

Observational Cosmology Using Galaxy Clusters + Cosmic Shear

and

Dark Energy Missions

Layout of the Course

Feb 3: Introduction / Overview / General Concepts

Feb 5: Age of Universe / Distance Ladder / Hubble Constant

Feb 10: Distance Ladder / Hubble Constant Distant Measures

Feb 12: SNe science / Baryonic Content / Dark Matter Content of Universe

Feb 17: Dark Matter + Cosmic Microwave Background

Feb 19: Cosmic Microwave Background + Large Scale Structure

Feb 26: Large Scale Structure / Baryon Acoustic Oscillations + Dark Energy

Mar 5: Dark Energy / Clusters / Cosmic Shear

Mar 12: Cosmic Shear / Dark Energy Missions

Mar 19: No Class

Mar 26: Other Unresolved Questions / Review for Final Exam

Apr 11: Final Exam

Today



Problem Set #3

Mailed it to you this morning
(and on the website)!

Due Tuesday, March 25, 2025

Review Material from Last Week

Enigma of Dark Energy

Already up to this point in the course, you have already seen many different pieces of evidence for some form of dark energy, which we have expressed as $\Omega_\Lambda > 0$

There is an overwhelming amount of evidence for its existence

→ SNe Search Experiments

Observed SNe in distant galaxies are observed to be fainter than they would otherwise be without dark energy

→ Late Integrated Sachs-Wolfe Effect

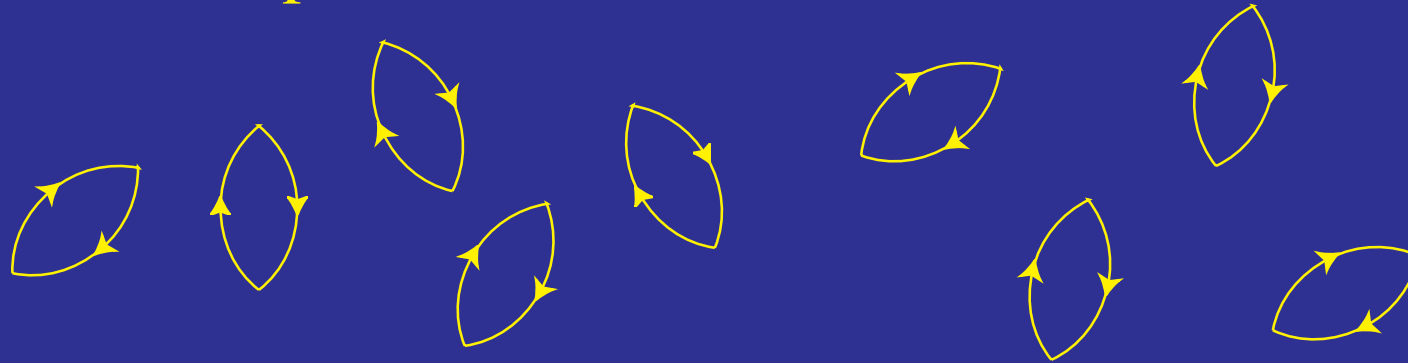
Dark Energy Affects the Differential Redshifting of CMB photons as they move in and out of gravitational potential. By cross correlating known galaxy clusters with CMB, we can observe this effect.

→ First Acoustic Peak of CMB Implies Universe is Flat, while other evidence indicates $\Omega_M \sim 0.3$ (Large Scale Flows, Kaiser Effect, Ratio of Baryons and Total Matter in Galaxy Clusters, Large Scale Structure, Baryon Acoustic Oscillations)

However, its nature remains an enigma

Enigma of Dark Energy

- **Constant energy density**, hence increasing net energy as universe expands consistent with data
- Quantum mechanics allows/predicts such phenomena in the form **vacuum energy**: empty space is alive with **virtual particles**



- **Naive prediction** is 10^{120} times **too big** and more sophisticated models still 10^{60} off

Credit Hu

→ Possibly more natural to explain dark energy as a scalar field that evolves with cosmic time...

Enigma of Dark Energy

In order to ascertain the form of dark energy, we parameterize its effects in terms as the w parameter:

$$P = w\rho c^2$$

Typically take $c = 1$

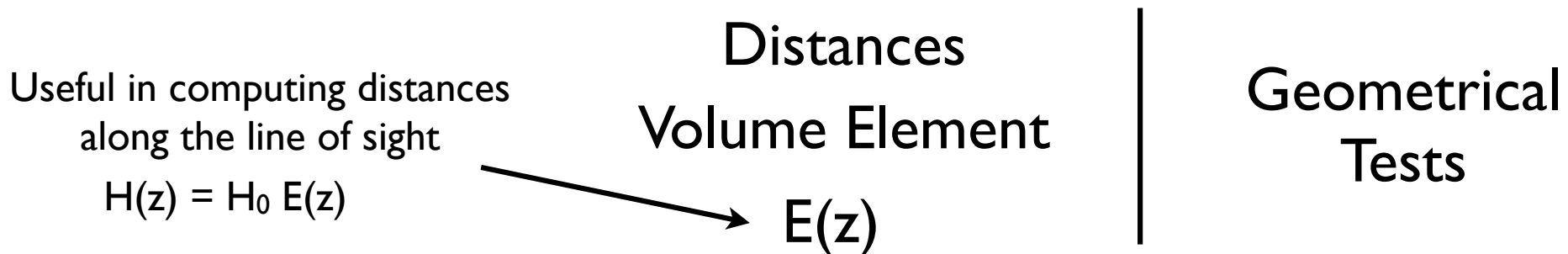
There are a few important cases:

Type dark energy	w	redshift scaling of DE density	dynamical significance
Cosmological Constant λ	-1	Constant	$z < 1$
Quintessence	$-1 < w < -1/3$	$(1+z)^{-1}$ for $w = -2/3$	earlier
Phantom Energy	$w < -1$	$(1+z)^{-1}$ for $w = -4/3$	later

How can we constrain the w parameter?

Generally, we constrain the w parameter in the same way we constrain many other cosmological parameters.

We constrain it by looking at the following quantities versus redshift (cosmic time, see earlier lecture):



Growth Factor (Rate at which structures in Universe Grow)

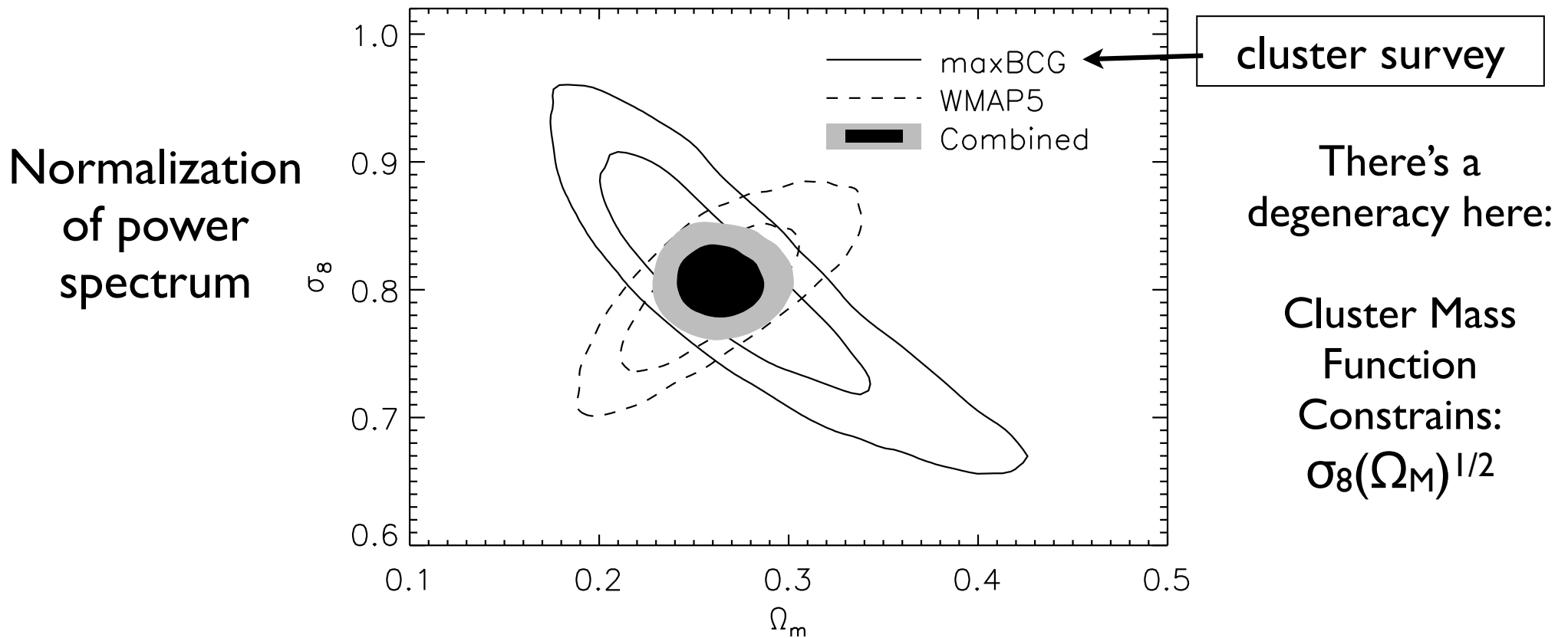
Galaxy clusters also provide us with important constraints on cosmology!

Why?

1. Density perturbations in universe grow in a regular, well-defined way.
2. Galaxy clusters are clear end result of the growth of density perturbations in universe
3. One can model the build-up of galaxy clusters primarily through gravitation, and so it is much simpler to model than lower mass (i.e., galaxy) systems.
4. Mass function of clusters depends sensitively on Ω_m the matter density and σ_8 the amplitude of density fluctuations
5. Clusters are relatively straightforward to identify in observable surveys

Value of Galaxy Clusters at $z \sim 0$

The Abundance of Galaxy Clusters with Various Masses Provides Strong Constraints on the Total Mass Density in the Universe and Normalization of the Power Spectrum



Rozo et al. 2010

So a higher σ_8 , lower Ω_M and lower σ_8 , higher Ω_M both match observations

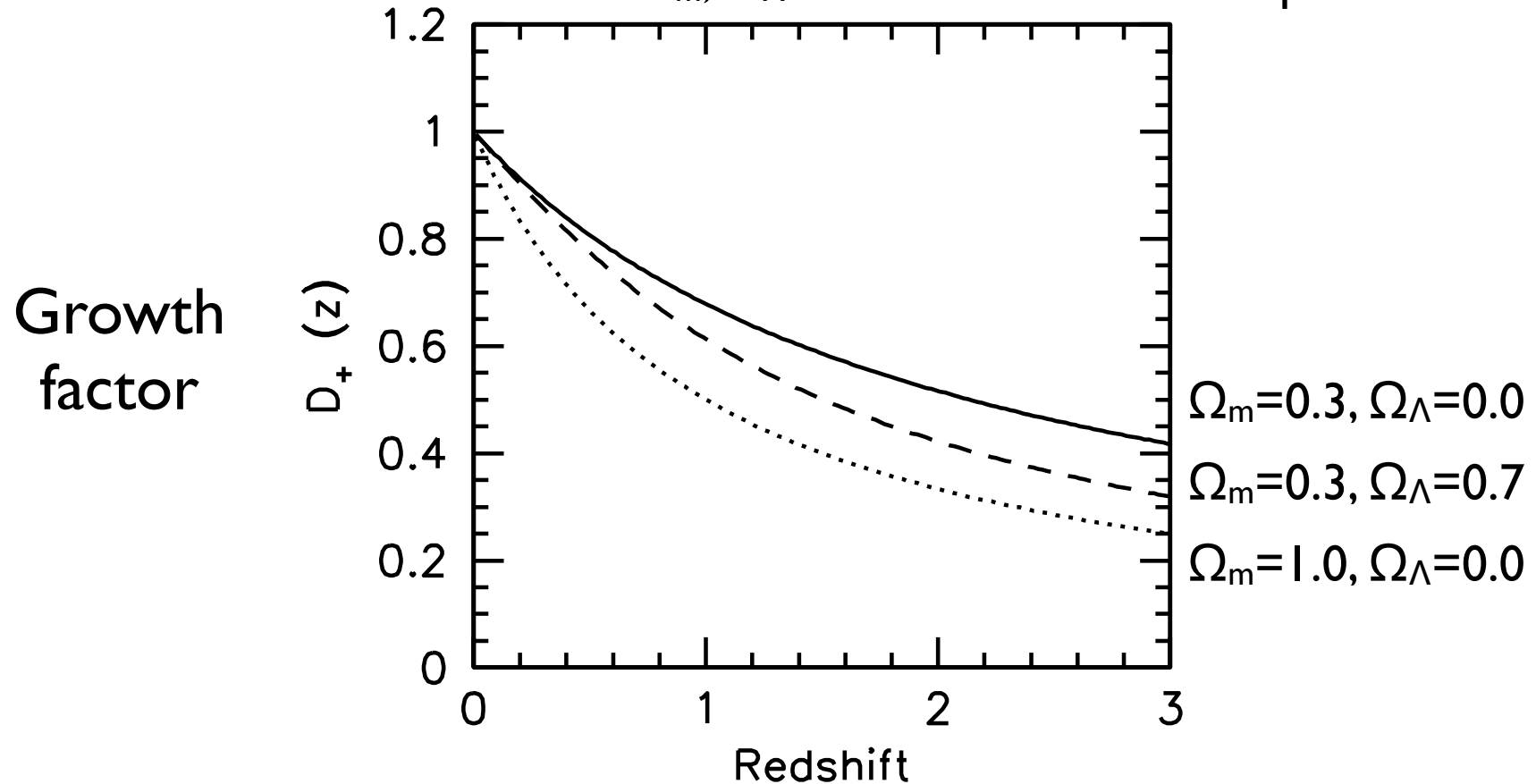
Value of Galaxy Clusters at $z>0$

The rate at which structures grow in the universe depends upon the cosmological parameters:

Depend upon the growth factor (linear regime):

$$D_+(a) = \frac{5a}{2} \Omega_m \left[\Omega_m^{4/7} - \Omega_\Lambda + \left(1 + \frac{1}{2} \Omega_m\right) \left(1 + \frac{1}{70} \Omega_\Lambda\right) \right]^{-1}$$

where a is size of universe and Ω_m, Ω_Λ are all evaluated in the past

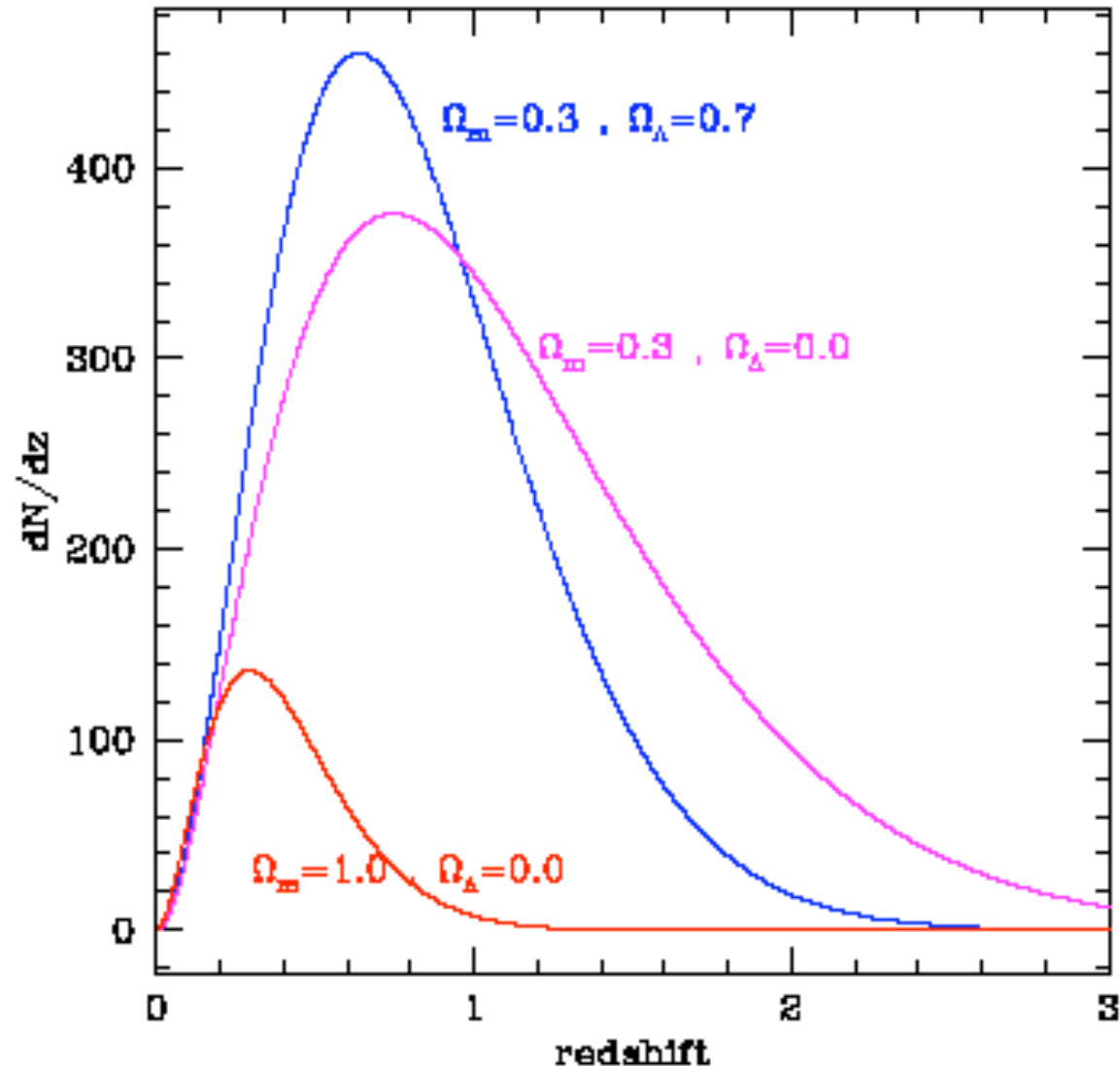


Different cosmological parameters imply different growth rates for clusters...

Simple Illustration of how many clusters one would expect to find in various cosmological models as a function of redshift

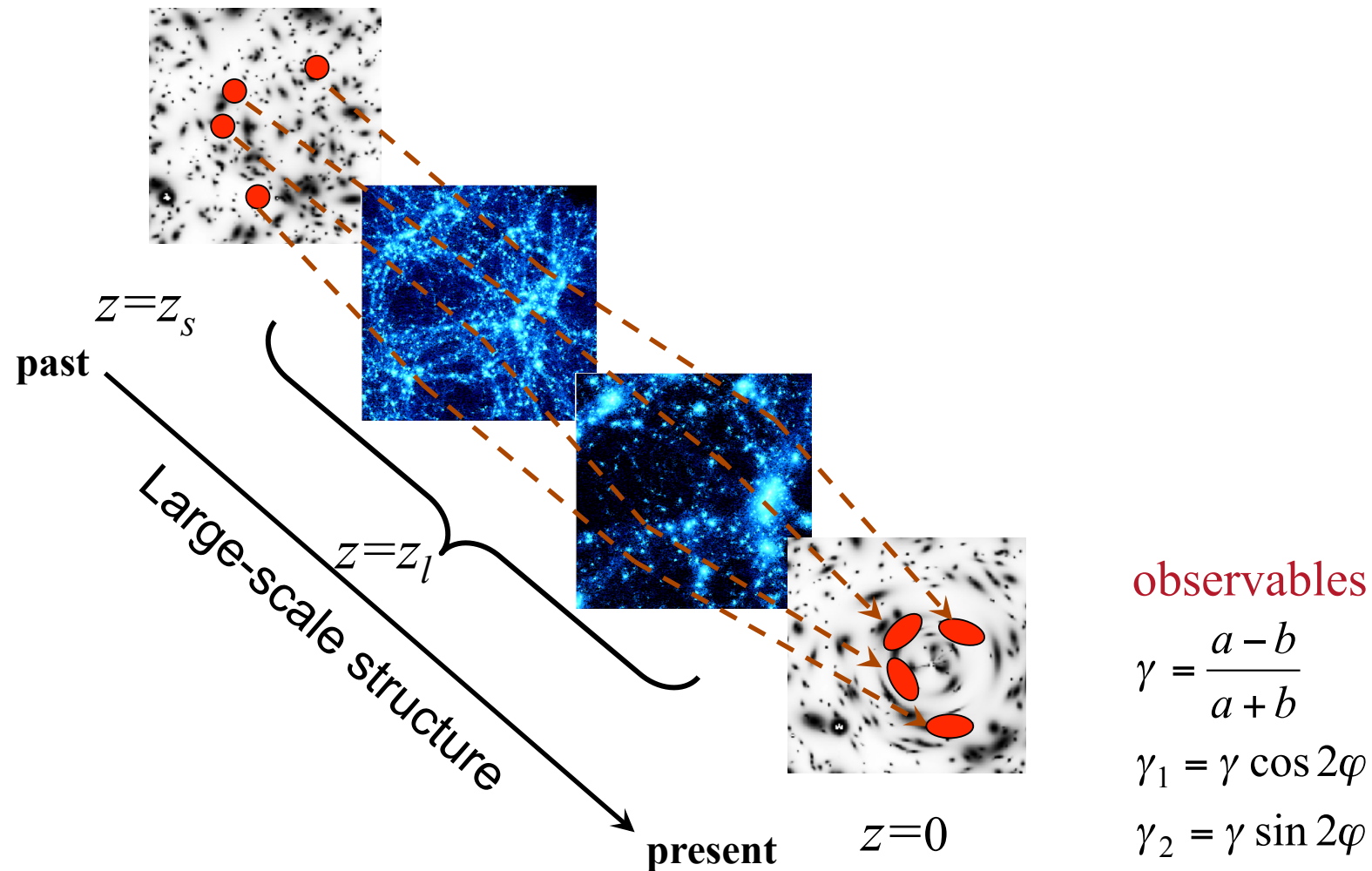
Note that there are essentially no clusters at high redshift in the $\Omega_m=1.0, \Omega_\Lambda=0.0$ model

The evolution of the cluster mass function also breaks degeneracy between σ_8 and Ω_M



Probing the Nature of Dark Energy: Using Cosmic Shear

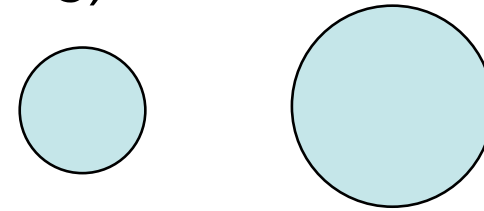
Gravitational lensing from collapsed masses has a systematic imprint on the shapes of galaxies, seen over large areas of sky, i.e., cosmic shear...



What effect does gravitational lensing have on galaxies we observe?

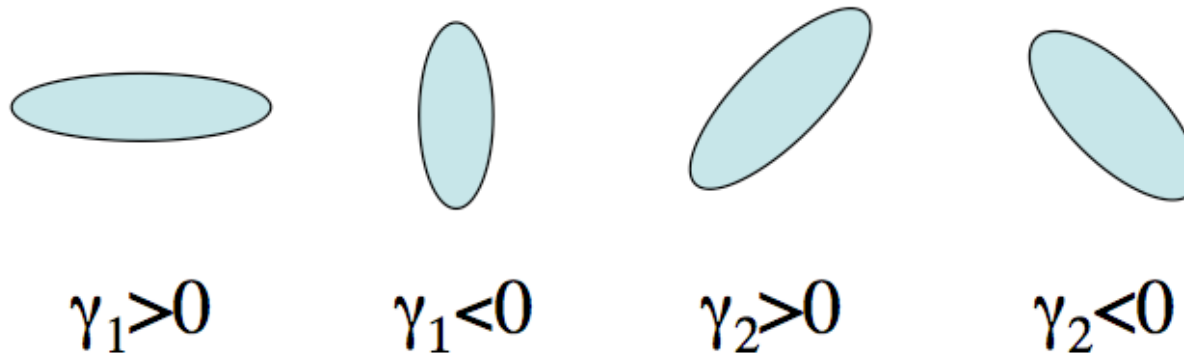
1. Magnification

- expressed as κ (called convergence)
- does not affect shape

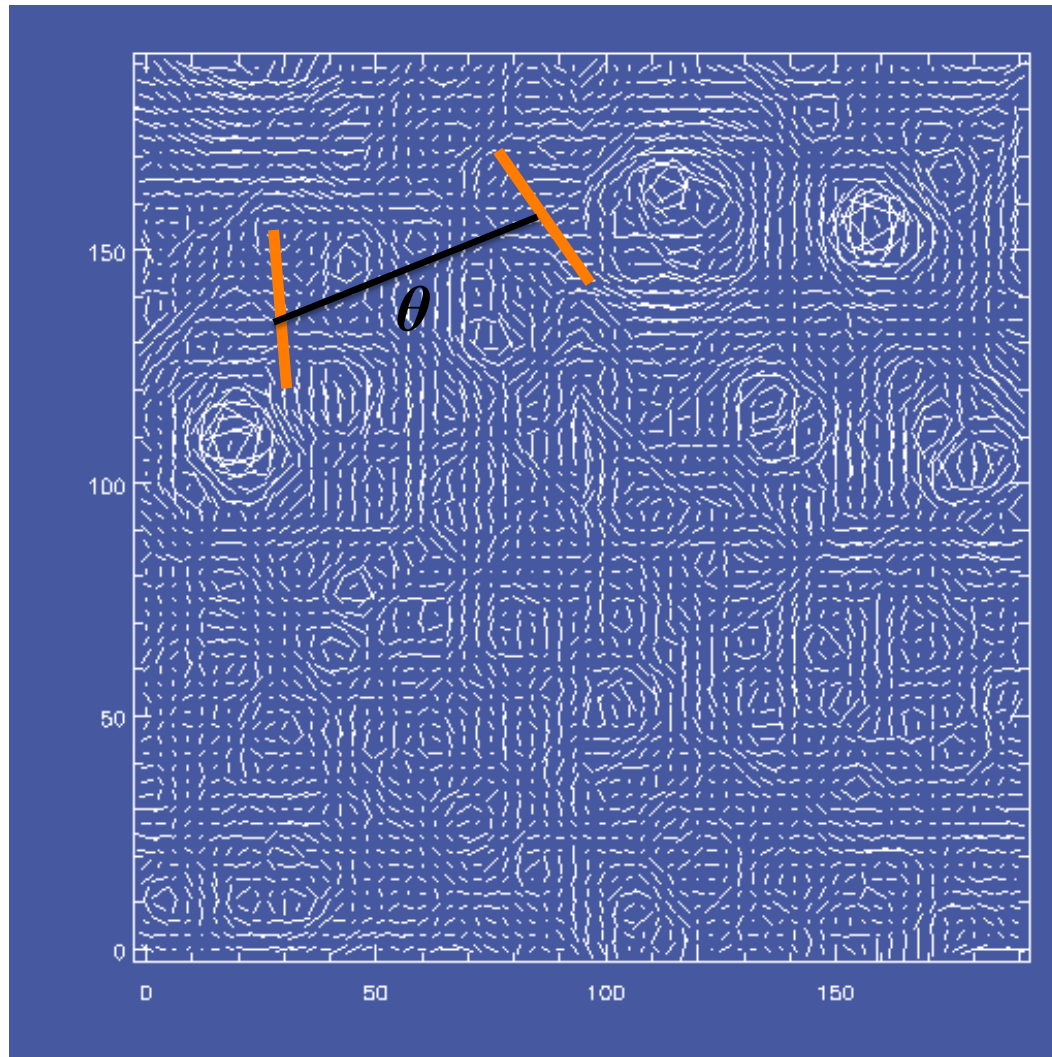


2. Shear

- expressed as γ (called the shear)



Determine correlation of shear measurement on different angular scales θ



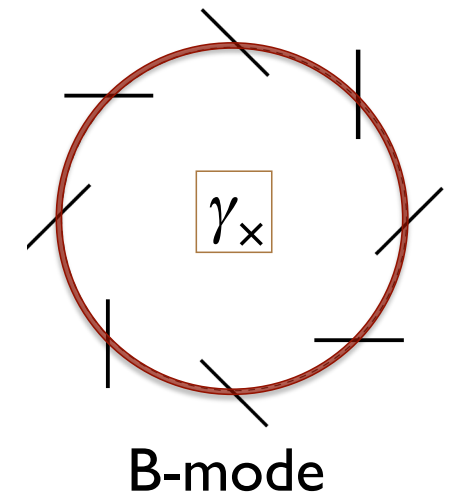
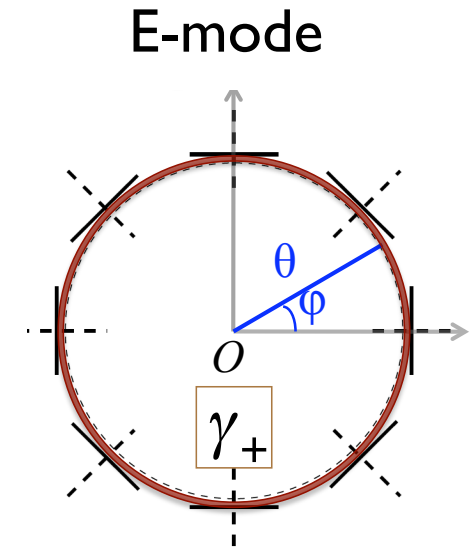
- Correlated images of distant galaxies over all angular scales
- Use images of all distant galaxies
- Correlation function method to measure the cosmic shear signals
- The lowest one is 2pt function

Determine correlation of shear measurement on different angular scales θ

similar to measures of the clustering or correlation function, determine the extent to which the shear of sources at a given separation θ is tangential

$$\langle \gamma_+ \rangle(\theta) \equiv \frac{1}{2\pi} \oint d\varphi \gamma_+(\theta, \varphi)$$

the diagram to right shows just one origin over which we can perform this averaging.



Also frequent to use ξ to represent this:

$$\xi_{++}(\theta) = \frac{1}{2\pi} \oint d\varphi \gamma_+(\theta, \varphi)$$

Can also measure in a similar way γ_x

$$\langle \gamma_x \rangle(\theta) = 0 \quad \leftarrow \text{a monitor of systematics}$$

New Material for This Week

And how do we go about computing power spectrum for large numbers of sources?

Convert from to angular power spectrum using
Fourier transform again:

Correlation Function
Type Parameters

$$\xi_{++}(\phi) \quad \langle \gamma_+ \rangle(\theta)$$



Power Spectrum
Type Parameters

$$P_\gamma(l) \quad P_\kappa(l) \quad C_{\gamma_i \gamma_j}(l)$$

Fourier Transform

What can we compare these angular power spectrum measurements against?

