# Lensing Probabilities for Spectroscopically Selected Galaxy-Galaxy Lenses

Greg Dobler (CfA)

FNAL, June 15th, 2007

Chuck Keeton (Rutgers), Adam Bolton (CfA), & Scott Burles (MIT)

# What *is* a Spectroscopically Selected g-g lens?

- Measure the spectrum of a galaxy
  - preferably with well characterized shape
  - resolve line emission
- Look for "rogue" emission lines
  - with a *larger redshift*
  - preferably *multiple* lines
- Observe photometrically
  - high spatial resolution
  - remove foreground galaxy

# How many are there?

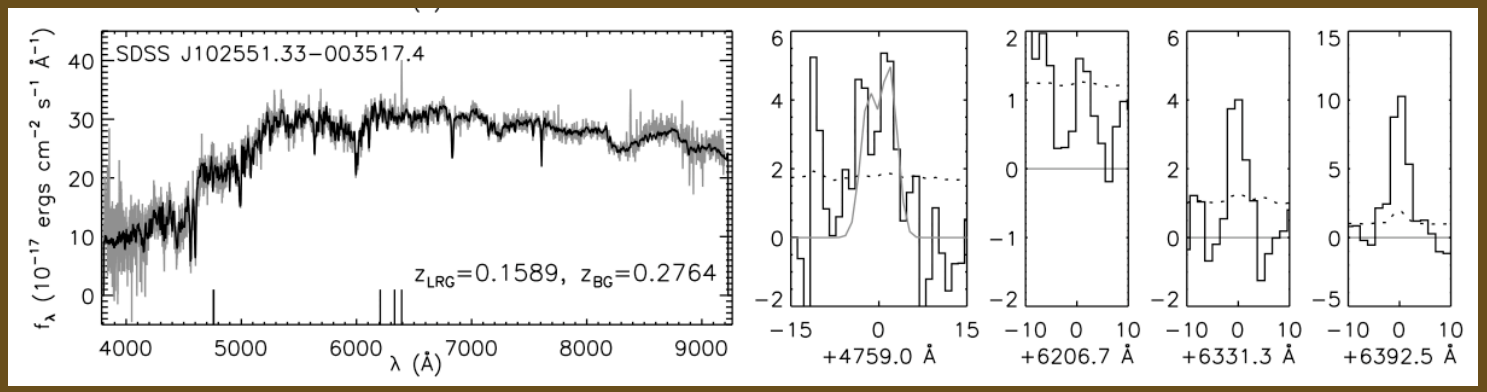
- Recent searches: Bolton et al. 2004, 2006; Willis et al. 2005, 2006
- The Sloan Lens ACS (SLACS) survey (Bolton et al 2004):

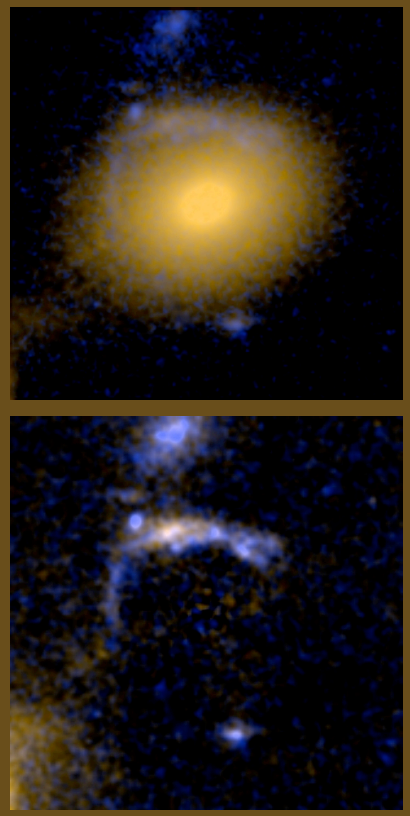
# How many are there?

- Recent searches: Bolton et al. 2004, 2006; Willis et al. 2005, 2006
- The Sloan Lens ACS (SLACS) survey (Bolton et al 2004):
  - Searched LRG spectra for rogue [OII] emission
  - [OII] emission may be from a background galaxy
  - Emission falls in the spectroscopic fiber
    - ⇒ the impact parameter may be small
    - ⇒ high likelihood of observing strong lensing
  - "False positives" reduced with secondary features (Hβ or [OIII] lines)
  - Follow up observations: HST

# How many are there?

- Recent searches: Bolton et al. 2004, 2006; Willis et al. 2005, 2006
- The Sloan Lens ACS (SLACS) survey (Bolton et al 2004):



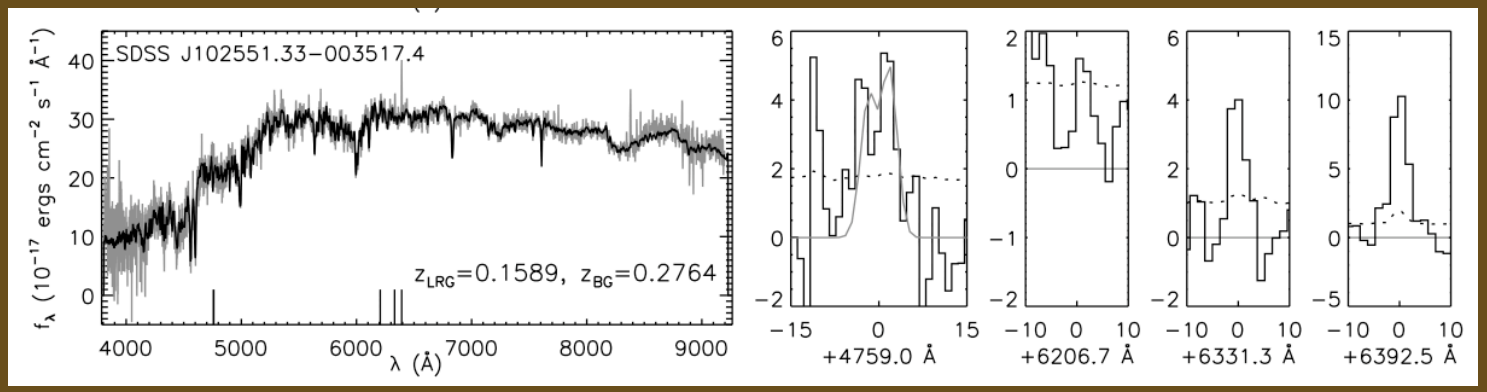



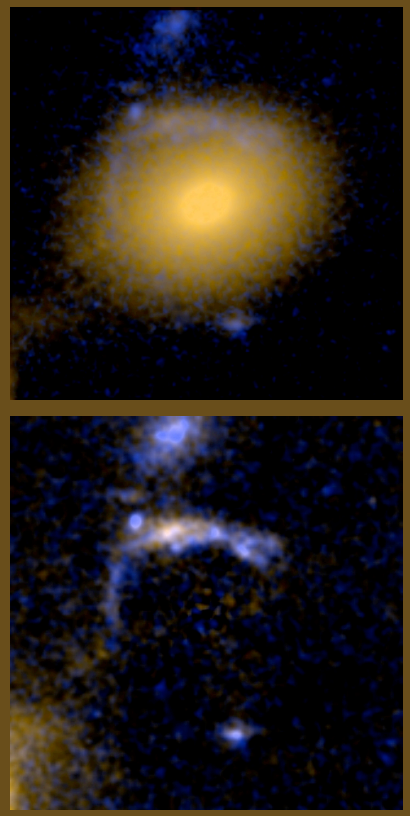
SDSS J102551, $z_{lens}$=0.16 $z_{src}$=0.28 (www.slacs.org)

# How many are there? …Many

- Recent searches: Bolton et al. 2004, 2006; Willis et al. 2005, 2006

- The Sloan Lens ACS (SLACS) survey (Bolton et al 2004):



