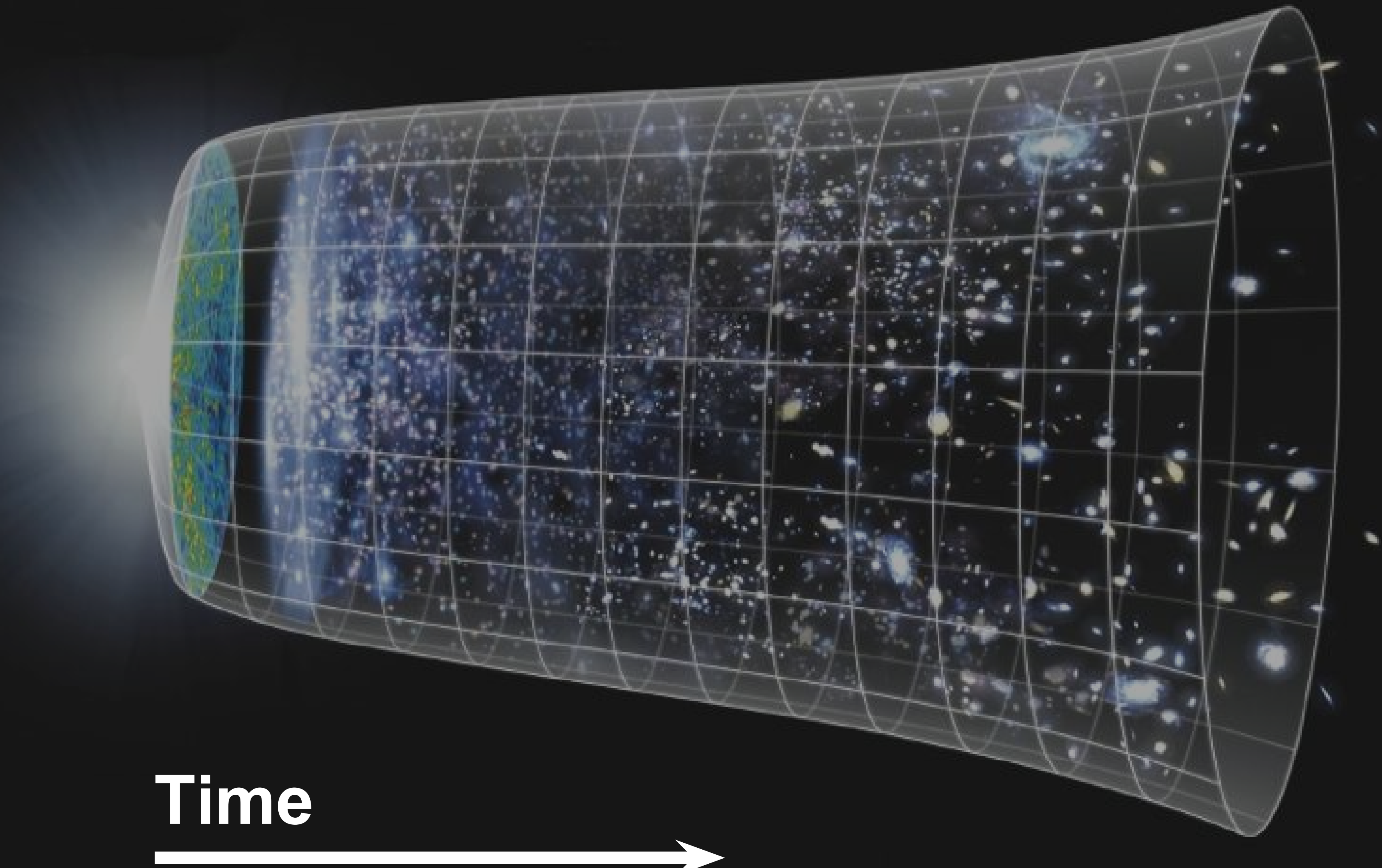
Cosmology with Strong Gravitational Lenses

Phil Marshall (SLAC)

SLAC Summer Institute, August 2017

LSST DESC
Dark Energy Science Collaboration

The expansion of the Universe is accelerating



and no-one knows why

Goals

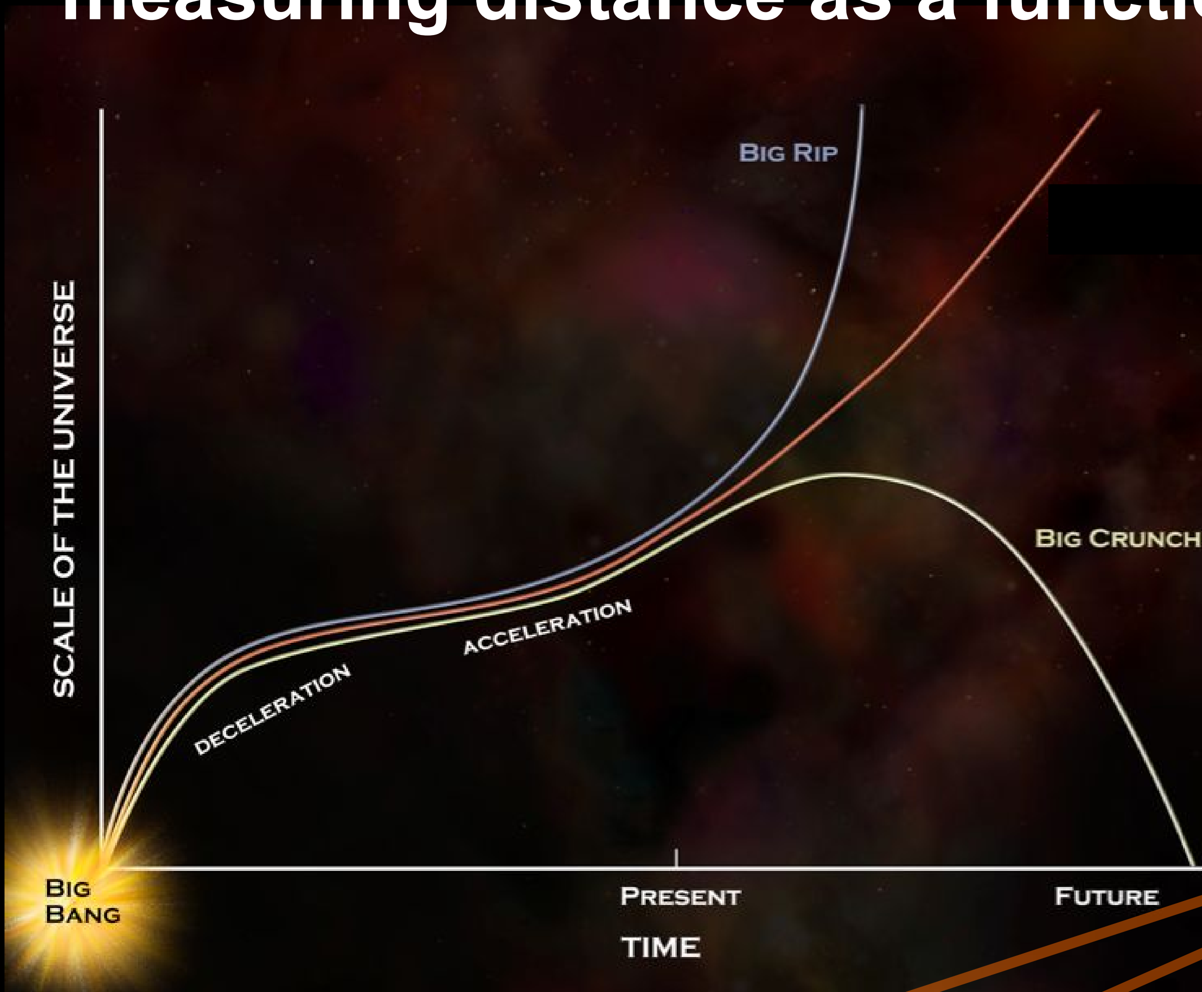
- Understand the basic, multi-faceted technique of “time delay lens cosmography”
- Be able to interpret its results, and ask the right questions about its systematic errors
- See the research opportunities on offer

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:

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

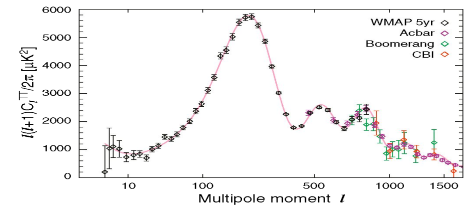
Measure distance $D(r)$ and redshift z,

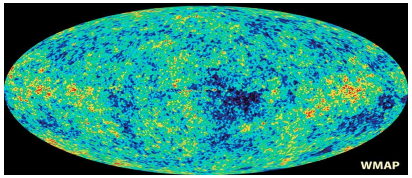
Then *infer parameters* H_0, $w(a)$, curvature *etc.*

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

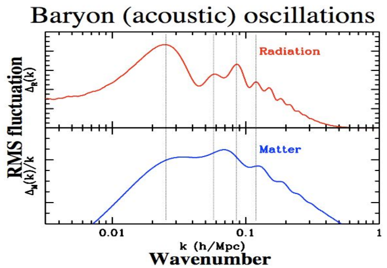
Measuring Distance

- **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

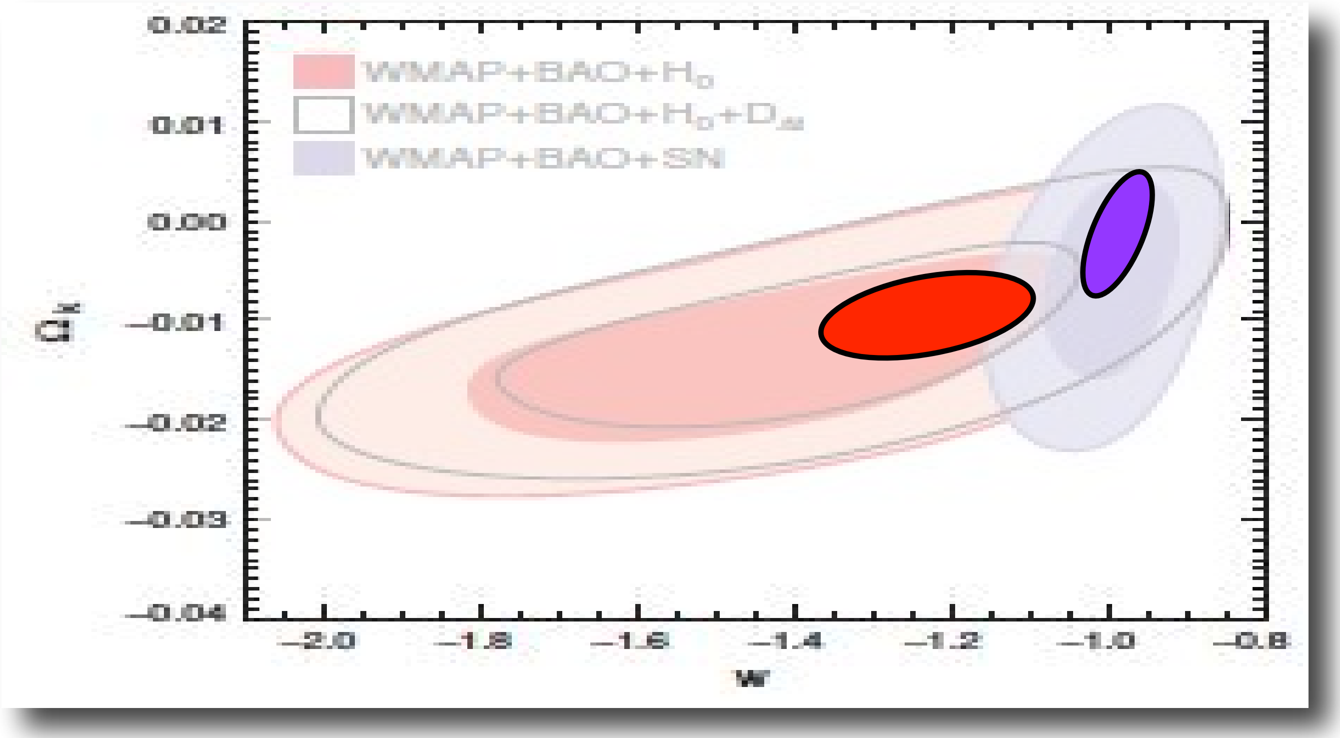


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

Do we need another one?

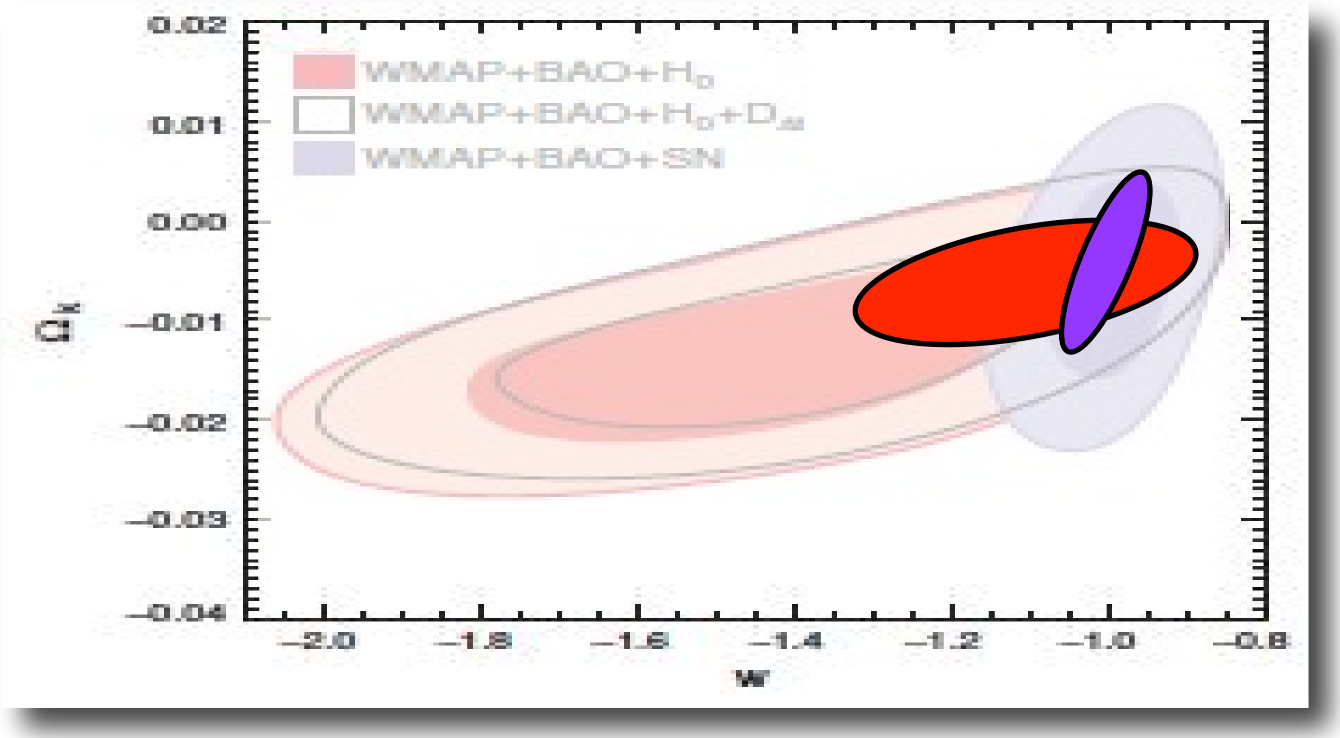
Accurate Cosmology

At high precision, systematic errors lead to dataset inconsistency:



