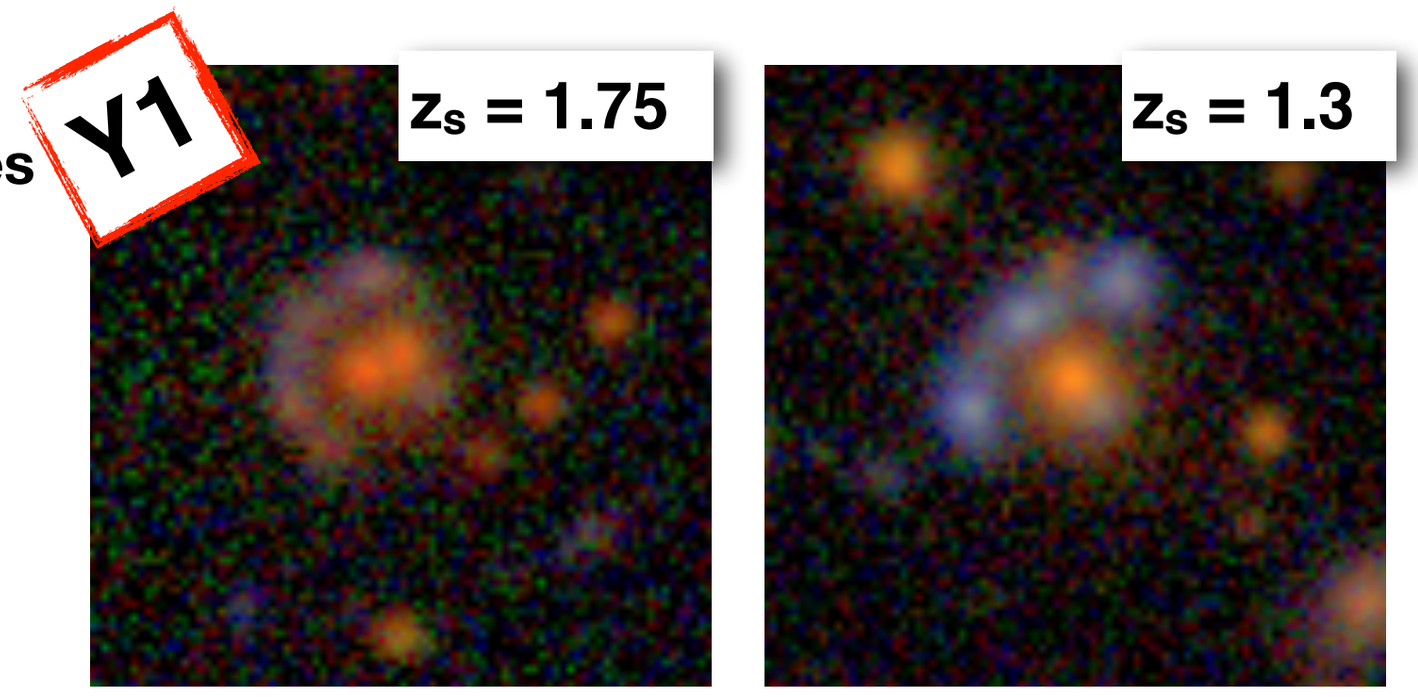
Candidate and Confirmed Lensing Systems

- <u>SV Search Program (250 deg$^{2)}$</u>
  - Visual scan by 20 people
  - **6 spec confirmed systems**
    (Nord+2015, arXiv:1512.03062)

- <u>Y1 Search Program (1000 deg$^{2)}$</u>
  - Catalog search: photometry, positions
  - Visual scan by 10 people
  - **7 spec confirmed systems**
    (Nord+2016, in prep.)
  - **100's med.-/high-quality candidates**
    (Diehl+2016, in prep.)

- <u>Spectroscopic Follow-up</u>
  - Magellan/IMACS:
    <10 hours in 2014/2015
  - Gemini South - GMOS:
    ~250 hrs over three years

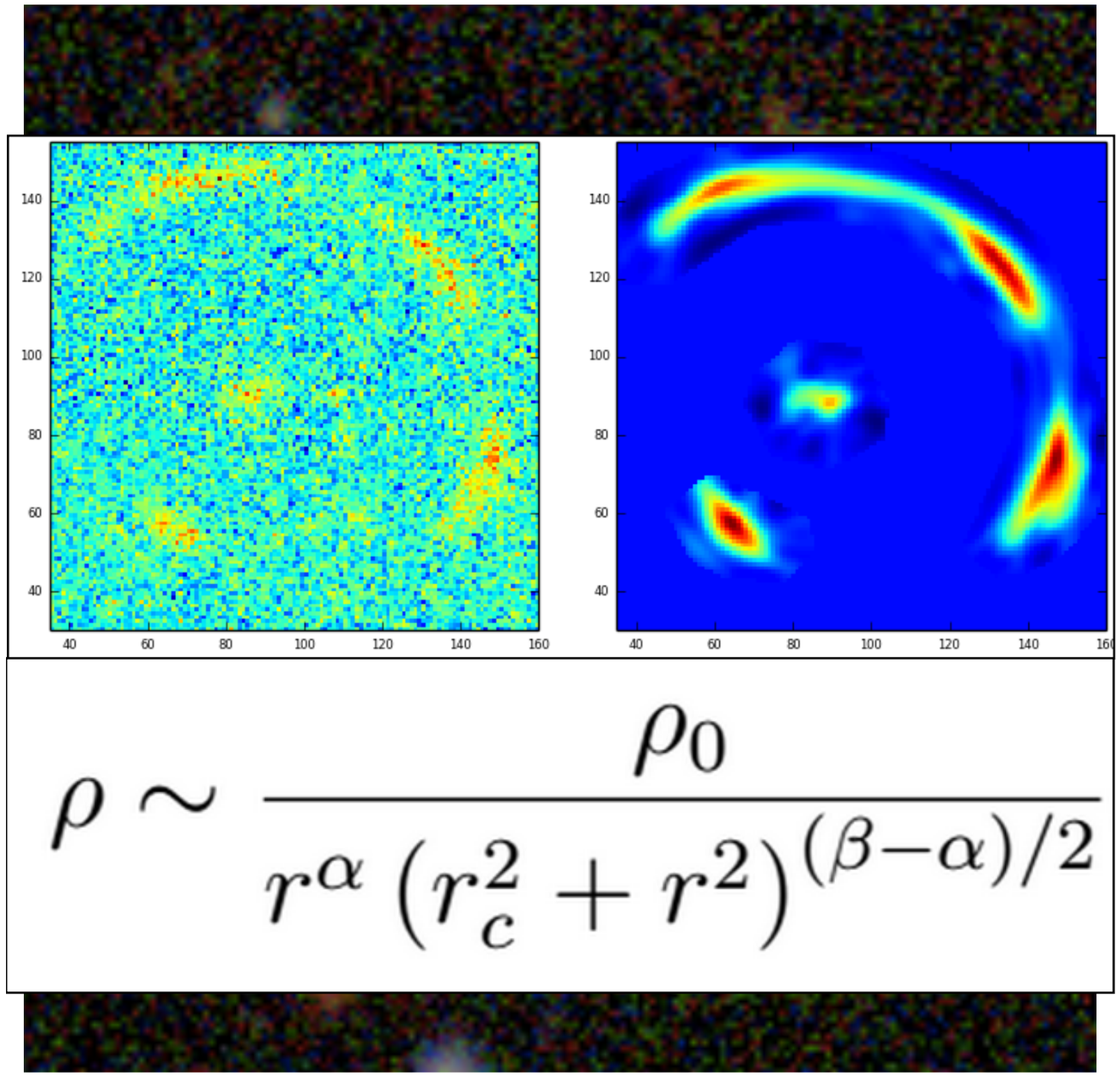




Dark Matter Halo Profile Studies

- Dark Matter halo profiles still have some mysteries due to baryonic effects, unknown nature of dark matter and more.

- A rare, interesting system
  - Found in Y1 Data
  - Profile *much* shallower than NFW with a huge core, >35 kpc
  - We can measure core because the lens' galaxies don't obscure a central image
  - HST imaging will allow more precise modeling.
    (Collet+2016, in prep.)



$$\rho \sim \frac{\rho_0}{r^{\alpha}\left(r_c^2 + r^2\right)^{(\beta-\alpha)/2}}$$

Lenses for Cosmology
Time delays

- ***The time delay*** between different light paths is proportional to the H_0 (Refsdal, 1964)
- ***The systematics*** are small quasar samples and mass modeling
- ***Complementary with CMB and SNe*** improves dark energy constraints by over 50% (Linder+2016)

