Dark Energy Missions +

Some Remaining Puzzles in Observational Cosmology

Review for Final Exam

Layout of the Course

Feb 5: Introduction / Overview / General Concepts
Feb 12: Age of Universe / Distance Ladder / Hubble Constant
Feb 19: Distance Ladder / Hubble Constant / Distance Measures
Feb 26: Distance Measures / SNe science / Baryonic Content
Mar 4: Baryon Content / Dark Matter Content of Universe
Mar 11: Cosmic Microwave Background
Mar 18: Cosmic Microwave Background / Large Scale Structure
Mar 25: Baryon Acoustic Oscillations / Dark Energy / Clusters
Apr 1: No Class
Apr 8: Clusters / Cosmic Shear / Dark Energy Missions
Apr 15: Dark Energy Missions / Remain Puzzles / Review for Final Exam

This Week

May 13: Final Exam

Final Exam

May 13, 2022

HL207, HL211

13:15-16:15

Review Material from Last Week

Dark Energy Experiments

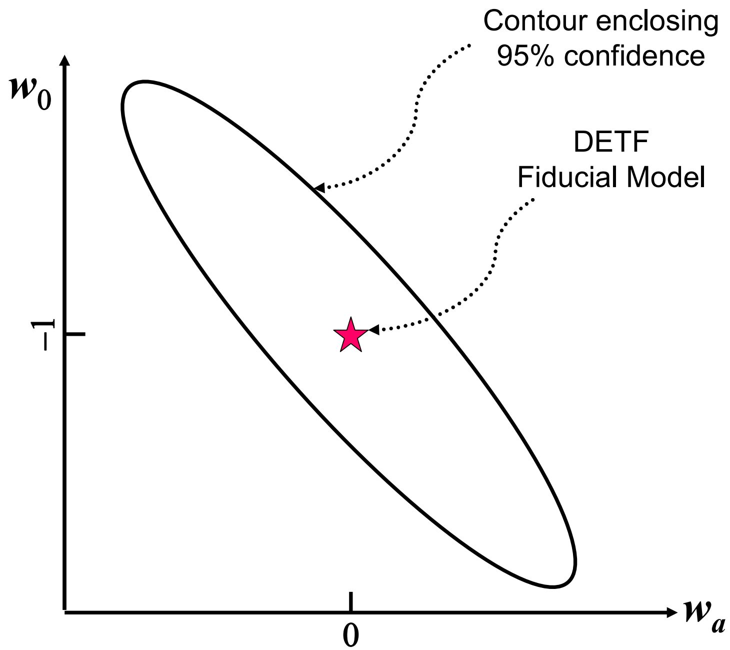
So the game is to determine the w parameter and how it depends on redshift

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 <u>DETF figure of merit</u> 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.

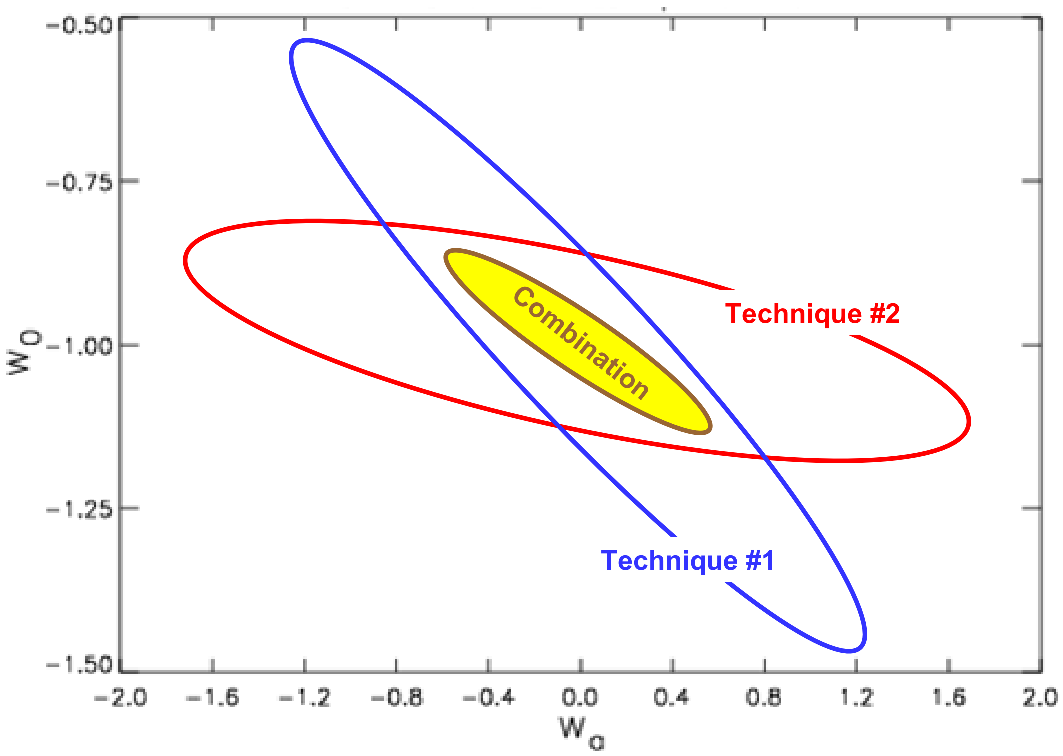


Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

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

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

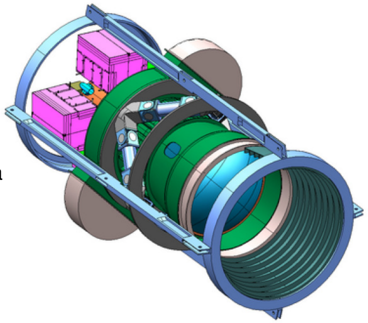
Weaknesses: Sensitive to Uncertainties in the Redshifts of the Lensed Galaxies

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

KIDS / DES

- ground based imaging survey at CTIO 4m telescope of Southern region (SZE-survey overlap)
- camera: 520Mpix, 2.2deg^2 FoV
- start: next year
- 5,000deg^2 in 4bands: g r i z
- DE probes: GC, BAOs, WL, SNIa
- objects: galaxies, galaxy clusters (with photometric redshifts)
- redshift range: $0<z<1.3$
- DE constraints: σ_w~5-15%



Source: http://www.darkenergysurvey.org/

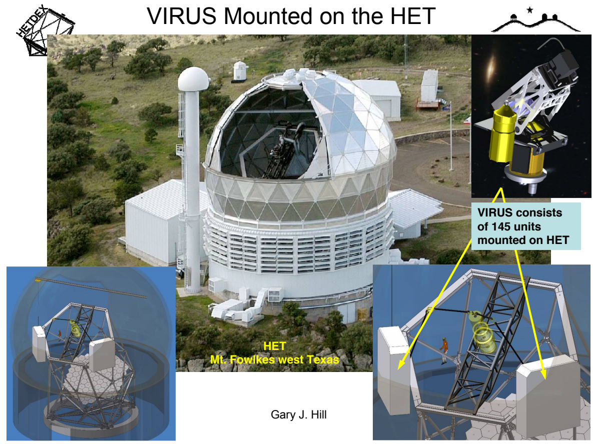
Dome and Facility Design

VERA C. RUBIN OBSERVATORY

Nancy Roman Telescope

New Material for This Week

The Hobby-Eberly Telescope
Dark Energy Experiment



Overview

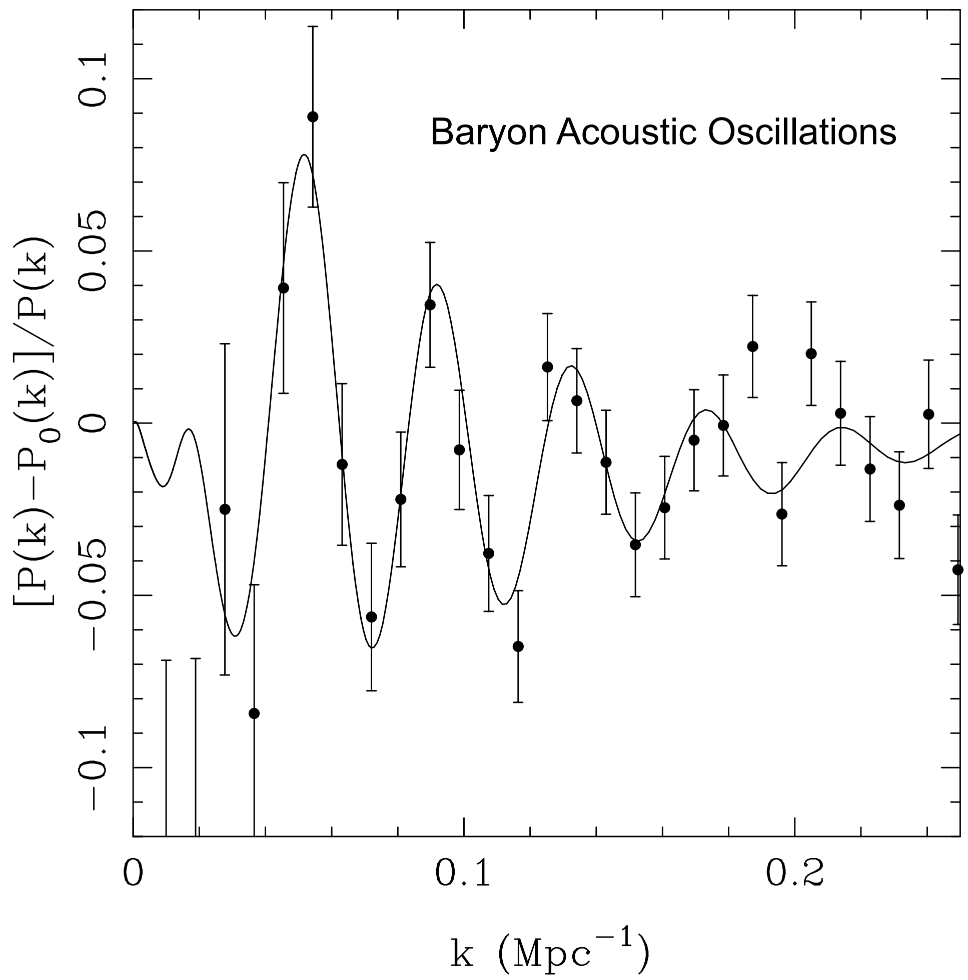
- Two observational approaches to make progress on DE
  - Get the tightest possible constraints at low redshift where effect of DE is stronger
  - Go to higher redshift where we can measure the evolution or verify that w(z) = -1
  - Both approaches are needed
- Almost all projects are focused at z<1.5
  - Due to obvious observational constraints
- 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)
- 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

Realization of HETDEX



Measuring Dark Energy Evolution

Dark energy, or its equation of state w(z), is mathematically well defined. It enters into the cosmological equations as:

$$H(z) = h\sqrt{\Omega_m (1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z')}{1+z'}dz'\right] + \Omega_k(1+z)^2}$$

↑ **Expansion rate** ↑ **Matter term** ↑ **Dark Energy term and w represents history** ↑ **Curvature term**

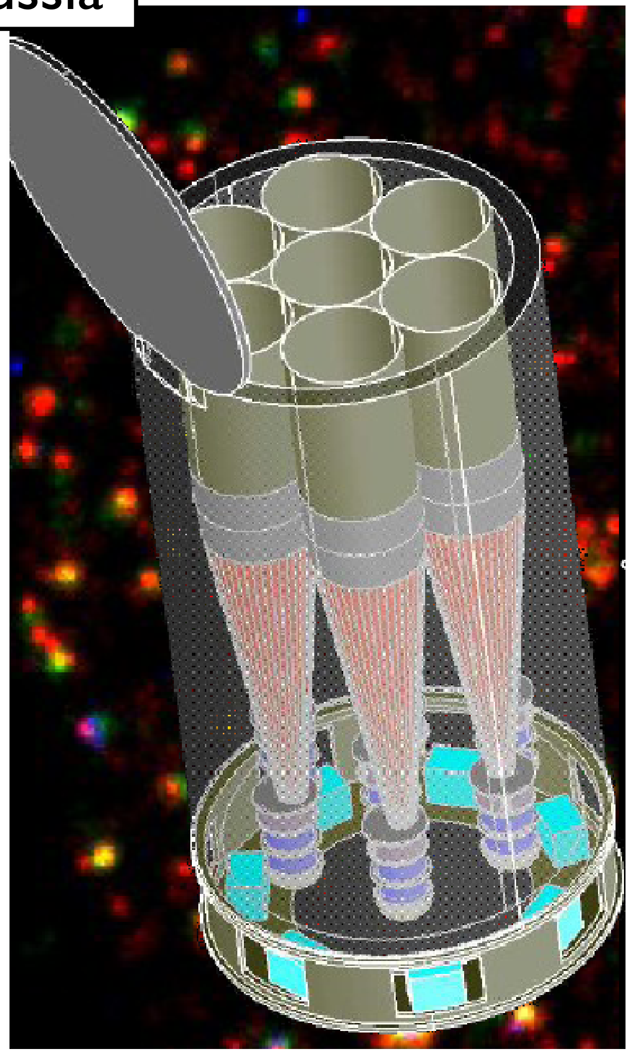
- With priors on $\Omega_M h^2$ from Planck and 3% on Ho we can achieve
  - $\sigma_H/H \sim 1\%$ at z~3 to directly detect w=-1 constant DE at 3-σ
- D_A(z=1089) will be constrained to sub-% accuracy by Planck
  - $\sigma_{D_A}/D_A \sim 1\%$ at z~3 to measure curvature to 0.2% (e.g. Knox 2006)

Few examples of more well known DE missions

c) eROSITA: the next X-ray survey telescope

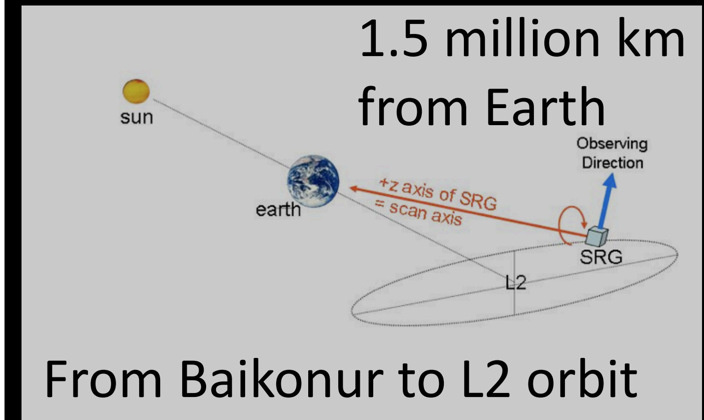
Collaboration between Germany / Russia

- 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: σ_w~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.

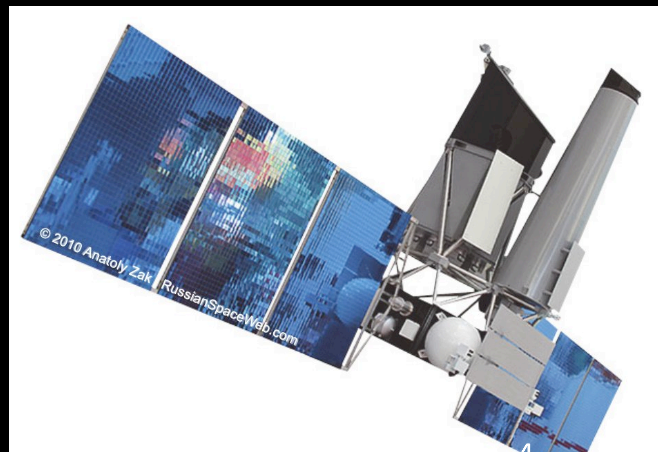
The (Near) Future:
eROSITA ~10^5 X-Ray Clusters



Zenit-2SB rocket
Fregat booster

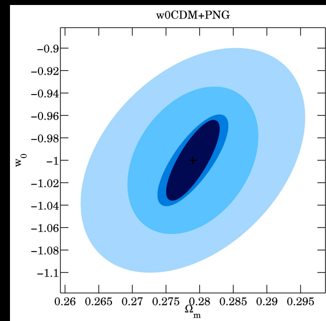
Talks P. Predehl, A. Merloni

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



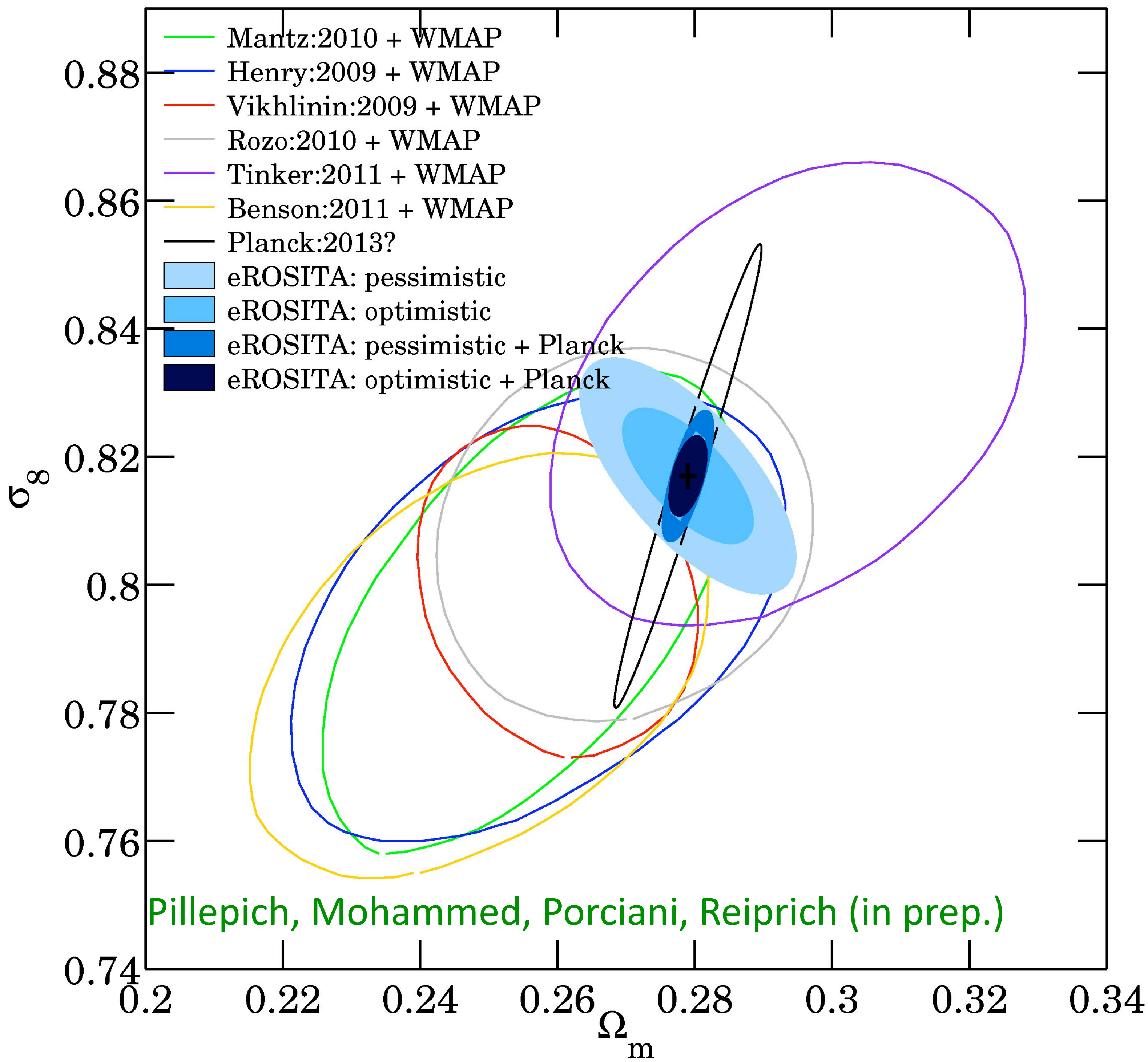
Projected Cosmological Constraints

- *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").



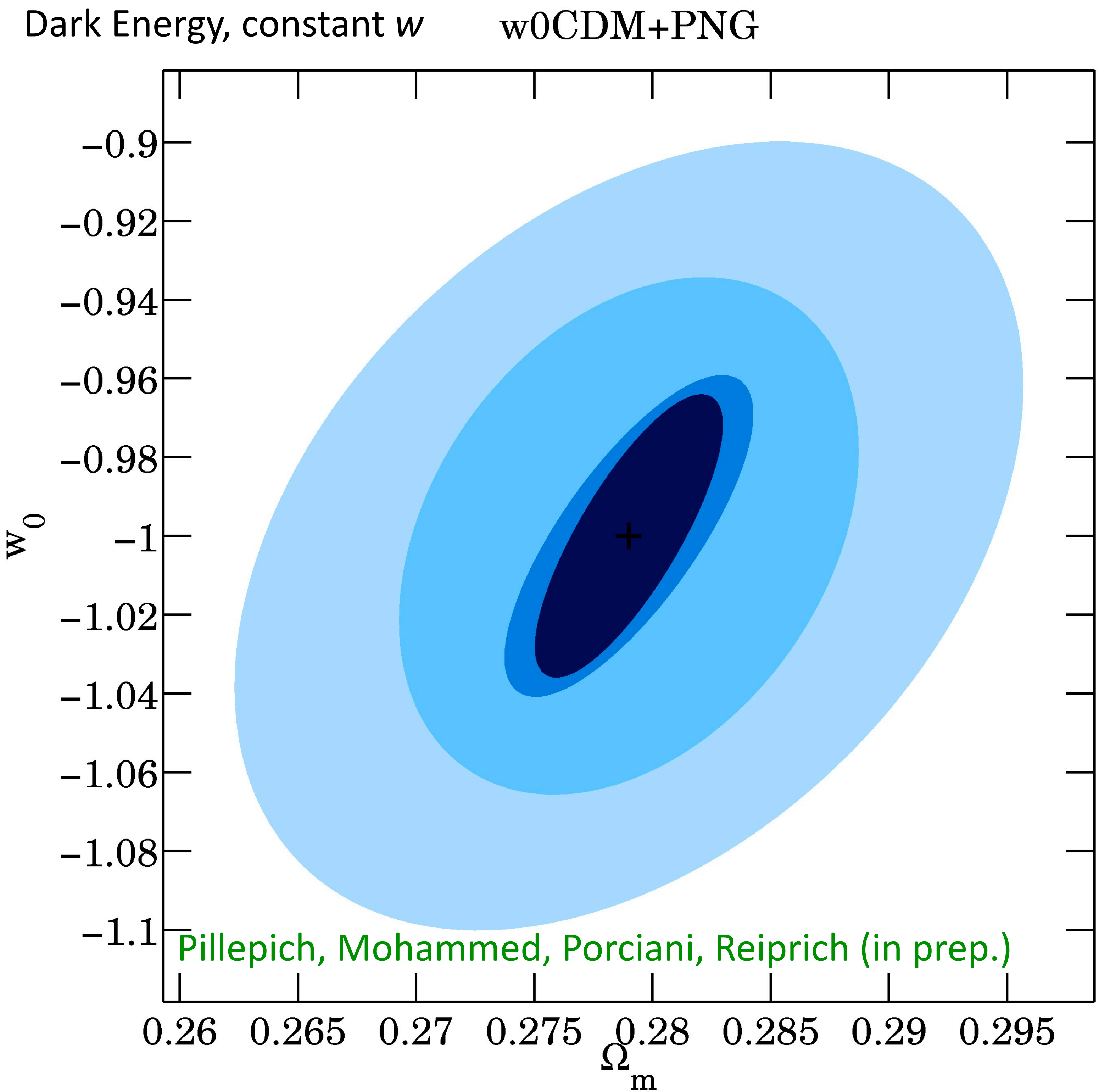
- Take into account expected redshift uncertainty.
- Apply two cosmological tests simultaneously; evolution of (i) cluster mass function and (ii) angular clustering.
- Several assumptions, e.g., hardware works, flat Universe, fiducial cosmology and L_X–M relation, redshifts, one sky for all, ….

LCDM+PNG



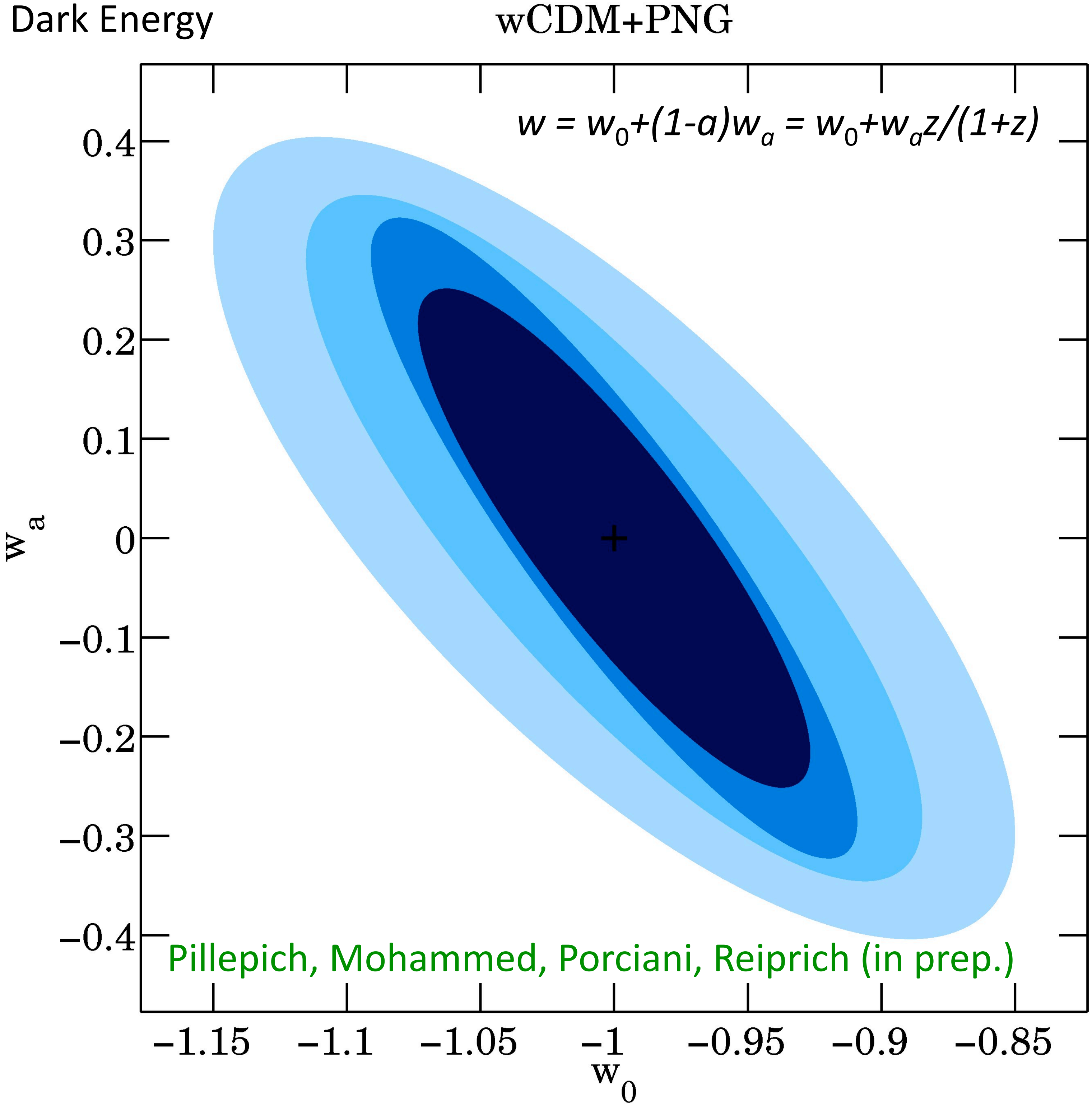
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy, constant *w*



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

Dark Energy



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

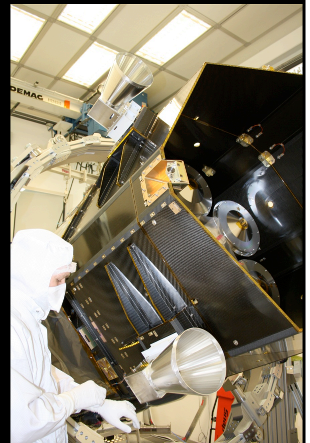
eROSITA Compared to DES and Euclid

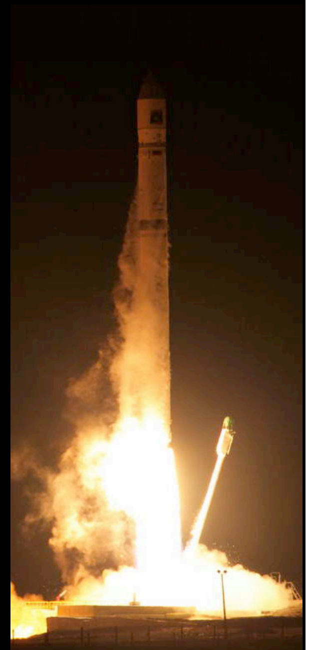
Data	Redshifts	Prior Scenario	Model	$\Delta f_{\rm NL}^{\rm local}$	$\Delta\sigma_8$	$\Delta\Omega_{\rm m}$	Δw_0	Δw_a	$\text{FoM}^{\rm DEFT,1\sigma}$
Stage IV									
eROSITA	photo-z	Pessimistic	LCDM+PNG	8.1	0.012	0.0101	-	-	-
eROSITA	spectro-z	Optimistic	LCDM+PNG	6.4	0.007	0.0060	-	-	-
eROSITA + Planck	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	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	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 (>300 for $f_{\rm NL}$=0)
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	-

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., Δw_{DE}<3%, but also on modified gravity, neutrino masses, primordial non-Gaussianity, ….





eROSITA: Some Results Based on Early Data

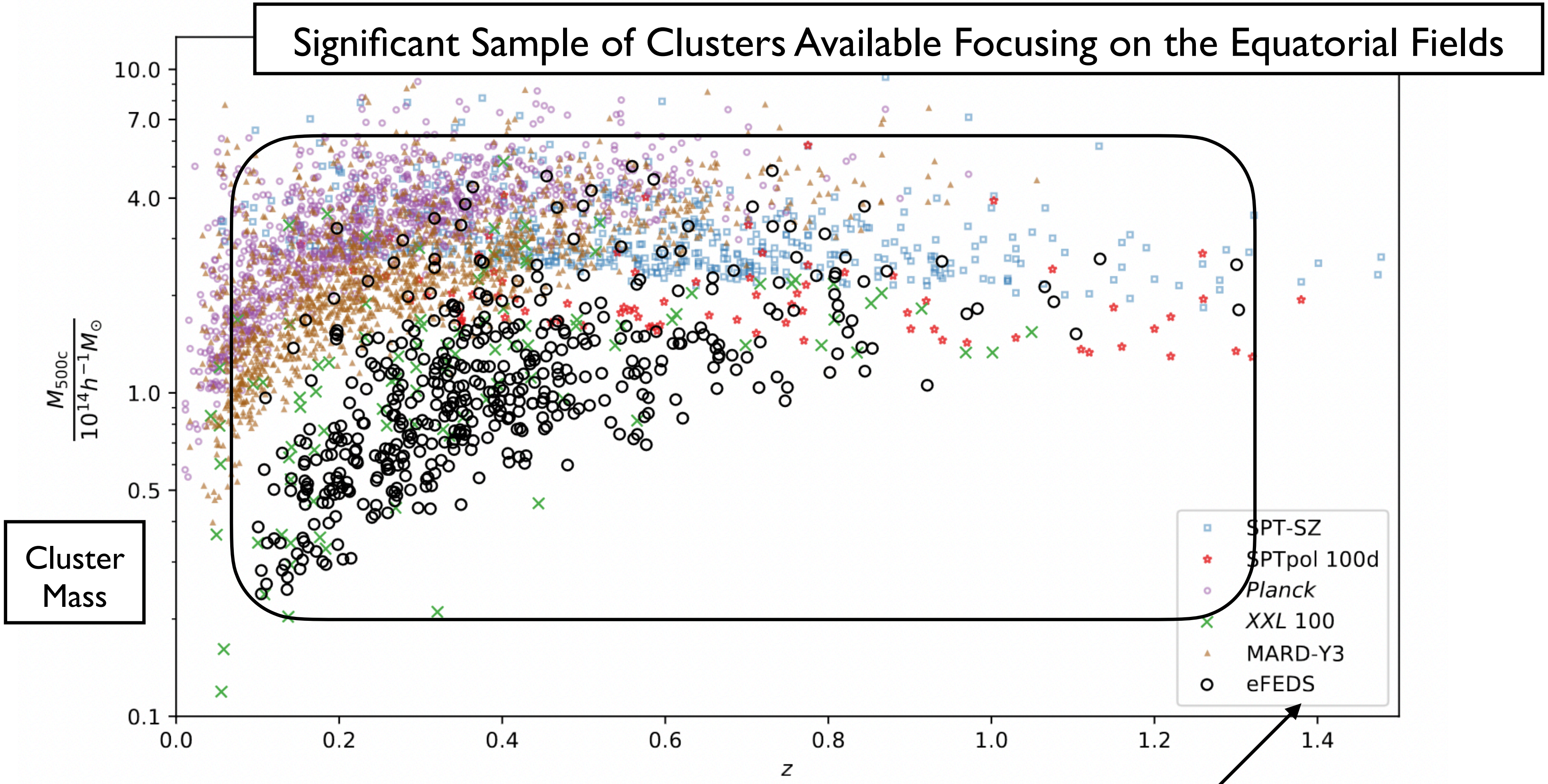


Figure 10. The mass and redshift of the eFEDS clusters (black circles), and those in the SPT-SZ survey (blue squares; Bleem et al. 2015), the SPTpol 100 degree^2 survey (red stars; Huang et al. 2020), the *Planck* mission (purple circles; Planck Collaboration et al. 2015), the brightest sample in the *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

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eROSITA: Some Results Based on Early Data

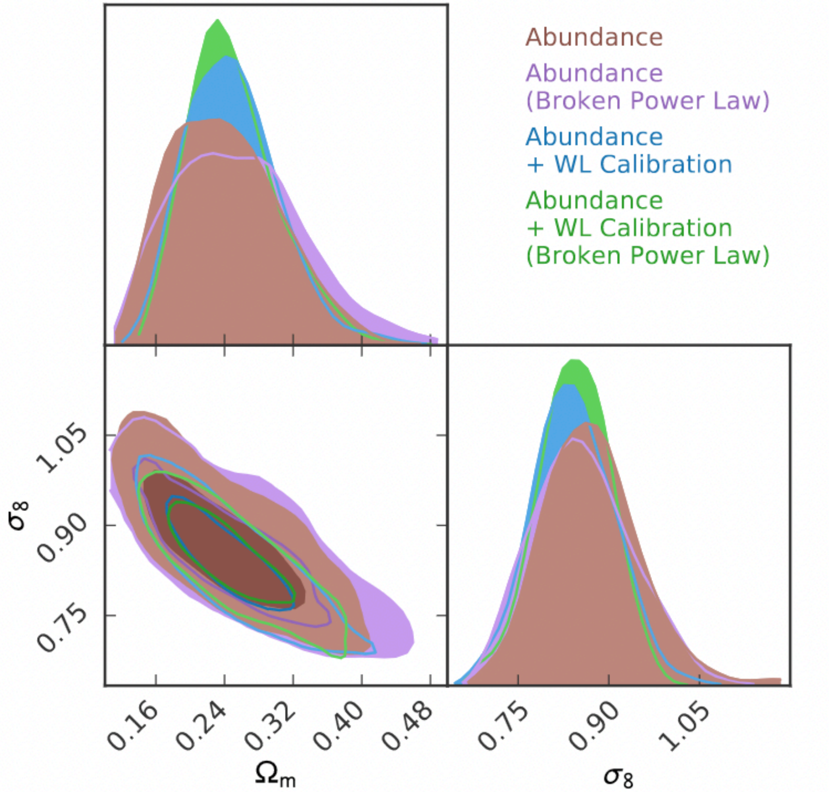

Figure 16. The constraints on Ω_m and σ_8 obtained from the modeling of the cluster abundance and that jointly with the weak-lensing mass calibration. The results based on the cluster abundance (the joint modeling) with and without the broken power-law scaling of the η–M–z relation are in purple and 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.

