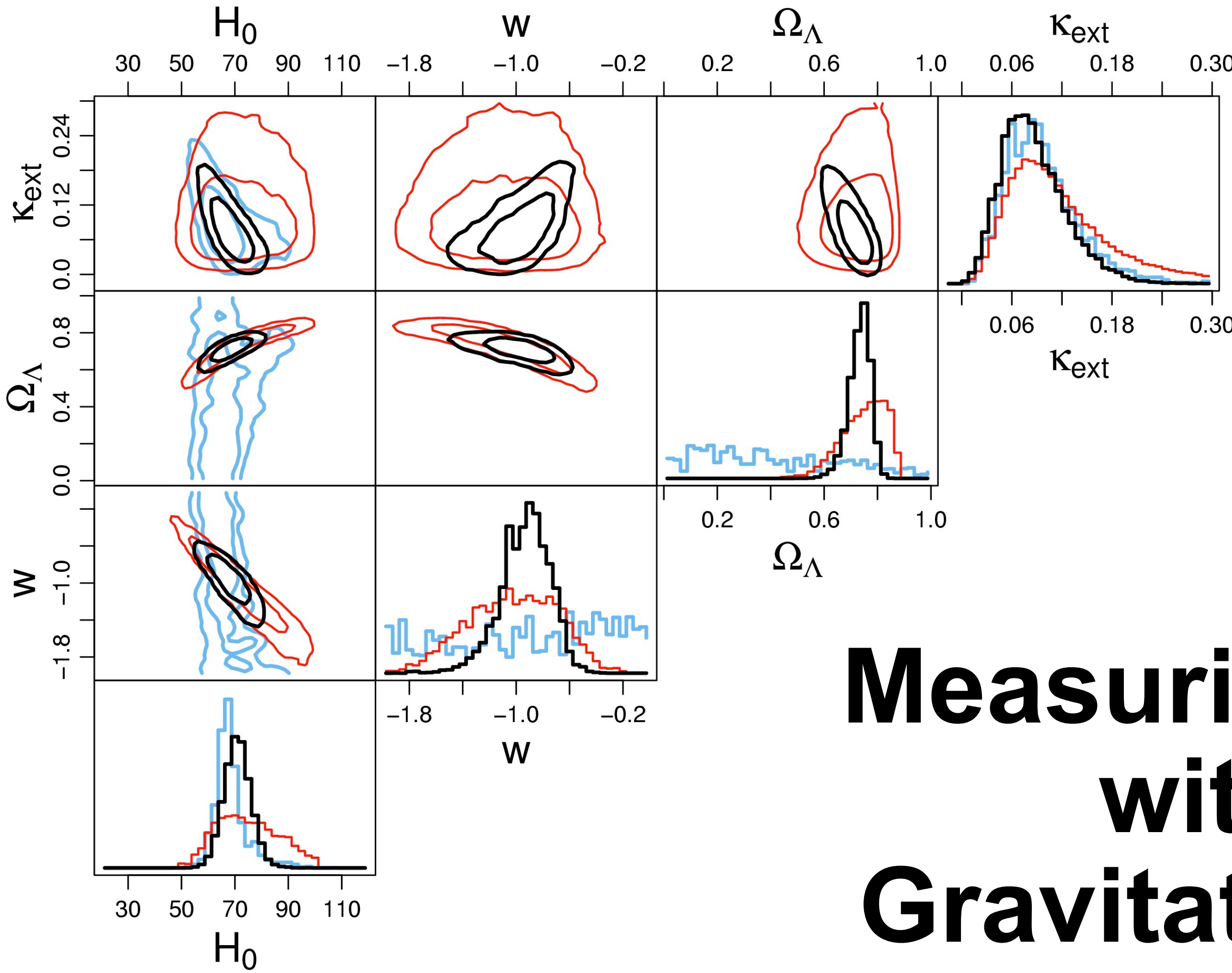


Measuring Distances with Time Delay Gravitational Lenses

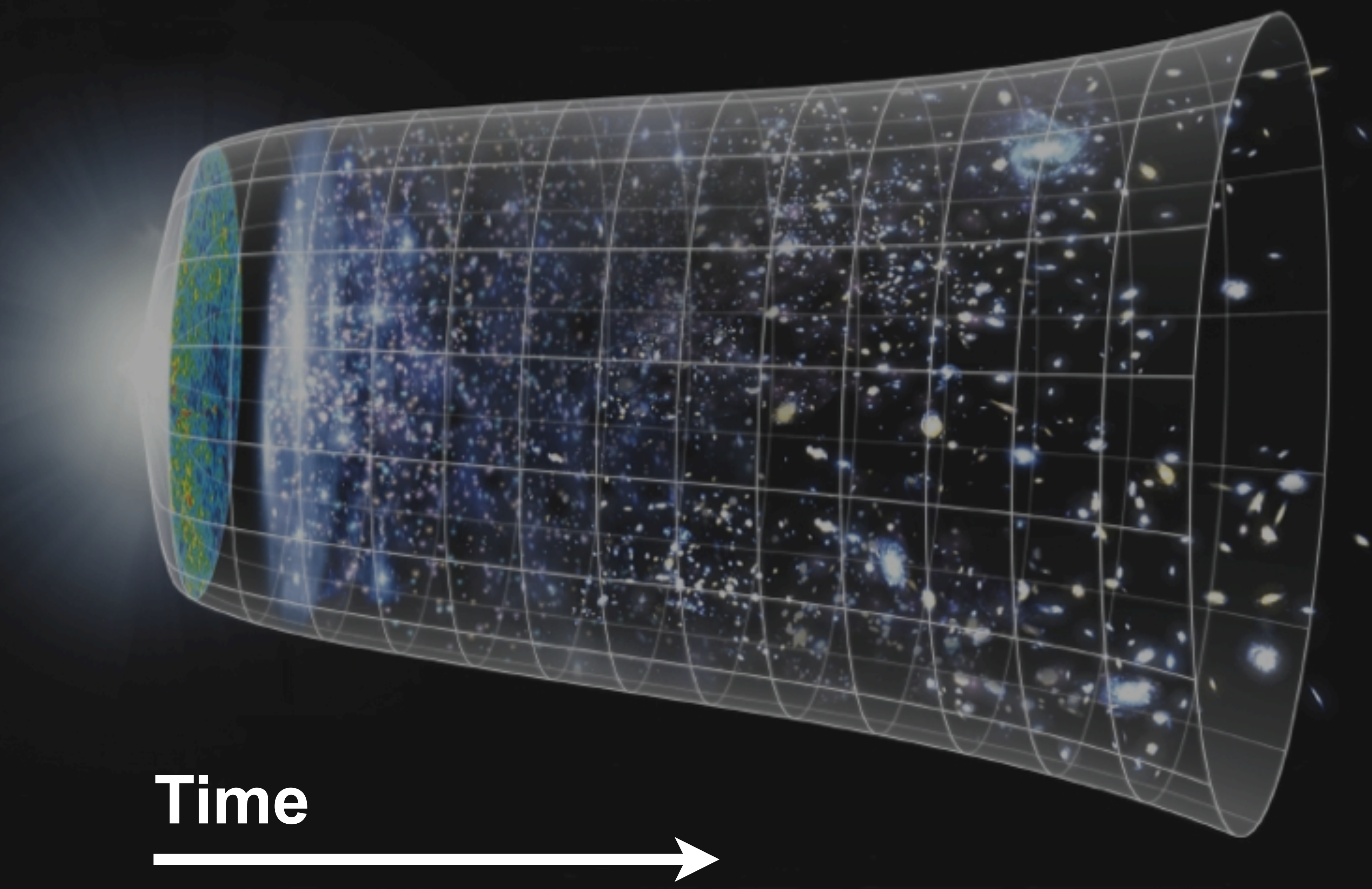
Phil Marshall

Kavli Institute for Particle Astrophysics and Cosmology,
SLAC National Accelerator Laboratory

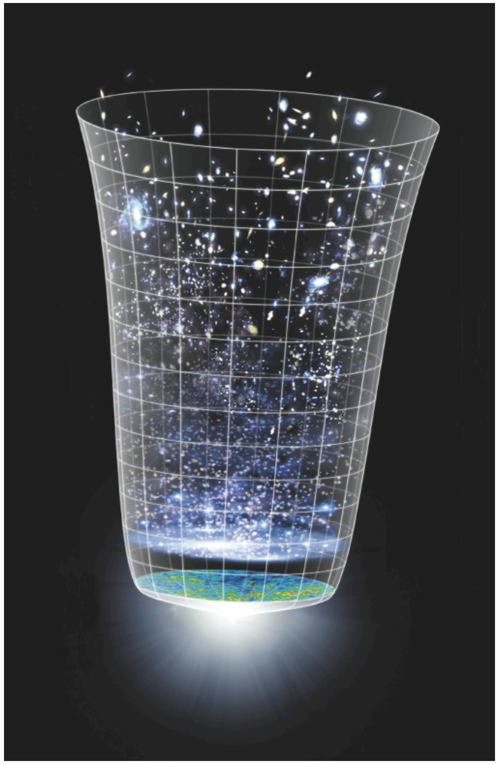
KIPAC

SLAC NATIONAL ACCELERATOR LABORATORY

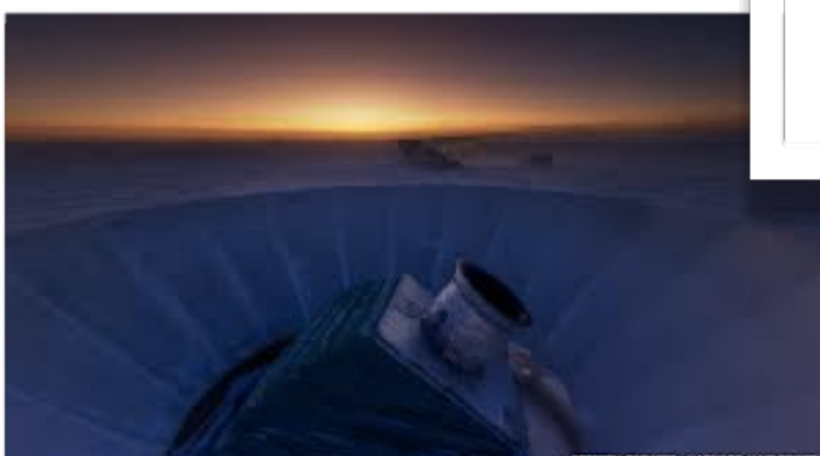
ASIAA/CCMS/IAMS/LeCosPA/NTU-Physics Joint Colloquium
National Taiwan University, March 2014

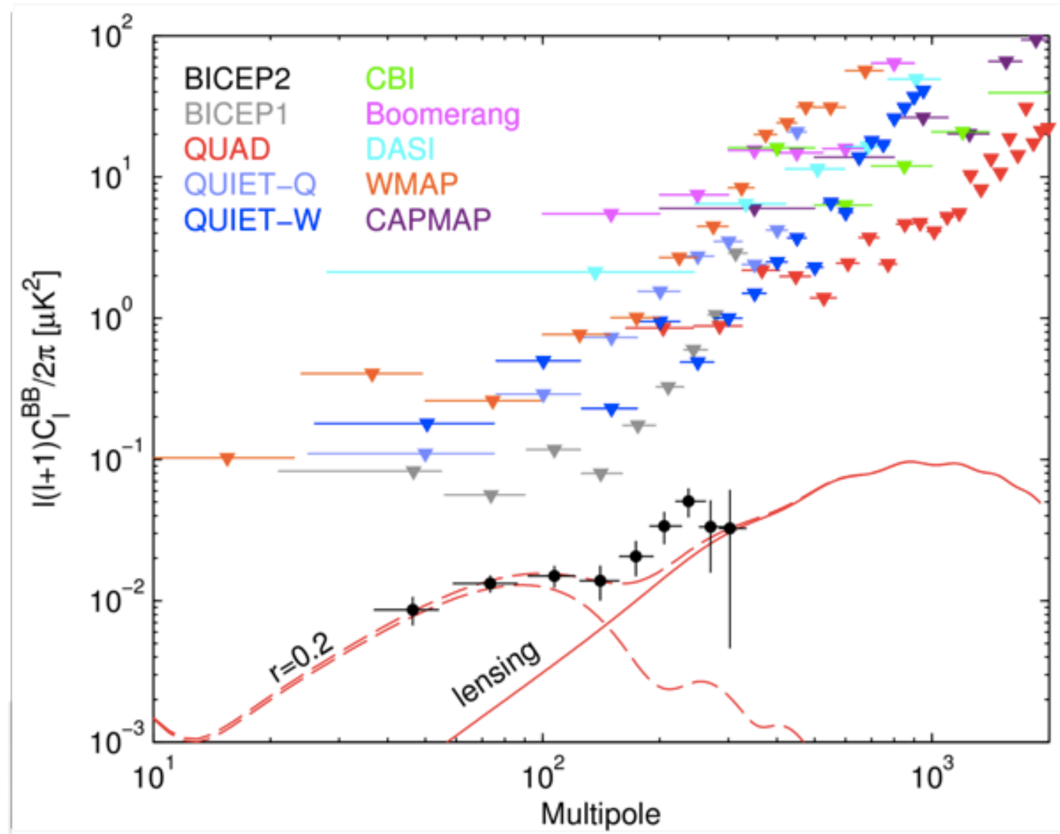

Time

The Initial Expansion was Fast



The Initial Expansion was Fast



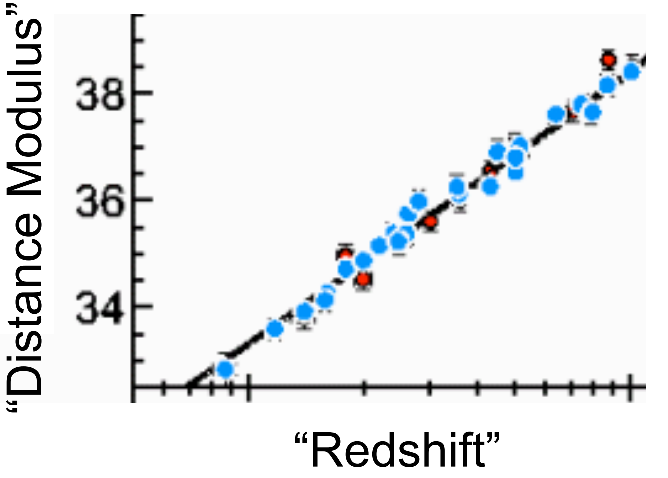


BICEP2 Results
Monday March 17, 2014

The Initial Expansion was Fast

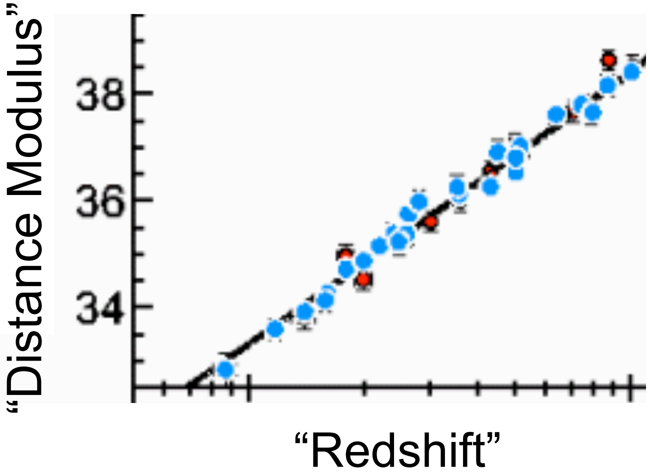
The Universe is Still Expanding...

Hubble and others found that distant galaxies all appear to be receding from us, with recession speed (“redshift”) proportional to distance.



The Universe is Still Expanding...

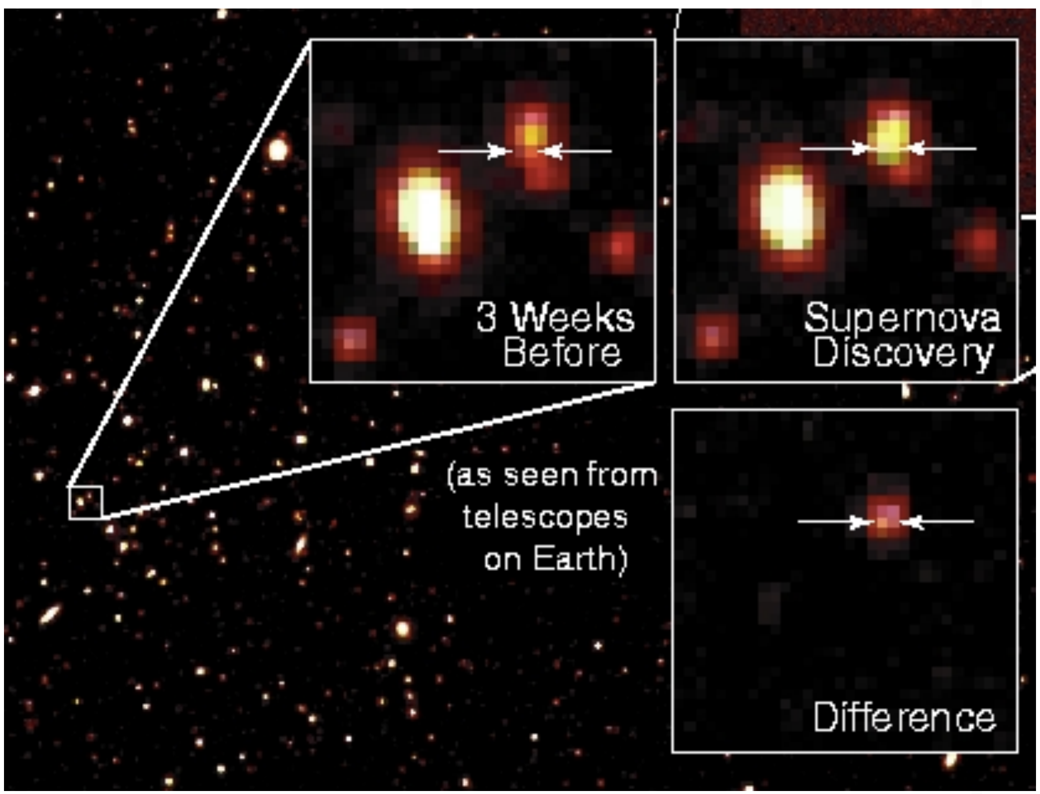
Hubble and others found that distant galaxies all appear to be receding from us, with recession speed ("redshift") proportional to distance.



Hubble's Law is what you get in a uniformly expanding Universe

... And at an *Accelerating Rate*

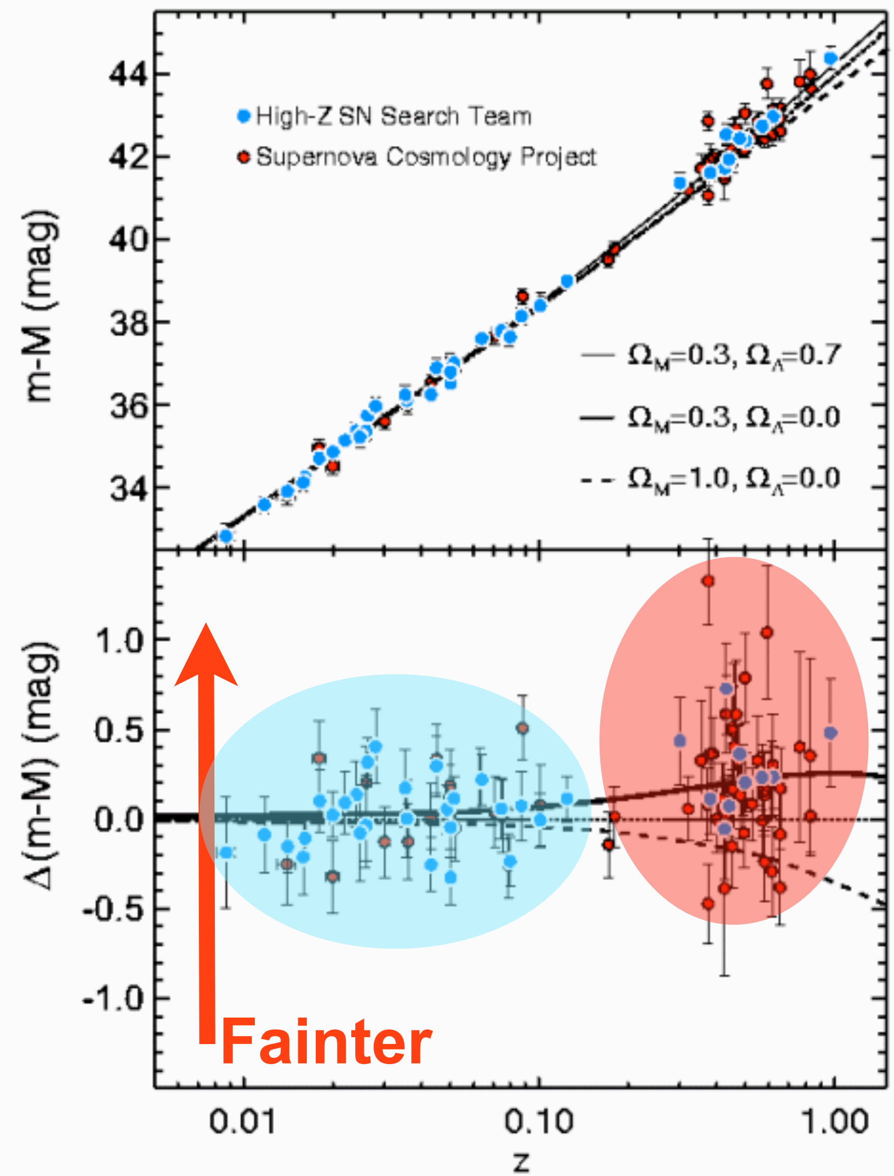
Type Ia Supernovae are "standard candles" - their brightness tells you their distance, and they are *very* luminous



... And at an *Accelerating Rate*

Type Ia Supernovae are "standard candles" - their brightness tells you their distance, and they are *very* luminous

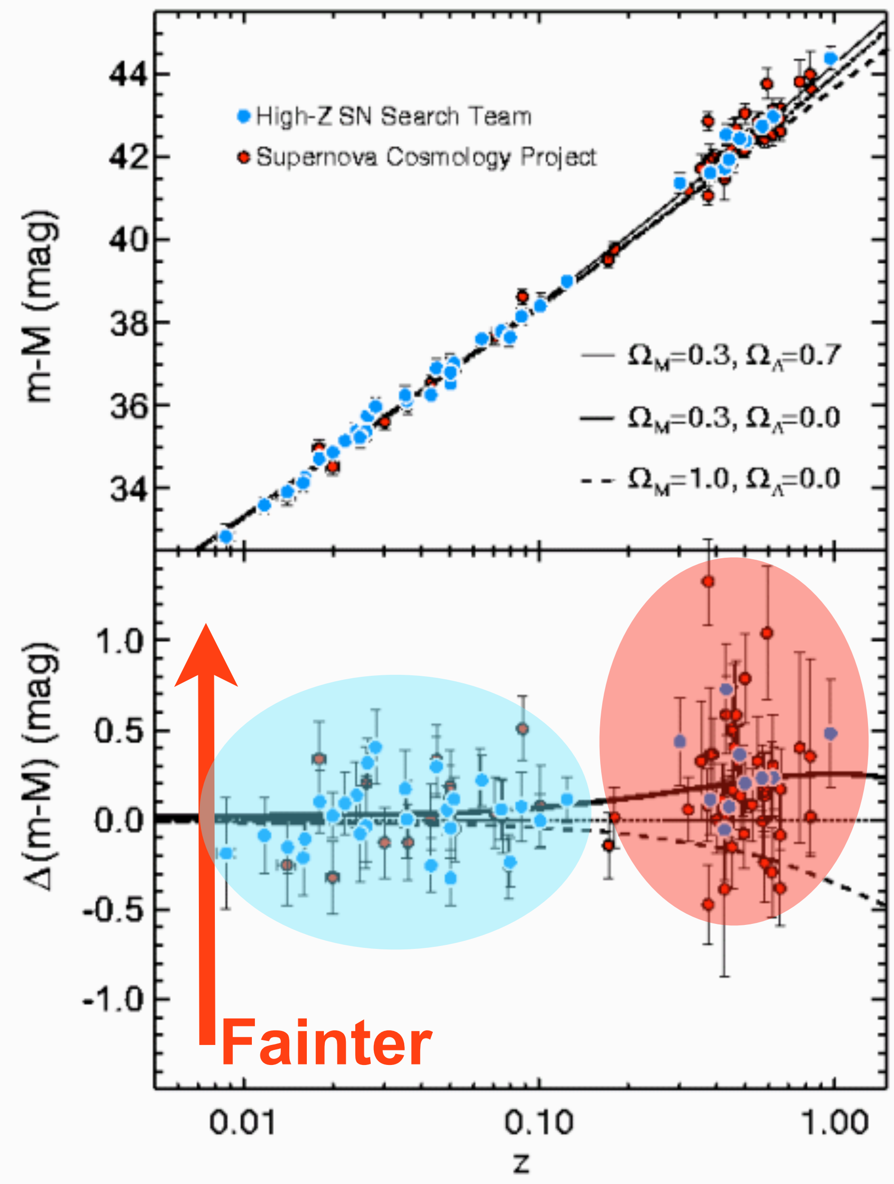
The most distant Type Ia Supernovae are fainter than we expected



Riess et al, Perlmutter et al 1998

... And at an *Accelerating Rate*

- Type Ia Supernovae are "standard candles" - their brightness tells you their distance, and they are *very* luminous
- The most distant Type Ia Supernovae are fainter than we expected

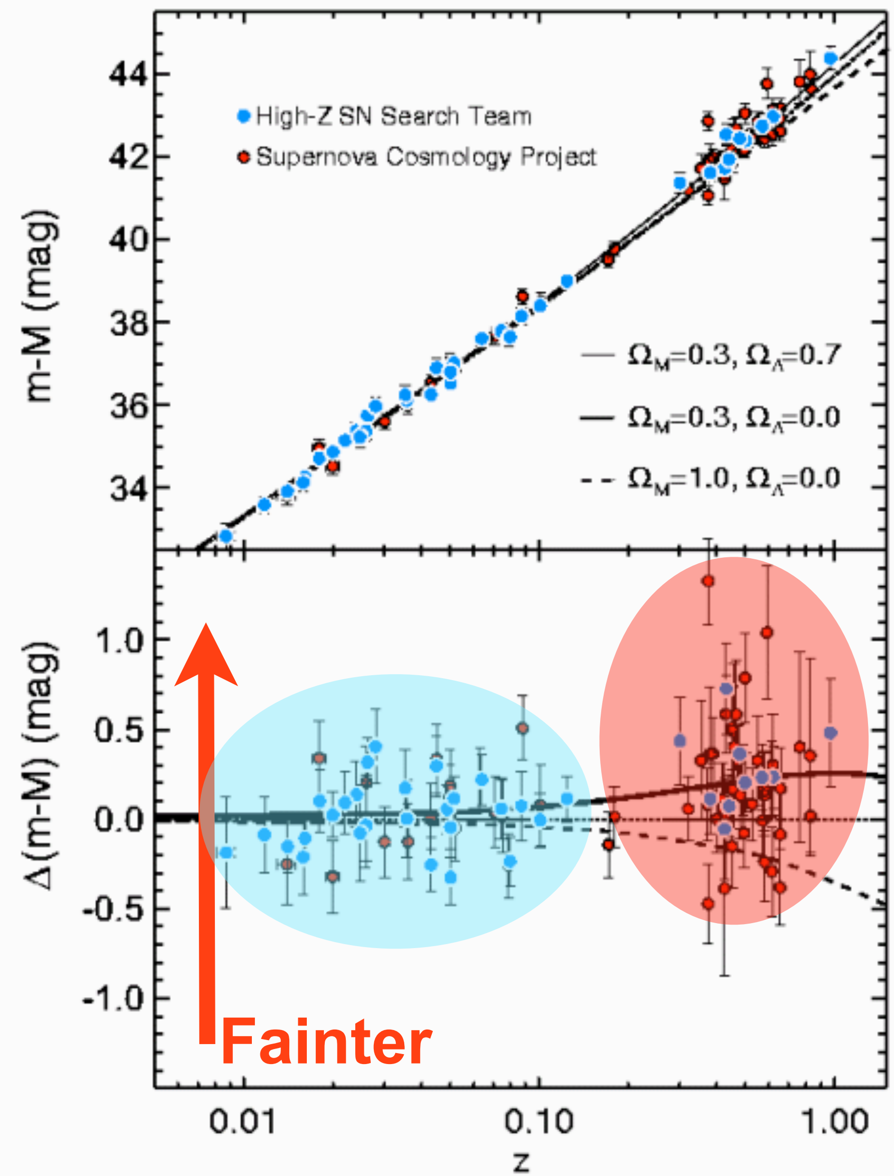


Riess et al, Perlmutter et al 1998

... And at an *Accelerating Rate*

Type Ia Supernovae are "standard candles" - their brightness tells you their distance, and they are *very* luminous

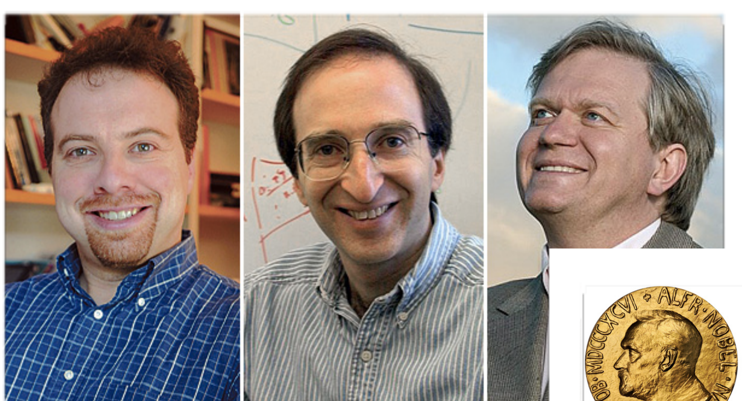
The most distant Type Ia Supernovae are fainter than we expected

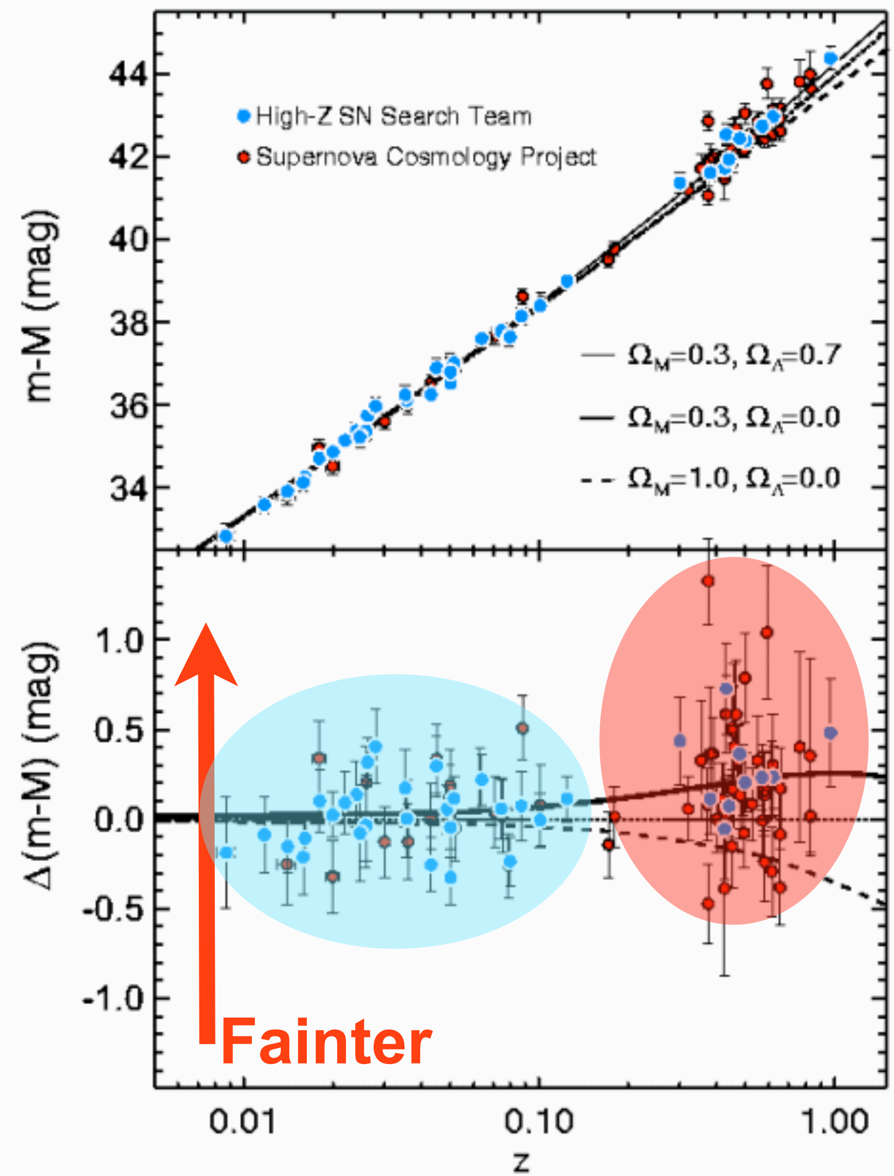


Riess et al, Perlmutter et al 1998

... And at an *Accelerating Rate*

- Type Ia Supernovae are "standard candles" - their brightness tells you their distance, and they are *very* luminous
- The most distant Type Ia Supernovae are fainter than we expected





Riess et al, Perlmutter et al 1998

Why?

