Cosmological Probes

詹虎
zhanhu@nao.cas.cn
国家天文台
北京大学科维理研究所

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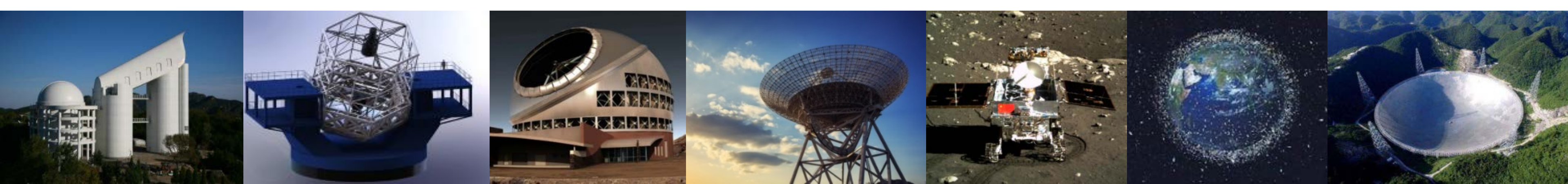
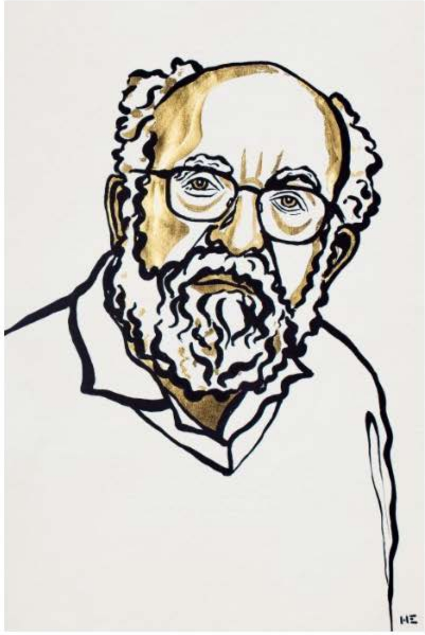


The Nobel Prize in Physics 2019

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

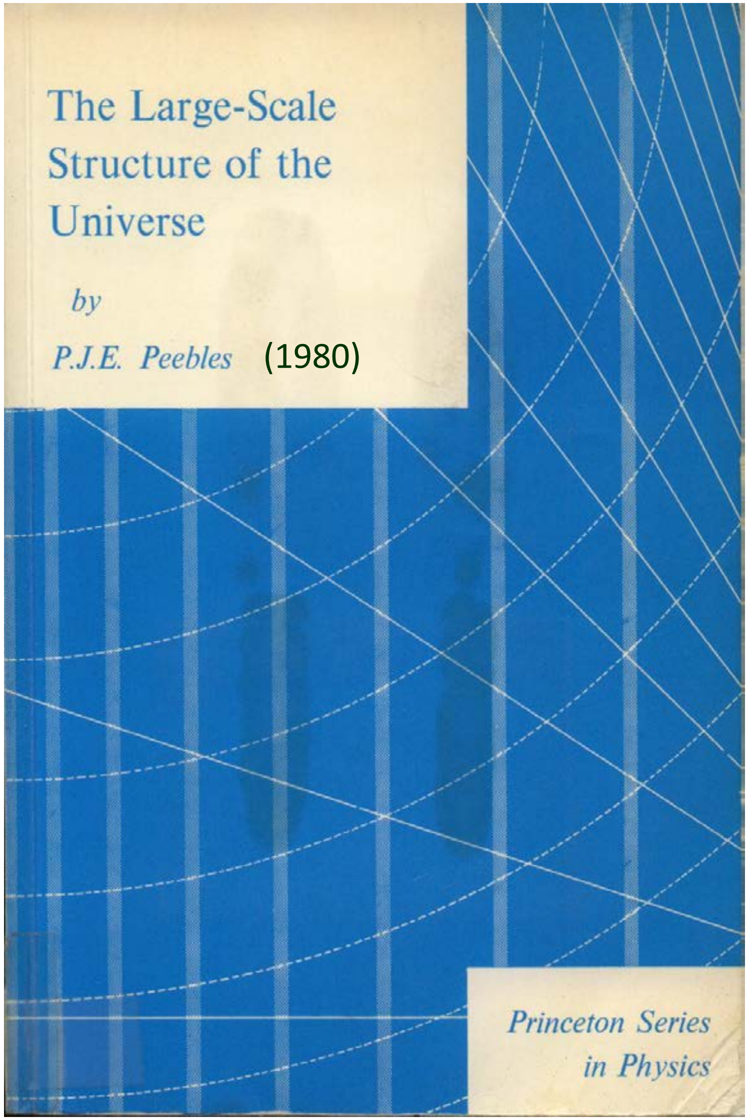
Prize share: 1/4

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."

Outline

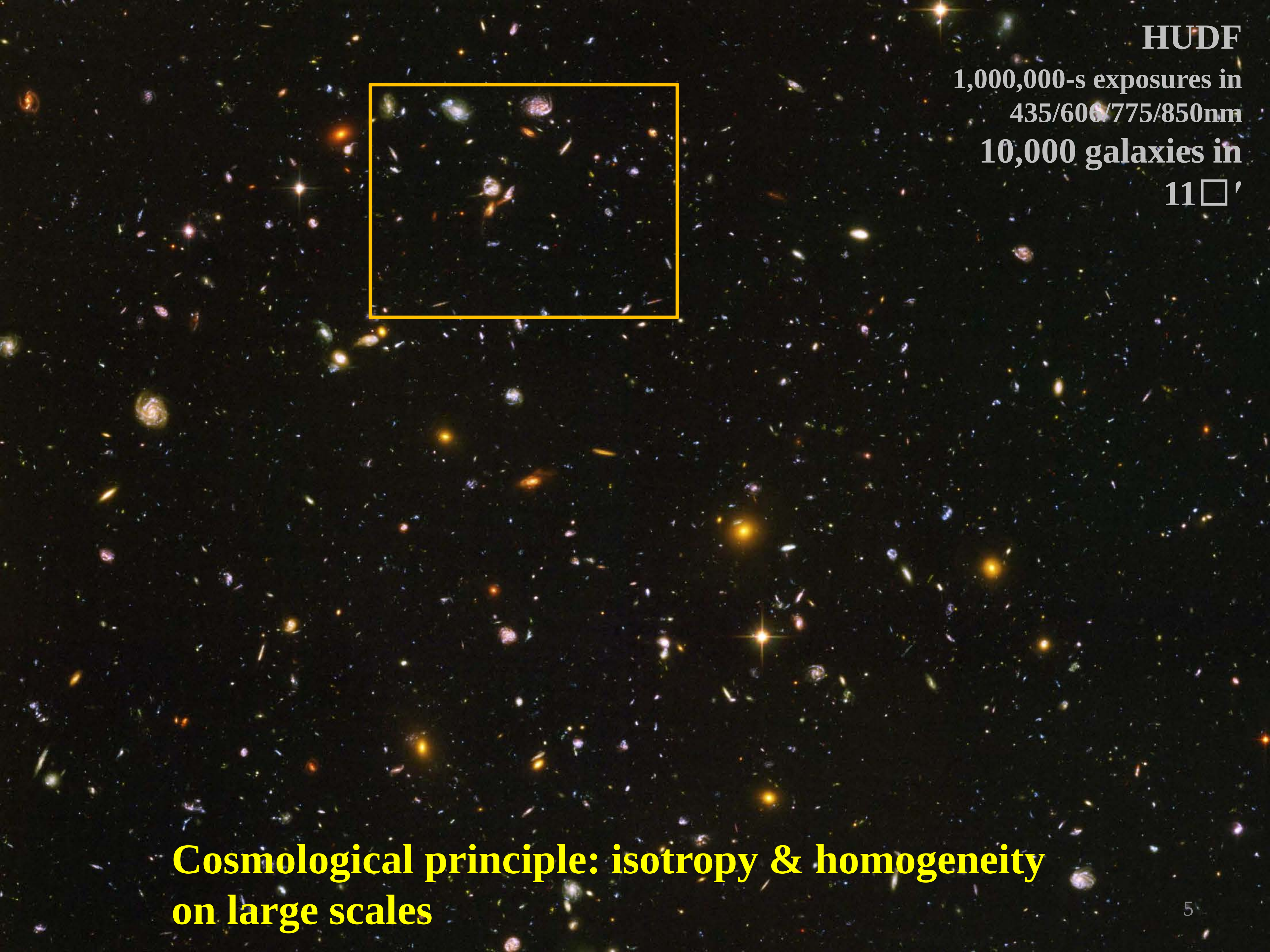
1. Introduction
2. Topics:
   - Dark Energy
   - Baryon Acoustic Oscillations
3. Future Surveys

Cosmological Studies

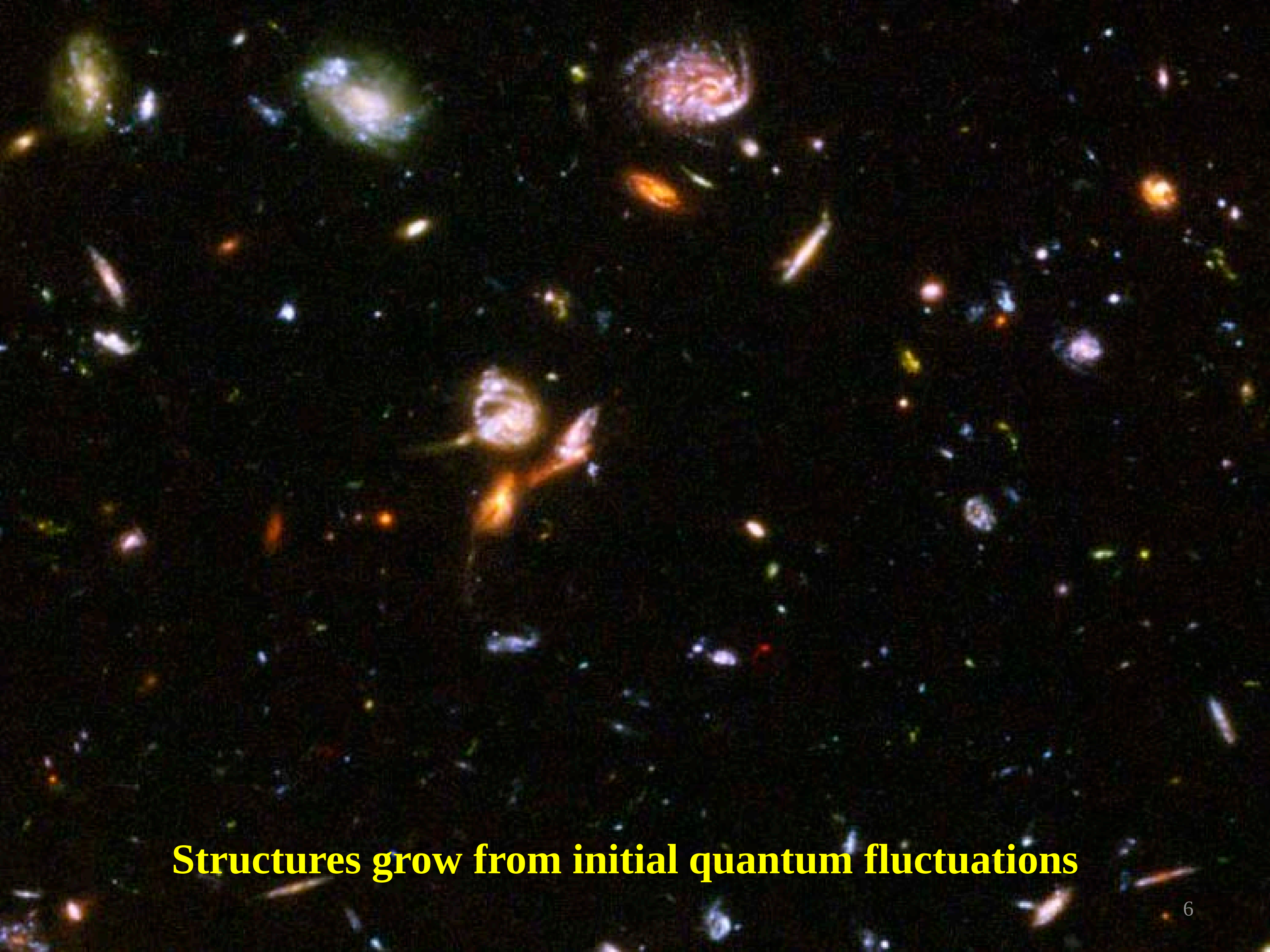


(1980)

CONTENTS

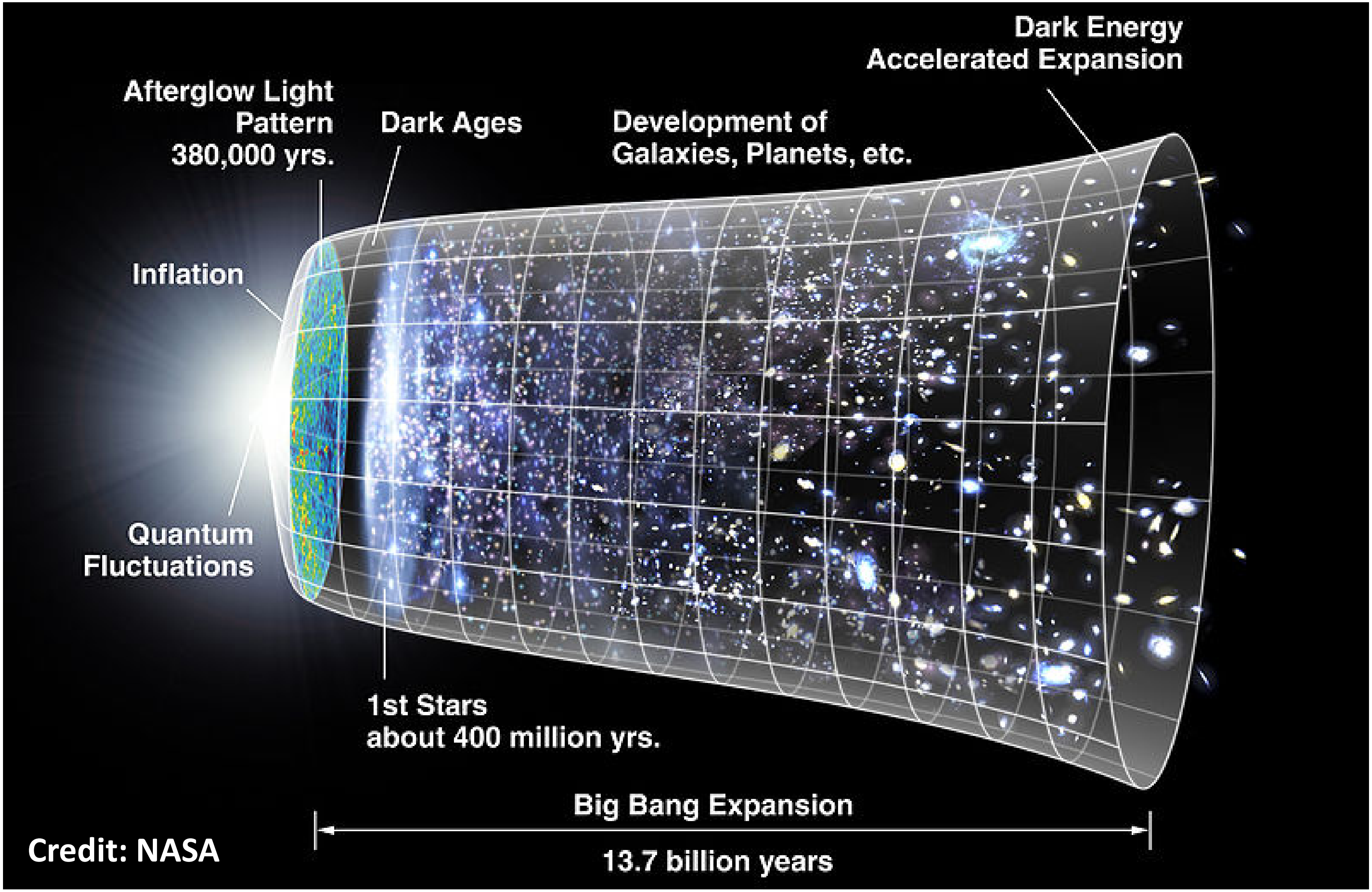


Cosmological principle: isotropy & homogeneity on large scales



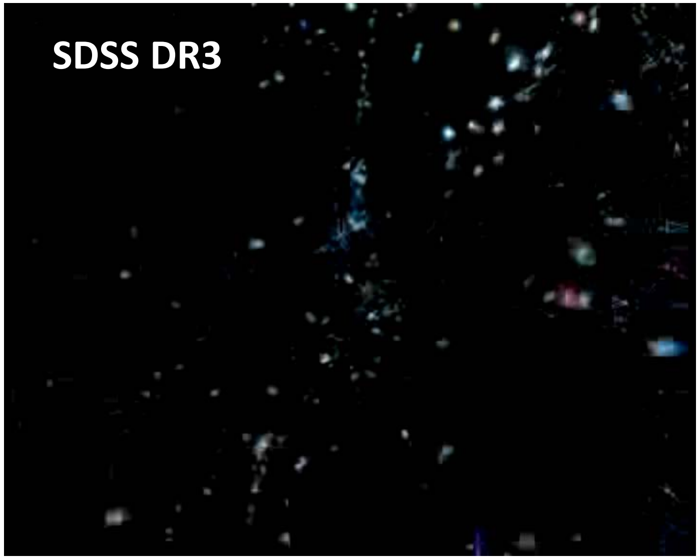
Structures grow from initial quantum fluctuations

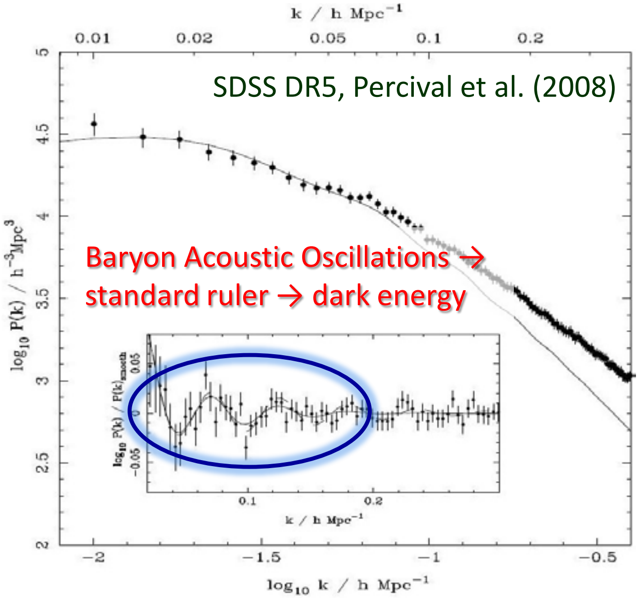
Evolution of the Universe



Statistical Tools

Peebles (1980)





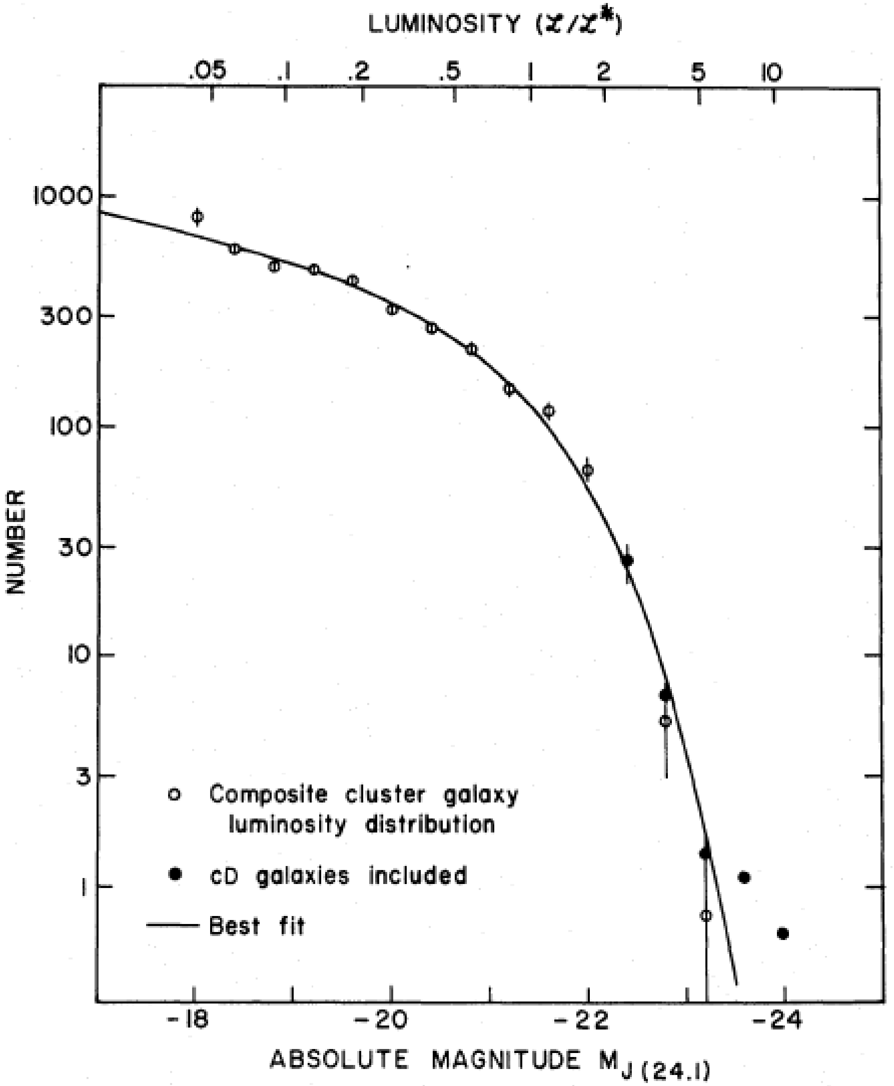
Galaxy Luminosity Function

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

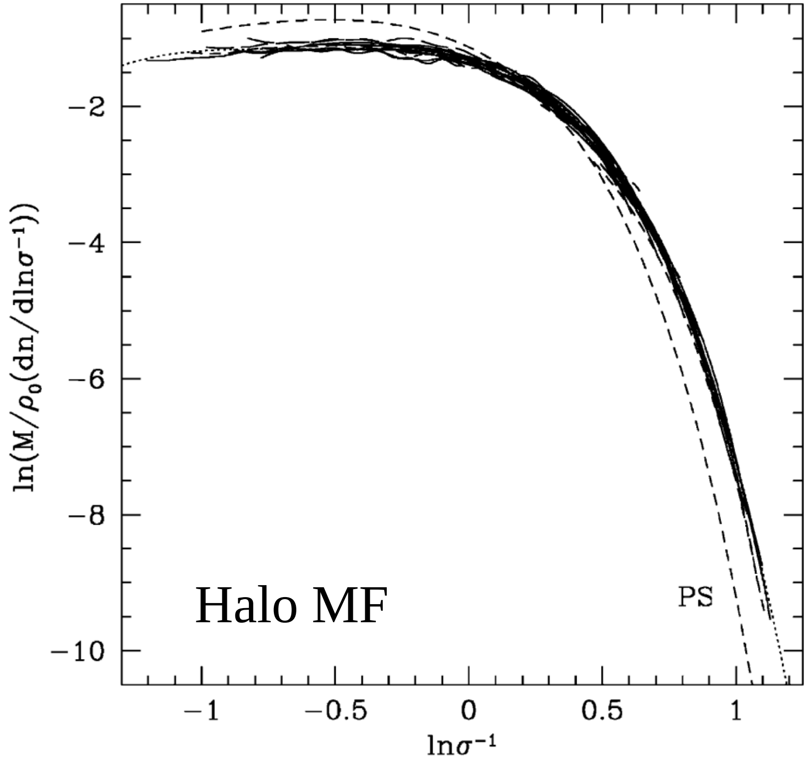
$$\Phi(L)dL = \Phi^*\left(L/L^*\right)^{\alpha} e^{-L/L^*} d\left(L/L^*\right)$$

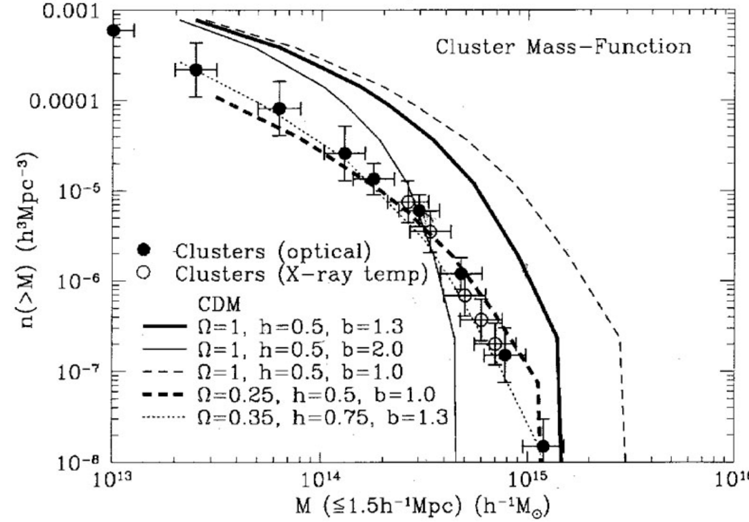
$$L^* \sim 2\times 10^{10} L_{sun} \qquad \alpha \sim -1 \sim -1.5$$

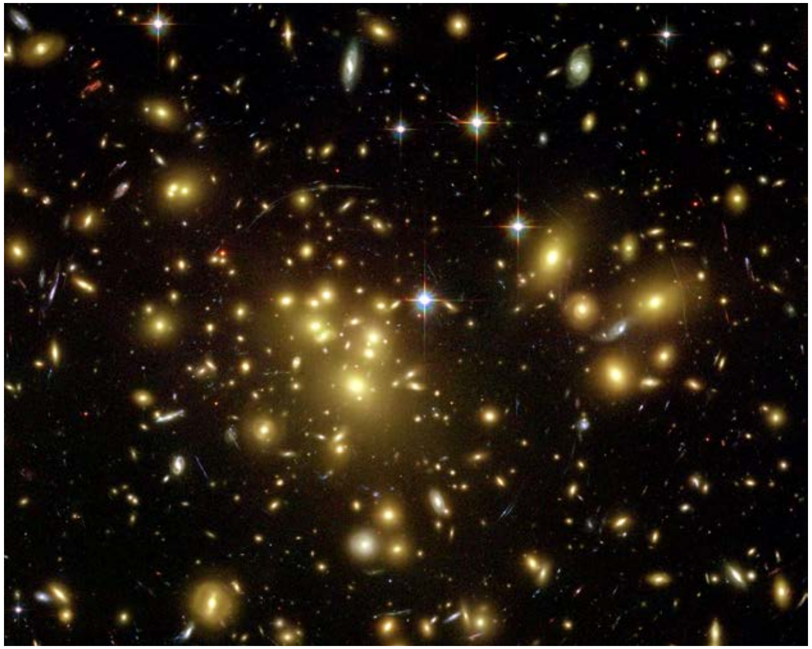
- Depends on the galaxy type, formation history, environment, etc.
- Evolves with time.