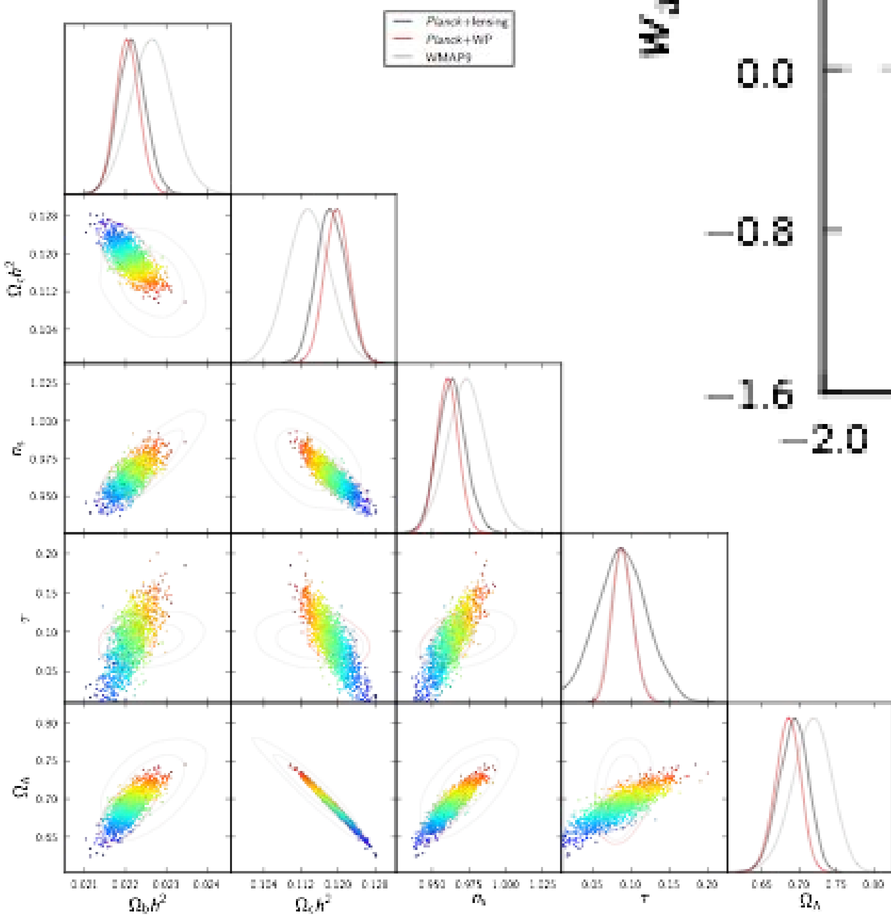
Accurate Cosmology

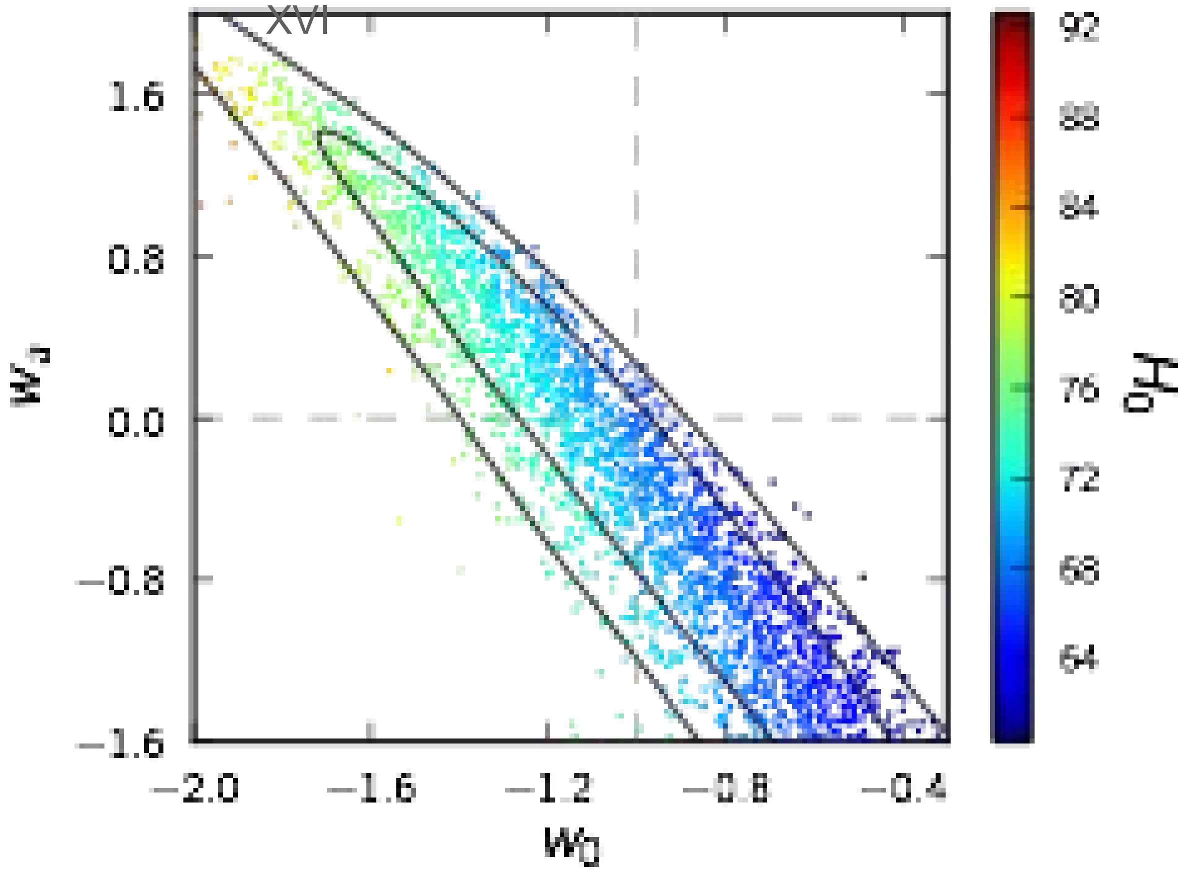
When all measurements are systematics limited, we learn best by having multiple datasets, where each one provides roughly competitive precision in at least one parameter



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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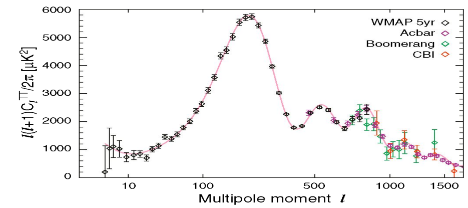

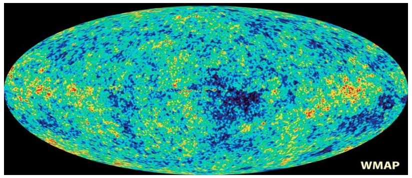

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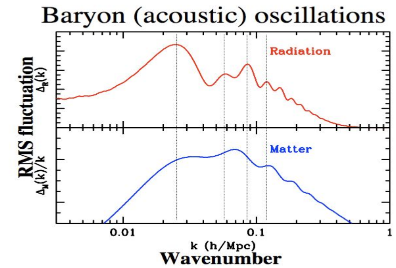
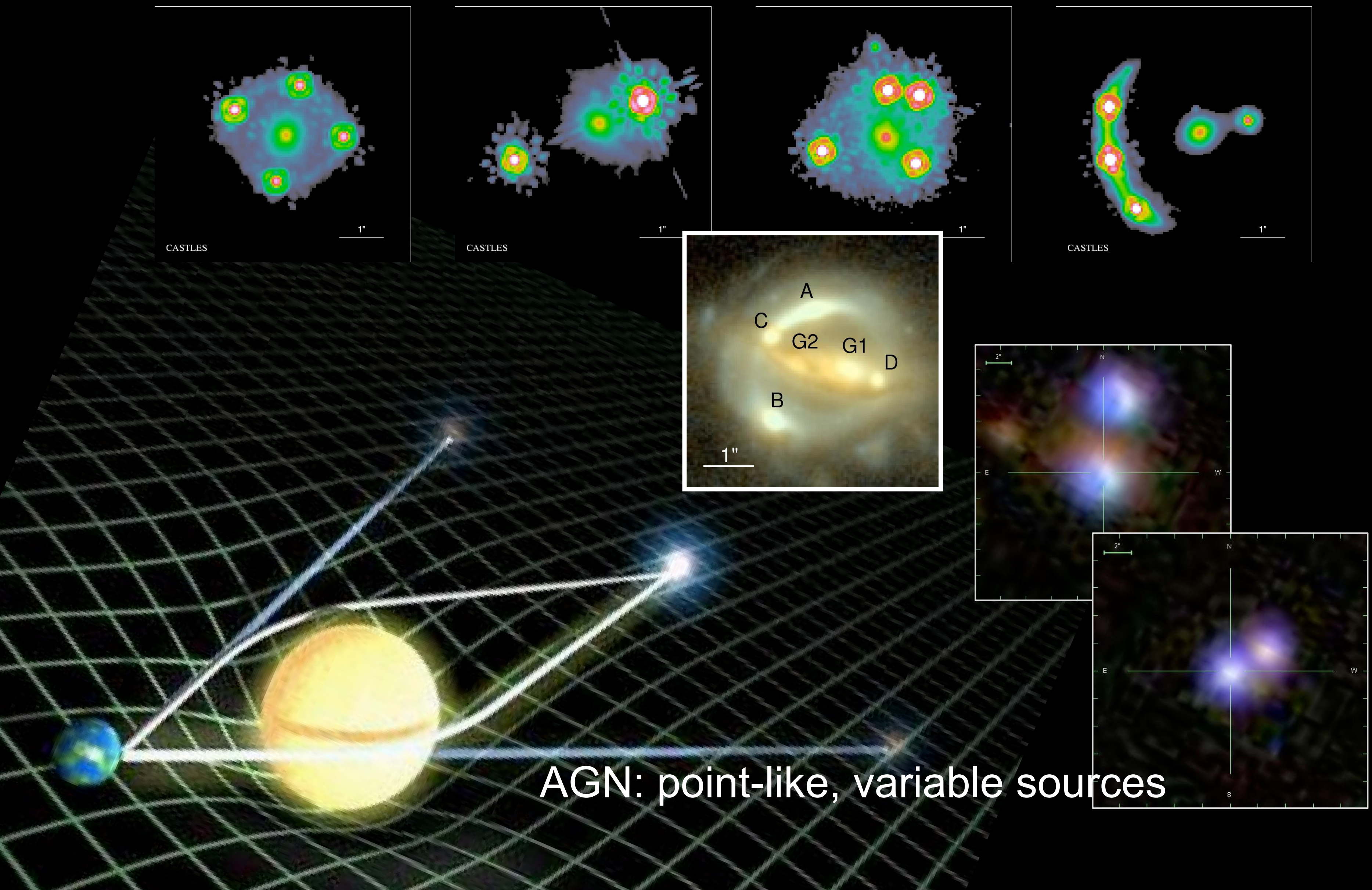


