Weak Lensing Cosmology from the Subaru Hyper Suprime-Cam Survey First Year Data

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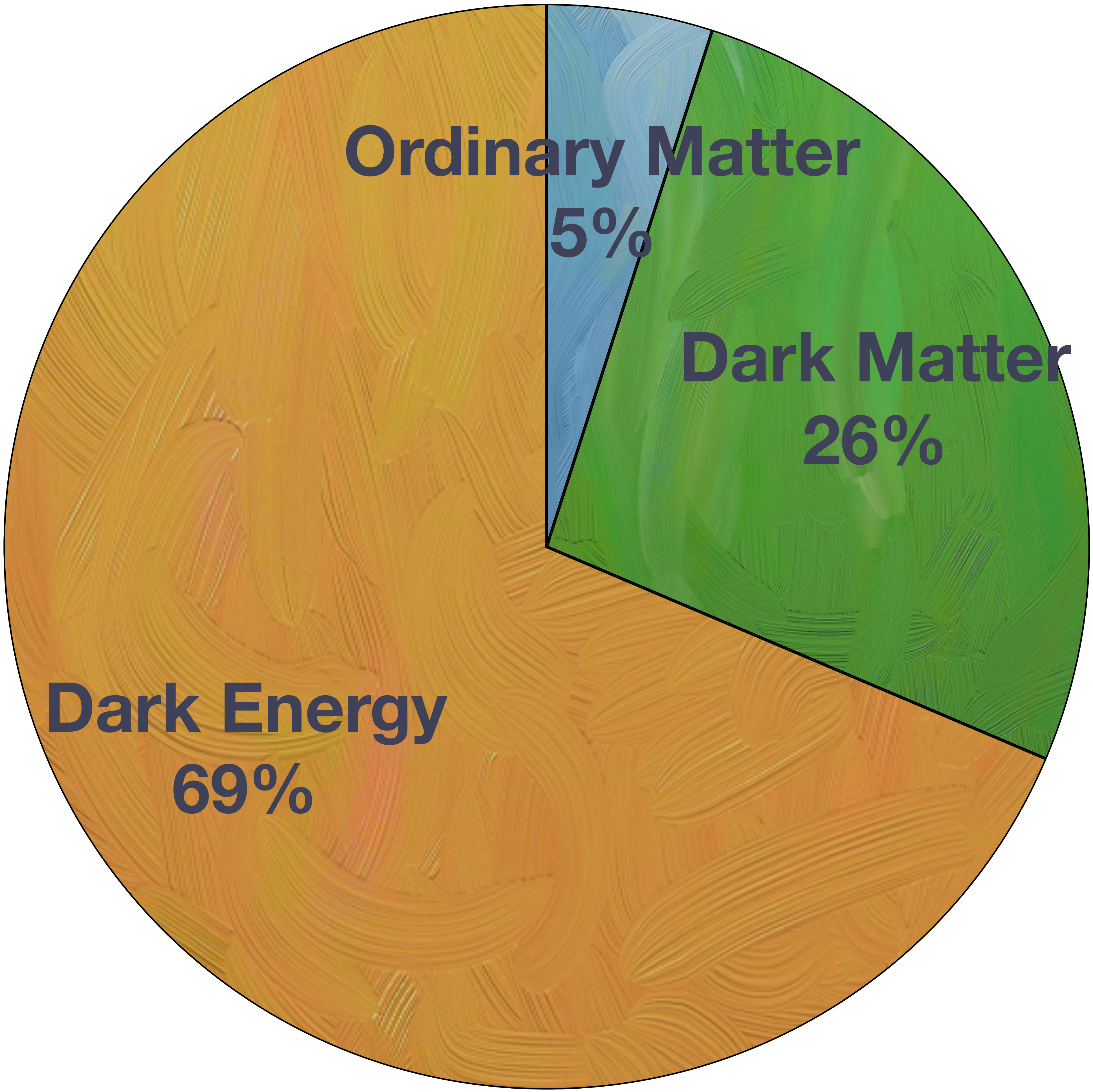
Nagoya University
On Behalf of the HSC Collaboration

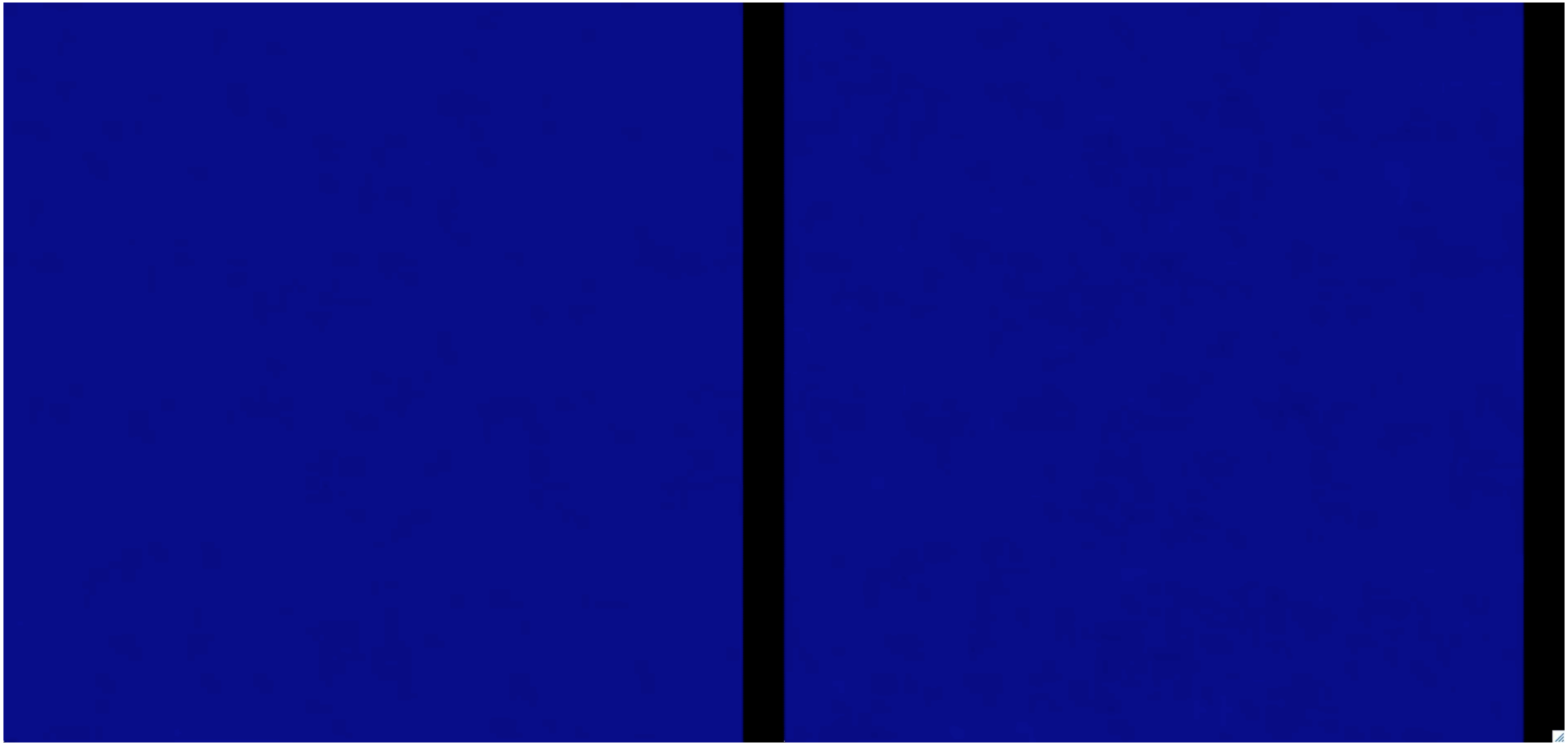
Outline

- Cosmic acceleration and dark energy
- Weak lensing cosmology
- Subaru Hyper Suprime-Cam (HSC)
  - First-year results from HSC survey
  - Cosmic shear in real space and Fourier space
  - Galaxy-galaxy lensing and clustering (ongoing work)
- Future prospects



Planck Collaboration (2018)

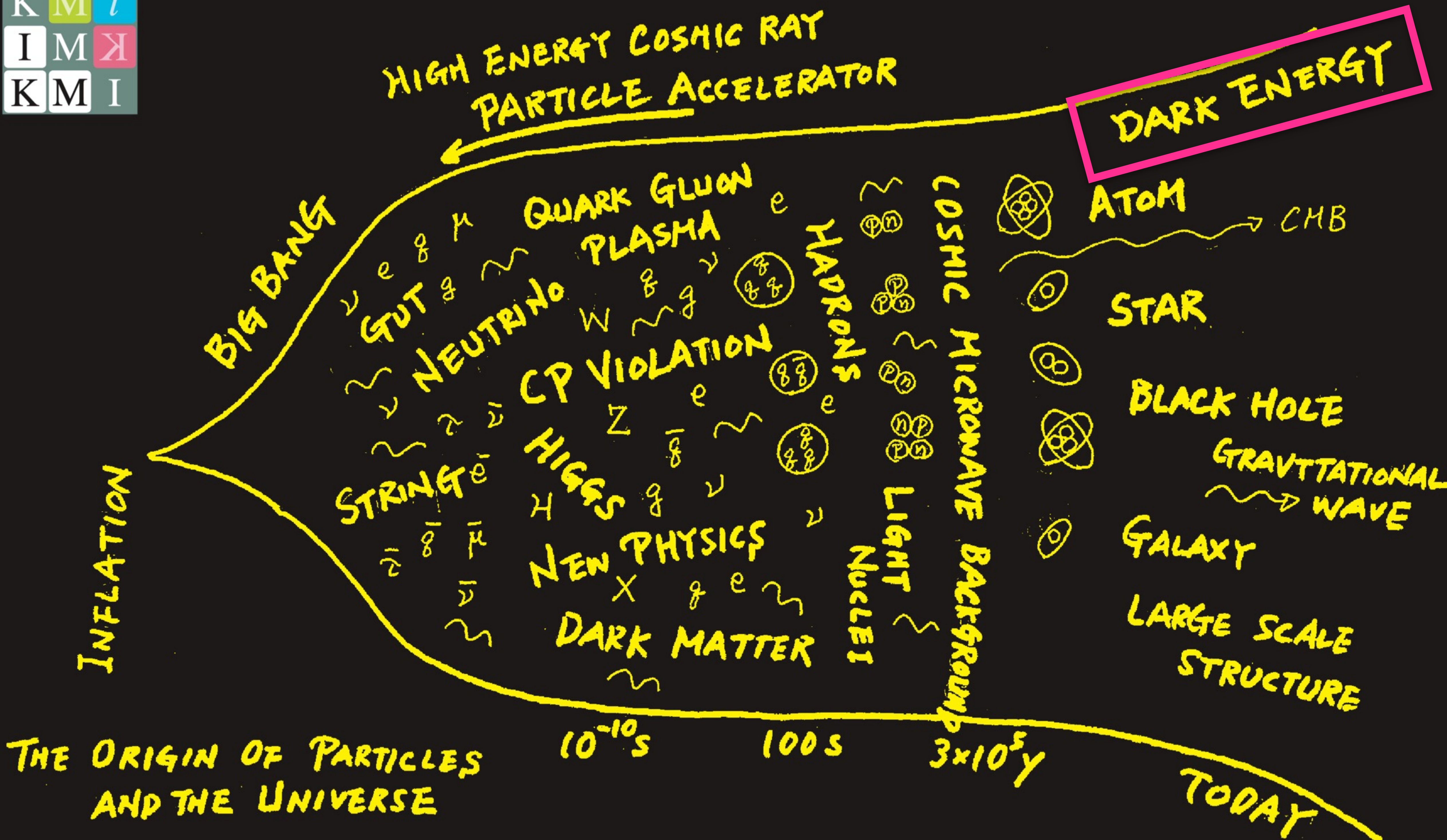
We Would **NOT** Exist without **Dark Matter**



Without Dark Matter

With Dark Matter

Credit: N. Yoshida



HIGH ENERGY COSMIC RAY
PARTICLE ACCELERATOR
DARK ENERGY
BIG BANG
INFLATION
QUARK GLUON PLASMA
GUT
NEUTRINO
CP VIOLATION
STRING
HIGGS
NEW PHYSICS
DARK MATTER
HADRONS
LIGHT NUCLEI
COSMIC MICROWAVE BACKGROUND
ATOM
CMB
STAR
BLACK HOLE
GRAVITATIONAL WAVE
GALAXY
LARGE SCALE STRUCTURE
10^-10 s
100 s
3×10^5 y
TODAY
THE ORIGIN OF PARTICLES AND THE UNIVERSE

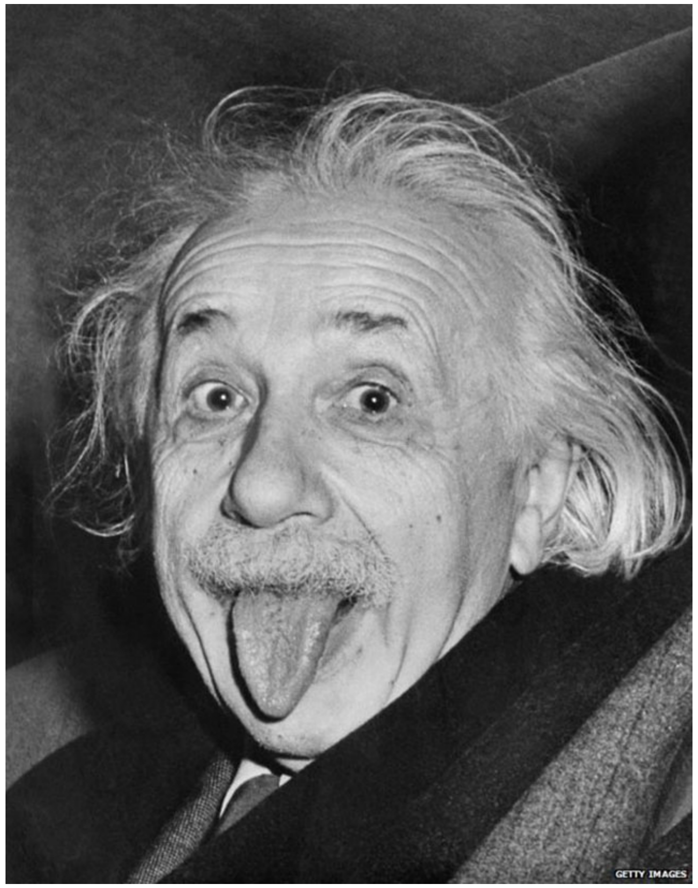
www.spacetelescope.org

The Universe has been evolved under the competition between

- **Gravity due to dark matter**, and
- **Accelerating expansion due to dark energy**.

Dark Sector of the Universe

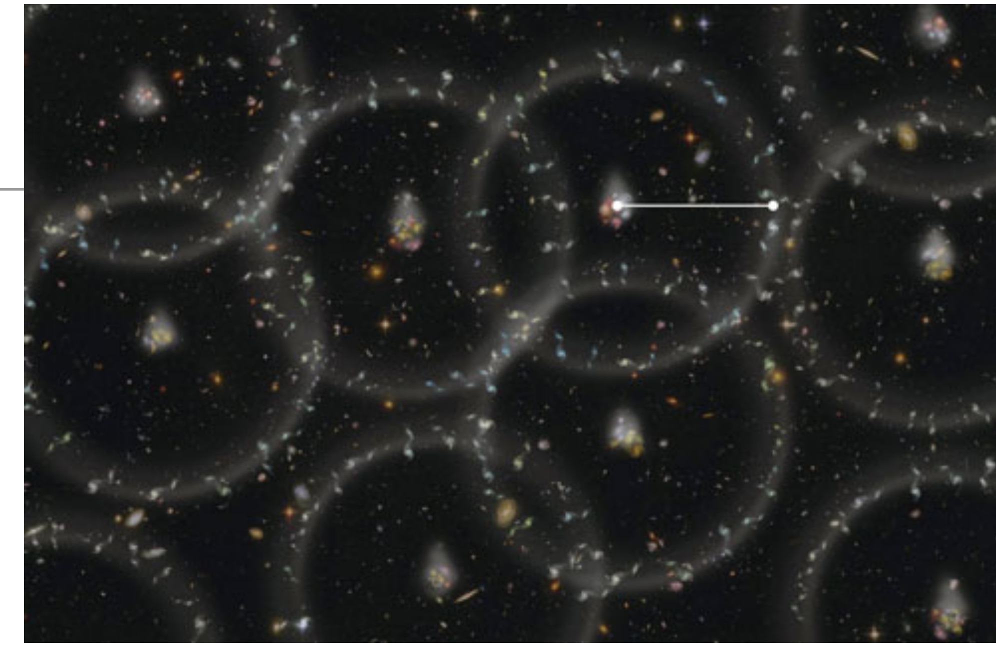
- **Dark Matter**
  - Non-luminous, unknown matter.
  - Source of gravity to form galaxies and galaxy clusters.
  - New particle?
- **Dark Energy**
  - Unknown energy.
  - Source of cosmic acceleration.
  - Breakdown of Einstein's GR?
  - Fifth force?



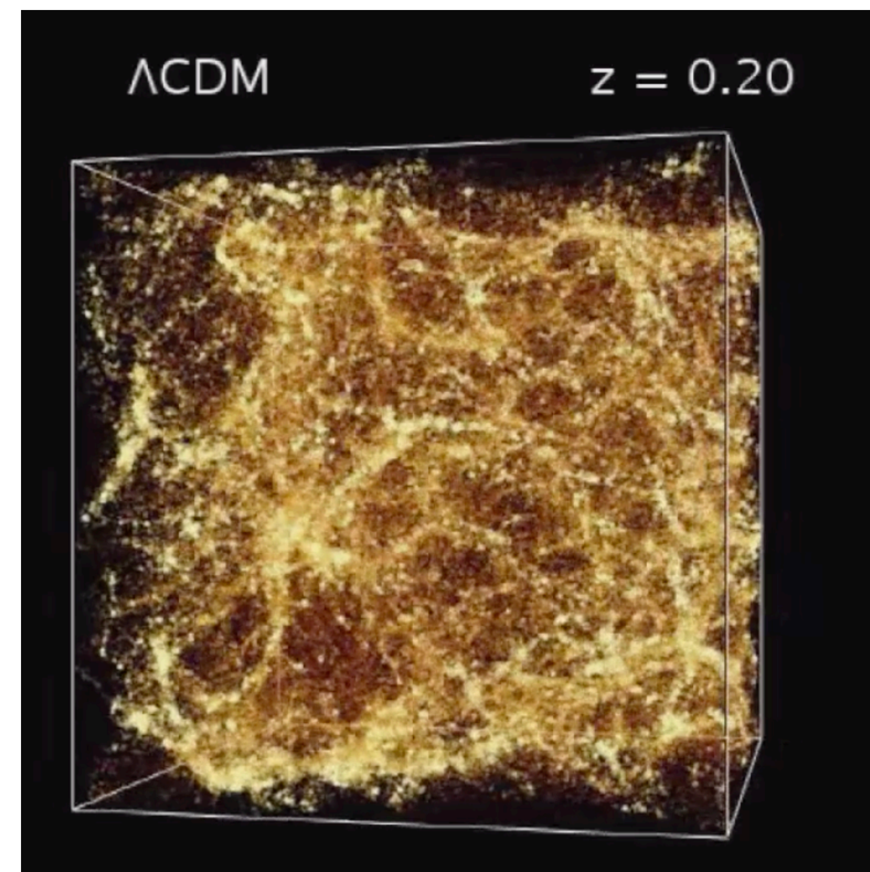
Cosmology Probes

- Geometry of the Universe
  - Type Ia supernovae (SN)
  - Baryon Acoustic Oscillations (BAO)
- Growth of structure
  - Cluster number count (CL)
  - Weak gravitational lensing (WL)
  - Redshift space distortions (RSD)

→ sensitive to modified gravity



Credit: SDSS/BOSS



Credit: ESA

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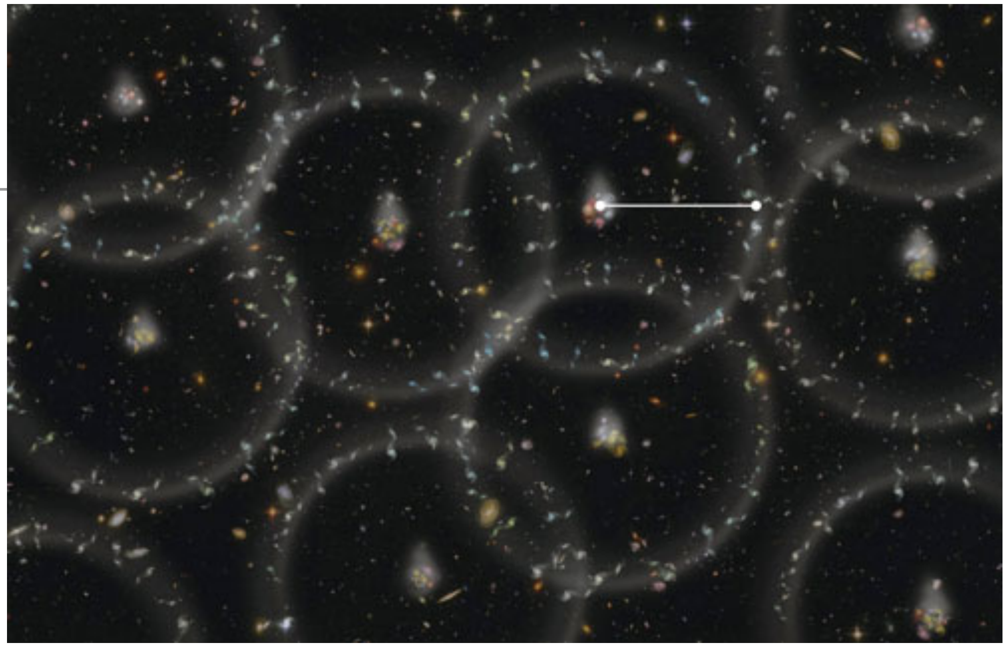
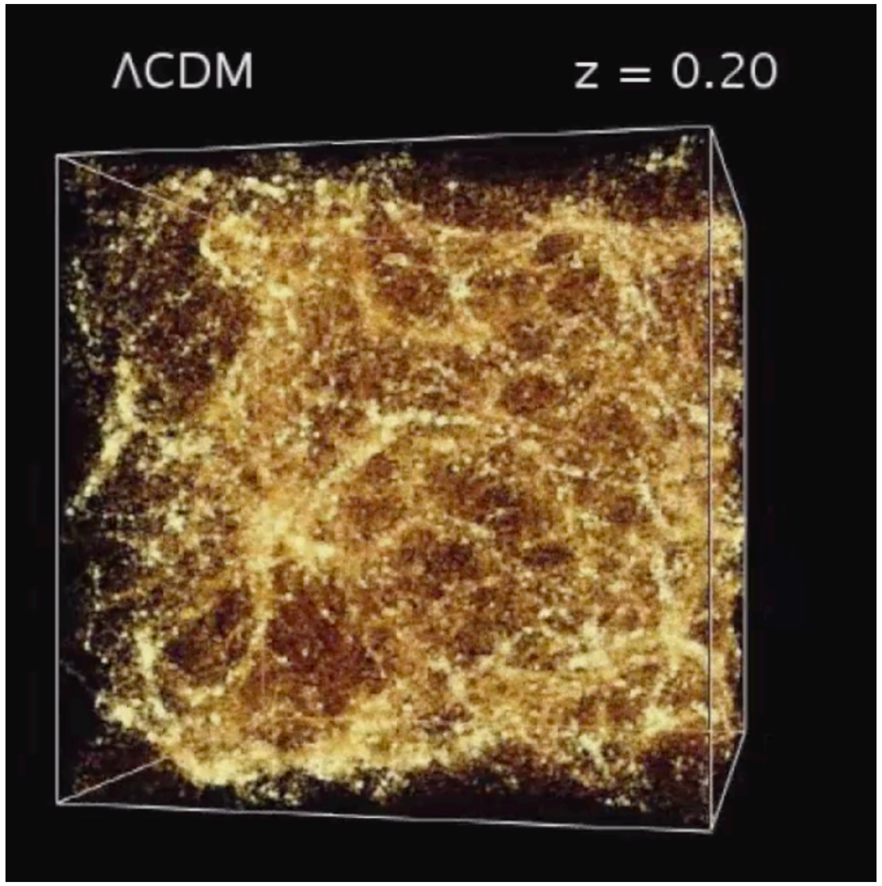
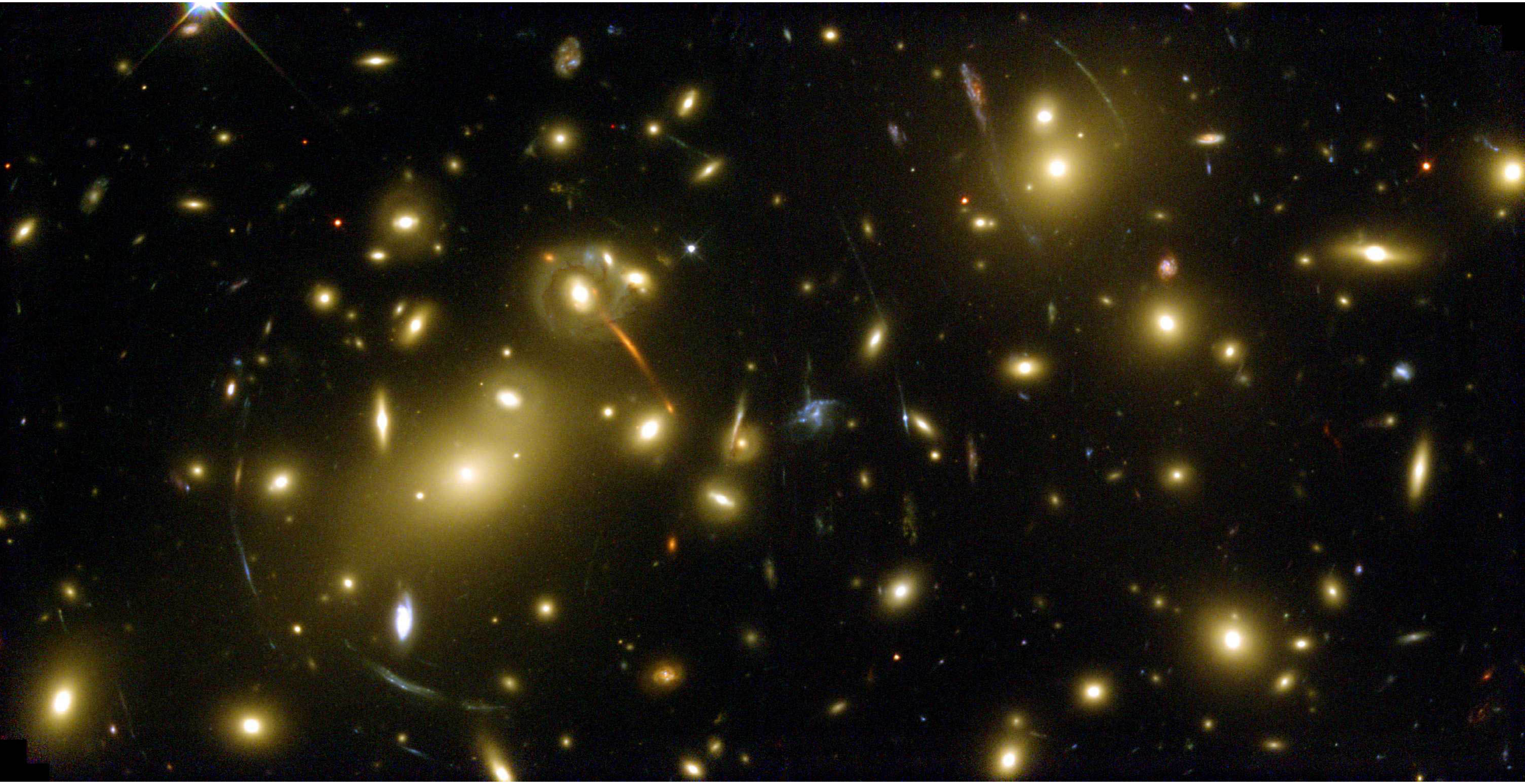


