Black holes, dark energy, and other dark matters

トンマゾ・トレウ

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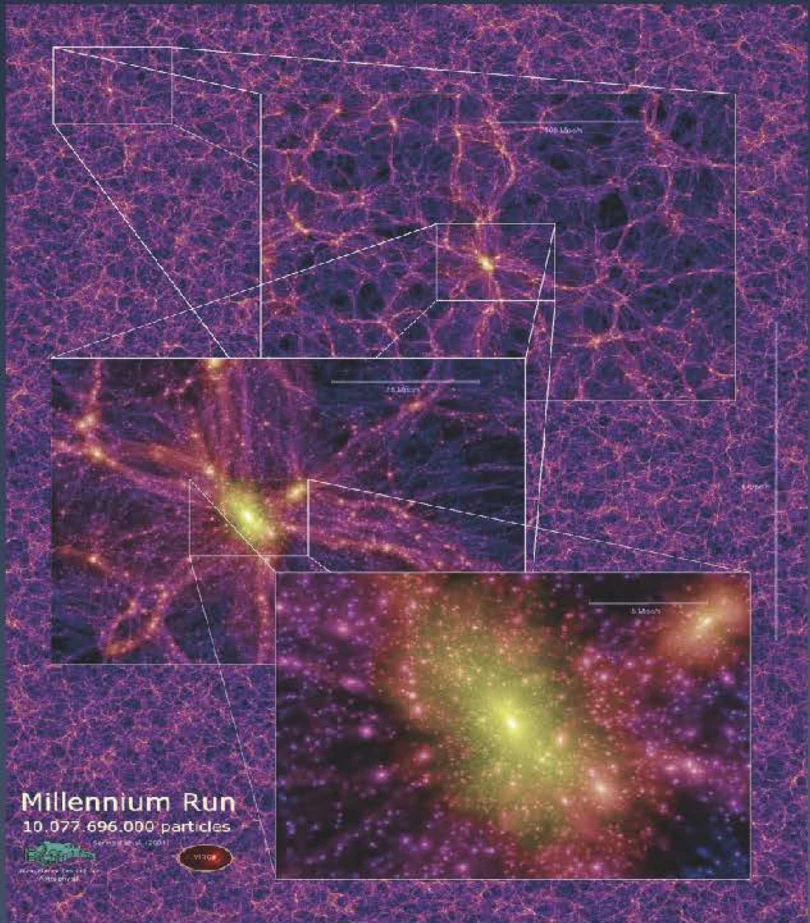
Many thanks to:

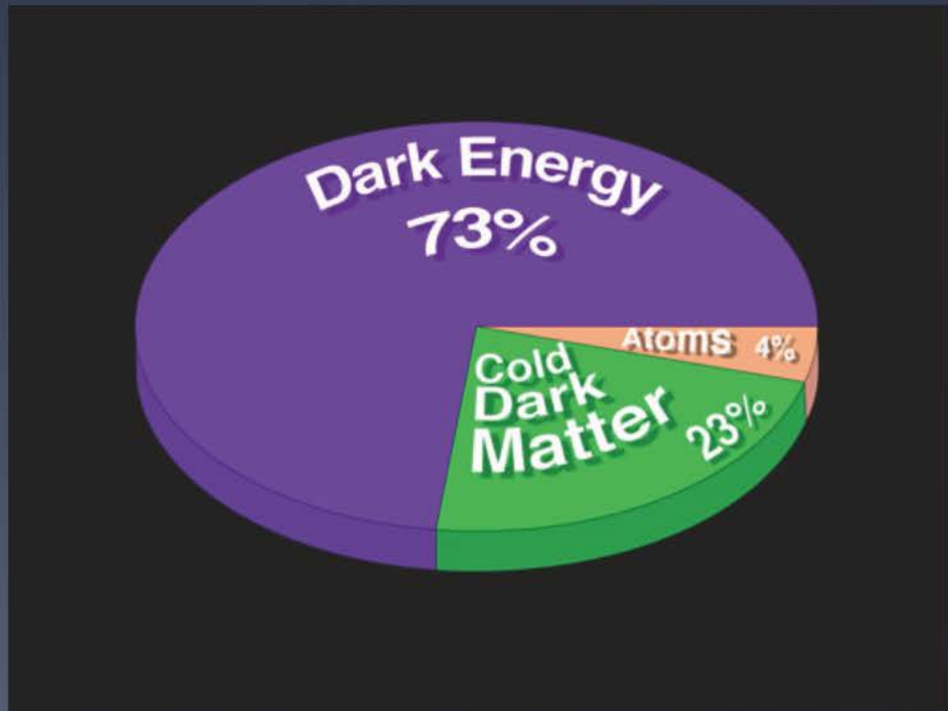
- **Matthew Auger (IoA)**
- Aaron Barth (UCI)
- **Vardha Bennert (CalPoly)**
- Roger Blandford (Stanford)
- **Brendon Brewer (Aukland)**
- Frederic Courbin (EPFL)
- Chris Fassnacht (UCD)
- Stefan Hilbert (Bonn)
- Leon Koopmans (Kapteyn)
- Matthew Malkan (UCLA)
- Georges Meylan (EPFL)
- **Phil Marshall (Oxford)**
- **Anna Pancoast (UCSB)**
- Dominique Sluse (EPFL)
- **Sherry Suyu (UCSB)**
- Malte Tewes (EPFL)
- **Jonghak Woo (SNU)**

Outline

- Introduction. The Dark Universe:
  - The standard cosmological model
  - Galaxy formation
  - The galaxy - black hole connection
- Key questions:
  - When and how did the first black holes form?
    - How do we measure black hole mass?
  - What is dark energy?
    - What is its equation of state?
- Some answers

The Dark Universe

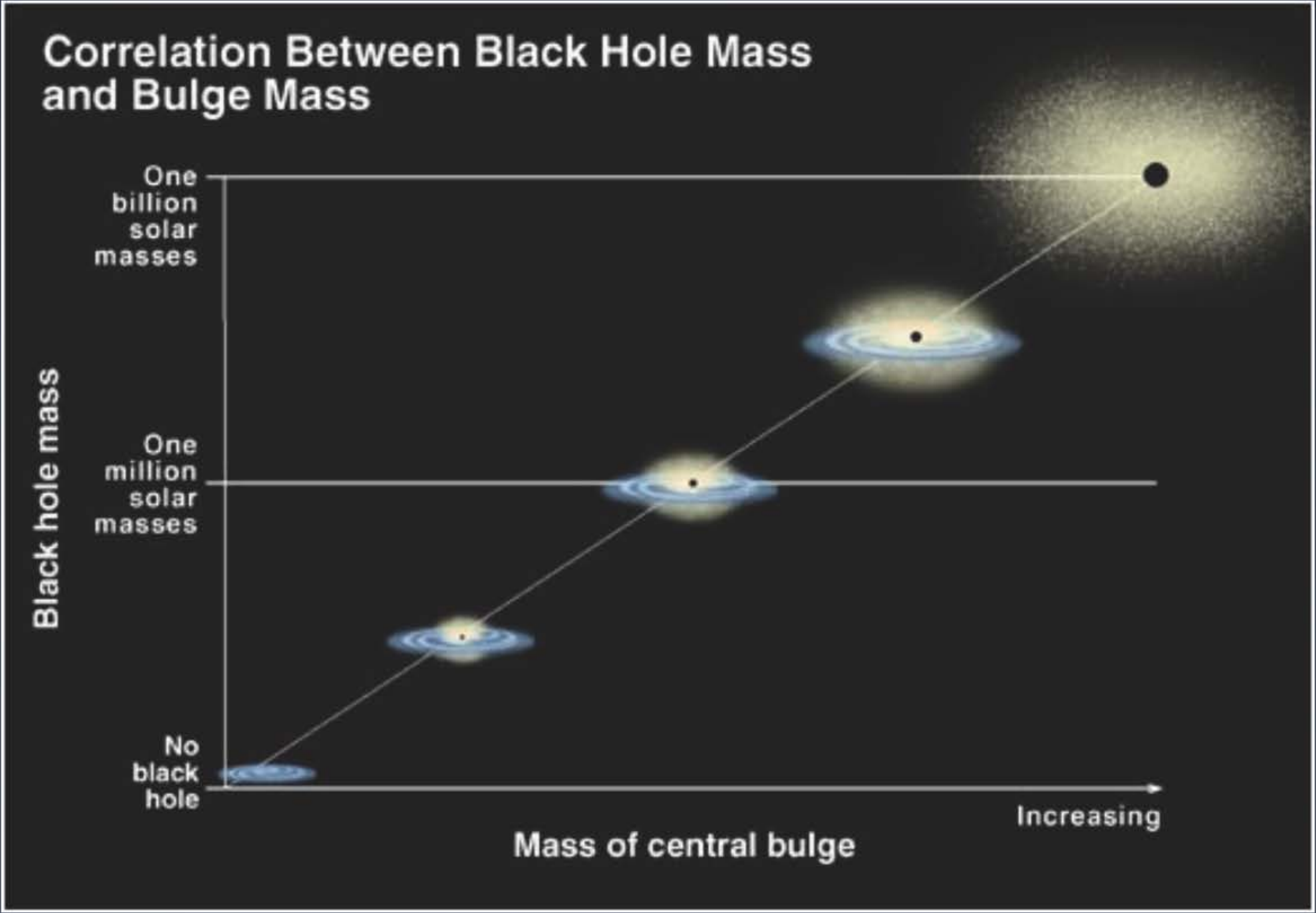




With dark matter goggles!!

But without your goggles...

A big dark surprise



Elliptical galaxies host supermassive black holes:

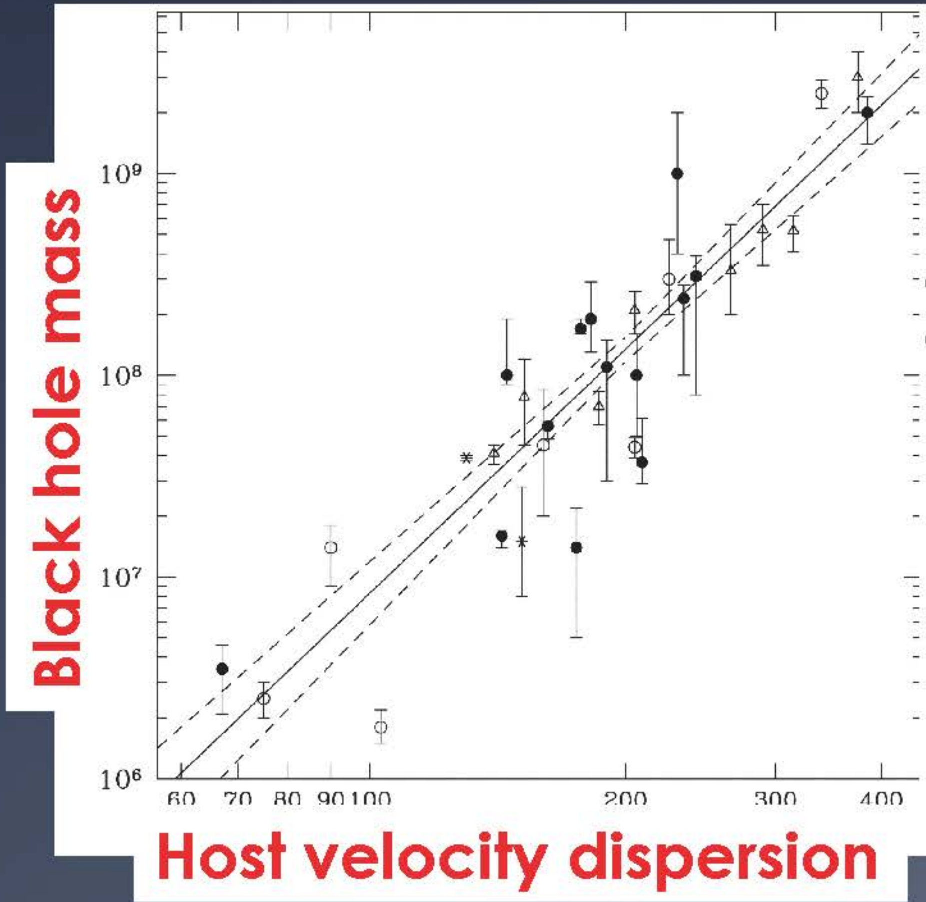
$M_{BH} = 0.2\% \ M_* \sim 0.01\%\text{-}0.001\% \ M_{DM}$

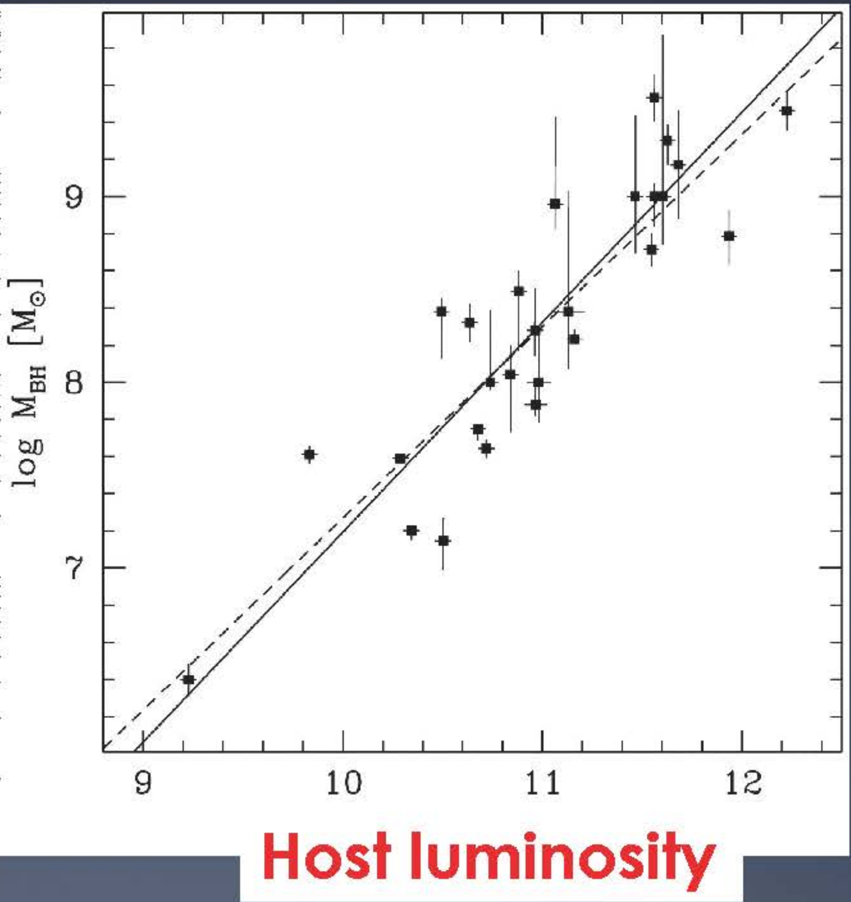
Key questions

1. When did the first black holes form? [How do we measure their mass?]
2. What is dark energy? [How do we measure the equation of state parameters?]

Black Holes

Black holes and host spheroids are connected





Gebhardt et al. 2001; Tremaine et al. 2002
Ferrarese & Merritt 2001; Gultekin et al. 2009

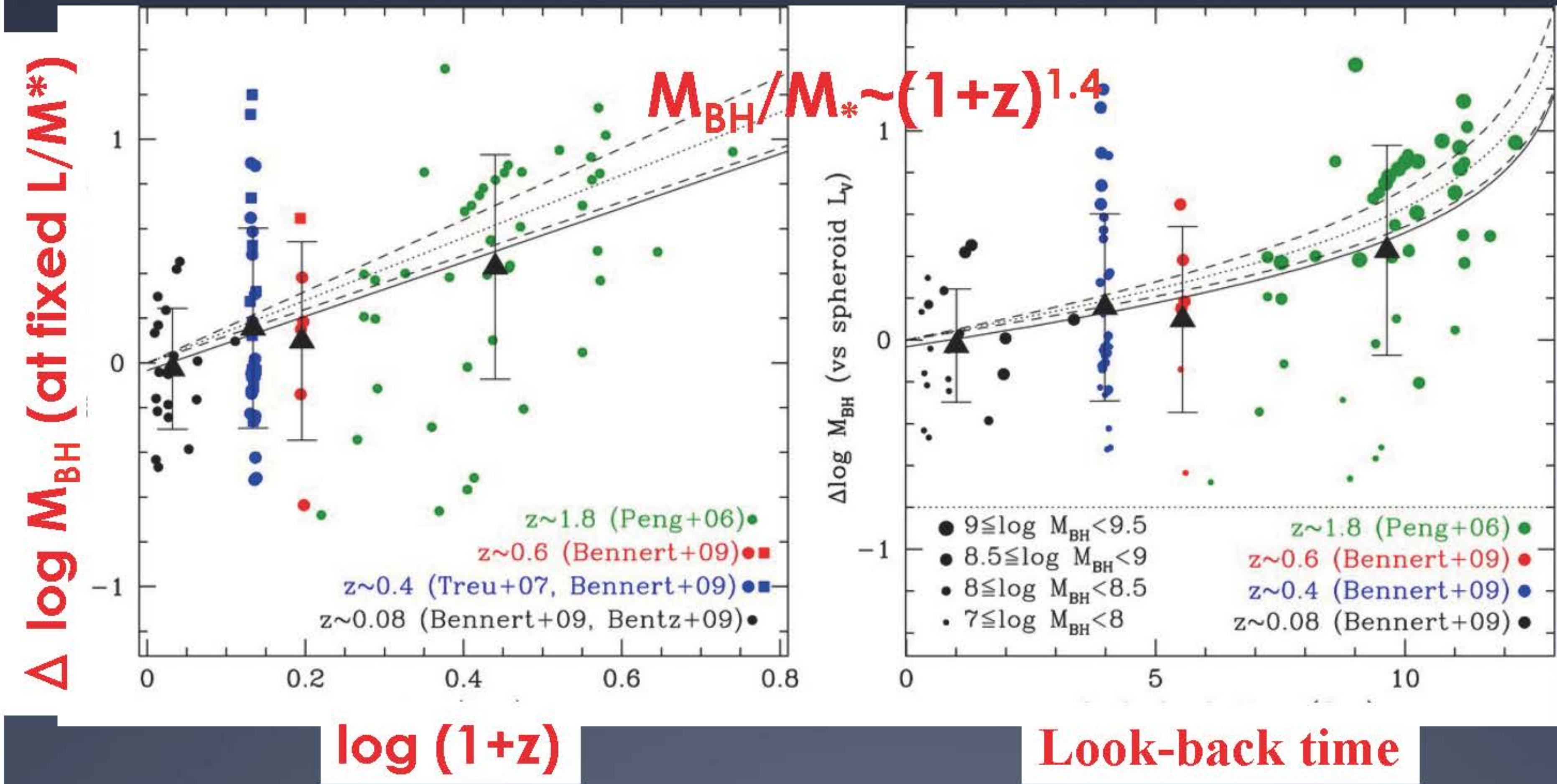
Marconi & Hunt 2003

How do black-holes and spheroids know about each other?

- The size of the BH dynamical sphere of influence is $R \sim M_{BH7} / (\sigma_{200})^2$ pc ~0.1-10 pc
- The size of the spheroid is of order kpc
- Black hole and galaxies evolve over cosmic time, in different ways. If you establish the correlations at one time they are not trivially preserved!!

The fundamental problem of co-evolution

Evolution of the MBH-host relation



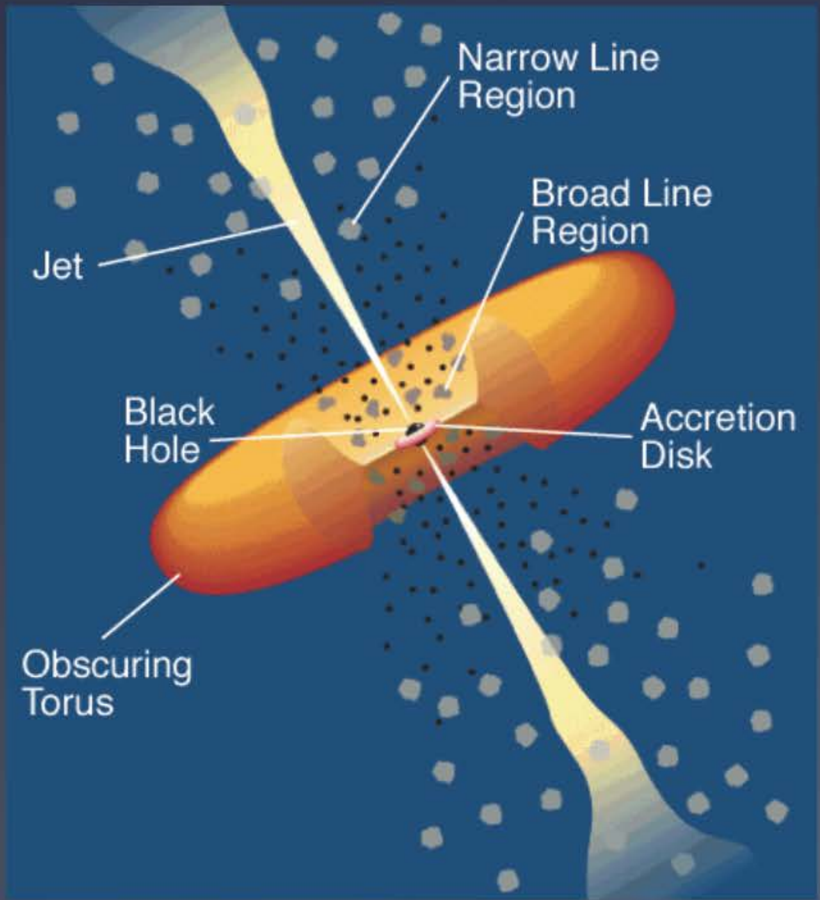
Treu et al. 2007; Bennert et al 2010, 2011; Merloni et al. 2010

VLT & Keck data coming up!

The first black holes?

