すばる広天域銀河サーベイによる基礎物理（fundamental physics）の探求（に向けて）

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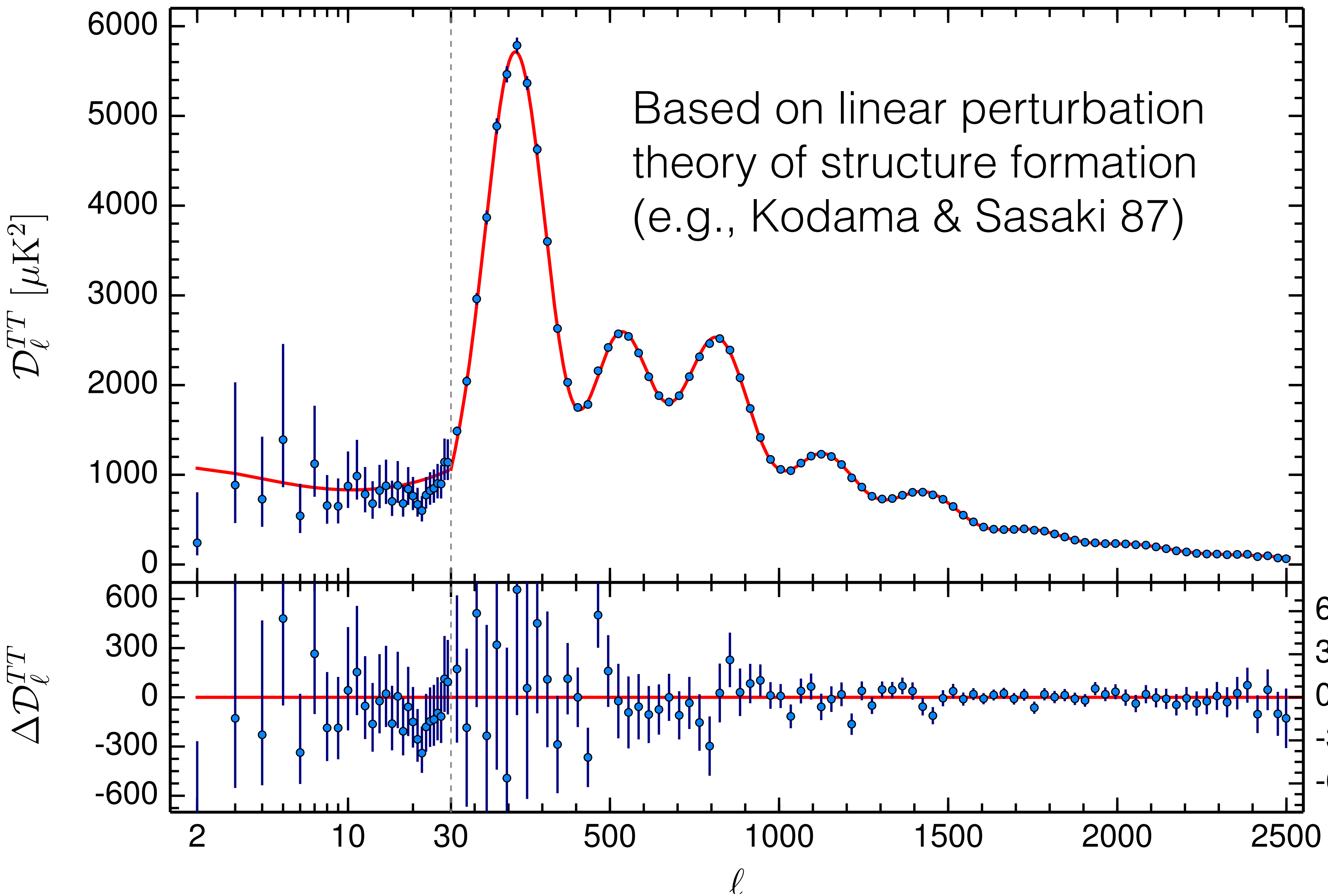
wpi

素粒子物理学の進展@京都大学, 2017年8月

Fundamental physics with cosmology

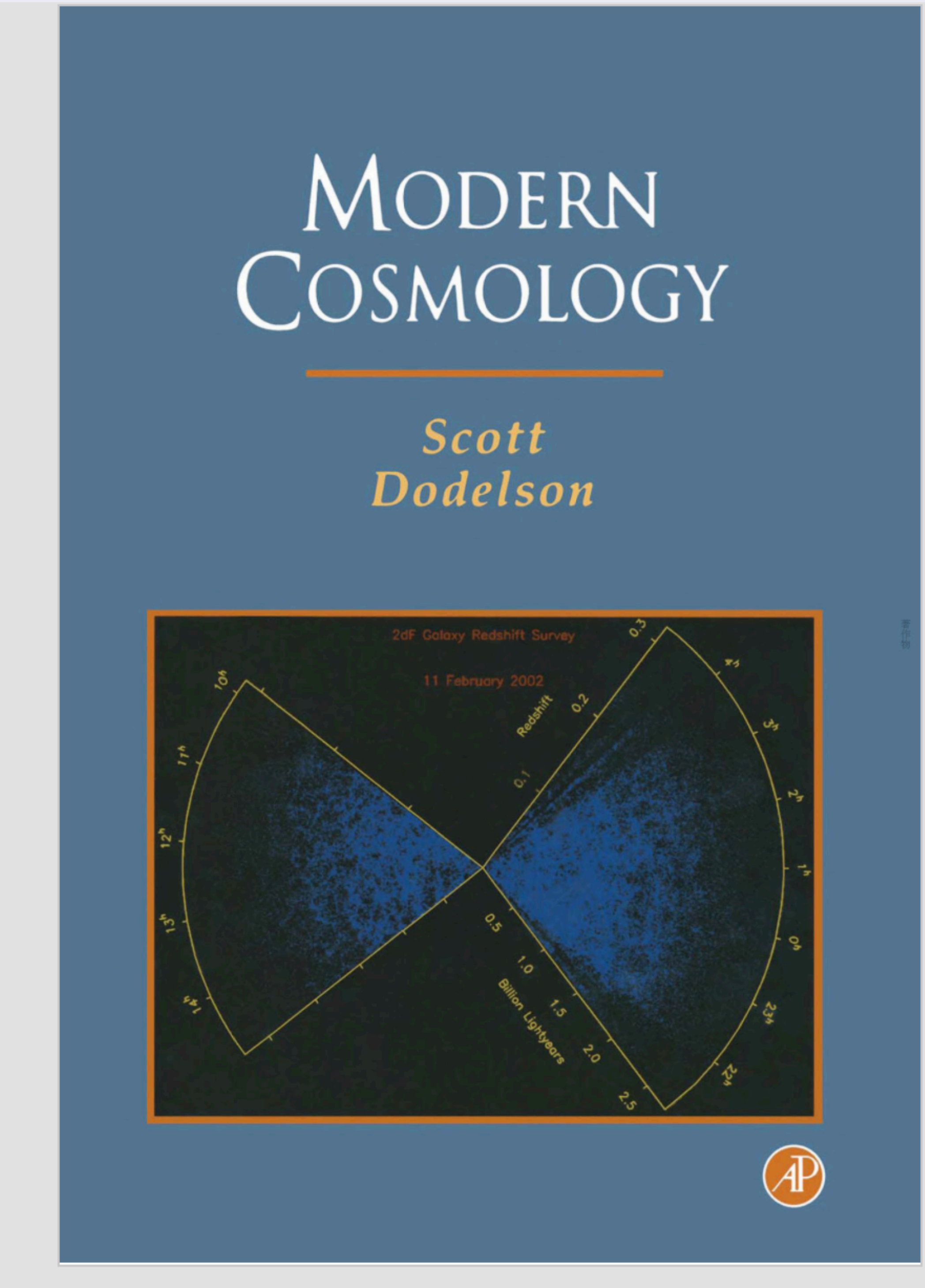
- Dark energy & Cosmic acceleration
- Neutrino mass
- The nature of dark matter
- Light relics (new particles beyond SM)
- The nature of primordial perturbations (the initial conditions of the Universe)

CMB success: the triumph of physics!



ΛCDM standard cosmological model

Parameter	Planck	
$100\theta_{\rm MC}$	1.04086 ± 0.00048	0.05%!
$\Omega_b h^2$	0.02222 ± 0.00023	
$\Omega_c h^2$	0.1199 ± 0.0022	
H_0	67.26 ± 0.98	
n_s	0.9652 ± 0.0062	5.6σ!
Ω_m	0.316 ± 0.014	
σ_8	0.830 ± 0.015	
τ	0.078 ± 0.019	
$10^9 A_s e^{-2\tau}$	1.881 ± 0.014	



(late-time) cosmology is easy!

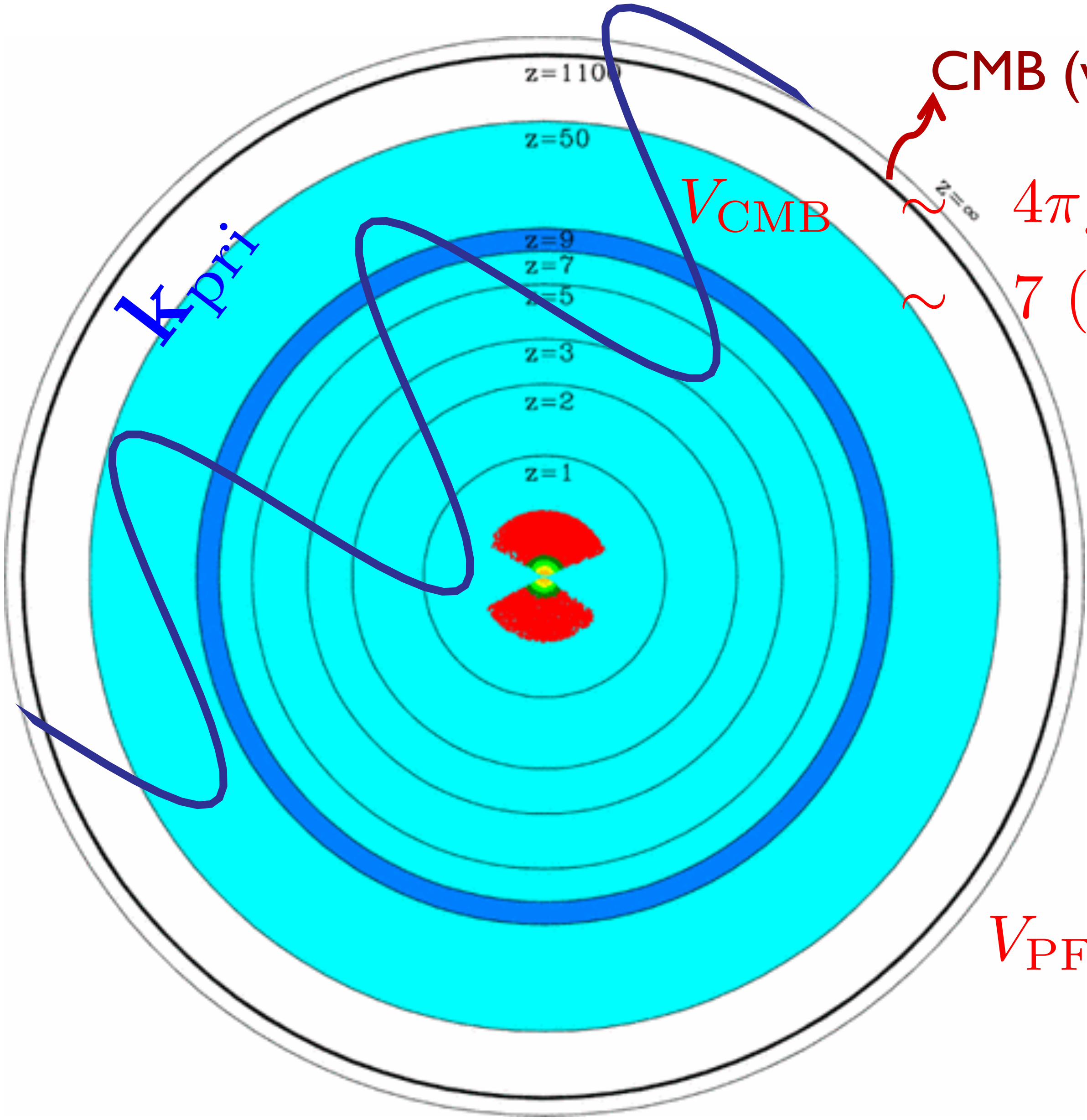
Modern Cosmology (Academic Press)
Scott Dodelson

This textbook is enough to understand the basics of structure formation

Will become ready to start research

Also see for cosmology/particle physics contents
arXiv:1503.08043, 1610.02743, 1703.00894, ...

CMB (~2D) vs. Galaxy Surveys (3D)



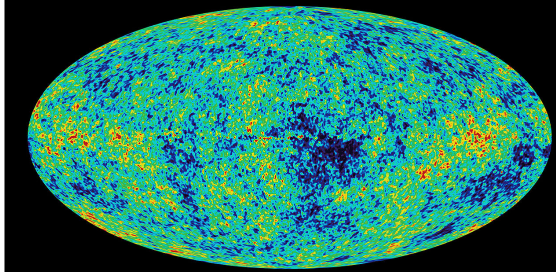
$$V_{\rm CMB} \sim 4\pi f_{\rm sky}(14\ {\rm Gpc})^2 \times (0.005\ {\rm Gpc})$$
$$\sim 7\ ({\rm Gpc}/h)^3$$

$$V_{\rm PFS} \sim 9\ ({\rm Gpc}/h)^3 (f_{\rm sky}\ 0.04)$$

A huge 3D volume is still available for cosmology

Tegmark & Zaldarriaga 09

Large-scale structure formation: ΛCDM model

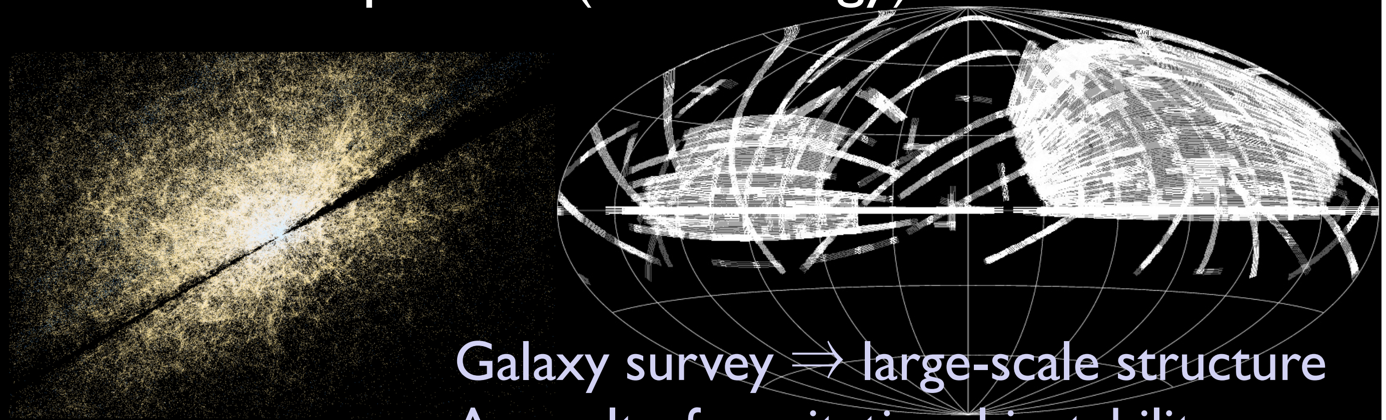


CMB ⇒initial conditions

Structure formation = Time evolution of matter inhomogeneities of each scale (wavelength)

