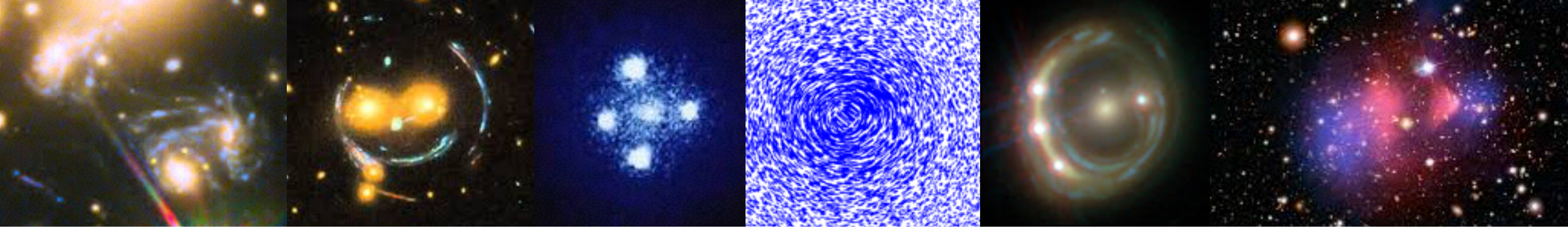

PHY-765 SS19 Gravitational Lensing Week 8

(strong)

Finding Gravitational Lenses

Kasper B. Schmidt
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Last week - what did we learn?

- We saw that GL conserves surface brightness
- We defined and expressed the magnification of sources

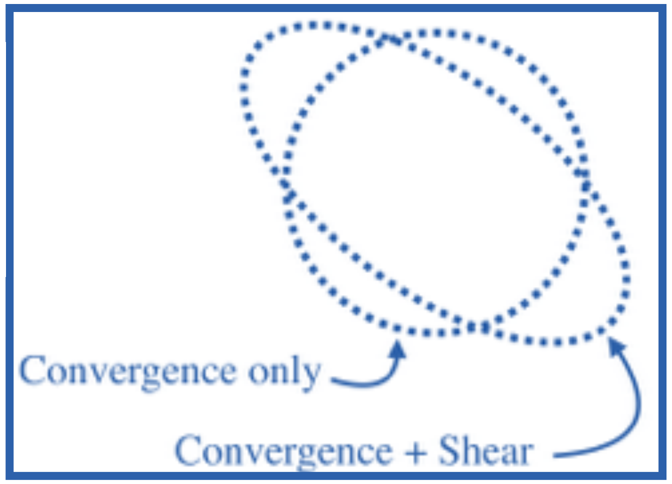
$$\boxed{\mu \equiv \frac{1}{\det \mathcal{A}(\boldsymbol{\theta})}} \quad \boxed{\mu = \frac{F(\boldsymbol{\theta})}{F(\boldsymbol{\beta})}} \quad \boxed{-2.5\log_{10}\left(\frac{F_1}{F_2}\right) = -2.5\log_{10}(\mu) = m_1 - m_2}$$

- Where $\mathcal{A}(\boldsymbol{\theta})$ is the Jacobian matrix: the transformation between **β** & **θ**

$$\mathcal{A}(\boldsymbol{\theta}) = \begin{pmatrix} 1 - \frac{\partial \alpha_i}{\partial \theta_i} & -\frac{\partial \alpha_i}{\partial \theta_j} \\ -\frac{\partial \alpha_j}{\partial \theta_i} & 1 - \frac{\partial \alpha_j}{\partial \theta_j} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\partial^2 \psi}{\partial \theta_i^2} & -\frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j} \\ -\frac{\partial^2 \psi}{\partial \theta_j \partial \theta_i} & 1 - \frac{\partial^2 \psi}{\partial \theta_j^2} \end{pmatrix} \equiv (\delta_{ij} - \boldsymbol{\Psi}_{ij})$$

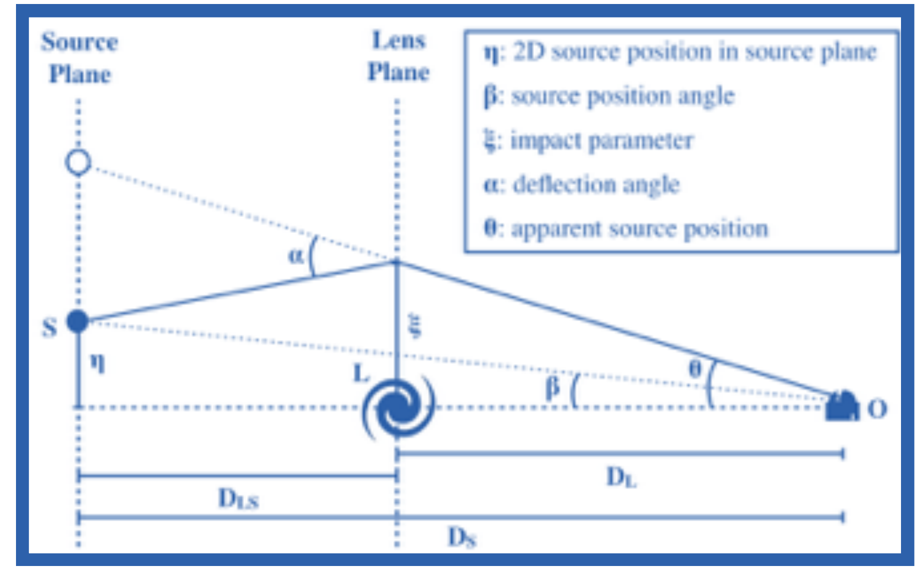
- Expressed magnification in terms of convergence and shear

$$\boldsymbol{\Psi}_{ij} \equiv \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix} \qquad \mu = \frac{1}{(1-\kappa)^2 - \gamma^2}$$



