Dark Energy: Cosmology with galaxy surveys

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ICREA / IFAE Barcelona

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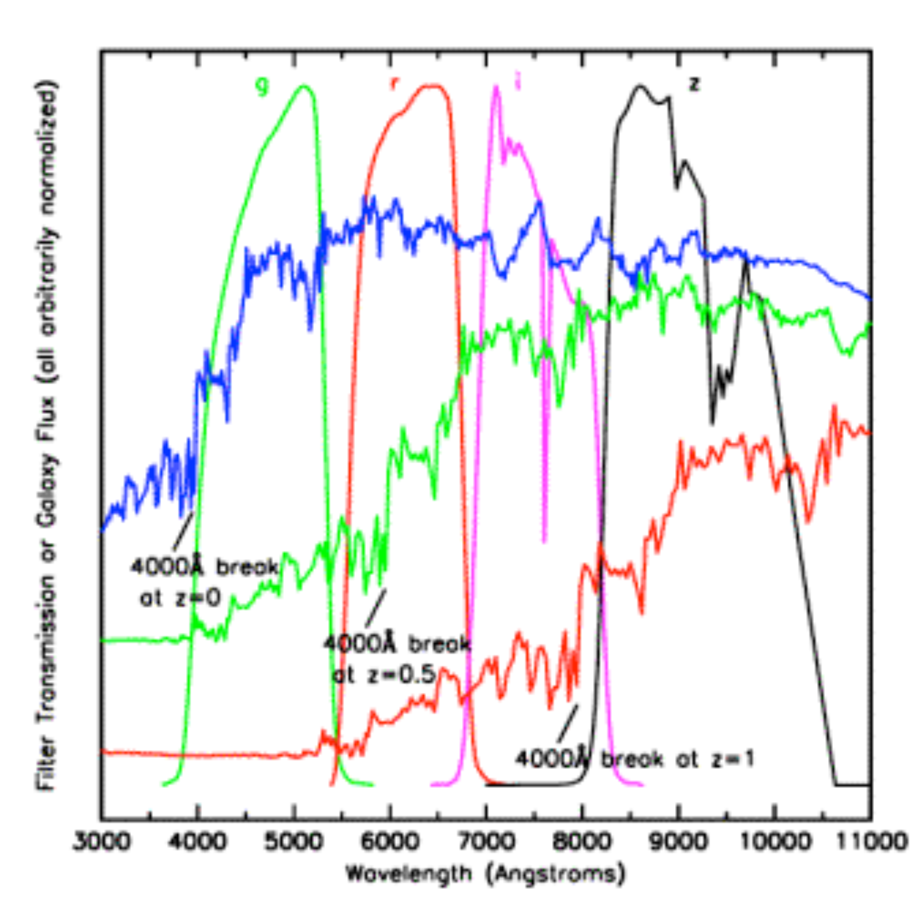
Outline

- Introduction: dark energy and galaxy surveys
- Quick survey of current and future galaxy surveys
- Kinematical probes: BOSS, Planck. Tensions
- Dynamical probes: **DES**, KiDS, HSC, Planck. Tensions?
- Status of the PAU Survey at ORM
- Conclusions

Intro: dark energy and galaxy surveys

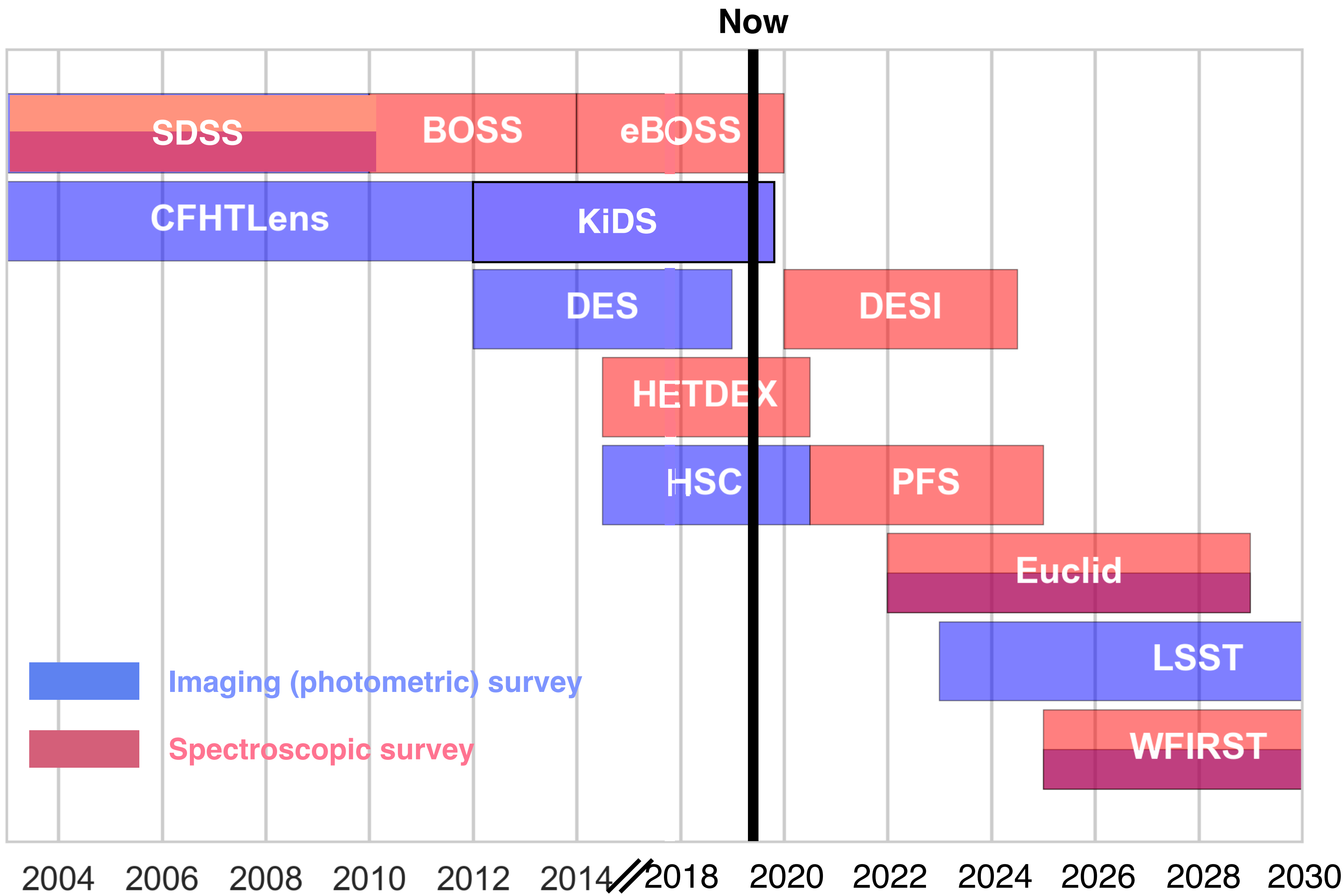
- What is causing the acceleration of the expansion of the universe?
  - Einstein's cosmological constant Λ?
  - Some new dynamical field ("quintessence," Higgs-like)? "Dark Energy"
  - Modifications to General Relativity?
- Dark energy effects can be studied in two main cosmological observables:
  - The history of the expansion rate of the universe (**kinematical**): supernovae, weak lensing, baryon acoustic oscillations (BAO), cluster counting, etc.
  - The history of the rate of the growth of structure in the universe (**dynamical**): weak lensing, large-scale structure, cluster counting, redshift-space distortions...
- For all probes, **large galaxy surveys are needed**:
  - **Spectroscopic**: 3D (redshift), medium depth, low density, selection effects, **BAO**
  - **Imaging**: "2.5D" (photo-z), deeper, higher density, no selection effects, **WL**

Spectroscopic redshift vs. photo-z



$$
\begin{array}{rccc}
\text{Spectroscopy:} & \sigma(z)/(1+z) & < & 0.001 \\
\text{Photo-z:} & \sigma(z)/(1+z) & \sim & 0.05
\end{array}
$$

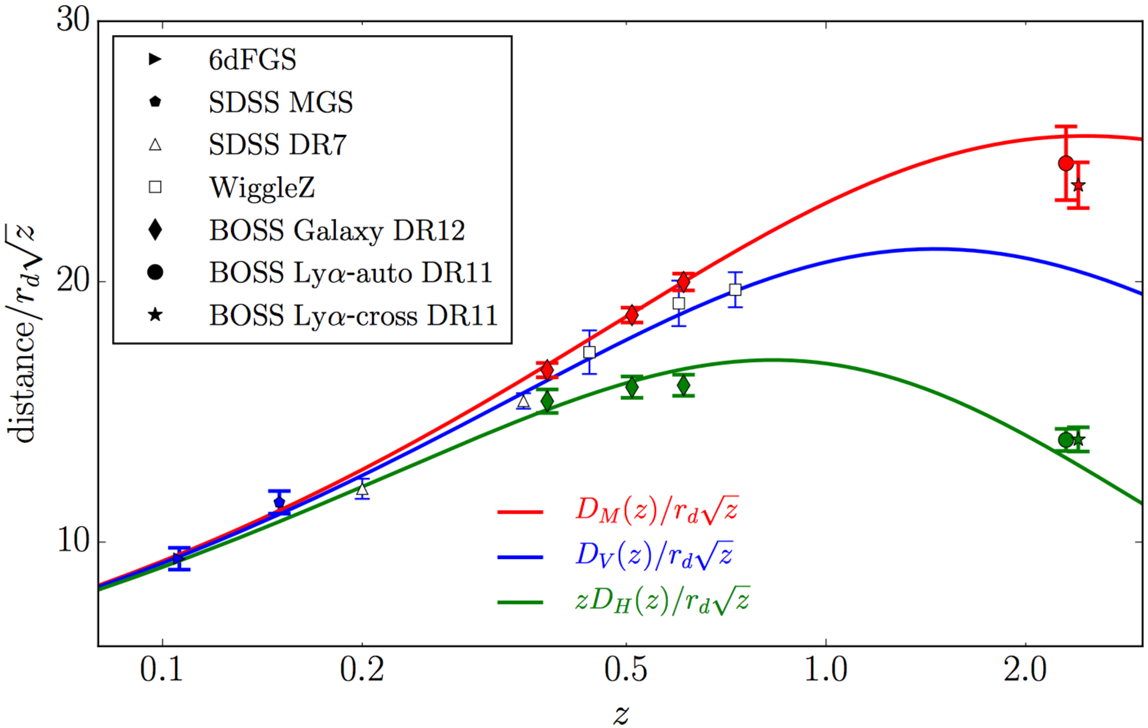
Survey of galaxy surveys



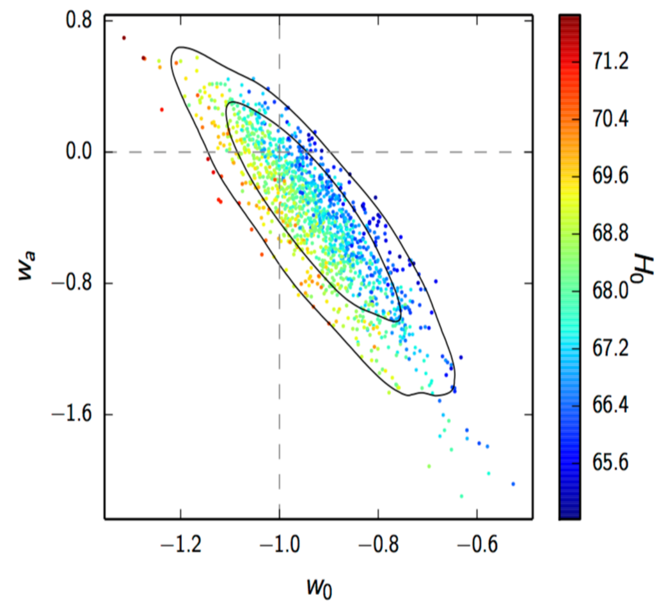
Kinematical probes: BAO

State of the art: BOSS (+ Planck +SNe)

- BOSS finished data taking in 2014: ~9,400 deg^2
- It measured the BAO scale in galaxies and Ly-α quasars



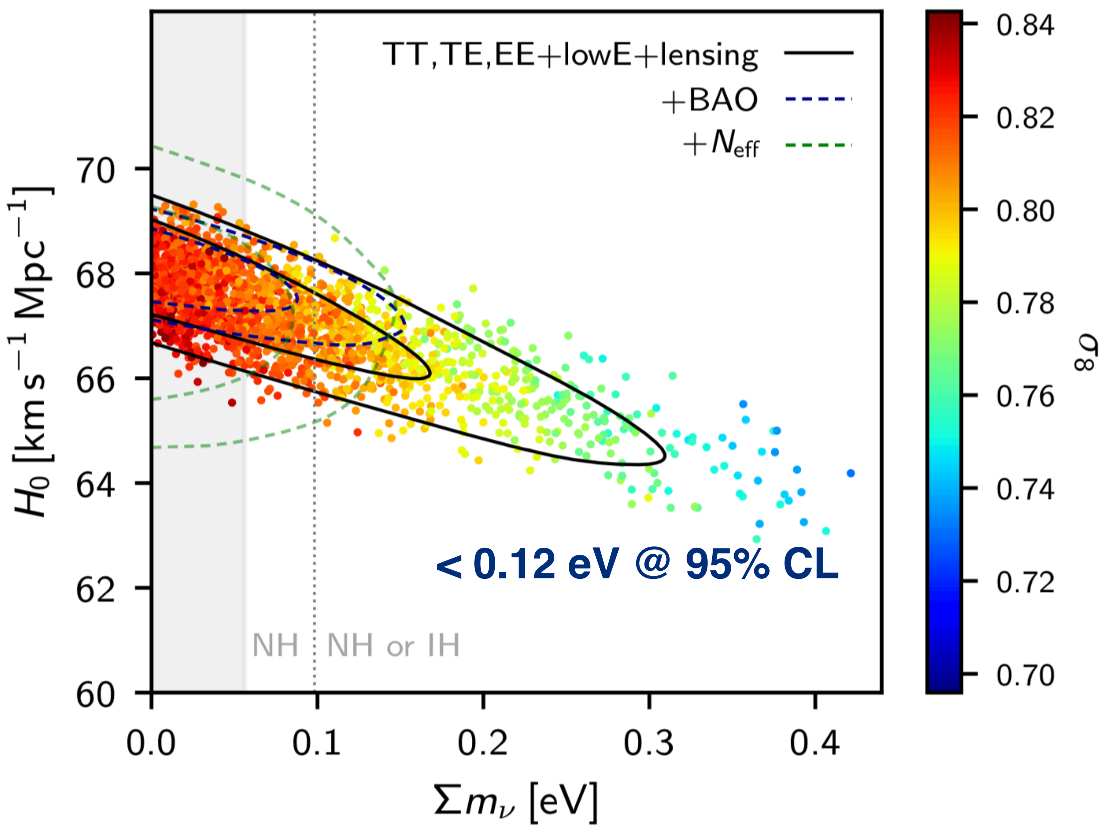
BOSS, MNRAS 470 (2017) 2617



Planck, A&A 594 (2016) A14
(Planck + BAO + SNe)

$w = p / \rho = w_0 + w_a \times (1-a)$, with
$w_0 = w$ (now)
$w_a = -\,dw / da$ (now)

Neutrino mass

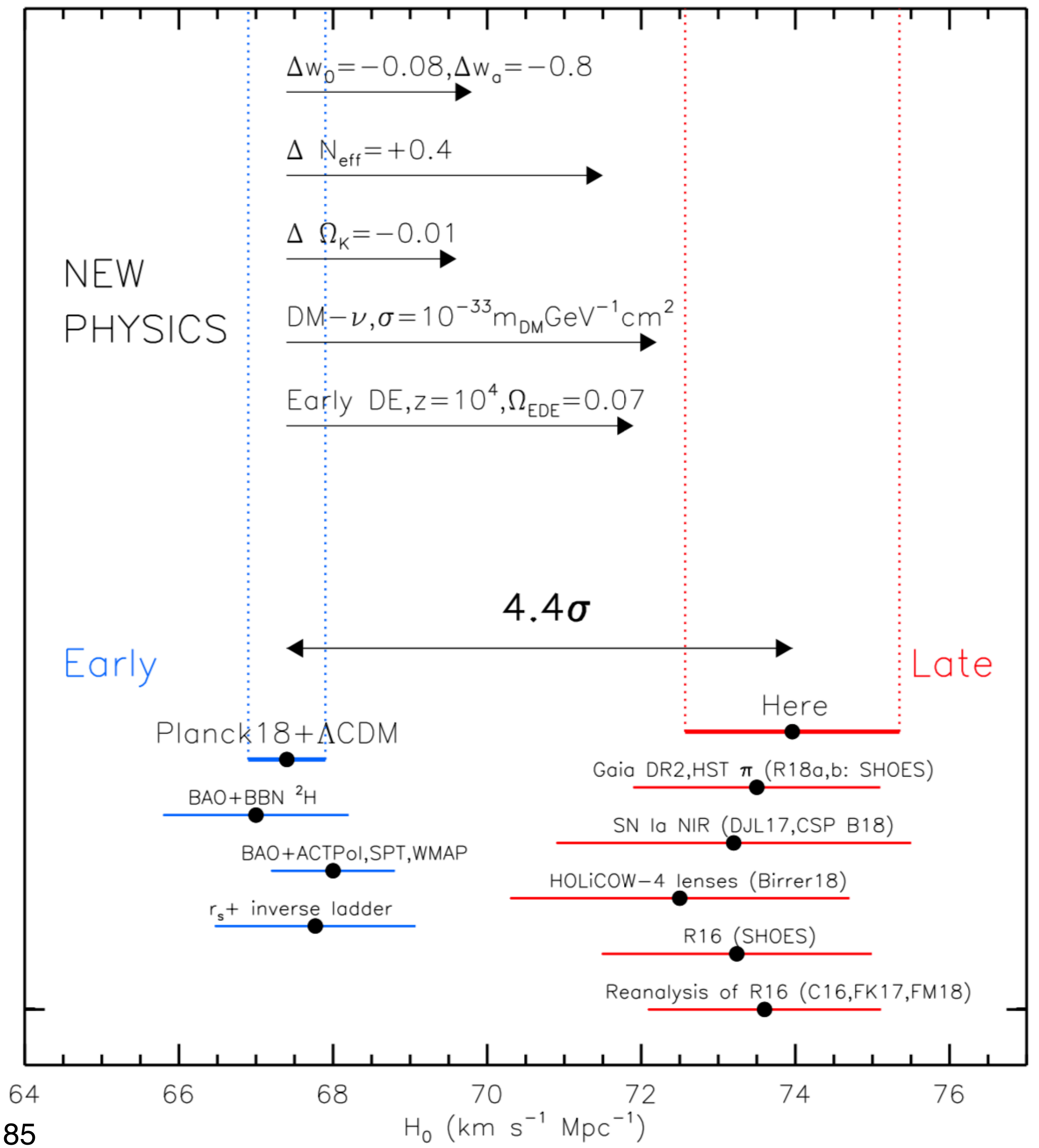


Planck, arXiv:1807.06209

All next generation surveys have the sensitivity to reach a detection

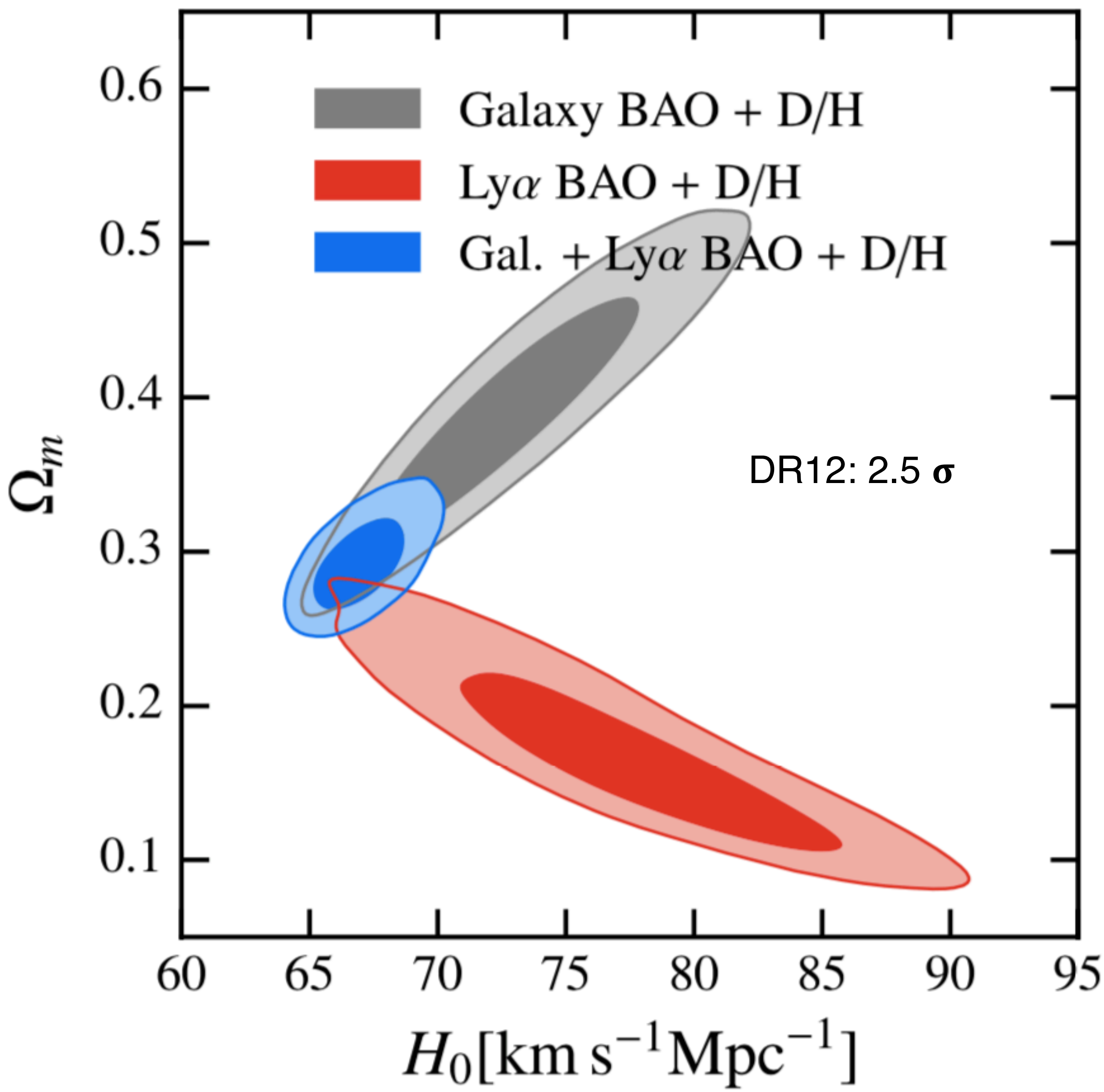
Ex: DESI (+ Planck) forecast a sensitivity ~ 0.02 eV

H_0: tension



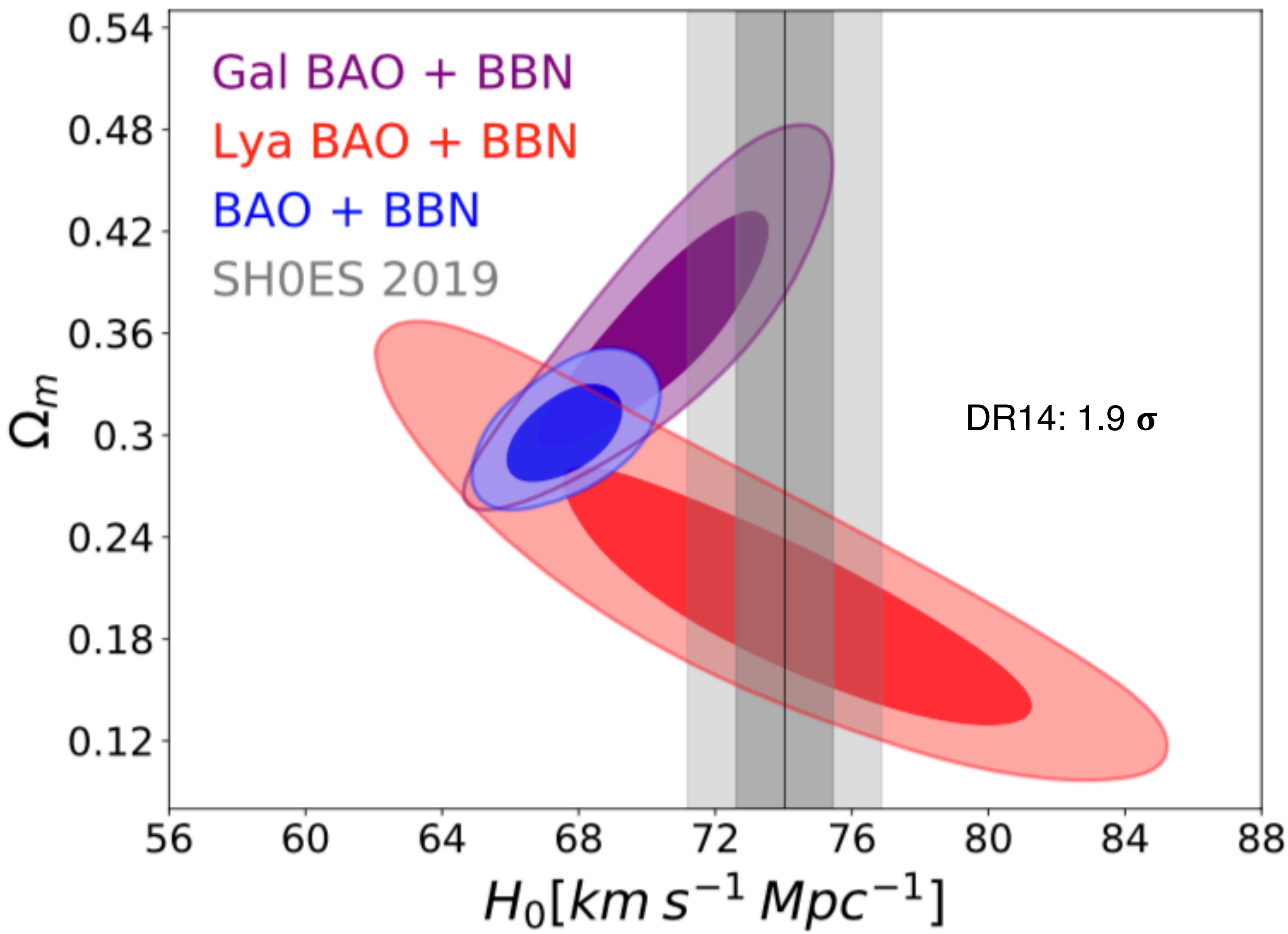
Riess et al, ApJ 876 (2019) 85

BAO internal tension?