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

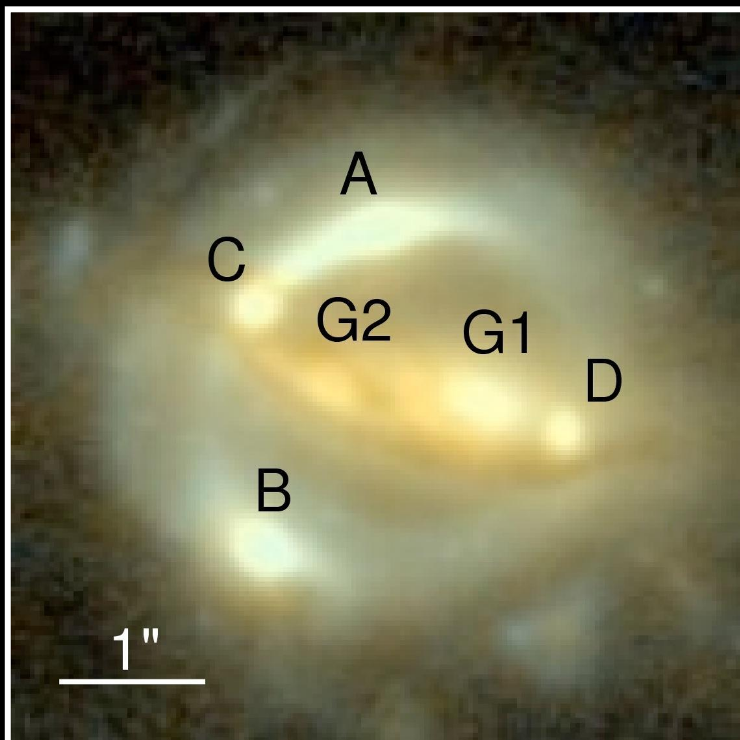
- **Gravitational lens time delays**

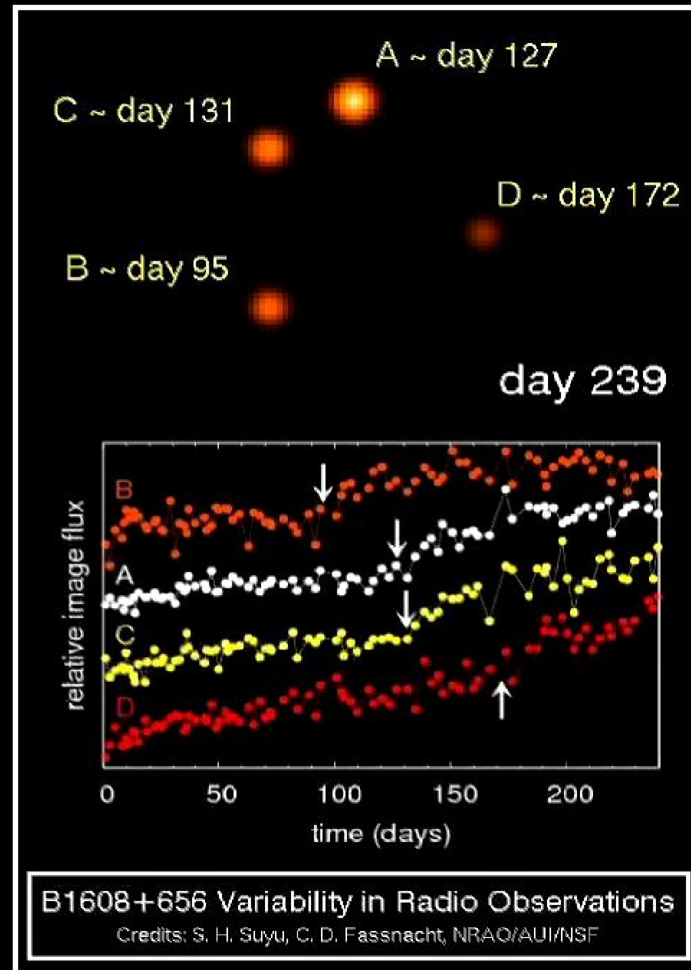
Strong Gravitational Lenses



AGN: point-like, variable sources

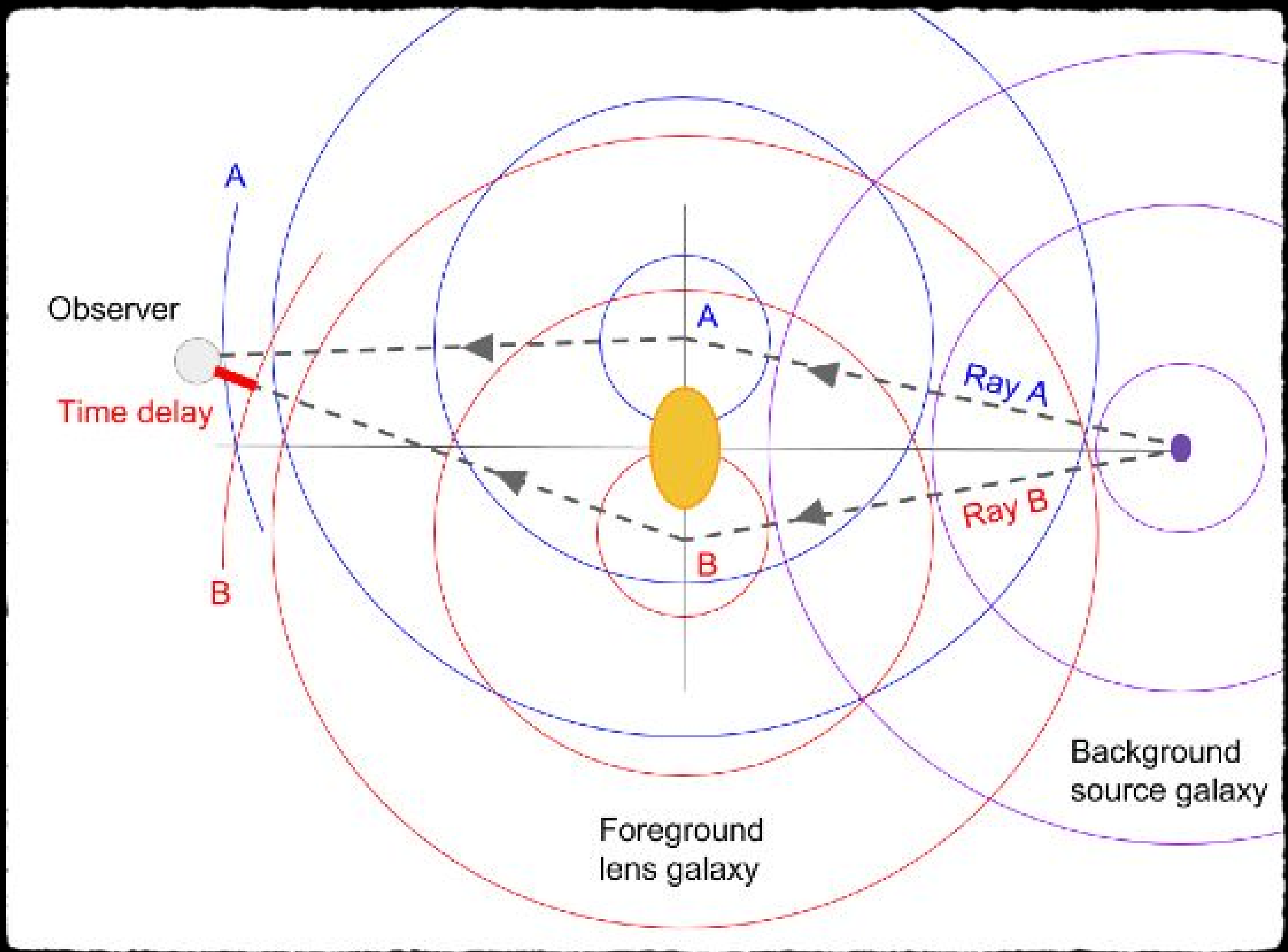
Time Delay Lenses



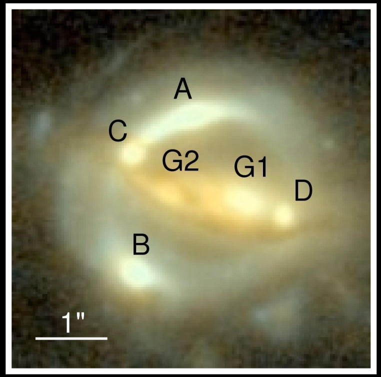


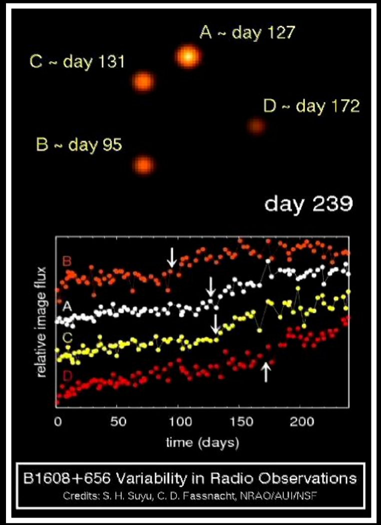
Point-like, variable sources:
different path lengths,
different travel times

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:

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

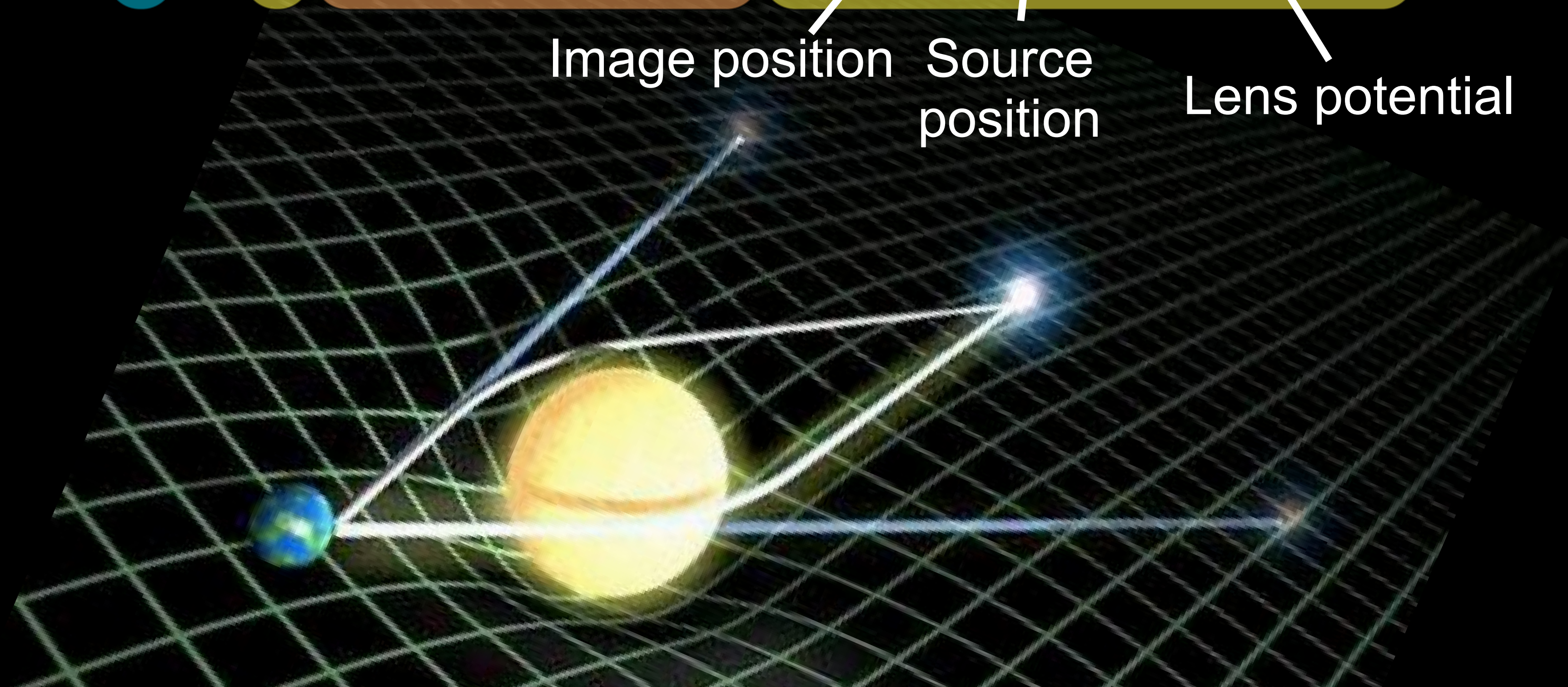


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Image position

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

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- 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*

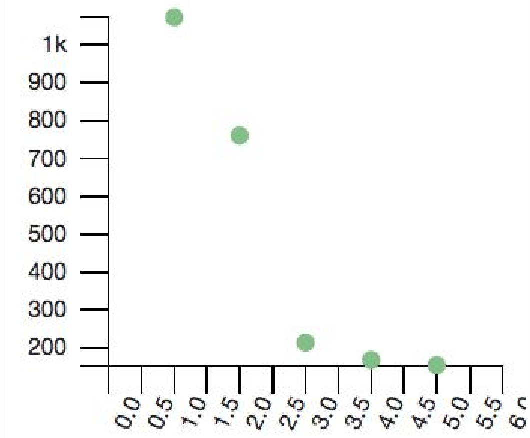
4 2016arXiv160700382S 2016/07 cited: 2
H0LiCOW II. Spectroscopic survey and galaxy-group identification of the strong gravitational lens system HE0435-1223
Sluse, D.; Sonnenfeld, A.; Rumbaugh, N. *and 15 more*

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**

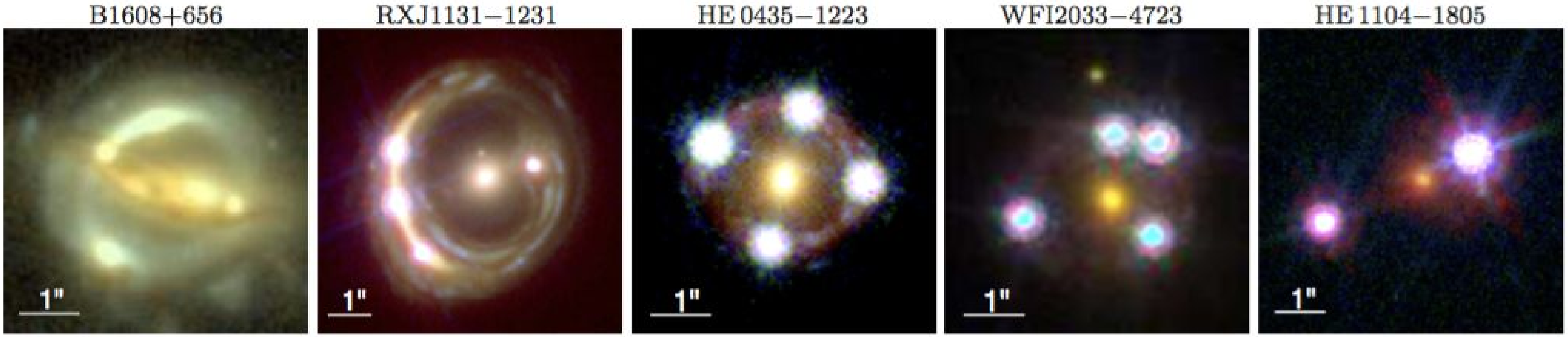
H-Index for results: refereed
Y-axis: **linear** log



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

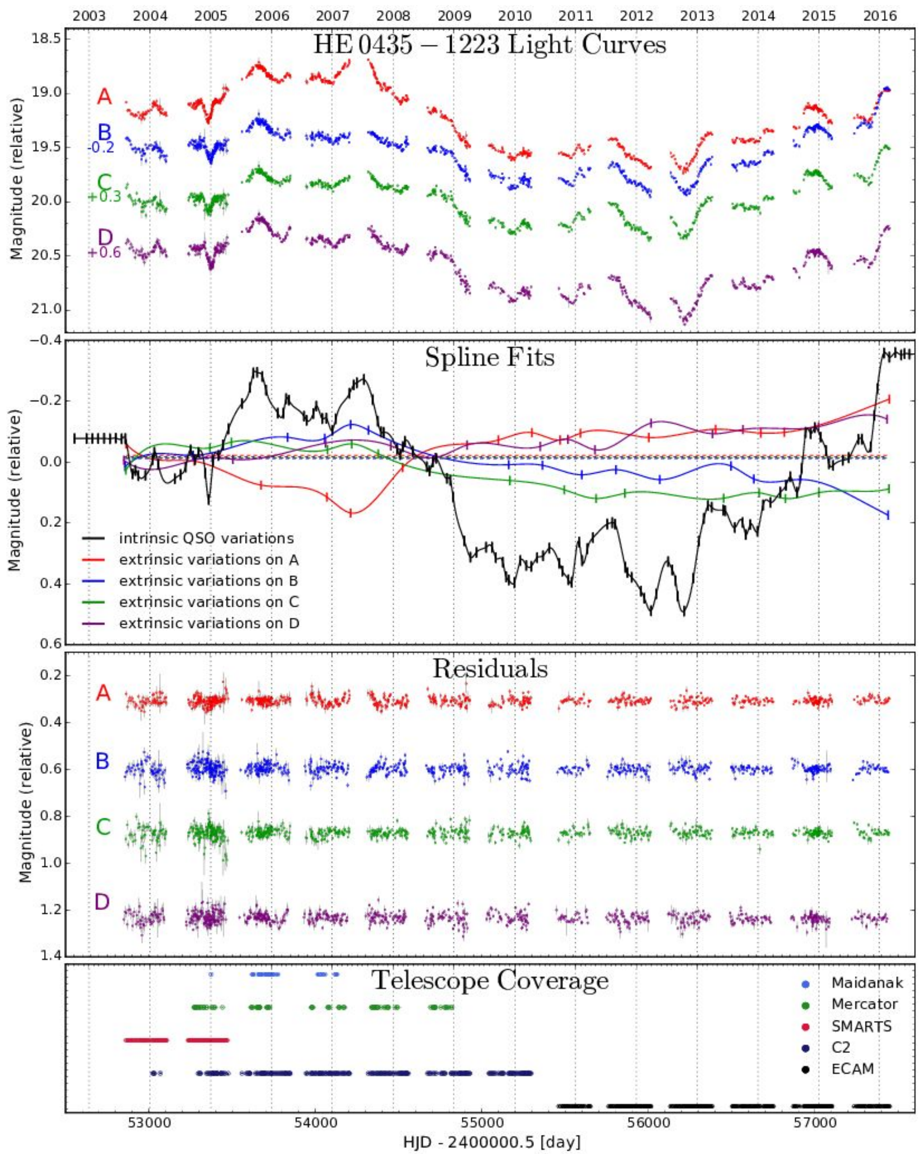
V. Bonvin,[1⋆] F. Courbin,[1] S. H. Suyu,[2,3,4] P. J. Marshall,[5] C. E. Rusu,[6] D. Sluse,[7] M. Tewes,[8] K. C. Wong,[9,4] T. Collett,[10] C. D. Fassnacht,[7] T. Treu,[11] M. W. Auger,[12] S. Hilbert,[13,14] L. V. E. Koopmans,[15] G. Meylan,[1] N. Rumbaugh,[11] A. Sonnenfeld,[16,11,17] and C. Spiniello[2]

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

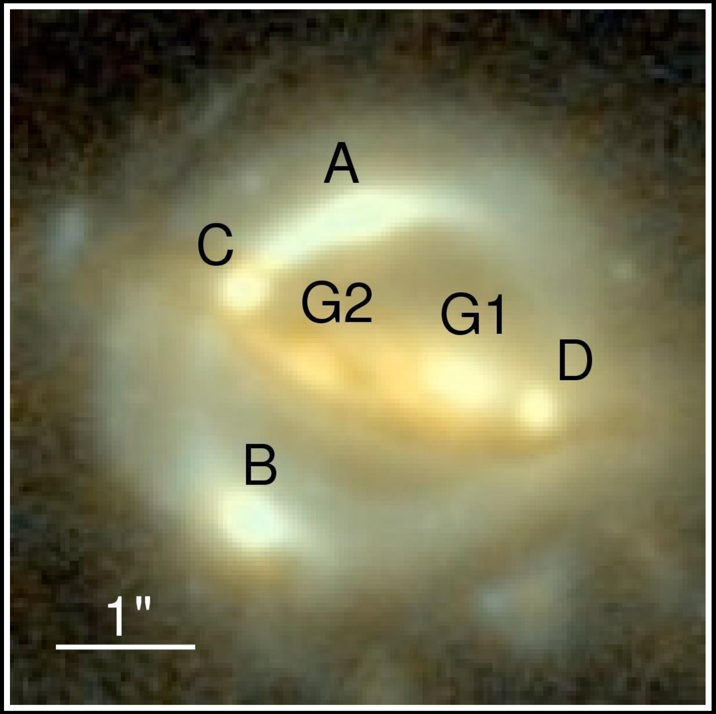


Multiple seasons (13 for HE0435) provide high accuracy (+/-1d) time delays

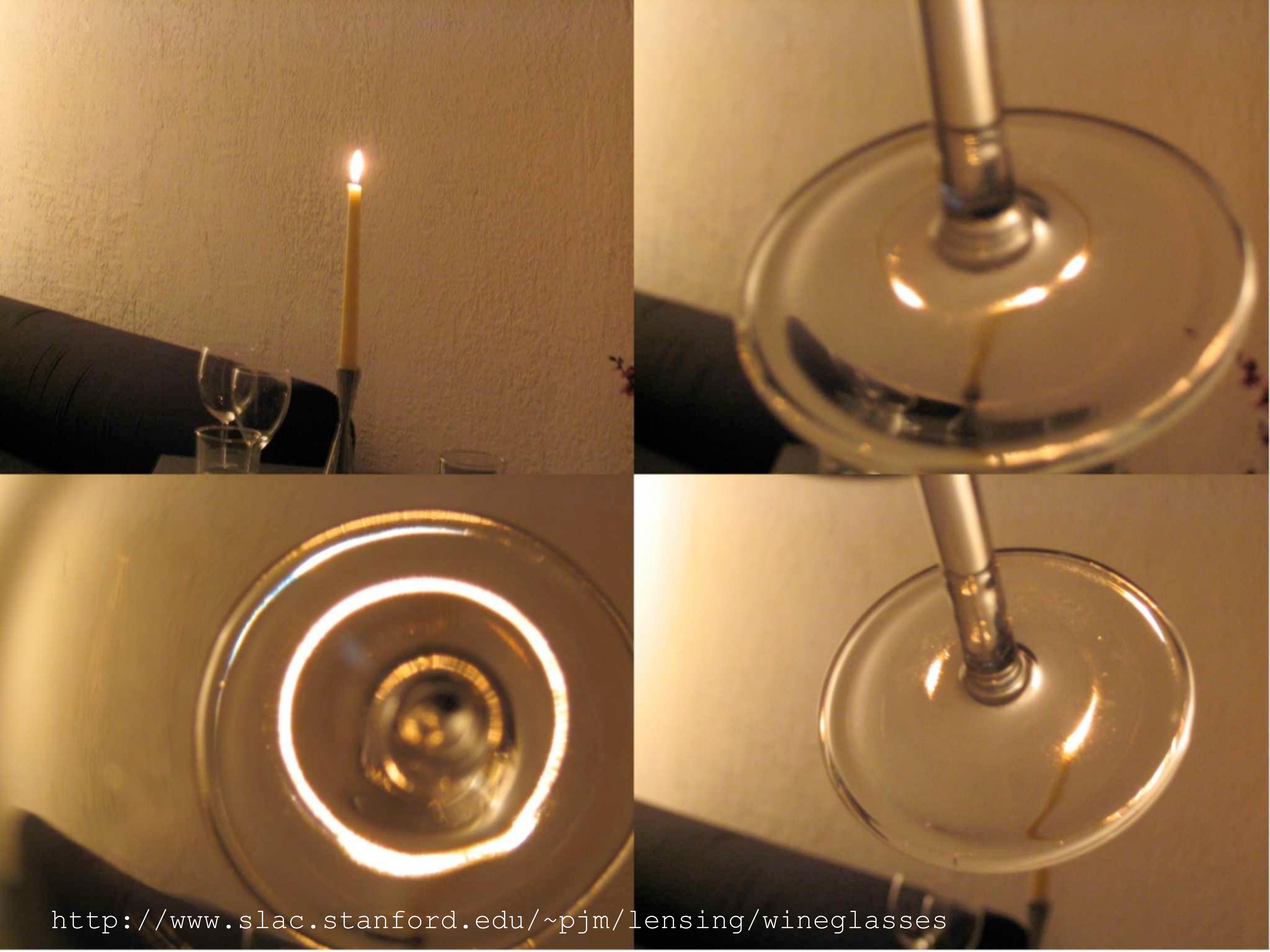
Model includes 1 intrinsic AGN light curve and 4 independent microlensing light curves

