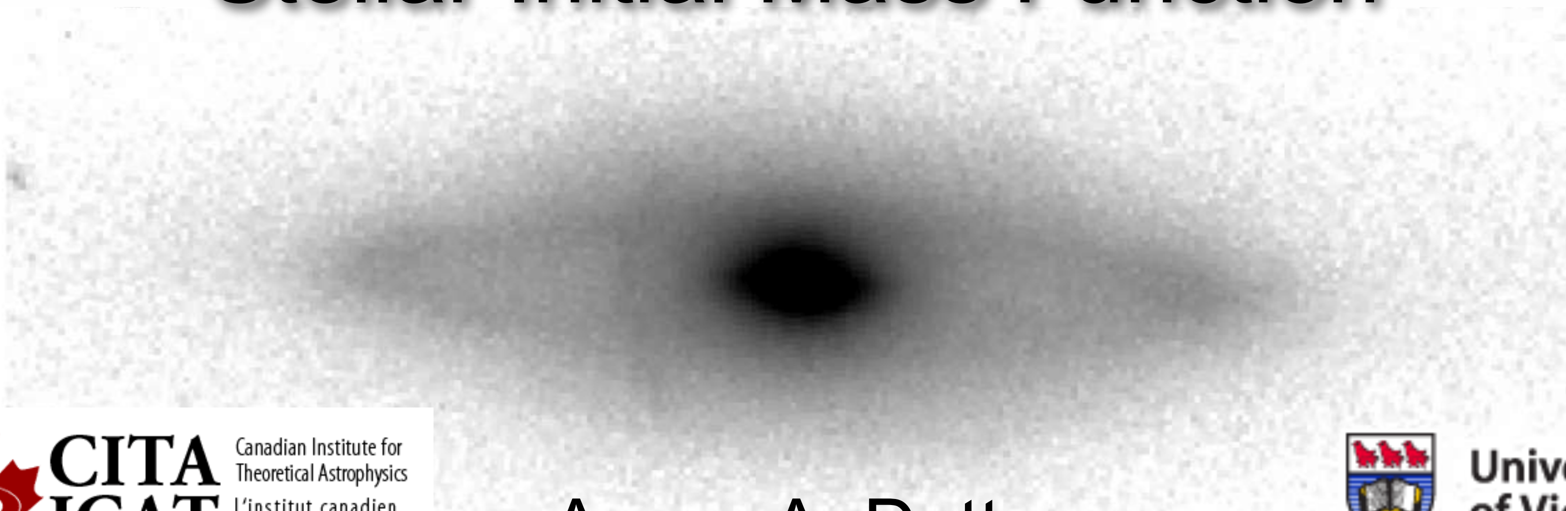
Dark Halo Contraction and the Stellar Initial Mass Function



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A.A.Dutton, C.Conroy, F.C.van den Bosch, L.Simard, J.T.Mendel, S.Courteau, A.Dekel, S.More, F.Prada, 2011, MNRAS in press, ***arXiv: 1012.5859***

A.A.Dutton, B.J.Brewer, P.J.Marshall, M.W.Auger, T.Treu, ***D.C.Koo****, A.S. Bolton, B.P.Holden, L.V.E.Koopmans, 2011, MNRAS in press,* ***arXiv: 1101.1622***

Image Credit: SWELLS

Motivation

- ***Dark Halo Contraction***
  - N-body simulations robustly predict the structure of LCDM haloes (e.g. Navarro et al. 1996, 2010; Macciò et al. 2008; Klypin et al. 2010)
  - But: **Observable DM = LCDM ⊗ galaxy formation** (**contraction:** Blumenthal et al. 1986; Gnedin et al. 2004; **expansion:** e.g. El-Zant et al. 2001; Read & Gilmore 2005)

- ***The Stellar Initial Mass Function (IMF)***
  - Fundamental characteristic of a simple stellar population
  - Key to many areas of astrophysics: stellar masses, star formation rates, chemical evolution, ionizing photons …

- **Fundamental Questions**
  - Is dark halo contraction universal?
  - Is the IMF universal?

The hope is 'yes', but nature may not be so kind

Dark Halo Contraction and the Stellar Initial Mass Function

Constraints from Scaling Relations

Dutton, Conroy, van den Bosch, Simard, Mendel, Courteau, Dekel, More, Prada, 2011, MNRAS in press, arXiv: 1012.5859

Constraints from Strong Lensing

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Constraints from Scaling Relations

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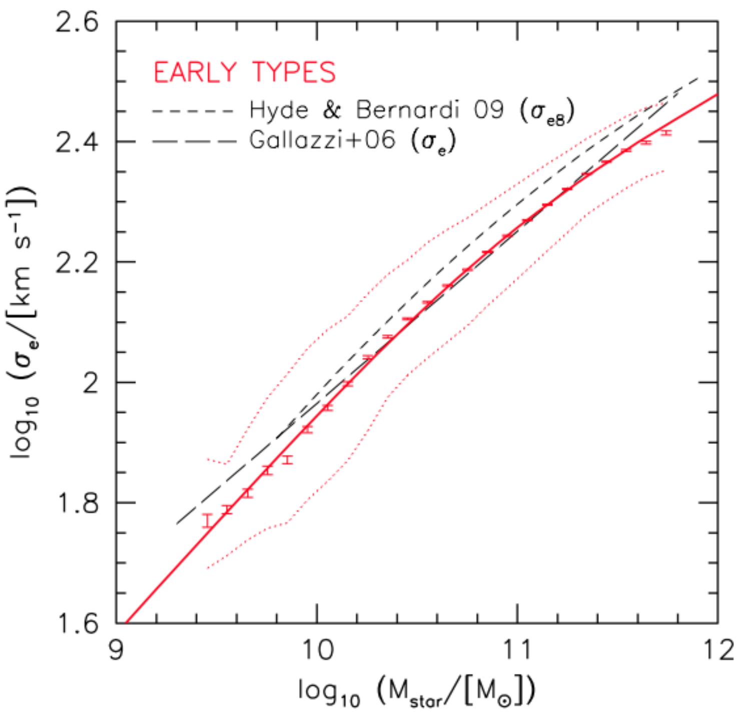
Faber-Jackson (1976)

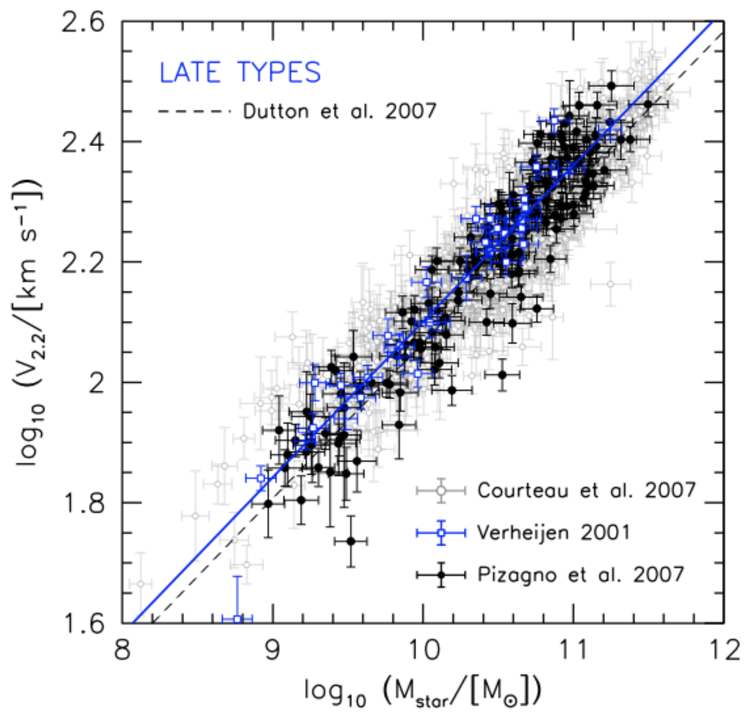
Velocity Dispersion



Stellar Mass

Tully-Fisher (1977)

