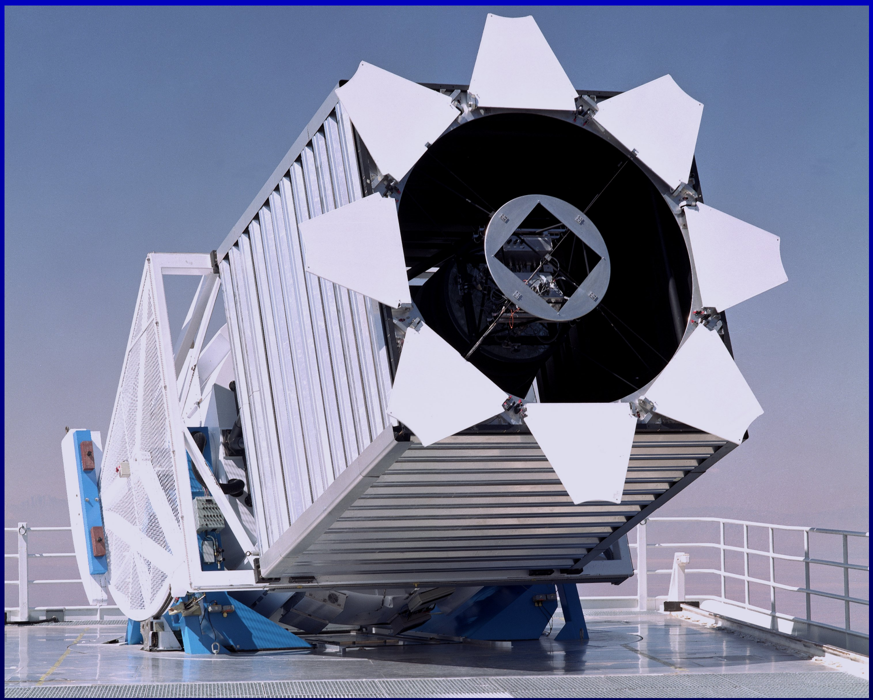


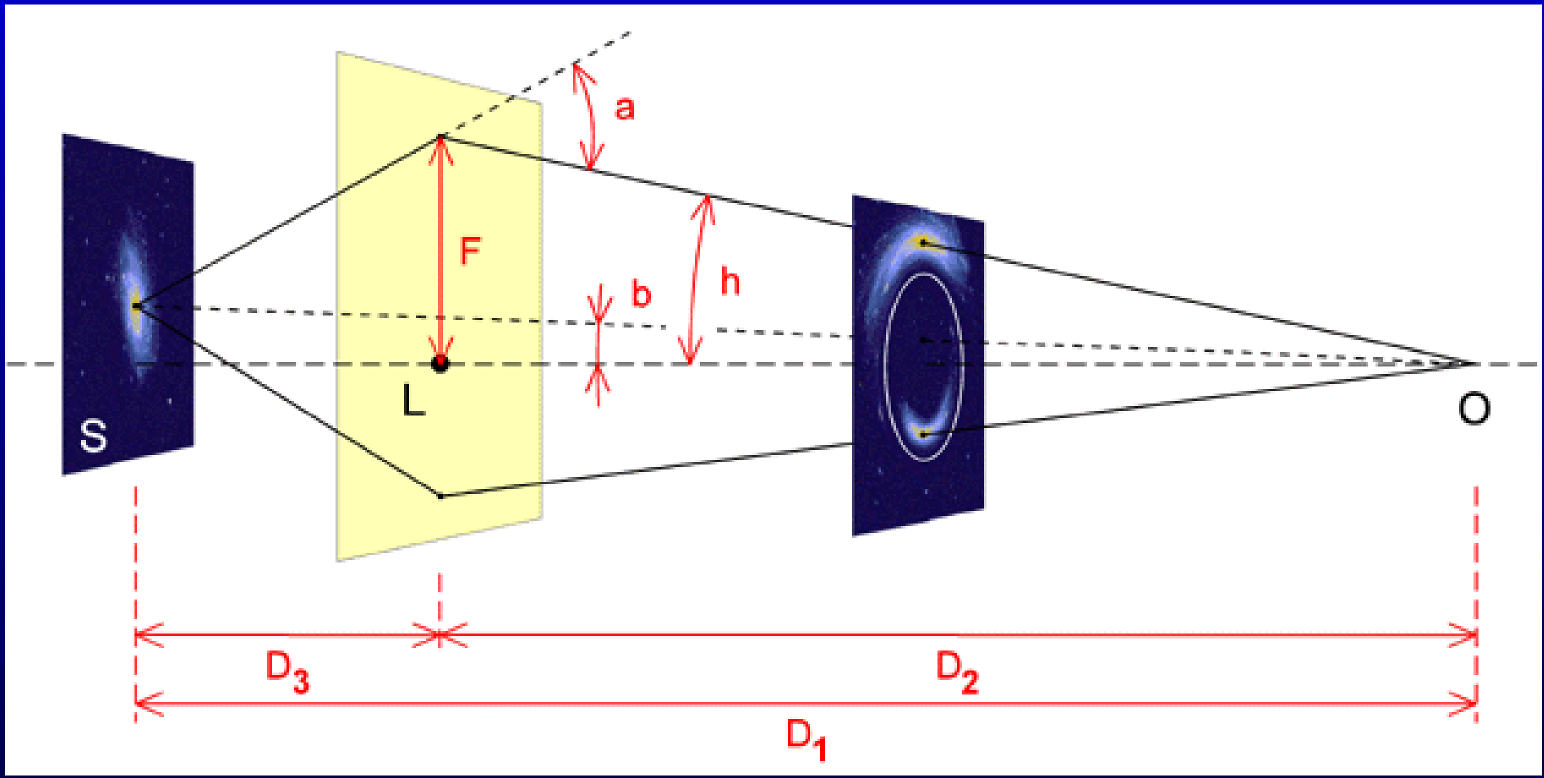
Cosmic Magnification with the SDSS

Ryan Scranton

29 August 2005

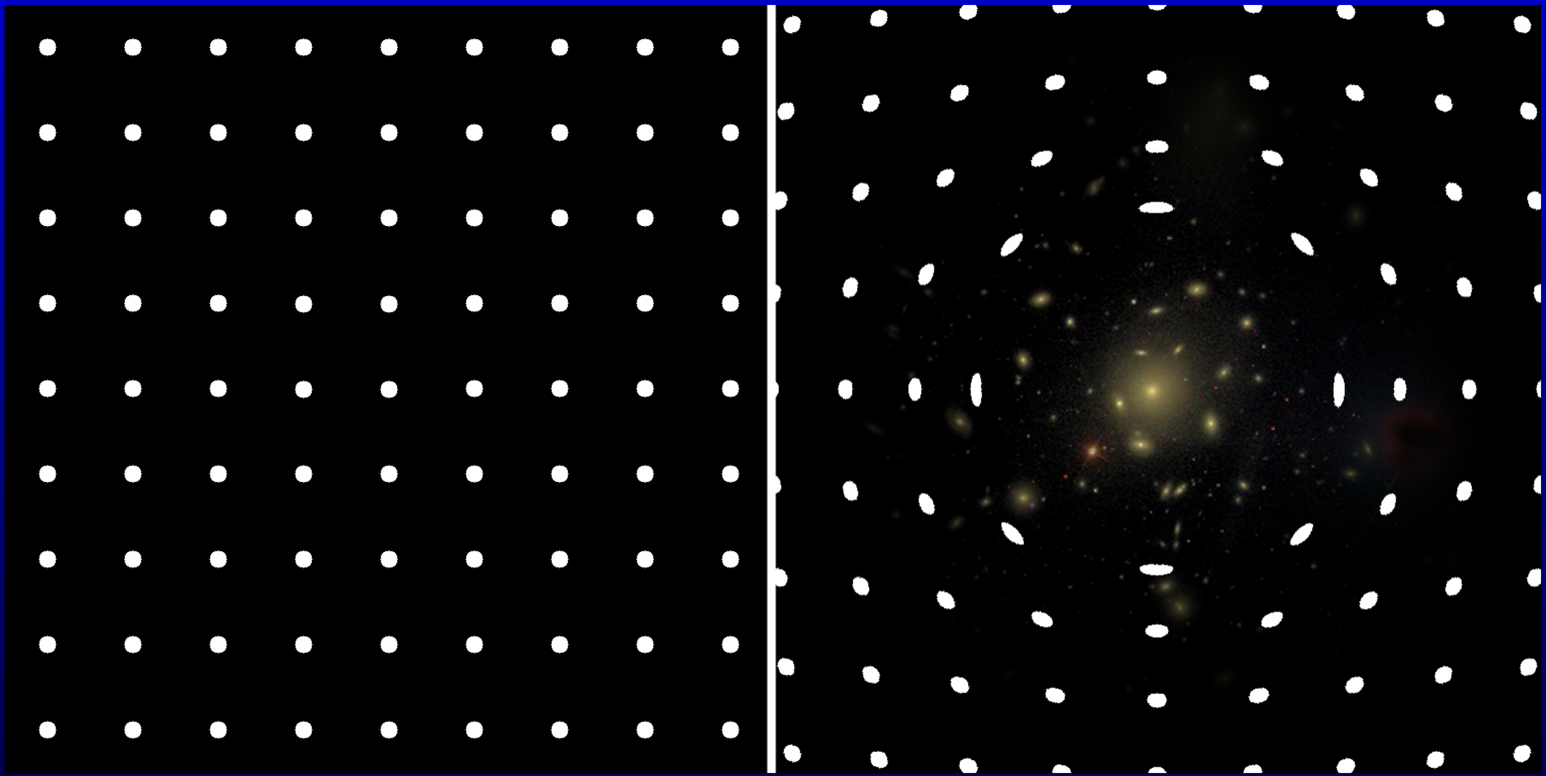
Brice Ménard, Gordon Richards, Bob Nichol, Adam Myers, Bhuvnesh Jain, Alex Gray, Mattias Bartelmann, Robert Brunner, Andrew Connolly, Ravi Sheth