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$$

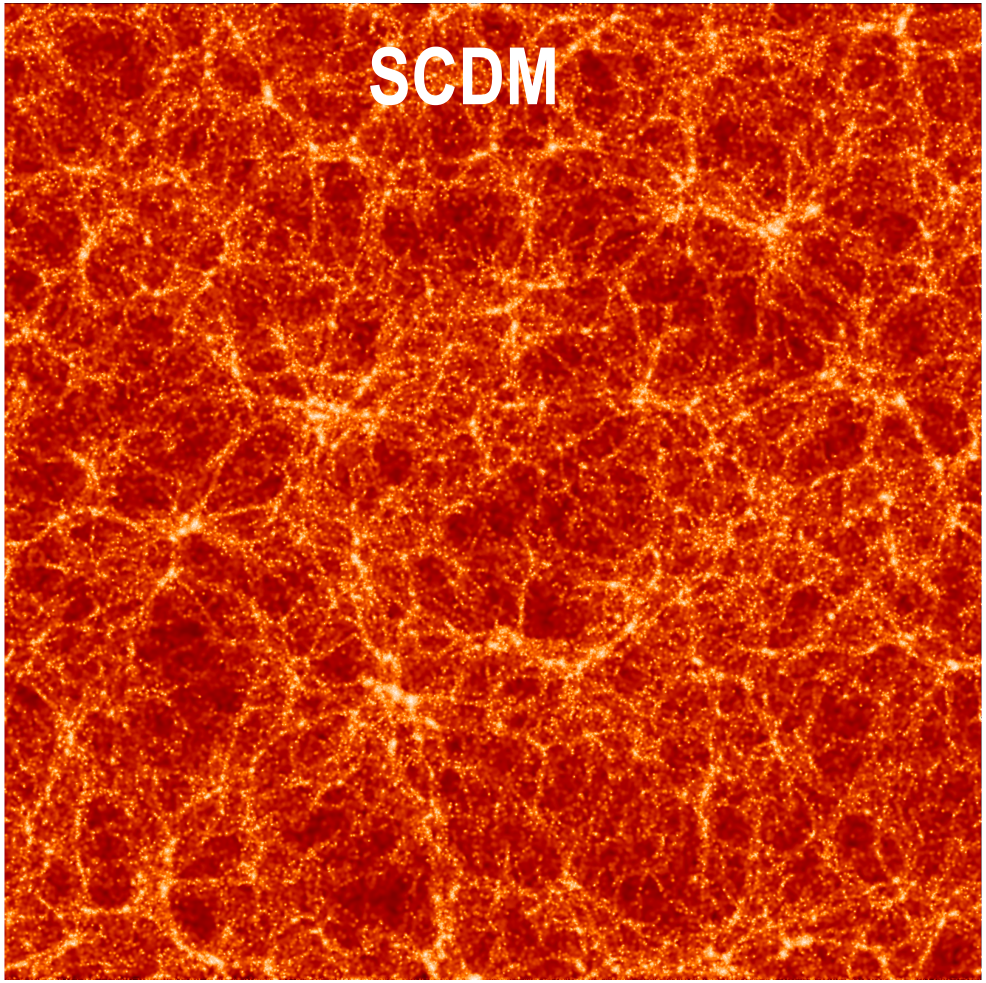
⟶ time



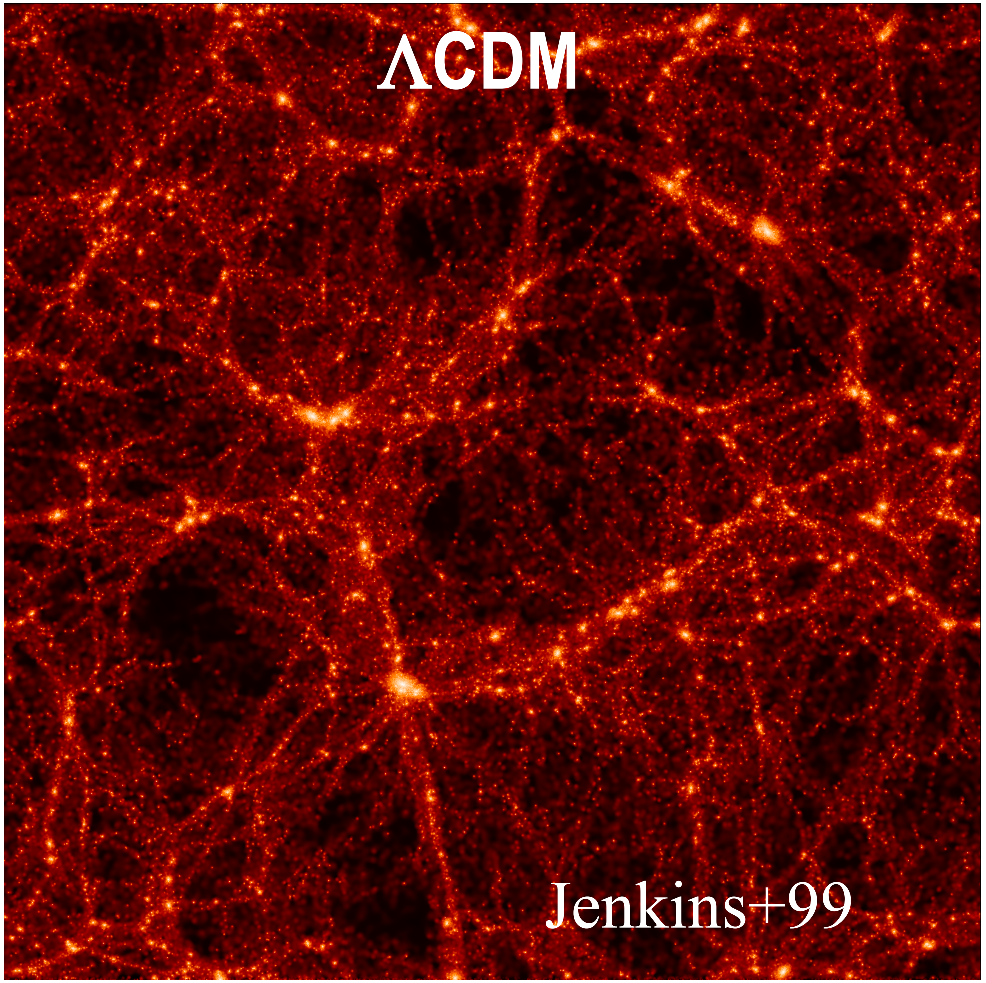
Galaxy survey ⇒ large-scale structure
A result of gravitational instability

Structure formation: Expansion vs. Dark matter

w/o Λ



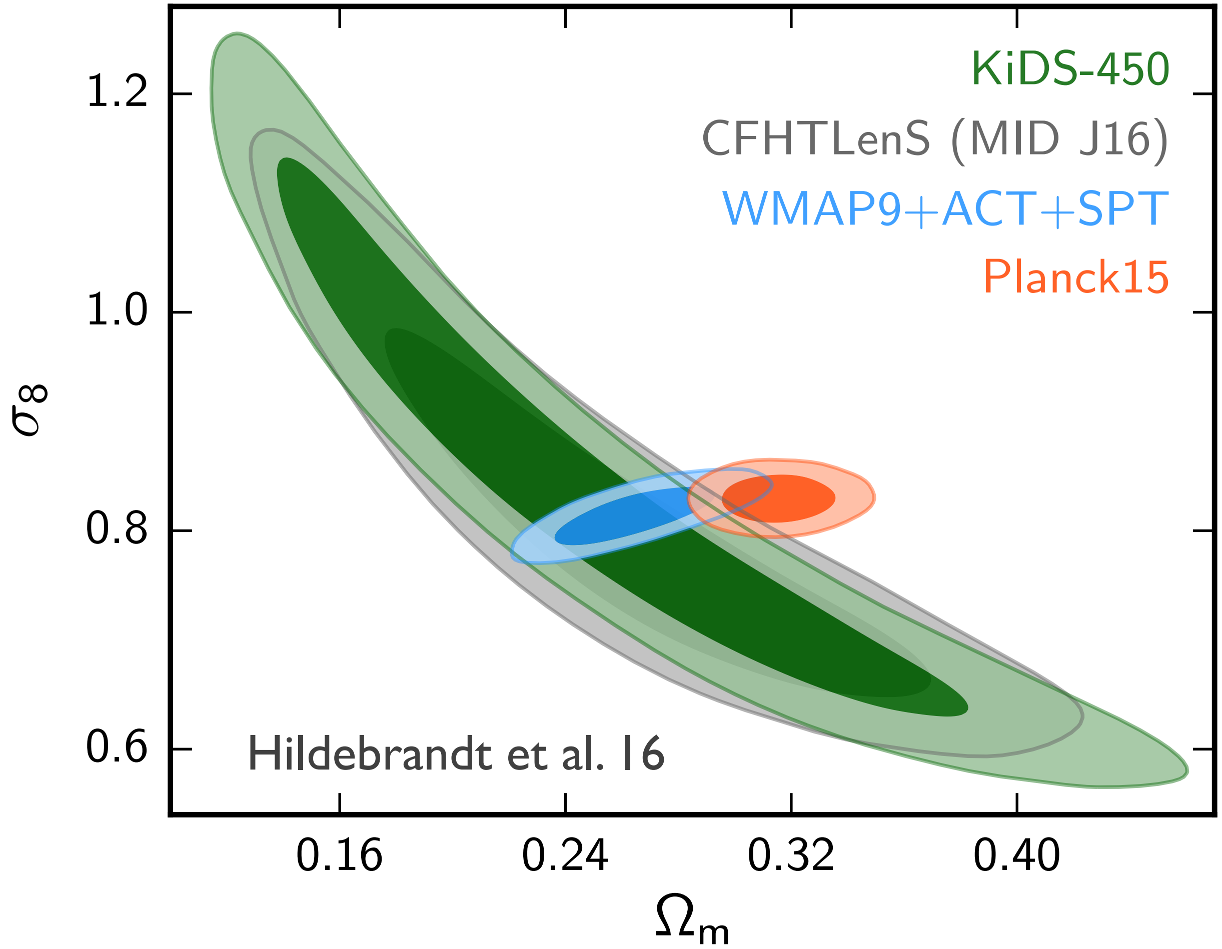
with Λ



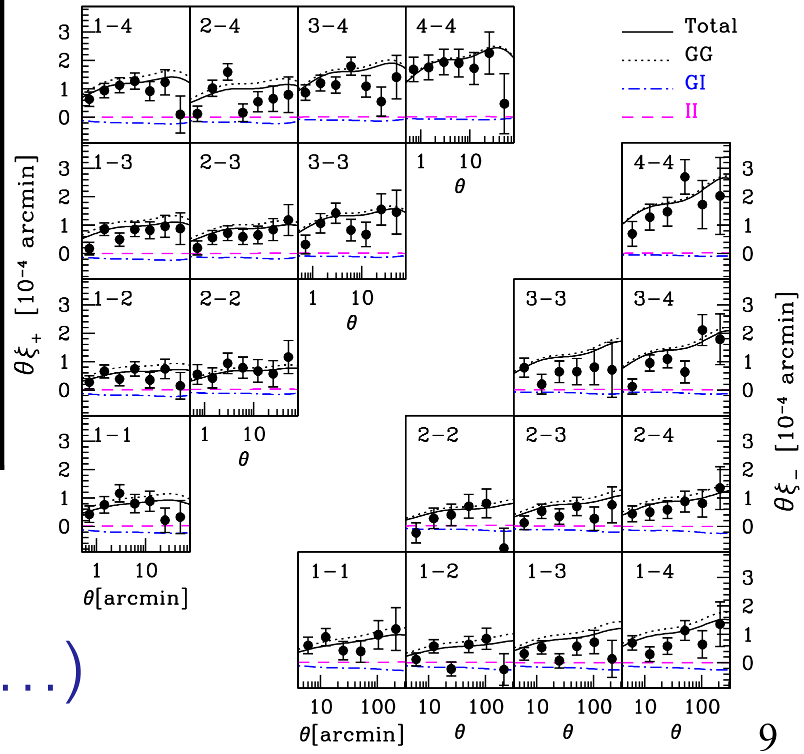
Similar CMB spectra in these two models

σ_8 tension? New physics?

σ_8: the **present-day** rms of mass density fluctuations of 8 Mpc/h scale
Planck σ_8 value: **extrapolated** of fluctuations from z~1100 assuming ΛCDM



- *Planck value is not consistent* with the results of LSS probes (e.g. weak lensing)



KiDS: the Kilo-Degree Survey (Leiden, …)

σ_8 tension? New physics?

fitting formula (Hu & Jain 04)

$$\sigma_8 \approx \frac{\delta_\zeta}{5.59\times10^{-5}}\left(\frac{\Omega_{\rm b}h^2}{0.024}\right)^{-1/3}\left(\frac{\Omega_{\rm m}h^2}{0.14}\right)^{0.563}(3.123h)^{(n_s-1)/2}\left(\frac{h}{0.72}\right)^{0.693}\frac{G_0}{0.76}$$

where $G_0 \approx 0.76\left(\frac{\Omega_m}{0.27}\right)^{0.236} F[\Omega_{\rm de}^{4/3}(1+w_{\rm de})]$

$$F(x) = (1+0.498x+4.88x^3)^{-1}$$

- σ_8 can be accurately computed in linear theory once the cosmological model is fixed
- Which physics can lower σ_8? – New physics?
  - Dark energy (w_{de}>-1)
  - Neutrino mass (e.g, 0.1eV neutrino mass can reconcile)
  - Modified gravity????

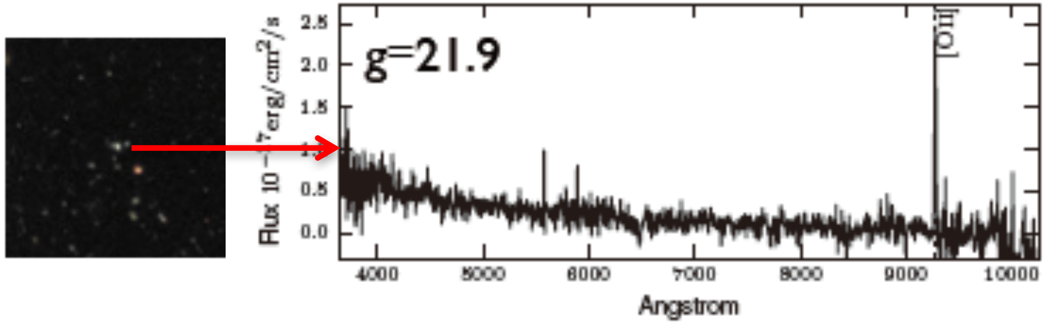
Galaxy survey; imaging vs. spectroscopy

Imaging

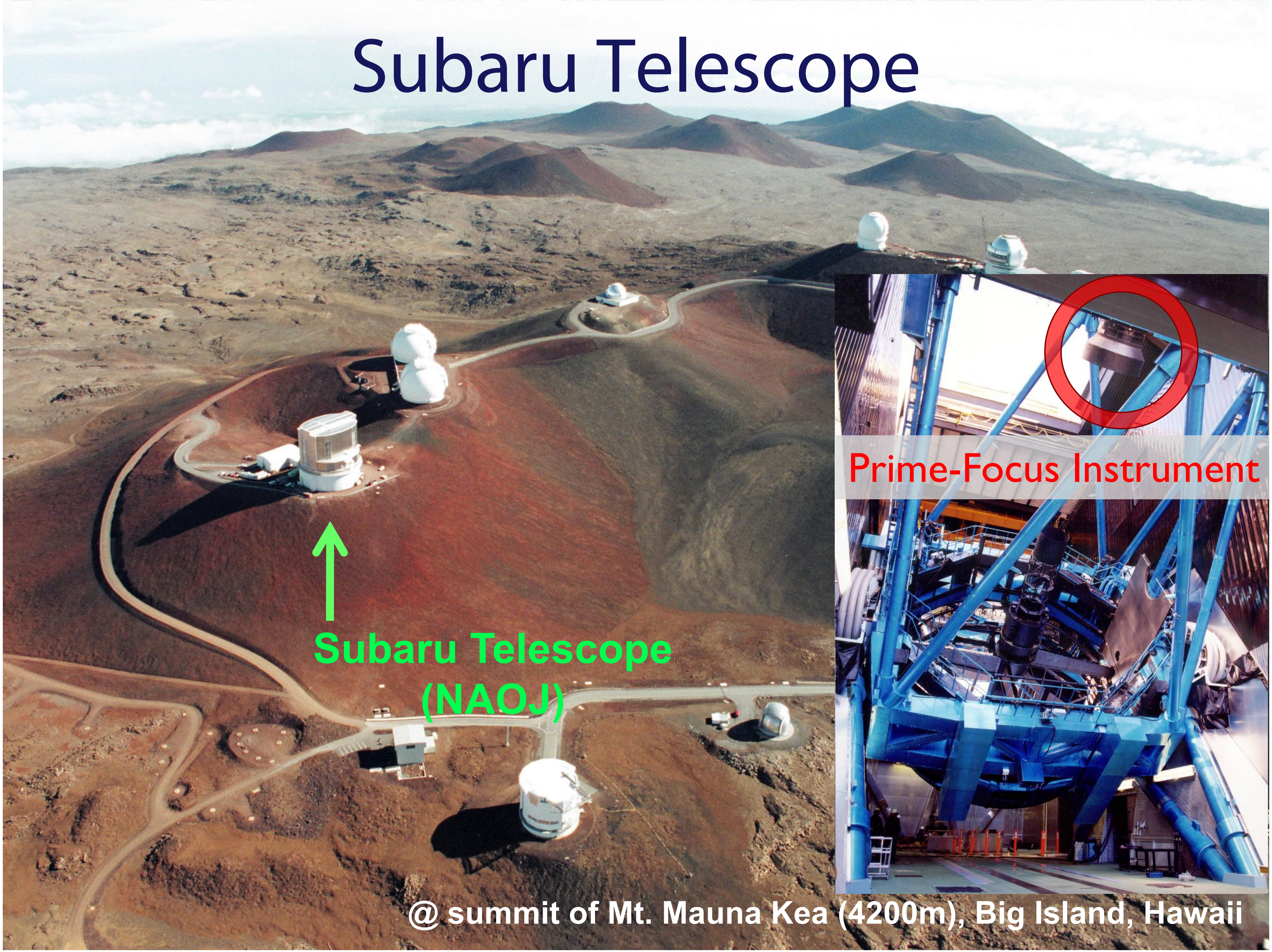
- Find objects
  - Stars, galaxies, galaxy clusters
- Measure the image shape of each object → *weak gravitational lensing*
- For cosmology purpose
  - *Pros*: many galaxies, a reconstruction of dark matter distribution
  - *Cons*: 2D information, limited redshift info. (photo-z at best)

Spectroscopy

- Measure the photon-energy spectrum of *target* object
- Distance to the object can be known → *3D clustering analysis*
- For cosmology
  - *Pros*: more fluctuation modes in 3D than in 2D
  - *Cons*: need the pre-imaging data for targeting; observationally more expensive (or less galaxies)



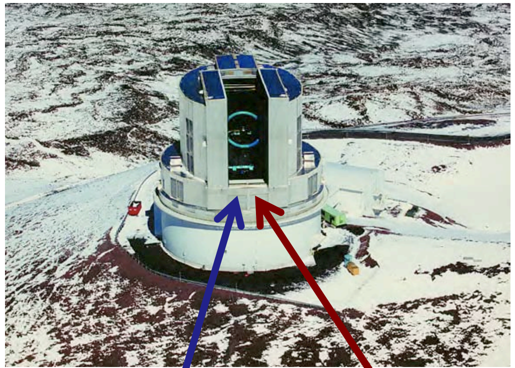
Subaru Telescope



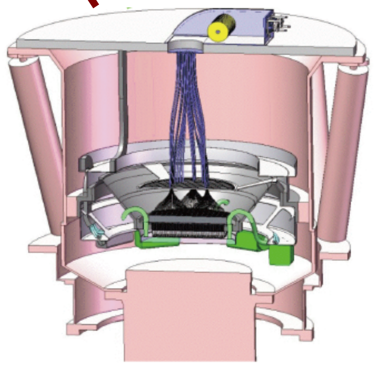
SuMIRe = Subaru Measurement of Images and Redshifts

H. Murayama (Kavli IPMU Director)

- IPMU director Hitoshi Murayama funded (~$32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper Suprime-Cam; ~$55M) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph; ~$80M) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies
- **Do SDSS-like survey at z>1**

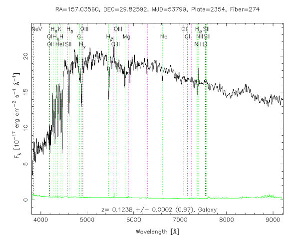


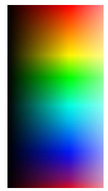
Subaru (NAOJ)



