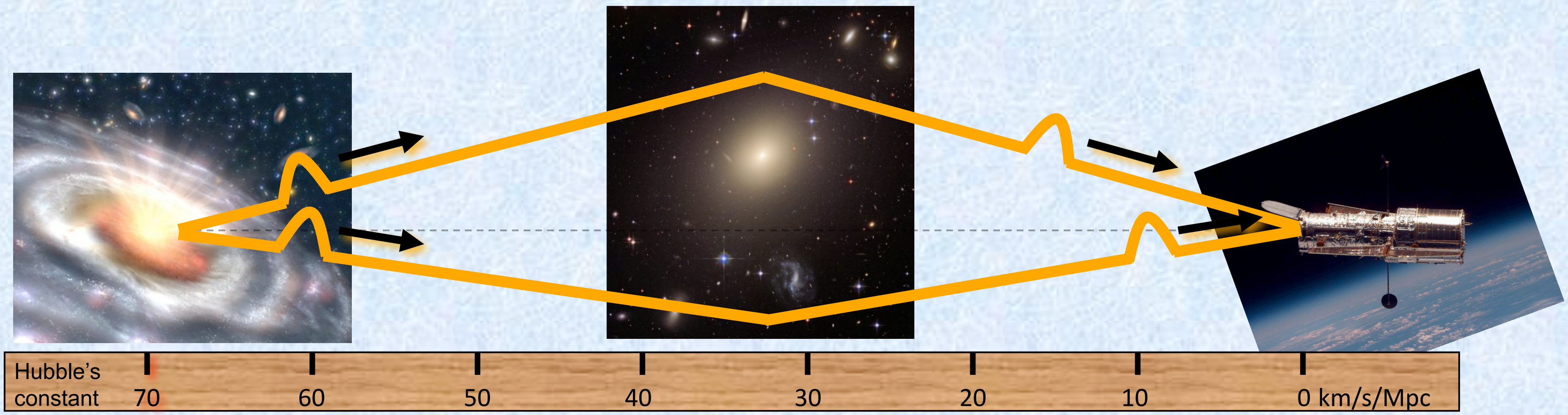
Cosmological Constraints from Gravitational Lens Time Delays

Dan Coe with Leonidas Moustakas

Caltech postdoc at JPL



Time Delay constraints: Outline

- Introduction
- Optimistic cosmological constraints (statistical uncertainties only)
  - Past, present, & future constraints on $\mathcal{T}_C$
  - Quantity vs. Quality
  - Future constraints on (h, Ω_m, Ω_{de}, Ω_k, w_0, w_a) from 4,000 LSST time delay lenses compared to other methods
- Systematics

I am not competing with your dark energy mission

- Time delays will be measured "for free"* by surveys already proposed
  - Pan-STARRS, DES, LSST, JDEM/IDECS, Euclid, OMEGA
  - Not proposing a new mission to accomplish this!
- Any large survey designed to repeatedly image large areas of sky will yield plenty of ancillary science, including time delay measurements

- * Supplementary observations may be useful but are not required

The work I will present is from Coe & Moustakas 2009 a,b,c

- Paper I: detailed lensing simulations
- Paper II: (astro-ph/0906.4108, resubmitted to ApJ) Constraints expected from LSST
  - statistical uncertainties only
  - assuming a flat universe, constant w, and Planck prior:

    $h \approx 0.7 \pm 0.007$ (1%)

    $\Omega_{de} \approx 0.7 \pm 0.005$

    $w \approx -1 \pm 0.026$
  - Dark Energy Figure of Merit less impressive
- Paper III: effect of systematic biases on derived cosmology

Previous investigations of time delay constraints on cosmology

- First proposed by Refsdal (1964) to constrain H_0
- Constraints on ther cosmological parameters explored by:
  - Lewis & Ibata (2002)
  - Linder (2004)
  - Mörtsell & Sunesson (2006)
  - Dobke et al. (2009)
- We present the most complete investigation of constraints on (h, Ω_m, Ω_{de}, Ω_k, w_0, w_a) including various priors

The Dark Ages

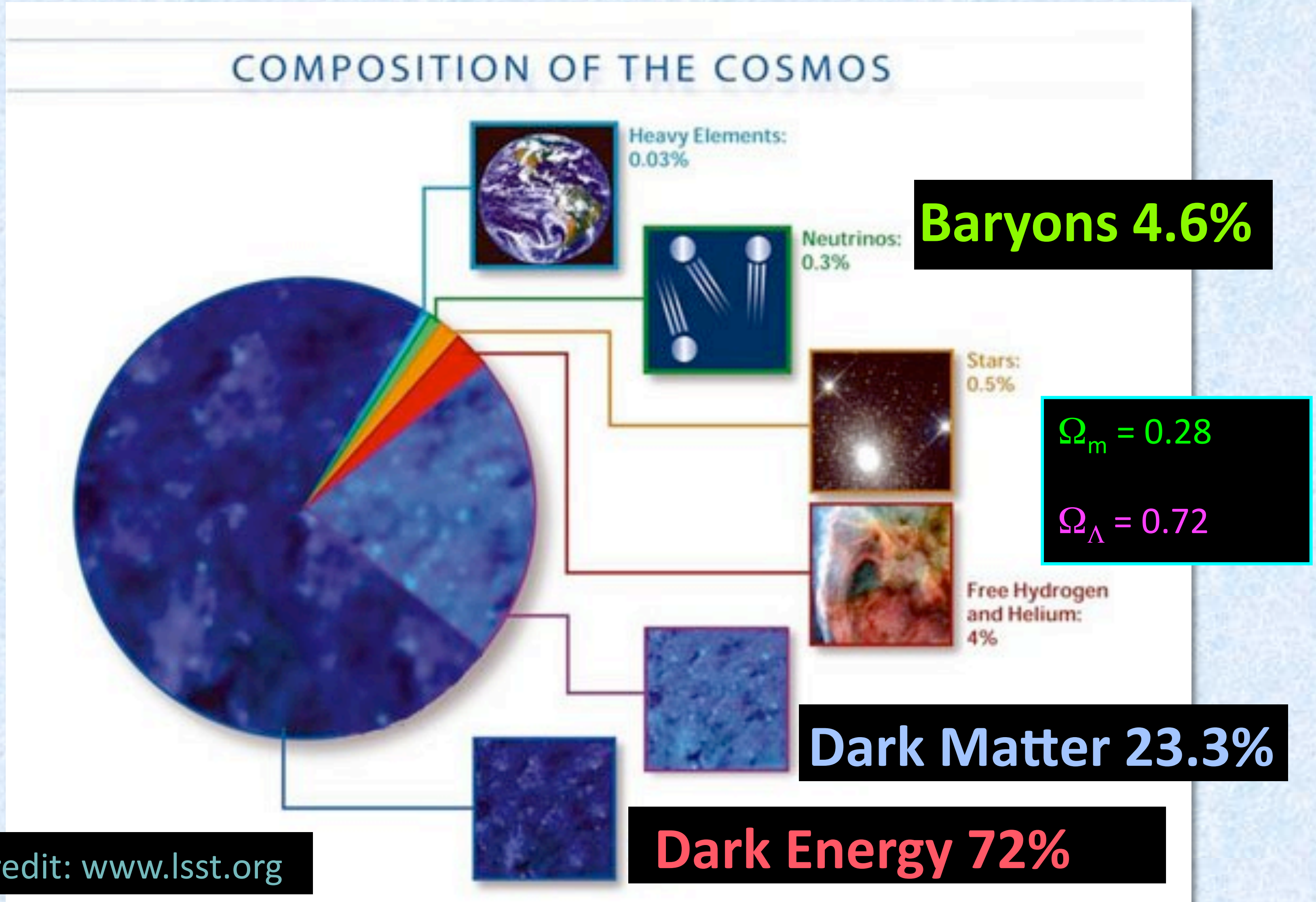
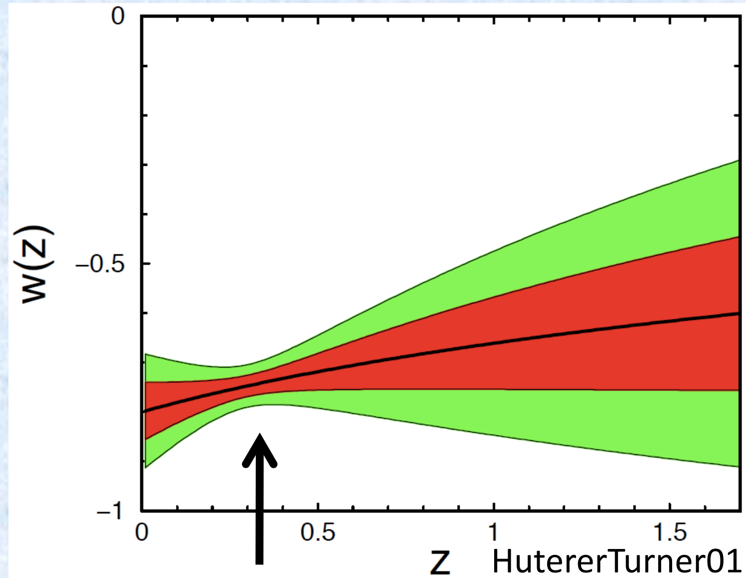


Image credit: www.lsst.org

Our ignorance about dark energy parameterized:

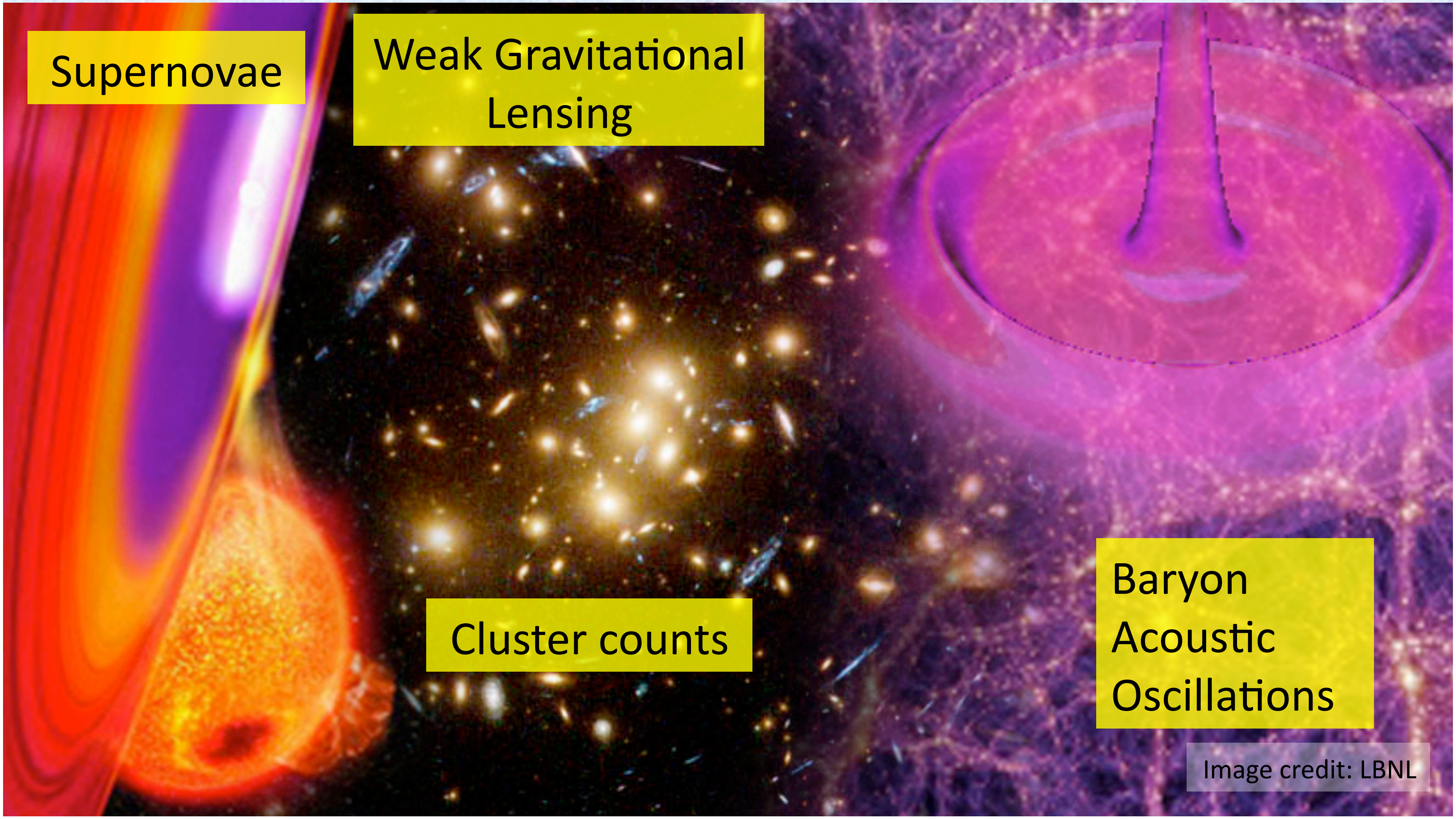
The Dark Energy Equation of State

- Vacuum energy with negative pressure? $P = w\rho$ ($w \sim -1$)
- Data is currently consistent with the "simplest theory", a cosmological constant Λ: $w = -1 =$ constant
- Exciting discoveries would be:
  - $w_0 \neq -1$ (current value $\neq -1$)
  - $w_a \neq 0$ (w is evolving)
    - $w(z) = w_0 + w_a (1-a) = w_0 + w_a\, z / (1+z)$
  - $w_p \equiv w(z_p) \neq -1$ ($w \neq -1$ at *any* z)
    - For a given experiment, w(z) is measured best at z_p, the "pivot redshift"
- Modified gravity? See Ali Vanderveld's talk next week

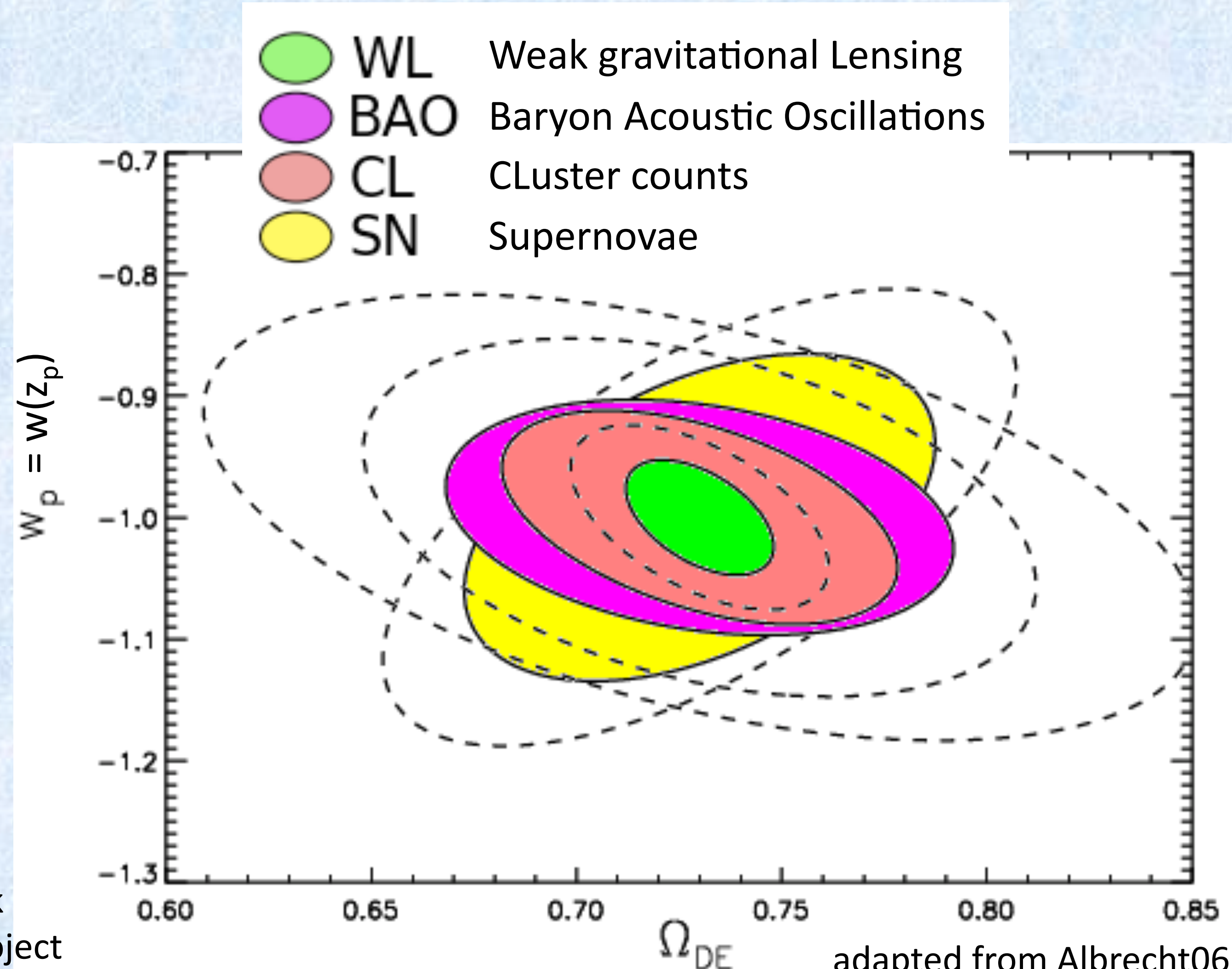


pivot redshift

The Dark Energy Task Force considered four methods of constraining w and the nature of dark energy