Rotation Velocity



Stellar Mass

Mass Models

$V^2_{total}(R) = V^2_{stars}(R)$ Known (from Obs. +SPS) up to IMF

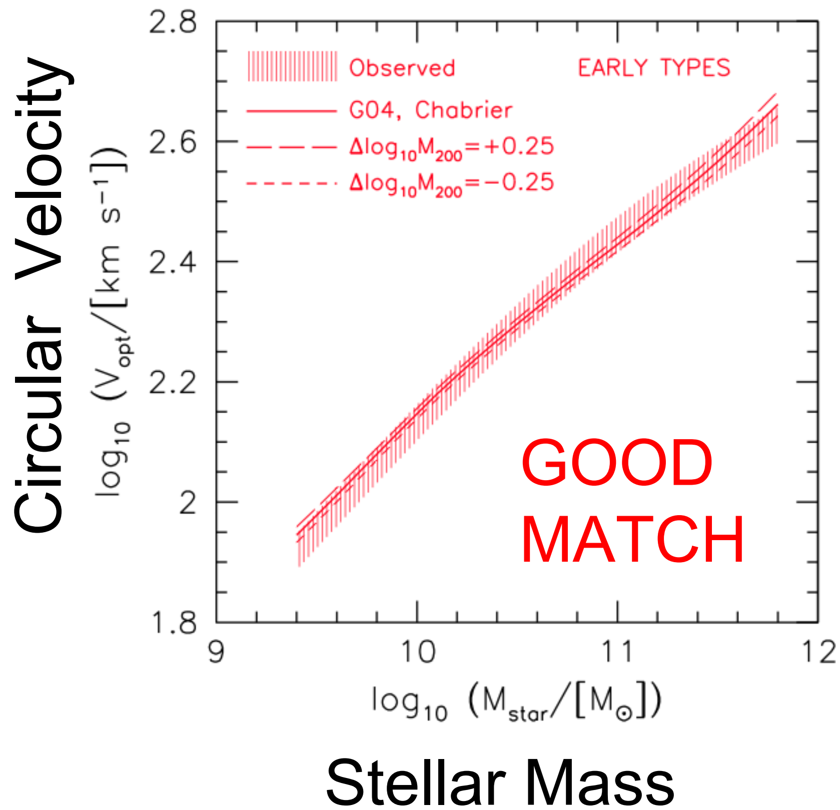
$+ V^2_{gas}(R)$ Known (from Obs.)

$+ V^2_{dark}(R)$ Known (in LCDM) up to halo response

For a given (SPS) stellar mass we observe an average V_{total} from TF / FJ relations and we can construct an average model V_{total} up to IMF and halo response.

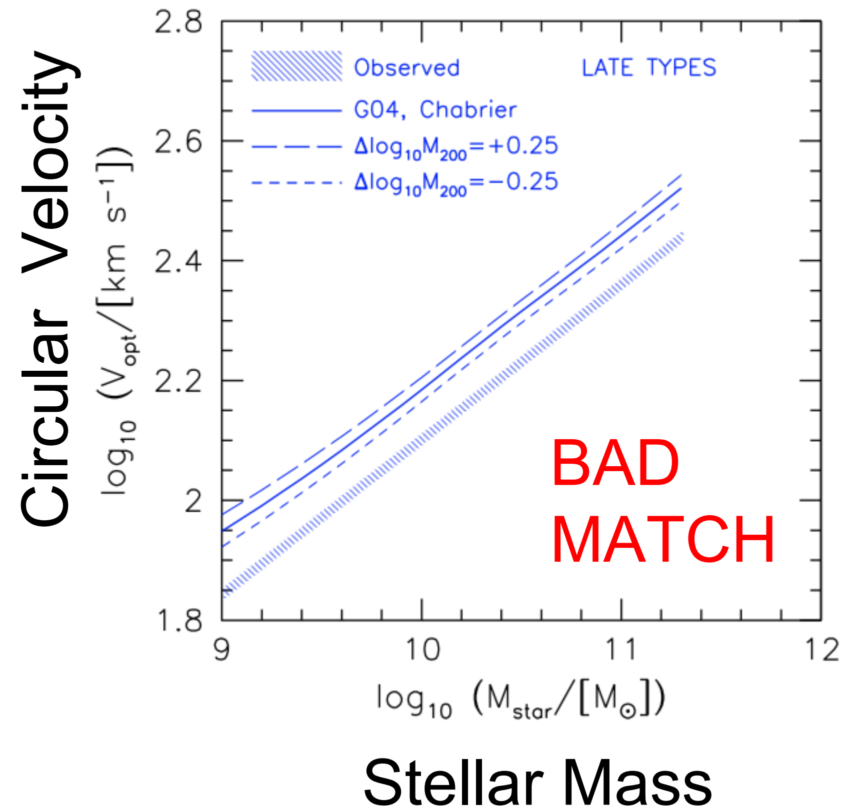
Model Scaling Relations: Chabrier IMF
Gnedin et al. (2004) halo contraction

Faber-Jackson (1976)