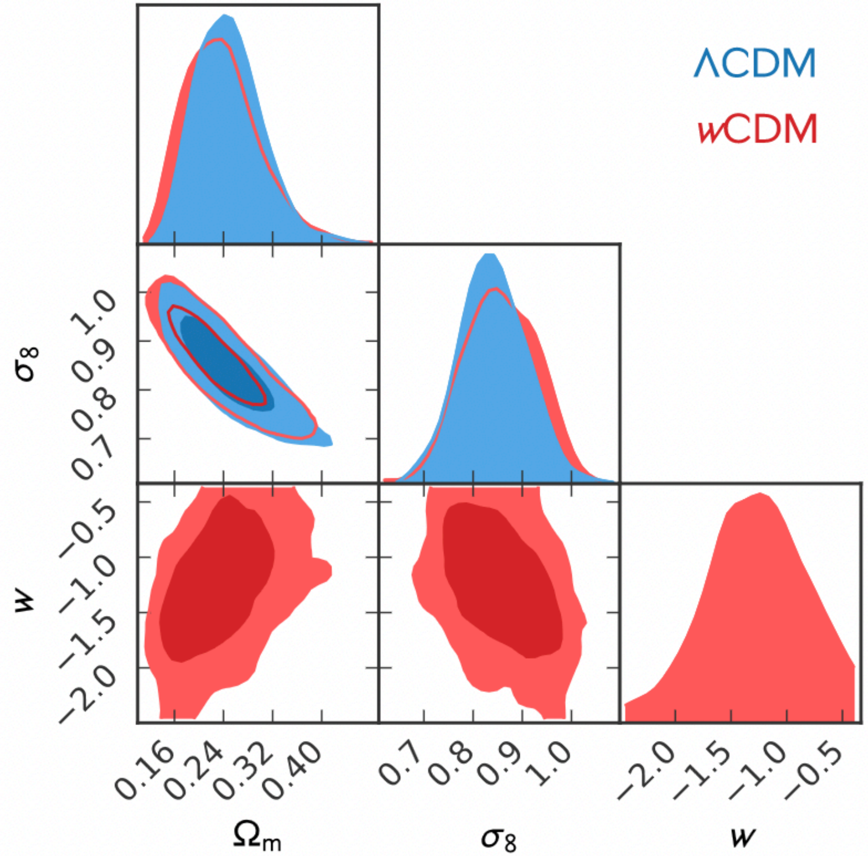

Figure 17. The cosmological constraints from the eFEDS clusters in the ΛCDM (blue) and wCDM (red) models. These constraints are obtained in the joint modeling of the weak-lensing mass calibration and the cluster abundance with the single power-law mass scaling of the count rate and with the Gaussian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

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eROSITA: Some Results Based on Early Data

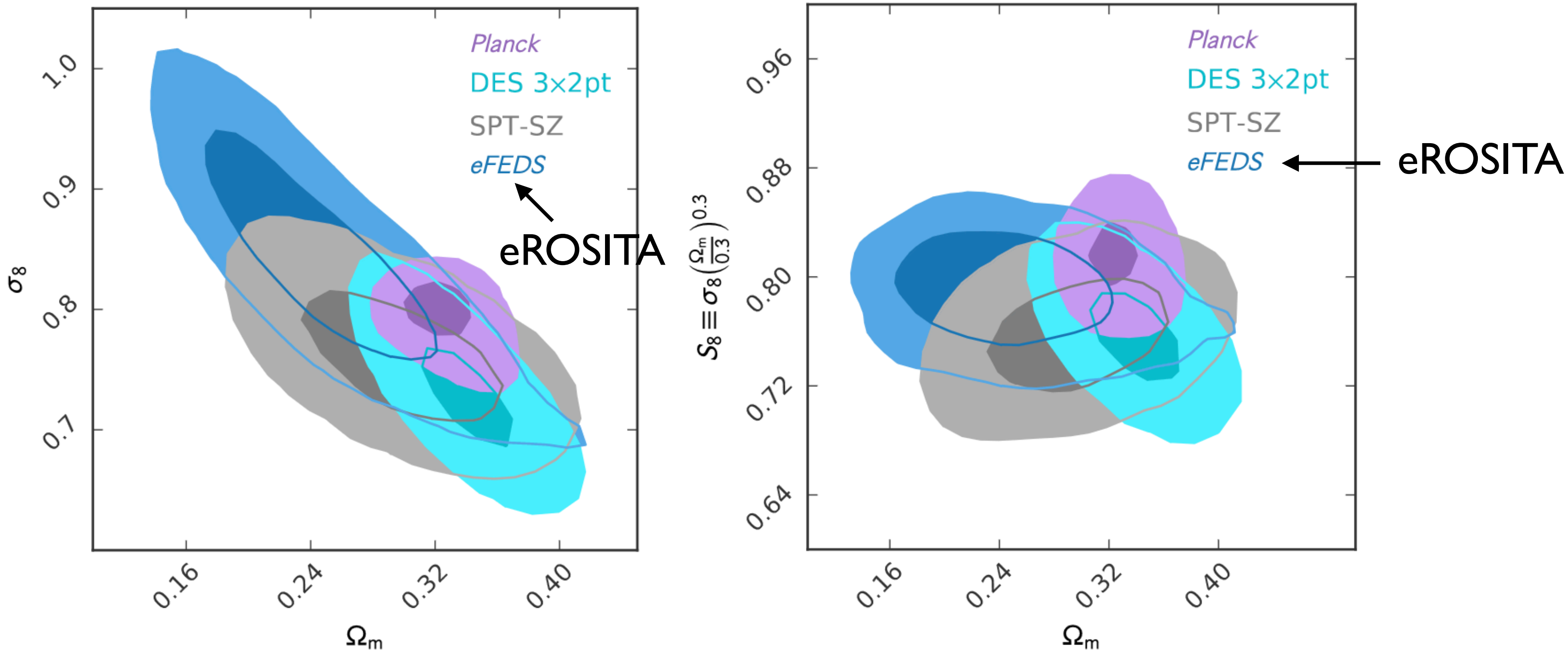

Figure 18. The comparisons of the cosmological parameters assuming the ΛCDM cosmology between the eFEDS clusters (blue) and the external results, including the anisotropy and polarization (TTTEEE + lowE) of CMB temperatures from *Planck* (purple; Planck Collaboration et al. 2020), the 3×2-point analysis 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 $\lesssim 1.2\sigma$.

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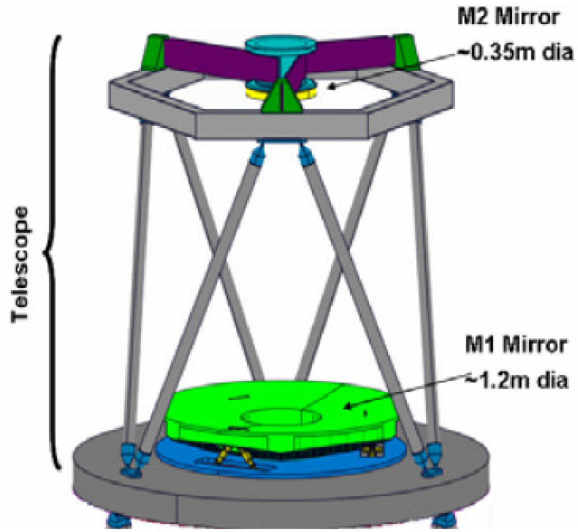
Few examples of more well known DE missions

d) EUCLID: the European DE Space Mission

- space-based optical/NIR imaging and spectroscopy survey
- 20,000deg^2 extragalactic survey
- start: 2023
- DE probes: WL, BAOs, GC
- σ_w~2%



similar mission plans in US for JDEM, became WFIRST likely with a stronger focus on SN Ia

Source: M. Schweitzer (MPE)

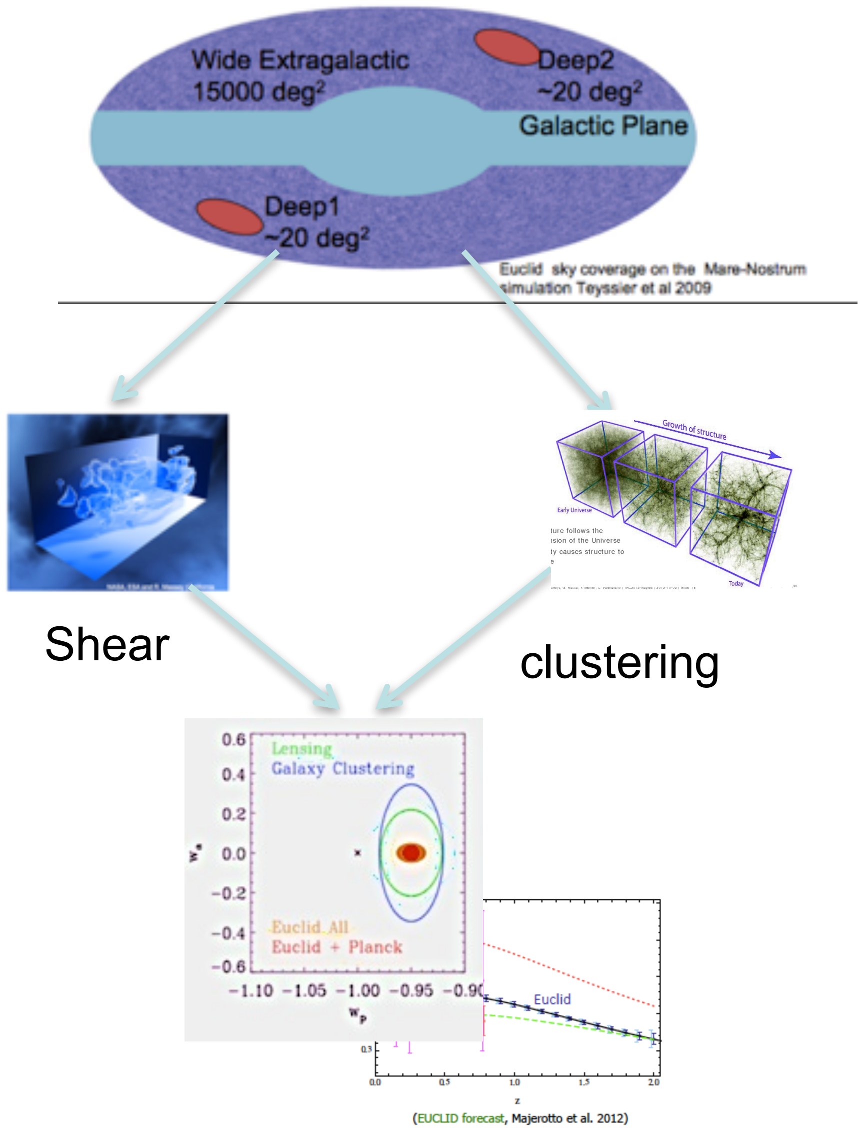
Euclid: an ESA space mission

Euclid was selected by ESA in Oct. 2011, Adopted in June 2012 in the cosmic vision program as the M2 mission to be launched in 2020

- Euclid is an ESA mission with a strong scientific consortium
- ESA provides the telescope and detectors (via industry), the satellite, launch and operation centers
- Countries provide the 2 instruments (VIS and NISP) and the ground segment (SGS)

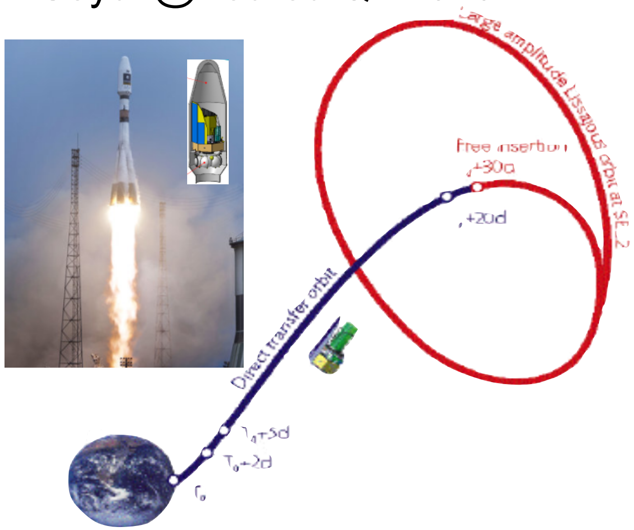
- The ground segment and related computing is a very expensive and challenging aspect of the project

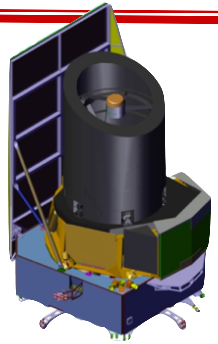
- EUCLID is under implementation an starting the construction of instrument and telecope
- For a launch In July of 2023 using SPACEX



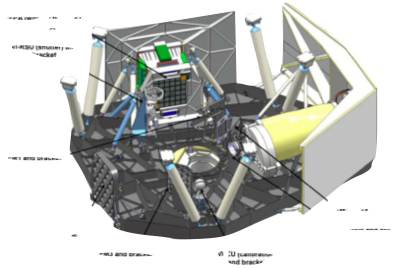
The ESA Euclid mission in one view

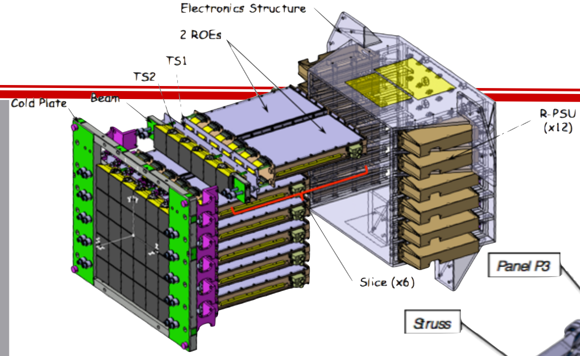
Soyuz@Kourou Q4 2020

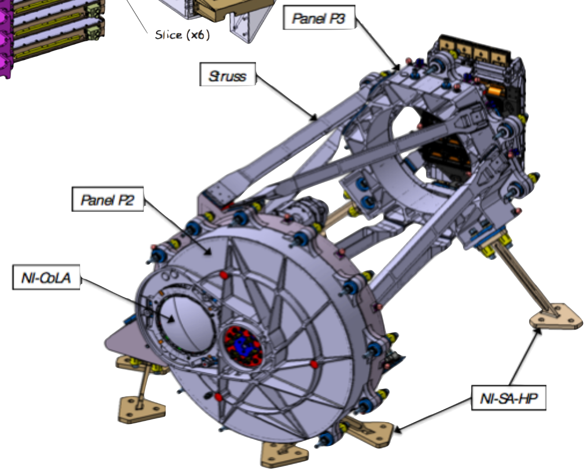


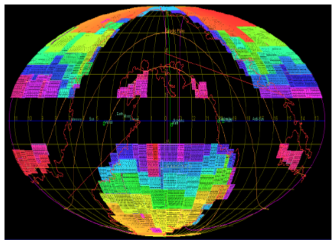


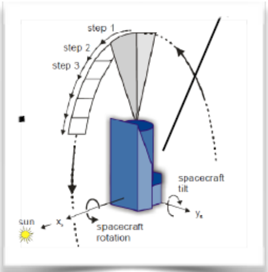
∅ 1.2m





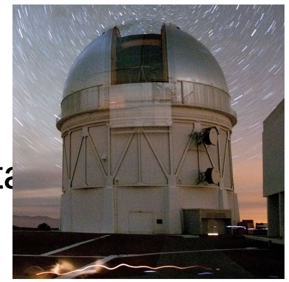




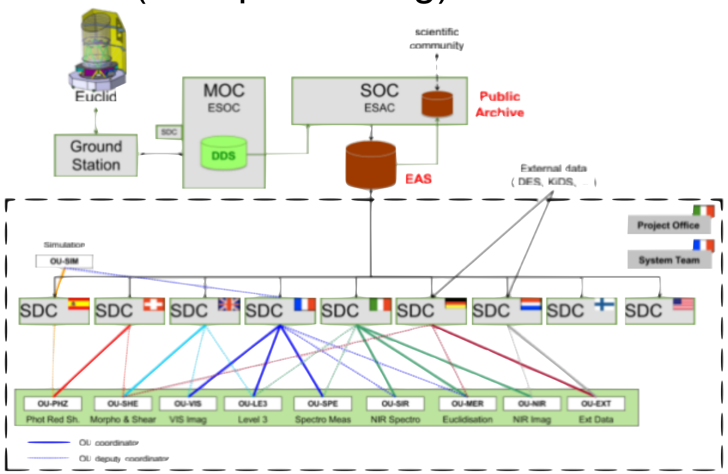


Survey:
6 years - 15000 deg^2

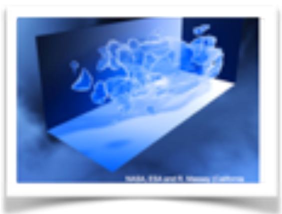
Ground-based photometric and spectroscopic data

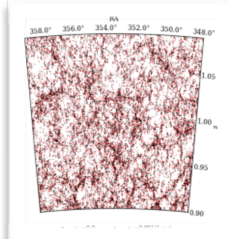


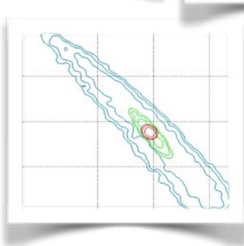
Science Ground Segment (data processing)



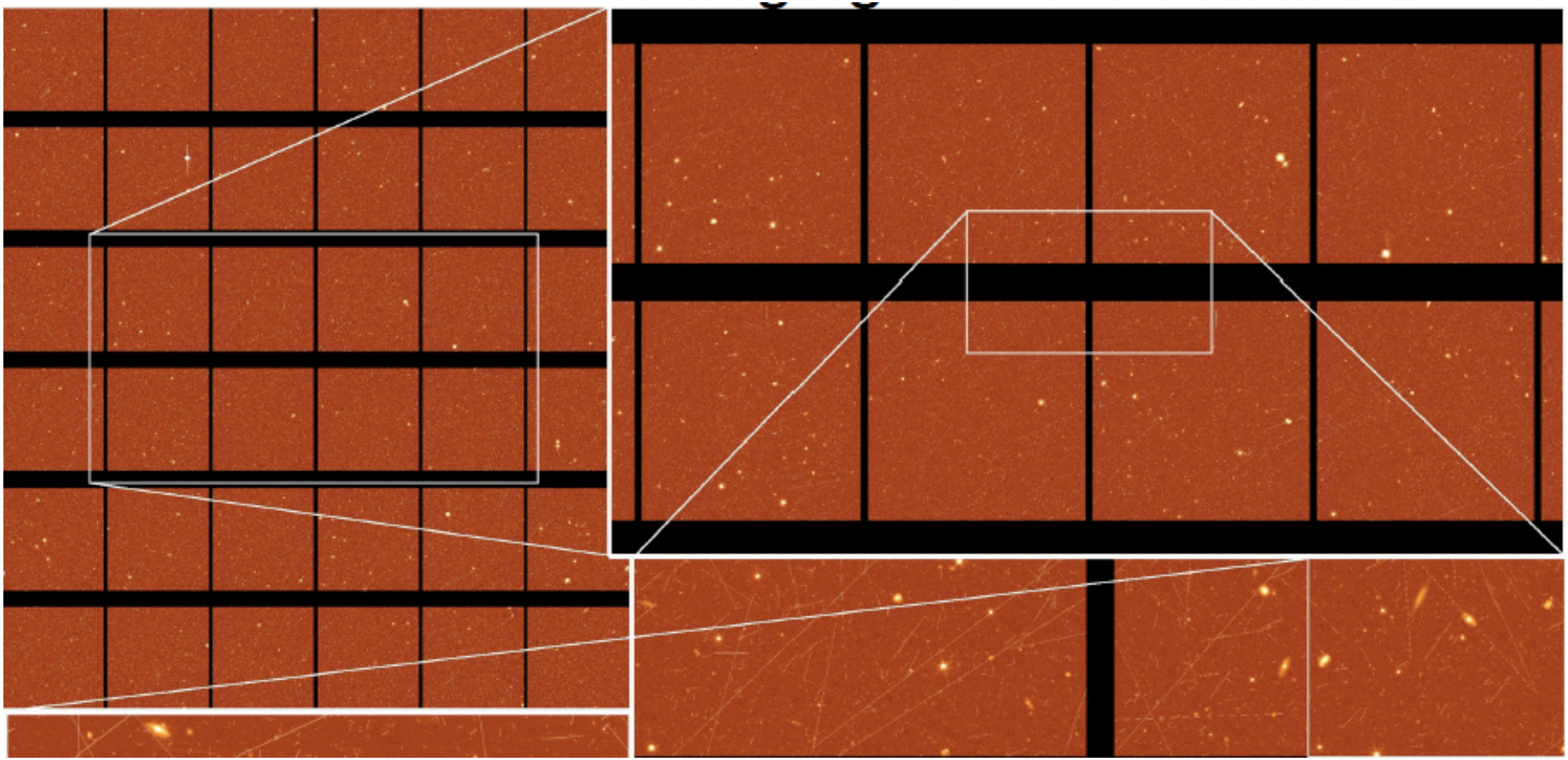
Science Working Groups Cosmology and legacy analysis



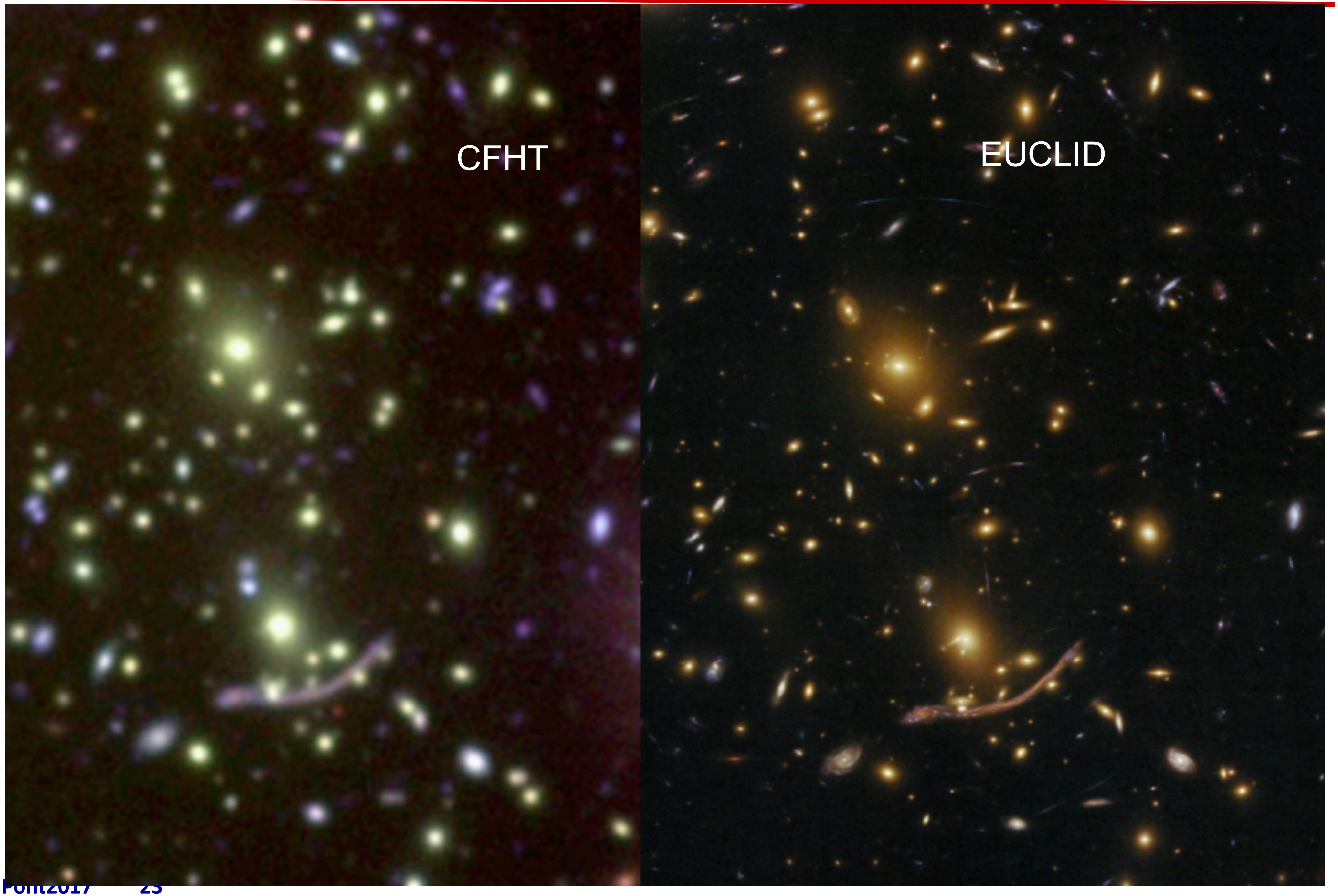




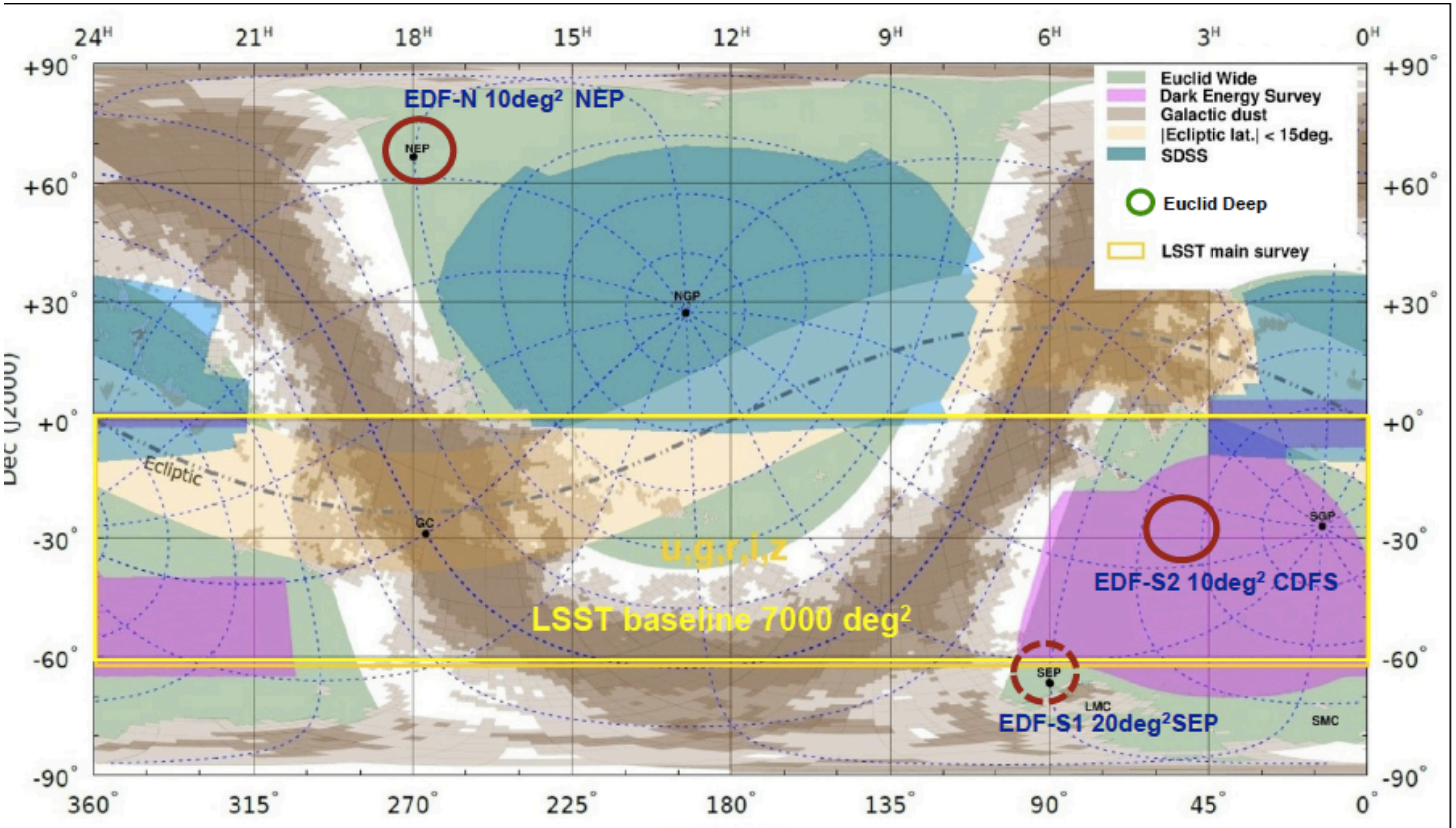
Euclid in simulation =VIS CCDs



Euclid is under simulation



Euclid deep surveys and external data



From J.-C. Cuillandre and the Survey WG

Deep survey

- 10 million source
- 1.5 millon for WL
- 150 000 with spectroscopy

External data

Mandatory ground basesd imaging in 4 bands for the WL photoz-s of all WL galaxies

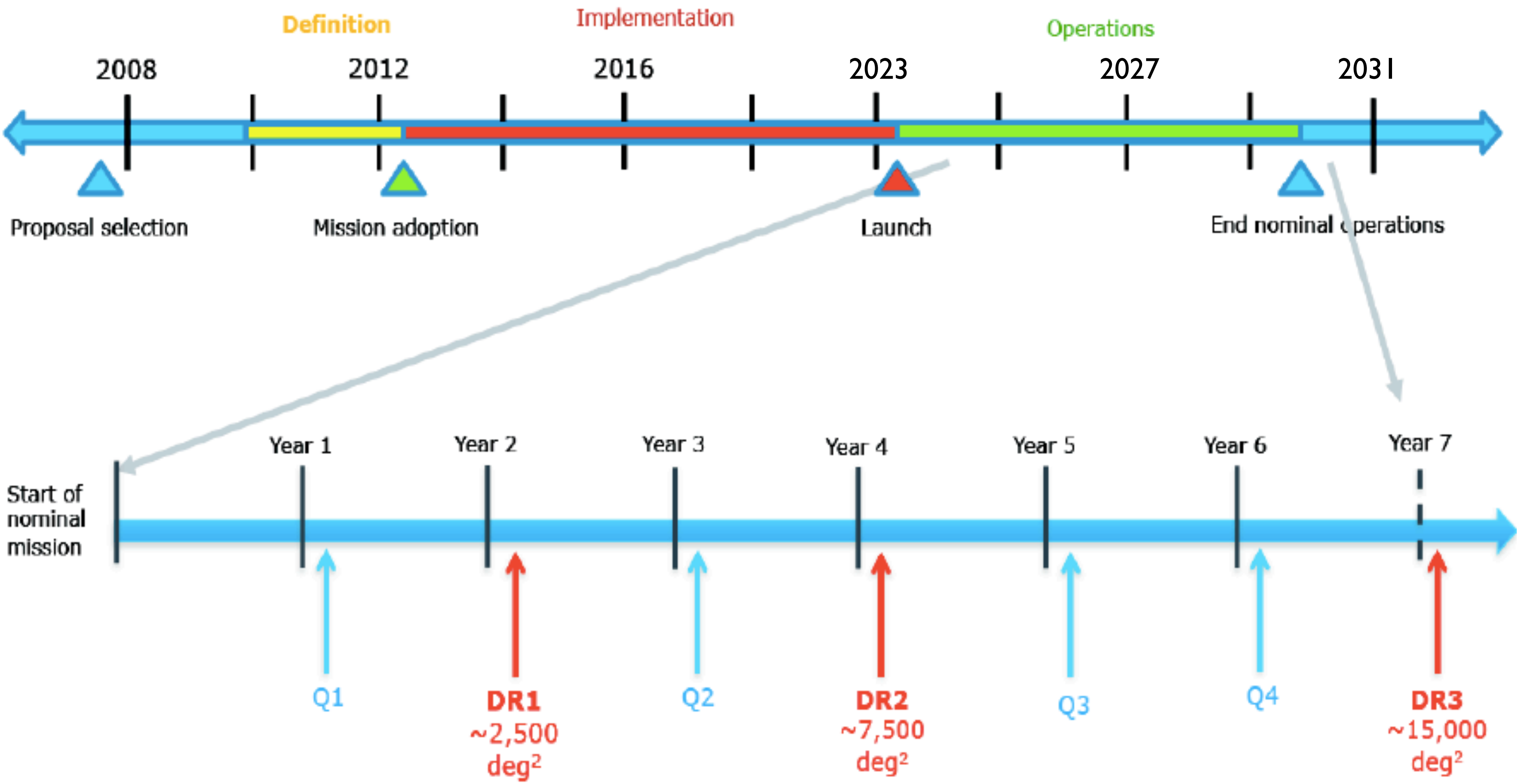
- 1x10 deg^2 North Ecliptic pole (EDF-N) + 1x20 deg^2 South Ecliptic pole (EDF-S1)