Dark Energy

Albrecht et al 2006 Dark Energy Task Force report

Dark Energy

“**Dark energy** appears to be the dominant component of the physical Universe, yet there is **no persuasive theoretical explanation for its existence or magnitude.**”

Albrecht et al 2006 Dark Energy Task Force report

Dark Energy

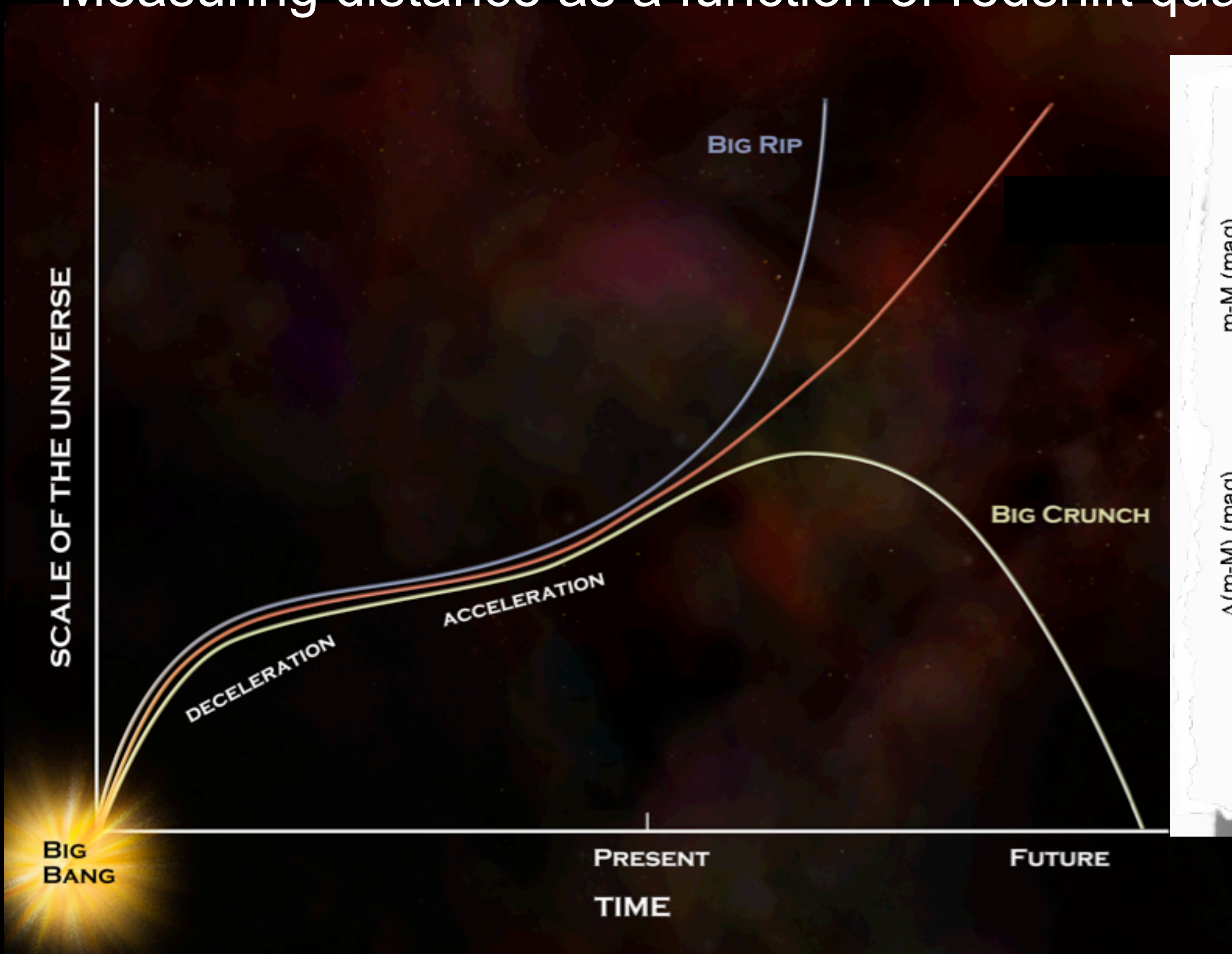
"**Dark energy** appears to be the dominant component of the physical Universe, yet there is **no persuasive theoretical explanation for its existence or magnitude.**"

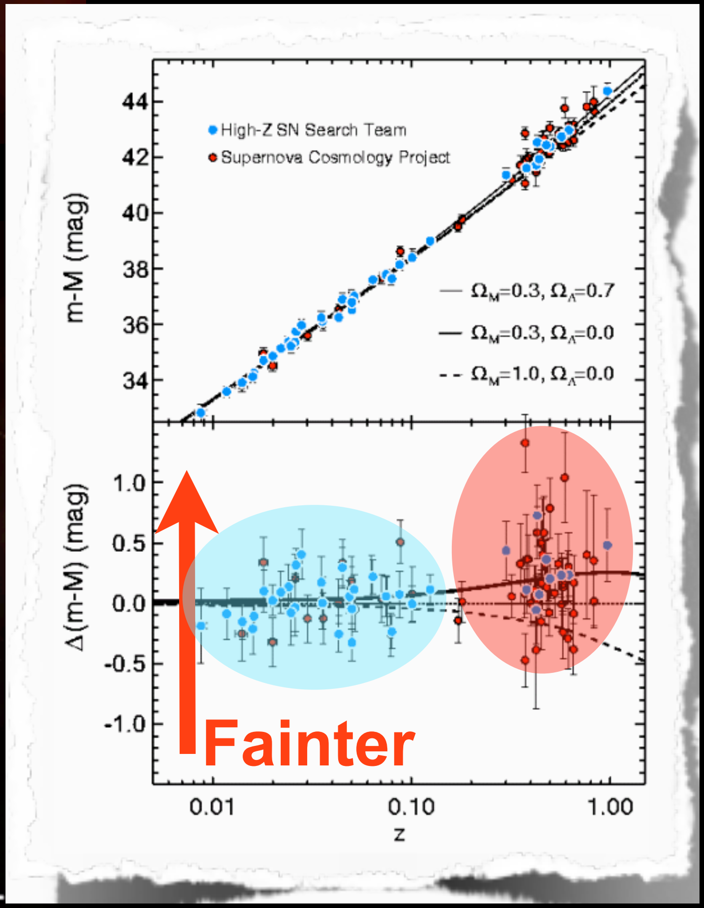
"The nature of **dark energy** ranks among the very **most compelling of all outstanding problems in physical science.** ***These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible.***"

Albrecht et al 2006 Dark Energy Task Force report

The Expansion of the Universe has been Accelerating

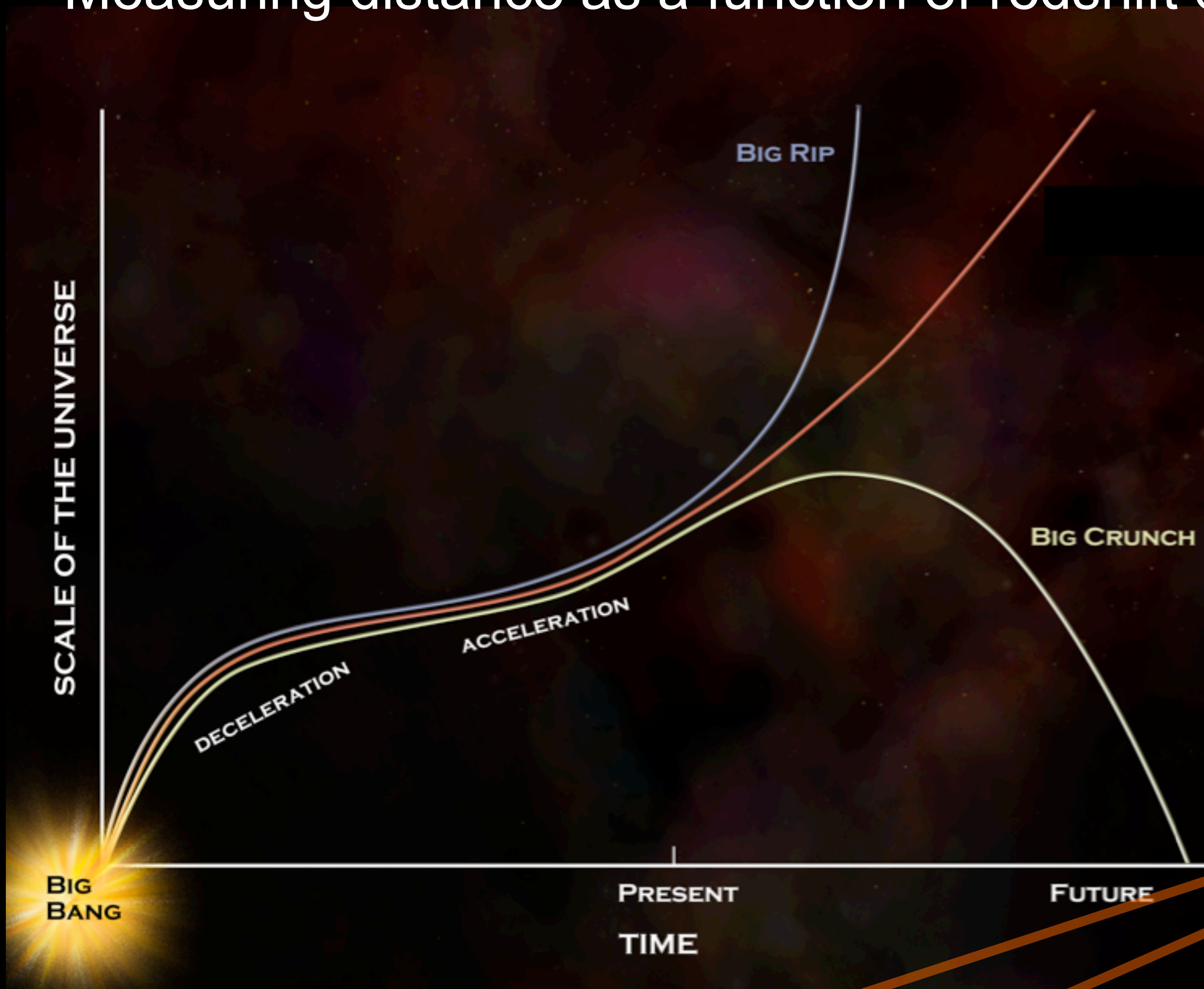
Measuring distance as a function of redshift quantifies this history





The Expansion of the Universe has been Accelerating

Measuring distance as a function of redshift quantifies this history



Hubble's Law:

$$cdt = a(t)dr \longrightarrow r = \int_0^z \frac{cdz}{H(z)}$$

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

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

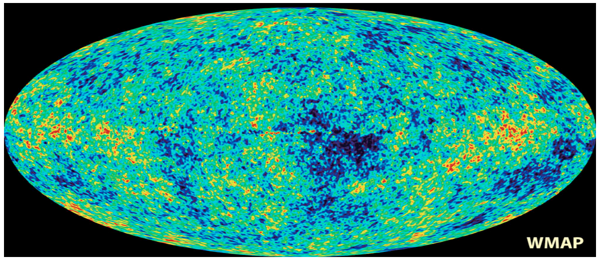
$$H^2(a) = H_0^2\left(\Omega_\mathrm{m} a^{-3} + \Omega_\mathrm{X} \exp\left[3\int_{\log a}^{0}(1+w)d\log a\right] + \Omega_\mathrm{k} a^{-2}\right)$$

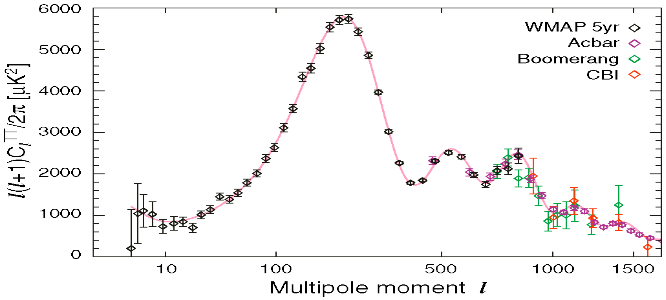
Standard candles, rulers, buckets, timers etc

- **Type Ia supernovae**: standard candles

Standard candles, rulers, buckets, timers etc

- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation

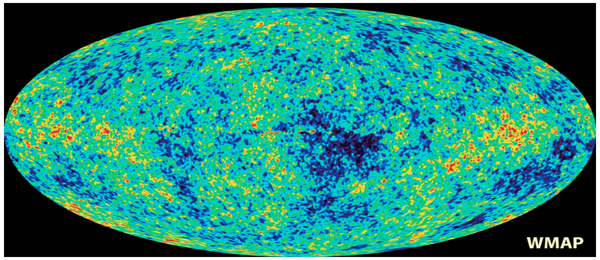


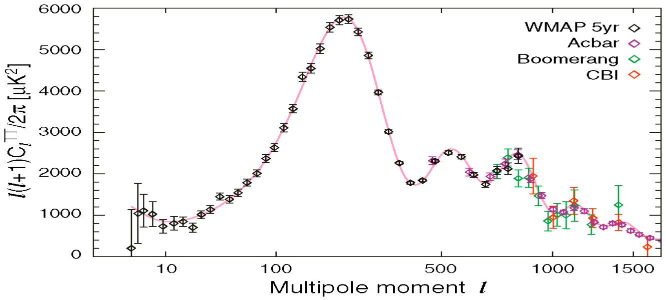


(sound speed x age of universe) subtends ~1 degree

Standard candles, rulers, buckets, timers etc

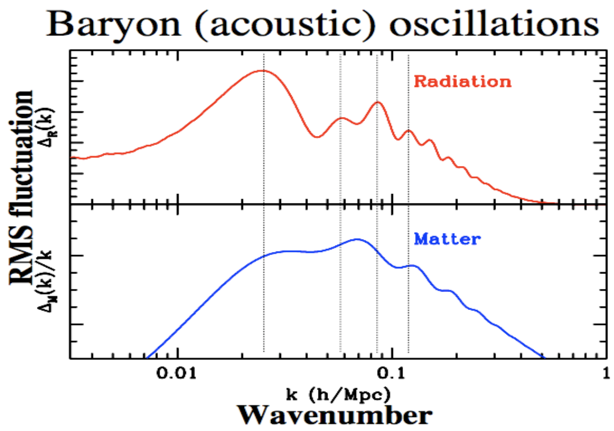
- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation





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

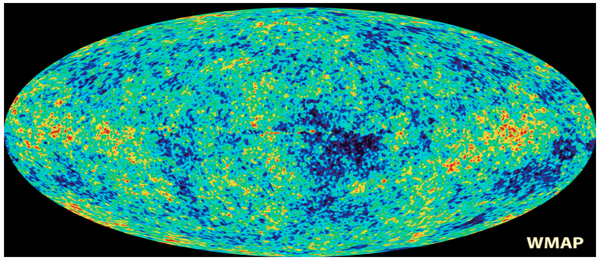
- **Baryon Acoustic Oscillations** in the galaxy clustering power spectrum

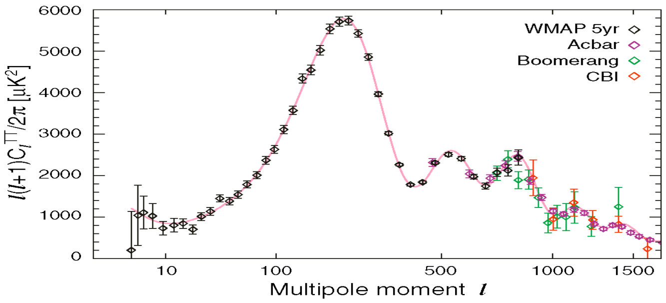


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

Standard candles, rulers, buckets, timers etc

- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation

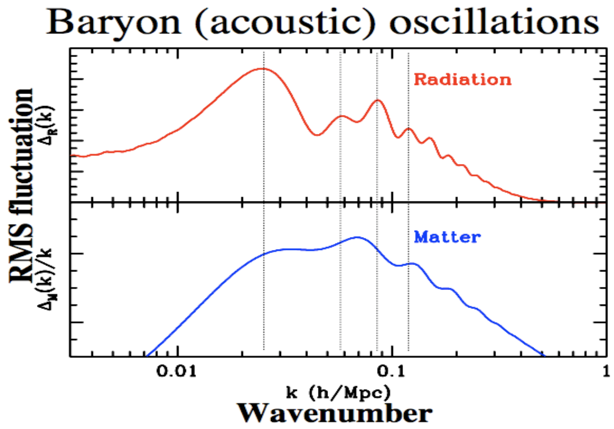




(sound speed x age of universe) subtends ~1 degree

- **Baryon Acoustic Oscillations** in the galaxy clustering power spectrum

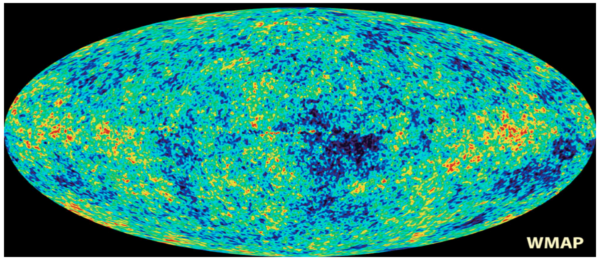
- Periods of **Cepheid** variable stars in local galaxies

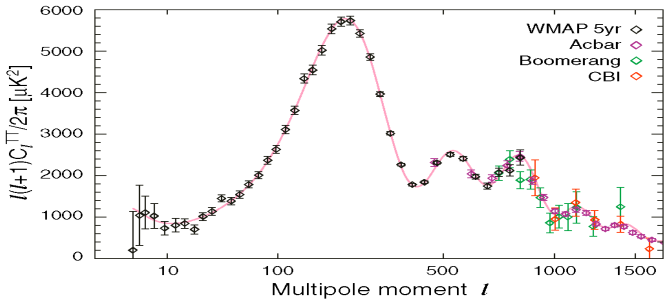


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

Standard candles, rulers, buckets, timers etc

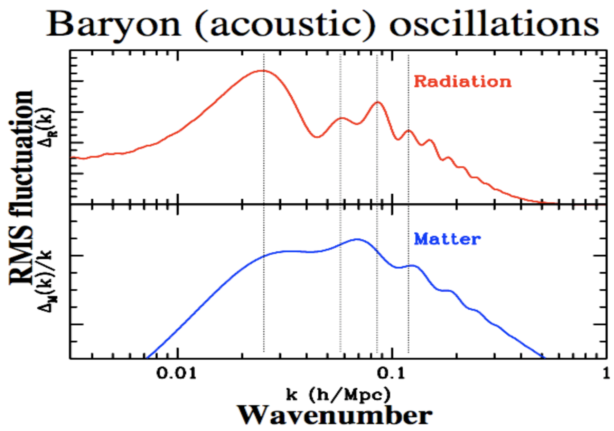
- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation





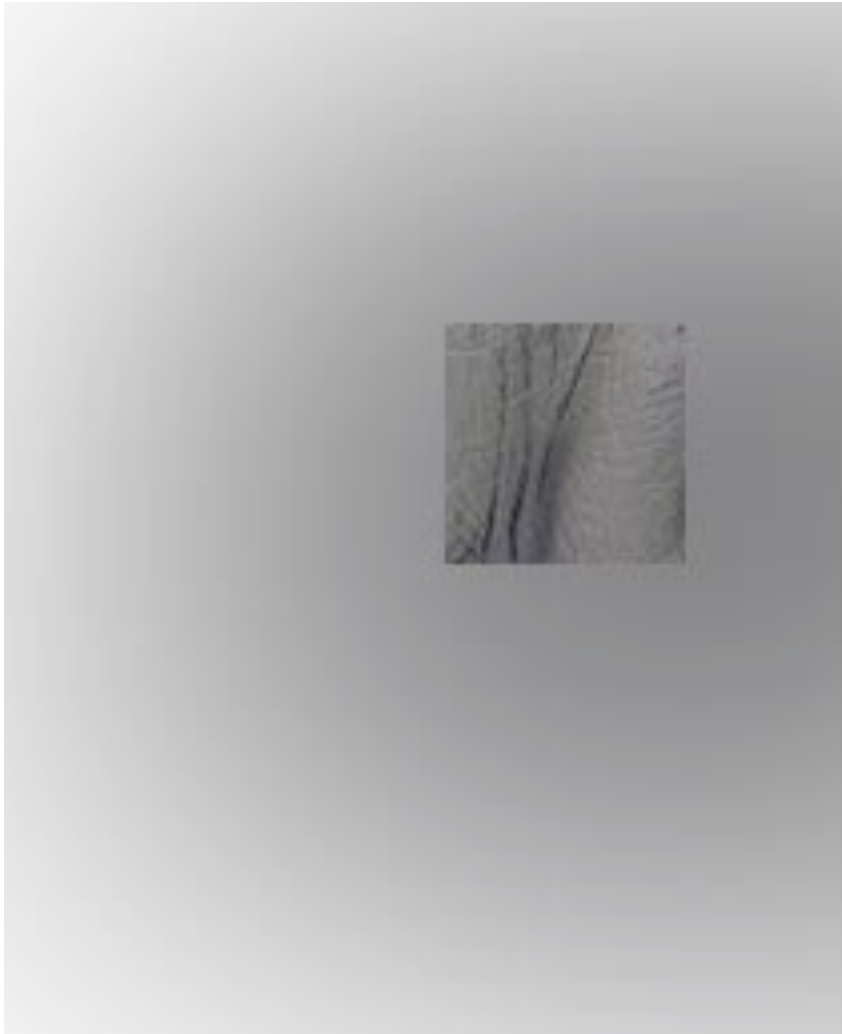
(sound speed x age of universe) subtends ~1 degree

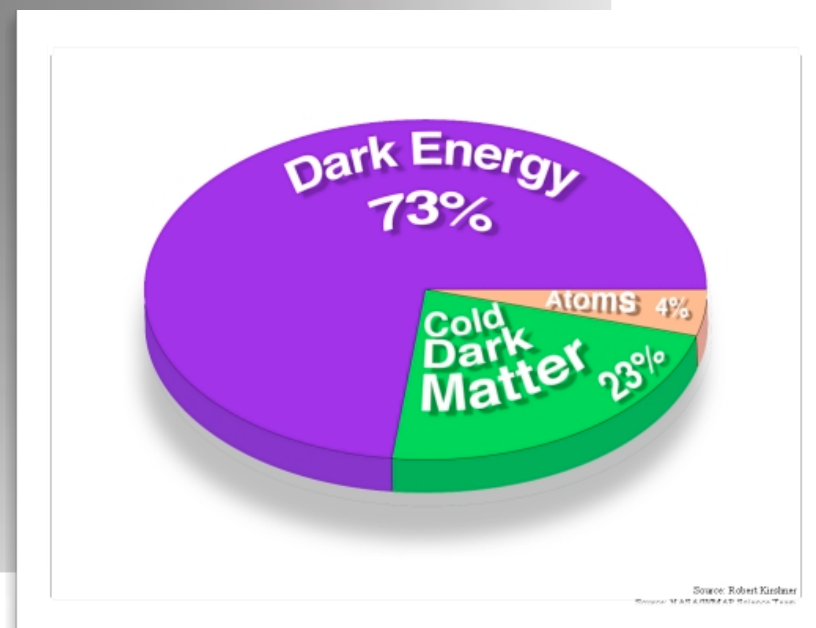
- **Baryon Acoustic Oscillations** in the galaxy clustering power spectrum
- Periods of **Cepheid** variable stars in local galaxies
- **Clusters of galaxies** - should contain the universal gas fraction wherever they are



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

What is this?



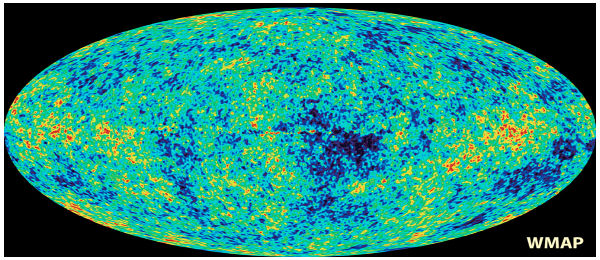


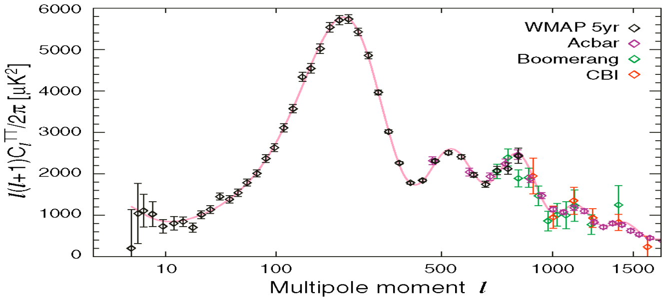
Here’s 4% of it in detail

Here it is, slightly better measured

Standard candles, rulers, buckets, timers etc

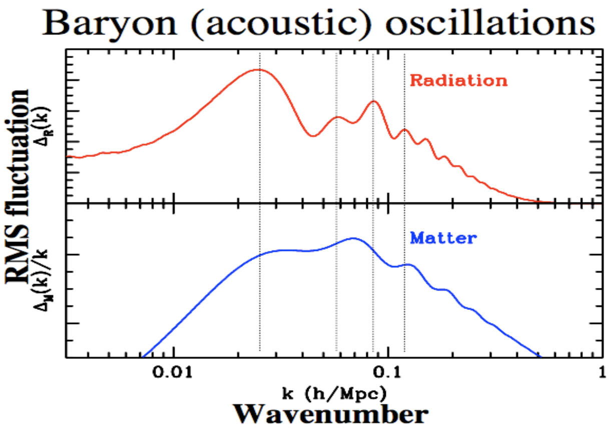
- **Type Ia supernovae**: standard candles
- Fluctuations in the **Cosmic Microwave Background** radiation





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

- **Baryon Acoustic Oscillations** in the galaxy clustering power spectrum

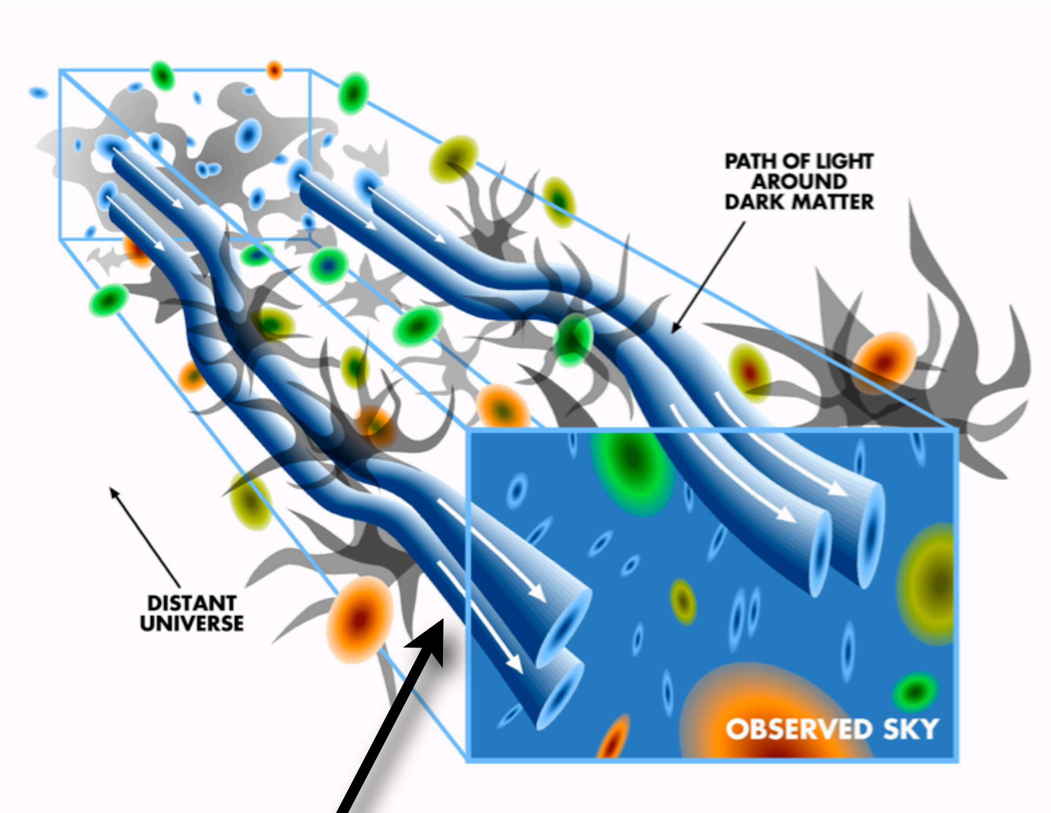


gas density fluctuations from CMB era are felt by dark matter - as traced by galaxies in the local(ish) universe

- Periods of **Cepheid** variable stars in local galaxies
- **Clusters of galaxies** - should contain the universal gas fraction wherever they are

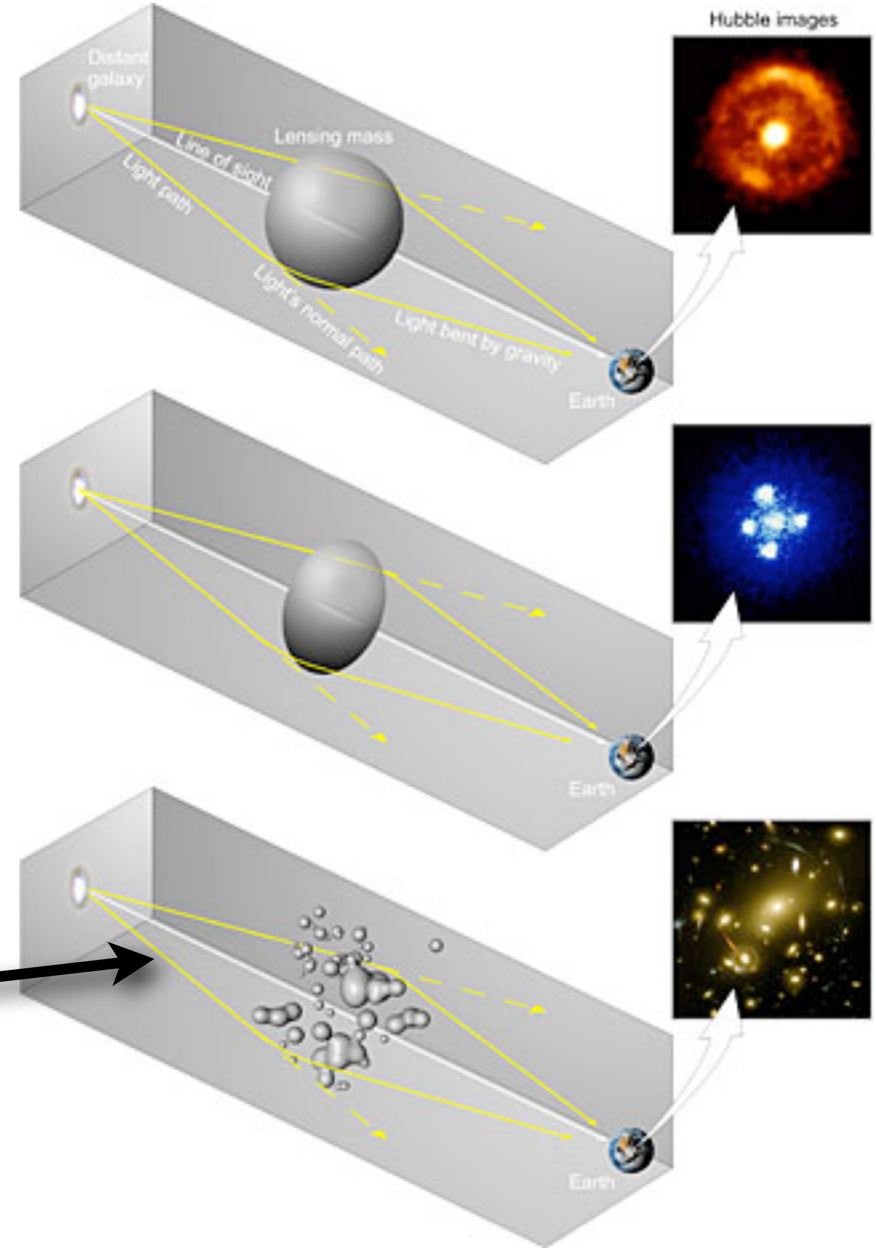
- **Something else?**

Gravitational Lensing

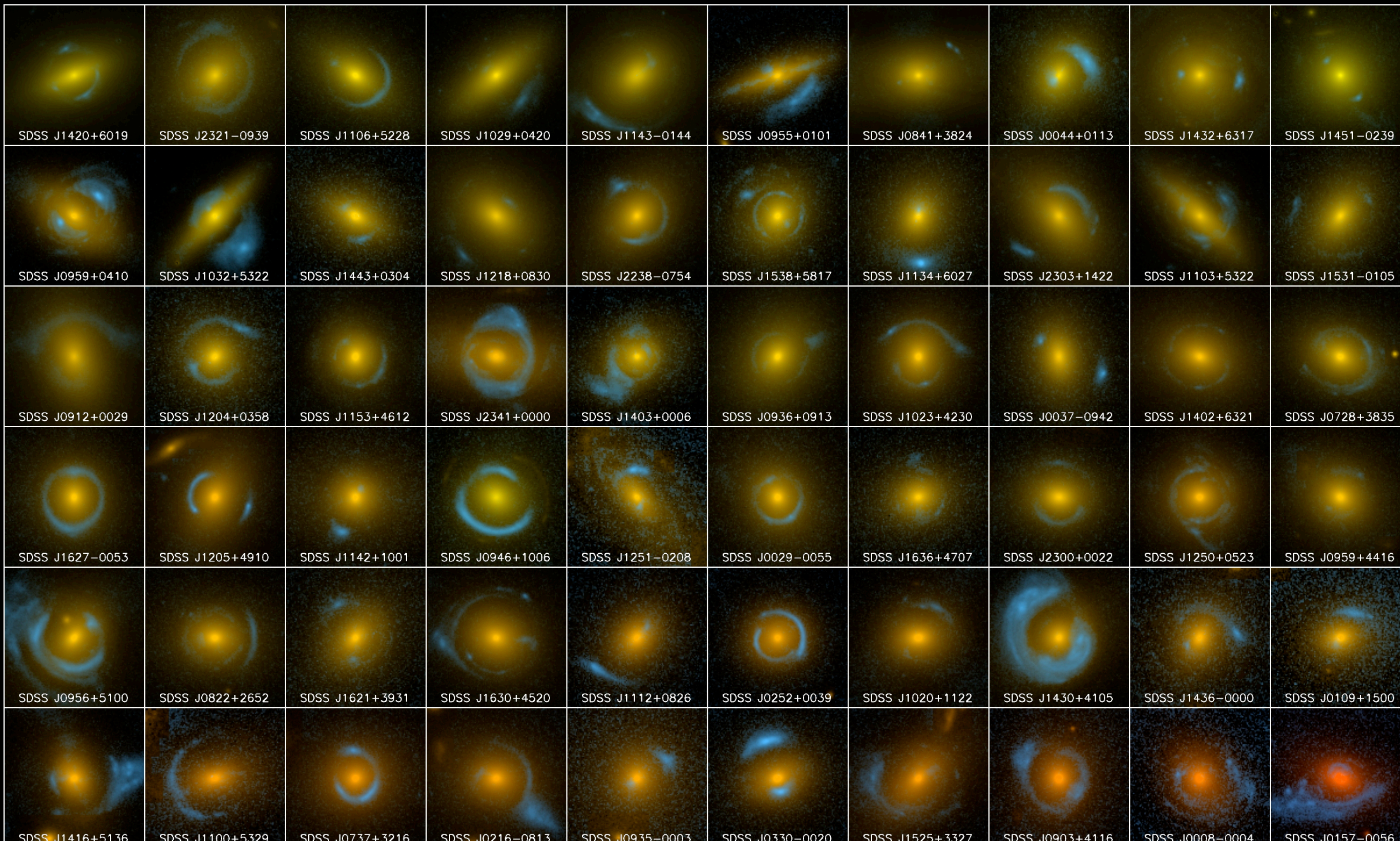


Weak lensing
(small distortions, ubiquitous)

Strong lensing
(multiple imaging, rare)



Strongly Lensed Galaxies

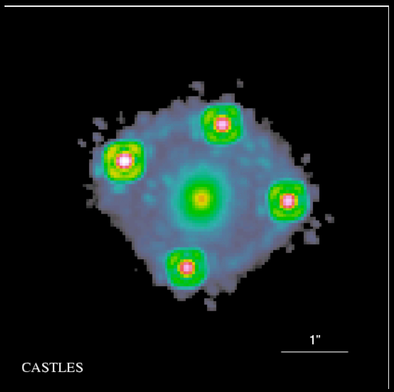


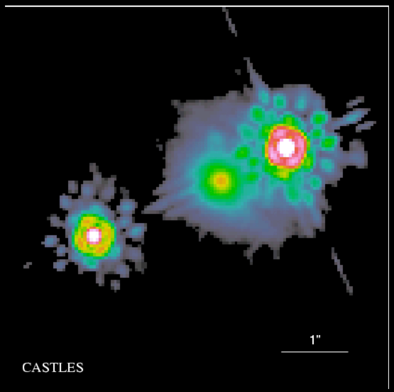
SLACS: The Sloan Lens ACS Survey www.SLACS.org

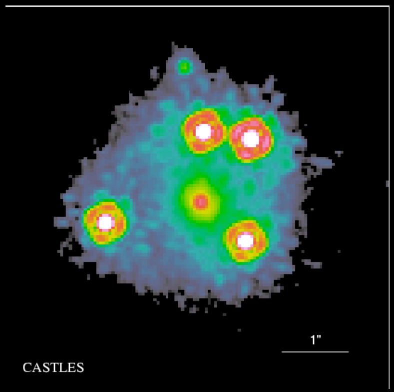
A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