Credit: SDSS/BOSS



Credit: ESA

(Strong) Gravitational Lensing



Abell 2188, Credit: NASA/ESA

Weak Gravitational Lensing

WL shear is only **a few %** of intrinsic shape of galaxies

Credit: Subaru HSC

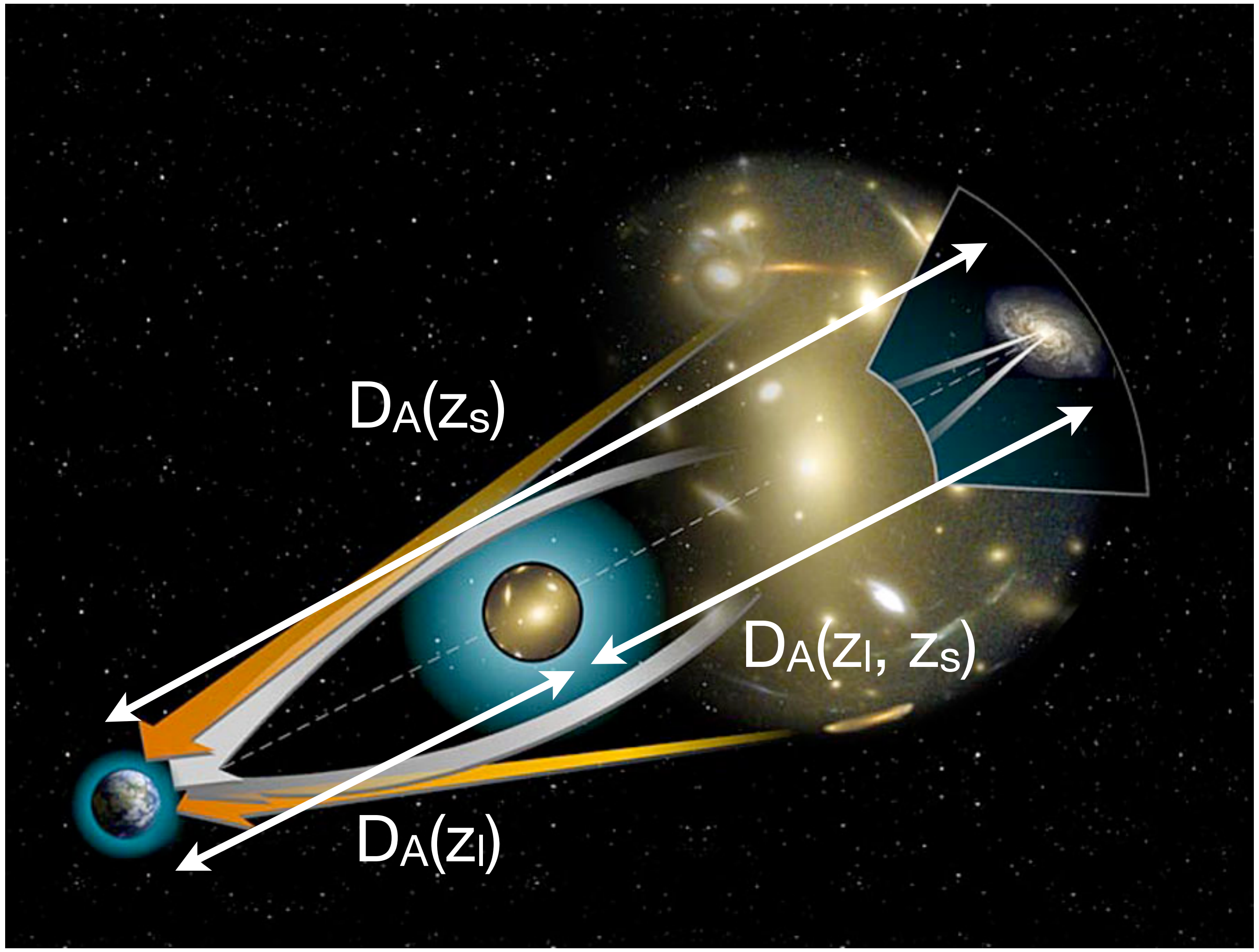
Weak Gravitational Lensing in a Nutshell

Weak lensing shear

$$\gamma \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

Matter density fluctuation

Geometry of the Universe



Weak lensing is a unique probe of
the matter (including **dark matter**) distribution

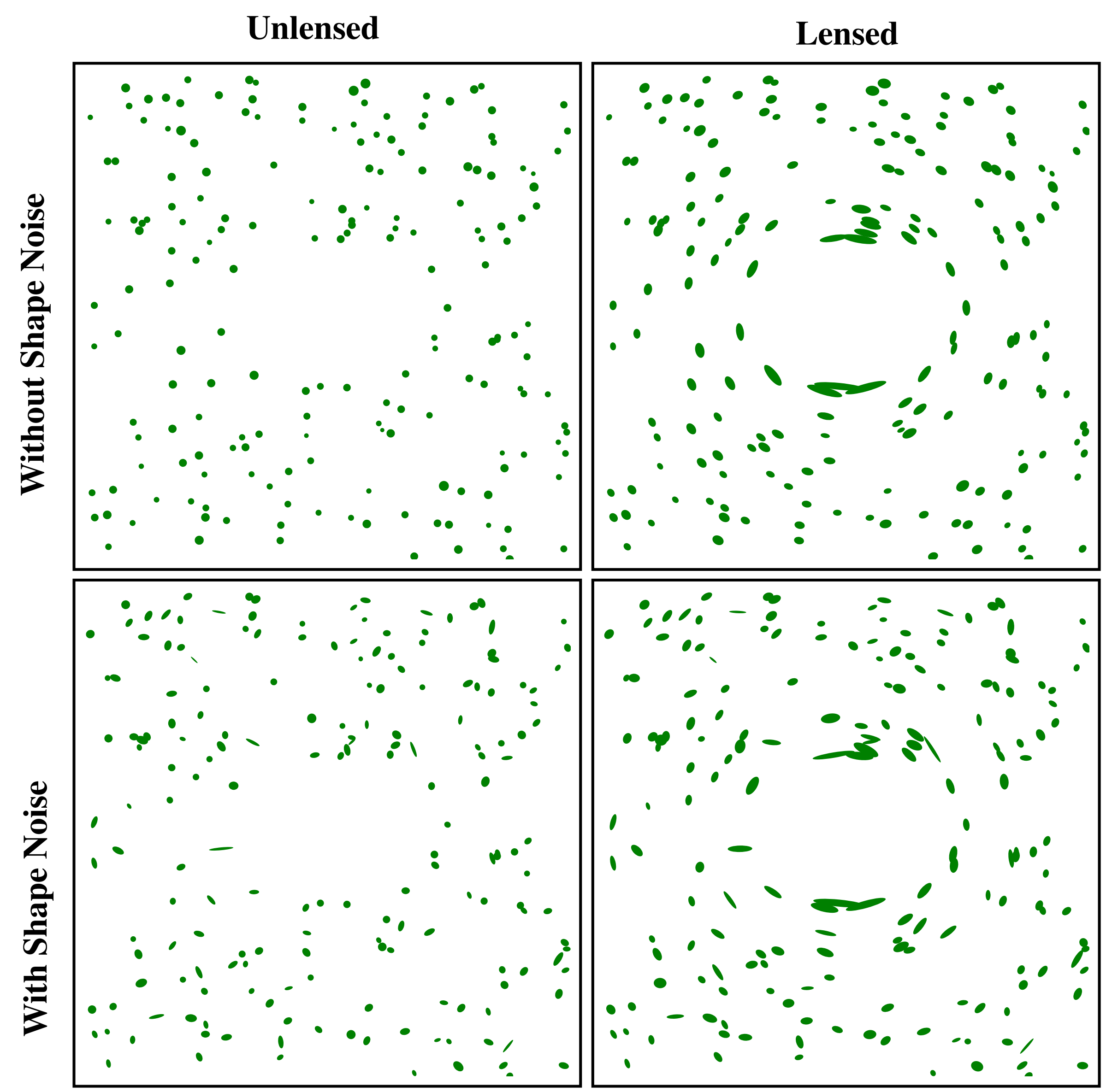
Weak Lensing Measurement

- Weak lensing coherently changes shapes of galaxies

$$\boxed{\gamma} \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

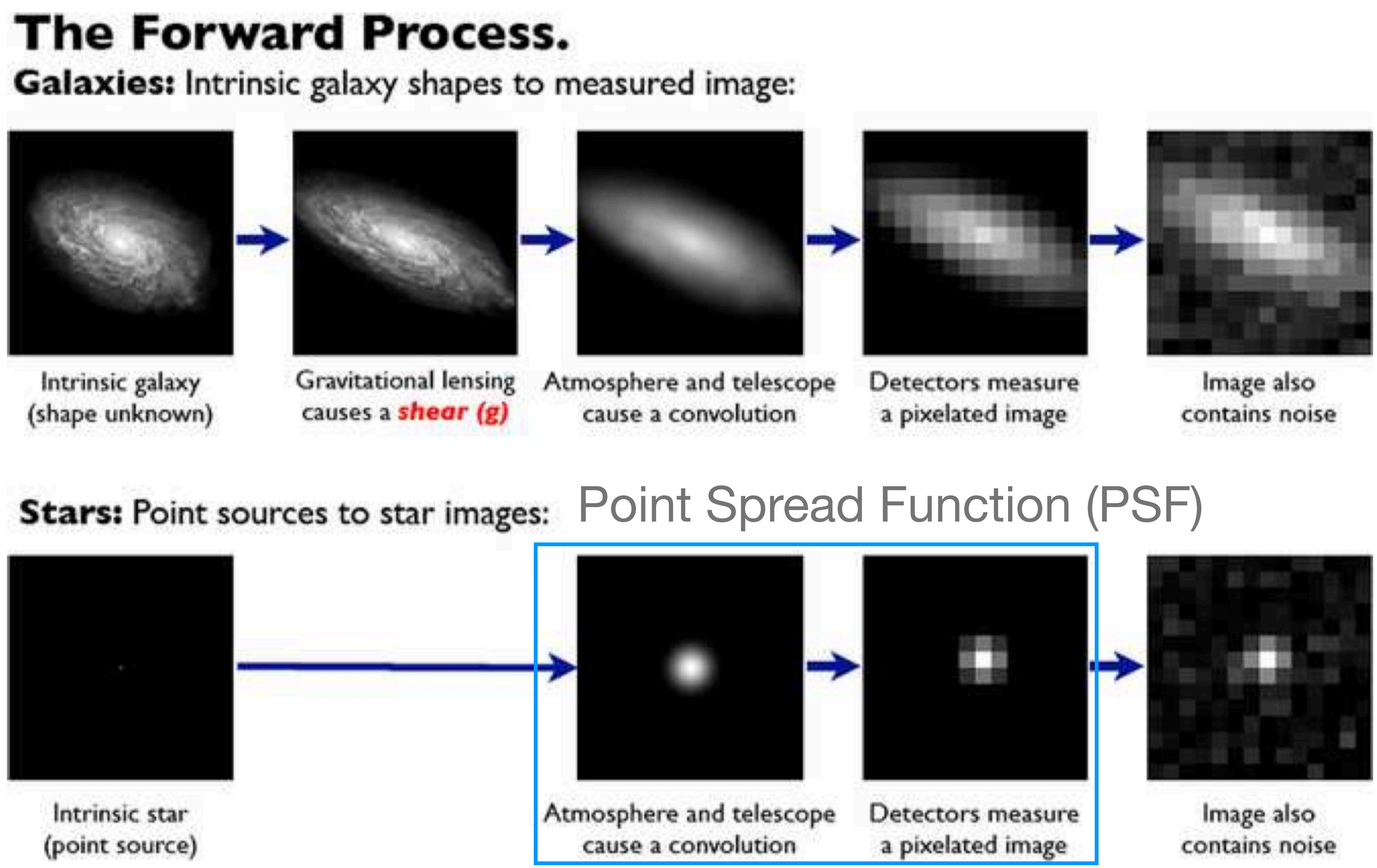
- Intrinsic shapes of galaxies (shape noise) can be beaten down using a number of galaxies, assuming the position angle is randomly oriented.

$$\sigma_\gamma = \frac{\sigma_{\gamma,\mathrm{int}}}{\boxed{\sqrt{N}}}$$



→ Need (at least) **thousands of galaxies** to perform a high signal-to-noise measurement

Galaxy Shape Measurement

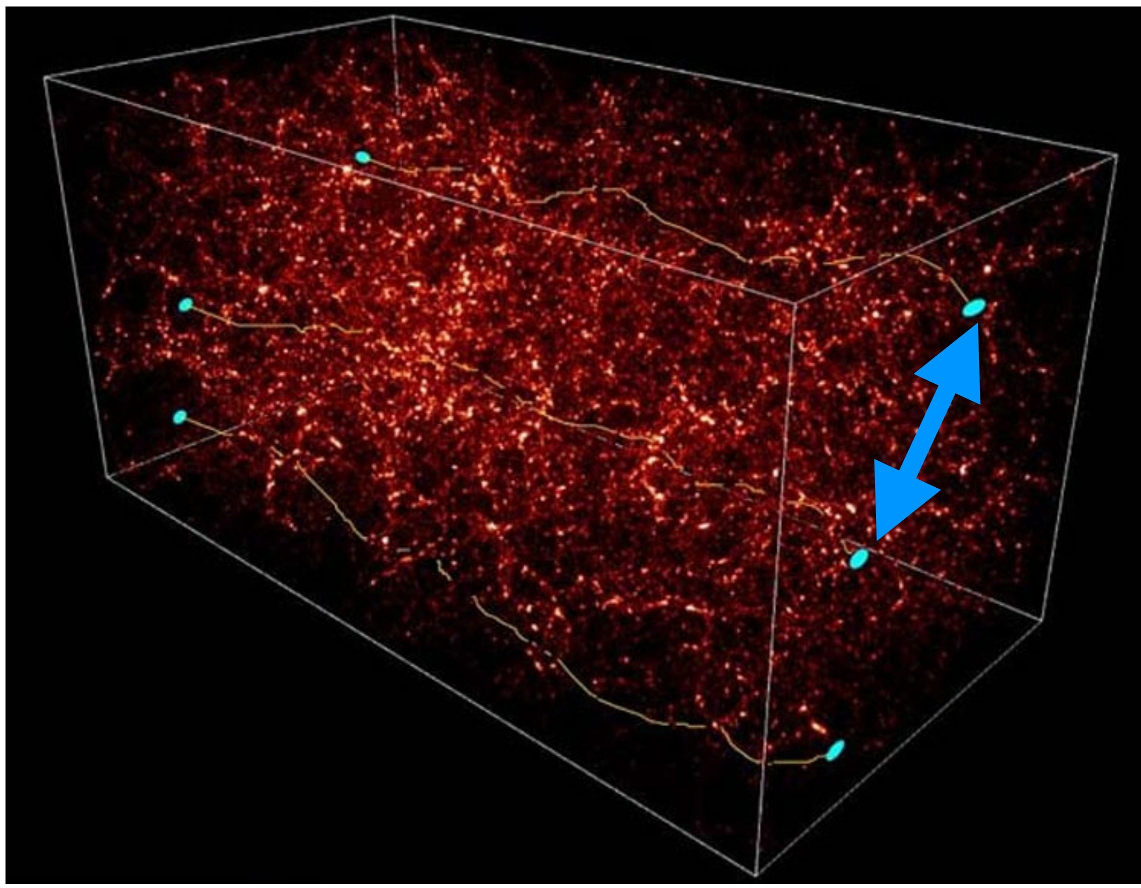


Superb image quality is required.

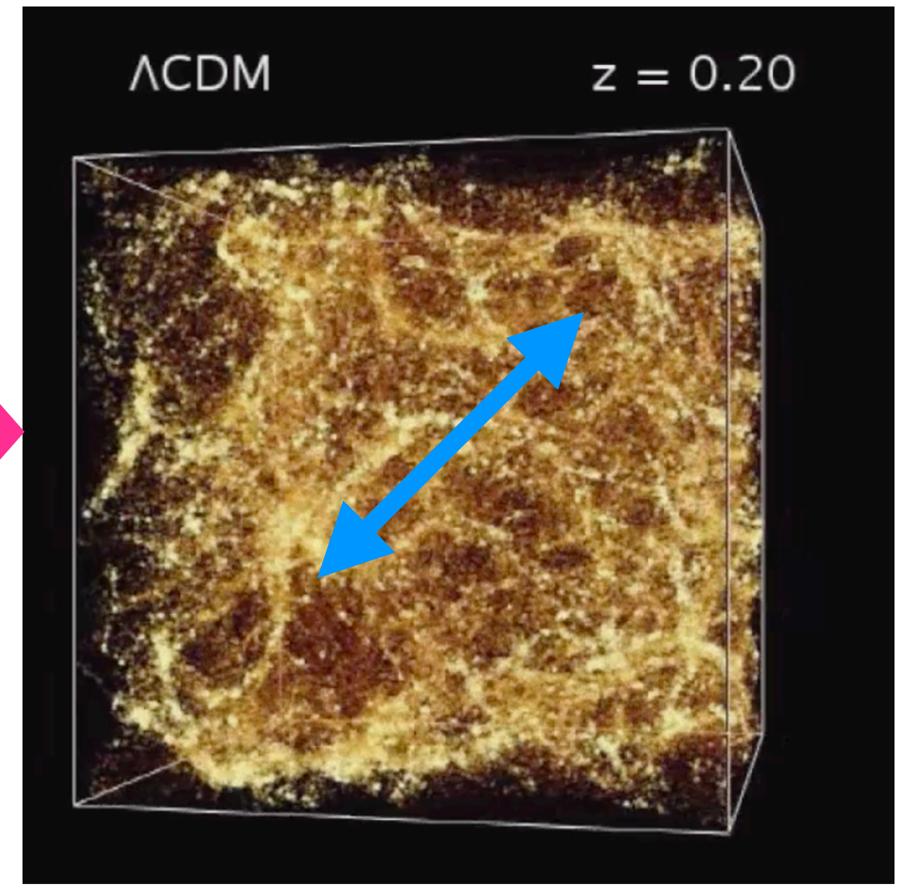
Credit: S. Bridle

Extracting Cosmological Information

Observations



Theory



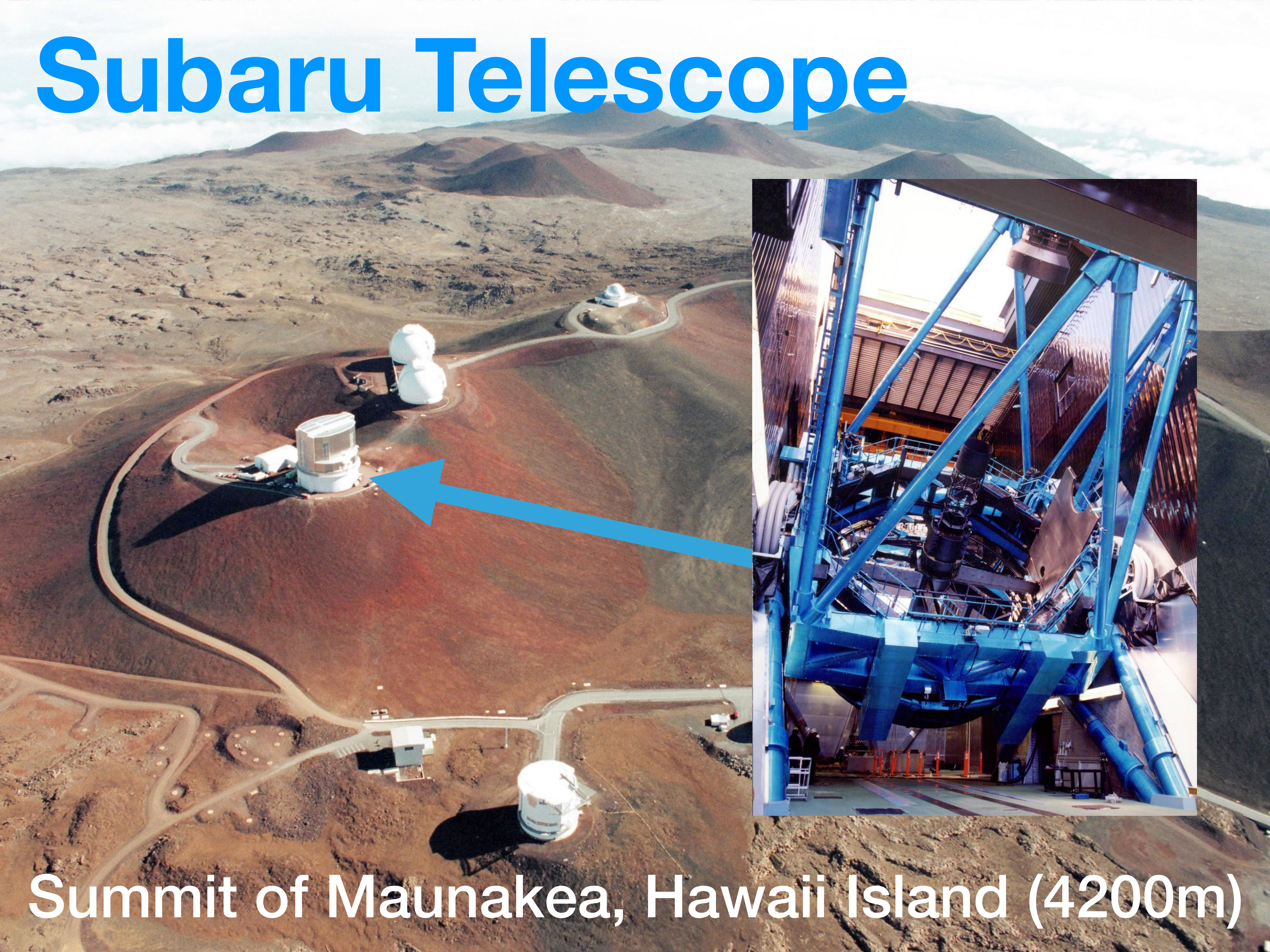
Compare through correlation functions

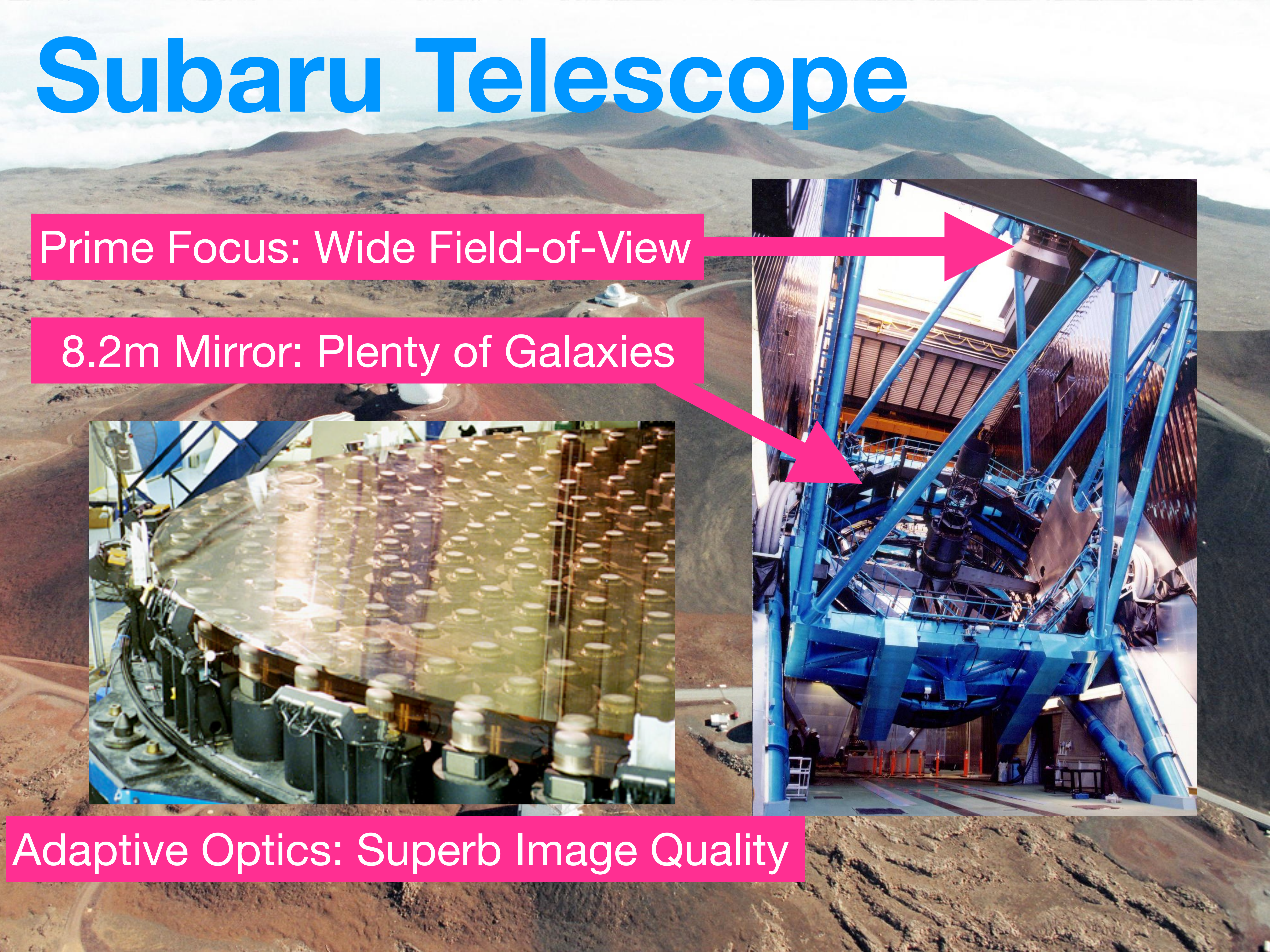
Need to observe **a large volume** of the Universe.

