Review on Cosmology and Dark Energy

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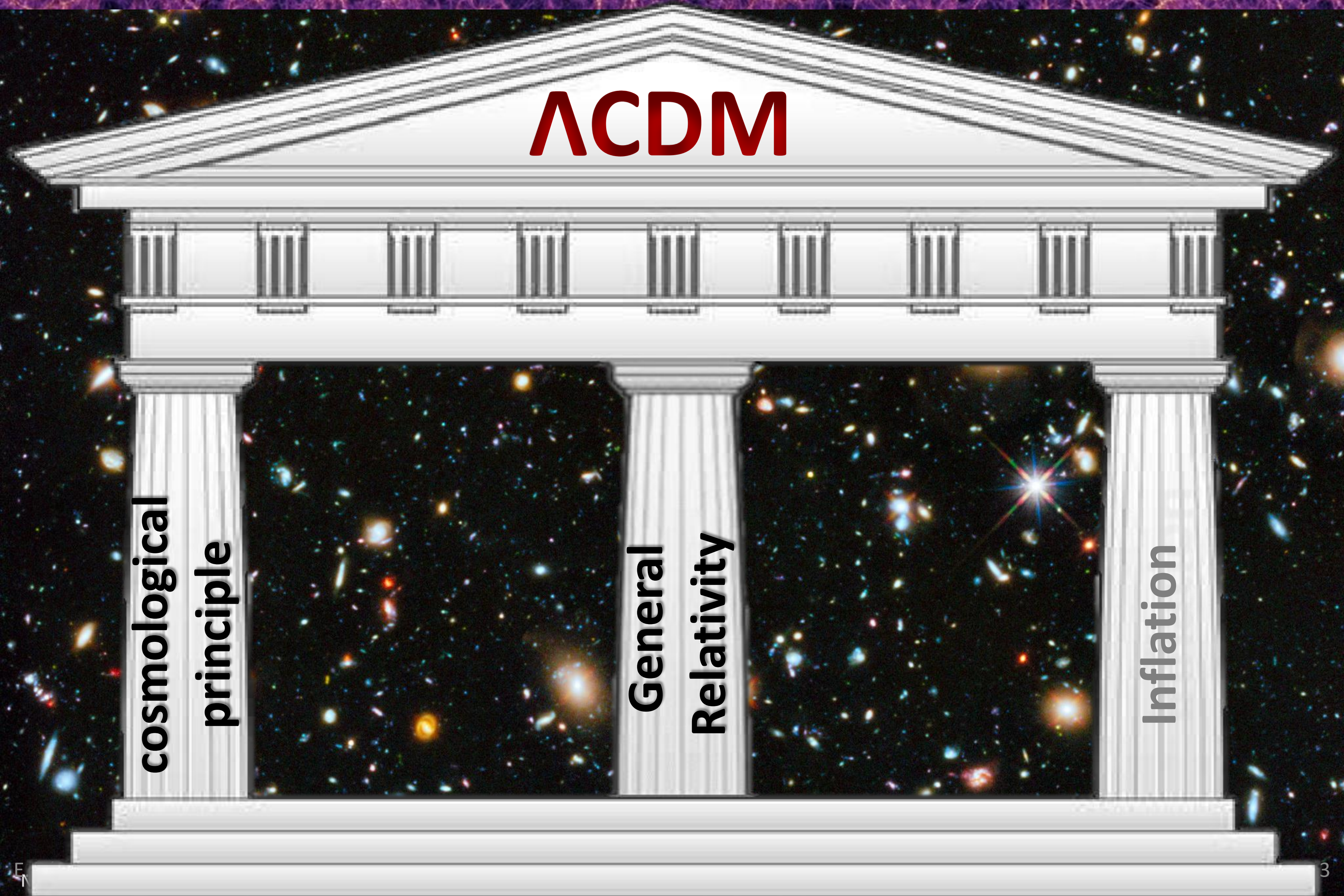
XLVIII International Meeting on Fundamental Physics
Benasque 2021

OUTLINE

- **ΛCDM.** *The Standard Model of Cosmology*
- **Observations.** *What is a Galaxy Survey and how it Works*
- **Spectroscopic Surveys**
- **Imaging Surveys**
- **Current Situation**: *CMB + Supernovae Ia + BAO (+ Tensions?)*
- **Current and Future Projects**: *DES, PAU, DESI, Rubin , Euclid*
- **Conclusions**

Cosmology Basis



The Big Bang today: ΛCDM

The Standard Model of Cosmology. Based on a huge quantity of precise observations

CMB → Ω_{TOT} ~1 (the Universe is spatially **FLAT**)

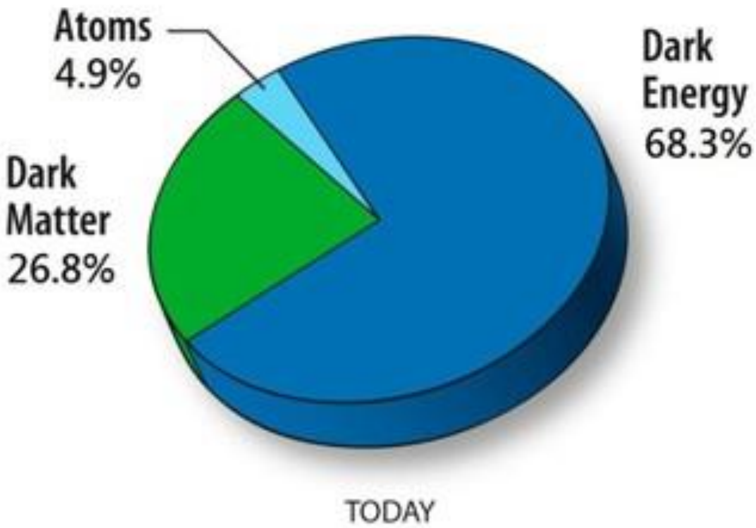
BBN+CMB → Ω_B ~ 0.05 → most of the universe is **NON-BARYONIC**

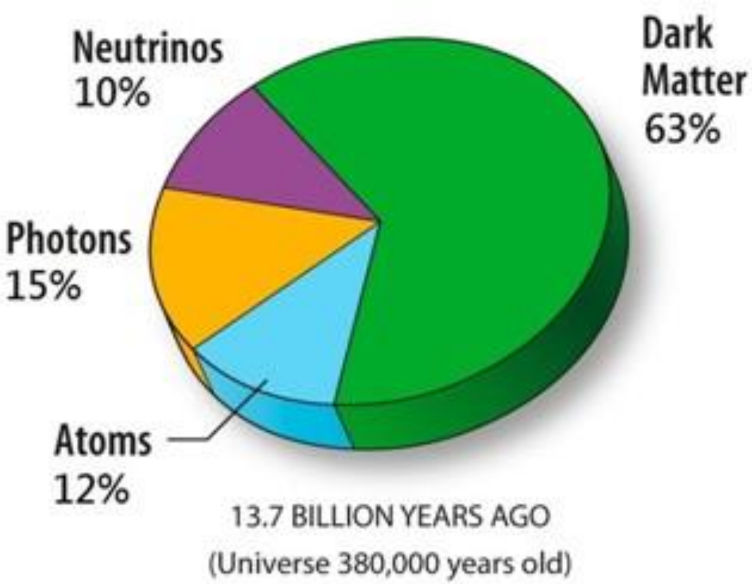
LSS+GALAXY DYNAMICS → **DARK MATTER!** ; Ω_{DM}~ 0.27

Supernovae Ia+LSS+CMB → **DARK ENERGY!** ; Ω_{DE} ~ 0.68

Large scale homogeneity
Hubble Law
Light elements abundances
Existence of the CMB
Fluctuations of the CMB
LSS
Stars ages
Galaxy evolution
Time dilation of the SN brightness
Temperature vs redshift (Tolman test)
Sunyaev-Zel´dovich Effect
Integrated Sachs-Wolf effect
Galaxies (rotation/dispersion)
Dark Energy (accelerated expansin)
Gravitacional lenses (weak/strong)
Consistency of all observacions

The Big Bang today: ΛCDM





Current Situation

Flat Universe with the critical density: ~10 hydrogen atoms/m^3

~95% of the matter-energy of the universe is dark:

- *~70% dark energy as the cosmological constant*
- *~25% of cold dark matter with unknown physical nature*
- *~5% baryonic matter*

ΛCDM requires physics beyond the Standard Model of particle physics to explain the early universe (inflation?), baryogenesis, dark matter?

Cosmology from Galaxy Surveys

What is causing the acceleration of the expansión of the universe?

- Cosmological Constant
- New field
- Modifications to General Relativity

Two main cosmological observables:

- **History of the expansion rate of the universe:**
  - SN1a, BAO, weak lensing, cluster counting…
- **History of the rate of growth structure of the universe:**
  - RSD, weak lensing, LSS, cluster counting…

For all these cosmological probes, LARGE GALAXY SURVEYS ARE NEEDED

- Spectroscopic: 3D (redshift), medium depth, low density, selection effects
- Imaging: “2.5D” (photo-z), deeper, higher density, no selection effects

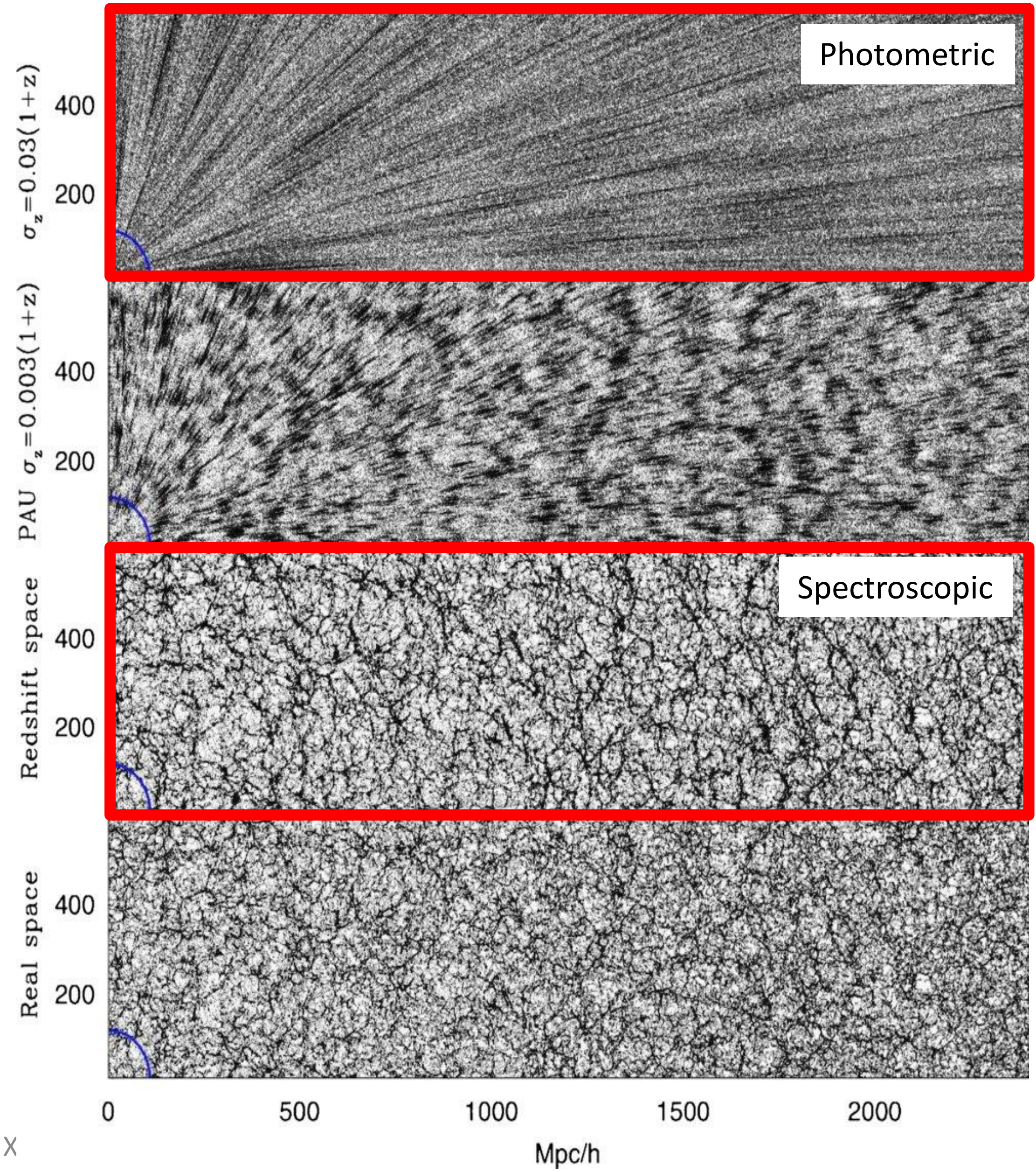
What is a Galaxy Survey

A map of a certain volume of the sky (as large as possible), that locates all its contents. To do this we need big telescopes (to see faint objects), and some method to measure redshifts.

The clustering signal is 3D. However, while angular positions are in general easy to measure, the radial distance is difficult. Two ways to do it:

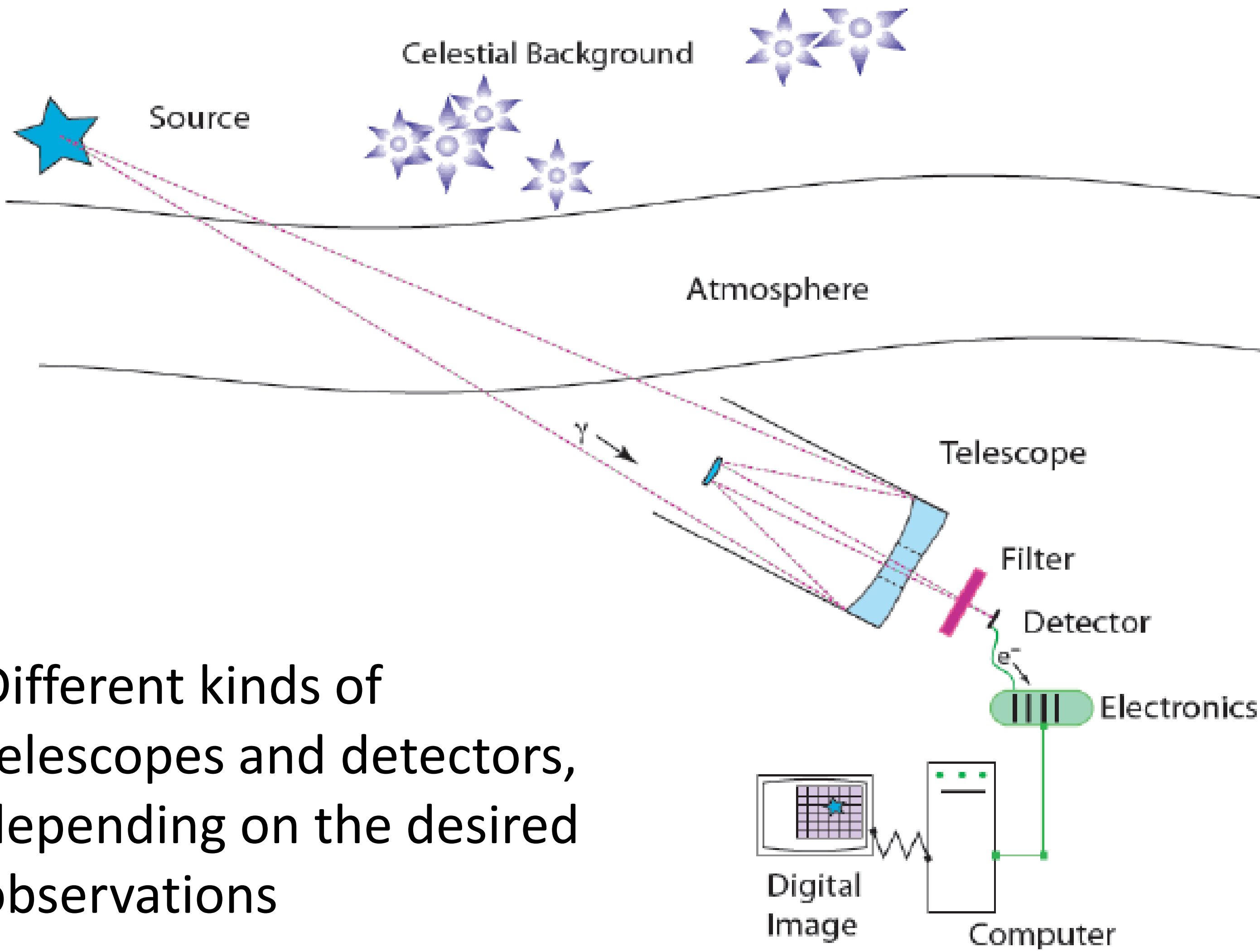
1) Spectrum of previously selected galaxies
2) Estimate from broadband colours with templates or training samples

Large advance in the last years and bright future, mainly due to technological developments that made possible larger and deeper surveys