PFS

HSC



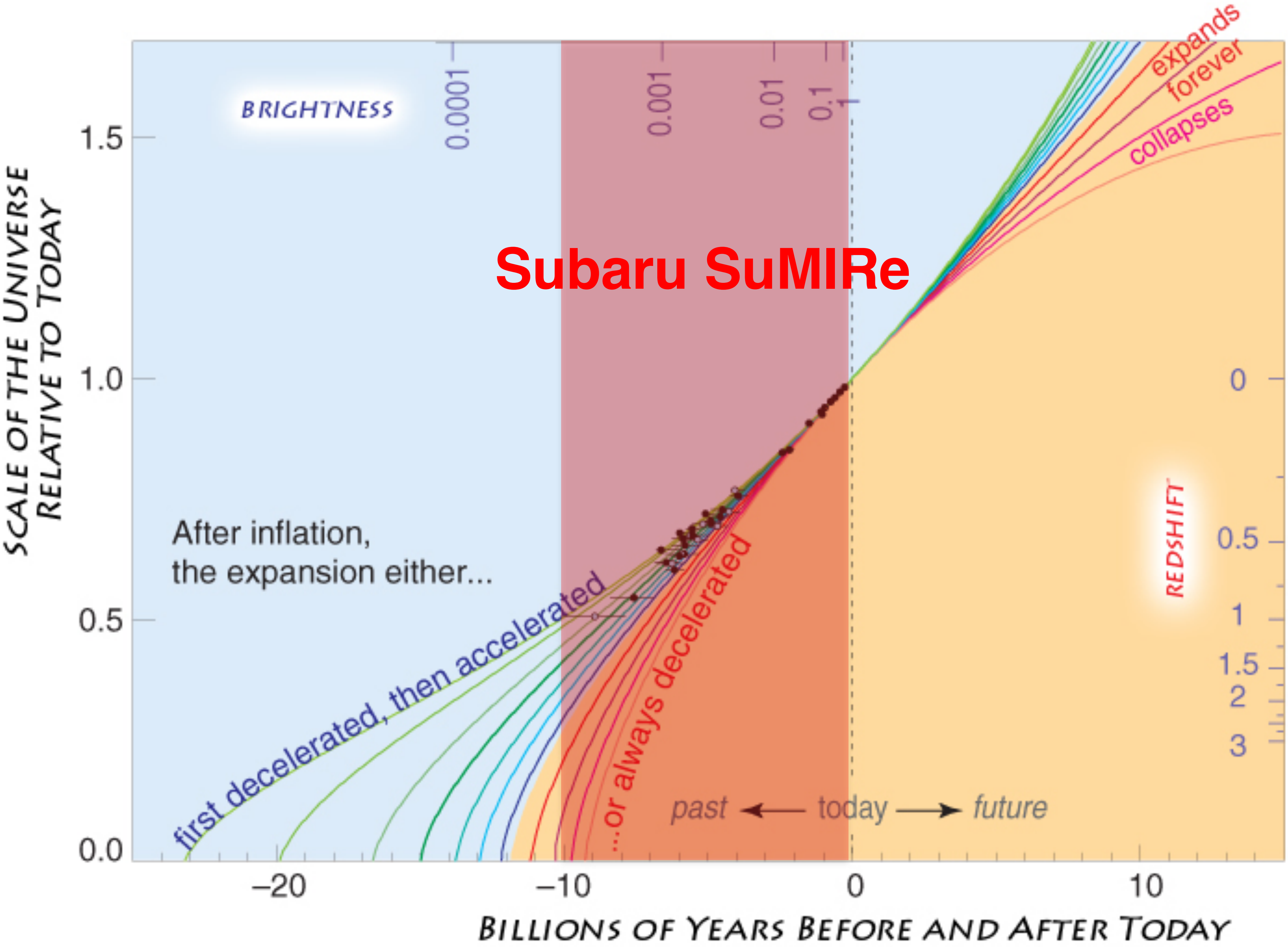


Imaging + Spectroscopy (1.5M gals for 2.5m SDSS)

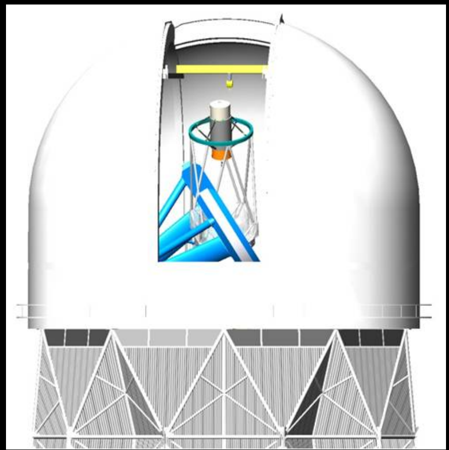
Distant (faint) universe = The universe in ***the past***

HSC+PFS can probe the 3D Universe at z~1!

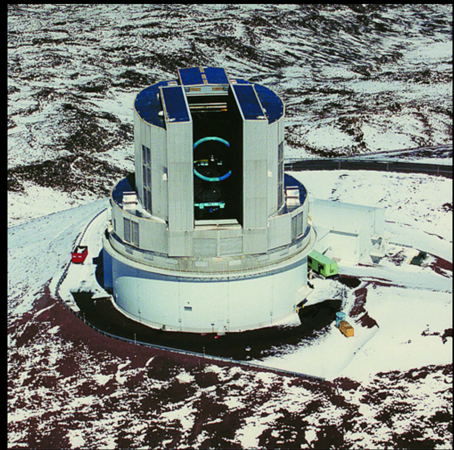

A journey through simulated universe (Millennium Simulation)


BRIGHTNESS
0.0001
0.001
0.01
0.1
1
expands
forever
collapses
Subaru SuMIRe
SCALE OF THE UNIVERSE RELATIVE TO TODAY
1.5
1.0
0.5
0.0
After inflation,
the expansion either...
first decelerated, then accelerated
...or always decelerated
REDSHIFT
0
0.5
1
1.5
2
3
past
today
future
–20
–10
0
10
BILLIONS OF YEARS BEFORE AND AFTER TODAY

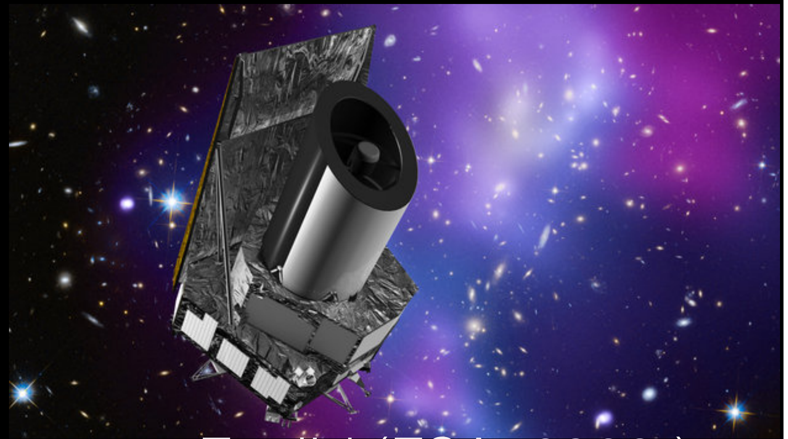
Wide-area galaxy survey



DESI (4m, LBL, 2019-)

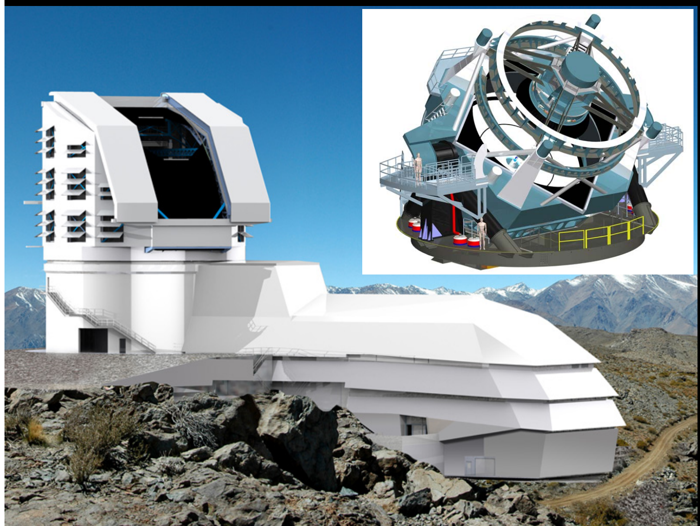


SuMIRe (2015-25)



Euclid (ESA, 2022-)

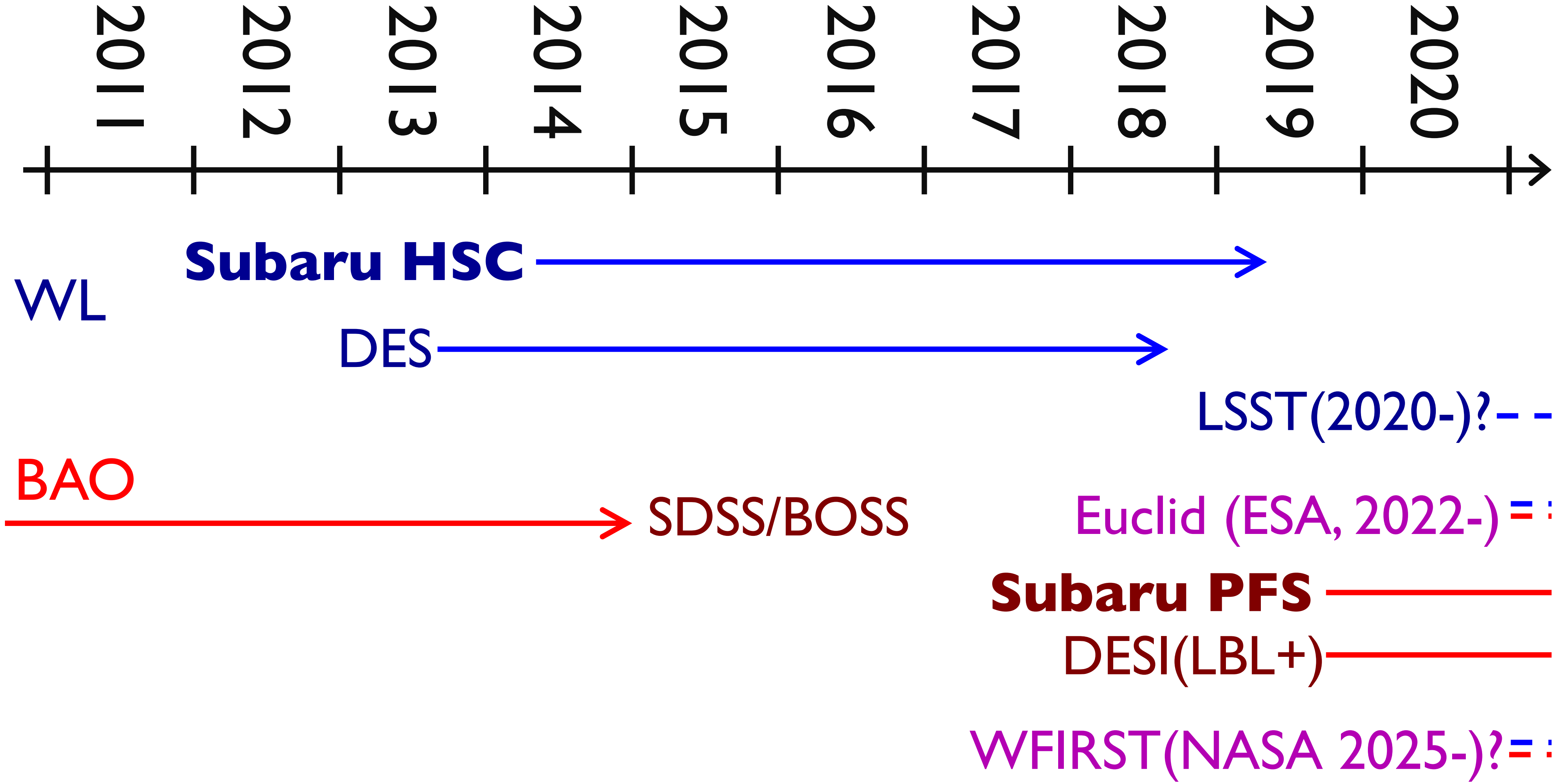
WFIRST (NASA, 2025-)



LSST (6.5m, SLAC, 2022-)

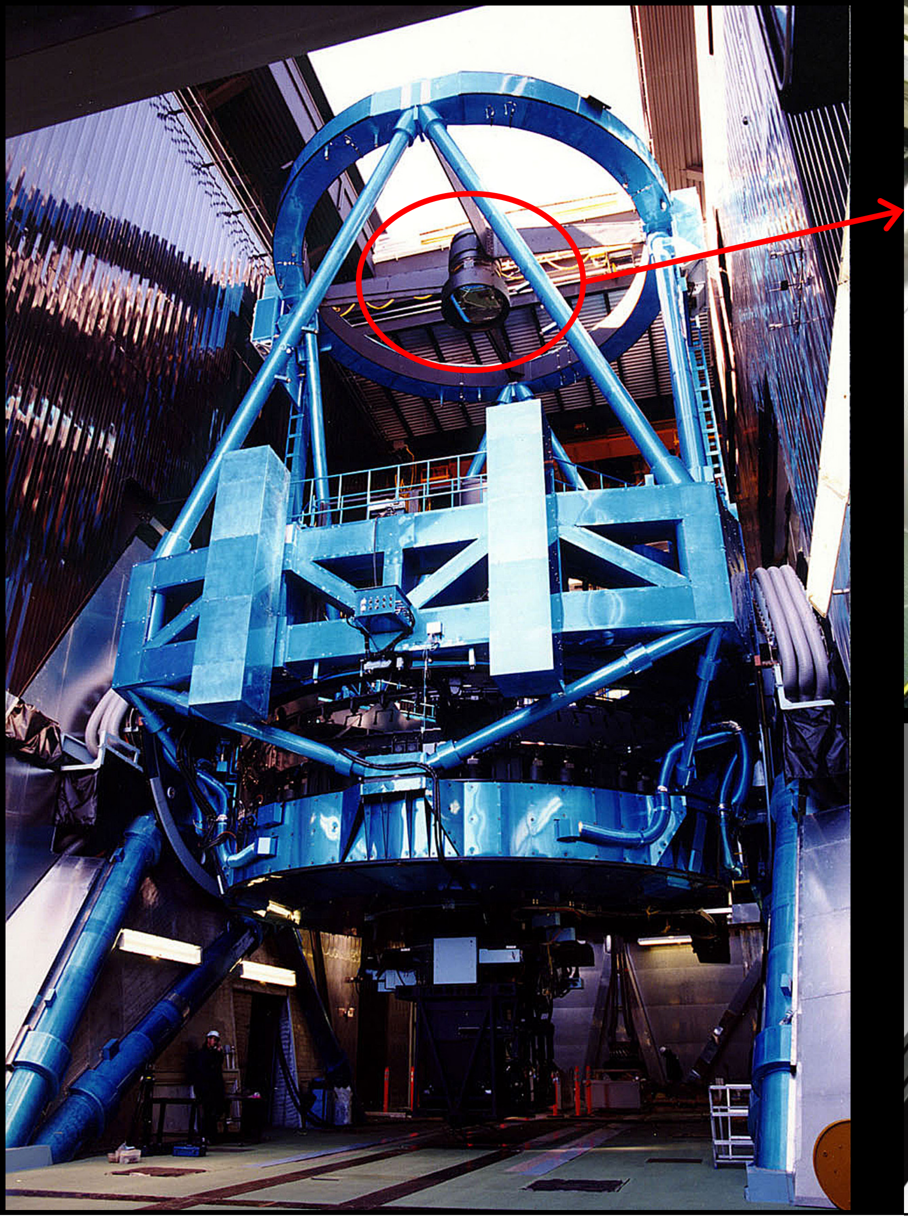
宇宙物理と素粒子物理の融合領域。2030年までは様々な展開・発展が約束。そのなかで日本SuMIReが先陣を切る

Time line (DE experiments)

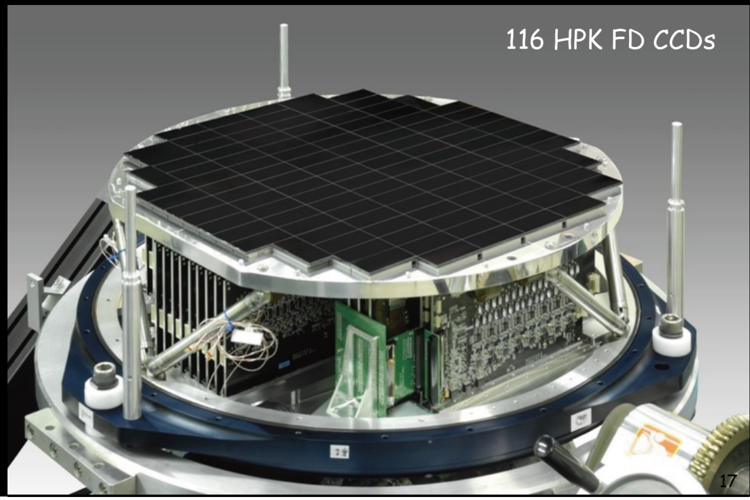


We are in a good position!

Hyper Suprime-Cam (HSC)



- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)
- Japan, Taiwan and Princeton



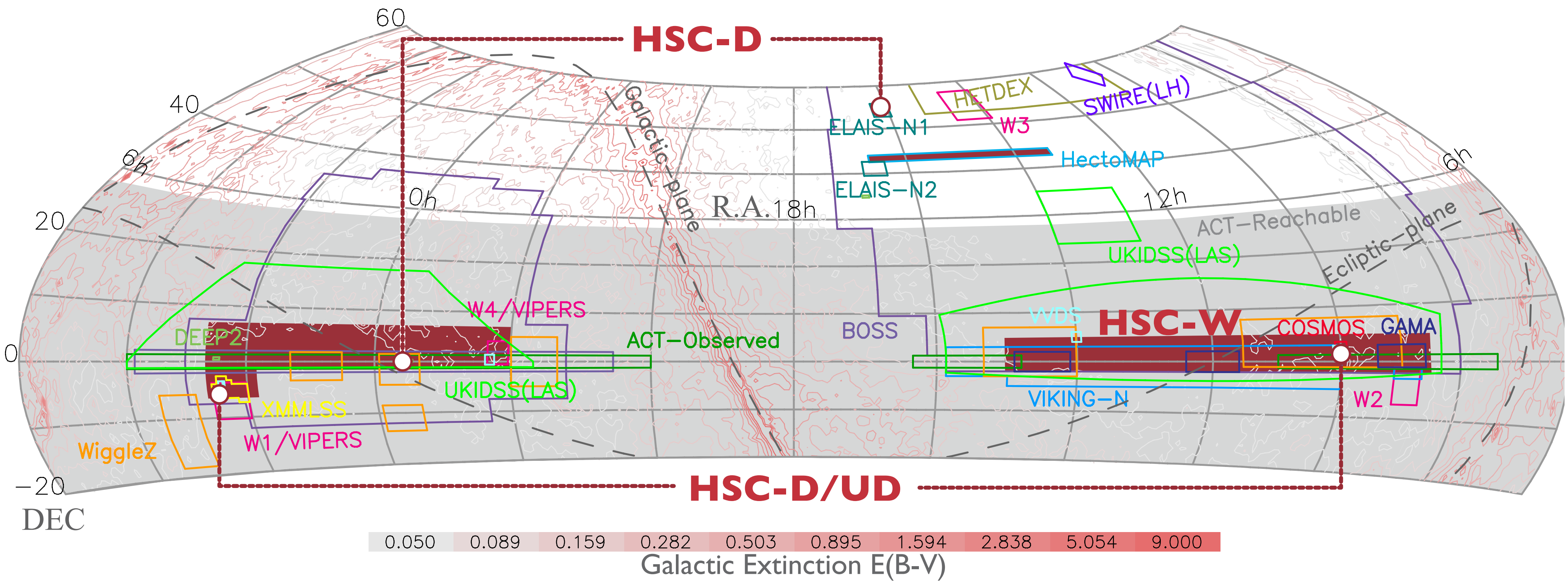
Hyper Suprime-Cam FoV

- **Fa**
- a co

HSC Collaboration

International collaboration (Japan, Taiwan, Princeton U.)