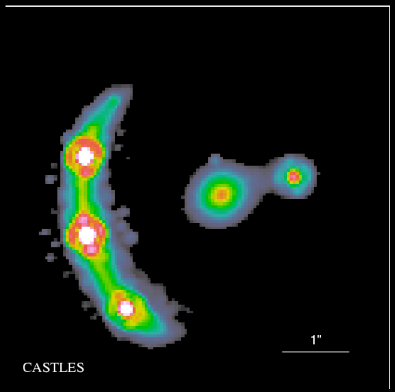
Image credit: A. Bolton, for the SLACS team and NASA/ESA

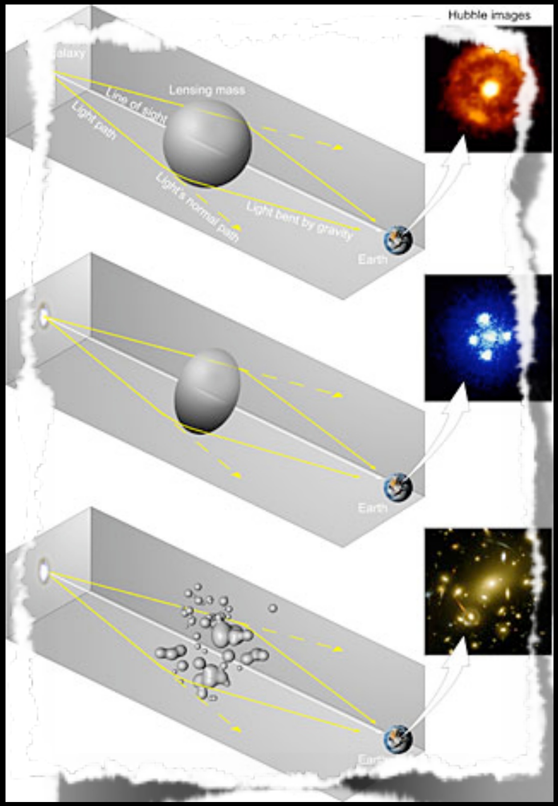
Strongly Lensed AGN

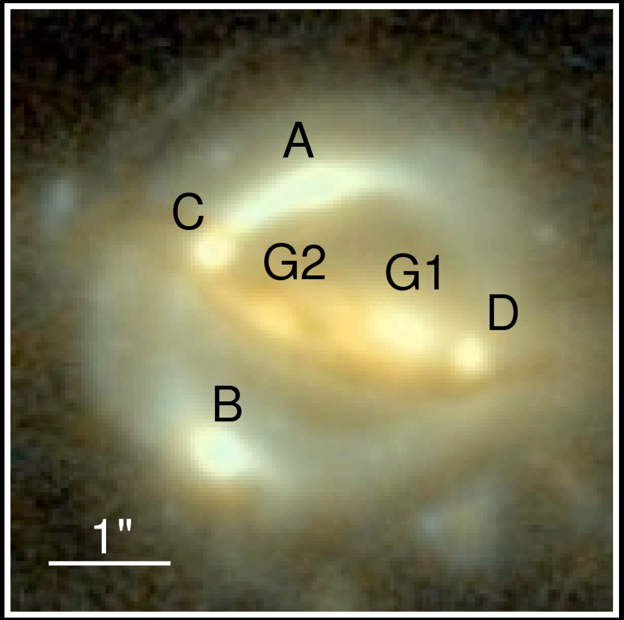


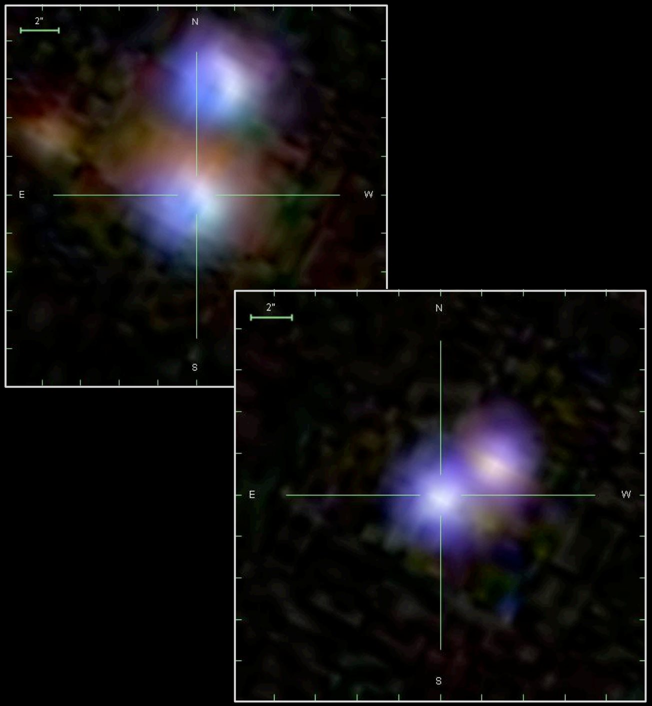






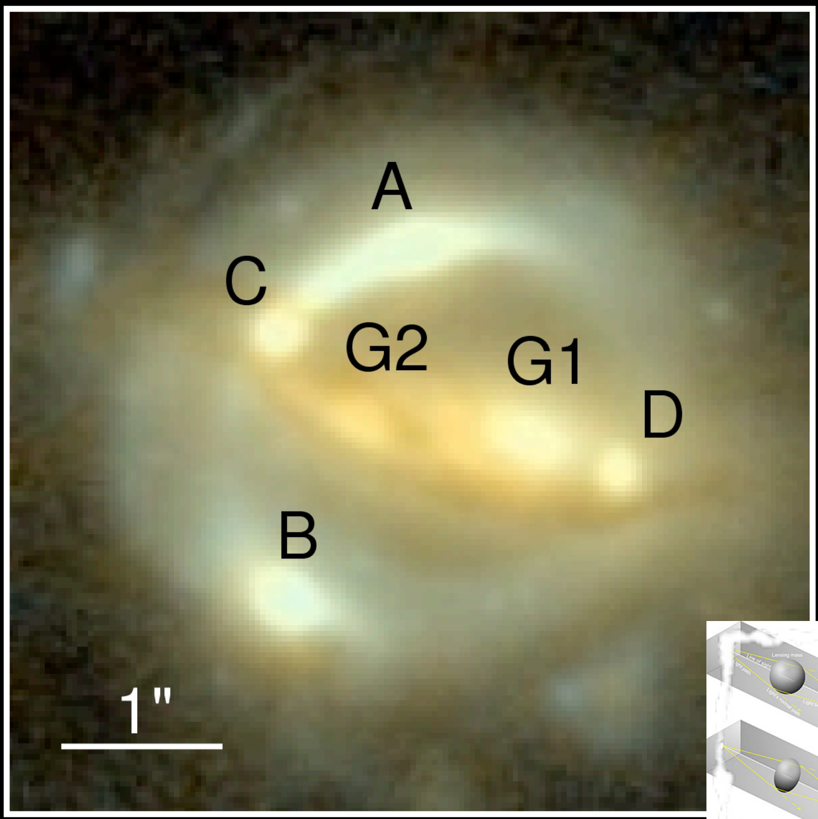


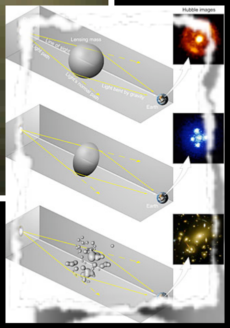


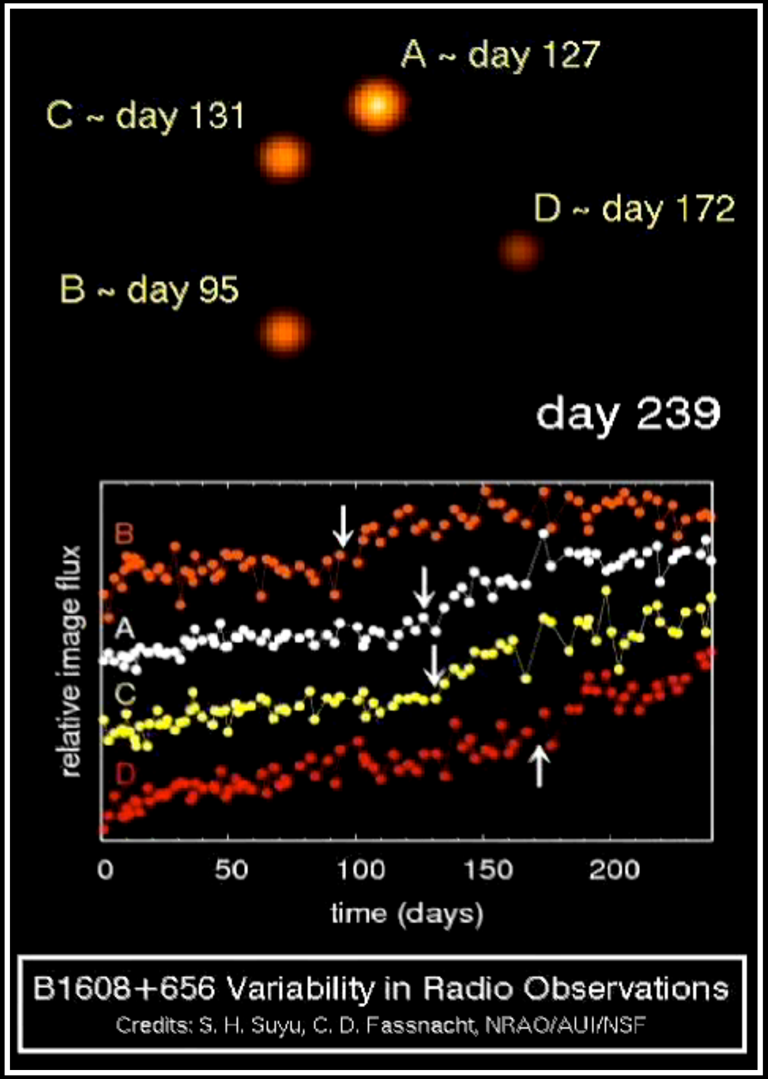


Point-like, variable sources

Time Delay Gravitational Lenses







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

Time delay distances

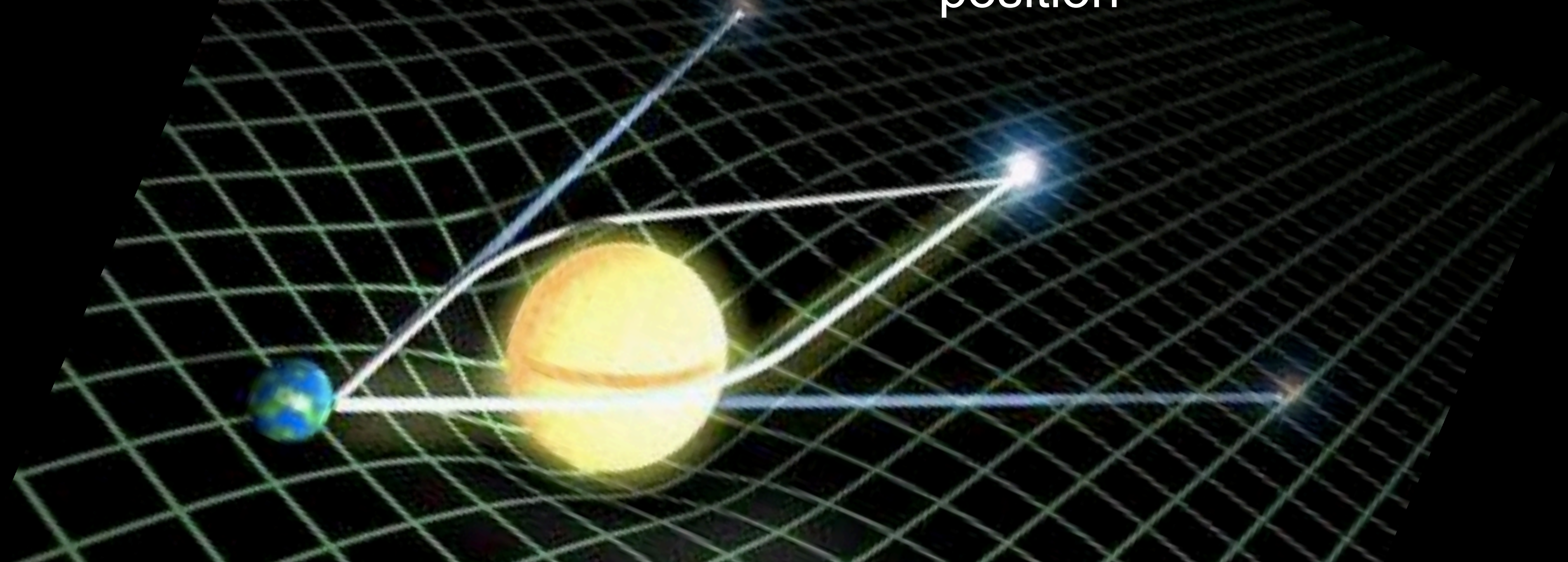
Signals from the AGN appear at different times -
this effect can be **predicted** with a **model** of the lens:

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

Image position

Source position

Lens potential



Time delay distances

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

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

Image position

Source position

Lens potential

We can only measure time delays Δt: these can be predicted as $\Delta t_{AB} = D \times (1/c_A' - 1/c_B')$

Compare predicted and observed time delays with **likelihood function Pr(obs|pred)** - multiply by terms for image positions, arc surface brightness etc, **infer D(H_0,w)**

B1608 - Google Maps - Gran Paradiso

File Edit View History Bookmarks Tools Help

http://maps.google.com/ Fermat would have loved this

B1608 - Google Maps

Web Images Videos **Maps** News Shopping Gmail more ▼ dr.phil.marshall@gmail.com | My Profile | My Account | Help | Sign out

Google maps [ ] Search Maps Show search options

Find businesses, addresses and places of interest.

Get Directions My Maps RSS Print Send Link

Collaborate Edit

San Jose Time Delays

Illustrating lens time delays - 4 routes, we know the average speeds for each (because we have a model for the traffic conditions!) and we measure the relative arrival times of four cars, in minutes. What's the map scale?

* Measure route lengths x in inches on the map

* Assume all cars leave at the same time, and use the average speeds v provided

* Each time delay gives an (almost) independent estimate of the map scale A, in inches per mile:

$(x2/v2 - x1/v1) = A*delay(2-1)$

14 views - Public
Created on Jan 14 - Updated < 1 minute ago
By Phil
Rate this map - Write a comment

Bright Variable Source

Route 1 (280): 39.3 mph, arrives first
45.9 mi - about 1 hour 6 mins (up to 1 hour 10 mins in

Route 2 (85): 39.9 mph, delay=4mins
49.2 mi - about 1 hour 11 mins (up to 1 hour 14 mins in

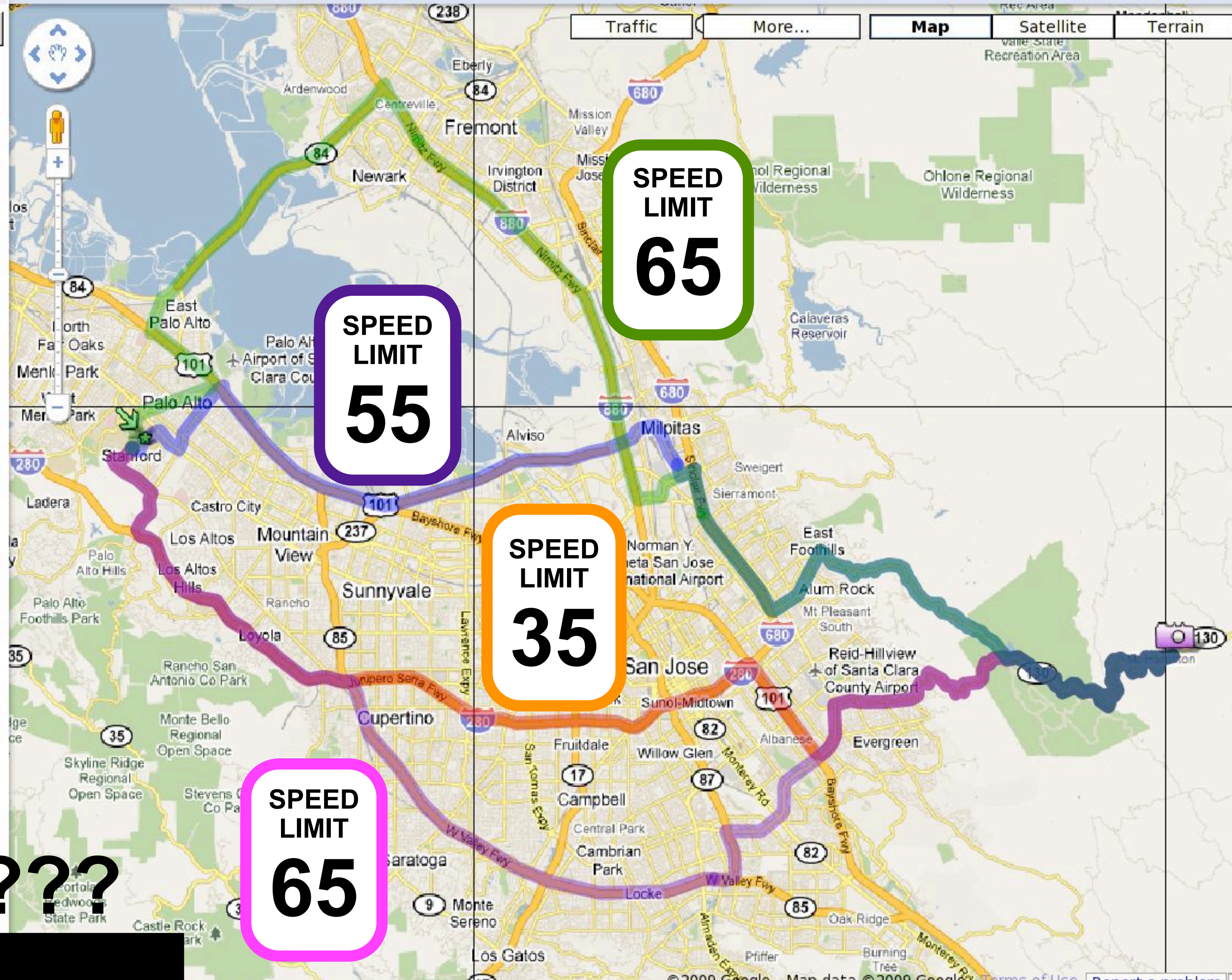
Route 3 (101): 33.9 mph, delay=10mins
45.2 mi - about 1 hour 15 mins (up to 1 hour 20 mins in

Route 4 (Dumbarton Bridge): 33.9 mph, delay=30mins
56.5 mi - about 1 hour 28 mins (up to 1 hour 40 mins in

Observer

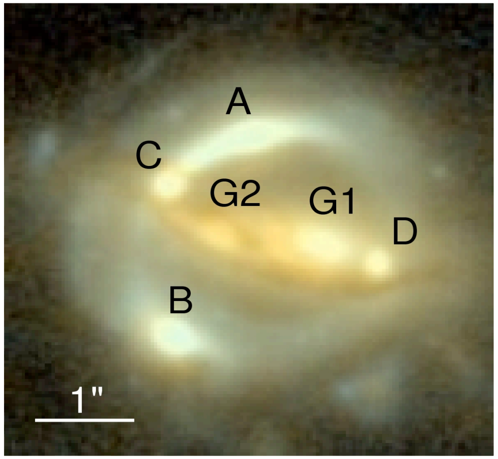
???

[redacted]



Done

Outline



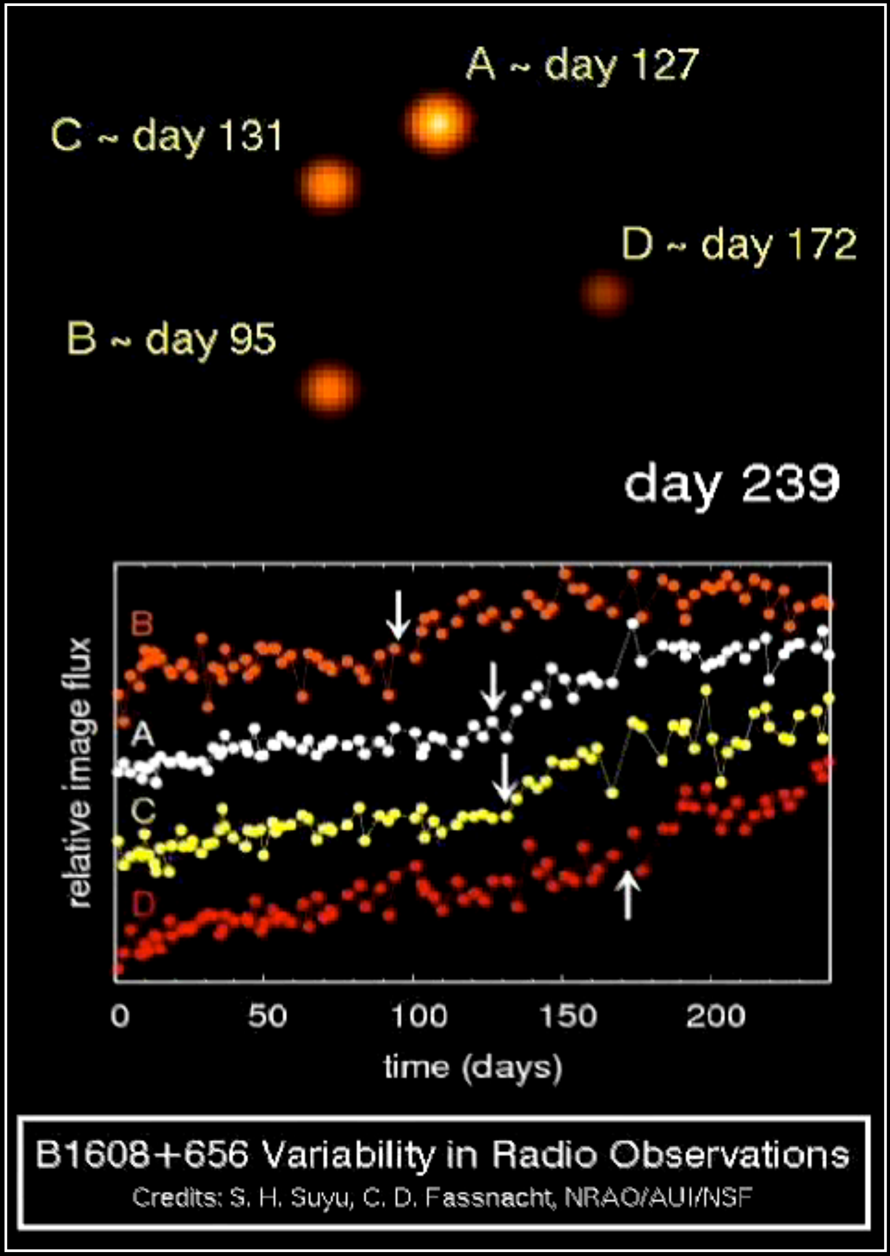
- Dark Energy from B1608 and RXJ1131
- Time delay lens cosmography with LSST

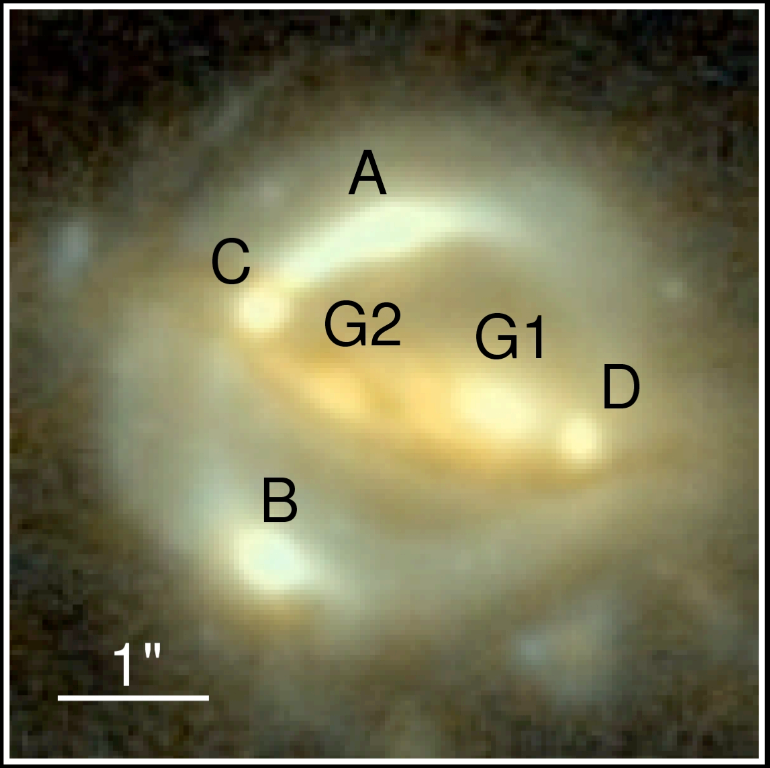
Two Accurate Time-Delay Distances from Strong Lensing: Implications for Cosmology

Sherry Suyu (ASIAA)
Matt Auger (IoA), Stefan Hilbert (MPE),
Phil Marshall (KIPAC), Tommaso Treu (UCSB),
Malte Tewes, Frederic Courbin, Georges Meylan (EPFL),
Chris Fassnacht (UC Davis), Roger Blandford (KIPAC),
Leon Koopmans (Kapteyn), Dominique Sluse (AIFA)

RXJ1131 & B1608 cosmography: Suyu et al (2013), astro-ph/1208.6010
RXJ1131 time delays: Tewes et al (2013), astro-ph/1208.6009
B1608 modeling: Suyu et al (2010), astro-ph/0910.2773

Precision Time Delays





VLA monitoring campaign

Relative time delays:

$\Delta t_{AB} = 31.5^{+2.0}_{-1.0}$ days

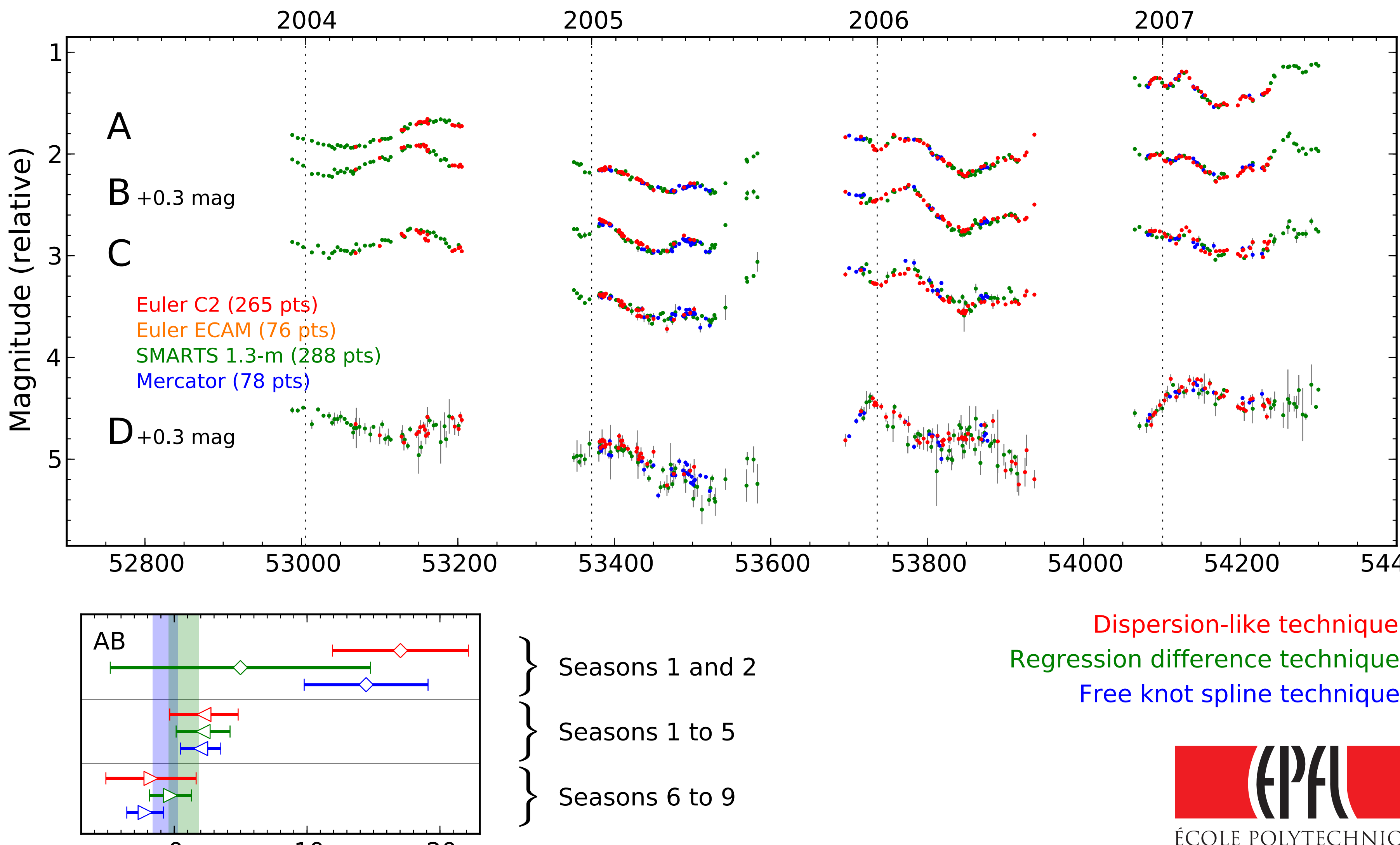
$\Delta t_{CB} = 36.0 \pm 1.5$ days

$\Delta t_{DB} = 77.0^{+2.0}_{-1.0}$ days

(Fassnacht et al. 1999, 2002)

Precision Time Delays

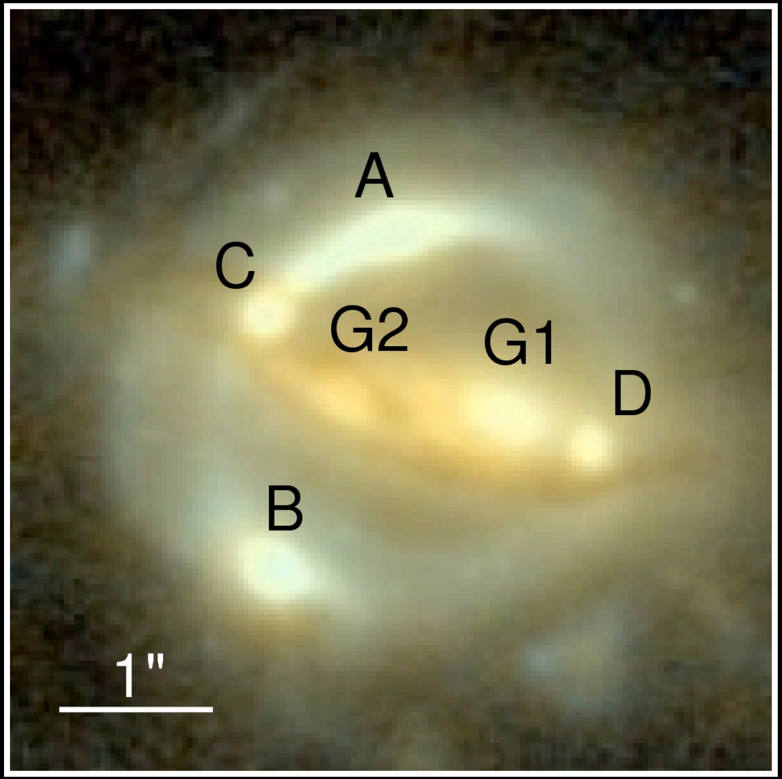
RXJ1131 is optically variable, monitored by the COSMOGRAIL team. Long-term monitoring essential



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

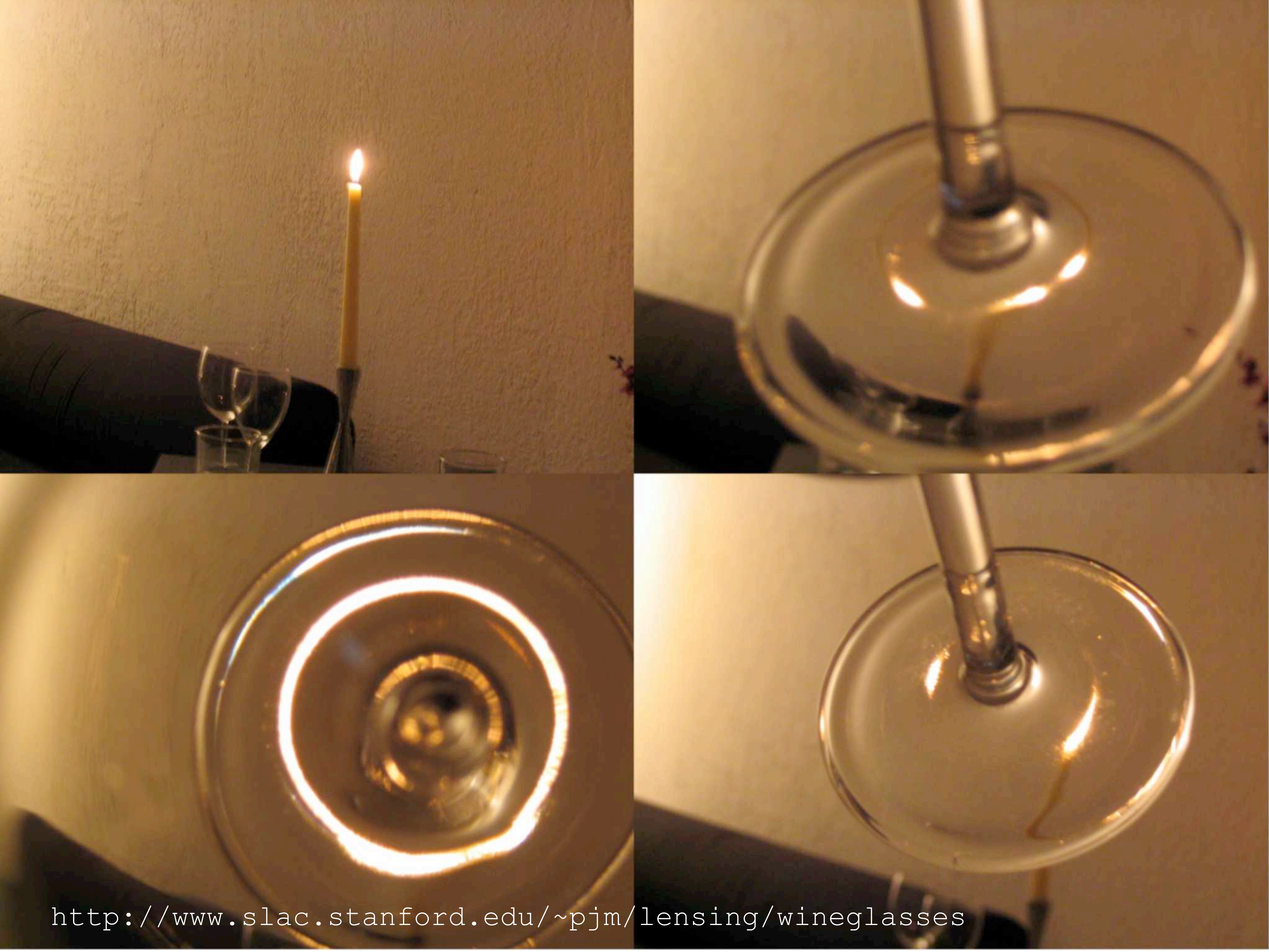
Lens modeling

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



z_d = 0.63 [Myers et al. 1995]
z_s = 1.39 [Fassnacht et al. 1996]

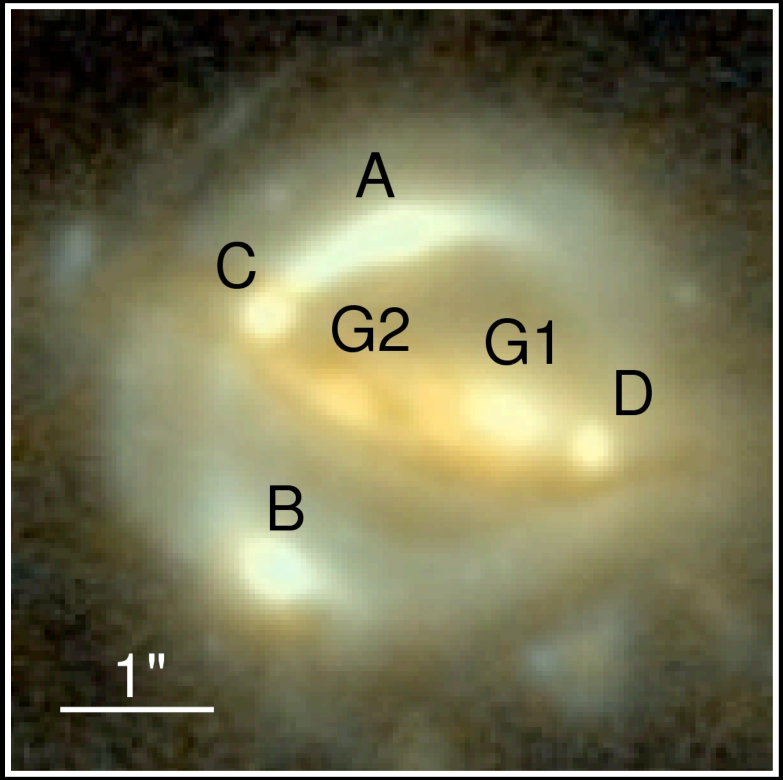
Q: How do you model a gravitational lens?