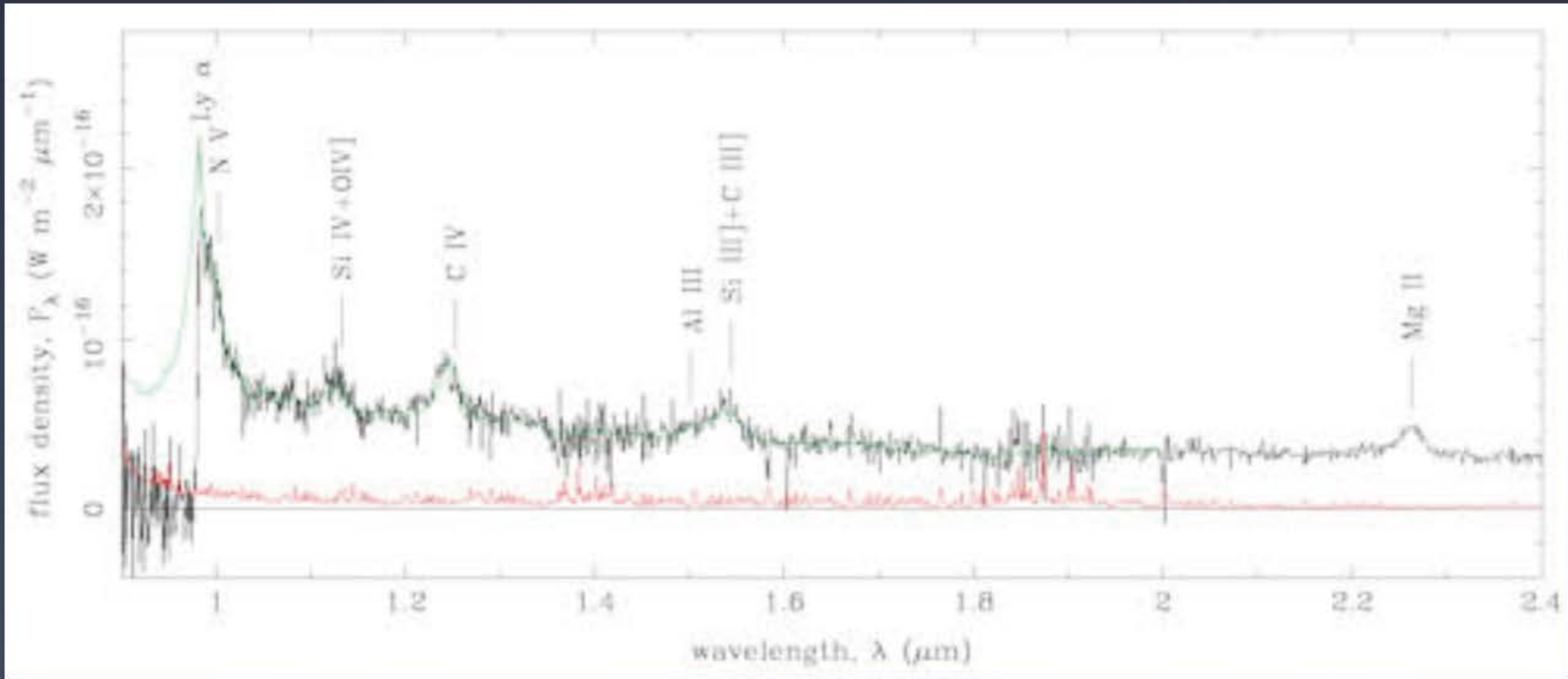
Z=7.085, Mortlock et al. 2010

Measuring Black hole masses



One needs: size of the orbit and speed of the orbit

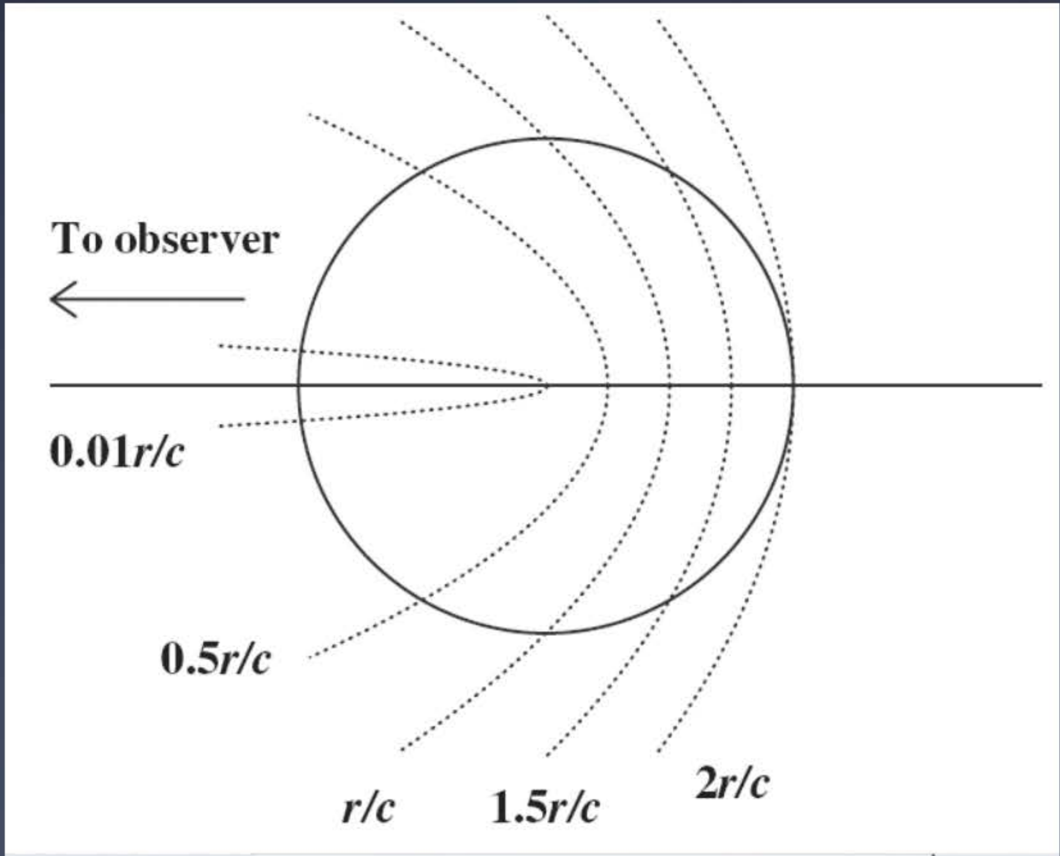
For high-z black holes



$$M_{BH} = 10^{8.58}\left(\frac{\sigma_{H\beta}}{3000\,\mathrm{km\,s^{-1}}}\right)^2\left(\frac{\lambda L_{5100}}{10^{44}\,\mathrm{erg\,s^{-1}}}\right)^{0.518}$$

can we do better?

Reverberation Mapping



Ring of gas with radius *r*

Gas along line of sight to observer will appear to respond with no delay

Gas that is furthest from observer will appear to have response delayed by $2r/c$

Mean lag time is r/c

Blandford & McKee 1982

Example of traditional results

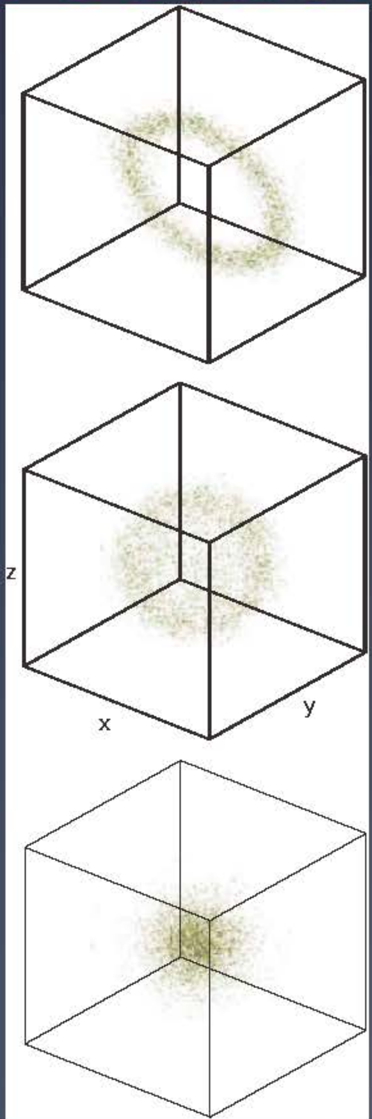
Table 13. Virial Products and Derived Black Hole Masses

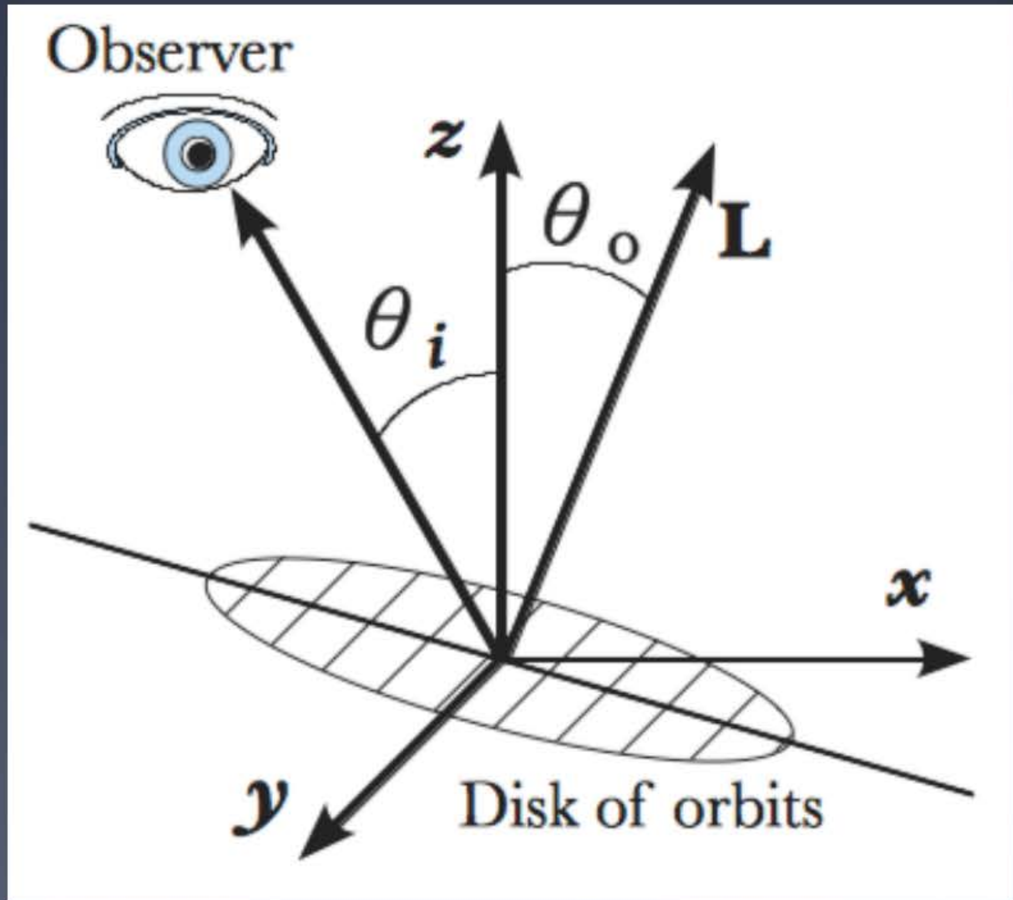
Object	$c\tau_{\rm cent}\sigma_{\rm line}^2/G$ (10^6 $M_\odot$)	$M_{\rm BH}$[a] (10^6 $M_\odot$)
Mrk 142	$0.40^{+0.12}_{-0.14}$	$2.17^{+0.68}_{-0.75}$
SBS 1116+583A	$1.05^{+0.33}_{-0.29}$	$5.80^{+1.84}_{-1.58}$
Arp 151	$1.22^{+0.16}_{-0.22}$	$6.72^{+0.89}_{-1.19}$
Mrk 1310	$0.41^{+0.12}_{-0.13}$	$2.24^{+0.68}_{-0.69}$
Mrk 202	$0.26^{+0.15}_{-0.10}$	$1.42^{+0.83}_{-0.56}$
NGC 4253	$0.32^{+0.21}_{-0.20}$	$1.76^{+1.15}_{-1.11}$
NGC 4748	$0.47^{+0.16}_{-0.21}$	$2.57^{+0.90}_{-1.14}$
NGC 5548	$14.9^{+3.4}_{-4.9}$	82^{+19}_{-27}
NGC 6814	$3.36^{+0.54}_{-0.56}$	$18.5^{+3.0}_{-3.1}$

[a] Assuming $f = 5.5$.

Bentz et al. 2009

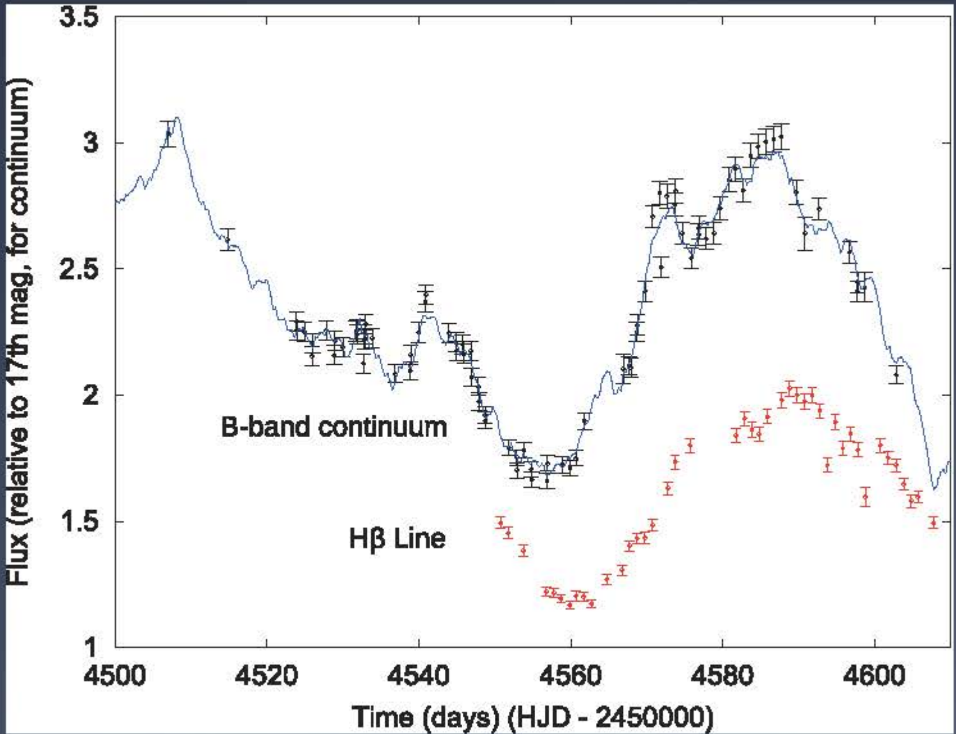
A new approach: Geometric and dynamical models

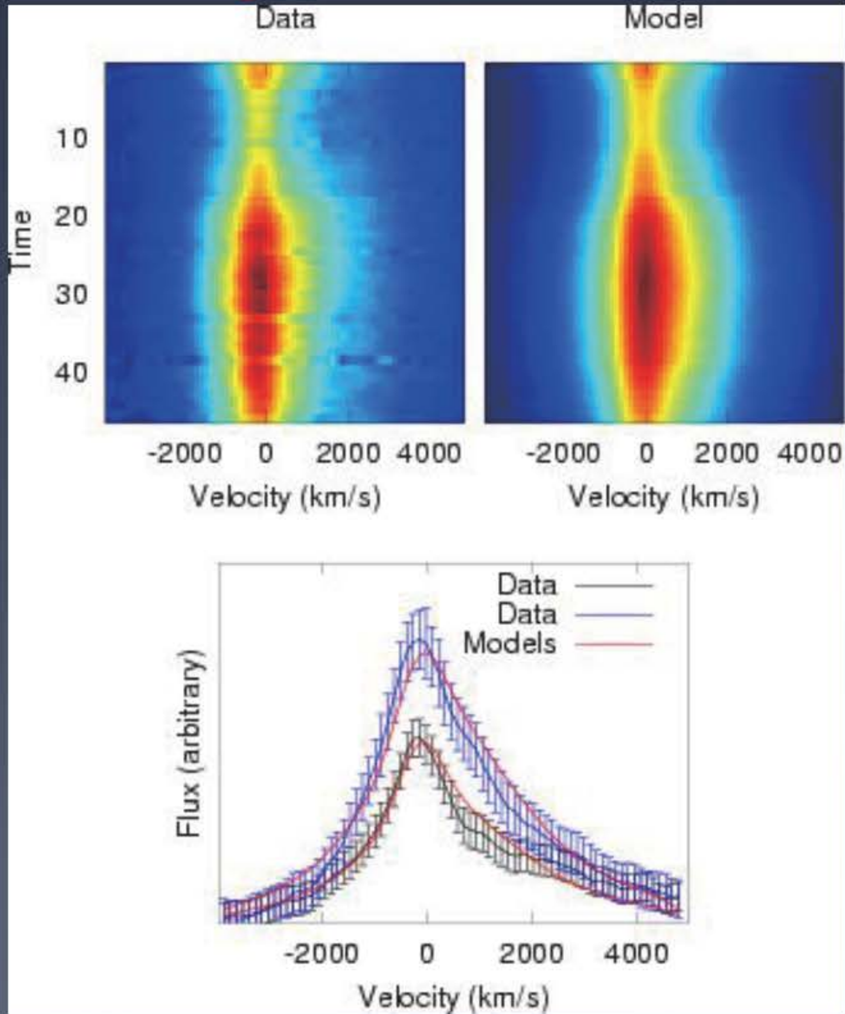




Pancoast, Brewer & Treu, 2011

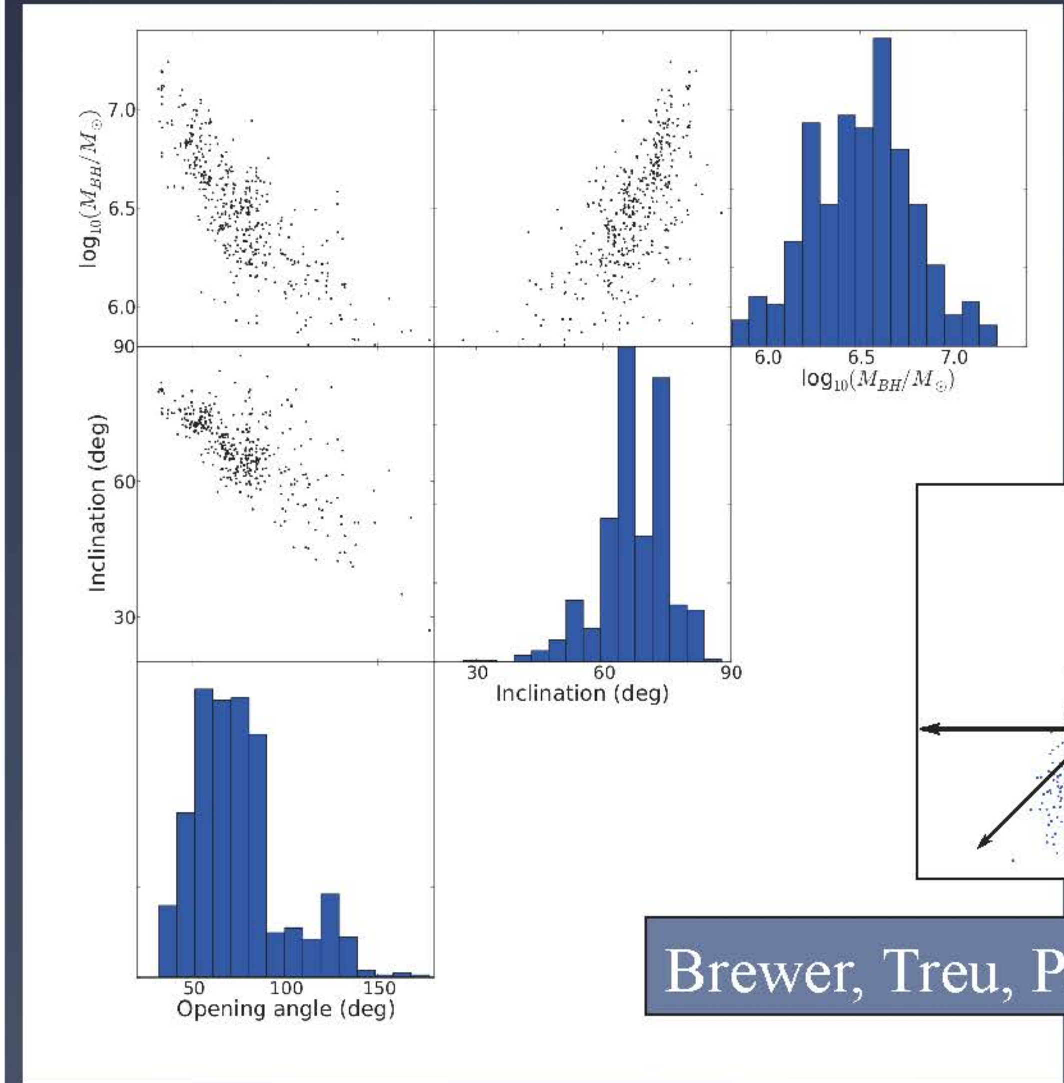
Geometric and dynamical models: Application to Arp 151

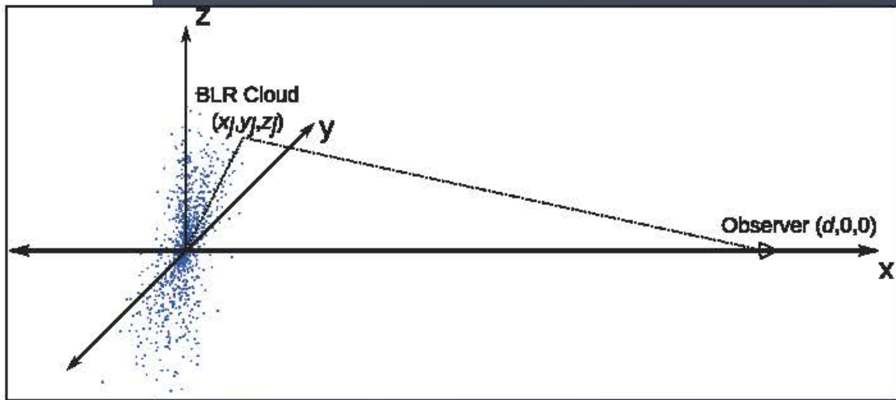




Brewer, Treu, Pancoast et al 2011

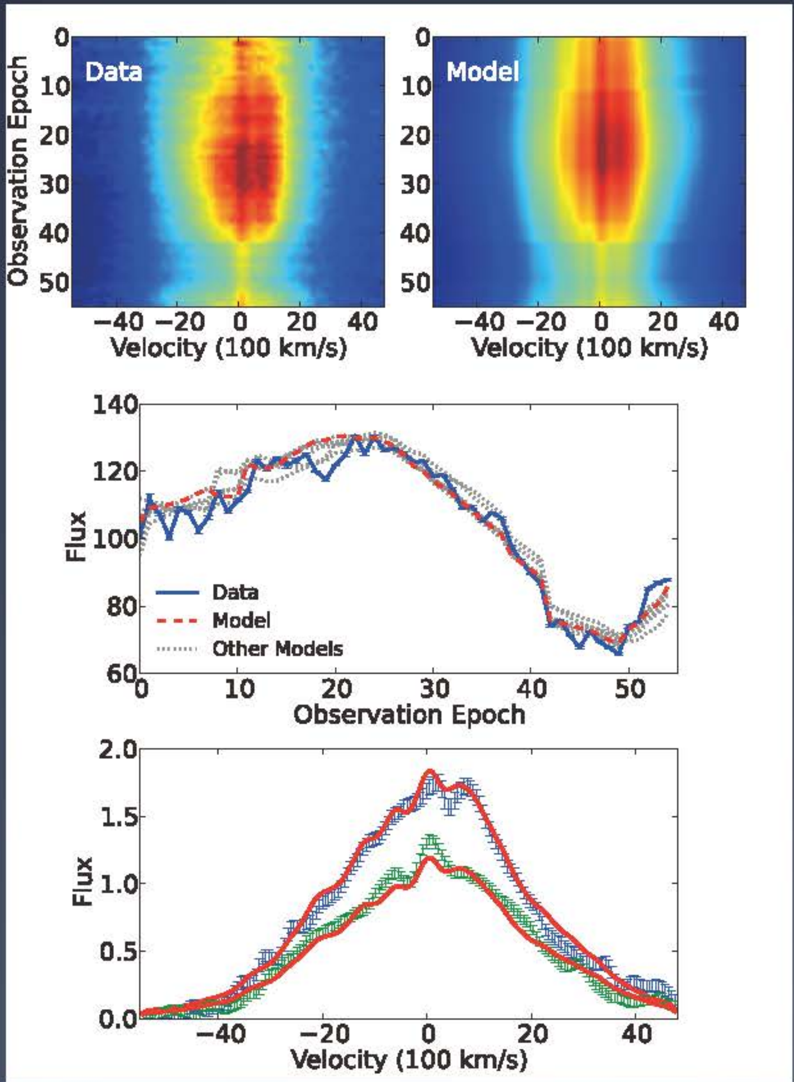
Geometric and dynamical models: Application to Arp 151