Addison et al, ApJ 853 (2018) 119

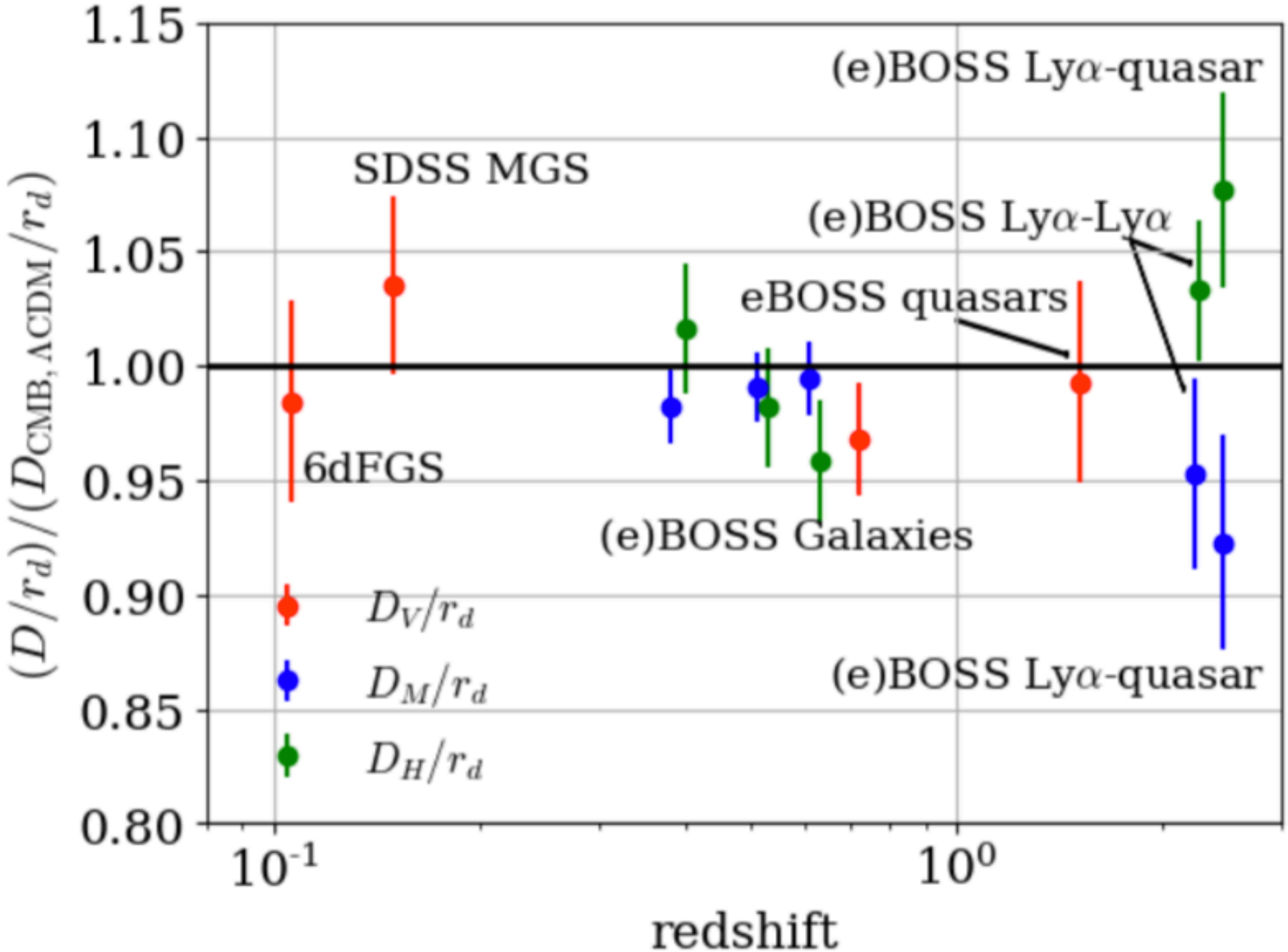
BAO internal tension?



DR14: 1.9 σ

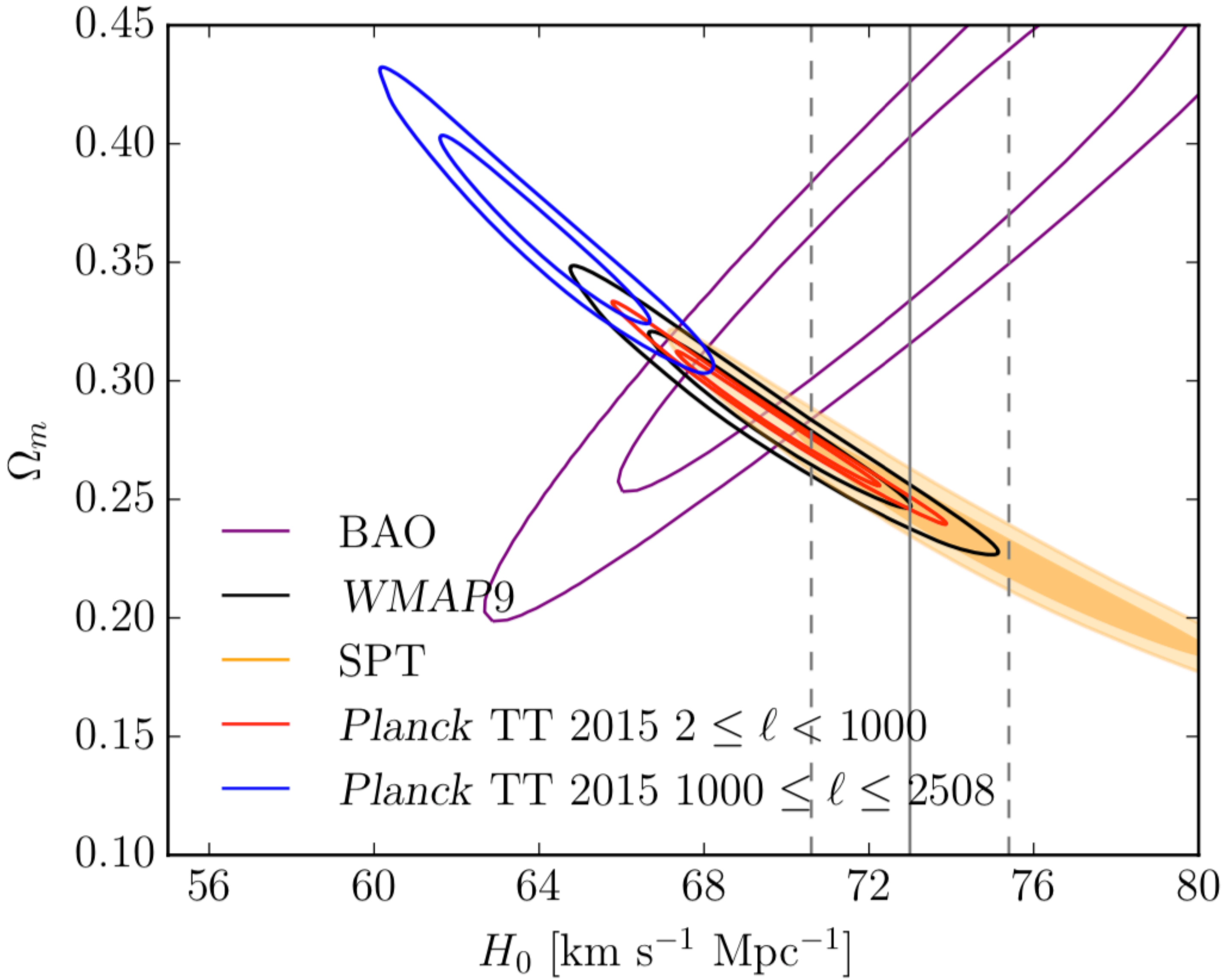
Cuceu et al, arXiv:1906.11628

BAO Ly-α internal tension?



Blomquist et al, A&A 629 (2019) A86

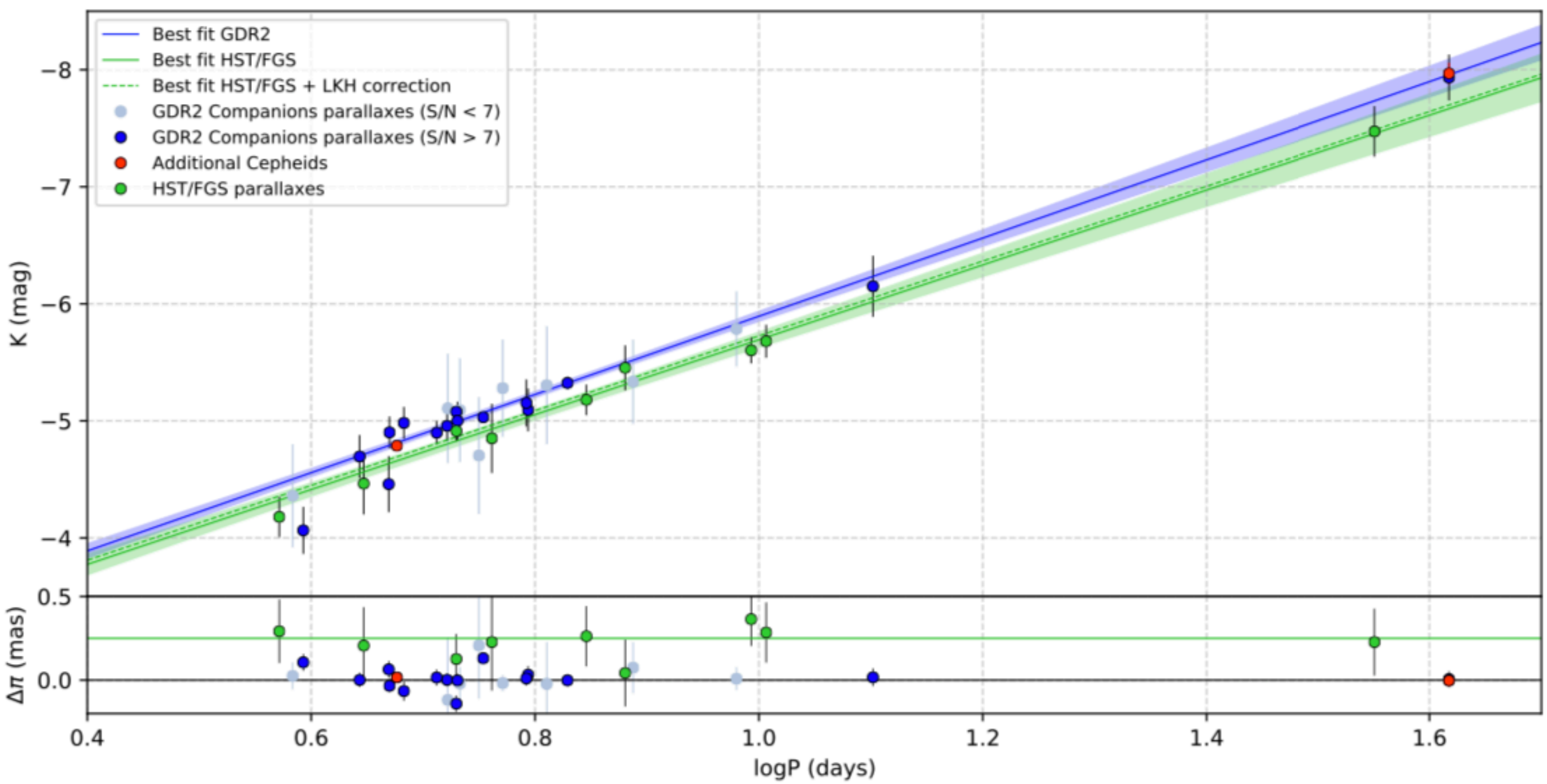
Planck internal tension?



Addison et al, ApJ 818 (2016) 132

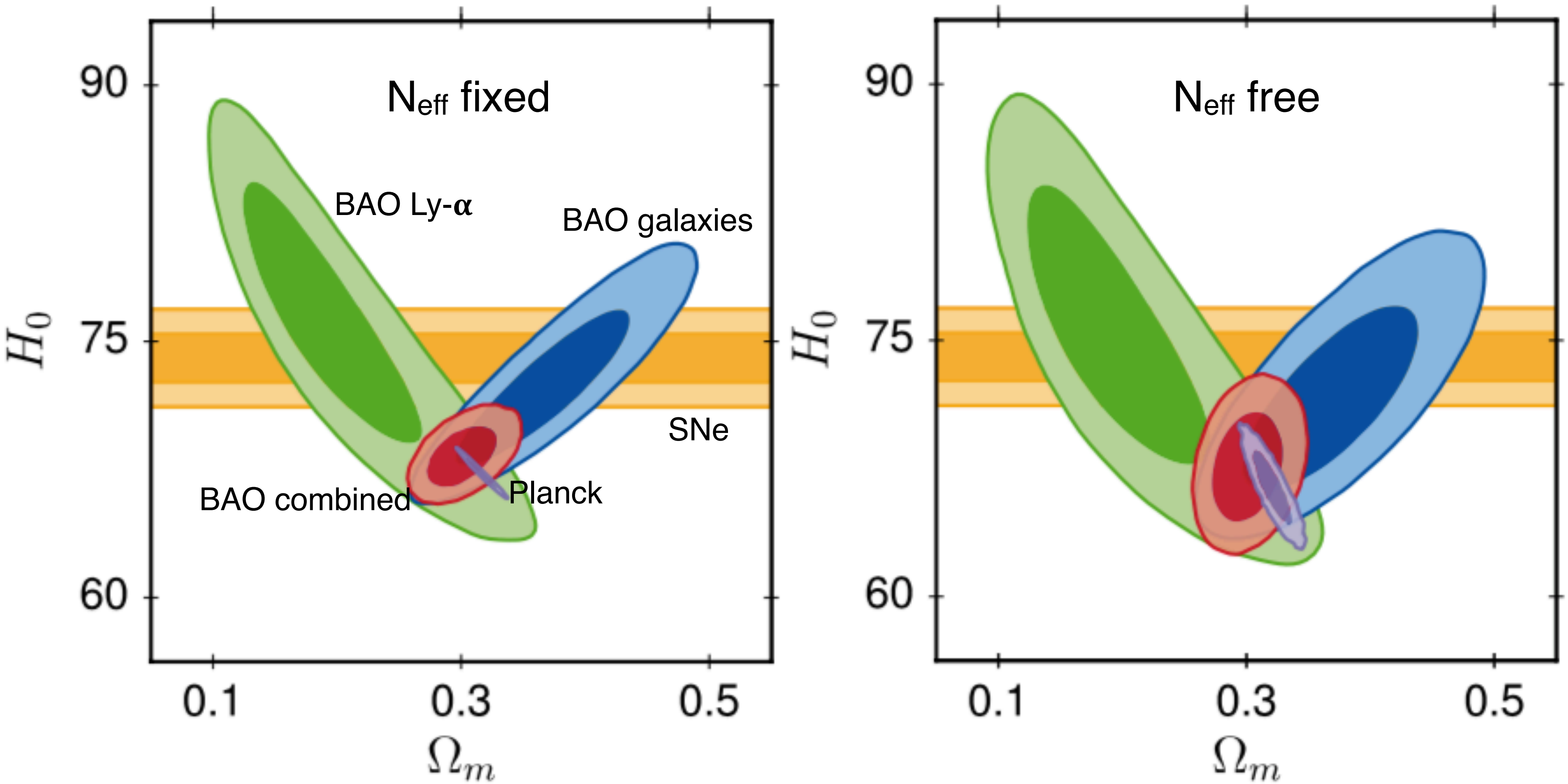
Systematics in direct measurement?

- Recent analysis of parallaxes of a Gaia Cepheid-companion sample produces a very different period-luminosity relation.
- This then translates into H_0 = (69 ± 2) km/s/Mpc.



Breuval et al, arXiv:1910.04694

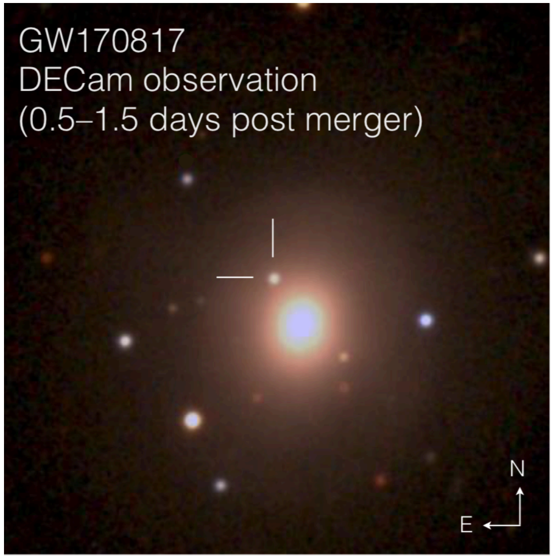
Does it help to float N_{eff}?



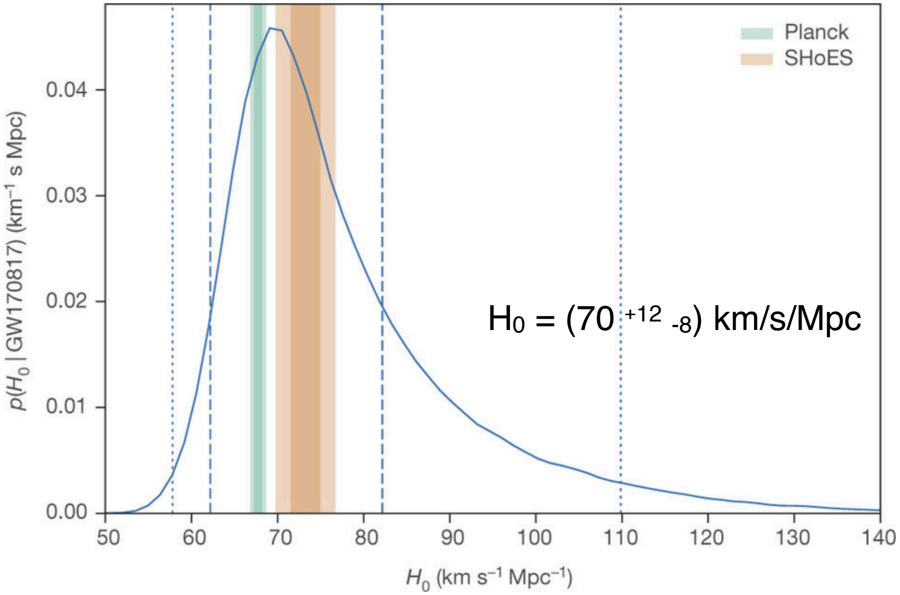
Schöneberg, Lesgourgues, Hooper, JCAP 1910 (2019) 029

H_0 from gravitational waves (I)

- Neutron star-neutron star mergers are "standard sirens": one can determine accurately the **distance** to the event from the GW signal.
- Since NS-NS mergers have optical counterparts, one can determine the host galaxy and its **redshift ➡ Hubble diagram**.
- From the one local event GW170817, one can already determine H_0.



z = 0.0098



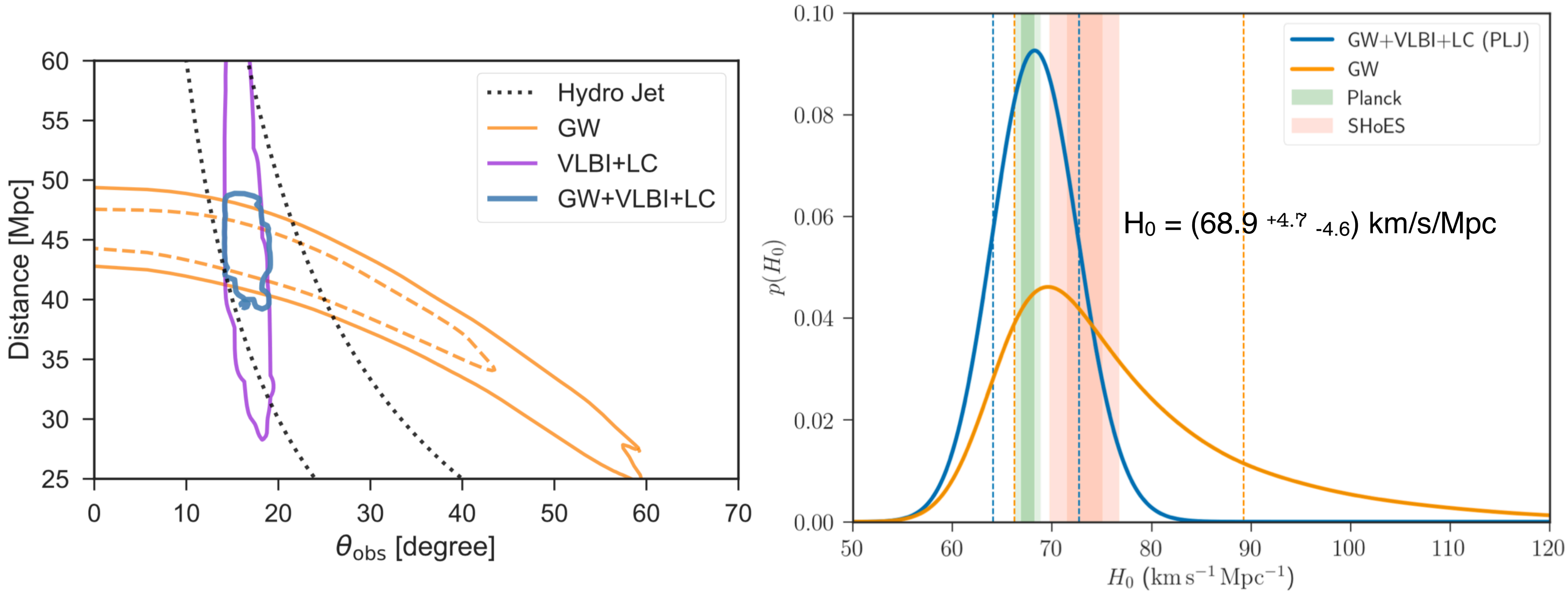
$H_0 = (70^{+12}_{-8})$ km/s/Mpc

Soares-Santos et al, ApJ 848 (2017) L16

Abbott et al (LIGO, Virgo, DES et al.), Nature 551 (2017) 85

H_0 from gravitational waves (II)

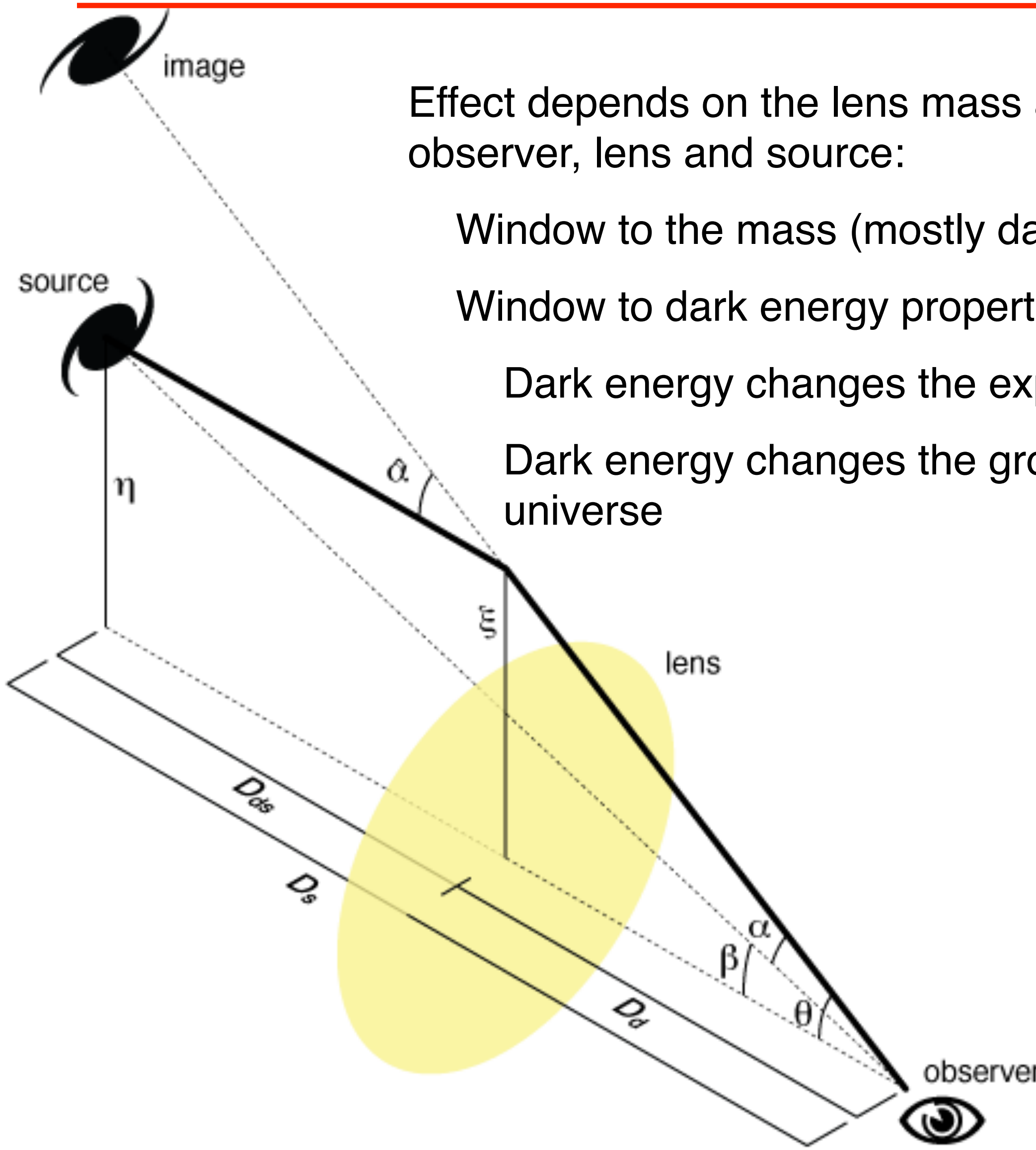
- Analyzing radio data, one can constrain the viewing angle, which is the leading systematic error, and reduce the overall error by half.
- It looks like 15-20 NS-NS mergers with reasonably favorable orientations might be enough to adjudicate the current H_0 discrepancy.
- A sample like this could already become available in late 2020.