- Applications: High-z sources and lens mass (κ) maps

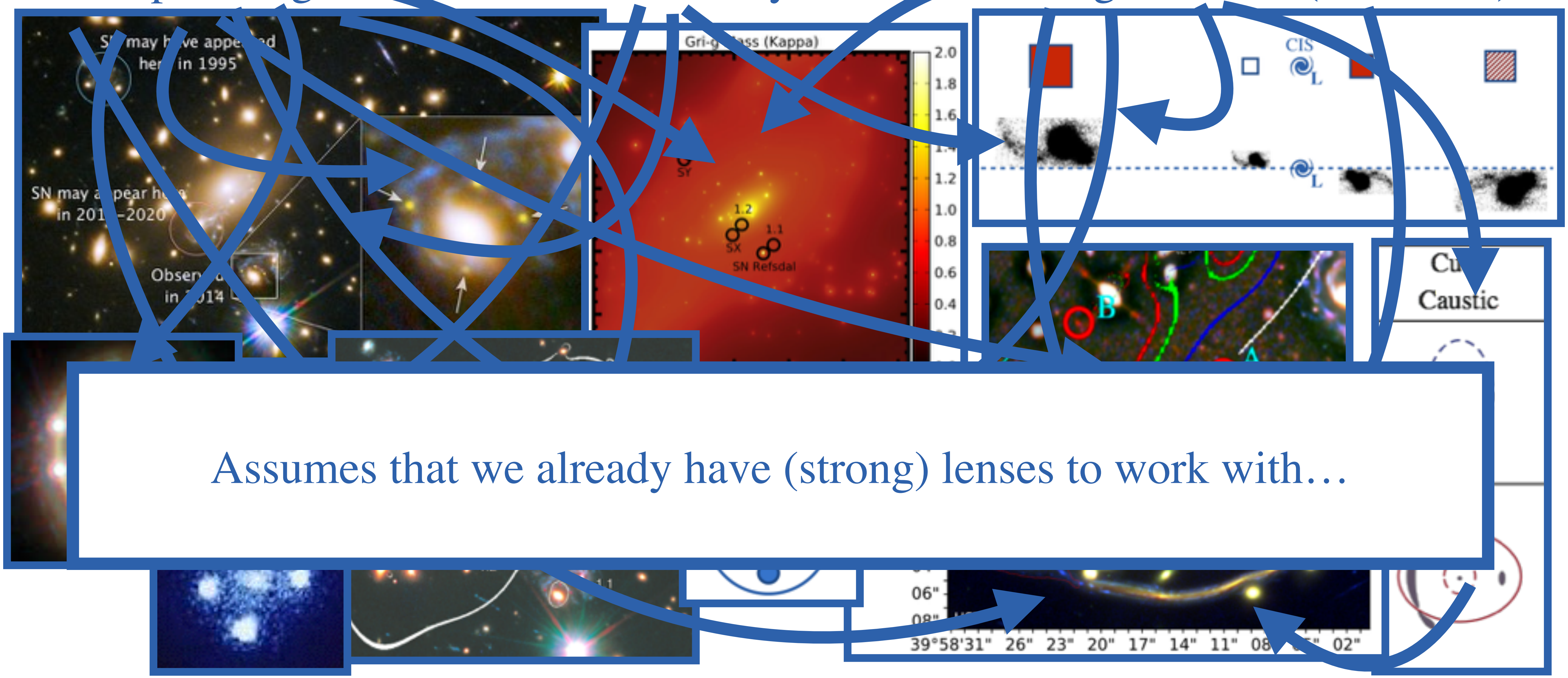
Last few weeks



- Derived the lens equation $\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$

- Consequences of the lens equation and GL theory

Multiple Images & Time Delays & Magnification (distortion)



Assumes that we already have (strong) lenses to work with…

The aim of today

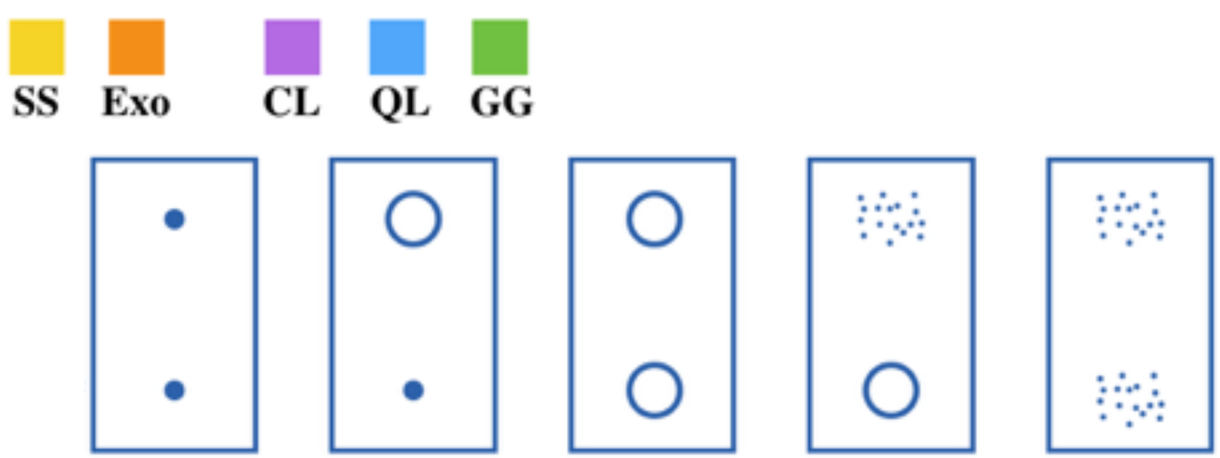
- How to actually find lenses to be able to exploit their great potential
  - probing the physics of lenses and sources
  - testing theory predictions

- Create a "shopping list" for confirming gravitational lenses

- Look at previous and current lens finding efforts

- Take a peak at the predicted future samples

The next two weeks:



Finding Lenses the Last 20 Years

QSO lenses

Cluster lenses

- OGLE I, II, III & IV (Microlensing - Week 9)
- Kochanek+98: CfA-Arizona Space Telescope Lens Survey (CASTLeS)
- Ebeling+01: Massive Cluster Survey (MACS)
- Myers+03 & Browne+03: The Cosmic Lens All-Sky Survey (CLASS)
- Oguri+06: The Sloan Digital Sky Survey Quasar Lens Search (SQLS)
- Bolton+06: The Sloan Lens ACS survey (SLACS)
- Hennawi+08: Survey for lensed arcs in SDSS
- Agnello+15 & Nord+16: STRong lensing Insight in the Dark Energy Survey
- Krone-Martins+18: Gaia DR2 Gravitational Lens Systems
- Agnello+17: DES+Gaia
- Frye+18: Massive lensing clusters from Planck and Herschel data
- LSST, WFIRST, JWST, ELTs (Week 14)

… incomplete (& biased)

Your Lens Finding Shopping List

- 2 groups w. pen & paper
- What would you need to confirm a gravitational lens in some data?
- 5-10 minutes

Your Lens Non-Finding Shopping List

- Same groups
- What is needed to reject candidate lenses in observations
  - Anything else than just inverting your “Lens Finding” list?
- 5 minutes

Lens Finding 'Shopping List'

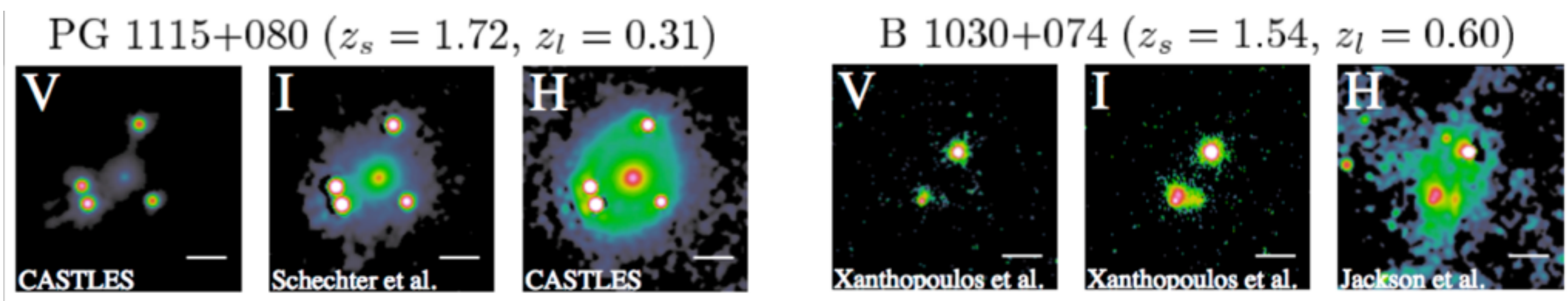
- $\gtrsim$2 images, i.e., multiple images (MI) within a few to tens of arc seconds of each other
- The redshift of MI should be identical (Δz at the sub-% level)
- Chemical composition derived from spectra of MI should be identical
- Line fluxes, line flux ratios and line shapes from spectra of MI should be similar
- The color (i.e., F_{band1}/F_{band2}) of MI should be identical as GL is achromatic
- Lens modeling of the system should be possible
- The location of images should be reproducible by lens model
  - MI should map back to the ~same location in the source plane
  - MI should obey position wrt. to critical curves of the model
- Any flux variation in images should be correlated (time delayed)
- A lens should be present at lower redshift than MI
- The object has an arc or ring like morphology
- Parity flips should match model predictions
- MI systems at different z should obey ordering wrt. critical curves for different z

Rejecting lenses

- Invert the list above, i.e., Different color, different redshift, variations uncorrelated, different line profile, no lens galaxy, no arc-like morphology, no parity flips in 3+ image systems, poor model agreement, etc.