Gravitational Lensing Basics



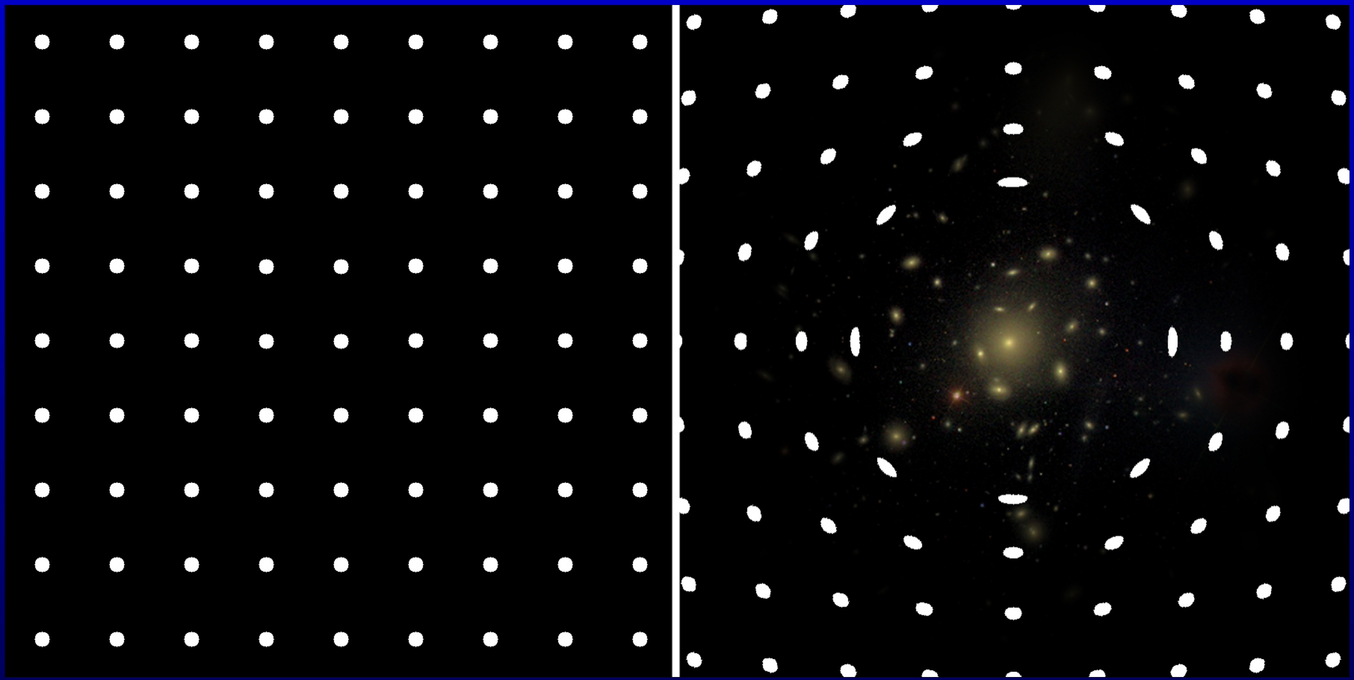
Leos Ondra
http://leo.astronomy.cz/grlens/grl0.html – Gravitational lensing with *Photoshop*

Two Effects of Gravitational Lensing



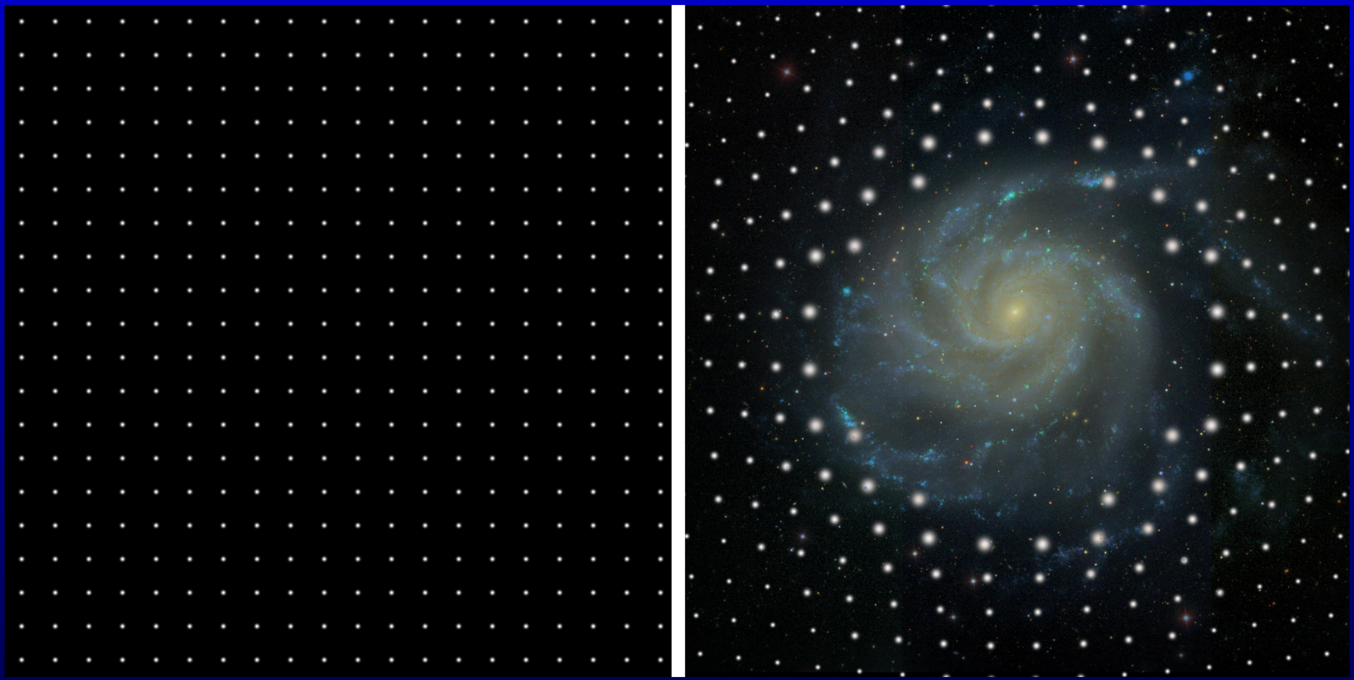
- Weak lensing of background sources introduces **shear** and **magnification**