Hotokezaka et al, Nature Astron. 3 (2019) 940

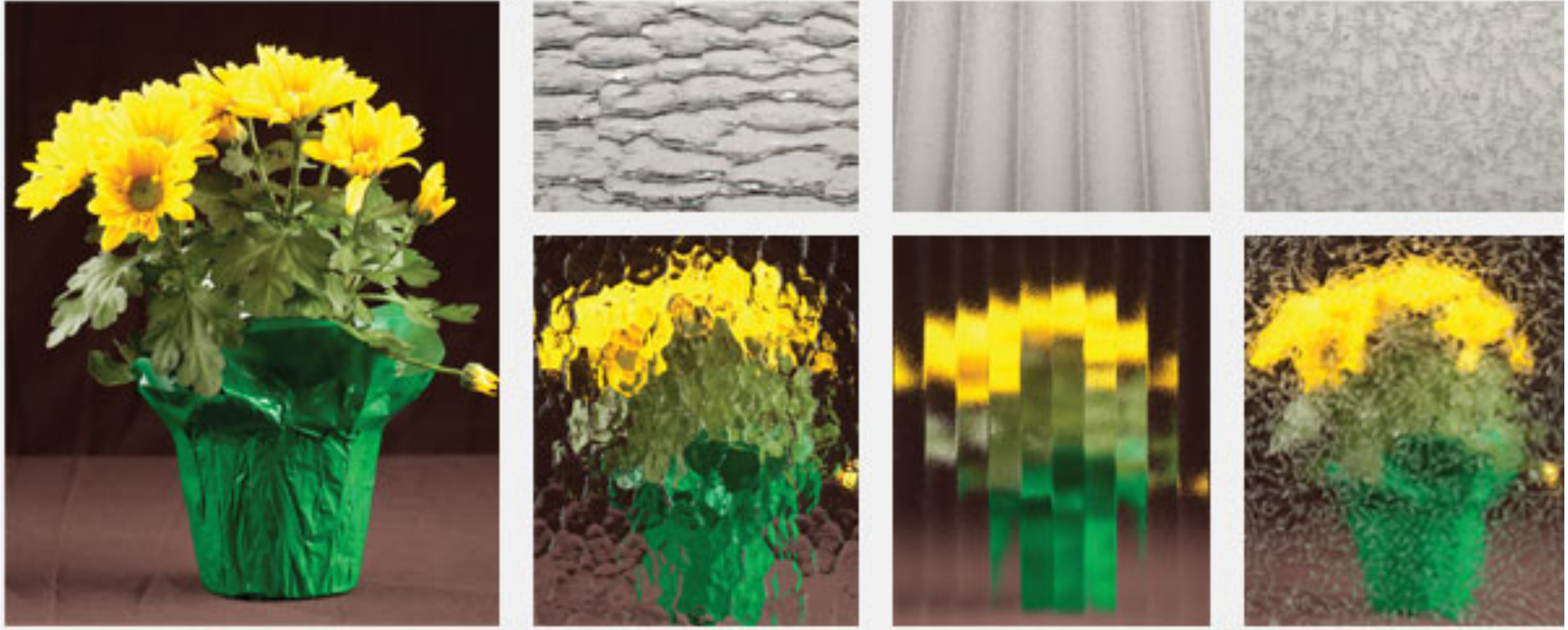
Dynamical probes: weak lensing

Weak gravitational lensing (I)

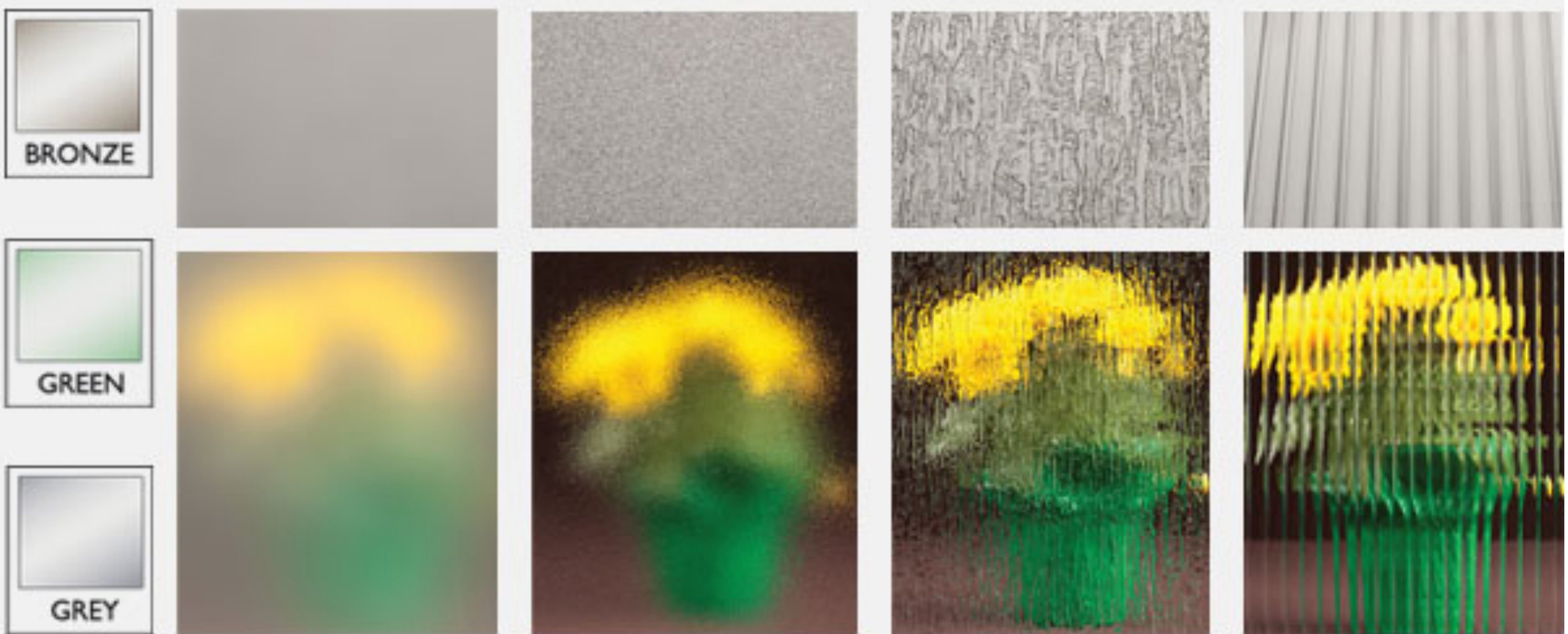


Effect depends on the lens mass and the distances between observer, lens and source:

- Window to the mass (mostly dark matter) distribution in the lenses
- Window to dark energy properties:
  - Dark energy changes the expansion rate: distances $\mathbf{D_d, D_s, D_{ds}}$
  - Dark energy changes the growth rate of mass structures in the universe



CLEAR ARCTIC FLUTEX GLUECHIP



Weak gravitational lensing (II)

- Linearized lens equation: $\vec{\beta} - \vec{\beta_0} = A(\vec{\theta_0})(\vec{\theta} - \vec{\theta_0})$

  source image

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

$$g_i = \gamma_i/(1-\kappa)$$

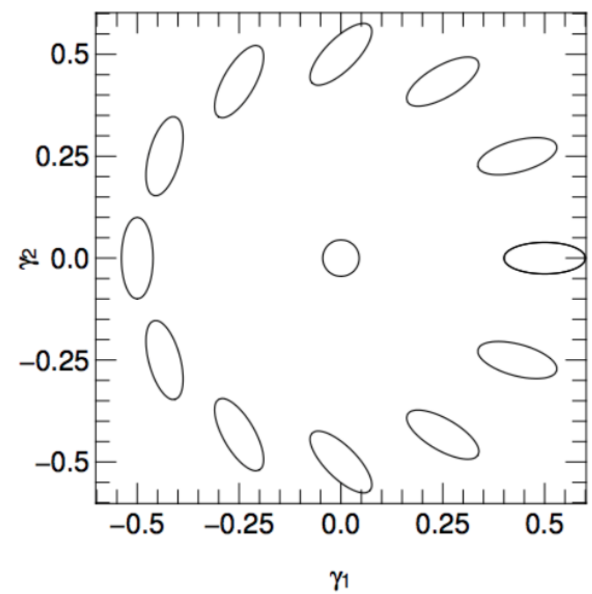
$$\kappa = \frac{1}{2}(\Psi_{,11} + \Psi_{,22}) = \frac{1}{2}\Delta\Psi$$

Ψ: lens-power-weighted integral of gravitational potential

Convergence: change in size 2D Poisson equation: 2*κ* gives us the matter density along the line of sight

$$\gamma = \gamma_1 + i\gamma_2 = |\gamma|e^{i2\phi} = \frac{1}{2}(\Psi_{,11} - \Psi_{,22}) + \Psi_{,12}$$

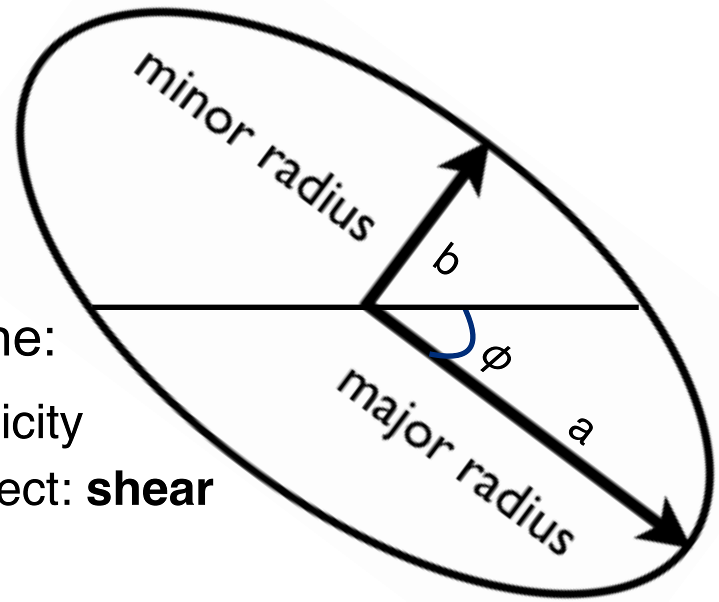
Shear: change in shape Spin-2 object Same information as *κ*



- Since we don't know the original sizes of the galaxies, ***κ*** can't be measured directly
- However, we can infer it from ***γ*** (or ***g***)

Weak gravitational lensing (III)

DARK ENERGY SURVEY



- Let's measure the **ellipticity** of a galaxy:

$$\epsilon = \frac{a-b}{a+b} e^{i2\phi}$$

- The measured ellipticity relates to the real one:

$$\epsilon = \frac{\epsilon^s + g}{1 + g^* \epsilon^s} \simeq \epsilon^s + \gamma$$

ϵ^s : real source ellipticity
γ : weak lensing effect: **shear**

- The expectation value of the measured ellipticity is:

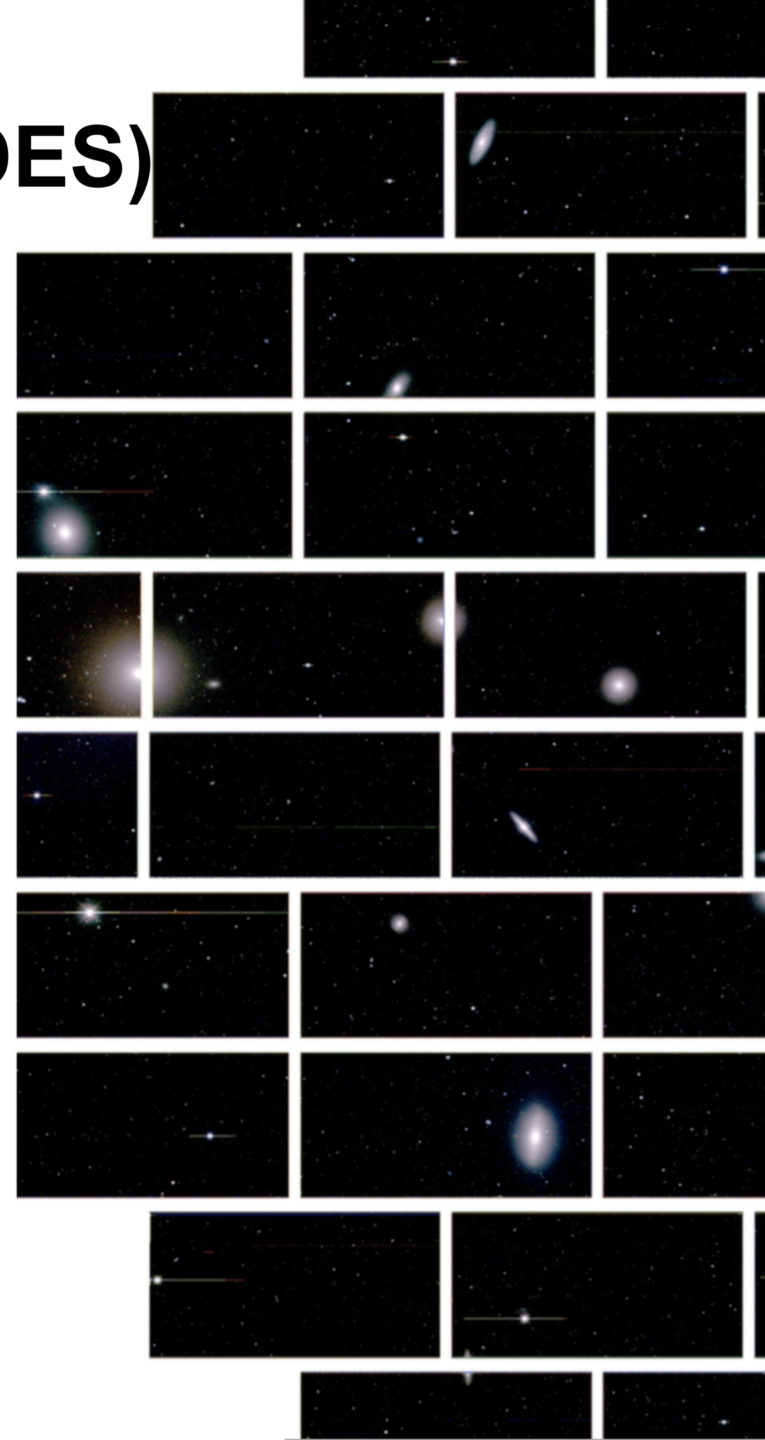
$$\langle \epsilon \rangle \simeq \langle \epsilon^s \rangle + \gamma = \gamma \,,$$ since $<\epsilon^s> = 0$

- So **the ellipticity is an unbiased estimator of the shear.**

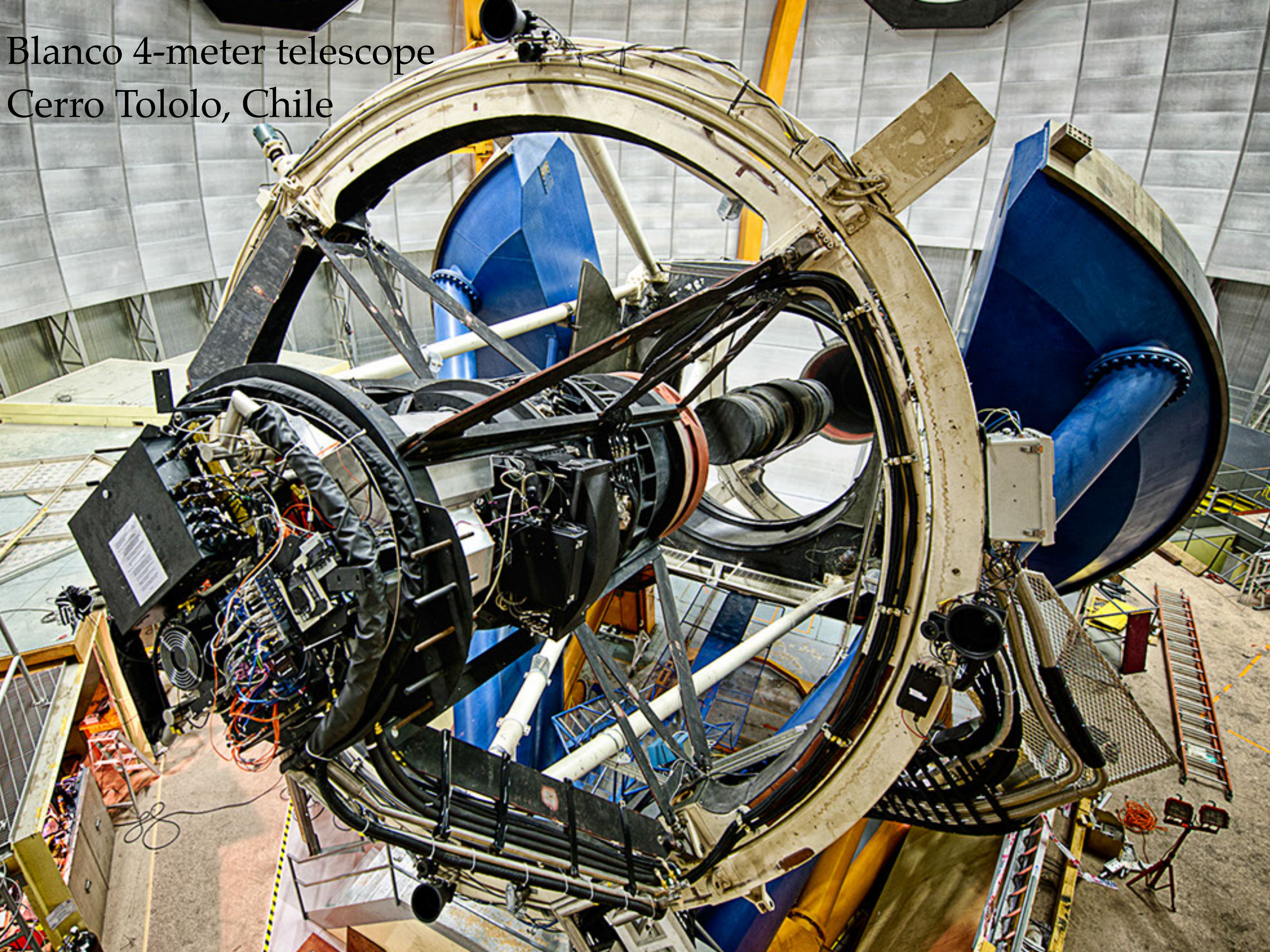
- However, it's a very noisy estimator: **$|\epsilon^s| \sim 0.3$, $|\gamma| \sim 0.01$.**
  We need very many galaxies and exquisite control of systematic errors.

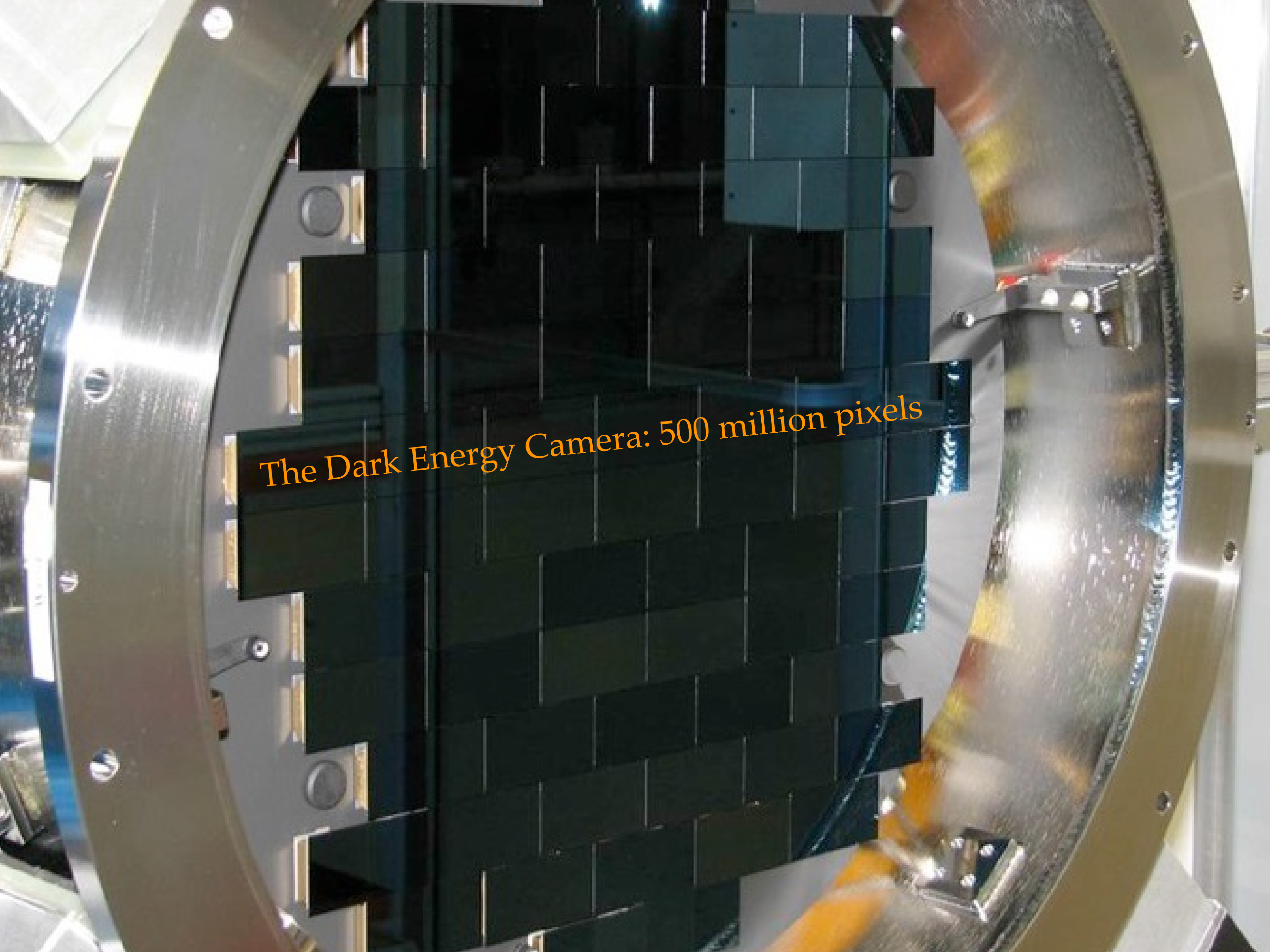
Dark Energy Survey (DES)

DARK ENERGY SURVEY



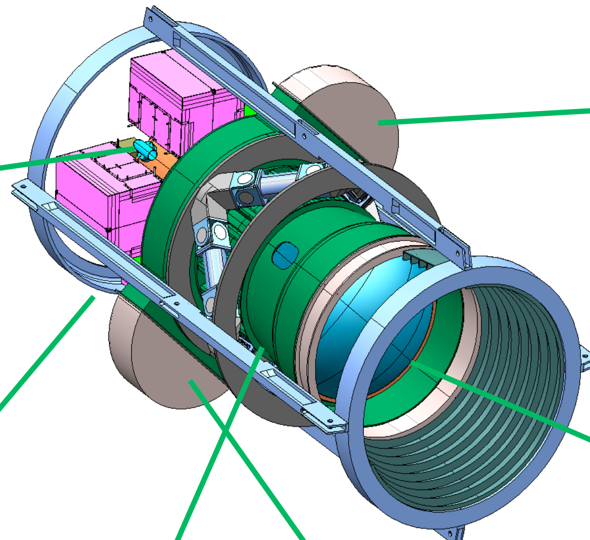
- Imaging galaxy survey on the 4-m Blanco telescope (Chile) to study Dark Energy.
- 350 scientists in 28 institutions in USA, Spain, UK, Brazil, Switzerland, Germany, Australia.
- Started in 2013, ended in Jan 2019: 577 nights in 6 seasons.
- Has mapped 1/8 of sky (5000 deg^2) to z ~ 1.3 in 5 optical bands: ~300 million galaxies.
- Four main dark energy probes:
  - Galaxy cluster counting.
  - Galaxy distribution (including BAO).
  - Type-Ia supernovae.
  - **Weak gravitational lensing.**