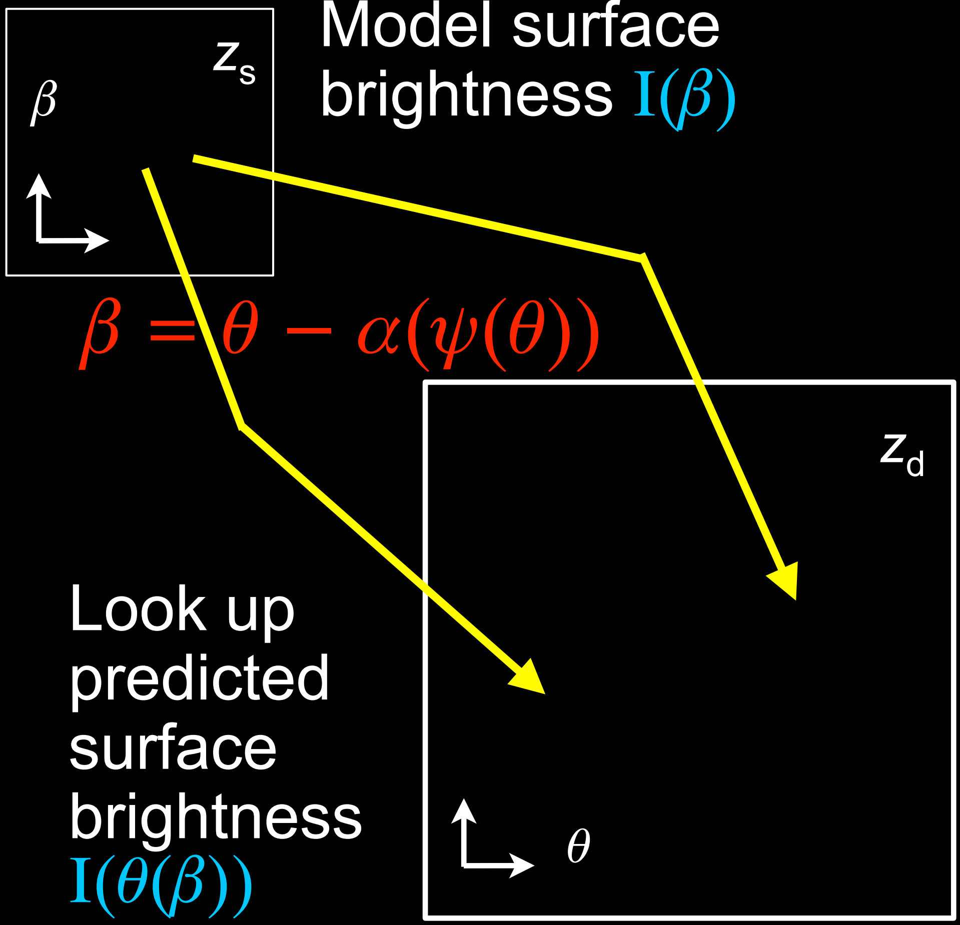
http://www.slac.stanford.edu/~pjm/lensing/wineglasses

Lens modeling

Q: How do you model a gravitational lens?



Model surface brightness $\mathrm{I}(\beta)$



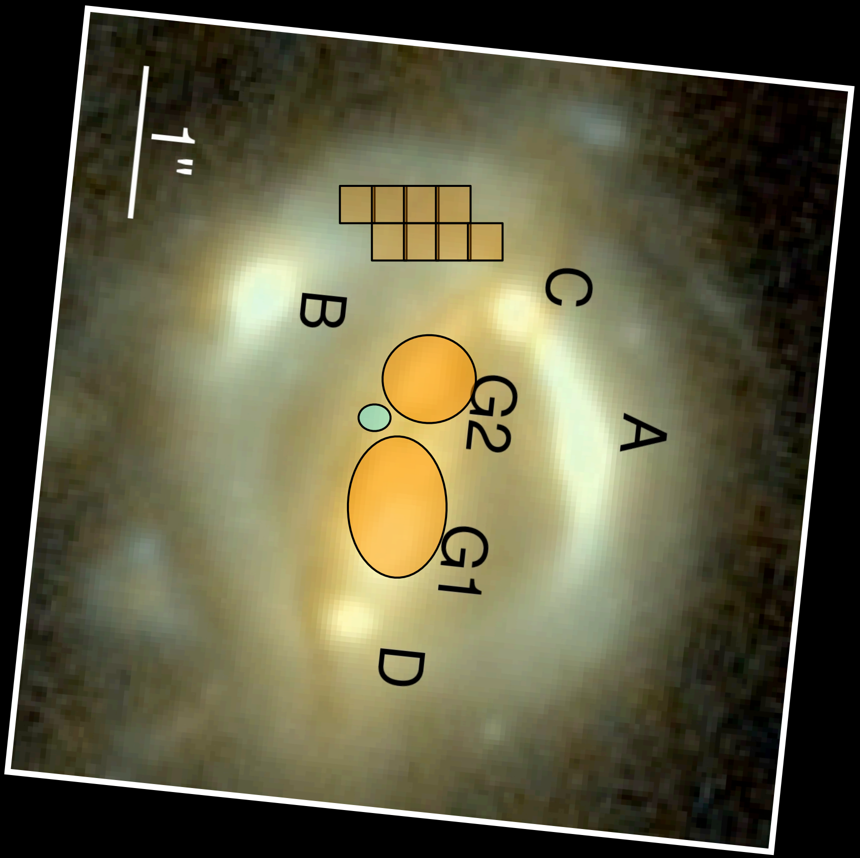
$$\beta = \theta - \alpha(\psi(\theta))$$

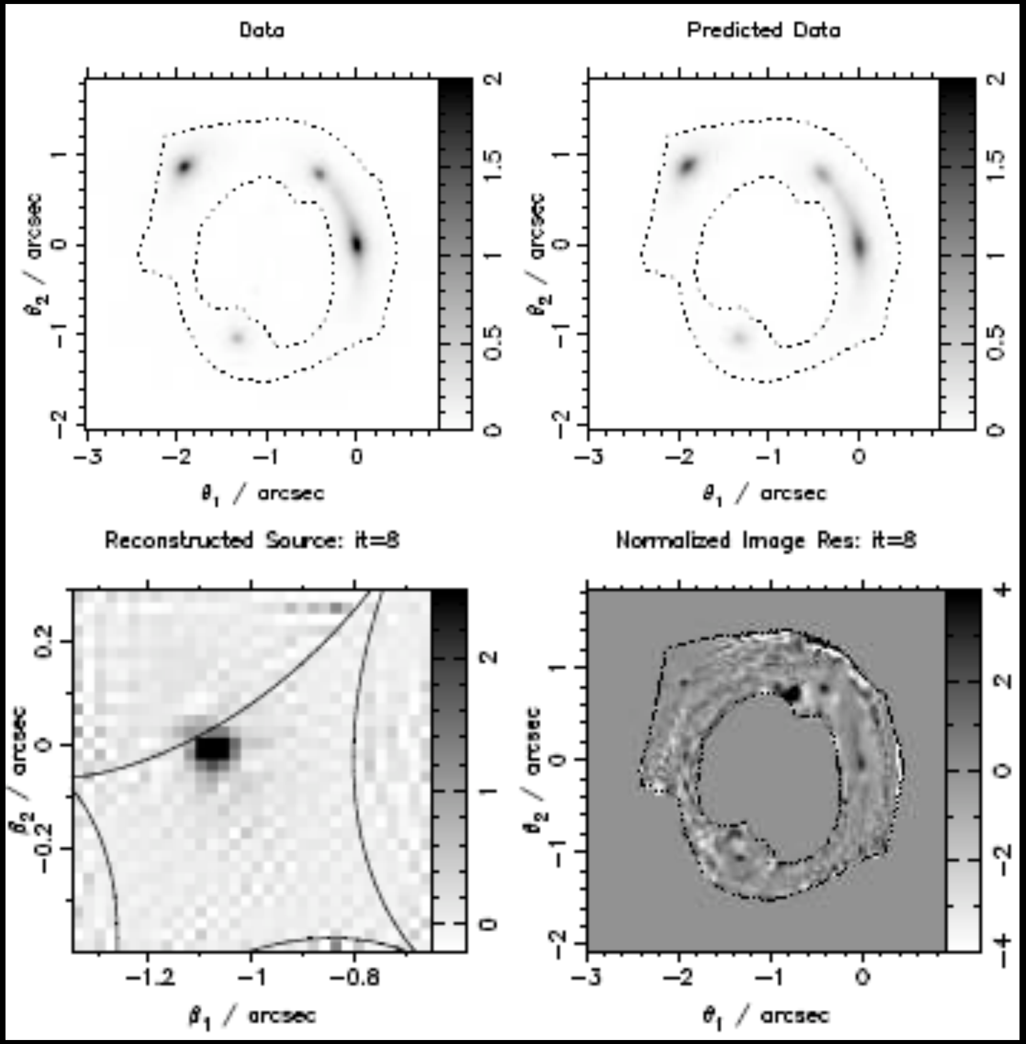
Look up predicted surface brightness $\mathrm{I}(\theta(\beta))$

$$\log \Pr(\psi \,|\, \mathrm{I}_{obs}) \sim \chi^2(\mathrm{I} - \mathrm{I}_{obs})/2 + \lambda S(\psi, \mathrm{I}(\beta))$$

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

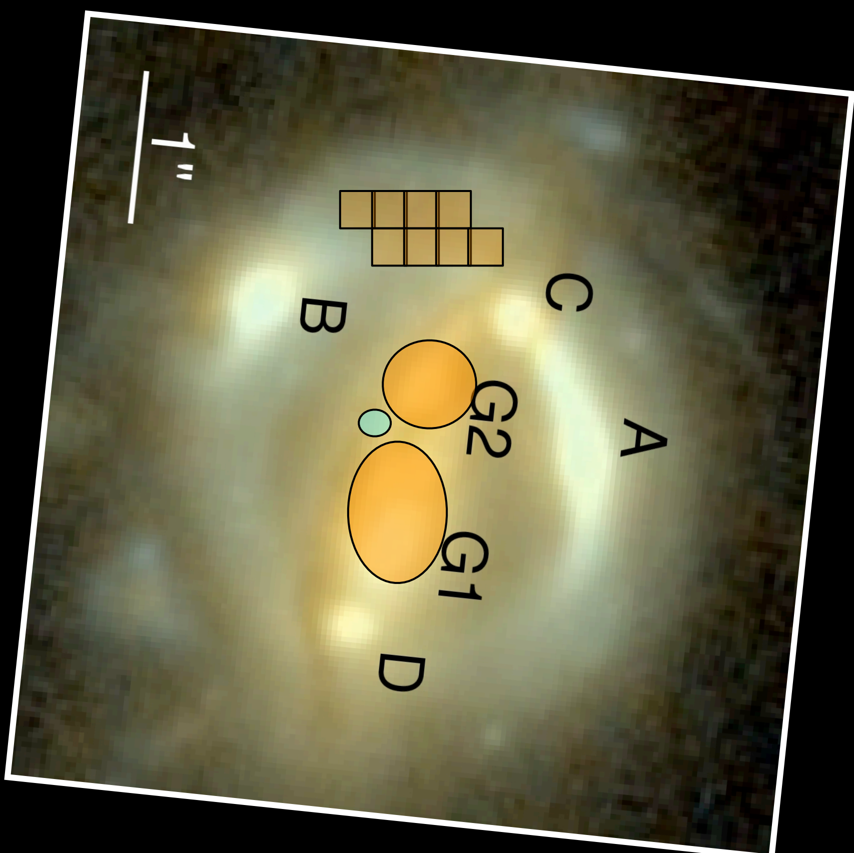


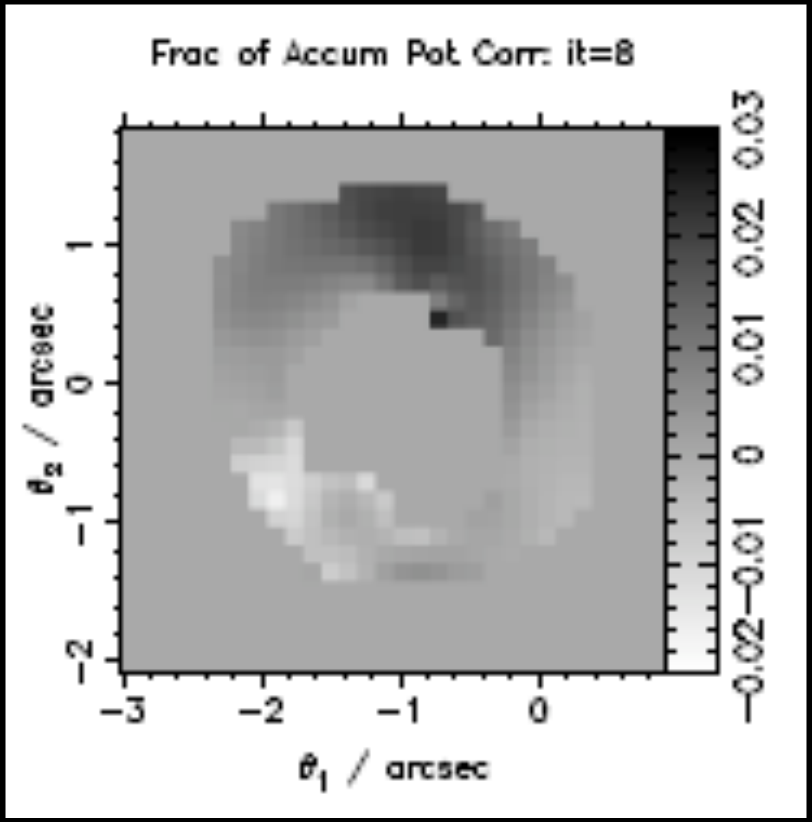


Source reconstruction on a grid of pixels

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



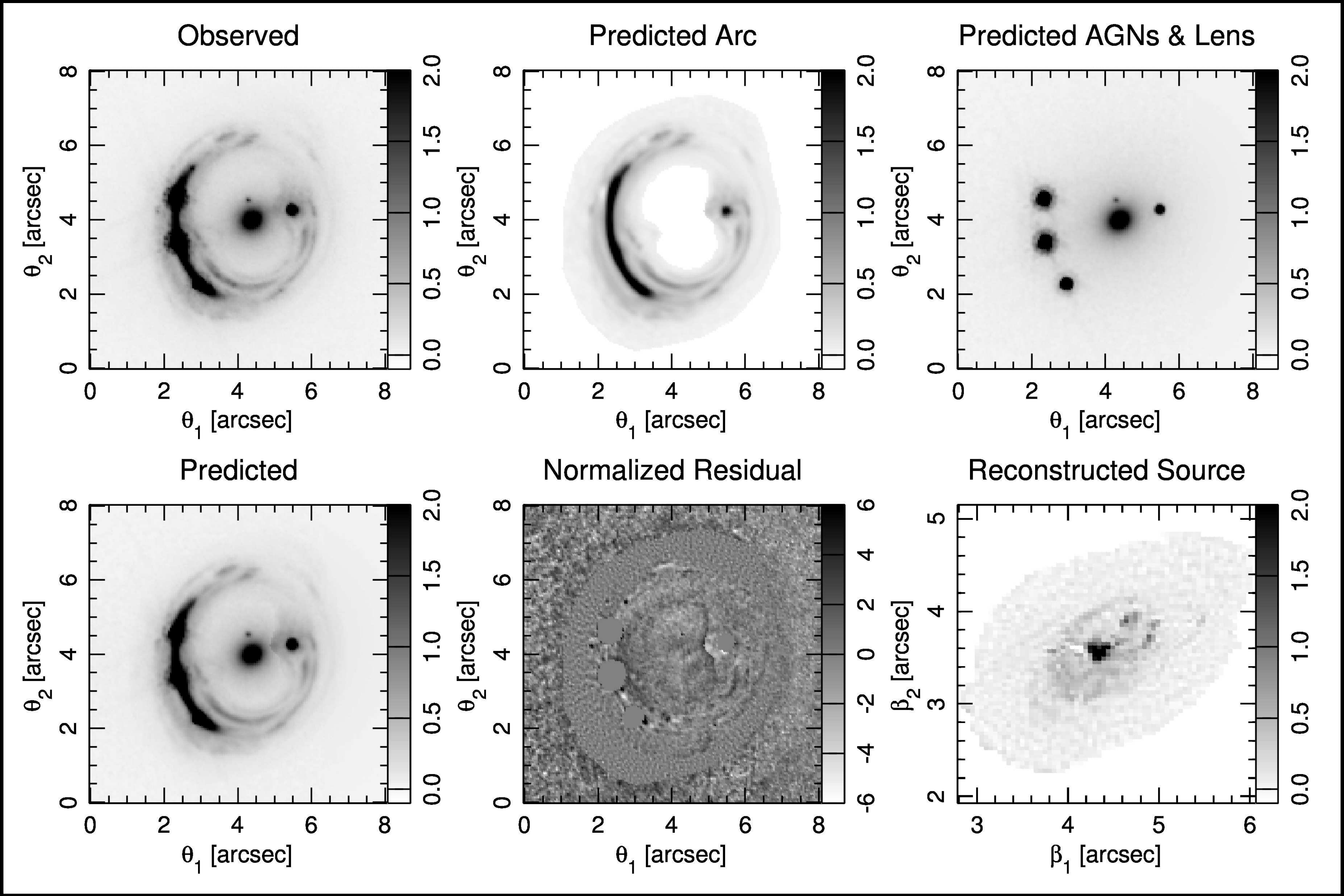


Potential is smooth to 2%!

RXJ1131-1231

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

Modeled in the same way as B1608



Inferring cosmological parameters

Let $\boldsymbol{\pi} = \{H_0, \Omega_{\rm m}, \Omega_\Lambda, w\}$ (cosmological parameters)
$\boldsymbol{\xi} = \{\boldsymbol{\pi}, \boldsymbol{\nu}\}$ (all model parameters)

We are after the **posterior PDF for π given the data, marginalised over the nuisance parameters ν:**

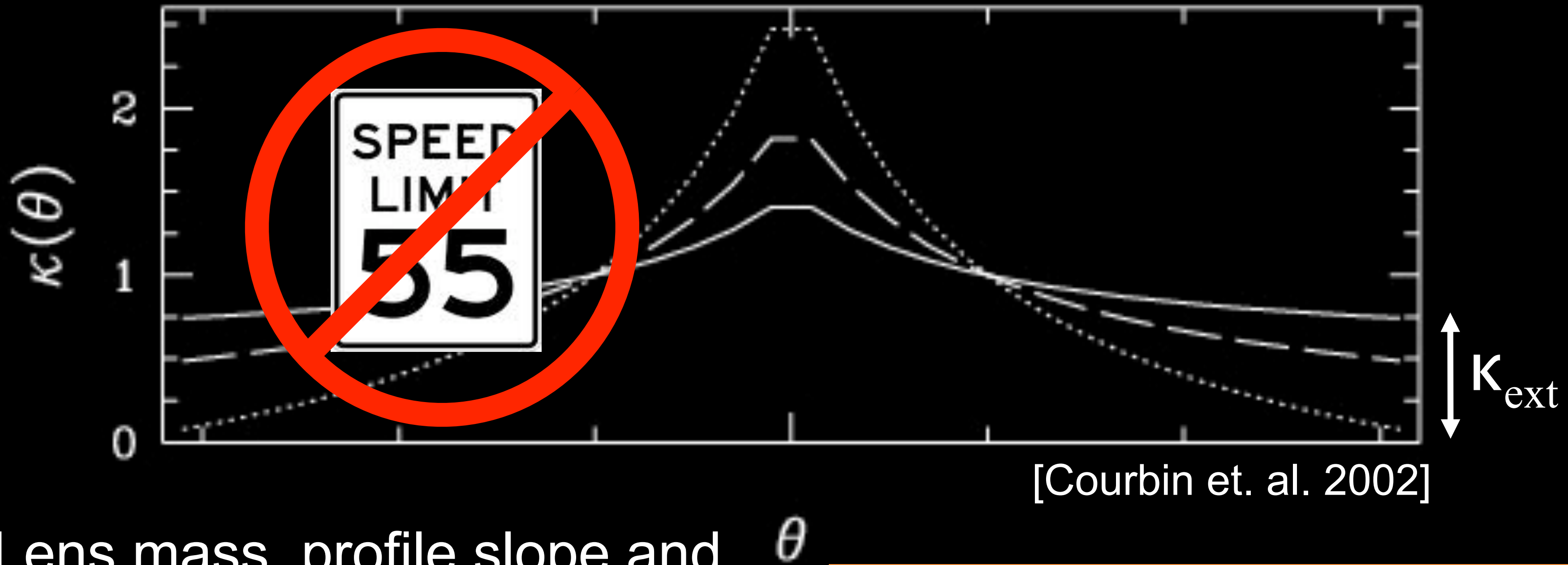
$$P(\boldsymbol{\pi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \sigma) = \int \mathrm{d}\boldsymbol{\nu}\, \mathrm{P}(\boldsymbol{\xi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \sigma)$$

where

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

Method: **importance sample** from **WMAP5 Pr(π)** and **Pr(ν),** using 3-dataset likelihood. What are ν and **Pr(ν)?**

“Mass-sheet” model degeneracy



[Courbin et. al. 2002]

Lens mass, profile slope and line of sight mass distribution are all ***degenerate***

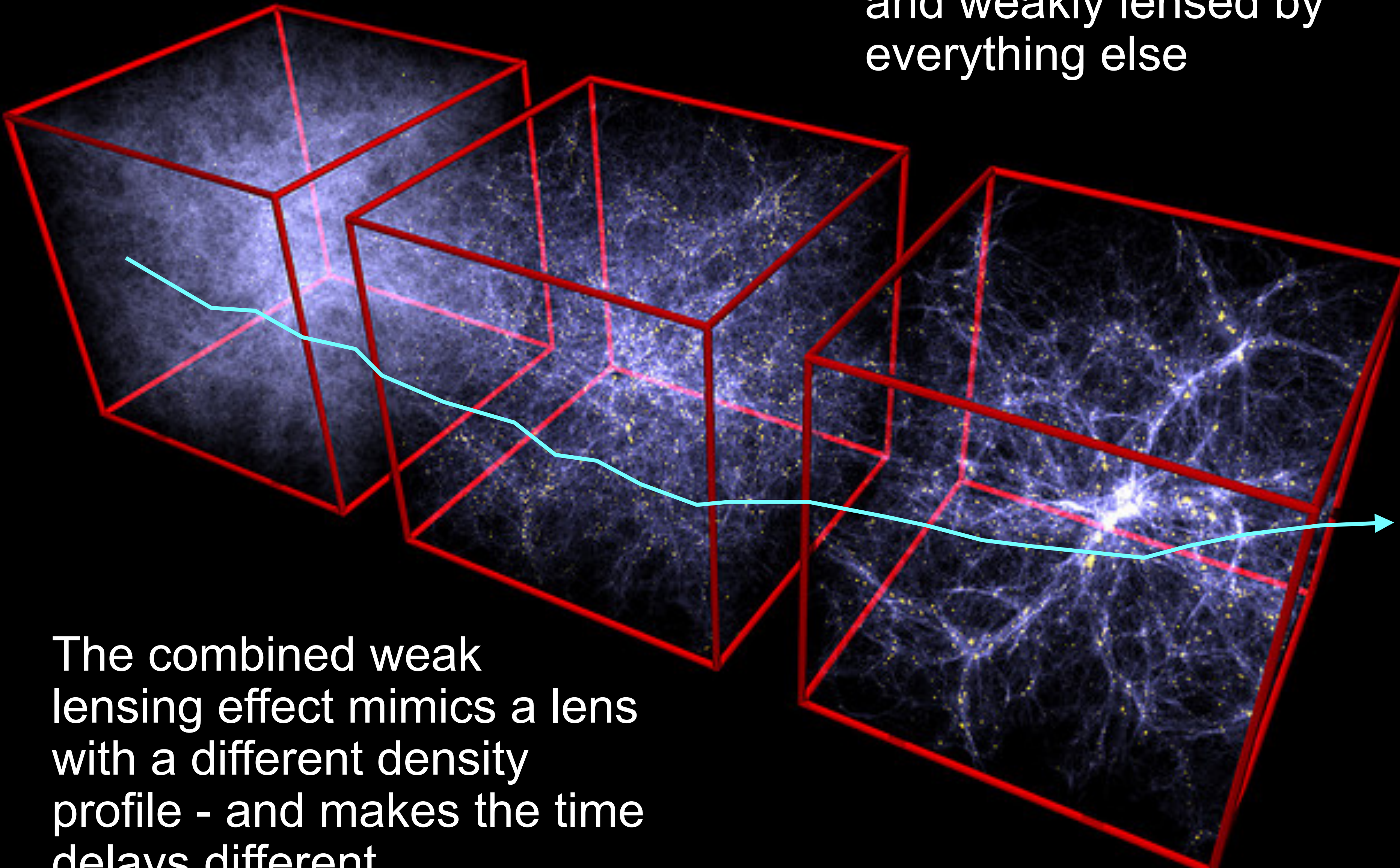
Lensing observables do not change, but

$$D_{\Delta t}^{\mathrm{true}} = \frac{D_{\Delta t}^{\mathrm{model}}}{1 - \kappa_{\mathrm{ext}}}$$

To break this degeneracy, we need *more information* about the mass distribution:

- Slope γ from arc thickness
- Stellar dynamics
- **Structures along the line of sight**

The source gets strongly lensed by the lens galaxy - and weakly lensed by everything else



The combined weak lensing effect mimics a lens with a different density profile - and makes the time delays different

B1608 - Google Maps - Gran Paradiso

File Edit View History Bookmarks Tools Help

http://maps.google.com/

Fermat would have loved this

B1608 - Google Maps

Web Images Videos **Maps** News Shopping Gmail more ▼

dr.phil.marshall@gmail.com | My Profile | My Account | Help | Sign out

Google maps find: accidents along the line of sight — Search Maps — Show search options

Find businesses, addresses and places of interest.

Get Directions My Maps

RSS Print Send Link

Collaborate — Edit

San Jose Time Delays

Illustrating lens time delays - 4 routes, we know the average speeds for each (because we have a model for the traffic conditions!) and we measure the relative arrival times of four cars, in minutes. What's the map scale?

* Measure route lengths x in inches on the map

* Assume all cars leave at the same time, and use the average speeds v provided

* Each time delay gives an (almost) independent estimate of the map scale A, in inches per mile:

(x2/v2 - x1/v1) = A*delay(2-1)

14 views - Public
Created on Jan 14 - Updated < 1 minute ago
By Phil
Rate this map - Write a comment

Bright Variable Source

Route 1 (280): 39.3 mph, arrives first
45.9 mi - about 1 hour 6 mins (up to 1 hour 10 mins in

Route 2 (85): 39.9 mph, delay=4mins
49.2 mi - about 1 hour 11 mins (up to 1 hour 14 mins in

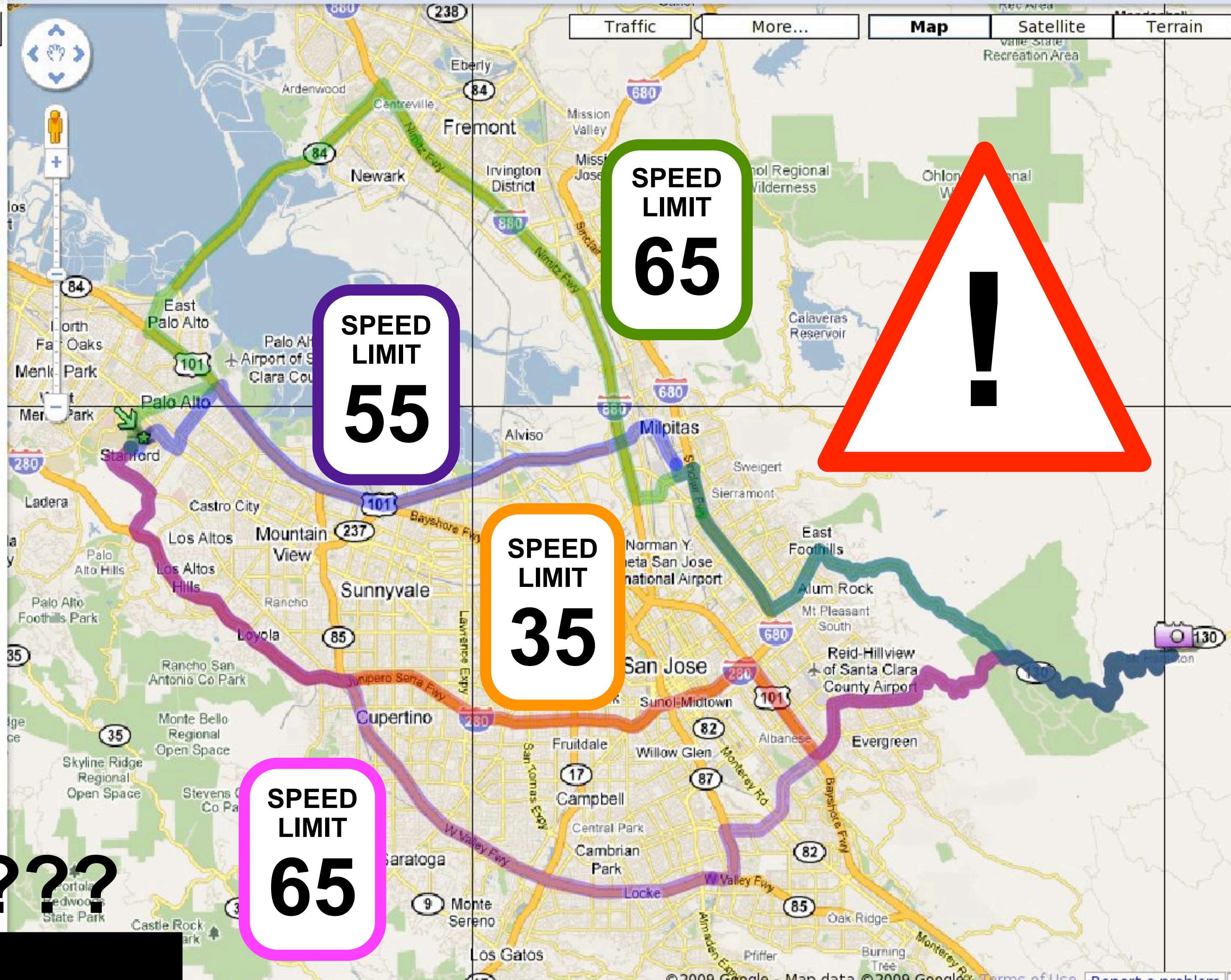
Route 3 (101): 33.9 mph, delay=10mins
45.2 mi - about 1 hour 15 mins (up to 1 hour 20 mins in

Route 4 (Dumbarton Bridge): 33.9 mph, delay=30mins
56.5 mi - about 1 hour 28 mins (up to 1 hour 40 mins in

Observer

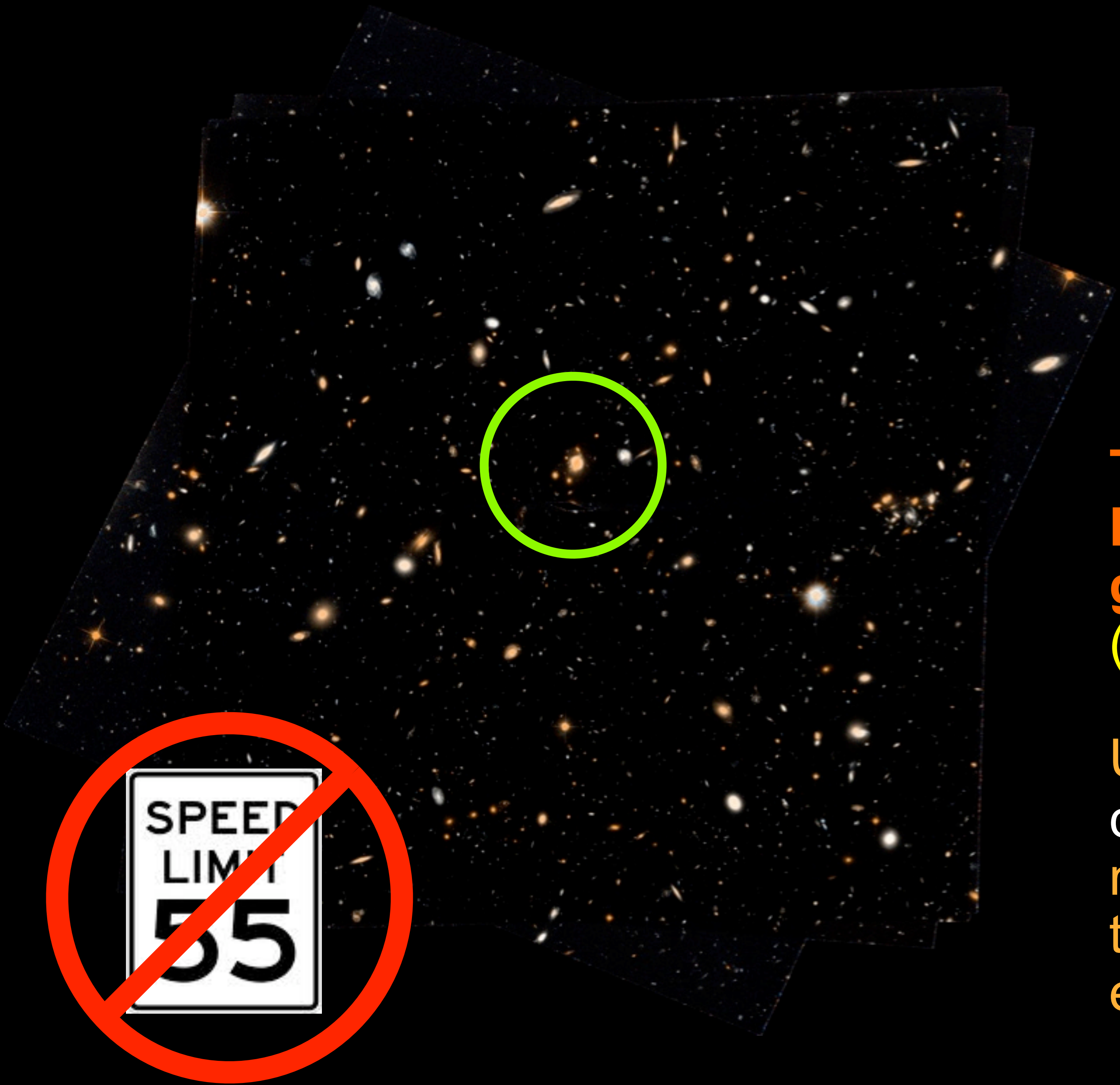
???