What is Necessary for Weak Lensing Cosmology?

- **A large number of galaxies** to perform a high signal-to-noise measurement
- **Superb image quality**
- Observations of **a large volume** of the Universe.

Subaru Hyper Suprime-Cam (HSC) is one of the best instruments to perform **precision weak lensing cosmology**.


Subaru Telescope
Summit of Maunakea, Hawaii Island (4200m)

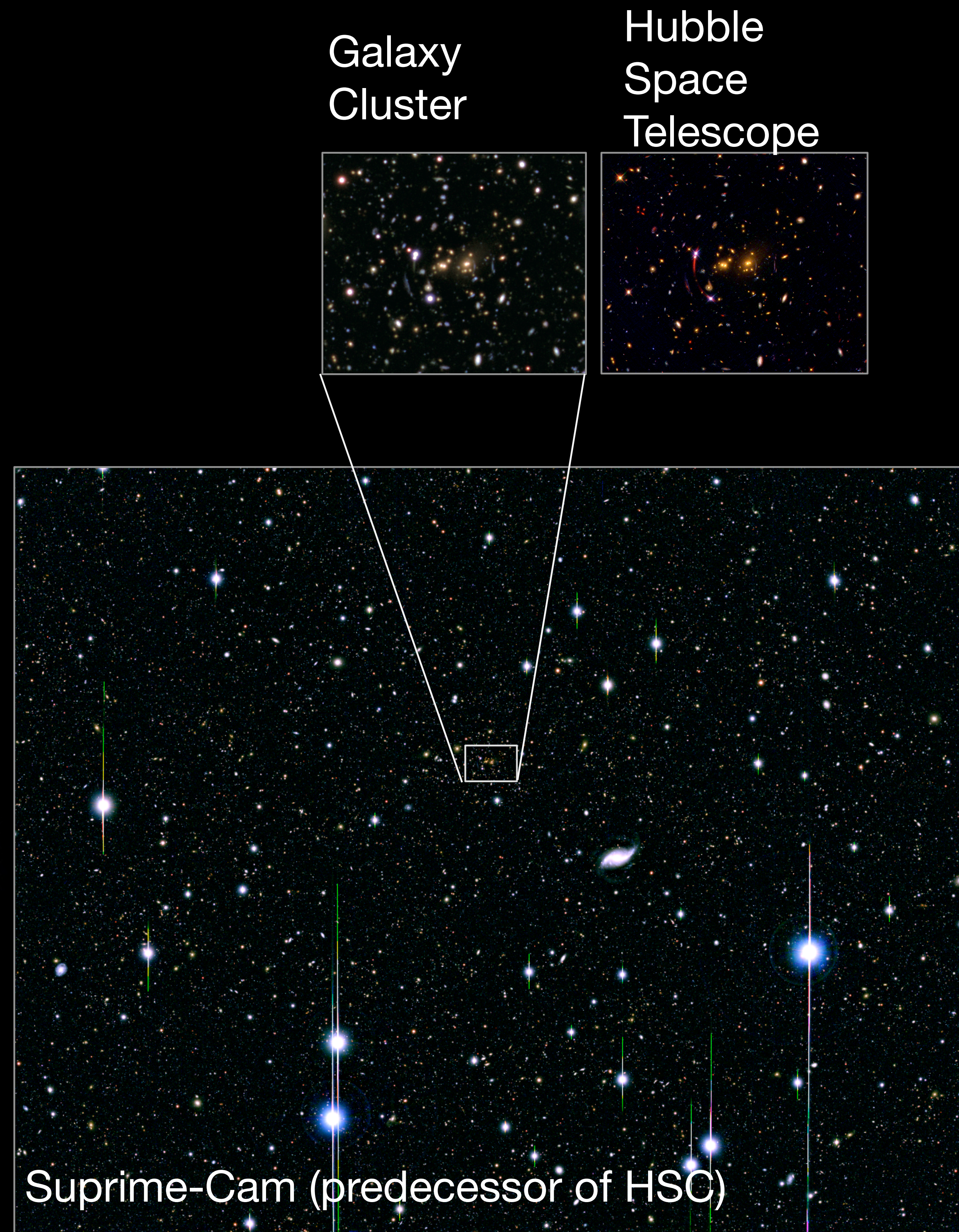

Subaru Telescope
Prime Focus: Wide Field-of-View
8.2m Mirror: Plenty of Galaxies
Adaptive Optics: Superb Image Quality

Hyper Suprime-Cam (HSC)

1 billion pixels
2GB/shot

114 2k x 4k back-illuminated
fully-depleted CCDs
developed by Hamamatsu and NAOJ

Miyazaki et al. (2018a)
Komiyama et al. (2018)

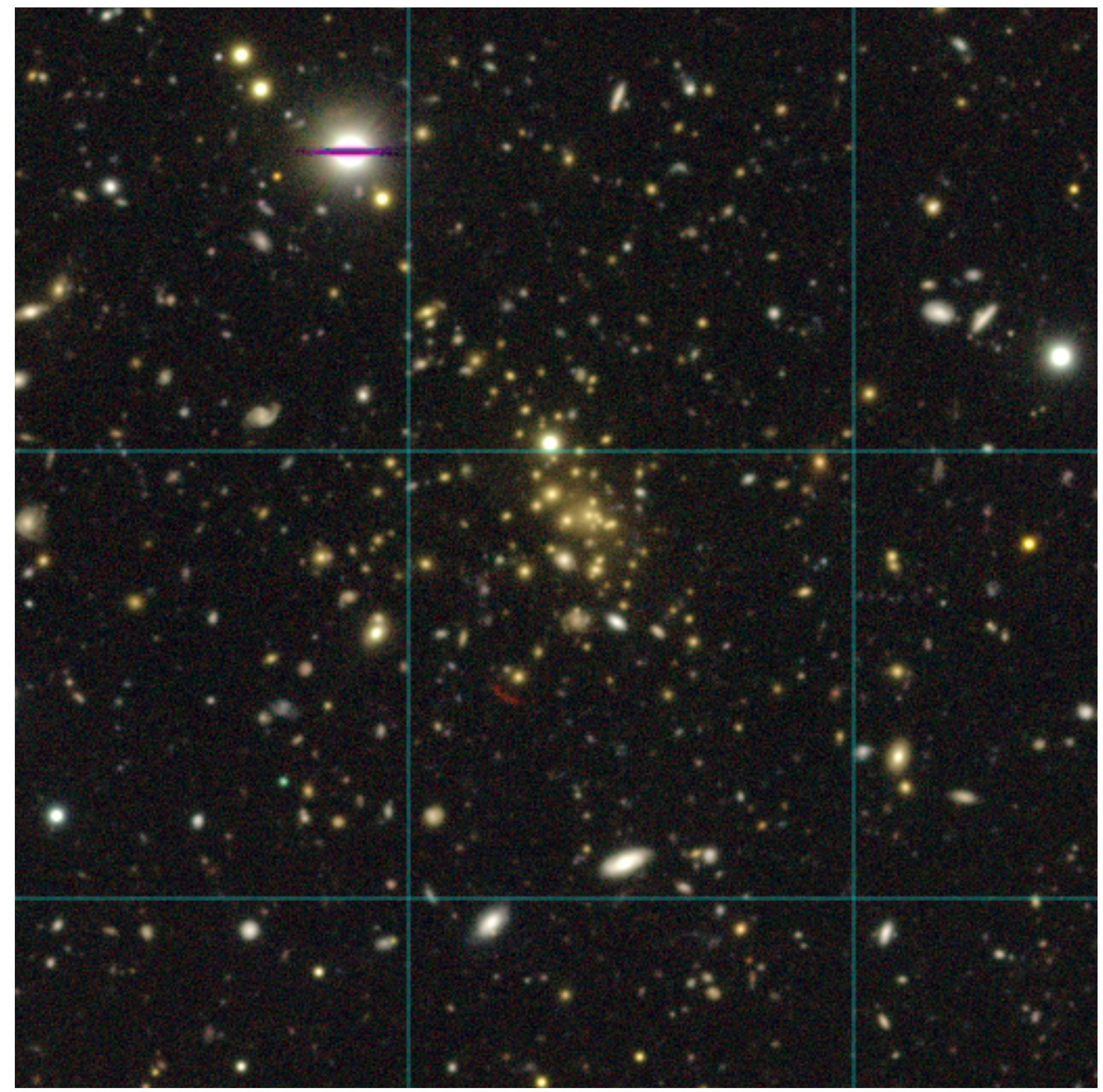

Galaxy Cluster
Hubble Space Telescope
Suprime-Cam (predecessor of HSC)


HSC Field-of-View

A galaxy cluster at z~1 is observed like…

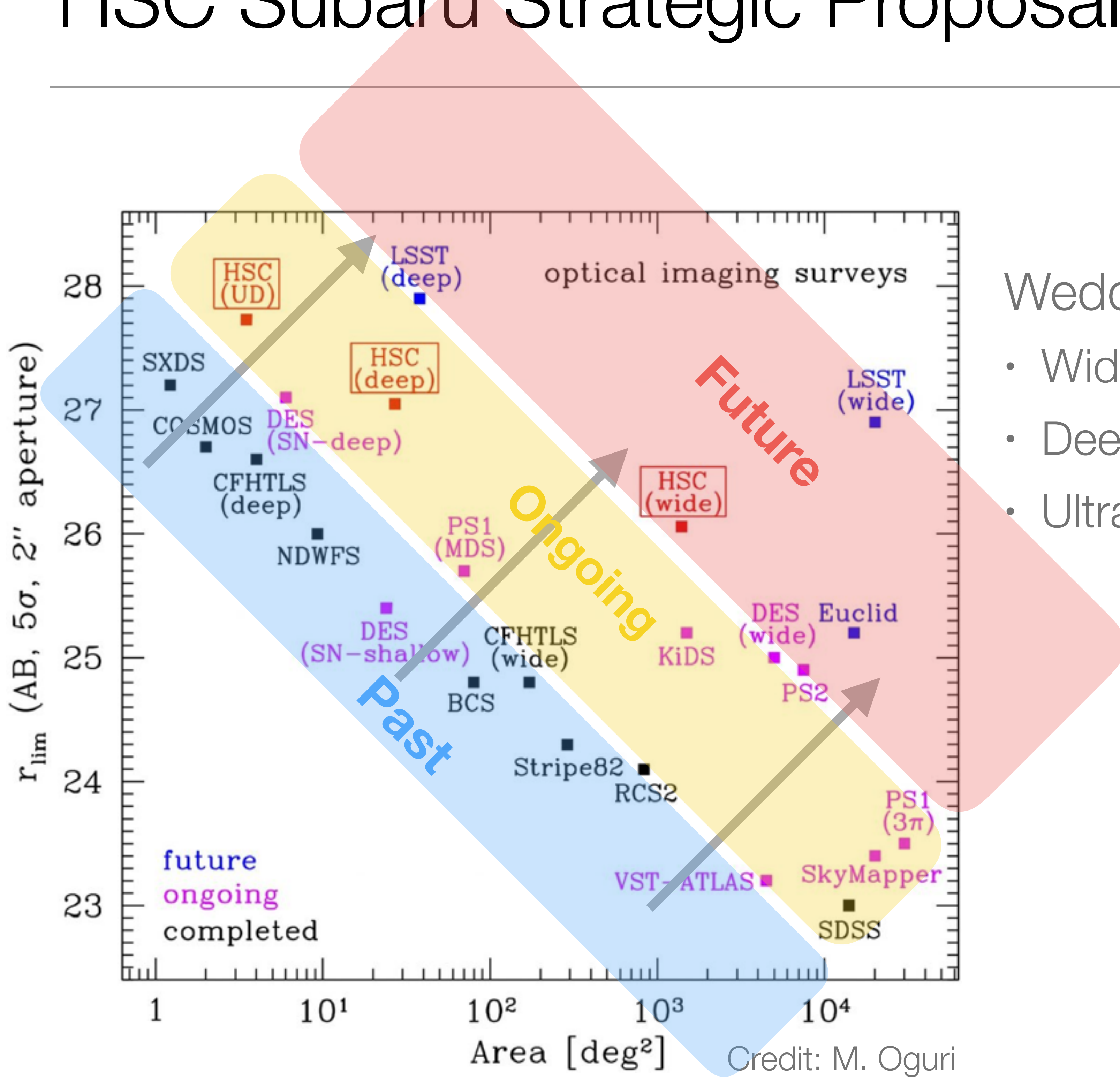
SDSS

HSC



HSC Subaru Strategic Program (SSP) Survey

HSC Subaru Strategic Proposal (SSP) Survey

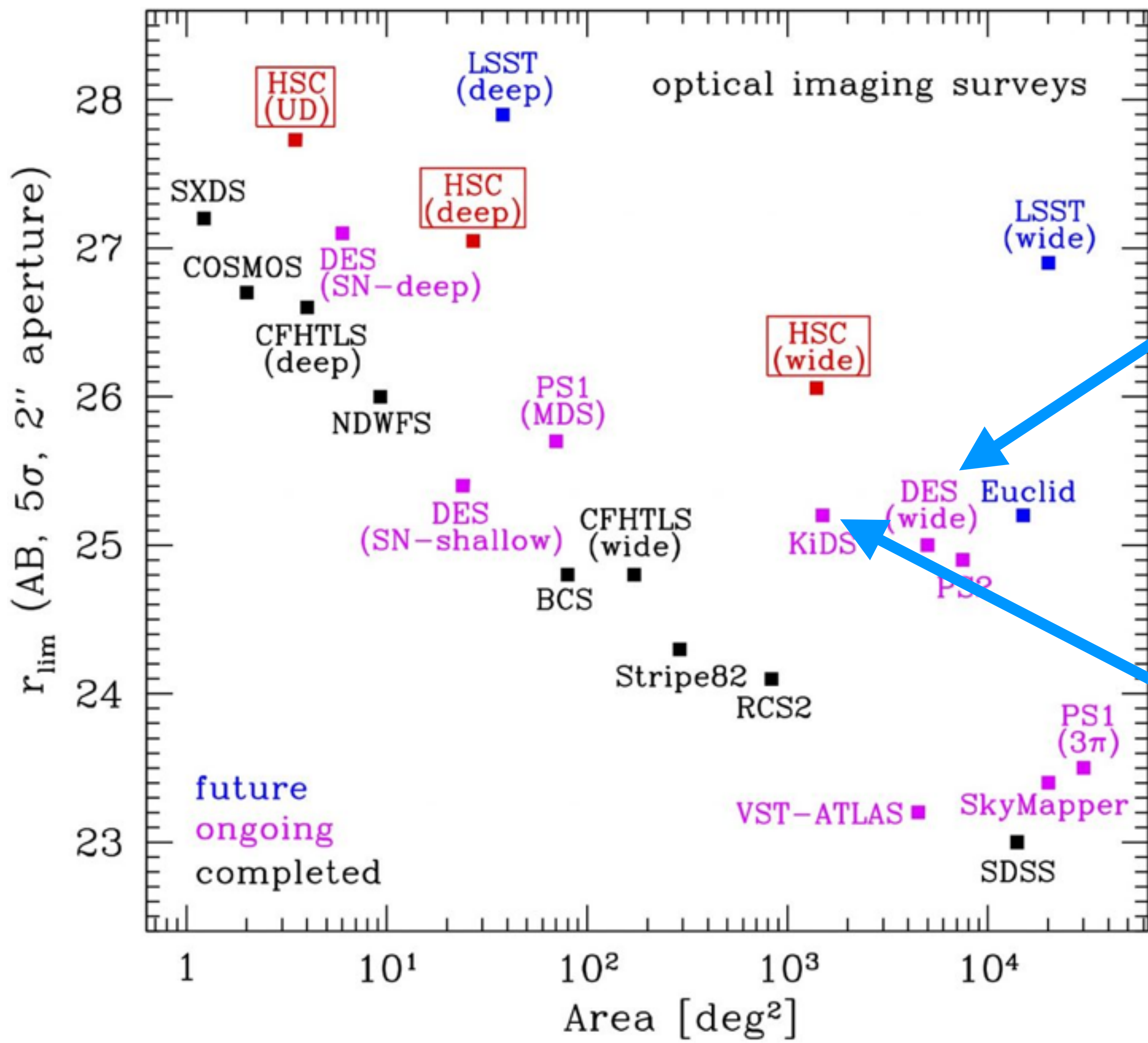


Credit: M. Oguri

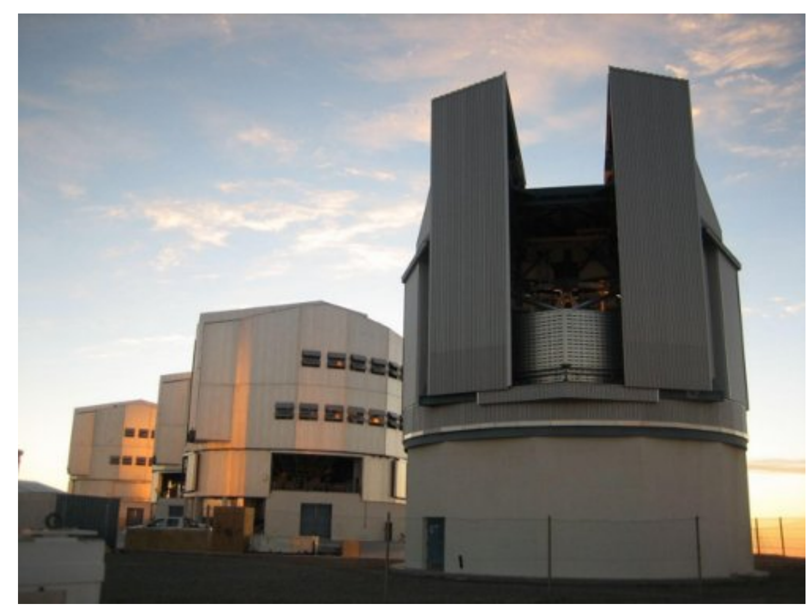
Wedding-cake-type survey

- Wide (1400 deg^2, i_{lim}~26, grizy)
- Deep (28 deg^2, i_{lim}~27, grizy + NBs)
- Ultradeep (3 deg^2, i_{lim}=27.7, grizy + NBs)

Competitors in the World



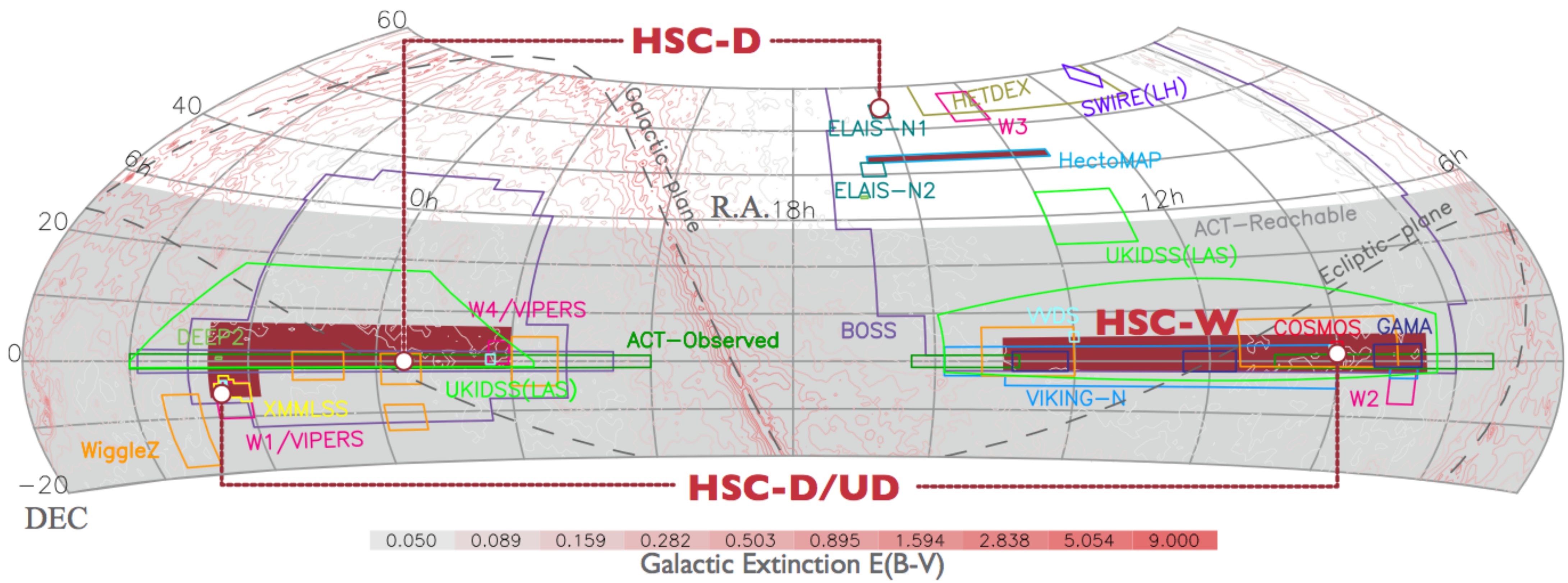
Dark Energy Survey (DES) led by USA
5000 deg^2, i_{lim}~24



Kilo-Degree Survey (KiDS) led by Europe
1500 deg^2, r_{lim}~25

Credit: M. Oguri, Dark Energy Survey

Survey Field



- HSC Survey Fields selected based on overlap with SDSS regions, and other interesting datasets (ACT, PB, VIKING, Spitzer, GAMA, VVDS, etc…)
- Spread along the equator
- For details, see a survey overview paper: Aihara et al. (2018a)

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Matter Density Reconstruction from Observables

Weak lensing shear is measured by averaging **galaxy shapes**

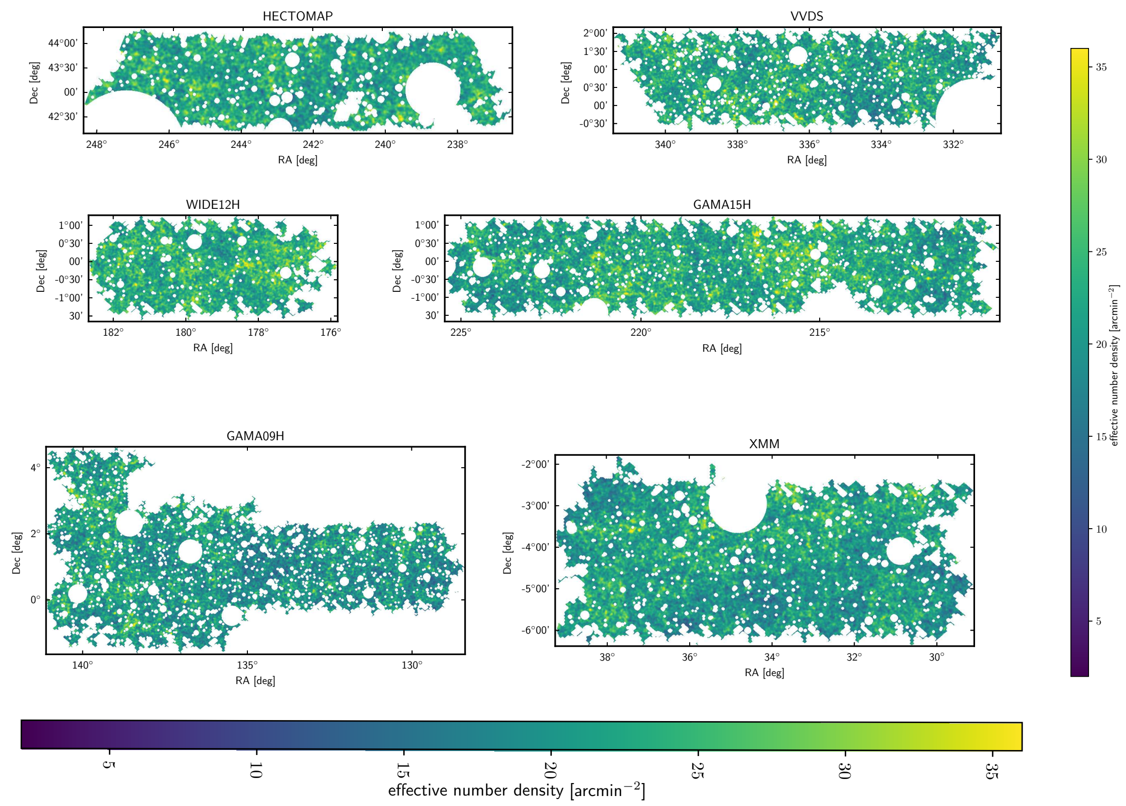
$$\gamma \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

Source galaxy redshift

Matter density fluctuation

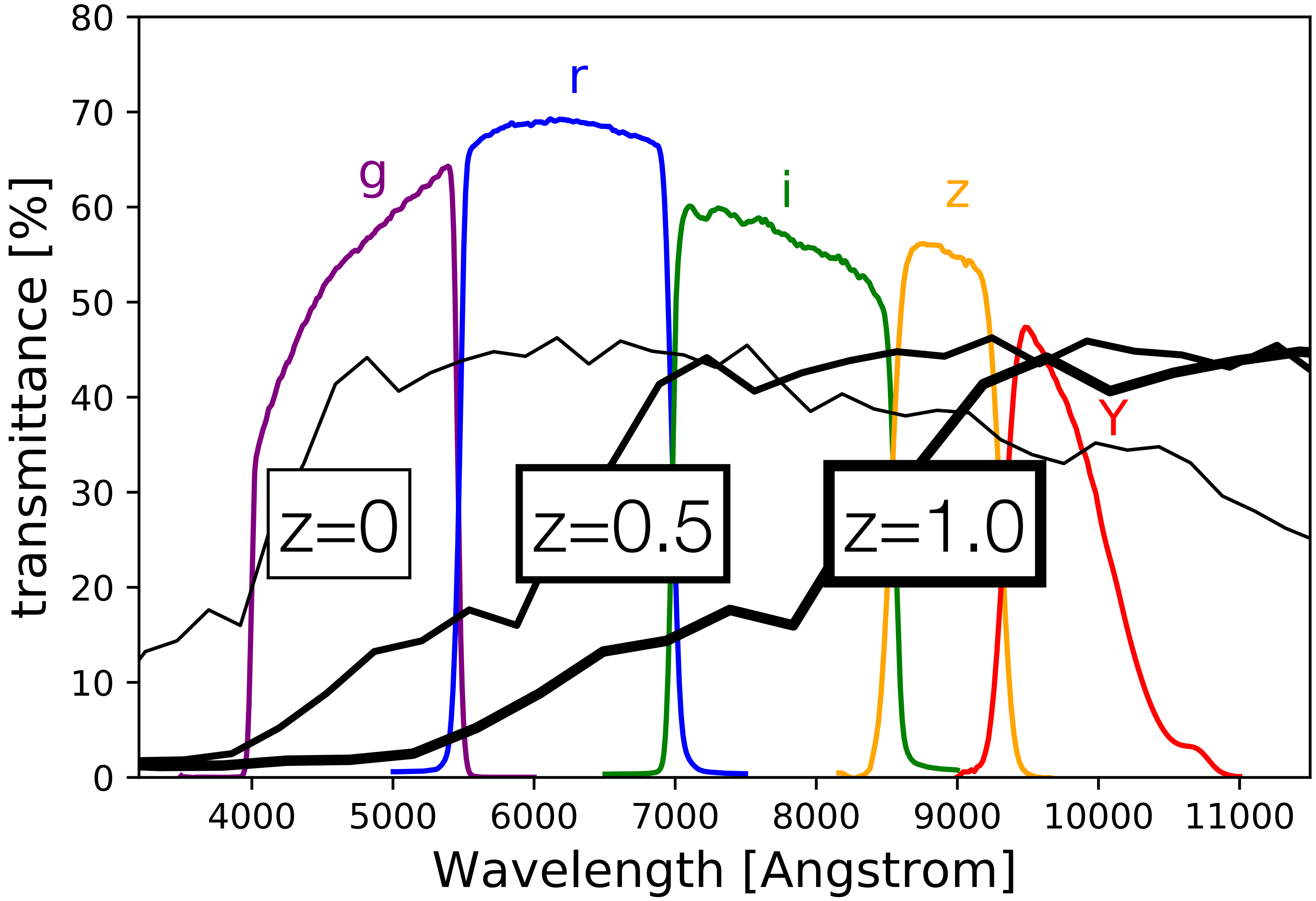
HSC First-year Galaxy Shape Catalog

- WIDE layer: 6 fields, 170deg^2
- Full-depth full-color: i~26 (5σ)
- Excellent seeing: FWHM~0.6”
  (c.f., DES~0.9”, KiDS~0.66”)
- High number density: n_g~23 gal/arcmin^2
  (c.f., DES~7 gal/arcmin^2, KiDS~10 gal/arcmin^2)
- i<24.5, resolution>1/3
- Calibrations based on image simulations.
- Publicly available.