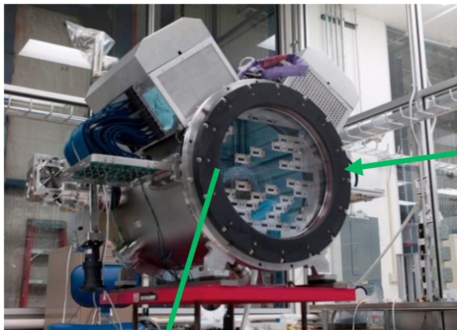

Blanco 4-meter telescope
Cerro Tololo, Chile


The Dark Energy Camera: 500 million pixels

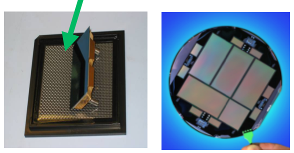
DARK ENERGY SURVEY

Components





Focal plane, Fermilab

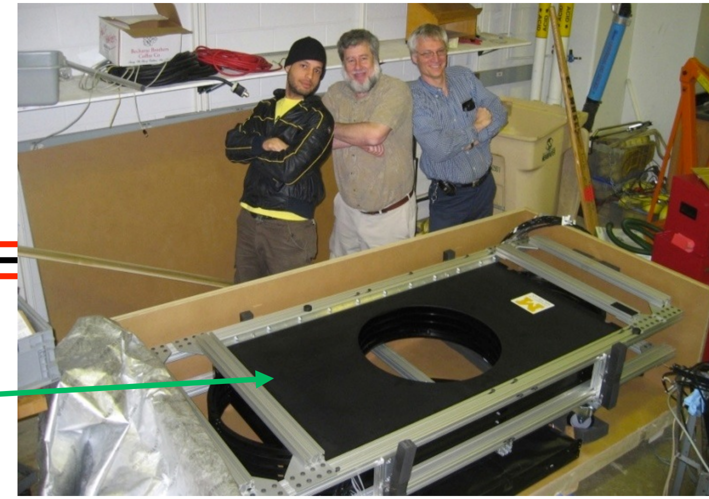


CCDs, Berkeley & Fermilab

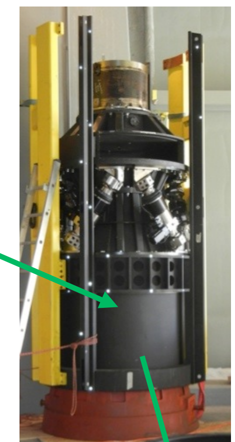
Electronics, IFAE, CIEMAT & Fermilab

Hexapod, Italy

Shutter, Bonn

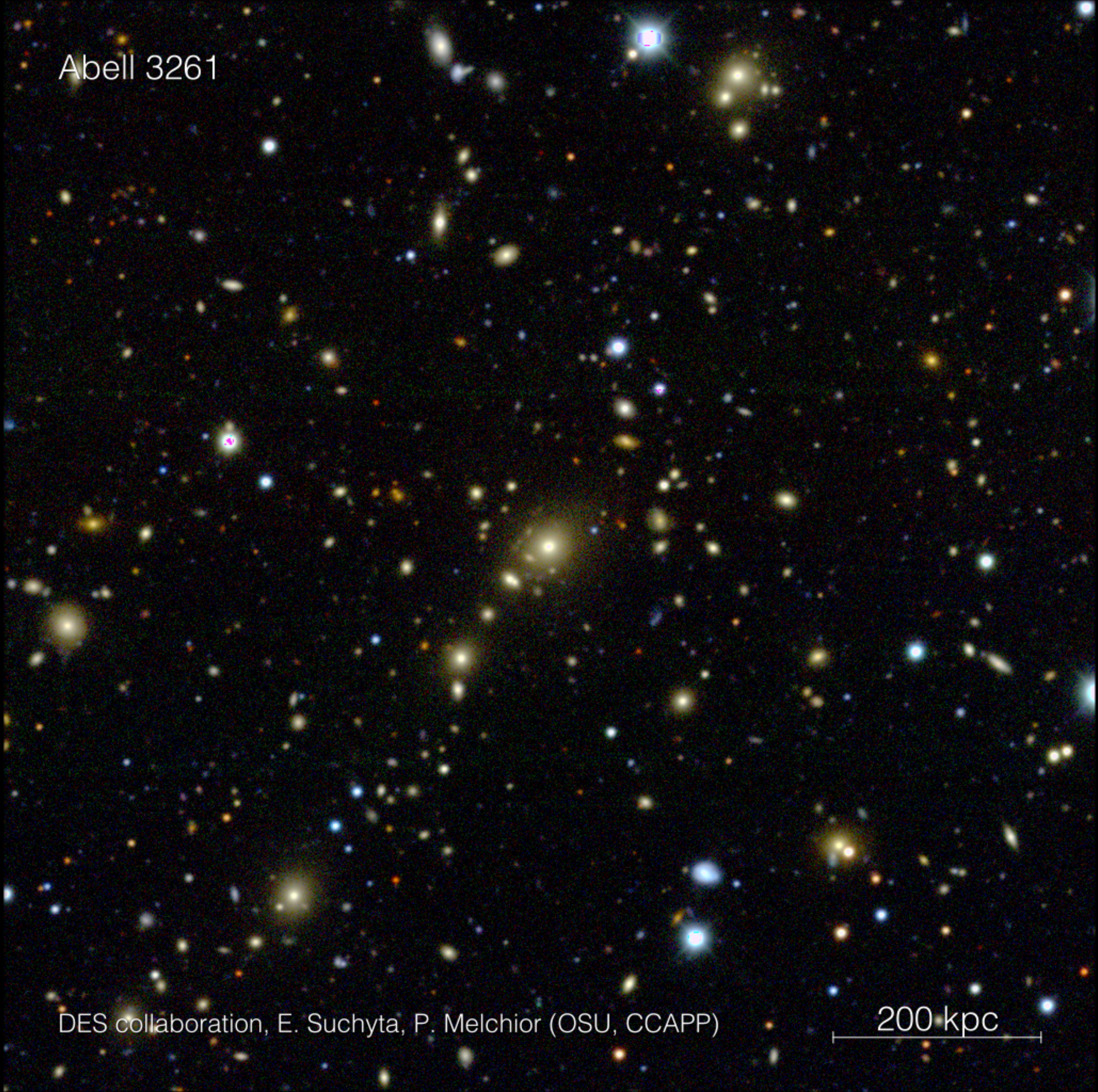


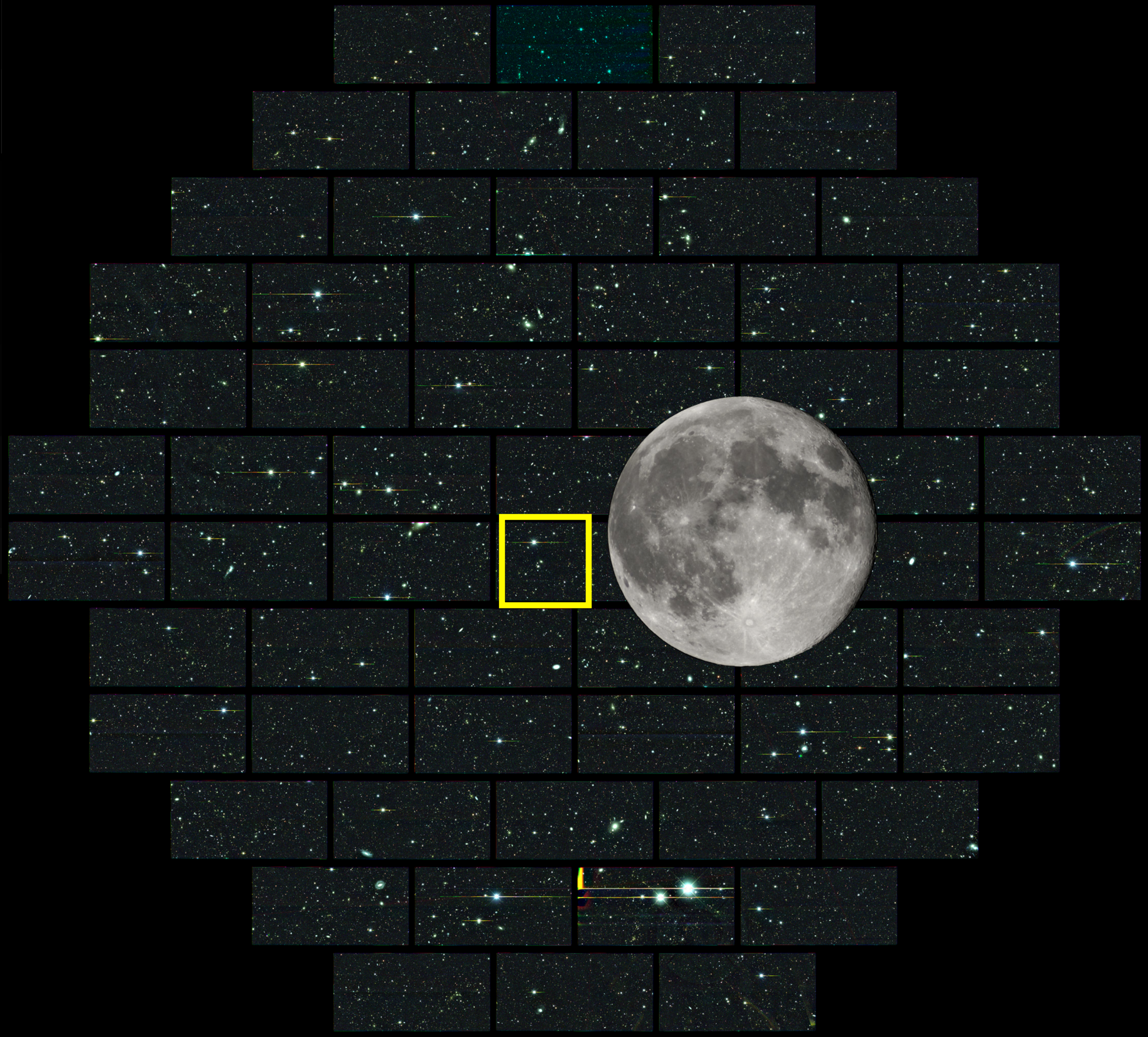
Filter exchanger, Michigan

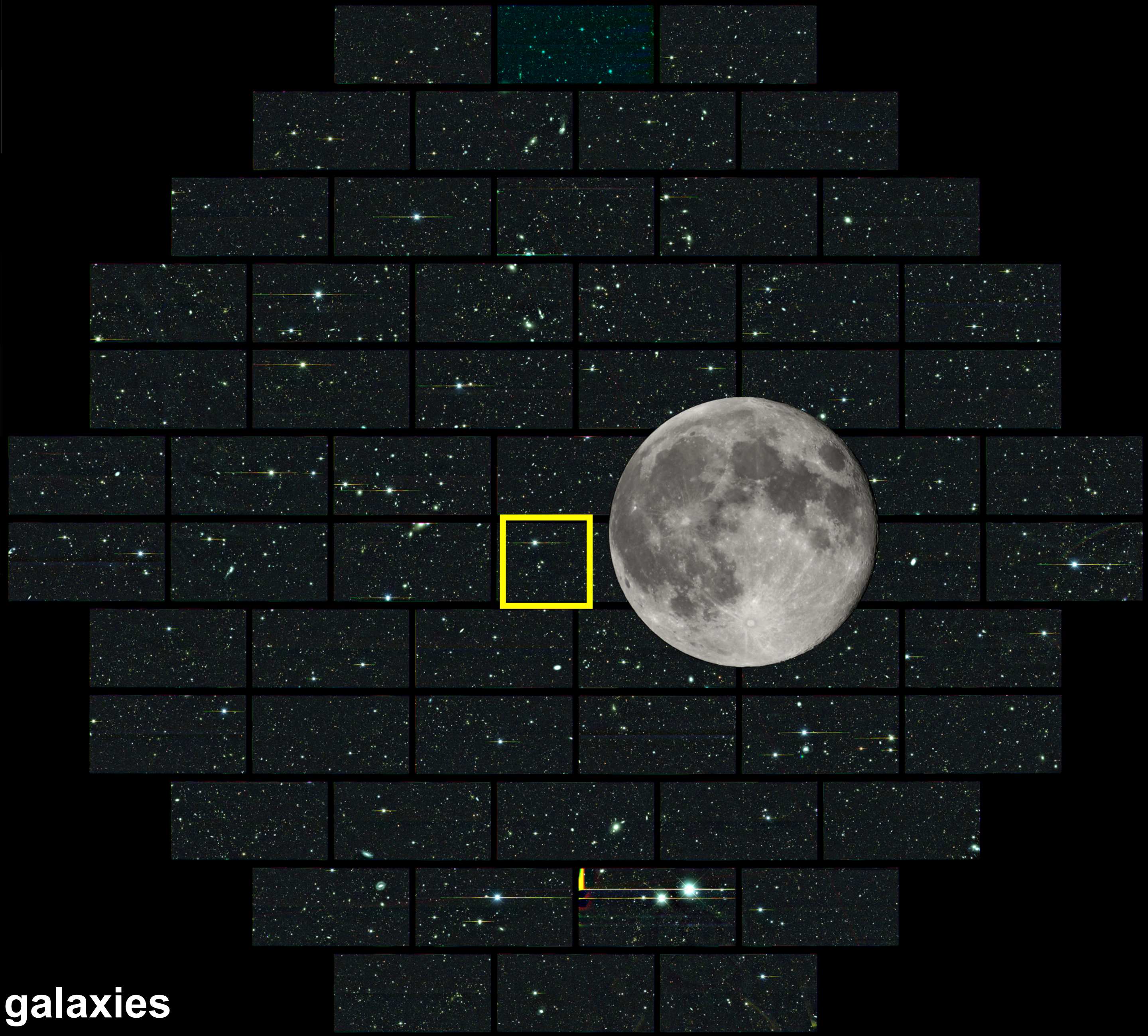


Barrel and box, Fermilab

Lenses, UK


Abell 3261
DES collaboration, E. Suchyta, P. Melchior (OSU, CCAPP)
200 kpc

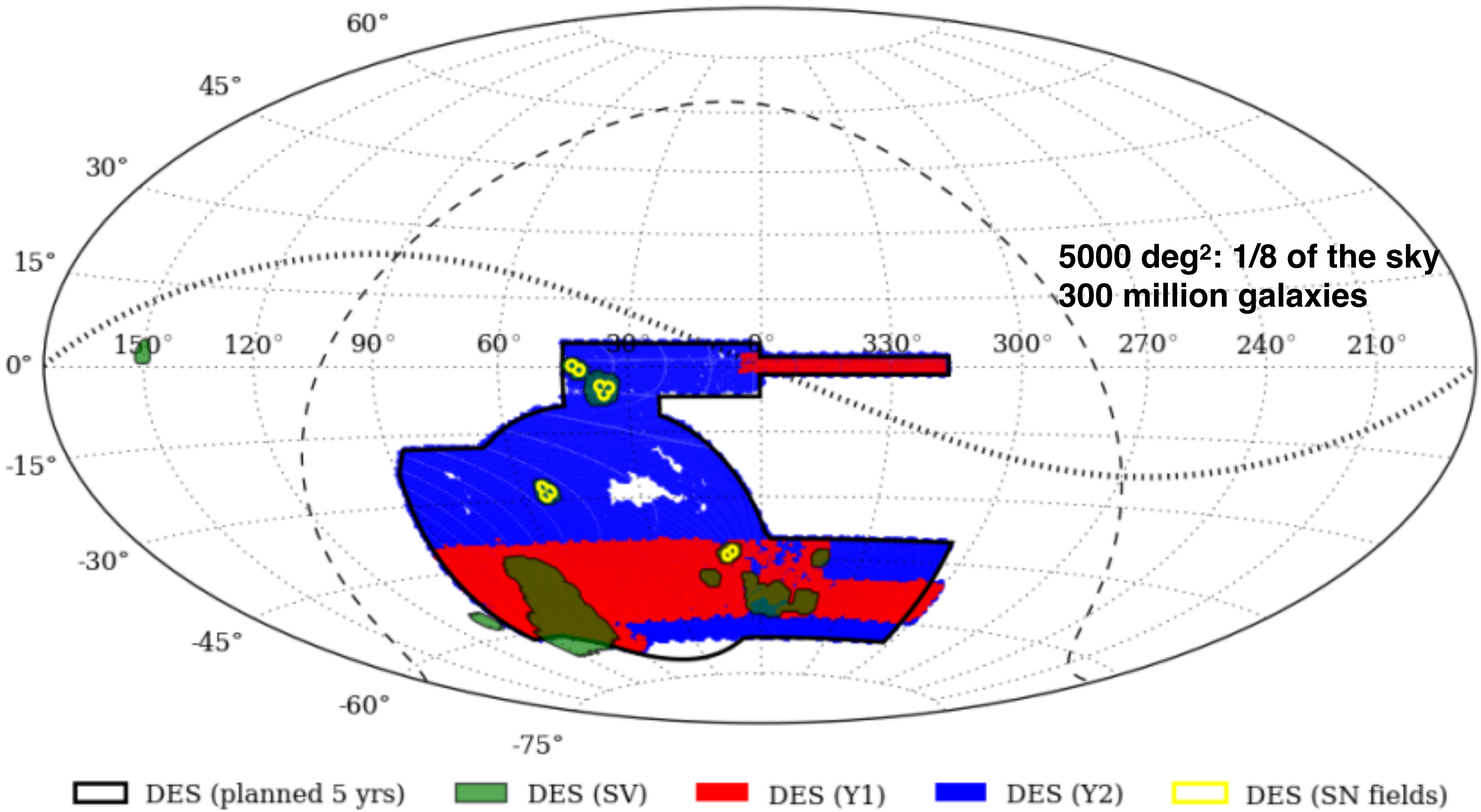




150 000 galaxies in a single image

DES coverage

DARK ENERGY SURVEY



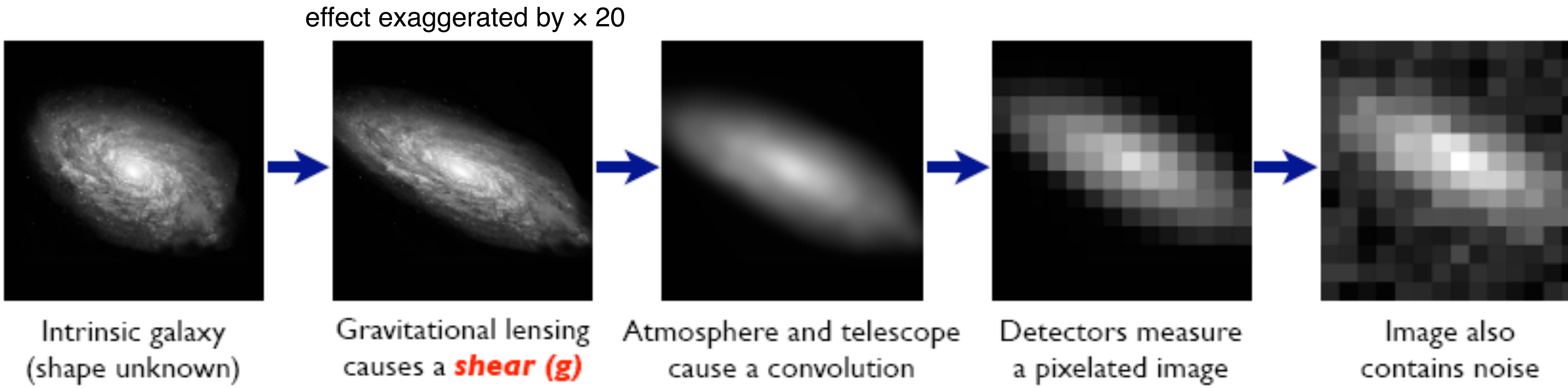
5000 deg²: 1/8 of the sky
300 million galaxies

From Galaxy to CCD Image

effect exaggerated by × 20

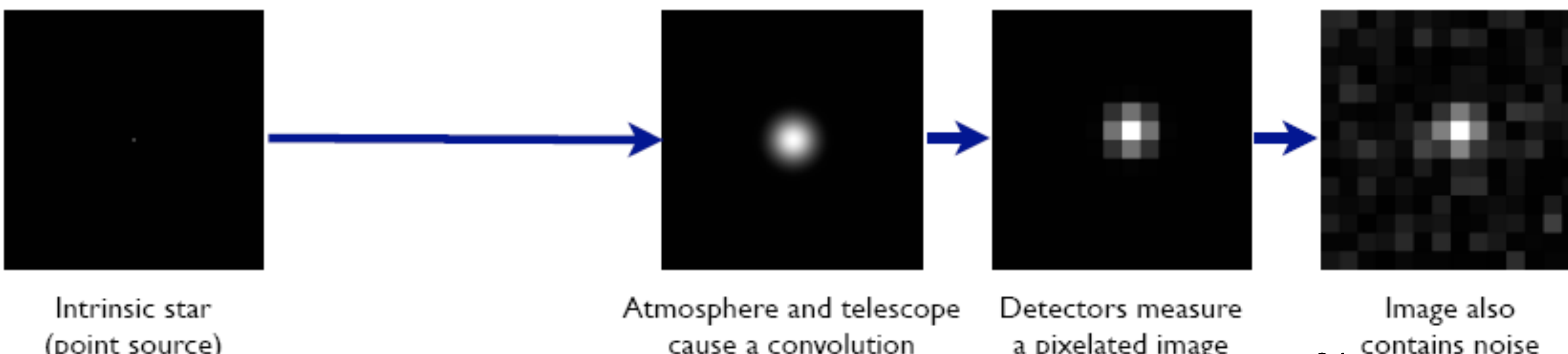
Intrinsic galaxy (shape unknown) | Gravitational lensing causes a ***shear (g)*** | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

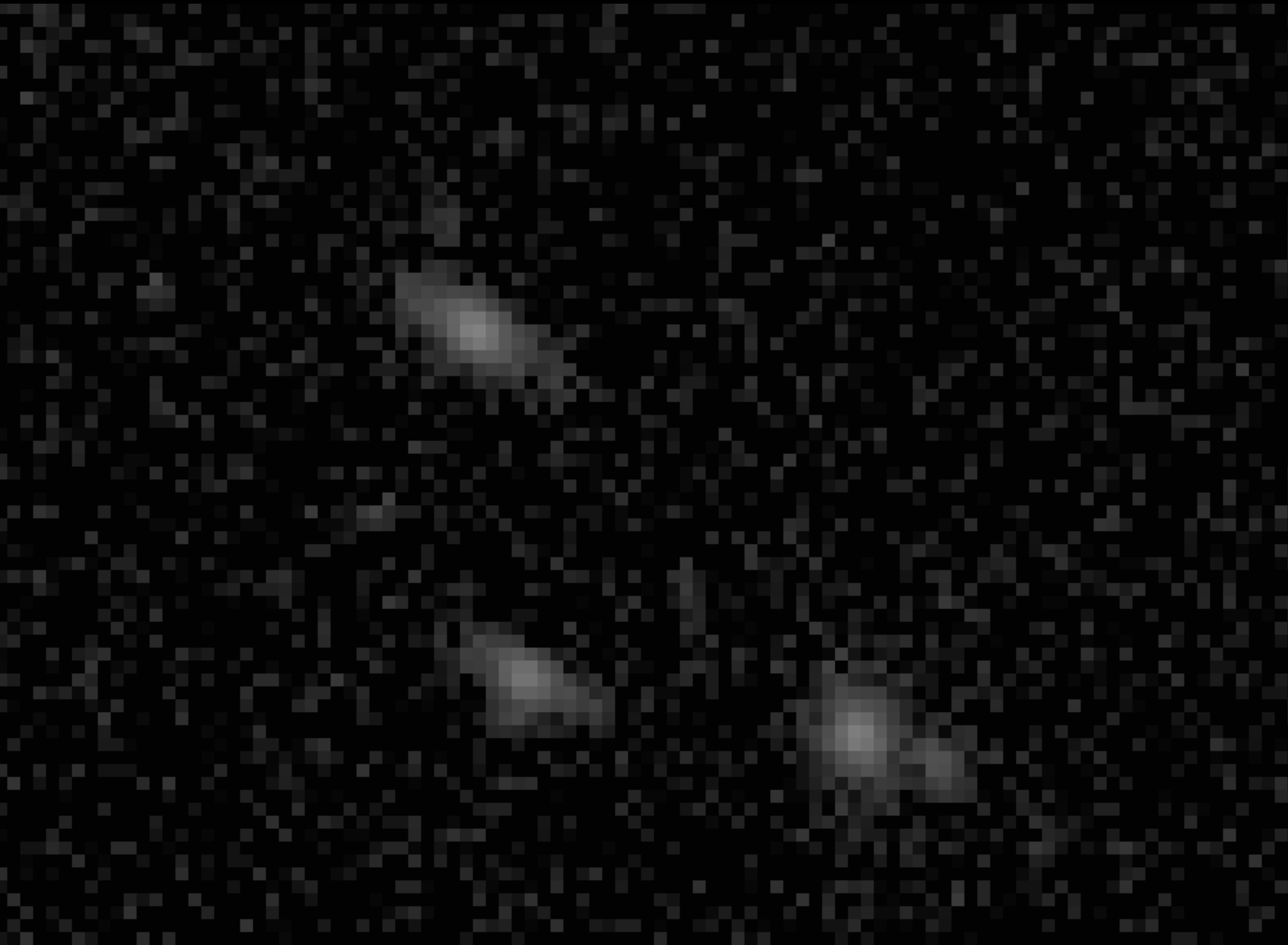
From Galaxy to CCD Image



From Star to CCD Image

PSF

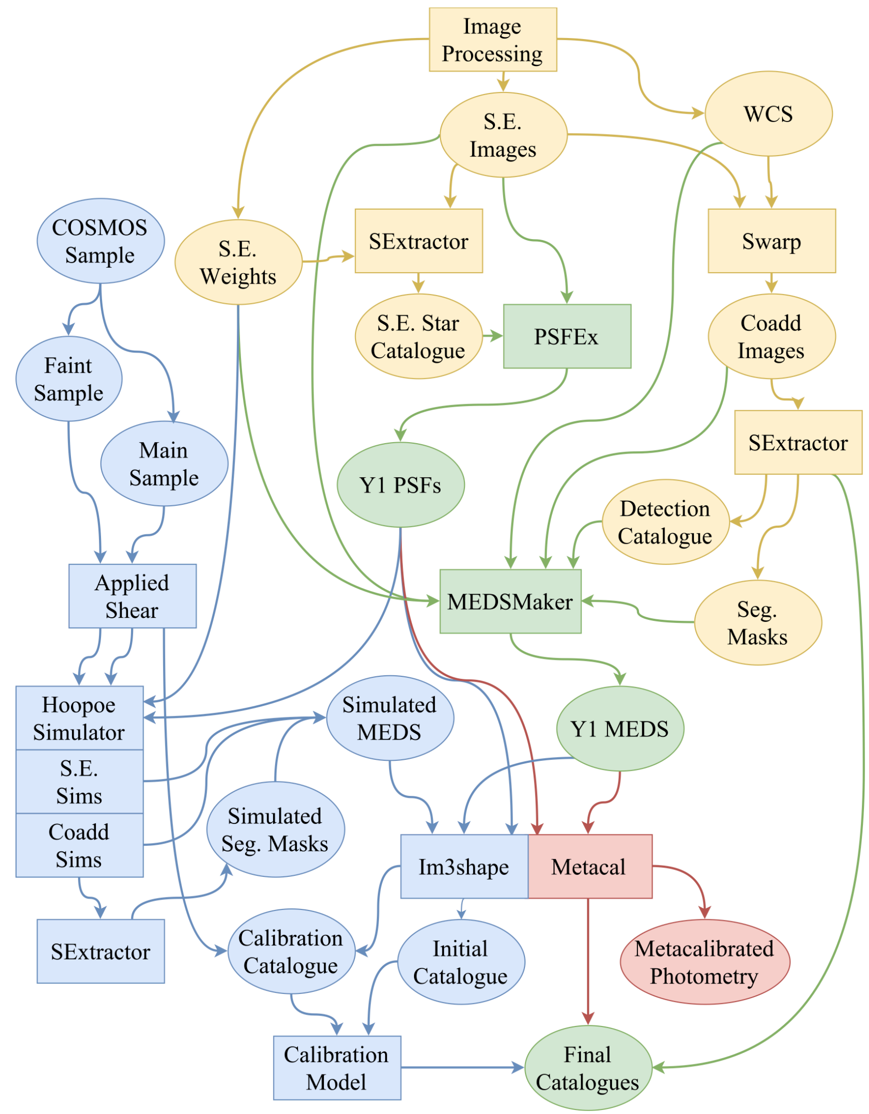




A huge effort!