HSC Survey Fields



- **Subaru 300 nights** granted (2014 – 19)
- HSC Survey Fields selected based on
  - Overlap with SDSS regions and other interesting, external datasets (ACT CMB, NIR, spectroscopic surveys, …); Low dust extinction; Spread in RA
- The main scientific objectives are
  - Wide: Cosmology, Deep: galaxy evolution, UD: cosmic reionization

First Data Release (DR1) of HSC SSP

28 Feb, 2017

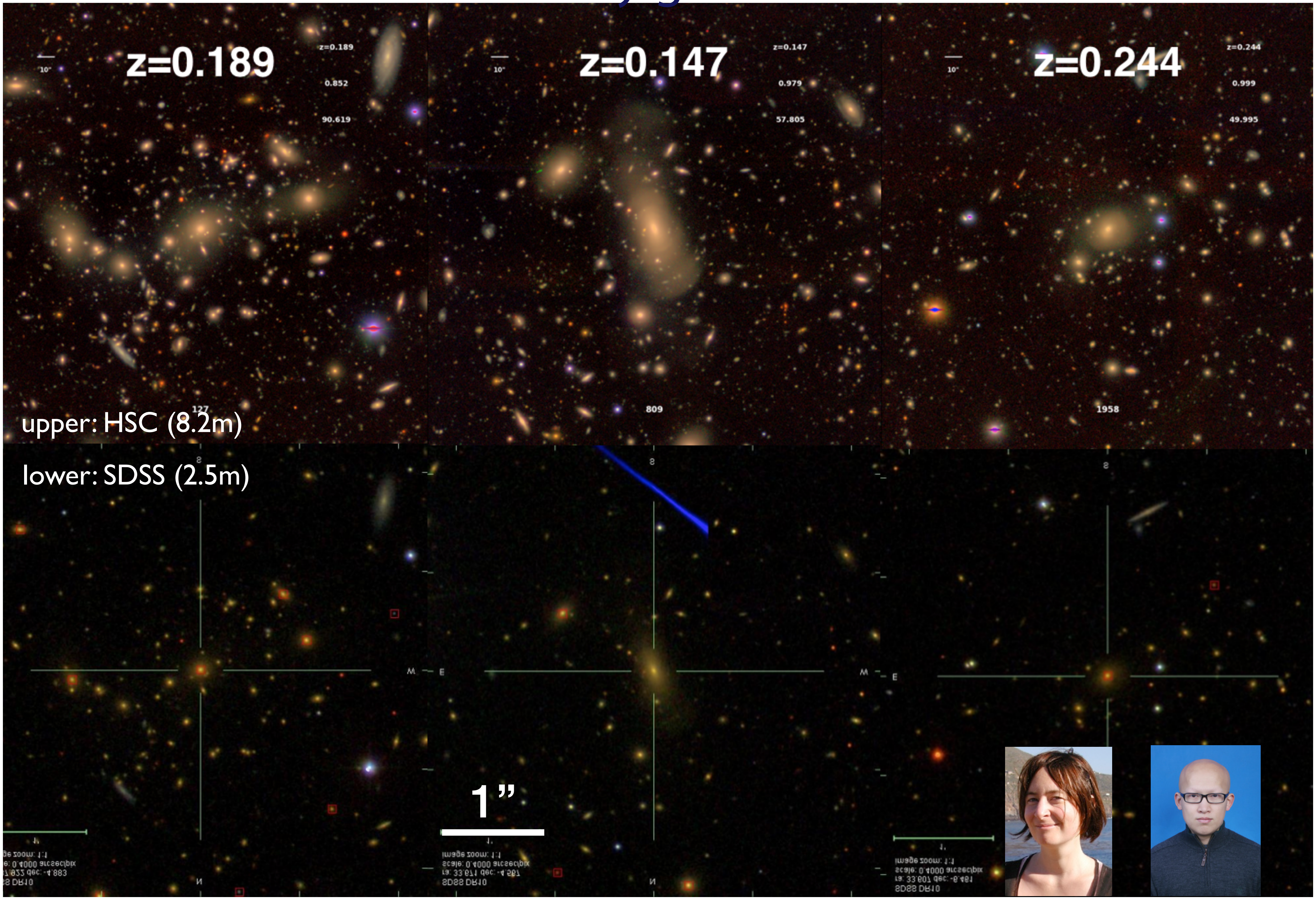
~60 Subaru nights, ~100 sq. deg., ~10^8 objects ≃10yrs SDSS

NAOJ News About Projects Access/Visiting Astronomical Information Gallery Search Japanese

First Public Data Release by the Hyper Suprime-Cam Subaru Strategic Program

February 28, 2017 | Topics

Nearby galaxies



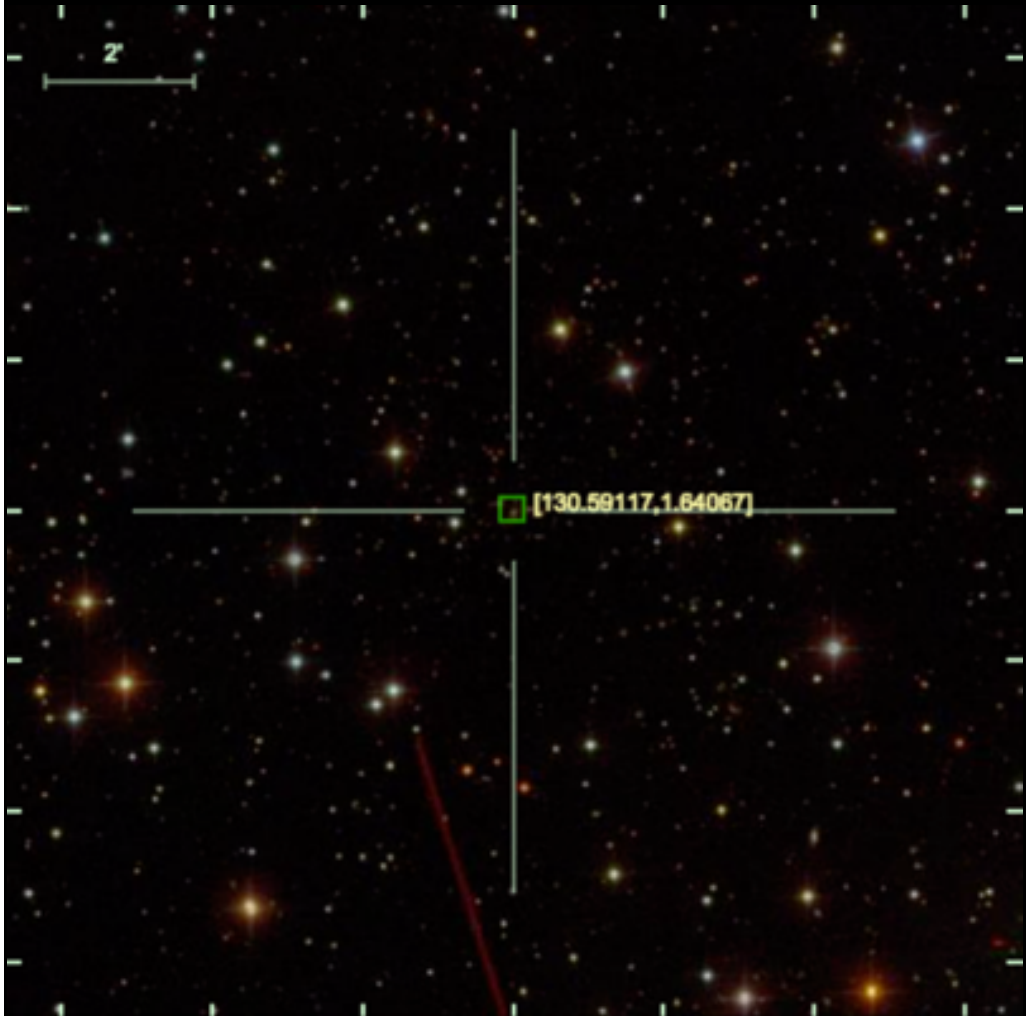
A. Leauthaud S. Huang

All data reduced by the HSC pipeline

Galaxy Clusters

M. Oguri

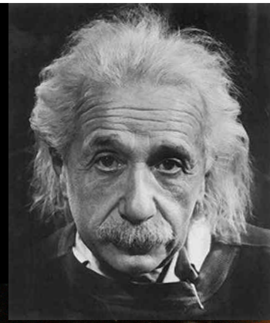
SDSS (2.5m, r<21, ~1″)



Subaru HSC (8.2m, r<26, 0.6″)

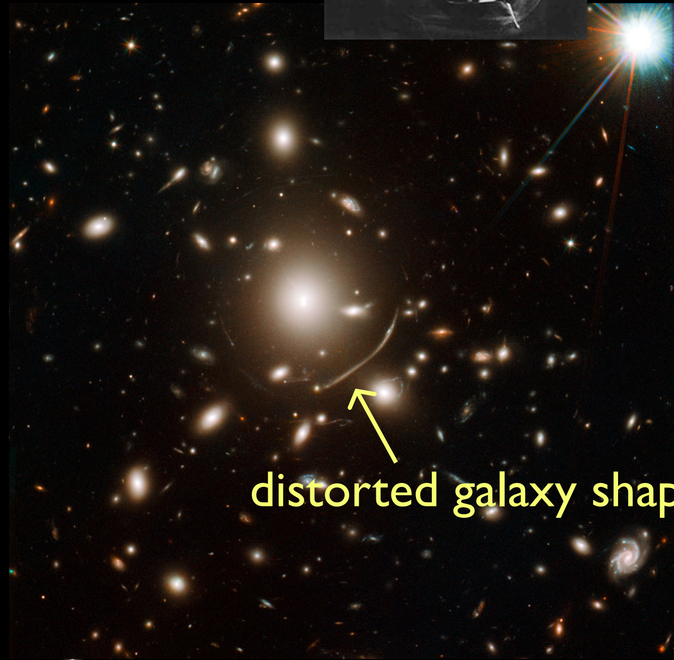
the same rich cluster region at z=0.41

Gravitational lensing = GR prediction



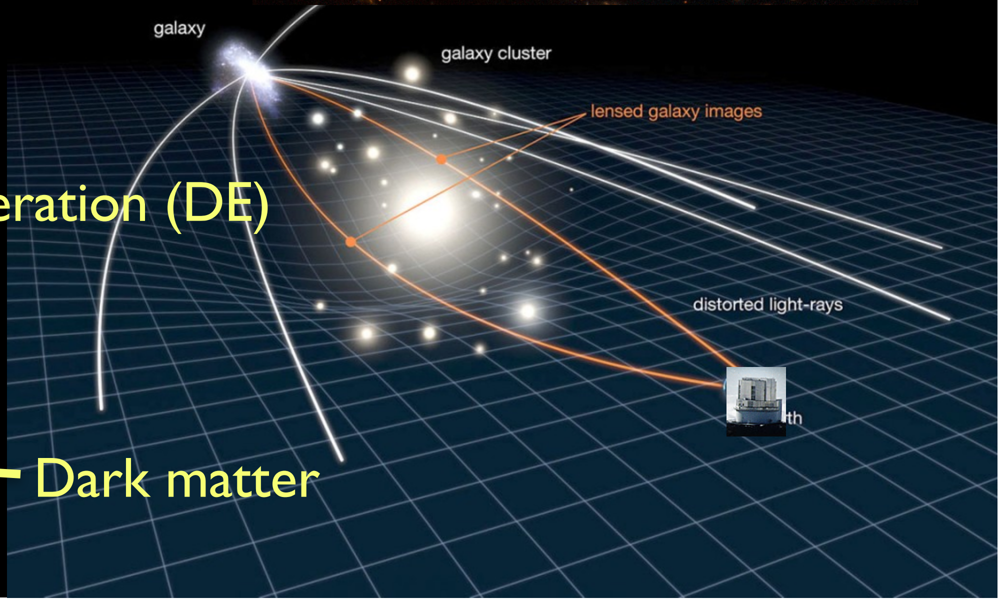
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Rightarrow \text{ light path: } \boldsymbol{x} = \boldsymbol{x}[z; g_{\mu\nu}]$$



Light-ray path, emitted from a distant galaxy, is bent by the foreground matter distribution

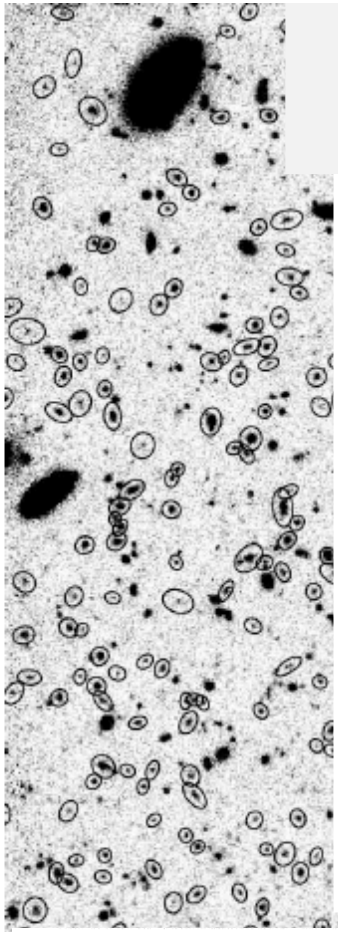
It causes a distortion in galaxy image

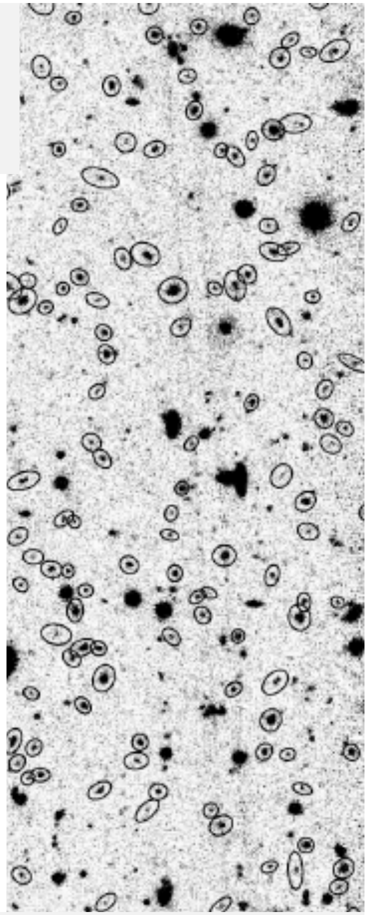


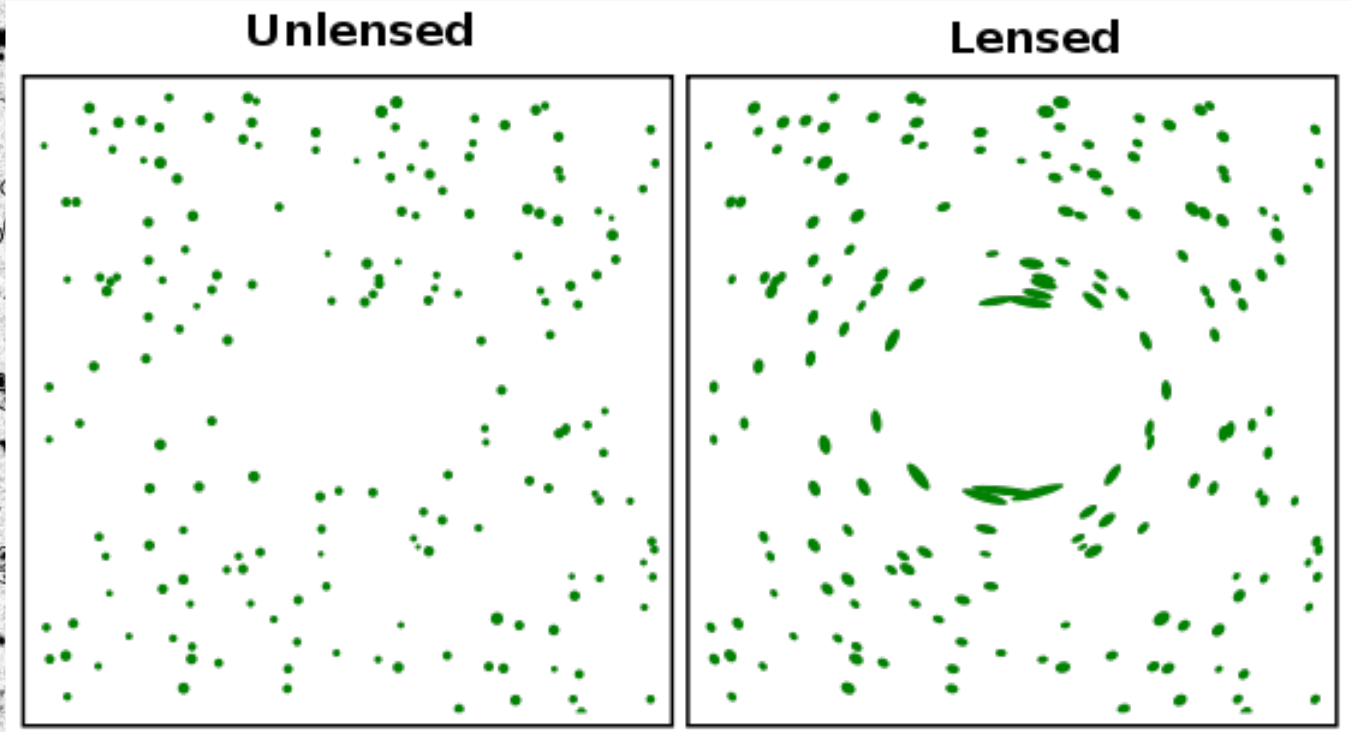
Cosmic acceleration (DE)