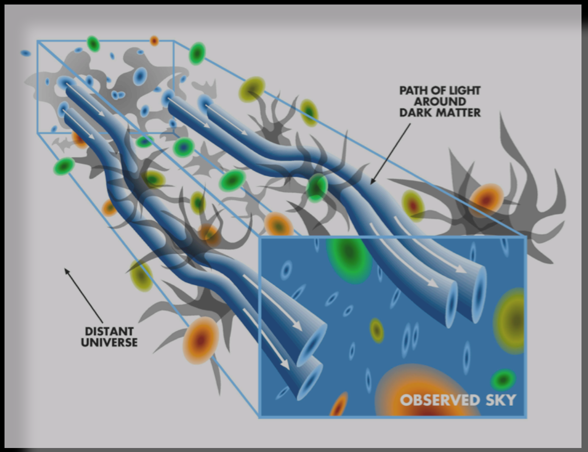
[redacted]



Done

"External Convergence"



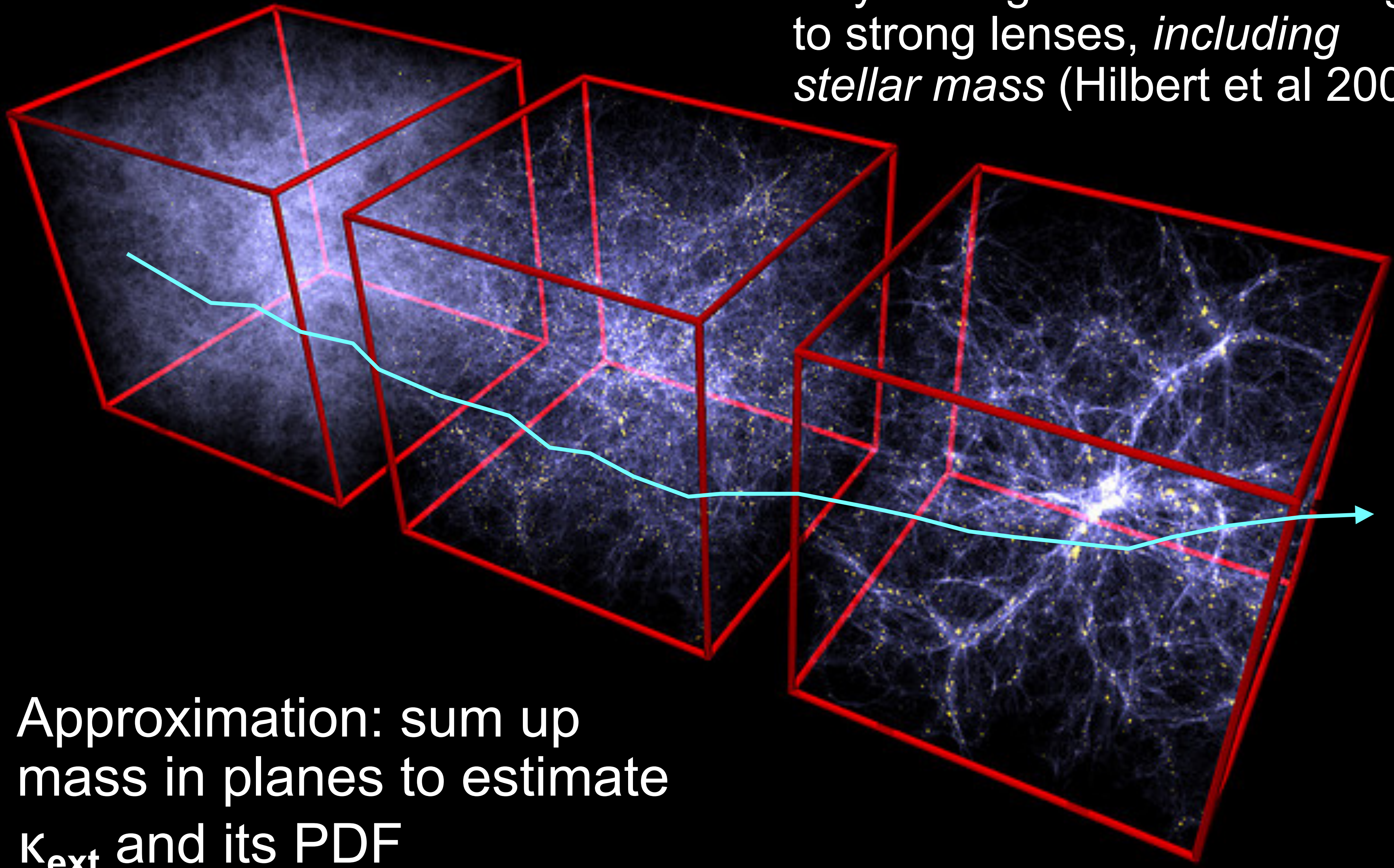


The B1608+656 field has twice the average galaxy density
(Fassnacht et al. 2009)

Use this observation to calibrate simulations of mass along line of sight to strong lenses, and estimate convergence

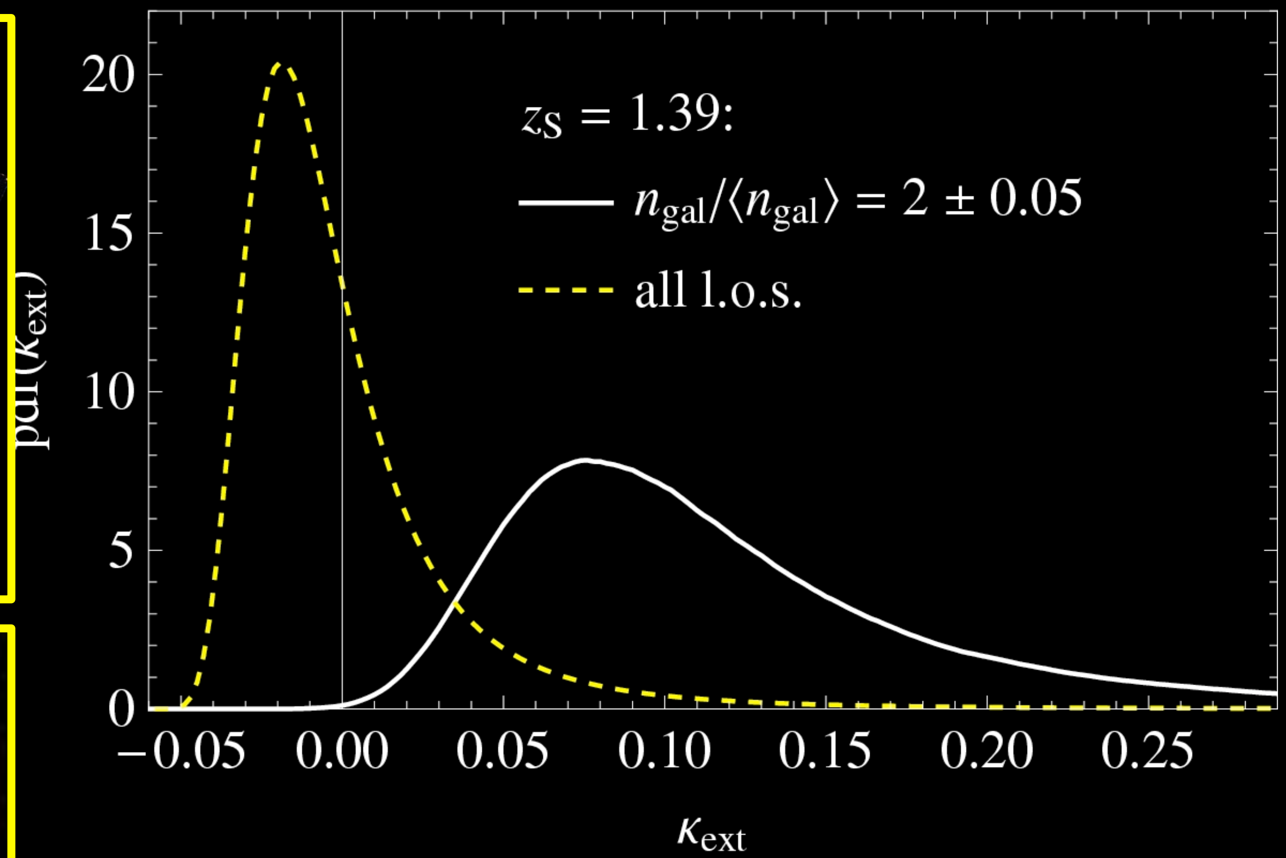
The Millennium Simulation

Ray tracing to find lines of sight to strong lenses, *including stellar mass* (Hilbert et al 2008)



Approximation: sum up mass in planes to estimate κ_{ext} and its PDF

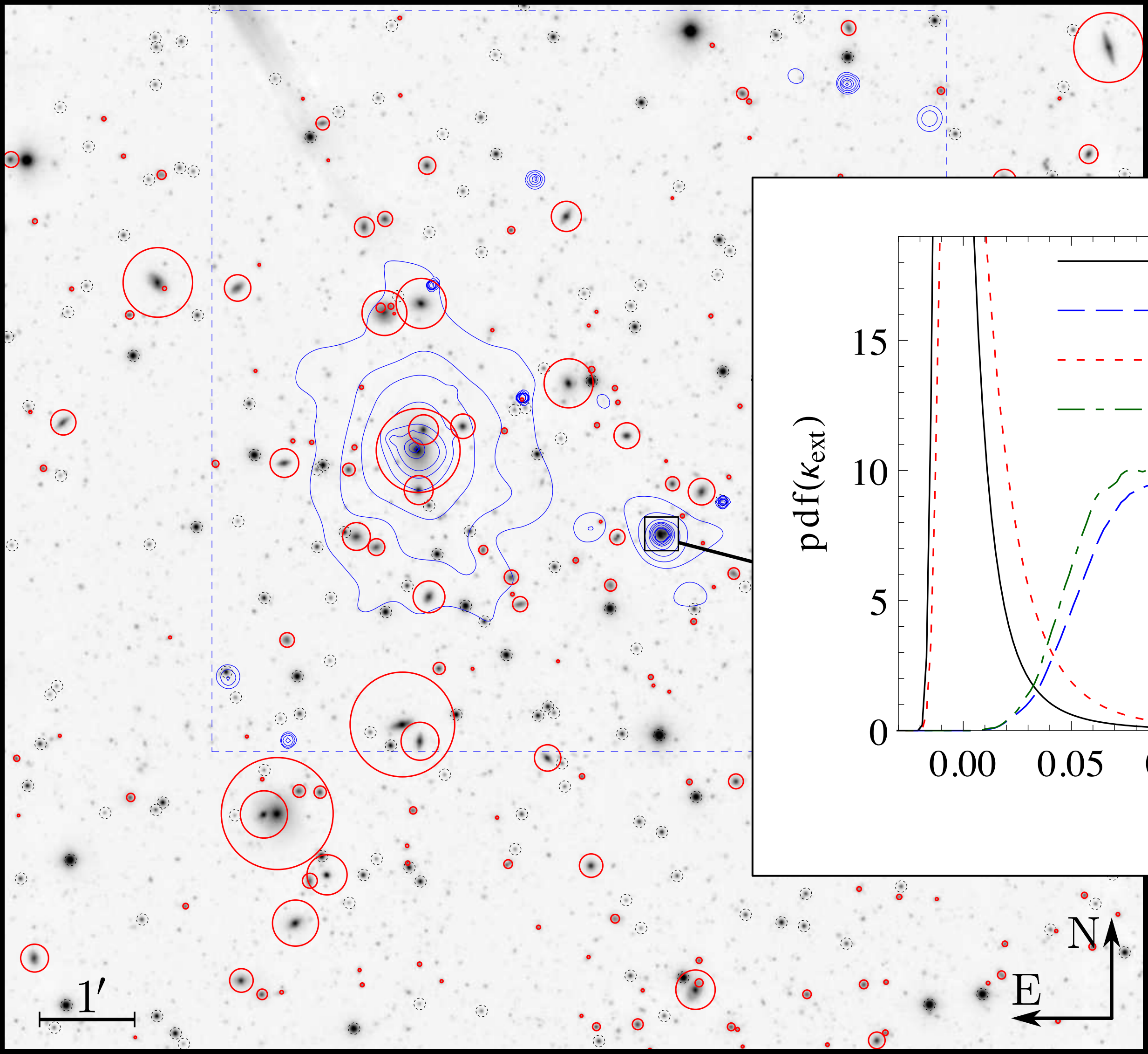
External Convergence Pr(κ_{ext})

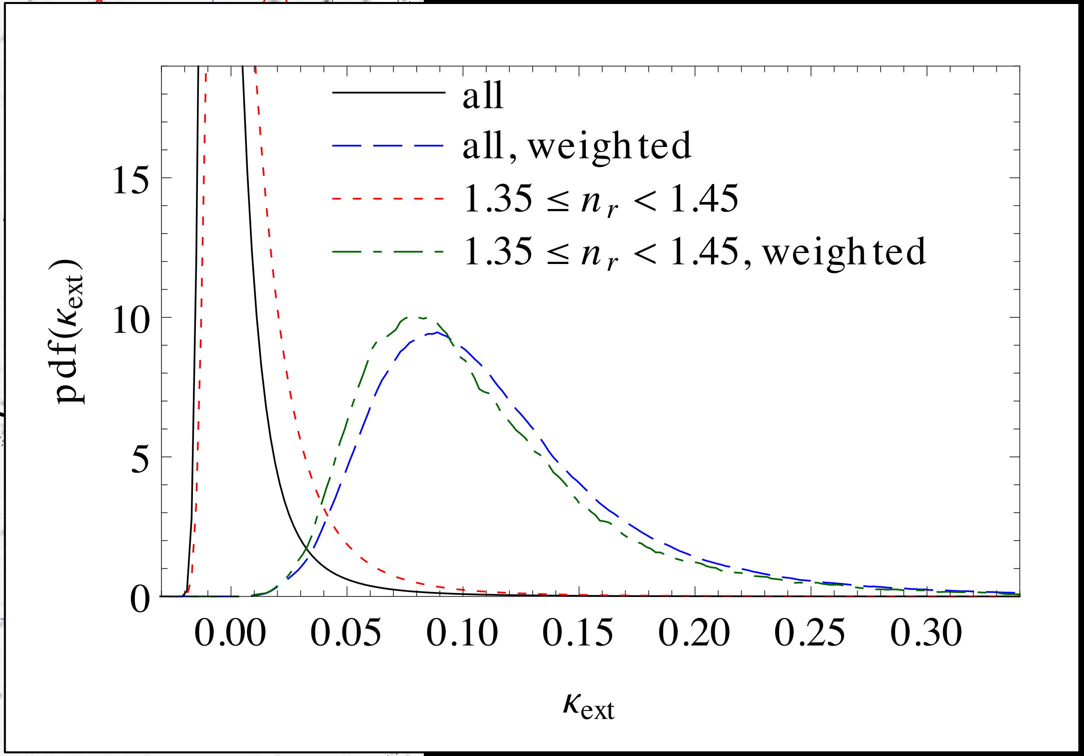


- Only choosing fields with **2x over-dense** in galaxy number counts (like B1608) gives a broader, offset **Pr(κ_{ext})**

RXJ1131-1231

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





Inferring cosmological parameters

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

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

We are after the **posterior PDF for π given the data, marginalised over the nuisance parameters ν:**

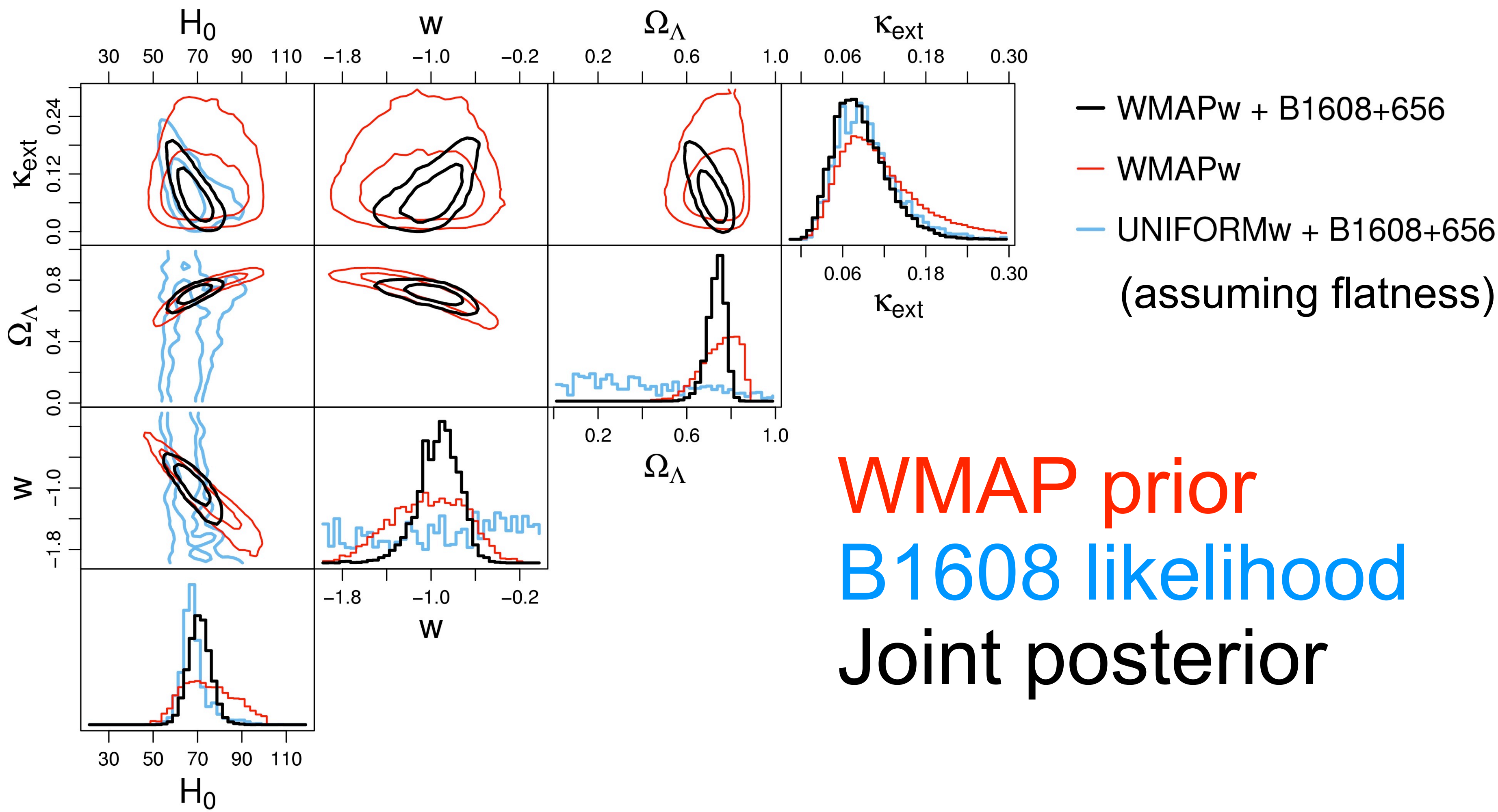
$$P(\boldsymbol{\pi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \sigma) = \int {\rm d}\boldsymbol{\nu}\, {\rm P}(\boldsymbol{\xi}|\boldsymbol{d}_{\rm ACS}, \boldsymbol{\Delta t}, \sigma)$$

where

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

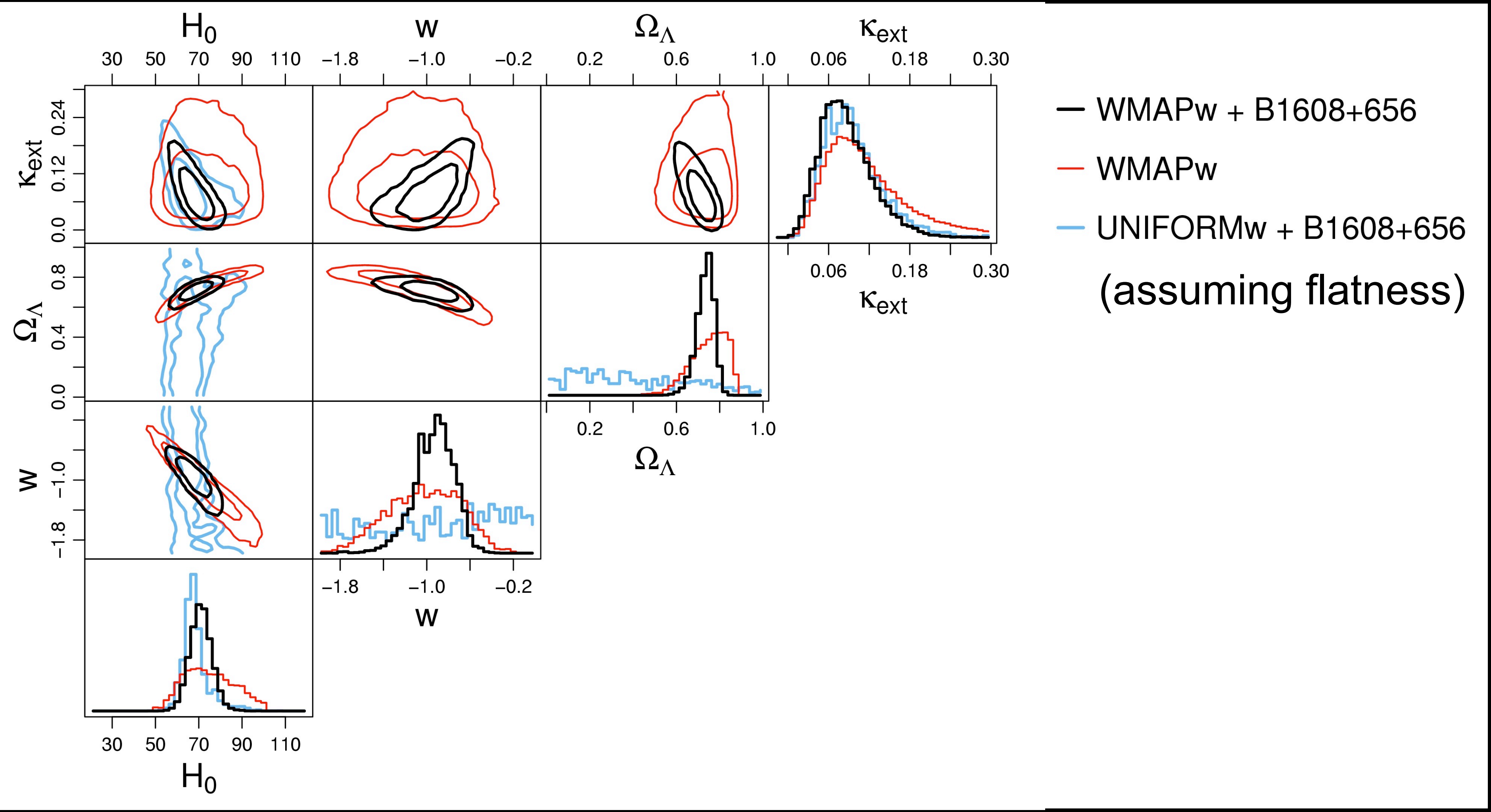
Method: **importance sample** from WMAP5 Pr(π) and Millenium Simulation Pr($\kappa_{\rm ext}$), using 3-dataset likelihood

Dark Energy from B1608

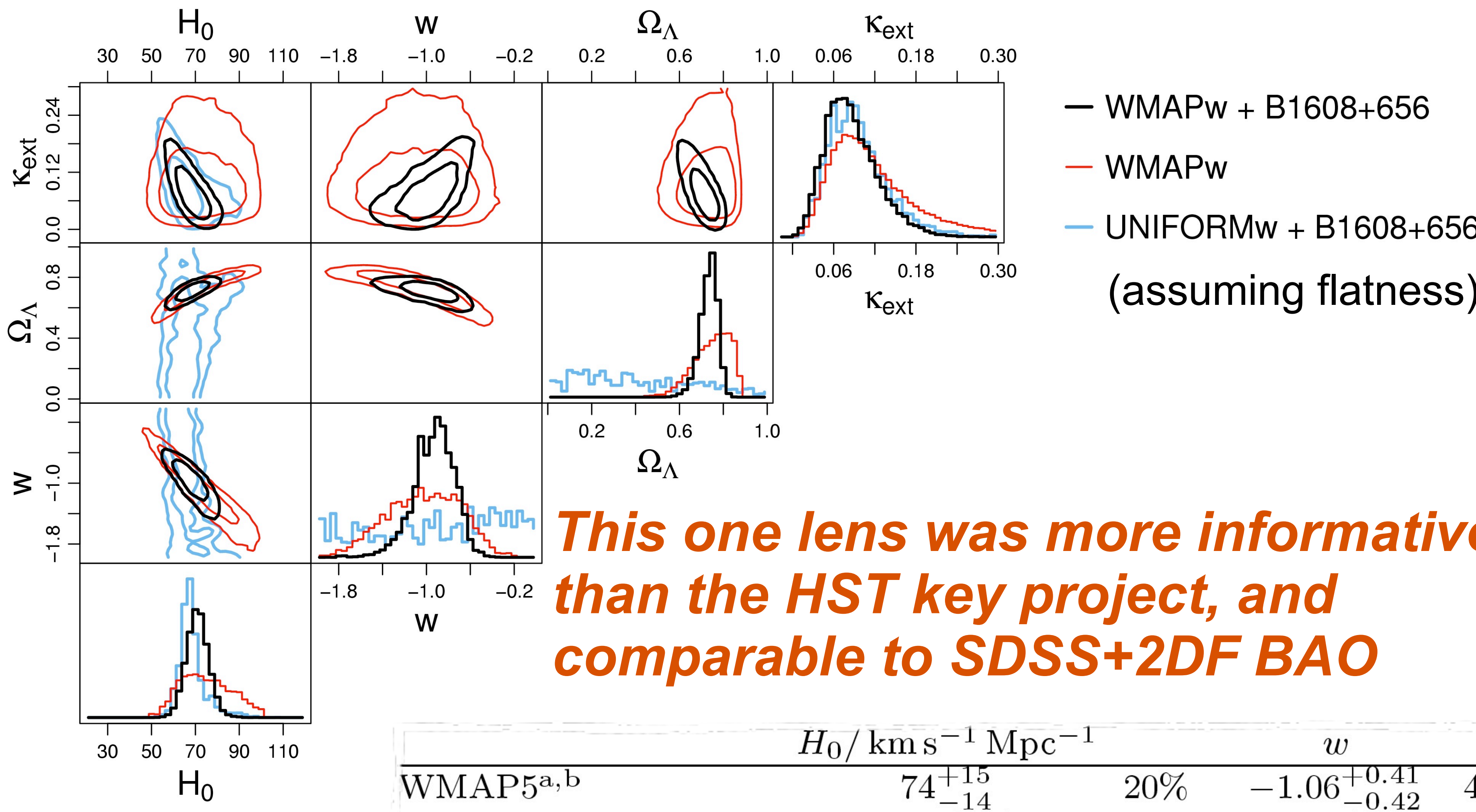


WMAP prior
B1608 likelihood
Joint posterior

Dark Energy from B1608



Dark Energy from B1608

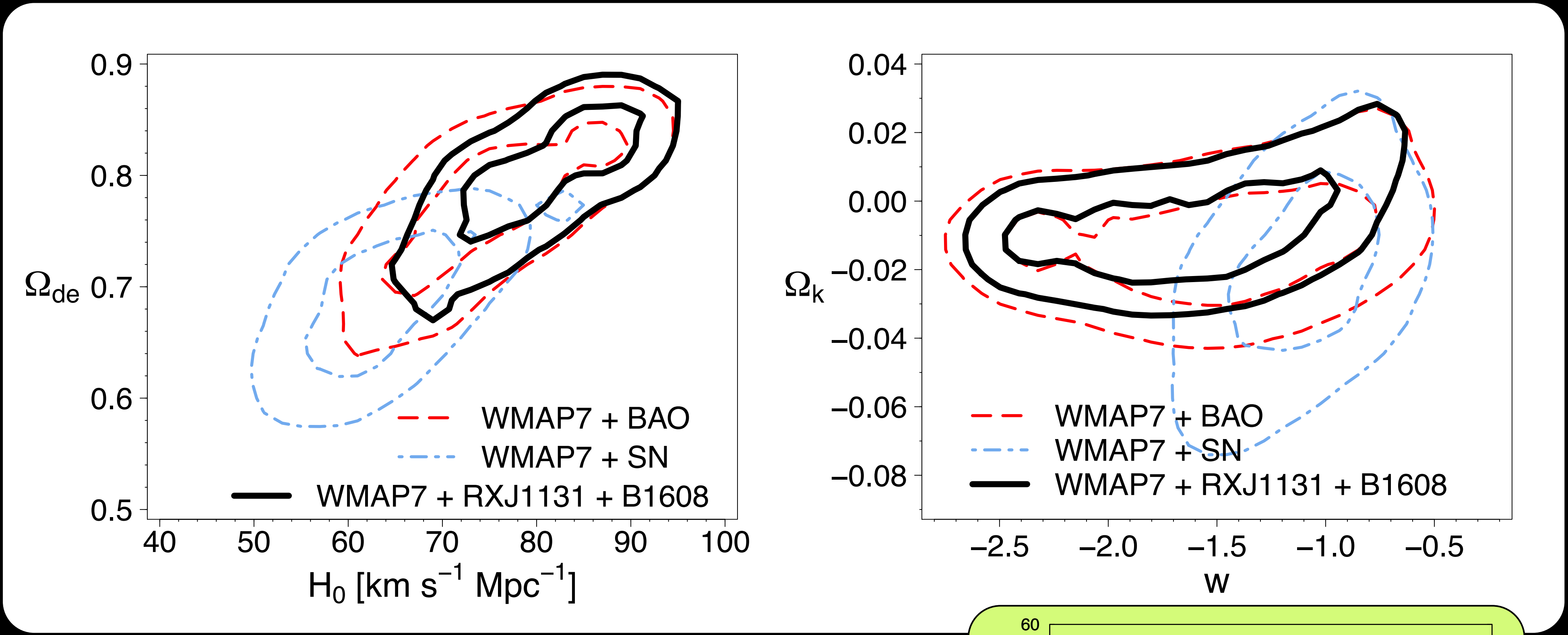


This one lens was more informative than the HST key project, and comparable to SDSS+2DF BAO

	$H_0/\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$		w	
WMAP5[a,b]	74^{+15}_{-14}	20%	$-1.06^{+0.41}_{-0.42}$	42%
WMAP5+*HST* KP[a,b,c]	$72.1^{+7.4}_{-7.6}$	10%	$-1.01^{+0.23}_{-0.22}$	23%
WMAP5+SN[a,b,d]	$69.4^{+1.6}_{-1.7}$	2.3%	$-0.977^{+0.065}_{-0.064}$	6.5%
WMAP5+BAO[a,b,e]	$73.9^{+4.7}_{-4.8}$	6.6%	$-1.15^{+0.21}_{-0.22}$	22%
WMAP5+Riess[f]	74.2 ± 3.6[g]	5.0%	-1.12 ± 0.12	12%
WMAP5+B1608	$\mathbf{69.7^{+4.9}_{-5.0}}$	**6.9%**	$\mathbf{-0.94^{+0.17}_{-0.19}}$	**18%**

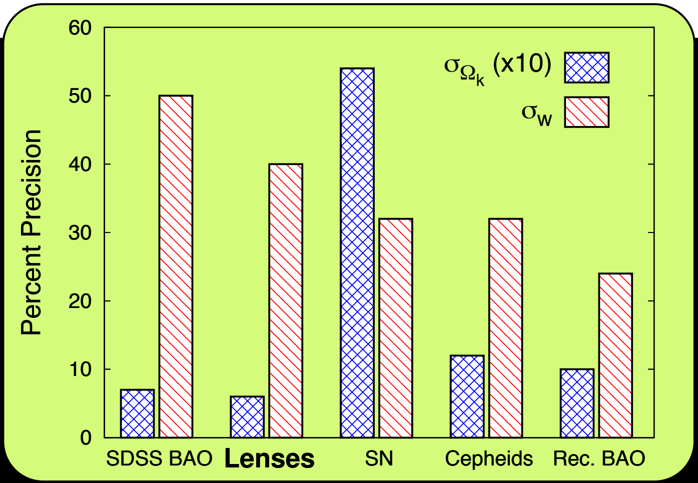
RXJ1131-1231 + B1608+656

Joint cosmological parameter analysis



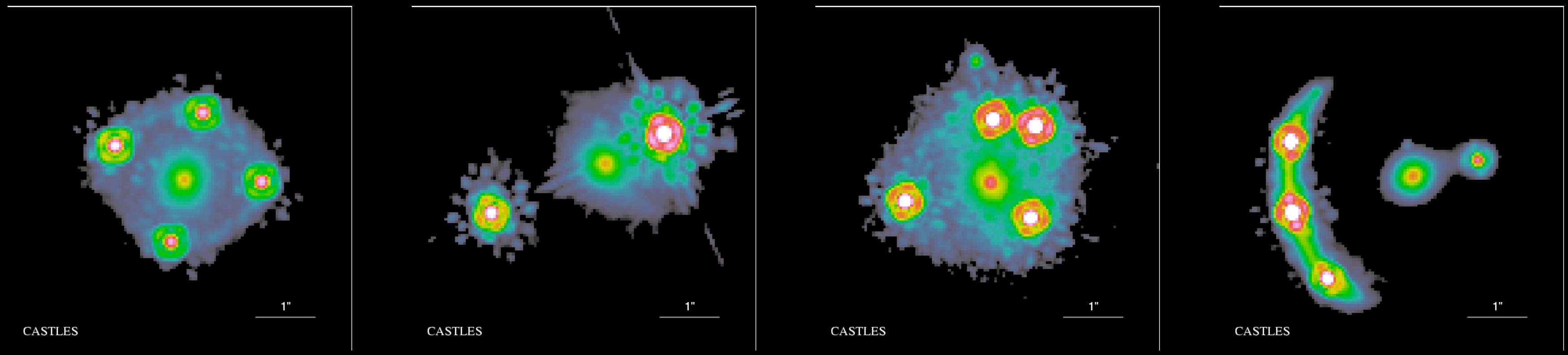
OwCDM model: variable w and curvature

- Comparable precision between probes →
- Curvature well-constrained
- Interesting tension between D_A and D_L?