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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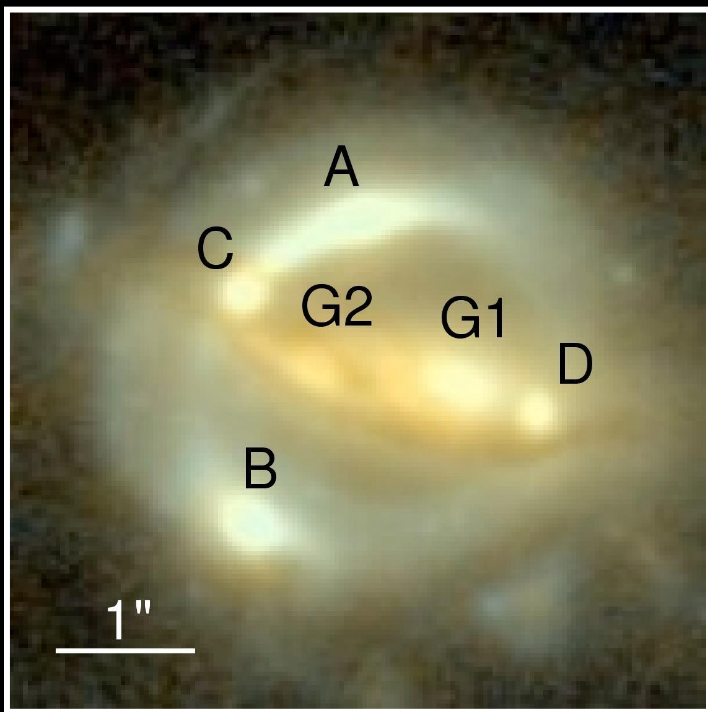
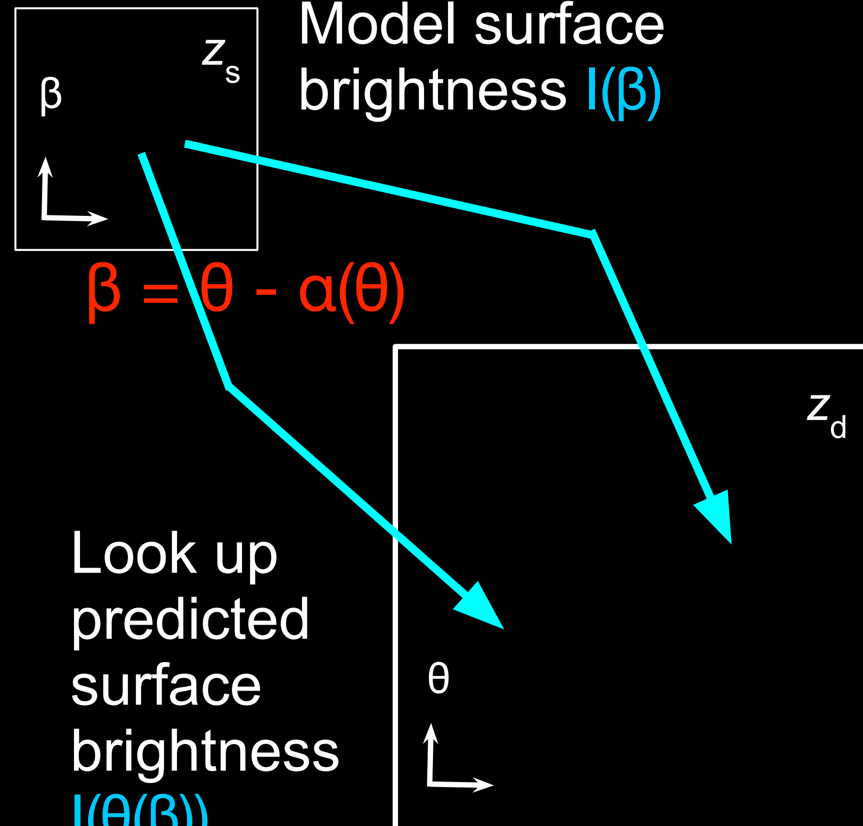


Model surface brightness $I(\beta)$

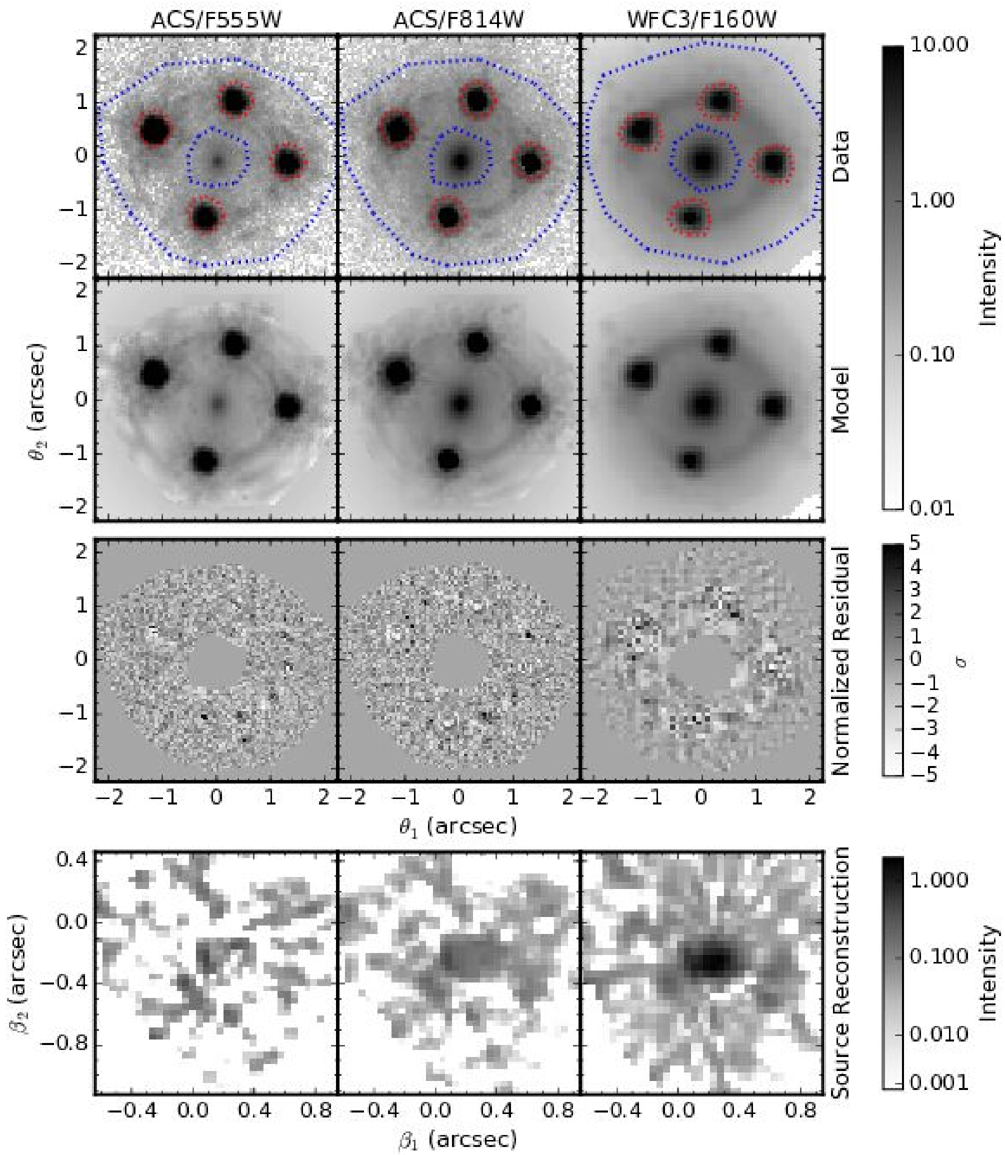


$\beta = \theta - \alpha(\theta)$

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 $\pi = \{H_0, \Omega_\mathrm{m}, \Omega_\Lambda, w\}$ (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:

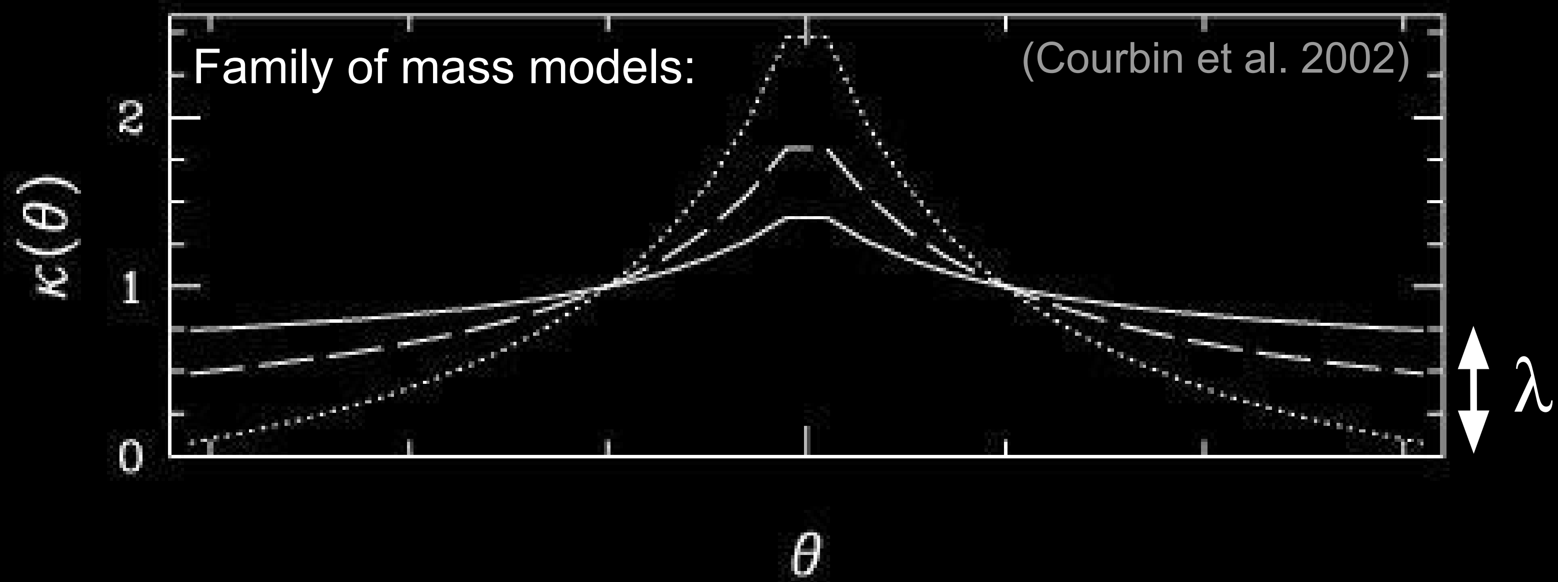
$$P(\pi|d_\mathrm{ACS}, \Delta t, \sigma) = \int \mathrm{d}\nu \, \mathrm{P}(\xi|d_\mathrm{ACS}, \Delta t, \sigma)$$

where

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

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

"Mass-sheet" transformation

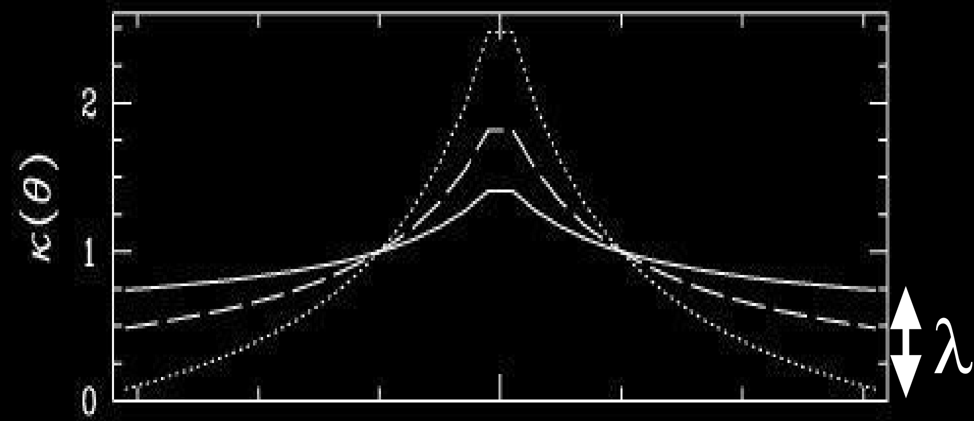


Predicted image is unchanged, but time delay predictions (and H0) are wrong:

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

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

“Mass-sheet” degeneracy



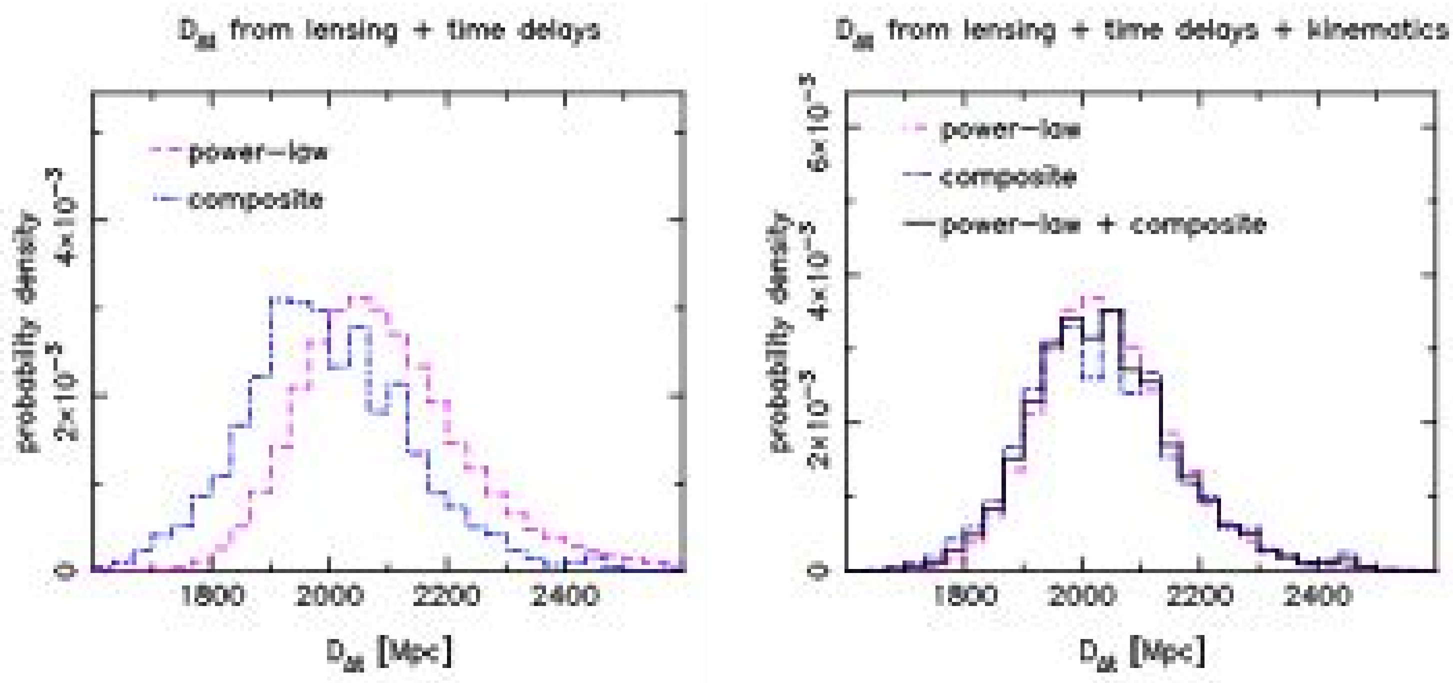
$$\kappa'(\theta) = (1-\lambda)\,\kappa(\theta) + \lambda$$

