Large-scale structure: the current status and future prospects

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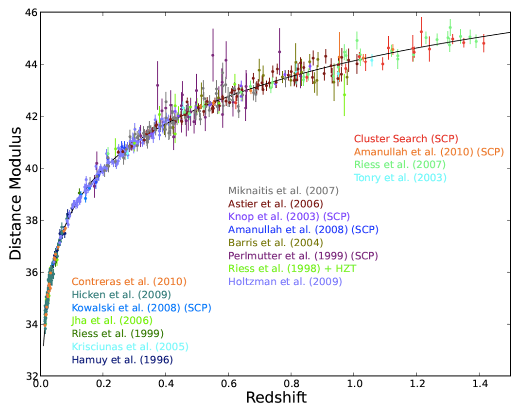
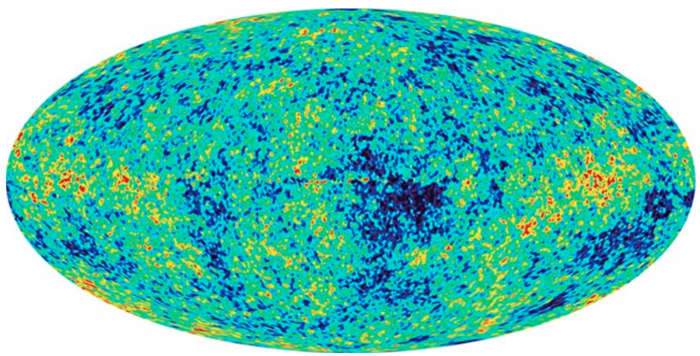
wpi

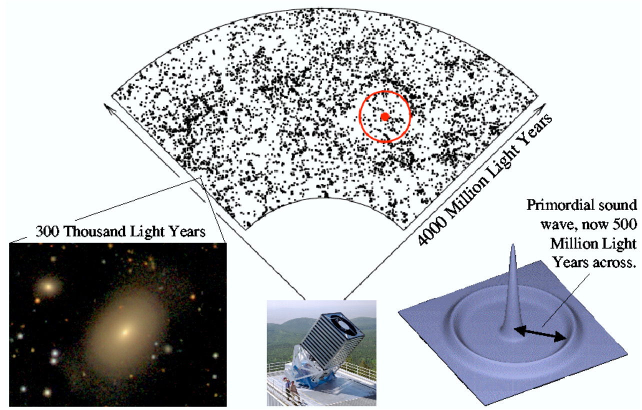
@ Osaka U Particle Physics Group, Jan 7, 2014

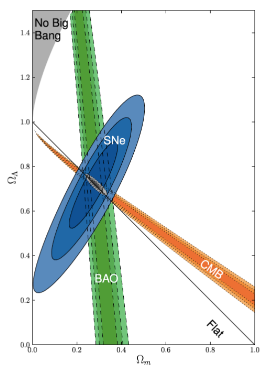
The golden age of cosmology

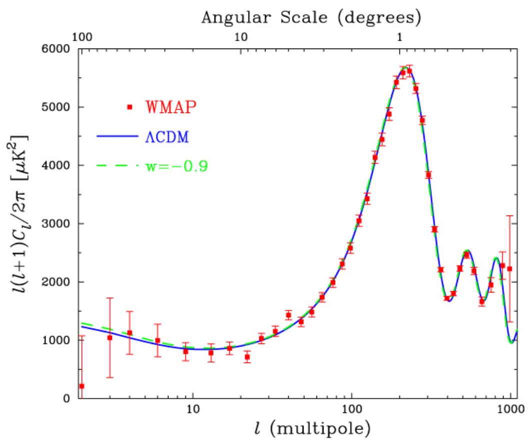
- Various data sets are now available
- The measurements keep being improved
- Can test cosmological models/scenarios very precisely: the expansion history and the growth of structure formation

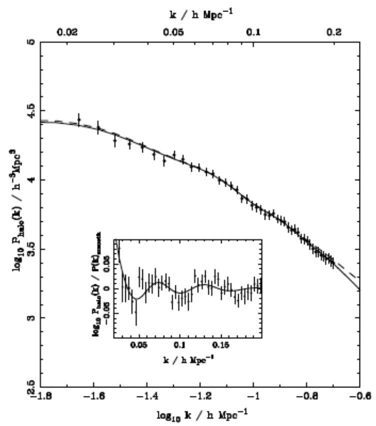




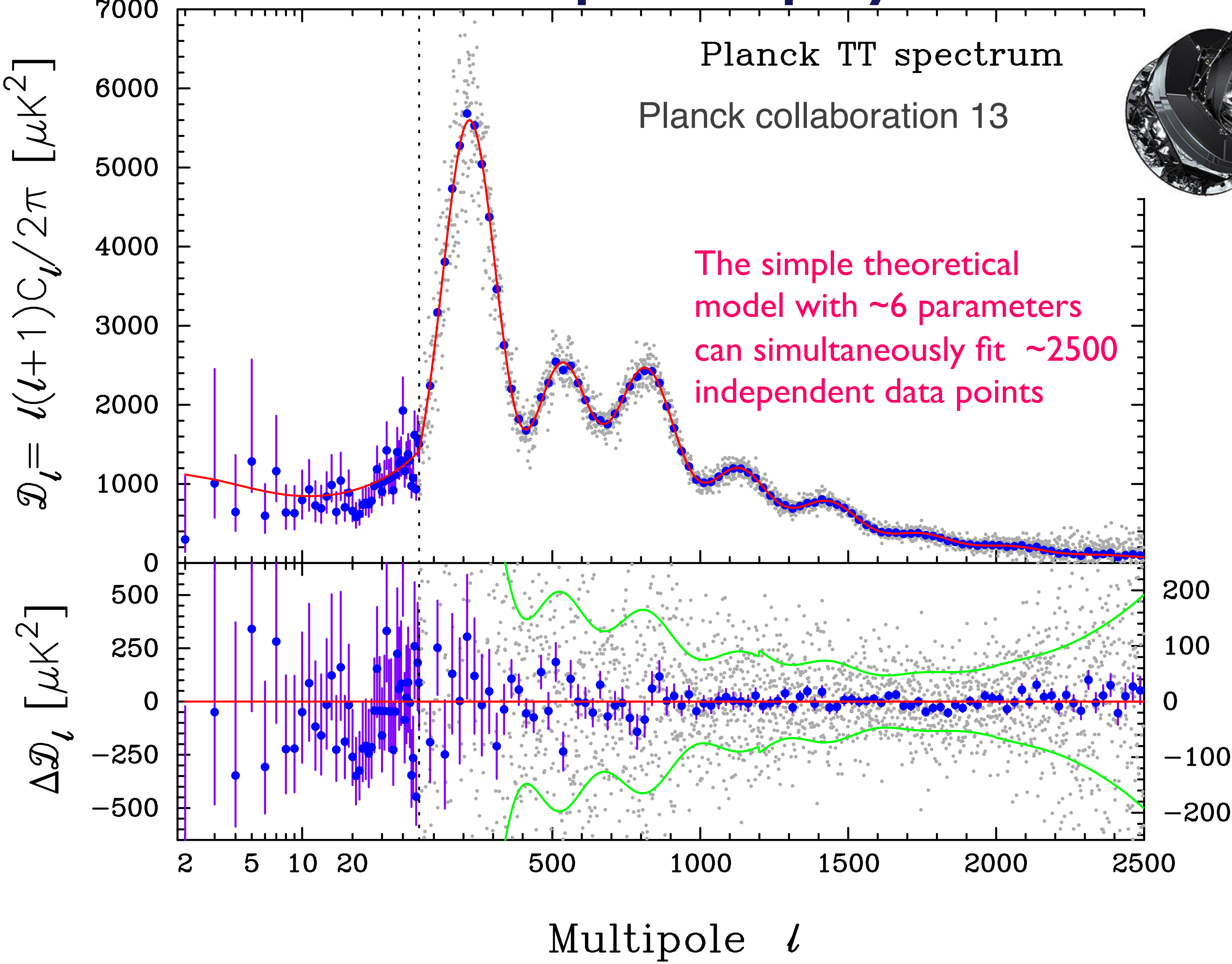


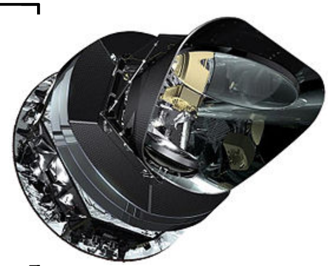






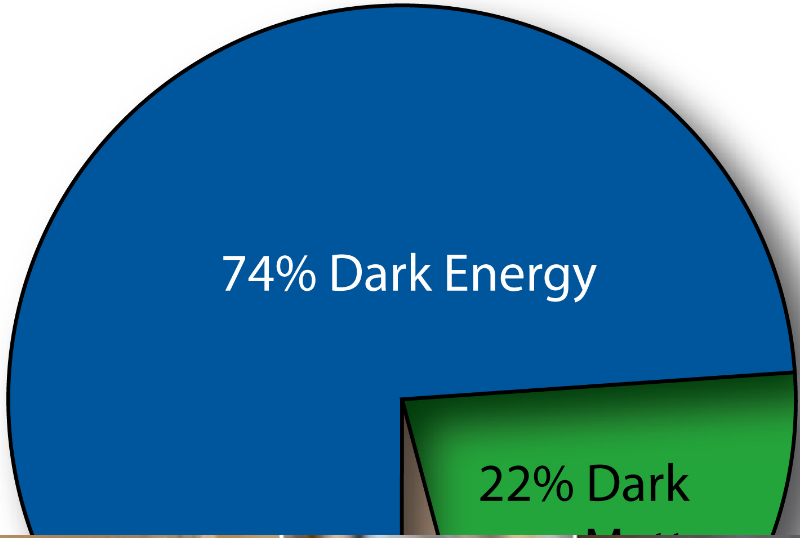
The triumph of physics!

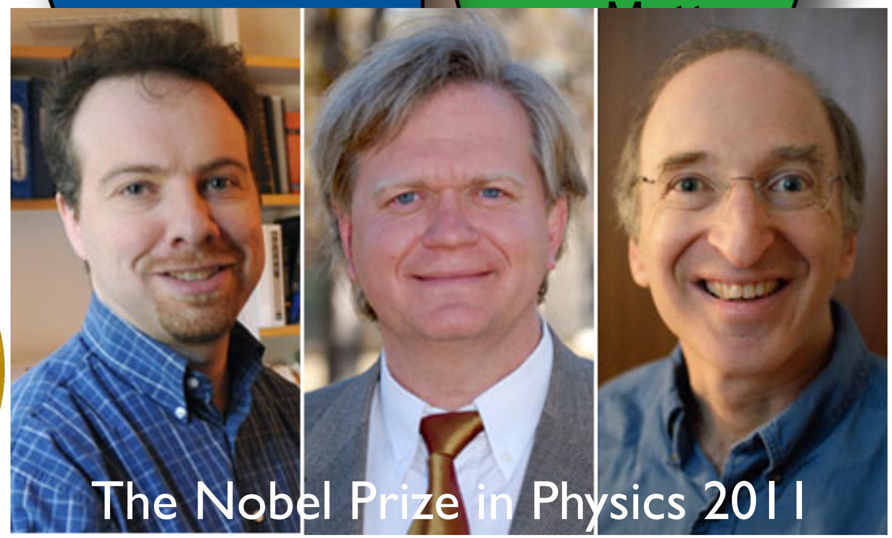




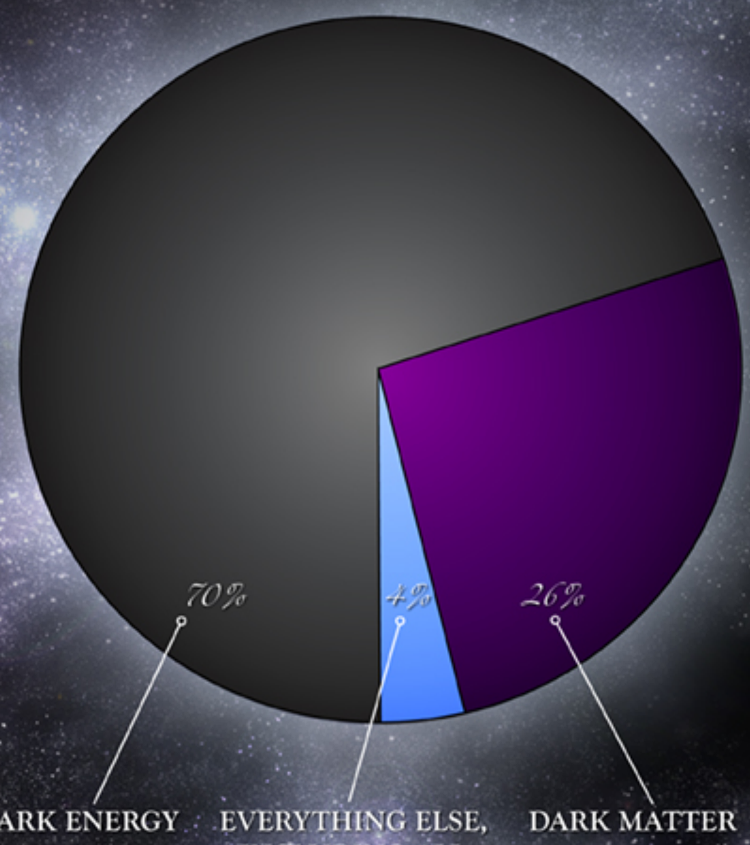
Big Questions in Cosmology

- What is the universe made of? – the nature of dark matter
- What is its fate? – the nature of dark energy
- How did the universe begin? – the nature of primordial fluctuations, the physics of the early universe





Scientific impact



Good media coverage in Japan

General book (now more than ~0.4M copies)

- The fate of our Universe and dark universe are attractive for general people
- Good for fund raising!

Cosmic acceleration problem: Dark energy or Modified gravity?

- *Observational fact is the cosmic acceleration (we haven't seen an evidence of dark energy existence)*

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\text{or} \quad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu} \right)$$

- ΛCDM model: based on Einstein gravity (GR) and specified by cosmological parameters (~6 parameters Ω_m, Ω_b, n_s, $\cdots$, $+\Lambda$)
- GR is valid on scales from ~1mm to 10Gpc (29 orders of magnitudes)?

Test of cosmic acceleration

- Geometrical test

$$H^2(z) = H_0^2\left[\Omega_{m0}(1+z)^3 - \frac{K}{H_0^2}(1+z)^2 + \underbrace{\frac{\rho_{\rm de}(z)}{\rho_{\rm cr0}}}_{\text{Dark Energy}}\right]$$

Dark Energy

  - CMB, Type-Ia SNe, Baryonic Acoustic Oscillation (BAO; discuss later)
- Growth of structure formation (in the linear regime)

$$\ddot{\delta}_m + \underbrace{2H\dot{\delta}_m}_{\text{Cosmic Expansion}} - \underbrace{4\pi G\bar{\rho}_m\delta_m}_{\text{Gravity}} = 0$$

Cosmic Expansion *Gravity*

  - Weak Lensing, Galaxy clustering, Counts of galaxy clusters
- *Goal*: Combine the geometrical and structure formation probes to distinguish DE and modification of gravity for the origin of cosmic acceleration

Growth of cosmic structure

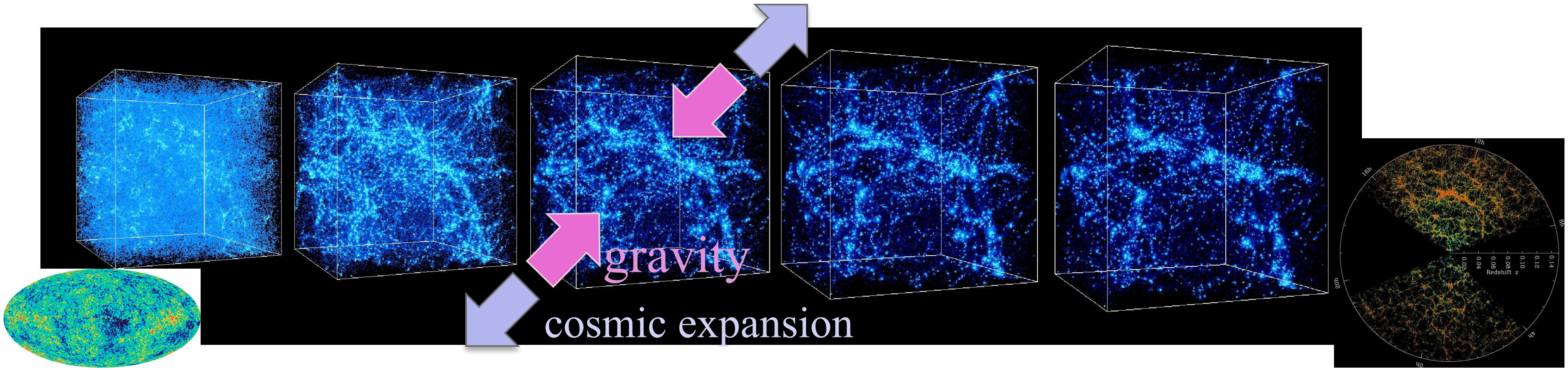
- The density fluctuation field of total matter (mainly CDM) in the linear regime

$$\delta_m(\boldsymbol{x},z) \equiv \frac{\rho_m(\boldsymbol{x},z) - \bar{\rho}_m(z)}{\bar{\rho}_m(z)} = D(z)\delta_m(\boldsymbol{x},z \approx 1000)$$

- The 2nd-order diff. eqn. to govern the redshift evolution of density pert.: (FRW eqns ＋ linearized Einstein eqns.) $\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$

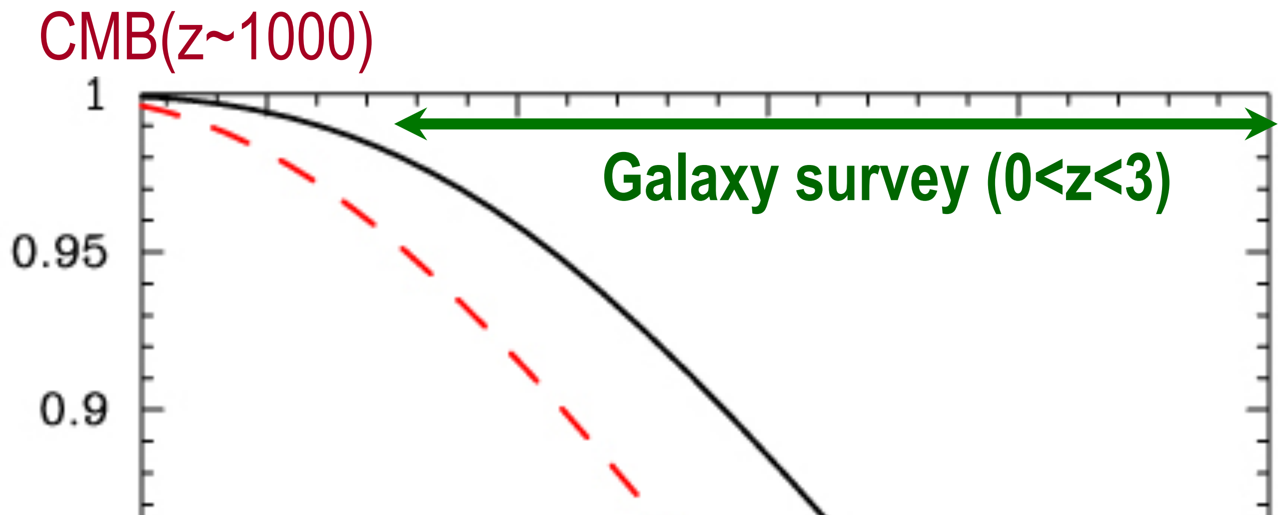
$$\ddot{D} + 2H\dot{D} - 4\pi G \bar{\rho}_m D = 0$$

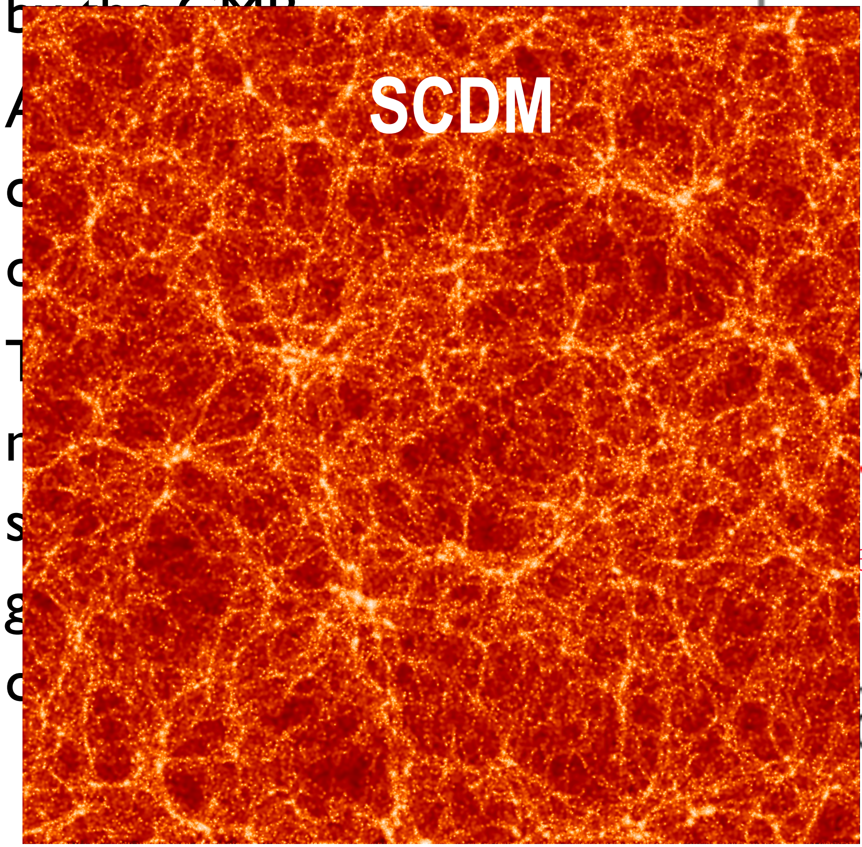
Friction due to cosmic exp. **Gravitational instability**

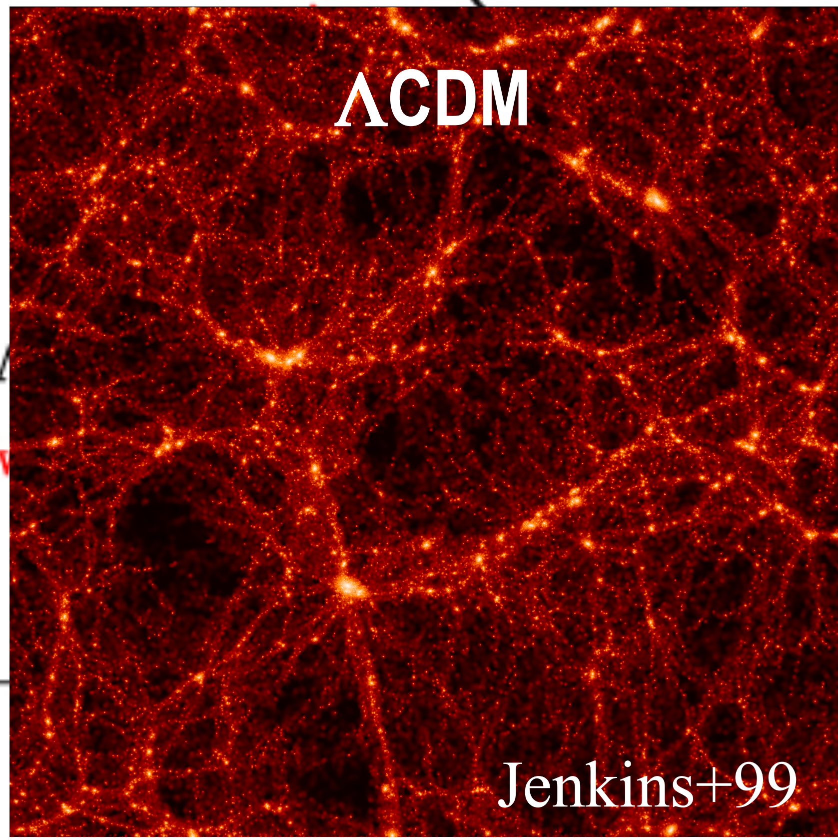


Growth Rate

- The initial conditions on the perturbations are well constrained by the CMB
- A c c
- T r s g c