Two Effects of Gravitational Lensing



- Shear distorts source image shapes (curl-free vector field)
- Galaxy-galaxy lensing & cosmic shear

Two Effects of Gravitational Lensing



- Magnification (μ) increases the angular size of source images.
- Increases flux (amplification) but decreases density on the sky (dilution).

Quantifying Cosmic Magnification I

Start with flux-limited background sample (e.g. QSOs):

$$\mathrm{n}_0(f)\,\mathrm{d}f = a_0\, f^{-s(f)}\,\mathrm{d}f \tag{1}$$

Lens images through foreground structure (e.g. local galaxies) with magnification μ

$$\begin{aligned} \mathrm{n}(f)\,\mathrm{d}f &= \frac{1}{\mu}\,\mathrm{n}_0\left(\frac{f}{\mu}\right)\frac{\mathrm{d}f}{\mu} \\ &= \mu^{s(f)-2}\,n_0(f)\,\mathrm{d}f \end{aligned} \tag{2}$$

Converting this to magnitude space, we get

$$\begin{aligned} \mathrm{N}(m)\,\mathrm{d}m &= \mu^{2.5\;s(m)-1}\,\mathrm{N}_0(m)\,\mathrm{d}m \\ &= \mu^{\alpha(m)-1}\,\mathrm{N}_0(m)\,\mathrm{d}m \end{aligned} \tag{3}$$

Quantifying Cosmic Magnification II

- If we are in the weak lensing regime ($\mu \approx 1$),

$$w_{\mathrm{GQ}}(\theta) = 12\pi^2\Omega_M(\alpha(m)-1)\int \mathrm{d}\chi\,\mathrm{d}k\;k\,\mathcal{K}(k,\theta,\chi)\,P_{gm}(k,\chi)$$
$$= (\alpha(m)-1)\times w_0(\theta), \quad (4)$$

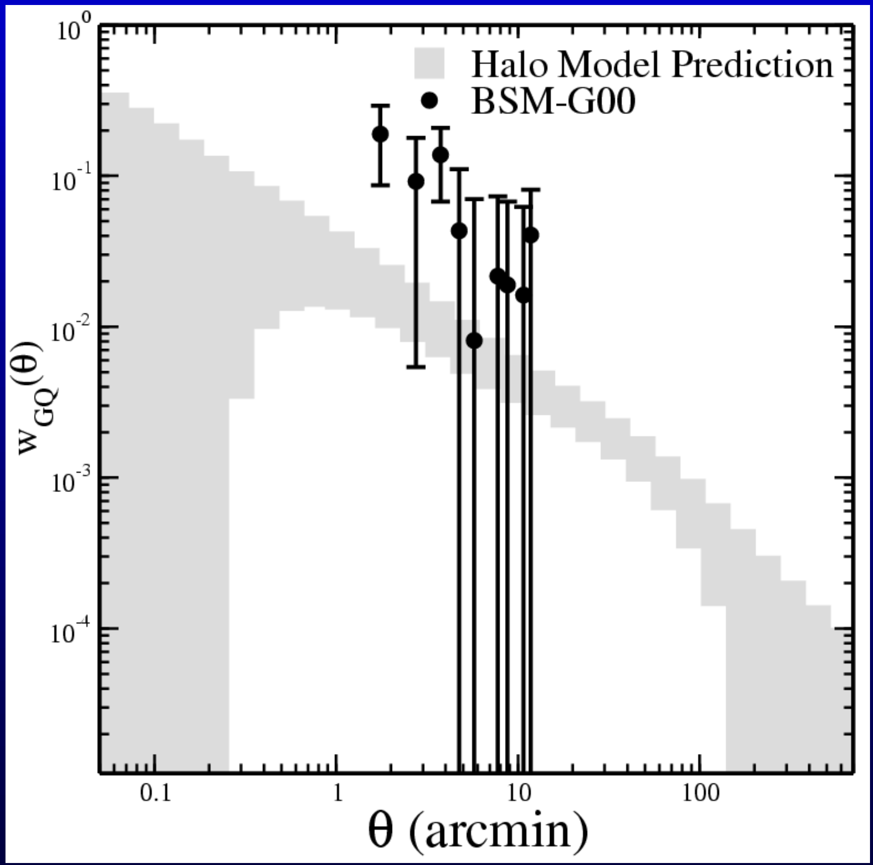
  where $\mathcal{K}$ depends on the foreground and background redshift distributions and $P_{gm}(k)$ is the galaxy-dark matter power spectrum.

- For $\alpha(m) > 1$, increasing amplification outweighs the dilution effect, yielding a positive cross-correlation. For $\alpha(m) < 1$, dilution wins and the cross-correlation is negative.

- Lensing signal amplitude is much smaller than intrinsic clustering, so redshift segregation is vital.

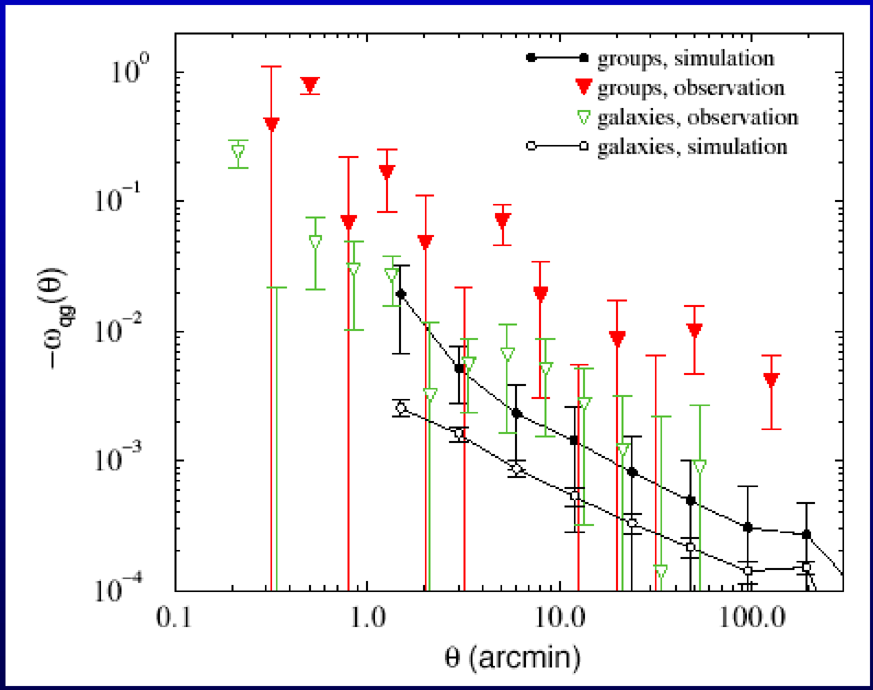
Controversy

- First lensing motivated measurements in late 1980s and early 1990s
  - ⋆ Lick, IRAS & APM galaxies, Abell & Zwicky clusters
  - ⋆ optical UVX and radio selected QSOs
- More recently, Guimaraes, Myers & Shanks (2003) used 2dF QSOs + APM & SDSS galaxy groups
- Consistently detect signal $\sim 10\times$ the expected lensing effect