+ 1x10 deg^2 at CDFS (EDF-S2)

- VIS limiting magnitude: 26.5 AB @10σ
- NISP limiting magnitude 26 H @ 5σ

+Spectro 5 10^{-17} erg.cm^{-2}.s^{-1} ; 3.5σ

Data release



Science with Euclid will start in 2024 **with Q1 and in** 2025 **with DR1**

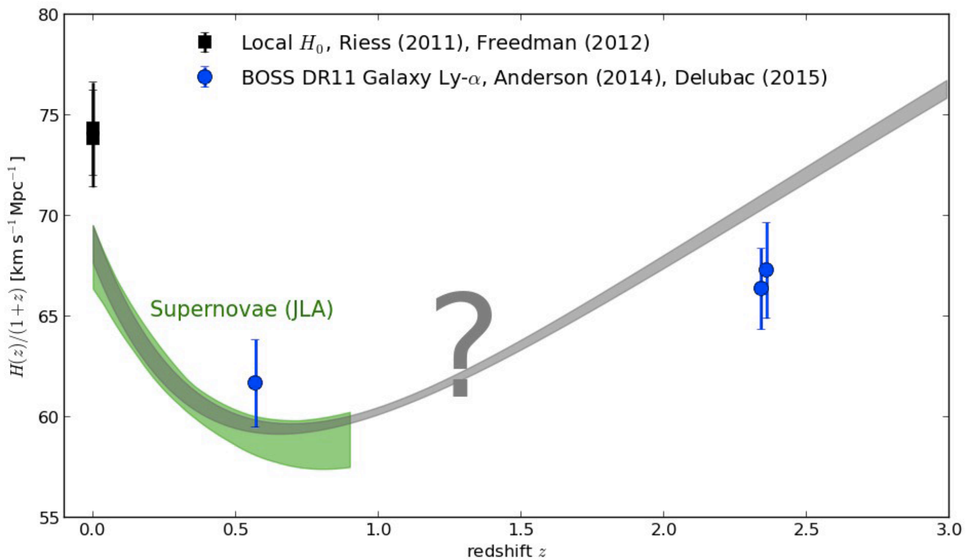
Exploring the DM/DE transition period : H(z)/D(z)

1 Expansion Rate (BAO):

$$H(z) = H_0 \left[\Omega_M (1+z)^3 + \Omega_{DE} \frac{\rho_{DE}(z)}{\rho_{DE}(0)} + \Omega_K (1+z)^2 \right]^{1/2}$$

2 Distance (SN, BAO, CMB):

$$D(z) = \frac{1}{(|\Omega_K| H_0^2)^{1/2}} S_K \left[(|\Omega_K| H_0^2)^{1/2} \int_0^z \frac{dz'}{H(z')} \right]$$



Euclid: Exploring the cosmic history with structure formation

3

Growth and growth rate (WL, Clusters, RSD):

$$G'' + \left(4 + \frac{H'}{H}\right) G' + \left[3 + \frac{H'}{H} - \frac{3}{2}\Omega_M(z)\right] G = 0$$

$$G = D_1/a \quad ; \quad f = d\ln(D) / d\ln(a)$$

4

Measuring the metrics: use probes that explore the 2 potentials

$$ds^2 = -(1 + 2\psi)\, dt^2 + (1 - 2\phi)\, a^2(t)\, dx^2$$

It is fundamental to have access to both potentials To distinguish effects

- Small scalar perturbations:

$$ds^2 = -(1 + 2\psi)\, dt^2 + (1 - 2\phi)\, a(t) d\vec{x}^2$$

- Non relativistic particules are sensitive to: ψ
- Relativistic particules are sensitive to: $\psi + \phi$

- Standard GR + no anisotrotic stress: $\psi = \phi$

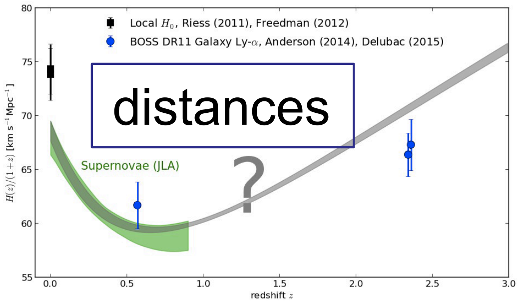
→ Poisson equation $k^2\phi = -4\pi G a^2 \sum \rho_i \Delta_i$

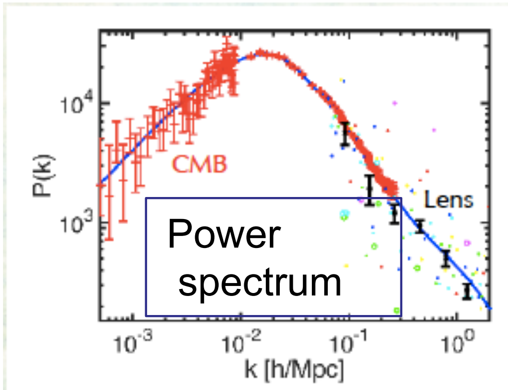
- Modified Gravity or Dynamical DE: $\psi = R\phi$

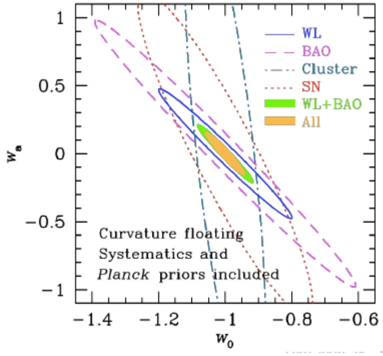
→ Poisson equation: $k^2\phi = -4\pi G Q a^2 \sum \rho_i \Delta_i$

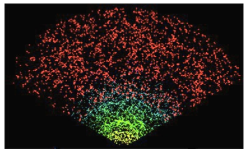
$Q(k,a)$, $R(k,a)$: imprints on clustering of DM, Gal and DE

A multi probe approach



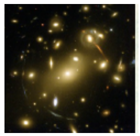






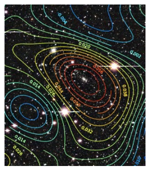
- *Clustering /Large scale structure (LSS) (BA0, RSD…)*
  distance + ordinary matter power spectrum
  + growth of structures (access to ϕ)

Spectroscopy
Redshift survey



- *Weak gravitational shear.*
  distance + dark matter power spectrum,
  growth of structure (access to (ϕ+ψ)

Imaging
Photometry



- *Galaxy cluster / Voids*
  count, power spectrum

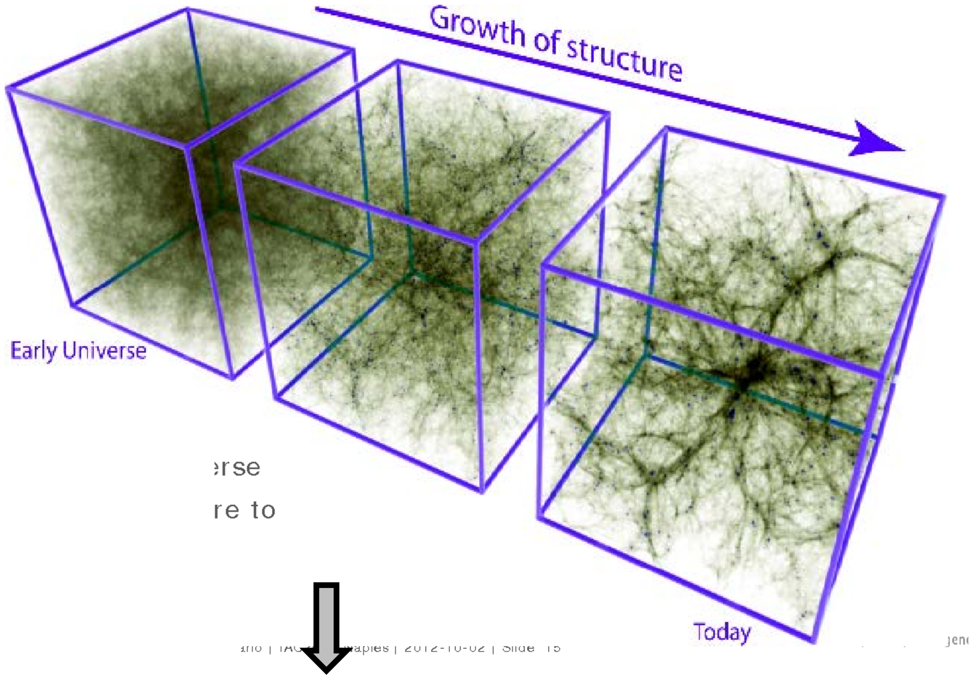
Photometry+
spectroscopy

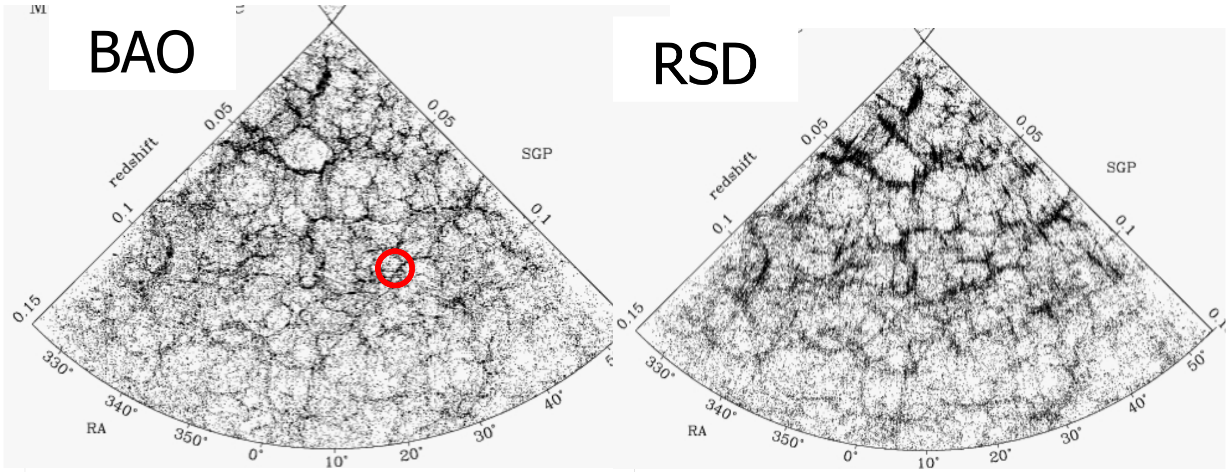
Primary: Galaxy Clustering: BAO + RSD

- 3-D position measurements of galaxies over 0.9<z<2

- Probes expansion rate of the Universe (BAO) and clustering history of galaxies induced by gravity (RSD); ψ, $H(z)$.

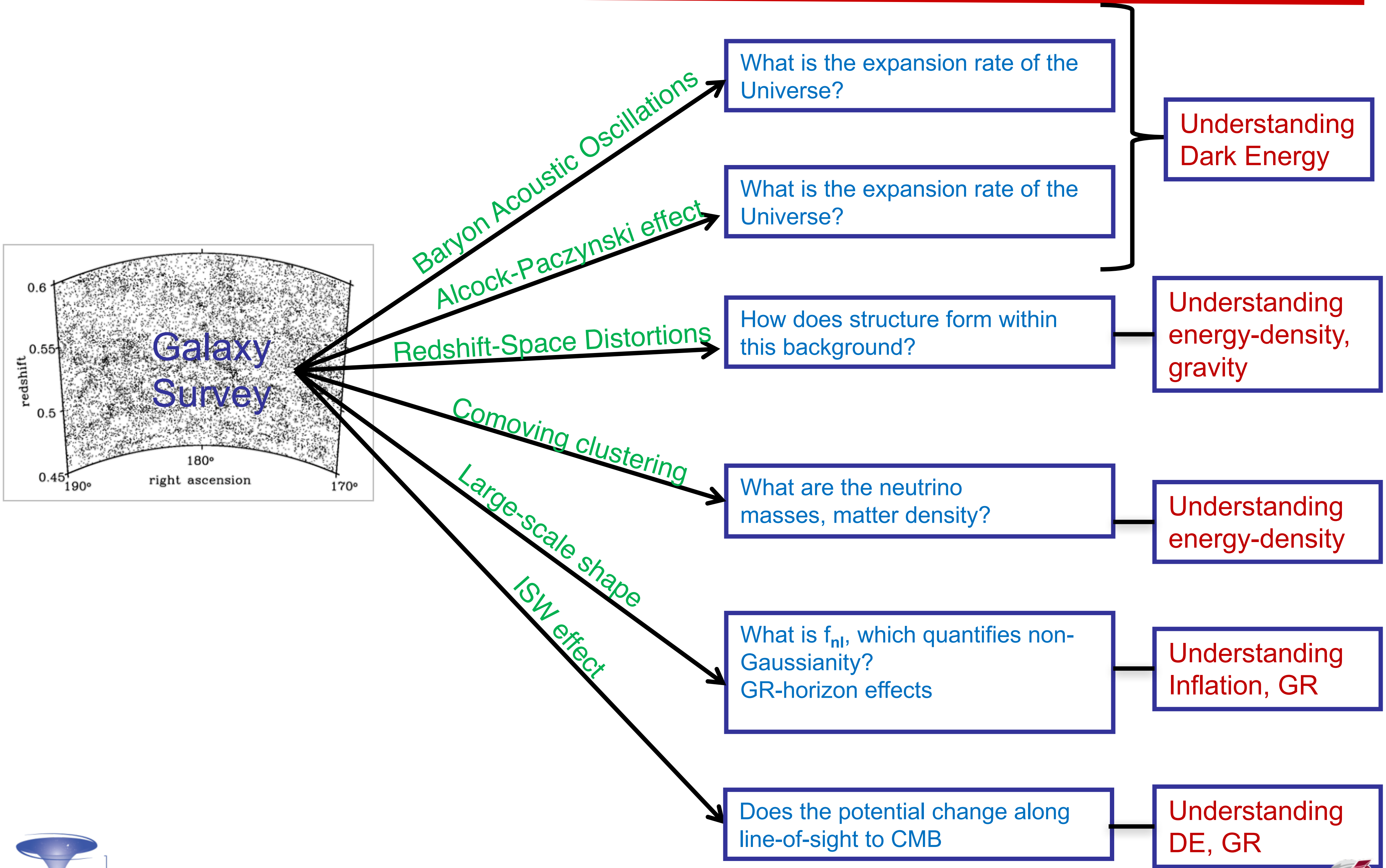
- Need high precision 3-D distribution of galaxies with spectroscopic redshifts from spectroscopy in NIR range.





35 million spectroscopic redshifts with 0.001 (1+z) accuracy over 15,000 deg^2

Primary probe 1: Euclid Redshift Survey



Primary probe 2: Weak Lensing

Cosmic shear over 0<z<2

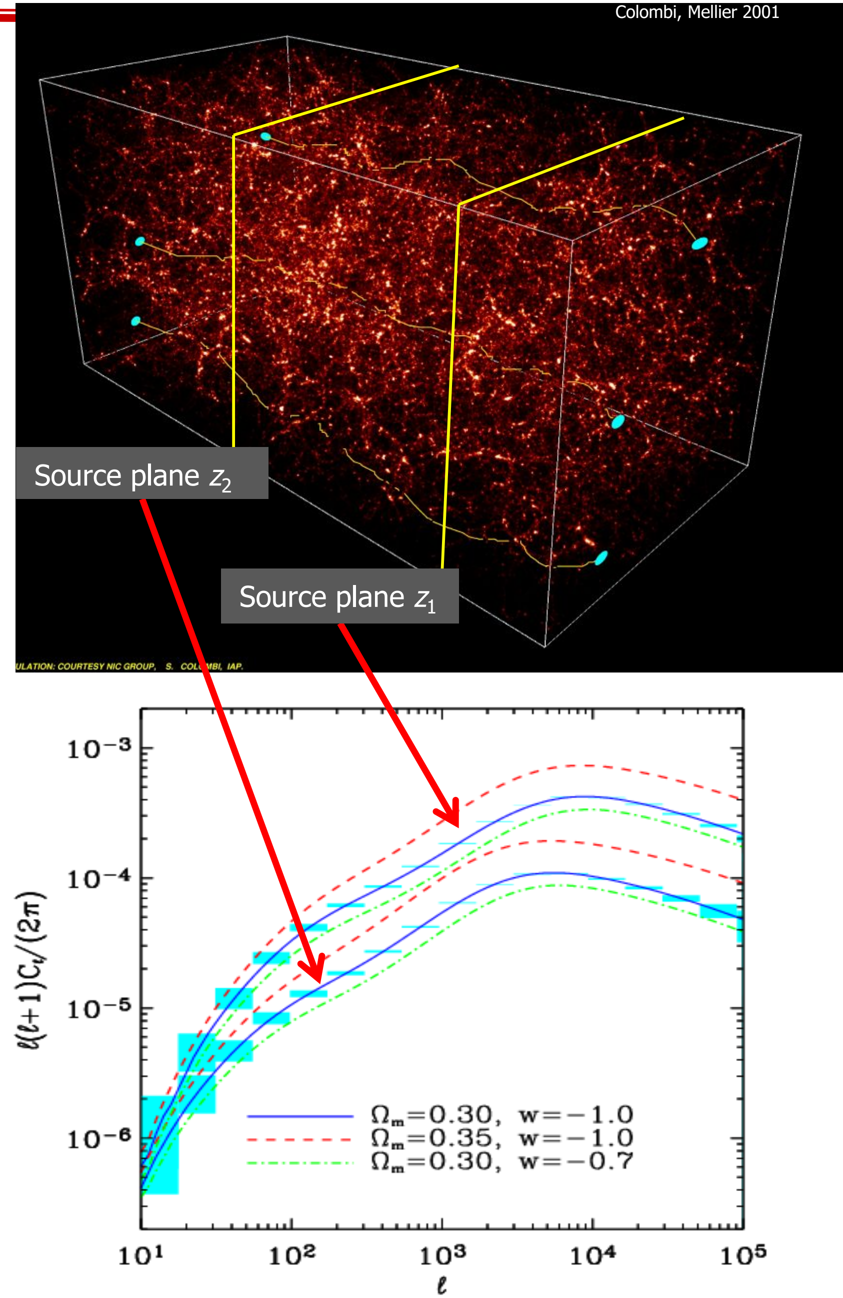
•Probes distribution of matter (Dark +Luminous): expansion history, lensing potential $\phi+\psi$.

→ Shapes+distance of galaxies: shear amplitude, and bin the Universe into slices.

→ "Photometric redshifts" sufficient for distances

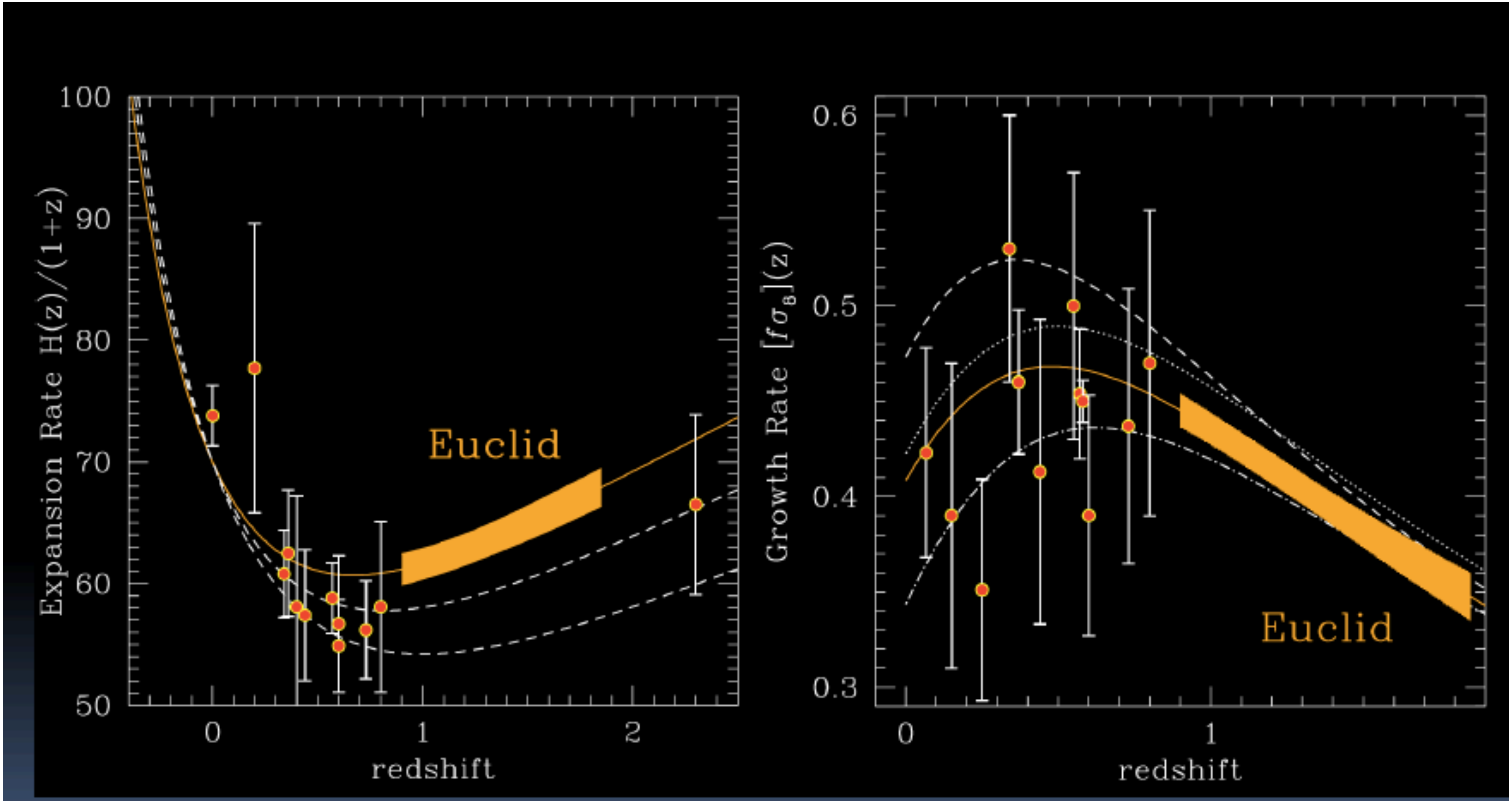
Shape measurement and photo-z's from optical an NIR data

1.5 billion galaxies over 15,000 deg^2
+shape and photo-z's



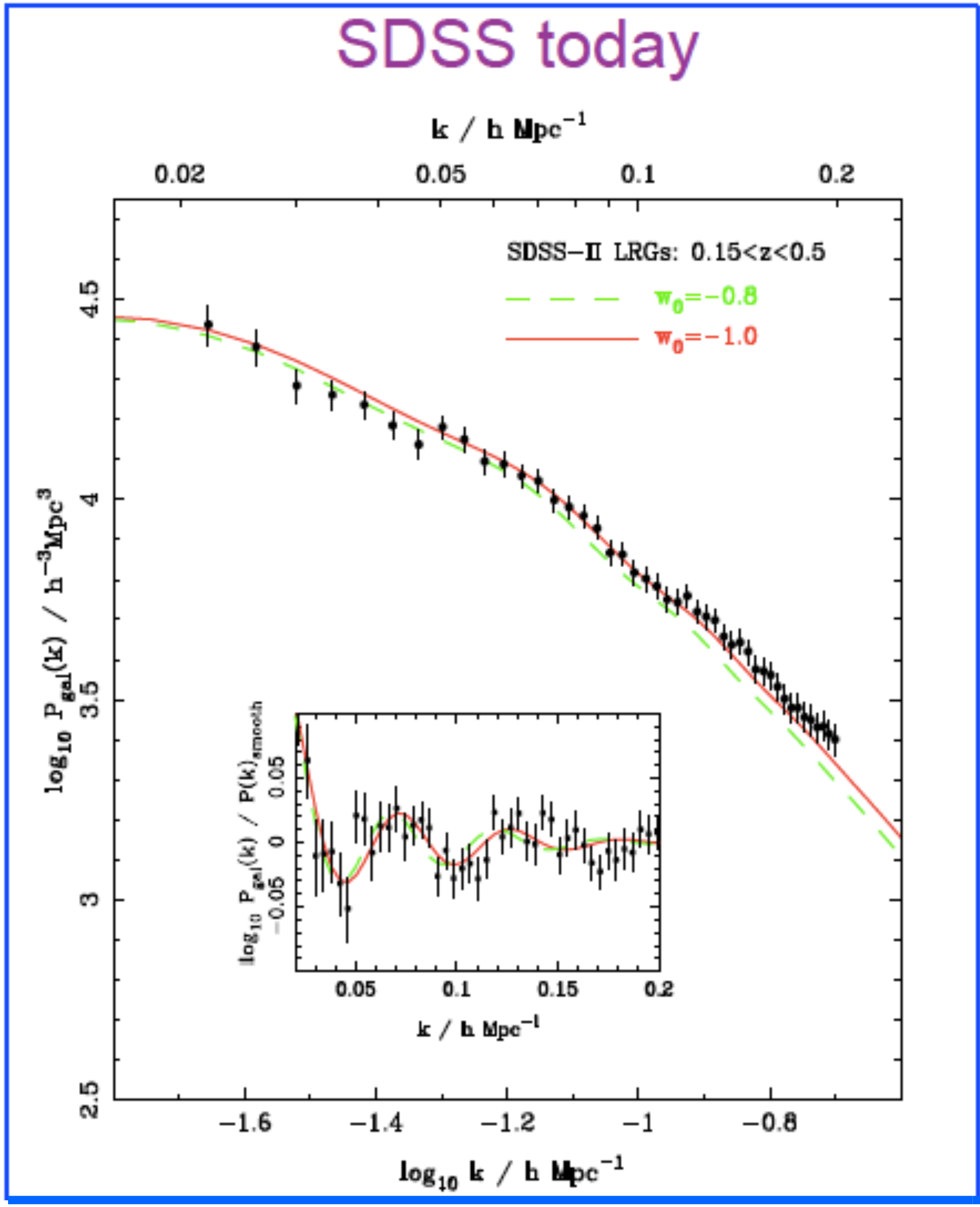
EUCLID: Exploring the DM-DE transition period

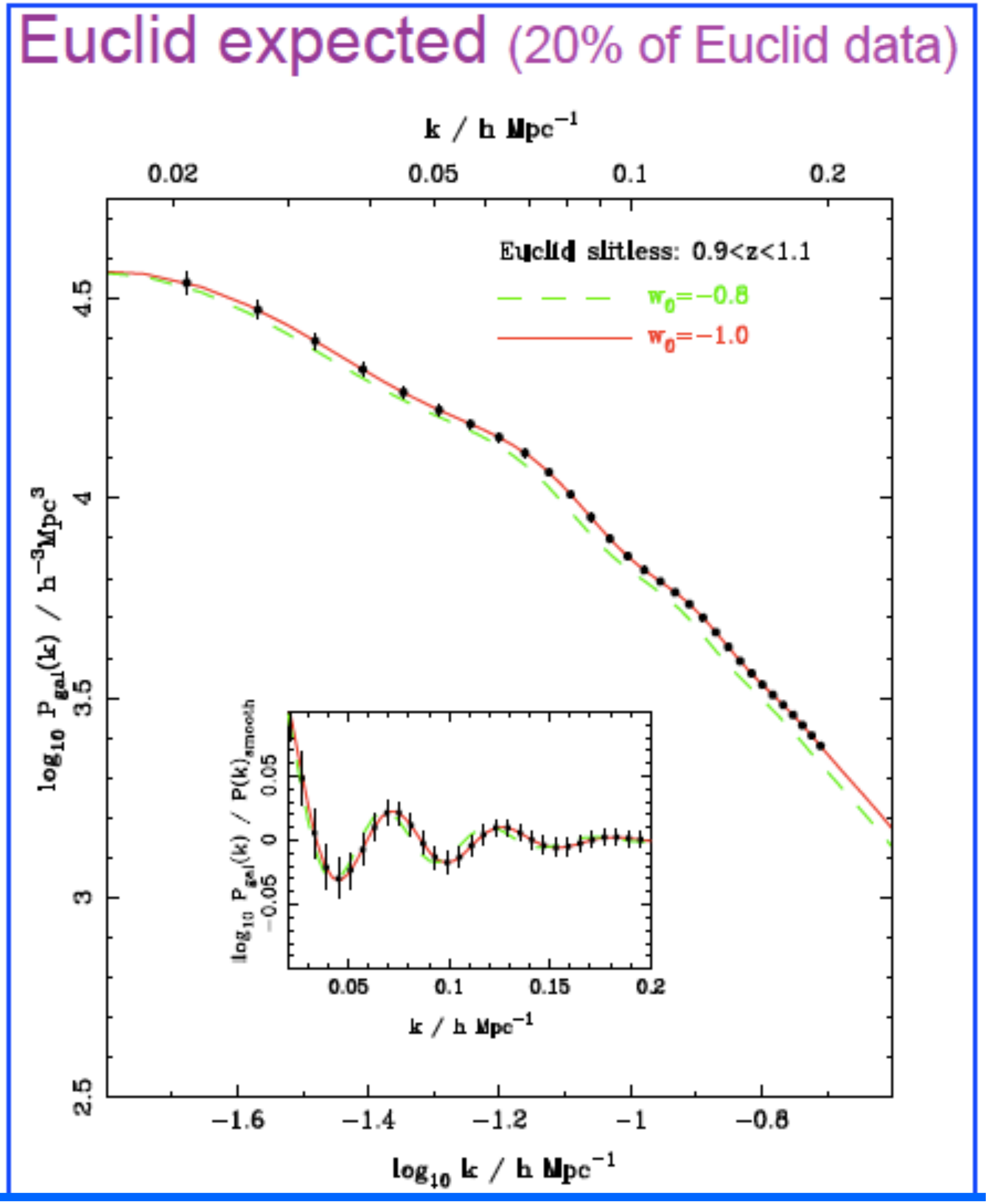
Euclid can explore the transition area with redshift survey only



