Alessandro Sonnenfeld (Leiden Observatory)

Galaxies and their dark matter halos

An observer's perspective

Universiteit Leiden
Leiden Observatory

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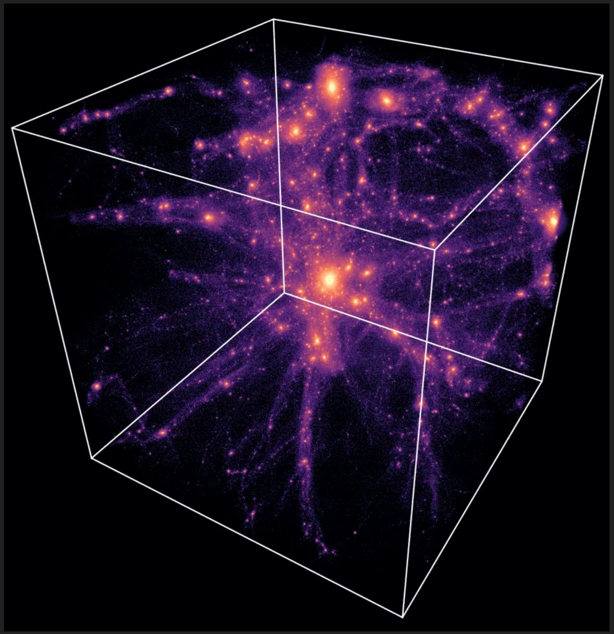
Part I: Introduction

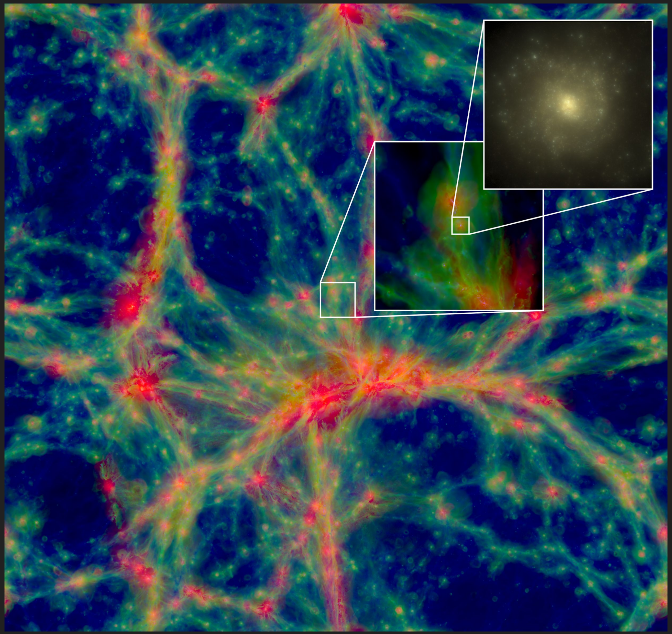
Questions

- What is dark matter?
  - What is the mass of the dark matter particle(s)?
  - How does dark matter interact with itself and/or with baryonic matter?
- What is dark energy?
  - Is it a cosmological constant, or does it evolve in time?
  - Does general relativity fail to describe the Universe on large scales?

Probes of dark matter and dark energy

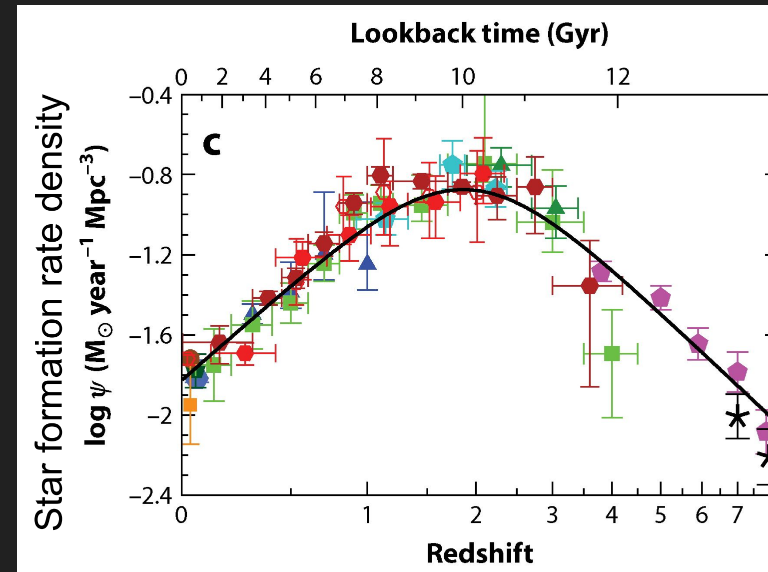
- Galaxy clusters
- Galaxy dynamics
- Cosmic microwave background
- Galaxy clustering
- Gravitational lensing
- Stellar streams from merging galaxies
- Supernovae
- Merging black holes/neutron stars





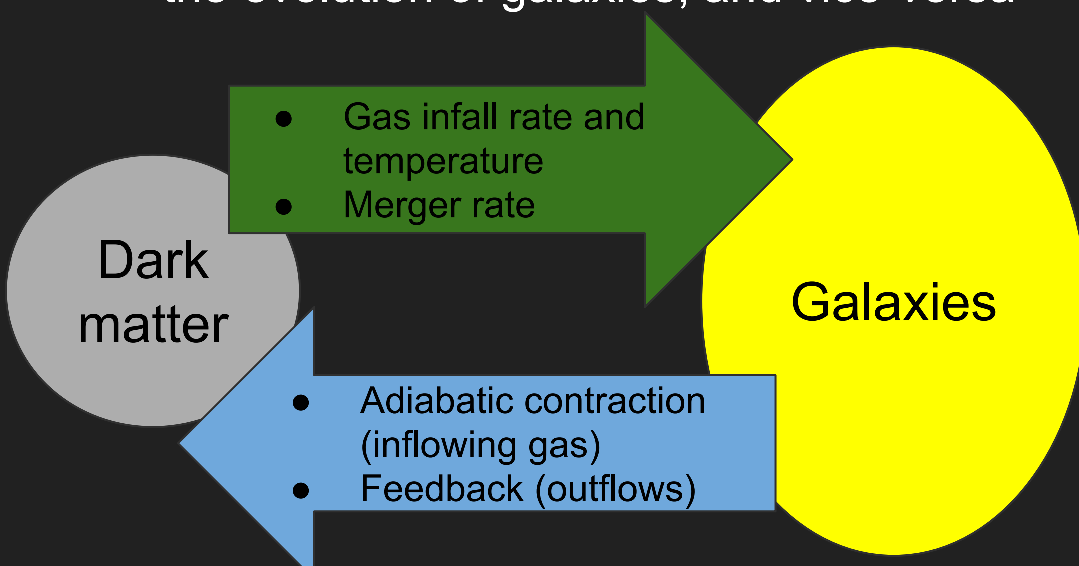
A toy description of galaxy evolution

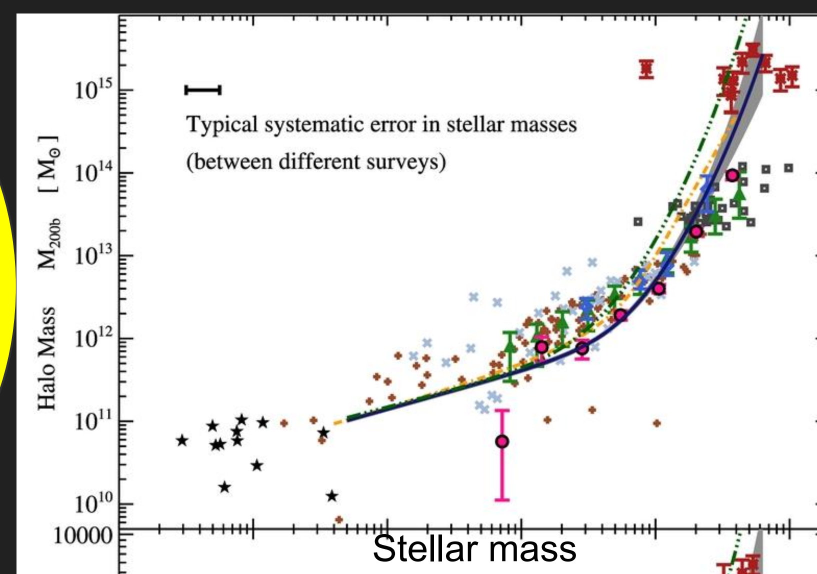
- Galaxies turn gas into stars
- Galaxies merge with other galaxies