Reduction of single-epoch images
Astrometric solution
Photometric calibration
Co-addition into deep images
Object detection
Flux measurement
Star / galaxy separation
PSF extraction from stars
Shape measurement on galaxies

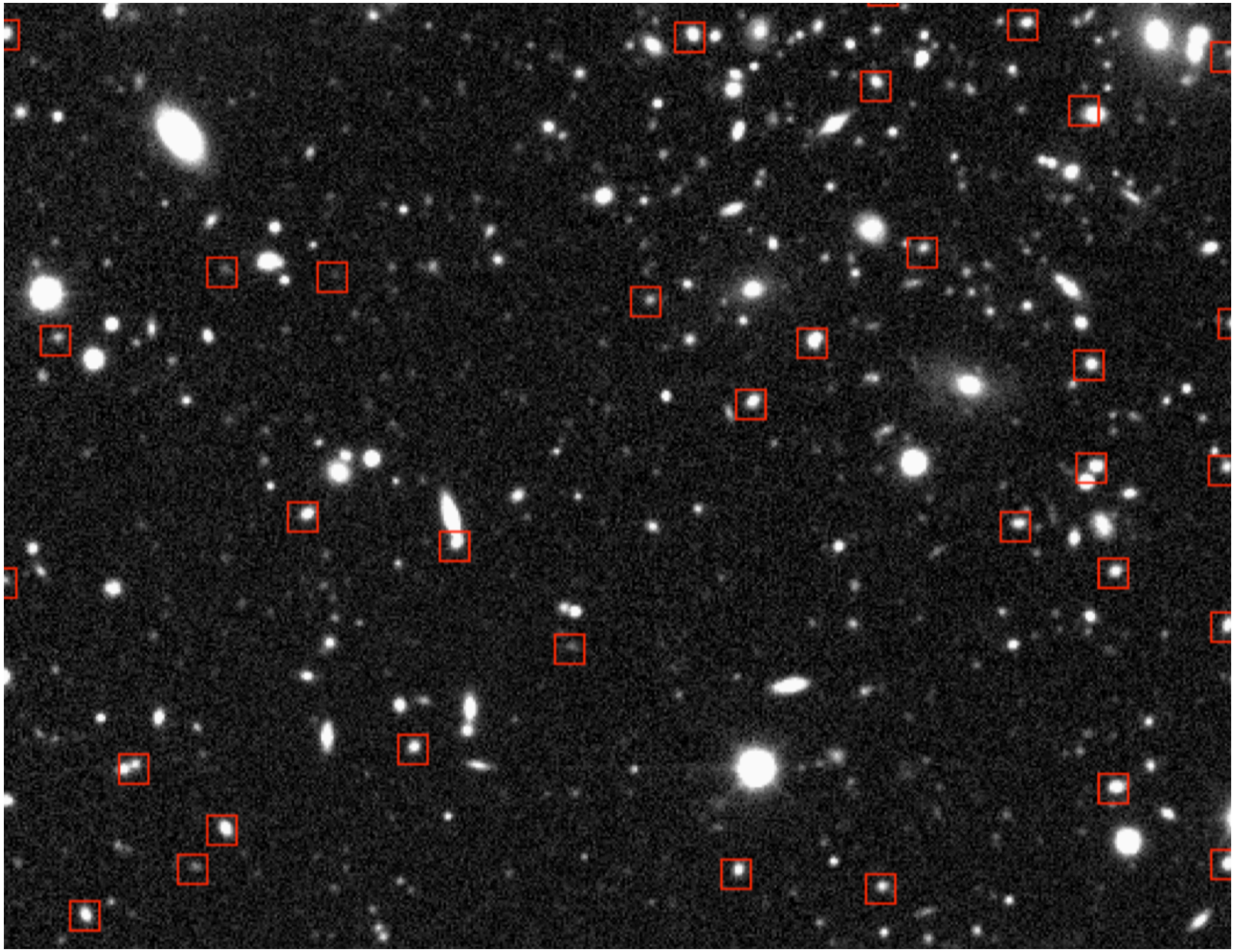
Each bubble can represent months of development and millions of CPU hours.



Tools: Balrog

DARK ENERGY SURVEY

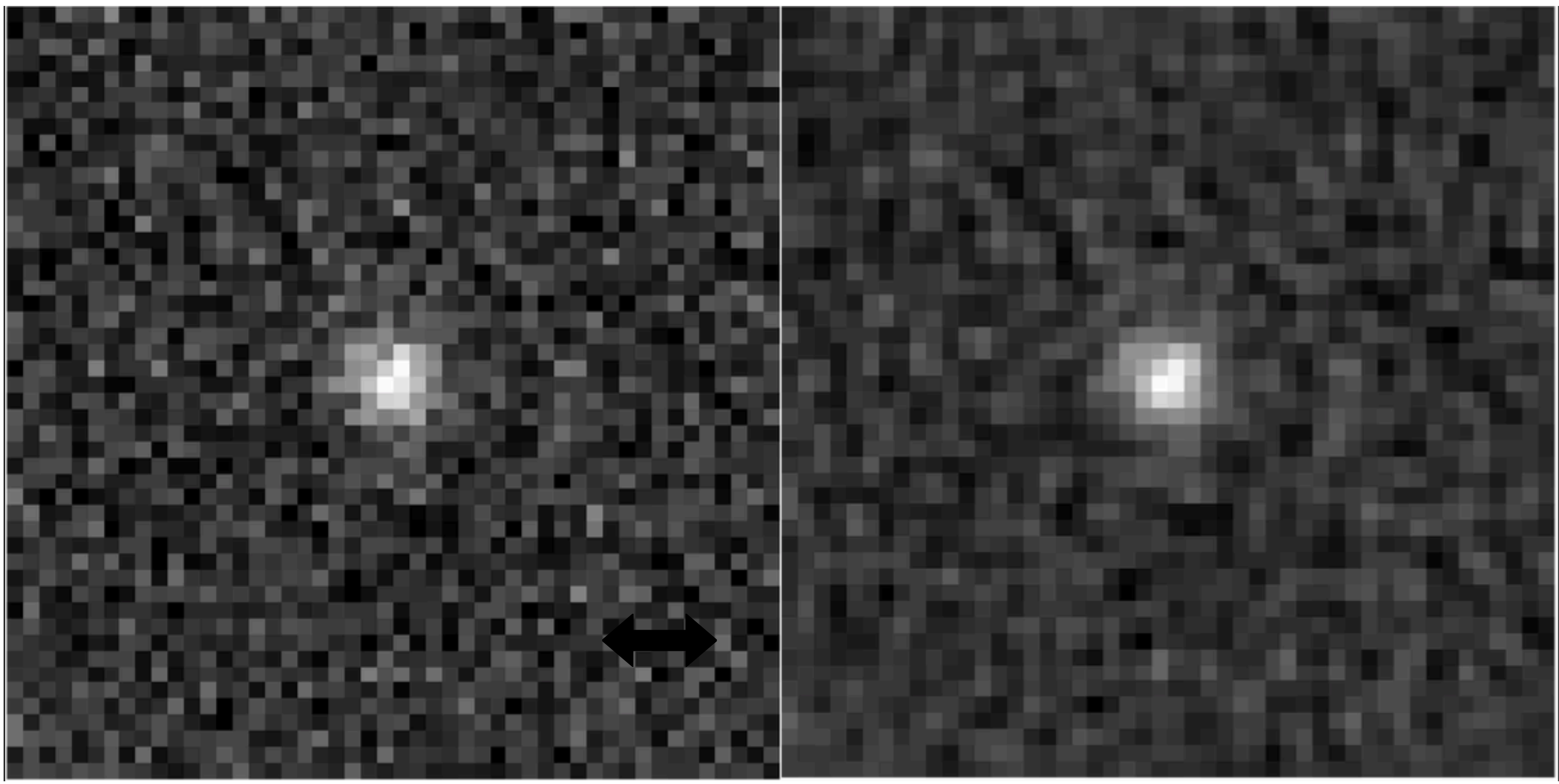
Embed simulated stars and galaxies into real images