Future "Stage IV" projected constraints from large space-based missions

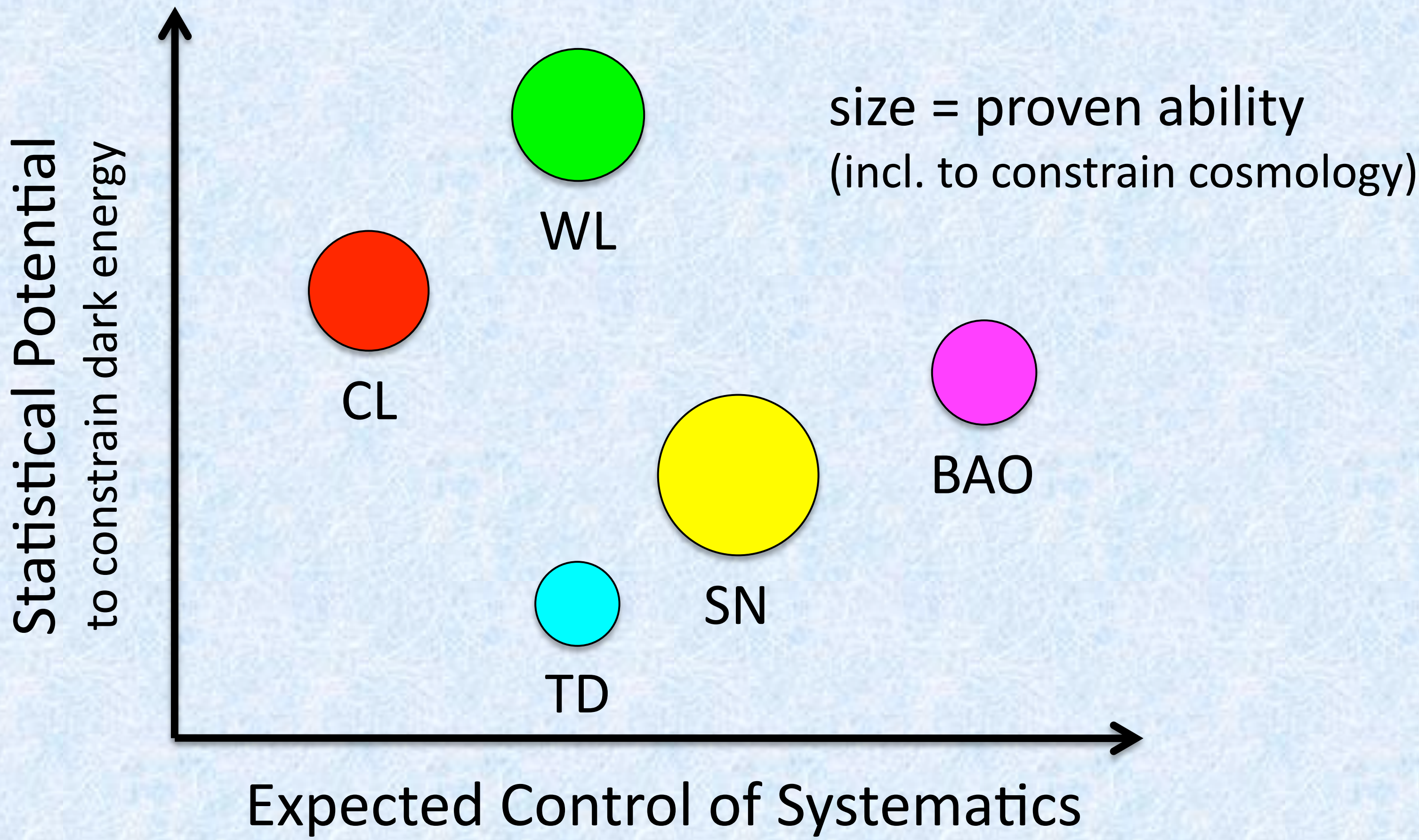


adapted from Albrecht06

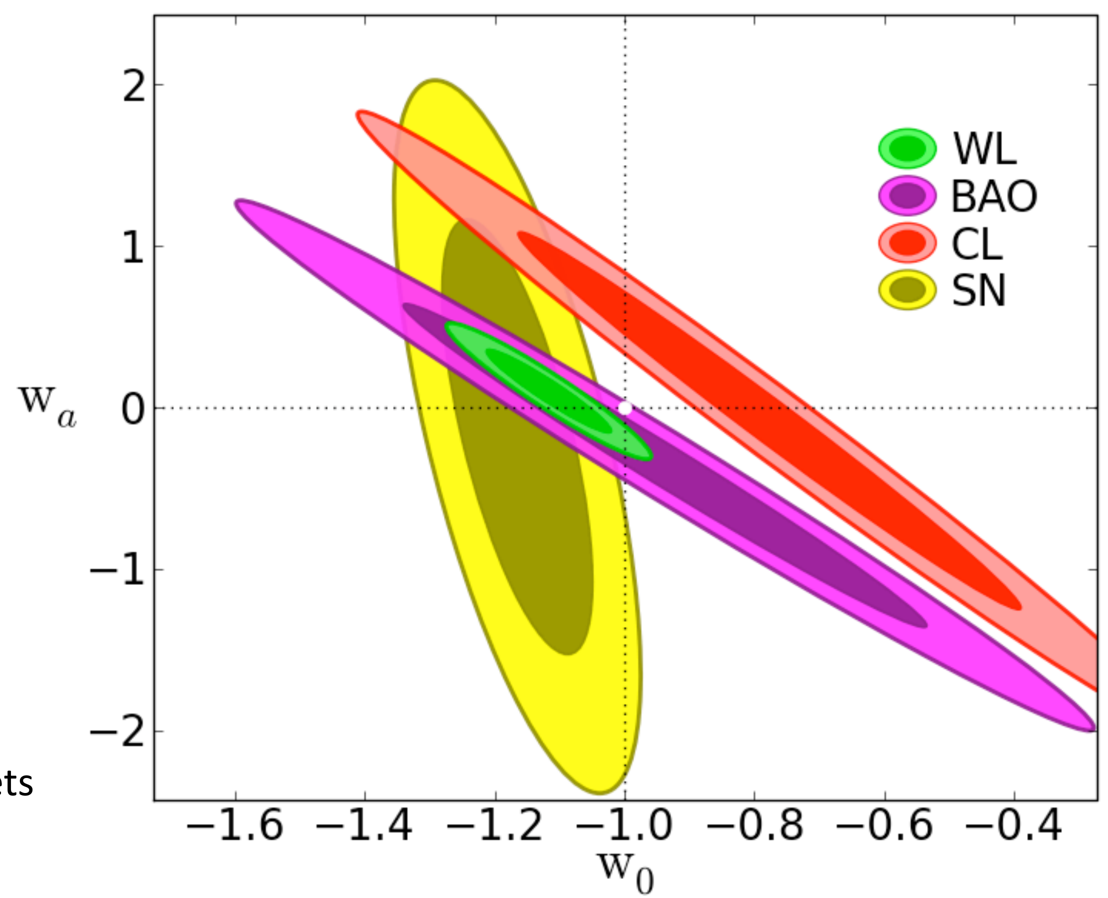
2-σ contours (optimistic & pessimistic)

Prior = Planck + HST Key Project (but not flatness)

No clear "best" probe

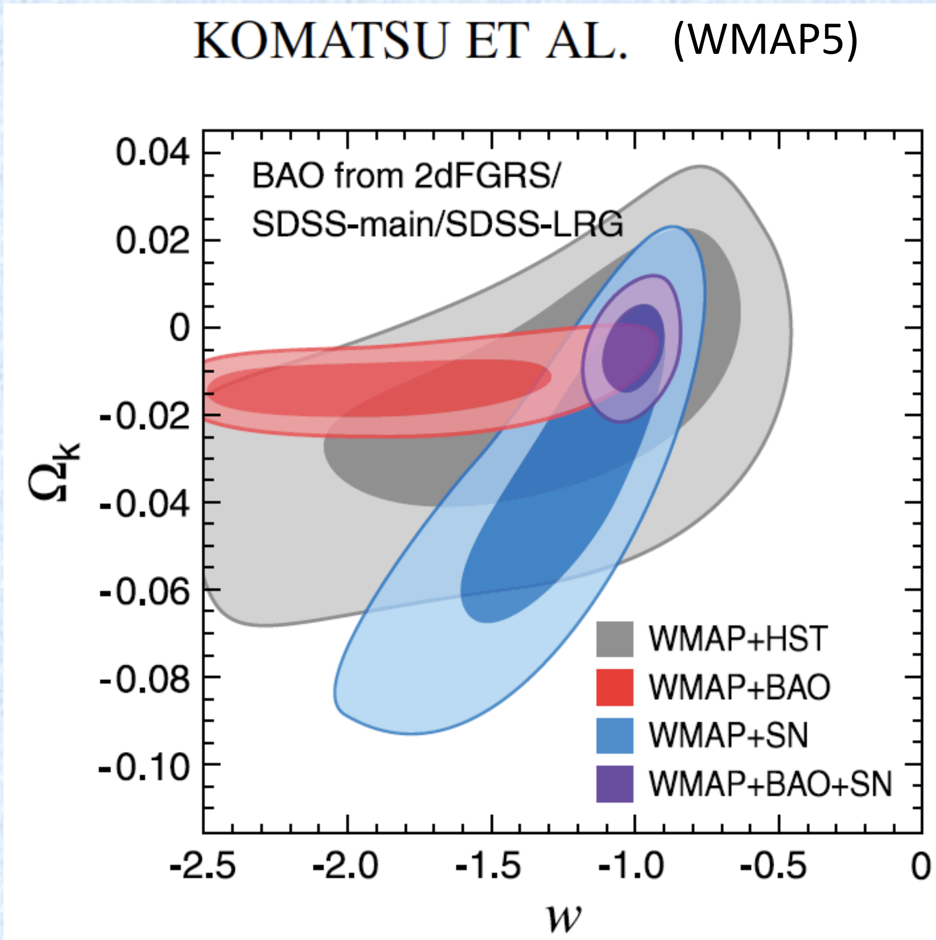


Best to combine probes to mitigate systematic uncertainties



(random offsets applied for illustration)

Multiple experiments are carried out in part because they have different systematics



Gravitational lens time delays can provide an additional measure of cosmology

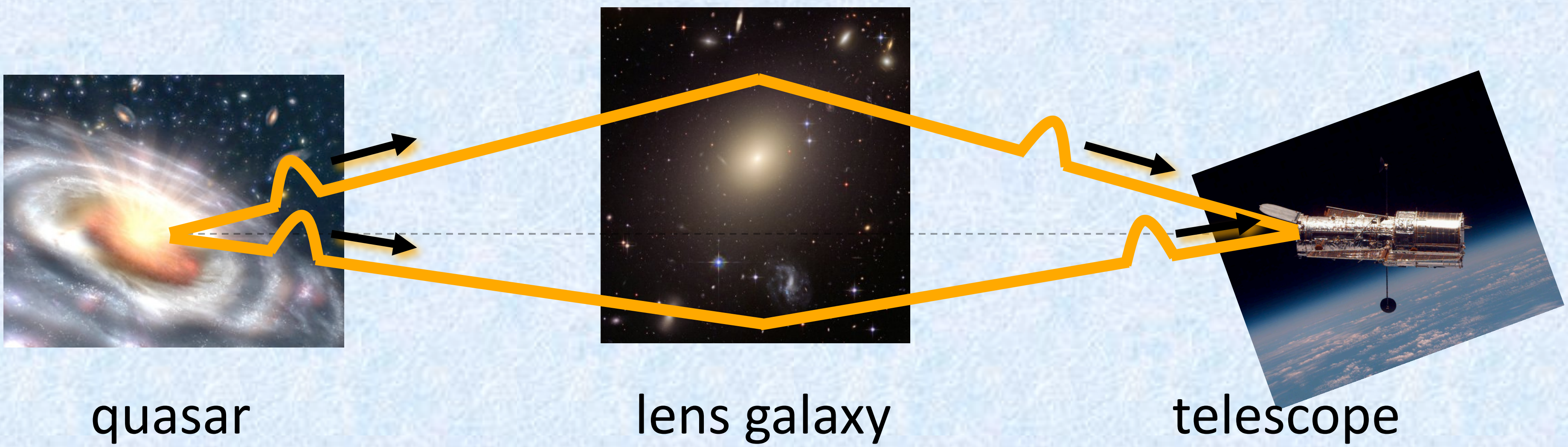
- Large surveys are being designed specifically to measure SN, WL, BAO, CL
- Time delays (TD) will be measured “for free” by some of these same surveys
  - Pan-STARRS, DES, LSST, JDEM/IDECS, Euclid…
- TD can contribute to the science cases

Gravitational Lens Time Delays

Light rays take multiple paths around the lens to our telescope, arriving at different times

In the example below,
the upper path passes closer to the lens
and thus takes longer because of the:

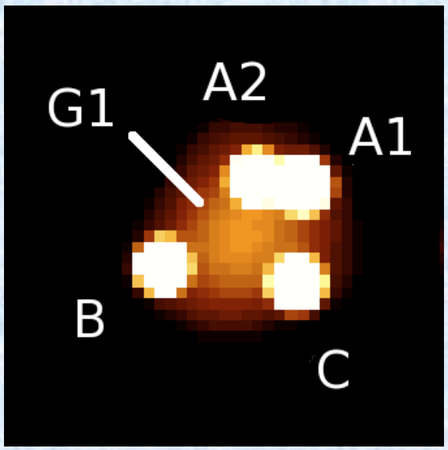
- greater deflection angle, making the path longer
- stronger gravitational potential and thus time dilation



Time Delay Measurement

Typical time delays are on the order of weeks to months and require years of monitoring to detect and measure reliably.

(PS1 & LSST will do this “for free”)



4”