Madau & Dickinson (2014)

- Huge diversity in galaxy population
- The dark matter distribution influences the evolution of galaxies, and vice-versa





Observational challenges

- Galaxy evolution is a multi-dimensional problem. Many relevant parameters: stellar mass, morphology, size, star formation rate, environment, central black hole mass, etc...
- Observations have errors. Observed space is not an accurate description of the truth, but a convolution with an error function
- Processes occur on cosmological time-scales. Need model to map progenitors to descendants

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Solution

- Combine different datasets
- Forward model

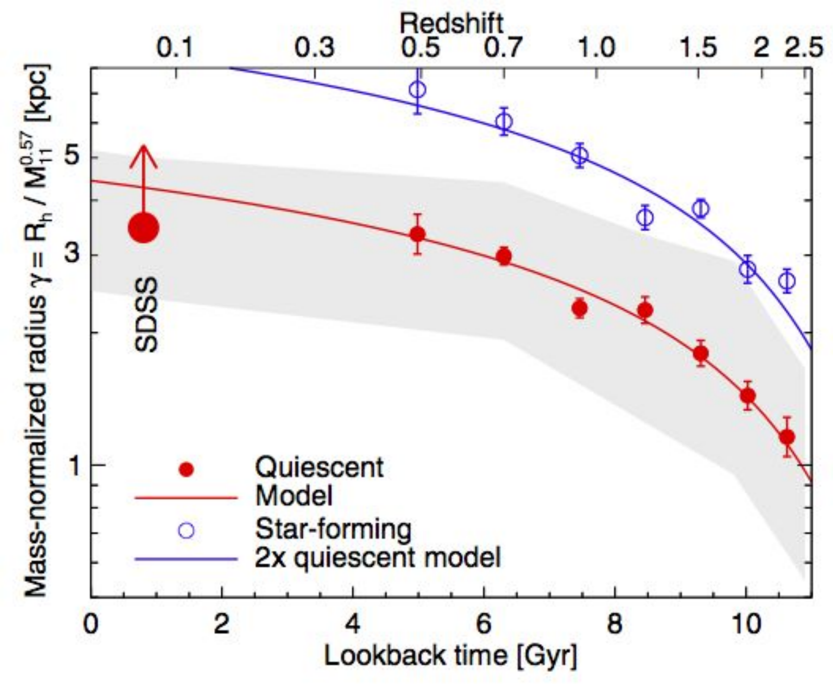
Part II: a generalized stellar-to-halo mass relation

Early-type galaxies

- Very little star formation activity, little gas, spheroidal stellar distribution
- Two-phase evolution scenario: intense star formation activity up to z ~ 2, then growth by mergers
- Rapid size evolution

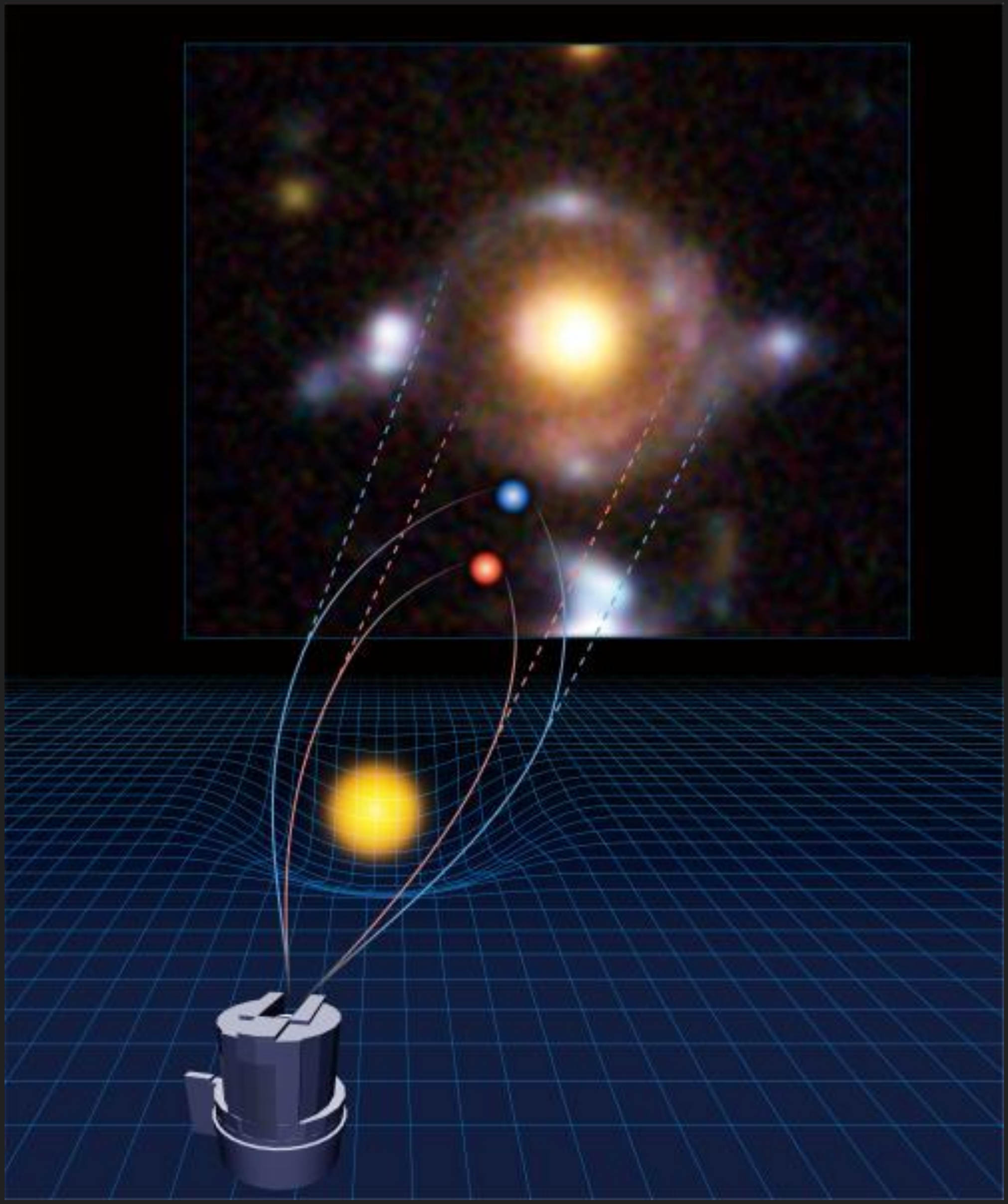
What are the properties of their dark matter halos?

- If merger history changes with halo mass, there should be a correlation between size and halo mass at fixed stellar mass



Newman et al. (2012)

Gravitational lensing



Strong

- Two or more images of the same source
- Typical image separation for z~0.5 lens, 10kpc
- Very high precision in determination of total projected mass
- Requires chance alignment between lens and source (rare event)
- Applications: time-delay cosmology, substructure detection

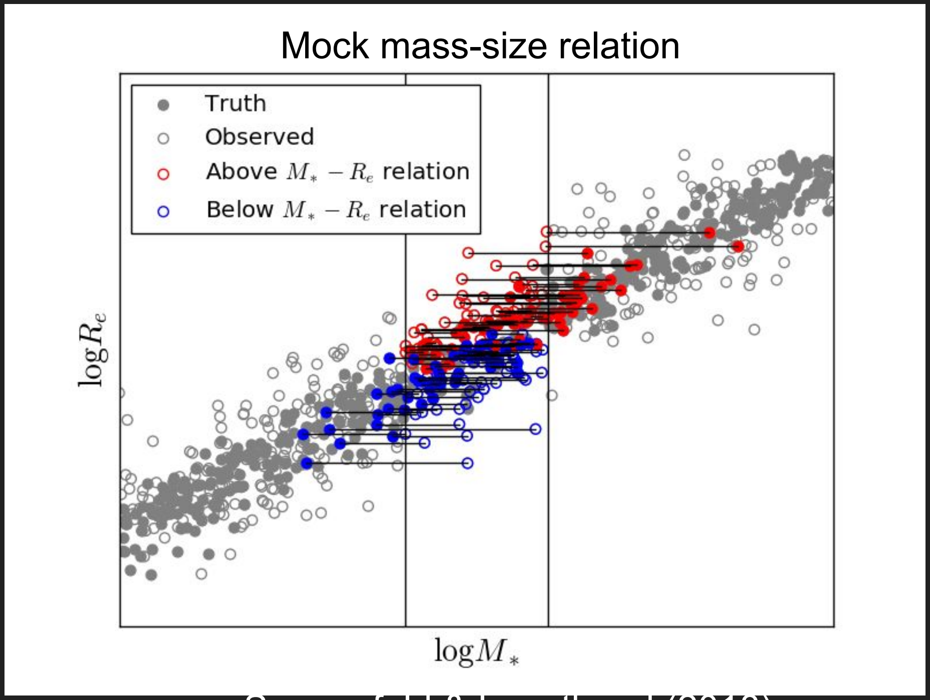
Weak

- Small image distortion: galaxies are preferentially aligned tangentially wrt center of mass distribution
- Degeneracy between intrinsic galaxy shape and lensing distortion: need to statistically combine many background sources and many lenses
- Strongest constraints at 100kpc-1Mpc scales

