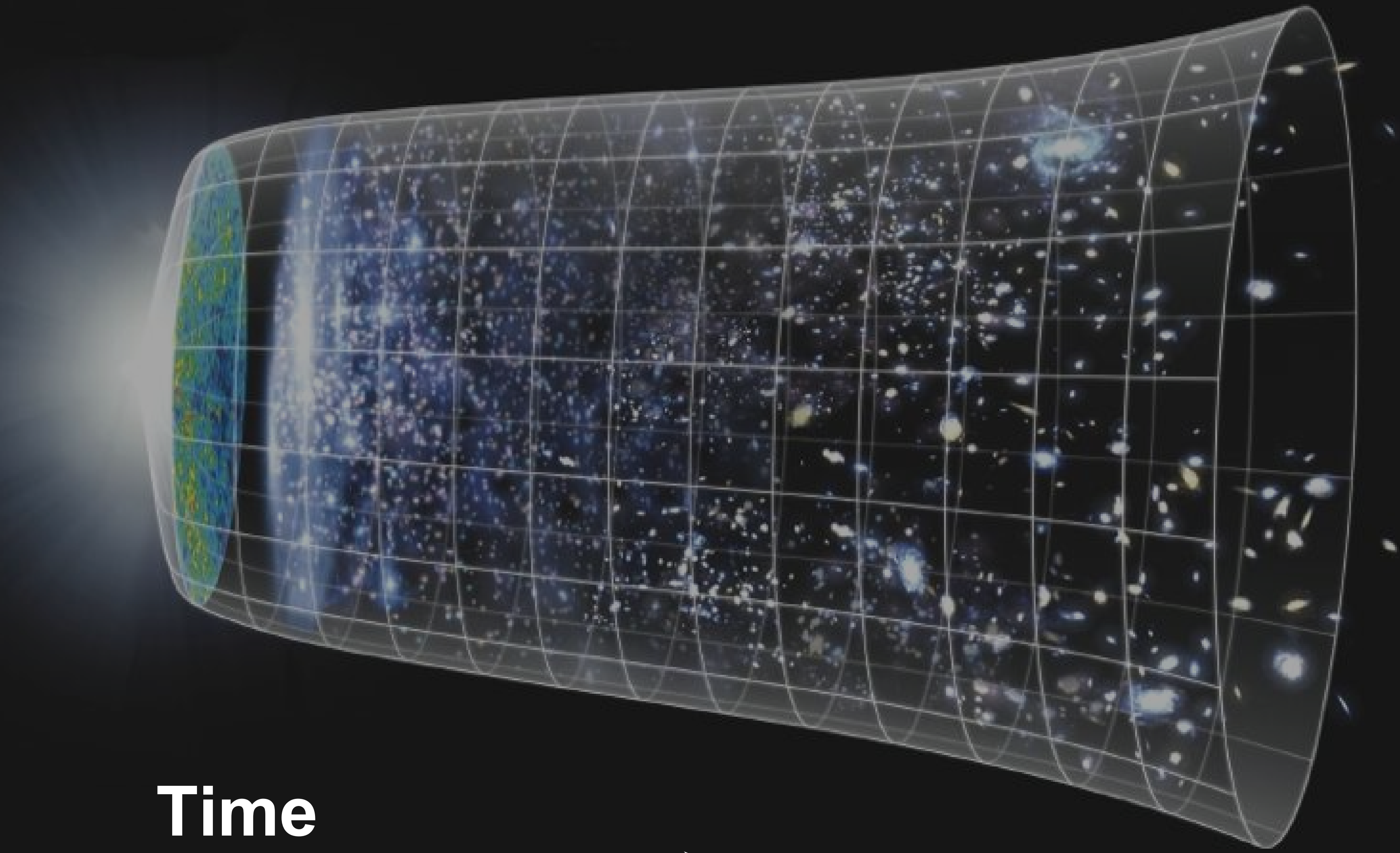
Cosmology with Strong Gravitational Lenses

Phil Marshall (SLAC)

LSST DE SChool, February 2017

The expansion of the Universe is accelerating



Time

and no-one knows why

Goals

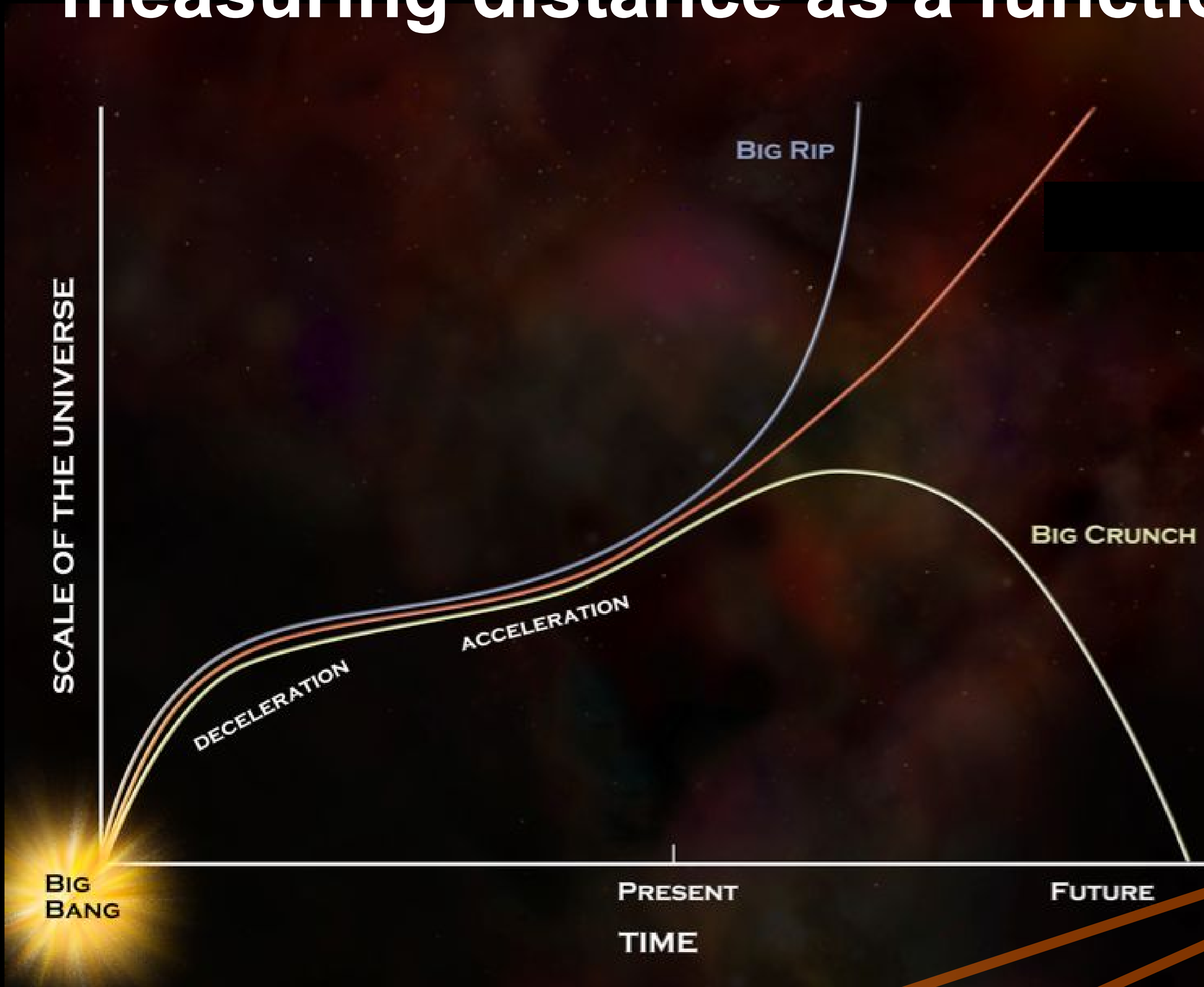
- Understand the basic, multi-faceted technique of “time delay lens cosmography”
- Be able to interpret its results, and ask the right questions about its systematic errors
- See the research opportunities on offer

Plan

- Introduction to time delay lenses, and how each one enables a cosmological distance measurement

- Time delay cosmography in practice:
  - Some recent results from the H0LiCOW project
  - Looking forward to hundreds of lenses with LSST
  - Residual systematic errors, and what we can do about them

Reconstruct our acceleration history by measuring distance as a function of redshift



Hubble's Law:

$$c\,dt = a(t)\,dr \longrightarrow r = \int_0^z \frac{c\,dz}{H(z)}$$

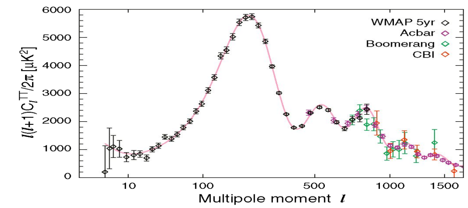
Measure distance $D(r)$ and redshift z,

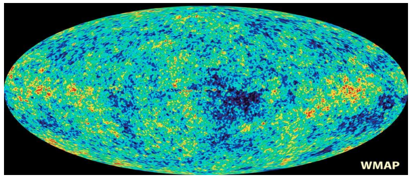
Then *infer parameters* H_0, $w(a)$, curvature *etc.*

$$H^2(a) = H_0^2\left(\Omega_{\rm m} a^{-3} + \Omega_{\rm X} \exp\left[3\int_{\log a}^{0}(1+w)\,d\log a\right] + \Omega_{\rm k} a^{-2}\right)$$

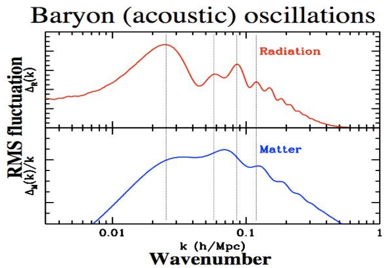
Measuring Distance

- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation
- **Baryon Acoustic Oscillations** in the galaxy clustering power spectrum
- Periods of **Cepheid** variable stars in local galaxies
- **Clusters of galaxies** should contain the universal gas fraction wherever they are





(sound speed x age of universe) subtends ~1 degree

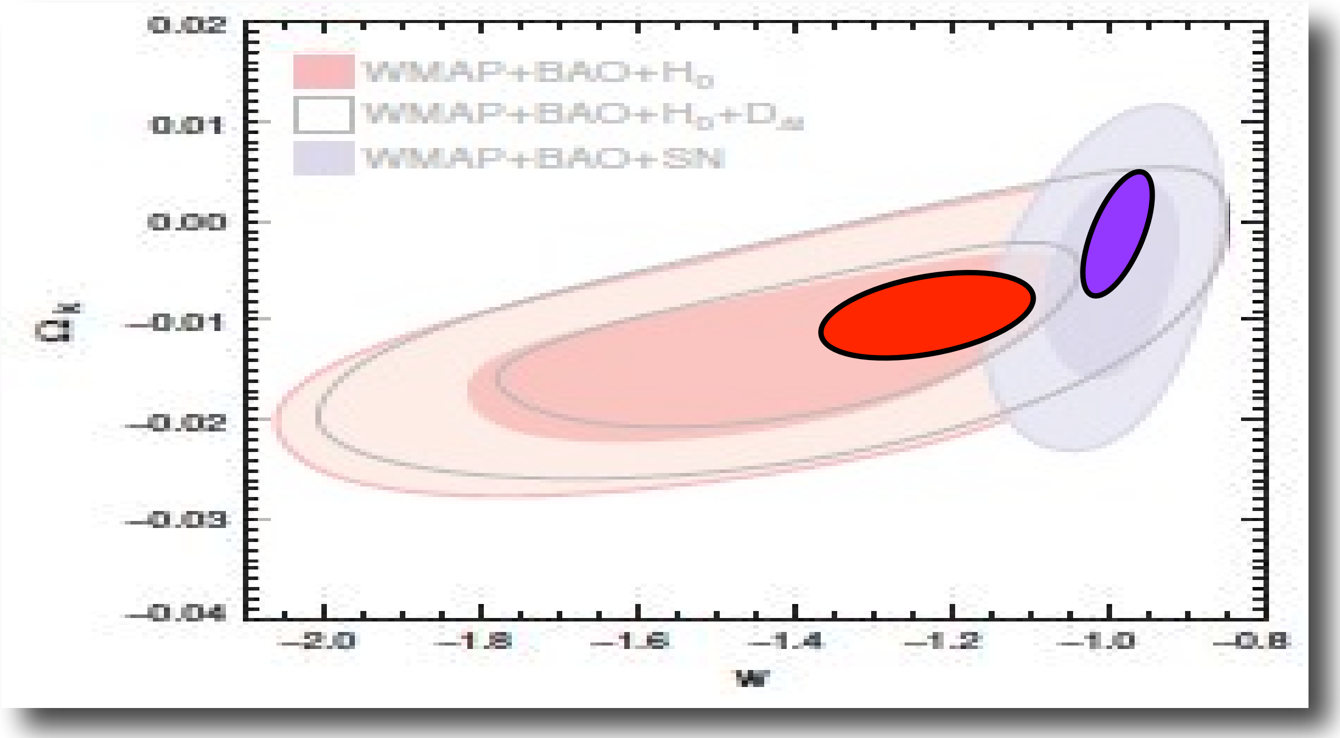


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

Do we need another one?

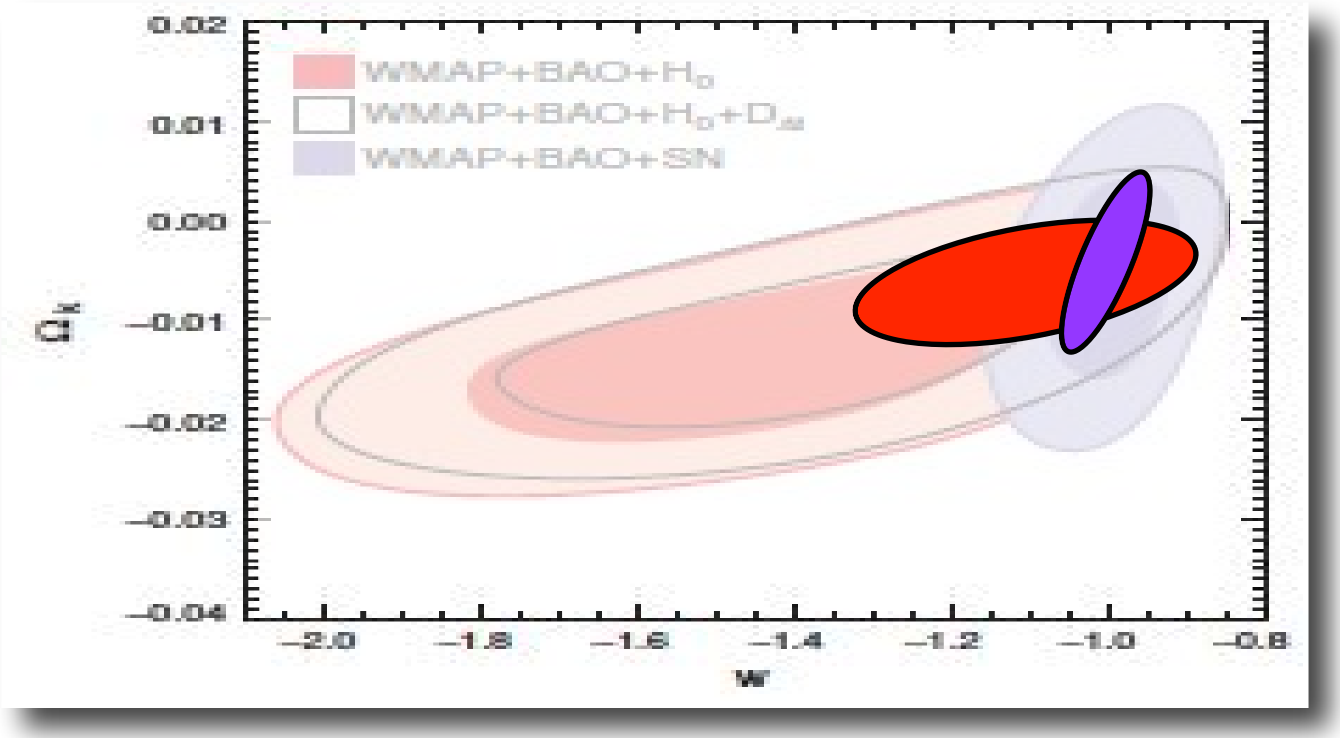
Accurate Cosmology

At high precision, systematic errors lead to dataset inconsistency:



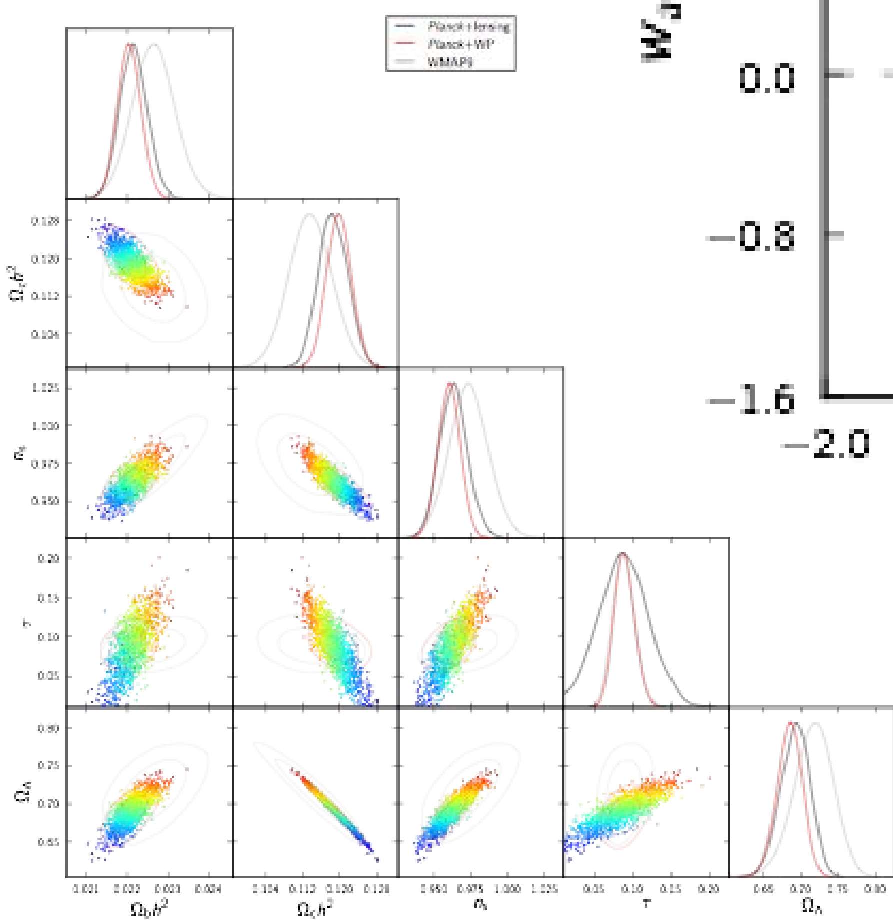
Accurate Cosmology

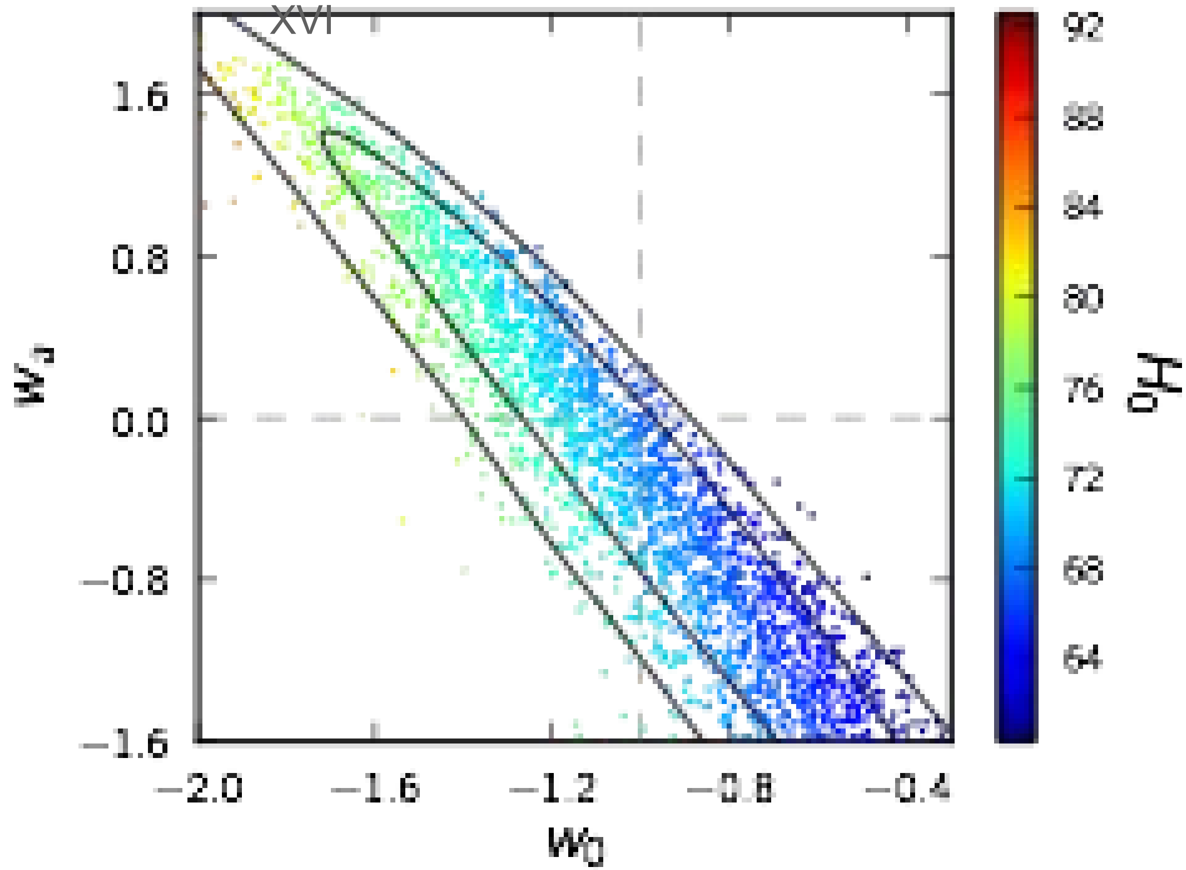
When all measurements are systematics limited, we learn best by having multiple datasets, where each one provides roughly competitive precision in at least one parameter



H_0 matters

Planck Collaboration 2013 Paper XVI





"Better measurements of H_0 provide critical independent constraints on dark energy, spatial curvature of the Universe, neutrino physics, and validity of general relativity."

Suyu et al 2012
KIPAC workshop

Measuring Distance

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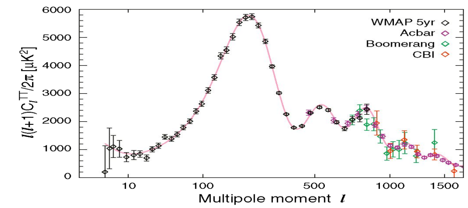

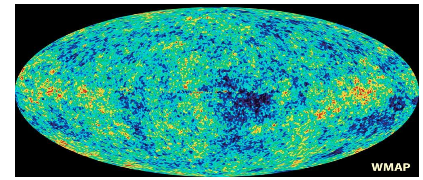

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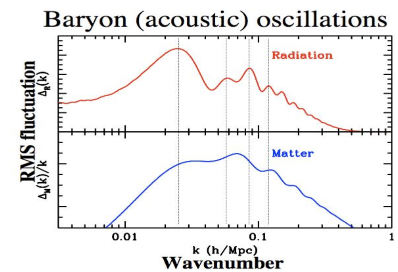
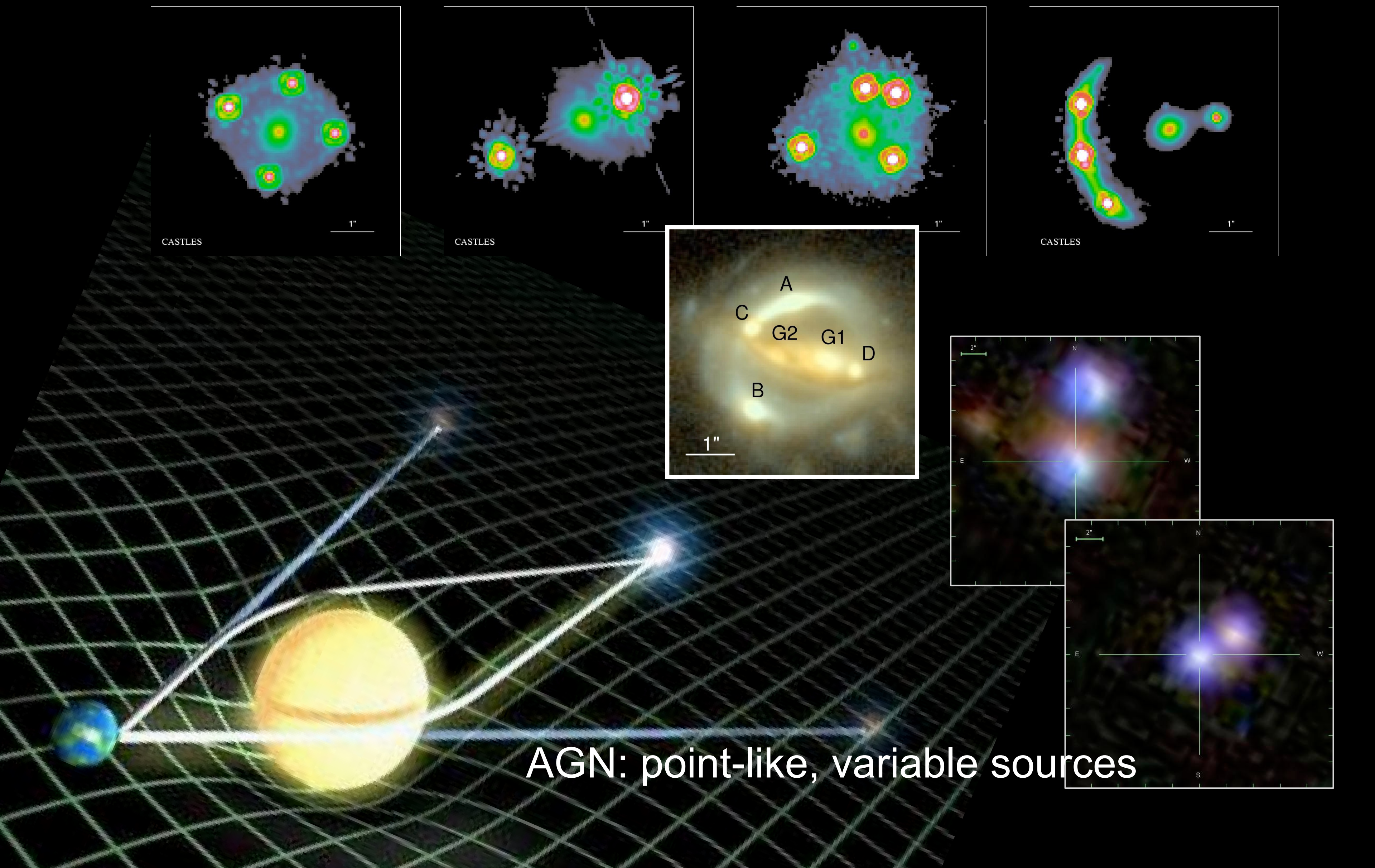