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

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

- 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

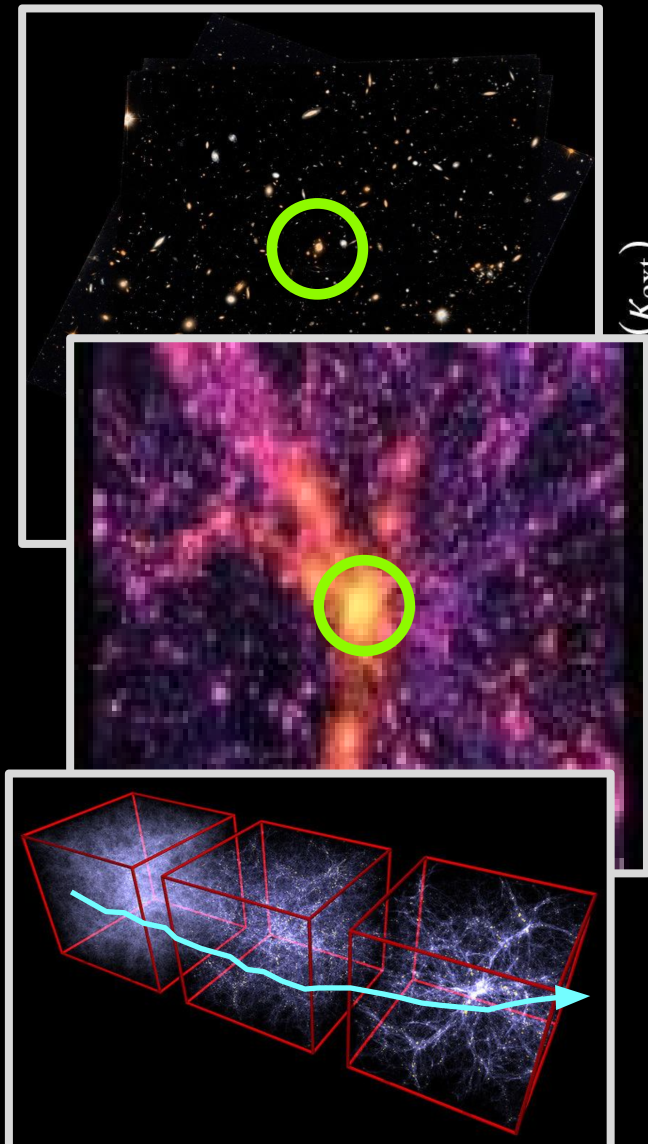
“Mass sheet” degeneracy

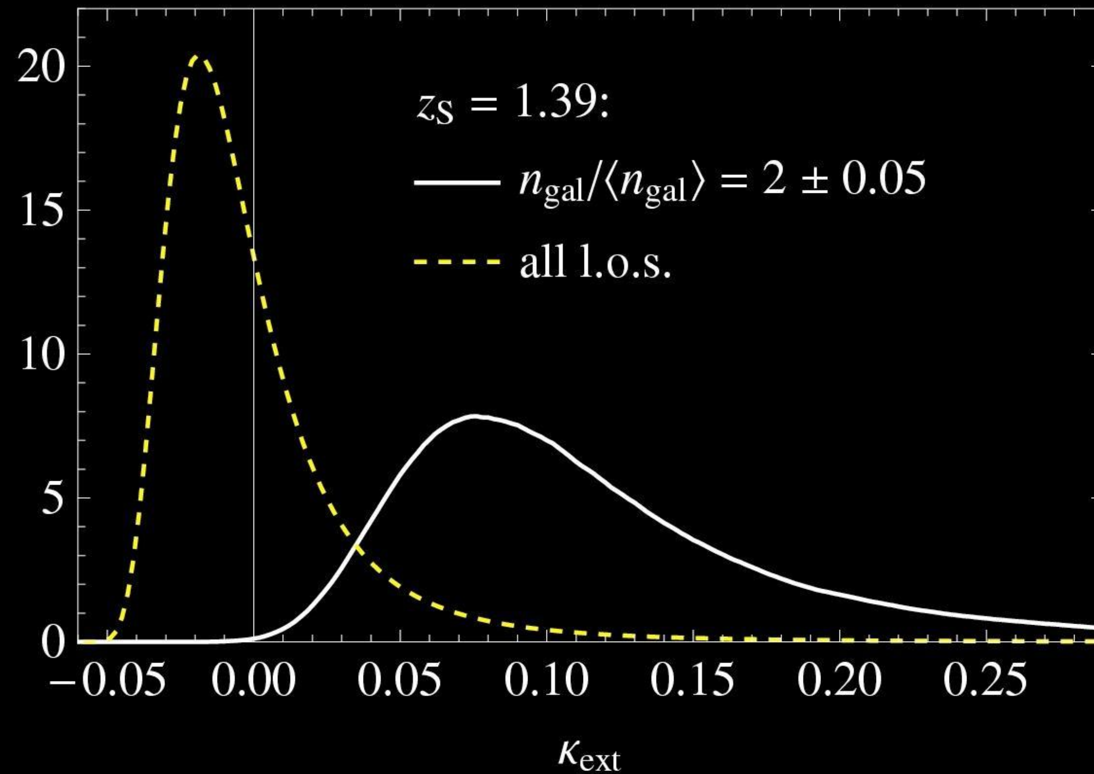


Using all the pixels in the HST Einstein ring image, *plus the velocity dispersion of the lens*, breaks the internal model degeneracy and reduces the systematic distance error to < 2%

(Suyu et al 2014)

External Convergence Pr(κ_{ext})





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

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

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

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

where

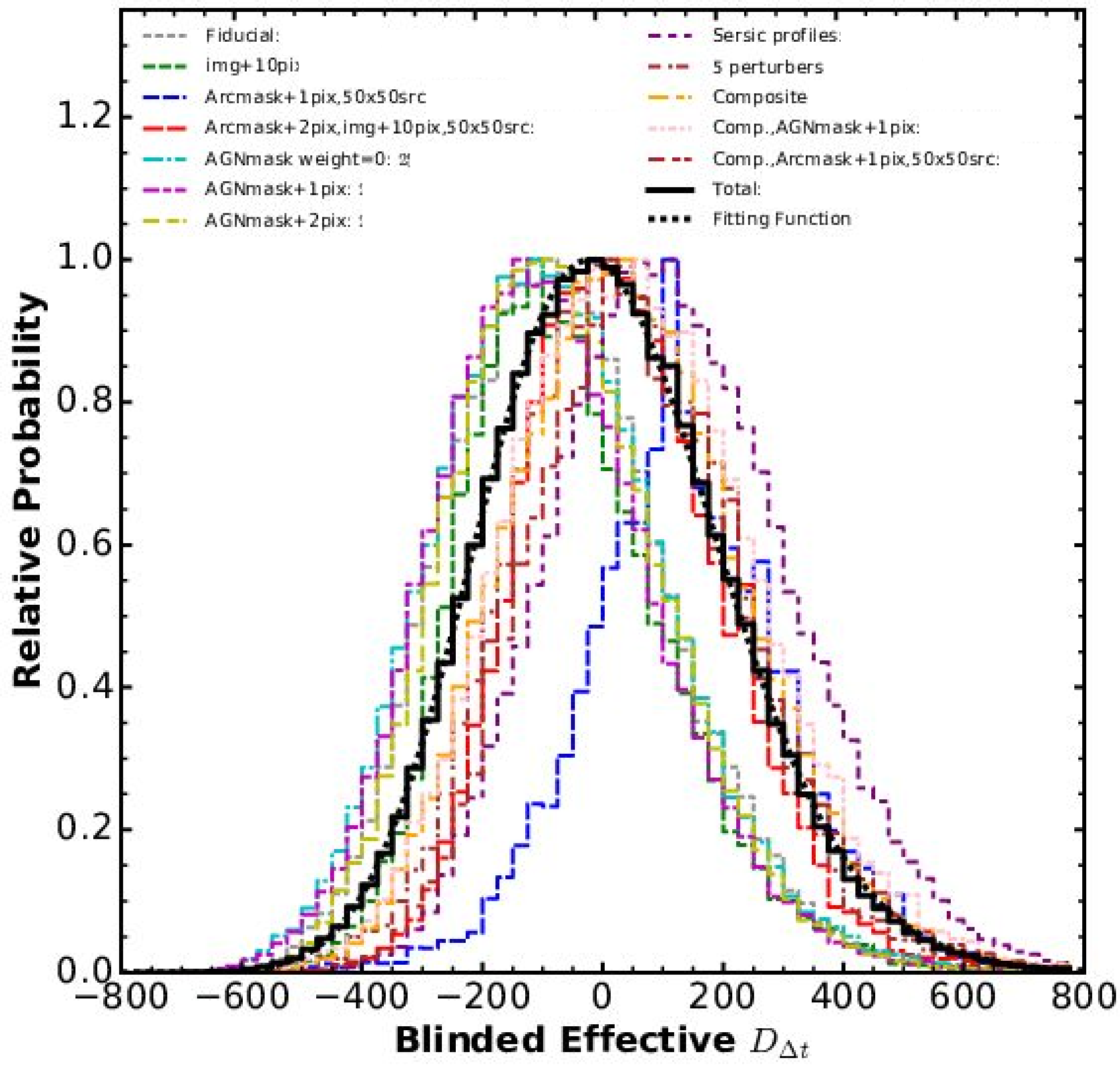
Prior

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

3-dataset likelihood

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

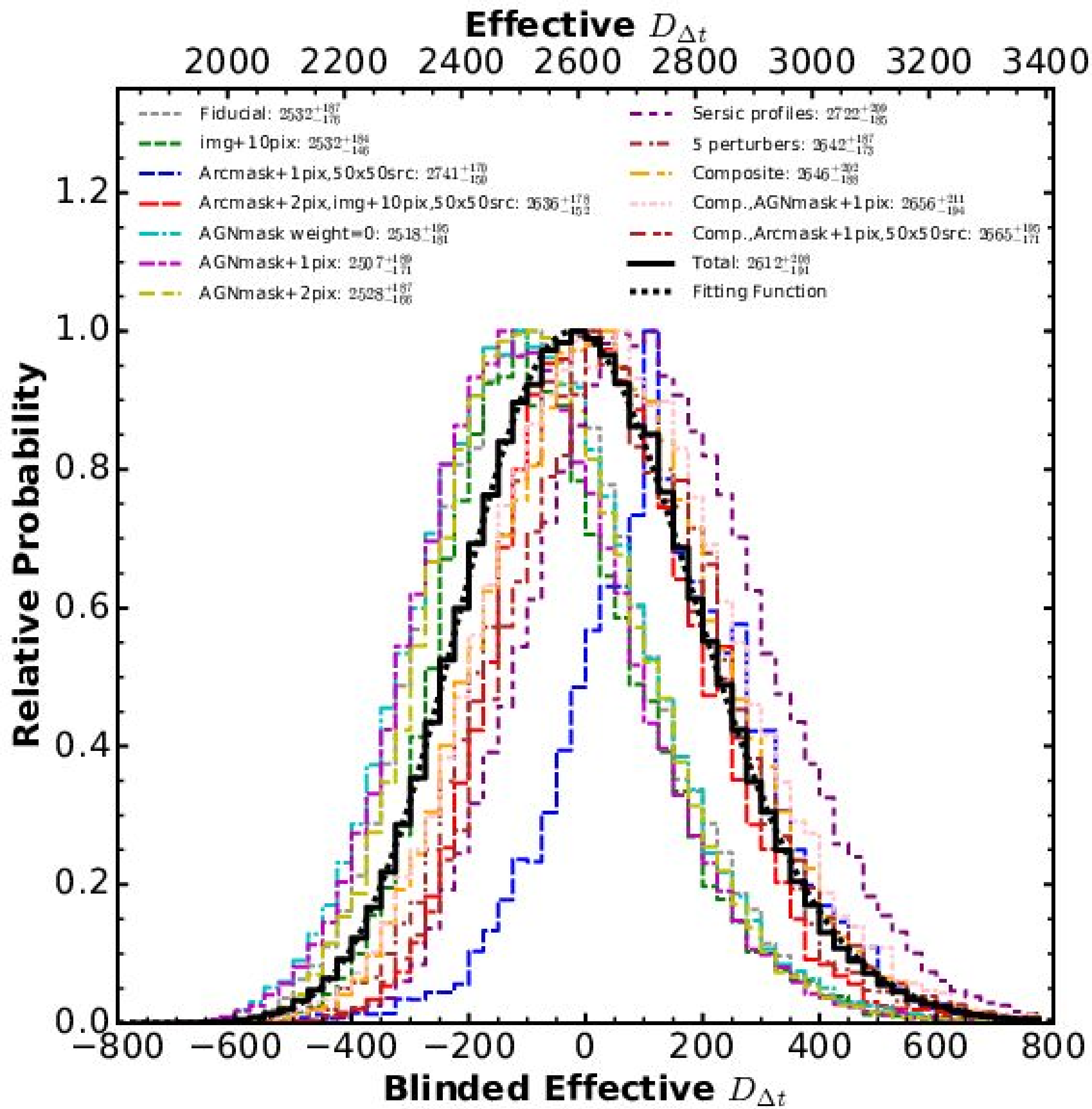
Distance Measurement



Choices in modeling lead to small offsets in time delay distance

These models can be averaged over, before unblinding

Distance Measurement



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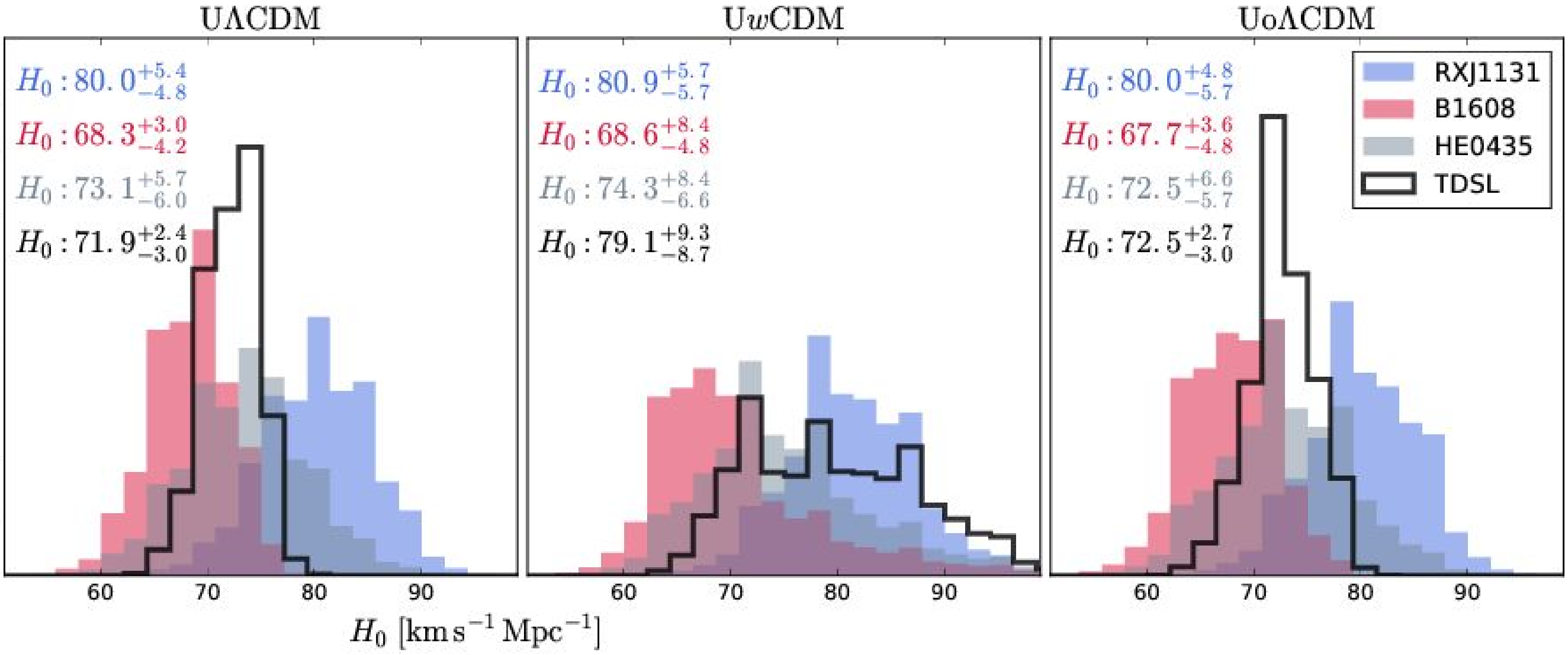
Cosmological Parameters