Halo/Cluster Mass Function



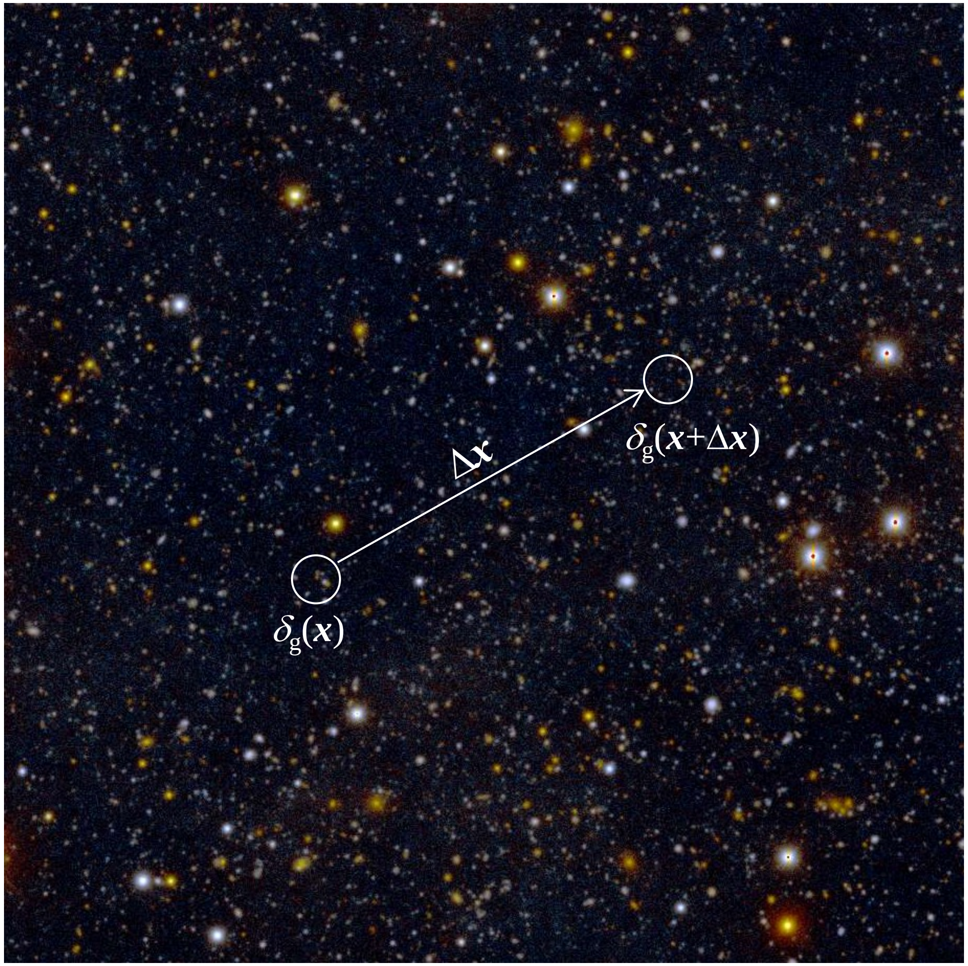




Halo/cluster mass function is sensitive to cosmological model and is an important dark energy probe.

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

$$\xi_g(\Delta x) = \langle \delta_g(\mathbf{x})\delta_g(\mathbf{x} + \Delta \mathbf{x}) \rangle$$

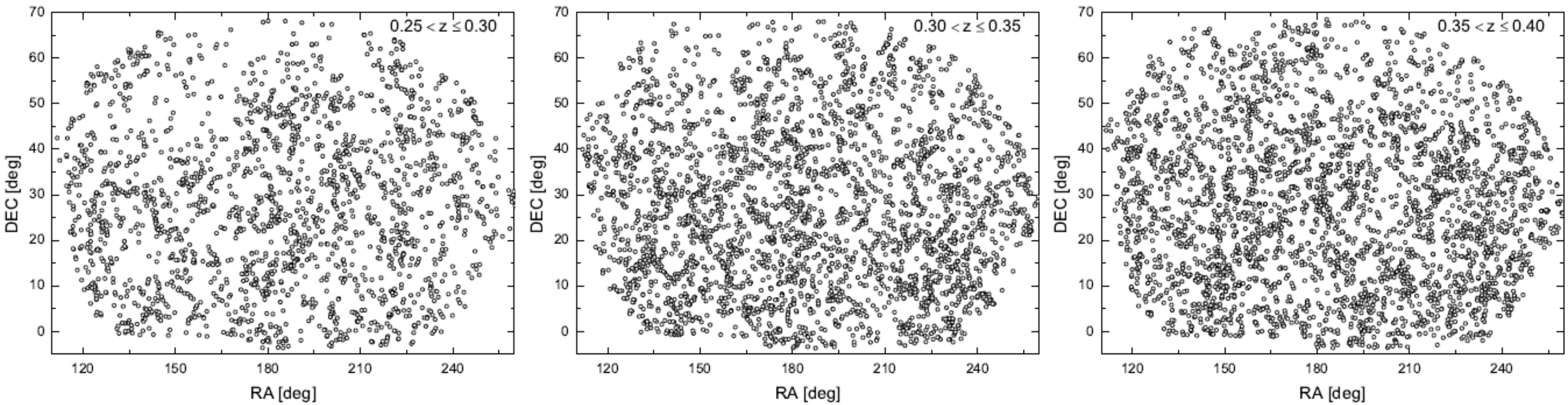
$$\approx b^2 \xi(\Delta x)$$ **On large scales**

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

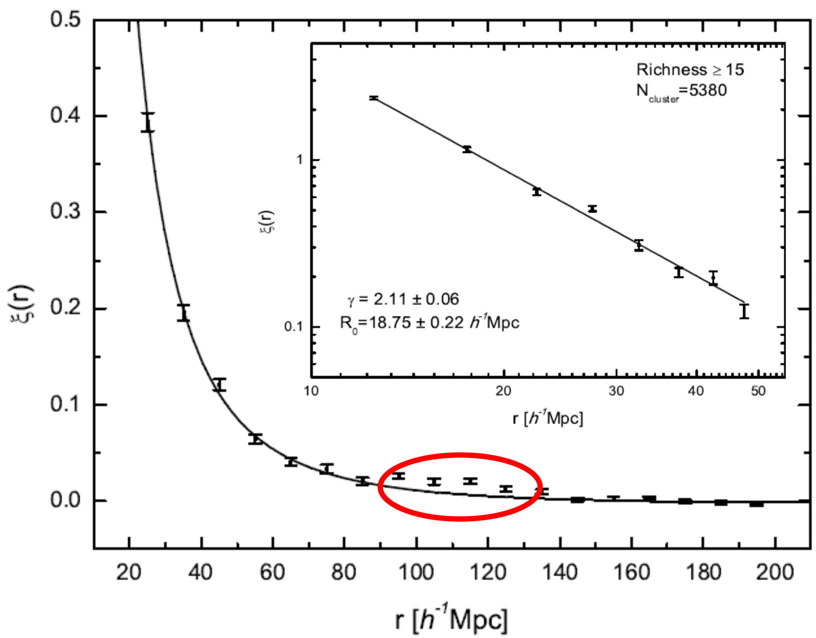
Suggested Exercise

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 γ ~ 2
- Correlation scale depends on the type of object:

  Galaxies: $r_0 \sim 5\ h^{-1}$ Mpc

  Clusters: $r_0 \sim 20\ h^{-1}$ 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: $$\langle \delta(\mathbf{k})\delta^*(\mathbf{k}')\rangle = (2\pi)^3 \delta^{\mathrm{D}}(\mathbf{k}-\mathbf{k}')P(\mathbf{k})$$

Correlation b/w Fourier modes

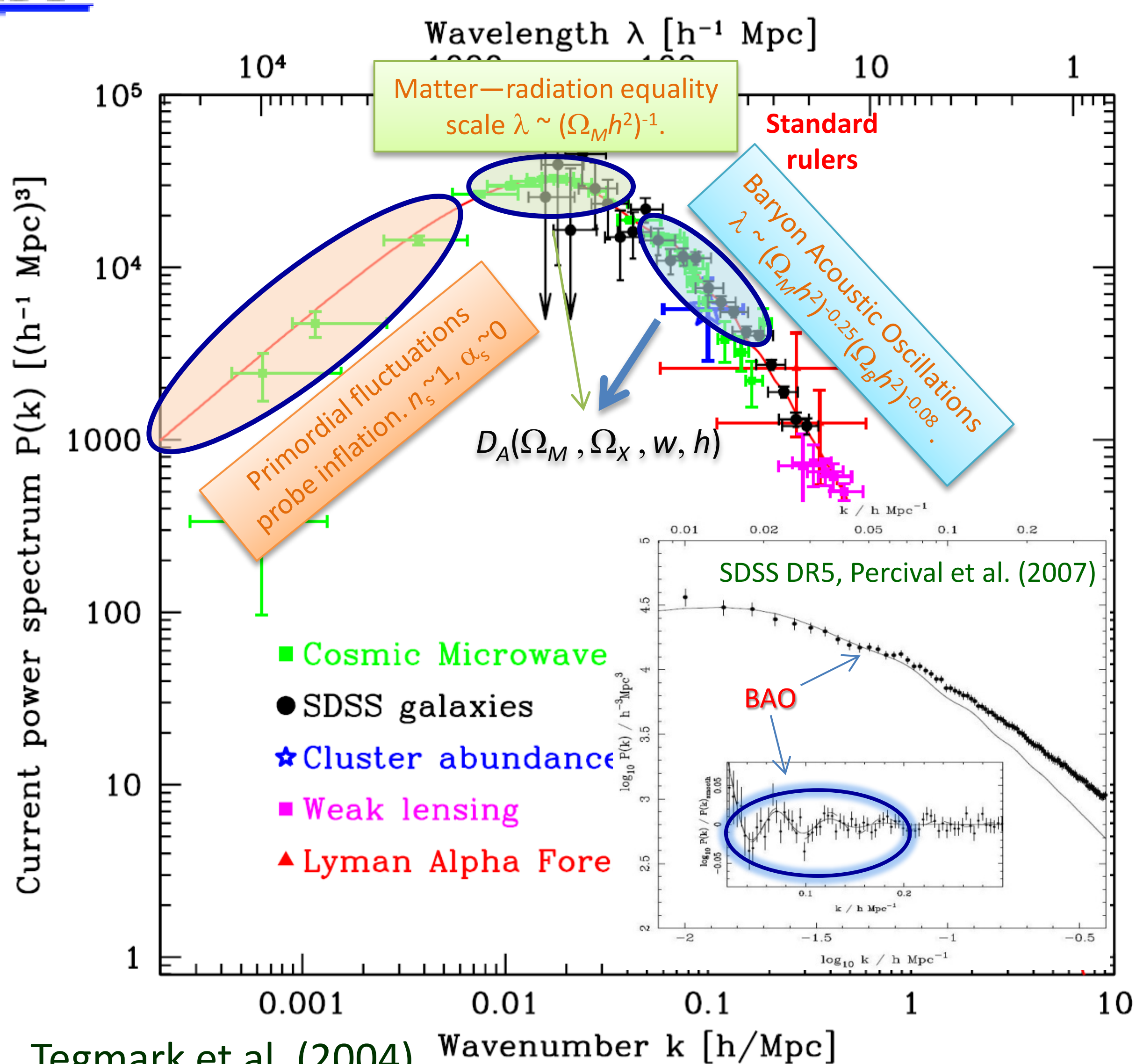
$$P(\mathbf{k}) = P(k)$$

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

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



Tegmark et al. (2004)

A Gaussian random field is completed 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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NAOC

Accelerated Cosmic Expansion

2011 Nobel Prize in Physics

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

Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

Adam G. Riess

Nobelprize.org

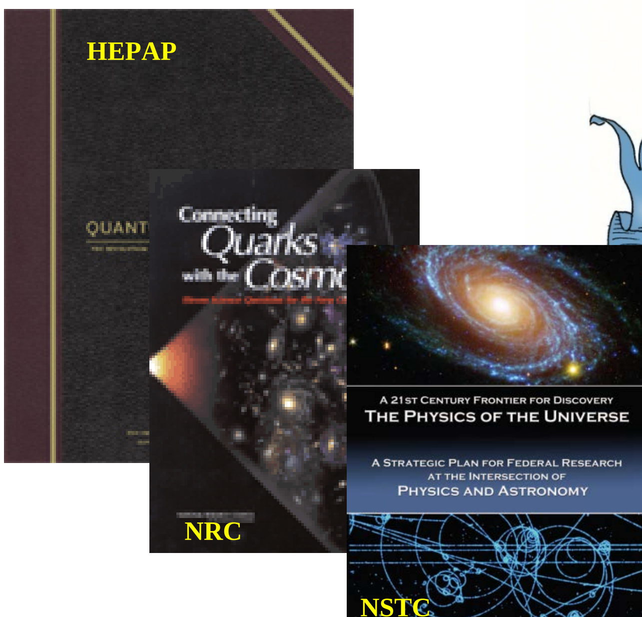
"Standardizable Candle"

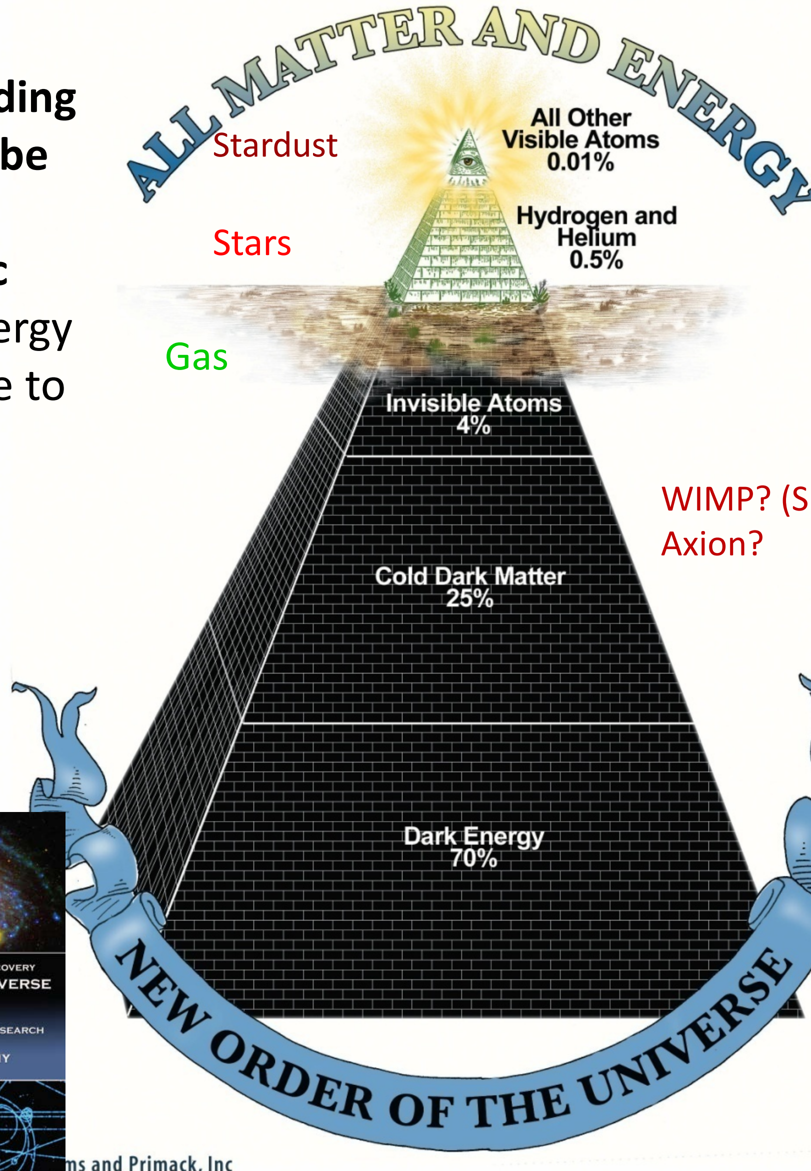
Image courtesy of David A. Hardy, © David A. Hardy/www

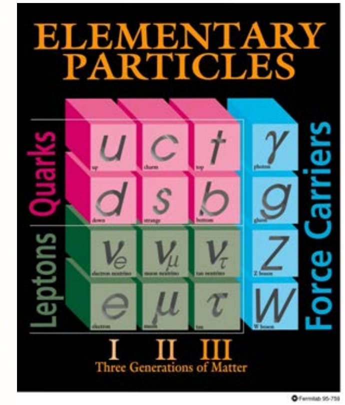
Type Ia supernova luminosity distances

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.







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

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

Accel. Expansion: Dark Energy

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

Hubble Parameter/
Friedmann Equation

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

Comoving Distance

$H = \dot{a}/a$

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

Growth of structure

$w = p_X/\rho_X$

effect of

Dark Energy

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

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

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

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

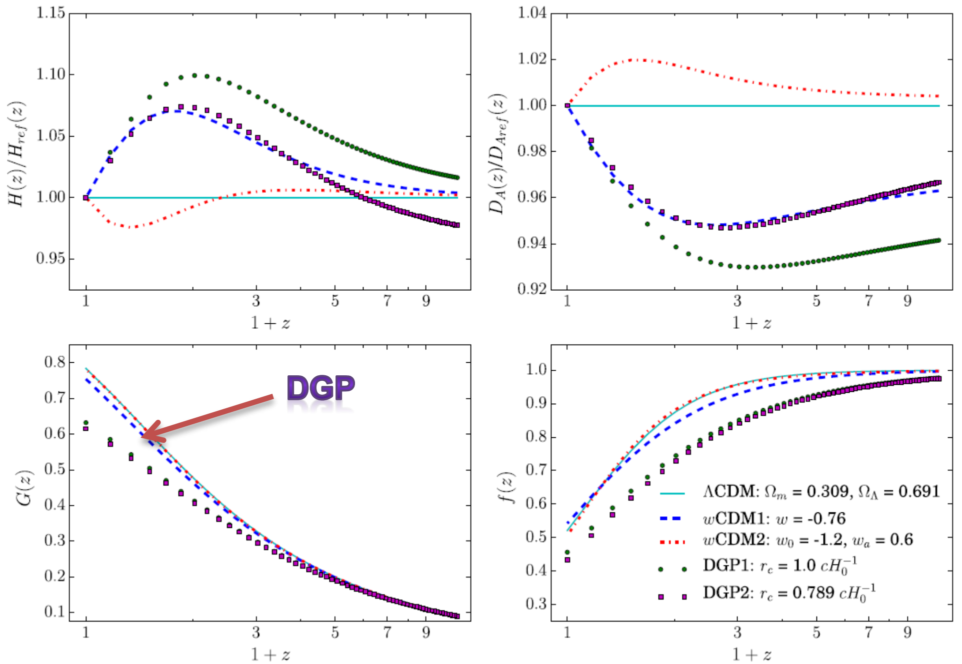
$$D_{\text{com}}(z) = \int_0^z \frac{c}{H(z)}dz$$

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

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 branewold (Dvali, Gabadadze, & Porrati 2000)



Zhan & Tyson (2018)
1707.06948

Accel. Expansion: More

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

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

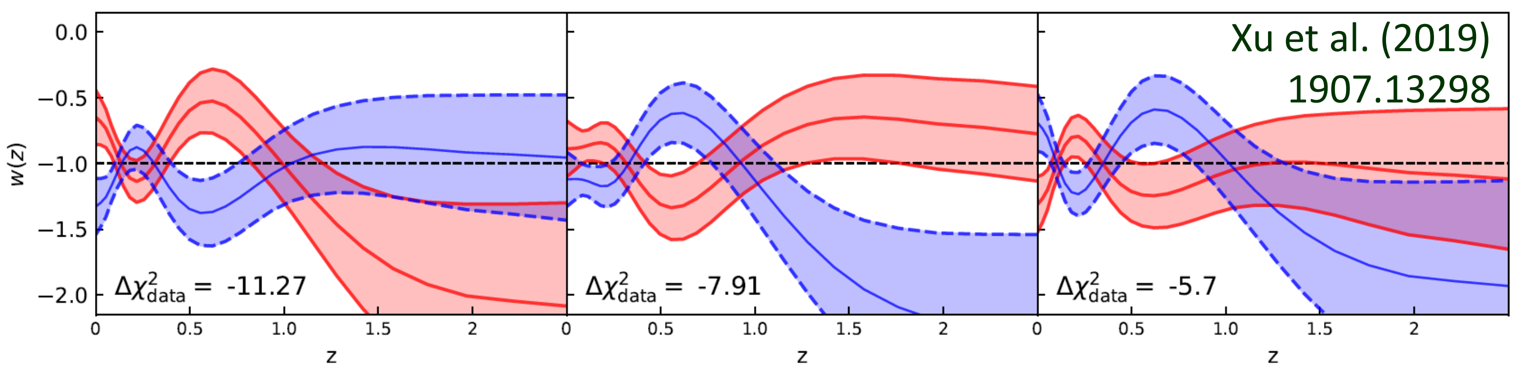
$$ds^2 = -(1+2\Psi)dt^2 + (1+2\Phi)a^2\delta_{ij}dx^i dx^j$$

The two metric perturbations might not be equivalent.