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

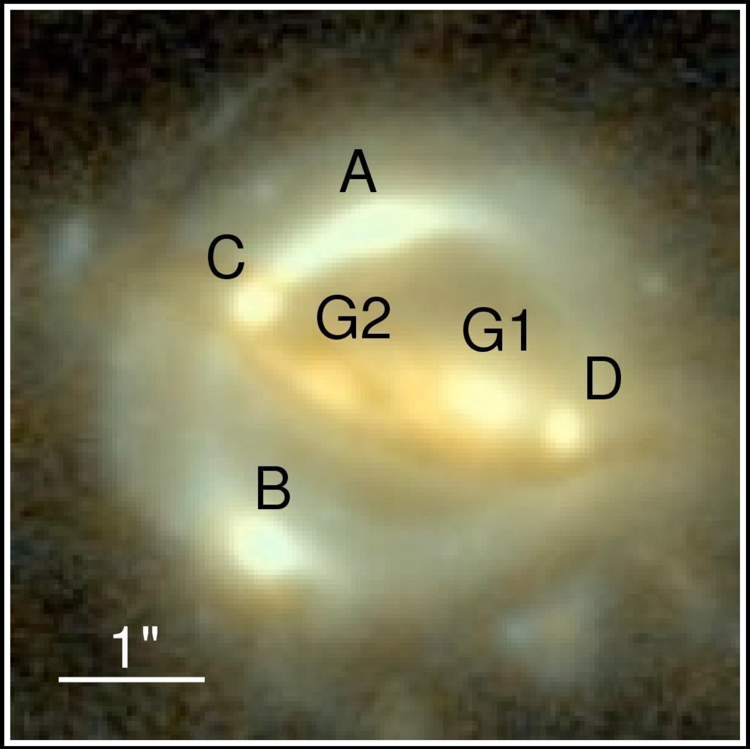
- **Gravitational lens time delays**

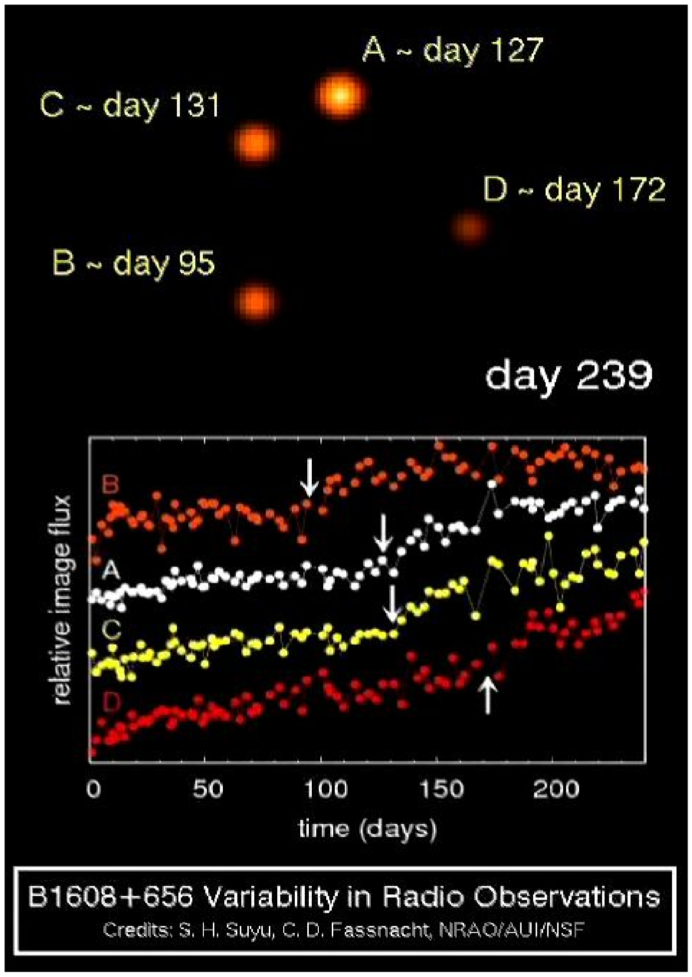
Strong Gravitational Lenses



AGN: point-like, variable sources

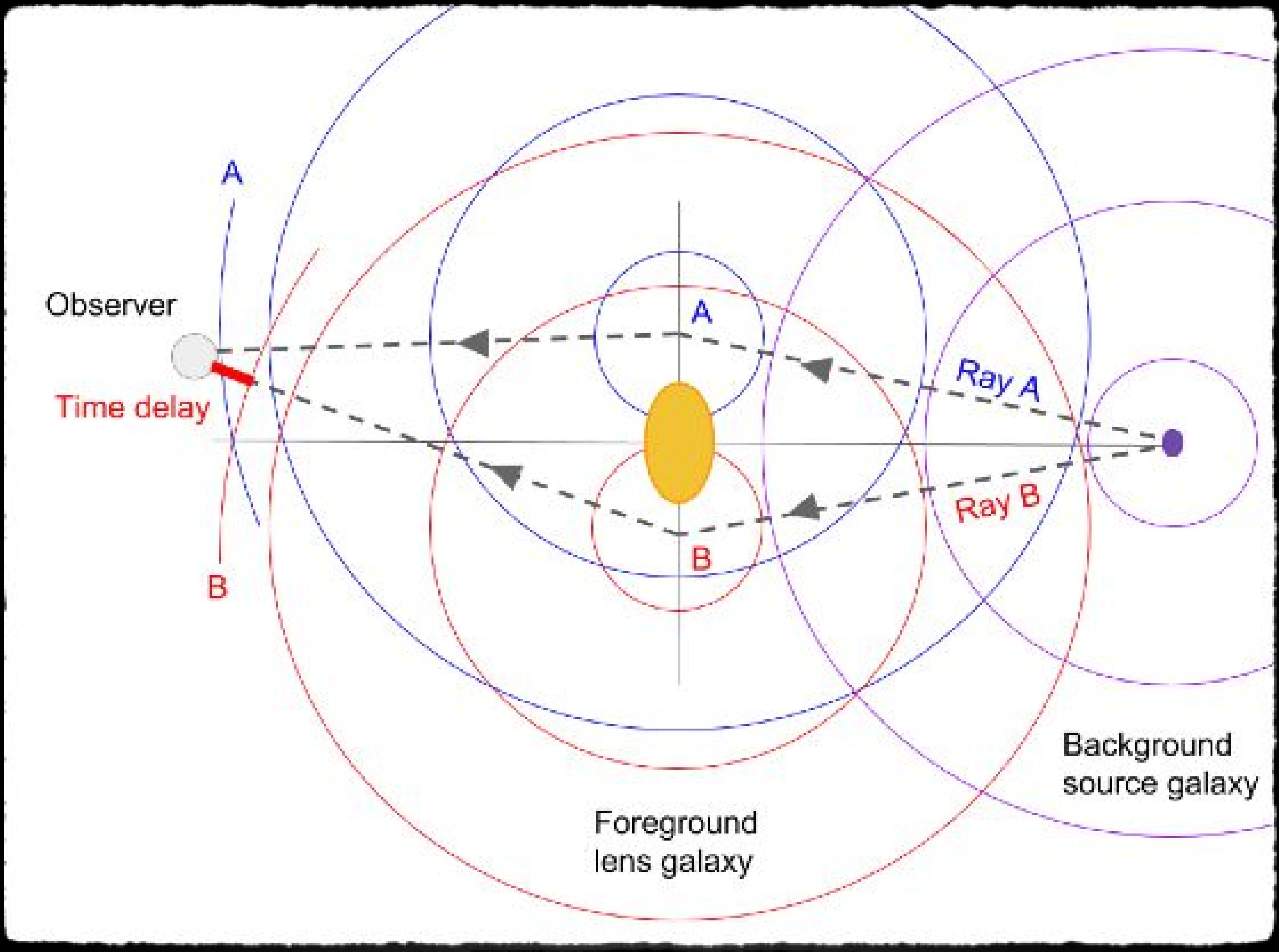
Time Delay Lenses

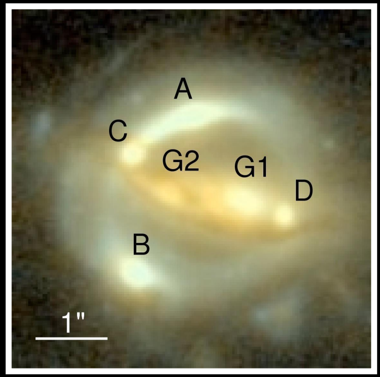


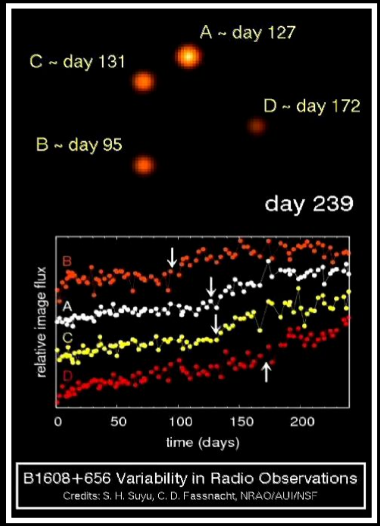


Point-like, variable sources:
different path lengths,
different travel times

Huygens Construction







Treu & Marshall 2016

Time Delay Distances

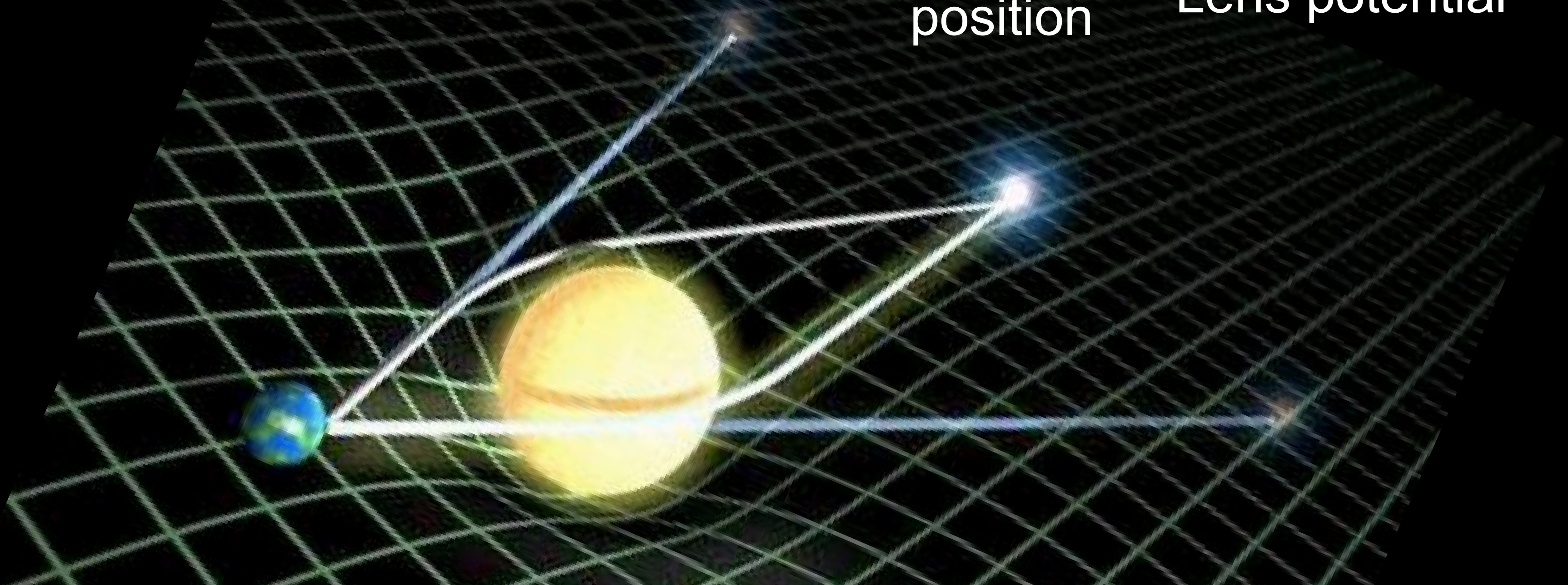
Signals from the AGN appear at different times - this effect can be **predicted** with a **model** of the lens:

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

Image position

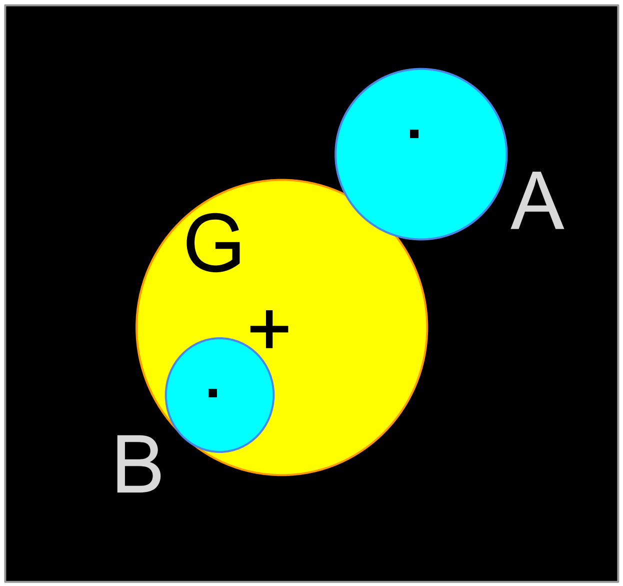
Source position

Lens potential



Singular Isothermal Sphere Model

LSST *gri* cutout



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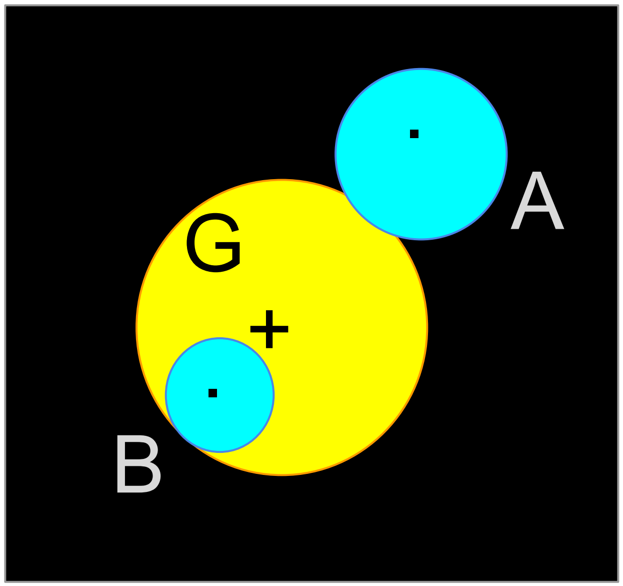

SIS FakeTeX Cheat-sheet

Potential $\Psi = \theta_E \theta$

Deflection $\boldsymbol{\alpha} = \nabla \Psi = \theta_E$

Lens equation $\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})$

Convergence $\kappa = \nabla^2 \Psi / 2 = \Psi' / 2\theta = \theta_E / 2\theta$

Shear $\gamma = (\kappa - \langle\kappa\rangle) = \theta_E / 2\theta = \kappa$

Magnification $\mu = 1/(1-2\kappa) = \theta/(\theta-\theta_E)$

Flux ratio $r = \mu_A / |\mu_B|$

Arrival time $t = (D_{\Delta t}/c)\ \Phi$

Fermat potential $\Phi = (\boldsymbol{\theta}-\boldsymbol{\beta})^2/2 - \Psi(\boldsymbol{\theta})$

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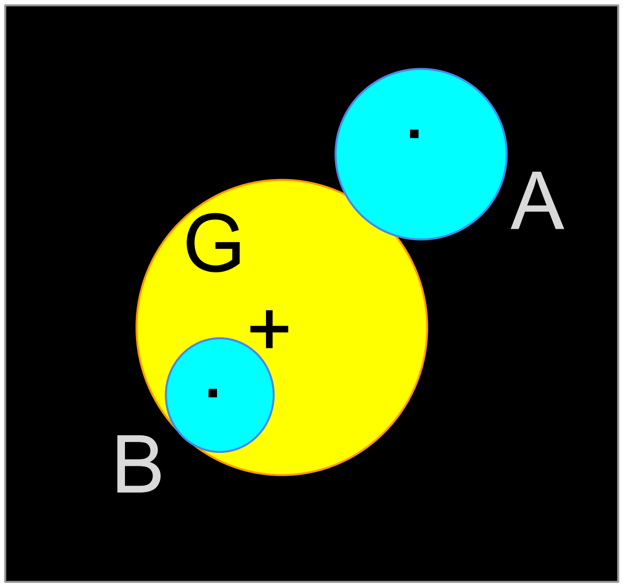

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1. Where is the source?
Write θ_A and θ_B in terms of β and θ_E

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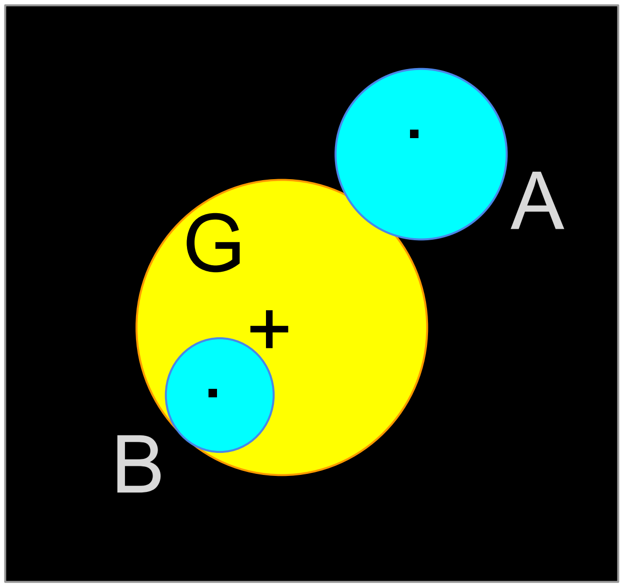
LSST *gri* cutout



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2. How does the flux ratio r change with source position? Write r in terms of θ_A and θ_B, and then θ_A and θ_B in terms of r and θ_E

SIS Model

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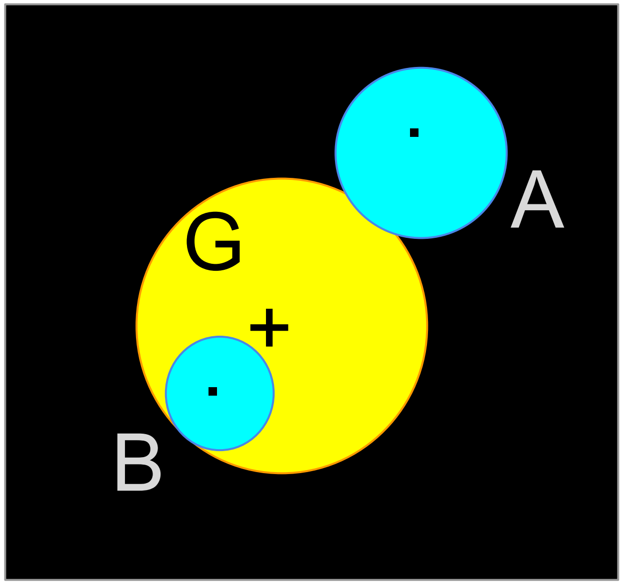

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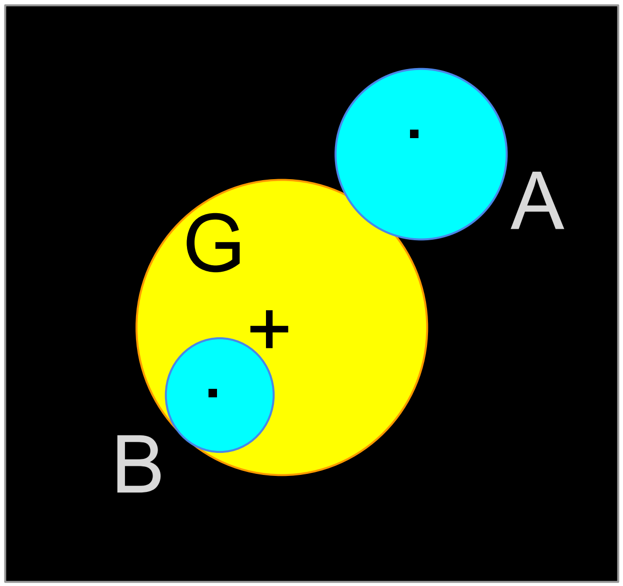
Arrival time $t = (D_{\Delta t}/c)\ \Phi$

Fermat potential $\Phi = (\boldsymbol{\theta}\text{-}\boldsymbol{\beta})^2/2 - \Psi(\boldsymbol{\theta})$

3. Which image arrives first?
Write Δt in terms of r and θ_E

SIS Model

LSST *gri* cutout



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Flux ratio $r = \mu_A/|\mu_B|$

Arrival time $t = (D_{\Delta t}/c)\ \Phi$

Fermat potential $\Phi = (\boldsymbol{\theta}-\boldsymbol{\beta})^2/2 - \Psi(\boldsymbol{\theta})$

4. What's a typical time delay for a galaxy-scale lens (θ_E = 1")? How about for a galaxy cluster? NB. $c = 36$ Mpc day^{-1} arcsec^2 rad^{-2}

Time Delay Distances

Signals from the AGN appear at different times - this effect can be **predicted** with a **model** of the lens:

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

Image position

Source position

Lens potential

$$\Delta t_{AB} = D_{\Delta t} \times \Delta\Phi_{AB}$$

Model predictions allow us to explore the joint likelihood for the distance and lens model parameters given the time delays, image positions, arc surface brightness etc

"H_0 from Strong Lensing"

First suggested by Refsdal (1964) - using Hubble's original Law for the distance, the only free parameter is H_0

- Prior to 2010, several attempts at measuring H_0 with lenses were made: significant scatter, systematic errors. *We now have better data and more advanced analysis software.*

- Time delays give a physical distance measurement, mostly sensitive to H_0 - but also to *the other cosmological parameters, including Dark Energy.*

Plan

- Introduction to time delay lenses, and how each one enables a cosmological distance measurement

- Time delay cosmography in practice:
  - Some recent results from the H0LiCOW project
  - Looking forward to hundreds of lenses with LSST
  - Residual systematic errors, and what we can do about them

H0LiCOW!

1 ☐ 2017MNRAS.465.4914B 2017/03 cited: 18
H0LiCOW - V. New COSMOGRAIL time delays of HE 0435-1223: H_0 to 3.8 per cent precision from strong lensing in a flat ΛCDM model
Bonvin, V.; Courbin, F.; Suyu, S. H. *and 15 more*

2 ☐ 2017MNRAS.465.4895W 2017/03 cited: 2
H0LiCOW - IV. Lens mass model of HE 0435-1223 and blind measurement of its time-delay distance for cosmology
Wong, Kenneth C.; Suyu, Sherry H.; Auger, Matthew W. *and 13 more*

3 ☐ 2016arXiv160701047R 2016/07 cited: 3
H0LiCOW III. Quantifying the effect of mass along the line of sight to the gravitational lens HE 0435-1223 through weighted galaxy counts
Rusu, Cristian E.; Fassnacht, Christopher D.; Sluse, Dominique *and 8 more*

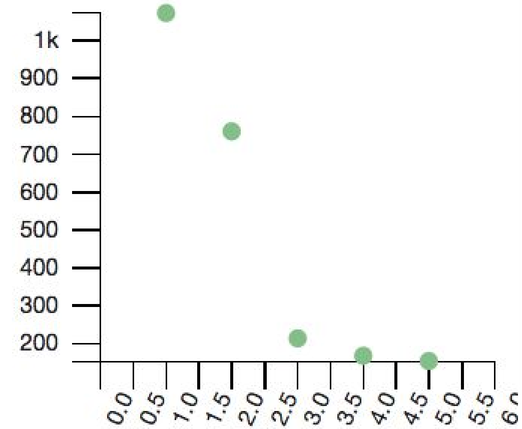
4 ☐ 2016arXiv160700382S 2016/07 cited: 2
H0LiCOW II. Spectroscopic survey and galaxy-group identification of the strong gravitational lens system HE0435-1223
Sluse, D.; Sonnenfeld, A.; Rumbaugh, N. *and 15 more*

5 ☐ 2016arXiv160700017S 2016/06 cited: 7
H0LiCOW I. H_0 Lenses in COSMOGRAIL's Wellspring: Program Overview
Suyu, S. H.; Bonvin, V.; Courbin, F. *and 21 more*

Years Citations Reads

total recent (90 day) reads : **2,370**

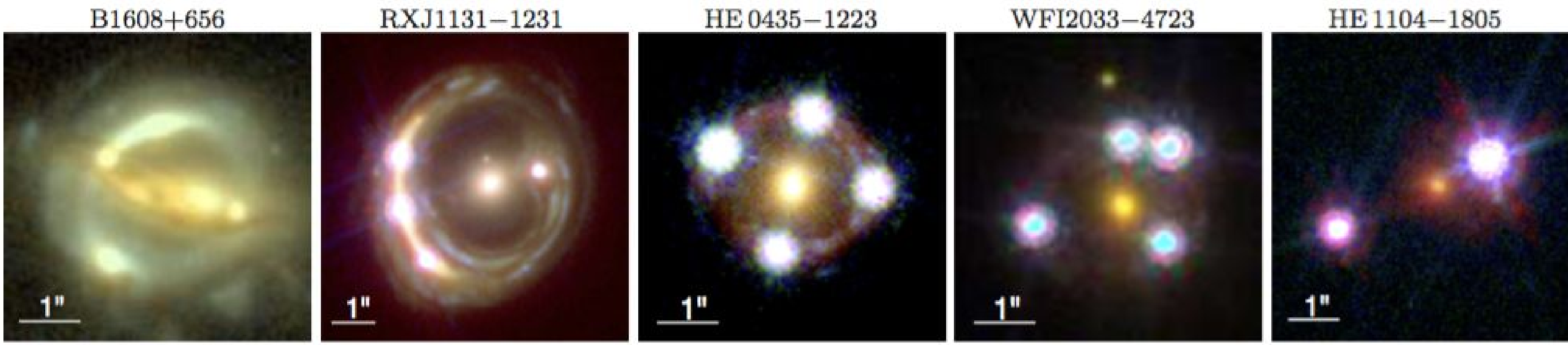
H-Index for results: ■ refereed
Y-axis: **linear** log



H0LiCOW V. New COSMOGRAIL time delays of HE 0435−1223: H_0 to 3.8% precision from strong lensing in a flat ΛCDM model

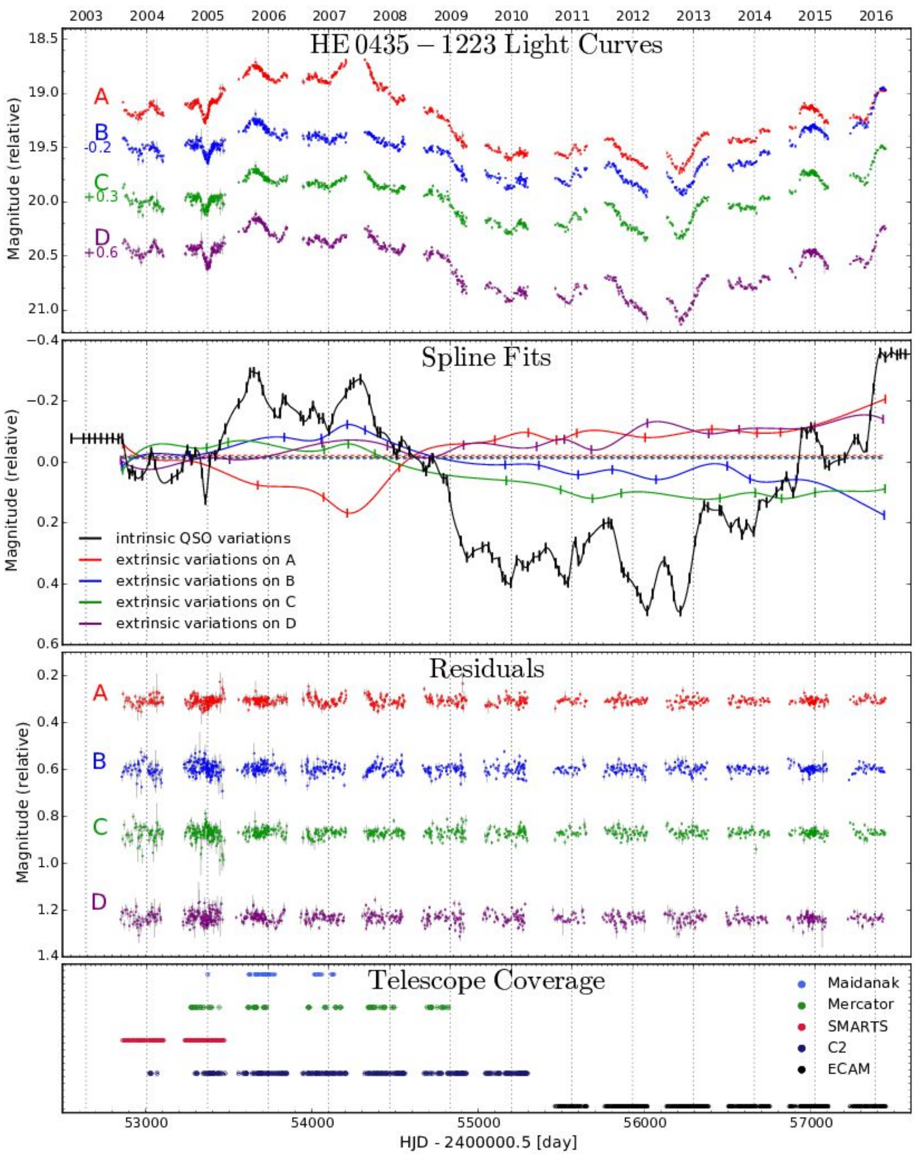
V. Bonvin,[1★] F. Courbin,[1] S. H. Suyu,[2,3,4] P. J. Marshall,[5] C. E. Rusu,[6] D. Sluse,[7] M. Tewes,[8] K. C. Wong,[9,4] T. Collett,[10] C. D. Fassnacht,[7] T. Treu,[11] M. W. Auger,[12] S. Hilbert,[13,14] L. V. E. Koopmans,[15] G. Meylan,[1] N. Rumbaugh,[11] A. Sonnenfeld,[16,11,17] and C. Spiniello[2]