How observations are done

Many observational effects in the measurement



Light source

The atmosphere

Telescope and optical system

Camera

Electronics+DaQ

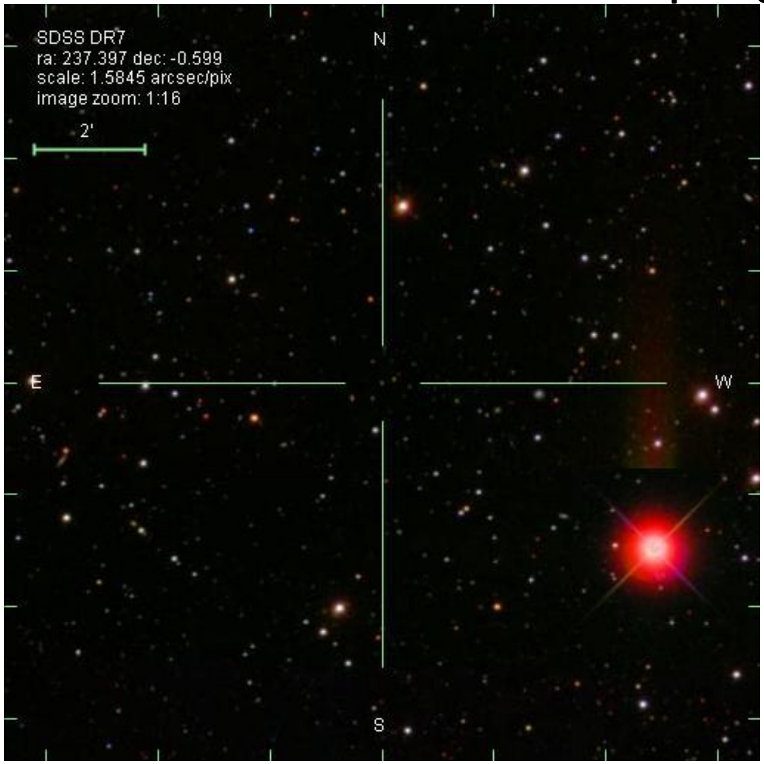
Data processing and calibration

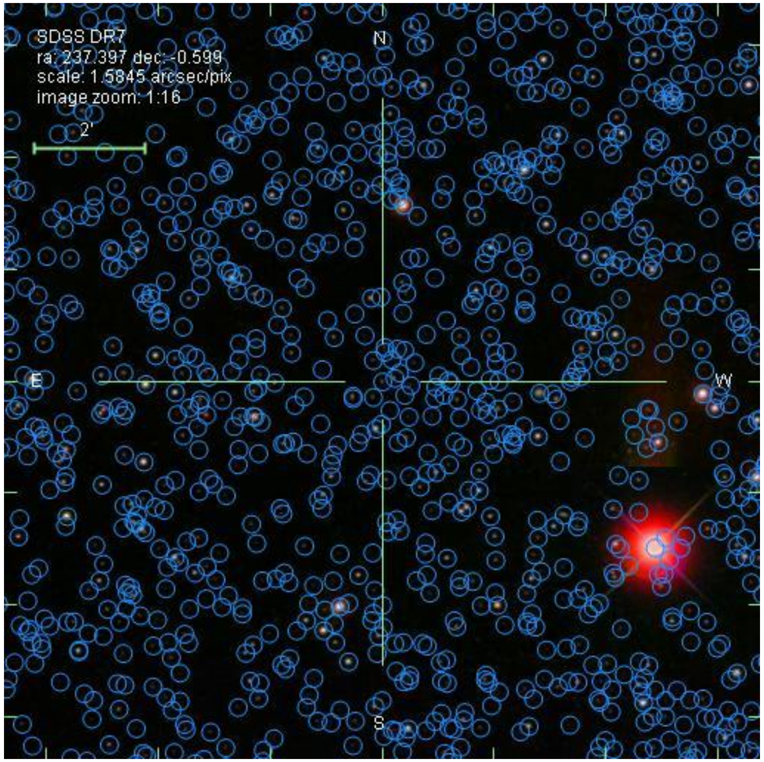
Scientific analysis

Different kinds of telescopes and detectors, depending on the desired observations

From images to results

The objects (usually galaxies) are detected using dedicated computing programs





To obtain cosmological results:

- Measure object´s position in the sky
- Classify objets: Stars, galaxies, quasars…?
- Measure z

Redshift (Spectroscopic) Galaxy Surveys

Measure the full 3D structure of Galaxy clustering

In a 2 step process:

First perform an imaging survey and select targets

Second, take spectra of the targets

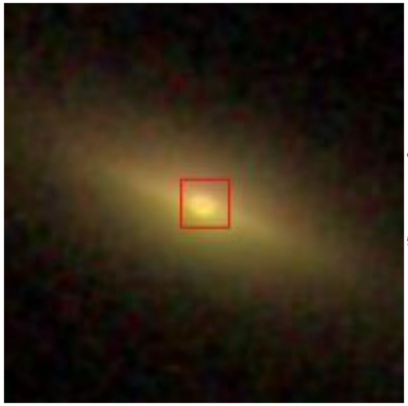
Main cosmological probes are:

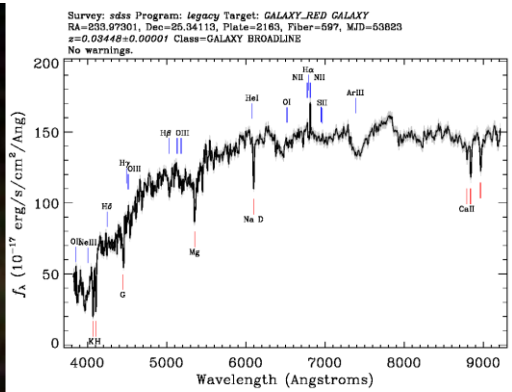
Baryon Acoustic Oscillations Scale

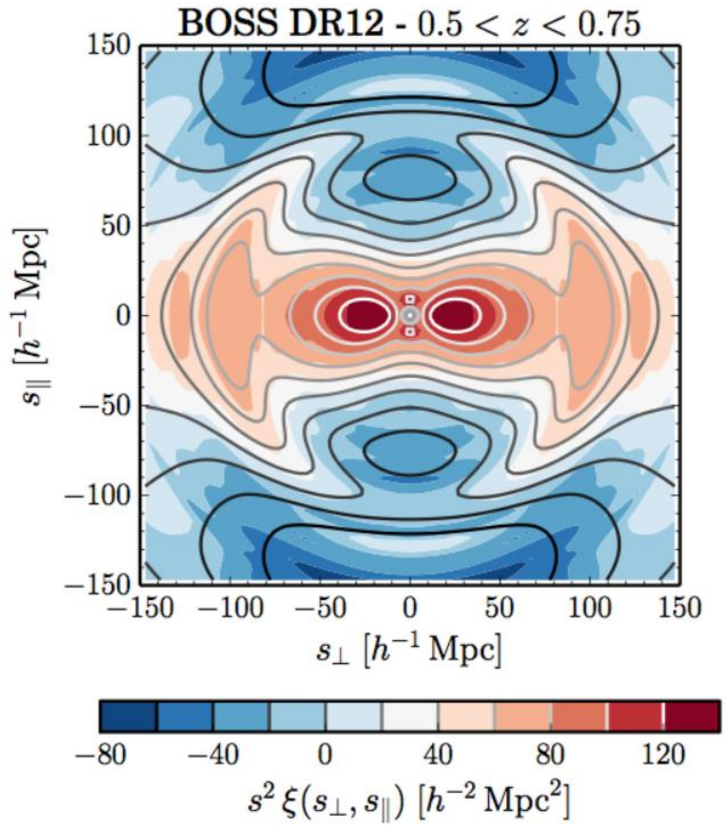
Redshift Space Distortions

Galaxy/Quasar Clustering

Lyman-Alpha Forest







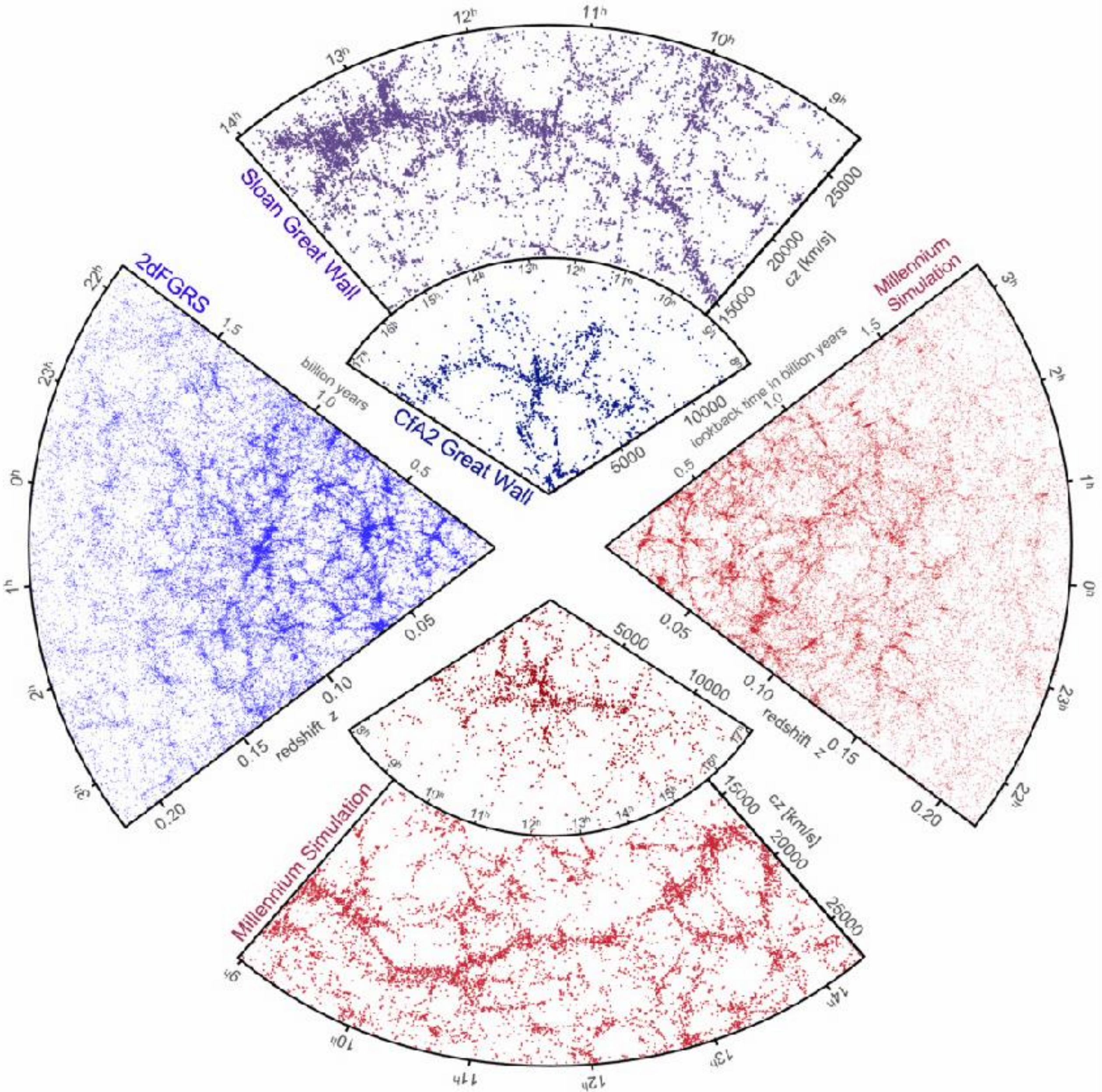
Redshift (Spectroscopic) Galaxy Surveys

Galaxy distribution in various redshift surveys and in mock catalogues constructed from the Millennium simulation.

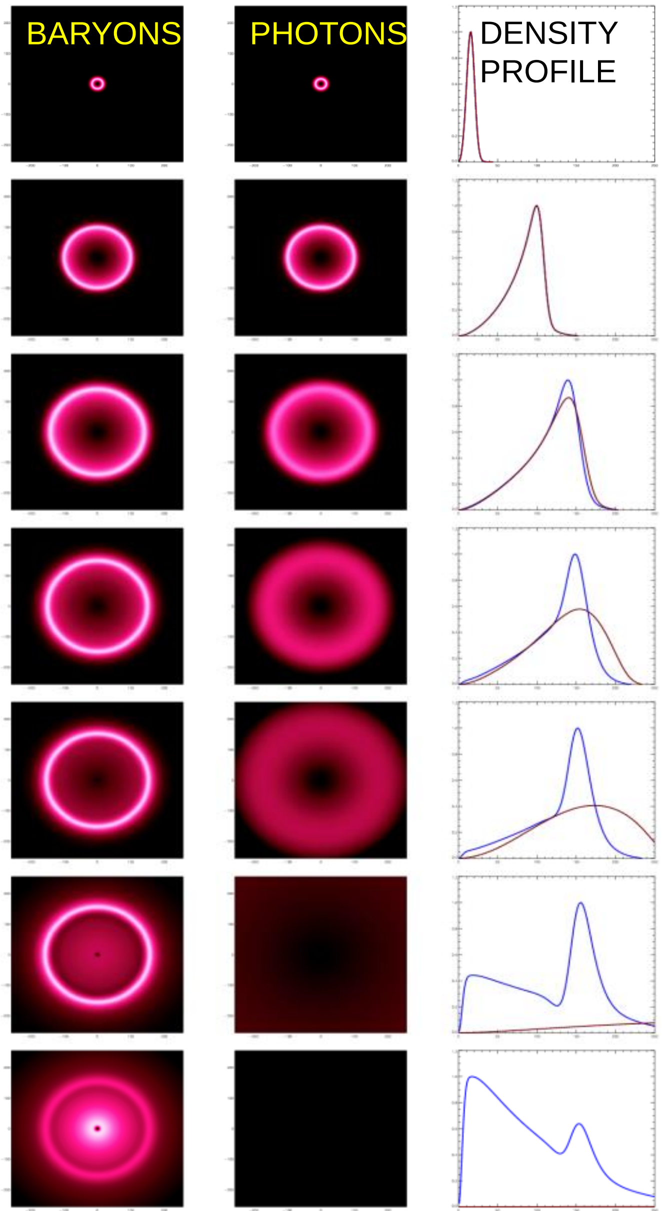
In blue: The small slice at the top shows the CfA2 "Great Wall", with the Coma cluster at the centre. Above is a section of the Sloan Sigital Sky Survey in with the "Sloan Great Wall" visible.

The wedge on the left shows one-half of the 2dF galaxy redshift survey.

In red: Millenium simulation



BAO



For *z*>>1000 the universe was a strongly coupled gas of photons and charged particles (and neutrinos and dark matter)

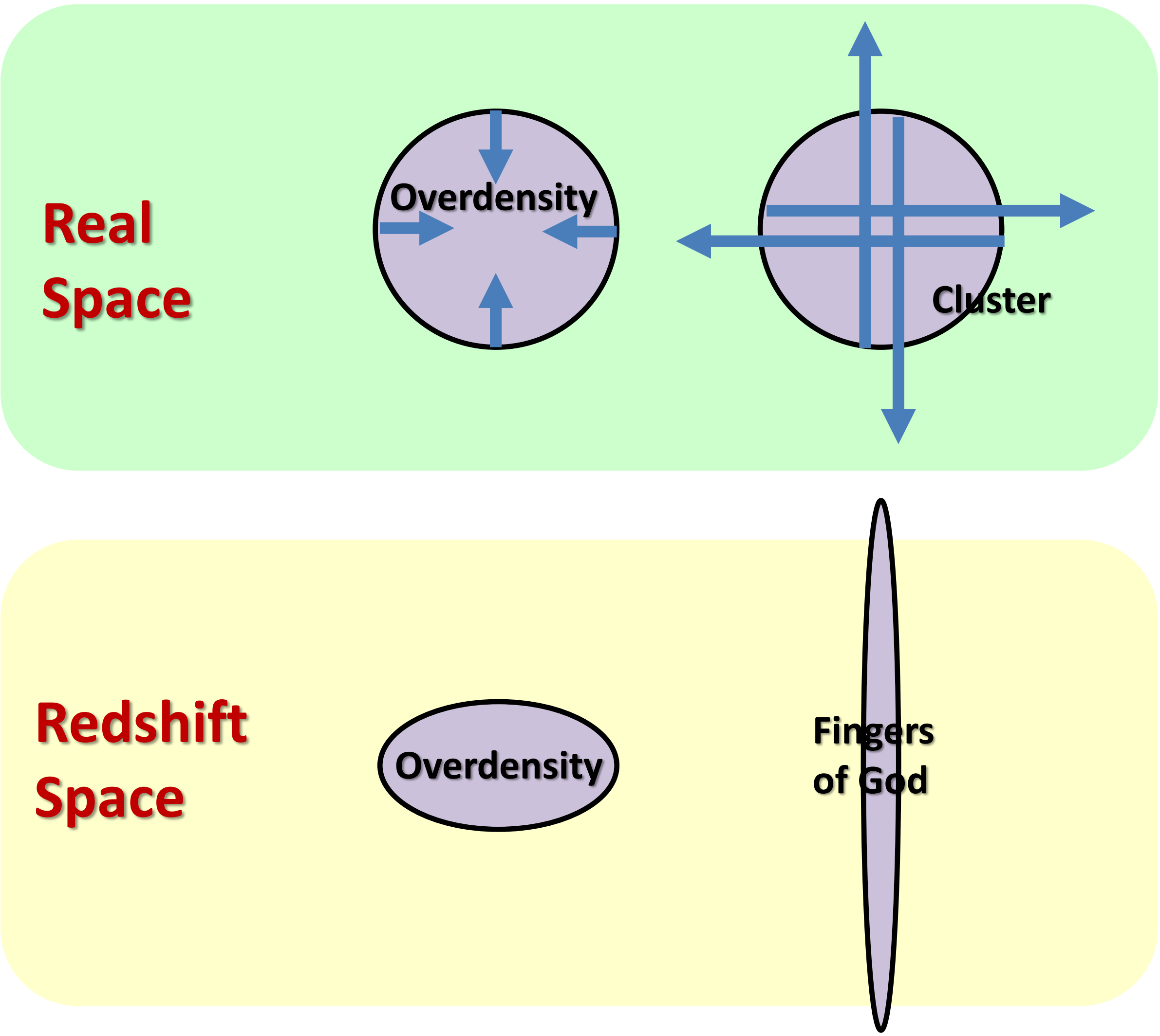
Overdensities make overpressures and a sound wave in the gas, wich propagates with velocity $c/\sqrt{3}$

For *z* ~ 1100 (*t* ~ 350 000 yr), temperature is low enough (3000 K) for the formation of hydrogen. Photons decouple and propagate freely (CMB)

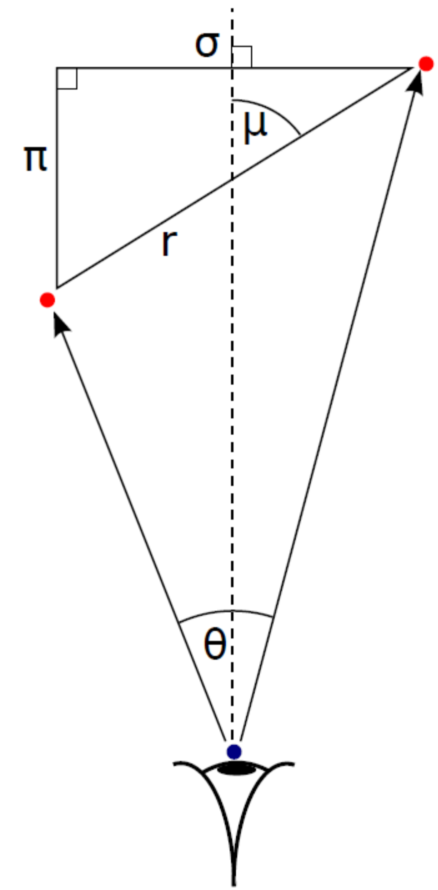
Photons quickly stream away, leaving the baryon peak stalled at ~150 Mpc.

