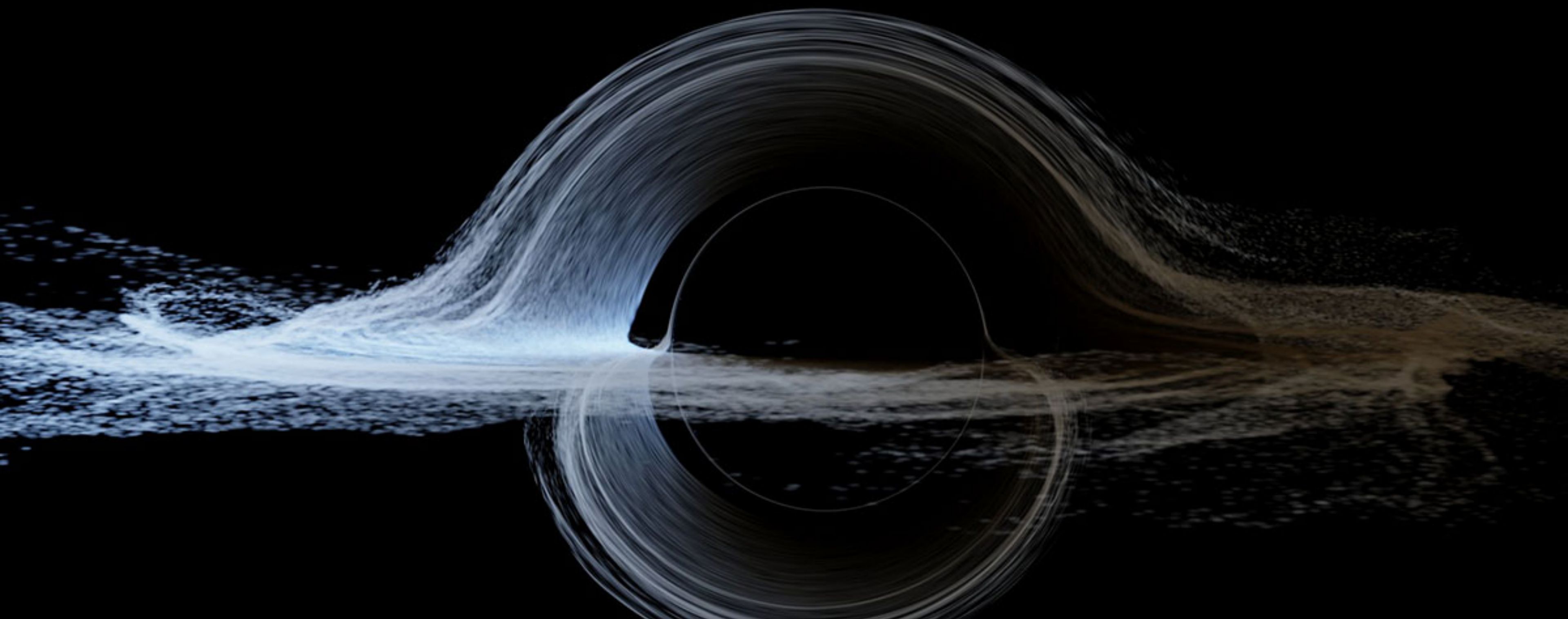

Single epoch microlensing statistics

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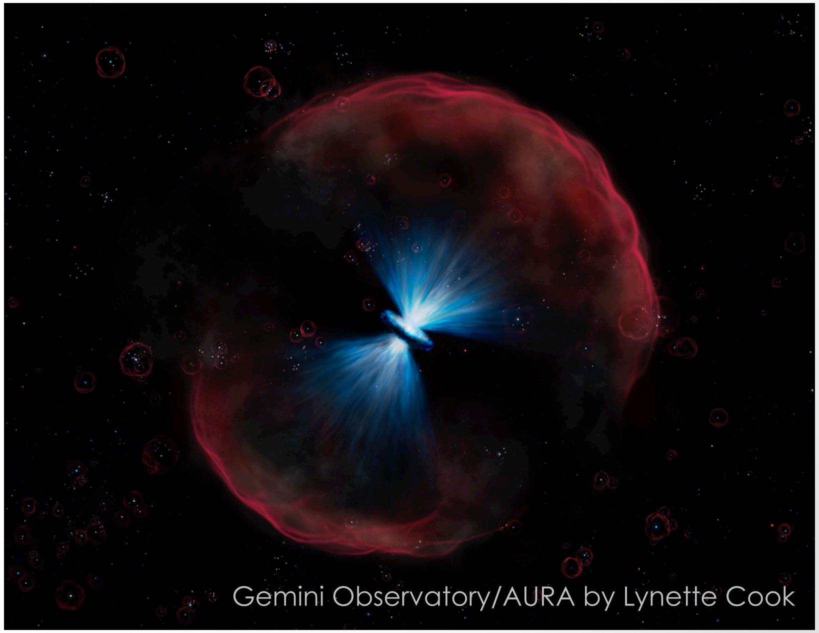
Manhattan Microlens 2017

Outline

- Quick refresher
  - What are we doing?
- Current results
  - The trouble with temperature profiles
- Brief technical summary
- Complications
  - Observational issues (briefly)
  - Simulation systematics
- Open questions



Title page image: James+15

Quick refresher…

- **The goal**: observational constraints on the structure of quasar central engines
- Easier: **accretion disks**
    - e.g. Bate+08, 11; Blackburne+14, 15; Chartas+12; Floyd+09; Keeton+06; Kochanek+04, 06; Macleod+15; Mediavilla +11, 15a,b; Morgan+08, 12; Motta+12; Muñoz+11, 16; Poindexter+08, 10, Rojas +14…
- Harder: **broad emission line regions**
    - e.g. O'Dowd+11,15; Sluse+11, 12; Guerras +13; Braibant+14, 16; Motta+17

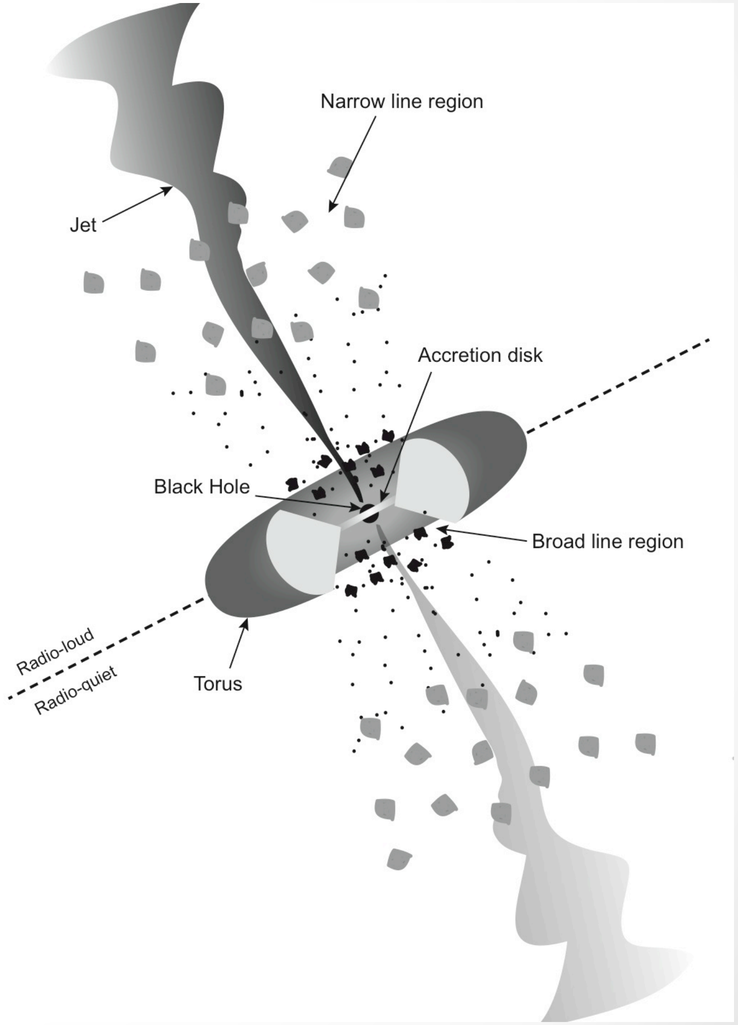
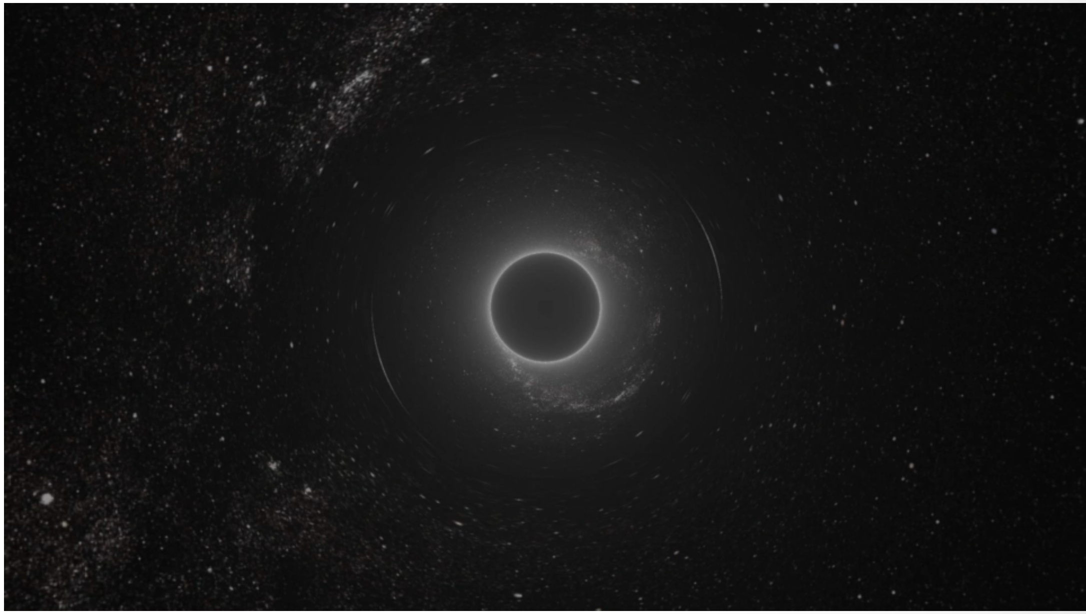


Image courtesy of Anthea King, via Urry & Padovani 95

Microlensed accretion disks

- Quasar continuum emission produced in an accretion disk
- **Hotter regions** are closer to the black hole. **More compact**, so **more strongly microlensed**
- Microlensing observations therefore (hopefully) allow us to **constrain radial temperature profile**:



American Museum of Natural History

$$r = r_s \left(\frac{\lambda}{\lambda_0}\right)^p \longrightarrow T \propto r^{-1/p}$$

Analysis techniques

Single epoch technique

(e.g. Bate+07, 08; Floyd+09; Jimenez-Vicente+14,15)

- Single observation
- Pros:
  - Observationally inexpensive
  - Computationally straight-forward
- Cons:
  - Sizes are often prior dependent
  - Time delays
  - Well-characterized macro-model required (macro-magnifications)
  - Differential extinction
  - Broad line contamination

Light curve technique

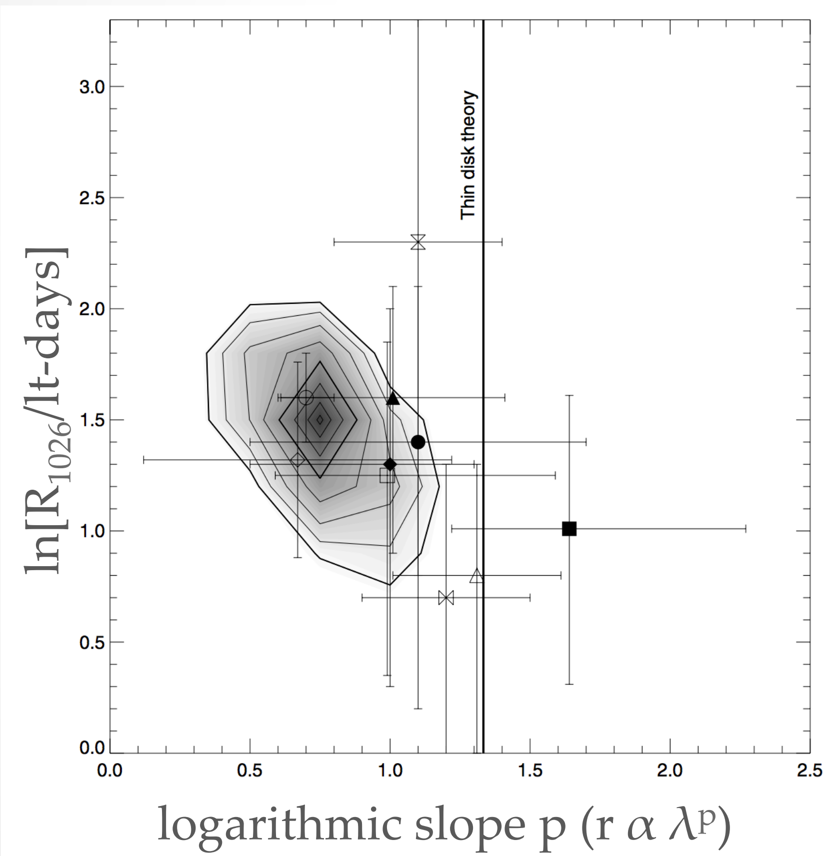
(e.g. Kochanek 04; Morgan+10; Macleod+15)

- Long-term monitoring
- Pros:
  - Less sensitive to lens model errors and differential extinction
  - Potentially much more information (disc orientation, unusual accretion disc structure, time delays, microlens masses…)
- Cons:
  - Observationally expensive
  - More complex simulations
  - Broad line contamination

The big (single epoch) puzzle

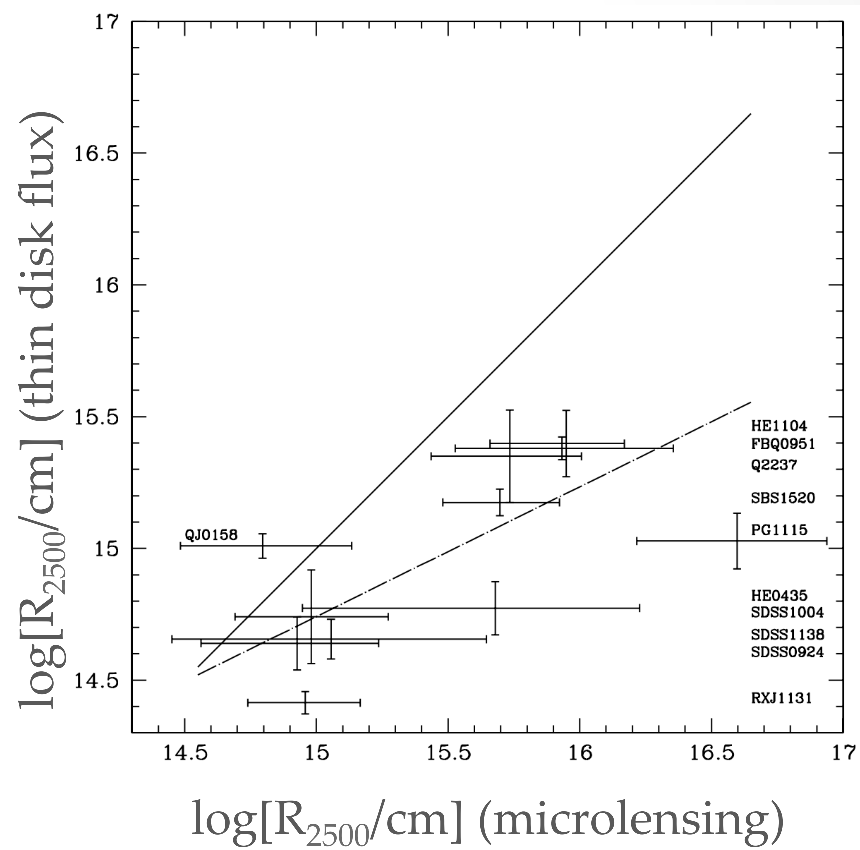
Single epoch technique

(Jimenez-Vicente+14; 8 quasars)



Lightcurve technique

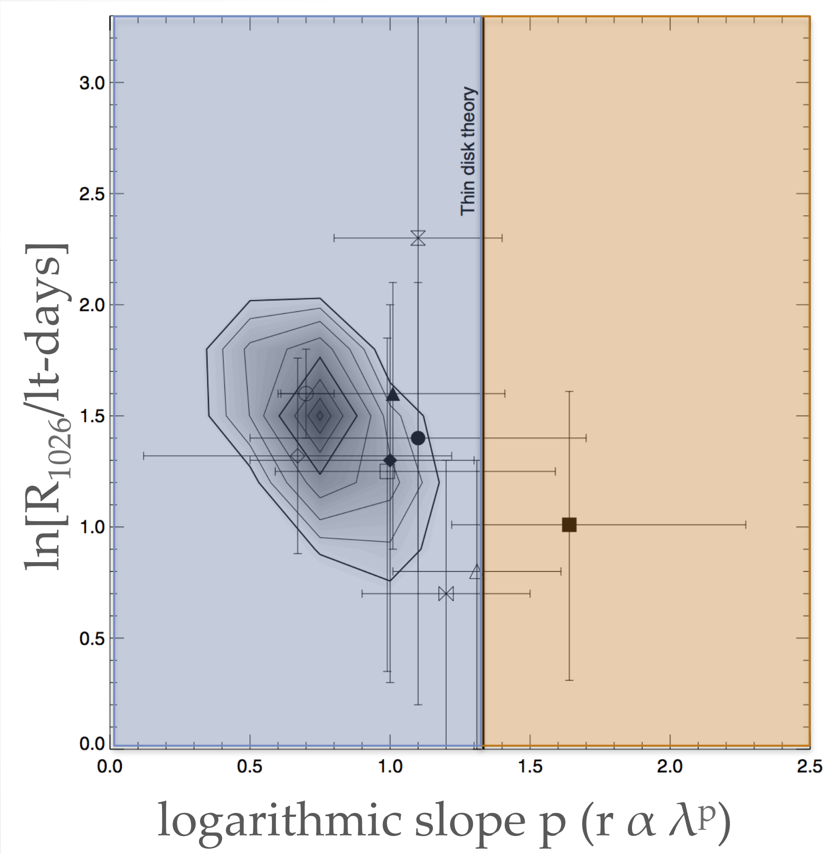
(Morgan+10; 11 quasars)



The big (single epoch) puzzle

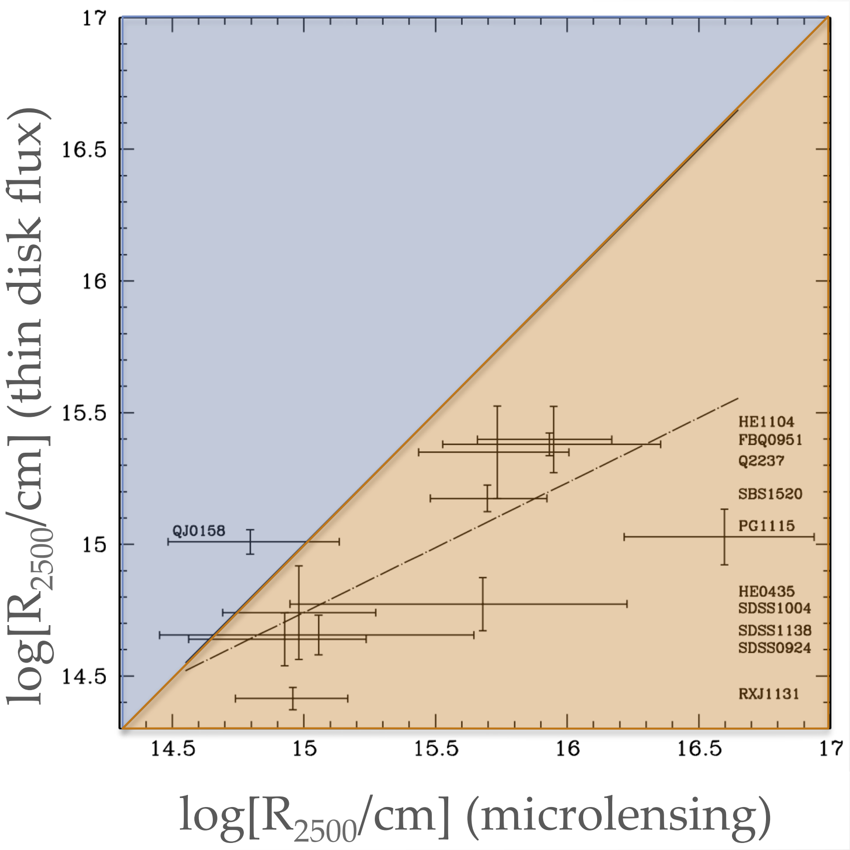
Single epoch technique

(Jimenez-Vicente+14; 8 quasars)



Lightcurve technique

(Morgan+10; 11 quasars)

