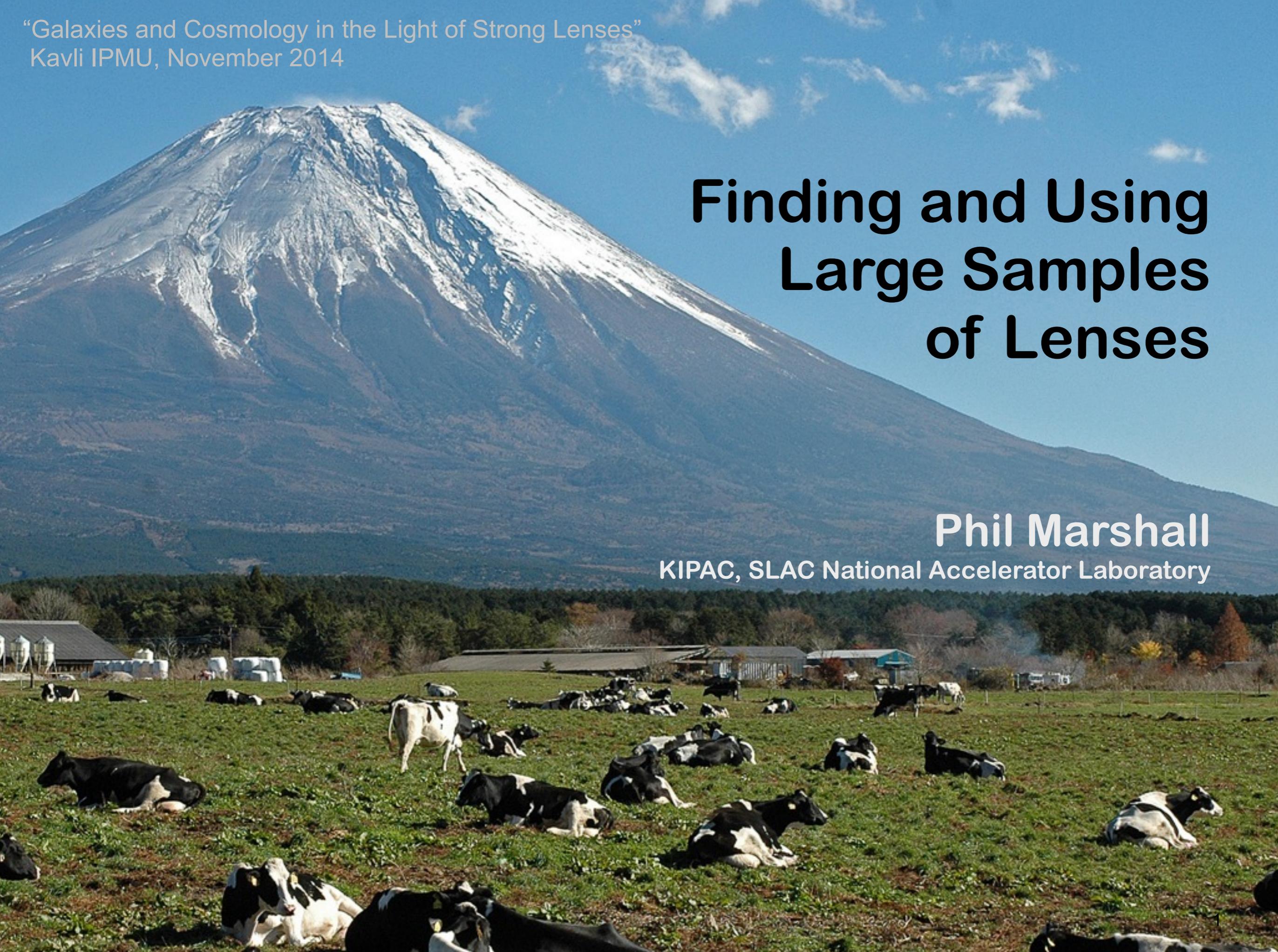


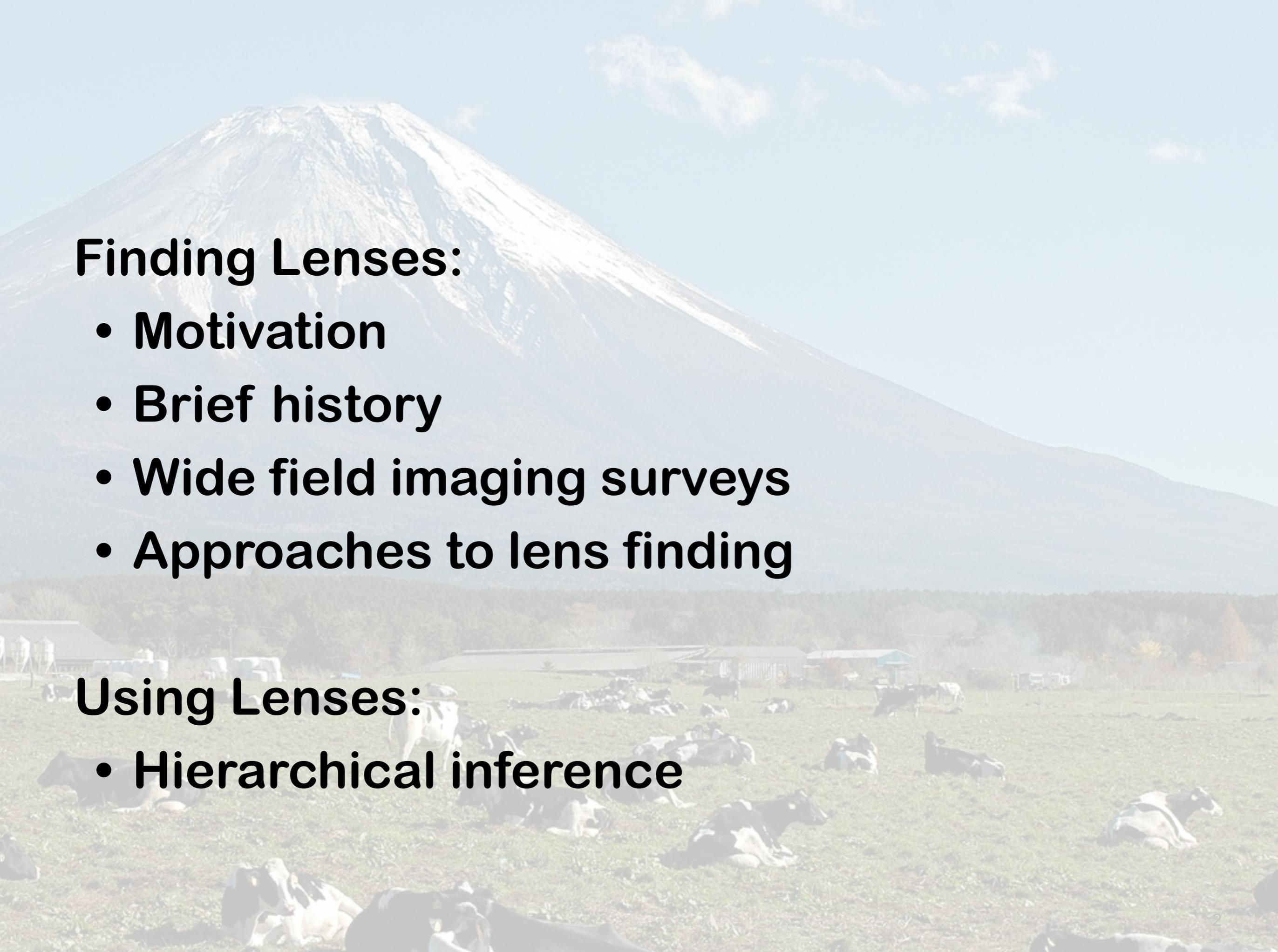
“Galaxies and Cosmology in the Light of Strong Lenses”  
Kavli IPMU, November 2014

# Finding and Using Large Samples of Lenses

Phil Marshall

KIPAC, SLAC National Accelerator Laboratory



The background of the slide features a large, snow-capped mountain, likely Mount Fuji, under a clear blue sky with a few wispy clouds. In the foreground, there is a green field with several black and white cows resting on the grass. In the middle ground, there are several farm buildings, including a large barn and smaller structures, with some trees scattered around.

## **Finding Lenses:**

- **Motivation**
- **Brief history**
- **Wide field imaging surveys**
- **Approaches to lens finding**

## **Using Lenses:**

- **Hierarchical inference**

## Finding Lenses:

- Motivation
- Brief history
- Wide field imaging surveys
- Approaches to lens finding

Biases:

galaxy-scale  
optical imaging

Length

## Using Lenses:

- Hierarchical inference

# Motivation



# Motivation

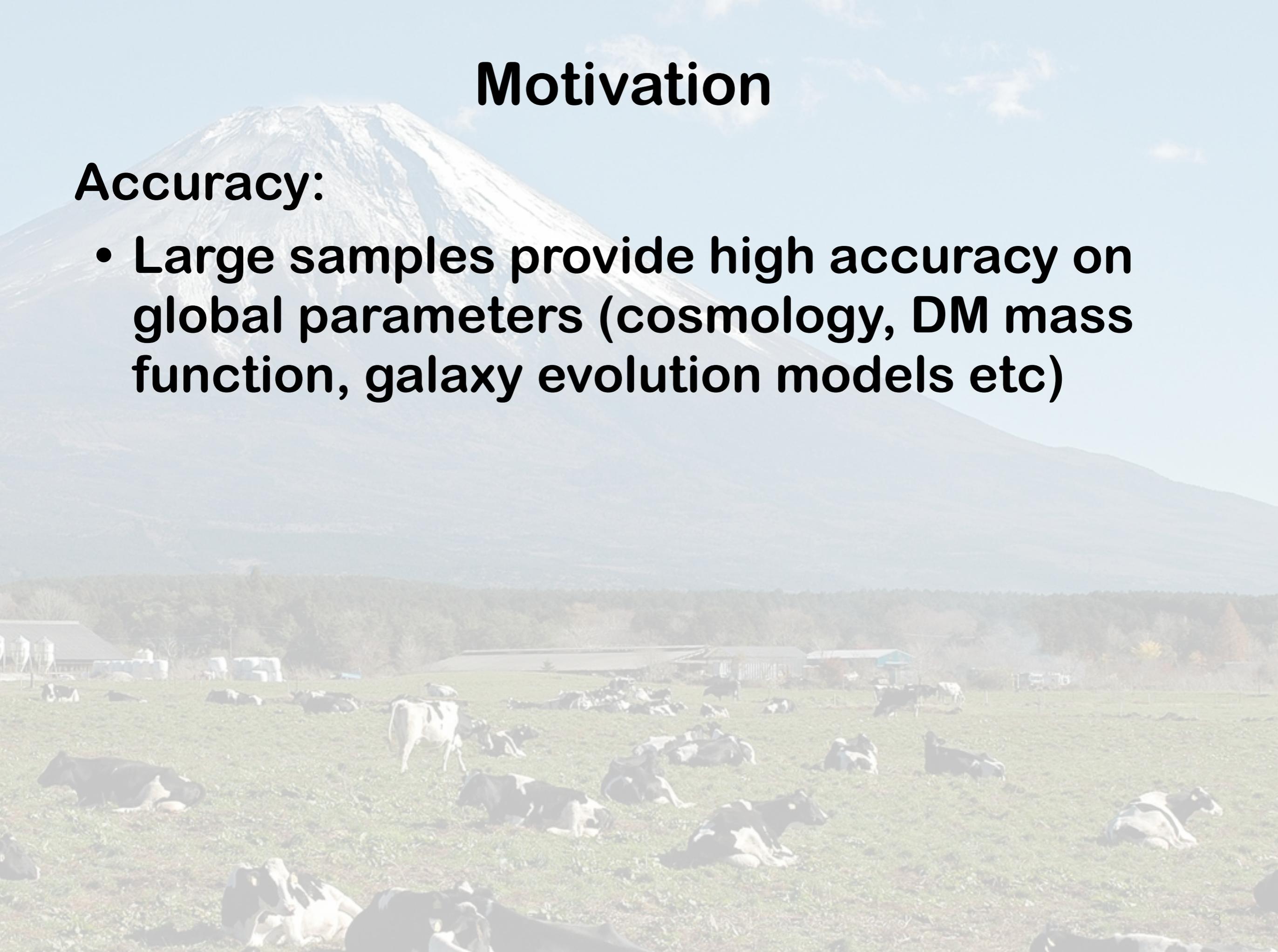
Accuracy:



# Motivation

## Accuracy:

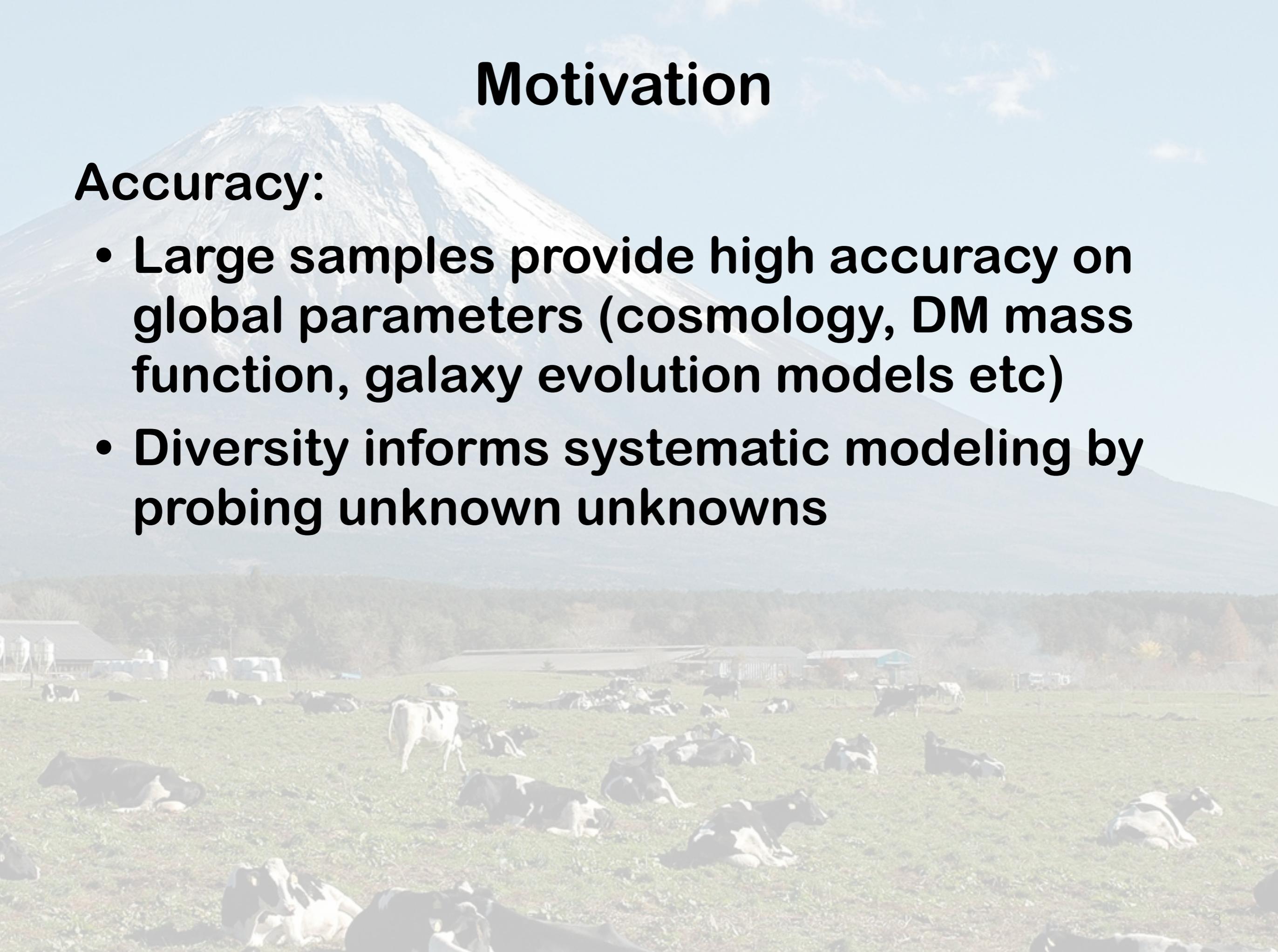
- Large samples provide high accuracy on global parameters (cosmology, DM mass function, galaxy evolution models etc)