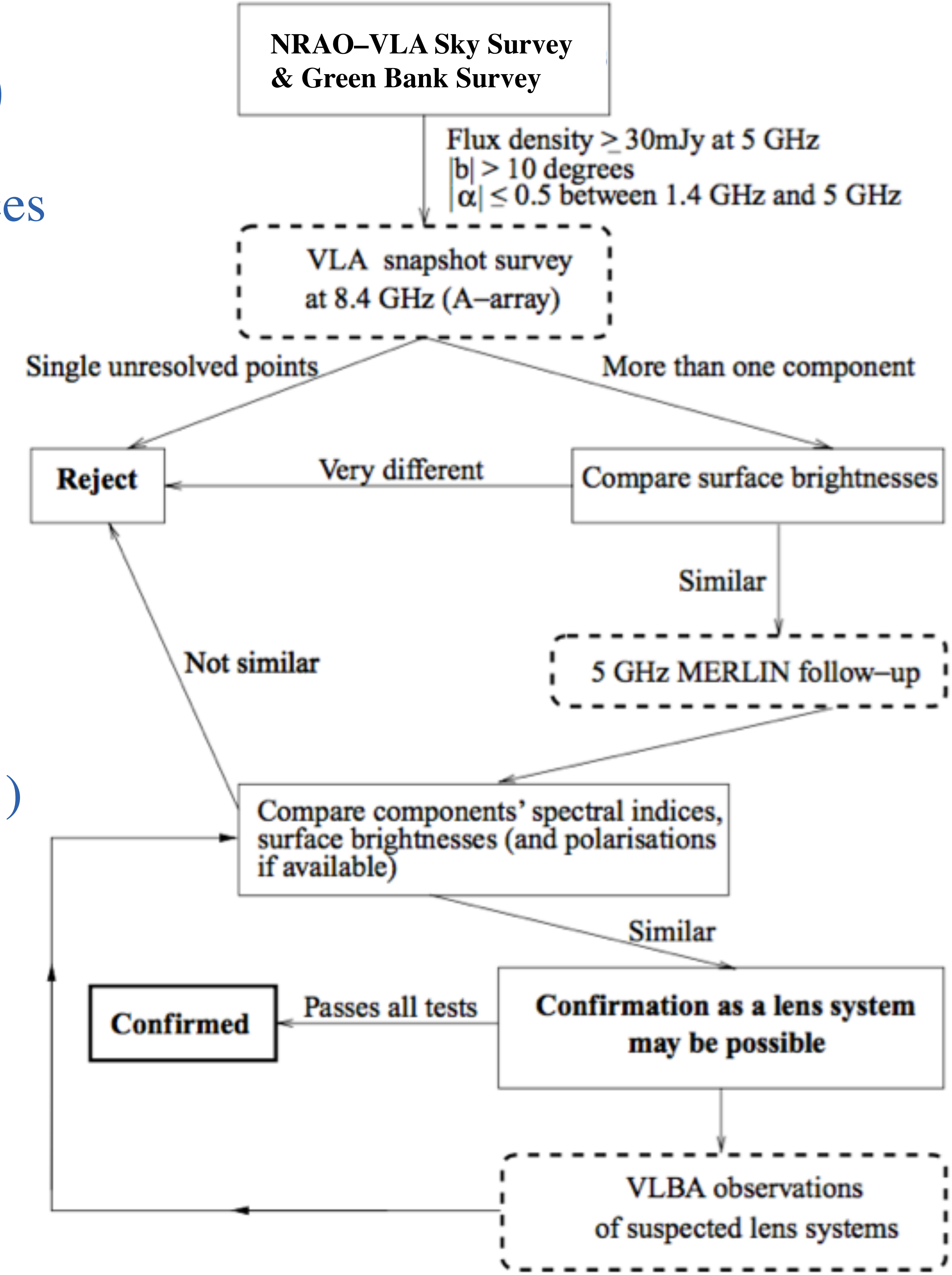
CASTLeS (Kochanek+98)

- Online repository of HST and radio data as well as refs for lens systems:
  - https://www.cfa.harvard.edu/castles/
  - 100 Multiple Imaged Systems (and 18 binary QSOs)
- Original CASTLeS project: HST H, V and I imaging of ~40 known lenses
  - Collecting information including redshifts
  - Modeling lenses to determine reliability
- As lens samples started to grow in the early 2000s they tried to keep up
  - Last paper reference is from 2006



CLASS (Browne+03)

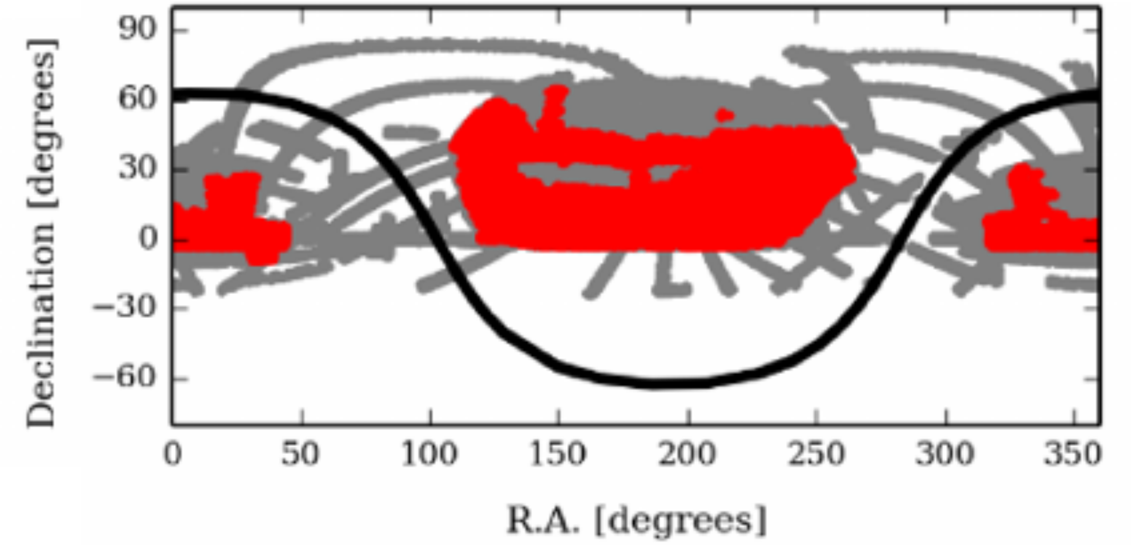
- Lensed flat f_ν spectrum radio sources
- 16503 sources observed with VLA
- Cut on spectral flatness (color)
- Cut on flux densities (brightness)
- Detail VLA observations
  - Multi component morphology?
  - image SB different (< ×4)
- High-resolution follow-up (<0.05'')
  - non-lens morphology revealed
  - image spectral index different
  - image polarization different
- Final sample contains 22 lenses
- Point source lensing rate:
  - 1:690 ± 190

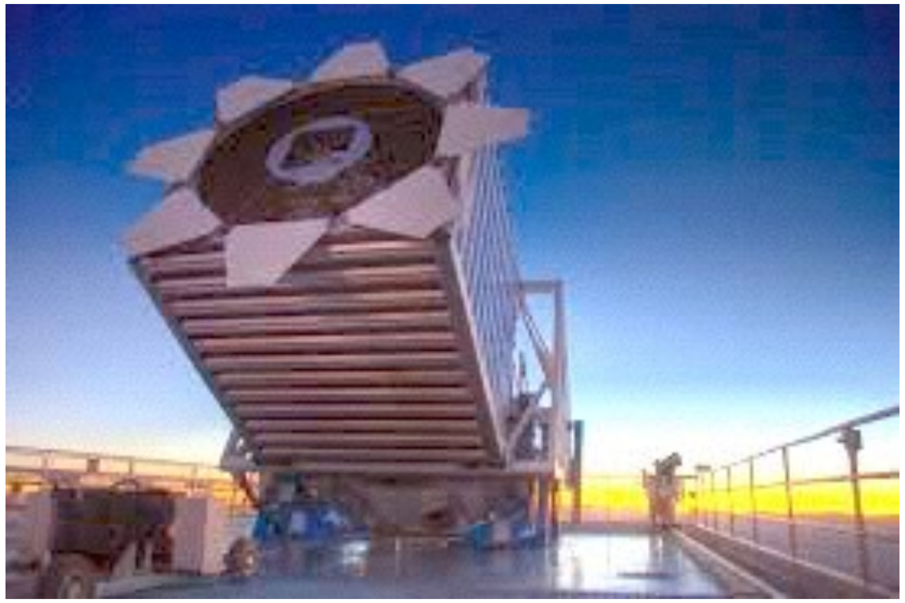


SDSS.org

- Survey(s) of >10000 deg^2 (1/4 of the sky)
  - w 2.5 telescope at Apache Point Observatory
- SDSS I/II (2000-2008)
  - ugriz broad band imaging (multi-epoch)
  - optical spectra of more than 700000 objects
- SDSS III (2008-2014)
  - Cont. ugriz and spec. mapping after upgrade
  - new instruments:
    - High-z (BOSS)
    - Milky Way (SEGUE-2 and APOGEE IR spectroscopy)
    - Exoplanets (MARVELS)
- SDSS IV (2014-2020)
  - Focus on eBOSS, APOGEE-2 and MaNGA (IFU spectroscopy)
- Currently there have been 14 data releases from SDSS
- >1.5×10^5 (10^6) spectroscopic (candidate) quasars from DR10 (Richards+15)
- Millions of galaxies with spectra and imaging