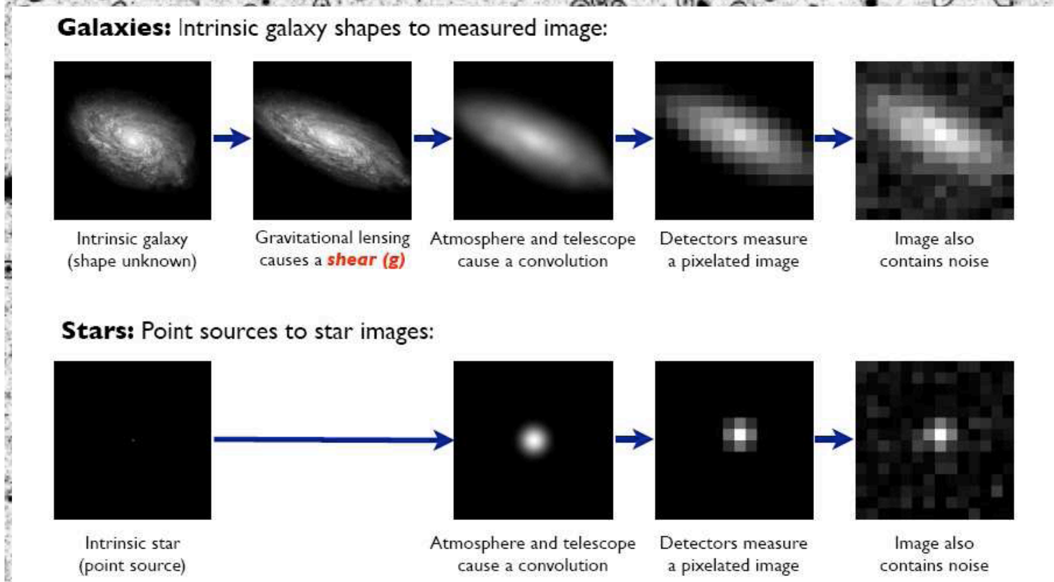
Lensing strength =
(geometry of the universe)
× (total matter of lens(es)) ← Dark matter

Weak lensing effect









- Extract **coherent distortion pattern** in different galaxy images
- Need to analyze **many galaxy** images to extract the signal
- All galaxies **lensed** more or less
- Tiny signal: **O(0.01) in ellipticity**
- A **sharp** image/an **accurate method**

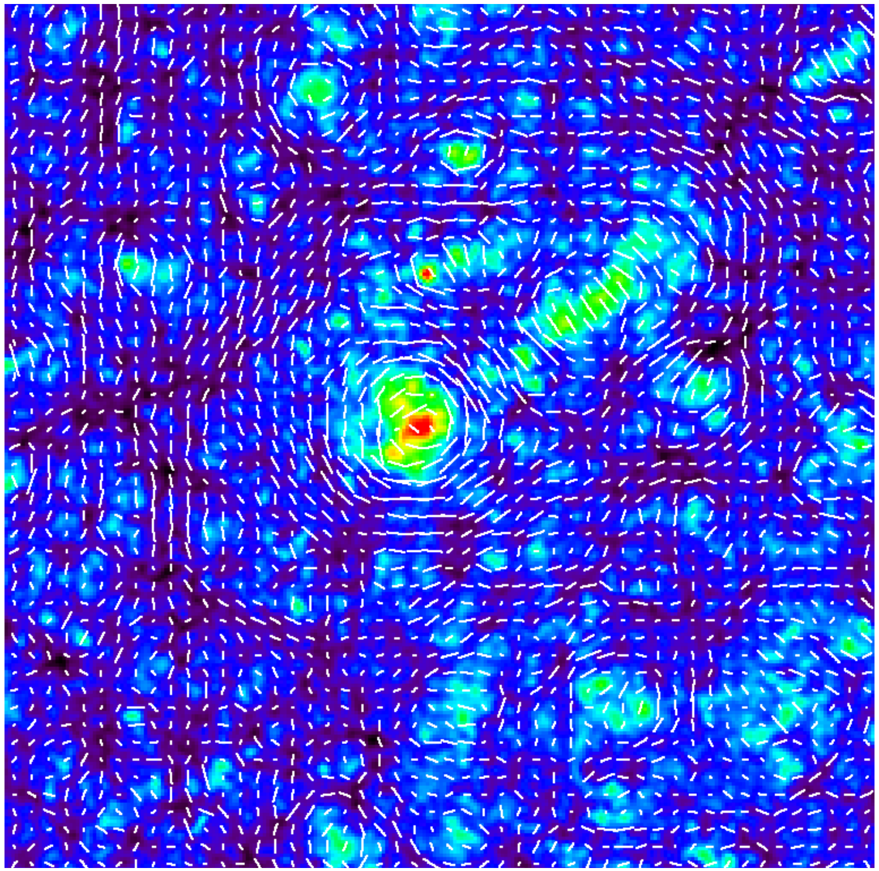
Weak lensing

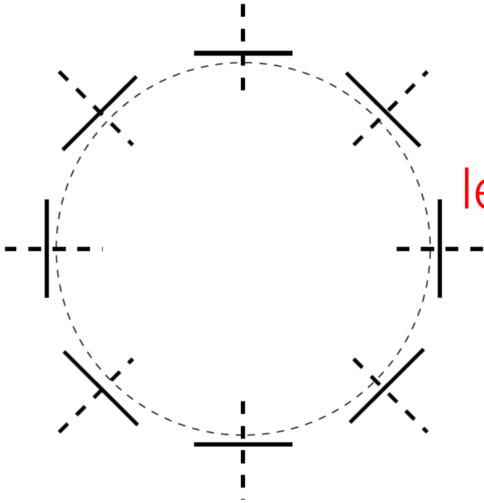
The signal is tiny: allows for a **direct reconstruction** of gravitational potential due to nonlinear matter distribution in the universe

shear $$\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}_{\rm photon\ path}(t)]$$

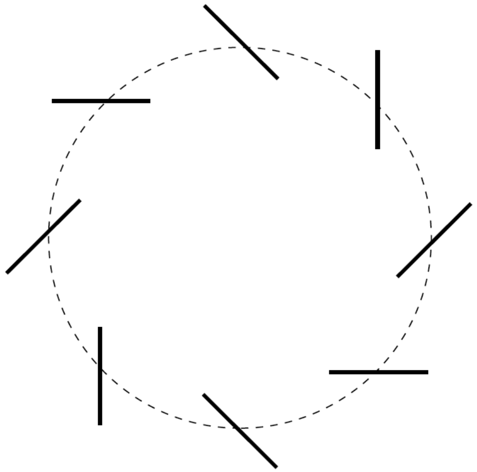
$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \bar{\rho}_m a^2 \delta_m(\mathbf{x}, t)$$

Simulated lensing map (color = 2D DM map, stick=shear)





lensing mode (E mode)



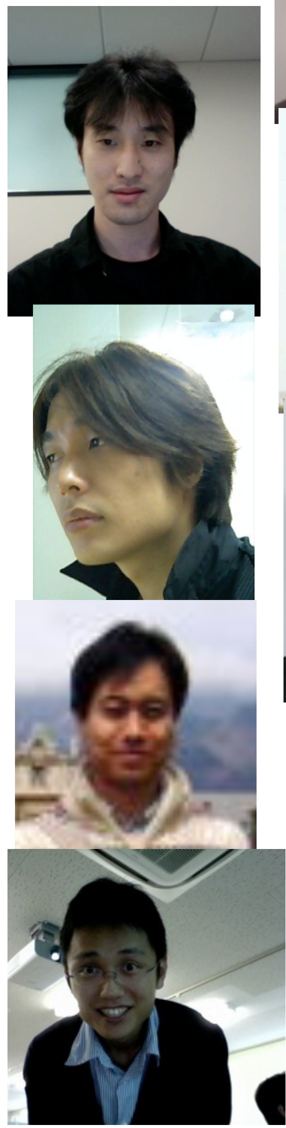
non-lensing mode (e.g., systematics) (B mode)

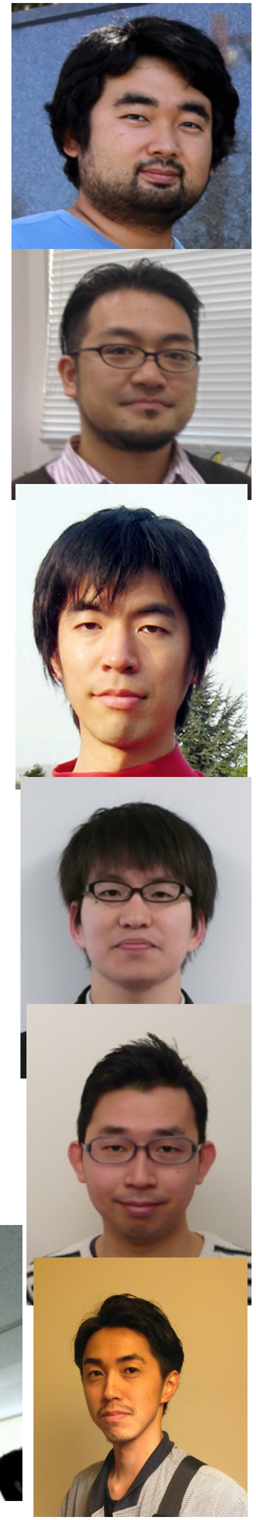
Subaru HSC weak lensing WG

Team members in Japan (2008-)

red=PD
blue=student

- Satoshi Miyazaki (NAOJ)
- Masahiro Takada (Kavli IPMU)
- Takashi Hamana (NAOJ)
- Masamune Oguri (U Tokyo/IPMU)
- Surhud More (IPMU)
- **Miyatake Hironao** (JPL/Caltech/IPMU)
- **Atsushi Nishizawa** (IPMU⇒Nagoya)
- **Chiaki Hikage** (IPMU)
- **Ryoma Murata** (IPMU)
- **Takahiro Nishimichi** (IPMU)
- **Masato Shirasaki** (NAOJ)
- Yuki Okura (RIKEN)
- Nobu Okabe (IPMU⇒Hiroshima)
- Ryuiichi Takahashi (Hirosaki)
- Yousuke Utsumi (Hiroshima)
- ….





Galaxy shape catalog now fixed (after 3 years work)!

About 1/10 data of the full 5-year data

R. Mandelbaum (CMU)

H. Miyatake (JPL/Caltech/IPMU)

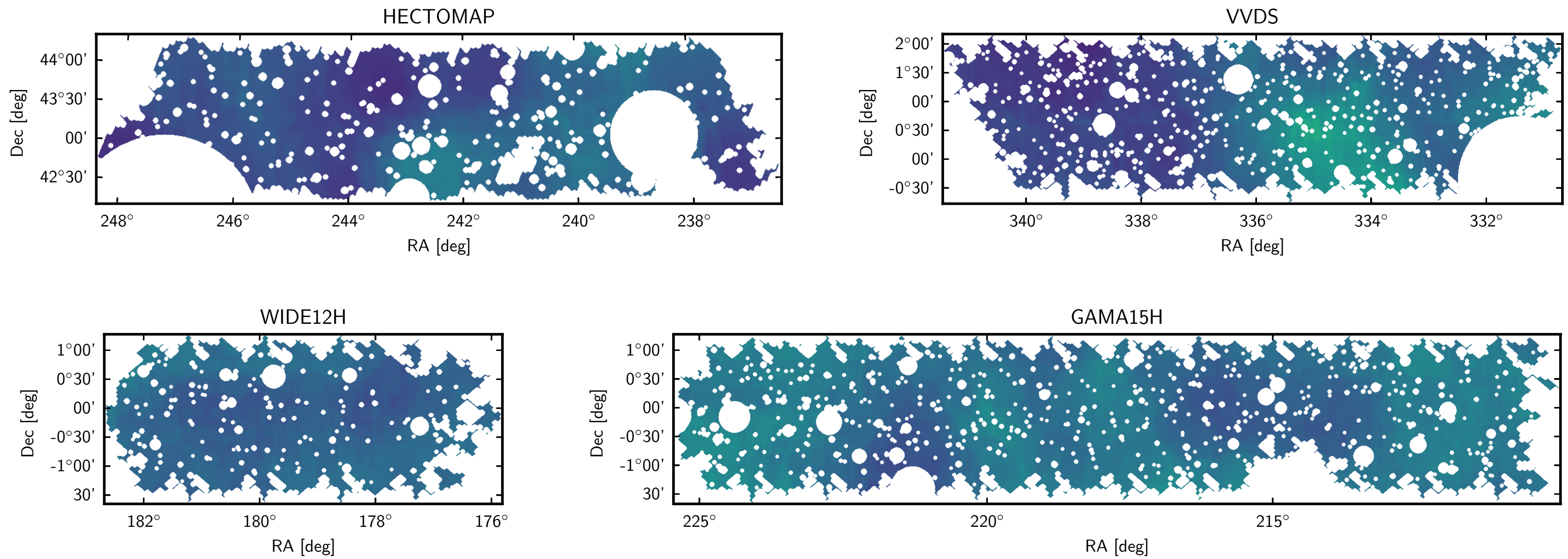
Publ. Astron. Soc. Japan (2014) 00(0), 1–41 1
doi: 10.1093/pasj/xxx000

galaxy shape

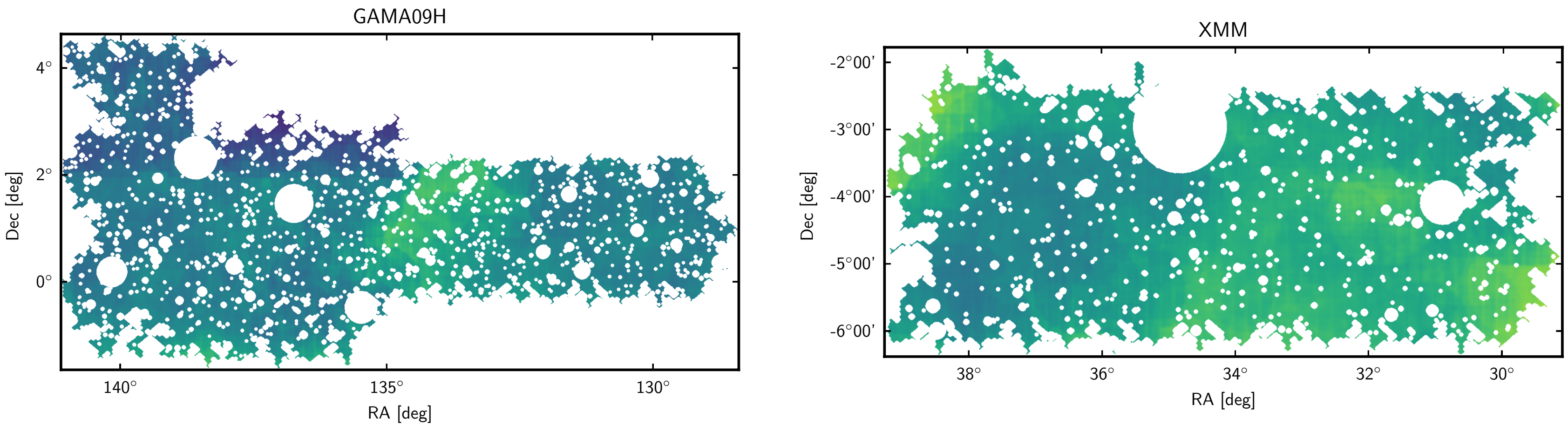
The first-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey

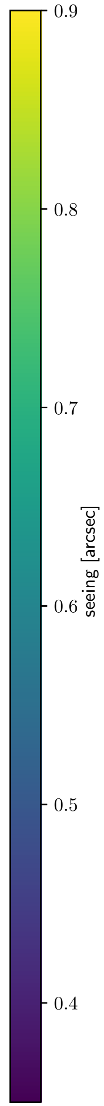
Rachel Mandelbaum[1], Hironao Miyatake[2,3], Takashi Hamana[4], Masamune Oguri[5,6,3], Melanie Simet[7,2], Robert Armstrong[8], James Bosch[8], Ryoma Murata[3,6], François Lanusse[1], Alexie Leauthaud[9], Jean Coupon[10], Surhud More[3], Masahiro Takada[3], Satoshi Miyazaki[4], Joshua S. Speagle[11], Masato Shirasaki[4], Cristóbal Sifón[8], Song Huang[3,9], Atsushi J. Nishizawa[12], Elinor Medezinski[8], Yuki Okura[13,14], Nobuhiro Okabe[15,16], Nicole Czakon[17], Ryuichi Takahashi[18], Will Coulton[19], Chiaki Hikage[3], Yutaka Komiyama[4,20], Robert H. Lupton[8], Michael A. Strauss[8], Masayuki

Subaru HSC = superb image quality



Subaru HSC typically **0.6" seeing** FWHM (spatial resolution)