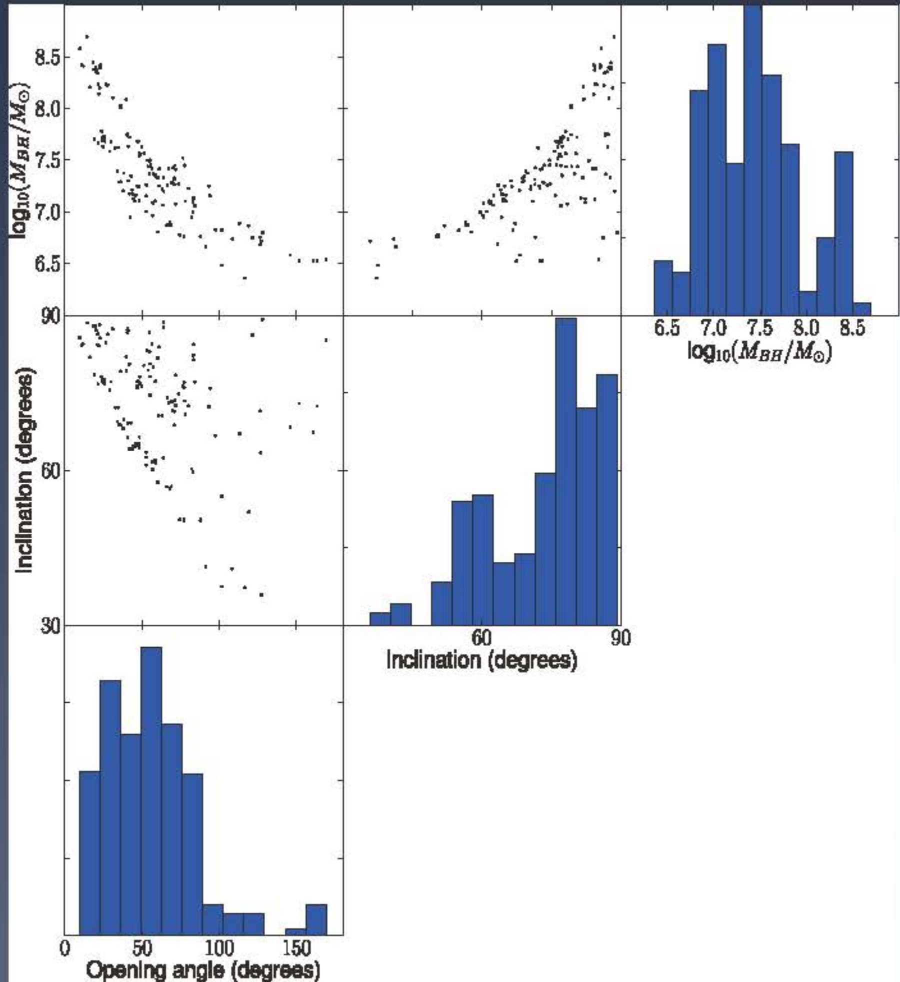




Brewer, Treu, Pancoast et al 2011

Geometric and dynamical models: Application to Mrk 150





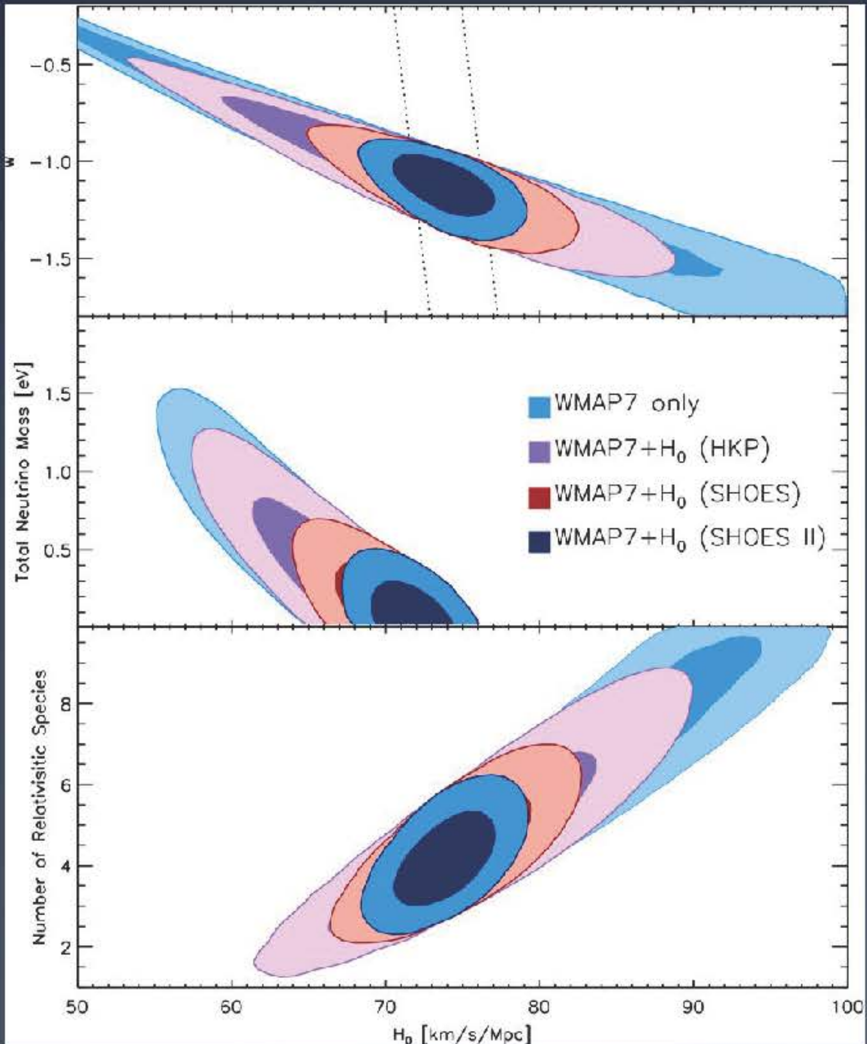
Pancoast, Brewer, Treu, et al 2011

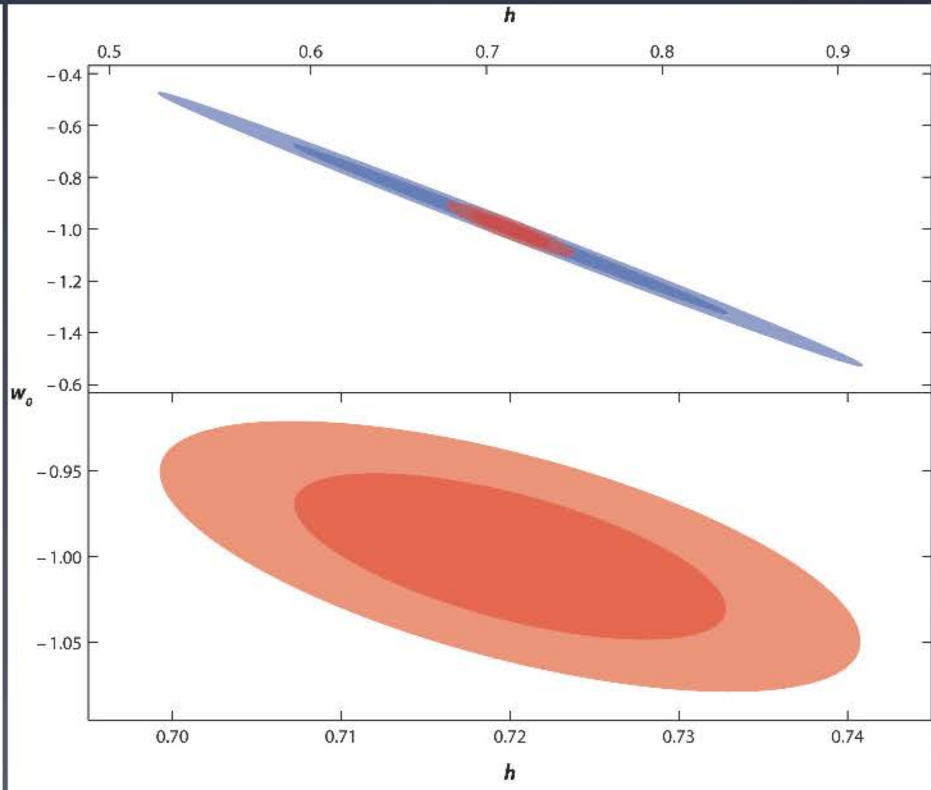
Black holes

- When did the first black holes form?
  - at $z>7$
- How do we measure their mass?
  - In the time domain, using reverberation mapping
- What are future prospects?
  - Future wide field surveys such as LSST and possibly WFIRST/ Euclid should discover black holes at $z>7$
  - LSST will also provide photometric light curves, which we can use to select targets for spectroscopic follow-up to measure their masses
  - Follow-up likely to be the bottle-neck. Need robotic telescopes.

Dark Energy

H_0 is an essential ingredient

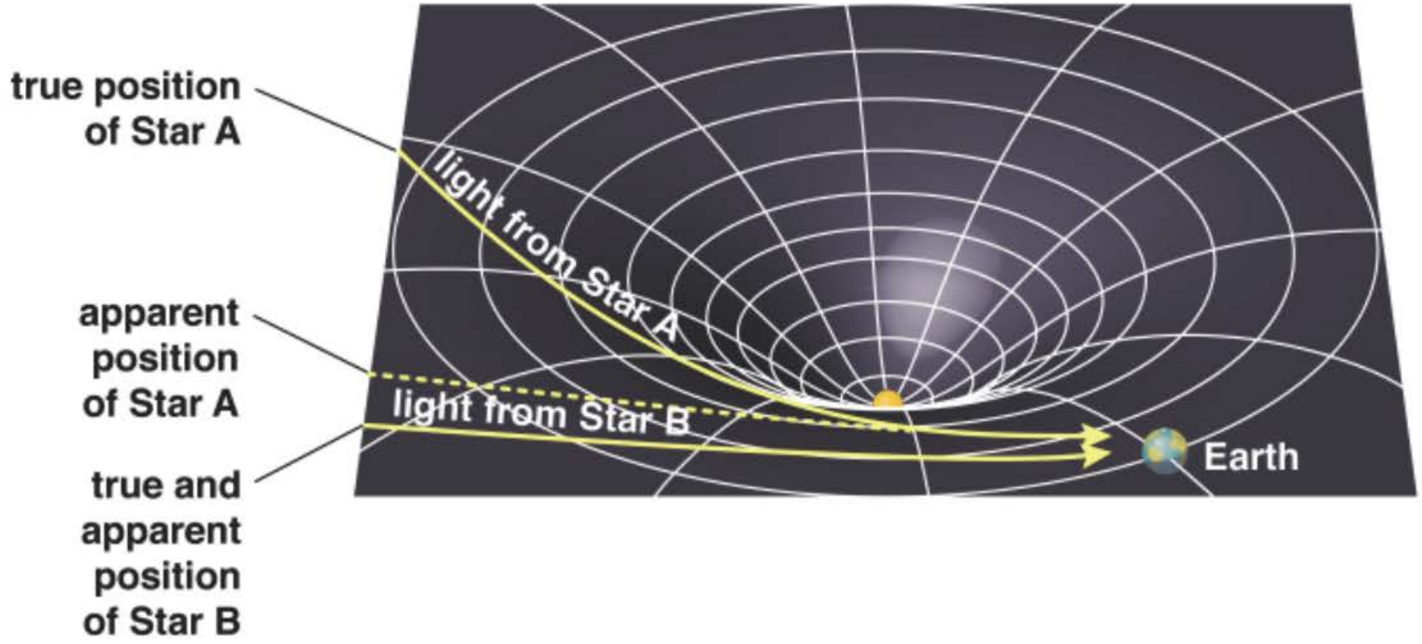




Freedman WL, Madore BF. 2010.
Annu. Rev. Astron. Astrophys. 48:673–710

Riess et al. 2011

What is Gravitational Lensing? Matter curves space…



…and in rare circumstances create multiple images

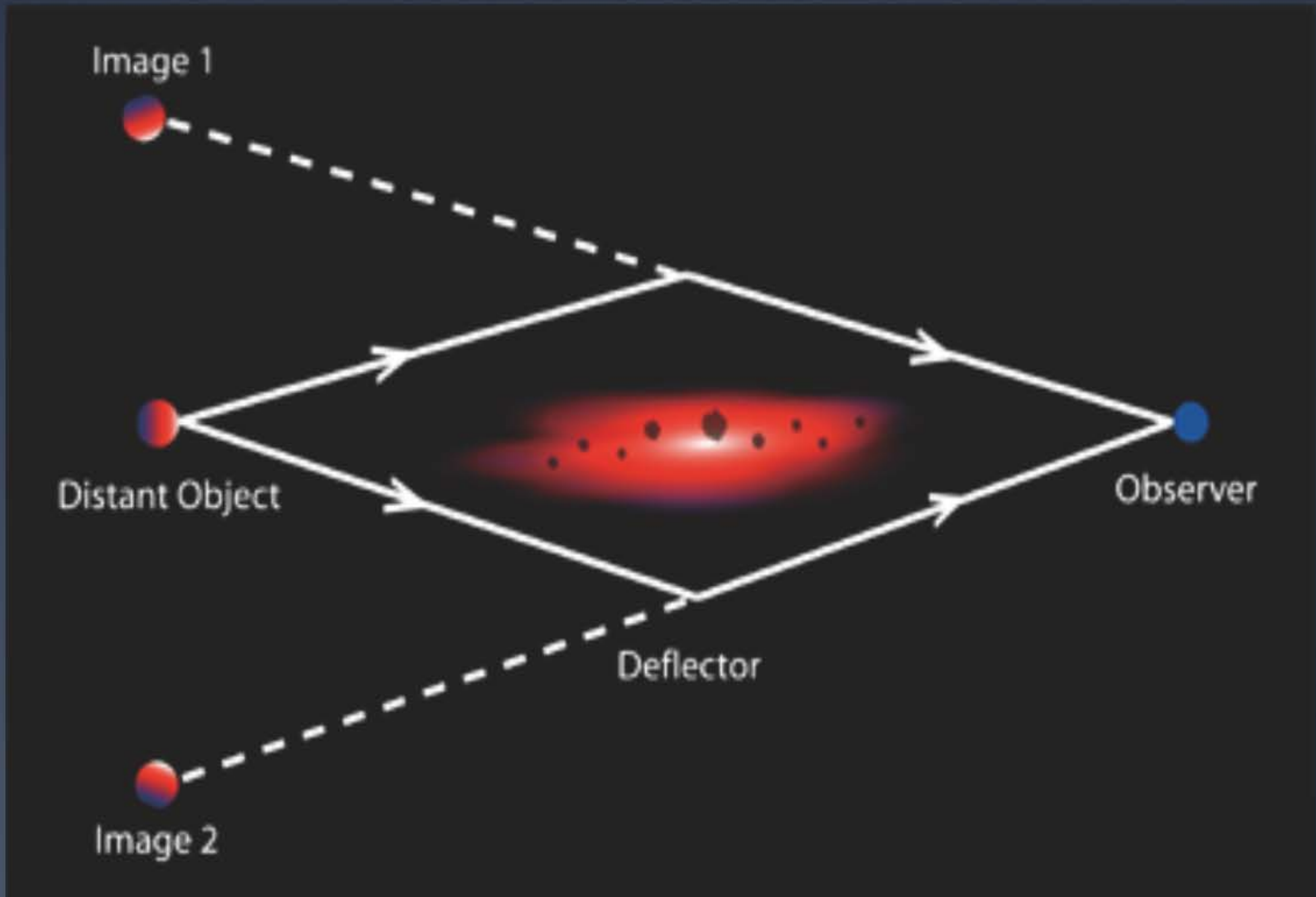
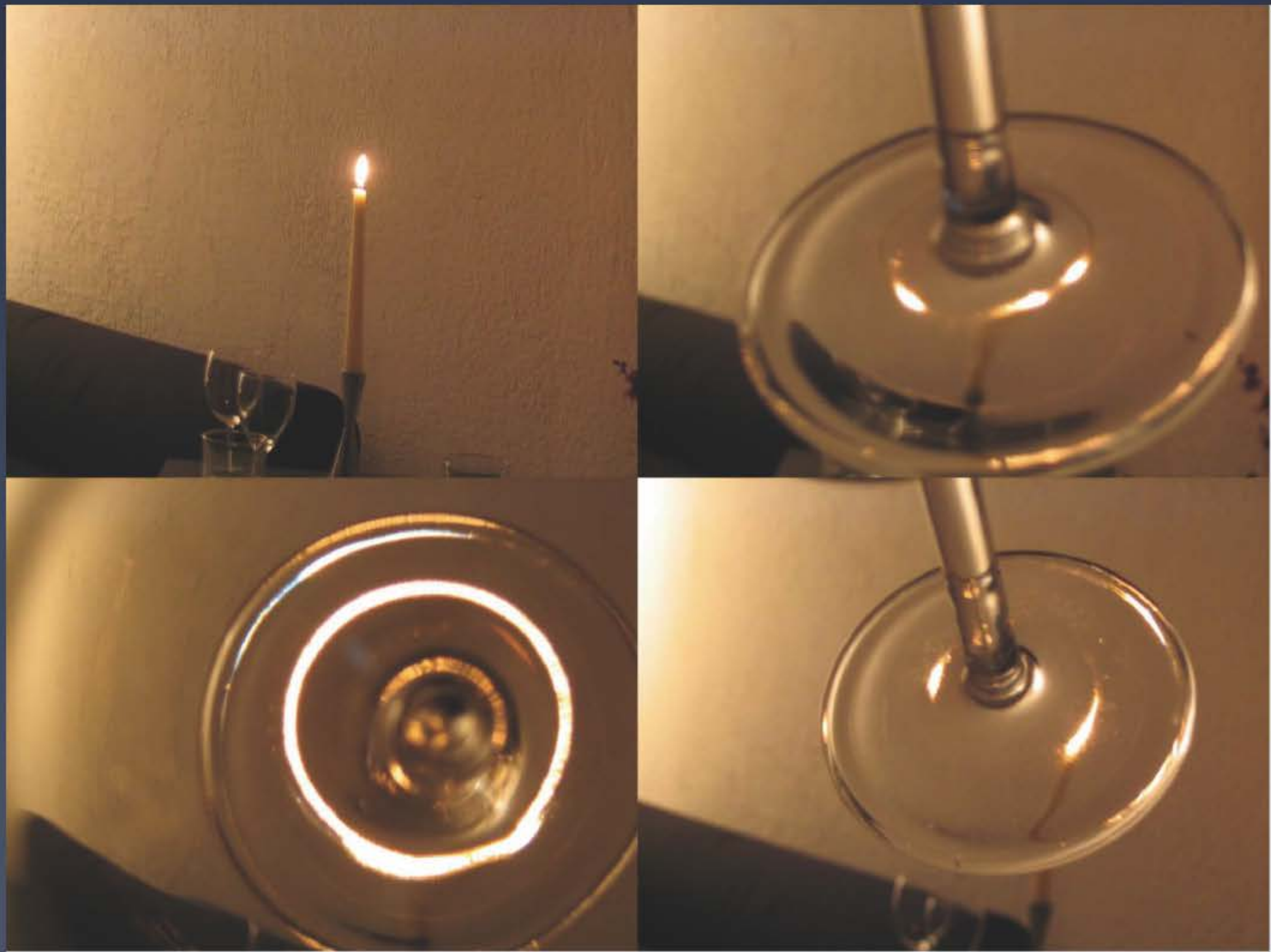


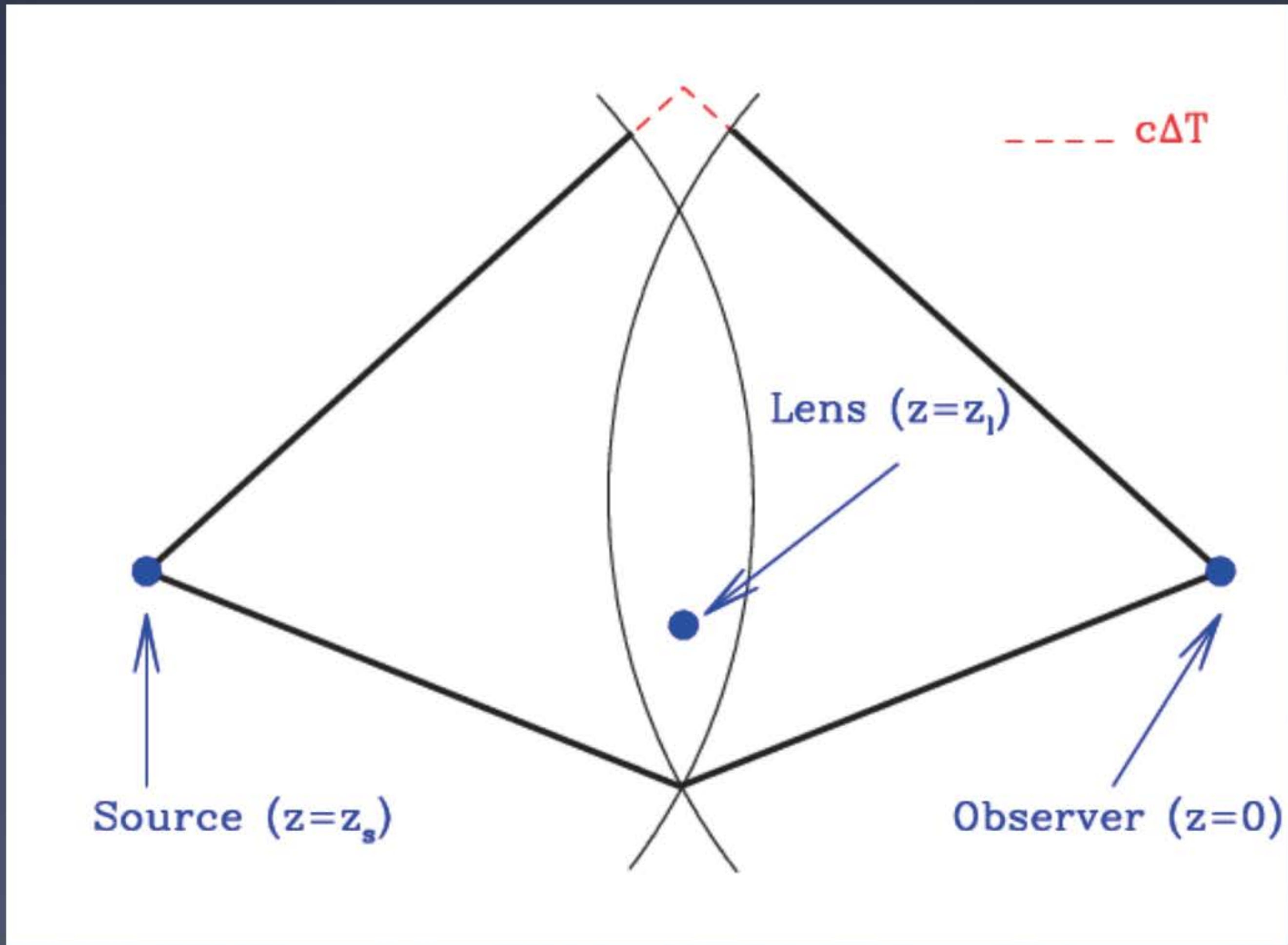
Image separation is a direct measurement of mass, luminous or dark!

Why is it called Lensing?



Courtesy of P.J.Marshall

Cosmography from time delays: how does it work?