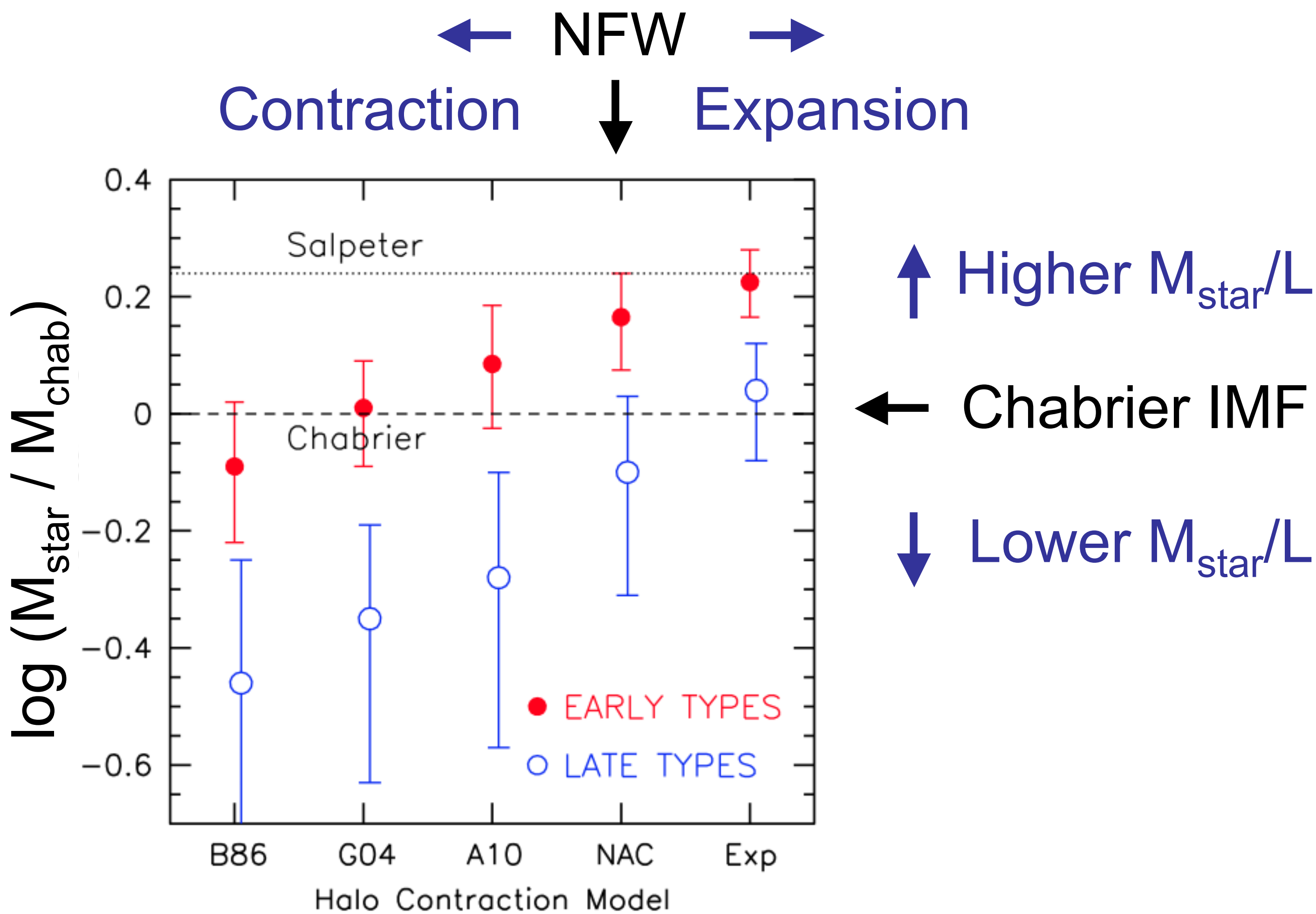
Agrees with Schulz et al. 2010

Tully-Fisher (1977)



Agrees with Dutton et al. (2007)

Degeneracy between IMF and halo contraction



Error bars are 2 sigma

Constraints from Strong Lensing

Dutton, Brewer, Marshall, Auger, Treu, Koo, Bolton, Holden, Koopmans, 2011, MNRAS in press, arXiv: 1101.1622

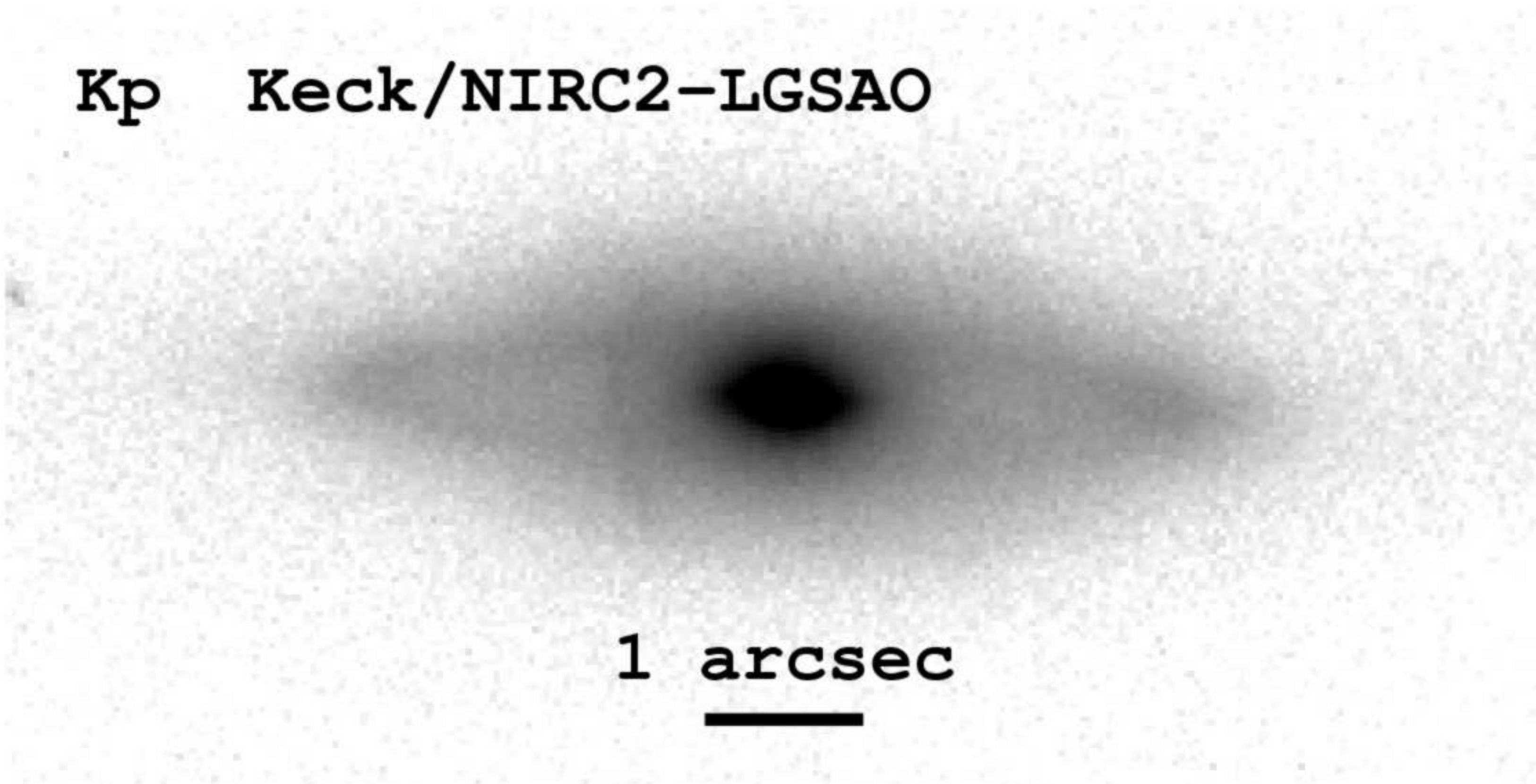
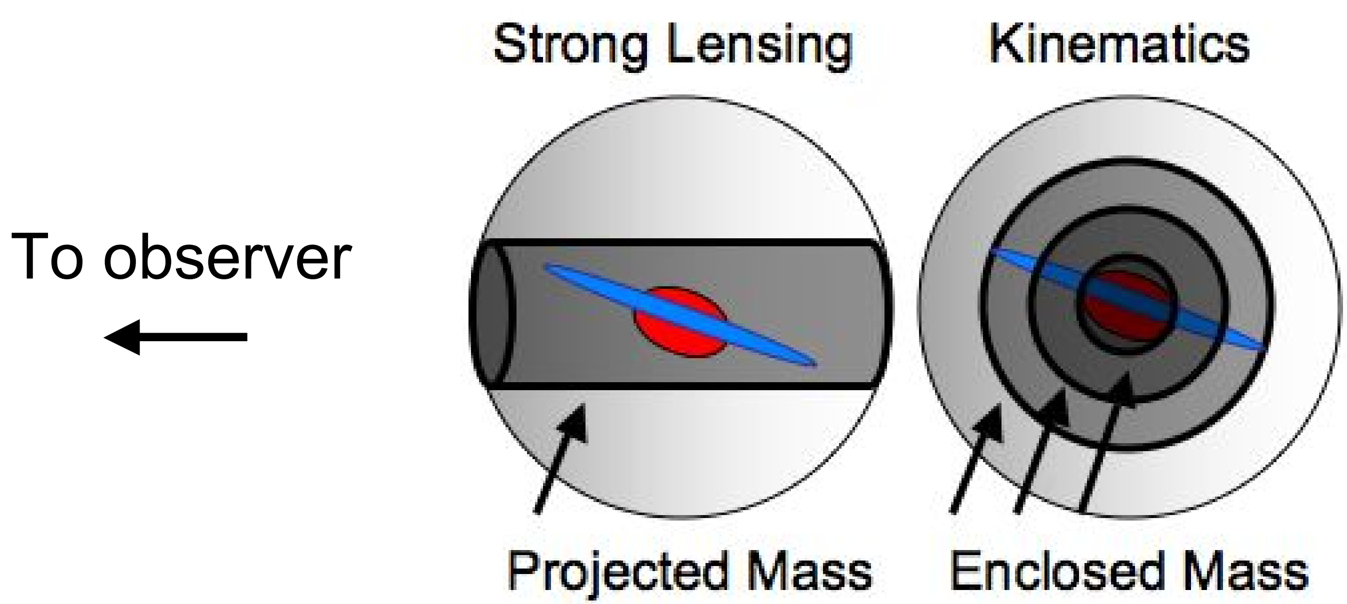


Image Credit: SWELLS

How can Strong Lensing Help?

