



Cosmological Probes

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2019.10.10



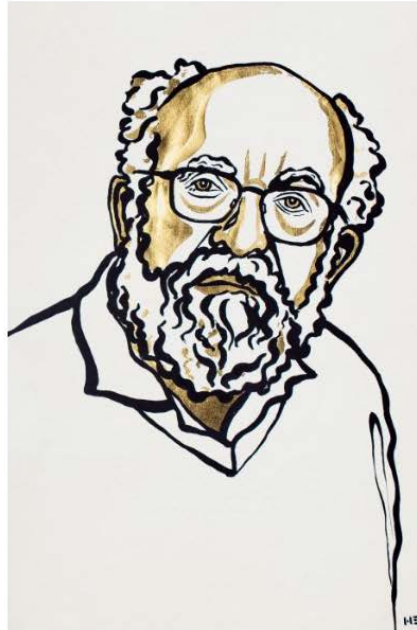
The Nobel Prize in Physics 2019



III. Niklas Elmedhed. © Nobel Media.

James Peebles

Prize share: 1/2



III. Niklas Elmedhed. © Nobel Media.

Michel Mayor

Prize share: 1/4



III. Niklas Elmedhed. © Nobel Media.

Didier Queloz

Prize share: 1/4

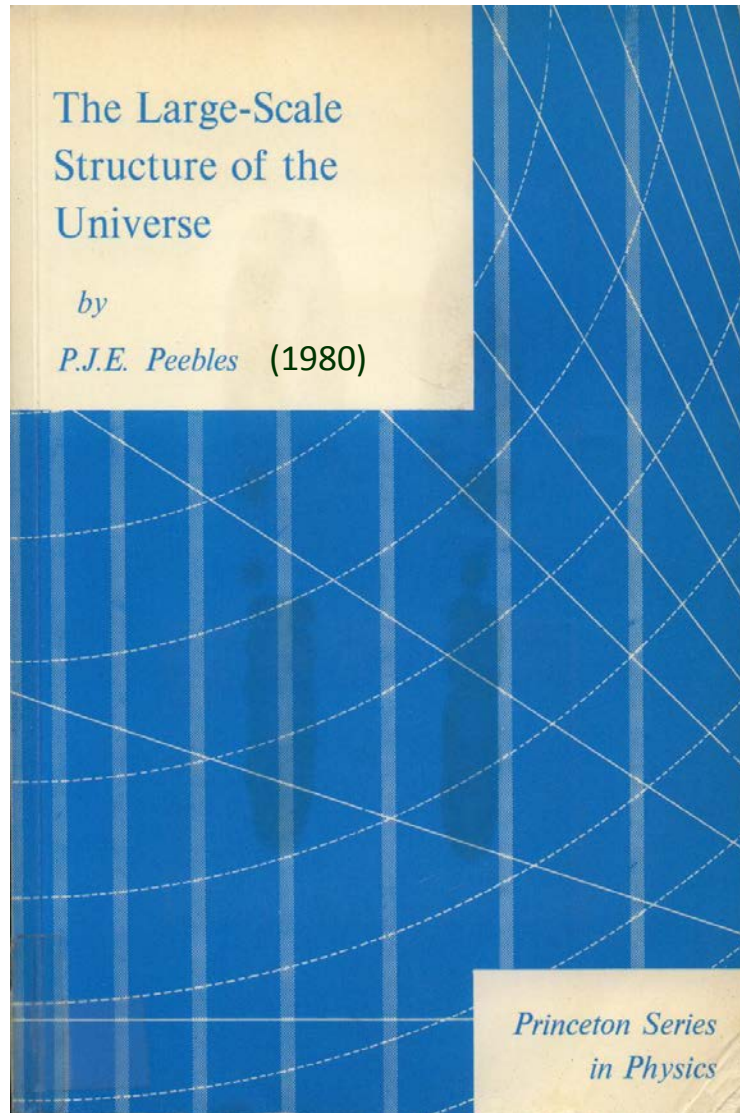
The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to **James Peebles "for theoretical discoveries in physical cosmology"**, the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star." ₂

Outline

1. Introduction
2. Topics:
 - Dark Energy
 - Baryon Acoustic Oscillations
3. Future Surveys

Cosmological Studies

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Homogeneous
background +
fluctuations

Evolution of
fluctuations

HUDF

1,000,000-s exposures in

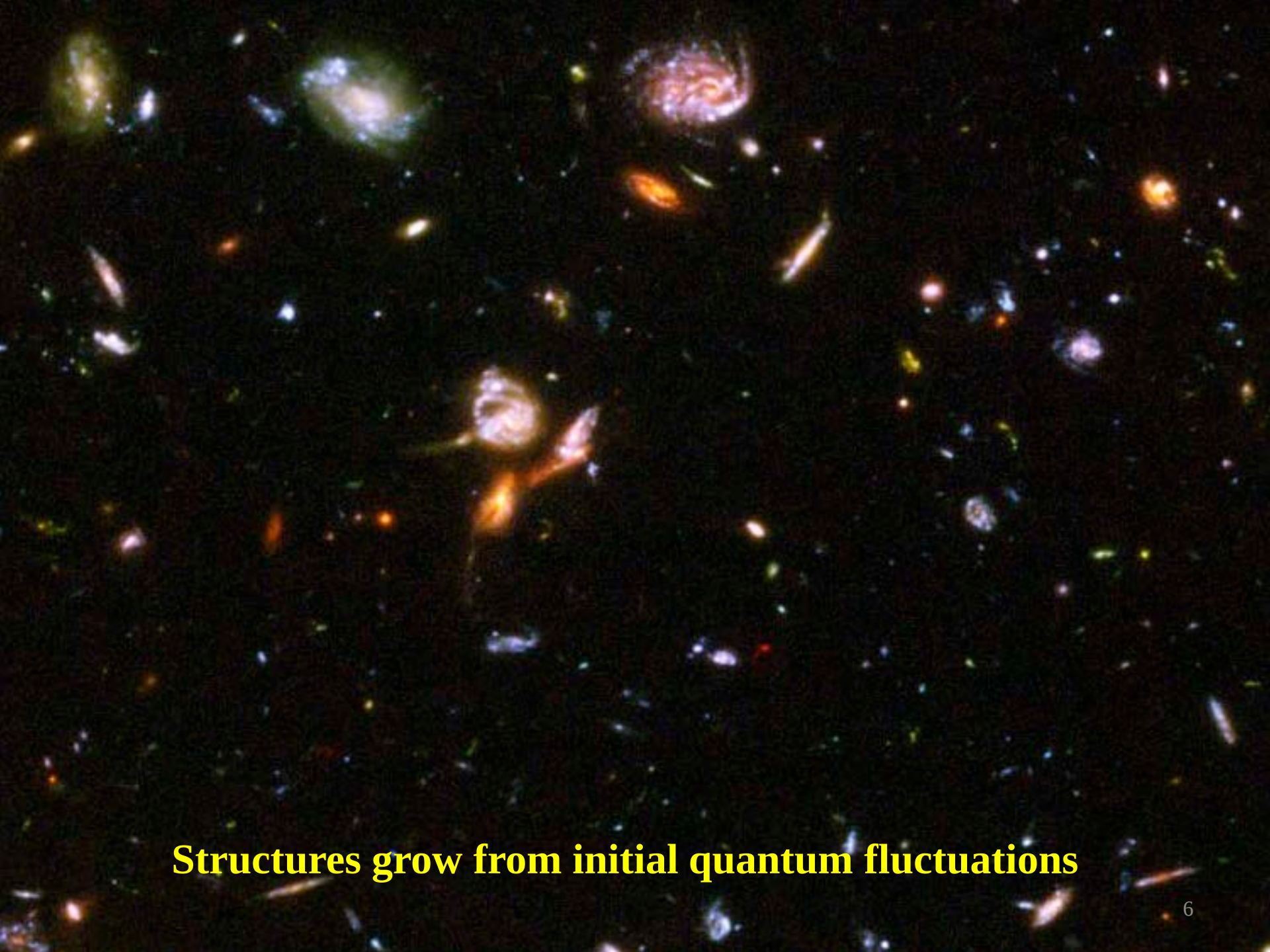
435/600/775/850nm

10,000 galaxies in

11 $\square'$

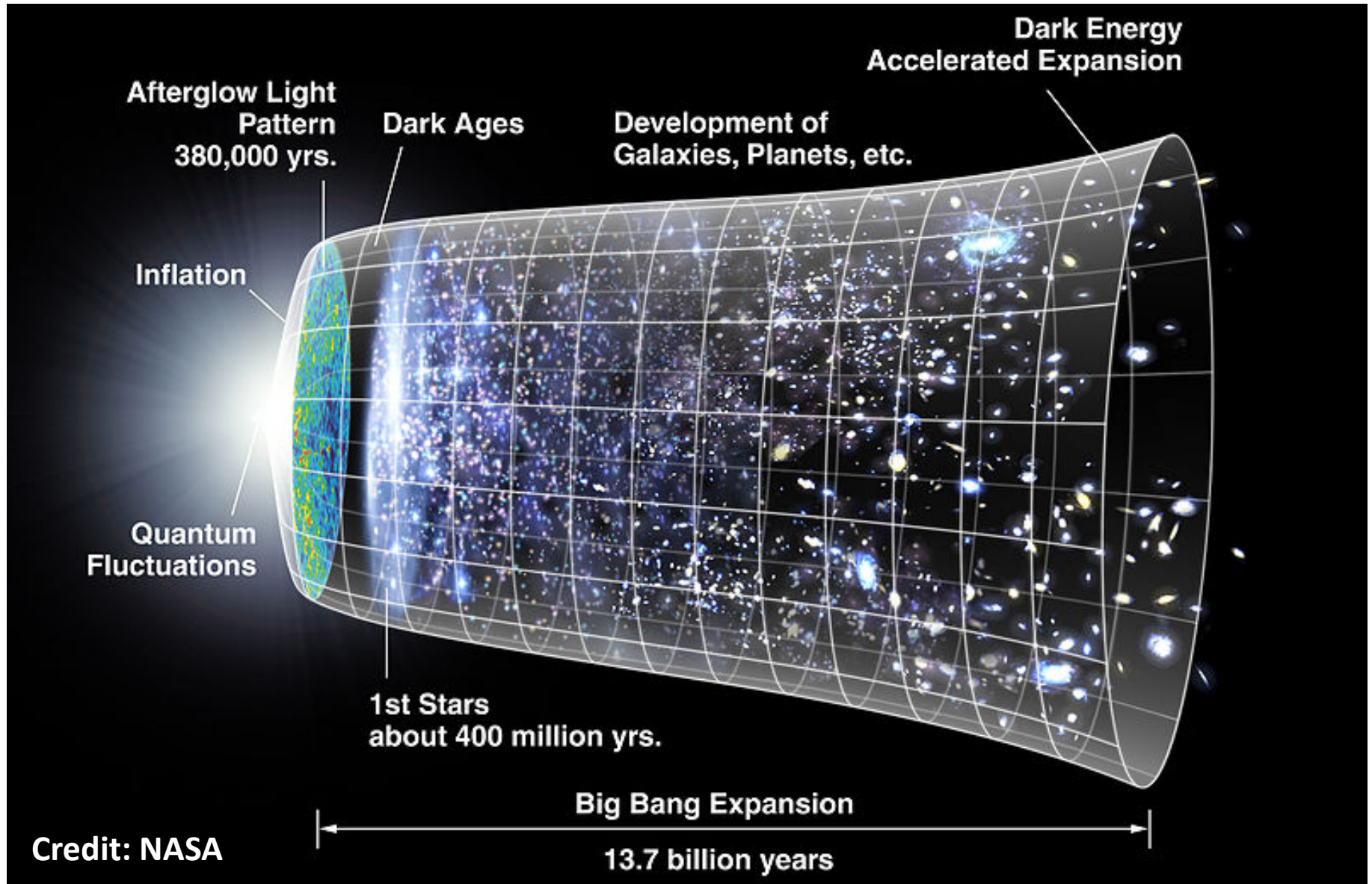


**Cosmological principle: isotropy & homogeneity
on large scales**



Structures grow from initial quantum fluctuations

Evolution of the Universe



Statistical Tools

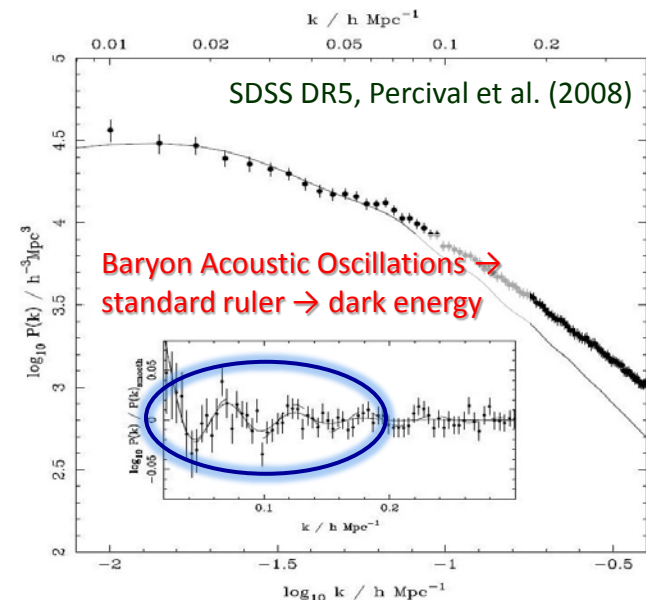
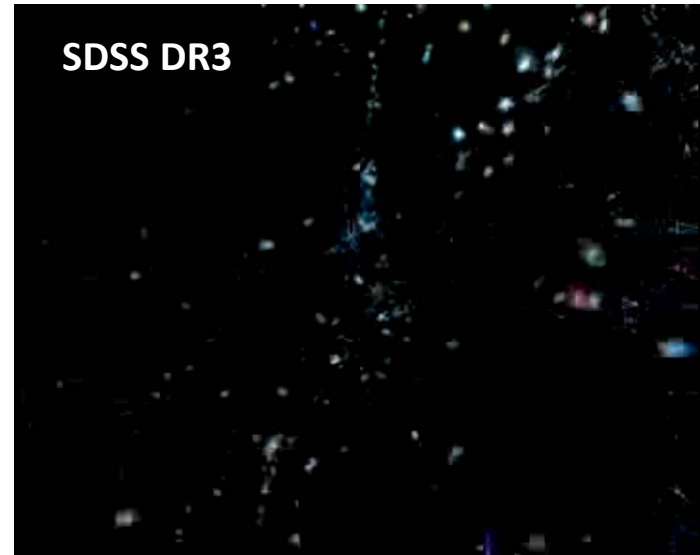
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Peebles (1980)

SDSS DR3

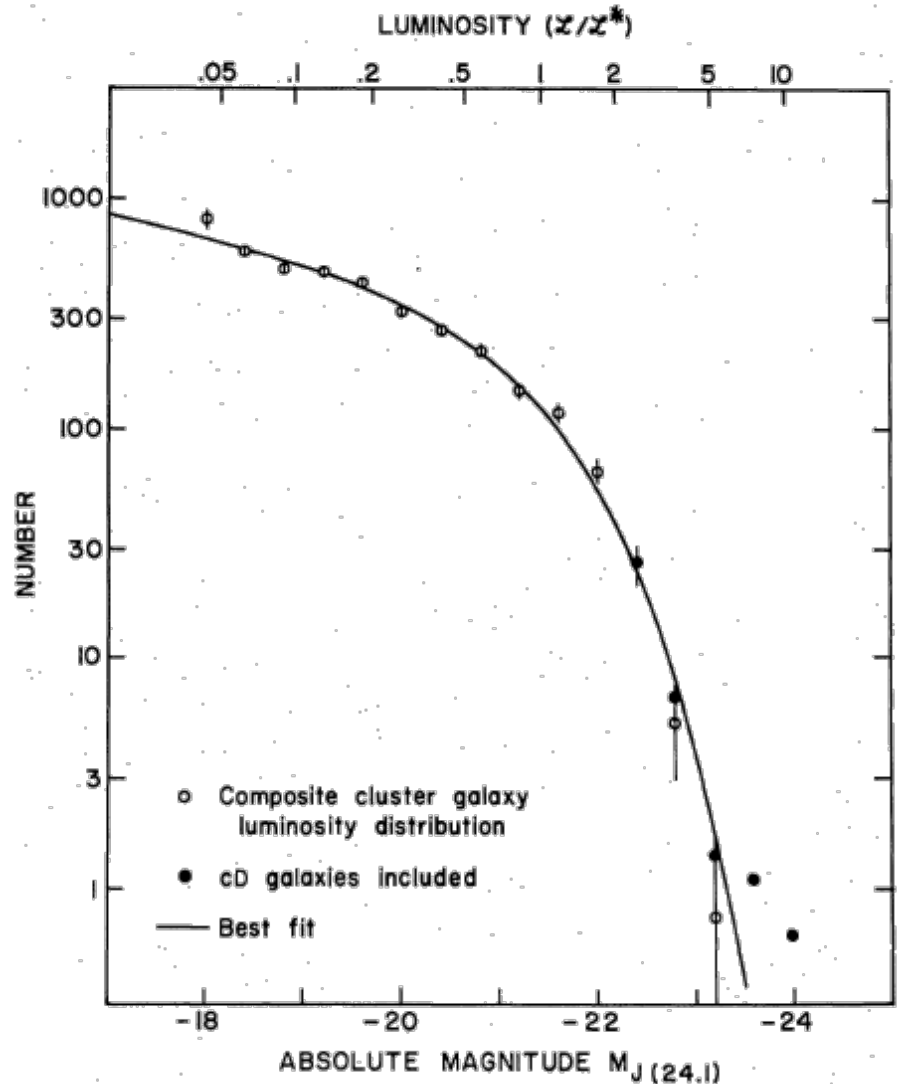


Galaxy Luminosity Function

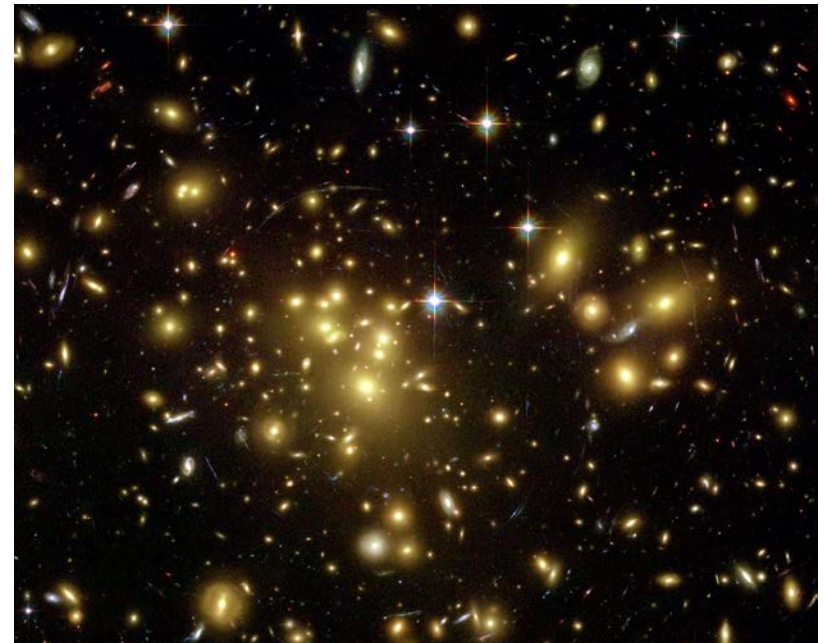
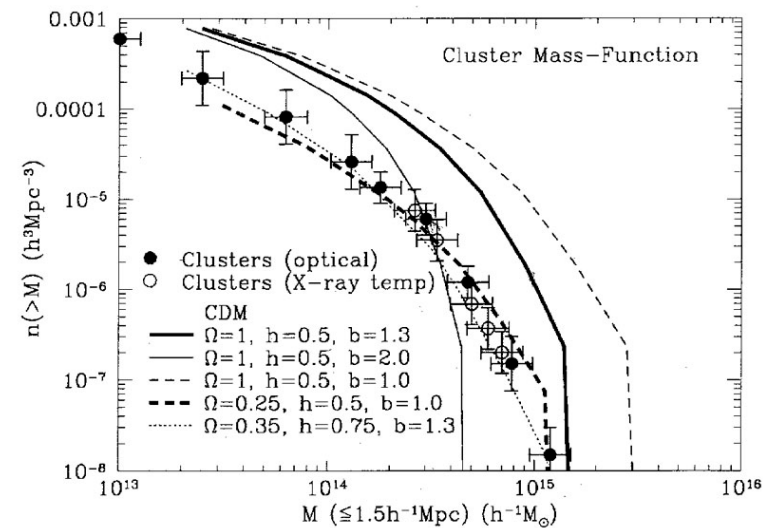
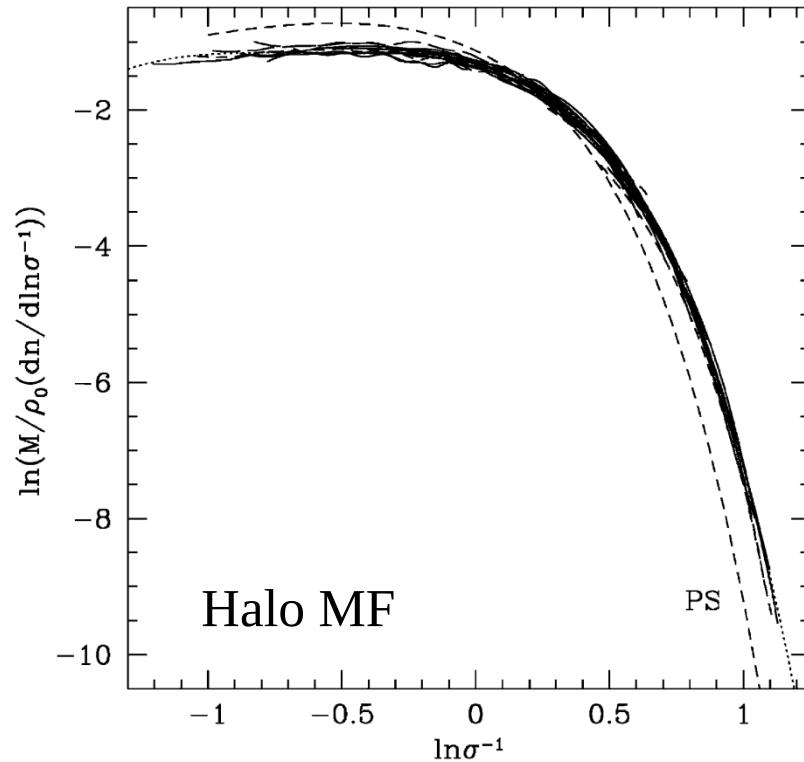
- Galaxy number density as a function of luminosity
- Schechter (1976):

$$\Phi(L)dL = \Phi^*(L/L^*)^\alpha e^{-L/L^*} d(L/L^*)$$

$$L^* \sim 2 \times 10^{10} L_{\text{sun}} \quad \alpha \sim -1 \sim -1.5$$
- Depends on the galaxy type, formation history, environment, etc.
- Evolves with time.