Mandelbaum, HM et al. (2018a)
Mandelbaum et al. (2018b)

Source Galaxy Redshifts



Redshift is estimated from photometric colors (called photo-z)

HSC First-year Science Highlights

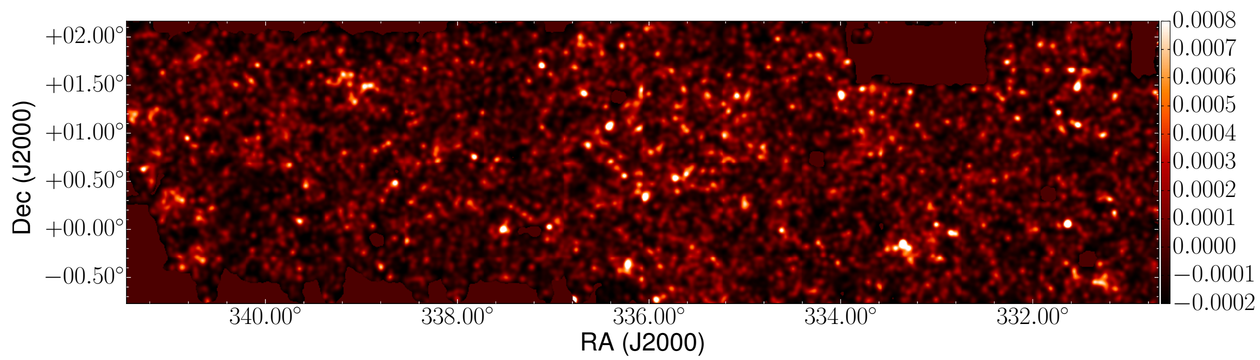
2D and 3D dark matter map

Cosmic shear in Fourier space and real space

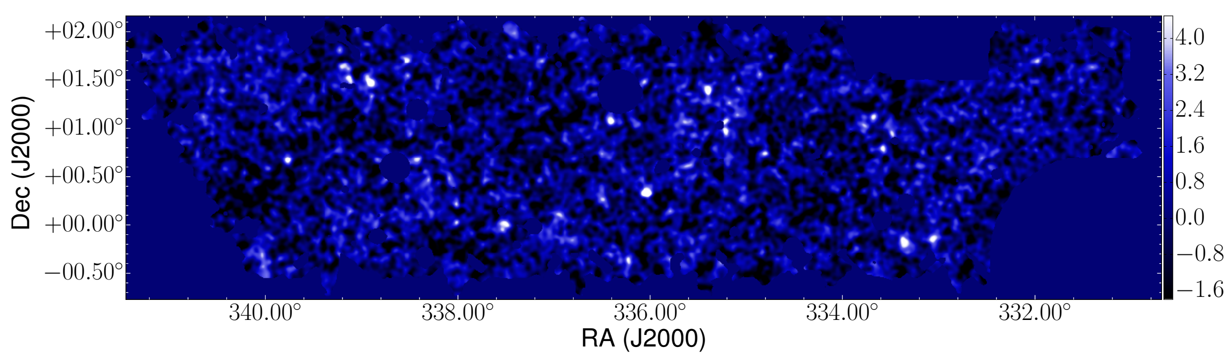
Galaxy-galaxy clustering + lensing

Dark Matter Distributions Reconstructed from WL

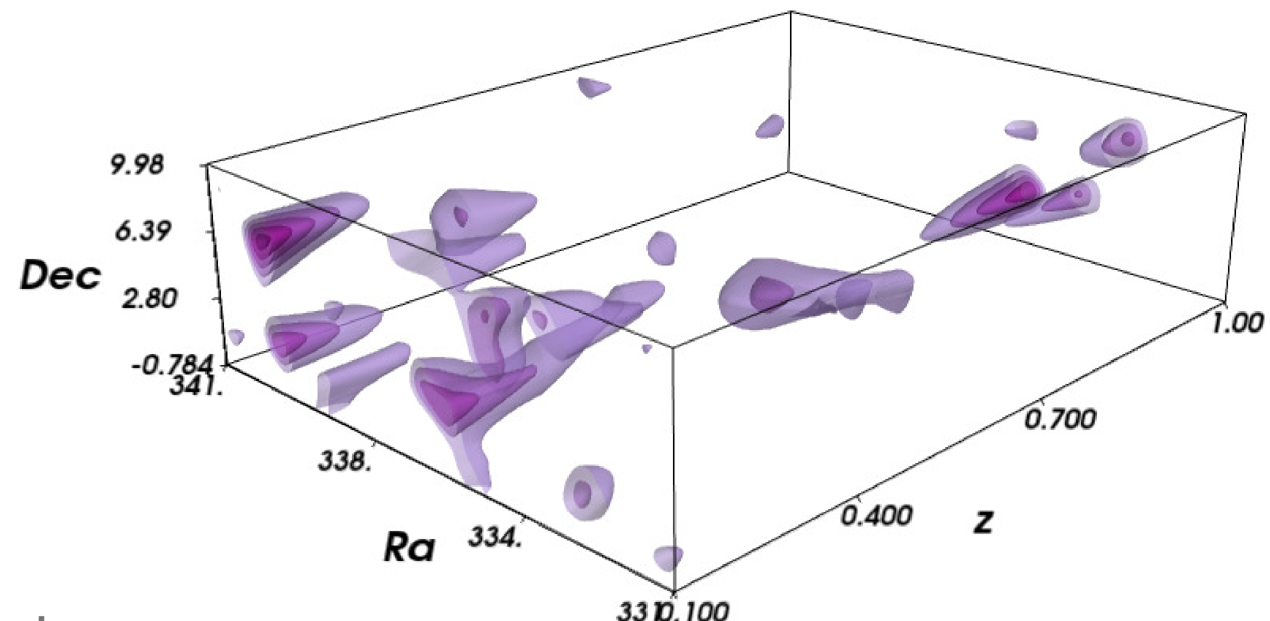
2D galaxy light distribution



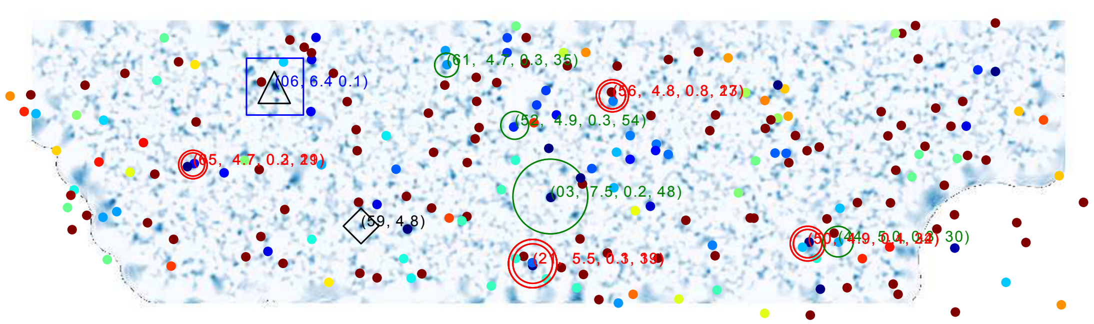
2D dark matter distribution



3D dark matter distributions



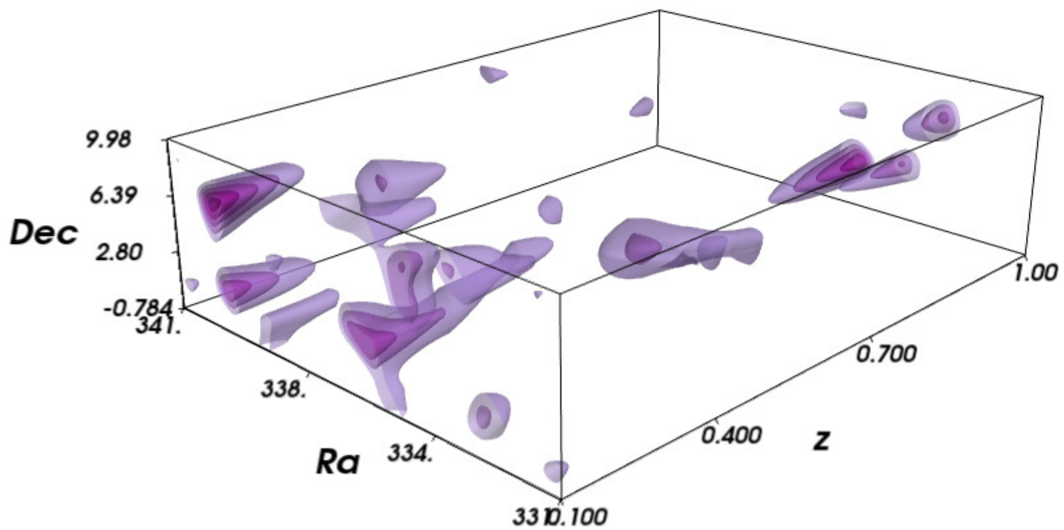
Galaxy clusters selected by dark matter peaks



Oguri et al. (2018), Miyazaki et al. (2018b)

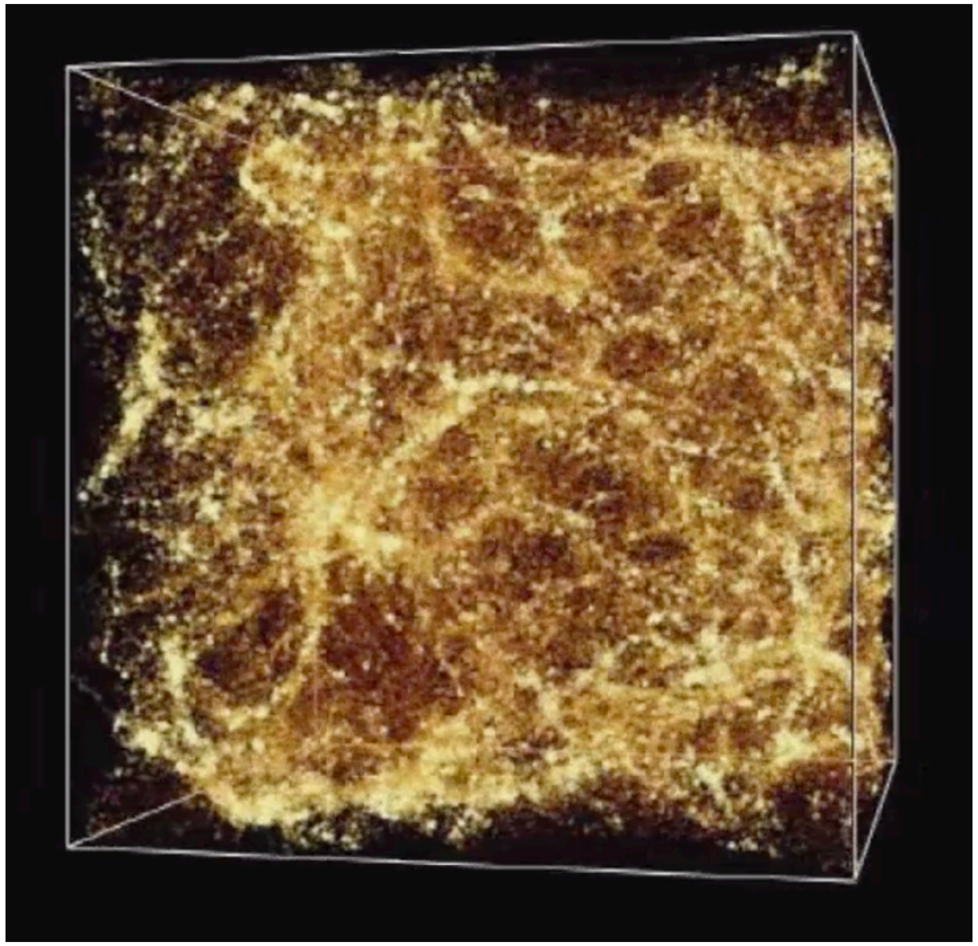
How Can We Compare Observations to Theory?

Observations



Oguri et al. (2018)

Theory

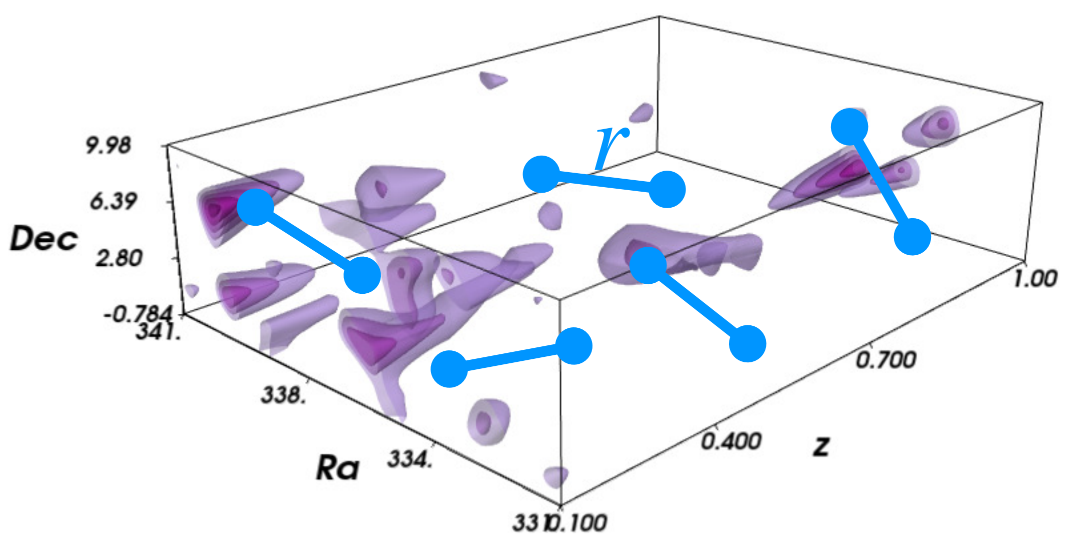


Credit: ESA

Initial condition of large scale structure is from quantum fluctuations. Theories cannot predict where are cluster, galaxies, and dark matter, but **can predict their statistical properties**.

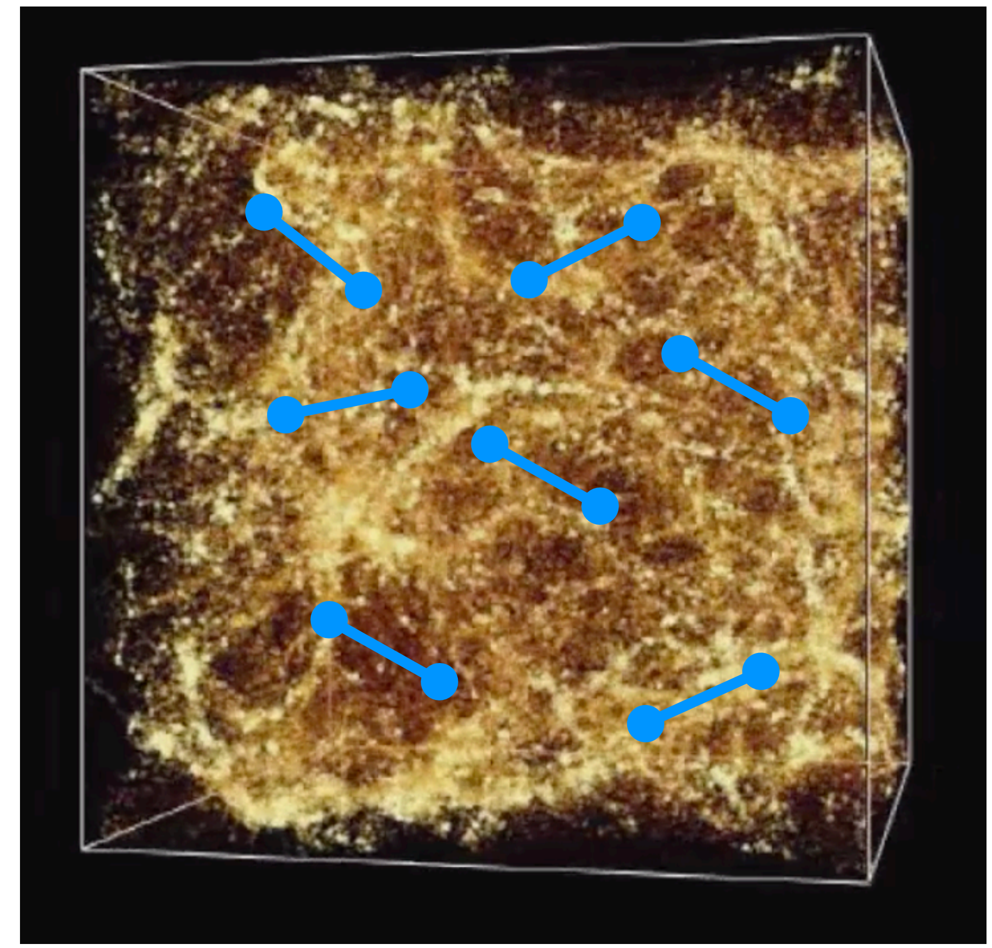
Correlation Function and Power Spectrum

Observations



Oguri et al. (2018)

Theory



Credit: ESA

$$\xi_{mm}(r) = \langle \delta_m(\vec{r}\,')\delta_m(\vec{r}\,' + \vec{r}) \rangle_{\vec{r}\,'}$$

Spatial correlation of matter fluctuations

Cosmological Constraints from Correlation Function

$$\xi_{mm}(r) = \langle \delta_m(\vec{r}')\delta_m(\vec{r}' + \vec{r}) \rangle_{\vec{r}'}$$

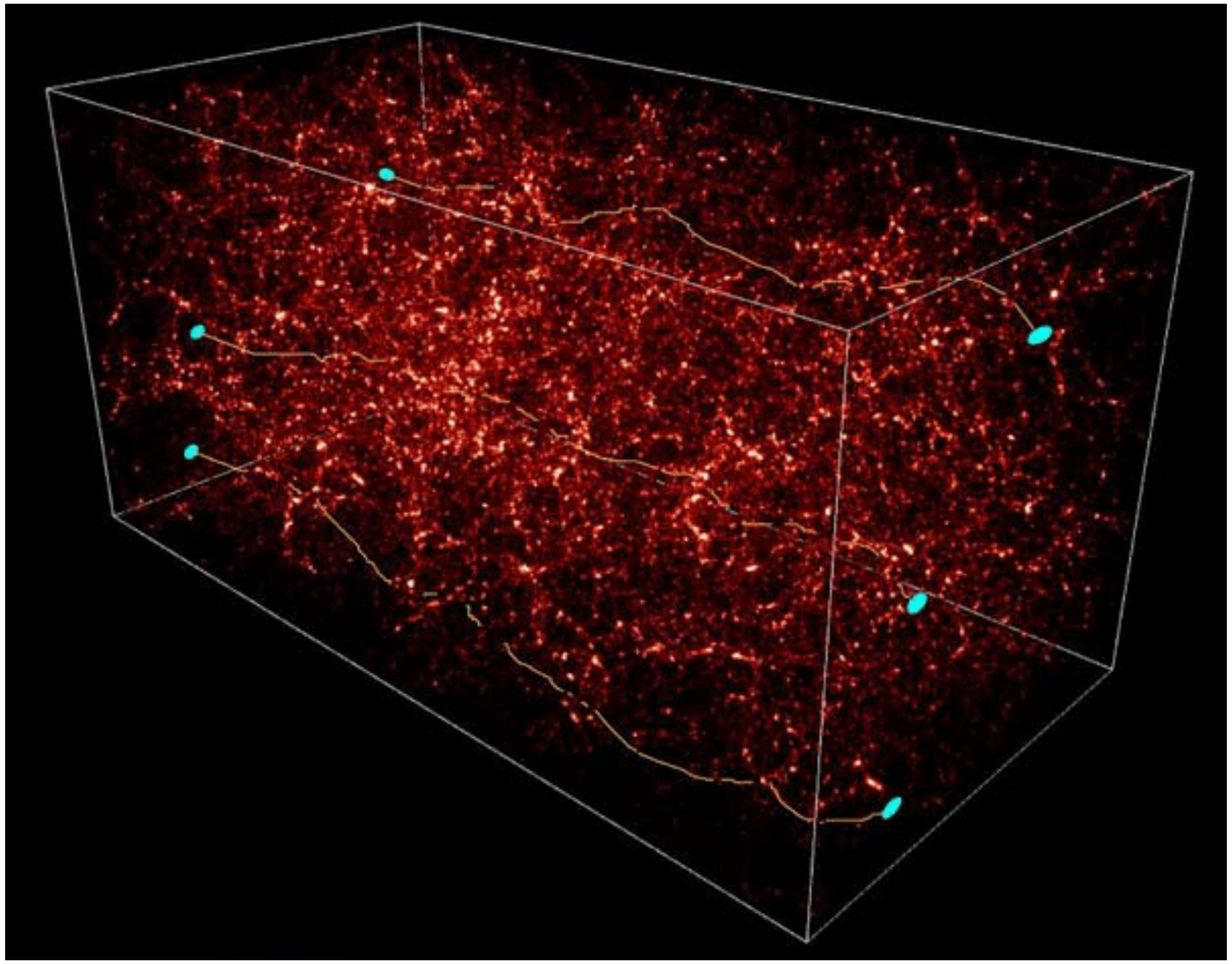
Amplitude of matter fluctuations σ_8

Growth of matter fluctuations $D(z)$

$D(z)$ can be measured by correlation function measurements in redshift slices. $D(z)$ is a function of

- Matter energy density Ω_m
- Dark energy density Ω_Λ , and
- Dark energy equation of state parameter $p = w\rho$.

Cosmological Weak Lensing: **Cosmic Shear**



Cosmic shear can infer matter correlation function.