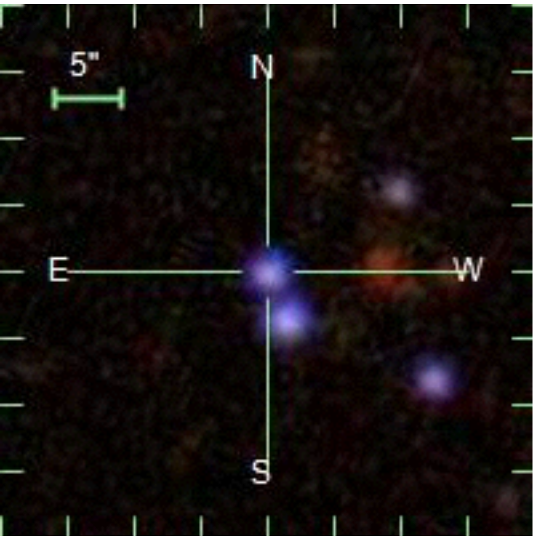
SDSS **spec.** & **photo.** (DR10) Fussilo+15

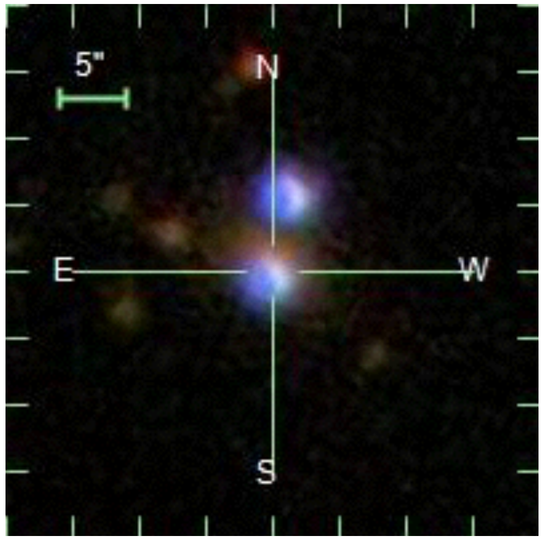


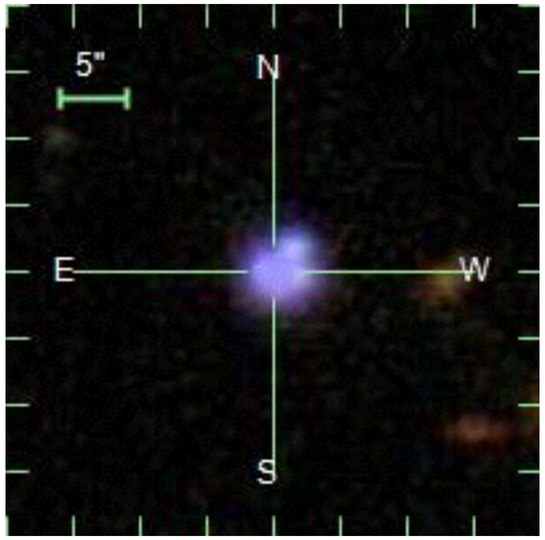


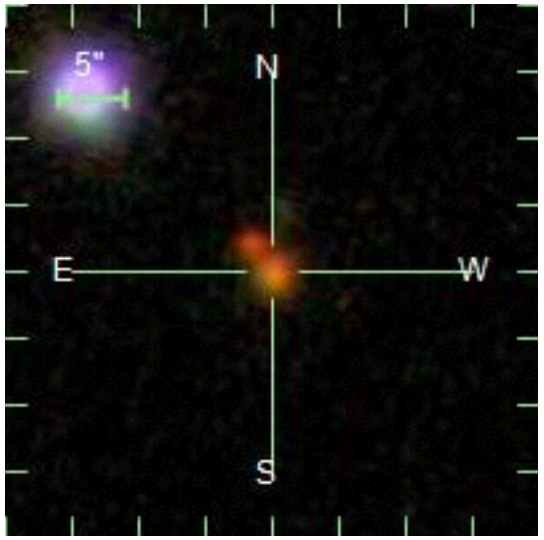
SDSS Lenses - QSOs (Oguri+06/Inada+12)

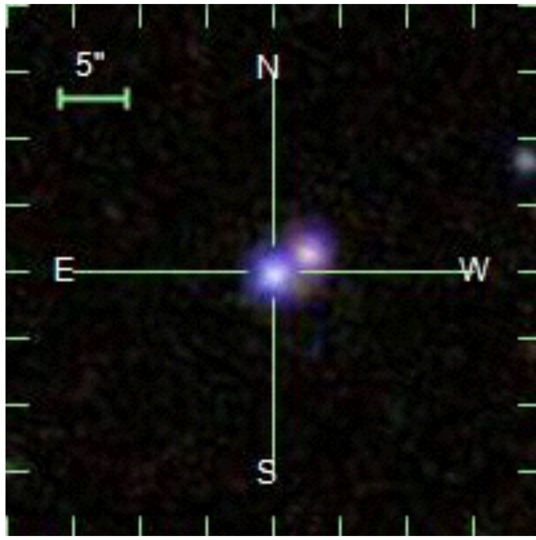
- SQLS presents quasar lenses found starting from $>10^5$ spec. SDSS QSOs
- Base their selection on either *morphology* (θ≲2.5'') or *color* (θ≳2.5'')
  - Morphological selection: Extended (non-PSF) sources with QSO spectrum
  - Color selection: Nearby objects with similar colors to QSO in 4 SDSS colors
- Perform extensive follow-up with various spectrographs and imagers
- http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls contains 62 lenses