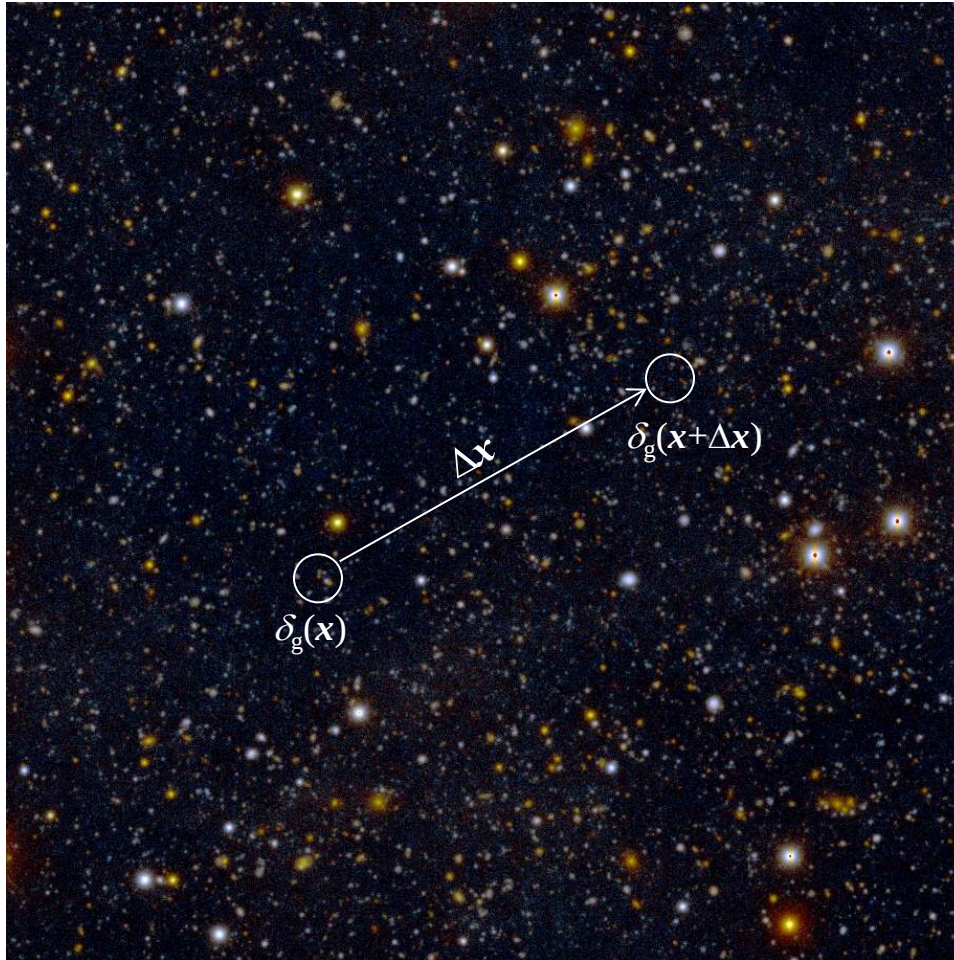
Halo/Cluster Mass Function



Halo/cluster mass function is sensitive to cosmological model and is an important dark energy probe.

Ref: Sheth & Tormen (1999)

Two-Point Correlation Function



Deep Lens Survey, Tyson & Wittman

Density fluctuation

$$\delta(\mathbf{x}) = n(\mathbf{x}) / \bar{n} - 1$$

Correlation Function

$$\xi(\Delta x) = \xi(\Delta \mathbf{x}) = \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \Delta \mathbf{x}) \rangle$$

Galaxy Correlation

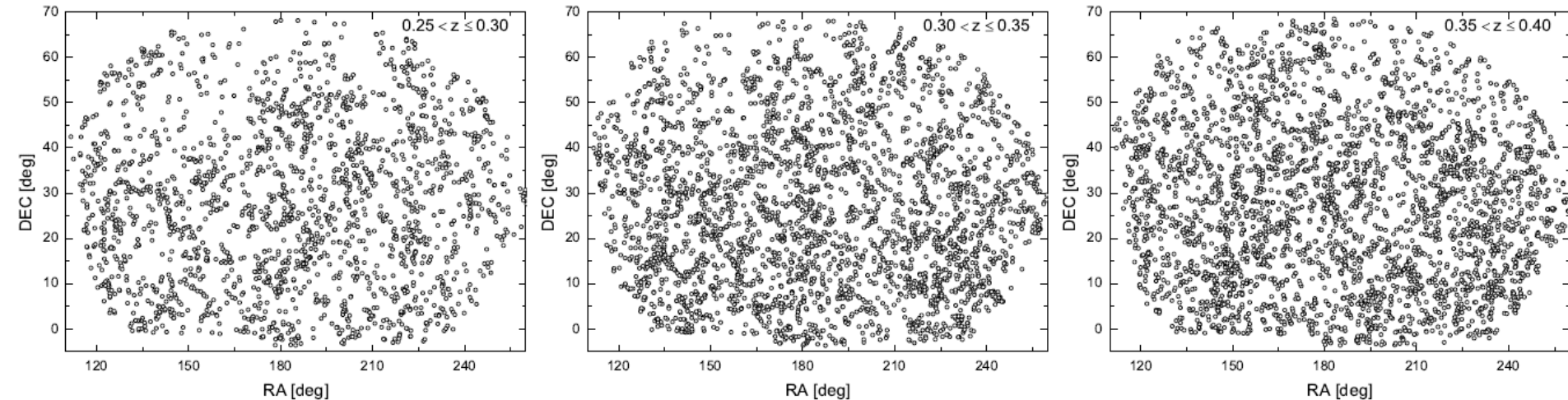
$$\begin{aligned} \xi_g(\Delta x) &= \langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x} + \Delta \mathbf{x}) \rangle \\ &\approx b^2 \xi(\Delta x) \quad \text{On large scales} \end{aligned}$$

- Isotropic
- Errors are correlated between different scales.
- Galaxy correlation is expected to be proportional to dark matter correlation on scales above tens of Mpc.

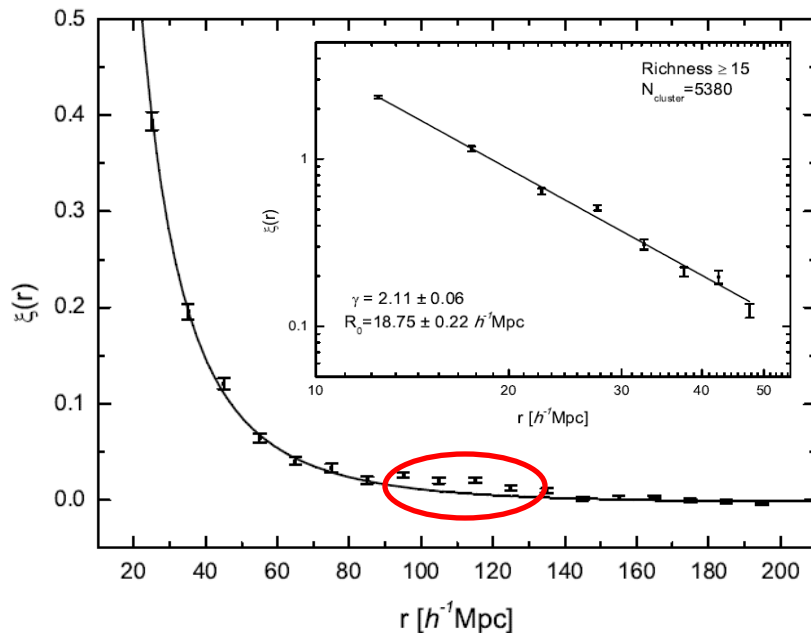
Suggested Exercise

1. **Implement practical algorithms for calculating the correlation functions (see, e.g., Kerscher et al. 2000, ApJL, 535, L13).**
2. **Generate a box of particles with uniform random coordinates, and calculate the correlation function of these particles.**
3. **How does the two-point correlation function change with the particle number density?**
4. **What is the variance of the correlation functions from an ensemble of simulations?**

Measurements of the CF



SDSS cluster correlations (Hong et al. 2012, ApJ, 749, 81)



- Power law on small scales:
 $\xi(r) = (r/r_0)^{-\gamma}$
- Exponent $\gamma \sim 2$
- Correlation scale depends on the type of object:
Galaxies: $r_0 \sim 5 h^{-1} \text{ Mpc}$
Clusters: $r_0 \sim 20 h^{-1} \text{ Mpc}$

Power Spectrum

Fourier Modes: $\delta(\mathbf{k}) = \int d^3\mathbf{x} e^{-i\mathbf{k}\mathbf{x}} \delta(\mathbf{x})$

$$\delta(\mathbf{x}) \in R \quad \therefore \delta(\mathbf{k}) = \delta^*(-\mathbf{k})$$

Definition: $\langle \delta(\mathbf{k}) \delta^*(\mathbf{k}') \rangle = (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') P(\mathbf{k})$ **Correlation b/w Fourier modes**

$$P(\mathbf{k}) = P(k)$$

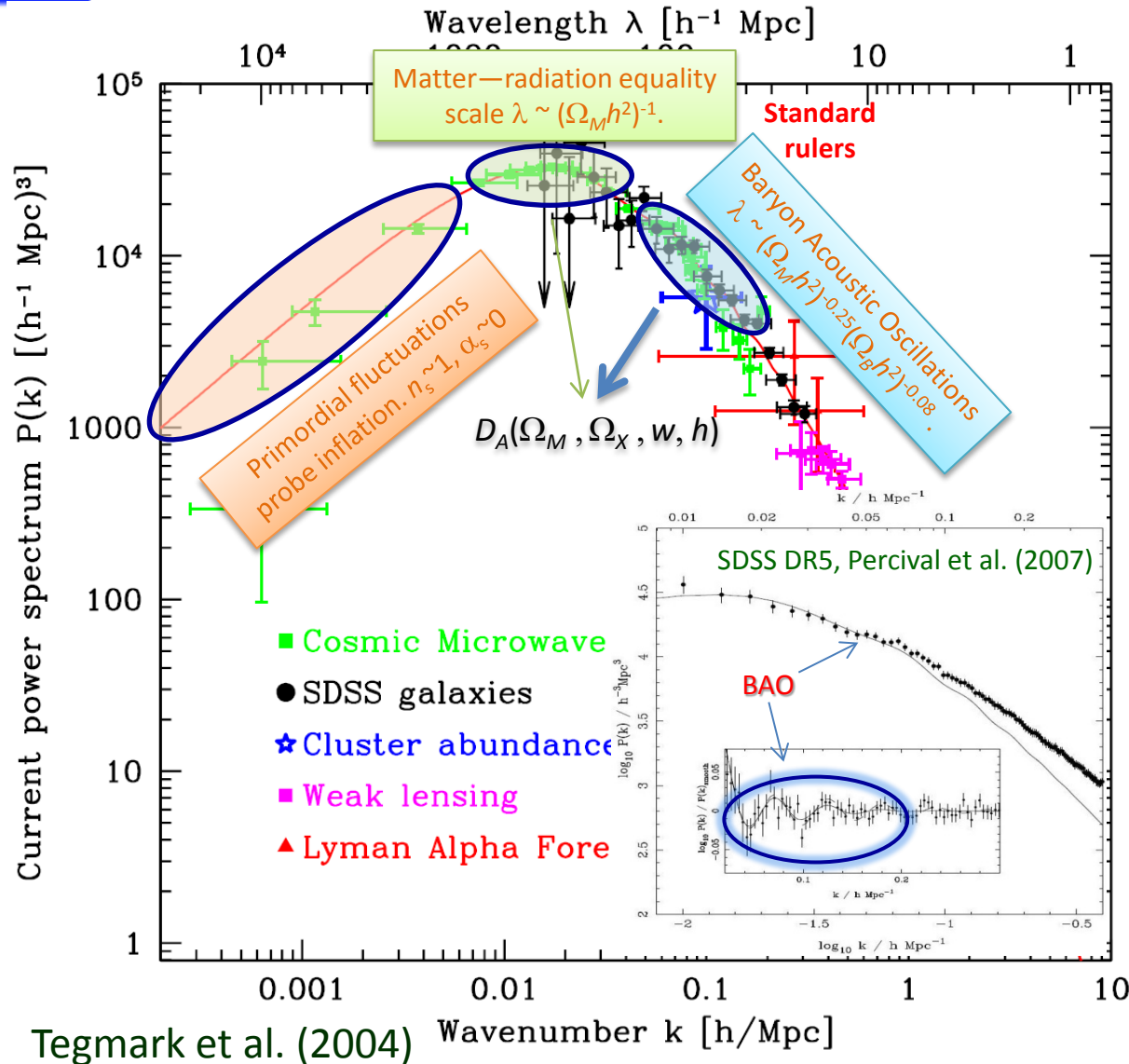
$$\begin{aligned} \langle \delta(\mathbf{k}) \delta^*(\mathbf{k}') \rangle &= \left\langle \int d^3\mathbf{x} e^{-i\mathbf{k}\mathbf{x}} \delta(\mathbf{x}) \int d^3\mathbf{x}' e^{-i\mathbf{k}'\mathbf{x}'} \delta(\mathbf{x}') \right\rangle \\ &= \int d^3\mathbf{x} d^3\mathbf{x}' \langle \delta(\mathbf{x}) \delta(\mathbf{x}') \rangle e^{-i\mathbf{k}\mathbf{x}} e^{-i\mathbf{k}'\mathbf{x}'} \\ &= \int d^3\Delta\mathbf{x} \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \Delta\mathbf{x}) \rangle e^{-i\mathbf{k}'\Delta\mathbf{x}} \int d^3\mathbf{x} e^{-i(\mathbf{k} - \mathbf{k}')\mathbf{x}} \\ &= \int d^3\Delta\mathbf{x} \xi(\Delta\mathbf{x}) e^{-i\mathbf{k}'\Delta\mathbf{x}} \int d^3\mathbf{x} e^{-i(\mathbf{k} - \mathbf{k}')\mathbf{x}} \\ &= (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') \int d^3\Delta\mathbf{x} \xi(\Delta\mathbf{x}) e^{-i\mathbf{k}'\Delta\mathbf{x}} \\ &= (2\pi)^3 \delta^D(\mathbf{k} - \mathbf{k}') 4\pi \int d\Delta x \frac{\Delta x \xi(\Delta x) \sin(k' \Delta x)}{k'} \end{aligned}$$

Suggested exercise



$$P(k) = 4\pi \int dr r^2 j_0(kr) \xi(r), \quad \xi(r) = \frac{1}{4\pi^2} \int dk k^2 j_0(kr) P(k)$$

Matter Power Spectrum



A Gaussian random field is completely described by the CF or PS.

Modes can grow outside the horizon or in the matter era. Small scale modes entered the horizon in the radiation era, so their amplitudes are lower than those of large-scale modes.

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1. Introduction
2. Topics:
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 - Baryon Acoustic Oscillations
3. Future Surveys

Accelerated Cosmic Expansion

2011 Nobel Prize in Physics

"for the discovery of the **accelerating expansion of the Universe** through observations of distant supernovae"

"Standardizable Candle"



Photo: U. Montan

Saul Perlmutter



Photo: U. Montan

Brian P. Schmidt



Photo: U. Montan

Adam G. Riess



Image courtesy of David A. Hardy, © David A. Hardy/www



Type Ia supernova
luminosity distances

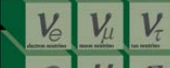
Physics beyond Standard Model

“... nothing short of a **revolution in** our understanding of **fundamental physics** will be required to achieve a full understanding of the cosmic acceleration.” – the Dark Energy Task Force, a joint committee to advise DoE, NASA, & NSF on future dark energy research.

ALL MATTER AND ENERGY

Stardust
Stars
Gas

All Other Visible Atoms
0.01%
Hydrogen and Helium
0.5%

ELEMENTARY PARTICLES						
Leptons	Quarks					
						
						
						
		I			Force Carriers	
		II				
		III				
		Three Generations of Matter				

Invisible Atoms
4%

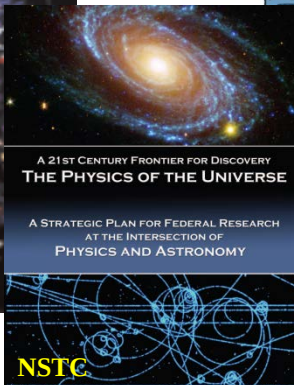
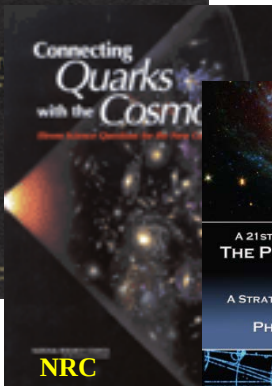
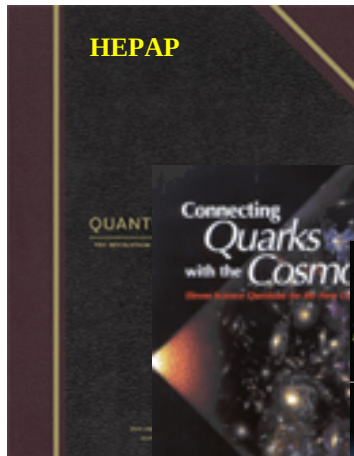
Cold Dark Matter
25%

Dark Energy
70%

WIMP? (SUSY: neutralino? gravitino?)
Axion?

Anthropic principle?
Back reaction?
Brane world?
Landscape?
Modified Gravity?
Quintessence?

NEW ORDER OF THE UNIVERSE



Accel. Expansion: Dark Energy

$$H^2(z) = H_0^2 \left\{ \underbrace{\Omega_M (1+z)^3}_{\text{matter}} + \underbrace{\Omega_K (1+z)^2}_{\text{curvature}} + \underbrace{\Omega_X \exp \left[3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right]}_{\text{dark energy}} \right\}$$

$$D_{\text{com}}(z) = \int_0^z \frac{c}{H(z)} dz$$

Comoving Distance

Hubble Parameter/
Friedmann Equation

$$H = \dot{a} / a$$

$$\ddot{\delta}_M + 2H\dot{\delta}_M = 4\pi G\rho_M\delta_M$$

Growth of structure

$$w = p_X / \rho_X$$

effect of
Dark Energy

$$\Omega_M + \Omega_K + \Omega_X = 1, \quad \rho_c = 3H_0^2 / 8\pi G$$

$$\Omega_M = \rho_M / \rho_c, \quad \Omega_K = -3kc^2 / 8\pi G\rho_c, \quad \Omega_X = \rho_X / \rho_c,$$

Dark energy is not directly observable; we have to infer its properties from its influence on the expansion and growth history of the universe.

Accel. Expansion: Modified Gravity

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_K (1+z)^2 \right] + \text{Contrib. of M.G.}$$

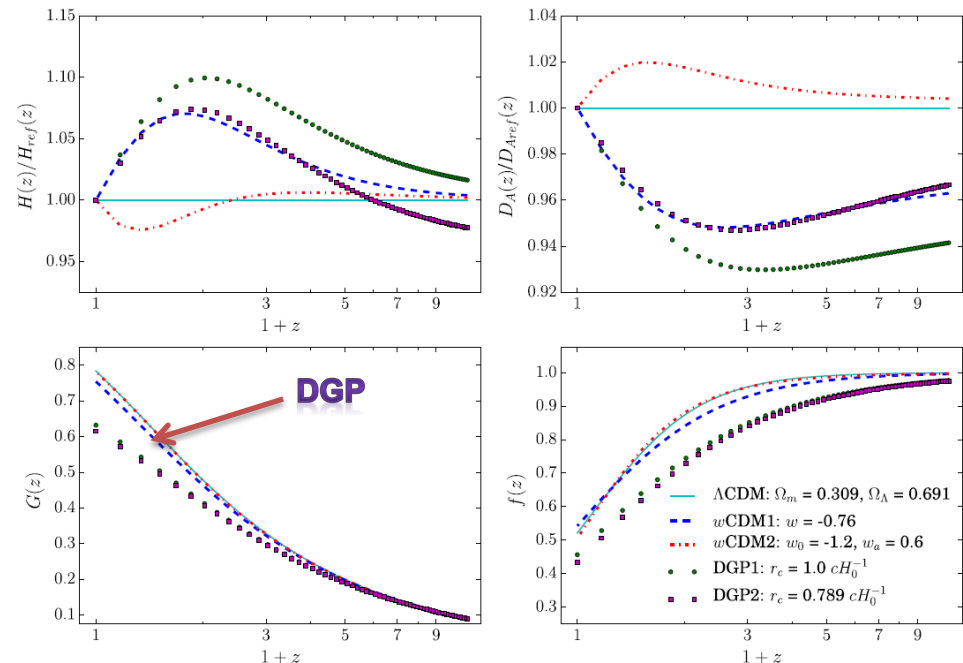
$$D_{\text{com}}(z) = \int_0^z \frac{c}{H(z)} dz$$

$$\ddot{\delta}_M + 2H\dot{\delta}_M = 4\pi G\rho_M\delta_M$$

Dark Energy **Modified Gravity**

If $H(z)$ is fixed by distance measurements, then dark energy and modified gravity will lead to different growth rates, hopefully.