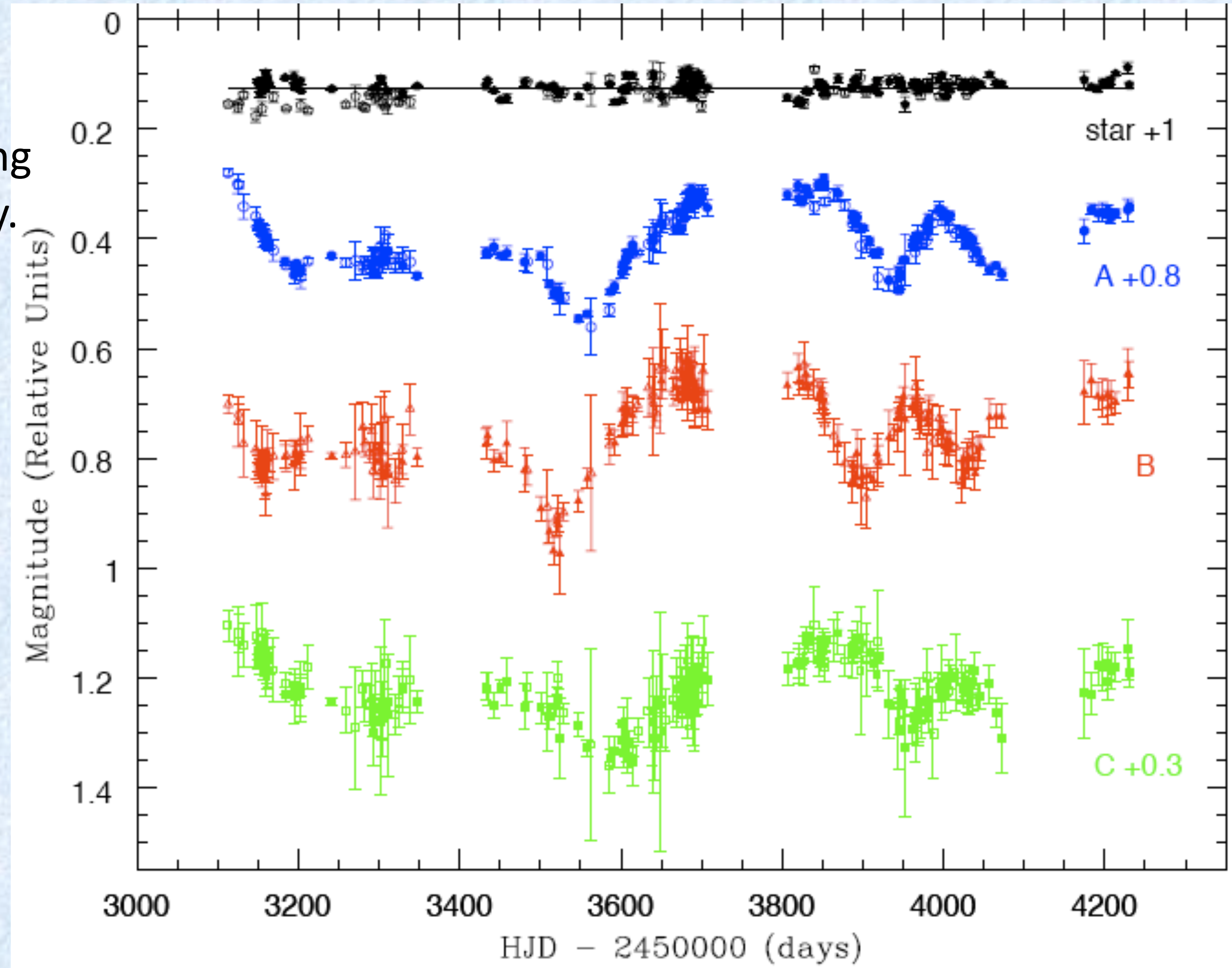
WFI J2033-4723

Vuissoz08

COSMOGRAIL

$z_L = 0.661$

$z_S = 1.66$

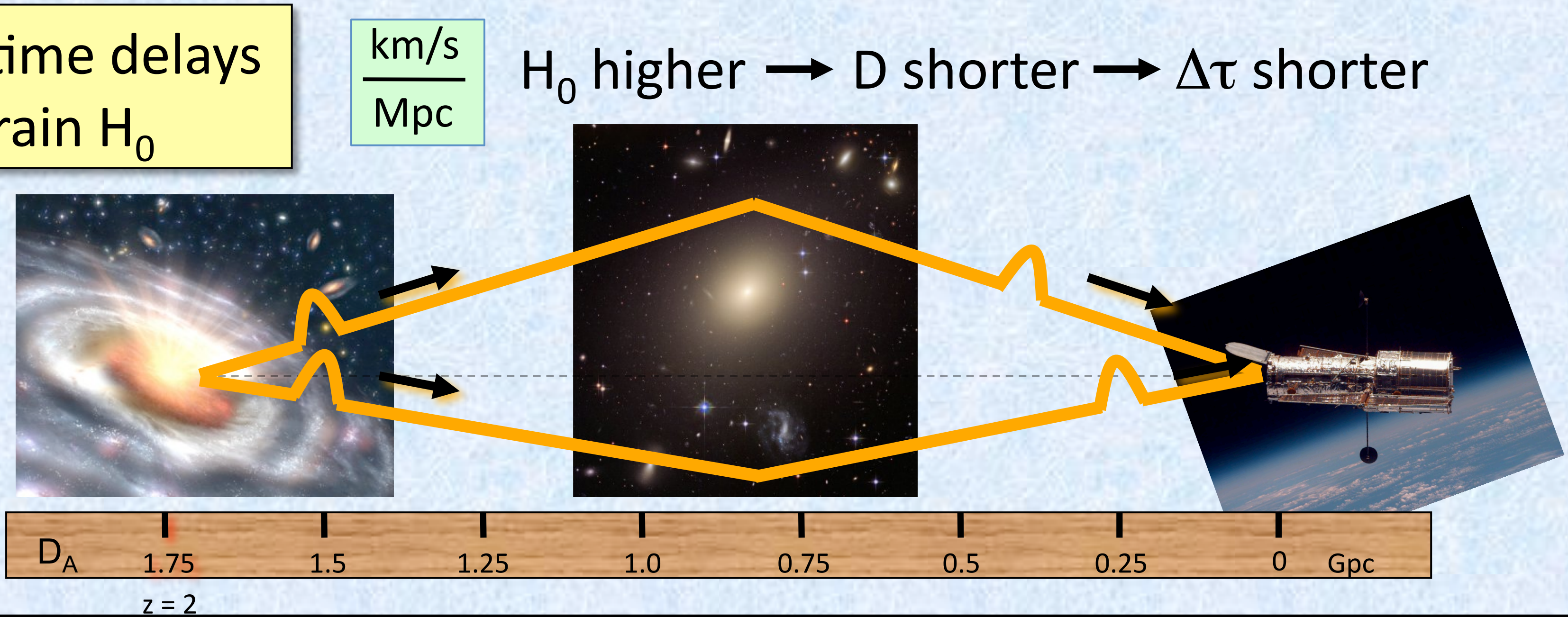


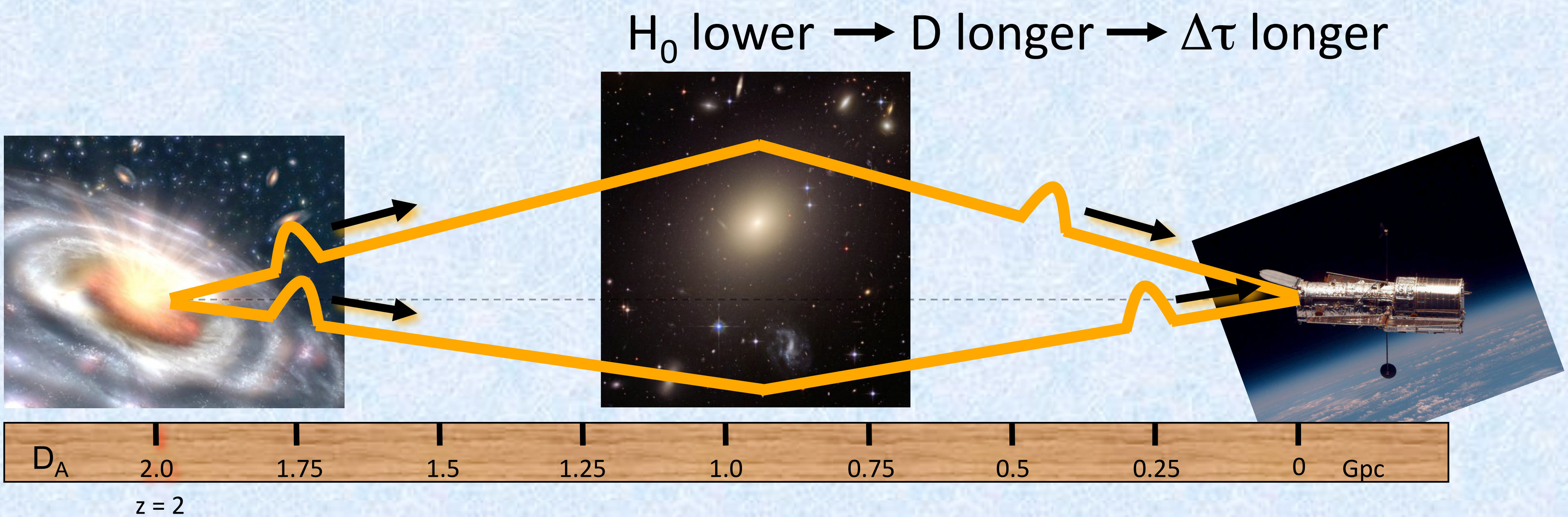
3 years

$$\Delta t_{B-A} = 35.5 \pm 1.4 \text{ days } (3.8\%)$$

$$\Delta t_{B-C} = 62.6^{+4.1}_{-2.3} \text{ days } \left(^{+6.5\%}_{-3.7\%}\right)$$

How time delays constrain H_0





Time delays actually constrain a ratio of angular diameter distances that depend on cosmology (not just H_0)

$$\Delta\tau = \mathcal{T}_C \, \mathcal{T}_\mathcal{L}$$

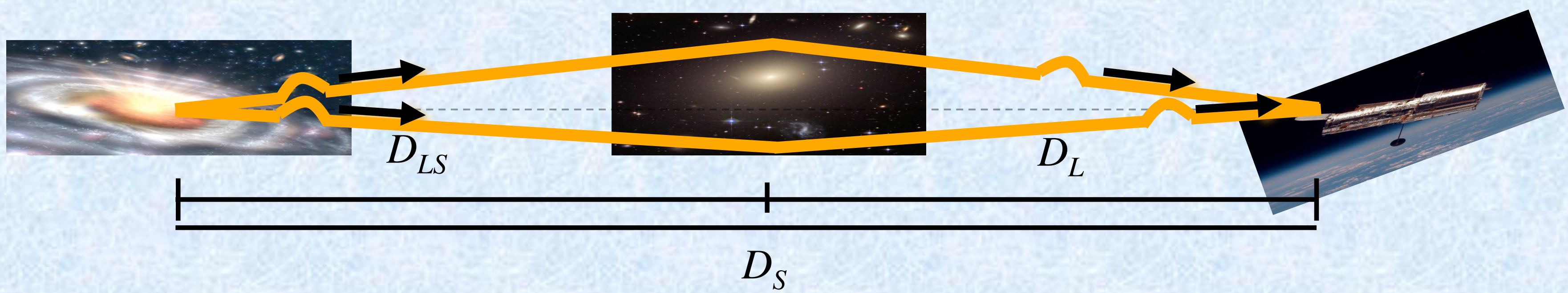
$\mathcal{T}_C$	$\mathcal{T}_\mathcal{L}$
cosmology	lens + enviro

$$\Delta\tau = \frac{(1+z_L)}{c}\frac{D_L D_S}{D_{LS}}\left[\tfrac{1}{2}\left|\boldsymbol{\theta}-\boldsymbol{\beta}\right|^2 - \phi\right]$$

$$\frac{\mathcal{E}(\Omega_m, \Omega_{de}, \Omega_k, \mathrm{w}_0, \mathrm{w}_a; z_L, z_S)}{H_0}$$

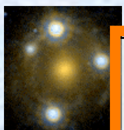
weaker dependence on other parameters → $\mathcal{E}(\Omega_m, \Omega_{de}, \Omega_k, \mathrm{w}_0, \mathrm{w}_a; z_L, z_S)$

strongest dependence on H_0 → H_0



Time delays are functions of:

- Distances + redshifts = cosmology ($\mathcal{T}_C$)



- Lens mass ✔ **Measured**
- Lens mass profile slope
- Lens environment **Large sources of uncertainty**
  - mass sheets & shear
- Line of sight structure
  - mass sheets & shear
- Substructure $\mathcal{T}_{\mathcal{L}}$

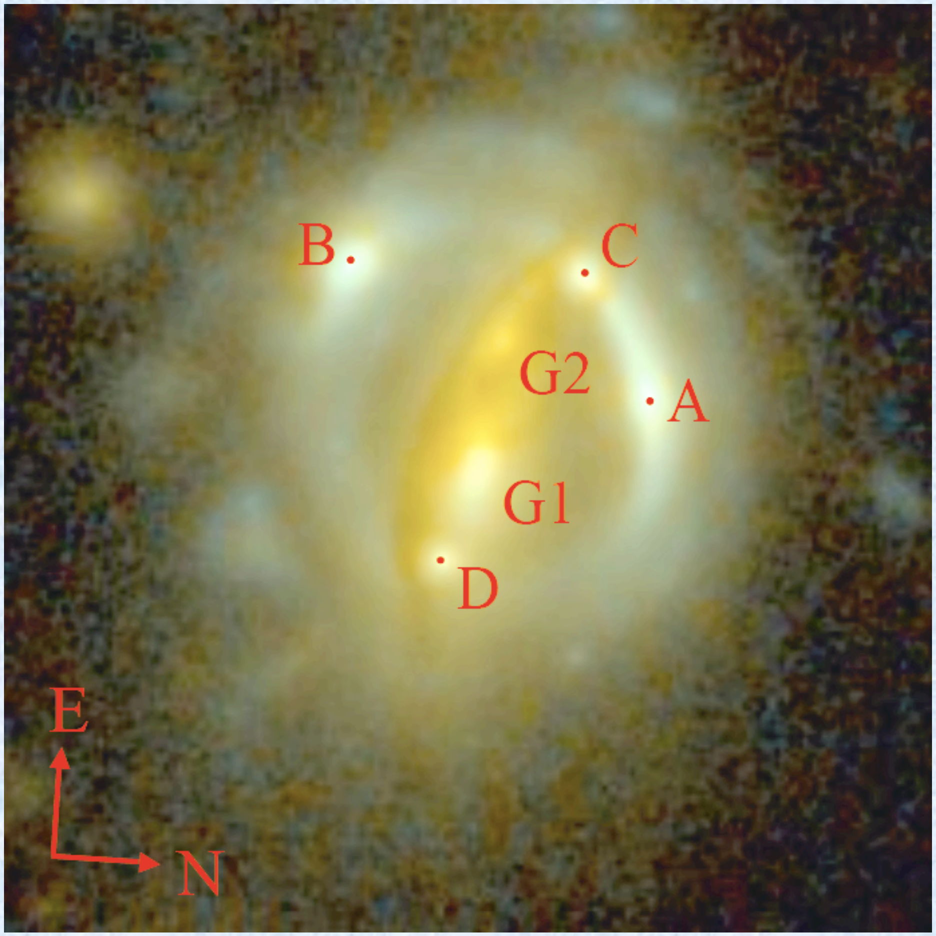
The Search for the "Golden Lens"

For a golden lens, $\mathcal{T}_{\mathcal{L}}$ would be measured extremely well.

Its owner would have the power to constrain $\mathcal{T}_C$ extremely well

(including the uncertainty of the time delay measurements).

A golden lens?



B1608+656 has been studied extensively (e.g., Koopmans03, Fassnacht06, Suyu09)

Koopmans03 found H_0 = 75 ± 6 km/s/Mpc, claiming the systematic uncertainties were < ~5%

A new estimate is forthcoming with total uncertainties of ~5% (Suyu et al., in prep.)

Time delay lenses are now realizing their potential to constrain cosmology

- Analyses of individual lenses historically yielded a wide range of values for H_0
  - possible but difficult
  - similarly, multiple types of Cepheids / Supernovae confounded early distance measurements
- A statistical ensemble of time delay lenses is now available, with better understood properties

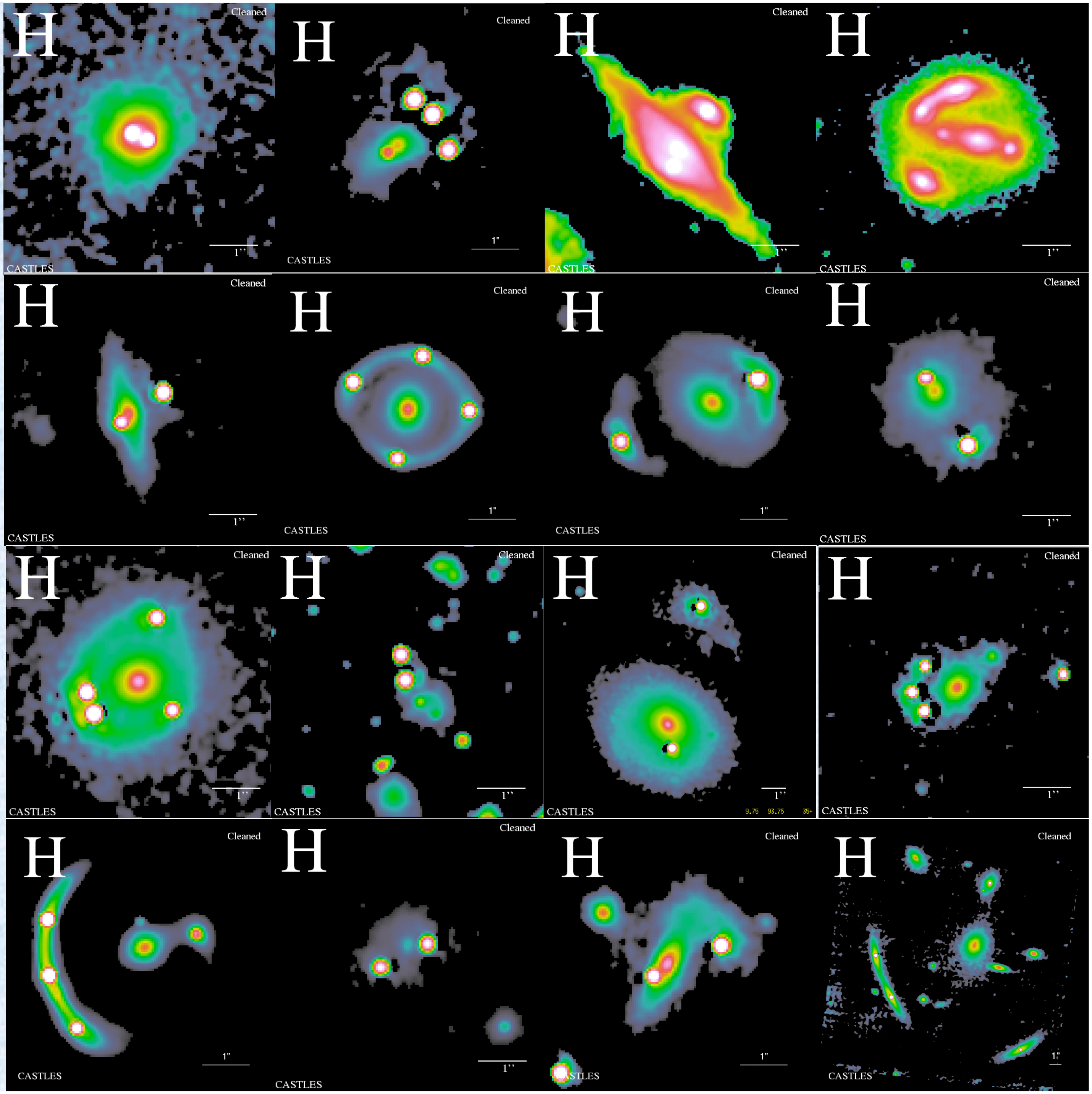
An alternative approach: Strength in numbers

- The HST Key Project to measure H_0 to 10% was based on 40 Cepheids (Freedman01)
- First detections of accelerating expansion required 50 & 60 supernovae (Riess98, Perlmutter99)
- We have currently measured reliable time delays for only 16 lenses and expect many more in the future

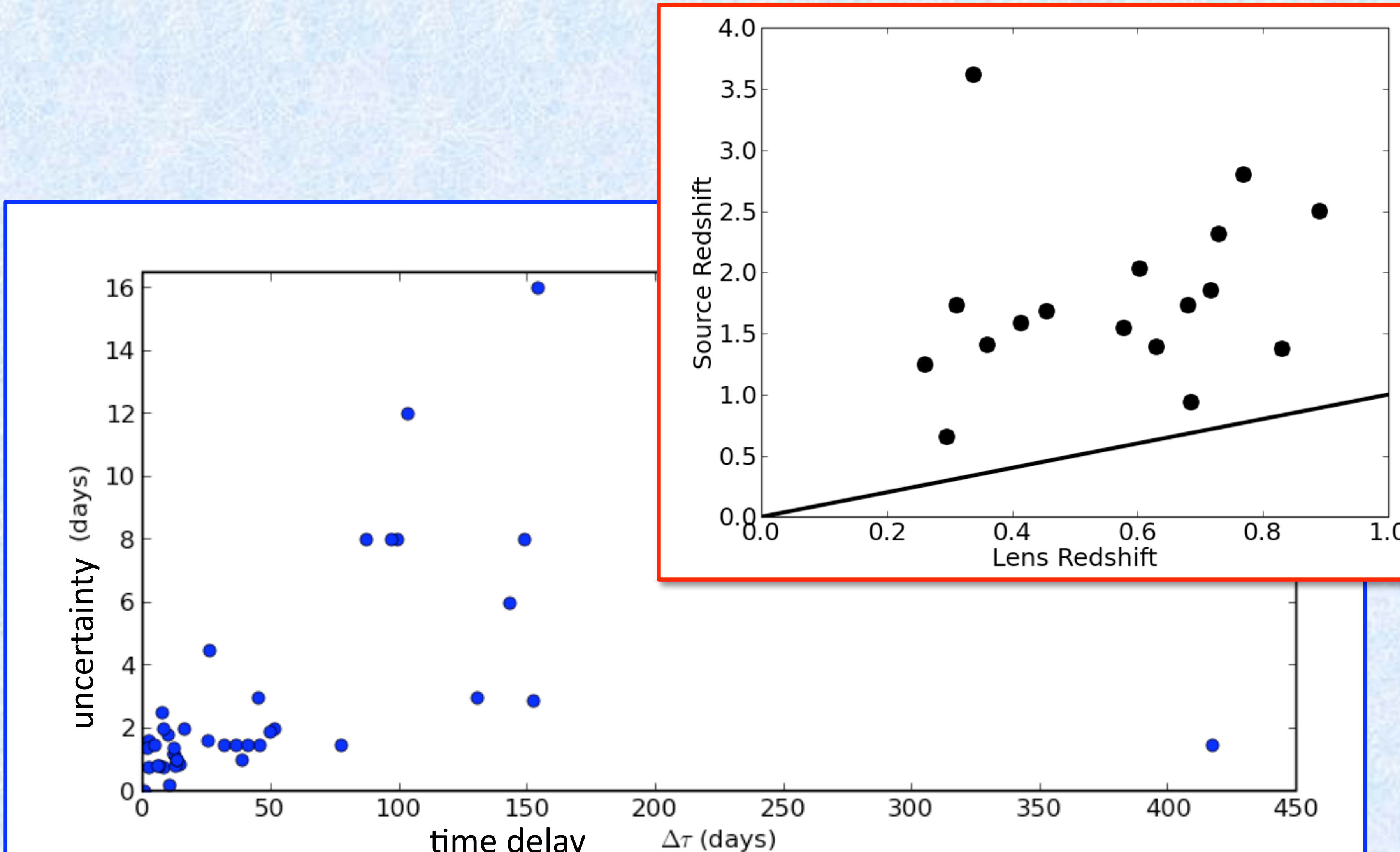
Time delays have been reliably measured for ~16 strong gravitational lenses

10 “Doubles”
6 “Quads”

CASTLES NICMOS/NIC2 H-band “cleaned” observations



Measured time delays and redshifts



from data complied by Oguri07

Based on time delays measured for 16 lenses, H_0 is constrained to ~10% (stat.), ~15% (total)

- Oguri07 (16 lenses):
  $H_0 = 68 \pm 6$ (stat.) ± 8 (syst.) km/s/Mpc
  $= 68 \pm 10$ km/s/Mpc

analytic assuming isothermal lens

- Saha06 (10 lenses):
  $H_0 = 72^{+8}_{-11}$ km/s/Mpc
- Coles08 (11 lenses):
  $H_0 = 71^{+6}_{-8}$ km/s/Mpc

"PixeLens" models minimal assumptions

Future surveys should yield many time delay lenses

Survey	lensed quasars	date
Pan-STARRS 1	1,000	2009-2012
LSST	4,000	2014-2024
SKA	10,000	2014-
JDEM / IDECS	100 - 1,000	2016?