The H0LiCOW sample



- 5 bright lensed quasars
- Found in radio/optical QSO searches
- Monitored for ~10 years with 1m-class telescopes by the COSMOGRAIL team
- Followed up with high S/N HST imaging and Keck spectroscopy, for detailed modeling

COSMOGRAIL Light Curves

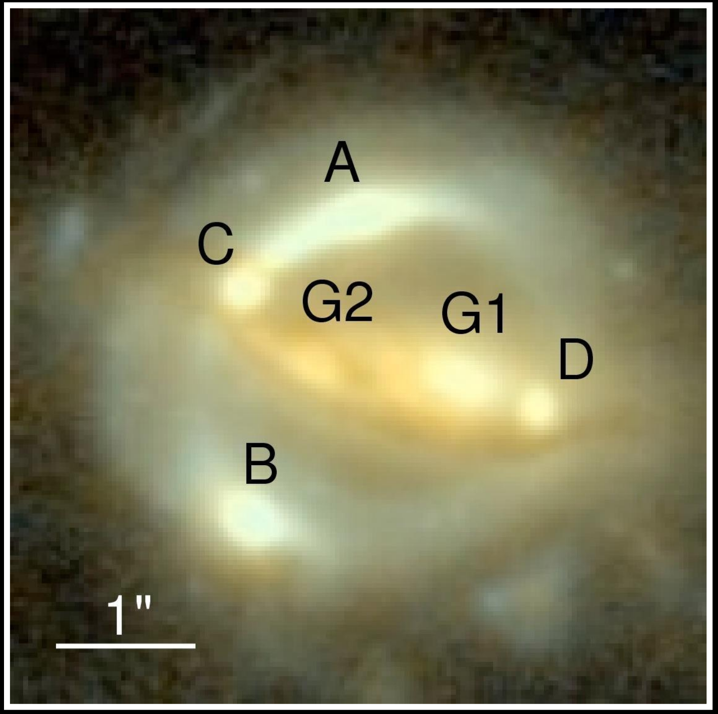


Multiple seasons (13 for HE0435) provide high accuracy (+/-1d) time delays

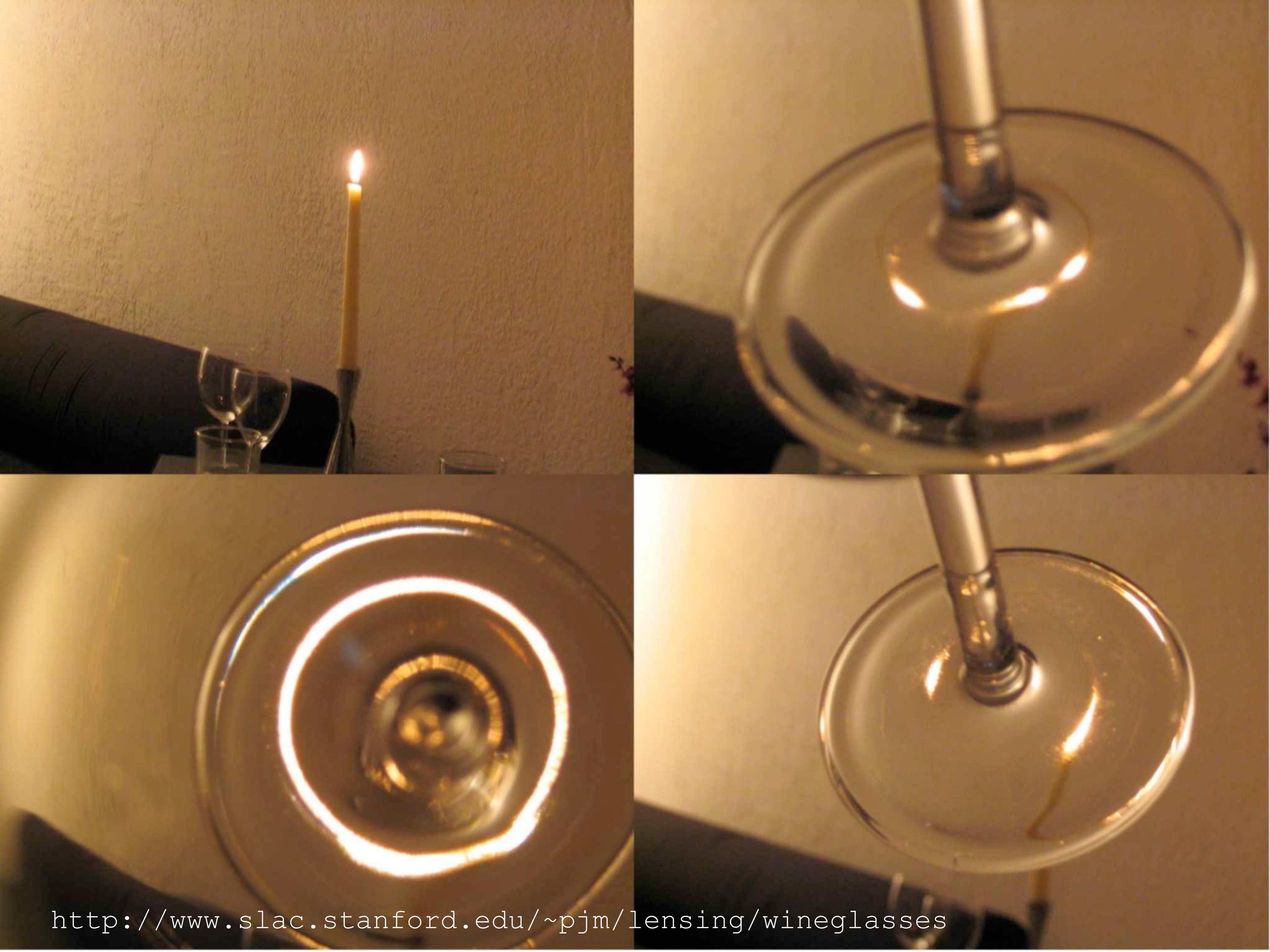
Model includes 1 intrinsic AGN light curve and 4 independent microlensing light curves

Lens modeling

Model the lens mass distribution, to predict the time delays and derive the distance.



Q: How do you model a gravitational lens?


http://www.slac.stanford.edu/~pjm/lensing/wineglasses

Lens modeling

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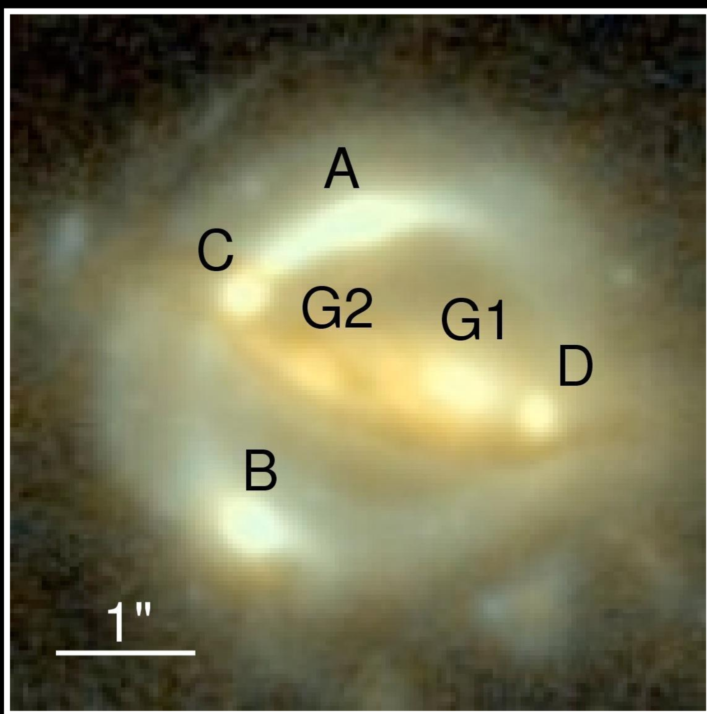
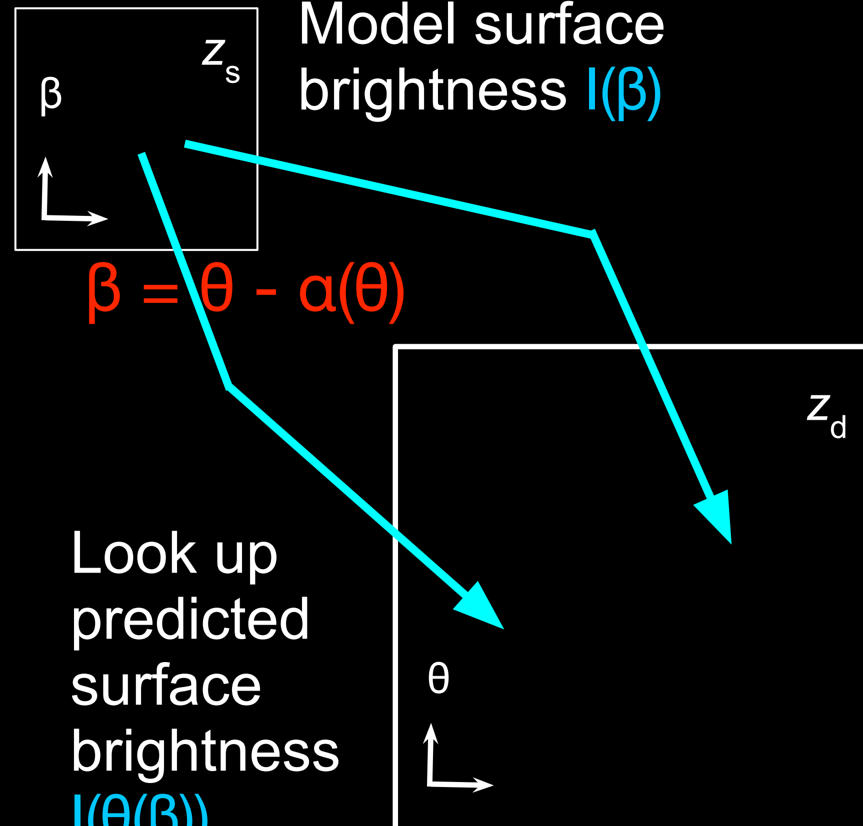




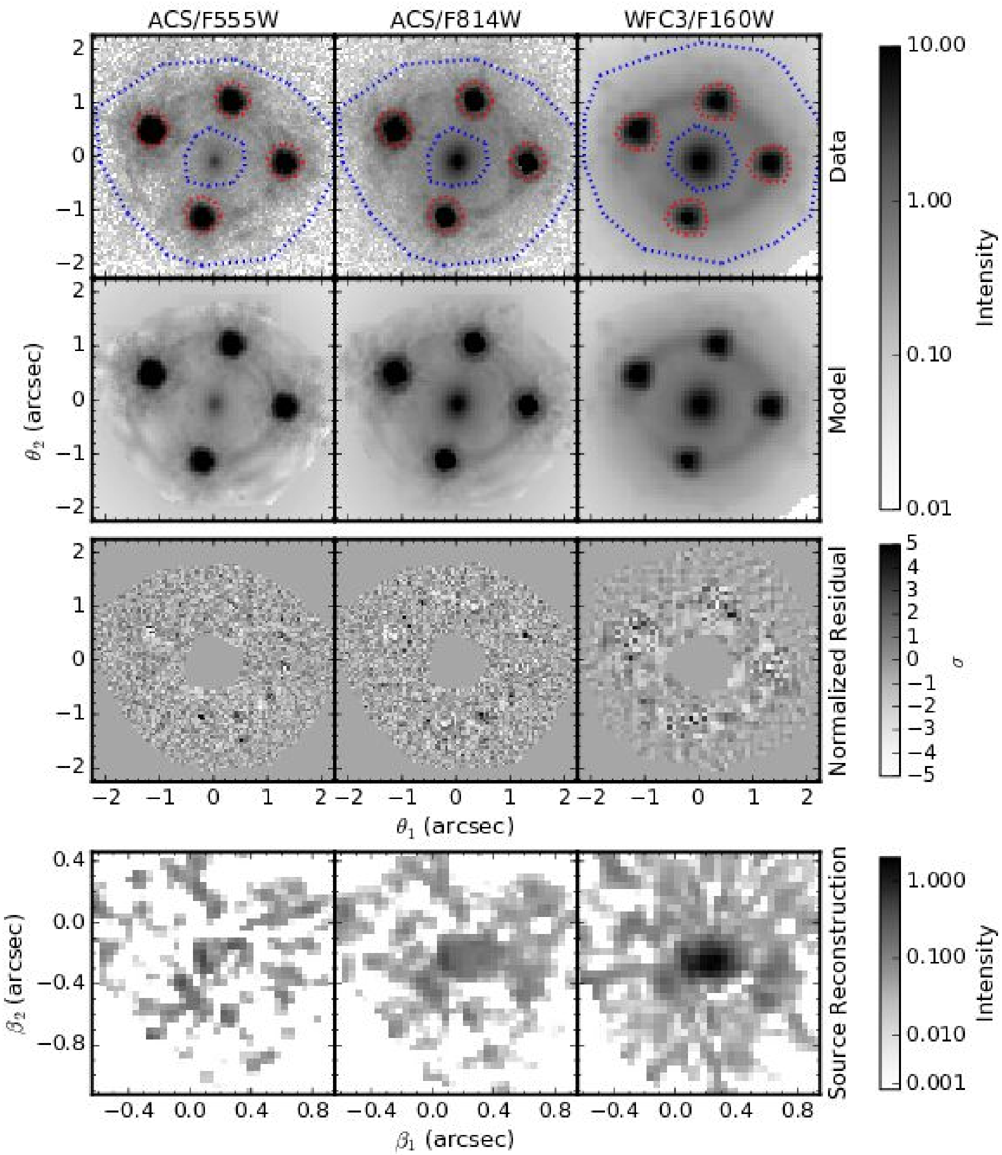
Model surface brightness $I(\beta)$

$\beta = \theta - \alpha(\theta)$

Look up predicted surface brightness $I(\theta(\beta))$

$$\log \Pr(\theta|I_{obs}) \sim \chi^2(I(\theta)-I(\theta)_{obs})/2 + S(I(\beta))$$

HST Lens Modeling



- Deep, high resolution images reveal Einstein Rings
- Residuals consistent with noise, reconstructed AGN host galaxy is plausible

Inferring cosmological parameters

Let $\pi = \{H_0, \Omega_{\rm m}, \Omega_\Lambda, w\}$ (cosmological parameters)

$\xi = \{\pi, \nu\}$ (all model parameters)

We are after the posterior PDF for p given the data, marginalised over the nuisance parameters n:

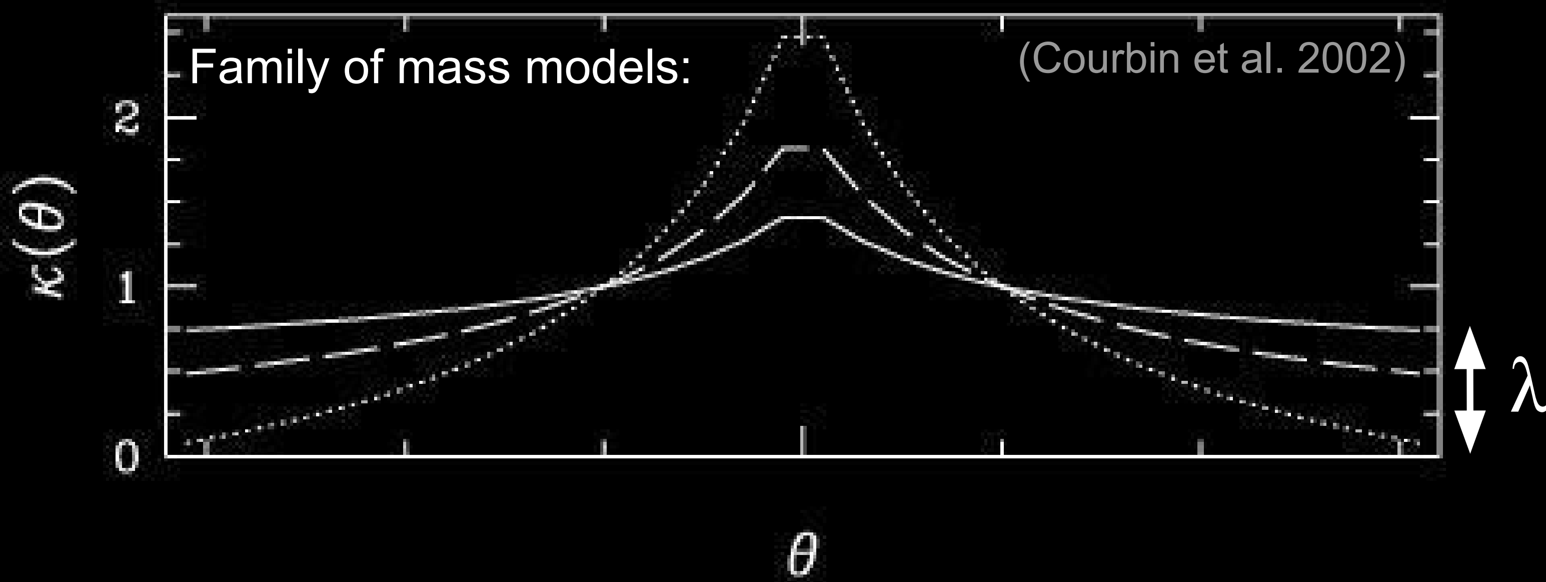
$$P(\pi | d_{\rm ACS}, \Delta t, \sigma) = \int {\rm d}\nu \, {\rm P}(\xi | d_{\rm ACS}, \Delta t, \sigma)$$

where

$$P(\xi | d_{\rm ACS}, \Delta t, \sigma) \propto \underbrace{P(d_{\rm ACS}|\xi)\, P(\Delta t|\xi)\, P(\sigma|\xi)}_{\text{3-dataset likelihood}} \overbrace{P(\xi)}^{\text{Prior}}$$

Method: importance sample from priors Pr(π) and Pr(v), using 3-dataset likelihood. What are v and Pr(v)?

“Mass-sheet” transformation

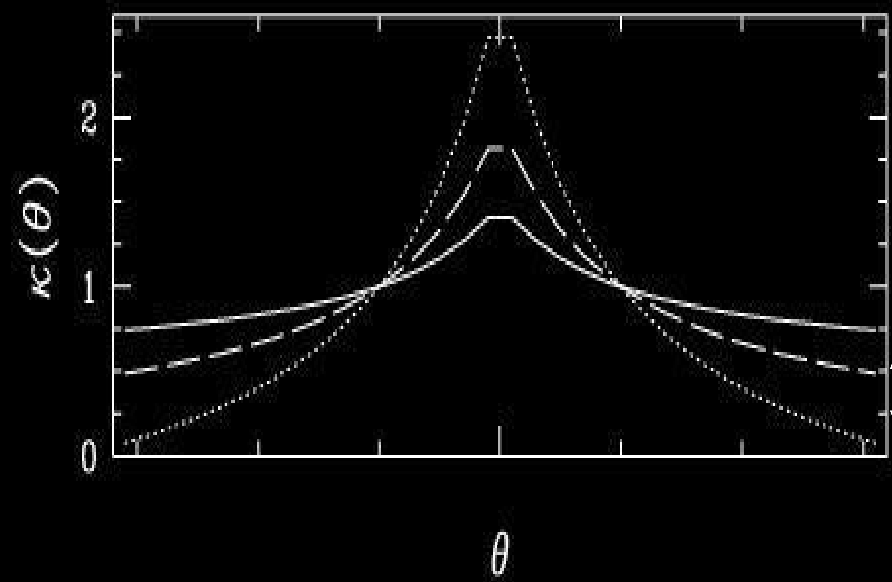


Predicted image is unchanged, but time delay predictions (and H0) are wrong:

$$\kappa'(\theta) = (1-\lambda)\,\kappa(\theta) + \lambda$$

$$t'(\theta) = (1-\lambda)\,t\,(\theta) \qquad \mu'(\theta) = \mu(\theta)\,/\,(1-\lambda)^2$$

“Mass-sheet” degeneracy



λ

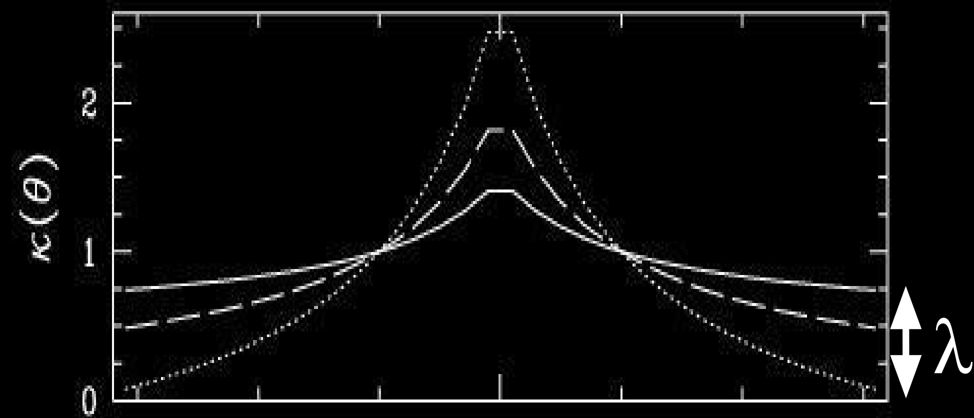
$$\kappa'(\theta) = (1-\lambda)\,\kappa(\theta) + \lambda$$

$$t'(\theta) = (1-\lambda)\,t\,(\theta)$$

$$\mu'(\theta) = \mu(\theta)\,/\,(1-\lambda)^2$$

With your neighbors, discuss strategies for breaking the mass-sheet degeneracy and be prepared to make suggestions in 5 mins’ time!

“Mass-sheet” degeneracy



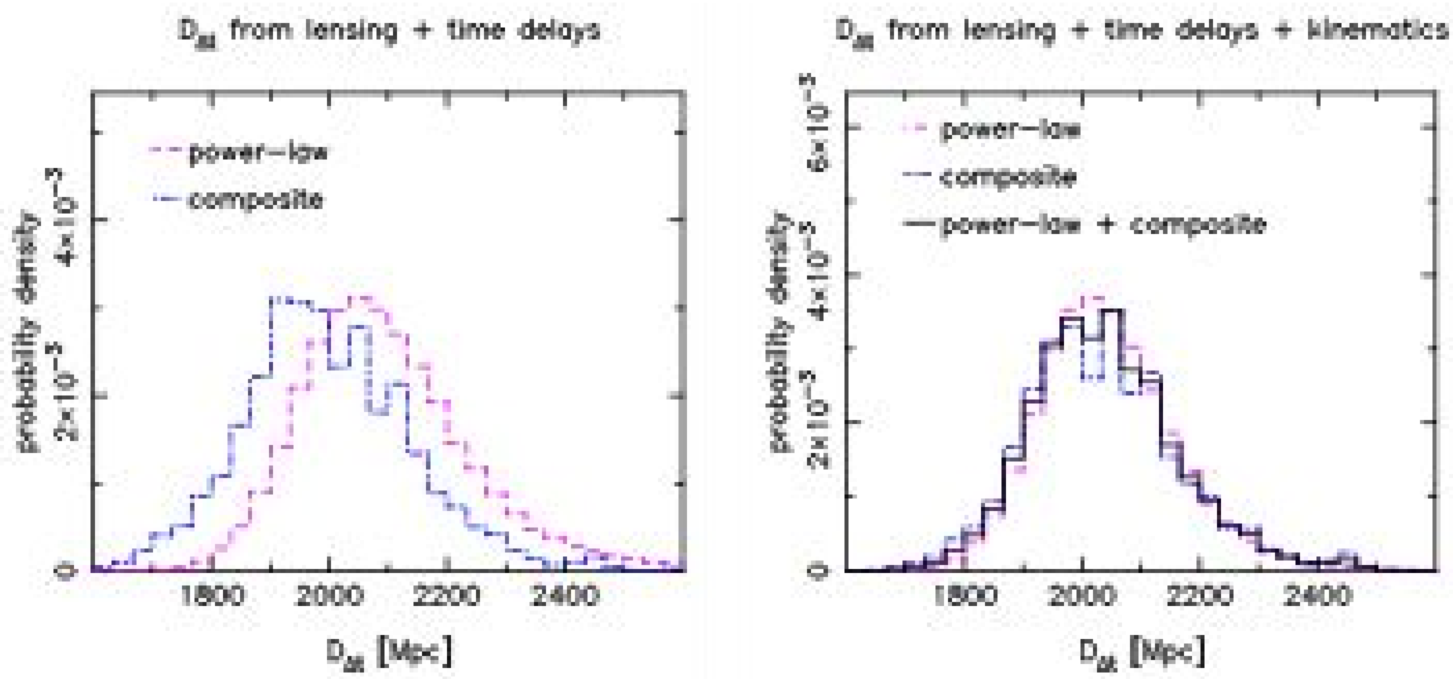
$$\kappa'(\theta) = (1-\lambda)\,\kappa(\theta) + \lambda$$

$$t'(\theta) = (1-\lambda)\,t\,(\theta)$$

$$\mu'(\theta) = \mu(\theta)\,/\,(1-\lambda)^2$$

- Know what $\kappa(\theta)$ is:
  - Assume plausible functional form, constrain with stellar dynamics, scaling relations
  - Measure “external convergence” due to local and line of sight structures and marginalize (ν) out
- Know what $\mu(\theta)$ is, e.g. from standard candle SNe Ia
- Be right on average, sampling λ with mean zero: tests on realistic simulations