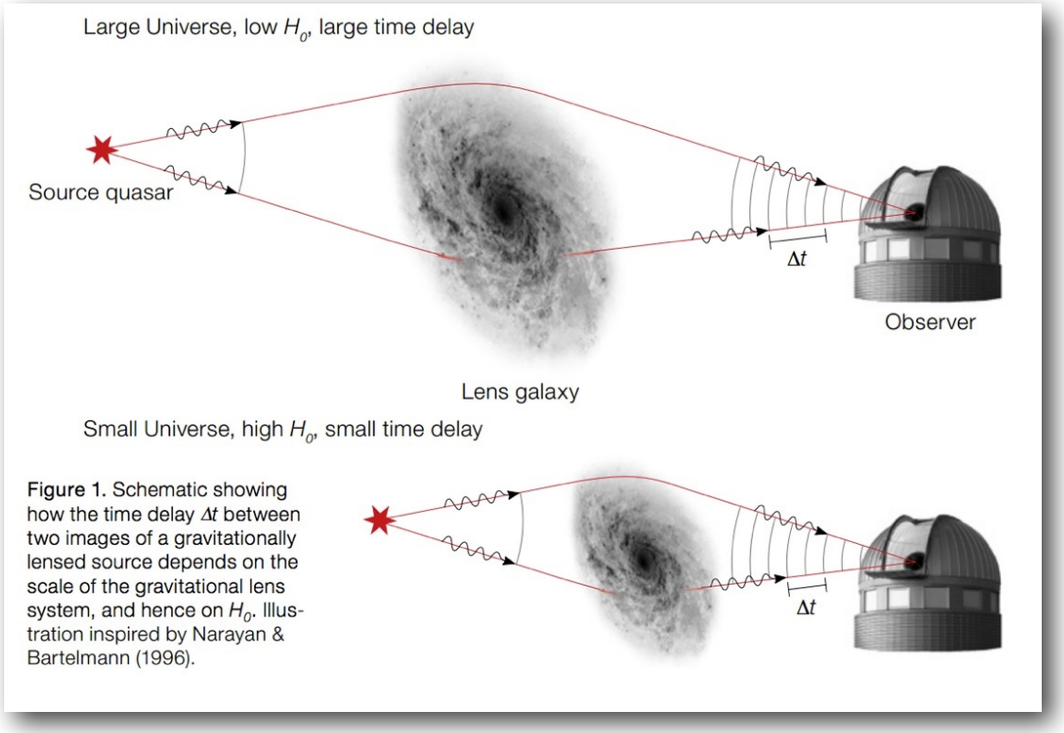
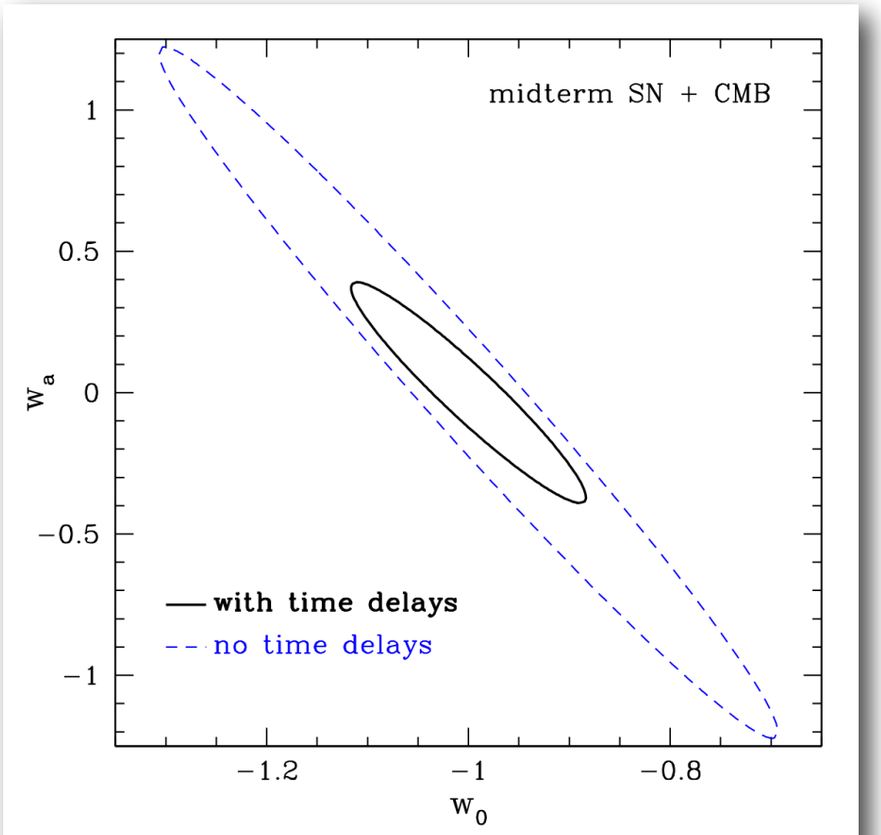


Figure 1. Schematic showing how the time delay Δt between two images of a gravitationally lensed source depends on the scale of the gravitational lens system, and hence on H_0. Illustration inspired by Narayan & Bartelmann (1996).



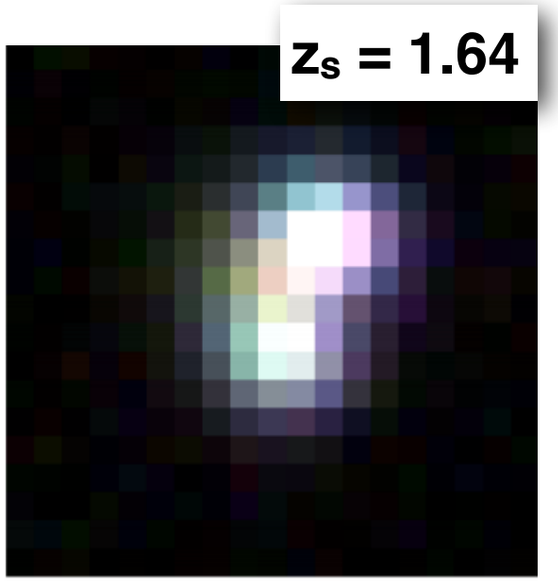
- Recent Developments
  - *Cepheids & supernovae:* ***73.24 ± 1.74 km s^{-1} Mpc^{-1}*** *(Riess+2016)*
  - *Time delays:* ***73 (+5.7 -6.0) km s^{-1} Mpc^{-1}*** *(Wong+2016 and the H0liCOW consortium)*
  - ***2-3σ*** *tension with CMB/Planck measurements*

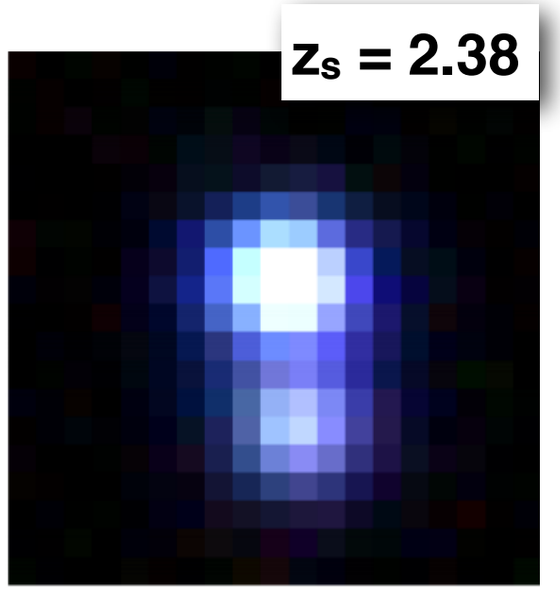
Lensed Quasars

STRong lensing **I**nsights into **D**ark **E**nergy **S**urvey

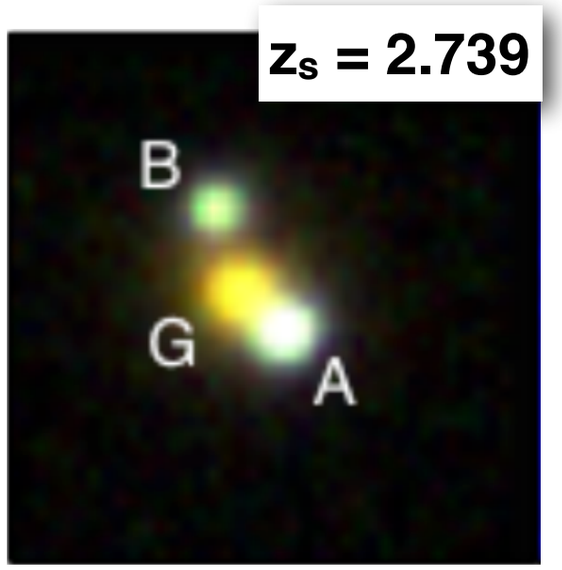
- **STRIDES**:
  Collaboration with external partners, led by T. Treu

- DES Lensed Quasars Discoveries
  - Agnello+2015, arxiv:1508.01203
  - Ostrovski+2016, arxiv:1607.01391
  - Lin+2016, in prep.