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

Dark Energy **Modified Gravity**

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!

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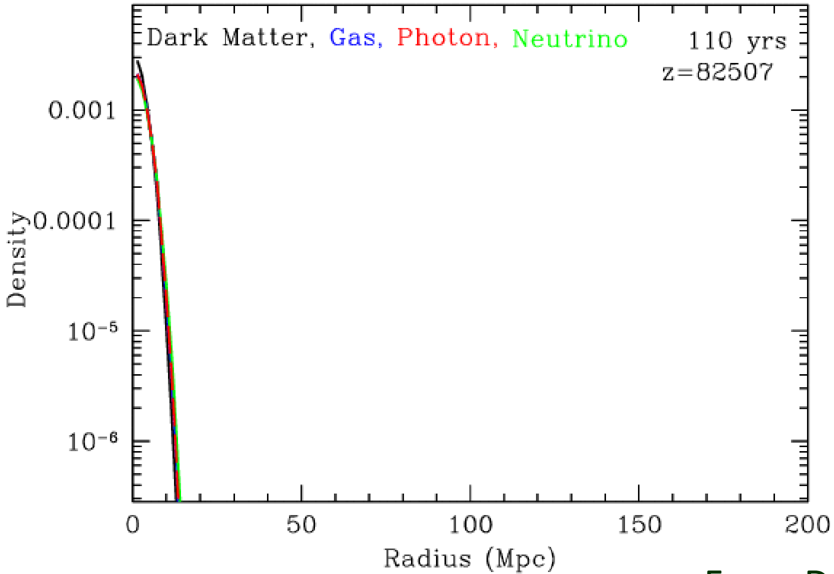
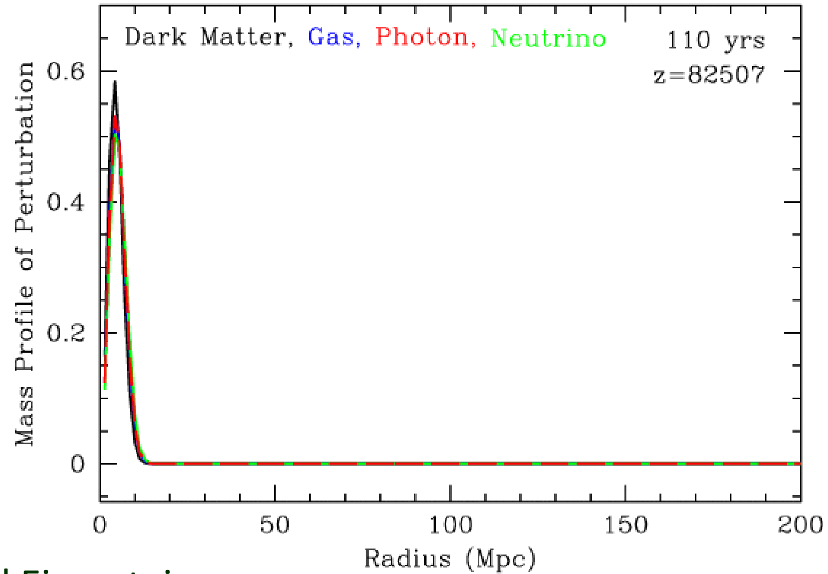
Perturbations around Recombination





From Daniel Eisenstein

Curvature perturbations →

Pressure imbalance in photon—baryon fluid →

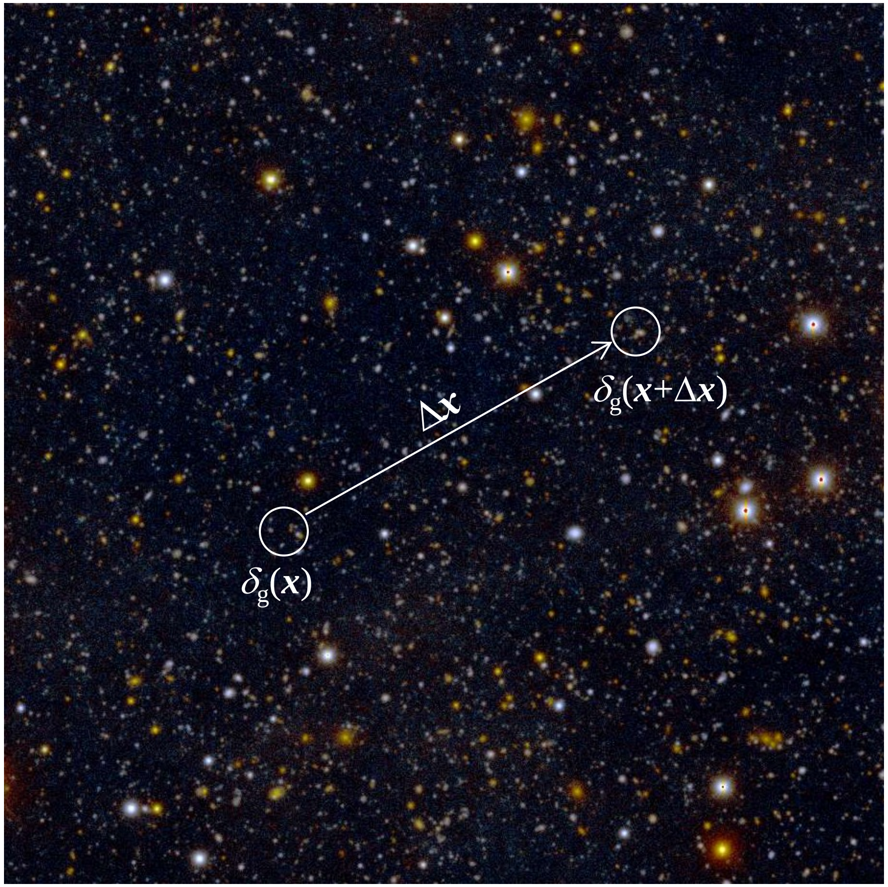
Sound waves (baryon acoustic oscillations) travel at ~ c /√3 before recombination and ~ 0 afterward →

Comoving sound horizon (R_S ~ 150 Mpc) freezes →

Excess correlation of density fluctuations at 150 Mpc →

Excess correlation of galaxies at 150 Mpc.

BAO Detection

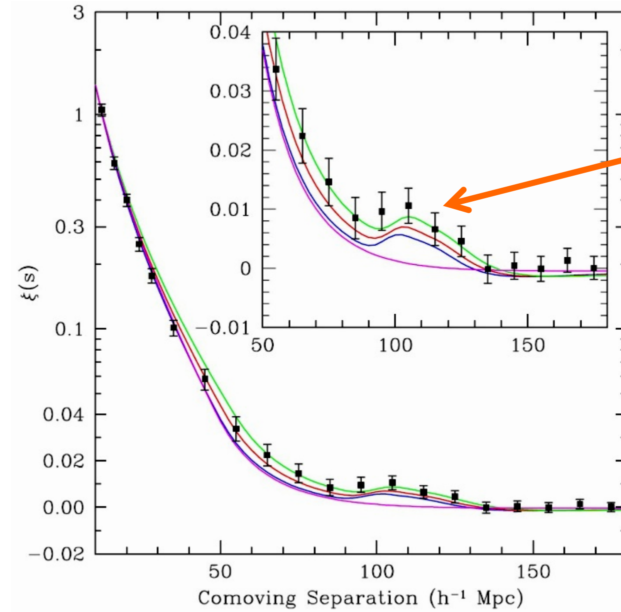


Deep Lens Survey, Tyson & Wittman

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

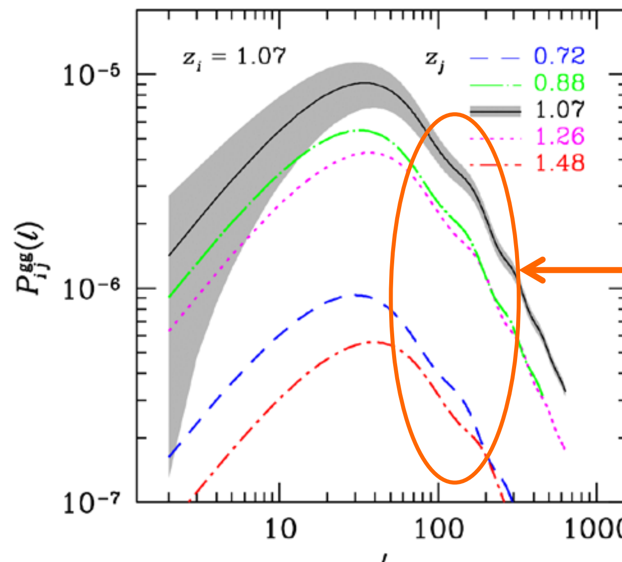
$$\xi(\Delta x) = \xi(\Delta \mathbf{x}) = \langle \delta_g(\mathbf{x}) \delta_g(\mathbf{x} + \Delta \mathbf{x}) \rangle$$ Correlation Function

$$P(k) = \mathrm{FT}\ \xi(\Delta x)$$ Power Spectrum



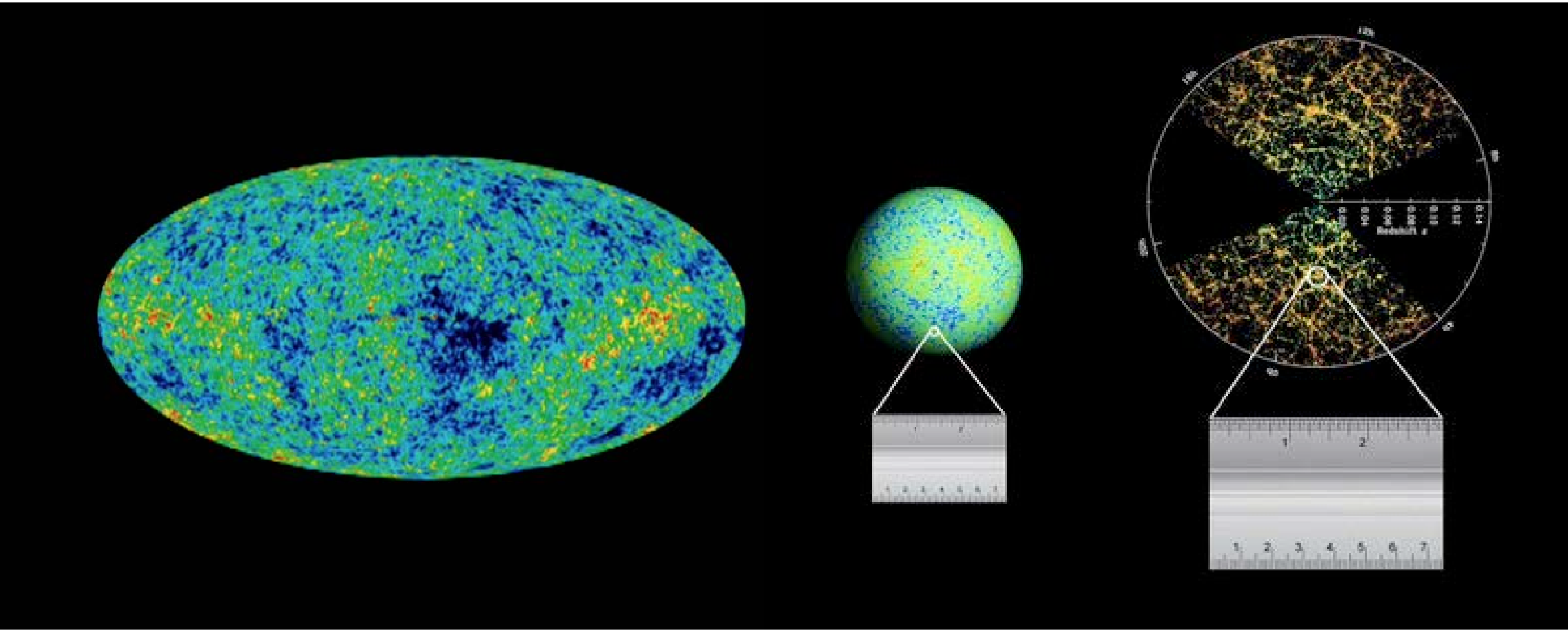
Baryon Acoustic Oscillations

SDSS LRGs Eisenstein et al (2005)



Baryon Acoustic Oscillations in multipole space

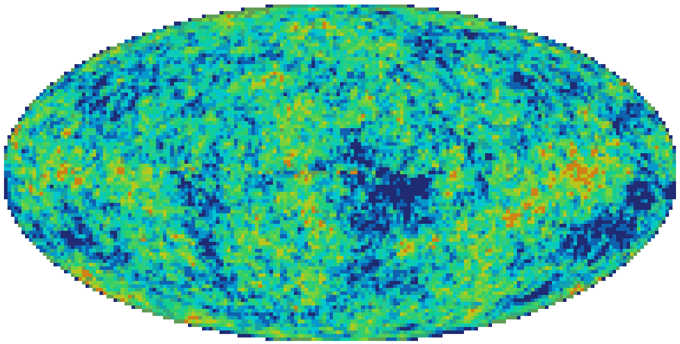
BAO: A Cosmological Probe



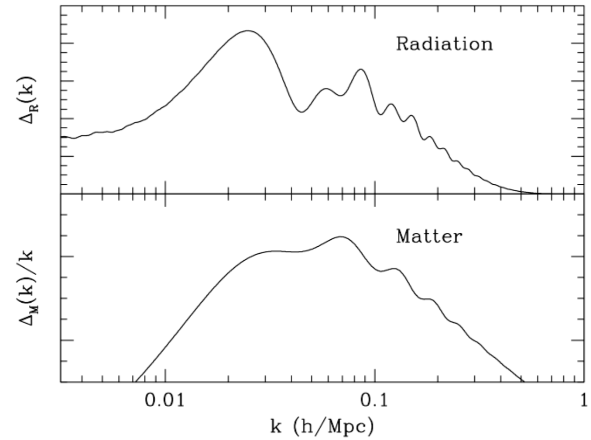
WMAP media @ map.gsfc.nasa.gov

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

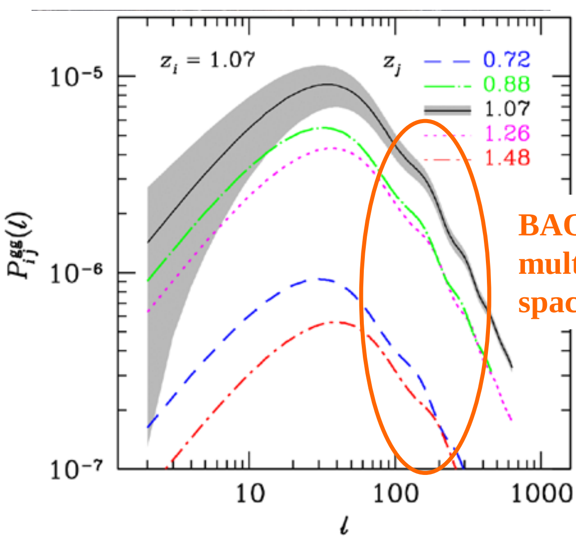
BAO: A Cosmological Probe



CMB temp. fluctuations (WMAP)



Imprints on the matter power spectrum (White 2005)



BAOs in multipole space

LSST galaxy angular PS
Zhan (2006)

R_S~150 Mpc

(Sound horizon at recombination)

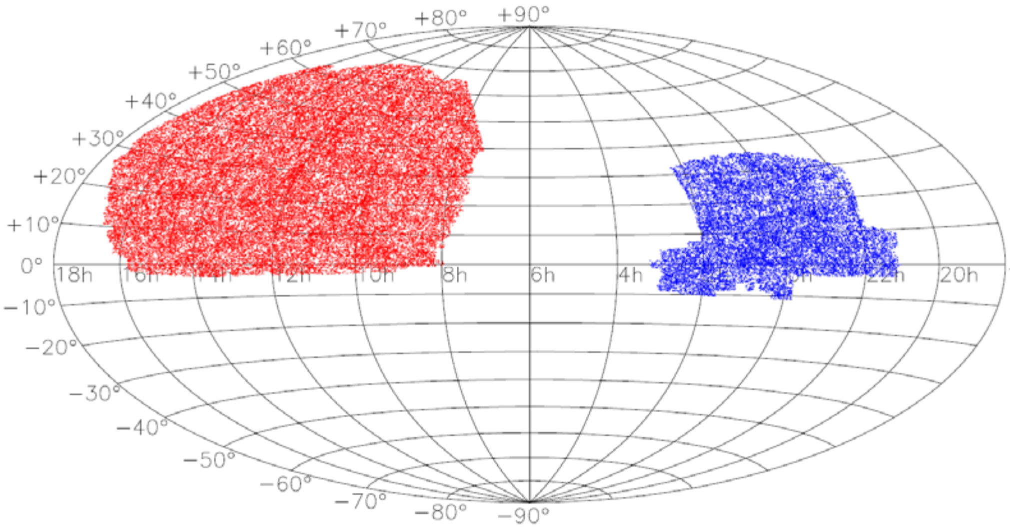
Angular diameter distance

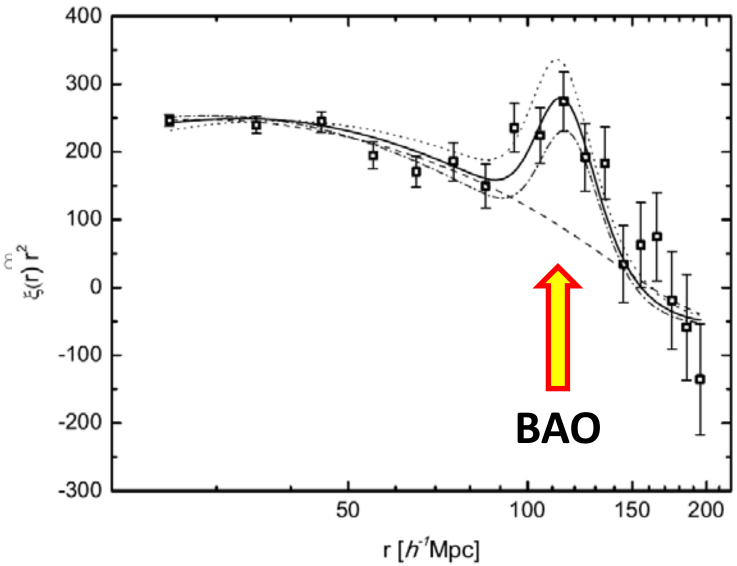
$R_S = \Delta\theta D_A$

$= c\Delta z/H$

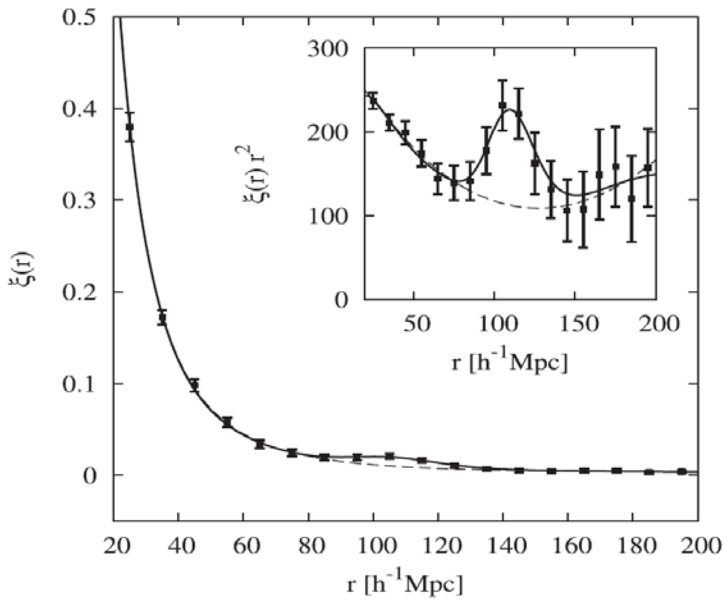
Redshift distortion➔
Growth rate➔ Test gravity

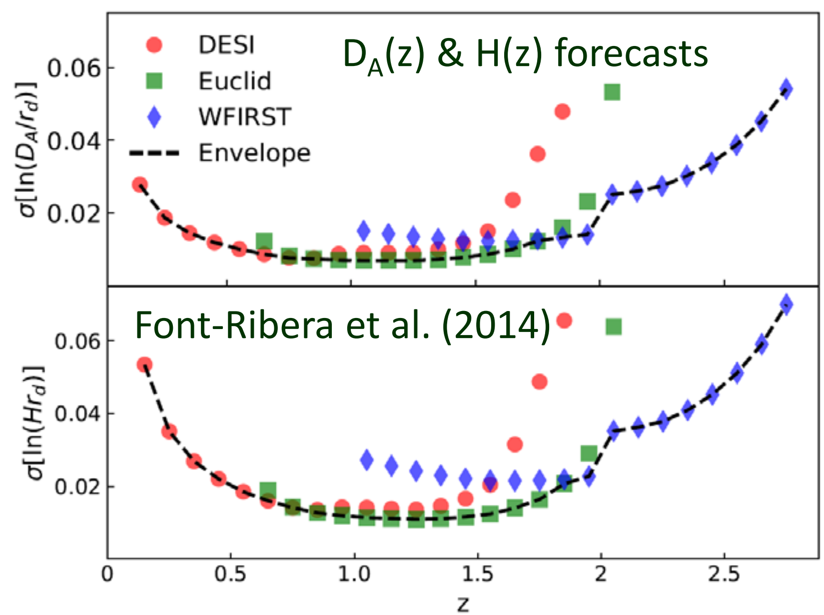
BAO Measurements





Hong et al. (2012, 2016)