Next Steps

- To reach 10% precision on *w*, and to check for residual systematic errors, we need ~4 systems each as well-measured as B1608



- Time delays coming from COSMOGRAIL project, HST data for modeling being analyzed by Wong & Suyu at ASIAA

Conclusions, Outlook

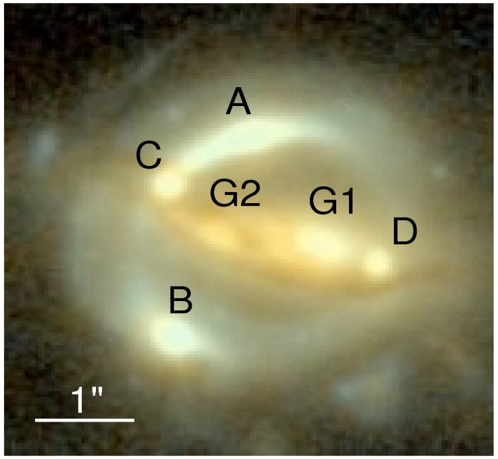
- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc but providing comparable precision

- To reach sub-percent precision on $H_0(w)$, we would need ~100-1000 time delay lens systems, each as well-measured as B1608

- Future samples of time-delay lenses ***could*** be a competitive cosmological probe -

  but we are going to need to find a lot more, and then measure them all...

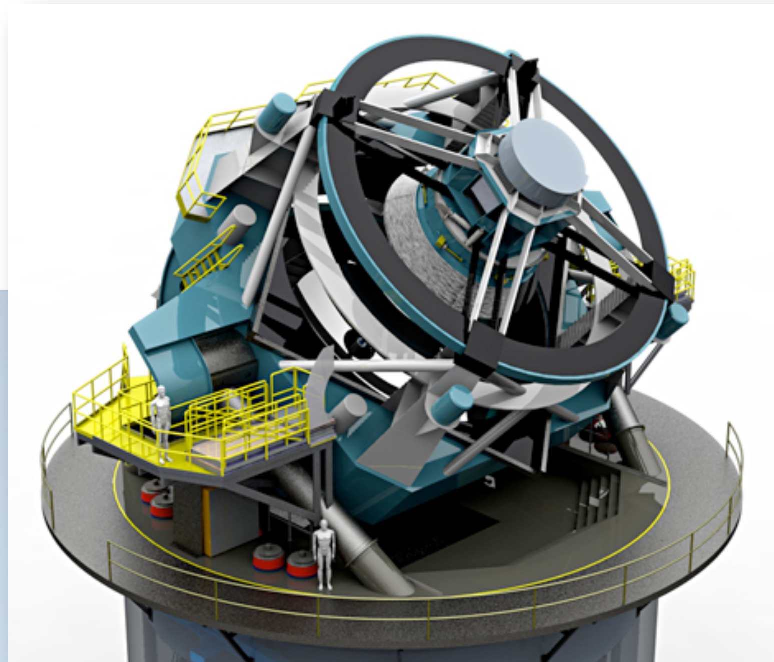
Outline



- Dark Energy from B1608 and RXJ1131
- Time delay lens cosmography with LSST

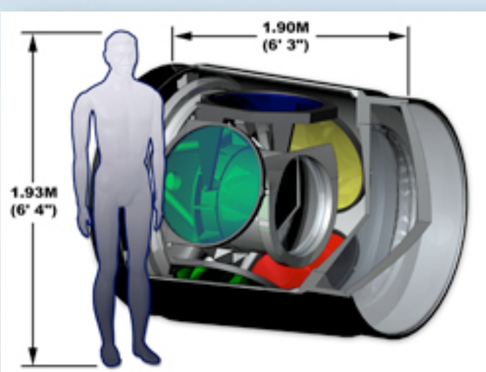
Large Synoptic Survey Telescope

Overview



High etendue survey telescope:
- **5.7m effective aperture**
- **10 sq degree field**
- **24 mag in 30 seconds**
- Visible sky mapped **every few nights**
- Cerro Pachon, Chile: **0.7” seeing**

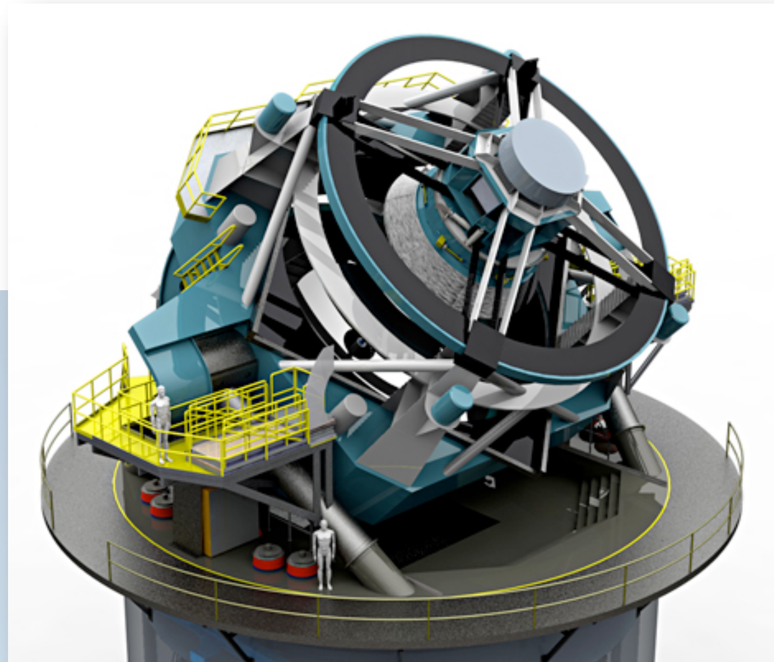
Ten year movie of the entire Southern sky



- **120 Petabytes of data** (1Pb = every book ever published)
- **All data to be made public:** nightly transient alerts, yearly data releases starting **2021** (+2yrs, worldwide)

Large Synoptic Survey Telescope

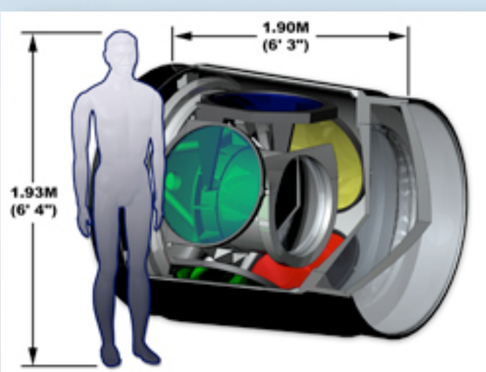
Overview



High etendue survey telescope:

- **5.7m effective aperture**
- **10 sq degree field**
- **24 mag in 30 seconds**
- Visible sky mapped **every few nights**
- Cerro Pachon, Chile: **0.7" seeing**

Ten year movie of the entire Southern sky

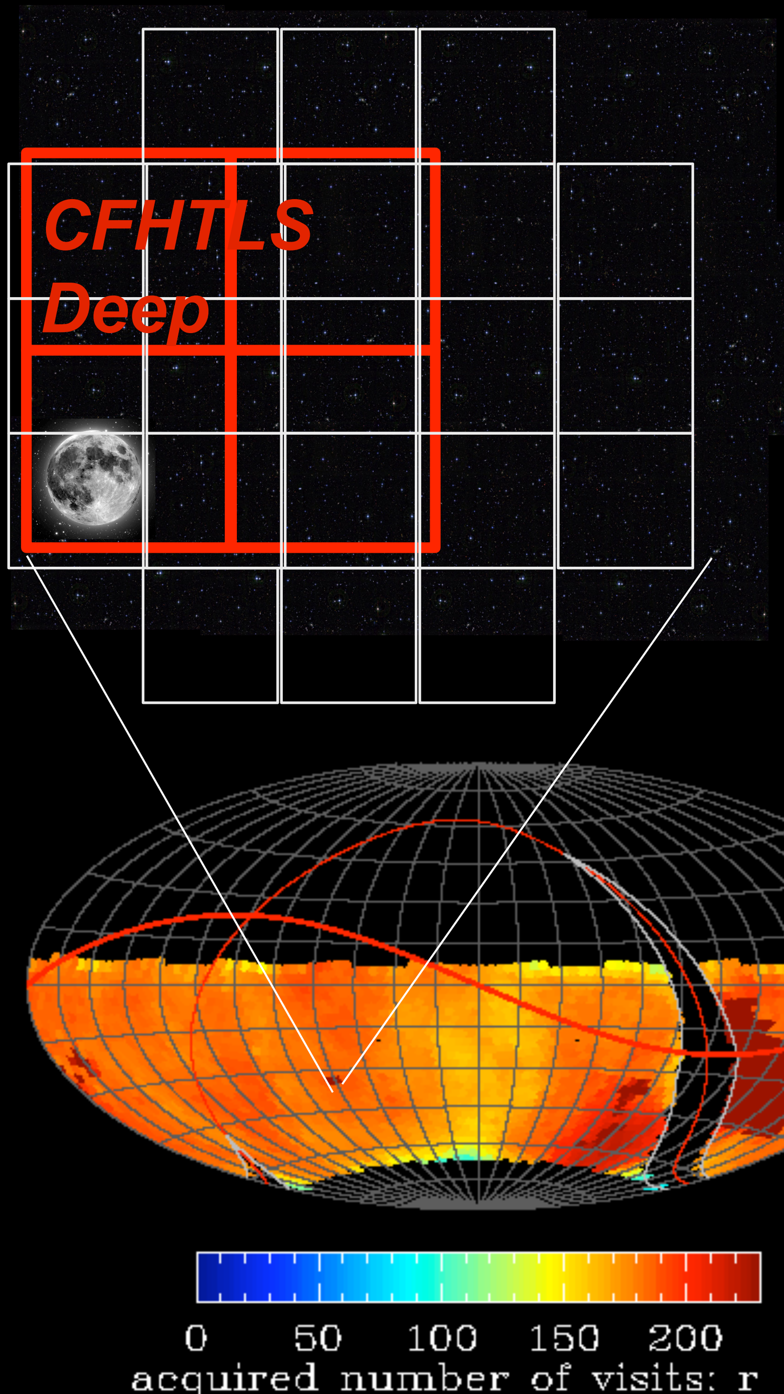


- **120 Petabytes of data**
  (1Pb = every book ever published)
- **All data to be made public:** nightly transient alerts, yearly data releases starting **2021** (+2yrs, worldwide)

Status

- **Top-ranked ground-based project** in the Astro 2010 Decadal Survey of US astronomy
- Joint NSF & DoE project (astronomers and HE physicists)
- Now approved: federal construction funding in the **2014 President's budget**
- Primary/Tertiary mirror was finished September 2013
- **First light in 2019, 2 years commissioning, survey to start in 2021**

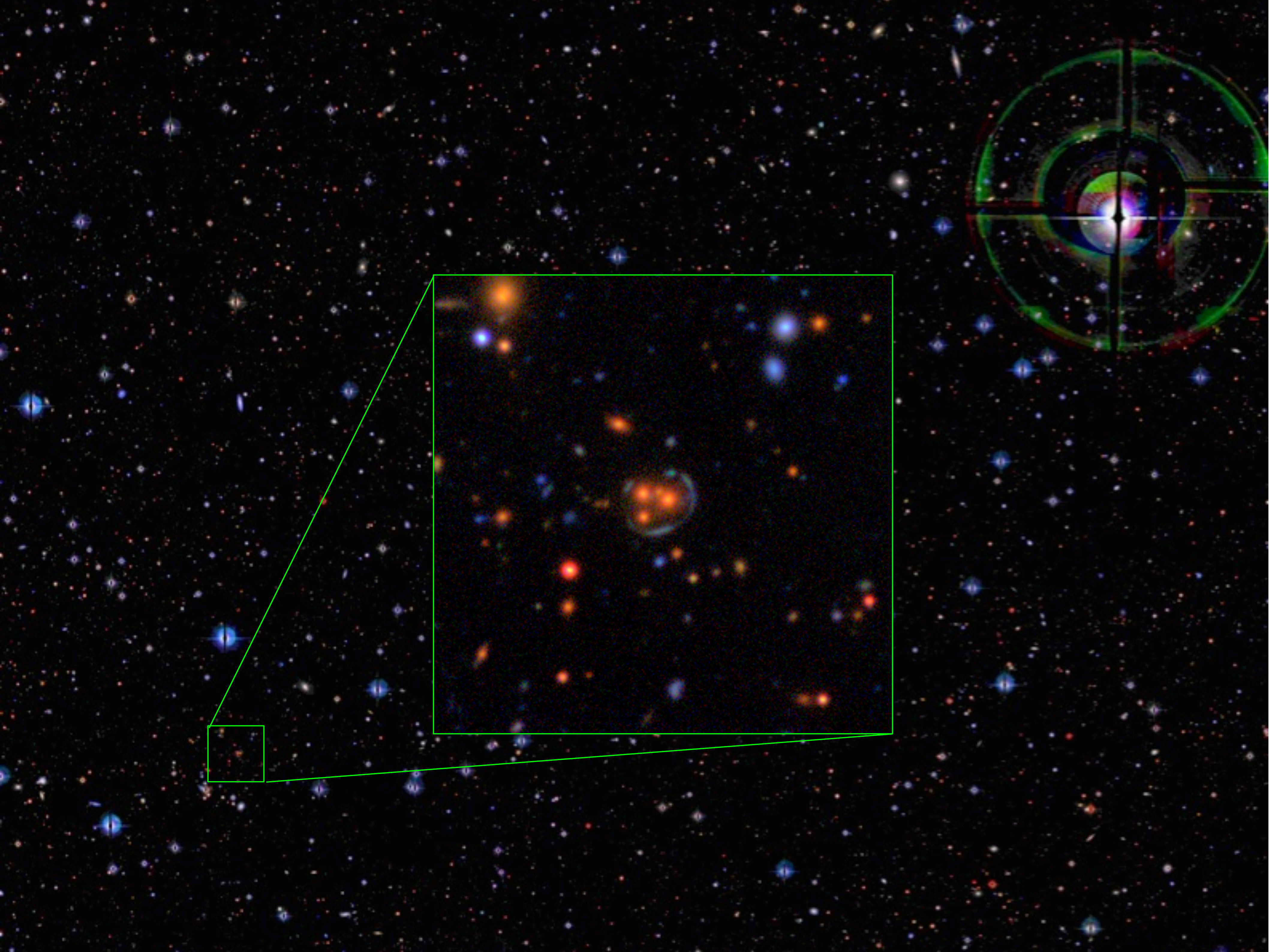
- **Science collaborations**, over 400 members. International affiliates negotiating to join, & contribute to operating costs.



The LSST survey

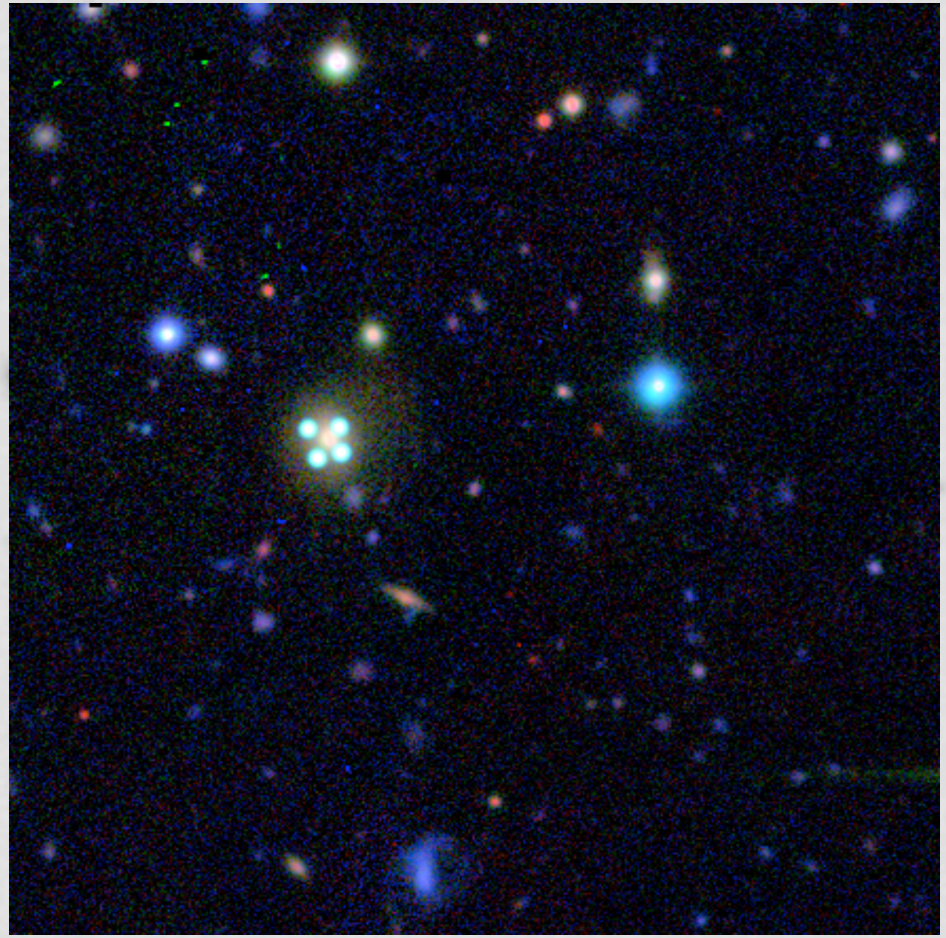
- **20000** sq deg
- **6** filters, ugrizy
- **10 years** planned, 800 visits per field
- **3 - 14 day** cadence
- depth ~ **24** mag per visit, ~ **27** mag after 10 years
- resolution **0.4-1.0"**

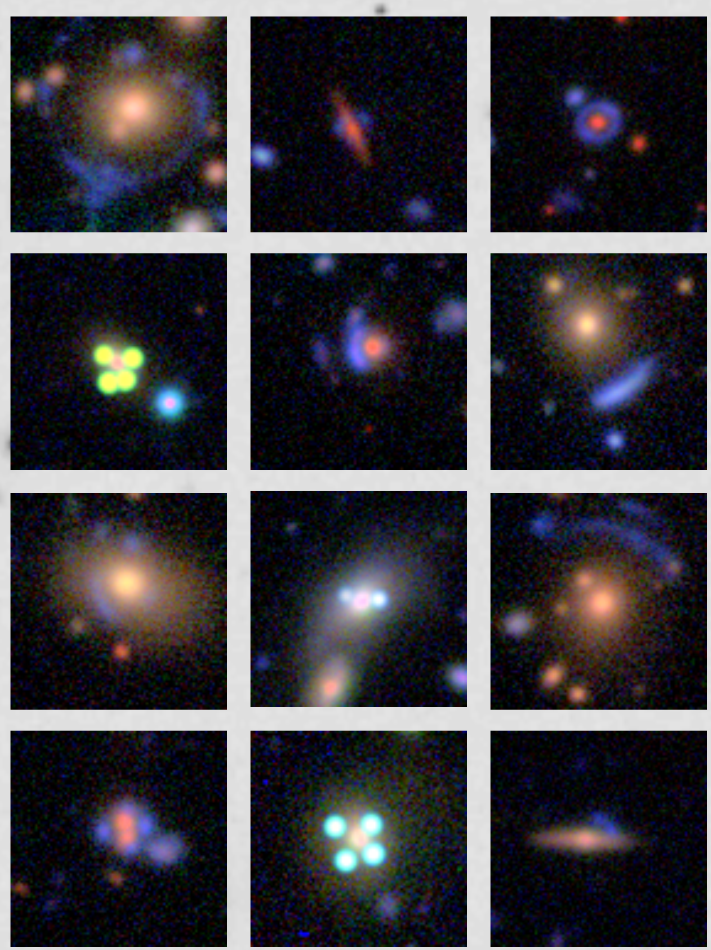
http://www.lsst.org



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

$10^{4\text{-}5}$ galaxy-scale lenses, 1000s of clusters...





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)

How many lensed quasars?

Survey	QSO (detected)		QSO (measured)	
	$N_{\rm nonlens}$	$N_{\rm lens}$	$N_{\rm nonlens}$	$N_{\rm lens}$
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)

How many lensed quasars?

Survey	QSO (detected) N_{nonlens}	QSO (detected) N_{lens}	QSO (measured) N_{nonlens}	QSO (measured) N_{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)
- **HSC**, **DES**, **PS1**: ~3000 lenses (400 quads);

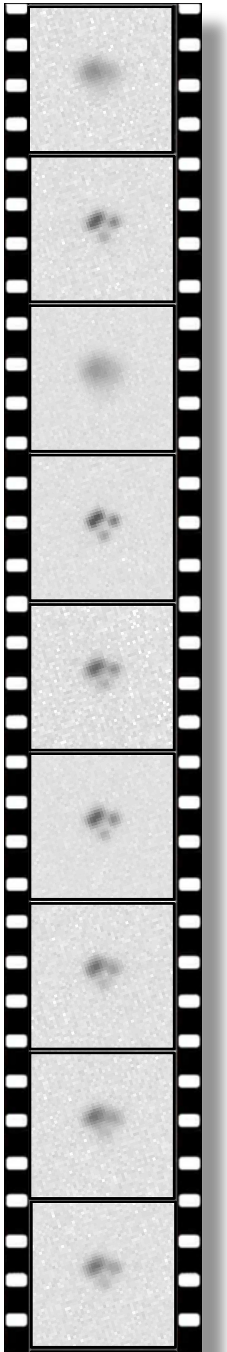
How many lensed quasars?

Survey	QSO (detected) N_{nonlens}	QSO (detected) N_{lens}	QSO (measured) N_{nonlens}	QSO (measured) N_{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%)

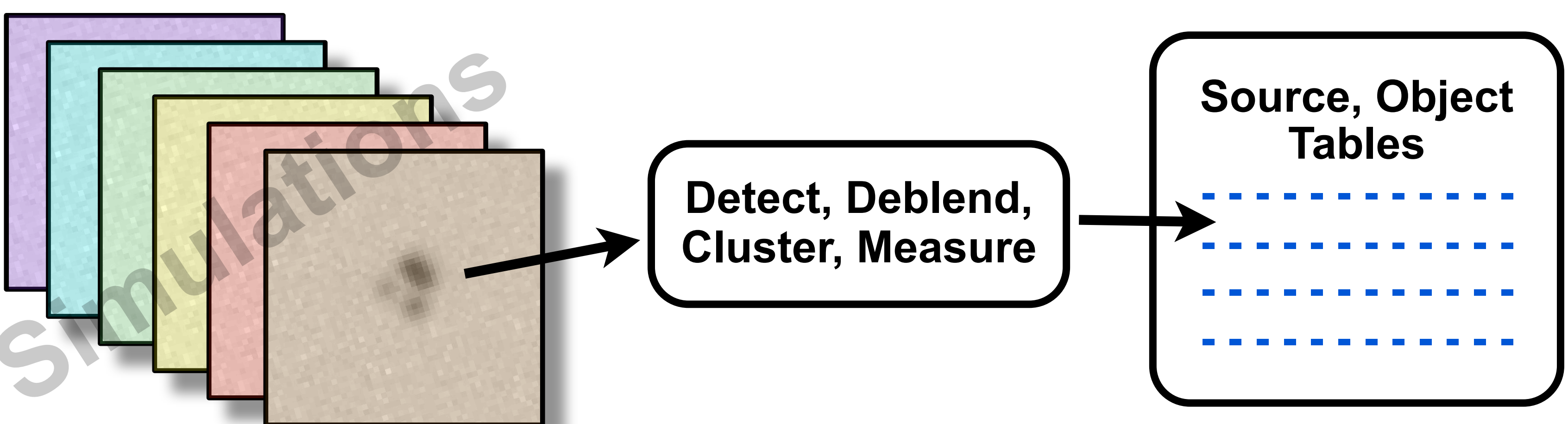
(Oguri & Marshall 2010)

- **LSST** should detect ~8000 lenses (1000 quads)
- **HSC**, **DES**, **PS1**: ~3000 lenses (400 quads);
- *Until LSST, additional monitoring will be needed.* **LSST itself should measure 3000 time delay lenses**, including **400 quads**

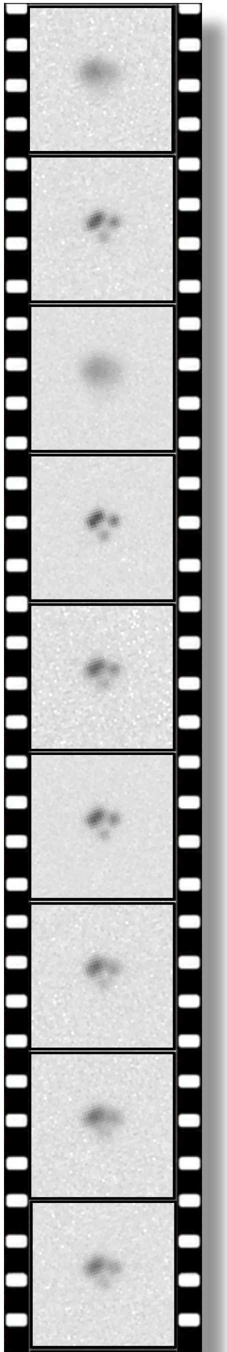
Lens detection



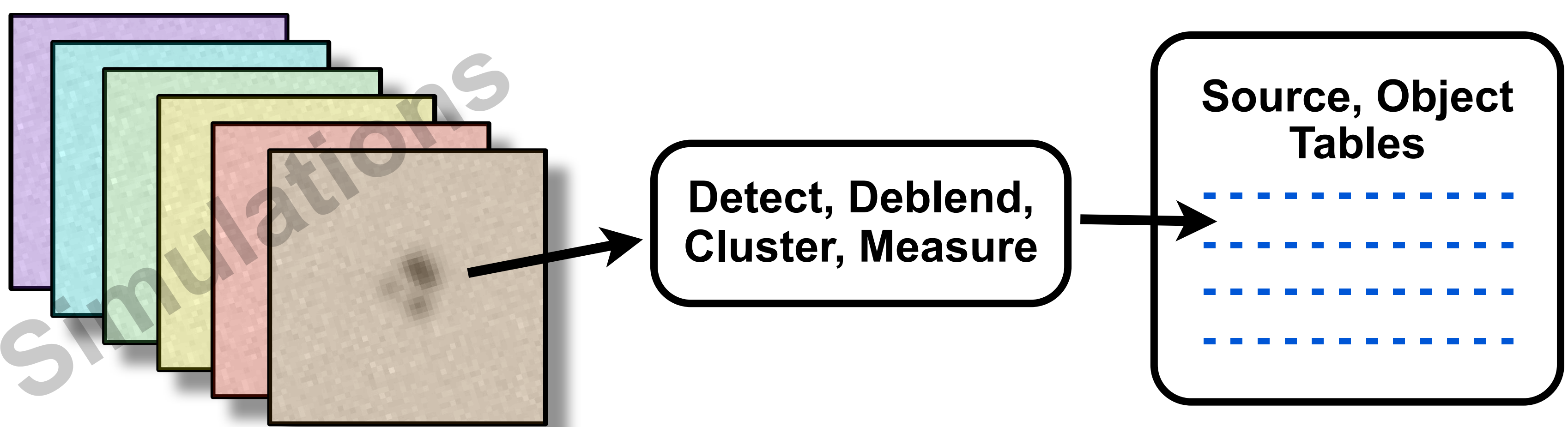
- **Catalog-based candidate detection.** *Needs: good* *deblender**, the right parameters (color, morphology, variability) saved, rapidly executable DB queries.*



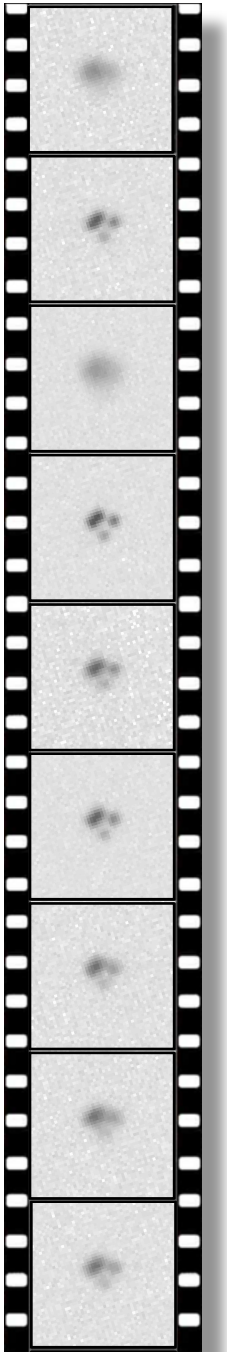
Lens detection



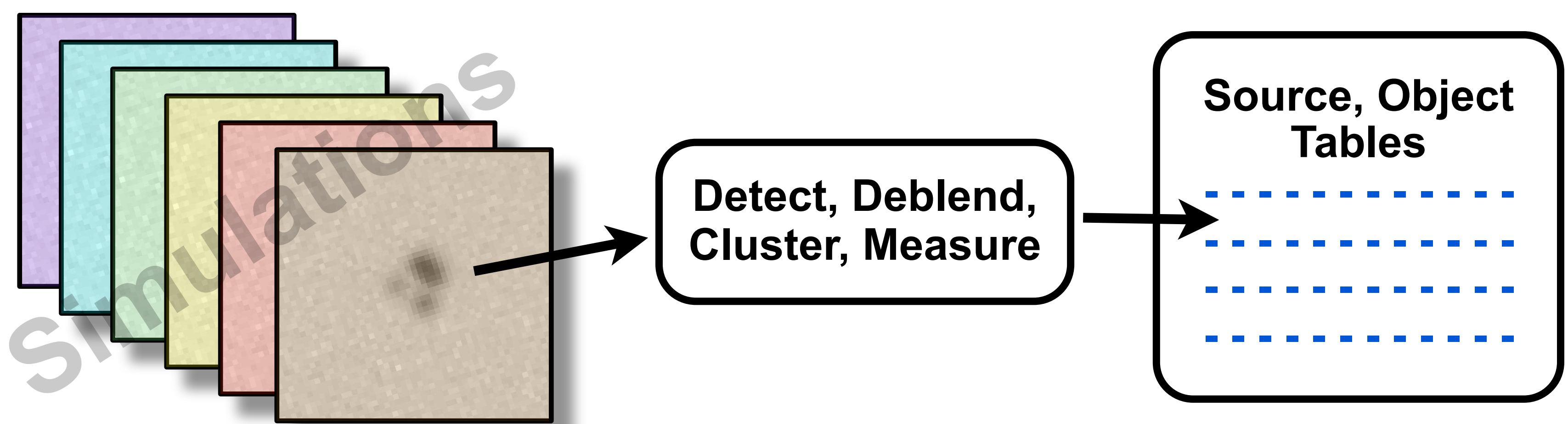
- **Catalog-based candidate detection.** *Needs: good deblender, the right parameters (color, morphology, variability) saved, rapidly executable DB queries.*
- **Image-based candidate classification**. *Needs: access to postage stamp images at data center in a "Multi-Fit," via level 3 API, reliable PSF models and image registration. Joint w/ Euclid? Practise w/ HSC!*



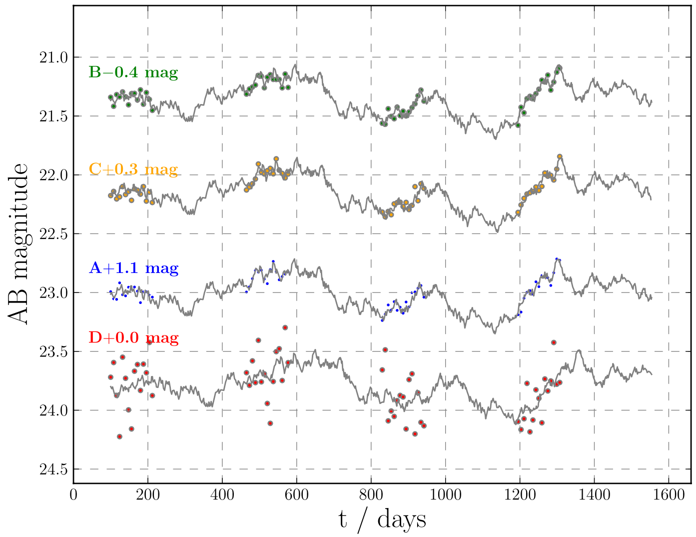
Lens detection



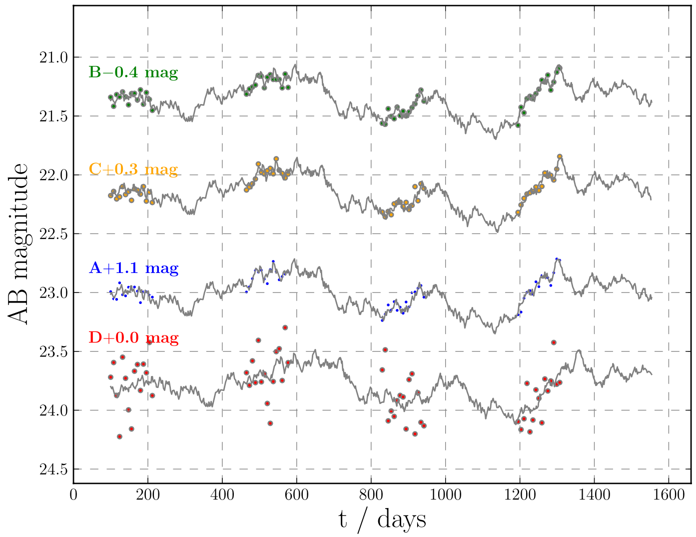
- **Catalog-based candidate detection.** *Needs: good deblender, the right parameters (color, morphology, variability) saved, rapidly executable DB queries.*
- **Image-based candidate classification**. *Needs: access to postage stamp images at data center in a "Multi-Fit," via level 3 API, reliable PSF models and image registration. Joint w/ Euclid? Practise w/ HSC!*
- **Candidate visualization for quality control.** *Needs: optimally-viewable color images, potential for crowd-sourcing*



Lens measurement



Lens measurement



- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*

Time Delay Challenge

Time Delay Challenge

Goals:

Time Delay Challenge

Goals:

1. Assess performance of current time delay estimation algorithms on LSST-like data

Time Delay Challenge

Goals:

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

Time Delay Challenge

Goals:

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

Time Delay Challenge

Goals:

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

Plan:

Time Delay Challenge

Goals:

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

Plan:

- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV

Time Delay Challenge

Goals:

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

Plan:

- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community “Good Teams” to infer time delays blindly, and submit results

Time Delay Challenge

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

Plan:
- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community “Good Teams” to infer time delays blindly, and submit results
- Publish paper on results together

Time Delay Challenge

Goals:

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

Plan:

- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community “Good Teams” to infer time delays blindly, and submit results
- Publish paper on results together

Time Delay Challenge

Goals:

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

Plan:

- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community “Good Teams” to infer time delays blindly, and submit results
- Publish paper on results together

Evil Team:

Time Delay Challenge

Goals:

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

Plan:

- “Evil Team” to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community “Good Teams” to infer time delays blindly, and submit results
- Publish paper on results together

Evil Team:

Kai Liao, Greg Dobler, Tommaso Treu (UCSB), Chris Fassnacht, Nick Rumbaugh (UCDavis), Phil Marshall (SLAC)

Time Delay Challenge

Goals:

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

Plan:

- "Evil Team" to generate large set of simulated lightcurves spanning expectations for Stage II-IV
- Challenge community "Good Teams" to infer time delays blindly, and submit results
- Publish paper on results openly