Challenges in weak lensing

- Observable: tangential shear
- Signal strength: ~0.01
- Noise: ~0.3
- Traditional approach:
  - group lens galaxies (or clusters) in bins based on an observable property (e.g. stellar mass)
  - Stack the weak lensing data over all lenses in the bin
- Problems:
  - Not all lenses are the same, some information is lost
  - Observational scatter introduces biases, especially when working in many dimensions

- Example: measuring weak lensing signal of lenses in bins of different size and same stellar mass
  - Observational errors scramble galaxies in the stellar mass-size plane



Sonnenfeld & Leauthaud (2018)

Bayesian hierarchical inference

- Sample of measurements from objects belonging to the same family
- Simultaneously infer parameters describing the population as a whole, as well as parameters describing individual objects

$\boldsymbol{\psi}$ Individual lens parameters (e.g. stellar mass, halo mass, etc.)

$\boldsymbol{\eta}$ Population hyper-parameters (e.g. average halo mass, scatter, etc.)

$\boldsymbol{d}$ Data (e.g. shear measurements, stellar mass measurements)

$$\mathrm{P}(\boldsymbol{\psi}) = \mathrm{P}(\boldsymbol{\psi}|\boldsymbol{\eta})$$

Prior distribution is a function of the population hyper-parameters

$$\mathrm{P}(\boldsymbol{\psi}_1, \ldots, \boldsymbol{\psi}_n, \boldsymbol{\eta}|\boldsymbol{d}) = \,?$$

$$\propto \mathrm{P}(\boldsymbol{\psi}_1, \ldots, \boldsymbol{\psi}_n, \boldsymbol{\eta})\mathrm{P}(\boldsymbol{d}|\boldsymbol{\psi}_1, \ldots, \boldsymbol{\psi}_n, \boldsymbol{\eta})$$

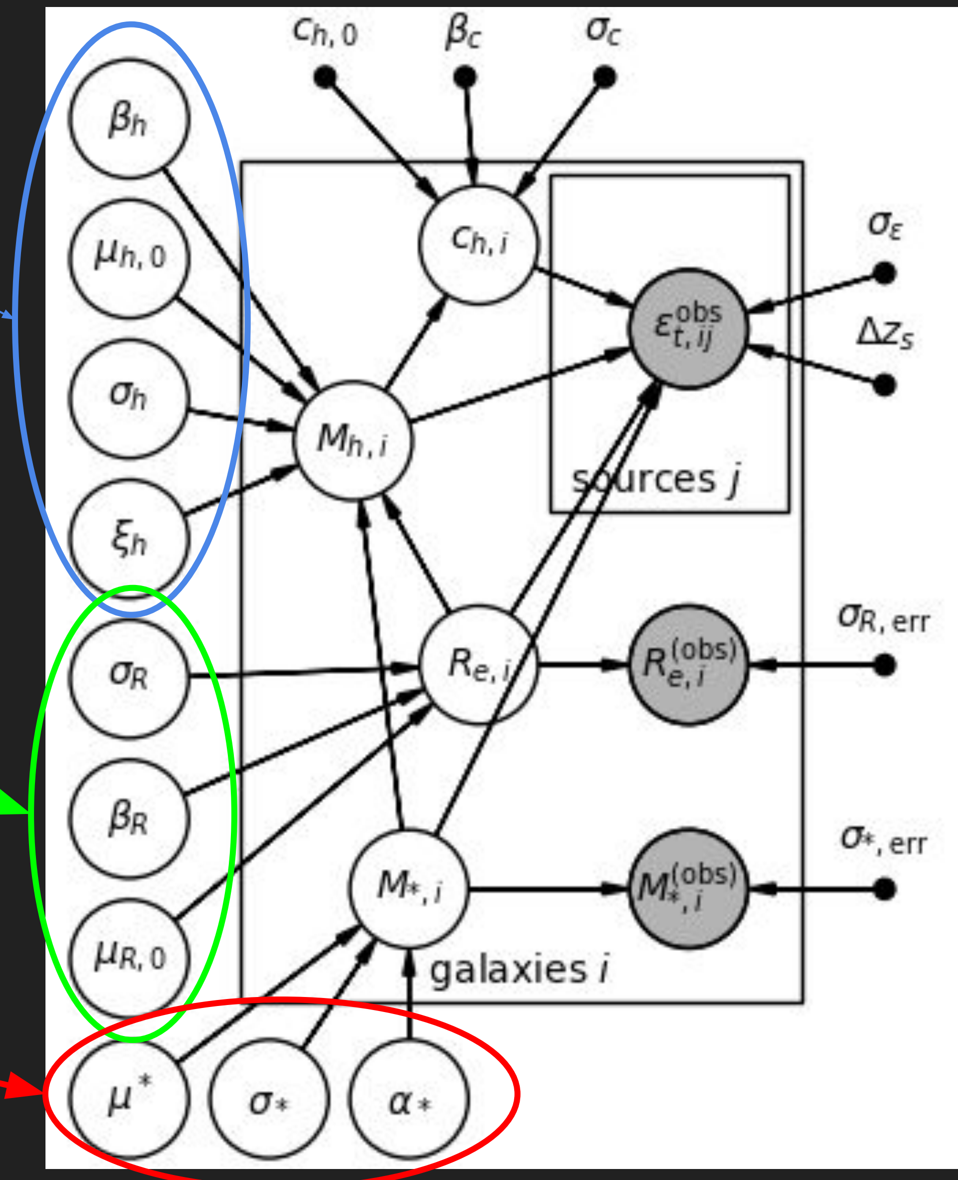
$$= \mathrm{P}(\boldsymbol{\psi}_1, \ldots, \boldsymbol{\psi}_n|\boldsymbol{\eta})\mathrm{P}(\boldsymbol{\eta})\mathrm{P}(\boldsymbol{d}|\boldsymbol{\psi}_1, \ldots, \boldsymbol{\psi}_n)$$

Bayesian hierarchical inference

Halo mass
hyper-parameters

Size
hyper-parameters

Stellar mass
hyper-parameters



Sonnenfeld & Leauthaud (2018)

Bayesian hierarchical inference: Examples (1)

TABLE 1
MODEL PARAMETERS

Parameter	Description
	Global Parameters
Ω_m	Matter density
w	Dark energy equation of state
α	Stretch standardisation
β	color standardisation
$\delta(0)$	Scale of the mass-magnitude correction
$\delta(\infty)/\delta(0)$	Redshift-dependence of mass-magnitude correction
$\delta\mathcal{Z}_i$	Systematics scale
$\langle M_B \rangle$	Mean absolute magnitude
	Survey Parameters
δS	Selection effect deviation
$\langle x_1^i \rangle$	Mean stretch nodes
$\langle c^i \rangle$	Mean color nodes
α_c	Skewness of color population
σ_{M_B}	Population magnitude scatter
σ_{x_1}	Population stretch scatter
σ_c	Population color scatter
κ_0	Extra color dispersion
κ_1	Redshift-dependence of extra color dispersion
	Supernova Parameters
m_B	True flux
x_1	True stretch
c	True color
z	True redshift
M_B	Derived absolute magnitude
μ	Derived distance modulus
	Input Data[a]
$\hat{m}_B$	Measured flux
$\hat{x}_1$	Measured stretch
$\hat{c}$	Measured color
C	Covariance on flux, stretch and color
$\hat{z}$	Observed redshift
$\hat{m}$	Determined mass probability
$\hat{p}$	Determined Ia probability