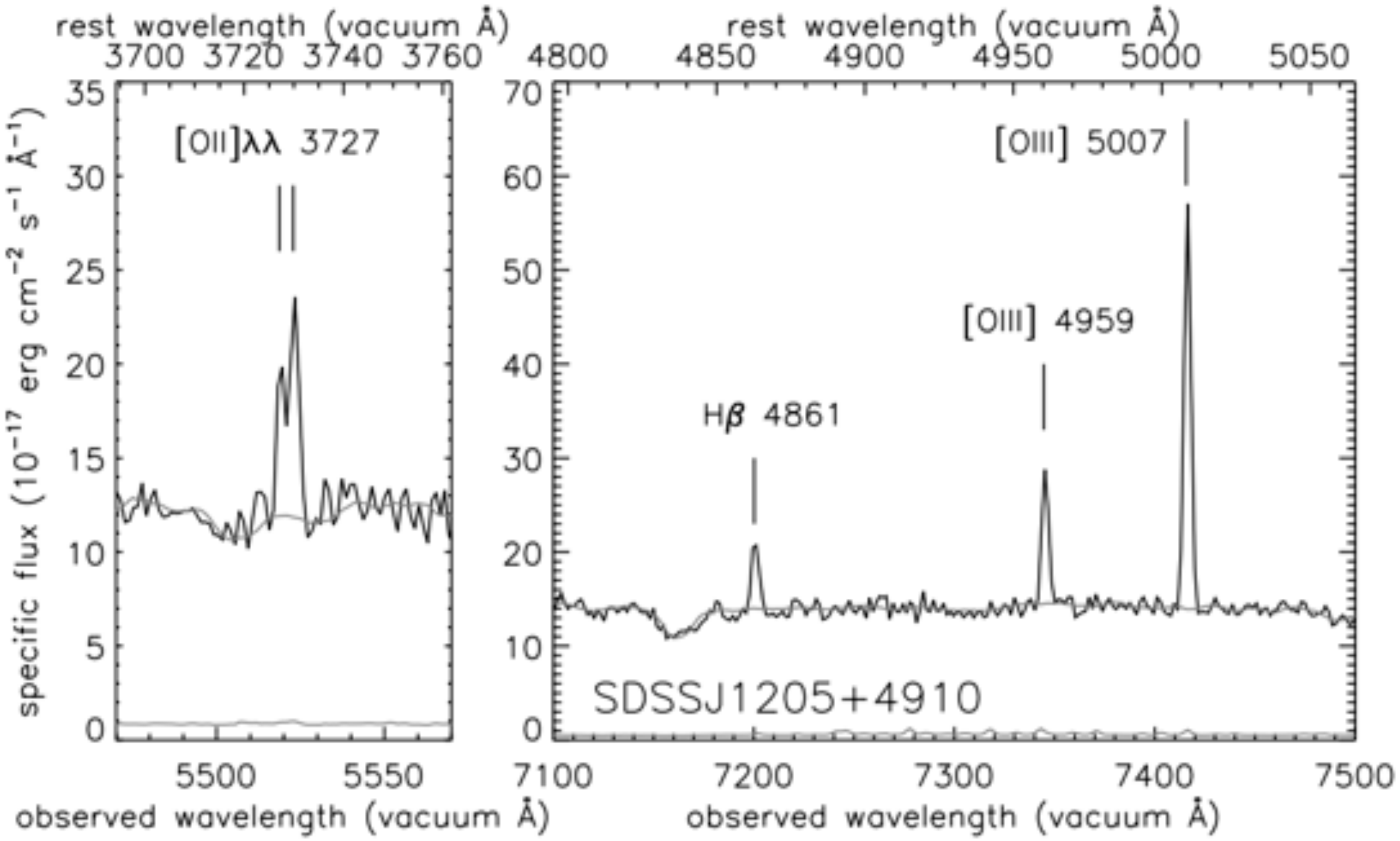




SDSS Lenses - Gal-Gal (Bolton+06)

- HST imaging snapshot program looking for galaxy-scale lenses in SDSS
- Galaxies for follow-up selected from SDSS spectra
  - Subtract PCA SDSS pipeline redshift fit components
  - Search for emission lines with $z > z$(main galaxy) within 3'' SDSS fiber radius