DGP: 5-D braneworld (Dvali, Gabadadze, & Porrati 2000)



Zhan & Tyson (2018)
1707.06948

Accel. Expansion: More

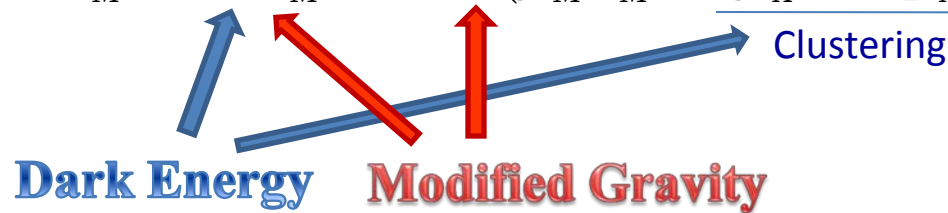
$$H^2(z) = H_0^2 \left\{ \Omega_M (1+z)^3 + \Omega_K (1+z)^2 + \Omega_X \exp \left[3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right] \right\}$$

$$D_{\text{com}}(z) = \int_0^z \frac{c}{H(z)} dz$$

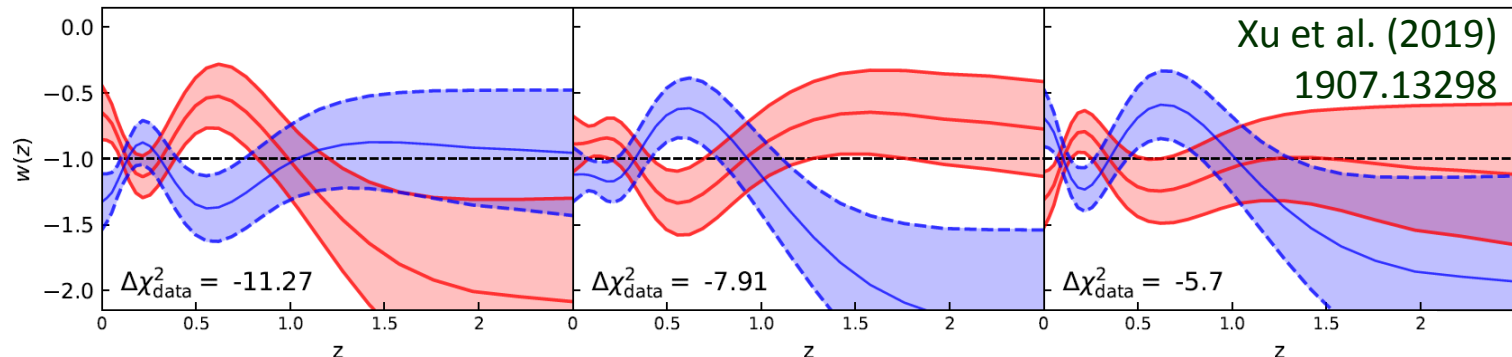
$$ds^2 = -(1+2\Psi)dt^2 + (1+2\Phi)a^2\delta_{ij}dx^i dx^j$$

$$\ddot{\delta}_M + 2H\dot{\delta}_M = 4\pi G(\rho_M \delta_M + \delta\rho_X + 3\delta p_X)$$

The two metric perturbations might not be equivalent.



It will be harder to distinguish dark energy from modified gravity, if more degrees of freedom are allowed.



Dark Energy Probes

- Type Ia supernovae: luminosity distance
- Weak gravitational lensing: angular diameter distance, growth of structure, matter power spectrum
- Baryon acoustic oscillations: angular diameter distance, Hubble parameter, structure growth rate
- Cluster counting: volume/distance, growth of structure
- Strong lensing: Hubble constant, time-delay distance
- CMB: angular diameter distance, integrated Sachs-Wolfe effect

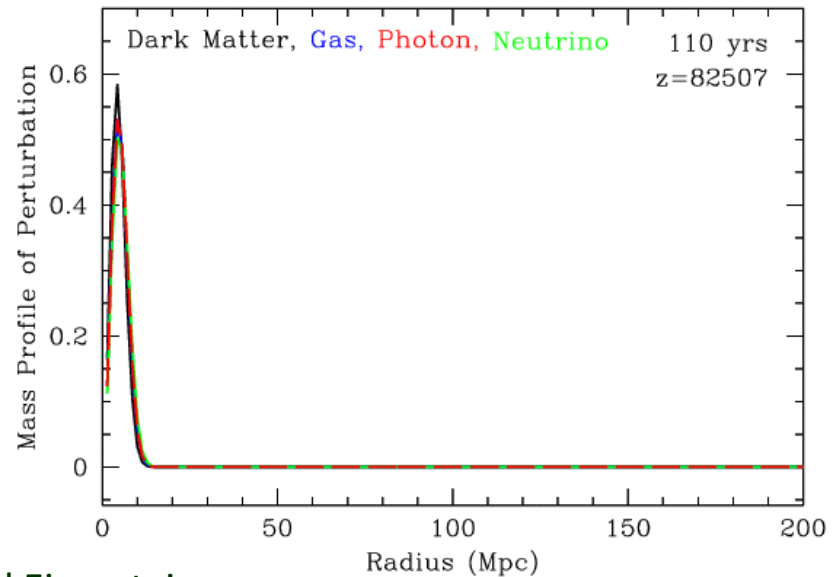
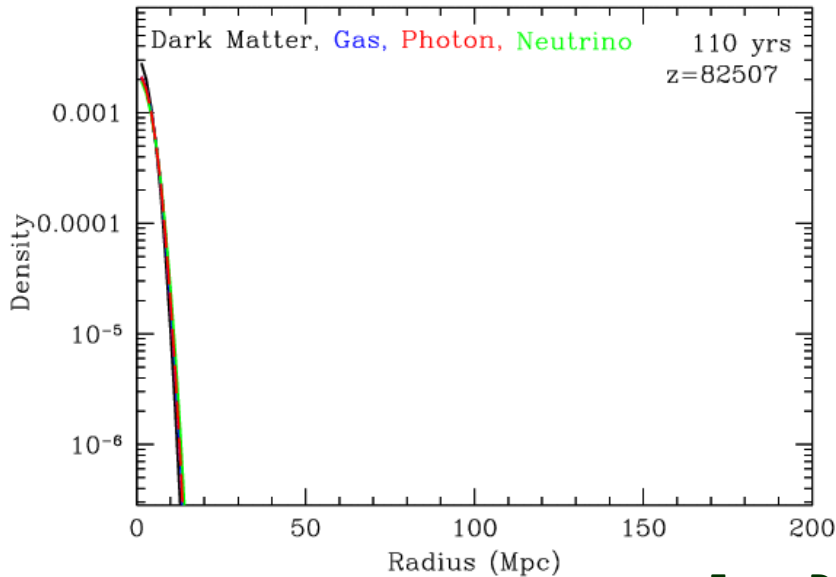
Expansion (D_A , D_L , H), growth, & power spectrum →
Dark energy, dark matter, gravity, neutrino mass,
cosmological parameters...

Large surveys!

Outline

1. Introduction
2. Topics:
 - Dark Energy
 - Baryon Acoustic Oscillations
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Perturbations around Recombination



From Daniel Eisenstein

Curvature perturbations →

Pressure imbalance in photon—baryon fluid →

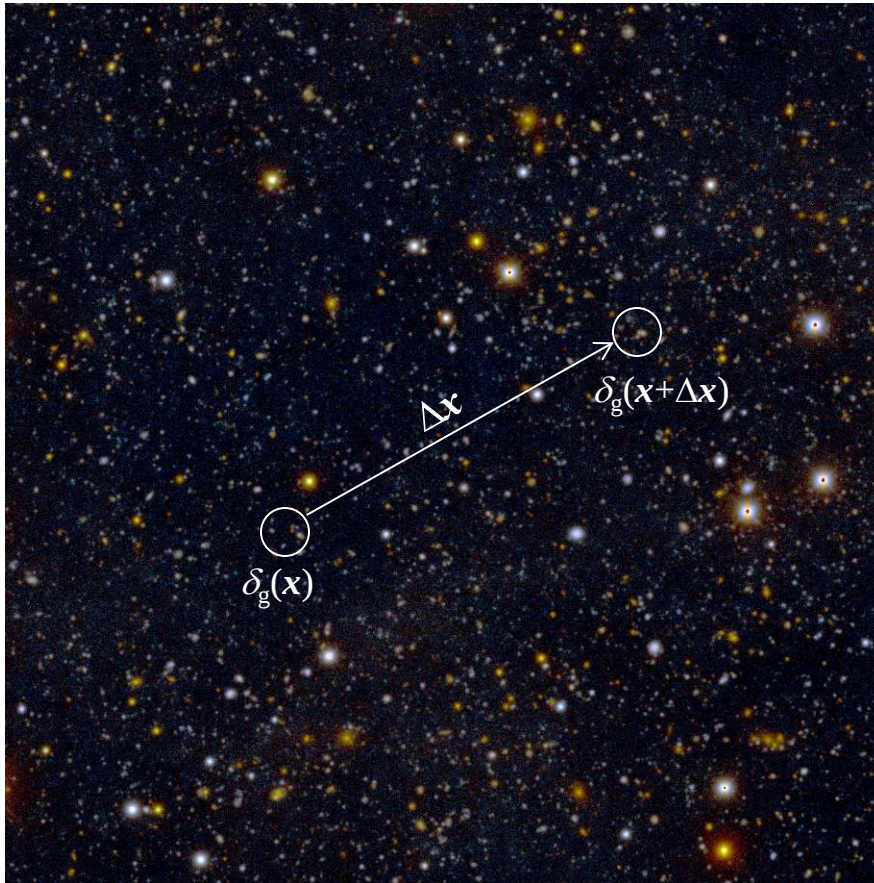
Sound waves (baryon acoustic oscillations) travel at $\sim c/\sqrt{3}$ before recombination and ~ 0 afterward →

Comoving sound horizon ($R_s \sim 150$ Mpc) freezes →

Excess correlation of density fluctuations at 150 Mpc →

Excess correlation of galaxies at 150 Mpc.

BAO Detection

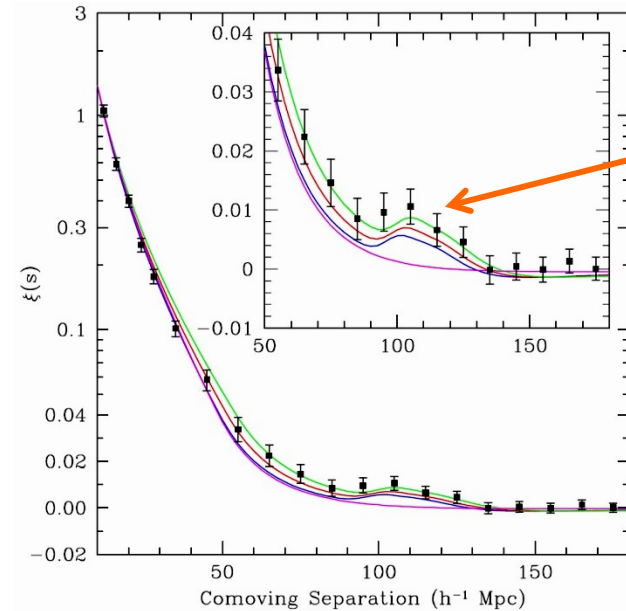


Deep Lens Survey, Tyson & Wittman

$$\delta_g(\mathbf{x}) = n_g(\mathbf{x}) / \bar{n}_g - 1$$

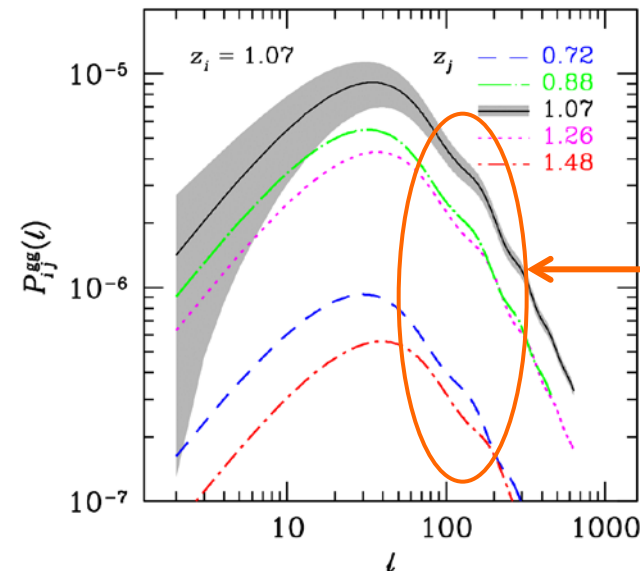
$$\xi(\Delta\mathbf{x}) = \xi(\Delta\mathbf{x}) = \langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x} + \Delta\mathbf{x}) \rangle \quad \text{Correlation Function}$$

$$P(k) = \text{FT } \xi(\Delta\mathbf{x}) \quad \text{Power Spectrum}$$



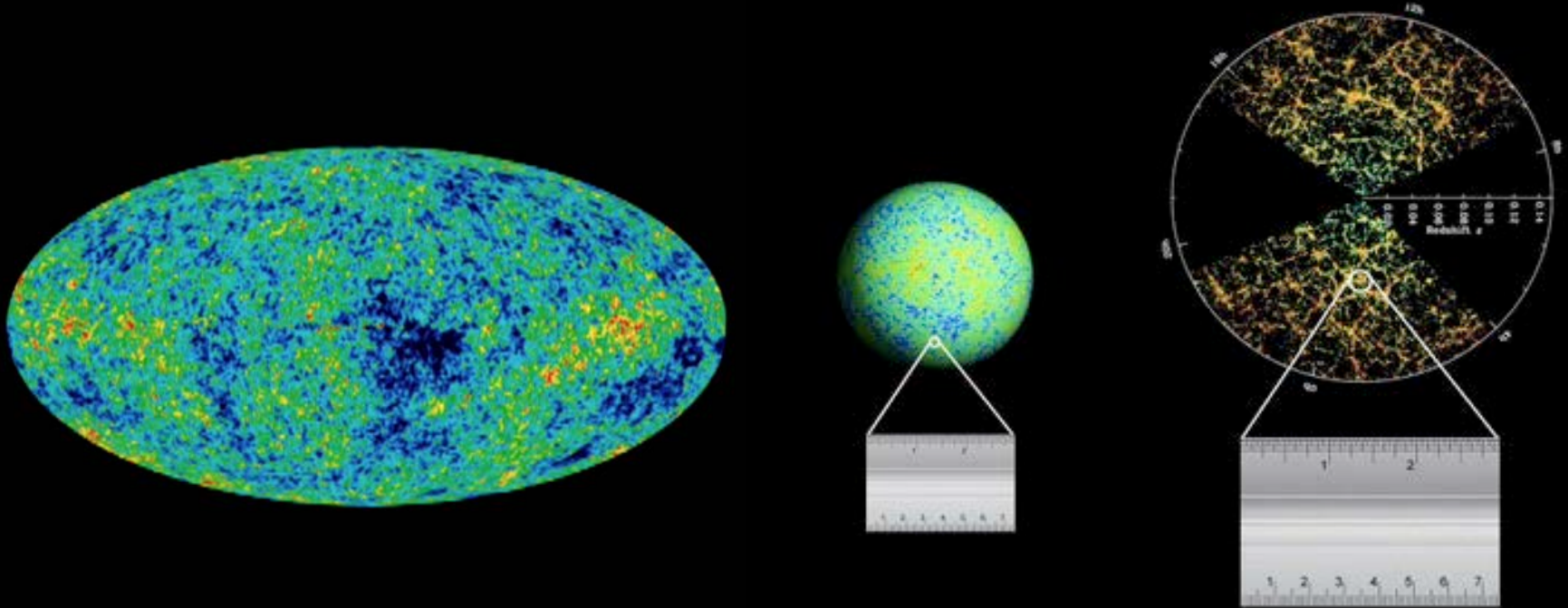
Baryon
Acoustic
Oscillations

SDSS LRGs
Eisenstein
et al (2005)



Baryon
Acoustic
Oscillations
in multipole
space

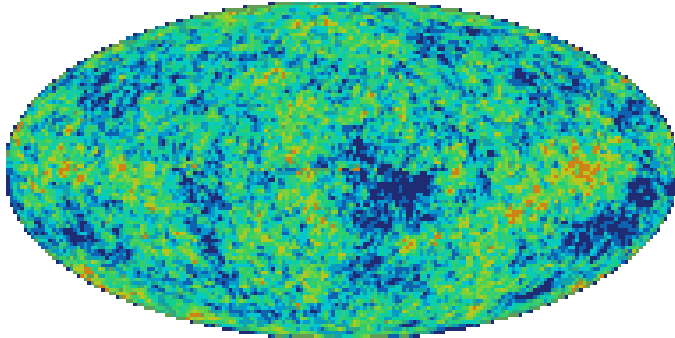
BAO: A Cosmological Probe



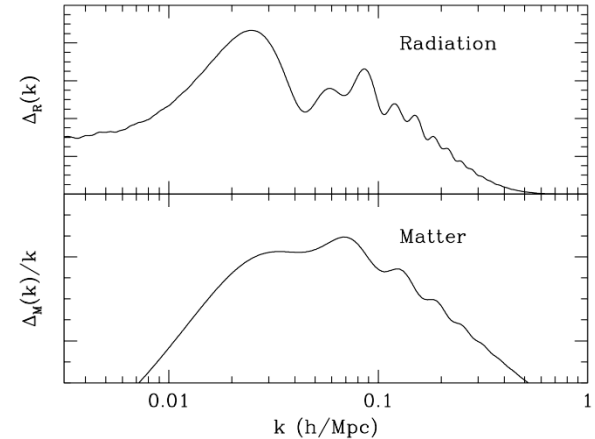
WMAP media @ map.gsfc.nasa.gov

Baryon Acoustic Oscillations (BAO) can be used a standard ruler to measure angular diameter distance (& Hubble parameter) and study cosmology.

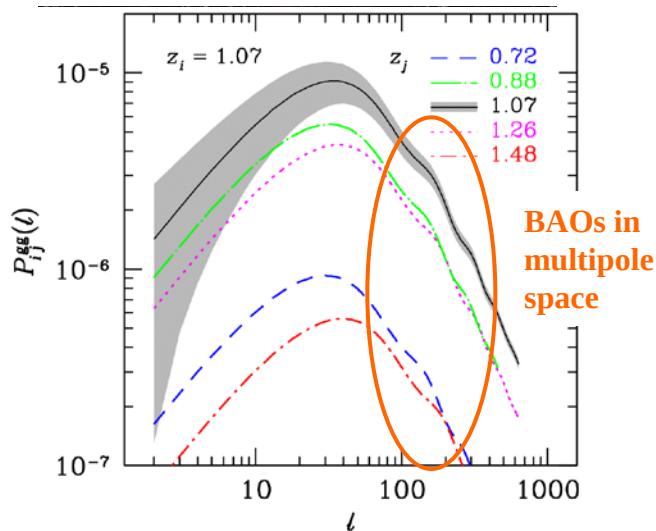
BAO: A Cosmological Probe



CMB temp. fluctuations (WMAP)



Imprints on the matter power spectrum (White 2005)



LSST galaxy angular PS
Zhan (2006)

$R_S \sim 150$ Mpc

(Sound horizon at recombination)

Angular diameter distance

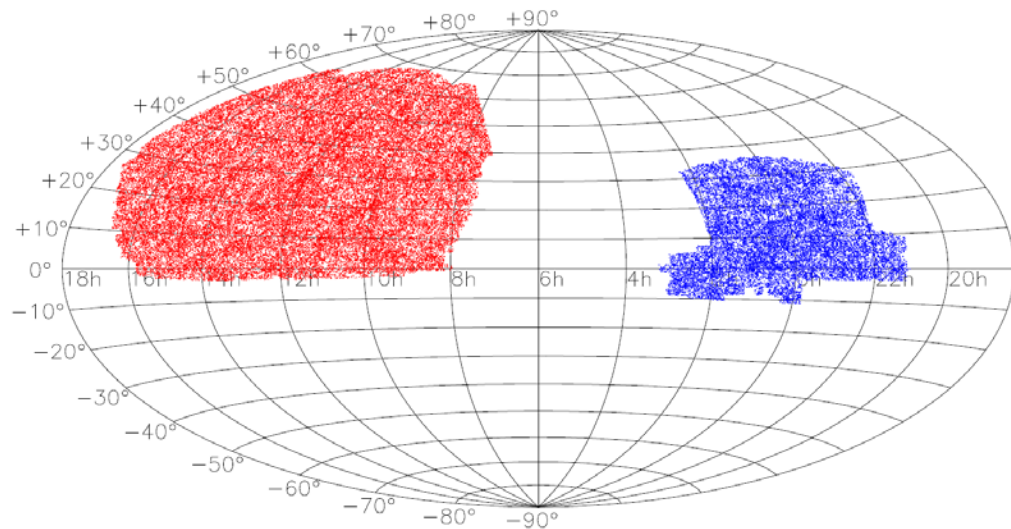
$$R_S = \Delta\theta D_A$$

$$= c\Delta z/H$$

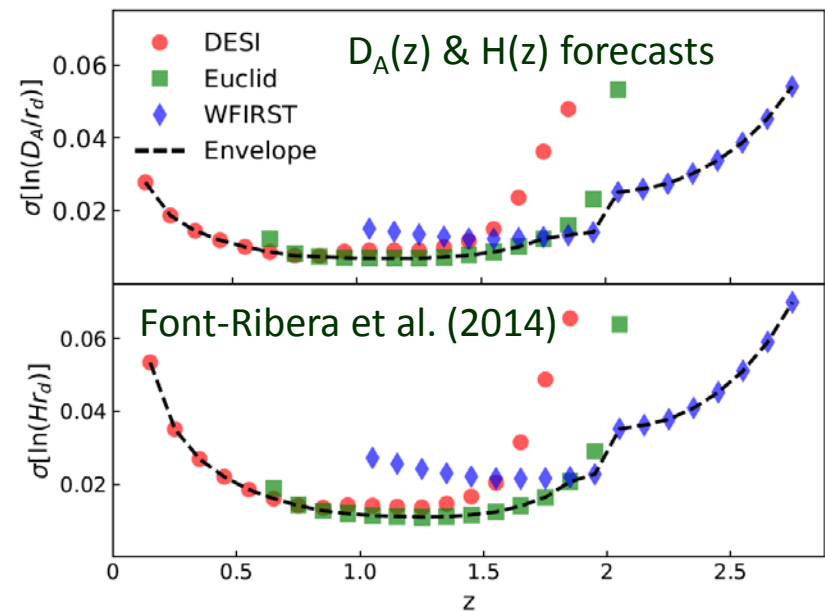
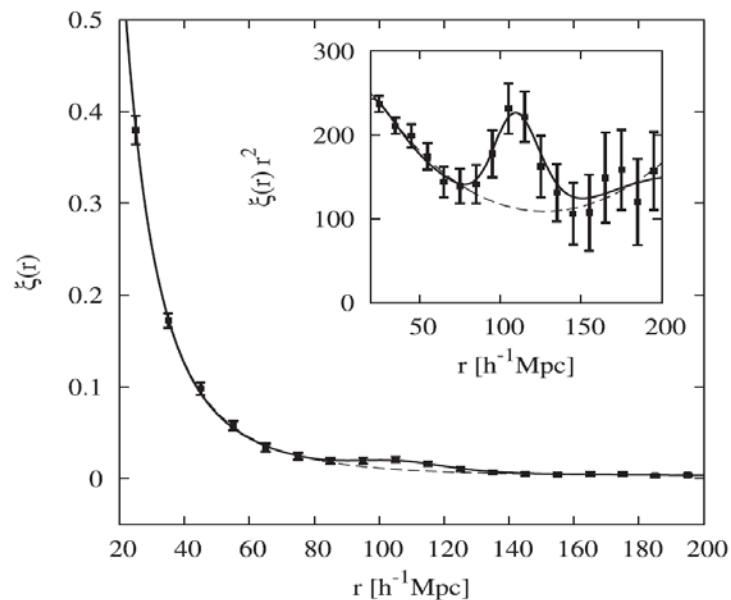
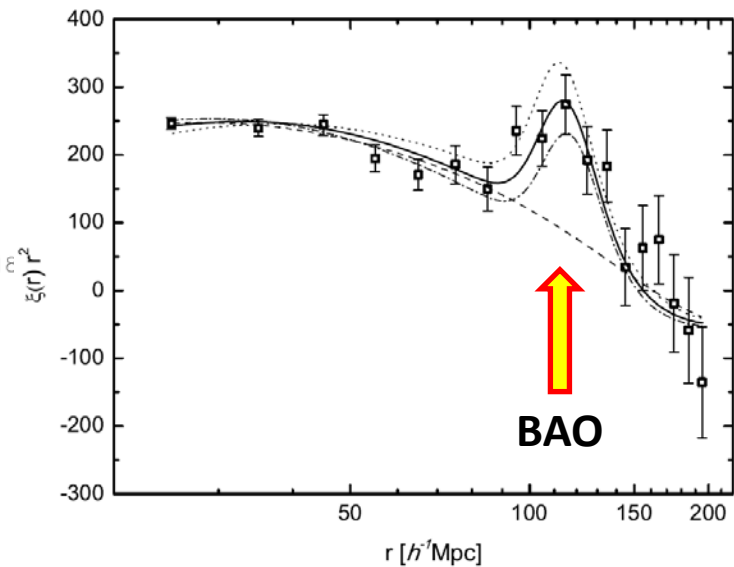
Redshift distortion →