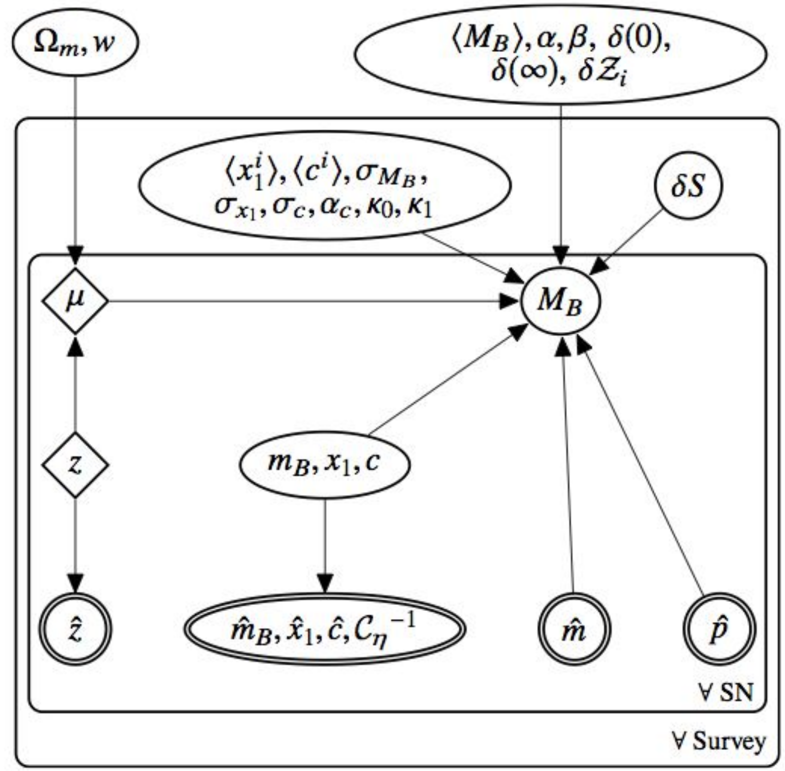


FIG. 2.— Probabilistic graphical model for our likelihood. Double-lined nodes represent observed variables, diamond nodes represent deterministic variables, single-lined ellipse nodes represent fit variables. The SN box represents observed variables and latent variables for each individual supernova, whilst the survey box represents survey-specific variables, which in general describe the supernova population for the survey and the systematics associated with it. Variables that appear outside both boxes represent top level model parameters.

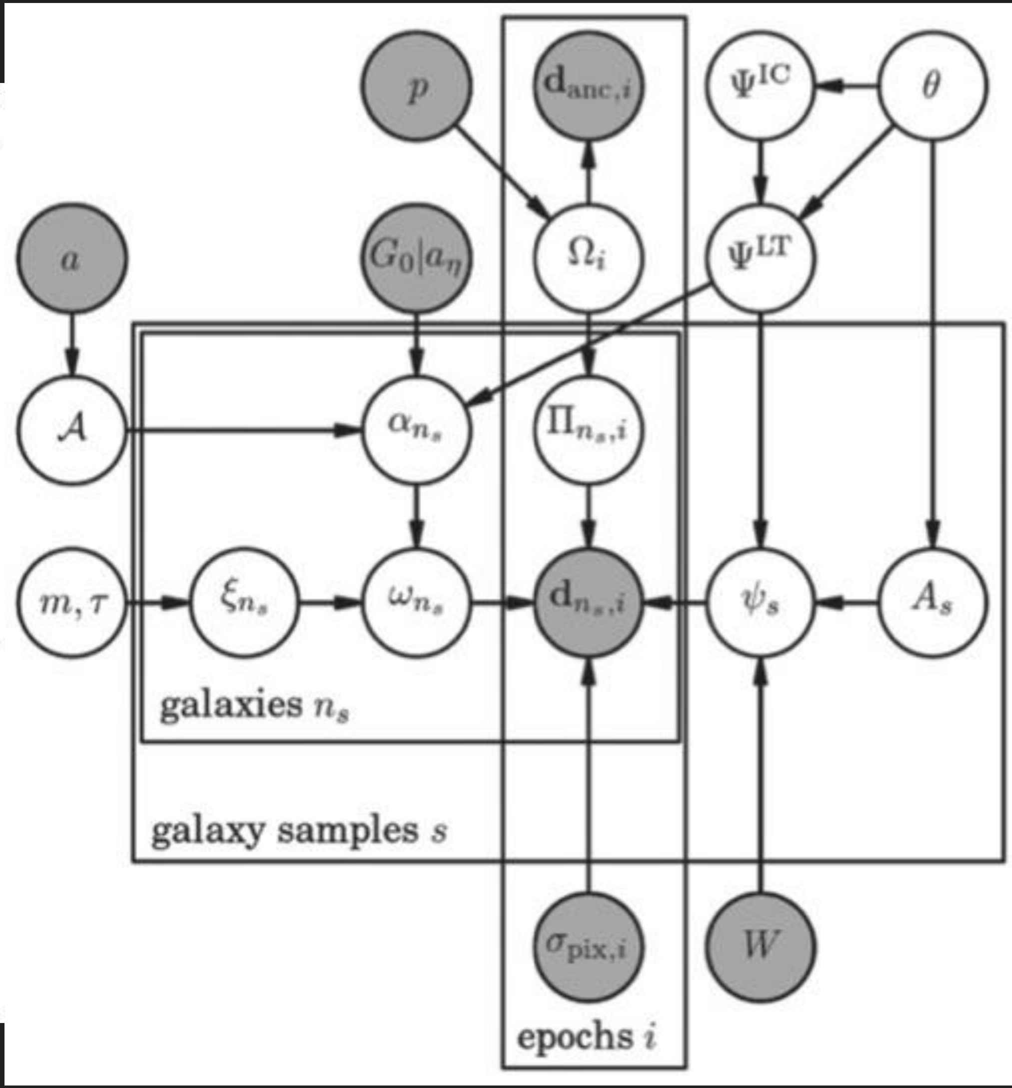
of the supernova, whilst $\hat{c}$ is the observed color, which, as it has measurement error, is different from c.

For the moment, let us consider a single supernova and

Hinton et al. (2018, DES collaboration)

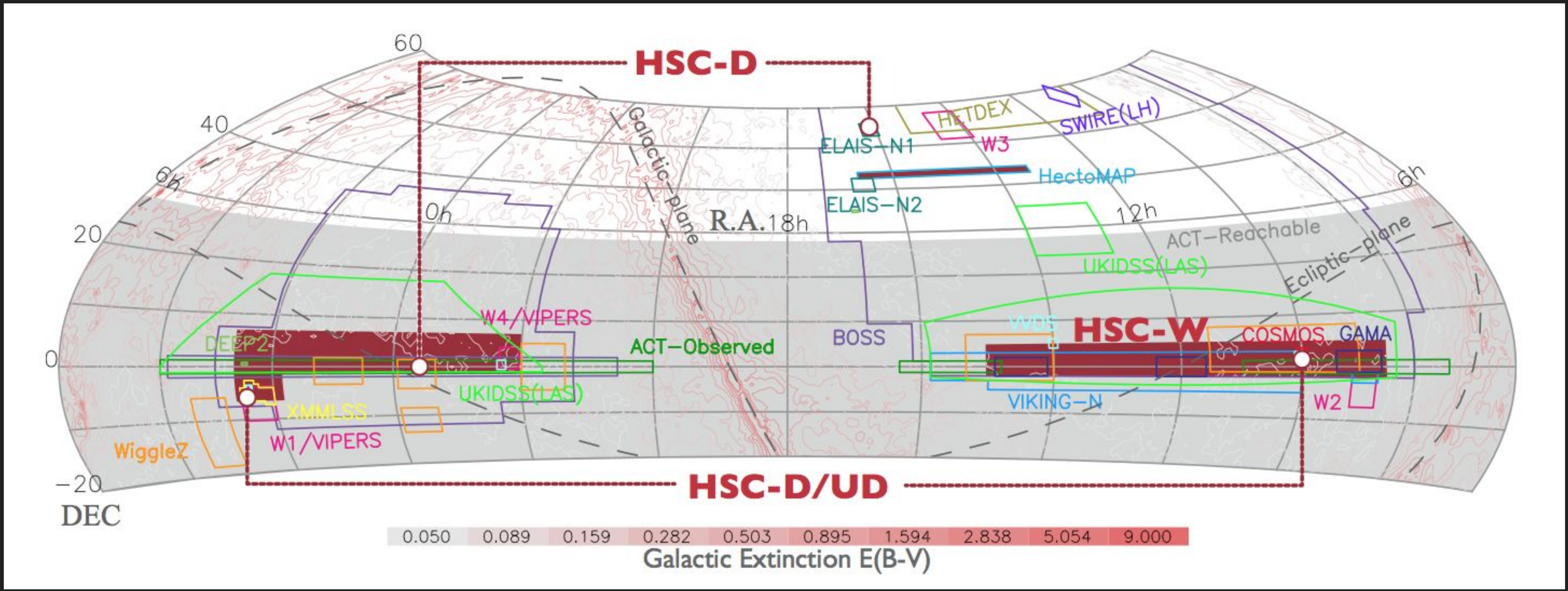
Bayesian hierarchical inference: Examples (2)

