High-z Universe probed via Lensing by QSOs (HULQ): Expected Number of QSO–QSO Lenses

Yoon Chan Taak[1,2] and Myungshin Im[1,2]
[1]*Center for the Exploration of the Origin of the Universe*
[2]*Astronomy Program, Department of Physics and Astronomy, Seoul National University*

The M_{BH}–σ_* relation for galaxies is a stand-out illustration of the co-evolution of galaxies and their central supermassive black holes (SMBHs); however, how this co-evolution occurs and whether this relation holds for SMBHs of the early universe is still a matter of debate. In order to study this at higher redshifts, quasi-stellar objects (QSOs) are the best targets, due to their large sample size and effective M_{BH} estimation. Nevertheless, it is difficult to examine properties of their host galaxies, simply due to the sheer brightness of the QSO itself. Here, we discuss a distinctive method in studying these QSO host galaxies, via gravitational lensing (GL). GL offers a unique approach in determining the mass of the lens object, in this case that of the host galaxy.

We present the expected number of such systems, considering QSOs as sources. The lens population is derived from SDSS QSOs and the M_{BH}–σ_* relation, while the source number density is obtained from the QSO luminosity function evolving with cosmic time. When taking galaxies as sources into account also, the simulations predict a sufficiently large sample of QSO lenses, which, after spectroscopic confirmation, will enable us to examine the M_{BH}–σ_* relation at various redshifts, and in turn, investigate the co-evolution of SMBHs and their host galaxies.

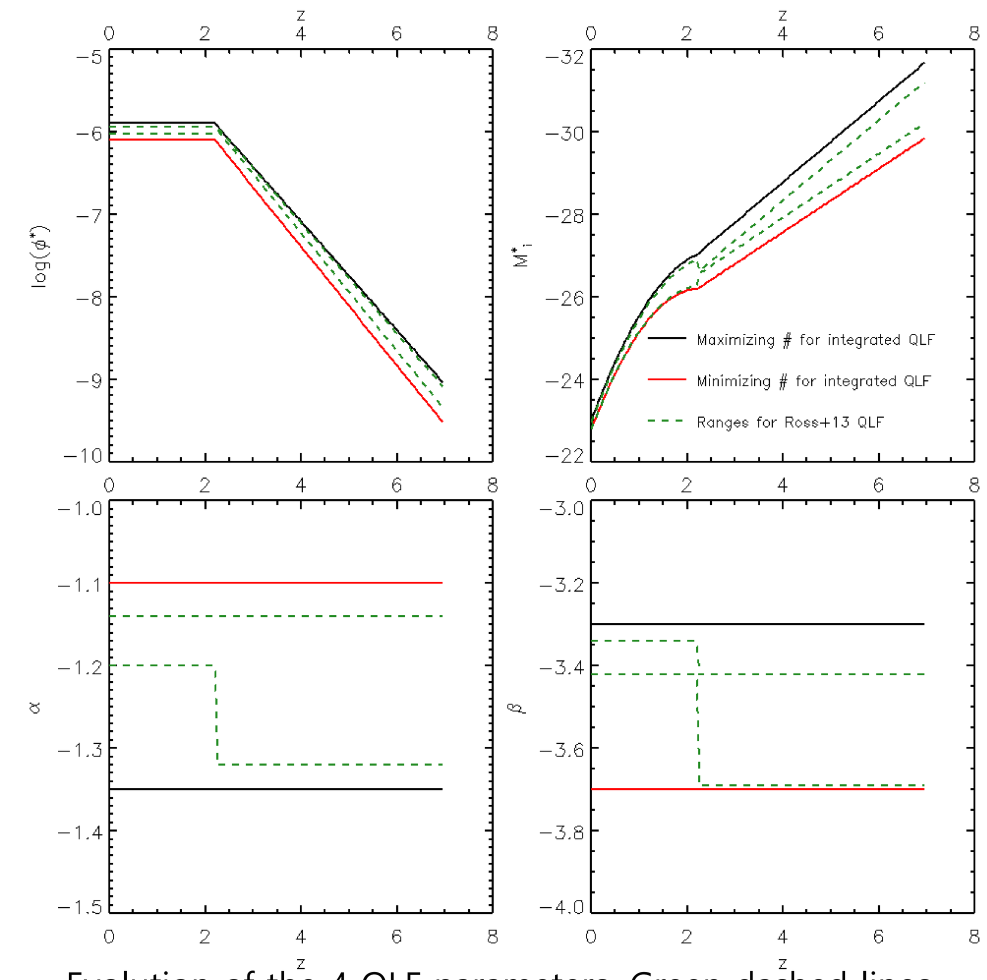
Image credit: Marvel Cinematic Universe Wikia