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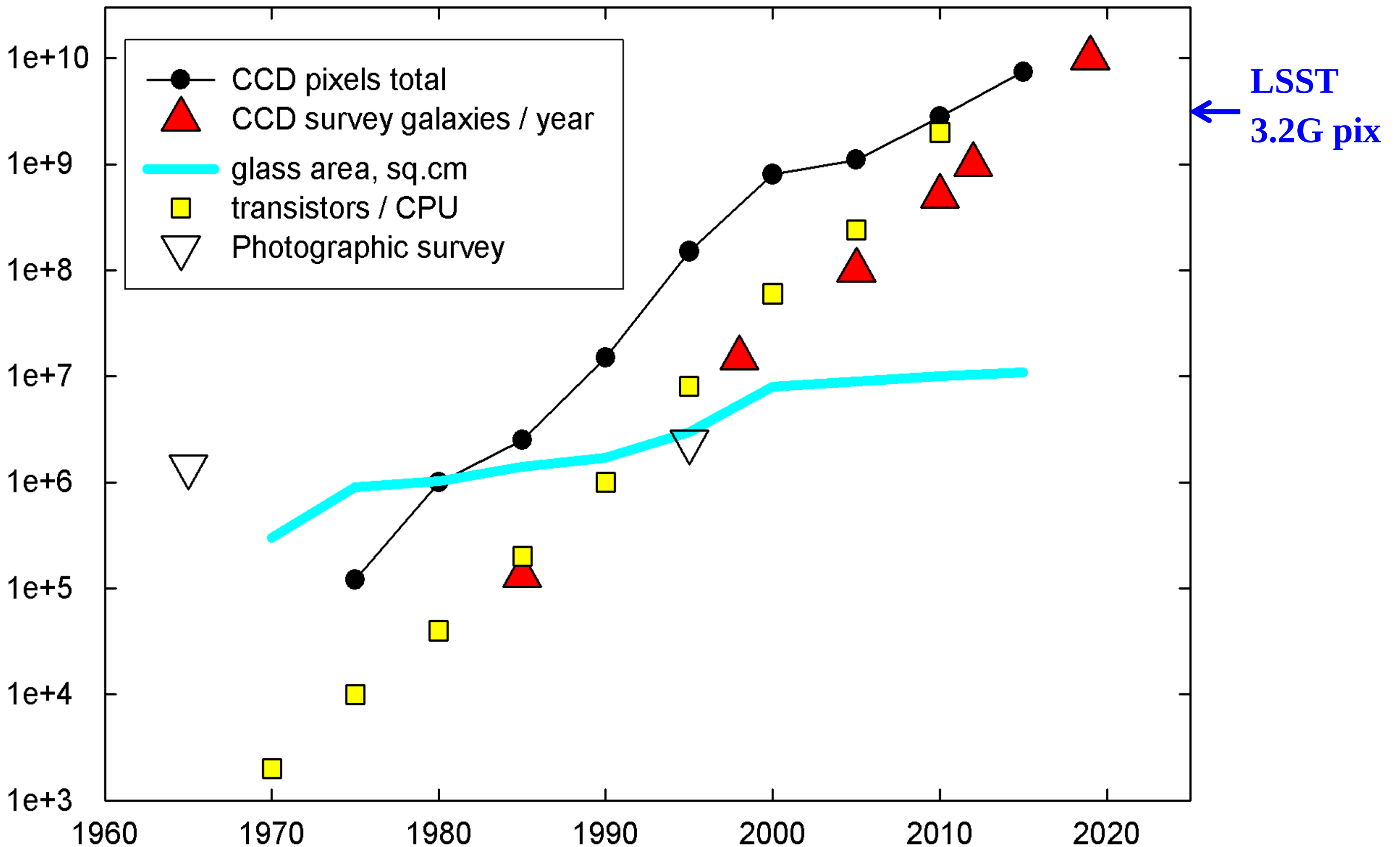
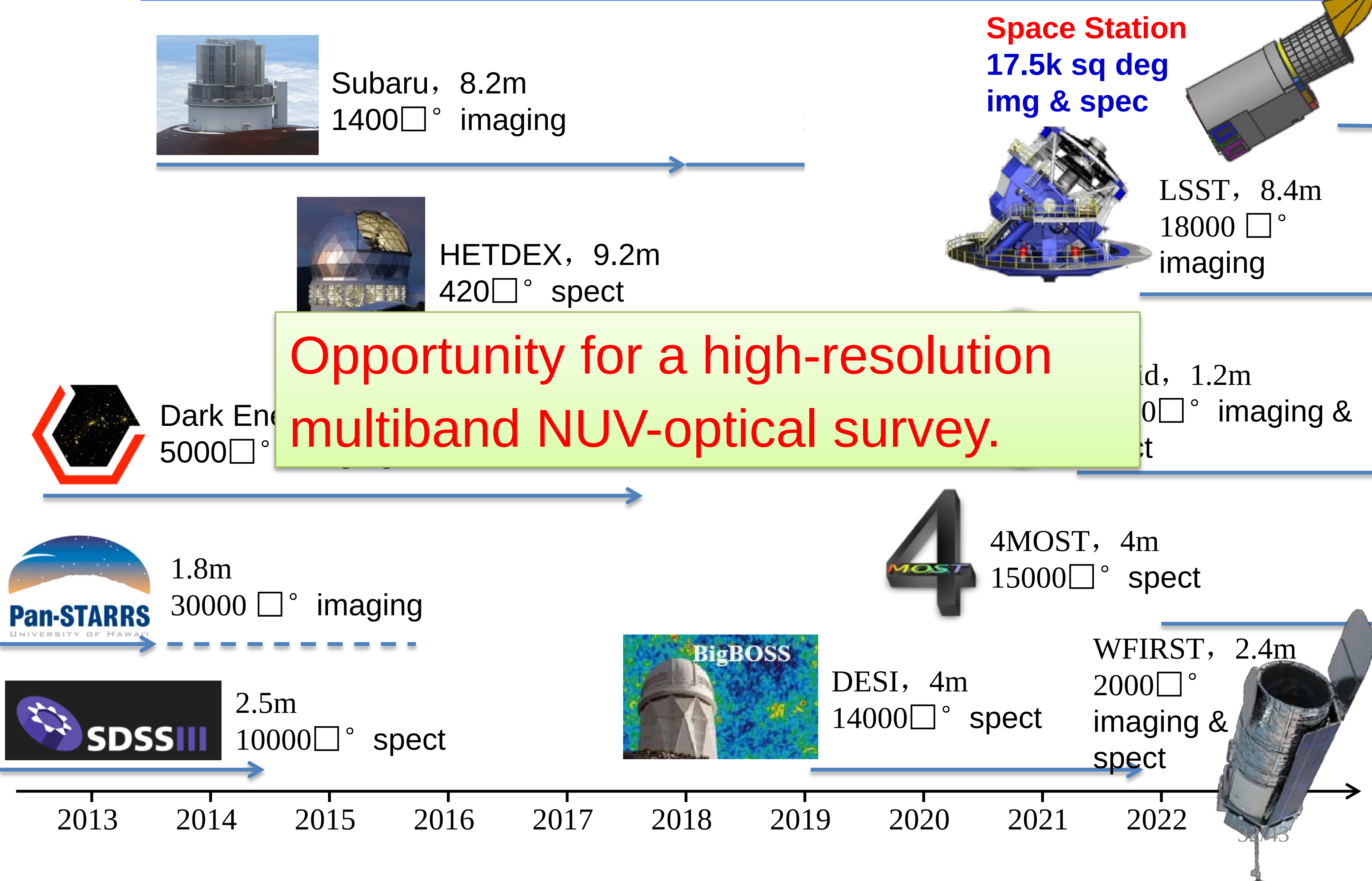
Trends in Optical Astronomy



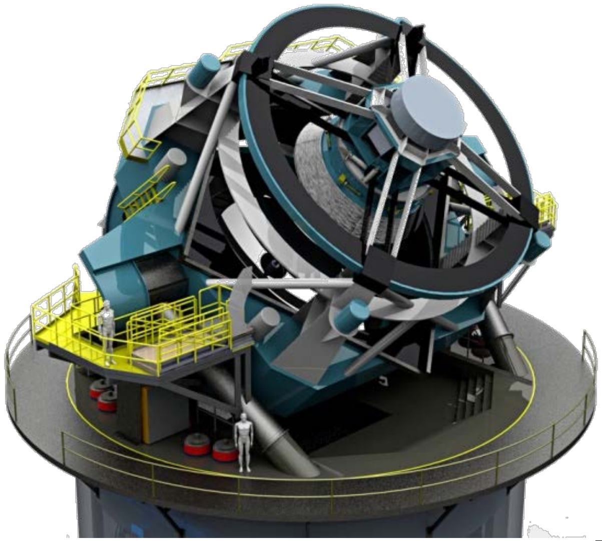
Survey projects open up enormous discovery space for astronomy!

Optical/IR Survey Landscape



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

Large Synoptic Survey Telescope



- 8.4-meter primary
- 9.6 deg^2 FOV
- 3.2 billion pixels
- 0.3–1.1 µm *ugrizy*
- 15-s exposures
- 18,000 deg^2
- **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

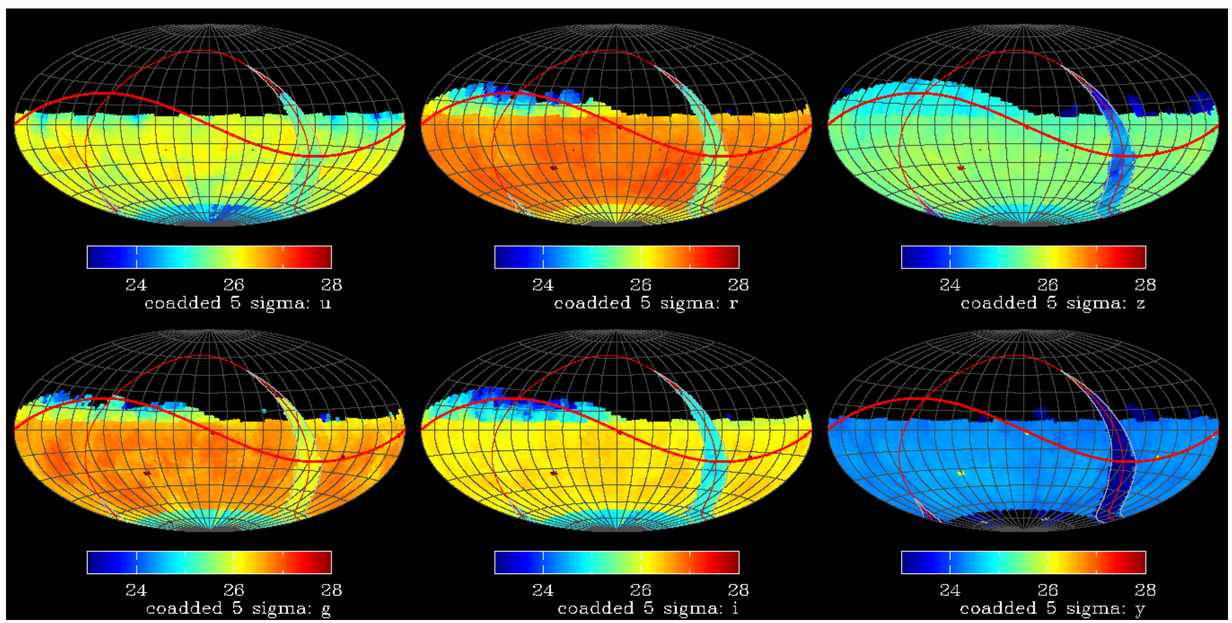
Science Drivers

Dark Energy

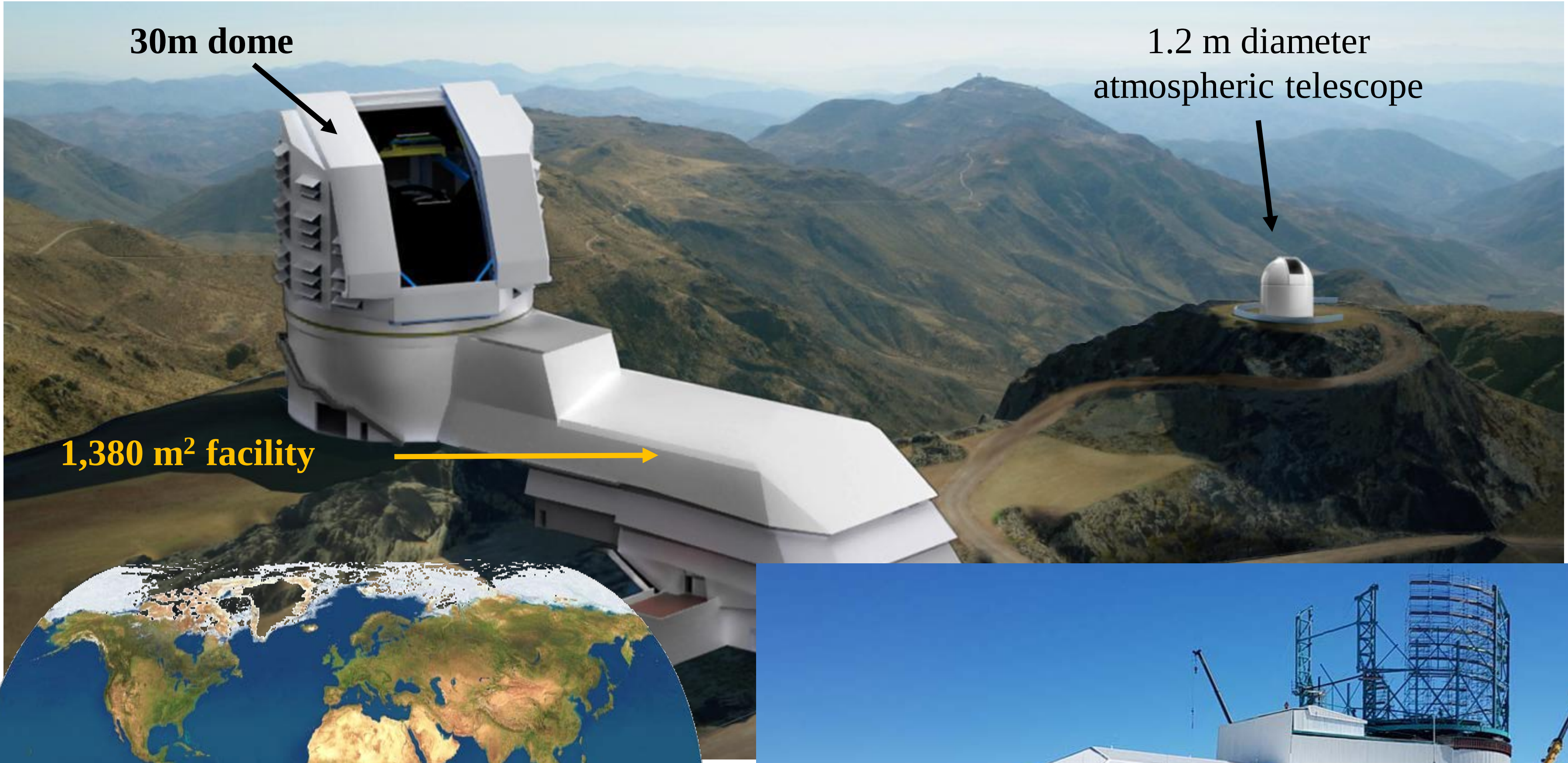
Transients

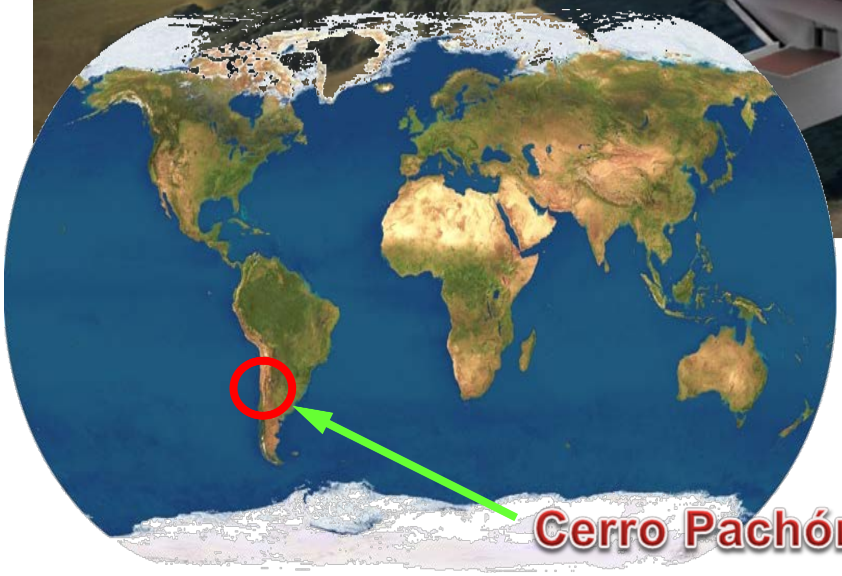
Solar System

Galactic Map

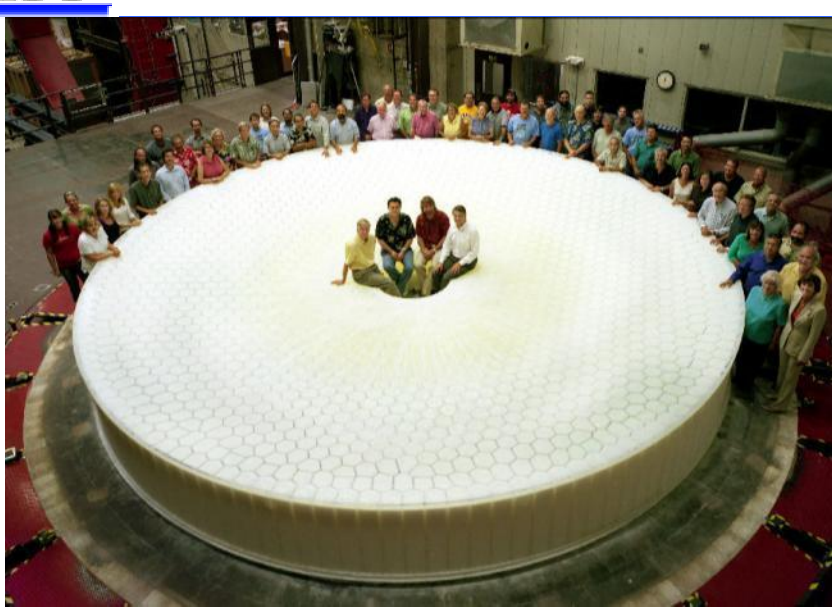


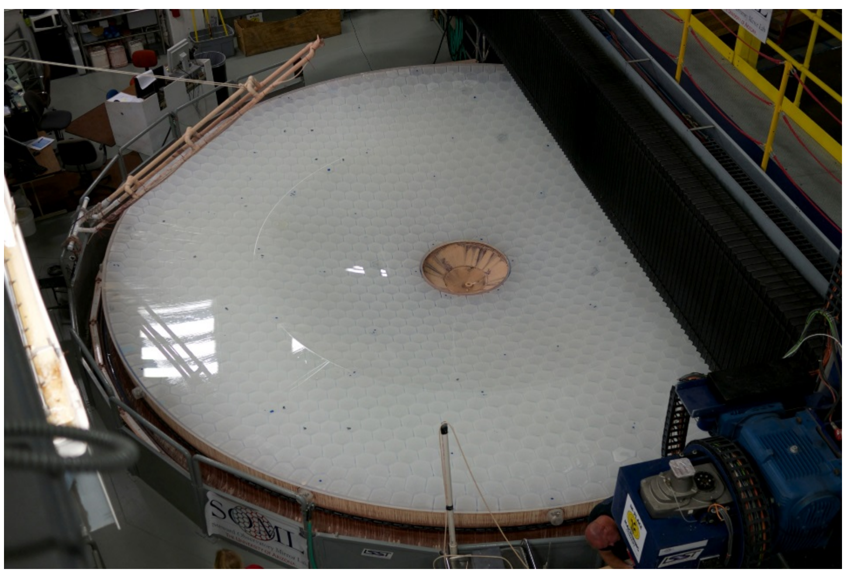
LSST Site: Cerro Pachón, Chile



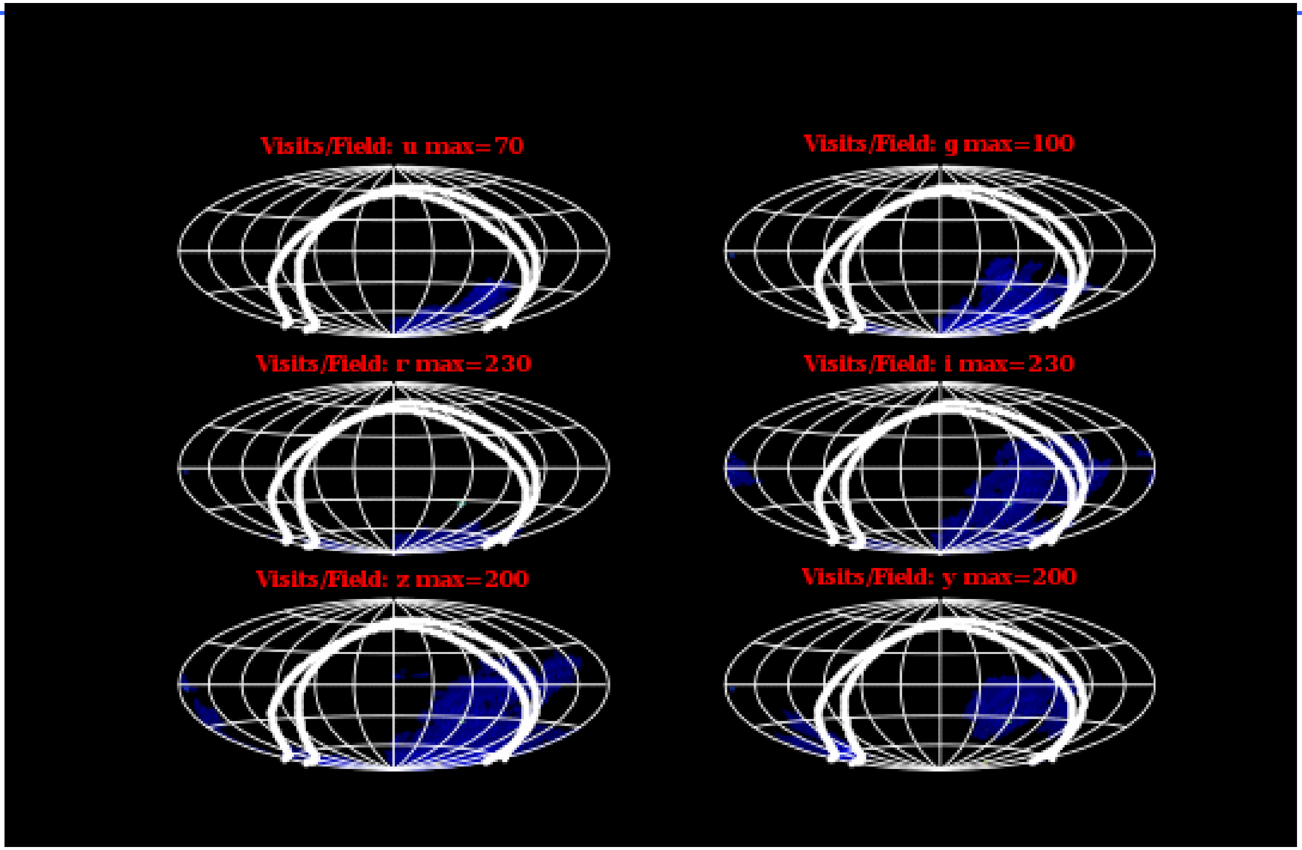


LSST Mirrors & Telescope Structure





LSST Operations Simulations



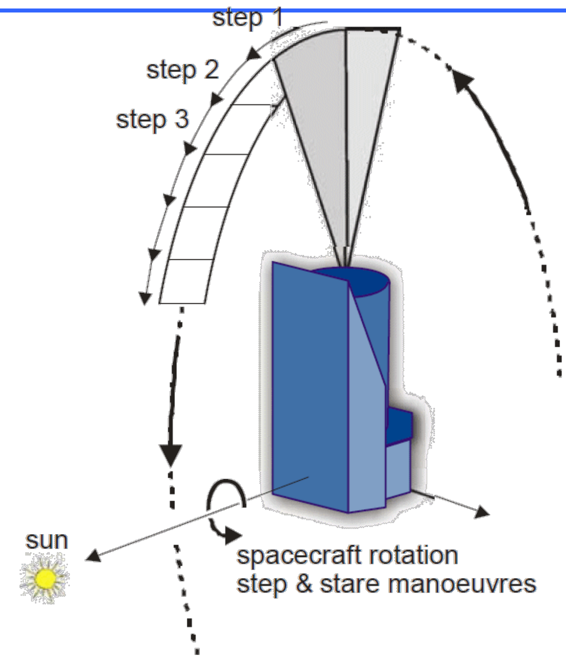
Each field will be observed 800+ times.

