Probing the galaxy-mass connection in TeraByte-scale imaging surveys

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UNIVERSITÉ DE GENÈVE

Overview

- galaxy evolution in the cosmological context
- galaxies are test particules in the Universe
- consensus on the “Lambda CDM cosmological standard model”, but:
    1. many unknowns (95% of the Universe content is unknown)
    2. what role do dark matter structures (=mass) play in galaxy evolution?
- mining the sky:
    1. gravitational lensing,
    2. galaxy clustering,
    3. abundance matching
- golden age for large-scale imaging sky surveys and challenges ahead: the case of HSC, LSST and Euclid

Outline

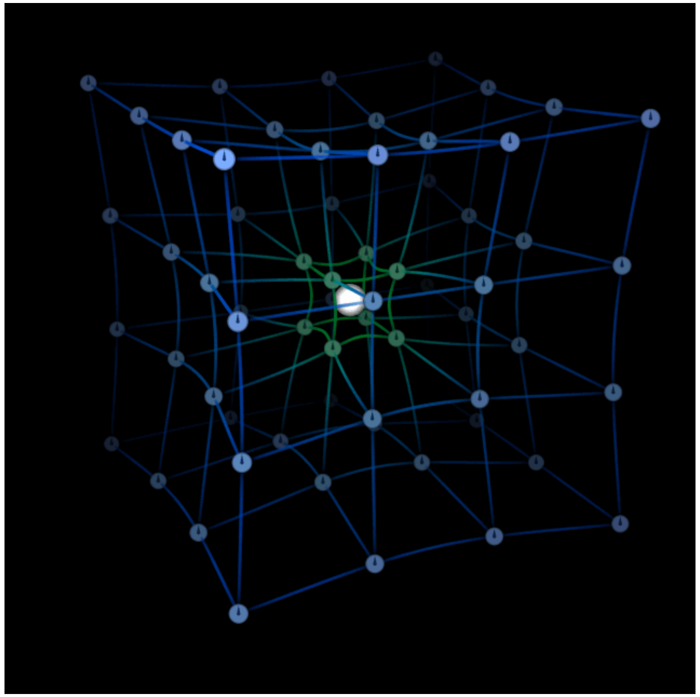
1. The cosmological context
2. Connecting galaxies to dark matter
3. The bright future of the dark: HSC, LSST & Euclid

1. The cosmological context

Measuring the Universe

Hypothesis: general relativity (Einstein, 1915) is the law of gravitation.
It relates the space-time curvature to its content:

$$G_{ik} = R_{ik} - \frac{1}{2} g_{ik} \mathcal{R} - \Lambda g_{ik} = \frac{8\pi G}{c^4} T_{ik}$$



Measuring the Universe

From the cosmological principle (homogenous and isotropic Universe) we write Einstein's equation in the Friedmann-Robertson-Walker metric:

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

+ assuming the matter/energy is a fluid represented by its equation of state: $p = w\rho c^2$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2}) - \frac{\Lambda c^2}{3}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}.$$

a = scale factor

= Friedmann's equations!

Measuring the Universe

Hubble parameter (def): $H(t) = \dot{a}/a$

$$H(t)^2 = H_0^2 \left(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2}\right)$$

= Einstein's GR equation in an homogenous and isotropic Universe

and redshift (def): $z = \frac{\lambda_e - \lambda_o}{\lambda_e}$ $\quad 1 + z = \frac{a(t_o)}{a(t_e)}$

Expansion rate of the Universe

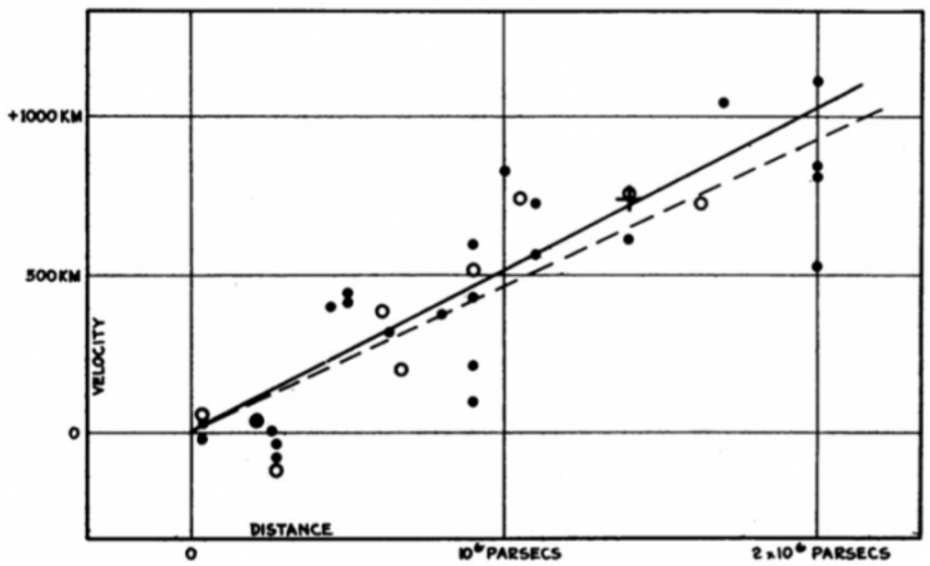
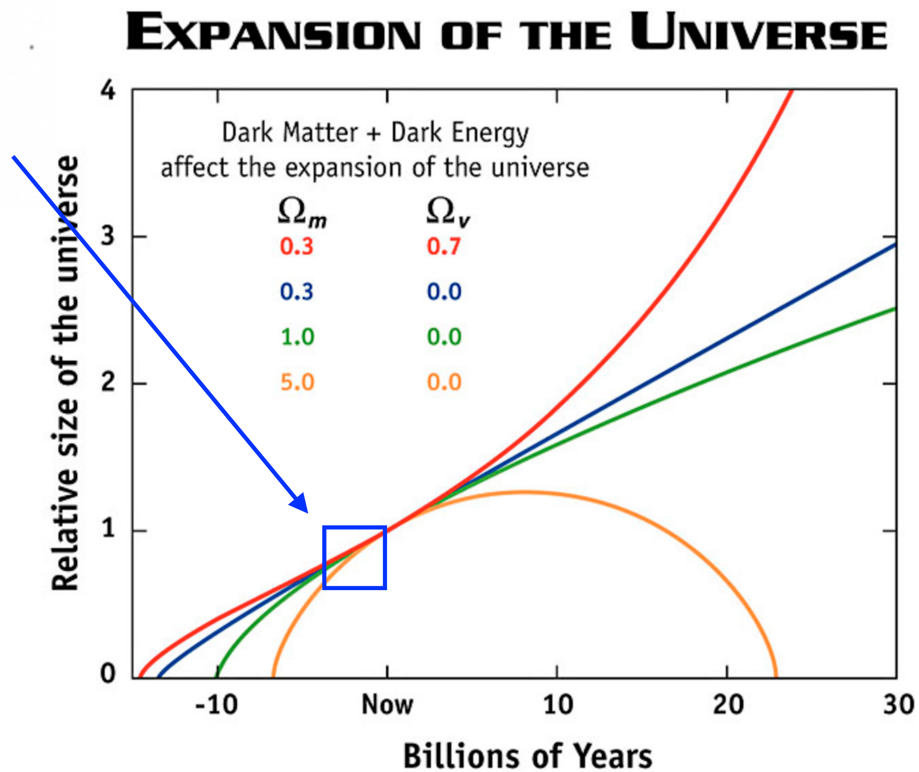


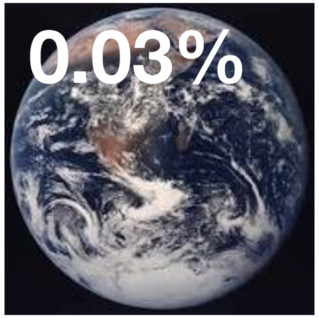
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Lemaître/Hubble's law: the expansion rate depends on the content of the Universe



1998: supernovae, the expansion is accelerating…

The composition of the Universe today (Planck15)

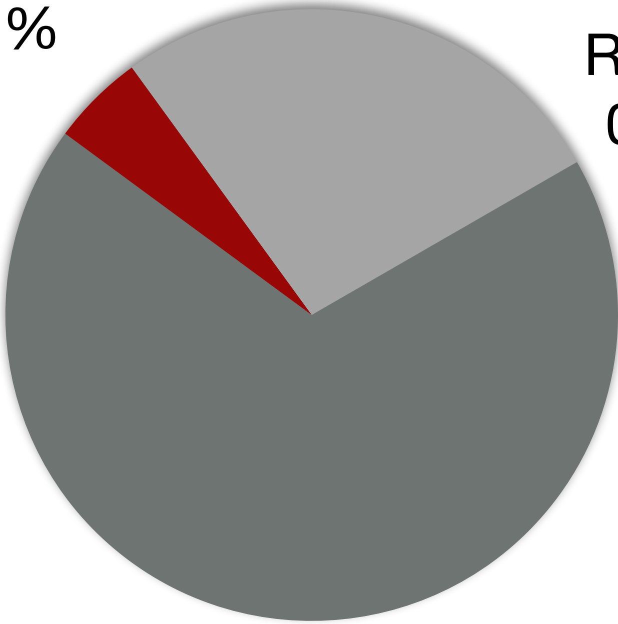


heavy elements

neutrinos

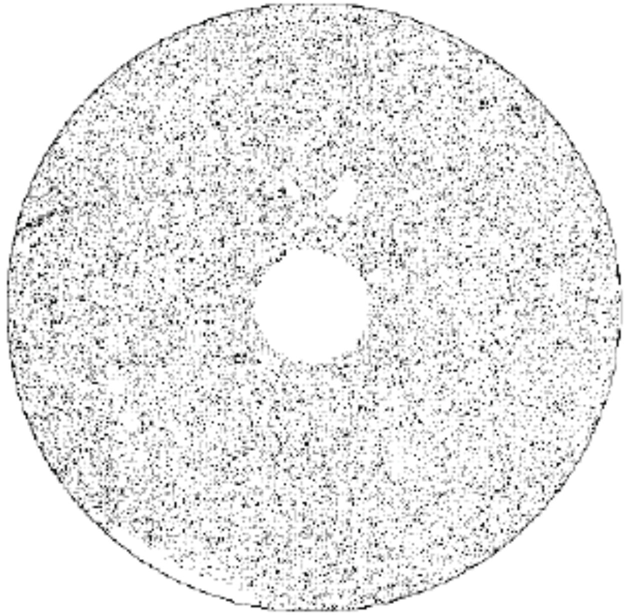
stars

gaz



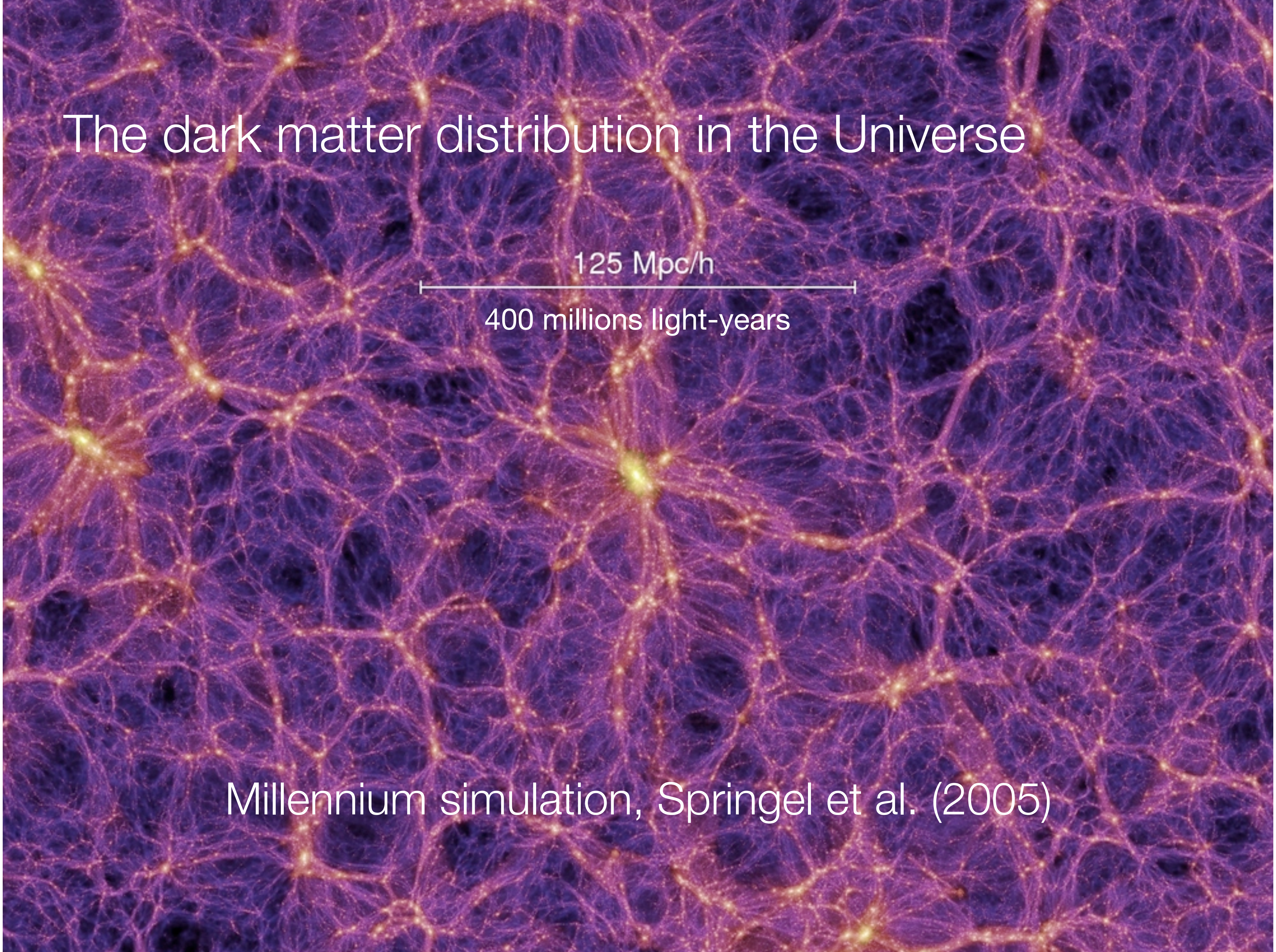
Inflation and the inhomogeneities in the Universe

- ~~The Universe is homogeneous and isotropic (cosmological principle)~~
- The Universe is statistically homogeneous and isotropic (cosmological principle)



Radio sources (Gregory & Condon,1991)

inhomogeneities originated from quantum fluctuations pushed to macroscopical scale by an exponential phase of expansion in the early Universe (inflation)?


The dark matter distribution in the Universe
125 Mpc/h
400 millions light-years
Millennium simulation, Springel et al. (2005)

How to describe density fluctuations?

Perturbations grow by gravitational instability

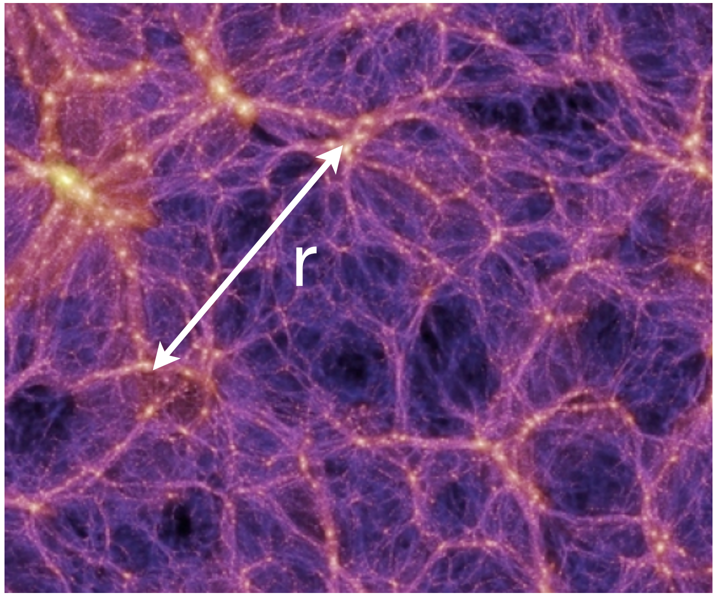
Density contrast: $\delta(\boldsymbol{d}, t) = \dfrac{\rho(\boldsymbol{d}, t) - \overline{\rho}(t)}{\overline{\rho}(t)}$

Gaussian field = statistical properties fully described by the 2-point correlation function:

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

or its Fourier transform, the matter power spectrum

$$P(k) = 2\pi \int_0^\infty \mathrm{d}r\, r^2 \frac{\sin kr}{kr} \xi(r)$$

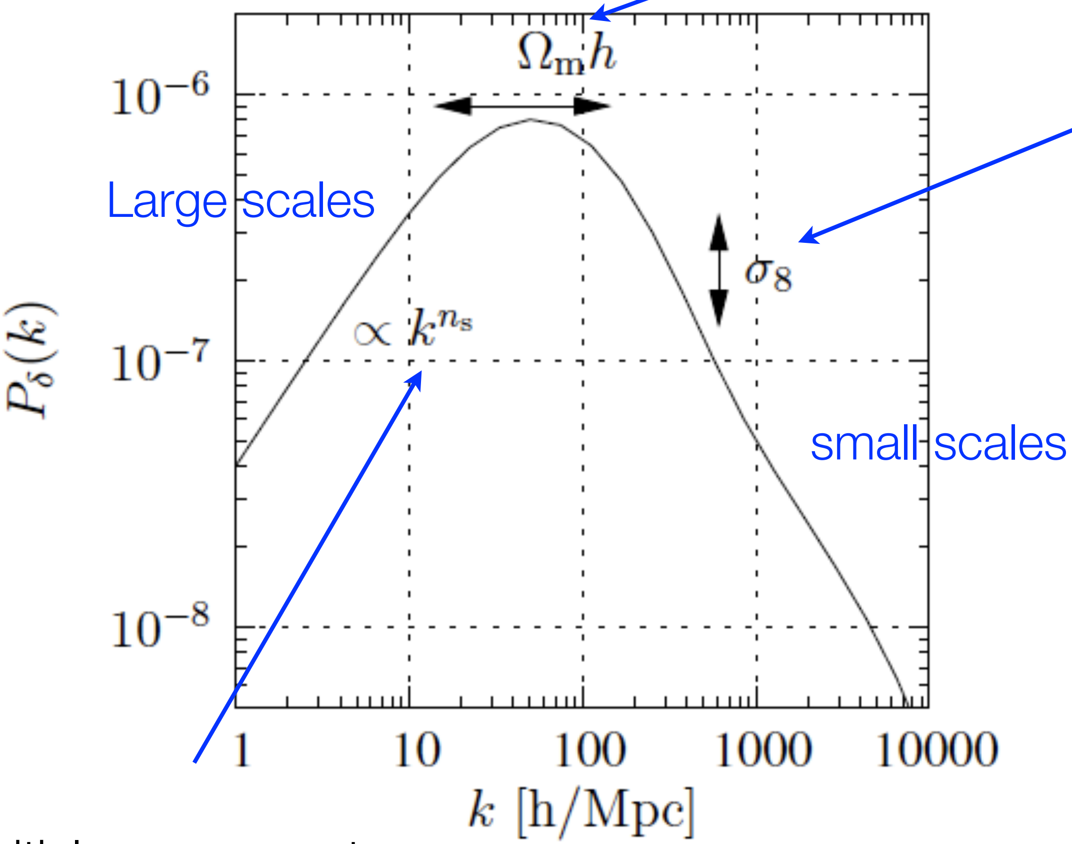


The matter power spectrum

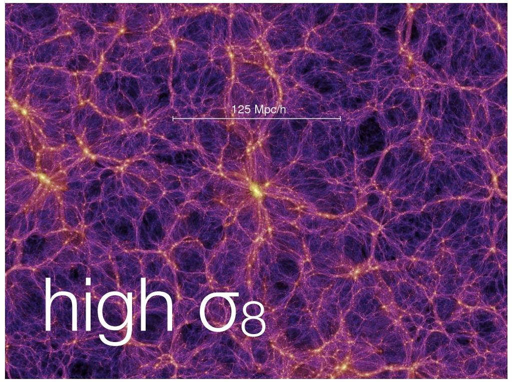
Translates the amplitude of density fluctuations

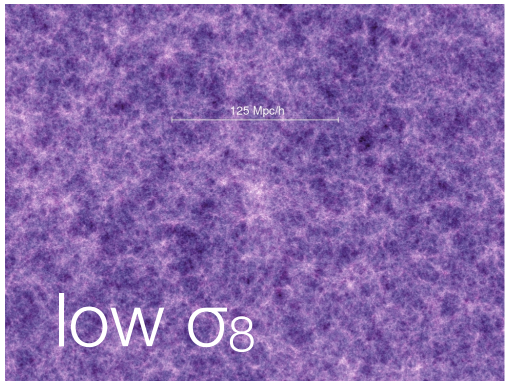
Matter density

Normalization = “clumpiness”