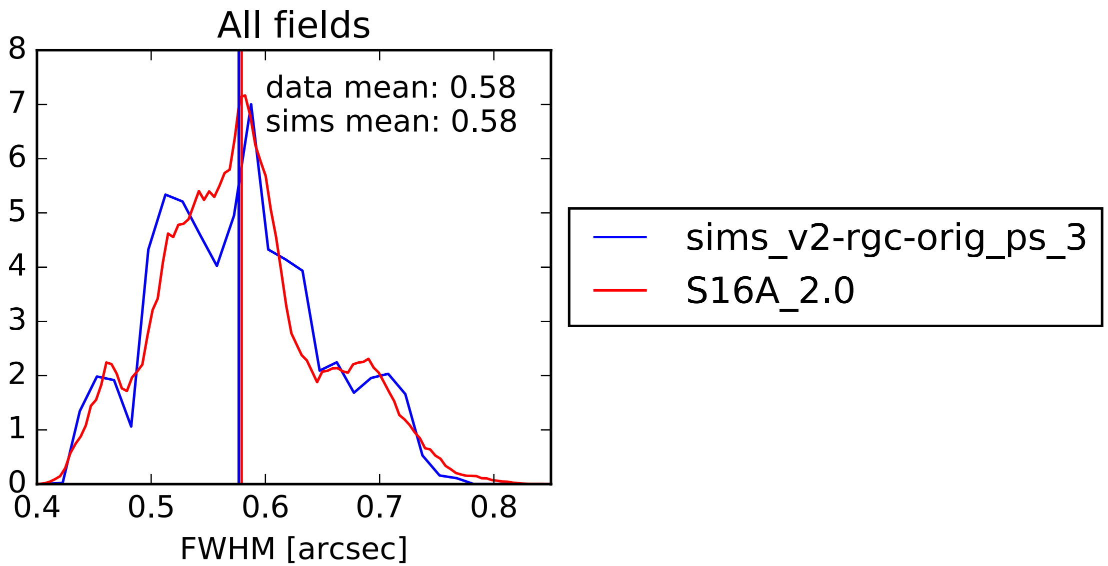


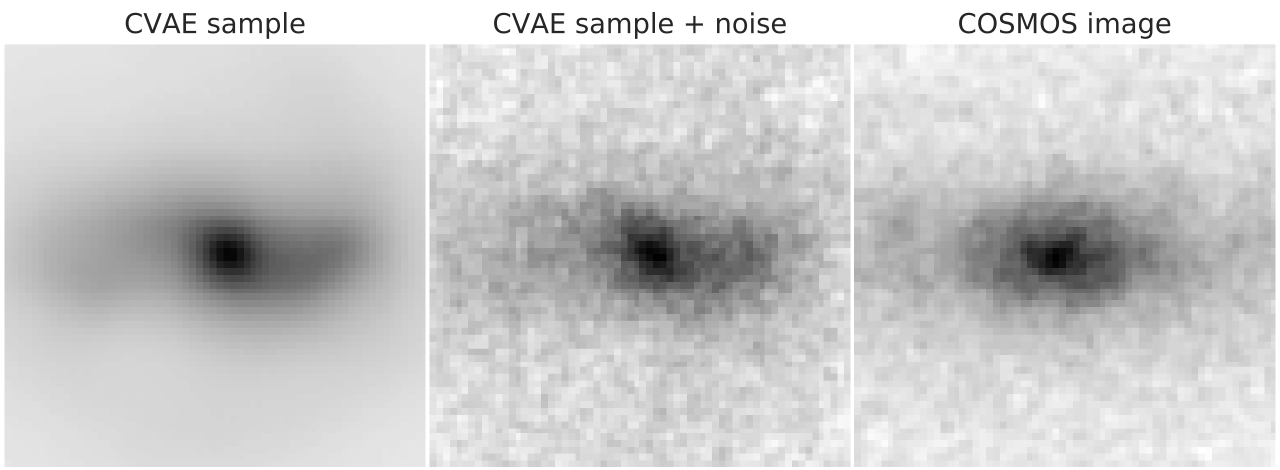


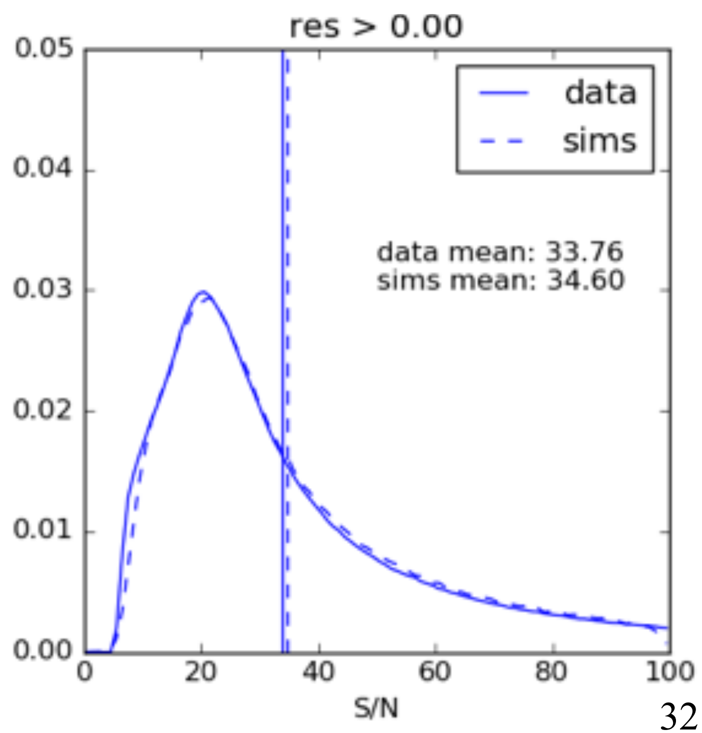
compared with the **Dark Energy Survey (DES; Fermilab): ~1"**

WL becoming experimental physics

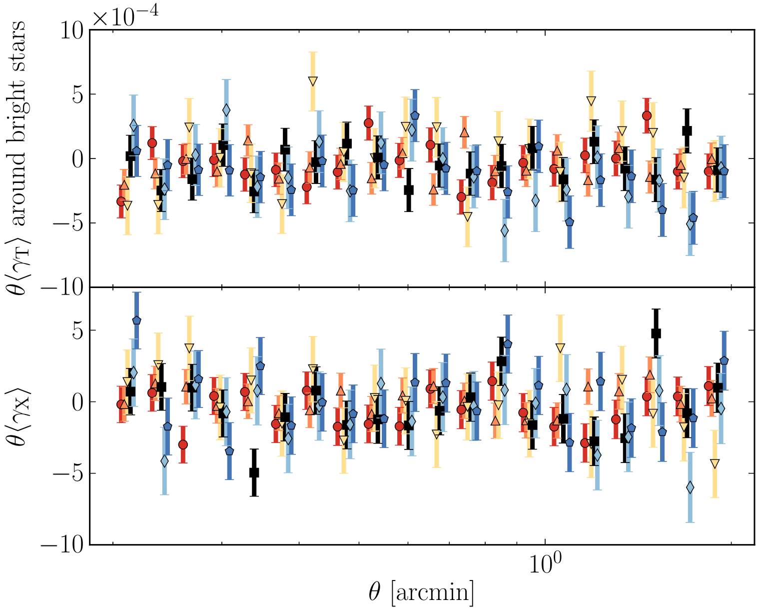
- Performed image simulations of galaxies based on the Hubble space data, fully taking into account the HSC data properties (pixel, seeing, noise, …)
- Use the image simulations to estimate calibration factors for the shape measurements



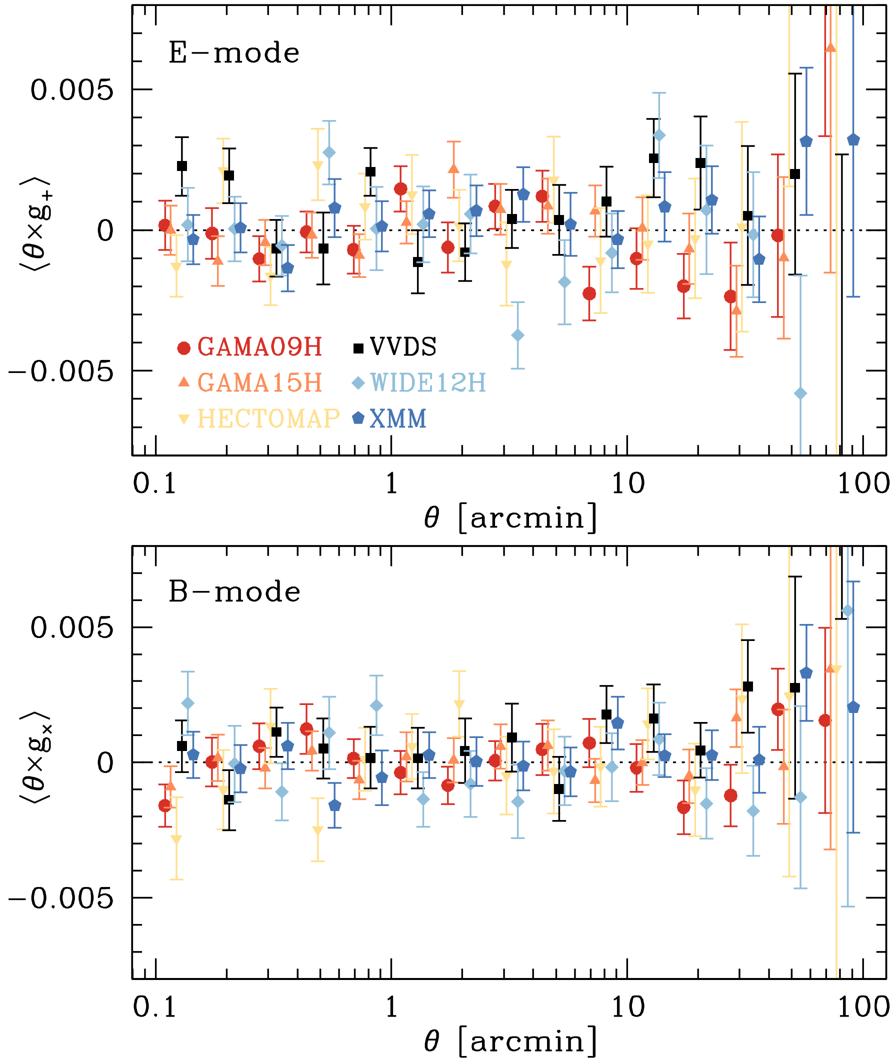


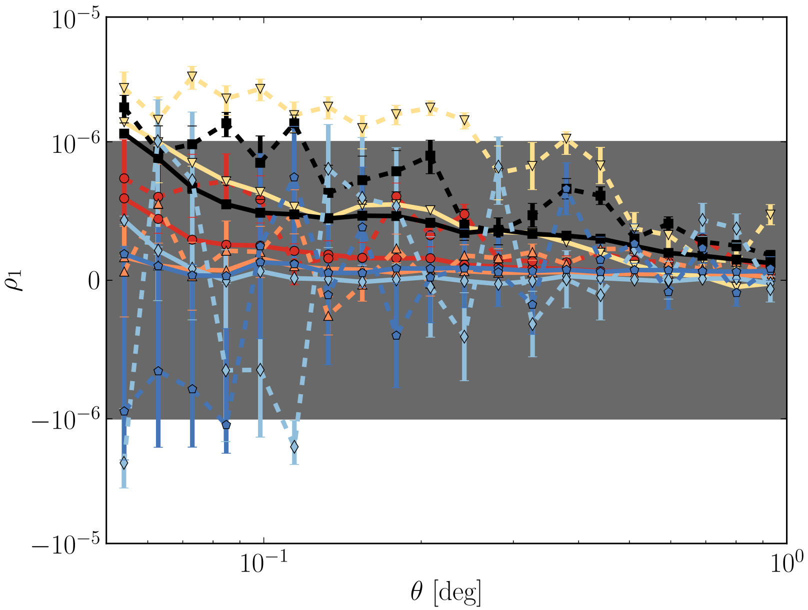


Null tests (tests of systematic errors)



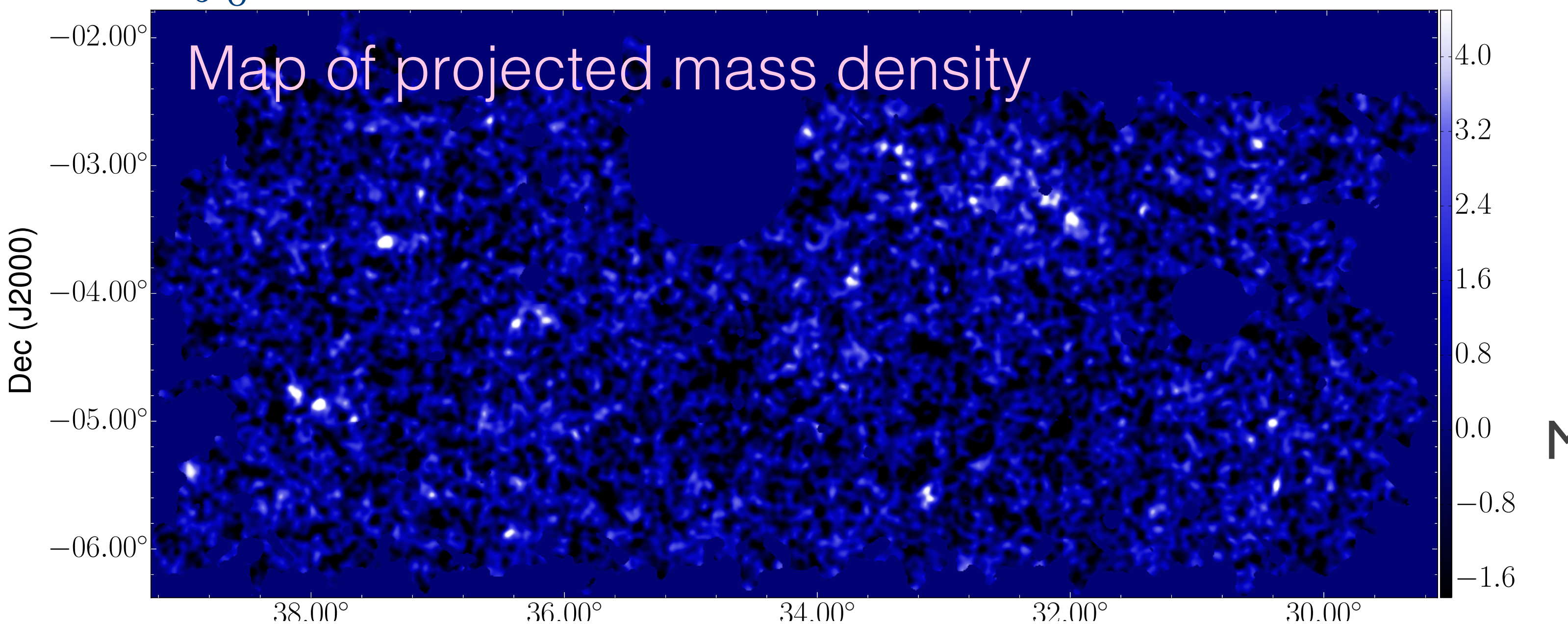
So far no major residual systematics



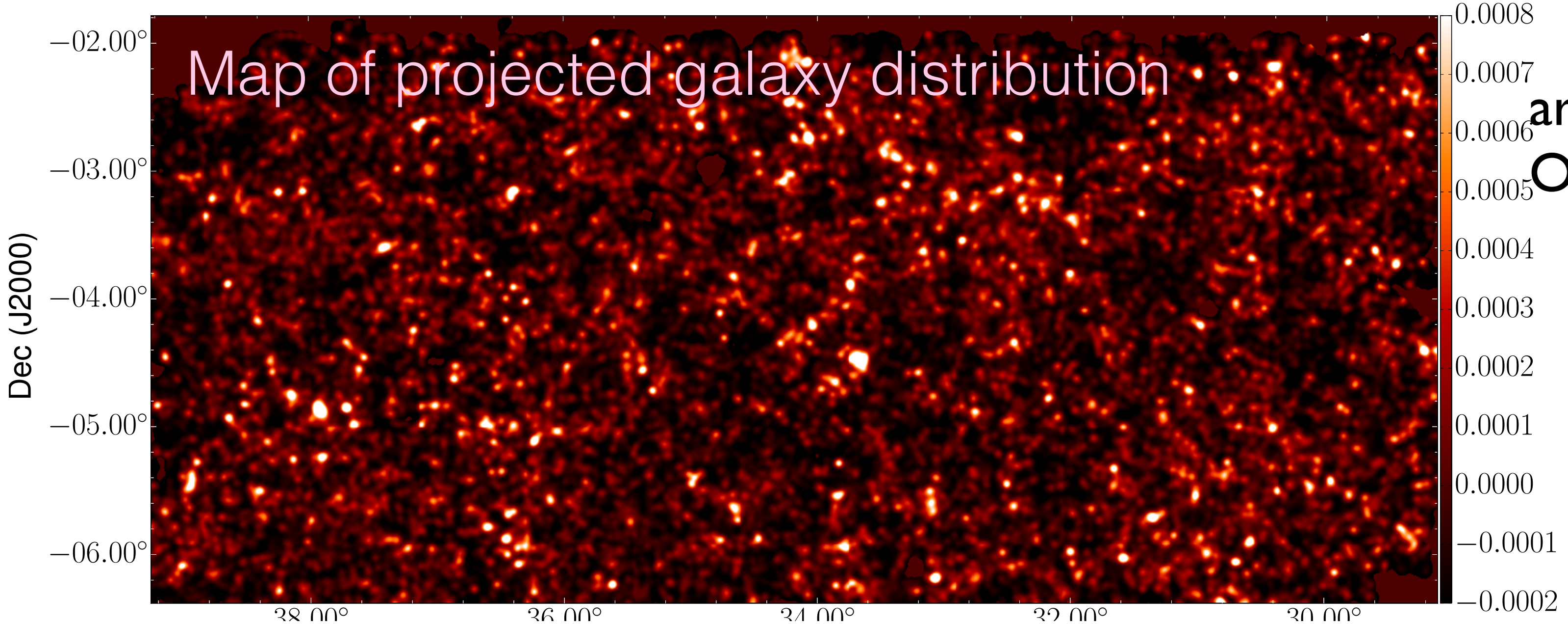


WL mass (dark matter) maps

$$\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}(t)] \rightarrow \Phi^{\mathrm{2D}} \sim \nabla^{-1} \nabla^{-1} \gamma_{ij} \rightarrow \Sigma_m^{\mathrm{2D}}(\boldsymbol{\theta})$$