Controversy

- First lensing motivated measurements in late 1980s and early 1990s
  - ⋆ Lick, IRAS & APM galaxies, Abell & Zwicky clusters
  - ⋆ optical UVX and radio selected QSOs
- More recently, Guimaraes, Myers & Shanks (2003) used 2dF QSOs + APM & SDSS galaxy groups
- Consistently detect signal $\sim 10\times$ the expected lensing effect



The Four Horsemen

- Photometric Calibration
  - ⋆ Small amplification effect requires excellent photometry
  - ⋆ Photographic plates not up to the challenge
- Redshift Overlap
  - ⋆ Physical clustering dominates lensing signal
  - ⋆ Require either spectroscopy or photometric redshifts for each object
- Uniform Selection Function
  - ⋆ Photographic plates have variable depth of field
  - ⋆ Spectroscopic surveys require detailed selection function
- Object Density
  - ⋆ Poisson errors dominate
  - ⋆ When object density is low, only systematic signal is detected

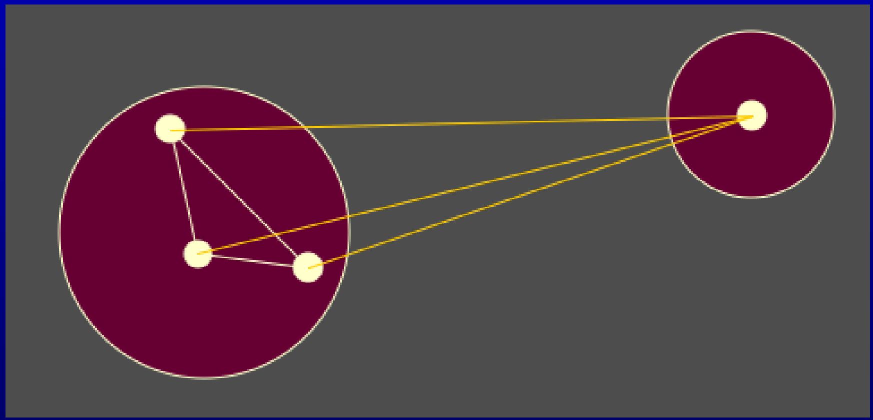
So Why Bother?

So Why Bother?

Because it's there

So Why Bother?

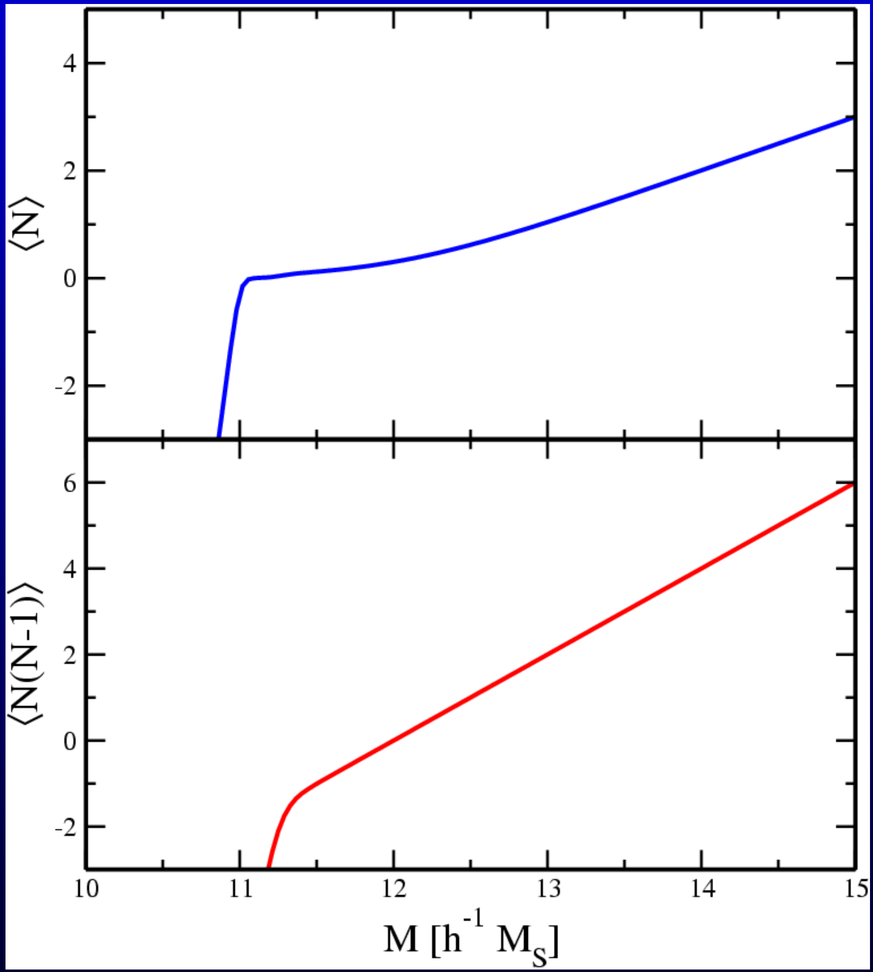
- Constraint on Halo Occupation Distribution
  - ⋆ $P_{gm}(k)$ is a function of $\langle N \rangle$ on all scales
  - ⋆ $w(\theta)$ function of $\langle N(N-1) \rangle$ on small scales
- Complement to shear statistics
  - ⋆ Similar to galaxy-galaxy lensing but deeper lenses, different systematics
  - ⋆ Bridges physical scale between galaxy-galaxy lensing and cosmic shear



Frieman

So Why Bother?