There is a special separation between galaxies: 150 Mpc, that can be used as a <u>STANDARD RULER</u>

RSD

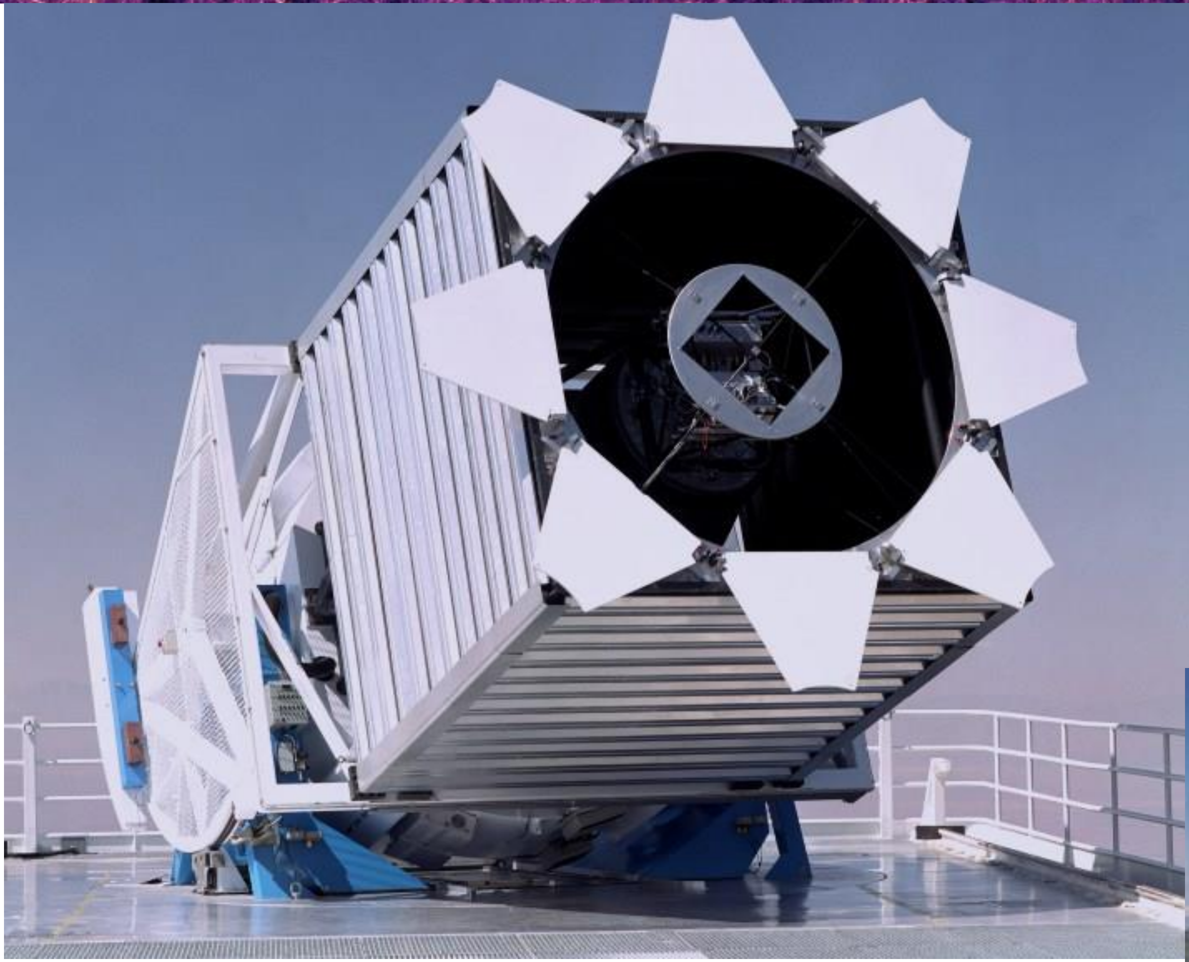


Real
Space
Overdensity
Cluster
Redshift
Space
Overdensity
Fingers
of God



σ
μ
π
r
θ

Redshift Survey: SDSS-IV



Apache Point Observatory

Dedicated 2.5m Telescope

Several projects from 2000 to 2020

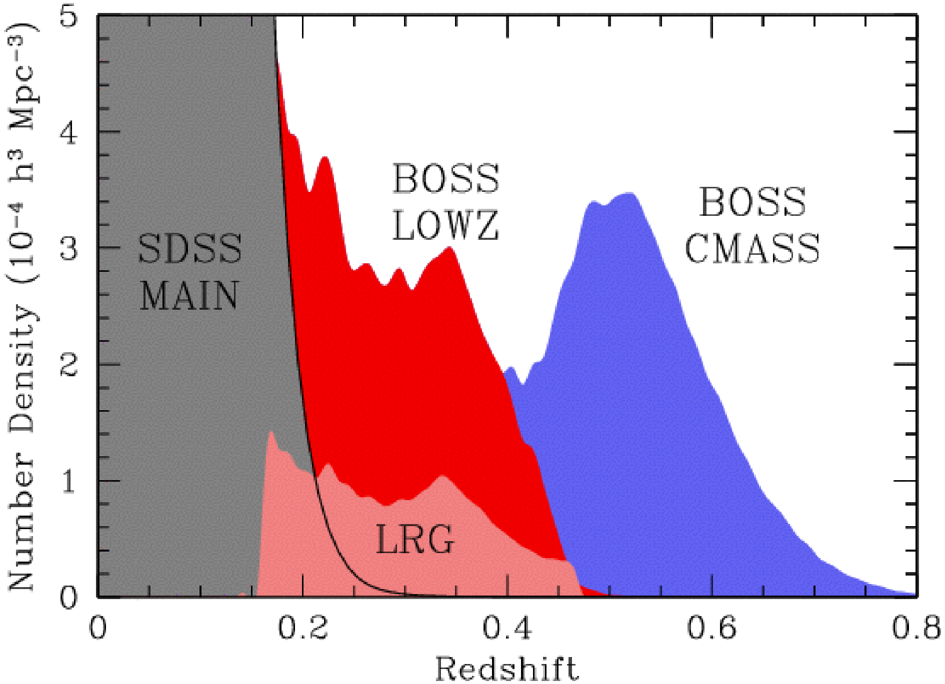
Several improvements in the setup during this period

Redshift surveys work on a 2 steps process:

1.- Imaging survey and target selection

2.- Spectra for selected targets

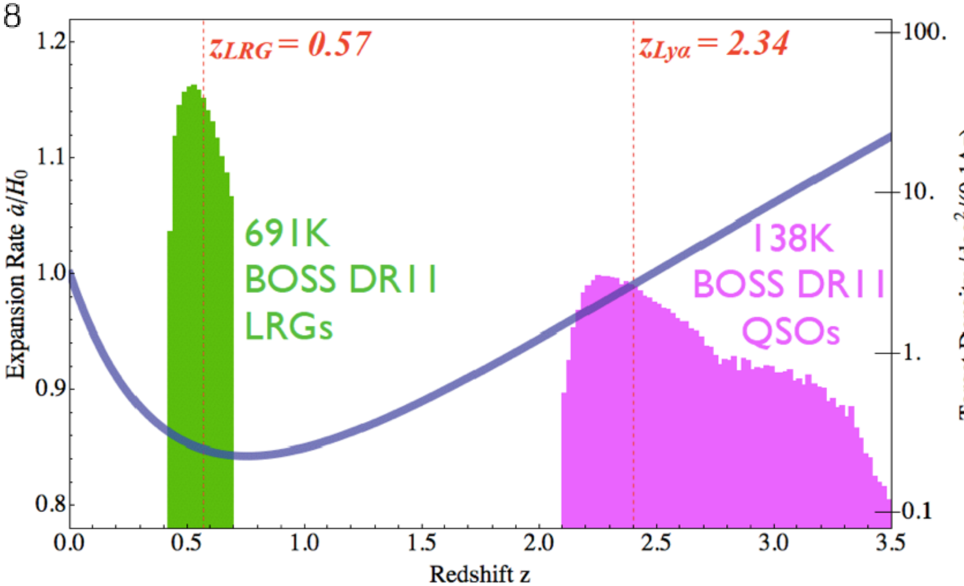
Redshift Survey: SDSS-IV



Several Galaxy samples, selected to map different redshift ranges

Luminous Red Galaxies (z < 0.4) → Brightest and reddest galaxies

CMASS Galaxies (0.4 < z < 0.7) → More luminous and massive galaxies



In addition, a quasar sample that covers the redshift range 2.15 < z < 3.5, to use the Ly-α forest as a cosmological probe

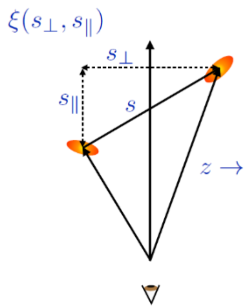
Anisotropic Correlation Function

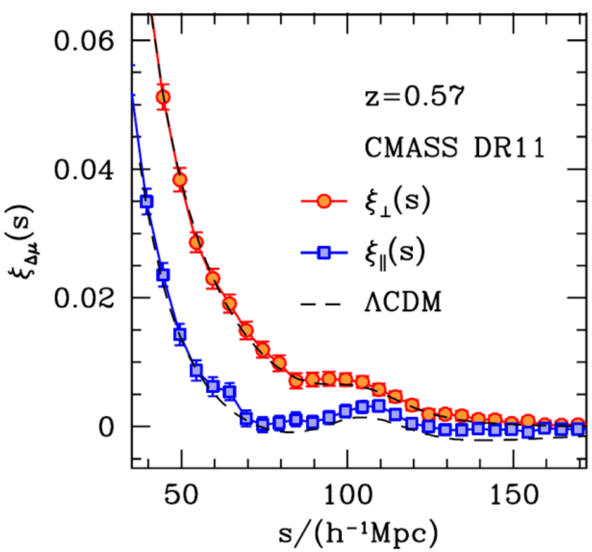
BOSS DR12 anisotropic correlation function

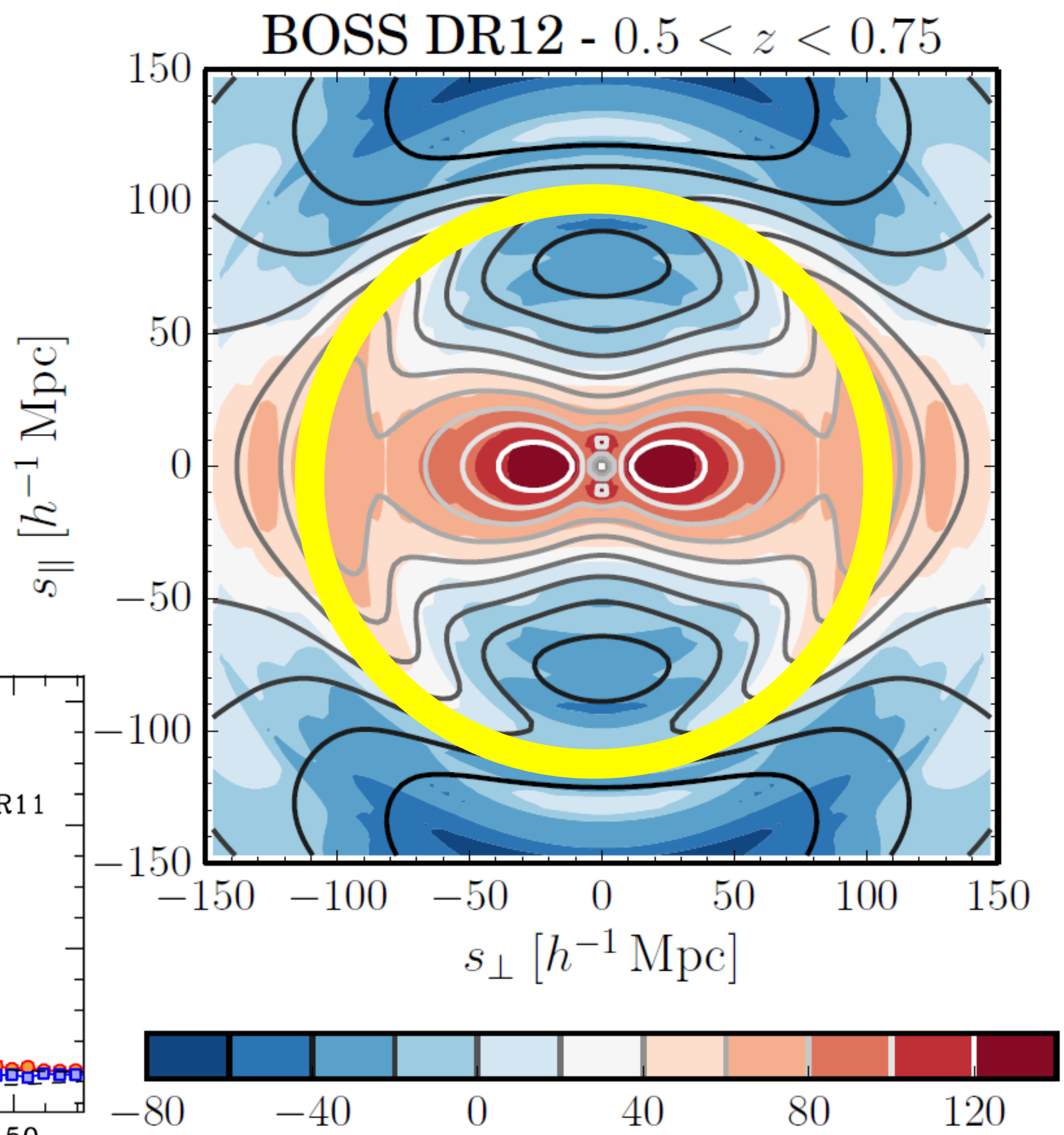
The BAO signal appears as a ring at s=110 Mpc/h