Strong lensing in terms of Fermat's principle

Fermat distance

Shapiro delay

$$t(\vec{\theta}) = \frac{(1+z_{\rm d})}{c}\frac{D_{\rm d}D_{\rm s}}{D_{\rm ds}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2-\psi(\vec{\theta})\right]$$

Excess time delay

geometric time delay

Observables: flux, position, and arrival time of the multiple images

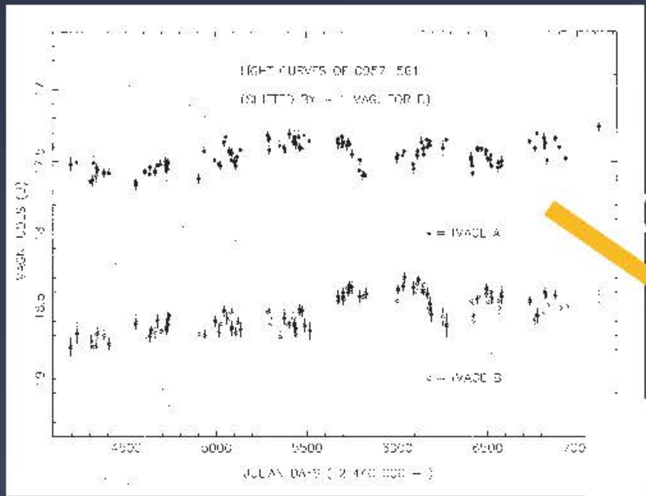
Cosmography from time delays: A brief history

* 1964 Method proposed
* 70s First lenses discovered
* 80s First time delay measured
  * Controversy. Solution: improve sampling
* 90s First Hubble Constant measured
  * Controversy. Solution: improve mass models
* 2002 Carnegie Centennial Symposium
  * Controversy. Solution: more constraints, e.g. stellar kinematics, extended sources
* 2000s: modern monitoring (COSMOGRAIL, Fassnacht & others)
* 2010 Putting it all together: precision measurements (6-7% from a single lens)

Cosmography with strong lenses: the 4 problems solved

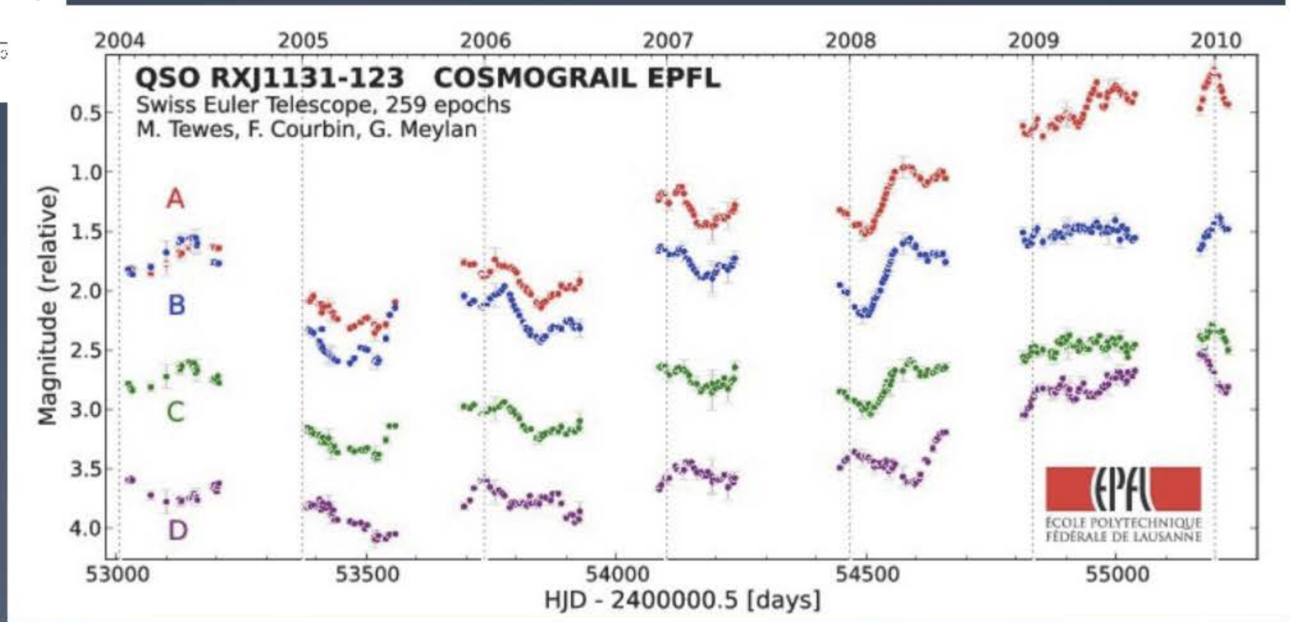
* Time delay – 2-3 %
  * Tenacious monitoring (e.g. Fassnacht et al. 2002); COSMOGRAIL (Meylan/Courbin)
* Astrometry – 10-20 mas
  * Hubble/VLA/(Adaptive Optics?)
* Lens potential (2-3%)
  * Stellar kinematics/Extended sources (Treu & Koopmans 2002; Suyu et al. 2009)
* Structure along the line of sight (2-3%)
  * Galaxy counts and numerical simulations (Suyu et al. 2009)
  * Stellar kinematics (Koopmans et al. 2003)

Cosmography with strong lenses: measuring time delays



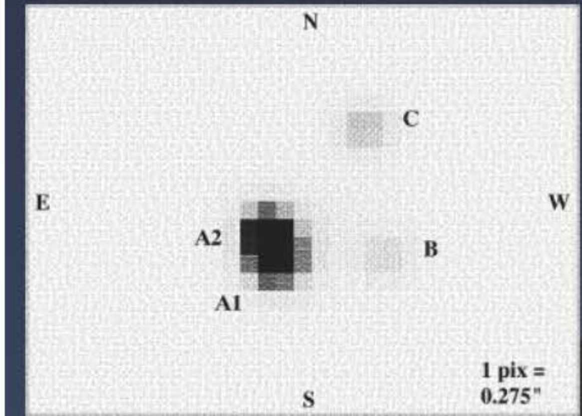
COSMOGRAIL: better data & better techinques

Vanderriest et al. 1989

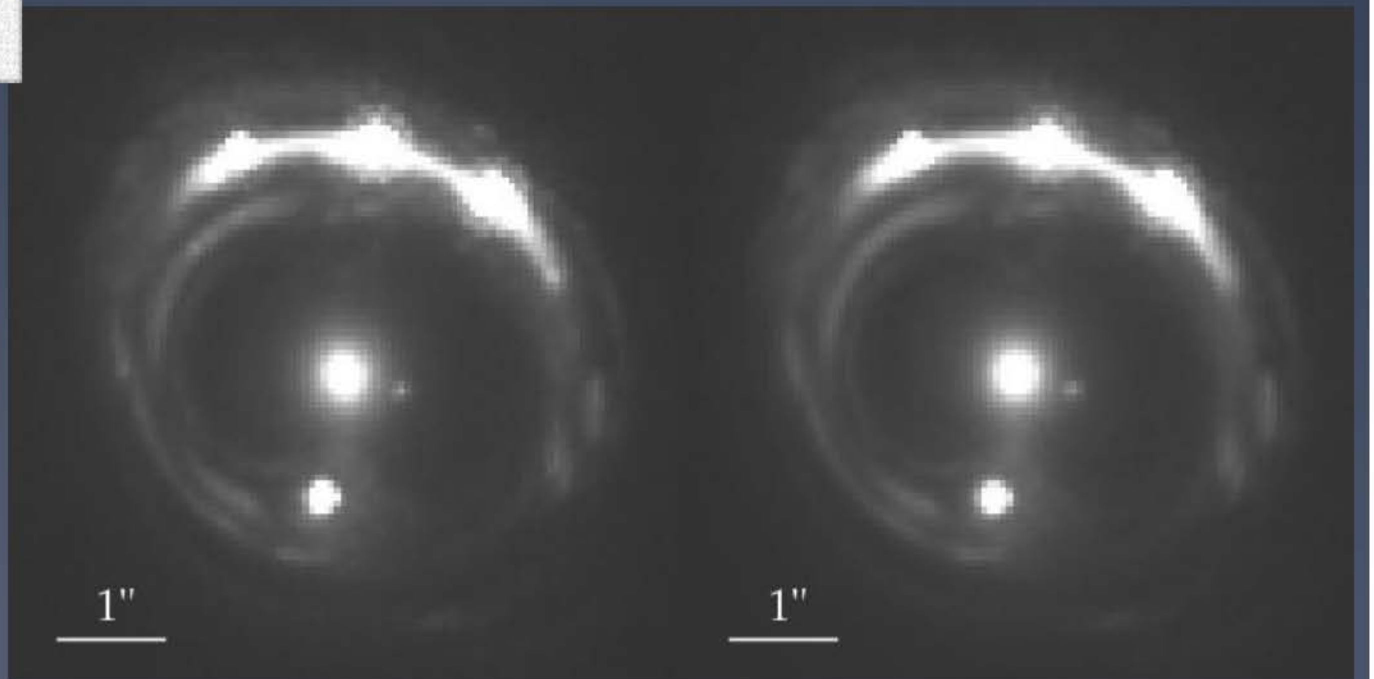


Cosmography with strong lenses: measuring the lens potential

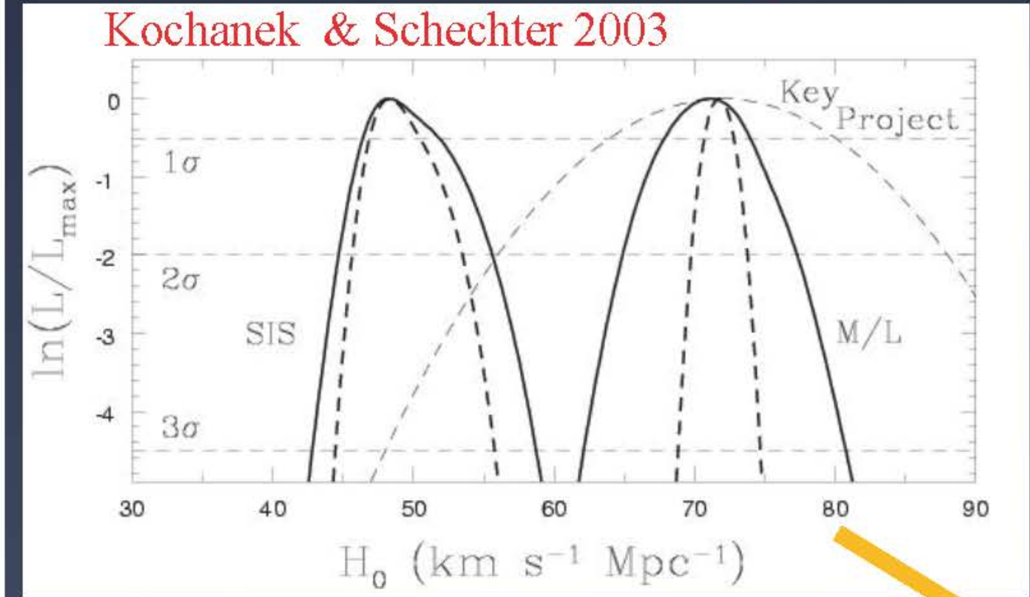
Schechter et al. 1997

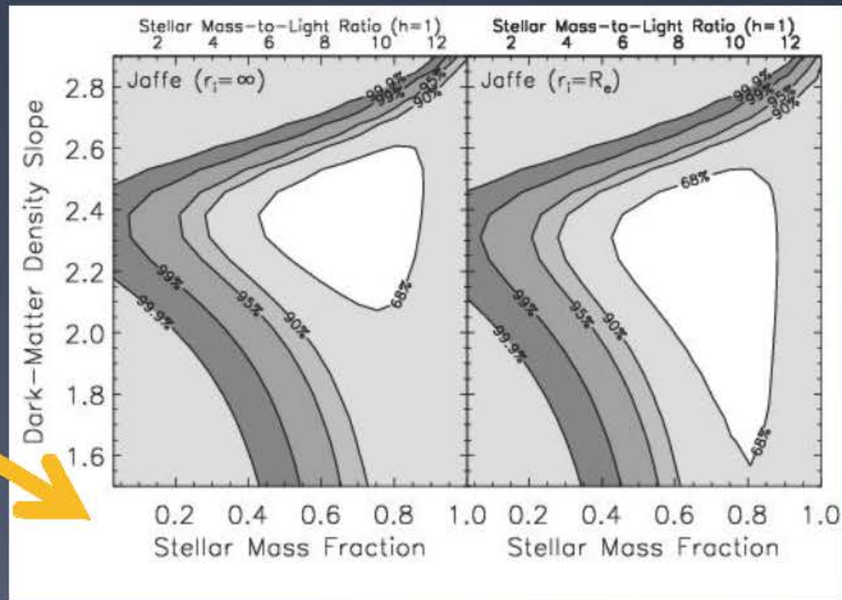


Host galaxy reconstruction; Suyu et al. 2012



Cosmography with strong lenses: measuring the lens potential

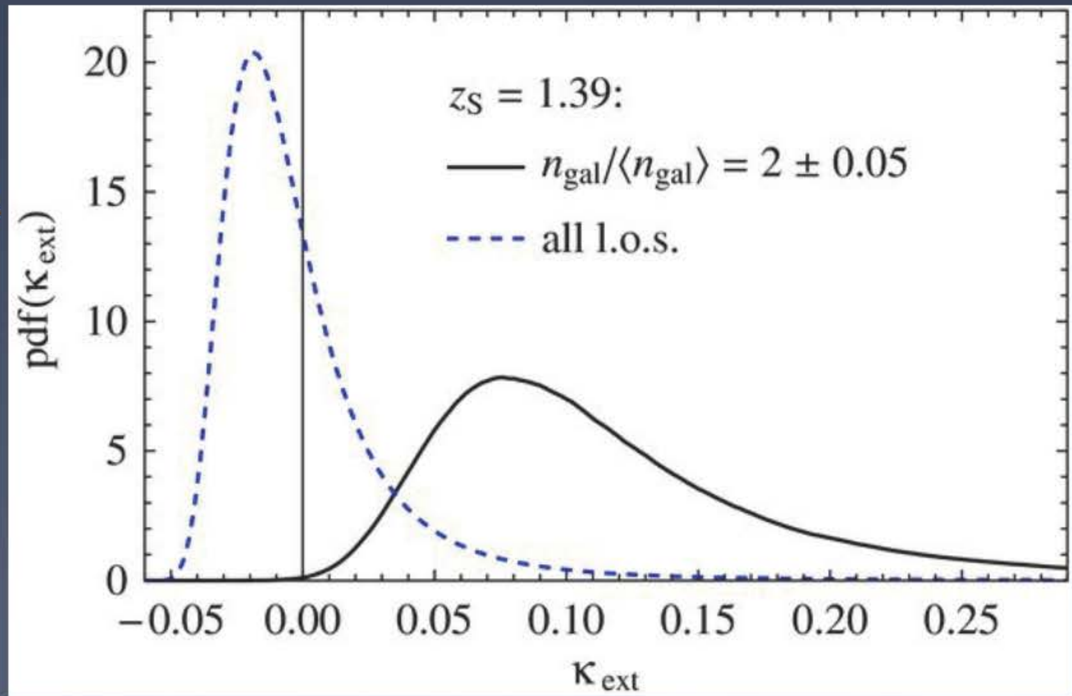




Stellar kinematics: Treu & Koopmans 2002

Cosmography with strong lenses: Structure along the line of sight

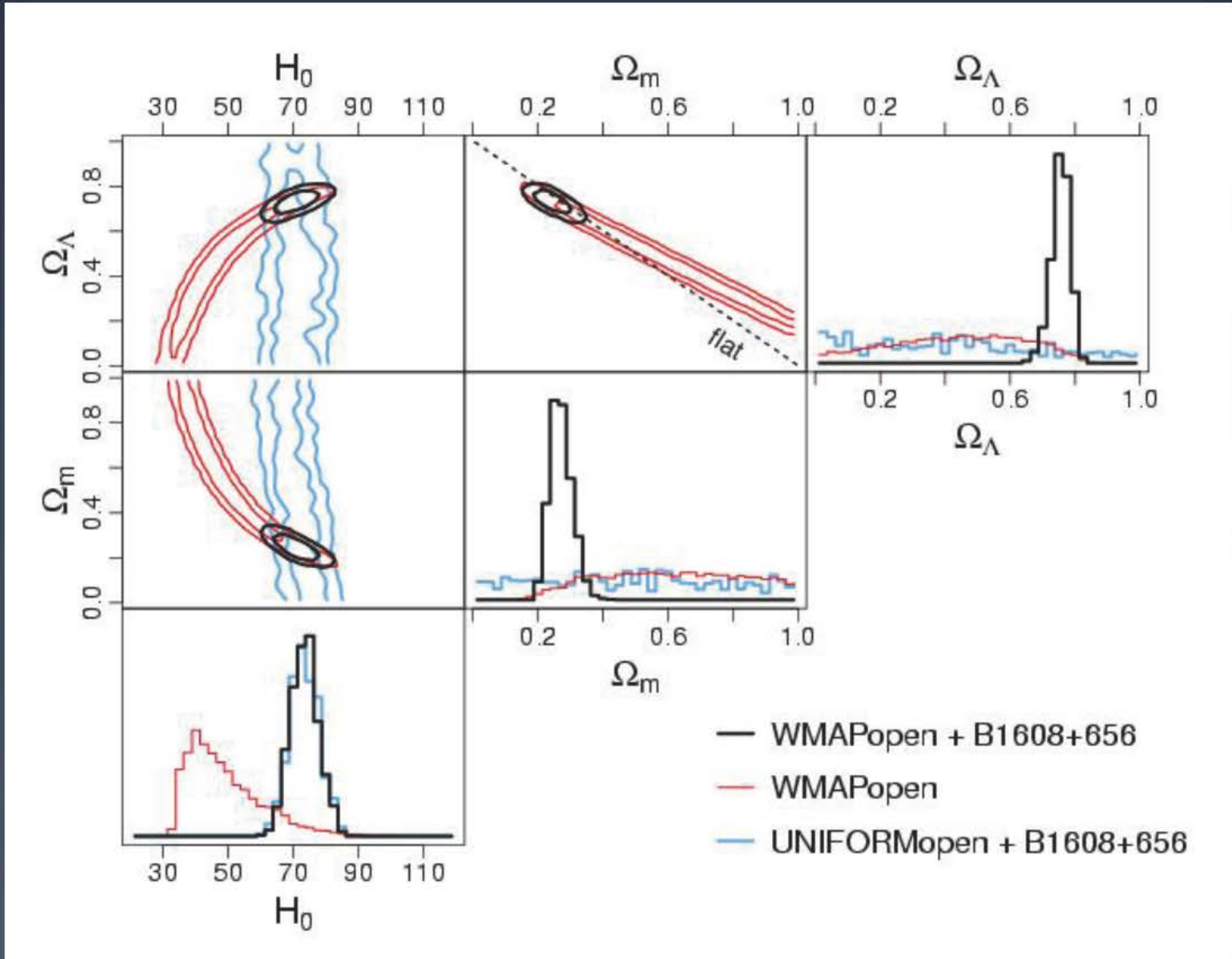
???



Suyu et al. 2010

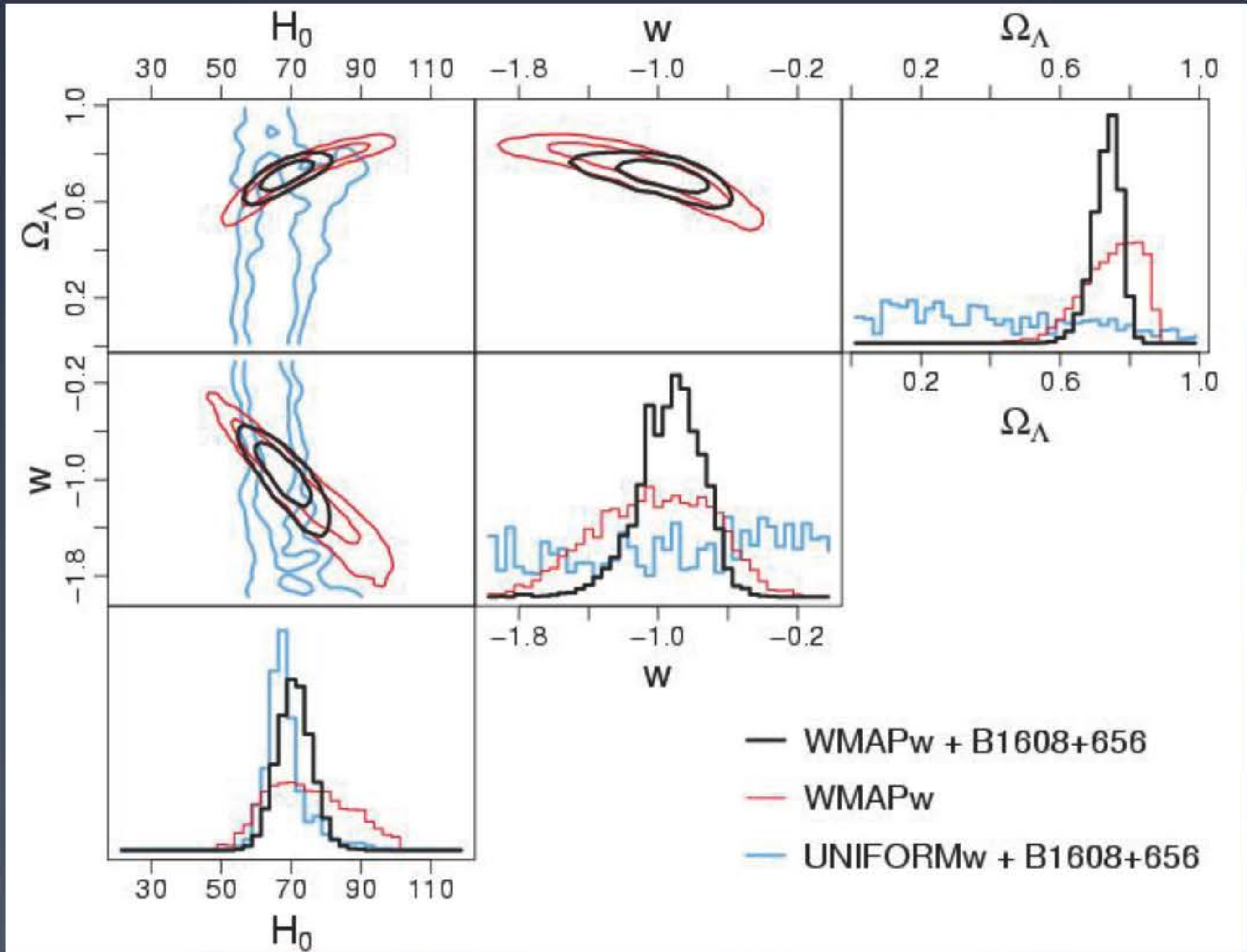
Pilot: B1608+656

B1608: Constraints for w=-1



Suyu et al. 2010

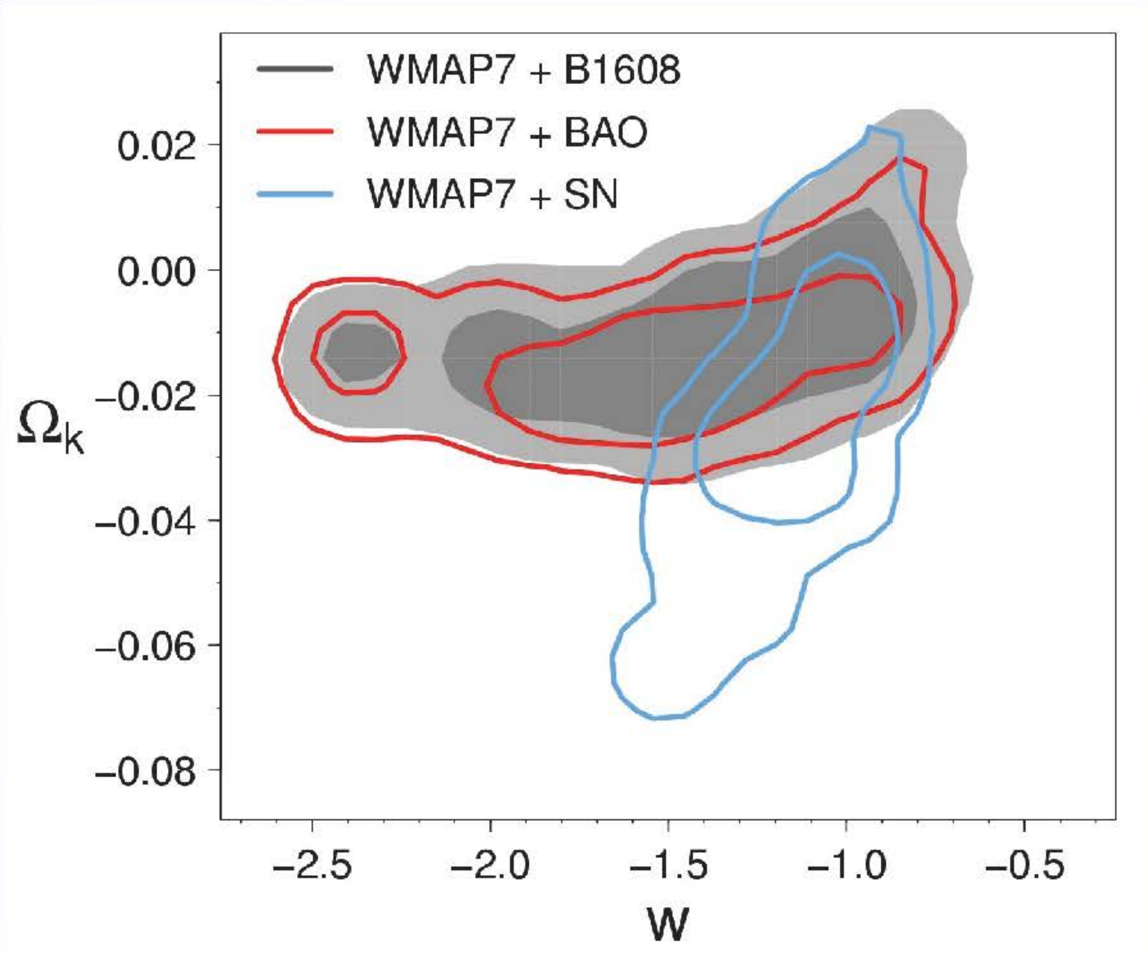
Assuming flatness



Suyu et al. 2010

B1608: Constraints on Dark Energy

For curved wCDM

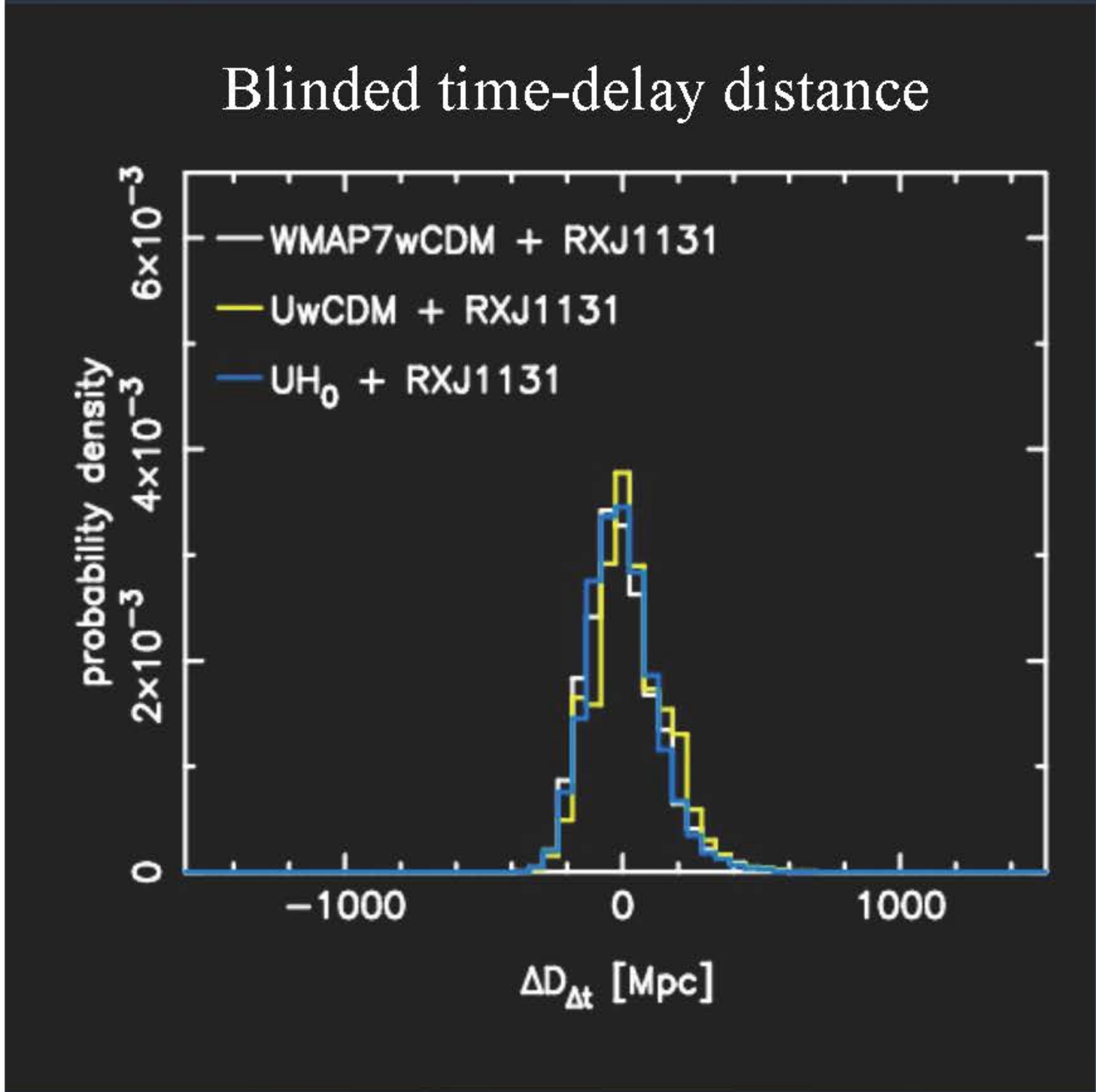


With WMAP7:

- B1608+656 is comparable to BAO [Percival et al. 2010]
- B1608+656 and BAO both primarily constrain Ω_k
- SN [Hicken et al. 2009] primarily constrains w

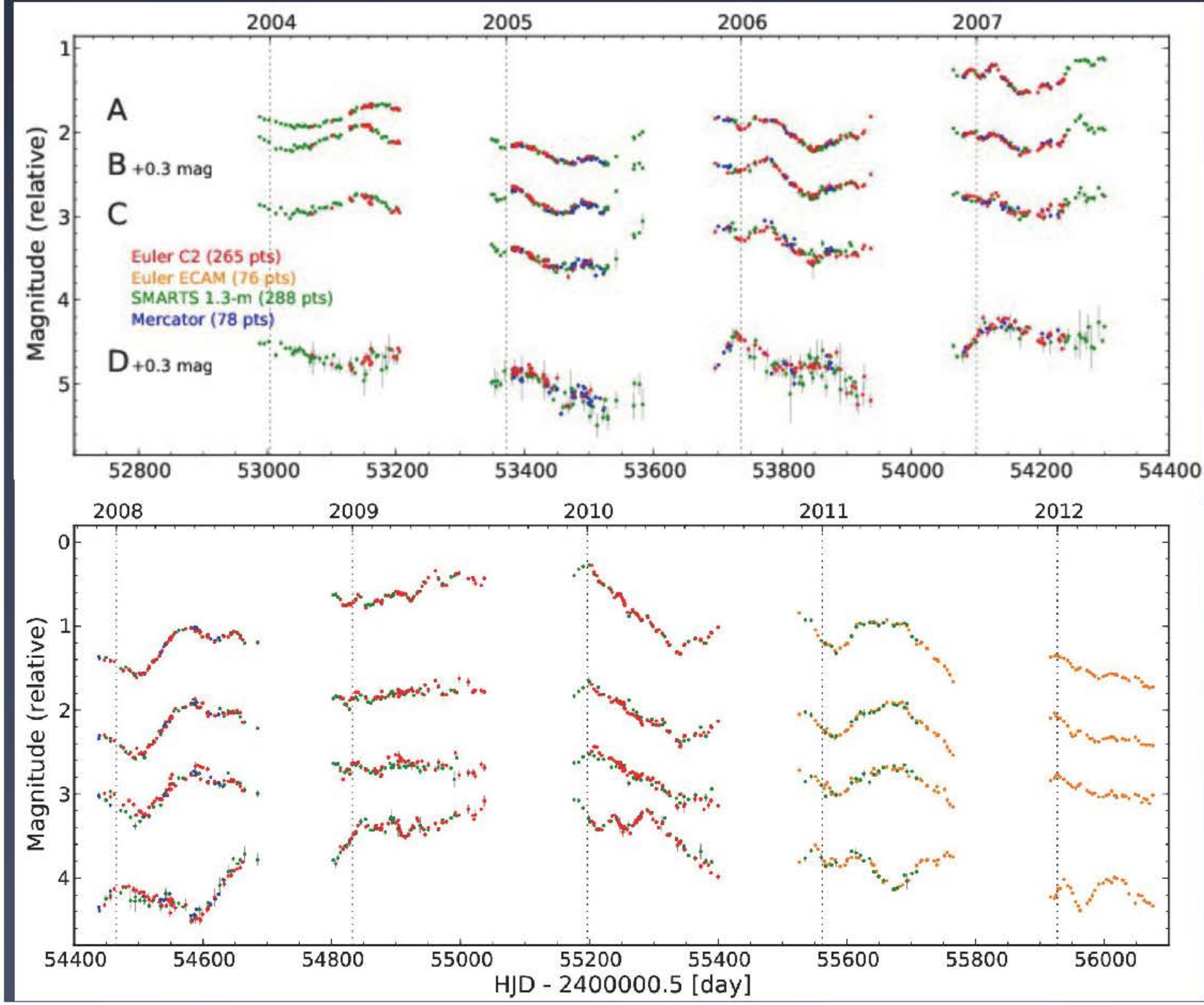
Blind Analysis: 1131-1231

Blind Analysis



- Prevents unconscious experimenter bias
- allows us to test for the presence of residual systematics, if any
- PDF centroids of cosmological parameters are hidden

Time delays of RXJ1131-1231



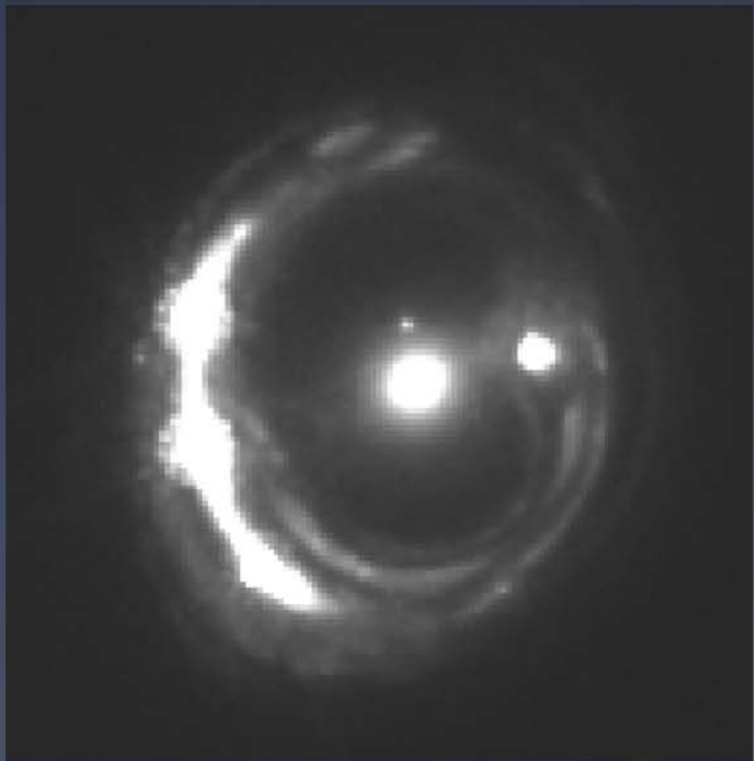
Time delay with 1.5% accuracy!

[Tewes et al. 12b (1208:6009)]

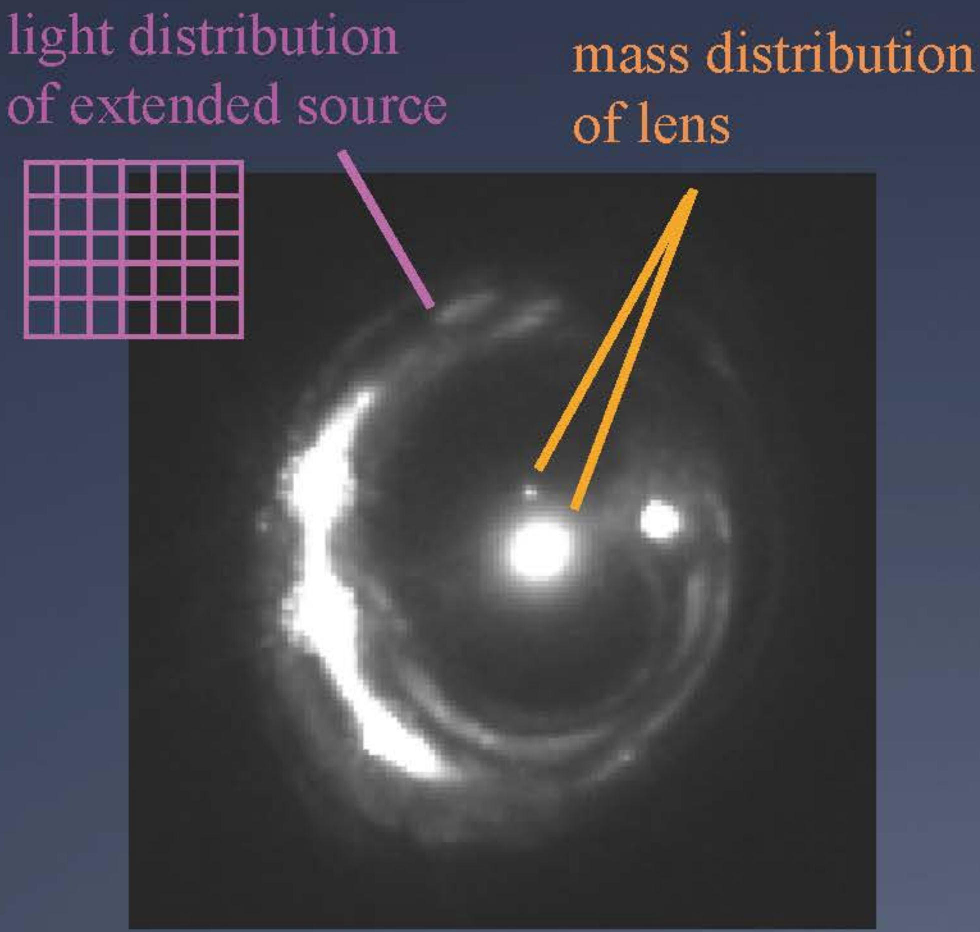
Based on state-of-the-art curve modeling techniques [Tewes et al. 12a (1208:5598)]

Lens Model

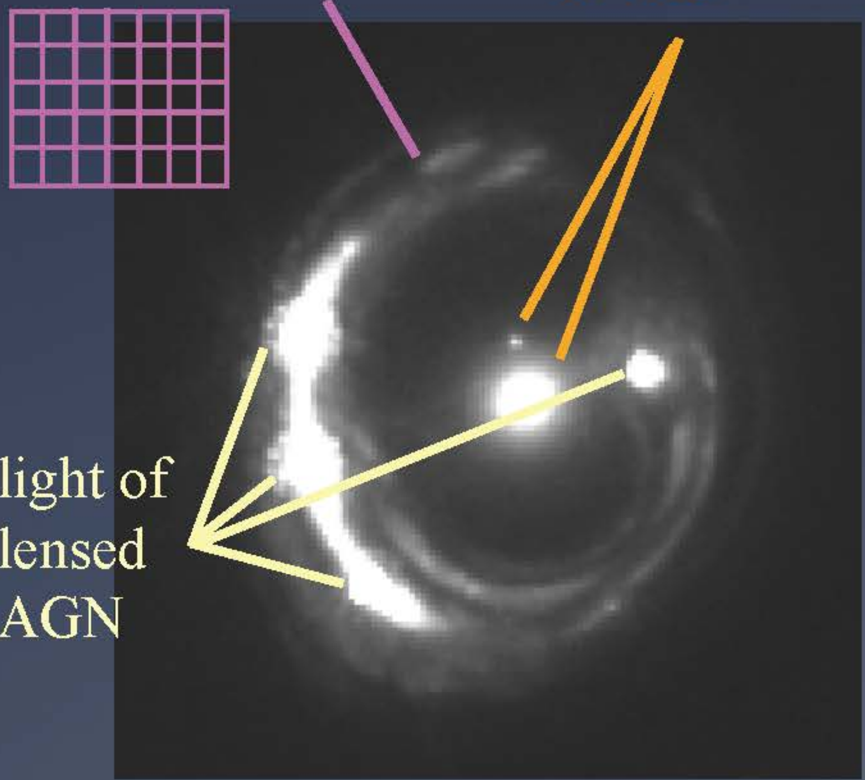
Observed Image



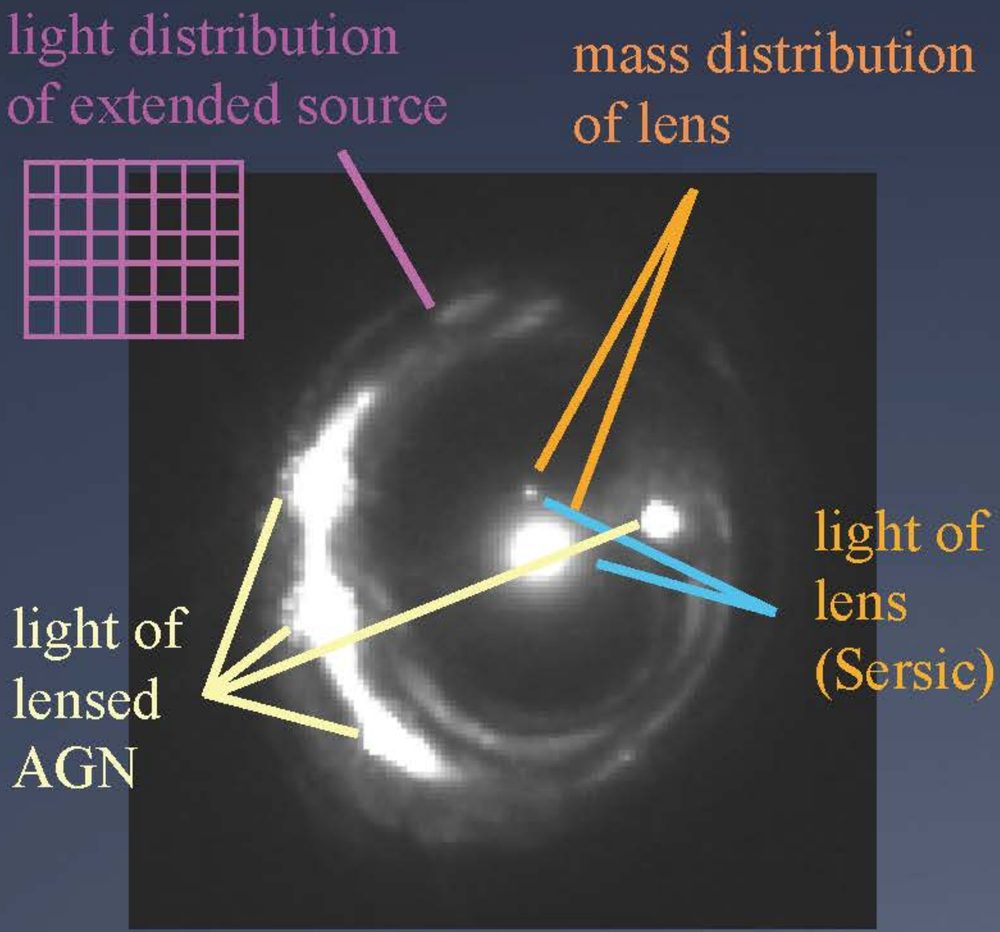
Lens Model


light distribution
of extended source
mass distribution
of lens

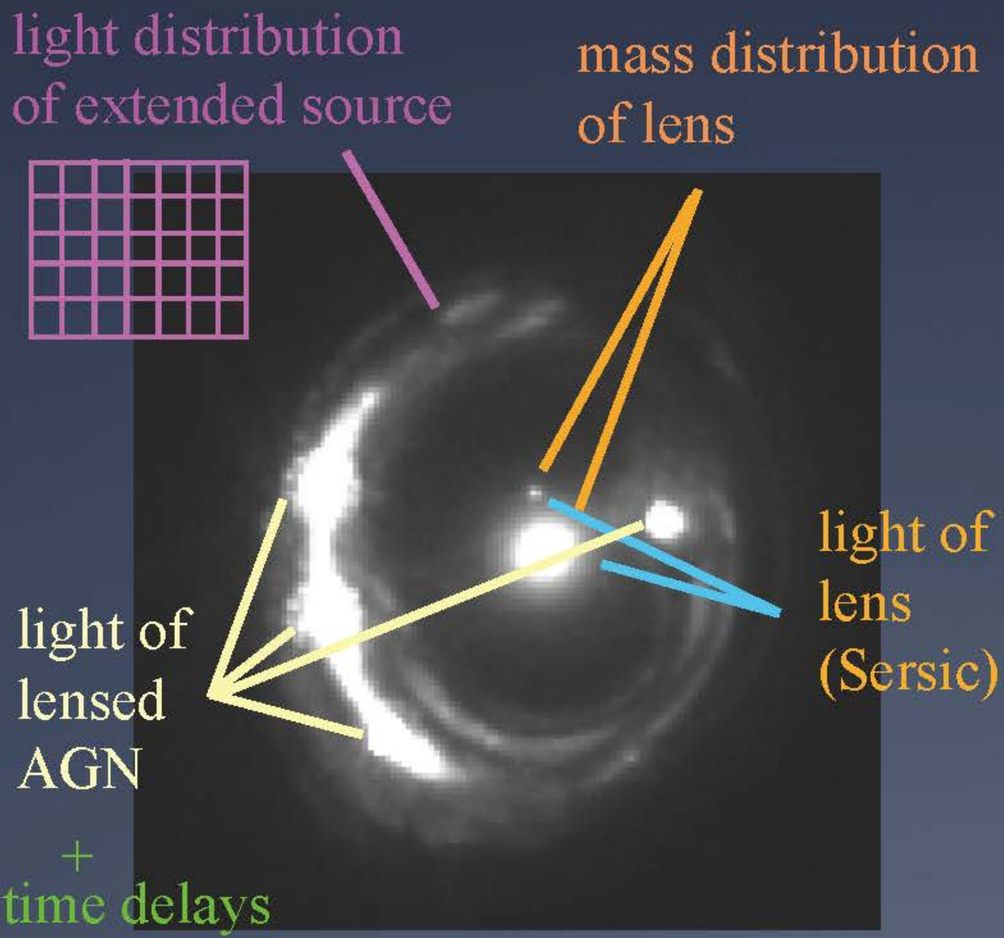
Lens Model


light distribution
of extended source
mass distribution
of lens
light of
lensed
AGN

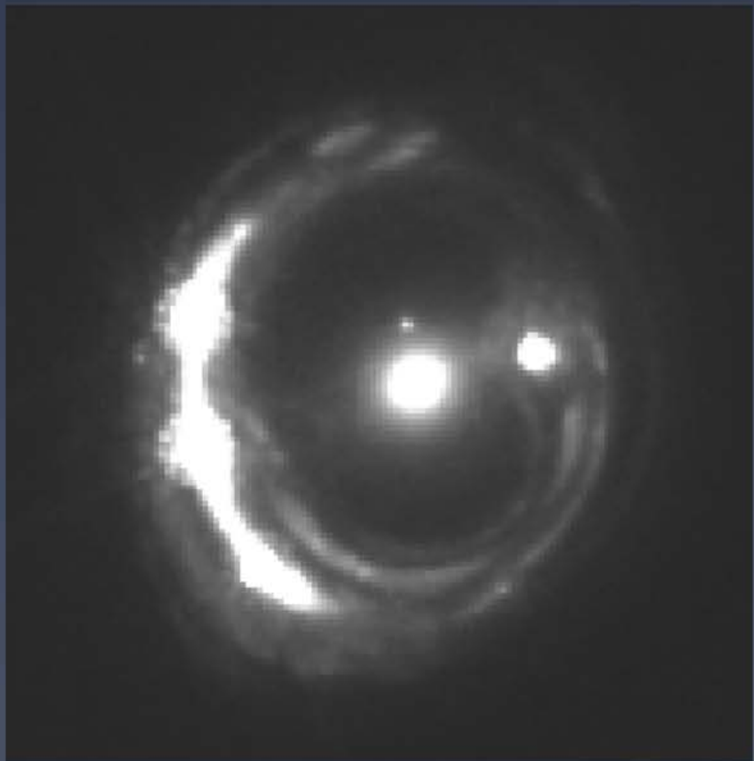
Lens Model

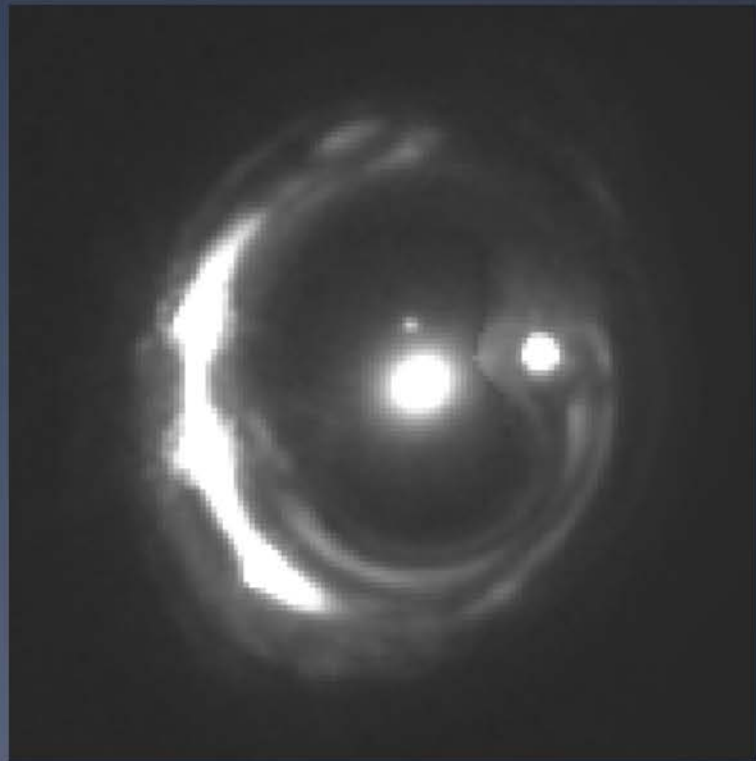

light distribution
of extended source
mass distribution
of lens
light of
lens
(Sersic)
light of
lensed
AGN