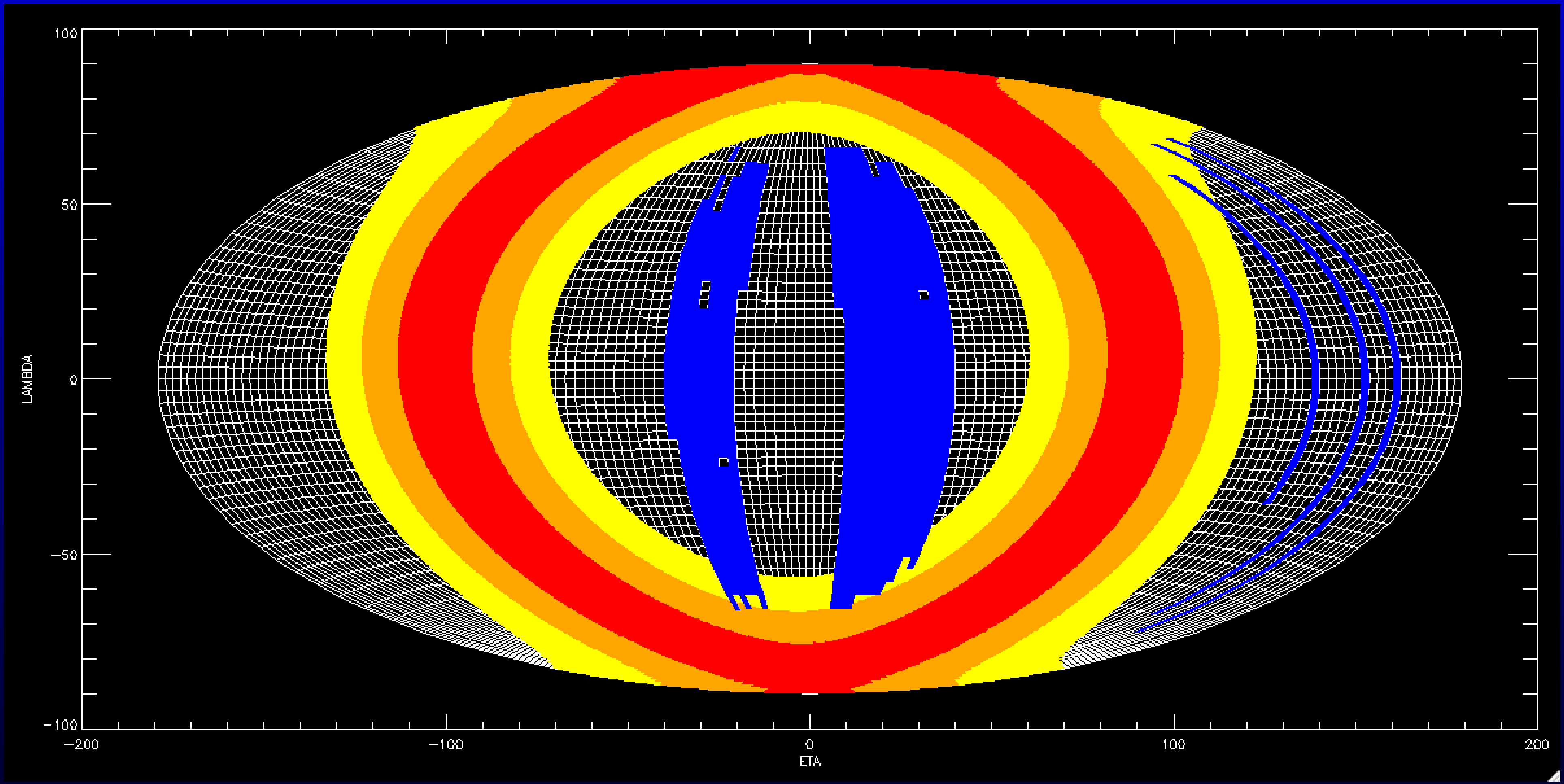
- Constraint on Halo Occupation Distribution
  - ⋆ $P_{gm}(k)$ is a function of $\langle N \rangle$ on all scales
  - ⋆ $w(\theta)$ function of $\langle N(N-1) \rangle$ on small scales
- Complement to shear statistics
  - ⋆ Similar to galaxy-galaxy lensing but deeper lenses, different systematics
  - ⋆ Bridges physical scale between galaxy-galaxy lensing and cosmic shear



The Data

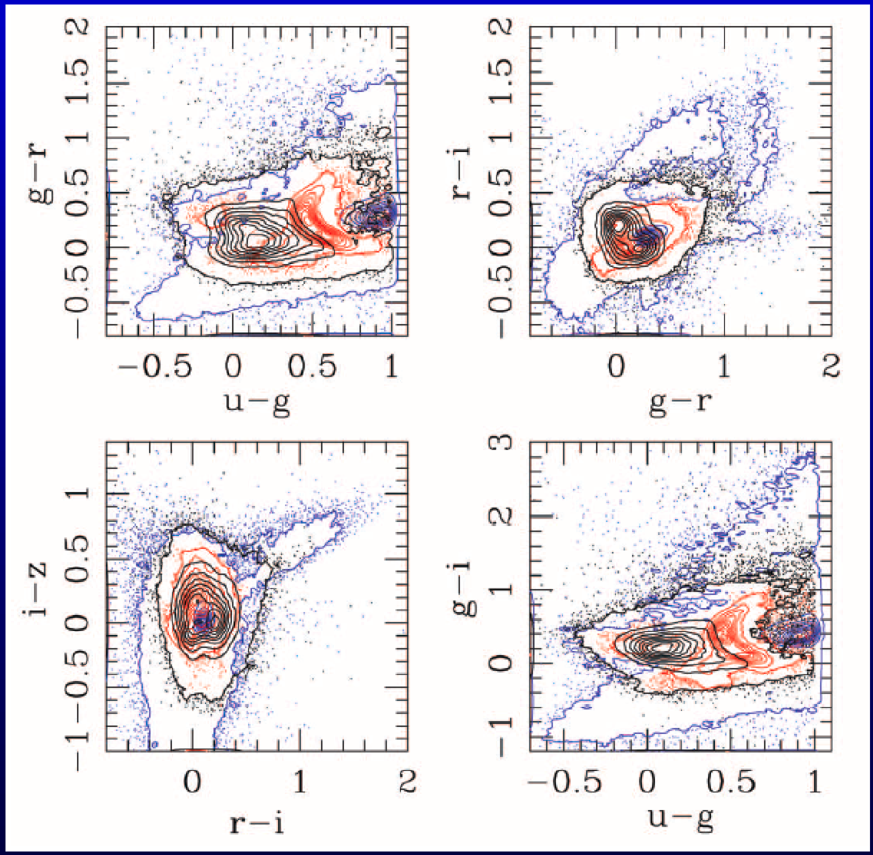
- SDSS DR3 photometric data
  - ⋆ 5 bands (u', g', r', i', z') stretching from near IR to near UV
  - ⋆ 5000 square degrees (1/8 total sky)
  - ⋆ North Galactic Cap & 3 South Galactic Stripes
- Remove areas with poor seeing ($> 1''.4$) and high Galactic extinction. Also block out regions around bright ($r' < 16$) galaxies and saturated stars
  $\Rightarrow$ 3800 square degrees
- 13 million galaxies with $17 < r' < 21$
  - ⋆ Mean redshift $z \sim 0.3$
  - ⋆ Maximum redshift $z \sim 0.75$
- 195,000 photometrically selected QSOs with $17 < g' < 21$. Use photometric redshifts to select $1 < z < 2.2$

Galaxy Area



Photometric QSO Selection

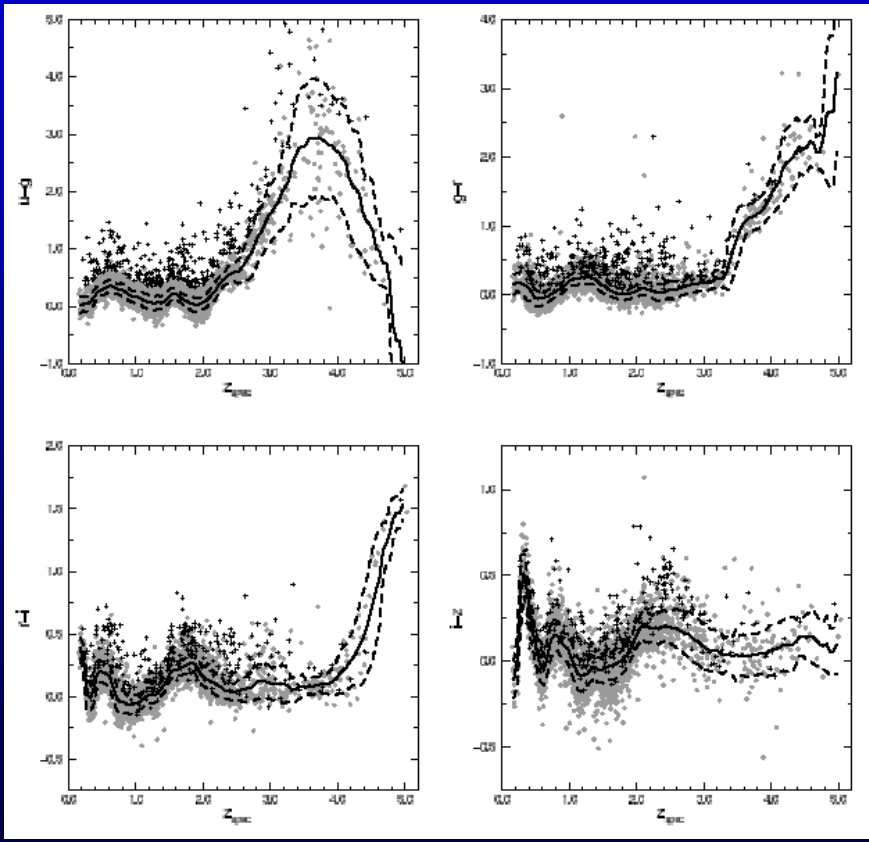
- Traditional QSO selection involves cuts in 2-D projections
- Kernel Density Estimation (KDE) uses full 4-D color space
  - ⋆ 2 training sets: QSOs & stars
  - ⋆ compute distance in color space to assign new objects
- SDSS spectroscopic selection 85% efficient for $i' < 19$
- KDE selection $> 95\%$ efficient for $g' < 21 \Rightarrow 10\times$ density