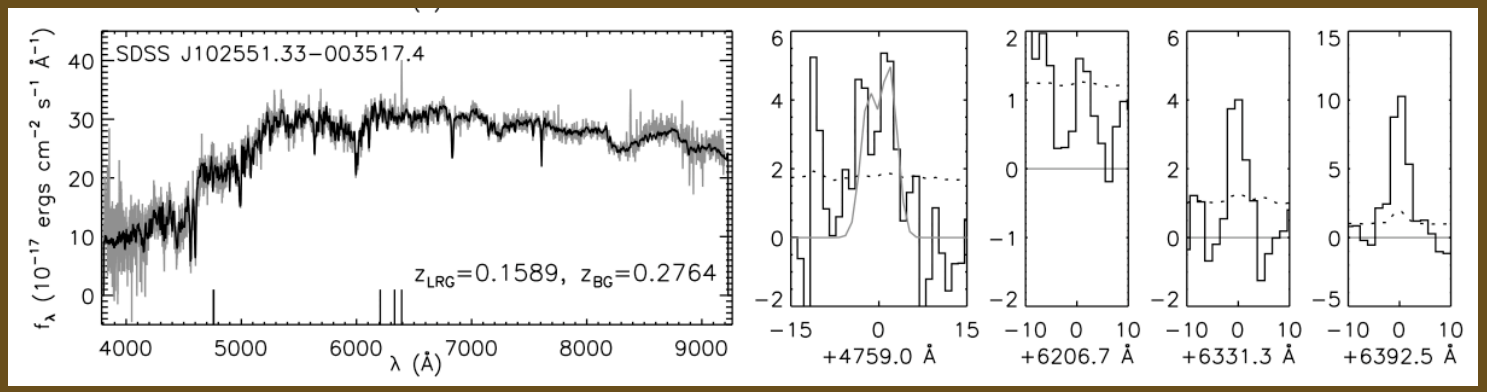
SDSS J102551, $z_{lens}$=0.16 $z_{src}$=0.28 (www.slacs.org)

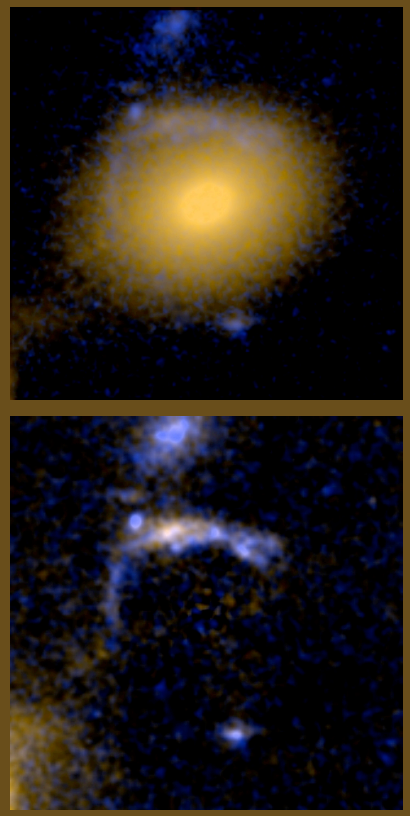
- For ~*51,000* LRG spectra, SLACS has uncovered ~ 60 new strong galaxy-galaxy lenses

# How many are there? …Many

- Recent searches: Bolton et al. 2004, 2006; Willis et al. 2005, 2006

- The Sloan Lens ACS (SLACS) survey (Bolton et al 2004):



SDSS J102551, $z_{lens}$=0.16 $z_{src}$=0.28 (www.slacs.org)

- For ~*51,000* LRG spectra, SLACS has uncovered ~ 60 new strong galaxy-galaxy lenses

**Is this number reasonable?**

# Lensing Probability

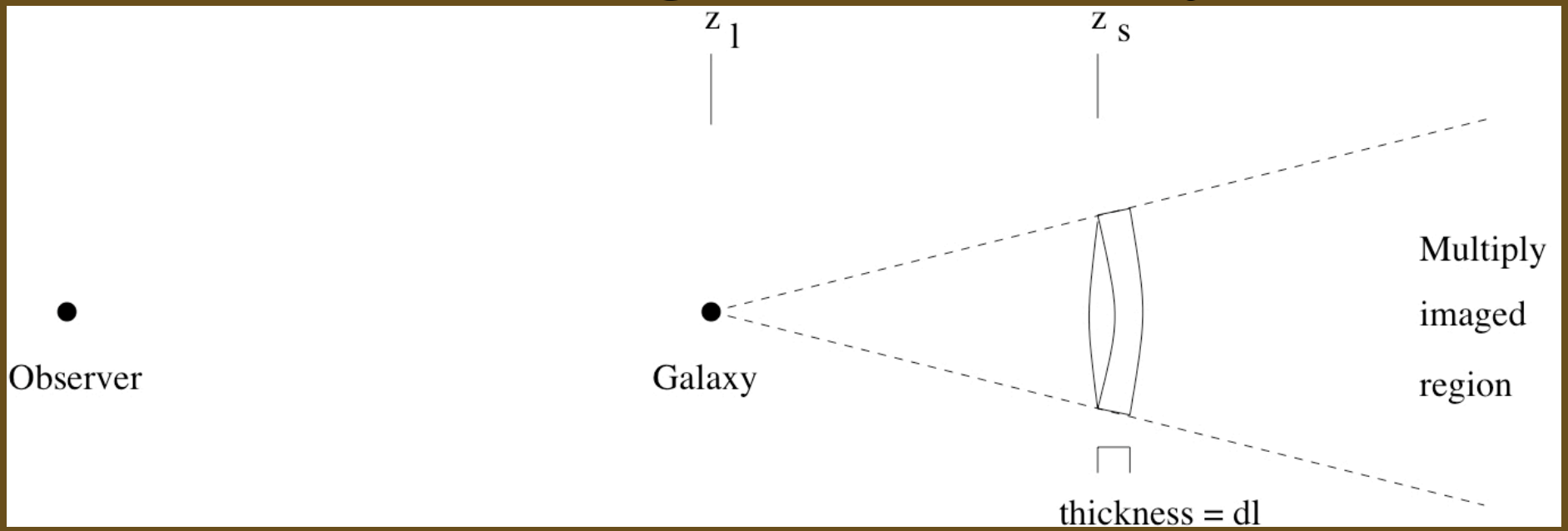
Unlike quasar lens statistics, we are not asking