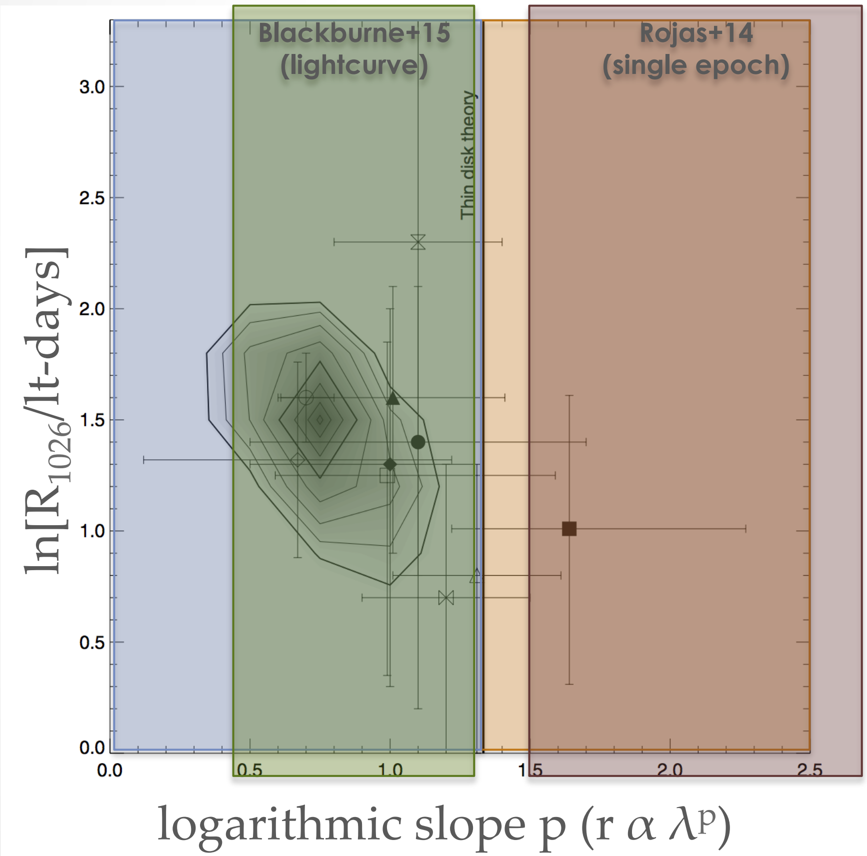


(… **caveats**)

The big (single epoch) puzzle

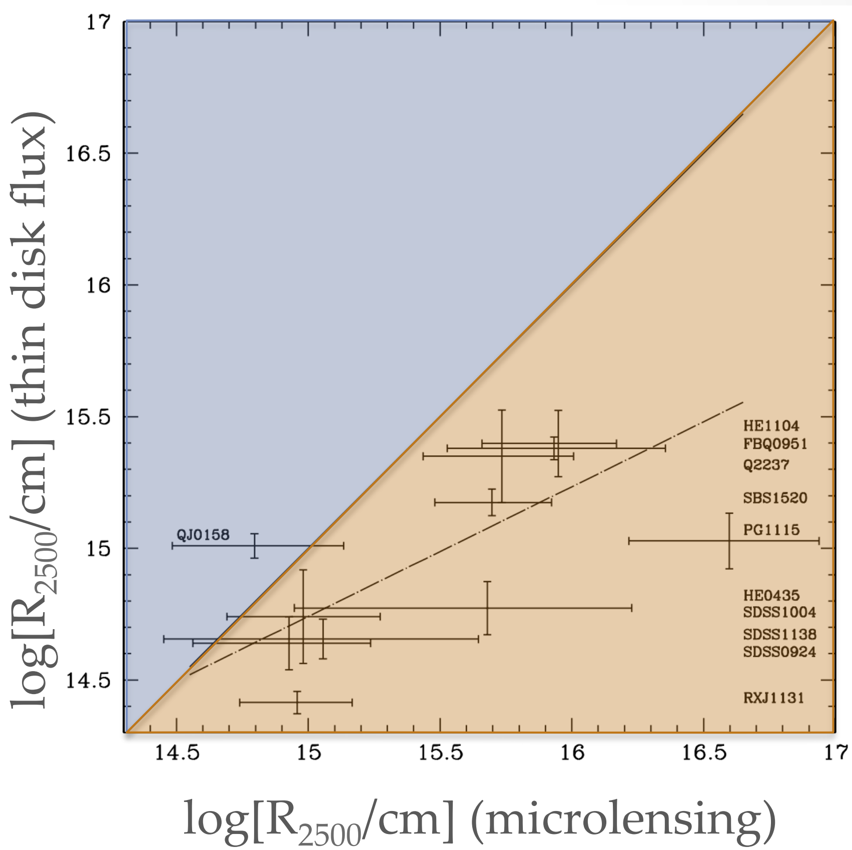
Single epoch technique

(Jimenez-Vicente+14; 8 quasars)



Lightcurve technique

(Morgan+10; 11 quasars)

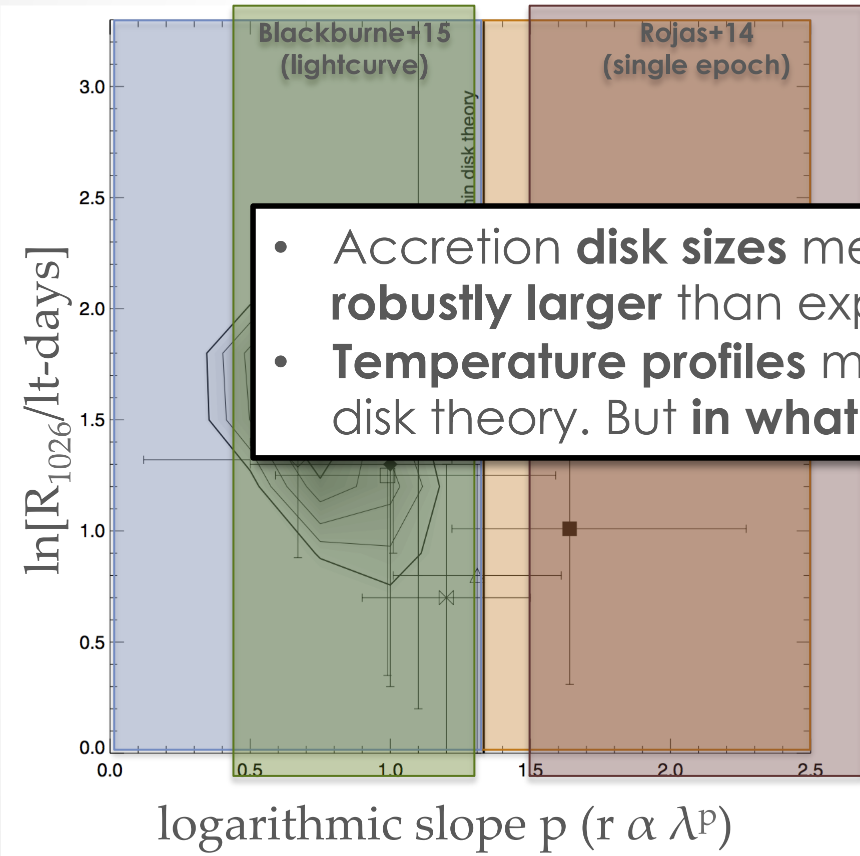


(… **caveats**)

The punchline

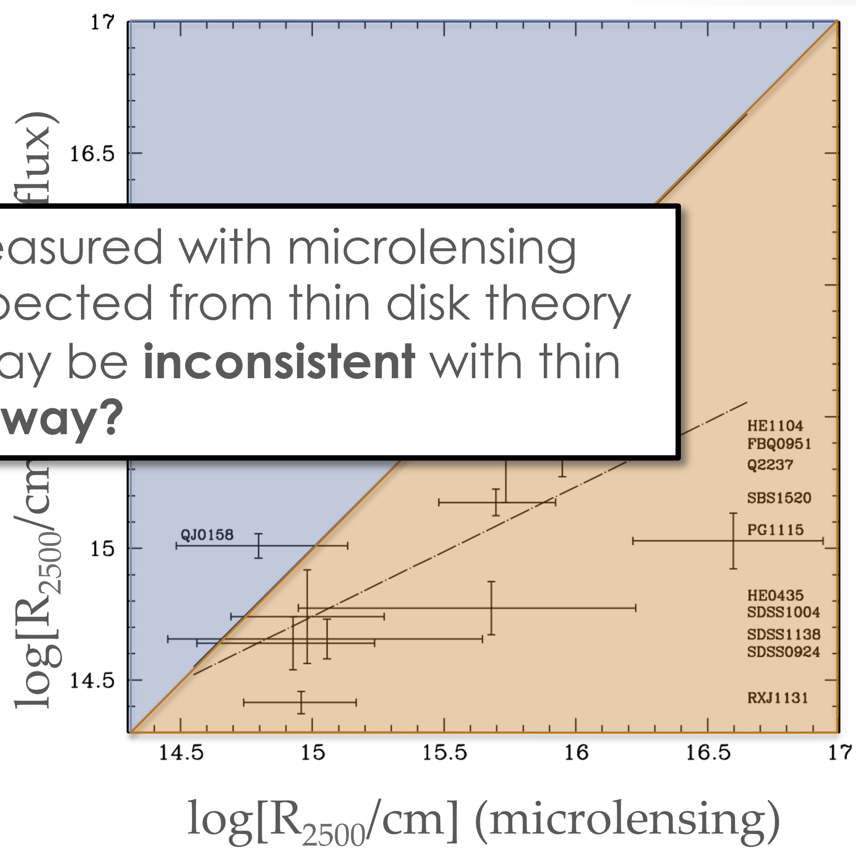
Single epoch technique

(Jimenez-Vicente+14; 8 quasars)



Lightcurve technique

(Morgan+10; 11 quasars)