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

Flux, position, shape…

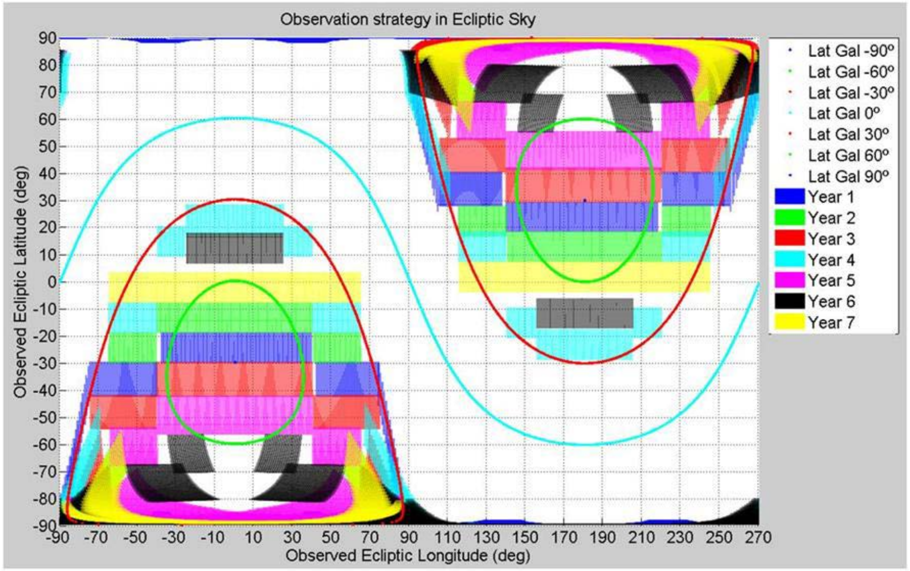
Euclid

- 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

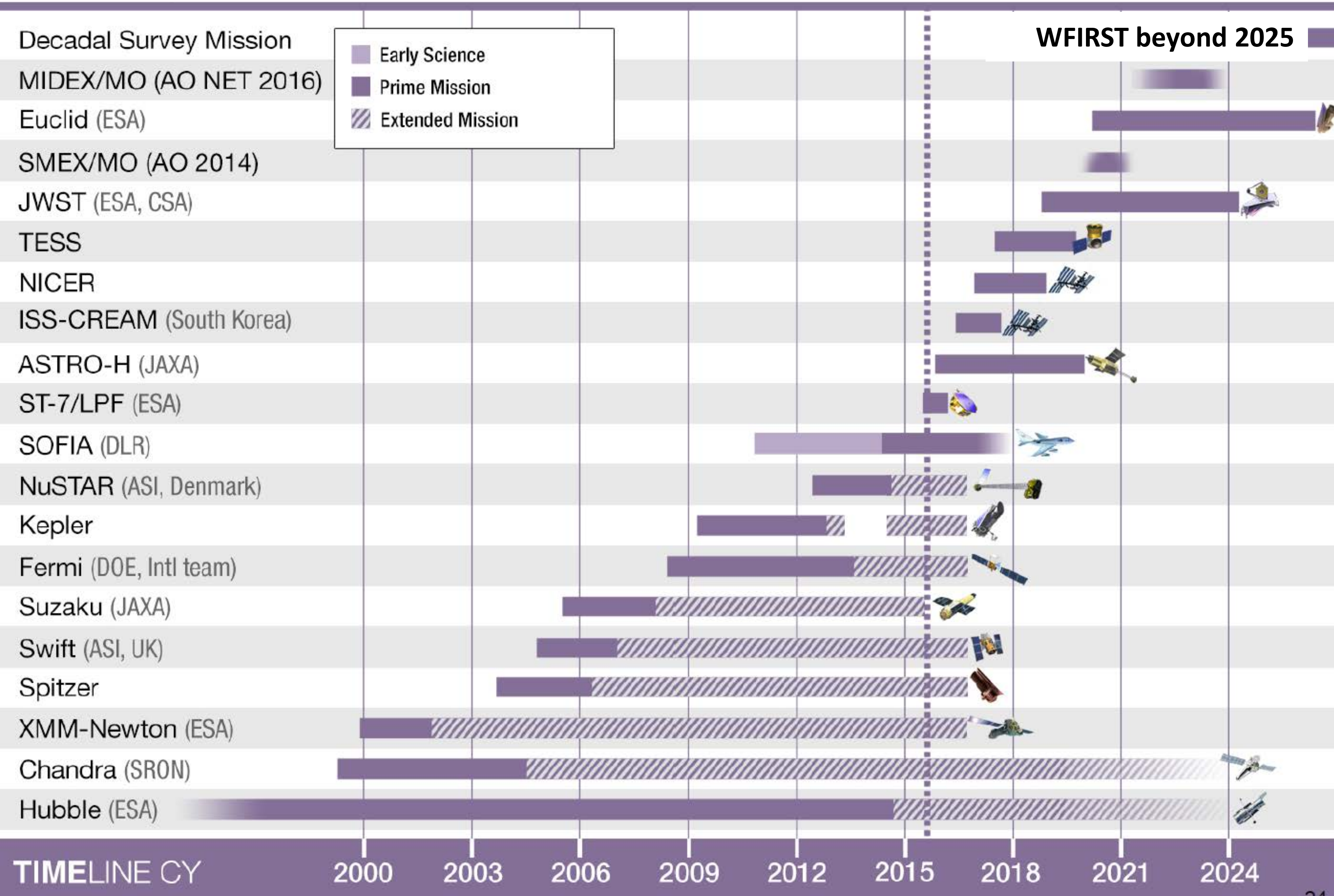


optical：24.5 mag (10σ extended src)
Y、J、H: 24 mag (5σ point src)
1.1—2μm: grism R=250

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



Astrophysics Timeline



Dates beyond 2016 are contingent upon the results of the 2016 Senior Review

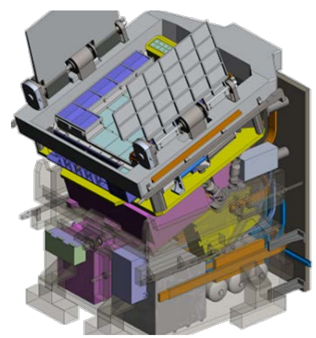
Optical Module for Astronomy

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

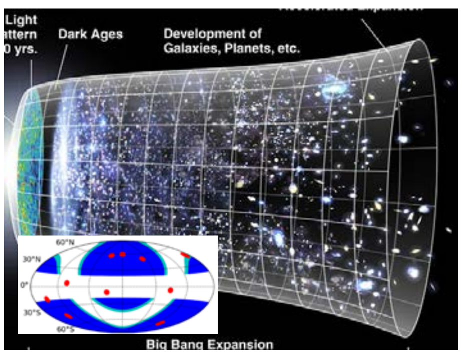
Instruments: **Survey Camera (SC), Terahertz Receiver (THz), Multichannel Imager (MCI), Integral Field Spectrograph (IFS), Cool-Planet Imaging Coronagraph (CPIC).**

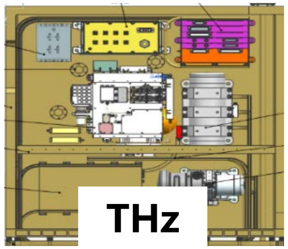
Mission: **wide-area multiband imaging & slitless spectroscopic survey (7yr); other key programs & GO programs (2+yr).**

Optical Module (~2024)

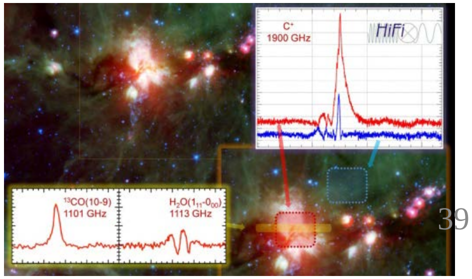


Survey Cam





THz



Optical Module for Astronomy

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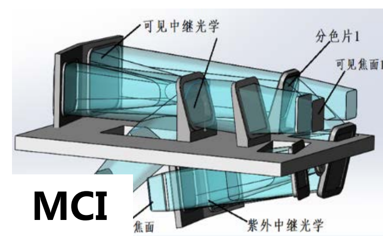
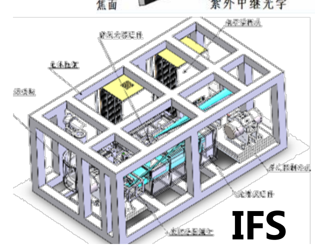
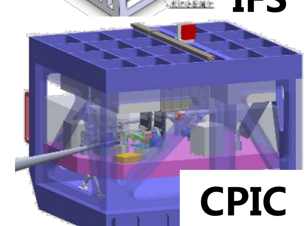
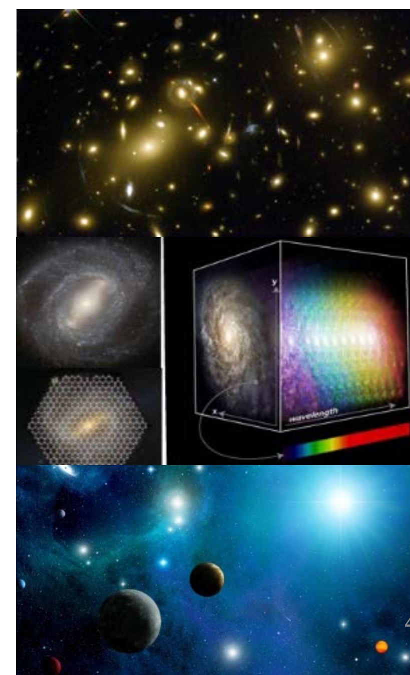


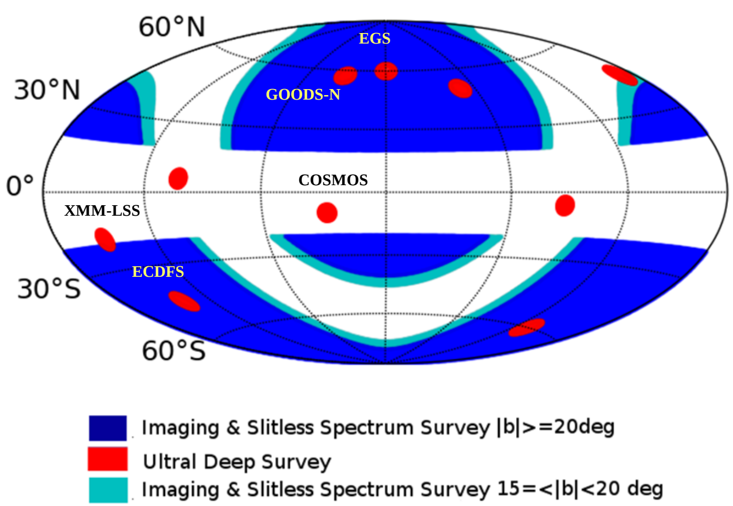






Survey Specs

- 17500□° imaging : 255-1000nm, ≥6 filters, avg ≥25.5^m (5σ, point source, AB mag);
- 17500□° slitless spect: 255-1000nm, R≥200, ≥22-23^m;
- 400□° 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-zs, dwarfs, LSBs, near field, halos properties…

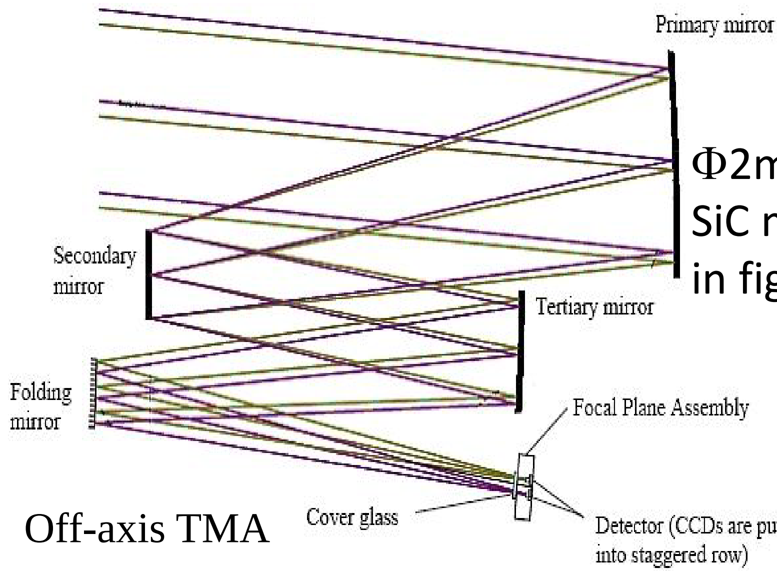
Milky Way: structure, satellites, dust, extinction…

Stellar science: formation, dwarfs, metal poor…

Solar system (high inclination): TNO、NEA…

Astrometry: reference frame, star clusters…

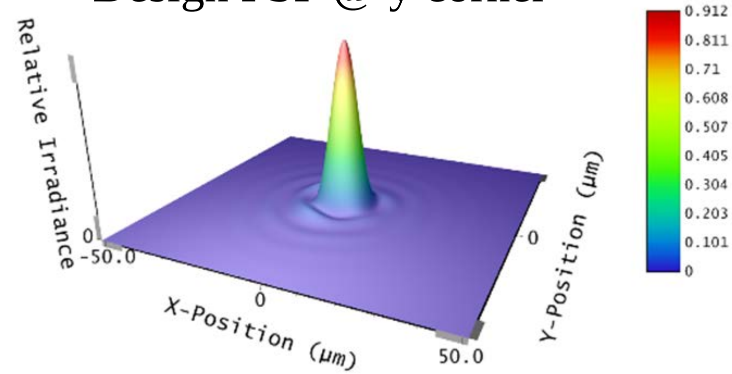
Optical Design & Survey Camera



Φ2m
SiC mirror
in figuring

Off-axis TMA

Design PSF @ y corner



Requirements

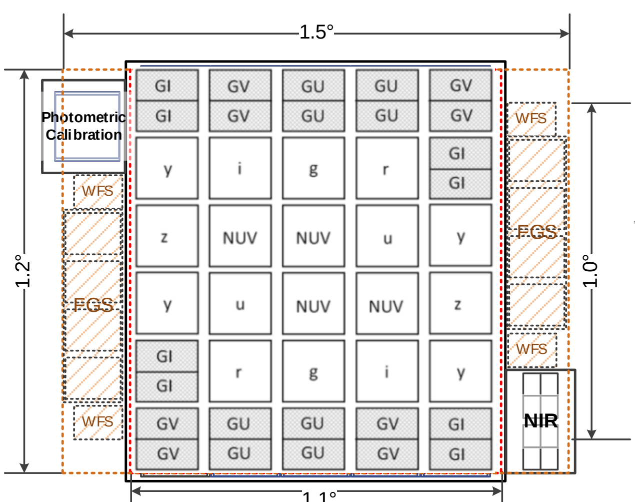
$R_{EE80} \leq 0.15$" @ 632.8nm

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

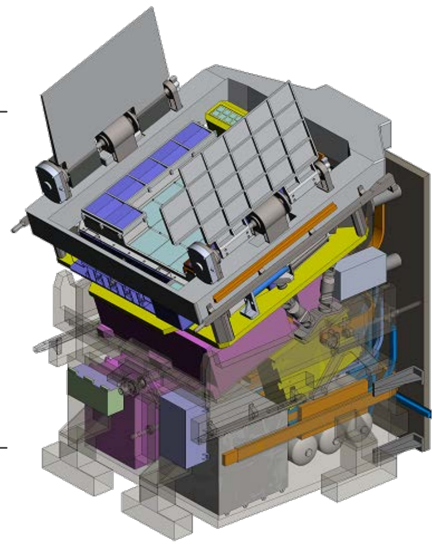
PSF + jitter sim

$R_{EE80} < 0.13$"

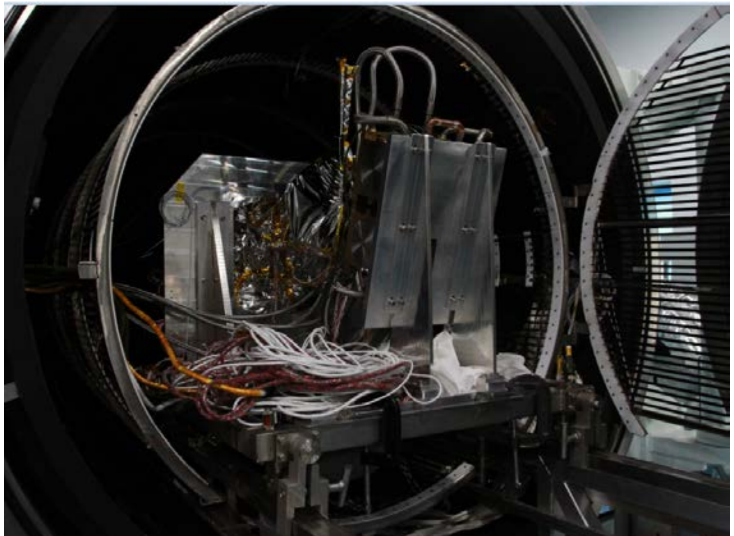
Pixel size 0.074"



Central FoV >1.1 sq deg



Survey Cam



Cryo cooling test

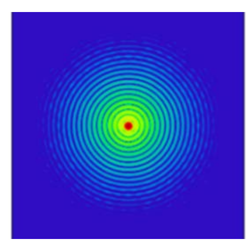
Comparison with Other Surveys

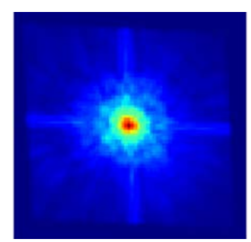
Project	Site/ orbit	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num Filters	Spect
			deg^2	″	10^9	deg^2	nm		
CSS-OS	LEO	~2024	**1.1**	**0.15** **0.074/pix**	**2.5**	**17500**	**255**—1000	≥6	yes
Euclid	L2	~2022	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	no yes
WFIRST	L2	>2025	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

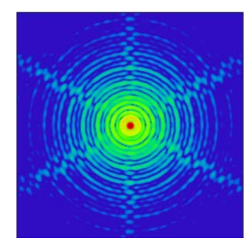
R_{EE80}: radius encircling 80% energy

	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"

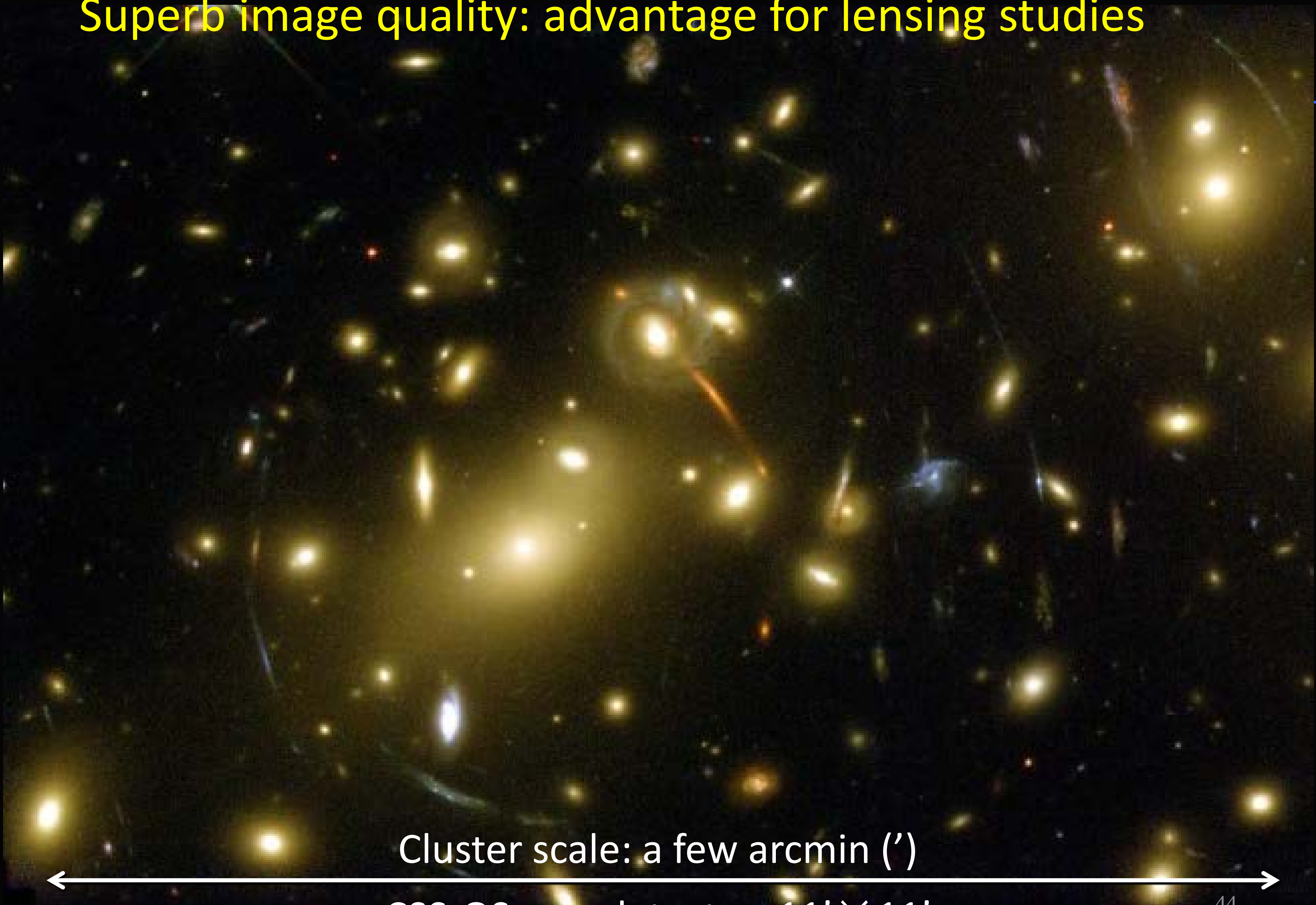
Dynamic sims: R_{EE80} ~0.13”


CSS-OS


HST


Euclid

Superb image quality: advantage for lensing studies

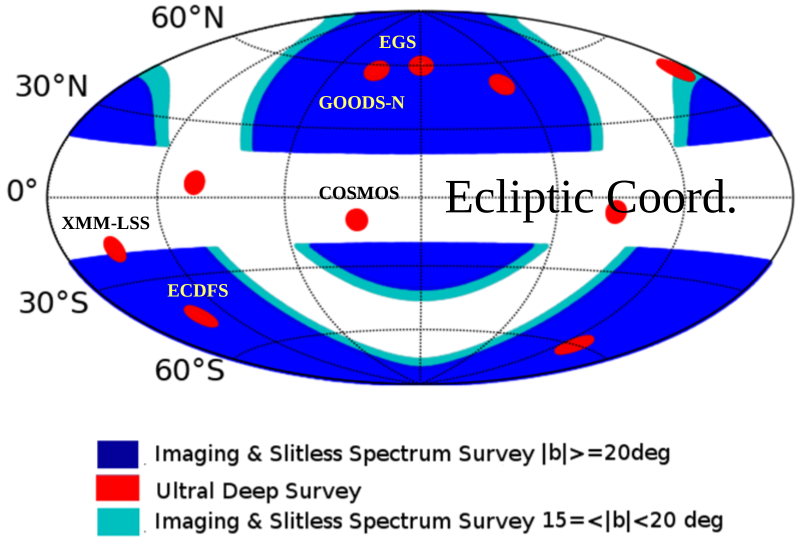


Cluster scale: a few arcmin (’)

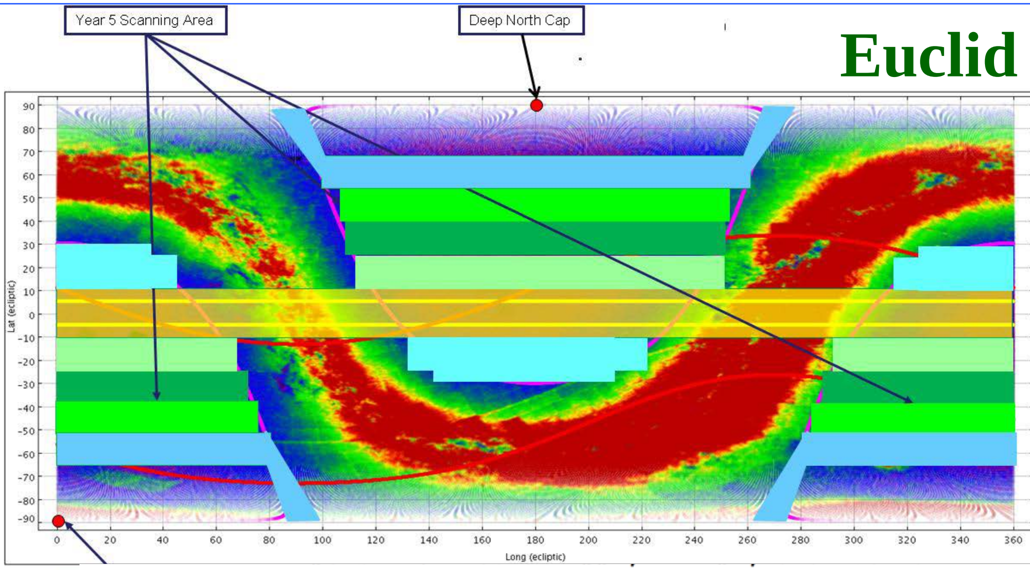
CSS-OS cam detector: 11’ × 11’