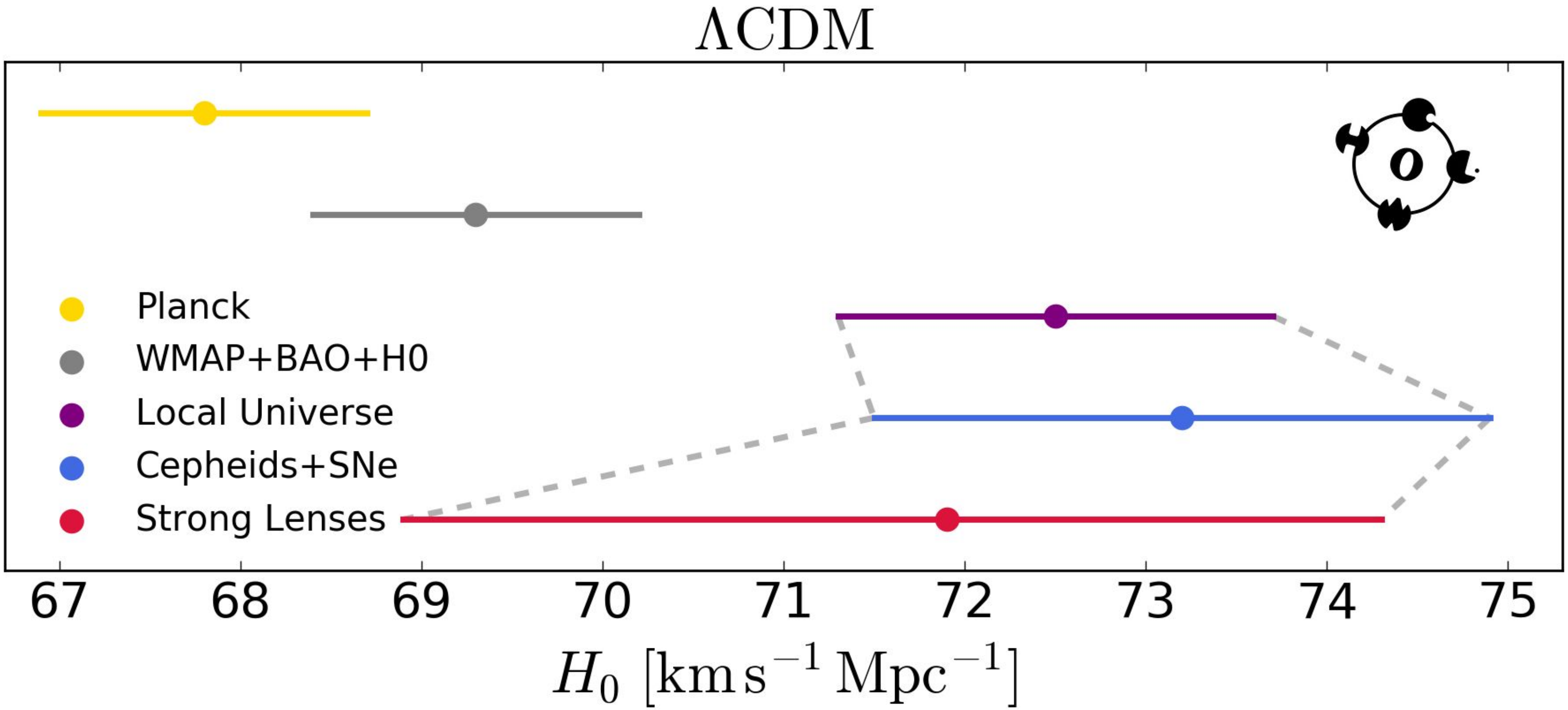


B1608 was not blinded, RXJ1131 was.

HE0435 was blinded, and fell in between.

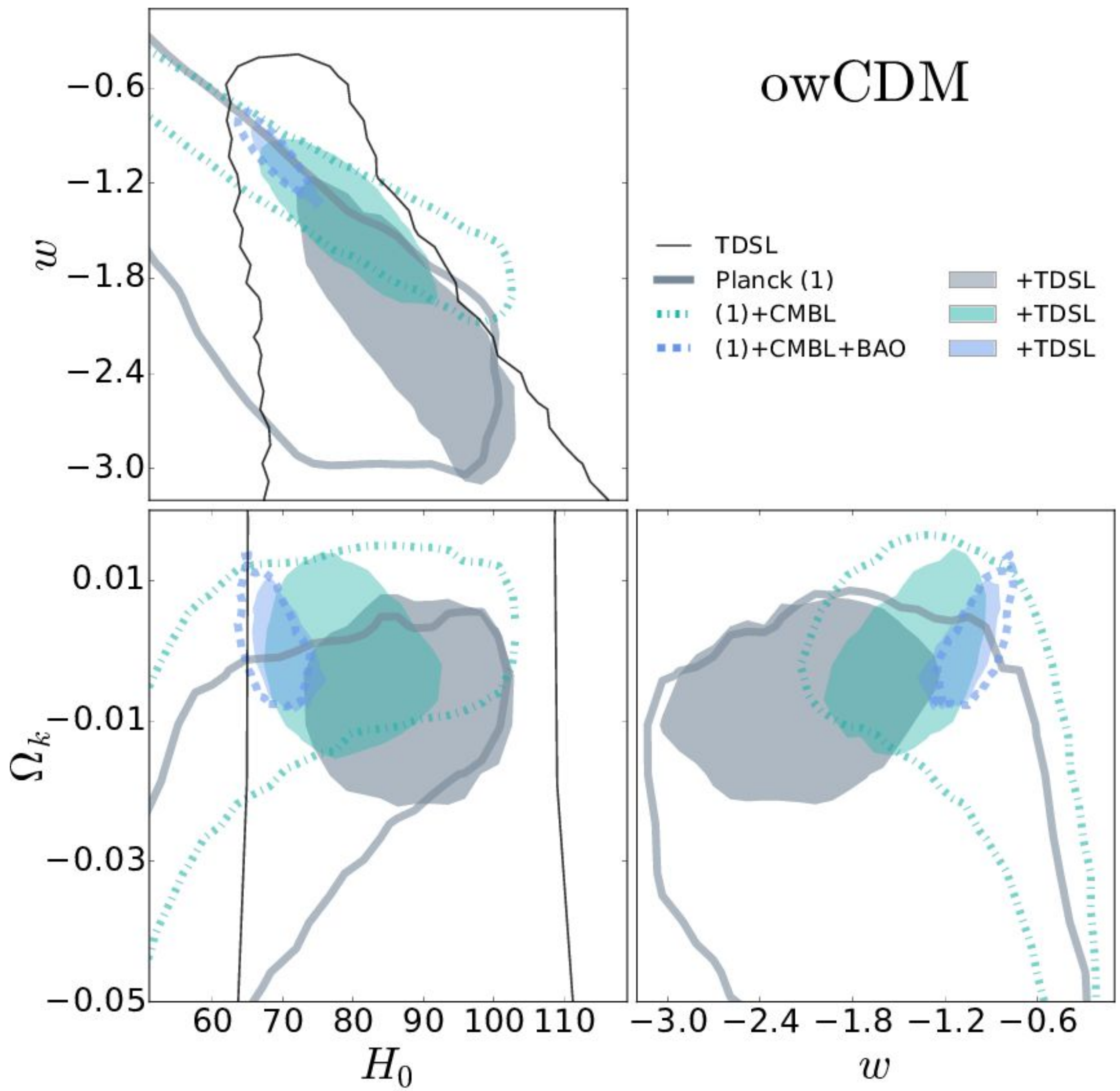
In ΛCDM, TDSL H_0 = 71.9 +/- 2.7 (3.8%)

Tension in H_0?



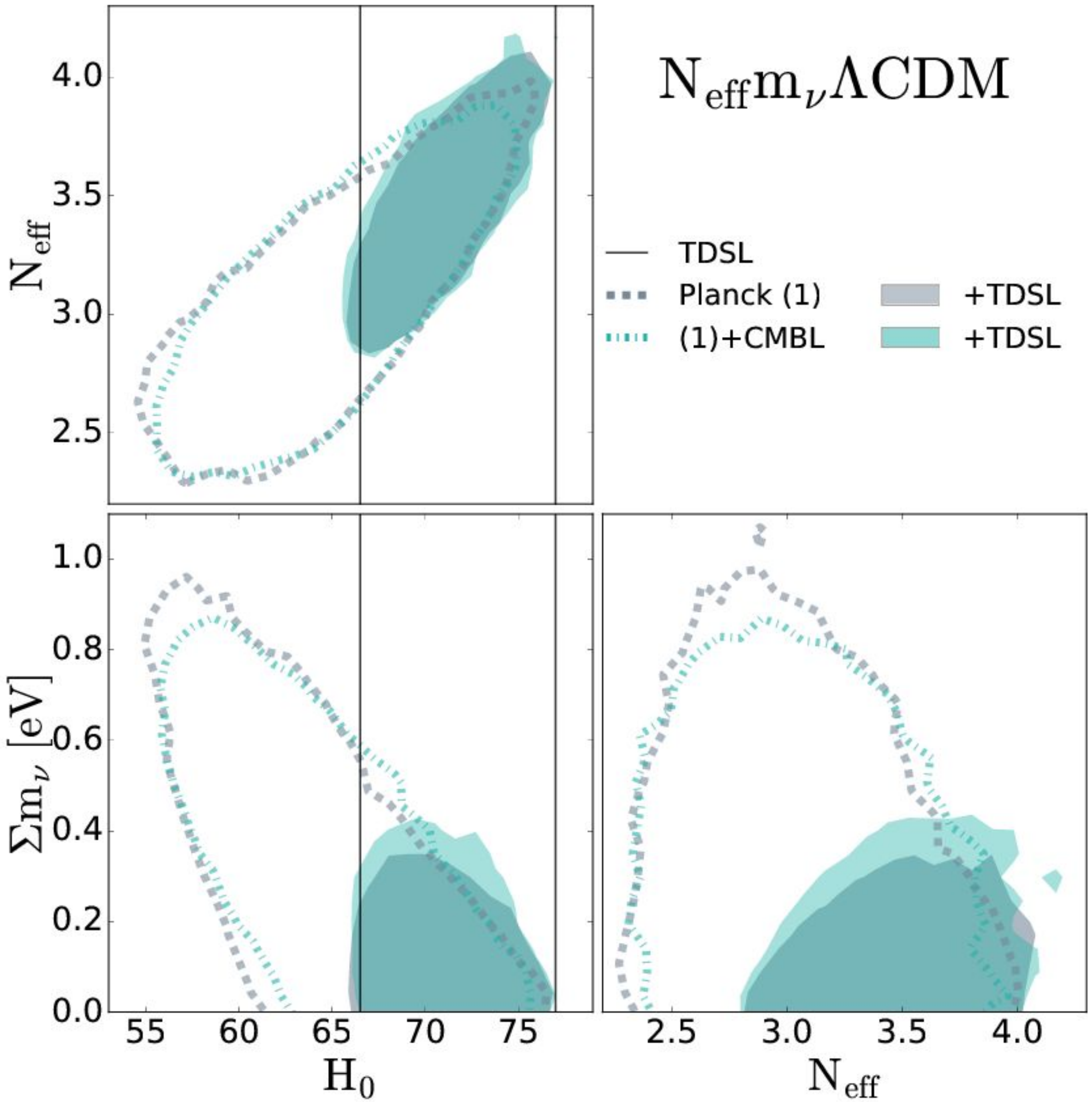
Strong lenses provide an independent measurement - blinding is crucial to avoid unconscious concordance either way

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

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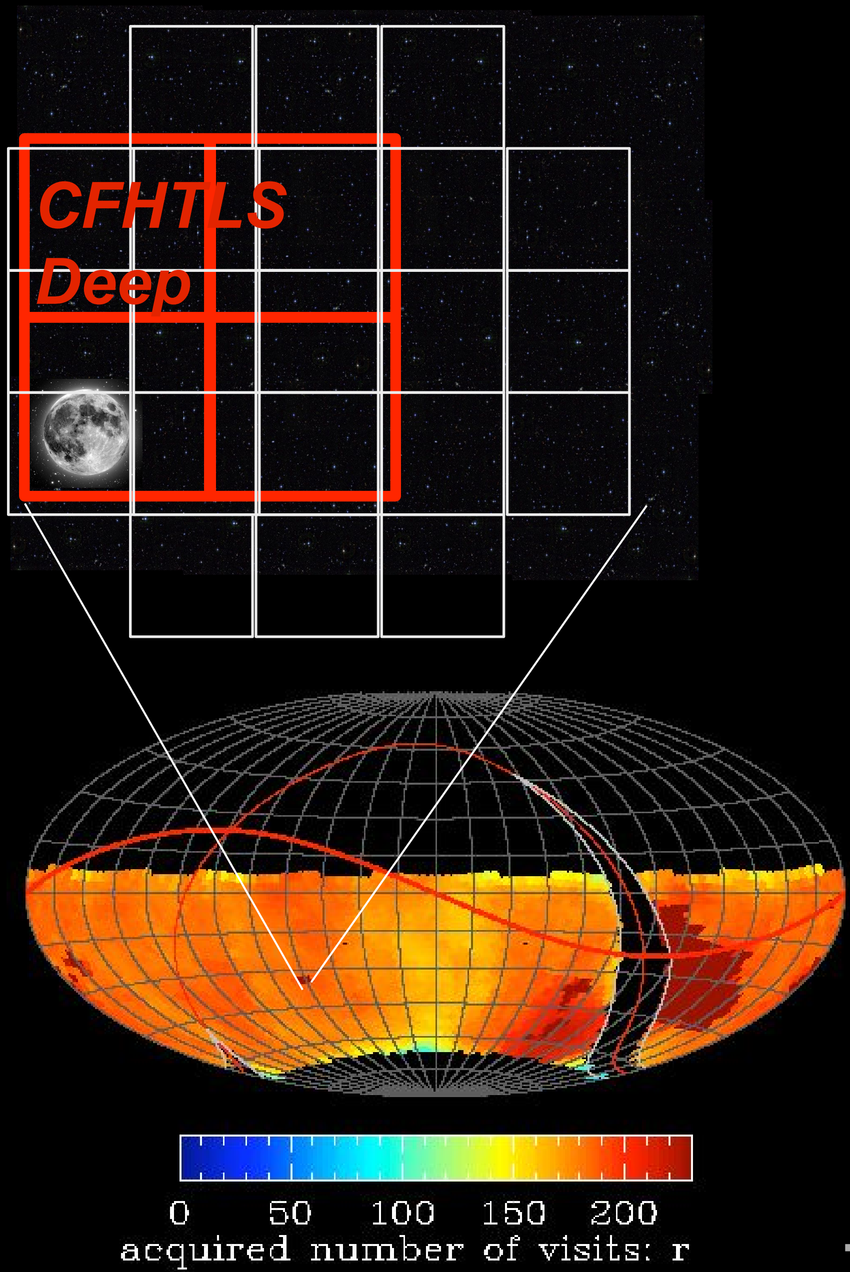
Time Delay Cosmography with LSST