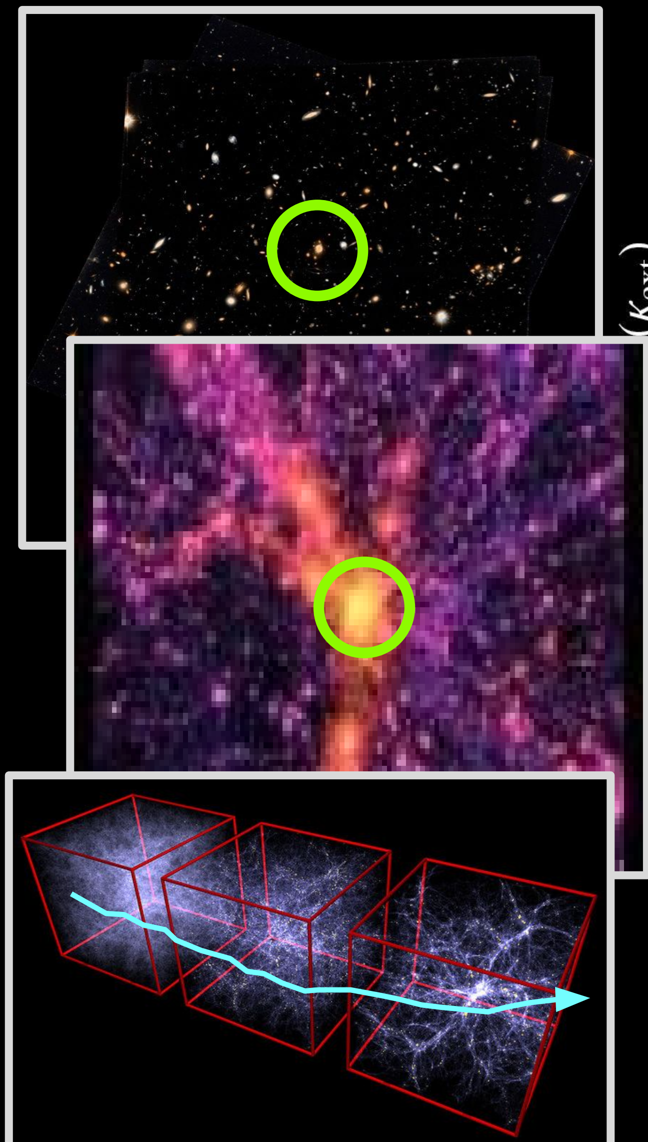
“Mass sheet” degeneracy

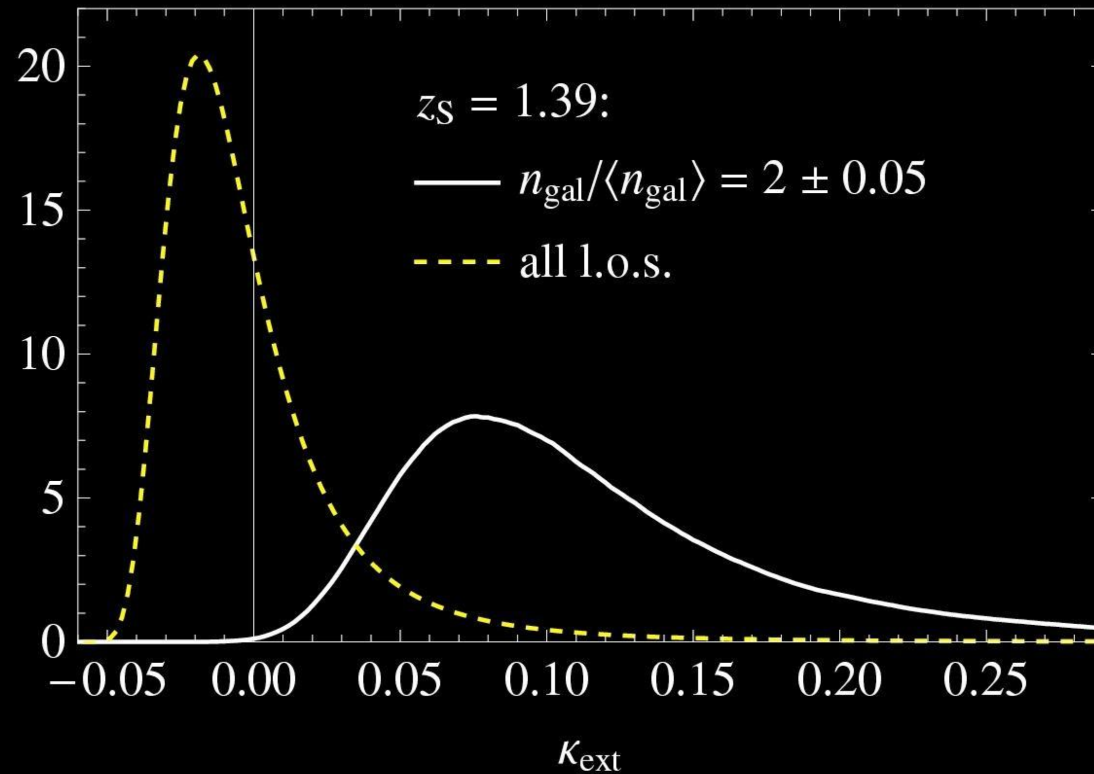


Using all the pixels in the HST Einstein ring image, *plus the velocity dispersion of the lens*, breaks the internal model degeneracy and reduces the systematic distance error to < 2%

(Suyu et al 2014)

External Convergence $\Pr(\kappa_{ext})$





Match N-body simulation sightlines to observed over-density in galaxy counts, building up $\Pr(\kappa_{ext})$

Inferring cosmological parameters

Let $\pi = \{H_0, \Omega_{\rm m}, \Omega_\Lambda, w\}$ (cosmological parameters)

$\xi = \{\pi, \nu\}$ (all model parameters)

We are after the posterior PDF for p given the data, marginalised over the nuisance parameters n:

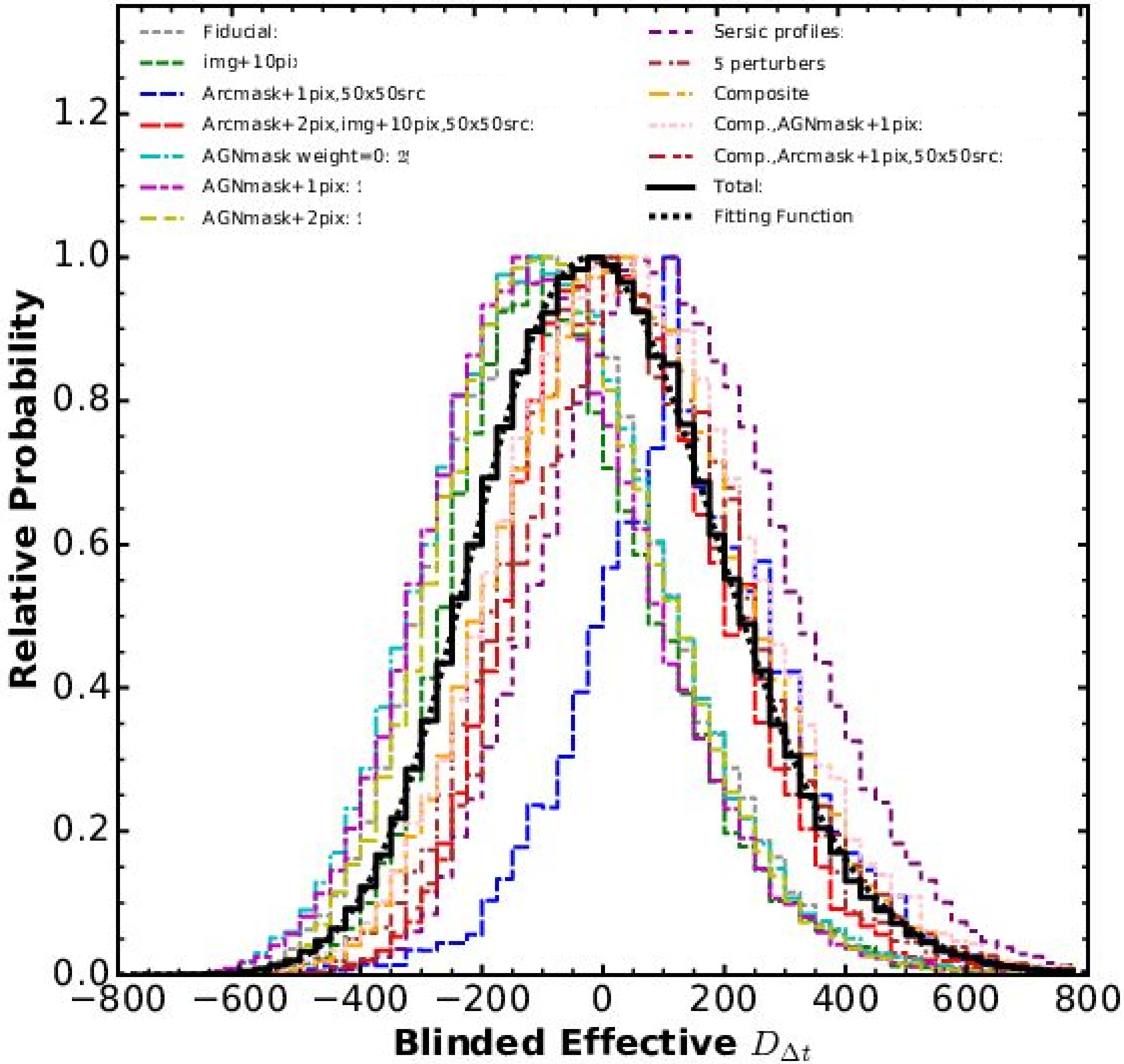
$$P(\pi|d_{\rm ACS}, \Delta t, \sigma) = \int {\rm d}\nu\, {\rm P}(\xi|d_{\rm ACS}, \Delta t, \sigma)$$

where

$$P(\xi|d_{\rm ACS}, \Delta t, \sigma) \propto \underbrace{P(d_{\rm ACS}|\xi)\, P(\Delta t|\xi)\, P(\sigma|\xi)}_{\text{3-dataset likelihood}} \overbrace{P(\xi)}^{\text{Prior}}$$

Method: importance sample from priors Pr(π) and Millenium Simulation Pr(κ_{ext}), using 3-dataset likelihood.

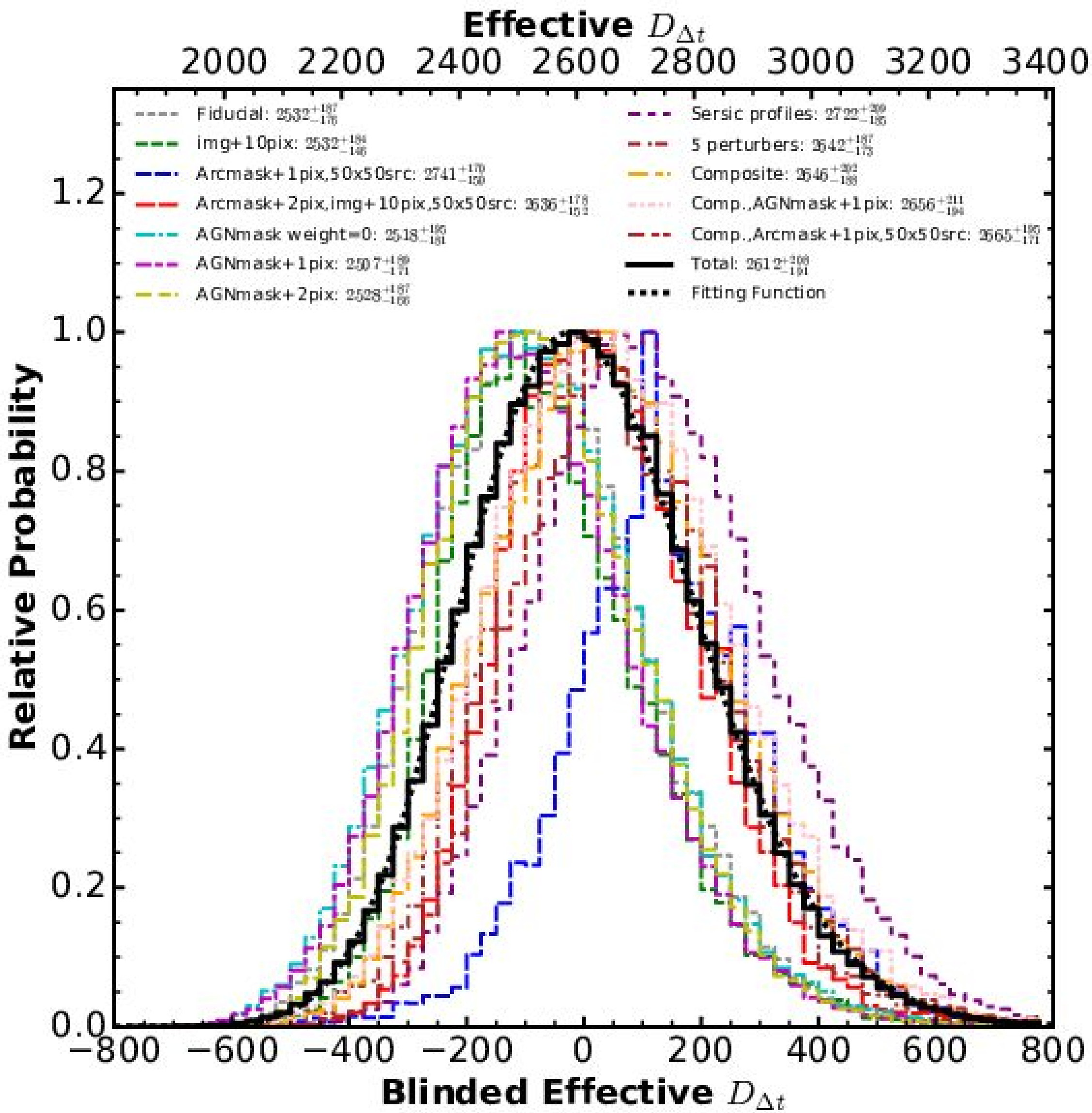
Distance Measurement



Choices in modeling lead to small offsets in time delay distance

These models can be averaged over, before unblinding

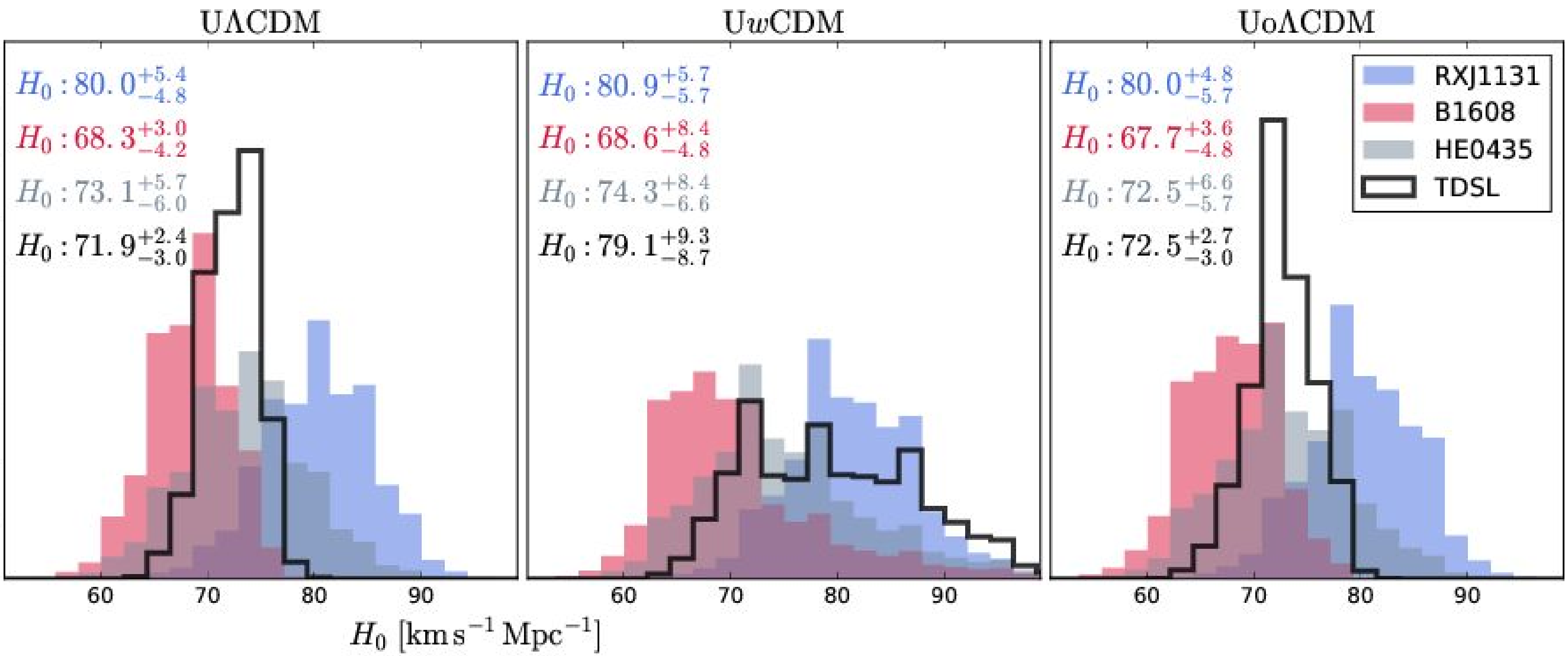
Distance Measurement



Choices in modeling lead to small offsets in time delay distance

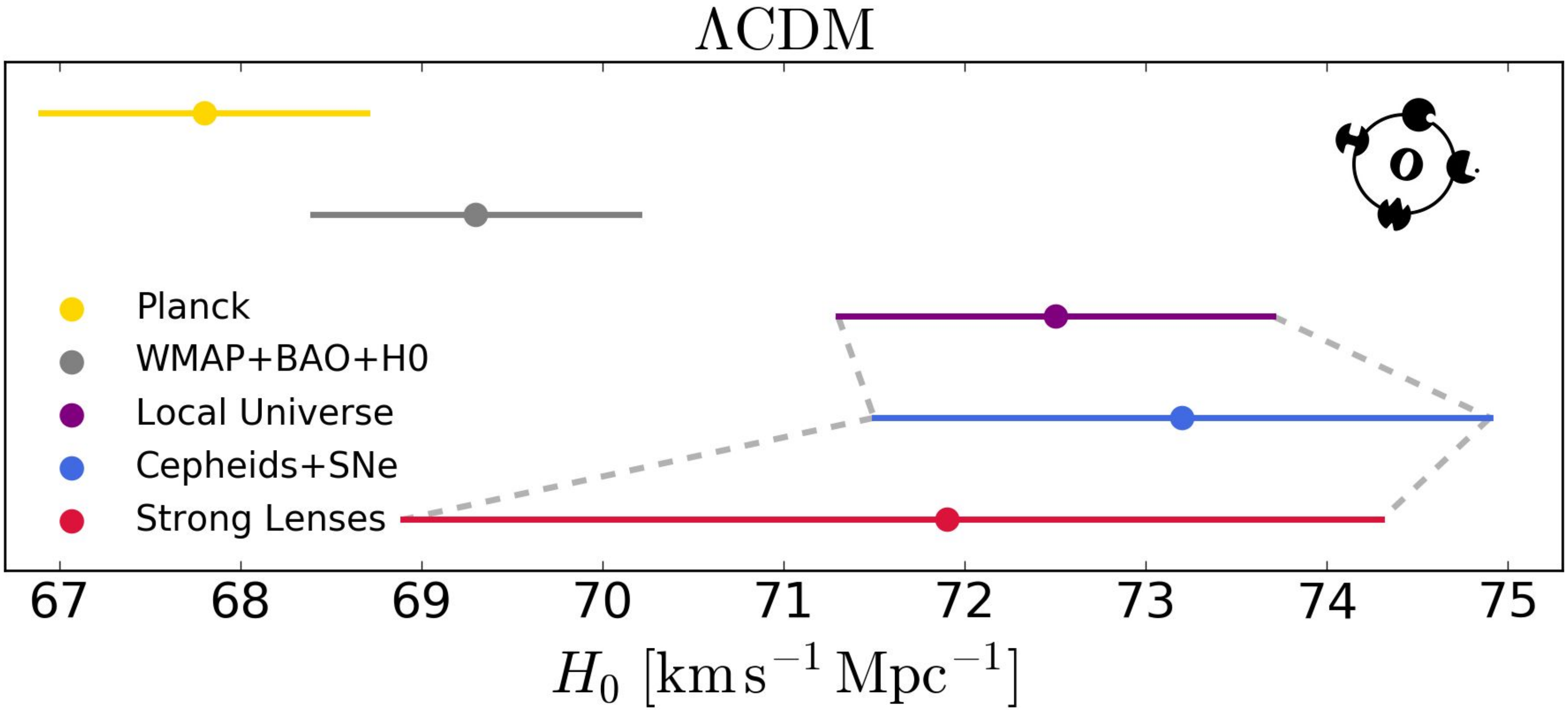
These models can be averaged over, before unblinding

Cosmological Parameters



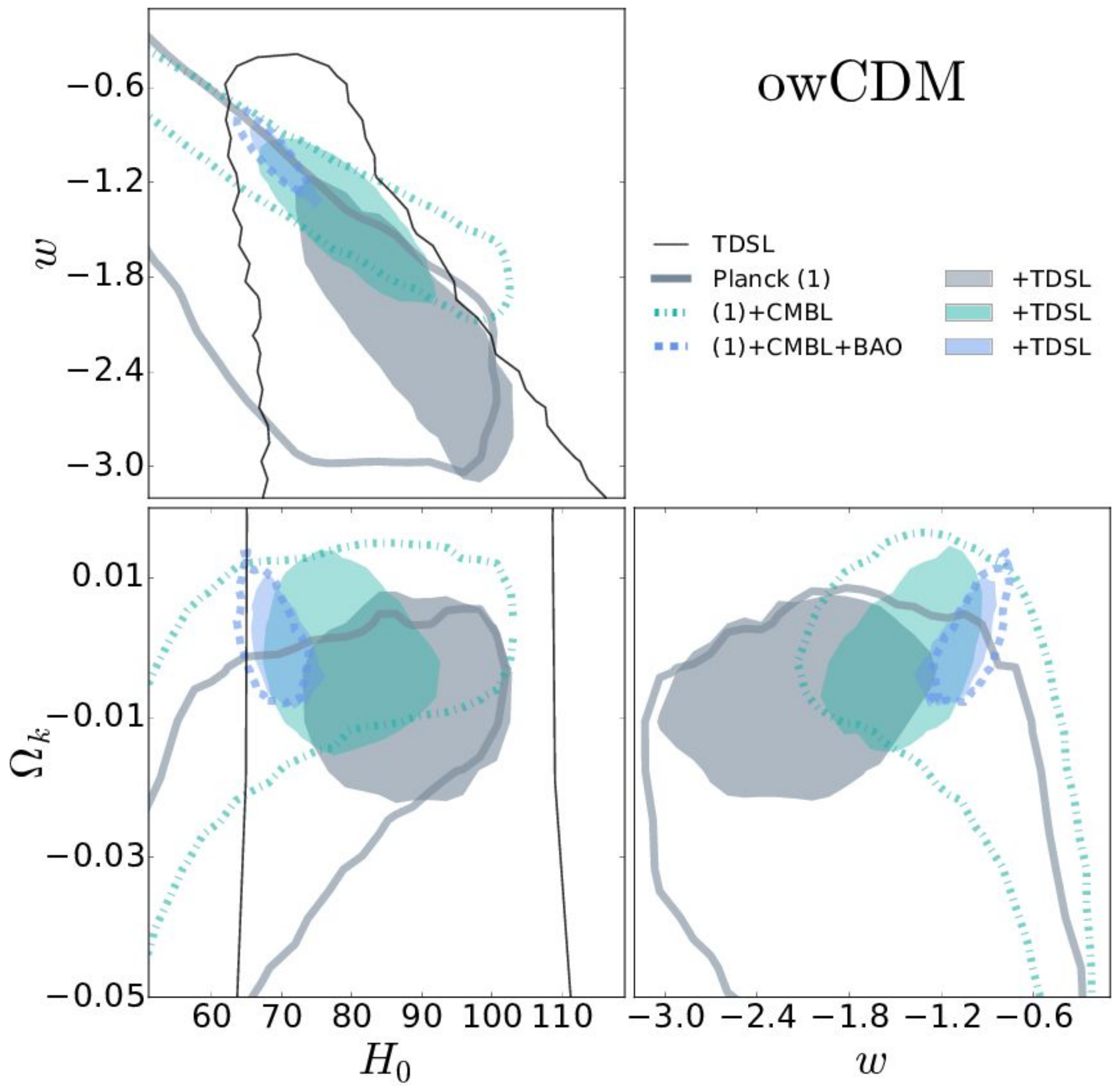
B1608 was not blinded, RXJ1131 was.
HE0435 was blinded, and fell in between.
In ΛCDM, TDSL H_0 = 71.9 +/- 2.7 (3.8%)

Tension in H_0?



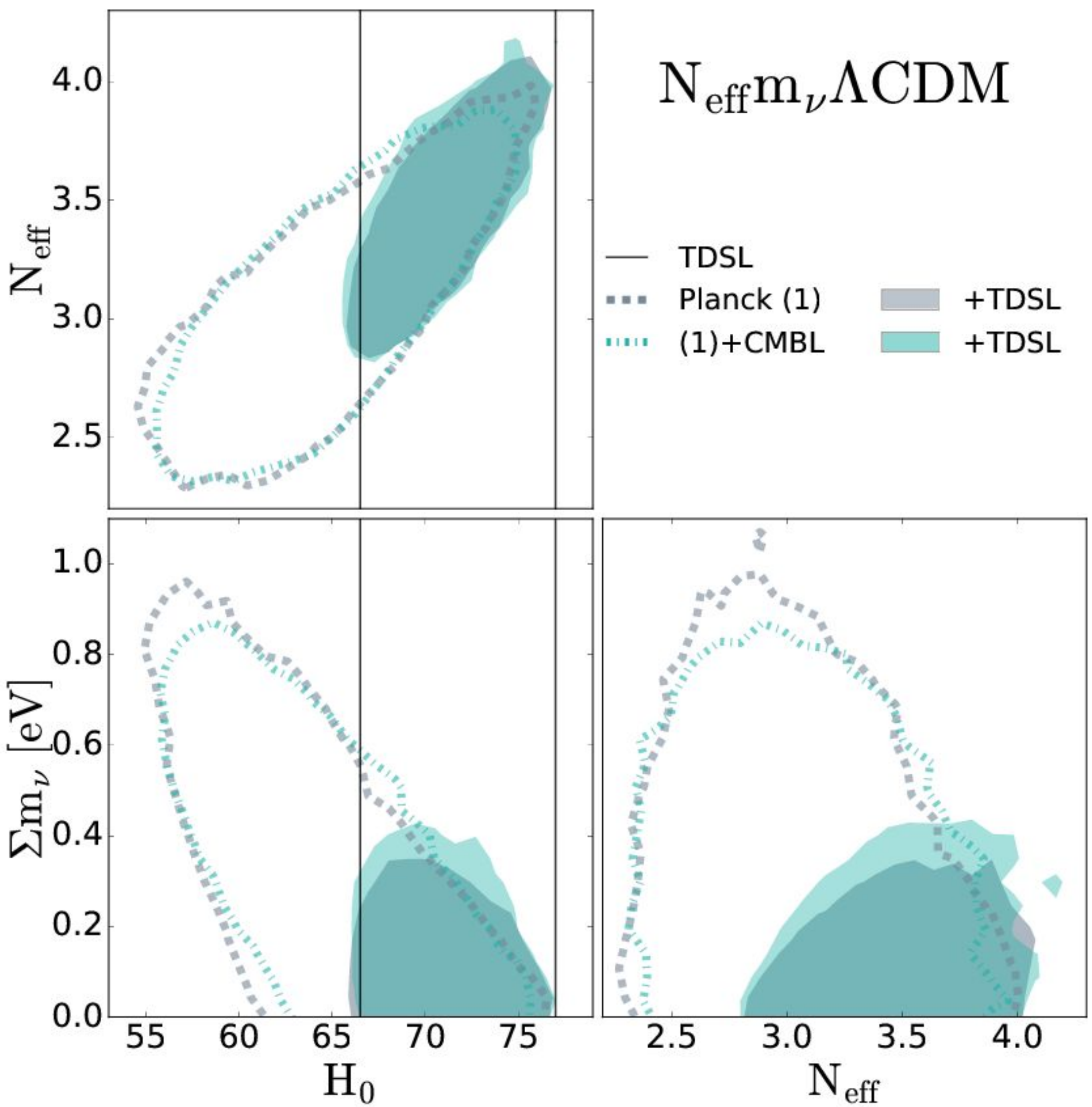
Strong lenses provide an independent measurement - blinding is crucial to avoid unconscious concordance either way

Dark Energy from CMB+SL



In higher dimension parameter spaces the tension is alleviated: owCDM is accessible

Cosmic Neutrinos from CMB+SL



The higher H_0 favors higher N_{eff} and lower neutrino mass

Plan

- Introduction to time delay lenses, and how each one enables a cosmological distance measurement

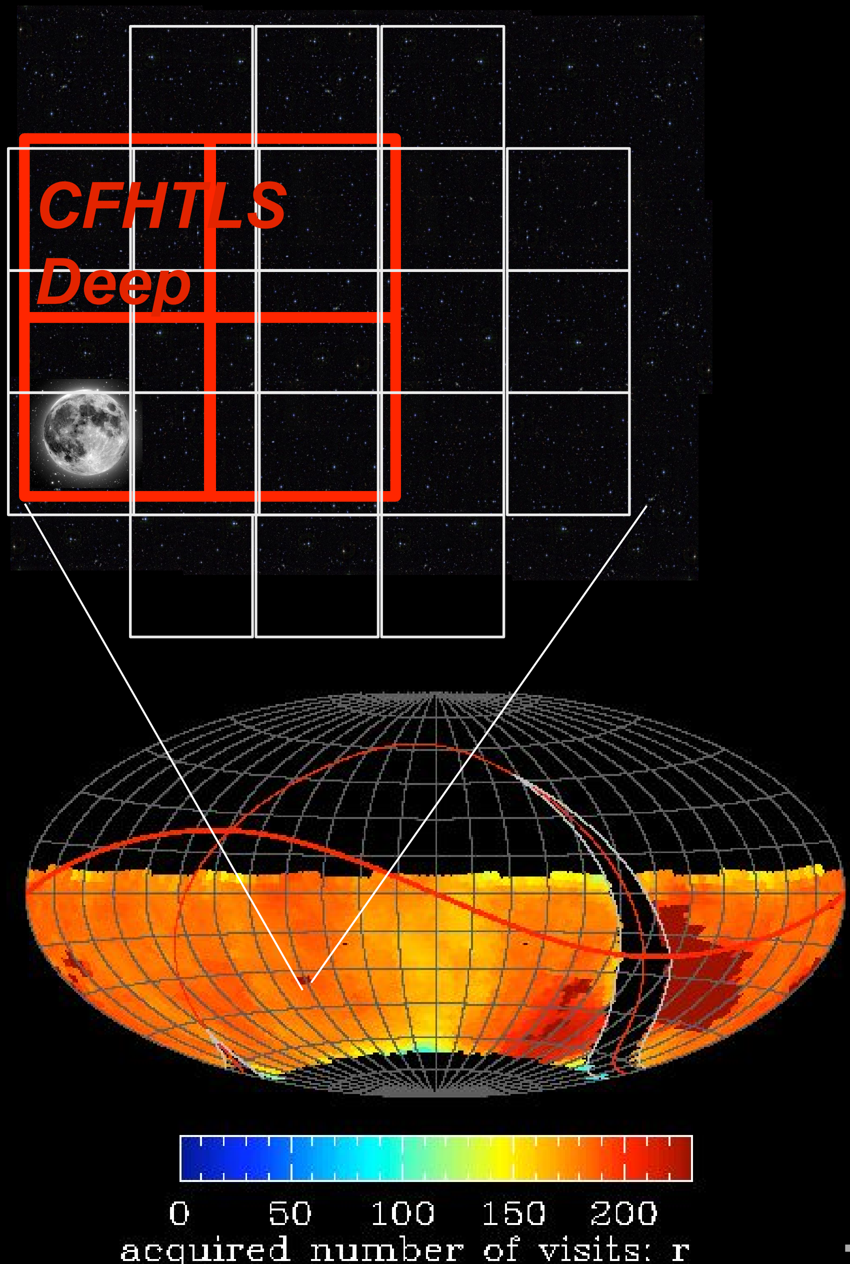
- Time delay cosmography in practice:
  - Some recent results from the H0LiCOW project
  - Looking forward to hundreds of lenses with LSST
  - Residual systematic errors, and what we can do about them

Time Delay Cosmography with LSST

- Time delay lenses are an interesting *independent* cosmological probe, with very different systematics to BAO, SNe etc but providing comparable precision

- To reach sub-percent precision on H_0, *w*, we would need ~100 time delay lens systems, each measured to H0LiCOW precision (5%)

- The LSST time-delay lenses could remain a competitive cosmological probe: but what will it take to achieve sub-percent accuracy?