Lens Model


light distribution
of extended source
mass distribution
of lens
light of
lens
(Sersic)
light of
lensed
AGN
+
time delays

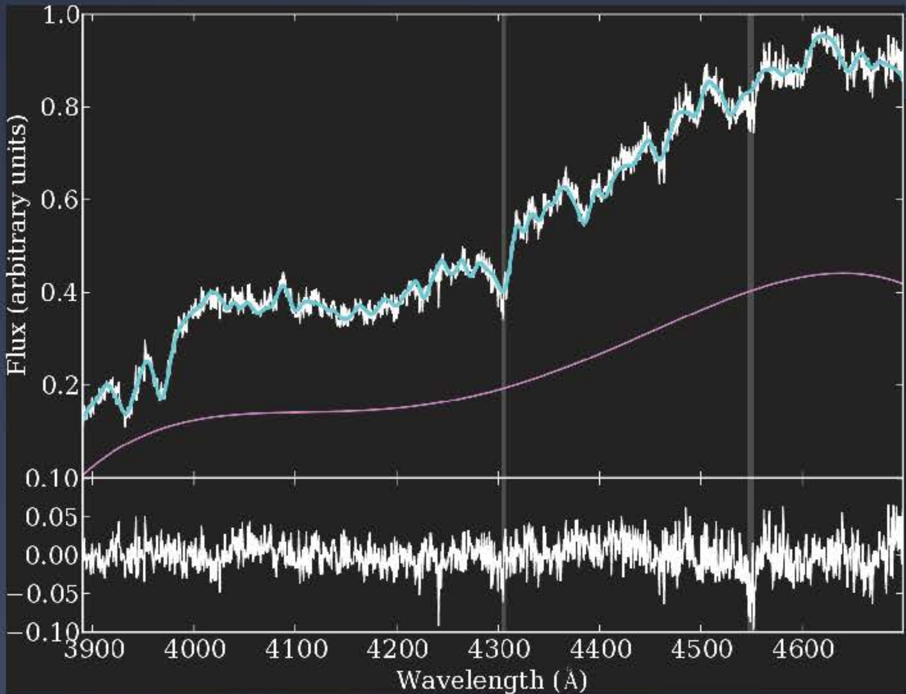
Lens Model





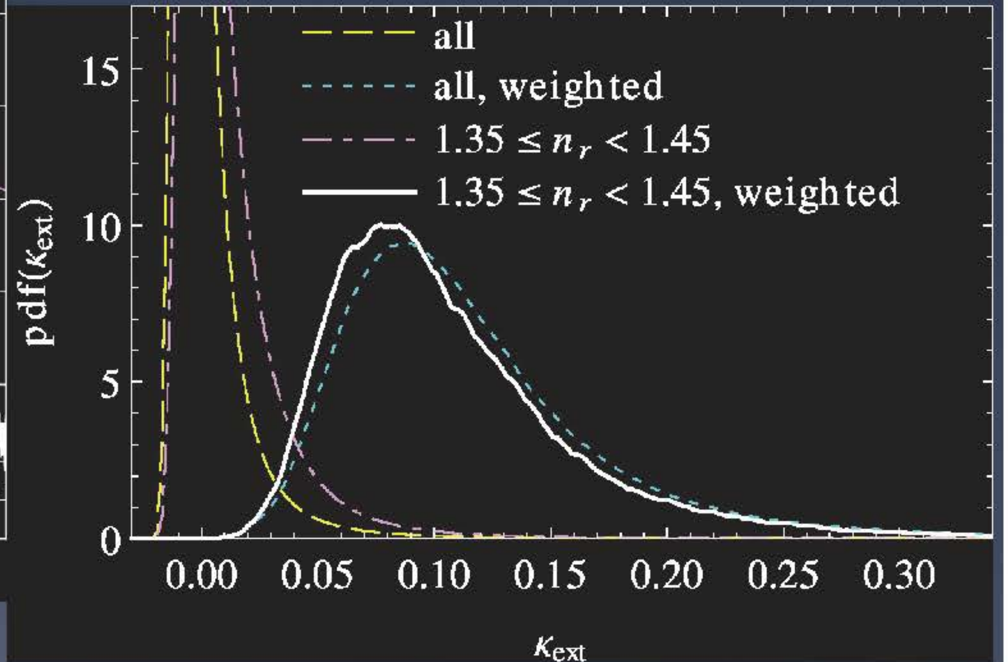
Line-of-sight Effects

Keck LRIS



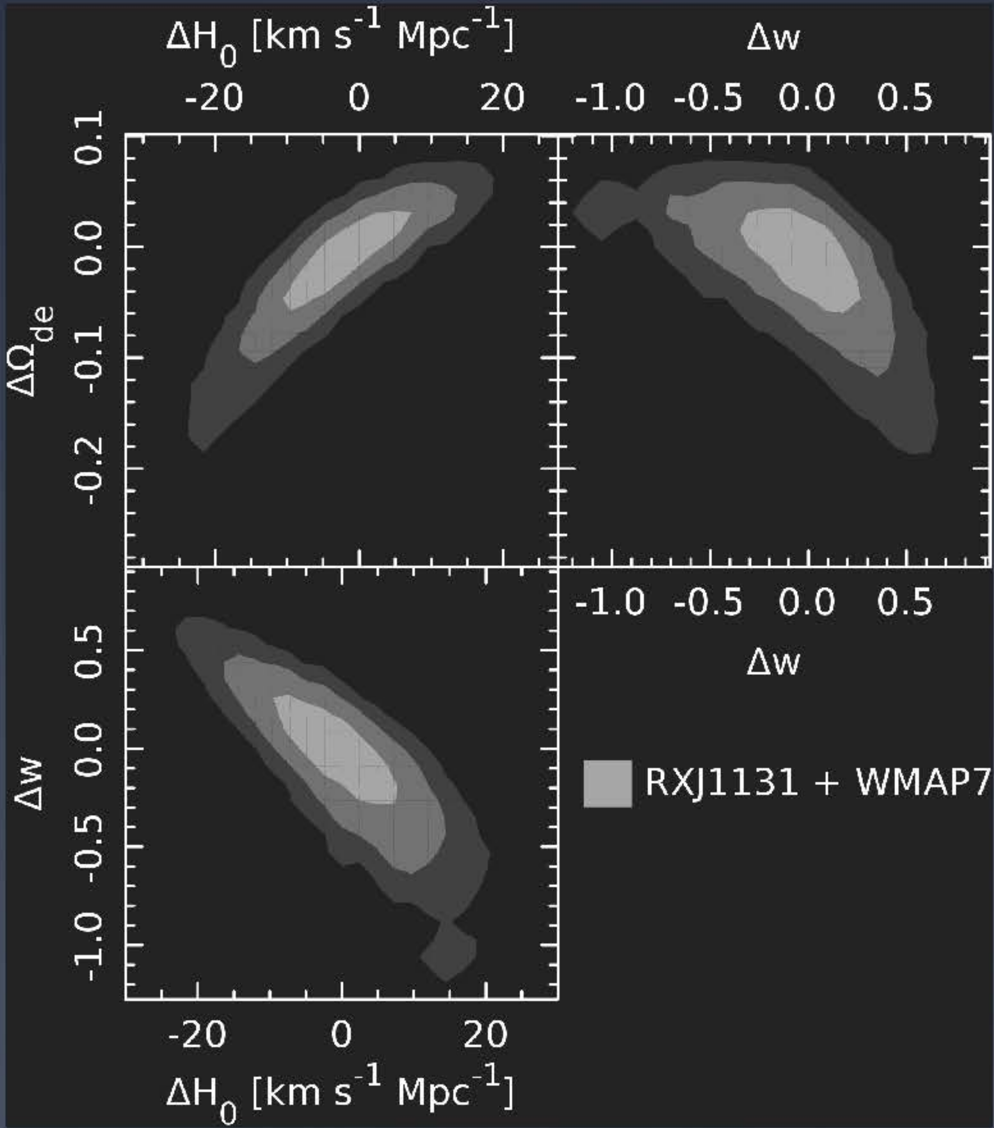
Velocity dispersion:
323 ± 20 km/s

Lens environment +
Millennium Simulation



[Suyu et al. 2012]

Cosmological Results



Blinded

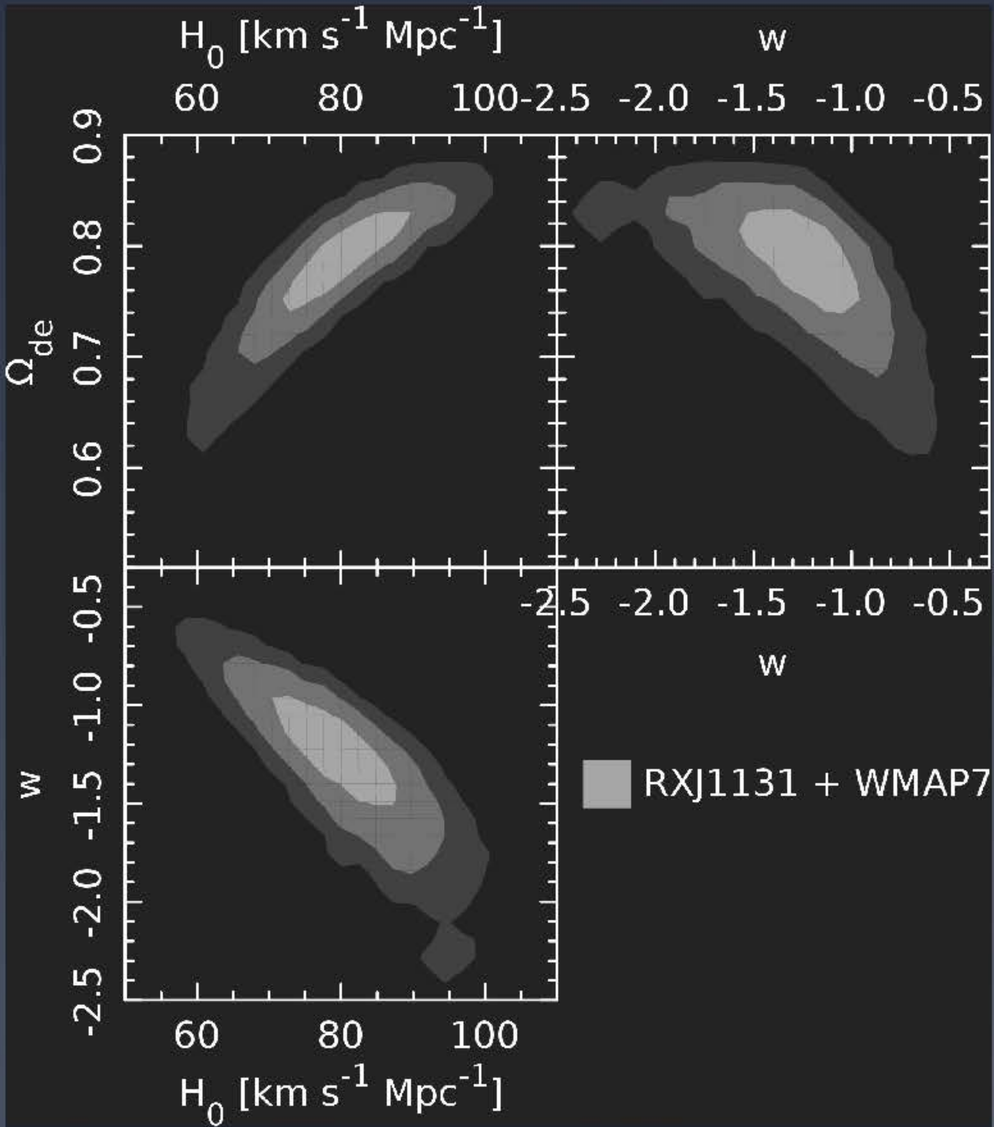
In combination with WMAP7 in flat wCDM cosmology

Precision comparable to that of B1608+656

Accuracy?

After completing the blind analysis and agreeing we would publish the results without modification once unblinded…

Cosmological Results



In combination with WMAP7 in flat wCDM cosmology:

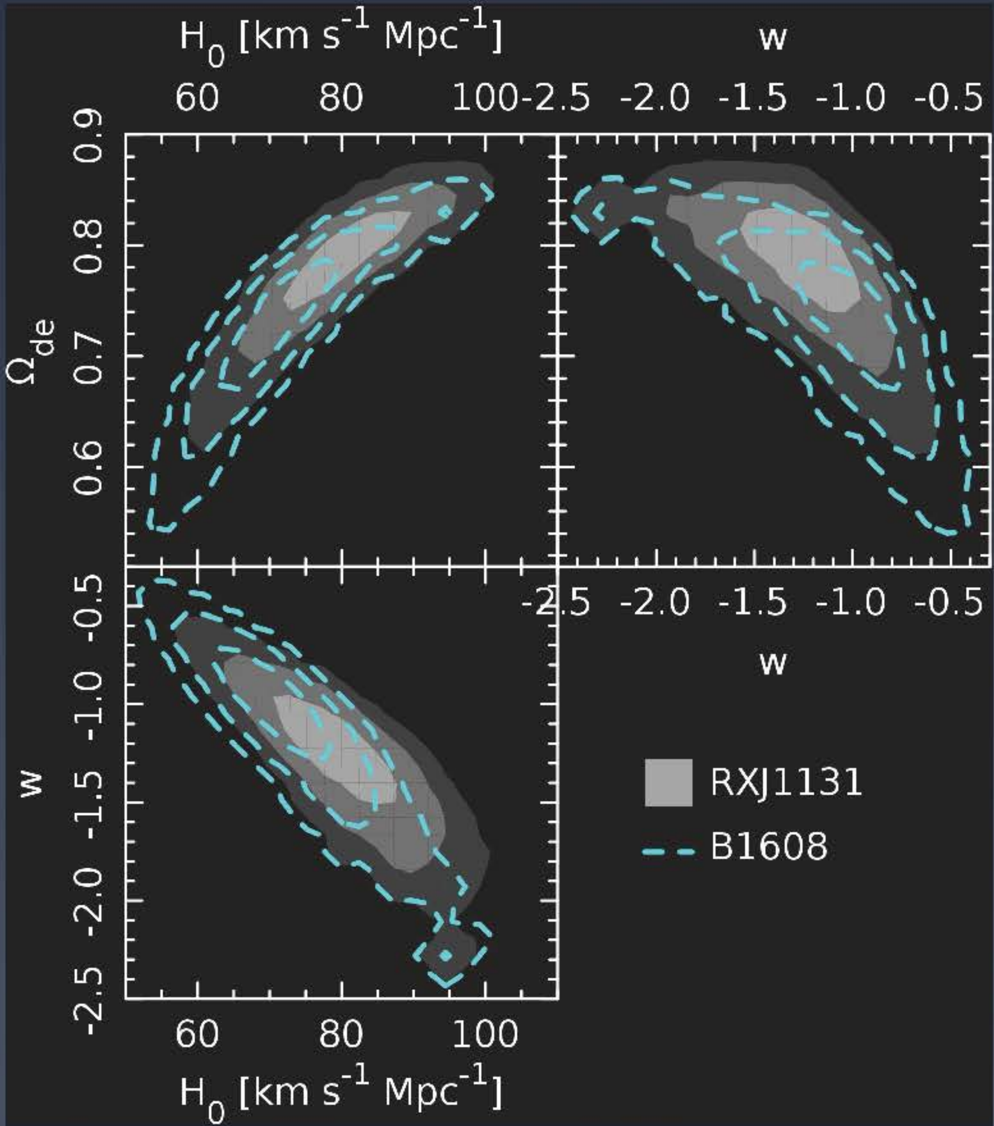
$$H_0 = 80.0^{+5.8}_{-5.7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$\Omega_{\mathrm{de}} = 0.79 \pm 0.03$$

$$w = -1.25^{+0.17}_{-0.21}$$

[Suyu et al. 2012 (arXiv:1208.6010)]

Consistency with B1608+656



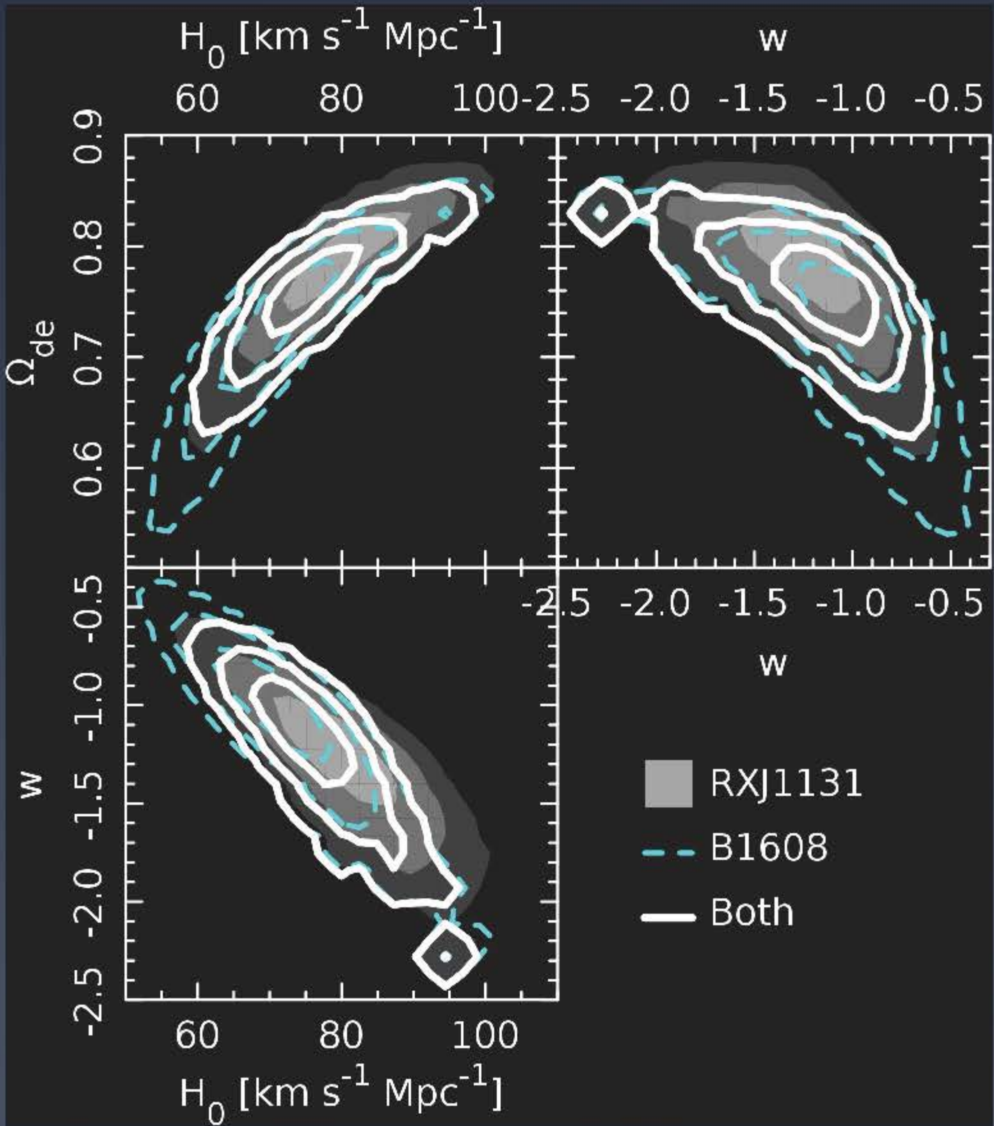
Two lenses share global cosmological parameters

$$\frac{P(H^{\mathrm{global}}|\boldsymbol{d}^{\mathrm{R}}, \boldsymbol{d}^{\mathrm{B}})}{P(H^{\mathrm{ind}}|\boldsymbol{d}^{\mathrm{R}}, \boldsymbol{d}^{\mathrm{B}})} = 3.2$$

Two lenses require independent cosmo. parameters

➡ Results of the lenses RXJ1131-1231 and B1608+656 are statistically consistent

Constraints from Two Lenses



In combination with WMAP7 in wCDM cosmology:

$$H_0 = 75.2^{+4.4}_{-4.2}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$\Omega_{\mathrm{de}} = 0.76^{+0.02}_{-0.03}$$

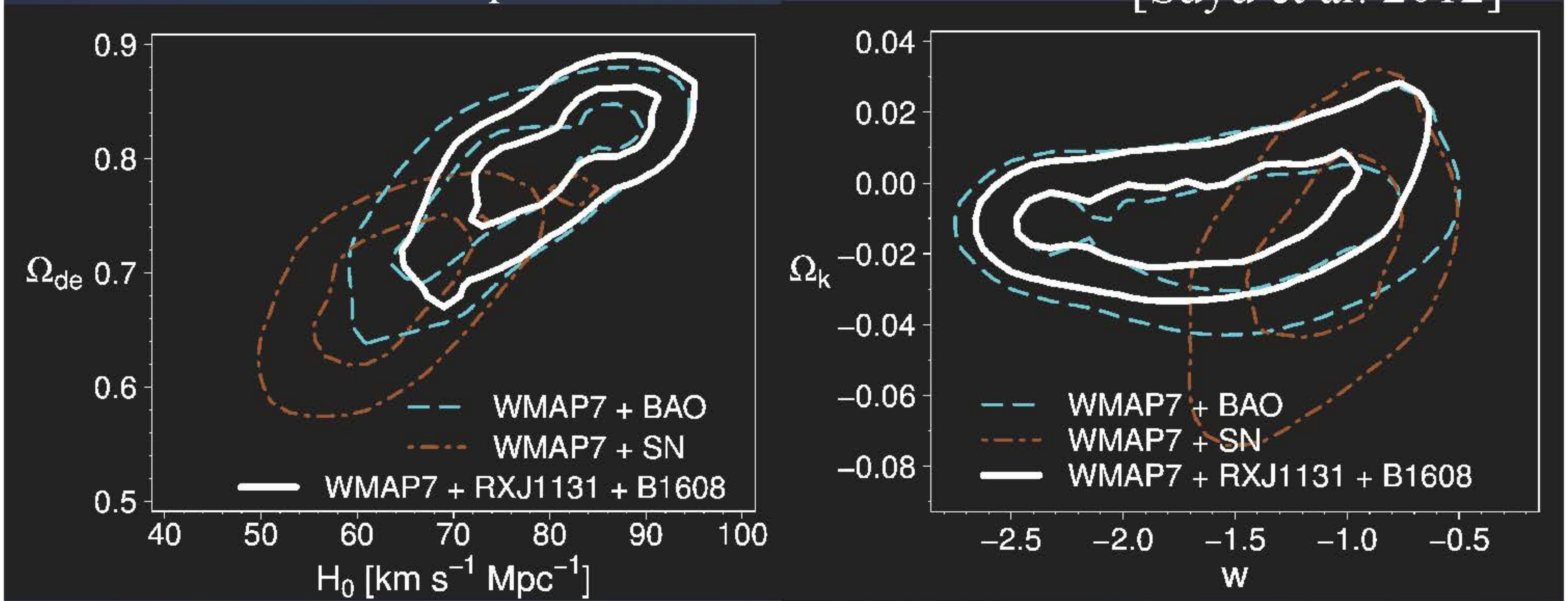
$$w = -1.14^{+0.17}_{-0.20}$$

[Suyu et al. 2012 (arXiv:1208.6010)]