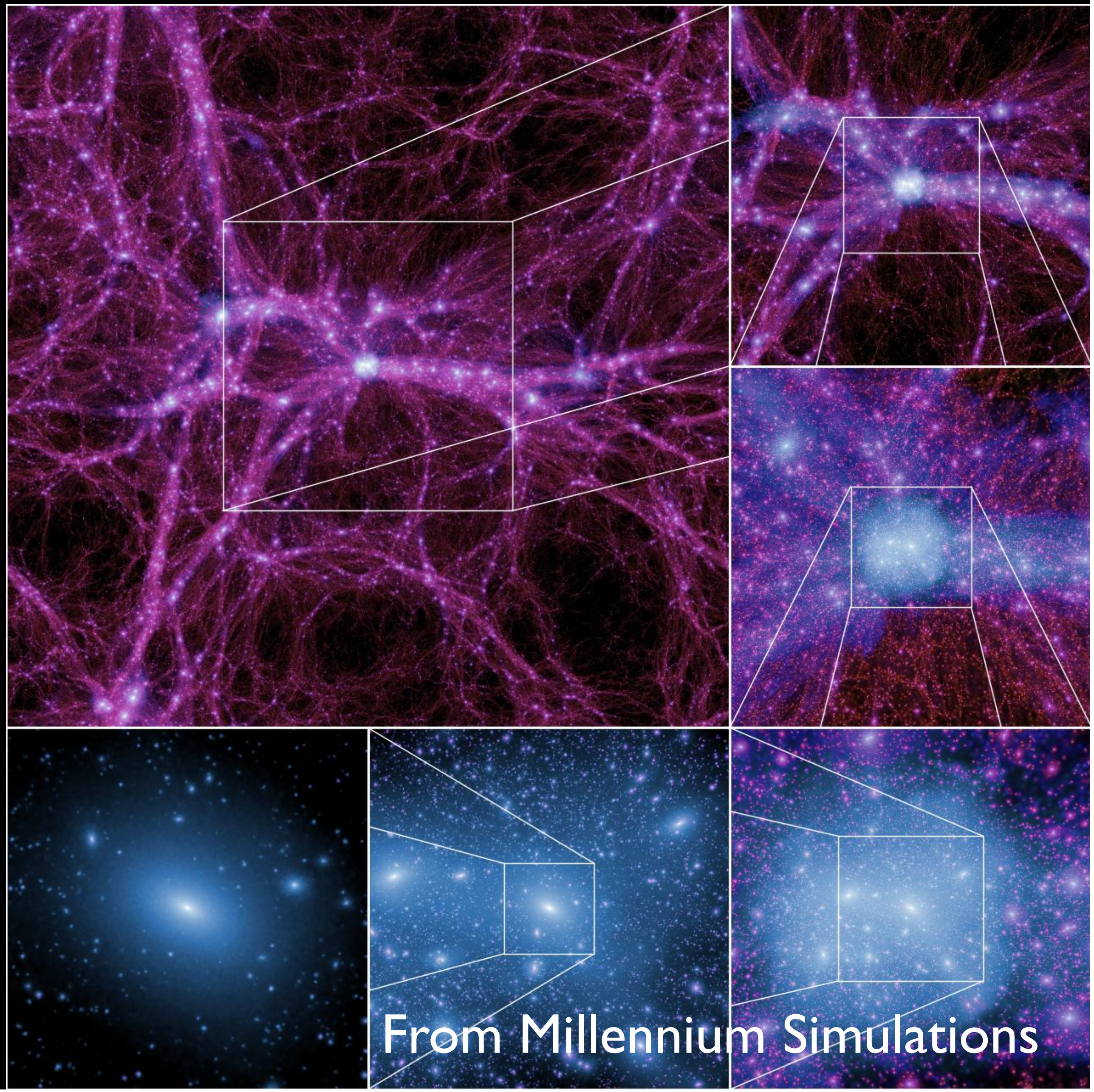






Simulating large-scale structure

- The initial conditions are now well constrained by CMB
- The structure formation at scales of interest is in the nonlinear regime
- Computer simulations are now a powerful, necessary tool to study the structure formation
- The models can be tested by precise data



A journey through the "*observed*" galaxy distribution (1.5M gals)

Sloan Digital Sky Survey (1999-) with the dedicated 2.5m telescope


A journey through simulated universe (Millennium Simulation)

Quantifying large-scale structure data

- Data compression: 2D (or 3D)

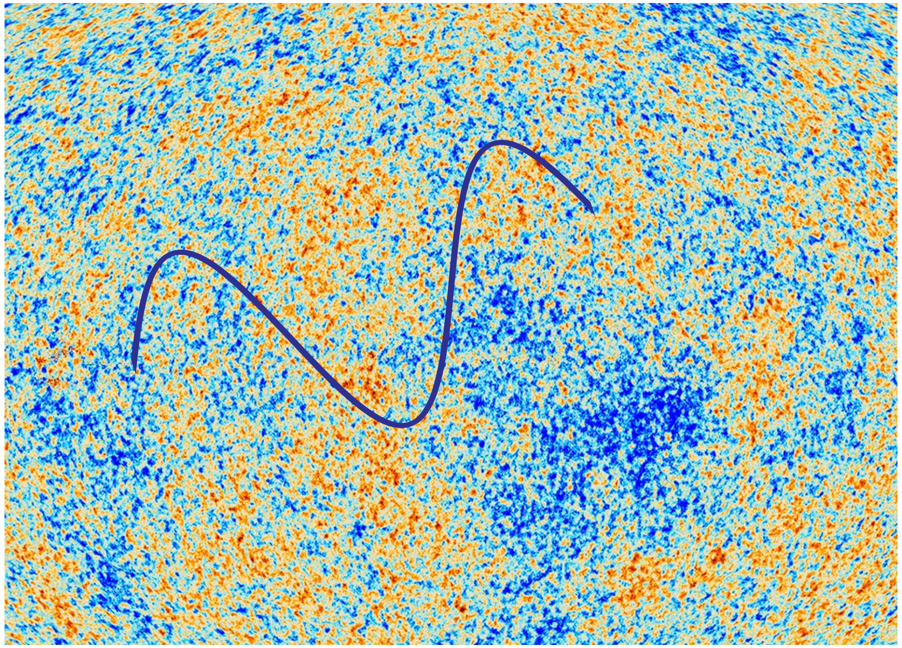
⇒ Fourier mode decomposition

$$O(\vec{x}) = \int \frac{d^3\vec{k}}{(2\pi)^3} \tilde{O}_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}$$

⇒ A conventional way is to measure the 2-point correlation function, known as power spectrum in Fourier space, (under the assumption of statistical isotropy)

$$P_O(k) \equiv \left\langle \left| \tilde{O}_{\vec{k}} \right|^2 \right\rangle$$

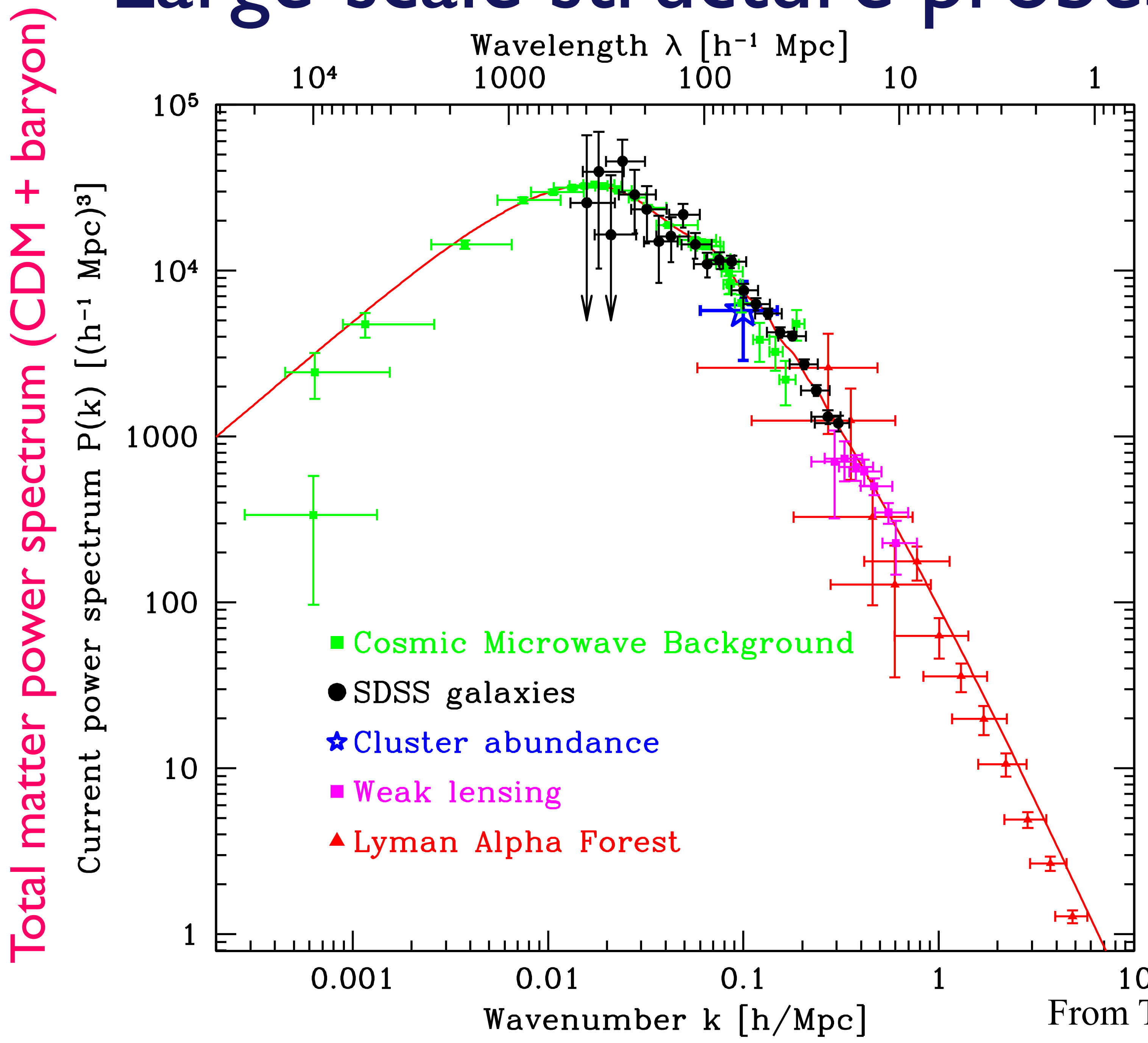
Theory predicts these correlation functions as function of cosmological parameters



The real-space correlation function, which is equivalent to the power spectrum

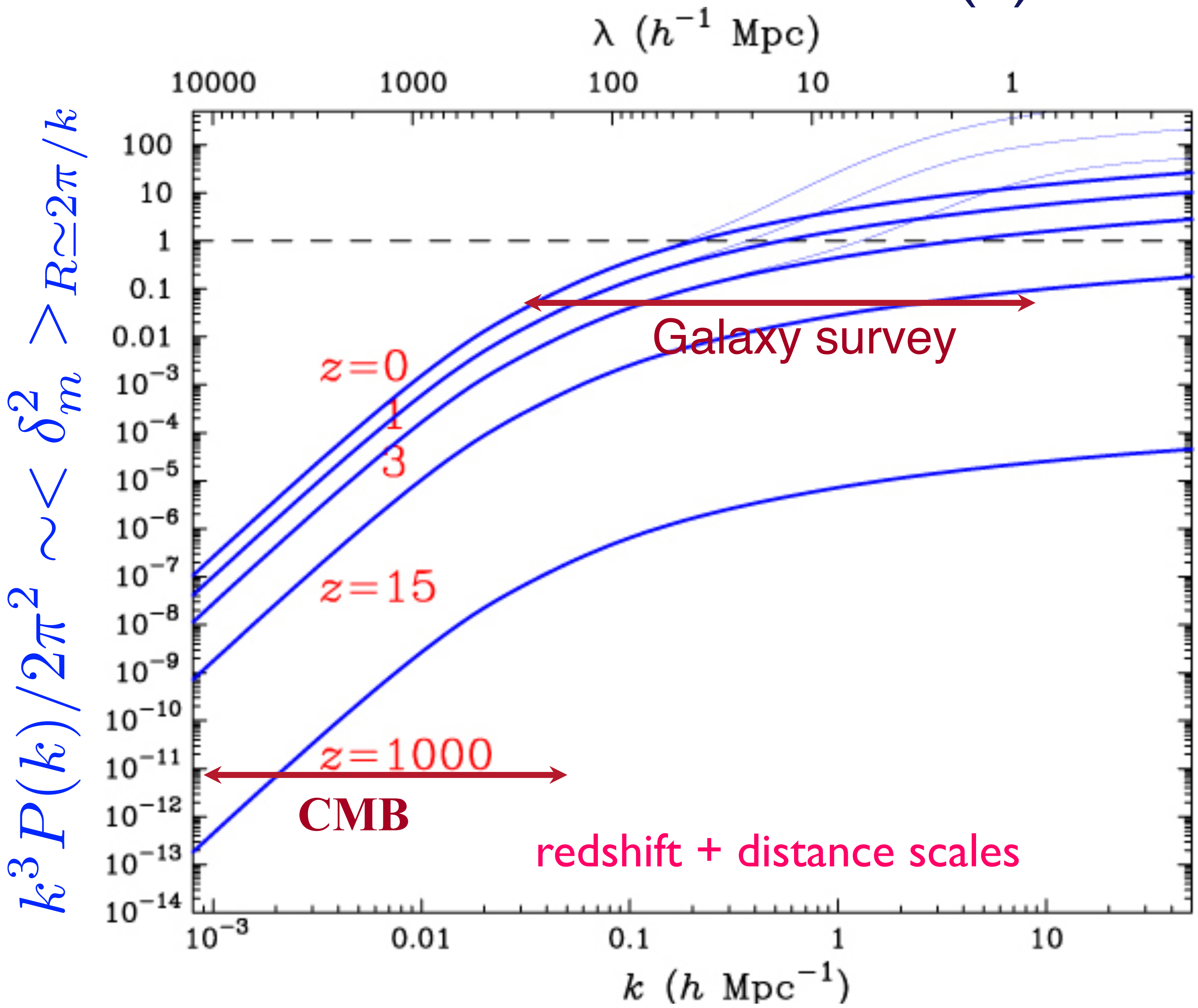
$$\xi_O(r) \equiv \int \frac{k^2 dk}{2\pi^2} P_O(k) j_0(kr)$$

Large-scale structure probes



From Tegmark+04

Structure formation via P(k)



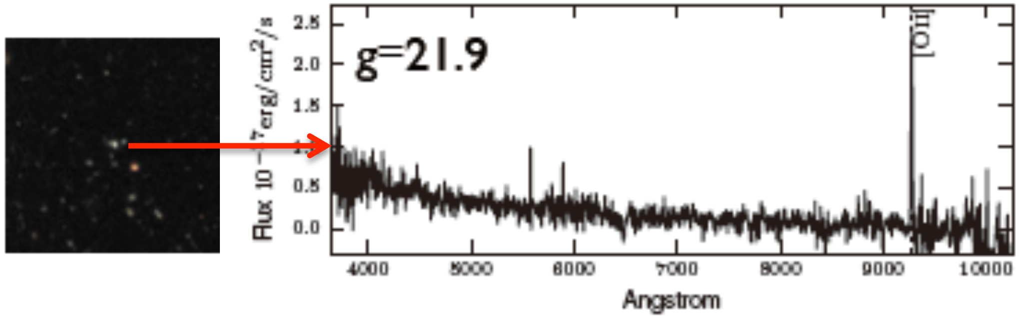
Galaxy survey; imaging vs. spectroscopy

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

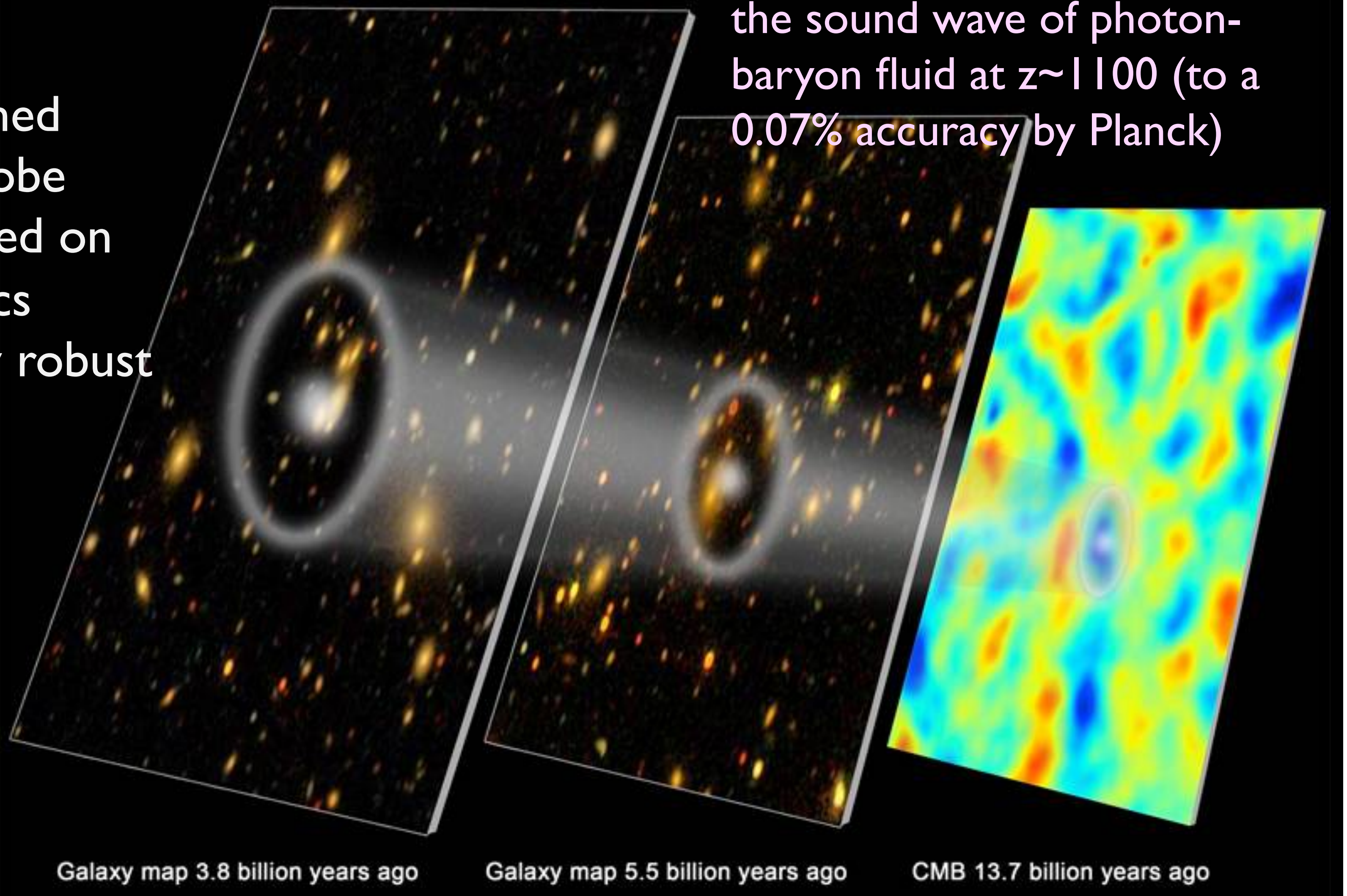
- Measure the photon-energy spectrum of *target* object
- Distance to the object can be known → *3D clustering analysis*
- For cosmology
  - *Pros*: more fluctuation modes in 3D than in 2D
  - *Cons*: need the pre-imaging data for targeting; observationally more expensive (or less galaxies)



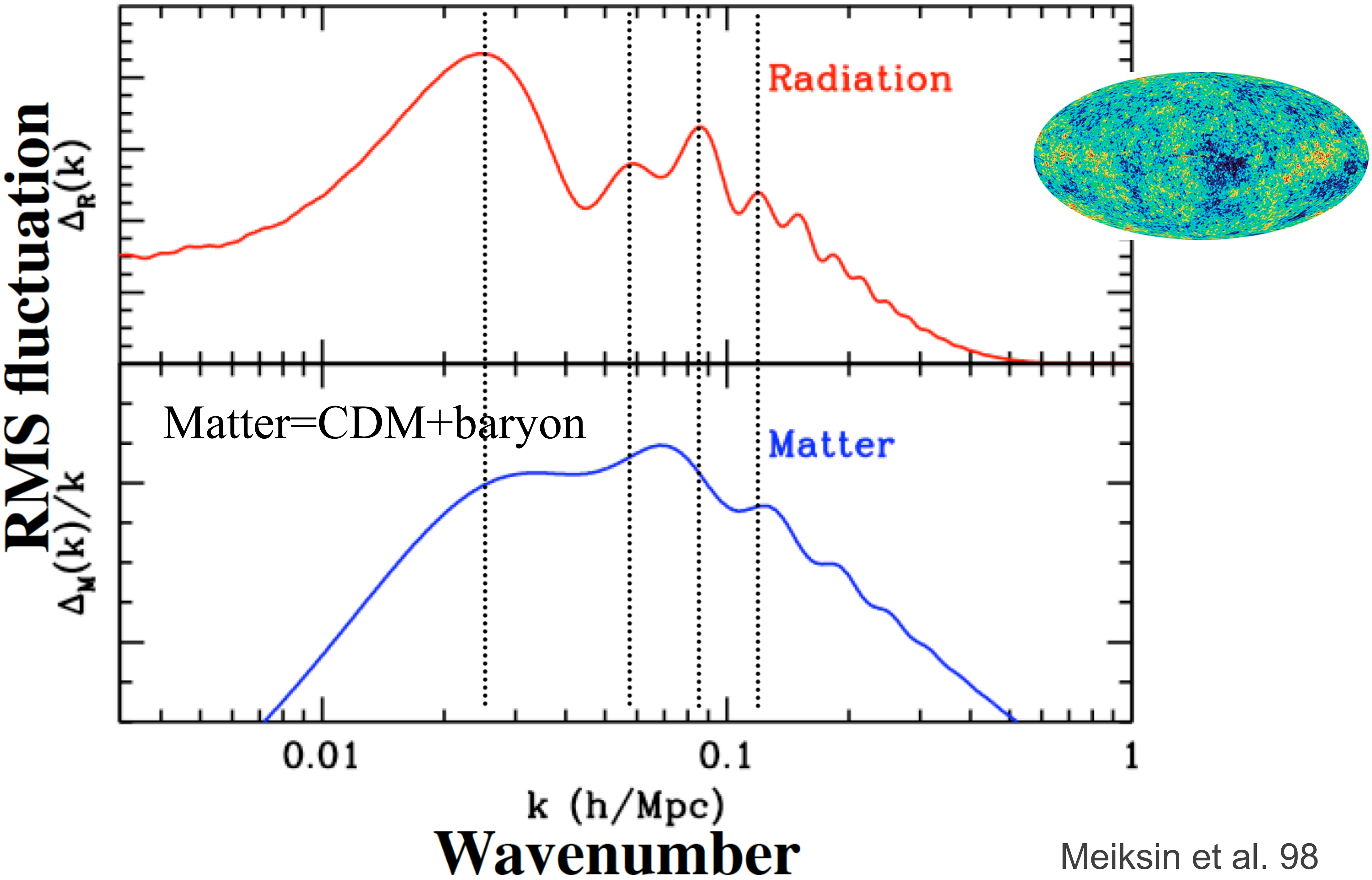
Baryon Acoustic Oscillation (BAO)

The typical scale of CMB anisotropies is determined by the sound wave of photon-baryon fluid at z~1100 (to a 0.07% accuracy by Planck)

Newly established geometrical probe since 2005, based on the CMB physics (therefore very robust method)



Baryonic Acoustic Oscillation (BAO)



Meiksin et al. 98

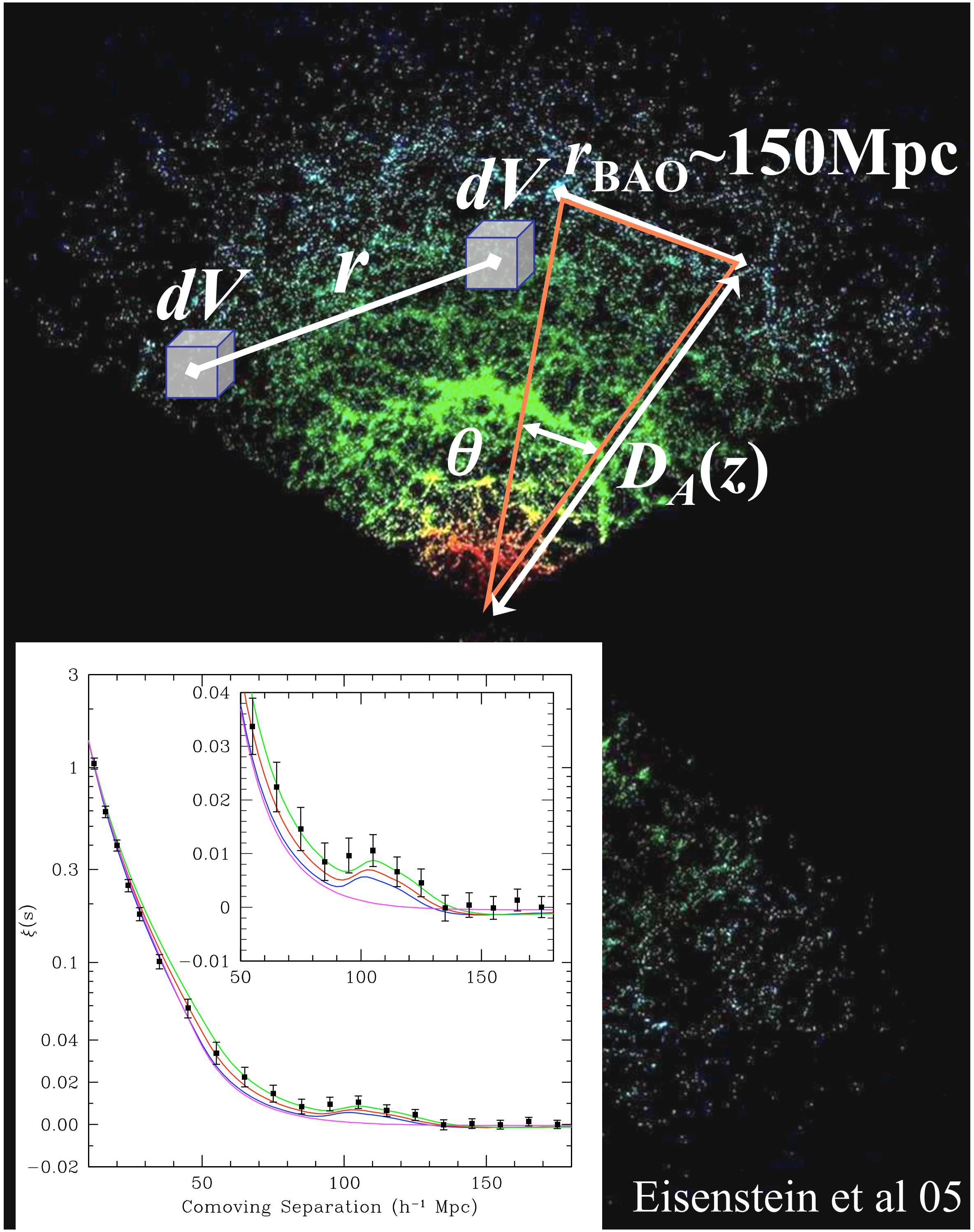
BAO (cont'd)