RSD distort the contours, which deviate from perfect circles

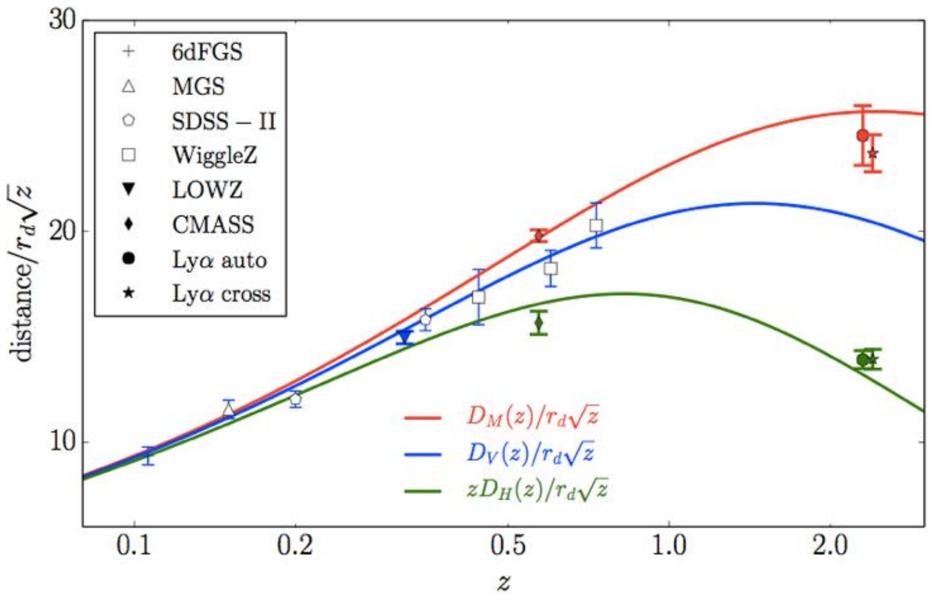
Fit to obtain cosmological parameters

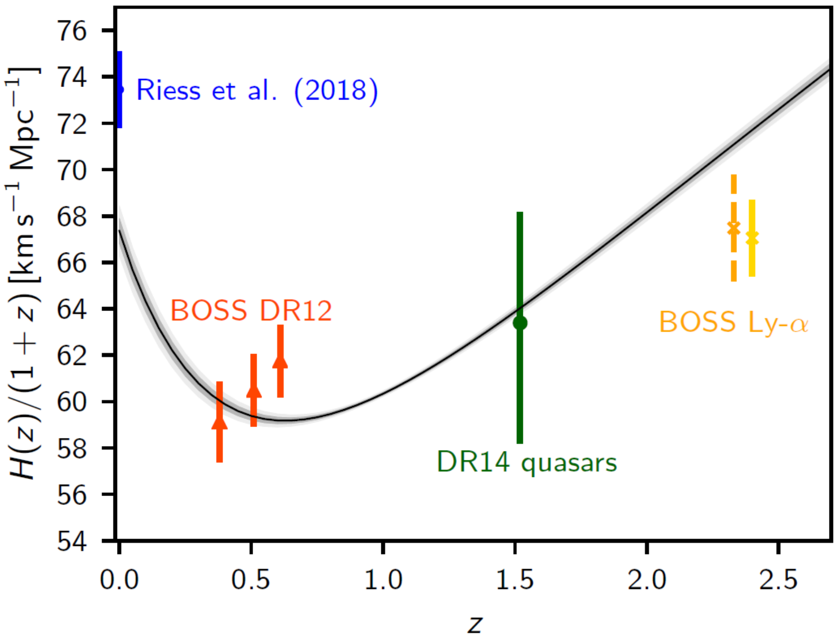


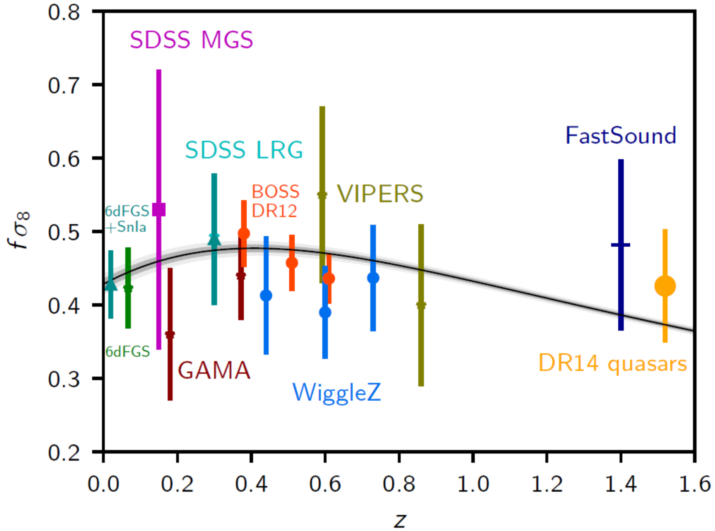




Main Measurements of Redshift Surveys







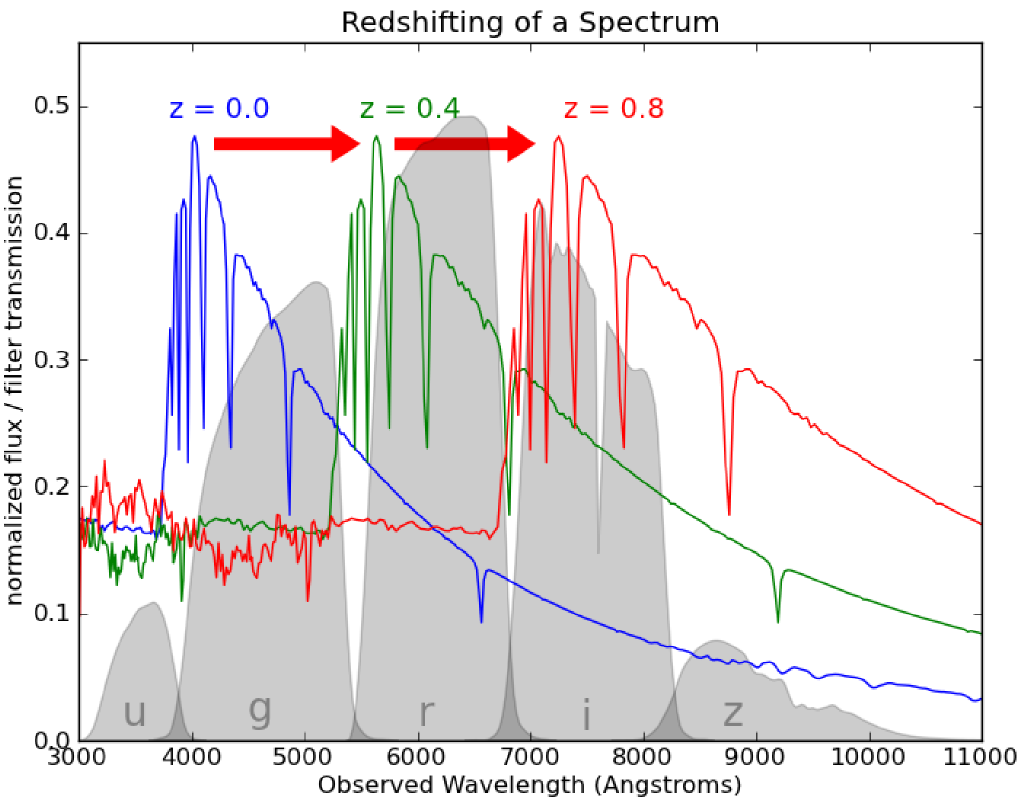
Imaging (Photometric) Galaxy Surveys

Measure the 2D projected structure of Galaxy clustering

Redshift is measured from galaxy fluxes in optical filters (photometric redshifts). Precision is much worse than in spectroscopic surveys, but all galaxies in the field of view are used.

Main cosmological probes are:

- Galaxy Clustering & BAO
- **Weak Gravitational Lensing**
- **Galaxy Clusters**
- SN1a

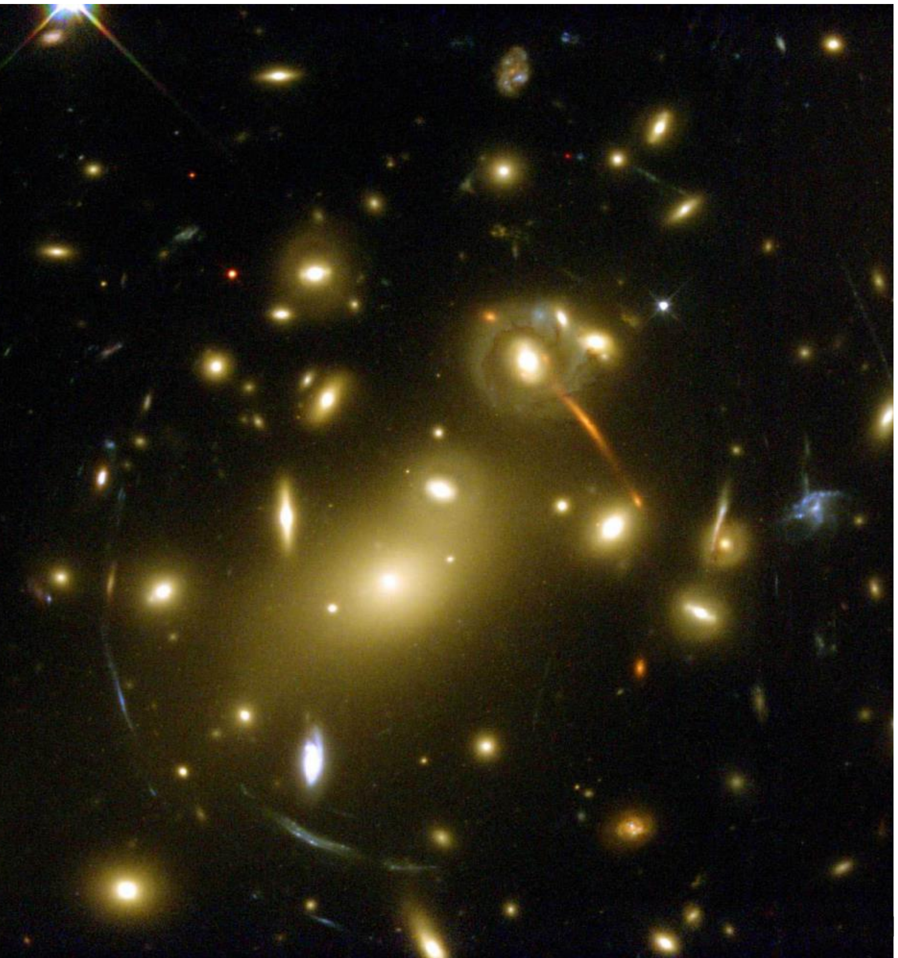


Gravitational Lensing

Radiation is deflected in gravitational fields → Image distortion

Since the effect comes from the gravitational field, it is sensitive to all matter/ energy, including dark matter and dark energy

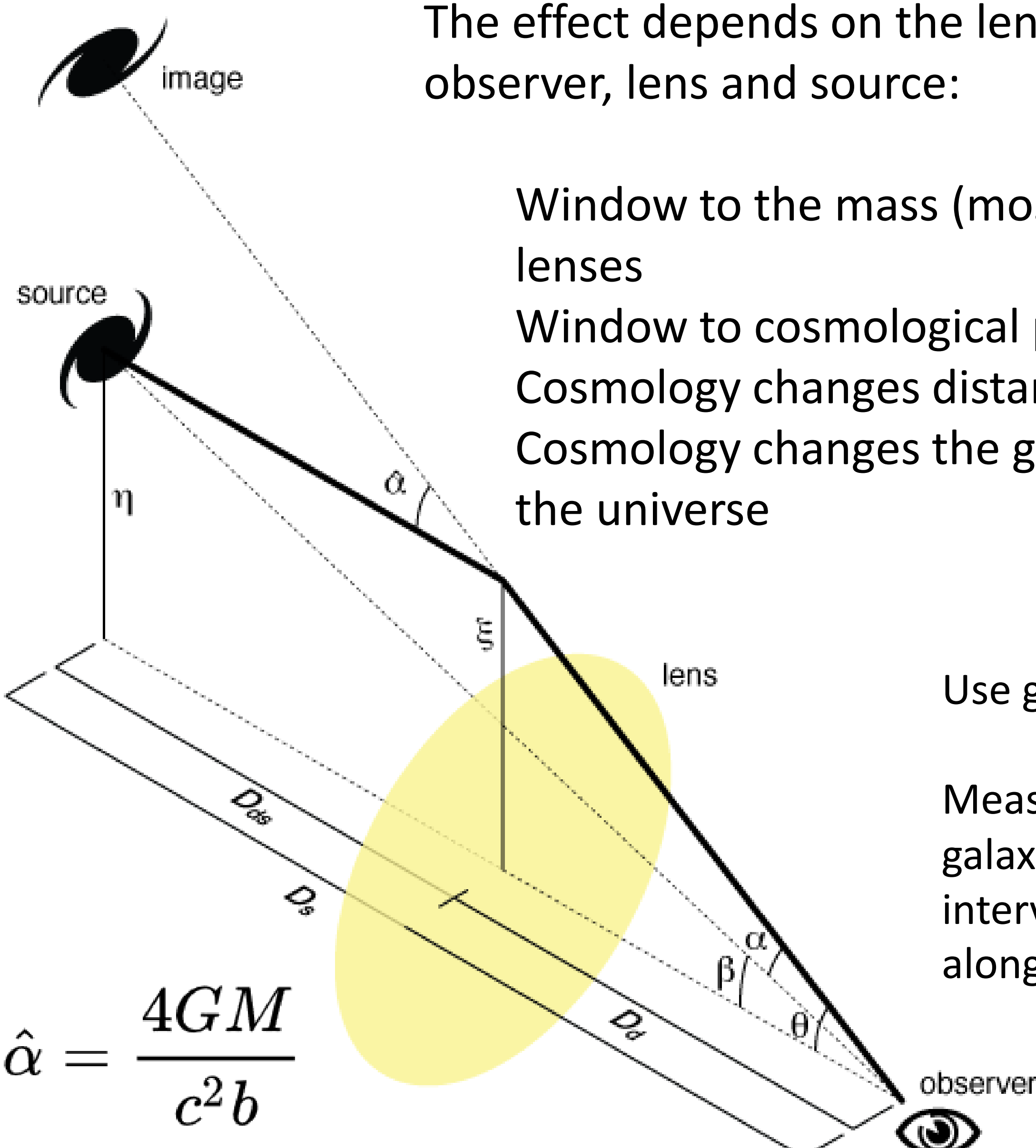
STRONG LENSING



WEAK LENSING

Weak Gravitational Lensing

The 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 cosmological parameters:
- Cosmology changes distances **Dd, Ds, Dds**
- Cosmology changes the growth rate of mass structures in the universe

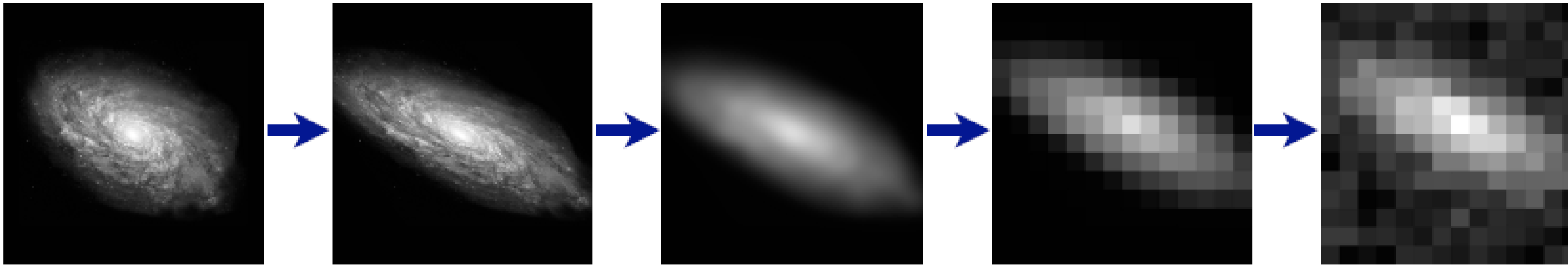
$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

Use galaxies as tracers

Measure the shapes of background galaxies → Galaxy shapes are distorted by intervening mass → Infer mass integrated along the line of sight

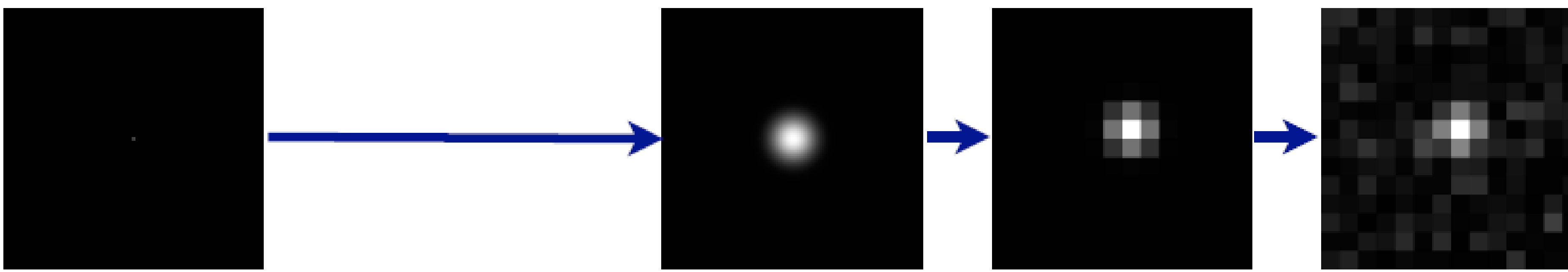
Weak Gravitational Lensing

Effect exagerated by x20



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

Stars: Point sources to star images:

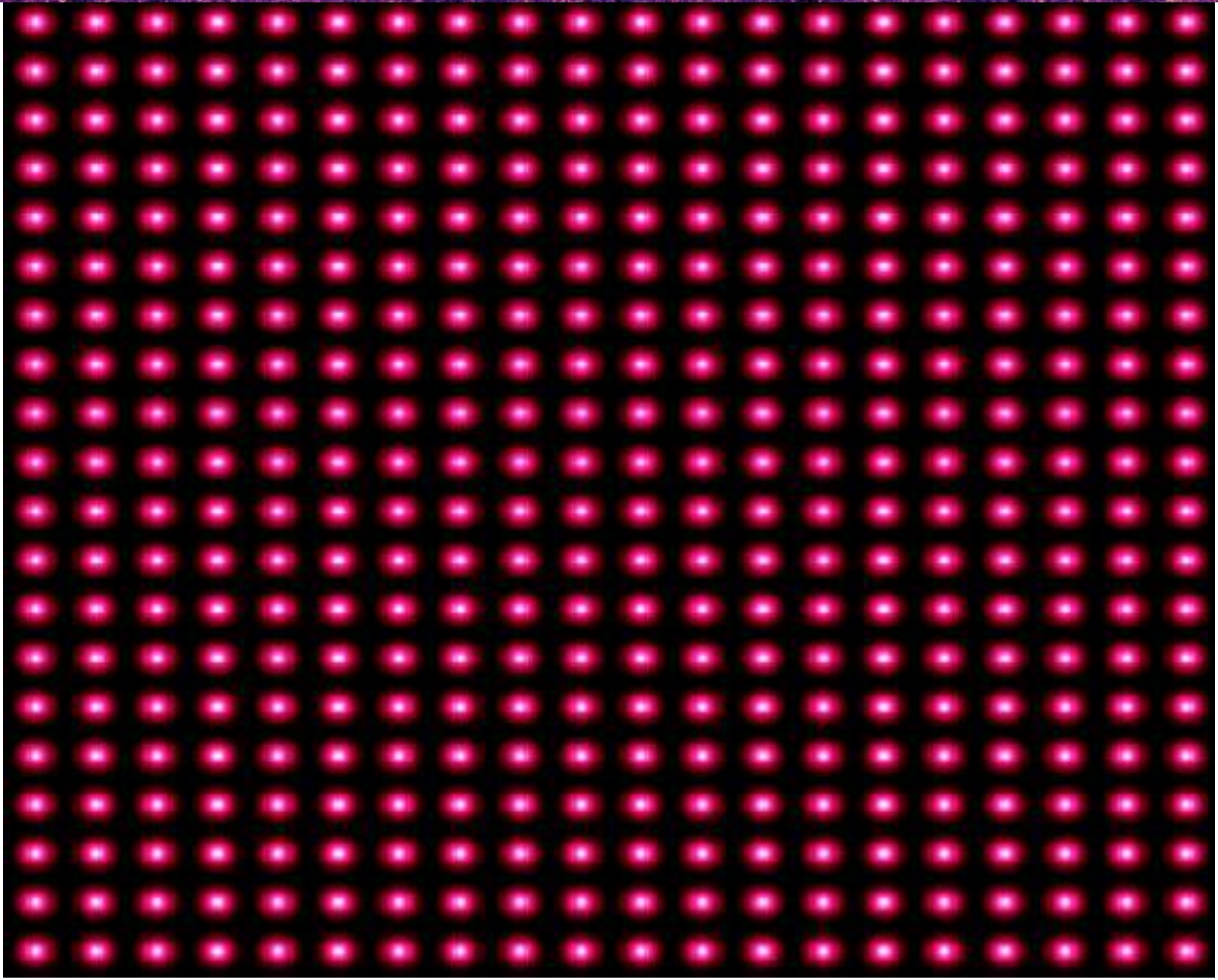


Intrinsic star (point source) | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