*"what is the probability that a source is lensed?"*

but rather,

*"what is the probability that a given galaxy* ***is*** *a lens?"*

# Lensing Probability



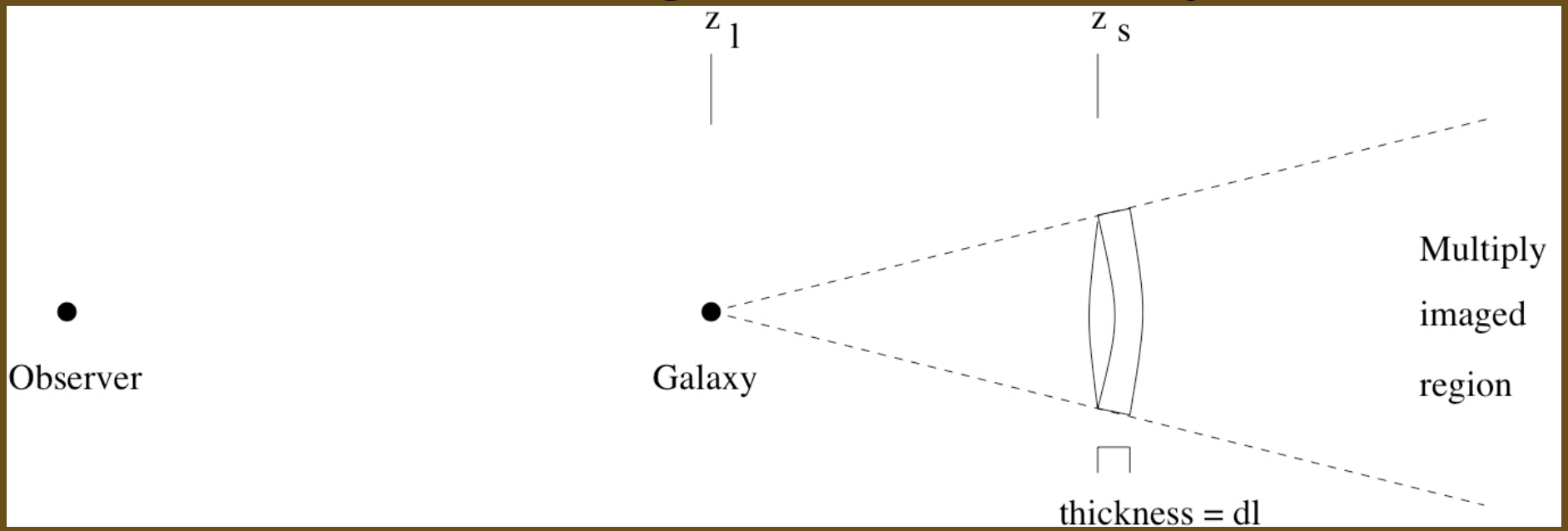

Unlike quasar lens statistics, we are not asking

*"what is the probability that a source is lensed?"*

but rather,

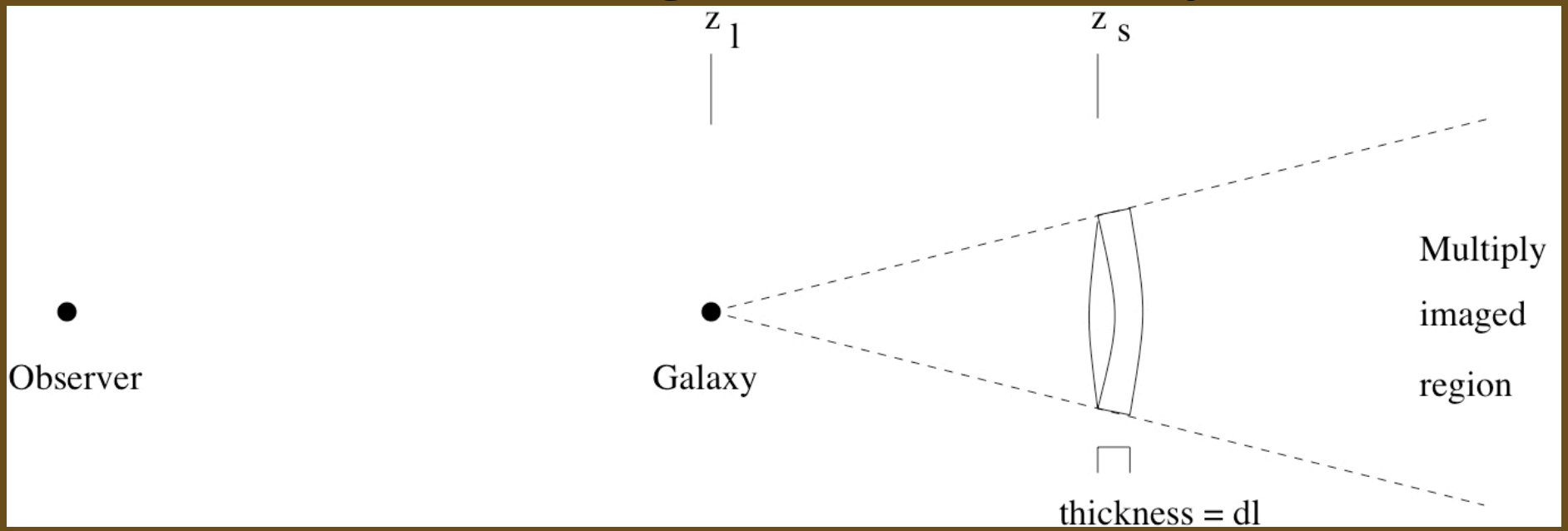
*"what is the probability that a given galaxy* ***is*** *a lens?"*

# Lensing Probability




$$P_G(\vec{G}_P, z_l) = \int_{V_{\text{ein}}} n_s(z_s, S)\, dV_{\text{ein}}$$

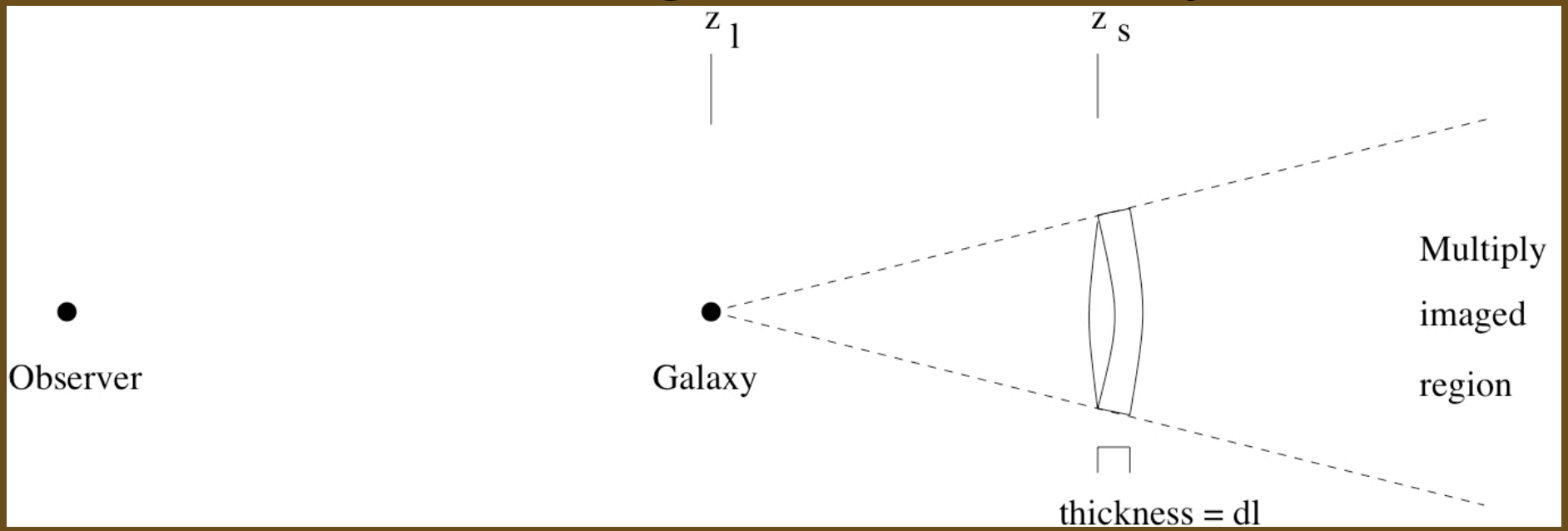
# Lensing Probability




$$P_G(\vec{G}_P, z_l) = \int_{V_{\rm ein}} n_s(z_s, S)\, dV_{\rm ein}$$

$$= \int_{z_l}^{\infty} \frac{dV}{dz_s} dz_s \int_M d\vec{u} \int_{L_0/\mu}^{\infty} \Phi(L)\, dL$$