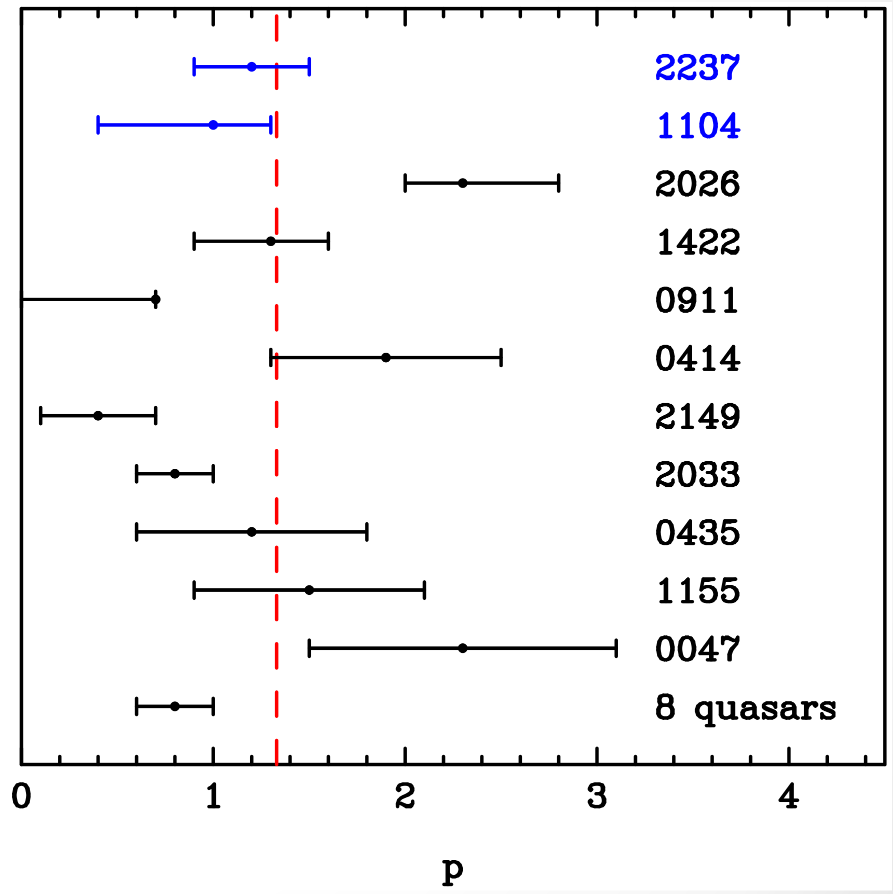
- Accretion **disk sizes** measured with microlensing **robustly larger** than expected from thin disk theory
- **Temperature profiles** may be **inconsistent** with thin disk theory. But **in what way?**

(… **caveats**)

Current results

- Accretion **disk sizes** measured with microlensing **robustly larger** than expected from thin disk theory
  - e.g. Morgan+10; Chartas+16

- What about temperature profiles?
  - 2237: Eigenbrod+08;
    1104: Blackburne+15;
    2026, 1422, 0911, 0414: Bate+17;
    2149, 2033, 0435: Motta+17;
    1155, 0047: Rojas+14;
    8 quasars: Jimenez-Vicente+14



Brief technical summary

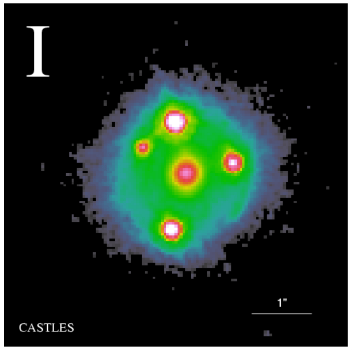
1. Gather observations:
   - Observe $m(\lambda)$ in lensed images (1,2)
   - Construct magnitude differences

     $$\Delta m(\lambda) = m_2(\lambda) - m_1(\lambda)$$
   - If possible, isolate microlensing signal (e.g. Mediavilla+09):

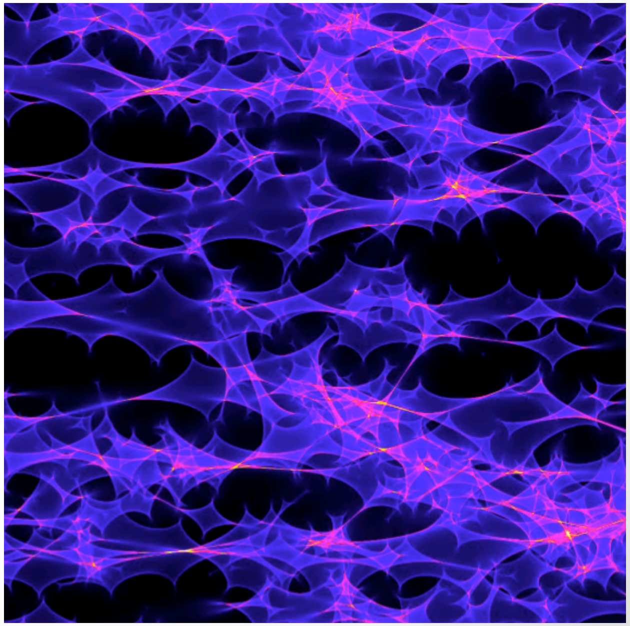
     $$\Delta m_{micro} = \Delta m_{continuum} - \Delta m_{line}$$

Magellan (Floyd+09)

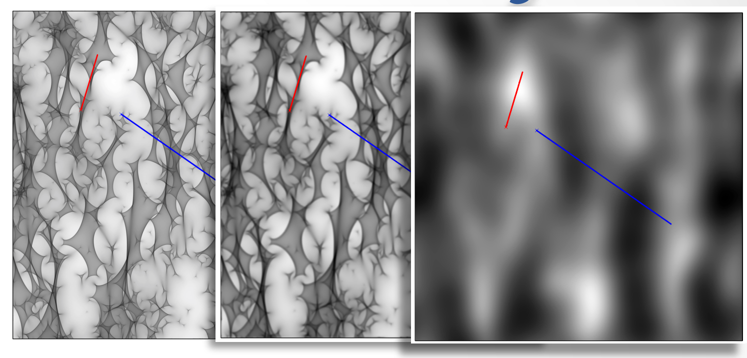
HST (CASTLES)



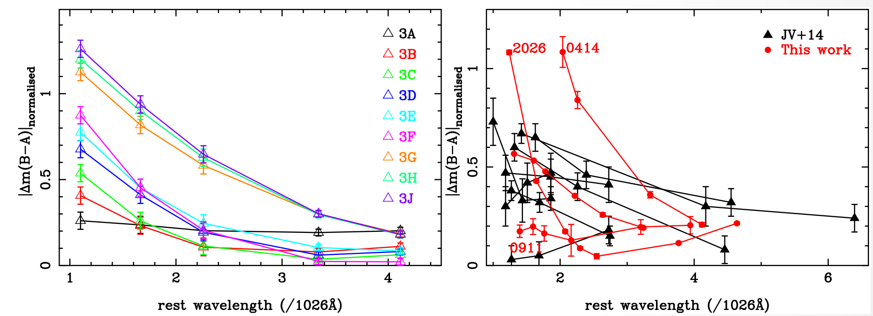
2. Prepare magnification maps
   - Lens model: convergence and shear
   - Generate maps, or GERLUMPH: https://gerlumph.swin.edu.au



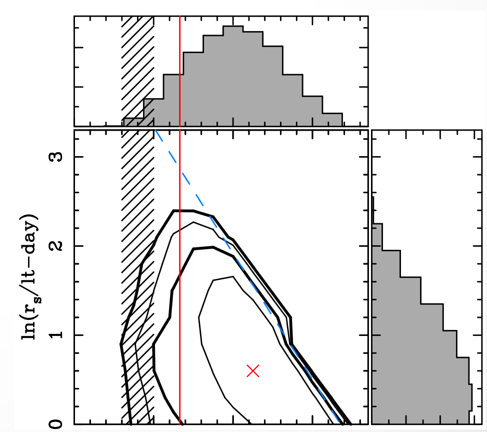
Brief technical summary



3. Microlensing simulations:
   - **Construct a large number of mock observations to compare with data**
   - For a given (r_s,p) combination:
     - Determine r(λ)
     - Convolve magnification maps with sources (usually Gaussian)
     - Sample maps to obtain (~10^8) simulated Δm(λ)
     - Compare with data (χ^2 comparison)
   - Sample (r_s,p), usually on a regular grid



$$r = r_s \left(\frac{\lambda}{\lambda_0} \right)^p$$

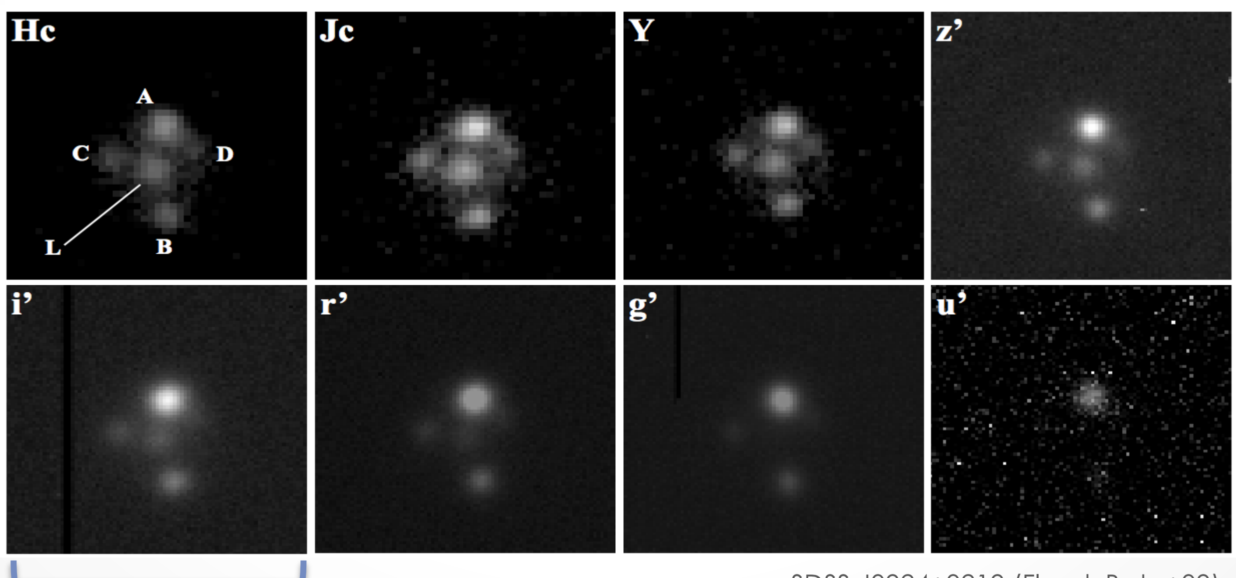


Complications

(The real reason we're here)

Observational issues

1. Time delays
2. Image de-blending
3. Broad line contamination
4. Differential extinction/millilensing



4″

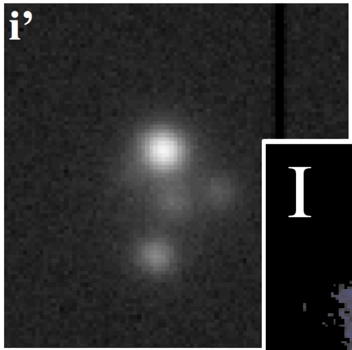
SDSS J0924+0219 (Floyd, Bate+09)