Complementary Observations

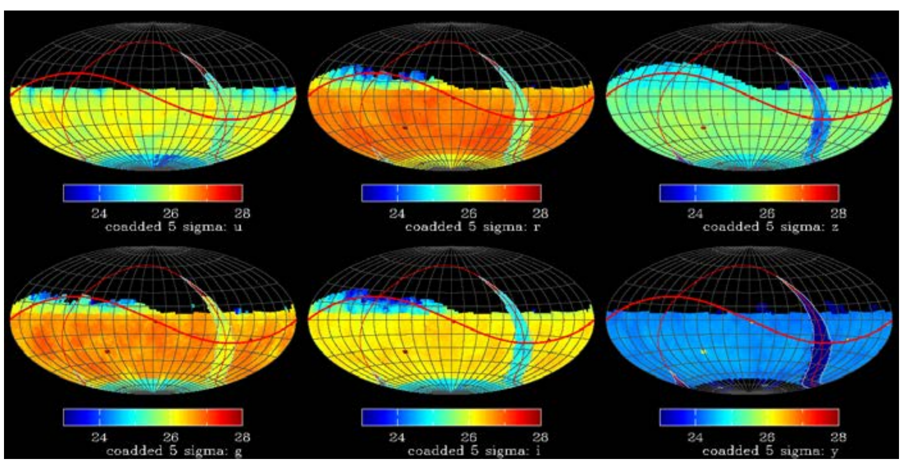
CSS-OS

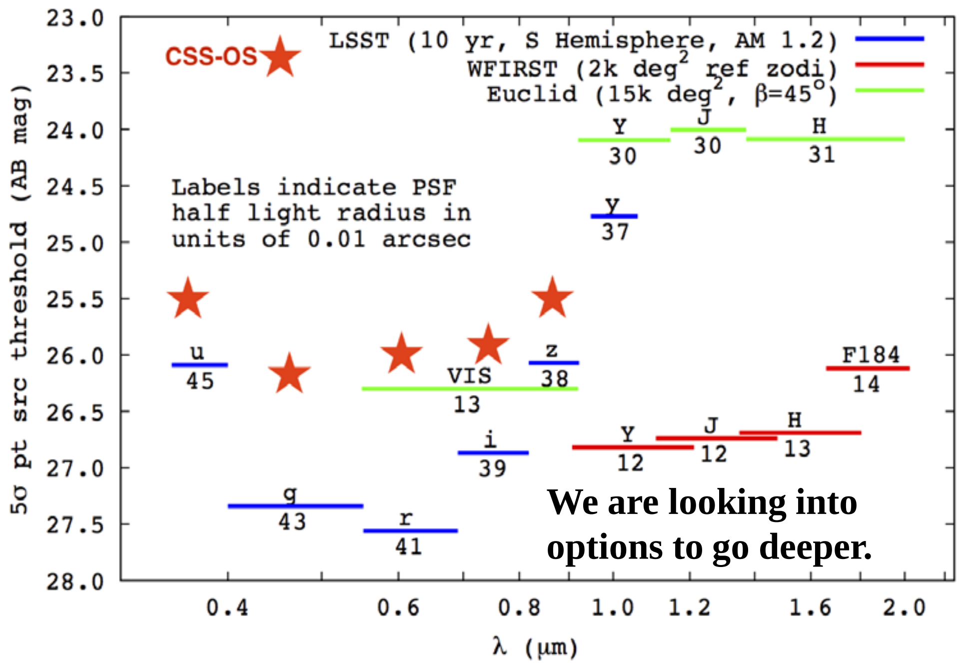


Euclid



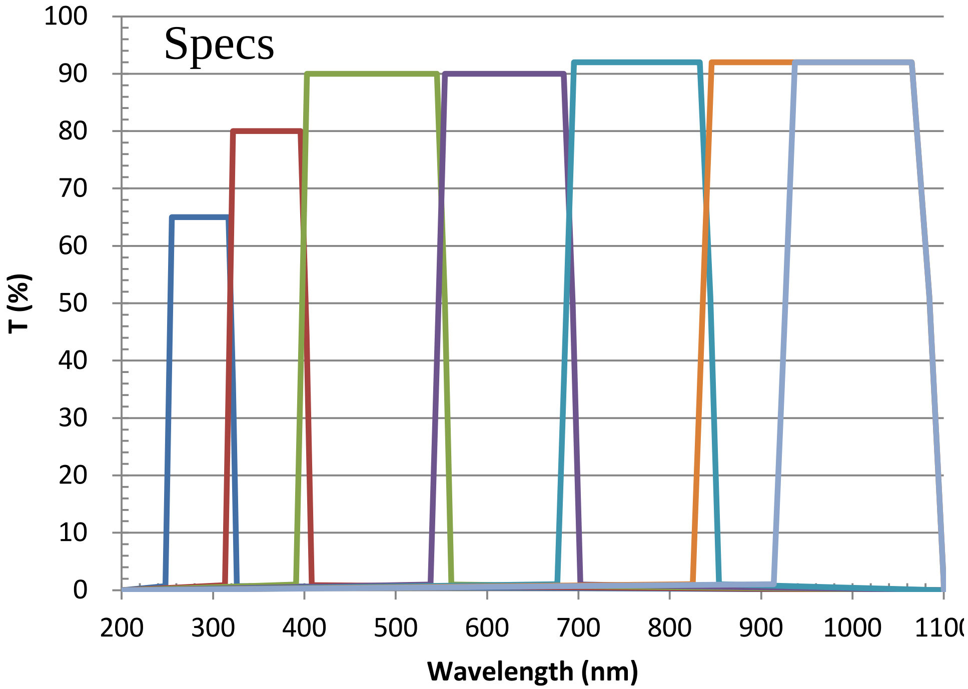
LSST

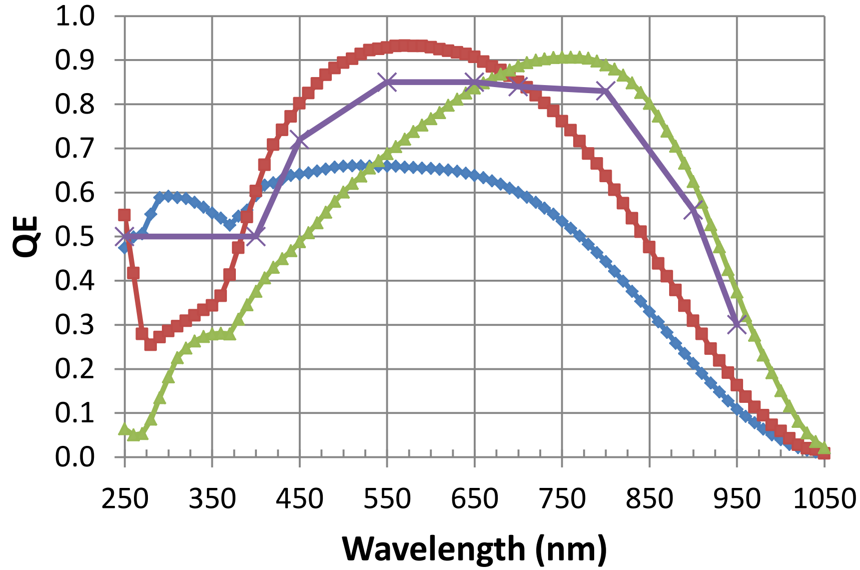




We are looking into options to go deeper.

Filters & Limiting Mags



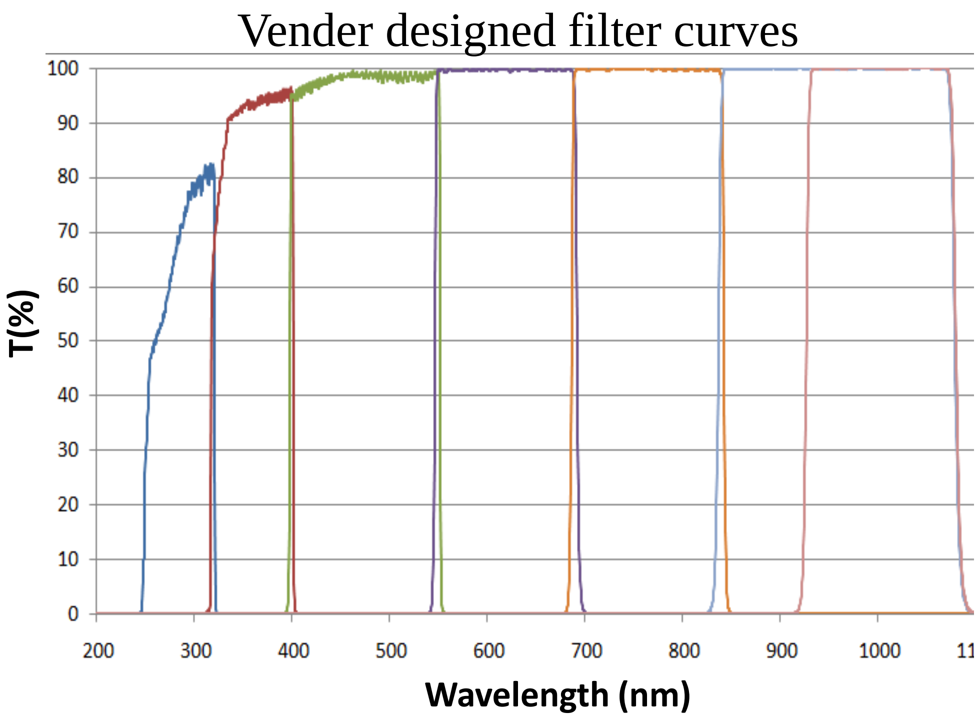


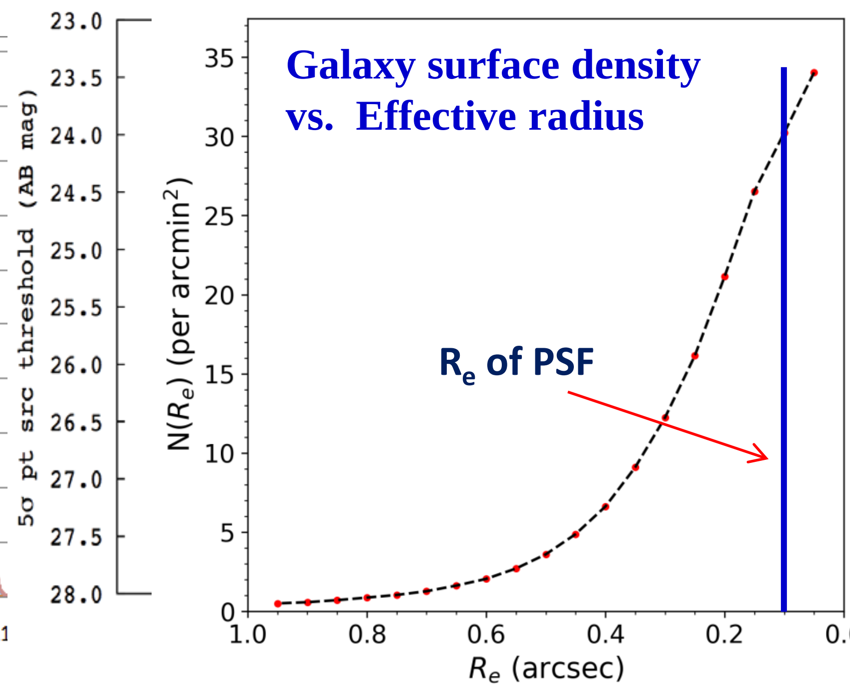
	t_{exp}	NUV*	u	g	r	i	z	y*
17500□°	2×150s	25.4	25.4	26.2	25.9	25.8	25.2	24.5
400□°	8×250s	26.7	26.7	27.4	27.1	26.9	26.4	25.7

*NUV & y: 4×150s

w/ ~0.2^{m} margin from design

Filters & Limiting Mags



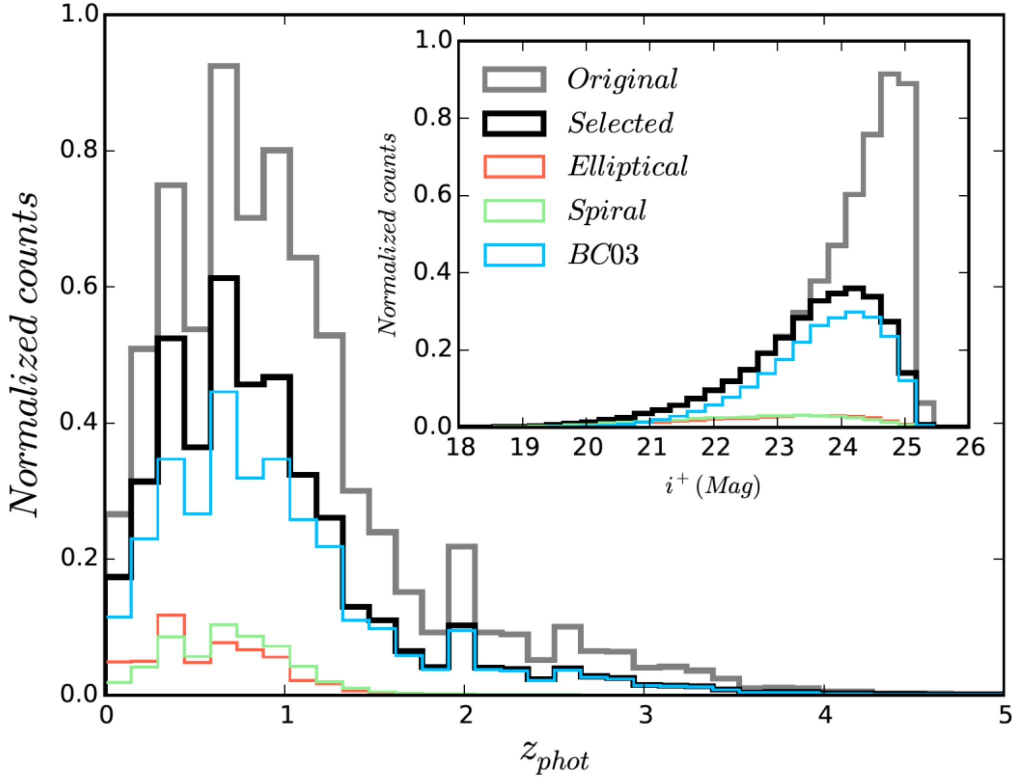


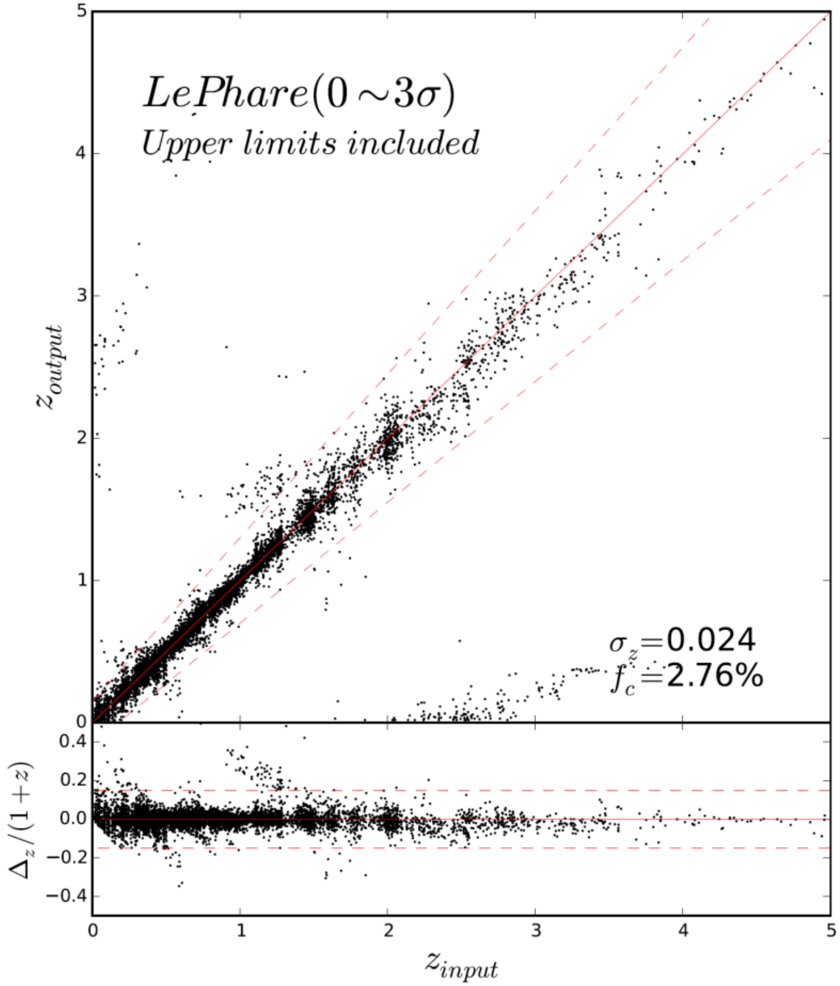
	t_{exp}	NUV*	u	g	r	i	z	y*
17500□°	2×150s	25.4	25.4	26.2	25.9	25.8	25.2	24.5
400□°	8×250s	26.7	26.7	27.4	27.1	26.9	26.4	25.7

*NUV & y: 4×150s

w/ ~0.2^m margin from design

Photo-z Estimates

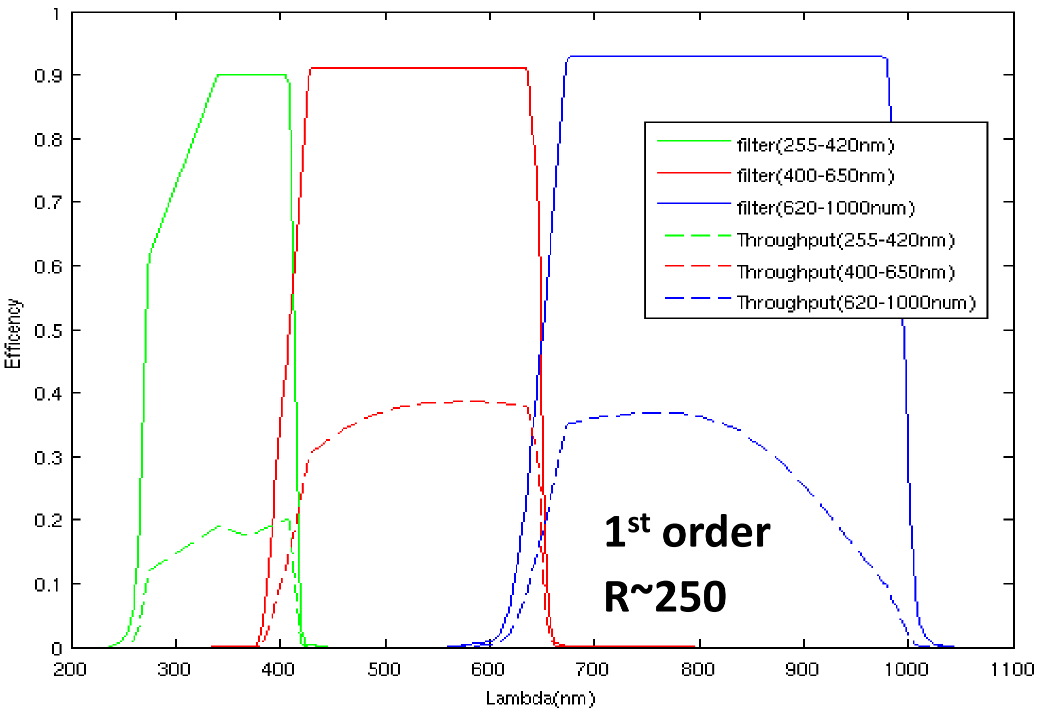


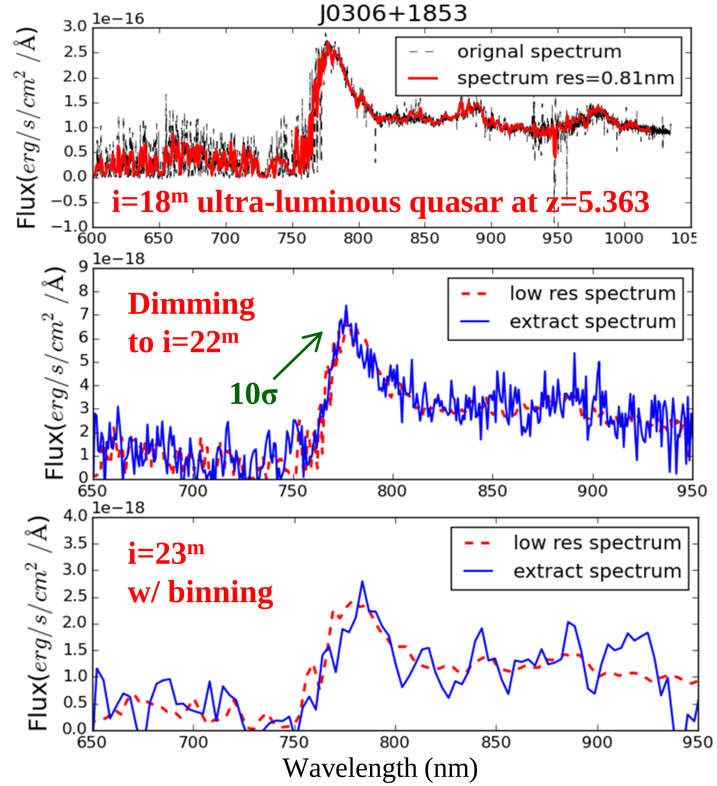


Galaxy dN/dz of a high-S/N mock sample (17.5/□′, σ_{z0}=0.024) for the CSS-OS based on COSMOS. If σ_{z0} is relaxed to 0.05, galaxy density ~ 29/□′.