# Lensing Probability

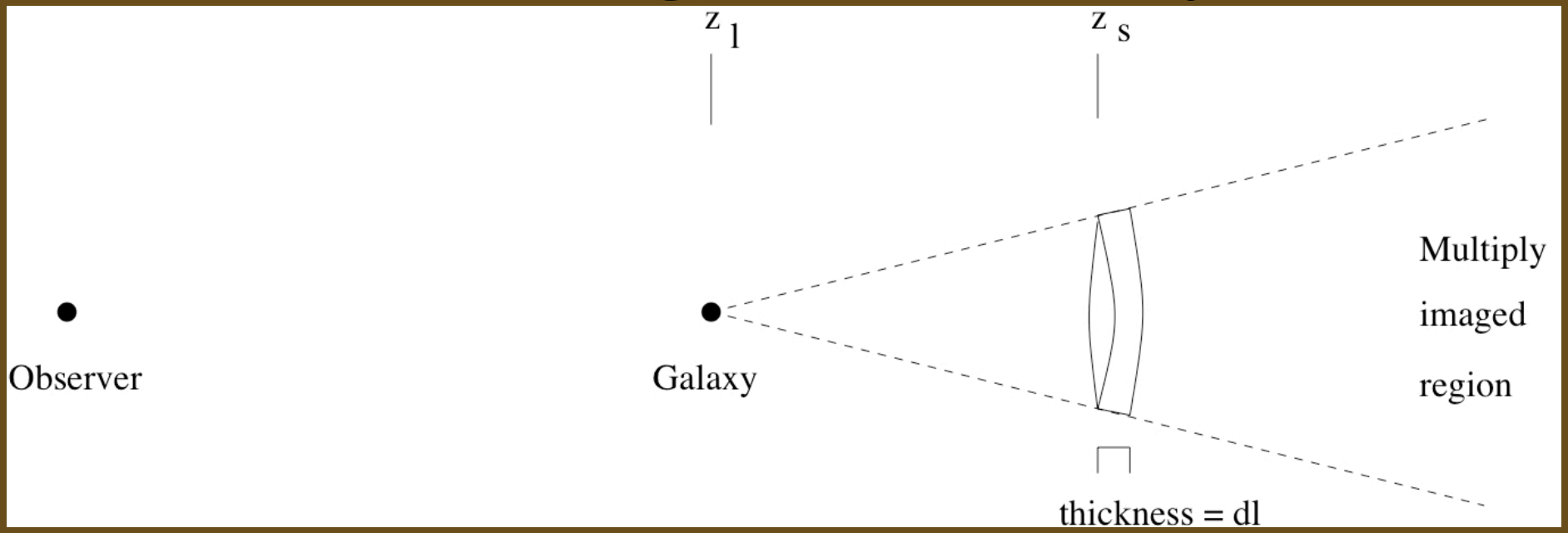



$$P_G(\vec{G}_P, z_l) = \int_{V_{\rm ein}} n_s(z_s, S)\, dV_{\rm ein}$$

$$= \int_{z_l}^{\infty} \frac{dV}{dz_s} dz_s \int_M d\vec{u} \int_{L_0/\mu}^{\infty} \Phi(L)\, dL$$

$$P_L = \frac{1}{N} \sum_{i=1}^{N} P_G(\vec{G}_{P,i}, z_{l,i})$$

# Lensing Probability




$$P_L(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu \geq \mu_{\text{cut}})$$

$$P_N(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu < \mu_{\text{cut}})$$

$$P_R = P_L + P_N$$

We choose $\mu_{cut} = 2$

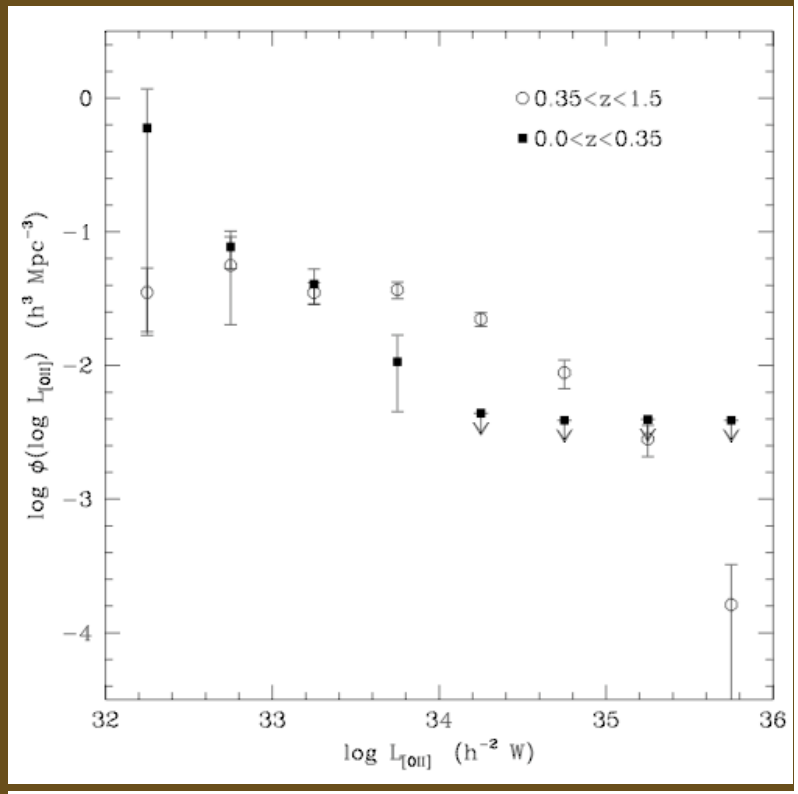
# Lens/Source Distributions

- SIE galaxy parameters $G_P$
  - SDSS LRG sample
    - $e$ , ellipticity
    - $\sigma$ , velocity dispersion
    - $z_l$ , lens redshift
  - External shear
    - $\gamma$ , amplitude (log-normal distribution)
    - $\phi_\gamma$ , angle (random between $0$ and $2\pi$)

- Source parameters
  - Schechter function LF (Hogg et al. 1998)
    - Convert OCDM to ΛCDM
    - Fix $0 \leq \beta \leq 3$ (Kennicutt 1992; Glazebrook et al 2003)
  - Radius varied $0.5 \leq R_s \leq 10$ kpc

# Lens / Source Distributions

- SIE galaxy parameters $G_P$
  - SDSS LRG sample
    - $e$ , ellipticity
    - $\sigma$ , velocity dispersion
    - $z_l$ , lens redshift
  - External shear
    - $\gamma$ , amplitude (log-normal distribution)
    - $\phi_\gamma$ , angle (random between $0$ and $2\pi$)
- Source parameters
  - Schechter function LF (Hogg et al. 1998)
    - Convert OCDM to ΛCDM
    - Fix $0 \le \beta \le 3$ (Kennicutt 1992; Glazebrook et al 2003)
  - Radius varied $0.5 \le R_s \le 10$ kpc

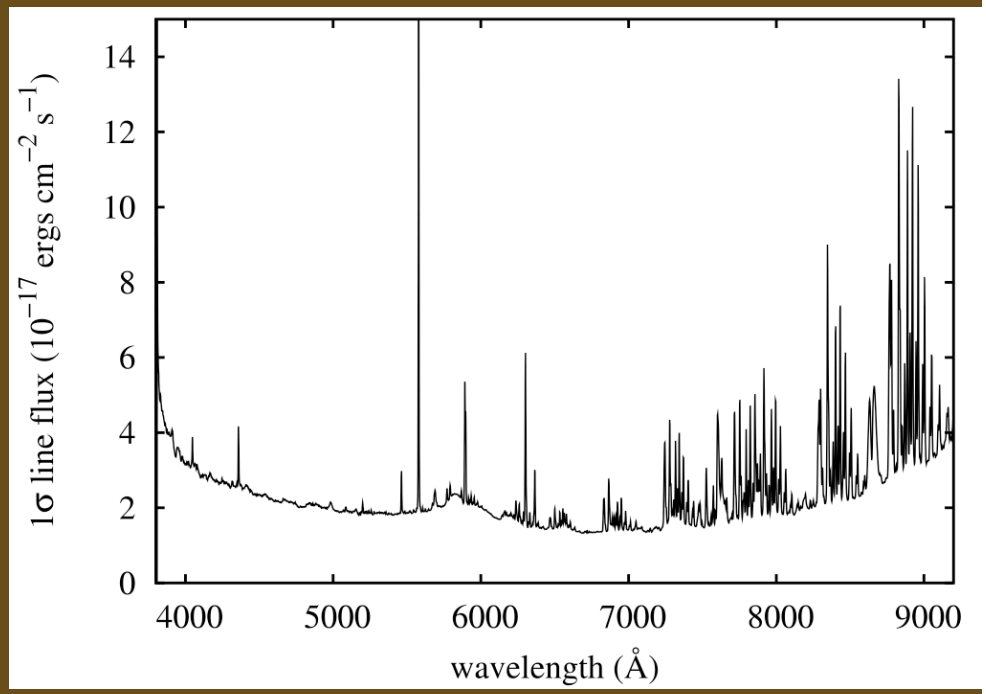



$$\Phi(L)dL = (1+z)^{\beta} n_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*} \frac{dL}{L_*}$$