# Motivation

## Accuracy:

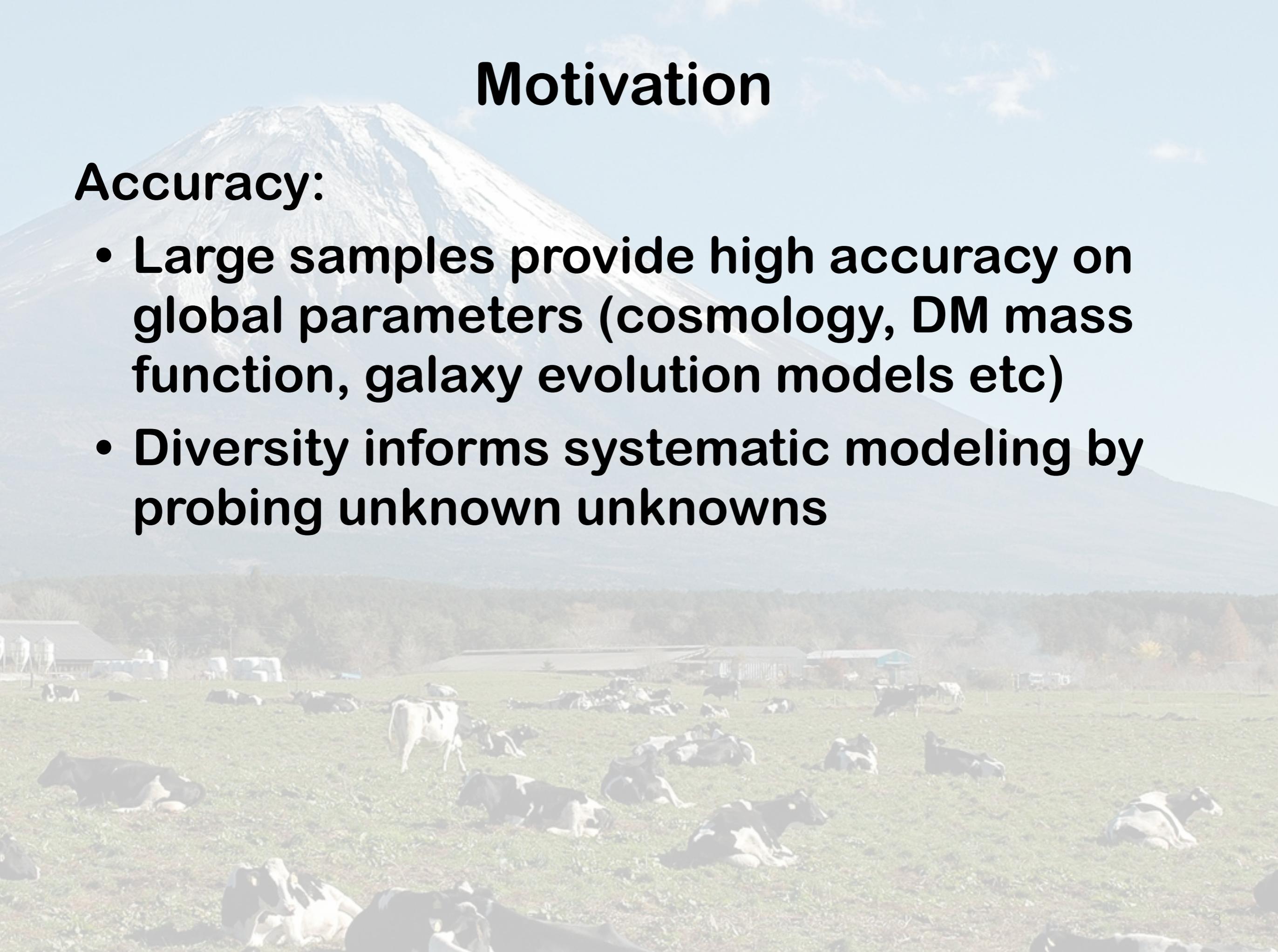
- Large samples provide high accuracy on global parameters (cosmology, DM mass function, galaxy evolution models etc)
- Diversity informs systematic modeling by probing unknown unknowns



# Motivation

## Accuracy:

- Large samples provide high accuracy on global parameters (cosmology, DM mass function, galaxy evolution models etc)
- Diversity informs systematic modeling by probing unknown unknowns



# Motivation

## Accuracy:

- Large samples provide high accuracy on global parameters (cosmology, DM mass function, galaxy evolution models etc)
- Diversity informs systematic modeling by probing unknown unknowns

## Discovery:



# Motivation

## Accuracy:

- Large samples provide high accuracy on global parameters (cosmology, DM mass function, galaxy evolution models etc)
- Diversity informs systematic modeling by probing unknown unknowns

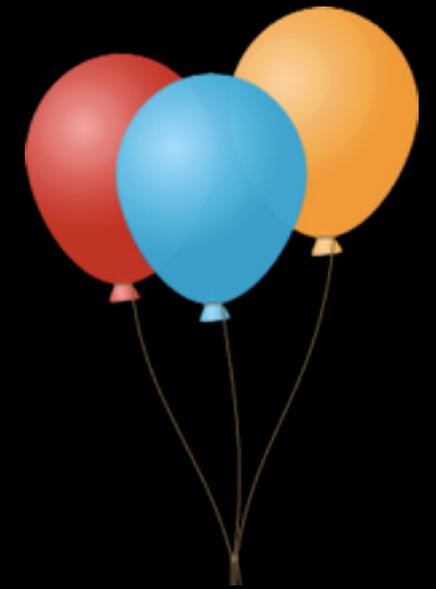
## Discovery:

- Large samples will contain surprises, extreme or exotic lenses enabling new types of investigation

# The first 10 years of industrial strong lensing

- **CLASS** (N lenses; Browne, Fassnacht)
- **SLACS** (N lenses; Bolton, Auger, Treu, Koopmans)
- **SQLS** (N lenses; Oguri, Inada)
- **HST** (N lenses; Moustakas, Marshall, Faure, Jackson, More, Pawase)
- **SL2S** (N lenses; Gavazzi, Sonnenfeld, More)
- **BELLS** (N lenses; Bolton, Brownstein)
- **SPT/Herschel** (N lenses; Vieira, Negrello)

$$N \sim 10^{1-2}$$



# The first 10 years of industrial strong lensing

- **CLASS** (N lenses; Browne, Fassnacht)
  - **Mine** the FIRST images, **follow-up** with VLA snapshot imaging
- **SLACS** (N lenses; Bolton, Auger, Treu, Koopmans)
  - **Mine** the SDSS spectra, **follow-up** with HST snapshot imaging
- **SQLS** (N lenses; Oguri, Inada)
  - **Mine** the SDSS catalog, **follow-up** with UH88 snapshot imaging
- **HST** (N lenses; Moustakas, Marshall, Faure, Jackson, More, Pawase)
  - **Mine** the images, inspect
- **SL2S** (N lenses; Gavazzi, Sonnenfeld, More)
  - **Mine** the CFHTLS catalogs and images, **follow-up** with HST/AO imaging
- **BELLS** (N lenses; Bolton, Brownstein)
  - **Mine** the BOSS spectra, **follow-up** with HST imaging
- **SPT/Herschel** (N lenses; Vieira, Negrello)
  - **Mine** the source catalogs, **follow-up** with HST/ALMA imaging

$$N \sim 10^{1-2}$$

# The first 10 years of industrial strong lensing

- **CLASS** (N lenses; Browne, Fassnacht)
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$$N \sim 10^{1-2}$$

# The next 10 years of industrial strong lensing

---

# The next 10 years of industrial strong lensing

---

- **SPT/Herschel/ALMA** ( $10^3$  lenses)
  - Mine the Herschel/SPT catalogs, follow-up with ALMA imaging

# The next 10 years of industrial strong lensing

---

- **SPT/Herschel/ALMA** ( $10^3$  lenses)
  - Mine the Herschel/SPT catalogs, follow-up with ALMA imaging
- **PS1** ( $10^{2-3}$  lenses)
  - Mine the PS1 catalogs and images, inspect, follow-up

# The next 10 years of industrial strong lensing

---

- **SPT/Herschel/ALMA** ( $10^3$  lenses)
  - Mine the Herschel/SPT catalogs, follow-up with ALMA imaging
- **PS1** ( $10^{2-3}$  lenses)
  - Mine the PS1 catalogs and images, inspect, follow-up
- **DES/KIDS/HSC** ( $10^3$  lenses each)
  - Mine the DES/KIDS/HSC catalogs and images, inspect, follow-up

# The next 10 years of industrial strong lensing

---

- **SPT/Herschel/ALMA** ( $10^3$  lenses)
  - Mine the Herschel/SPT catalogs, follow-up with ALMA imaging
- **PS1** ( $10^{2-3}$  lenses)
  - Mine the PS1 catalogs and images, inspect, follow-up
- **DES/KIDS/HSC** ( $10^3$  lenses each)
  - Mine the DES/KIDS/HSC catalogs and images, inspect, follow-up
- **Euclid** ( $10^{4-5}$  lenses)
  - Mine the Euclid catalogs and images, inspect, follow-up

# The next 10 years of industrial strong lensing

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- **SPT/Herschel/ALMA** ( $10^3$  lenses)
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  - Mine the Euclid catalogs and images, inspect, follow-up
- **LSST** ( $10^4$  lenses)
  - Mine the LSST catalogs and images, inspect, follow-up

# The next 10 years of industrial strong lensing

---

- **SPT/Herschel/ALMA** ( $10^3$  lenses)
  - Mine the Herschel/SPT catalogs, follow-up with ALMA imaging
- **PS1** ( $10^{2-3}$  lenses)
  - Mine the PS1 catalogs and images, inspect, follow-up
- **DES/KIDS/HSC** ( $10^3$  lenses each)
  - Mine the DES/KIDS/HSC catalogs and images, inspect, follow-up
- **Euclid** ( $10^{4-5}$  lenses)
  - Mine the Euclid catalogs and images, inspect, follow-up
- **LSST** ( $10^4$  lenses)
  - Mine the LSST **catalogs** and images, inspect, follow-up
- **SKA** ( $10^{4-5}$  lenses)
  - (Make and?) mine the SKA source catalogs, inspect, follow-up

# Upcoming Imaging Surveys

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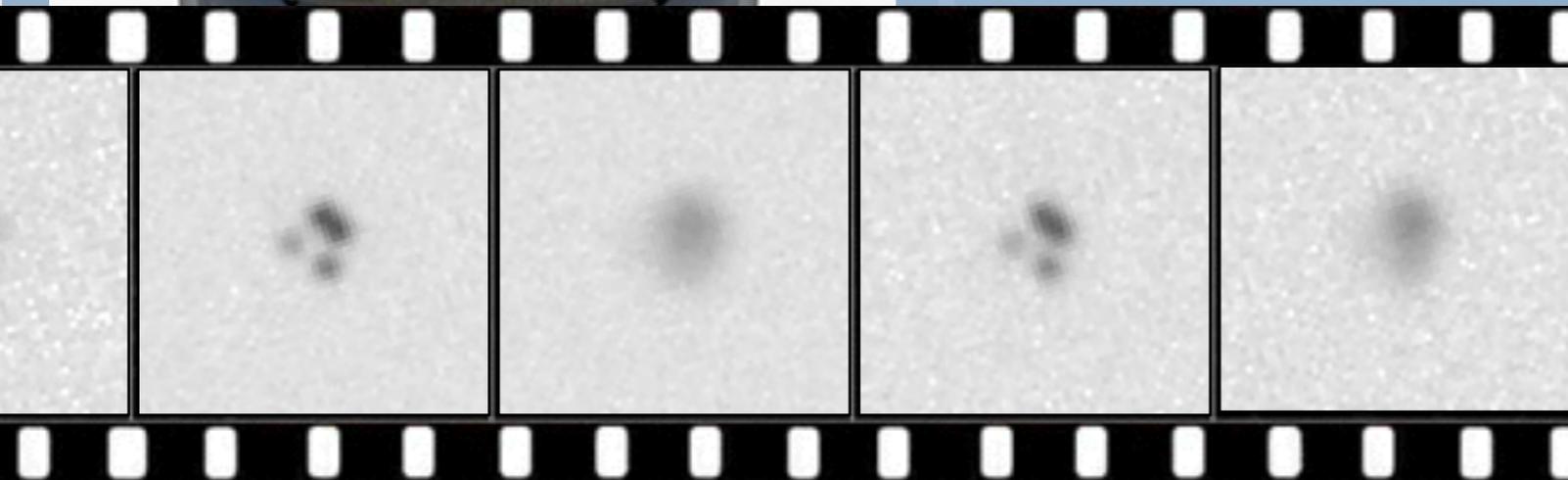
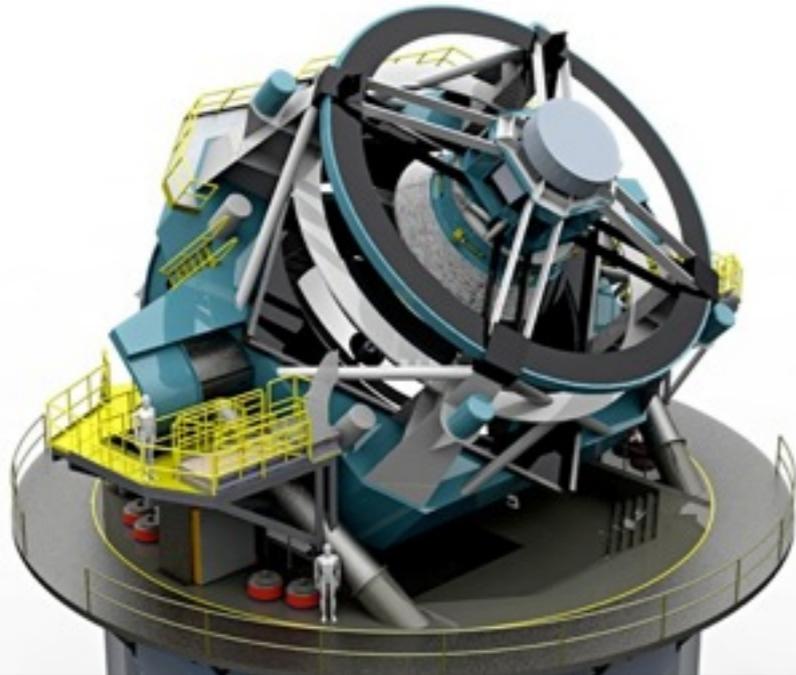
- PS1, DES, HSC, KIDS: ~1000 lensed quasars, 100s of group and cluster arcs
- LSST:  $10^{3-4}$  lensed quasars, 100s of lensed SNe,  $10^4$  arcs and rings
- Euclid:  $10^5$  galaxy-scale lenses
- SKA: few  $10^5$  systems

**key words: “Science Book”**



# Imaging Surveys

- 6m aperture, 10 sq deg field, 24th mag depth in 30 seconds, ugrizy
- 0.4-1.0" seeing (Cerro Pachon)
- 10 year, 18000 sq deg survey, 200 visits per object per band
- 5-10 day cadence