- Measure galaxy clustering strengths: 2pt correlations (or P(k))

$$dP = \bar{n}_g^2 \left[1 + \xi_g(r)\right] dV^2$$

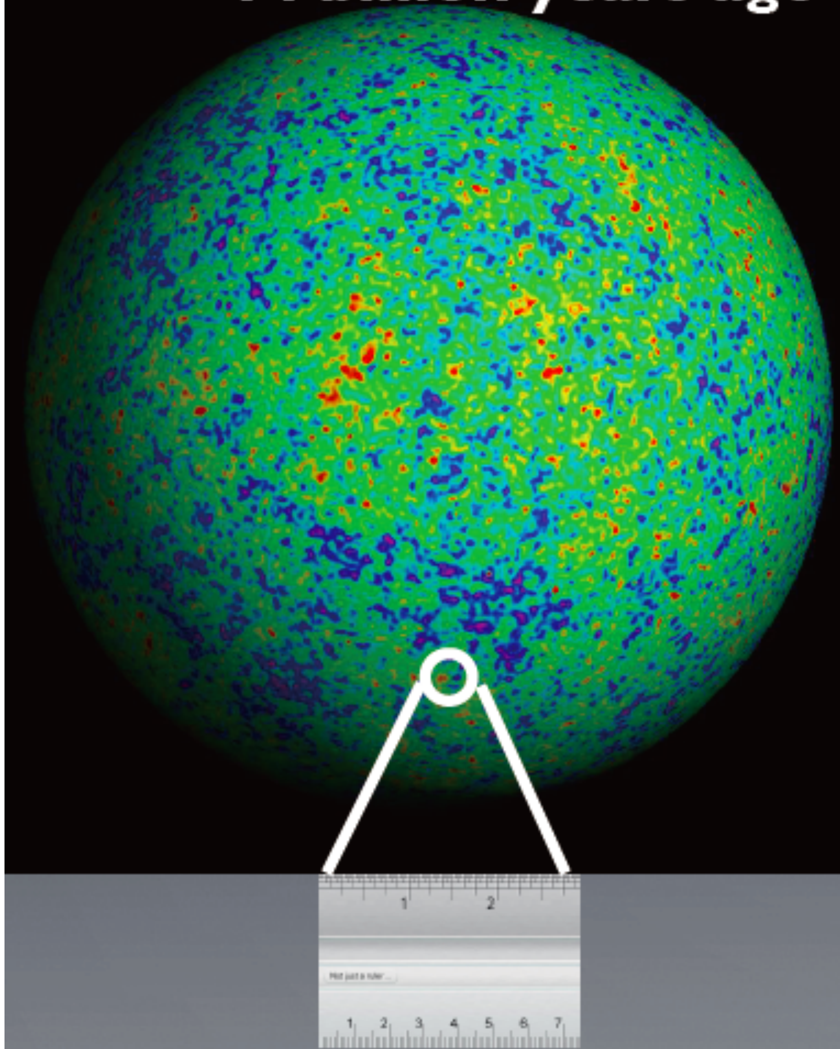
- Find a tiny excess in the galaxy pairs at BAO scale (a priori known from CMB to be ~150Mpc)

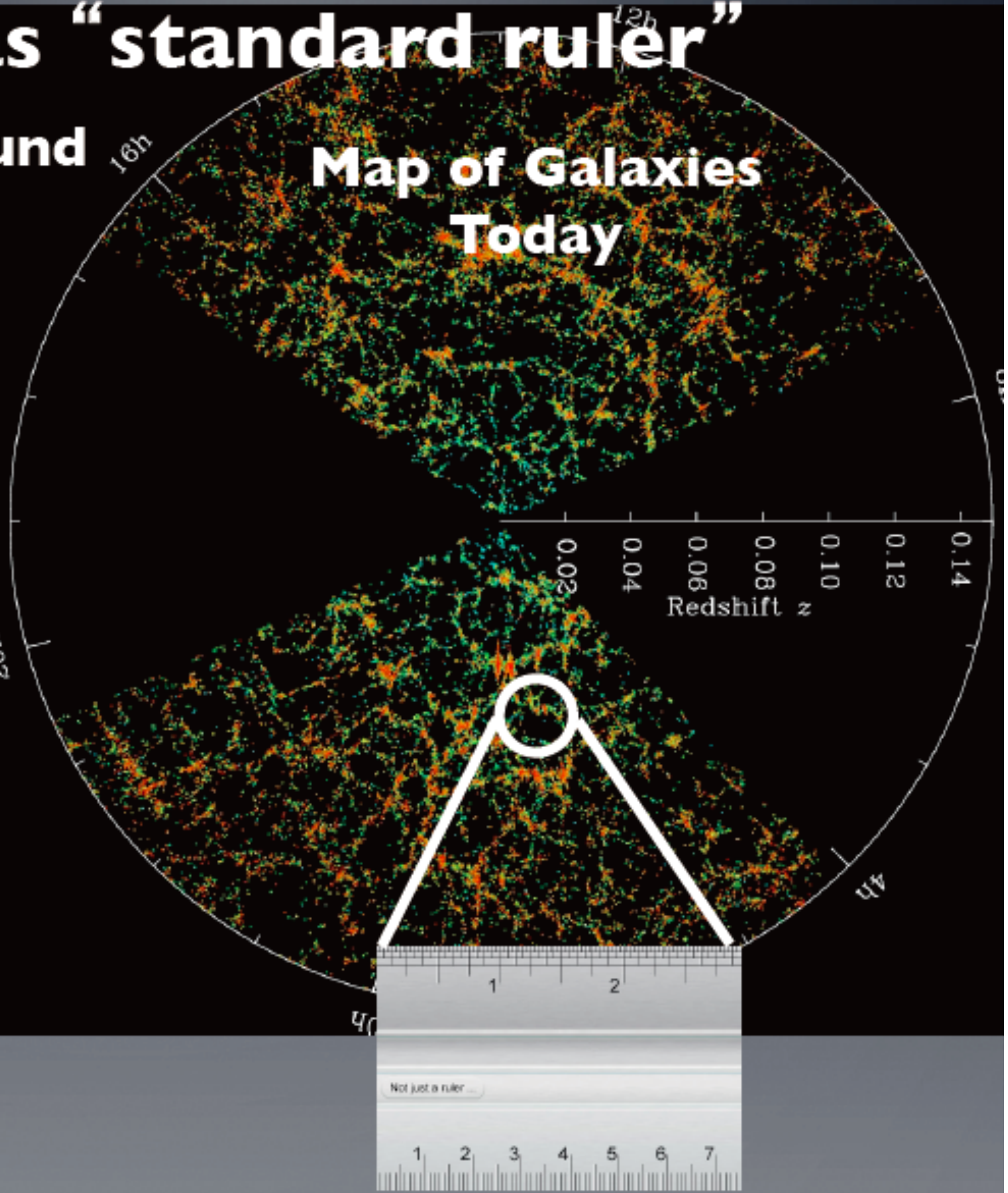
$$r_{\rm BAO} = D_A(z)\theta_{\rm obs}$$



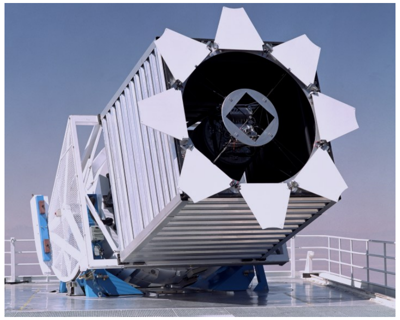
Sound waves as “standard ruler”

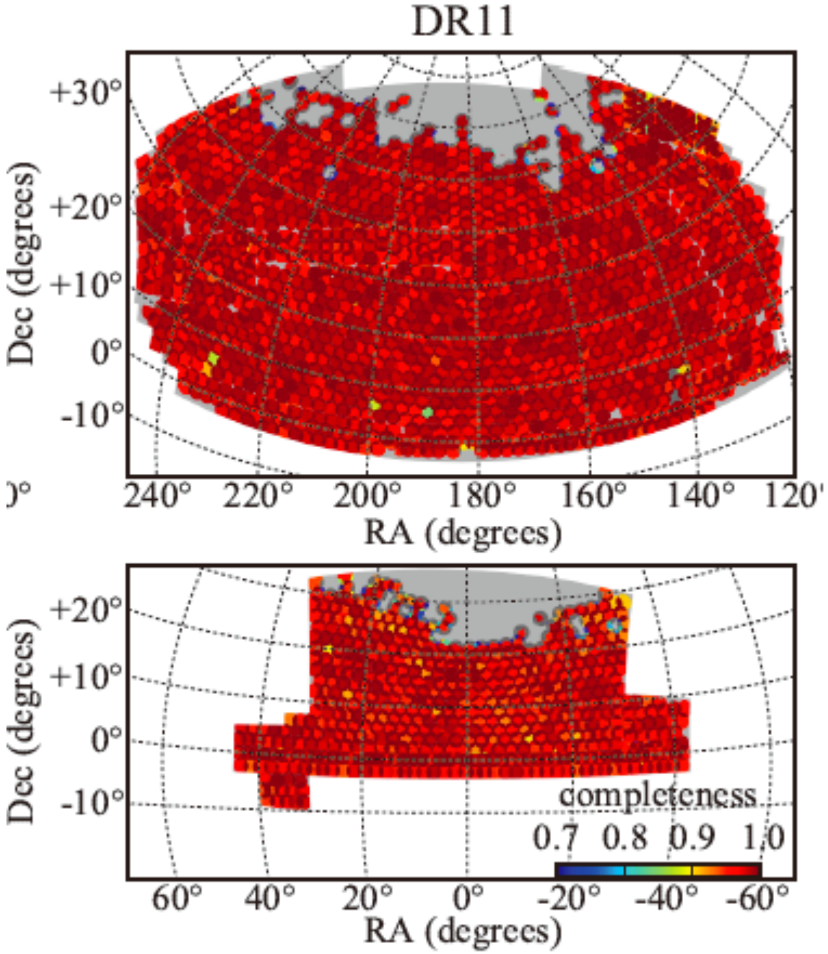
Cosmic Microwave Background
14 billion years ago





Baryon Oscillation Spectroscopic Survey (BOSS: 1999-)

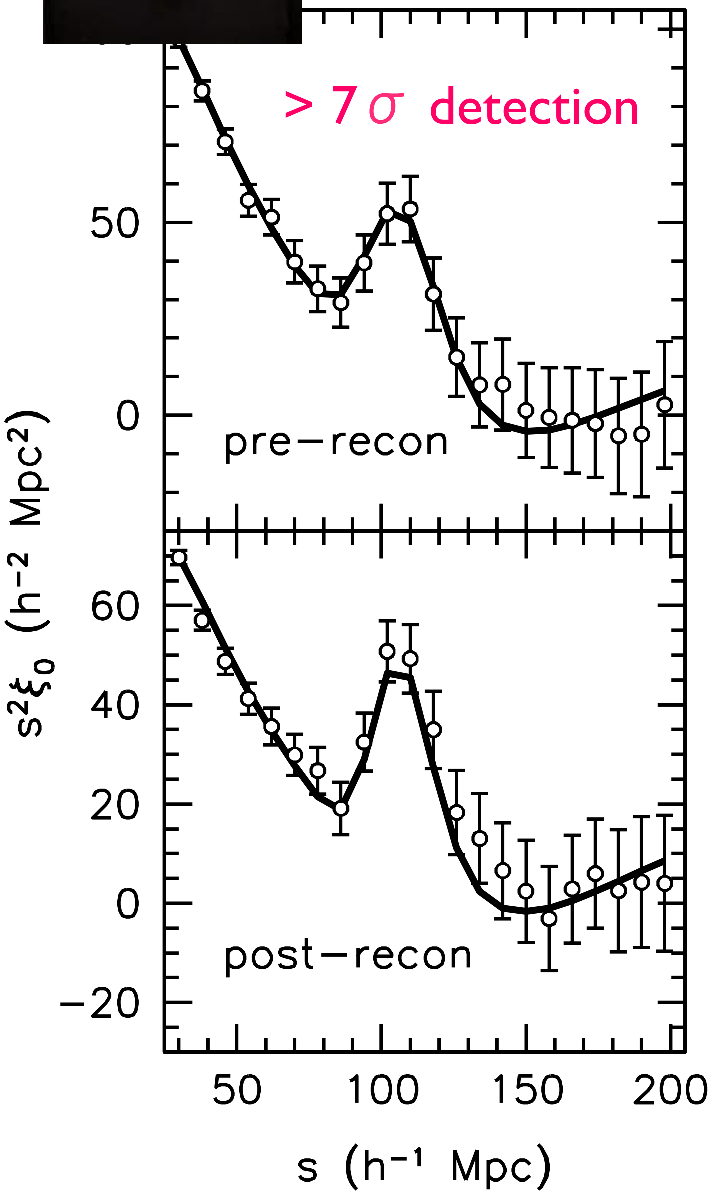




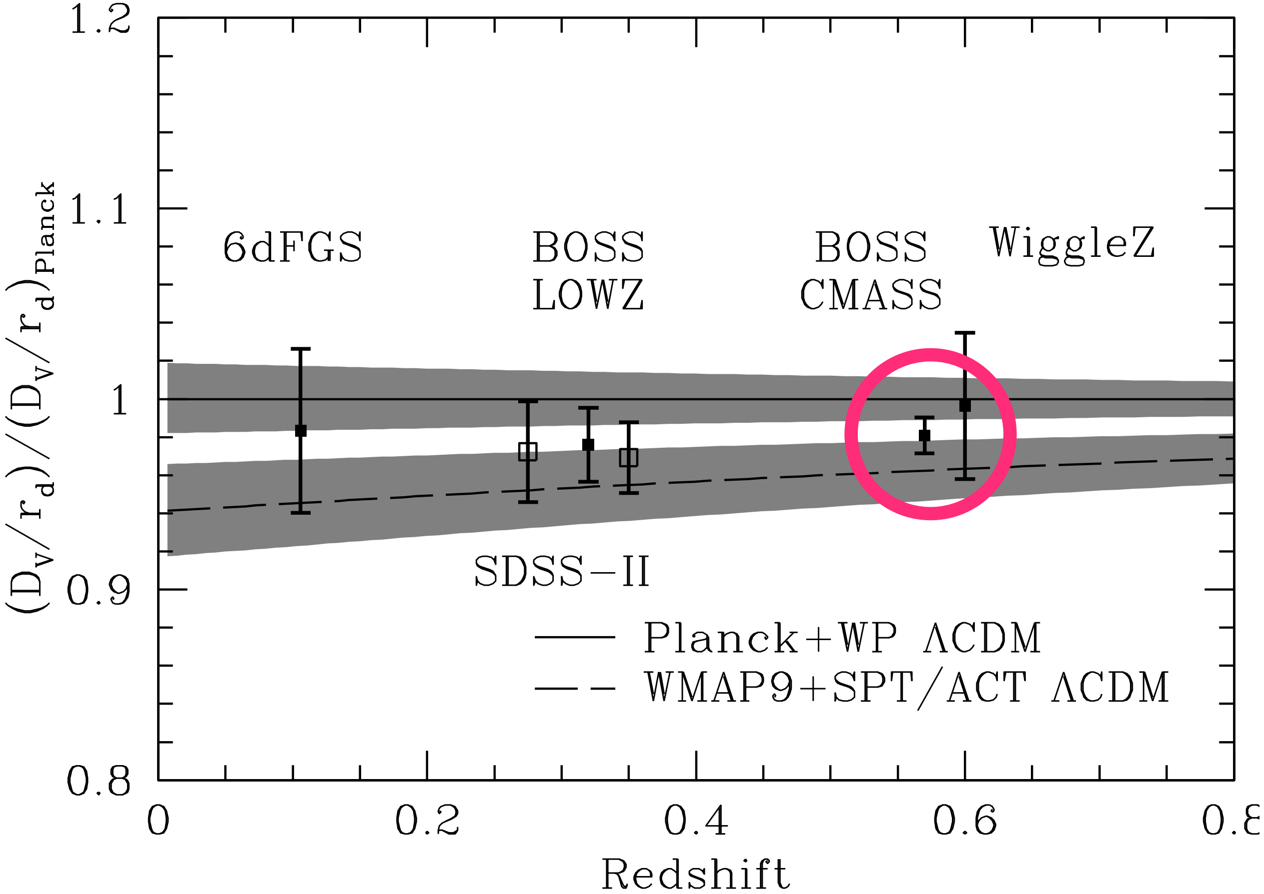
- The BAO-dedicated spectroscopic survey, a part of the 3rd generation of SDSS (SDSS-III), using the dedicated 2.5m telescope in NM, USA
- U. Tokyo is the participation institute (anyone at U. Tokyo has access to the data)
- The new BAO result using the Data Release 11 (DR11) just announced (Dec 18, 2013)

BOSS DR11 BAO (Anderson+13)

Shun Saito (IPMU)

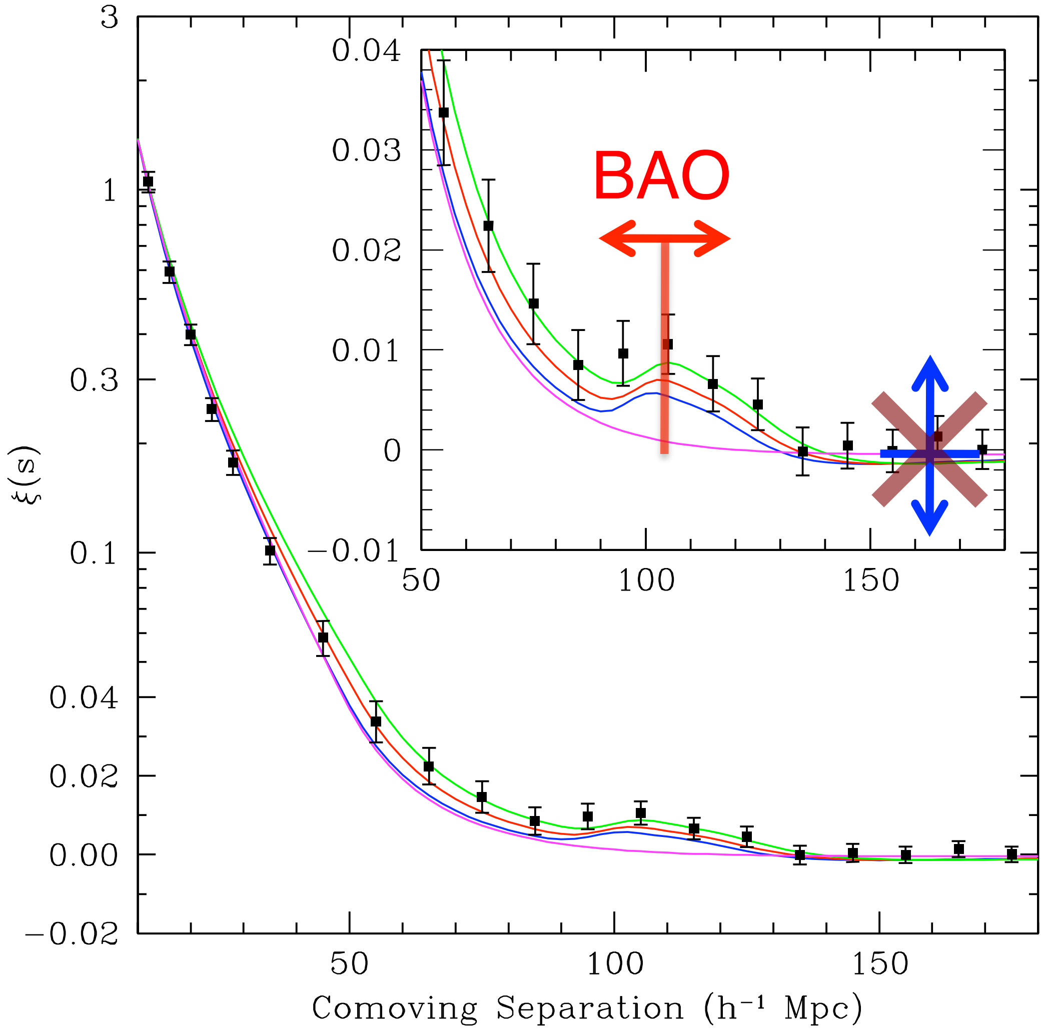


$D_V(z = 0.57) = (2056 \pm 20 \text{ Mpc})(r_{\text{BAO}}/r_{\text{BAO,fid}})$



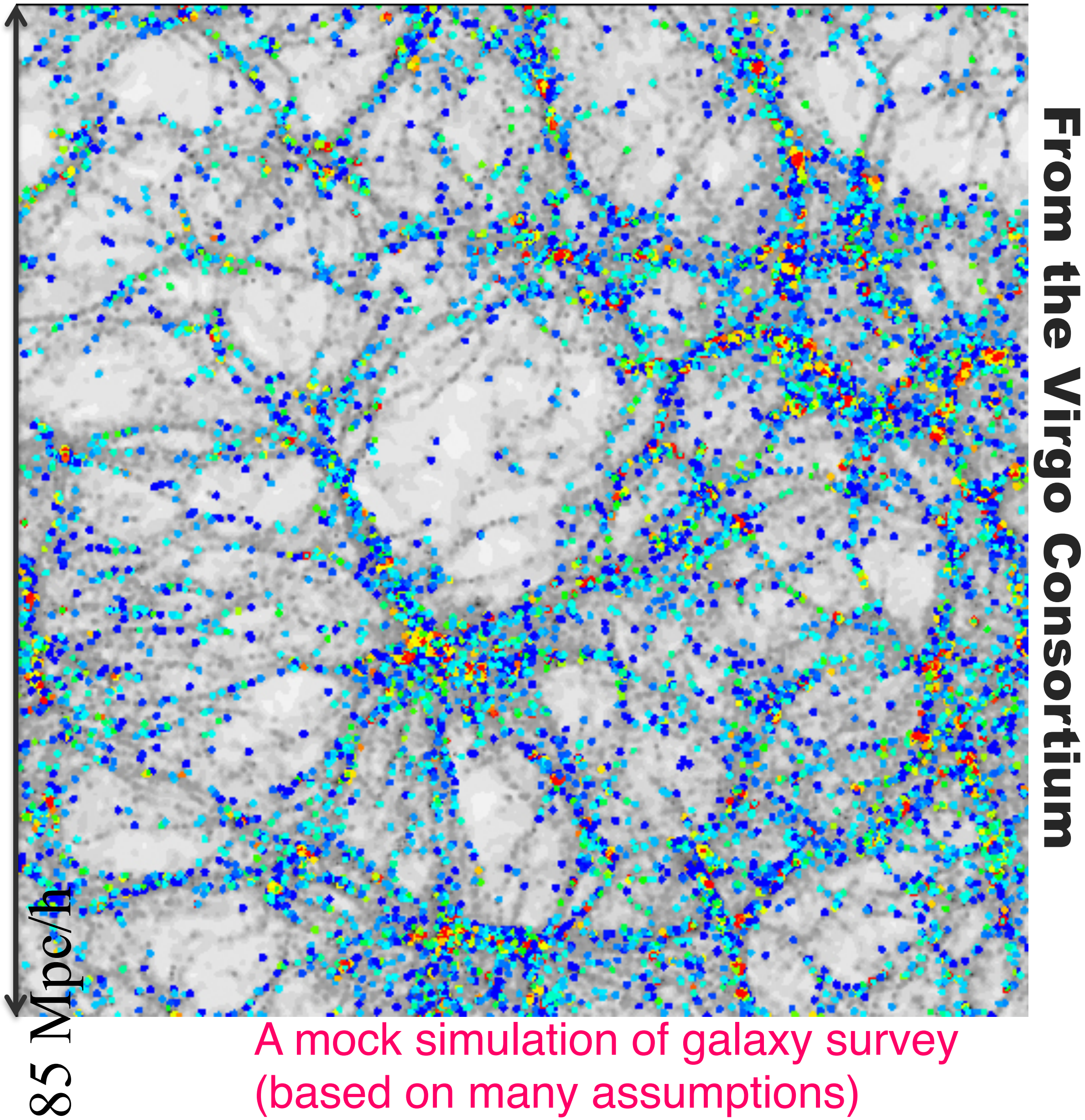
A 2σ-level tension between BAO and CMB constraints; we should wait for the 2nd-yaer Planck result, coming around Sep 2014)

BAO not full story in galaxy data!