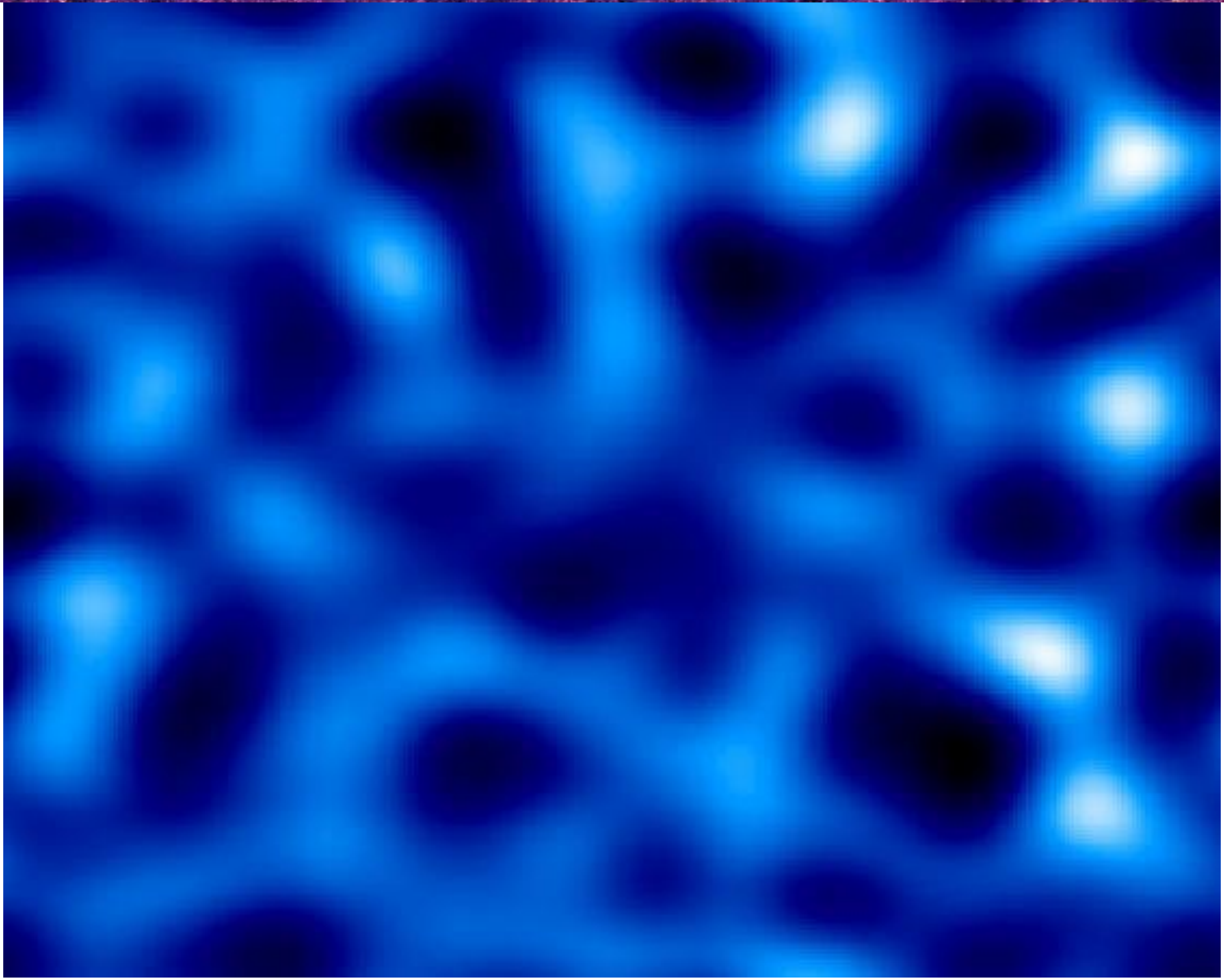
Small and difficult to measure effect, but observable

Control the measurement using known pointlike objects → stars

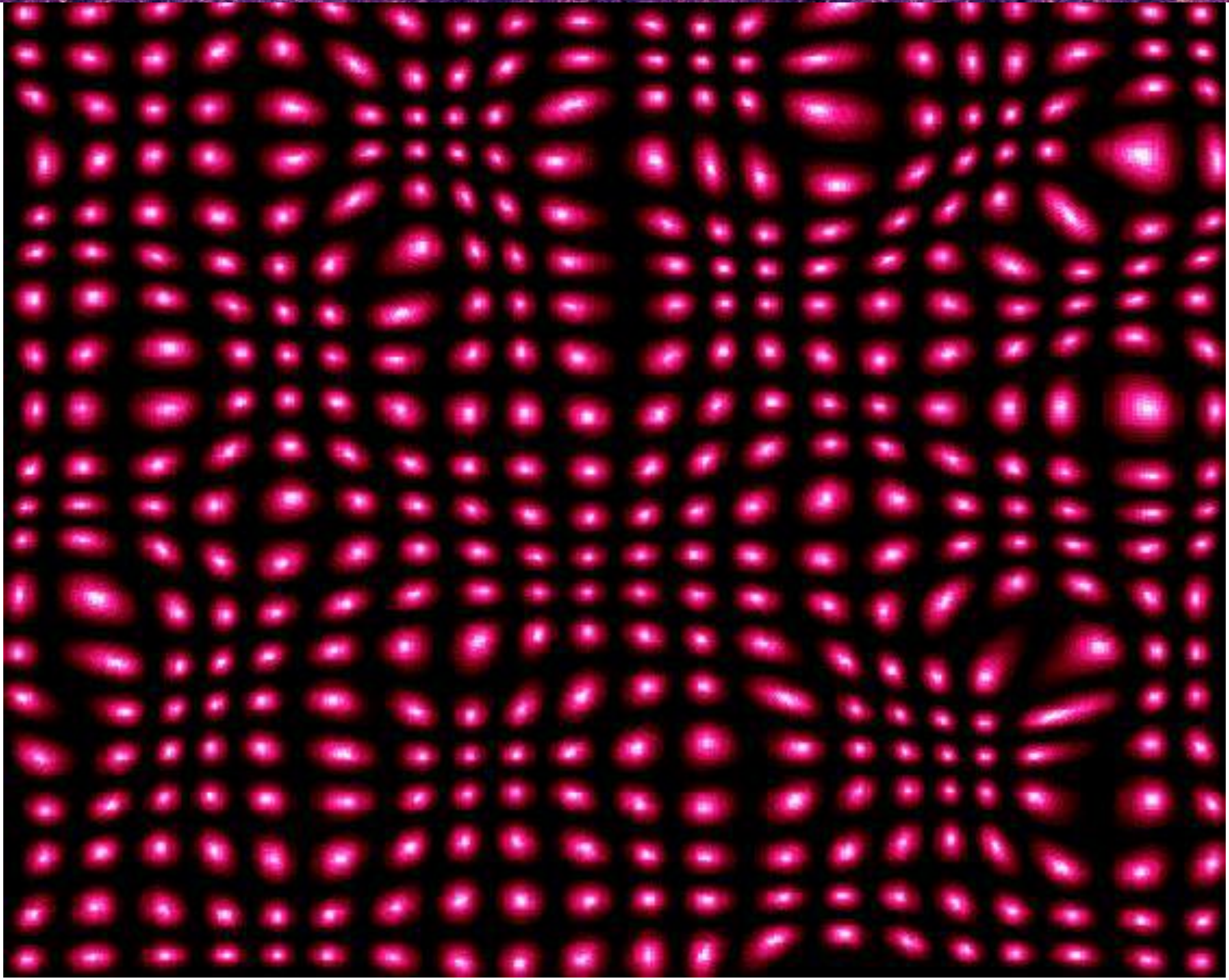
Weak Gravitational Lensing



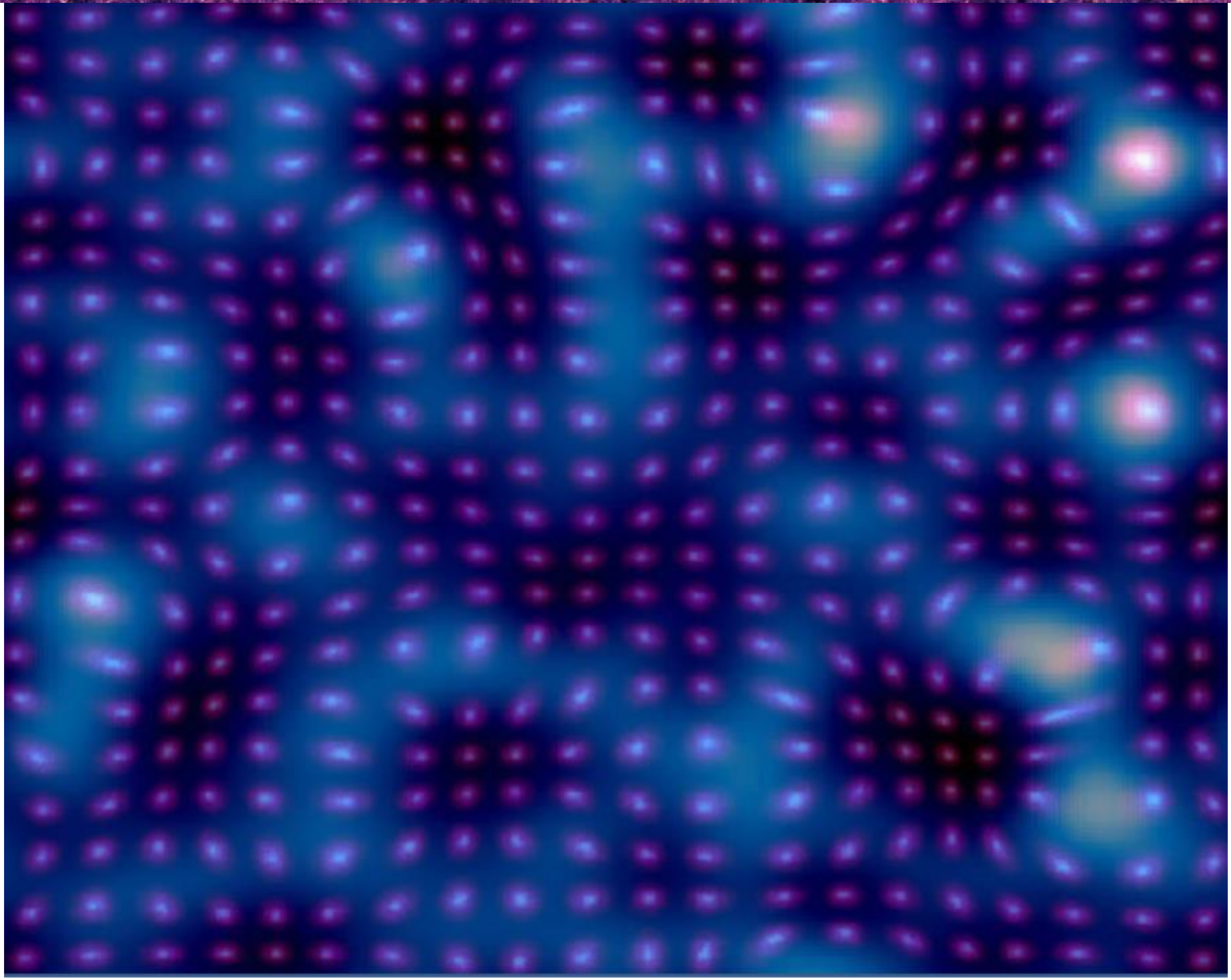
Weak Gravitational Lensing



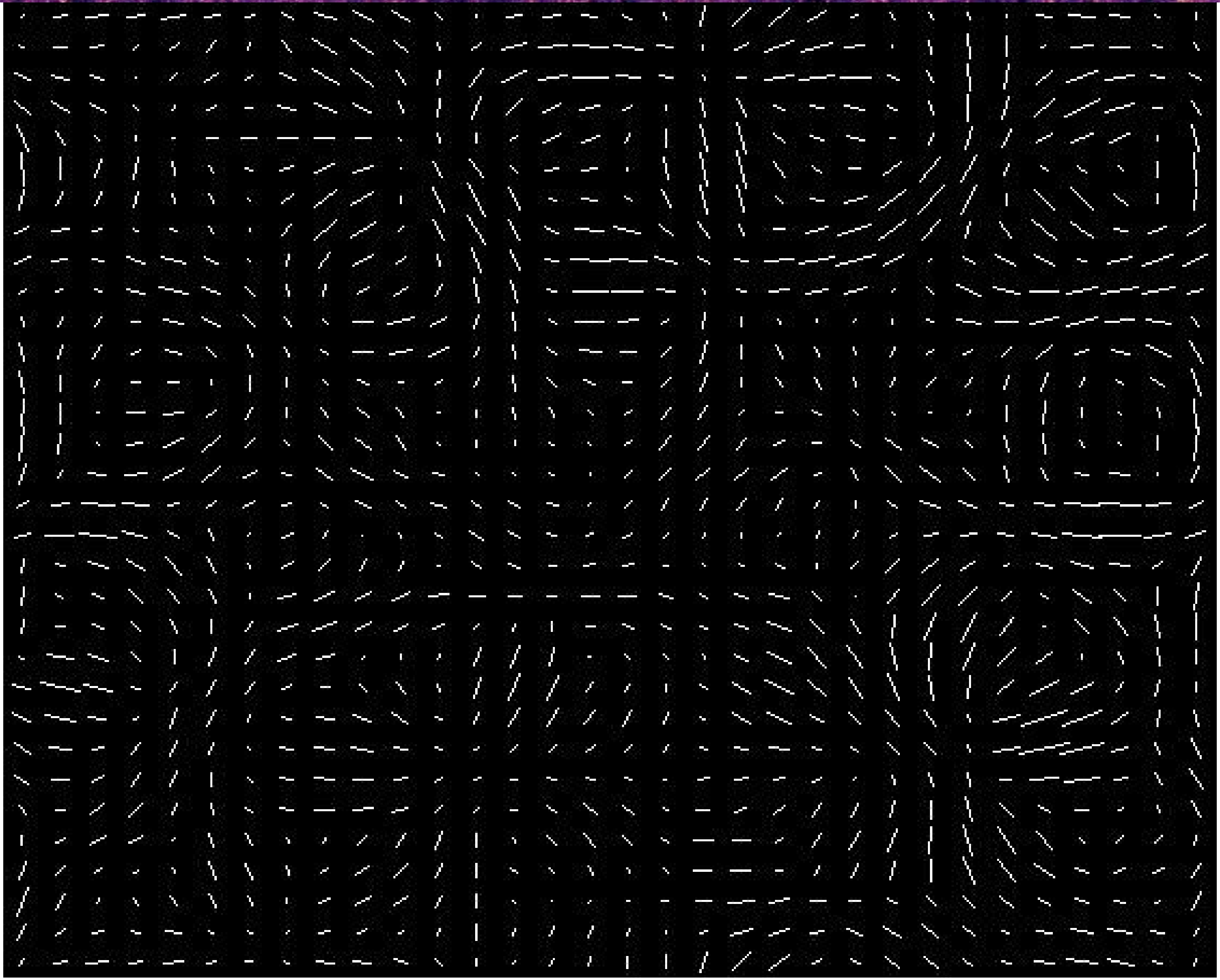
Weak Gravitational Lensing



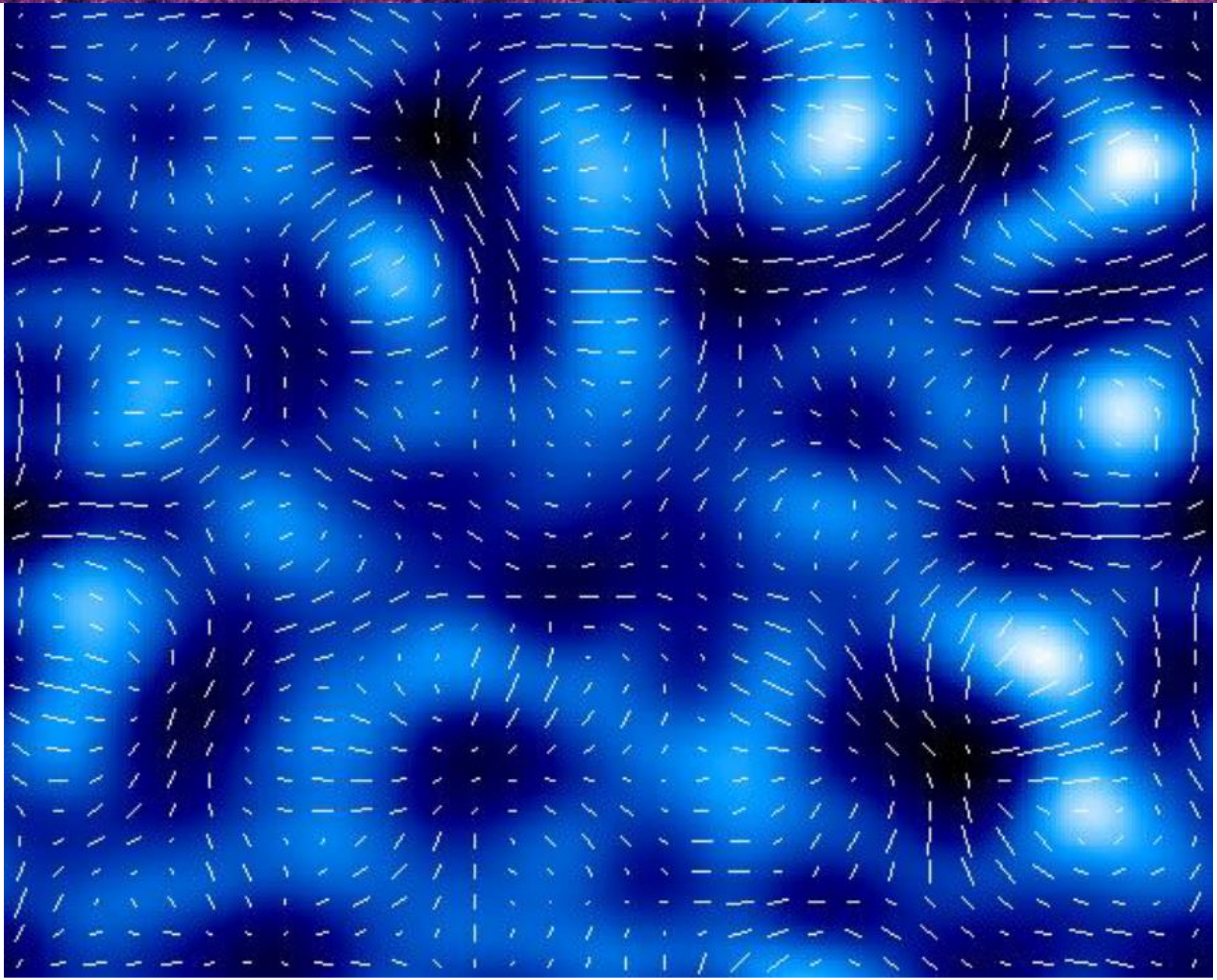
Weak Gravitational Lensing



Weak Gravitational Lensing



Weak Gravitational Lensing



Combine Probes in Imaging Surveys

Beyond individual probes

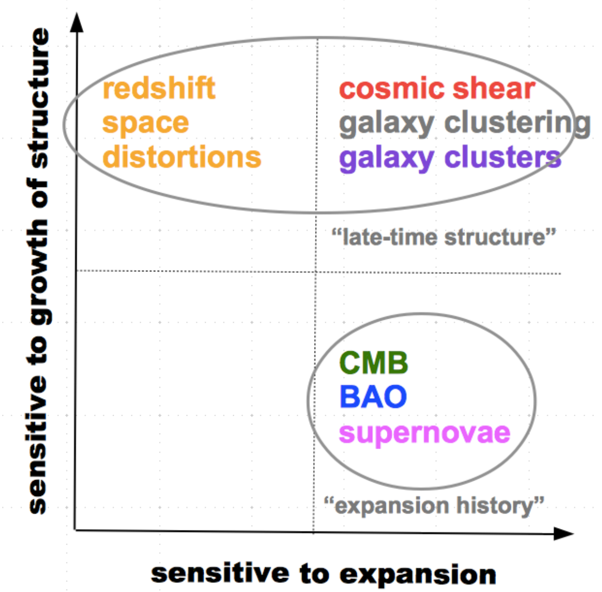
There are many observational probes for dark energy:

Distance probes: SN1a, BAO, CMB, weak lensing, Galaxy clusters…

Growth of structure probes: CMB, RSD, weak lensing, clusters…

No single technique is sufficiently powerful to improve the current knowledge on dark energy by one order of magnitude →

COMBINATION OF TECHNIQUES

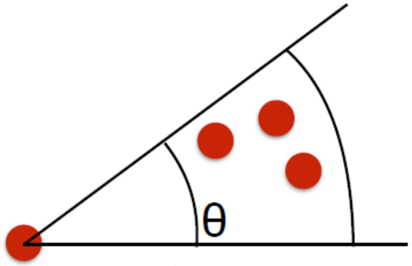


Combine Probes in Imaging Surveys

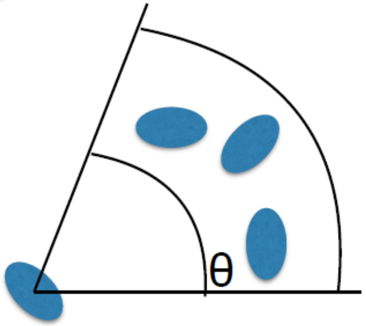
Beyond individual probes → 3x2pt Analysis in DES

We can measure more properties of galaxies than only their positions:
Colors, spectra, shape and we can correlate them

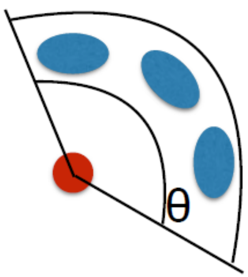
Correlations



- $w(\theta)$
  Galaxy density (position) correlation function



- $\xi_+(\theta)$, $\xi_-(\theta)$
  Shear (shape) correlation functions

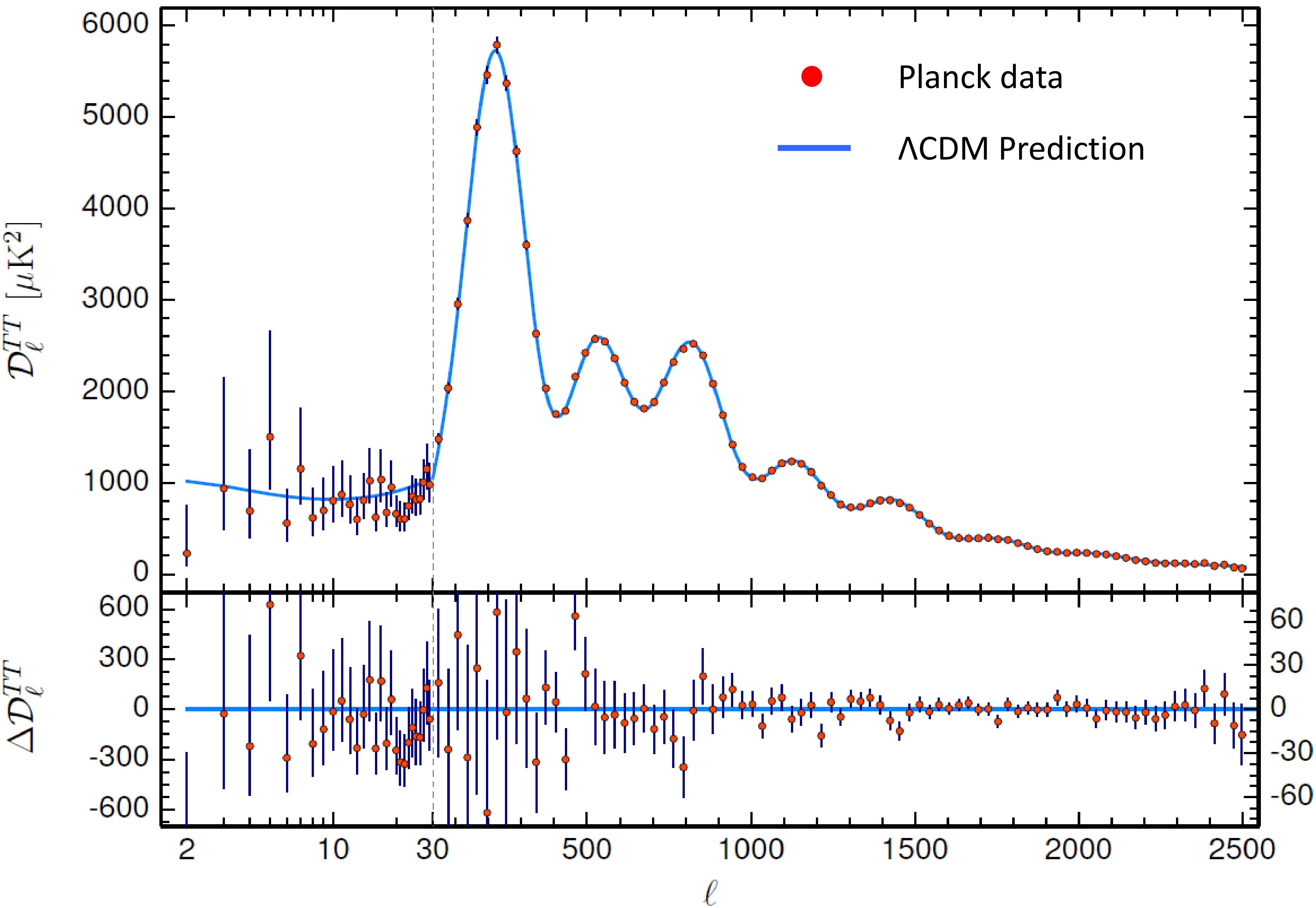


- $\gamma_T(\theta)$
  Shear around galaxies (galaxy-galaxy lensing)