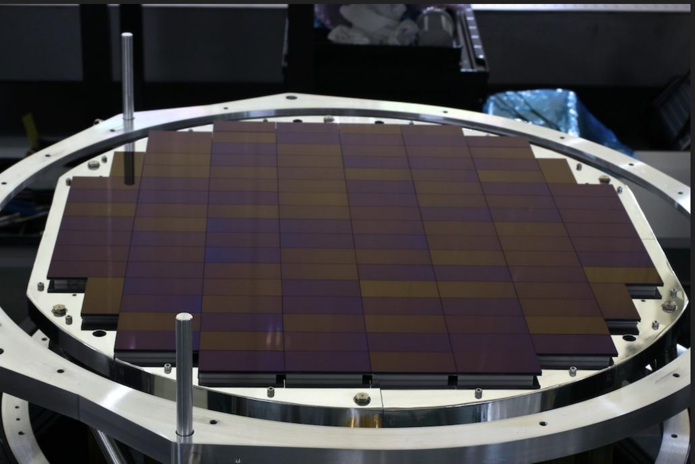
Parameter	Description
θ	Cosmological parameters
Ψ^{IC}	Initial conditons for the 3D gravitational potential
Ψ^{LT}	Late-time 3D gravitational potential
ψ_s	2D lens potential (given source photo-z bin s)
A_s	Parameters for the line-of-sight source distribution
$\Pi_{n_s,i}$	PSF for galaxy n_s observed in epoch i
Ω_{i}	Observing conditions in epoch i
$\{\omega_{n_s}\}$	Galaxy model parameters; $n_s = 1,..., n_{\mathrm{gal},s}$
$\{\alpha_{n_s}\}$	Parameters for the distribution of $\{\omega_{n_s}\}$
$\{\xi_{n_s}\}$	Scaling parameters for $\{\omega_{n_s}\}$
m, τ	Hyperprior parameters for $\{\xi_{n_s}\}$
$\mathcal{A}$	Hyperparameter for $\{\alpha_{n_s}\}$ classifications
$\{\boldsymbol{d}_{n_s,i}\}$	Pixel data for galaxies $n_s = 1,..., n_{\mathrm{gal},s}$ in epoch i
$G_0 \| a_\eta$	Prior specification for $\{\alpha_{n_s}\}$
s	Source sample (e.g., photo-z bin)
W	Survey window function
$\boldsymbol{d}_{\mathrm{anc},i}$	Ancillary data for PSF in epoch i
p	Prior parameters for observing conditions
a	Prior parameters for $\mathcal{A}$
$\sigma_{\mathrm{pix},i}$	Pixel noise rms in epoch i
I	Model selection assumptions



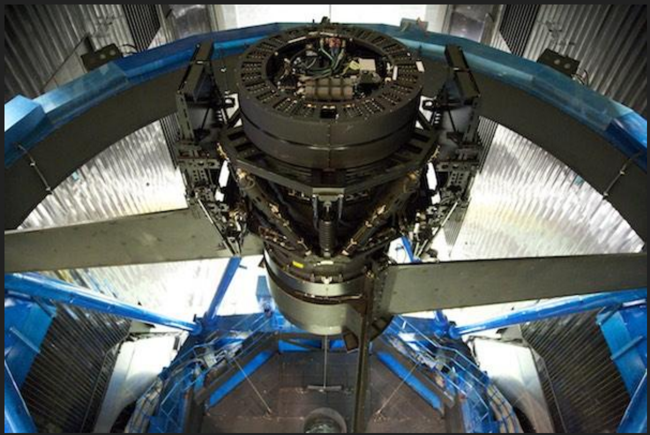
Schneider et al. (2015)

Hyper Suprime-Cam Survey





- ~1,000 square degrees
- Depth ~26 mag (i-band)
- Typical seeing 0.7”



An HSC view of the CMASS galaxy sample. Halo mass as a function of stellar mass, size and Sérsic index.

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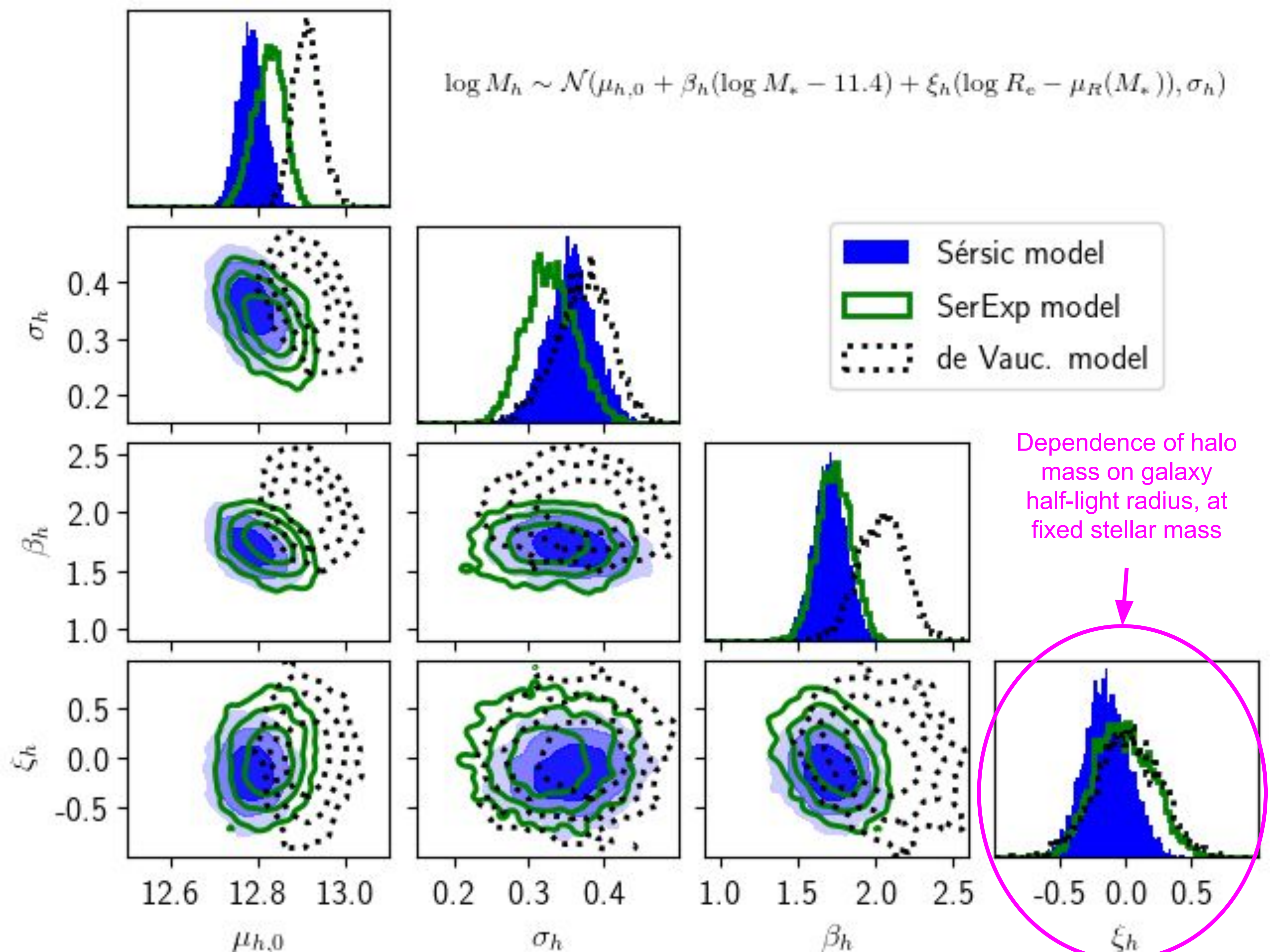
- 10,000 massive galaxies (M* > 10^11) from BOSS CMASS sample (median redshift z~0.55)
- Stellar masses and sizes from HSC grizy photometry
- HSC weak lensing shape measurements on 140 square degrees
- Bayesian hierarchical inference of halo mass-stellar mass-size-Sersic index relation