- Measure *the single length scale* (BAO) from the galaxy distribution
- *Can't yet reliably* use the clustering amplitude information for cosmology, due to galaxy bias uncertainties, even though much higher signal-to-noise ratios in the amplitude signals
- The amplitude uncertainty is marginalized over to obtain the distance constraints

Galaxy bias uncertainty



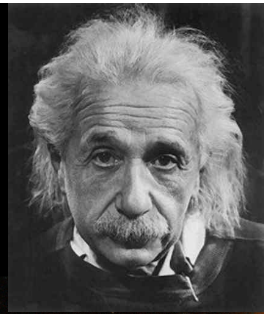
A mock simulation of galaxy survey
(based on many assumptions)

- Galaxies are "*biased*" tracers of DM distribution

$$\delta_g \neq \delta_m$$

- Can't yet model galaxy formation from the first principle
- The bias uncertainty limits a reliable use of the clustering amplitude for cosmology

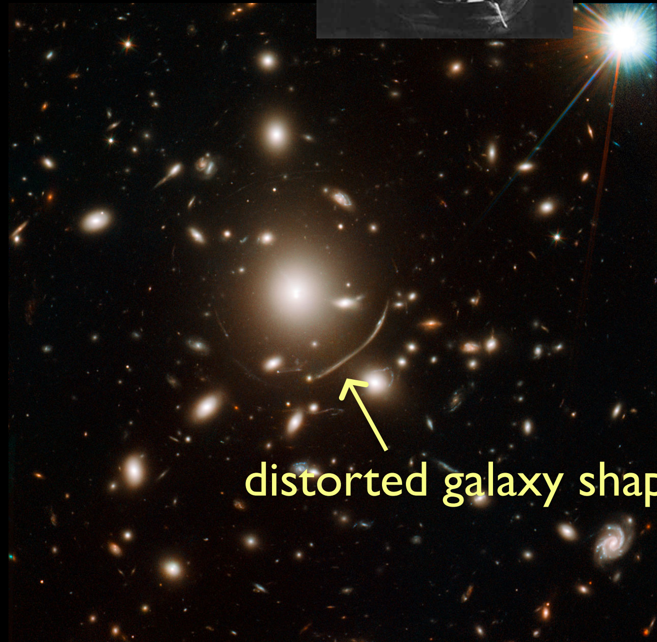
Gravitational Lensing =Einstein's prediction



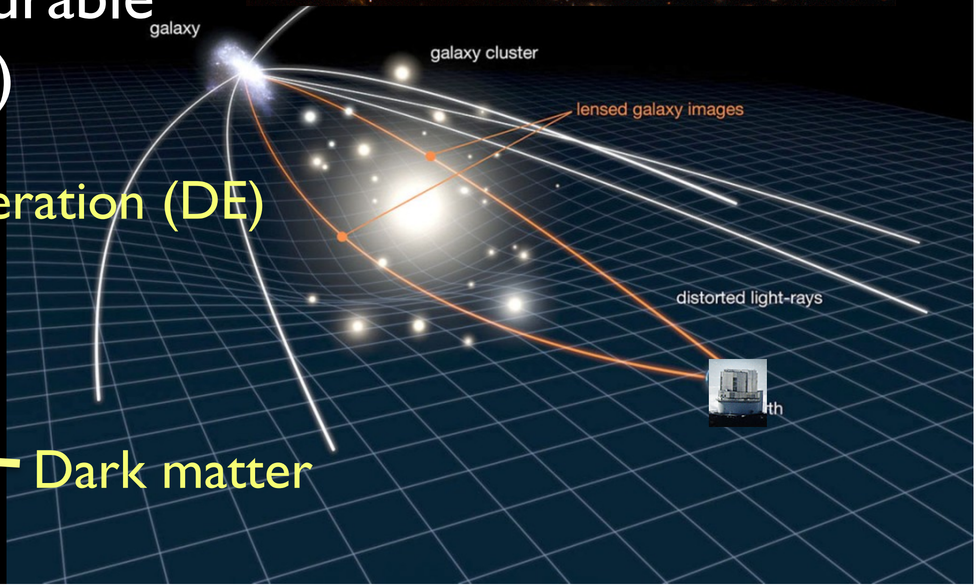
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

The *curved* space-time bends "light path"



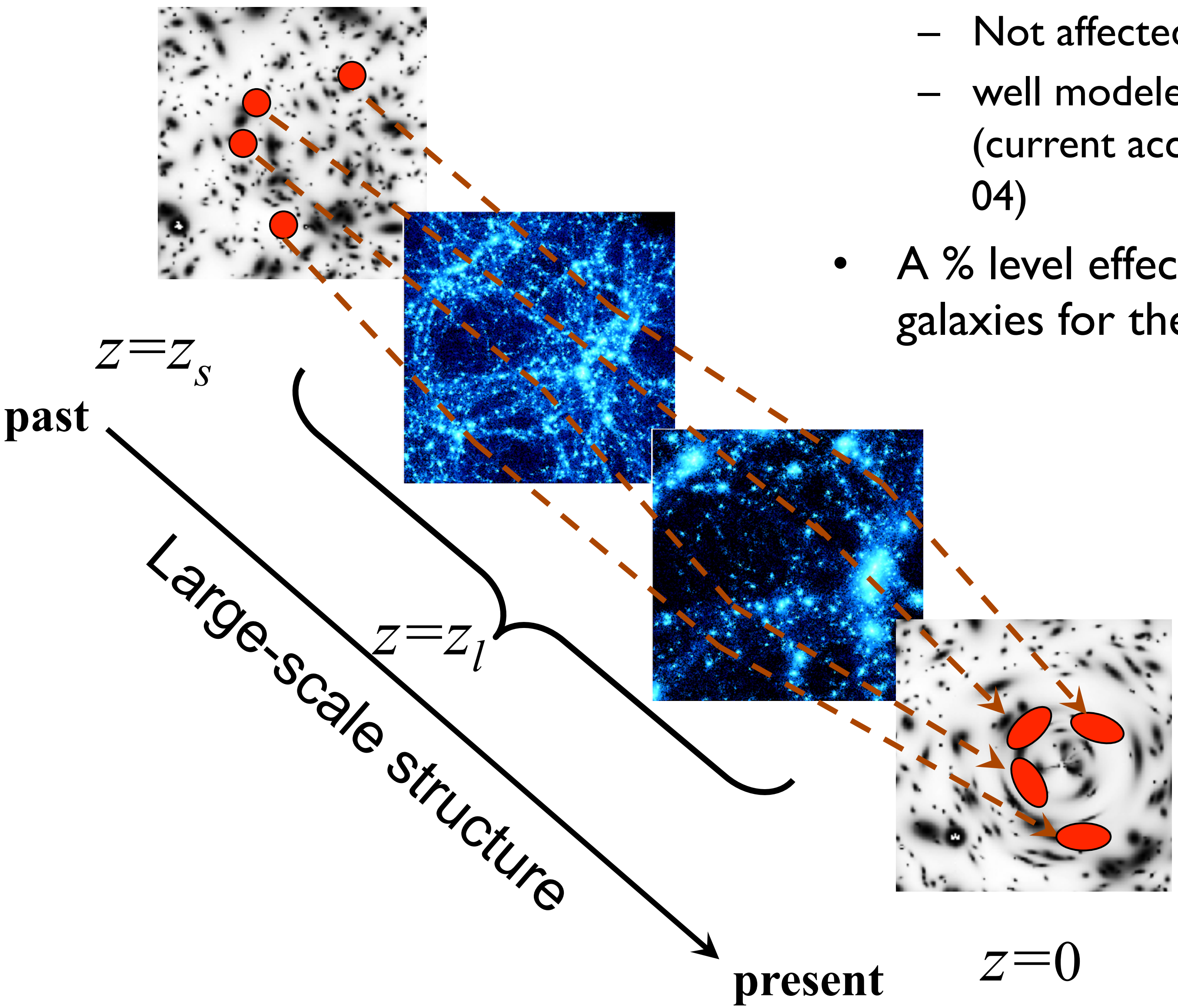
The curvature of space-time is measurable via galaxy shapes (free of galaxy bias!)



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

Every galaxy gravitationally lensed!

- Arises from total matter clustering
  - Not affected by galaxy bias uncertainty
  - well modeled based on simulations (current accuracy, <10% White & Vale 04)
- A % level effect; needs numerous ($\sim 10^8$) galaxies for the precise measurements



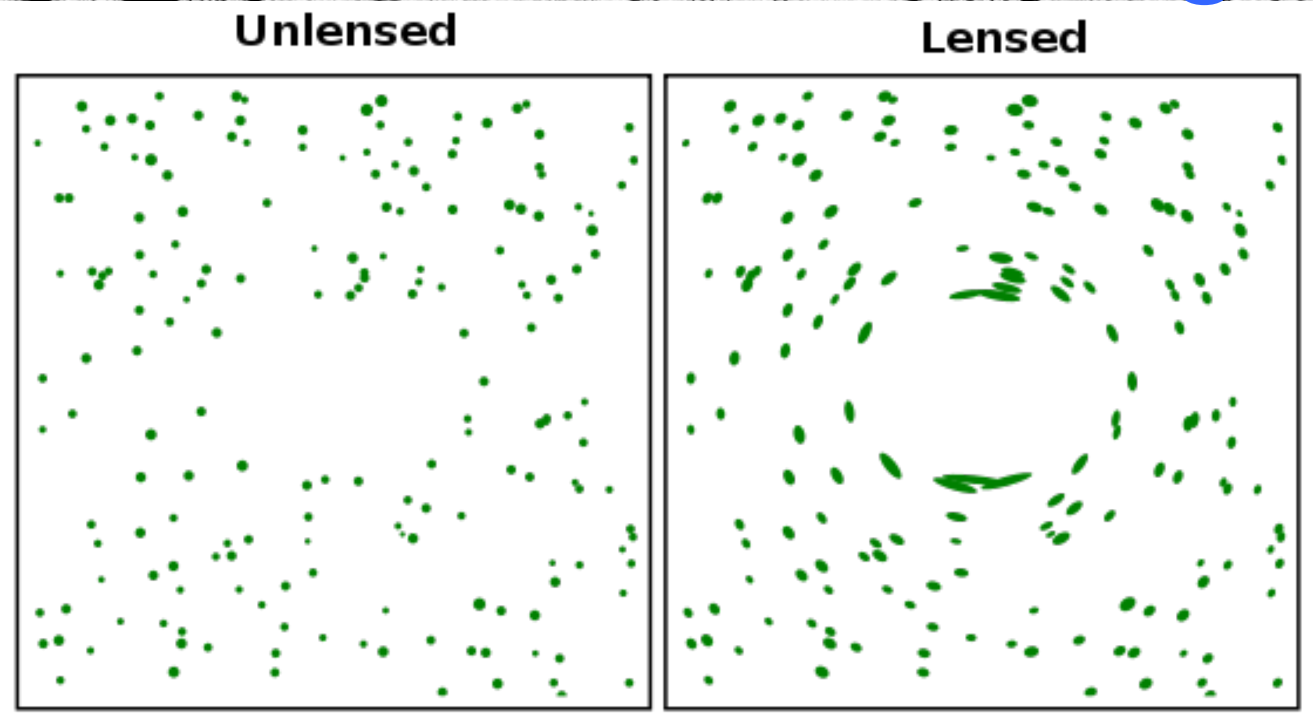
observables

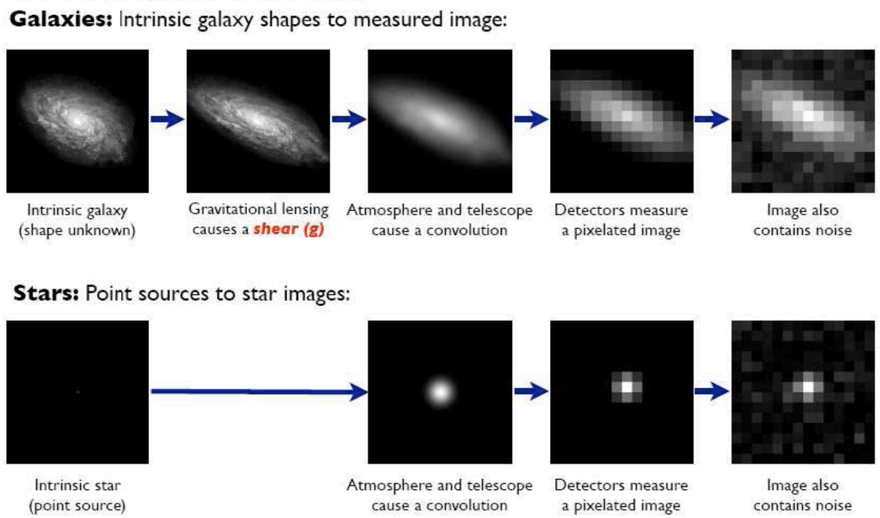
$$\gamma = \frac{a-b}{a+b}$$

$$\gamma_1 = \gamma \cos 2\varphi$$

$$\gamma_2 = \gamma \sin 2\varphi$$

Statistical weak lensing





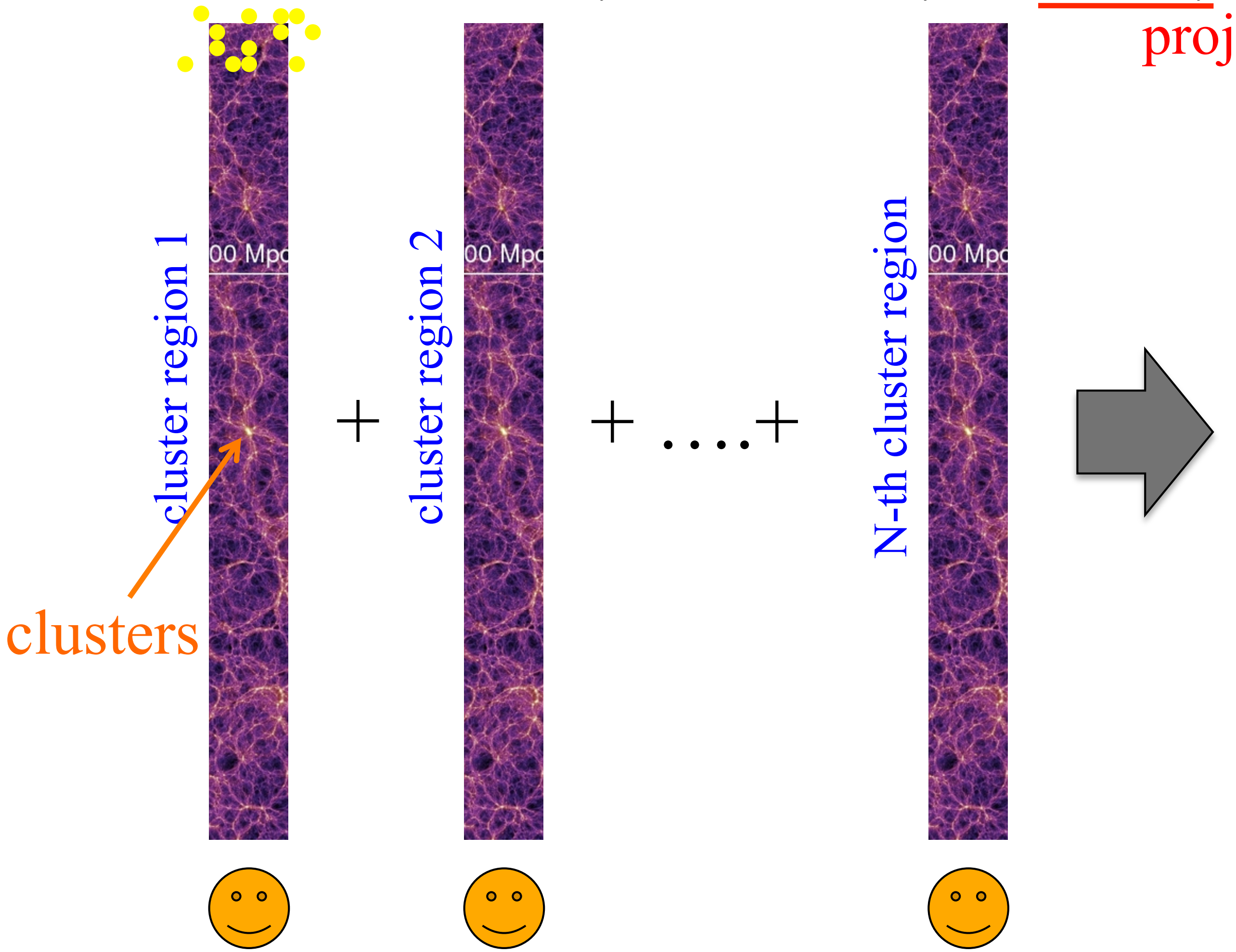
- Need statistics to reduce the intrinsic shape contamination
- Excellent image quality and deep image needed for an accurate WL measurement
- Issues; accurate shape measurements, PSF correction, pixelization effect

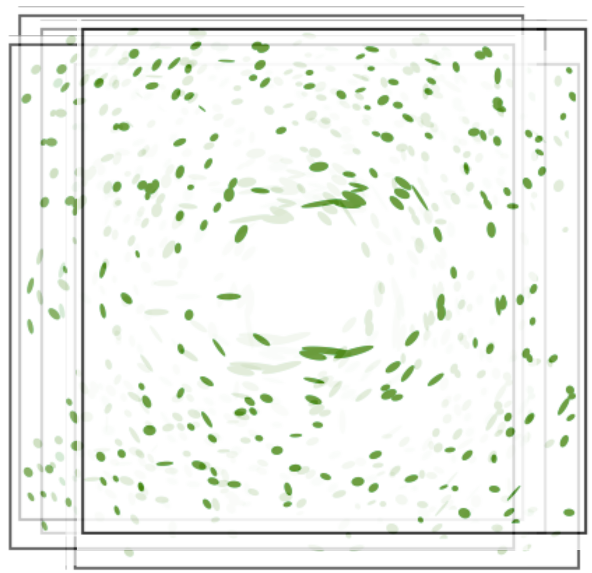
Stacked lensing: halo-shear correlation

$$\gamma_+^{\text{obs}}(\theta_i) = \gamma_+^{\text{cluster}}(\theta_i) + \underline{\gamma_+^{\text{LSS}}(\theta_i)} + \varepsilon_+(\theta_i)$$

projection effect

Oguri & MT 11





Less affected by projection effect, intrinsic alignment, sys. errors ....

$$\langle\gamma_+\rangle(\theta) = \frac{1}{N_{cl}} \sum_{a=1}^{N_{cl}} \sum_{|\vec{\theta}'| \subset \theta} \gamma_{+(a\text{-th cluster})}(\vec{\theta}') \approx \left\langle \gamma_+^{\text{cluster}} \right\rangle(\theta)$$

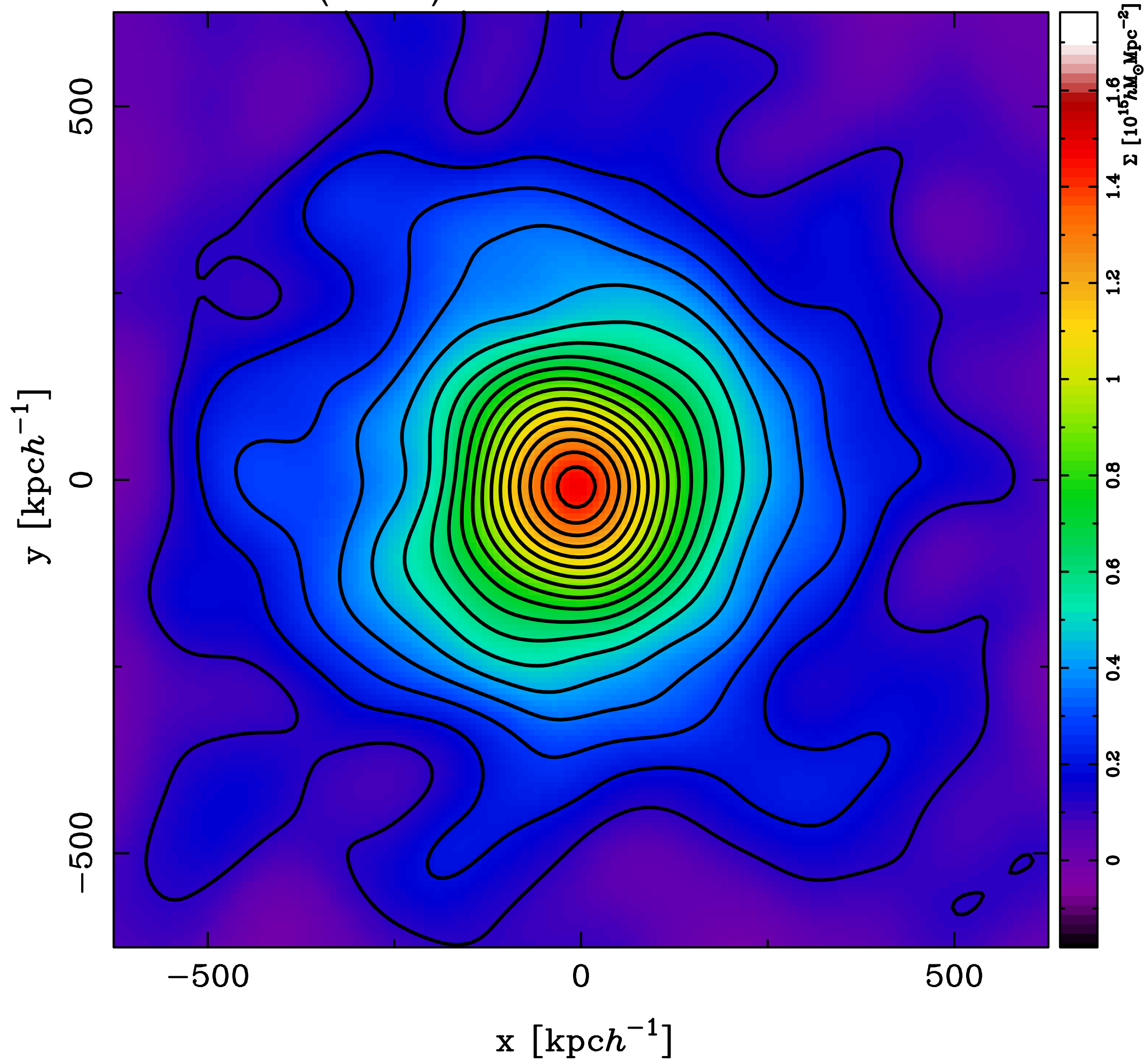
Note: halo center

N. Okabe (IPMU)

Average DM distribution of galaxy clusters

Okabe, MT, Umetsu, Graham, Futamase 10
Okabe+13

$N = 52$



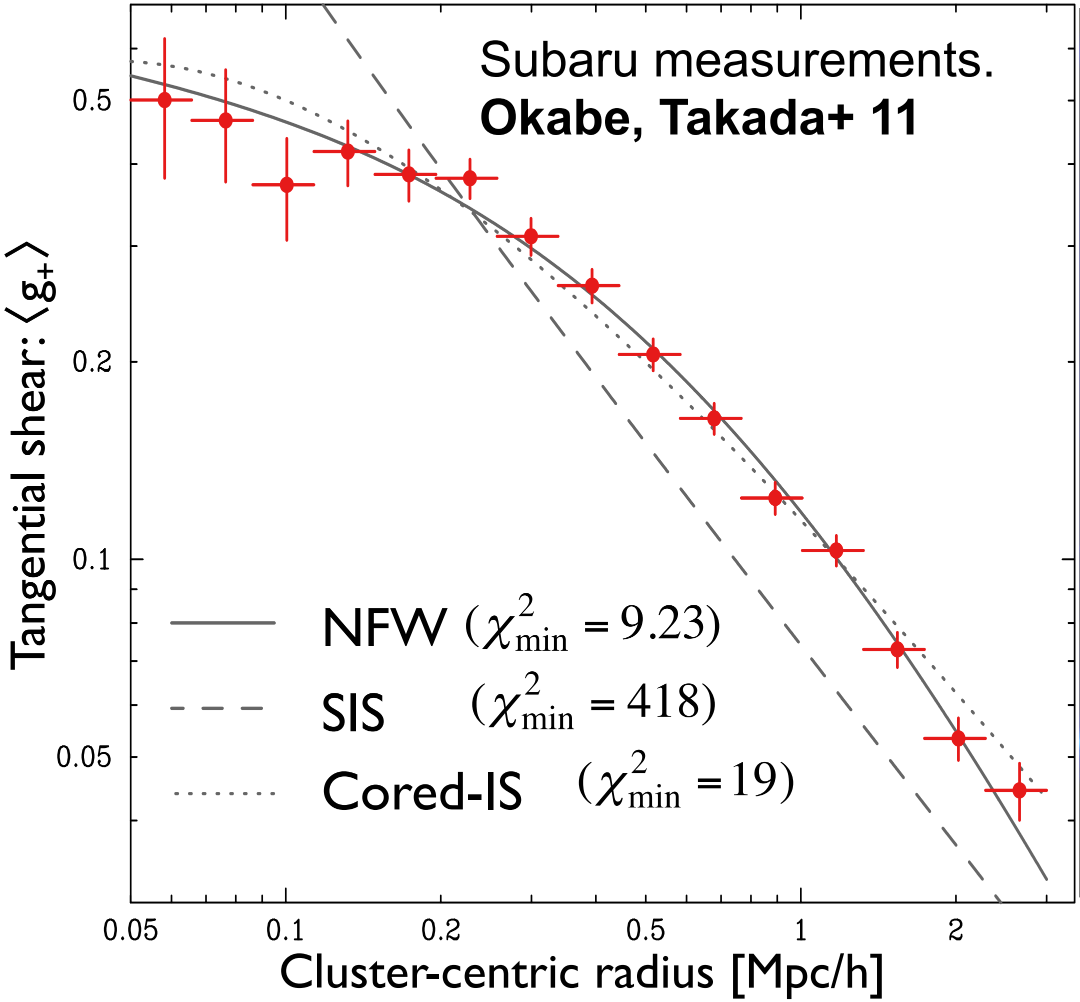
Stacked cluster lensing (all the ROSAT-selected clusters in z=0.15-0.3)

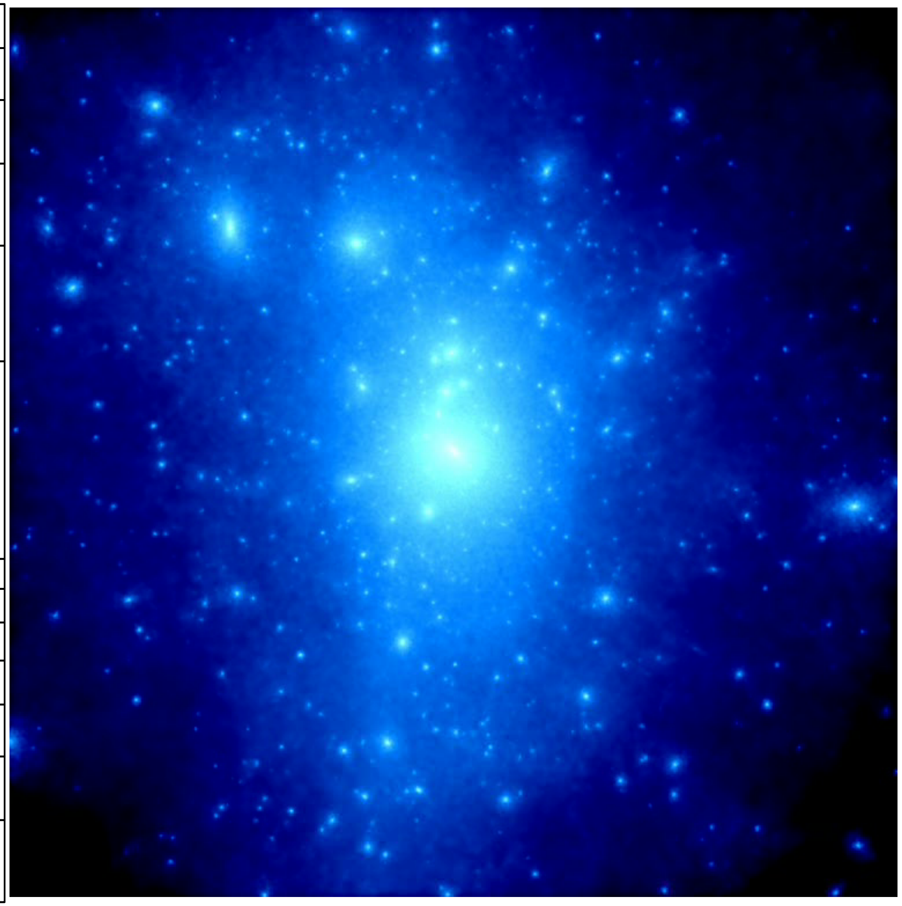
Have obtained Subaru data of *all* the 52 previously-known, X-ray luminous clusters in 0.15<z<0.3; S/N~50

Used ~*1M* galaxies in total for WL analysis

This projected started in 2005; it has taken 6 years so far (10 nights)

Stacked Lensing (contd.)