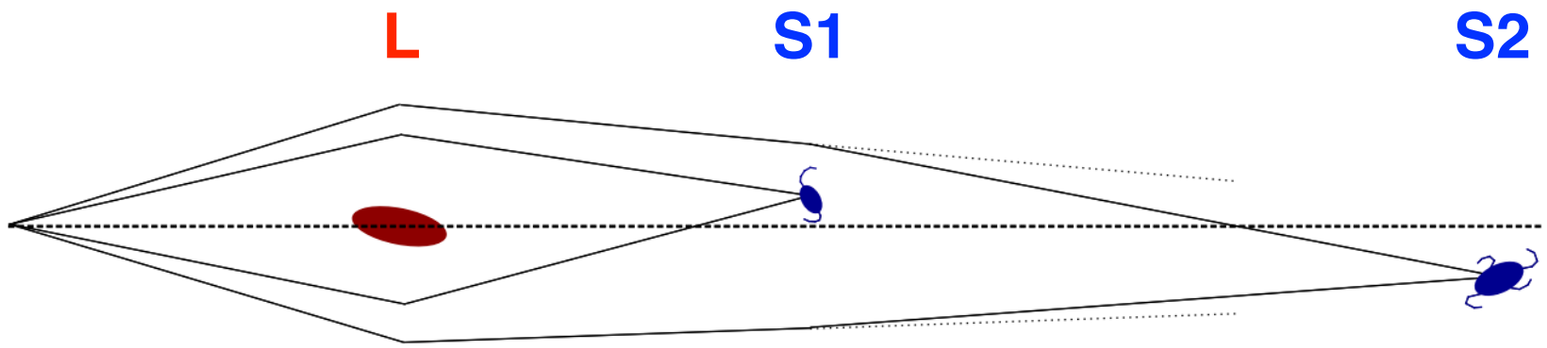


- Follow-up Campaigns
  - Spectroscopy:
    6 nights on NTT
  - Photometric monitoring:
    La Silla 2.2m: 1.5 hr/night, Oct-Apr.
  - AO imaging:
    SOAR, Keck



- *Continued lens-finding and growing the monitoring campaigns will make possible new and competitive cosmological constraints.*

Lenses for Cosmology
Double-source systems



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

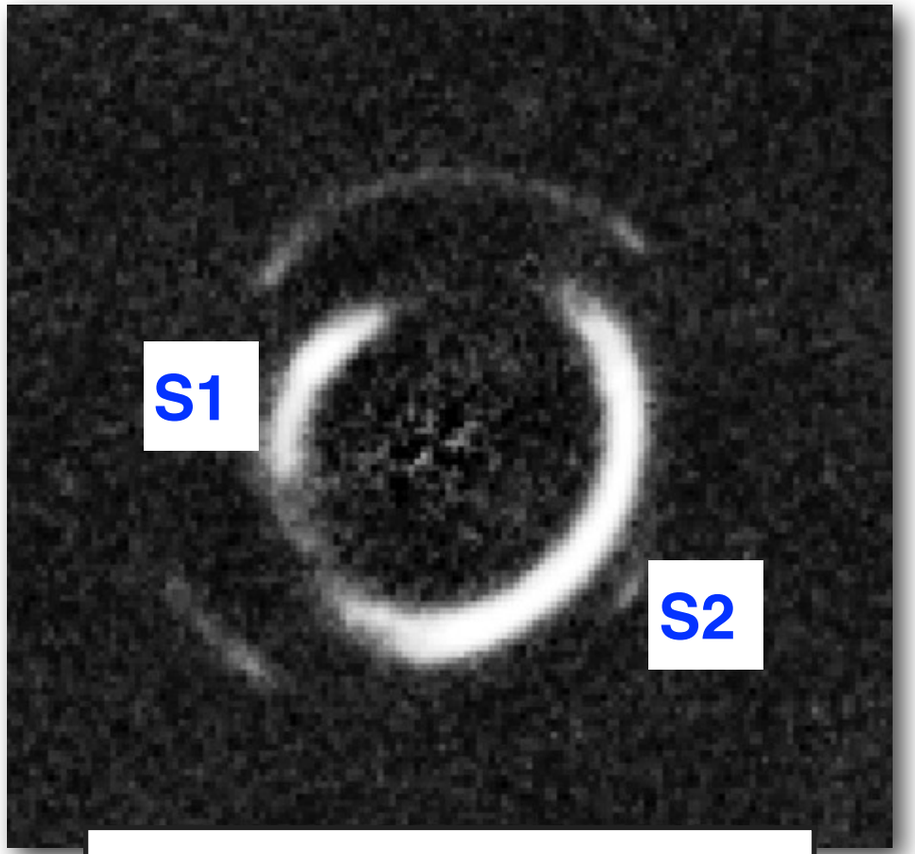
$$D_{ij}(\, z_L,\, z_s\, ;\, H_0,\, \Omega_M,\, \Omega_\Lambda,\, w\,)$$

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

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

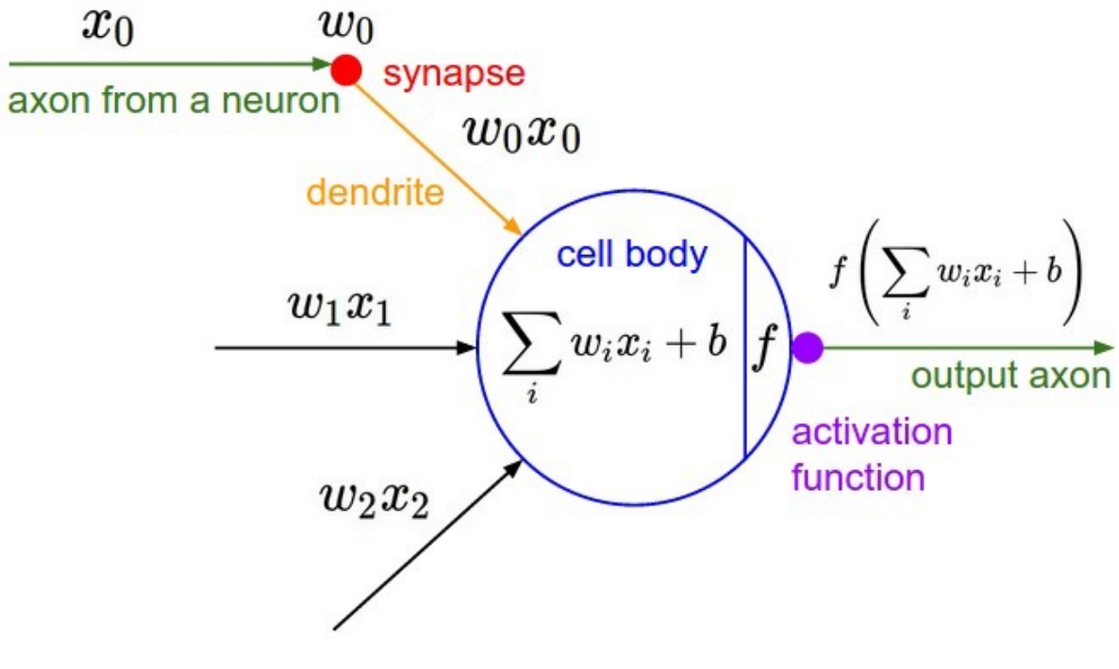
- To date, only **1** has been found.

- *We expect* ***~10 in DES*** *(Gavazzi+2008)*



SDSSJ0946+1006

Deep Learning and Neural Nets

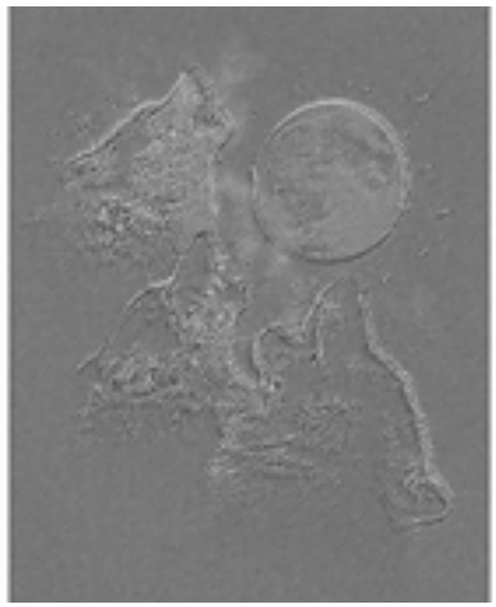


- Neural Nets are made of neurons (filters) that process input image data.