Growth rate → Test gravity

BAO Measurements



Hong et al. (2012, 2016)



Outline

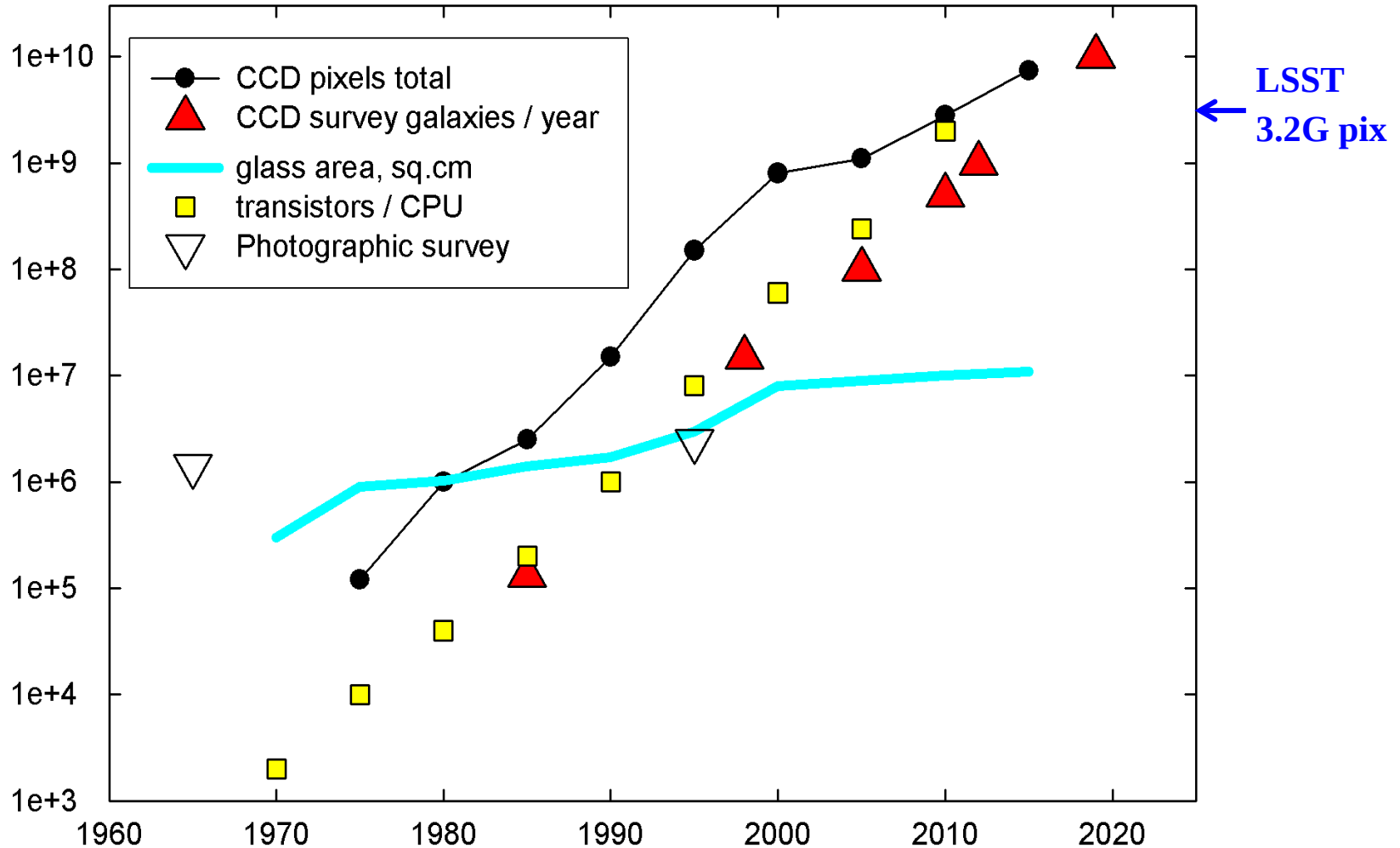
1. Introduction

2. Topics:

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- Baryon Acoustic Oscillations

3. Future Surveys

Trends in Optical Astronomy



Survey projects open up enormous discovery space for astronomy!

Optical/IR Survey Landscape

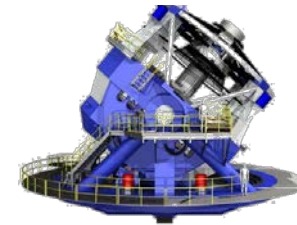
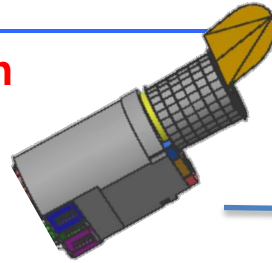


Subaru, 8.2m
1400 $\square^\circ$ imaging



HETDEX, 9.2m
420 $\square^\circ$ spect

Space Station
17.5k sq deg
img & spec



LSST, 8.4m
18000 $\square^\circ$ imaging

Opportunity for a high-resolution
multiband NUV-optical survey.



Dark Energy
5000 $\square^\circ$

id, 1.2m
0 $\square^\circ$ imaging &
t



1.8m
30000 $\square^\circ$ imaging



4MOST, 4m
15000 $\square^\circ$ spect

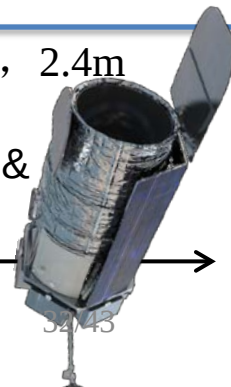


2.5m
10000 $\square^\circ$ spect



DESI, 4m
14000 $\square^\circ$ spect

WFIRST, 2.4m
2000 $\square^\circ$ imaging &
spect



2013

2014

2015

2016

2017

2018

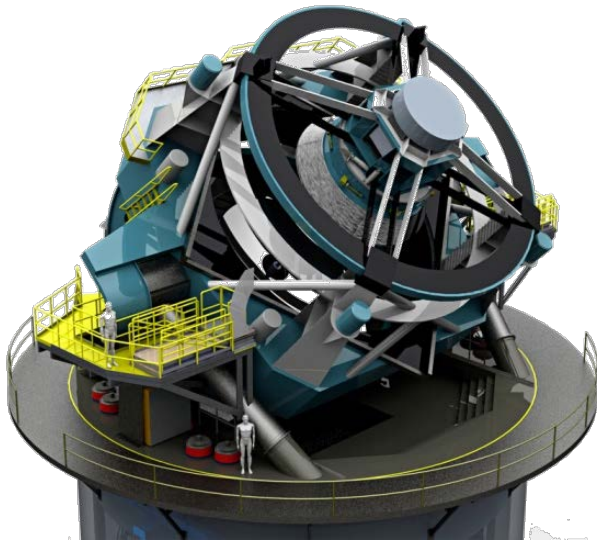
2019

2020

2021

2022

Large Synoptic Survey Telescope



- 8.4-meter primary
- 9.6 deg² FOV
- 3.2 billion pixels
- 0.3–1.1 μm *ugrizy*
- 15-s exposures
- 18,000 deg²
- **500 PB/10 years**

- *u* 25.8 mag (56 exp.)
- *g* 27.0 mag (80 exp.)
- *r* 27.2 mag (180 exp.)
- *i* 27.0 mag (180 exp.)
- *z* 25.7 mag (164 exp.)
- *y* 24.4 mag (164 exp.)

www.lsst.org

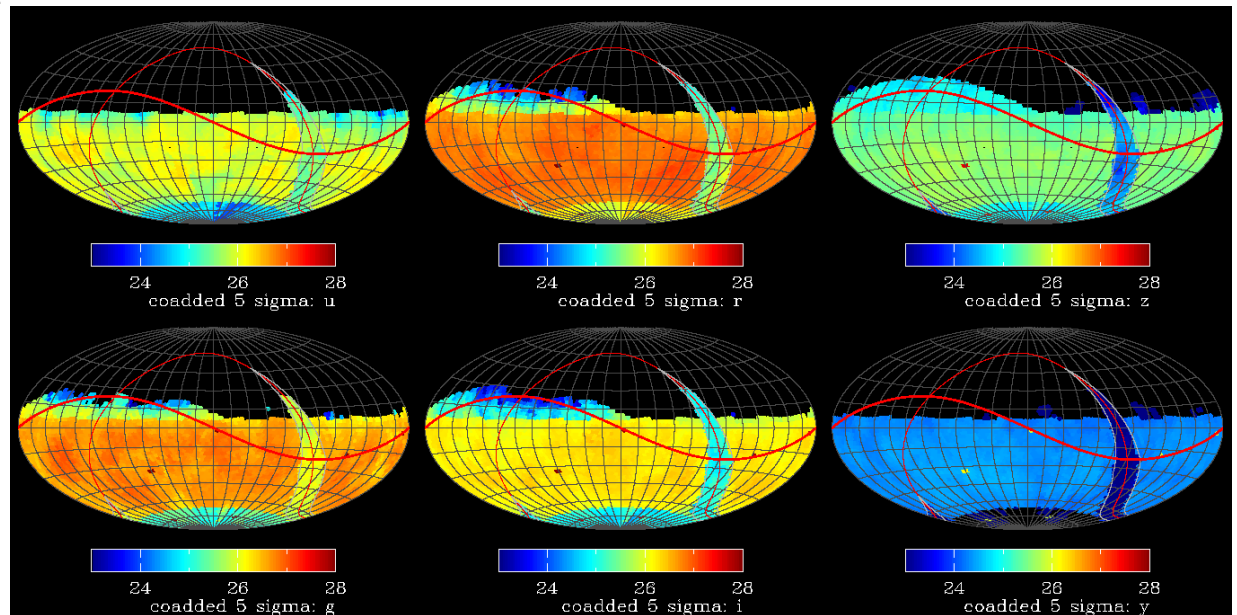
Science Drivers

Dark Energy

Transients

Solar System

Galactic Map



LSST Site: Cerro Pachón, Chile

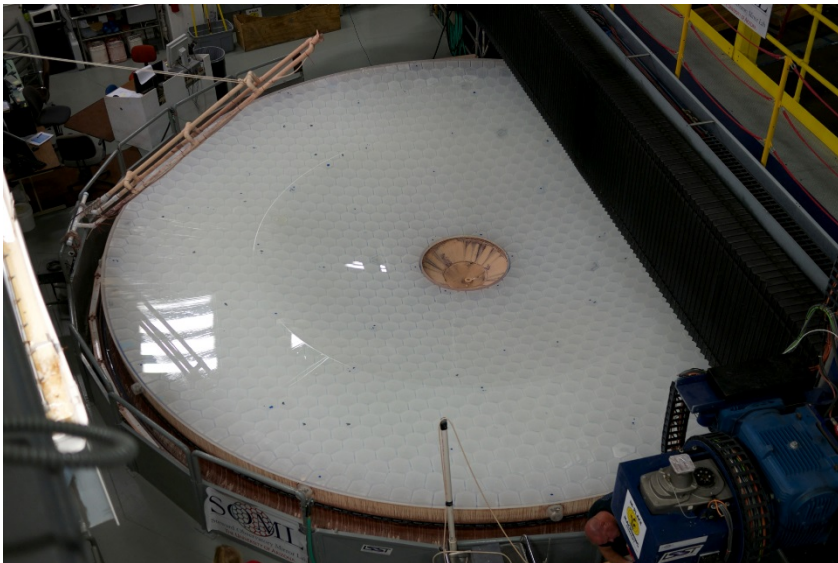
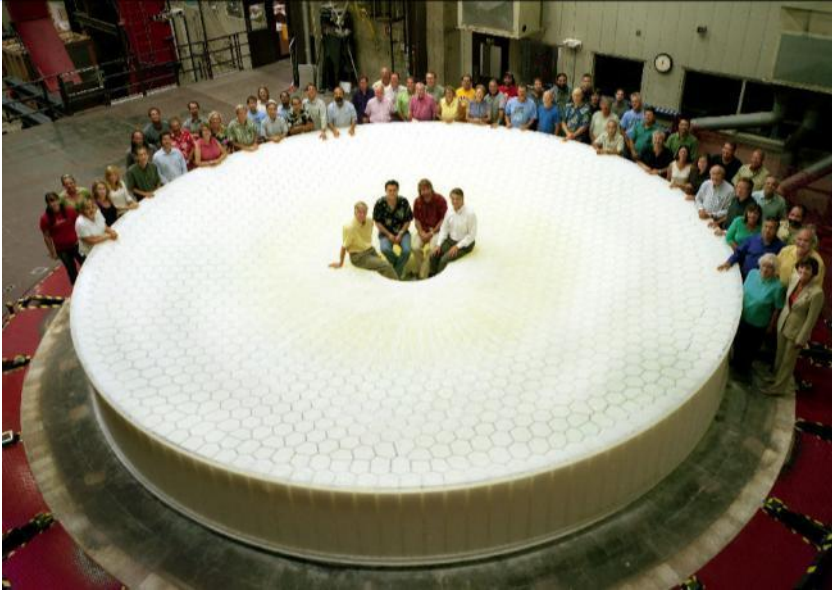
30m dome

1.2 m diameter
atmospheric telescope

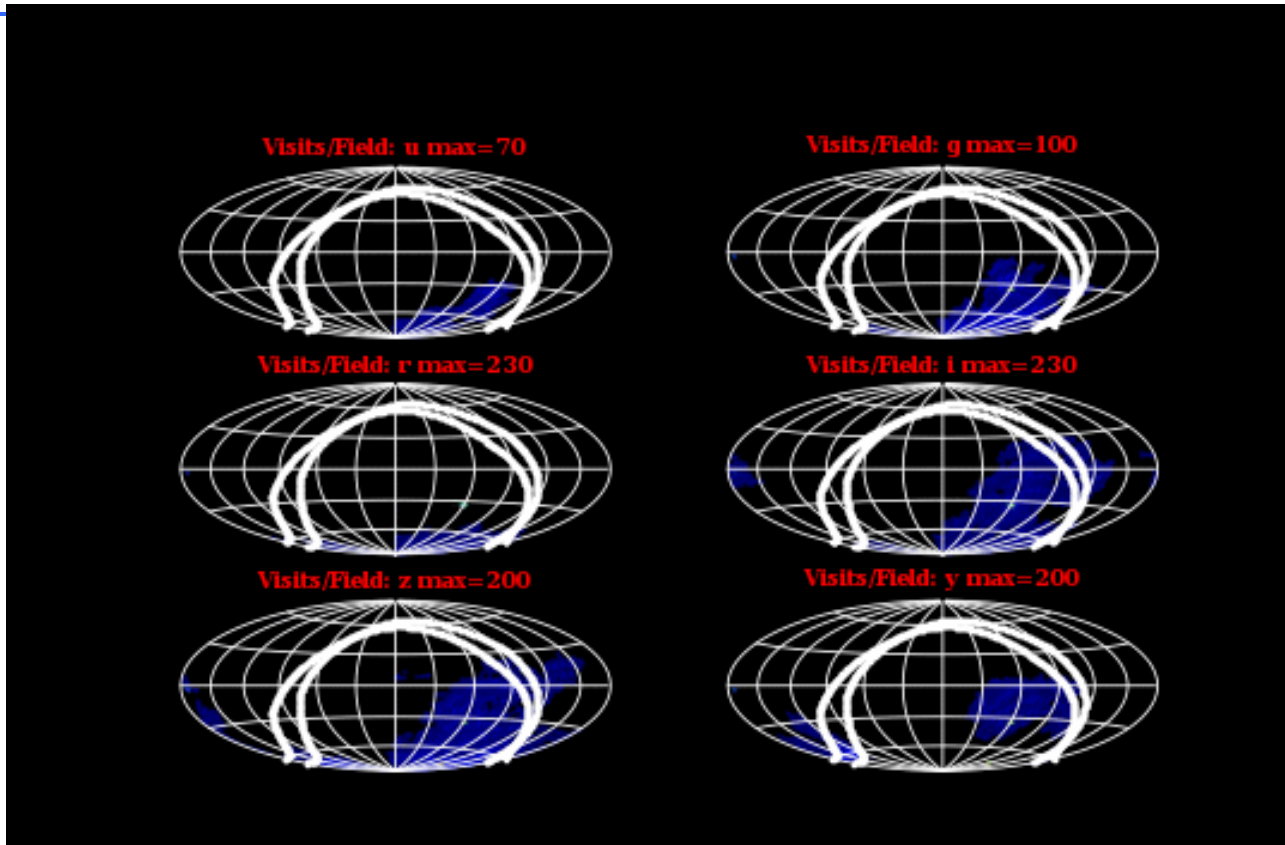
1,380 m² facility



LSST Mirrors & Telescope Structure



LSST Operations Simulations



Each field will be observed 800+ times.

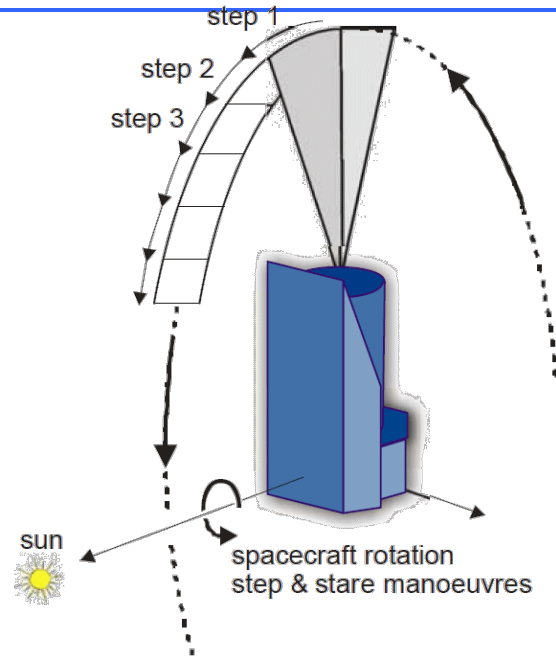
Roughly **20B galaxies, 17B stars, 7 trillion observations & 30 trillion measurements**

Flux, position, shape...

Euclid

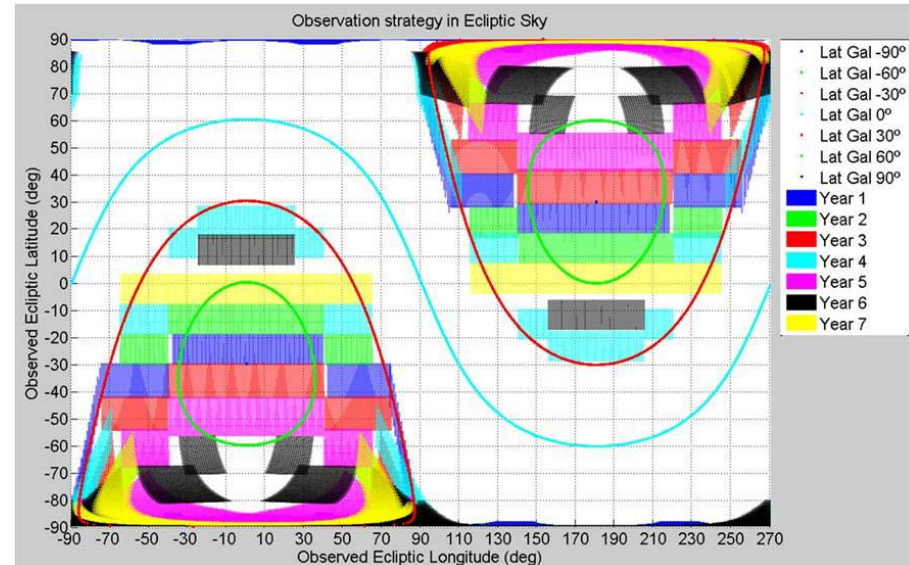


- Aperture: 1.2m
- Optical Band:
550—900nm
0.56 sq deg FoV
600M pixels
- NIR:
920—2000nm
0.55 sq deg FoV
67M pixels
- 15,000 sq deg sky



optical: 24.5 mag (10σ extended src)
Y、J、H: 24 mag (5σ point src)
1.1—2 μ m: grism R=250

Science drivers: **dark energy**, dark matter, gravity theory, high-z objects, galaxy evolution, near-field cosmology, & exoplanets.



Astrophysics Timeline

Decadal Survey Mission
 MIDEX/MO (AO NET 2016)
 Euclid (ESA)
 SMEX/MO (AO 2014)
 JWST (ESA, CSA)
 TESS
 NICER
 ISS-CREAM (South Korea)
 ASTRO-H (JAXA)
 ST-7/LPF (ESA)
 SOFIA (DLR)
 NuSTAR (ASI, Denmark)
 Kepler
 Fermi (DOE, Intl team)
 Suzaku (JAXA)
 Swift (ASI, UK)
 Spitzer
 XMM-Newton (ESA)
 Chandra (SRON)
 Hubble (ESA)

Early Science

Prime Mission

Extended Mission

WFIRST beyond 2025

TIMELINE CY

2000 2003 2006 2009 2012 2015 2018 2021 2024

Optical Module for Astronomy

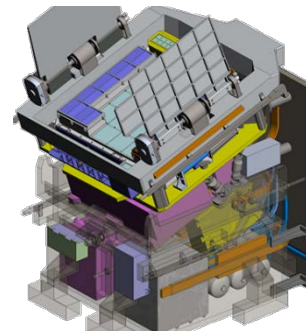
A 2m space telescope in the same orbit as the China Manned Space Station, serviceable while docking with the station.

Instruments: Survey Camera (SC), Terahertz Receiver (THz), Multichannel Imager (MCI), Integral Field Spectrograph (IFS), Cool-Planet Imaging Coronagraph (CPIC).