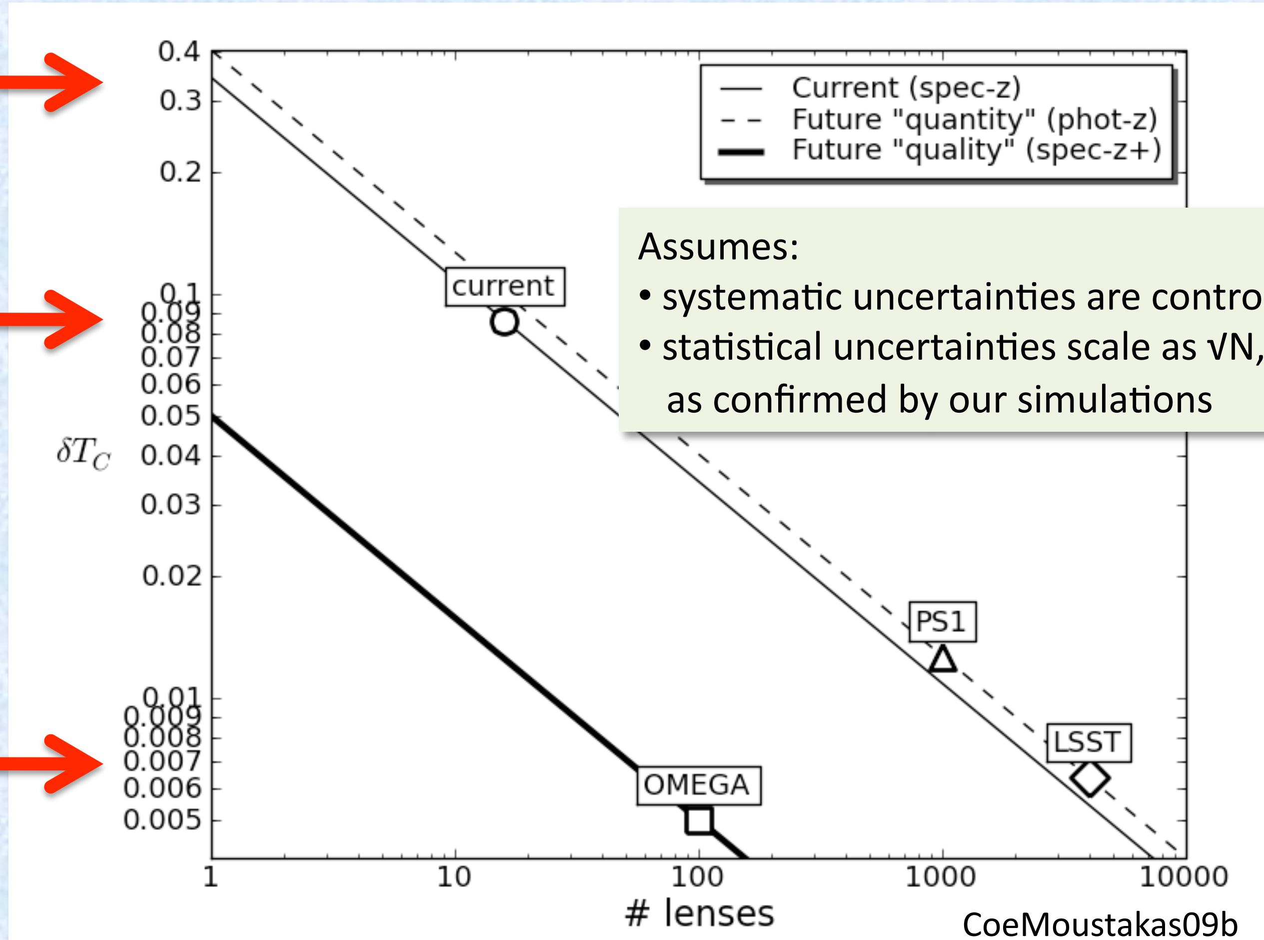
~ 1 / 1,000 galaxies strongly lenses a background galaxy
~ 1 / 10 of the background galaxies are quasars
Quasars are sufficiently variable to yield time delay measurements

Cosmological uncertainties may be huge for a single lens, should be small for an ensemble of thousands

~34% for a single lens:
h = 0.46 – 0.94

~10% currently for 16 lenses

~1% for thousands



Assumes:

- systematic uncertainties are controlled
- statistical uncertainties scale as √N, as confirmed by our simulations

LSST & OMEGA represent an even trade in quality vs. quantity

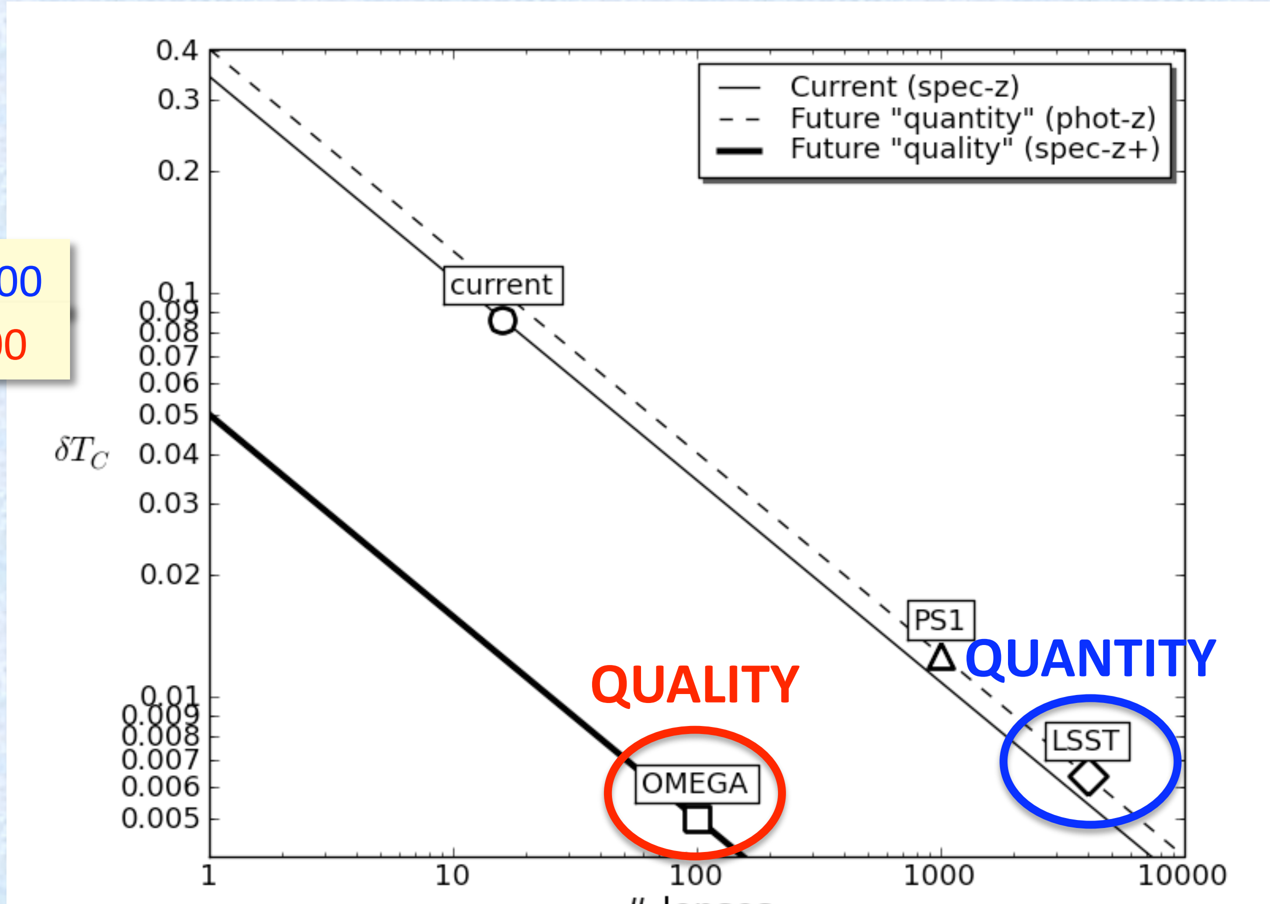
Measure time delays for 4,000 lenses or study 100 in great detail?

LSST: 0.64% = 40% / √4,000

OMEGA: 0.5% = 5% / √100

Or do both as a cross-check and to obtain tighter combined constraints:

LSST + OMEGA: 0.4%



CoeMoustakas09b

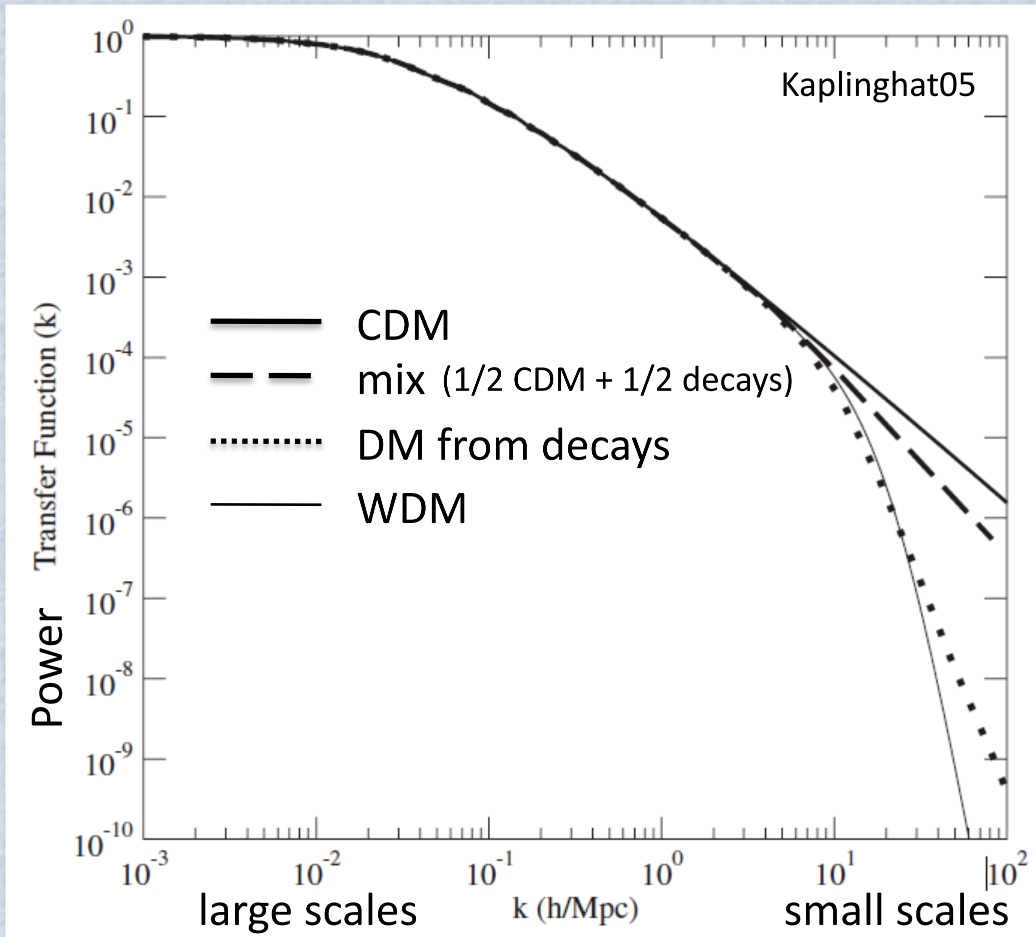
OMEGA Mission Concept

P.I. Moustakas

(Bolton, Bullock, Cheng, Coe, Fassnacht, Keeton, Kochanek, Lawrence, Marshall, Metcalf, Natarajan, Peterson, Shecman, Wambsganns)

- Dedicated space-based observatory monitoring ~100 time delay lenses
- ~1.5-m mirror,
  near-UV -- near-IR + spectra
- Precise measurements of fluxes, positions, and time delays
- Constraints on nature of dark matter particle from small-scale power cutoff

Power spectrum on small scales (galaxy substructure) would be suppressed by warm DM or DM decay

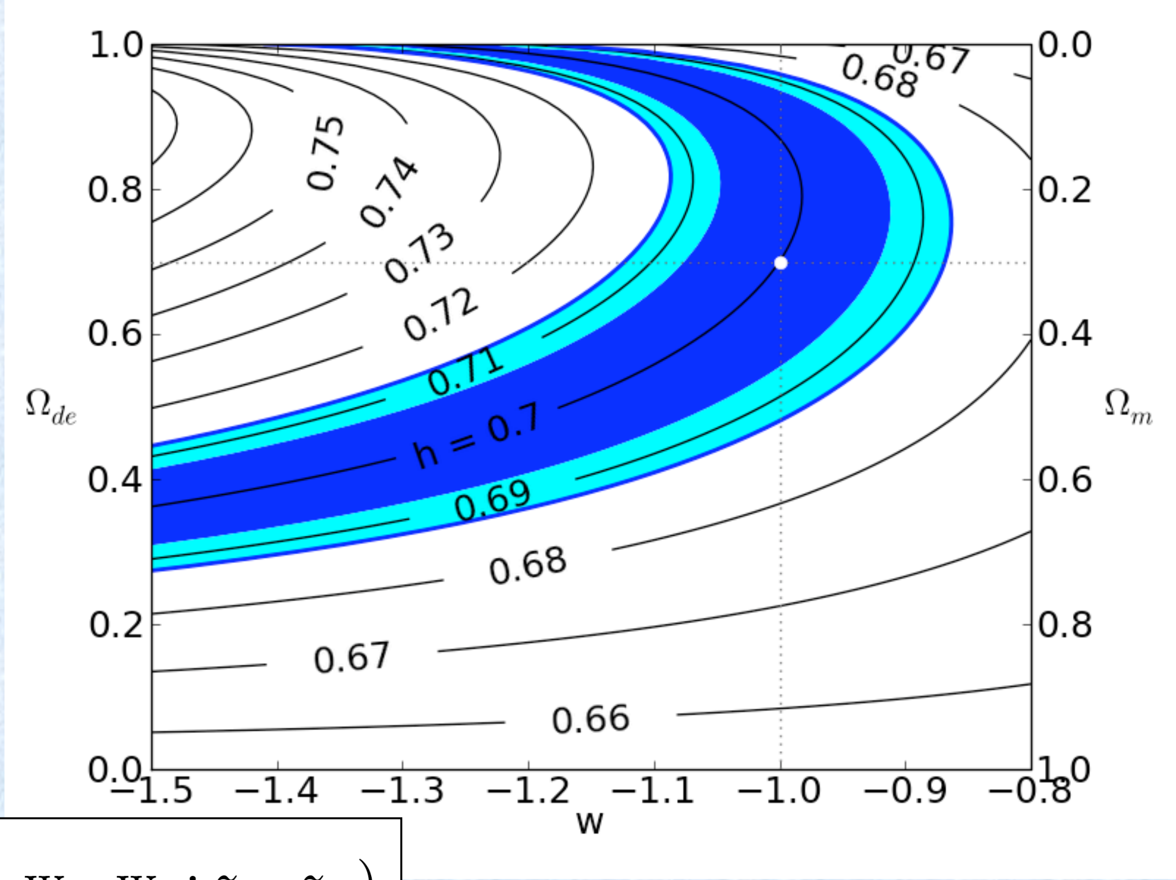


Propagate LSST $\mathcal{T}_C$ uncertainty to cosmological parameters

$\delta\mathcal{T}_C$ = 0.64% (LSST)

Flat universe,
constant w,
perfect h

Here, all redshifts
$z_L = 0.5$, $z_S = 2.0$;
redshift ensemble
($z_L = 0.5 \pm 0.15$; $z_S = 2.0 \pm 0.75$)
helps somewhat

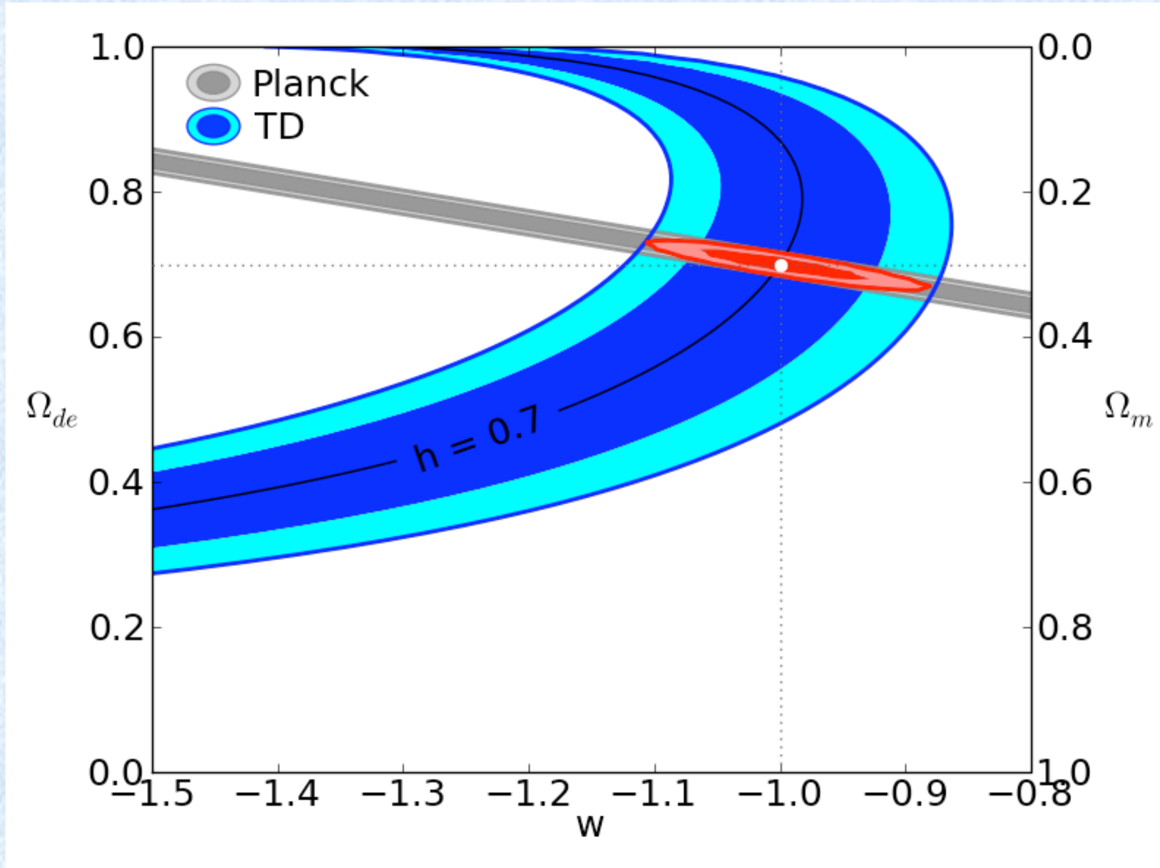


$$\mathcal{T}_C = \frac{\mathcal{E}(\Omega_m, \Omega_{de}, \Omega_k, \mathrm{w}_0, \mathrm{w}_a; z_L, z_S)}{H_0}$$