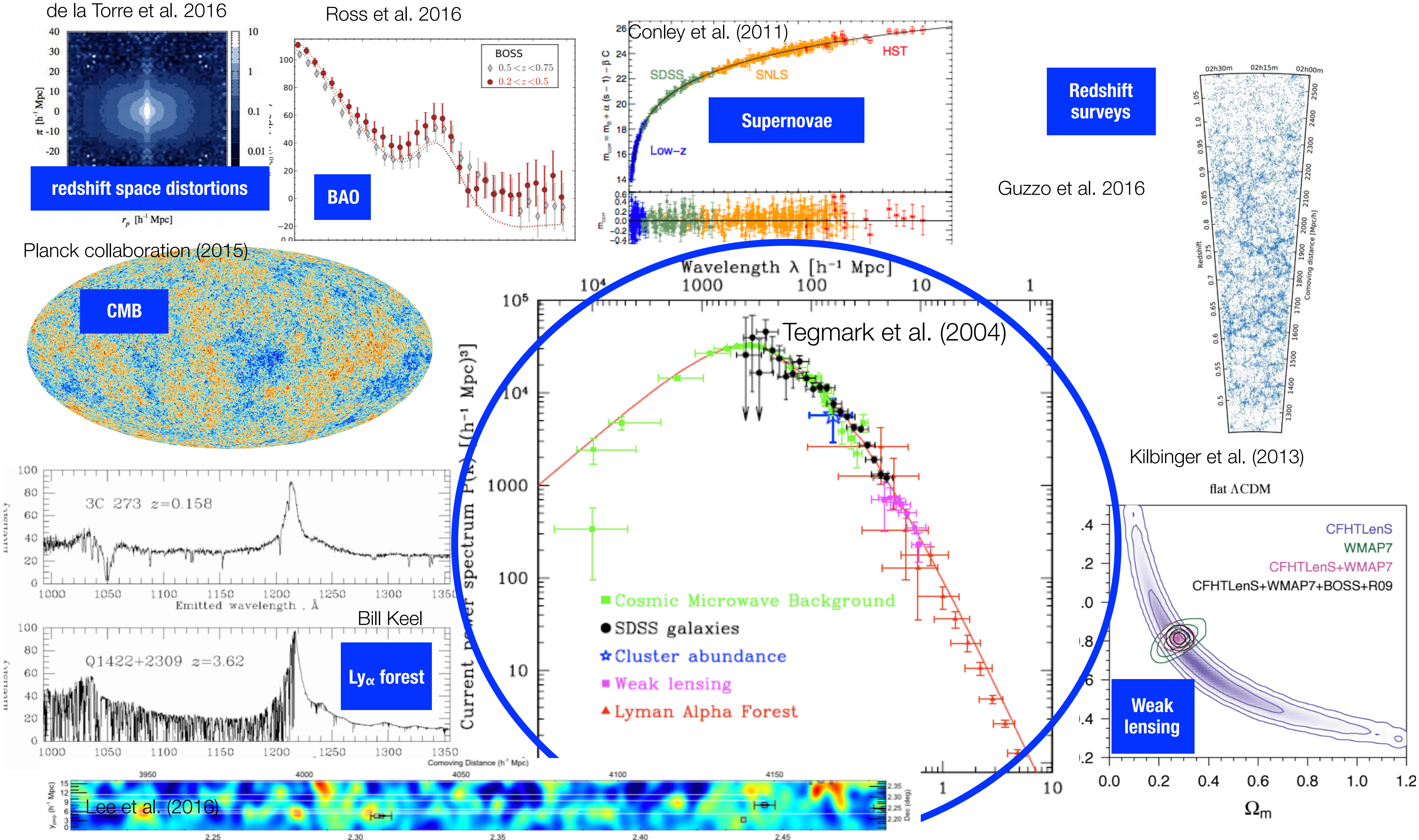


Initial power spectrum (scale independent)





Cosmological probes



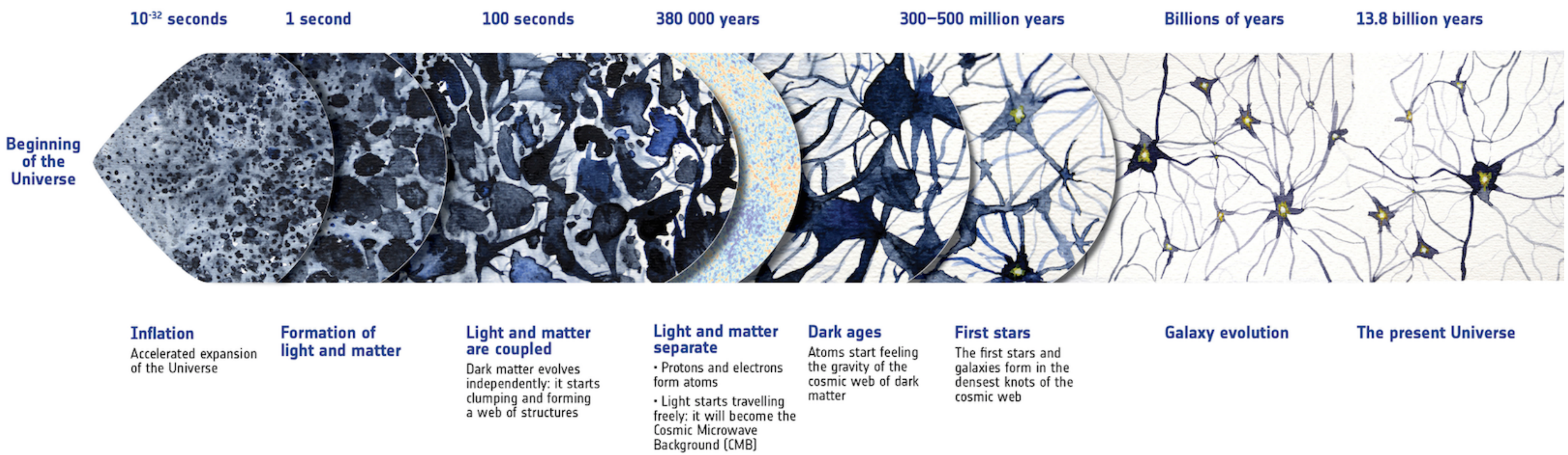
Cosmological probes

redshift space distortions
cosmic Microwave Background (CMB)
baryon acoustic oscillations (BAO)
cosmic shear
lyman-alpha forest
supernovae
lensed QSO's
element abundance
galaxy-galaxy lensing+bias
galaxy cluster abundance
…

The cosmological standard model in one slide

- the Universe is homogeneous and isotropic (hypothesis)
- flat (?)
- expanding and accelerating today (why?) (measured)
- is dominated by (cold?) dark matter (what?) and dark energy
- structures grow by gravitational instabilities of primordial tiny fluctuations
- that experienced a huge expansion during an early inflation period
- consensus on so-called ΛCDM model

The history of the Universe



dominated by radiation

dominated by matter

accelerated expansion

Open questions

Question	Probes	Experiments (non exhaustive)
inflation	gravitational waves	Ligo, LISA
dark energy	matter power spectrum (lensing, BAO, etc.)	HSC, LSST, Euclid, redshift surveys, etc.
dark matter	lensing, high energy physics	LSST, Euclid, Athena, CTA, Particule physics experiment, etc.
origine of gravity	RSD, BAO, lensing	LSST, Euclid, etc.

Galaxies in the cosmological context

- primordial Universe: drives galaxies formation
- galaxy evolution further driven by dark matter
- non collisional -> ignoring the nature of dark matter is not a limiting factor to understand galaxy evolution
- effect of dark energy on galaxy evolution remains debated
- the power spectrum is a excellent representation of dark matter on large scales, but we need a refined description on small scales

The halo model

Cooray & Sheth (2002)

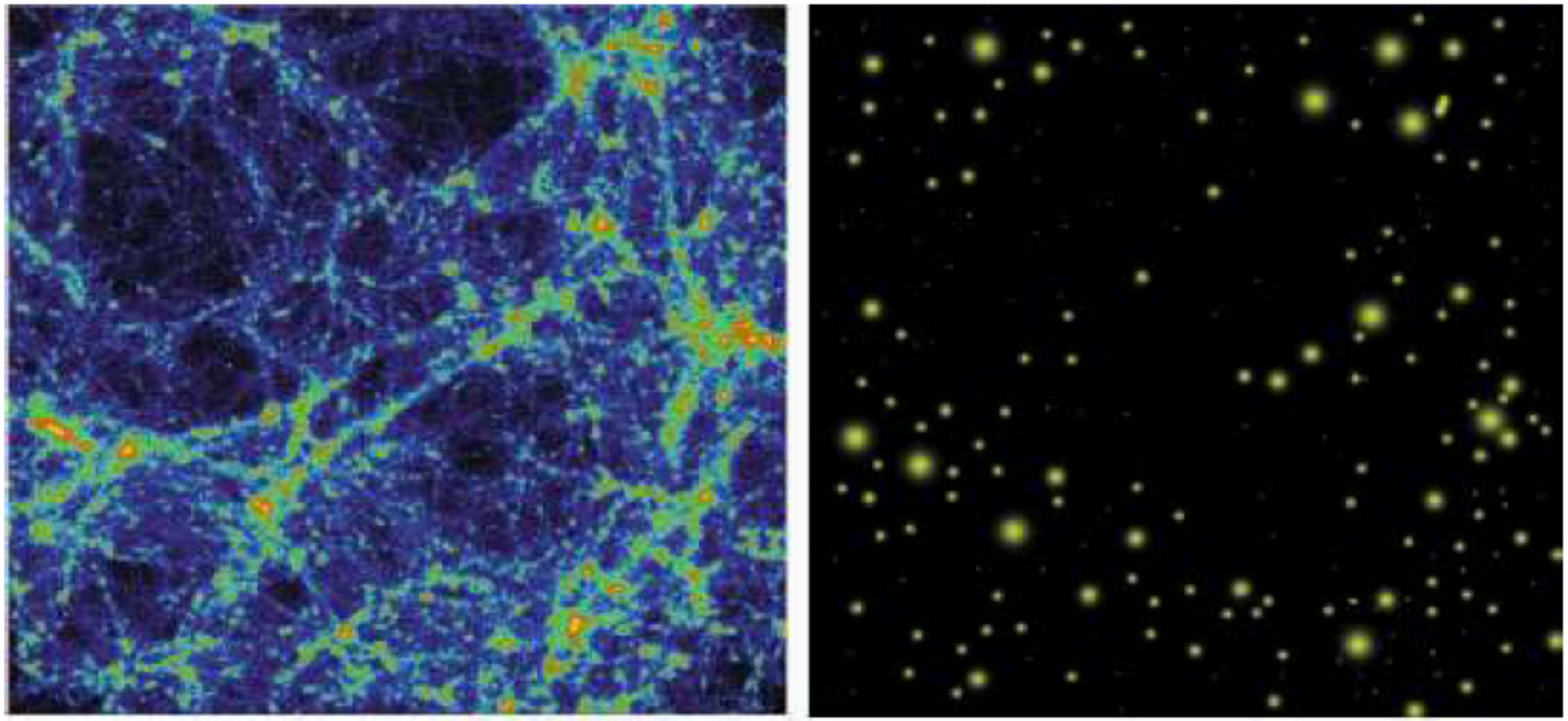
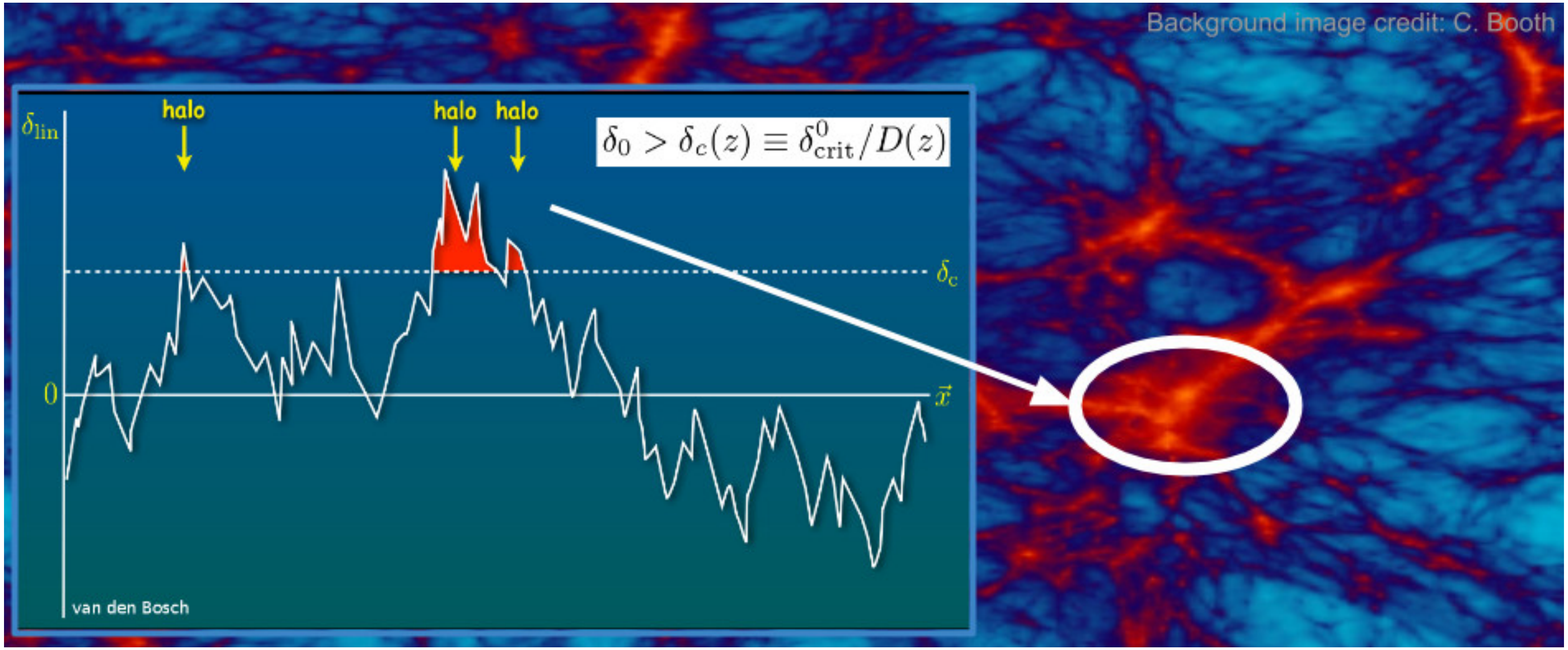


Fig. 1. The complex distribution of dark matter (a) found in numerical simulations can be easily replaced with a distribution of dark matter halos (b) with the mass function following that found in simulations and with a profile for dark matter within halos.

Press & Schechter formalism

Press & Schechter (1974): dark matter haloes collapse above critical density threshold (that's it!)

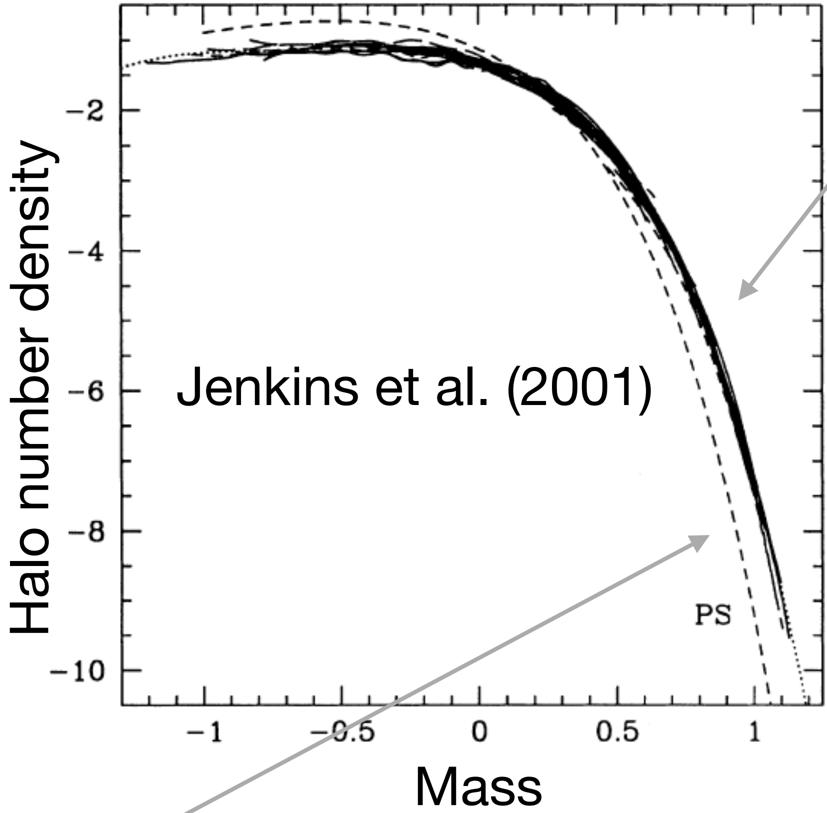


Press & Schechter formalism

- very powerful
- only need 3 ingredients to describe the dark matter distribution on galaxy scale:
    - halo abundance (halo mass function)
    - halo density profile
    - halo clustering (bias)

The halo mass function

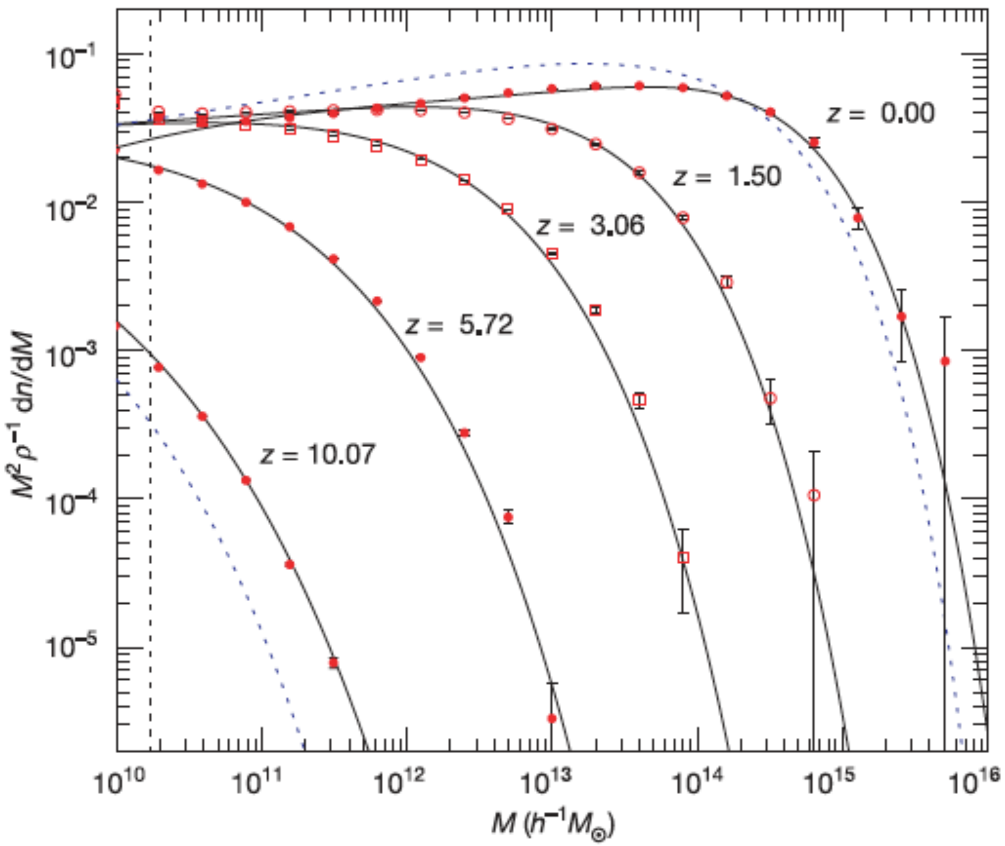
N-body simulations



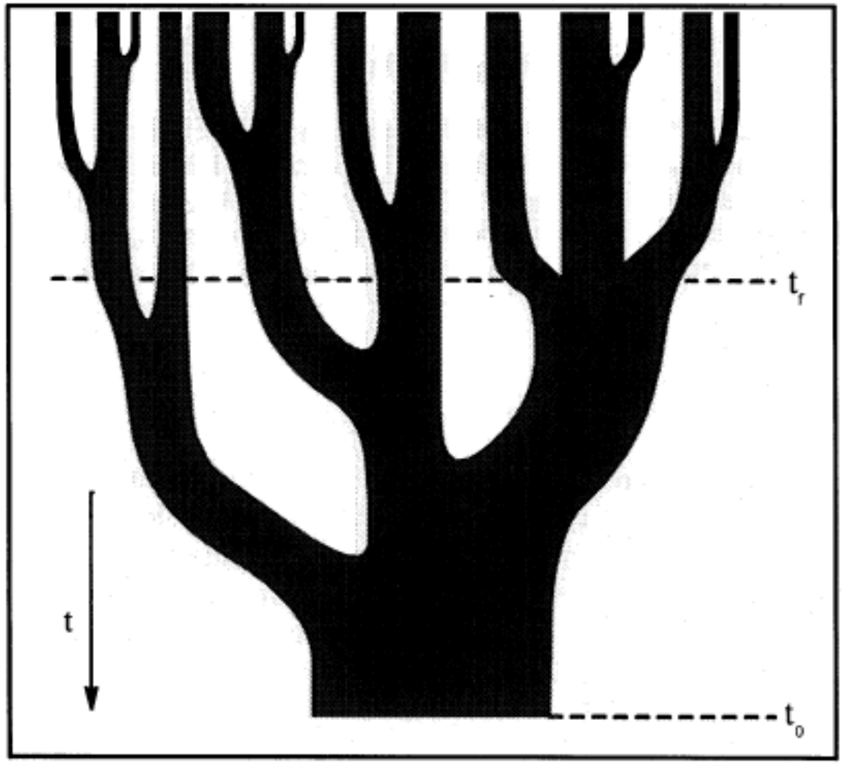
theoretical prediction from P&S

The halo mass function evolution

Small haloes form first, then merge together

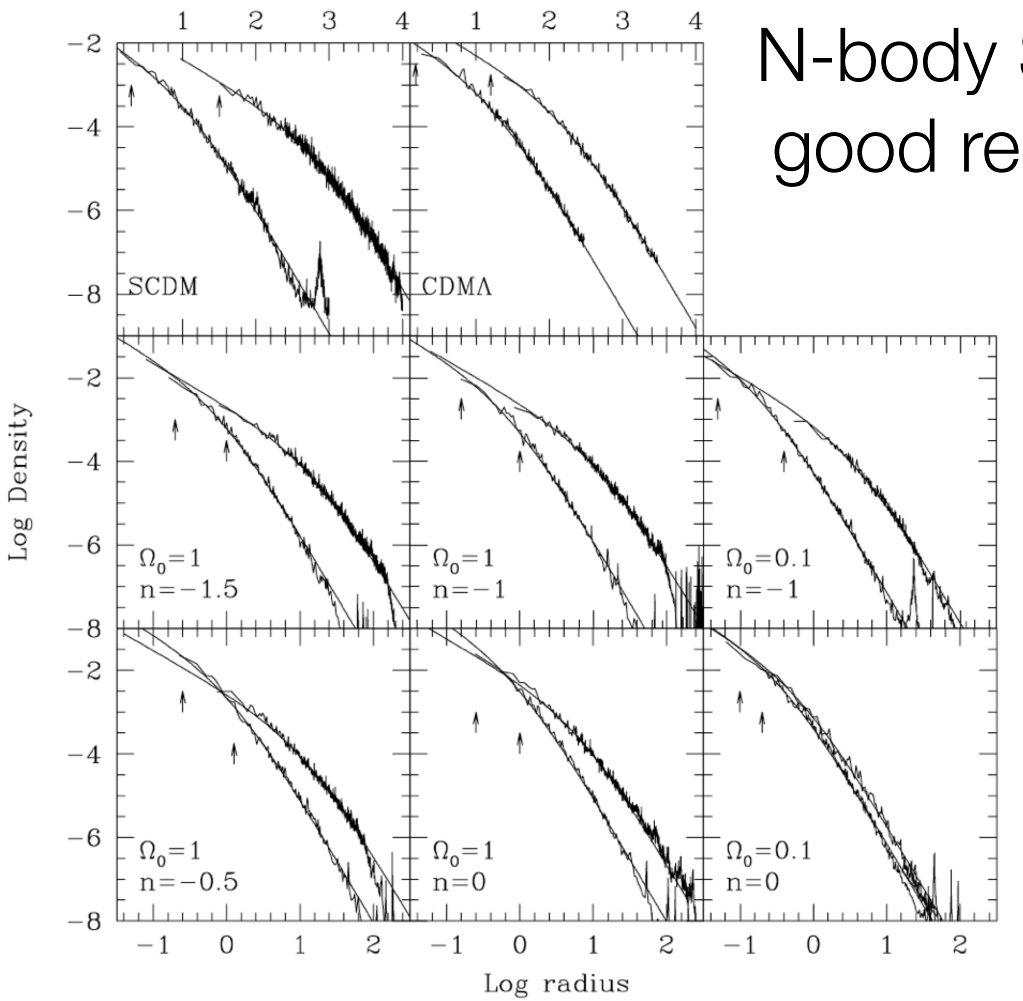


Millenium simulation (Springel et al. 2005)