$\log M_h \sim \mathcal{N}(\mu_{h,0} + \beta_h(\log M_* - 11.4) + \xi_h(\log R_e - \mu_R(M_*)), \sigma_h)$
Sérsic model
SerExp model
de Vauc. model
Dependence of halo mass on galaxy half-light radius, at fixed stellar mass
$\mu_{h,0}$
σ_h
β_h
ξ_h
12.6
12.8
13.0
0.2
0.3
0.4
1.0
1.5
2.0
2.5
-0.5
0.0
0.5

The dependence of halo mass on galaxy size at fixed stellar mass using weak lensing

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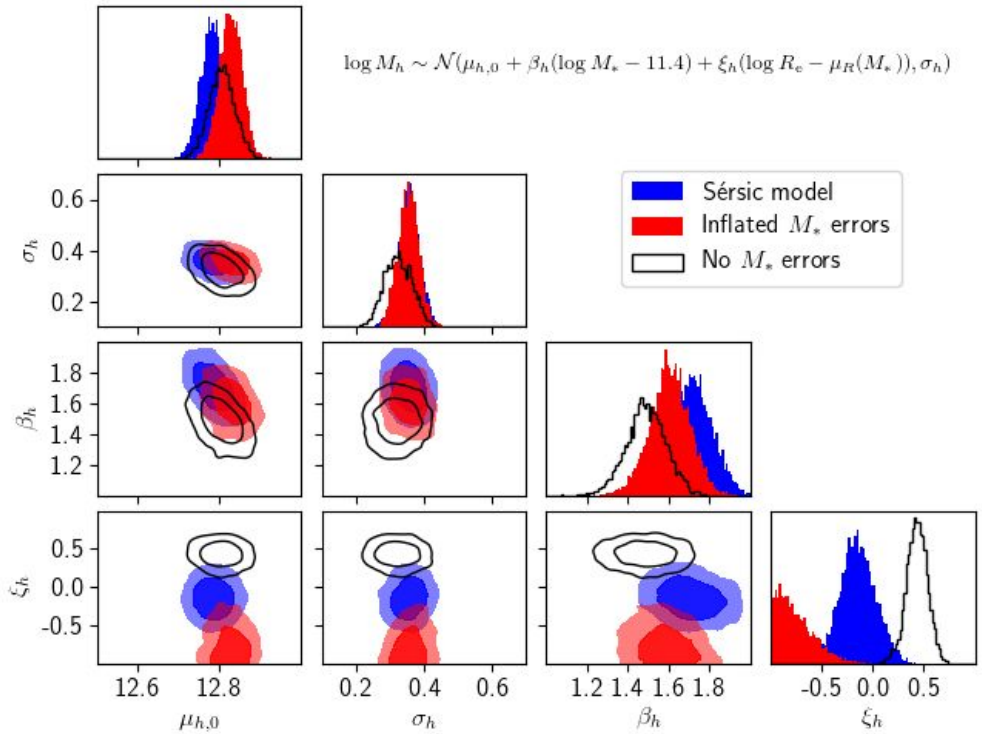
ABSTRACT
Stellar mass has been shown to correlate with halo mass, with non-negligible scatter. The stellar mass–size and luminosity–size relationships of galaxies also show significant scatter in galaxy size at fixed stellar mass. It is possible that, at fixed stellar mass and galaxy colour, the halo mass is correlated with galaxy size. Galaxy–galaxy lensing allows us to measure the mean masses of dark matter haloes for stacked samples of galaxies. We extend the analysis of the galaxies in the CFHTLenS catalogue by fitting single Sérsic surface brightness profiles to the lens galaxies in order to recover half-light radius values, allowing us to determine halo masses for lenses according to their size. Comparing our halo masses and sizes to baselines for that stellar mass yields a differential measurement of the halo mass–galaxy size relationship at fixed stellar mass, defined as $M_h(M_*) \propto r_{eff}^{\eta}(M_*)$. We find that, on average, our lens galaxies have an $\eta = 0.42 \pm 0.12$, i.e. larger galaxies live in more massive dark matter haloes.



Sonnenfeld et al. (2019)

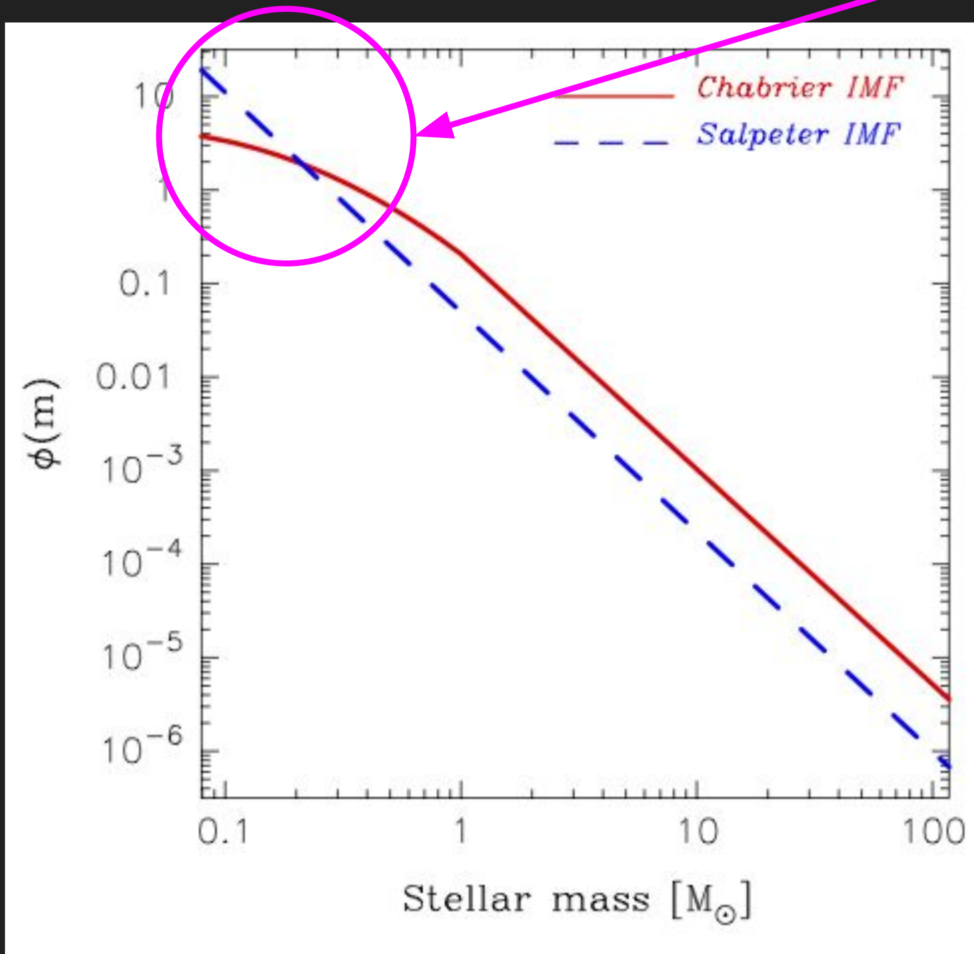
Part III: strong lensing constraints on the stellar IMF of massive galaxies

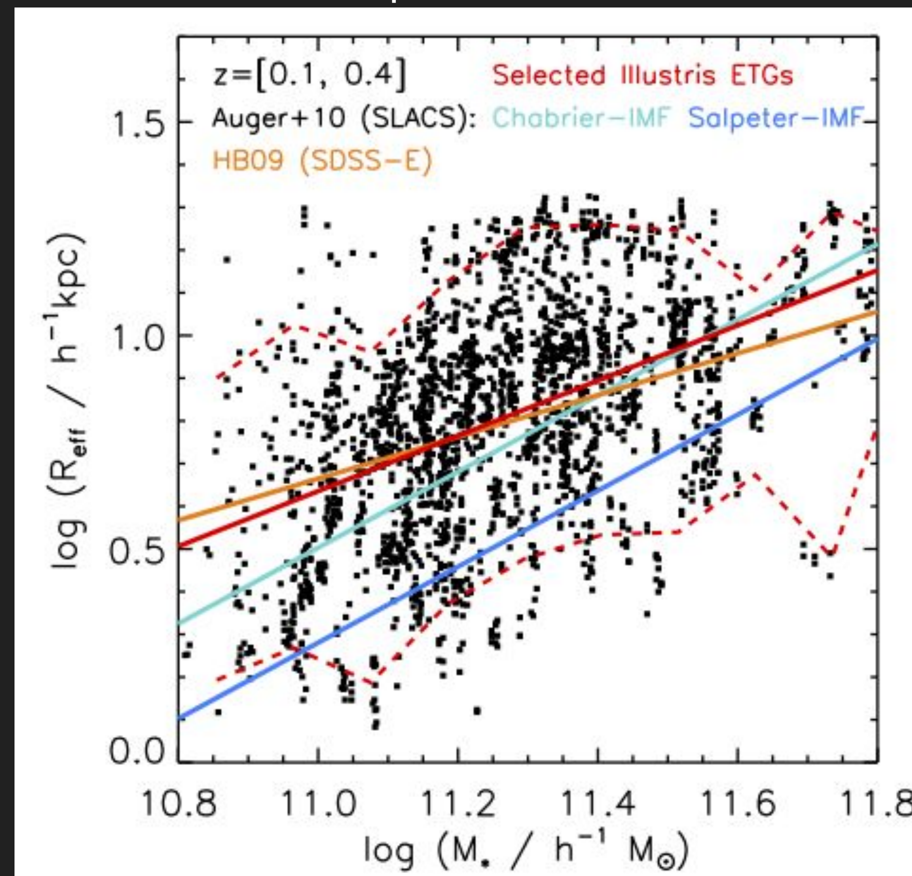
The stellar initial mass function (IMF): main systematic in stellar mass measurements