Richards et al. (2004)

QSO Photometric Redshifts

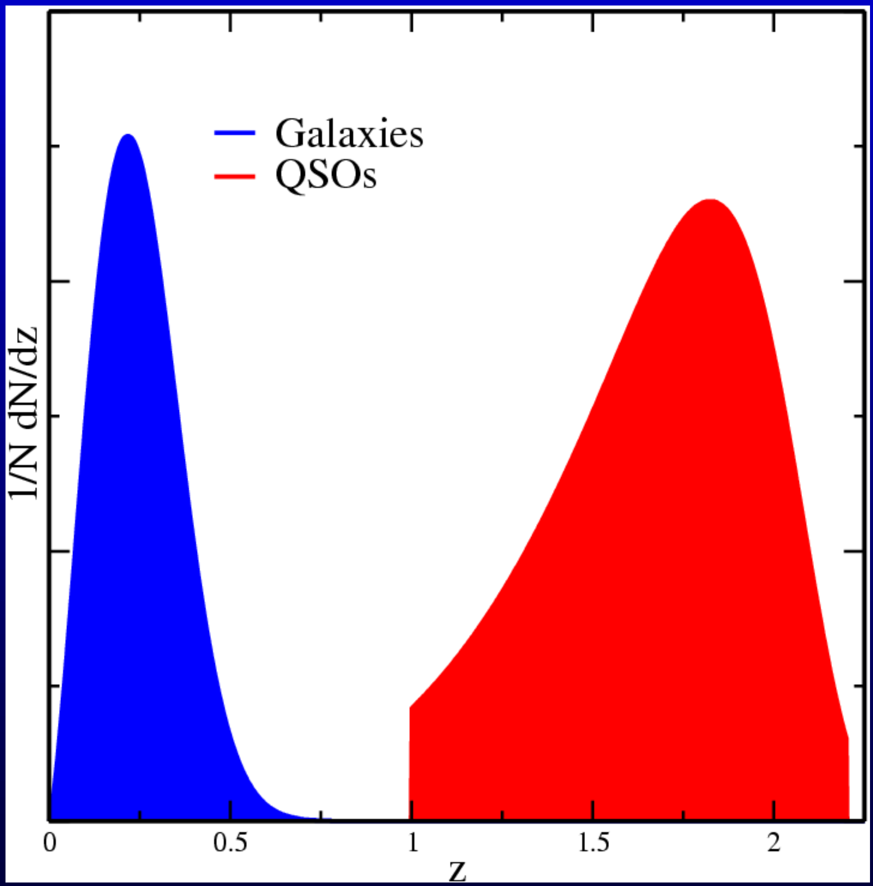
- QSO Spectrum: Power-law + broad emission lines
- Photometric redshifts driven by redshifting of emission lines through SDSS filters
- Calculate probability of photo-z as a function of $z \Rightarrow$ upper and lower redshift bounds and probability within bounds
- For $1 < z < 2.2$, mean probability ~ 0.85



Weinstein et al. (2004)

QSO Photometric Redshifts

- QSO Spectrum: Power-law + broad emission lines
- Photometric redshifts driven by redshifting of emission lines through SDSS filters
- Calculate probability of photo-z as a function of $z \Rightarrow$ upper and lower redshift bounds and probability within bounds
- For $1 < z < 2.2$, mean probability ~ 0.85

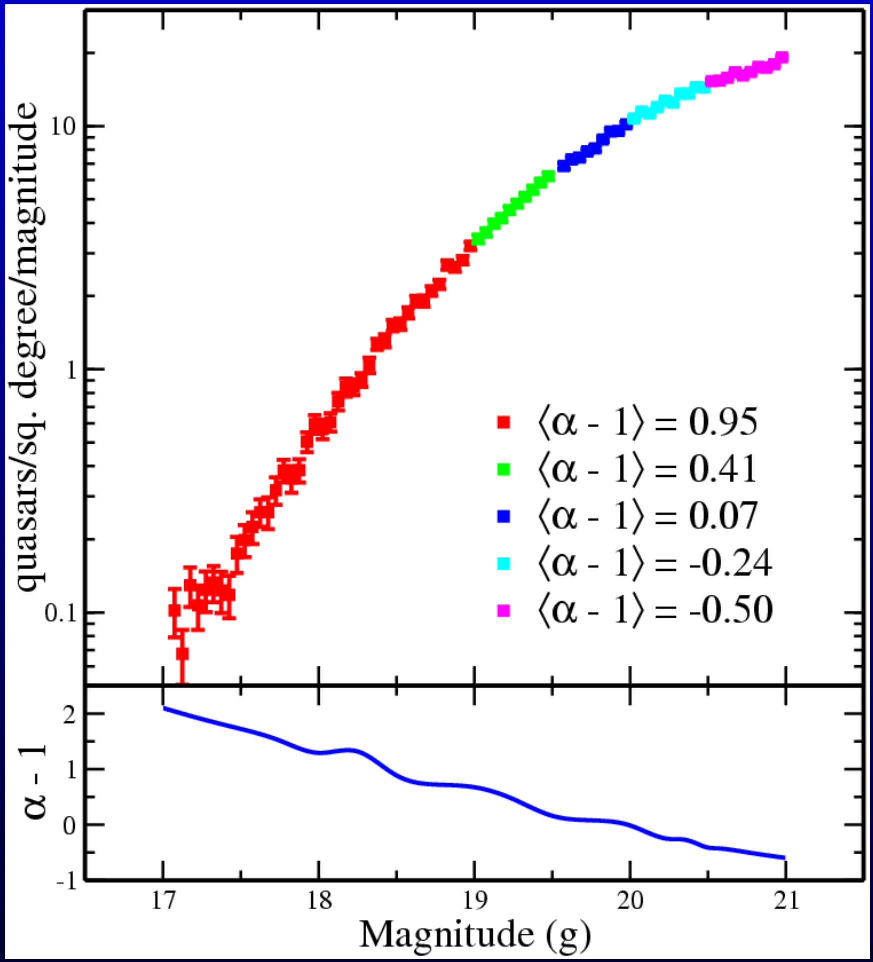


Measurement in g'

- Select 5 magnitude bins in g': $17 < g' < 19$, $19 < g' < 19.5$, $19.5 < g' < 20$, $20 < g' < 20.5$, $20.5 < g' < 21$
- Calculate $\langle\alpha - 1\rangle$ in each bin:

$$\langle\alpha - 1\rangle = \frac{\int N(m)(\alpha(m) - 1)}{\int N(m)} \quad (5)$$

- Expect to see positive correlation for $g' < 19.5$ and negative correlation for $g' > 20$