Red: simulated object

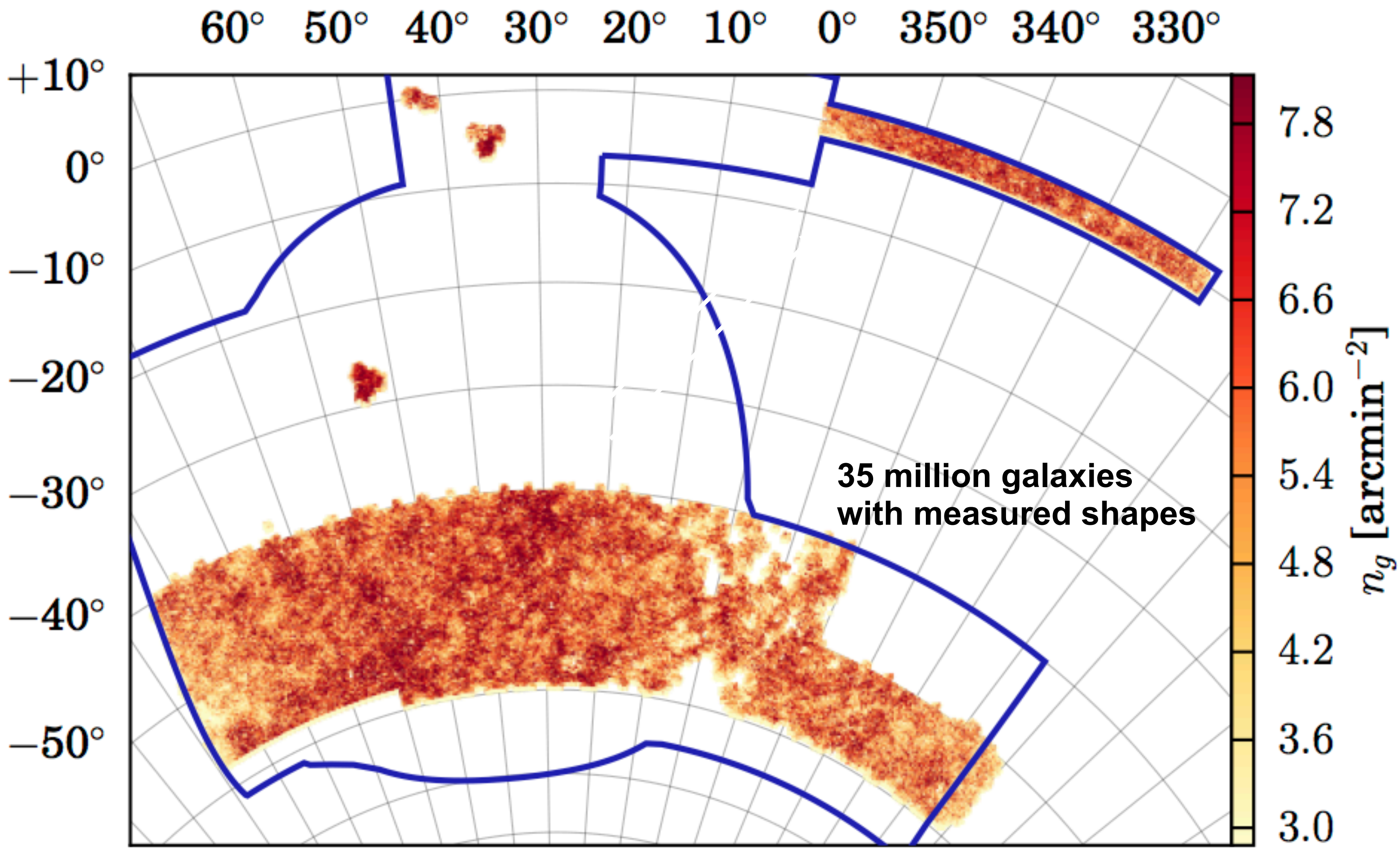
Tools: Metacalibration

original image deconvolved, sheared, reconvolved

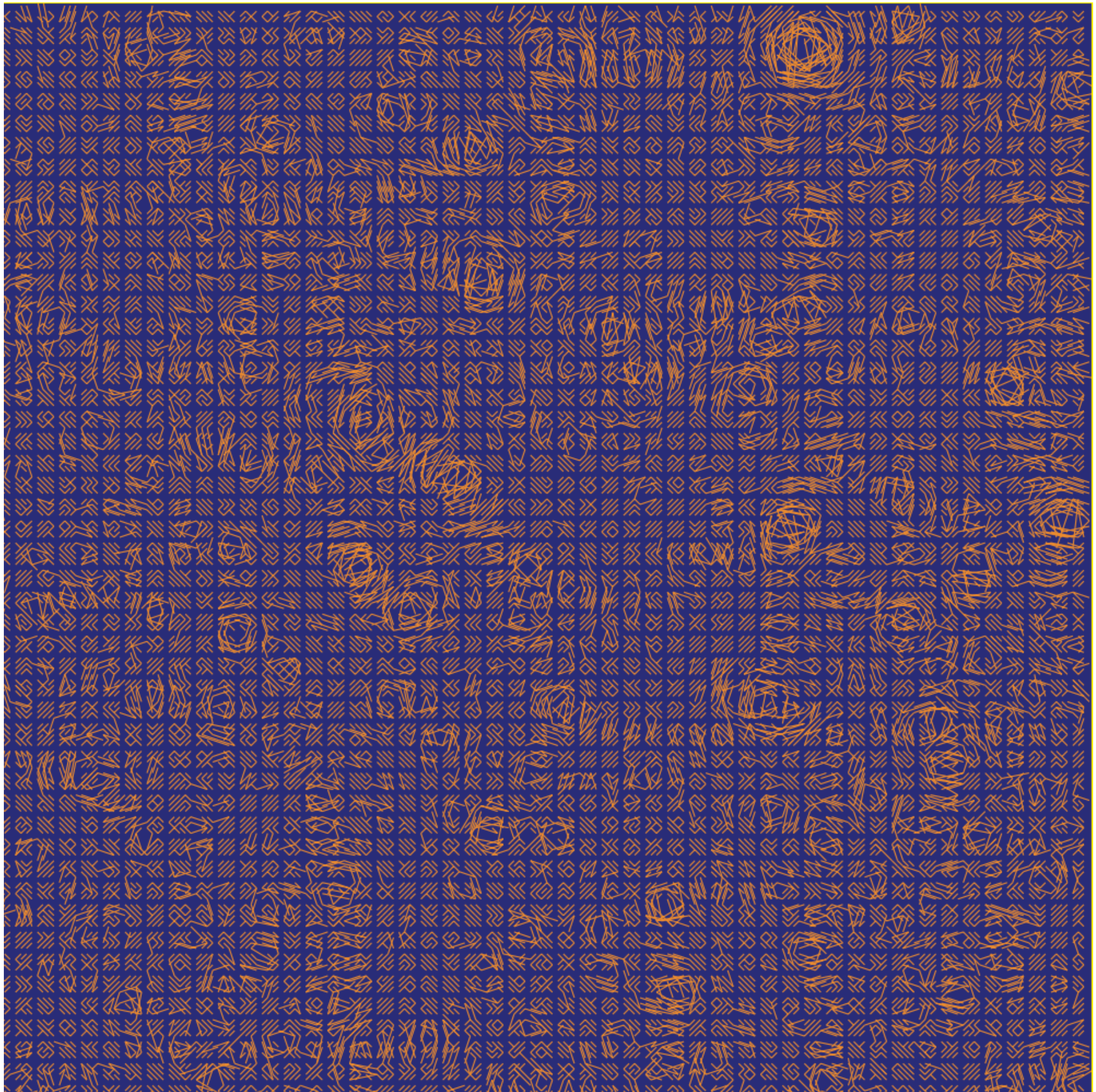


measure ellipticity: get sensitivity to shear

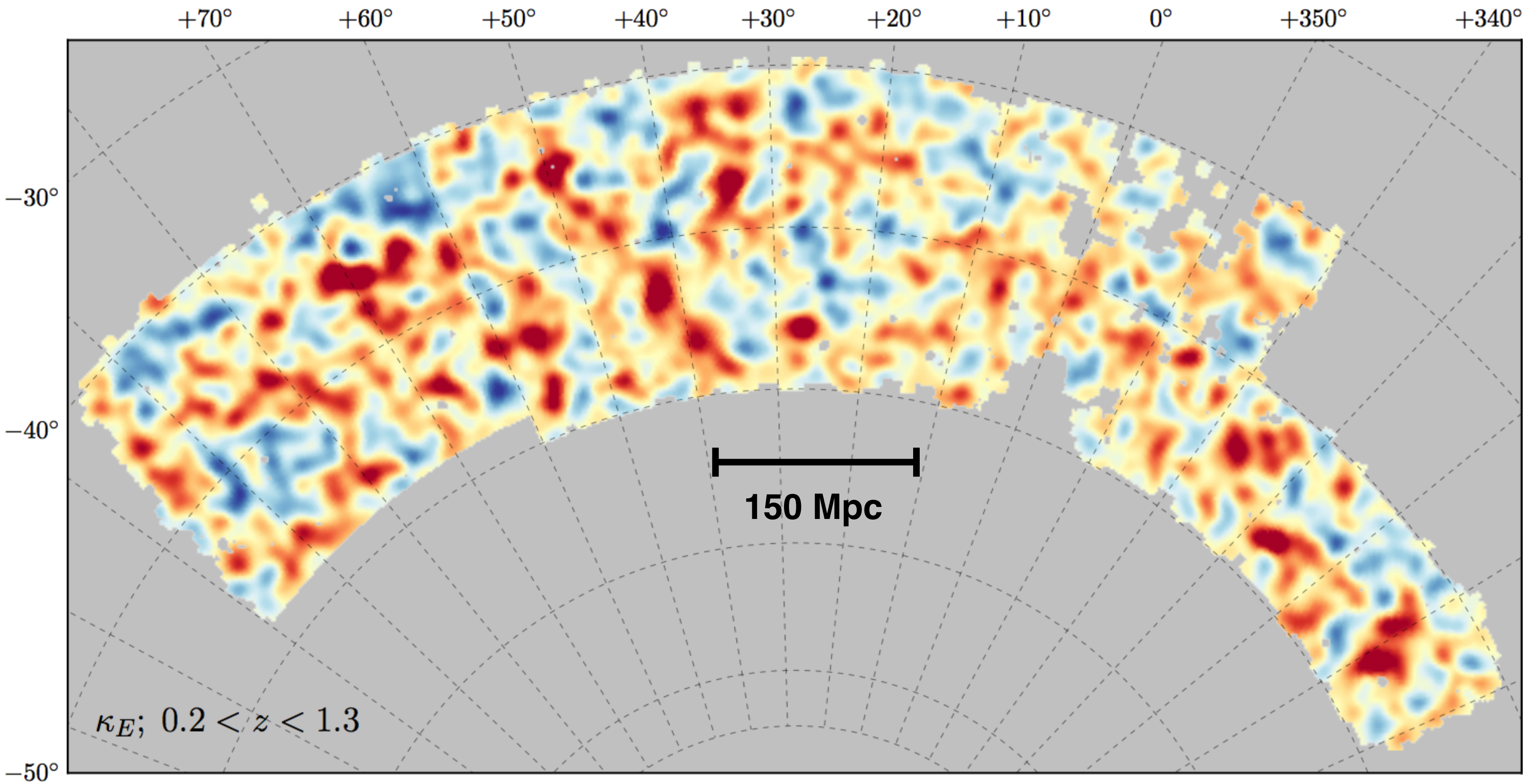
DES Year-1 sample



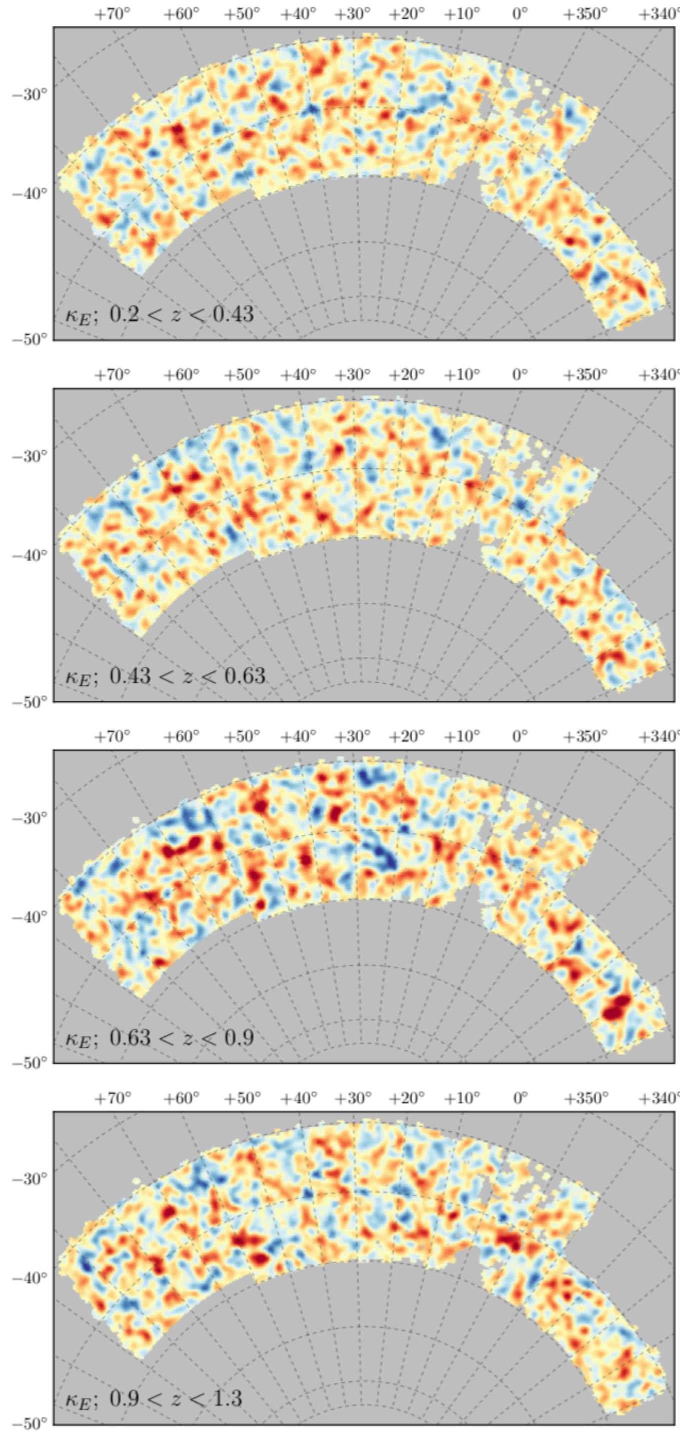
A shear map tells us where the mass is



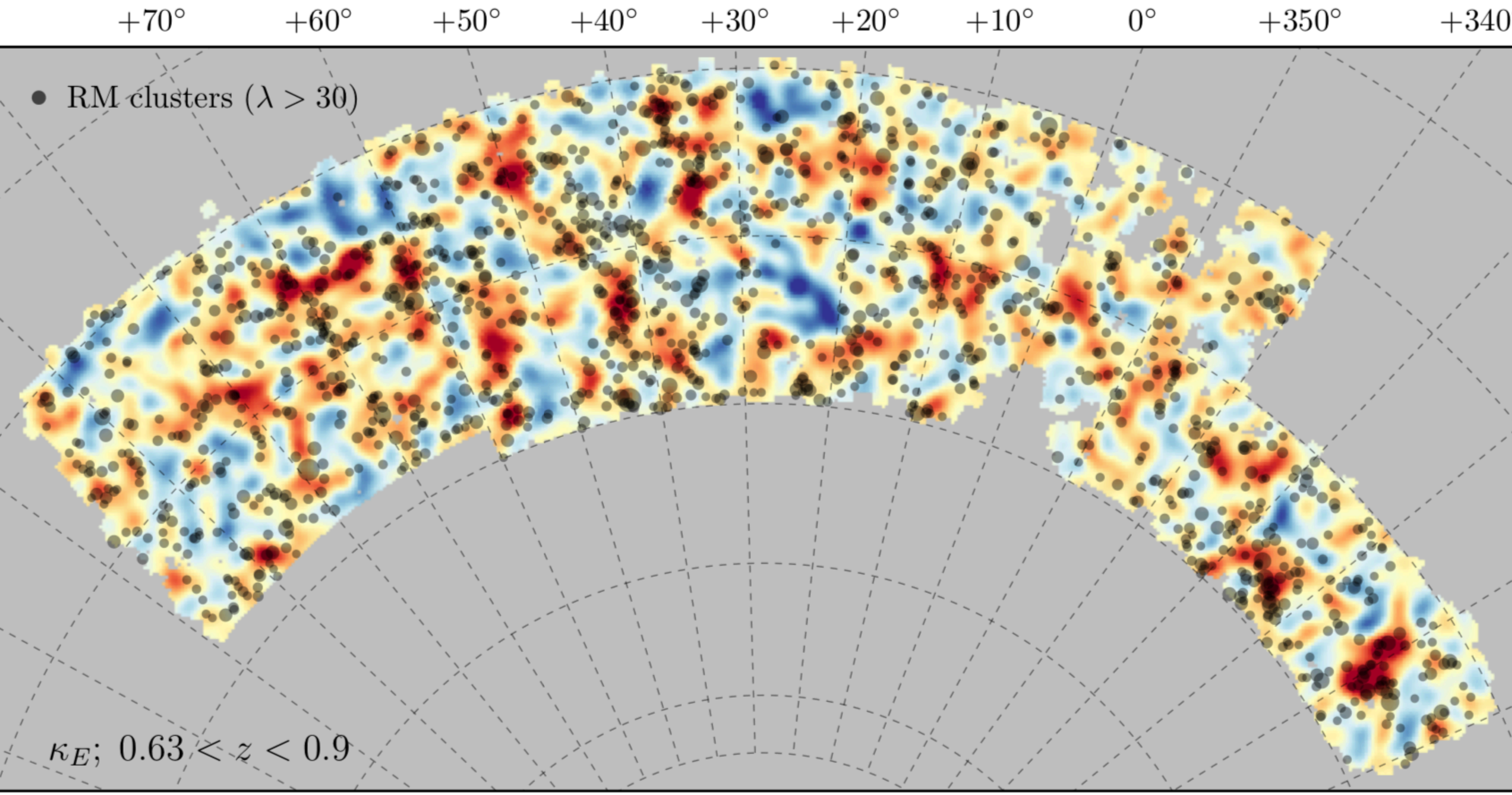
DES Year-1 mass map

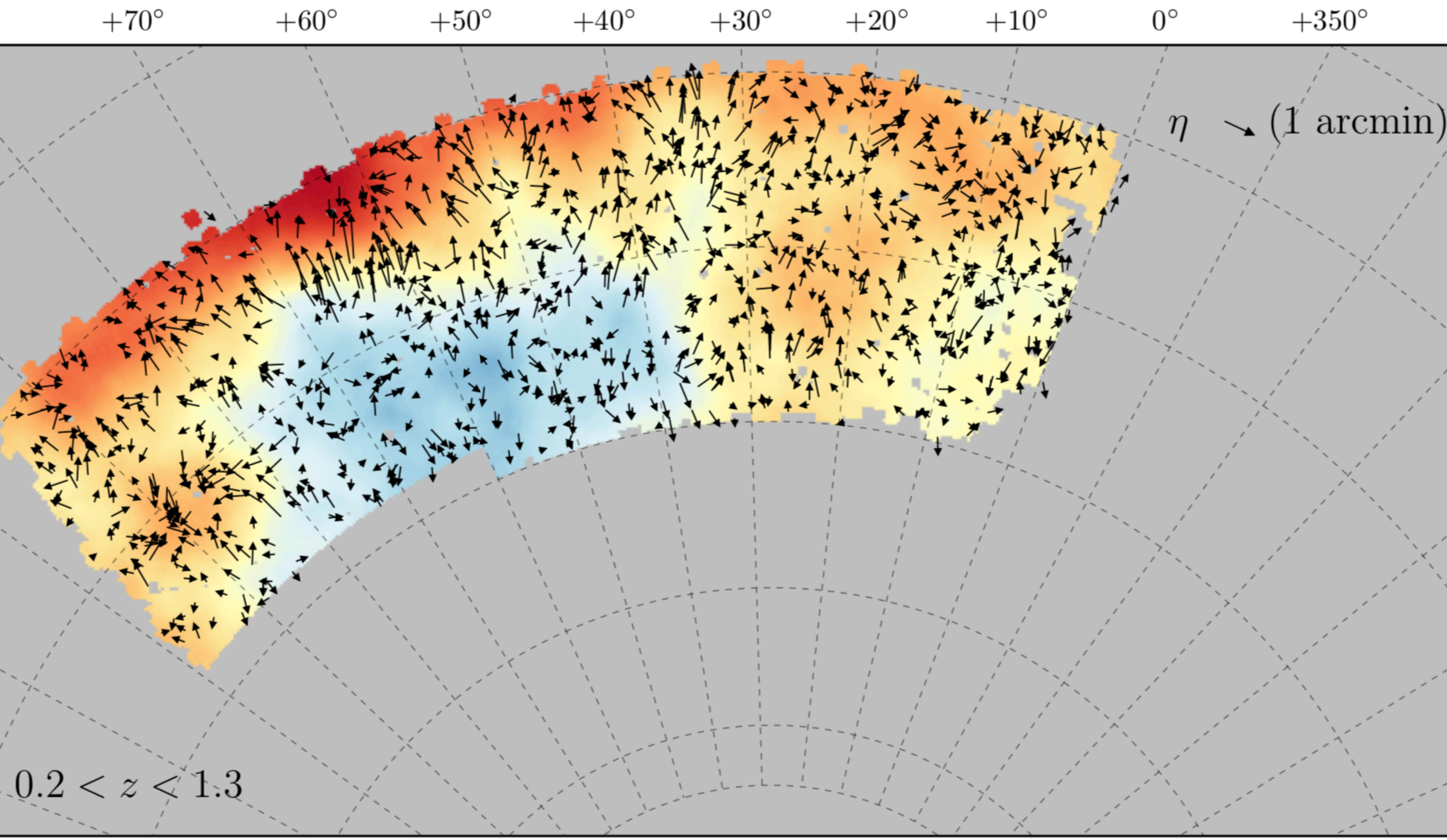


Chang et al (DES Collaboration), MNRAS 475 (2018) 3165


+70° +60° +50° +40° +30° +20° +10° 0° +350° +340°
−30°
−40°
−50°
κ_E; $0.2 < z < 0.43$
+70° +60° +50° +40° +30° +20° +10° 0° +350° +340°
−30°
−40°
−50°
κ_E; $0.43 < z < 0.63$
+70° +60° +50° +40° +30° +20° +10° 0° +350° +340°
−30°
−40°
−50°
κ_E; $0.63 < z < 0.9$
+70° +60° +50° +40° +30° +20° +10° 0° +350° +340°
−30°
−40°
−50°
κ_E; $0.9 < z < 1.3$

DES Year-1 mass map

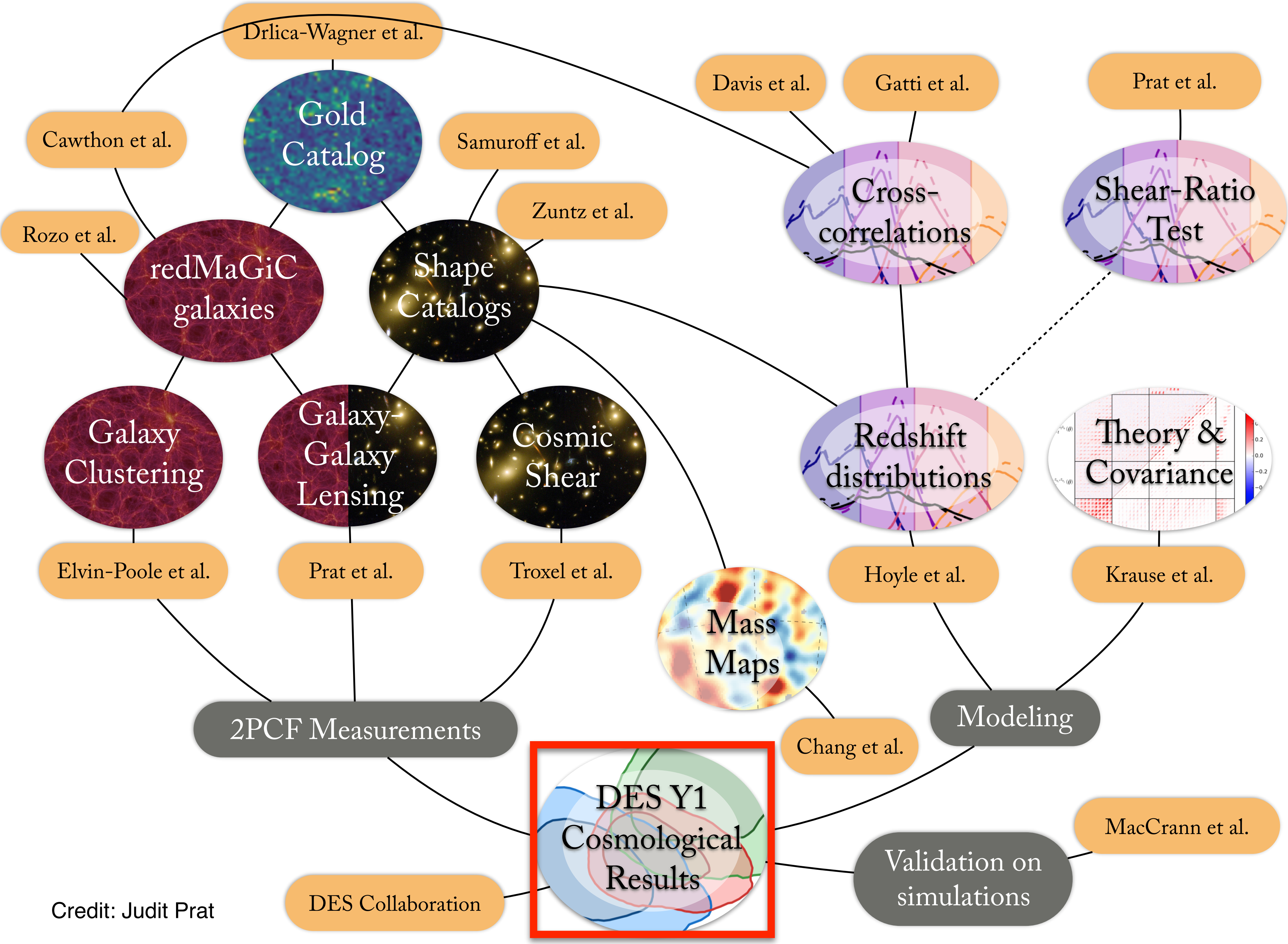


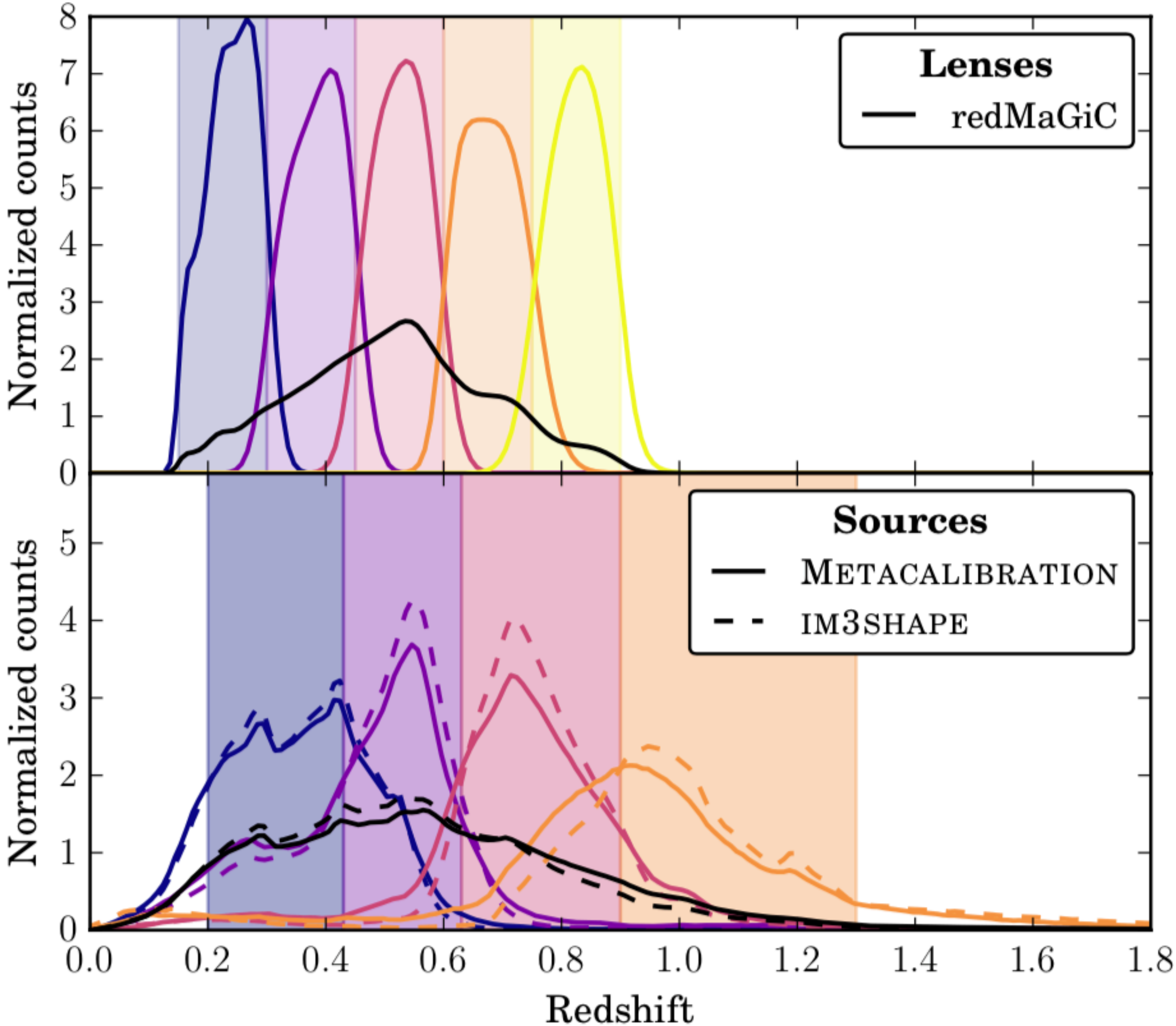


Blue: regions of low gravitational potential

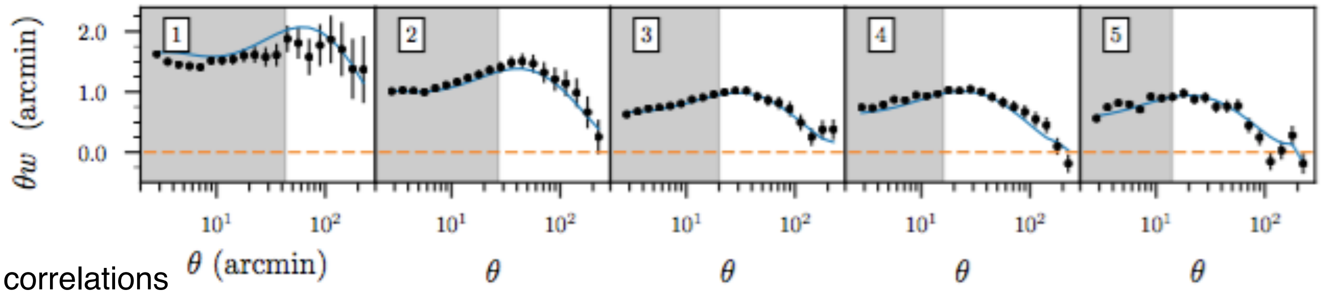
Red: regions of high gravitational potential

Arrows: deflection field (direction and strength of the gravitational force)

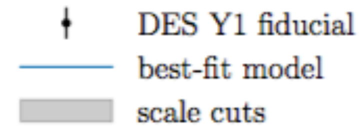

Drlica-Wagner et al.
Gold Catalog
Cawthon et al.
Samuroff et al.
Zuntz et al.
Rozo et al.
redMaGiC galaxies
Shape Catalogs
Davis et al.
Gatti et al.
Prat et al.
Cross-correlations
Shear-Ratio Test
Galaxy Clustering
Galaxy-Galaxy Lensing
Cosmic Shear
Redshift distributions
Theory & Covariance
Elvin-Poole et al.
Prat et al.
Troxel et al.
Mass Maps
Hoyle et al.
Krause et al.
2PCF Measurements
Chang et al.
Modeling
DES Y1 Cosmological Results
MacCrann et al.
Validation on simulations
DES Collaboration
Credit: Judit Prat



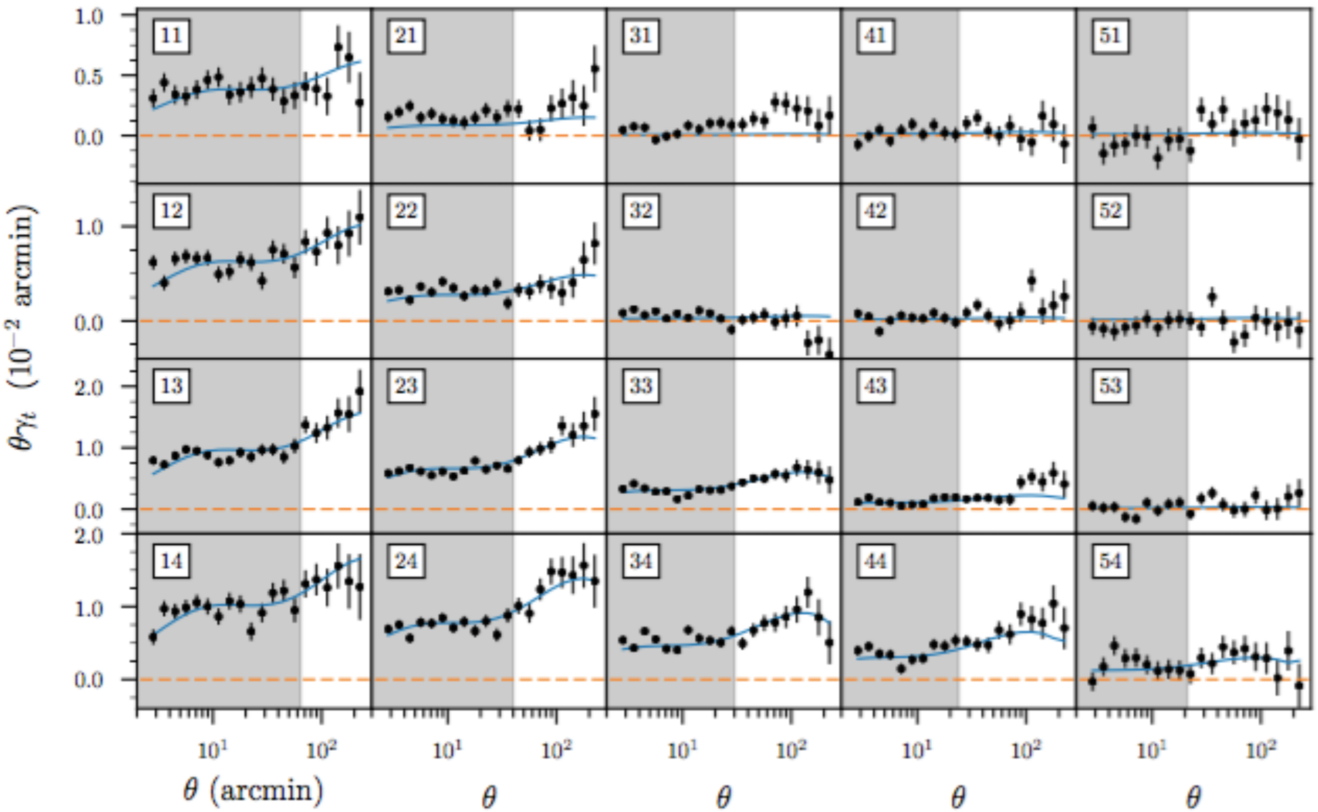
DES Collaboration, PRD 98 (2018) 043526



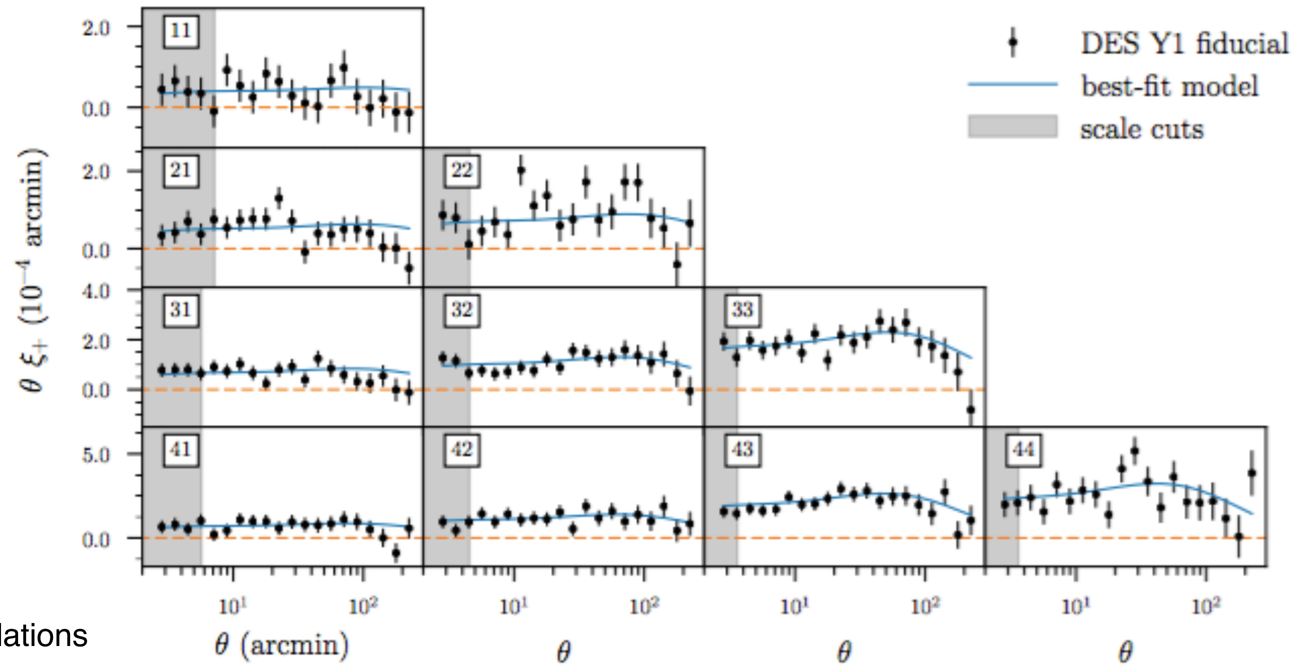
galaxy-galaxy correlations
(lens-lens)



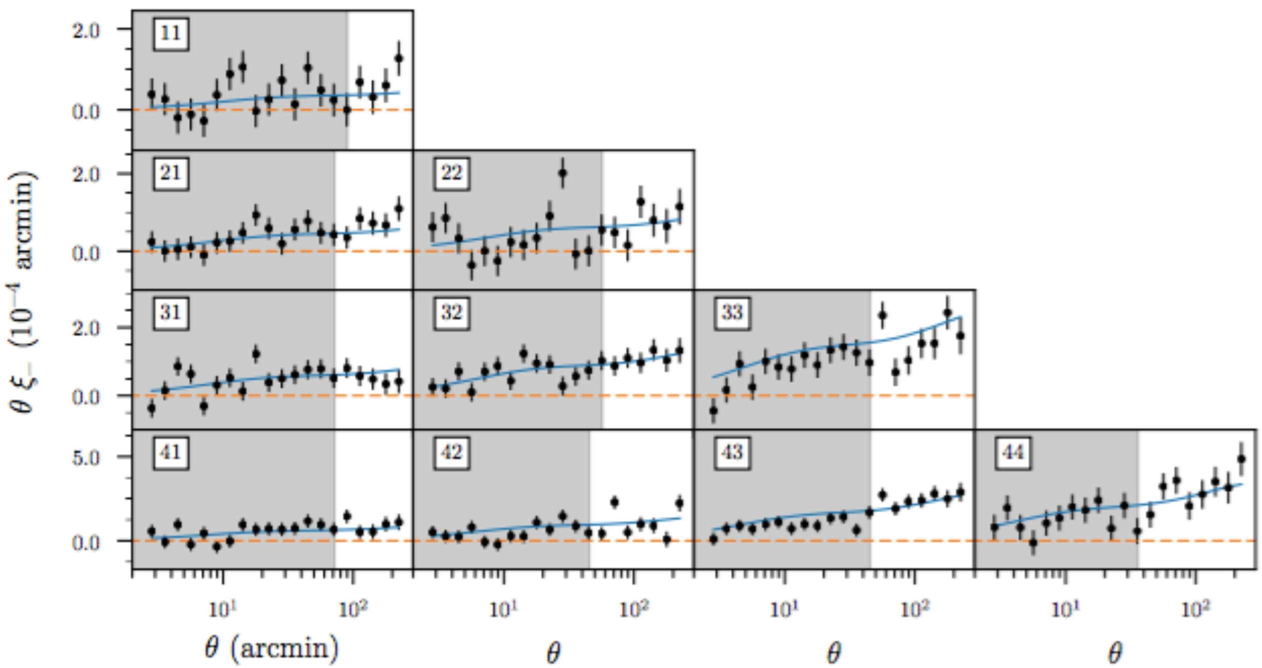
galaxy-shear correlations
(lens-source)