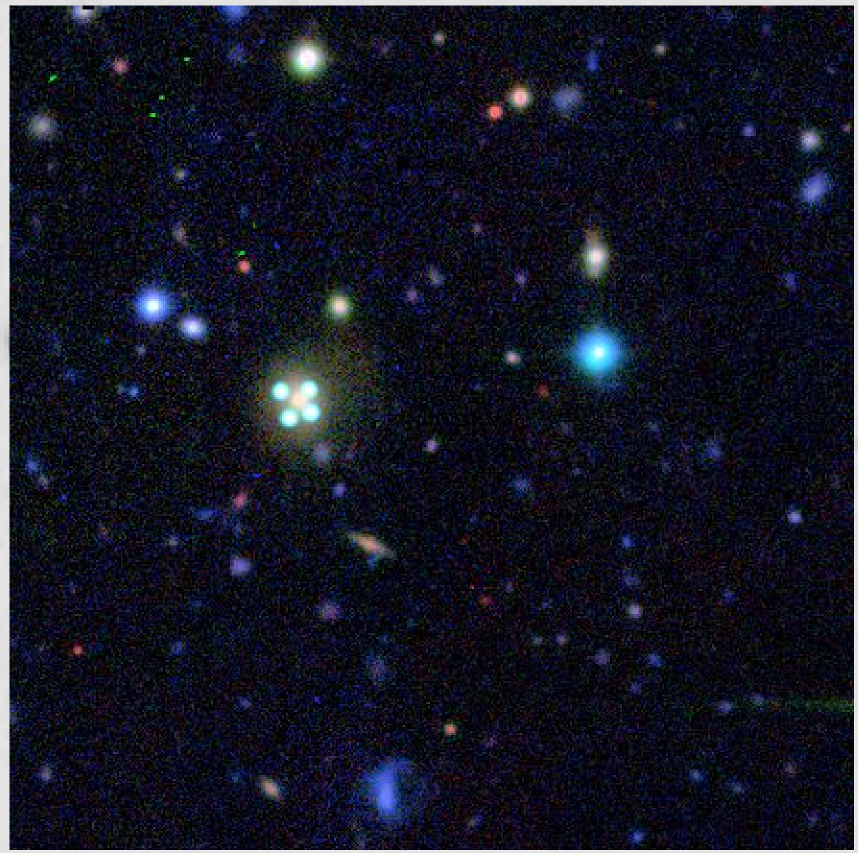
The LSST Strong Lens Discovery and Monitoring Campaign

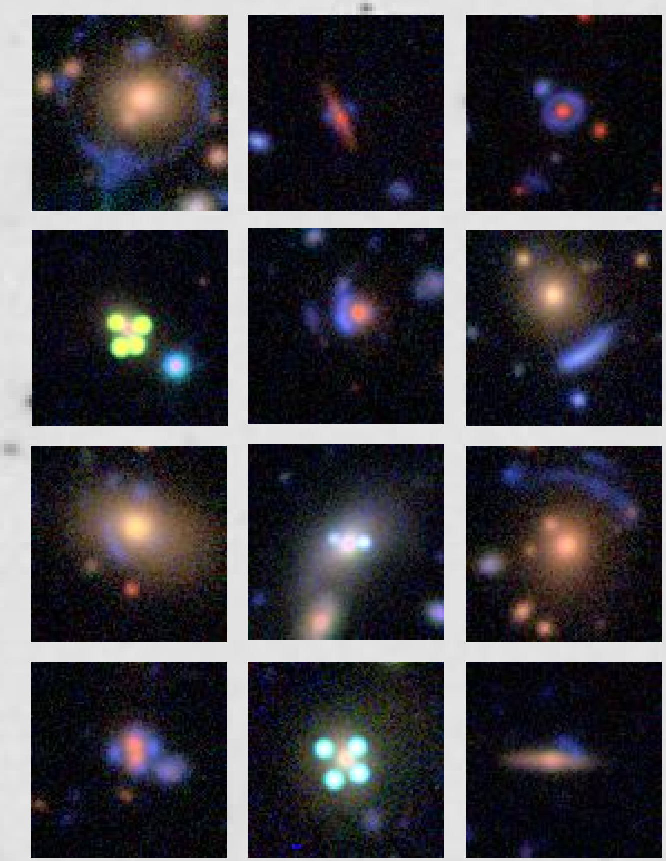
- 18000 sq deg
- 6 filters, ugrizy
- 10 years, 800 visits/field
- 5 day cadence (ugrizy)
- ~ 24 mag per visit
- Resolution 0.4-1.0”

http://www.lsst.org

The LSST image archive will contain a *lot* of lenses

10^4 galaxy-scale lenses, 100s of lensed supernovae





CFHTLS images + Space Warps sims, SL2S lenses (More, Marshall et al)

How many lensed quasars?

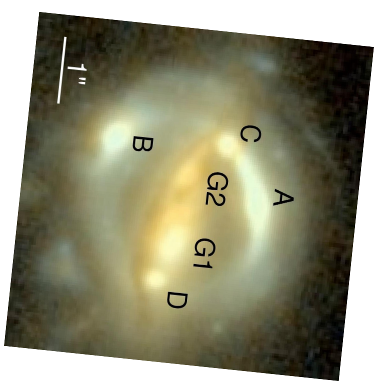
Survey	QSO (detected) $N_{\rm nonlens}$	QSO (detected) $N_{\rm lens}$	QSO (measured) $N_{\rm nonlens}$	QSO (measured) $N_{\rm lens}$
SDSS-II	1.18×10^5	26.3 (15%)	3.82×10^4	7.6 (18%)
SNLS	9.23×10^3	3.2 (12%)	3.45×10^3	1.1 (13%)
PS1/3π	7.52×10^6	1963 (16%)	...	...
PS1/MDS	9.55×10^4	30.3 (13%)	3.49×10^4	9.9 (14%)
DES/wide	3.68×10^6	1146 (14%)	...	...
DES/deep	1.26×10^4	4.4 (12%)	6.05×10^3	2.0 (13%)
HSC/wide	1.76×10^6	614 (13%)	...	...
HSC/deep	7.96×10^4	29.7 (12%)	4.30×10^4	15.3 (13%)
JDEM/SNAP	5.00×10^4	21.8 (12%)	5.00×10^4	21.8 (12%)
LSST	2.35×10^7	8191 (13%)	9.97×10^6	3150 (14%)

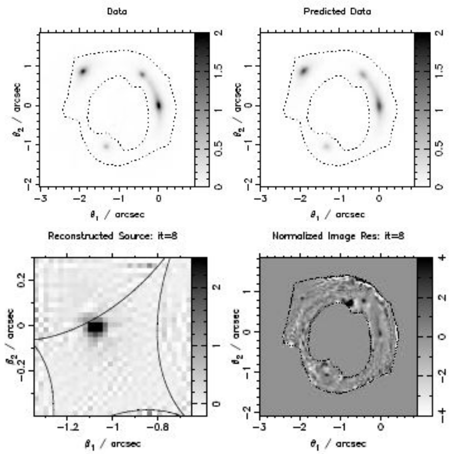
(Oguri & Marshall 2010)

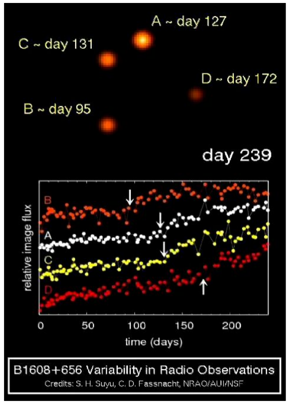
- **LSST** should *detect* ~8000 lenses (1000 quads)
- **STRIDES** aims to monitor ~30 **DES** lenses
- **LSST** should be able to monitor **~3000** systems, but how many will yield accurate time delays?

Dark Energy from 100 LSST lenses

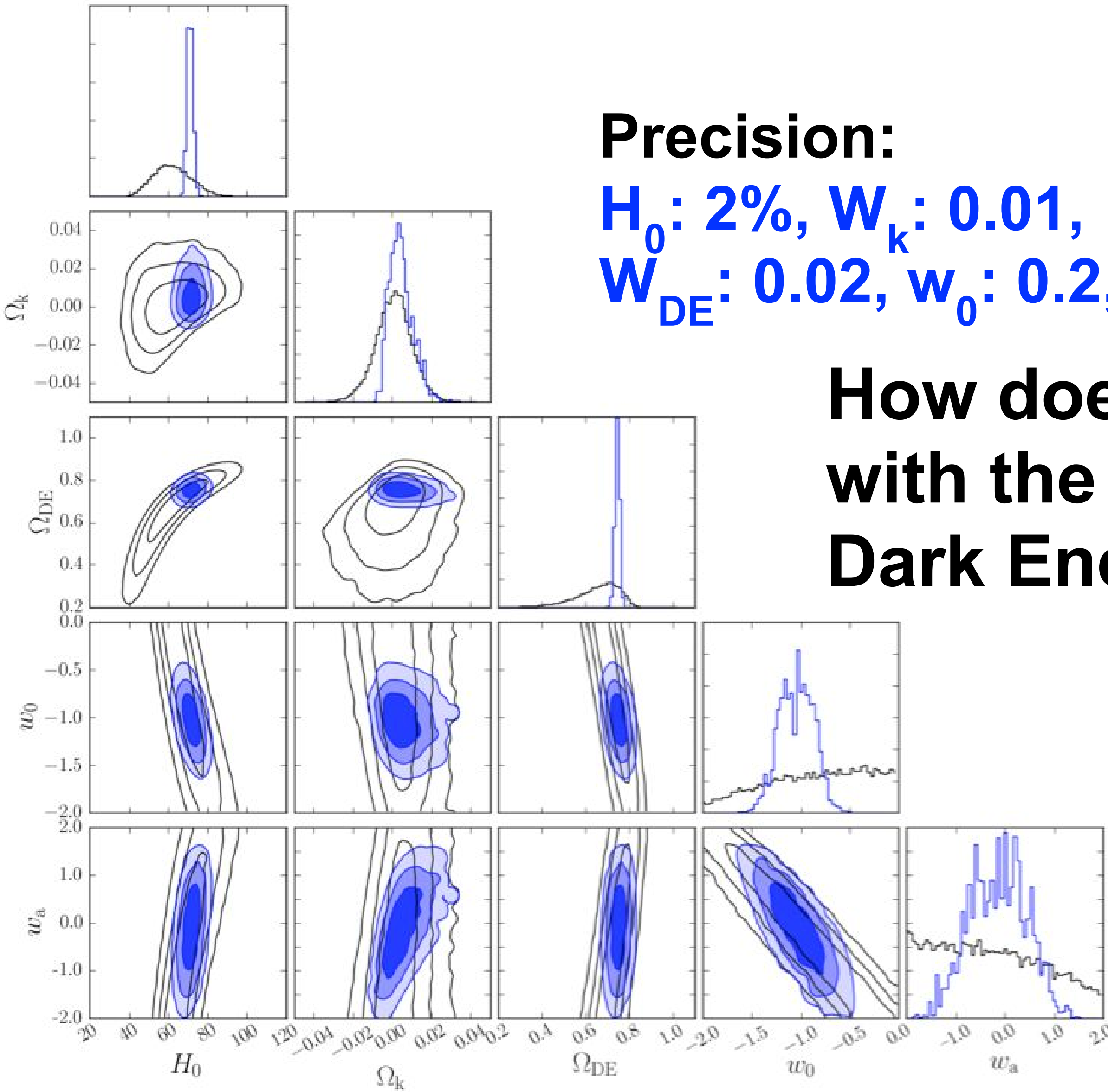
Suppose we have just 100 LSST lenses with spectroscopic redshifts, lens galaxy velocity dispersions, HST-grade ring modeling and good time delays, such that detailed analysis of individual lenses gives **5% precision on each time delay distance**







Dark Energy from 100 LSST lenses

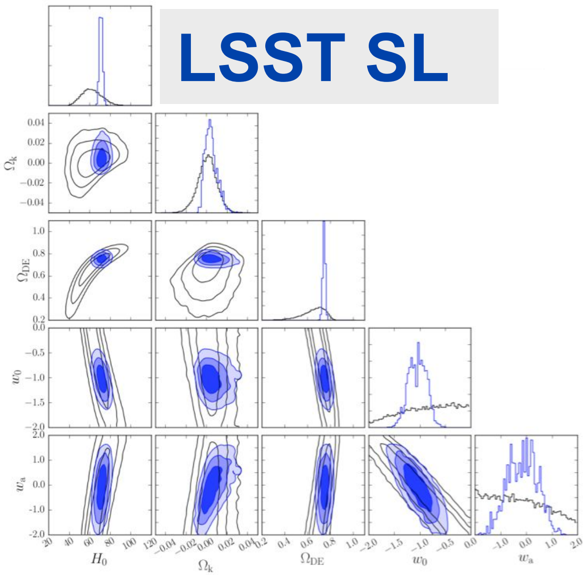


Precision:

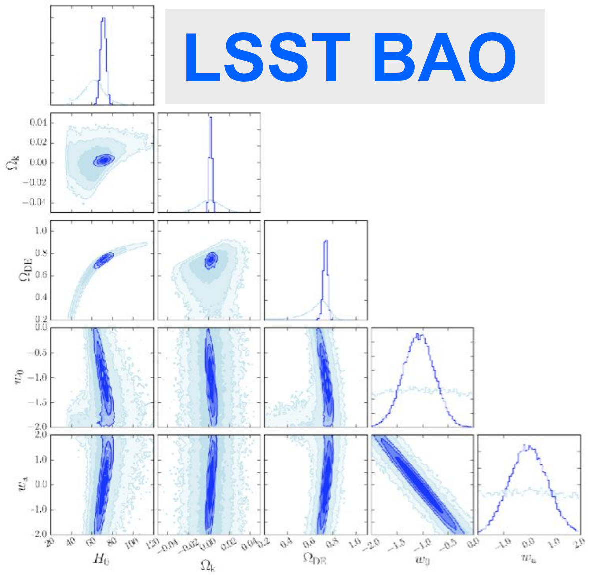
H_0: 2%, W_k: 0.01,
W_{DE}: 0.02, w_0: 0.2, w_a: 0.7

How does this compare with the other LSST Dark Energy probes?

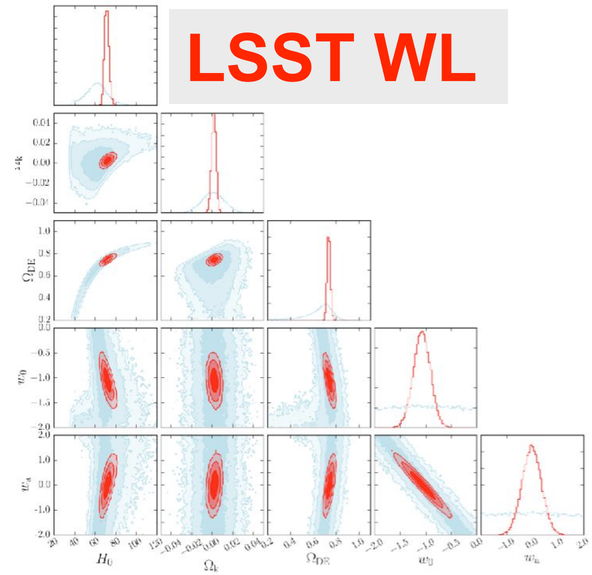
Dark Energy from 100 LSST lenses



w0:0.2, wa:0.7



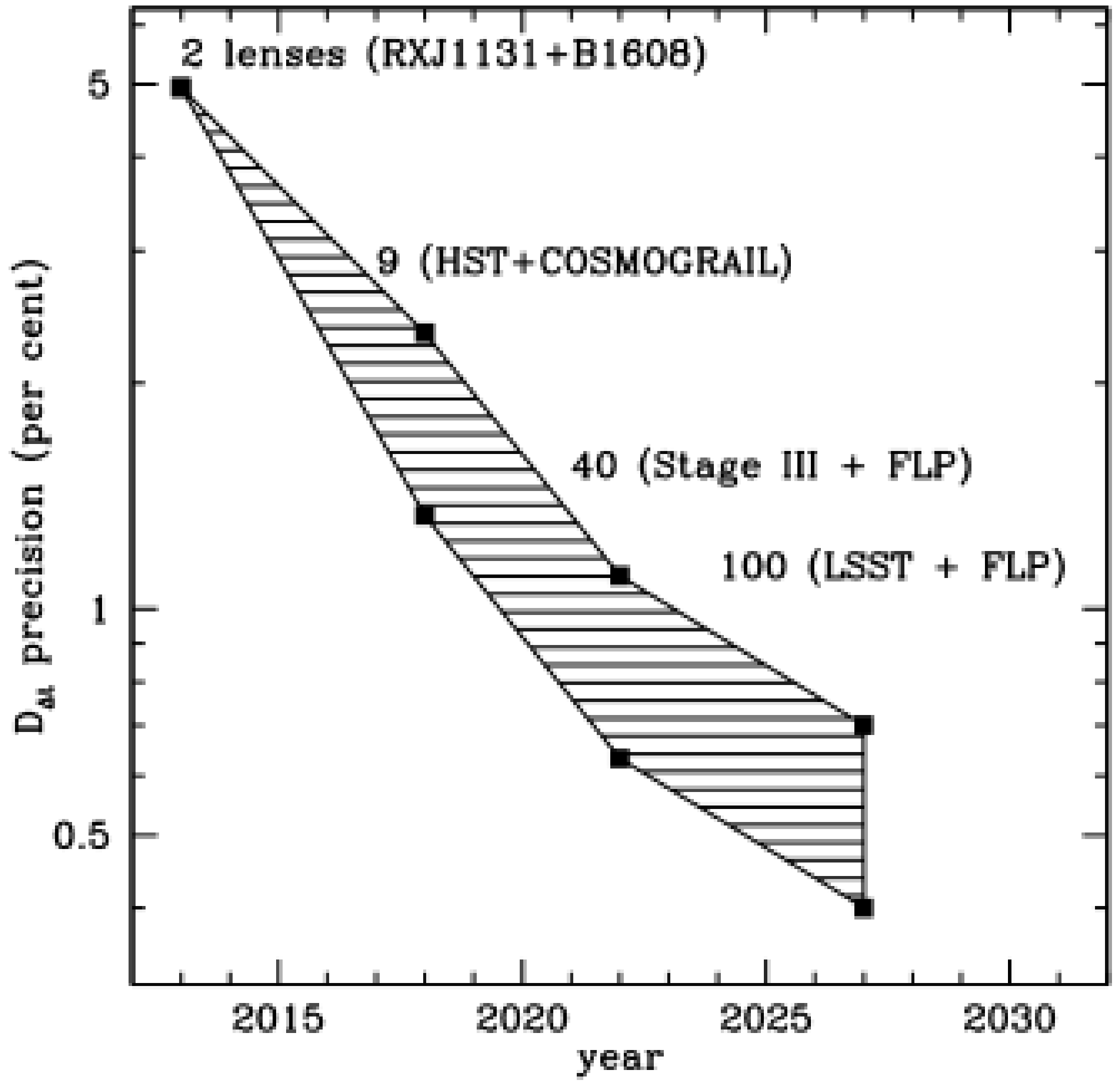
w0:0.4, wa:1.0



w0:0.2, wa:0.5

100 lenses found and monitored with LSST, and followed-up to H0LiCOW levels or better, would yield Dark Energy constraints competitive with the other DESC probes

Time Delay Cosmography Roadmap



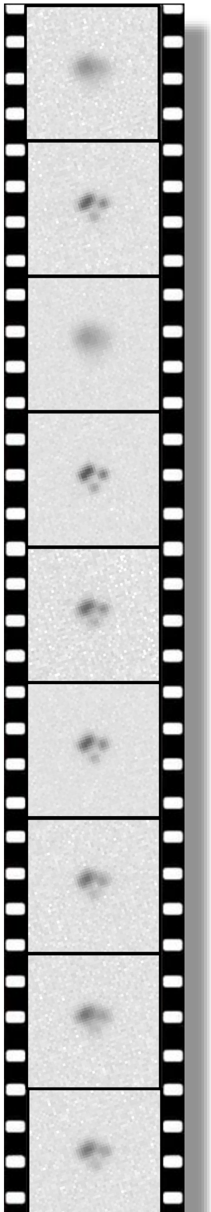
Treu & Marshall 2016

LSST Time Delay Lens Cosmography

Each key analysis step is either a logistical challenge or a potential source of systematic error, or both:

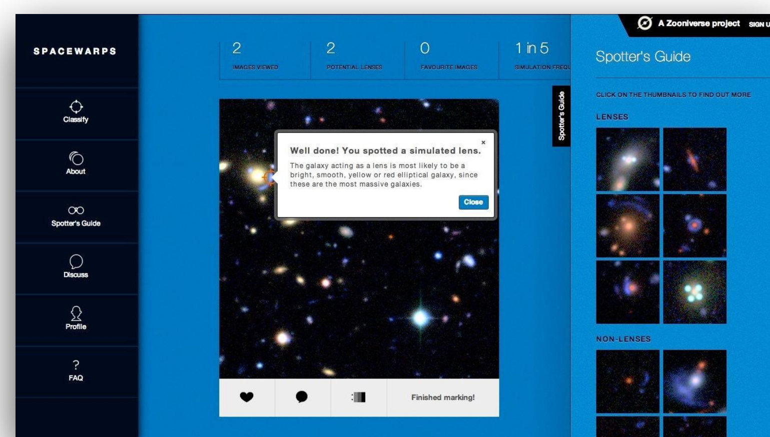
- Find 1000s of lensed AGN and SNe
- **Measure 100s of time delays** to few % precision
- Obtain high resolution follow-up imaging and spectroscopy, **constrain lens mass distributions**
- Reconstruct each lens' density **environment**
- Parametrize systematics and marginalize out
- Blind inference of cosmological parameters

Lens detection at LSST scale

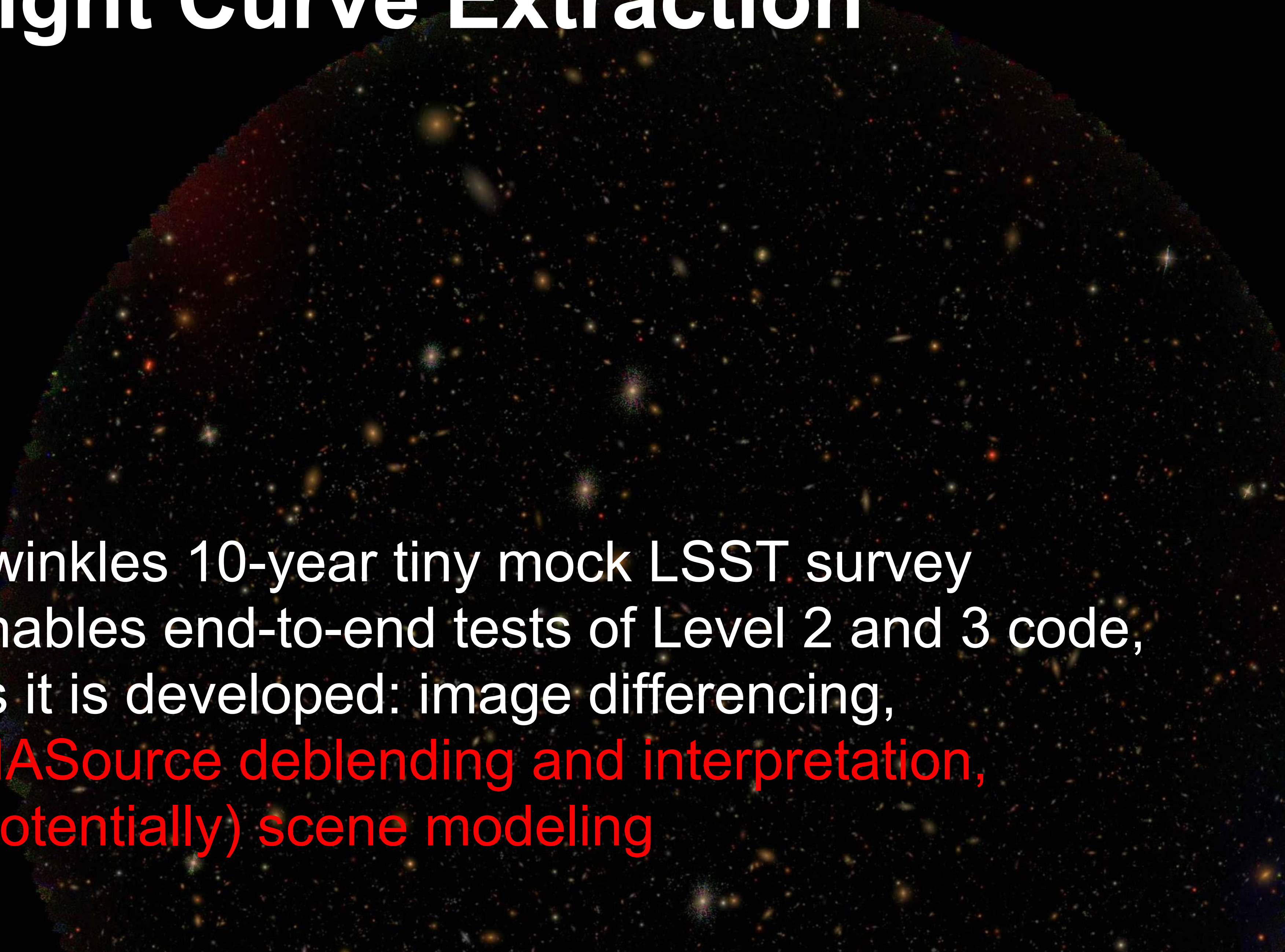


- **Catalog-based candidate detection.** *Needs: good deblender, the right parameters (color, morphology, variability) saved, rapidly executable DB queries, intelligent alert brokering for lensed SNe*
- **Image modeling for candidate classification.** *Needs: access to postage stamp images at data center in a "Multi-Fit," via Level 3 API, reliable PSF models and image registration. Or, convnets*

- **Candidate visualization for quality control.** *Needs: optimally-viewable color images, web-based system for crowd-sourcing*



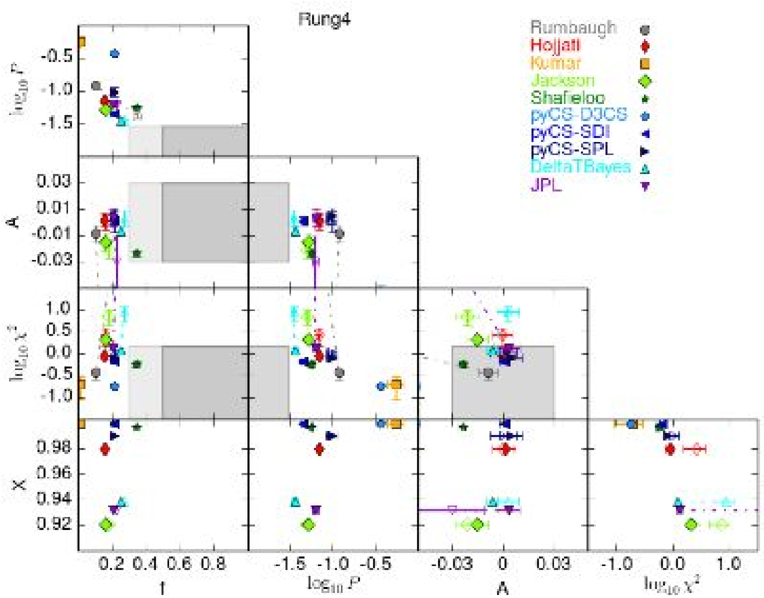
Light Curve Extraction

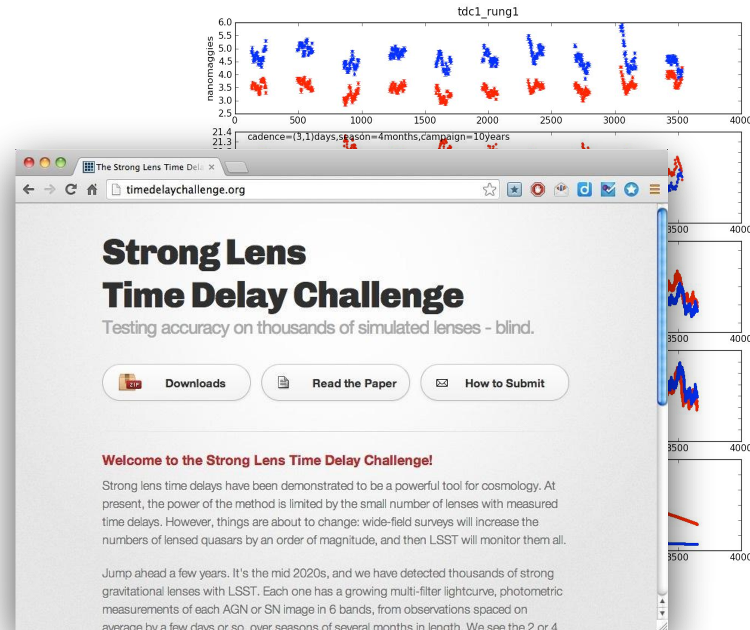


Twinkles 10-year tiny mock LSST survey enables end-to-end tests of Level 2 and 3 code, as it is developed: image differencing, DIASource deblending and interpretation, (potentially) scene modeling

Time delay measurement

The “Time Delay Challenges” are answering the question, how many accurate time delays can we expect from LSST?