1. Introduction

- **Co-evolution of SMBHs and Their Host Galaxies**
  - Well-known relations btw SMBH and host galaxy
  - High-z: uncertain, due to inaccurate galaxy properties (QSO-host decomposition issues, etc.)
- **Gravitational Lensing (GL) via QSO Host Galaxies**
  - GL: enables determination of mass of lensing object
  - Many QSOs are discovered at high-z
  - Host galaxy properties unclear, due to QSO brightness
- **HULQ: High-z Universe probed via Lensing by QSOs**
  - Find GL systems with QSO hosts as lenses (QSO lenses)
  - Measure M_{host} via GL analysis
  - Establish M_{BH}–σ_* relation at several redshifts, and check co-evolution of SMBHs and their hosts

2. Number Estimation with Simulations

- **Lens Population**
  - SDSS DR7 Quasar Property Catalog (Shen+11) + M_{BH}–σ_* relation (σ_{max} = 400km/s; Kormendy & Ho 13)
    → Distribution function of σ of QSO host galaxies
- **Source Population**
  - QSO lum. function (QLF) at various redshifts
  - $\Phi(M,z) = \dfrac{\Phi(M^*)}{10^{0.4(\alpha+1)(M-M^*)} + 10^{0.4(\beta+1)(M-M^*)}}$
    - ❖ 0 < z < 2.2: Pure Luminosity Evolution (Φ^* const.)
      $M_i^*(z) = M_i^*(z=0) - 2.5(k_1 z + k_2 z^2)$
    - ❖ 2.2 < z < 7: Luminosity Evol. & Density Evol.
      $\log[\Phi^*(z)] = \log[\Phi^*(z=2.2)] + c_1(z-2.2)$
      $M_i^*(z) = M_i^*(z=2.2) + c_2(z-2.2)$