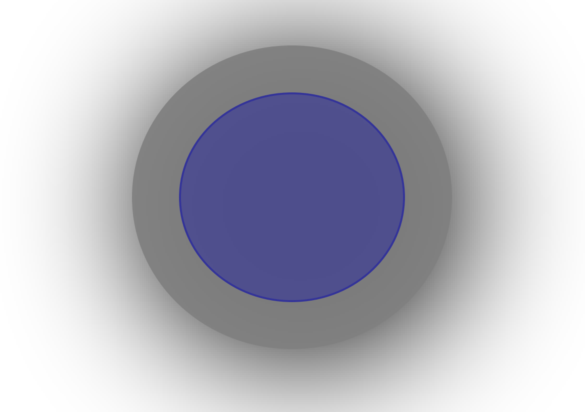
Kinematics measures mass enclosed in spheres

Strong Lensing measures projected mass and ellipticity



Strong Lensing Ellipticity vs Stellar Ellipticity

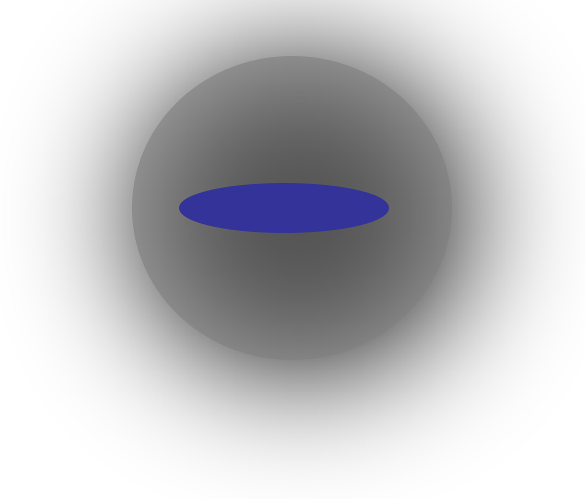
1) Face-on Disk + Spherical Halo



a) q_{lens}=1 (⇒ spherical halo)

b) q_{lens}=0.6 (⇒ flattened halo)

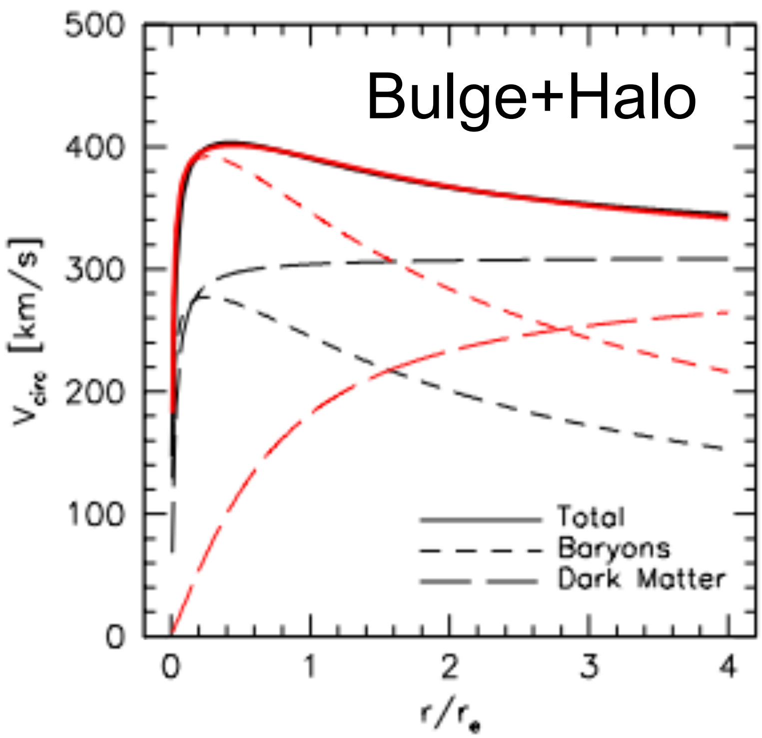
2) Edge-on Disk + Spherical Halo

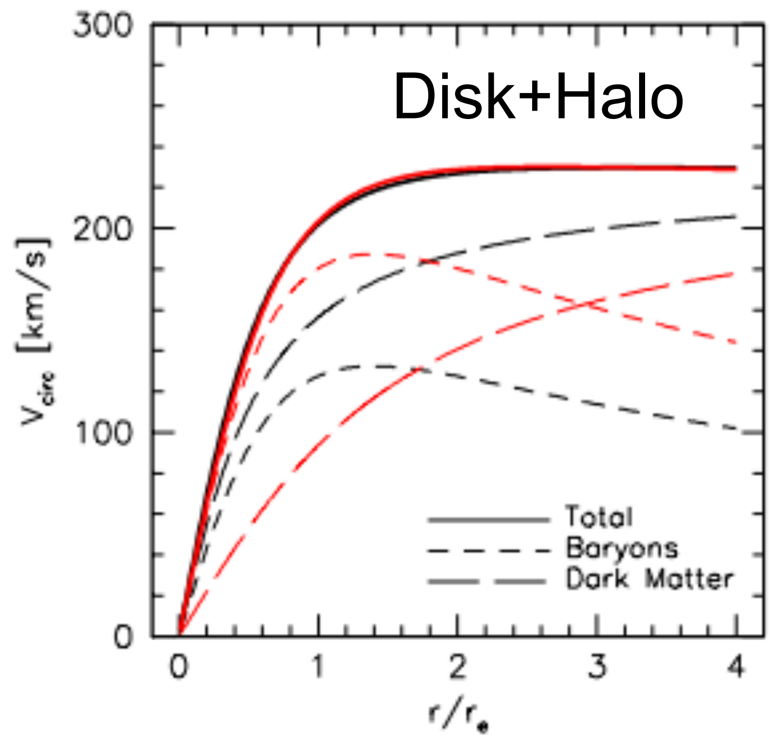


a) q_{lens}=1 (⇒dark matter dominated)

b) q_{lens}=0.2 (⇒disk dominated)