Lacey and Cole (1993)

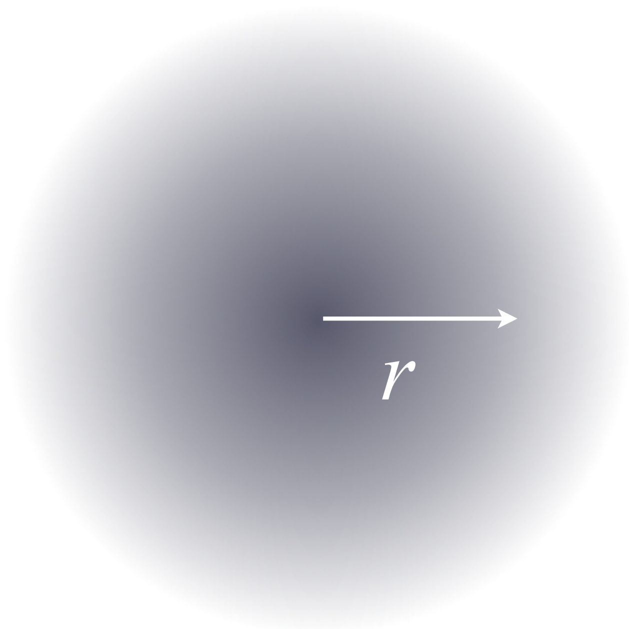
The halo density profile



Navarro, Frenk & White (1997)

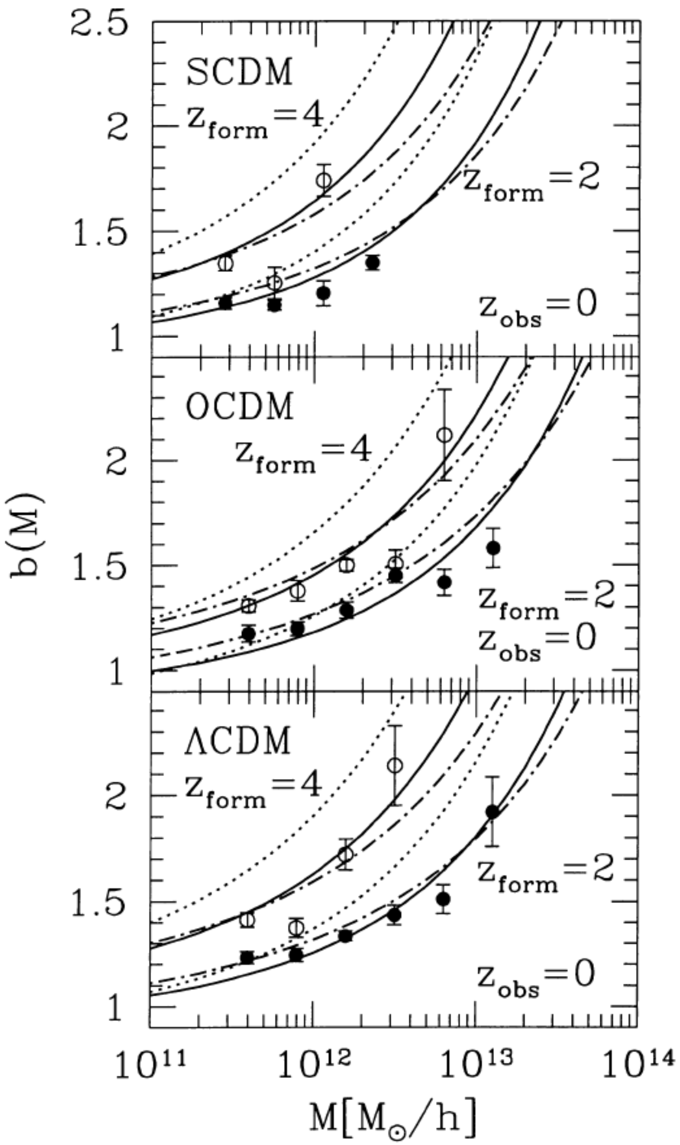
N-body Simulations suggest NFW is a good representation of density profile

$$\rho_{\rm h}(r|M) = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}$$

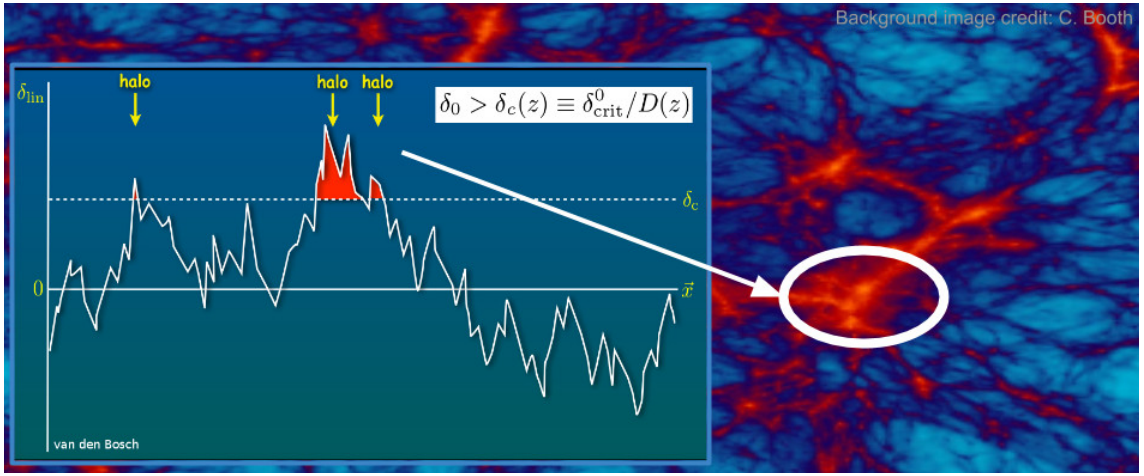


Halo clustering (bias)

Sheth & Tormen (1999)

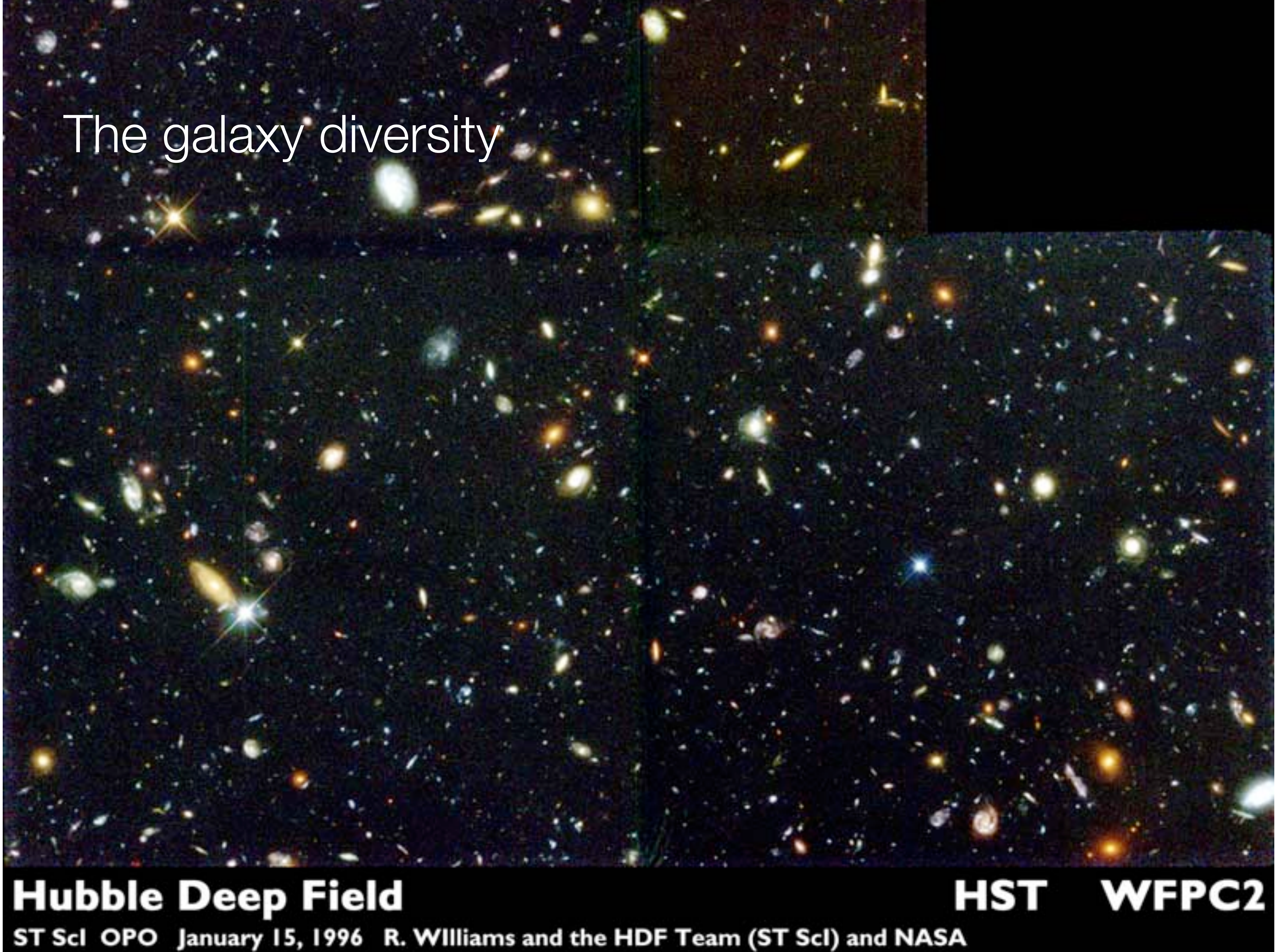


Haloes are "biased" tracers of the matter density fluctuations

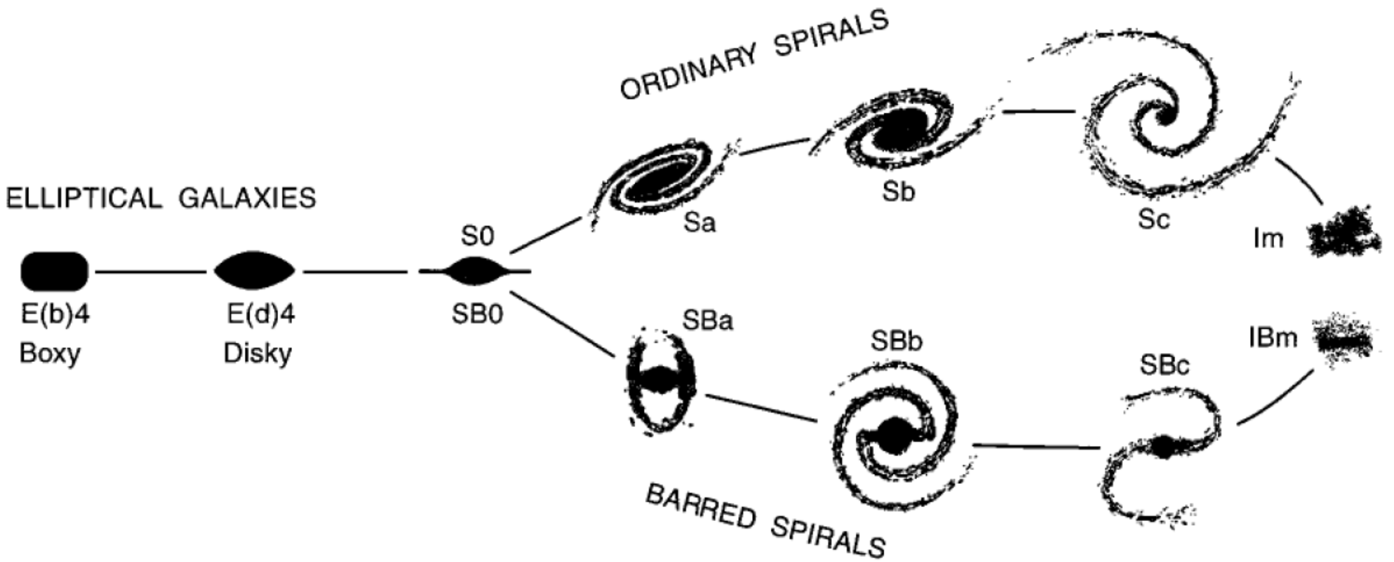


2. Connecting galaxies to dark matter

The galaxy diversity



The galaxy zoology: the Hubble sequence



dwarf, irregular,
+ peculiar galaxies and
active galactic nuclei

Kormendy & Bender (1996)

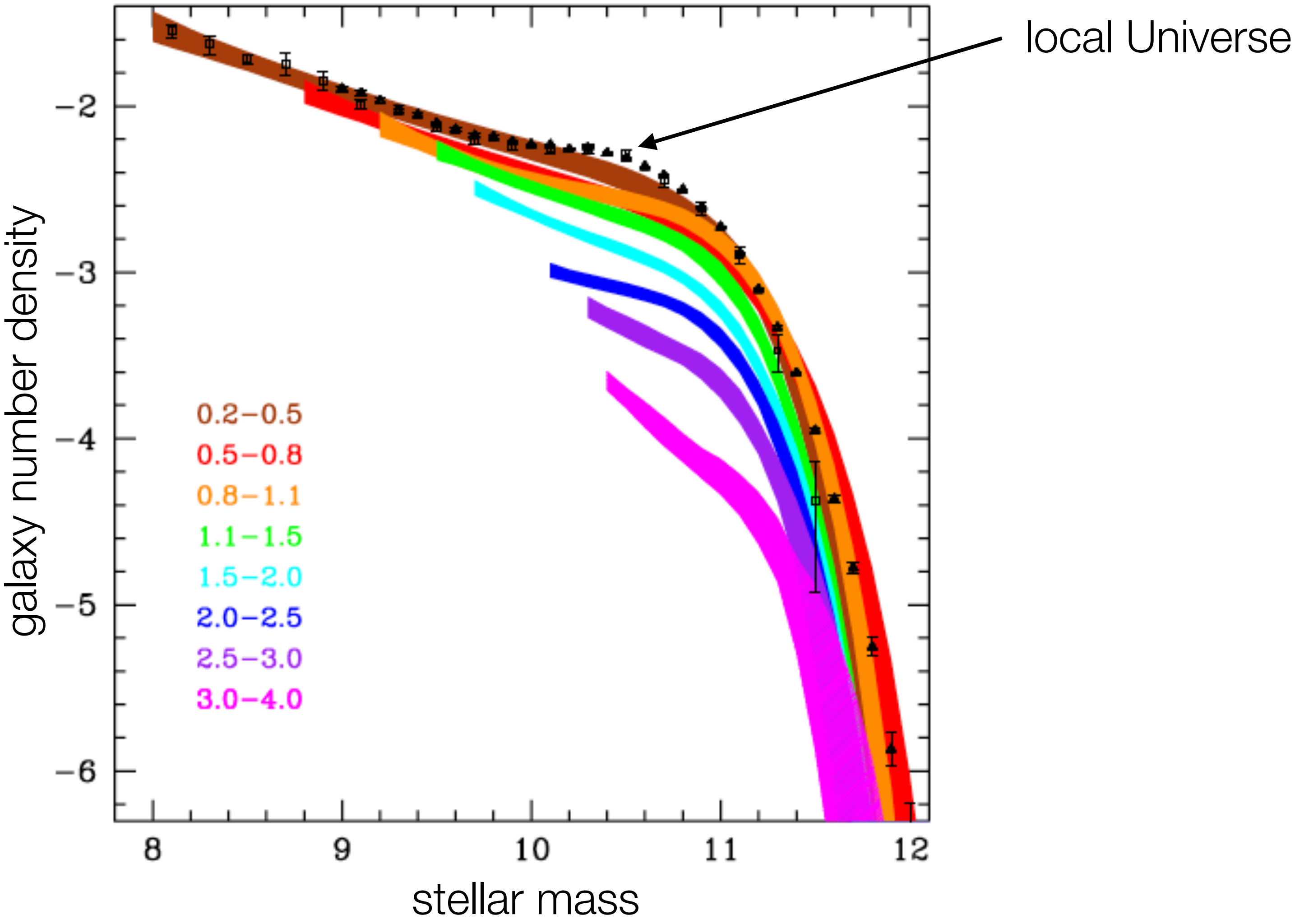
Elliptical galaxies
or early-type galaxies
or “red” galaxies

Spiral (disk) galaxies
or late-type galaxies
or “blue” galaxies

rare objects but carry
some precious information
about galaxy evolution

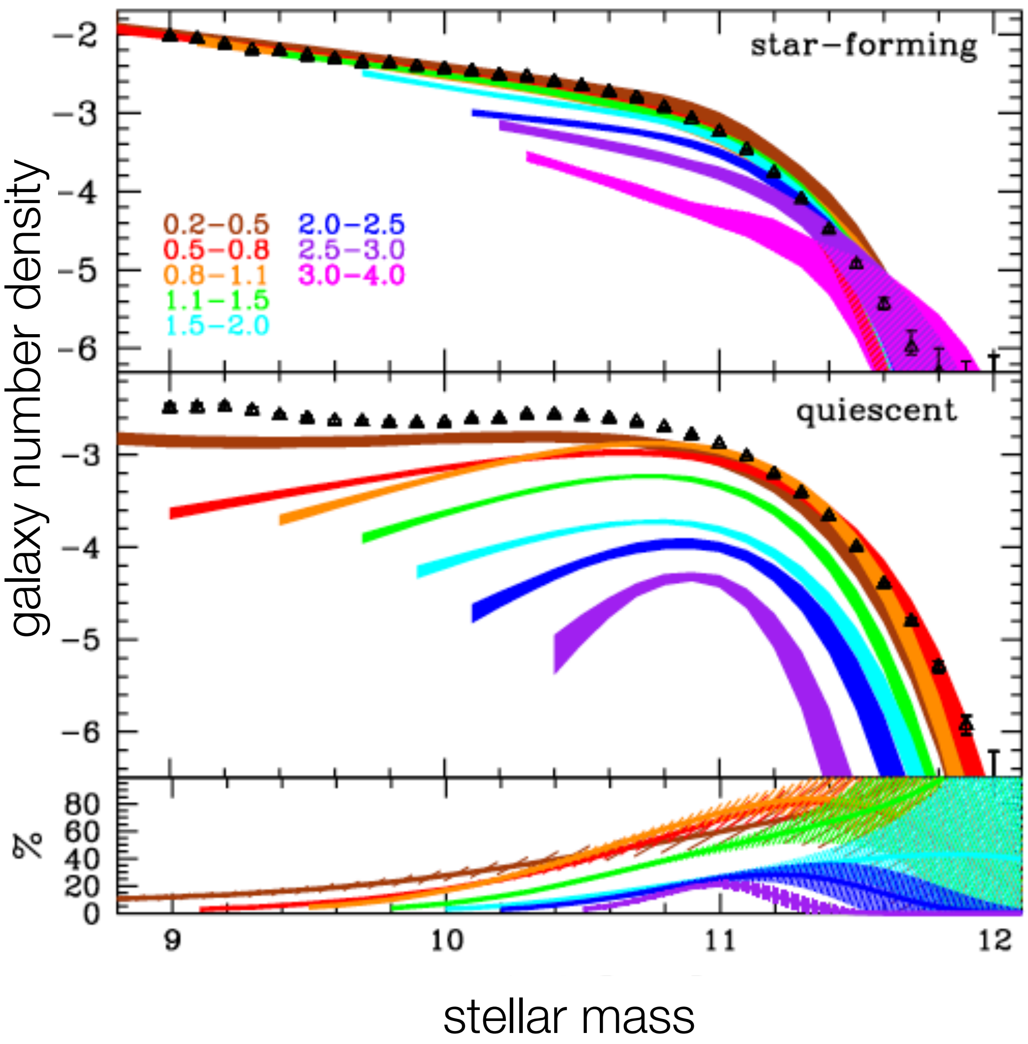
How did galaxies form and evolve from the initial baryon density field to the galaxy diversity as seen today?