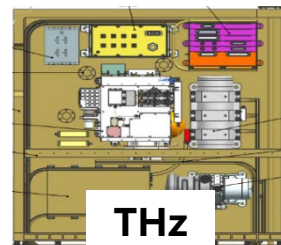
Mission: wide-area multiband imaging & slitless spectroscopic survey (7yr); other key programs & GO programs (2+yr).



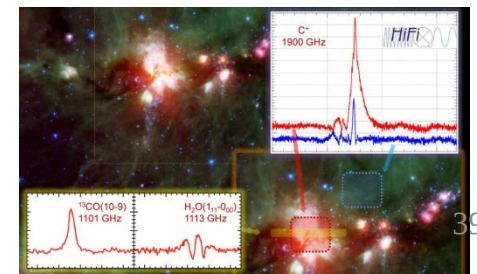
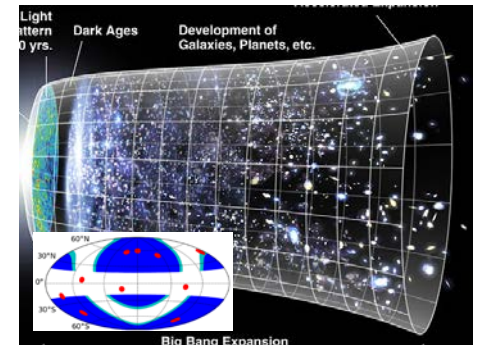
Optical Module (~2024)



Survey Cam



THz



Optical Module for Astronomy

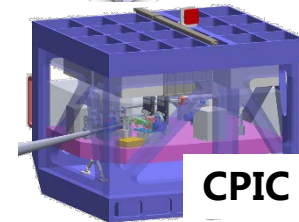
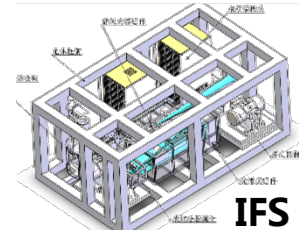
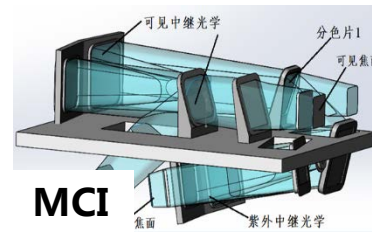
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Mission: wide-area multiband imaging & slitless spectroscopic survey (7yr); other key programs & GO programs (2+yr).

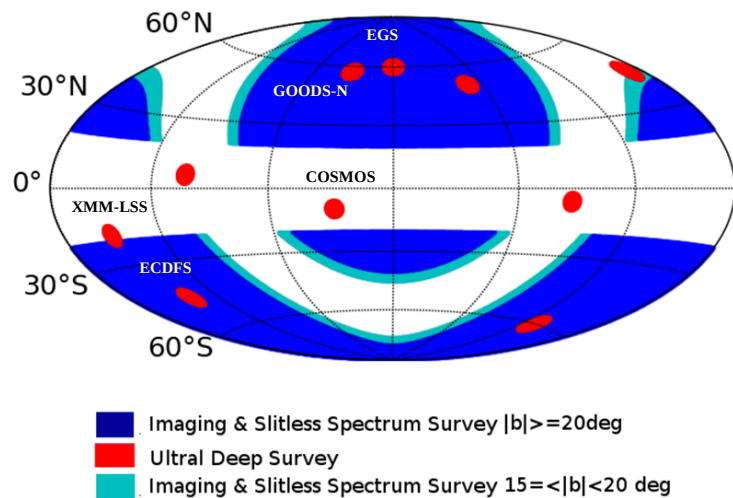


Optical Module (~2024)



Survey Specs

- **17500 $\square^\circ$ imaging** : 255-1000nm, ≥ 6 filters, avg $\geq 25.5^m$ (5σ , point source, AB mag);
- **17500 $\square^\circ$ slitless spect**: 255-1000nm, $R \geq 200$, $\geq 22-23^m$;
- **400 $\square^\circ$ deep imaging & spect**: at least 1^m deeper.



Ecliptic Coord.

Deep fields will be finalized later; sim results for demo only.

Science

Cosmology: dark energy, dark matter, gravity, large-scale structure, neutrinos, primordial non-Gaussianity...

AGNs: high- z AGNs, clustering, dual AGNs, variability, UV excess, host galaxies...

Galaxies: formation & evolution, mergers, high- z s, dwarfs, LSBs, near field, halos properties...

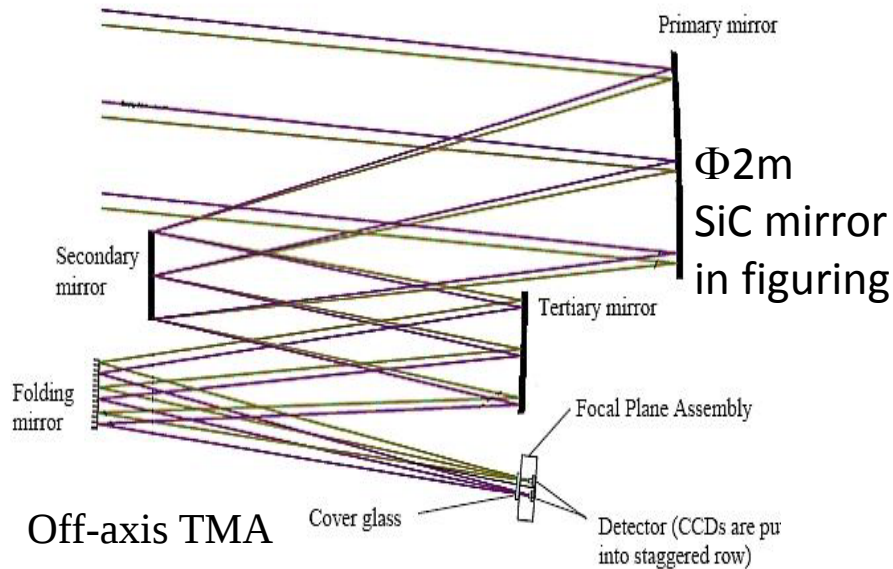
Milky Way: structure, satellites, dust, extinction...

Stellar science: formation, dwarfs, metal poor...

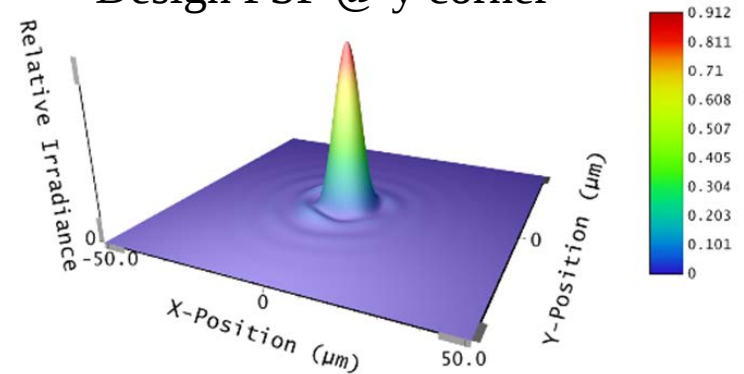
Solar system (high inclination): TNO、NEA...

Astrometry: reference frame, star clusters...

Optical Design & Survey Camera



Design PSF @ y corner



Requirements

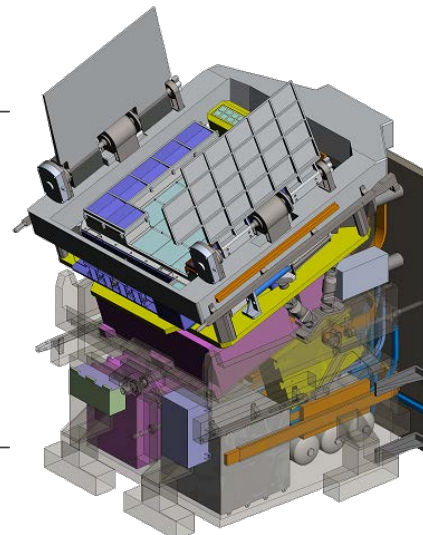
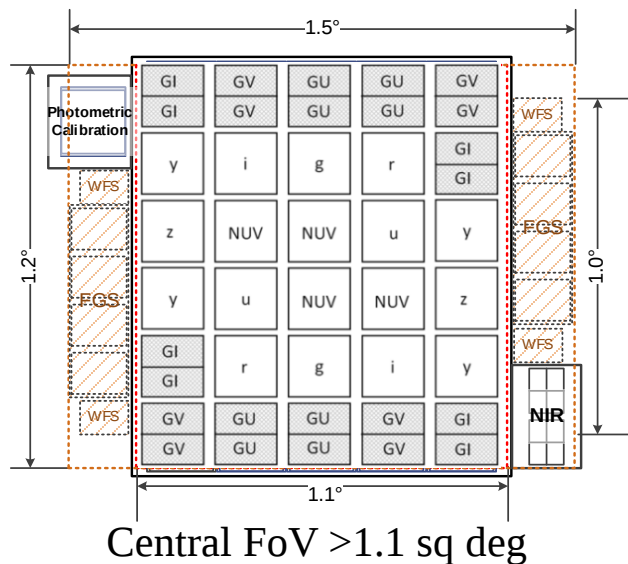
$$R_{EE80} \leq 0.15'' @ 632.8\text{nm}$$

$$e_{\text{avg}} \leq 0.05, e_{\text{max}} \leq 0.15$$

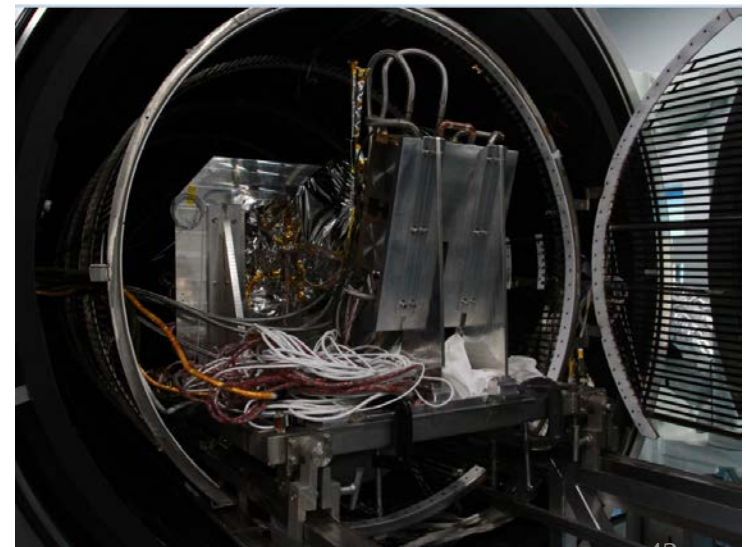
PSF + jitter sim

$$R_{EE80} < 0.13''$$

Pixel size 0.074"



Survey Cam



Cryo cooling test

Comparison with Other Surveys

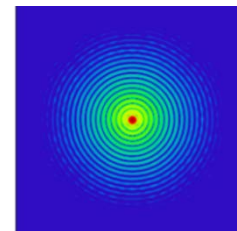
Project	Site/ orbit	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num Filters	Spect
			deg ²	"	10 ⁹	deg ²	nm		
CSS-OS	LEO	~2024	1.1	0.15 0.074/pix	2.5	17500	255 —1000	≥6	yes
Euclid	L2	~2022	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	no yes
WFIRST	L2	>2025	0.28	>0.2	0.3	~2000	927—2000	4	yes
LSST	Chile	2023	9.6	~0.54	3.2	18000	320—1050	6	no

R_{EE80} : radius encircling 80% energy

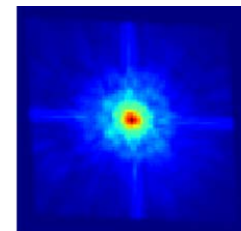
	CSS-OS	HST/ACS WFC	Euclid VIS	WFIRST J
R_{EE50}	0.1"	0.06"	0.13"	0.12"
R_{EE80}	0.15"	0.12"	~0.23"	~0.24"



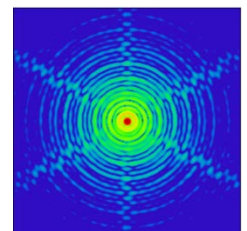
Dynamic sims: $R_{EE80} \sim 0.13''$



CSS-OS

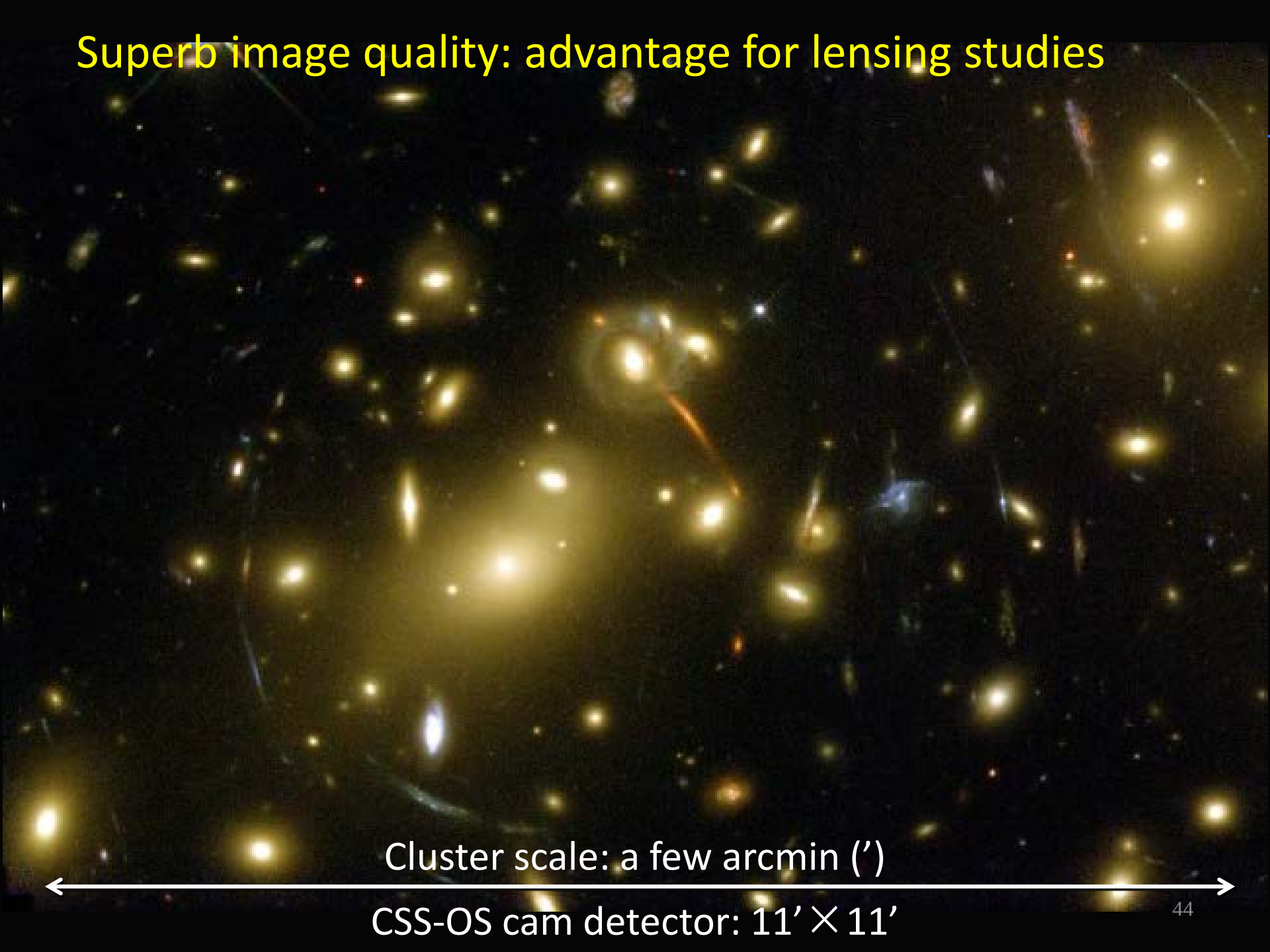


HST



Euclid

Superb image quality: advantage for lensing studies



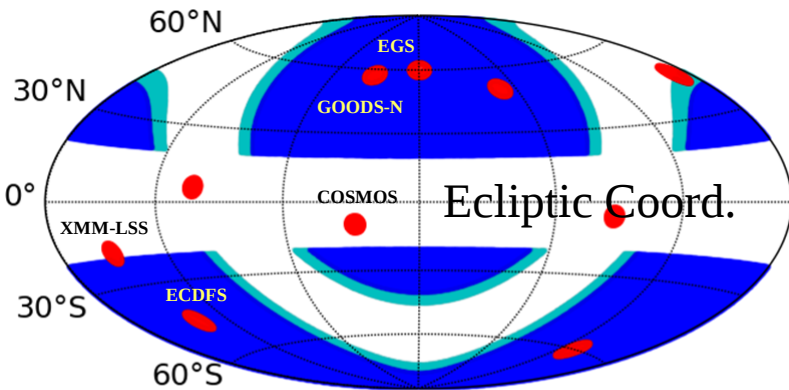
Cluster scale: a few arcmin (')

CSS-OS cam detector: $11' \times 11'$



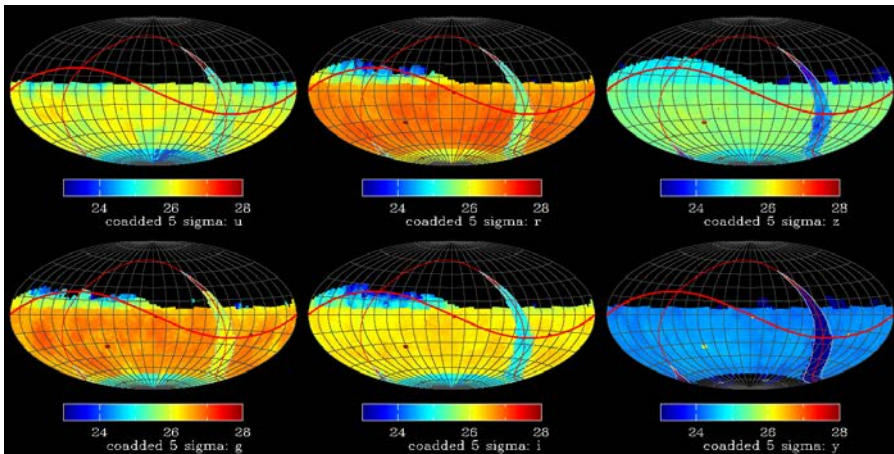
Complementary Observations

CSS-OS

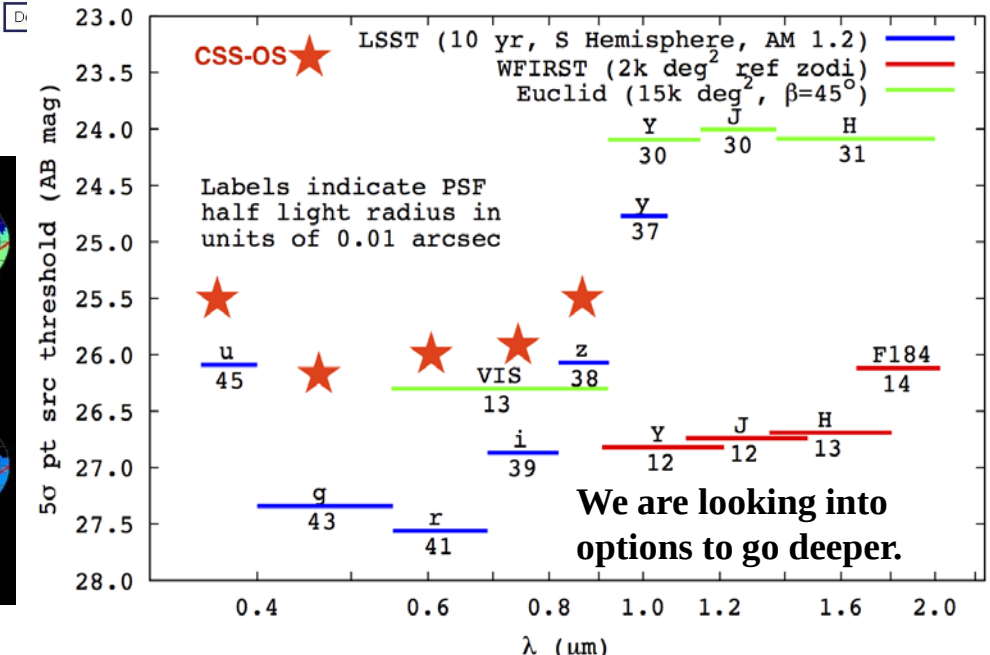
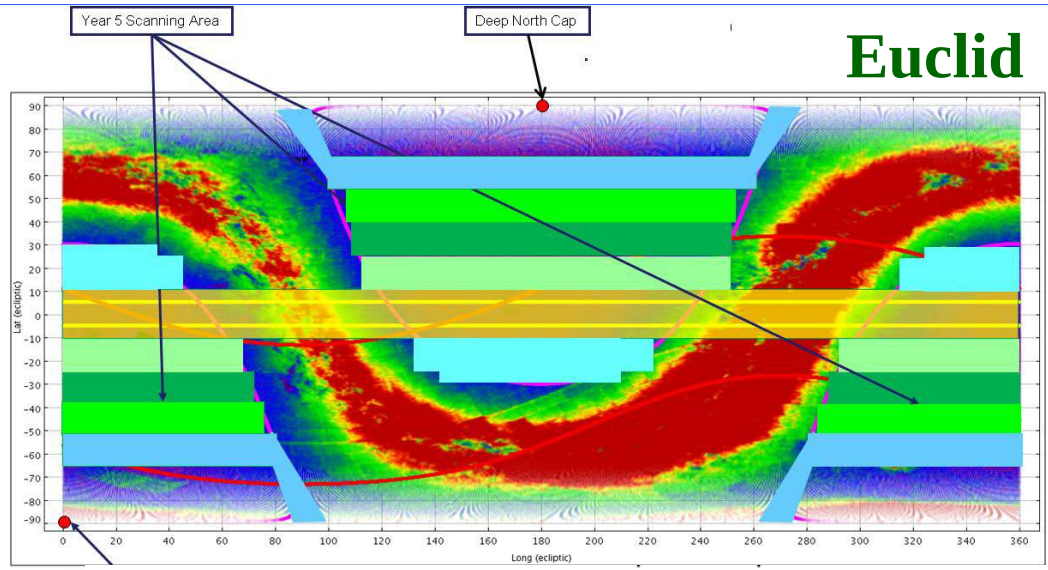


- Imaging & Slitless Spectrum Survey $|b| > 20^\circ$
- Ultral Deep Survey
- Imaging & Slitless Spectrum Survey $15 \leq |b| < 20^\circ$