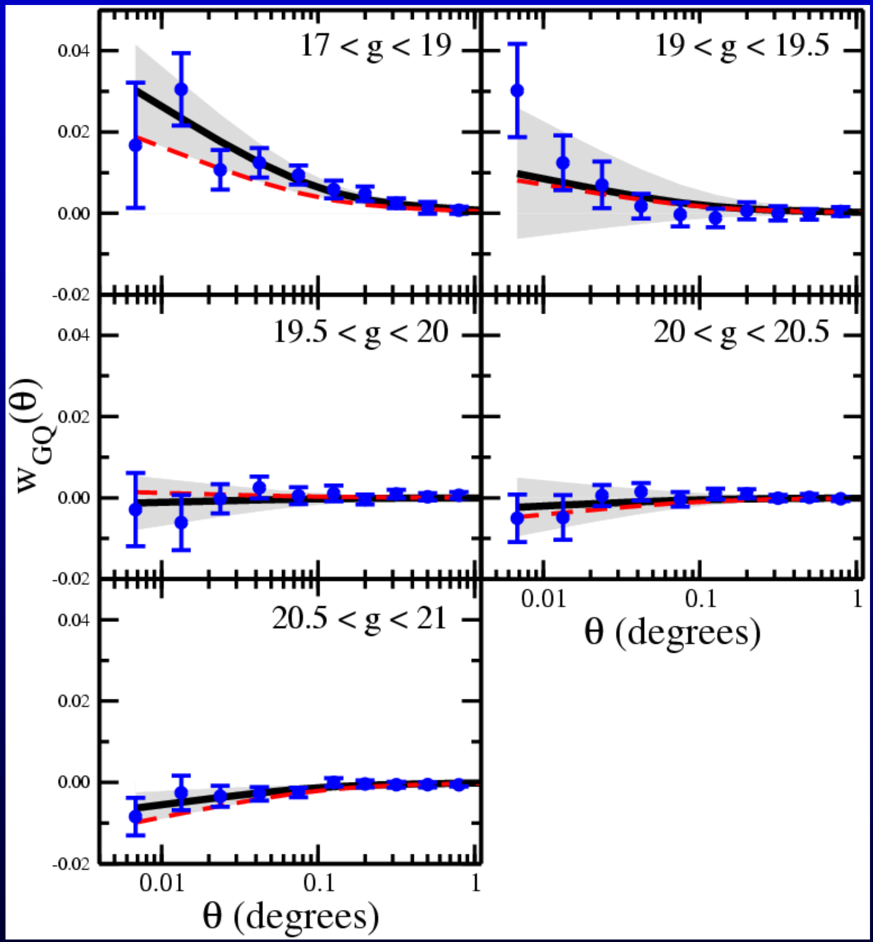
Measurement in g'

- Select 5 magnitude bins in g': $17 < g' < 19$, $19 < g' < 19.5$, $19.5 < g' < 20$, $20 < g' < 20.5$, $20.5 < g' < 21$

- Calculate $\langle \alpha - 1 \rangle$ in each bin:

$$\langle \alpha - 1 \rangle = \frac{\int \mathrm{N}(m)(\alpha(m) - 1)}{\int \mathrm{N}(m)} \quad (6)$$

- Expect to see positive correlation for $g' < 19.5$ and negative correlation for $g' > 20$



Optimal Signal

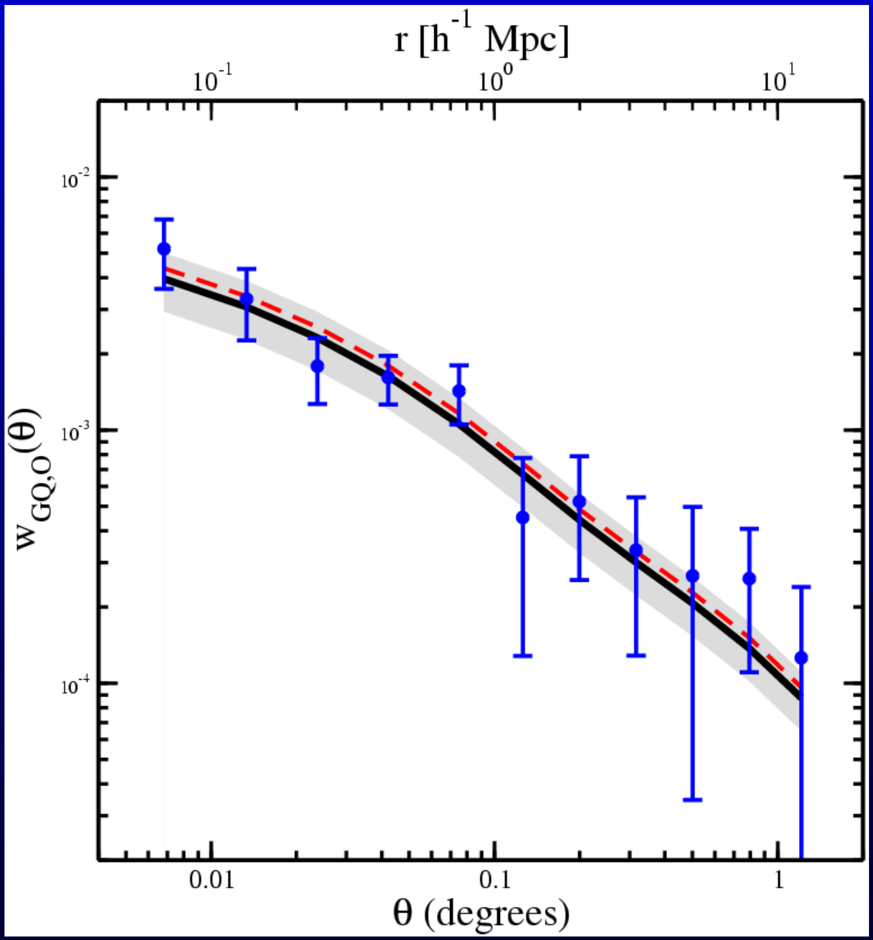
- Magnitude bin measurements verify amplitude of expected signal and variation with $\langle\alpha - 1\rangle$
- $\langle\alpha - 1\rangle$ for full QSO sample very close to zero
- To extract full lensing significance, use second moment:
  - ⋆ Re-calculate estimator weighting each QSO by $\alpha(m) - 1$
  - ⋆ Expected signal:

$$w_{\rm GQ,O}(\theta) = \langle(\alpha - 1)^2\rangle \times w_0(\theta) \qquad (7)$$

- Instead of canceling, positive and negative correlations add coherently

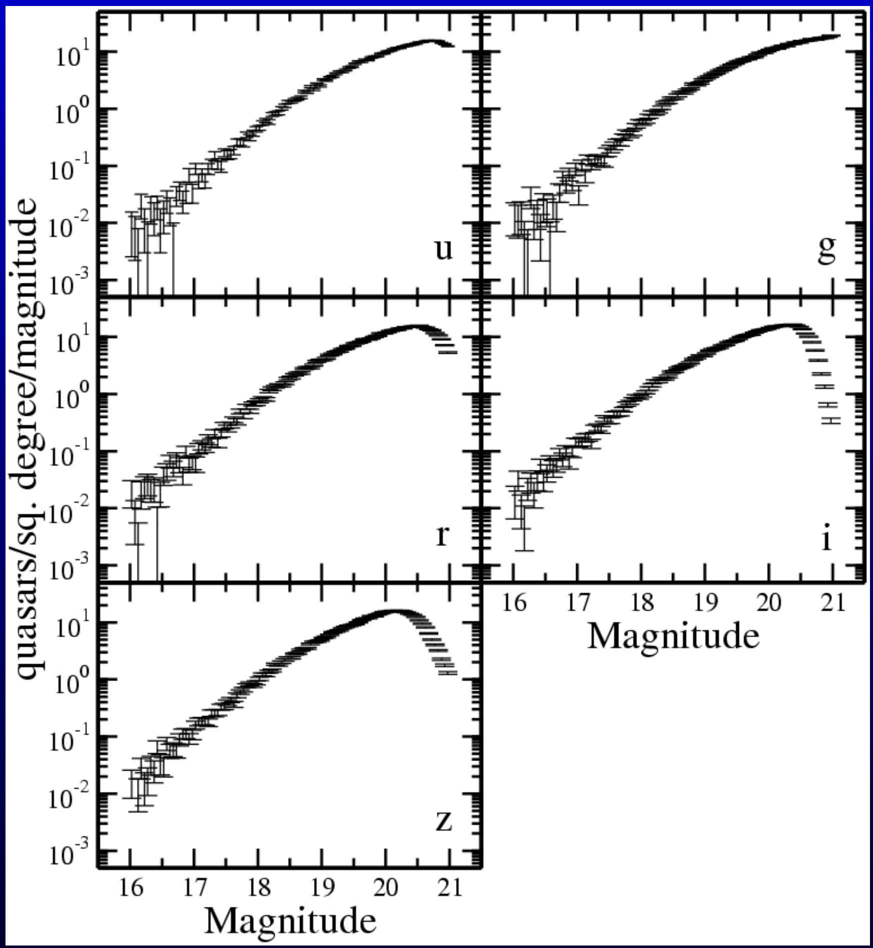
Optimal g'