$z_{FG} = 0.2150$

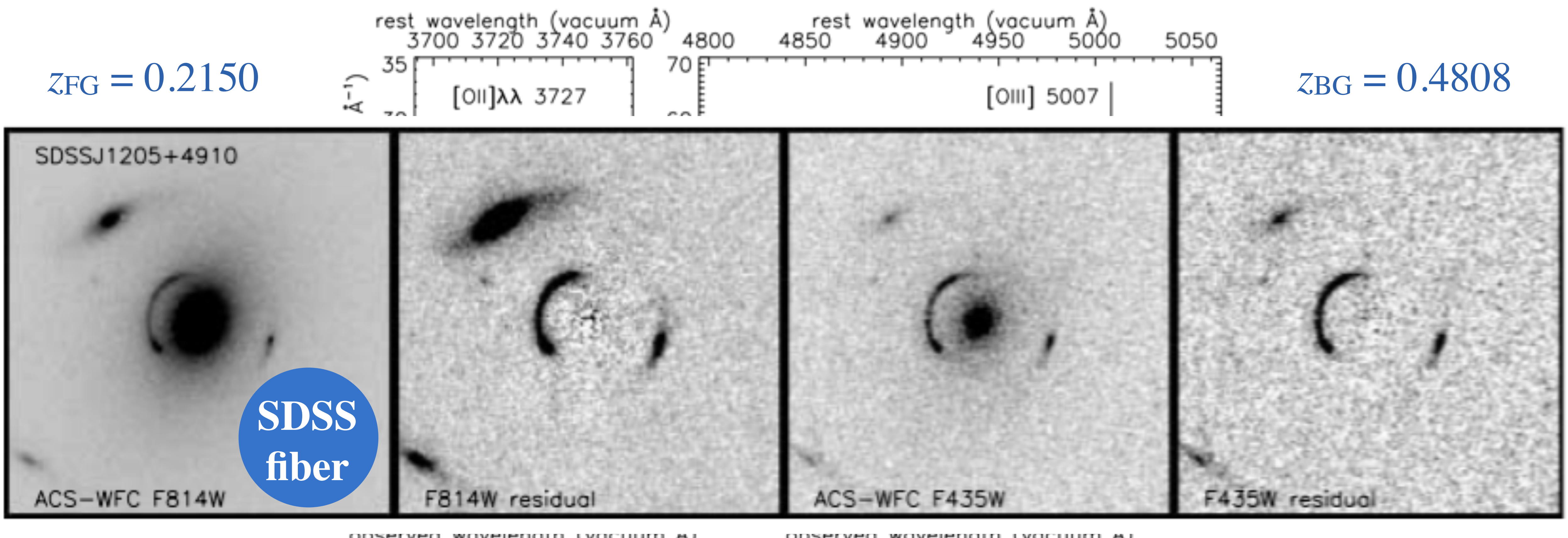


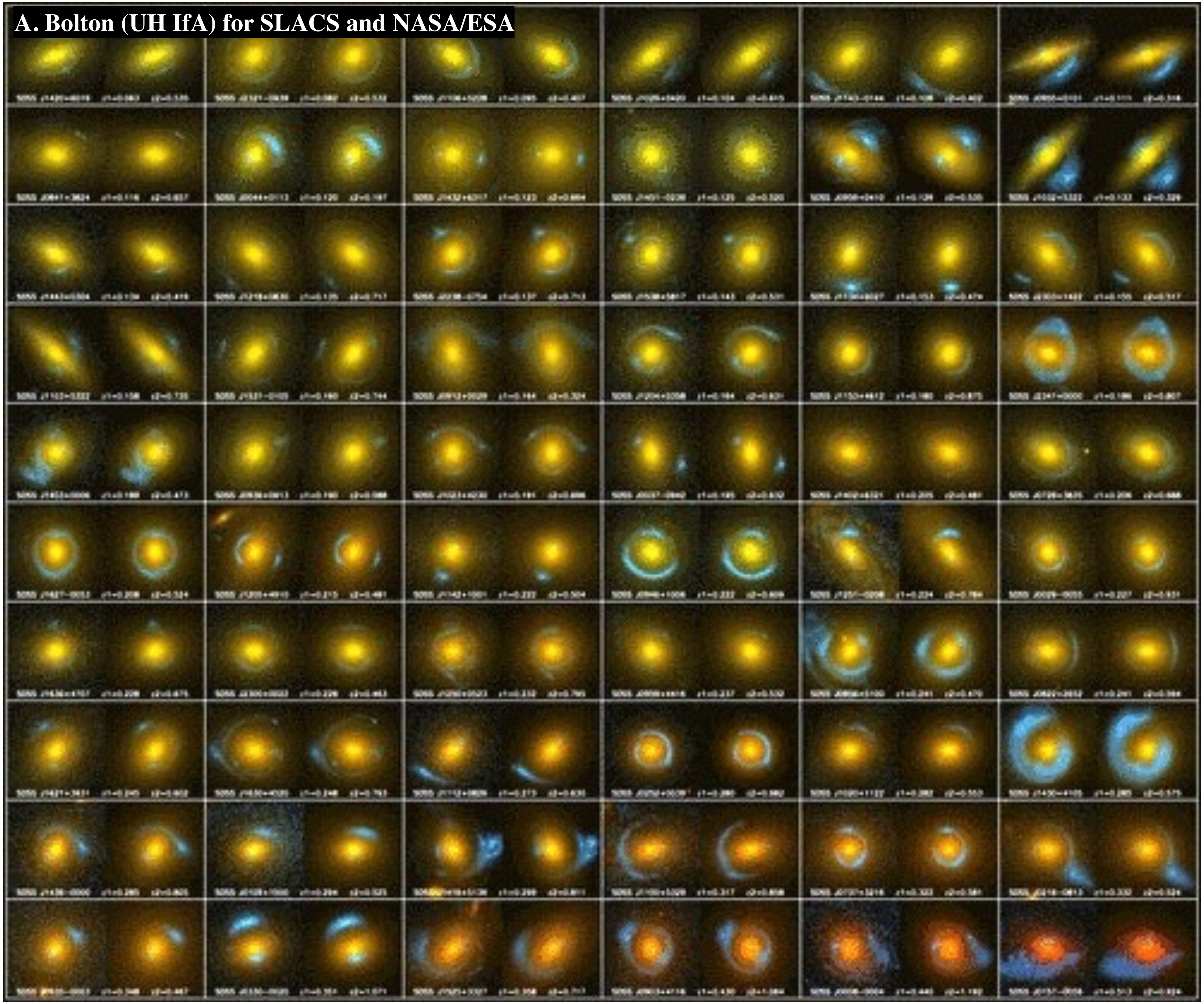
$z_{BG} = 0.4808$

SDSS Lenses - Gal-Gal (Bolton+06)

- HST imaging snapshot program looking for galaxy-scale lenses in SDSS
- Galaxies for follow-up selected from SDSS spectra
  - Subtract PCA SDSS pipeline redshift fit components
  - Search for emission lines with $z > z$(main galaxy) within 3'' SDSS fiber radius
- Measure velocity dispersion σ for such spectra to get θ_E assuming an SIS
  - Followed up the candidates with larger θ_E to increase lensing chance
- Auger+09 presents 85 definite galaxy-scale lenses from SLACS

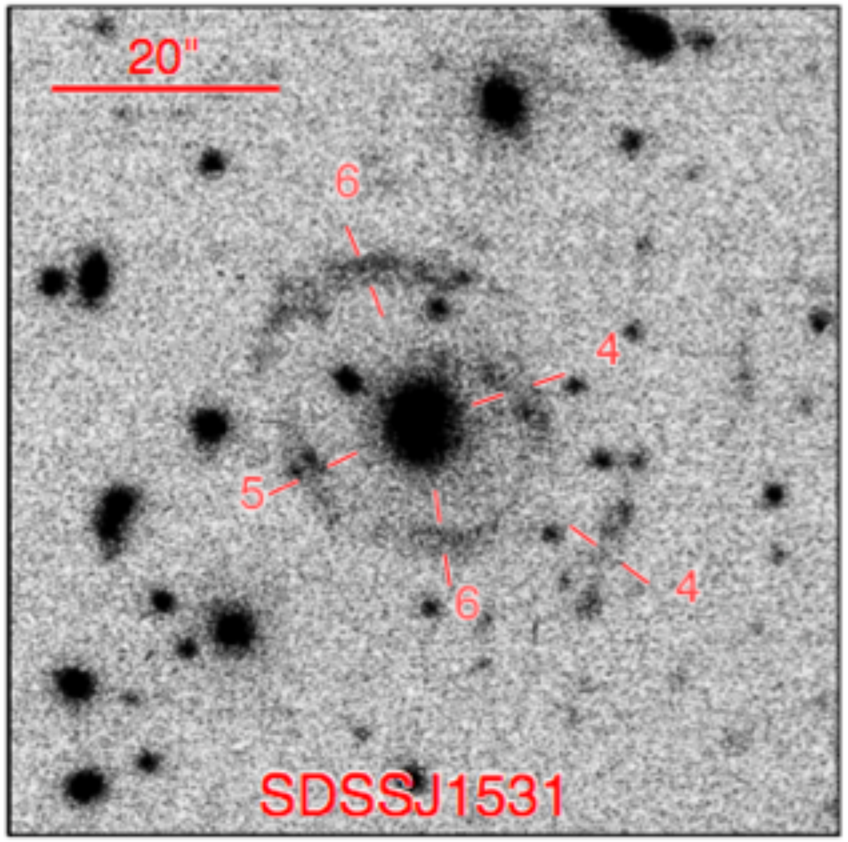
$z_{FG} = 0.2150$ $z_{BG} = 0.4808$

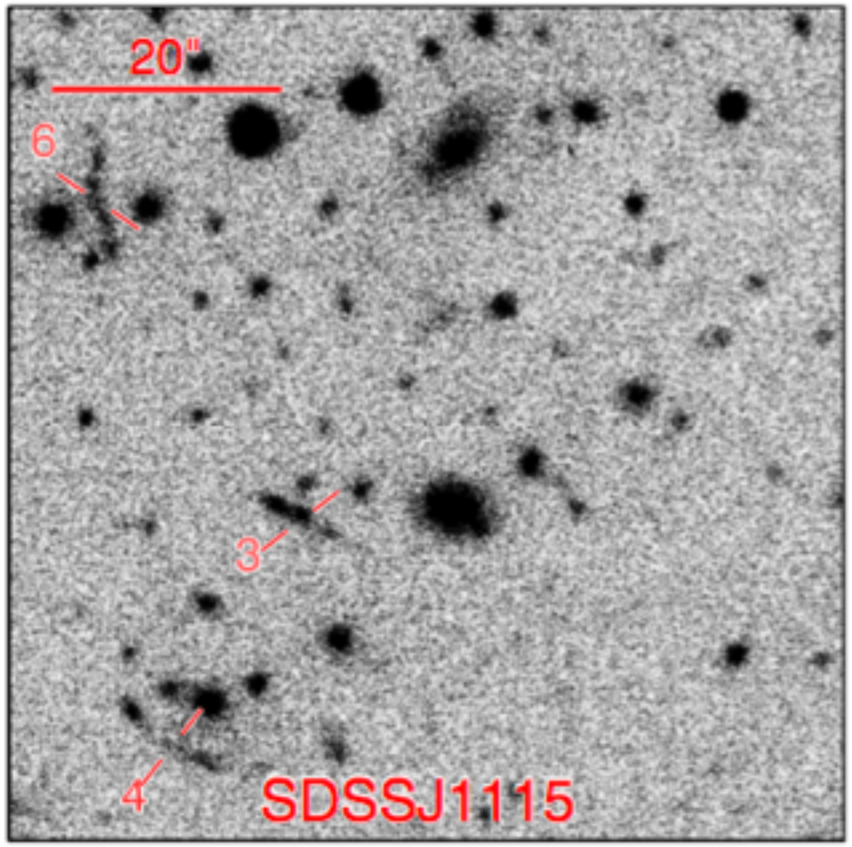



A. Bolton (UH IfA) for SLACS and NASA/ESA

SDSS Lenses - Arcs (Hennawi+08)