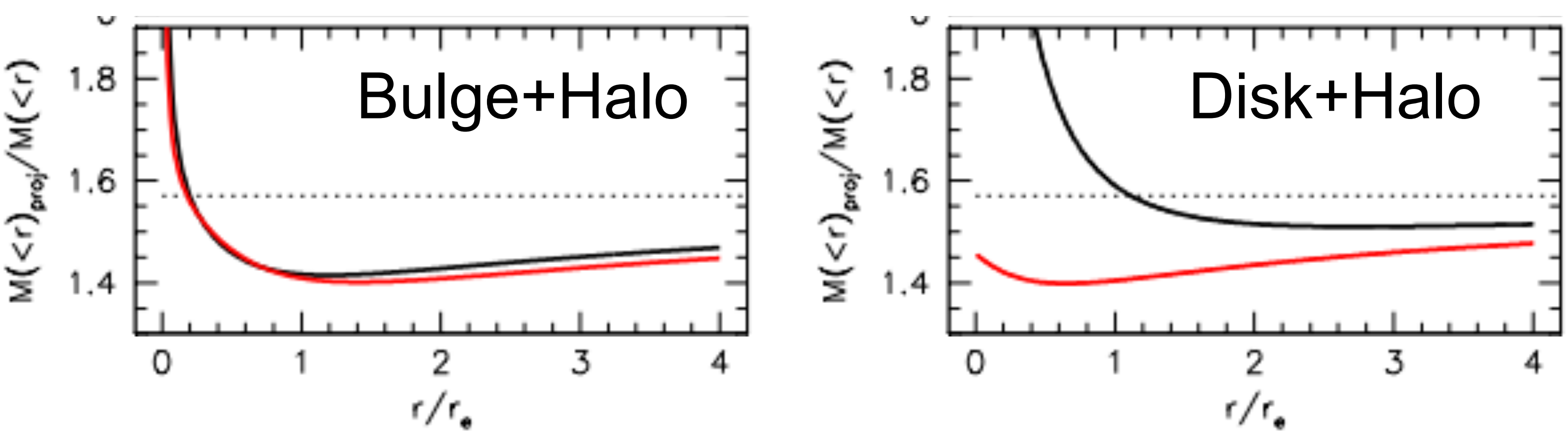
The Bulge-Halo and Disk-Halo Degeneracies





- Baryons (bulge or disk) have same structure, different stellar mass
- Structure of dark matter halo compensates
- Same total 3D mass profile

Projected Mass / Spherical Mass vs Radius



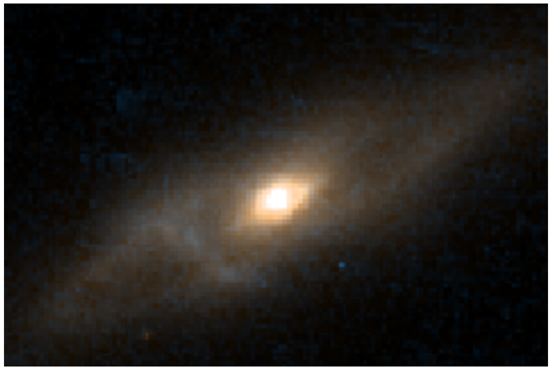
- For a spherical system (e.g. bulge-halo) the ratio between projected and spherical mass is **independent** of the relative contribution of bulge and halo.

- For a disk-halo system, the ratio between projected and spherical mass is **dependent** on the relative contribution of disk and halo.

Summary: How can Strong Lensing Help?

Disk-dominated lenses

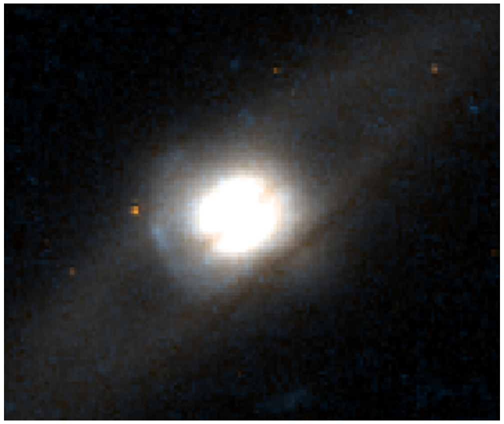
✔ New information from projected mass and ellipticity can help break disk-halo degeneracy



Bulge-dominated lenses

✖ No new information to break bulge-halo degeneracy

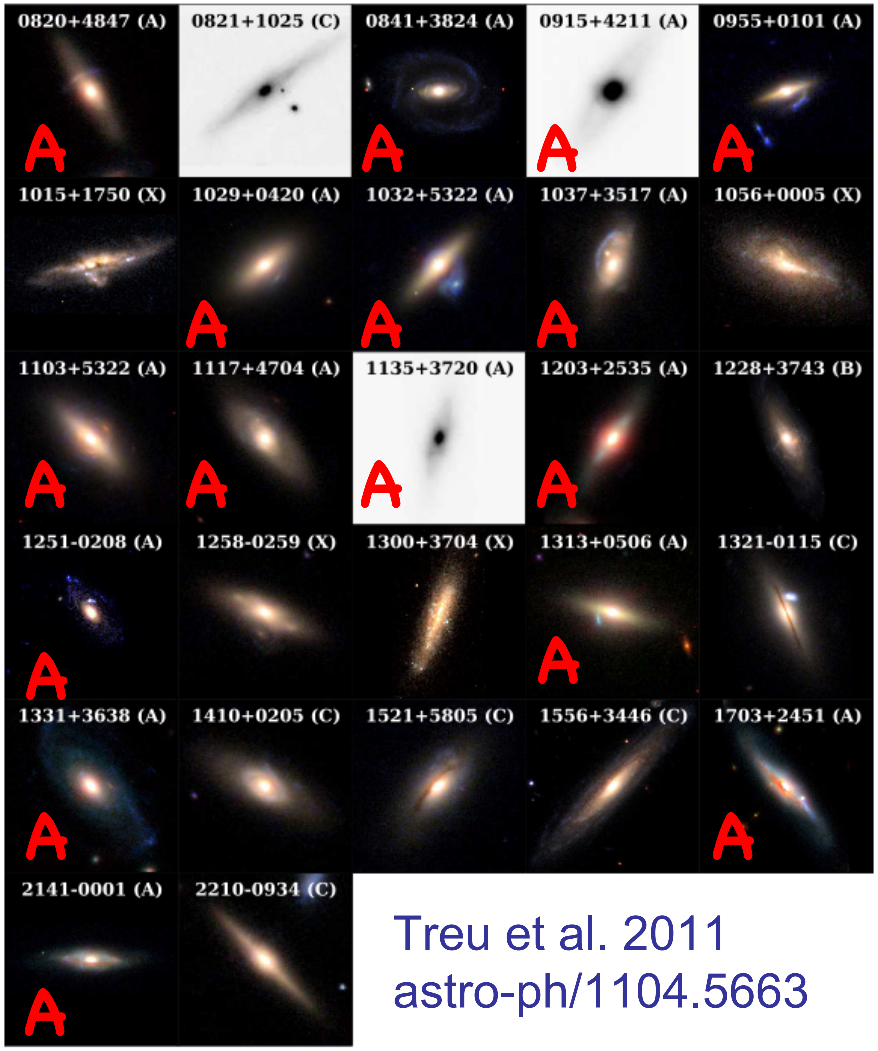
✔ Upper limit on stellar mass within critical curve, independent of dynamical state



Previous studies have used bulge dominated spirals:
B1600 (Maller et al. 2000); Q2237 (Trott & Webster 2002)