Ideal single epoch observations

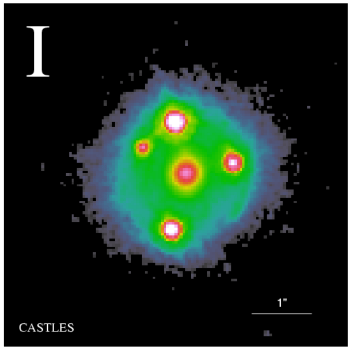
- Observe **close image pairs**
  - Time delays are negligible
  - (Makes de-blending harder)
- Use **HST** if possible
  - Makes image de-blending easier!
  - (Not a long-term solution)
- **Narrow** or **medium-band filters**
  - Tune to avoid broad line contamination
    (e.g. Mosquera+09, 11; Bate+17)

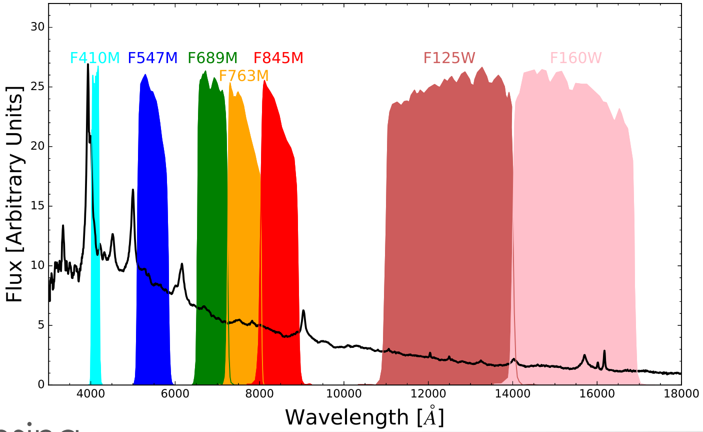
OR

- **Spectroscopy**
  - Explicitly avoids broad line contamination
  - Establish a **clean unmicrolensed baseline**
    (e.g. Mediavilla+09, 11; Motta+12, 17; Rojas+14)
  - (Broad lines are interesting too!)
- Radio/mid-IR observations
  - Too large for microlensing, small enough for millilensing
  - (Maybe? e.g. Sluse+13)



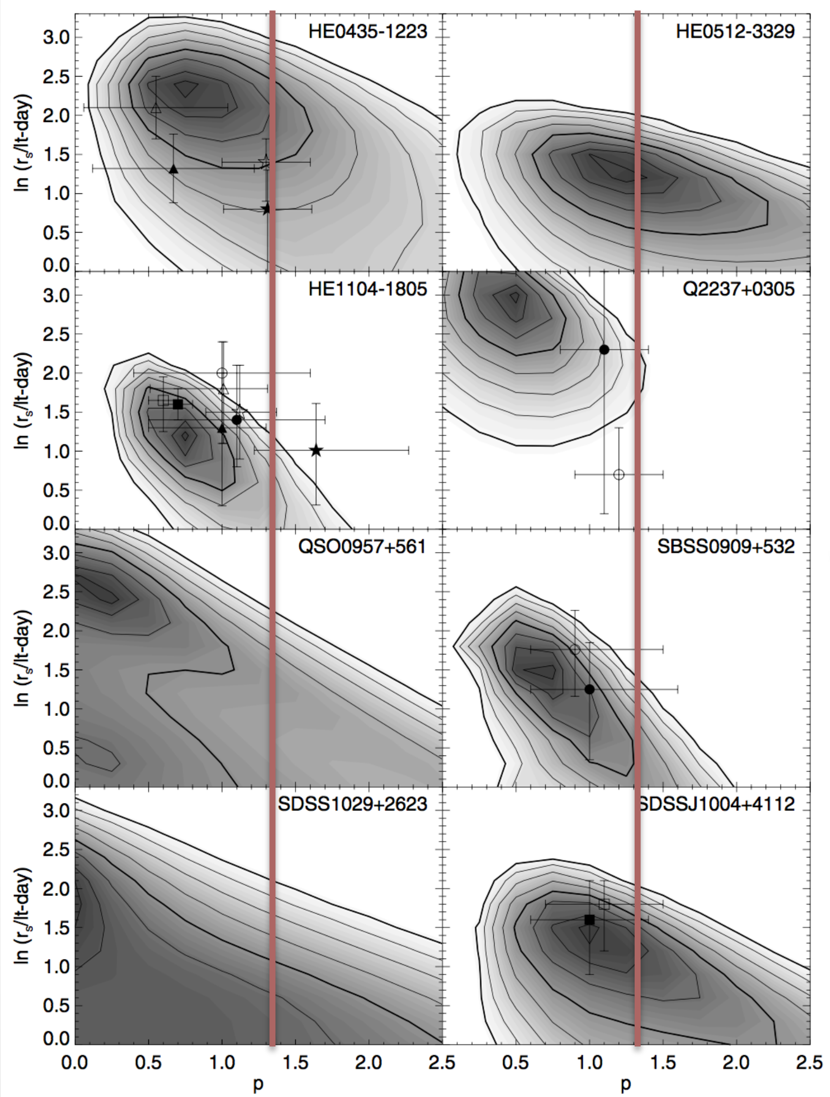
Magellan (Floyd+09)

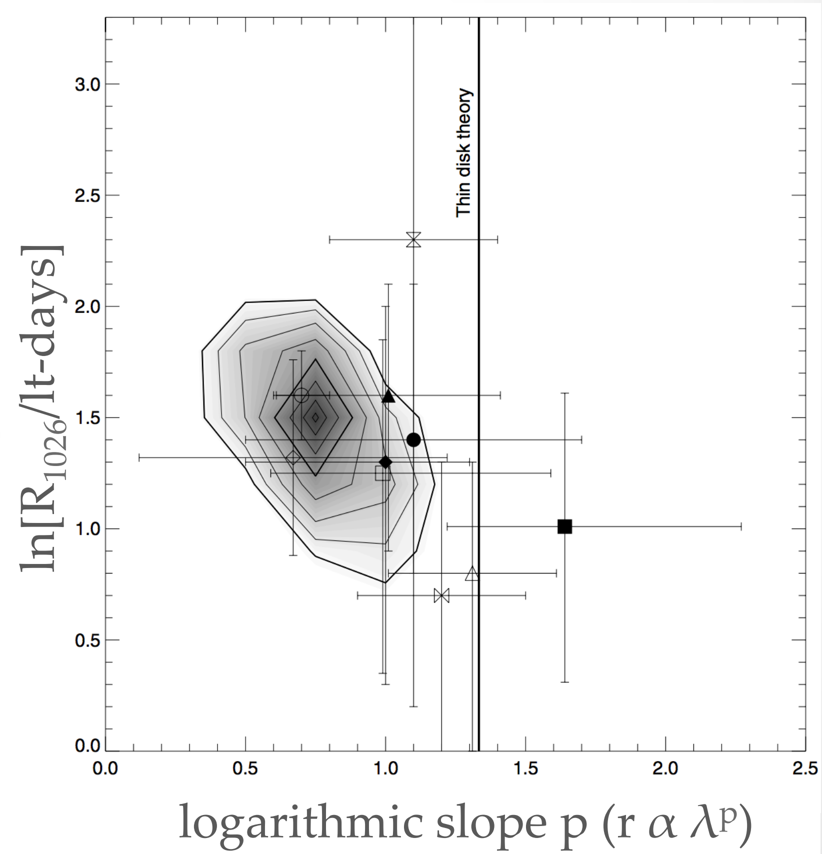
HST (CASTLES)