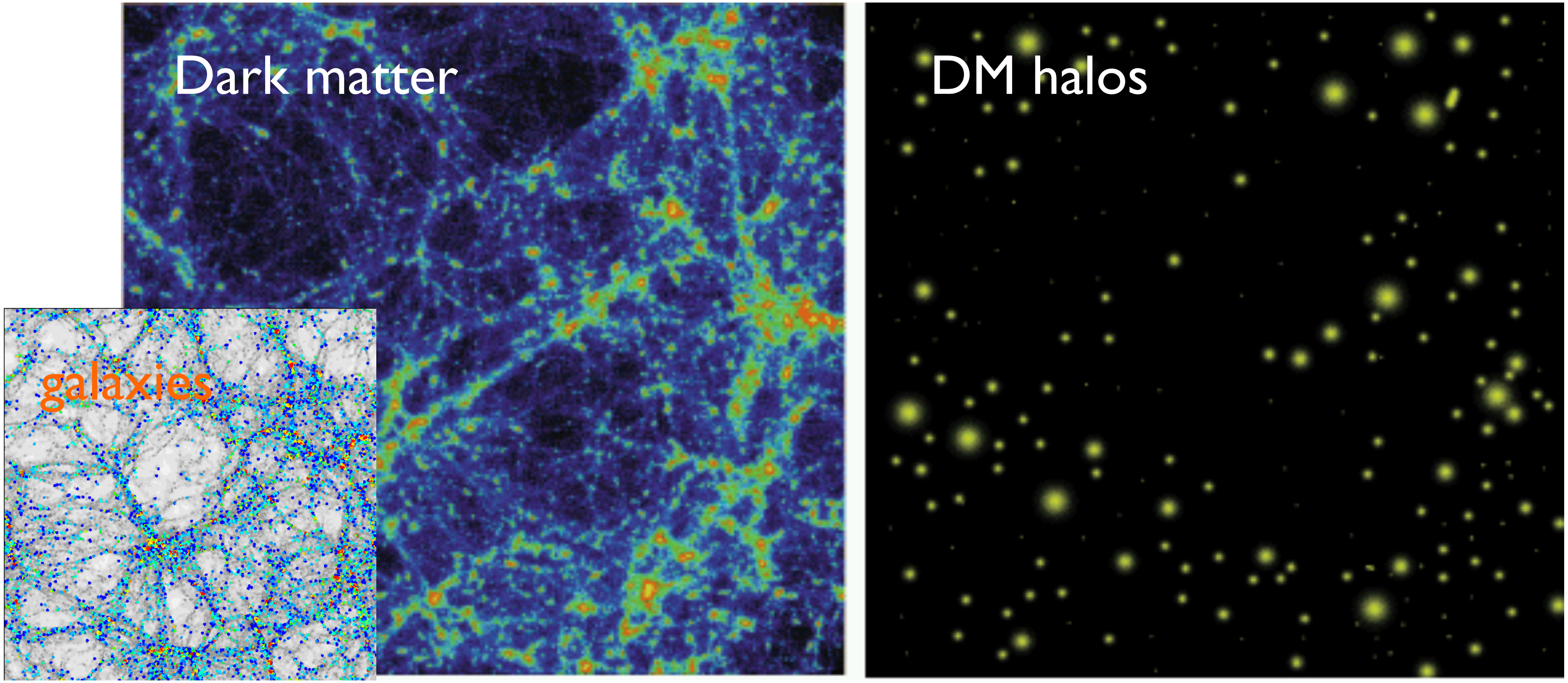


The precise meas. of mean mass: M_{vir}/10^14=6.75$^{+0.33}_{-0.32}$ (4%), c_{vir}=4.10$^{+0.21}_{-0.20}$(5%)
Excellent agreement with CDM simulation predictions

Lensing and Clustering Complementarity

- Synergy btw imaging and spectroscopic surveys for the *same* region of the sky
- Weak lensing; can *directly* probe dark matter distribution around the *spectroscopic* galaxies
- Galaxy clustering; can probe 3D large-scale structure at a particular redshift, and also probe the peculiar velocity field via RSD
- Combining the two can calibrate *systematic errors* inherent in each probe, allowing us to derive improved cosmological constraints
- The synergy not yet been fully explored (The simple Fisher calculation doesn't give a strong synergy though)
- (Cosmic shear; a harder problem unfortunately)

Galaxy – DM Connection



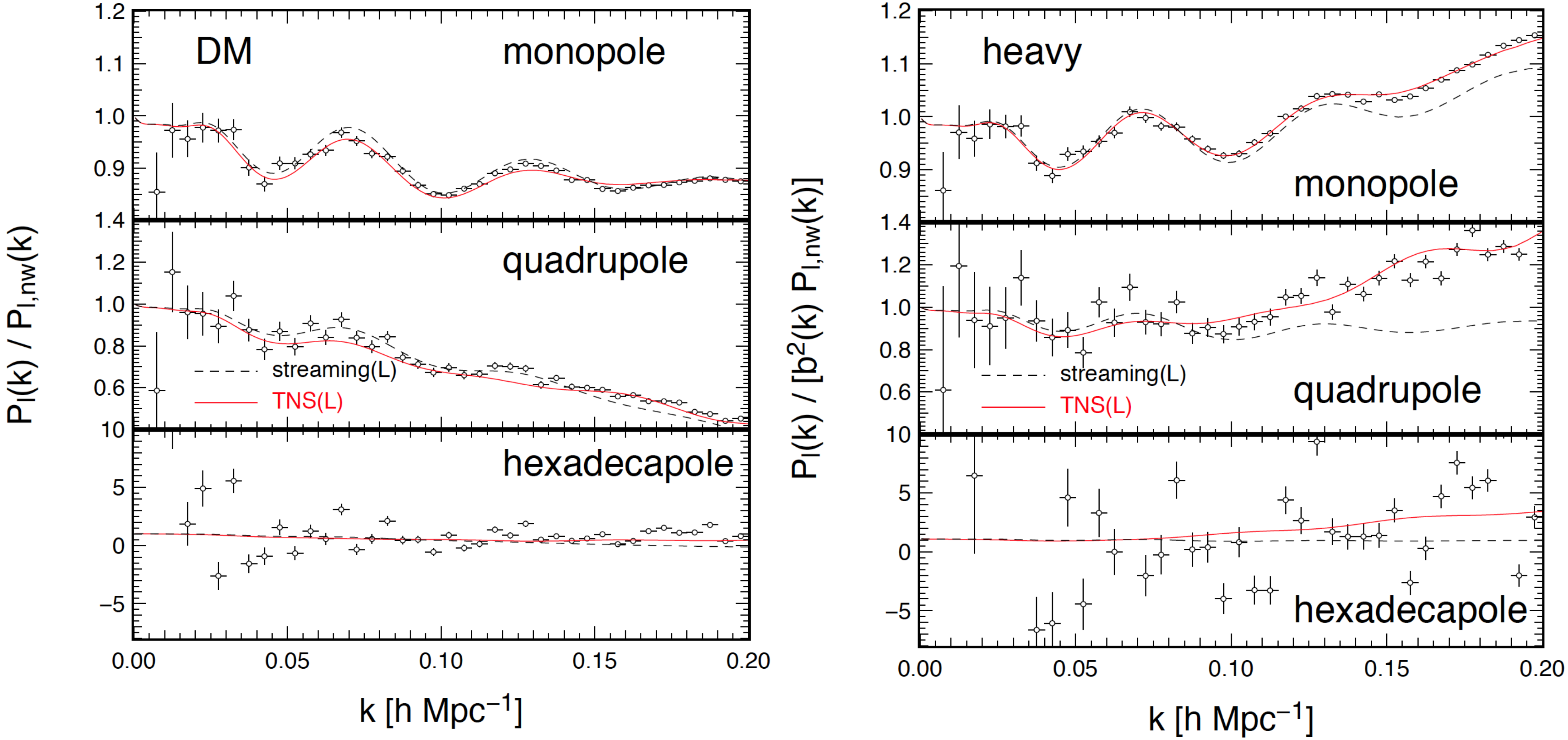
- Dark matter halo = a region where dark matter is spatially concentrated
- Galaxies are very likely to be formed in dark matter halos
- Clustering of dark matter halos, instead of galaxies, are relatively easy to model based on simulations and/or analytical models

DM halo clustering

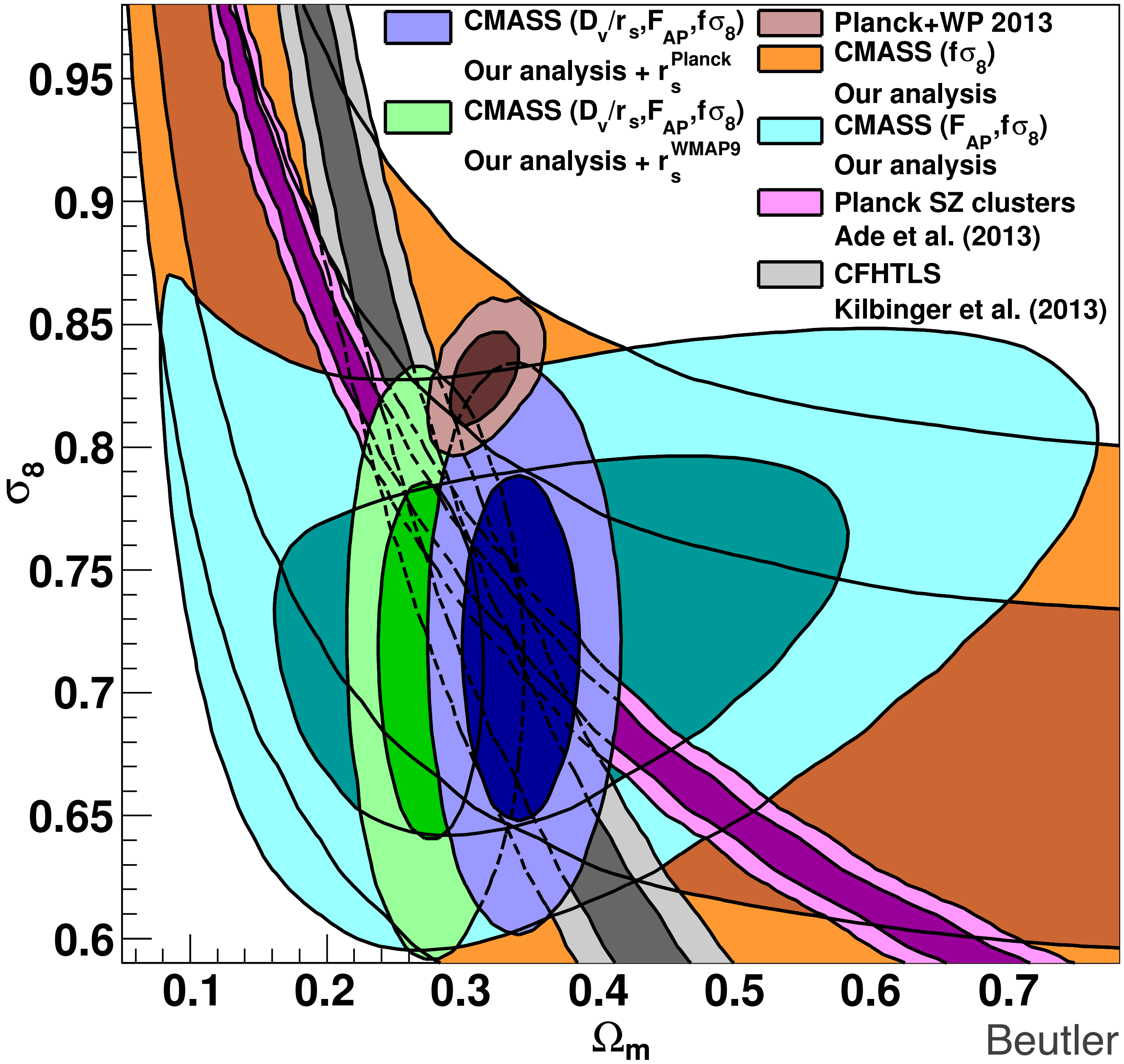
- Various efforts and promising progresses in developments of DM halo clustering based on simulations & analytical methods
- k_{max}=0.1 ⇒ 0.2 h/Mpc is equivalent to a factor 8 larger survey volume

Nishimichi & Taruya 11

Baldauf+10; Okumura+12; Matsubara & Sato12; Nishizawa+13



Planck versus LSS tension

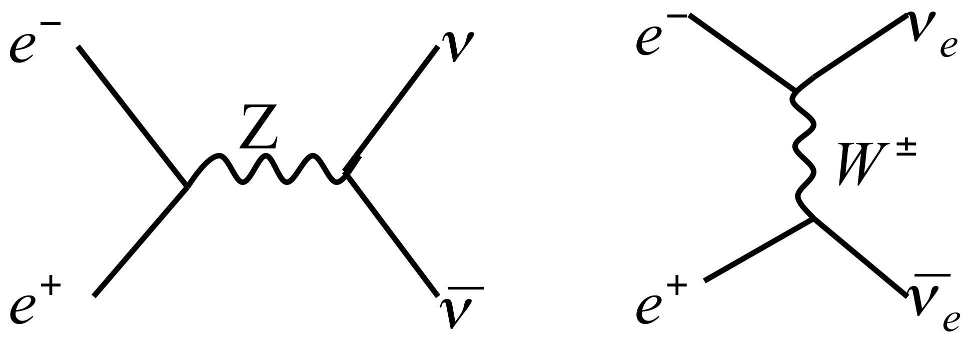


- The σ_8 and Ω_m values inferred from the best-fit ΛCDM model of Planck data is higher from those of all the LSS probes (various independent data sets)
- A possible solution
  - Neutrino mass (~0.2eV)
  - Dark energy
  - Modified gravity

Beutler et al. BOSS collab. 13

Cosmic Thermal History

Thermal equilibrium $f(\varepsilon) = \left[\exp(\varepsilon / T) \pm 1\right]^{-1}$



$\gamma, \nu, \bar{\nu}, e^-, e^+$

$T_\gamma = T_e = T_\nu$

T~ a few MeV: neutrinos decouple

Neutrinos didn't annihilate to photons

$\nu, \bar{\nu}$ $\quad \gamma, e^-, e^+$ $\quad T_\gamma = T_e = T_\nu$

T~0.5MeV: electrons and positrons annihilate

$e^- + e^+ \to 2\gamma$

$\nu, \bar{\nu}$ $\quad \gamma$, a few p, e^- $\quad T_\gamma > T_\nu$

T~1eV: matter-radiation equality

T~0.24eV(~3000K): recombination, CMB

$\gamma, \quad e^- + p \to H$

n_ν,0~100 cm^-3

Neutrinos mass!

- The experiments (Kamiokande, SK, SNO, KamLAND) imply the total mass, m_tot>0.06 eV; but the mass scale yet unknown
- Neutrinos became non-relativistic at redshift when $T_{\nu,\mathrm{dec}} \sim m_\nu$

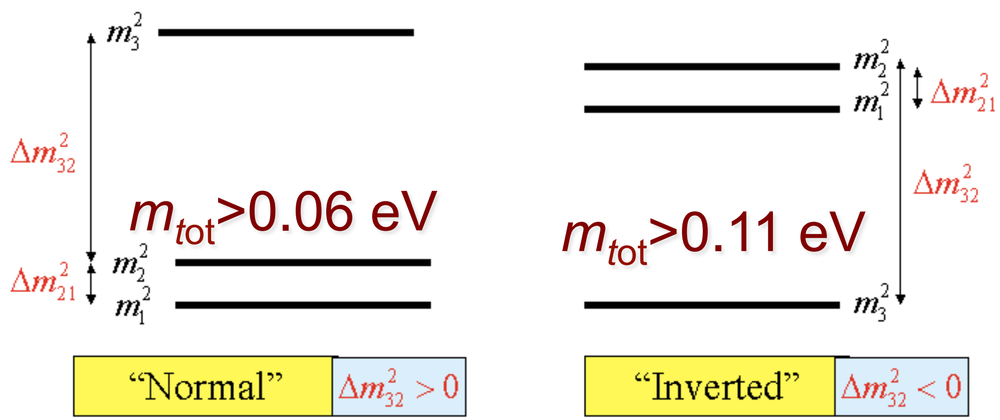
$$1 + z_{\mathrm{nr}} \approx 189\left(m_\nu / 0.1\mathrm{eV}\right)$$

  – If *m_nu>0.6eV*, the neutrino became non-relativistic before recombination, therefore larger effect on CMB, vice versa

- The cosmological probes measure the total matter density: CDM + baryon + massive neutrinos

$$\Omega_{\mathrm{m0}} = \Omega_{\mathrm{cdm0}} + \Omega_{\mathrm{baryon0}} + \Omega_{\nu 0}$$

$$f_\nu \equiv \frac{\Omega_{\nu 0}}{\Omega_{\mathrm{m0}}} = \frac{m_{\nu,\mathrm{tot}}}{94.1\mathrm{eV}\Omega_m h^2} > 0.005$$



ν+ΛCDM model

- Neutrinos are very light compared to CDM/baryon
- The phase-space distribution of neutrinos, even after decoupling, obeys the relativistic FD dist. (specified by m_ν)
- The thermal velocity at redshift z relevant for LSS is larger than the gravity induced peculiar velocity

$$\sigma_\nu(z) = \sqrt{\left\langle \frac{p^2}{2m_\nu} \right\rangle} \approx 1800\mathrm{km/s}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)^{-1}(1+z)$$

  – Even a massive cluster can't much trap neutrinos

- *The free-streaming scale*, the distance neutrino can travel with the thermal vel. during cosmic expansion

$$\lambda_{\mathrm{fs}}(z) \approx \sigma_\nu H^{-1} a^{-1} \Rightarrow k_{\mathrm{fs}}(z) \approx \frac{0.037}{(1+z)^{1/2}}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)\left(\frac{\Omega_m}{0.3}\right)^{1/2} h\ \mathrm{Mpc}^{-1}$$

λ_fs is a 100Mpc scale, similar to BAO scales

Massive neutrino effect on structure formation

- A mixed DM model: Structure formation is induced by the density fluctuations of total matter

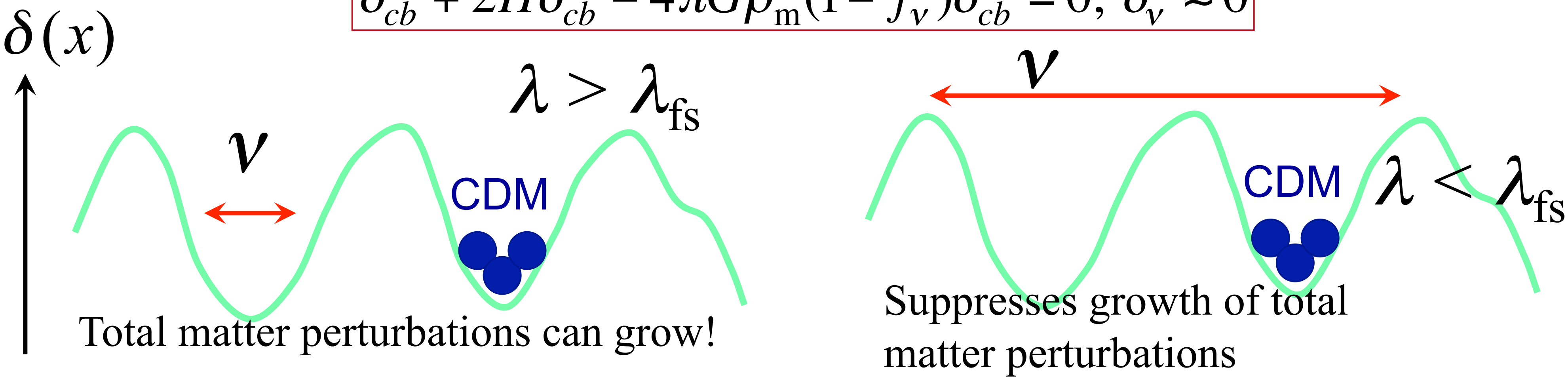
$$\delta_m = \frac{\bar{\rho}_c\delta_c + \bar{\rho}_b\delta_b + \bar{\rho}_\nu\delta_\nu}{\bar{\rho}_c + \bar{\rho}_b + \bar{\rho}_\nu} \equiv f_c\delta_c + f_b\delta_b + f_\nu\delta_\nu$$

- The neutrinos slow down LSS on small scales
  - On large scales $\lambda > \lambda_{fs}$, the neutrinos can grow together with CDM

$$\delta_c = \delta_b = \delta_\nu$$

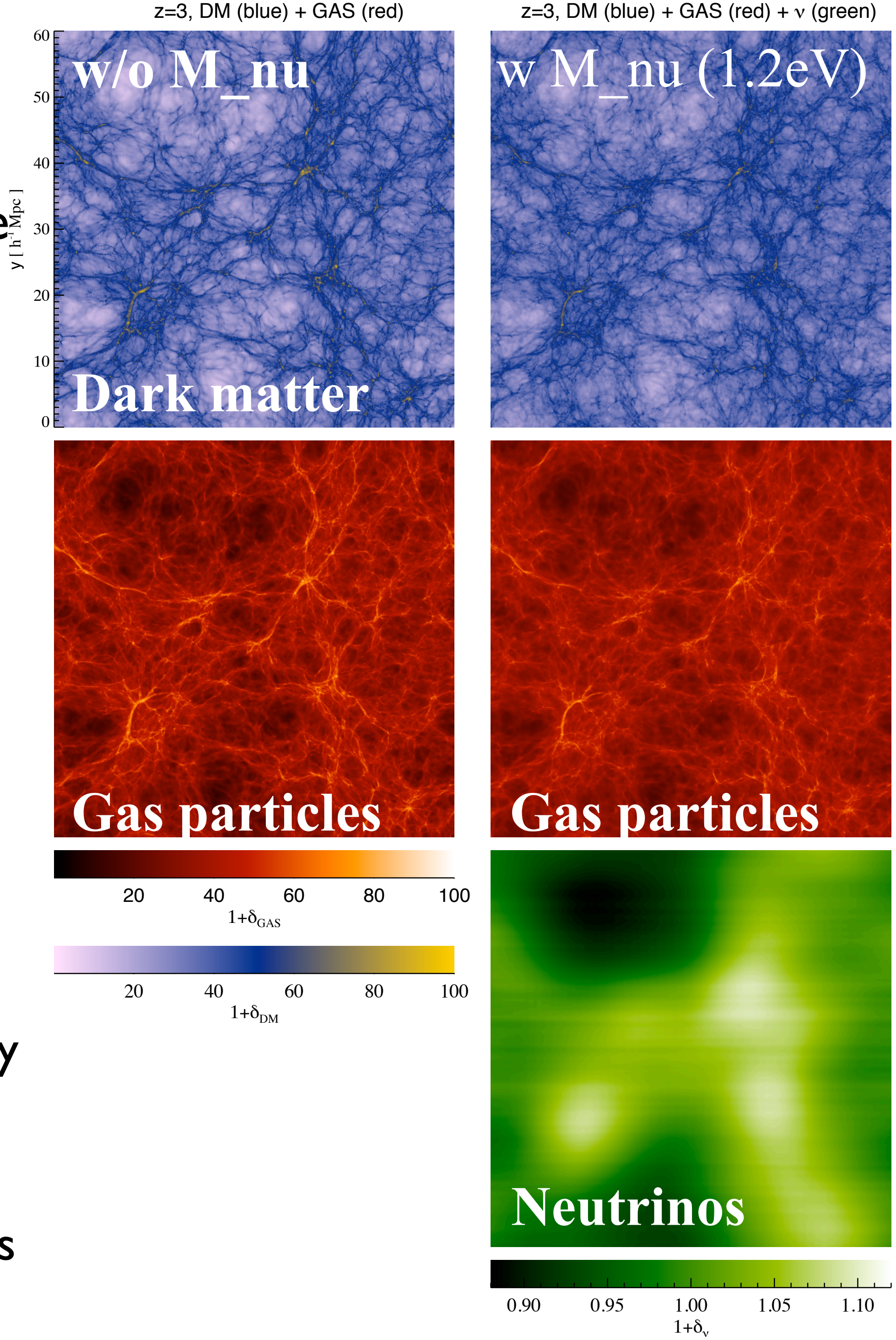
  - On small scales $\lambda < \lambda_{fs}$, the neutrinos are smooth, $\delta_\nu = 0$, therefore weaker gravitational force compared to a pure CDM case

$$\ddot{\delta}_{cb} + 2H\dot{\delta}_{cb} - 4\pi G\bar{\rho}_{\rm m}(1 - f_\nu)\delta_{cb} = 0,\ \delta_\nu \approx 0$$