- Filters (with parameters, w_i) activate features in the data, x_i

Image

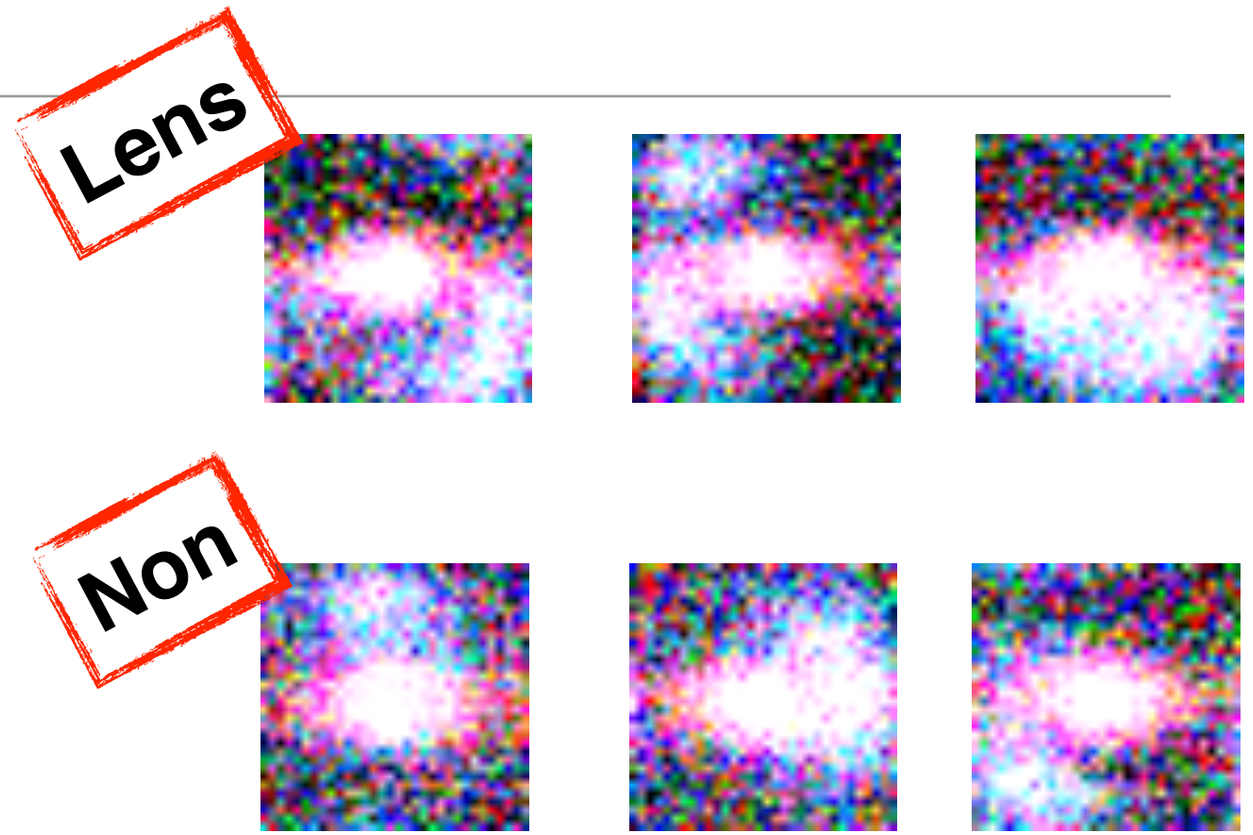
Example Features



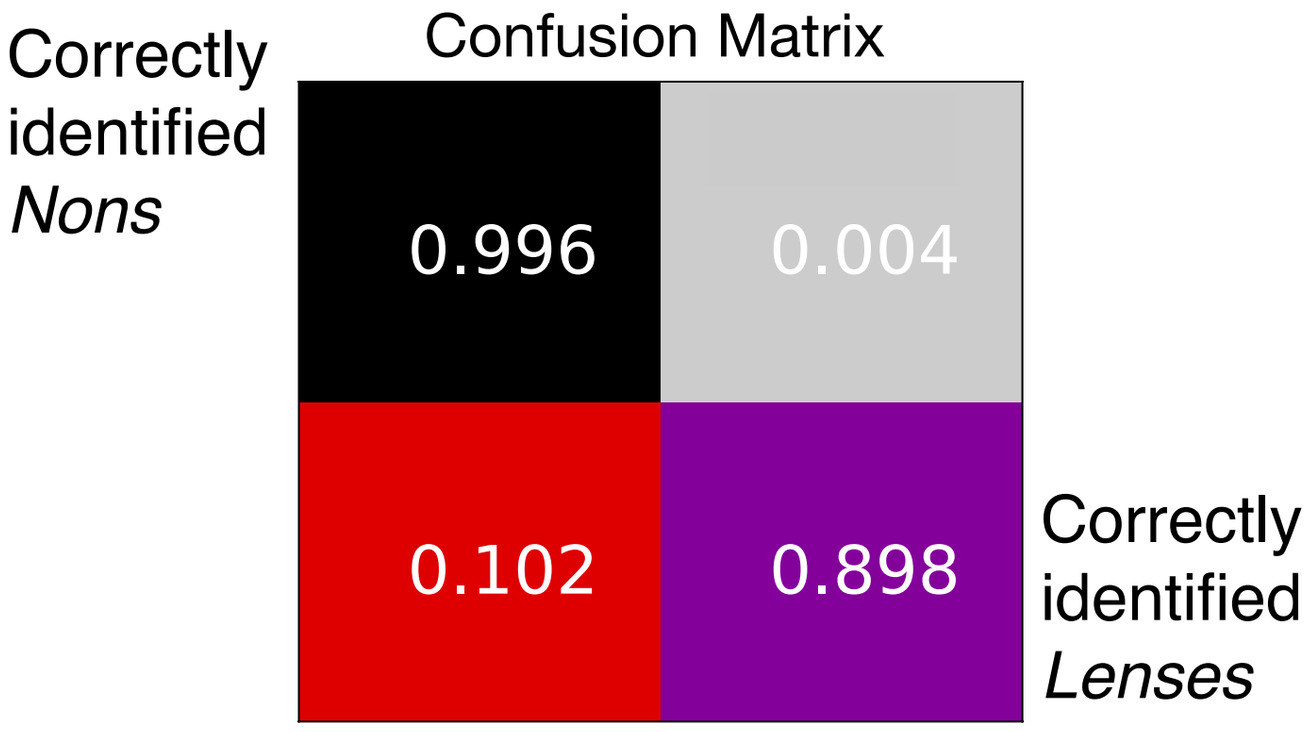
- Important features are learned:
  multiple layers (deep) of neurons are tested and filter parameters, **w,** are adjusted

Deep Lensing

- Simulated images
  - LensPop (Collett+2015)
  - reproduces DES characteristics
    - noise levels, exposure time, psf, filters/colors, pixel scale
- Training sets:
  - 10k lenses, 10k non-lenses
  - 32 x 32 pix

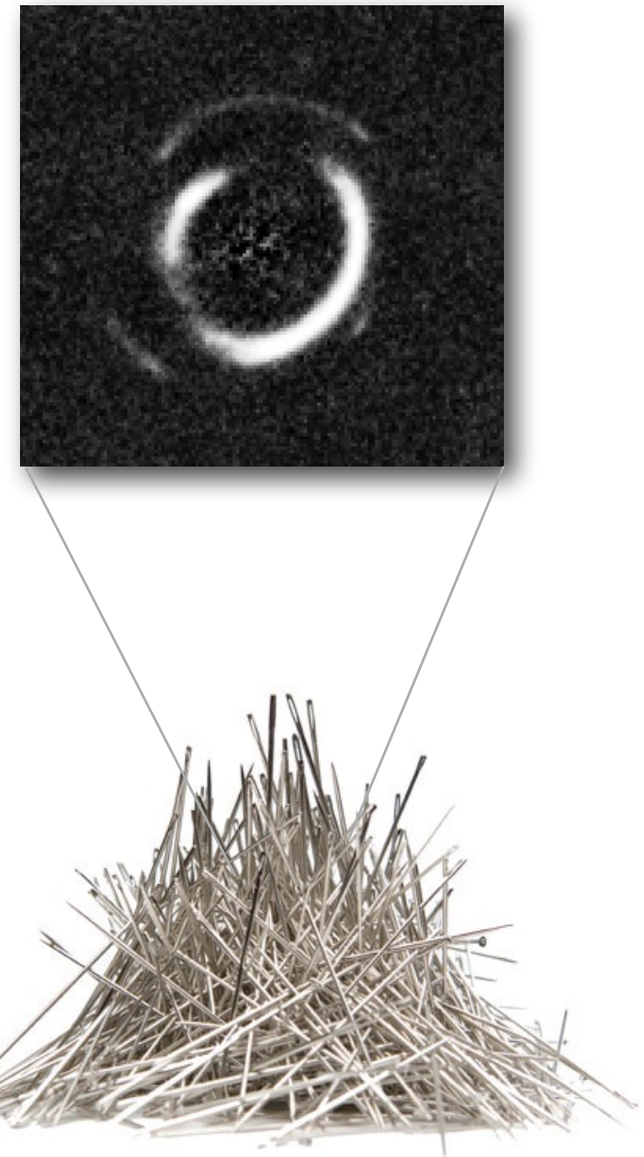


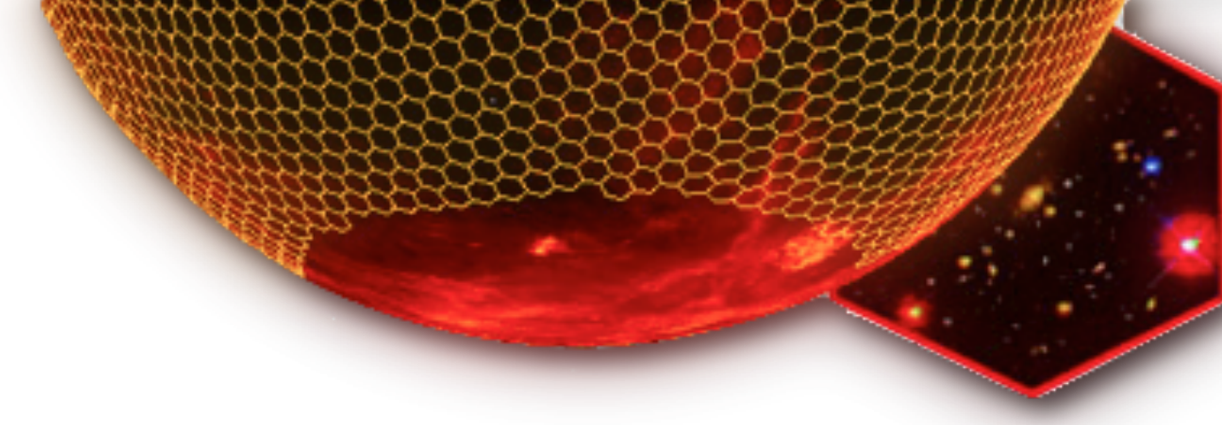
- Software:
  - Theano on a laptop
  - 3-layer neural net
- Key goals/questions:
  - Can we remove humans from the search process?
  - Can we pinpoint specific kinds of lenses good for cosmology?



DES Strong Lensing

- **DES could find ~2000 lenses — 2x as all previously discovered.**
- Some of them will be optimal for cosmological measurements:
  - lensed quasars, supernovae
  - multiple-source lensing systems
- **Spectroscopic Follow-up and photometric monitoring** programs are well-underway.
- **Multiple papers and projects** are underway with both candidate and confirmed lenses.
- The process of finding objects is challenging. Techniques like **neural nets** may be critical for surveys like DES and LSST.