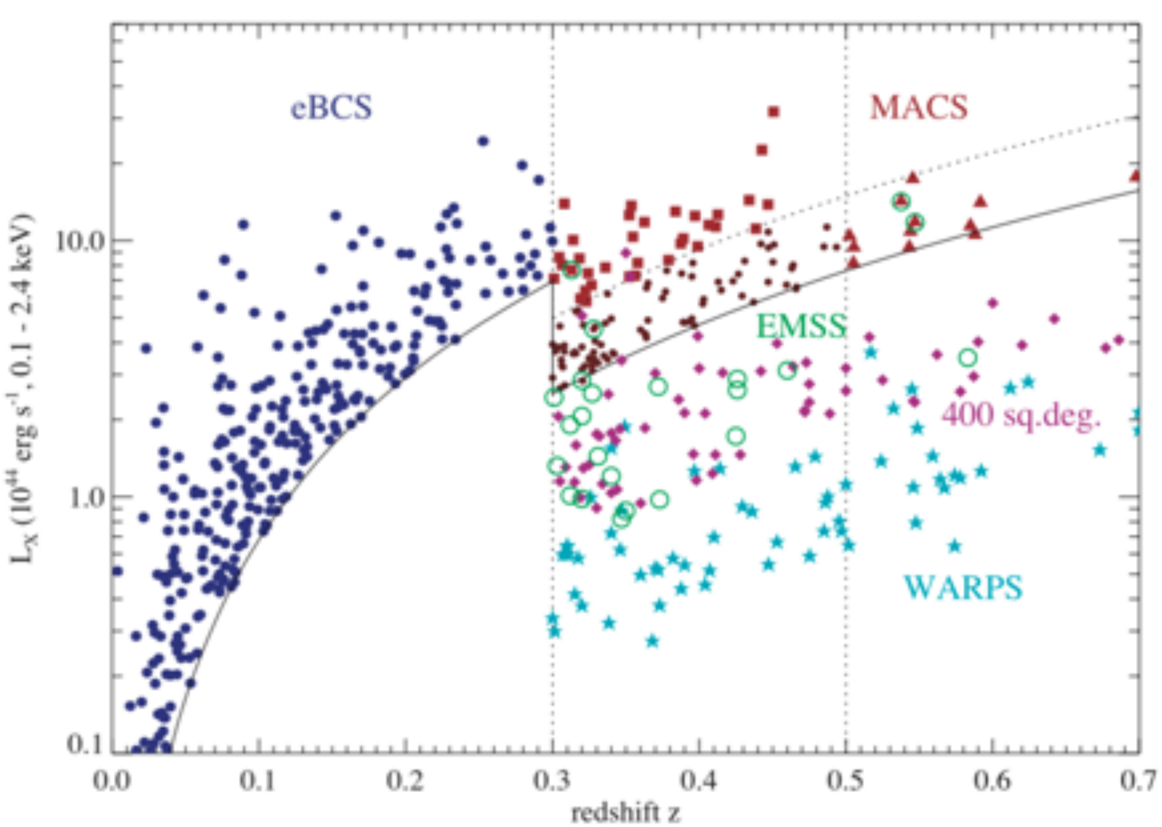
- Targeting richest SDSS clusters with deep follow-up
  - Wisconsin-Indiana-Yale NOAO 3.5m (WYIN)
  - University of Hawaii 88 inch (UH88)
- Target clusters from 8000deg^2 (DR5)
  - Selected with RCS algorithm (Gladders & Yee 2005)
    - have red sequence of early type galaxies
    - create over densities in position, mag and color space
- ~2×10^4 massive galaxy clusters at $0.05 < z_{\mathrm{photo}} < 0.6$
- Follow-up imaging visually inspected for arcs
- Resulted in 16(+12) new lensing clusters
  - 240 candidates followed up



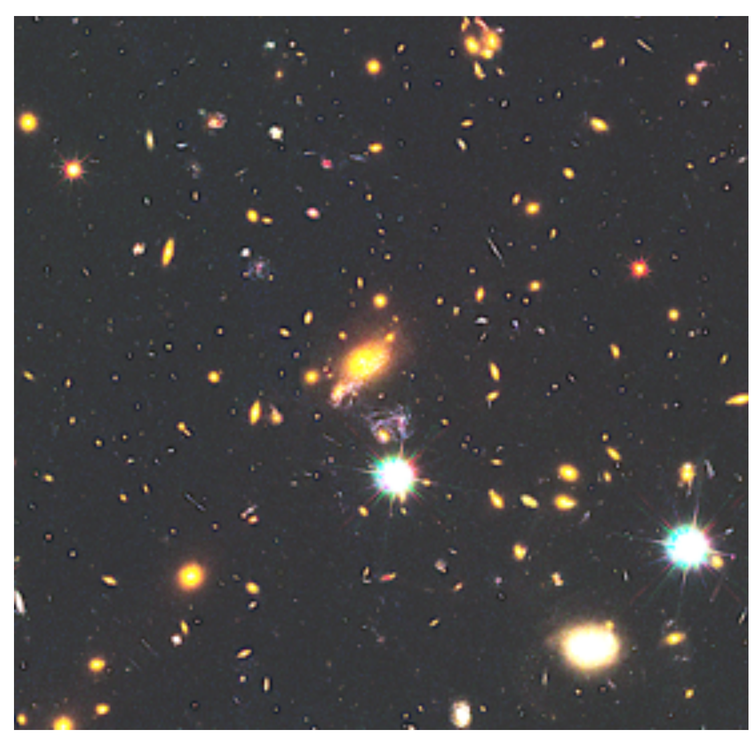


Clusters - MACS (Ebeling+01/10)

- Not actually a lensing survey → Massive cluster survey
- High-z X-ray luminous clusters selected from ROSAT bright source catalog
  - Followed up spectroscopically to confirm cluster redshifts
- 124 spec. confirmed clusters $0.3 < z < 0.7$
  - http://www.ifa.hawaii.edu/~ebeling/clusters/MACS.html
- Selected for HFF, GLASS, CLASH, RELICS etc.



MACS 1149

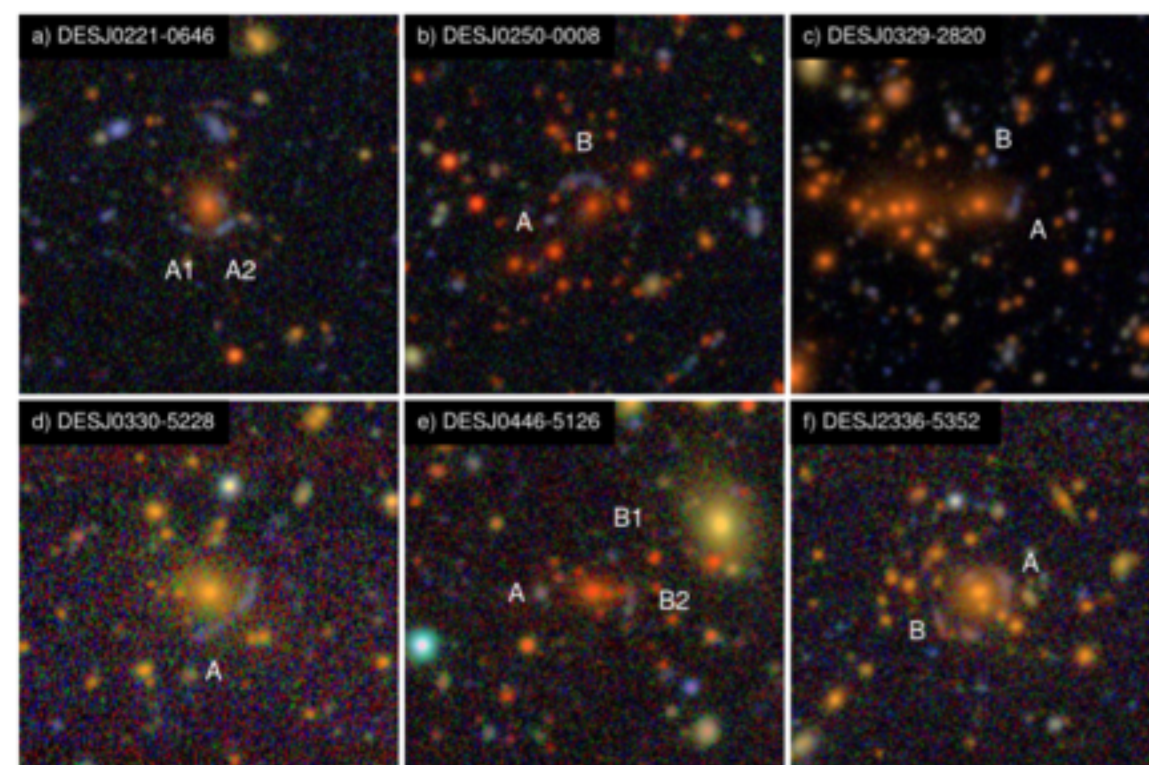


MACS 0416

DES - STRIDES

- DES: The Dark Energy Survey (2013-2018)
  - Imaging 5000deg^2 of the southern sky in grizY
- STRIDES: STRong lensing Insight in the Dark Energy Survey:
  - Aims at ~100 new lenses from DES