Cosmological Probe Comparison I

WMAP7owCDM prior

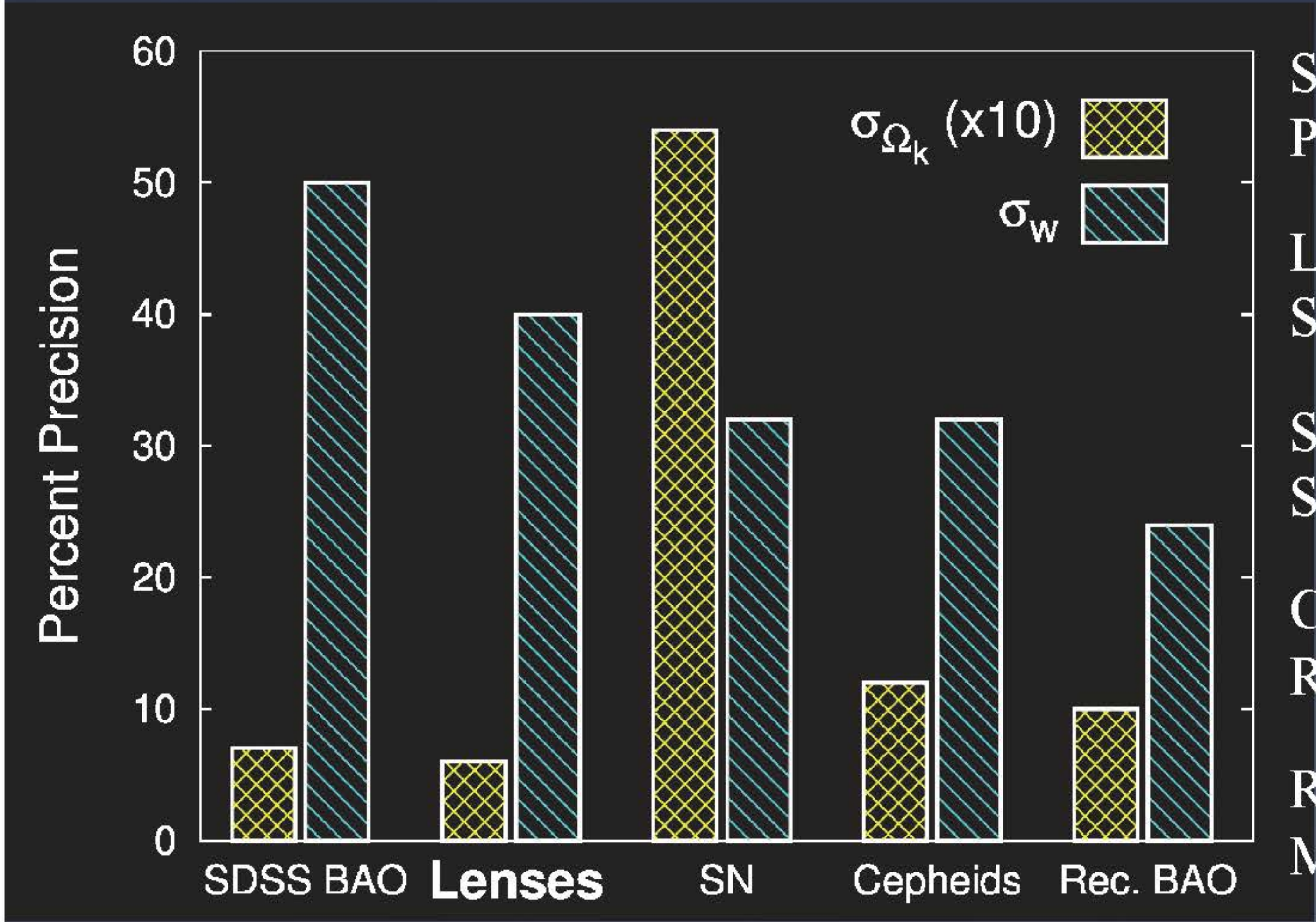
[Suyu et al. 2012]



- contour orientations are different: complementarity b/w probes
- contour sizes are similar: lensing is a competitive probe

Cosmological Probe Comparison II

WMAP7owCDM prior



SDSS BAO:
Percival et al. 2010

Lenses:
Suyu et al. 2012

Supernovae:
Suzuki et al. 2012

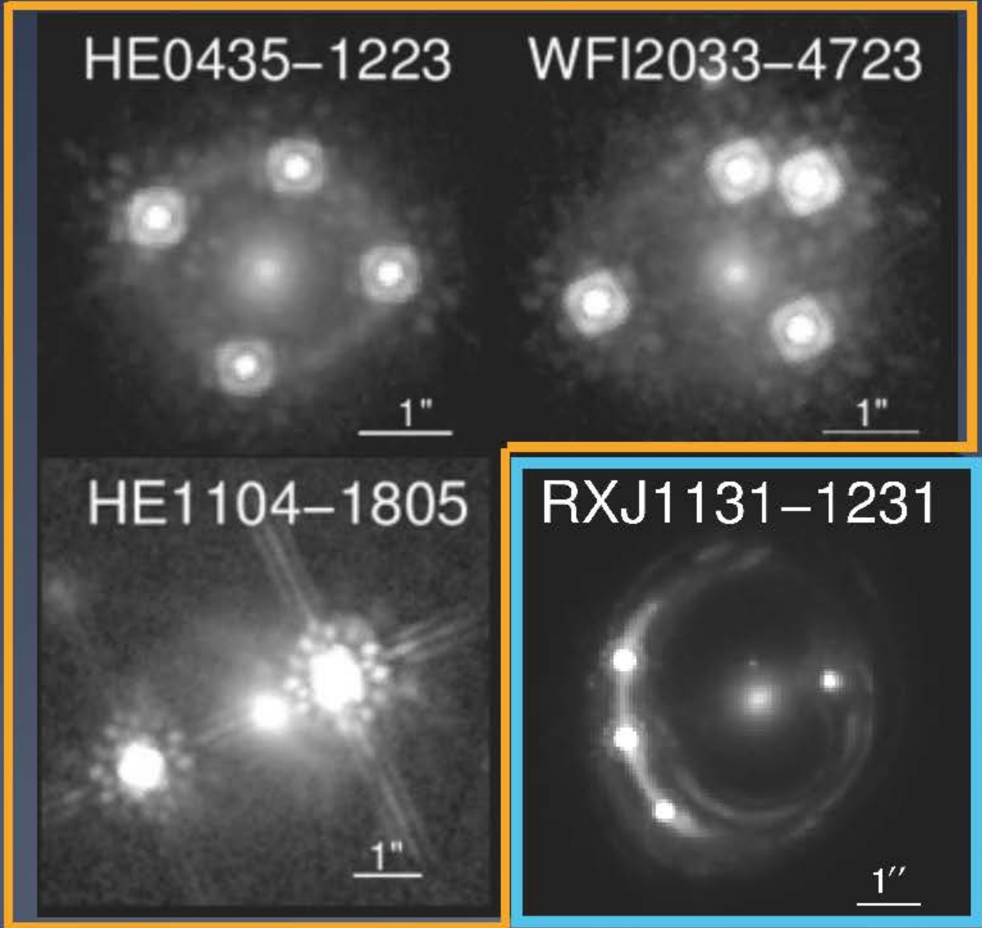
Cepheids:
Riess et al. 2011

Reconstructed BAO:
Mehta et al. 2012

Immediate Prospects

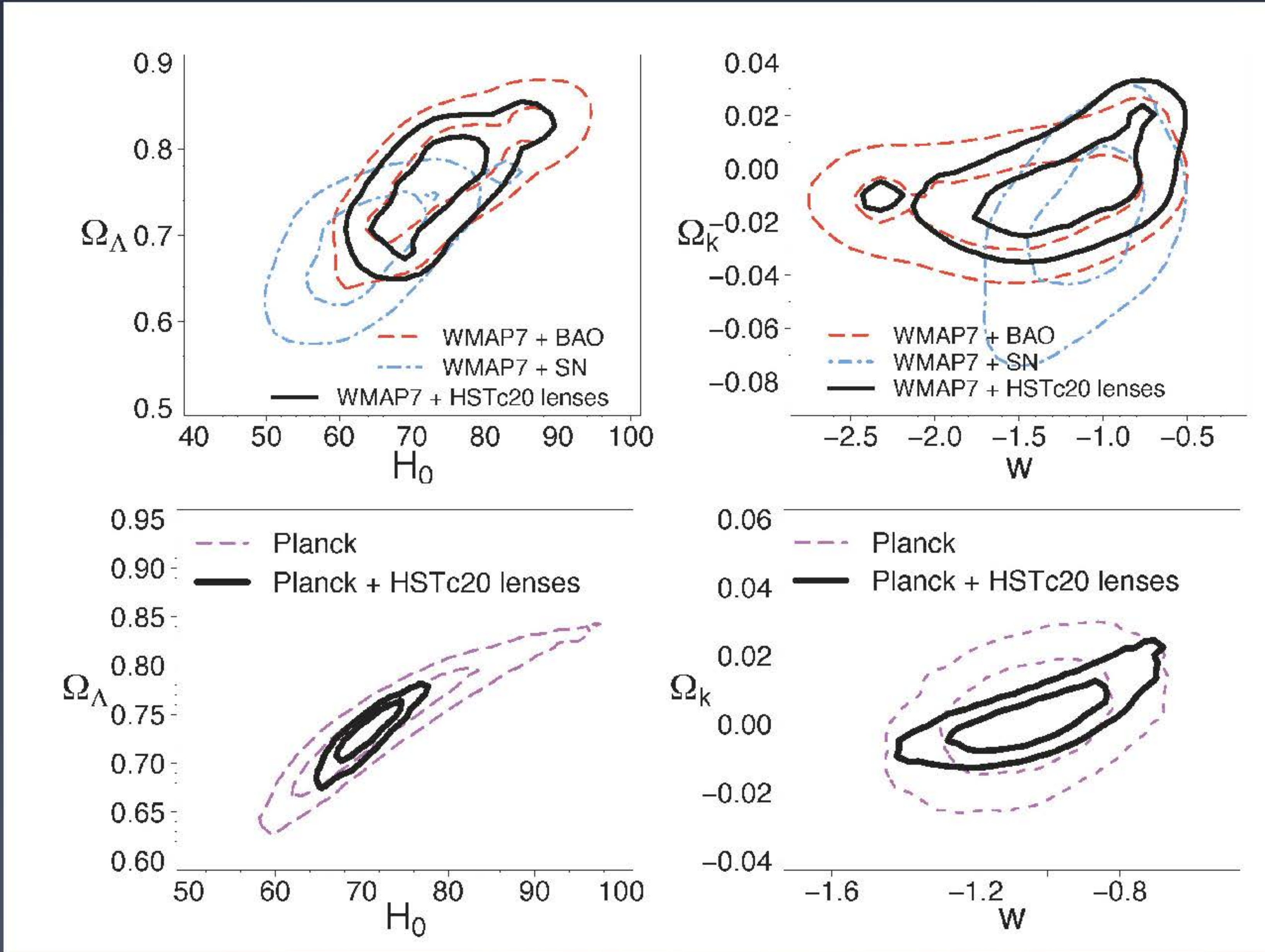
- time delays of lensed quasars from optical monitoring
- expect to have delays with a few percent error for ~20 lenses

HST cycle 20 follow up

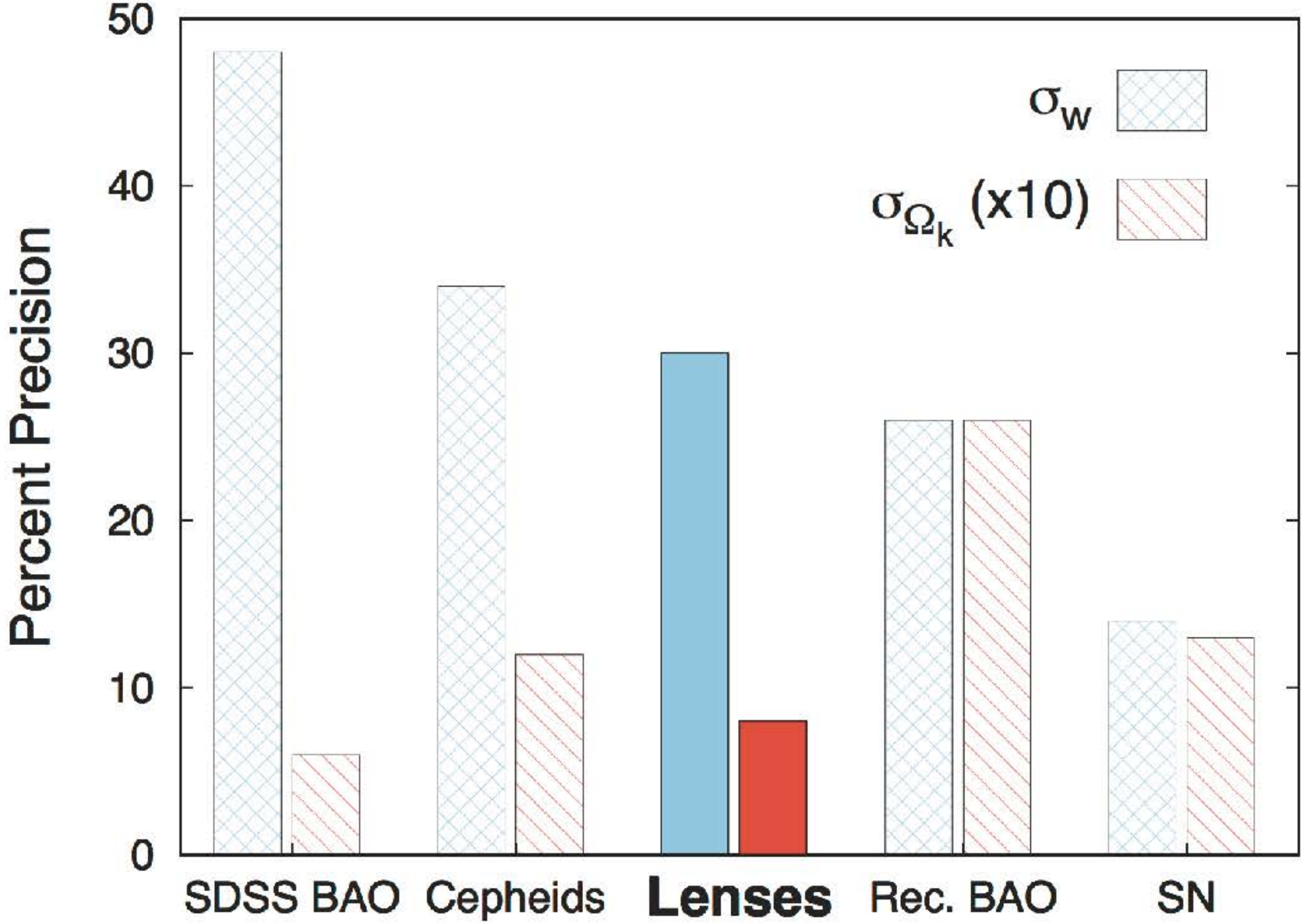


HST archival images for lens modeling

Immediate prospects

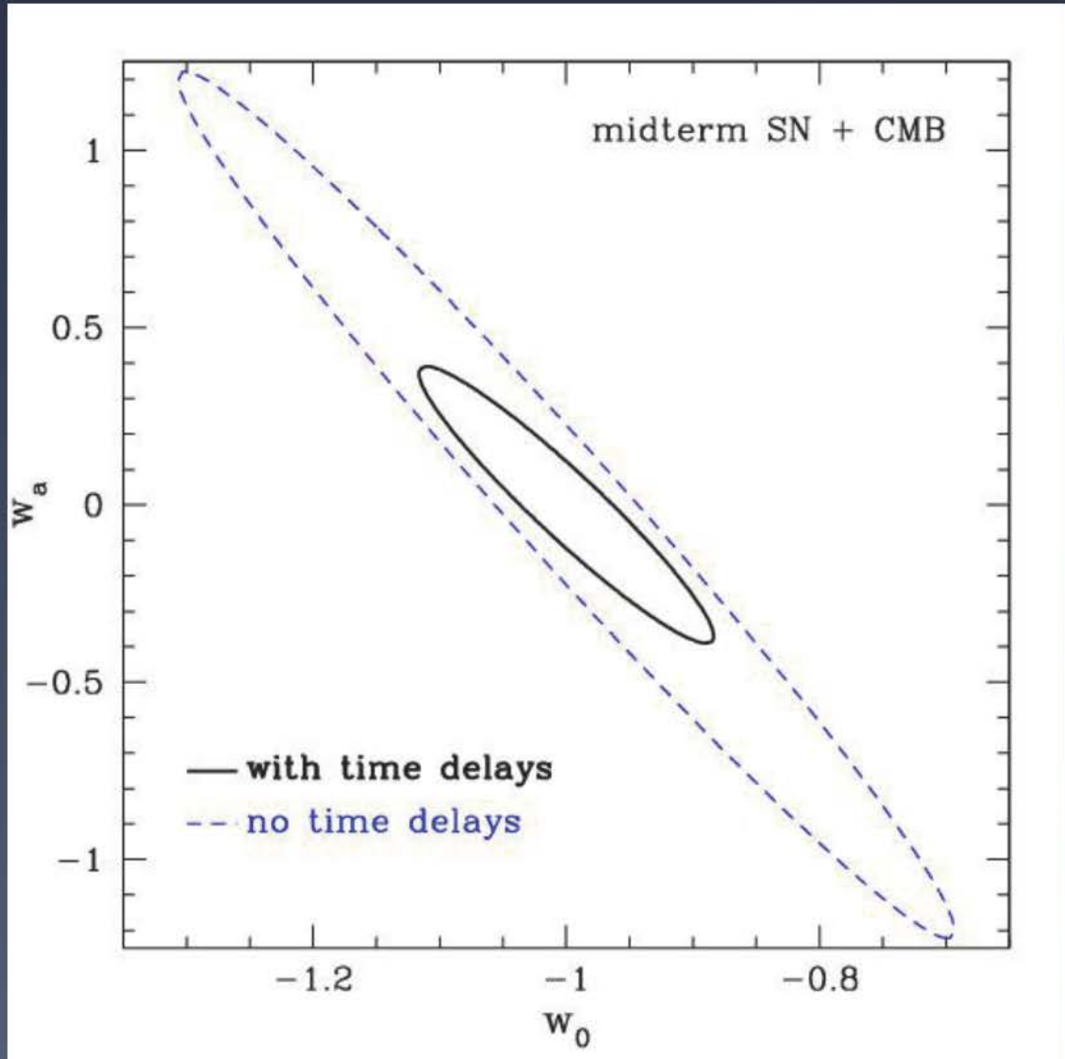


Immediate prospects



Future Prospects

- Currently ~10 lenses have precise time-delays
- Future telescopes (e.g. LSST) will discover and measure 100s of time delays (Oguri & Marshall 2010; Treu 2010)
- A time delay survey could provide very interesting constraints on dark energy



Linder 2011

Dark Energy

- Gravitational time delays can provide accurate measurements of H0 (~6% for a single lens) and other cosmological parameters
- In combination with other diagnostics, e.g. CMB, it can help constrain w and its evolution
- This is a global measurement with completely independent systematic uncertainties than the distance ladder method, providing a very useful complementary tool
- The next step is analyzing more systems(~5 feasible soon)
- In the longer run LSST and other time-domain surveys will enable hundreds of such measurements

Key questions with answers

1. When did the first black holes form? [How do we measure their mass?]
    1. At z>7. Using reverberation mapping
2. What is the equation of state of dark energy [What is dark energy?]
    1. Consistent with w=-1, non evolving, at the moment; cosmological constant?

The end

Dark Matters

The mass density profile of dark matter halos

- Is the dark matter profile universal and "cuspy" as suggested by simulations?
- If not, it may be a sign that dark matter is warm or self- interacting

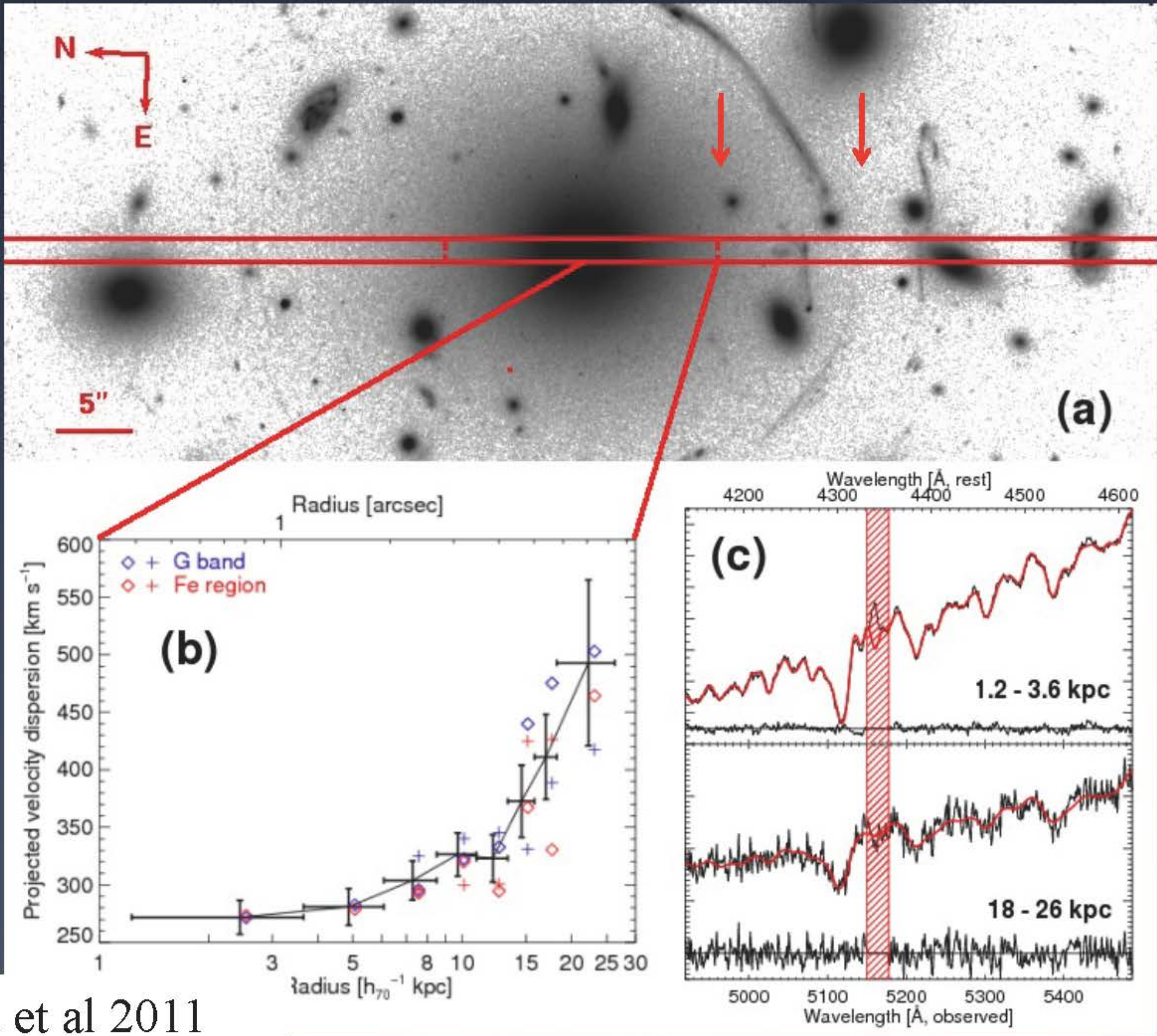
Observational challenges…

- Precision over a large dynamic range in mass
- Disentangle luminous and dark matter
- Control systematics