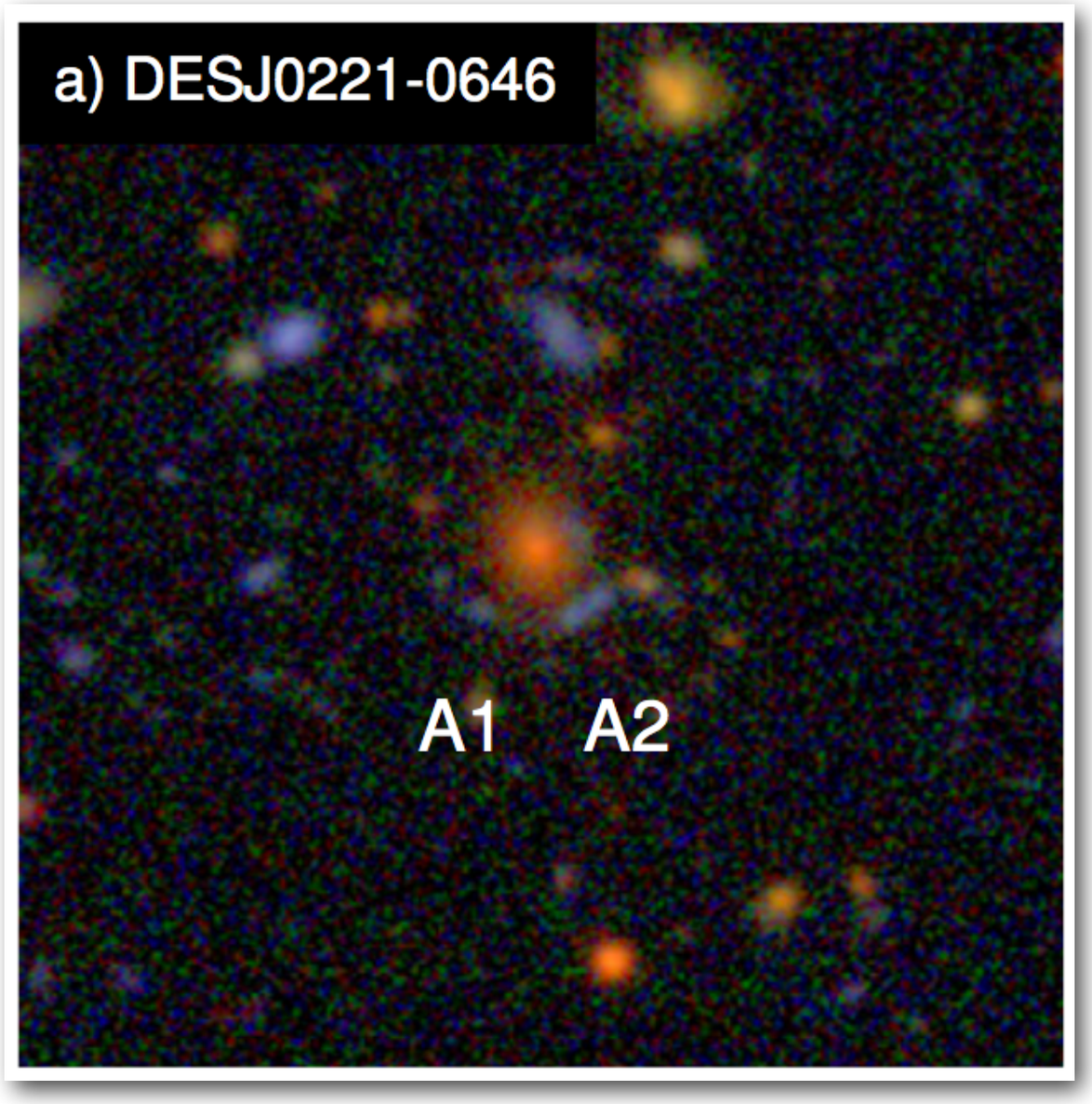




Extras

Image Searches

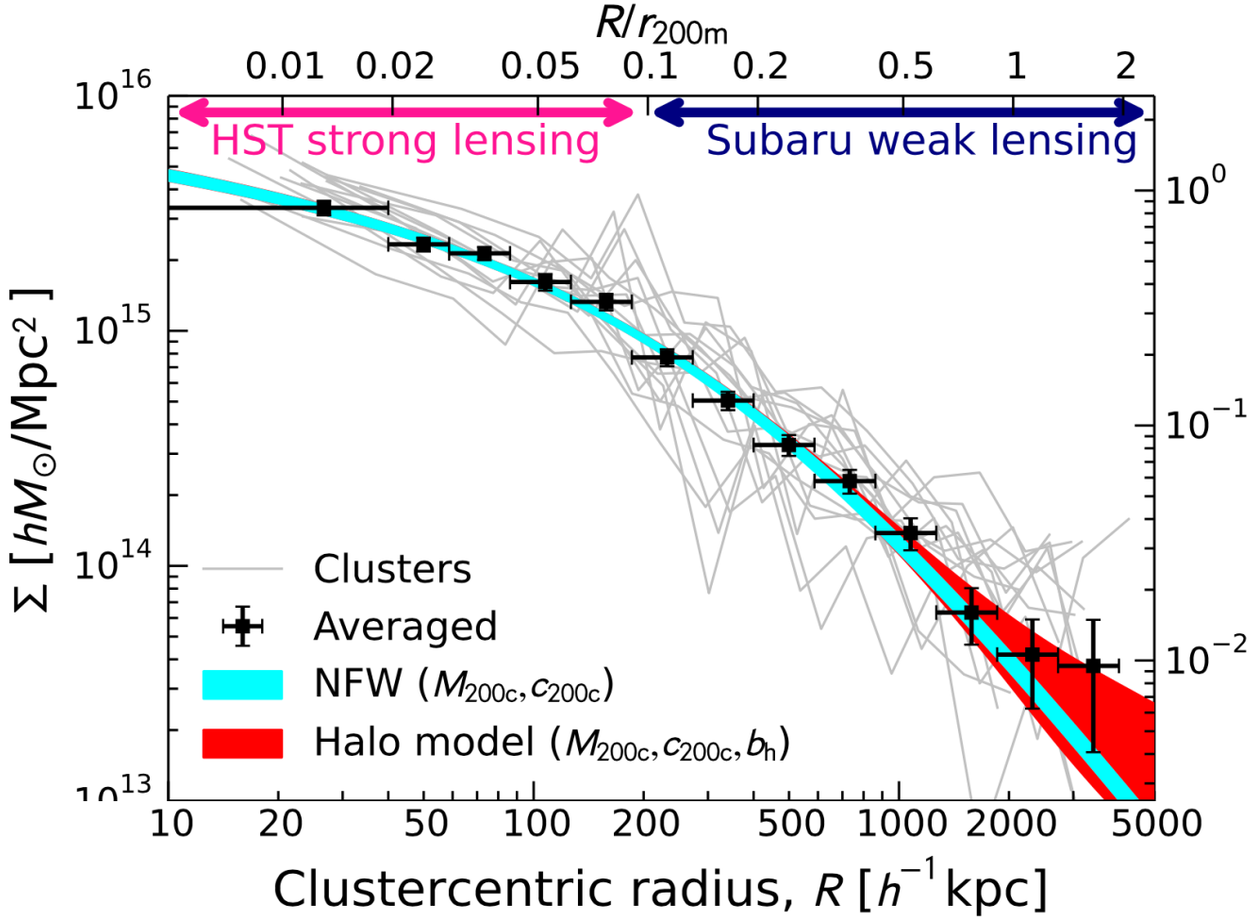
- Search Program
  - Visual scan (SV data, 250 sq. deg.)
- Follow-up
  - Gemini South LLP
  - Magellan



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
- 16 stacked clusters
  - 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.

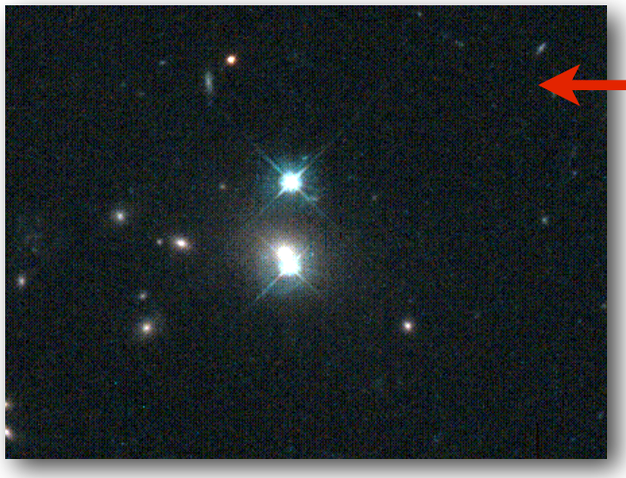


Umetsu++2015

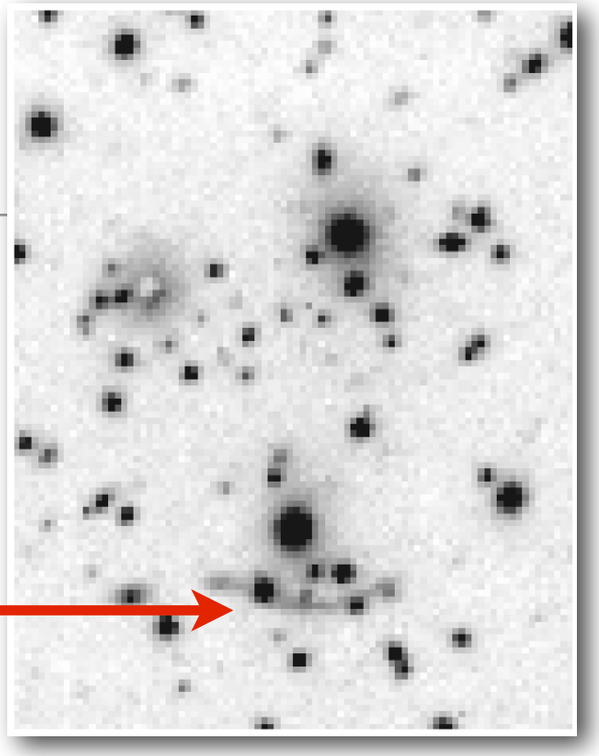
Spectroscopic Follow-up: Gemini South Telescope