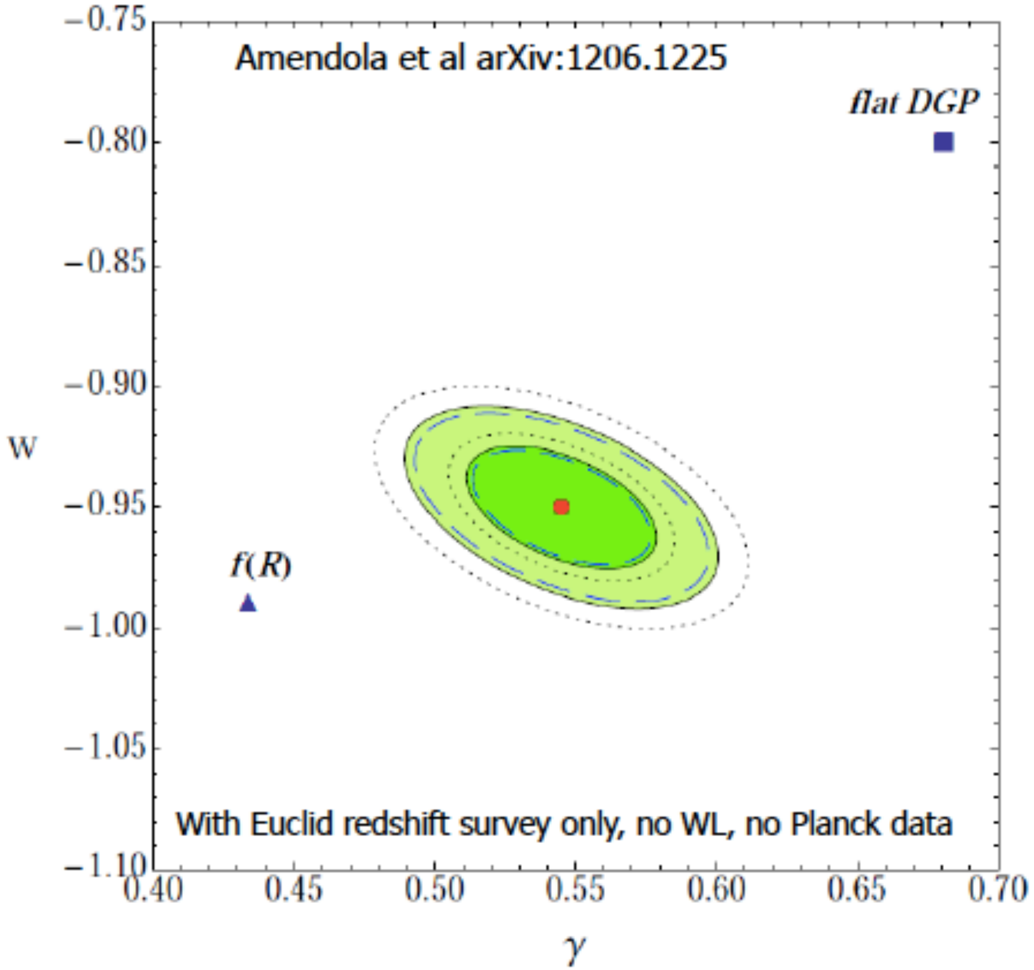
Credit: G.Guzzo

EUCLID : galaxy power spectrum





Performance using clustering only

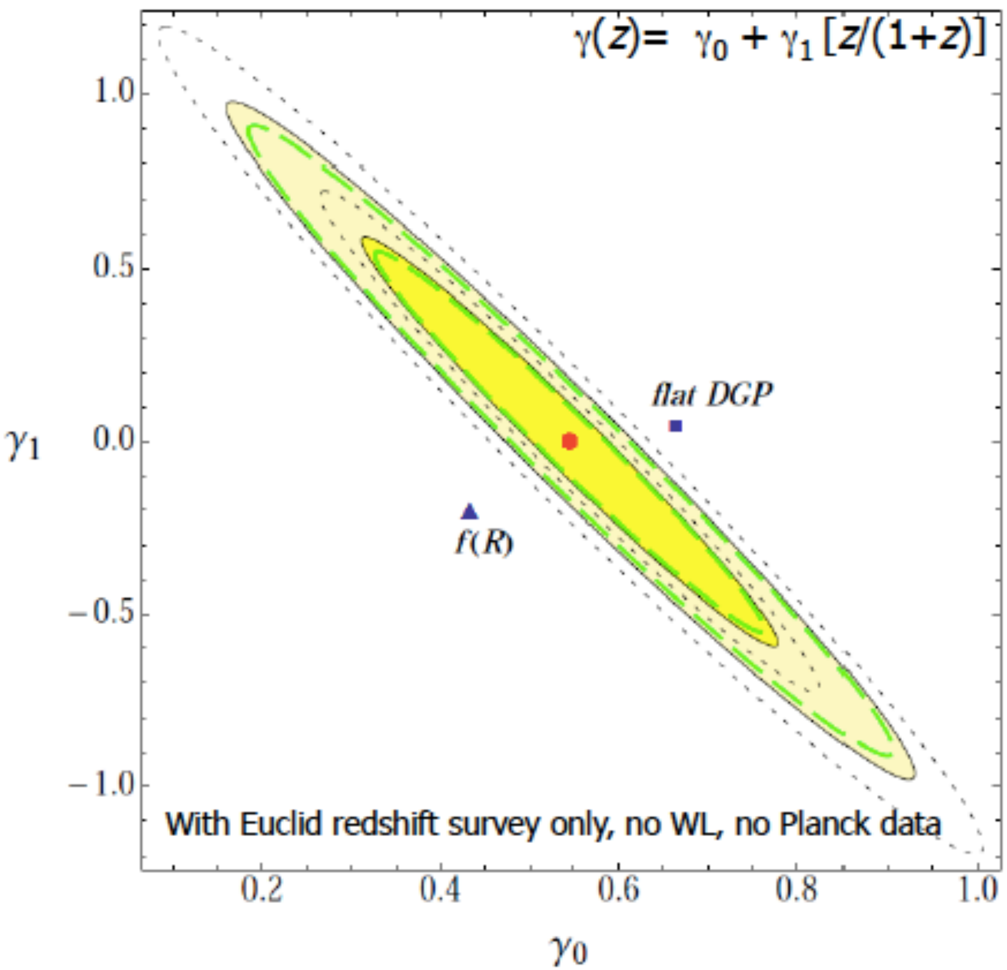


1/2−σ marginalised probability regions, constant γ and w

Reference = green regions

Optimistic = blue long-dashed ellipses

Pessimistic= black short-dashed ellipses



1−σ, 2−σ marginalised probability regions for γ_0 and γ_1

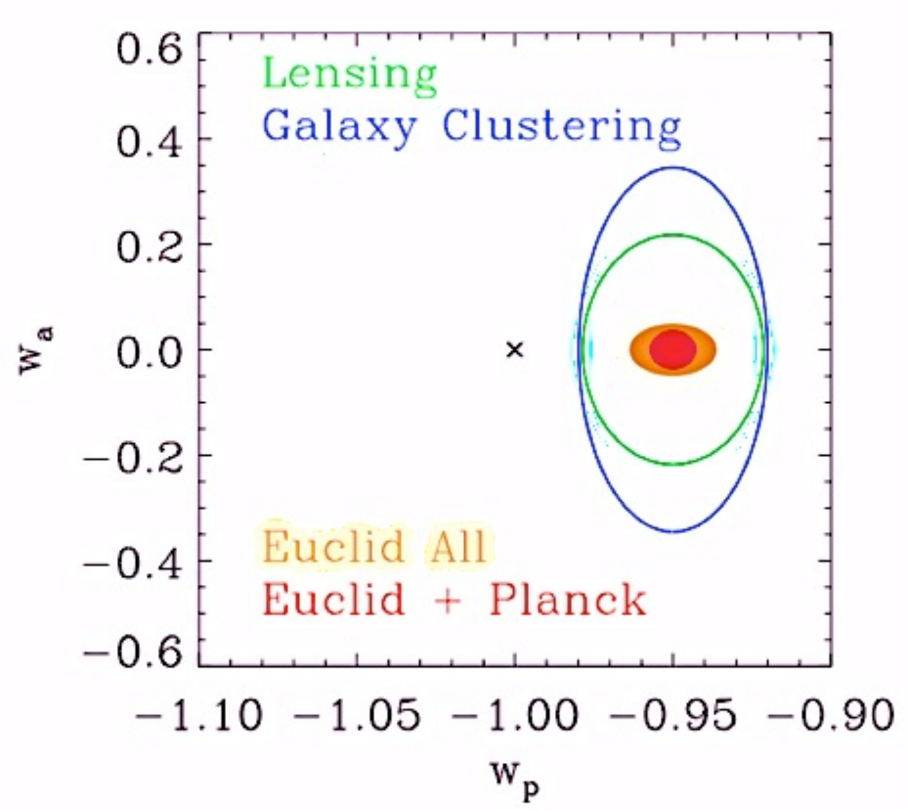
Reference = yellow regions

Optimistic = green long-dashed ellipses

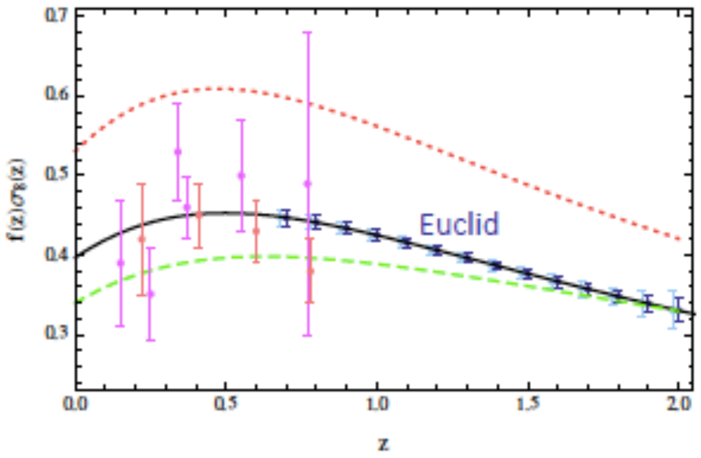
Pessimistic= black doted ellipses

Dark Energy analyses

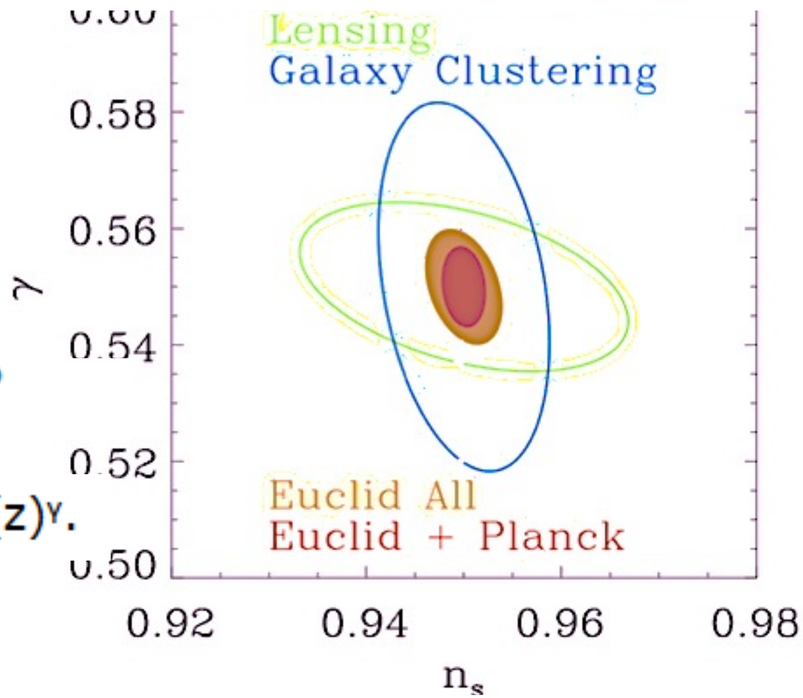
Variation in time



Growth rate



(EUCLID forecast, Majerotto et al. 2012)



$f \sim \Omega^{\gamma}$; $\gamma = 0.55$?

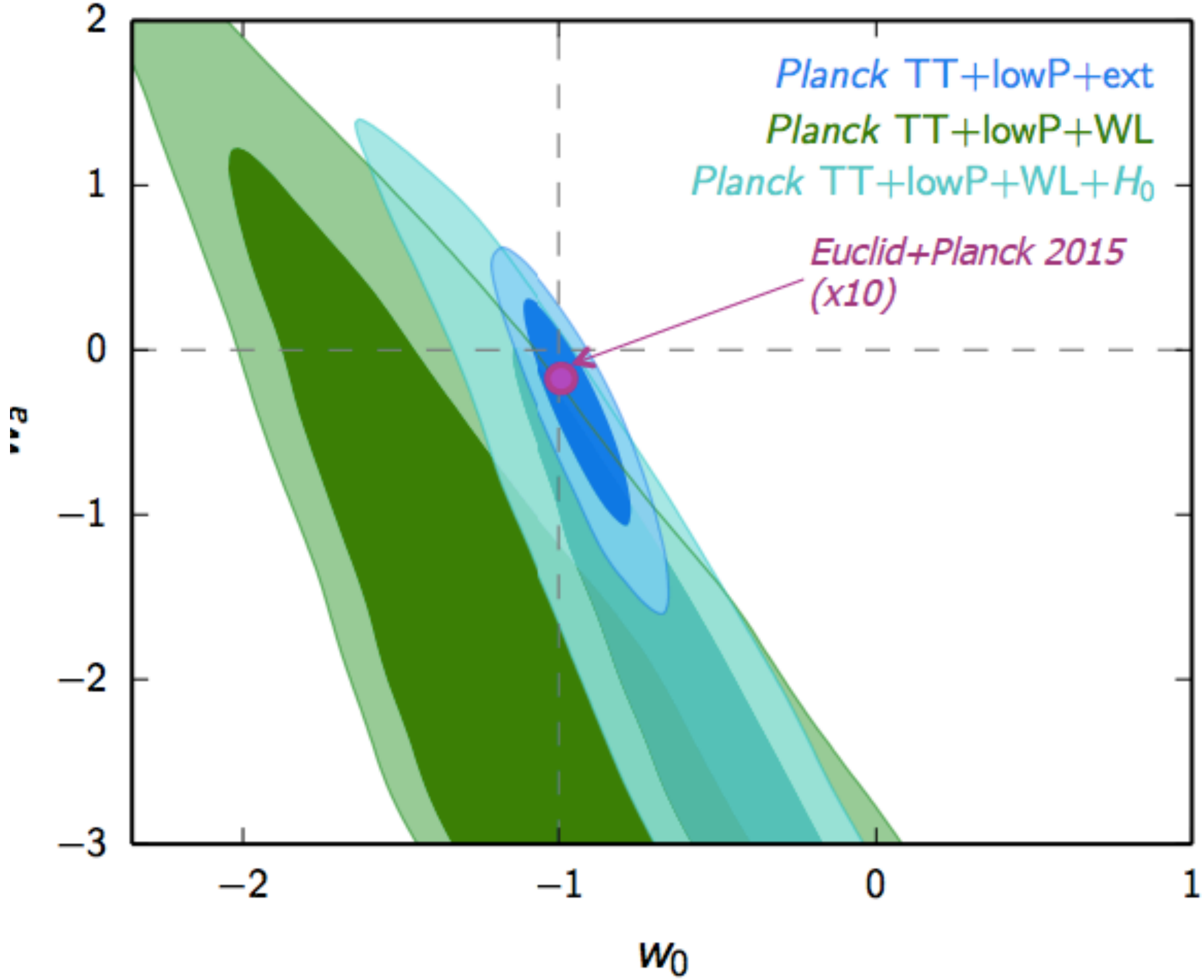
The growth rate well described by $f(z)=\Omega_m(z)^{\gamma}$.

Euclid Forecast for the Primary Program

Ref: Euclid RB arXiv:1110.3193	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_{ν} /eV	f_{NL}	w_p	w_a	FoM $= 1/(\Delta w_0 \times \Delta w_a)$
Euclid primary (WL+GC)	0.010	0.027	5.5	0.015	0.150	430
EuclidAll (clusters,ISW)	**0.009**	**0.020**	**2.0**	**0.013**	**0.048**	**1540**
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	**6000**
Current (2009)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>40**	**>400**

- DE equation of state: $P/\rho = w$, and $w(a) = w_p + w_a(a_p - a)$
- Growth rate of structure formation: $f \sim \Omega^{\gamma}$; **Assume systematic errors are under control**
- From Euclid data alone, get FoM=$1/(\Delta w_a \times \Delta w_p)$ > 400→ ~1% precision on w's.
- **Notice neutrino constraints -> minimal mass possible ~ 0.05 eV!**

Euclid Post-Planck Forecast for the Primary Program



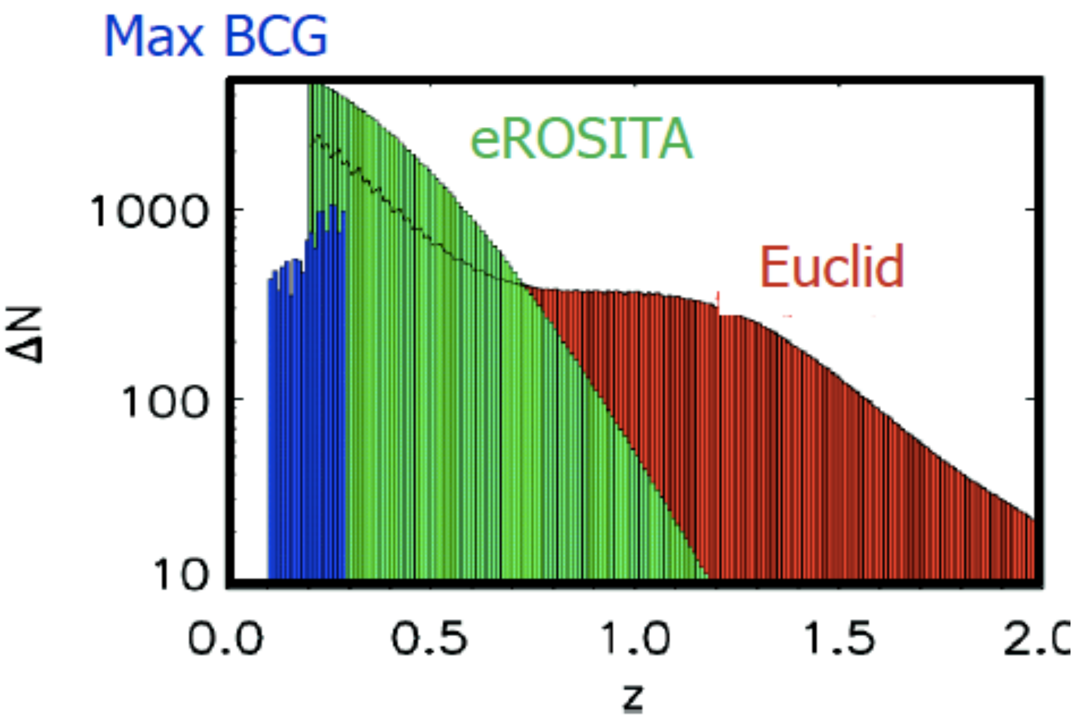
Dark Energy		
w_p	w_a	FoM $= 1/(\Delta w_0 \times \Delta w_a)$
0.015	0.150	430
0.013	**0.048**	**1540**
0.007	0.035	**6000**
0.100	**1.500**	**~10**
>10	**>40**	**>400**

DE equation of state: $P/\rho = w$, and $w(a) = w_p + w_a(a_p - a)$

From Euclid data alone, get FoM=$1/(\Delta w_a \times \Delta w_p)$ > 400→ ~1% precision on w's.

Clusters of galaxies

- Probe of peaks in density distribution
- Nb density of high mass, high redshift clusters very sensitive to
  - primordial non-Gaussianity and
  - deviations from standard DE models
- Euclid data will get for free:
  - Λ-CDM: all clusters with M>2 .10^{14} Msol detected at 3-σ up to z=2
    - → 60,000 clusters with 0.2<*z*<2 ,
    - → 1.8 10^4 clusters at *z* > 1.
  - ~ 5000 giant gravitational arcs
    - → accurate masses for the whole sample of clusters
    - → dark matter density profiles on scales >100 kpc

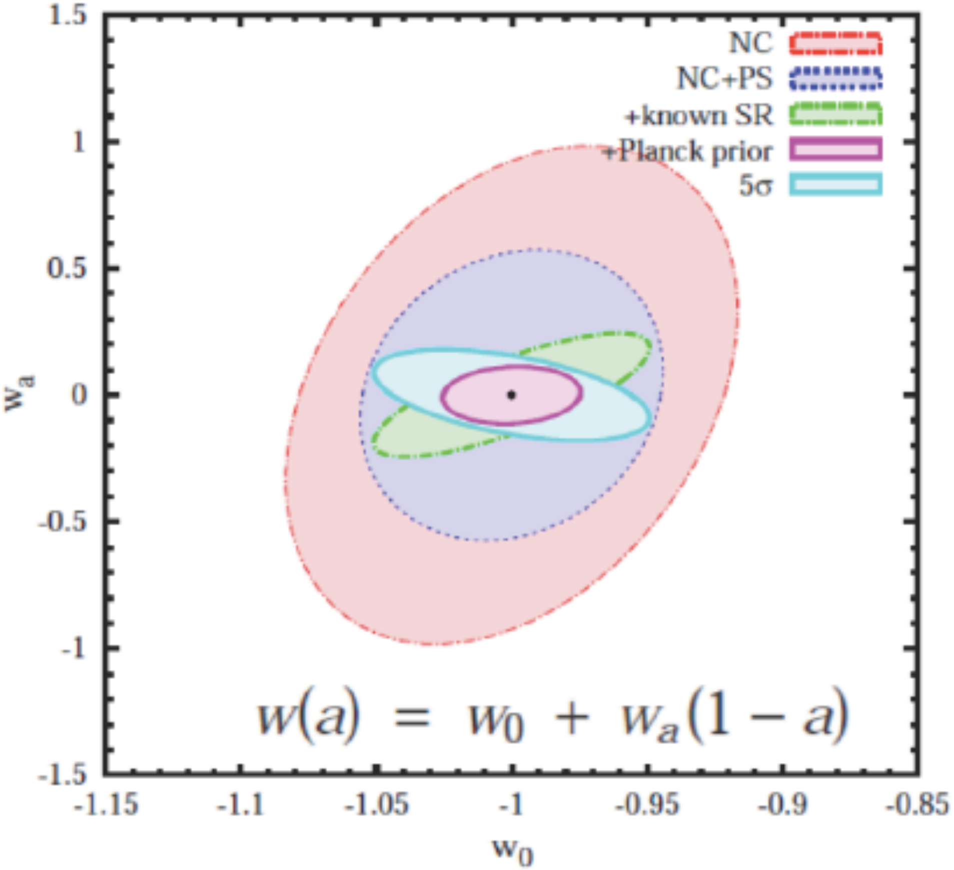


→ Synergy with Planck and eROSITA

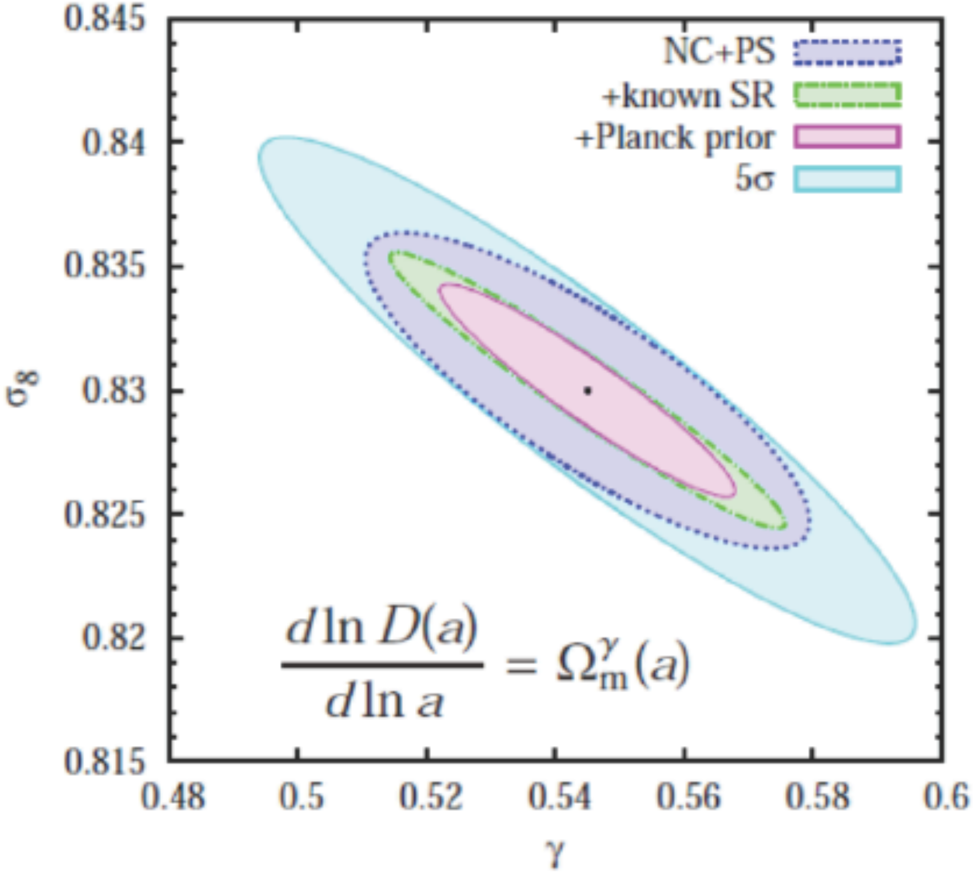
Cosmology with clusters of galaxies in Euclid

important probe for Dark energy!

Constraints on homogeneous dark energy



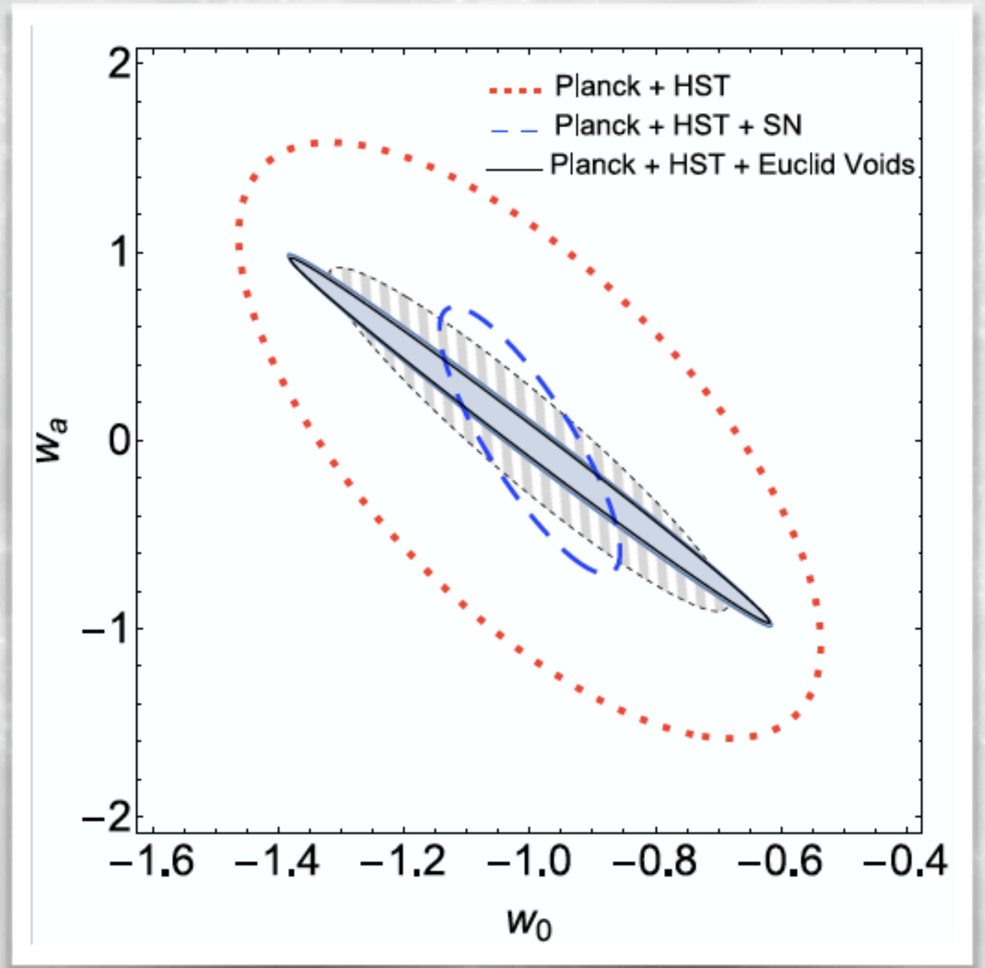
Constraints on fluctuations and growth rate



Sartoris et al. 2015 arXiv:1505.02165

NC: Cluster Number counts ; **PS**: Cluster Power Spectrum, **SR**: Cluster Scaling Relation

Cosmology with voids in Euclid

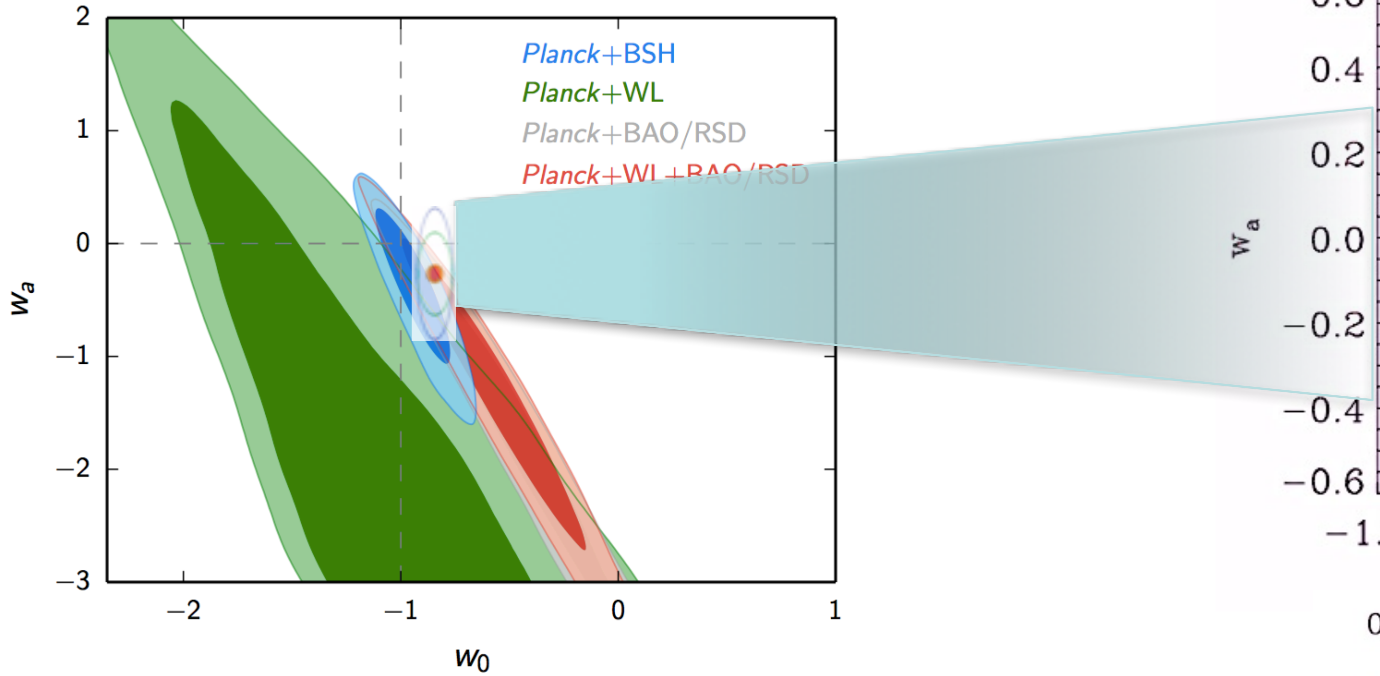


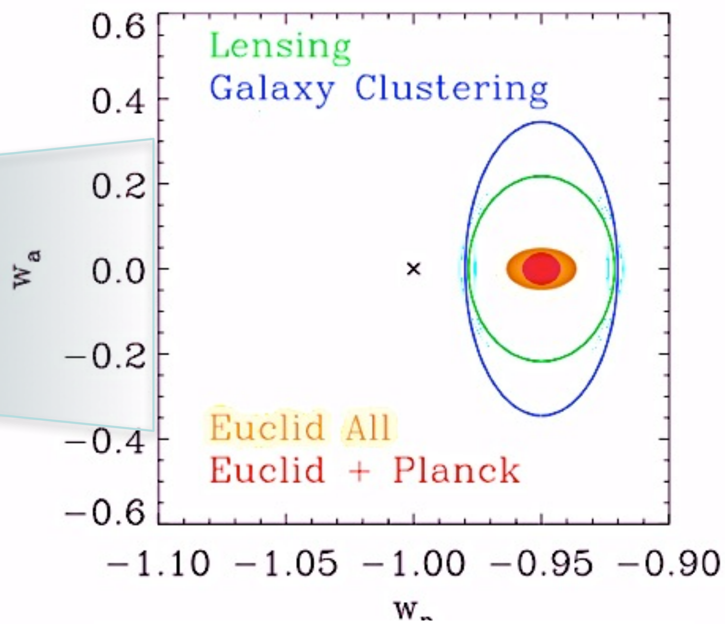
Pisani et al. 2015 (Phys. Rev. D; arXiv:1503.07690)

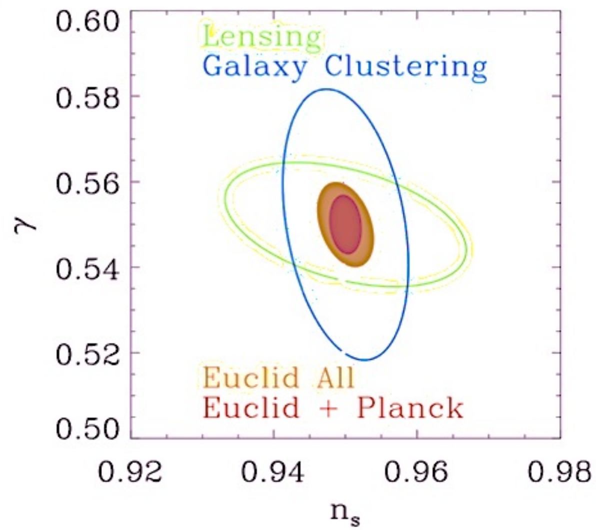
We expect 1 Million of voids !

Need to combine all probes....

Planck coll 2015.