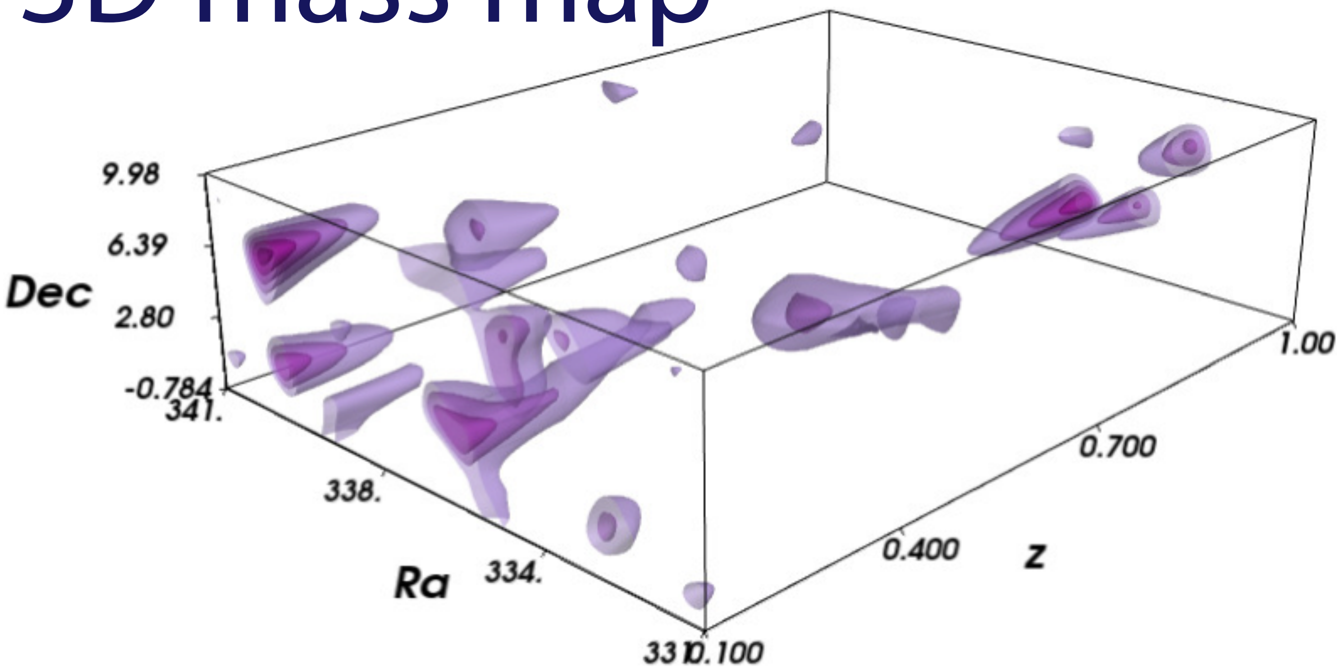


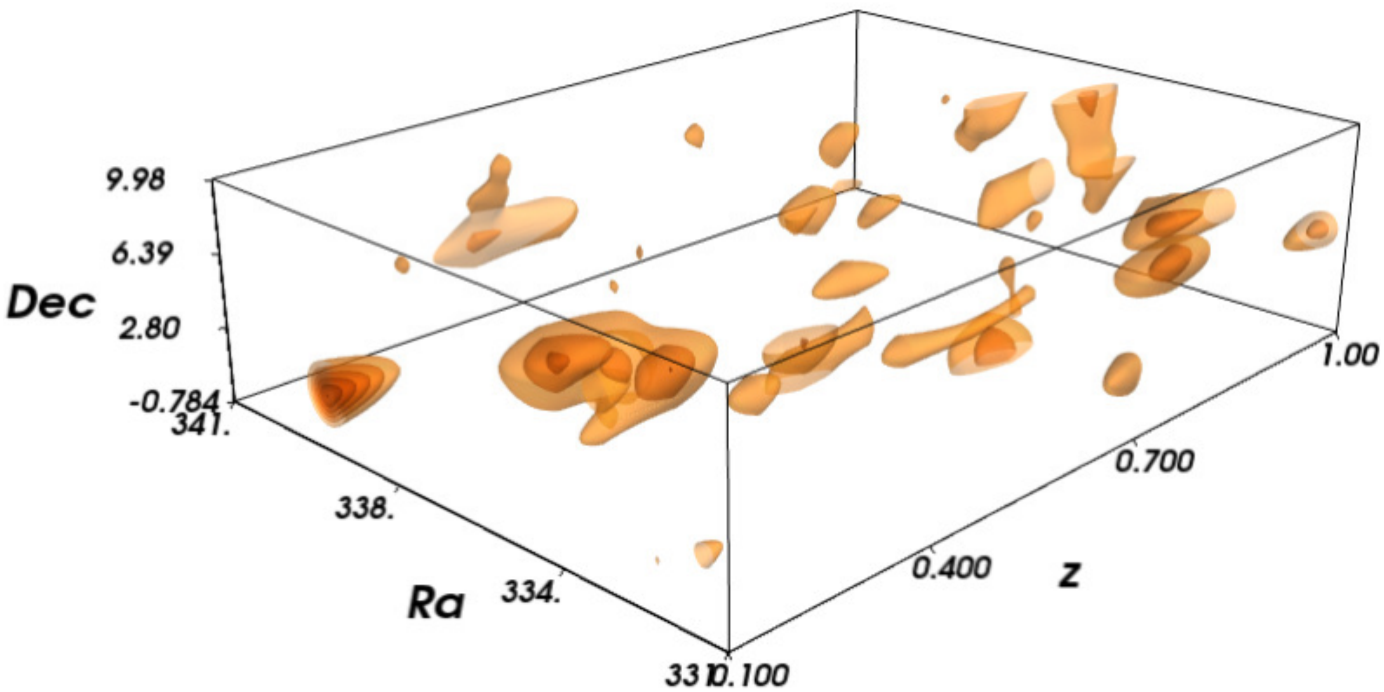
Masamune Oguri (Tokyo/IPMU)



arXiv:1705.06792
Oguri et al.

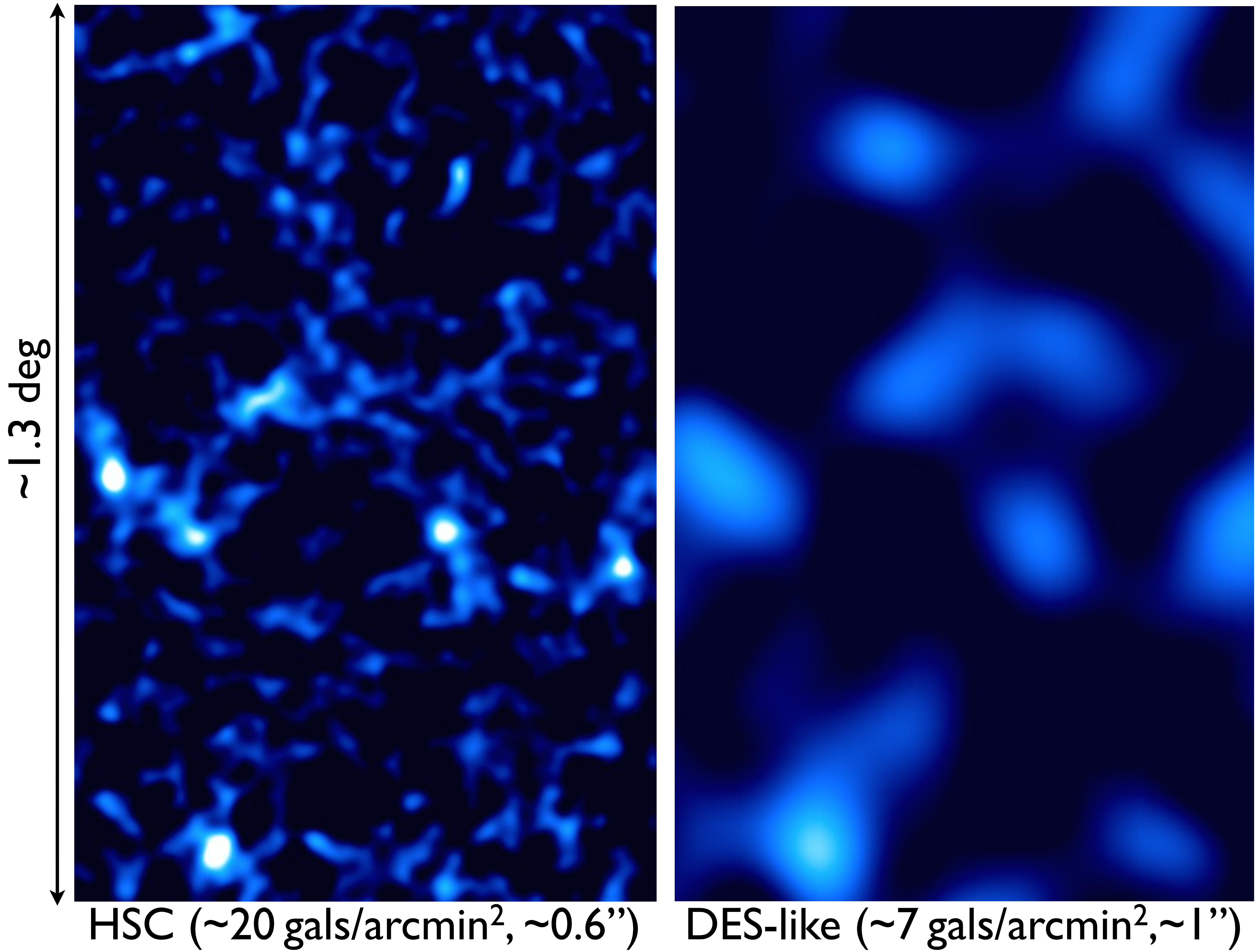
3D mass map





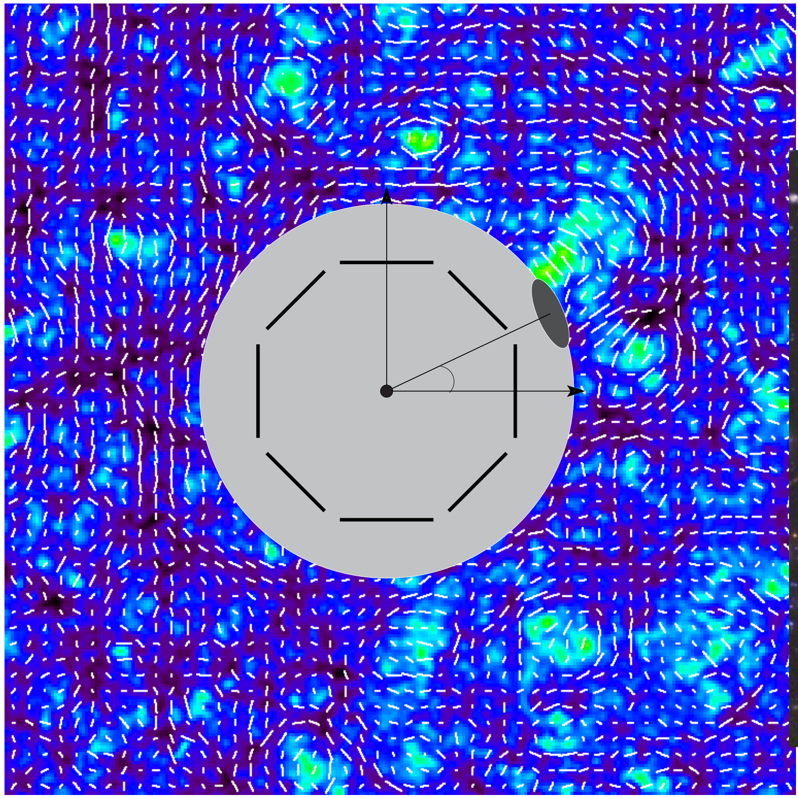
Combining the galaxy shapes and photometric redshift of each galaxy (approximate distance measure), we can recover the 3D distribution of matter

Mass and galaxy maps show a nice correspondence

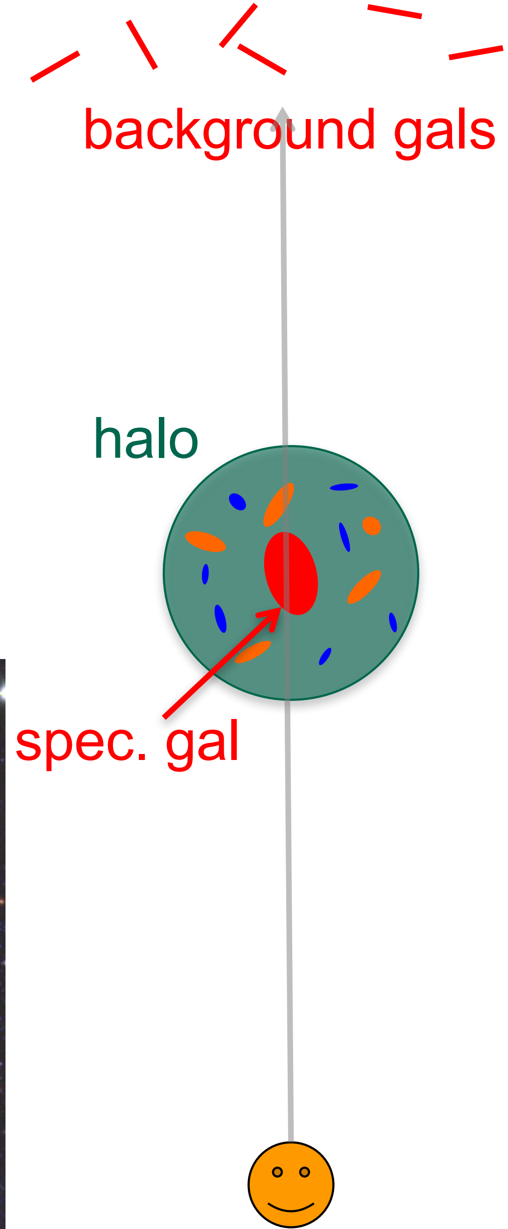

~1.3 deg
HSC (~20 gals/arcmin², ~0.6")
DES-like (~7 gals/arcmin²,~1")

Galaxy(cluster)-shear lensing

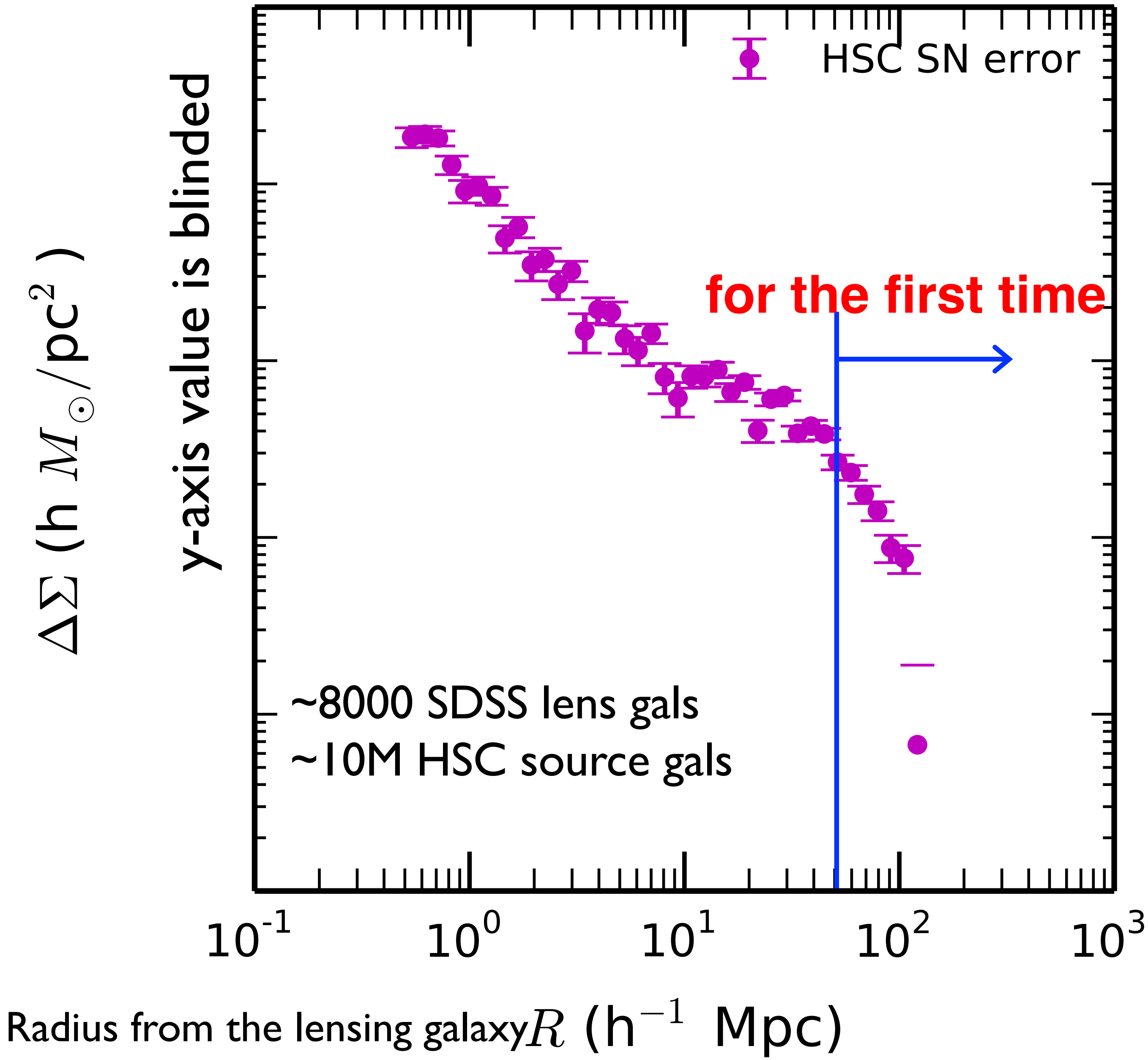
- HSC SSP survey regions have a full overlap with the SDSS spectroscopic survey fields (=bright, massive galaxies)
- Measure a coherent ***tangential* shear pattern** of background galaxies, around each SDSS galaxy $\Rightarrow$ can probe the average **mass distribution** around the galaxies



Subaru data



HSC galaxy-galaxy lensing



- The average, projected mass density profile around galaxies
- Clearly show **the existence of DM** around bright galaxies
- The superior HSC data allows for a detection of very tiny signal **up to ~100Mpc**
- Large-scale signal = **clean** (more in the linear regime)

Challenges in WL cosmology

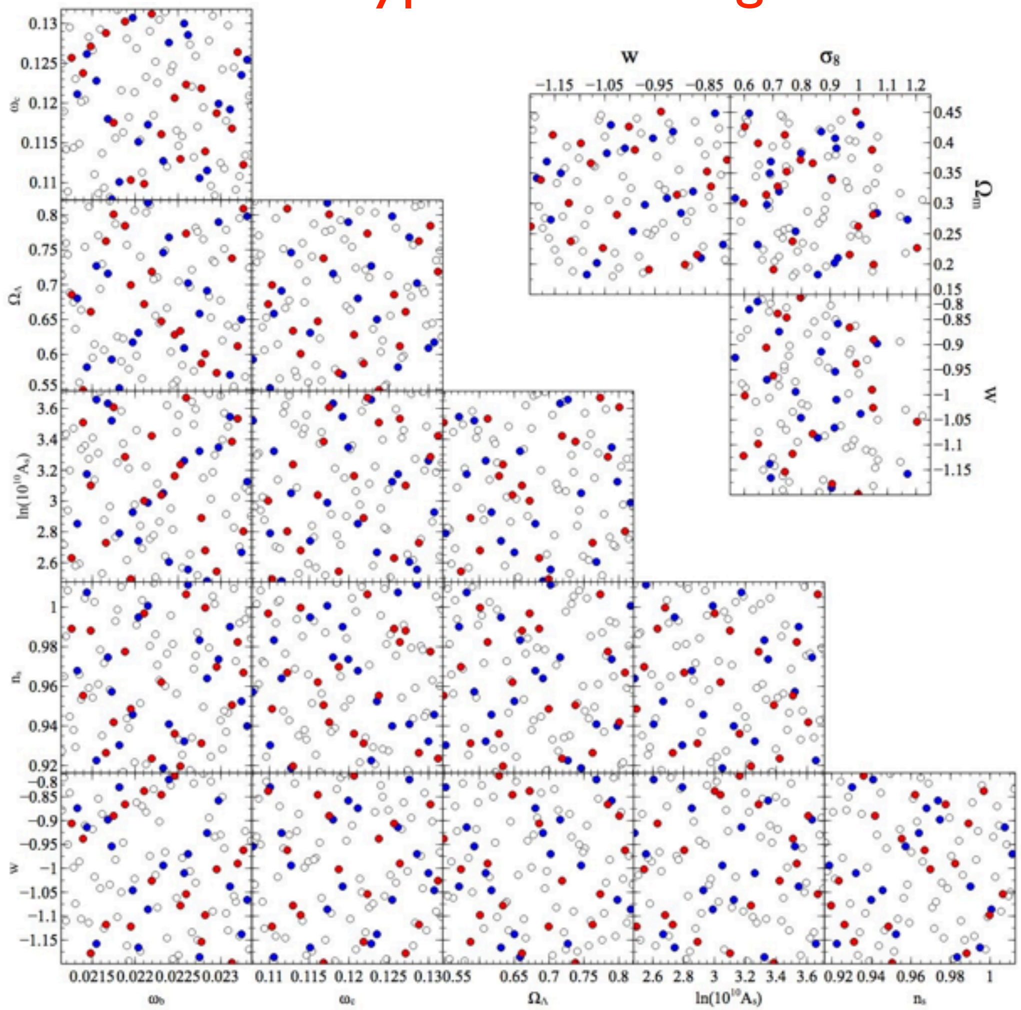
- Residual systematic errors in shape measurements 😄
- Blending in galaxies in deep Subaru data 😵
- Uncertainties in photometric redshifts (distances to source galaxies) 😕
- Nonlinearities in structure formation 😄
- Baryonic (astrophysical) effects on structure formation ☹️
- Galaxy bias uncertainty ☹️

Halo Emulator

Nishimichi et al. in prep.