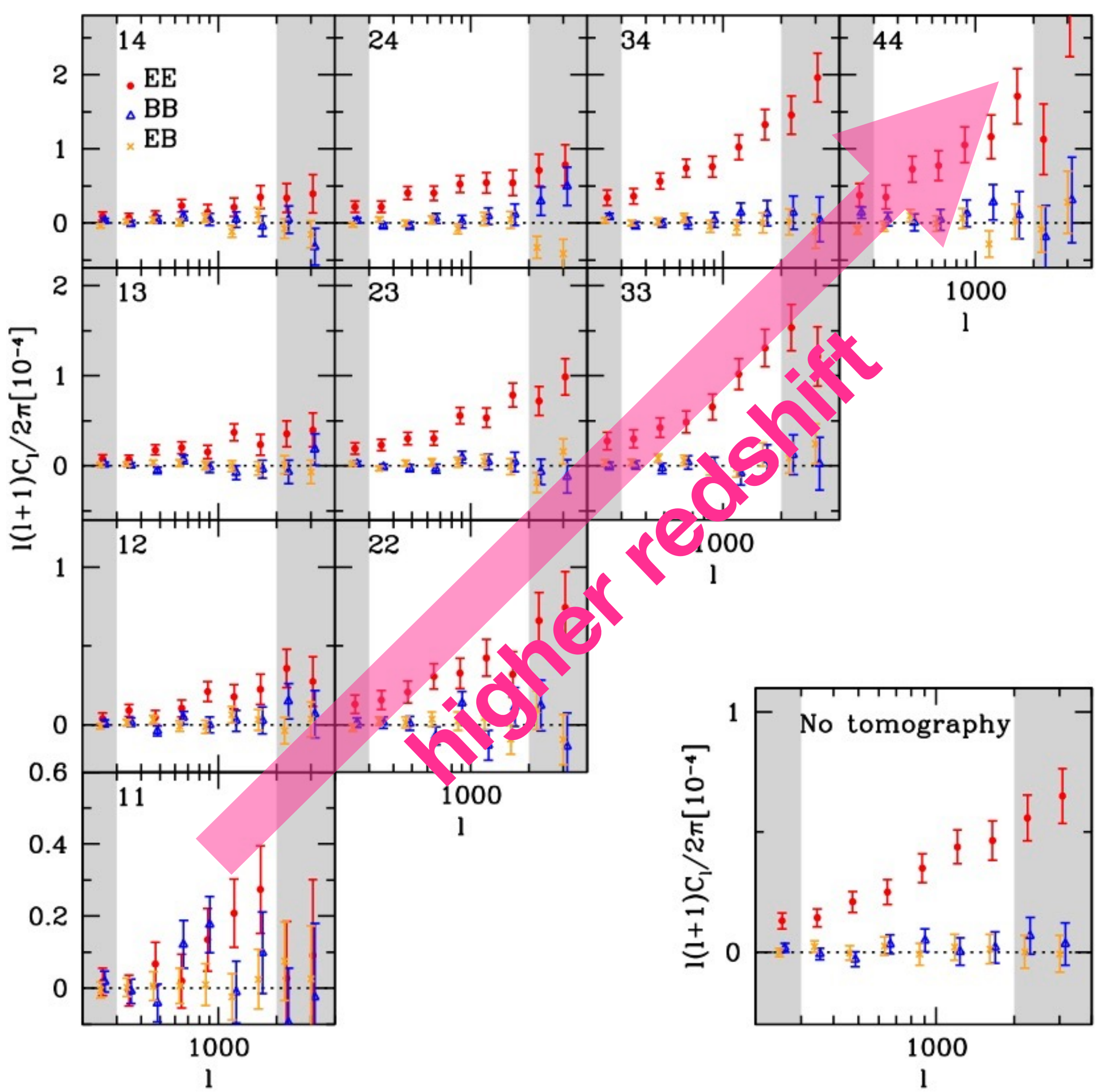
$$\xi_{\gamma\gamma}(r) = \langle \gamma(\vec{r}')\gamma(\vec{r}' + \vec{r}) \rangle_{\vec{r}'}$$

$$\Rightarrow \xi_{mm}(r)$$

Cosmic shear can be measured in **Fourier Space**.

$$\xi_{\gamma\gamma}(r) \Rightarrow C_l^{\gamma\gamma}$$

Cosmic Shear Tomographic **Power Spectra**



bin1: 0.3<z<0.6, bin2: 0.6<z<0.9
bin3: 0.9<z<1.2, bin4: 1.2<z<1.5

4-bin tomography in 0.3 < z < 1.5

Focused on 300 < ℓ < 1900 to avoid potential systematic effects

- high ℓ : baryon feedback
- low ℓ : residual shape noise

S/N of cosmic shear is ~16

BB & EB signals are consistent with zero

Hikage et al. (2019)

Blind Analysis is Essential to Avoid Confirmation Bias

Blind Analysis

Galaxy shapes were changed by multiplying a blinded number.

Our analysis was unblinded when we are confident on systematic tests listed in the table.

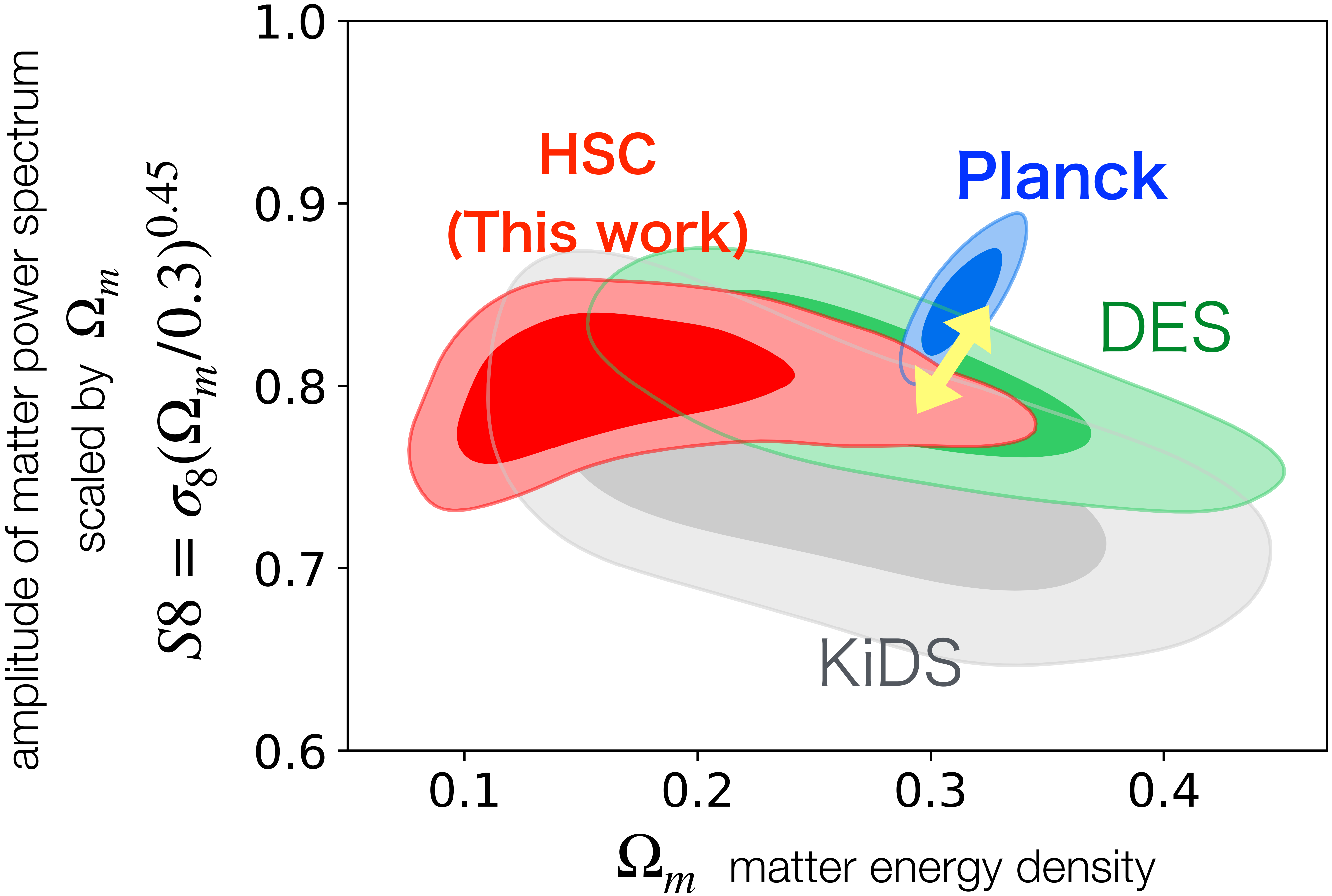
Parameter	symbols	prior
physical dark matter density	$\Omega_c h^2$	flat [0.03,0.7]
physical baryon density	$\Omega_b h^2$	flat [0.019,0.026]
Hubble parameter	h	flat [0.6,0.9]
scalar amplitude on $k = 0.05\mathrm{Mpc}^{-1}$	$\ln(10^{10} A_s)$	flat [1.5,6]
scalar spectral index	n_s	flat [0.87,1.07]
optical depth	τ	*flat [0.01,0.2]*
neutrino mass	$\sum m_\nu$ [eV]	fixed (0)†, fixed (0.06) or flat [0,1]
dark energy EoS parameter	w	fixed (-1)† or flat $[-2, -0.333]$
amplitude of the intrinsic alignment	A_{IA}	flat $[-5, 5]$
redshift dependence of the intrinsic alignment	η_{eff}	flat $[-5, 5]$
baryonic feedback amplitude	A_B	fixed (0)† or flat $[-5, 5]$
PSF leakage	$\tilde{\alpha}$	Gauss $(0.057, 0.018)$
residual PSF model error	$\tilde{\beta}$	Gauss $(-1.22, 0.74)$
uncertainty of multiplicative bias m	$100\Delta m$	Gauss $(0, 1)$
photo-z shift in bin 1	$100\Delta z_1$	Gauss $(0, 2.85)$
photo-z shift in bin 2	$100\Delta z_2$	Gauss $(0, 1.35)$
photo-z shift in bin 3	$100\Delta z_3$	Gauss $(0, 3.83)$
photo-z shift in bin 4	$100\Delta z_4$	Gauss $(0, 3.76)$

Cosmology   Intrinsic alignment   Baryonic effect

PSF modeling error   Photo-z uncertainties

Hikage et al. (2019)

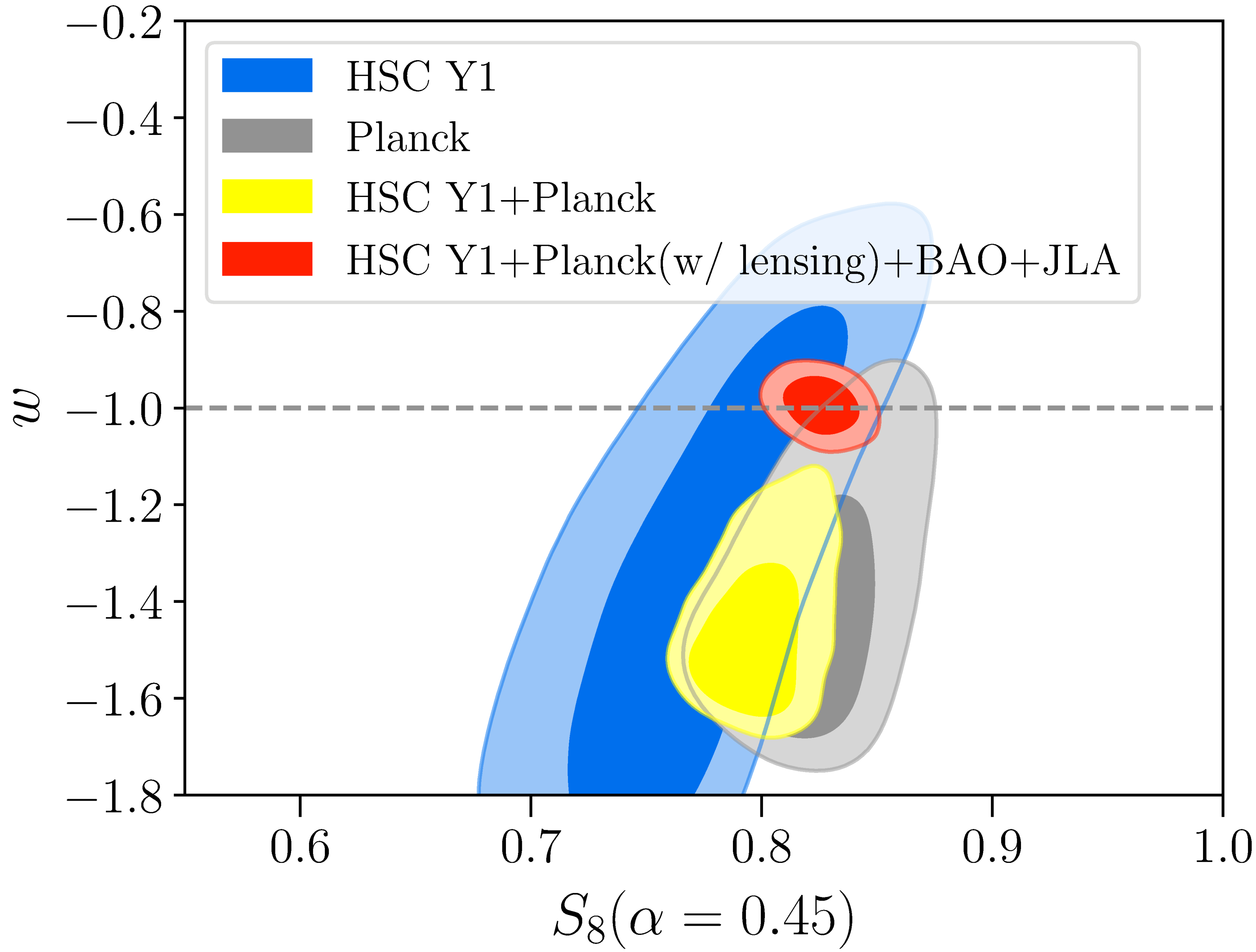
Cosmological Constraint on σ_8 and Ω_m



No significant inconsistency between Planck and HSC

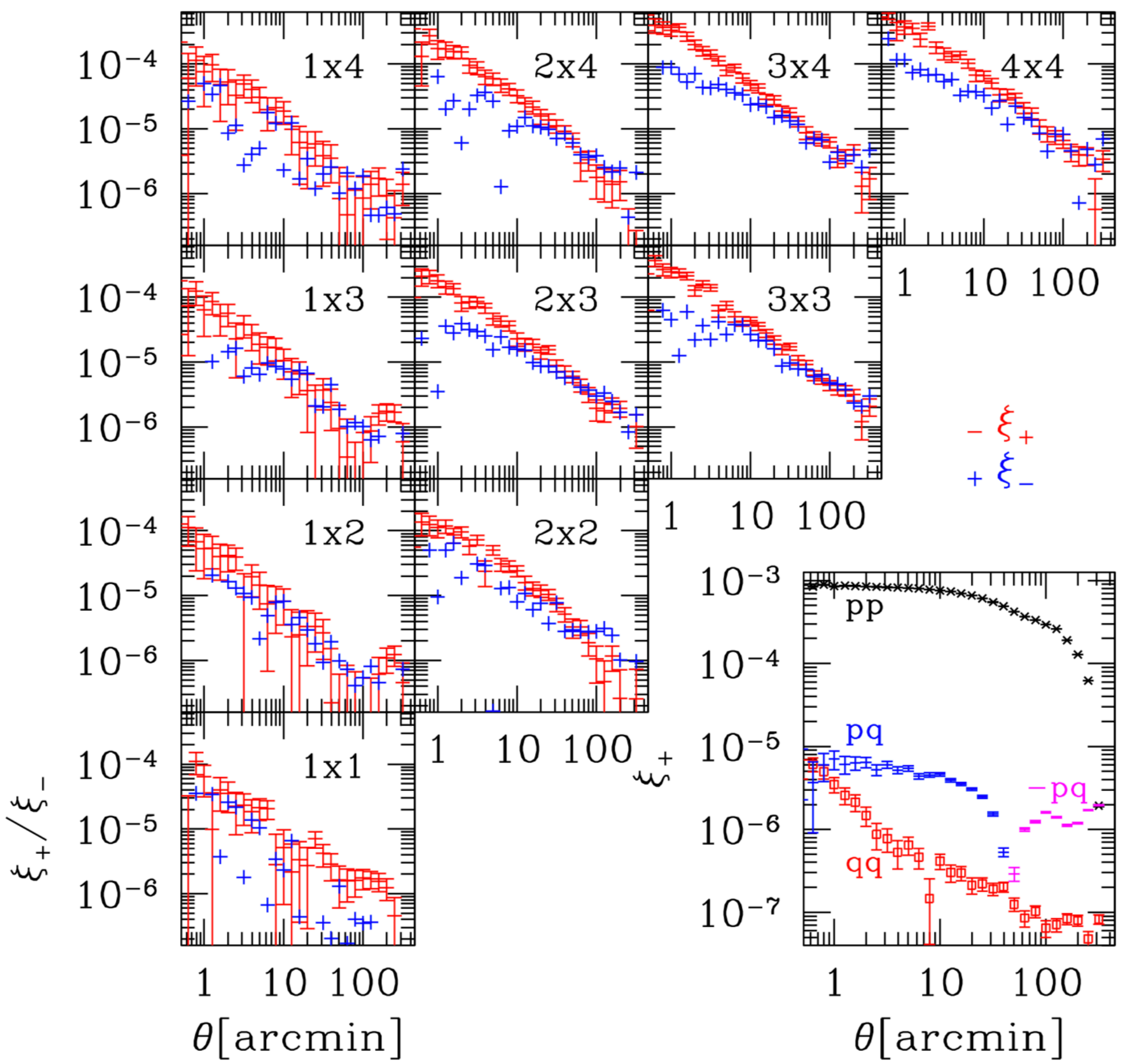
Hikage et al. (2019)

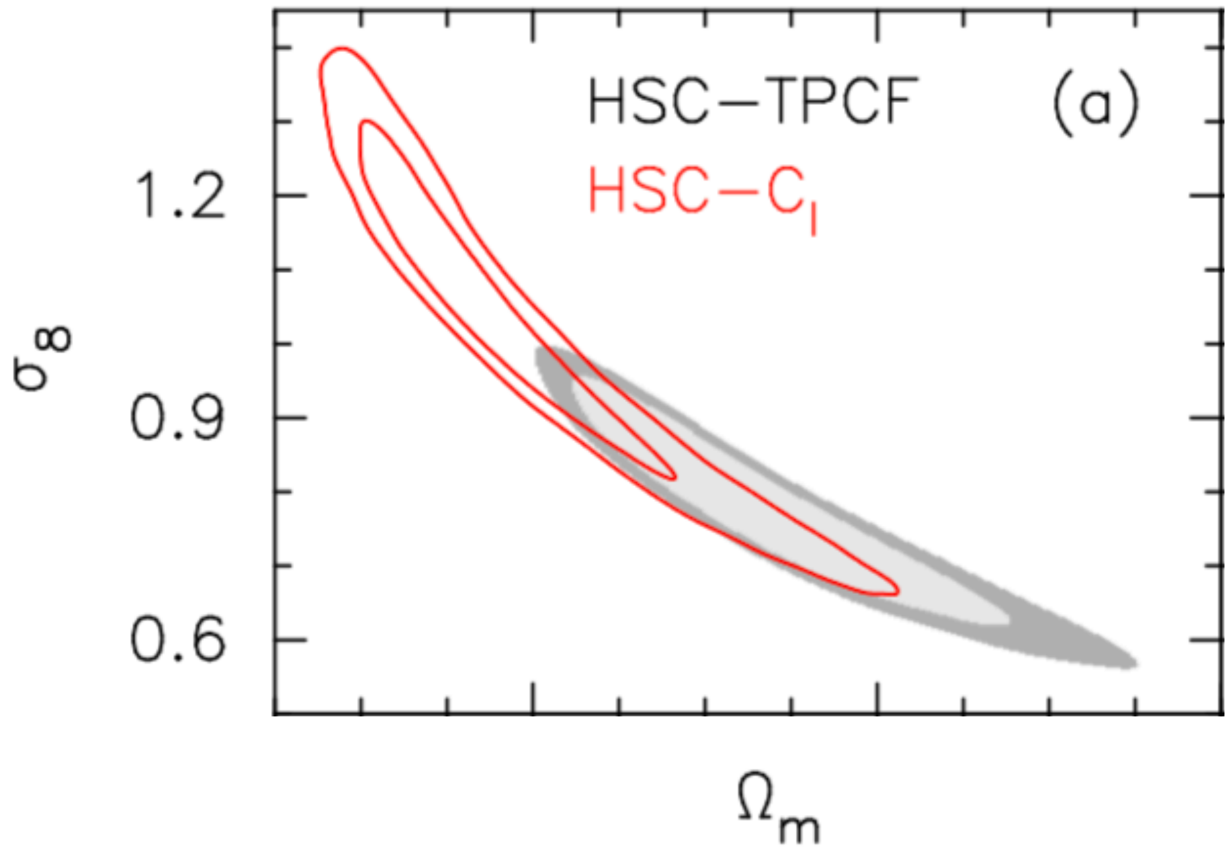
Constraints on the Nature of Dark Energy



The constraint is still weak, but will be more stringent with the full HSC data.

Cosmic Shear Tomographic **Correlation Functions**





Consistent with the power spectra measurement

Hamana et al. (2019)

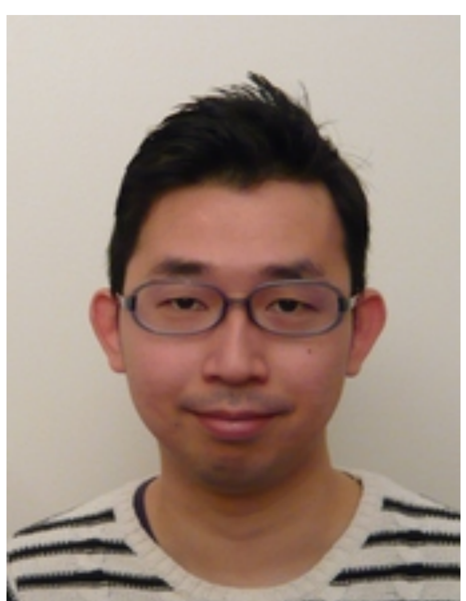
Galaxy-galaxy Lensing x Galaxy-galaxy Clustering

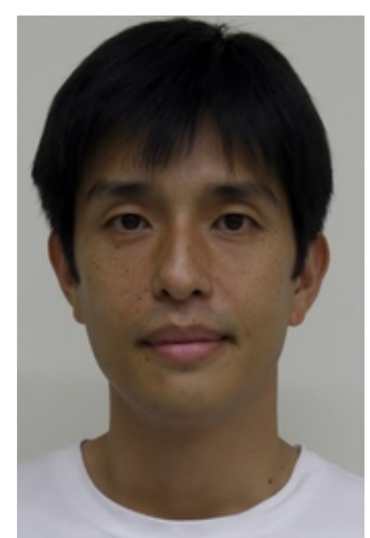
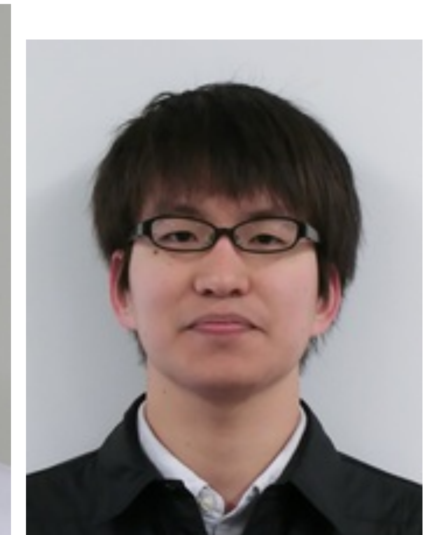
Combine lensing and clustering signals to extract cosmological constraints





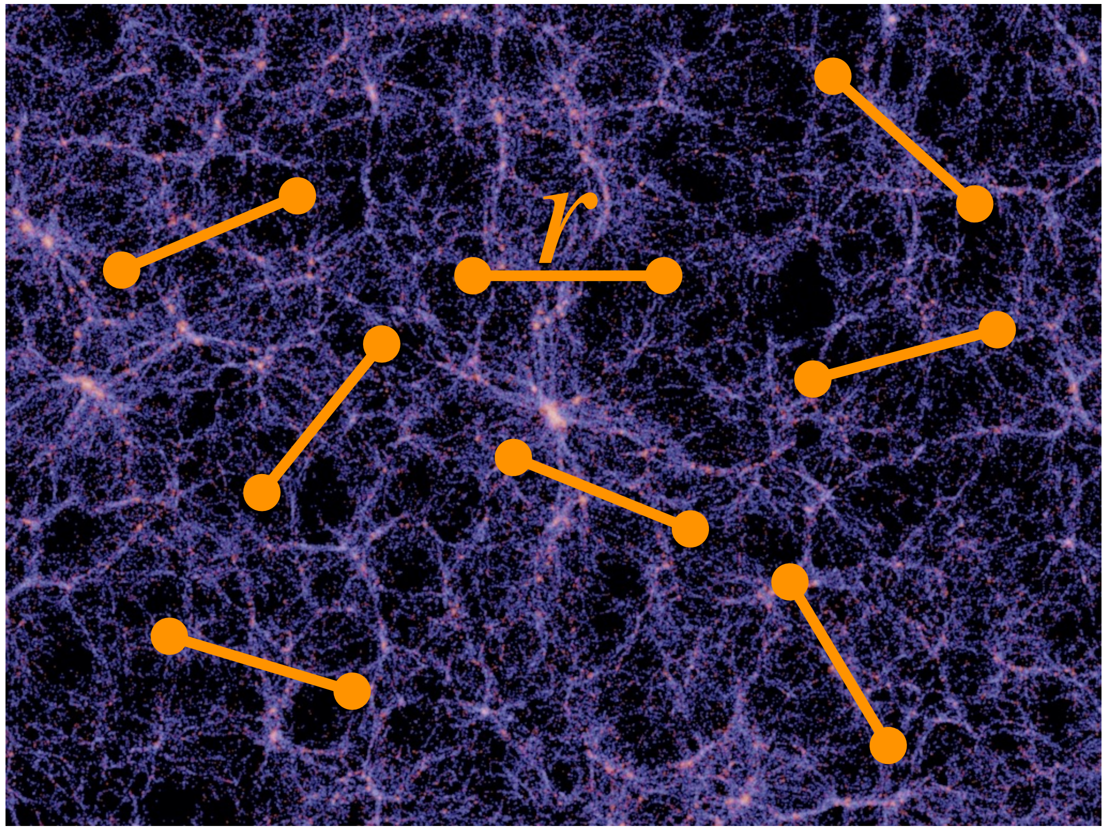





Galaxy-galaxy Clustering Measurement

Galaxy Distribution



$$\xi_{gg}(r) = \langle \delta n_g(\vec{r}\,')\delta n_g(\vec{r}\,' + \vec{r}) \rangle_{\vec{r}\,'}$$

Galaxy galaxy clustering measures how likely a neighboring galaxy exists at distance *r* from a galaxy.