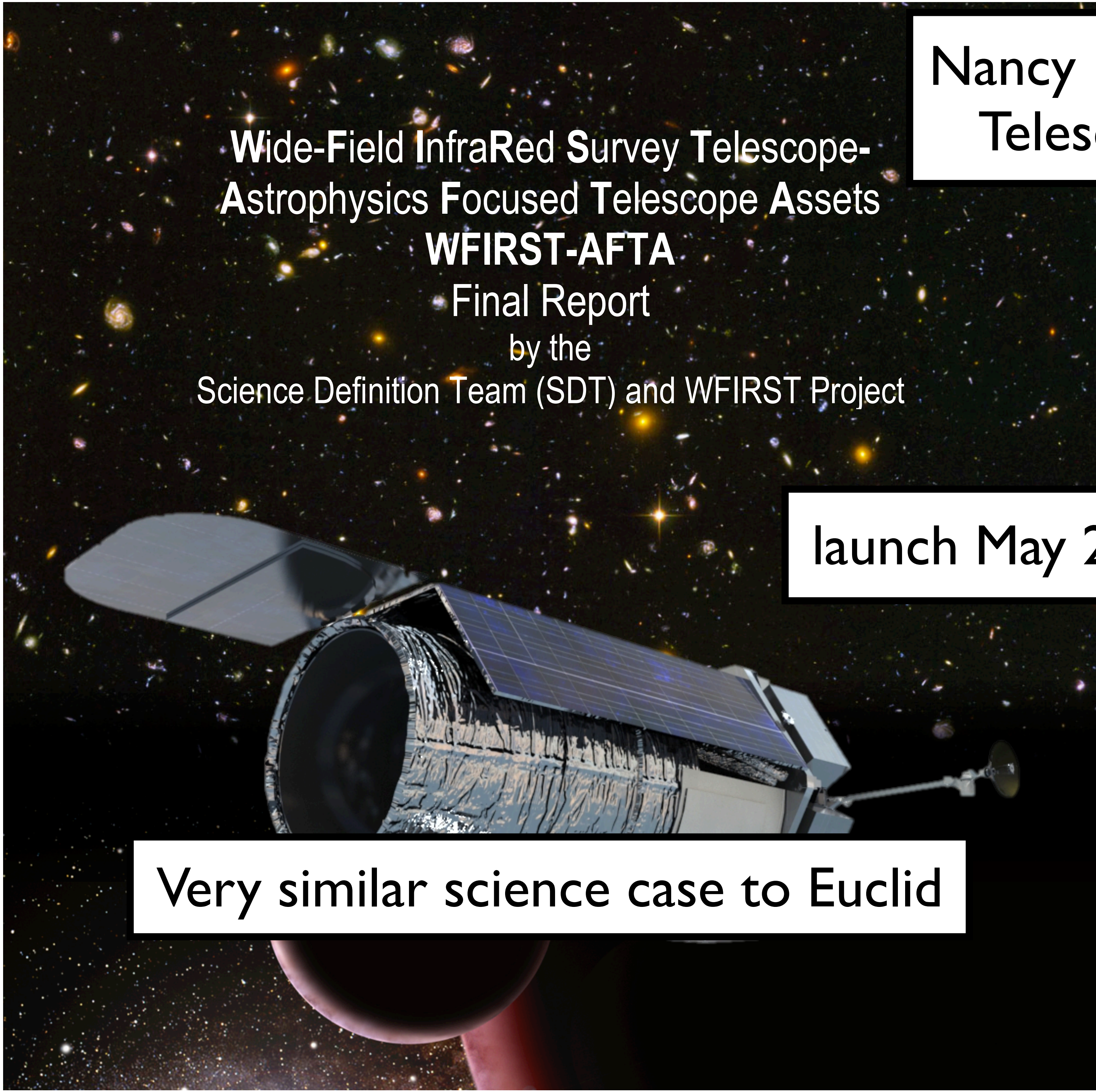






$f \sim \Omega^{\gamma}$; $\gamma = 0.55$?

The growth rate well described by $f(z)=\Omega_m(z)^{\gamma}$.

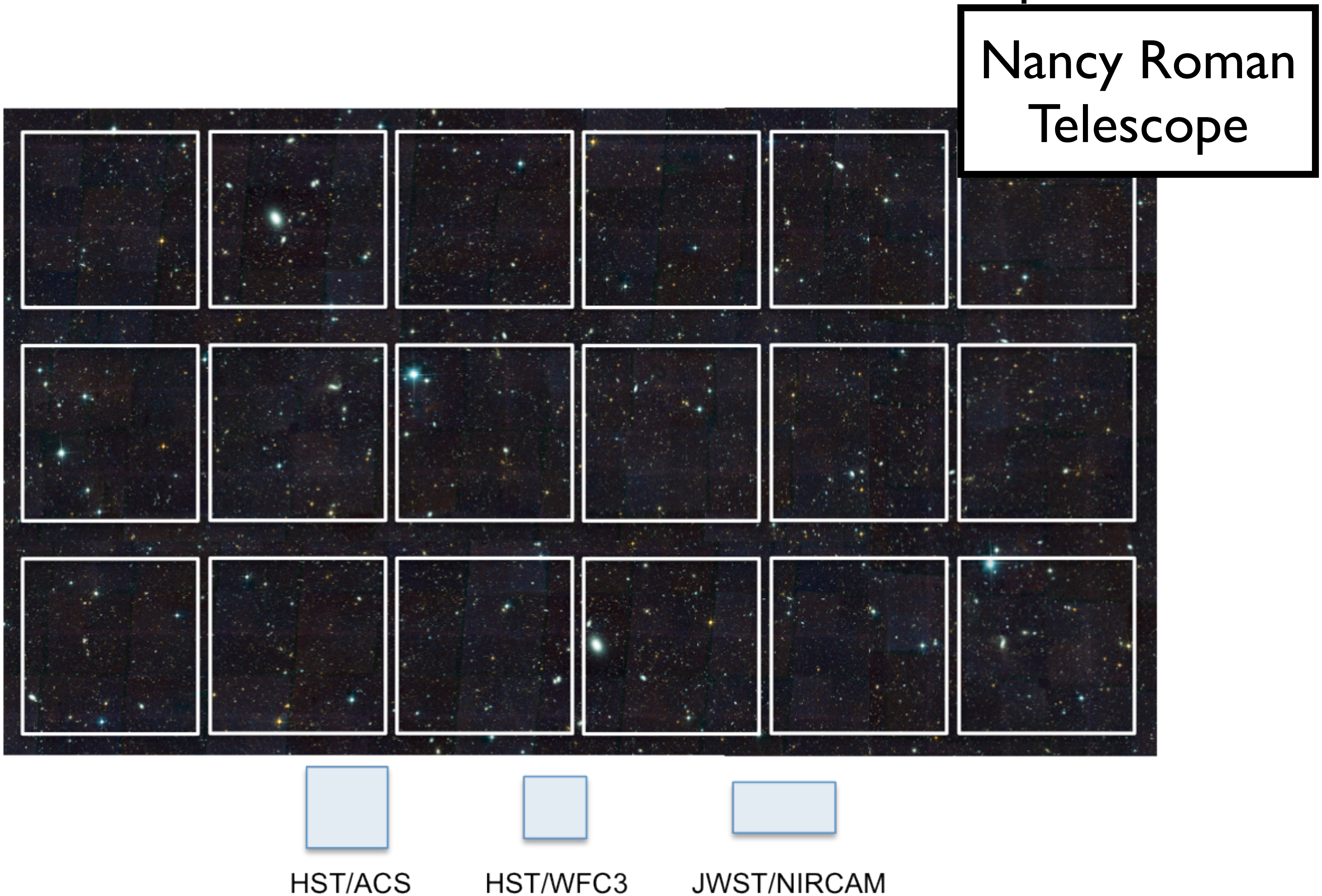


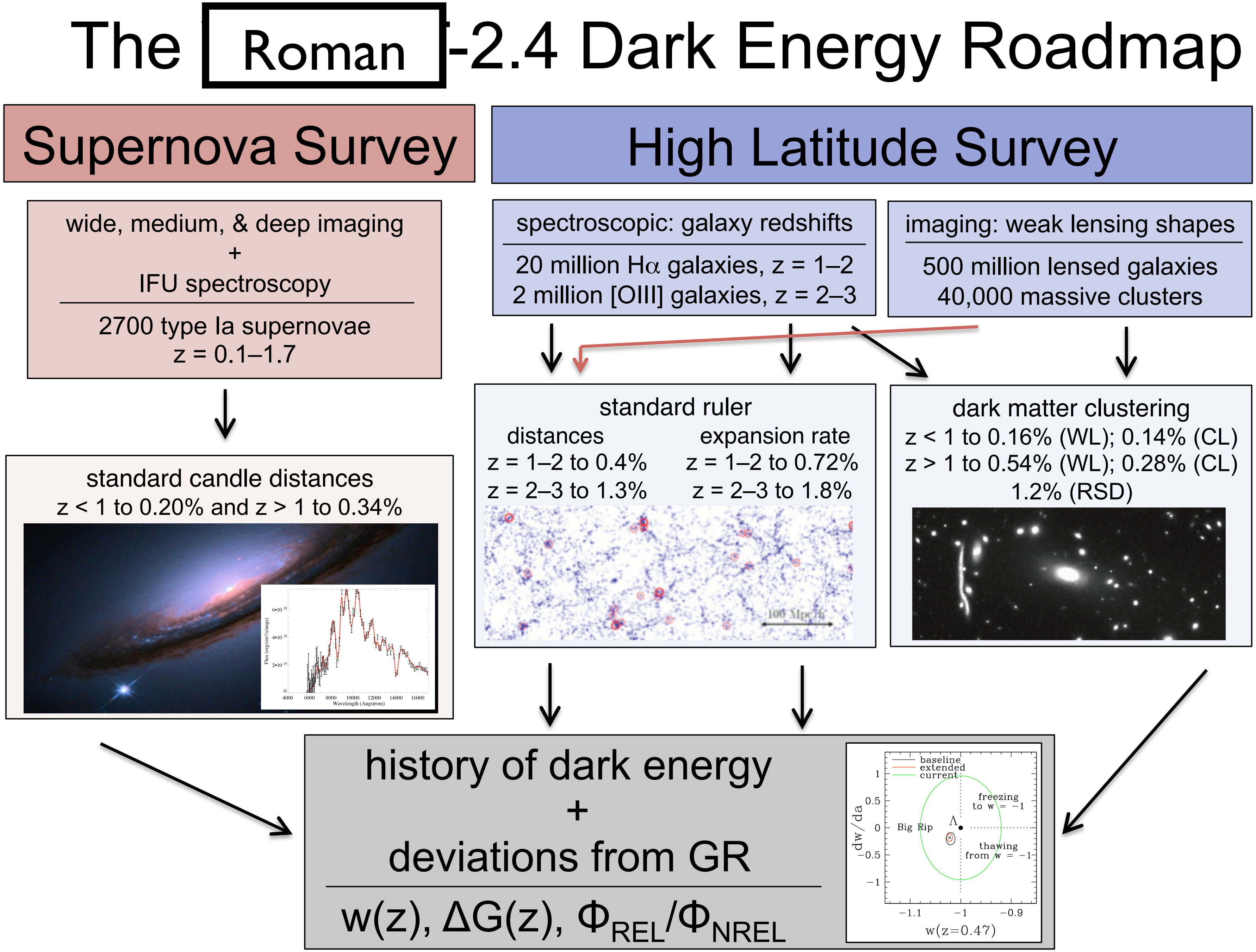
Nancy Roman Telescope

launch May 2027?

Very similar science case to Euclid

WFIRST Wide-Area Field of View from Space




The Roman -2.4 Dark Energy Roadmap
Supernova Survey
High Latitude Survey
wide, medium, & deep imaging
+
IFU spectroscopy
2700 type Ia supernovae
z = 0.1–1.7
spectroscopic: galaxy redshifts
20 million Hα galaxies, z = 1–2
2 million [OIII] galaxies, z = 2–3
imaging: weak lensing shapes
500 million lensed galaxies
40,000 massive clusters
standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%
standard ruler
distances
z = 1–2 to 0.4%
z = 2–3 to 1.3%
expansion rate
z = 1–2 to 0.72%
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), ΔG(z), Φ_REL/Φ_NREL
baseline
extended
current
freezing to w = −1
Big Rip
Λ
thawing from w = −1
dw/da
w(z=0.47)

Roman Figure of Merit

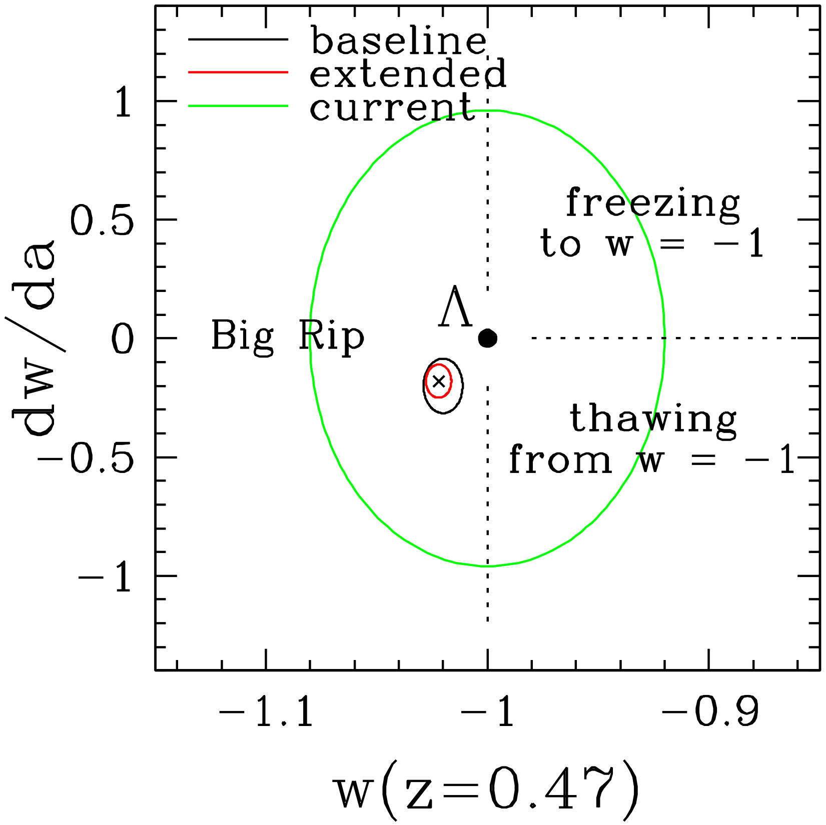
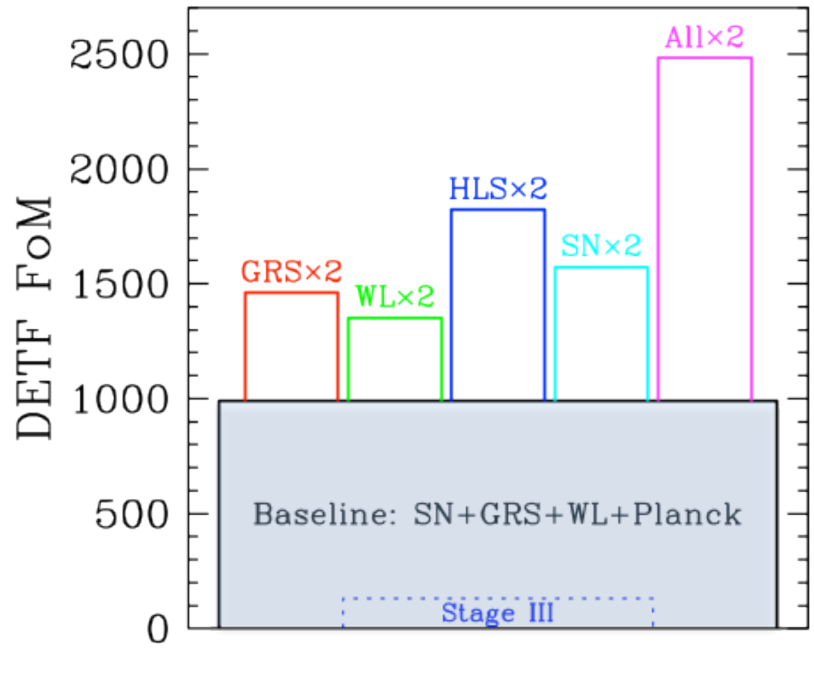
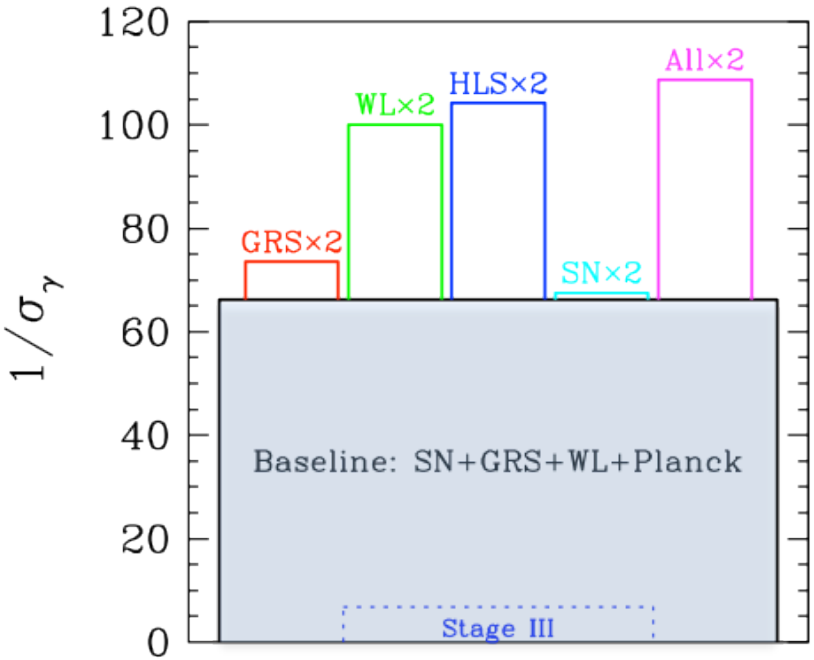


Figure 2-7: $\Delta\chi^2 = 1$ error ellipses on the value of the dark energy equation-of-state parameter w at redshift z = 0.47 (the redshift at which it is best determined by WFIRST-2.4) and its derivative with respect to expansion factor dw/da. The green ellipse, centered here on the cosmological 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-



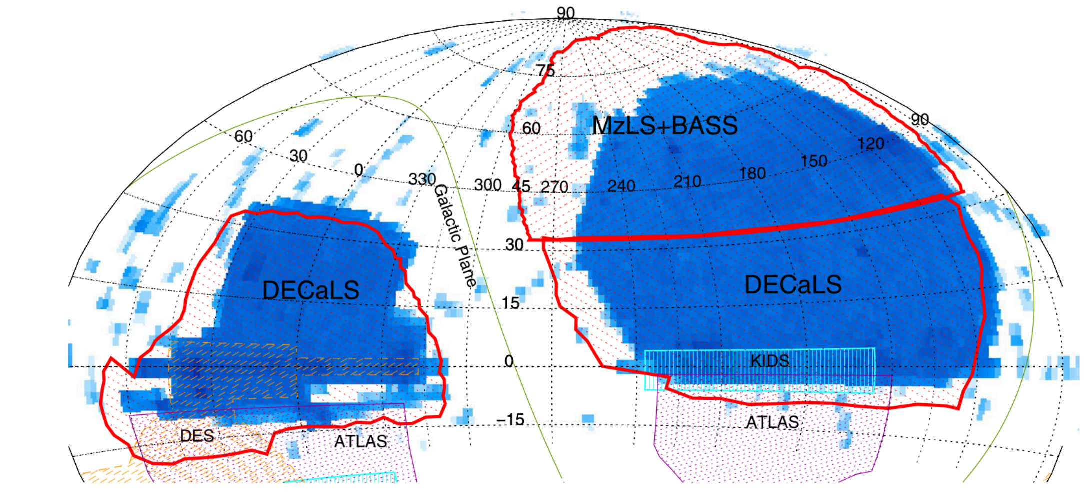


DESI Survey

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

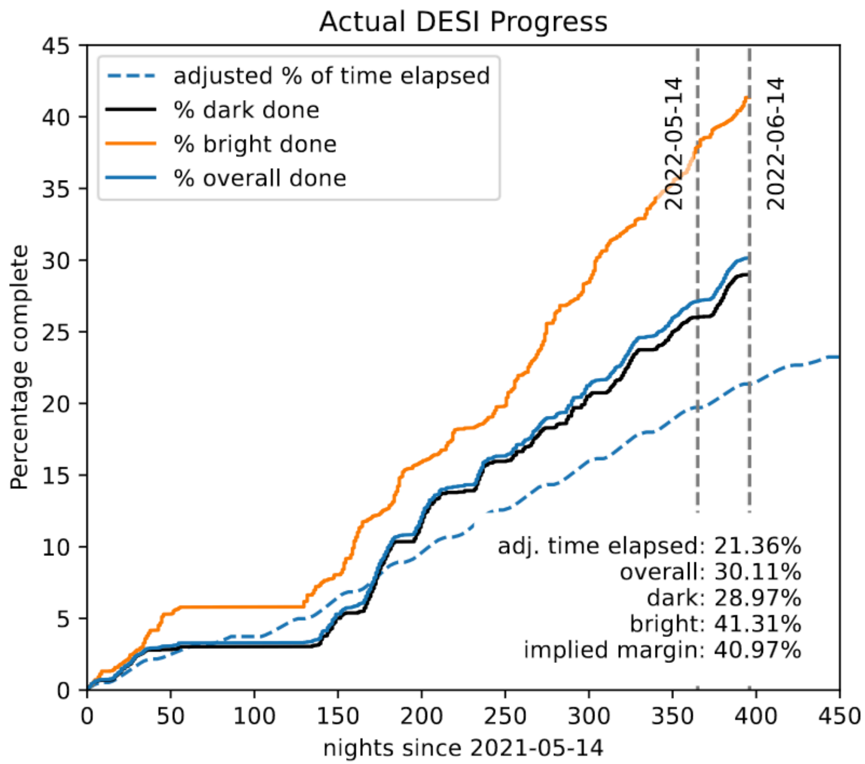
5000 redshifts per mask

Map galaxies and QSO redshifts and positions over 16000 deg^2 area



Dey+2018

Redshifts acquired slowly

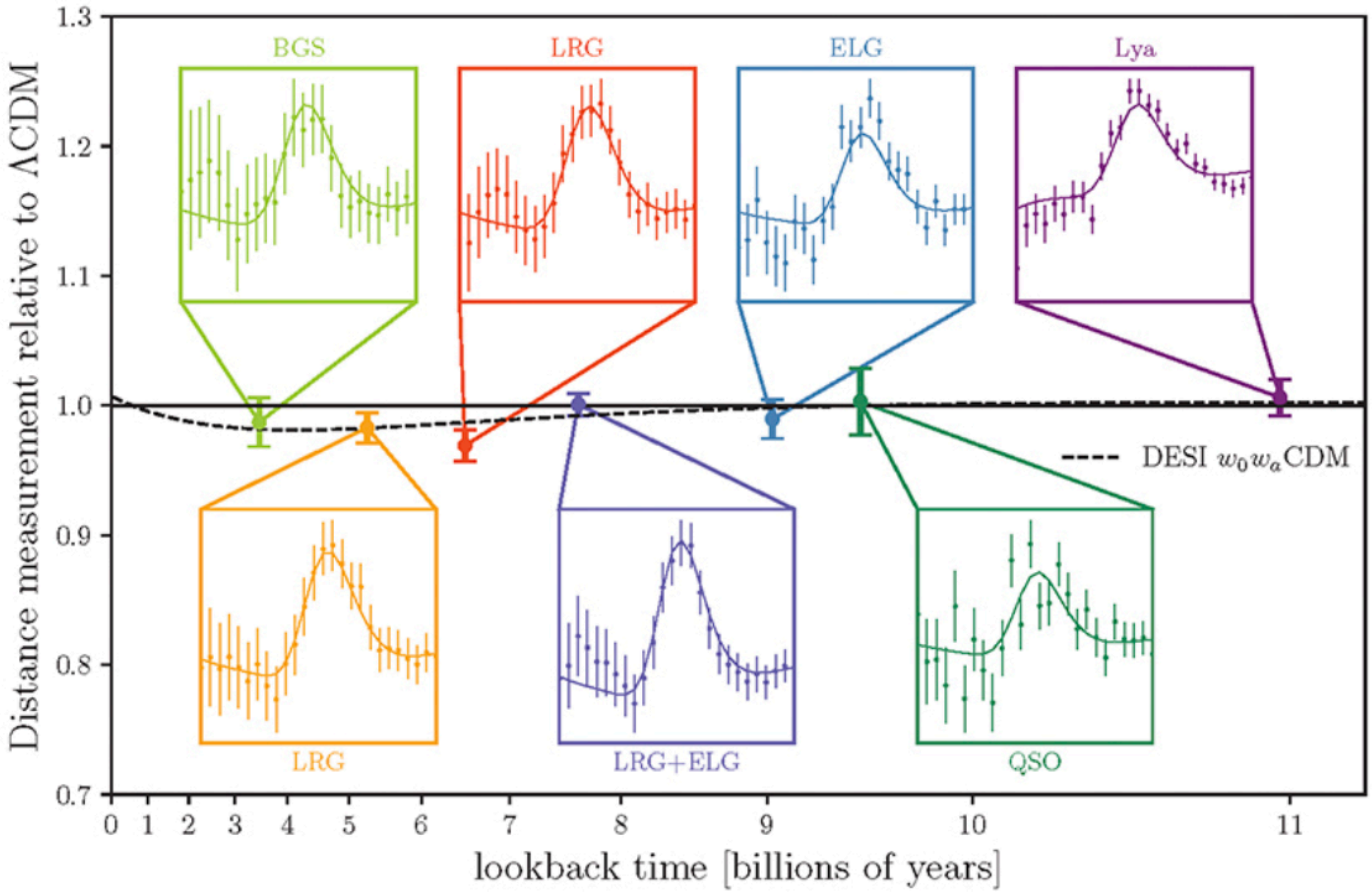


Schafsky + 2022

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

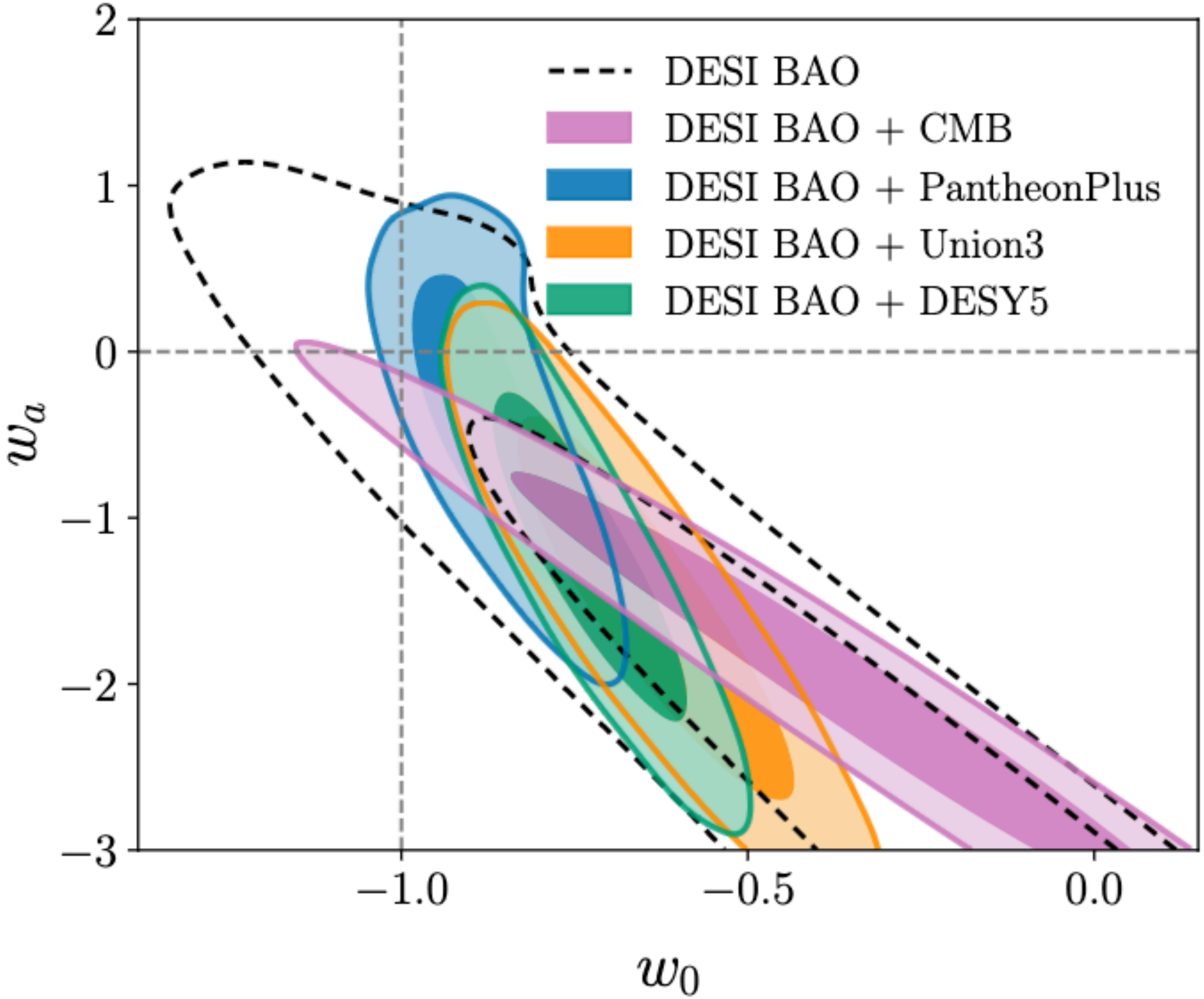


Should give 1 if dark energy is cosmological constant

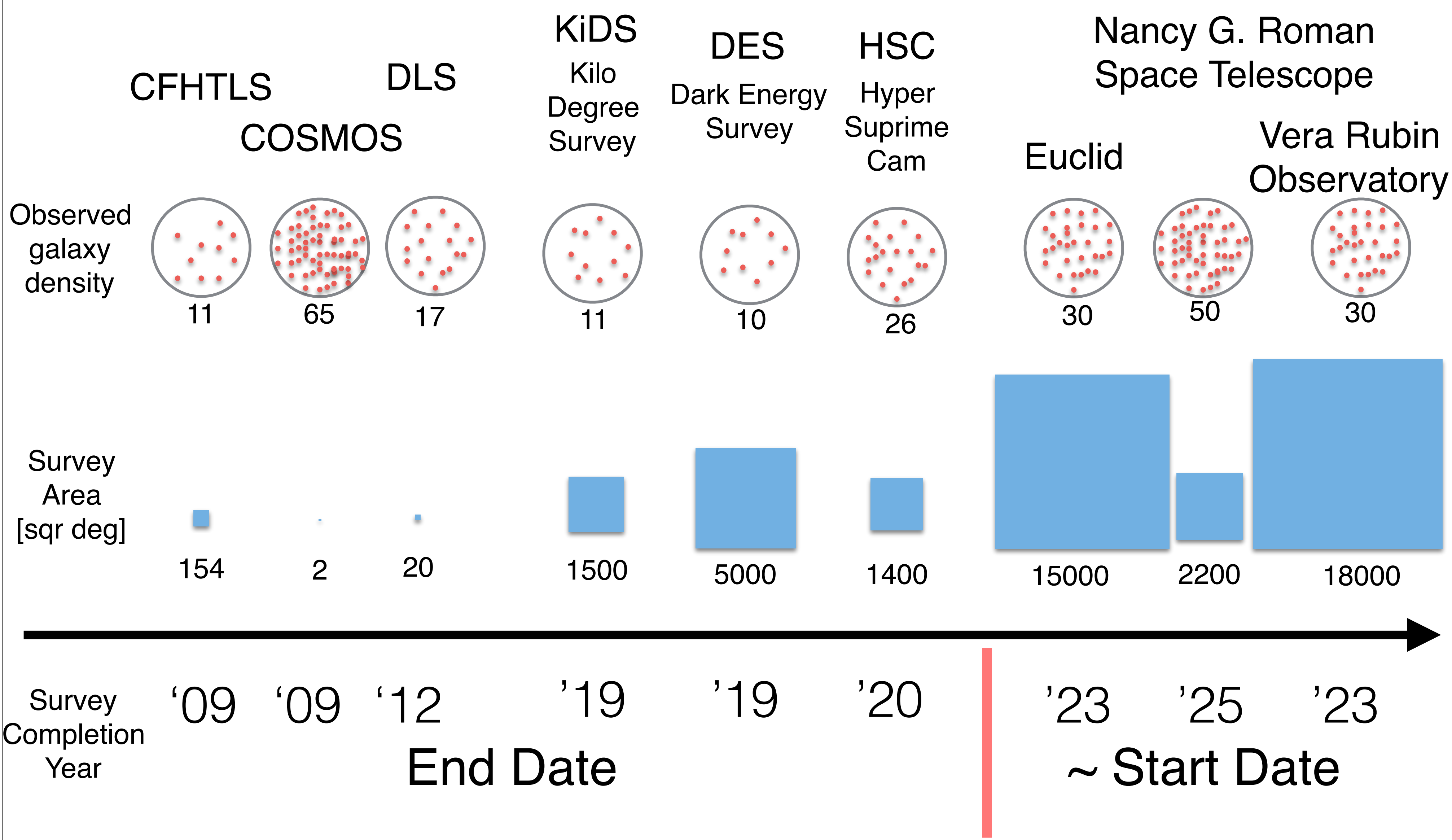
DESI Survey

First Year Results

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



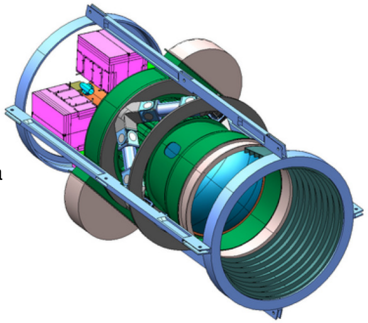
Photometric Dark Energy Surveys



Credit: Krause

KIDS / DES

- ground based imaging survey at CTIO 4m telescope of Southern region (SZE-survey overlap)
- camera: 520Mpix, 2.2deg^2 FoV
- start: next year
- 5,000deg^2 in 4bands: g r i z
- DE probes: GC, BAOs, WL, SNIa
- objects: galaxies, galaxy clusters (with photometric redshifts)
- redshift range: 0<z<1.3
- DE constraints: σ_w~5-15%



Source: http://www.darkenergysurvey.org/

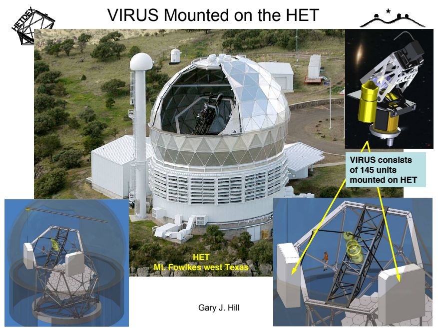
Dome and Facility Design

VERA C. RUBIN OBSERVATORY

Nancy Roman Telescope

The Hobby-Eberly Telescope
Dark Energy Experiment

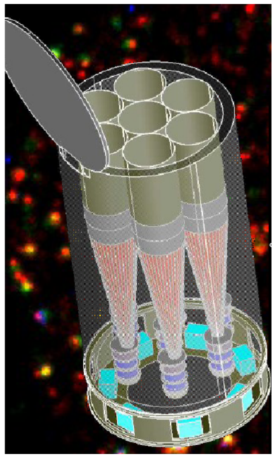
VIRUS Mounted on the HET



eRosita X-ray Telescope

c)