The galaxy statistics (e.g. the stellar mass function)



Ilbert et al. (2013)

The galaxy statistics (e.g. the stellar mass function)



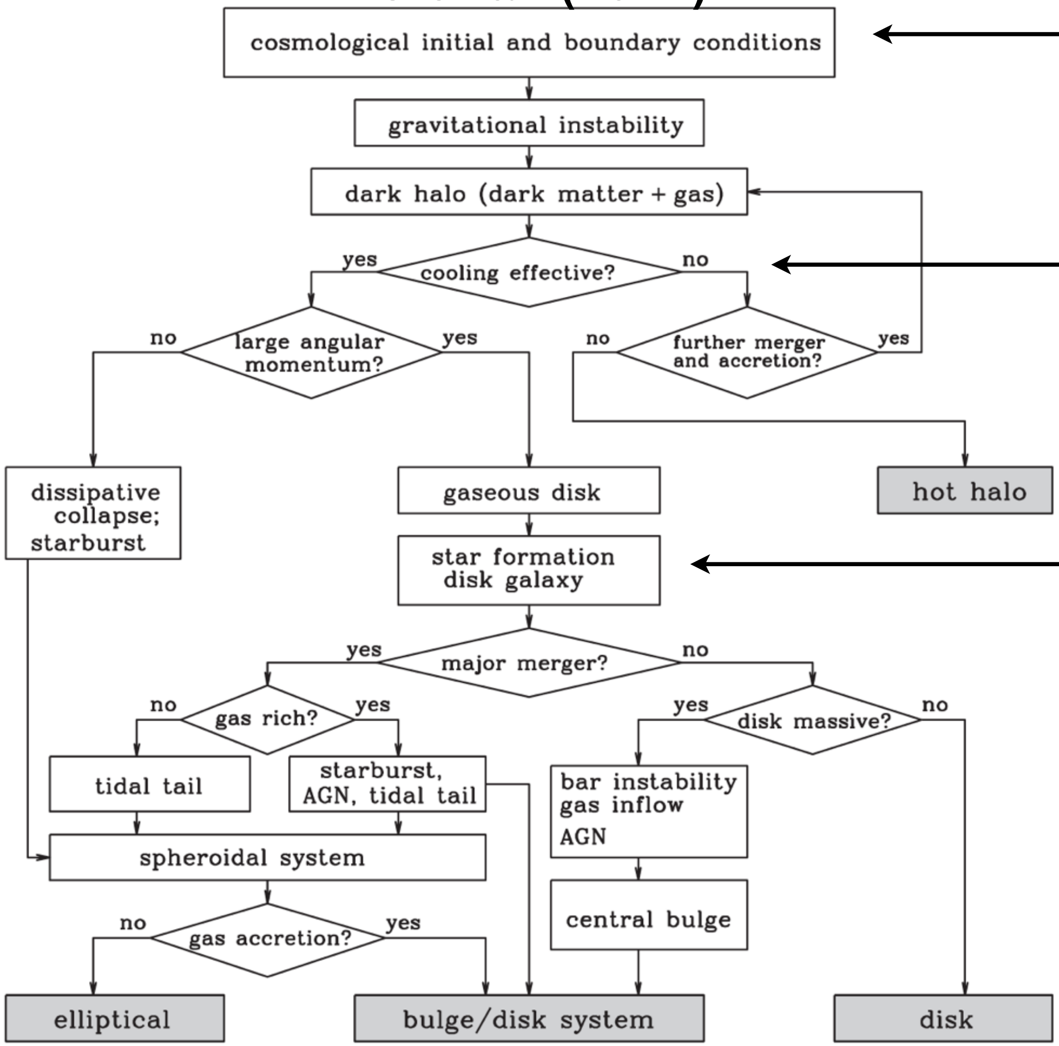
- all galaxies. redshift evolution
- sf galaxies. Dominate at faint luminosity/low z
- passive galaxies. Dominate at bright luminosity

WHY?

Ilbert et al. (2013)

What is the interplay between physical processes?

Mo et al. (2011)



ΛCDM cosmology

no cooling, no star

star formation stops

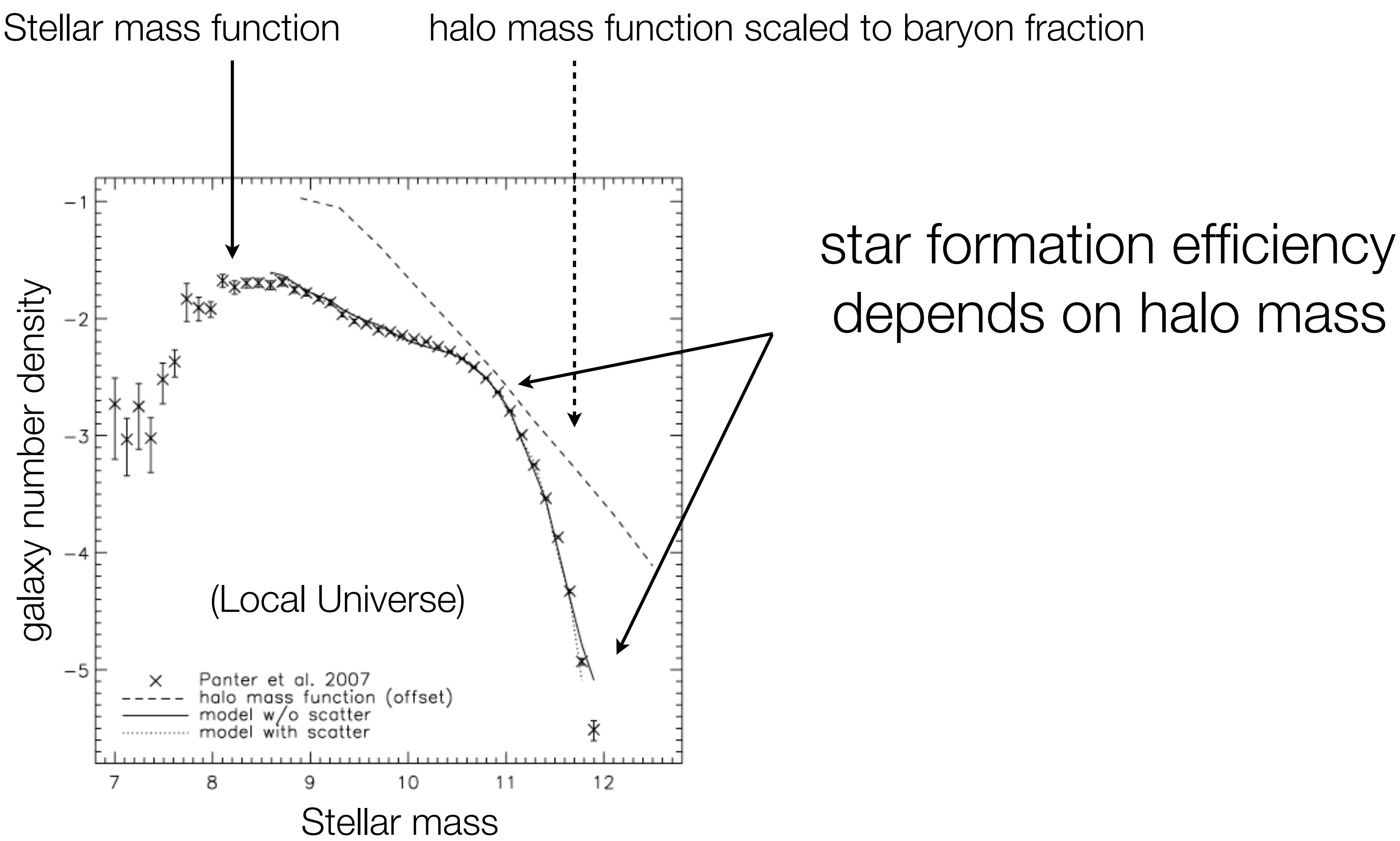
or star formation goes on

galaxy evolution: depends on halo mass, environment and redshift

Hubble sequence observed today

(images: SDSS, Blanton & Hogg)

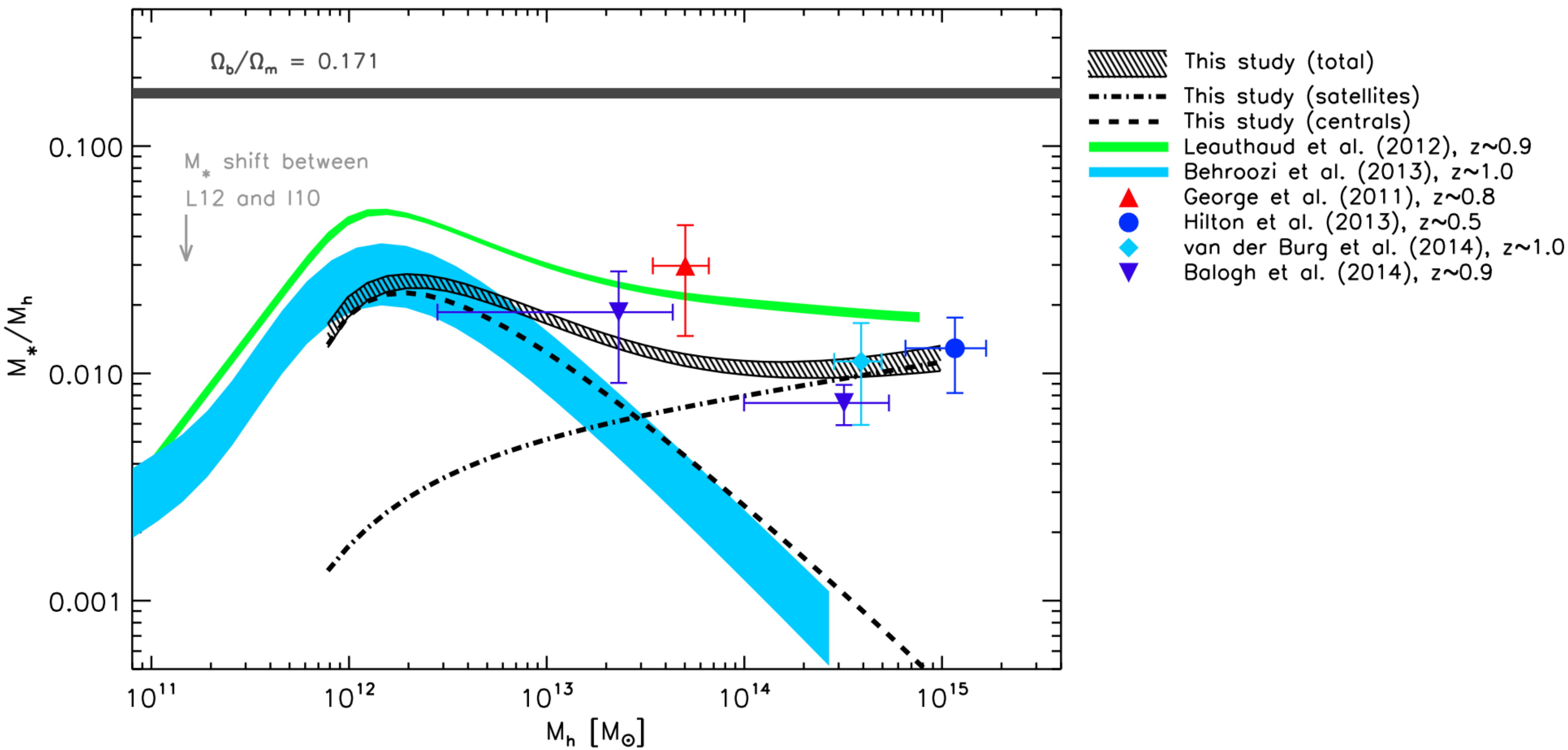
Star formation (in)efficiency in dark matter haloes



Moster et al. (2010)

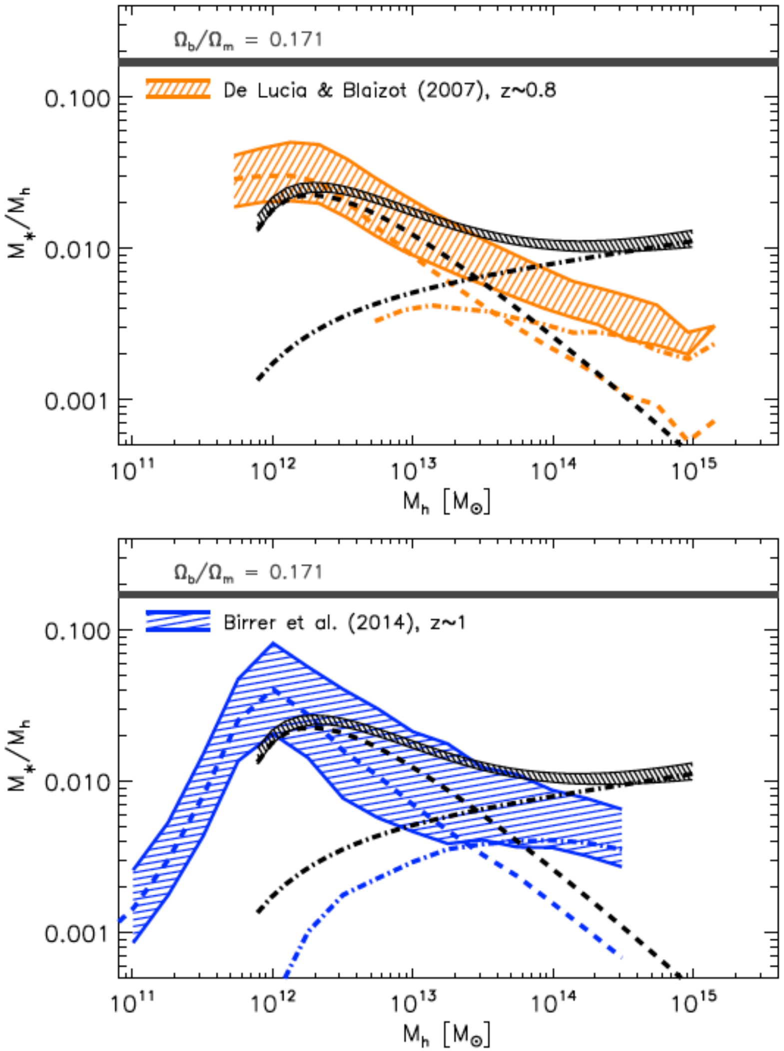
Linking dark matter to galaxies

Measurements at z~1: the big impact of satellites



JC et al. (2015)

Semi-analytical numerical simulations

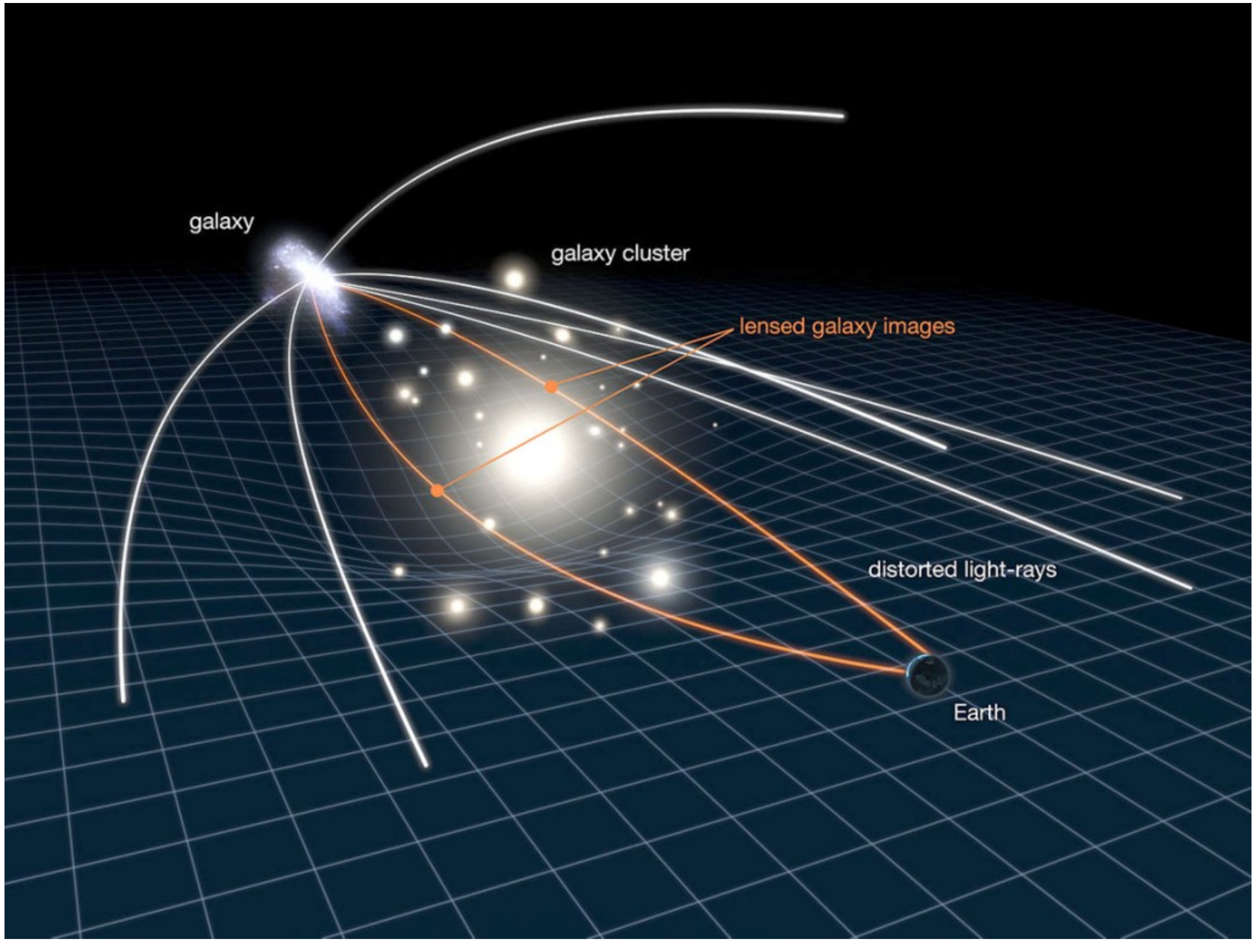


JC et al. (2015)

Significant progress of simulations in the past 10 years but many unknowns

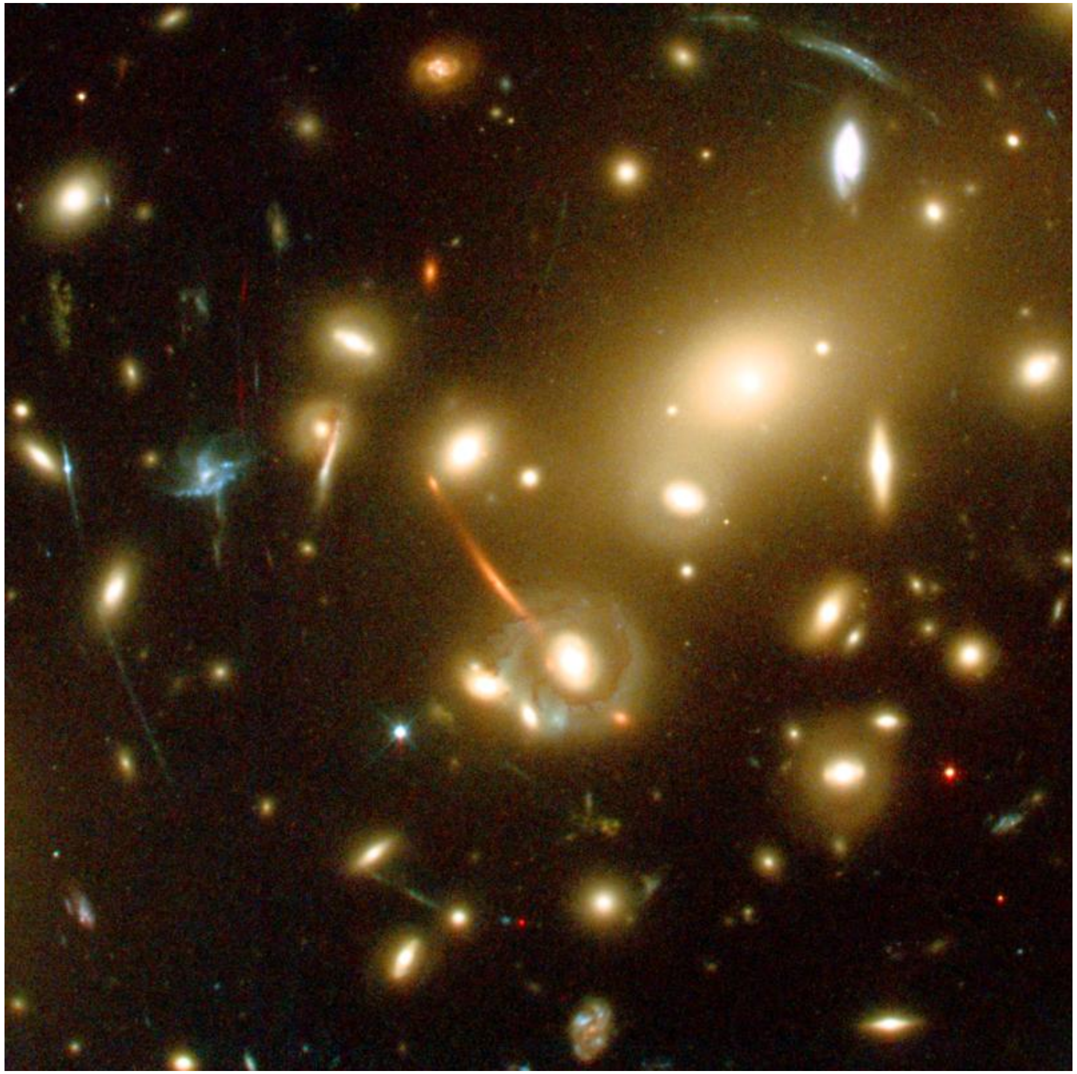
e.g. simulations fail to reproduce star-formation in medium-mass satellites, etc.