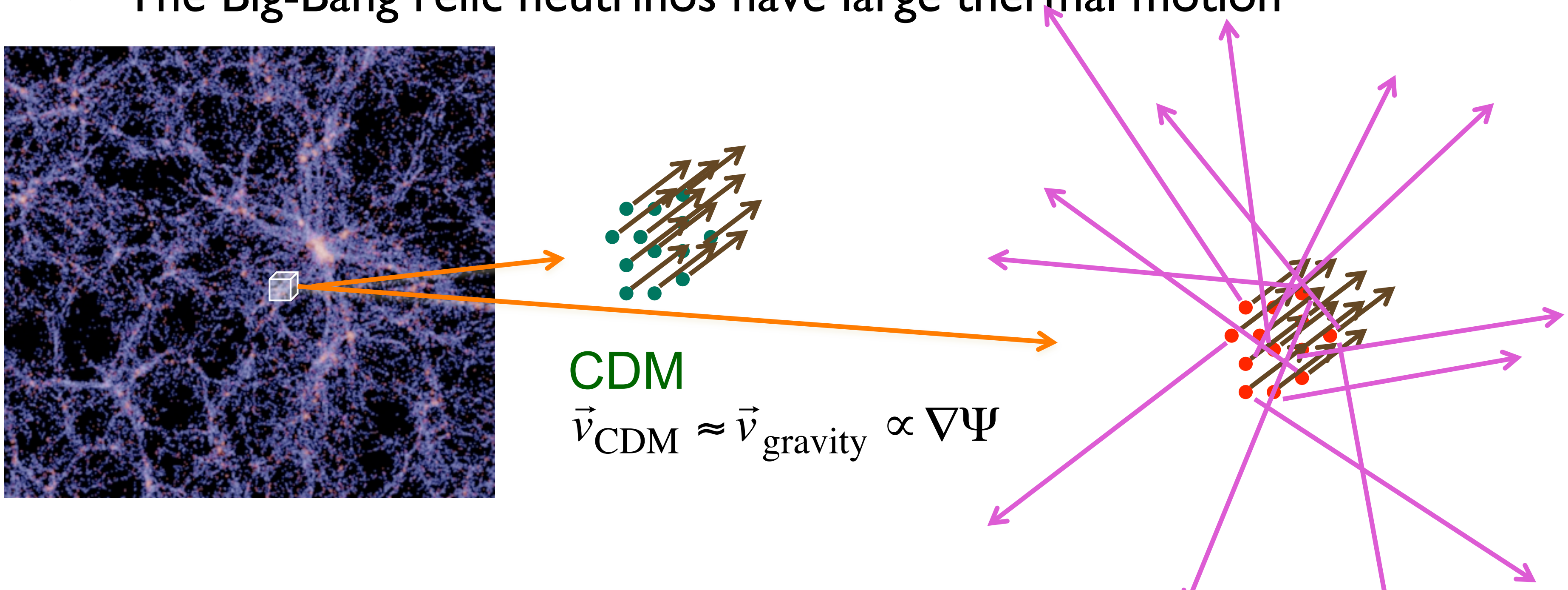
Modeling SF in a mixed DM model

- Need to include the effect of massive neutrinos to interpret the high-precision cosmological data
- Analytical attempts
  - Based on the perturbation theory (Sato et al. 08, 09; Shoji & Komatsu 09; Swanson et a. 10)
  - Only applicable to the weakly NL regime
  - Used to obtain the upper limit: M_nu<0.6 eV (95% C.L.)
- Simulation attempts
  - Several groups have started the study (Brandbyge & Hannestad 08; Viel, Haehnelt, & Springel 10)
  - Still very difficult to include neutrinos with masses <1 eV



C+H DM simulation (CDM + Neutrinos)

- Structure formation in the real universe is caused by CDM + neutrinos
- The Big-Bang relic neutrinos have large thermal motion



CDM

$$\vec{v}_{\mathrm{CDM}} \approx \vec{v}_{\mathrm{gravity}} \propto \nabla\Psi$$

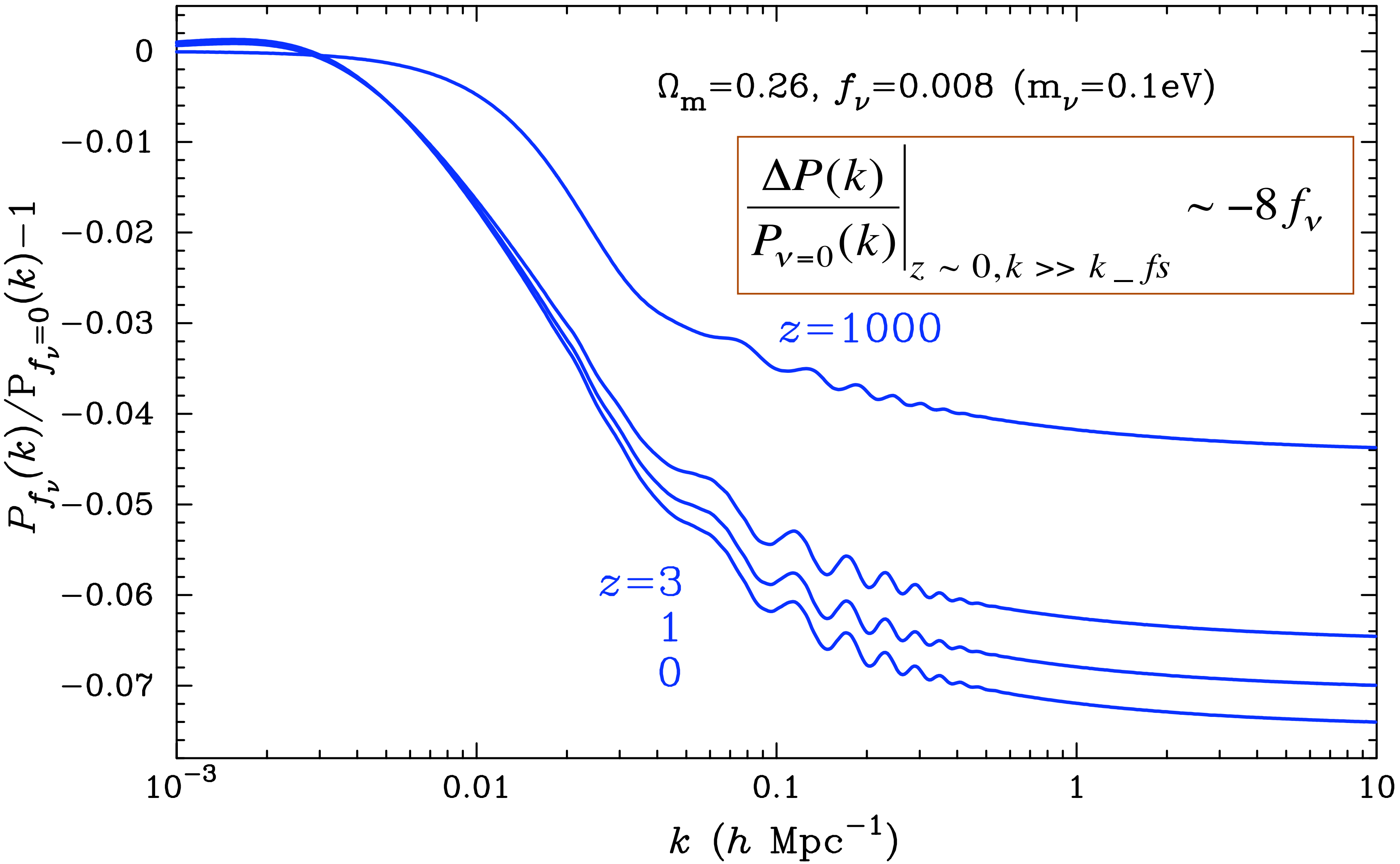
Neutrinos $\vec{v}_{\nu} \approx \vec{v}_{\mathrm{gravity}} + \vec{v}_{\mathrm{thermal}}$

$$\sigma_{\nu}(z) = \sqrt{\left\langle \frac{p^2}{2m_{\nu}} \right\rangle} \approx 1800\mathrm{km/s}\left(\frac{m_{\nu}}{0.1\mathrm{eV}}\right)^{-1}(1+z)$$

The r.m.s. thermal velocity > the velocity dispersion of galaxy clusters (~1000km/s): neutrinos can't much cluster on small scales (free-streaming)

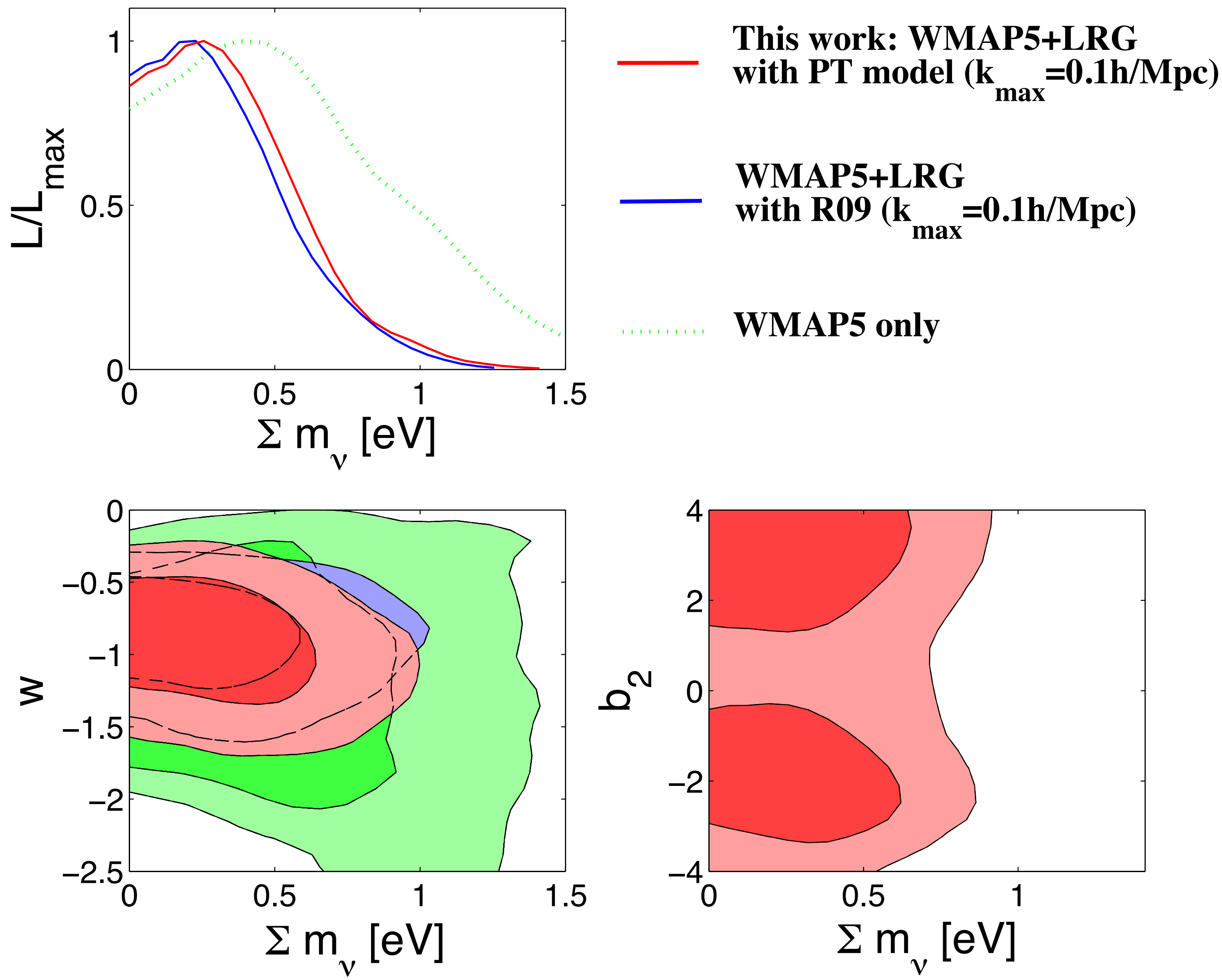
Suppression of linear P(k) (contd.)

- A more realistic f_nu~0.01 (m_nu~0.1eV): the neutrinos became non-relativistic after z~10^3
- The power spectrum amplitude is suppressed by ~8%



Neutrino mass constraint with SDSS DR7 LRG power spectrum

MT & Taruya 11

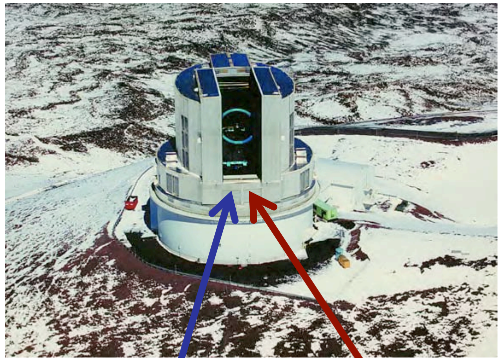


d the power trum measured n the SDSS DR7 catalog (Reid et 9)

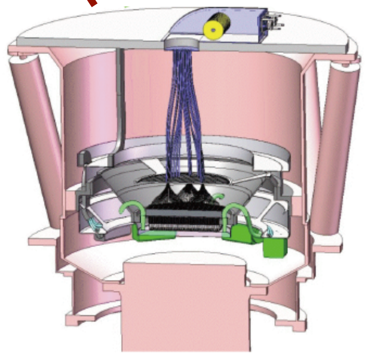
PT model can match the sured power trum by sting the bias meters, up to ax~0.2Mpc/h

SuMIRe = Subaru Measurement of Images and Redshifts

- IPMU director Hitoshi Murayama funded (~ $32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper SuprimeCam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) 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

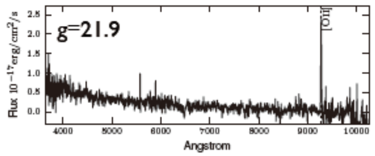


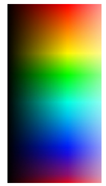
Subaru (NAOJ)



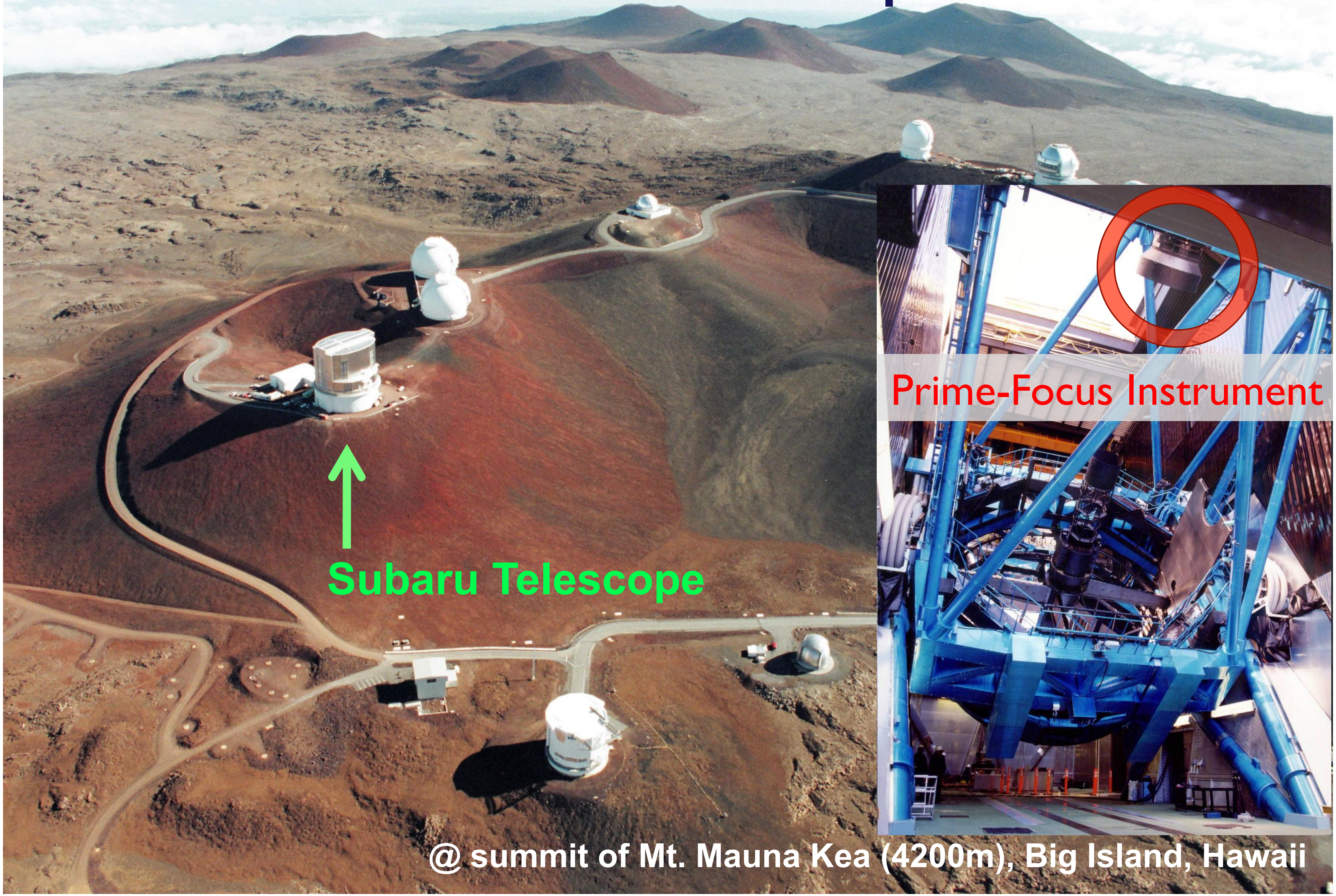
PFS

HSC



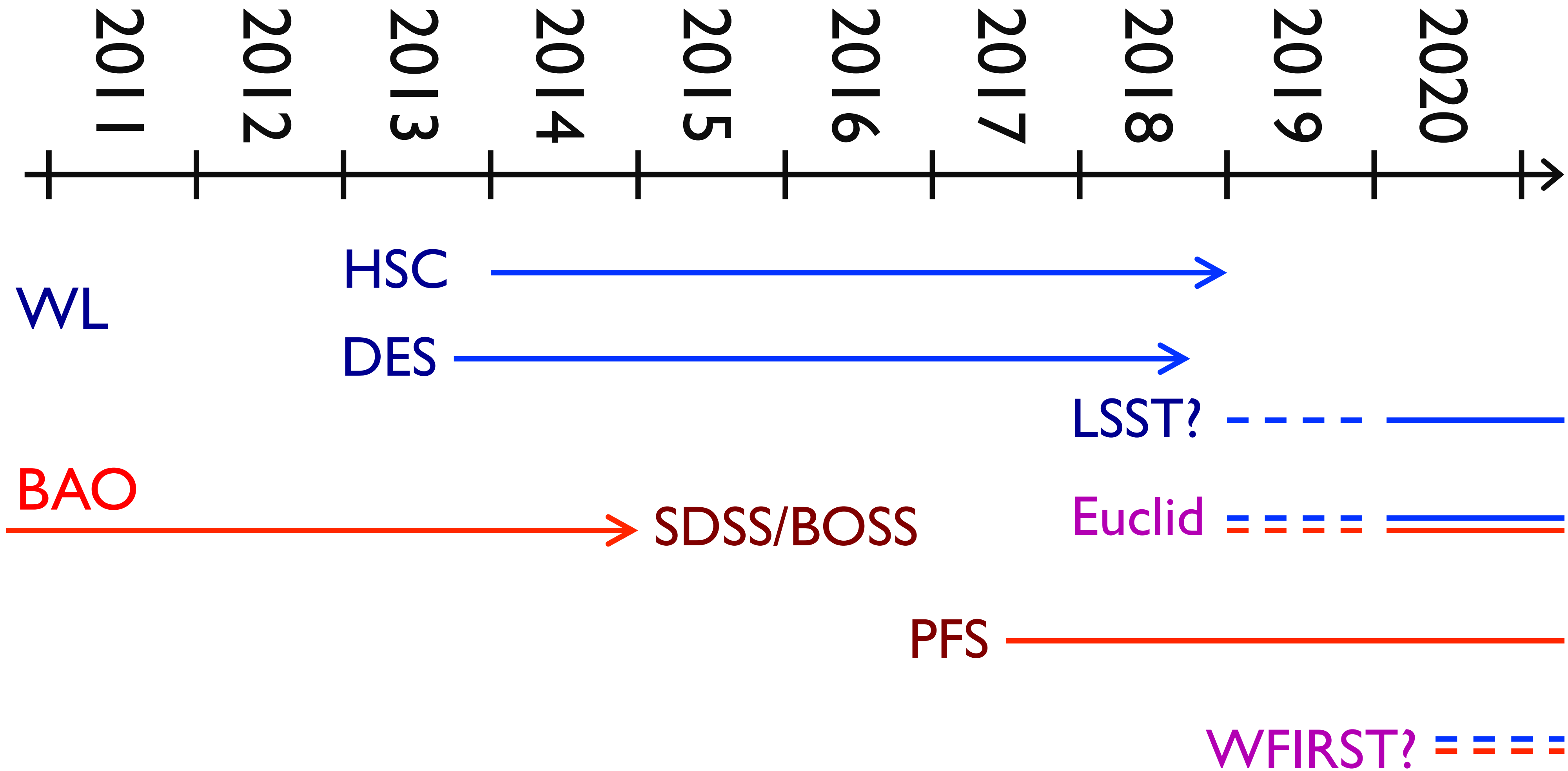


Subaru Telescope



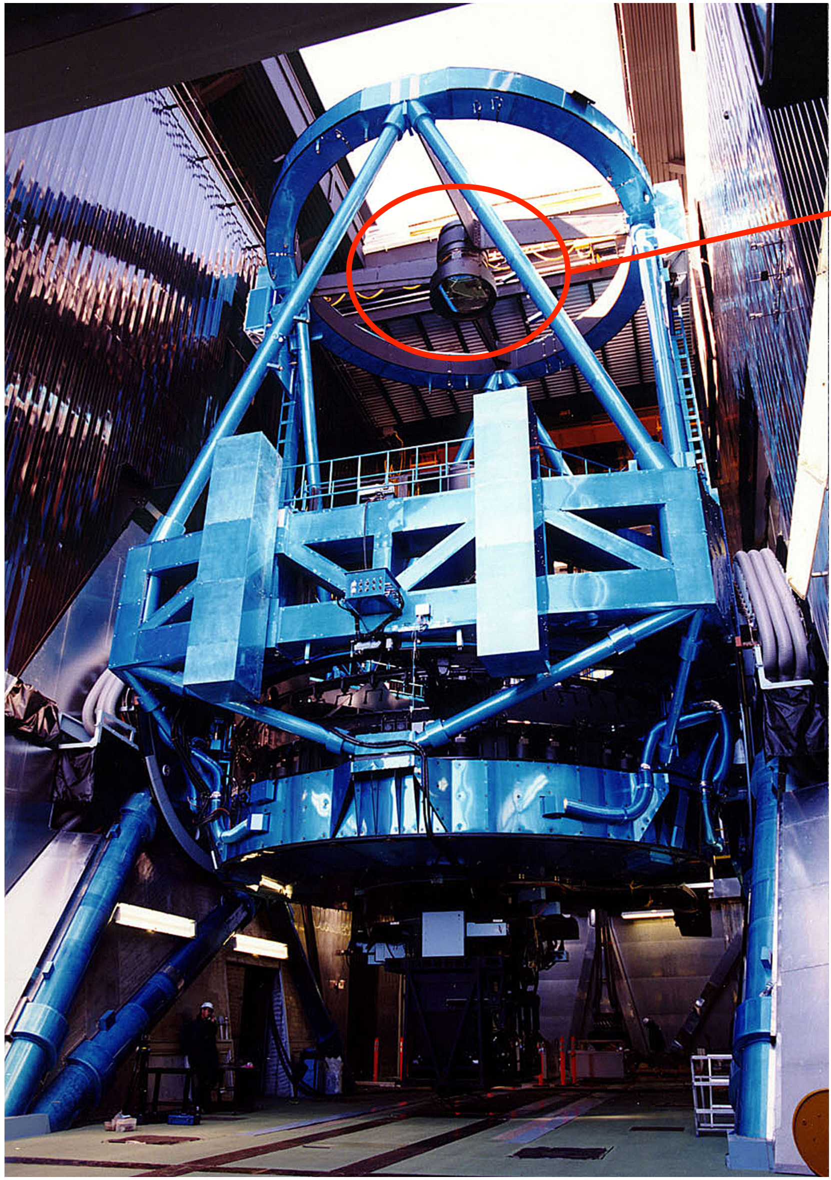

Dark Energy Competition
SDSS III
BOSS (2009-)
KIDS (2012-)
BigBOSS (2015?-)
A Proposal to NOAO for the
BigBOSS Experiment
at Kitt Peak National Observatory
October 1, 2010
DARK ENERGY SURVEY
DES (2012-)
Euclid (2020)
LSST
Large Synoptic Survey Telescope
LSST (2020?-)
WFIRST (2020?-)
WFIRST
Wide-Field Infrared Survey Telescope

Time line (DE experiments)

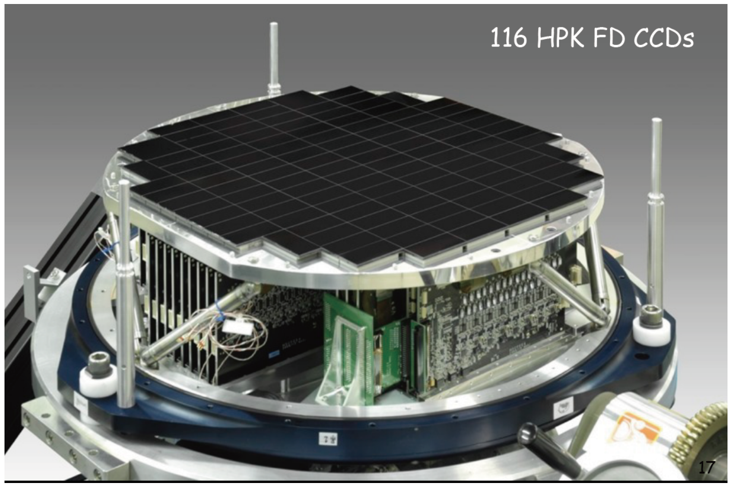


We are in a good position!