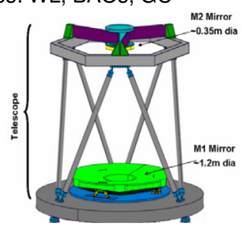
- space-based X-ray cluster survey
- currently build at MPE in Garching
- start: 2012
- all sky coverage
- DE probes: GC, BAOs
- objects: 100,000 galaxy clusters
- redshift range: 0<z<1.5
- DE constraints: σ_w~5%
- requires large ground-based follow-up program for identification and redshifts



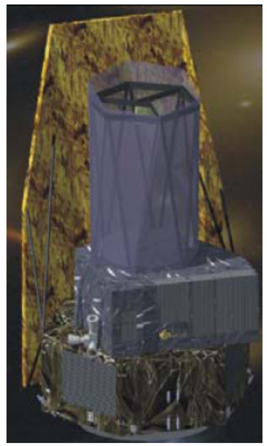
Euclid Telescope

d) E ... on

- space-based optical/NIR imaging and spectroscopy survey
- 20,000deg^2 extragalactic survey
- start: >2016
- DE probes: WL, BAOs, GC
- σ_w~2%



similar mission plans in US for JDEM, (Joint Dark Energy Mission) likely with a stronger focus on SN Ia



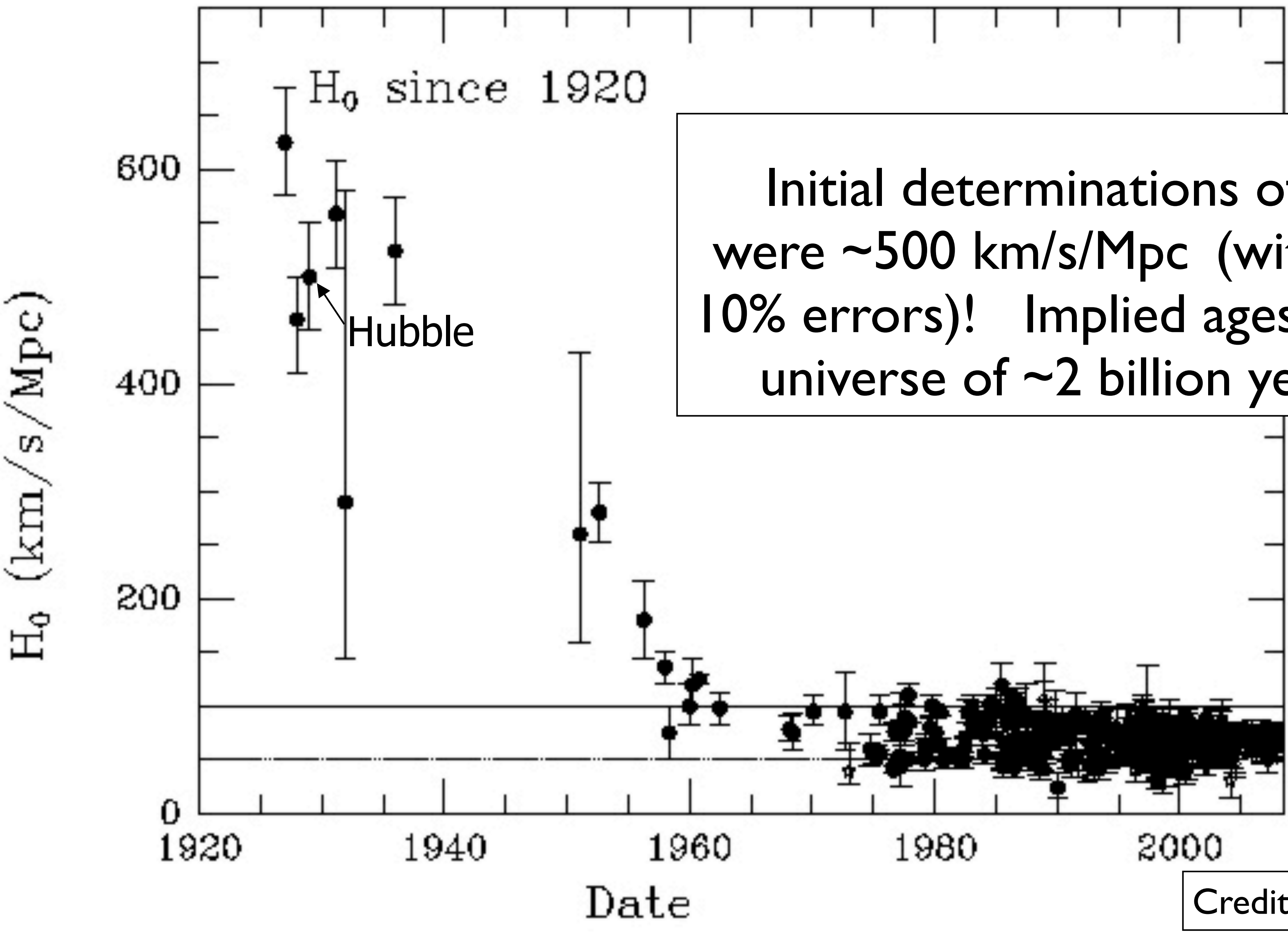
Source: M. Schweitzer (MPE)

Unsolved Tensions between Different Probes Trying to Measure the Cosmological Parameters

Focus on

H_0 = Hubble Constant

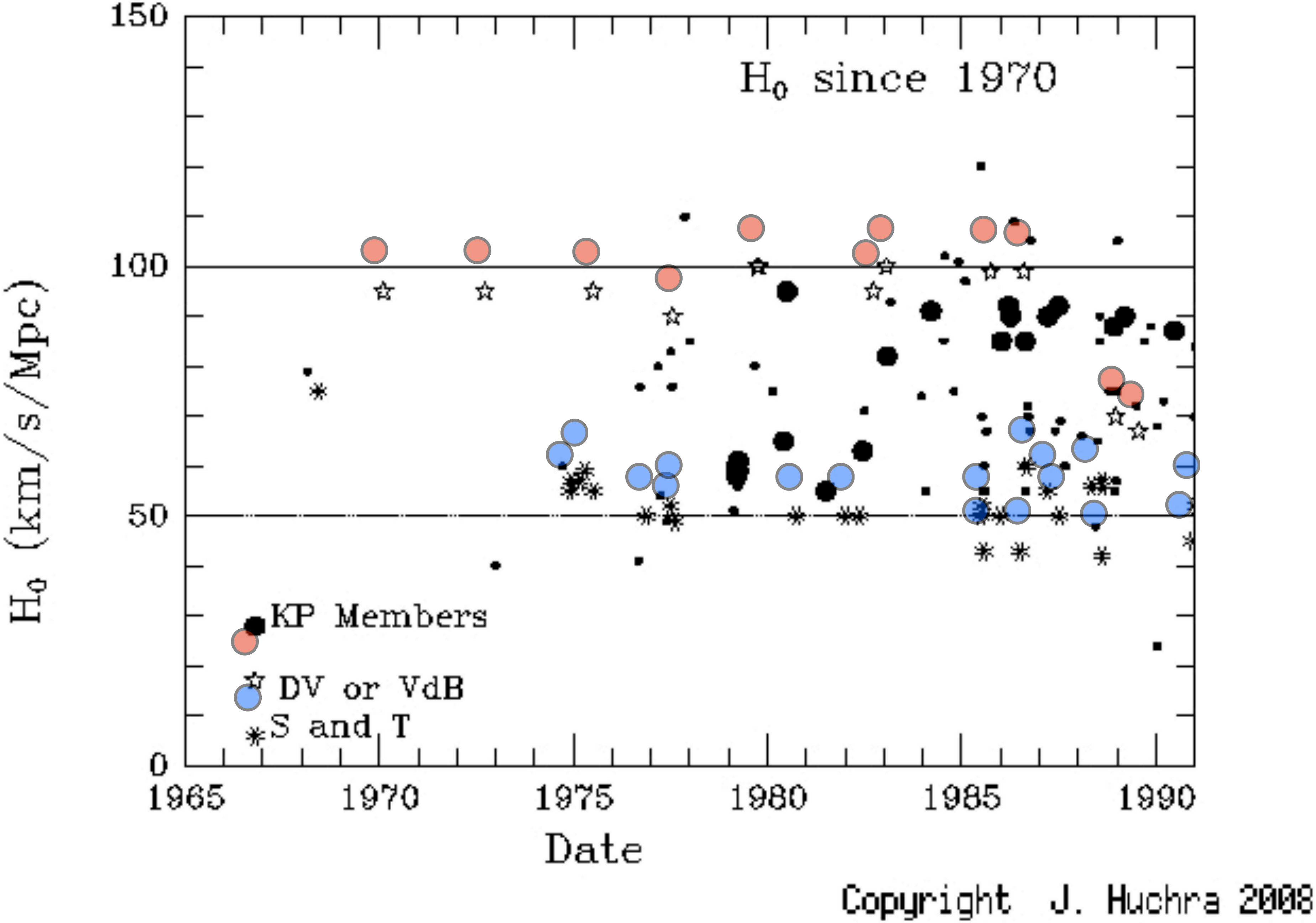
Hubble constant determinations vs. time (from Lecture 2)



Initial determinations of H_0 were ~500 km/s/Mpc (with just 10% errors)! Implied ages of the universe of ~2 billion years!

Credit: J. Huchra

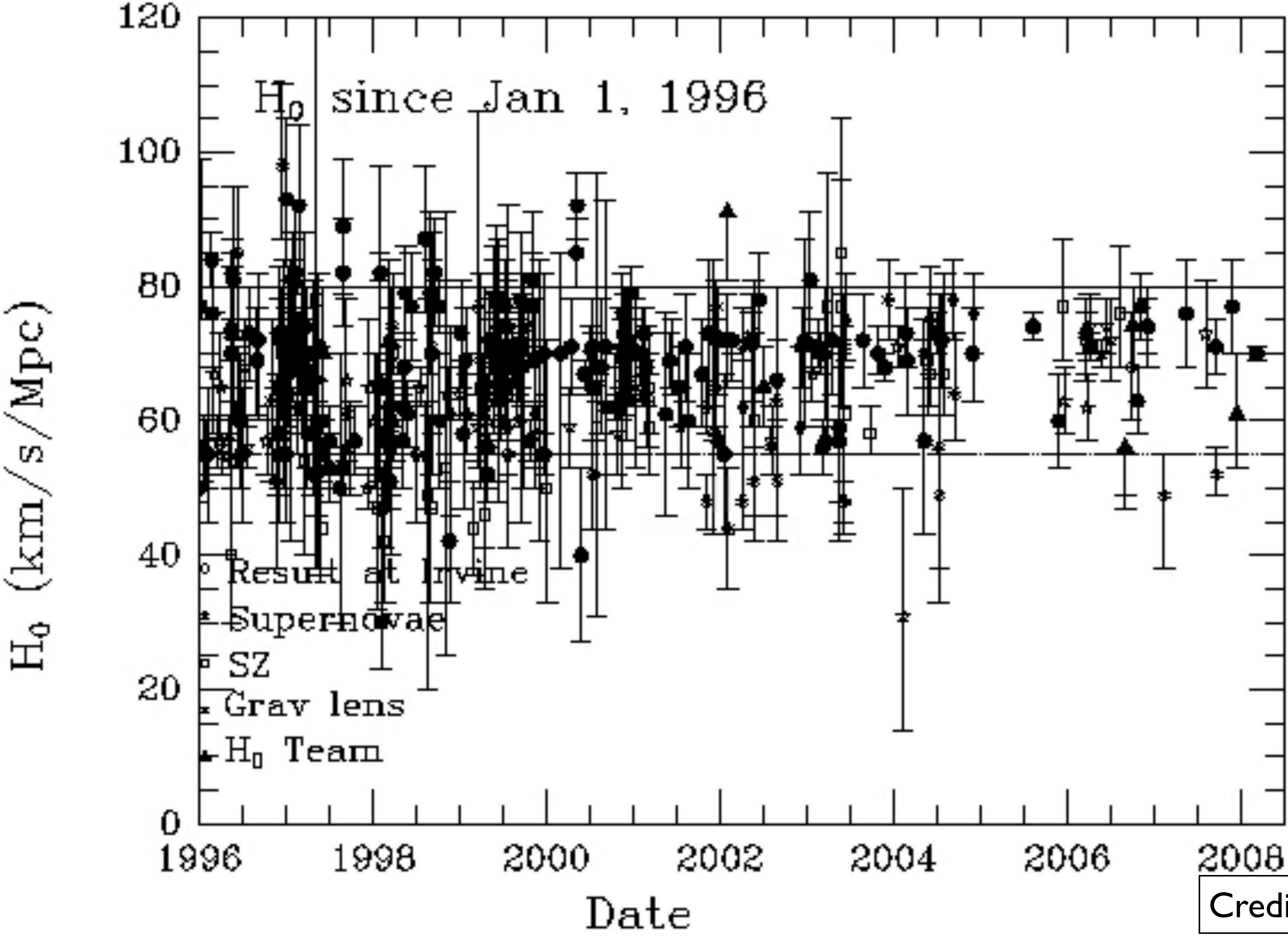
Hubble constant determinations vs. time (from Lecture 2)



Hubble constant determinations vs. time

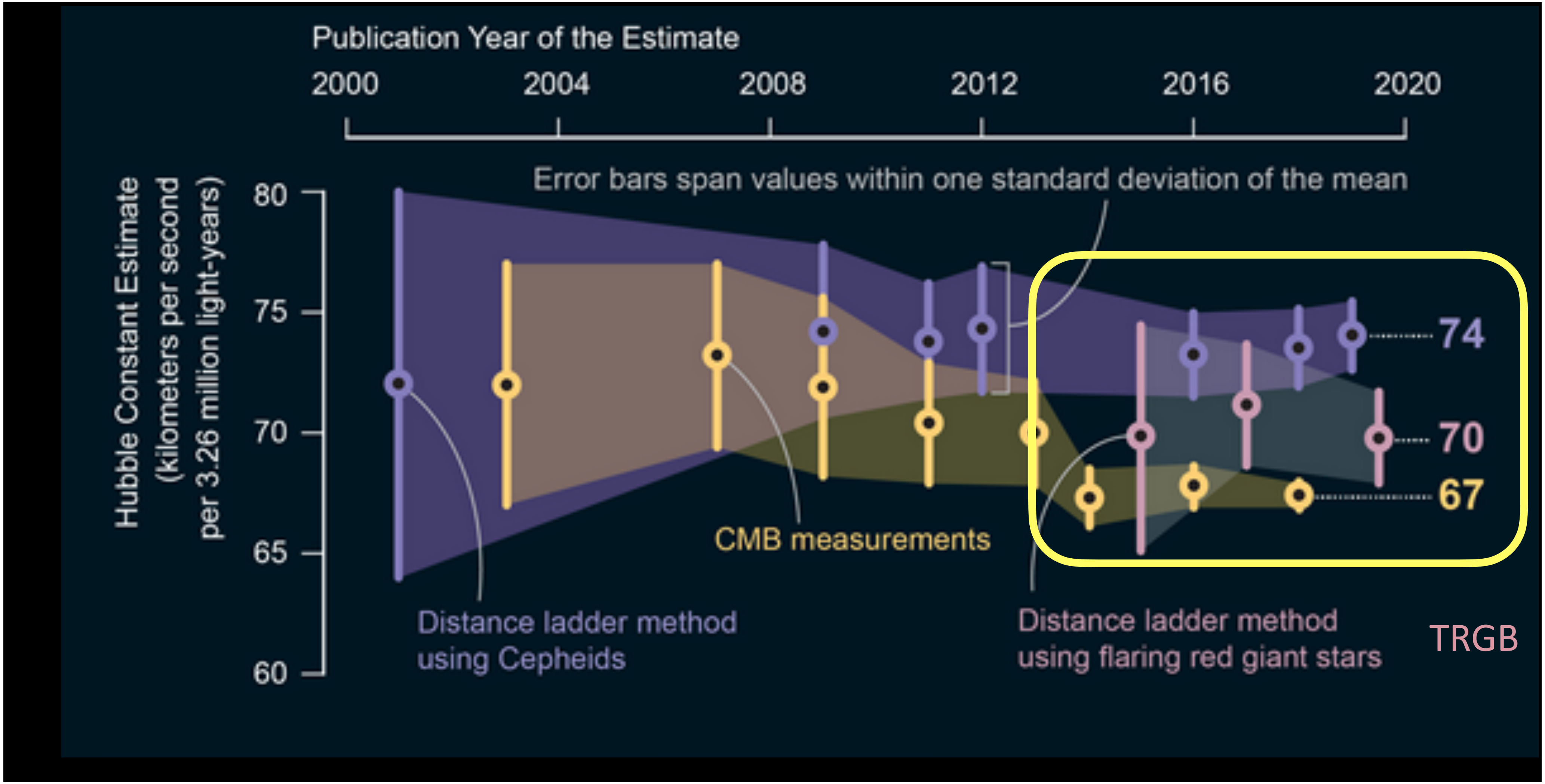
(after observations began with Hubble Space Telescope)

(from Lecture 2)



Credit: J. Huchra

Hubble constant determinations vs. time



An apparent discrepancy has arisen between the value of the Hubble constant derived from nearby studies using a Cepheid distance ladder

and that measured from the CMB (particularly Planck)

H_0 tension

Riess etal (2019):

H_0 = 74.03 ± 1.42 km/s/Mpc

(1.9% measurement)

Planck (2019):

H_0 = 67.44 ± 0.58 km/s/Mpc

(0.9% measurement)

Discrepant by 6.59 km/s/Mpc

(≈ 10% discrepancy, or 4.3σ)

As Adam Riess emphasises *this is not a small discrepancy.*

Credit: Efsthathiou

Hubble Constant

from Distance Ladder made with Cepheids

A Direct, Local Measurement of H_0 to percent precision

The SH_0ES Project (2005)

(Supernovae, H_0 for the dark energy Equation of State)

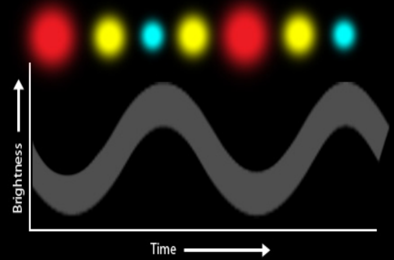
A. Riess, L. Macri, D. Scolnic, S. Casertano, A. Filippenko, W. Yuan, S. Hoffman, +

Measure H_0 to percent precision <u>empirically</u> by:

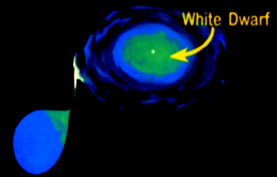
- A strong, simple ladder: Geometry → Cepheids → SNe Ia

Multiple ways

Pulsating Stars,
10^5 $L_\odot$, P-L relation



<u>Exploding Stars</u>,
10^9 $L_\odot$, σ~ 5%



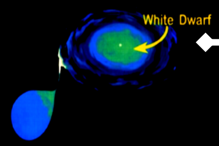
An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

--Reduce systematics w/ consistent data along ladder and NIR
--Thorough propagation of statistical and systematic
--HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

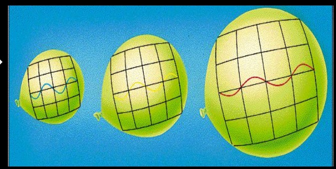
Credit: Riess

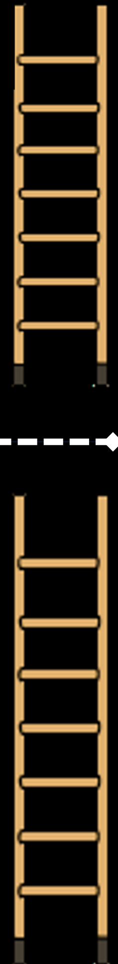
Distance Ladders: Simple & Empirical, Must be Consistent

SN Ia

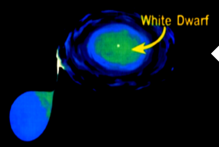


Redshifts

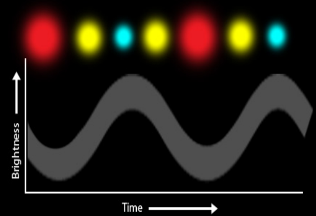




SN Ia

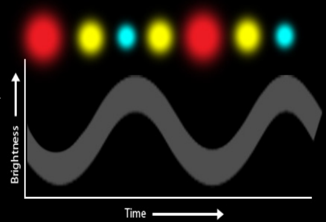


Cepheids



Geometry
(many ways)

Cepheids



Hubble Flow:
D~Gpc, z~0.1

Cross-calibrate:
D~10-40 Mpc

Anchors:
D~Kpc or Mpc

Nutrition Facts

Serving size 1 potato (148g/5.2oz)

Amount per serving
Calories **73**

% Daily Value*

Astrophysical modeling	0%
General Relativity	<1%
LCDM	<1%

⚠ WARNING

Same object types on different rungs must be standardized and measured consistently!

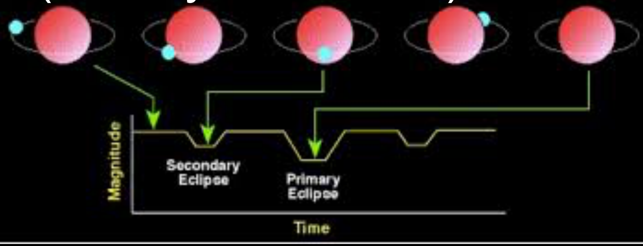
Credit: Riess

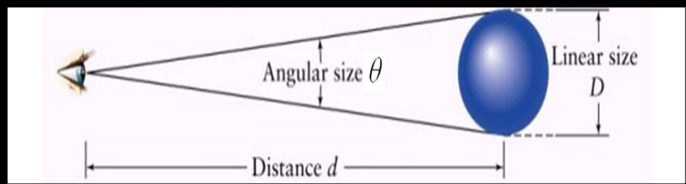
Three Sources of Geometric Distances to Calibrate Cepheids

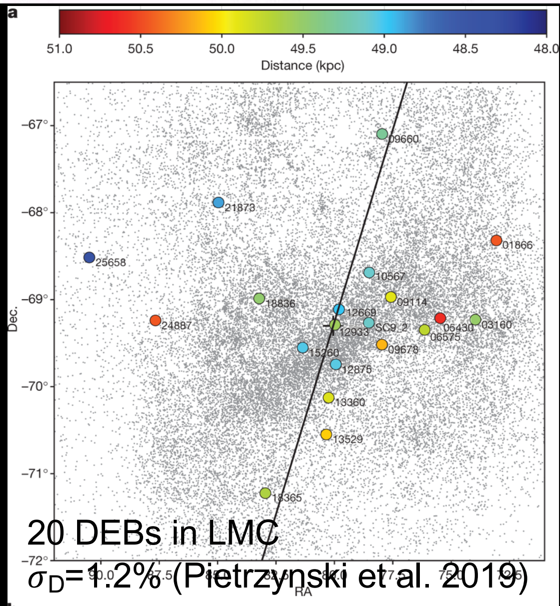
Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

Detached Eclipsing Binaries in LMC

(Pietrzynski+2019)





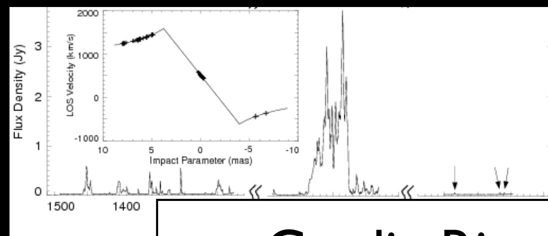


20 DEBs in LMC

σ_D=1.2% (Pietrzynski et al. 2019)

Masers in NGC 4258, Keplerian Motion

(Reid+2019)



Credit: Riess

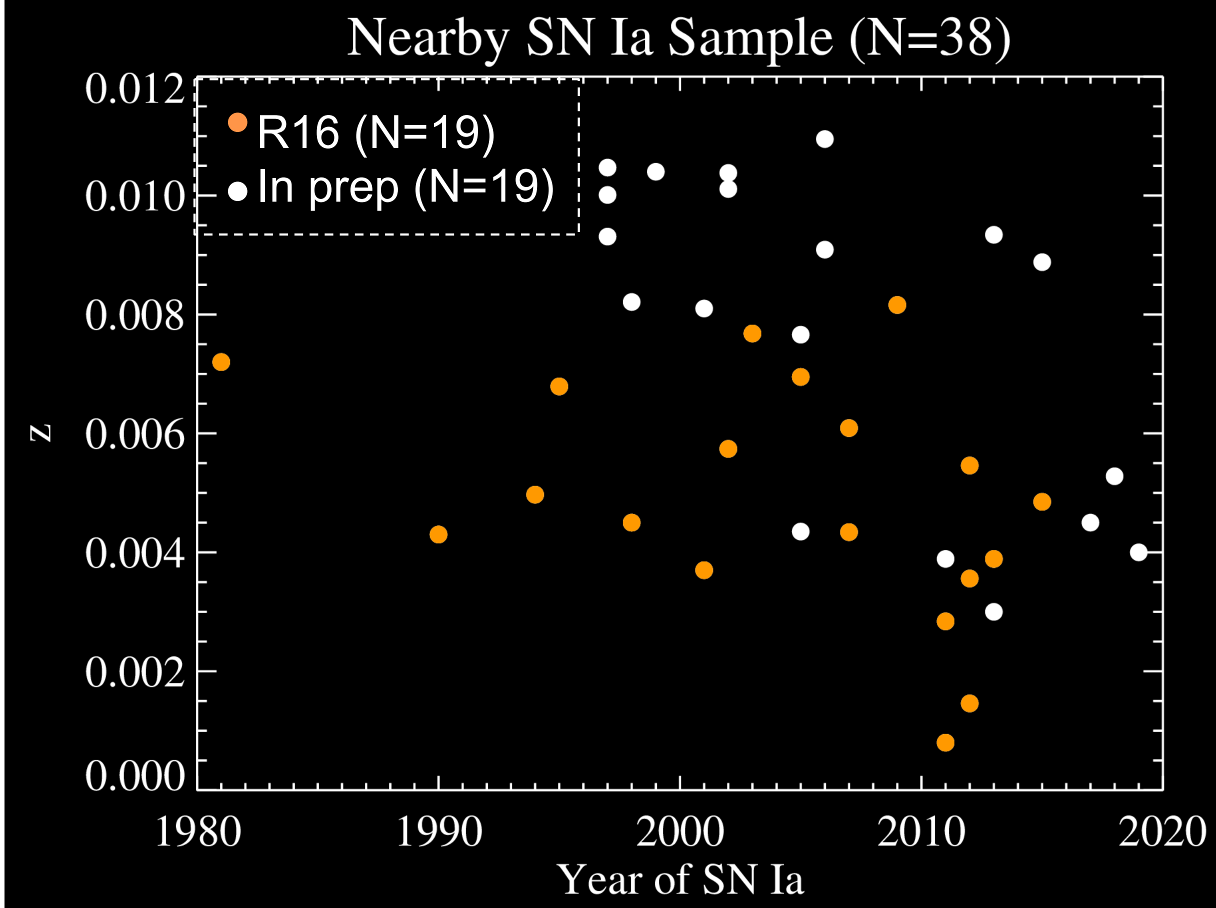
Step 2: Cepheids to Type Ia Supernovae

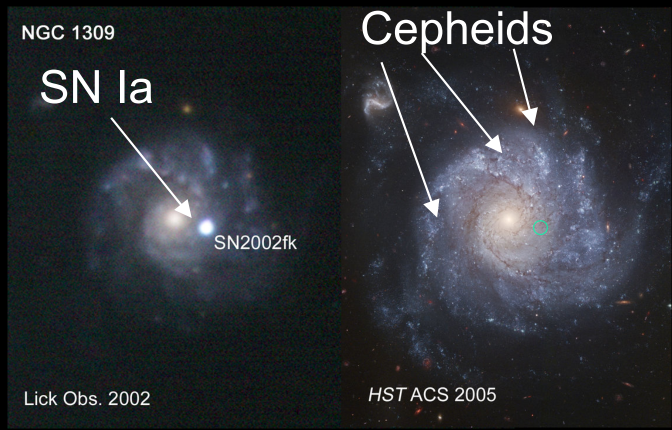
Number nearby SN Ia limits H_0 precision, $\sigma = \frac{6\%}{\sqrt{N}}$

SN Ia Requirements: A_V<0.5, normal, pre-max, digital

Host Requirements: Late-type, z≤0.01, not-edge on

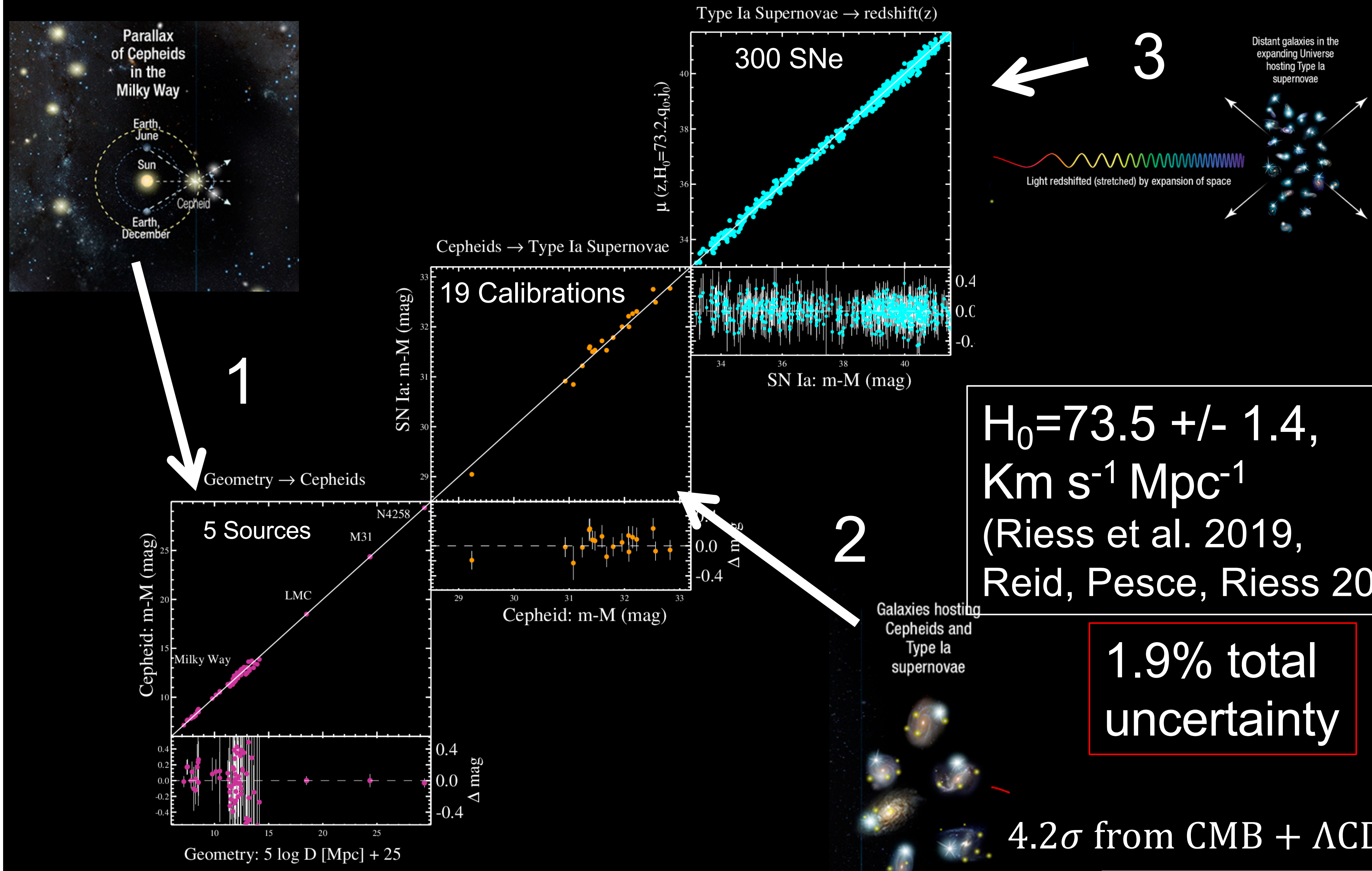
<u>2020 Complete sample</u> (new ones @ 1.5/yr)





Credit: Riess

The Hubble Constant in 3 Steps: Present Data



H_0=73.5 +/- 1.4, Km s^{-1} Mpc^{-1}
(Riess et al. 2019, Reid, Pesce, Riess 2019)

1.9% total uncertainty

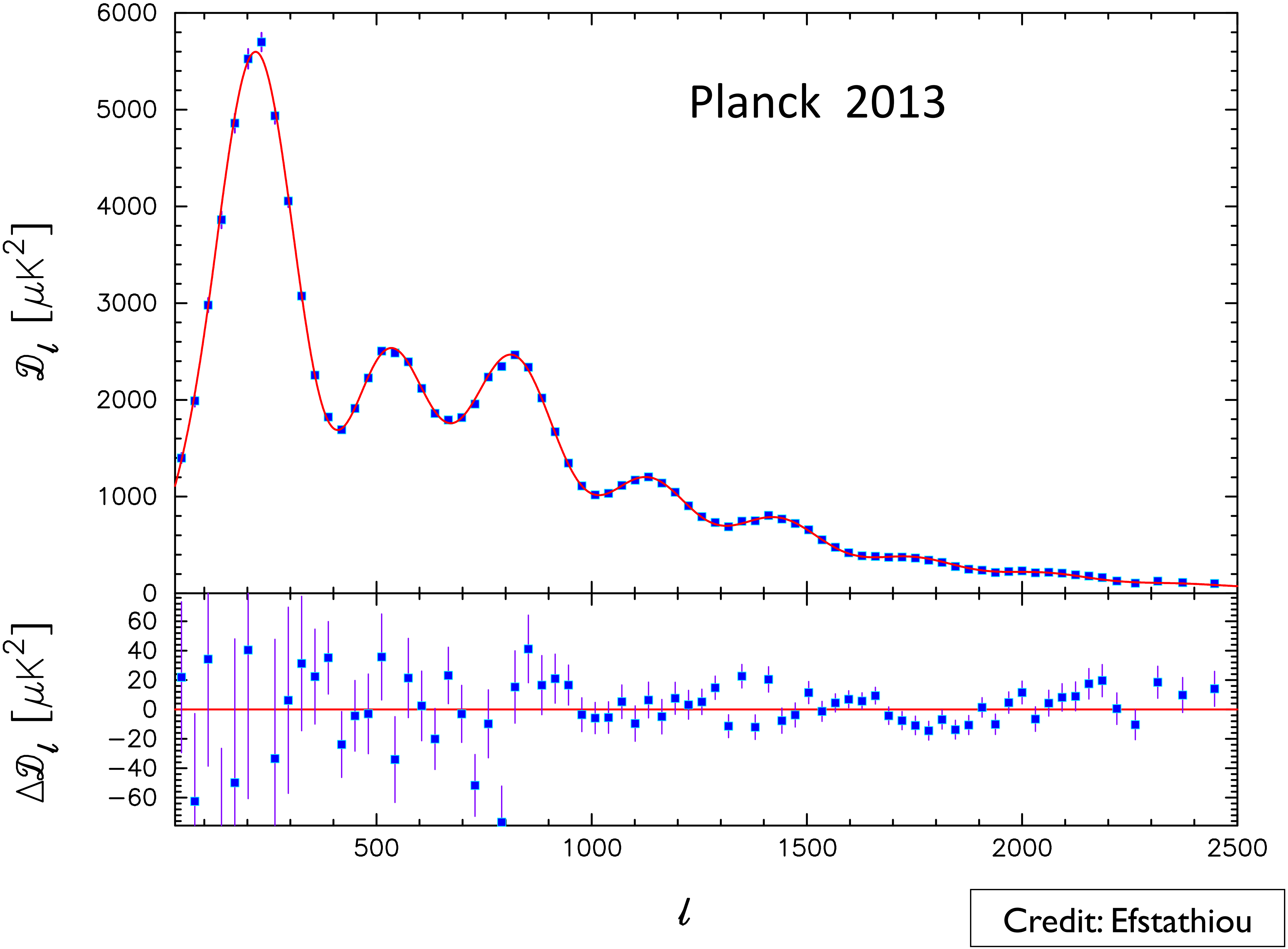
4.2σ from CMB + ΛCDM !