The galaxy-mass connection: gravitational lensing

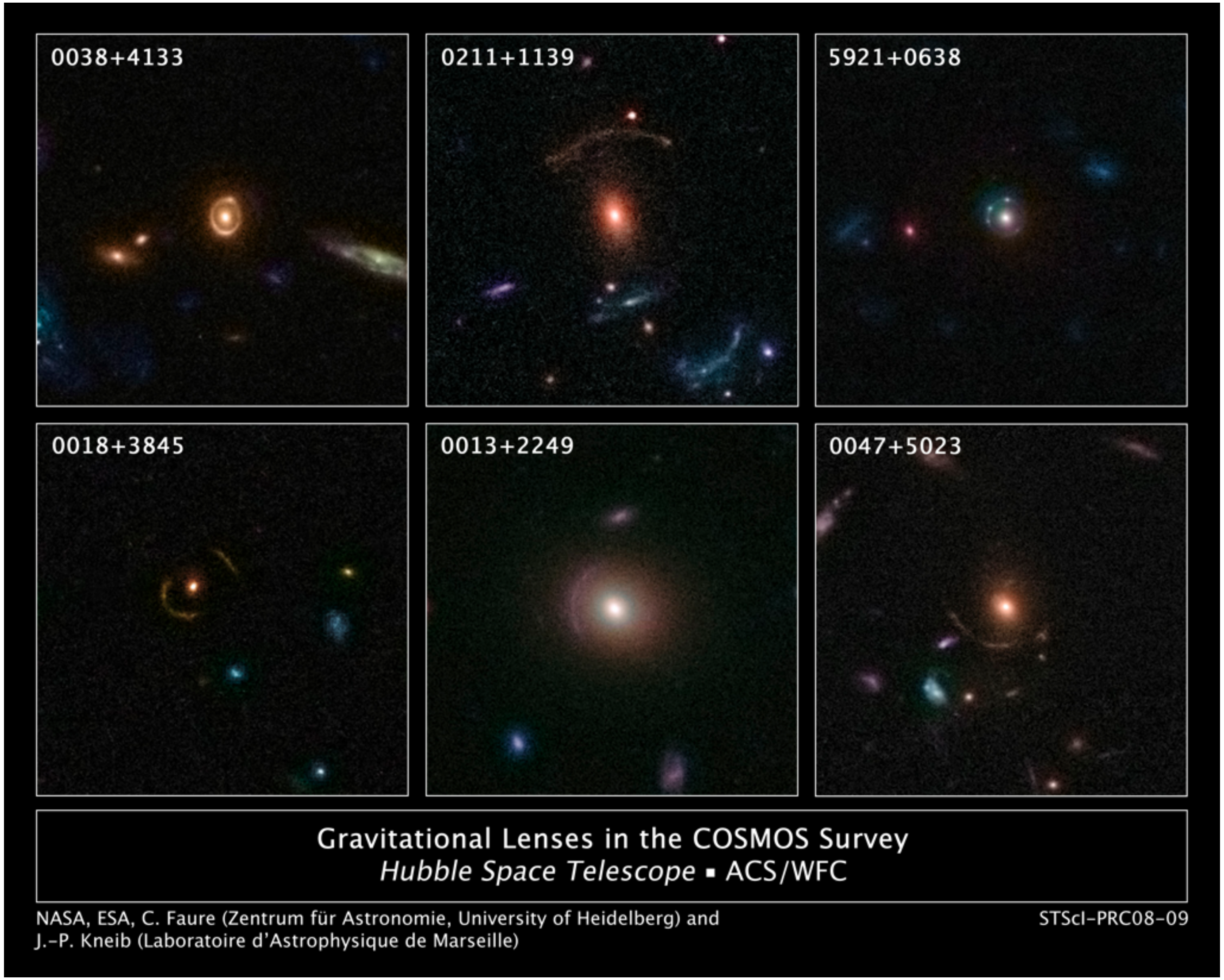


Two types of lensing

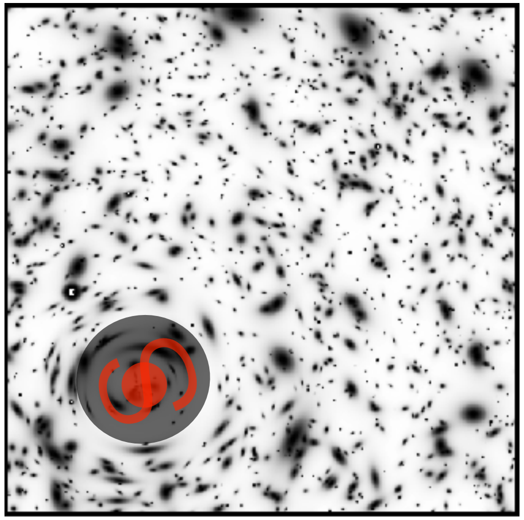
- lensing causes
  - distortion (shear)
  - and magnification (convergence) of background images



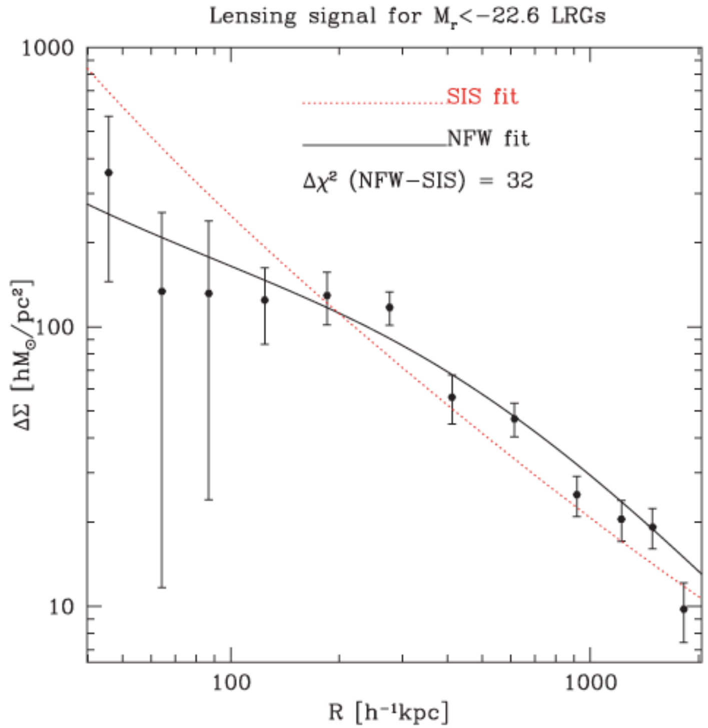
Strong lensing



Weak lensing: stacking millions of galaxies



~thousands

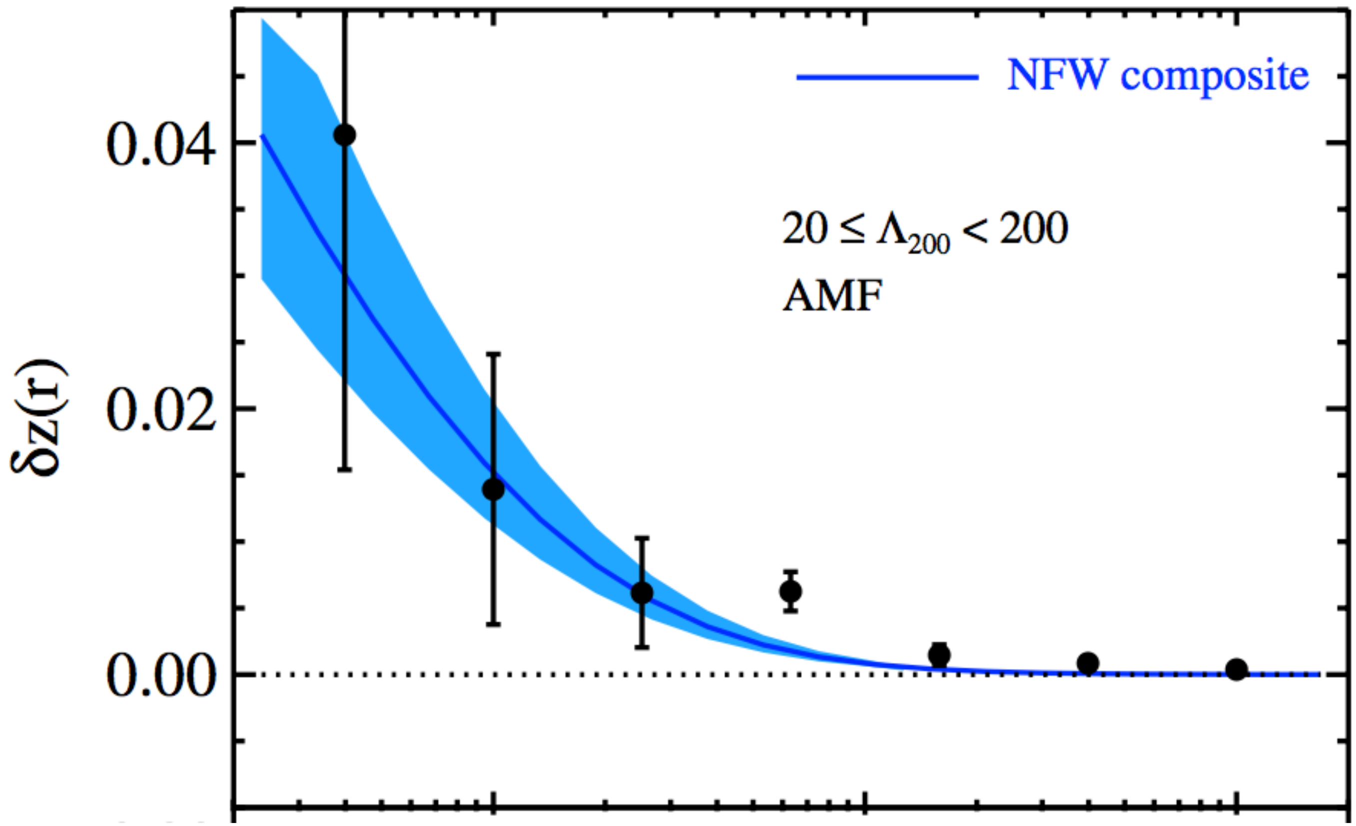


Galaxy-galaxy lensing: mass probed statistically from stacked lensing profiles

Mandelbaum et al. (2006)

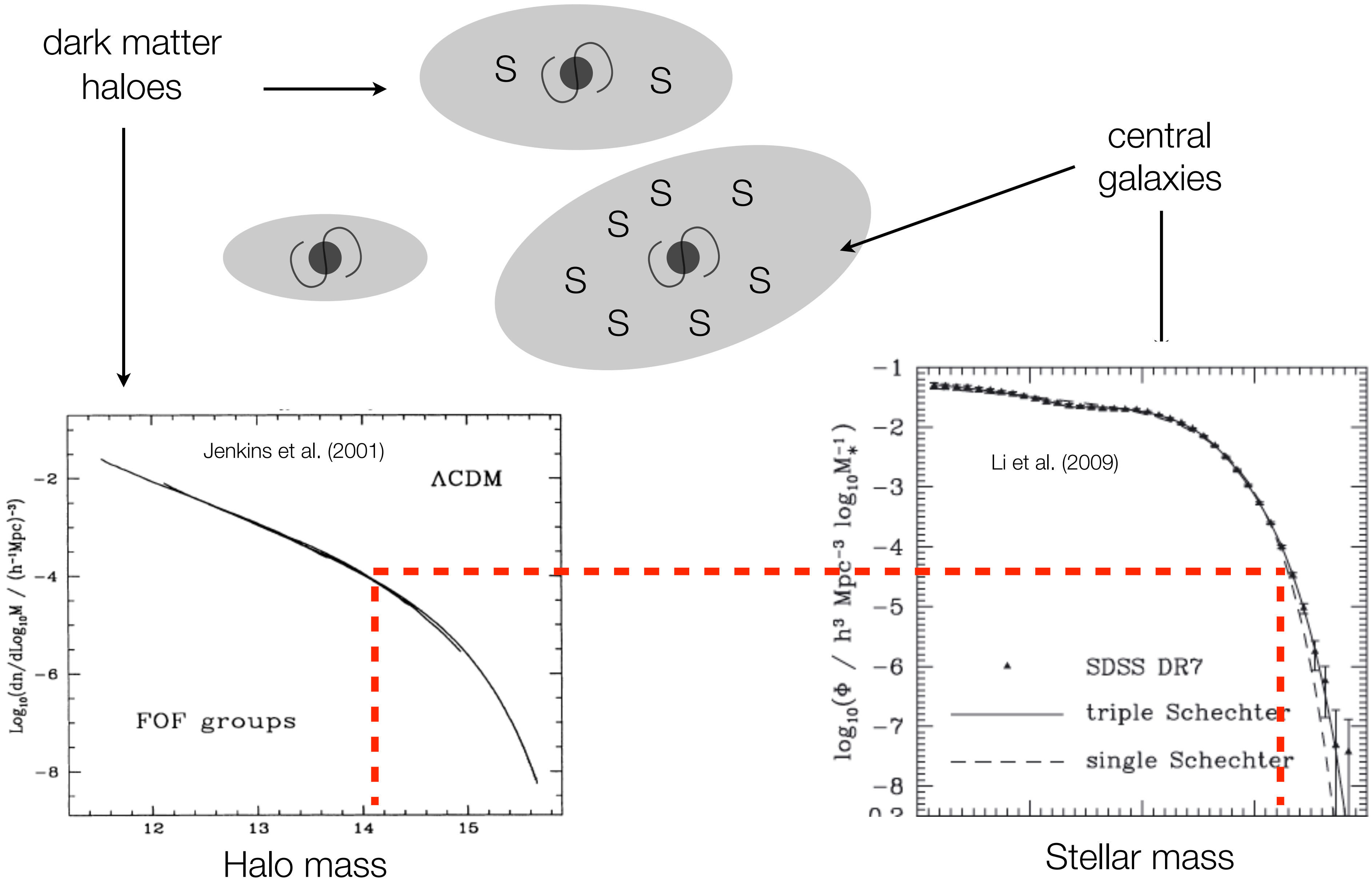
Magnification: the redshift enhancement effect

Increased mean redshift of background lensed population behind clusters

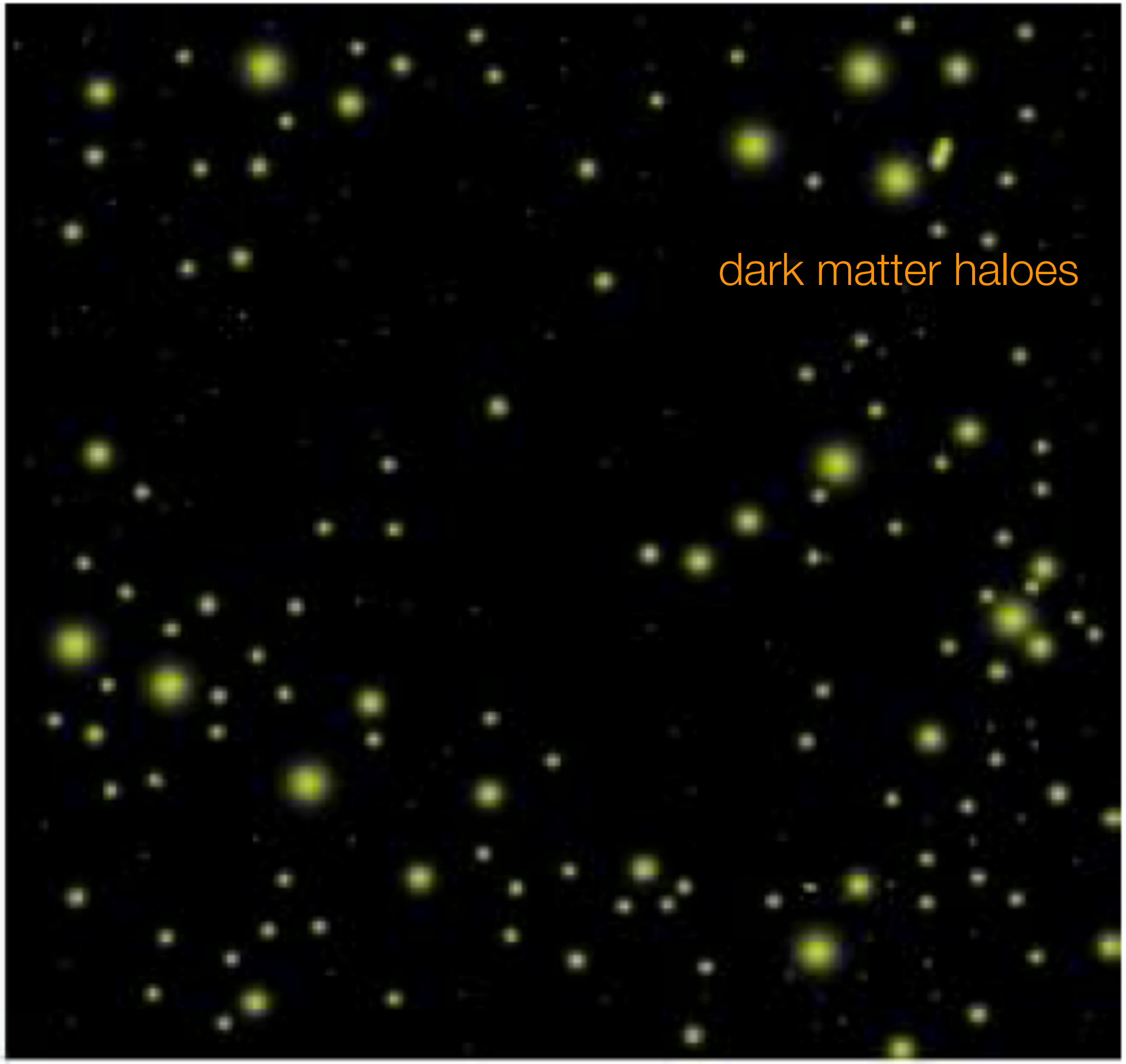


JC, Broadhurst & Umetsu (2013)

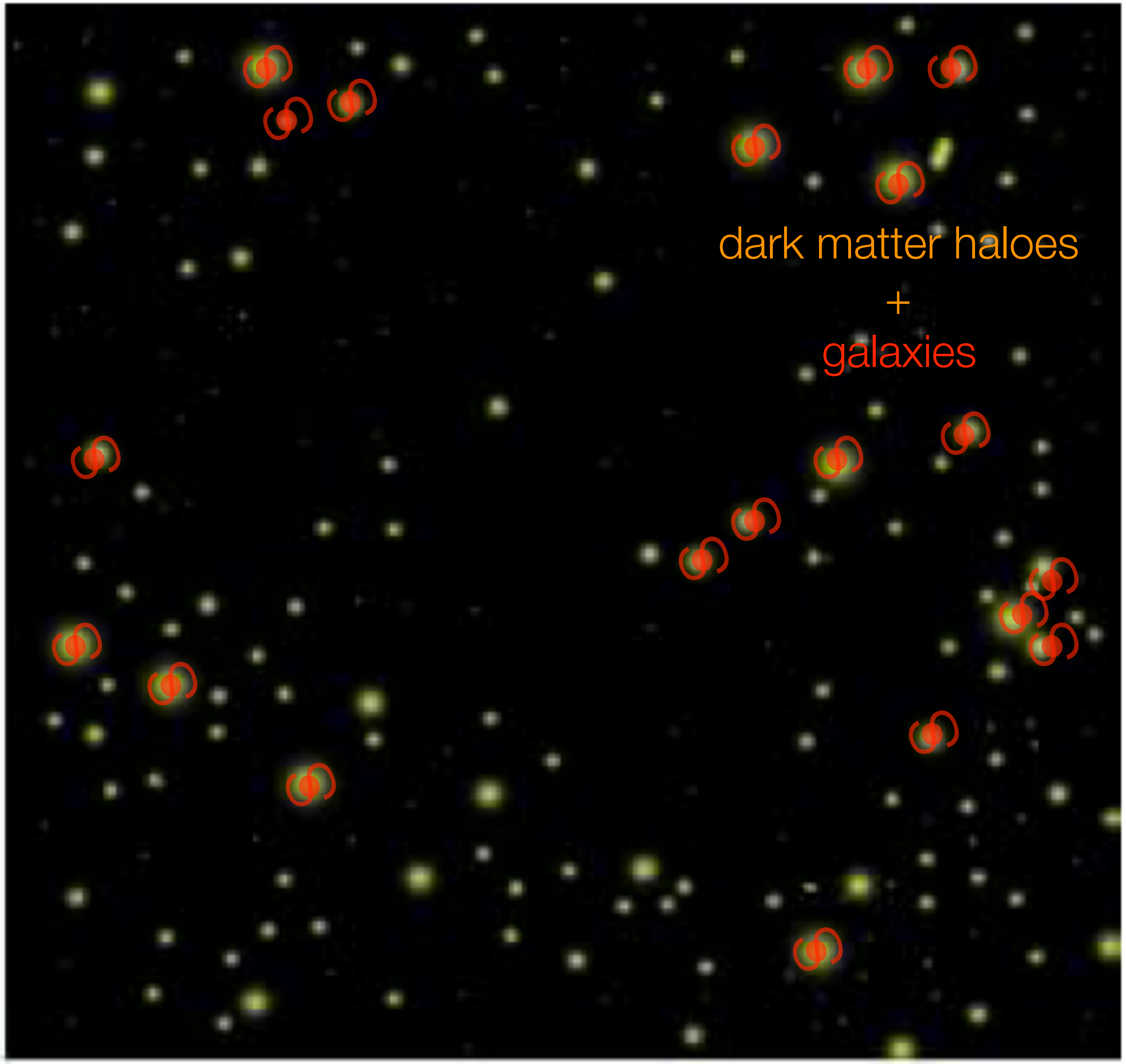
The galaxy-mass connection: abundance matching