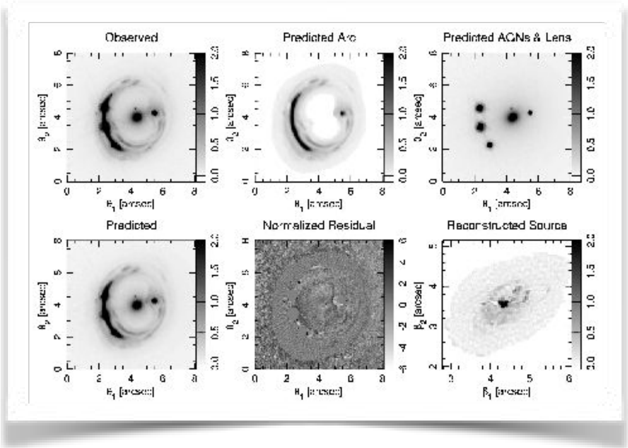


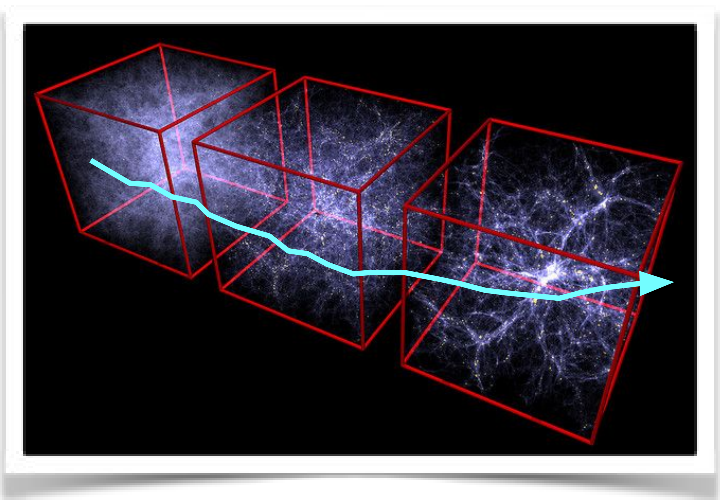


The single-filter TDC1 results suggest a sample of 400 should be possible...

A good bet is that the multi-band TDC2 is likely to be won by a hierarchical chromatic AGN+microlensing model... Lensed SNe?

Mass modeling



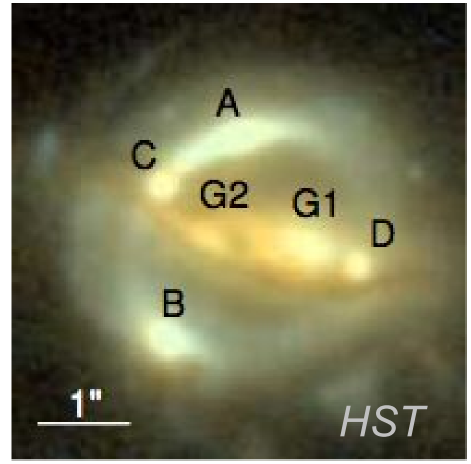


- **High accuracy lens modeling**. *Needs: high res follow-up with JWST, ELTs, IFUs.* *Well-sampled, high flexibility mass models, constrained with lensing and spatially-resolved kinematics. Joint inference validated on realistic simulated systems*

- **Environment density characterisation.** *Needs: M*, photo-z, weak shear catalogs for all galaxies within ~5 arcmin radius of many sightlines.* *10^{6-9} dimensional inference code?*

Following up 100 lenses?

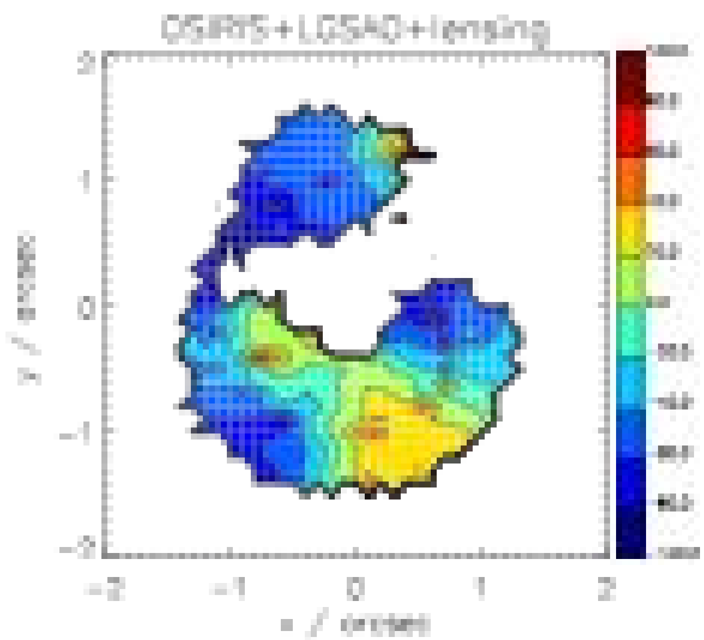
High resolution Einstein Ring imaging, IFU observations for spatially resolved lens kinematics.



Total imaging costs:

- Keck (2015): ~300 hrs
- Keck (NGAO): ~35 hrs
- **TMT: ~6 hrs**
- **JWST: ~ few dozen orbits**

IFU data will be more expensive:
1 hour *per lens* with TMT, i.e. 2 nights per year for 10 years



Meng,Treu, Marshall et al 2015

SL Working Group Strategy

With your neighbors, discuss the following choices facing the SL working group:

- By what criteria should we select a Gold Sample of 100 lenses for expensive JWST and ELT follow-up? What impacts will our choices have?
- When should we start applying for JWST and TMT time? (JWST: 2018-2024, E-ELT: 2024+, LSST DR1: 2024)

SL Working Group Strategy

Goals

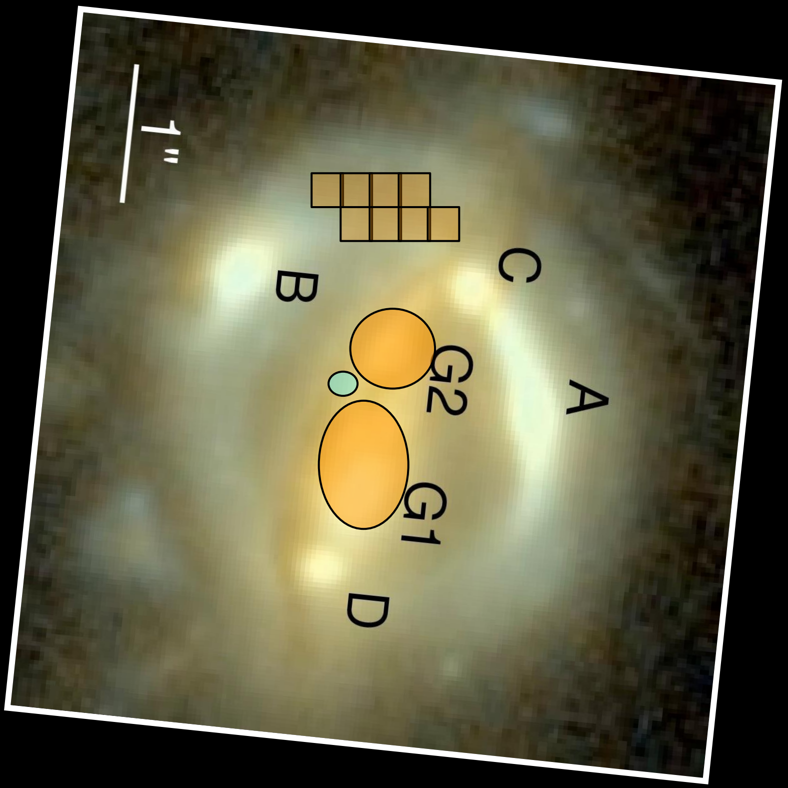
- Understand the basic, multi-faceted technique of “time delay lens cosmography”
- Be able to interpret its results, and ask the right questions about its systematic errors
- See the research opportunities on offer

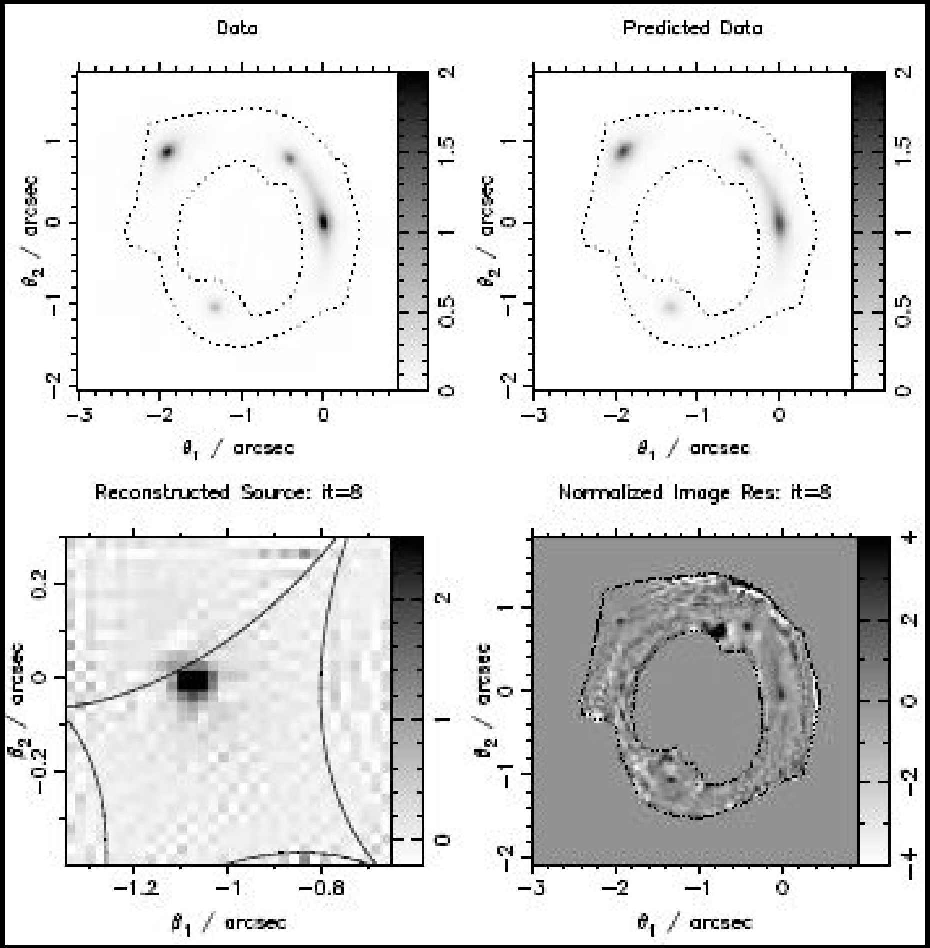
Extra slides

B1608 and RXJ1131 Lens Modeling Details

B1608+656: lens model

2 elliptically-symmetric, power-law density profile (index γ), galaxies, plus pixelated linear corrections to lens potential; **good fit** to HST/ACS imaging, after dust correction, and radio image positions

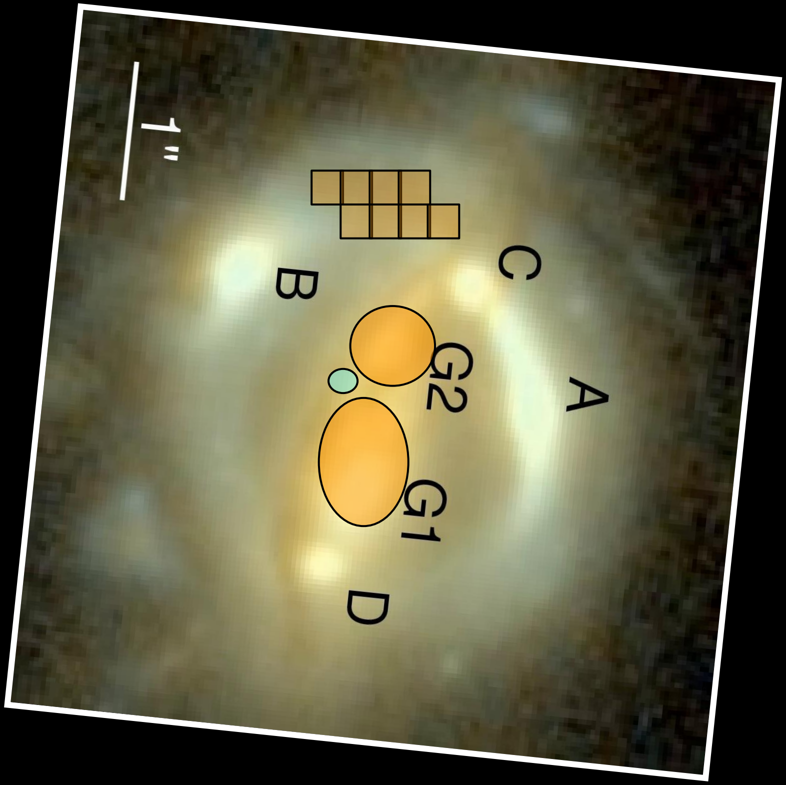


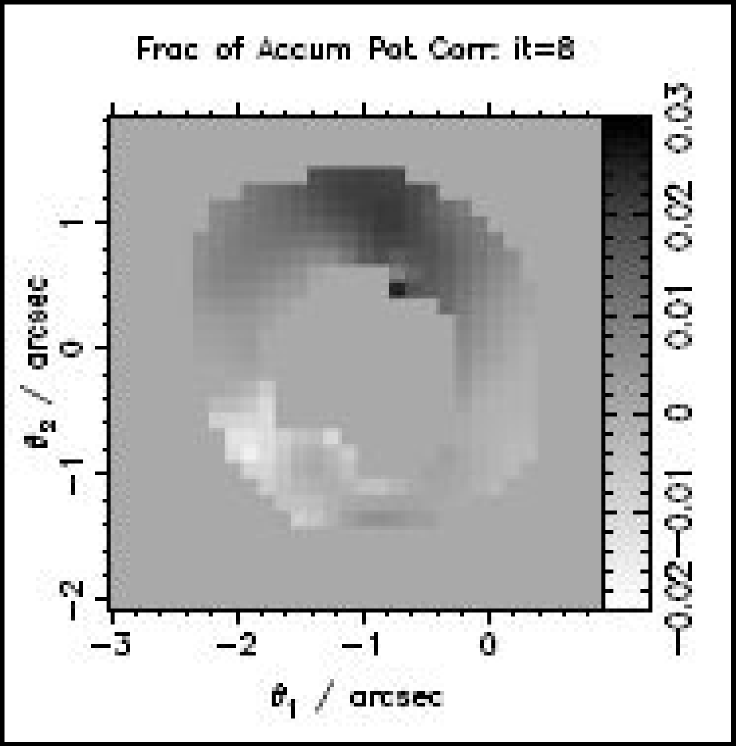


Source reconstruction on a grid of pixels

B1608+656: lens model

2 elliptically-symmetric, power-law density profile (index γ), galaxies, plus pixelated linear corrections to lens potential; **good fit** to HST/ACS imaging, after dust correction, and radio image positions

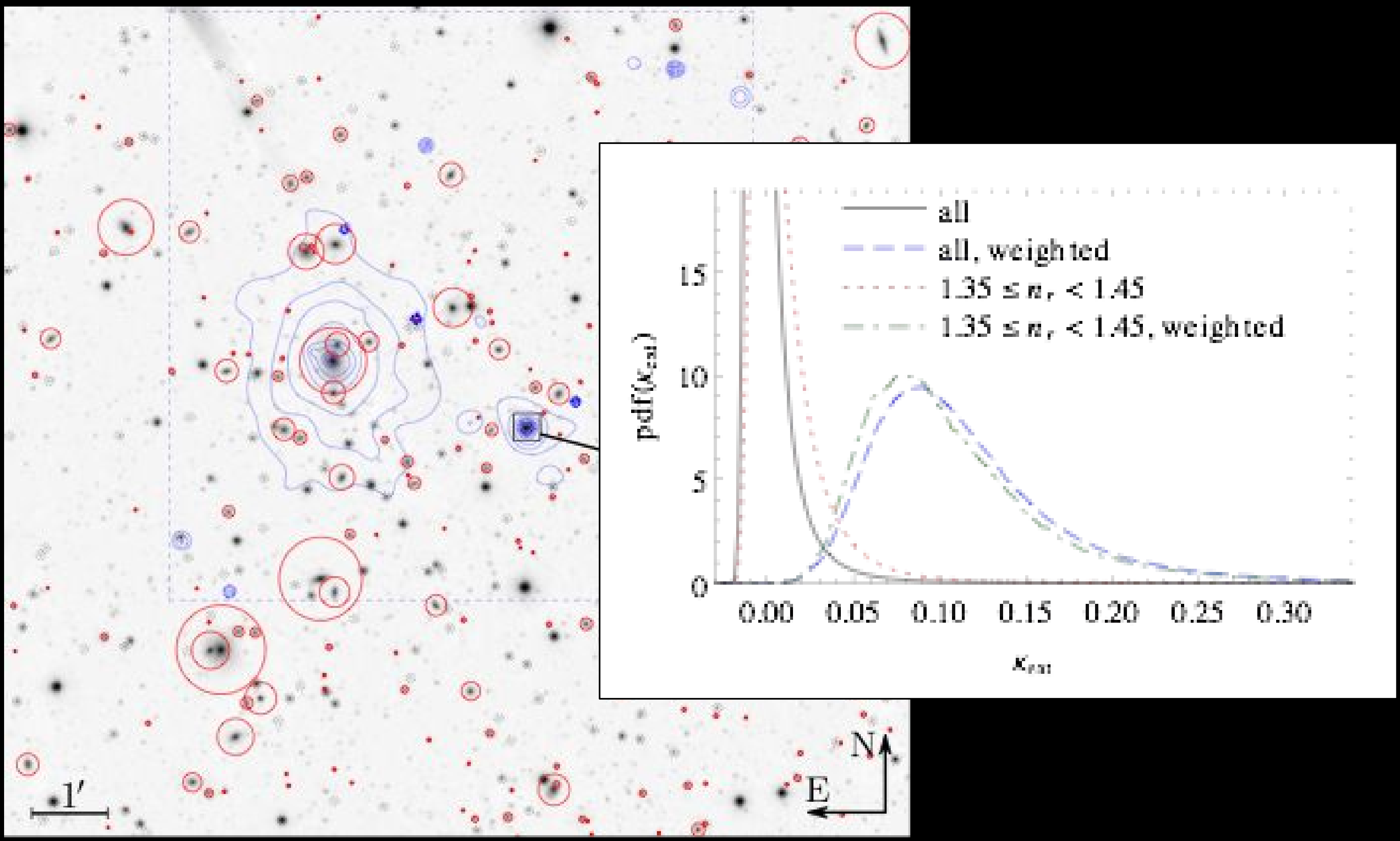




Potential is smooth to 2%!

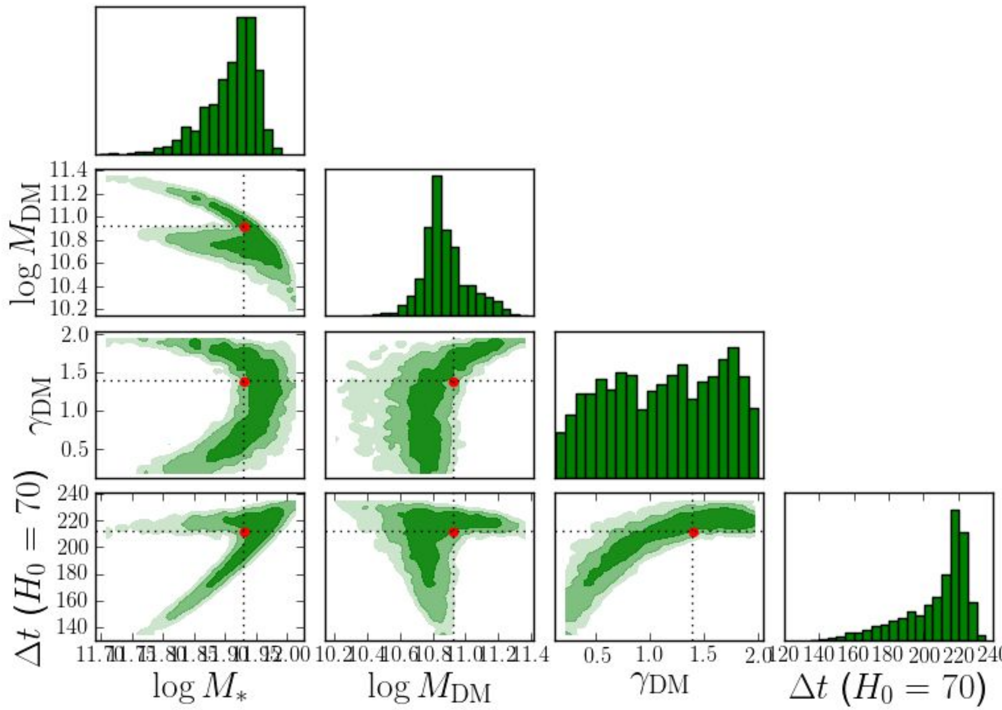
RXJ1131-1231

Model requires external shear, consistent with nearby foreground cluster. Include shear in the ray tracing κ_{ext} analysis



Hierarchical Inference

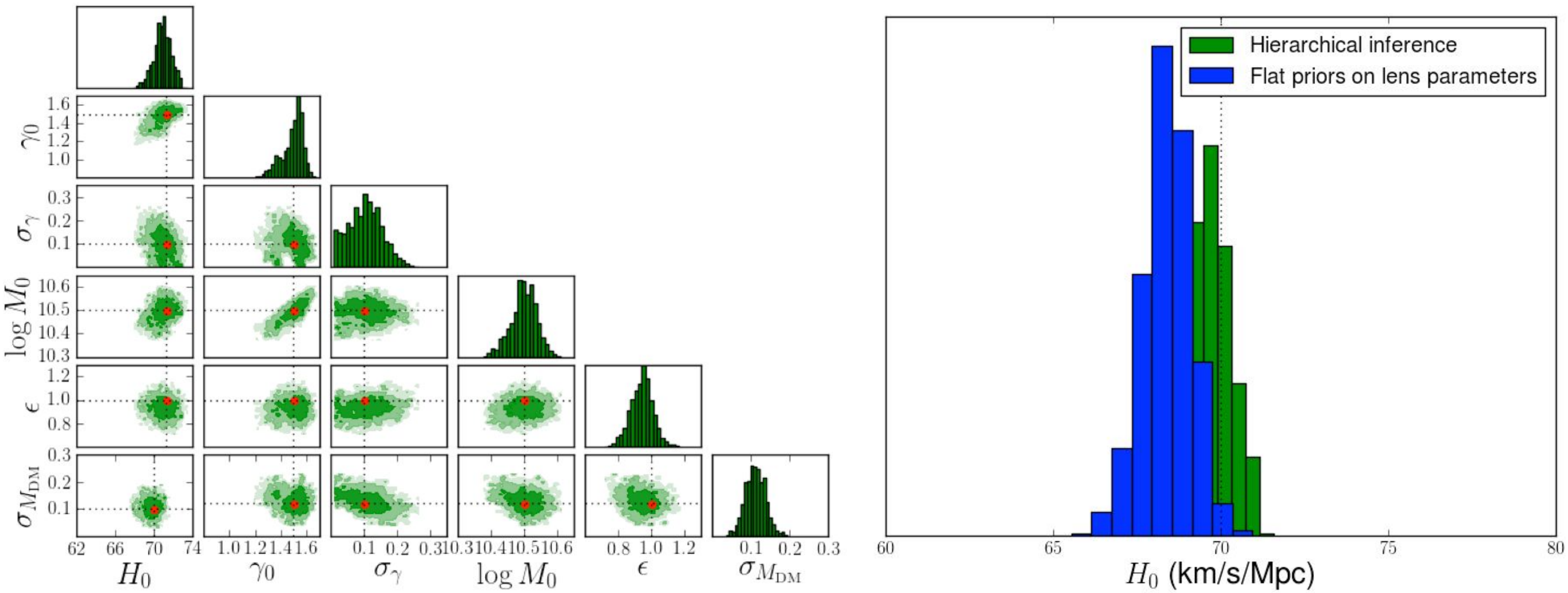
Even more flexible lens models



Can we further reduce the lens modeling error by using models that are “too flexible” combined with the self-similarity of massive galaxies, and constrain the lens population simultaneously with cosmology?