*Simultaneous Fit: Retain interdependence of data and parameters

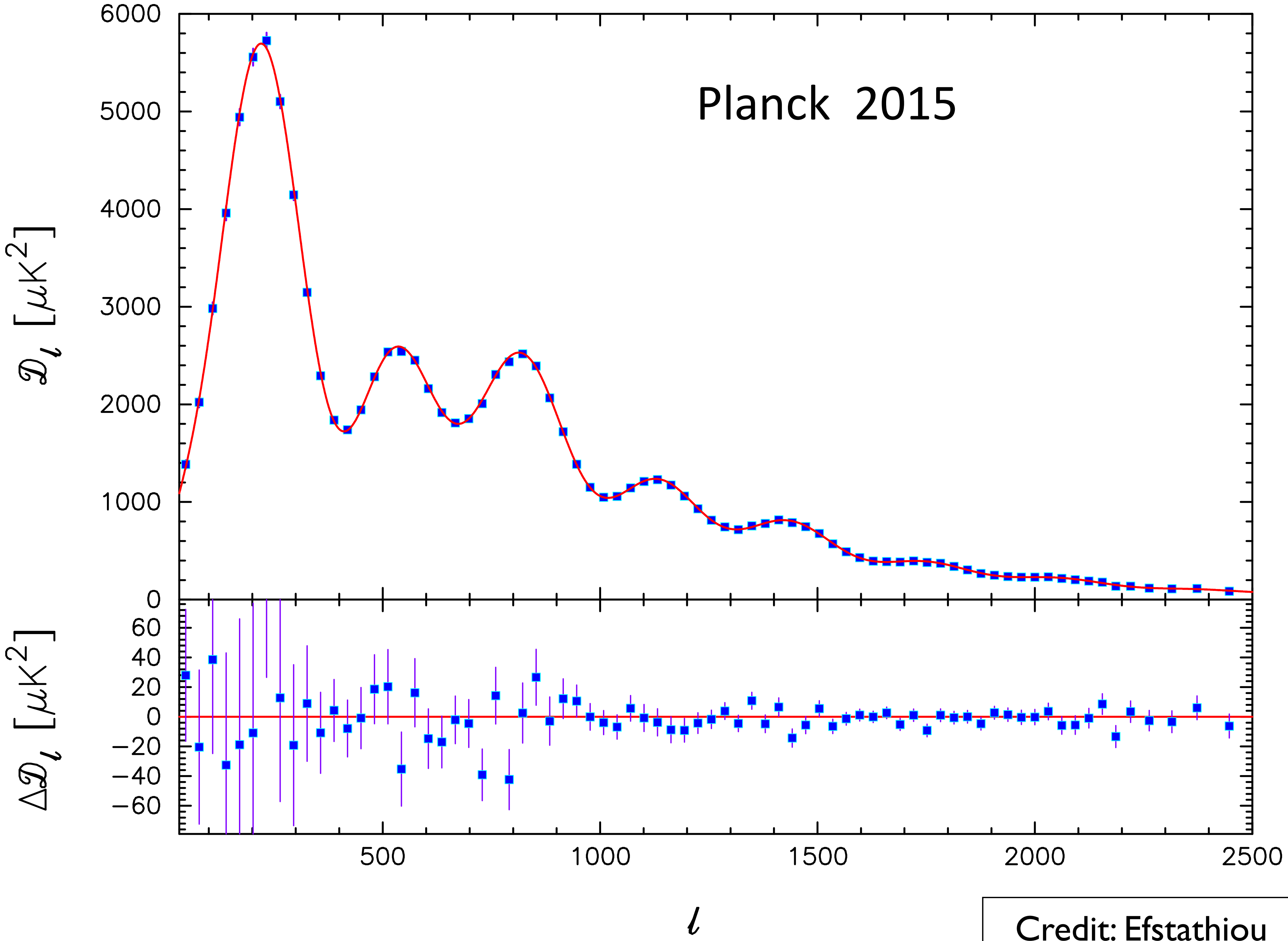
Credit: Riess

Hubble Constant

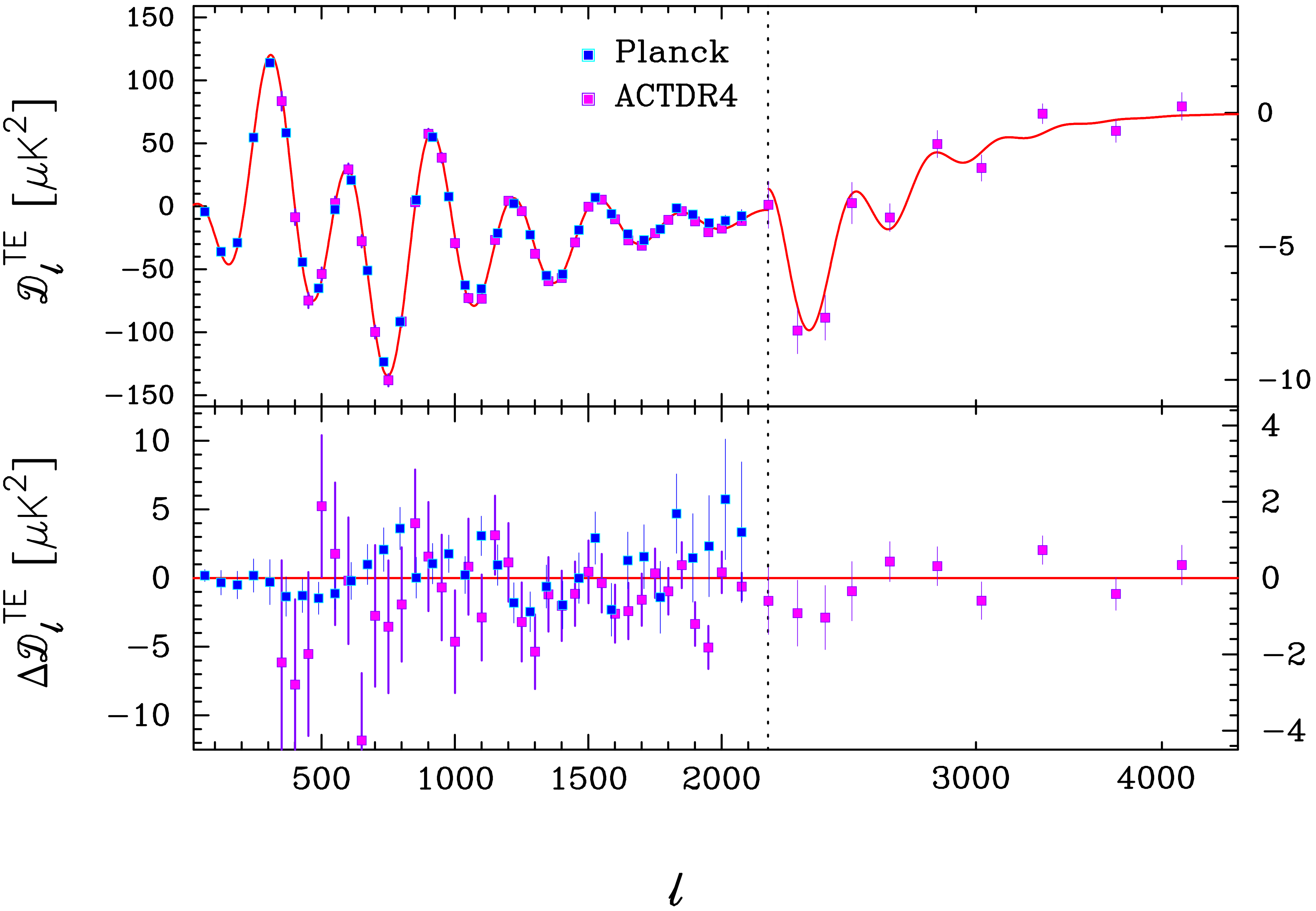
from CMB experiments (most recently Planck)



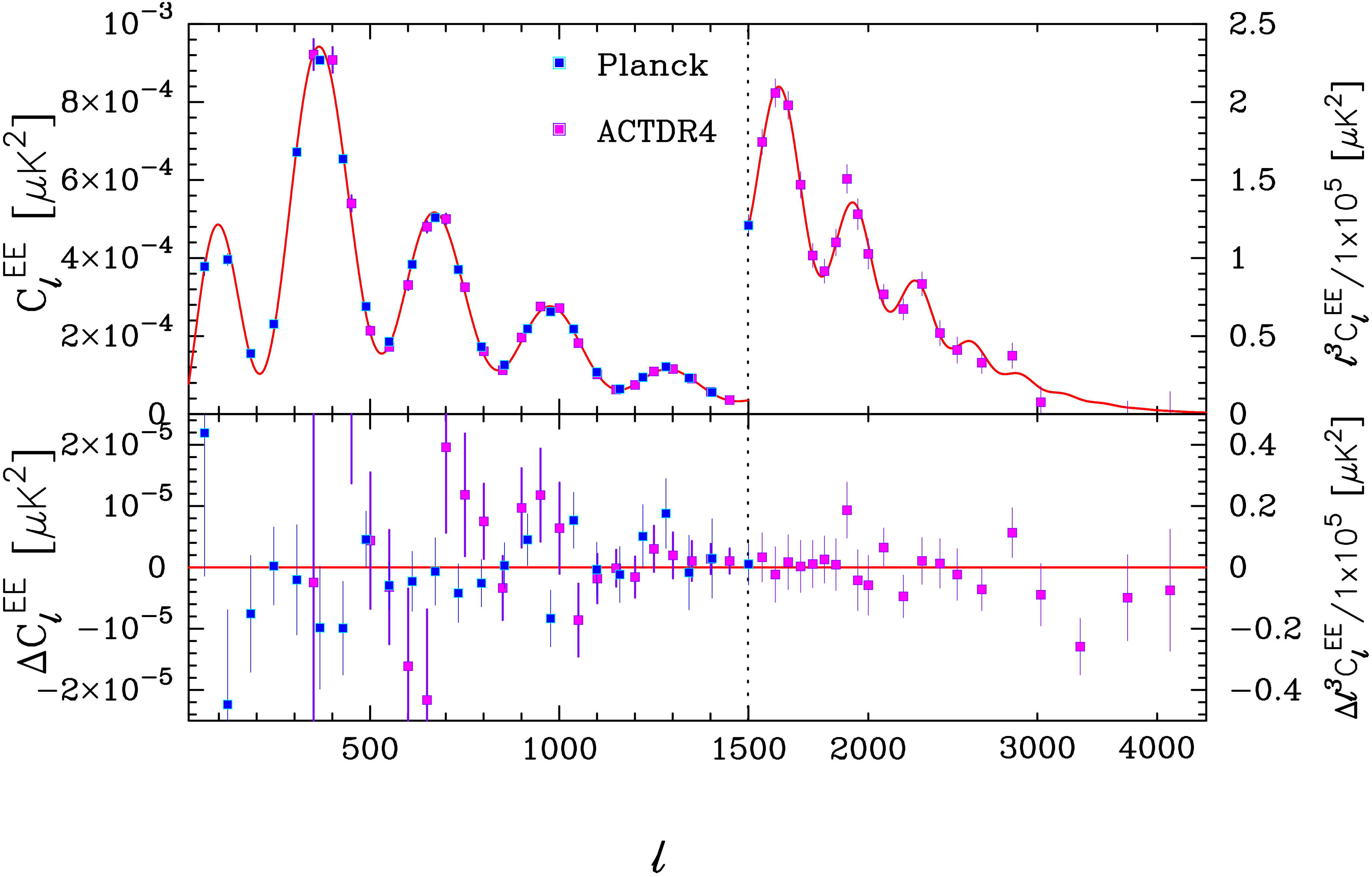
Planck 2013
6000
5000
4000
3000
2000
1000
0
60
40
20
0
−20
−40
−60
500
1000
1500
2000
2500
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
Credit: Efstathiou



Credit: Efstathiou

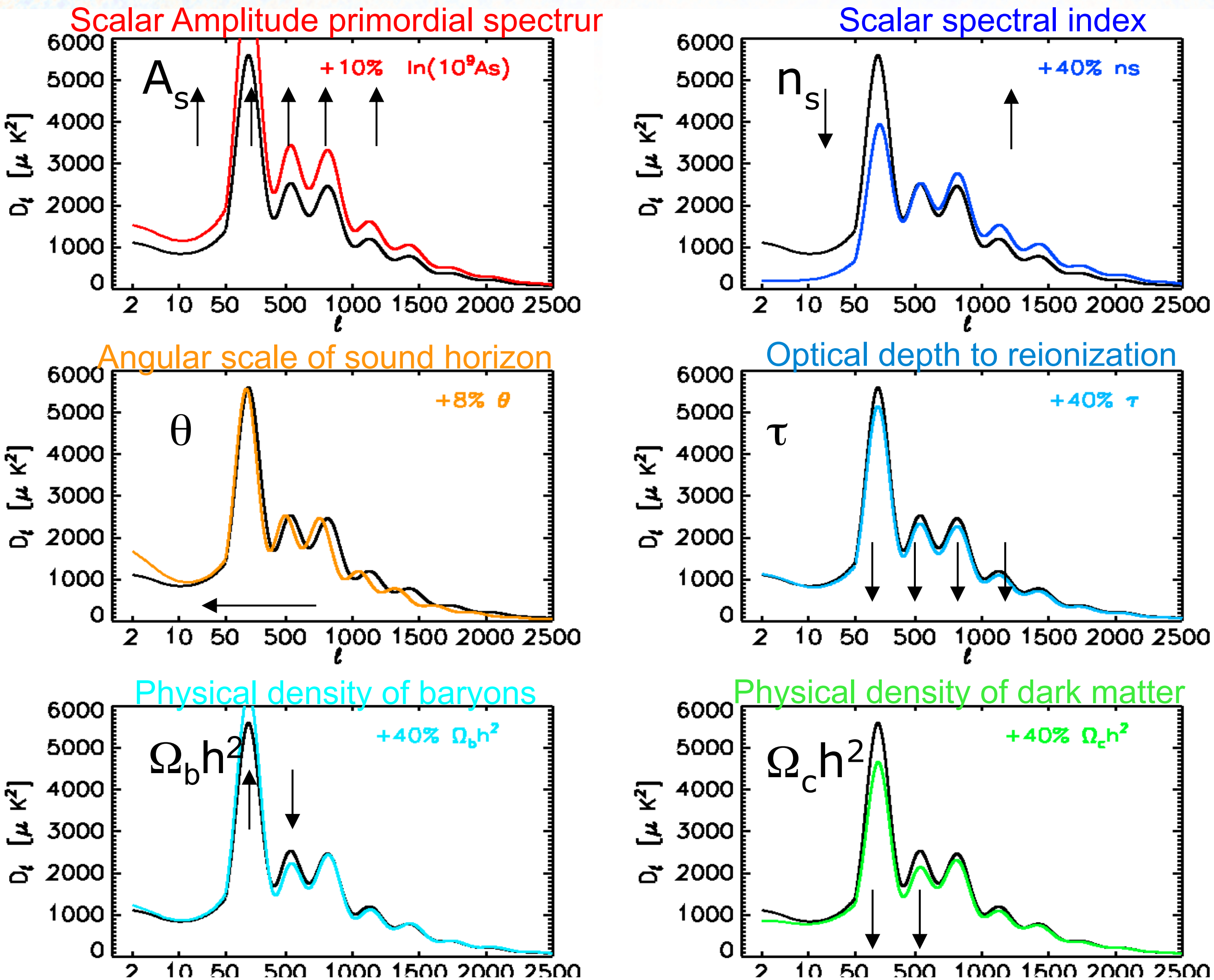


Credit: Efstathiou



Credit: Efstathiou

6 ΛCDM parameters



- Initial conditions A_s, n_s:

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

- Acoustic scale of sound horizon θ
- Reionization τ

- Dark Matter density $\Omega_c h^2$
- Baryon density $\Omega_b h^2$

Assumptions:

- Adiabatic initial conditions
- Neff=3.046
- 1 massive neutrino 0.06eV.
- Tanh reionization (Δz=0.5)

planck

Credit: Galli

Baseline ΛCDM results 2018

(Temperature+polarization+CMB lensing)

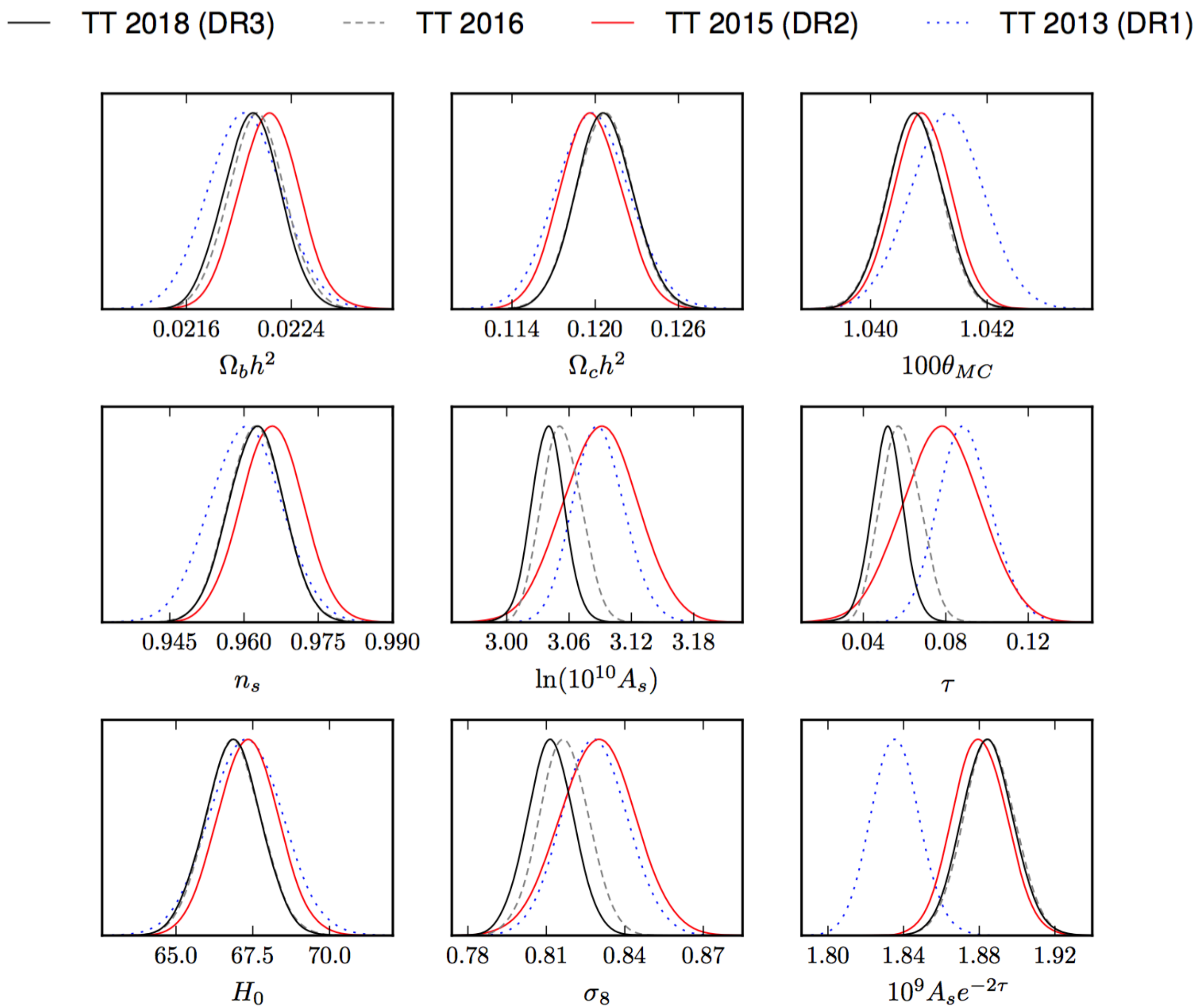
	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

Robust against changes of likelihood, <0.5σ.

- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- τ lower and tighter due to HFI data at large scales.
- n_s is 8σ away from scale invariance (even in extended models, always >3σ)
- Best (indirect) **0.8%** determination of the Hubble constant to date.

Credit: Galli

Take away message stable across releases



Changes across releases compatible with statistical fluctuations and systematics corrections.

ΛCDM is a good fit to the data
No evidence of preference for classical extensions of ΛCDM

Just a few (2-3σ) outliers.

esa

Credit: Galli

No "classical" extension of ΛCDM where H_0 is high from Planck data alone

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

More "sophisticated" extensions needed…

Planck collaboration 2018, 1807.06209

Credit: Galli

CMB measurements

Planck 2018	H_0=67.4±0.5
Reid+ 2019	H_0=73.5±1.4

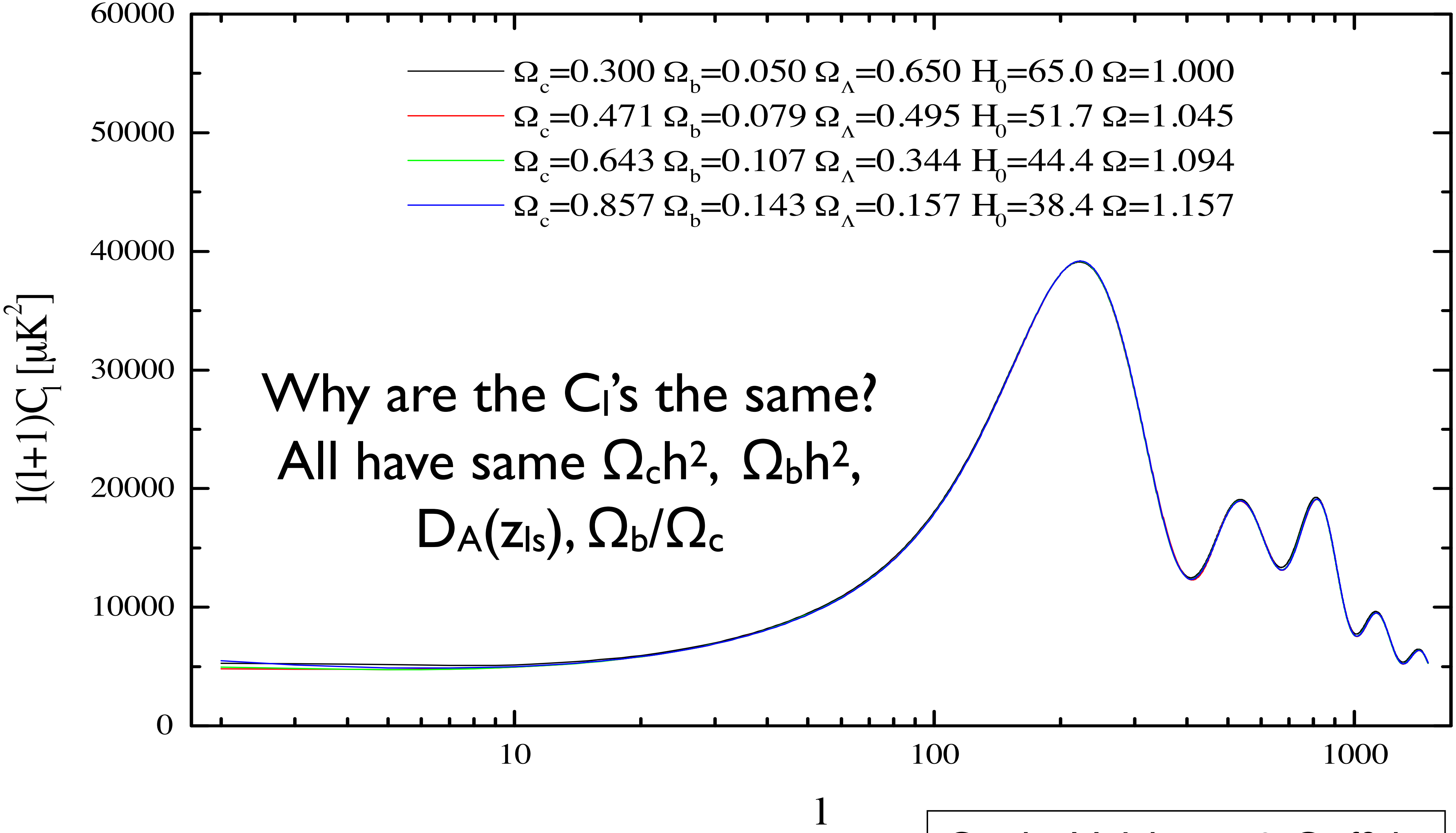
- WMAP and SPT give somewhat larger but still consistent with Planck values of H_0
  - WMAP9* H_0=70 ± 2.2 [Km/s/Mpc] (Hinshaw et al. 2013)
  - SPT-SZ H_0=73.3 ± 3.5 (Aylor et al. 2017)
  - SPTPol (TE,EE) H_0 =71.2 ± 2.12 (Henning+17)
  - ACTPol (TT,TE,EE) H_0 =67.3 ± 3.6 (Louis+17)
- Are these consistent with the low H_0 Planck measurement? When adding BAO, yes!
  - Combining WMAP ACT and SPT with BAO to decrease errors low H_0
    - WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
      H_0= 68.1 ± 0.7 (Aubourg+ 2015)
    - WMAP9+ACT+SPT + BAO (BOSS DR11+6dFGS)
      H_0 = 69.3 ± 0.7 (Bennet+ 2014)
  - Planck, WMAP and SPT are consistent with each other.

*NB: these were obtained using slightly different assumptions for

Credit: Galli

Degeneracies:

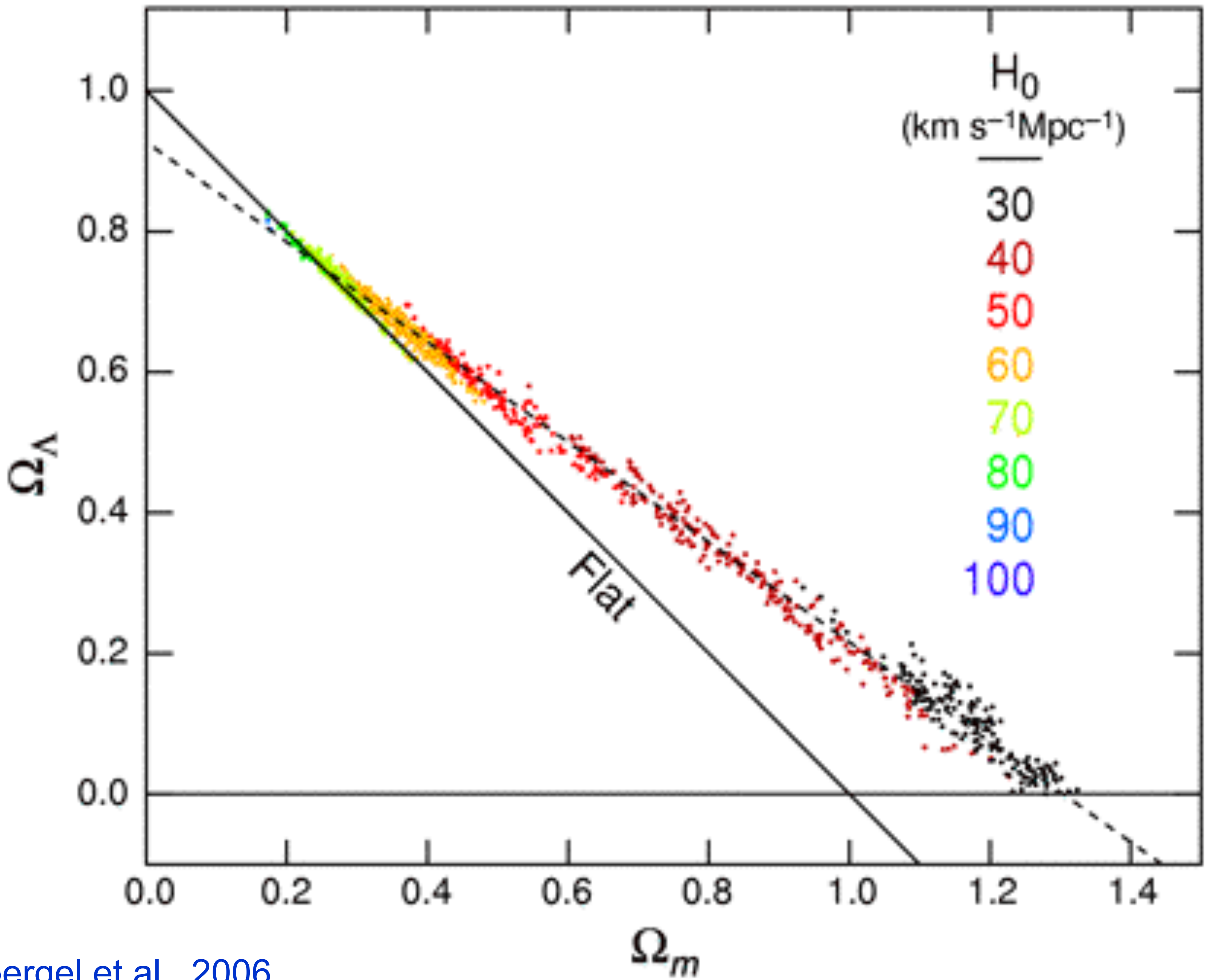
Multiple Sets of Cosmological Parameters give Same CMB Power Spectrum



Why are the C_l's the same?
All have same $\Omega_c h^2$, $\Omega_b h^2$, $D_A(z_{ls})$, Ω_b/Ω_c

Credit: Melchiorri & Griffiths

Degeneracies in Deriving H_0 from CMB



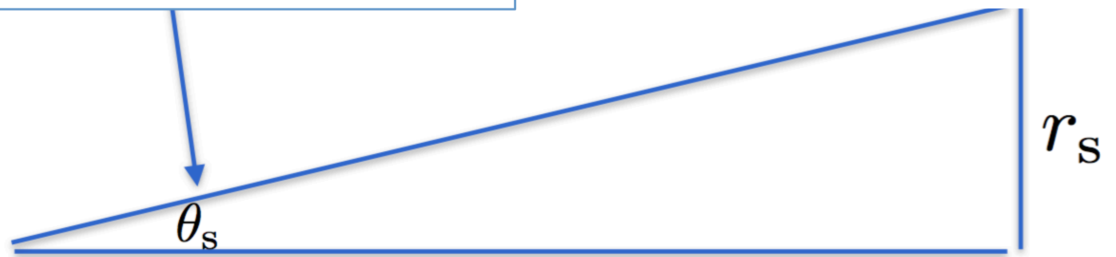
Spergel et al., 2006

Indirect measurement of the Hubble constant from the CMB

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks



H(z) here is the expansion rate of the universe at **early** times

$$D_A(z = 1100) = \int_0^z dz'/H(z')$$

H(z) here is the expansion rate of the universe at **late** times

Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$$H^2(z) = \mathbf{H_0}^2(\Omega_m (z+1)^3 ..)$$

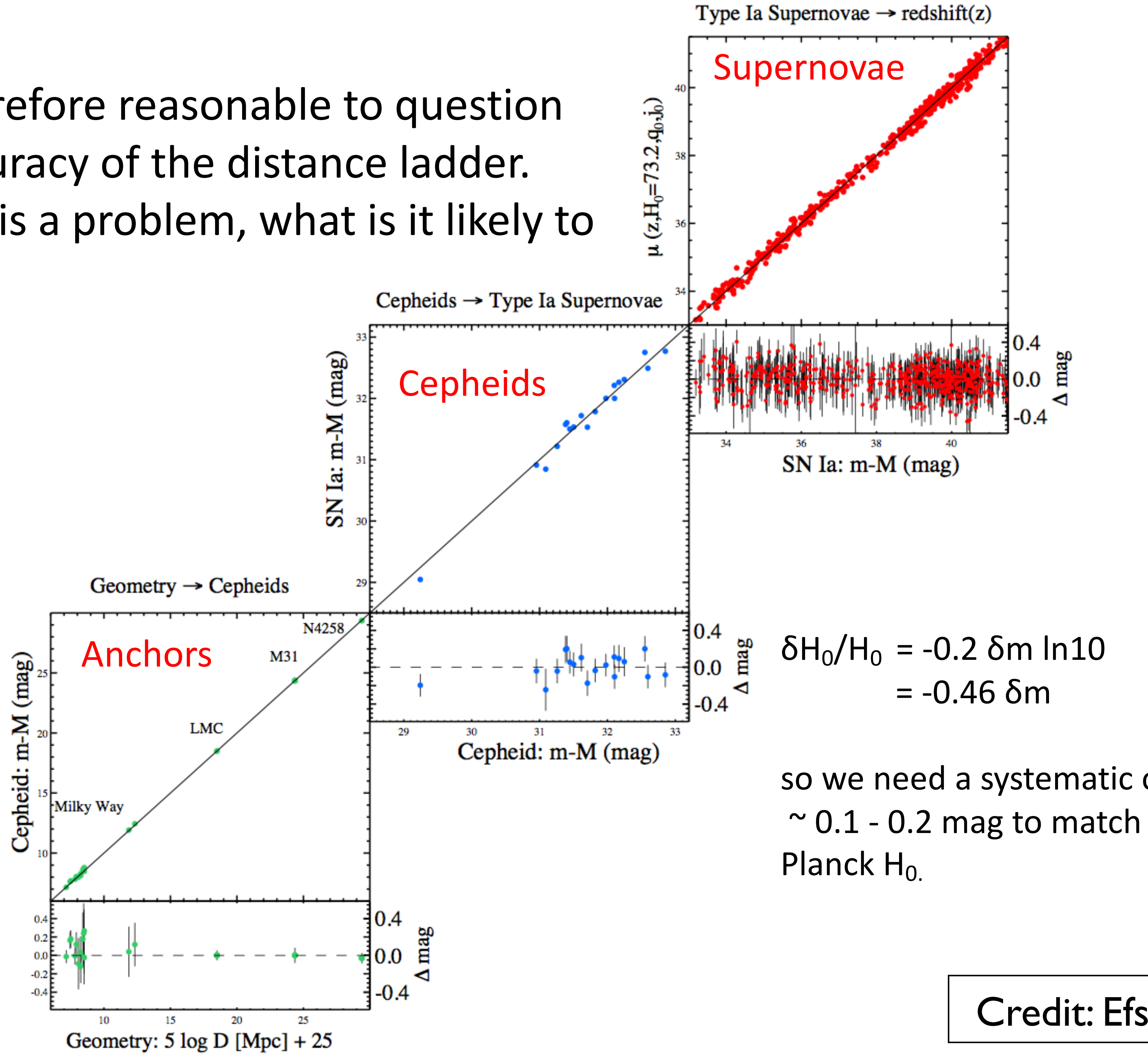
Model dependent!