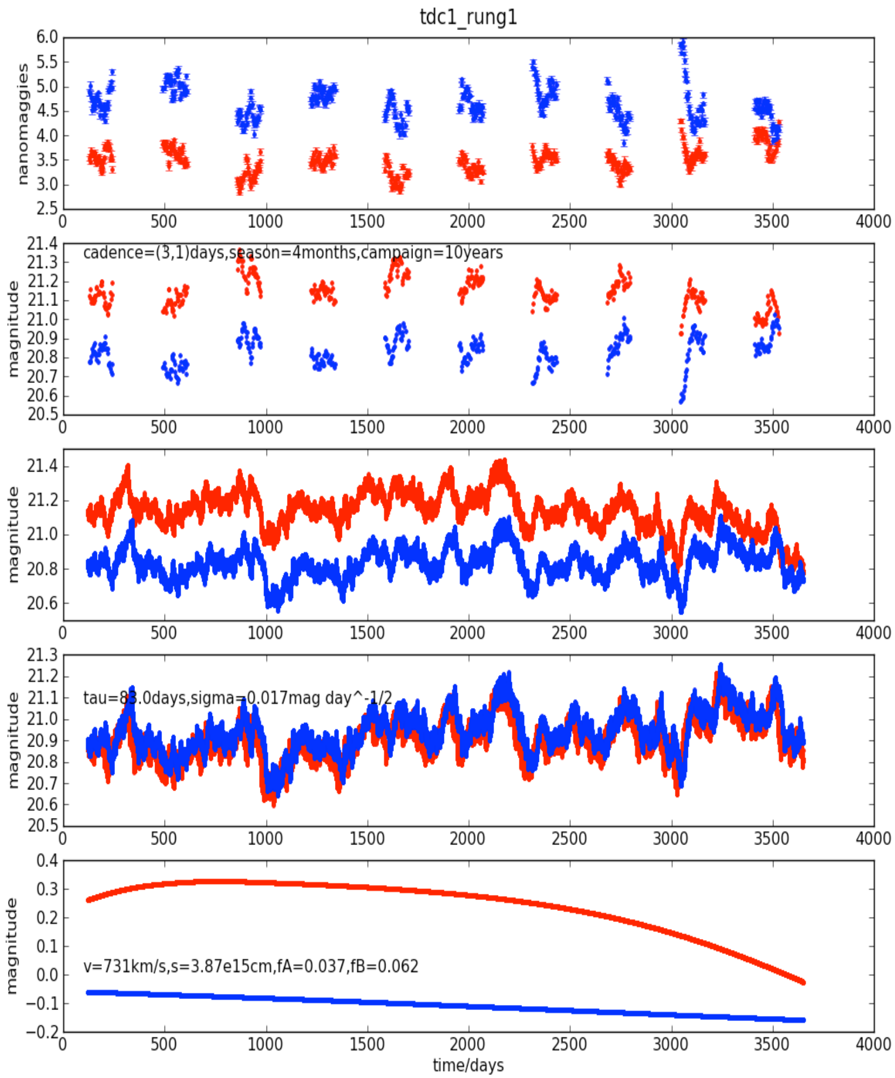
Evil Team:

Kai Liao, Greg Dobler, Tommaso Treu (UCSB), Chris Fassnacht, Nick Rumbaugh (UCDavis), Phil Marshall (SLAC)

Deadline: July 1st, 2014

LSST TDC: example lightcurves

10 years, 3 day cadence



Mock data

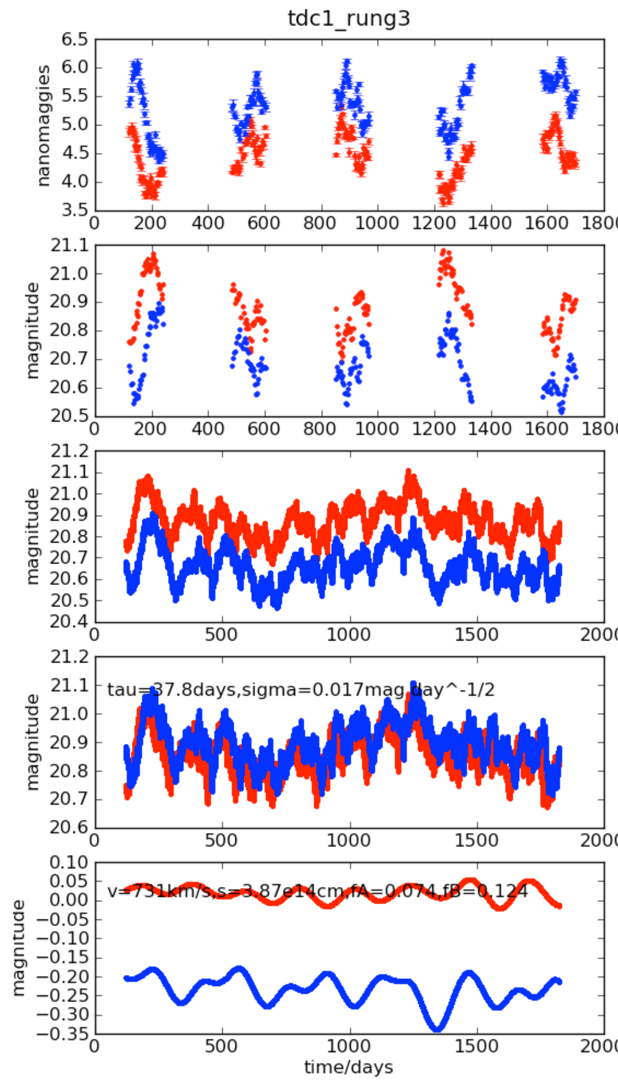
- without noise

- fully sampled

- no lensing

- microlensing

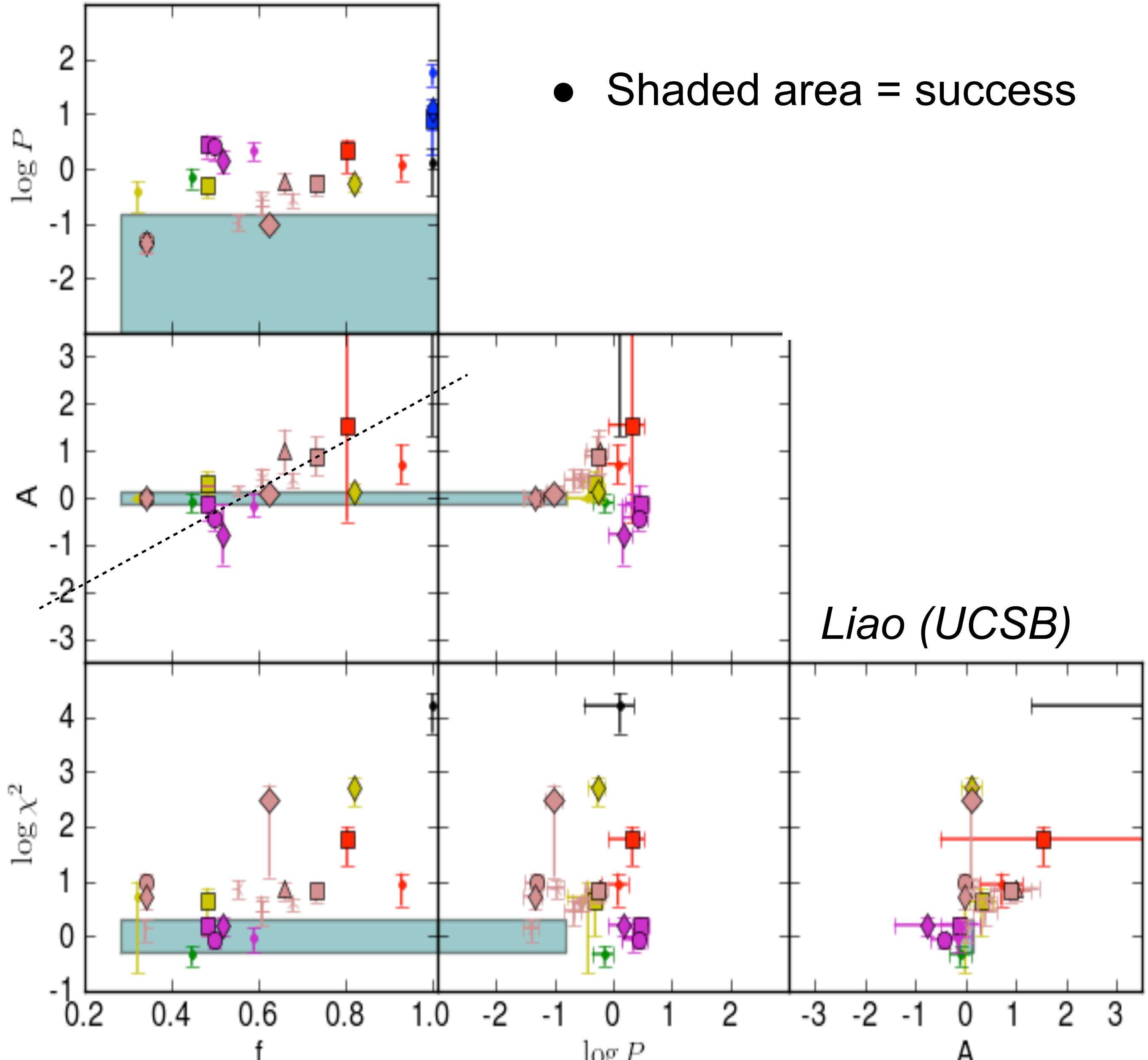
5 years, 3 days



TDC0: challenge qualifying

Metrics:
- Precision P
- Accuracy A
- Fraction f
- Goodness of fit

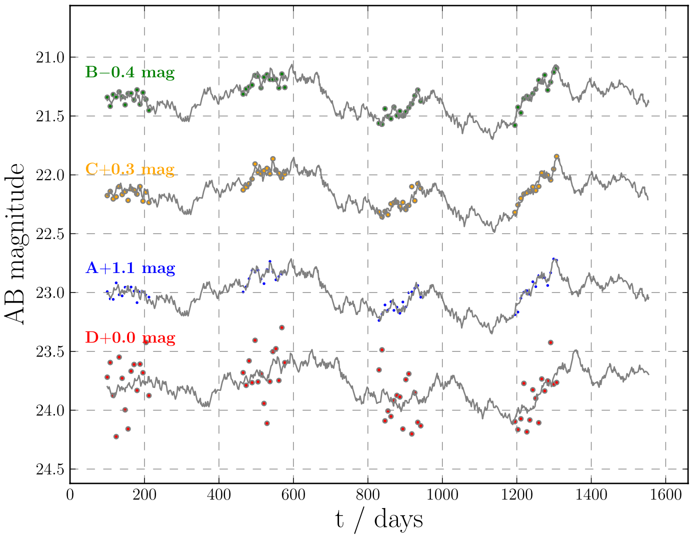
TDC0 qualifying:
- ~50 datasets
- 7 teams, 27 entries
- 3 teams have beaten 15% P, A so far
- Goal: *A=0.2%*



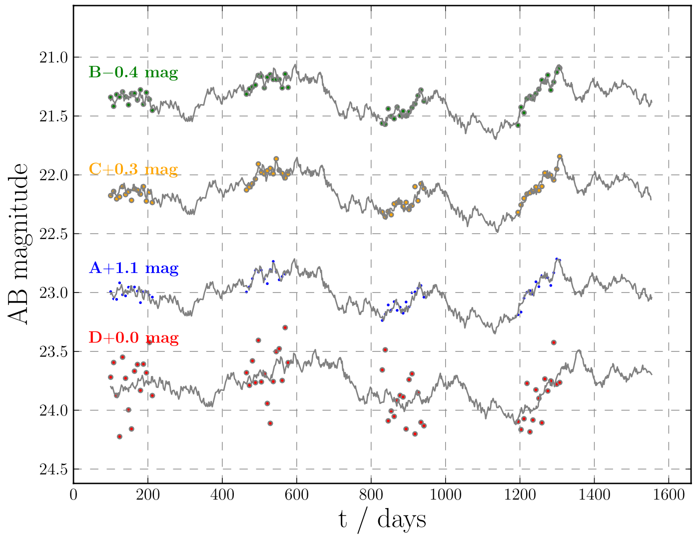
- Shaded area = success

Liao (UCSB)

Lens measurement

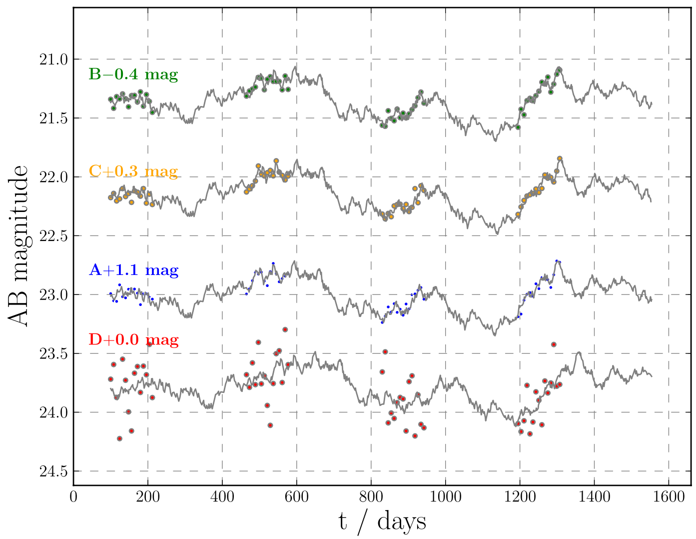


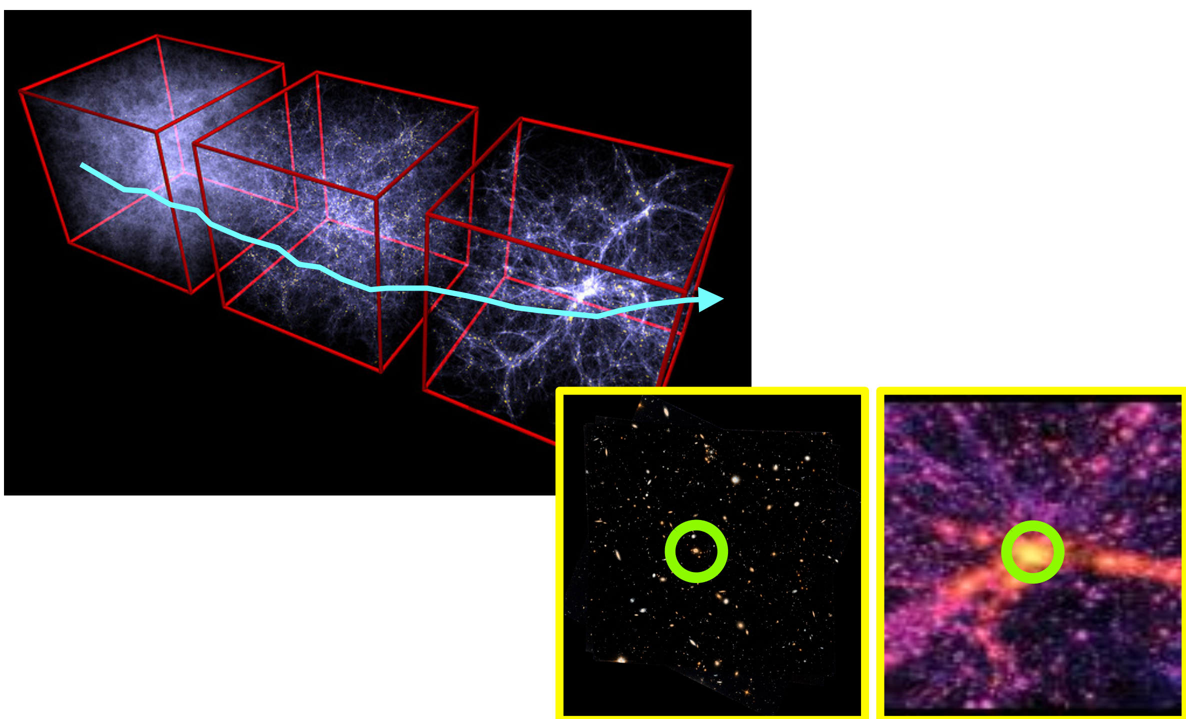
Lens measurement

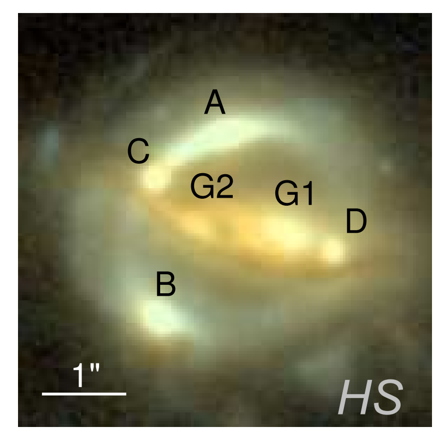


- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*

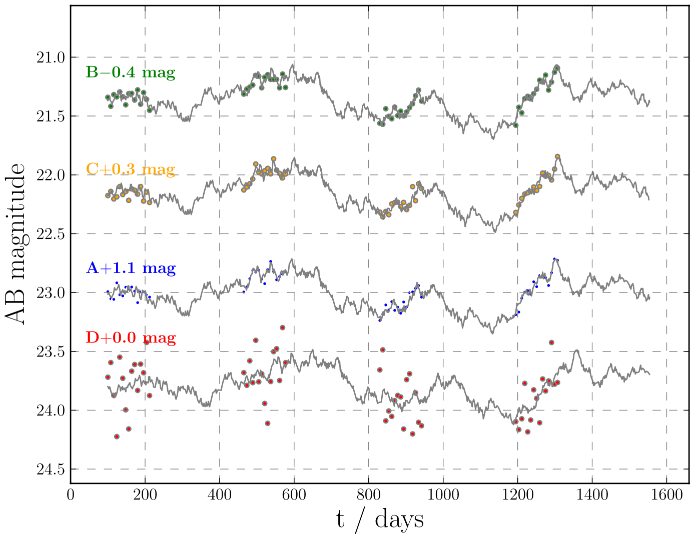
Lens measurement



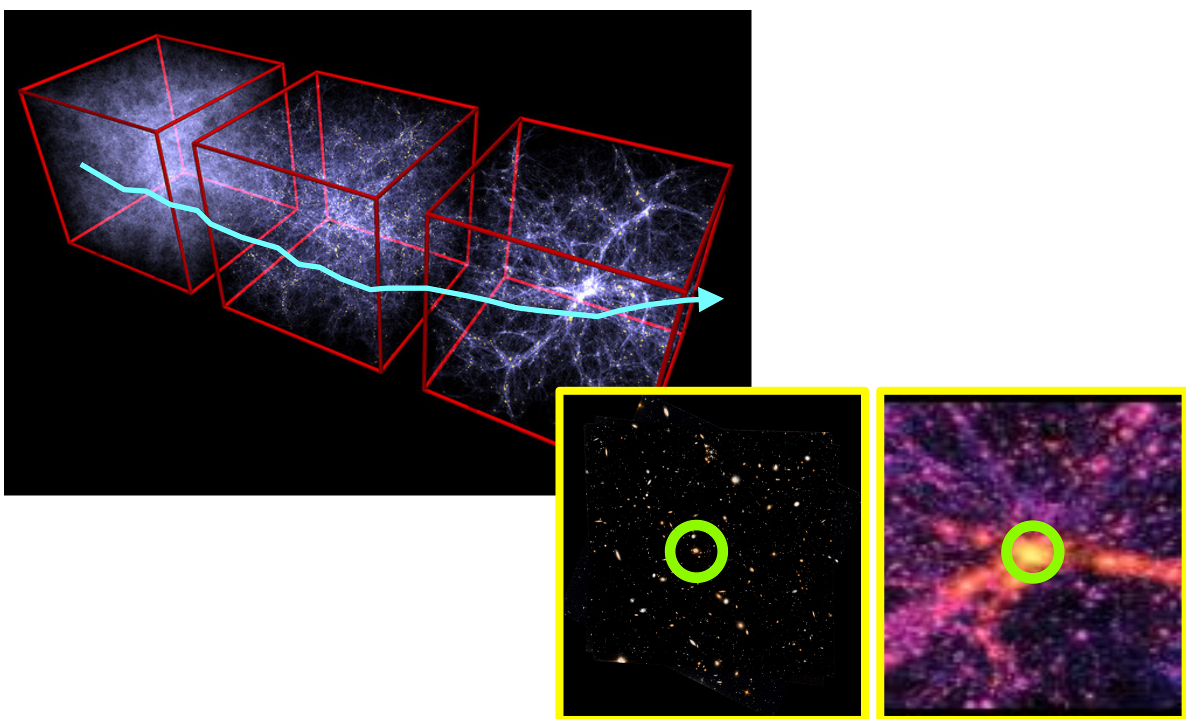


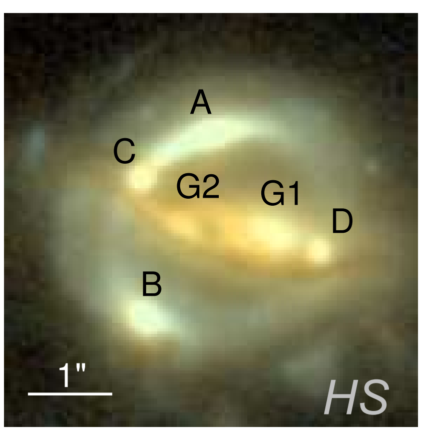


Lens measurement

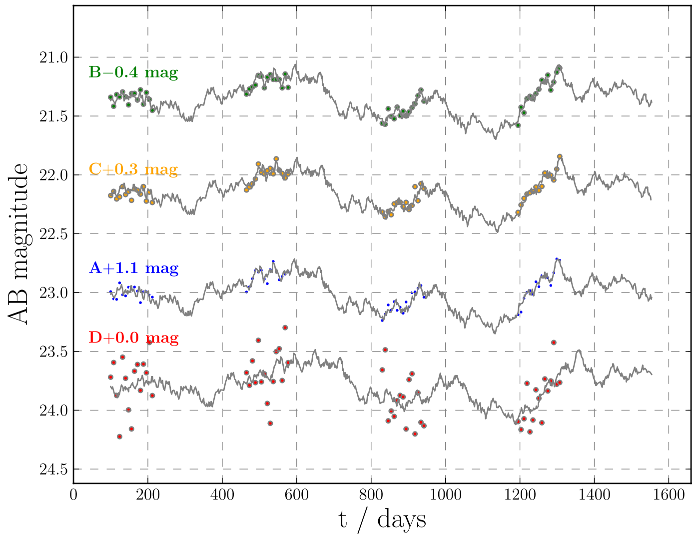


- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*

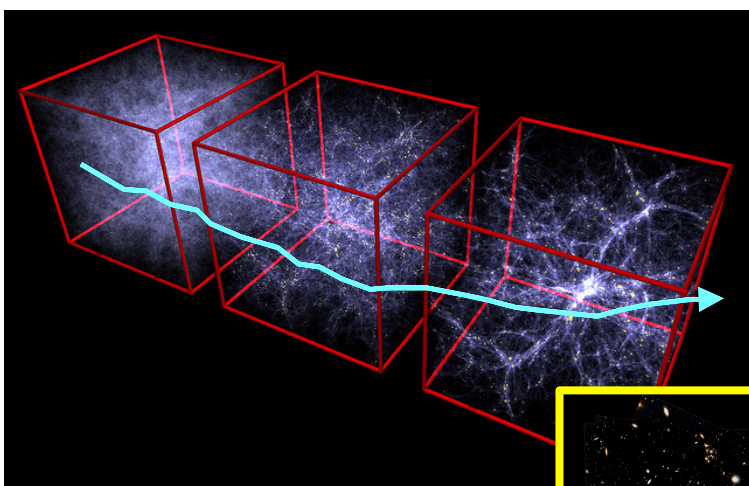


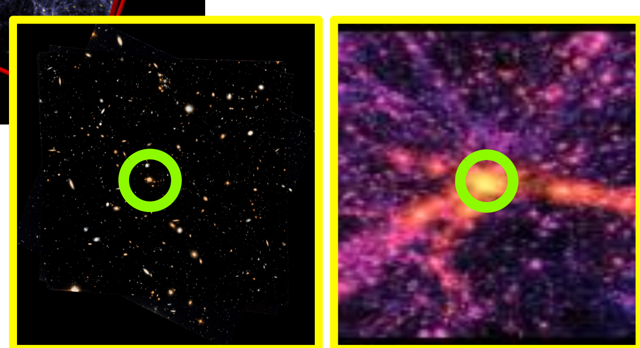


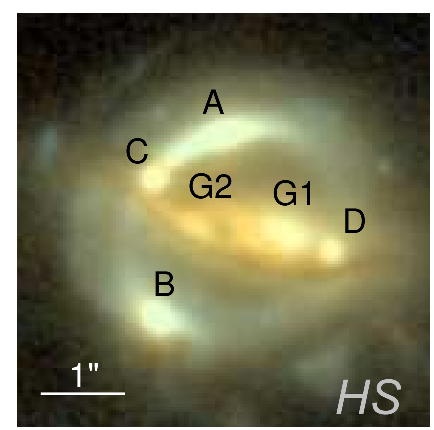
Lens measurement



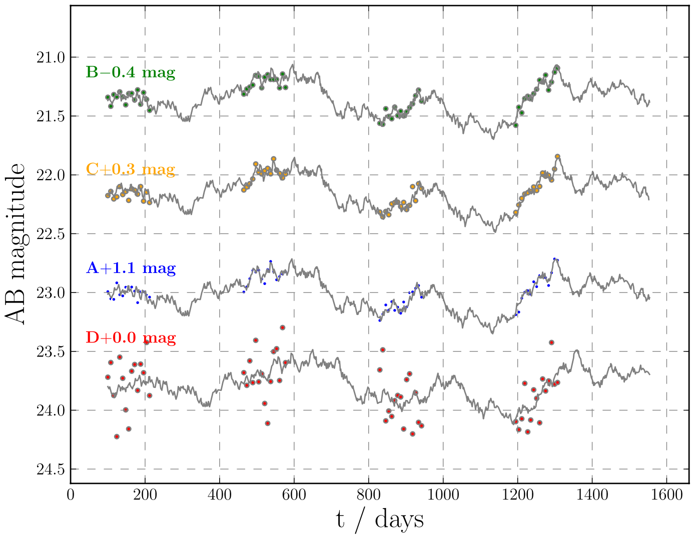
- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*
- **Detailed pixel modeling**. *Needs: high res follow-up: JWST, ELTs*



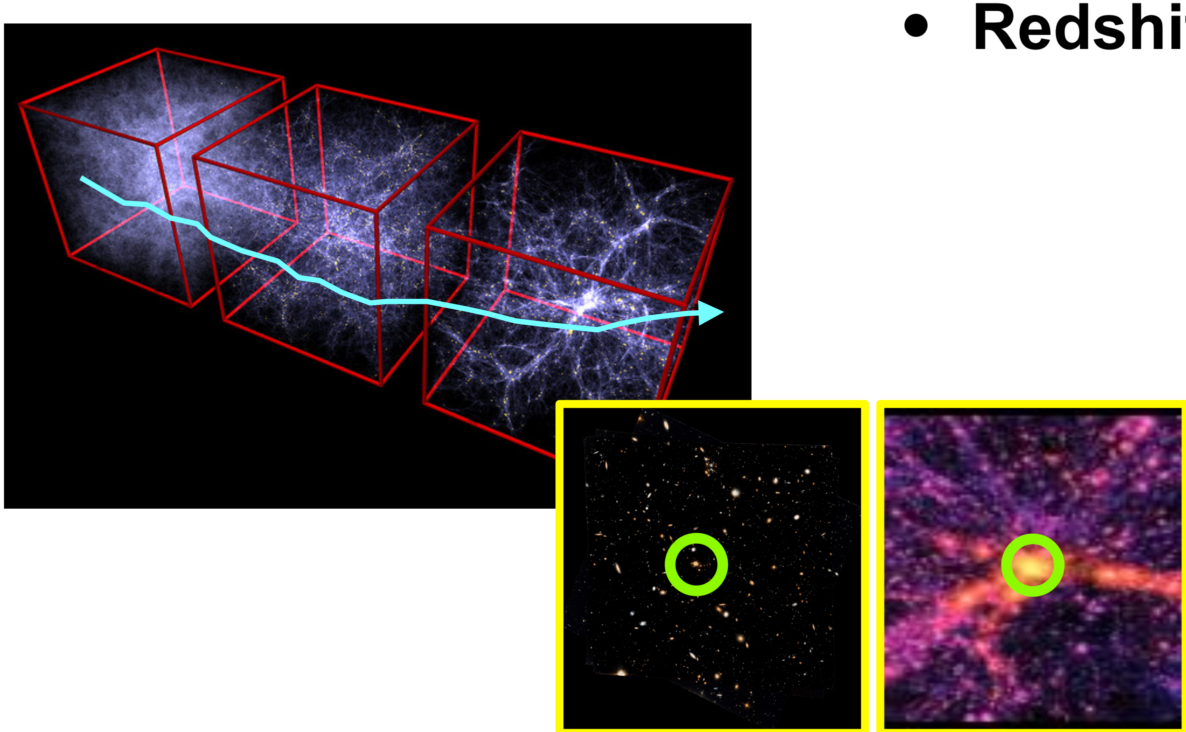


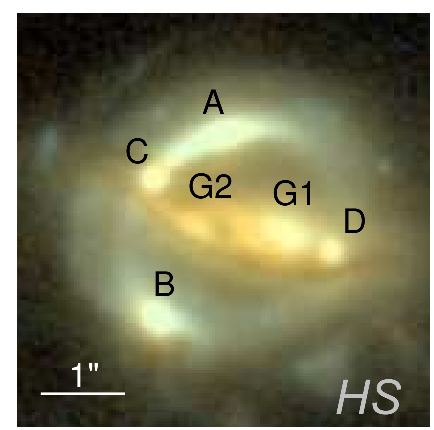


Lens measurement

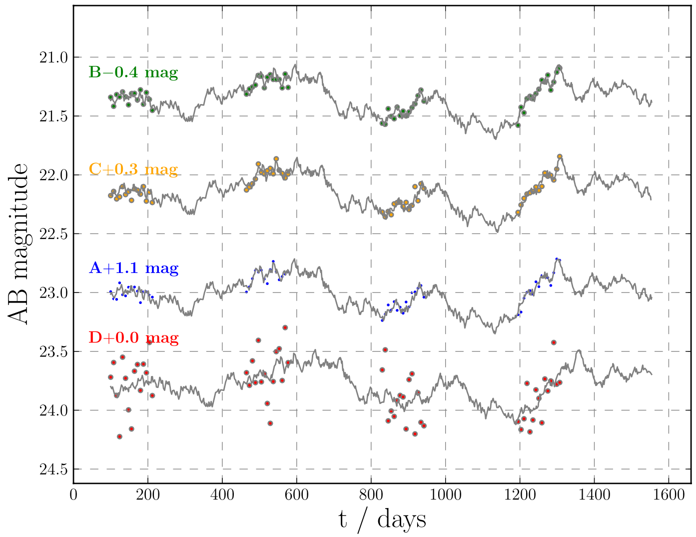


- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*
- **Detailed pixel modeling**. *Needs: high res follow-up: JWST, ELTs*
- **Redshifts.** *Needs: deep spectra*

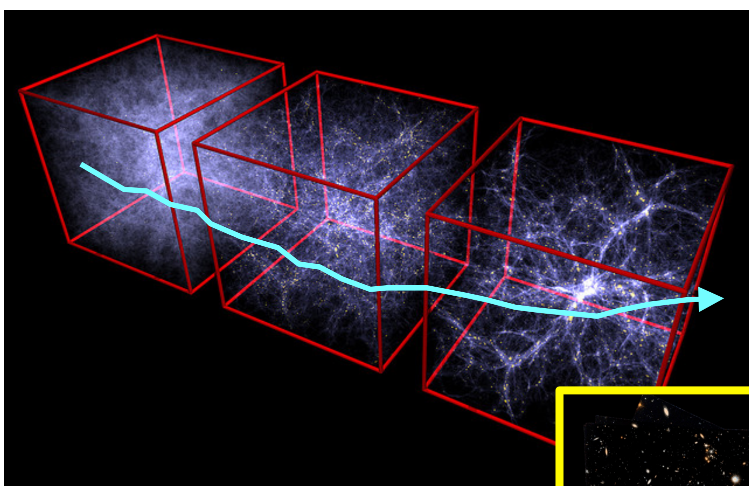


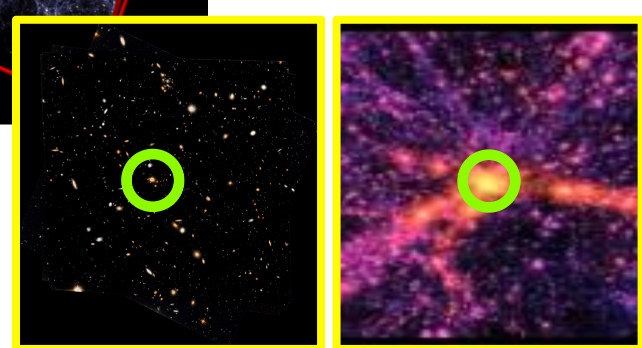


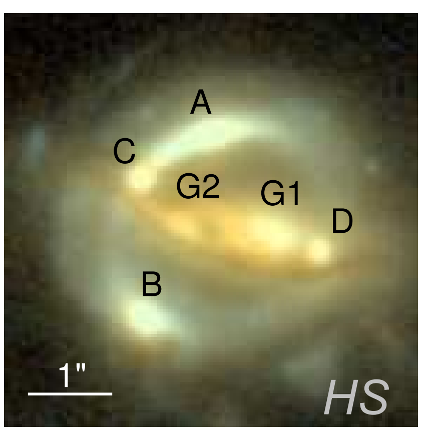
Lens measurement



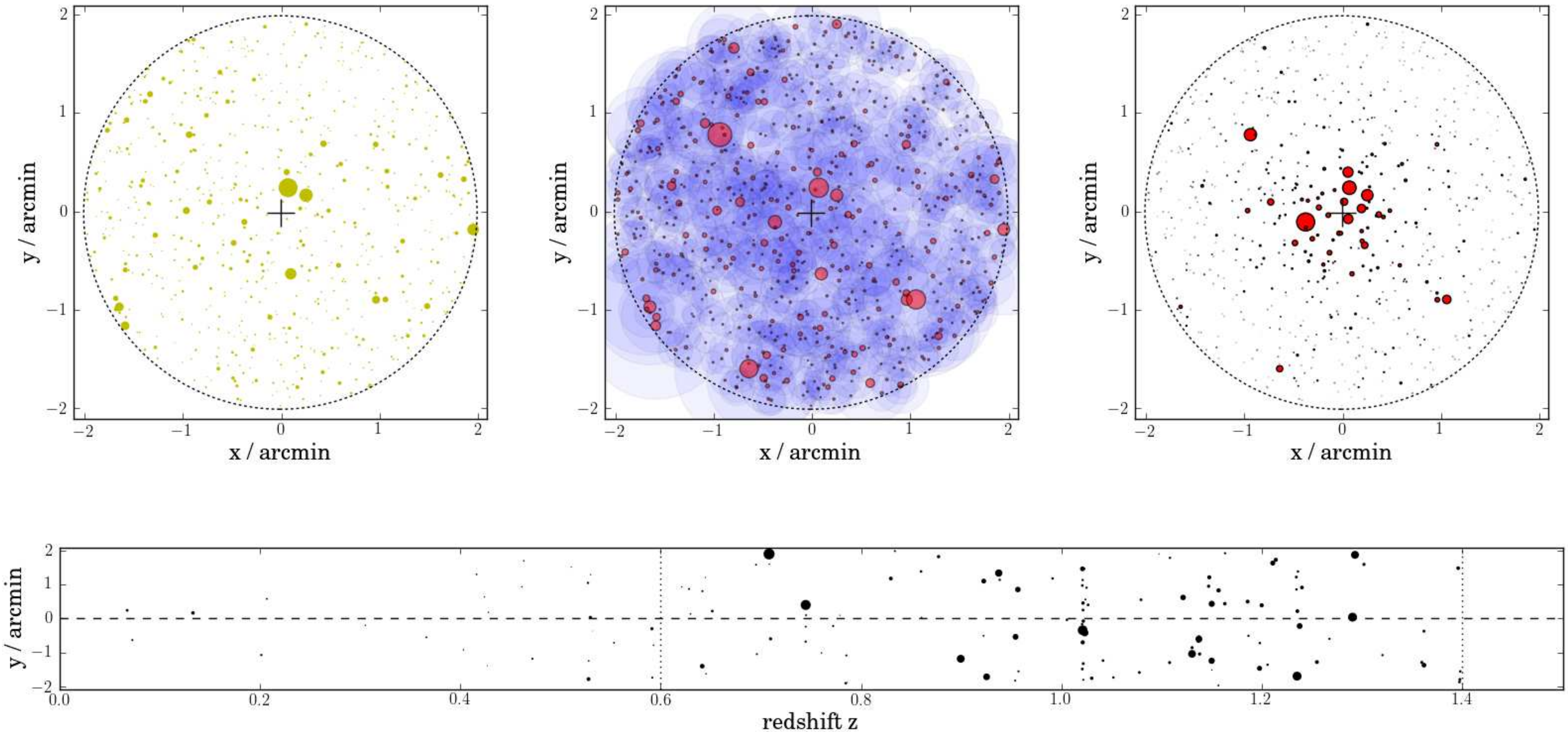
- **Time delay estimation.** *Needs: good photocal, long seasons, regular sampling, optimal lightcurve extraction, multi-filter AGN/SN+microlensing model.*
- **Detailed pixel modeling**. *Needs: high res follow-up: JWST, ELTs*
- **Redshifts.** *Needs: deep spectra*
- **Environment density characterisation.** *Needs: M* and z (photo-z?) for all galaxies within ~5 arcmin radius*