DES Collaboration, PRD 98 (2018) 043526



shear-shear correlations
(source-source)



DES Collaboration, PRD 98 (2018) 043526

Modeling

DARK ENERGY SURVEY

Correlations between shapes in redshift bins i, j

$$\hat{\xi}^{ij}_{\pm}(\theta) = \frac{1}{2\pi} \int d\ell \ell J_{0/4}(\theta\ell) P^{ij}_{\kappa}(\ell)$$

$$P^{ij}_{\kappa}(l) = \int_0^{\chi_H} d\chi \frac{q^i(\chi) q^j(\chi)}{\chi^2} P_\delta(\frac{l}{\chi}, \chi)$$

Hubble constant (rate of expansion)

Geometry (distances: expansion)

$$q^i(\chi) = \frac{3}{2} \Omega_m \left(\frac{H_0}{c}\right)^2 \frac{\chi}{a(\chi)} \int_\chi^{\chi_H} d\chi' n^i(\chi') \frac{\chi' - \chi}{\chi}$$

Mass density of the Universe

$$P_\delta(k, z) = A \frac{T^2(k, z)}{a^2} \frac{D^2(z)}{D^2(0)} k^{n_s}$$

Amplitude of clustering: inhomogeneity

Dynamics (rate of growth of structure)

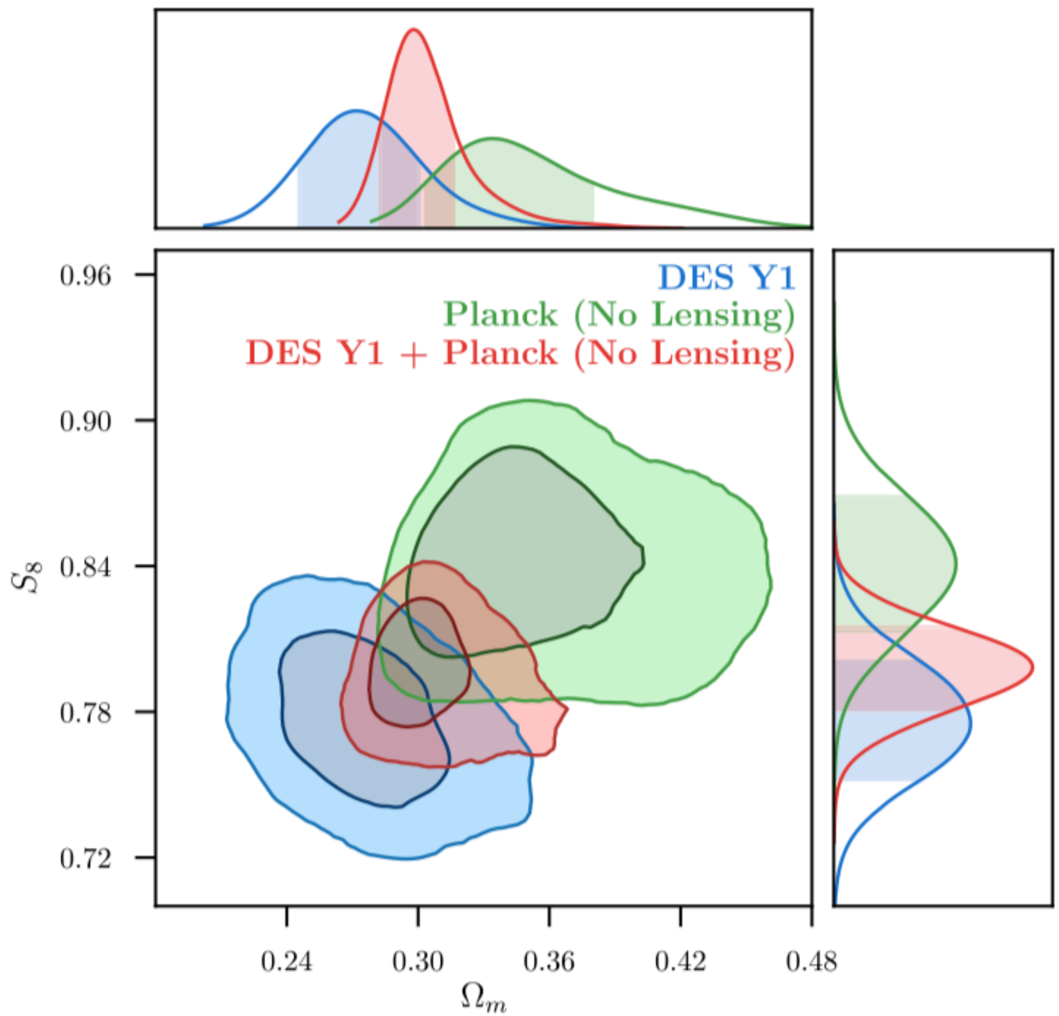
DES-Y1 cosmological results

DARK ENERGY SURVEY

- $\boldsymbol{S_8} = \sigma_8 (\Omega_m / 0.3)^{0.5}$ describes the **inhomogeneity of the matter distribution now**: σ_8 is the standard deviation of the matter-density distribution in spheres of radius 8 Mpc/h.

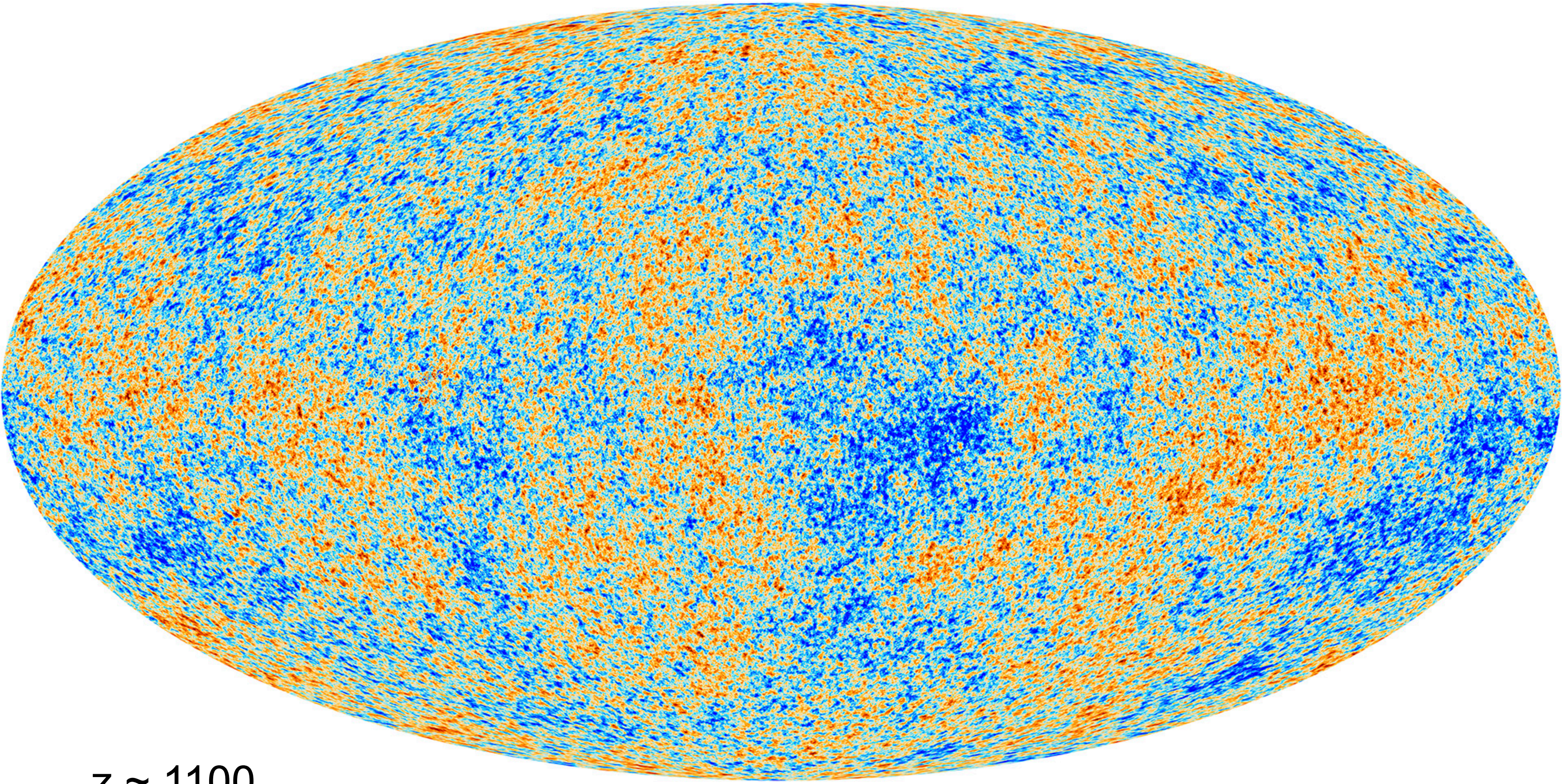
- **Ω_m : fraction of matter in the total matter-energy of the universe now**.

- First measurement in late universe with **precision comparable to CMB**.



DES Collaboration, PRD 98 (2018) 043526

Planck CMB temperature map



z ~ 1100
t ~ 380,000 yrs

$$\frac{\delta\rho}{\rho} \sim 10^{-5} \xrightarrow[\text{gravitation}]{} \frac{\delta\rho}{\rho} \gg 1$$

DES-Y1 cosmological results

DARK ENERGY SURVEY

- $S_8 = \sigma_8\,(\Omega_m / 0.3)^{0.5}$ describes the **inhomogeneity of the matter distribution now**: σ_8 is the standard deviation of the matter-density distribution in spheres of radius 8 Mpc/h.
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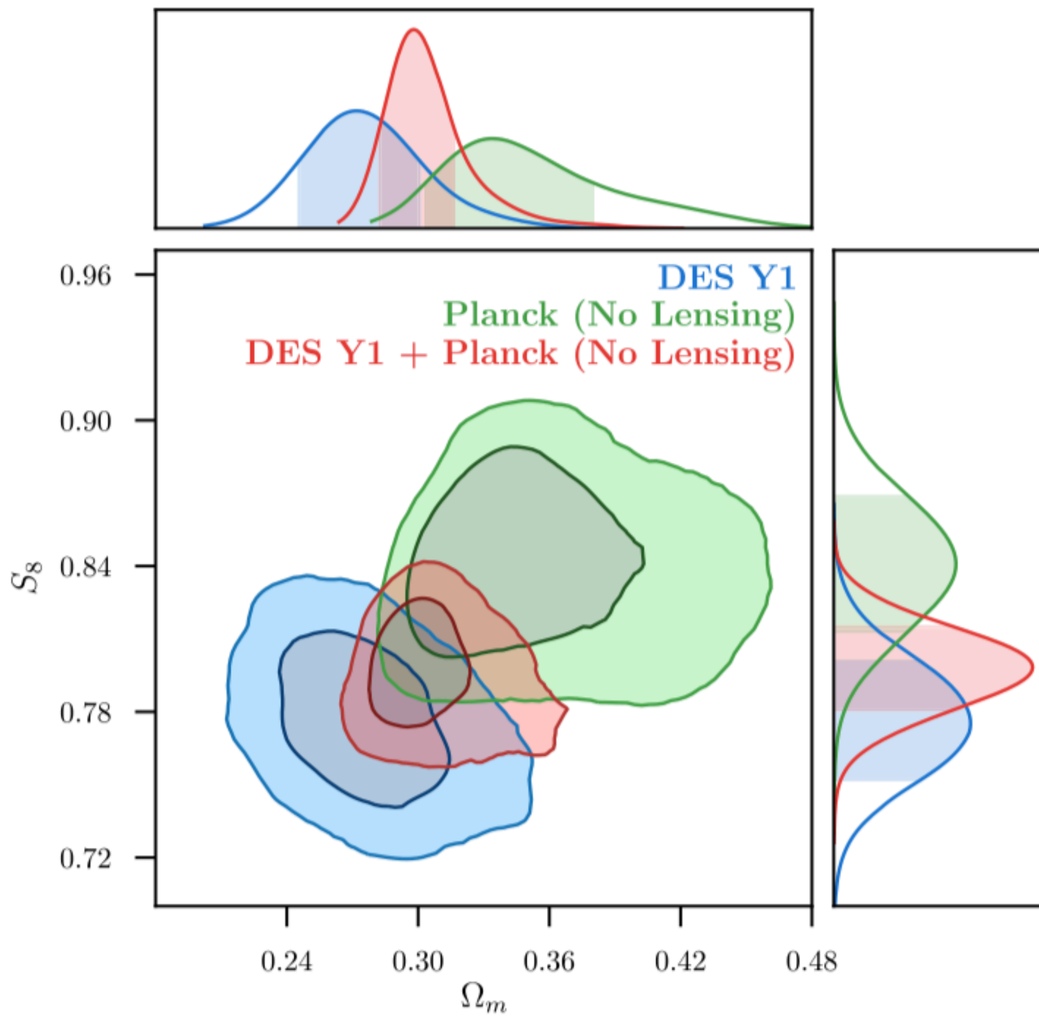
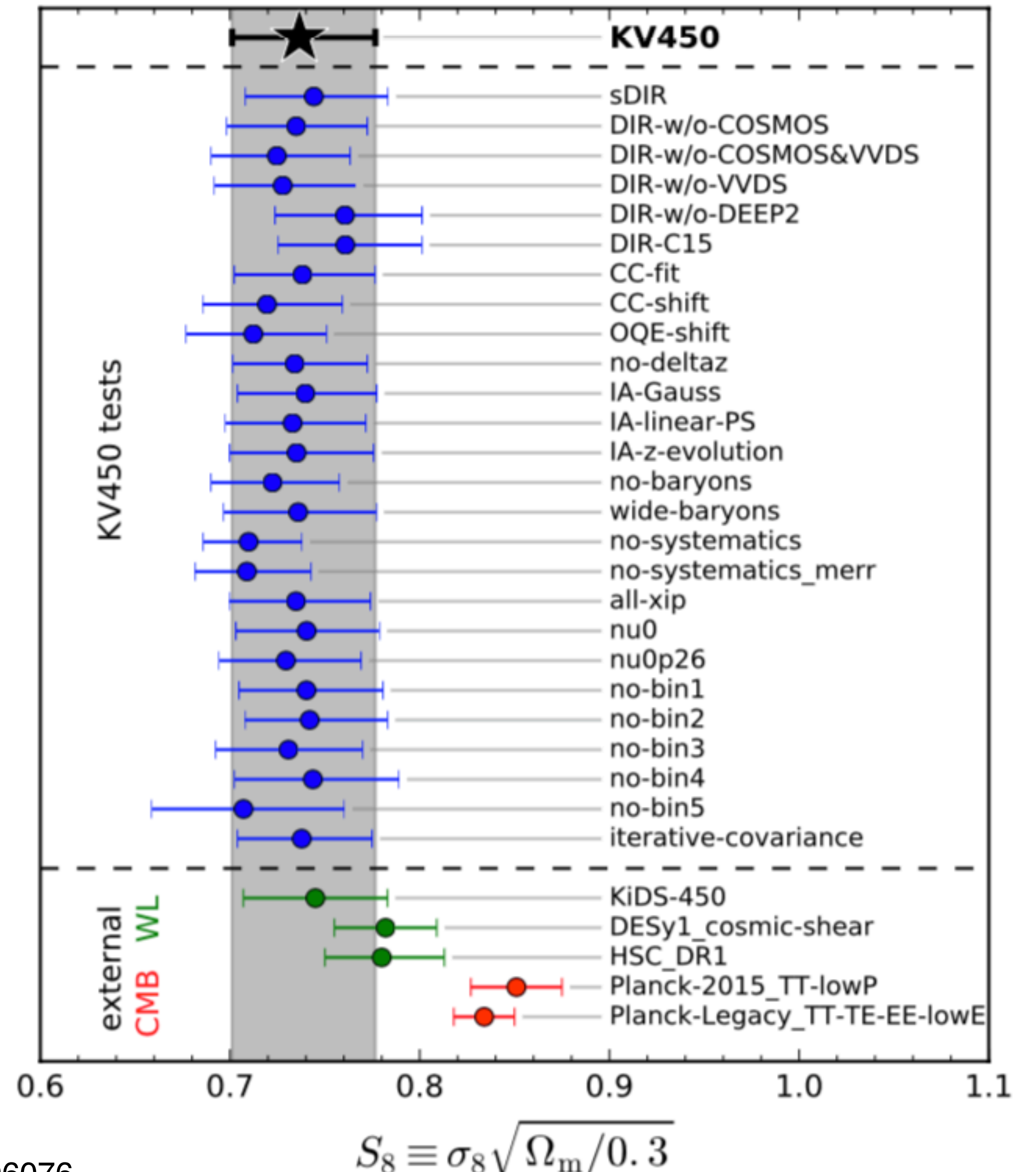


DES Collaboration, PRD 98 (2018) 043526

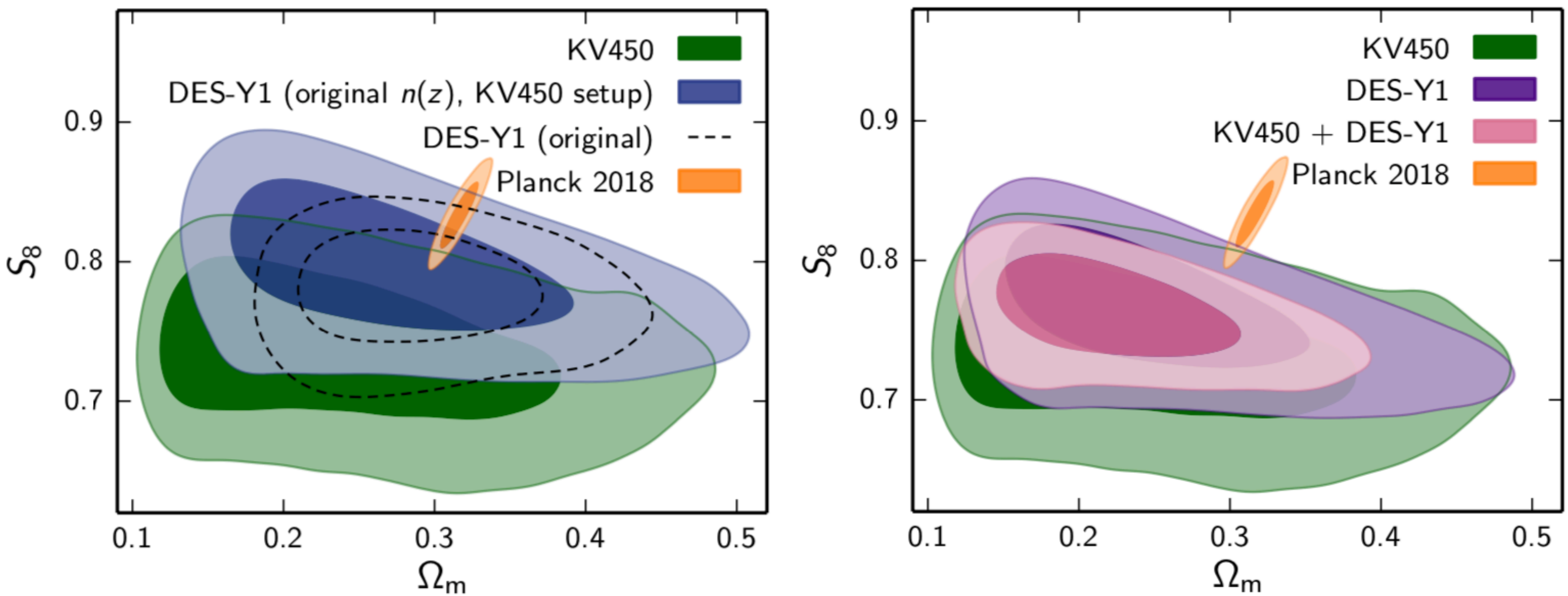
σ_8: tension?



Hildebrandt et al, arXiv:1812.06076

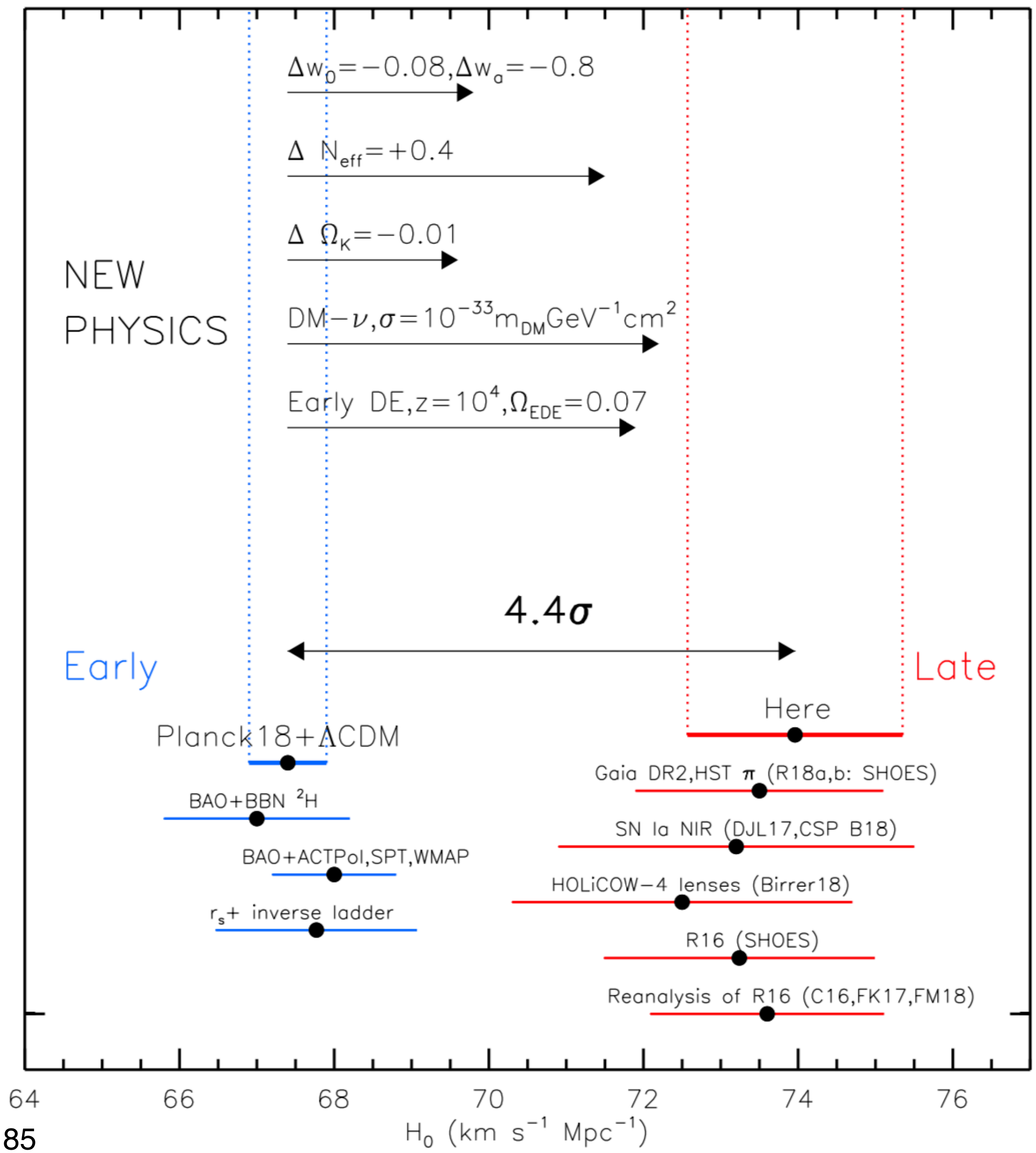
σ_8: tension?

- KiDS have re-analyzed the DES-Y1 data set, using their photo-z calibration method.