Bate+17

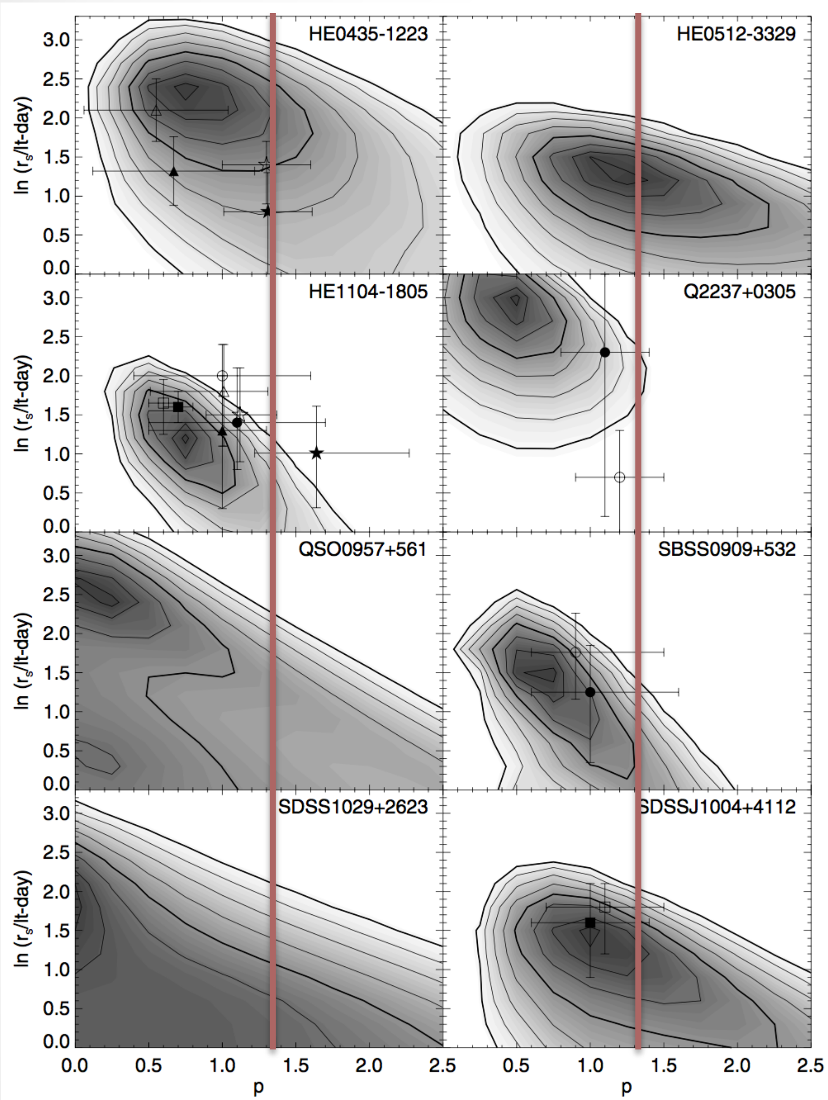
Systematics: a single epoch case study

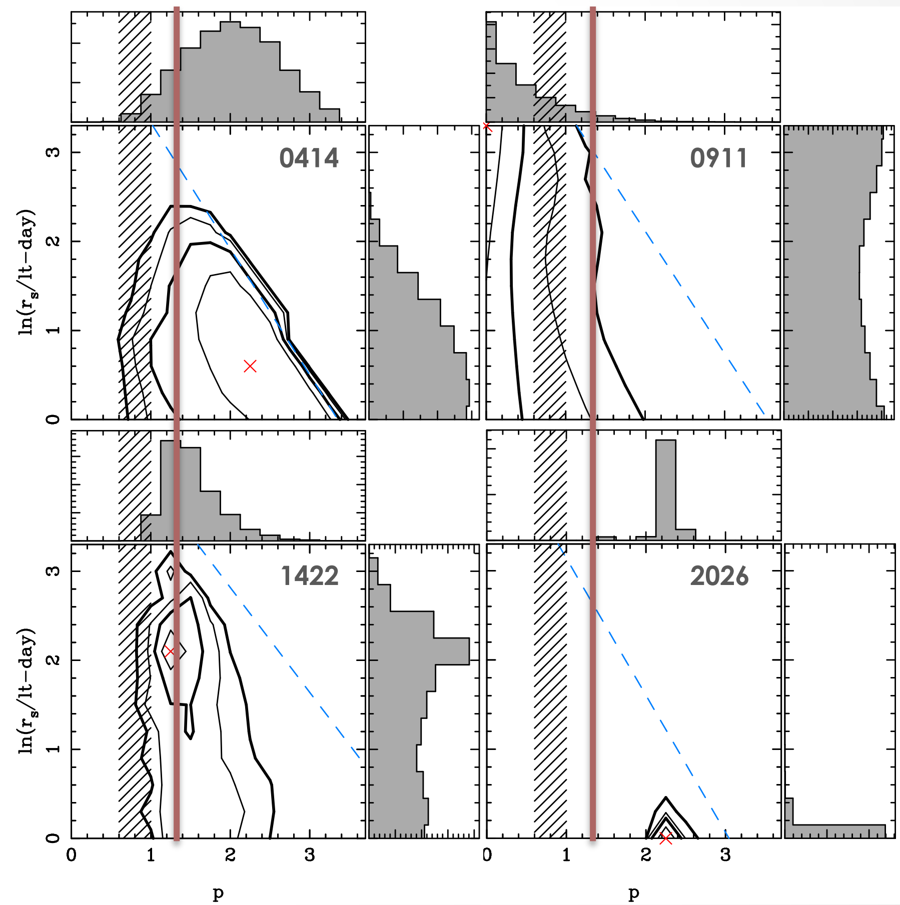




Jimenez-Vicente+14

Systematics: a single epoch case study

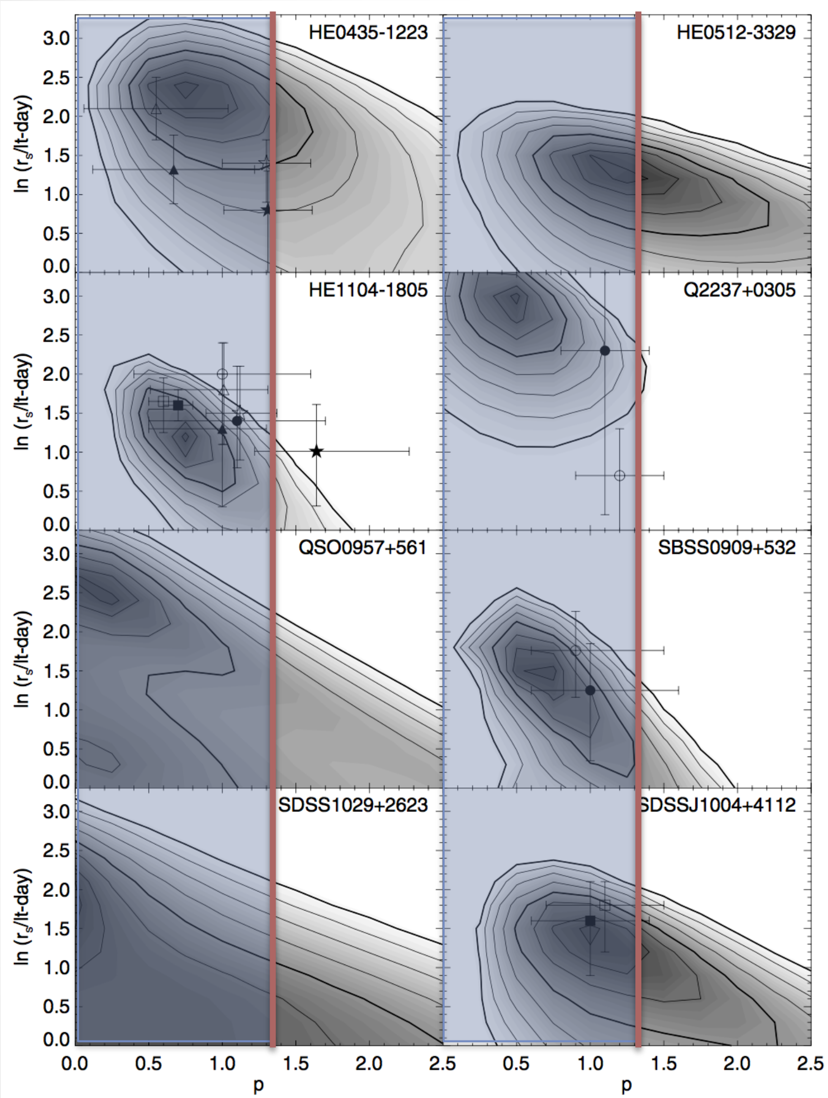




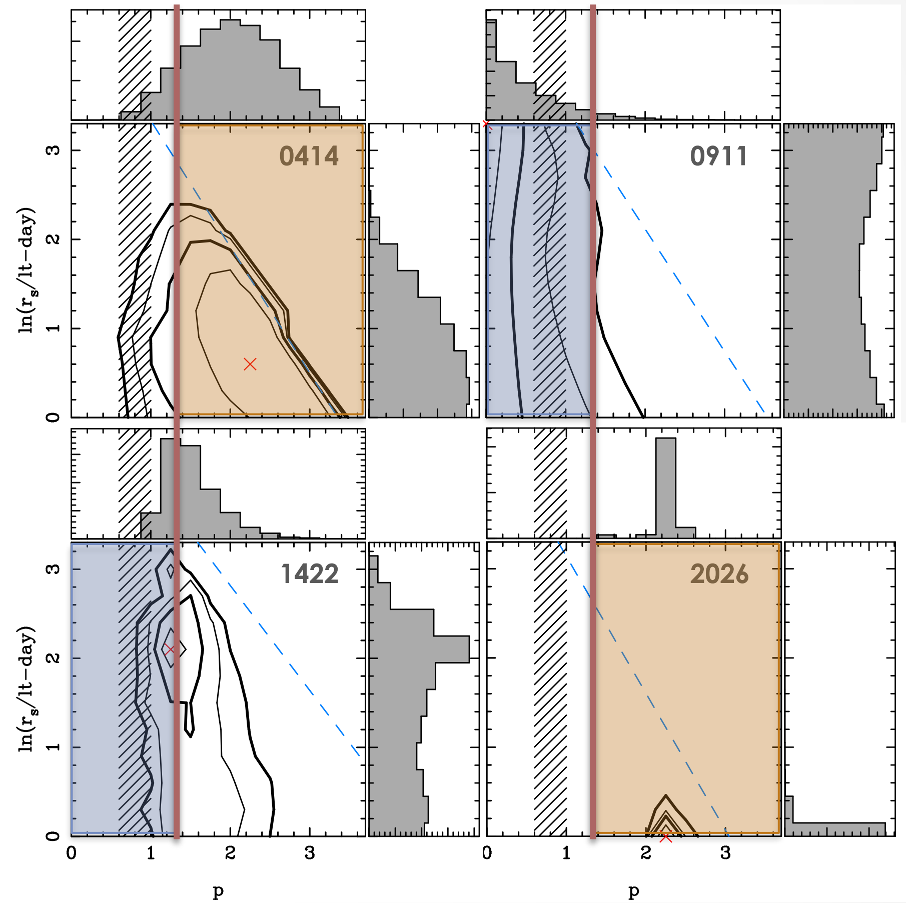
Jimenez-Vicente+14

Bate, O'Dowd, Vernardos+17

Systematics: a single epoch case study

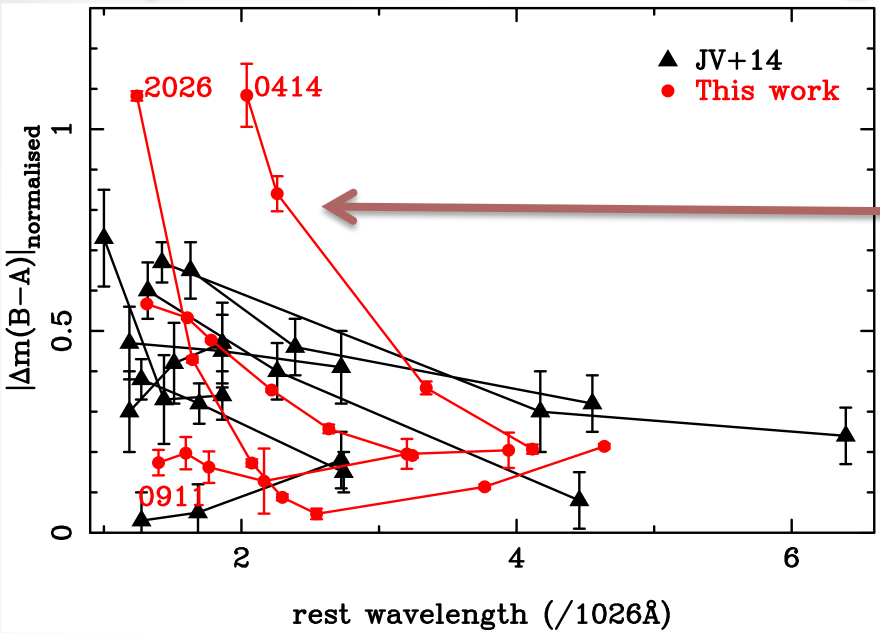


Jimenez-Vicente+14



Bate, O'Dowd, Vernardos+17

Systematics: a single epoch case study

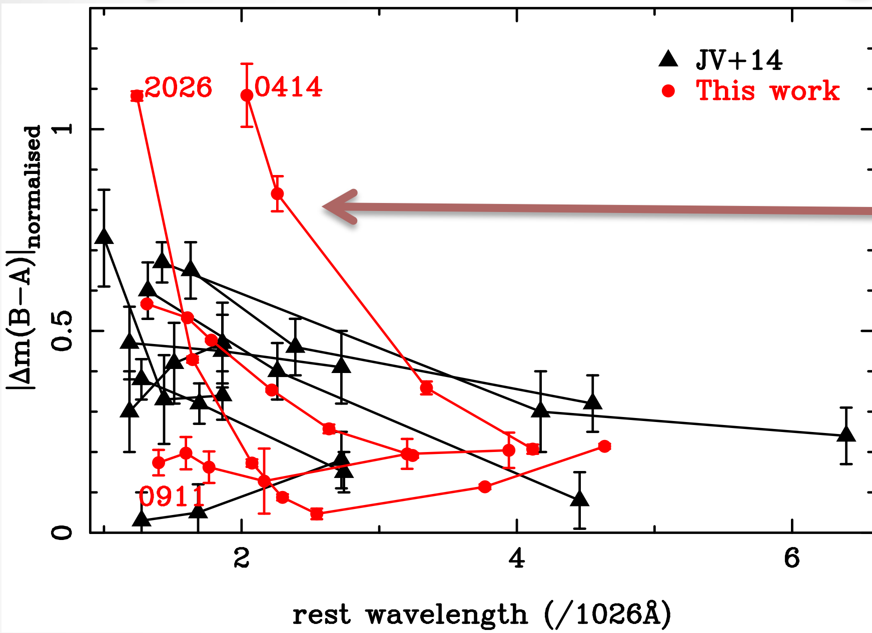


0414 and 2026 show stronger microlensing than JV+14 sample

(Important **caveats**:
- Smooth matter fraction
- Differential extinction)

Bate, O'Dowd, Vernardos+17

Systematics: a single epoch case study



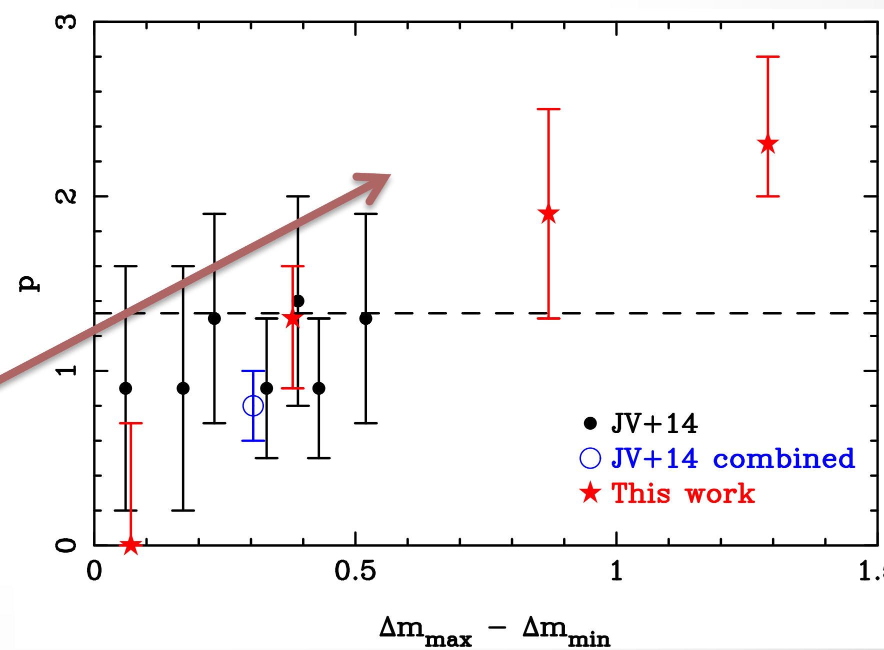
0414 and 2026 show stronger microlensing than JV+14 sample

(Important **caveats**:
- Smooth matter fraction
- Differential extinction)

Measured p in:

$$r = r_s \left(\frac{\lambda}{\lambda_0}\right)^p \qquad T \propto r^{-1/p}$$

appears to **correlate with strength of chromatic effect**

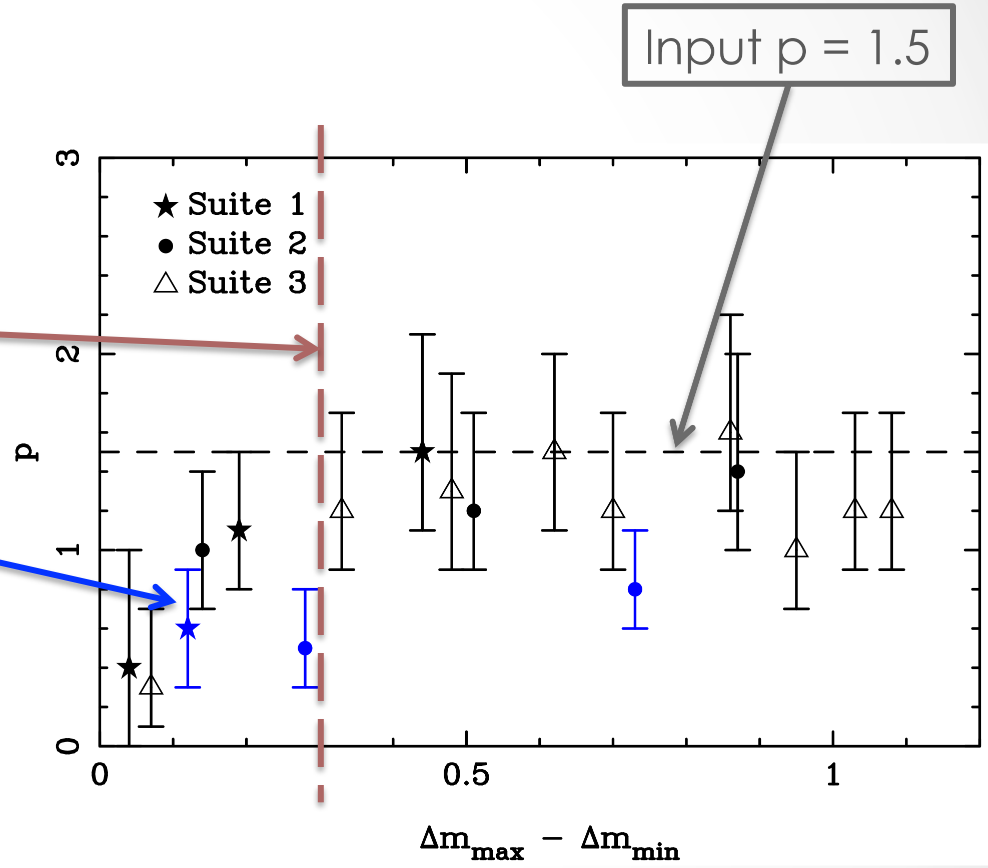


Bate, O'Dowd, Vernardos+17

Mock observation test

- Ran suites of (blinded) **mock observations**
- How well is the input power-law recovered?
- **Good above Δm ~ 0.3**
- Outliers when observations do not roughly converge to macro-magnification (within ~ 0.4 mag)

- Caveat: appropriate for MG 0414+0534 (high magnification)



$$r = r_s \left(\frac{\lambda}{\lambda_0}\right)^p$$

Bate, O'Dowd, Vernardos+17

So what does this mean?

Downsides:

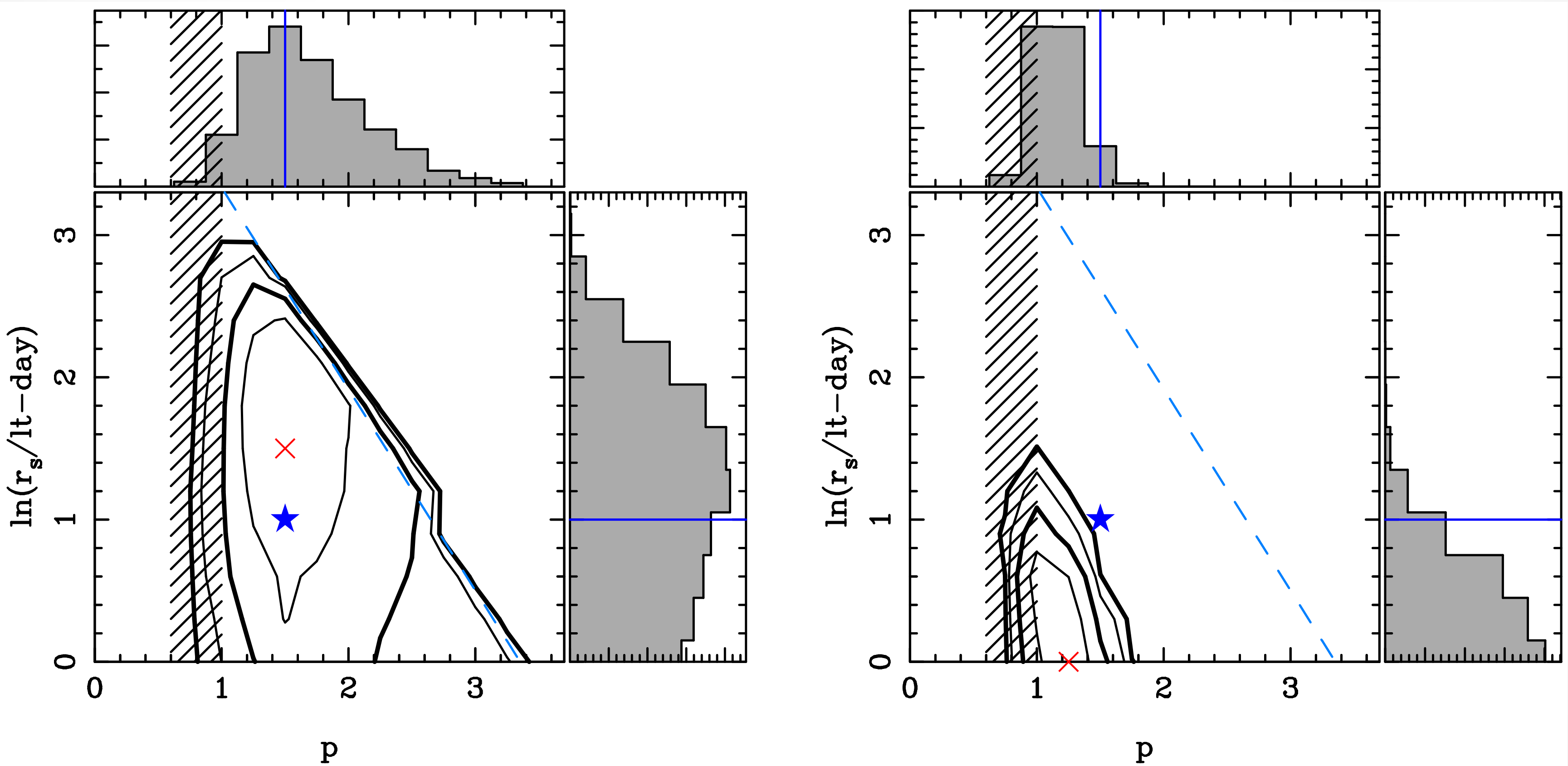
- Single epoch measurements showing **low chromatic variation likely under-estimate p**.
- Stacking exacerbates this problem.