(what are the essential elements?)

Here's the equation:

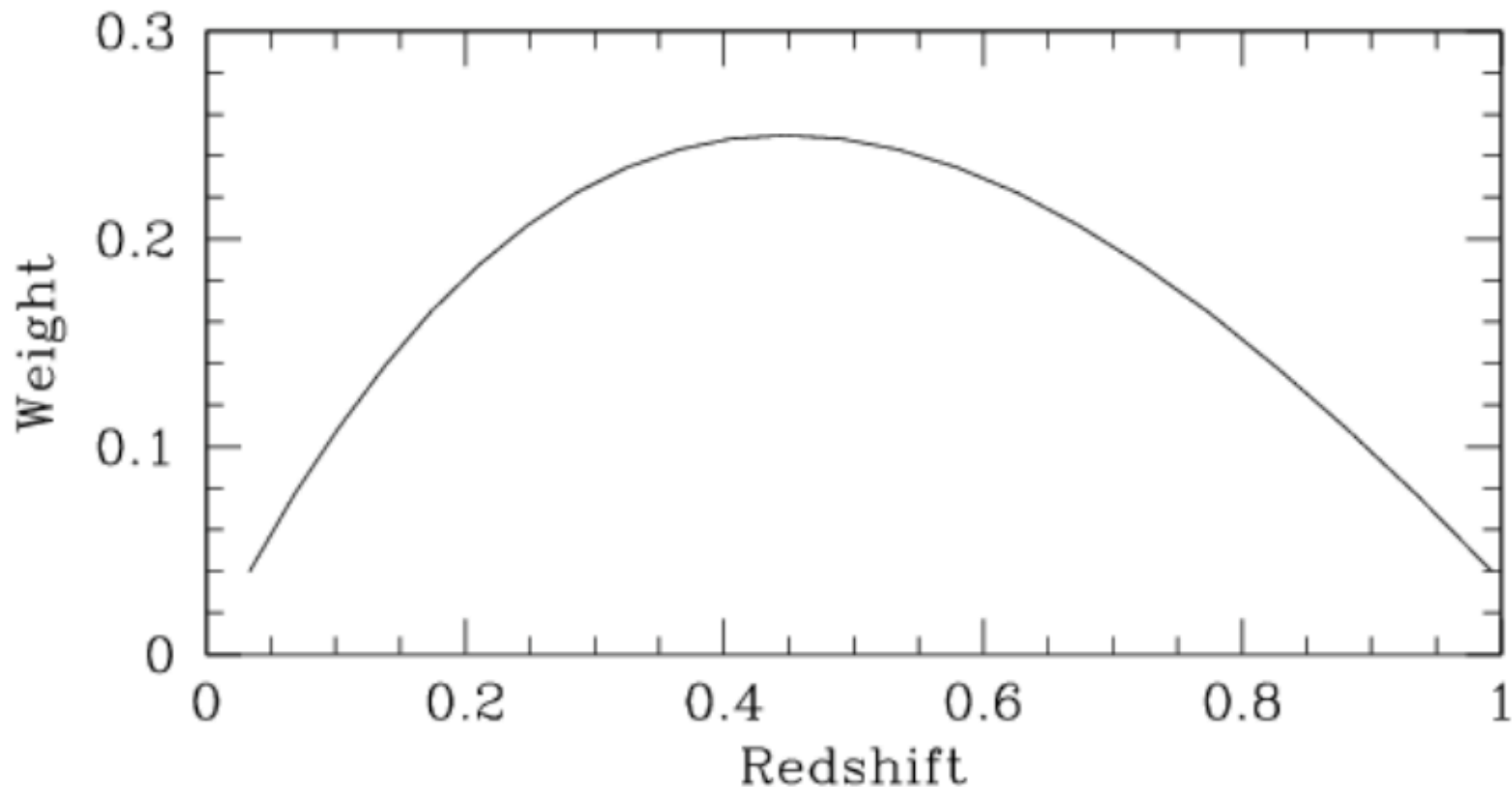
$$\gamma(\boldsymbol{\theta}) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

lensing efficiency growth of mass perturbations

- Lensing efficiency function: W_{gl}
 - Overall amplitude is proportional to Ω_m , i.e. Ω_{de} if combined with CMB or a flat universe is *a priori* assumed
 - Sensitive to Hubble expansion through d_A , i.e. DE
 - Depends on source redshift – main uncertainty in cosmic shear measurements if redshift info is not available
- Mass clustering part: δ
 - Sensitive to primordial power spectrum (amplitude and shape)
 - Redshift history of the growth rate is sensitive to DE.

How do we weight different sources in computing power spectrum from weak lensing?

Masses “half way” in between the background source and us (the observers) have the biggest effect on the gravitational shear of the observed background sources.



Because of this dependence, very important to be able to quantify the redshift distribution of the background sources

Recall how perturbations (and collapsed structures) grow at different rates depending on the cosmology

The rate at which structures grow in the universe depends upon the cosmological parameters:

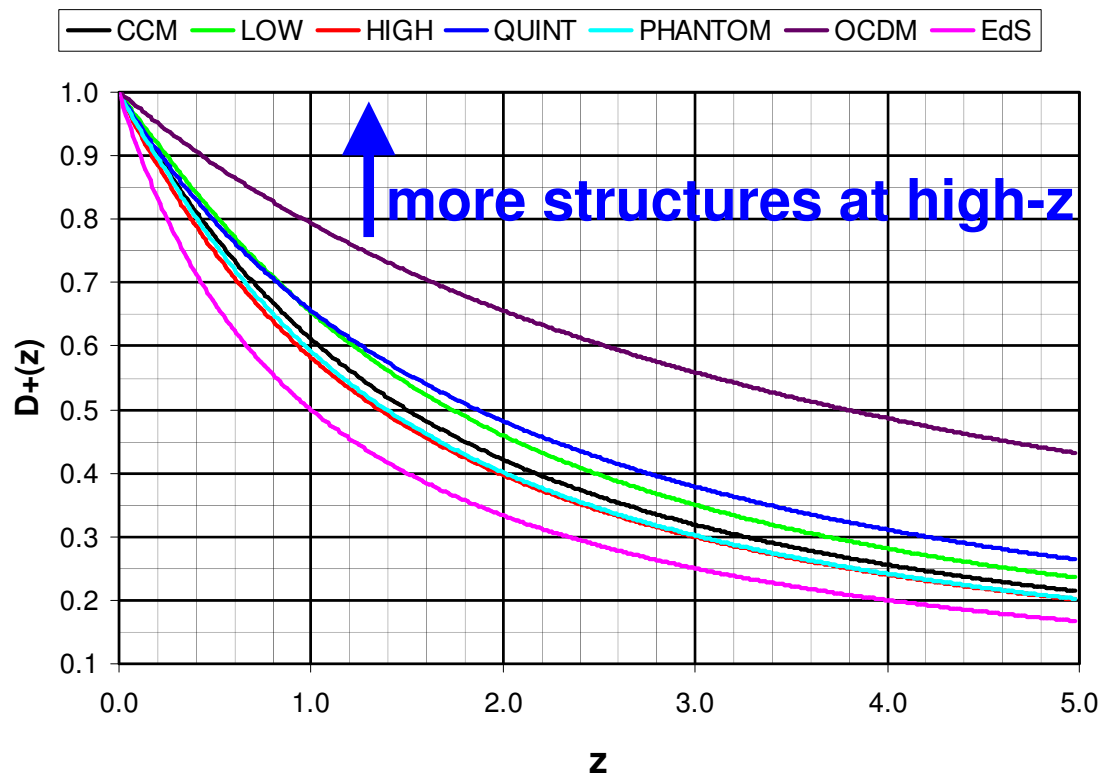
Depend upon the growth factor (linear regime):

$$D_+(a) = \frac{5a}{2} \Omega_m \left[\Omega_m^{4/7} - \Omega_\Lambda + \left(1 + \frac{1}{2} \Omega_m \right) \left(1 + \frac{1}{70} \Omega_\Lambda \right) \right]^{-1}$$

where a is size of universe and Ω_m, Ω_Λ are all evaluated in the past

$[\Omega_m, \Omega_{DE}, w]$

Growth Factor



EdS
[1.0,0,0]

OCDM
[0.3,0,0]

QUINT
[0.3,0.7,-0.5]

HIGH
[0.4,0.6,-1]

CCM
[0.3,0.7,-1]

PHANTOM
[0.3,0.7,-1.3]

LOW
[0.2,0.8,-1]

structure grow efficiently when $\Omega = 1$ (since density is closer to 1 where slight overdensities cause collapse)

How do we expect the shear power spectrum to look?

Formula:

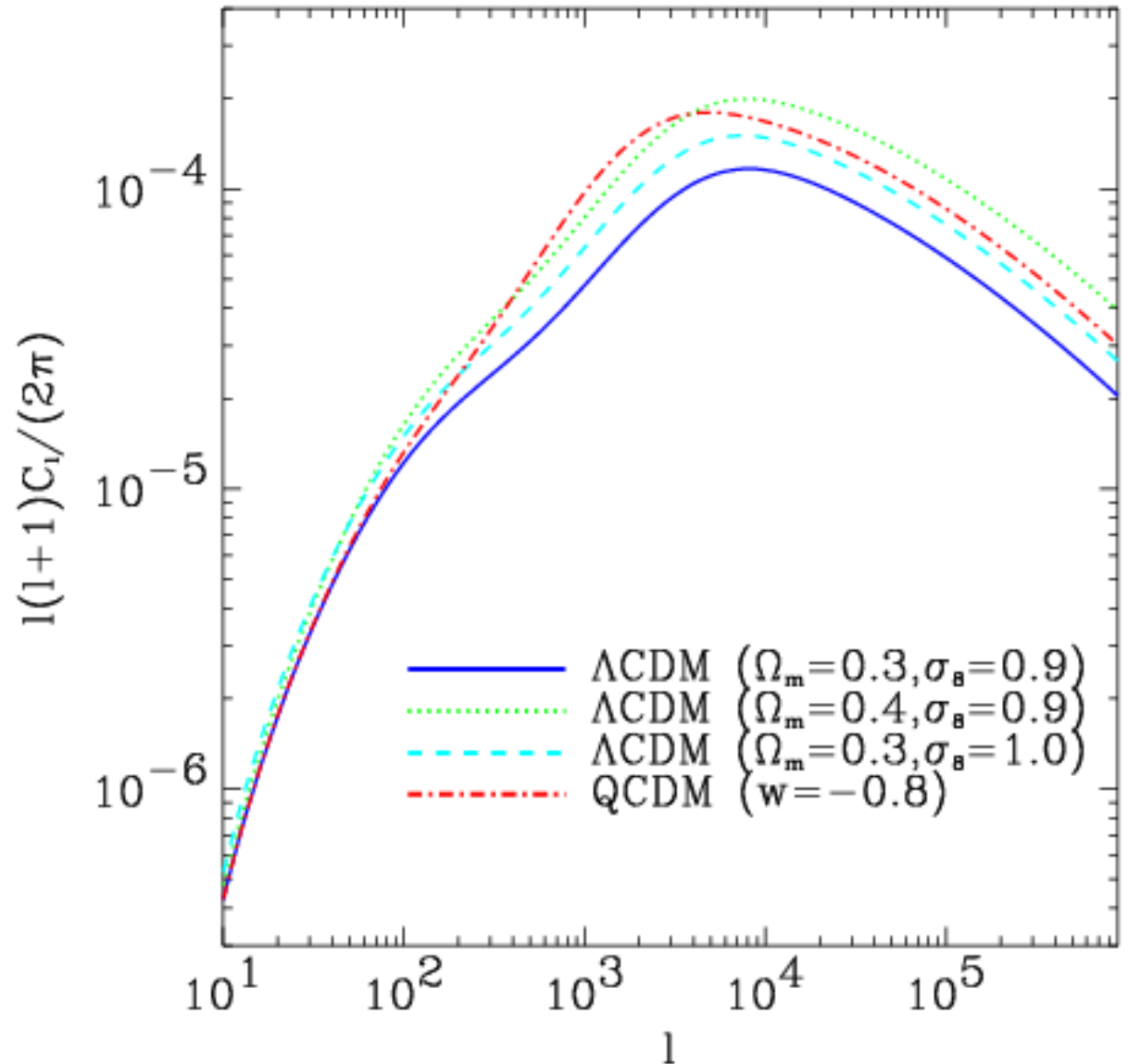
$$\gamma(\theta) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L)$$



Fourier
Transform



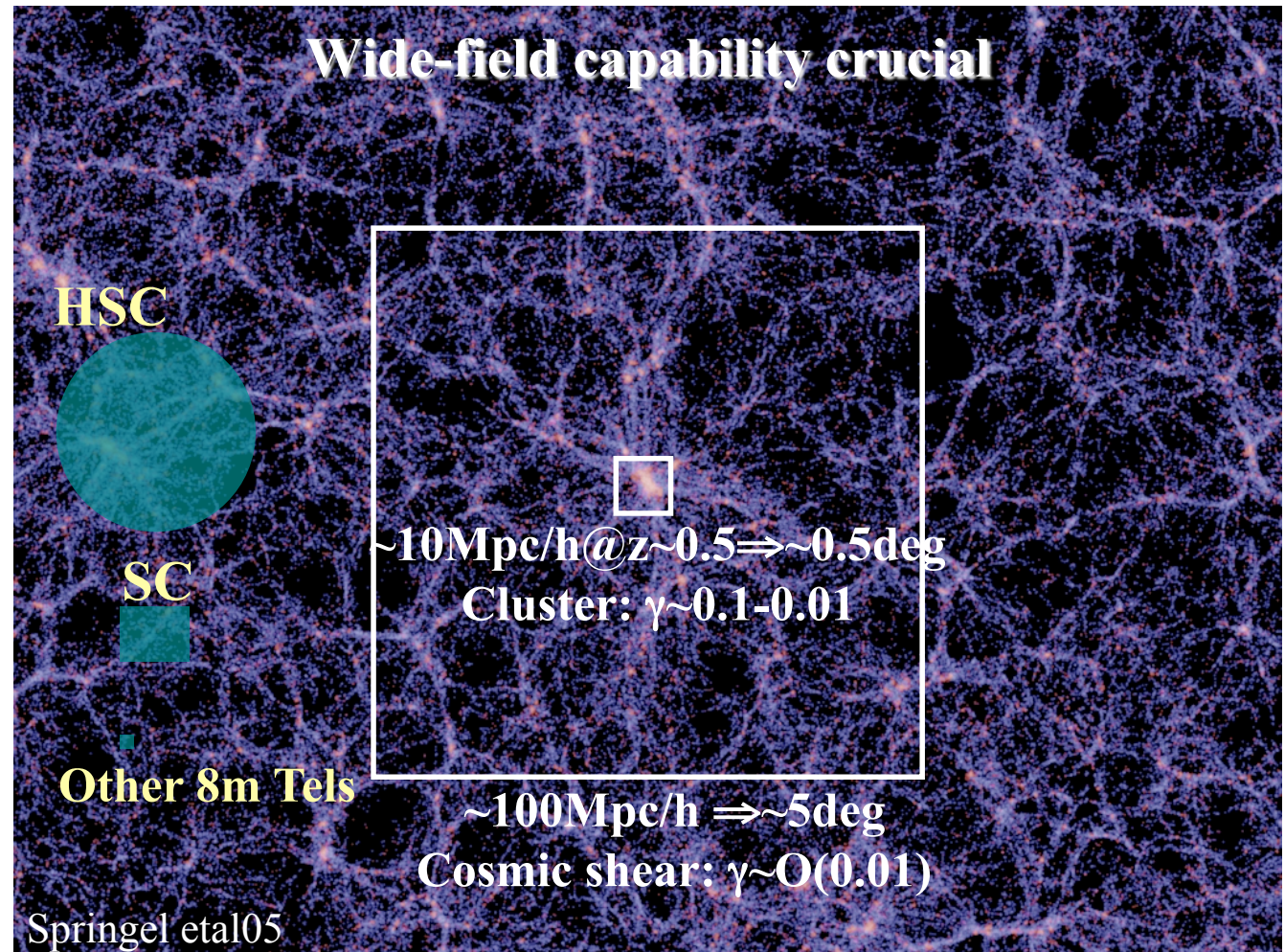
$$P_\gamma(l) \quad P_\kappa(l) \quad C_{\gamma_i \gamma_j}(\ell)$$



To measure a weak lensing signal, we need a very wide-area survey -- to probe the density fluctuations from many lines of sight

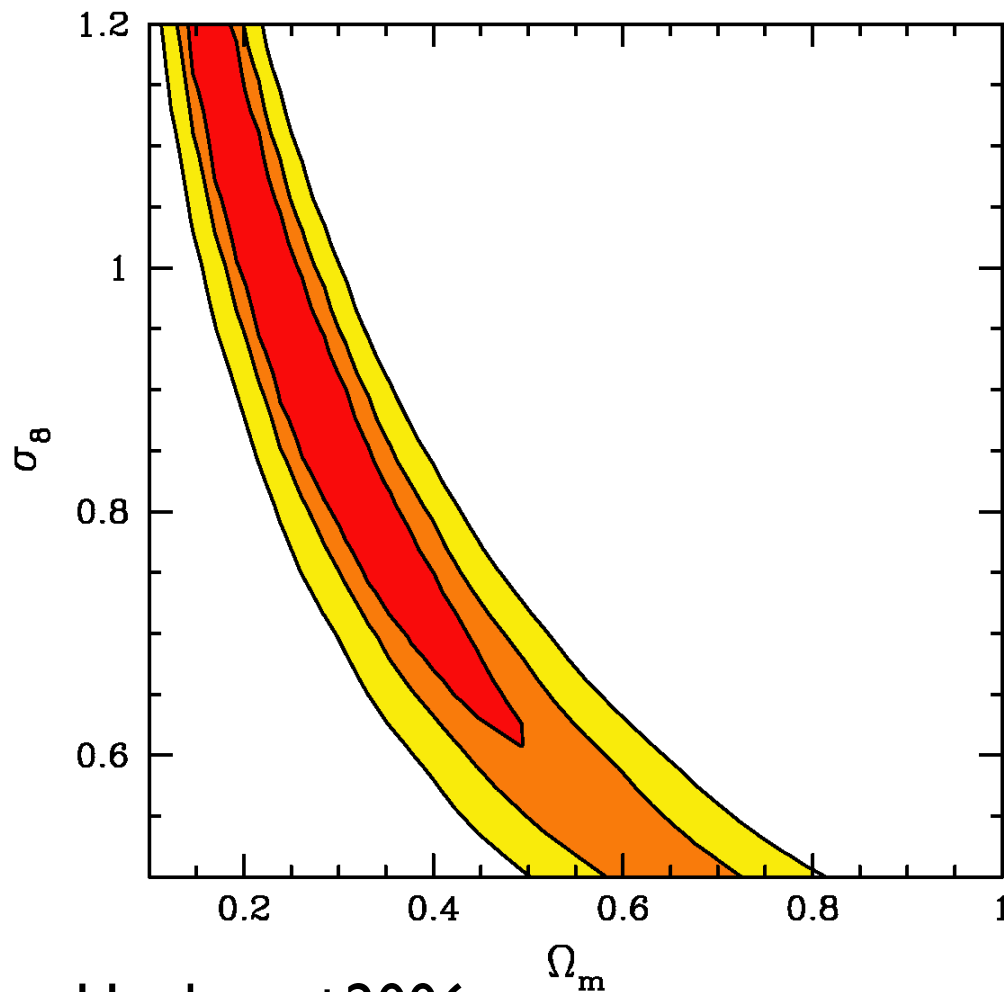
Why?

Large
Variation in
Structure in
Universe



What can cosmic shear teach us about various cosmological parameters?

Consider the following example from CFHT-LS (22 deg²), one of the first significant probes of cosmic shear:

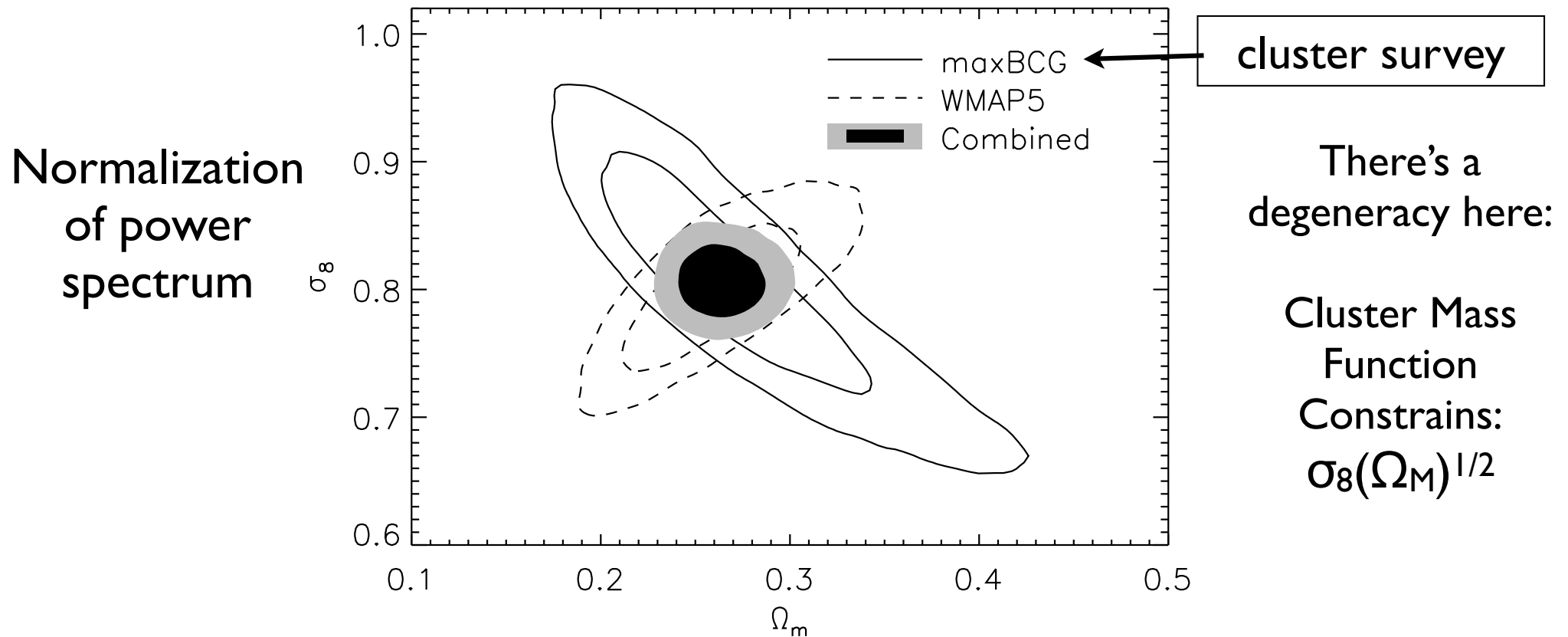


Constrained Quantity in Cosmic Shear Analyses:

$$\sigma_8 (\Omega_m)^{0.6}$$

Hoekstra+2006

These are similar types of constraints as we derive looking at the mass function of galaxy clusters (earlier in this lecture)



There's a degeneracy here:

Cluster Mass Function Constrains:
 $\sigma_8(\Omega_M)^{1/2}$

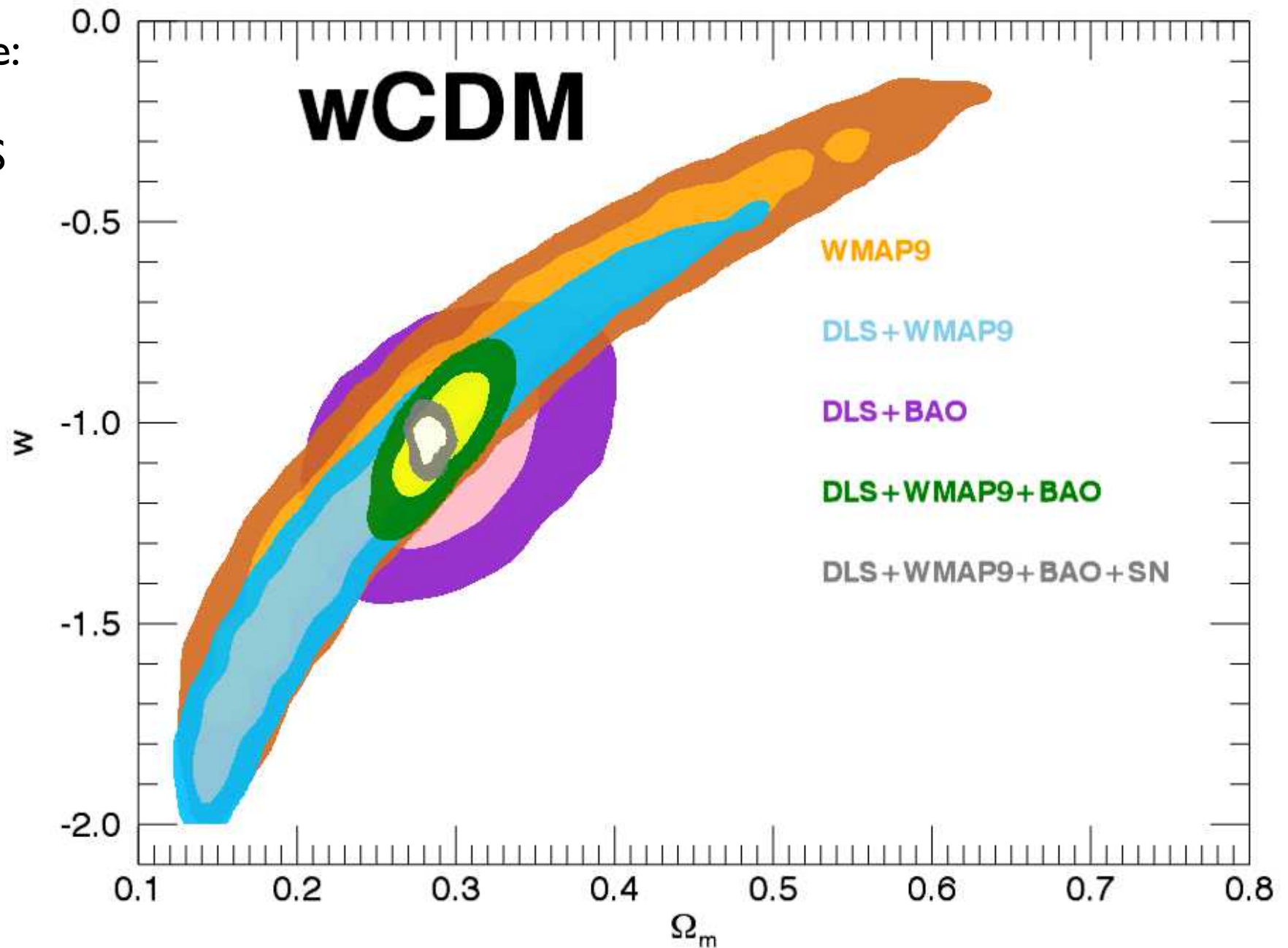
So a higher σ_8 , lower Ω_M and lower σ_8 , higher Ω_M both match observations

Rozo et al. 2010

What constraints can we set on w with these experiments?

One Example:

DEEP LENS
SURVEY



What are some of the most notable cosmic shear studies from 2000 to 2018:

Author(s)	Survey Field	Area	σ_8 Constraints	Ω_m Constraints	w Constraints
Van Waerbeke et al. (2000)	VIRMOS-Descart (CFHT)	$\approx 2.1 \text{ deg}^2$	$\sigma_8 = 0.91 \pm 0.06$	$\Omega_m = 0.3$ (assumed)	Not considered
Bacon et al. (2000)	WHT Survey	$\approx 1.5 \text{ deg}^2$	$\sigma_8 = 0.97 \pm 0.13$	$\Omega_m = 0.3$ (assumed)	Not considered
Wittman et al. (2000)	Deep Lens Survey (DLS)	$\approx 0.6 \text{ deg}^2$	$\sigma_8 = 0.8 \pm 0.2$	$\Omega_m = 0.3$ (assumed)	Not considered
Hoekstra et al. (2002)	RCS	$\approx 53 \text{ deg}^2$	$\sigma_8 = 0.86 \pm 0.04$	$\Omega_m = 0.3$ (assumed)	Not considered
Van Waerbeke et al. (2002)	VIRMOS-Descart (CFHT)	$\approx 8.5 \text{ deg}^2$	$\sigma_8 = 0.88 \pm 0.05$	$\Omega_m = 0.3$	Not considered
Jarvis et al. (2003)	CTIO Survey	$\approx 75 \text{ deg}^2$	$\sigma_8 = 0.71 \pm 0.06$	$\Omega_m = 0.3$ (assumed)	Not considered
Heymans et al. (2005)	COMBO-17	$\approx 1 \text{ deg}^2$	$\sigma_8 = 0.78 \pm 0.08$	$\Omega_m = 0.3$	Not considered
Van Waerbeke et al. (2005)	CFHTLS	$\approx 22 \text{ deg}^2$	$\sigma_8 = 0.85 \pm 0.06$	$\Omega_m = 0.3$	Not considered
Hoekstra et al. (2006)	CFHTLS	$\approx 22 \text{ deg}^2$	$\sigma_8 = 0.85 \pm 0.06$	$\Omega_m = 0.24 \pm 0.04$	Not considered
Fu et al. (2008)	CFHTLS	$\approx 57 \text{ deg}^2$	$\sigma_8 = 0.80 \pm 0.05$	$\Omega_m = 0.25$	Not considered
Schrabback et al. (2010)	COSMOS	$\approx 1.64 \text{ deg}^2$	$\sigma_8 = 0.68 \pm 0.06$	$\Omega_m = 0.3$	Not considered
Kilbinger et al. (2013)	CFHTLenS	$\approx 154 \text{ deg}^2$	$\sigma_8 = 0.79 \pm 0.03$	$\Omega_m = 0.27 \pm 0.02$	w = -1 (assumed)
Heymans et al. (2013)	CFHTLenS	$\approx 154 \text{ deg}^2$	$\sigma_8 = 0.77 \pm 0.05$	$\Omega_m = 0.3$	w = -1 (assumed)
Jee et al. (2015)	Deep Lens Survey (DLS)	$\approx 20 \text{ deg}^2$	$\sigma_8 = 0.81 \pm 0.06$	$\Omega_m = 0.26 \pm 0.05$	w = -1.13 ± 0.25
Hildebrandt et al. (2017)	KiDS-450	$\approx 450 \text{ deg}^2$	$\sigma_8 = 0.745 \pm 0.039$	$\Omega_m = 0.26 \pm 0.04$	w = -1.02 ± 0.10
Troxel et al. (2018)	DES Year 1	$\approx 1321 \text{ deg}^2$	$\sigma_8 = 0.782 \pm 0.027$	$\Omega_m = 0.267 \pm 0.017$	w = -0.82 ± 0.20

Observational Challenges — Intrinsic Alignments

In order to measure the effect that gravitational lensing has on background galaxies, we assume that the relative orientation of galaxies is random

Any alignment between the orientation of galaxies is assumed to result from gravitational lensing by intervening masses

But what if the relative orientation of galaxies is not random?