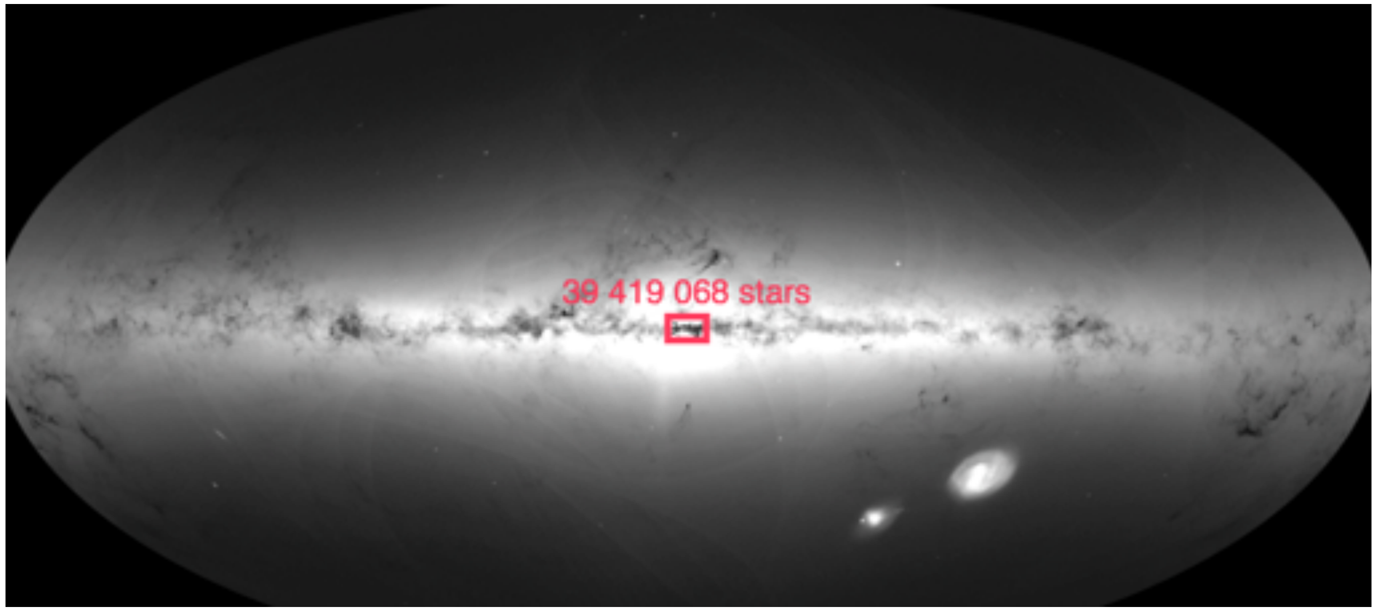
- Agnello+15: 2 lensed QSOs
  - QSO candidates based on DES+WISE colors
  - Using non-PSF morphology as indicator of lensing
  - Follow-up spectroscopy to confirm candidates



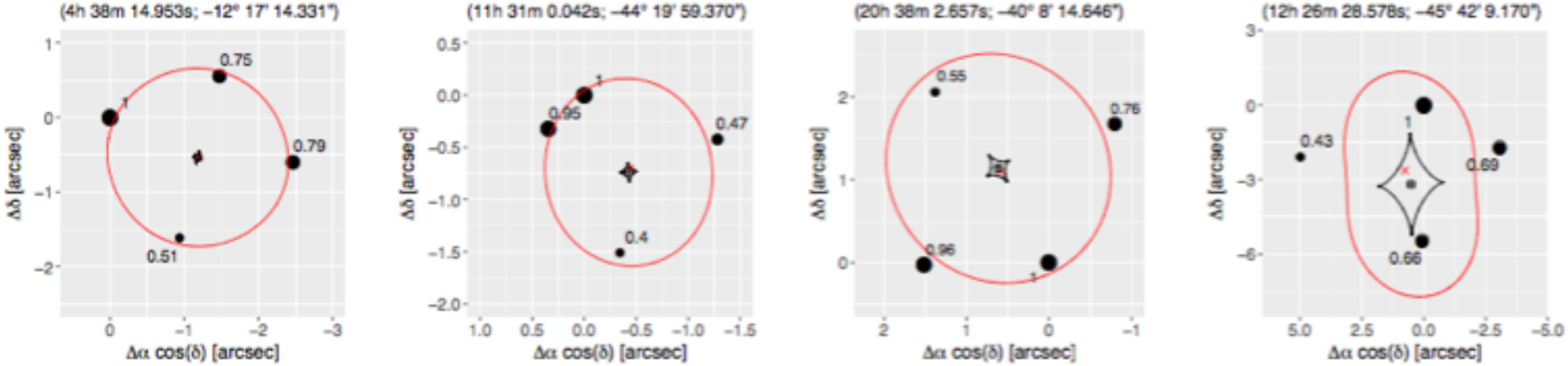
- Agnello+18: 4 QSO lenses and ~100 cand.
  - Scanned 5000 deg^2
  - Using 5 methods incl. morphology and color
- Nord+16: 6 cluster lenses (3 new)
  - Visual inspection of imaging 250deg^2
  - Relying on color and morphology
  - Gemini spectroscopic follow-up

Gaia

- ESA mission to map our galaxy
  - Gaia collaboration+16 & 18
- DR2 came out April 2018:
  - 1.7×10^9 sources with positions
  - 1.3×10^9 sources with parallaxes



- Krone-Martins+18
  - Crossmatch Gaia DR2 to existing QSO catalogs from WISE & SDSS
  - Look for close pairs (<6”)
  - Used machine learning method to assign lensing probability
  - Modeled the lenses as SIEs + external shear to confirm lens morphology



- Lemon+18 crossmatched Gaia DR2 to SDSS and PS1 and found 24 new lenses.

Predicting numbers of QSO lenses

- Oguri & Marshall+10 aimed at predicting number of lenses
- Focus on multi-epoch data (potentially enabling time-delay measurements)
- Assume lens galaxies are ellipticals with SIE surface mass density (κ)
- They formulate the lensing rate (probability) as an integral over $d\theta$ and dz
- This can be integrated over the survey volume and source luminosity functions
- Integrating this over redshift interval provides estimate for N_{lenses}

Survey	QSO (detected) $N_{\mathrm{non\text{-}lens}}$	QSO (detected) N_{lens}	QSO (measured) $N_{\mathrm{non\text{-}lens}}$	QSO (measured) N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)	3.82×10^4	7.6 (18 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)	3.45×10^3	1.1 (13 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)	–	–
PS1/MDS	9.55×10^4	30.3 (13 per cent)	3.49×10^4	9.9 (14 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)	–	–
DES/deep	1.26×10^4	4.4 (12 per cent)	6.05×10^3	2.0 (13 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)	–	–
HSC/deep	7.96×10^4	29.7 (12 per cent)	4.30×10^4	15.3 (13 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)	9.97×10^6	3150 (14 per cent)

(…) = percentage quads

So in summary…

- Searching for gravitational lensing is an ongoing endeavor
  - A ‘shopping list’ tailored for your survey is a good starting point
- Large data-sets and extensive follow-up is needed to overcome lens-rarity
- Focused on a few selected methods and surveys including:
  - Literature sample selection and follow-up
  - Radio sources
  - SDSS QSO and arc searches
  - DES QSO and arc searches
  - Cluster searches
- Current and future surveys have the potential to reveal thousands of GLs