Images:
SWELLS-cycle 18

Sloan Wfc Edge-on Late-type Lens Survey



Treu et al. 2011
astro-ph/1104.5663

Redshifts from SDSS

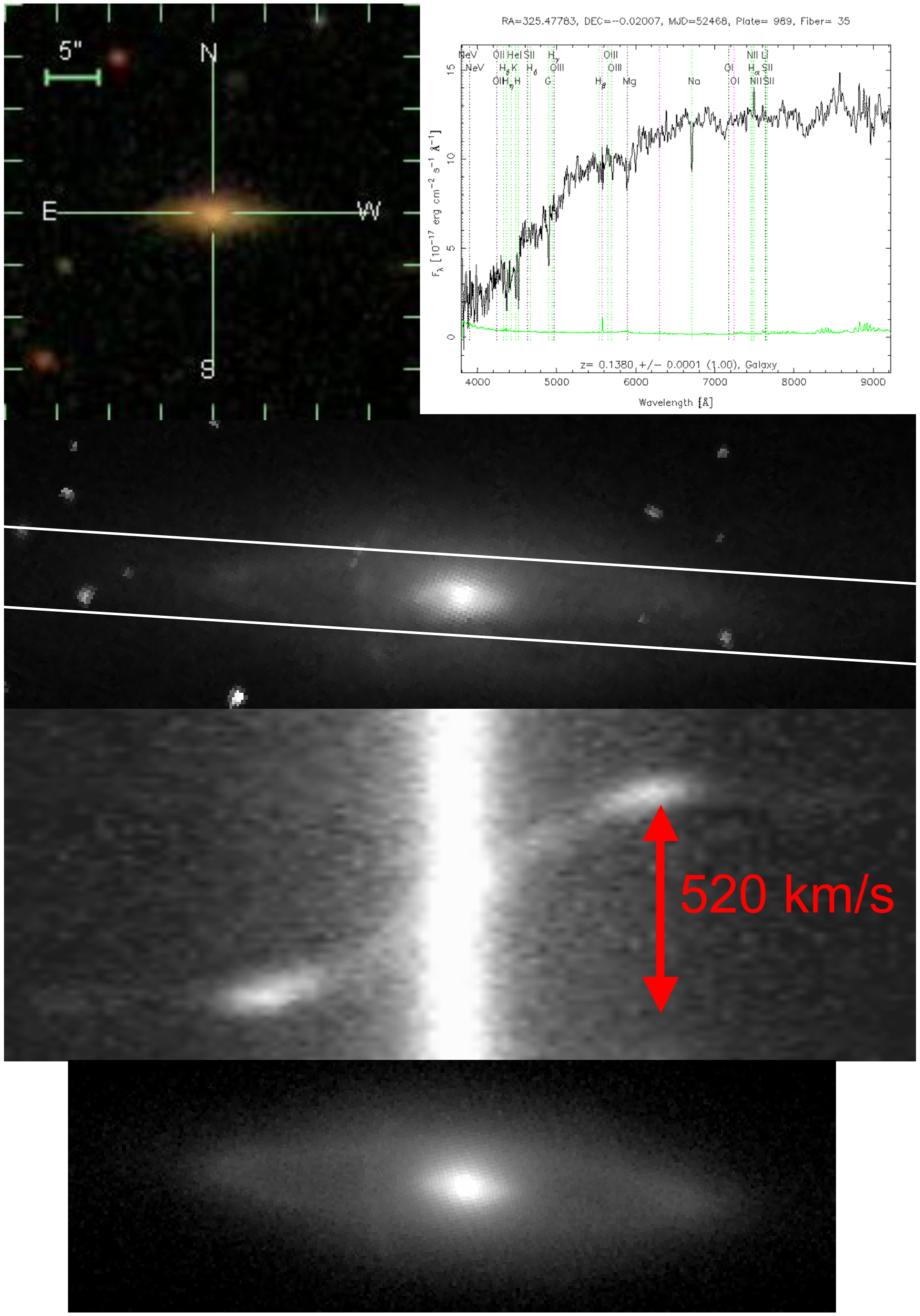
Multi-band optical Imaging from HST (Cycle 16s, 18, PI: Treu)

NIR Imaging from Keck LGS-AO (PIs: Koo, Treu)

Long-slit kinematics from Keck (PIs: Koo, Treu)

Current A-grade lenses:
- 8 from SLACS
- 6 from cycle 16s
- 2 from K-band AO

Success Rate = 42% (8/19)



J2141-0001

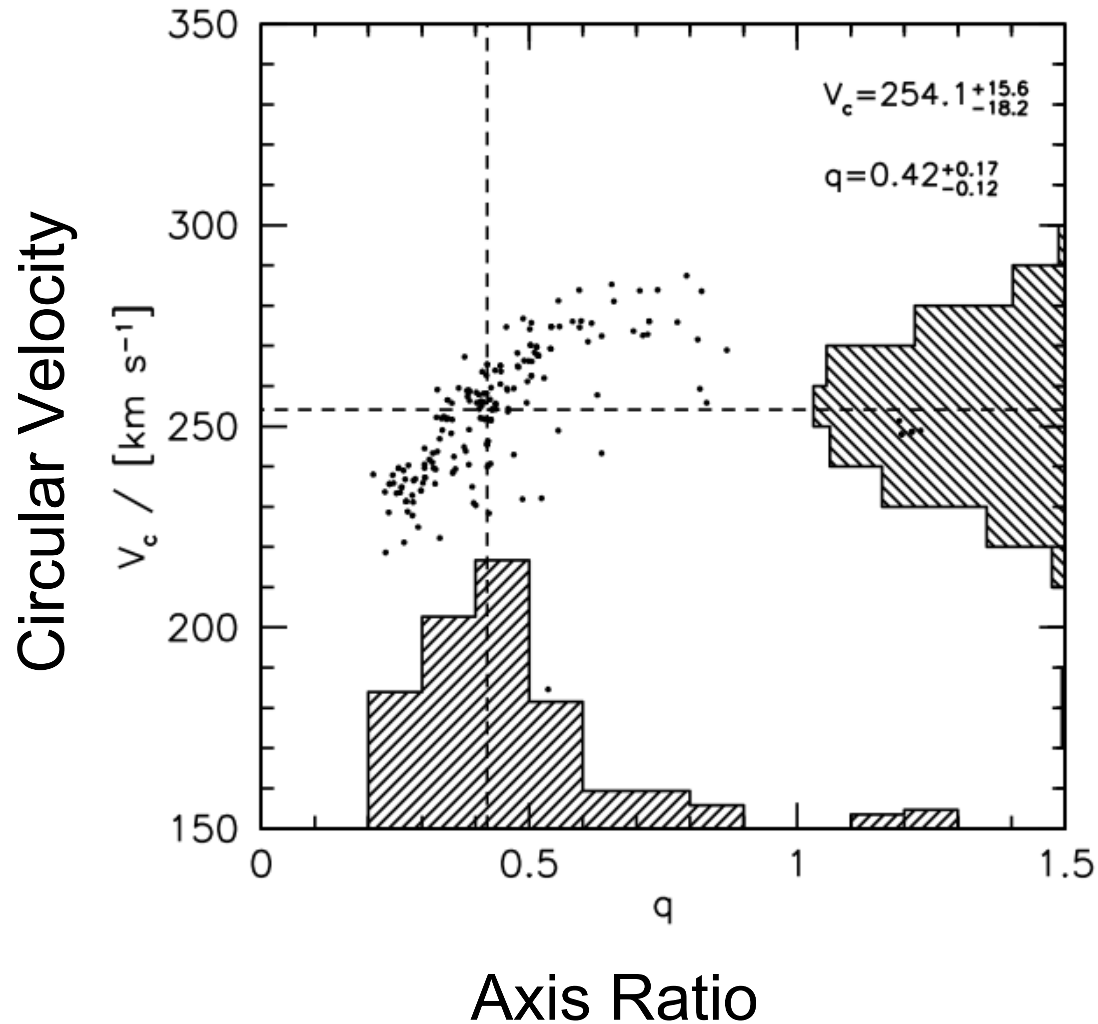
- SDSS spectra: zl=0.1380, zs=0.7127
- SDSS imaging: red, disky looking