Springel et al. (2005), Croton et al. (2006)

Amplitude of Galaxy-galaxy Clustering Signal

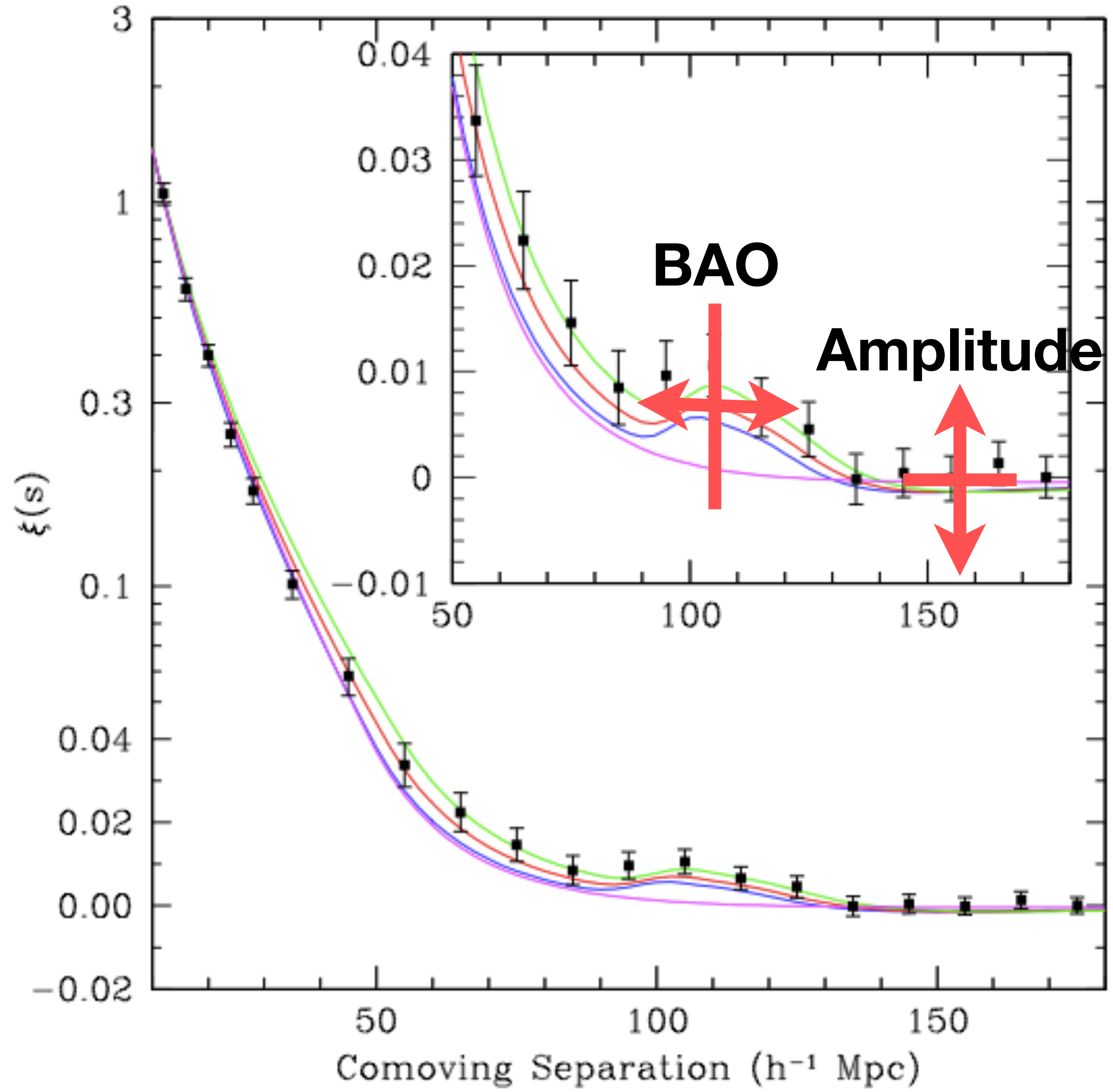
Baryon acoustic oscillations (BAO)

Sensitive to geometry of Universe

Amplitude of g-g clustering signal

Sensitive to Growth of structure, e.g., σ_8

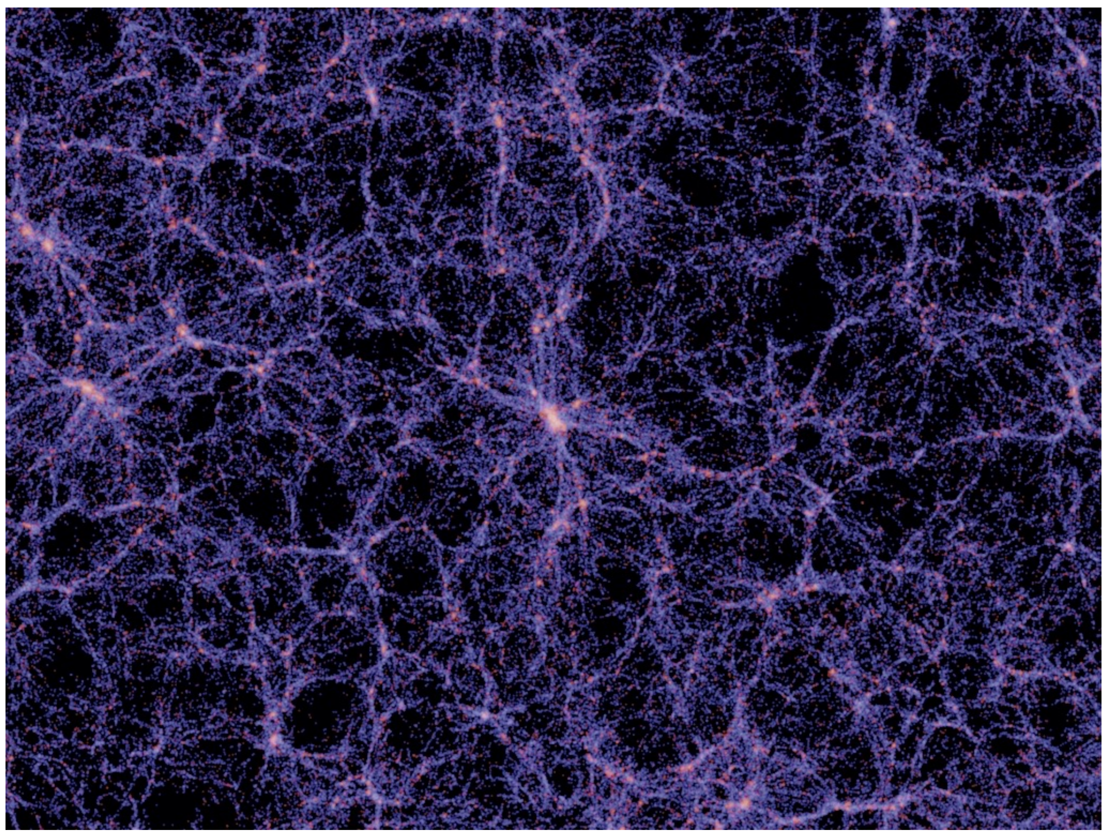
More signal-to-noise compared to BAO



Eisenstein et al. (2005)

Galaxies: Biased Tracer of Dark Matter

Galaxy Distribution



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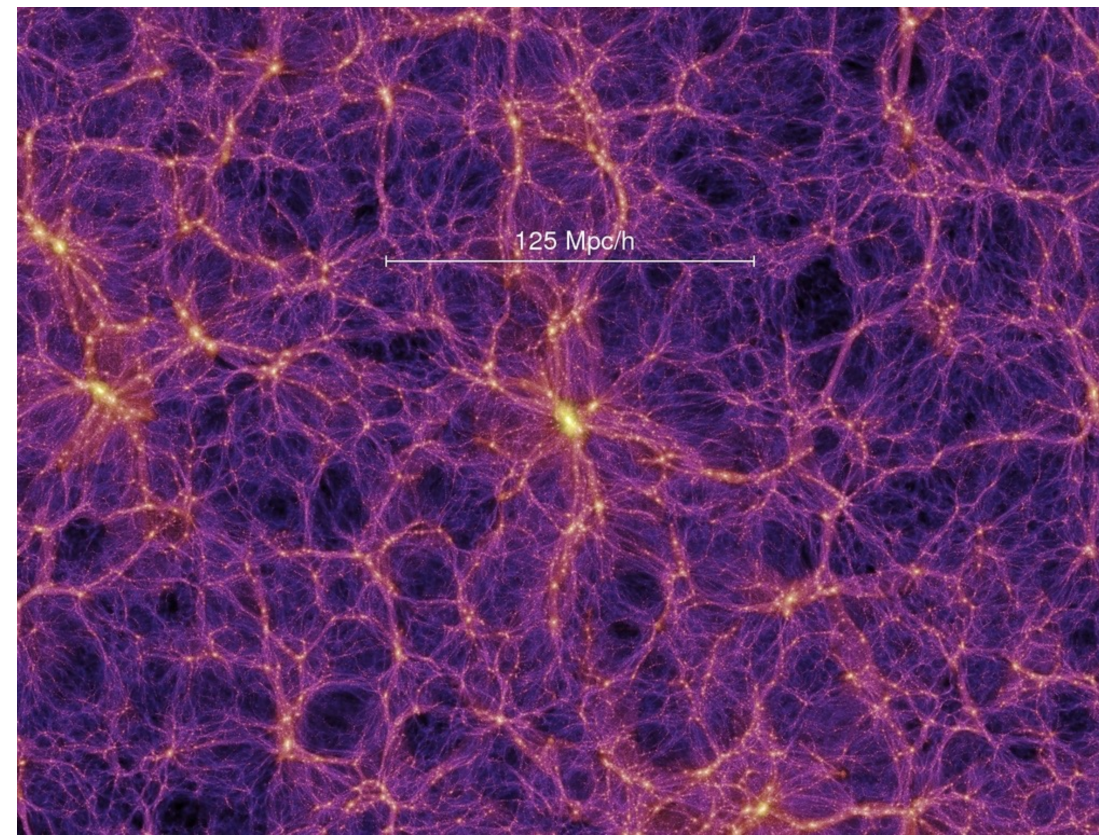
Dark Matter Distribution

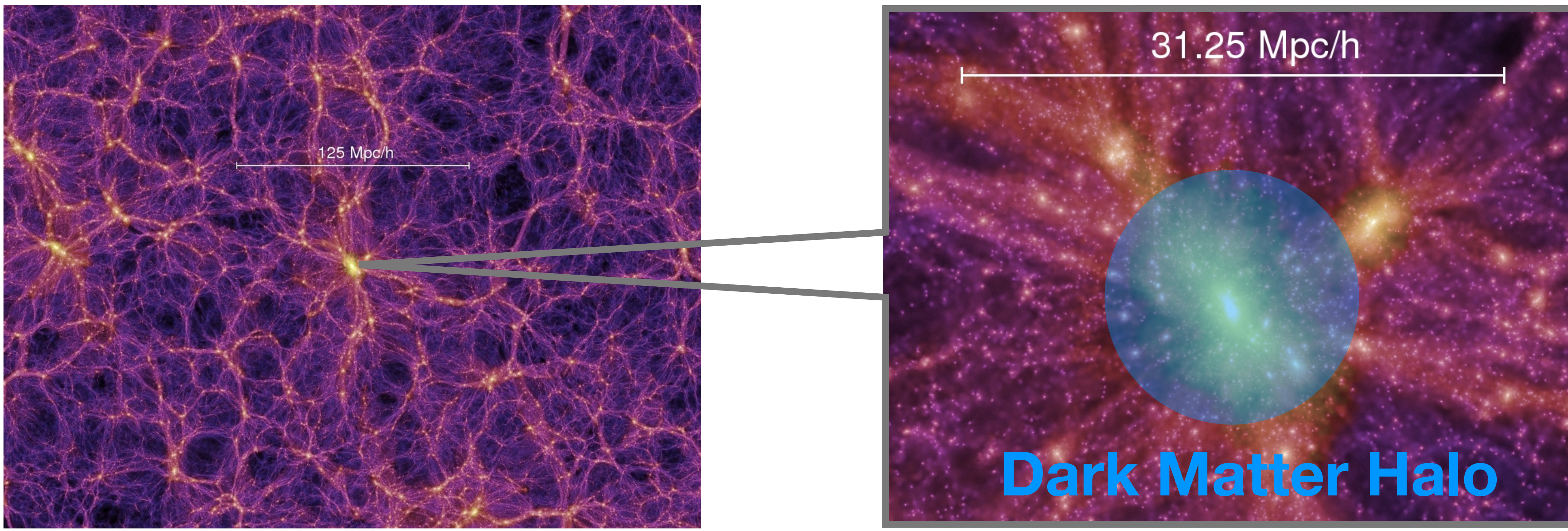


Since most of matter in the Universe is dark matter, we need to use dark matter distribution to extract cosmological information. Galaxy distribution cannot be directly used.

Springel et al. (2005), Croton et al. (2006)

How Does Galaxies Populate the Universe?

Dark Matter Distribution



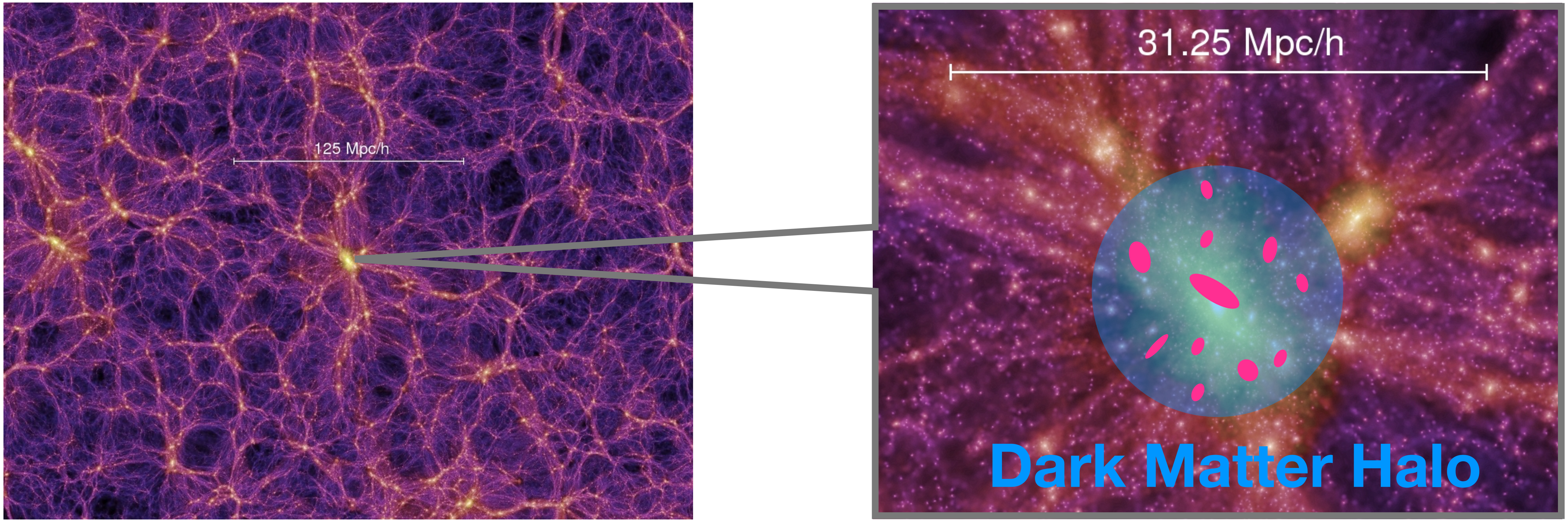
Dark matter collapses into **dark matter halos**.

Self-gravitating systems of dark matter

Springel et al. (2005), Croton et al. (2006)

How Does Galaxies Populate the Universe?

Dark Matter Distribution



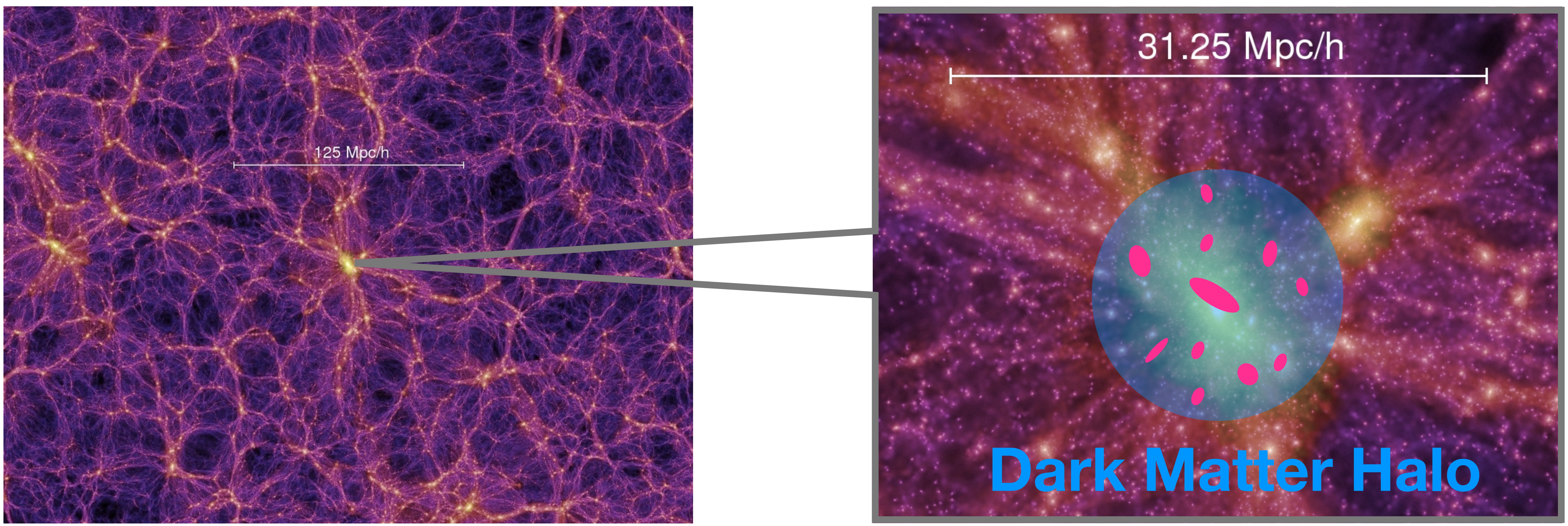
Dark matter collapses into **dark matter halos**.

Galaxies are formed in halos as a result of gas accretion.

Springel et al. (2005), Croton et al. (2006)

Calibration by Galaxy-galaxy Weak Lensing

Dark Matter Distribution



Dark matter halos are **the biased tracer** of the underlying dark matter distribution.

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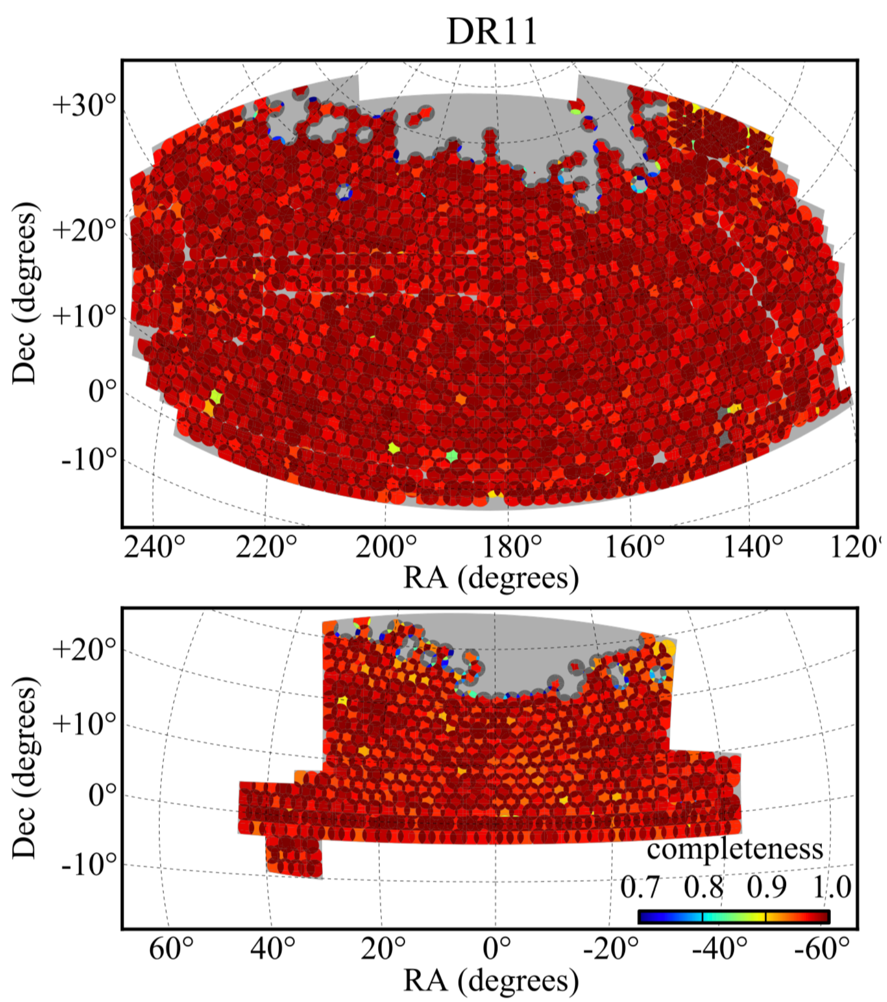
Weak lensing measurement around galaxies (= average dark matter distributions around galaxies) can be used to calibrate the connection between them.

Springel et al. (2005), Croton et al. (2006)

HSC x BOSS Measurement

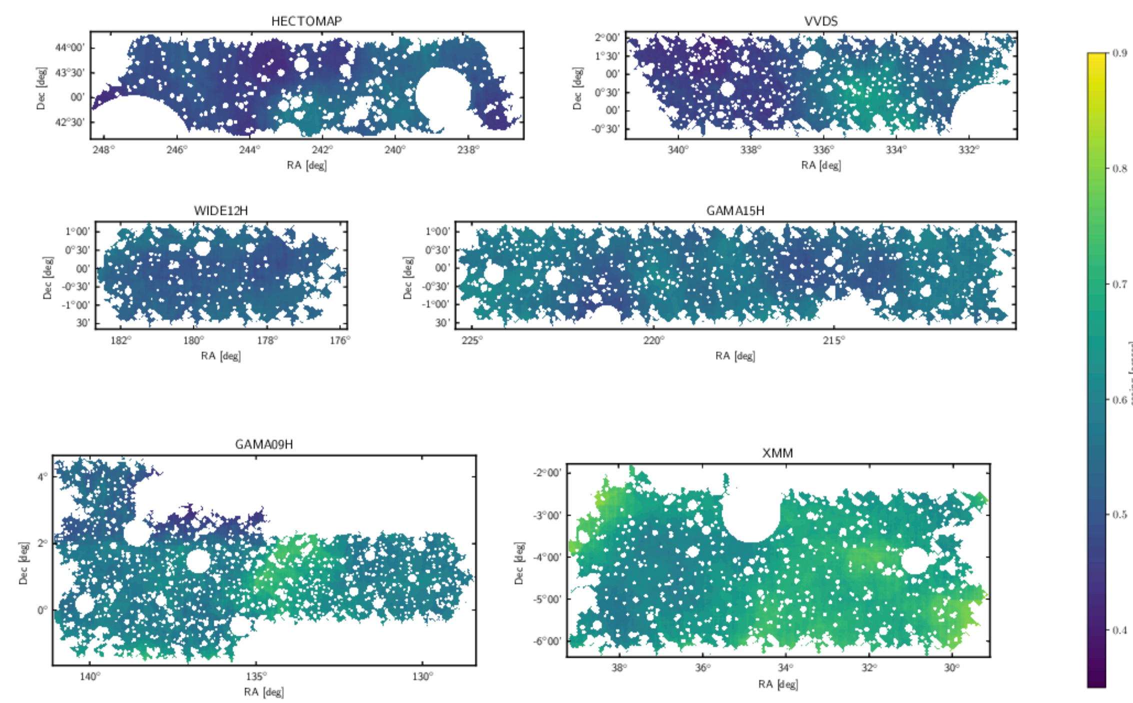
SDSS-III/BOSS DR11 spec-z sample

- ~8300 deg^2
- z = [0.15, 0.35], [0.47, 0.55], [0.55, 0.70]
- Luminosity cut is applied to obtain volume-limited sample.