ense



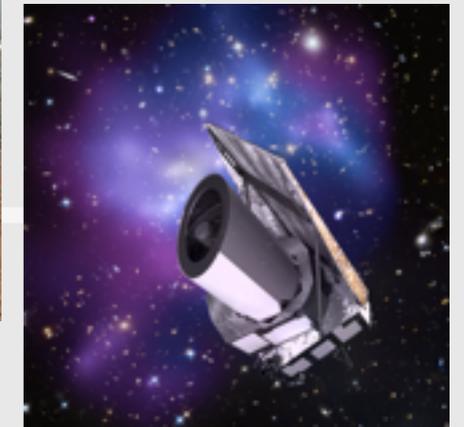




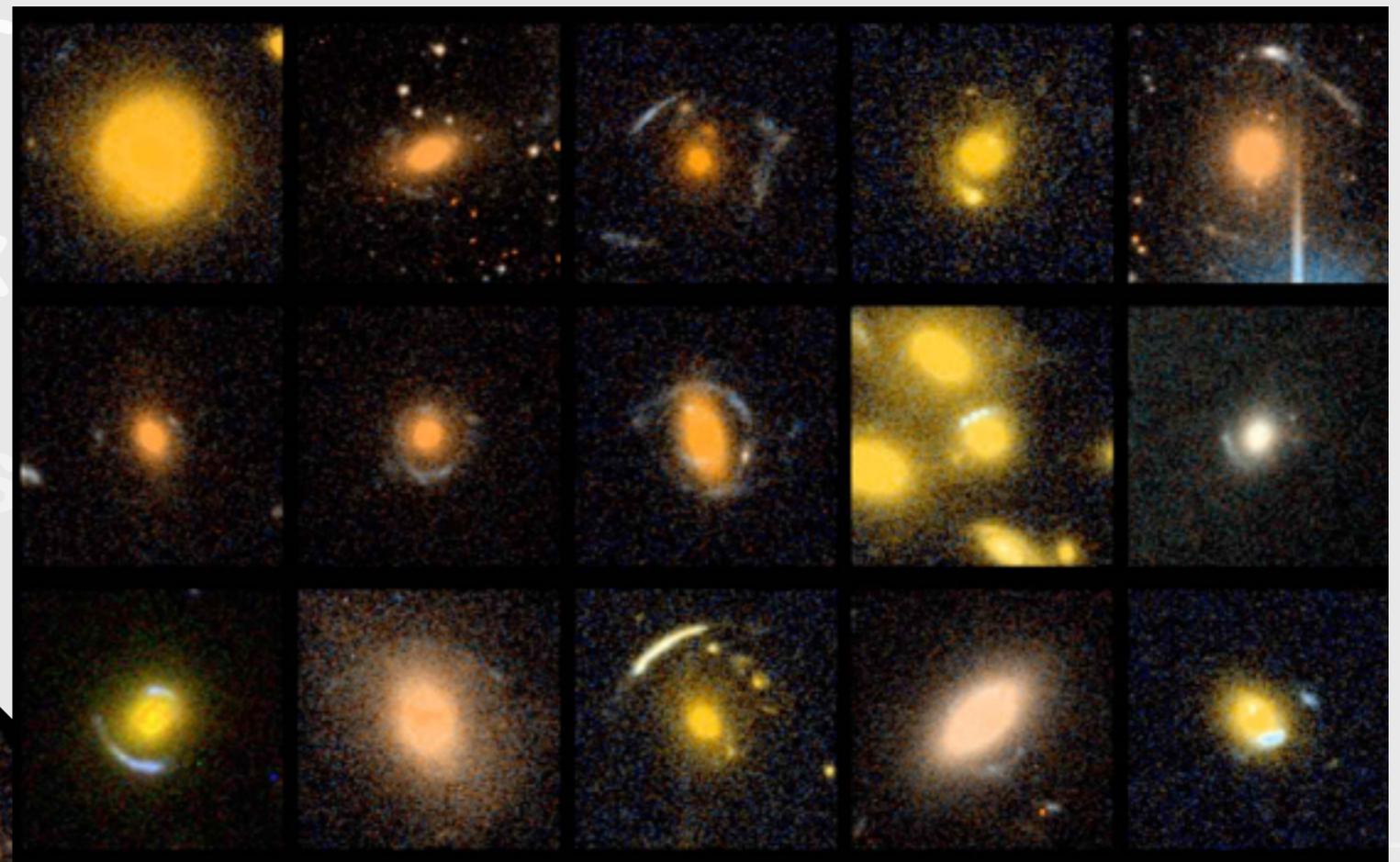


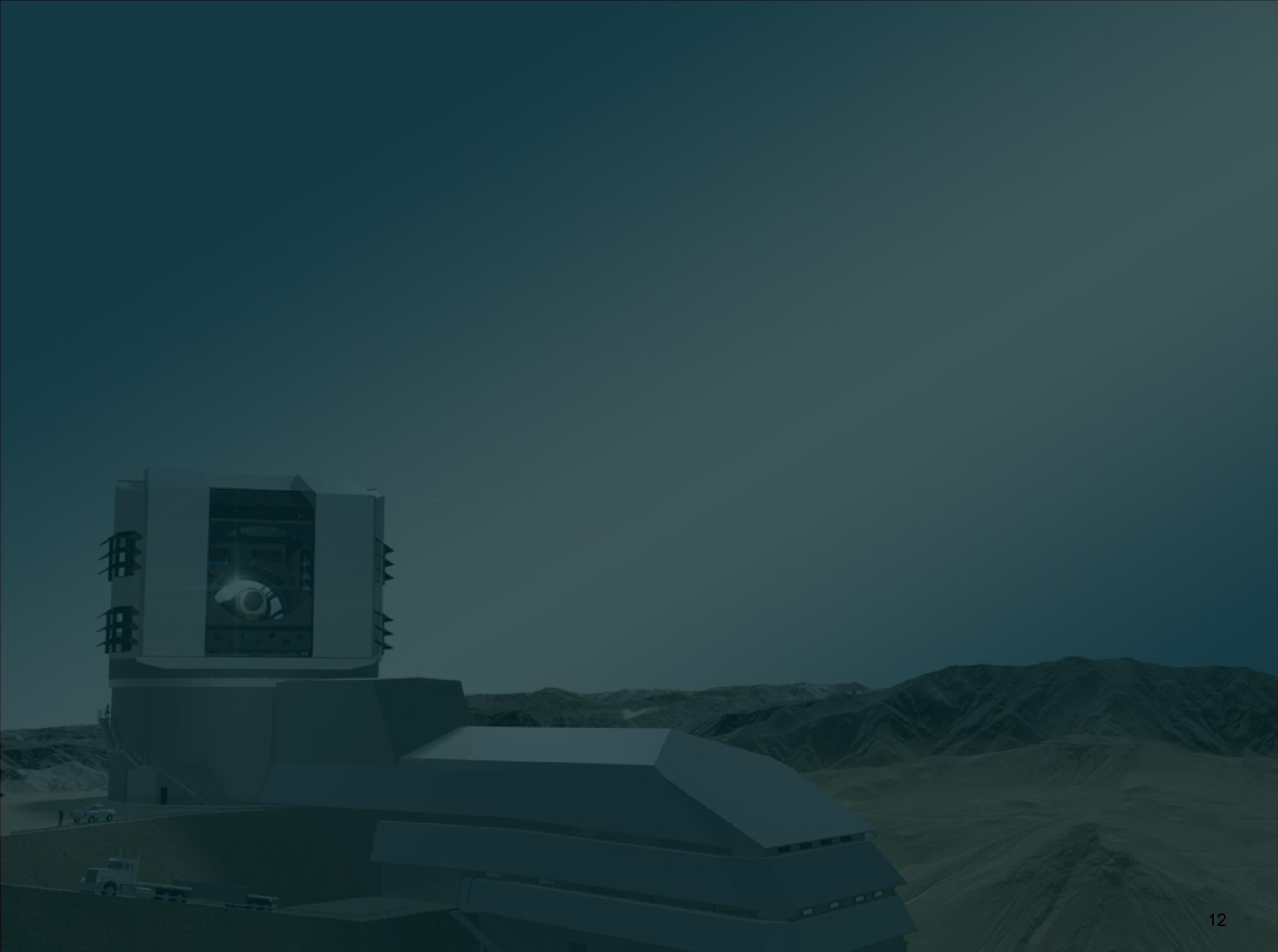


# Euclid, SKA Imaging Surveys

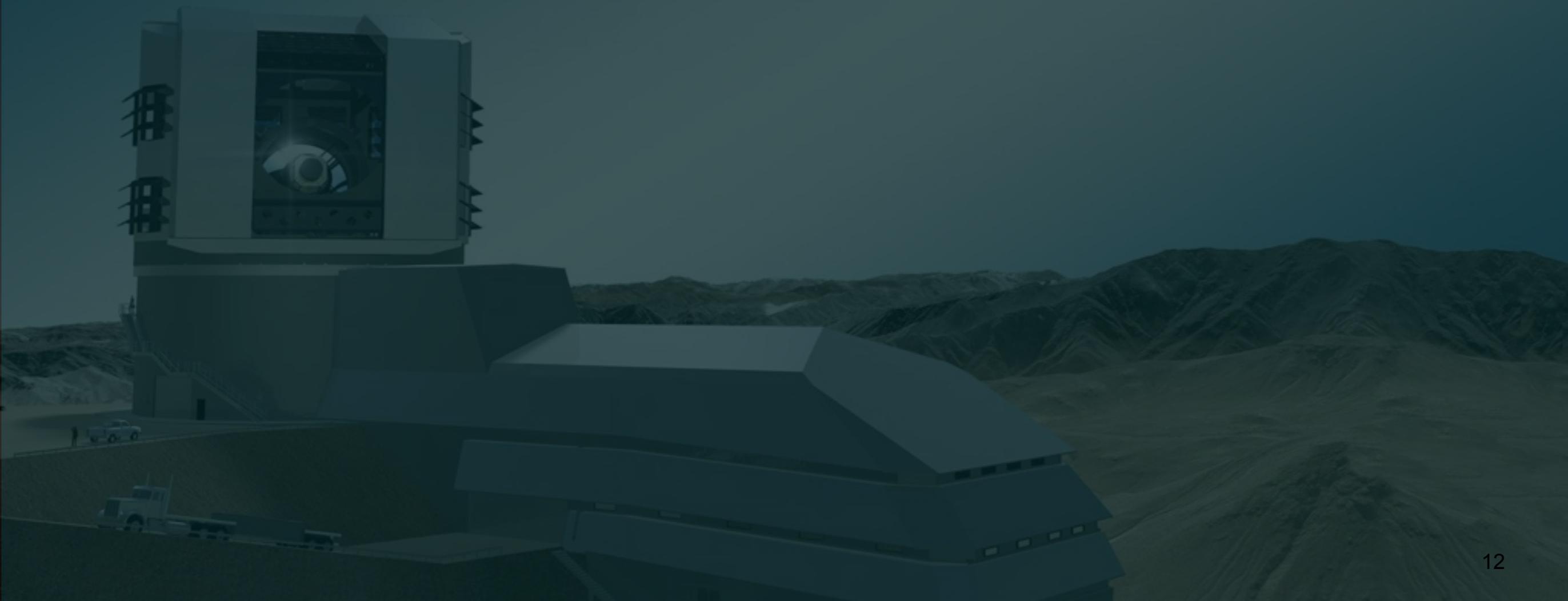


- 0.1-0.3" image quality, 15000 sq deg
- Approaching the 10 lenses per sq deg seen in HST images (COSMOS, HAGGLEs): sources are mostly star-forming galaxies
- Galaxy structure and evolution studies, on a heavily industrialised scale

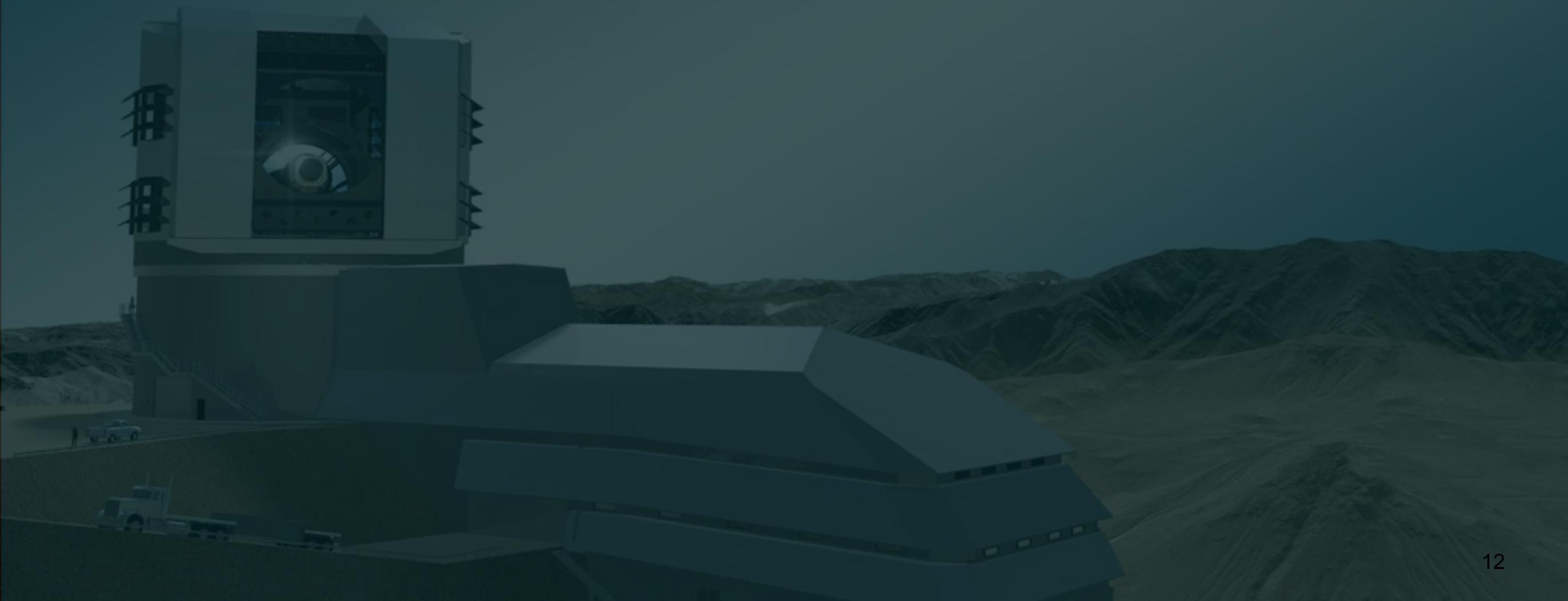




**Wide-field high resolution imaging surveys  
will contain 100,000 strong lenses**



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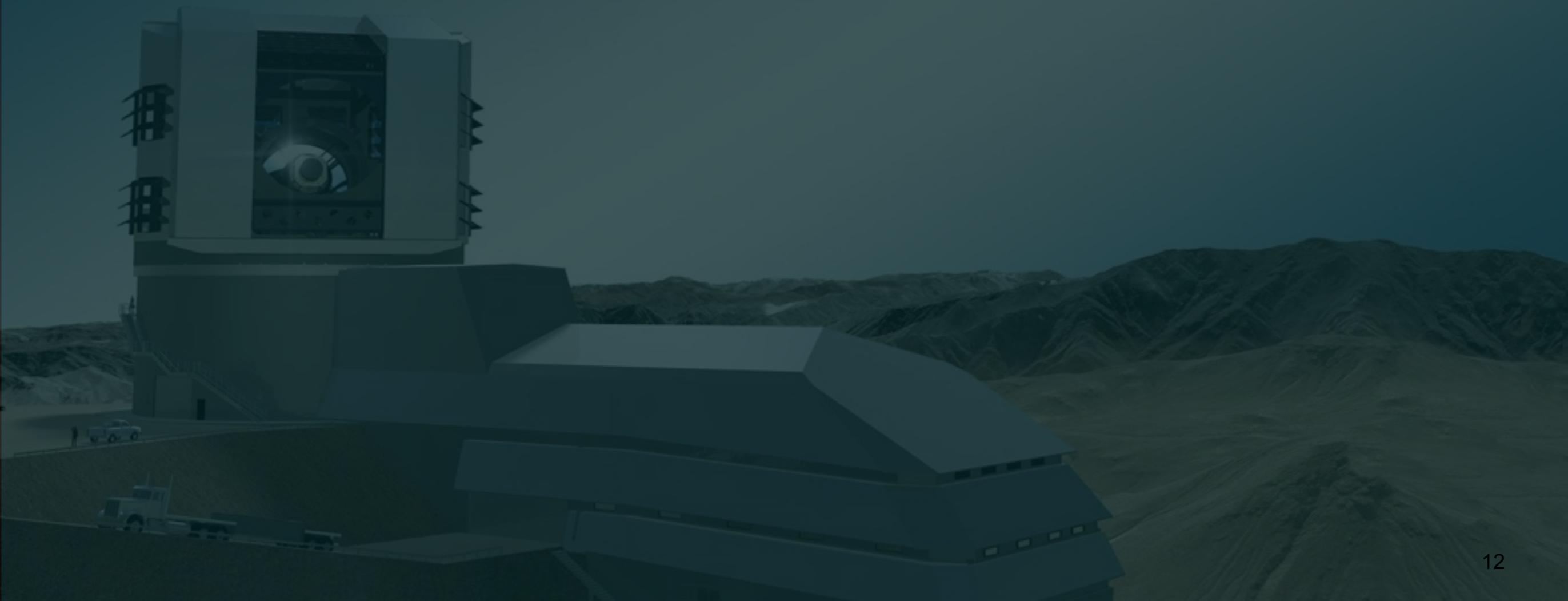
**How might we find them?**



Wide-field high resolution imaging surveys  
will contain 100,000 strong lenses

How might we find them?

- ★ Automated, model-based lens target  
and candidate selection



Wide-field high resolution imaging surveys  
will contain 100,000 strong lenses

## How might we find them?

- ★ Automated, model-based lens target and candidate selection
- ★ Crowd-sourced quality control

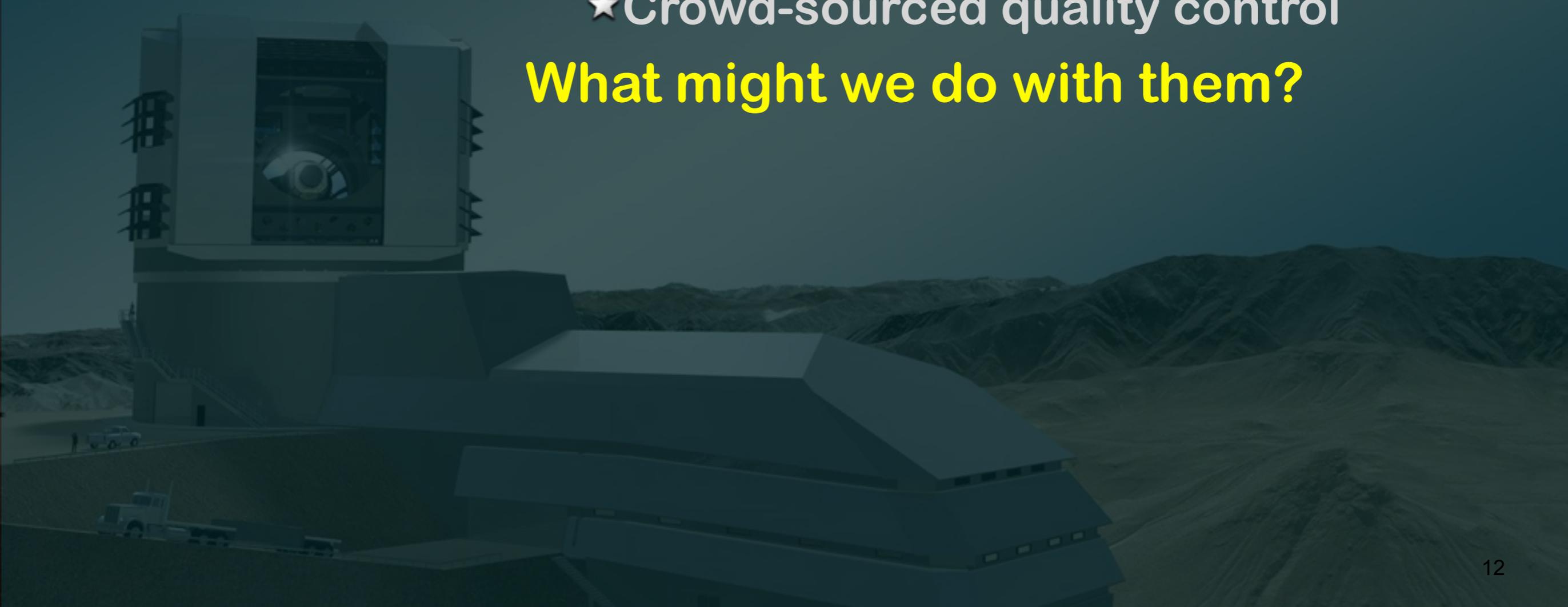


**Wide-field high resolution imaging surveys  
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**How might we find them?**

- ★ Automated, model-based lens target and candidate selection
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**What might we do with them?**





**Wide-field high resolution imaging surveys  
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## **How might we find them?**

- ★ Automated, model-based lens target and candidate selection
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## **What might we do with them?**

- ★ Gild a selection of them



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## **How might we find them?**

- ★ Automated, model-based lens target and candidate selection
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## **What might we do with them?**

- ★ Gild a selection of them
- ★ Statistical analysis of all ze lenses



Wide-field high resolution imaging surveys  
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## How might we find them?