- **Large and Long Program**
  - **90 hours of telescope time per year for three years**
  - **1-4 hours per candidate**
  - **Many important nuances to Gemini observing**

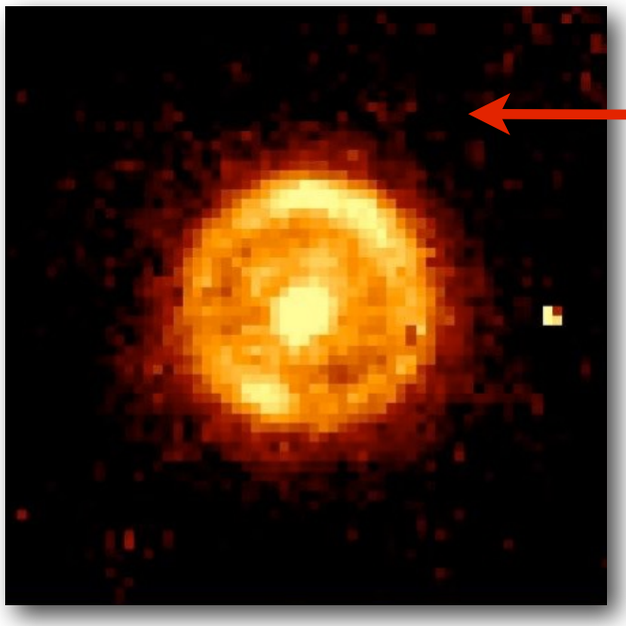
Historical Milestones



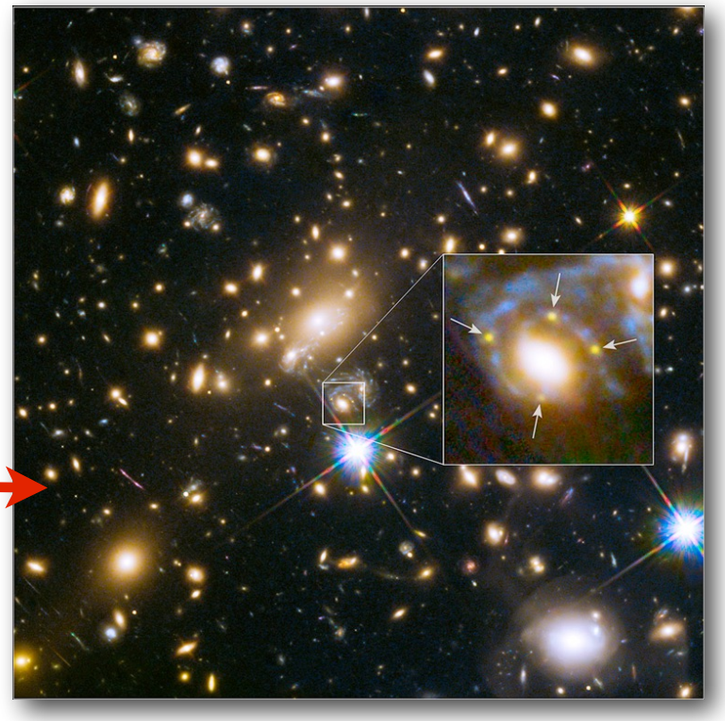
- 1979: First lensed system
  - Twin Quasar SBS 0957+561
    (Walsh, Carswell, Weyman)



- 1986: First lensed galaxy (arcs)
  - Galaxy Cluster Abell 370
    (Lynds & Petrosian 1986; Soucail et al. 1987)



- 1998: First Einstein Ring
  - Galaxy JVAS B1938+666
    (King et al.)

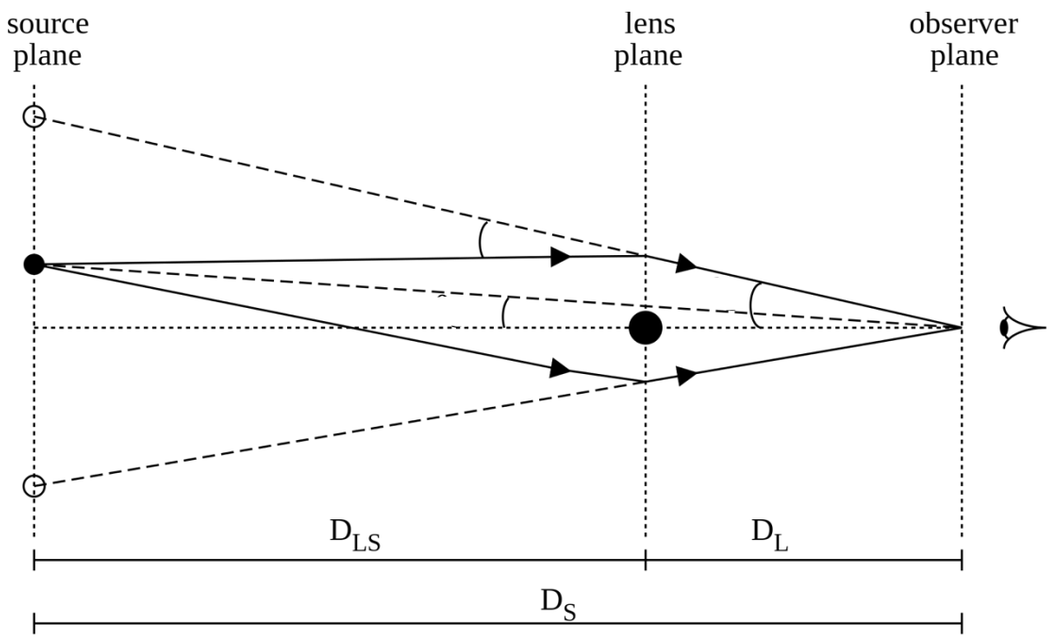


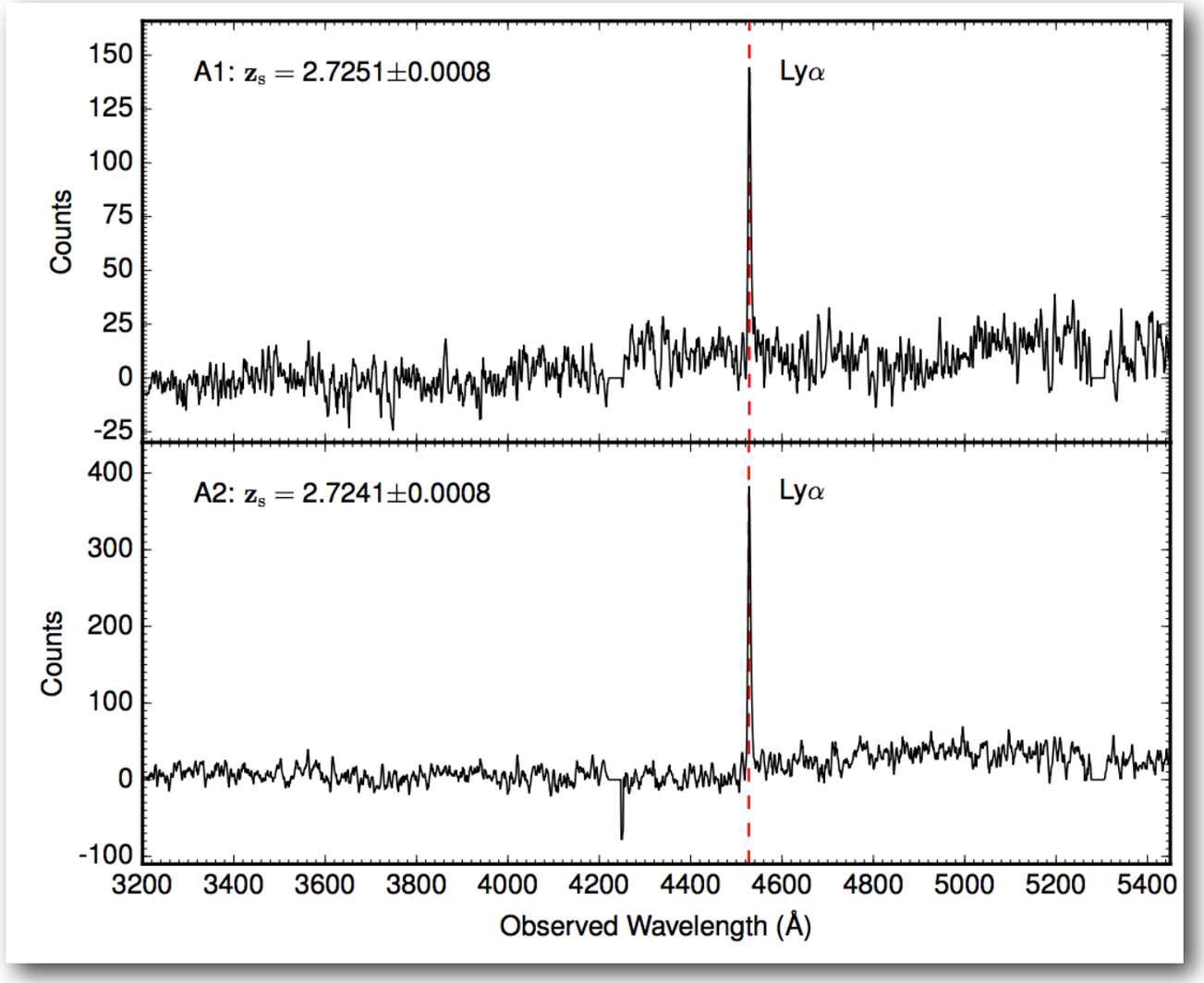
- 2014: First multiply imaged supernovae
  - MACS J1149.6+2223
    (Kelly et al., 2014)