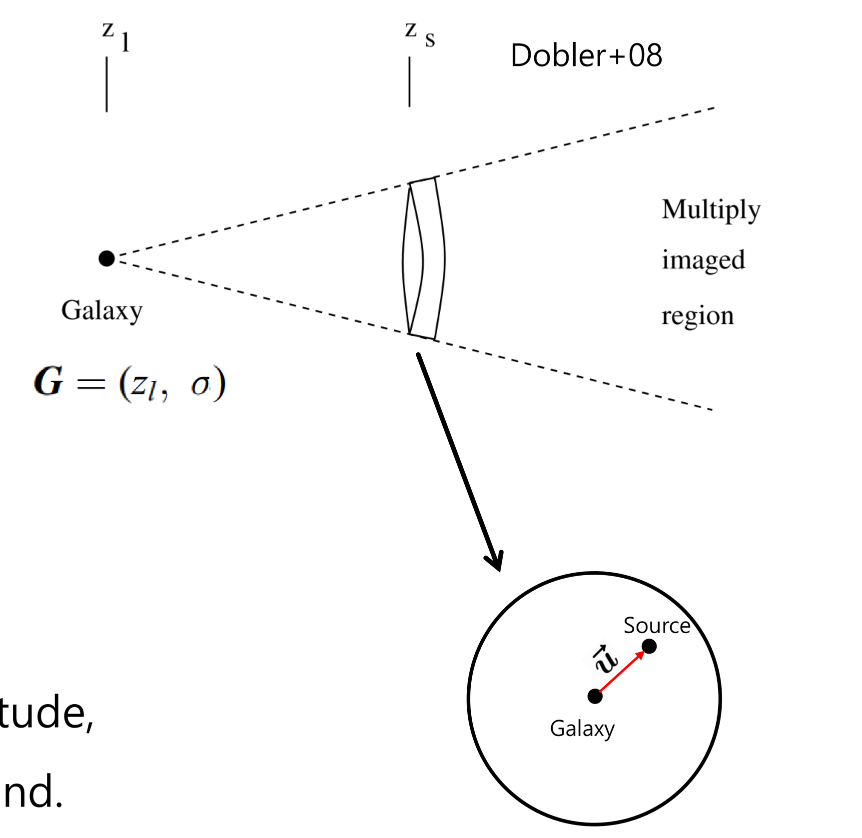


Evolution of the 4 QLF parameters. Green dashed lines indicate the QLF ranges from Ross+13 (SDSS DR9 i'), and the black and red solid lines show the limiting QLFs that maximize and minimize the QLF integrated above m_{lim}.

- **Calculations**
  - V_{Ein}: volume of multiply imaged region for a lens
  - (Prob. of galaxy being a lens)
    $= (\text{Prob. of source being within } V_{Ein})$
    $= (\text{Number of sources within } V_{Ein})$
    $= \int_z (\text{Number density of sources brighter than flux limit}) \times dV_{Ein}(z)$
  - $P(\boldsymbol{G}) = \int_{V_{Ein}} n_s(z_s,\ F_{lim}/\mu_2)\,\mathrm{d}V$
    $= \int_{z_s=z_l}^{\infty} \frac{\mathrm{d}V}{\mathrm{d}z_s\,\mathrm{d}\vec{\boldsymbol{u}}}\mathrm{d}z_s \times n_s(z_s,\ F_{lim}/\mu_2)\,\pi R_{Ein}^2$

    $\frac{\mathrm{d}V}{\mathrm{d}z_s\,\mathrm{d}\vec{\boldsymbol{u}}} = \frac{c}{H_0}\frac{(1+z_s)^2\,D_s^2}{[\Omega_M\,(1+z_s)^3 + \Omega_\Lambda]^{1/2}} = f(z_s)$

    $n_s(z_s,\ F_{lim}/\mu_2) = \int_{L_{lim}/\mu_2}^{\infty} \Phi(L,\ z_s)\,\mathrm{d}L$