HSC first-year shape catalog

- 137 deg^2, <z>~1.0
- Galaxy shape catalog is blinded

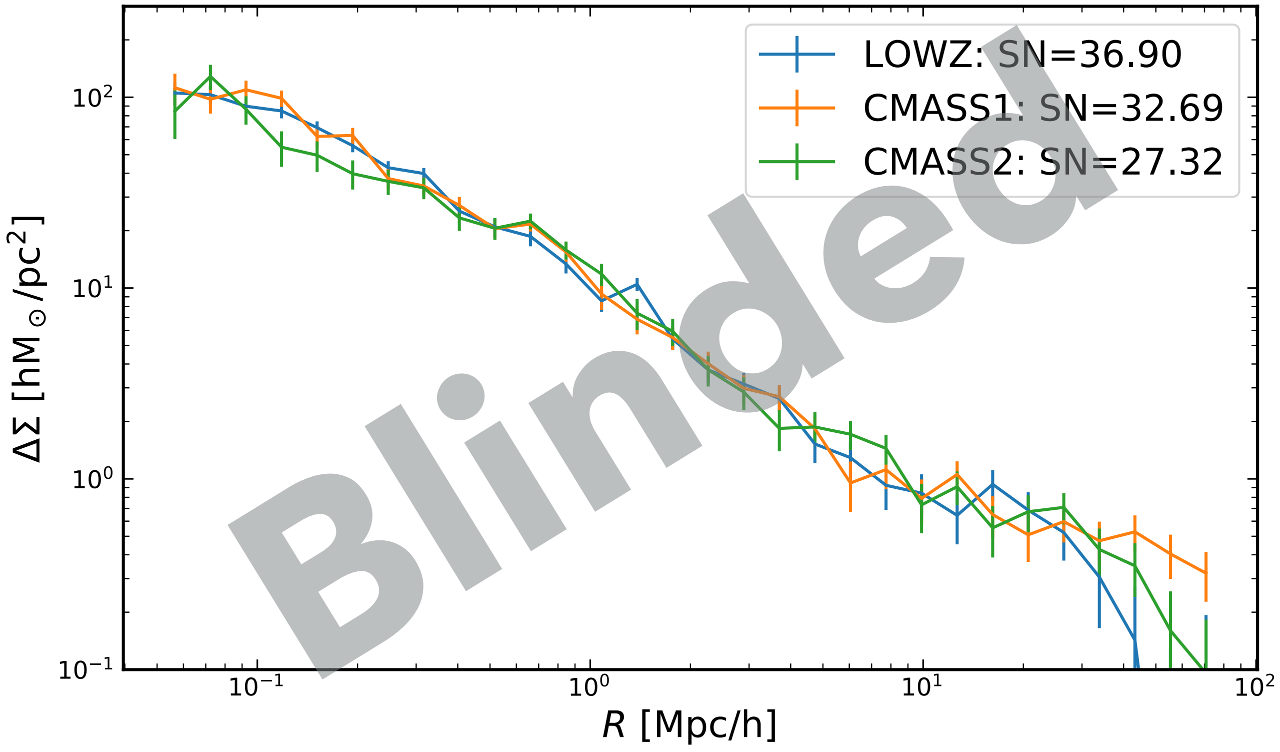


g-g lensing signal

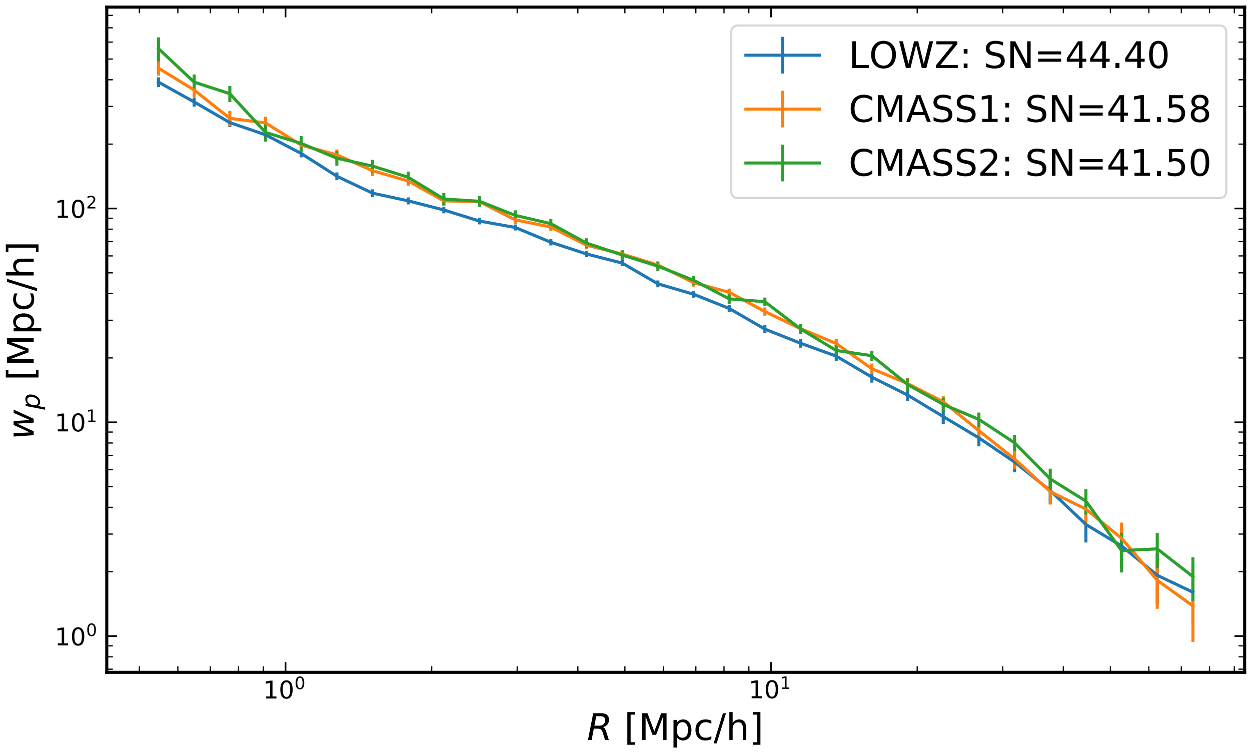
g-g clustering signal

Measurements

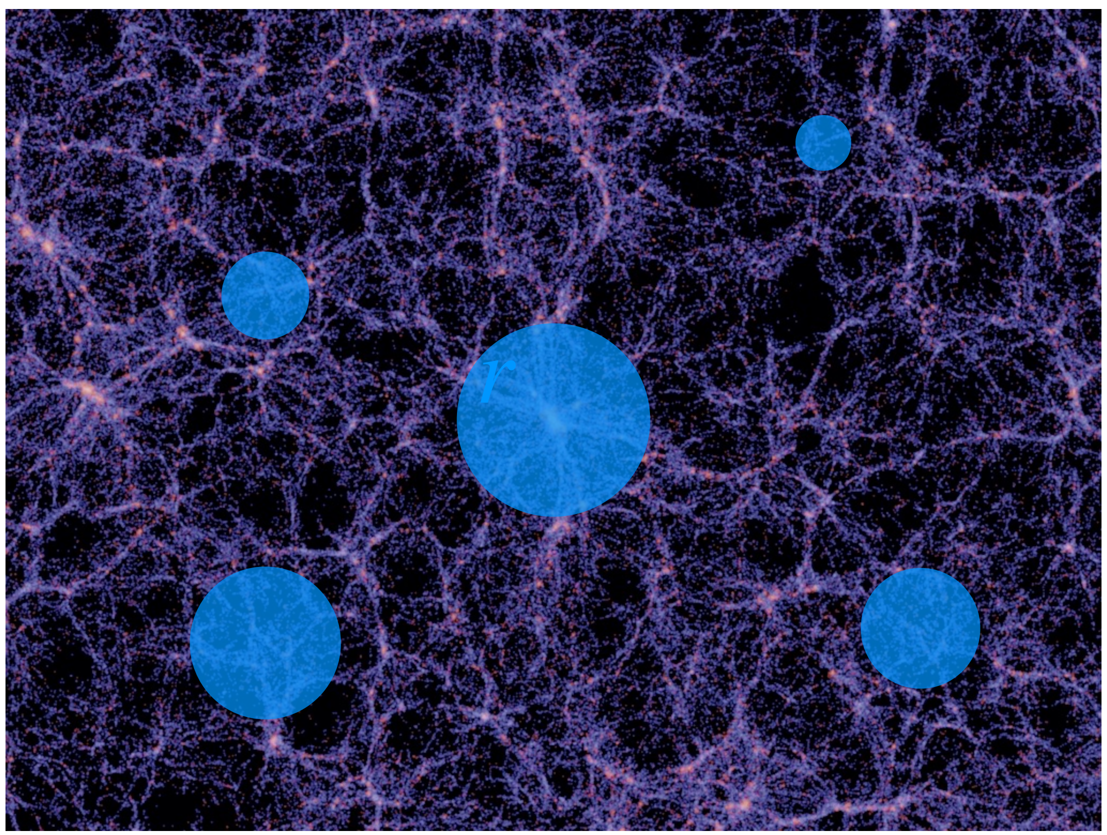
g-g lensing



g-g clustering



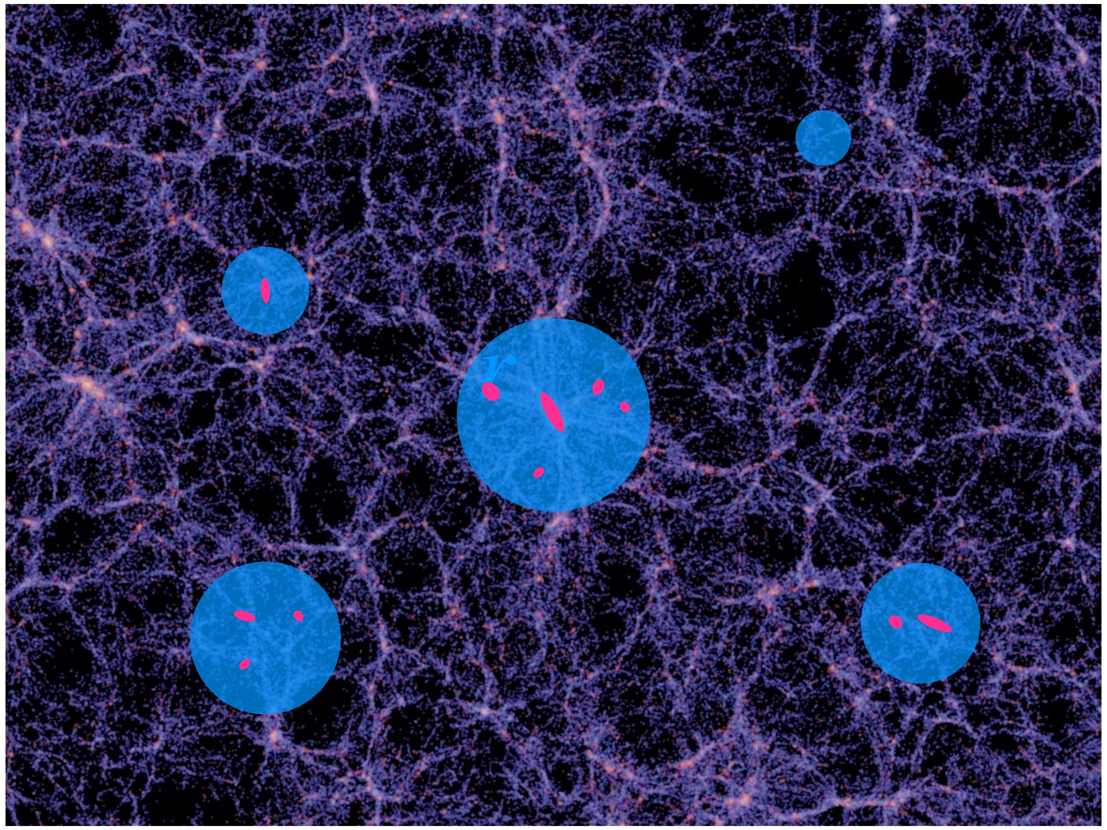
Modeling Lensing Signal



Cross-correlation function of **dark matter halos** and **surrounding dark matter**

$$\xi_{hm}(r) = \langle \delta n_h(\vec{r}\,')\delta_m(\vec{r}\,' + \vec{r}\,)\rangle_{\vec{r}\,'}$$

Modeling Lensing Signal



Cross-correlation function of **dark matter halos** and **surrounding dark matter**

$$\xi_{hm}(r) = \langle \delta n_h(\vec{r}')\delta_m(\vec{r}' + \vec{r})\rangle_{\vec{r}'}$$

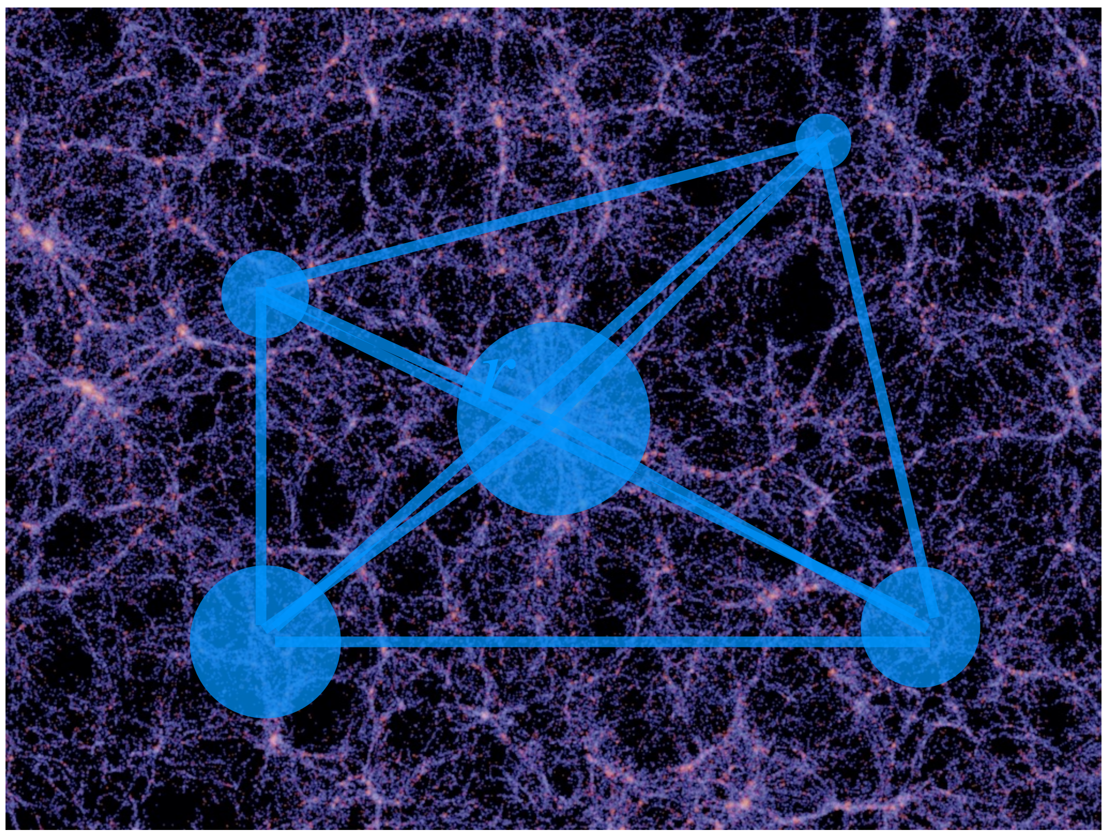
$$\otimes$$

How galaxies populate DM halos

$$N_g(M)$$

Lensing Signal $\xi_{gm}(r)$

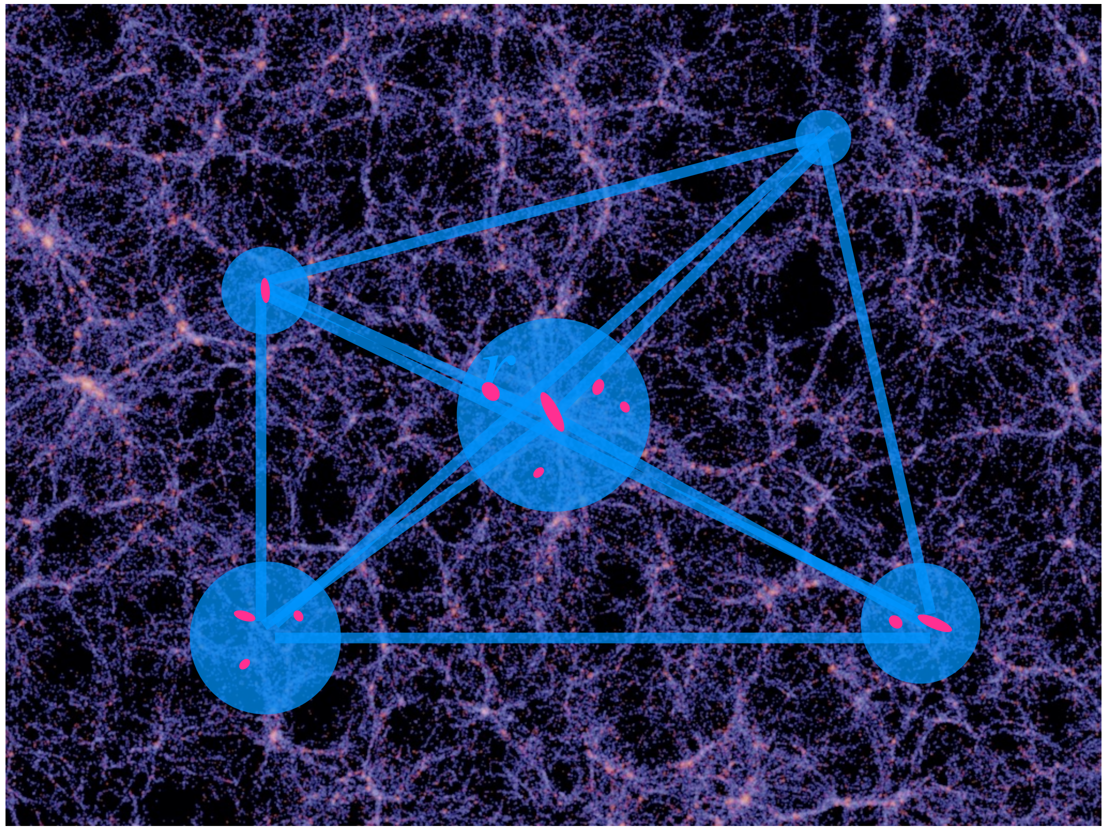
Modeling Clustering Signal



Correlation function of **dark matter halos**

$$\xi_{hh}(r; M_1 \, . M_2) = \langle \delta n_h(\vec{r}\,')\delta n_h(\vec{r}\,' + \vec{r}\,) \rangle_{\vec{r}\,'}$$

Modeling Clustering Signal



Correlation function of **dark matter halos**

$$\xi_{hh}(r; M_1 \, . \, M_2) = \langle \delta n_h(\vec{r}\,') \delta n_h(\vec{r}\,' + \vec{r}\,) \rangle_{\vec{r}\,'}$$

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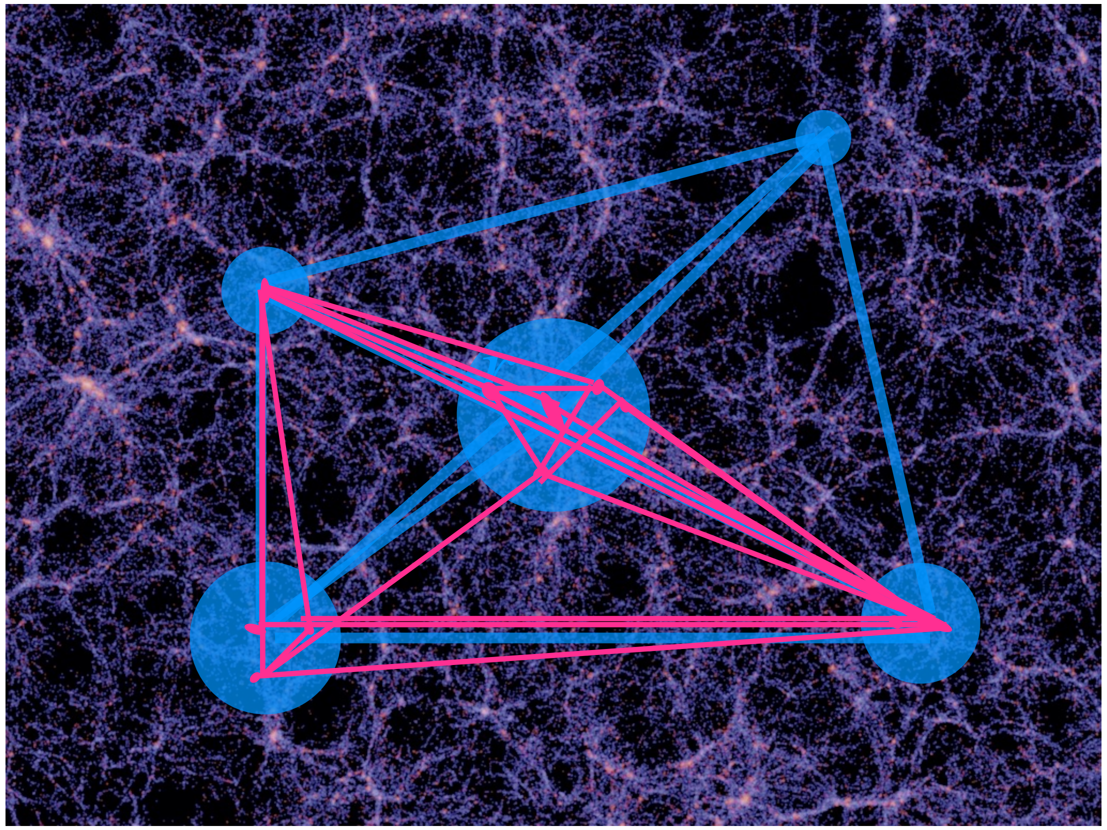
How galaxies populate DM halos

$$N_g(M)$$

Modeling Clustering Signal



Correlation function of **dark matter halos**

$$\xi_{hh}(r; M_1 . M_2) = \langle \delta n_h(\vec{r}\,') \delta n_h(\vec{r}\,' + \vec{r}) \rangle_{\vec{r}\,'}$$

$$\otimes$$

How galaxies populate DM halos

$$N_g(M)$$

↓

Clustering Signal $\xi_{gg}(r)$

Major Challenge: Building a Robust Model

Correlation Functions

$\xi_{hm}(r; M_h, z; \theta)$

$\xi_{hh}(r; M_{h1}, M_{h2}, z; \theta)$

$\otimes$

Galaxy populations

How galaxies populate a dark matter halo

→

Lensing signal

Clustering signal

θ: Cosmological parameters

Major Challenge: Building a Robust Model

Correlation Functions

$\xi_{hm}(r; M_h, z; \theta)$

$\xi_{hh}(r; M_{h1}, M_{h2}, z; \theta)$

$\otimes$

Galaxy populations

How galaxies populate a dark matter halo

Lensing signal

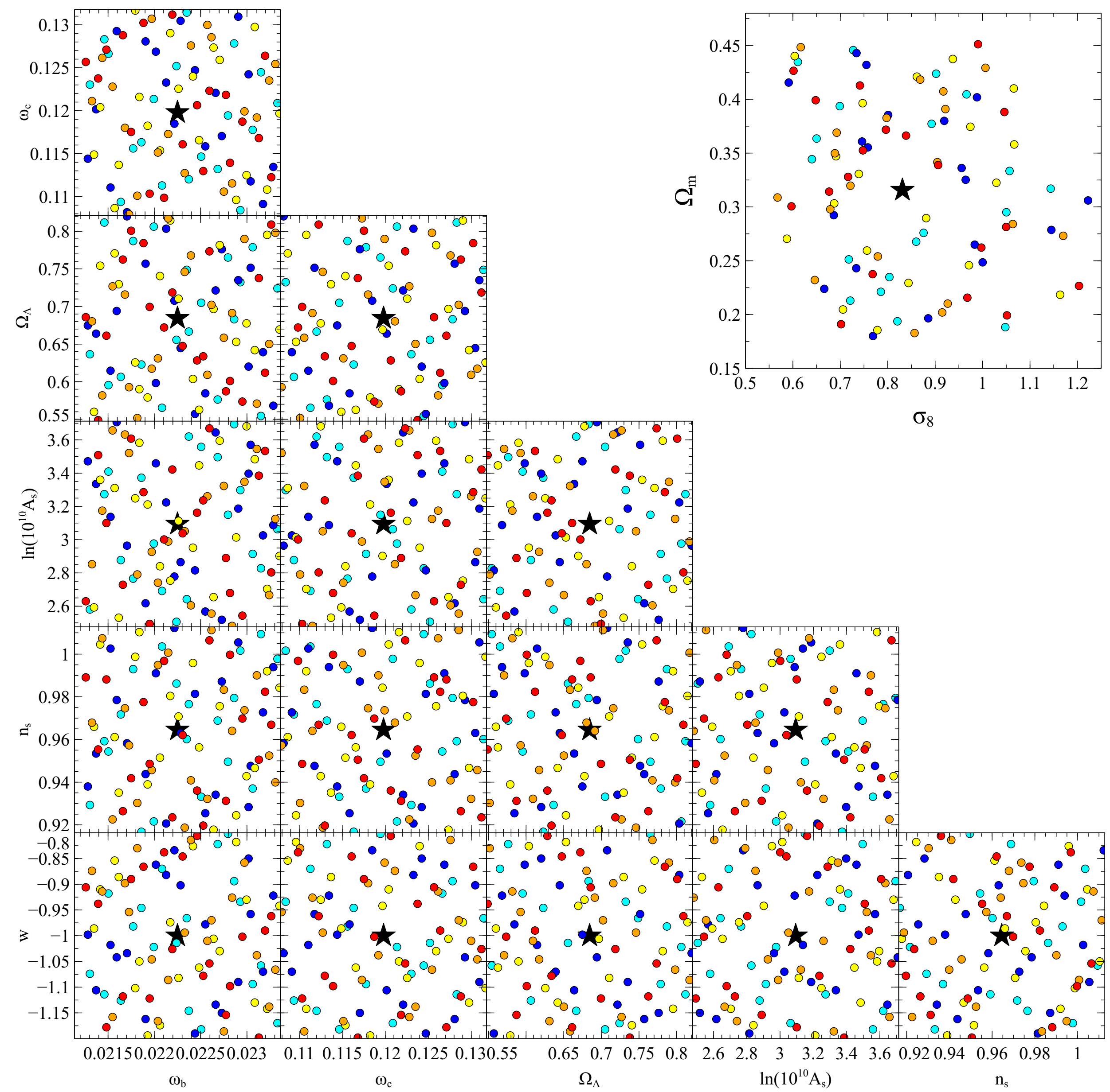
Clustering signal

- It is not straight forward to model the connection between halos and underlying dark matter distributions.
- In previous studies, analytical fitting formulae have been used, which can cause systematic bias.