# SLACS Parameters

$$P_G(\vec{G}_P, z_l) = \int \frac{dV}{dz_s} dz_s \int d\vec{u} \int_{L_0/\mu}^{\infty} \Phi(L) dL$$

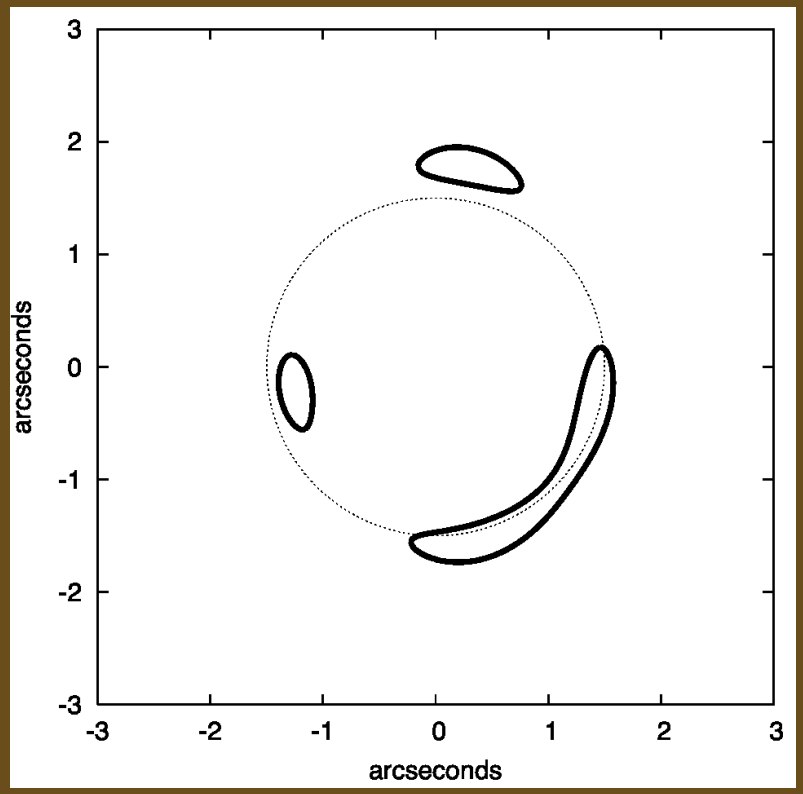
- LRG redshift
  - $0.15 \leq z_l \leq 0.65$
- [OII] redshift
  - $z_l + 0.017 \leq z_s \leq 0.9$
- Flux limit
  - $S_0 = 6.0 \times 10^{-17}$ erg/s/cm$^2$
  - includes the requirement: $S/N \geq 3$
- SDSS fiber size
  - $r_{\mathrm{fib}} = 1.5''$

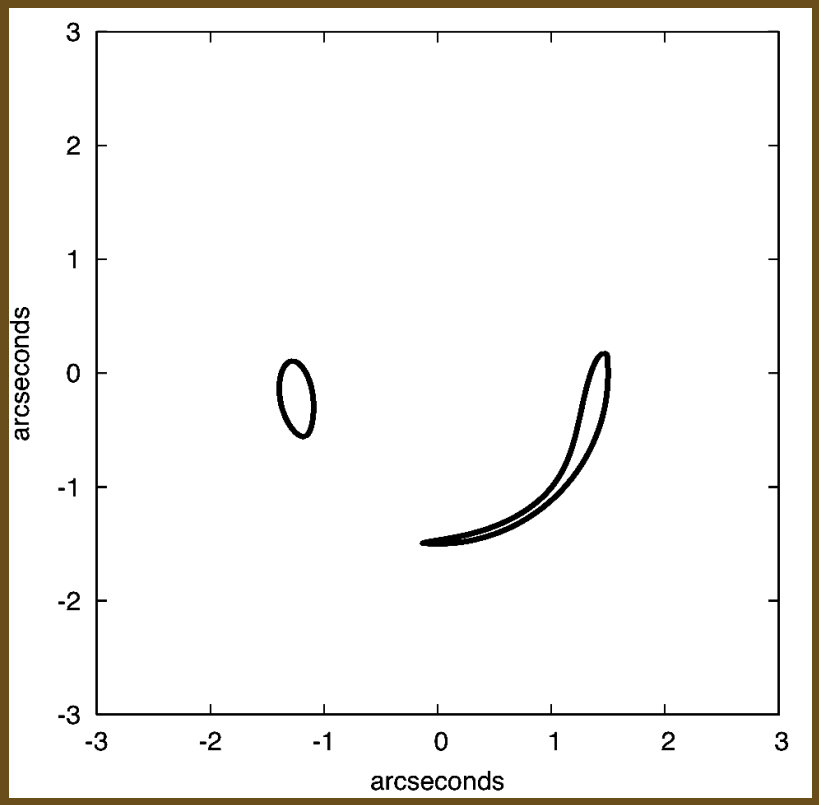



Bolton et al. (2004)

# Dependence on Parameters

- Fiber cut creates a bias against
  - large $\sigma$ lenses
  - large $R_s$ sources