(Sonnenfeld, Marshall et al in prep)

Hierarchical inference reduces bias

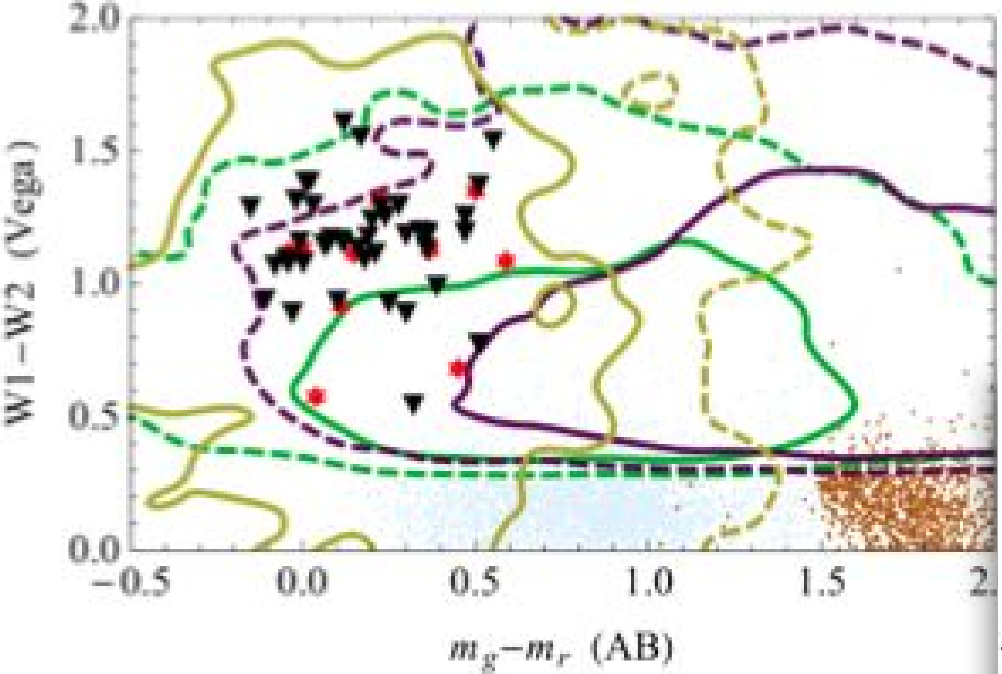


(Sonnenfeld, Marshall et al in prep)

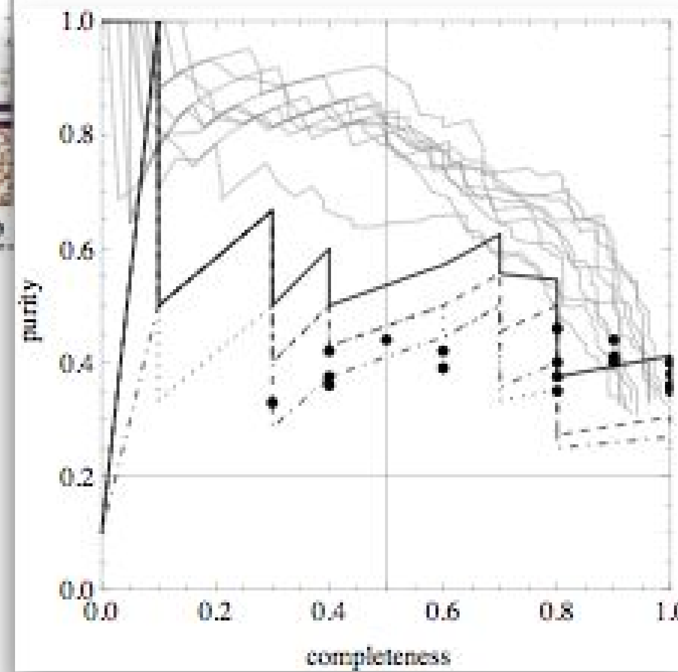
- Uninformative priors on individual object parameters lead to biases if objects are *not unrelated.*
- Adding 6 hyper-parameters to model the lens galaxy population in a hierarchical inference removes the bias with no loss of precision.

Lens Finding

Lens Target Selection

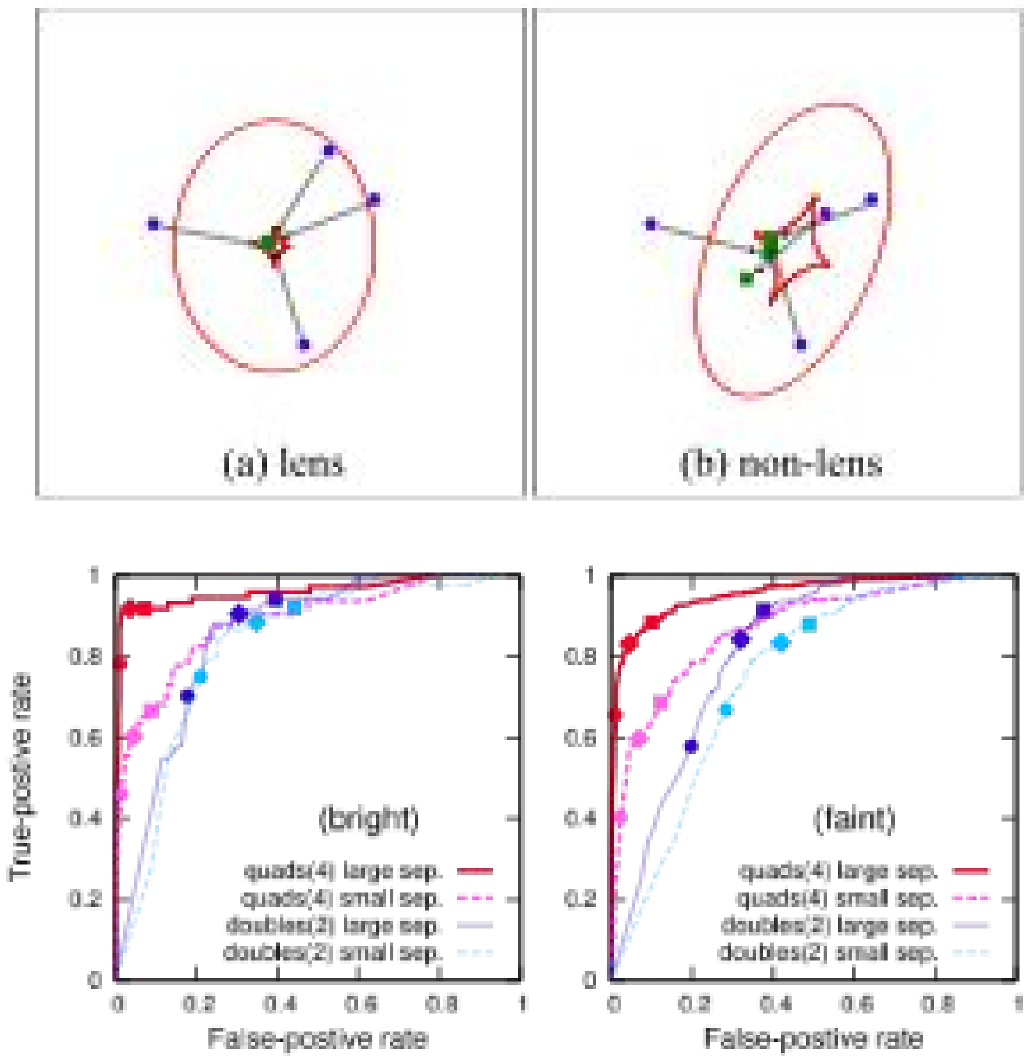


WISE IR color helps separate lenses from contaminants



ANN can be trained to return lenses with >90% completeness at ~30% purity (Agnello, Marshall et al 2014)

Lens Candidate Selection

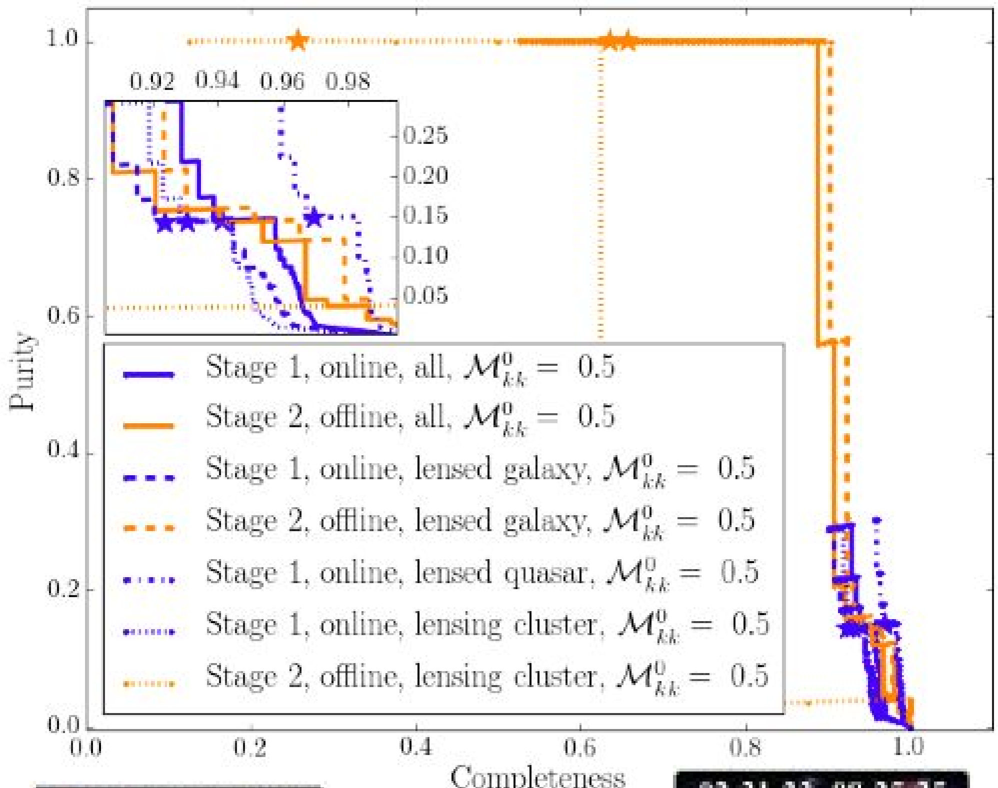


Projection of (g, z) images onto (quasar, LRG) images to identify quasar light. Conjugate points input to source plane model, score = chisq

Quads detected at high completeness, even down to z=24 in CFHTLS data

(Chan, Marshall et al 2014)

Crowd-sourced Visual Inspection



Space Warps system performs comparably to machine classifiers (90% completeness, at 30% purity) on objects similar to training set

Some evidence of imagination-driven sensitivity to unusual lenses
(Marshall et al in prep)

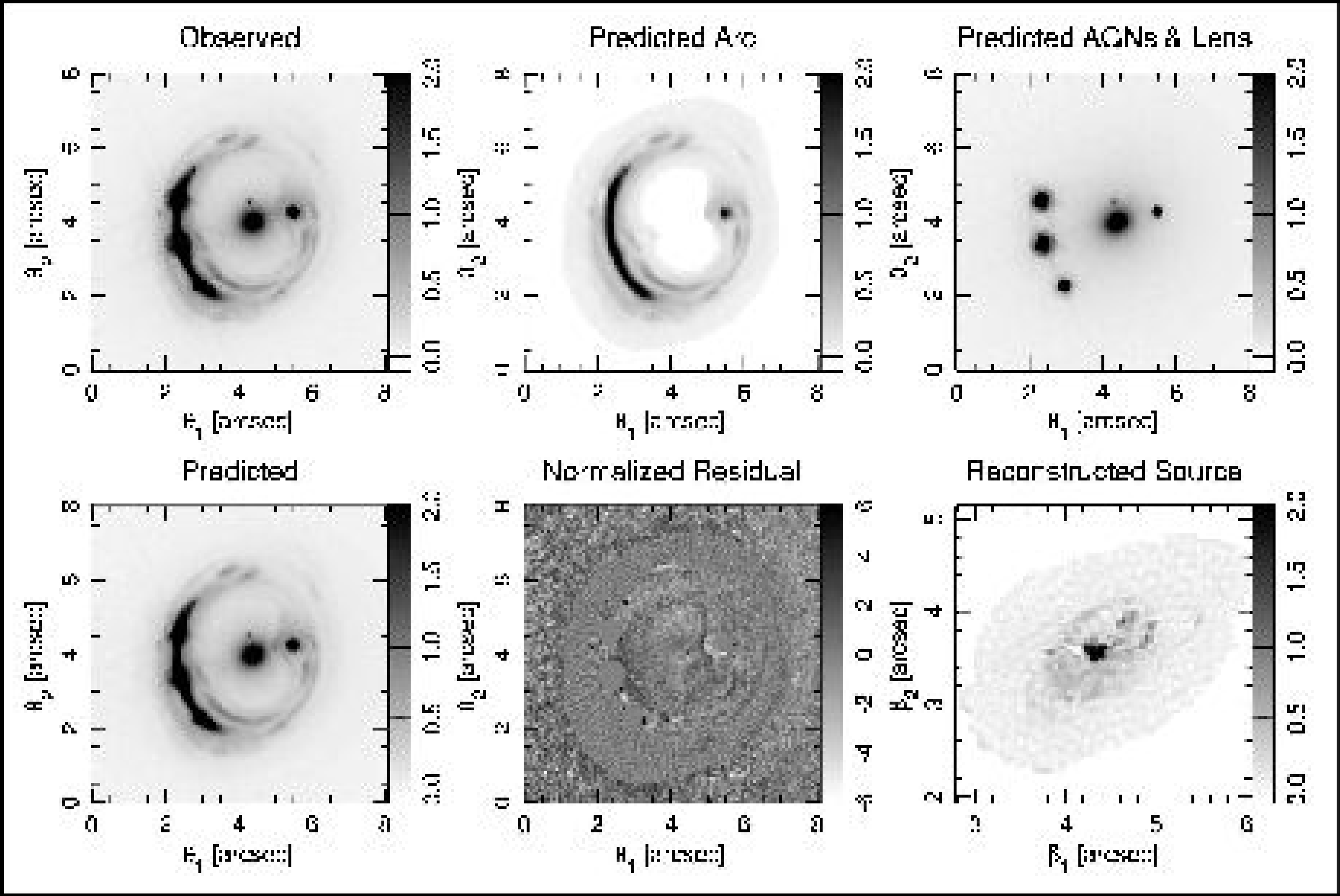
http://spacewarps.org

Blinding

RXJ1131-1231

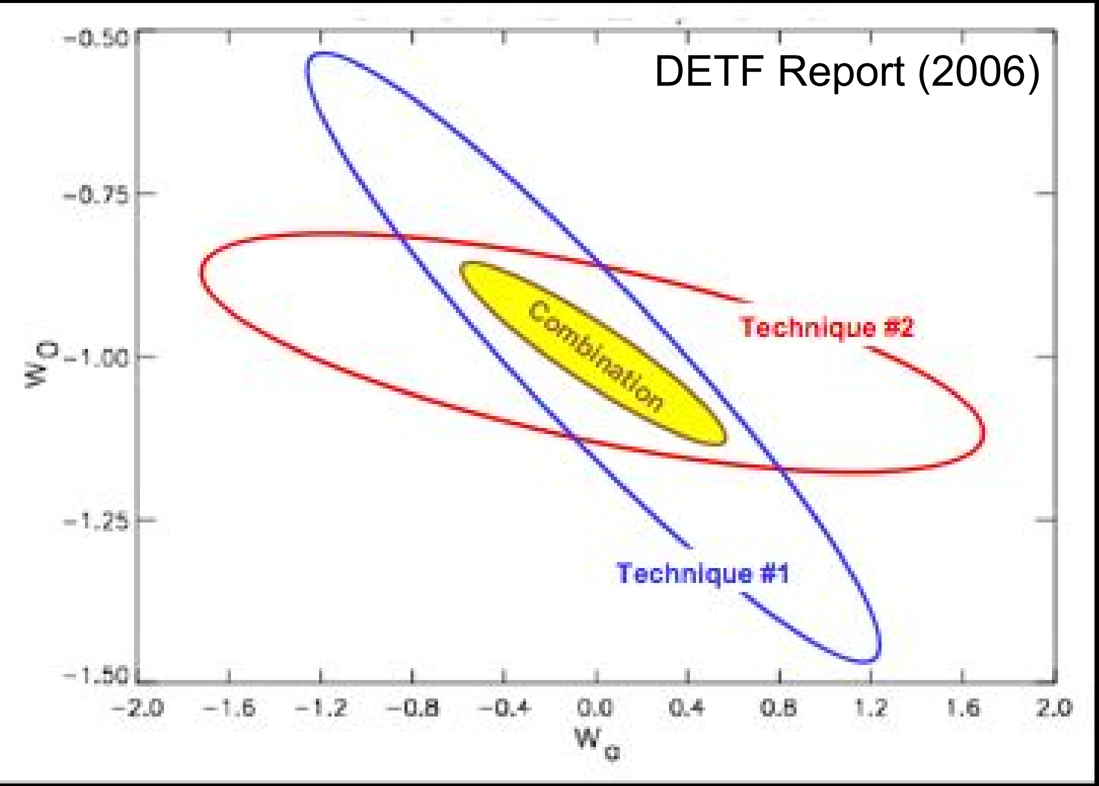
Bright, quad-lensed quasar, observed with HST/ACS.

Modeled in the same way as B1608



RXJ1131-1231

Blind cosmological parameter analysis, importance-sampling WMAP7

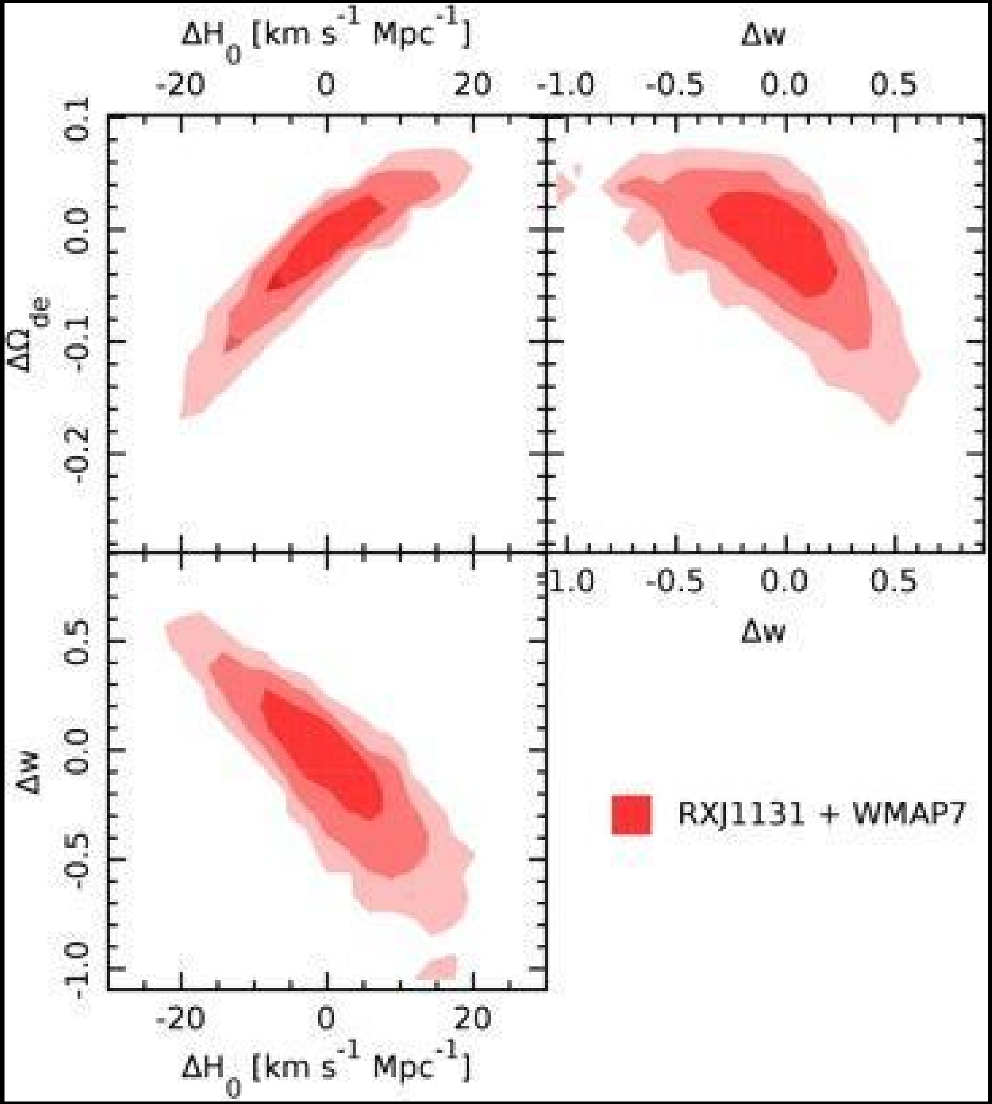


"A fiducial point in this parameter space is chosen; usually the dark energy is set to Λ – as appropriate if we want to assess the ability of an experiment to detect small deviations from Λ"

Hirata & Eisenstein (2009)

RXJ1131-1231

Blind cosmological parameter analysis, importance-sampling WMAP7



All posterior PDFs plotted with *centroids offset to zero*

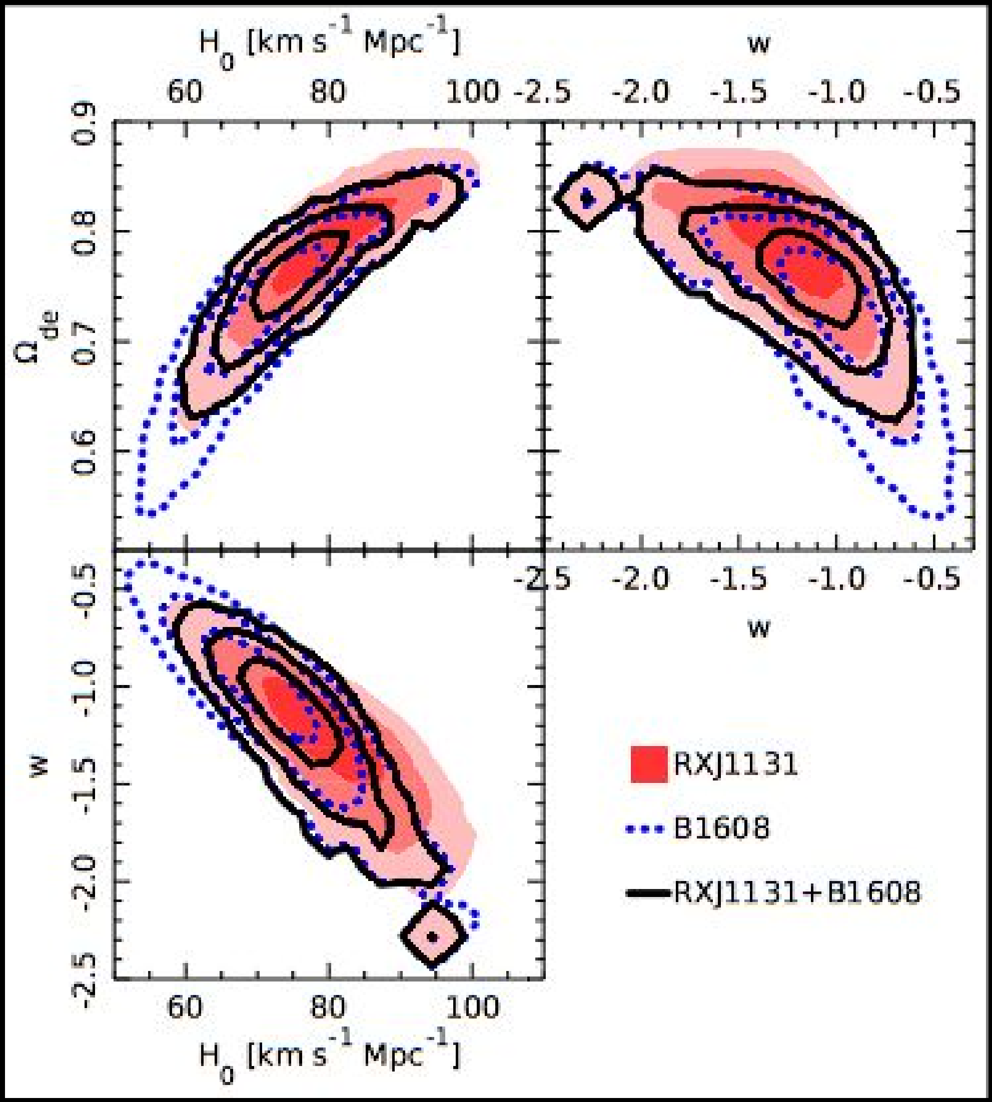
PDF shapes and sizes can be used as the analysis proceeds, but no looking at the answer until all authors agree to “open the box”

Precision:

- H_0 to 6 km/s/Mpc (5)
- w to 0.19 (0.18)
- W_{DE} to 0.03

RXJ1131-1231

Unblinded cosmological parameter analysis



Accuracy:

- H_0 = 80 +/- 6 km/s/Mpc
- w = -1.25 +/- 0.19
- W_{DE} = 0.79 +/- 0.03

No significant difference between RXJ1131 and B1608 likelihoods

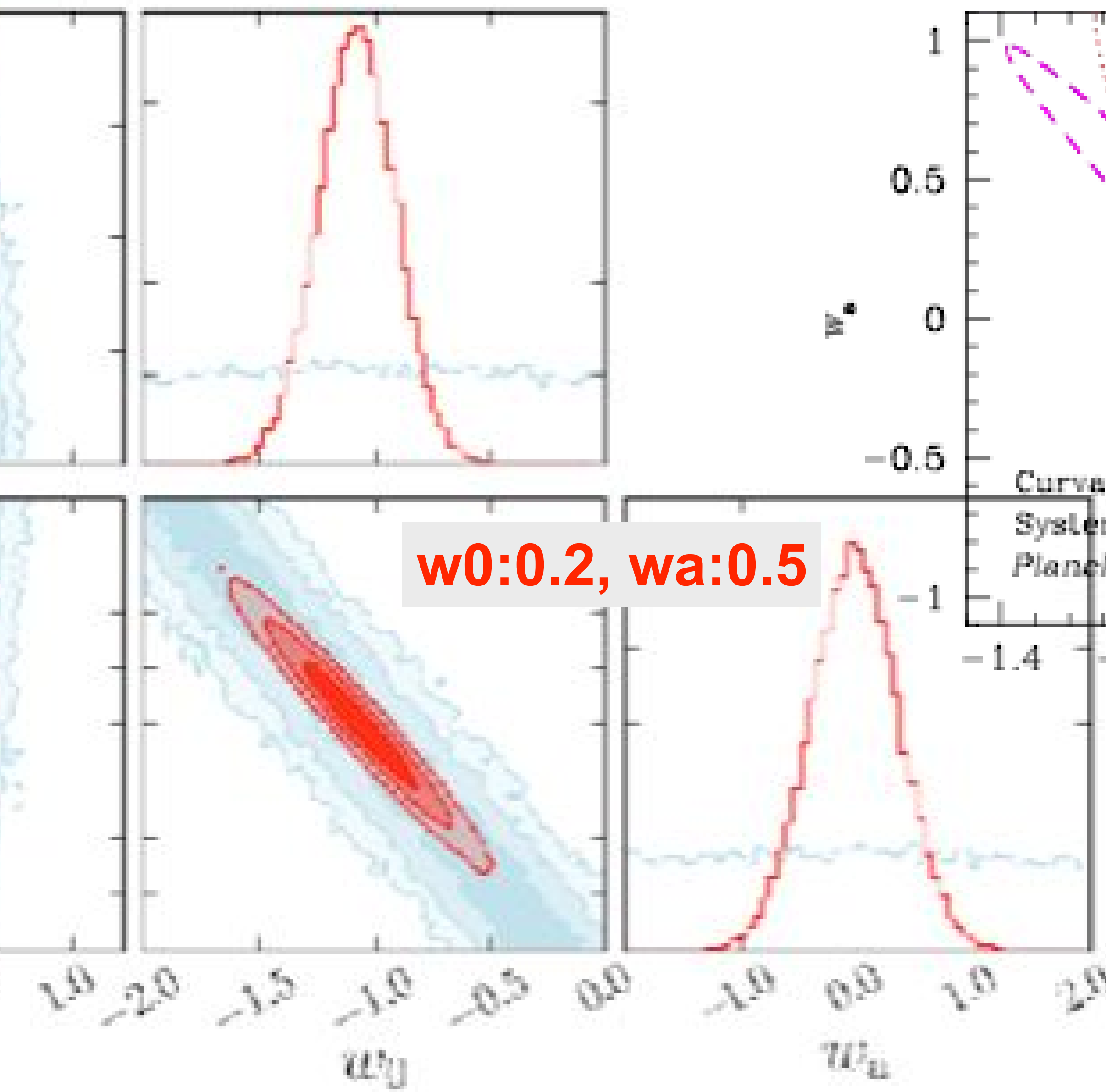
$$F = \frac{P(d^R, d^B | \mathrm{H}^{\mathrm{global}})}{P(d^R | \mathrm{H}^{\mathrm{ind}})\, P(d^B | \mathrm{H}^{\mathrm{ind}})}$$

$$F = \frac{\langle L^R L^B \rangle}{\langle L^R \rangle \langle L^B \rangle}$$

A joint analysis is justified

DESC, Joint Probes

LSST Science Book WL forecast



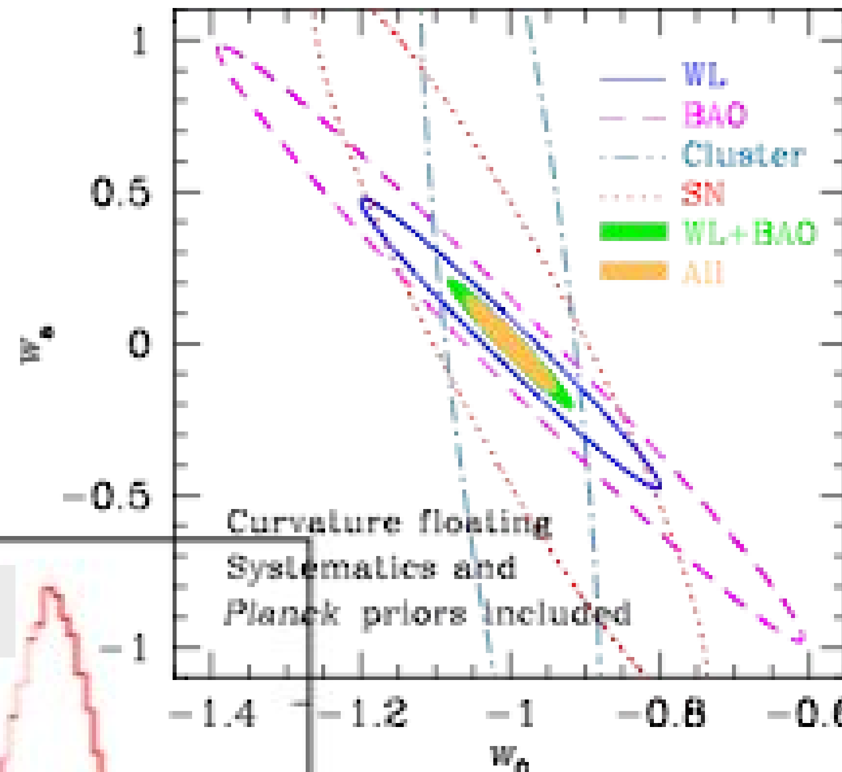


Fig 15.1 1–σ error contours of the dark energy EOS parameters w0 and wa from LSST WL shear power spectra

Fig 15.3 ... The BAO and WL results are based on galaxy–galaxy, galaxy–shear, and shear–shear power spectra only. Adding other probes such as strong lensing time delay (§ 12.4), ISW effect (§ 13.7), and higher-order galaxy and shear statistics (§ 13.5 and § 14.4) will further improve the constraints.