… can be overcome in clusters by combining methods

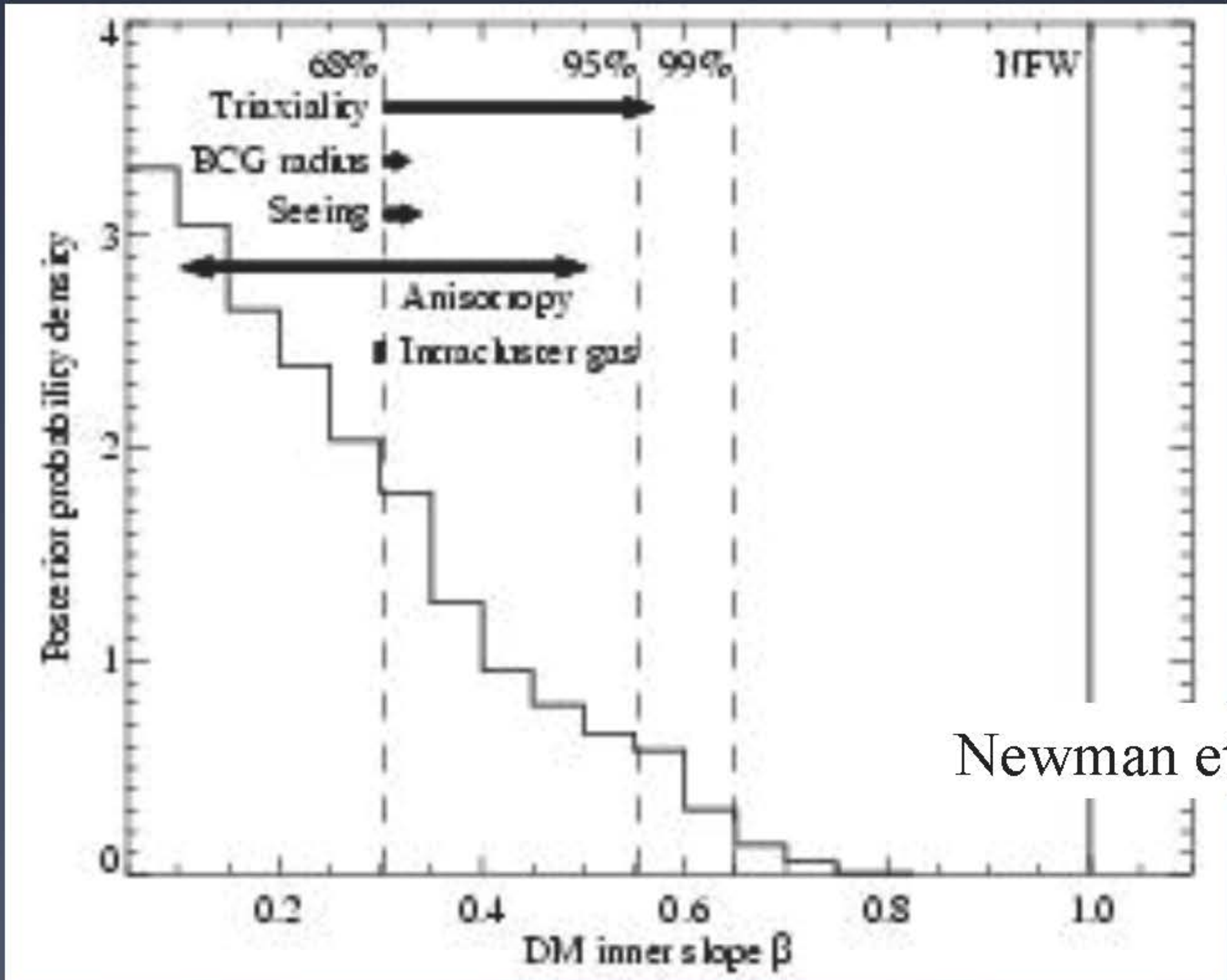
- Stellar kinematics (<30 kpc)
- Strong lensing (<100 kpc)
- X-ray (0.05 – 0.5 Mpc)
- Weak lensing (0.1-3 Mpc)

Sand, Treu, Ellis 2002; Sand et al. 2004,2008; Newman et al. 2009,2011



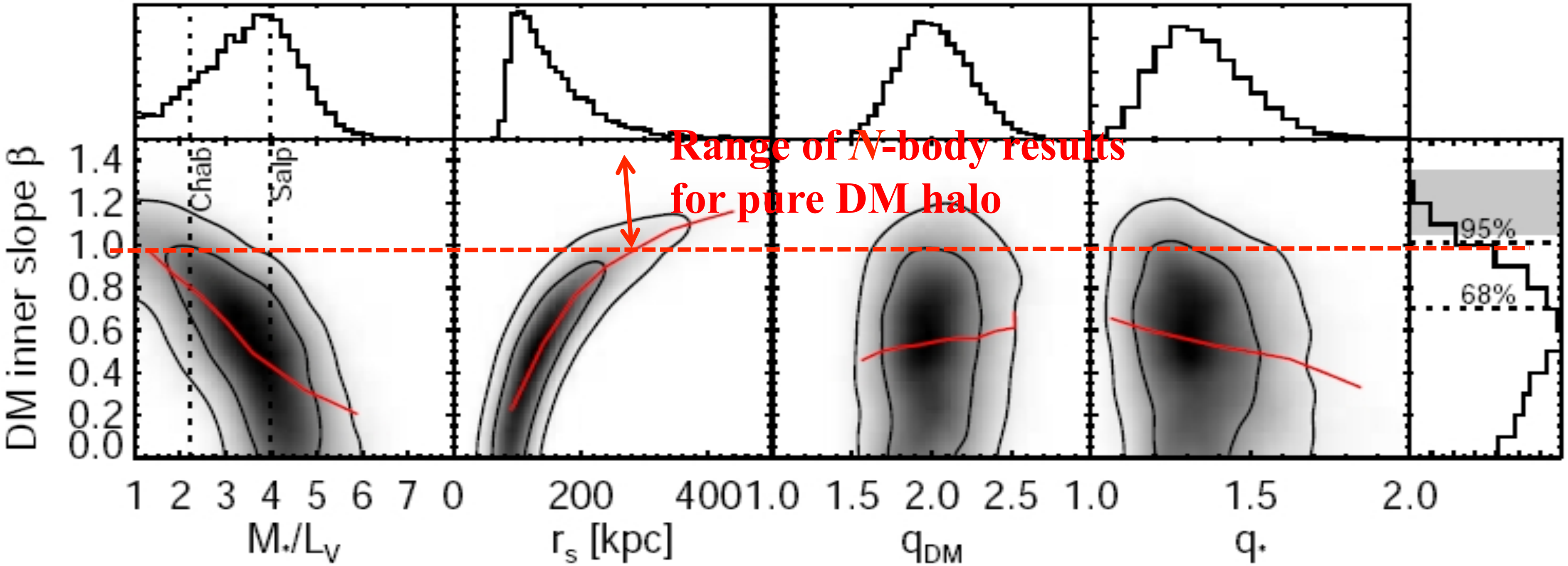
Newman et al 2011

Results for Abell 611



Newman et al. 2009

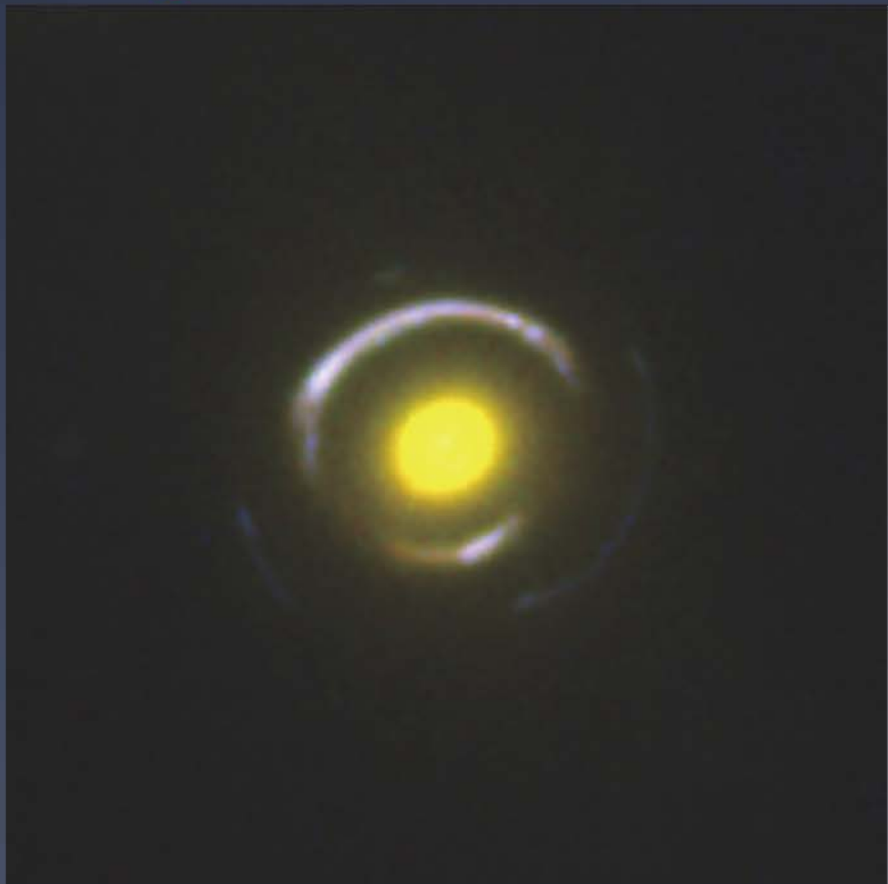
Results for Abell 383

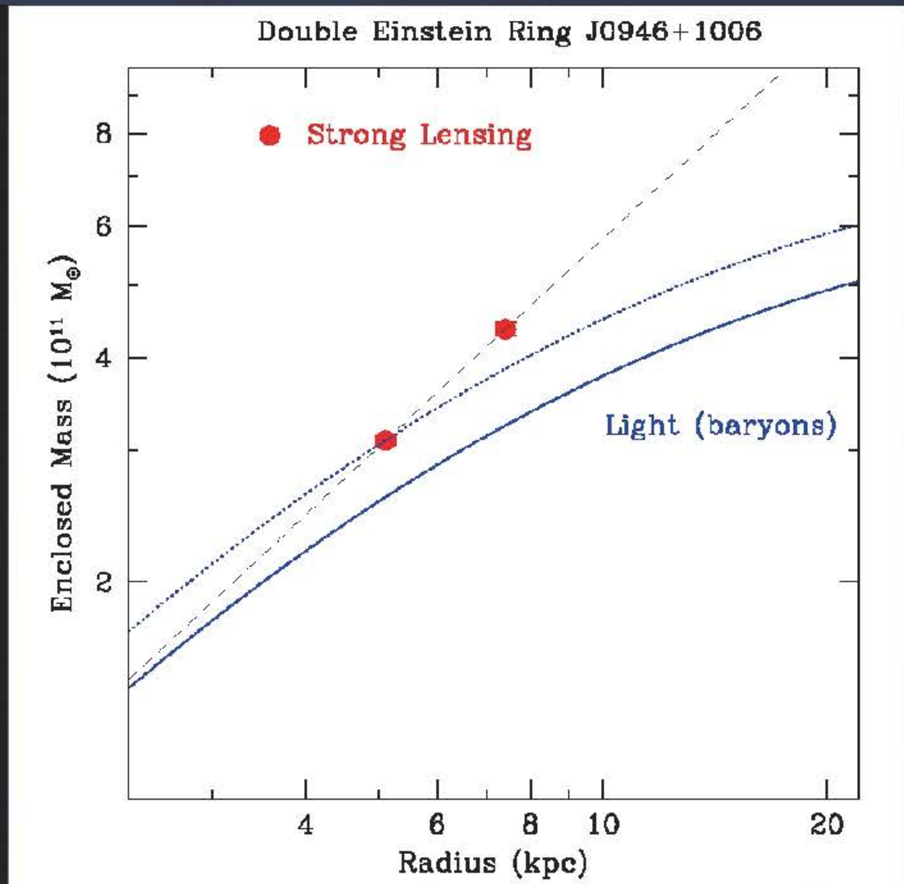


Newman et al. 2011

More clusters on the way

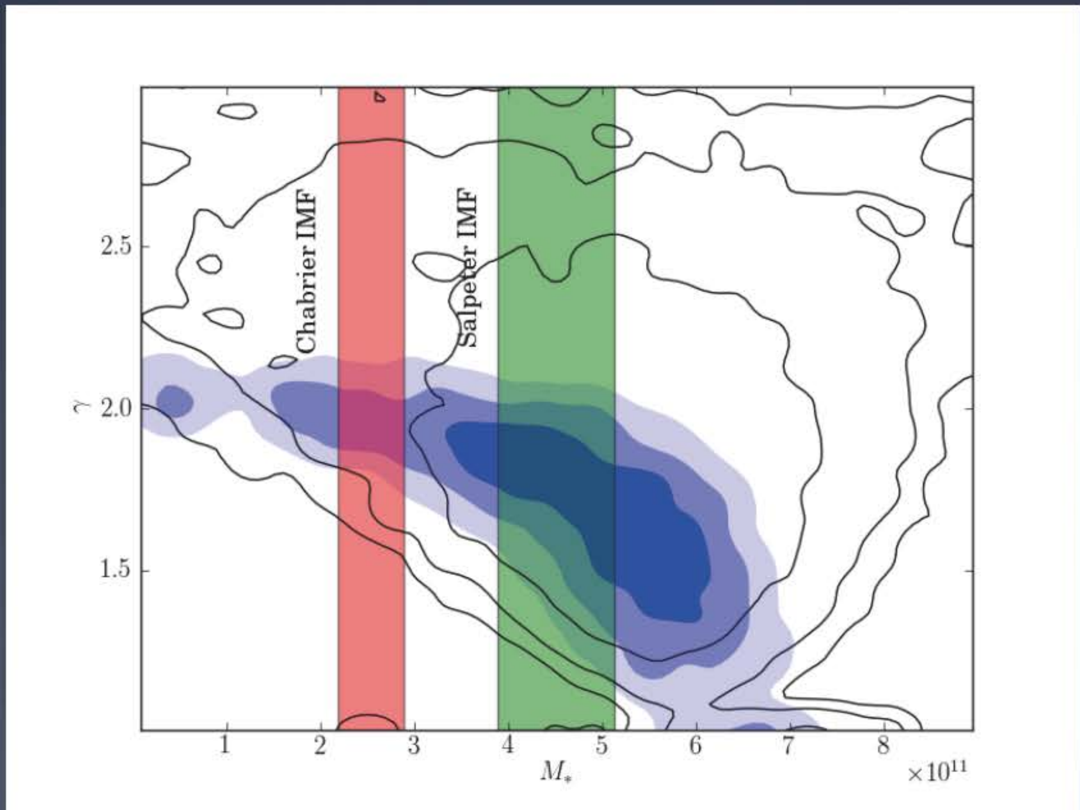
In galaxies it is harder, but if you choose the right target…





Gavazzi, TT et al. 2008; Sonnenfeld, TT et al. 2011

Baryonic and non-baryonic dark matter in the "Jackpot"

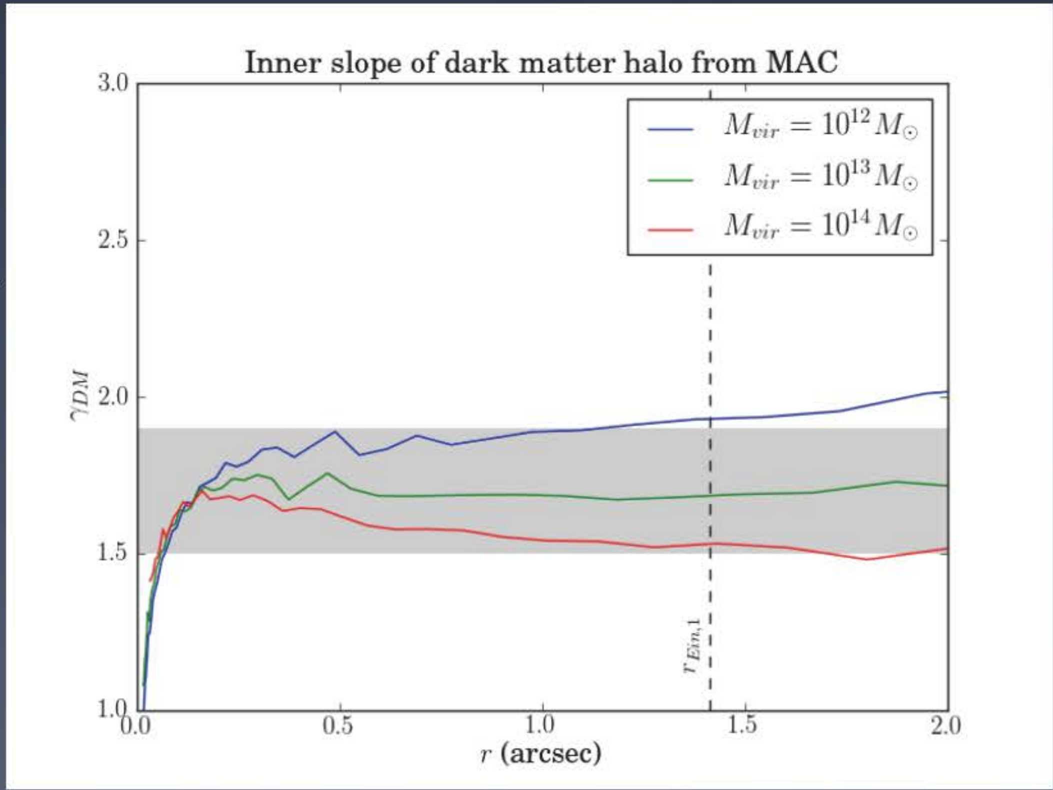


Gavazzi, TT et al. 2008; Sonnenfeld, TT et al. 2011

The role of baryons

* Baryonic cooling and star formation tends to drive material towards the center and thus make the inner slope steeper than for DM only

* In simulations, the amount of steepening depends on the cluster merger history and the details of baryonic physics, because dynamical friction can counterbalance - at least in part - the effect



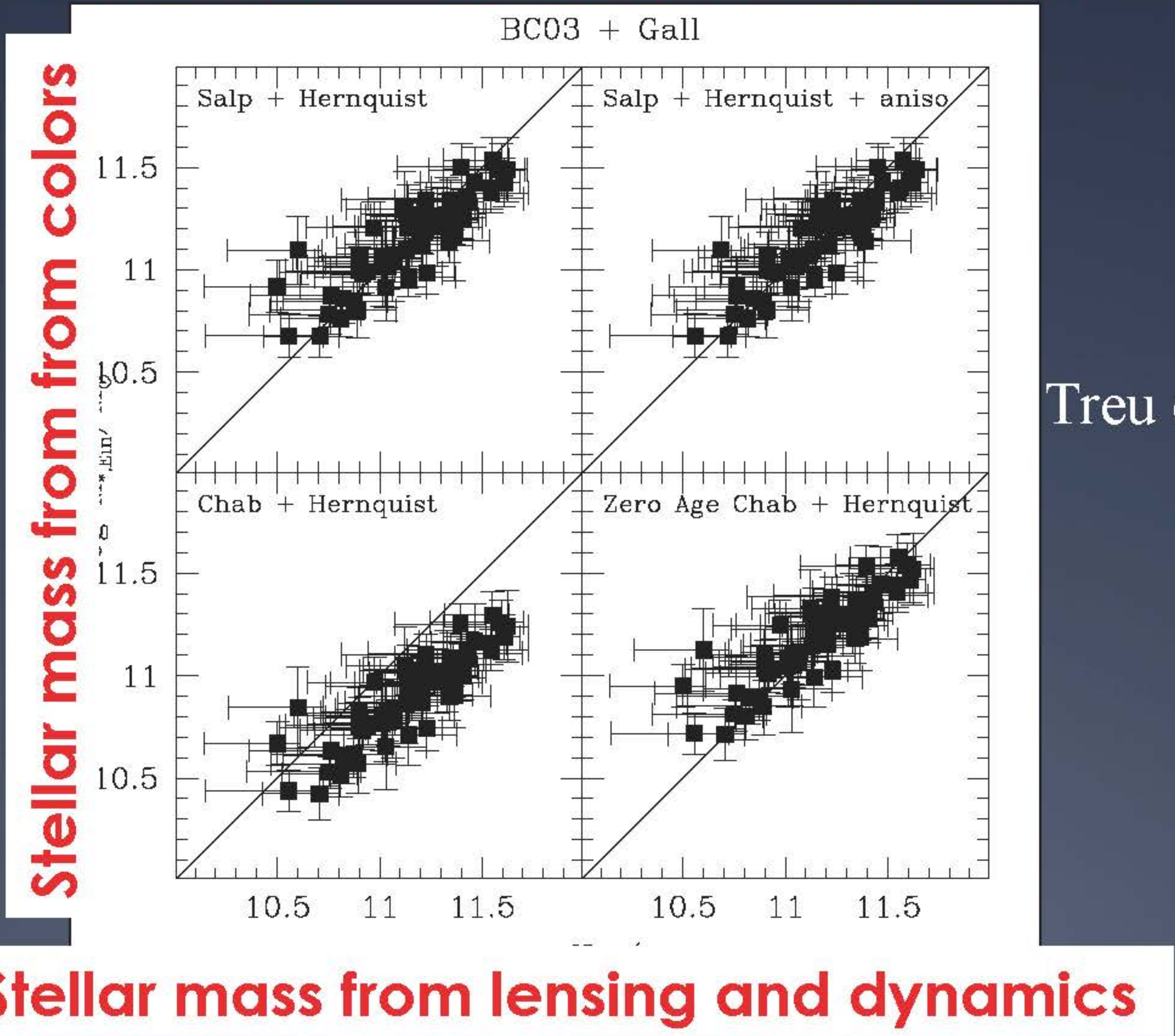
Sonnenfeld et al. 2011

Universal Halos or Universal

Stellar Initial Mass function?

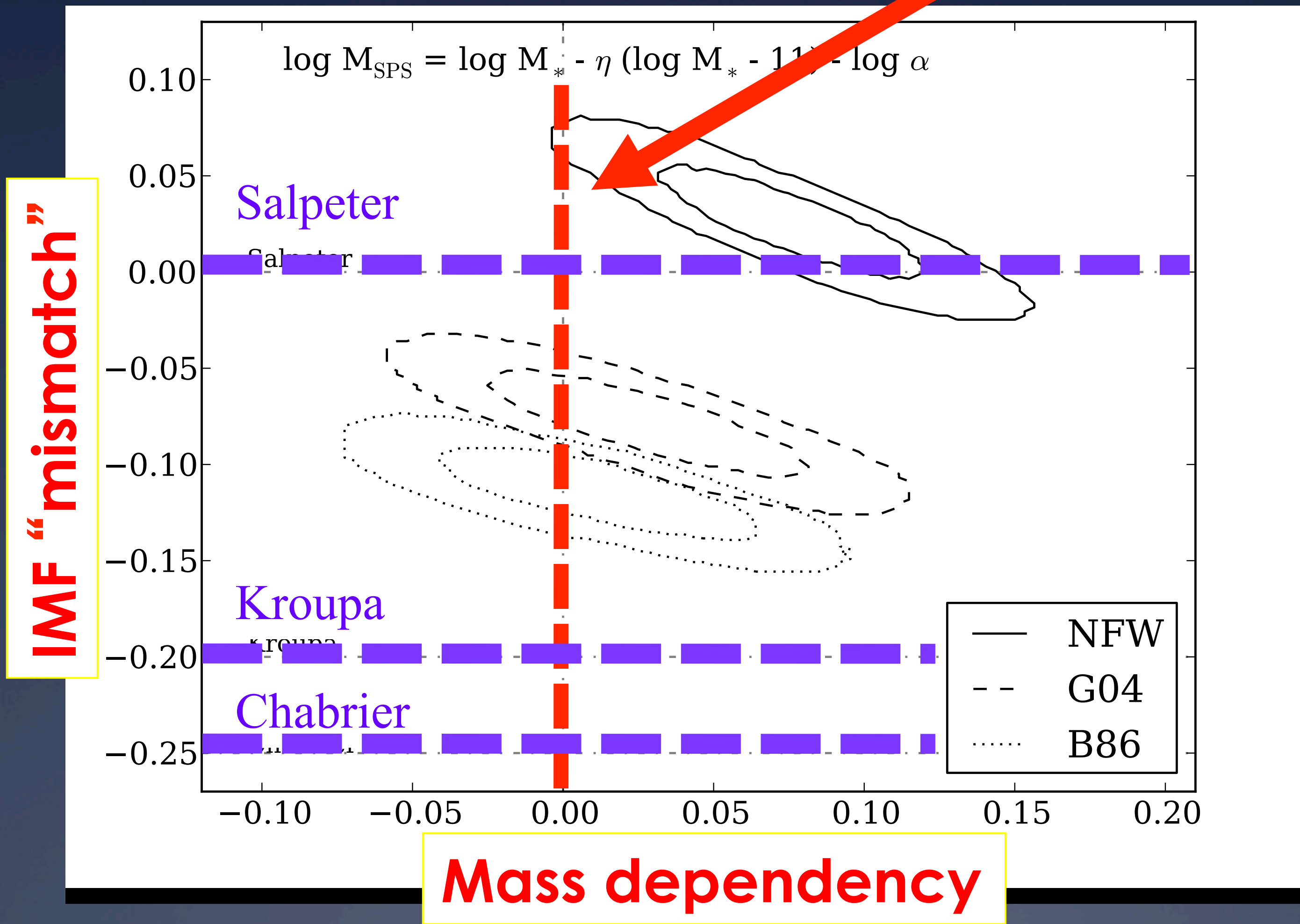
(Baryonic or non baryonic?)

Massive ellipticals have "too much" dark matter?



Treu et al. 2010

Universal halos or IMF?



Auger, TT et al. 2010