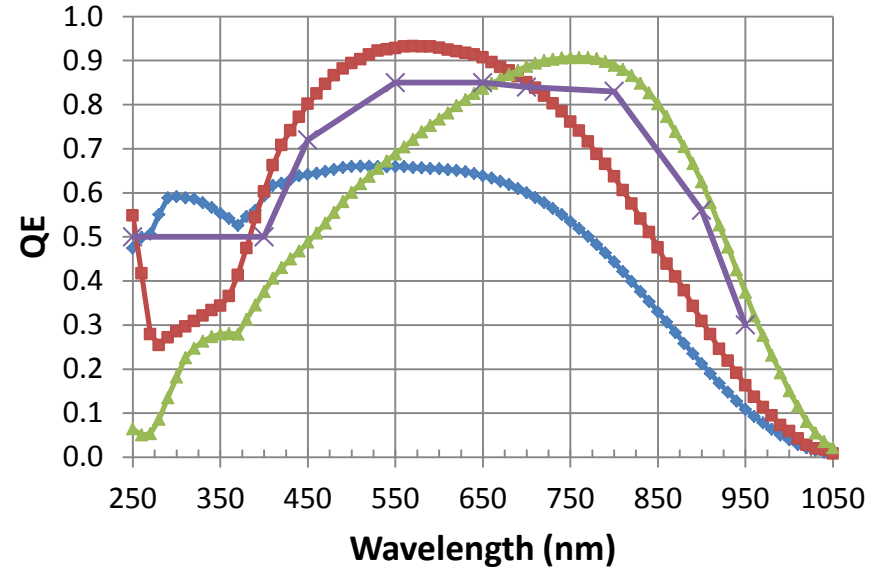
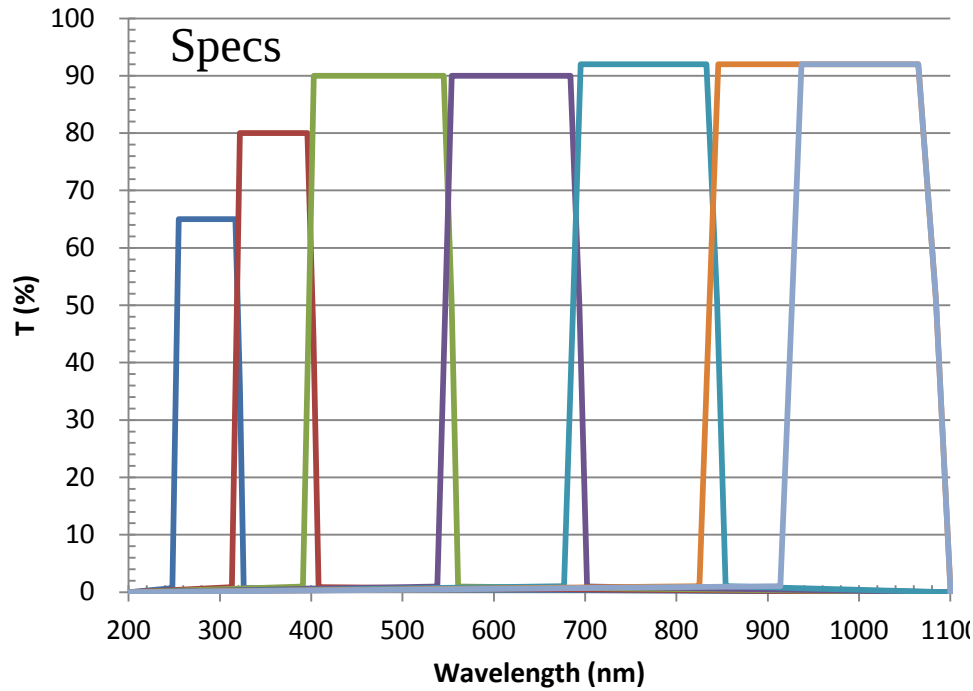
LSST



Euclid



Filters & Limiting Mags



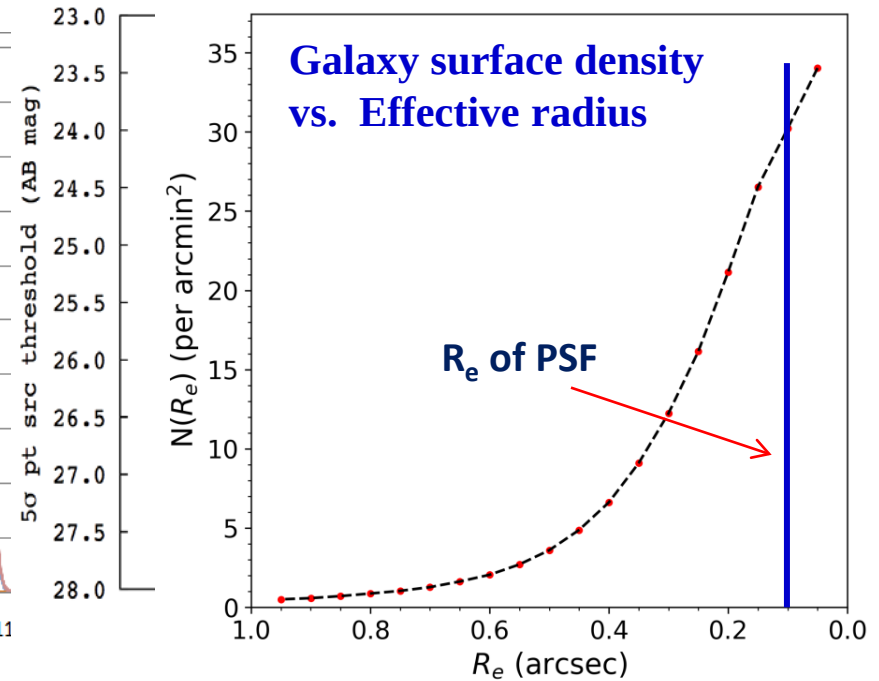
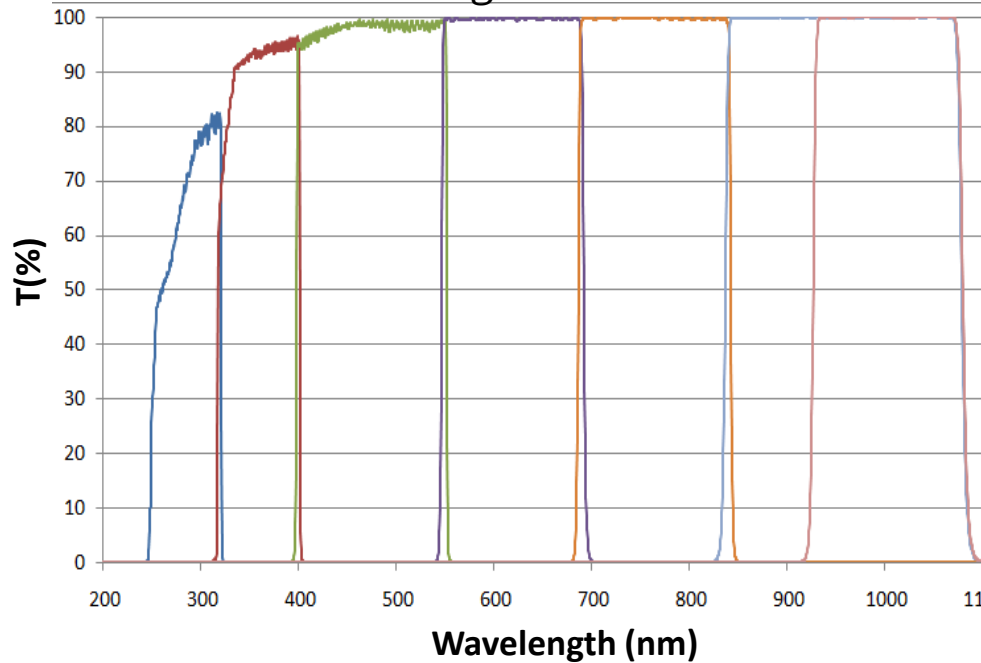
	t_{exp}	NUV*	u	g	r	i	z	y*
17500 $\square^\circ$	$2 \times 150\text{s}$	25.4	25.4	26.2	25.9	25.8	25.2	24.5
400 $\square^\circ$	$8 \times 250\text{s}$	26.7	26.7	27.4	27.1	26.9	26.4	25.7

*NUV & y: $4 \times 150\text{s}$

w/ $\sim 0.2^m$ margin from design

Filters & Limiting Mags

Vender designed filter curves

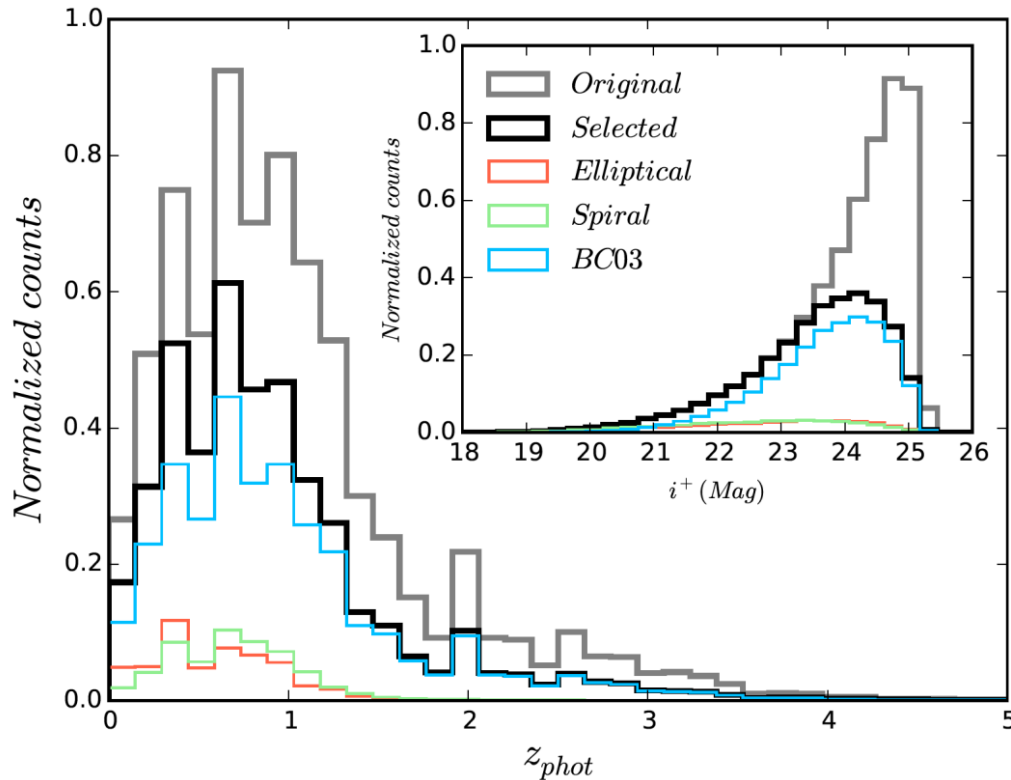


	t_{exp}	NUV*	u	g	r	i	z	y*
17500 □ °	$2 \times 150\text{s}$	25.4	25.4	26.2	25.9	25.8	25.2	24.5
400 □ °	$8 \times 250\text{s}$	26.7	26.7	27.4	27.1	26.9	26.4	25.7

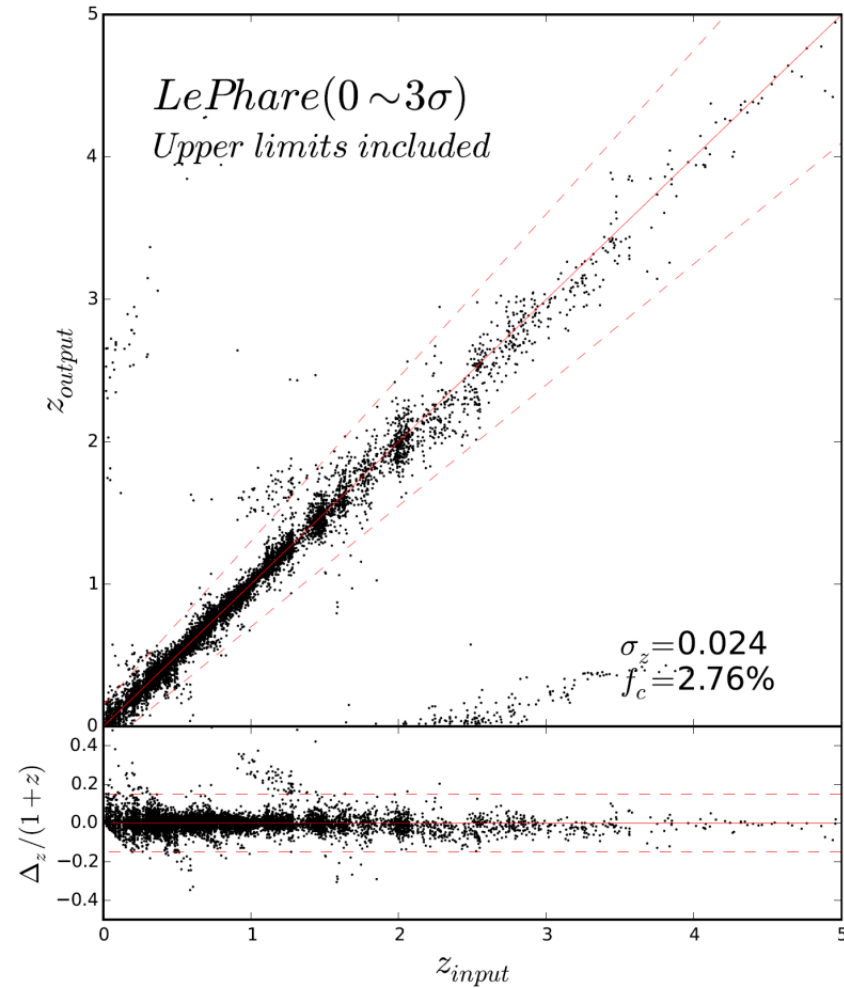
*NUV & y: $4 \times 150\text{s}$

w/ $\sim 0.2^{\text{m}}$ margin from design

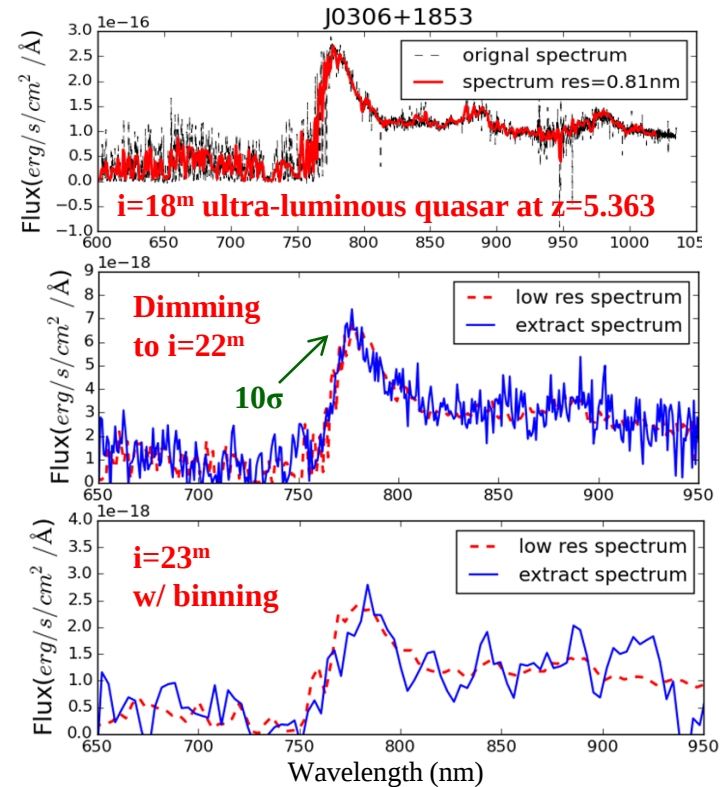
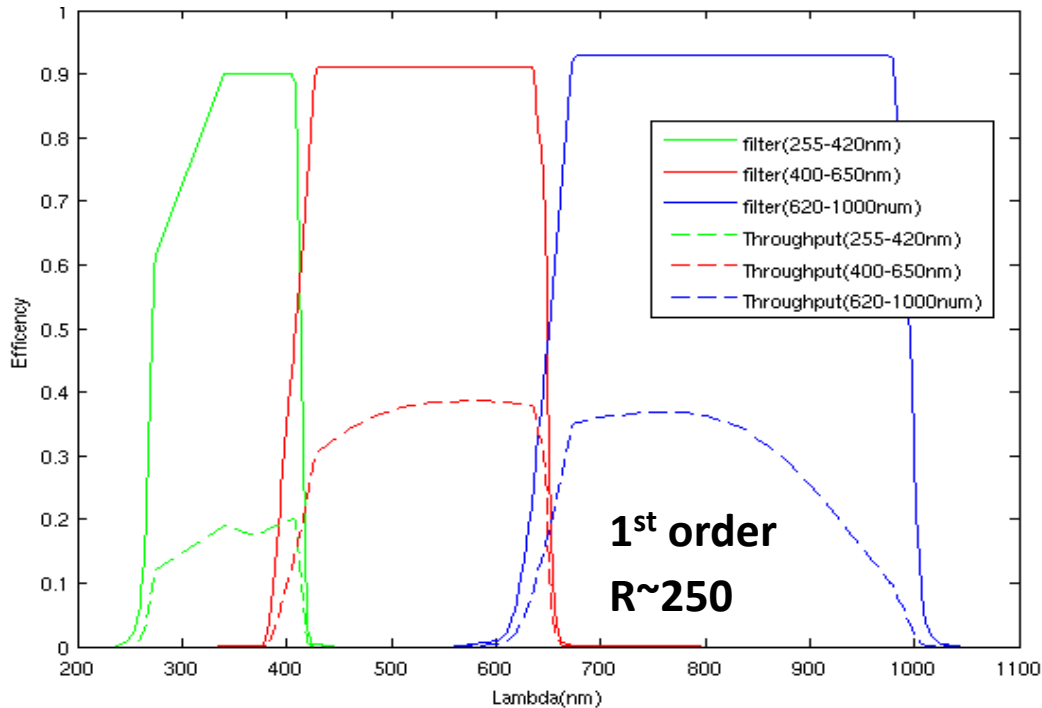
Photo-z Estimates



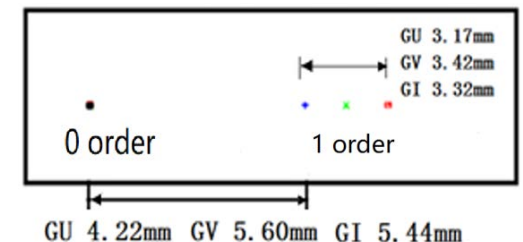
Galaxy dN/dz of a high-S/N mock sample ($17.5/\square'$, $\sigma_{z_0}=0.024$) for the CSS-OS based on COSMOS. If σ_{z_0} is relaxed to 0.05, galaxy density $\sim 29/\square'$.



Gratings & Limiting Mags



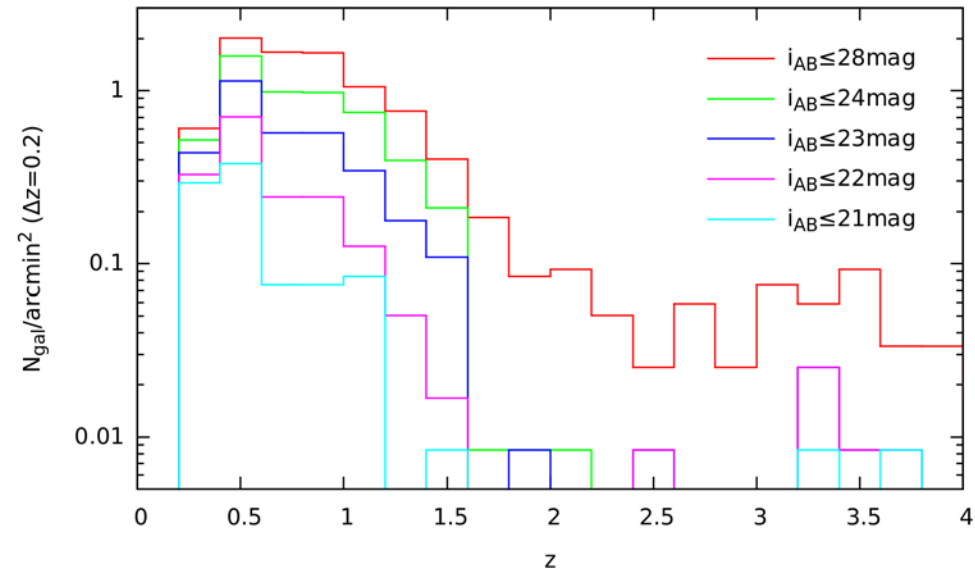
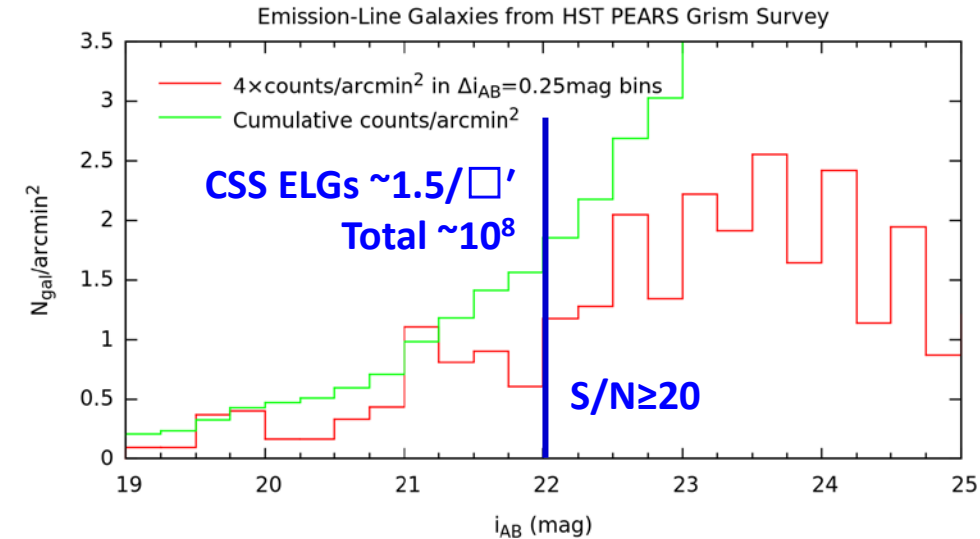
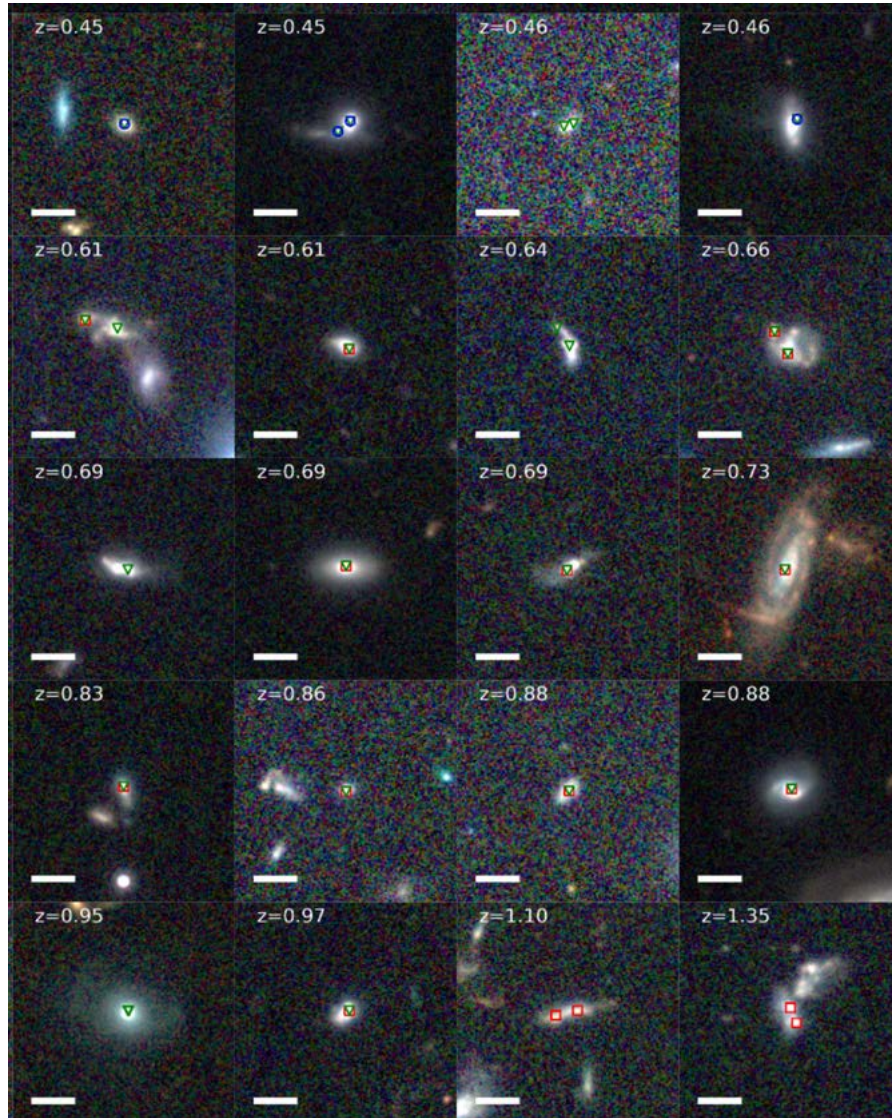
	t_{exp}	GU	GV	GI
17500 □ °	4 × 150s	22.5	23.4	23.4
400 □ °	16 × 250s	23.7	24.6	24.5