Such alignment could result from tidal interactions of galaxies on each other (if galaxies are nearby)

Seems clear that shallower surveys would be more affected than deeper surveys

Observational Challenges — Intrinsic Alignments

In fact, galaxies have been shown to exhibit some intrinsic alignments, but to first order it is not a huge concern

Good technique for ensuring that Intrinsic Alignment do not bias one's results is to exclude sources from the analysis that have similar redshifts

Other Challenges / Possible Systematic Errors

The shear signal one derives from observations is very sensitive to knowledge of the intrinsic redshift distribution of the sources (originally just used redshifts from HDF North)

In comparing with the predictions from cosmological models, the shear signal dependences on the clustering of sources at very small scales -- where the power spectrum is non-linear and baryonic physics may be important. Deficiencies in our knowledge of the latter two processes may affect weak lensing results.

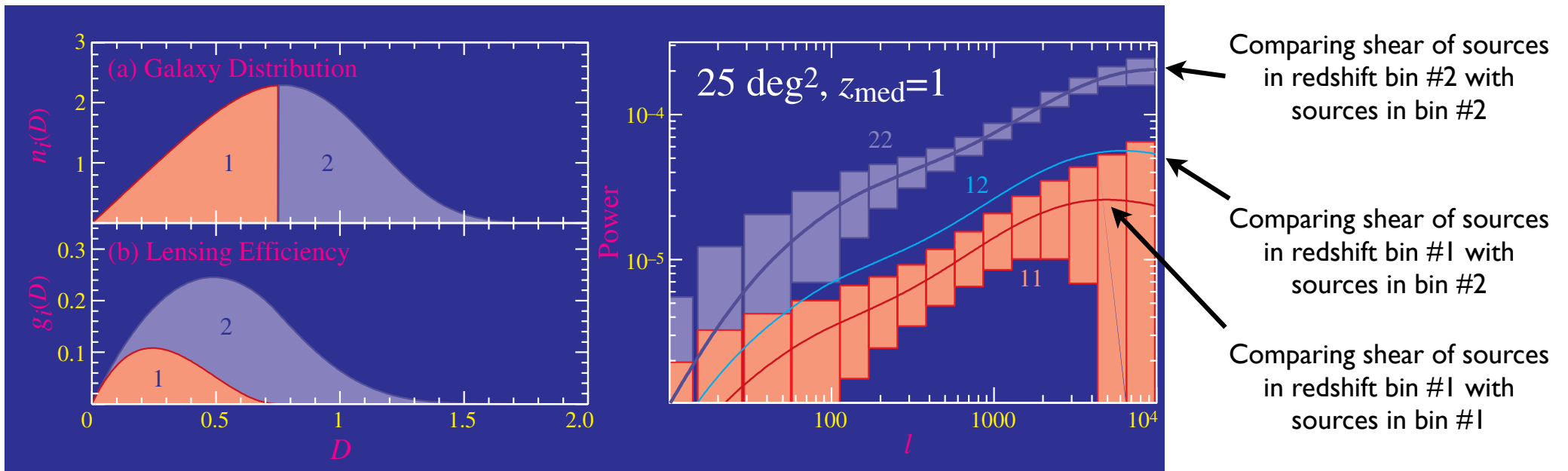
Cosmic Shear: Lots of Potential For Setting the Best Future Constraints

From the Dark Energy Task Force Report:

WL also emerging technique. Eventual accuracy will be limited by systematic errors that are difficult to predict. If the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program.

Cosmic Shear: Lots of Potential For Setting the Best Future Constraints

One can take advantage of the redshifts one can estimate for background sources to measure the growth of structures as a function of redshift. More distant sources will pass by much more structure along the line of sight



Notice that there is much more power in the shear signal cross-correlating sources in the more distant redshift sample (#2) than the closer one (#1)

Dark Energy Experiments

So the game is to determine the w parameter and how it depends on redshift

There are four standard methods:

1. Supernovae Ia

- use of standard candles to establish distance-redshift relation
- first established existence of dark energy 10 years ago

2. Baryonic Acoustic Oscillations

- gives us a standard rod to establish distance-redshift relation and Hubble parameter-redshift relation with low systematics

3. Galaxy Clusters

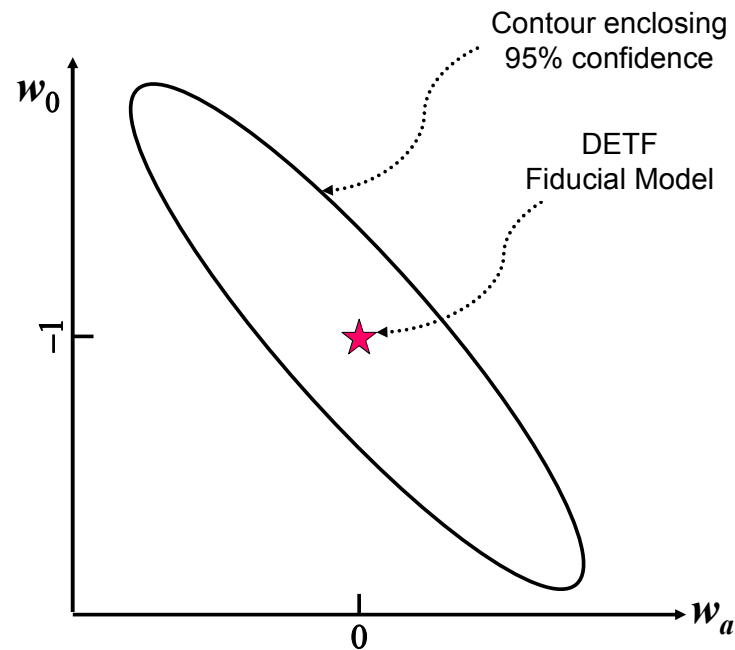
- provide us with sensitive probe of growth of structure
- early evidence for low Ω_m

4. Weak Gravitational Lensing

- provide us with sensitive probe of growth of structure
- powerful technique still in process of realizing full potential

Power of the techniques in constraining dark energy are quantified in terms of the “Figure of Merit”

The **DETF figure of merit** is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0 – w_a plane. Larger figure of merit indicates greater accuracy.



The DETF figure of merit is defined as the reciprocal of the area of the error ellipse in the w_0 – w_a plane that encloses the 95% C.L. contour. (We show in the Technical Appendix that the area enclosed in the w_0 – w_a plane is the same as the area enclosed in the w_p – w_a plane.)

By combining multiple techniques, one can make huge gains in terms of the “Figure of Merit,” i.e., constraining both w and w_a .

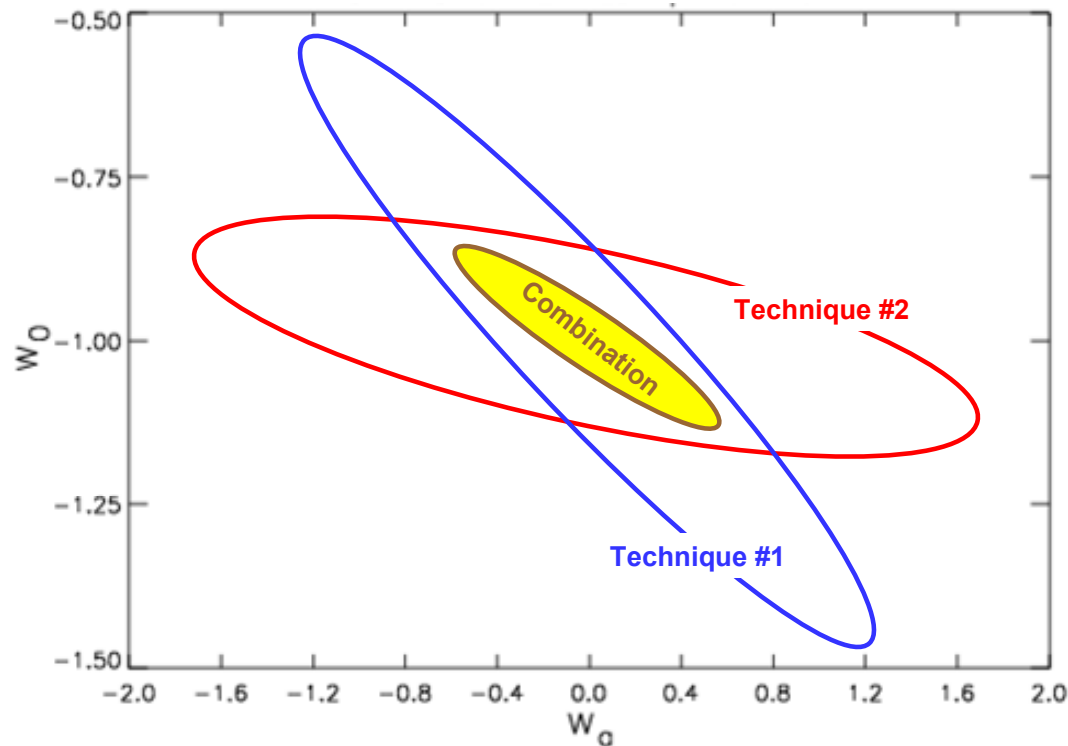


Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Baryon Acoustic Oscillations

Extra Power in Matter Power Spectrum at
Distance of First Acoustic Oscillation

Dark Energy Observables: $D_A(z)$, $H(z)$

Strengths: Least Affected by Systematics

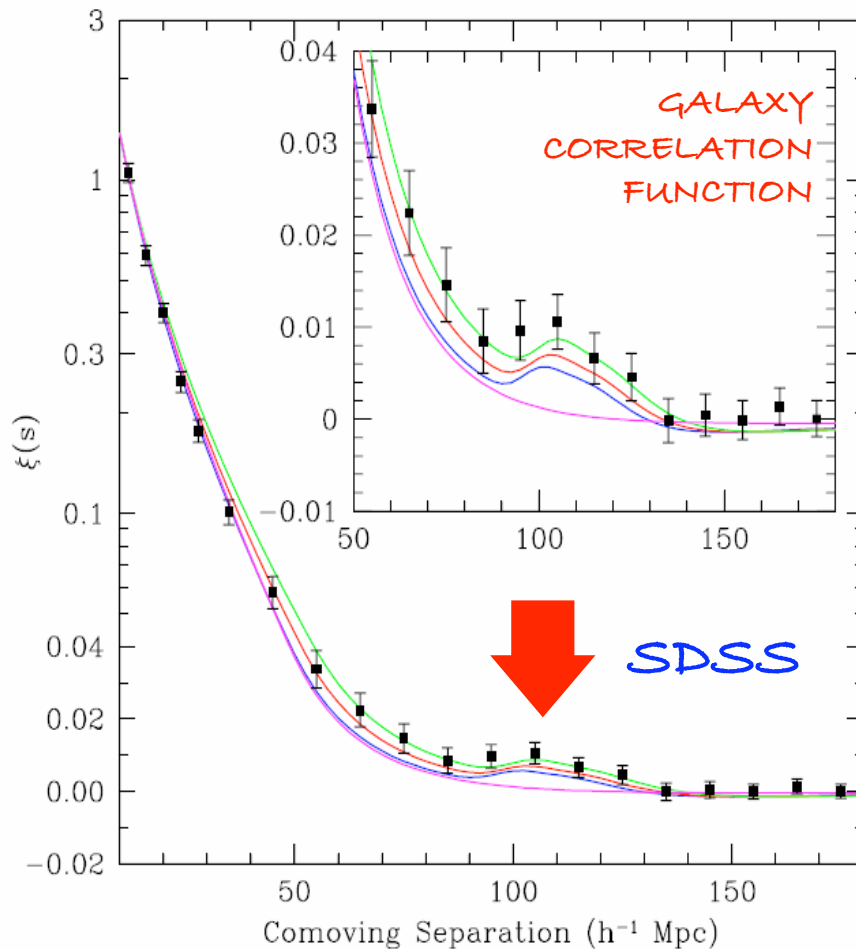
Weaknesses: Most Leverage at $z > 1$ where changes in dark energy model have smallest effect

Sensitive to Errors in the Redshifts of
the Sources Probed

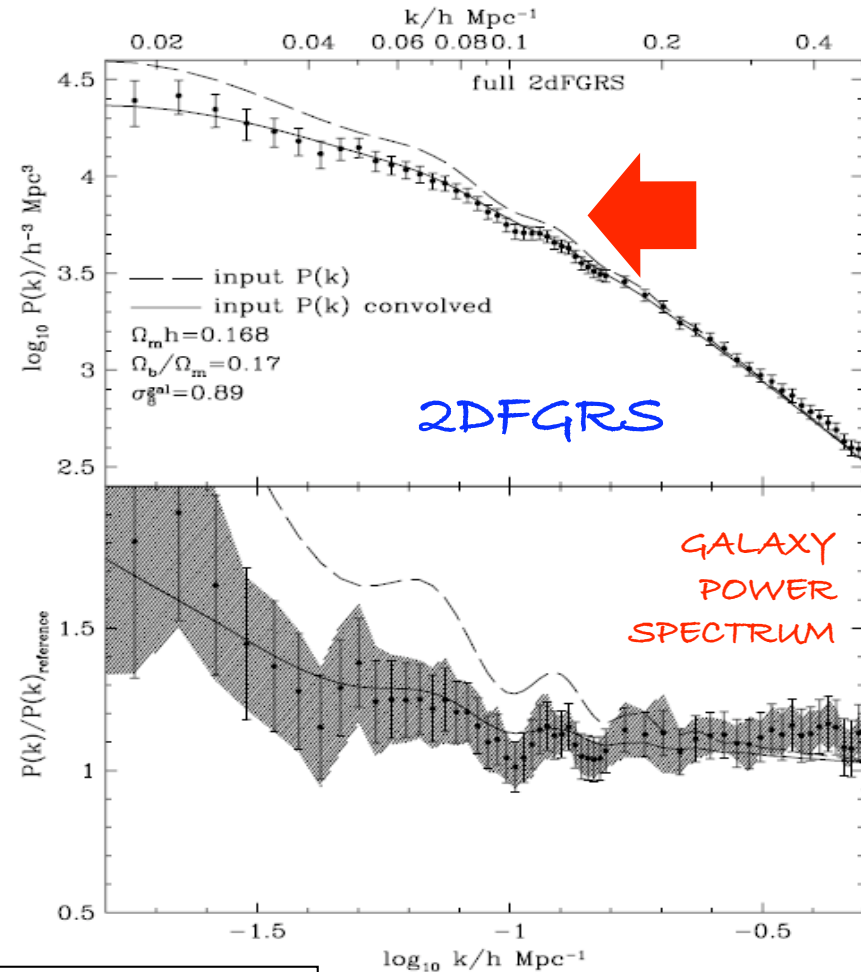
Potential in Large Area Survey: Uncertainties in the redshift estimates for individual sources can largely be overcome by covering large areas of sky

By measuring the correlation function for a galaxy survey we can look for this bump
(from baryon acoustic oscillations)

SDSS: EISENSTEIN ET AL. (2005)



2DFGRS: COLE ET AL. (2005)

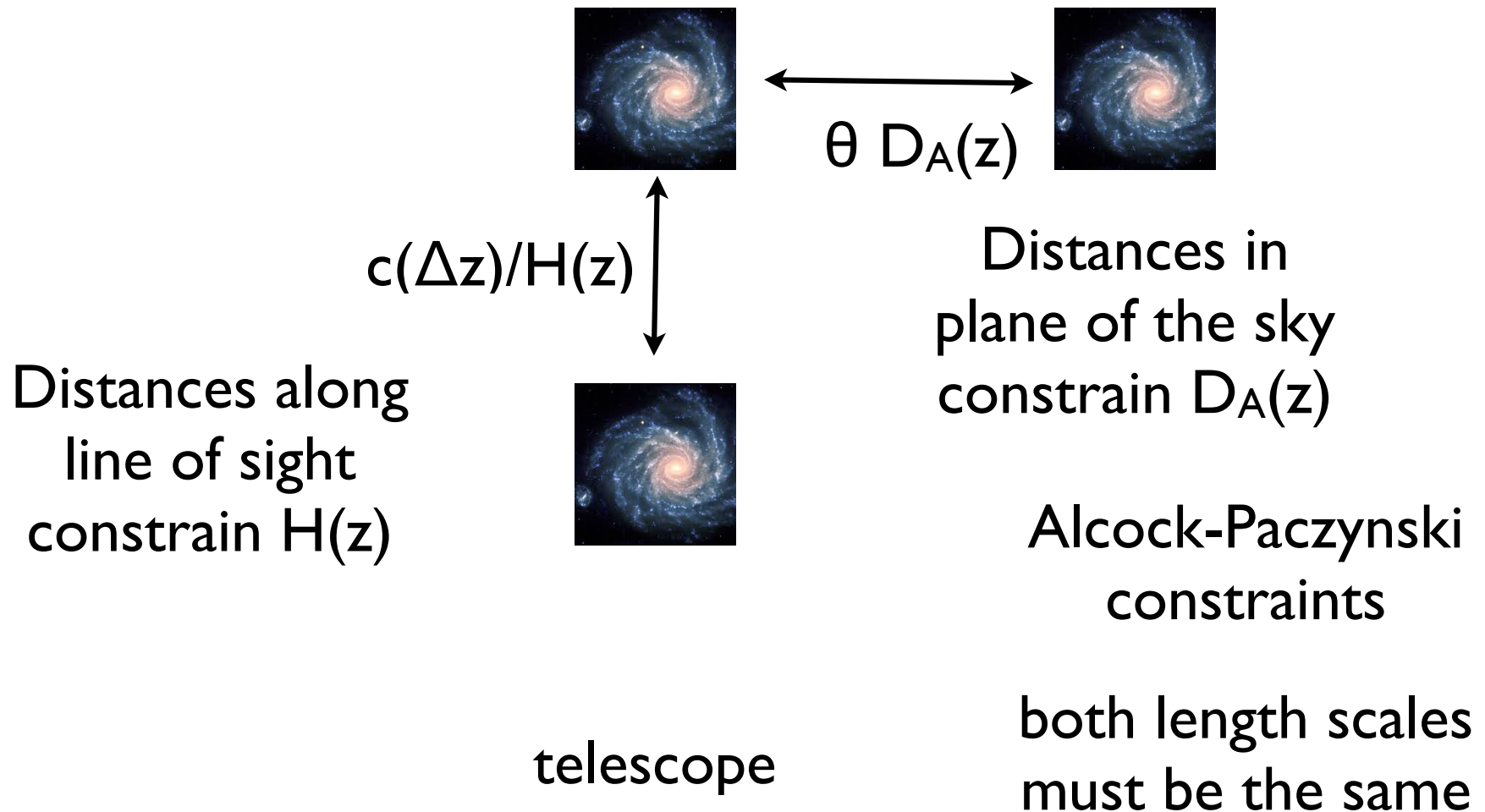


First Measurements

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Baryon Acoustic Oscillations:

Dark Energy Observables: $D_A(z)$, $H(z)$



These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Galaxy Cluster Counting:

Dark Energy Observables: Volume(z), Growth Factor (z)

Strengths: Very sensitive to Growth Factor,
Many Different Techniques to Find Clusters

Weaknesses: Substantial Uncertainties in Baryonic Physics Needed to Predict x-ray, SZ, or optical signature of clusters

Potential in Large Area Survey: Useful in further calibrating cosmic shear signal

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Supernovae (SN):

Dark Energy Observables: $D_L(z)$

Strengths: Most Established Technique, Very Powerful if SN are in fact a standard candle

Weaknesses: Systematic Uncertainties, Possible Evolution in SNe, Light Curve Fitting Uncertainties

Potential in Large Area Survey: Large Number of SNe found in large area surveys should allow further calibration of systematics

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Weak Lensing:

Dark Energy Observables: $D_A(z)$, Growth Factor (z)

Strengths: Technique with Most Power,
Allows Constraints on Both Expansion and
Growth Rate for Matter Perturbations

Weaknesses: Sensitive to Uncertainties in the Redshifts
of the Lensed Galaxies

Need Full Knowledge of the Diversity of Spectra at
Intermediate Redshift

Potential in Large Area Survey: Large Area
Observations Should Allow One to Calibrate Out Any
Systematics

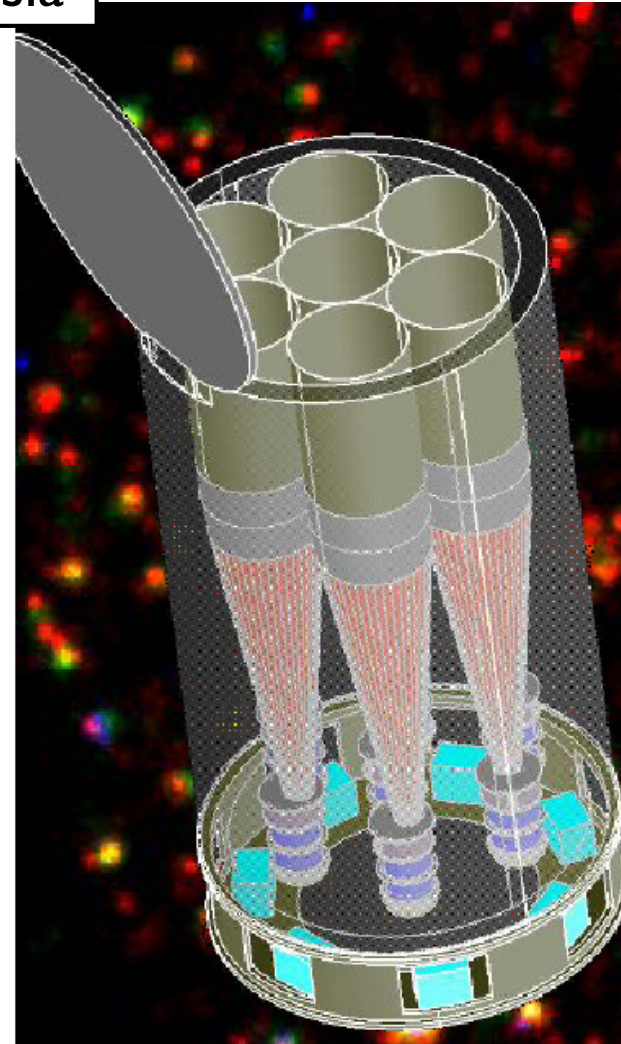
Some well known DE missions

e-ROSITA: State of the art x-ray survey telescope

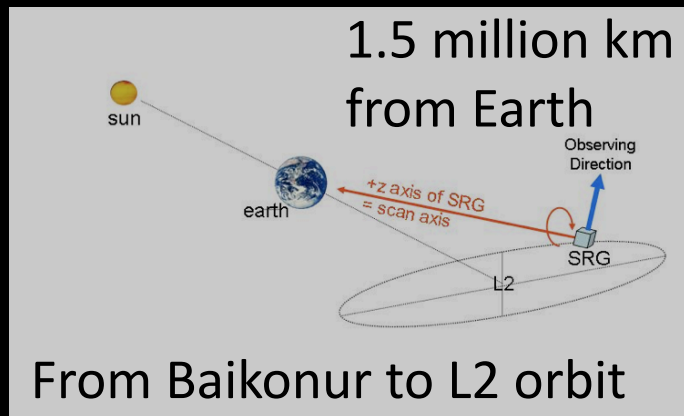
Collaboration between Germany / Russia

- space-based X-ray cluster survey
- currently build at MPE in Garching
- start: 2019
- all sky coverage
- DE probes: GC, BAOs
- objects: 100,000 galaxy clusters
- redshift range: $0 < z < 1.5$
- DE constraints: $\sigma_w \sim 5\%$
- requires large ground-based follow-up program for identification and redshifts

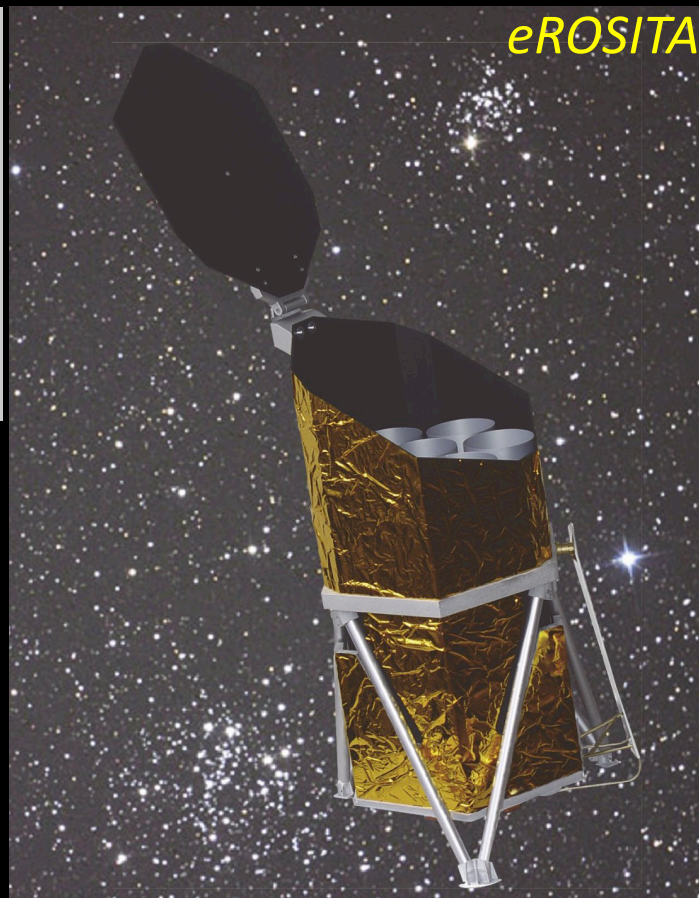
Note: E-ROSITA ceased operations after the beginning of the Ukraine invasion in Feb 2022. It had completed 4 of 8 all sky surveys. Analysis is ongoing.