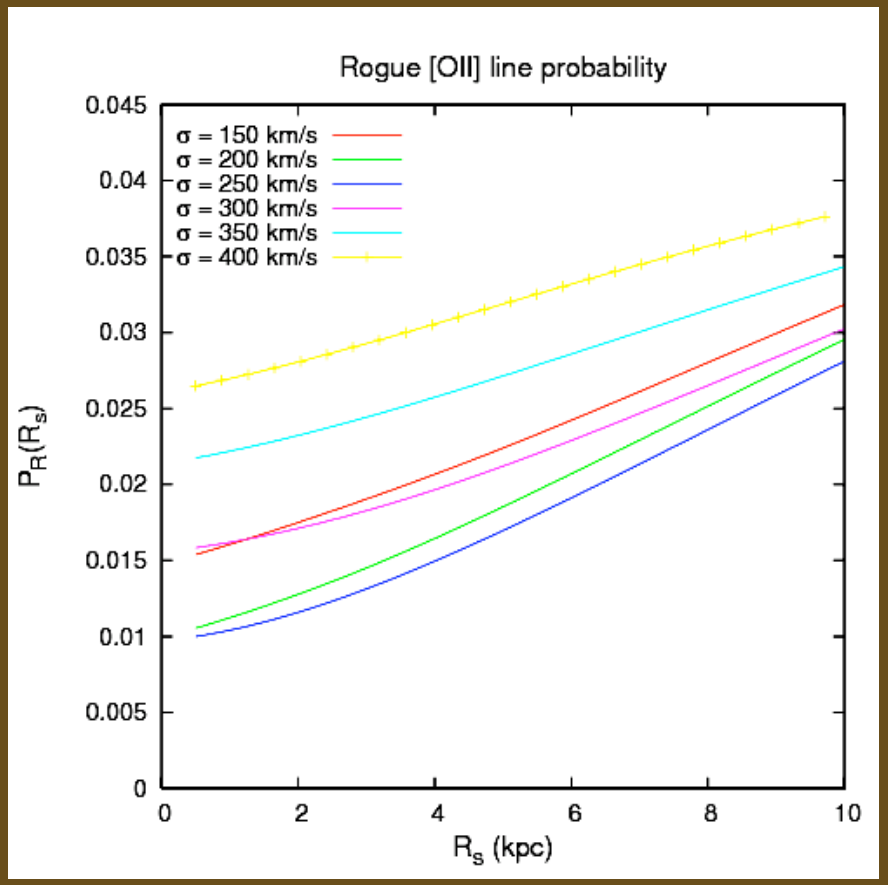
# Dependence on Parameters

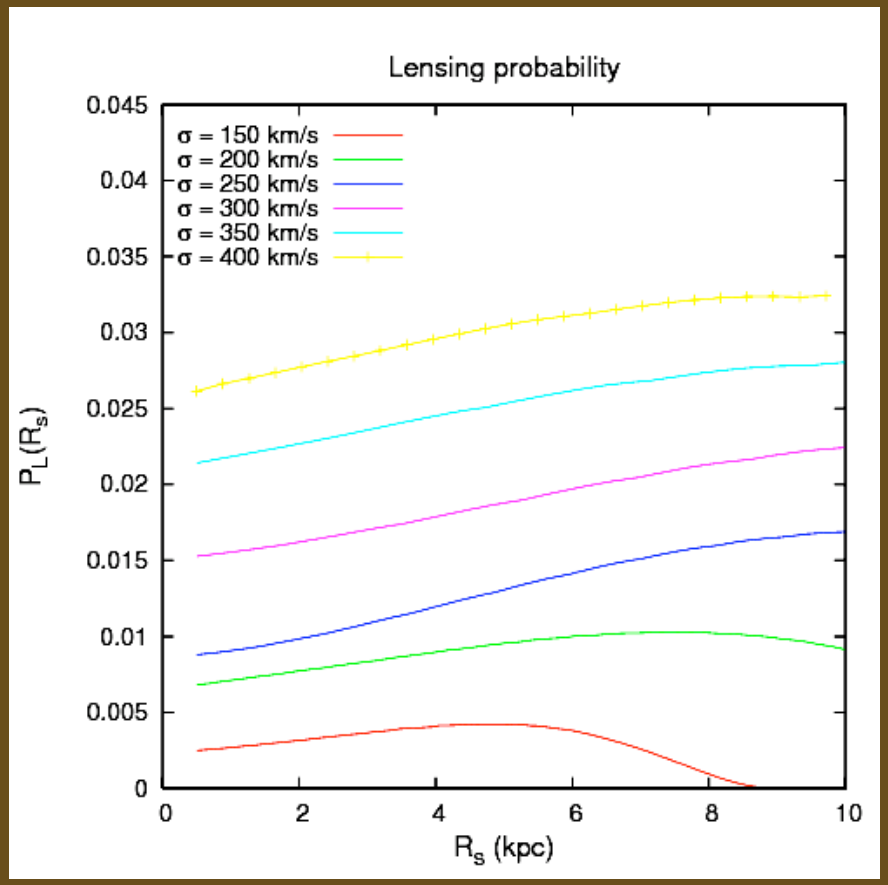
- Dependence on $\sigma$
  - $P_R$ is non-monotonic in $\sigma$
  - $P_L$ increases with $\sigma$

$$P_L(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu \geq \mu_{\text{cut}})$$

$$P_N(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu < \mu_{\text{cut}})$$

$$P_R = P_L + P_N$$



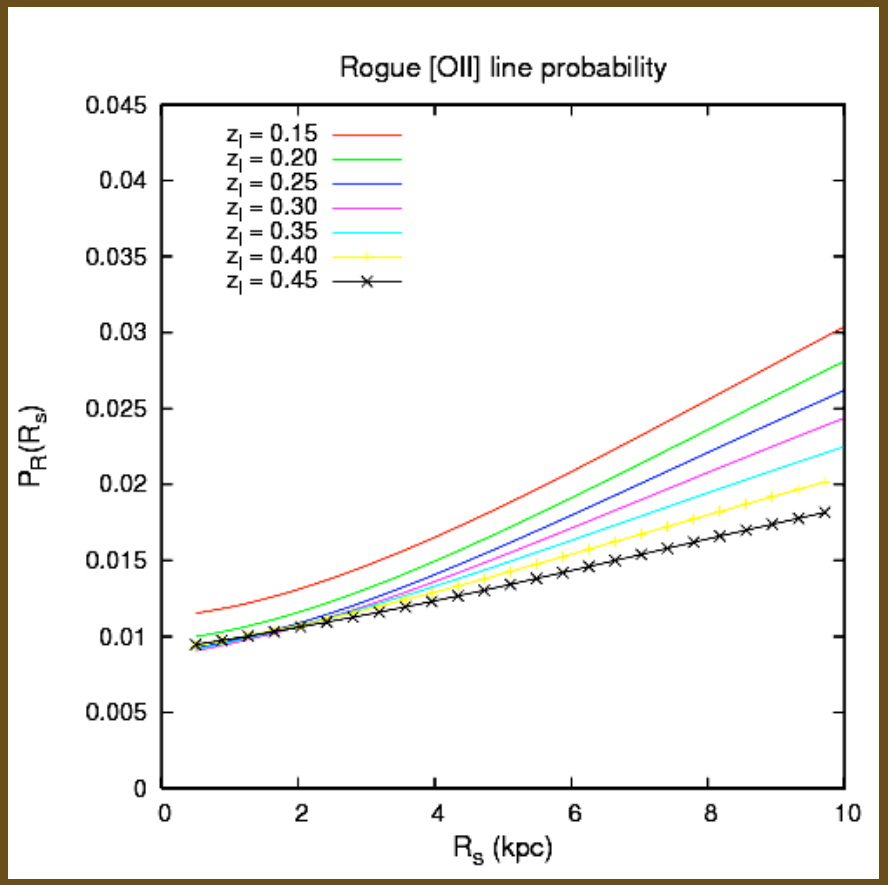
# Dependence on Parameters

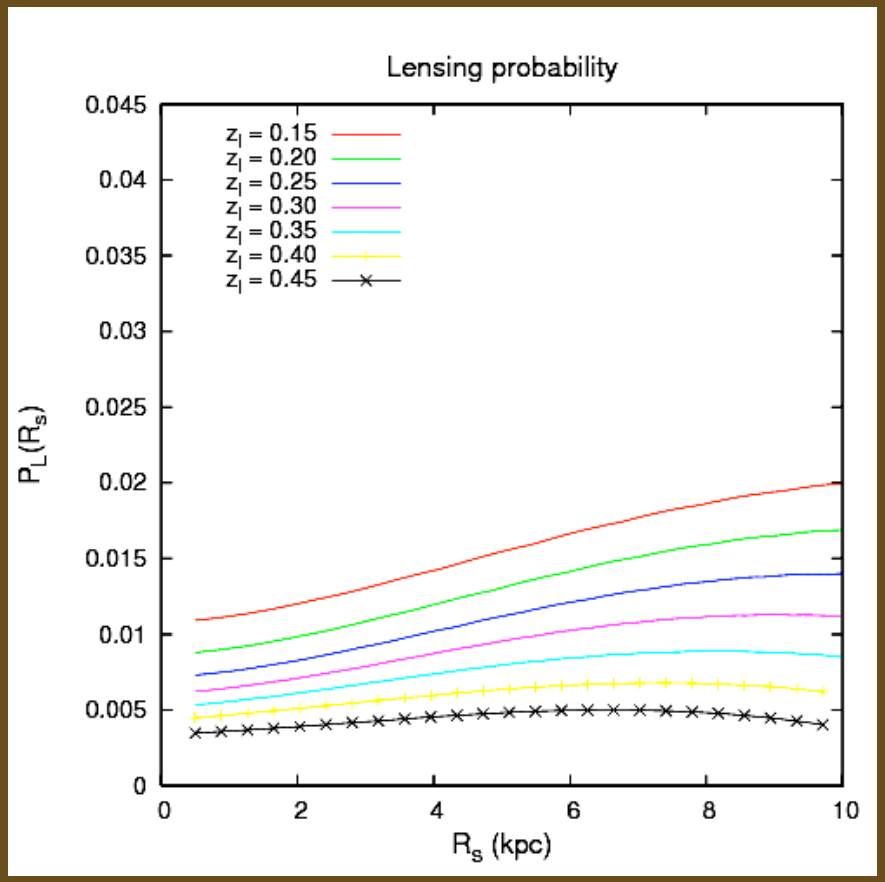
- Dependence on $z_l$
  - $P_R$ and $P_L$ **decrease** with $z_l$

$$P_L(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu \geq \mu_{\text{cut}})$$