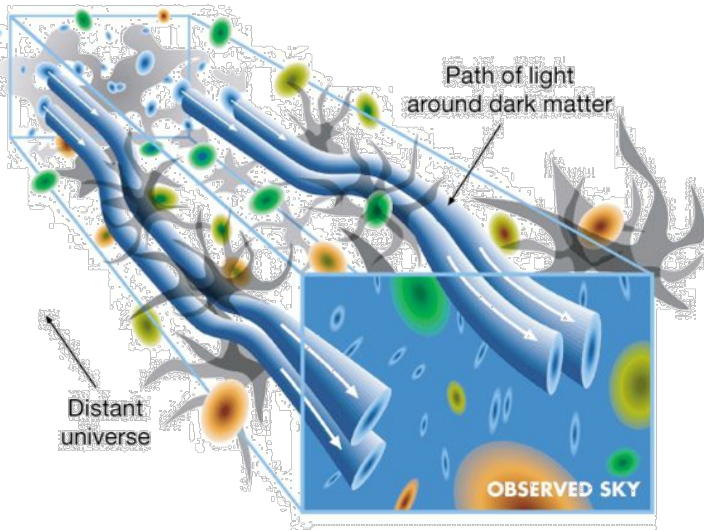
Broadband limiting mag w/ ~0.2^m margin

Galaxies from Slitless Spectroscopy

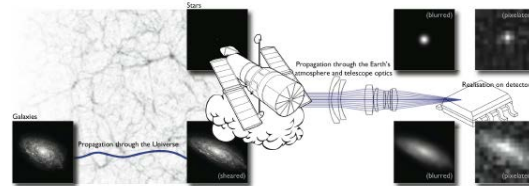
Checking against HST PEARS Survey: $120/\square'$, 550-1050nm, $R \approx 69-131$, $i_{AB} \lesssim 28^m$



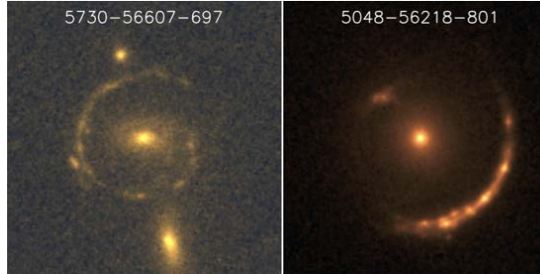
Survey Science: Gravitational Lensing



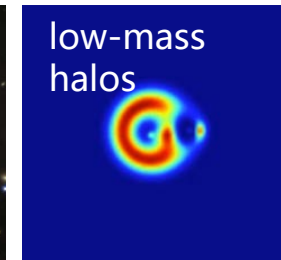
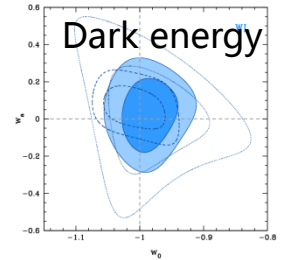
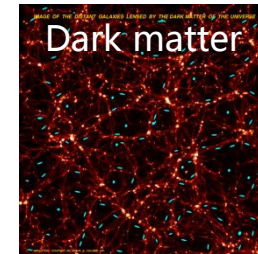
Gravitational distortion



Weak lensing

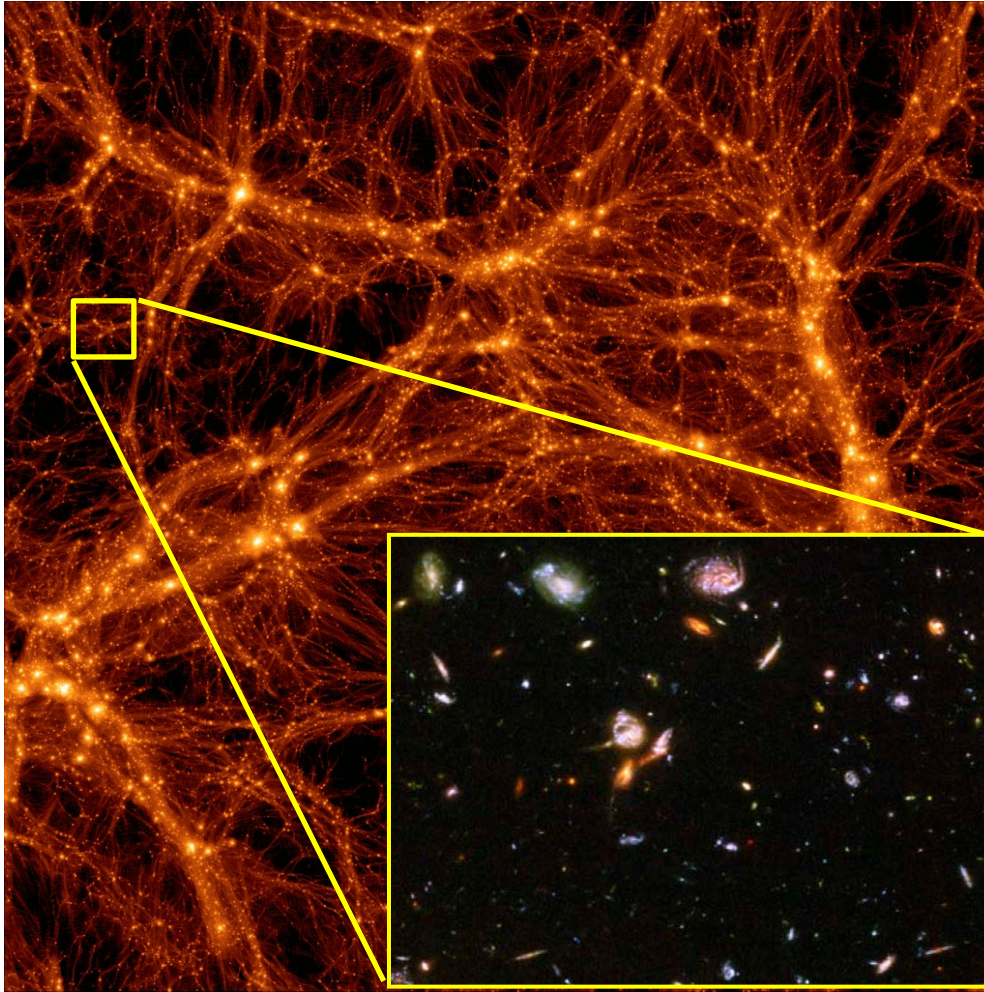


Strong lensing

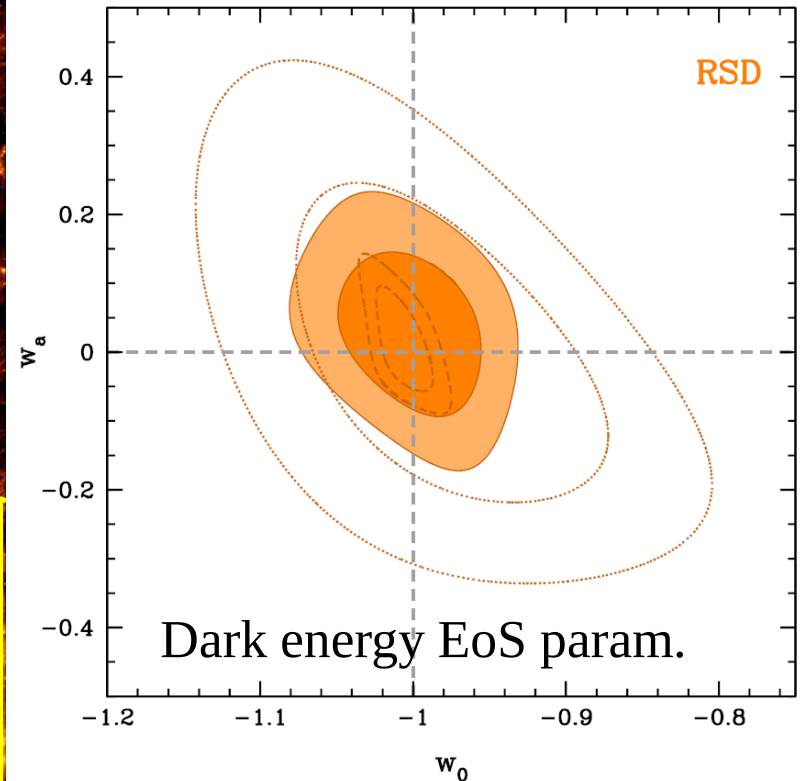


- Mapping the dark matter distribution in the universe;
- Testing dark energy models and gravity theories with precision measurements of the cosmic expansion history;
- Cataloging 10^5 strong lensing systems, including thousands of multiply imaged QSO systems, to measure dark matter particle properties, H_0 , and more.

Survey Science: Large-Scale Structure



Statistics of galaxy distribution for dark matter & dark energy studies.



Reducing errors on the dark energy EoS parameters by ~ 10 times over current obs.

Survey Science: Galaxies & AGNs

The CSS-OS unprecedented large-area high-resolution imaging and slitless spectroscopy data, together with observations of the Terahertz Detector, Multi-Channel Imager, and Integral Field Spectrograph, will characterize the formation and evolution of galaxies and AGNs as well as their interaction with the environment over cosmic time.

Survey of high- z
galaxies & AGNs



Details of the
“cosmic noon”



Charactering the
local universe



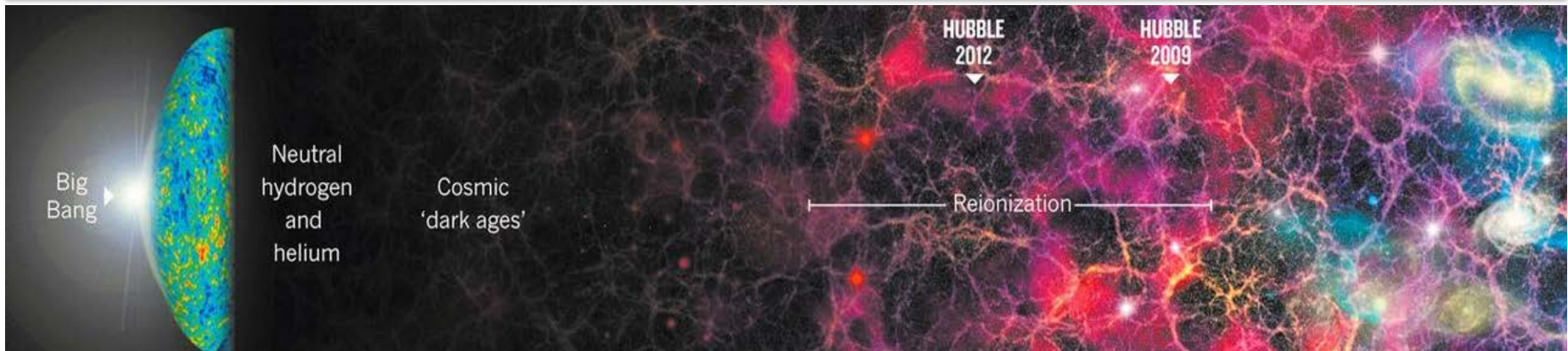
Time: 13.8B yr
redshift: $z \sim 1100$

13.8~13.5B yr
 $z = 1100 \sim 20$

13.5~12.8B yr
 $z = 20 \sim 6$

10~8B yr
 $z = 2 \sim 1$

present
 $z = 0$



Universe: igbang
Galaxy:

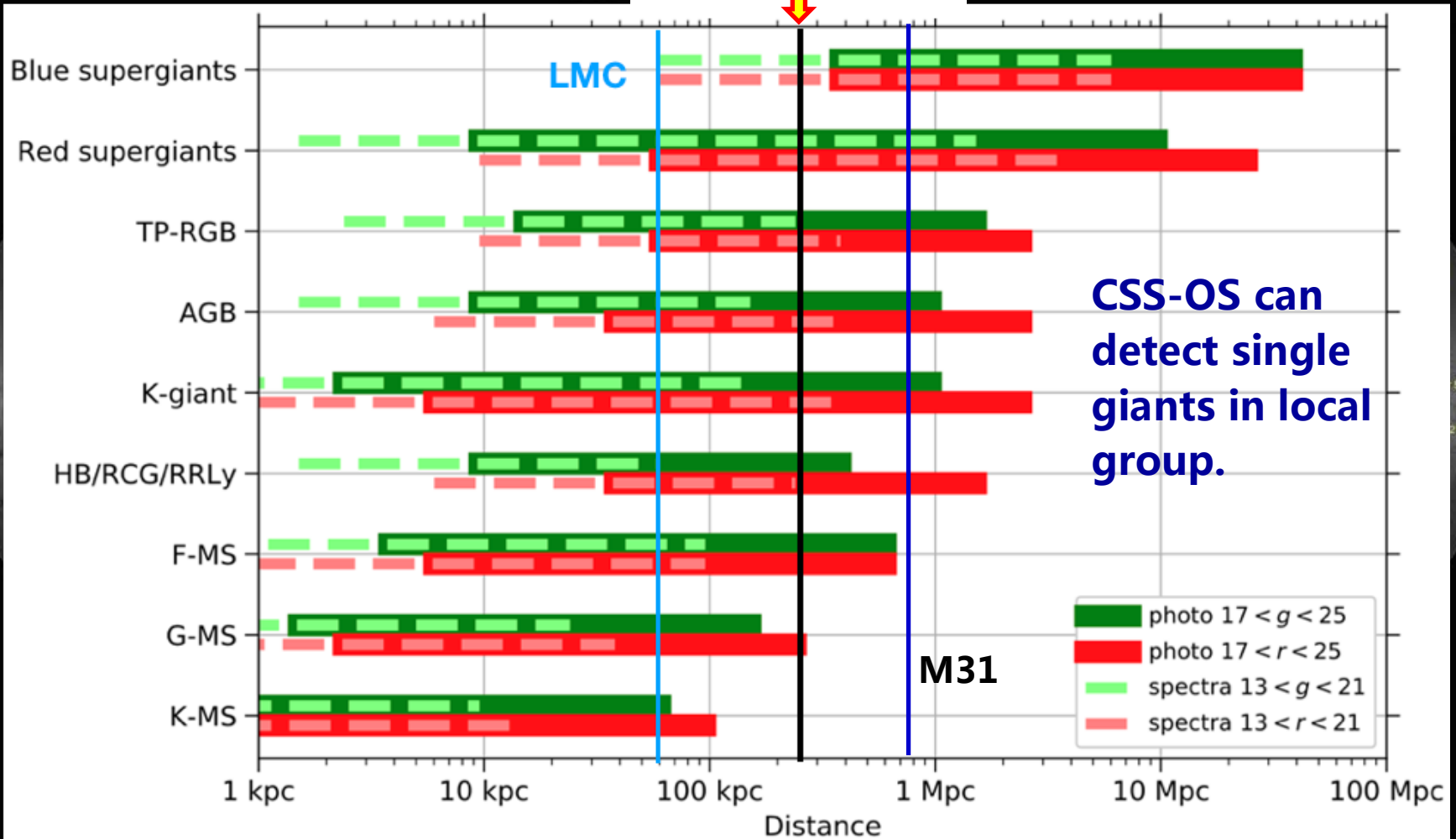
dark ages

seed of LSS, reionization
first stars

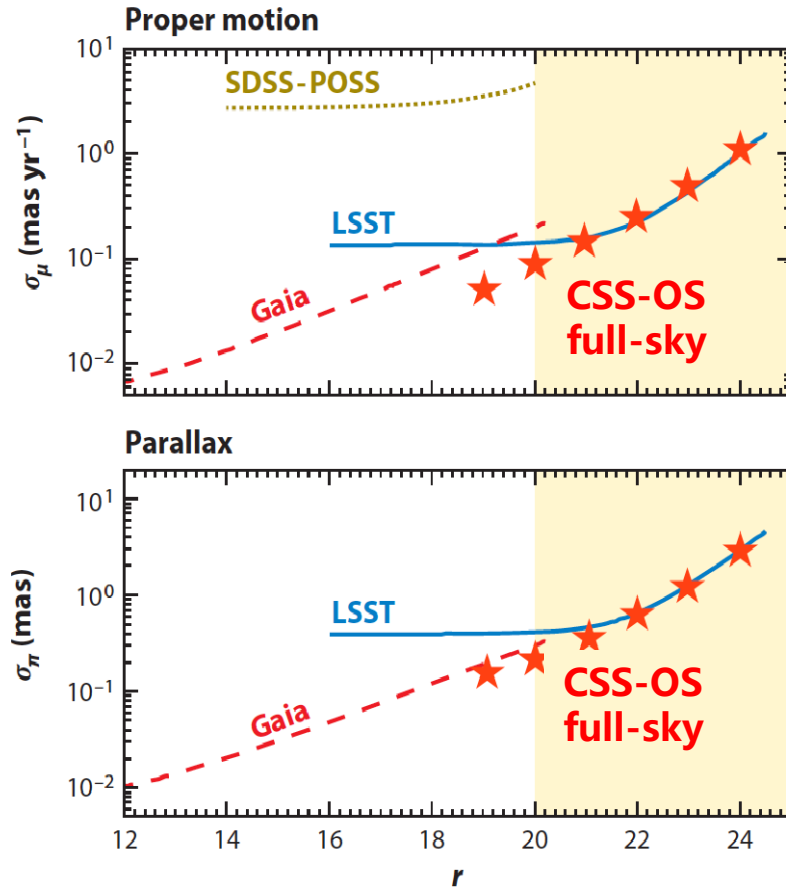
acceleration
peak of formation → quick evol

Survey Science: Milky Way & Local Group

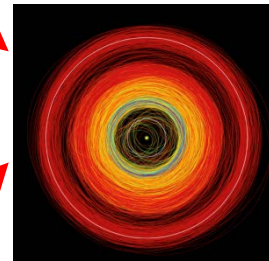
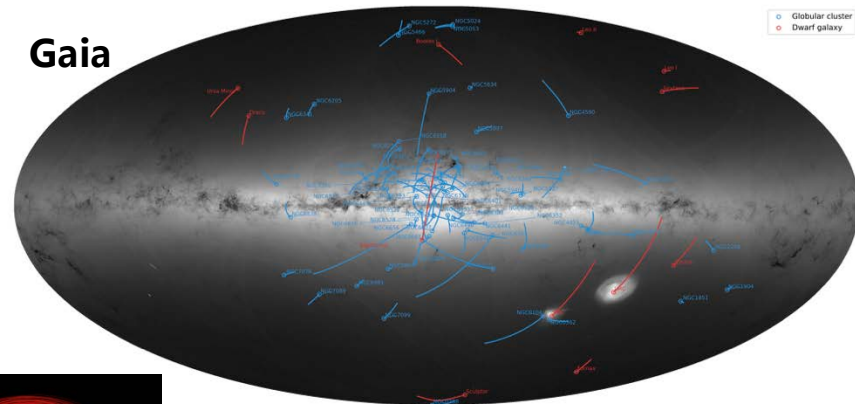
Edge of MW



Survey Science: Astrometry & Solar Sys.

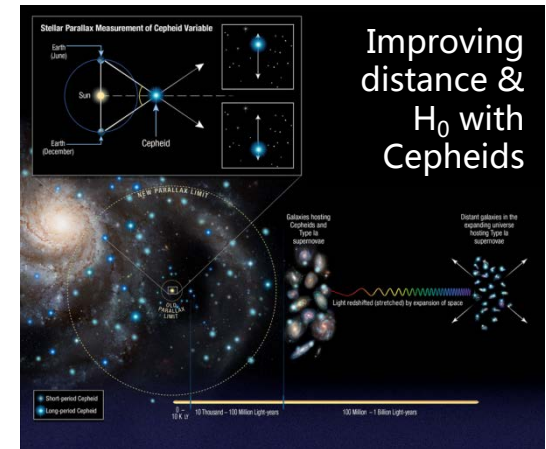


Gaia



Astro. Orbit (Gaia)

Greatly improving astrometry on the faint end!