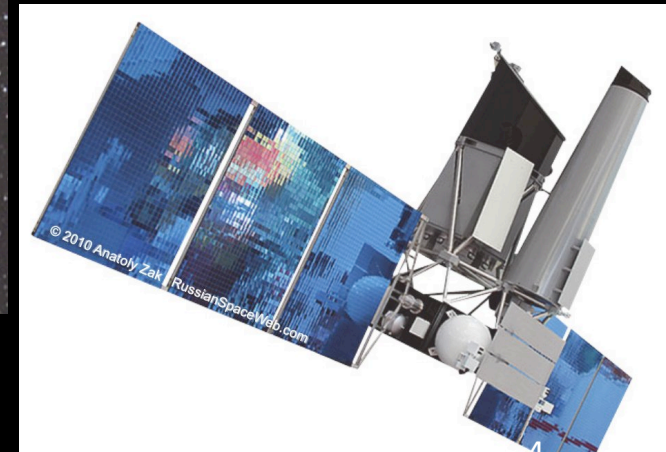
The (Near) Future: *eROSITA* $\sim 10^5$ X-Ray Clusters



Zenit-2SB rocket
Fregat booster



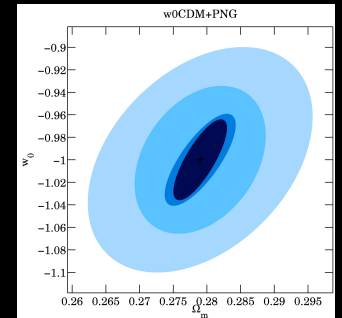
Spektr-RG mission
Navigator platform
ART-XC / *eROSITA*



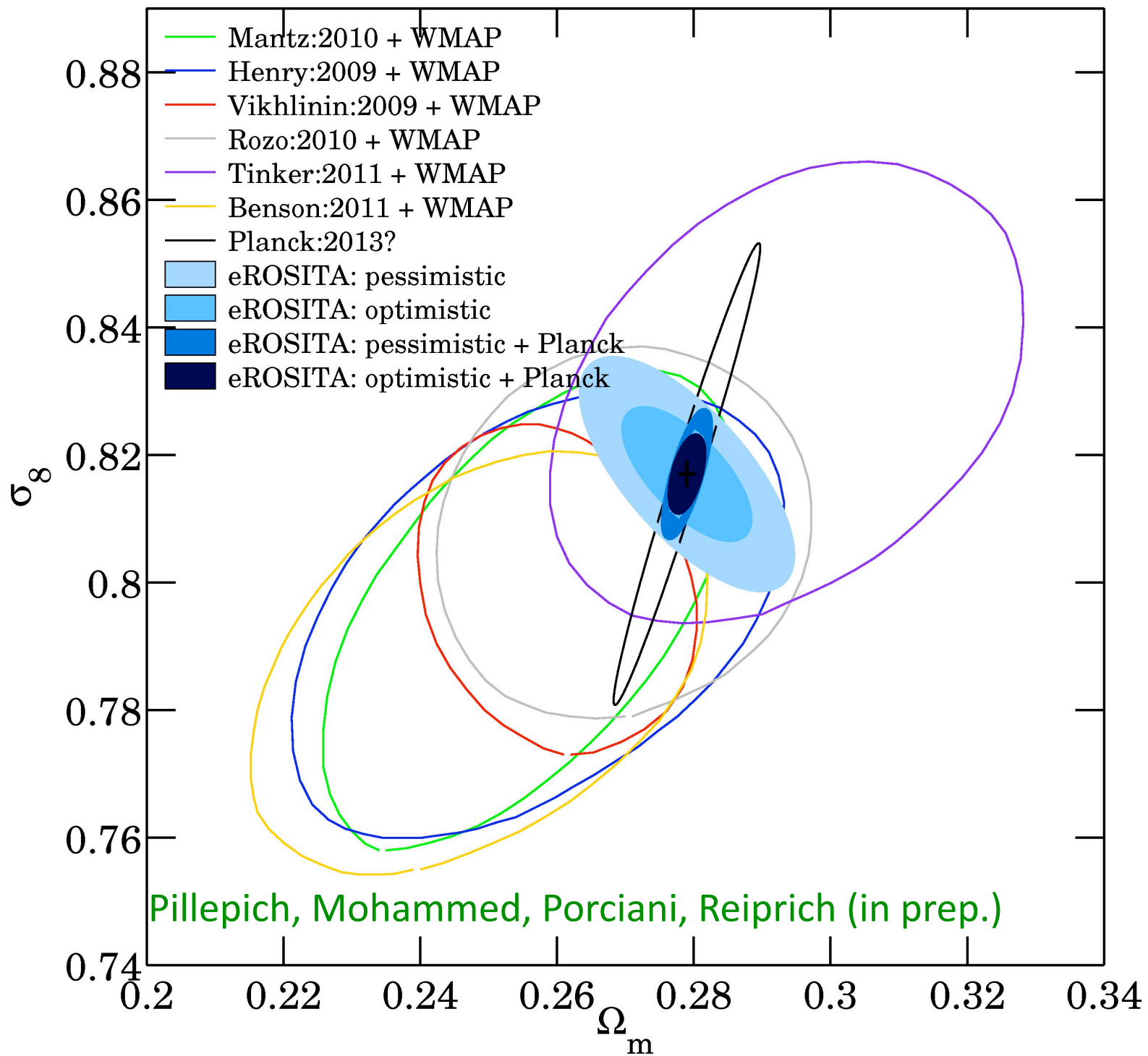
Talks P. Predehl, A. Merloni

Projected Cosmological Constraints

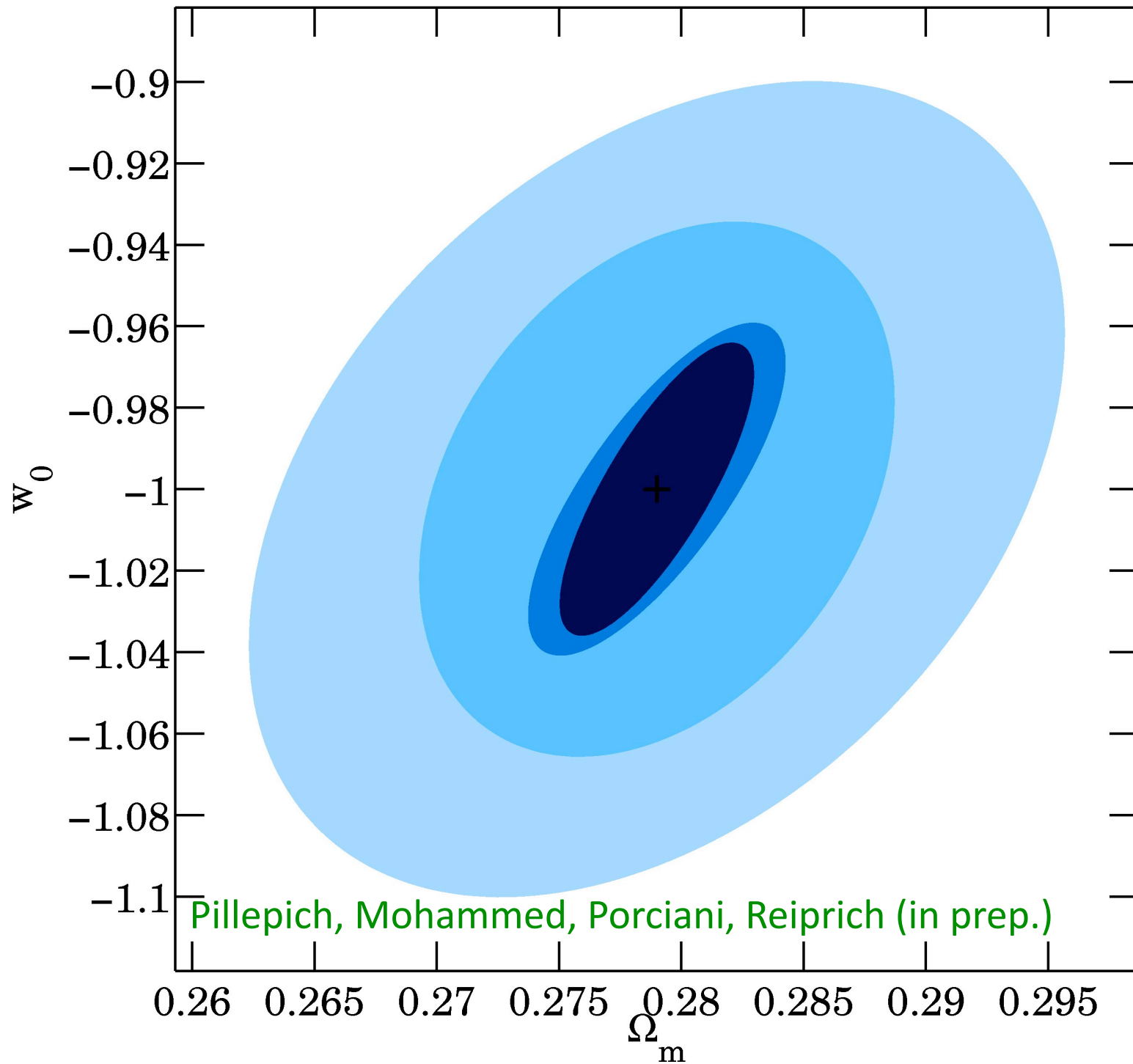
- *eROSITA*-specific forecasts, taking into account photons registered at detector; assume that clusters get detected if at least 50 source photons received.
- Include cluster physics; scatter in L_x-M relation accounted for, fit scaling relation parameters simultaneously with cosmology (“self-cal”).
- Take into account expected redshift uncertainty.
- Apply two cosmological tests simultaneously; evolution of (i) cluster mass function and (ii) angular clustering.
- Several assumptions, e.g., hardware works, flat Universe, fiducial cosmology and L_x-M relation, redshifts, one sky for all,



LCDM+PNG



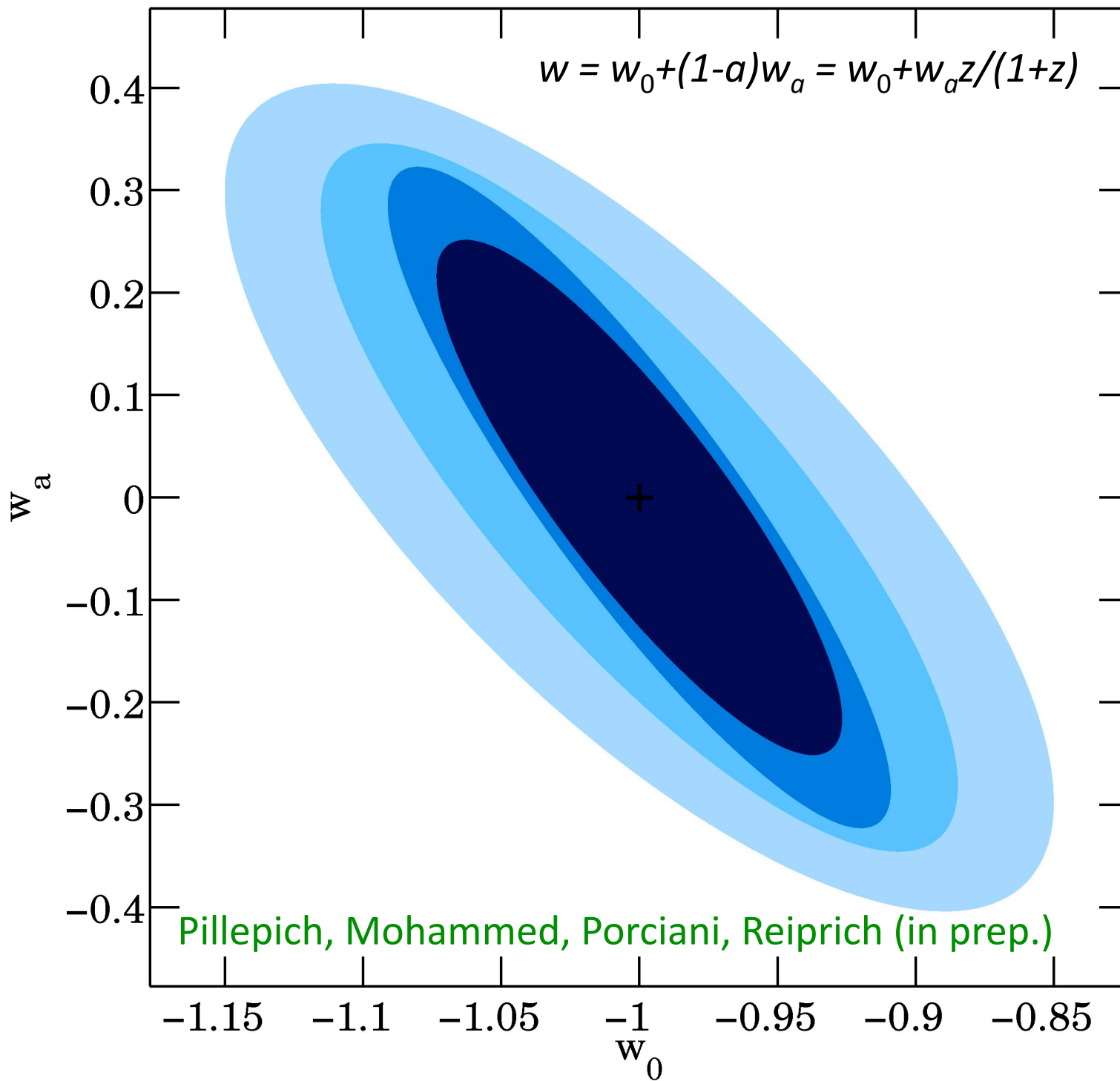
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)



See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy

wCDM+PNG



See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

eROSITA Compared to DES and Euclid

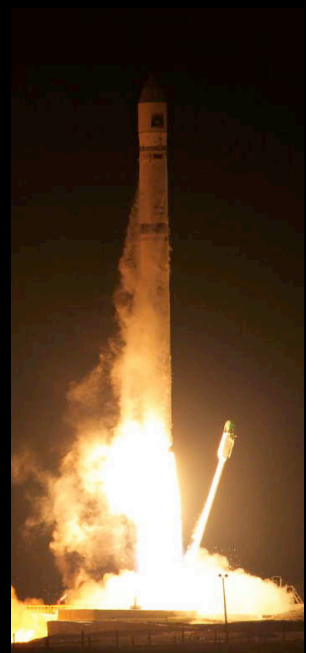
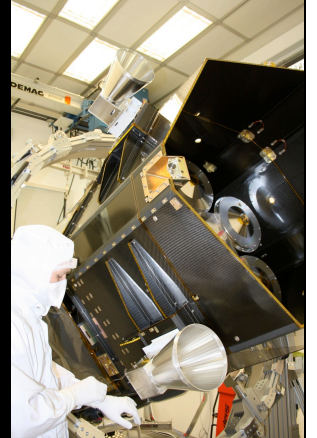
Data	Stage	Redshifts	Prior Scenario	Model	$\Delta f_{\text{NL}}^{\text{local}}$	$\Delta \sigma_8$	$\Delta \Omega_m$	Δw_0	Δw_a	FoM ^{DEFT, 1σ}
eROSITA	Stage IV	photo-z	Pessimistic	LCDM+PNG	8.1	0.012	0.0101	-	-	-
eROSITA		spectro-z	Optimistic	LCDM+PNG	6.4	0.007	0.0060	-	-	-
eROSITA + Planck		photo-z	Pessimistic	LCDM+PNG	6.5	0.006	0.0021	-	-	-
eROSITA + Planck		spectro-z	Optimistic	LCDM+PNG	5.0	0.004	0.0015	-	-	-
eROSITA	Stage IV	photo-z	Pessimistic	w0CDM+PNG	8.2	0.016	0.0109	0.066	-	-
eROSITA		spectro-z	Optimistic	w0CDM+PNG	6.6	0.009	0.0063	0.043	-	-
eROSITA + Planck		photo-z	Pessimistic	w0CDM+PNG	6.9	0.007	0.0034	0.026	-	-
eROSITA + Planck		spectro-z	Optimistic	w0CDM+PNG	5.6	0.005	0.0025	0.023	<1%, <3%	
eROSITA	Stage IV	photo-z	Pessimistic	wCDM+PNG	8.2	0.018	0.0120	0.098	0.27	57.4
eROSITA		spectro-z	Optimistic	wCDM+PNG	6.6	0.011	0.0066	0.075	0.23	103.1
eROSITA + Planck		photo-z	Pessimistic	wCDM+PNG	7.0	0.007	0.0036	0.059	0.21	179.4
eROSITA + Planck		spectro-z	Optimistic	wCDM+PNG	5.7	0.006	0.0026	0.048	0.16	263.3
DES	Stage III	photo-z	WL+2D photometric	wCDM+PNG	8.6	0.009	0.0082	0.093	0.61	-
DES + Planck		photo-z	WL+2D photometric	wCDM+PNG	8.2	0.009	0.0074	0.090	0.35	-
Euclid	Stage IV	photo-z	WL+2D photometric	wCDM + PNG	4.7	0.005	0.0048	0.054	0.32	-
Euclid		spectro-z	WL+2D spectroscopic	wCDM + PNG	5.7	0.005	0.0051	0.051	0.35	-
Euclid + Planck		photo-z	WL+2D photometric	wCDM + PNG	4.5	0.005	0.0044	0.052	0.20	-
Euclid + Planck		spectro-z	WL+2D spectroscopic	wCDM + PNG	5.3	0.005	0.0037	0.035	0.15	-

>300 for $f_{\text{NL}}=0$

Pillepich, Mohammed, Porciani, Reiprich (in prep.); Merloni et al. (arXiv:1209.3114).
DES and Euclid from Giannantonio et al. (2012).

Summary of Statistics/Precision

- *eROSITA* will increase statistics by 1-2 ord. of mag.
- It will discover 100k clusters, among them *all* massive ones in the observable Universe and, hopefully, many more bullet-like clusters.
- It will likely be the first “Stage IV” dark energy probe world-wide.
- It will yield competitive and complementary constraints on dark matter, e.g., $\Delta\Omega_M < 1\%$, dark energy, e.g., $\Delta w_{DE} < 3\%$, but also on modified gravity, neutrino masses, primordial non-Gaussianity,



eROSITA: Some Results Based on Early Data

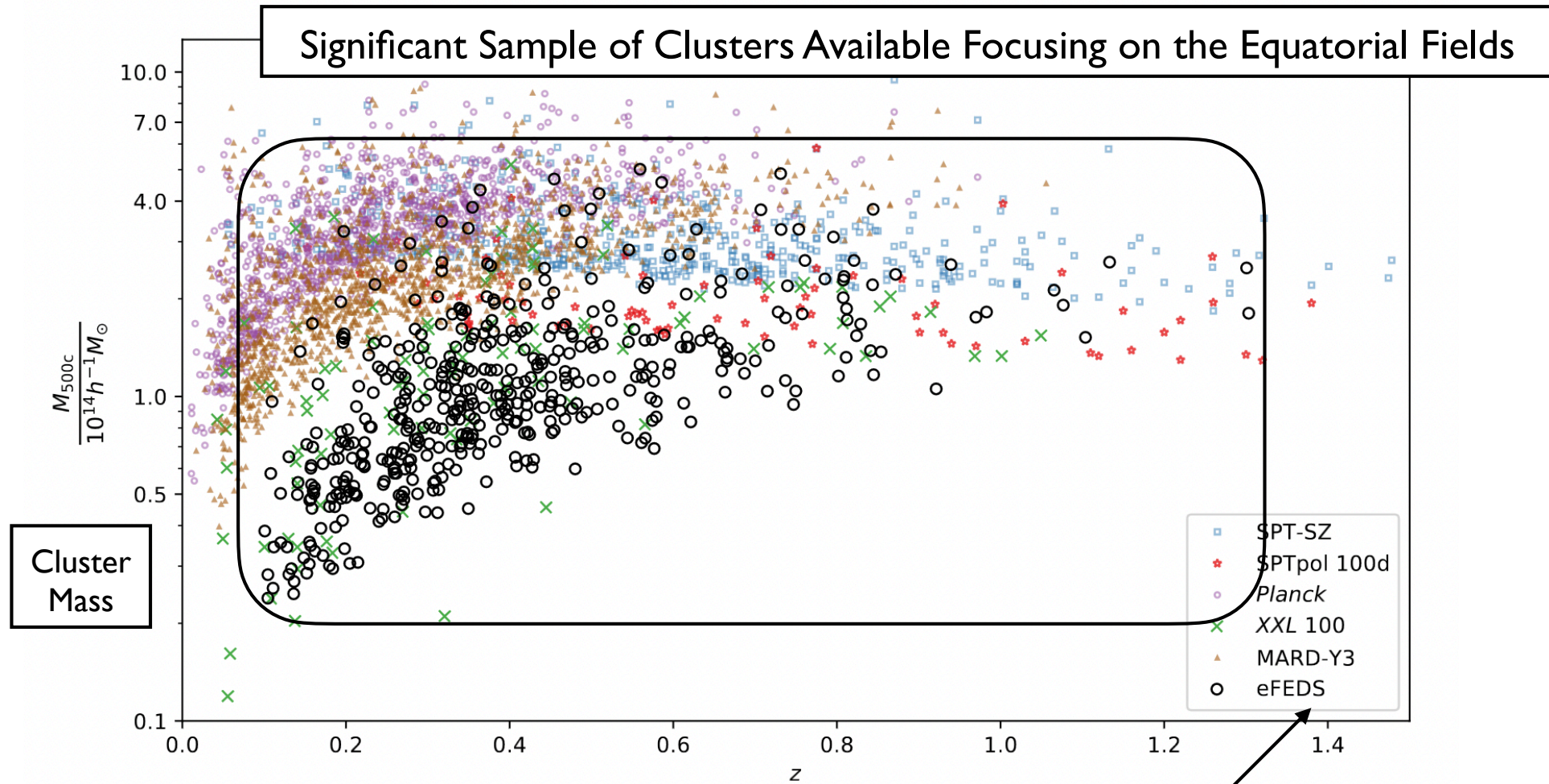


Figure 10. The mass and redshift of the eFEDS clusters (black circles), and those in the SPT-SZ survey (blue squares; Bleem et al. 2015), the SPTpol 100 degree² survey (red stars; Huang et al. 2020), the Planck mission (purple circles; Planck Collaboration et al. 2015), the brightest sample in the XXL survey (green crosses; Pacaud et al. 2016), and the X-ray MARD-Y3 sample (brown triangles; Klein et al. 2019). When plotting the eFEDS sample, we additionally include the two clusters at $z \approx 1.3$ that satisfy both the X-ray and optical selections.

eFEDS = e-ROSITA Final Equatorial Deep Survey

Equatorial Survey has Weak-Lensing Information Available to Calibrate Masses of Galaxy Clusters, so this is reason to focus first on them

eROSITA: Some Results Based on Early Data

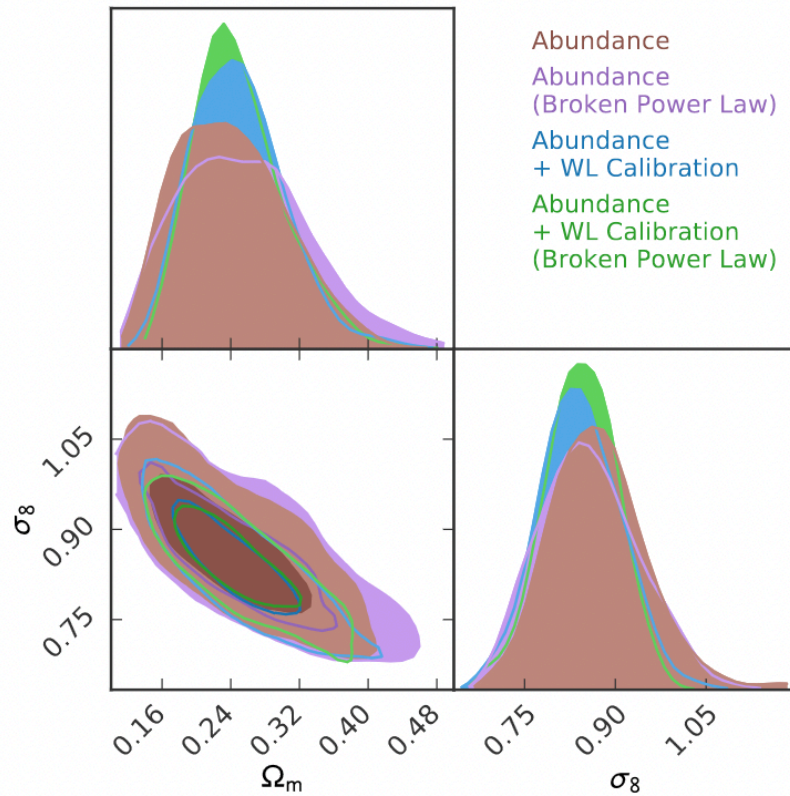


Figure 16. The constraints on Ω_m and σ_8 obtained from the modeling of the cluster abundance and that jointly with the weak-lensing mass calibration. The results based on the cluster abundance (the joint modeling) with and without the broken power-law scaling of the η - M - z relation are in purple and brown (green and blue), respectively. For the modeling of the cluster abundance (brown and purple contours), the informative priors are applied to the parameters of the η - M - z relation (see Section 4.3). The contours indicate the 68% and 95% confidence levels.

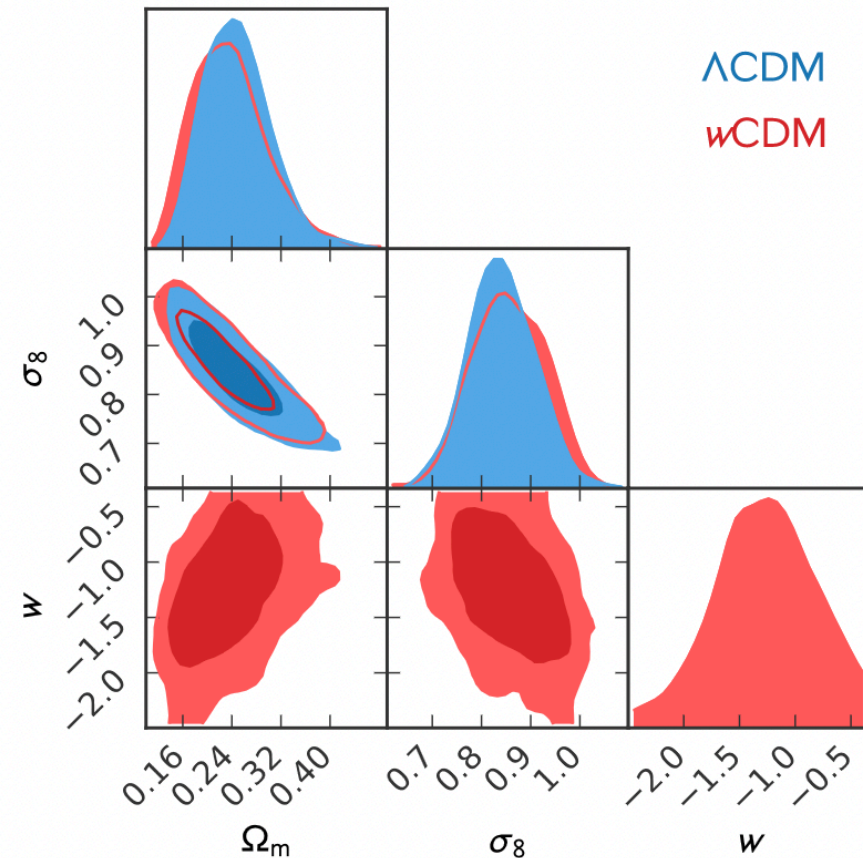


Figure 17. The cosmological constraints from the eFEDS clusters in the Λ CDM (blue) and w CDM (red) models. These constraints are obtained in the joint modeling of the weak-lensing mass calibration and the cluster abundance with the single power-law mass scaling of the count rate and with the Gaussian priors applied to the parameters of the X-ray completeness. The contours indicate the 68% and 95% confidence levels.

eROSITA: Some Results Based on Early Data

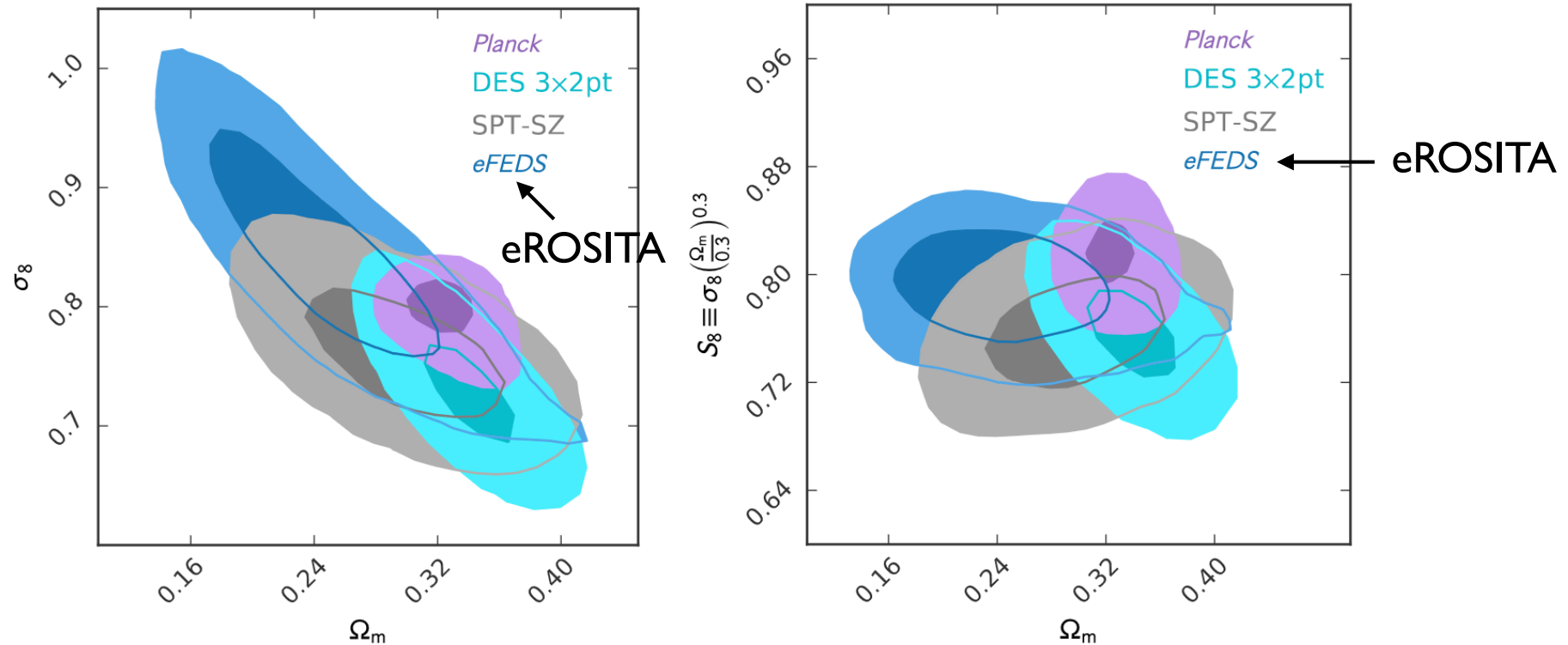


Figure 18. The comparisons of the cosmological parameters assuming the Λ CDM cosmology between the eFEDS clusters (blue) and the external results, including the anisotropy and polarization (TTTEEE + lowE) of CMB temperatures from *Planck* (purple; [Planck Collaboration et al. 2020](#)), the 3 \times 2-point analysis from the Dark Energy Survey (cyan; [Abbott et al. 2022](#)), and the clusters in the SPT-SZ survey (grey; [Bocquet et al. 2019](#)). In the left (right) panel, the constraints on Ω_m and σ_8 ($S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.3}$) are shown. The contours indicate the 68% and 95% confidence levels. The eFEDS results are in agreement with the external constraints at a level of $\lesssim 1.2\sigma$.