Hyper Suprime-Cam Project



- All instruments at Mauna Kea
- The *largest* camera in the world
- 3m high
- 3 tons weighed
- 116 CCD chips (870 millions pixels)



HSC First Light Image of M31

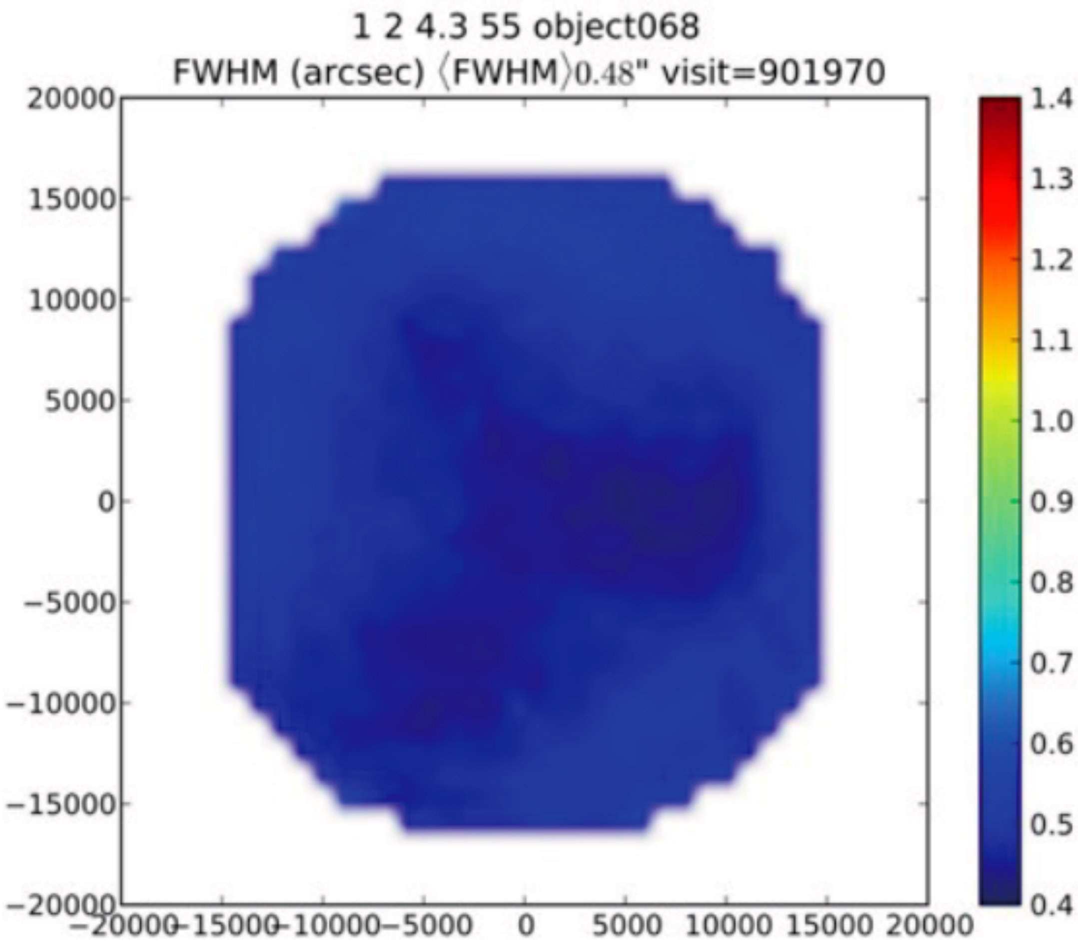
S. Miyazaki
(NAOJ)

N. Yasuda

S. Bickerton

Performance Test 4: Image Quality Uniformity

Feb2, 2013 Seeing 0''.4 ~ 0''.6 FWHM



← DES

← HSC

10 sec exp

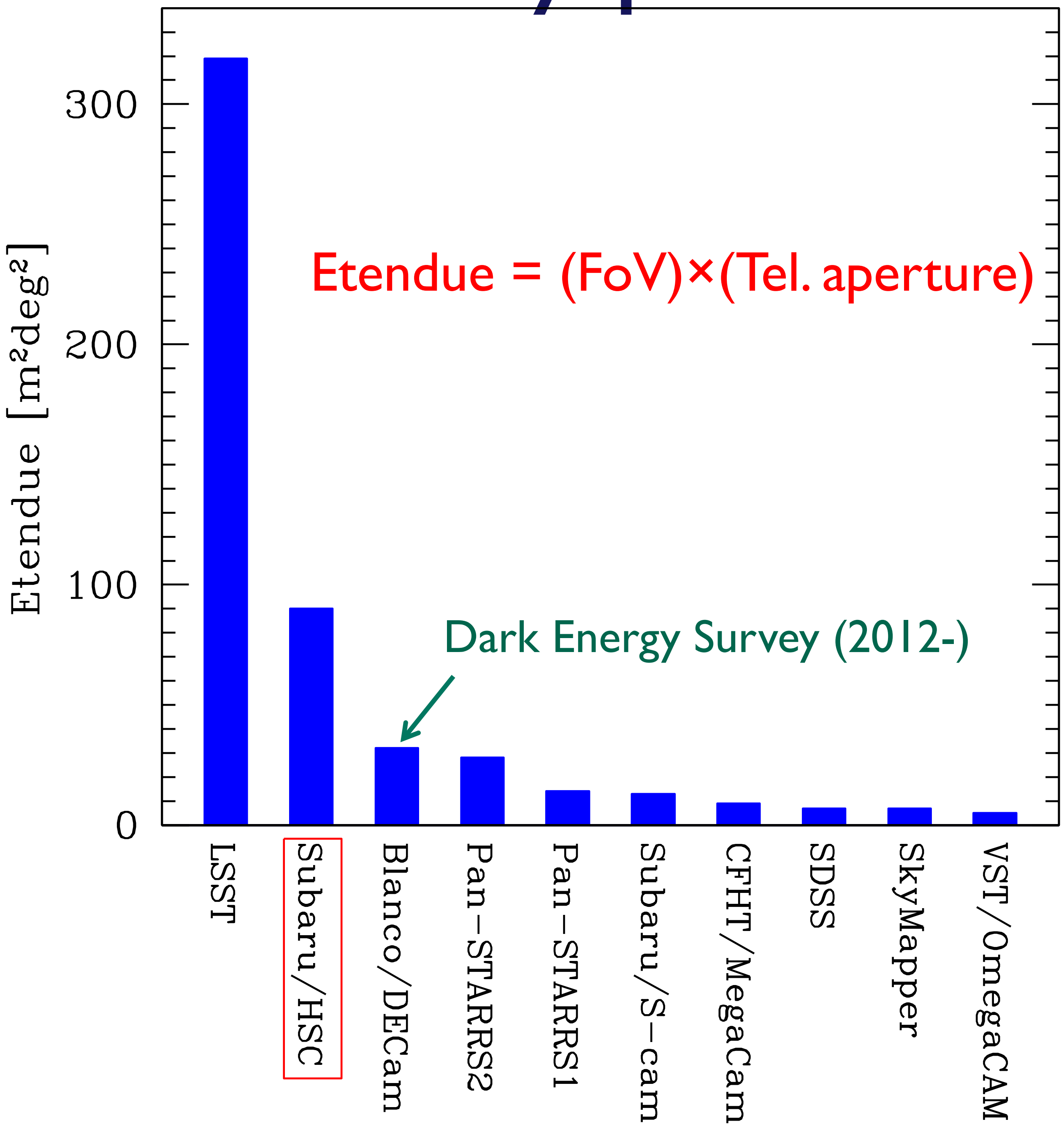
i'-band

EL: 55

The 1st year science verification data of **DES** (~200 sq. degs) shows ~1.1" FWHM for the median seeing

From S. Miyazaki (HSC PI, NAOJ)

Survey power of HSC

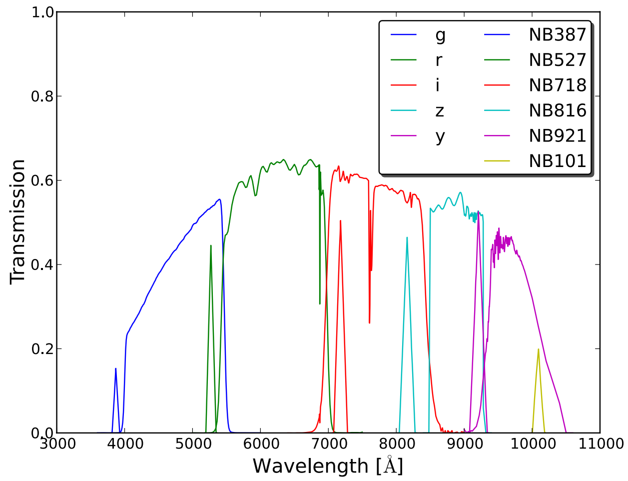


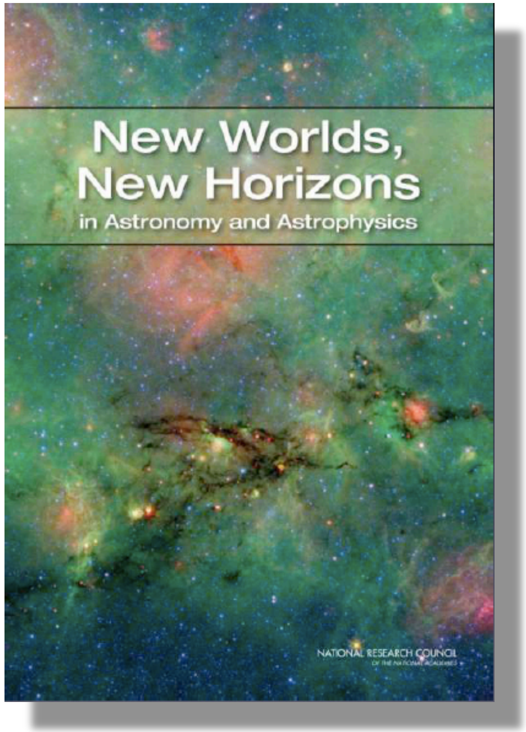
- Photon collecting power of 8.2m Subaru Tel.
- FoV
- In addition, excellent image quality

→ *These make HSC the most powerful survey camera/ telescope before LSST*

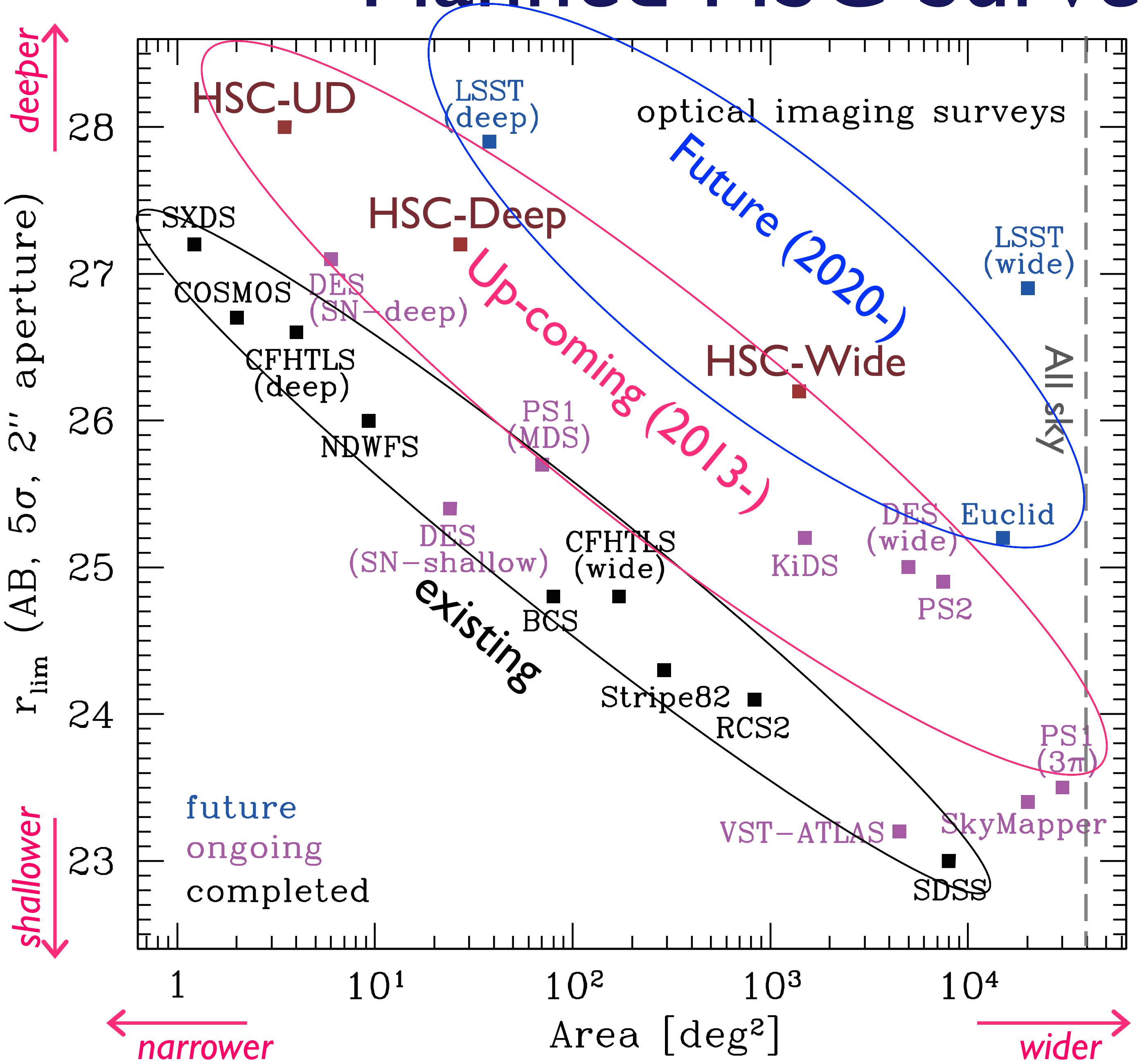
Planned HSC Survey

- Wide Layer: 1400 sq. degs., *grizy* (i_{AB}=26, 5σ)
  - Weak gravitational lensing
  - Galaxy clustering, properties of z~1 L_* galaxy
  - *Dark Energy*, *Dark Matter*, neutrino mass, the early universe physics (primordial non-Gaussianity, spectral index)
- Deep Layer: 28 sq. degs, *grizy*+NBs (*i*=27)
  - For calibration of galaxy shapes for HSC-Wide WL
  - Lyman-alpha emitters, Lyman break galaxies, QSO
  - Galaxy evolution up to z~7
  - *The physics of cosmic reionization*
- Ultra-deep Layer: 2FoV, *grizy*+NBs (i~28)
  - Type-Ia SNe up to z~1.4
  - LAEs, LBGs
  - Galaxy evolution
  - *Dark Energy, the cosmic reionization*





Planned HSC Survey



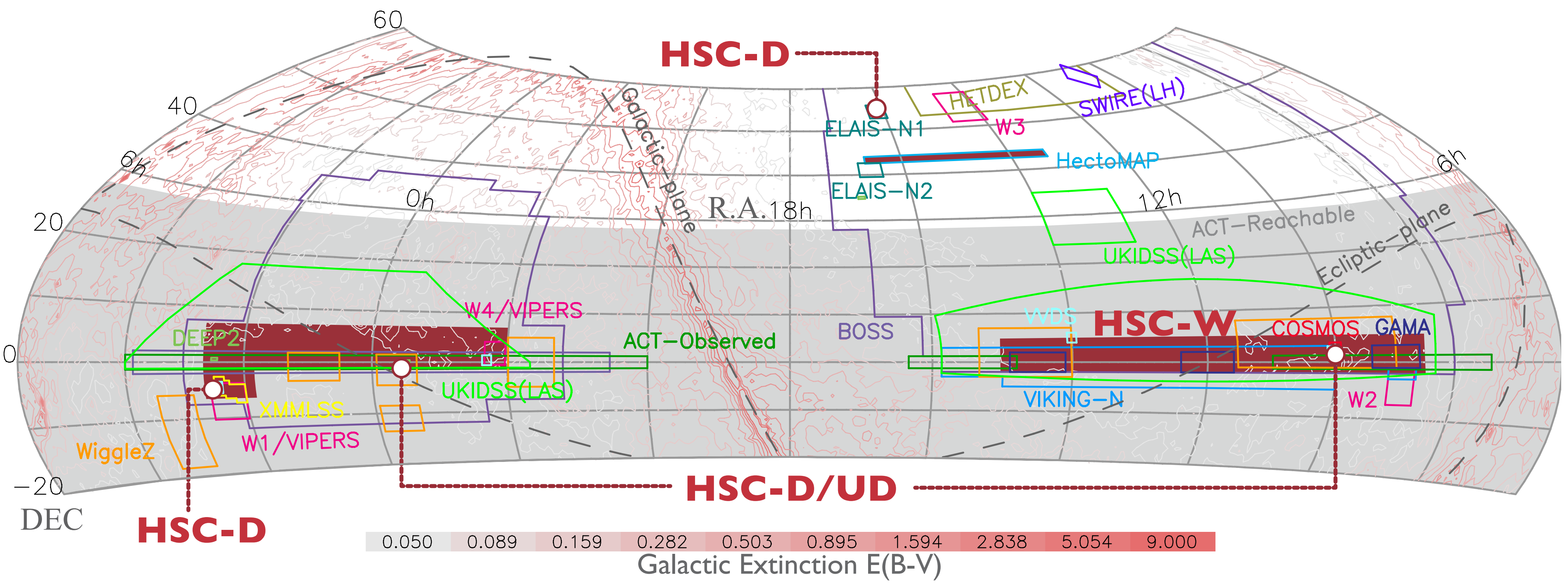
Black: existing

Magenta: upcoming

Blue: future

HSC Layers will explore new regions in survey parameter space

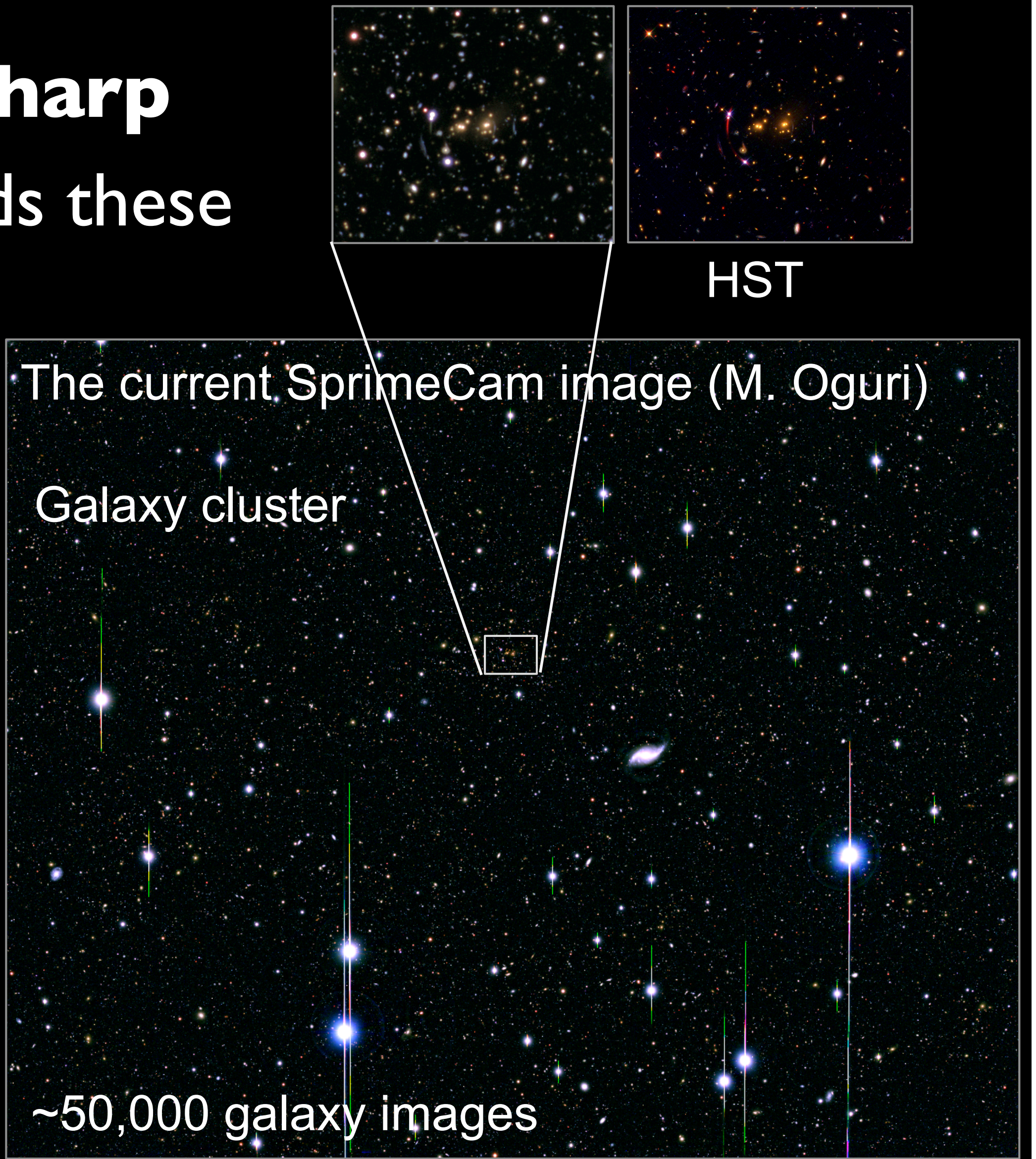
HSC Survey Fields



- The HSC fields are selected based on …
  - Synergy with other data sets: SDSS/BOSS, The Atacama Cosmology Telescope CMB survey (from Chile), X-ray (XMM-LSS), spectroscopic data sets
  - Spread in RA
  - Low dust extinction

Subaru Telescope: wide FoV & excellent image quality

- **Fast, Wide, Deep & Sharp**
- a cosmological survey needs these

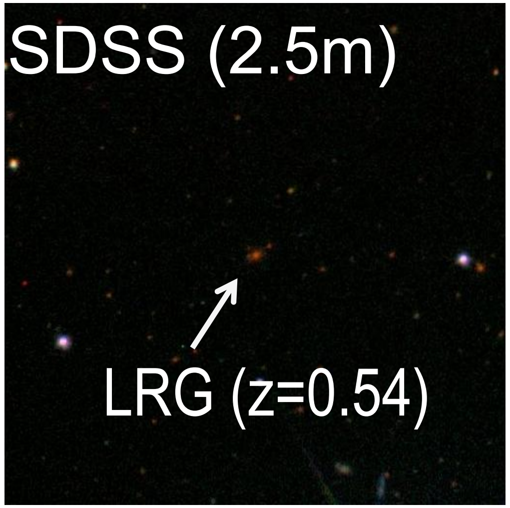


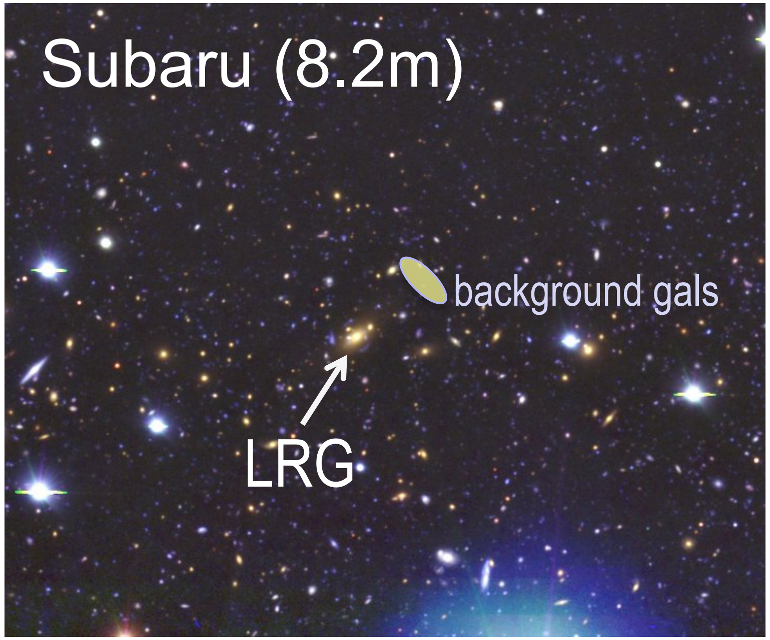
wi

Hyper Suprime-Cam FoV

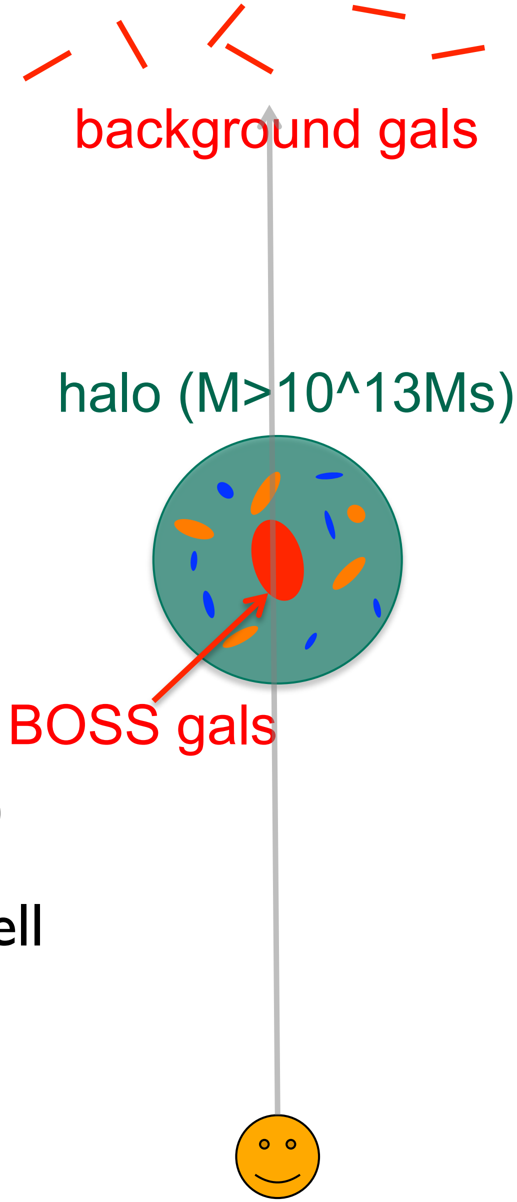
- **Fast**
- a cos

Synergy btw HSC and BOSS





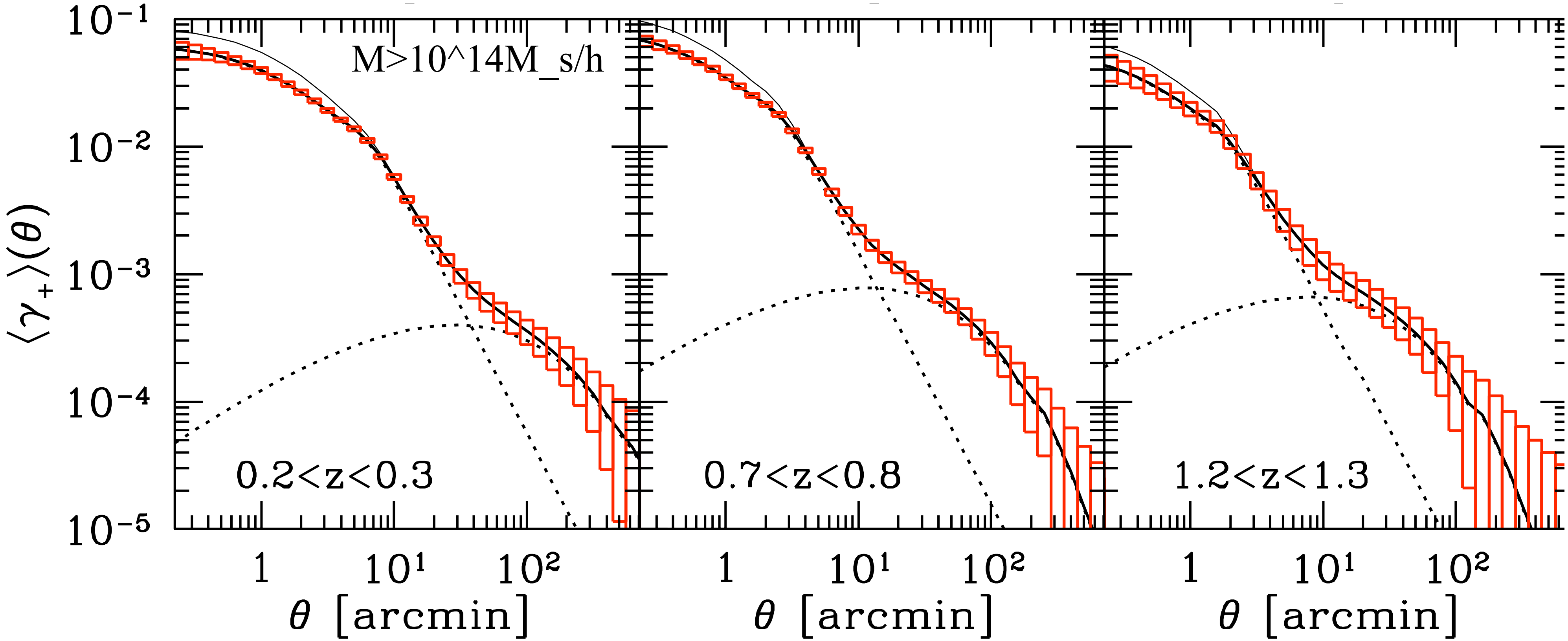
Credit: Masayuki Tanaka (NAOJ)