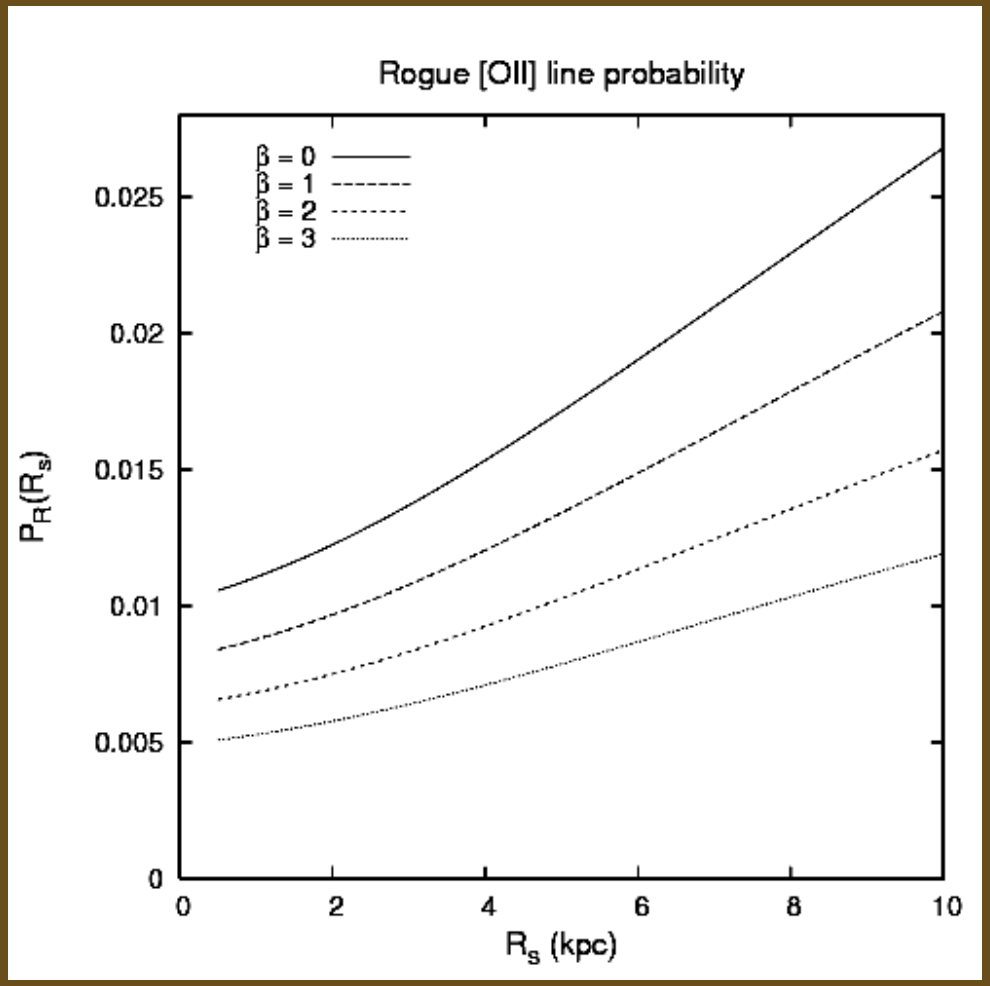
$$P_N(\vec{G}_P, z_l) = P_G(\vec{G}_P, z_l \mid \mu < \mu_{\text{cut}})$$