- HST discovery image I-band (SLACS)
  - Cusp lens configuration
  - Disk dominated galaxy
  - High disk inclination (78 deg)
  - Dusty

- Keck long slit spectra:
  - strong and extended emission lines
  - star forming ring at 2.5 arcsec
  - V_{max} = 260 km/s

- Keck K-band LGS-AO imaging
  - Disk dominated (bulge fraction ~20%)
  - Bulge is disky (pseudo bulge)
  - Disk scale length 3.7kpc

J2141-0001: SIE Lens model



- Singular Isothermal Ellipsoid (SIE) lens model
- Axis ratio from lensing
  $q_{lens}=0.42$ (+0.17,-0.12)
- Axis ratio of stars
  $q_{disk}=0.31$
  $q_{bulge}=0.53$

$q_{lens} \approx q_{star}$

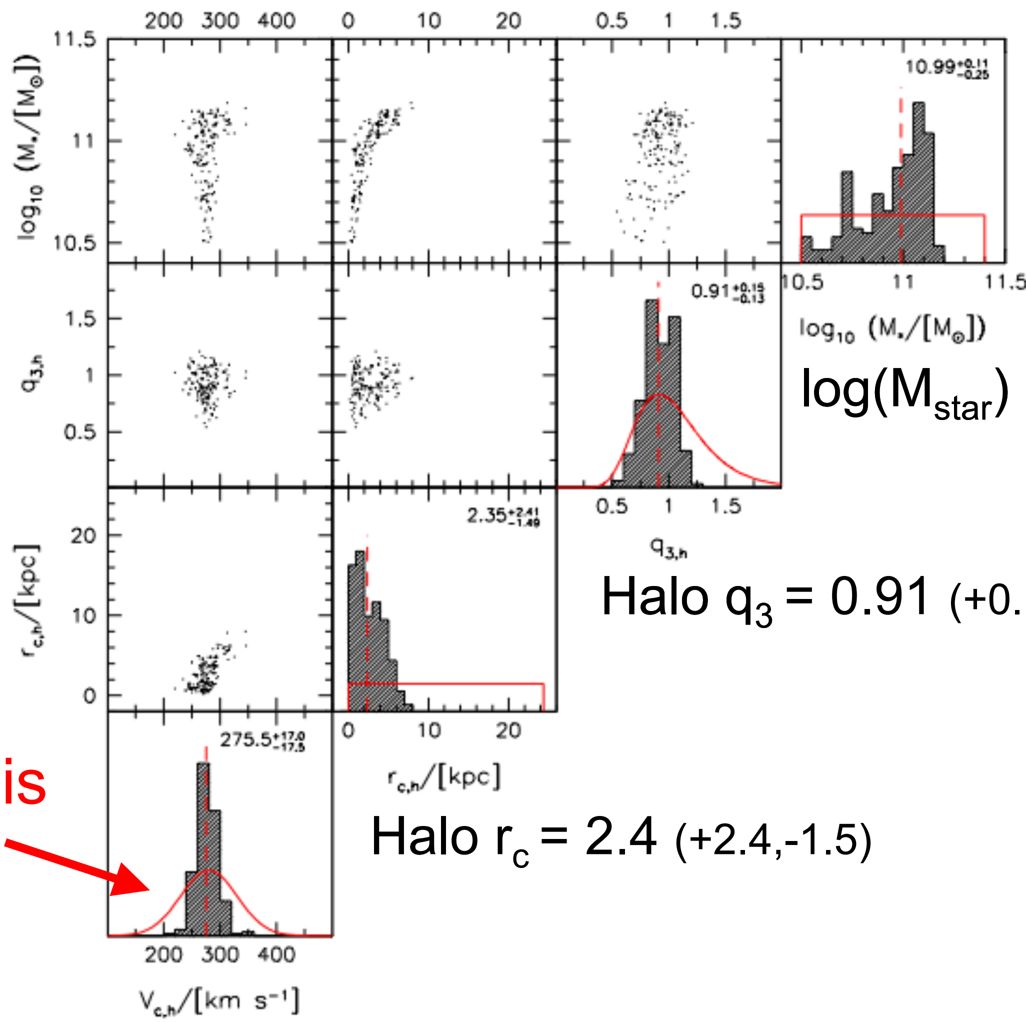
J2141-0001: Bulge, Disk, Halo Model

log(M_{star})

Halo q_3

Halo r_c

red curve is the prior



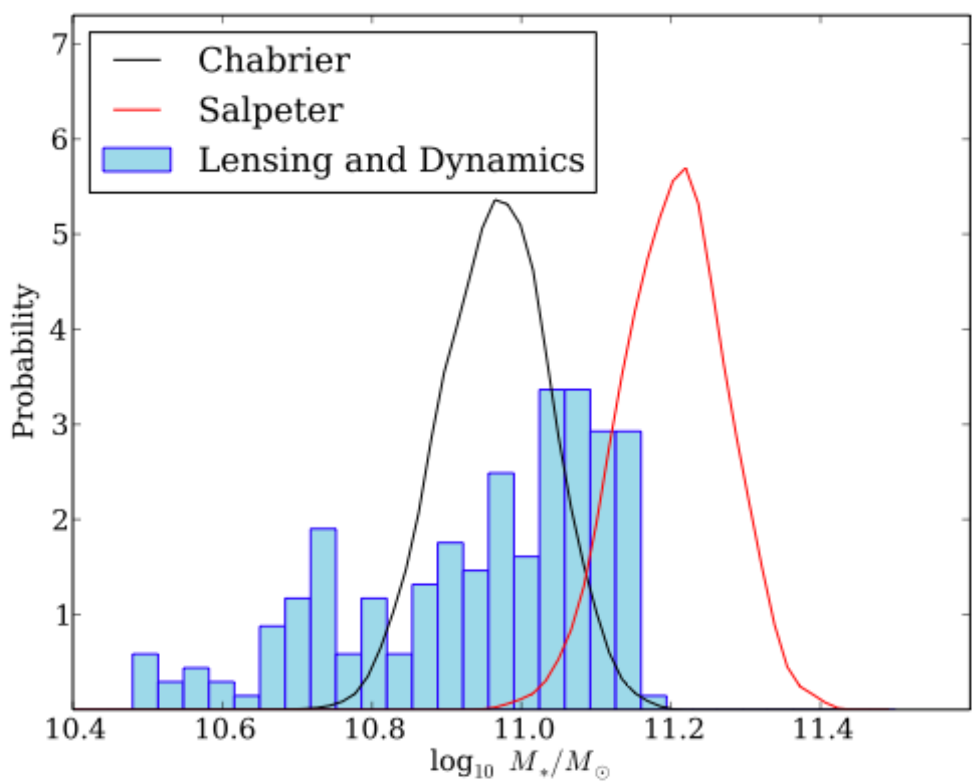
log(M_{star}) = 10.99 (+0.11,-0.25)

Halo q_3 = 0.91 (+0.15,-0.13)

Halo r_c = 2.4 (+2.4,-1.5)

Halo V_c = 275 (+17,-18)

Comparison with SPS Models



Stellar mass from stellar population systhesis models using BVIK magnitudes (Auger et al. 2009)