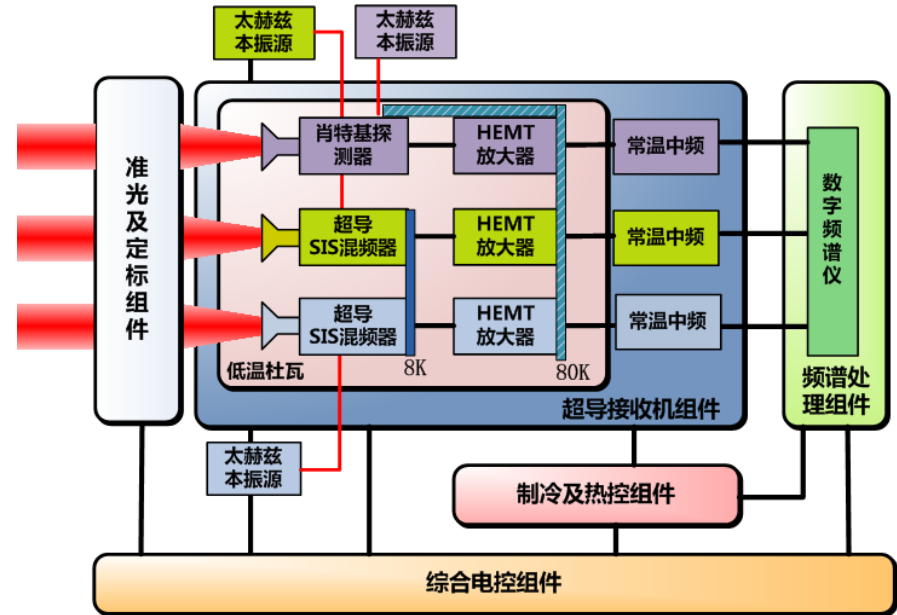
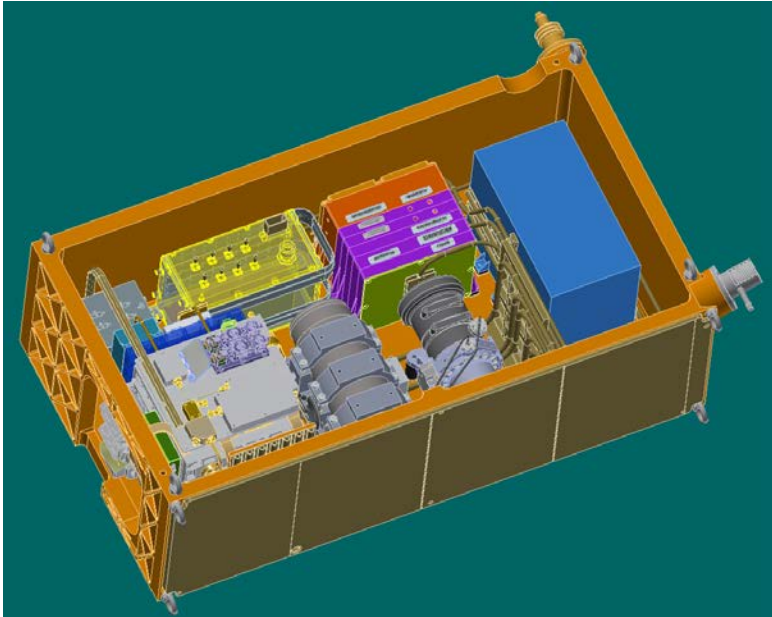


CU3 - CORE PROCESSING FOR GAIA



Coordination Unit 3 group picture taken at the CU3 Plenary meeting held in Heidelberg in 2007

Terahertz Receiver



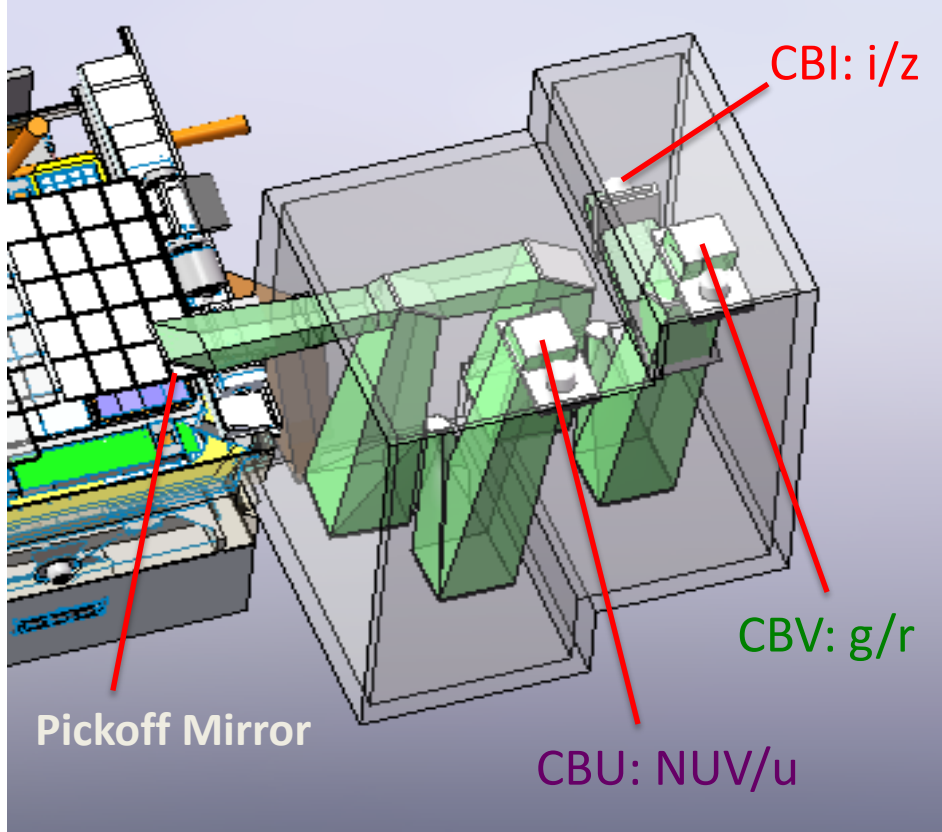
Specifications

Frequency	0.41-0.51THz
Bandwidth	$\geq 2\text{GHz}$
Resolution	$\geq 100\text{kHz}$
Sensitivity	$< 150\text{mK}$ (200s)
Cryocooling	$\geq 10\text{mW@8K}$

- **410~510GHz spectral line survey**
 - Searching for new atomic and molecular species and physical & chemical processes
 - Complementary with Herschel (410~480GHz)
- **Carbon cycle (CI, 492GHz)**
 - Evolution of molecular clouds in early-stage
 - Filamentary structure in molecular clouds

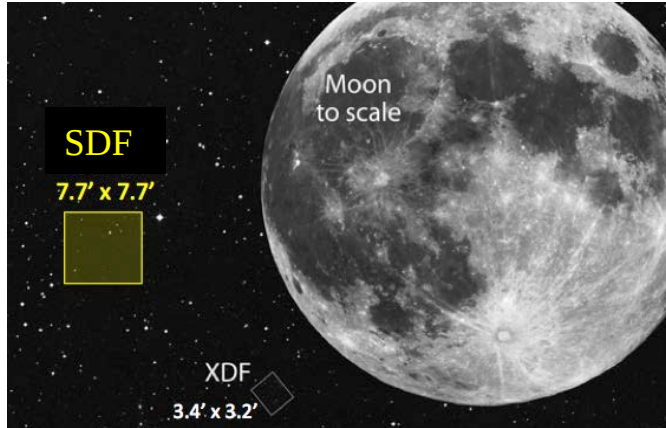
Multi-Channel Imager

MCI conceptual design



- 3-channel simultaneous observation
 - 0.25-0.4 μm (CBU)
 - 0.4-0.7 μm (CBV)
 - 0.7-1.0 μm (CBI)
- 20+ filters to select
- 9Kx9K e2v CCDs, 0.05"/pix, FOV $\geq 7.5' \times 7.5'$
- High Precision Photometry (<0.5% , visible) with HST Standards, calibration for the survey.

Multi-Channel Imager



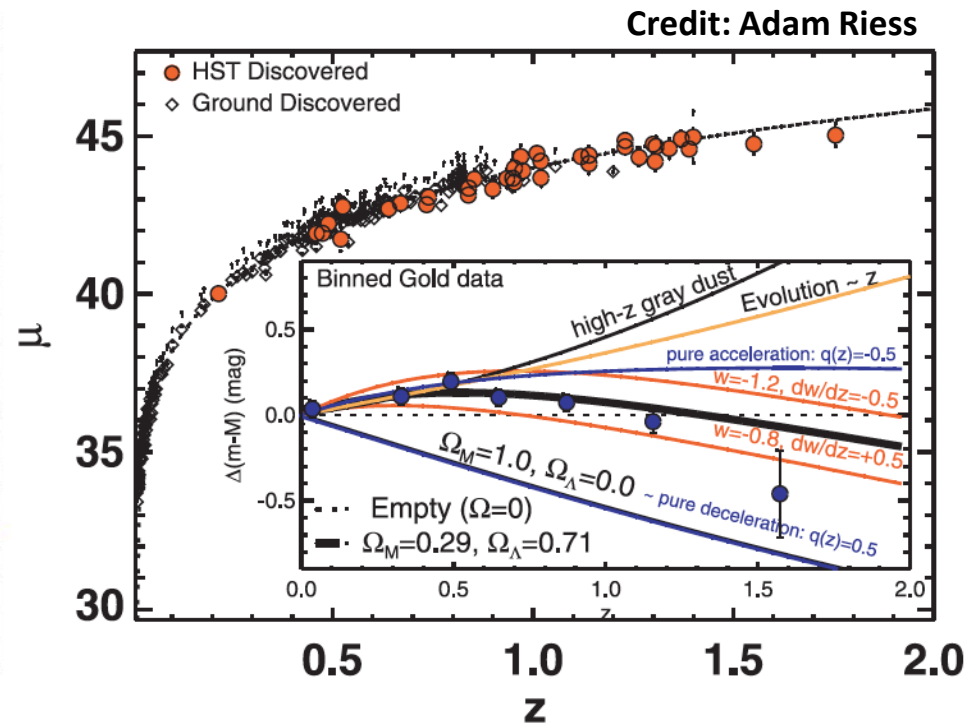
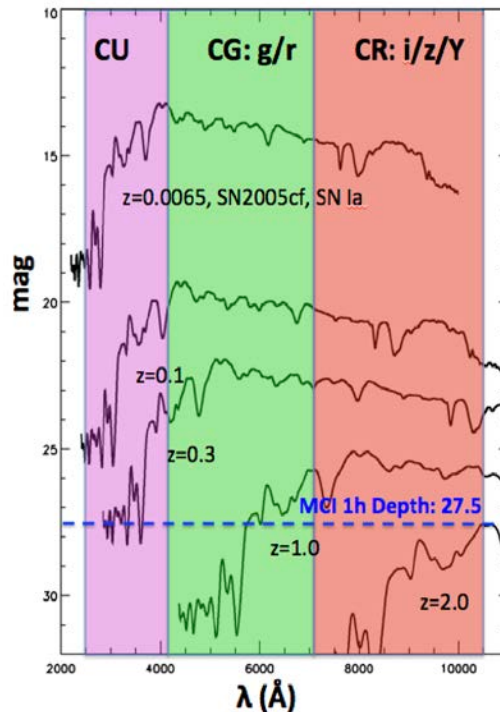
Sciences with (3-filter simultaneous) CSST Super Deep Fields

- SN Ia Cosmology and Highest-z SN
- Completeness of Galaxies used for WL, Clustering, ...
- Galaxy & BH Co-Evolution
- ...

Potential SDFs:

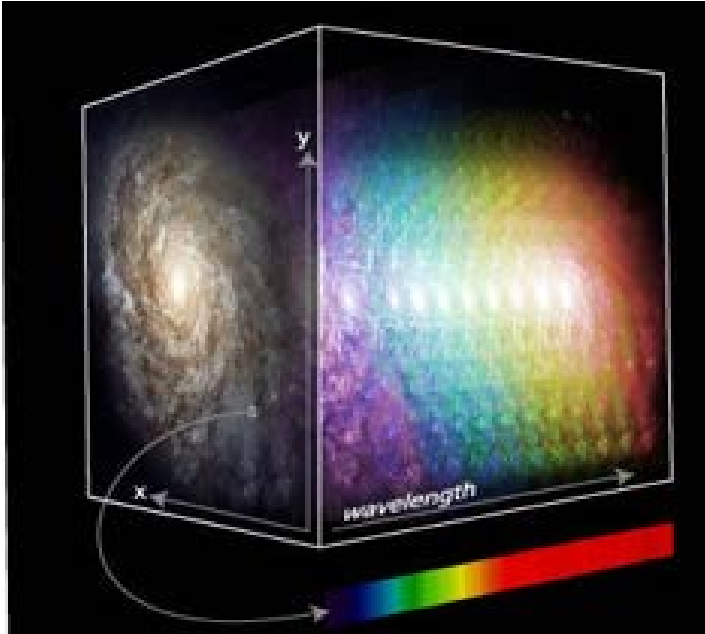
- HST XDF
- Galaxy Cluster (Illingworth+2013)
- Galaxy Cluster
- JWST UDF

5 fields, 300 $\square'$
tot, CBV $\geq 30^m$

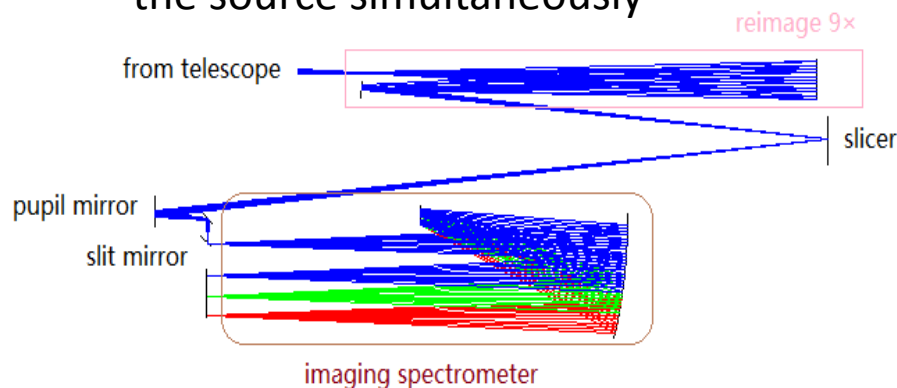


Credit: Adam Riess

Integral Field Spectrograph



Taking spectra of different parts of the source simultaneously



Specifications

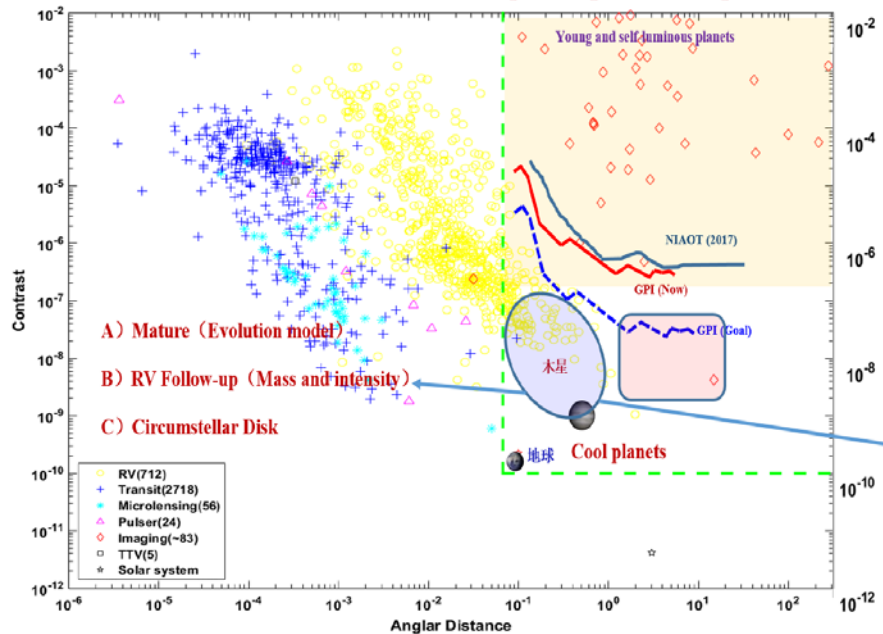
Spatial Resolution	0.2''
Spatial Elements	30x30
Field-of-view	6''x6''
Filling factors	100%
Wavelength Coverage	0.35-1.0um
Spectral resolution	$R \geq 1000$, 0.175nm/pixel

❖ Super-massive black holes and its surroundings

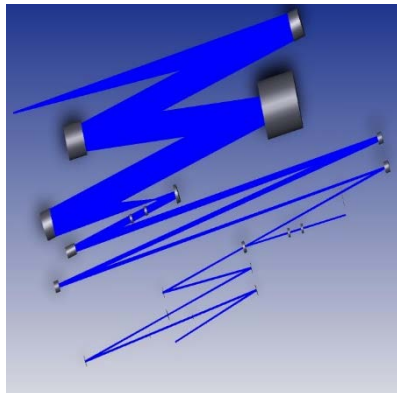
- ❖ Measuring the BH masses
- ❖ Feeding and feedback of BHs
- ❖ Star clusters and star-formation around the BHs
- ❖ Tidal-disruption events
- ❖ Star-formation of galaxies
 - ❖ Mergers, BCDs, Lyman-Break Analogs
- ❖ ...

Cool-Planet Imaging Coronagraph

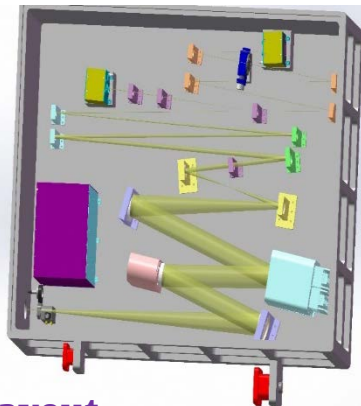
40PC, >1GYrs F/G/K stars, ≤ 10 AU Jupiter/Neptune and Super Earth



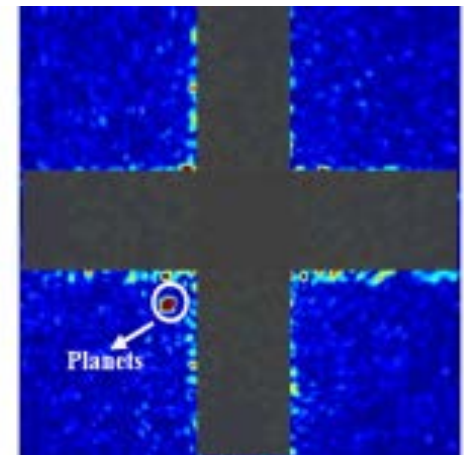
Contrast vs. angular separation



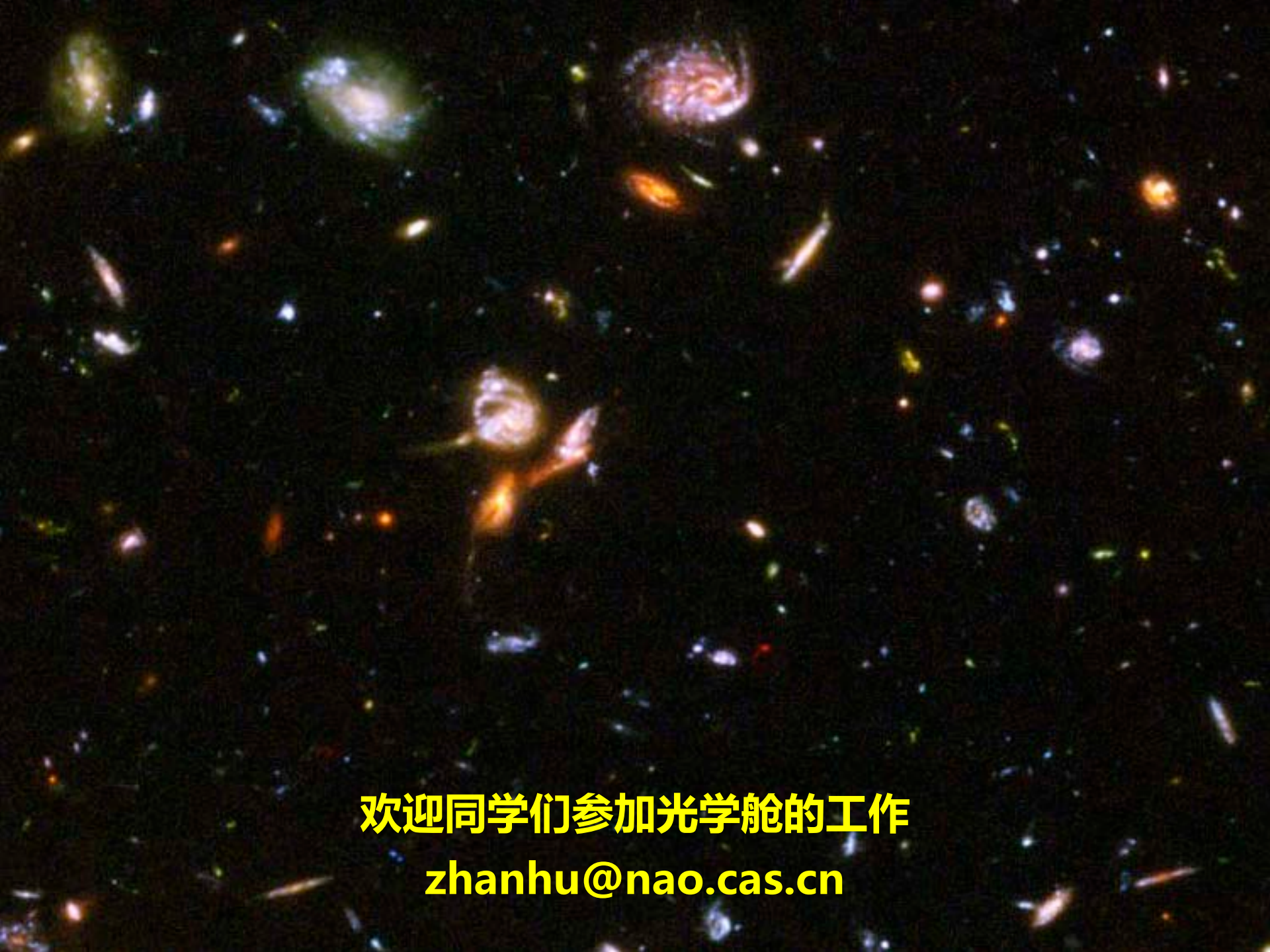
Optics layout



Vacuum chamber test reaching 10^{-9} contrast



- **Wavelength:** 0.6-0.9 μ m (goal: 1.6 μ m)
 - **Bandwidth:** 3~10%
 - **FOV:** 2.5" $\times$ 2.5" obs, 20" $\times$ 20" targeting
 - **IWA:** $\leq 0.55''$ @ 0.63 μ m, 1.2" @ 1.5 μ m
 - **Contrast:** 10^{-8} (0.6-0.9 μ m) or better
- **Searching for mature planets around solar-type stars**
 - **RV follow up & planet formation & evolution**
 - **Physics of circumstellar disk**



欢迎同学们参加光学舱的工作

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