Planck to the rescue

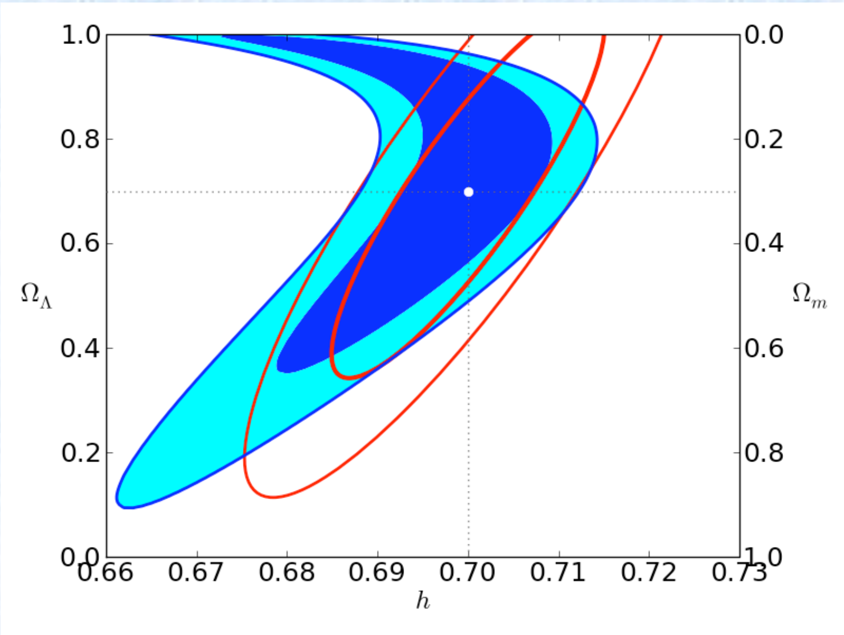
CMB and TD constraints complement each other well

Combined constraints are tight

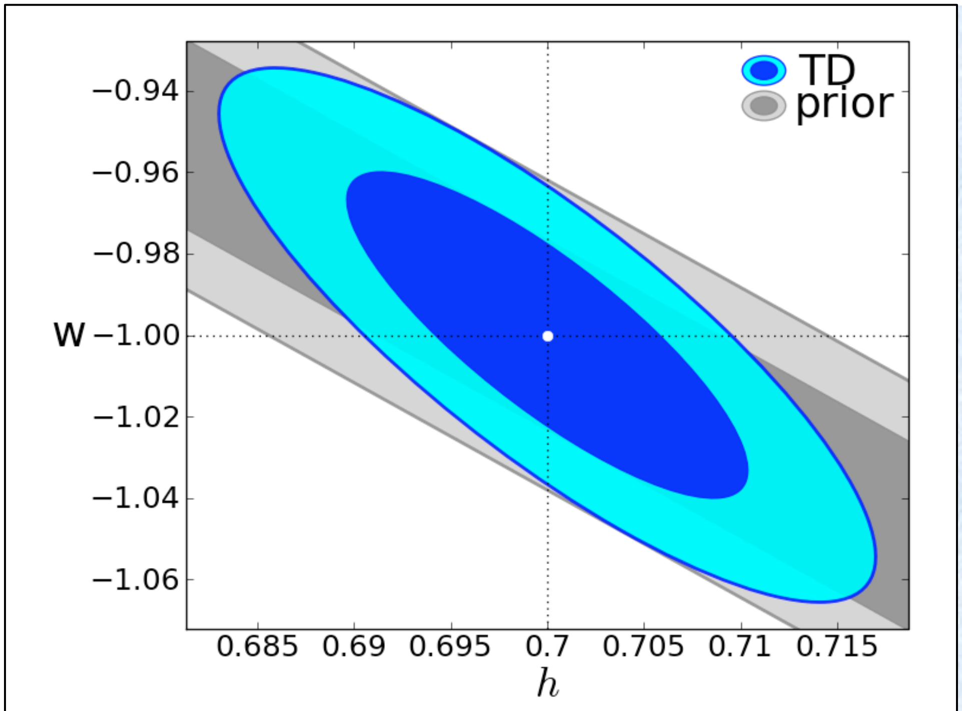


Fisher matrix analysis to probe large parameter space

- Produces confidence ellipses
- Uncertainties approximated optimistically by Gaussians
- See my Fisher matrix "quick-start guide" (arXiv:0906.4123)
  - Software available



  - also see DETFast, Fisher4Cast, iCosmo

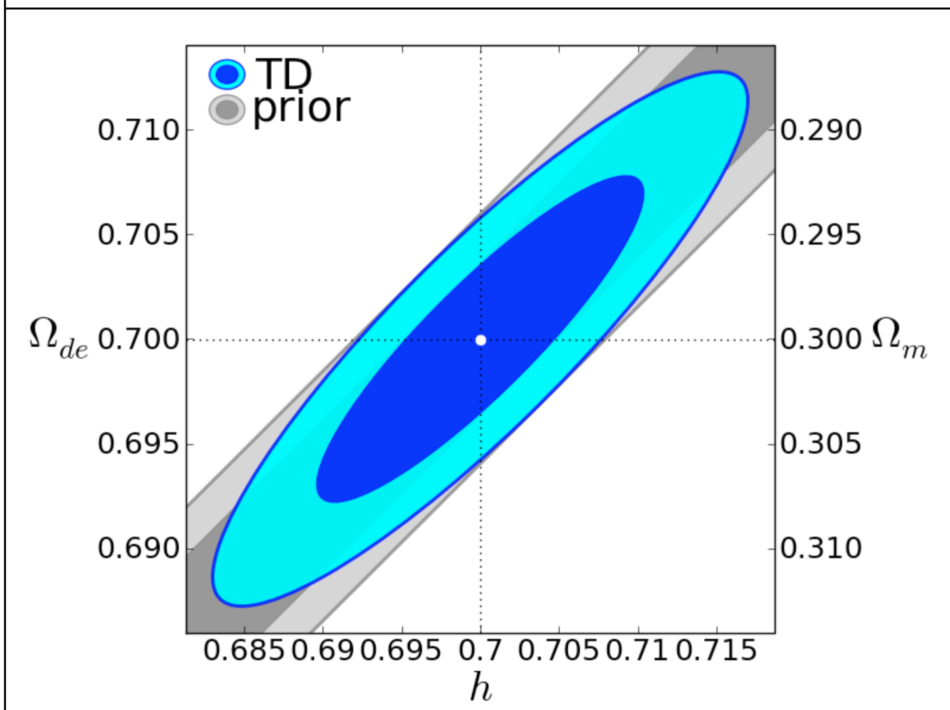


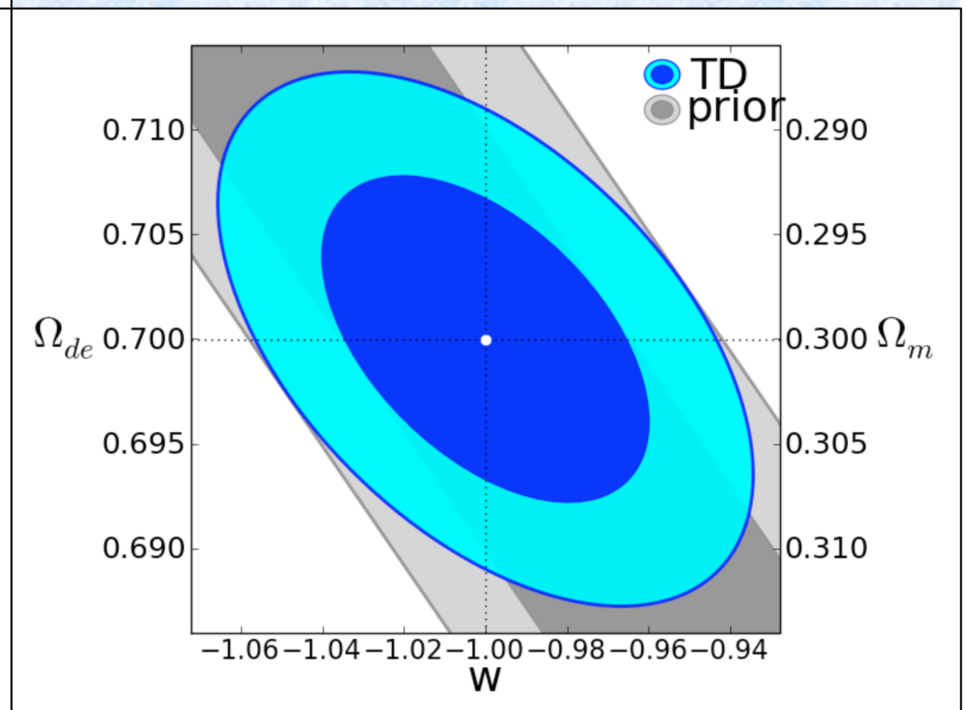
Cosmological constraints from **LSST time delays** assuming a flat universe, constant w, and a Planck prior:

$h \approx 0.7 \pm 0.007$ (1%)

$\Omega_{de} \approx 0.7 \pm 0.005$

$w \approx -1 \pm 0.026$

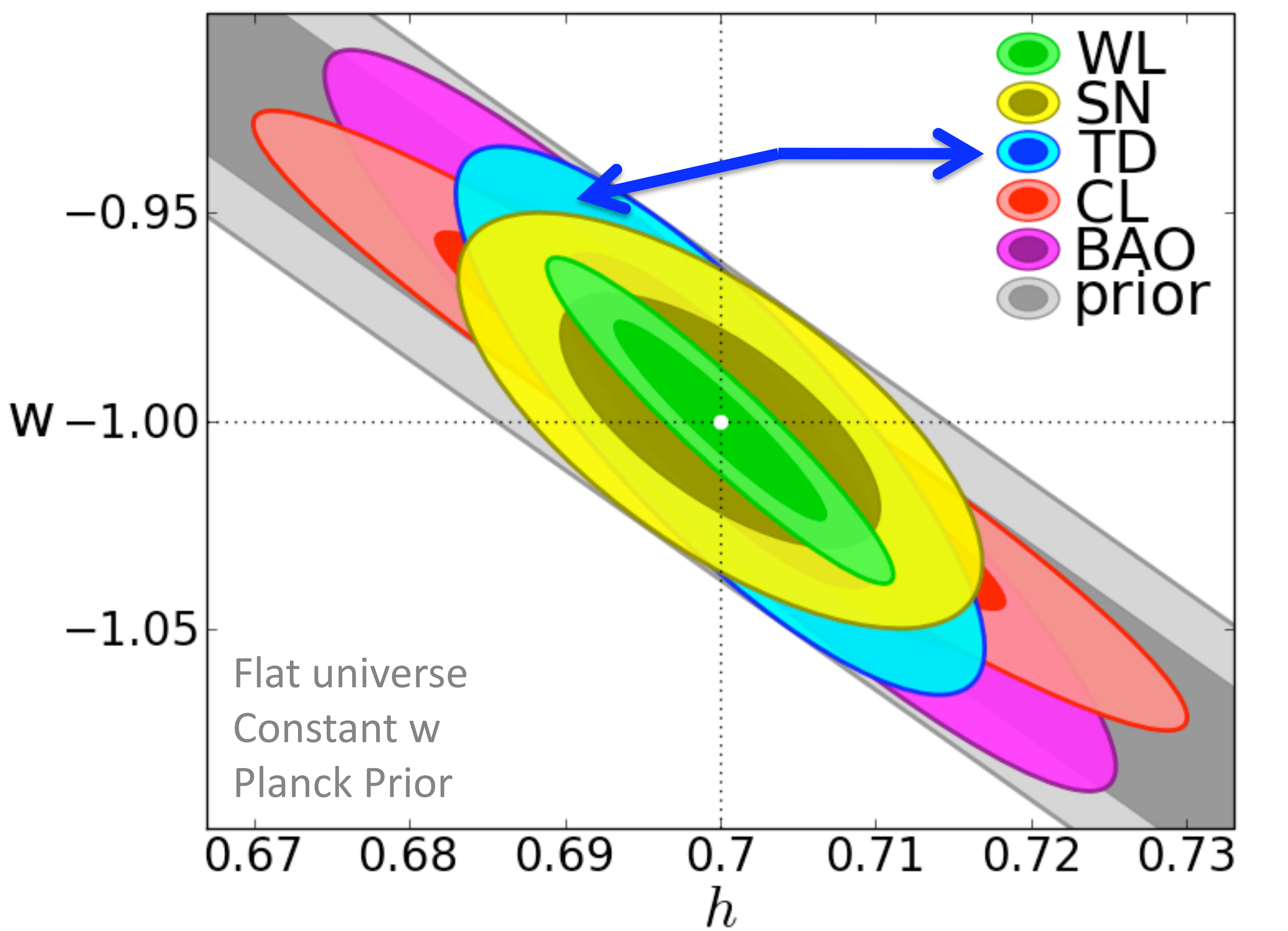




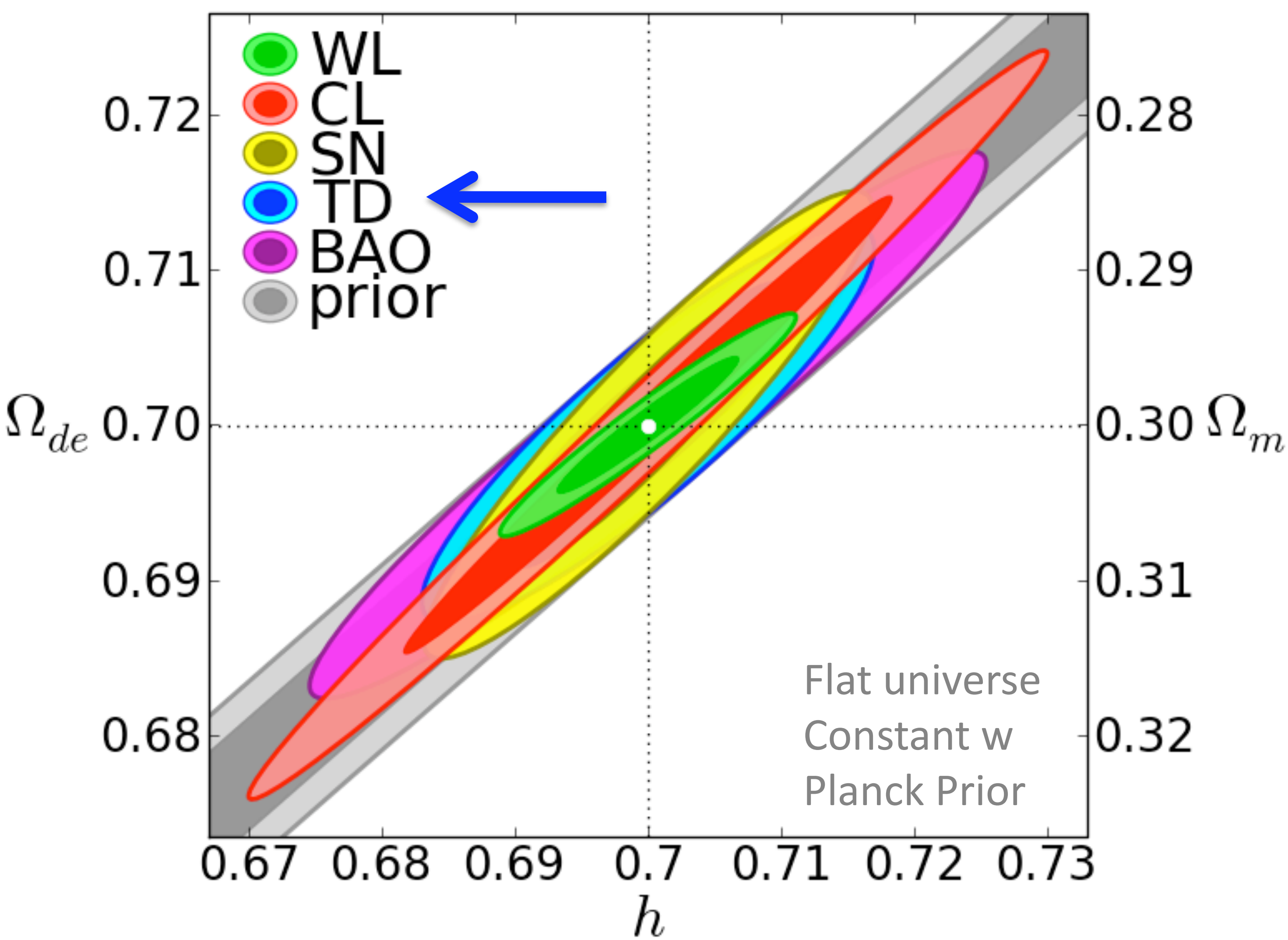
Comparison to other "Stage IV" experiments

- Expected constraints for future WL / SN / CL / BAO experiments provided by the Dark Energy Task Force encoded in Fisher matrices in their `DETFast` software
- Again, assuming:
  - Flat universe
  - Constant w (can be ≠ -1, but not time-varying)
  - Planck prior

Stage IV constraints (TD from LSST)



Stage IV constraints (TD from LSST)