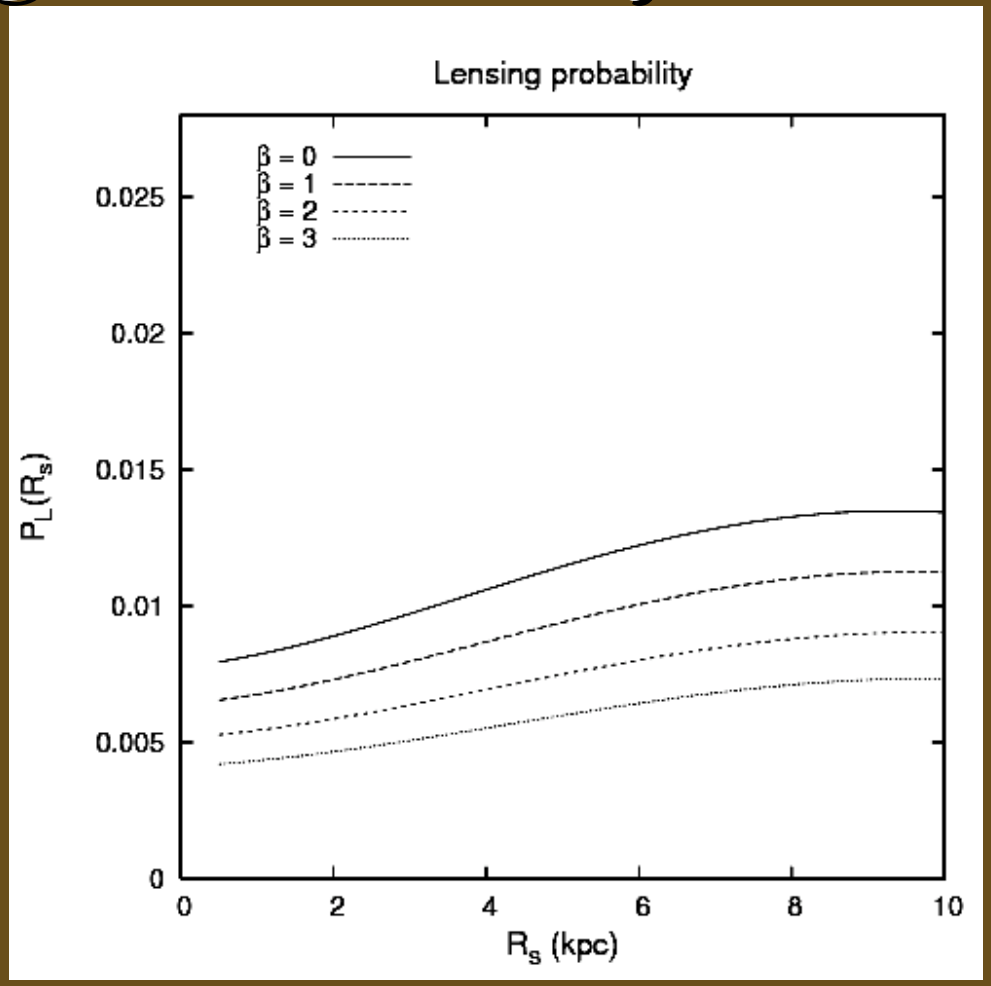
$$P_R = P_L + P_N$$



# Total Lensing Probability



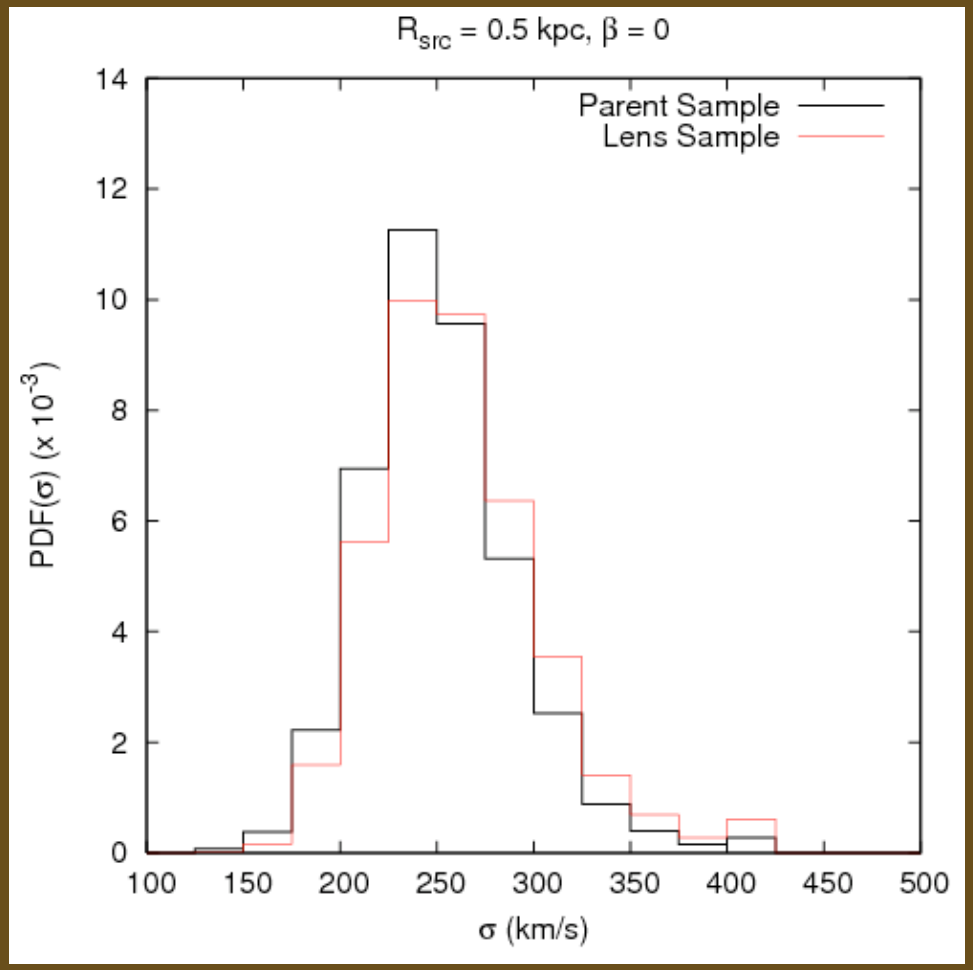



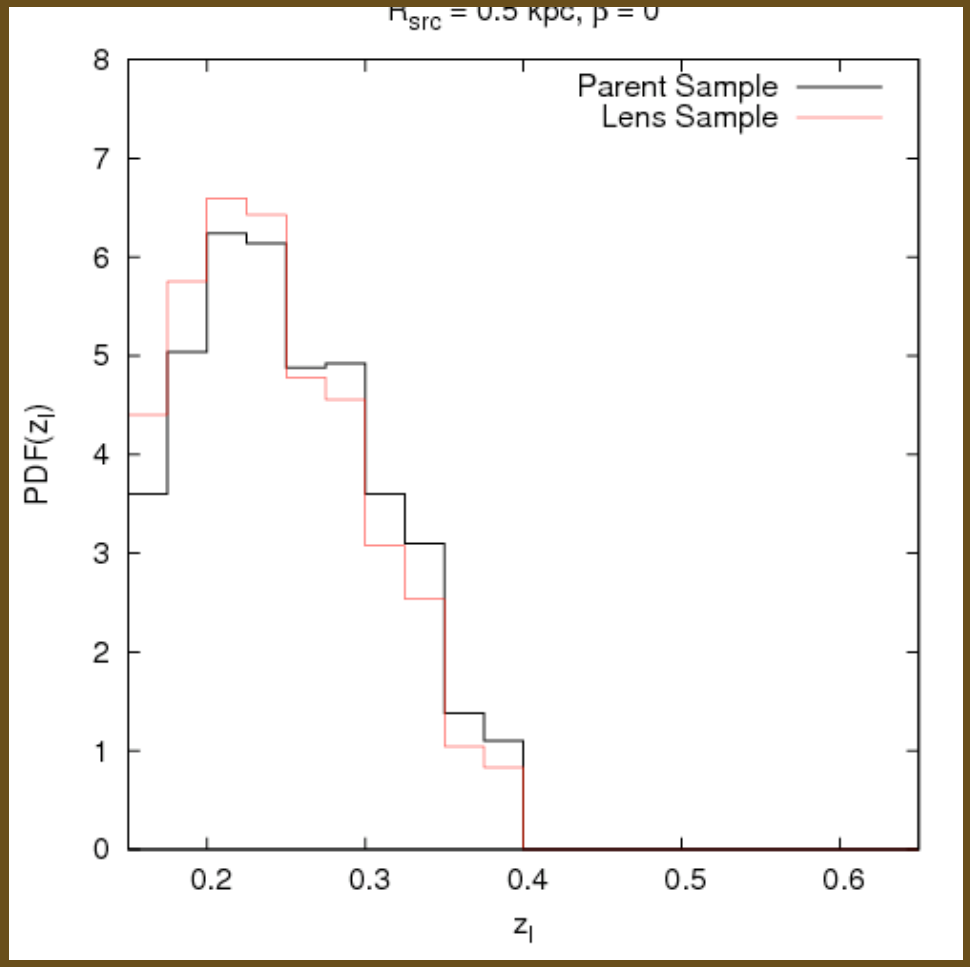

$$P_R = 0.5\text{-}2.7\%, \quad P_L \sim 0.4\text{-}1.3\%$$

⇒ Out of *51,000* LRG spectra, *~250-1,380* should contain rogue [OII] lines

Of those, *~210-690* should show evidence of strong lensing with follow up

# Biases in the Lens Population




The lens population is slightly biased towards:

- *Higher* velocity dispersion
- *Lower* redshift

# g-g Lens Statistics Results

- Significant selection effects
  - Size of the spectroscopic fiber
  - Velocity dispersion
  - LRG redshift

- Detection Probabilities
  - total rogue emission probability ~ *0.5-2.7%*
  - total lensing probability ~ *0.4-1.3%*
  - out of *51,000* LRG's:
    - ~ *250-1,380* should have rogue [OII] emission lines
    - ~ *210-690* should show strong lensing with follow up observations

- Systematic Effects
  - Lens classification ($\mu_{cut}$ , morphology, qualitative vs quantitative)
  - Source size and LF evolution

- SLACS has found far fewer (~ *60*, likely due to further selection effects)

# g-g Lens Statistics Results

- Significant selection effects
  - Size of the spectroscopic fiber
  - Velocity dispersion
  - LRG redshift

- Detection Probabilities
  - total rogue emission probability ~ *0.5-2.7%*
  - total lensing probability ~ *0.4-1.3%*
  - out of *51,000* LRG's:
    - ~ *250-1,380* should have rogue [OII] emission lines
    - ~ *210-690* should show strong lensing with follow up observations

- Systematic Effects
  - Lens classification ($\mu_{cut}$ , morphology, qualitative vs quantitative)
  - Source size and LF evolution

- SLACS has found far fewer (~ *60*, likely due to further selection effects)

MANY LENSES ARE WAITING TO BE FOUND IN THE SPECTRA!

# Source Luminosity Function

$$\Phi(L)dL = (1+z)^{\beta} n_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*} \frac{dL}{L_*}$$

Must convert Hogg et al. (1998) [OII] LF ($0.3 \leq z \leq 1.5$) from OCDM to ΛCDM:

1. Fix evolution parameter, $0 \leq \beta \leq 3$
2. Postulate ($n_*$, $\alpha$, $L_*$)
3. Draw a "mock" source population in a ΛCDM cosmology
4. "Observe" this sample and bin with an OCDM cosmology
5. Repeat this process many times to match LF from Hogg et al (1998)

# Source Luminosity Function

$$\Phi(L)dL = (1+z)^{\beta} n_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*} \frac{dL}{L_*}$$

Must convert Hogg et al. (1998) [OII] LF ($0.3 \leq z \leq 1.5$) from OCDM to ΛCDM:

1. Fix evolution parameter, $0 \leq \beta \leq 3$
2. Postulate ($n_*$, $\alpha$, $L_*$)
3. Draw a "mock" source population in a ΛCDM cosmology
4. "Observe" this sample and bin with an OCDM cosmology
5. Repeat this process many times to match LF from Hogg et al (1998)

TABLE 1. SOURCE O II LF PARAMETERS

| $n_*$ ($10^{-3}$ Mpc$^{-3}$) | $\log L_*$ (erg/s) | $\alpha$ | $\beta$ |
|---|---|---|---|
| 4.09 | 42.34 | -1.15 | 0 |
| 2.16 | 42.31 | -1.13 | 1 |
| 0.90 | 42.37 | -1.17 | 2 |
| 0.62 | 42.18 | -1.09 | 3 |