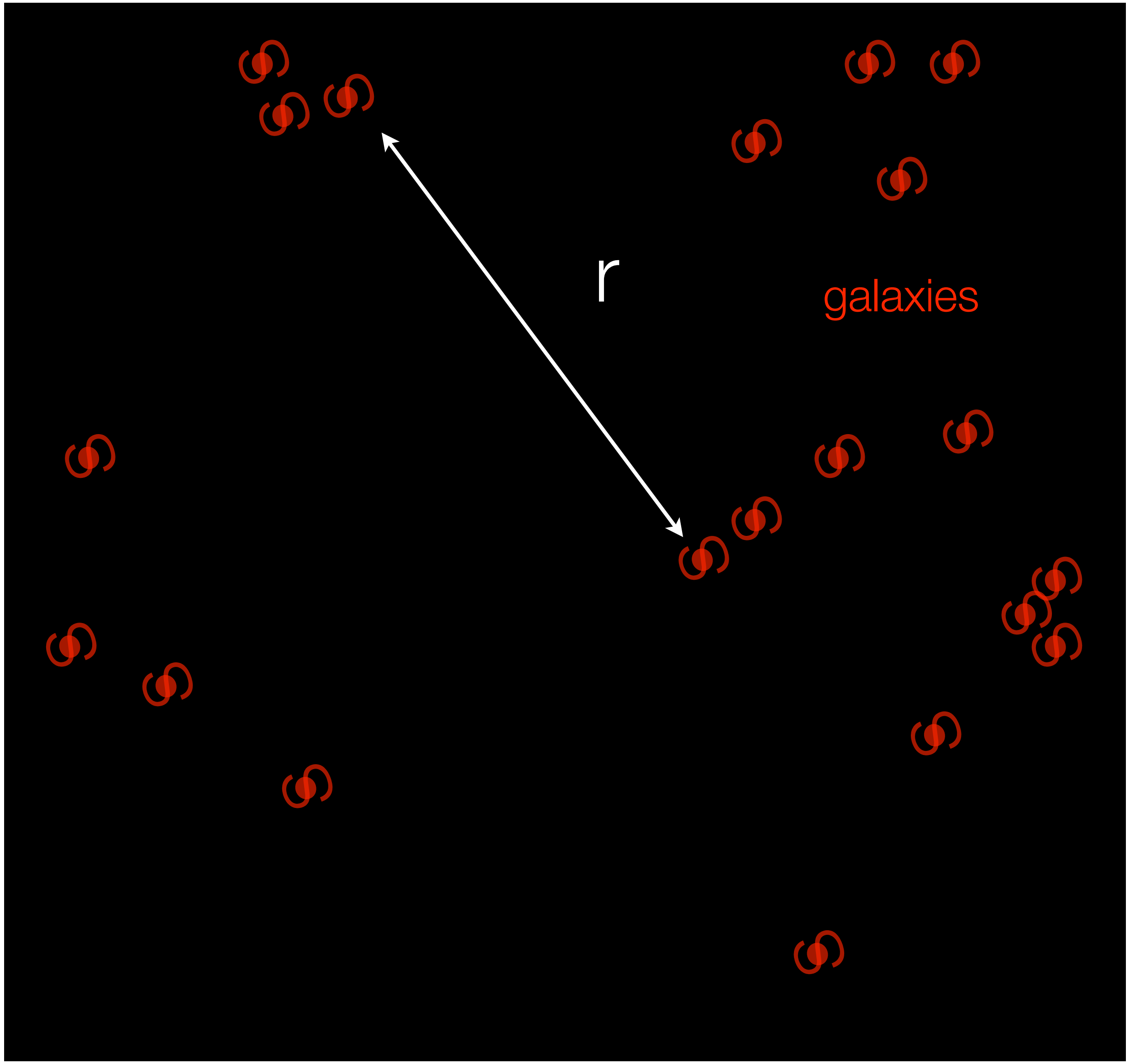
The galaxy-mass connection: clustering



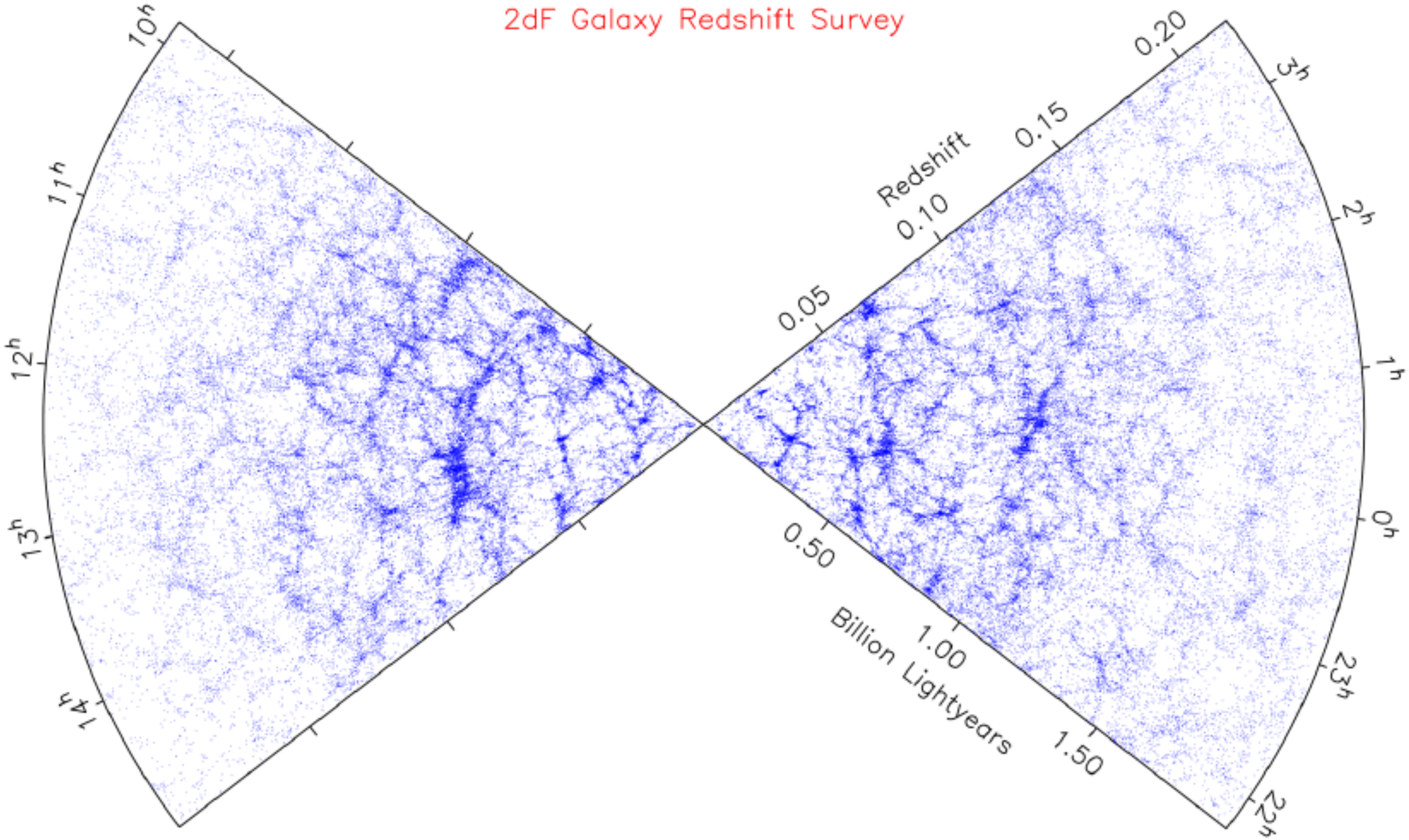
The galaxy-mass connection: clustering



The galaxy-mass connection: clustering

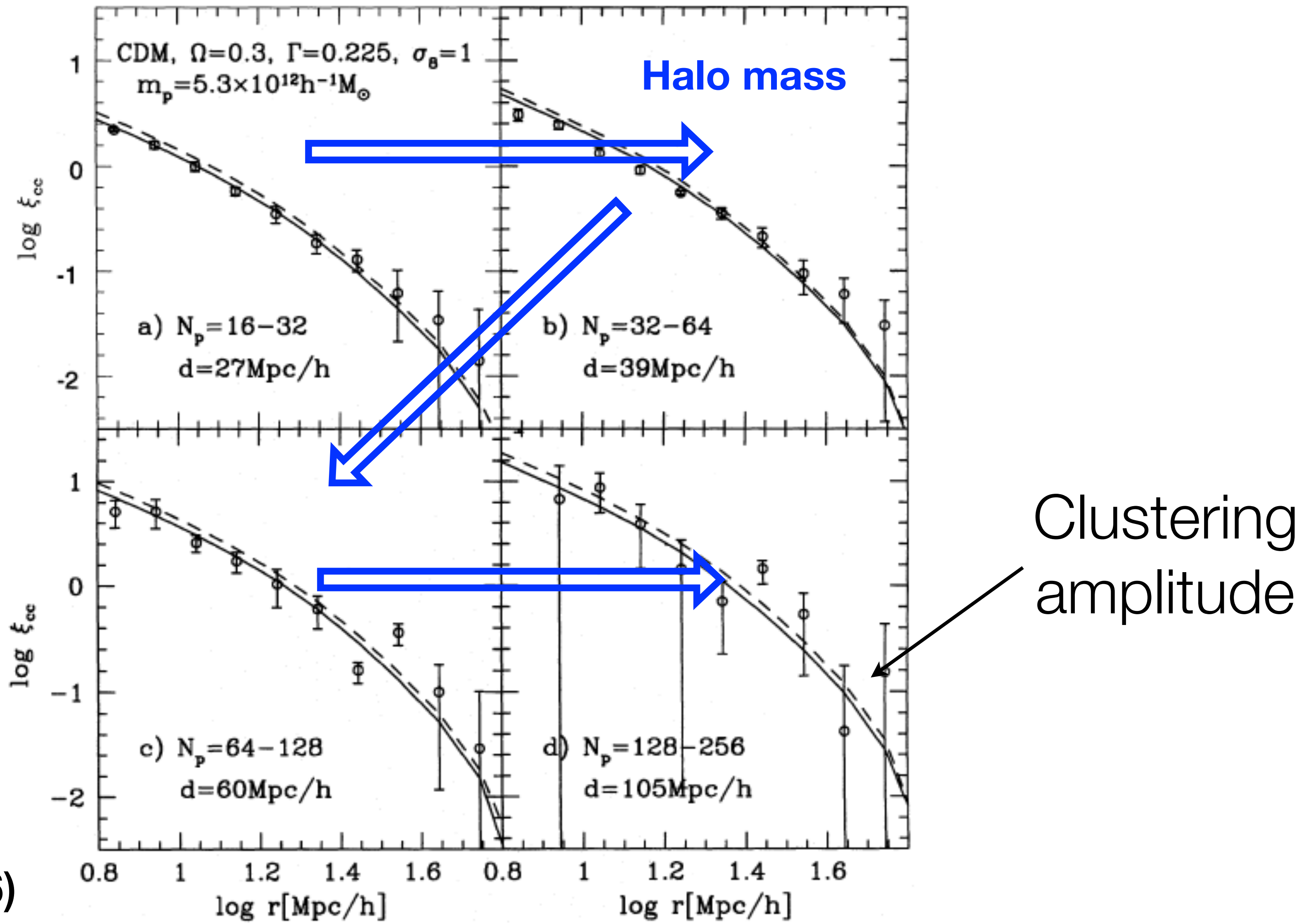


The large scale bias



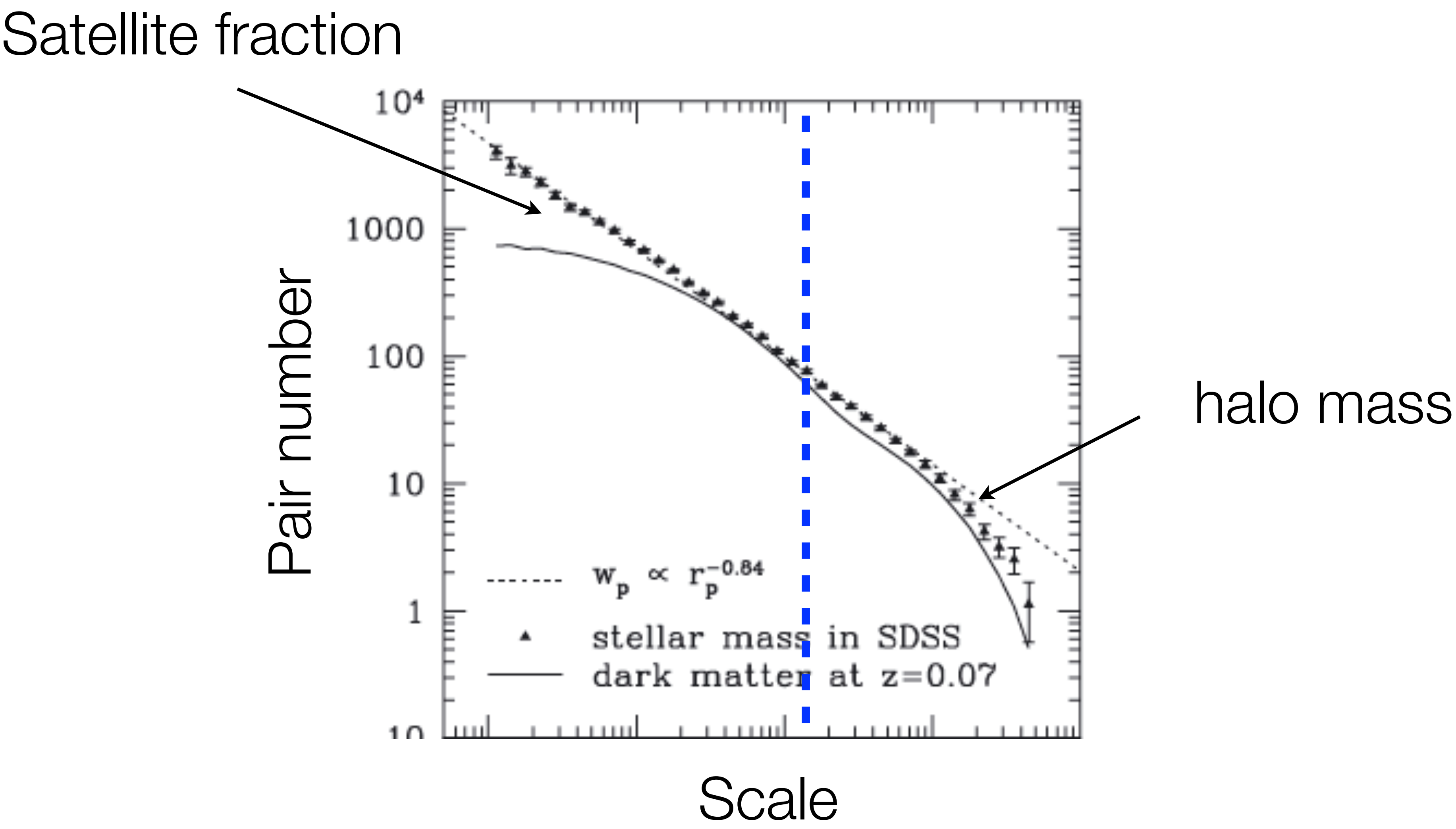
The large scale bias

large-scale clustering probes the halo mass



Mo & White (1996)

Clustering also probes satellites



Combining everything

- galaxy lensing: direct measurement of mass
- abundance matching: central galaxies
- clustering: satellite galaxies
- + hyp.: galaxies divide into central+satellite and halo bias only depends on halo mass (if not -> assembly bias, e.g. Y.-T. Lin et al. 2015)
- = “halo occupation distribution (HOD)” formalism

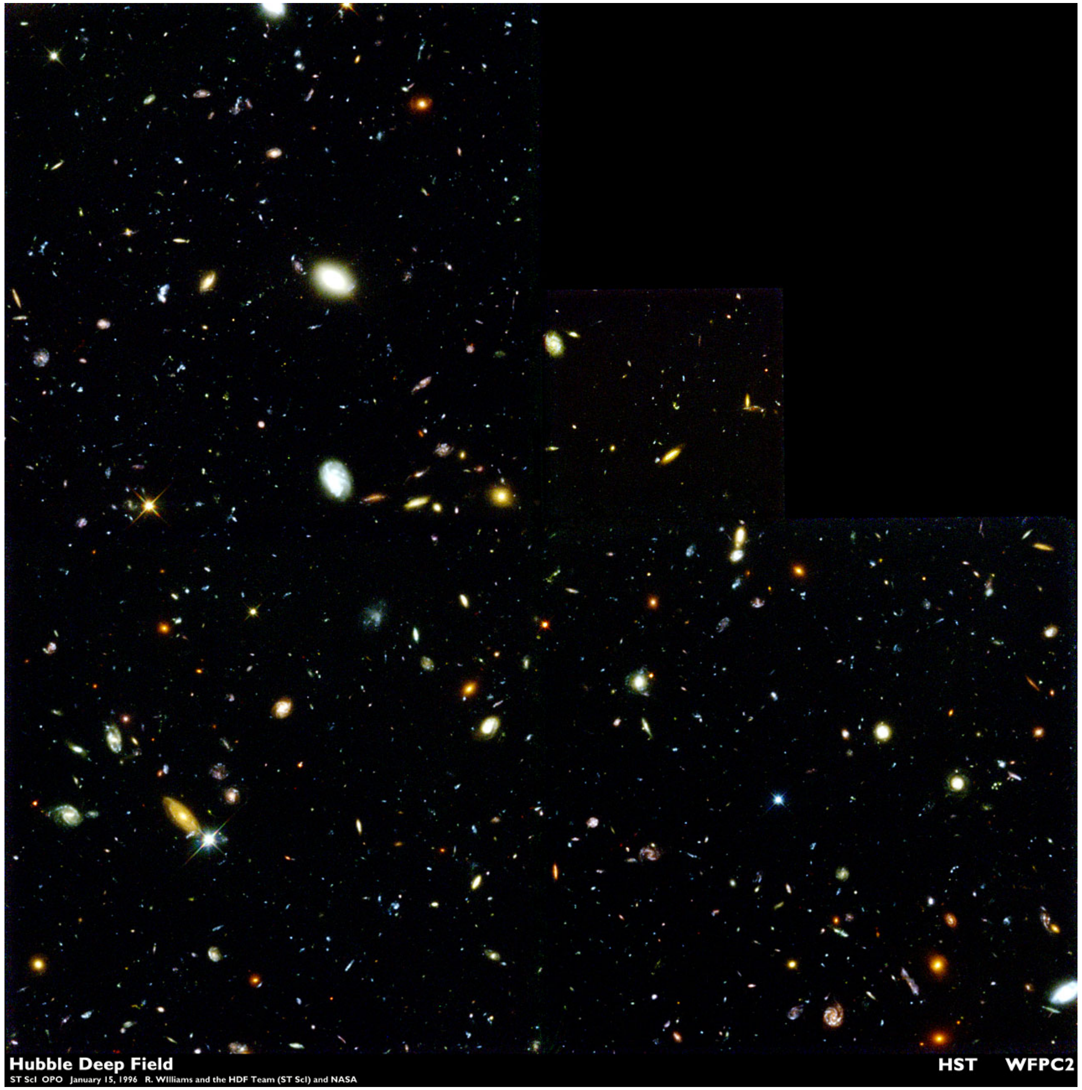
Clustering/lensing studies in the literature

- Berlind/Weinberg/Kravstov/Zheng (2002): HOD, clustering
- Behroozi/Moster/Yang (2004-10): abundance matching, CLF
- Cacciato/van den Bosh/More (2009): pioneering work on combining clustering and lensing
- Leauthaud/Tinker (2012): clustering, lensing + CMF (satellites!)
- Mandelbaum, Miyatake, More et al. (2014): BAO sample, application to cosmological parameters
- Zu, Mandelbaum et al. (2015): red/blue galaxies in the SDSS
- Coupon et al. (2015): low-mass and large-scale measurement of HOD in CFHTLS

3. The bright future of the dark: HSC, LSST & Euclid

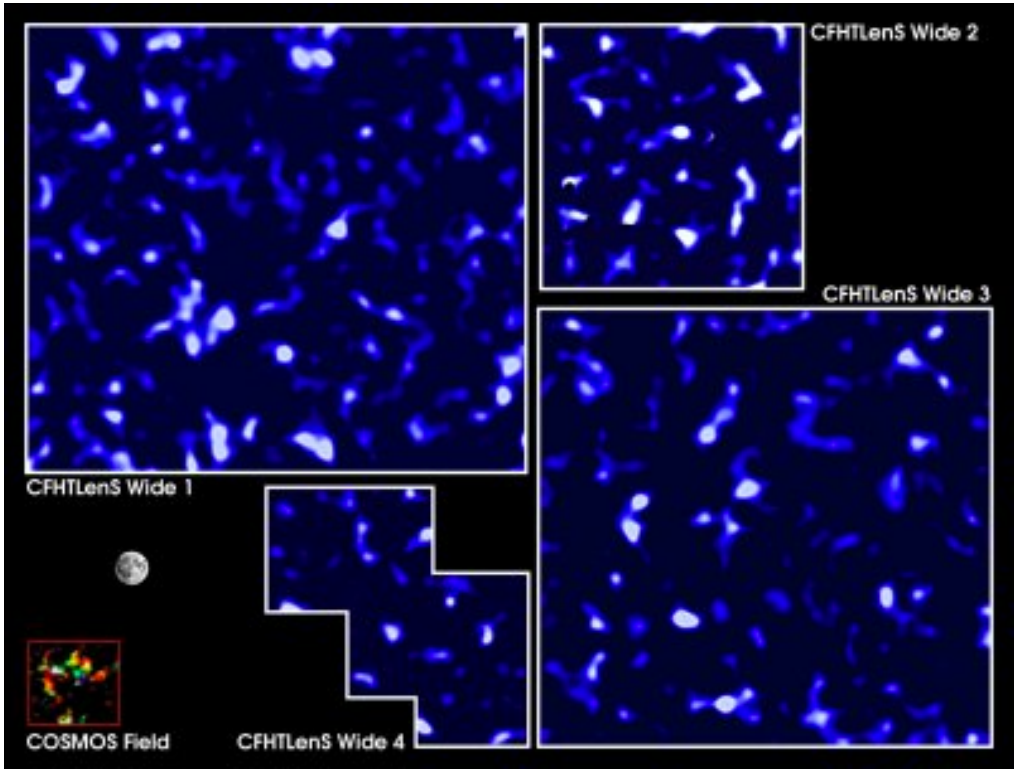
A long history of extragalactic surveys

- 1995 – 2005: era of deep "pencil beam surveys"
- optical and near-IR surveys, dedicated to galaxy evolution
- HDF, GOODS, COMBO-17, GEMS, SWIRE, COSMOS, CFHT 12k, DLS, HUDF, CFHTLS Deep/SNLS, UKIDSS, etc.