- 1Gpc/h or 2 Gpc/h, **N_{part}=2048^3** for each realization
- 24 (20) realizations for Planck
- 60 realizations for different cosmologies
- 21 snapshots over 0<z<1.5 (stepped by growth rate)
- **~200Tb** (so far)
- Prost-processing (Rockstar)
  - Halos & subhalos
  - Halo center: the potential minimum
  - SO mass. Every member DM particle belongs to one halo (avoid double counting)

Latin Hypercube Design



$\omega_b : \pm 5\%, \quad \omega_c : \pm 10\%, \quad \Omega_{\rm de} : \pm 20\%$

$\ln(10^{10} A_s) : \pm 20\%, \quad n_s : 5\%, \quad w_{\rm DE} : \pm 20\%$

jupyter tutorial Last Checkpoint: 06/29/2017 (autosaved)

Logout

File Edit View Insert Cell Kernel Help

Not Trusted

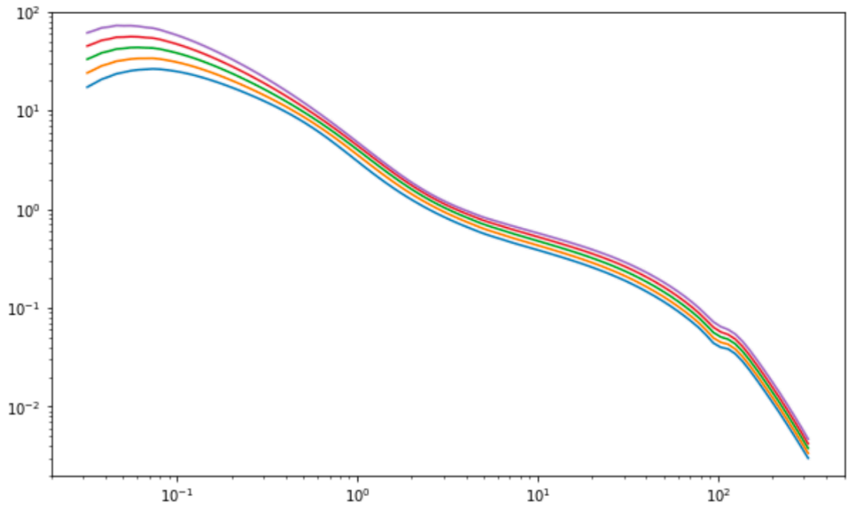
Python 2

Code

how to plot DeltaSigma(R) for a mass threshold halo sample

In [9]:
```
rs = np.logspace(-1.5,2.5,100)

plt.figure(figsize=(10,6))

Mmin = 3e12

for snap in [0,5,10,15,20]:
    emu.set_cosmology_predefined(0,snap)
    dsigma = emu.get_DeltaSigma_massthreshold(rs,Mmin)
    plt.loglog(rs,dsigma)
plt.ylim(0.002,100)
```

Out[9]: (0.002, 100)



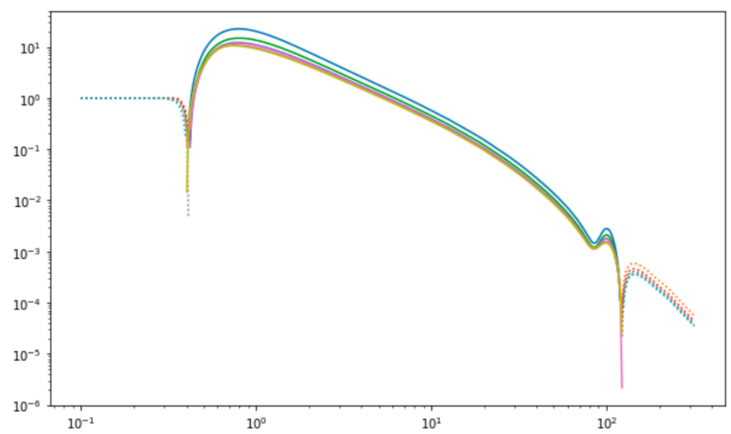
$$\xi_{\mathrm{m}}(r;z),\ \frac{\mathrm{d}n}{\mathrm{d}M},\ \xi_{\mathrm{hm}}(r;z,M),\ \xi_{\mathrm{hh}}(r;z,M_1,M_2)$$

$$\Sigma(R;z,M),\ \Delta\Sigma(R;z,M),\ w_{\mathrm{hh}}(R;z,M_1,M_2),\cdots$$

as a function of cosmological model, redshift, mass, separation, ….

how to plot halo-halo correlation for a mass threshold halo sample

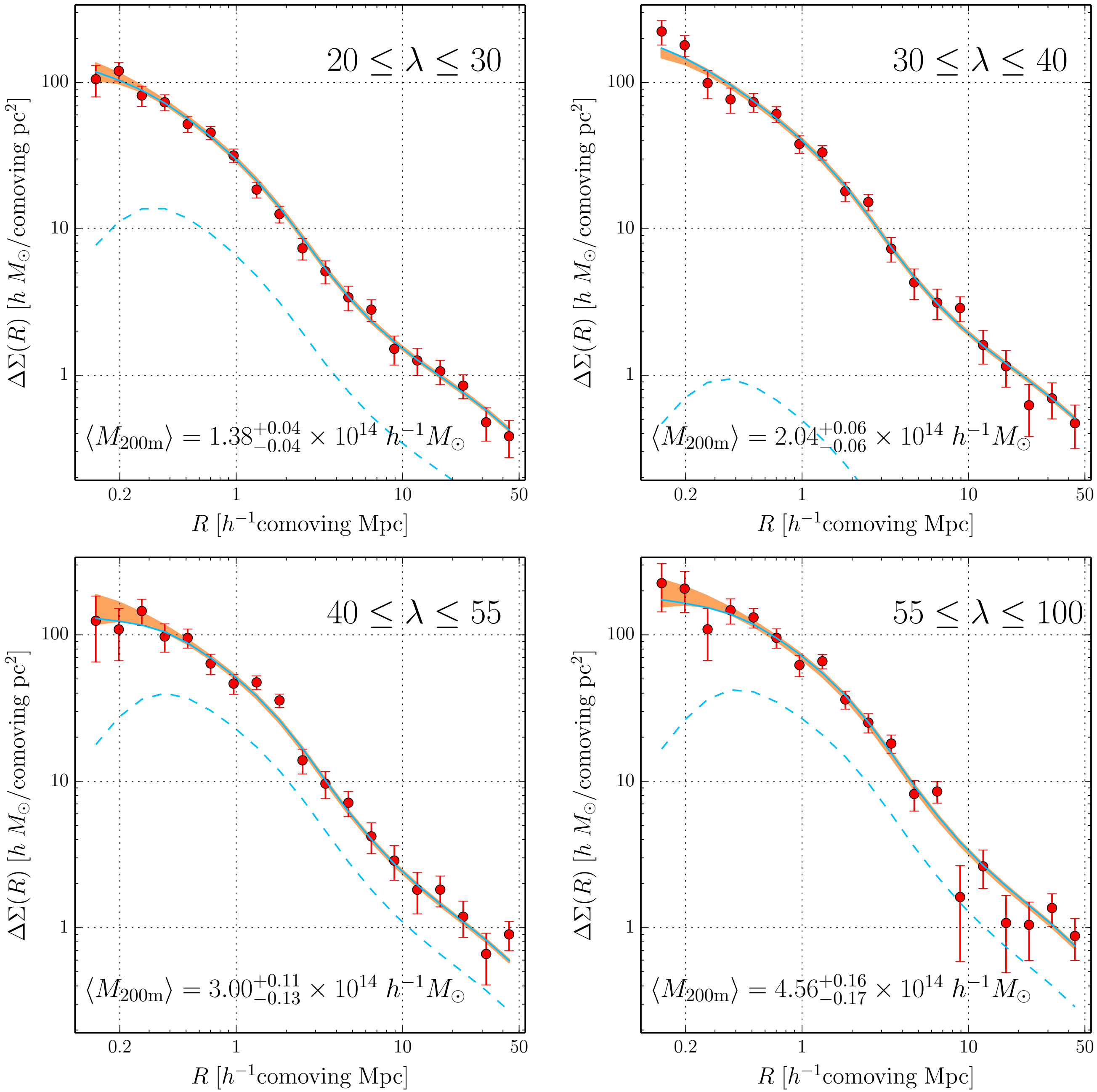
In [11]:
```
rs = np.logspace(-1,2.5,400)

Mmin = 3e12

plt.figure(figsize=(10,6))

for snap in [0,5,10,15,20]:
    emu.set_cosmology_predefined(0,snap)
    xih = emu.get_xiauto_massthreshold(rs,Mmin)
    plt.loglog(rs,xih)
    plt.loglog(rs,-xih,':')
```



Developing the python package for Halo Emulator

Emulator can reproduce the measurements

Murata et al. 17



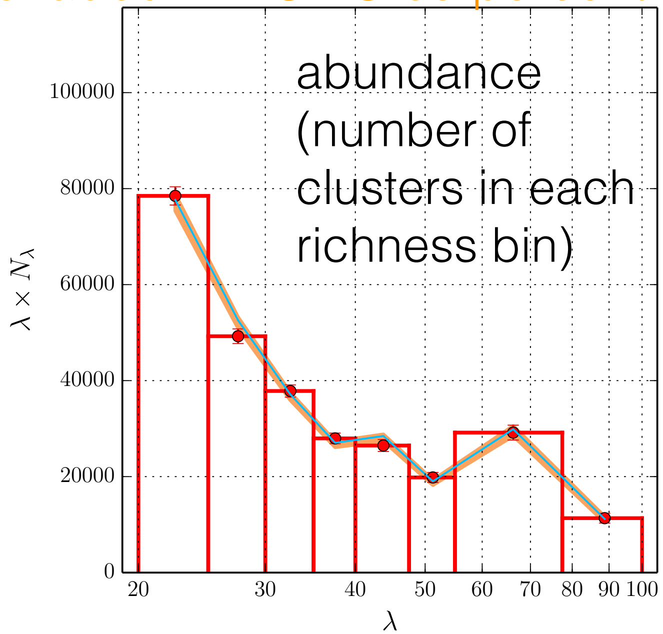
Planck cosmology

$\chi^2_{\rm min}/{\rm dof} = 79.5/75$

$\langle M_{200m,\ 20\le\lambda\le100} \rangle = 1.91^{+0.05}_{-0.05} \times 10^{14}\ h^{-1} M_\odot$

8,312 clusters
39M galaxy shapes

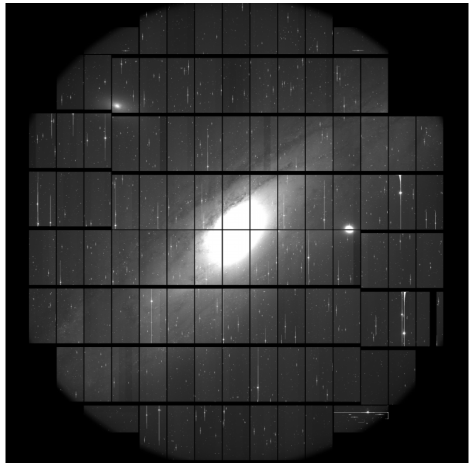
shaded = MCMC 68 percentile

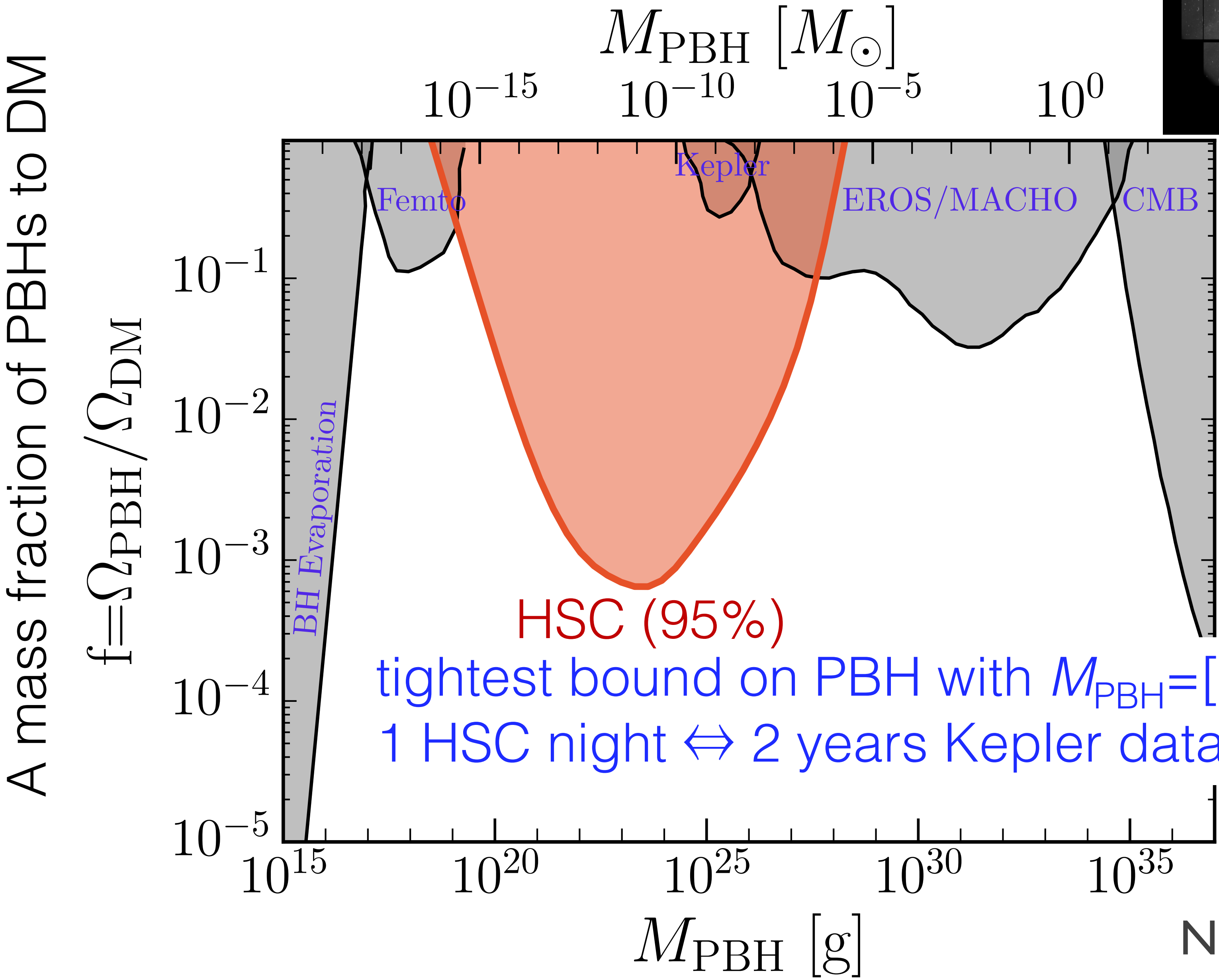


Other particle physics/cosmology science

- Boundary of dark matter halo (self-interacting DM)
- Dark matter annihilation: Subaru PFS measurement of dwarf galaxy, WL mass and Fermi cross-correlation
- Isocurvature perturbation
- Curvature (Ω_K~10^{-3}): multiverse (string theory)
- Primordial non-Gaussianity
- Microlensing due to primordial black hole/cosmic string
- Axion (relic light particles)
- ….

HSC microlensing constrain on PBH abundance





dense (2min) cadence data of M31

tightest bound on PBH with $M_{\rm PBH}=[10^{20},10^{28}]$g

1 HSC night ⇔ 2 years Kepler data

Niikura, MT, + 17

Summary

- **The wide-field capability of Subaru** is so unique, and very powerful for survey-oriented astronomy/cosmology
- **Hyper Suprime-Cam (HSC)** = Wide-field imager
  - HSC SSP survey: 2014 – 2019(20)
  - **First public data release (28 Feb, 2016)**
- **so many science cases in interdisciplinary fields between cosmology and particle physics**
  - Neutrino mass
  - Relic light particles
  - Primordial perturbations