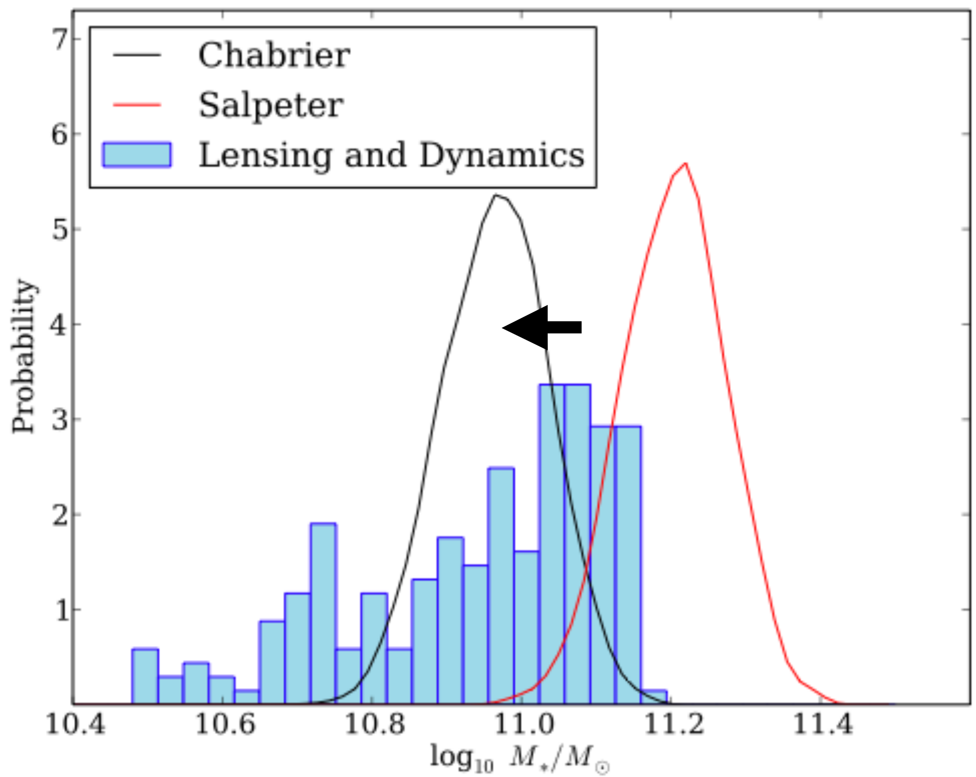
Chabrier (2003) IMF
$\log_{10} (M_{star} / M_{sun})$ = **10.97 ± 0.07**

Salpeter (1955) IMF
$\log_{10} (M_{star} / M_{sun})$ = **11.23 ± 0.07**

Lensing+Kinematics
$\log_{10} (M_{star} / M_{sun})$ = **10.99 +0.11 -0.25**

Marginally favors Chabrier over Salpeter IMF

Comparison with SPS Models



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Lensing+Kinematics
$\log_{10}(M_{star} / M_{sun})$ = **10.99 +0.11 -0.25**

Strongly favors Chabrier over Salpeter IMF

Accounting for cold gas (in a statistical sense) lowers stellar mass by up to 0.10±0.05 dex

Dark Halo Contraction and the Stellar IMF

- ***Constraints from Scaling Relations*** (Dutton et al. 2011b, 1012.5859)

  - Dark Halo Contraction and the Stellar IMF cannot both be universal.

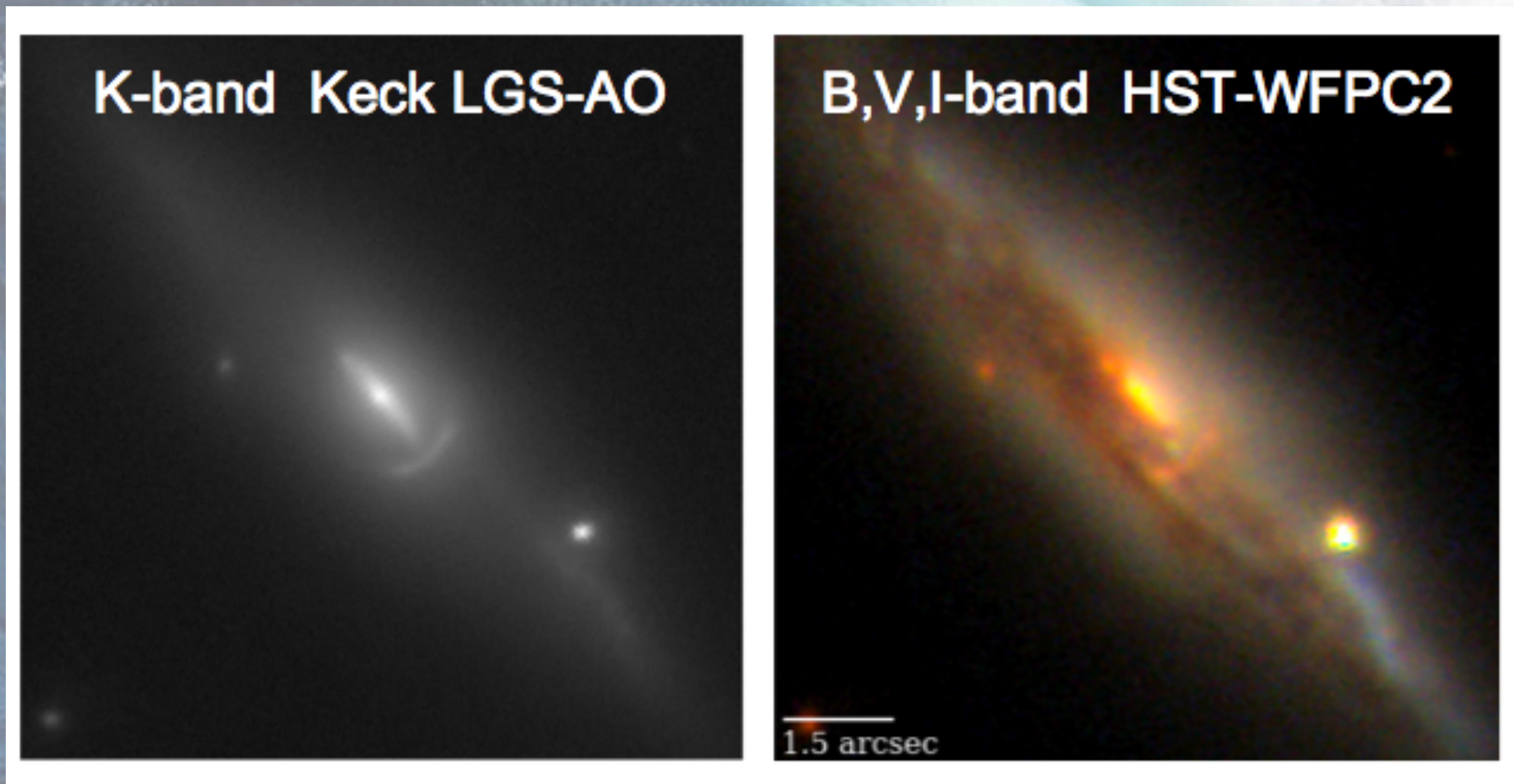
  - **For a Universal Chabrier IMF:**
    Early-types are consistent with standard adiabatic contraction;
    Late-types are inconsistent with standard adiabatic contraction.

  - **For a Universal halo response model:**
    Early-types require heavier IMFs than late-types.

- ***Constraints from Strong Lensing*** (Dutton et al. 2011c, 1101.1622)

  - Strong lensing provides unique information: projected mass and ellipticity
  - Analysis of the spiral galaxy lens SDSS J2141-0001 strongly favors
    a Chabrier IMF over a Salpeter IMF.

K-band imaging sees through the dust



SWELLS J1703+2451