Image: Dark Energy Camera, from http://darkenergydetectives.org

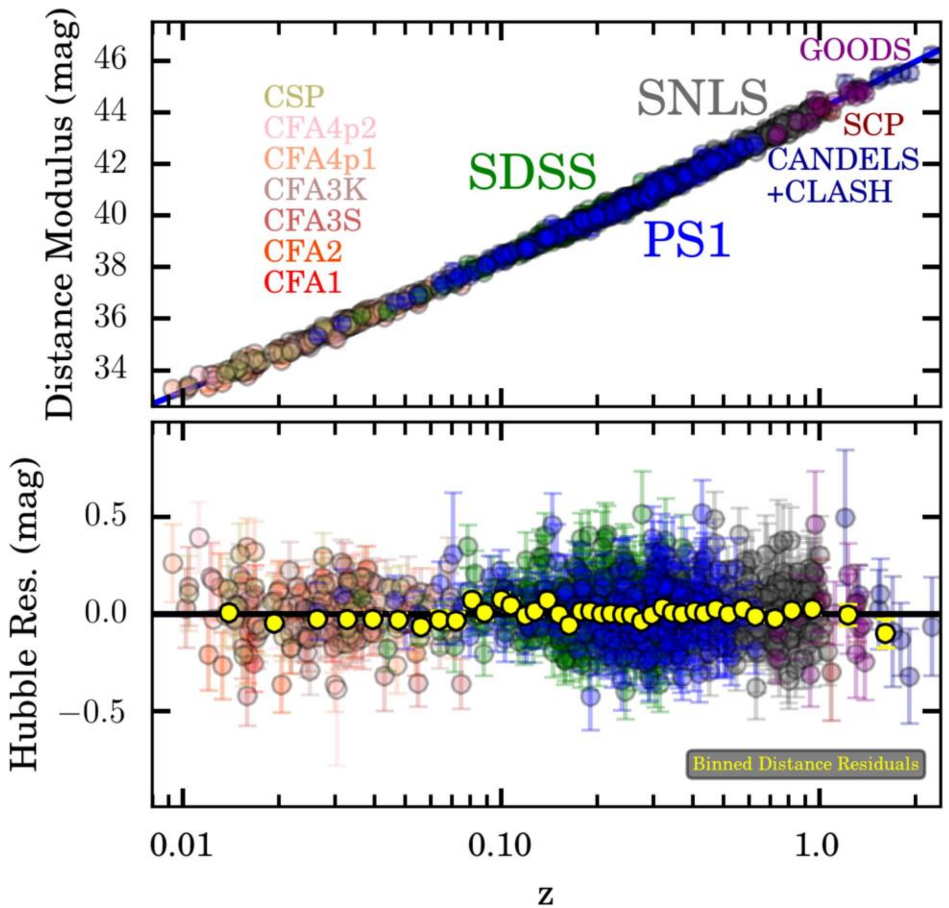
CURRENT STATUS OF COSMOLOGY

Planck measurements of the CMB

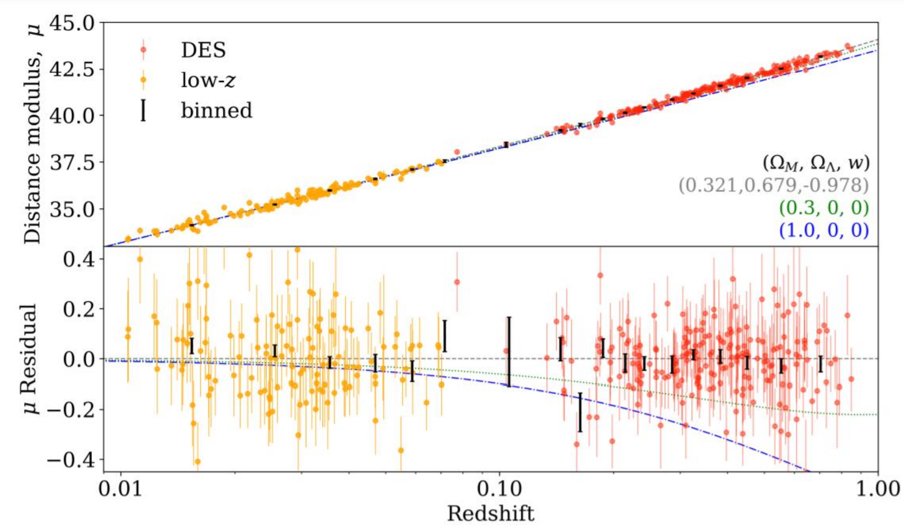


Pantheon and DESY3 measurements of SN1a

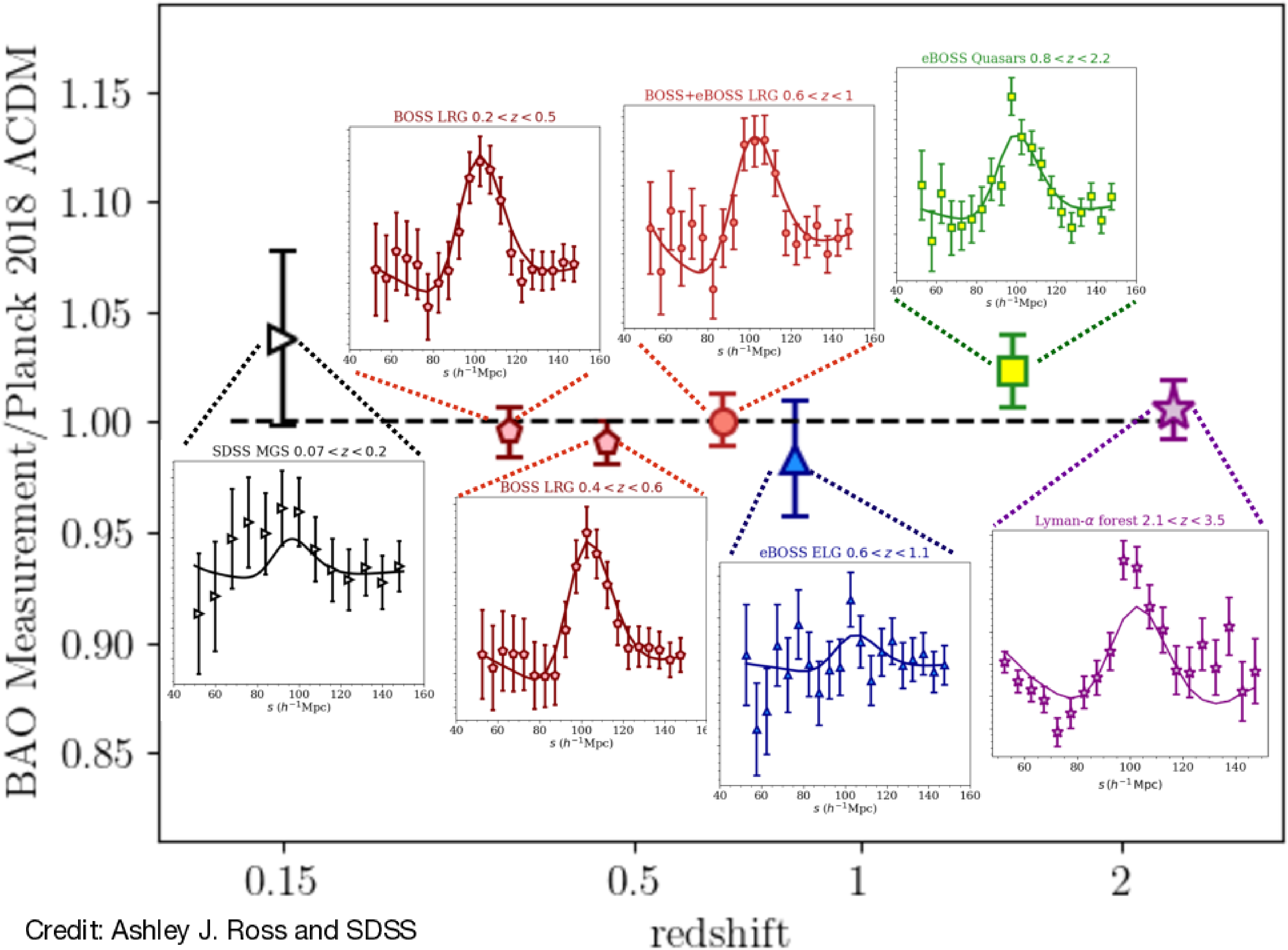
PanStarrs PS1 Pantheon Sample



DES Y3 Sample

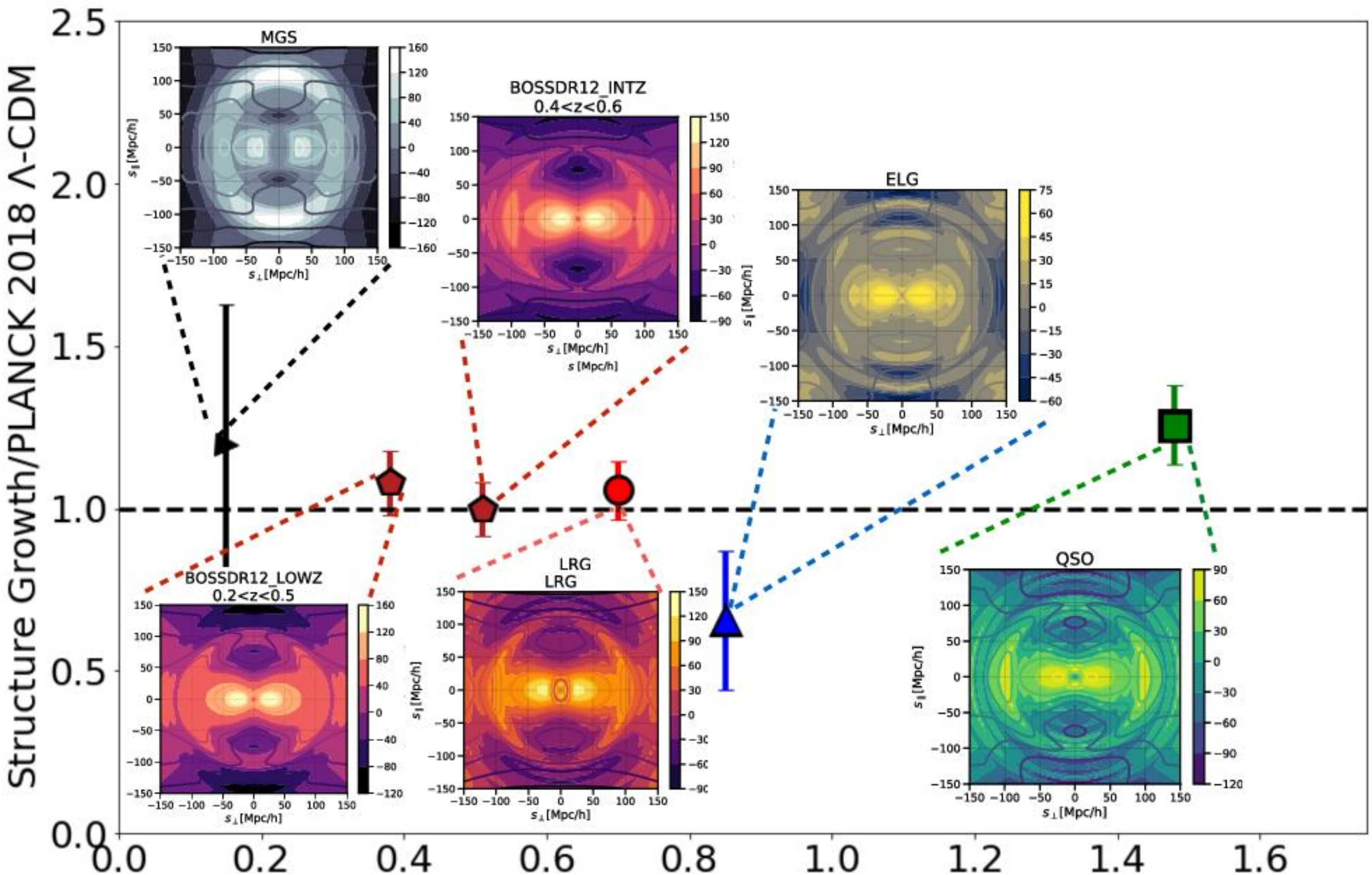


SDSS-IV final measurement of BAO



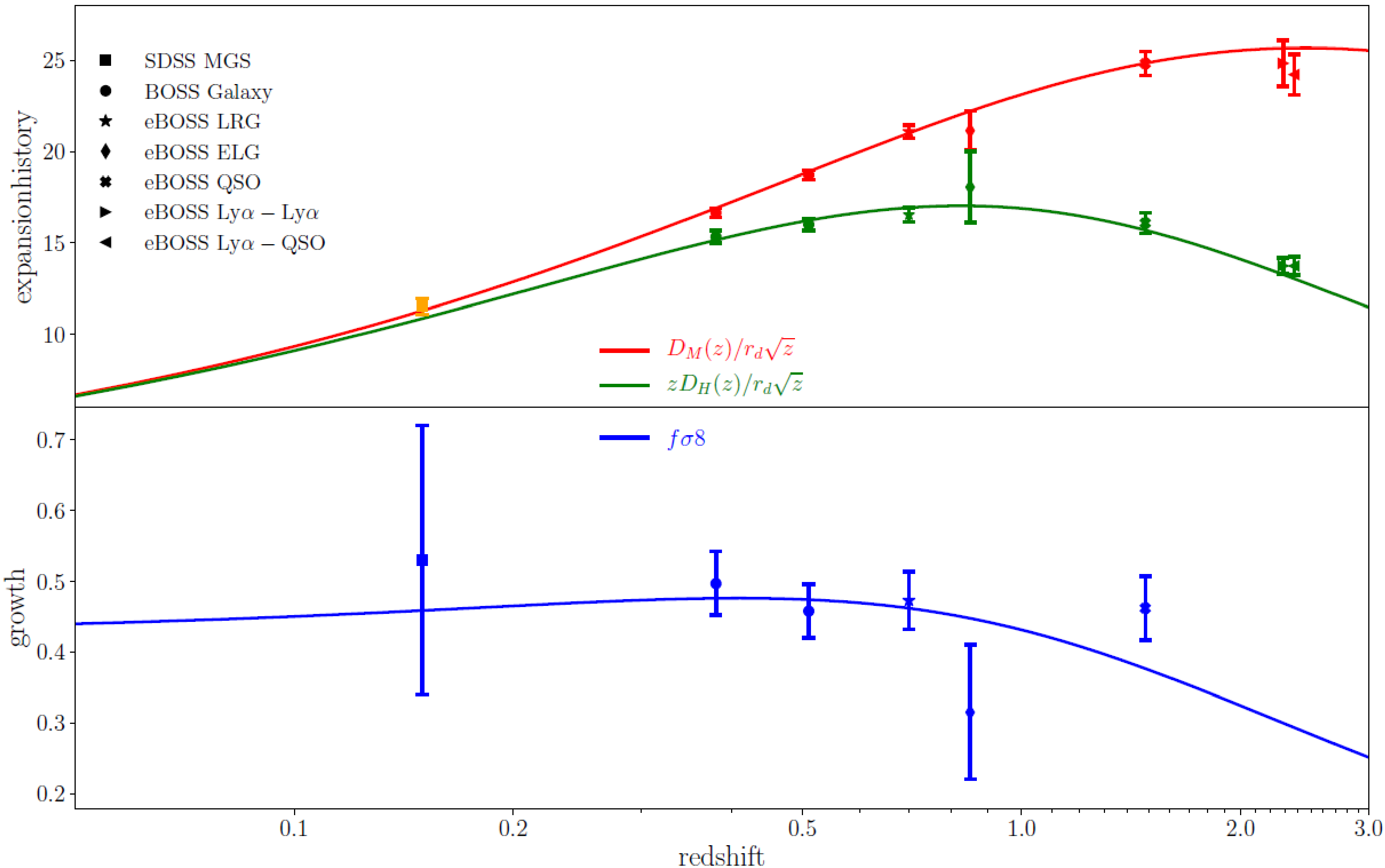
Credit: Ashley J. Ross and SDSS

SDSS-IV final measurement of RSD



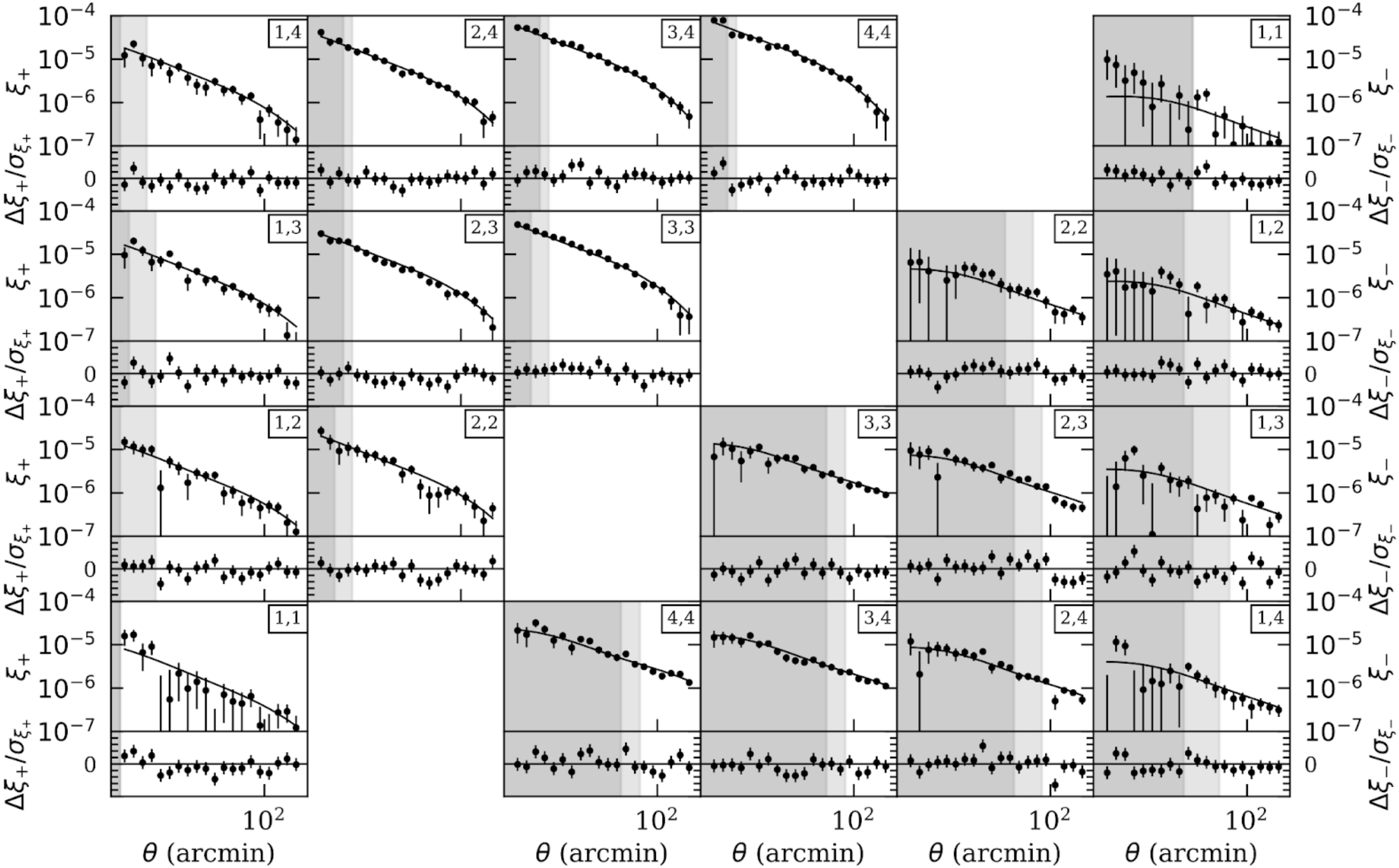
Credit: M.Vargas-Magaña and SDSS.

SDSS-IV measurements of LSS

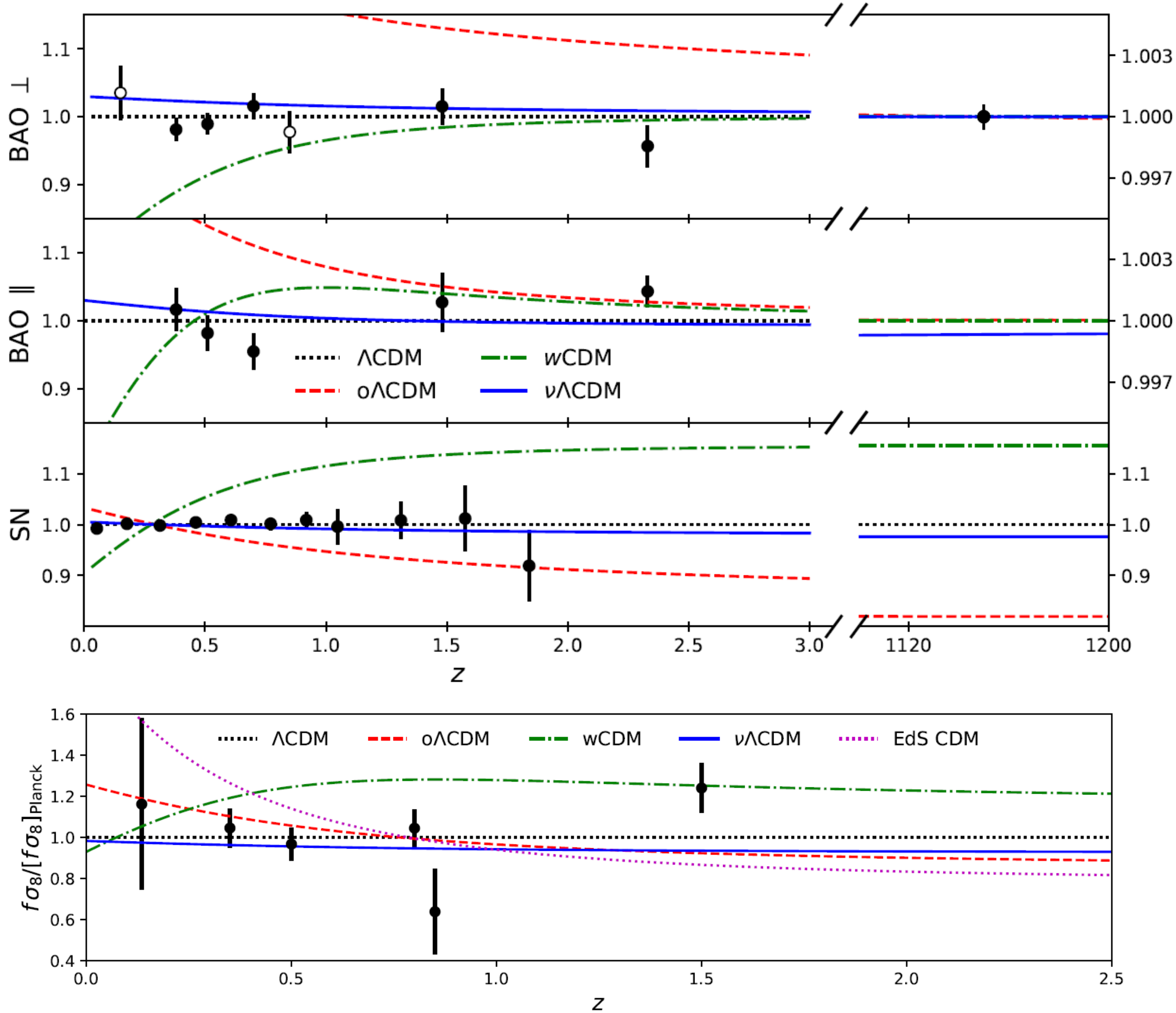


DES-Y3 measurements of Weak Lensing

Weak Lensing results are dominated by DES Measurements



Current Situation: All described by ΛCDM



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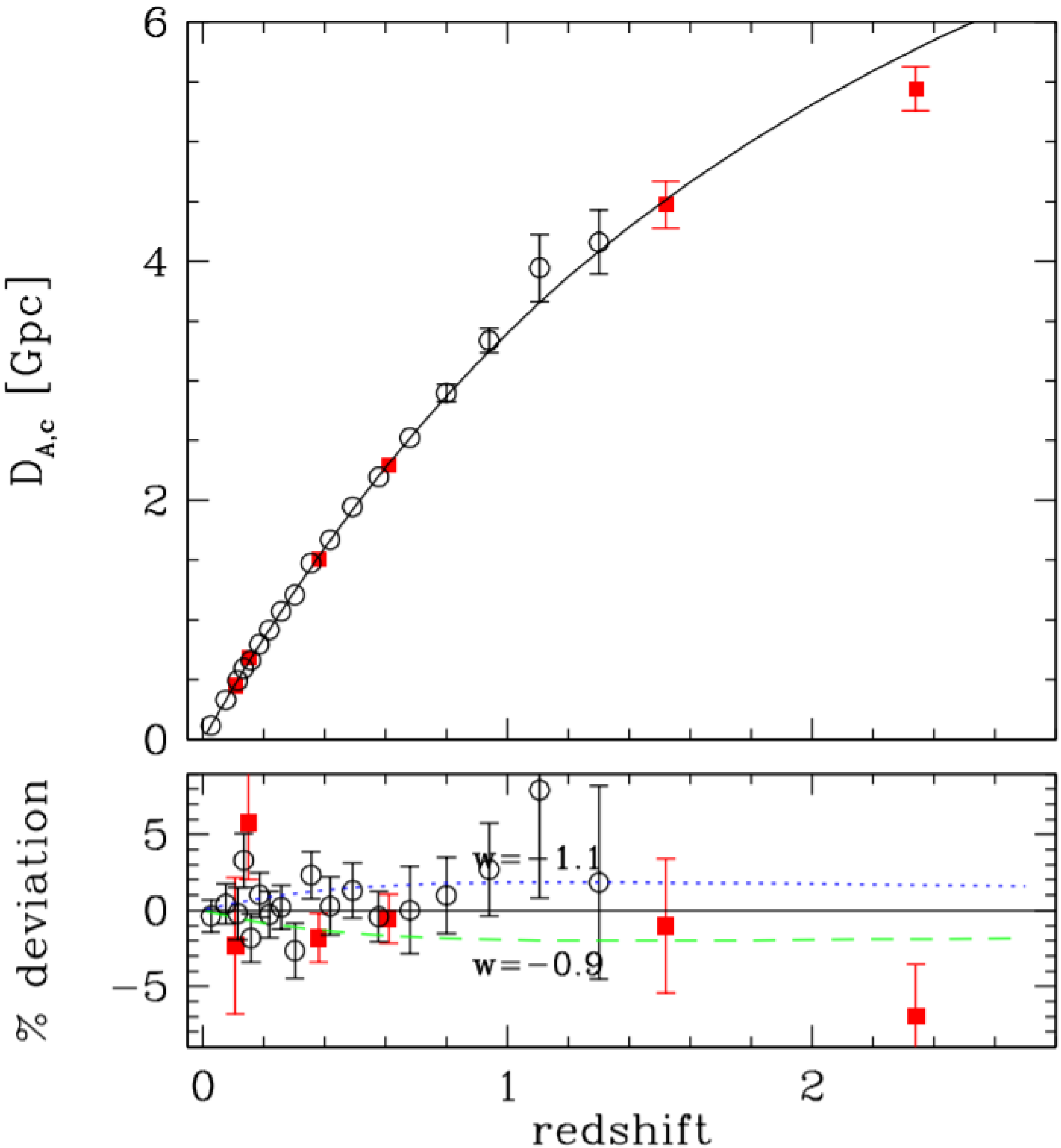