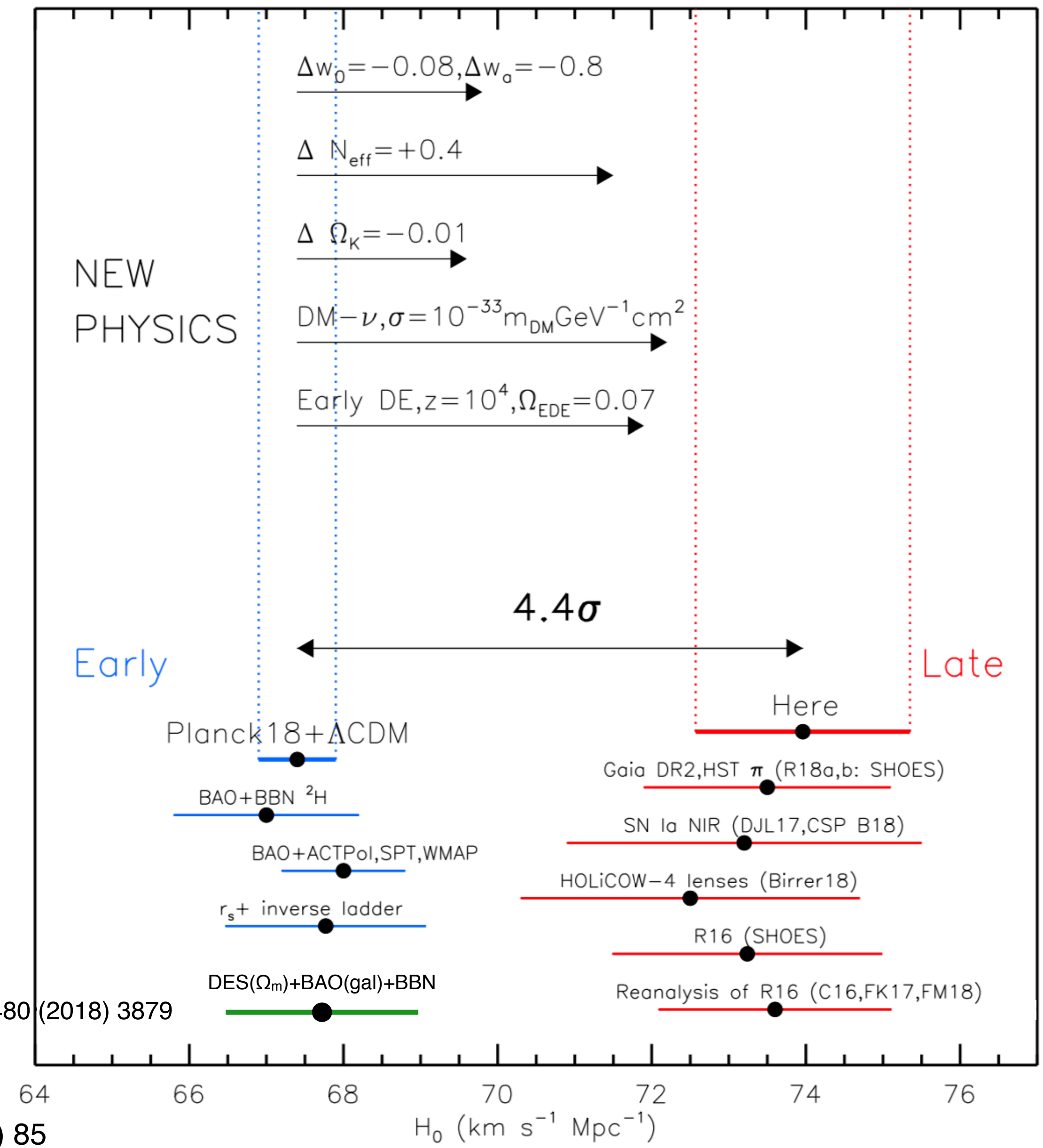
Joudaki et al, arXiv:1906.09262

H_0: tension



Riess et al, ApJ 876 (2019) 85

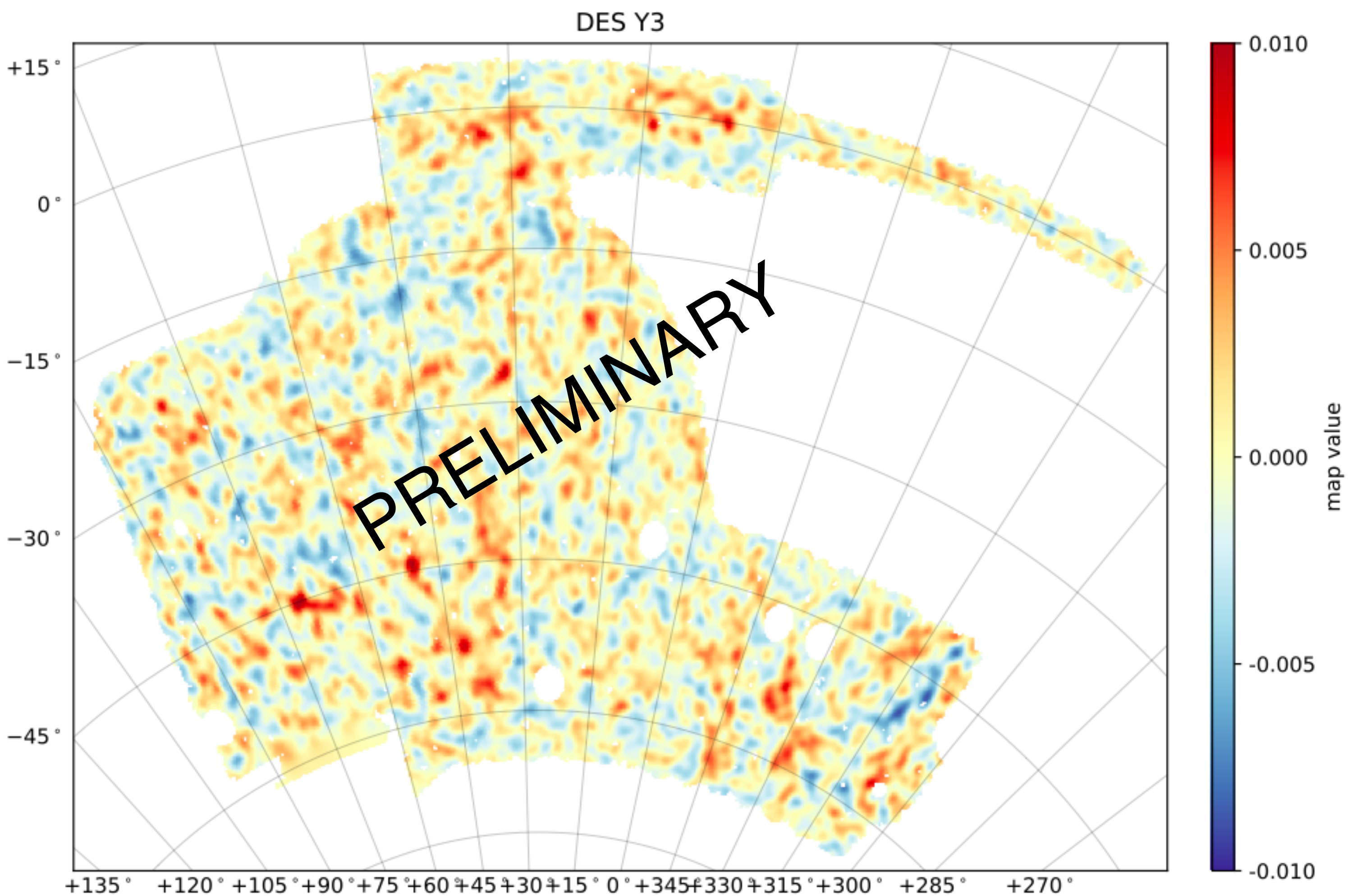
H_0: tension



DES Collaboration, MNRAS 480 (2018) 3879

Riess et al, ApJ 876 (2019) 85

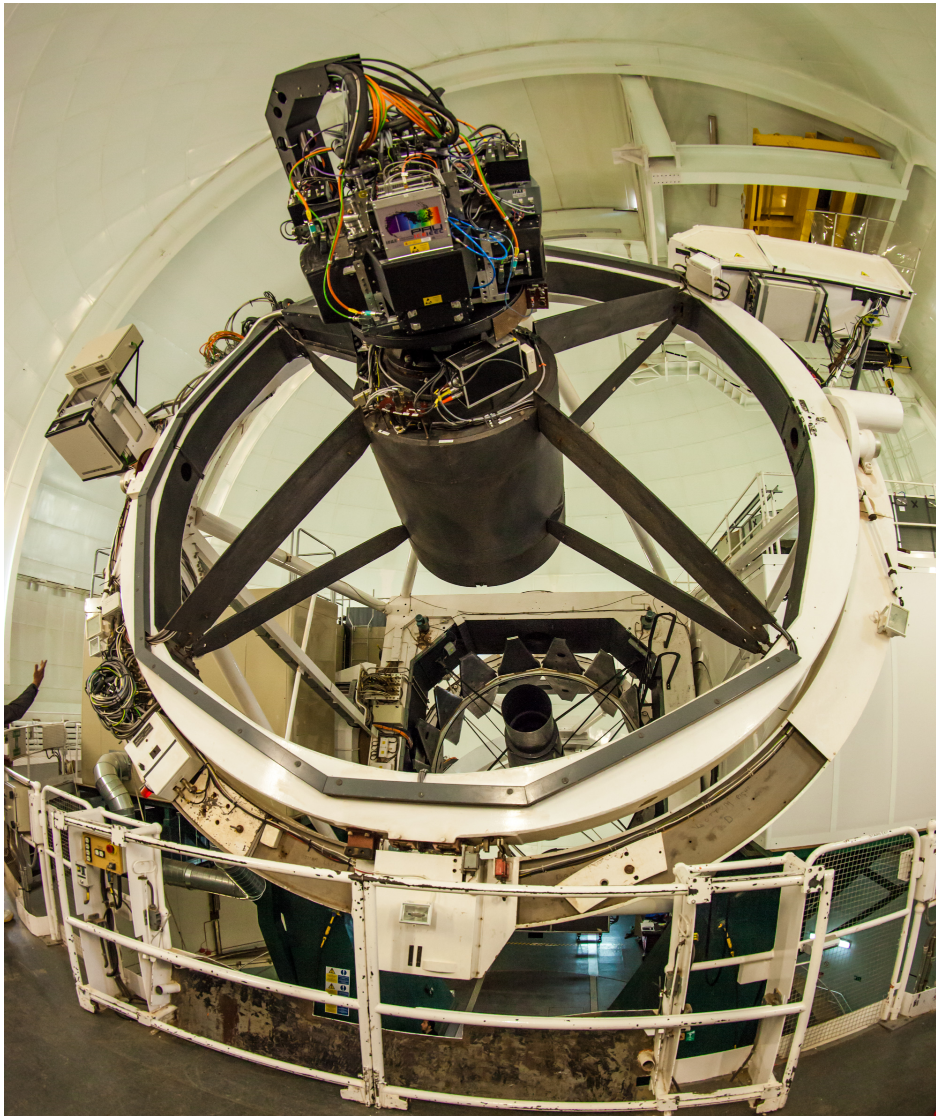
DES Year-3 mass map



Marco Gatti

The PAU survey at the ORM

- PAUCam built by Spanish consortium (Consolider-2010 project) led by IFAE.
- 40 narrow-band filters provide very precise redshifts.
- >100-night survey at WHT, including partners from Bonn, Leiden, ETH Zurich, Durham, UCL:
  - Redshift-space distortions.
  - Weak-lensing magnification.
  - **Intrinsic galaxy alignments.**
  - **Photo-z calibration for DES, KiDS, Euclid, LSST…**
- Commissioning took place in 2015; science verification in spring 2016; survey started in fall 2016.
- First papers just published.

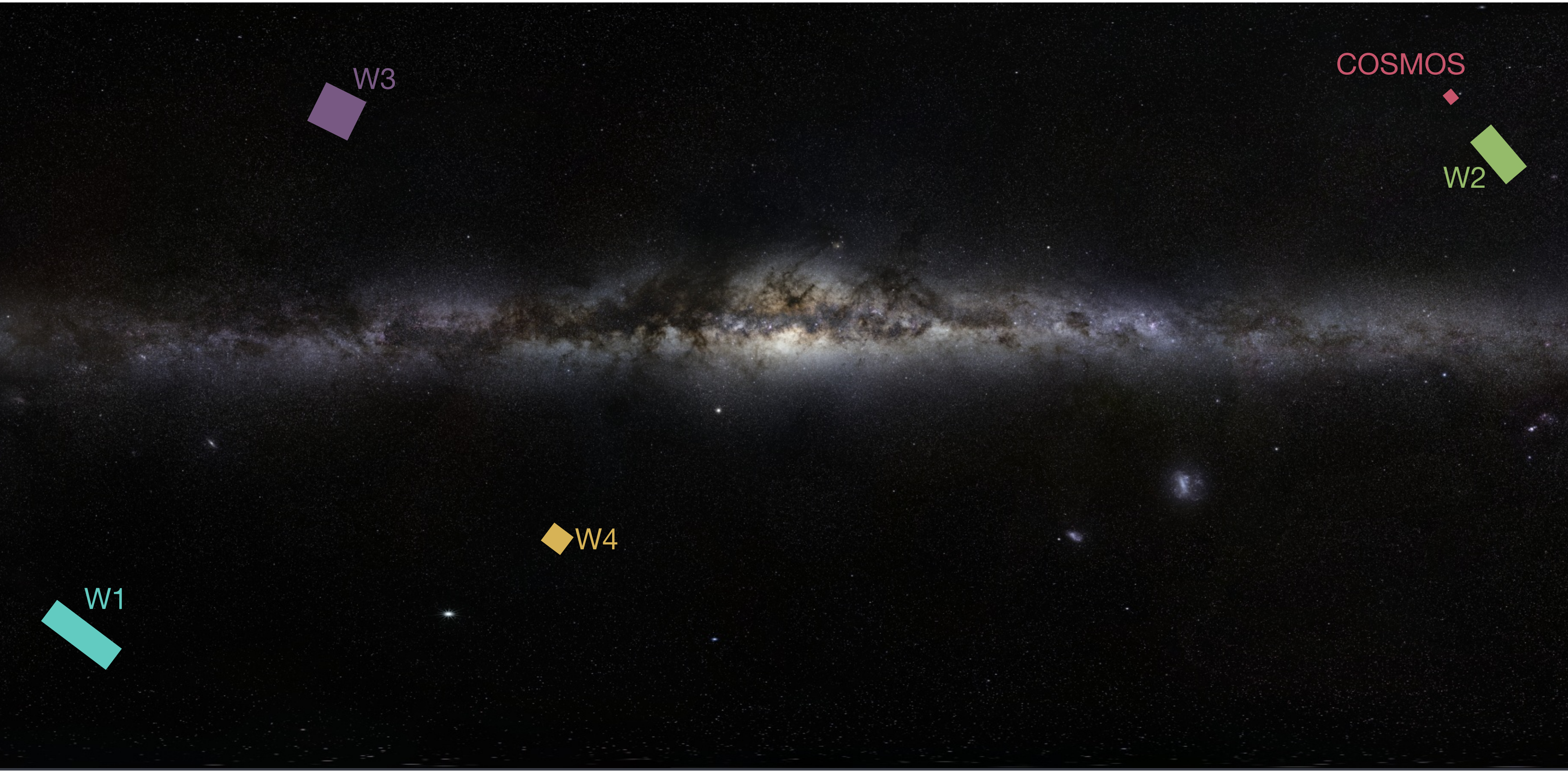


PAU observation periods

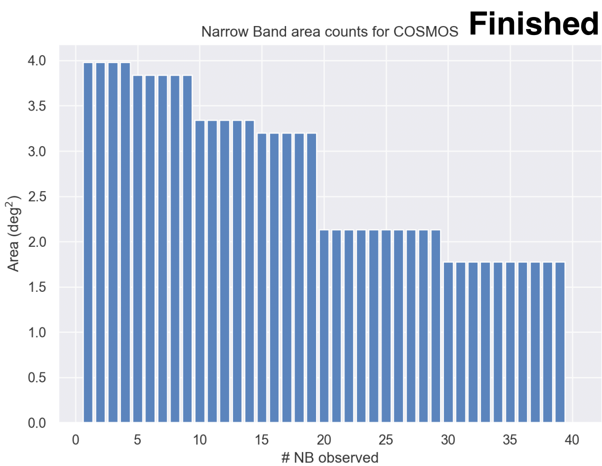
	nights	BAD	POOR	GOOD	TECHNICAL	LOST TECH	GOOD DATA
2015B	10	4	3	3	2.2	1	2
2016A	13	5.7	1.5	5.8	0.8	0.0	5.8
2016B	20.5	10.6	2.2	7.7	0.9	0.8	6.9
2017A	27.5	7.8	3.4	16.3	4.1	2.4	13.9
2017B	28	13.2	4.5	10.3	1.0	0.7	9.6
2018A	24.5	6.1	2.9	15.5	0.1	0.0	15.5
2018B	37	10.6	3.9	22.5	4.1	4.0	18.5
2019A	36	10.9	2.0	23.1	0.0	0.0	23.1
All	196.5	68.9 (35%)	23.4 (12%)	104.2 (53%)	13.2	8.9(5%) PAU: 3.3 WHT: 5.6	95.3 (49%)

- We have been very successful with the ES and NL TACs, and OK with the UK.
- We have requests from external users: more nights to PAU Survey (3:1).
- Unfortunately, bad weather has reduced our efficiency of good observations to about 50%.

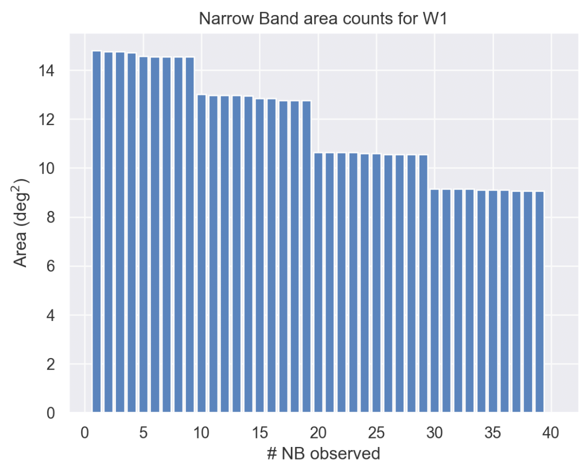
Fields of the PAU survey



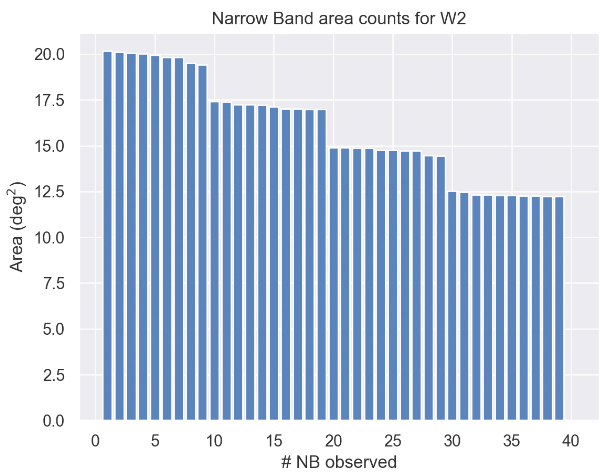
Field coverage



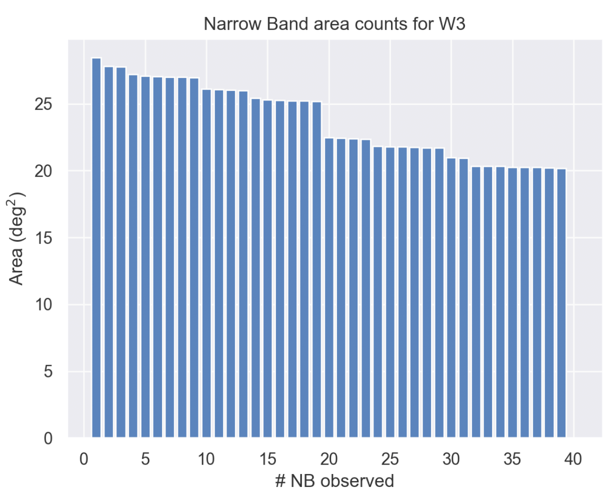
1.8 deg²



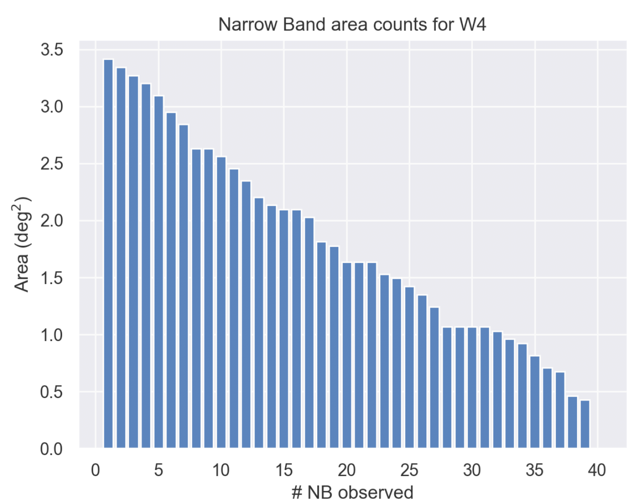
9 deg²



12.4 deg²



20.1 deg²



0.4 deg²

Total: 44 deg²
with 40 NB

PAU publications

- Five papers published so far:
  - L. Tortorelli et al., “The PAU Survey: A forward modeling approach for narrow-band imaging,” JCAP 11 (2018) 035 (arXiv:1805.05340).
  - L. Cabayol et al., “The PAU Survey: Star-galaxy separation with multi narrow-band data,” MNRAS 483 (2019) 529 (arXiv:1806.08545).
  - **M. Eriksen et al., “The PAU Survey: Early demonstration of photometric redshift performance in the COSMOS field,” MNRAS 484 (2019) 4200 (arXiv:1809.04375).**
  - C. Padilla et al., “The Physics of the Accelerating Universe Camera,” AJ 157 (2019) 246 (arXiv:1902.03623).
  - L. Cabayol et al., “The PAU Survey: Background light estimation with deep learning techniques,” MNRAS in press (arXiv:1910:02075).
- Several other papers are in preparation: calibration, photometry, operations. First science papers expected for 2020.

Photo-z measurements

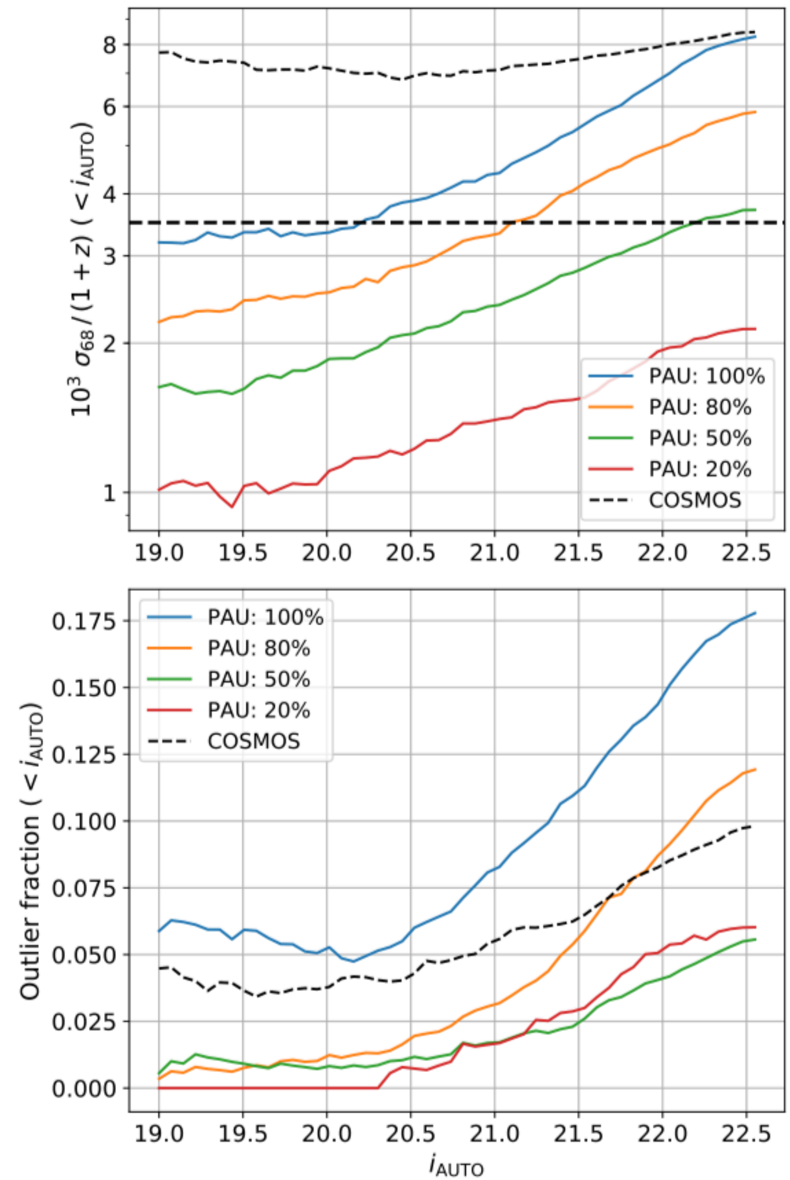
- First results obtained using a sample of galaxies matched to those in the COSMOS field with spectroscopic redshifts.

- Using a quality cut that keeps 50% of the galaxies in the sample, we match the expectations from simulations:

$$\sigma_{68}(z) \lesssim 0.0035 \times (1+z)$$

- Already **better than any previous narrow-band survey:** COMBO-17, ALHAMBRA, COSMOS32.

- Results are being improved using machine-learning techniques.



M. Eriksen et al., MNRAS 484 (2019) 4200

Conclusions

- Dark Energy is a profound mystery that deserves the attention is receiving.
- Imaging/Spectroscopy, Ground/Space are complementary and synergistic:
    - Imaging: efficient; deep; 2.5D for many methods; allows weak lensing.
    - Spectroscopy: 3D info for BAO, RSD.
    - Space: exquisite, stable PSF for lensing; access to near-infrared.
    - Ground: larger telescopes allow fast, wide, deep surveys.
- BOSS, DES-Y1 results represent the first powerful test of ΛCDM in the local universe.
- Tensions start to appear in H_0 (kinematical) and, maybe, in σ_8 (dynamical).
- DES-Y3 (2020) and DES-Y6 (2022) will combine all probes (SNe, clusters) and provide unprecedented constraints on the cosmological parameters.
- In the next decade, DESI, Euclid, and LSST will increase the precision on the dark energy parameters by an order of magnitude.