How to find and confirm lenses in three easy steps

2. Find relative positions

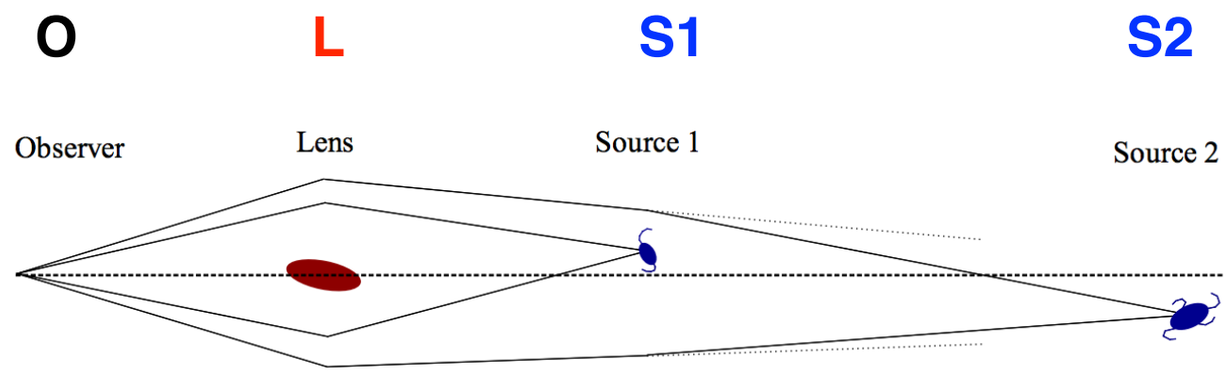
- Obtain spectra to measure redsfhits and angular diameter distances
  - Patterns in spectral features determine spectroscopic redshift (similar to photo-z)
  - Determine whether the source is farther away than the lens.
  - errors: <1%





Confirming 6 systems took > 10 hours on Gemini 8m telescope. There isn't yet enough telescope time in the world to follow-up and confirm 1000's of lenses.

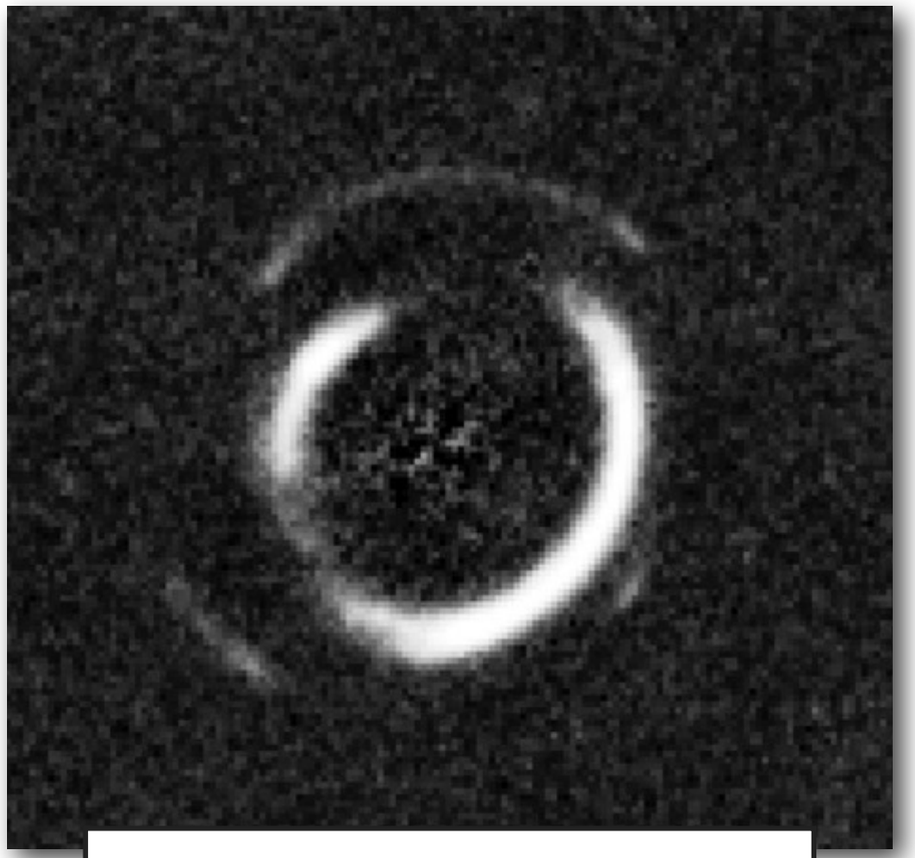
Cosmological Constraint F



- Double-source system
  - distance is a function Hubble parameter and matter and dark energy densities
    - Dij(H0, Om, Ode)
  - The ratio of angular diameter distances provides constraints Om, Omde in depend of hubble parameter

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

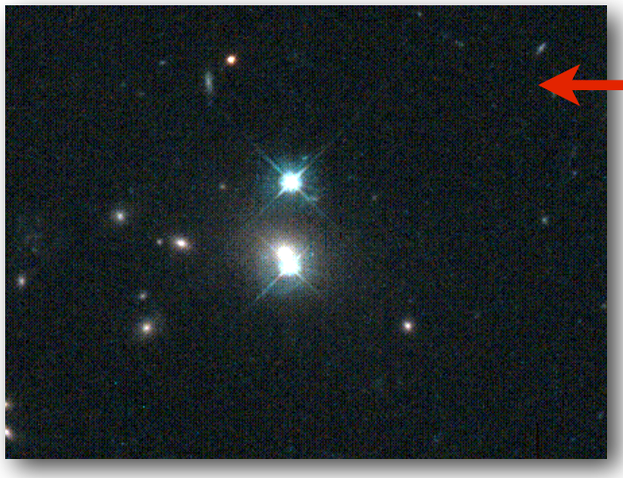
- Dependent on mass reconstruction (geometric simplicity of system)
- Expect O(10) in DES (Gavazzi++, 2008)



SDSSJ0946+1006

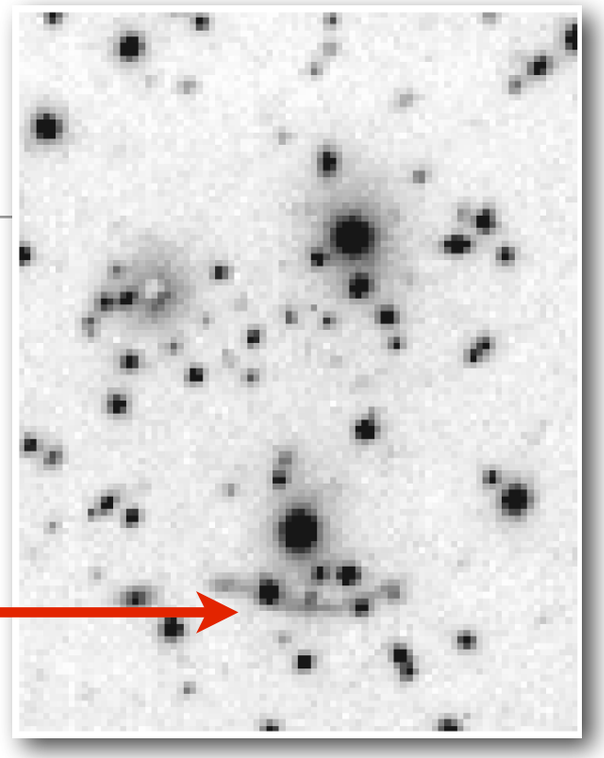
50 billion years
in the future

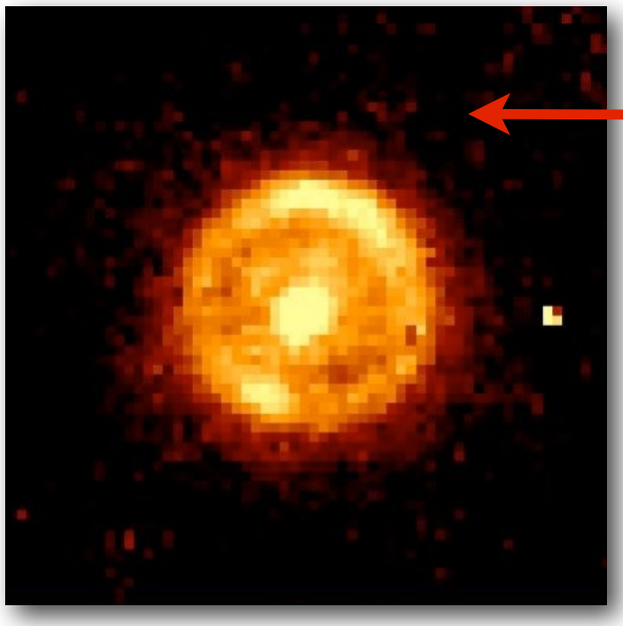
Historical Milestones



- 1979: First lensed system
  - Twin Quasar SBS 0957+561
    (Walsh, Carswell, Weyman)