Time Delay Challenge

The Time Delay Challenge

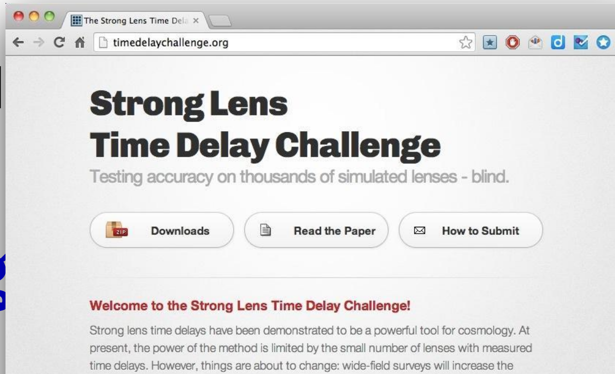
Goals:

1. Assess performance of current time delay estimation algorithms on LSST-like light curve data
2. Assess impact of baseline LSST observing strategy on time delay accuracy, and possibly recommend changes

Plan:

3. The “Evil Team” generated large set of simulated lightcurves spanning expectations for Stage II-IV
4. Challenged community “Good Teams” to infer time delays blindly, and submit results
5. Published paper on results together: Liao, M

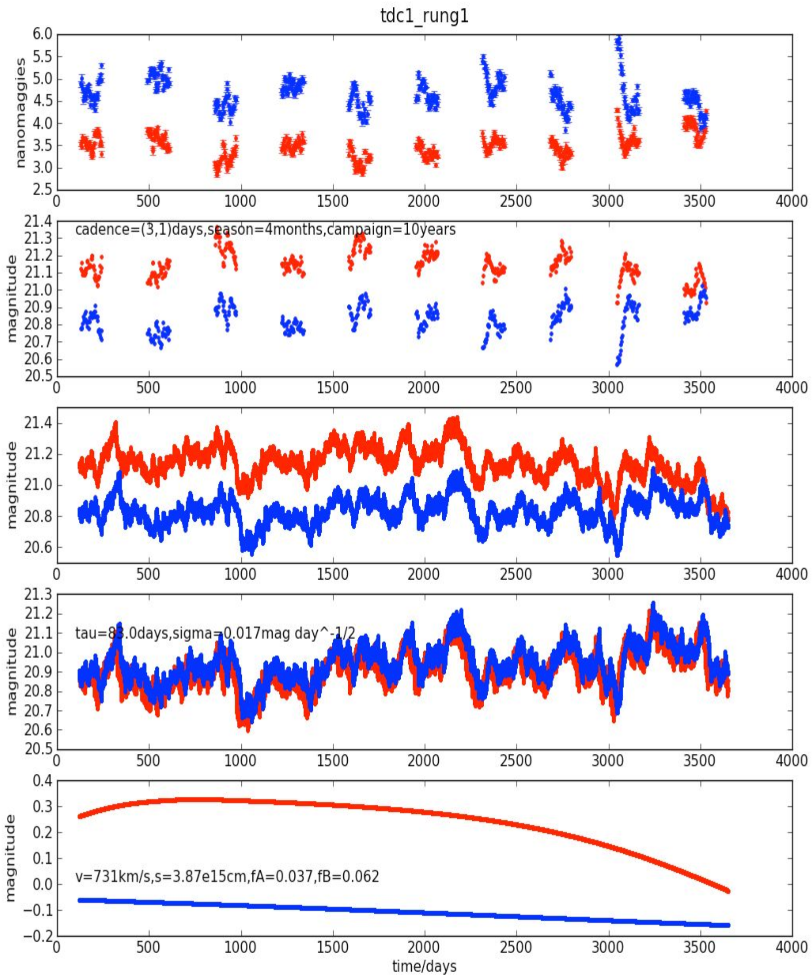
http://timedelaychallenge.org



TDC example lightcurves

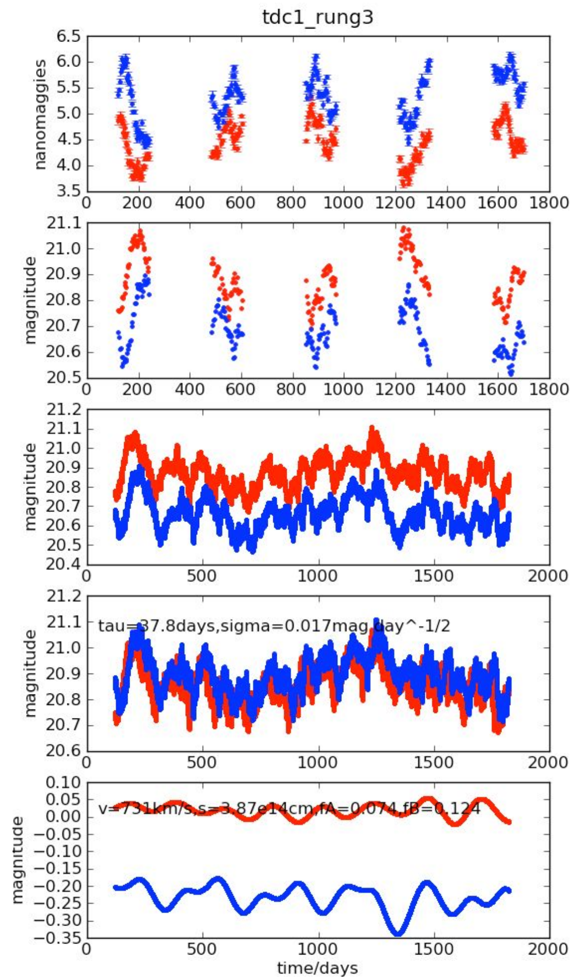
10 years, 3 day cadence

5 years, 3 days

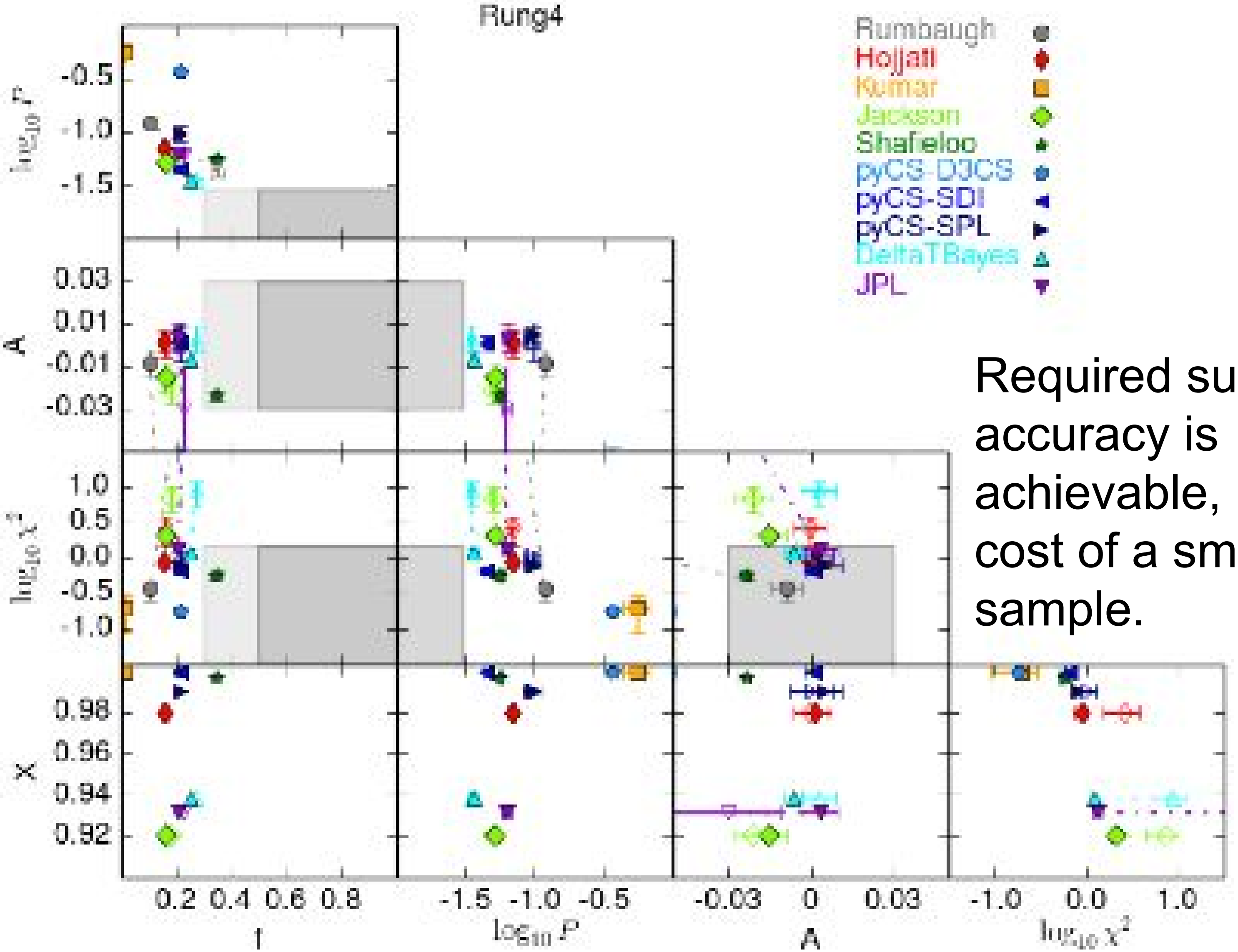


Mock data

- without noise
- fully sampled
- no lensing
- microlensing

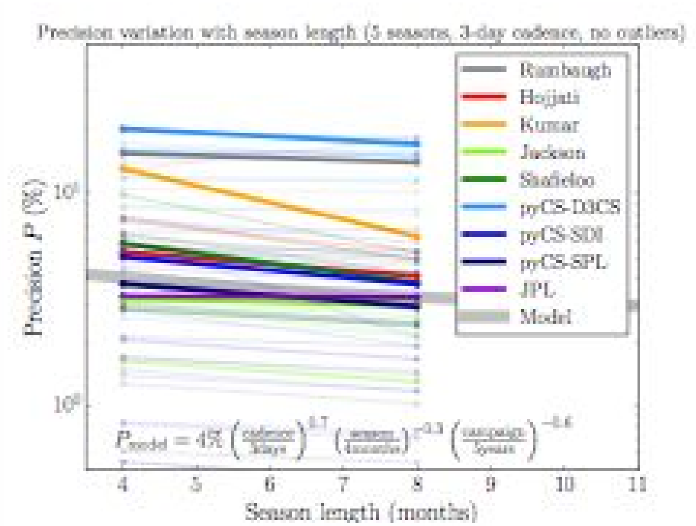


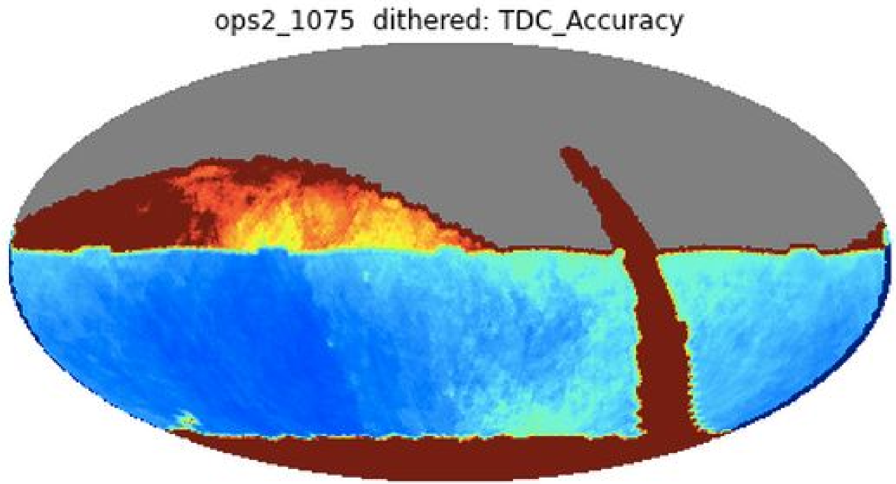
TDC: 400 cosmographic lenses

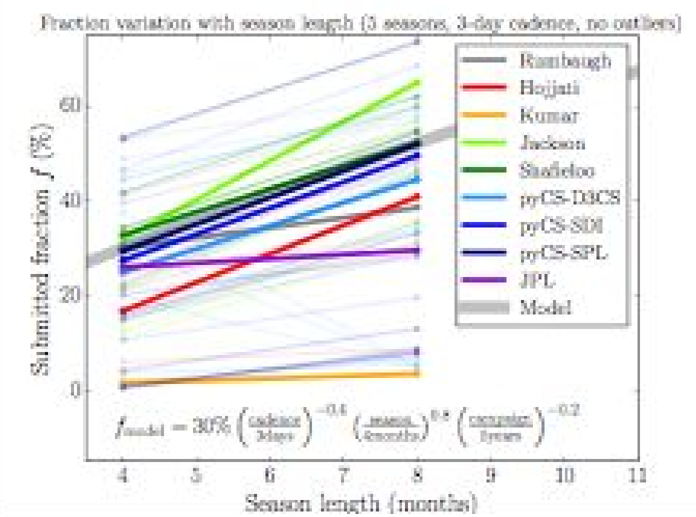


Required sub-percent accuracy is achievable, but at the cost of a smaller sample.

TDC: observing strategy







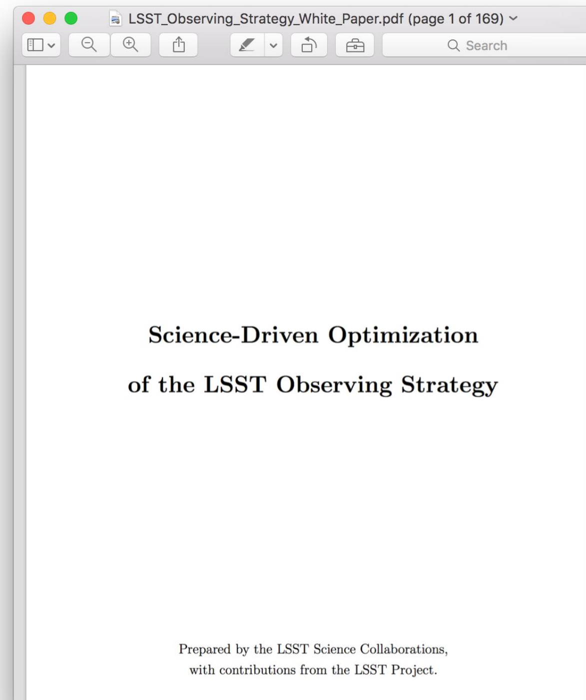
Cadence drives precision; season length matters most for the useable fraction.

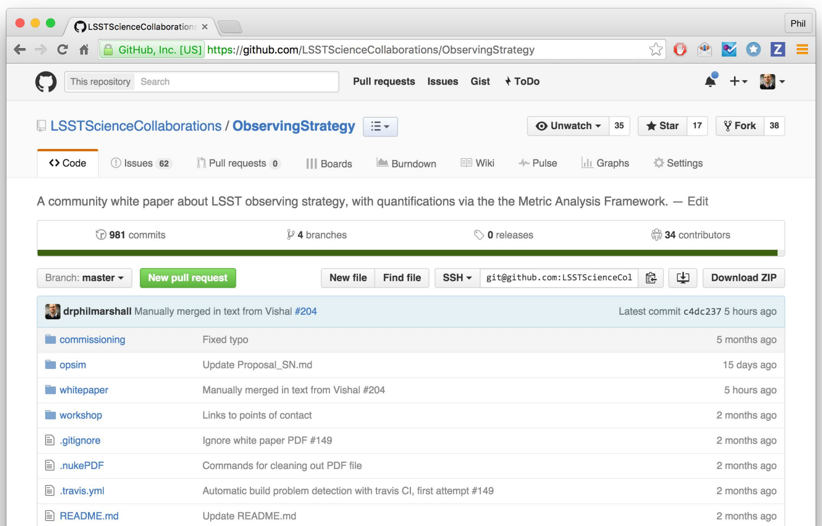
TDC metrics now coded into LSST project's framework, to inform observing strategy

The LSST Observing Strategy

Community-led project to evaluate simulated survey cadences with science-driven metrics, and publish the results

Contributions welcome!





http://github.com/LSSTScienceCollaborations/ObservingStrategy

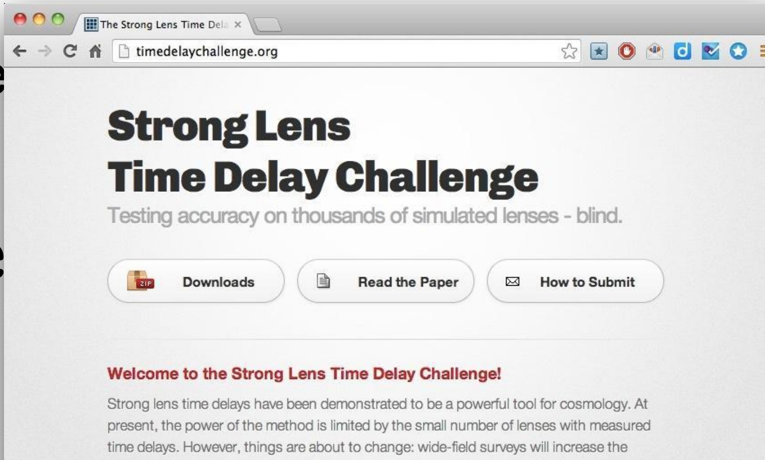
Time Delay Challenge 2

Goal: assess performance of current time delay estimation algorithms on multi-filter LSST-like light curve data

Plan:

- The "Evil Team" has re-formed and is generating a large set of simulated light curves
- We will challenge community "Good Teams" to infer time delays and H_0 blindly, and submit results, this summer
- We will publish a paper on results toge

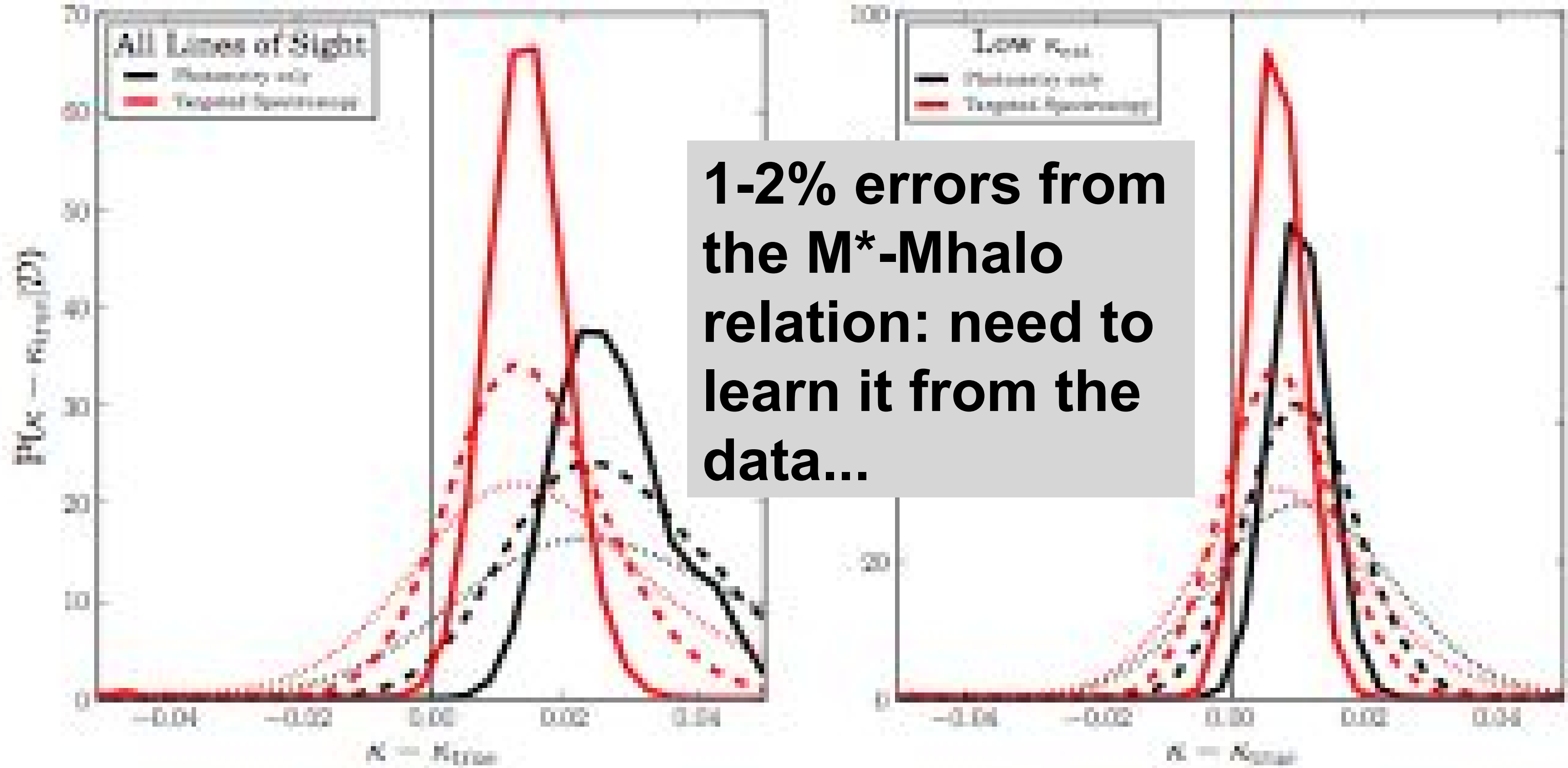
http://timedelaychallenge



Kai Liao, Phil Marshall, Tommaso Treu,

Better Mass Modeling

Lightcone Reconstruction



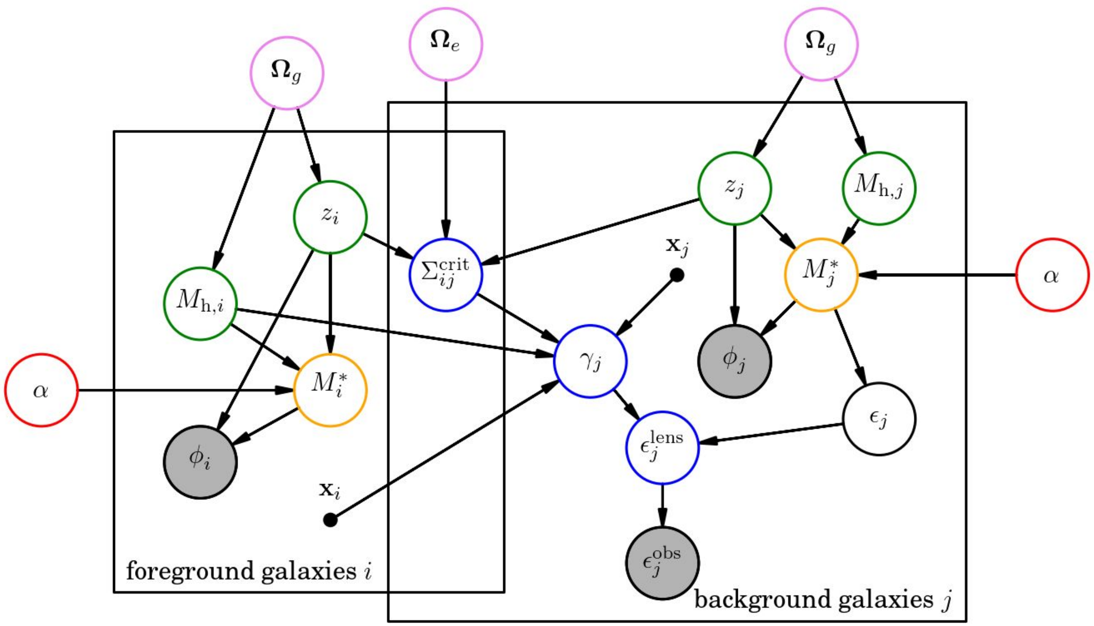
1-2% errors from the M*-Mhalo relation: need to learn it from the data...

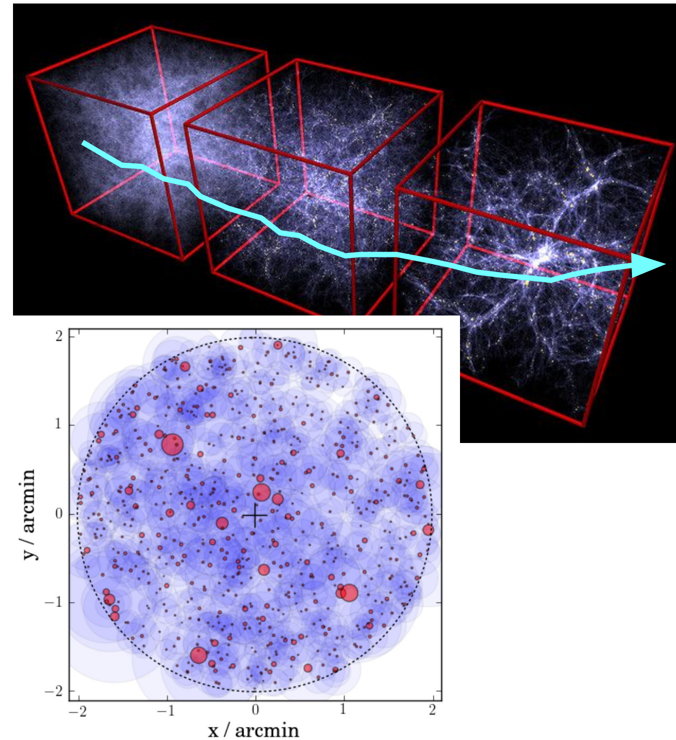
Collett, Marshall et al (2013):

Line of sight mass reconstruction from photometric catalogs, calibrated with and tested against the Millennium Simulation.

What will sub-percent distance accuracy take?

High Resolution 3D Mass Mapping





What might sub-percent distance accuracy take?

- Constrain halo model with all available weak lensing data, to break free from strong assumptions?
- Enormous joint inference, needs correct multi-plane lensing. Addresses cluster mass systematic too.