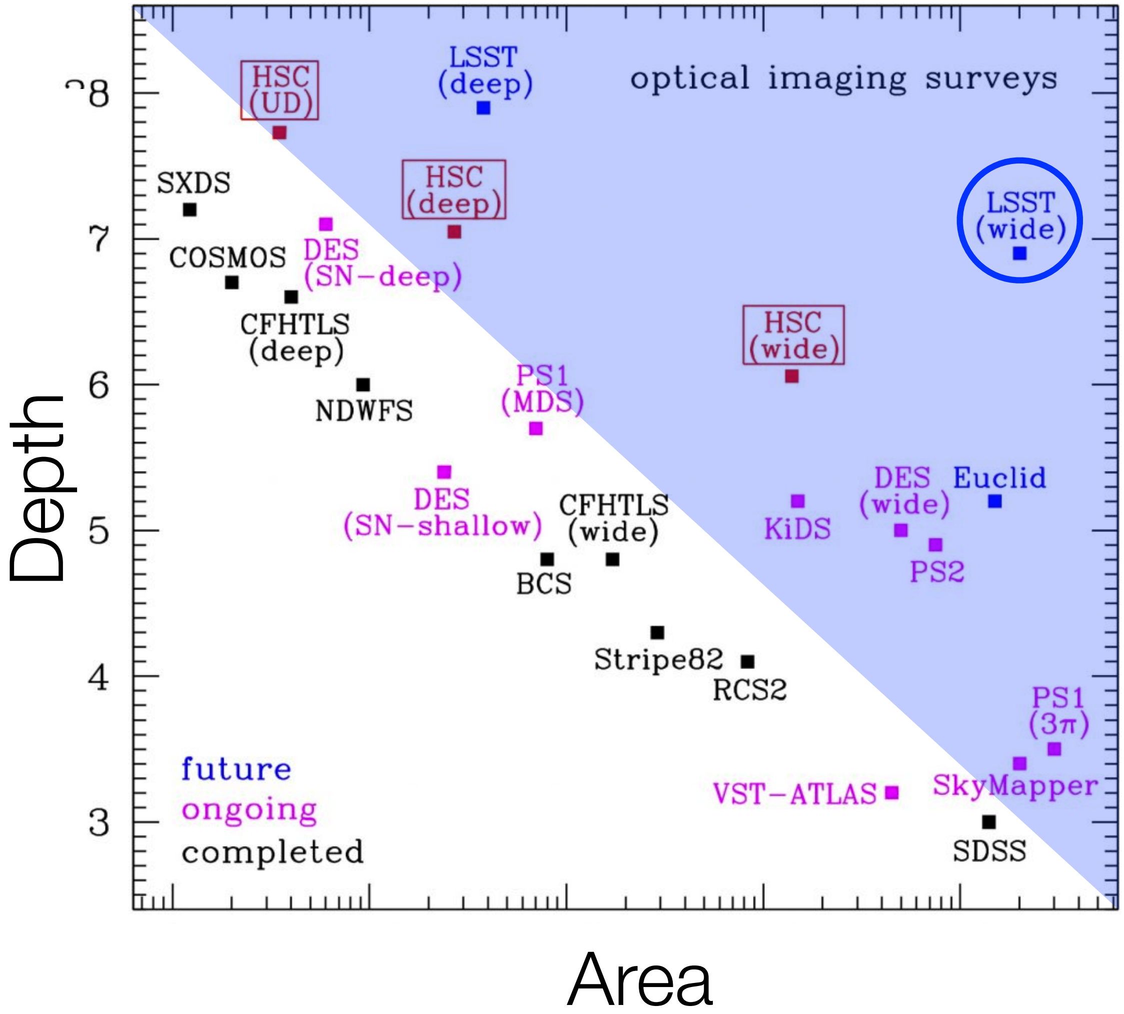
A long history of extragalactic surveys

- 2005— 2015: era of wide-field surveys
- optical and near-IR surveys, dedicated to galaxy evolution and cosmology
- RCS2, SDSS, CFHTLS Wide, Pan-STARRS, NGVS, KIDS, Skymapper



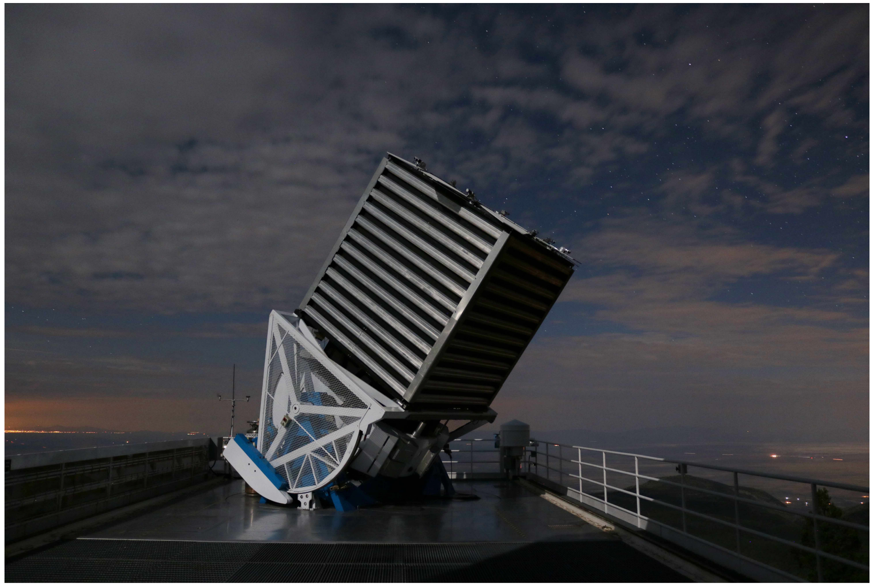
A long history of extragalactic surveys

- > 2015: era of wide-field *and* deep surveys
- optical and near-IR surveys, dedicated to galaxy evolution and cosmology
- HSC, LSST, Euclid, DES, WFIRST
- + ultra deep surveys (JWST)

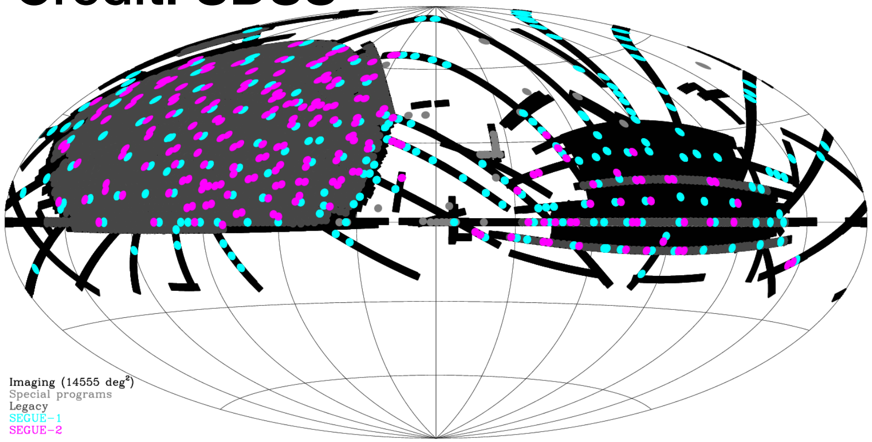


Entirely new parameter space

A word on the Sloan Digital Sky Survey

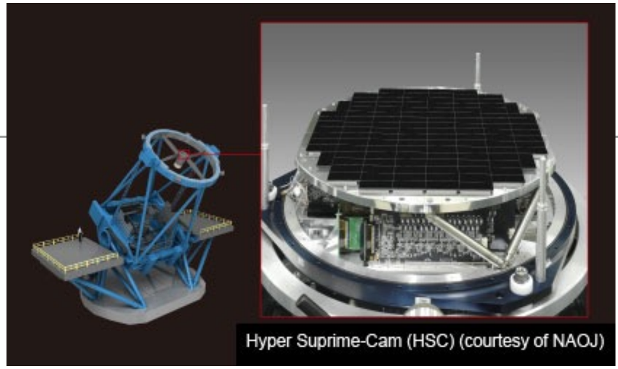


Credit: SDSS



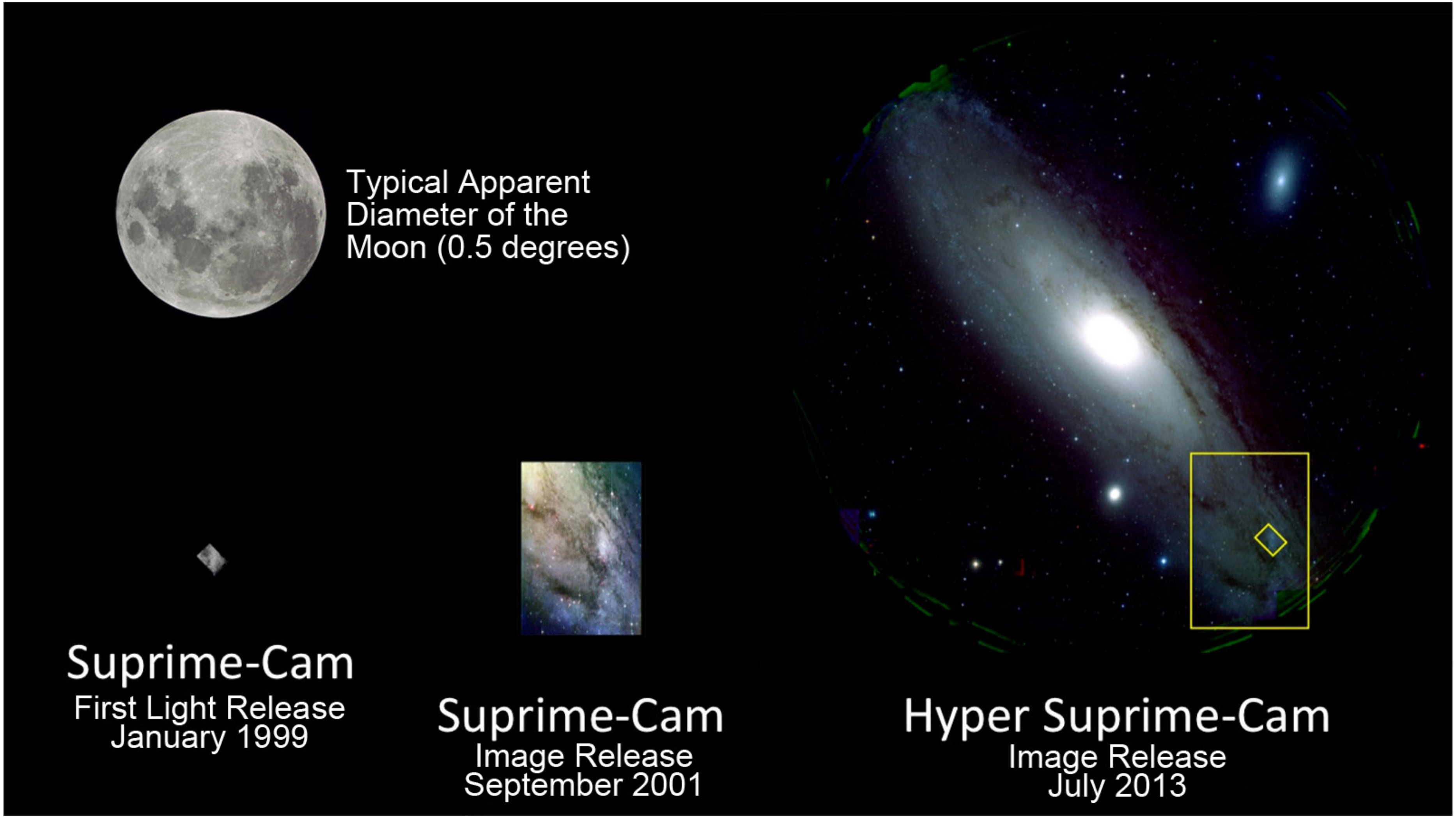
- big step in wide field surveys
- medium deep survey, (1.2 m mirror!), 1/3 of the sky
- major discoveries in galaxy evolution, cosmology and solar system
- dedicated telescope, data reduction and distribution given high priority
- = huge impact on astronomy

Hyper-Suprime-Cam (HSC)

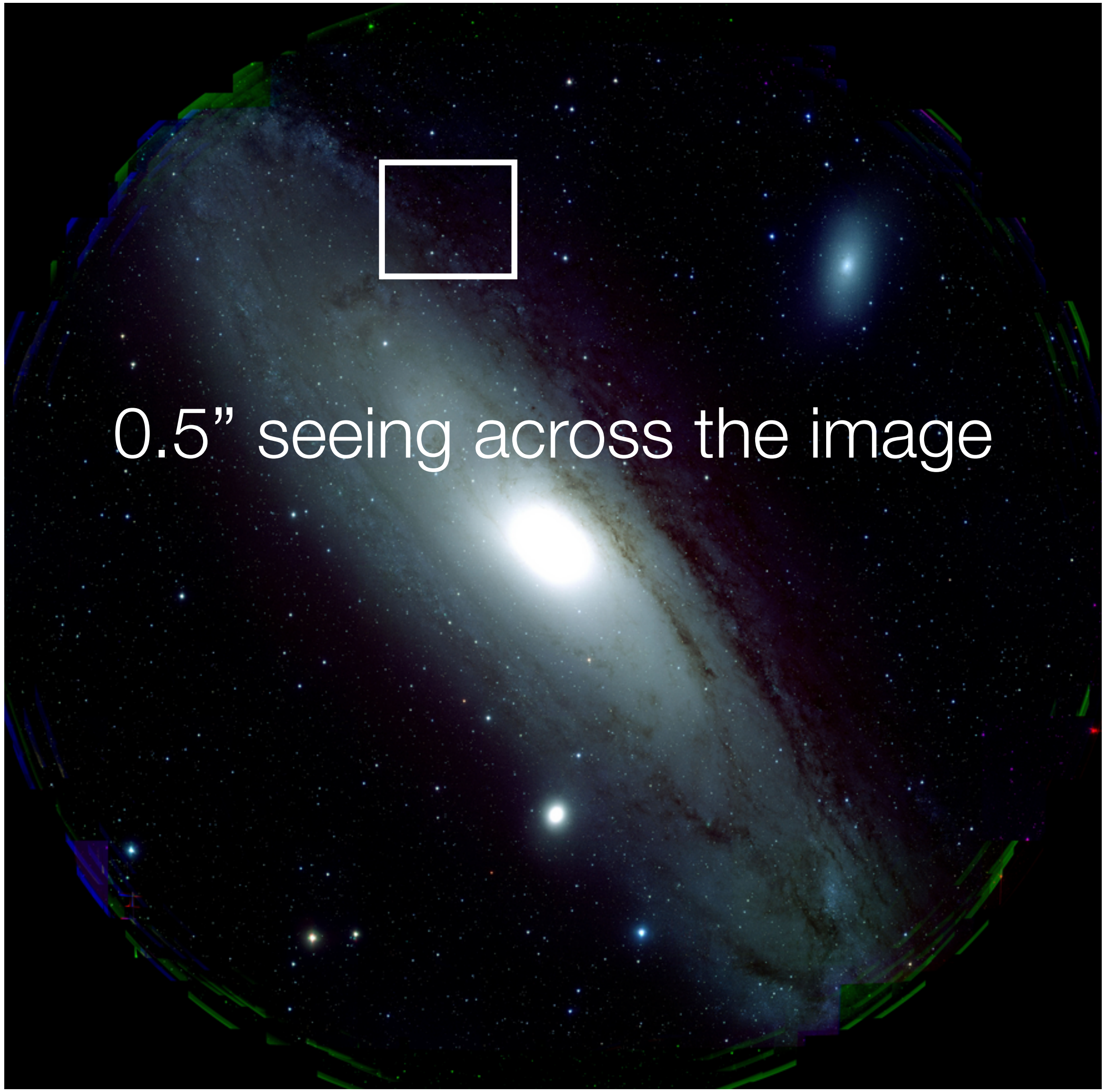


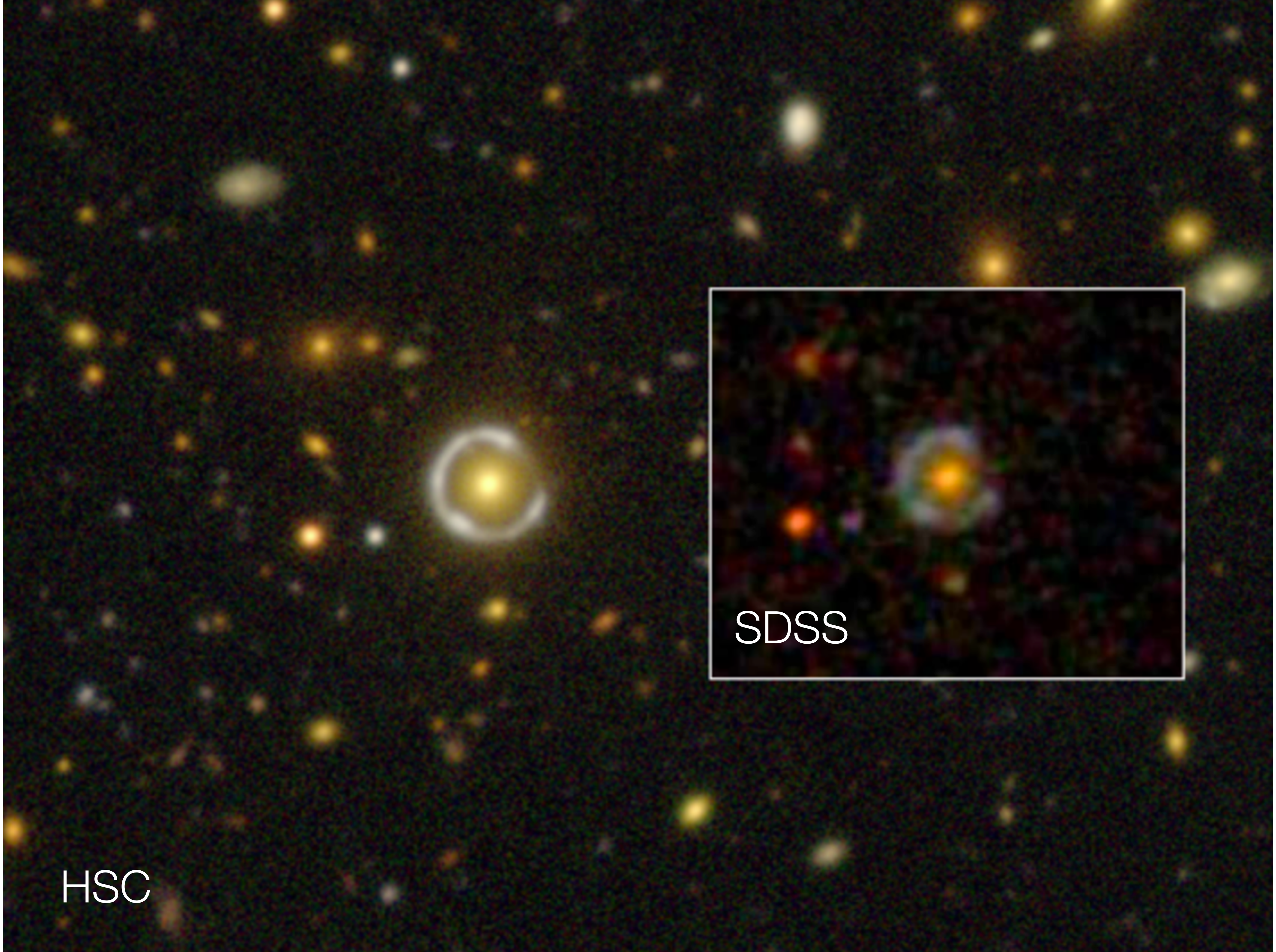
- brand new camera at Subaru (Hawaii)
- 104 chips used for science (+12 for guiding)
- ~ 0.9 billion pixels
- 3 Tons

HSC first light

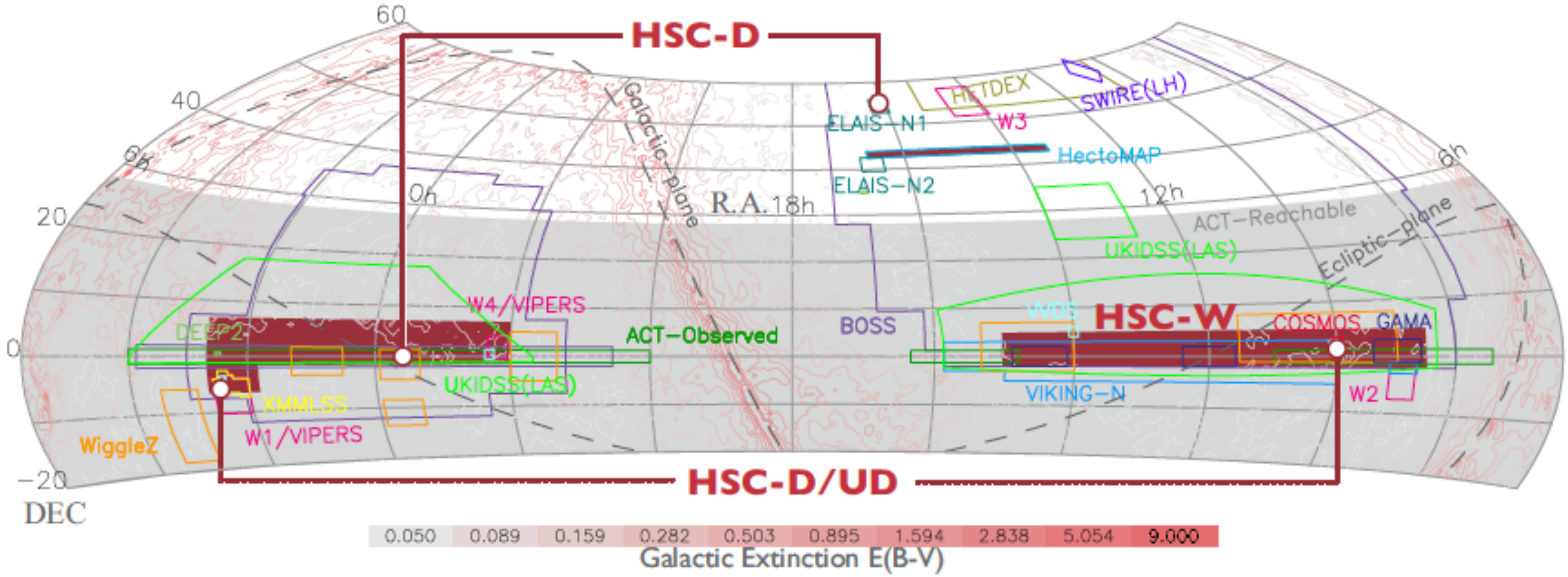


HSC first light




SDSS
HSC

The HSC survey



- Princeton/Japan/Taiwan collaboration, 170 scientists
- 300 nights granted, 30% of the survey done as of summer 2016
- three layers in 5 broad-band filters : wide/1400 deg2, deep/24 deg2, ultra deep/3 deg2
- + narrow-band filter survey in deep and ultra deep
- first public data release in February 2017