- 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

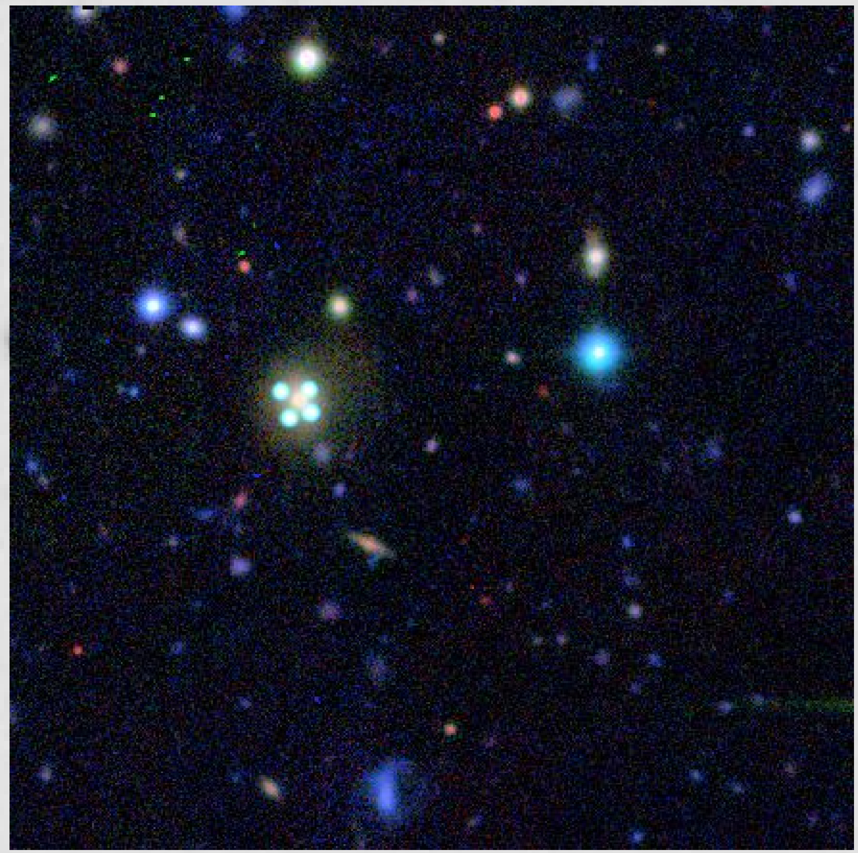
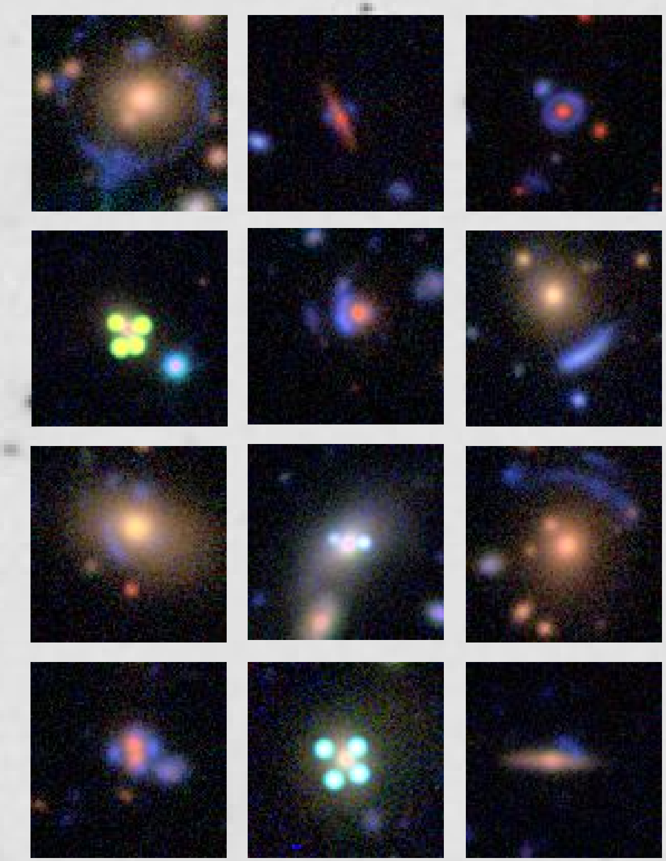


- 18000 sq deg
- 6 filters, ugrizy
- 10 years, 800 visits/field
- 5 day cadence (ugrizy)
- ~ 24 mag per visit
- Resolution 0.4-1.0”

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)

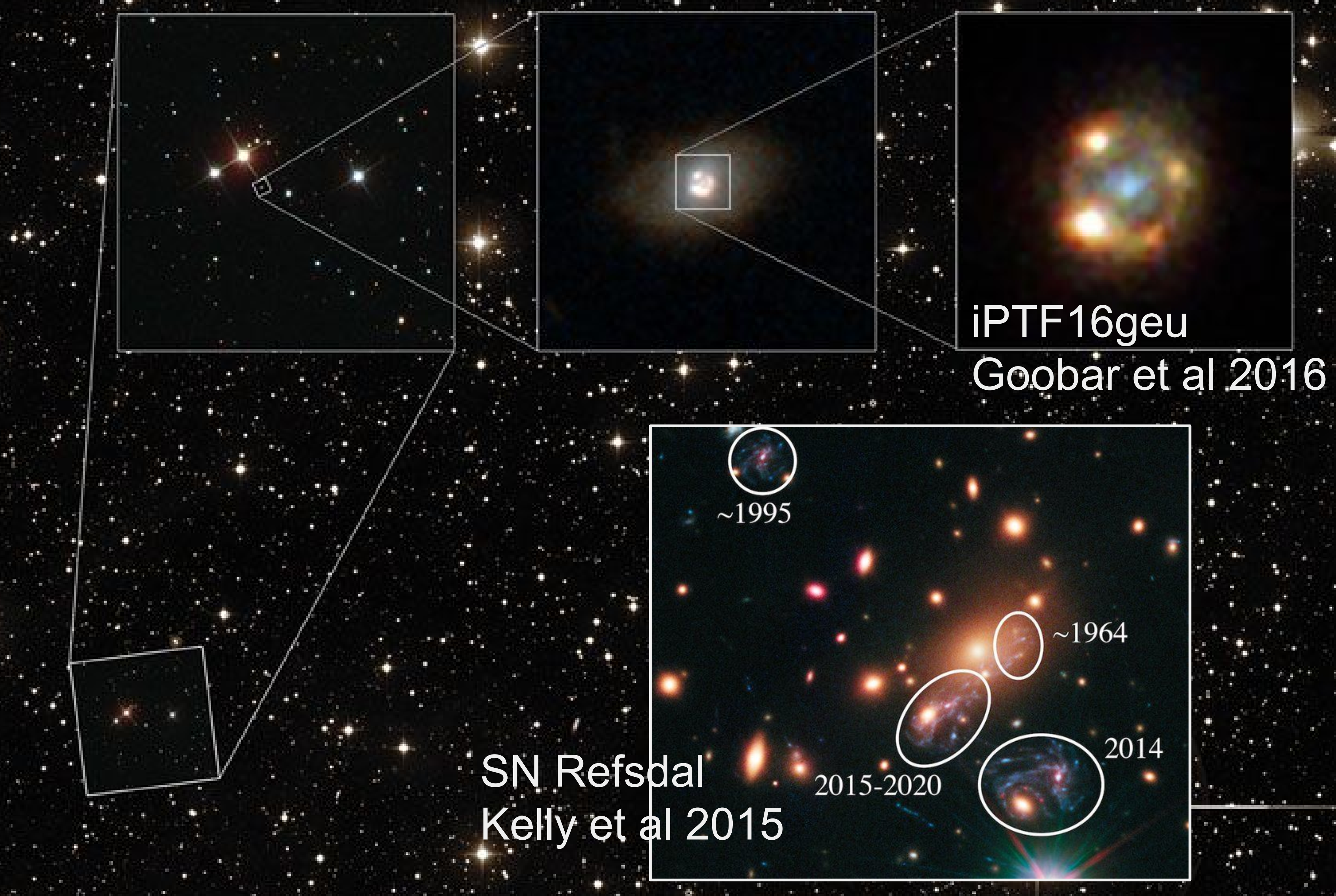
How many lensed quasars?

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?

What about lensed supernovae?



How many lensed supernovae?

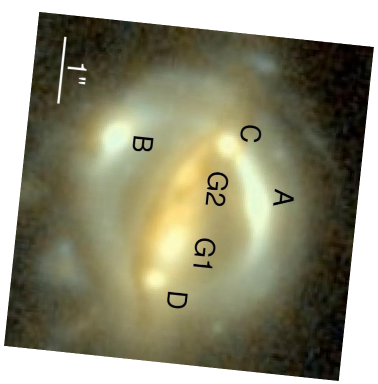
Survey	SN (Ia) N_{nonlens}	SN (Ia) N_{lens}	SN (cc) N_{nonlens}	SN (cc) N_{lens}	Note
SDSS-II	4.34×10^2	0.003 (54%)	1.09×10^3	0.01 (40%)	
SNLS	7.52×10^2	0.03 (24%)	1.44×10^3	0.05 (26%)	
PS1/3π	3.34×10^4	0.28 (53%)	8.23×10^4	0.97 (39%)	detections only
PS1/MDS	2.93×10^3	0.09 (32%)	6.05×10^3	0.16 (30%)	
DES/wide	8.30×10^4	2.7 (29%)	1.62×10^5	4.9 (29%)	detections only
DES/deep	8.95×10^2	0.04 (22%)	1.80×10^3	0.07 (24%)	
HSC/deep	1.10×10^3	0.06 (18%)	2.56×10^3	0.13 (21%)	
JDEM/SNAP[a]	1.36×10^4	2.9 (13%)	5.39×10^4	12.0 (18%)	
LSST	1.39×10^6	45.7 (32%)	2.88×10^6	83.9 (30%)	

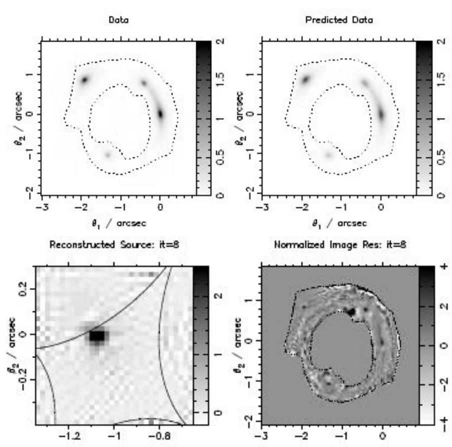
(Oguri & Marshall 2010)

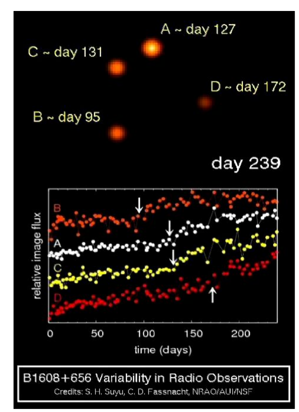
- **LSST** should discover ~130 multiply-imaged, well-resolved lensed SNe (~50 Type Ia)
- Similar number again of small image separation, low time delay, unresolved systems (Goldstein et al 2016)

Dark Energy from 100 LSST lenses

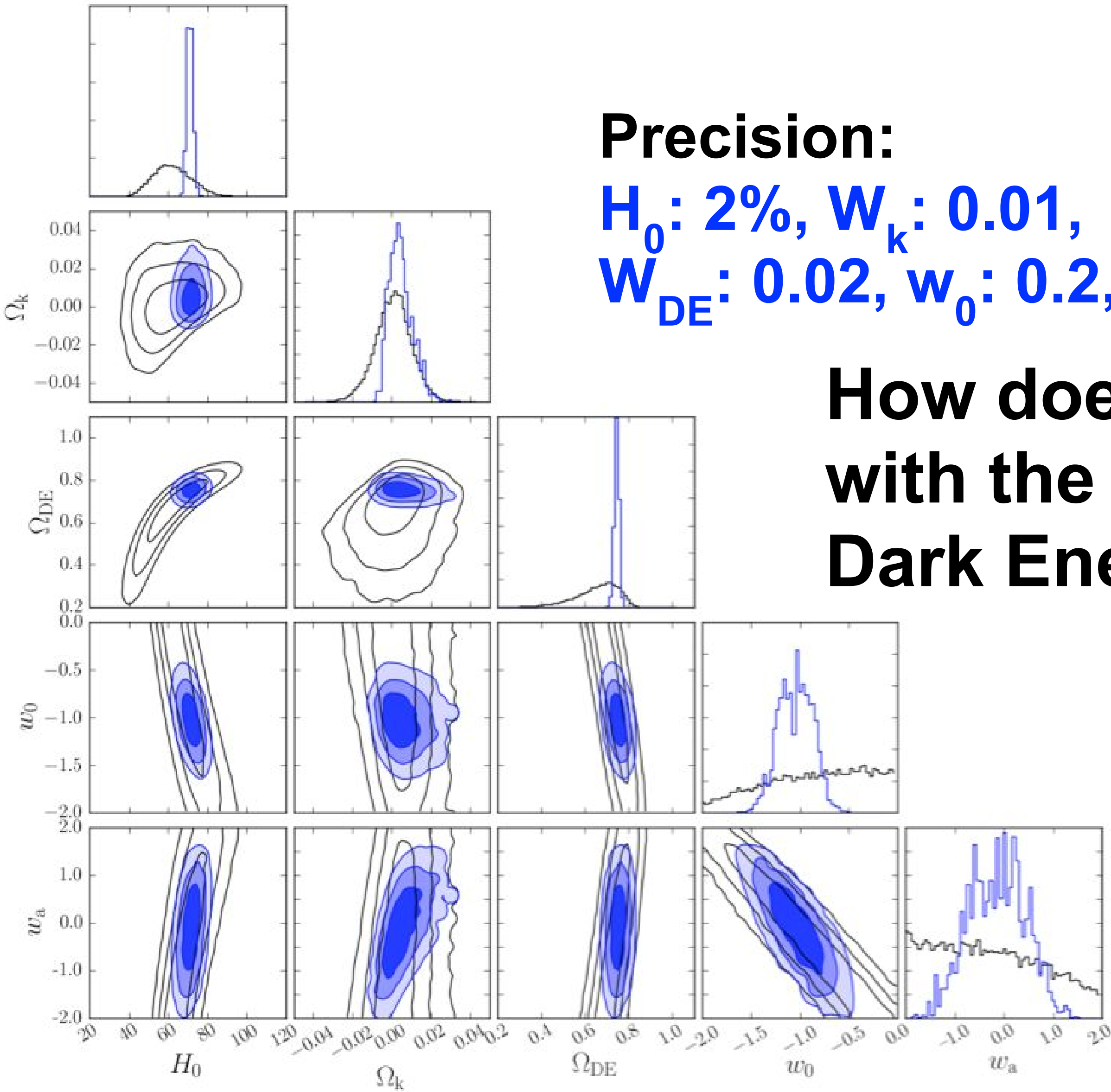
Suppose we have just 100 LSST lenses with spectroscopic redshifts, lens galaxy velocity dispersions, HST-grade ring modeling and good time delays, such that detailed analysis of individual lenses gives **5% precision on each time delay distance**







Dark Energy from 100 LSST lenses

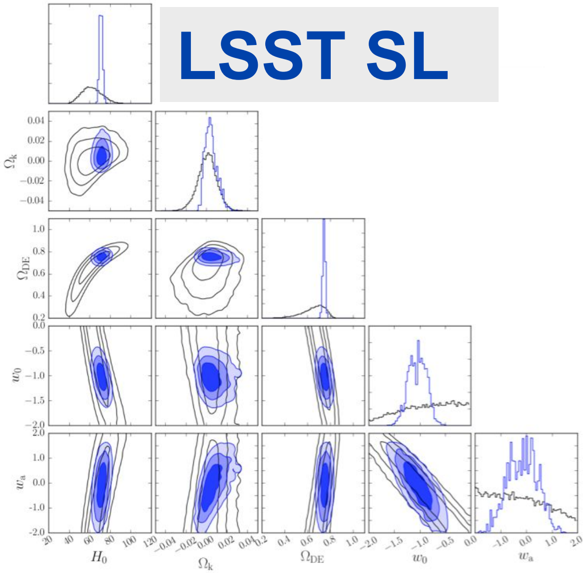


Precision:

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

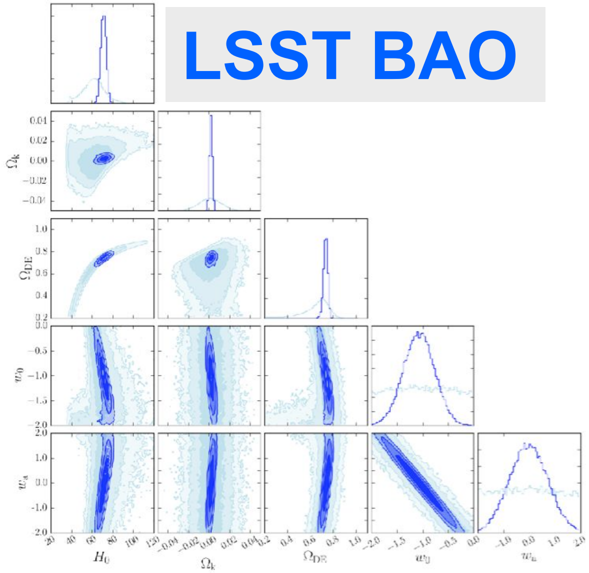
How does this compare with the other LSST Dark Energy probes?