- 105,000 QSOs
- 8σ detection of lensing against null
- Excellent match to expected signal
- For $z \sim 0.3$, detecting lensing on scales from $60\,h^{-1}$ kpc to $10\,h^{-1}$ Mpc



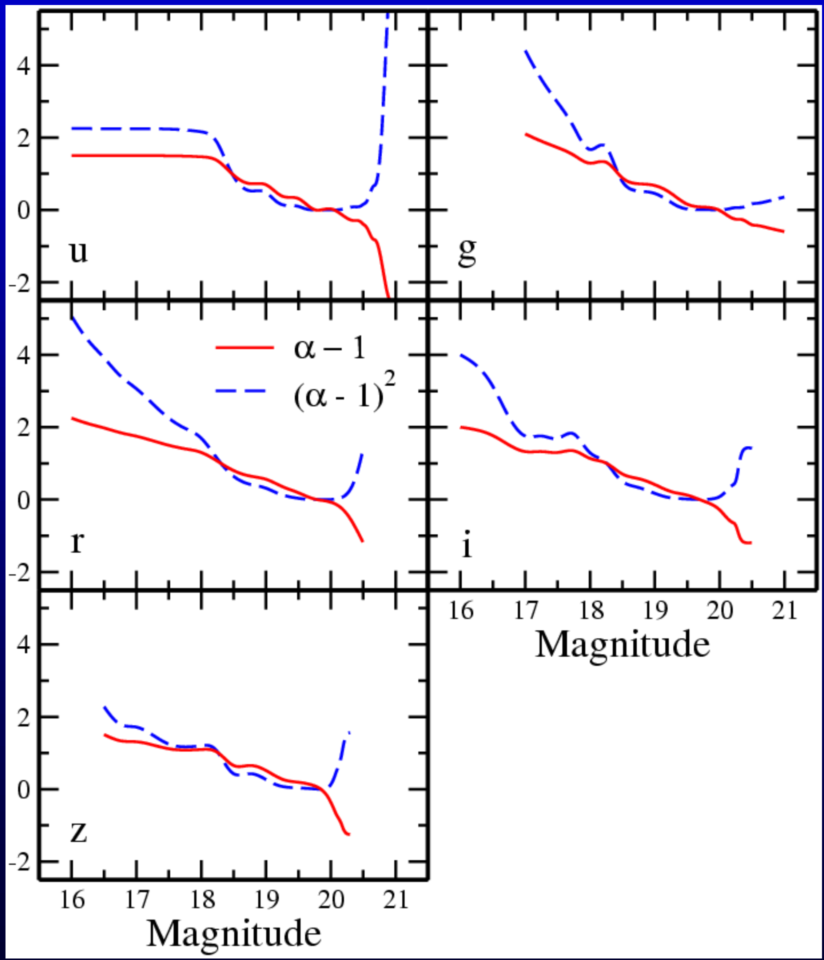
Optimal in All Bands

- For other bands, incompletion is an issue at the faint end
- 60,000 - 75,000 QSOs
- Good to excellent match to expected signal in all cases
- At least 4σ detection in each band



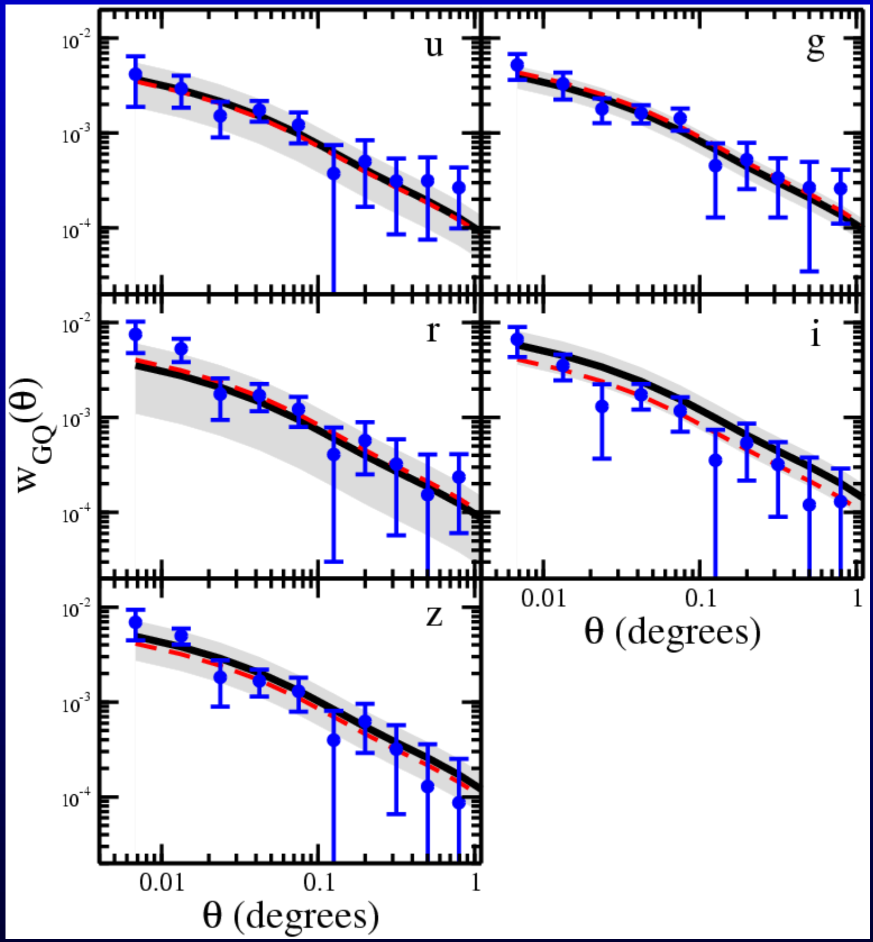
Optimal in All Bands

- For other bands, incompletion is an issue at the faint end
- 60,000 - 75,000 QSOs
- Good to excellent match to expected signal in all cases
- At least 4σ detection in each band



Optimal in All Bands

- For other bands, incompletion is an issue at the faint end
- 60,000 - 75,000 QSOs
- Good to excellent match to expected signal in all cases
- At least 4σ detection in each band



Summary & Future Applications

- Previous galaxy-QSO measurements detected much stronger signal than predicted by lensing, but were likely dominated by systematic effects
- Using photometric QSOs and galaxies from SDSS DR3, we observe a signal with the expected amplitude. Signal also exhibits expected variation in amplitude and sign with varying $\alpha(m)$.
- Optimally combining all of our g' selected QSOs, we detect cosmic magnification of QSOs at 8σ. All SDSS filters give signficances $> 4\sigma$.
- Combining cosmic magnification with $w(\theta)$ should provide excellent constraints on galaxy halo occupation statistics.
- The techniques used for efficient QSO selection readily applicable to next generation of large, multi-band surveys. Cosmic magnification excellent complement to planned cosmic shear surveys.