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This talk:



Wide-field high resolution imaging surveys  
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## How might we find them?

- ★ Automated, model-based lens target and candidate selection
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## This talk:

- ★ How to think about lens finding

Wide-field high resolution imaging surveys will contain 100,000 strong lenses

## How might we find them?

- ★ Automated, model-based lens target and candidate selection
- ★ Crowd-sourced quality control

## What might we do with them?

- ★ Gild a selection of them
- ★ Statistical analysis of all ze lenses

## This talk:

- ★ How to think about lens finding
- ★ How to think about large samples

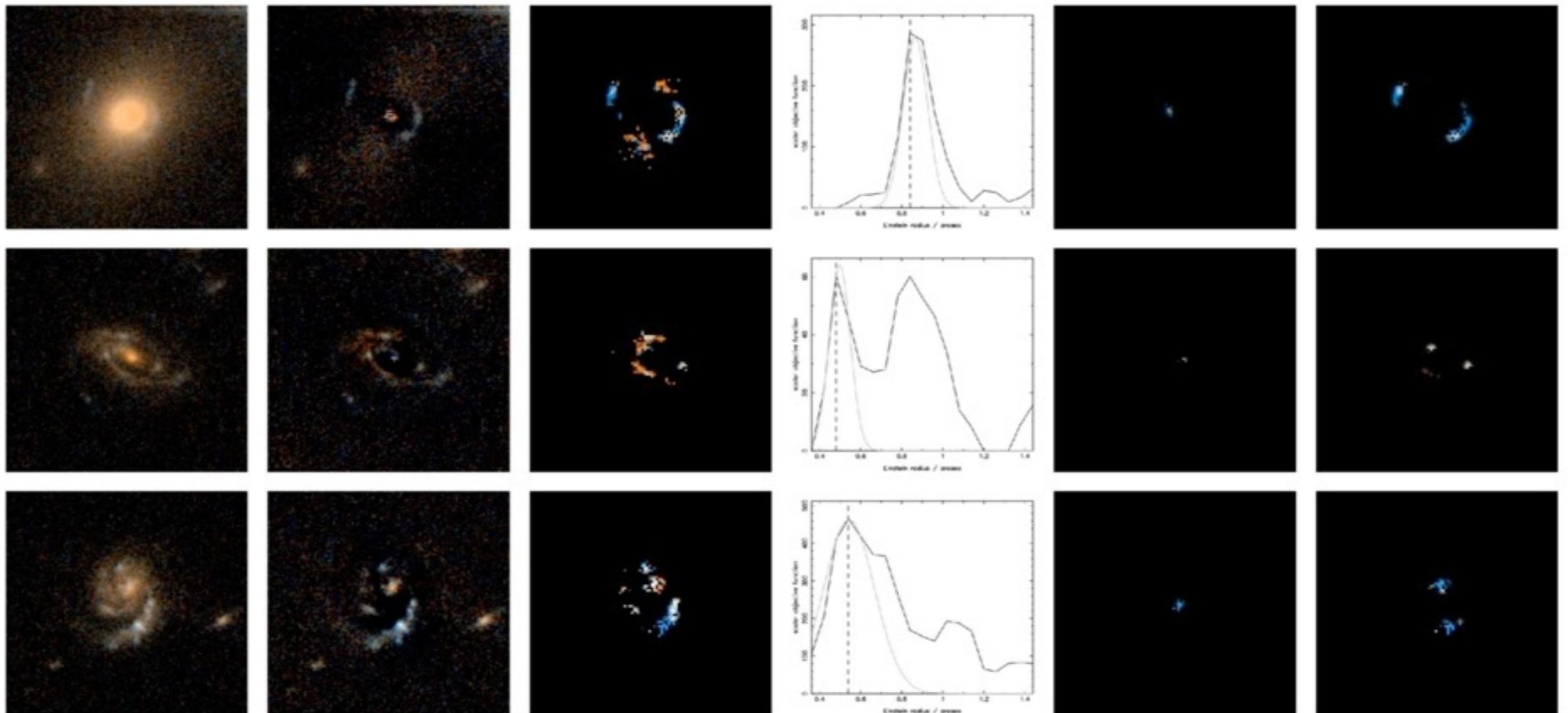
# Thinking about Lens Finding

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For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**

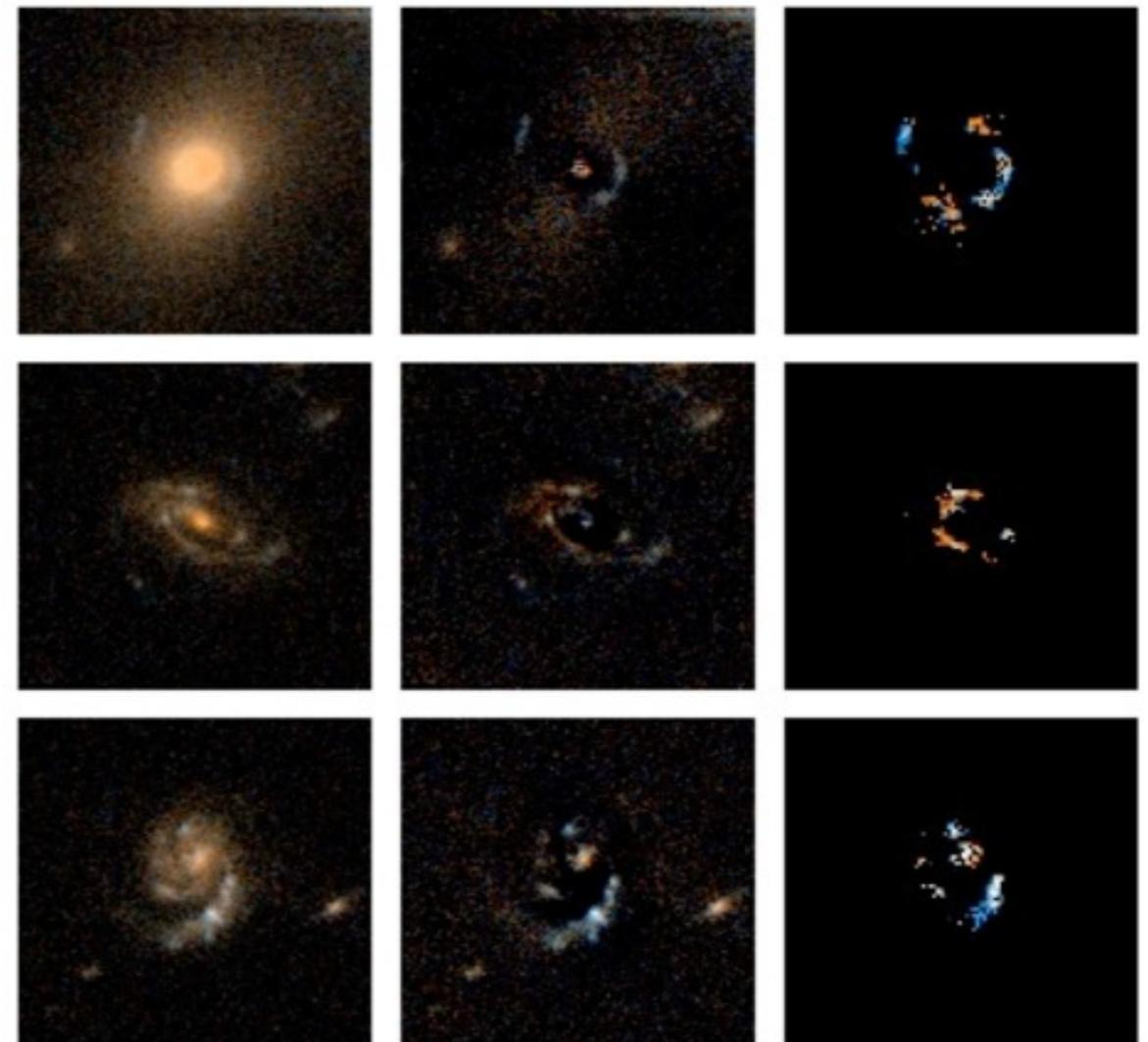
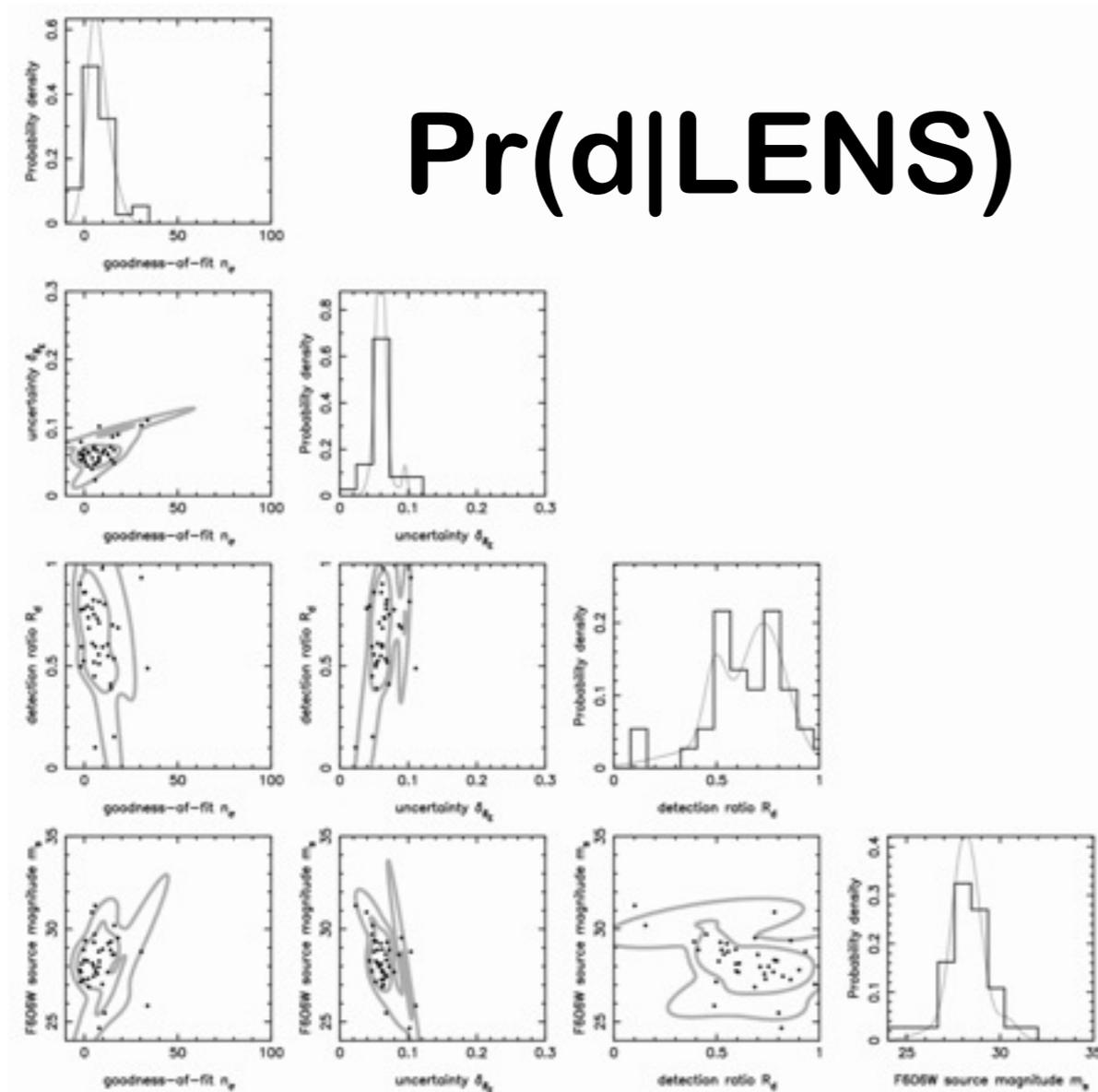
# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



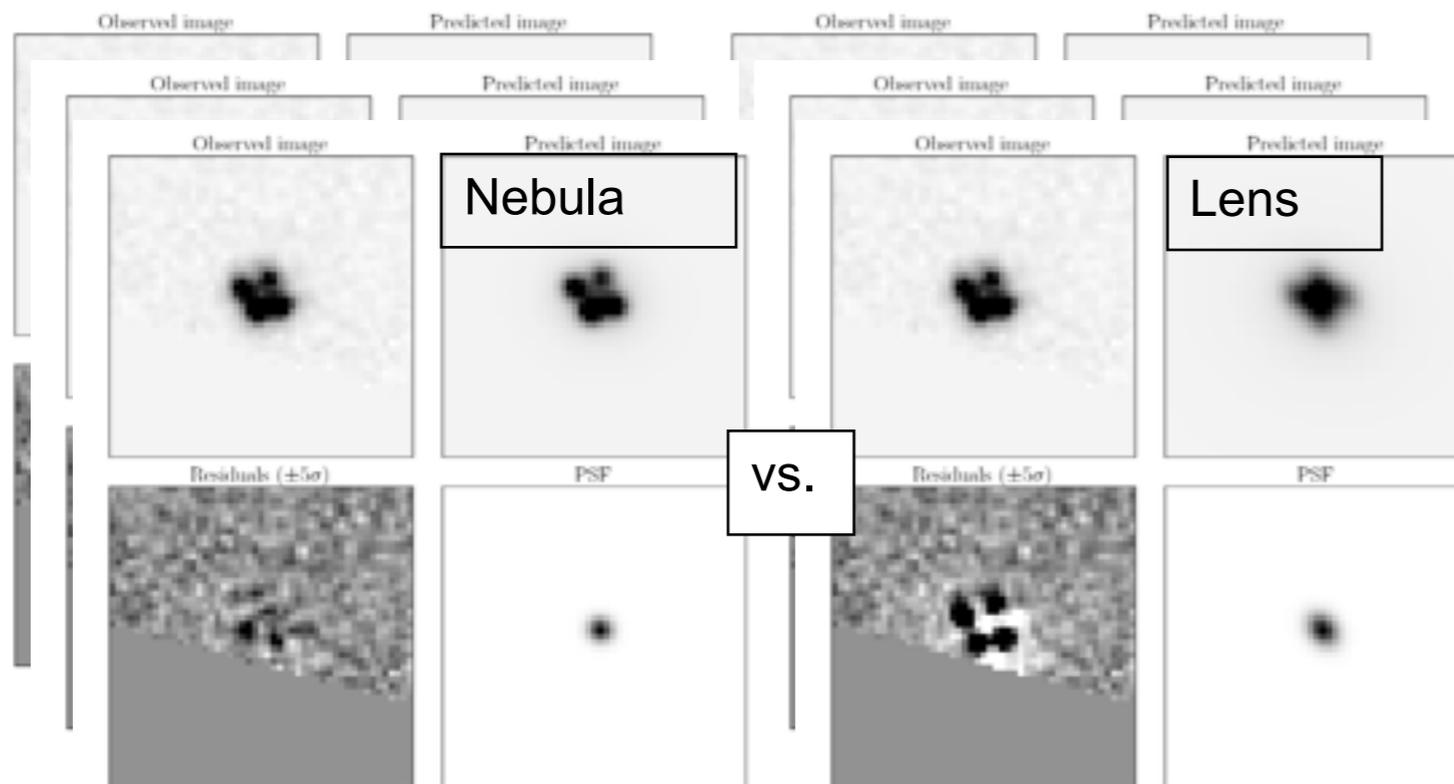
# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