Dark Energy from 100 LSST lenses



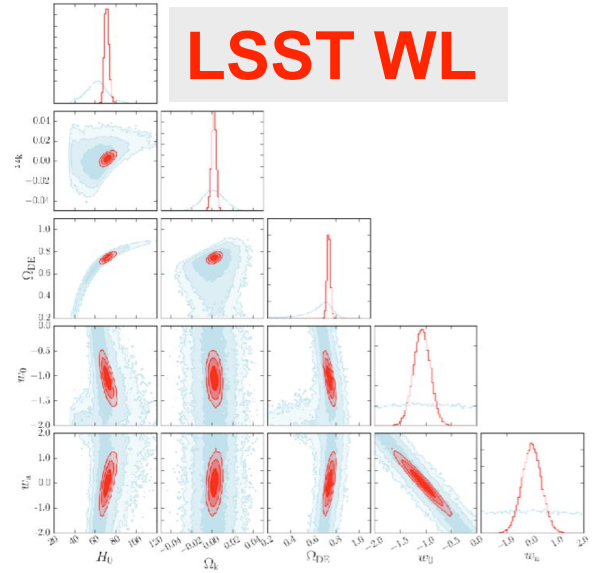
LSST SL

w0:0.2, wa:0.7



LSST BAO

w0:0.4, wa:1.0

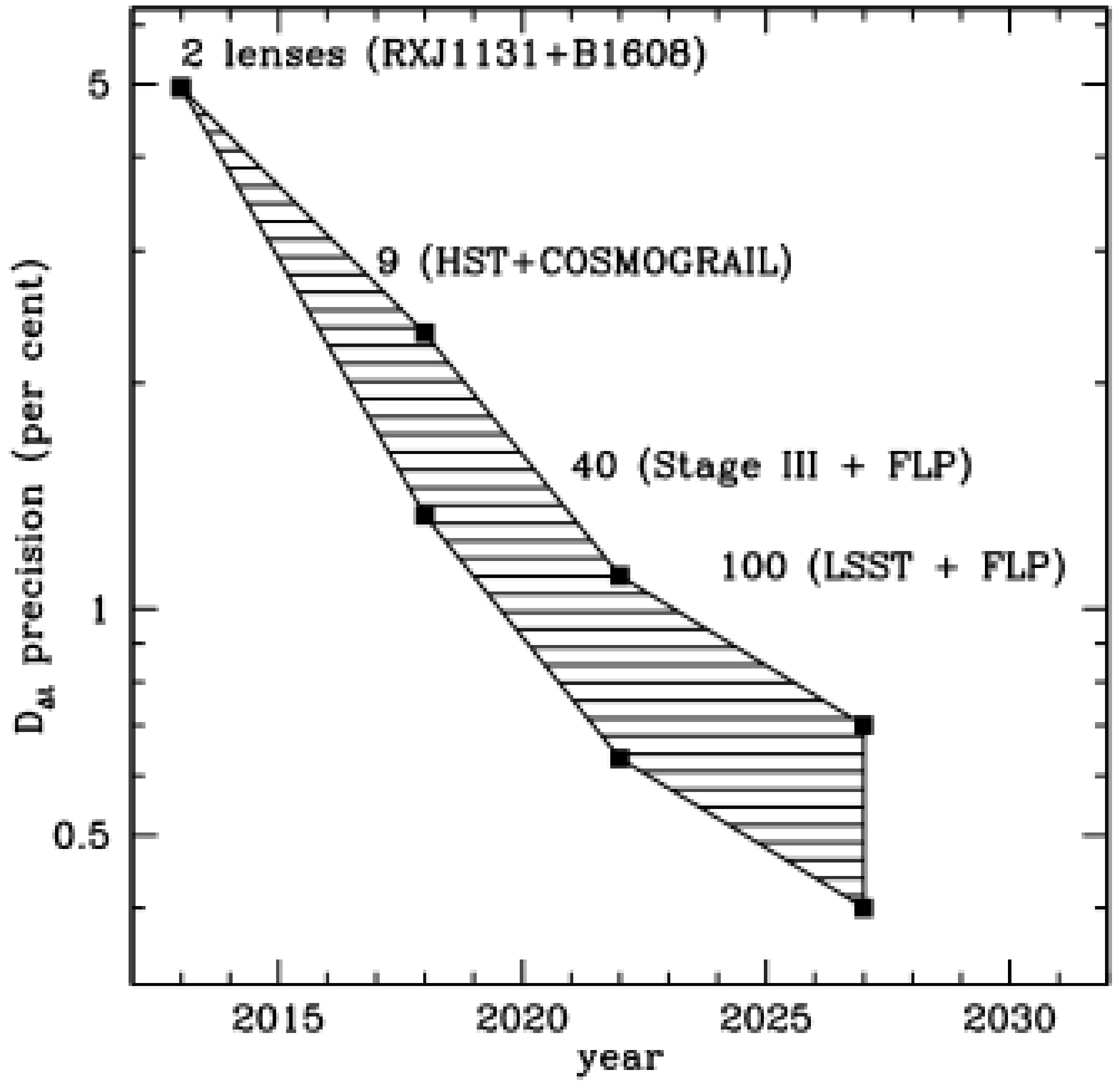


LSST WL

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



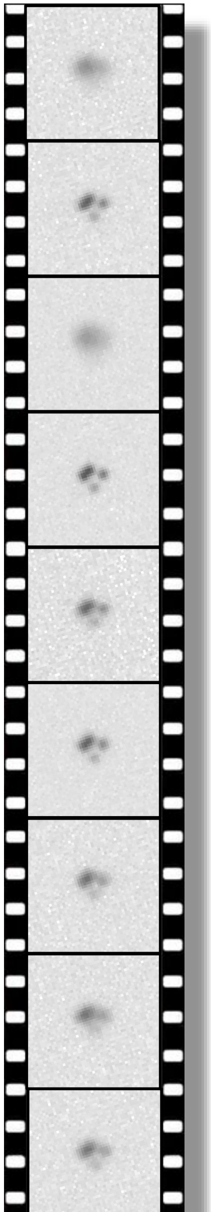
Treu & Marshall 2016

LSST Time Delay Lens Cosmography

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

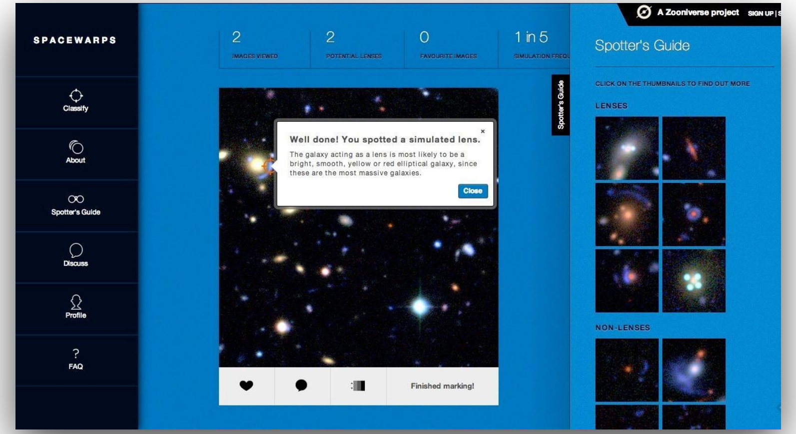
- Find 1000s of lensed AGN and SNe
- **Measure 100s of time delays** to few % precision
- Obtain high resolution follow-up imaging and spectroscopy, **constrain lens mass distributions**
- Reconstruct each lens' density **environment**
- Parametrize systematics and marginalize out
- Blind inference of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

Lens detection at LSST scale



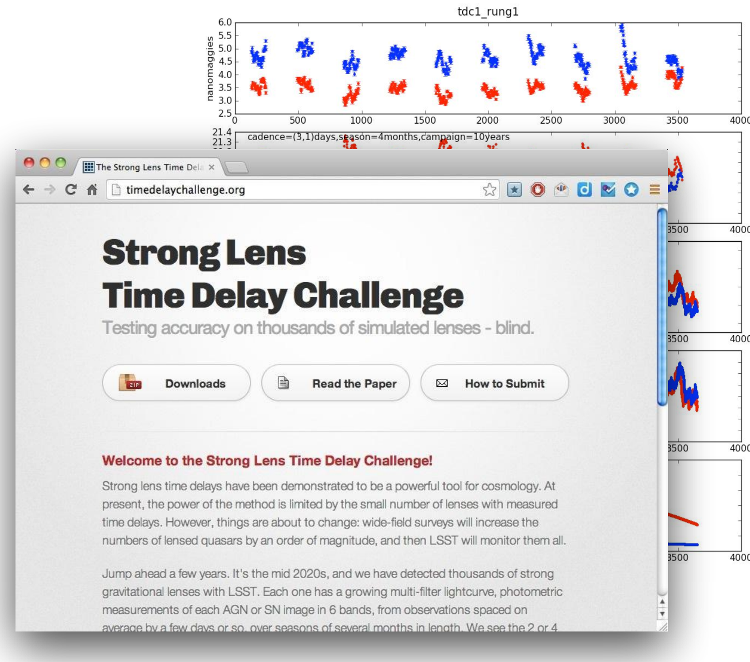
- **Catalog-based candidate detection.** *Needs: good deblender, the right parameters (color, morphology, variability) saved, rapidly executable DB queries, intelligent alert brokering for lensed SNe*
- **Image modeling for candidate classification.** *Needs: access to postage stamp images at data center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

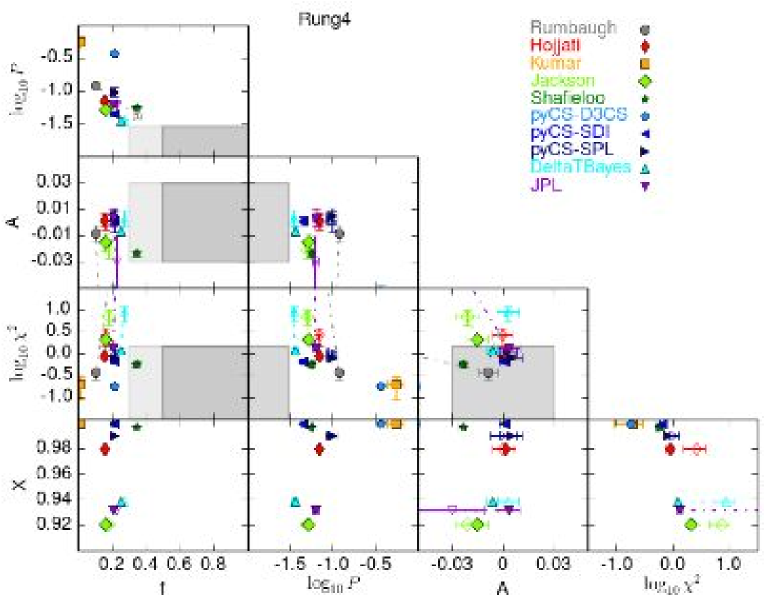
- **Candidate visualization for quality control.** *Needs: optimally-viewable color images, web-based system for crowd-sourcing*



Time delay measurement

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

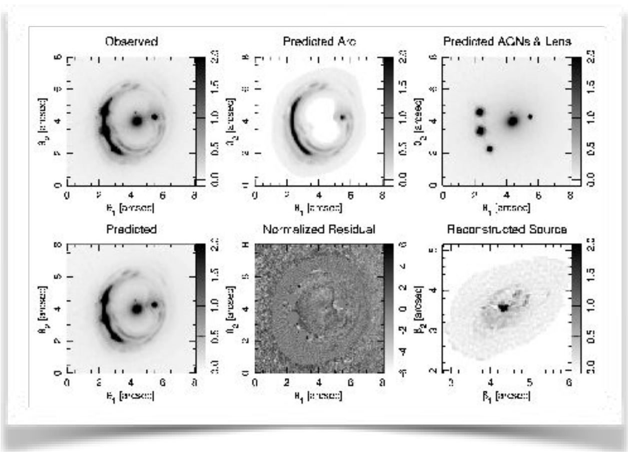




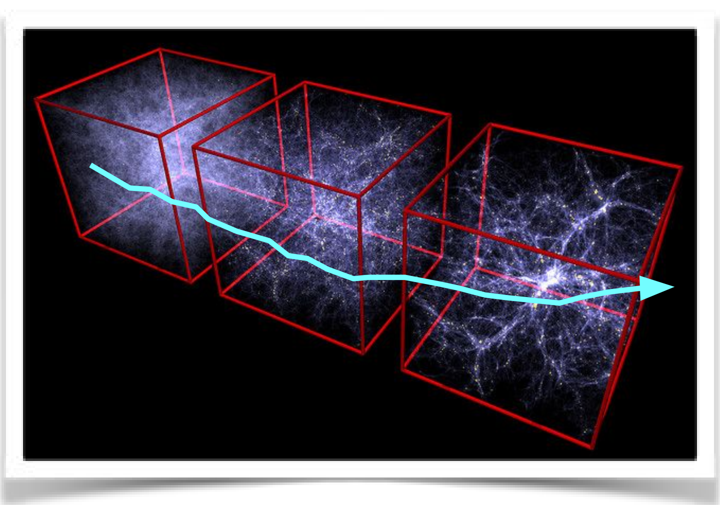
The single-filter TDC1 results suggest a sample of 400 should be possible...

TDC2 will test our ability to measure time delays from low-cadence, multi-filter data. Will lensed SNe be easier?

Mass modeling



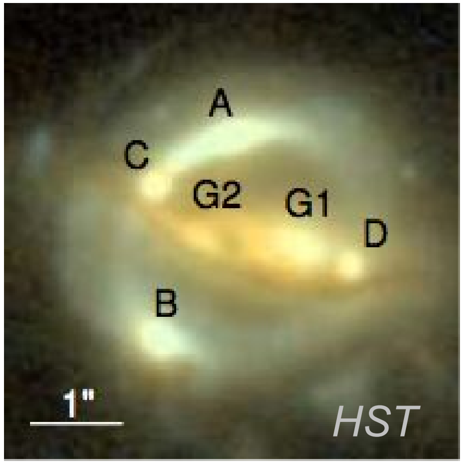
- **High accuracy lens modeling**. *Needs: high res follow-up with JWST, ELTs, IFUs. Well-sampled, high flexibility mass models, constrained with lensing and spatially-resolved kinematics. Joint inference validated on realistic simulated systems*



- **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?*

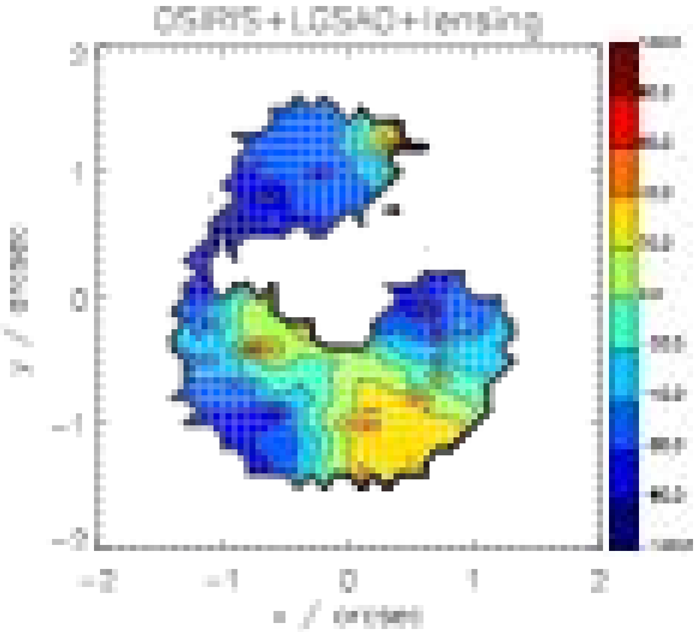
Following up 100 lenses?

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

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