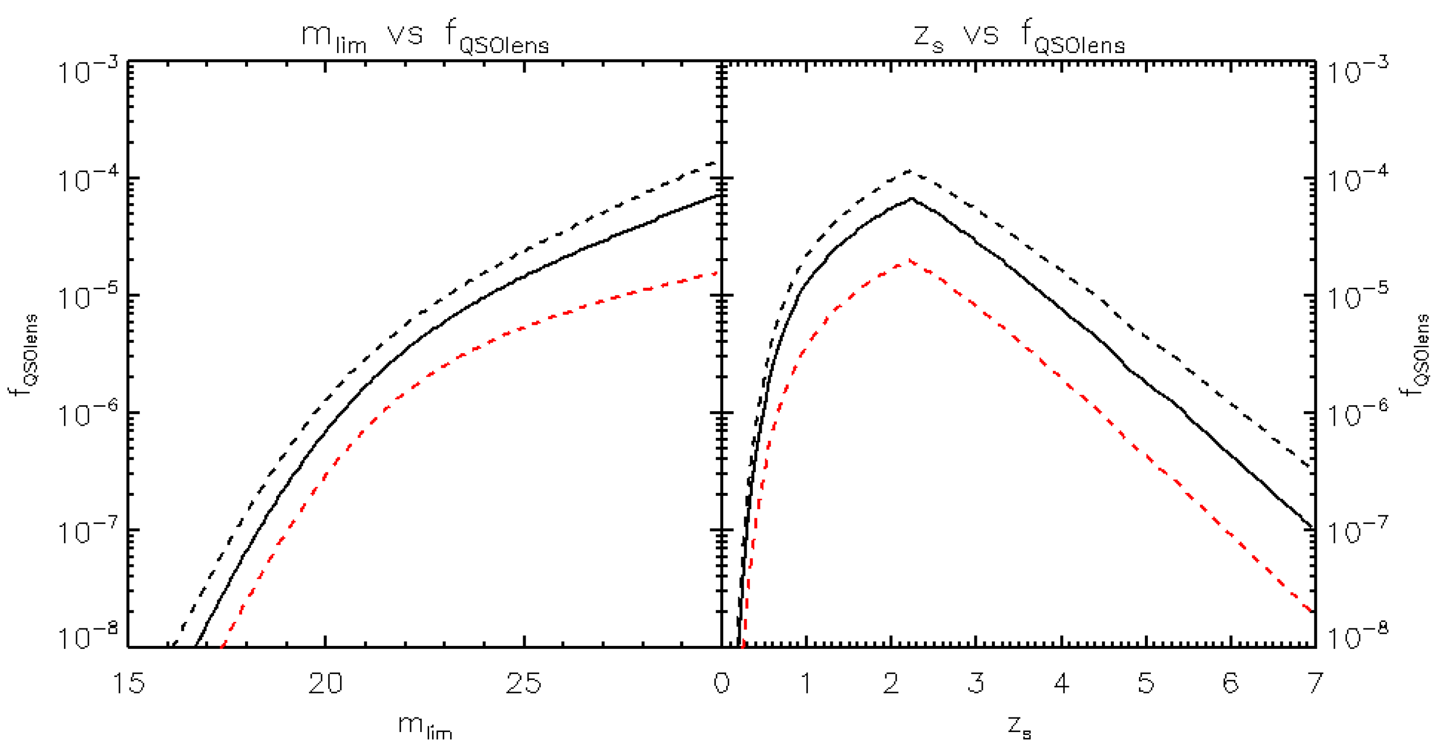


$\vec{\boldsymbol{u}}$: angular vector in source plane

  - So, for a given QLF (as a function of z) and limiting magnitude, the probability of a specific galaxy being a lens can be found.
  - $\sum_{\text{QSO hosts}} P(\boldsymbol{G})$: expected number of QSO host galaxies

3. Results

- **Lensing QSO Fractions**
  - $f_{QSOlens}$: fraction of QSO lenses among all QSOs
  - Deeper images yields higher fraction of QSO–QSO lenses
    - Fainter lensed images can be detected
  - Most source QSOs are at z_s ~ 2
    - Integrated QLF is maximized at this redshift



- **Expected # of QSO Lenses for Various Surveys**
  - Obtain $f_{QSOlens}$ for a survey limit from above graph
  - Estimate # of known QSOs, by correcting the SDSS sample with survey area
  - Multiply these two to get expected # for each survey
  - PS1/3π is most promising

Survey Name	$m_{lim,i}$	Expected # of known QSOs	Expected # of QSO lenses
SDSS DR14	21.3	5.4 x 10^5	1.2
PS1/3π	23.1	> 5.4 x 10^5	> 3.5
HSC/Wide	25.9	5.4 x 10^4	1.1
HSC/Wide DR1	26.4	3.9 x 10^3	0.090
HSC/Deep	26.8	1.0 x 10^3	0.028
LSST (planned)	26.8	> 5.4 x 10^5	15

4. Future Work

- **Observation Effects**
  - Current results only consider limiting magnitudes
  - Seeing, L_{QSO}/L_{image}, etc. must be accounted for
- **QSO–Galaxy Lenses**
  - Similar process, with galaxies as sources
  - Consider effects of ellipticity, size, B/T, etc. of source galaxies
  - GLF >> QLF, so expected # will increase significantly
- **Search for QSO Lenses**
  - PS1/3π, along with HSC/Wide data, will be inspected
  - Check high resolution archival images (e.g. *HST*) of QSOs