Multi-filter, multi-epoch data,  
unknown PSF

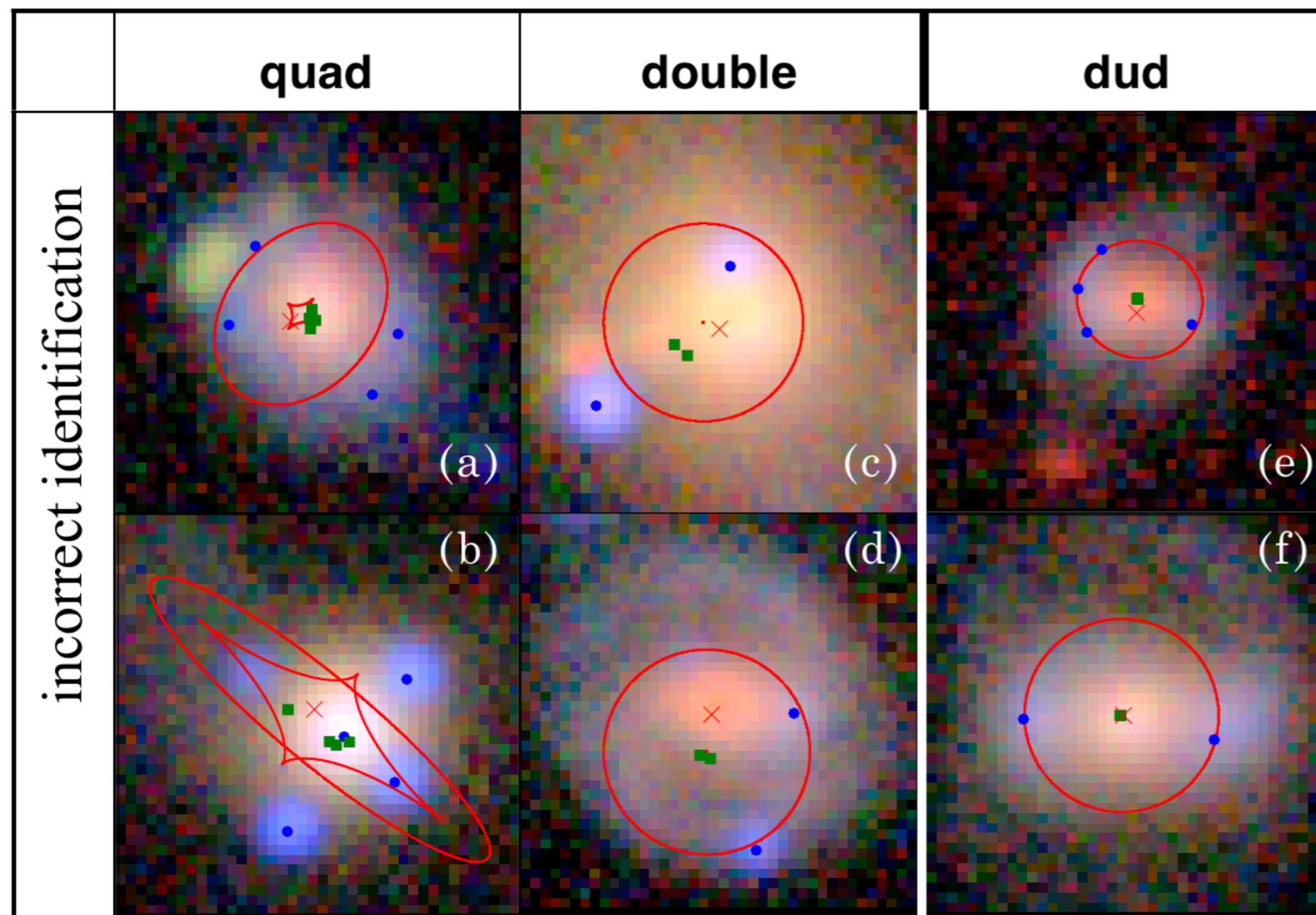
**Lenstractor**  
(Marshall, Agnello et al)

Robotic lensed  
QSO candidate  
detection

Classification  
based on explicit  
model comparison,  
 $\Pr(d|LENS) /$   
 $\Pr(d|NEBULA)$

# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



## Chitah

(Chan et al 2014)

Robotic lensed QSO candidate detection

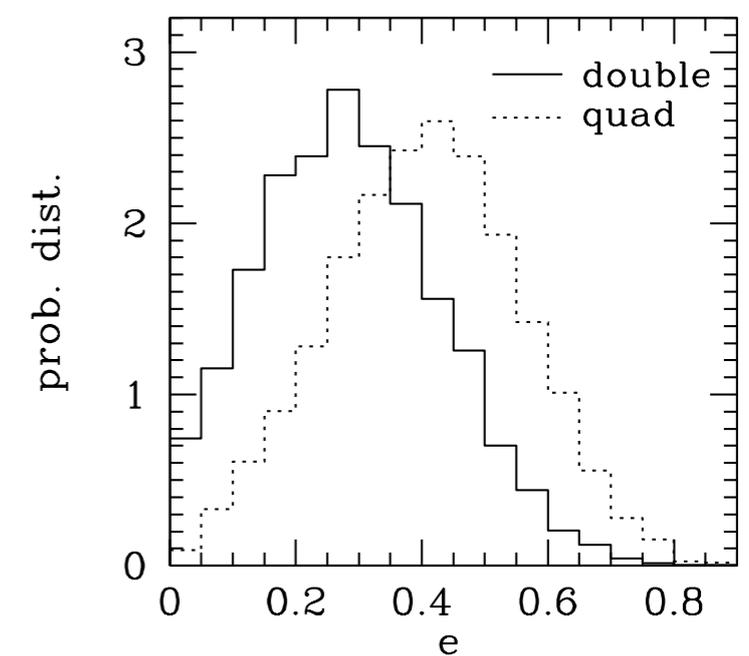
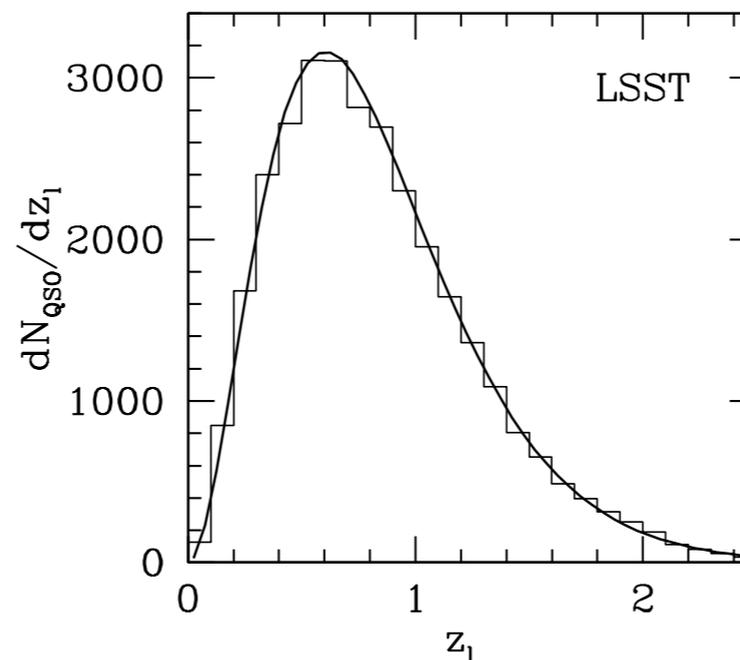
Classifies based on optimized  $\Pr(d|x, \text{LENS})$  from explicit model

# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**

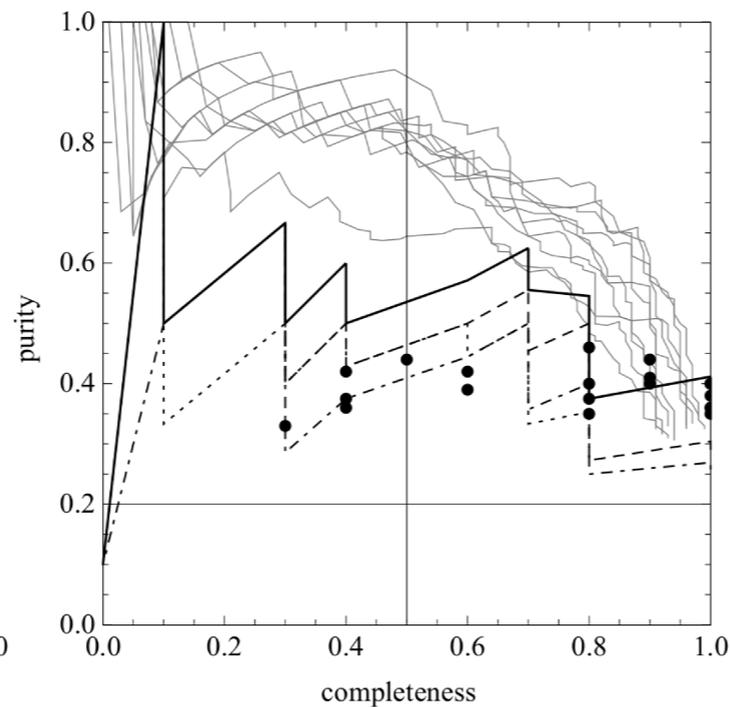
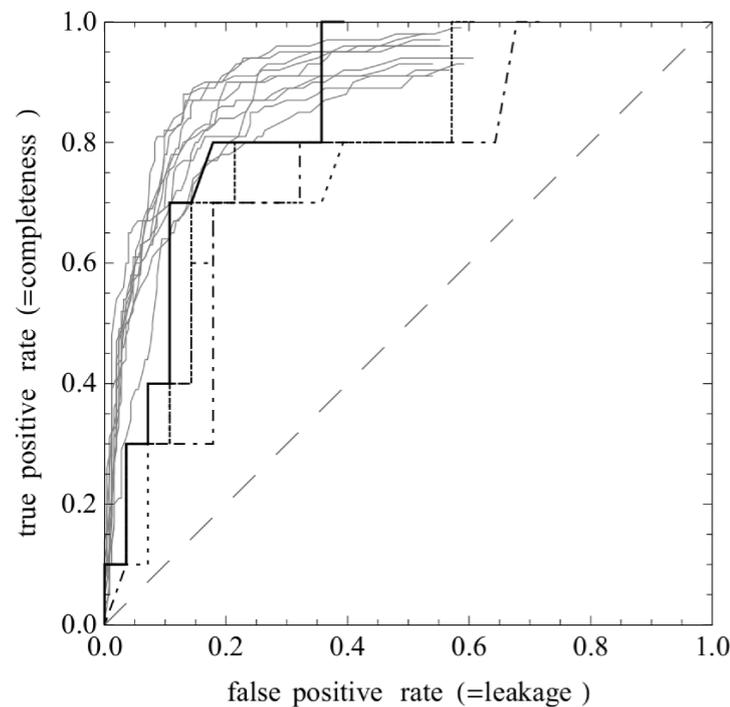
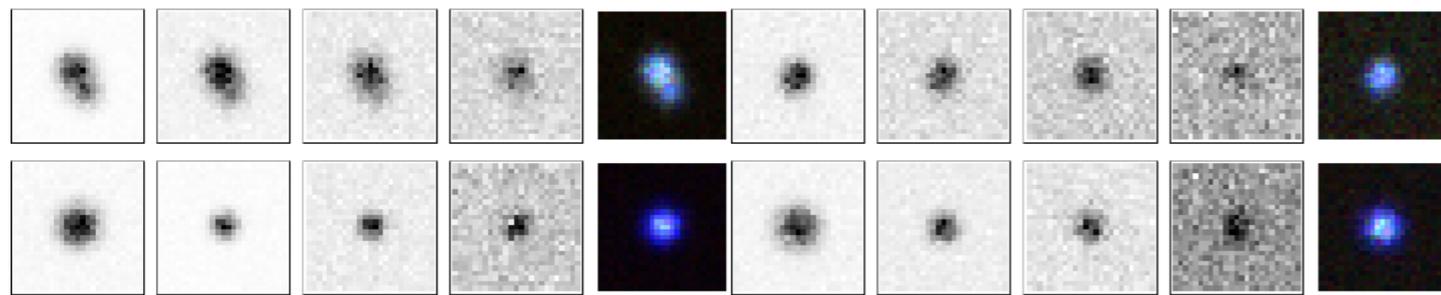
$$\Pr(d|\text{LENS}) = \int \Pr(d|x, \text{LENS}) \Pr(x|\text{LENS})$$

The lens model parameter prior  $\Pr(x|\text{LENS})$  is non-trivial, but was sampled by OM10...



# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



## Lens Mining (Agnello et al 2014)

Supervised machine learning methods - implicit lens model (prior) enters via the training set





Pre-selection



Objects



Pre-selection





Pre-selection



Objects





Catalog



Pre-selection



Objects



ML



Targets





Training  
Objects



Training  
Objects



Validation  
Objects



Training  
Objects



Validation  
Objects



Labelled  
Objects

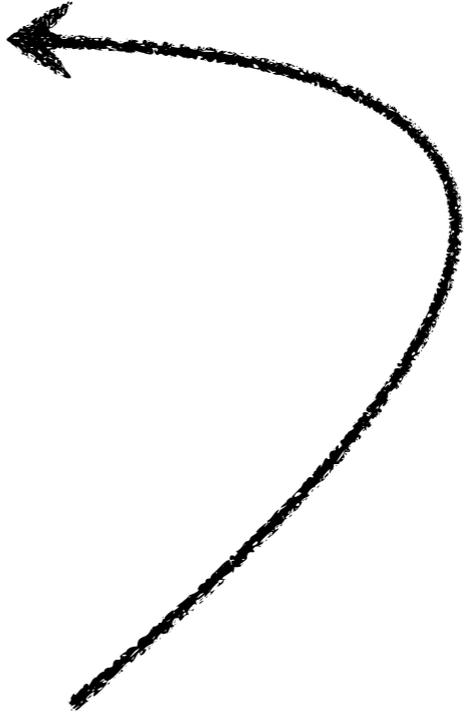
Training  
Objects

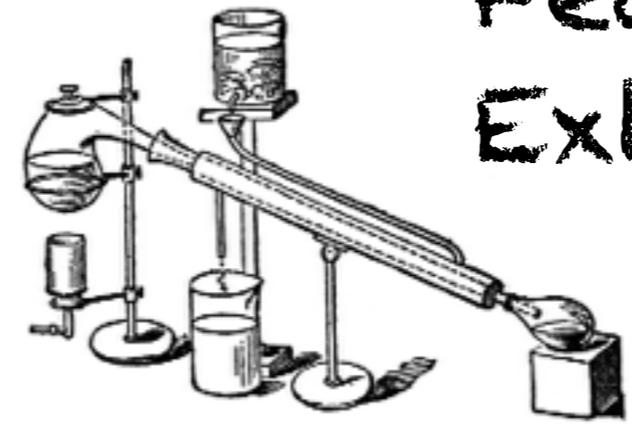


Validation  
Objects



Labelled  
Objects

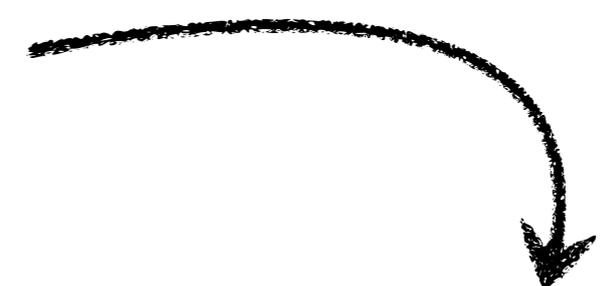




Feature  
Extraction



Features



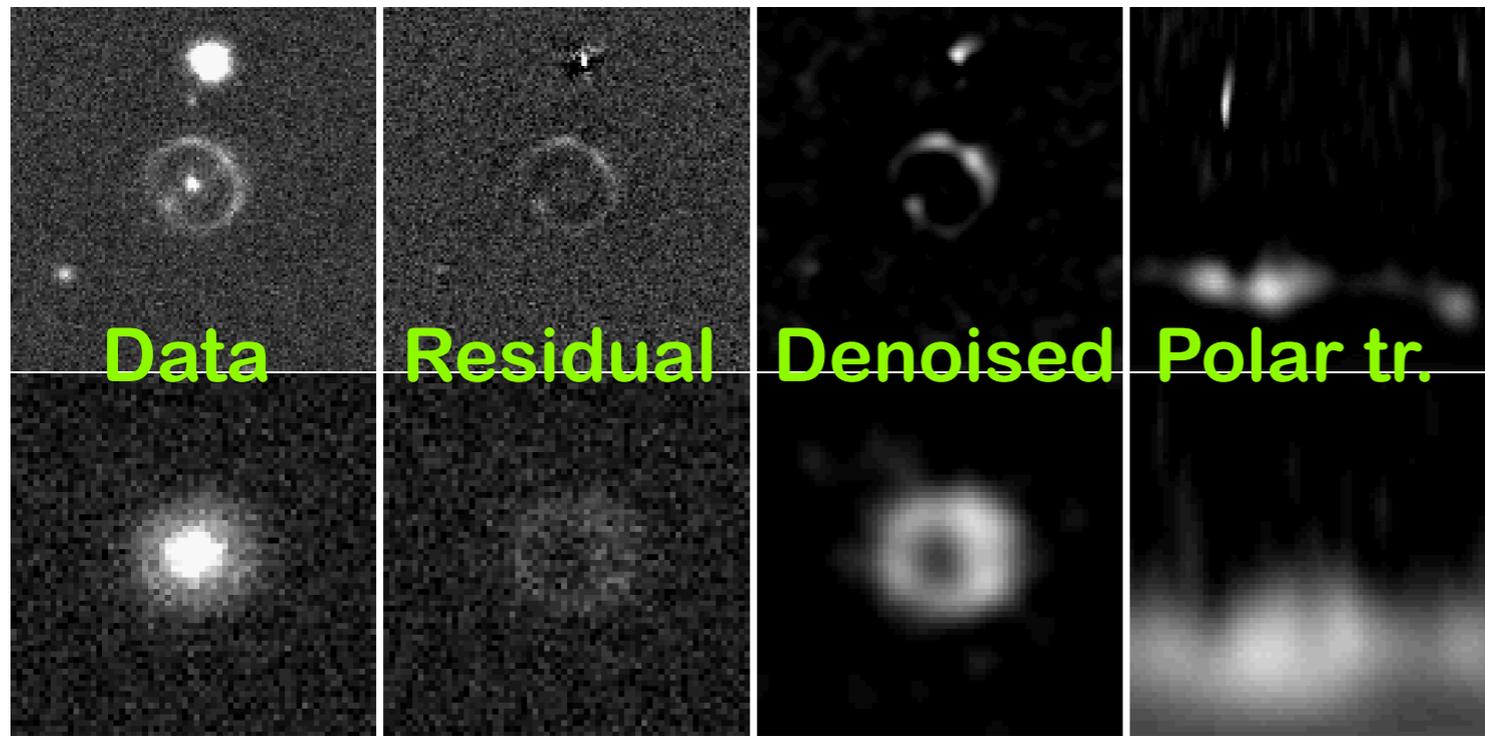
Candidates



# Thinking about Lens Finding

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For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**