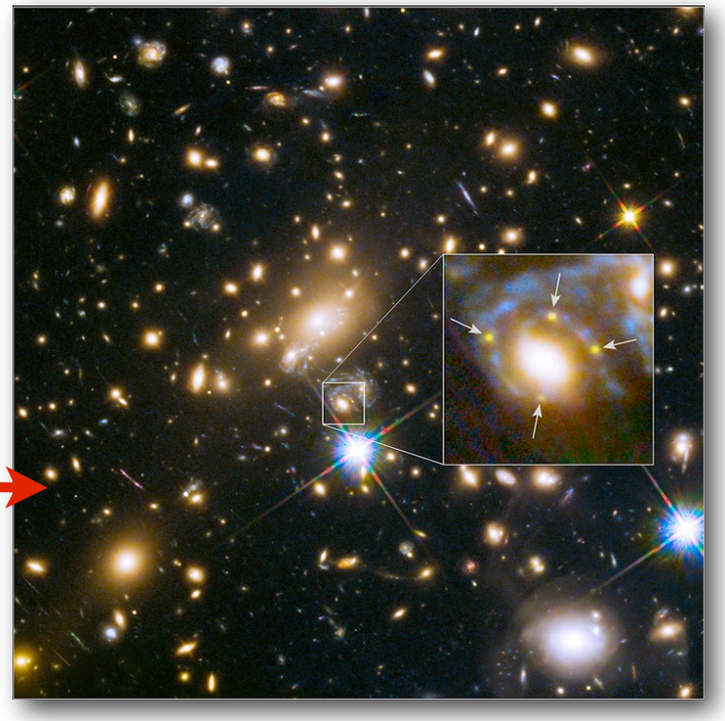
- 1986: First lensed galaxy (arcs)
  - Galaxy Cluster Abell 370
    (Lynds & Petrosian 1986; Soucail et al. 1987)





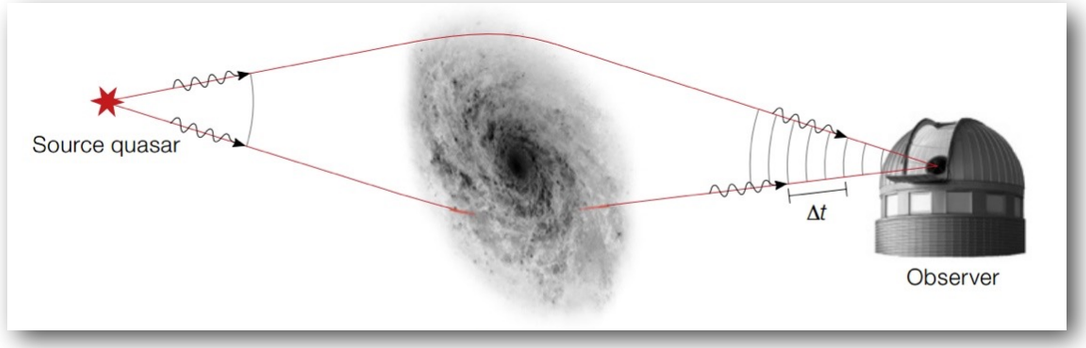
- 1998: First Einstein Ring
  - Galaxy JVAS B1938+666
    (King et al.)

- 2014: First multiply imaged supernovae
  - MACS J1149.6+2223
    (Kelly et al., 2014)

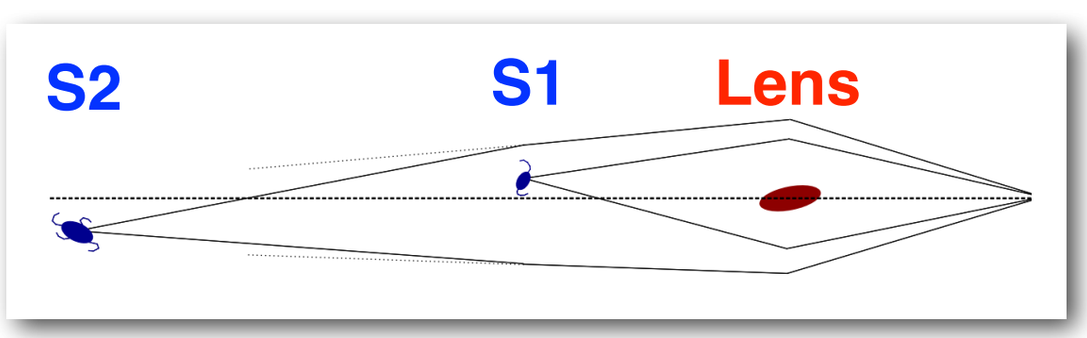


Lenses for Cosmology

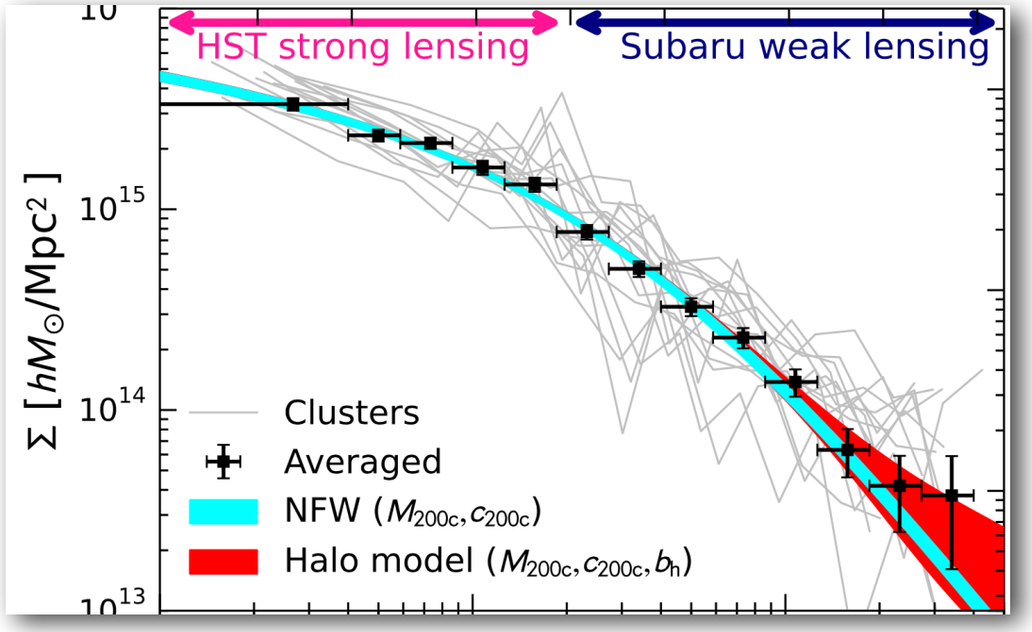
Hubble constant, H_0: proportional to the time delay between different light paths (Refsdal, 1964, Tewes++2012).



Dark energy density, Ω_Λ: constrained by ratio of distances in rare multi-source systems (Collett++2015, Linder, 2016).



Dark matter halo profiles reveal the growth of structure and constrain cosmological models (Jullo++2015).



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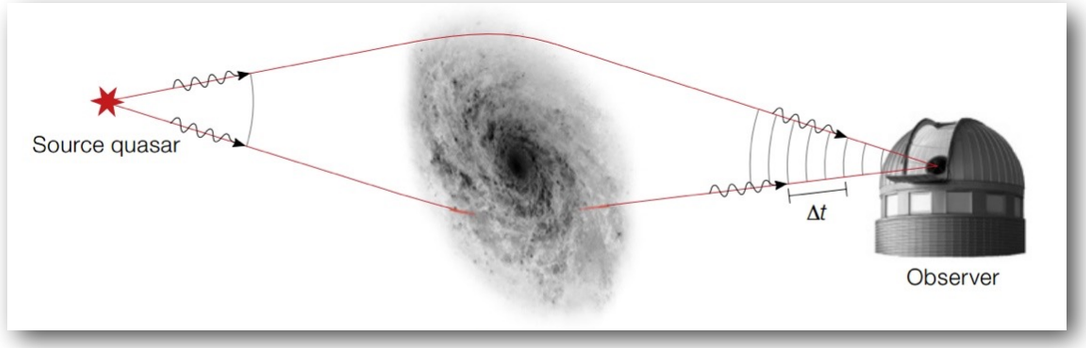

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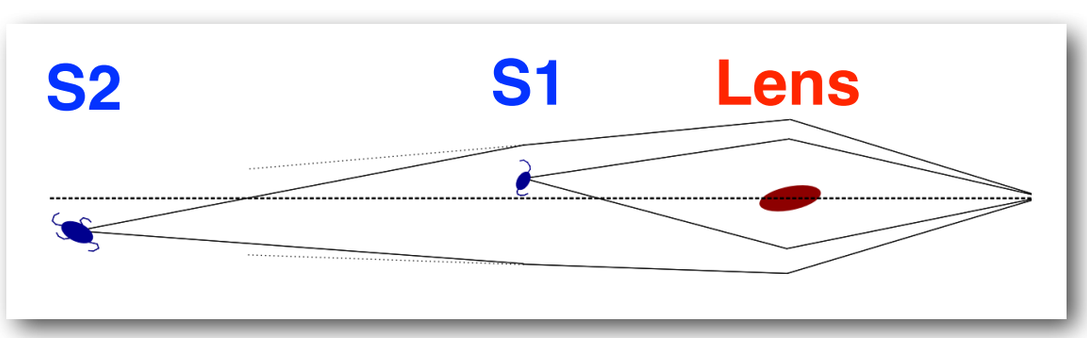

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