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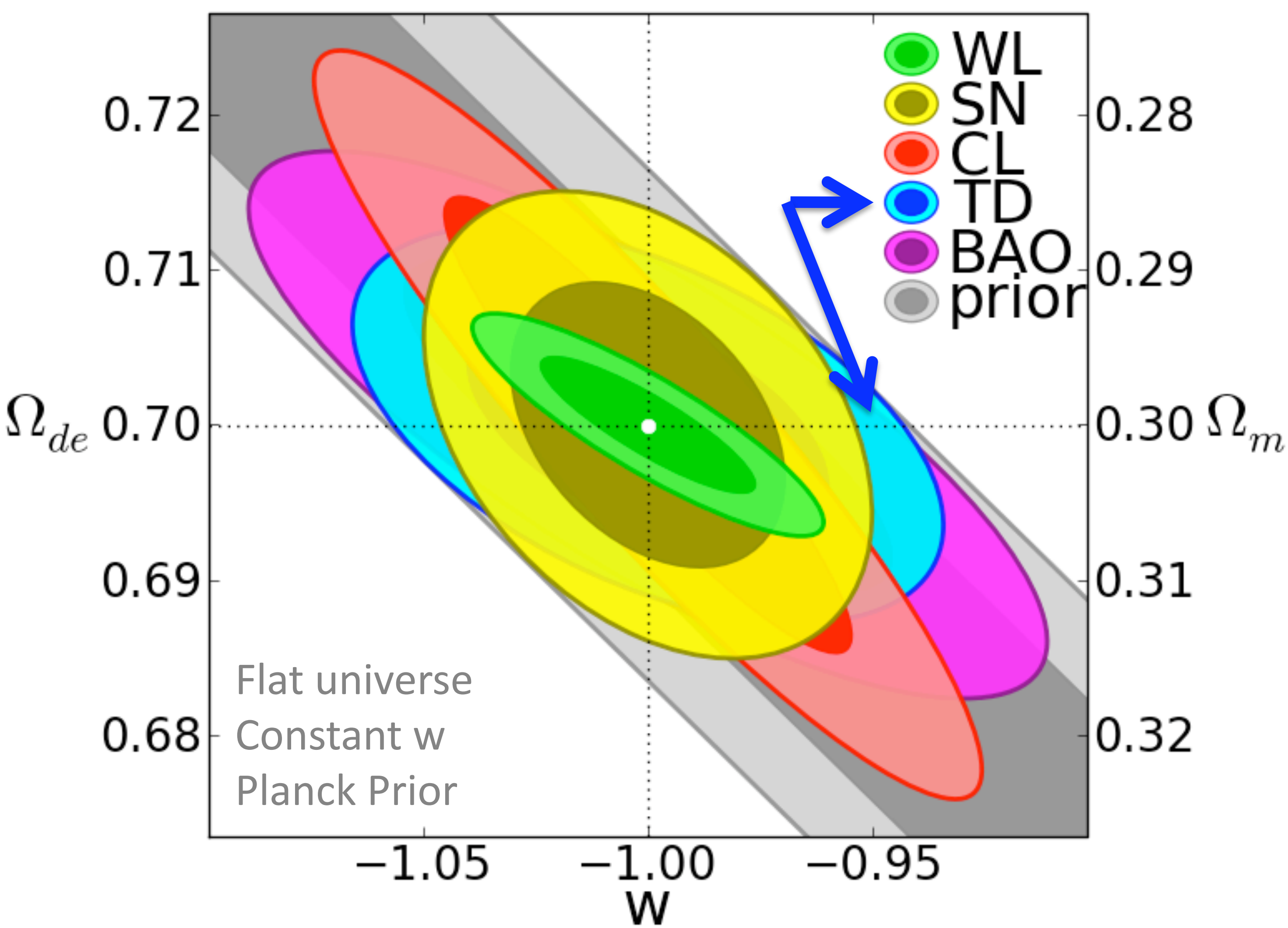
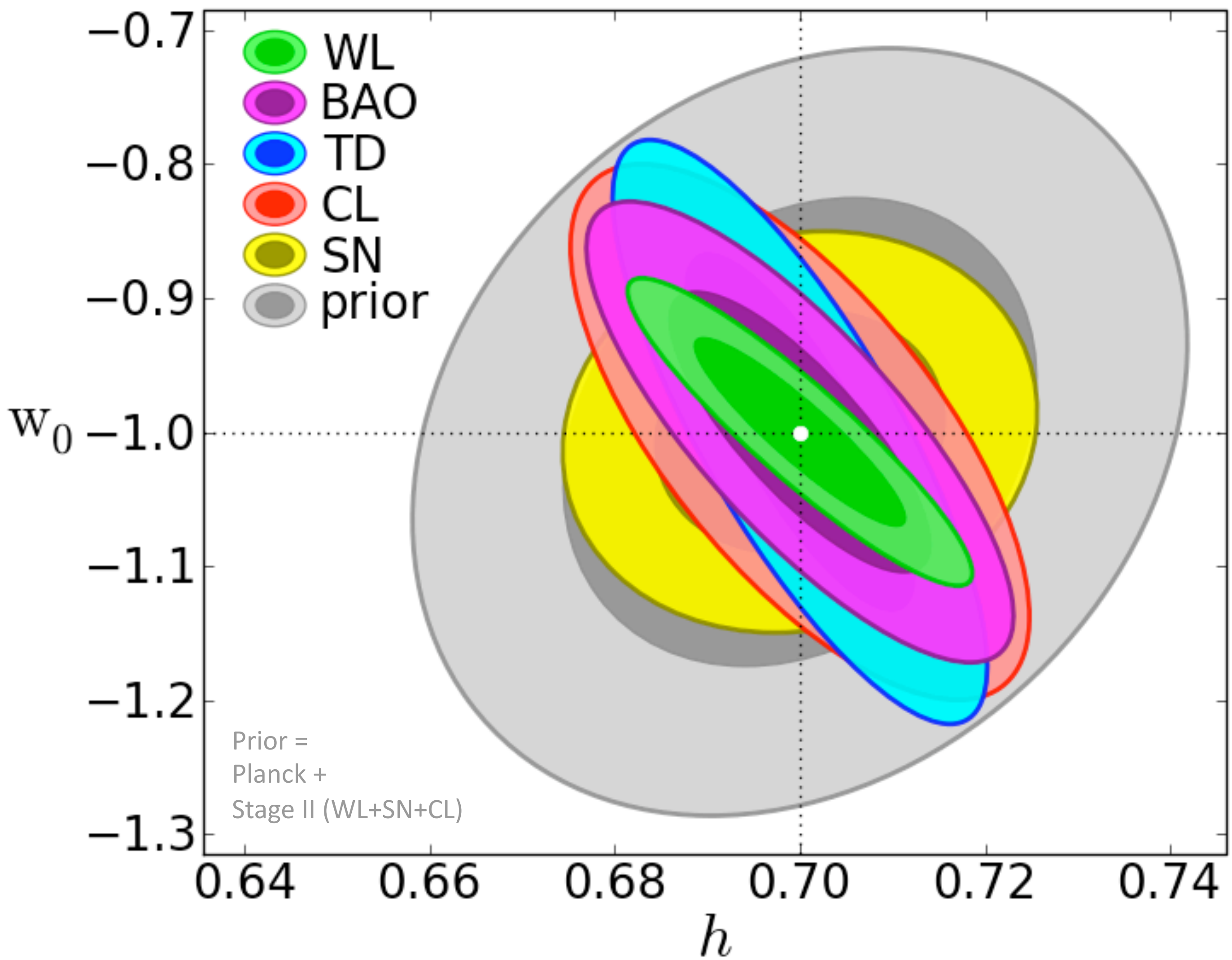


Now for a general cosmology

- Curvature allowed (Ω_k)
- Time-varying w allowed (w_0, w_a)
- Planck prior
- Stage II (near-future) WL+SN+CL prior
- …all similar to the DETF analysis

Stage IV constraints (TD from LSST)



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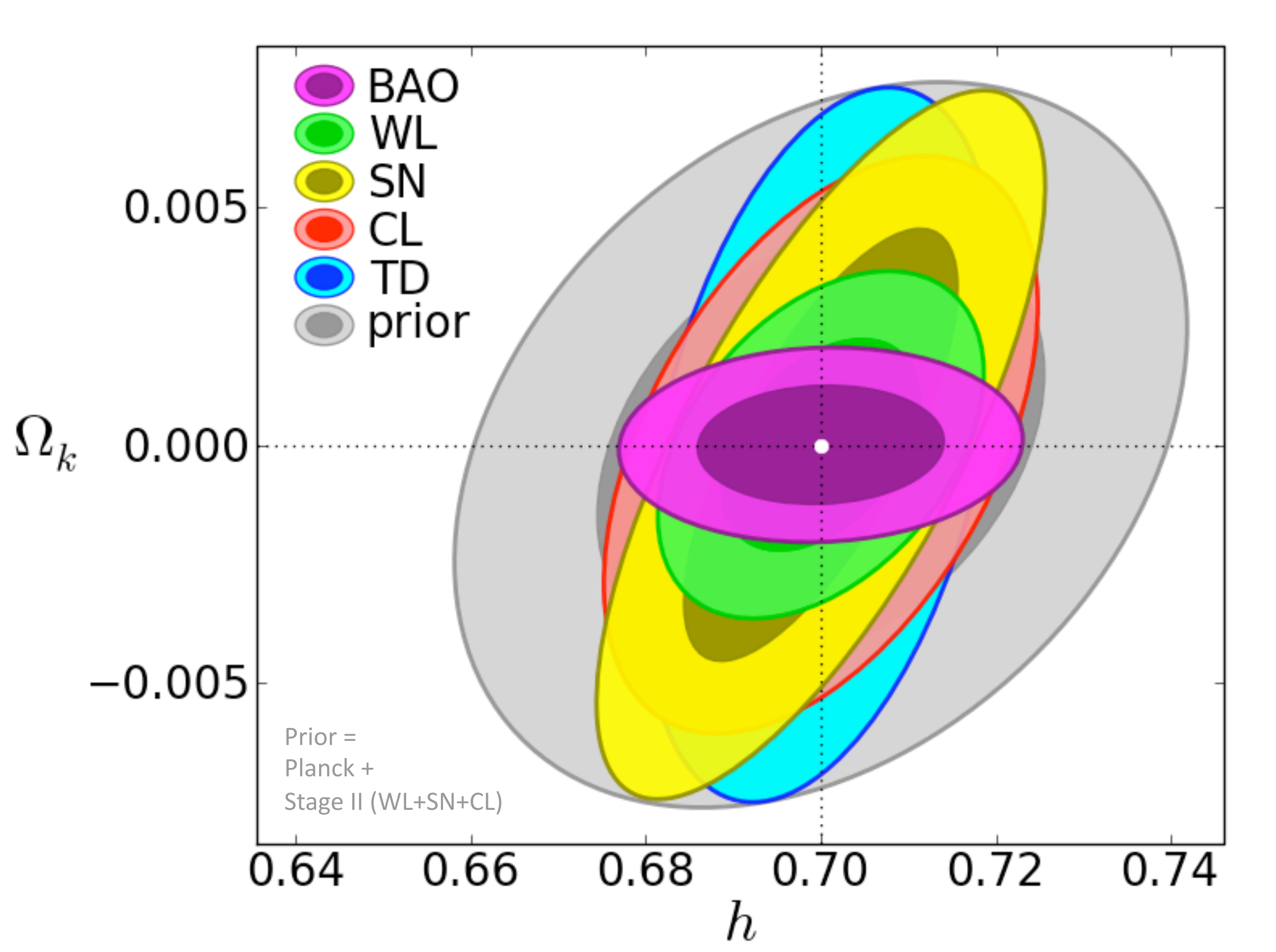
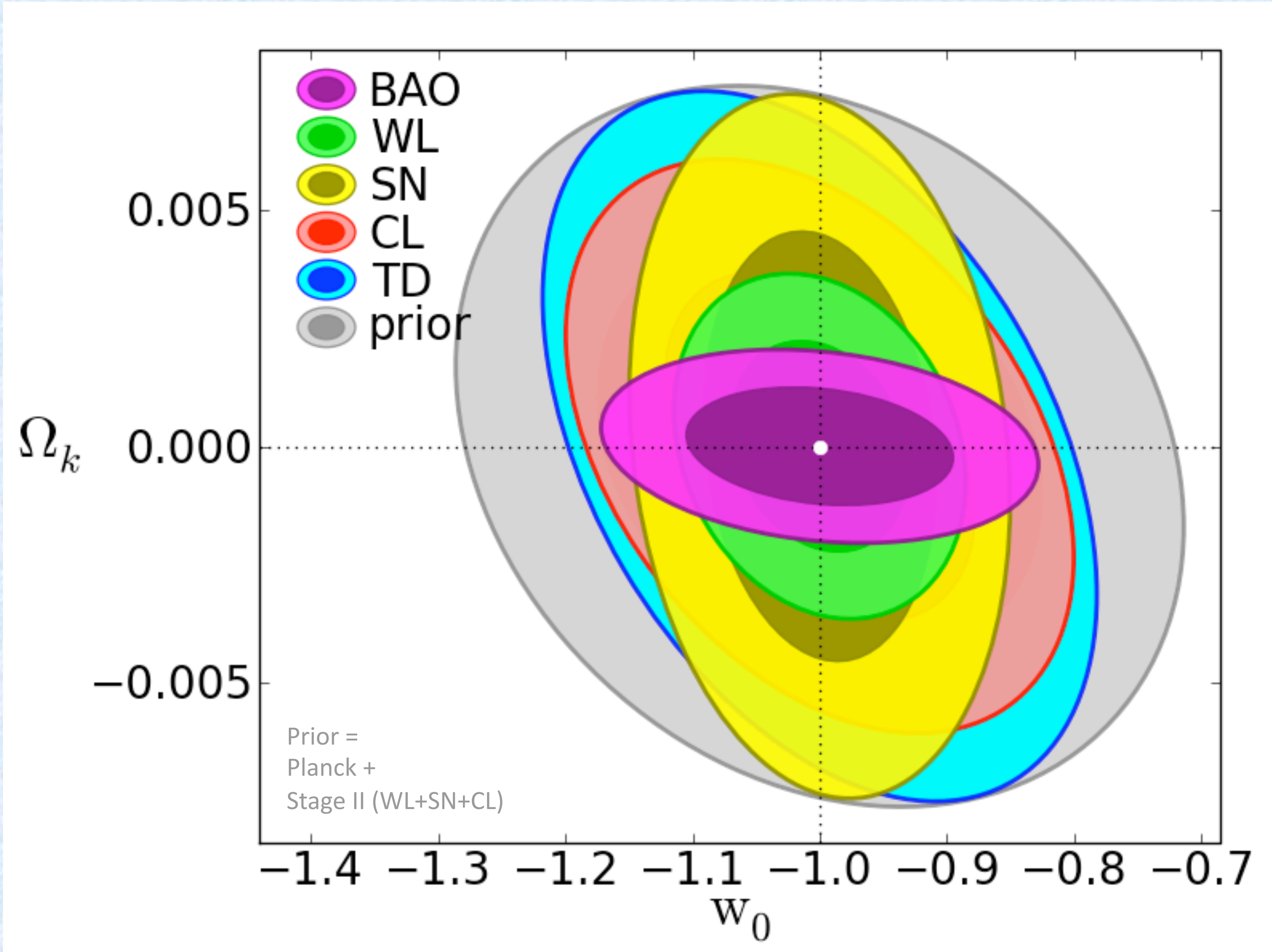
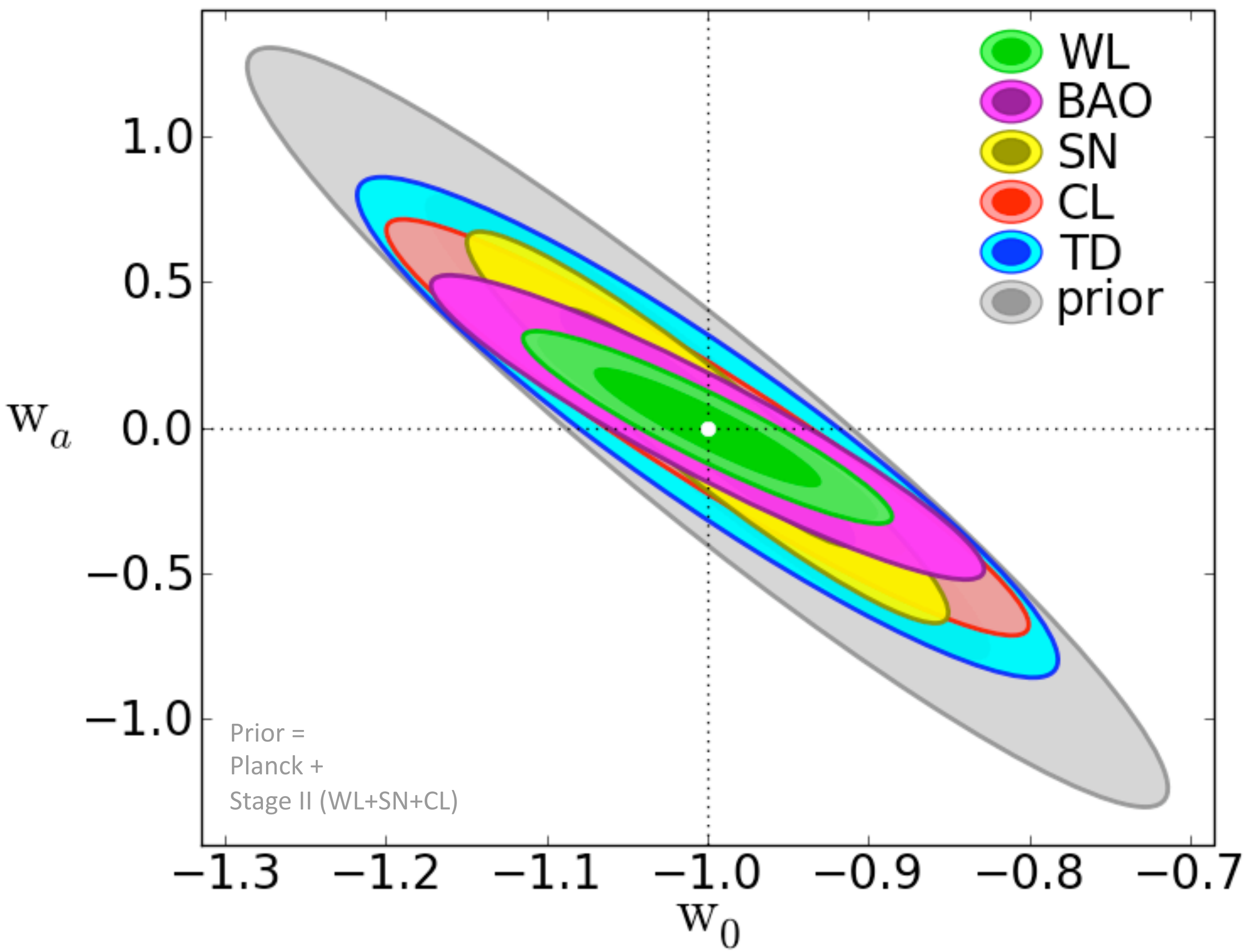