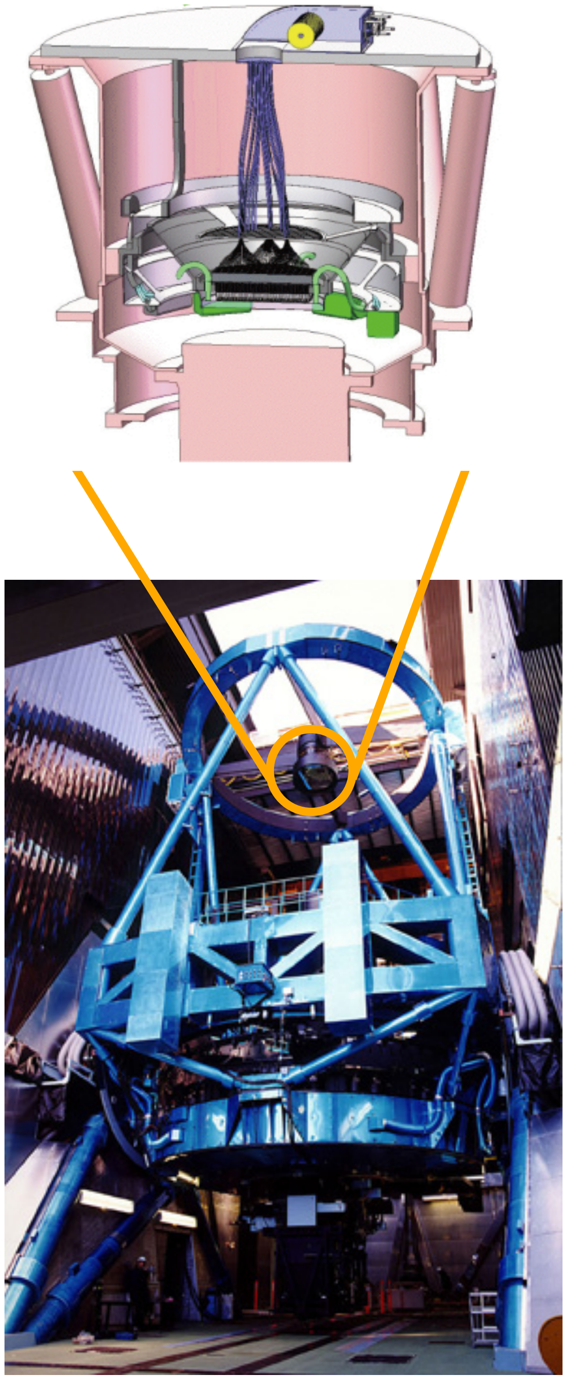
- The deep HSC data will add background galaxies as well as member galaxies around each BOSS gal
- Cross-correlation of BOSS gals with HSC galaxies (shapes and positions)
- WL, galaxy clustering, CMB lensing, SZ, X-ray….

Forecast for stacked lensing with HSC

Oguri & MT 10



- HSC can achieve a high S/N detection of stacked WL signals out to z~1.3
- Small-angle signals are from one halo (the mean halo mass and the average shape of mass profile)
- Large-angle signals are from the mass distribution in large-scale structure



Prime Focus Spectrograph (PFS)

- Multi object fiber spectrograph for 8.2m Subaru
- International collaboration; Japan (IPMU+), Princeton, JHU, Caltech/JPL, LAM, Brazil, ASIAA
- Initiated by the stimulus funding (~$30M secure); ~$80M needed for the instrumentation
- The current baseline design
  - The same optics to HSC
  - 2400 fibers
  - 380-1300nm wavelength coverage
  - R~2000, 3000, 5000 (blue, red, NIR)
- The target first light; around 2017
- Capable of various science cases: cosmology, galaxy, galactic archeology

PFS collaboration

Caltech

Jet Propulsion Laboratory
California Institute of Technology

NAOJ

ACADEMIA SINICA

PRINCETON UNIVERSITY

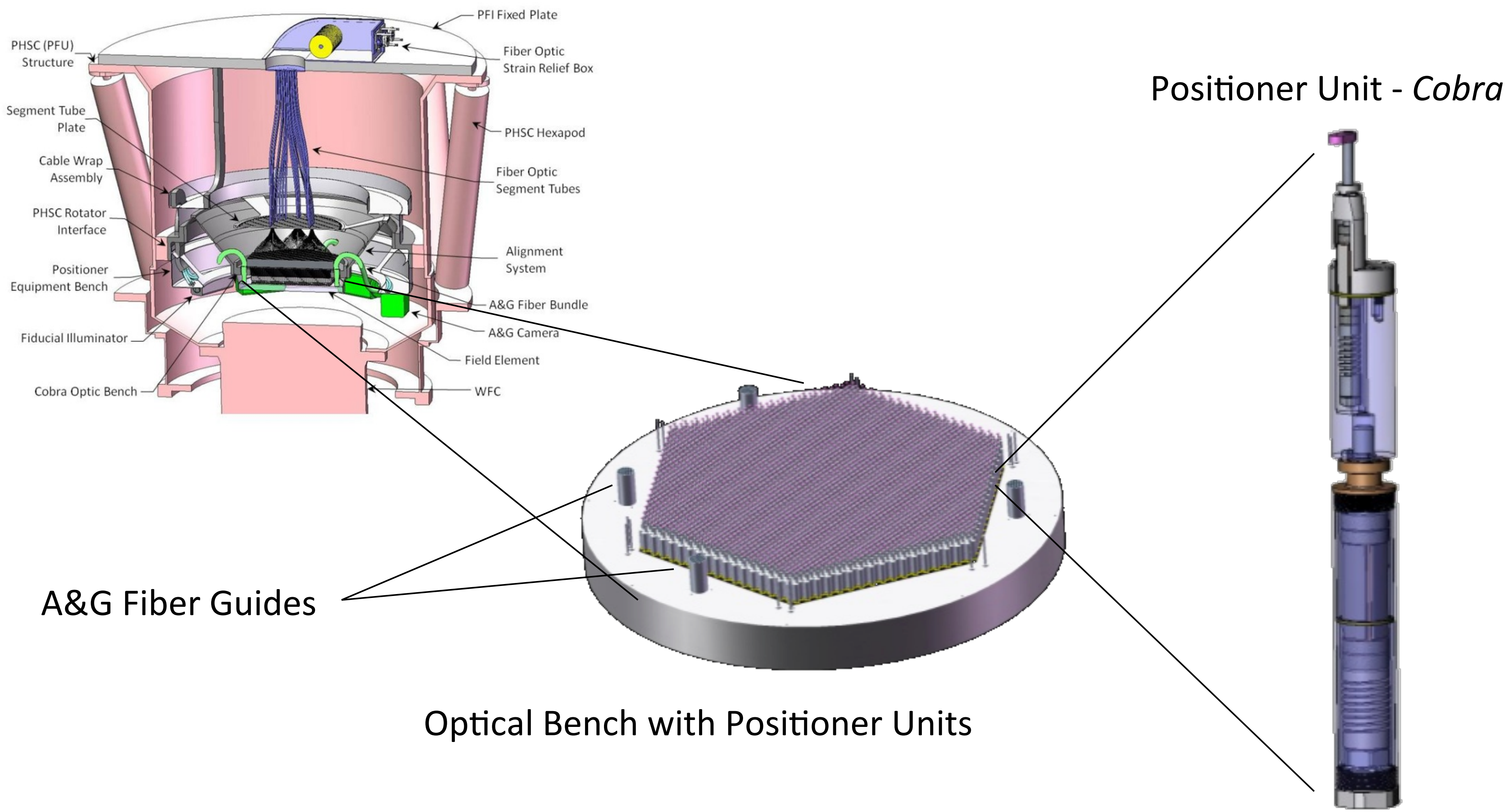
KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

LNA LABORATÓRIO NACIONAL DE ASTROFÍSICA

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

JOHNS HOPKINS UNIVERSITY

PFS Positioner



Optical Bench with Positioner Units

Cobra system is the most essential part of PFS, and will be built at JPL

Designed to achieve 5 μ m accuracy in < 8 iterations (40 sec)

arXiv:1206.0737 Takada, Ellis, Chiba, Greene et al. (PASJ in press)

DRAFT VERSION AUGUST 1, 2013
Preprint typeset using LaTeX style emulateapj v. 5/2/11

EXTRAGALACTIC SCIENCE, COSMOLOGY AND GALACTIC ARCHAEOLOGY WITH THE SUBARU PRIME FOCUS SPECTROGRAPH (PFS)

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Draft version August 1, 2013

ABSTRACT

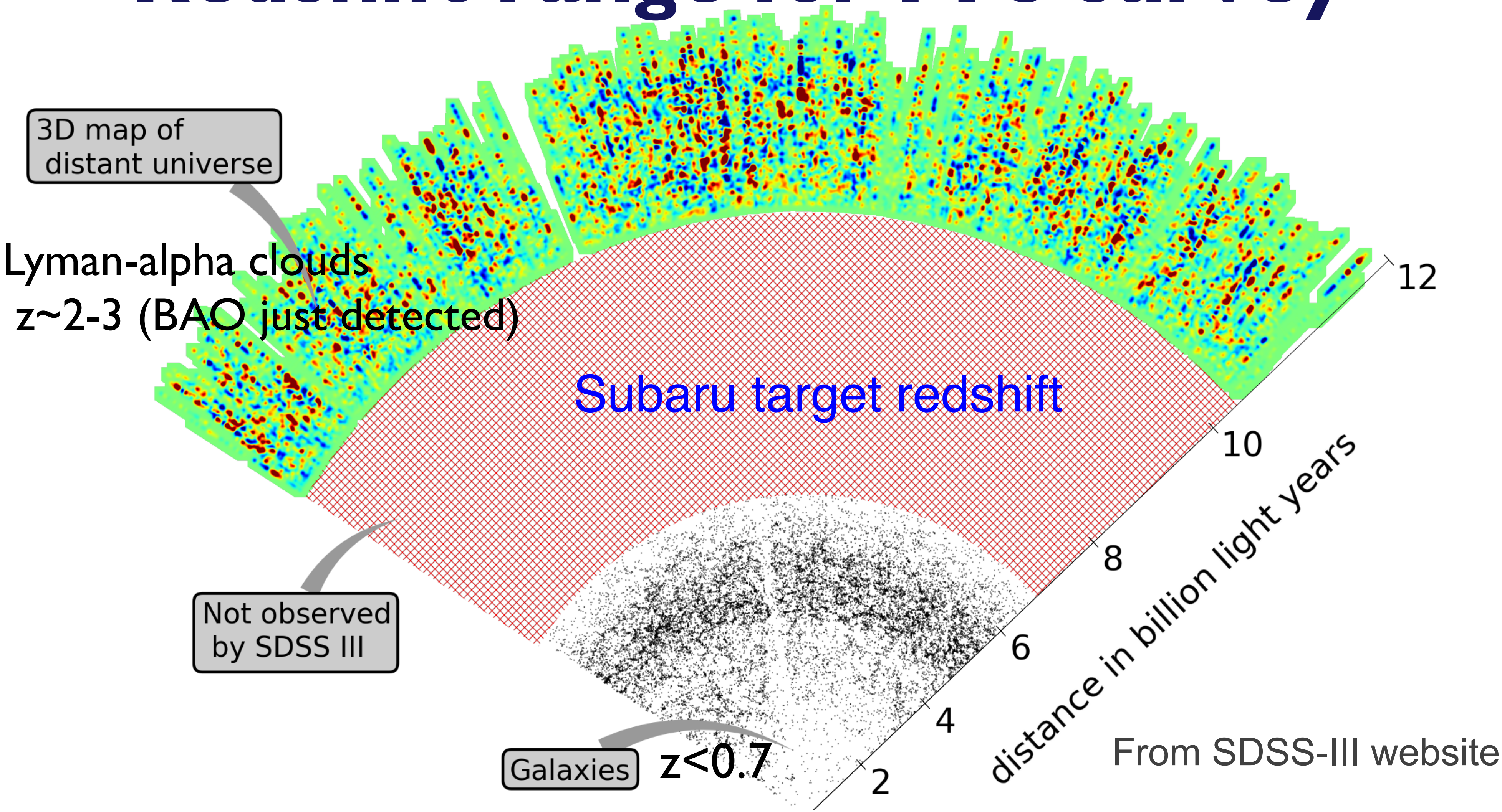
The Subaru Prime Focus Spectrograph (PFS) is a massively-multiplexed fiber-fed optical and near-infrared 3-arm spectrograph ($N_{\rm fiber}$=2400, 380$\leq \lambda \leq$ 1260nm, 1.3 degree diameter hexagonal field), offering unique opportunities in survey astronomy. Following a successful external design review the instrument is now under construction with first light anticipated in late 2017. Here we summarize the science case for this unique instrument in terms of provisional plans for a Subaru Strategic Program of $\simeq$300 nights. We describe plans to constrain the nature of dark energy via a survey of emission line galaxies spanning a comoving volume of $9.3h^{-3}$Gpc^3 in the redshift range $0.8 < z < 2.4$. In each of 6 independent redshift bins, the cosmological distances will be measured to 3% precision via the baryonic acoustic oscillation scale, and redshift-space distortion measures will be used to constrain structure growth to 6% precision. In the near-field cosmology program, radial velocities and chemical abundances of stars in the Milky Way and M31 will be used to infer the past assembly histories of spiral galaxies and the structure of their dark matter halos. Data will be secured for 10^6 stars in the Galactic thick-disk, halo and tidal streams as faint as $V \sim 22$, including stars with $V < 20$ to complement the goals of the Gaia mission. A medium-resolution mode with $R = 5,000$ to be implemented in the red arm will allow the measurement of multiple α-element abundances and more precise velocities for Galactic stars, elucidating the detailed chemo-dynamical structure and evolution of each of the main stellar components of the Milky Way Galaxy and of its dwarf spheroidal galaxies. The M31 campaign will target red giant branch stars with 21.5$< V <$22.5, obtaining radial velocities and metallicities over an unprecedented area of 65 deg^2. For the extragalactic program, our simulations suggest the wide wavelength range of PFS will be particularly powerful in probing the galaxy population and its clustering over a wide redshift range. We propose to conduct a color-selected survey of $1 < z < 2$ galaxies and AGN over 16 deg^2 to $J \simeq$23.4, yielding a fair sample of galaxies with stellar masses above $\sim 10^{10} M_\odot$ at $z \simeq 2$. A two-tiered survey of higher redshift Lyman break galaxies and Lyman alpha emitters will quantify the properties of early systems close to the reionization epoch. PFS will also provide unique spectroscopic opportunities beyond these currently-envisaged surveys, particularly in the era of Euclid, LSST and TMT.

Science Objectives: Three Pillars

All science cases are based on a spectroscopic follow-up of objects taken from the HSC imaging data (extending the SDSS to z~1-2)

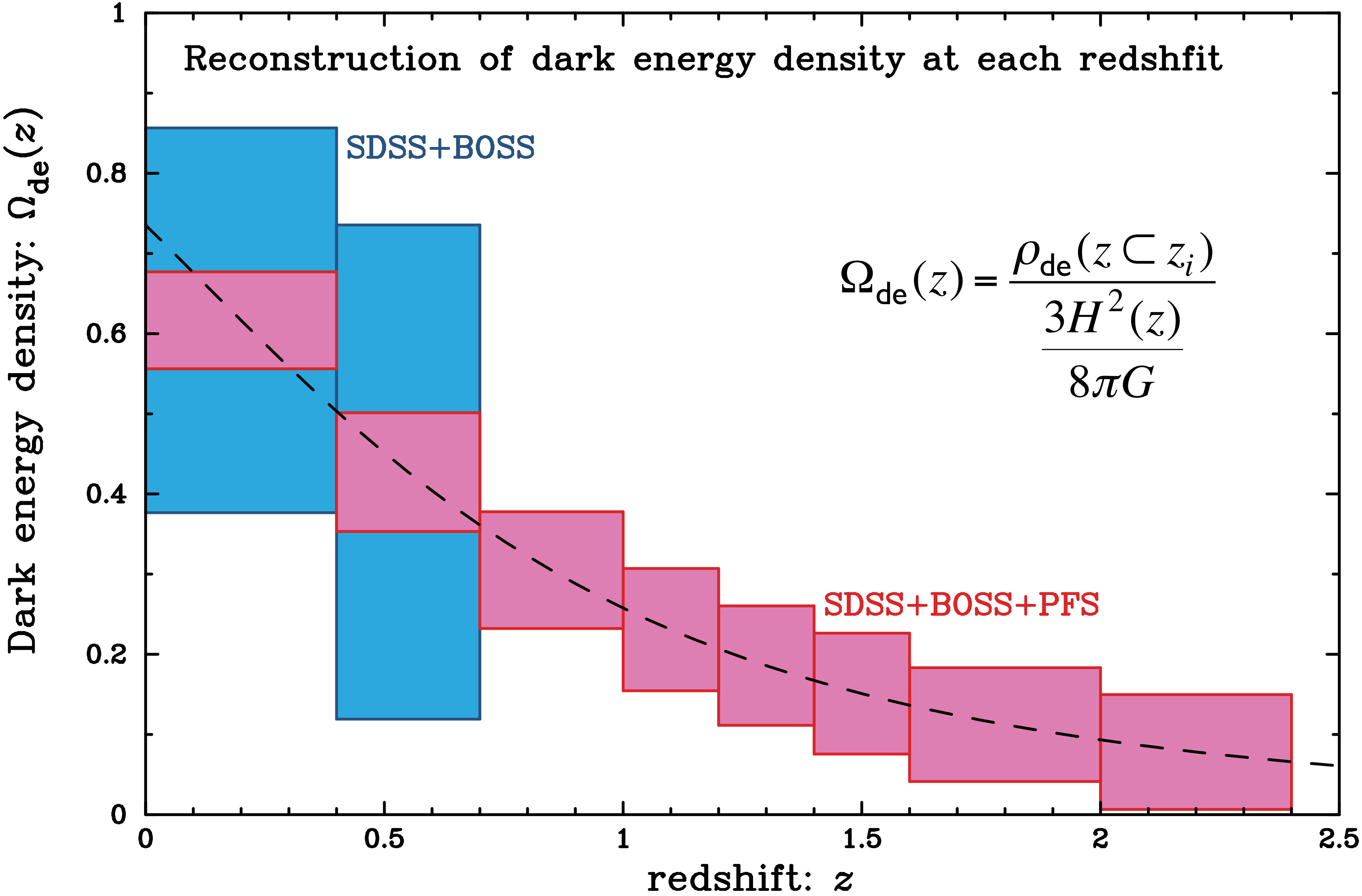
- Cosmology
  - ~4M redshifts of emission-line galaxies
  - BAO at each of 6 redshift bins over $0.8<z<2.4$
  - Cosmology with the joint experiment of WL and galaxy clustering (HSC/PFS)
- Galaxy evolution studies
  - A unique sample of galaxies (~1M) up to z~2, with the aid of the NIR arm
  - Dense sampling of faint galaxies (also many pairs of foreground/background gals)
  - Studying cosmic reionization with a sample of LAEs, LBGs and QSOs
- Galactic Archaeology
  - ~1M star spectra for measuring their radial velocities
  - Use the 6D phase-space structure, in combination with GAIA in order to study the origin of Milky Way (also use the M31 survey)
  - Use a medium-resolution-mode survey of ~0.1M stars to study the chemo-dynamical evolution of stars in Milky Way

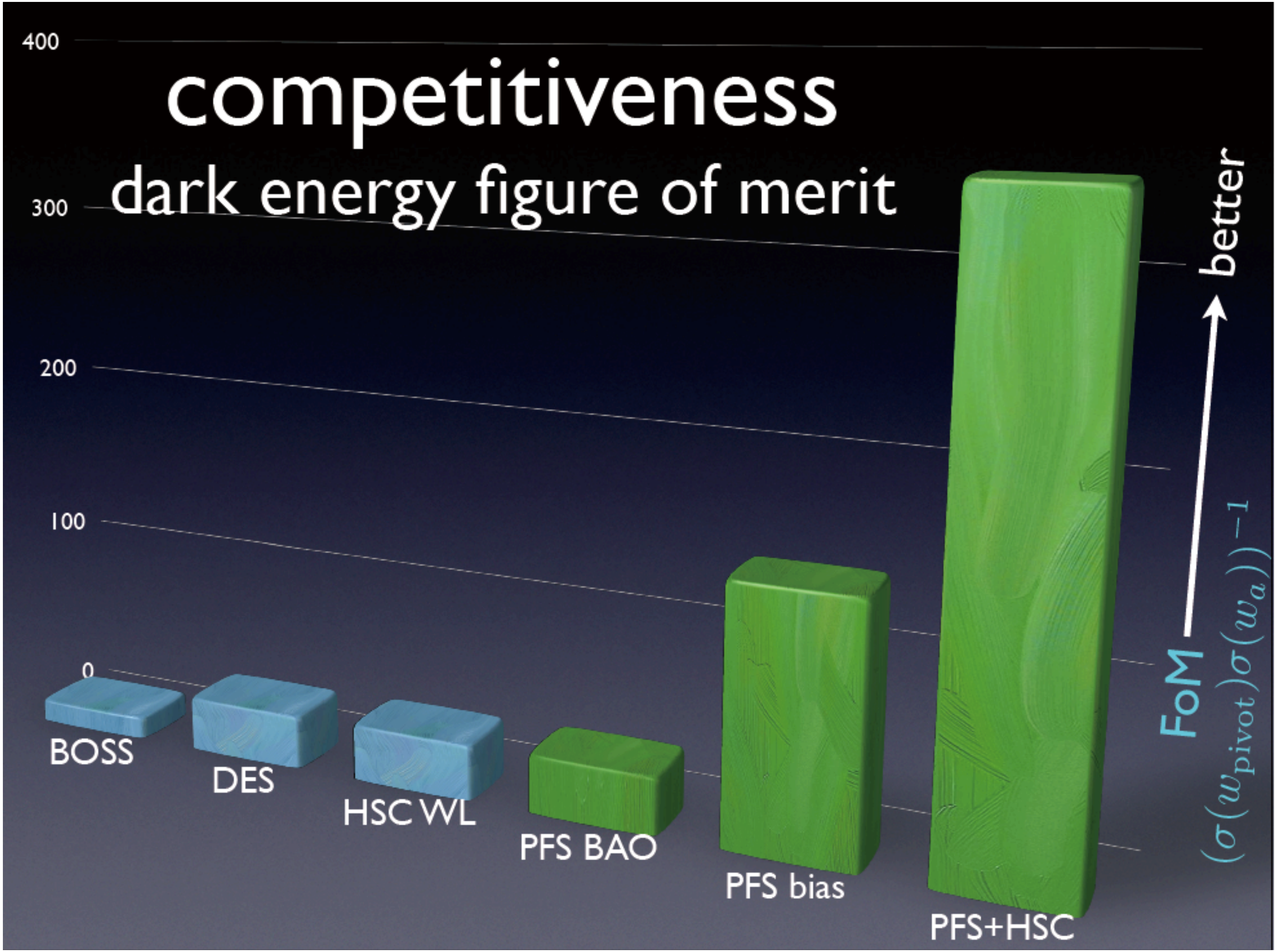
Redshift range for PFS survey



- 0.7<z<2 universe not yet observed
- SuMIRe = Imaging & spectroscopic surveys of the *same* region of the sky with the *same* telescope

Model-independent DE reconstruction




competitiveness
dark energy figure of merit
400
300
200
100
0
BOSS
DES
HSC WL
PFS BAO
PFS bias
PFS+HSC
better
FoM
$(\sigma(w_{\rm pivot})\sigma(w_a))^{-1}$

Summary

- Large-scale structure survey (imaging and spectroscopy) is powerful probe of cosmology: dark energy, inflation, neutrino mass
- Weak lensing and galaxy clustering are complementary
- Significant observational progresses in recent years:
  - The recent BOSS BAO achieved a 1% accuracy of distance measurement
  - The recent WL results show about 5% accuracy of the clustering amplitudes
- Some tension between Planck CMB and LSS probes
- Challenges: nonlinear effects and galaxy bias
- Future: The Japanese led project, SuMIRe = Subaru Measurement of Images and Redshifts (PI: Hitoshi Murayama)
  - Further stregthen unique capabilities of 8.2m Subaru Telescope (other projects all 4m-class telescopes besides LSST)
  - Hyper Suprime-Cam Survey (HSC) = imaging of 1B gals (starting from 2014)
  - Prime Focus Spectrograph (PFS) = redshifts of 4M gals