Upsides:

- Correctly recovers input accretion disc parameters given:
  - Sufficiently large chromatic variation.
  - Rough convergence to unmicrolensed baseline.

What about the **results in the literature**?

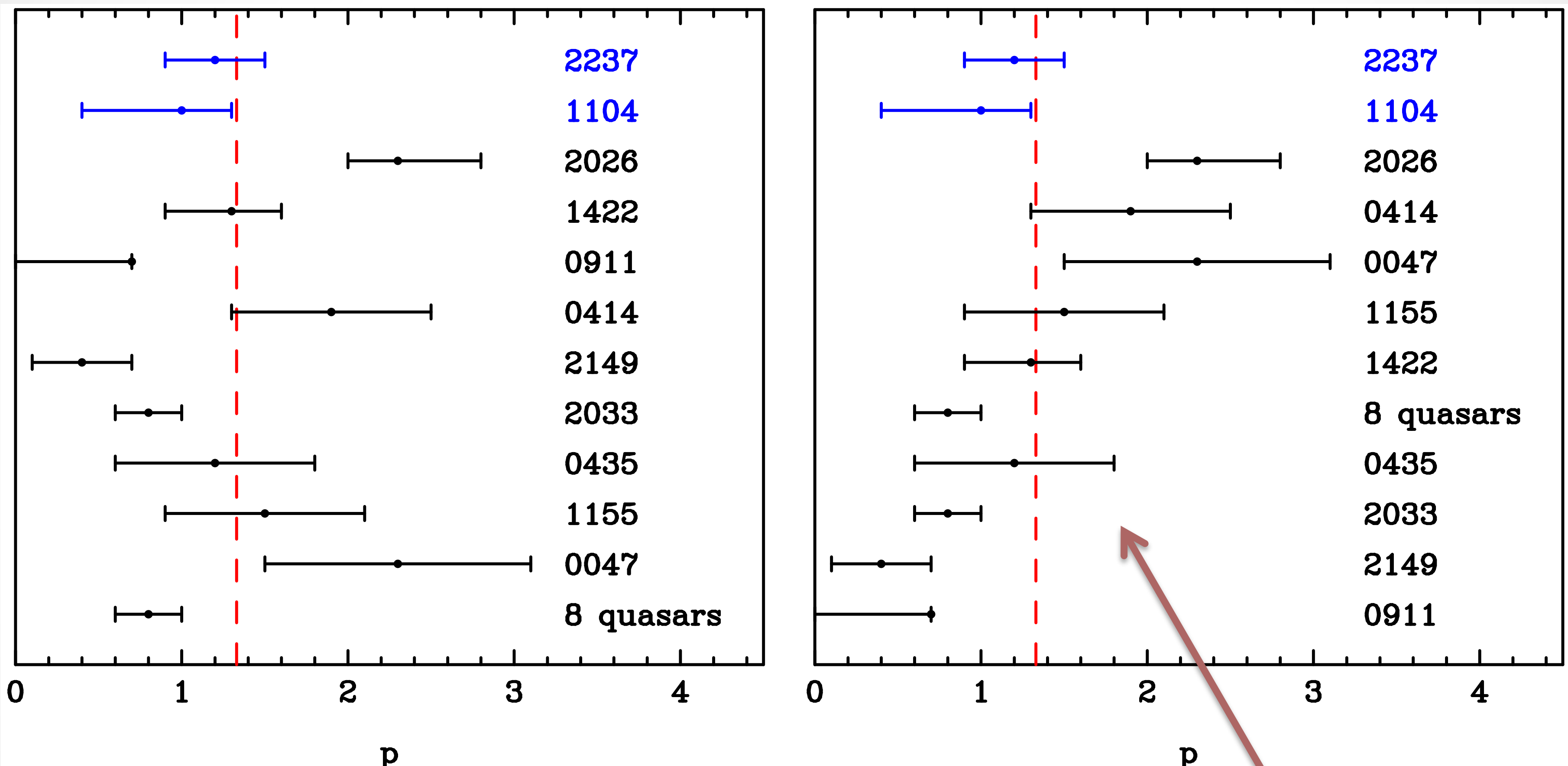
Be careful when stacking…



Single **high-chromatic variation** observation

Stacked with **three other low-chromatic variation** observations

Recent literature results



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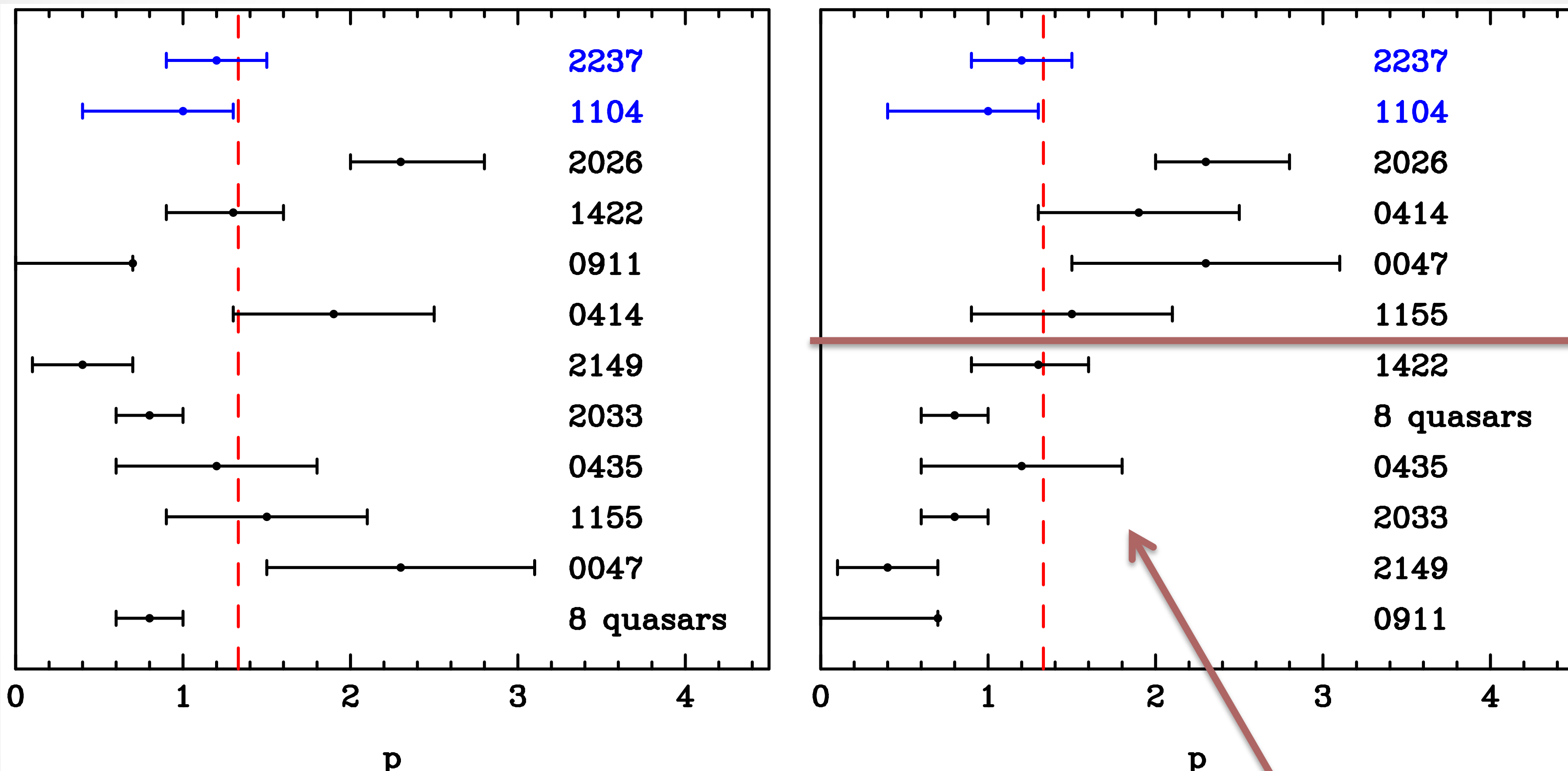
Increasing chromatic variation
(bottom to top)

Recent literature results



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Increasing chromatic variation
(bottom to top)

What have we learned?

- Based on small(ish) suites of mock observations
- These things help:
  - Beating down **observational errors** (ground-based-like to HST-like)
  - **Stacking**, but make sure they're meaningful measurements
- These things cause trouble:
  - **Low chromatic variation** leads to under-predicting p
  - Ratios in the reddest filter that **do not roughly converge to the unmicrolensed baseline** also lead to under-predicting p
  - Priors still dominate for single observations

PRELIMINARY

What have we learned?

- Who knows? (Maybe you do?)
  - **Magnification**: do low/high magnification lenses systematically bias accretion disk constraints?
  - **Smooth matter fractions:** can we save time by simulating only one (e.g. JV+14)? How well can we recover it (e.g. Schechter +14)?
  - Impact of:
    - **Lens modelling errors**? (Vernardos & Fluke 2014)
    - **Broad line contamination**?
    - Poorly measured **macro-magnifications/baselines**?
  - Variations in the underlying disk population. What if accretion disks aren't smooth (e.g. Dexter & Agol 2011)?
  - Other biases?
- **What can we do better?**

Something to aim for?

A simple (online) tool:

1. Users **upload chromatic microlensing** data
   - Flags to indicate presence of possible contaminants: time delays, broad lines, etc
   - Fields to input calibrators: radio or mid-IR data, narrow emission line measurements
2. **Select lens models** from a library (à la GERLUMPH) or input your own
   - Generates magnification maps if necessary
3. Single epoch microlensing simulations **run remotely**
4. Returns **accretion disc constraints**
   - Warns when data may produce spurious constraints
   - Provides full error analysis, including systematics

An automated way to analyse thousands of observations

What have we learned?

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