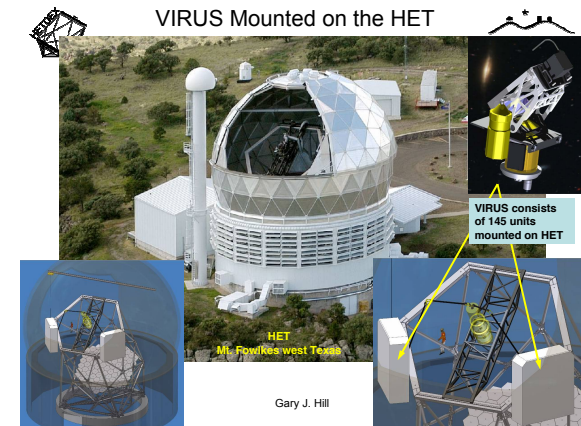
Other well known DE missions:



The Hobby-Eberly Telescope
Dark Energy Experiment

Overview

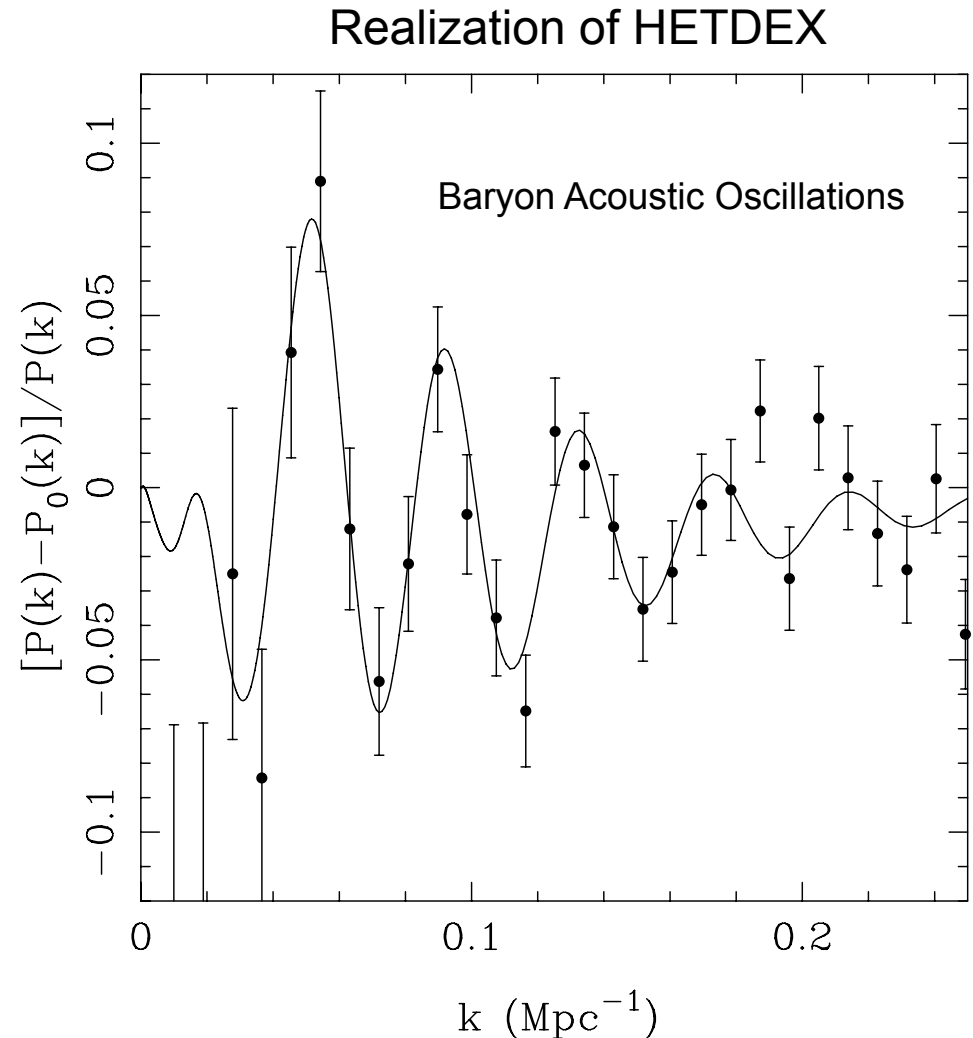
- Two observational approaches to make progress on DE
 - Get the tightest possible constraints at low redshift where effect of DE is stronger
 - Go to higher redshift where we can measure the evolution or verify that $w(z) = -1$
 - Both approaches are needed
- Spectroscopic BAO at high redshift
 - One method to measure $H(z)$ directly as well as $D_A(z)$
 - Only method that can be applied at $z > 2$
 - Method with smallest systematic worries (particularly at $z > 1.5$)
- Almost all projects are focused at $z < 1.5$
 - Due to obvious observational constraints
- Aims of HETDEX
 - Measure the expansion rate to percent accuracy at $z > 2$
 - Provide a direct constraint on the density of DE at $z > 2$
 - Provide the best measure of curvature



Executed from 2021 to 2024

HETDEX Approach

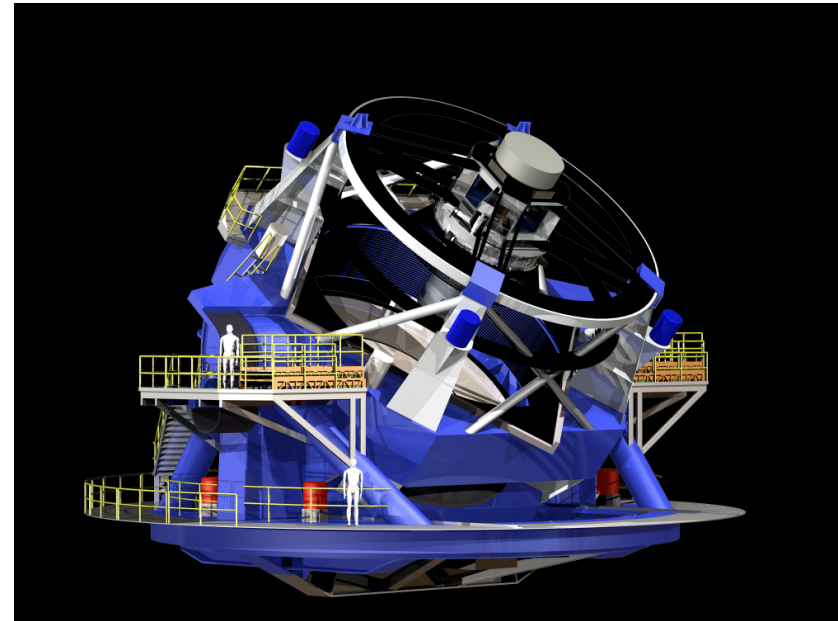
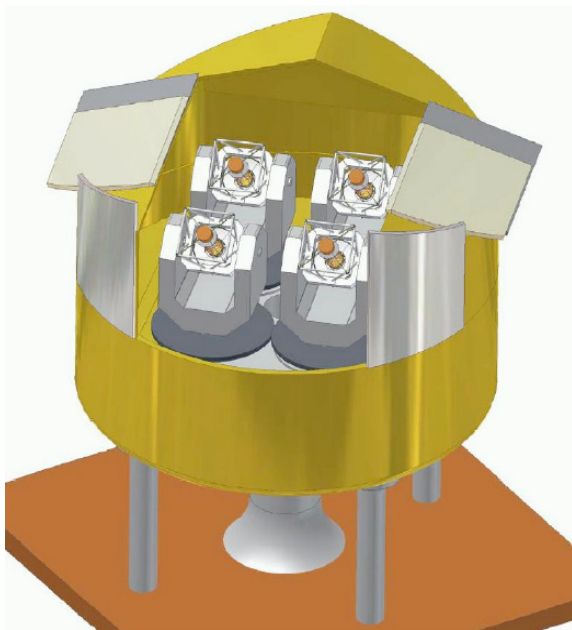
- Survey duration 3 calendar years
- 1 million tracers in 8 cubic Gpc volume
 - Total survey area 400 sq. degrees with redshift range $1.9 < z < 3.8$
 - goal 1.5 million in 650 sq. deg
- Constraints (3 year)
 - H to 1.5-2%, D_A to 1-1.5%
 - Depending on tracer bias
- Ly- α emitting galaxies
 - Numerous
 - Easily detected with integral field spectrograph
- 145 integral field spectrographs, known as VIRUS
 - 42,000 spectra per exposure



Other well known DE missions:

LSST: The Large Synoptic Survey Telescope

- start: > 2025
- 20000-30,000deg² in 6 bands
- DE constraints: $\sigma_w \sim$ few %



Source: <http://pan-starrs.ifa.hawaii.edu/public/>; <http://www.lsst.org/lsst>

Vera Rubin Telescope



~~LSST~~ in a Nutshell

-
- The LSST is an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground based telescope, a 3.2 Gpix camera, and an automated data processing system.
 - Over a decade of operations the LSST survey will acquire, process, and make available a collection of over 5 million images and catalogs with more than 37 billion objects and 7 trillion sources. Tens of billions of time-domain events will be detected and alerted on in real-time.
 - The LSST will enable a wide variety of complementary scientific investigations, utilizing a common database and alert stream. These range from searches for small bodies in the Solar System to precision astrometry of the outer regions of the Galaxy to systematic monitoring for transient phenomena in the optical sky. LSST will also provide crucial constraints on our understanding of the nature of dark energy and dark matter.

Summary of High Level Requirements



Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

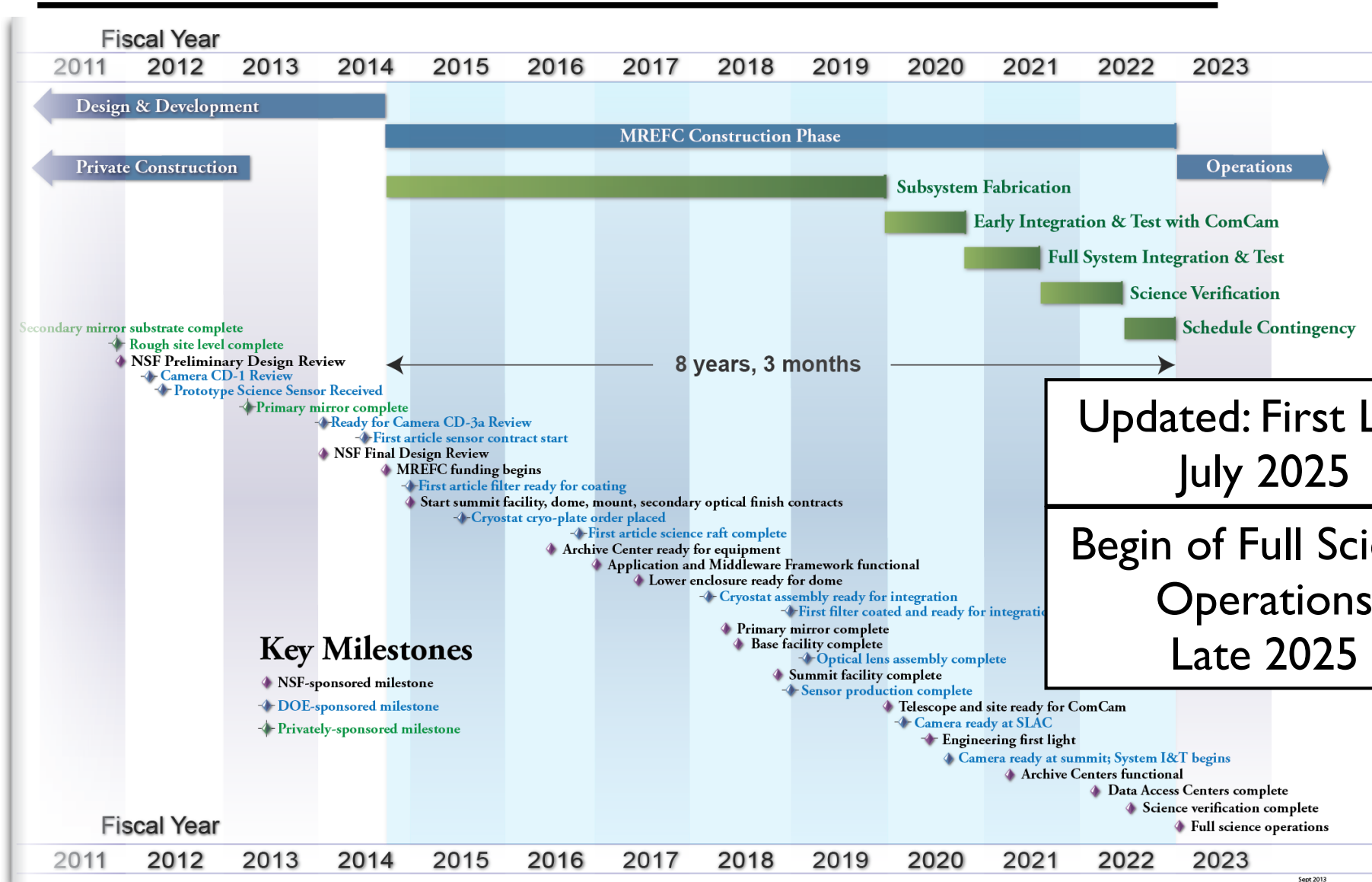
The LSST Science Book

- **Contents:**
 - Introduction
 - LSST System Design
 - System Performance
 - Education and Public Outreach
 - The Solar System
 - Stellar Populations
 - Milky Way and Local Volume Structure
 - The Transient and Variable Universe
 - Galaxies
 - Active Galactic Nuclei
 - Supernovae
 - Strong Lenses
 - Large-Scale Structure
 - Weak Lensing
 - Cosmological Physics

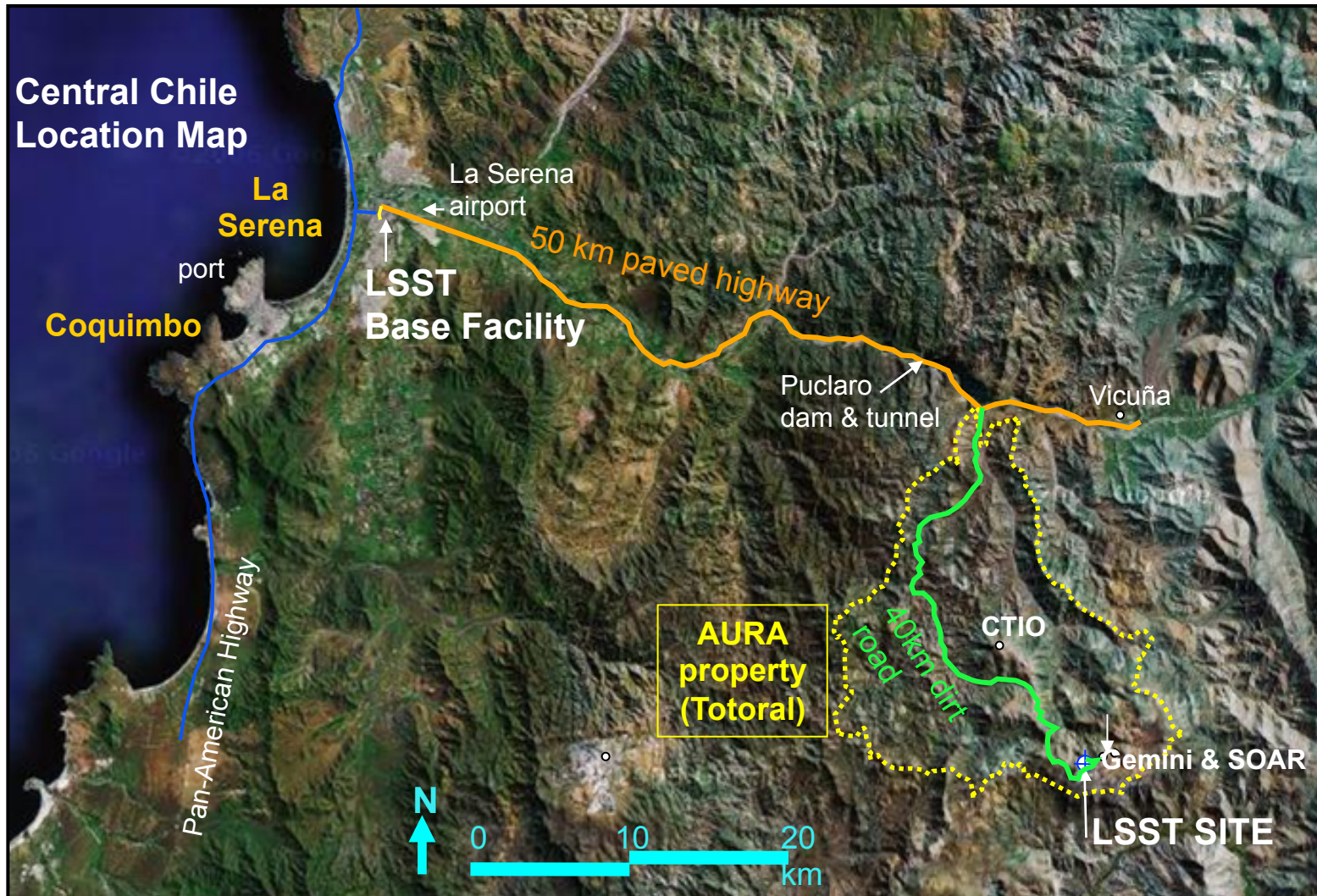
Dark Energy



Integrated Project Schedule



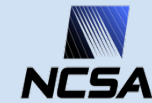
LSST Will be Sited in Central Chile



Dome and Facility Design



LSST OPERATIONS: SITES AND DATA FLOWS



Archive Site

Archive Center

Alert Production
Data Release Production
Calibration Products Production
EPO Infrastructure

Long-term Storage (copy 2)

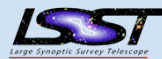
Data Access Center

Data Access and User Services

Dedicated Long Haul Networks

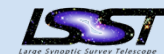
Two redundant 40 Gbit links from La Serena to Champaign, IL (existing fiber)

HQ Site



Science Operations
Observatory Management
Education and Public Outreach

Summit and Base Sites



Telescope and Camera
Data Acquisition
Crosstalk Correction
Long-term storage (copy 1)
Chilean Data Access Center

Ultimate LSST Deliverable: Reduced Data Products



*A petascale supercomputing system at the **LSST Archive** (at NCSA) will process the raw data, generating reduced image products, time-domain alerts, and catalogs.*

Large Synoptic Survey Telescope
the widest, fastest, deepest eye of the new digital age

Searches History Read FITS File Preferences Catalogs Plot Layers Background Monitor

Search by Position 21.41;0.13;EQ_J2000;Type=CENTER;Filter=all;Image Size=0.0278 deg

LSST Image Data

goodSeeingCoaddId	tract	patch	filterName	ra	dec	fluxMag0	fluxMag0Sigma	measureOfWhm
19922944	0	304,0	u	21.458185000	0.104445058	6.20470132e+10	0.000000	1.699982
19922945	0	304,0	g	21.458185000	0.104445058	6.22800114e+10	0.000000	1.699982
19922946	0	304,0	r	21.458185000	0.104445058	6.43898982e+10	0.000000	1.699982
19922947	0	304,0	i	21.458185000	0.104445058	6.58835005e+10	0.000000	1.699982
19922948	0	304,0	z	21.458185000	0.104445058	6.12743987e+10	0.000000	1.699982

LSST Multi-Color 1.2x

LSST Filter u 1x LSST Filter g 1x LSST Filter r 1x LSST Filter i 1x LSST Filter z 1x

Data Access Centers in the U.S. and Chile will provide end-user analysis capabilities and serve the data products to LSST users.

LSST From the User's Perspective



- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Level 1

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations (“sources”), and ~30 trillion measurements (“forced sources”), produced annually, accessible through online databases.
- Deep co-added images.

Level 2

- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and APIs enabling development of analysis codes.

Level 3

Galaxies



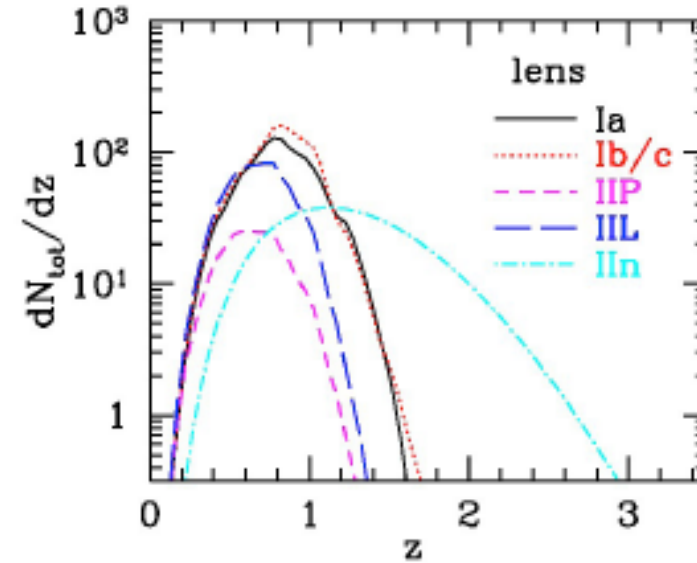
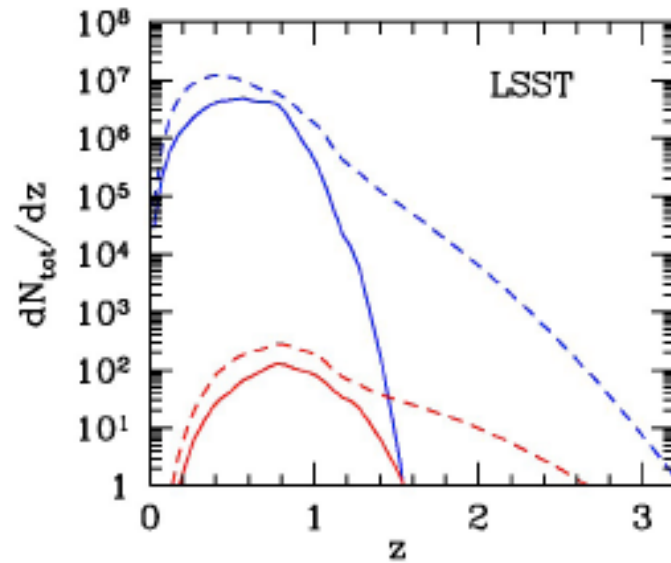
-
- **LSST will be a unique tool for studies of galaxy formation and galaxy properties.**
 - **The database will include photometry for 10^{10} galaxies from the Local Group to $z > 6$.**
 - **We will have 6-band photometry for 4×10^9 galaxies.**
 - **Key diagnostic tools will include:**
 - **Luminosity functions**
 - **Color-luminosity relations**
 - **Size-luminosity relations**
 - **Quantitative morphological classifications**
 - **Dependence on environment**

Supernovae



- Roughly 10^3 supernovae have been discovered throughout the history of all astronomy.
- LSST will find $> 10^7$ over its ten-year duration, spanning a broad redshift range, with precise, uniform calibration.
- This will undoubtedly revolutionize the field, allowing large samples for studies of systematic effects and additional parametric dependences.
- $\sim 10^5$ SNe Ia will be found in the “deep drilling fields” with well-measured lightcurves in all six colors. This will be an excellent sample for precision cosmology.
- The large sample size will also allow us (for the first time) to conduct SN Ia cosmology experiments as a function of direction in the sky, providing stringent tests of the fundamental cosmological assumptions of homogeneity and isotropy.

Sample Size Estimates: Lensed SNe

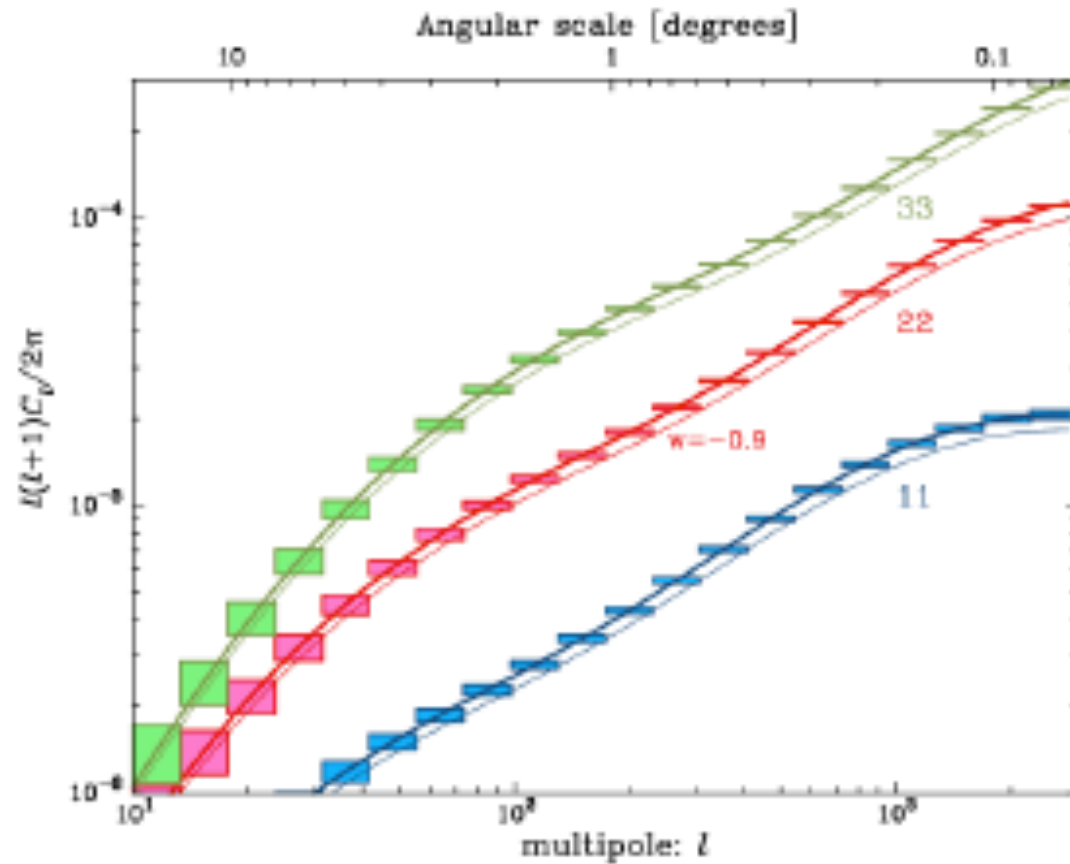


Precision Cosmology: Constraints on Dark Energy

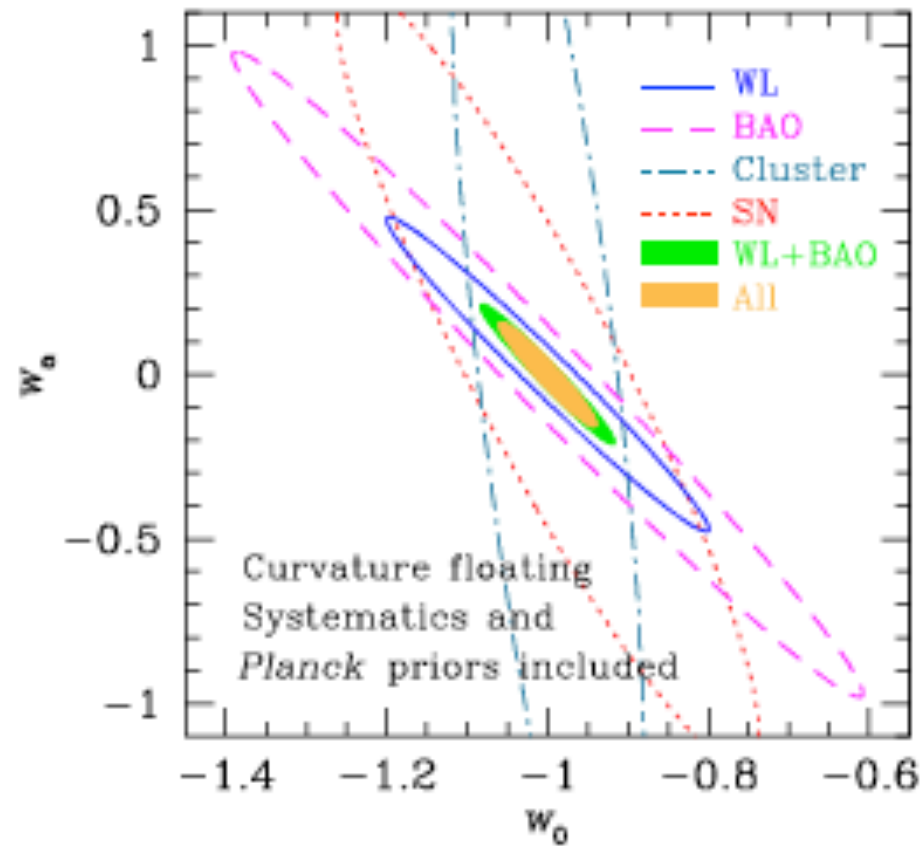


- **LSST will probe the nature of Dark Energy via a distinct set of complementary probes:**
 - SNe Ia's as “standard candles”
 - Baryon acoustic oscillations as a “standard rulers”
 - Studies of growth of structure via weak gravitational lensing
 - Studies of growth of structure via clusters of galaxies
- **In conjunction with one another, this rich spectrum of tests is crucial for reduction of systematics and dependence on nuisance parameters.**
- **These tests also provide interesting constraints on other topics in fundamental physics: the nature of inflation, modifications to GR, the masses of neutrinos.**

Shear Power Spectra as a Function of Redshift



Separate and Joint Constraints on the Dark Energy Equation of State



Other well known DE missions:

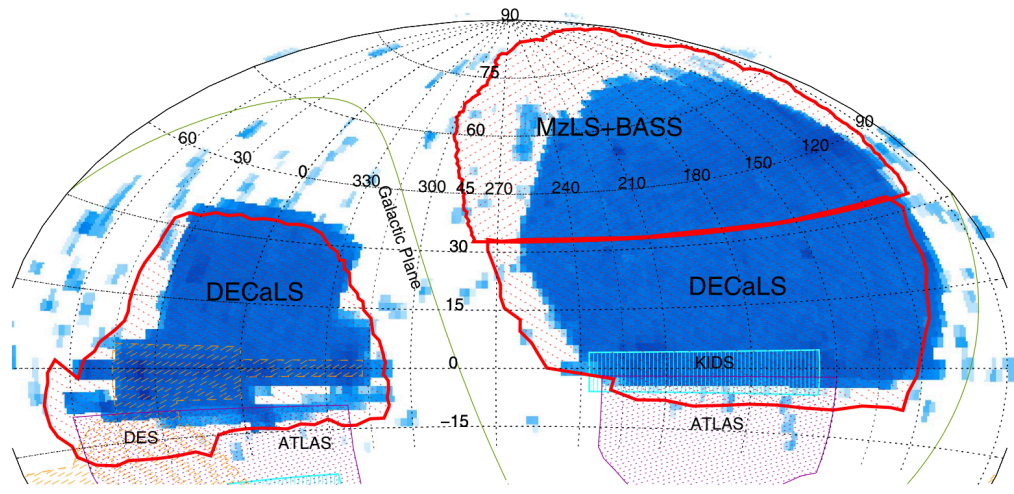
DESI Survey

Dark Energy Spectroscopic Instrument (DESI) situated at NSF Mayall 4-m telescope at Kitt Peak National Observatory