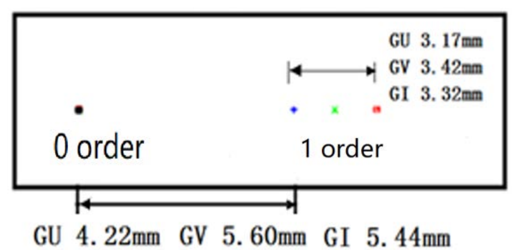
Cao et al. (2018)
1706.09586

Gratings & Limiting Mags





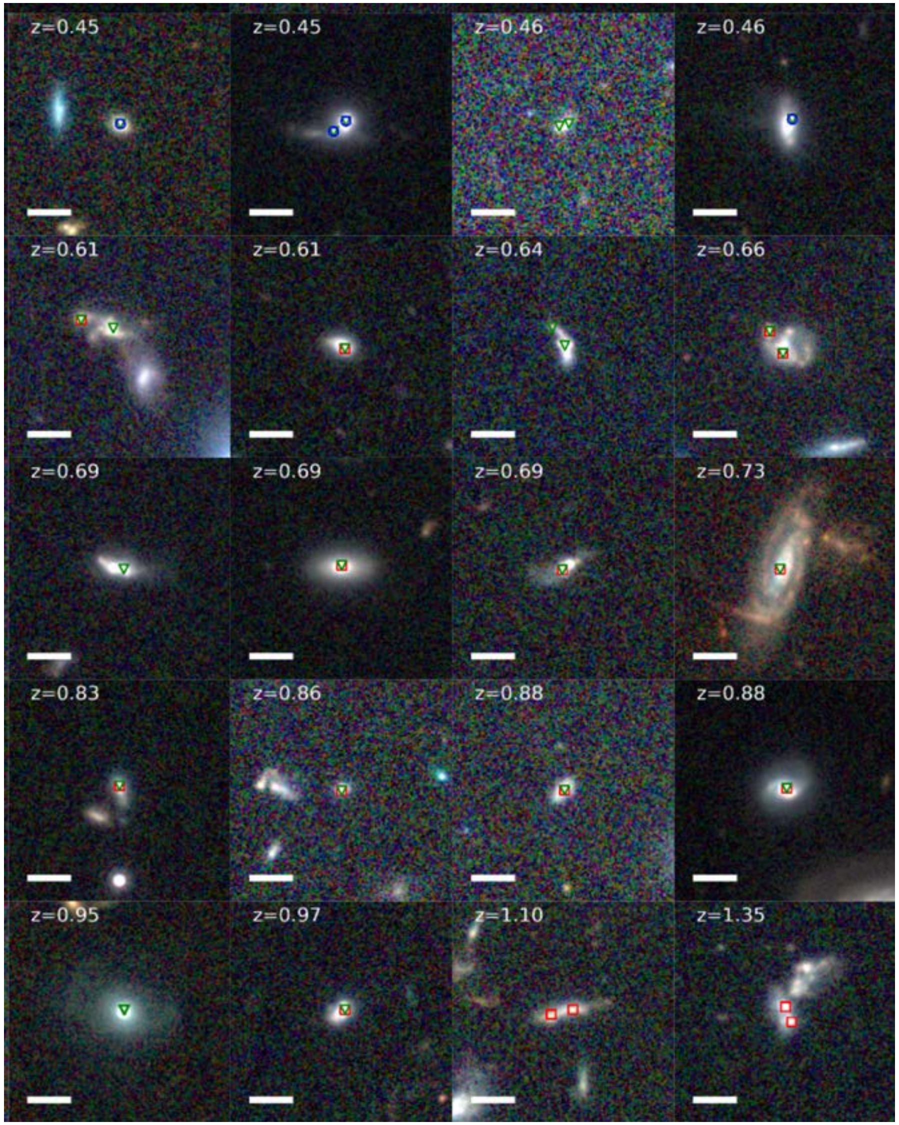
	t_{exp}	GU	GV	GI
17500□°	4×150s	22.5	23.4	23.4
400□°	16×250s	23.7	24.6	24.5

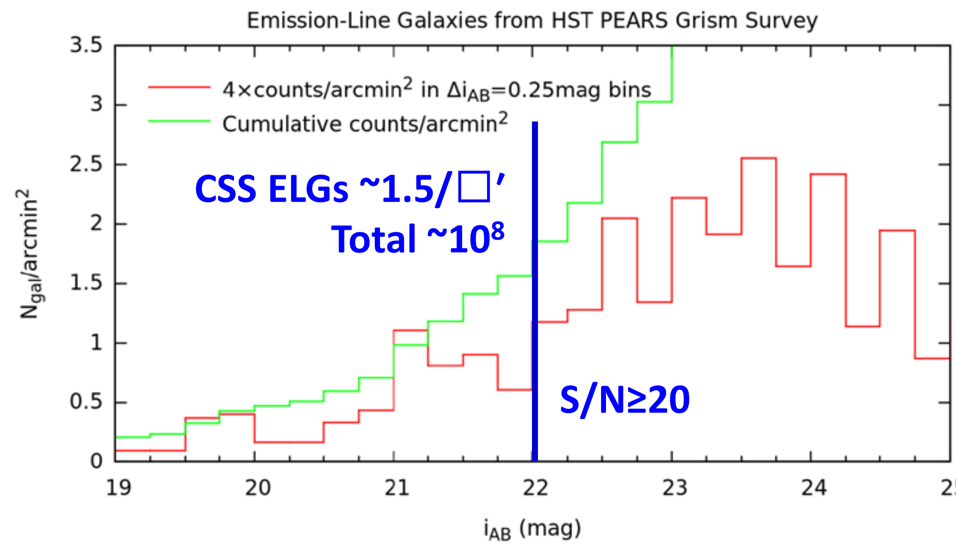


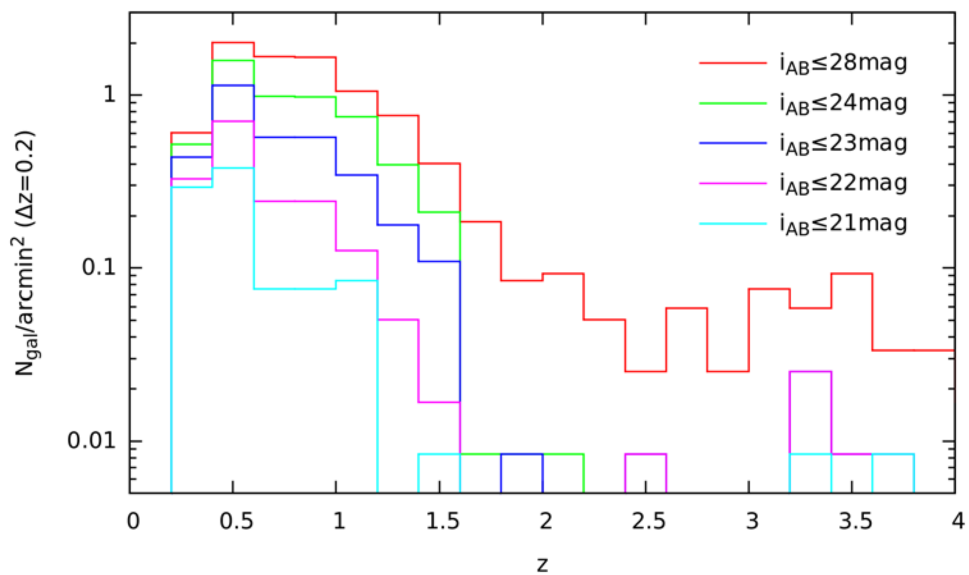
Broadband limiting mag w/ ~0.2^m margin

Galaxies from Slitless Spectroscopy

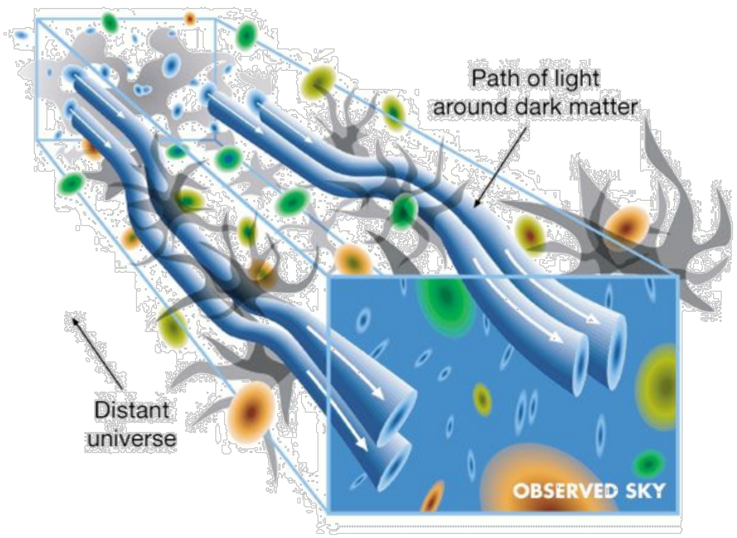
Checking against HST PEARS Survey: 120/□′， 550-1050nm， $R\simeq 69$-131， $i_{AB}\lesssim 28^{m}$



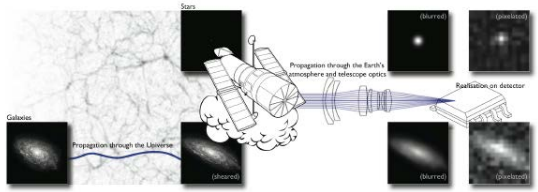


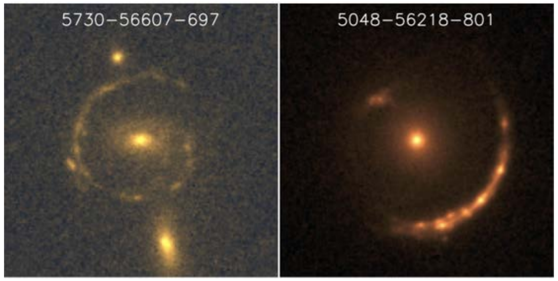


Survey Science: Gravitational Lensing

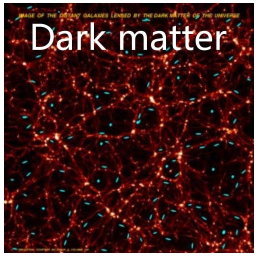


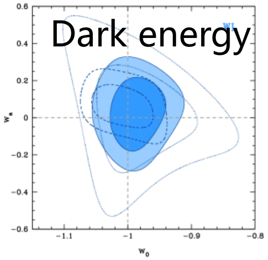
Gravitational distortion

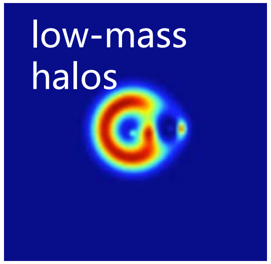

Weak lensing



Strong lensing

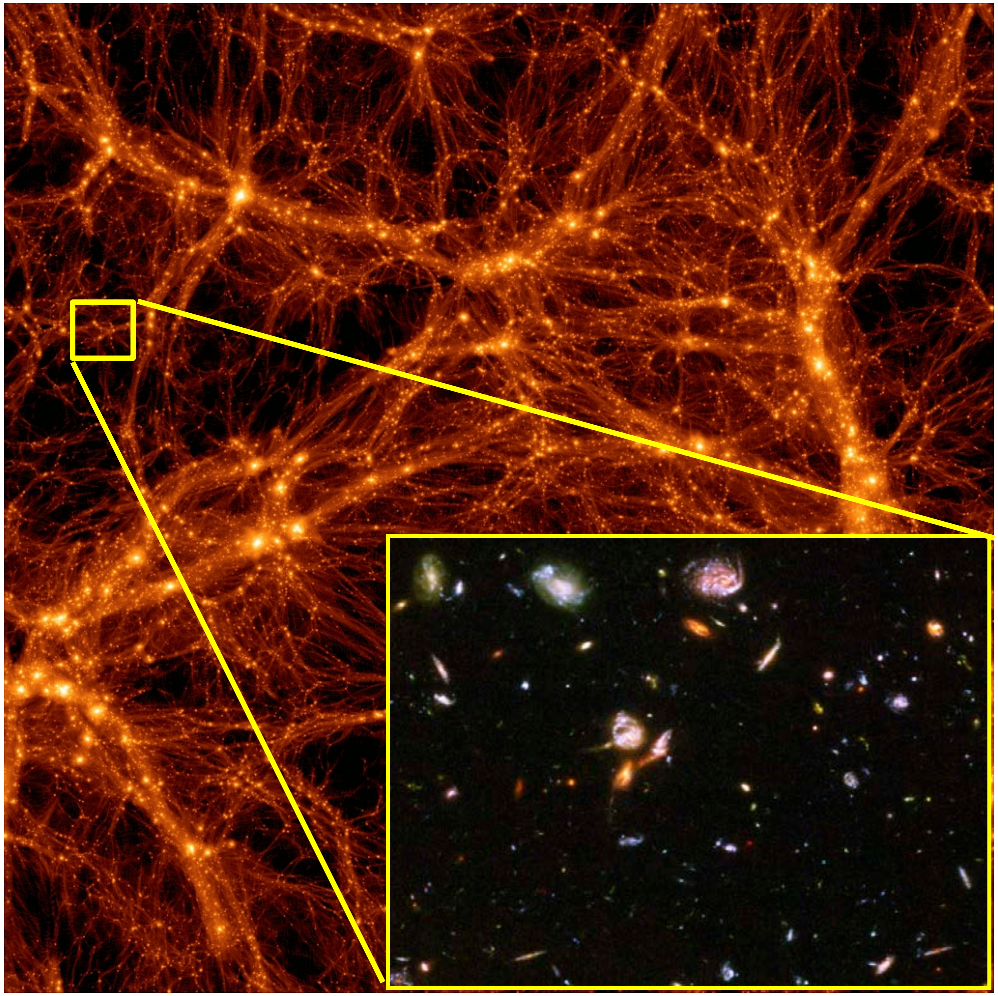




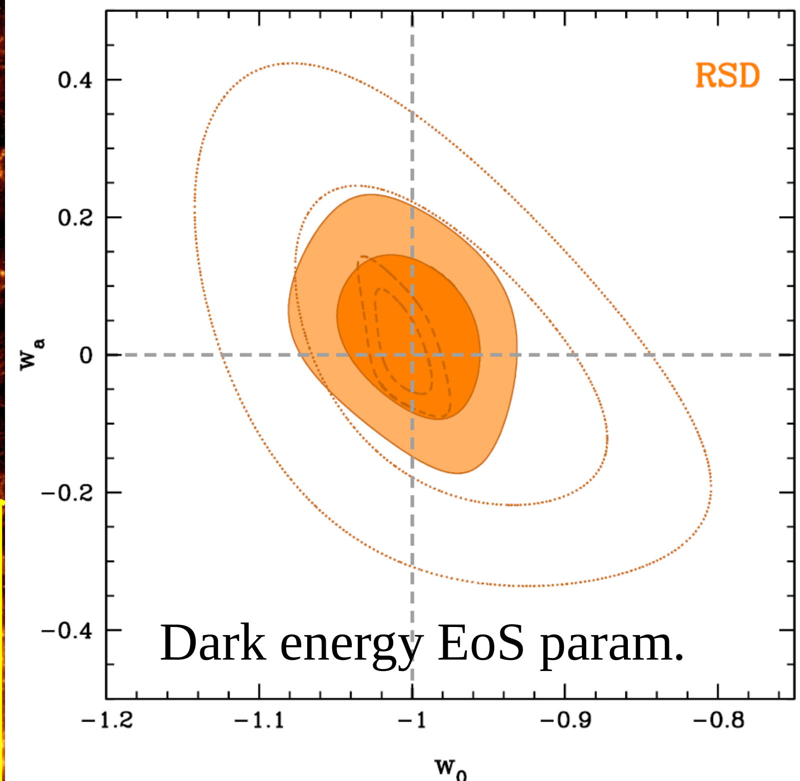


- Mapping the dark matter distribution in the universe;
- Testing dark energy models and gravity theories with precision measurements of the cosmic expansion history;
- Cataloging 10^5 strong lensing systems, including thousands of multiply imaged QSO systems, to measure dark matter particle properties,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

Gong et al. arXiv:1901.04634

Survey Science: Galaxies & AGNs

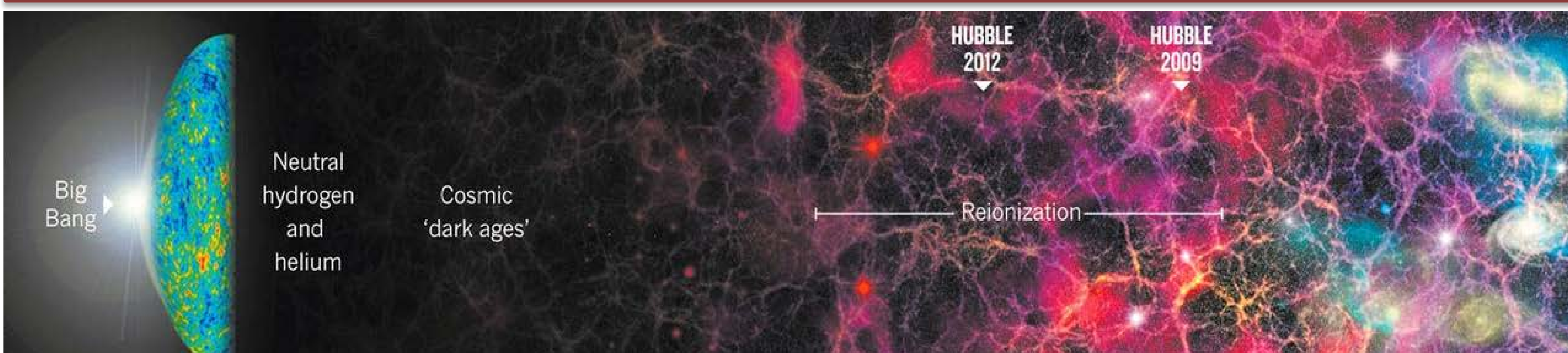
The CSS-OS unprecedented large-area high-resolution imaging and slitless spectroscopy data, together with observations of the Terahertz Detector, Multi-Channel Imager, and Integral Field Spectrograph, will characterize the formation and evolution of galaxies and AGNs as well as their interaction with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

Survey of high-z galaxies & AGNs

Details of the "cosmic noon"

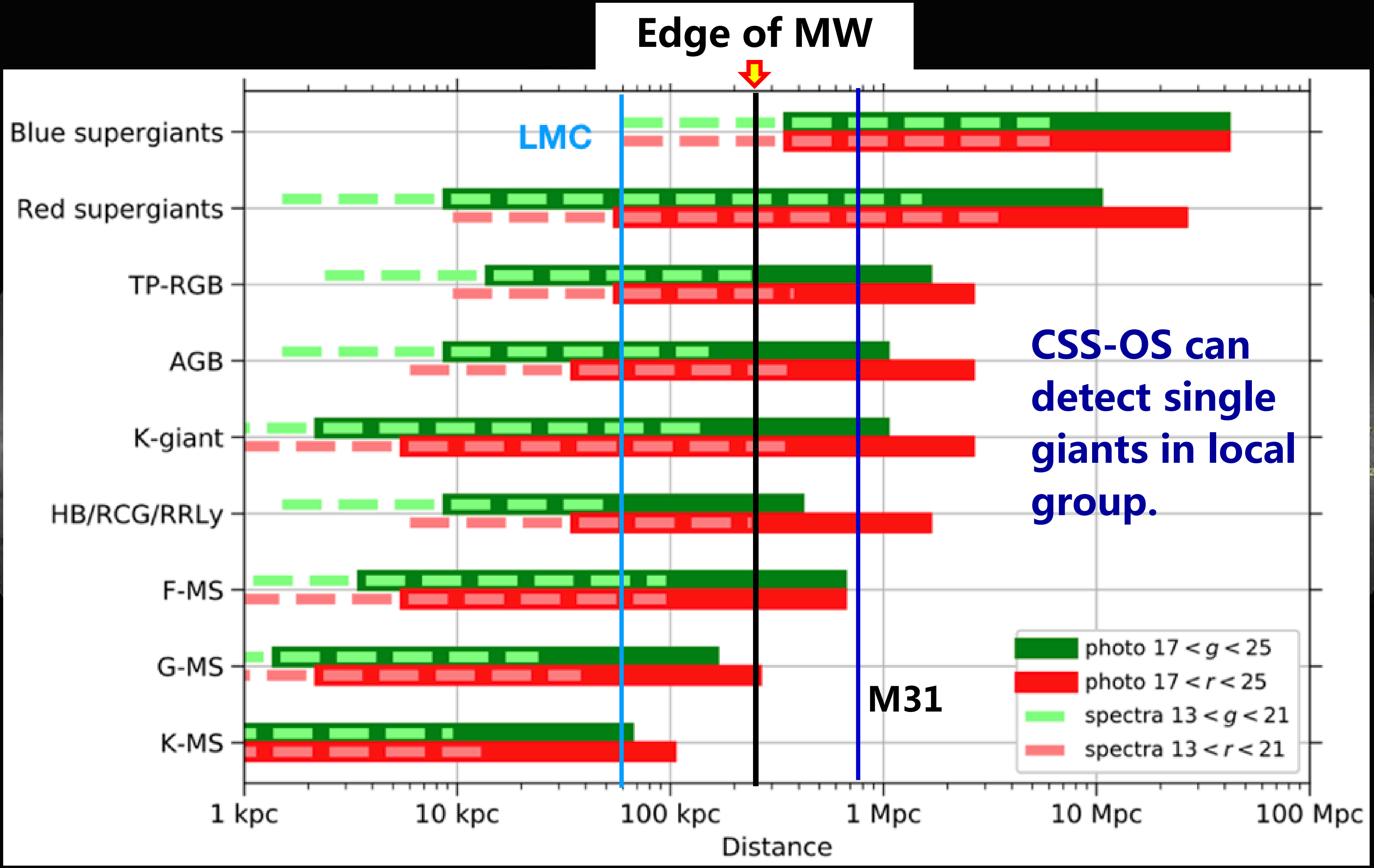
Charactering the local universe

Time：	13.8B yr	13.8～13.5B yr	13.5～12.8B yr	10～8B yr	present
redshift：	z～1100	z = 1100～20	z = 20～6	z = 2～1	z = 0



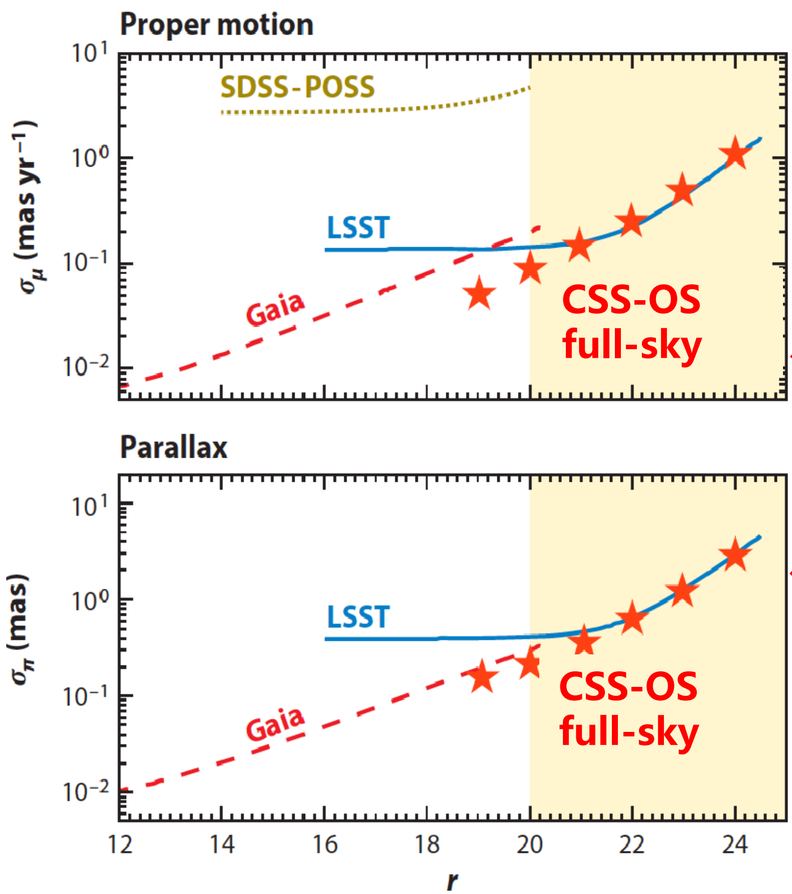
Universe：	igbang	dark ages	seed of LSS, reionization		acceleration
Galaxy：			first stars	peak of formation →	quick evol

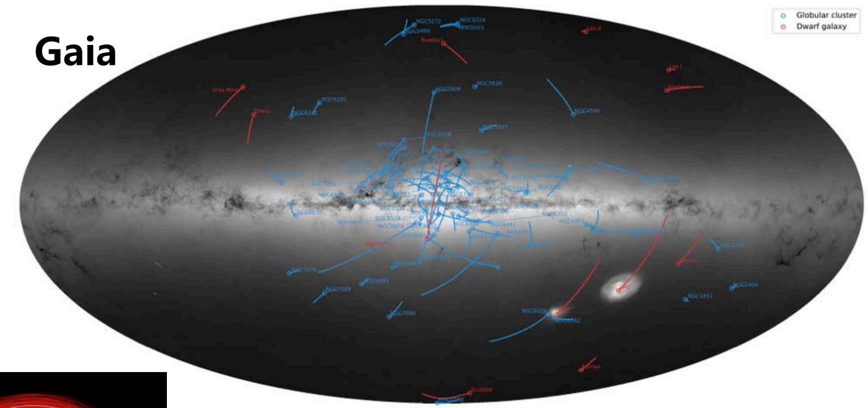
Survey Science: Milky Way & Local Group

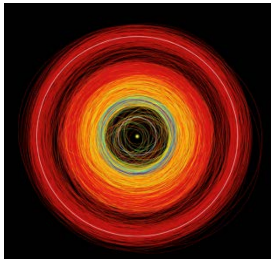


CSS-OS can detect single giants in local group.