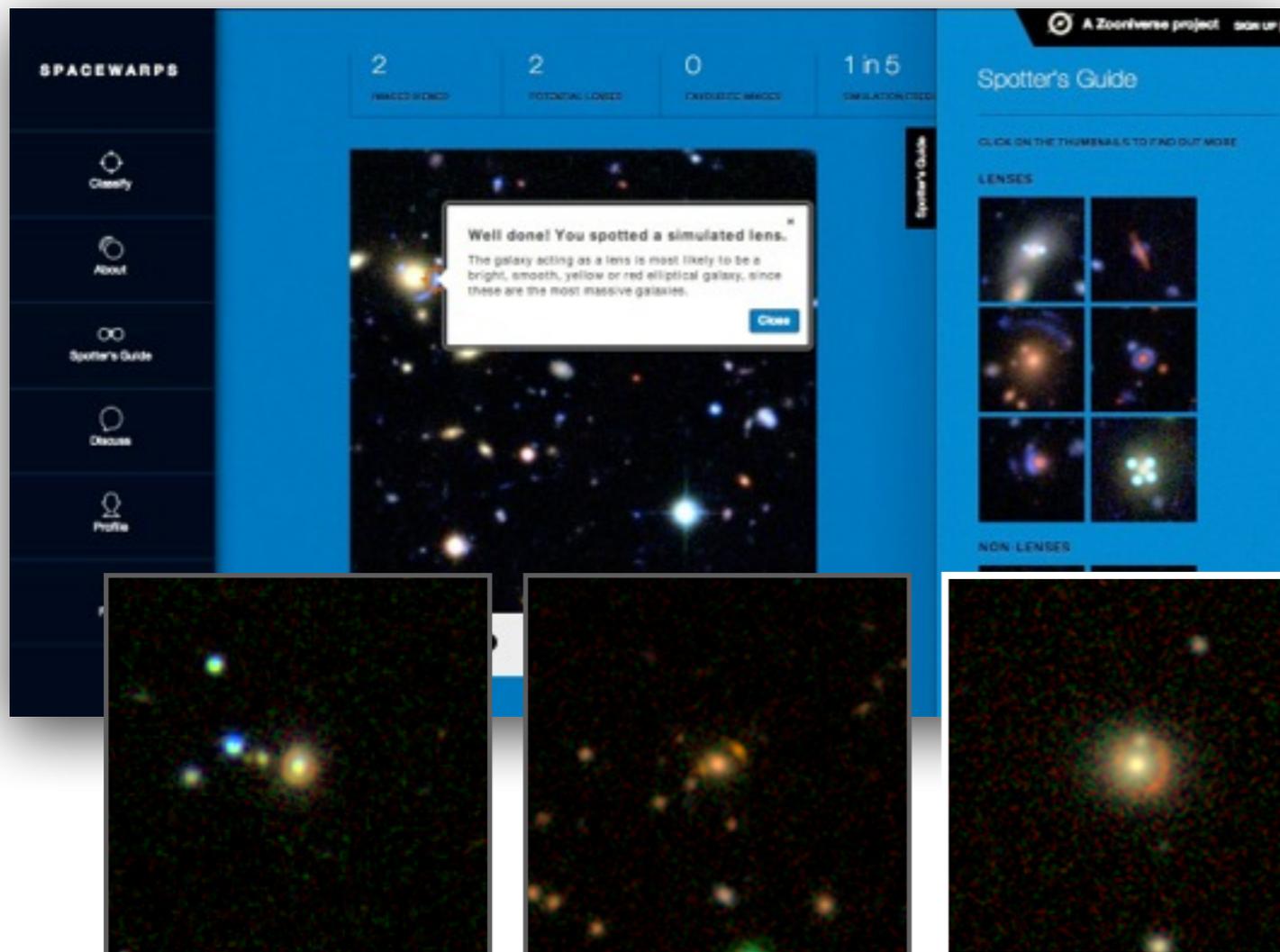
RingFinder  
(Gavazzi et al 2014)

PCAFinder  
(Joseph et al 2014)

Subtract lens light,  
process residuals,  
provide ranked  
candidates for  
**inspection**

# Thinking about Lens Finding

For a system to qualify as a lens candidate, it must be **explained by a plausible lens model**

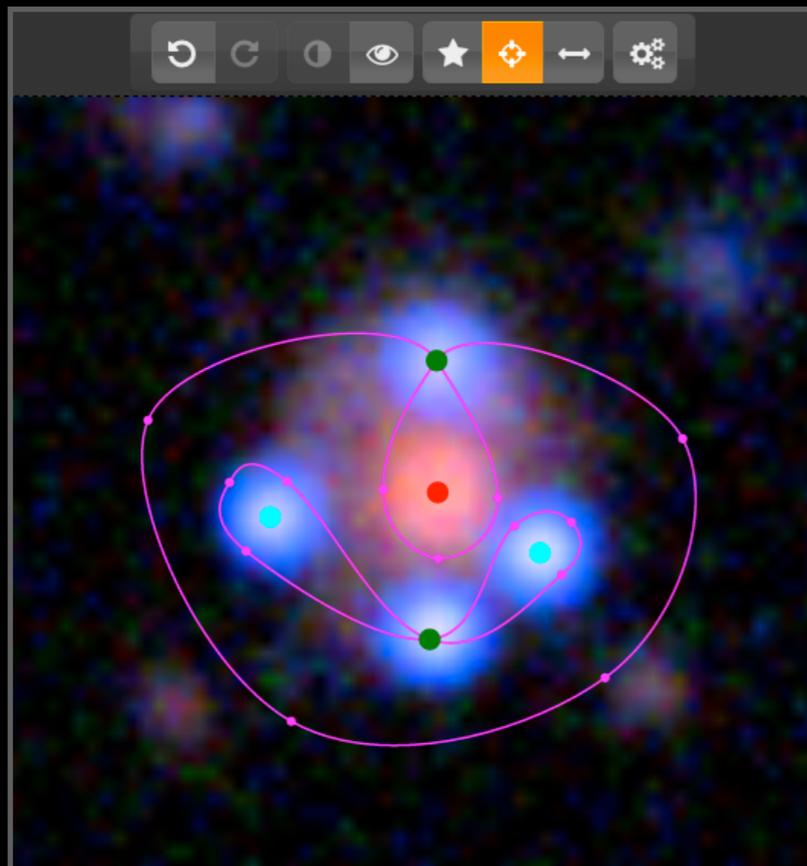


**Space Warps**  
(Marshall, More, Verma et al)

Crowd-sourced image inspection, mental modeling. Supervised via training set (but imagination remains)

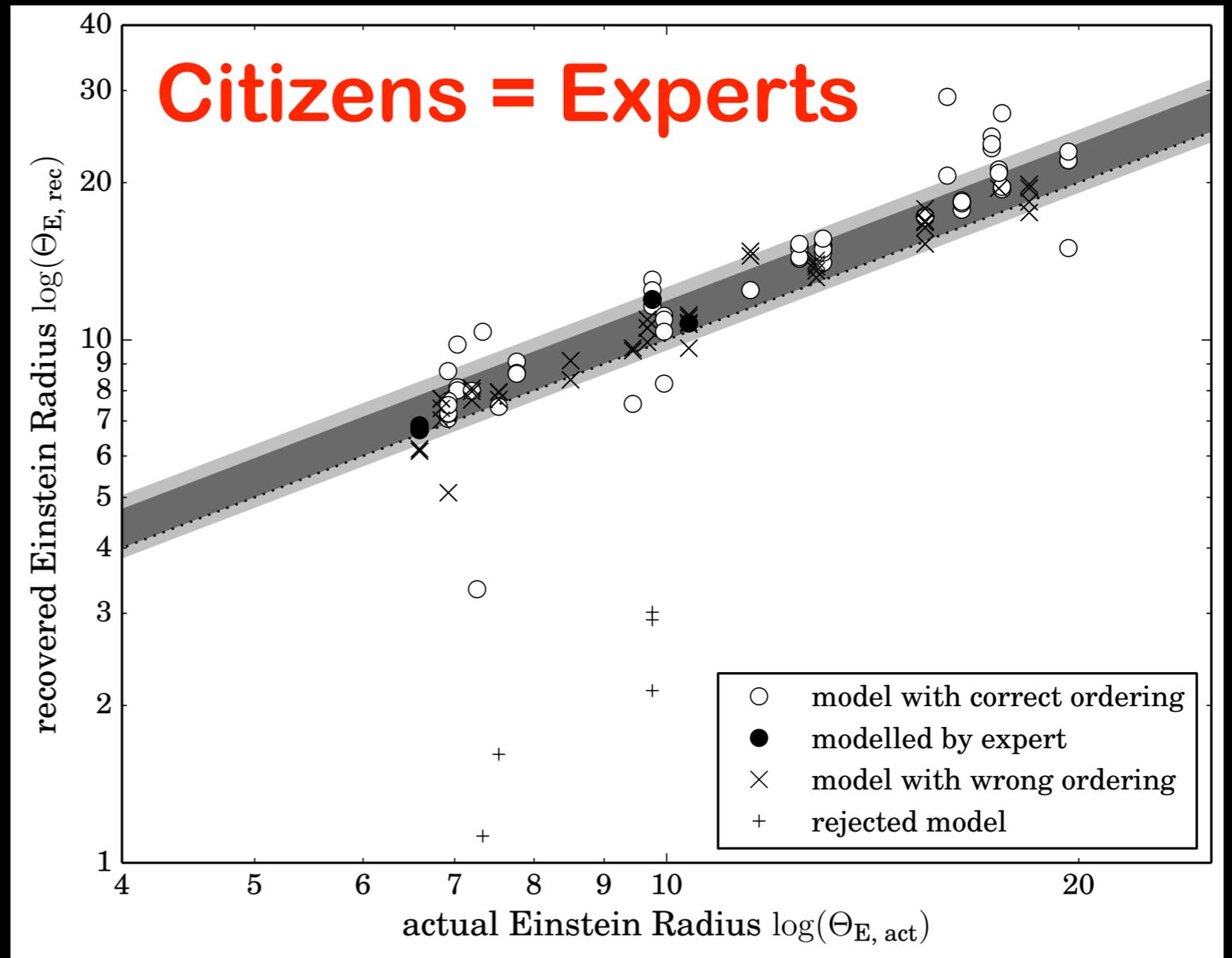
# Crowd-sourced Lens Modeling

Visual inspection for candidate quality control: can we do better than “mental modeling”?



“SpaghettLens”

Kueng et al 2014



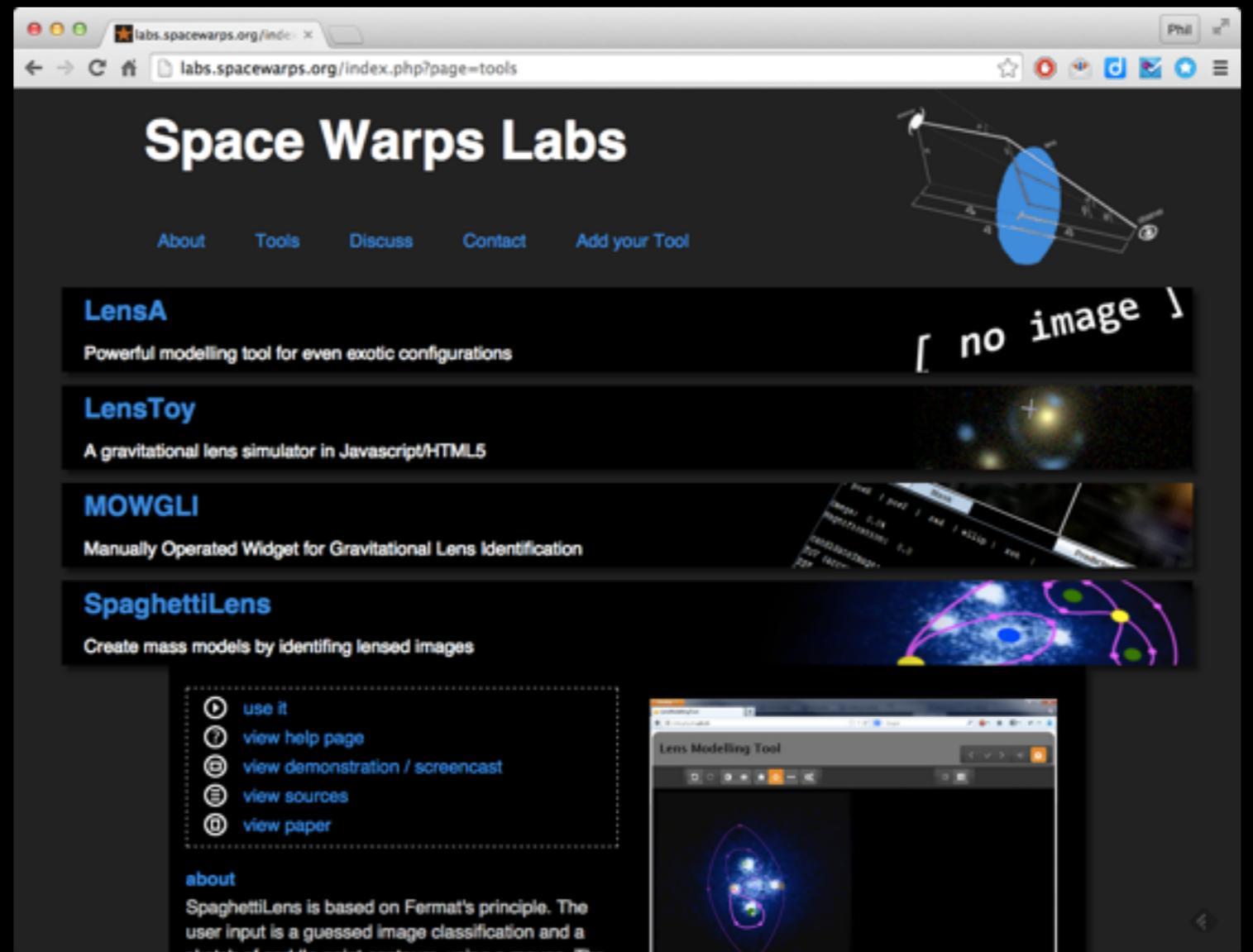
# Crowd-sourced Lens Modeling

Visual inspection for candidate quality control: can we do better than “mental modeling”?

Under construction:  
labs.spacewarps.org

Platform for hosting  
web-based lens  
modeling code

Shareable results  
pages enable  
collaborative model  
exploration and  
optimization



The screenshot shows the Space Warps Labs website interface. The browser address bar displays 'labs.spacewarps.org/index.php?page=tools'. The main heading is 'Space Warps Labs' with a navigation menu including 'About', 'Tools', 'Discuss', 'Contact', and 'Add your Tool'. Below the heading, there are four tool cards:

- LensA**: Powerful modelling tool for even exotic configurations. The image placeholder shows '[ no image ]'.
- LensToy**: A gravitational lens simulator in Javascript/HTML5. The image shows a simulated lensing event with a source and lens.
- MOWGLI**: Manually Operated Widget for Gravitational Lens Identification. The image shows a lensed image with a grid overlay.
- SpaghettLens**: Create mass models by identifying lensed images. The image shows a lensed image with overlaid mass model contours.

Below the tool cards, there is a list of actions for SpaghettLens:

- use it
- view help page
- view demonstration / screencast
- view sources
- view paper

An 'about' section for SpaghettLens is also visible, stating: 'SpaghettLens is based on Fermat's principle. The user input is a guessed image classification and a sketch of saddle point contours, using a mouse. The'.

Rafi Kueng PhD Thesis

# Community Lens Modeling

The screenshot displays the Master Lens Database interface. The main page shows a search for 224 Gravitational Lens Systems. A dropdown menu lists various discovery programs, including Sloan Lens ACS (SLACS), BOSS Emission-Line Lensing Survey (BELLS), SDSS WPC2 Edge-on Late-type Lens Survey (SWELLS), Sloan Lens ACS Extra (SLACSextra), Sloan Digital Sky Survey Quasar Lens Search (SDSS-QLS), UKIRT Infrared Deep Sky Survey (UKIDSS), Cosmic Lens All-Sky Survey (CLASS), Cosmological Evolution Survey (COSMOS), Jodrell/VLA Astrometric Survey (JVAS), Extended Groth Strip / DEEP2 Survey (EGS), Dark Energy Survey (DES), PanSTARRS (PanSTARRS), and SL2S (SL2S).

The detailed view for system RXJ1131-1231 includes the following data:

Parameter	Value
System Name	RXJ1131-1231
Alternate Name	
Reference Frame	
Equinox	J2000
RA Hrs	11
RA Mins	31
RA Secs	51
RA [°]	172.9625
Dec Degrees	-12
Dec Arcmin	31
Dec Arcsec	57
Dec [°]	-12.5325
z_Lens	0.295
z_Source	0.658
Description	
Fiber_Lens	I
Fiber_Source	I
Fluxes	
mag_Lens	17.88
mag_Source	16.74
vdisp	
vdisp error	
Einstein_R ["]	3.8
Einstein_R error ["]	
Number Images	4
Lens Grade	A
Morphology	
Multiplicity	
Discovery Kind	
References	CASTLES

The interface also features an image of the lens system and a plot showing the lensing geometry. The plot is titled "RXJ1131" and shows the positions of the lens and source galaxies in arcseconds, with labels for the Einstein radius (100") and the lensing grade (A).