How stellar masses are measured:

- Measure light distribution
- Assume a stellar population model
- Fit model parameters based on observed light
- Extrapolate model down to very small stars

These stars contribute very little to the light of a galaxy, but contribute a lot to the mass: uncertainty in M/L of up to a factor of 2!





Xu et al. (2017)

Strong lensing constraints on stellar IMF

$$\theta_{\rm Ein} = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_d D_s}}$$

- Strong lensing constrains total mass (upper limit on stellar mass)
- Statistical sample and/or complementary information (e.g. weak lensing, stellar kinematics) can help us disentangle stellar and dark matter mass (under some assumptions on stellar and dark matter profile)

$$\alpha_{\rm IMF} = \frac{M_*^{\rm (true)}}{M_*^{\rm (fixed\ IMF)}}$$ IMF mismatch parameter

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Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI). I. Automatic search for galaxy-scale strong lenses

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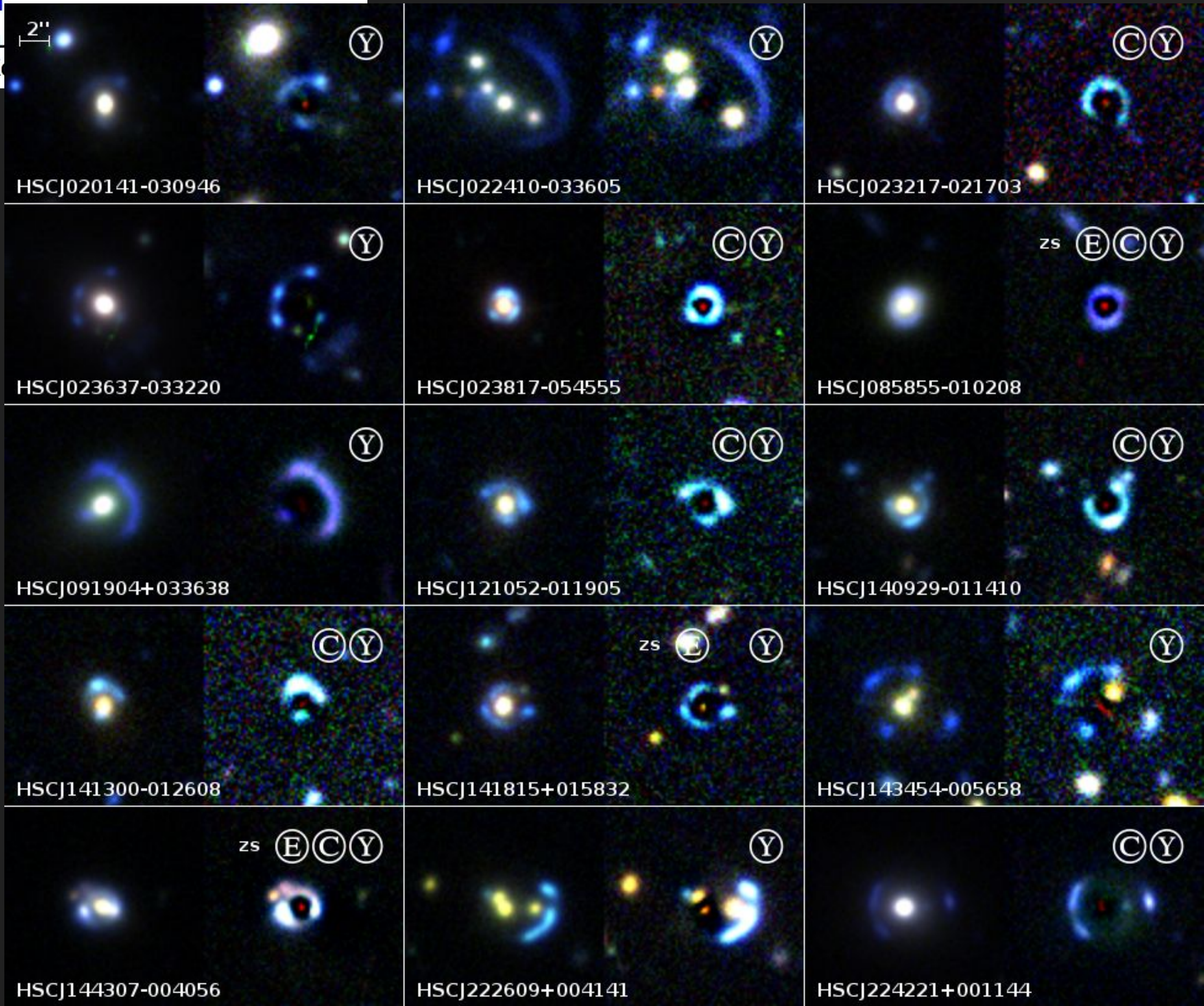
Finding strong lenses

- Current size of SuGOHI sample: ~200 grade A/B lenses
- ~80 in CMASS (22 with spectroscopy)