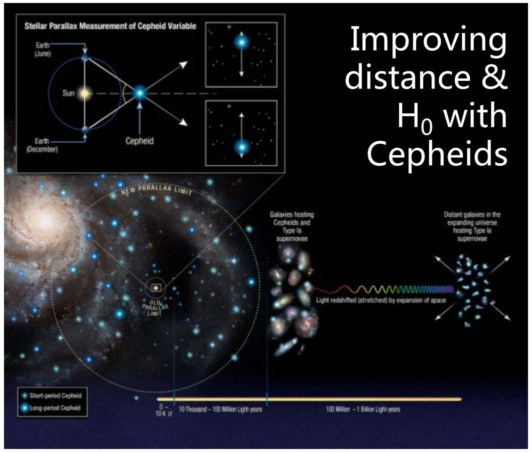
Survey Science: Astrometry & Solar Sys.



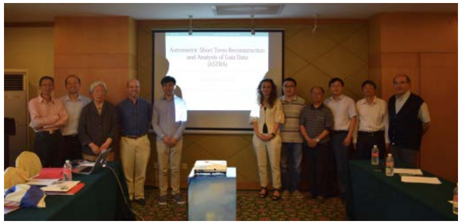




Astro. Orbit (Gaia)



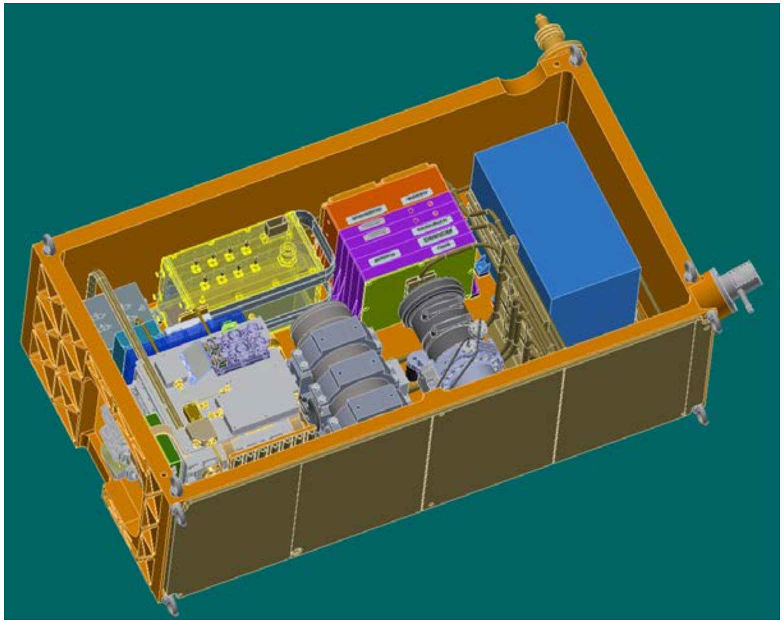
Greatly improving astrometry on the faint end!

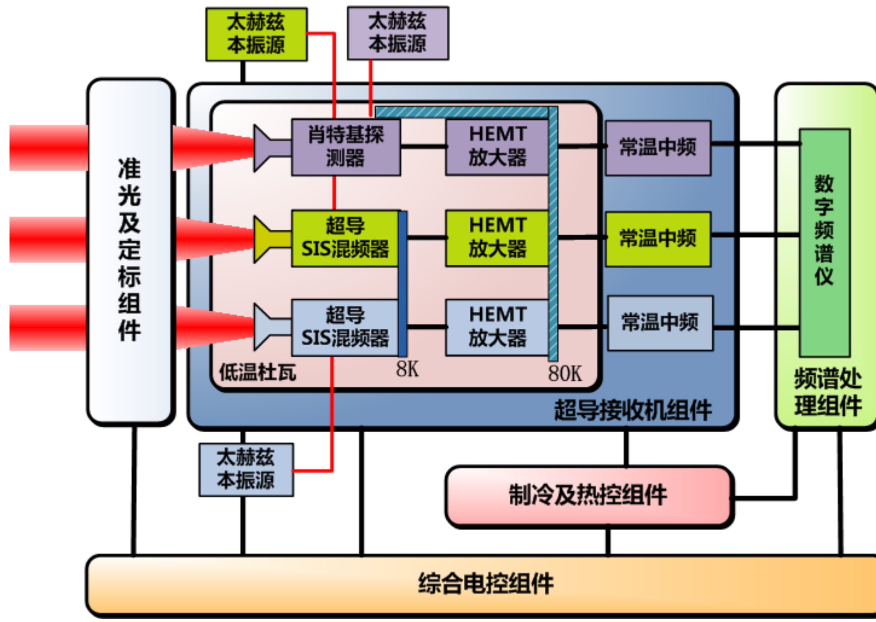


CU3 - CORE PROCESSING FOR GAIA

Coordination Unit 3 group picture taken at the CU3 Plenary meeting held in Heidelberg in 2017

Terahertz Receiver

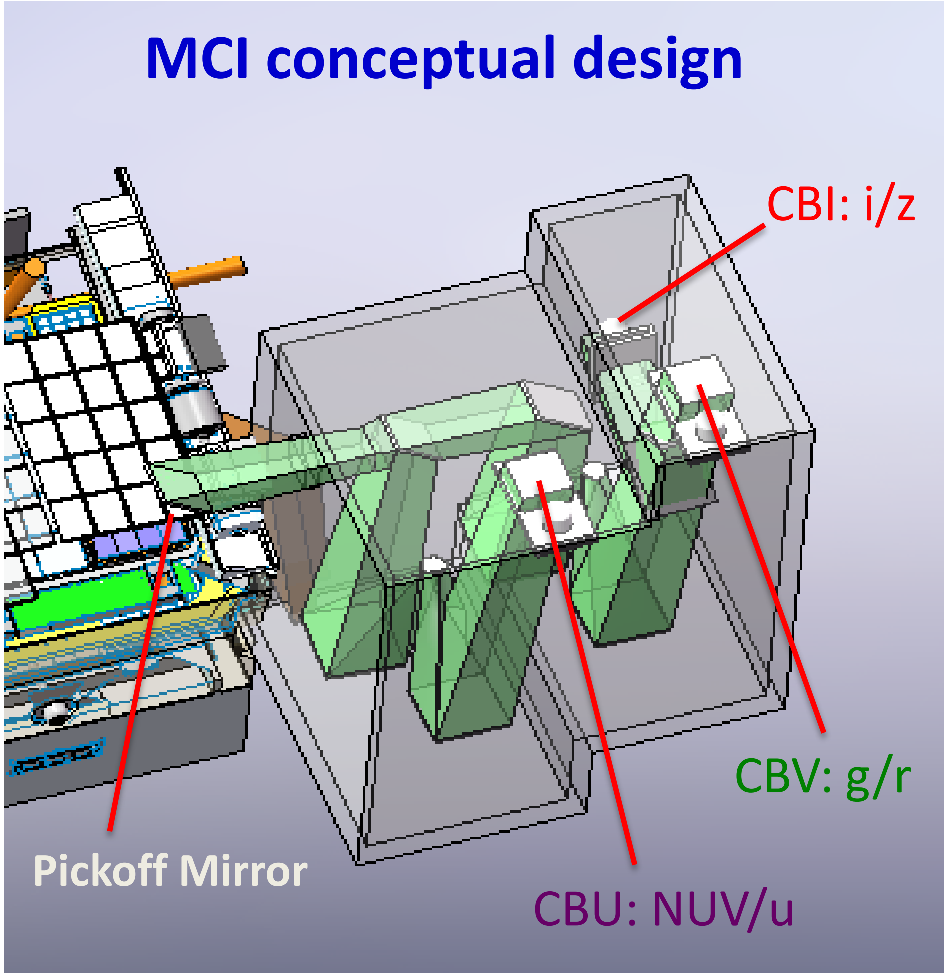




Specifications	
Frequency	0.41-0.51THz
Bandwidth	≥2GHz
Resolution	≥100kHz
Sensitivity	<150mK (200s)
Cryocooling	≥10mW@8K

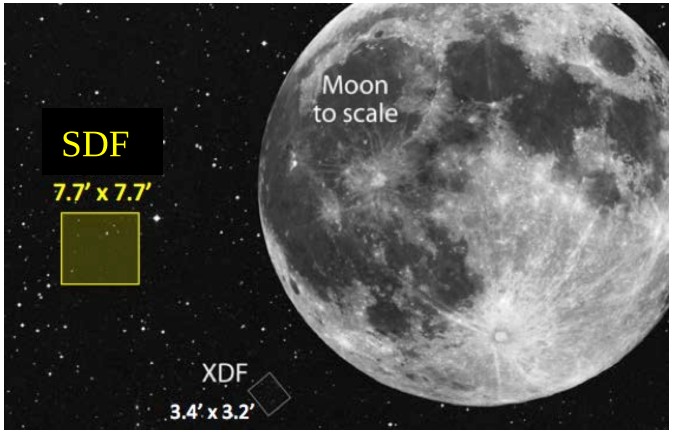
- **410~510GHz spectral line survey**
  - Searching for new atomic and molecular species and physical & chemical processes
  - Complementary with Herschel (410~480GHz)
- **Carbon cycle (CI, 492GHz)**
  - Evolution of molecular clouds in early-stage
  - Filamentary structure in molecular clouds

Multi-Channel Imager



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

Multi-Channel Imager



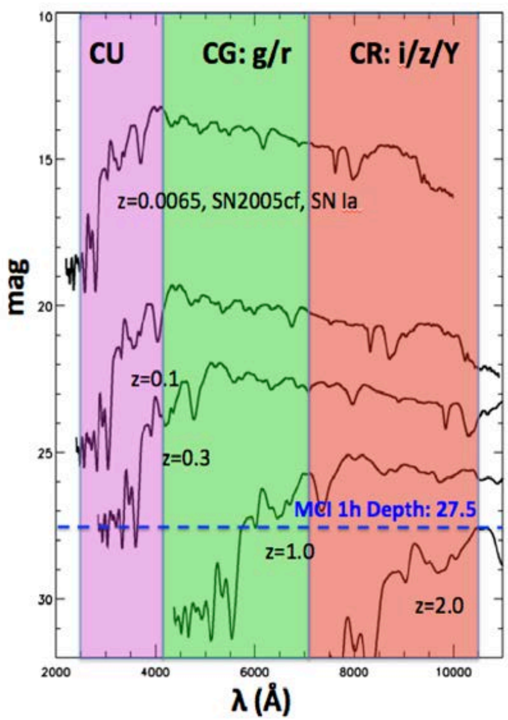
Sciences with (3-filter simultaneous) CSST Super Deep Fields

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

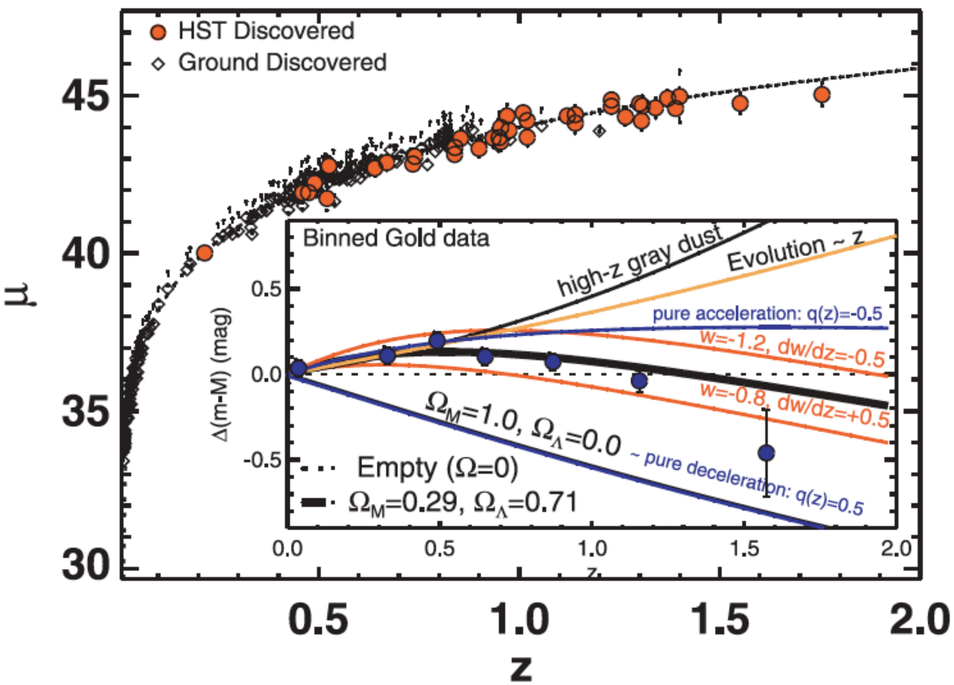
Potential SDFs:

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

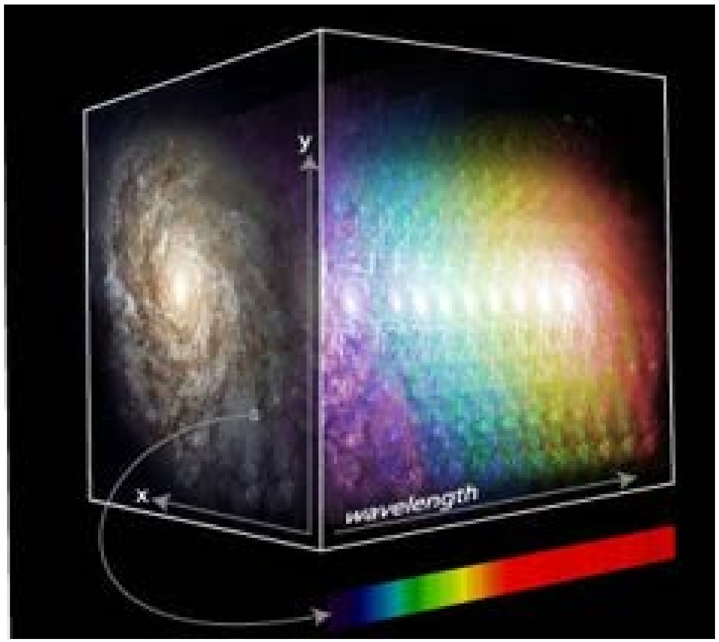
5 fields, 300 □′ tot, CBV ≥30^{m}



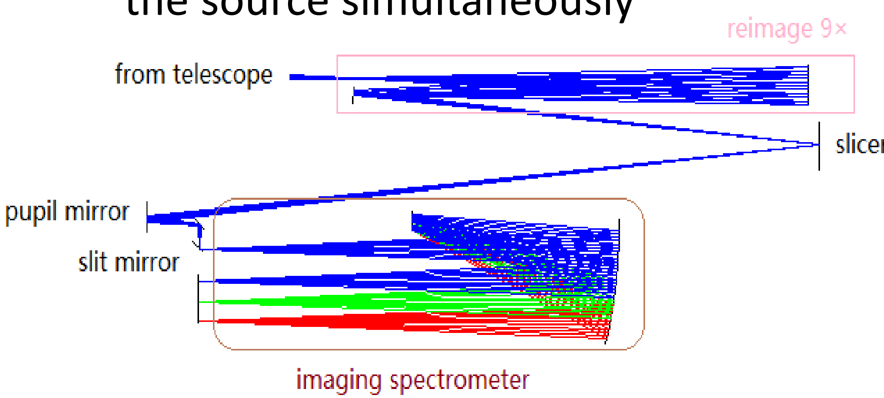
Credit: Adam Riess



Integral Field Spectrograph



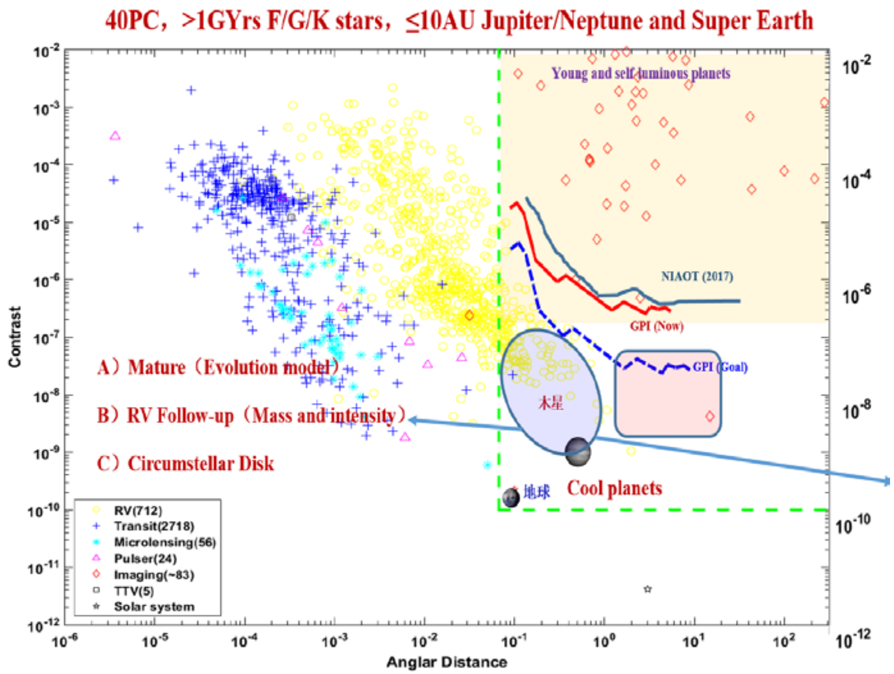
Taking spectra of different parts of the source simultaneously



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≥ 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**
- **…**

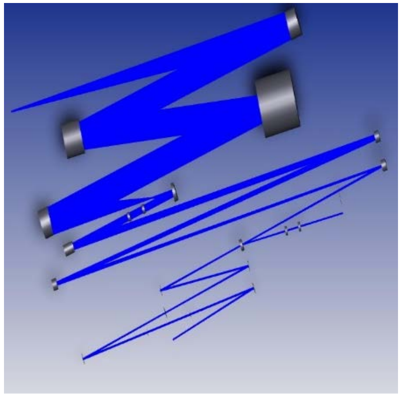
Cool-Planet Imaging Coronagraph

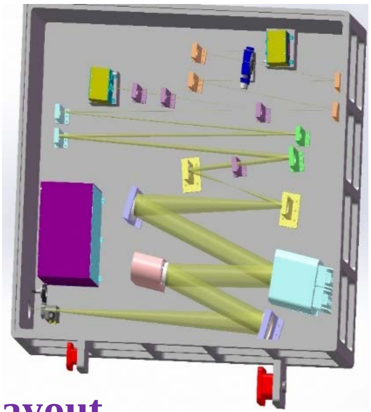


Contrast vs. angular separation

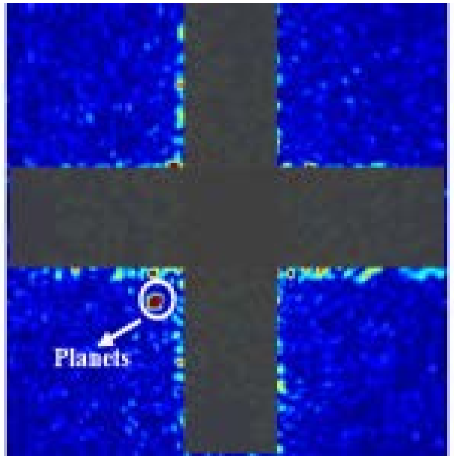
- **Wavelength**： 0.6-0.9μm (goal: 1.6μm)
- **Bandwidth**： 3~10%
- **FOV**： 2.5″×2.5″ obs, 20″×20″ targeting
- **IWA**： ≤0.55″@ 0.63μm, 1.2"@1.5μm
- **Contrast**： 10^{-8} (0.6-0.9μm) or better

- **Searching for mature planets around solar-type stars**
- **RV follow up & planet formation & evolution**
- **Physics of circumstellar disk**

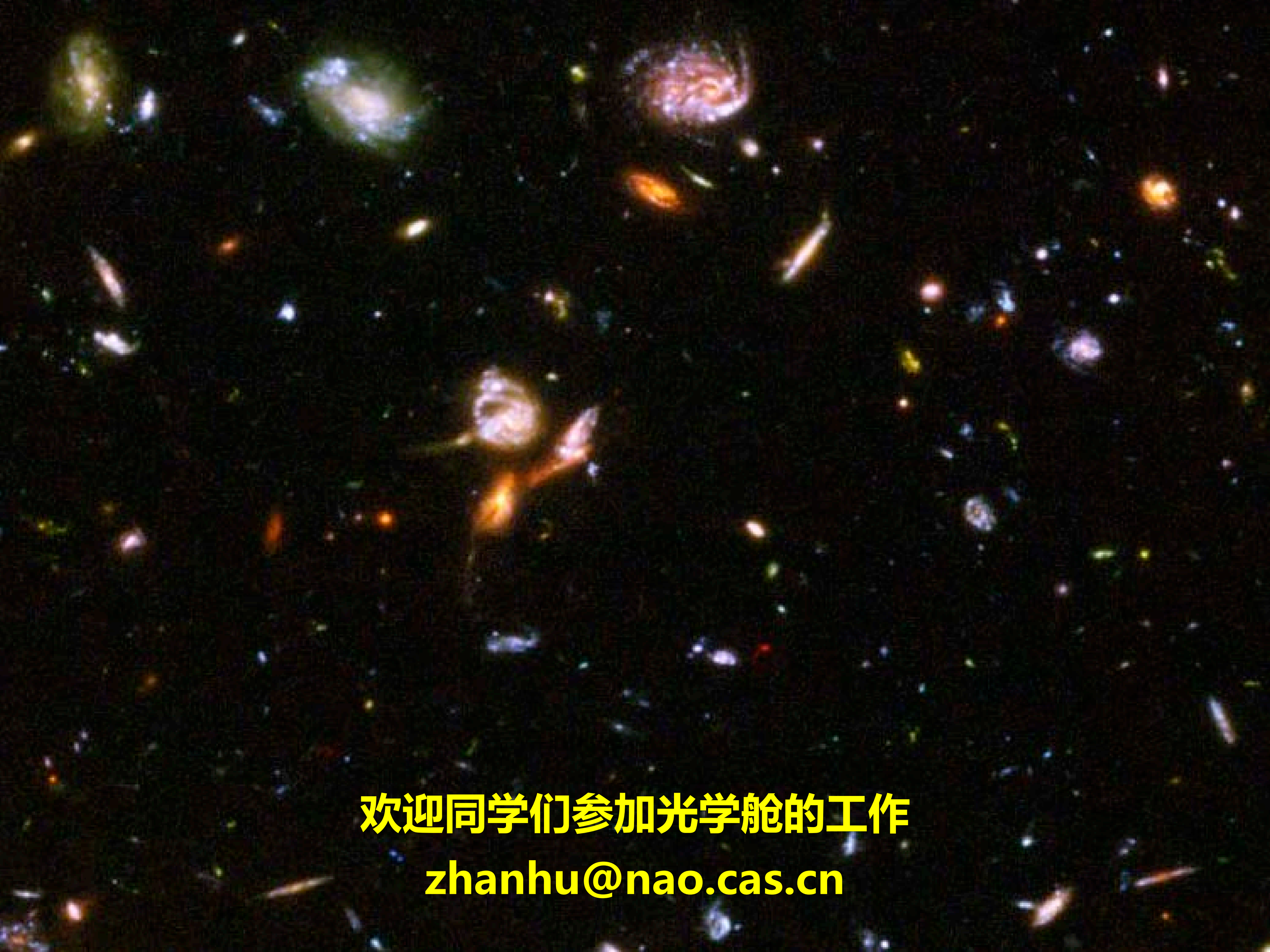




Optics layout



Vacuum chamber test reaching 10^{-9} contrast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zhanhu@nao.cas.cn