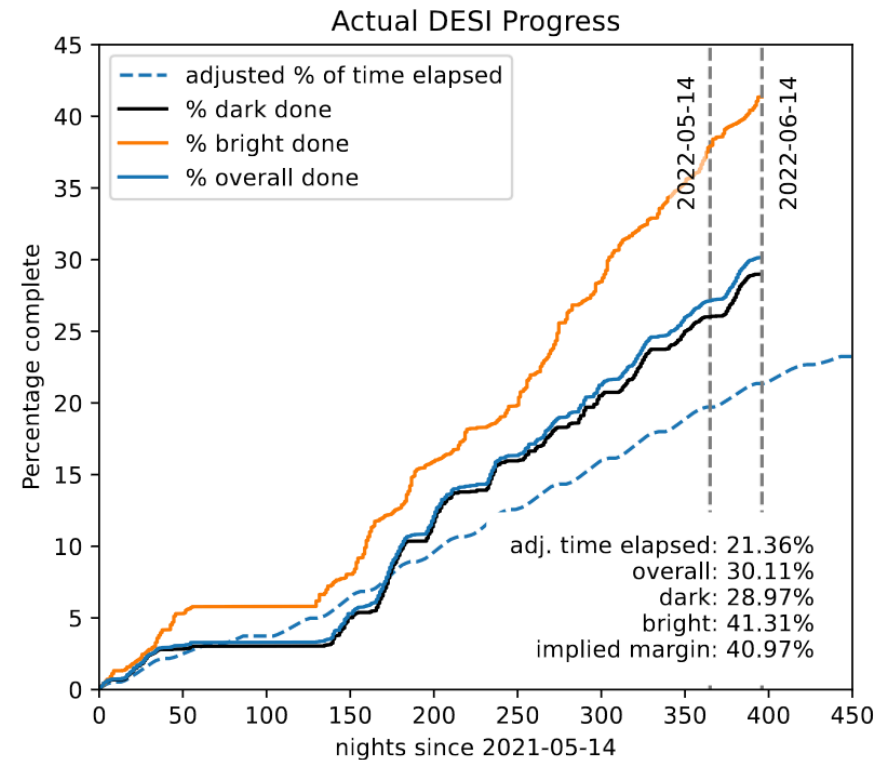
5000 redshifts per mask

Map galaxies and QSO redshifts and positions over 16000 deg² area

Redshifts acquired slowly



Dey+2018

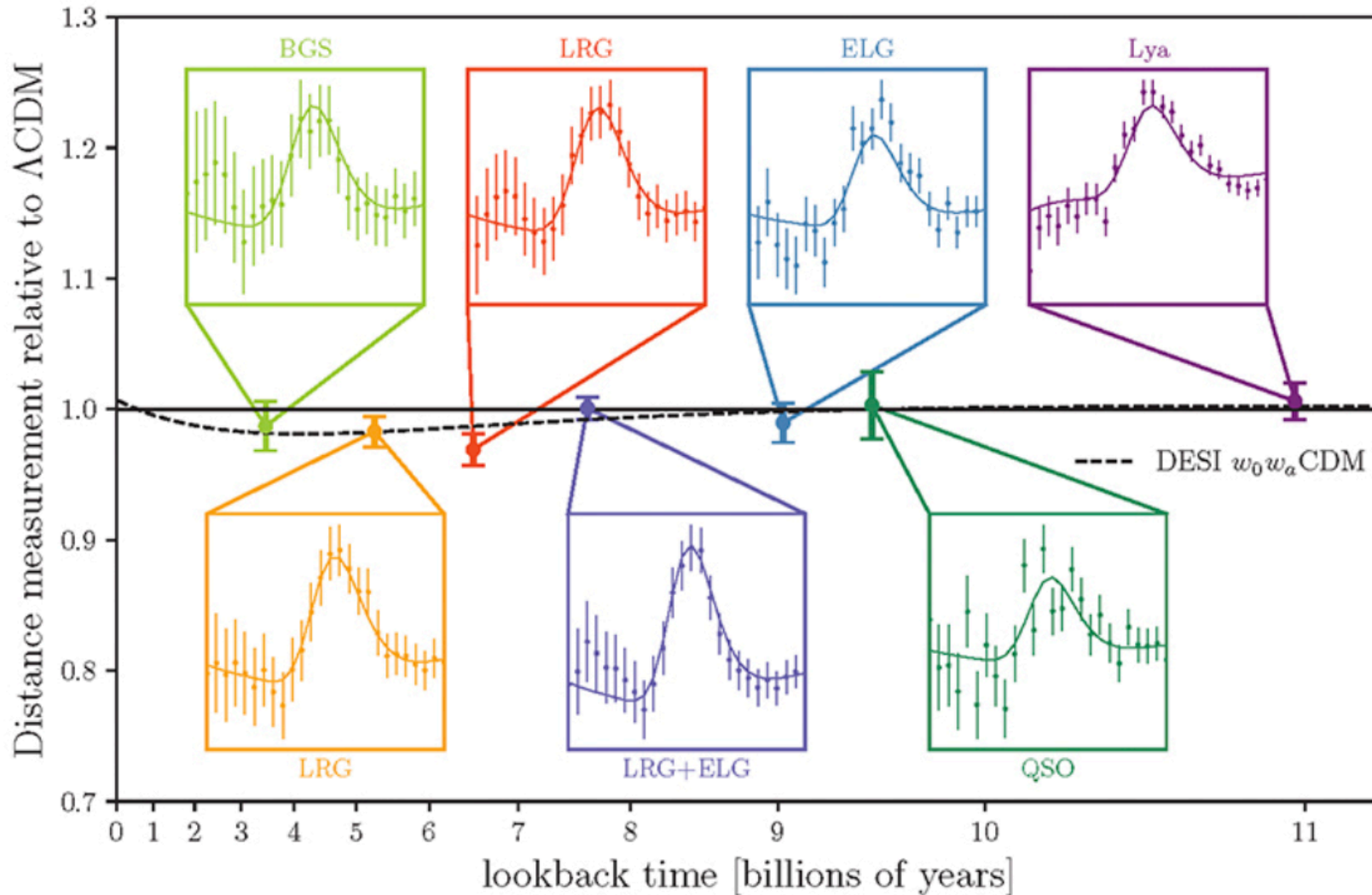


Schafsky + 2022

DESI Survey

First Year Results
based on 30 million galaxies,
3 million QSOs

Here is a Measurement of the Baryon
Acoustic Oscillation Scale at Different
Redshifts

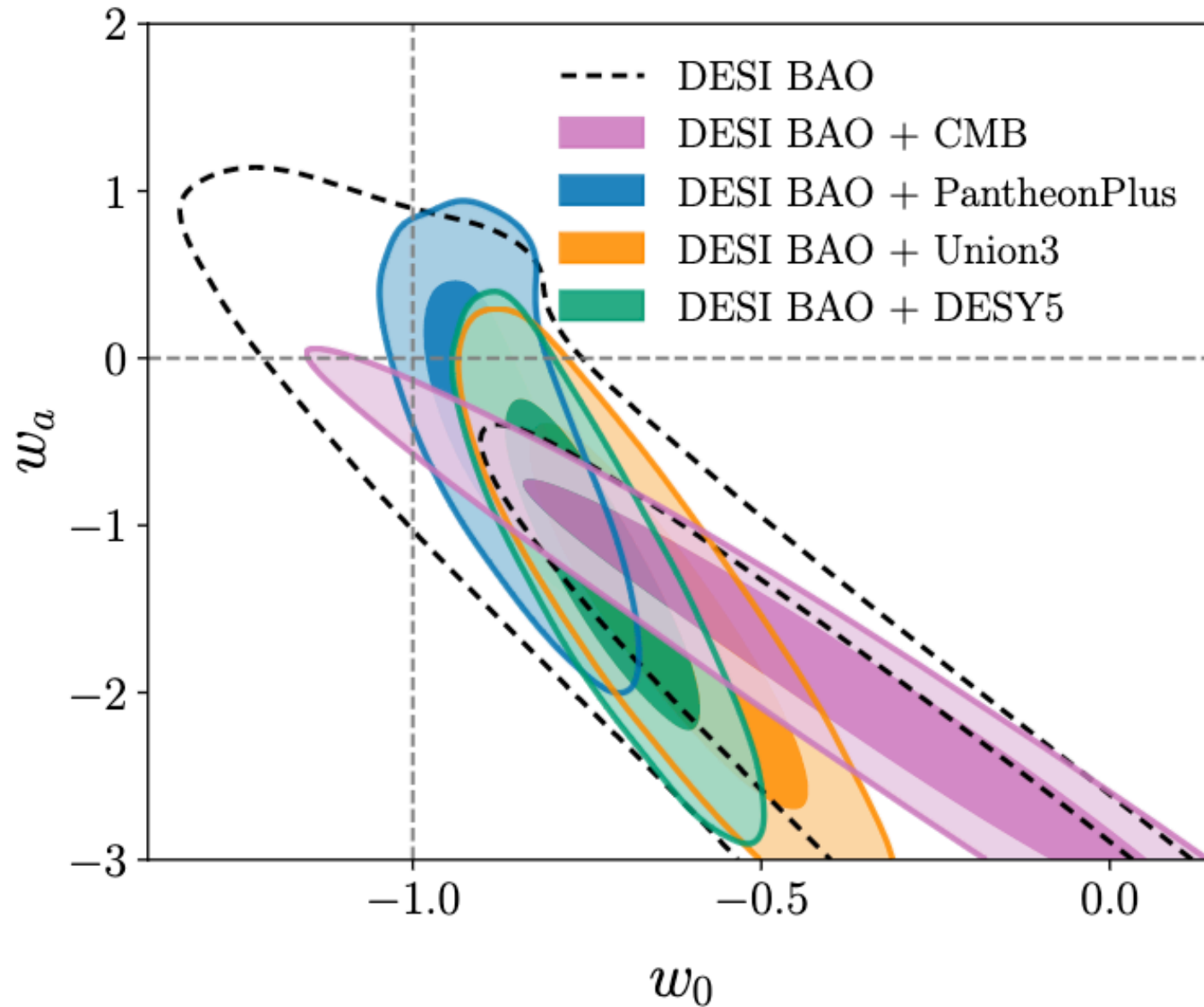


Should give 1
if dark energy
is
cosmological
constant

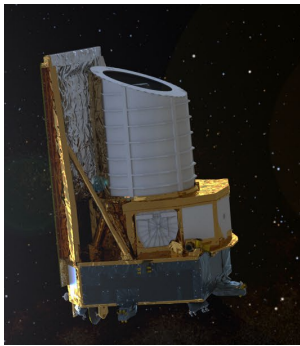
DESI Survey

First Year Results

~2-3 sigma tension with cosmological constant model ($w_0 = -1, w_a = 0$)



Few examples of more well known DE missions



Euclid – Telescope and Instruments

Telescope:

1.2 meter primary diameter

Silicon Carbide 3-mirror Korsch anastigmat

Two Instruments:

VIS – wide band visible imaging array instrument

NISP – near-IR spectrometer and photometer

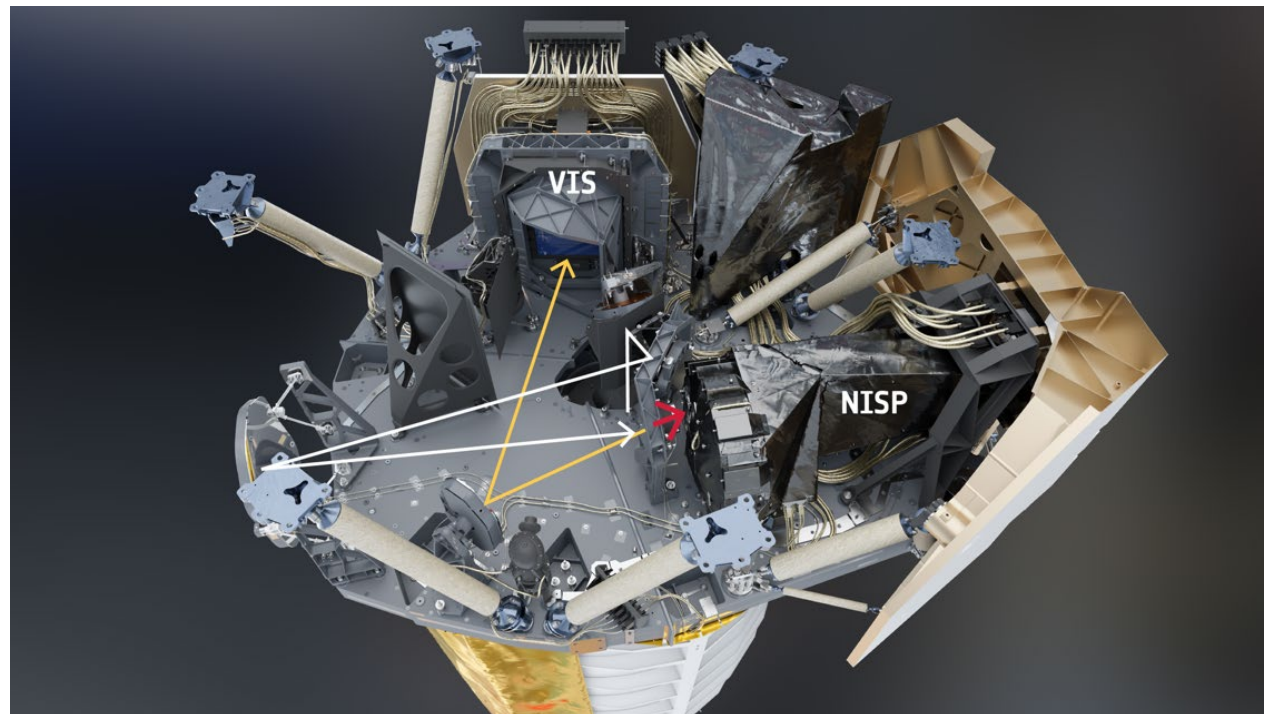
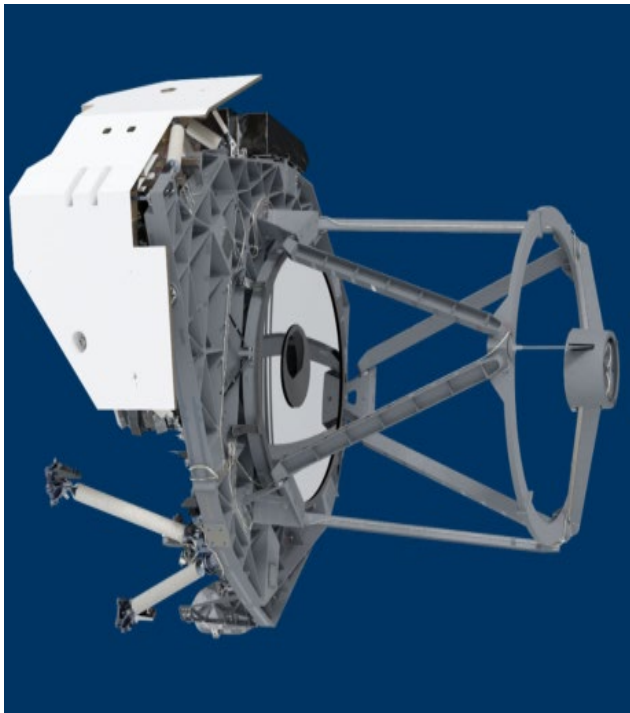


Image credit: Airbus Defense and Space / ESA

Slide from a talk by Seiffert/Rhodes/Teplitz)

Euclid Mission

Euclid Satellite



01/05/2024

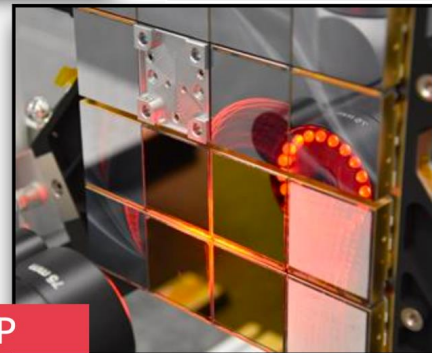
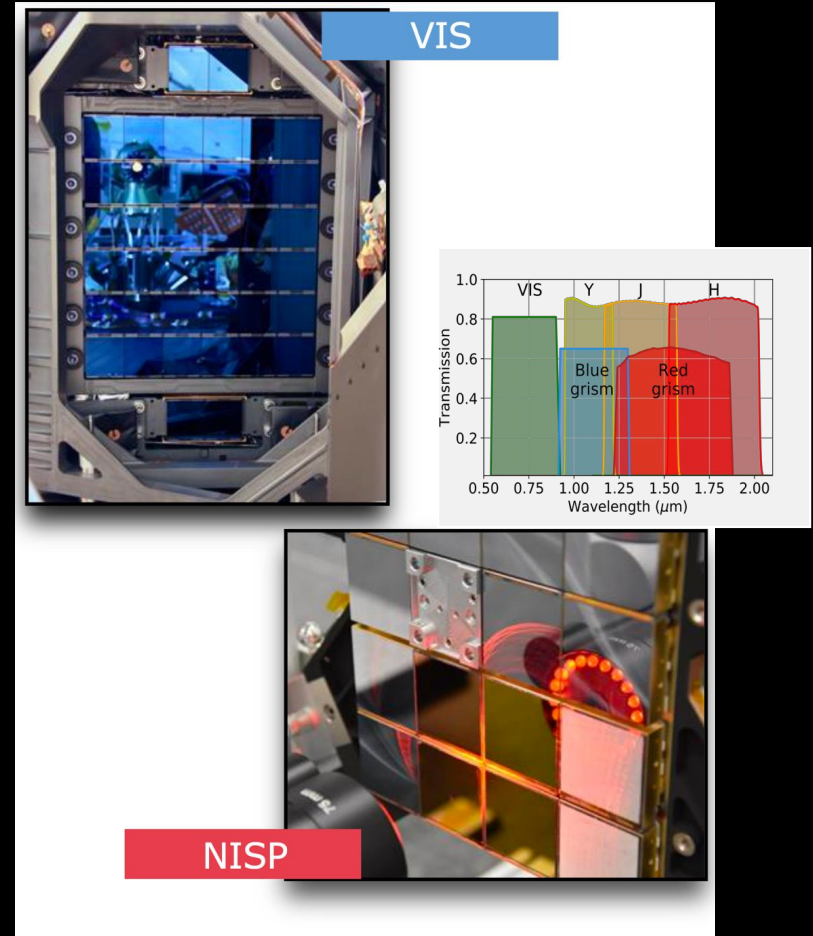
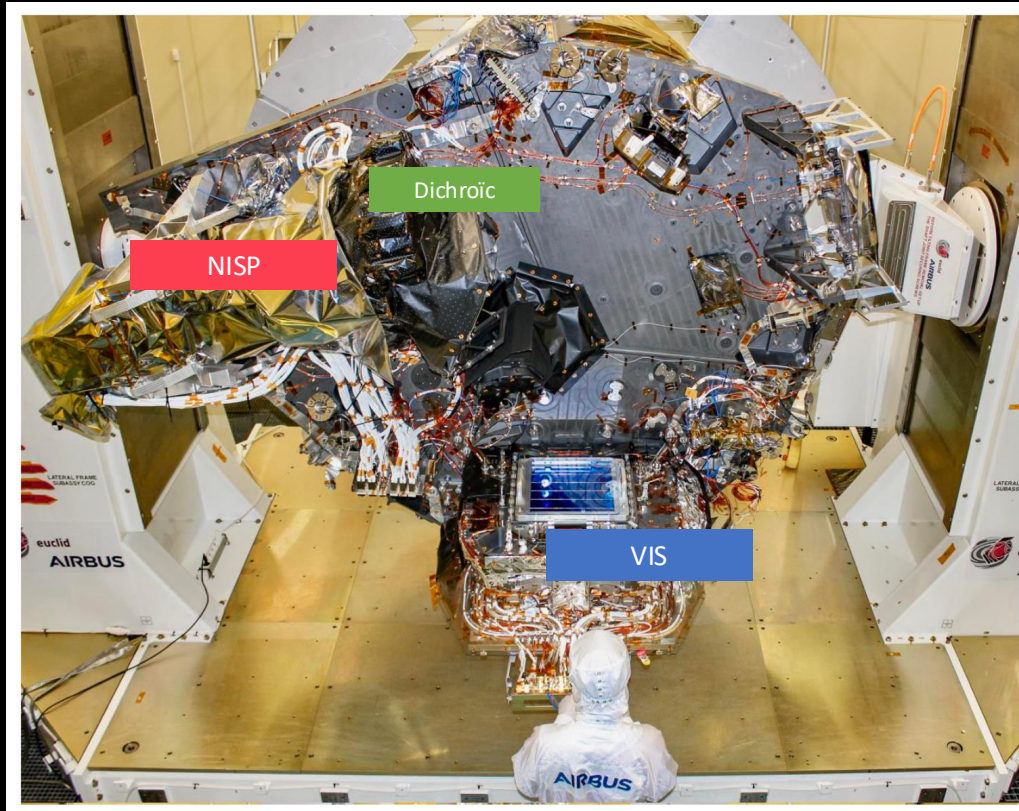
Cristobal Padilla

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Using slides from a talk by Cristobal Padilla

Euclid Mission

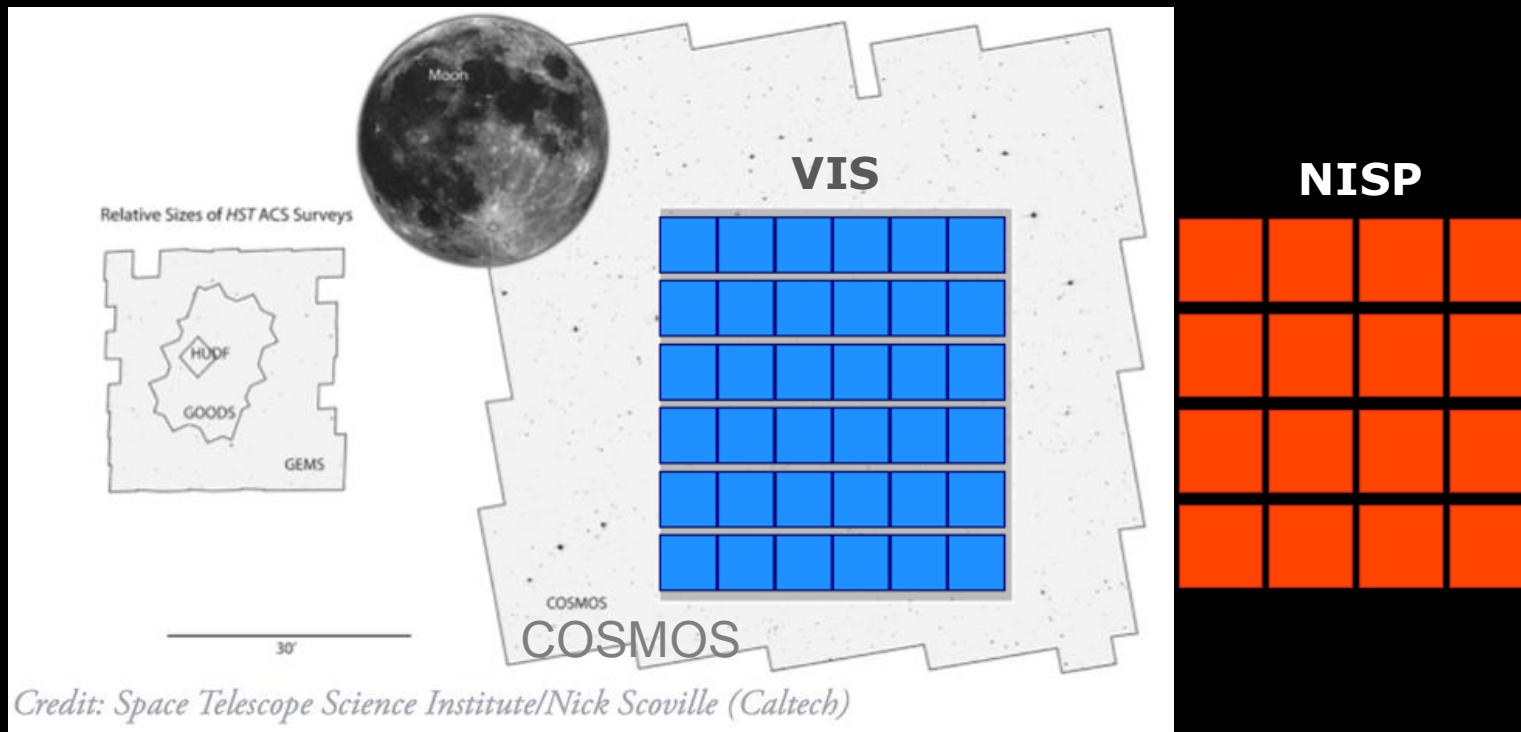
Instruments



Euclid Mission



Twin wide-field imagers and NIR spectrograph



Euclid is the first panoramic space telescope ever: $10 \text{ deg}^2 / \text{day}$ in the Wide survey
Euclid field = 0.54 deg^2

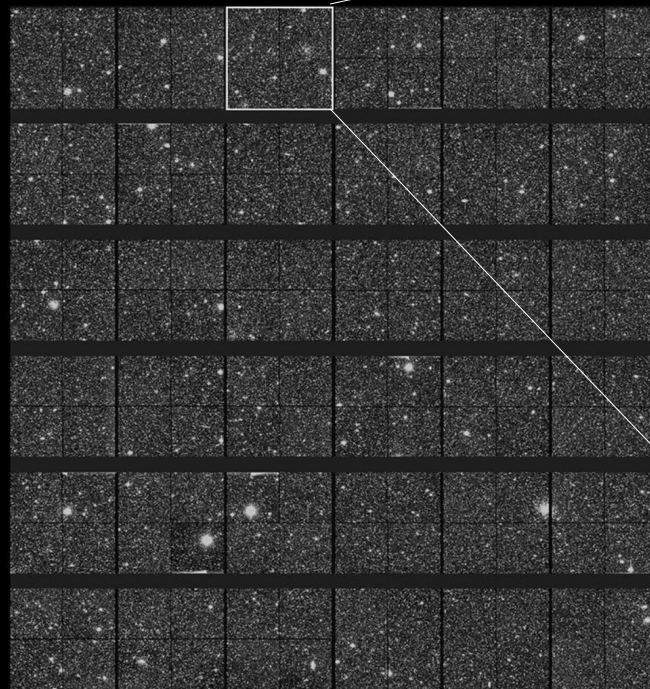
Using slides from a talk by Sandrine Pires

Euclid Mission

VIS instrument

Cropper et al. 2024

EARLY COMMISSIONING TEST IMAGE, VIS INSTRUMENT



Credit : EC VIS team



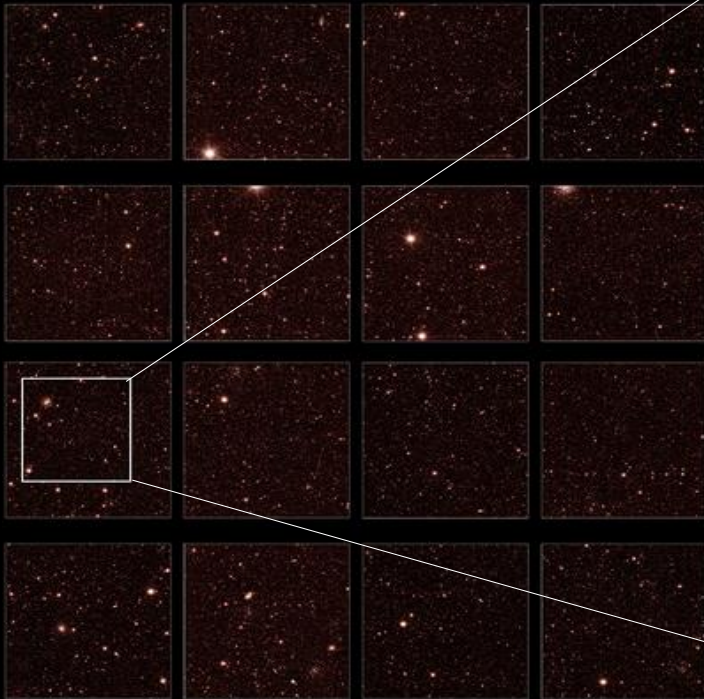
Using slides from a talk by Sandrine Pires

Euclid Mission

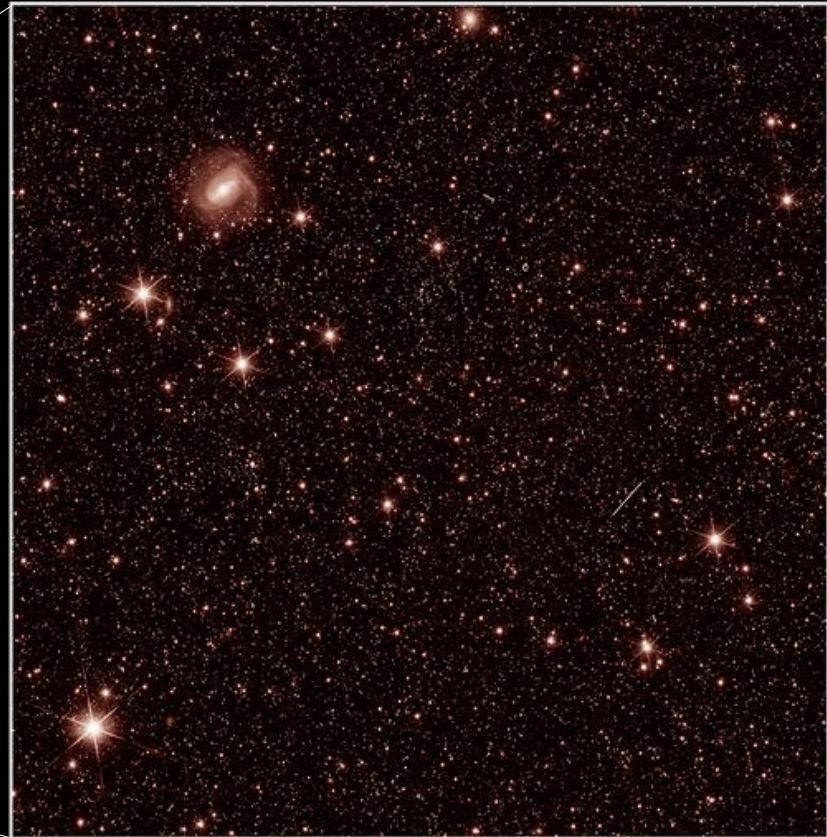
NISP Instrument

Jahnke et al. 2024

EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT



Credit : EC NISP team



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Using slides from a talk by Sandrine Pires

Euclid Mission

Euclid Imaging (NISP+VIS)



- Galaxy shapes (1.5 billion) and shear maps
- Weak gravitational lensing
- Strong gravitational lensing
- Photometric SEDs (VIS +YJH +additional photom.)
- Photometric redshifts
- Galaxy morphologies
- Galaxy surface brightness profiles
- Galaxy clusters

Cristobal Padilla

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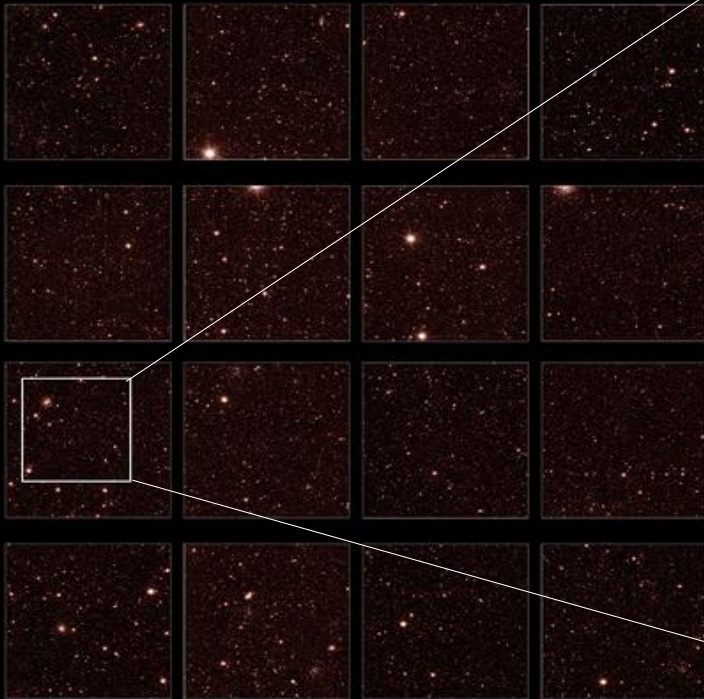
Using slides from a talk by Cristobal Padilla