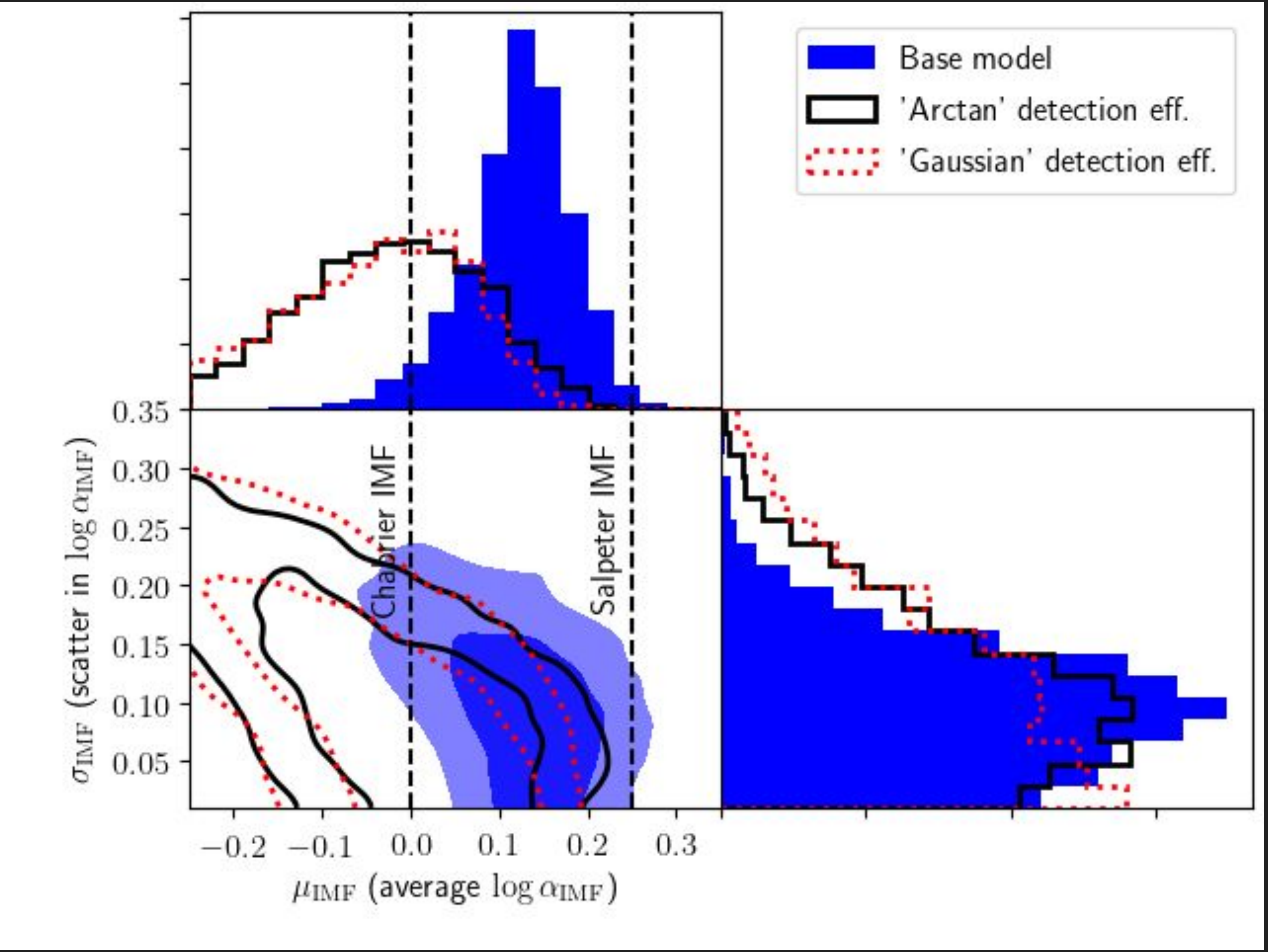
Statistical strong lensing

- The sample: 22 lens galaxies from CMASS (same as WL study) with spectroscopic data
- Goal: infer distribution of IMF mismatch parameter of the sample
- Bayesian hierarchical model, with prior on halo mass from weak lensing
- Strong lensing selection effects are modeled explicitly

$$\mathrm{P}(\boldsymbol{\psi}|\boldsymbol{\eta}) = \mathcal{F}_{\mathrm{sel}}(\boldsymbol{\psi}, \boldsymbol{\eta})\mathrm{P}_{\mathrm{CMASS}}(\boldsymbol{\psi}|\boldsymbol{\eta})$$

$$\mathrm{P}(\boldsymbol{\psi}, \boldsymbol{\eta}|\boldsymbol{d}) \propto \mathrm{P}(\boldsymbol{\eta})\mathrm{P}(\boldsymbol{\psi}|\boldsymbol{\eta})\mathcal{F}_{\mathrm{sel}}(\boldsymbol{\psi}, \boldsymbol{\eta})\mathrm{P}_{\mathrm{CMASS}}(\boldsymbol{\psi}|\boldsymbol{\eta})\mathrm{P}(\boldsymbol{d}|\boldsymbol{\psi})$$

Prior on halo mass distribution
from weak lensing



Sonnenfeld et al. (in prep.)

Part IV: future prospects

Future prospects

$$P(M_h, \ldots | M_*, \ldots) = ?$$

- Weak lensing:
  - Extend analysis of HSC data to explore the relation between halo mass (and/or halo concentration) and various observed properties: velocity dispersion, group richness (see work by L. Kawinwanichakij), black hole mass, galaxy formation time

- Strong lensing:
  - Bring sample of SuGOHI lenses to ~1,000
  - Follow-up observations from PFS
  - Simultaneous strong and weak lensing analysis
  - Break the degeneracy between halo density profile and stellar IMF
  - Head-start in the LSST era (10,000 ~ 100,000 lenses)

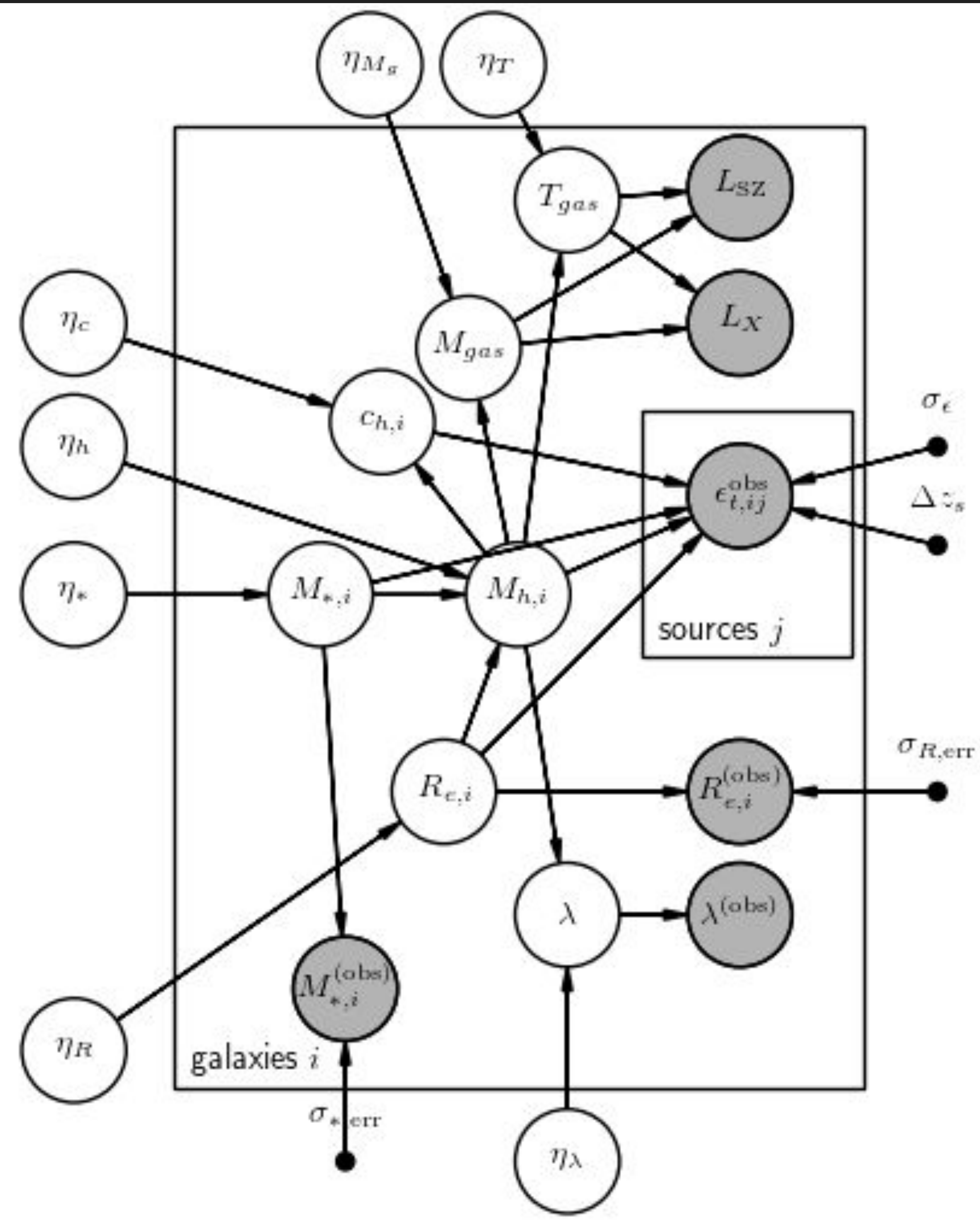

η_{M_g}
η_T
T_{gas}
L_{SZ}
L_X
M_{gas}
η_c
$c_{h,i}$
η_h
$\epsilon^{obs}_{t,ij}$
σ_ϵ
Δz_s
η_*
$M_{*,i}$
$M_{h,i}$
sources j
$R_{e,i}$
$R^{(obs)}_{e,i}$
$\sigma_{R,err}$
λ
$\lambda^{(obs)}$
$M^{(obs)}_{*,i}$
η_R
galaxies i
$\sigma_{*,err}$
η_λ


Photo Credit: Jon Ward


eROSITA

Prime focus spectrograph

- Galaxy evolution: ~200,000 galaxies at $0.7 < z < 2.0$
- Transition phase from star-forming to quiescent: key for understanding quenching.
- Modeling/data analysis challenge: how to observationally disentangle various effect that are linked to quenching? (e.g. halo mass, stellar mass, environment, outflows)

Summary

- Understanding the galaxy-halo connection is key for both cosmology and galaxy evolution science
- Observational challenges require appropriate inference tools. Key is forward modeling
- HSC weak lensing is allowing exploration of dependence of halo mass on various galaxy properties
- Combination with other datasets (X-ray, SZ, richness,...) will help improve halo mass estimates
- HSC strong lensing is allowing measurements of the stellar IMF of massive galaxies (PFS will allow full exploitation): head start in the statistical strong lensing era