<http://masterlens.astro.utah.edu/>



## Finding Lenses:

- Motivation
- Brief history
- Wide field imaging surveys
- Approaches to lens finding

## Using Lenses:

- Hierarchical inference

# Analyzing Strong Lens Ensembles

---

More lenses means higher precision

**Sonnenfeld & Marshall**

# Analyzing Strong Lens Ensembles

---

More lenses means higher precision

- **Requires joint analysis**

**Sonnenfeld & Marshall**

# Analyzing Strong Lens Ensembles

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More lenses means higher precision

- **Requires joint analysis**
- **Samples are imprinted with selection**

**Sonnenfeld & Marshall**

# Analyzing Strong Lens Ensembles

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More lenses means higher precision

- **Requires joint analysis**
- **Samples are imprinted with selection**
- **Individual objects make up populations**

**Sonnenfeld & Marshall**

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**Sonnenfeld & Marshall**

# Analyzing Strong Lens Ensembles

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Models of ensembles are **hierarchical**

Sonnenfeld & Marshall

# Analyzing Strong Lens Ensembles

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More lenses means higher precision

- Requires joint analysis
- Samples are imprinted with selection
- Individual objects make up populations

Models of ensembles are **hierarchical**

Extract maximum information from **data**

Sonnenfeld & Marshall

# Analyzing Strong Lens Ensembles

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More lenses means higher precision

- Requires joint analysis
- Samples are imprinted with selection
- Individual objects make up populations

Models of ensembles are **hierarchical**

Extract maximum information from **data**

Fit for selection function

Sonnenfeld & Marshall

# Simple Example: 100 Lensed Quasars

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- Suppose we follow up 100 time delay lenses. We'll want to combine them to infer the Hubble constant

# Simple Example: 100 Lensed Quasars

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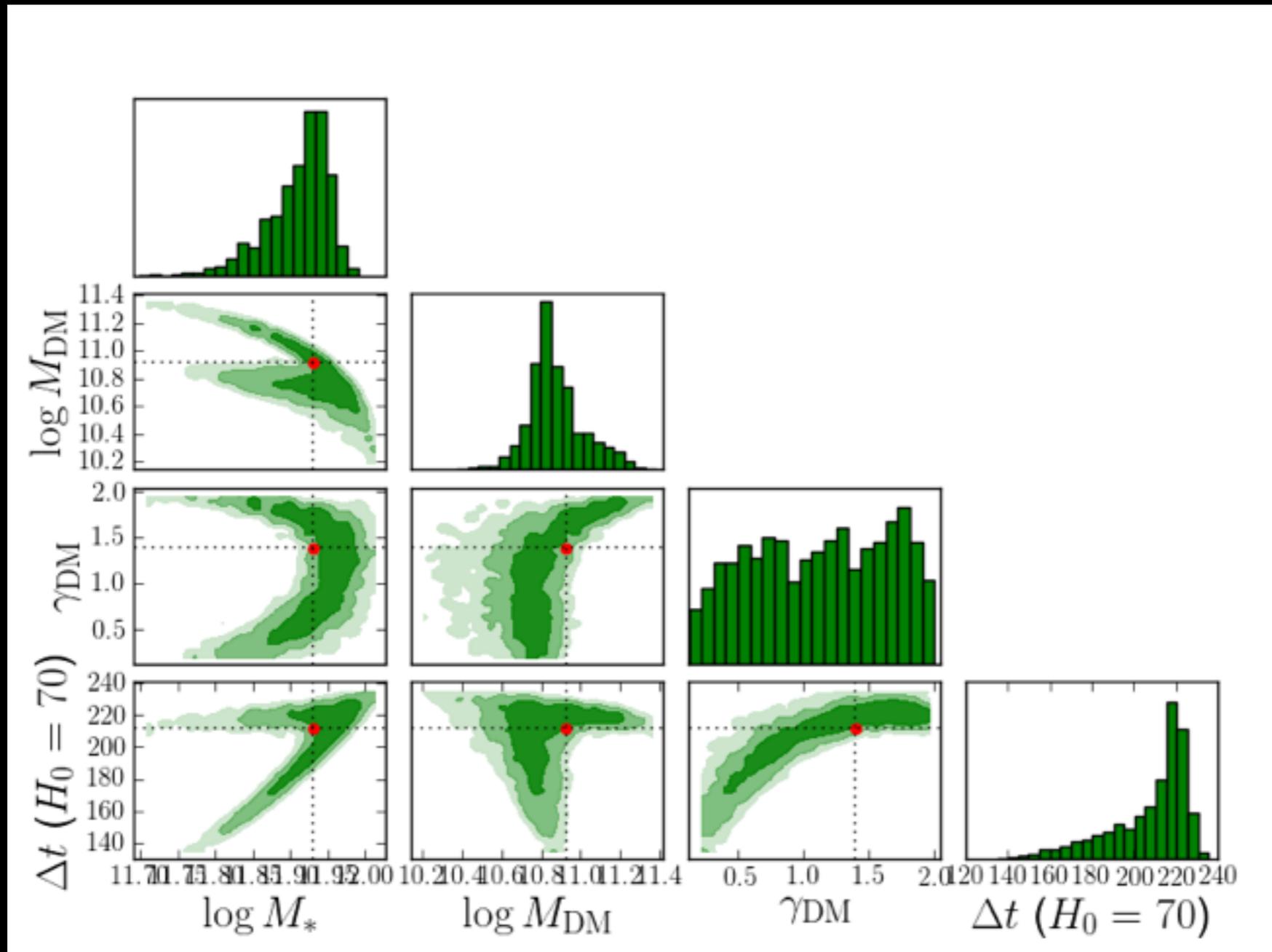
- Suppose we follow up 100 time delay lenses. We'll want to combine them to infer the Hubble constant
- We don't want to introduce systematic errors by using an over-simplistic density profile - but if we go flexible, the prior will be important

# Simple Example: 100 Lensed Quasars

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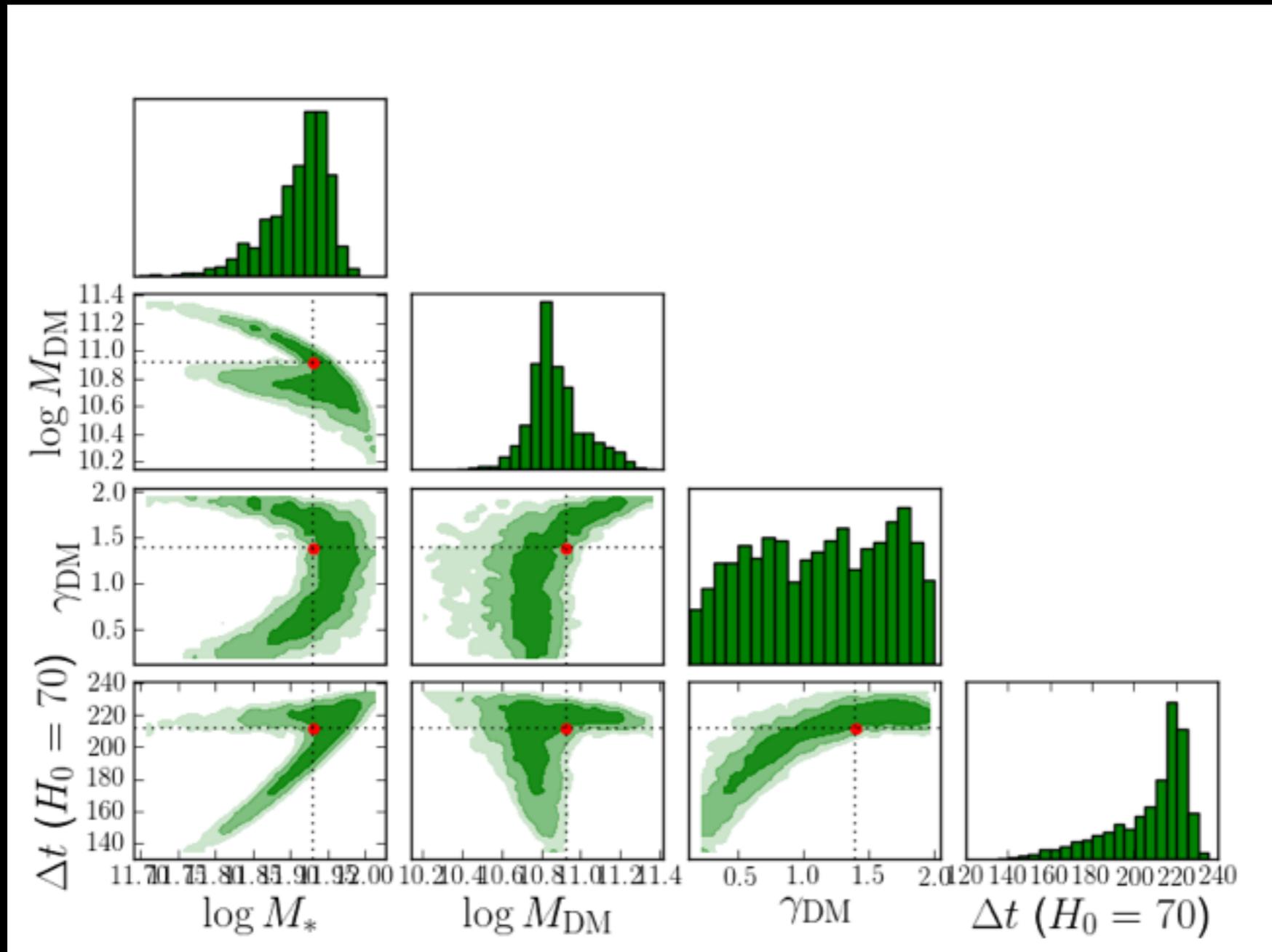
- Suppose we follow up 100 time delay lenses. We'll want to combine them to infer the Hubble constant
- We don't want to introduce systematic errors by using an over-simplistic density profile - but if we go flexible, the prior will be important
- Solution: make weak assumption that massive galaxies are somehow self-similar, and infer this conditional PDF (scaling relation plus scatter) simultaneously with the cosmological parameters

# 100 Spherical Cows



Double image configuration, spherical symmetry, known QSO positions, stellar mass to 0.1dex, radial magnification ratio (from extended source) to 1.5%

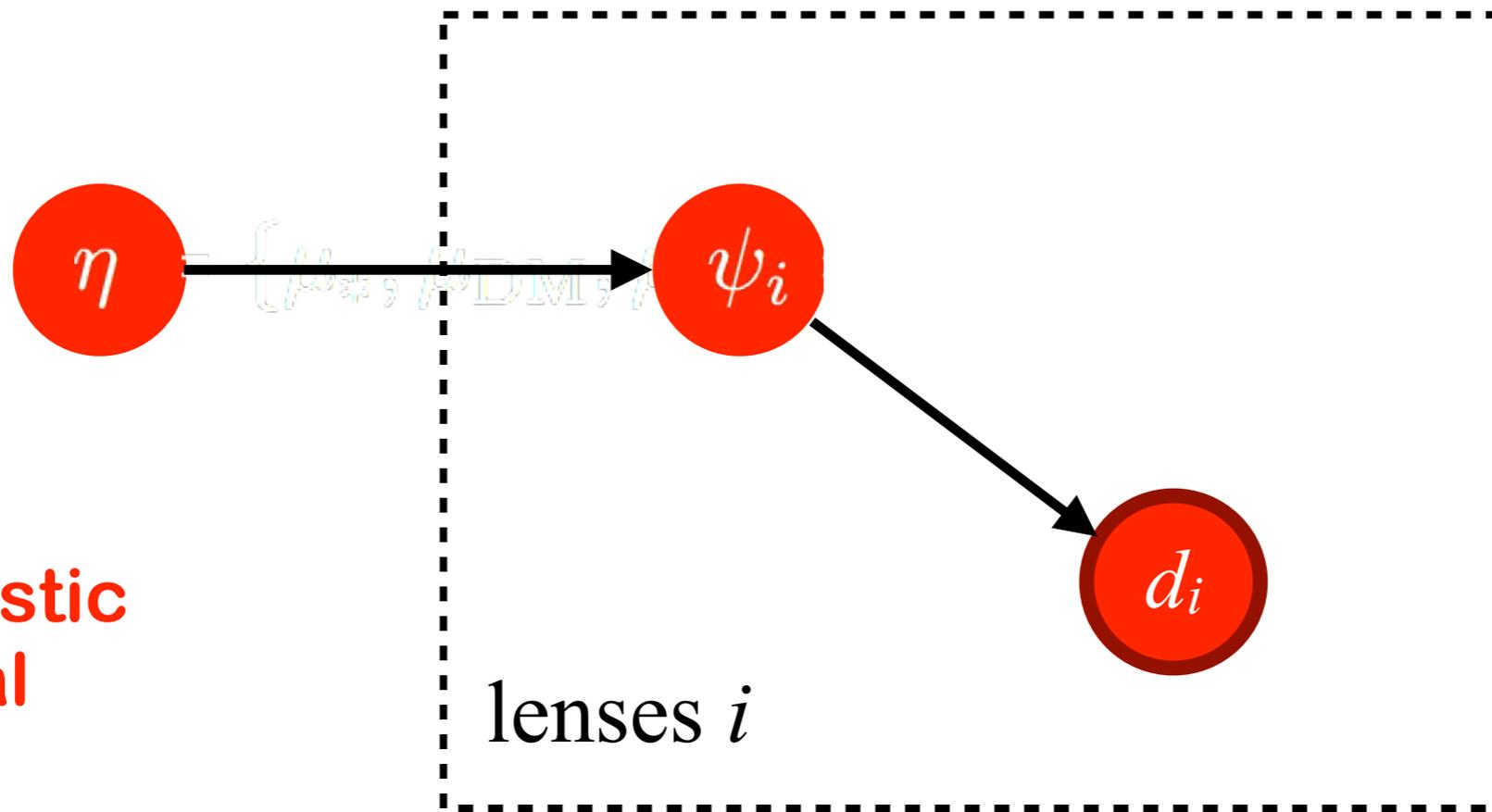
# 100 Spherical Cows



Double image configuration, spherical symmetry, known QSO positions, stellar mass to 0.1dex, radial magnification ratio (from extended source) to 1.5%

# Joint analysis: inferring $H_0$

$$P(\eta|d) = P(\eta)P(d|\eta) = P(\eta) \prod_i \int d\psi_i P(d|\psi_i)P(\psi_i|\eta)$$



**Probabilistic  
Graphical  
Model**

- **Global hyper-parameters:**  $\eta = \{\mu_*, \mu_{\text{DM}}, \mu_\gamma, \sigma_*, \sigma_{\text{DM}}, \sigma_\gamma, H_0\}$
- **Individual lens parameters:**  $\psi_i = \{M_{*,i}, M_{\text{DM},i}, \gamma_{\text{DM},i}, R_{e,i}\}$

# Inferring $H_0$

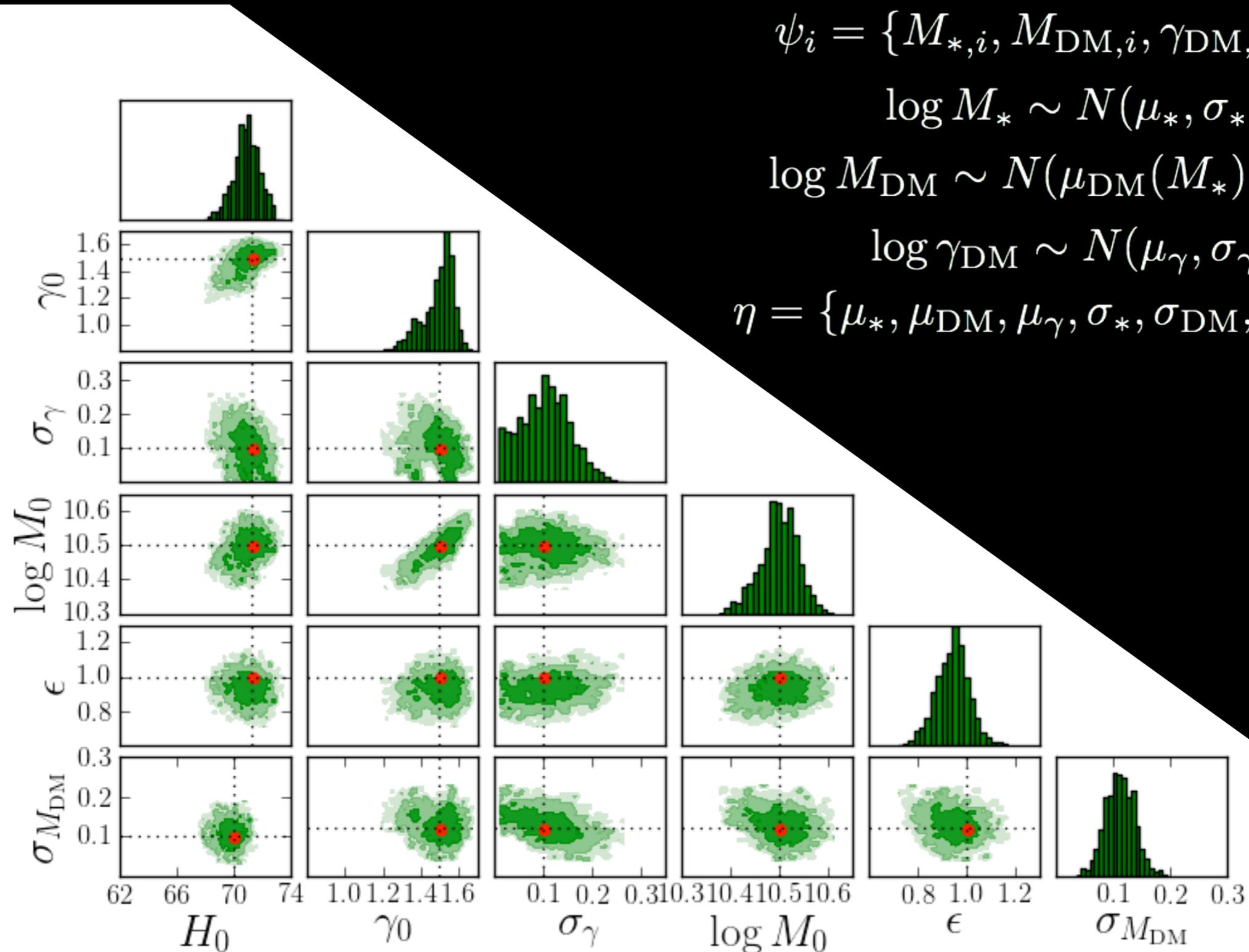
$$P(\eta|d) = P(\eta)P(d|\eta) = P(\eta) \prod_i \int d\psi_i P(d|\psi_i) P(\psi_i|\eta)$$