Euclid Mission

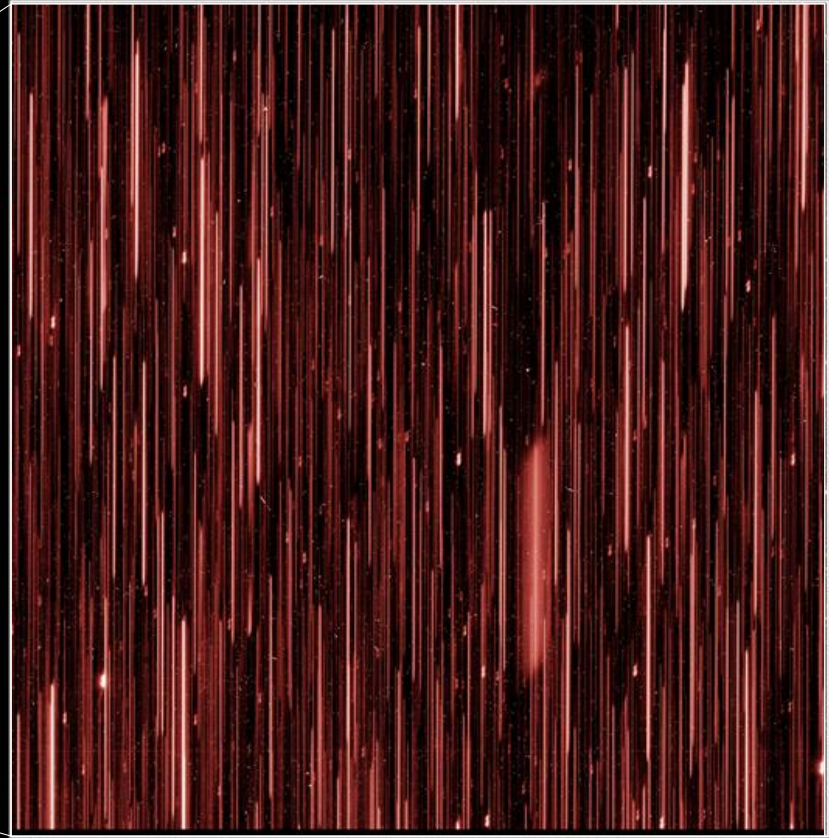
NISP Instrument

Jahnke et al. 2024

EARLY COMMISSIONING TEST IMAGE, NISP INSTRUMENT



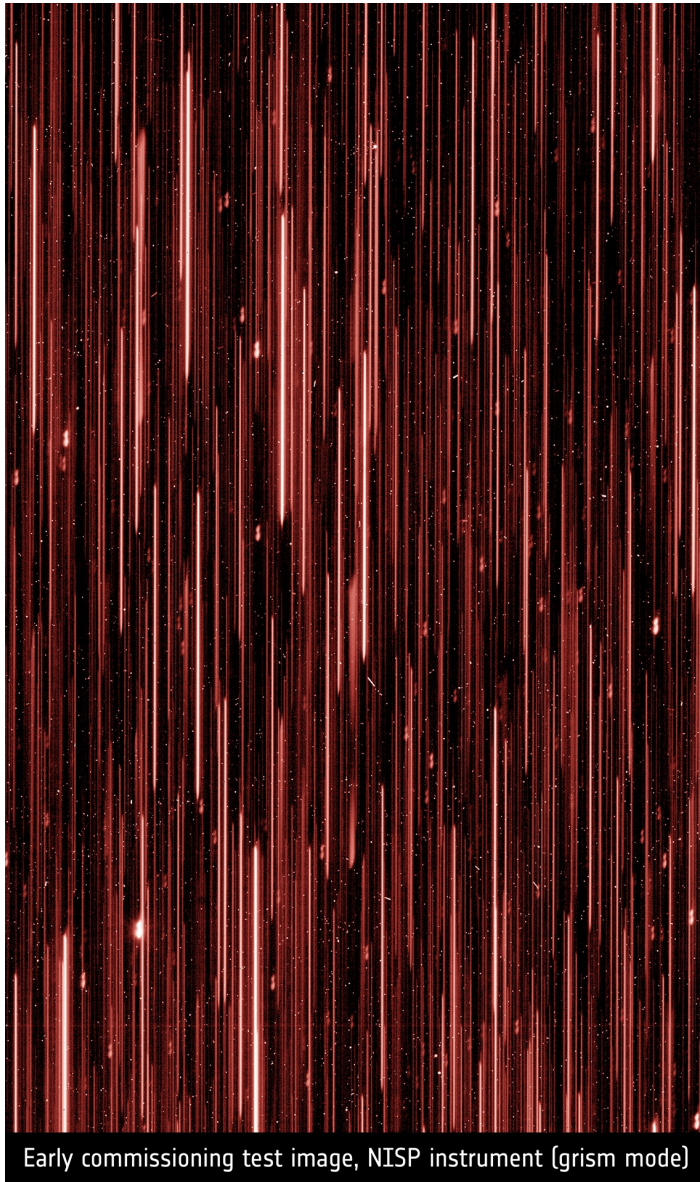
Credit : EC NISP team



Using slides from a talk by Sandrine Pires

Euclid Mission

Euclid Spectroscopy (NISP)



Early commissioning test image, NISP instrument (grism mode)

- Emission line Spectroscopic redshifts of more than 25 m galaxies
- Galaxy clustering and 3D cosmic web
- Spectroscopic classification
- Spectral features
- Unbiased AGN survey
- Luminous Lyman- α emitters
- Reionization
- Photometric redshift calibration/training

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Euclid Mission

Successful Launch on July 1st, 2023



01/05/2024

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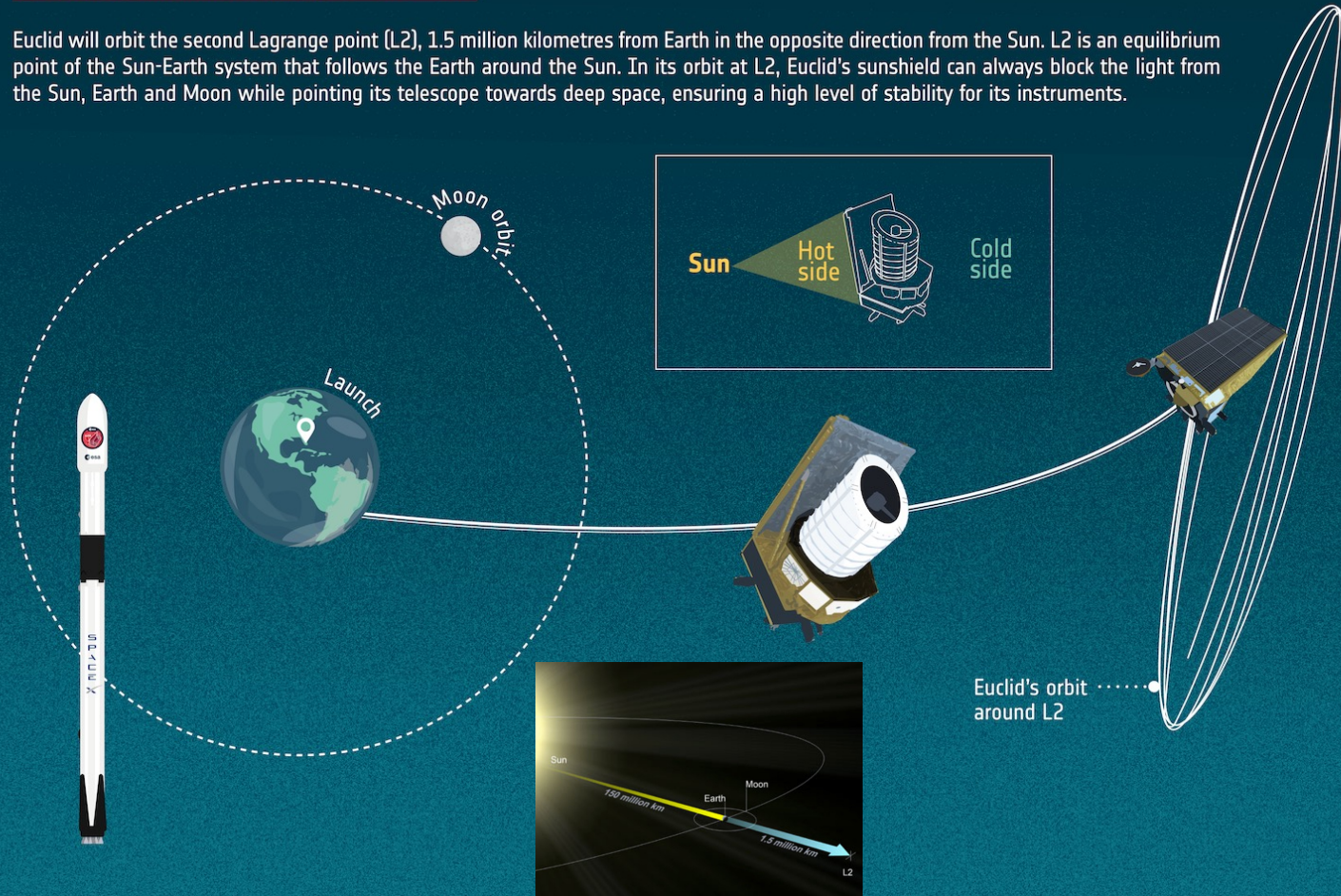
Using slides from a talk by Cristobal Padilla

Euclid Mission



EUCLID'S JOURNEY TO L2

Euclid will orbit the second Lagrange point (L2), 1.5 million kilometres from Earth in the opposite direction from the Sun. L2 is an equilibrium point of the Sun-Earth system that follows the Earth around the Sun. In its orbit at L2, Euclid's sunshield can always block the light from the Sun, Earth and Moon while pointing its telescope towards deep space, ensuring a high level of stability for its instruments.



- **Launch (L)**

- **L+2 days:**

Euclid is on its way to L2

- **L+2 weeks:**

Euclid cool-down is complete

- **L+4 weeks:**

Euclid in orbit around L2

- **L+4 weeks:**

Telescope aligned and all instruments turned on

- **L+1-3 months:**

Testing of scientific performance and readiness for science

- **L+3 months:**

Euclid begins its survey

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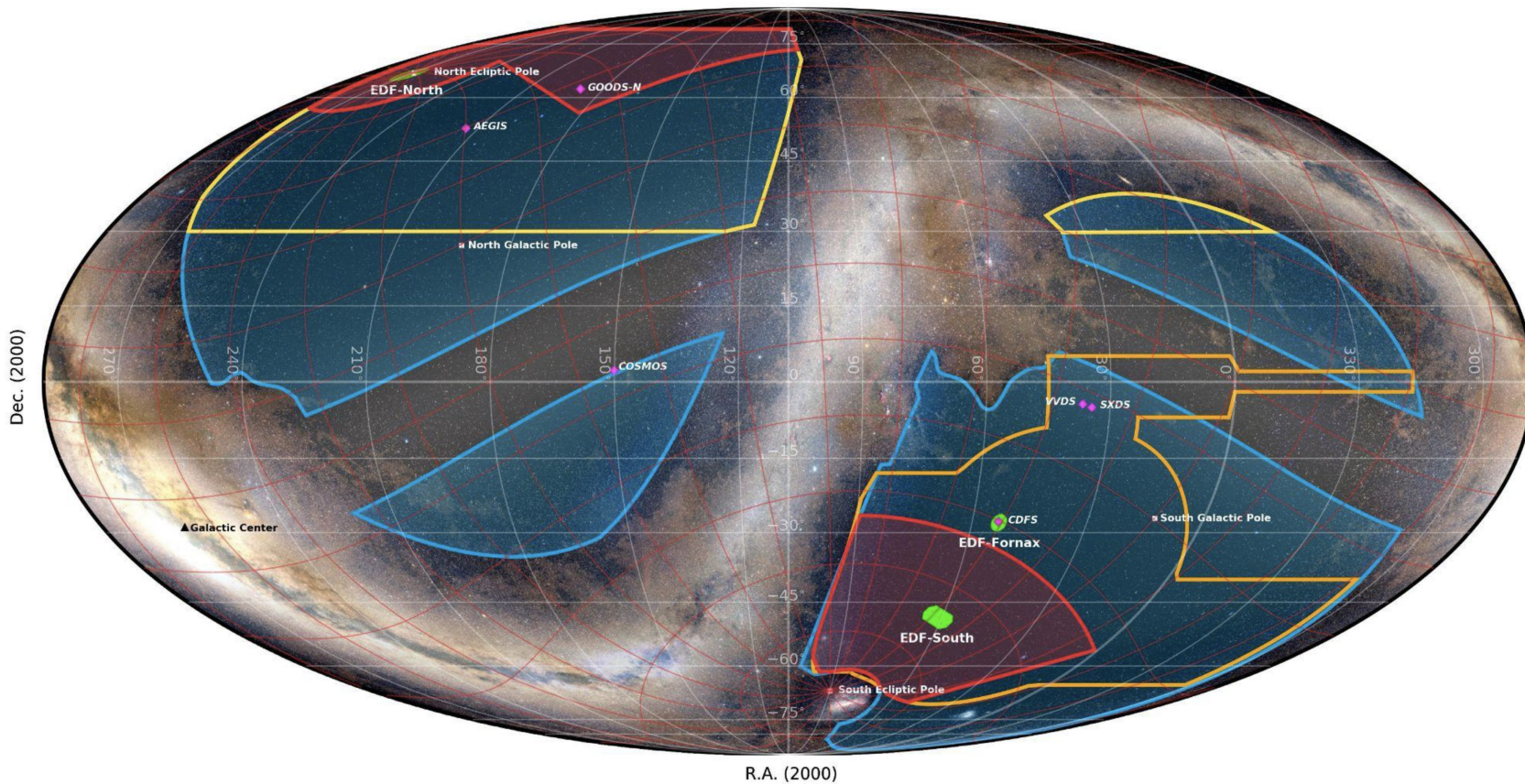
Euclid Mission



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Euclid Mission

Euclid Survey



Euclid large FoV observes ~10 deg²/day in the wide survey with exquisite image sharpness

The Euclid Wide Survey DR1 area maximizing the overlap with DES : North = 821 deg², South = 1657 deg² [Mollweide Celestial]

- Euclid Wide Survey region of interest : 17,354 deg²
- Euclid DR1 area, 2023 : 2500 deg²
- DES, griz, 2013–19 : 4500 deg² overlap with the region of interest
- Euclid Deep Fields [total 43 deg²]
- UNIONS [CFIS / JEDIS-g / Pan-STARRS / WISHES], ugriz, 2017–27 : 4800 deg²

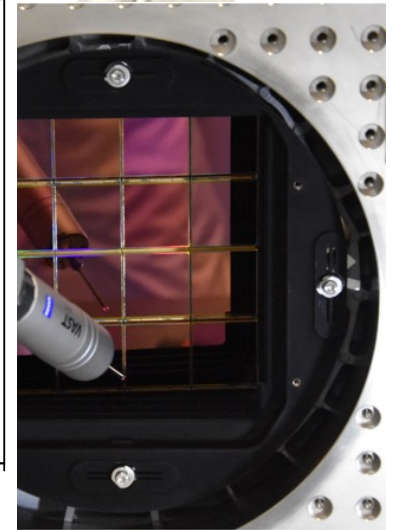
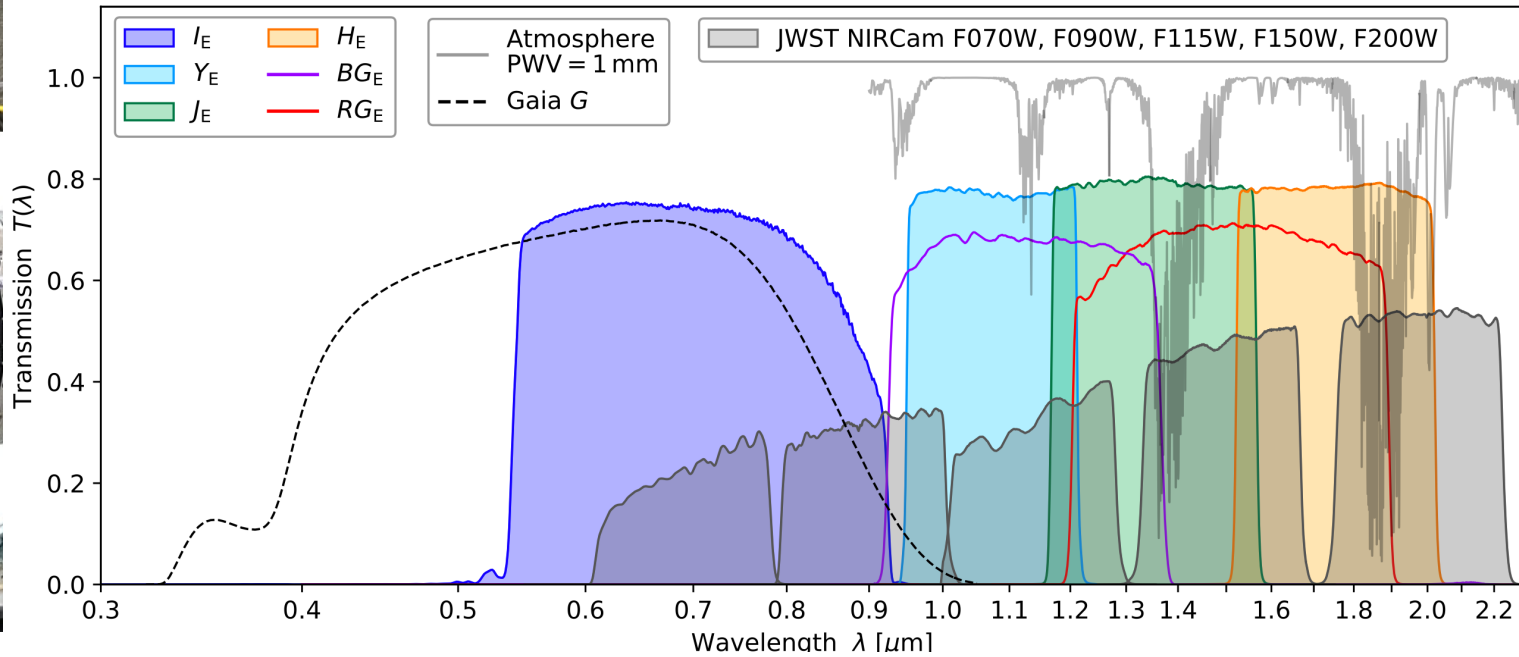


Background image: Euclid Consortium / Planck Collaboration / A. Mellinger

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Euclid Mission

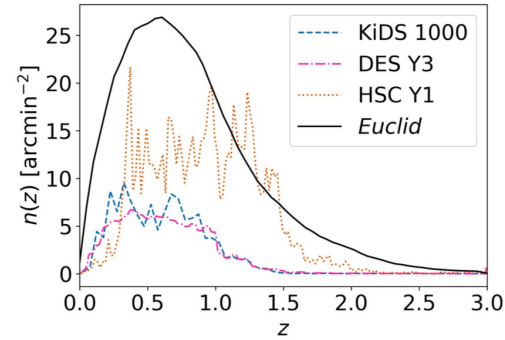
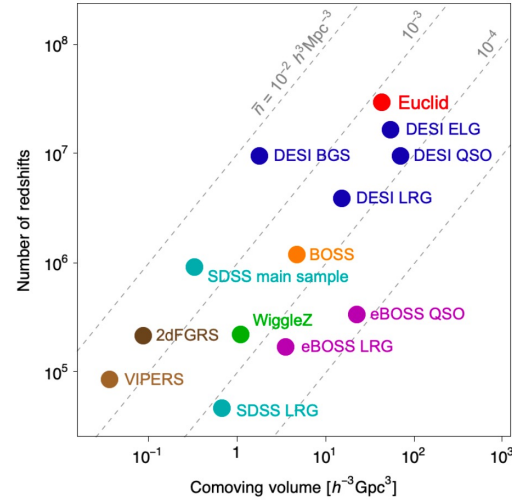
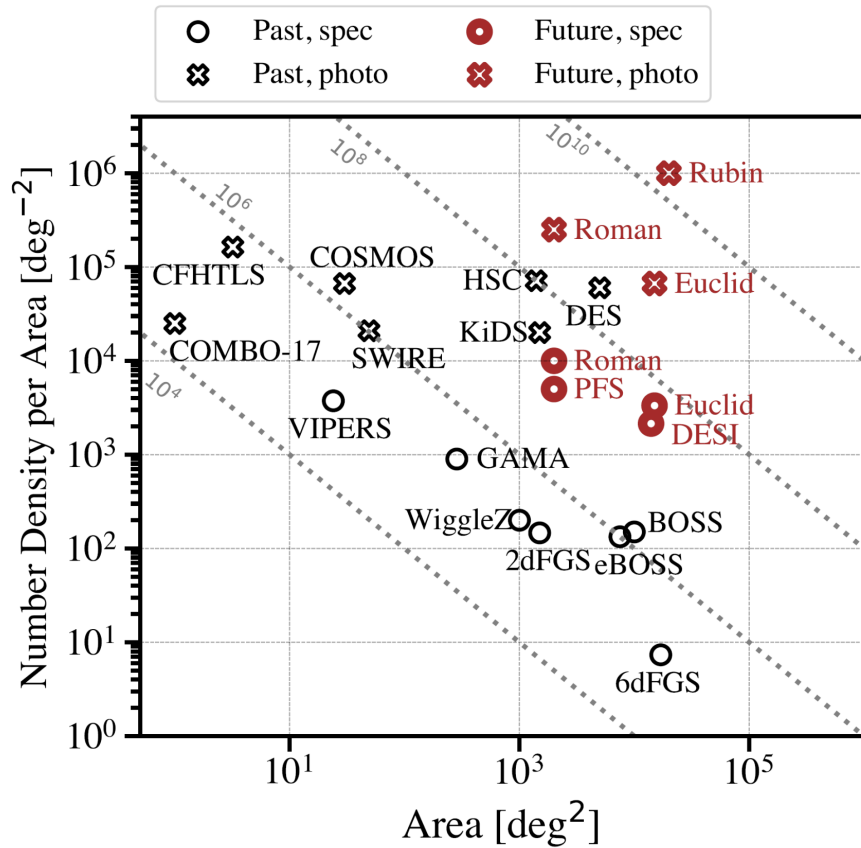
Instrument characteristics				
Near-infrared spectrometer and photometer (NISP)				
Field-of-view	0.763 deg × 0.722 deg			
Capability	Near-infrared imaging photometry			Near-infrared spectroscopy
Wavelength range	Y (920 - 1146 nm)	J (1146 - 1372 nm)	H (1372 - 2000 nm)	1100 - 2000 nm
Sensitivity	24 mag 5 σ point source	24 mag 5 σ point source	24 mag 5 σ point source	3 × 10 ⁻¹⁶ erg cm ⁻² s ⁻¹ 3.5 σ unresolved line flux
Detector Technology	16 arrays 2k × 2k near-infrared sensitive HgCdTe detectors			



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Euclid Mission

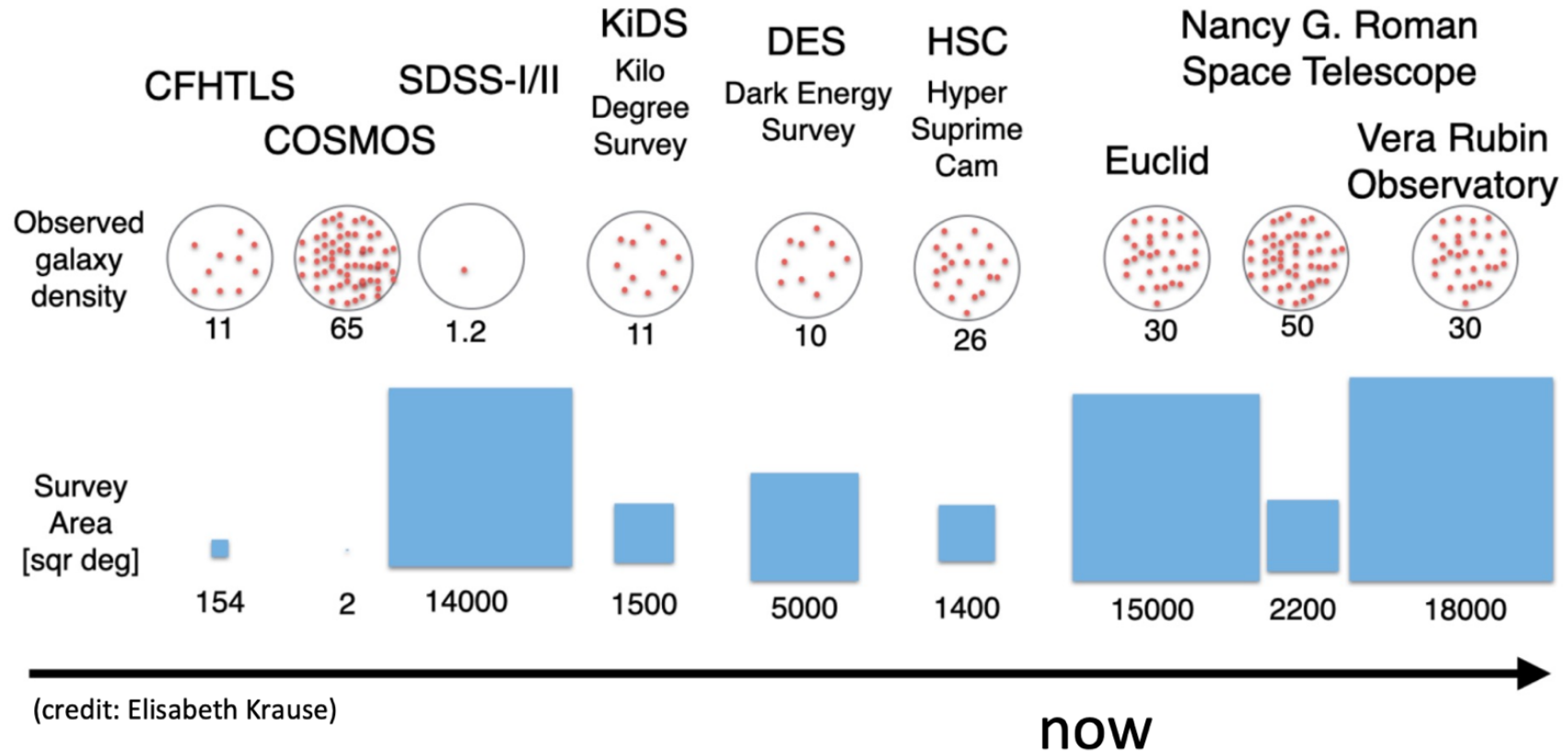
The Euclid Survey in Context



Unprecedented volume coverage with objects up to redshift >2

Euclid Mission

Euclid WL vs. Stage III & IV experiments

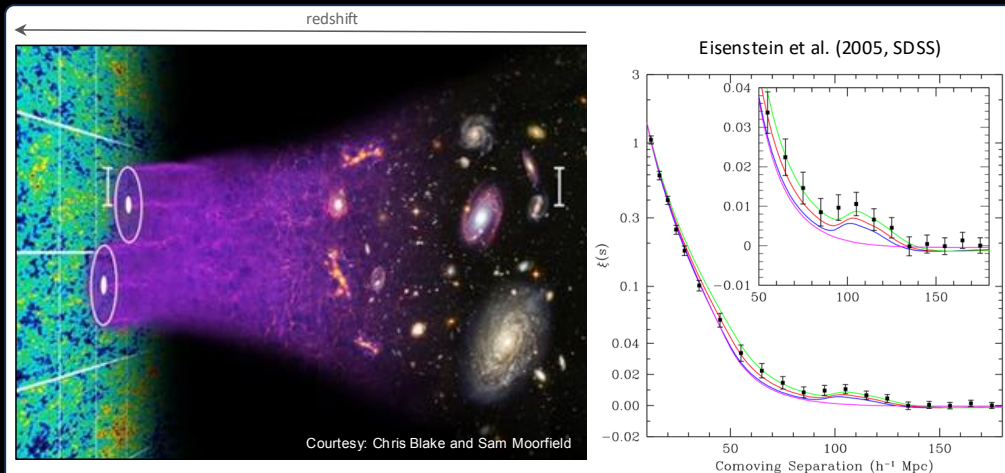


Unprecedented volume coverage with objects up to redshift 2

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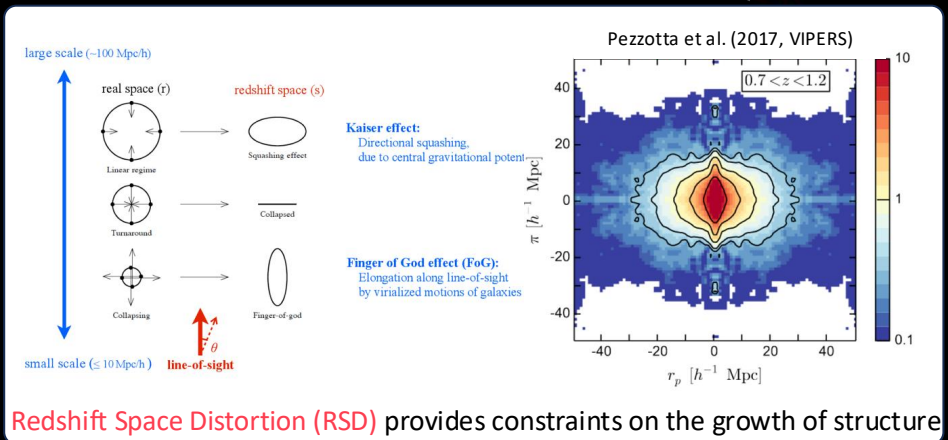
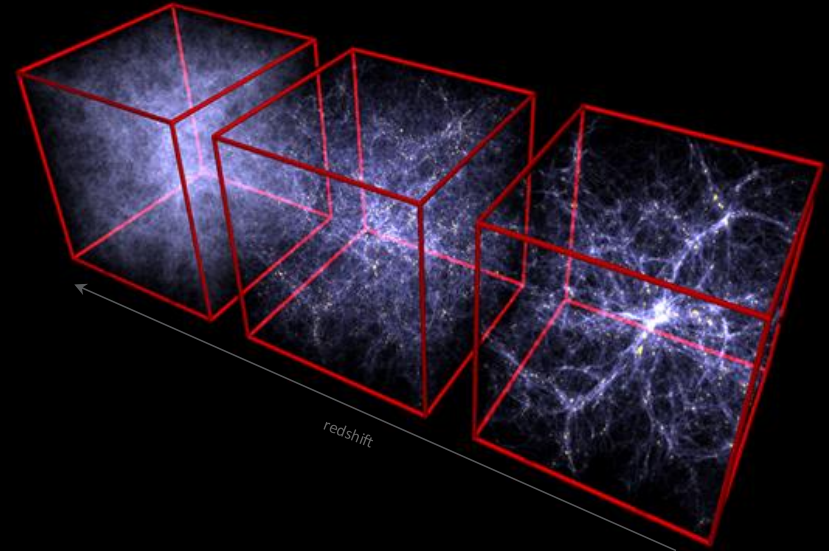
Euclid Mission