Credit: Galli

Are there problems with H0 from Cepheids + Distance Ladder?

Perhaps — see next slide

It is therefore reasonable to question the accuracy of the distance ladder.
If there is a problem, what is it likely to be?



$\delta H_0/H_0 = -0.2\ \delta m \ln 10$
$= -0.46\ \delta m$

so we need a systematic of ~ 0.1 - 0.2 mag to match the Planck H_0.

Credit: Efsthathiou

Does the SH_0ES team
(who uses Cepheid) agree?

Not so much…

Robust? Seven Sources of Cepheid Geometric Calibration

Independent Geometric Source	σ_D	H_0
NGC 4258 H_20 Masers: Reid, Pesce, Riess 2019	1.5%	72.0
LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019) AGREES WITH GAIA EDR3	1.3%	74.2
Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7
Milky Way 50 Gaia+HST, Long P Parallaxes: Riess+ 2018	3.3%	73.7
Milky Way Short P Cepheid Binary Gaia Companion Parallax: Breuval+20	3.8%	72.7
Milky Way Short P Cepheid Cluster Gaia Parallax: Breuval+20	3.2%	73.6

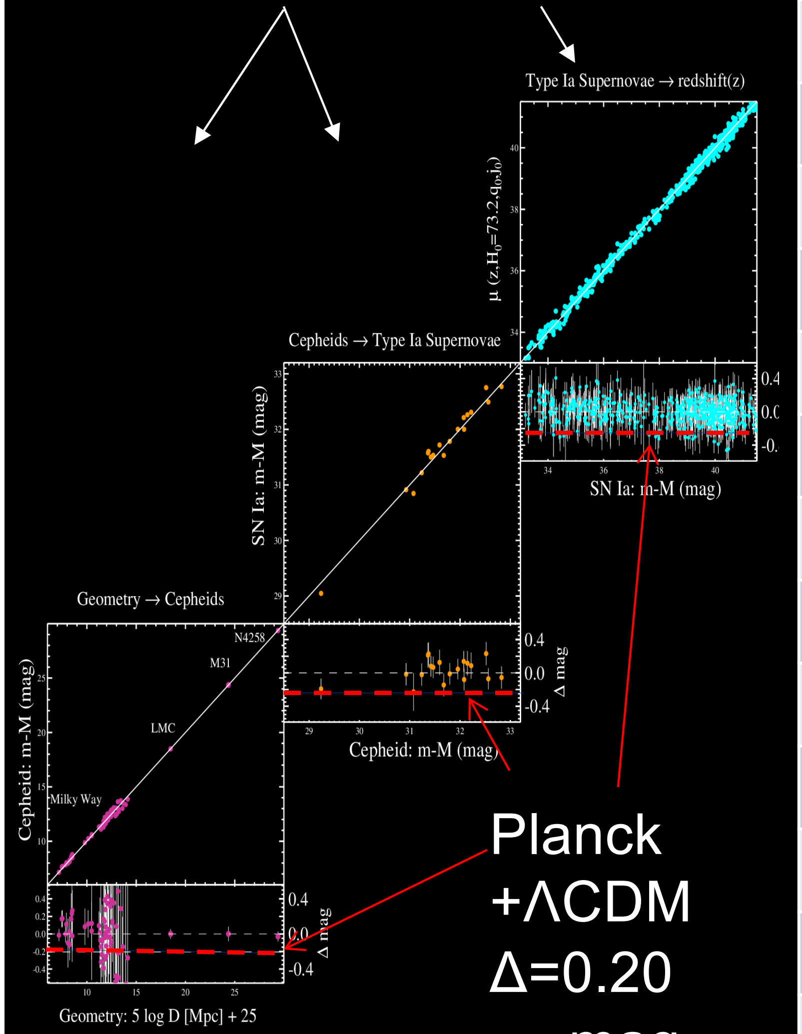
Consistent Results ($\leq 2\sigma$), *Independent Systematics*

Credit: Riess

Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

$$5\log H_0 = M_B^0 + 5a_B + 25$$



Analysis Variants	H_0
Best Fit (2019)	73.5
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.4
Reddening Law: Bulge-like (N15)	73.9
No Cepheid Outlier Rejection (normally 2%)	73.8
No Correction for Cepheid Extinction	75.2
No Truncation for Incomplete Period Range	74.6
Metallicity Gradient: None (normally fit)	74.0
Period-Luminosity: Single Slope	73.8
Period-Luminosity: Restrict to P>10 days	73.7
Period-Luminosity: Restrict to P<60 days	74.1
Supernovae z>0.01 (normally z>0.023)	73.7
Supernova Fitter: MLCS (normally SALT)	75.4
Supernova Hosts: Spiral (usually all types)	73.6
Supernova Hosts: Locally Star Forming	73.8
Optical Cepheid Data only (no NIR)	[illegible]

Credit: Riess

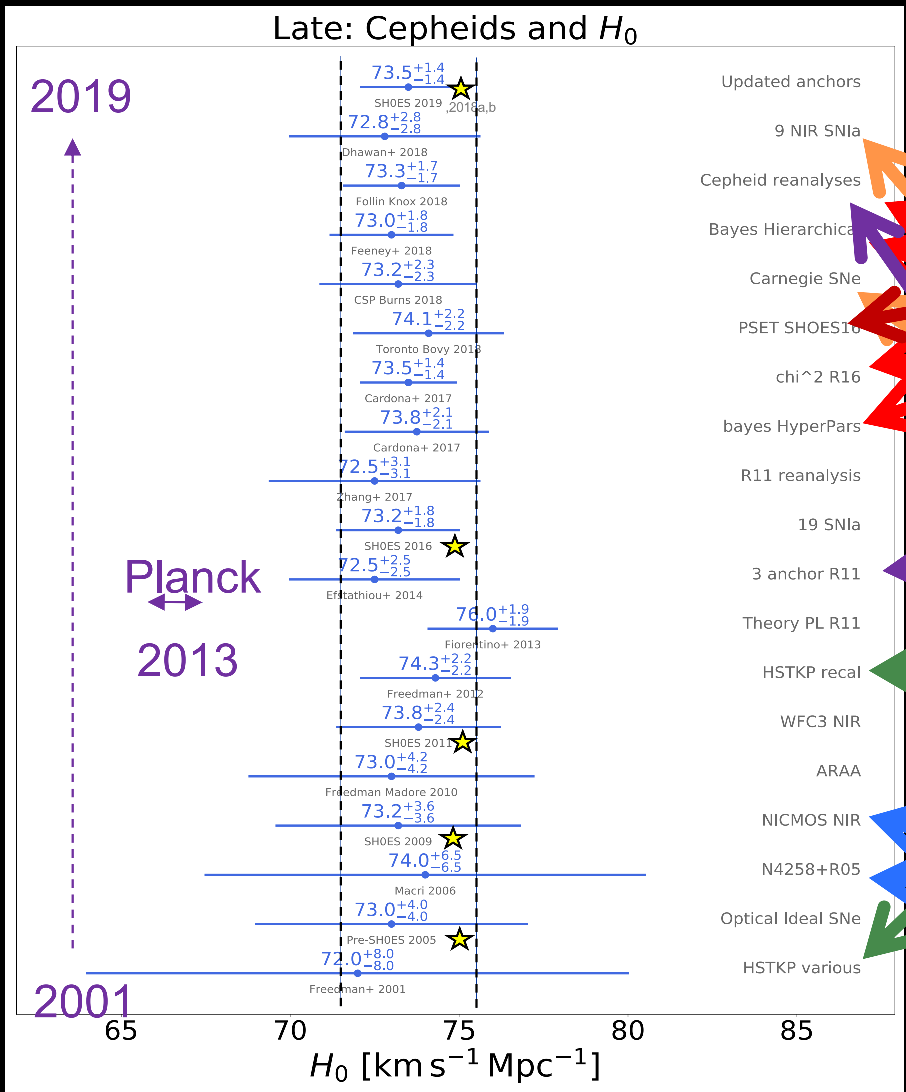
Frequently Asked Questions: technical, see backup slide

- Could we live in a giant void (9% in H_0)?
  No, LSS Theory and SN Ia mag-z limit σ~0.6% in H_0
  Odderskov et al. (2016) , Wu & Huterer (2017), Kenworthy, Scolnic, Riess 2019
- Is HST WFC3-IR flux scale linear to 1%?
  Yes, calibrated to σ=0.3% in H_0 across 15 mag
  Riess, Narayan, Calamida 2019
- Does Cepheid crowding compromise accuracy?
  No, amplitude data confirms locality of crowding
  Riess, Yuan, Casertano, Macri, Scolnic 2020
- Is there a difference in SN Ia at ends of distance ladder?
  No, correlations of Hubble residuals < σ=0.3% in H_0
  Jones et al 2018

Credit: Riess

Cepheids+SN Ia Ladder, Most Widely Replicated: 2001-2019

Why Cepheids? Advantages: 1) longest-range 2) most calibrations 3) consistent photometry along ladder 4) most tested…



SH_0ES results (★) *cumulative* but compared to present… consistent

grad student problem set! (Toronto)

Different analyses

Different SNe, wavelength

"Planck People"

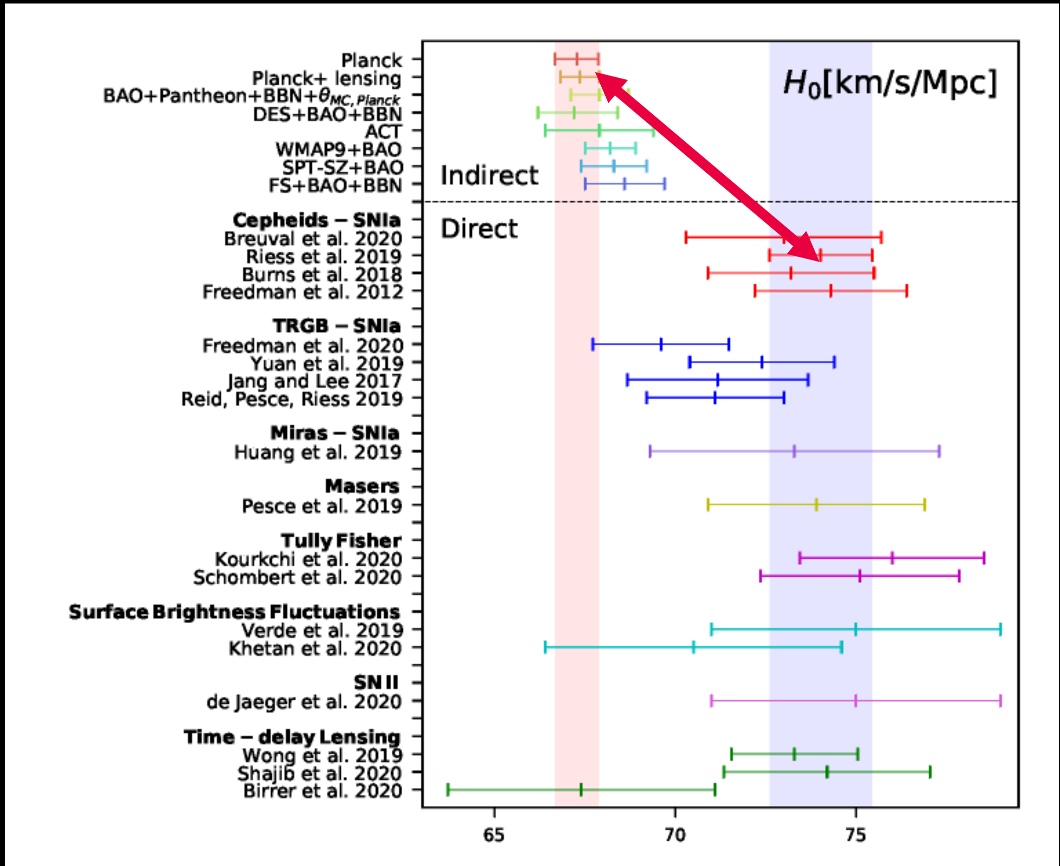
Different Team (KP), photometry, Cepheids, wavelengths

Different HST Instruments

Credit: Riess

The Hubble Constant Tension, Discrepancy, Problem, Crisis

Status late 2020



Compilation from Di Valentino(2020)

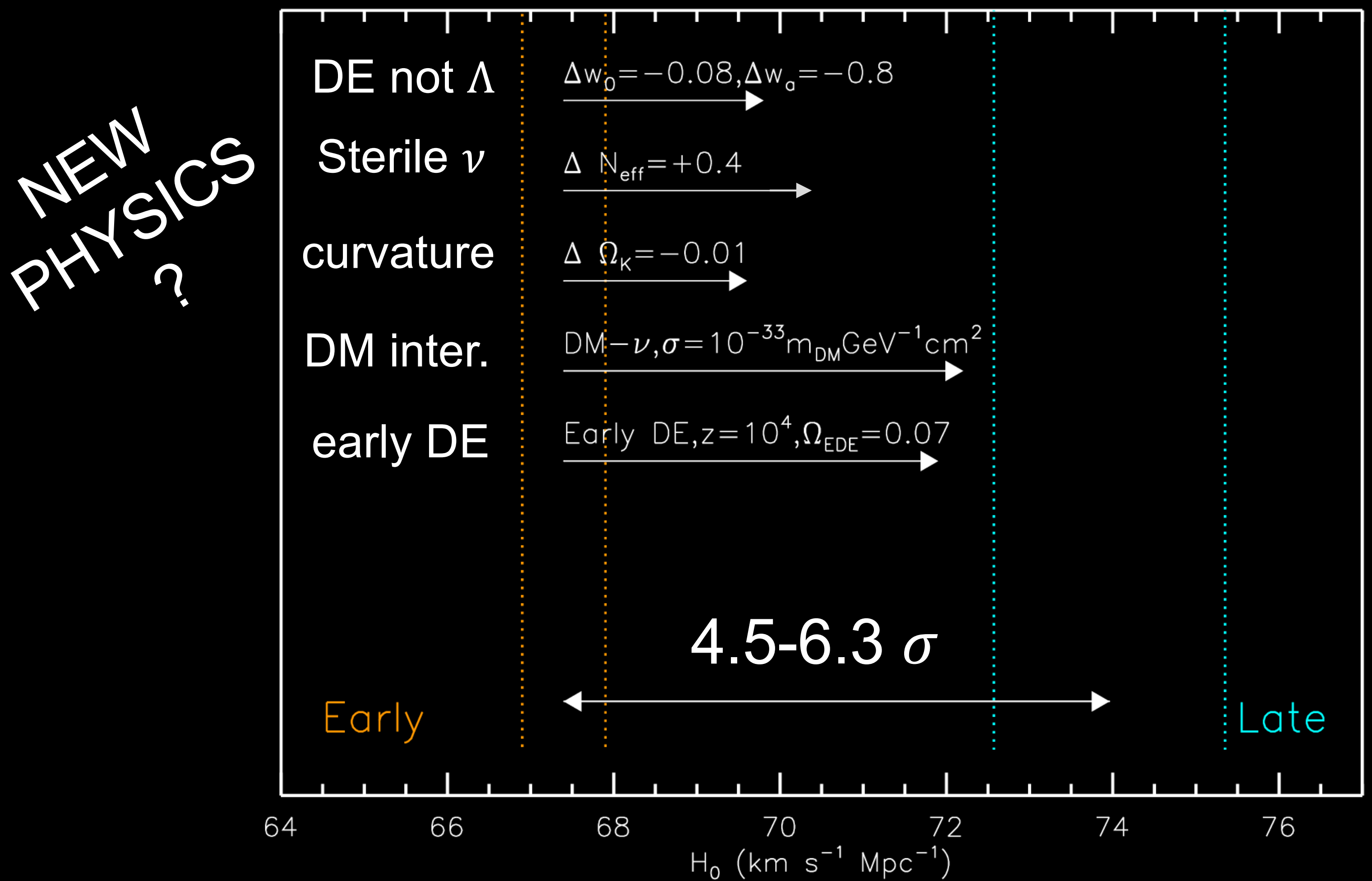
KITP 2019 (Verde, Treu, Riess 2019)

"does not appear to depend on the use of any one method, team or source"

No Cepheids: 4.5-5.3σ
No TRGB: 5.7-6.3σ
No lens: 5.0σ
No SN Ia: 4.9σ
No Cepheids or TRGB: 5.3σ
No Planck: 4.4-4.9σ
No CMB: 4.0-4.5σ
(Riess 2019, Nature Reviews)

Credit: Riess

Cause Early vs Late Difference? Newton: “Feign No Hypothesis”



“The Hubble Hunter’s Guide”, Knox and Millea, 2019: “Most Likely”: Increase Expansion Rate Pre-recombination->reduce sound horizon by 5-8%

Mechanisms: Early DE or sterile (self-interacting) neutrinos

Claims: better fit to CMB, new CMB features, cosmic birefringence as evidence of CMB coupling to EDE/ALPs or pNG Boson (Capp

Credit: Riess

The CMB people agree their method is indirect

Indirect measurement of the Hubble constant from the CMB

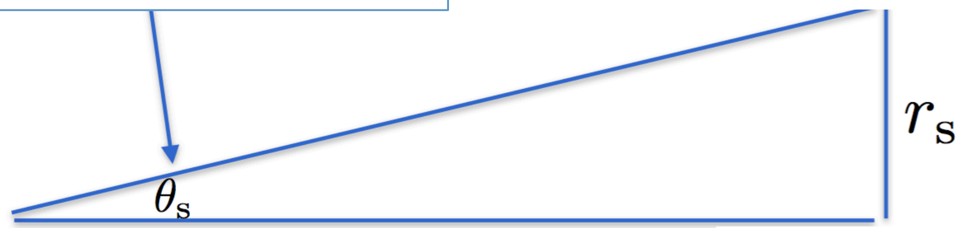
planck

Calculate the **physical dimension of sound horizon** assumes model for sound speed and expansion of the universe before recombination (after measuring ω_m and ω_b)

$$r_s = \int_{z_s}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Measure the **angular scale of sound horizon** from the position of the peaks

H(z) here is the expansion rate of the universe at **early** times



$$D_A(z=1100) = \int_0^z dz'/H(z')$$

H(z) here is the expansion rate of the universe at **late** times

Infer the distance to the last scattering surface, which depends on H_0 Friedmann equation, infer H_0.

Expansion rate after recombination

$H^2(z)=\mathbf{H_0^2}(\Omega_m\,(z+1)^3..)$

Model dependent!

Credit: Galli

Is this the only hotly debated disagreement in observational cosmology?

No!

Also a matter of σ_8

SLIDE FROM PREVIOUS LECTURE on σ_8

While deriving correlation function and Power spectrum from galaxy survey, one thing we are particularly interested in is the normalization of the power spectrum

$$P_0(k) = A\, k^{n_s}$$

(related to the A parameter here)

(n_s = 1)

This is defined using this parameter σ_8 (intended to represent the root-mean-squared fluctuations in a 8 h^{-1}Mpc volume):

$$\sigma_{8,g}^2 := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1$$

(8 h^{-1} Mpc was chosen because appeared close to 1)

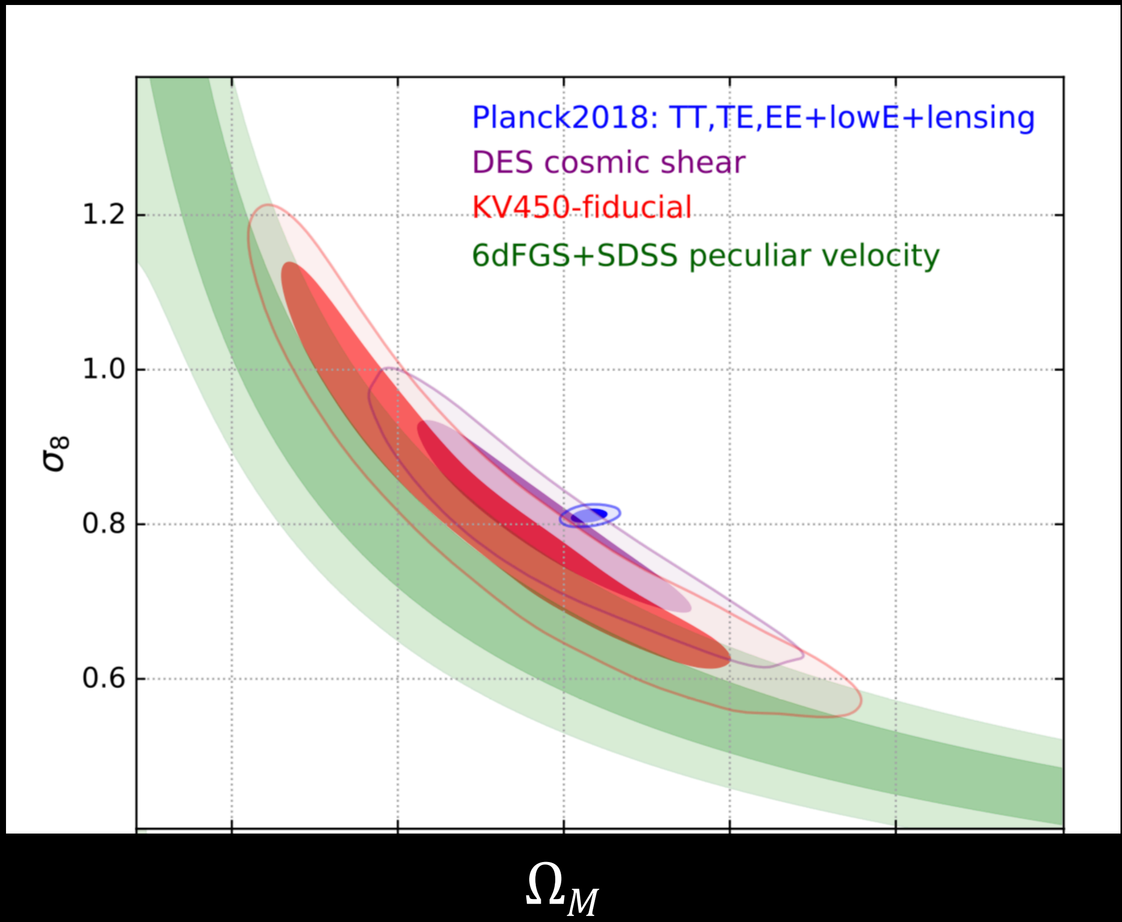
Size of density fluctuations in a volume really defines the amplitude of power spectrum

Tension in σ_8

Another Early vs Late Tension? Matter clumpiness, σ_8

RMS matter fluctuation, σ_8 , (r=8 h^{-1} Mpc), 0.8 Early vs late divide

~3 σ from lensing and peculiar velocities, independently



6dFGS+SDSS

Said, K et al 2020, MNRAS,497, 1275

"…deviates by more than 3σ from the latest Planck CMB measurement. Our results favour … a Hubble constant $H_0 > 70$ km s^{-1} Mpc^{-1} or a fluctuation amplitude $\sigma_8 < 0.8$ or some combination of these. "

Can We Believe Measurements without Explanation?

Don't sweep "problems" under the rug

"Problems" are often clues!

- ~~Precession of Mercury~~ Solved!
- ~~Solar Neutrino Problem~~ Solved!
- ~~Missing Baryon Problem~~ Solved!
- Lithium Problem
- CMB Cold Spot
- Flat rotation curves/ what/where is dark matter?
- Accelerating Universe/ why Λ so small?

Credit: Riess

Final Exam

May 15, 2022
HL207, HL211
13:15-16:15

Study Guide for Exam

1. In general, please have a basic understanding of everything discussed in lecture. If you do not understand it, please read the supplementary readings, the textbook, or ask Ivana, Thomas, your classmates, or me. [Questions are helpful for improving the course – since I can use your feedback to improve the clarity of the lectures.]

2. Familiarize yourself with all the homework problems and solutions to these problems given on the course web site; expect to find 1-2 problems on the exam that are very similar to homework problems.

3. Please be familiar with the three different methods of estimating the age of the universe observationally and how this compares with estimates based on the Hubble constant. Be capable of explaining the basic idea behind each.

4. Have a basic idea of how the extragalactic distance ladder is set up and the basic challenges in measuring the Hubble constant. Be able to provide a brief explanation for the techniques used to set up the distance ladder. You should also have a basic understanding of the two methods to determine H_0 which are entirely independent of the distance ladder.

Study Guide for Exam

5. Be capable of discussing in detail how we can determine the baryon and dark matter density of the universe. Have a basic understanding of the many different approaches we have to determine these quantities. You will be tested on your understanding of the basic concepts and your ability to clearly explain them.

6. Be familiar with what we can learn about the cosmological parameters from the cosmic microwave background TT, TE, EE, and BB power spectra and how these power spectra are measured. Be capable of explaining why the cosmic microwave background radiation shows a coherent polarization and what additional information the polarization signal gives us about the universe.

7. While you are not expected to precisely remember all the equations seen in class, you should know how they scale against most of the important variables.

8. Have a solid understanding of what the matter power spectrum is and why it has the basic shape that it does and how we can constrain it on various scales. Understand how astronomers measure the clustering of galaxies in real observations, the challenges in doing so, the different types of clustering measures, and how astronomers can use clustering to constrain the matter power spectrum. How is the spatial scale of the peak of the matter power spectrum related to the cosmological parameters and why?

Study Guide for Exam

9. Have an understanding of the basic manner in which density perturbations grow with cosmic time, how this depends on the spatial scale, and how it depends upon whether the universe is radiation or matter-dominated. Also have an understanding of how baryon acoustic oscillations are introduced onto the matter power spectrum and what we can learn about the universe by thoroughly quantifying the properties of these oscillations.

10. How do astronomers describe the normalization of the power spectrum? What experiments did we discuss in class to constrain the normalization and how does each work?

11. Have a basic idea of the three different approaches astronomers use to find galaxy clusters and how astronomers use galaxy clusters to constrain various cosmological parameters.

12. Be familiar with the four main techniques for constraining the dark energy properties of the universe (supernovae Ia, galaxy cluster searches, baryon acoustic oscillations, cosmic shear). Be capable of explaining how each works and know the basic steps that are essential to the use of each technique. What are the strengths and weaknesses of each technique?

Study Guide for Exam

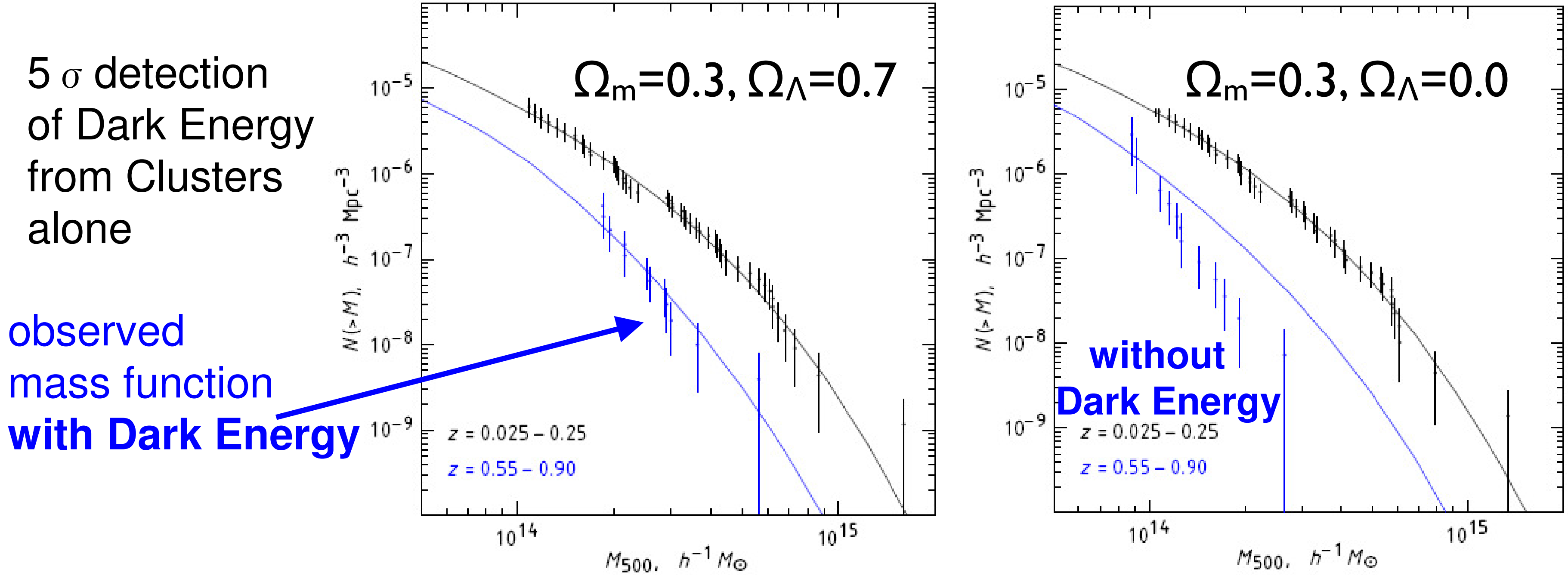
13. Be familiar with the ways that quantities like the luminosity distance, angular size distance, the Hubble parameter depend on the cosmological parameters (in particular Ω_m and Ω_Λ).

14. Have a basic understanding of which parameters the many different experiments discussed in class allow us to constrain, what (if any) degeneracies exist, and how astronomers can put together the observational constraints from many different experiments to establish the values of Ω, Ω_m, Ω_Λ, Ω_b, H_0, ...

15. While most of the exam should be relatively easy if you have a good understanding of all the concepts and material discussed in lecture, some questions will include a few parts where I will expect a greater mastery of the course material, supplementary readings, and textbook. This material will be what I use to determine who merits very high marks in the course (>=8.5 or 9), so you should not stress if you are not able to answer all the questions on the exam perfectly.

One example exam problem:

Counting the number of galaxy clusters on the sky versus apparent mass can provide a powerful constraint on the cosmological parameters... as illustrated from the comparison below:



Vikhlinin et al. 2009 (Chandra Cluster Cosmology Project)

The angular diameter distance $D_A(z)$, comoving volume, and growth factor all depend on redshift in a characteristic way depending on the cosmology. Explain how each factor would affect the comparison shown here.