HSC survey science goals

Weak-Lensing Cosmology

Galaxies at Low-Intermediate Redshifts

Galaxies at High Redshifts

Galaxy Clusters

Transient Objects

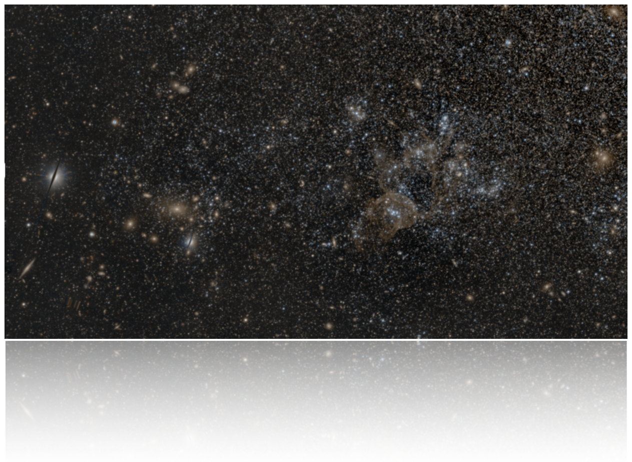
Solar System Bodies

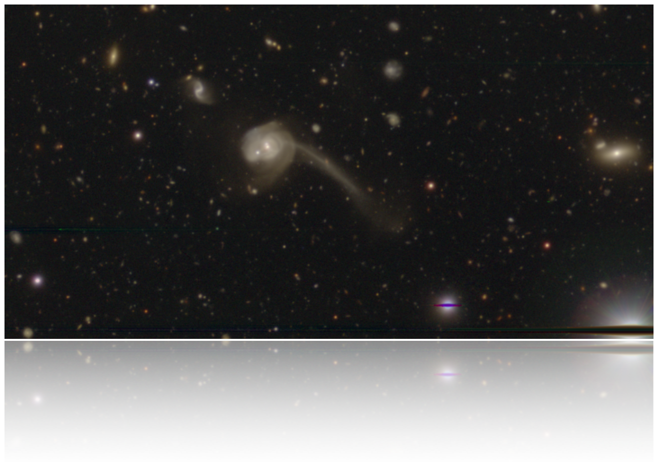
Supermassive Blackholes and AGNs

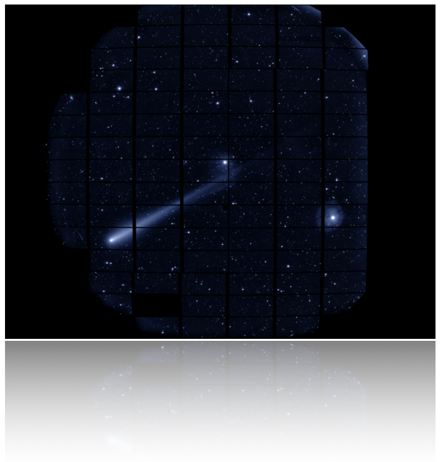
Milky Way

Strong Lensing

Photometric Redshifts



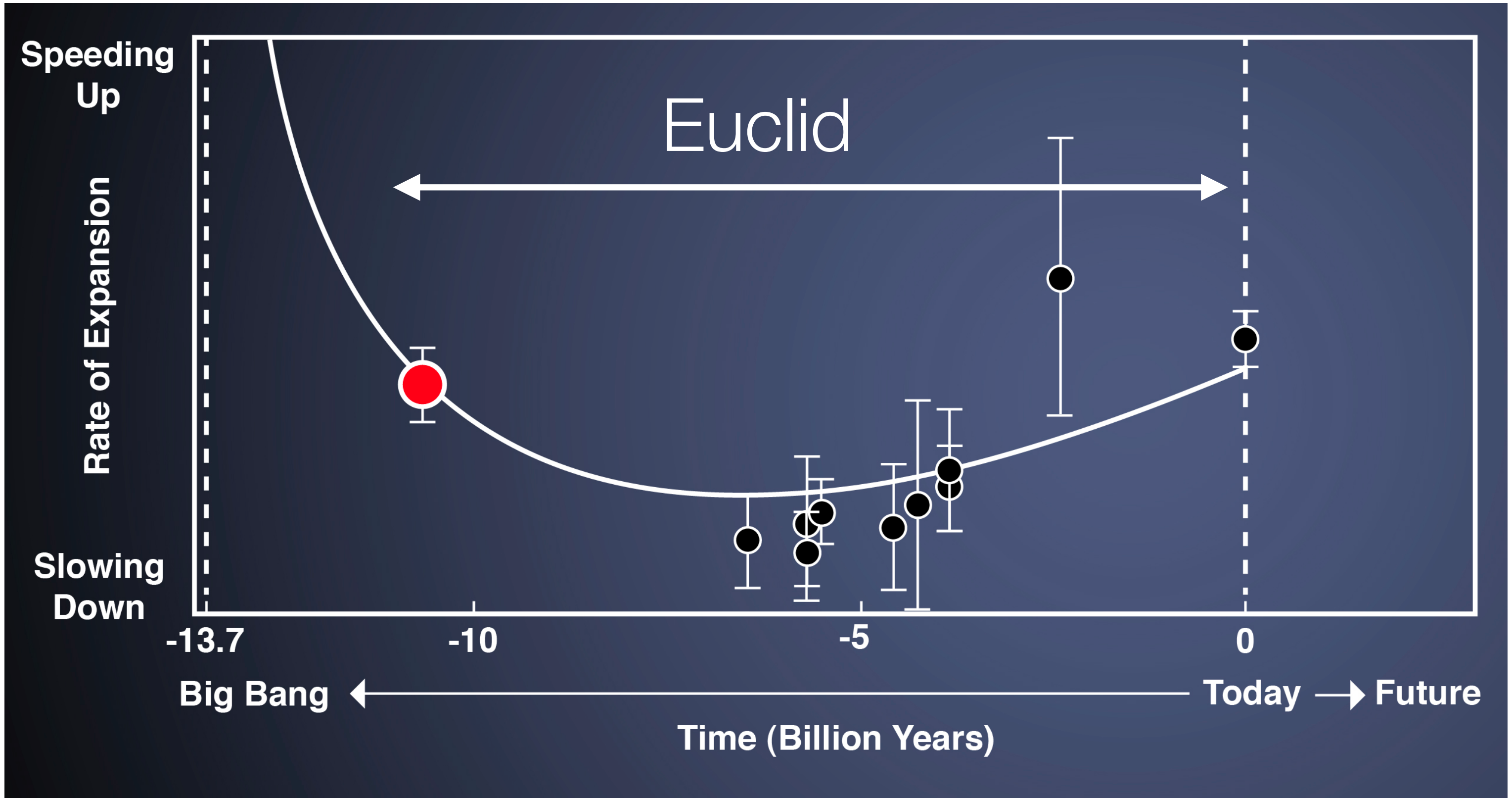




The Euclid mission

- Euclid will probe the time evolution of the EOS through the growth rate of cosmological structures
- 1. using weak gravitational lensing
- 2. using galaxy clustering: BAO and redshift space distortions
- + legacy science: galaxy clusters, strong lensing, galaxy evolution

The Euclid mission



Credit: BOSS collaboration

Challenges of the Euclid mission

- Euclid will probe the time evolution of the EOS through the growth rate of cosmological structures
- Weak gravitational lensing:
  - shapes and distance from 1.5 billion galaxies
  - over 15000 deg2 (the entire dark extragalactic sky
  - 10 “redshift bins” up to z=2 -> need for highly accurate photometric redshifts
- BAO:
  - spectrum degeneracies
  - redshift fitting

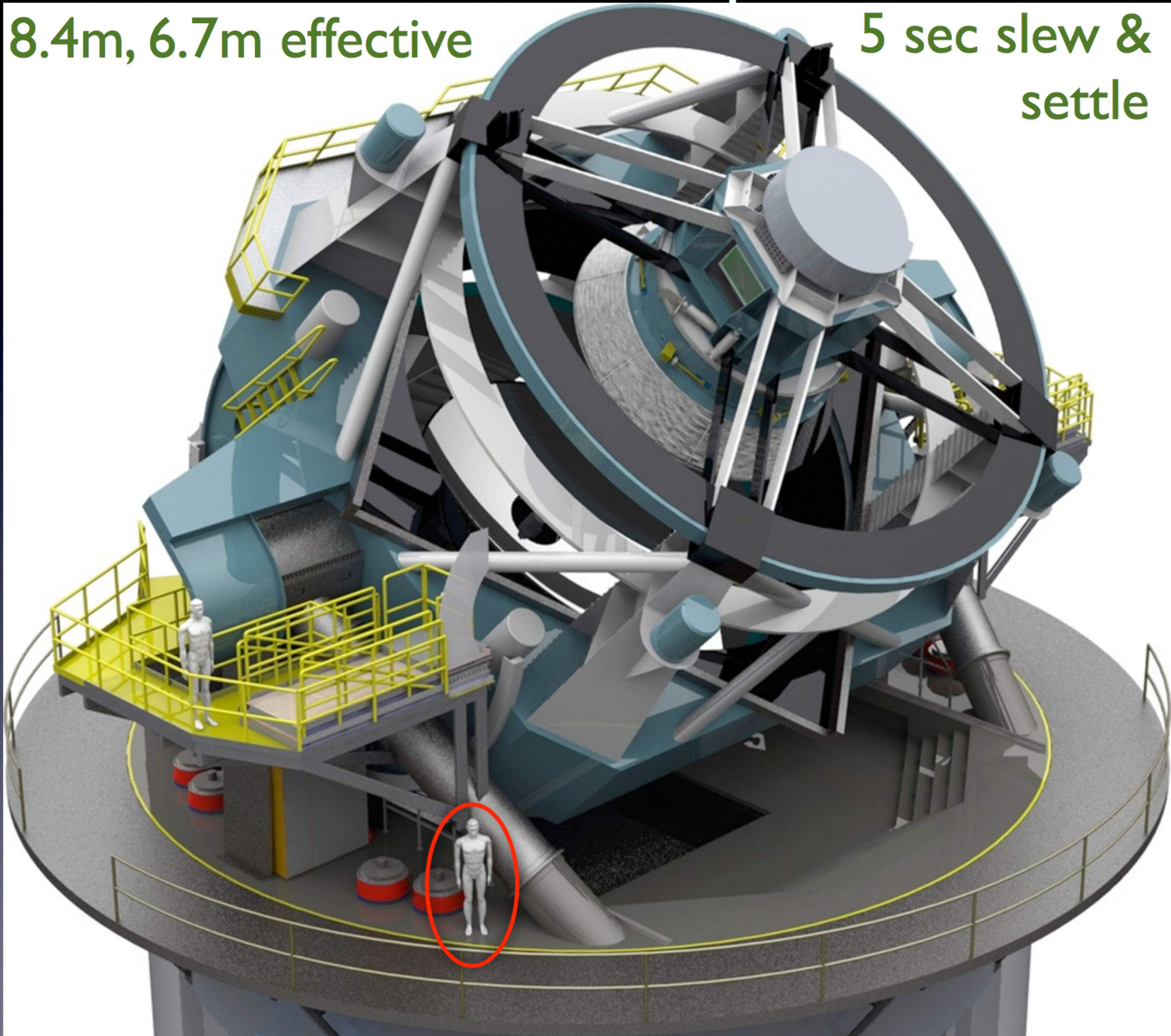
The Large Synoptic Survey Telescope (LSST)

- “super” HSC survey: + time domain (new!) + huge area
- dedicated ground-based telescope
- 1/3 of the sky observed every 4 nights
- experience from SDSS/HSC in data management
- enhanced science when combined with Euclid and WFIRST (high resolution lensing, high redshift, galaxy morphology/star formation history)

LSST Telescope

8.4m, 6.7m effective

5 sec slew & settle



Challenges of LSST

- huge amount of data
- rapid response to transient events
- combination with other projects (Euclid, WFIRST, etc.) — discussions between LSST and Euclid
- a number of issues are addressed in HSC -> major step further for the preparation for LSST

Conclusions

The galaxy-mass connection is key

- we ignore 95% of what the Universe is made of but we know precisely how it behaves
- toolbox for probing dark matter is well proven
- = revolution for galaxy evolution: the connection with dark matter enhances our view (star formation efficiency, low- vs high- mass physics)
- many questions remain: AGN feedback, medium-mass regime, galaxy formation in the early Universe, etc.

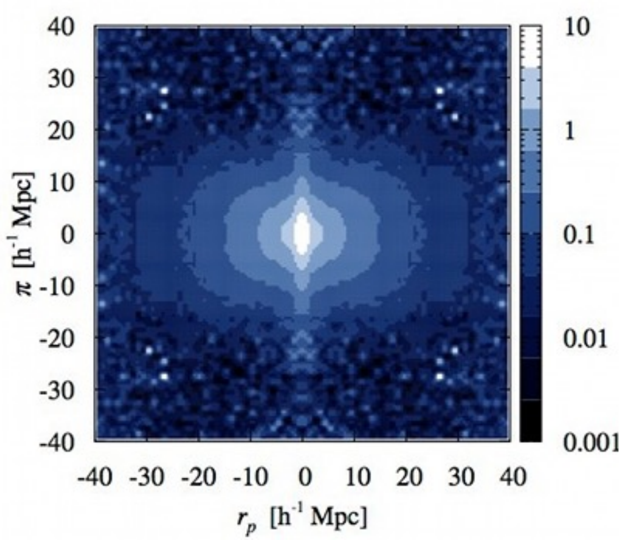
Bright future

- current and future imaging surveys enter an entirely new parameter space
- HSC superb data quality is very promising, the science impact is expected to be high
- it is paving the way to Euclid and LSST
- the data management for LSST remains challenging but will enormously benefit from the experience of HSC

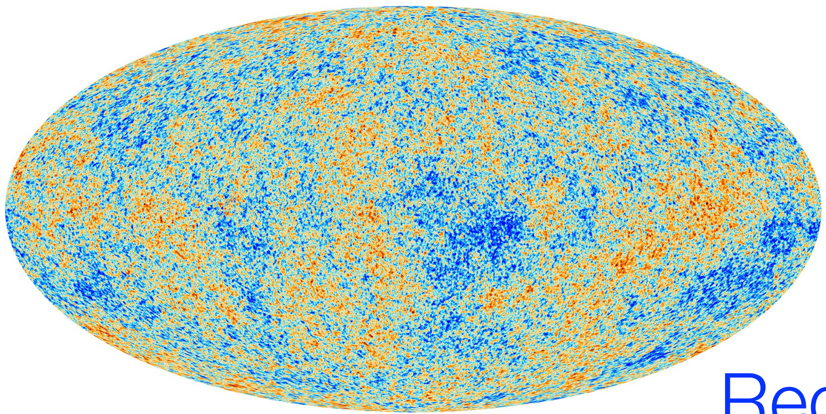
Extra slides

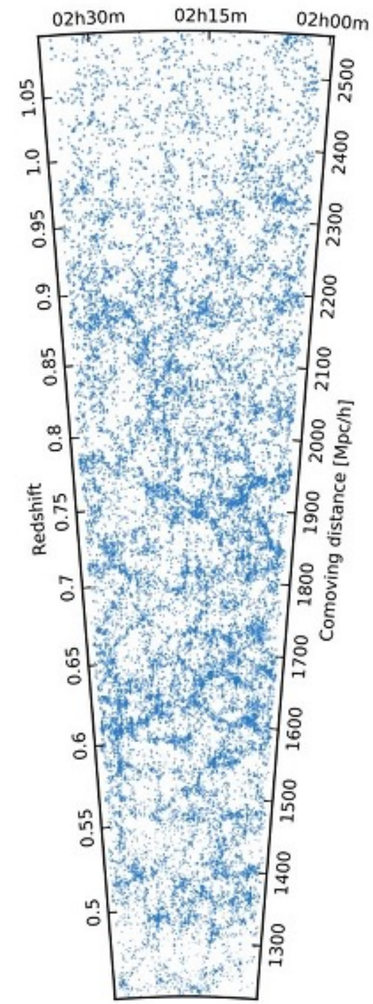
Cosmological probes

RSD (de la Torre et al. 2013)



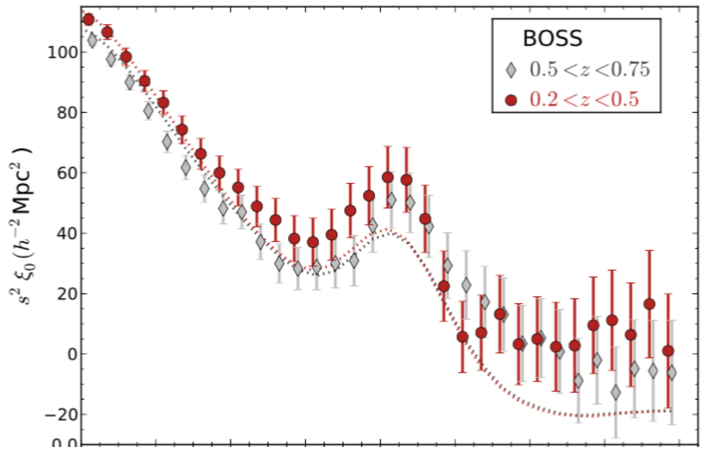
CMB (Planck collaboration 2015)



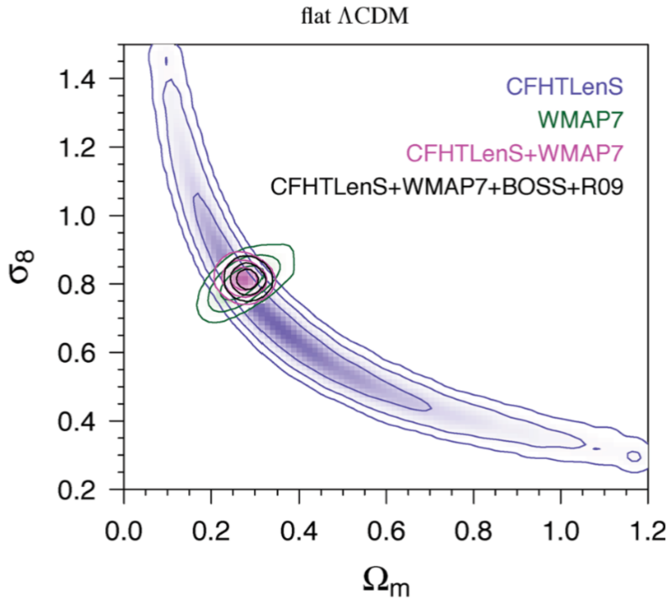


Redshift surveys (Guzzo et al. 2013)

Cosmological probes

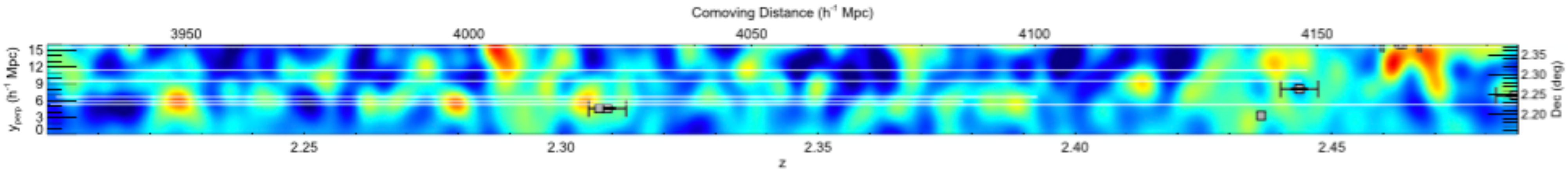


BAO (Ross et al. 2016)

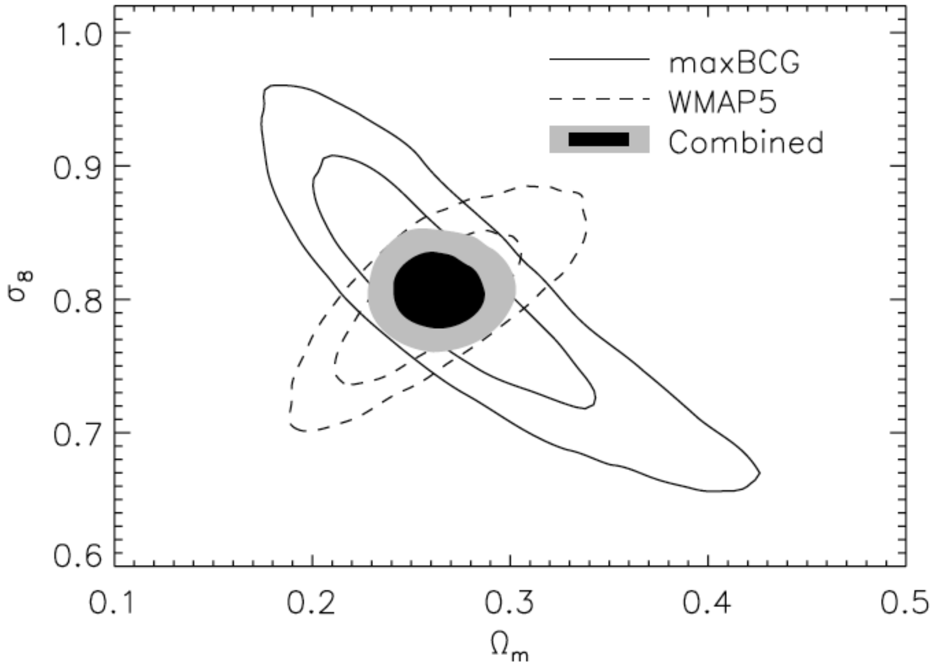


Cosmic shear (Kilbinger et al. 2013)

Lyman-alpha forest (Lee et al. 2016)

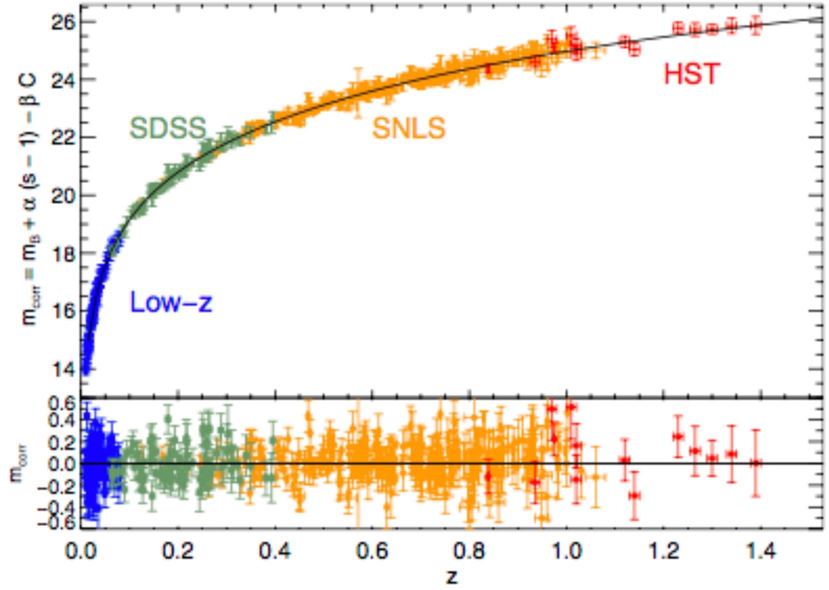


Cosmological probes



Cluster abundance
(Rozzo et al. 2010)

Supernovae
(Conley et al. 2011)



+ Element abundance, galaxy-galaxy lensing, lensed QSO's
+ near future: gravitational wave astronomy!