Dark Emulator

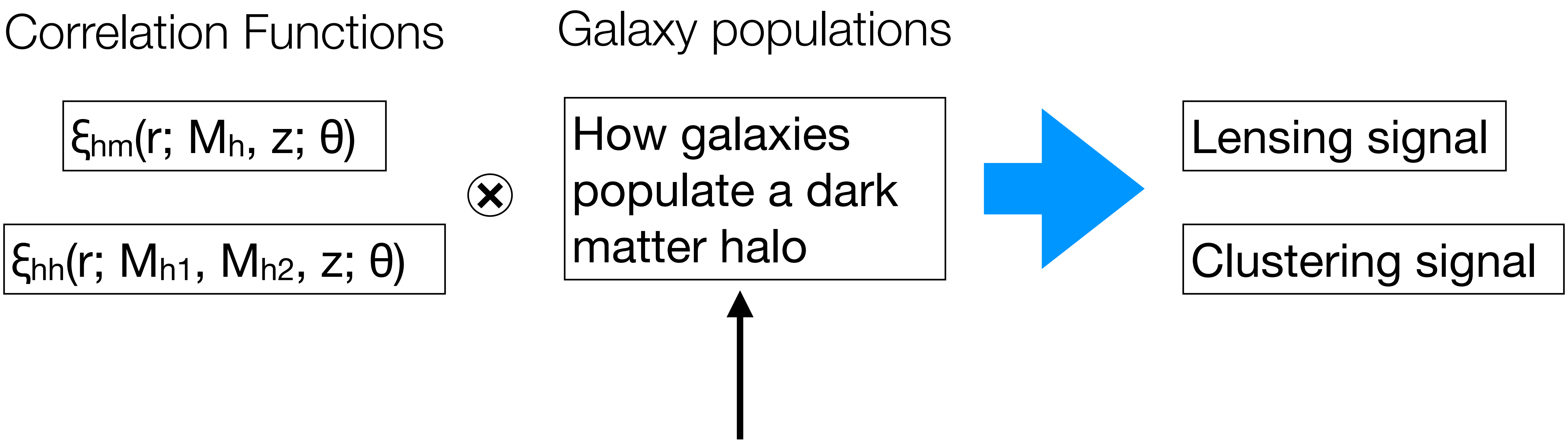
- Dark Emulator provides the following summary statistics for a given cosmology
  - Halo-matter correlation function: ξ_{hm}
  - Halo-halo correlation function: ξ_{hh}
- Measure summary statistics in 1 $[\mathrm{Gpc}/h]^3$ and 2 $[\mathrm{Gpc}/h]^3$ simulations with 2048^3 particles for 101 cosmological parameter sets.
- Interpolate these measurements to a given cosmology using Gaussian process.
- **We no longer rely on fitting formulae!**

$\theta=(\omega_b, \omega_c, \Omega_\Lambda, A_s, n_s, w)$



Nishimichi et al. (2018)

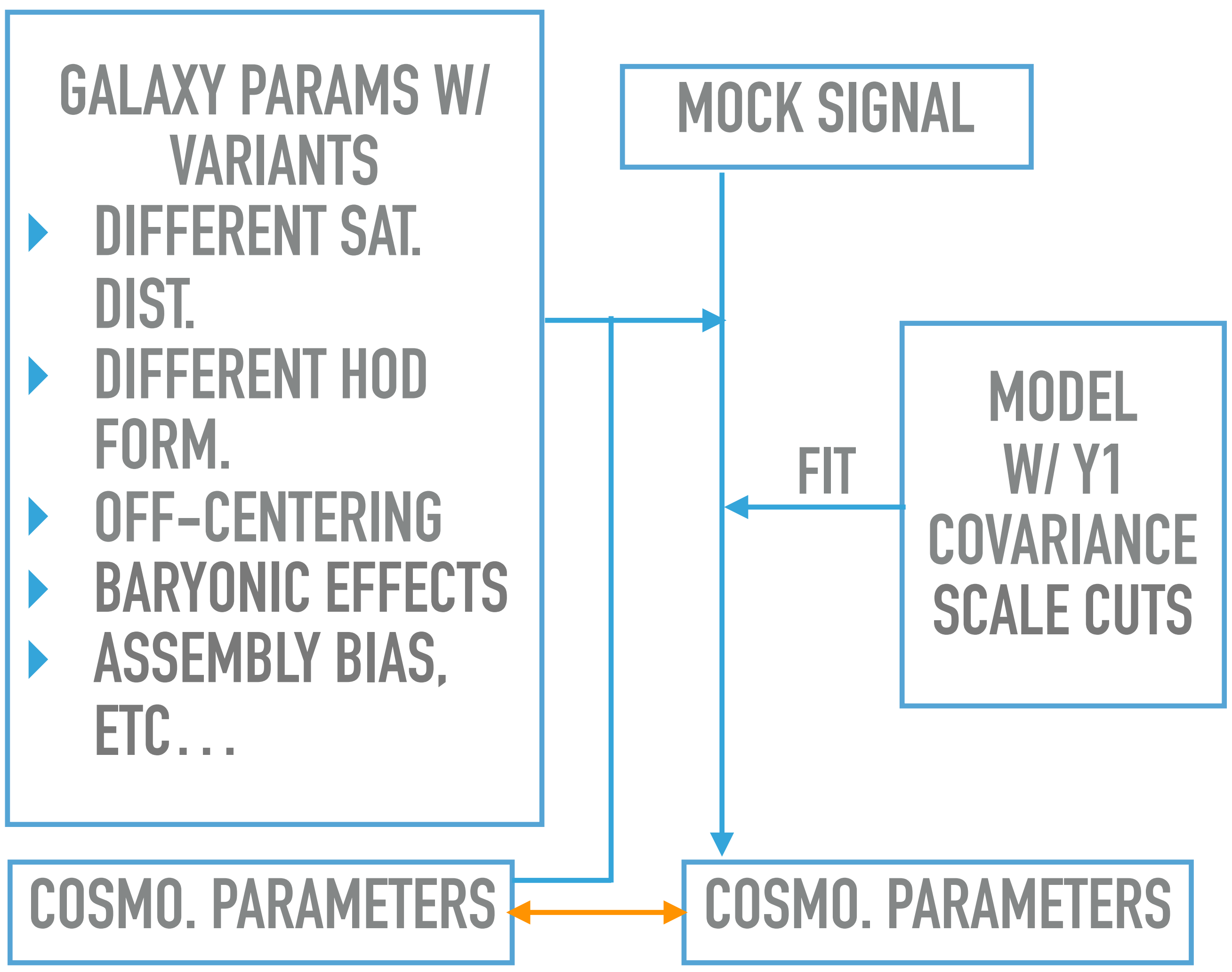
Major Challenge: Building a Robust Model



- Nobody knows what is the “correct” model of galaxies.
- We adopt an empirical, standard model (halo occupation distribution; HOD) and see if it is robust against possible population models of galaxies.

Cosmology Challenge

Test the robustness of our model by fitting mocks with variants.

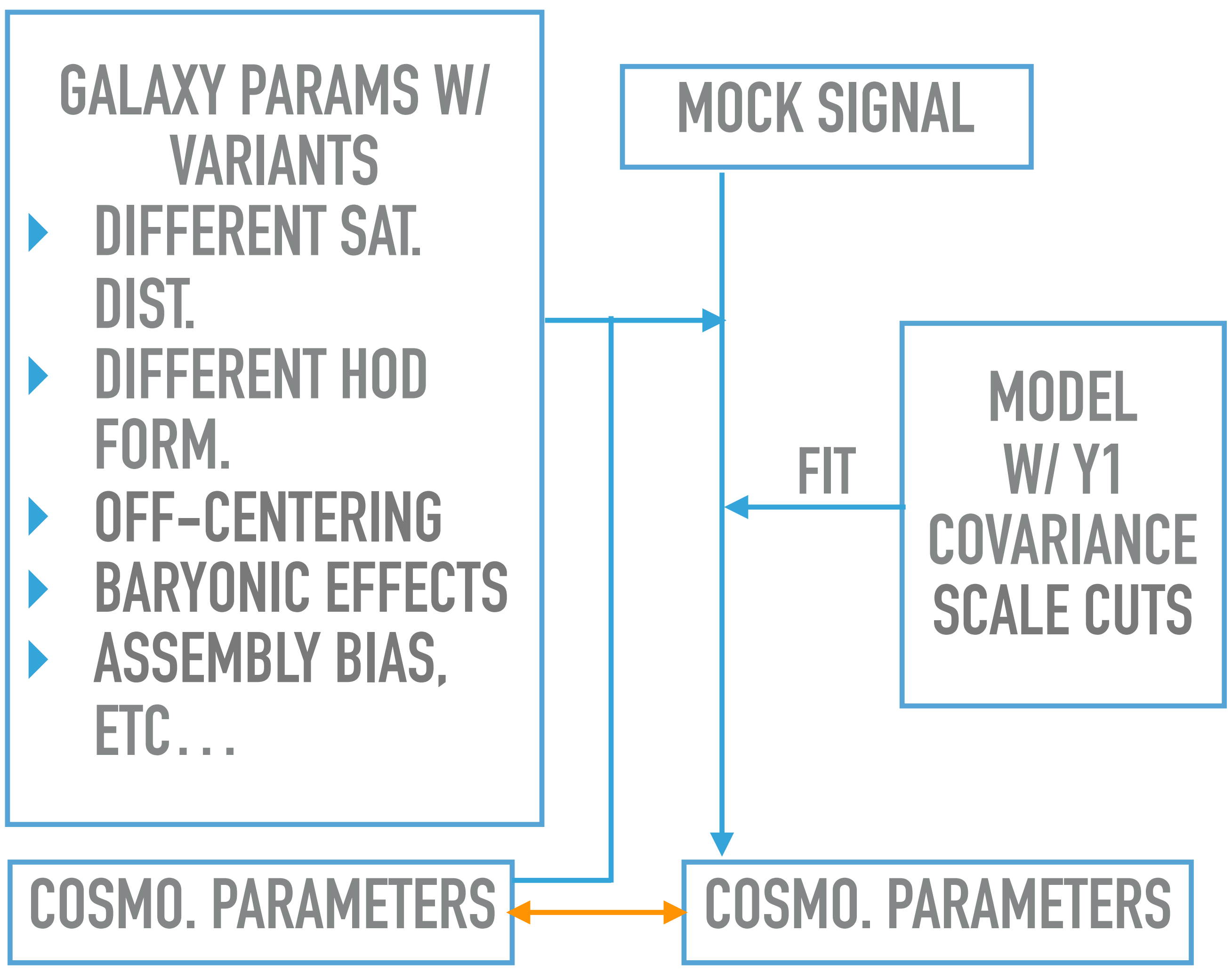


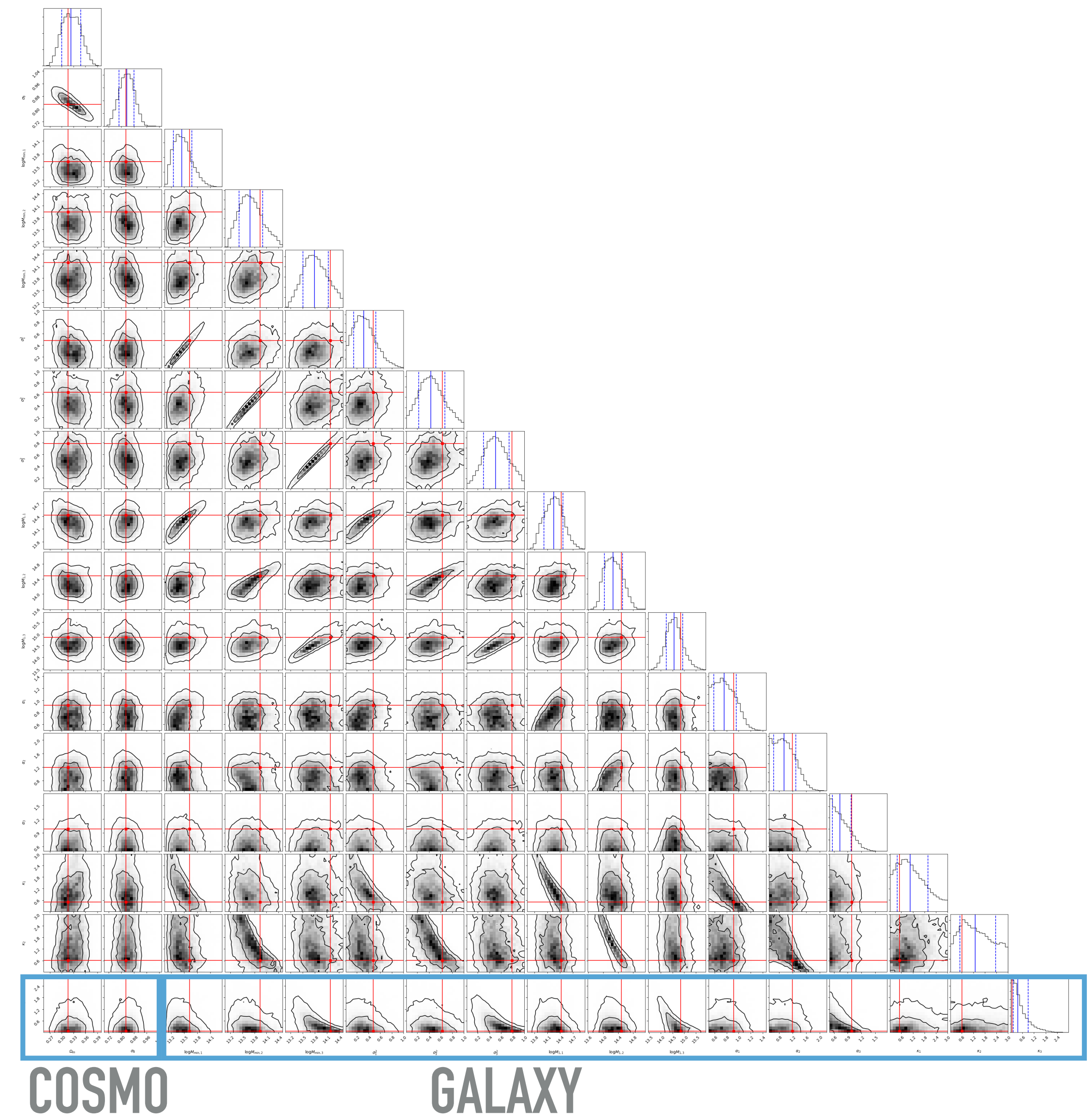
Our "fiducial" model

- "Standard" HOD (Zheng et al. 2005)
- Off-centering PDF: Gaussian
- Satellite distribution: NFW

Cosmology Challenge

Test the robustness of our model by fitting mocks with variants.

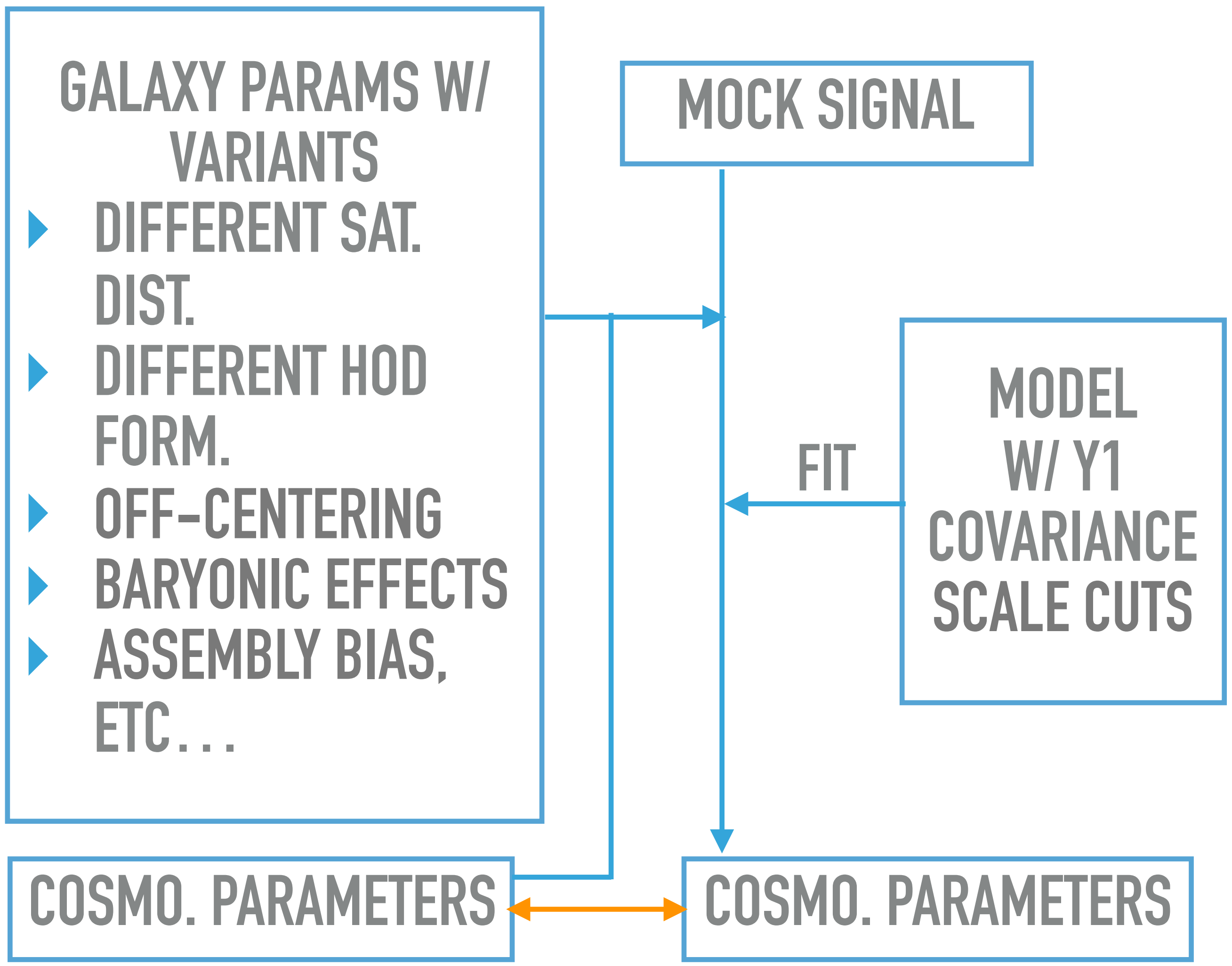


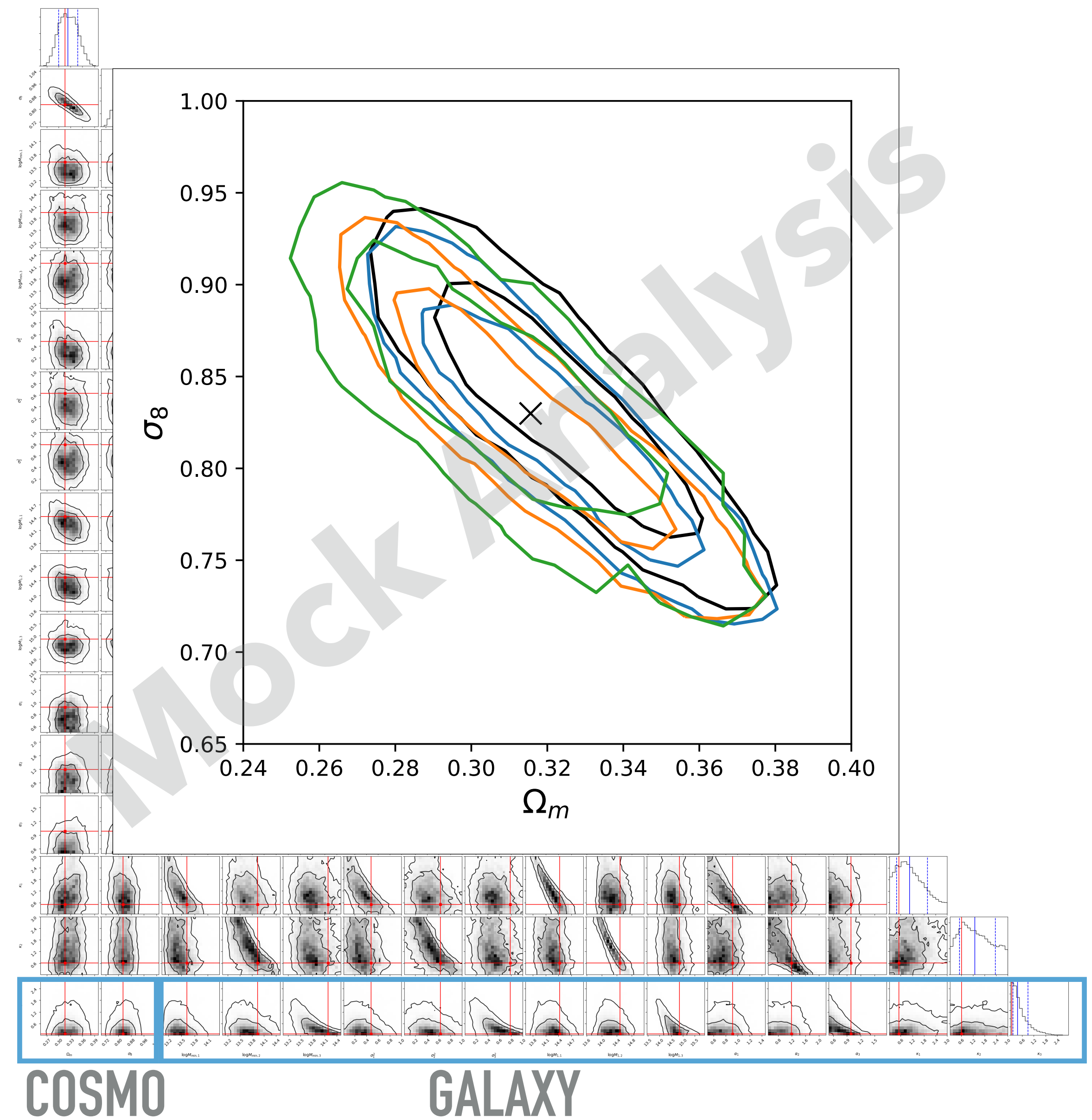


HM et al. (in prep)

Cosmology Challenge

Test the robustness of our model by fitting mocks with variants.





HM et al. (in prep)

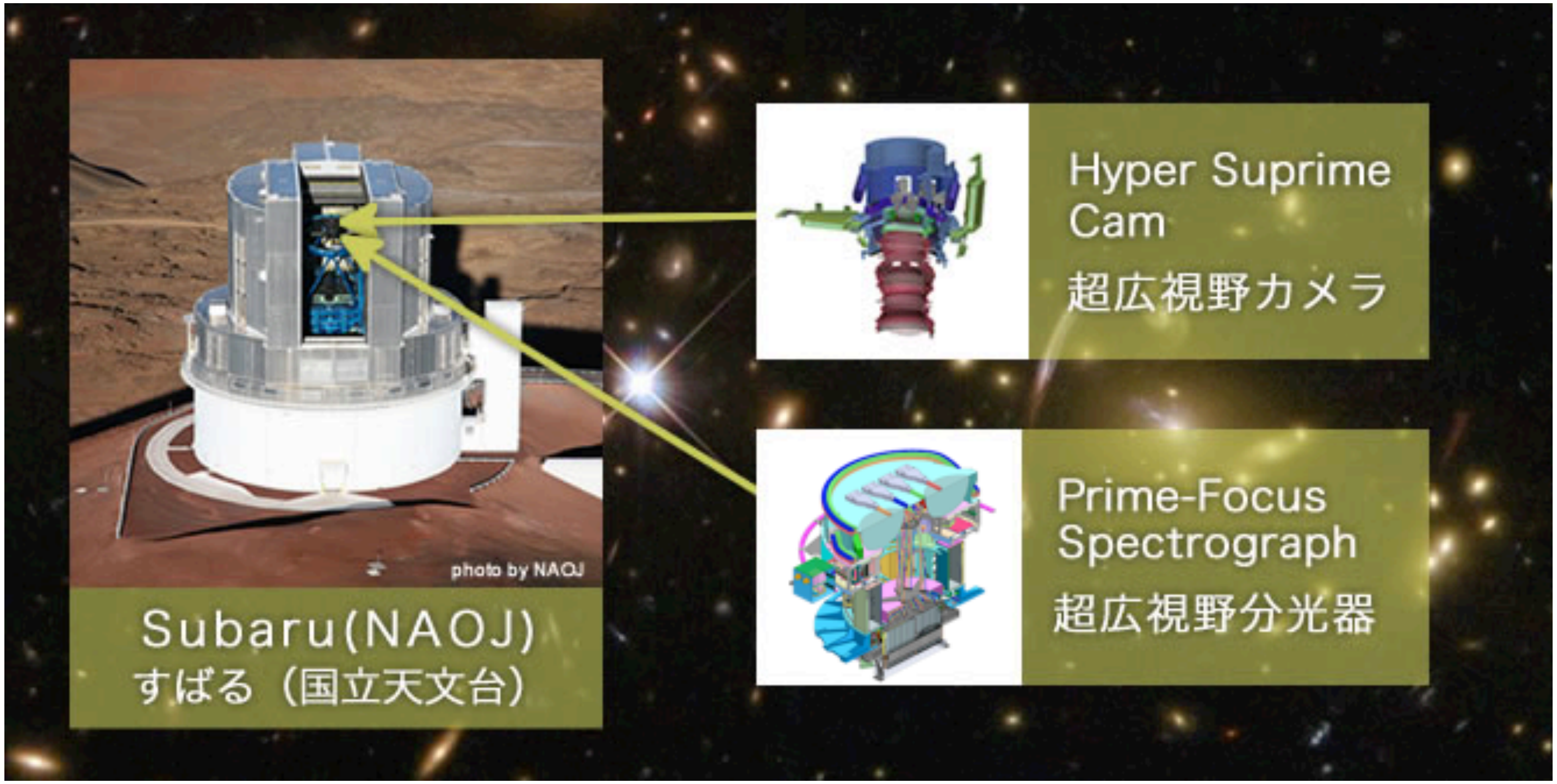
The cosmology challenge is almost done.
Stay tuned for cosmological constraints!

Future Prospects

HSC Third-year Analysis and Beyond

- We are currently creating the galaxy shape catalog based on the HSC data up to the third year of the survey
- Survey area will be extended from 140 deg^2 to 270 deg^2.
- We plan to complete the HSC SSP survey in 2020 to reach 1400 deg^2.

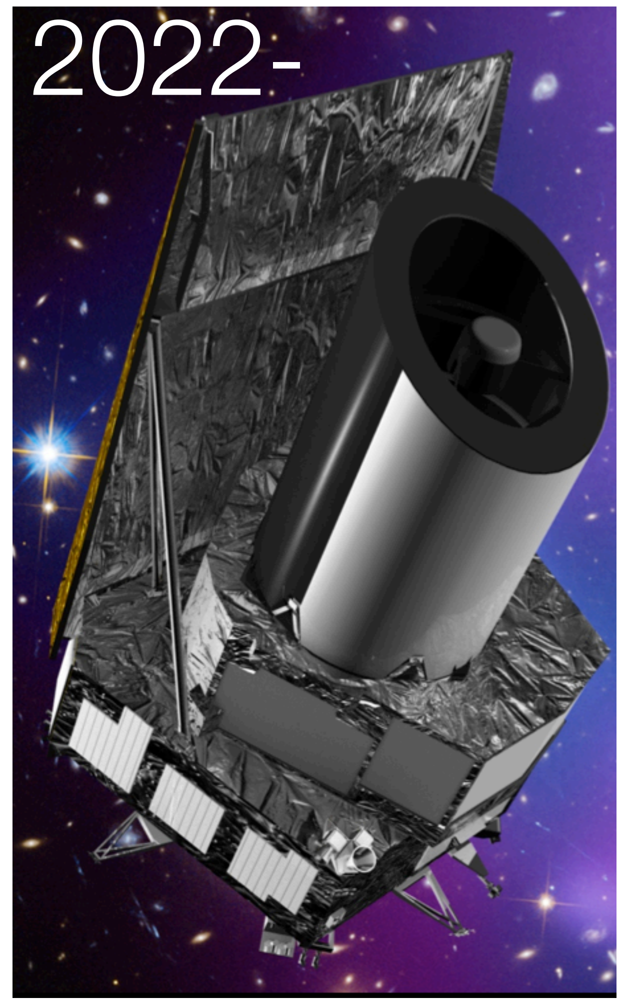
SuMIRe Subaru Measurement of Images and Redshifts



Prime Focus Spectrograph

- 1.3 deg diameter field of view covered by 2400 fibers.
- The SSP survey is expected to start in 2022.
- BAO and combined cosmology analysis with HSC is one of the main science drivers.

Galaxy Imaging Surveys in 2020s



LSST (USA)
15,000 deg^2, i_{lim}~27

Euclid (EU)
15,000 deg^2
J_{lim}~24

WFIRST (USA)
2,200 deg^2,J_{lim}~27

Summary

- Subaru Hyper Suprime-Cam (HSC) started the imaging survey in 2014.
- HSC is a unique instrument that enables a wide and deep survey.
- The first-year cosmology results are coming out!
- The Prime Focus Spectrograph (PFS) survey will start in 2022, and 3 large imaging surveys are planned in 2020s
- We are living the golden era of observational cosmology!