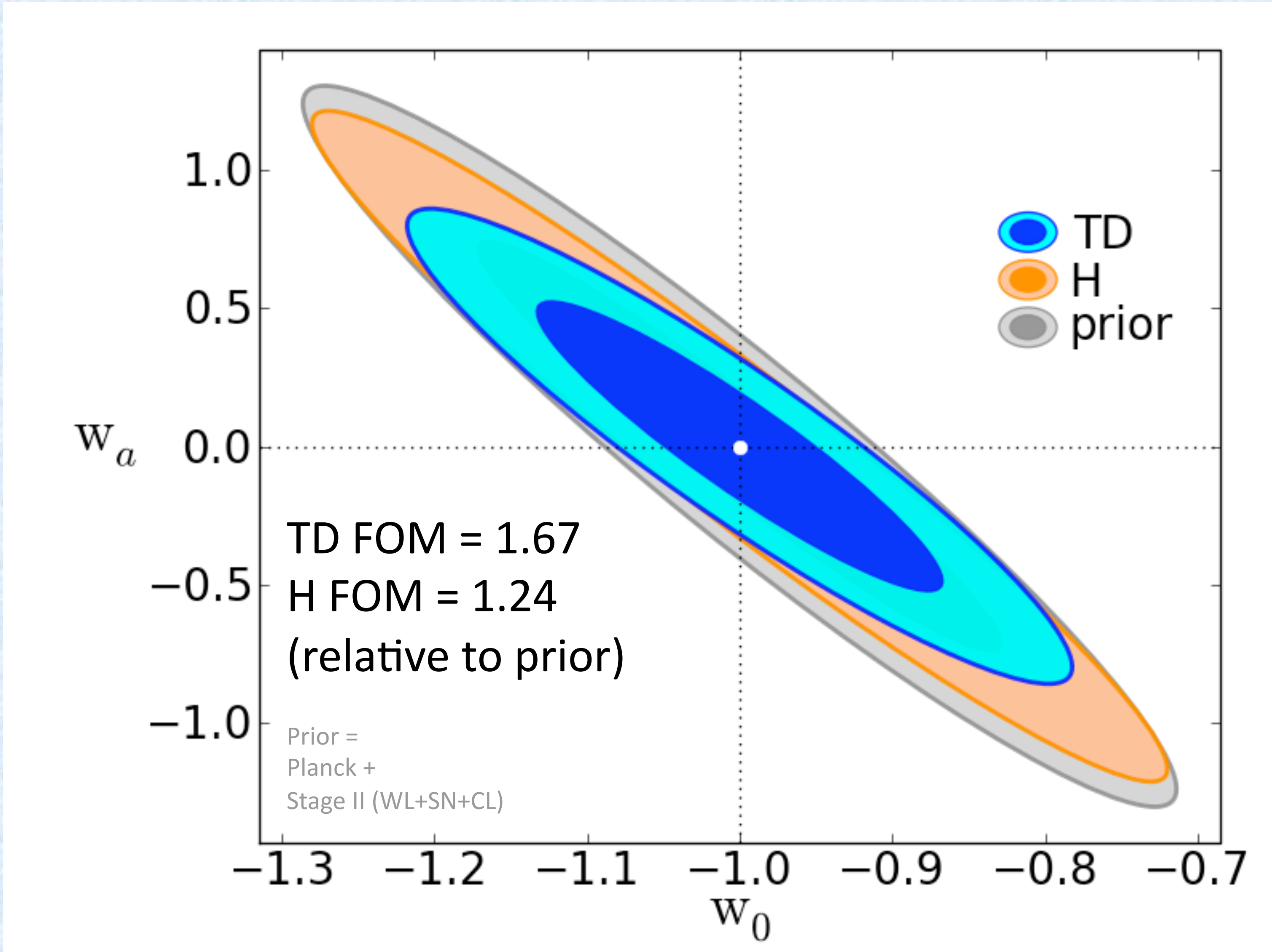
Stage IV constraints (TD from LSST)



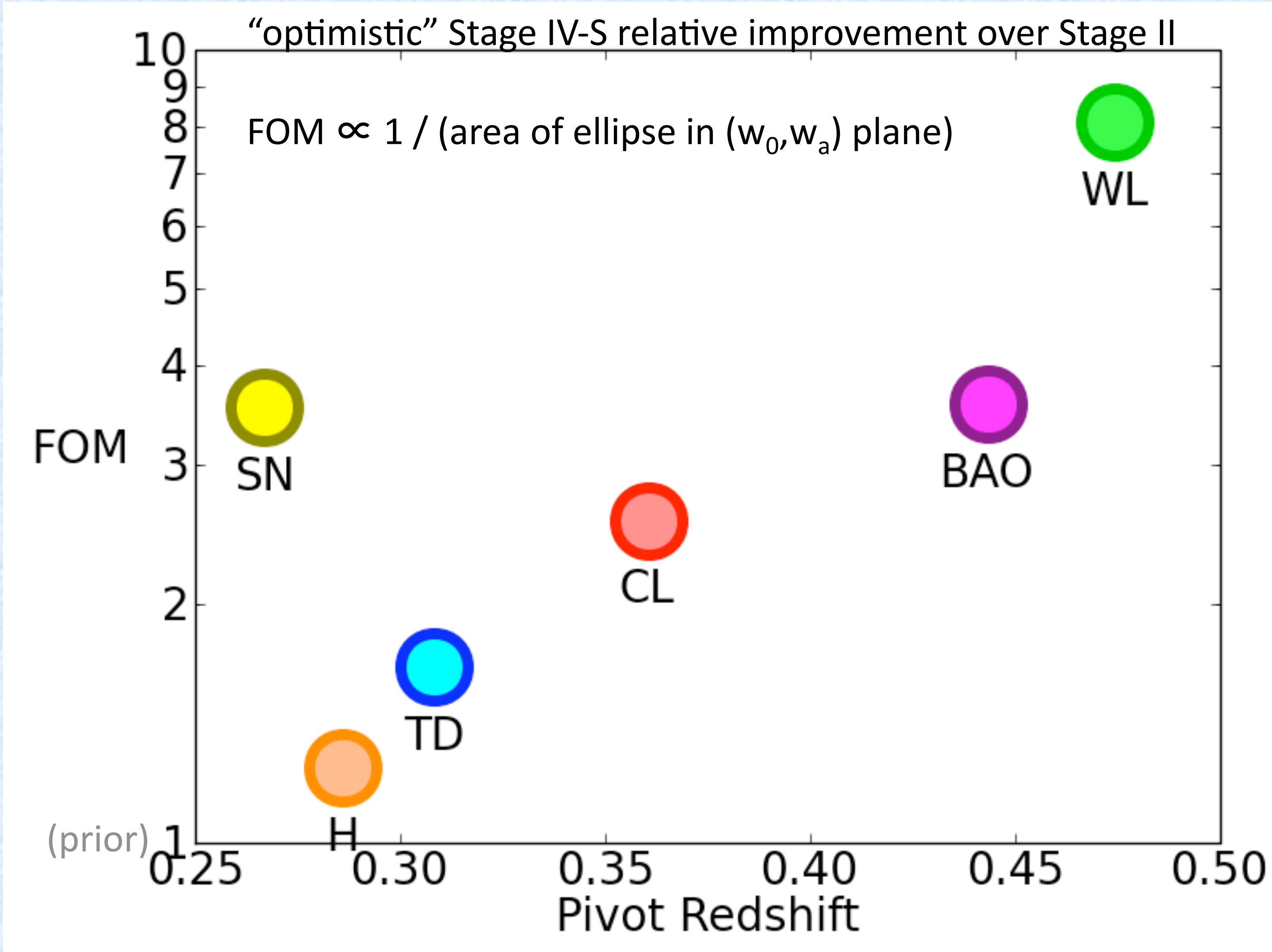
Stage IV constraints (TD from LSST)



Time delays provide more than just a constraint on H_0



Dark Energy Task Force “Figure of Merit”



Outline

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- ✓ Optimistic cosmological constraints (statistical uncertainties only)
  - Past, present, & future constraints on $\mathcal{T}_C$
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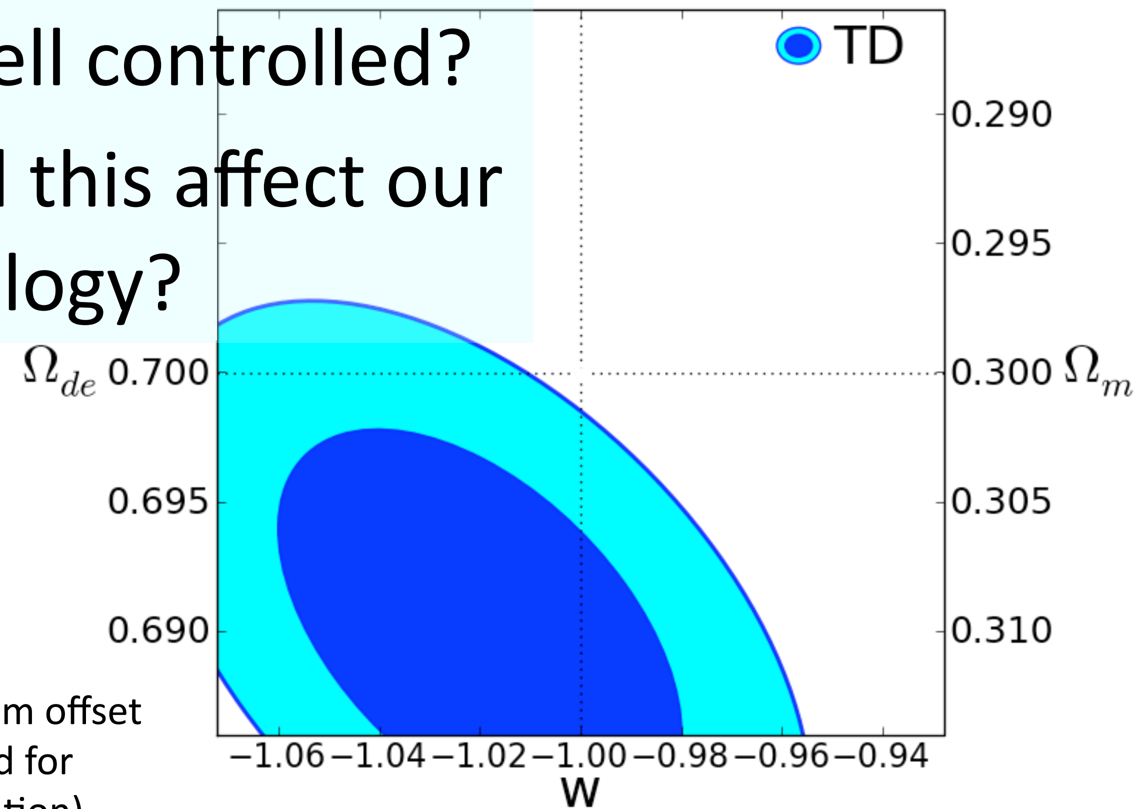
  - Future constraints on (h, Ω_m, Ω_{de}, Ω_k, w_0, w_a) from 4,000 LSST time delay lenses compared to other methods
- Systematics

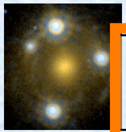
Our constraints may be *precise* but will they be *accurate*?

- What are the systematics?
- Can they be well controlled?
- If not, how will this affect our derived cosmology?



(random offset applied for illustration)

Time delays are functions of:

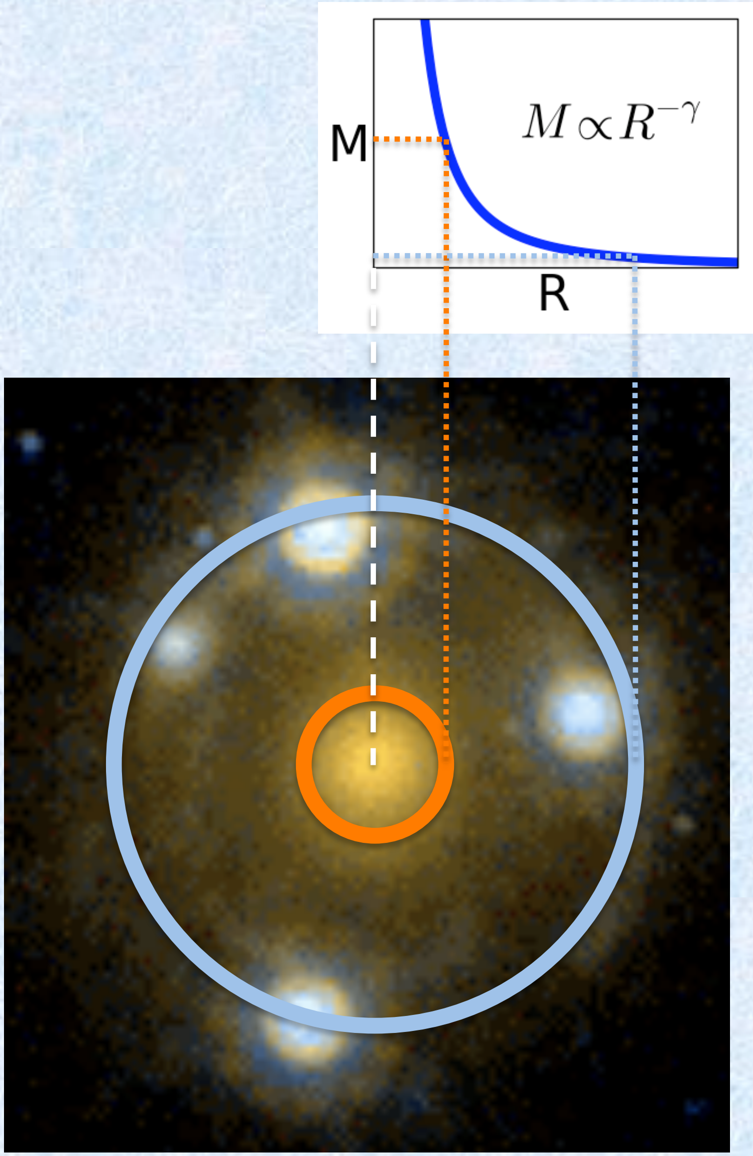
- Distances + redshifts = cosmology ($\mathcal{T}_C$)
-  Lens mass ✔ **Measured**
- Lens mass profile slope
- Lens environment **Large sources of uncertainty**
  - mass sheets & shear
- Line of sight structure
  - mass sheets & shear
- Substructure $\mathcal{T}_\mathcal{L}$

Potential systematics

variable	magnitude	corrected to
Lens mass profile slope	~10%	~5%
Environment mass sheet	~20%	~5%
Line-of-sight mass sheet	~5%	~1%
External shear	~5%	~0% (random scatter)
Substructure	~1%	~0% (random scatter)

Our work further motivates efforts to control these systematics.

Mass profile slope from Lensing + Dynamics



Assuming the lens galaxy's mass profile has a power-law slope, that slope can be determined by measuring the mass within two radii:

R_{Ein}, the Einstein radius by lensing: multiple image positions

R_{eff}, the lens galaxy's effective radius by velocity dispersion measurements

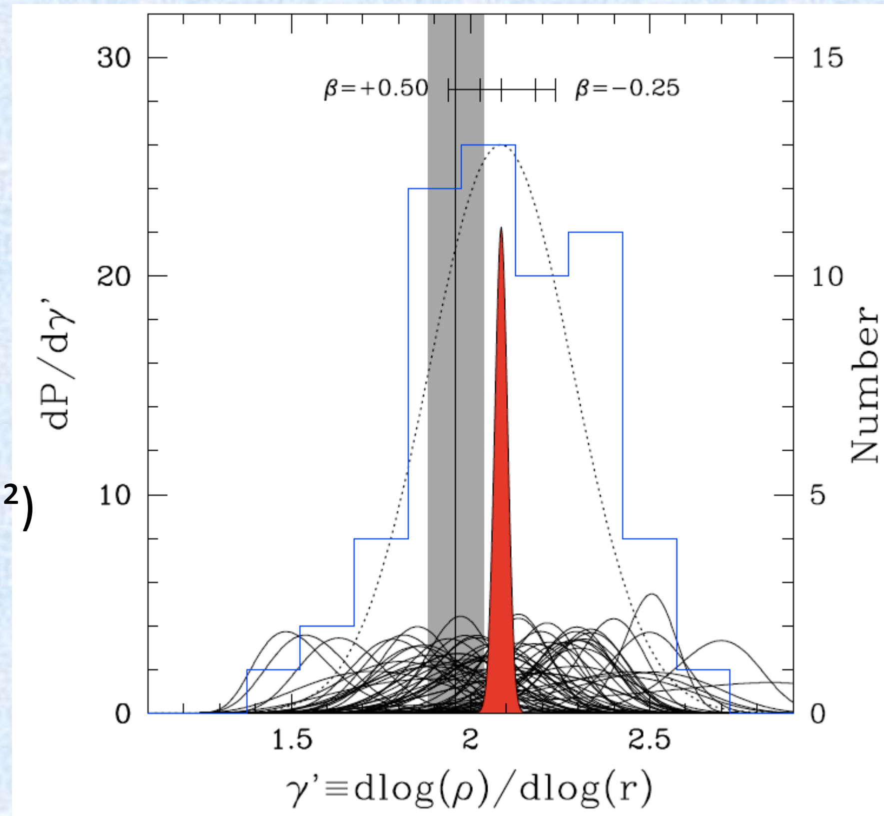
Slope measurements reveal the average lens is roughly isothermal

Koopmans09 analyzed 58 SLACS lenses, all early type galaxies.
Found the average lens is slightly steeper than isothermal ($\rho \propto r^{-2}$):