Lightcone reconstruction



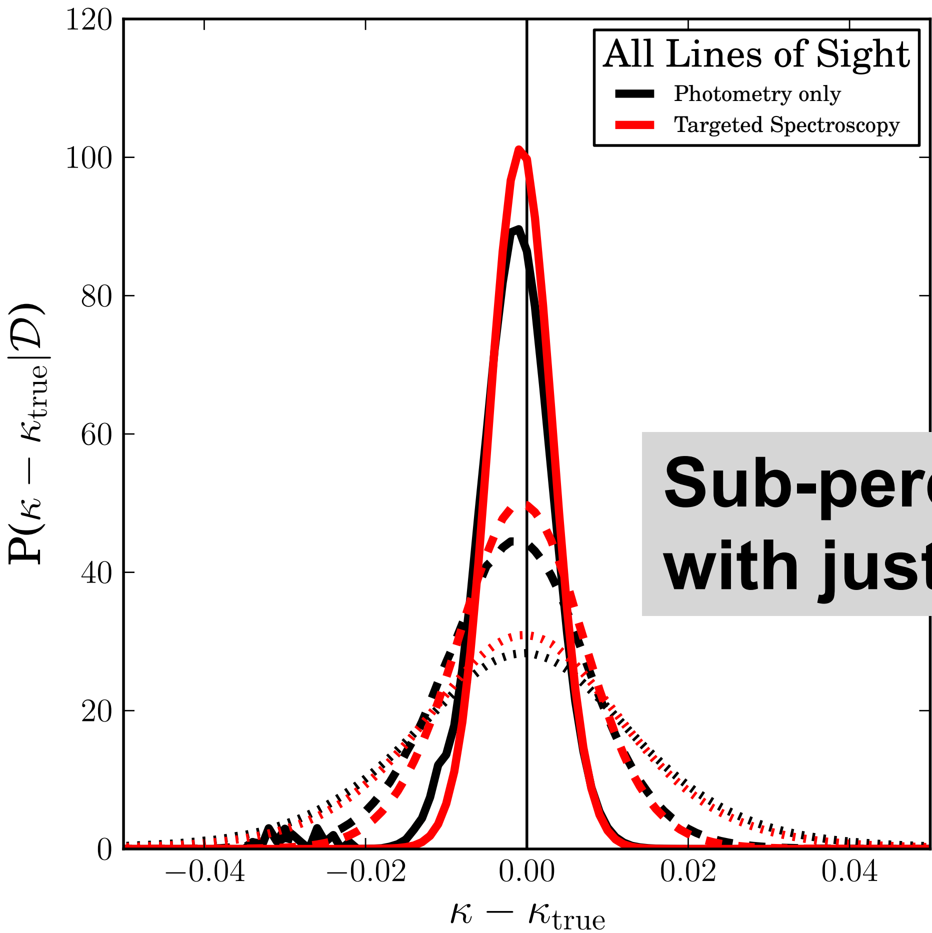
Collett, Marshall et al 2013 in prep:

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

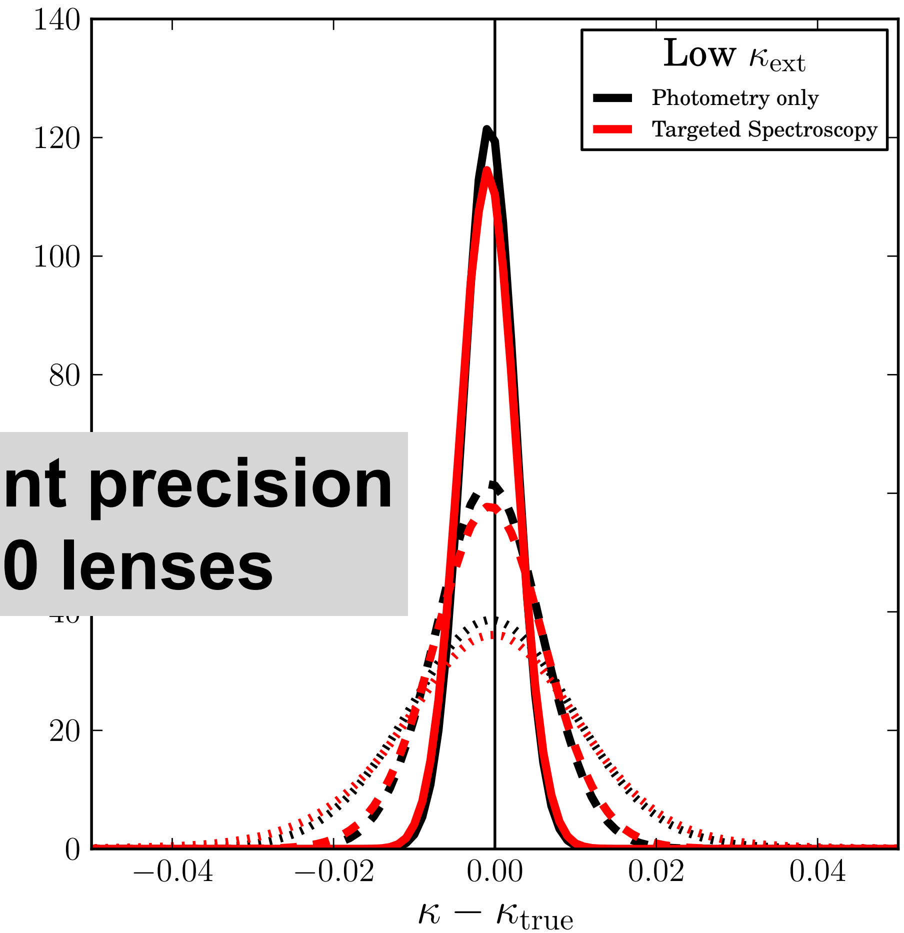
What will sub-percent distance accuracy take?

Lightcone reconstruction

Large Synoptic Survey Telescope



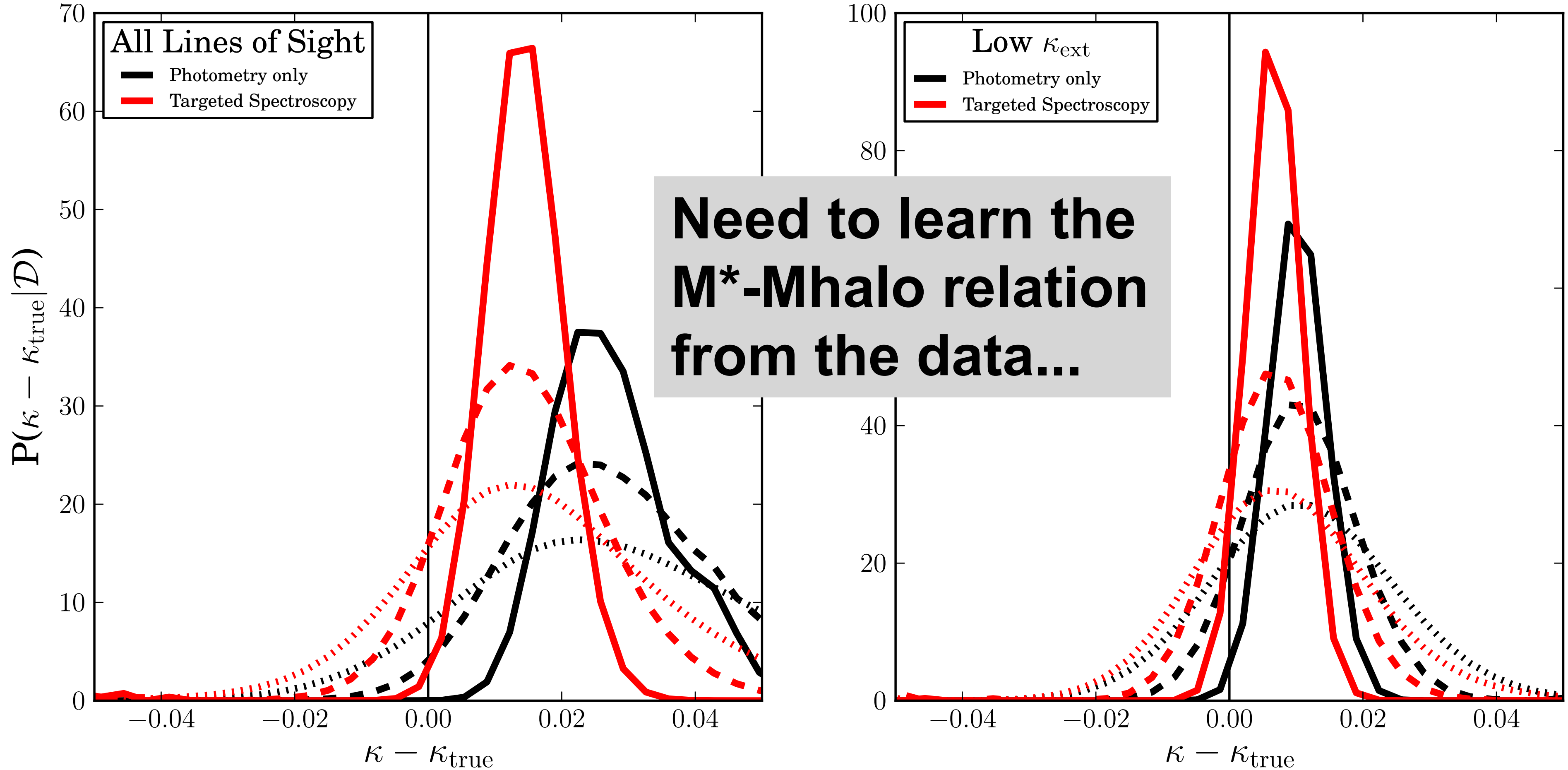
Sub-percent precision with just 20 lenses



Collett, Marshall et al 2013 in prep:
Line of sight mass reconstruction from photometric catalogs, calibrated with and tested against the Millennium Simulation.
What will sub-percent distance accuracy take?

Lightcone reconstruction

Large Synoptic Survey Telescope



Need to learn the M*-Mhalo relation from the data...

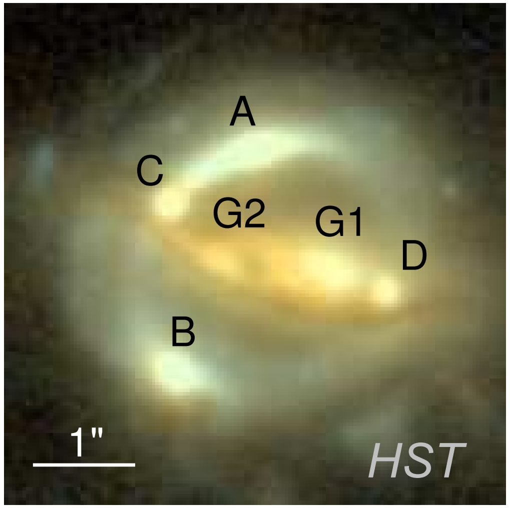
Collett, Marshall et al 2013 in prep:

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

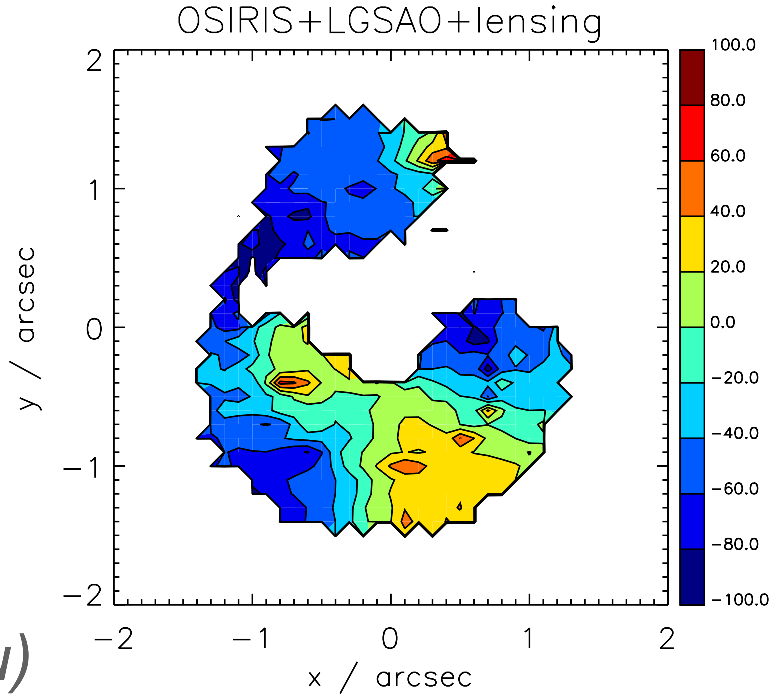
What will sub-percent distance accuracy take?

Following up 1000 lenses

IFU observations (standard in 2025). *Redshifts, lens kinematics, 3D ring images all in one shot.*



Exposure time ~ D^2 R^2 for faint extended sources: it's the Einstein Rings we need.



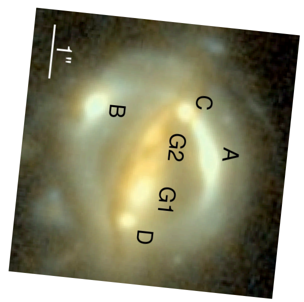
How much telescope time for 1000 lenses?

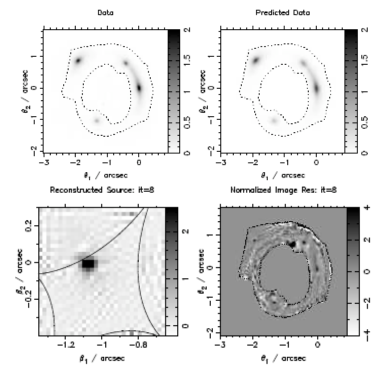
- **Keck (2012): ~3000 hrs**
- **Keck (NGAO): ~350 hrs**
- **TMT: ~60 hrs**
- **JWST: ~1000 snapshots (few hundred orbits)**

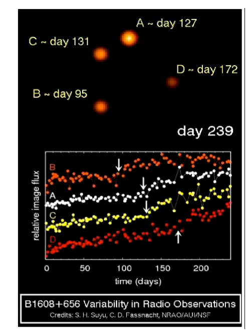
(Simulations and ETC with T. Treu)

Dark Energy from just 100 LSST quads

B1608-style cosmological parameter analysis:





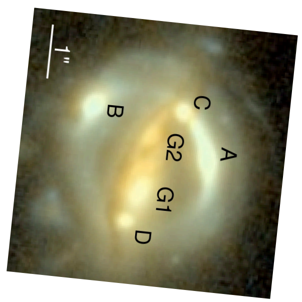


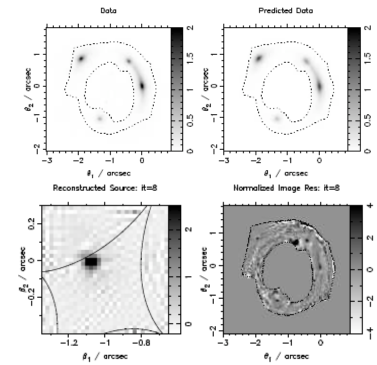
- Assume:

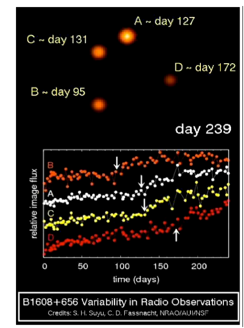
Sandford, Marshall et al in prep

Dark Energy from just 100 LSST quads

B1608-style cosmological parameter analysis:





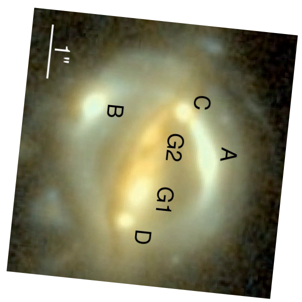


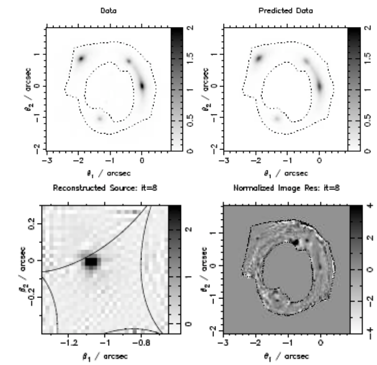
- Assume:
  - ***spectroscopic redshifts,*** *lens galaxy* ***velocity dispersions, JWST/ELT ring modeling*** *and* ***good time delays,***

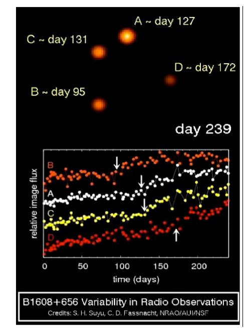
Sandford, Marshall et al in prep

Dark Energy from just 100 LSST quads

B1608-style cosmological parameter analysis:





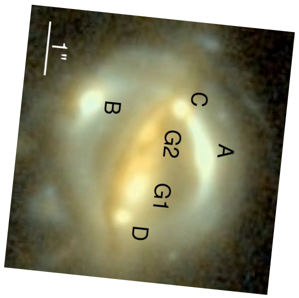


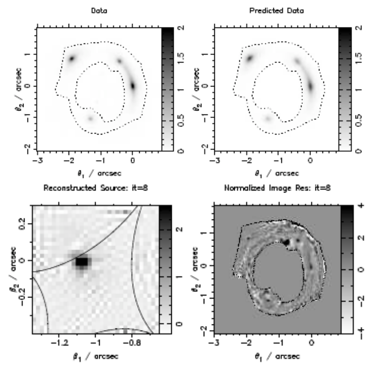
- Assume:
  - ***spectroscopic redshifts,*** *lens galaxy* ***velocity dispersions, JWST/ELT ring modeling*** *and* ***good time delays,***
  - *such that* ***detailed analysis*** *of individual lenses gives* ***5% precision on each time delay distance***

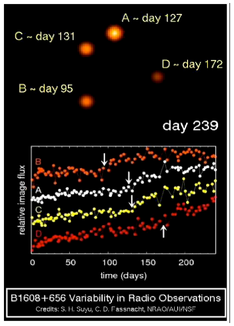
Sandford, Marshall et al in prep

Dark Energy from just 100 LSST quads

B1608-style cosmological parameter analysis:





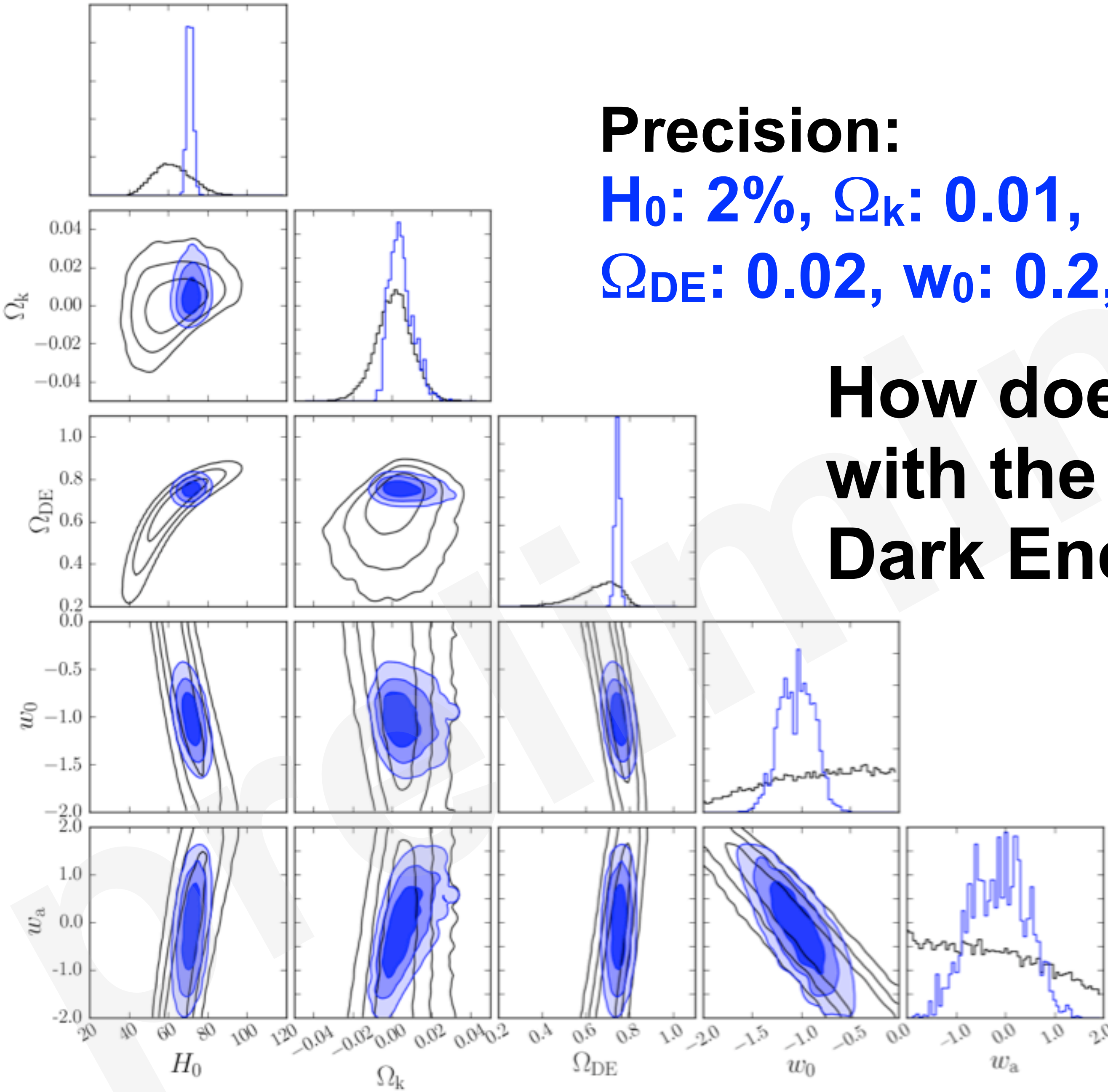


- Assume:
  - ***spectroscopic redshifts,*** *lens galaxy* ***velocity dispersions, JWST/ELT ring modeling*** *and* ***good time delays,***
  - *such that* ***detailed analysis*** *of individual lenses gives* ***5% precision on each time delay distance***

- **Importance-sample** the **Planck prior**

Sandford, Marshall et al in prep

Dark Energy from just 100 LSST quads



Precision:

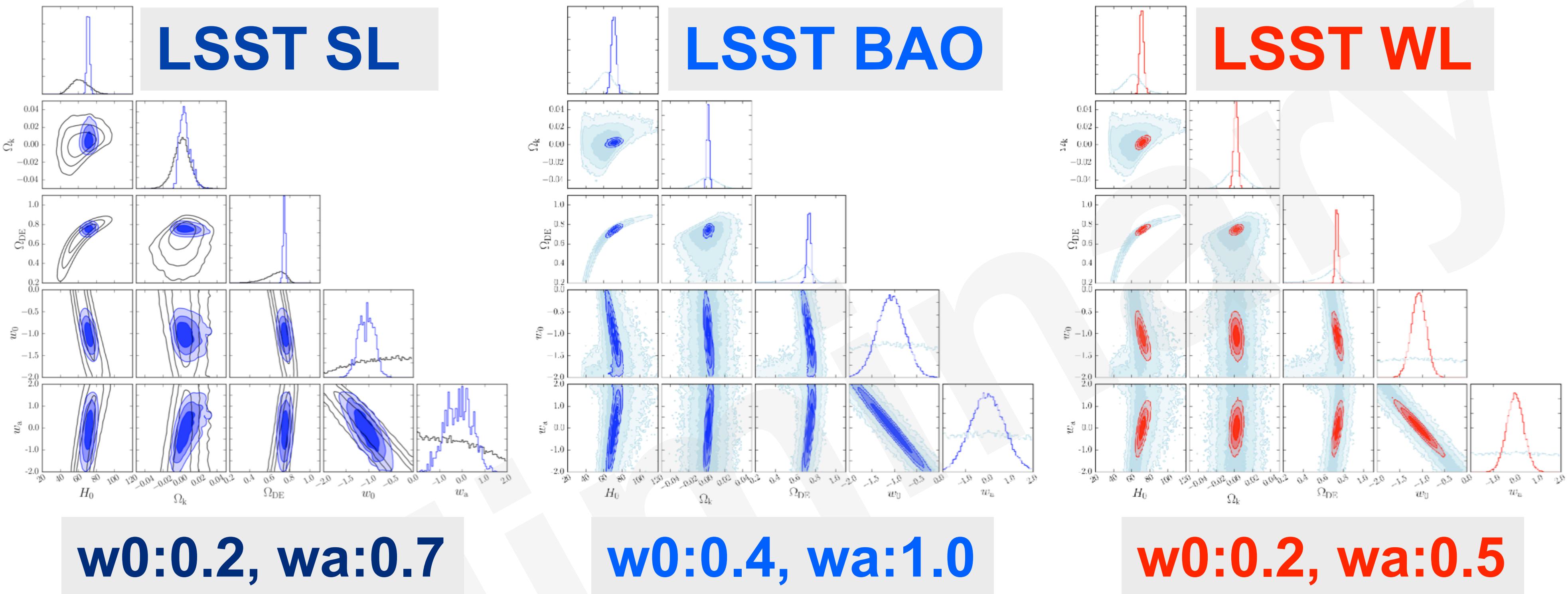
H_0: 2%, Ω_k: 0.01,

Ω_{DE}: 0.02, w_0: 0.2, w_a: 0.7

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

Sandford, Marshall et al in prep

Dark Energy from 100 LSST quads



5% time delay distances to 100 lenses found and monitored with LSST, and followed-up to B1608 levels, would yield ***Dark Energy constraints competitive with the primary LSST probes***

Sandford, Marshall et al in prep

Conclusions, Outlook

Conclusions, Outlook

- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc

Conclusions, Outlook

- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data

Conclusions, Outlook

- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data
- A competitive Stage IV Dark Energy experiment will require ~1000 B1608-like systems

Conclusions, Outlook

- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data
- A competitive Stage IV Dark Energy experiment will require ~1000 B1608-like systems
- PS1, DES and HSC should *find* enough lenses

Conclusions, Outlook

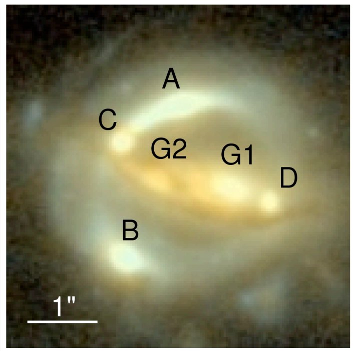
- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data
- A competitive Stage IV Dark Energy experiment will require ~1000 B1608-like systems
- PS1, DES and HSC should *find* enough lenses
- Time delays may need to come from LSST, which will monitor some 3000 lenses. Follow-up observations are feasible - and will enable a *lot* of extra science

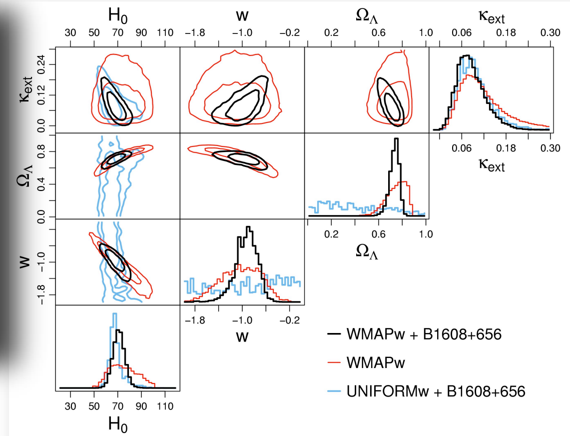
Conclusions, Outlook

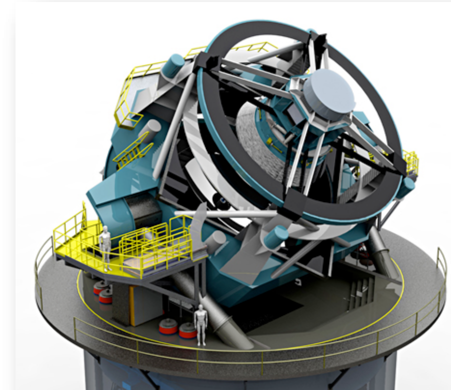
- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data
- A competitive Stage IV Dark Energy experiment will require ~1000 B1608-like systems
- PS1, DES and HSC should *find* enough lenses
- Time delays may need to come from LSST, which will monitor some 3000 lenses. Follow-up observations are feasible - and will enable a *lot* of extra science
- Data model has to keep up with statistical precision: prevent systematic errors by testing analysis against simulations of ever-increasing realism

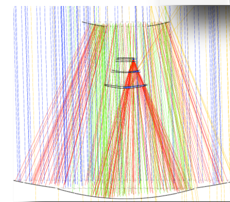
Conclusions, Outlook

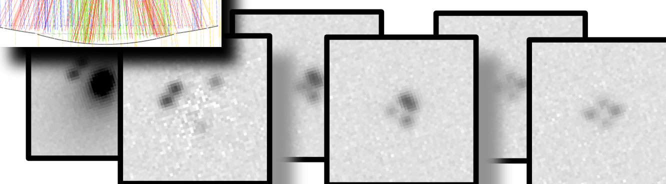
- Time delay lenses are an interesting independent cosmological probe, with very different systematics to BAO, SNe etc
- B1608 and RXJ1131 each provide comparable constraints on H_0 and w to all current BAO data
- A competitive Stage IV Dark Energy experiment will require ~1000 B1608-like systems
- PS1, DES and HSC should *find* enough lenses
- Time delays may need to come from LSST, which will monitor some 3000 lenses. Follow-up observations are feasible - and will enable a *lot* of extra science
- Data model has to keep up with statistical precision: prevent systematic errors by testing analysis against simulations of ever-increasing realism

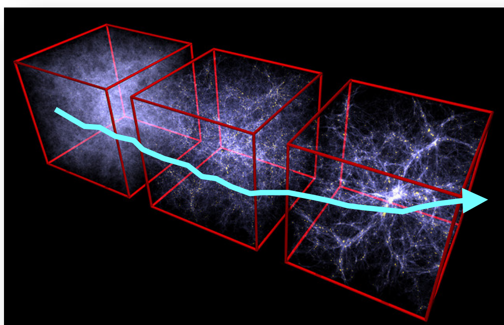

A
C
G2
G1
D
B
1"


H_0
w
Ω_Λ
κ_{ext}
WMAPw + B1608+656
WMAPw
UNIFORMw + B1608+656

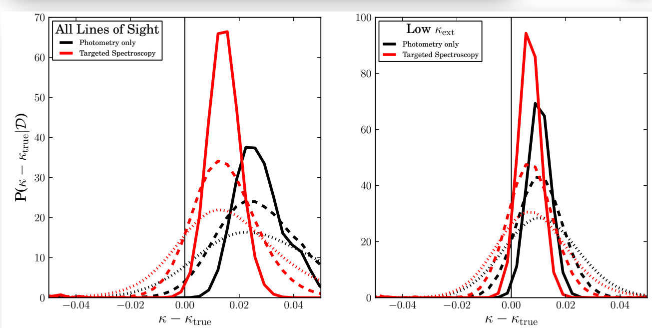


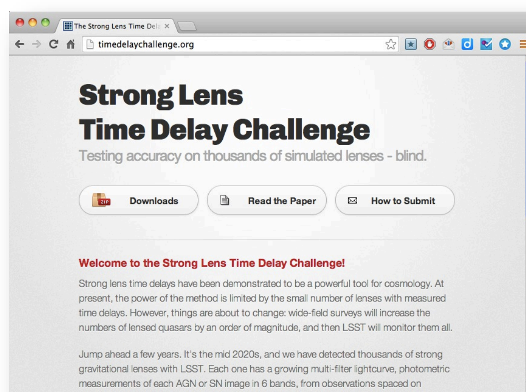


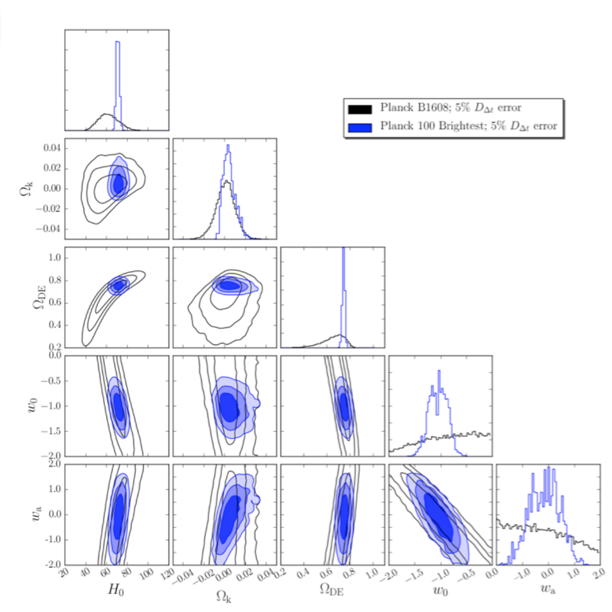




Questions


All Lines of Sight
Photometry only
Targeted Spectroscopy
Low κ_{ext}
Photometry only
Targeted Spectroscopy
$P(\kappa - \kappa_{true}|\mathcal{D})$
$\kappa - \kappa_{true}$


The Strong Lens Time Dela
timedelaychallenge.org
Strong Lens
Time Delay Challenge
Testing accuracy on thousands of simulated lenses - blind.
Downloads
Read the Paper
How to Submit
Welcome to the Strong Lens Time Delay Challenge!
Strong lens time delays have been demonstrated to be a powerful tool for cosmology. At present, the power of the method is limited by the small number of lenses with measured time delays. However, things are about to change: wide-field surveys will increase the numbers of lensed quasars by an order of magnitude, and then LSST will monitor them all.
Jump ahead a few years. It's the mid 2020s, and we have detected thousands of strong gravitational lenses with LSST. Each one has a growing multi-filter lightcurve, photometric measurements of each AGN or SN image in 6 bands, from observations spaced on


Planck B1608; 5% $D_{\Delta t}$ error
Planck 100 Brightest; 5% $D_{\Delta t}$ error
H_0
Ω_k
Ω_{DE}
w_0
w_a