3D Galaxy Clustering



Baryonic Acoustic Oscillation (BAO) provides a cosmic standard ruler and is sensitive to the expansion history

Courtesy: Chris Blake and Sam Moorfield

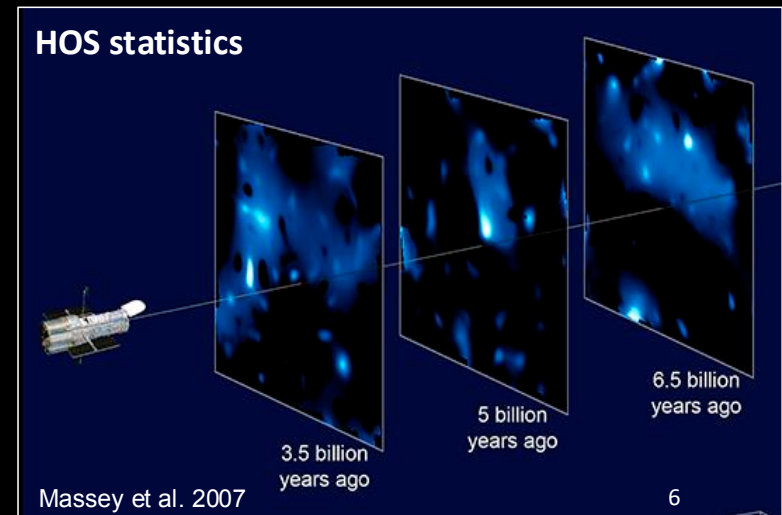
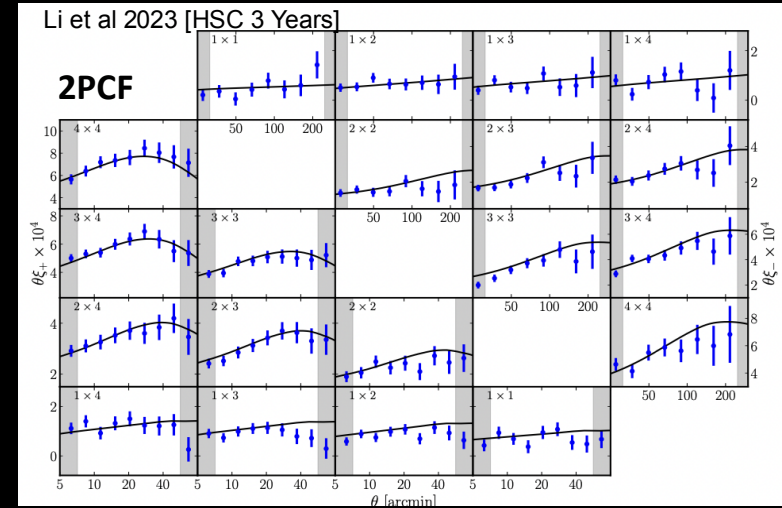
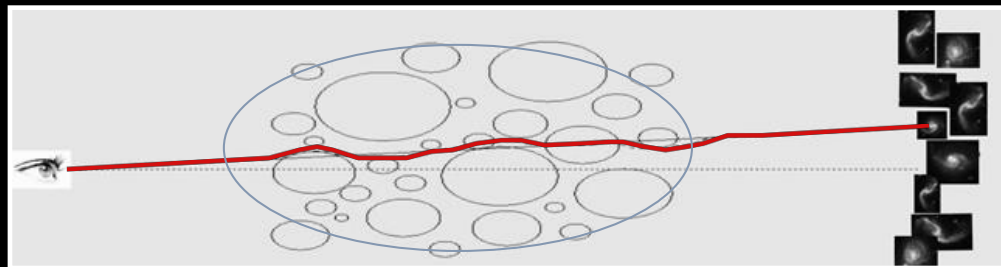


Redshift Space Distortion (RSD) provides constraints on the growth of structure

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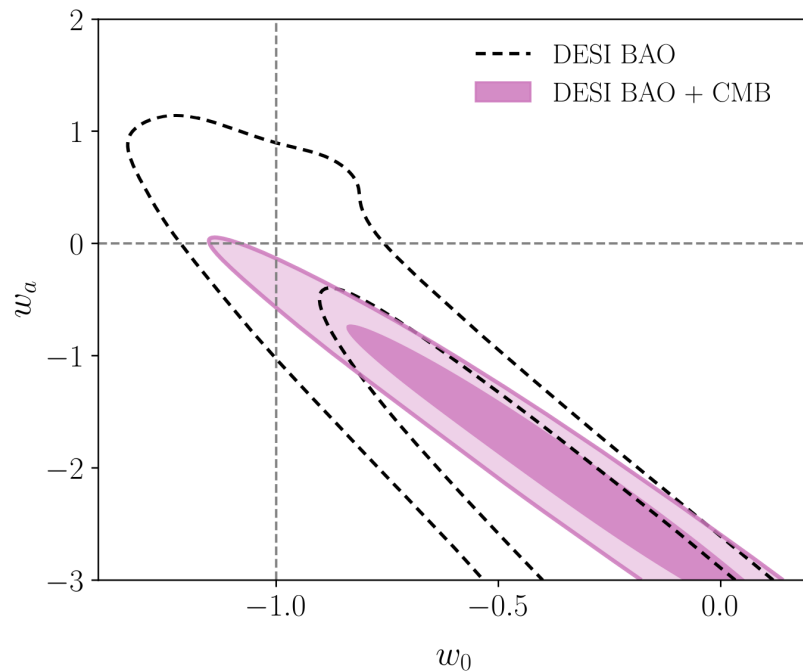
Weak Gravitational Lensing



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Euclid Mission

First results from DESI



Level of discrepancy with Λ CDM cosmological constant DE from

DESI BAO + CMB +

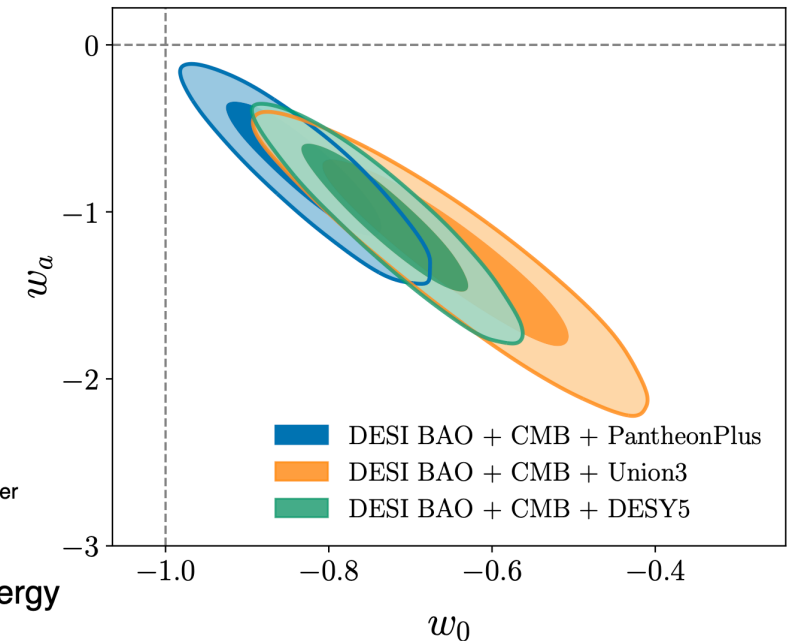
Pantheon+: 2.5σ

Union3: 3.5σ

DES-SN5YR: 3.9σ

*Bayes factors and other metrics in paper

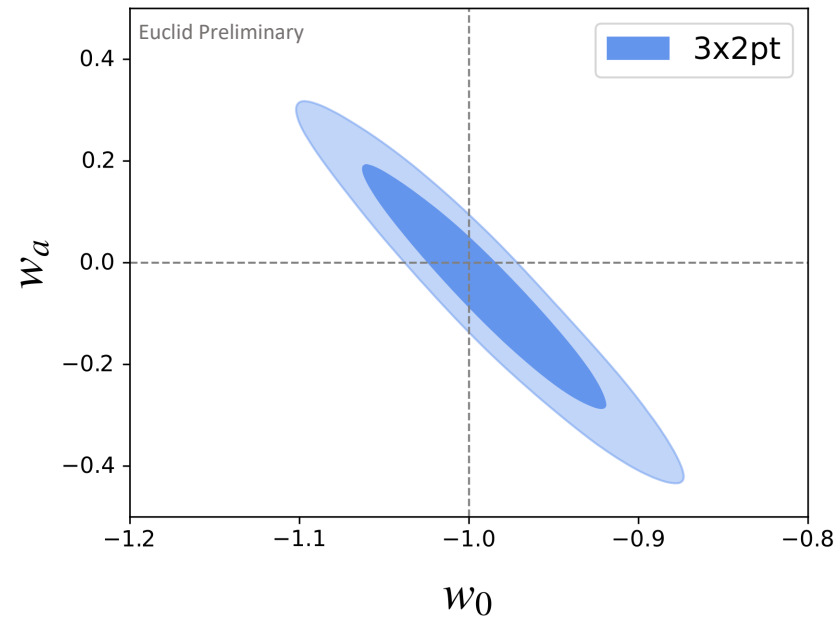
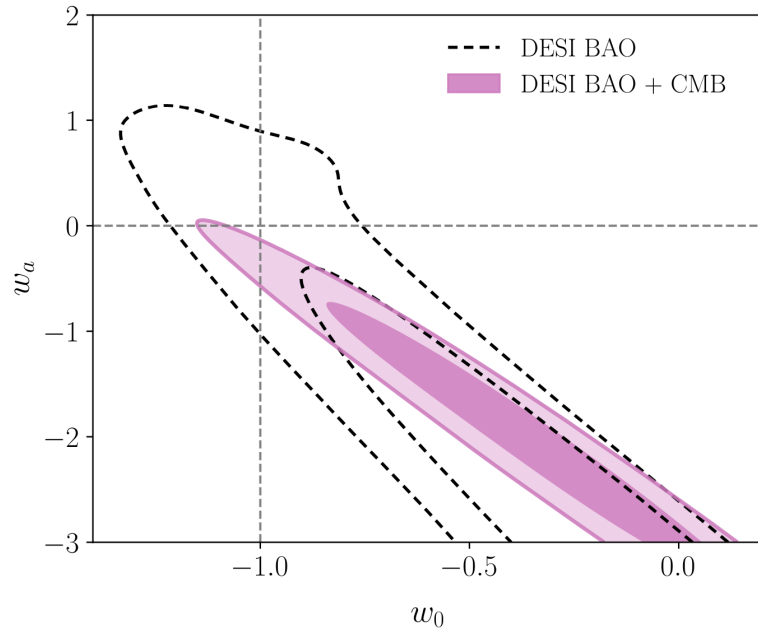
Hints of “thawing” dark energy



A lot of excitement because of hints in discrepancies in the DE equation of state parameters when combined with other survey data

Euclid Mission

First results from DESI: expected from Euclid



The errors we will be able to obtain with Euclid data will hopefully also give us results that makes the Dark Energy very interesting

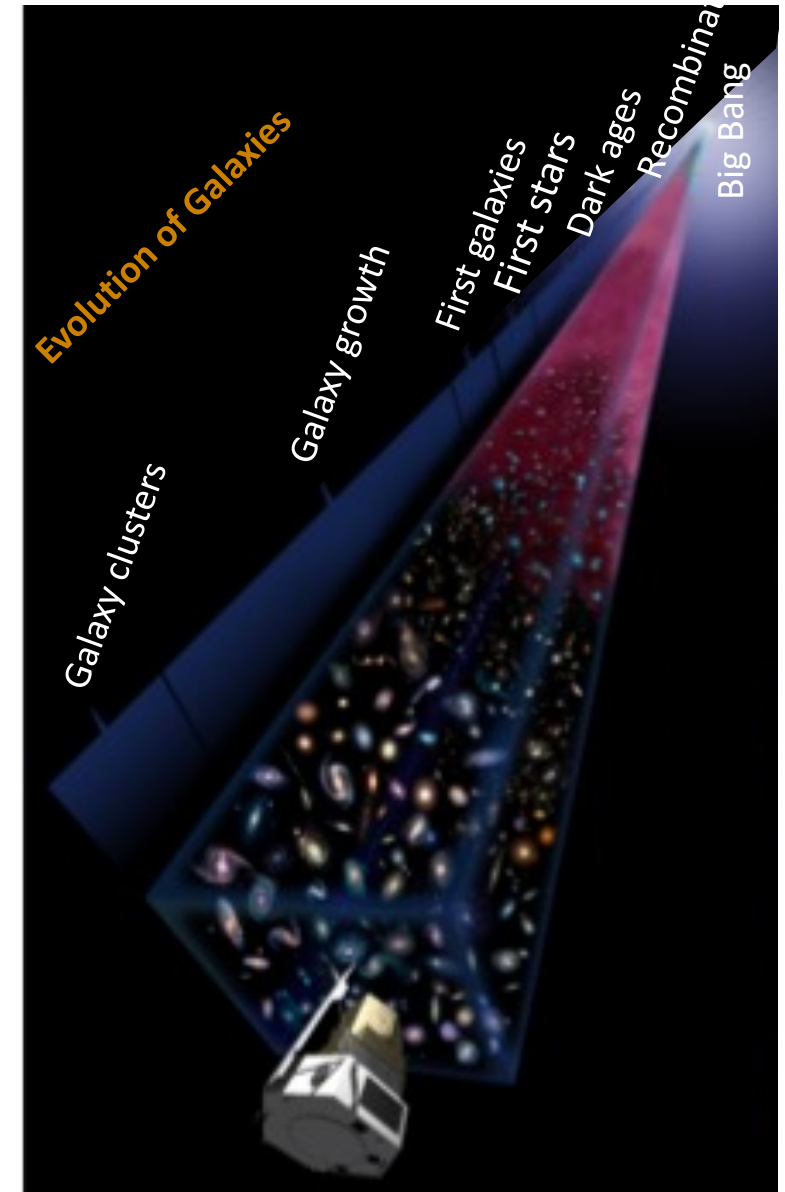
Euclid Mission

Euclid Additional Science

- 10^5 galaxy clusters
- **Cosmic Voids**
- **Cross-correlations with CMB** temperature and lensing
- 10^5 **strong gravitational lenses**
- Transients in Deep fields
 - ~ 50 **Super-luminous SNe** / year (Inserra+17)
- Galaxy formation and evolution
 - Census of **AGN** at $1 < z < 3$
 - Galaxy **morphologies** at $z > 1$
 - **Lyman break galaxies** at $z > 7$
 - High- z **quasars**
- Milky Way
 - Census of **brown dwarf** stars
 - **Satellites & environs**

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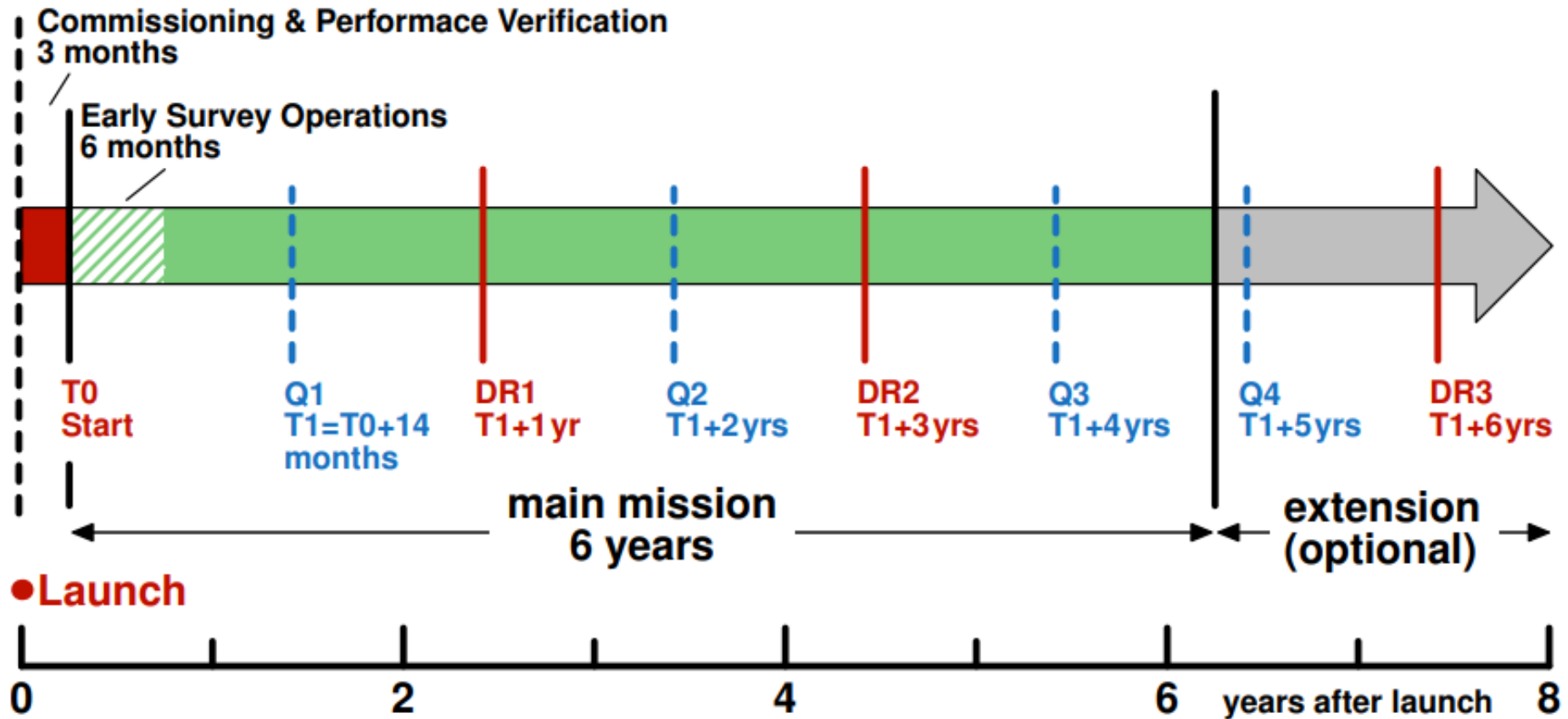
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Euclid Mission

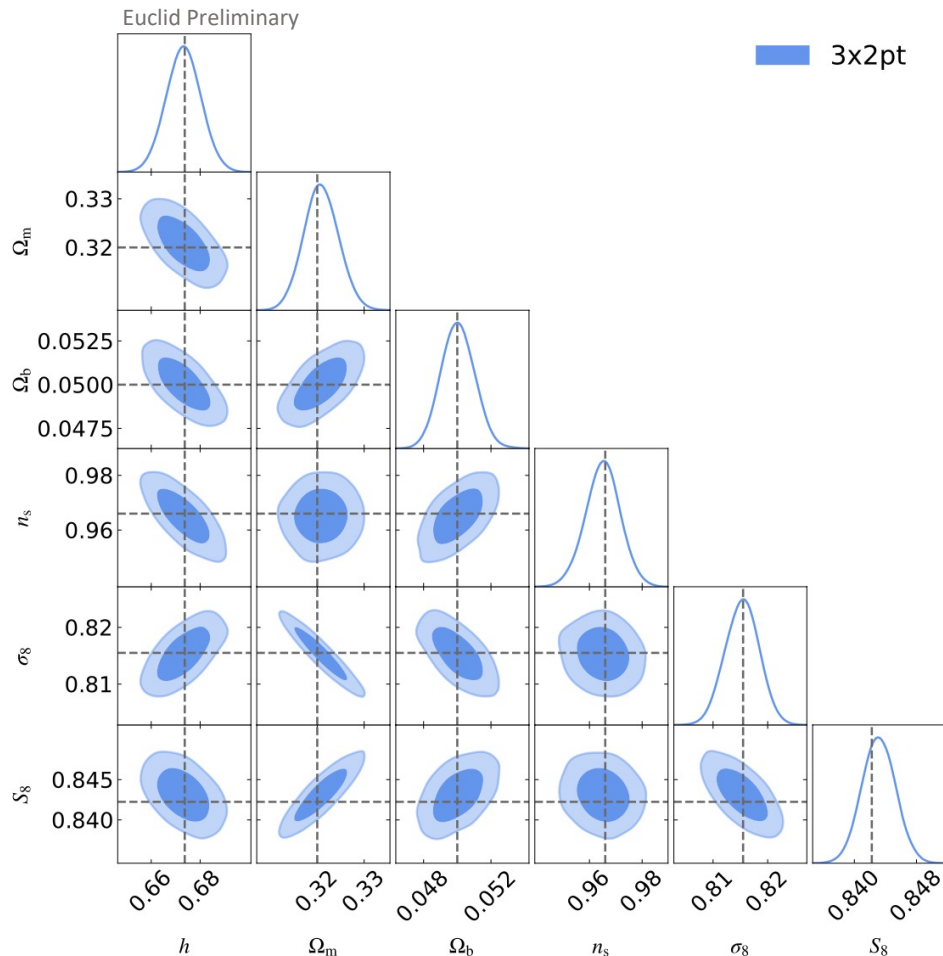
The Euclid Data Releases



First Cosmology results in 2026 and several public releases afterwards that will continue to produce interesting physics results

Euclid Mission

Summary



- **Euclid** will observe **1/3** of sky at redshifts up to **> 2**
 - The results will provide high precision results in the **Dark Energy Equation of state** and other cosmological parameters
- Spacecraft, system and instruments **work as expected**
 - We expect first science papers soon
- Legacy data will also help understanding key fundamental topics in **non-cosmological science**

Stay tuned:

The Euclid Consortium page: www.euclid-ec.org

ESAs *Euclid* page: www.esa.int/Science_Exploration/Space_Science/Euclid

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Nancy Roman
Telescope

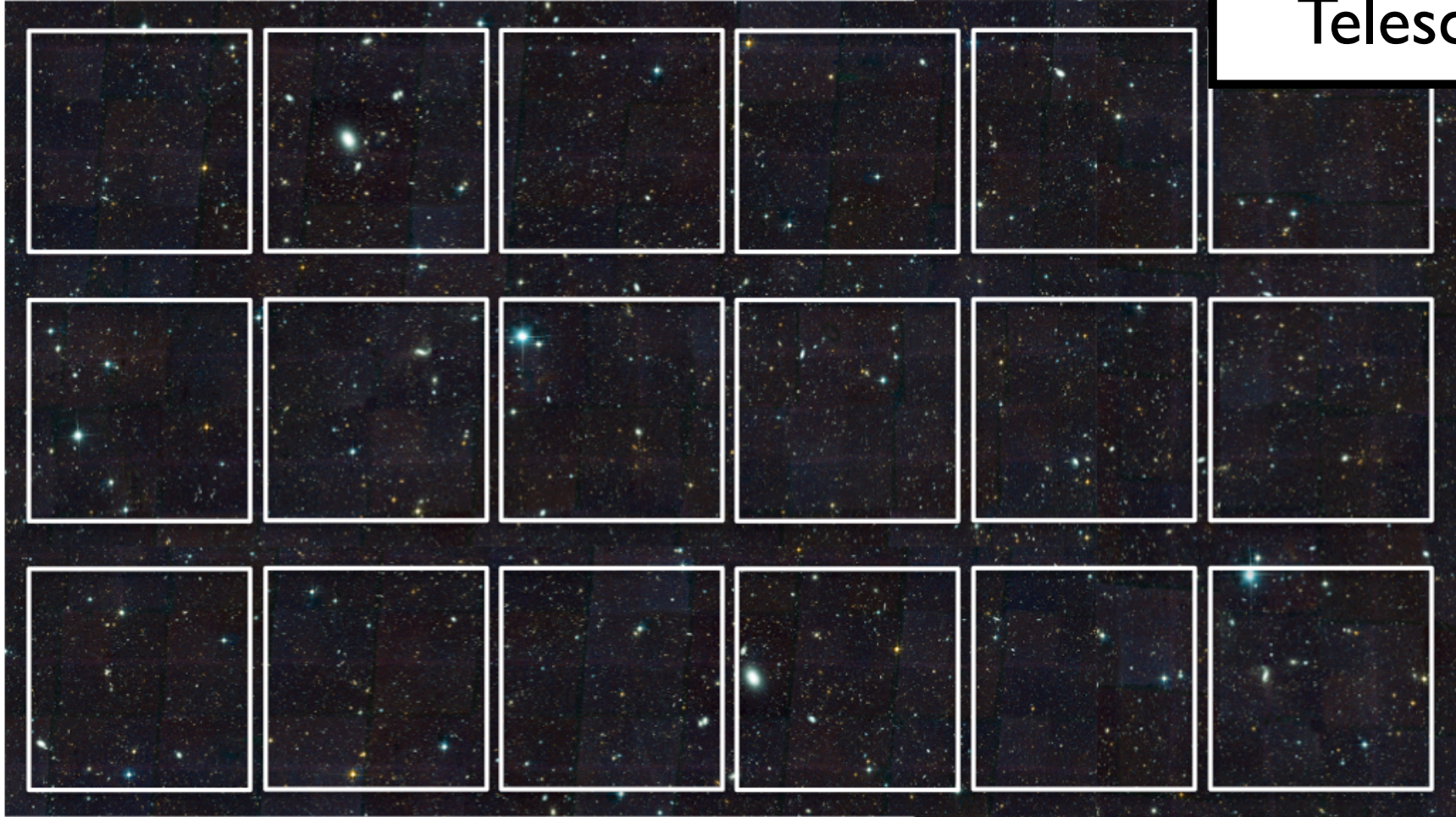
Wide-Field InfraRed Survey Telescope-
Astrophysics Focused Telescope Assets
WFIRST-AFTA
Final Report
by the
Science Definition Team (SDT) and WFIRST Project

launch May 2027?



WFIRST Wide-Area Field of View from Space

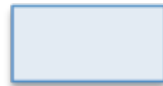
Nancy Roman
Telescope



HST/ACS



HST/WFC3



JWST/NIRCAM

The **Roman** -2.4 Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
 $z = 0.1-1.7$



standard candle distances
 $z < 1$ to 0.20% and $z > 1$ to 0.34%

High Latitude Survey

spectroscopic: galaxy redshifts
20 million H α galaxies, $z = 1-2$
2 million [OIII] galaxies, $z = 2-3$

imaging: weak lensing shapes
500 million lensed galaxies
40,000 massive clusters



standard ruler

distances	expansion rate
$z = 1-2$ to 0.4%	$z = 1-2$ to 0.72%
$z = 2-3$ to 1.3%	$z = 2-3$ to 1.8%

dark matter clustering

$z < 1$ to 0.16% (WL); 0.14% (CL)
 $z > 1$ to 0.54% (WL); 0.28% (CL)
1.2% (RSD)



history of dark energy
+
deviations from GR

$w(z)$, $\Delta G(z)$, Φ_{REL}/Φ_{NREL}

Roman

Figure of Merit

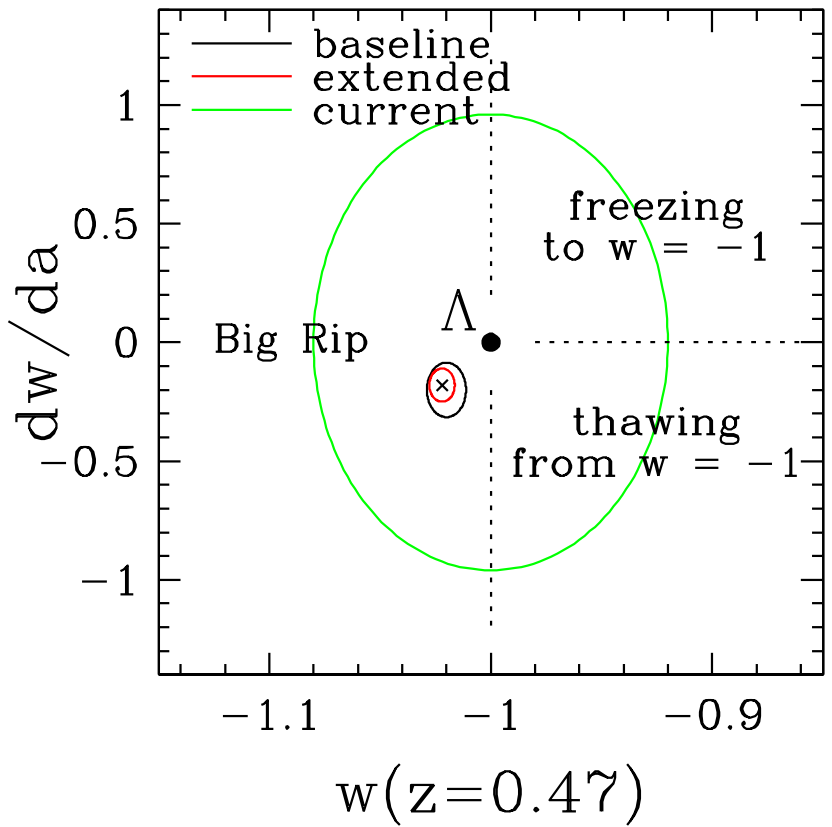


Figure 2-7: $\Delta\chi^2 = 1$ error ellipses on the value of the dark energy equation-of-state parameter w at redshift $z = 0.47$ (the redshift at which it is best determined by WFIRST-2.4) and its derivative with respect to expansion factor dw/da . The green ellipse, centered here on the cosmological constant model ($w = -1, dw/da = 0$), represents current state-of-the-art constraints from a combination of CMB, SN, BAO, and H_0 data.²⁰ For this figure, we have imagined that the true cosmology is $w(z=0.47) = -1.022$ and $dw/da = -0.18$, well within current observational constraints. The black ellipse shows the error forecast for the baseline WFIRST-2.4 SN, GRS, and WL surveys, combined with CMB data from Planck, a local supernova cali-