γ = 2.085 ± 0.20 (~10% scatter)
$\langle\gamma\rangle$ = 2.085 ± 0.02
(~1% uncertainty in average slope)

$$\rho_{\rm tot} \propto r^{-2.085}$$

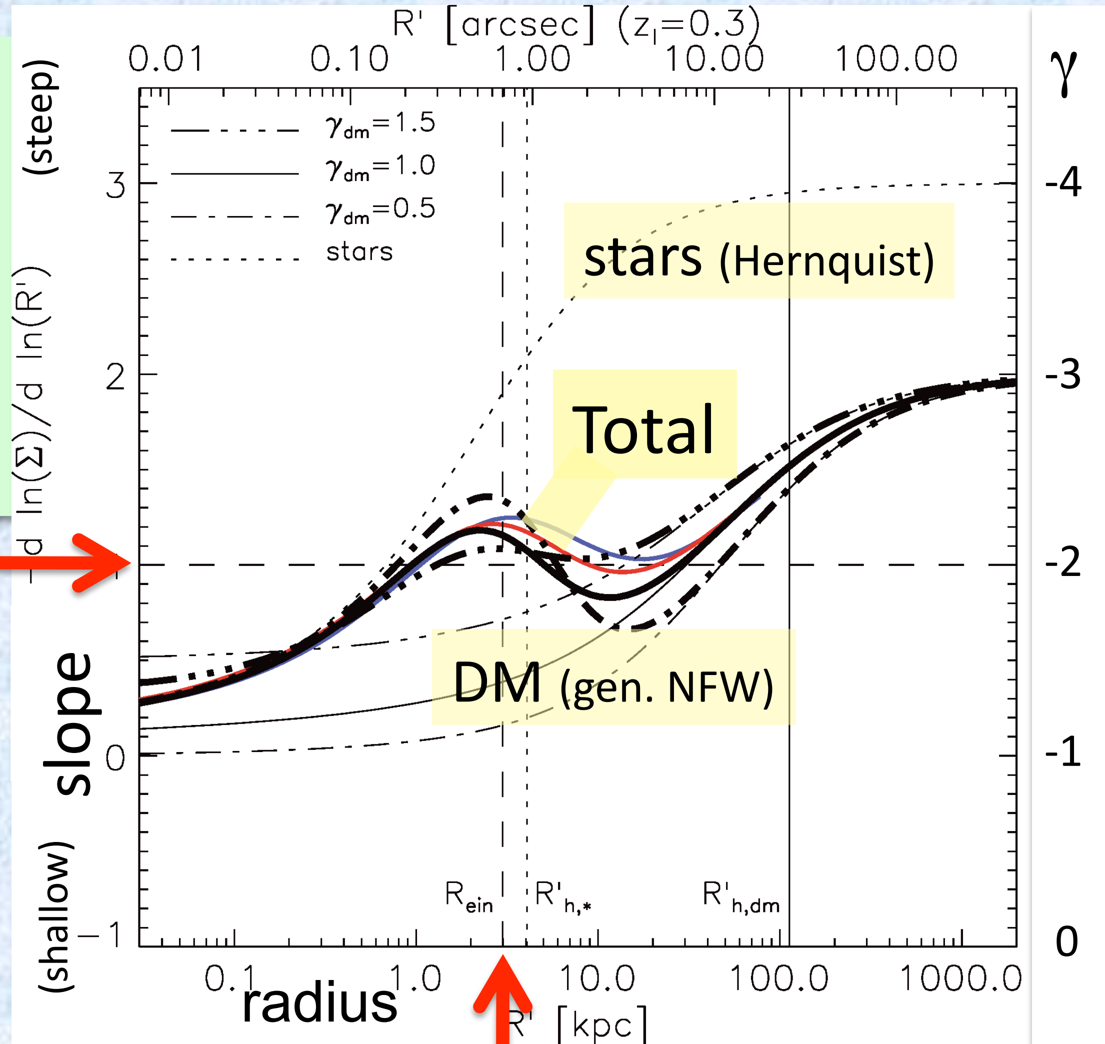
Assuming an isothermal model ($\rho \propto r^{-2}$) in the analysis of time delay lenses could bias $\mathcal{T}_C$ high (H_0 low) by 8.5% (e.g., 74 → 68 km/s/Mpc)



Bulge-Halo conspiracy

Bulge (stars) and
halo (dark matter)
seem to conspire,
adding up to
an isothermal profile
near the Einstein radius

isothermal



Einstein radius

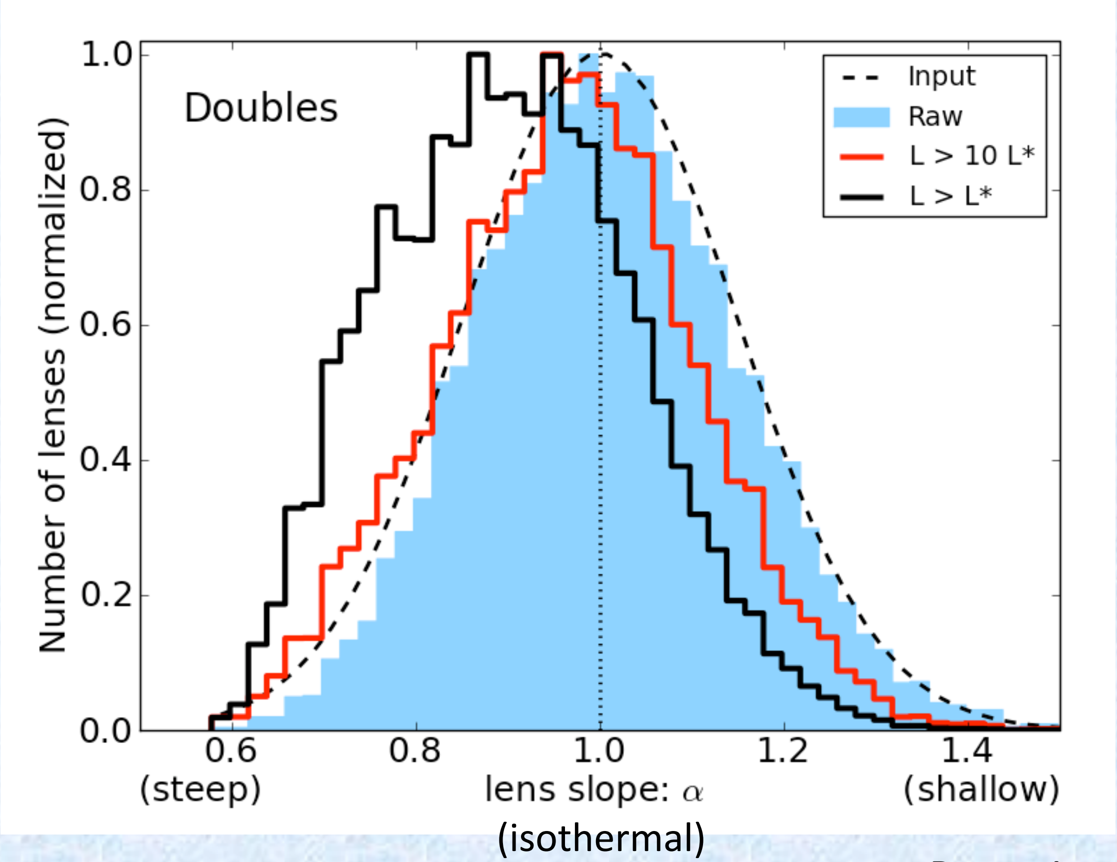
Theoretical work
(van de Ven 09)

Selection bias for steeper lenses?

Steeper lenses strongly lens more background objects but to lower magnification

A deeper survey may be more biased to steeper lenses

Appears to be an issue for doubles but not quads



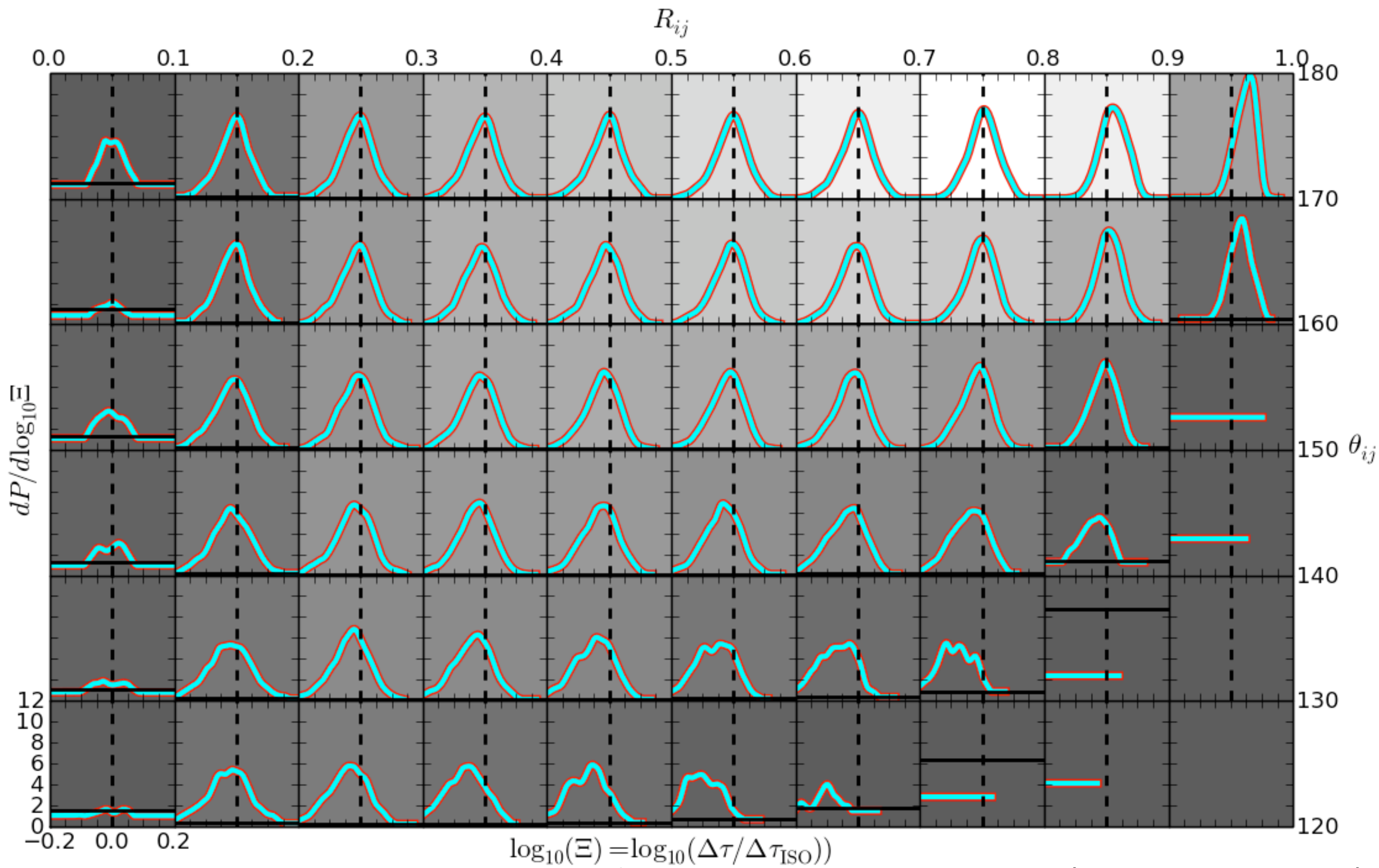
Paper I

Quantity vs. Quality: Mass slopes

- Quantity: Assume a prior on mass slopes
  - for example, $\gamma = -2.085 \pm 0.20$
  - or simply assume the average lens is isothermal
- Quality: Measure the slope of each lens
- Either way, systematic errors in slope measurements would affect our results
  - even our prior would also be based on slope measurements derived elsewhere

A well informed prior:

Bias can also be a function of image configuration

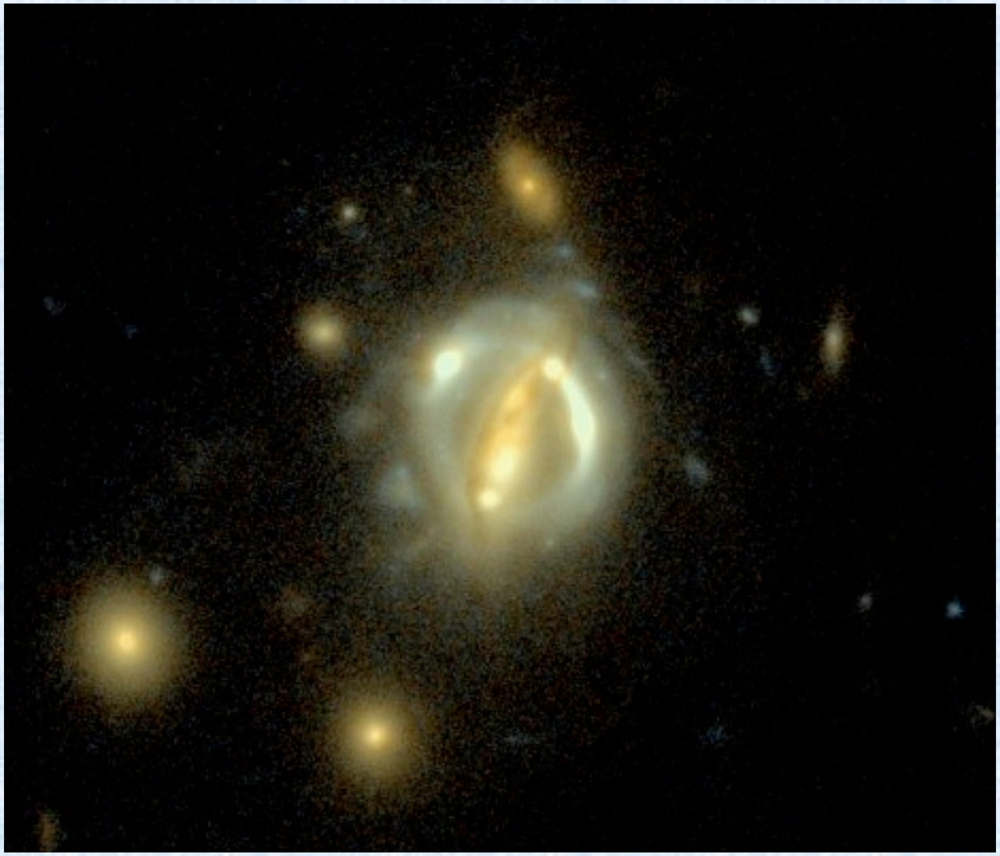


from simulations in Paper I (see also Oguri07)

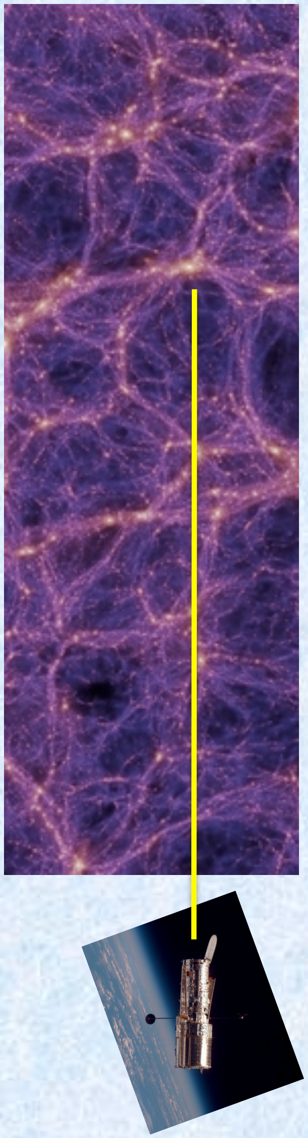
Nearby group members add “mass sheet”, biasing $\mathcal{T}_C$ high (H_0 low)

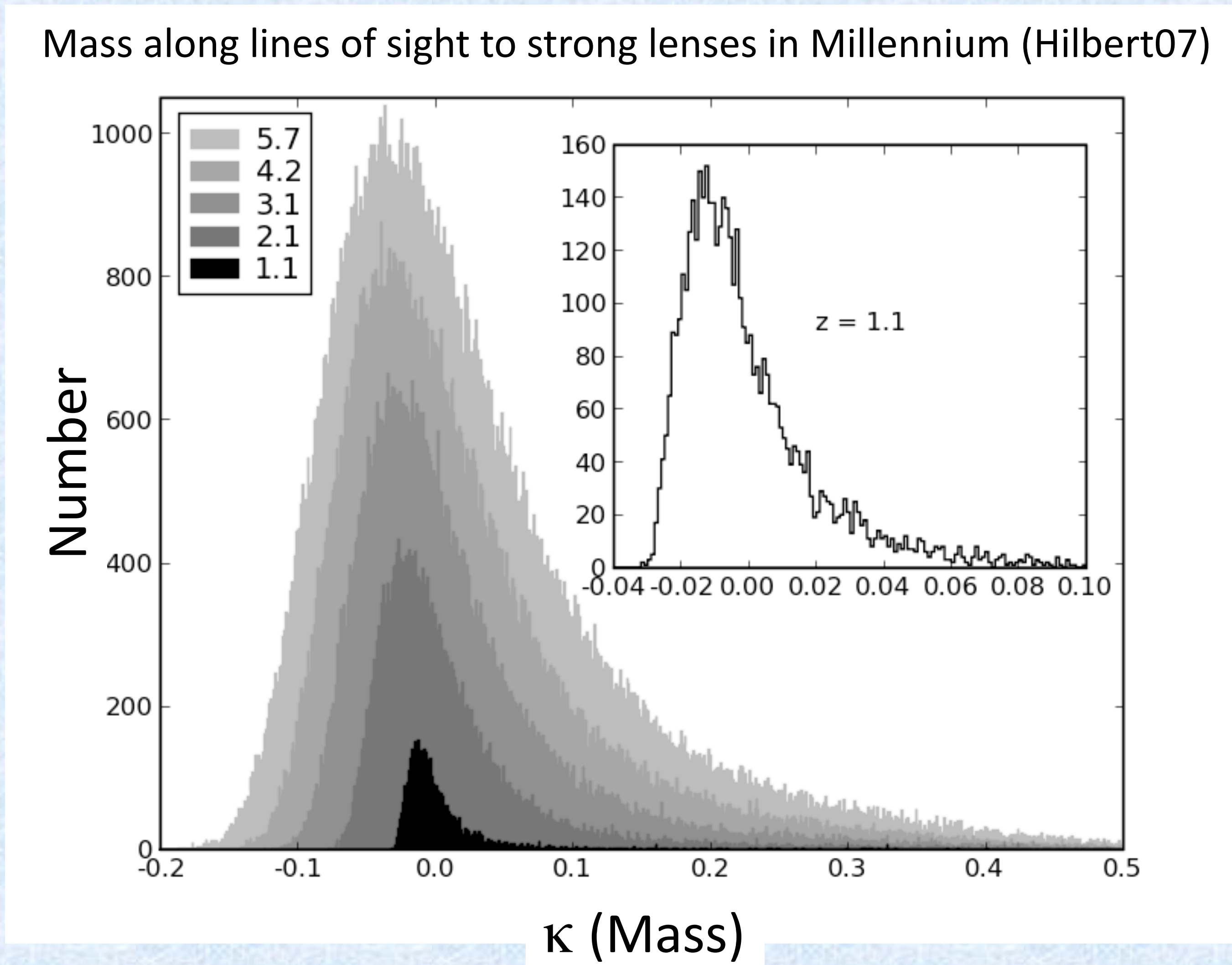
Bias is potentially large and must be corrected for.

Either use a prior
on mass sheet,
or for each lens,
identify group members
spectroscopically and
estimate their contributions
to the mass sheet
(see work by Fassnacht, Auger, Momcheva)



Line of sight galaxies can also add mass sheets, biasing $\mathcal{T}_C$ high (H_0 low) (but less so)





If systematic biases persist, how will our derived cosmology be biased?

- Work in progress (Paper III)
- Any bias which is consistent across all lenses as a function of lens and source redshift *may* only affect (bias) our derived H_0, leaving other parameters (Ω_m, Ω_{de}, Ω_k, w_0, w_a) measured robustly

Gravitational Lens Time Delays offer "free" and independent cosmological constraints

- LSST time delays from 4,000 lenses should constrain
  $h \approx 0.7 \pm 0.007$ (1%)
  $\Omega_{de} \approx 0.7 \pm 0.005$
  $w \approx -1 \pm 0.026$
  assuming a flat universe, constant w, and Planck
- LSST and OMEGA (~4,000 vs. ~100 lenses) represent an even trade in "quality vs. quantity". Combined constraints would be even tighter.
- New dedicated mission not required.