Likelihood  $P(d|n)$  can be approximated as a sum over samples drawn from interim posterior:

$$\begin{aligned} P(d|n) &= \int P(d|y) P(y|n) \\ &= \int P(d|y) P(y) [ P(y|n) / P(y) ] \\ &\sim 1/N \sum [ P(y|n) / P(y) ]_k \\ &\sim 1/N \sum w_k \end{aligned}$$

**MCMC sample each lens once, then sum importances in next level of inference**

# Inferring $H_0$ (and other hyper-parameters)



$$\psi_i = \{M_{*,i}, M_{\text{DM},i}, \gamma_{\text{DM},i}, R_{e,i}\}$$

$$\log M_* \sim N(\mu_*, \sigma_*)$$

$$\log M_{\text{DM}} \sim N(\mu_{\text{DM}}(M_*), \sigma_{\text{DM}})$$

$$\log \gamma_{\text{DM}} \sim N(\mu_\gamma, \sigma_\gamma)$$

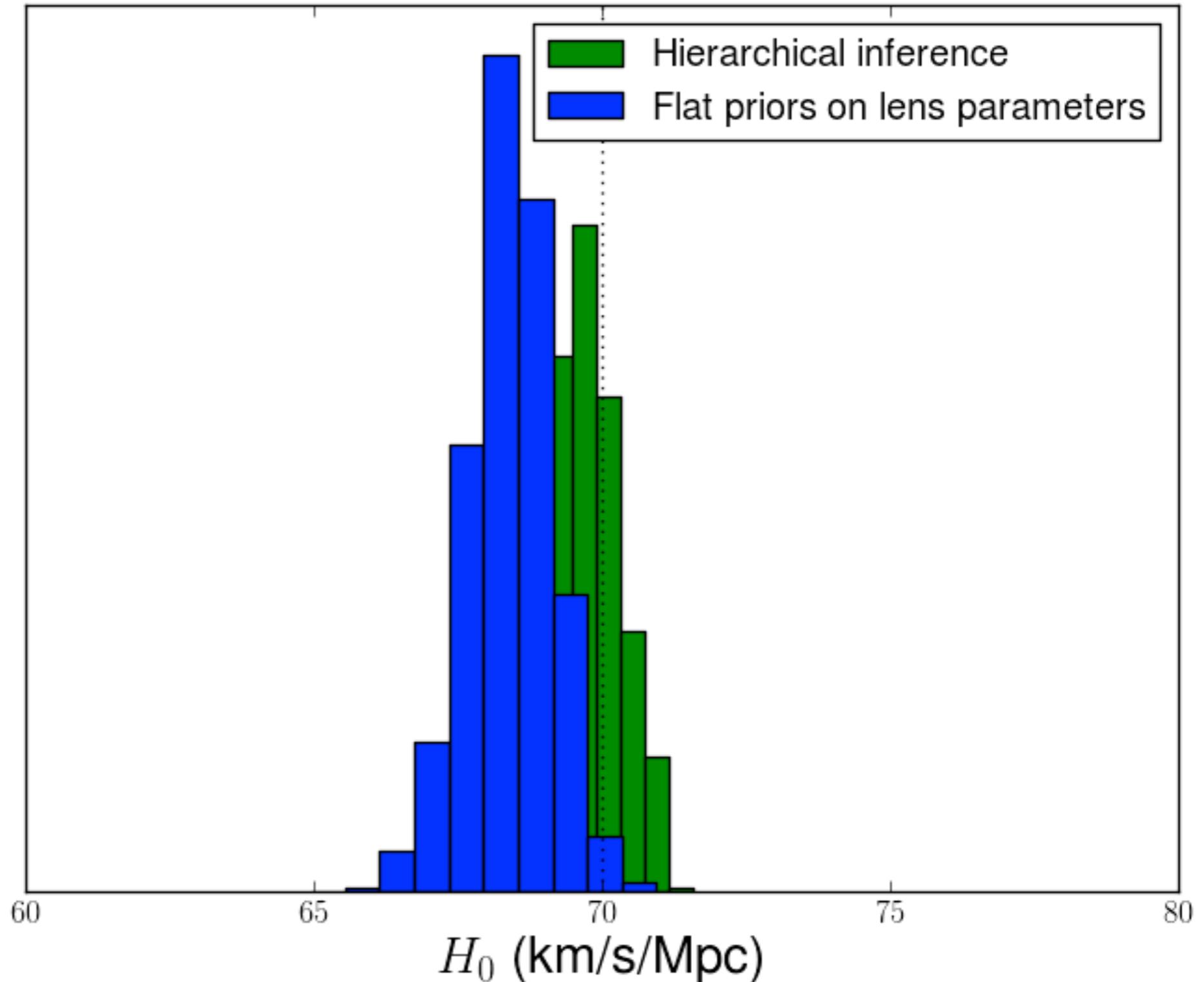
$$\eta = \{\mu_*, \mu_{\text{DM}}, \mu_\gamma, \sigma_*, \sigma_{\text{DM}}, \sigma_\gamma, H_0\}$$

# Inferring $H_0$

**Uninformative priors** on individual object parameters **lead to bias** if the objects are not unrelated

In this simple case the cosmological **hierarchical inference is unbiased**

Added 6 nuisance parameters to describe lens galaxy population, incurred **no loss of cosmographic precision**



# More Hierarchical Inference Examples

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- **Disk and bulges in SWELLS (Brewer et al)**
- **Dark halo M-c in CASSOWARY (Auger et al)**
- **Subhalo populations (Vegetti et al)**
- **ETG density profiles (Sonnenfeld et al)**

# Dark and stellar matter in ETGs

## THE SL2S GALAXY-SCALE LENS SAMPLE. V. DARK MATTER HALOS AND STELLAR IMF OF MASSIVE ETGS OUT TO REDSHIFT 0.8

ALESSANDRO SONNENFELD<sup>1\*</sup>, TOMMASO TREU<sup>1,2†</sup>, PHILIP J. MARSHALL<sup>3</sup>, SHERRY H. SUYU<sup>4</sup>, RAPHAËL GAVAZZI<sup>5</sup>,  
MATTHEW W. AUGER<sup>6</sup>, AND CARLO NIPOTI<sup>7</sup>

*Draft version October 6, 2014*

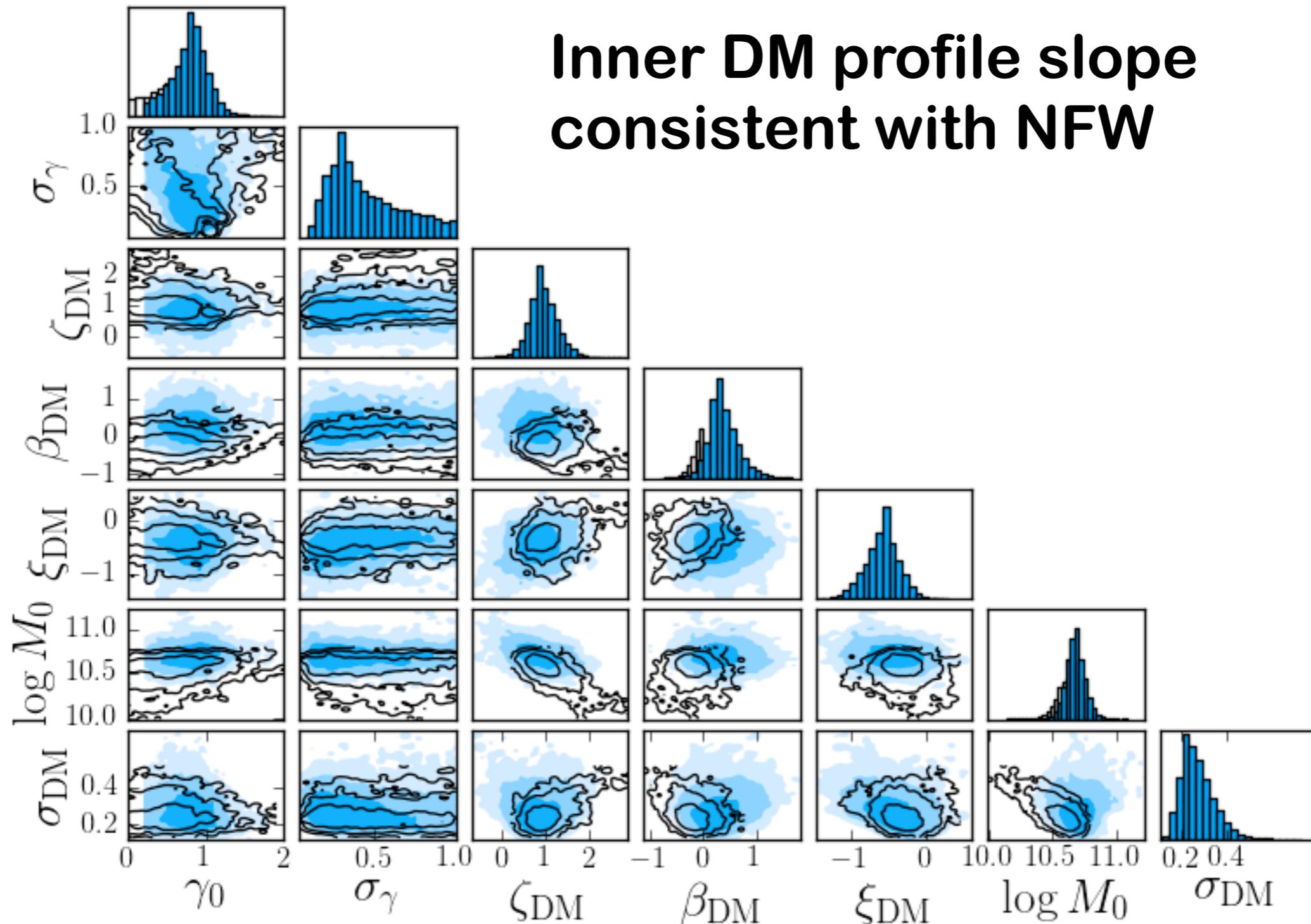
### ABSTRACT

We investigate the cosmic evolution of the internal structure of massive early-type galaxies over half of the age of the Universe. We perform a joint lensing and stellar dynamics analysis of a sample of 81 strong lenses from the SL2S and SLACS surveys and combine the results with a hierarchical Bayesian inference method to measure the distribution of dark matter mass and stellar IMF across the population of massive early-type galaxies. Lensing selection effects are taken into account. We find that the dark matter mass projected within the inner 5 kpc increases for increasing redshift, decreases for increasing stellar mass density, but is roughly constant along the evolutionary tracks of early-type galaxies. The average dark matter slope is consistent with that of an NFW profile, but is not well constrained. The stellar IMF normalization is close to a Salpeter IMF at  $\log M_* = 11.5$  and scales strongly with increasing stellar mass. No dependence of the IMF on redshift or stellar mass density are detected. The anti-correlation between dark matter mass and stellar mass density supports the idea of mergers being more frequent in larger dark matter halos.

*Subject headings:* galaxies: fundamental parameters — gravitational lensing —

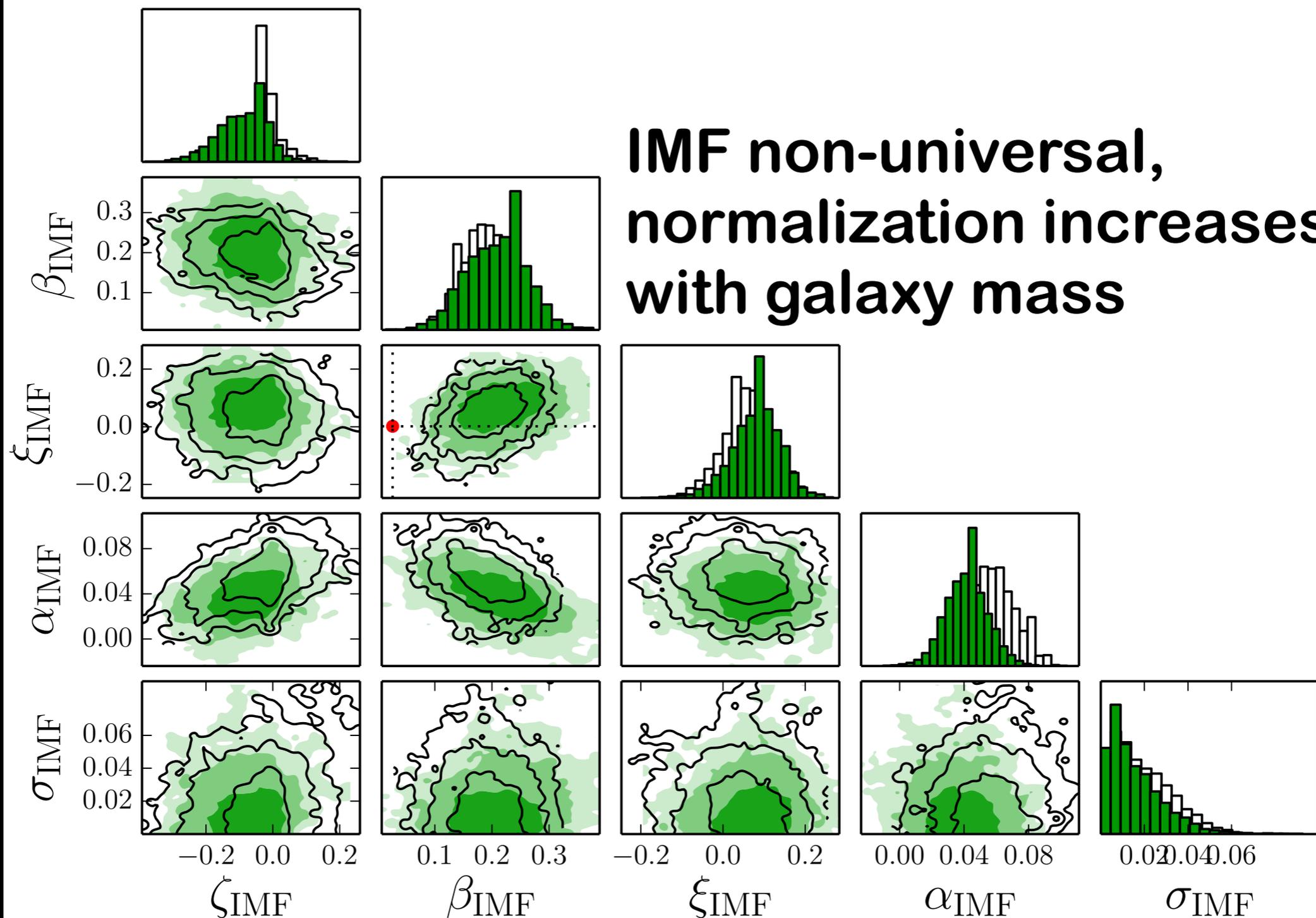
# Dark and stellar matter in ETGs

$$\gamma_{\text{DM}} = \gamma_0 + N(0, \sigma_\gamma) \quad ; \quad \log M_{\text{DM}} = \zeta_{\text{DM}}(z - 0.3) + \beta_{\text{DM}}(\log M_* - 11.5) + \xi_{\text{DM}} \log \Sigma_* / \Sigma_0 + \log M_0 + N(0, \sigma_{M_{\text{DM}}})$$



# Dark and stellar matter in ETGs

$$\log \alpha_{\text{IMF}} = \zeta_{\text{IMF}}(z - 0.3) + \beta_{\text{IMF}}(\log M_* - 11.5) + \xi_{\text{IMF}} \log \Sigma_* / \Sigma_0 + \alpha_{\text{IMF},0} + N(0, \sigma_{\text{IMF}})$$



# Conclusions

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- **Wide field imaging surveys will contain 10-1000 times more lenses than we currently have**
- **Pure samples are enabled by high image quality and depth, but we'll need good software instrumentation for catalog and image mining, and significant amounts of human quality control**
- **Lens candidacy requires a model: explicit, implicit or mental. Each approach has pros and cons**
- **Accuracy: large samples have great potential for accurate galaxy evolution, dark matter and dark energy studies**
- **Discovery: large samples will contain novel and exotic systems with new applications**