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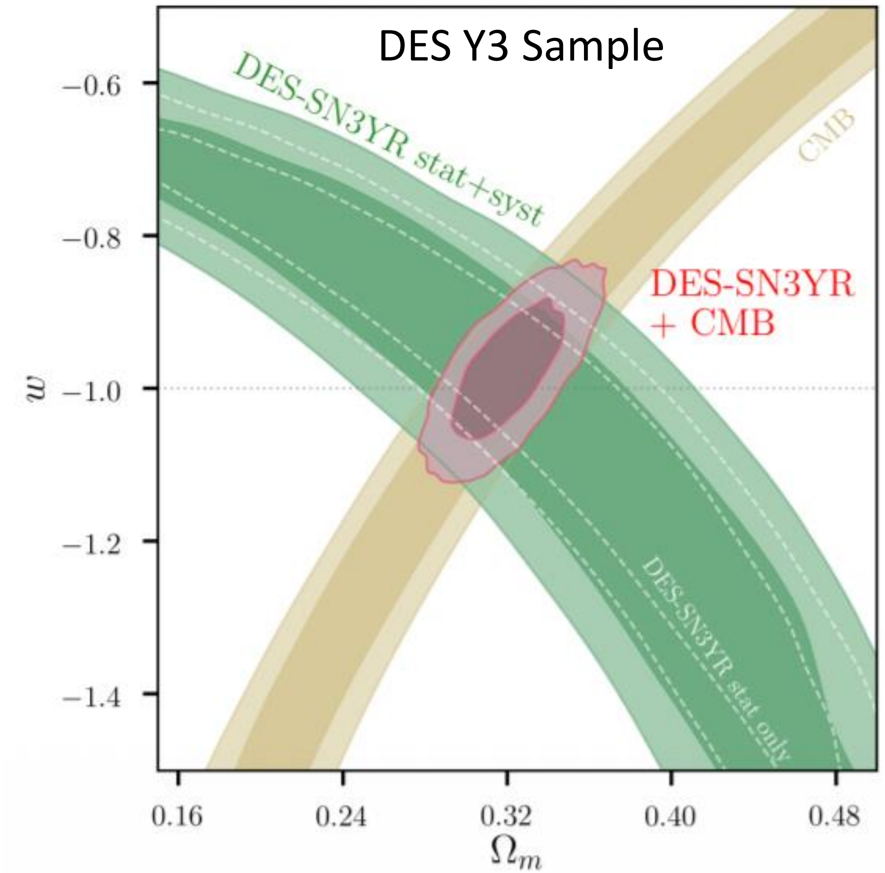
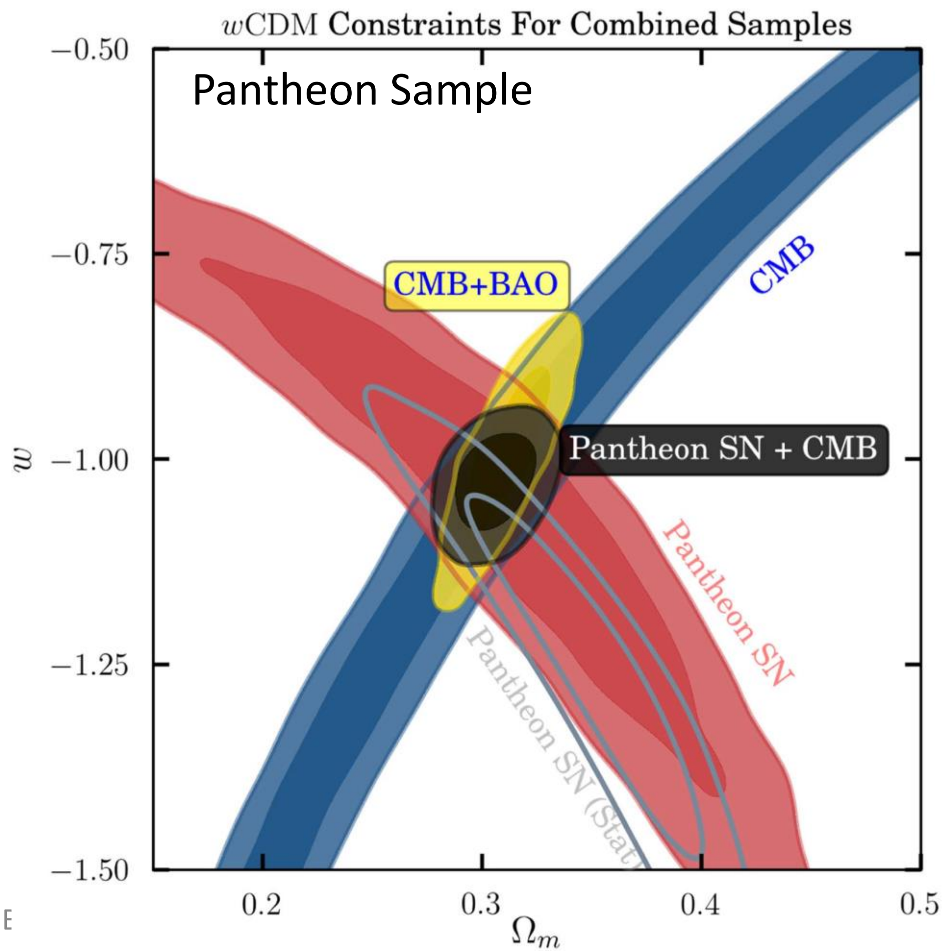
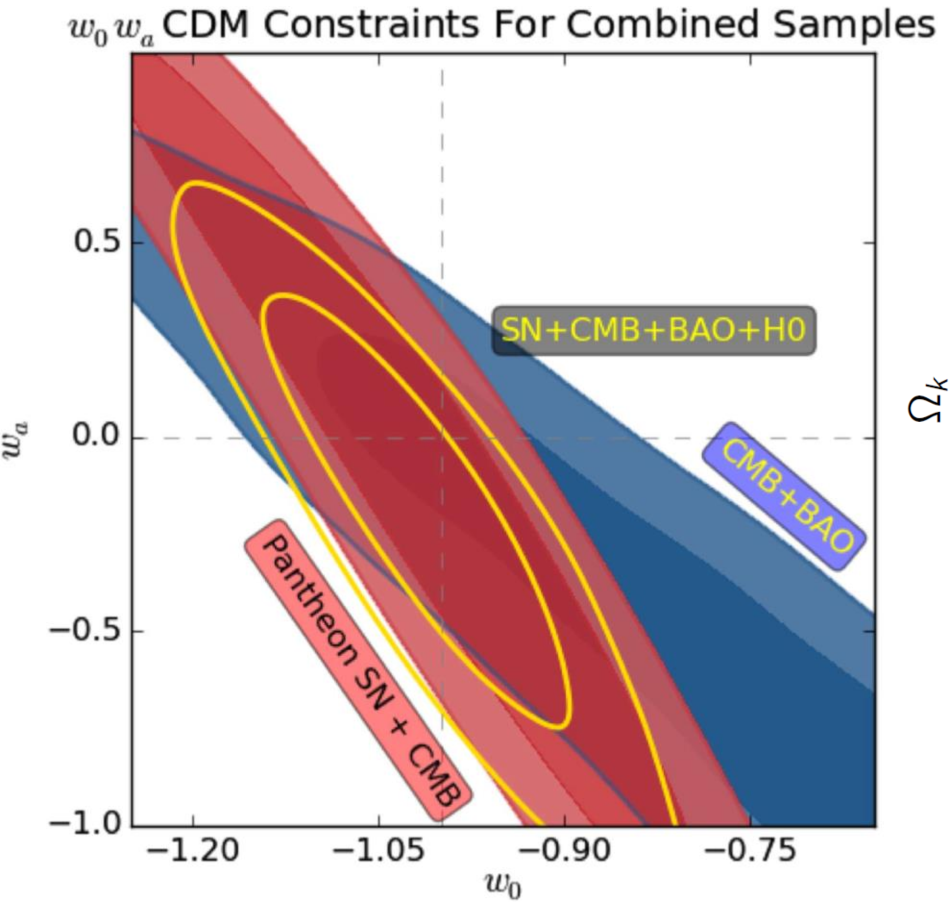


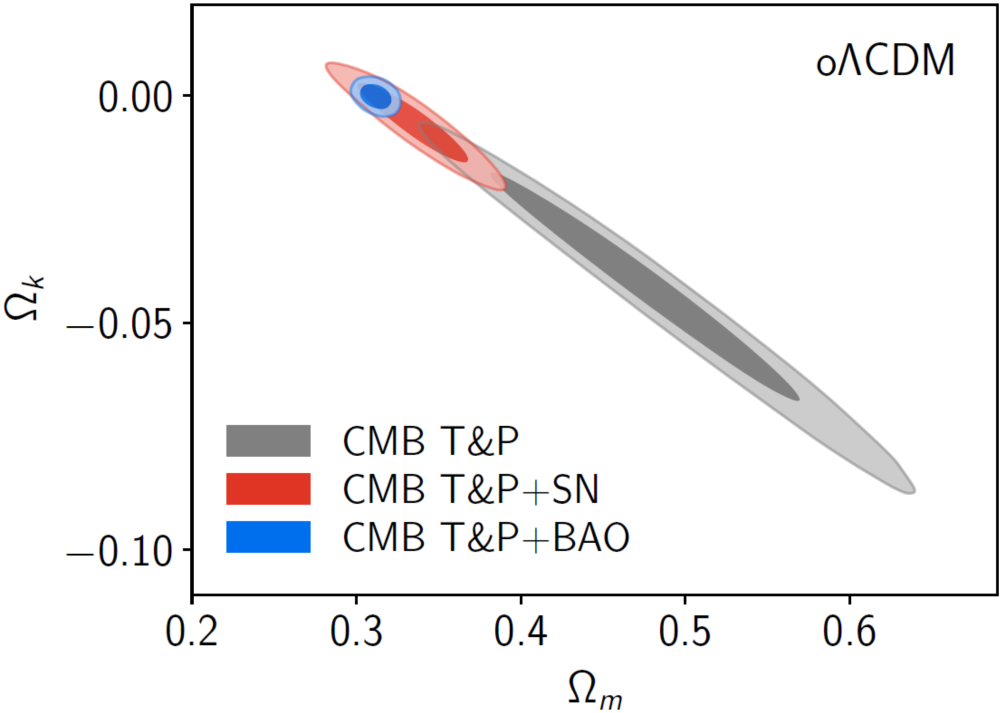
The cosmological constant remains as a good explanation for dark energy



New mesurements in the near future with larger and deeper surveys

Current Situation: All described by ΛCDM





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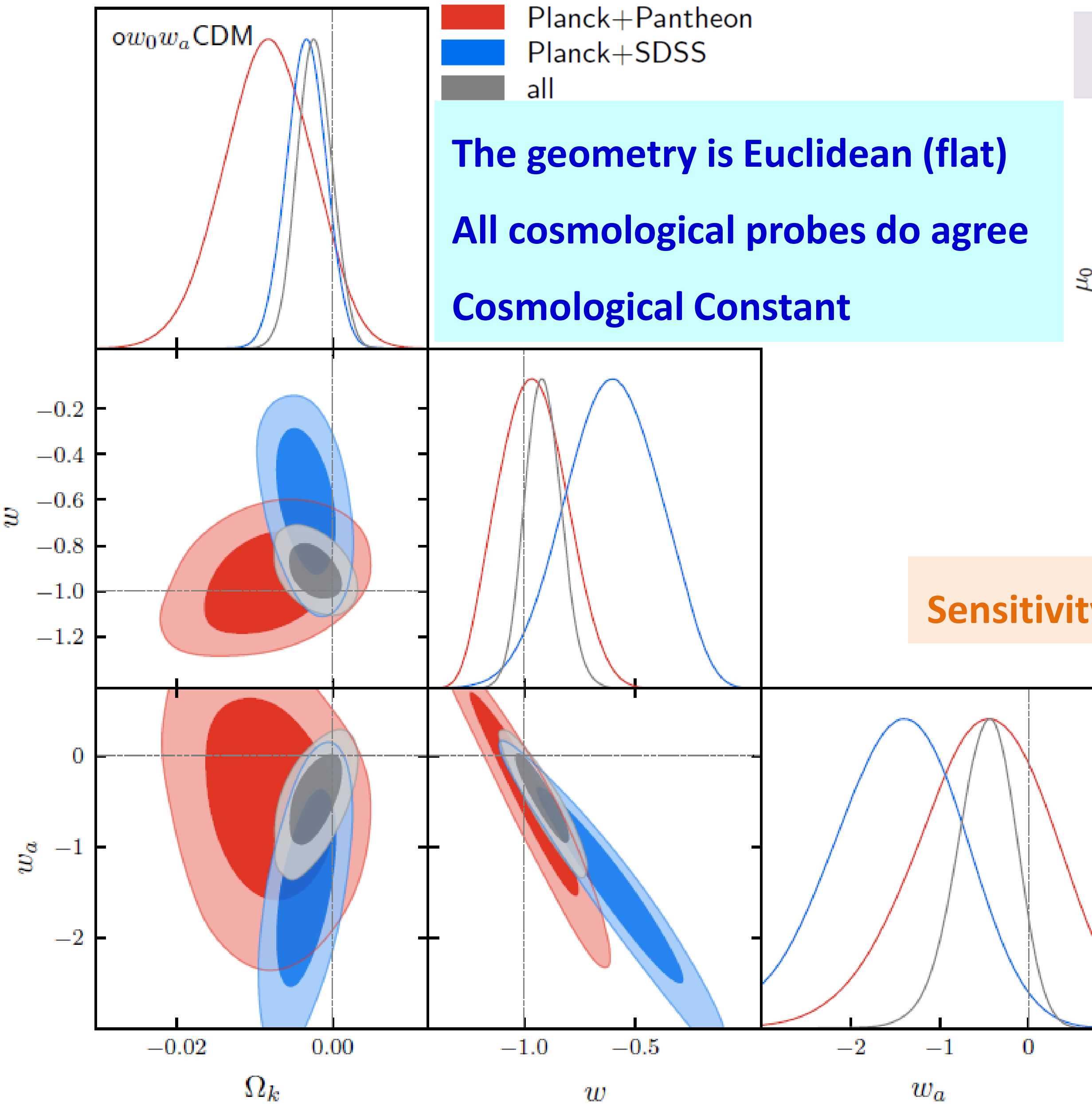
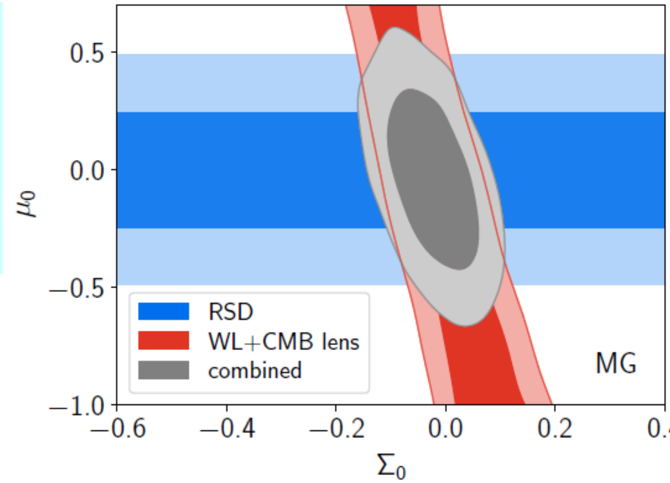


The geometry is Euclidean (flat)

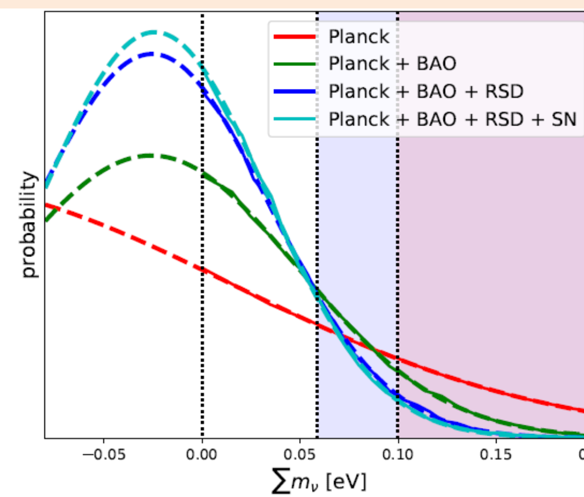
All cosmological probes do agree

Cosmological Constant

No deviations from GR observed

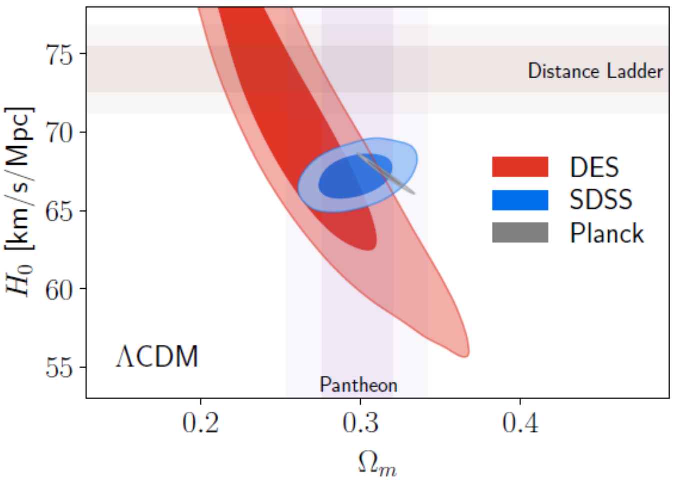


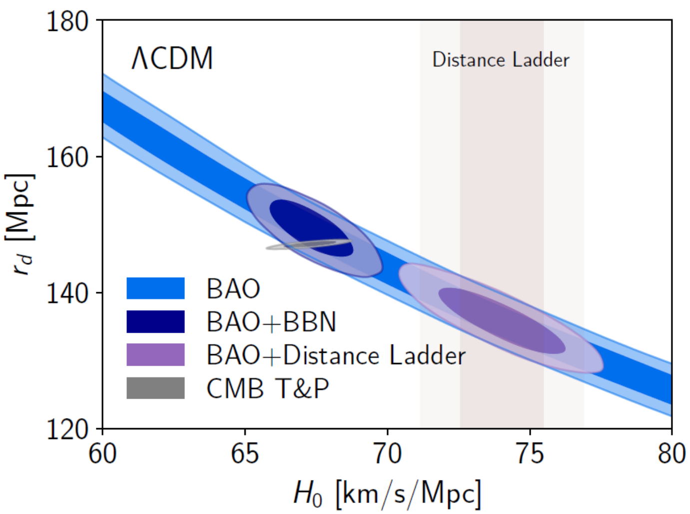
Sensitivity to neutrino mass: $\Sigma m_\nu < 0.2$ eV



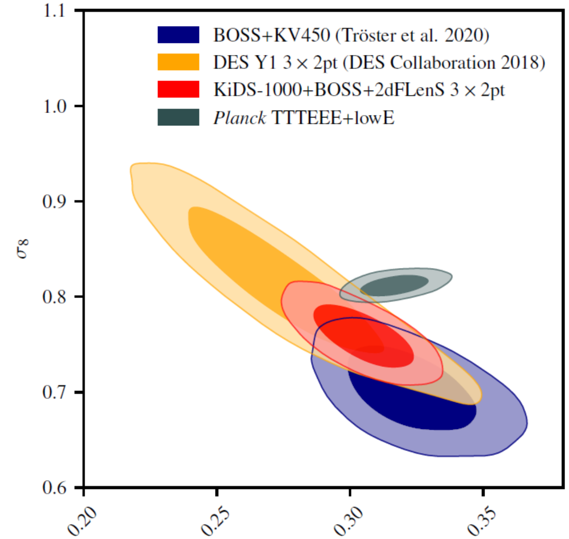
A couple of results are in tension

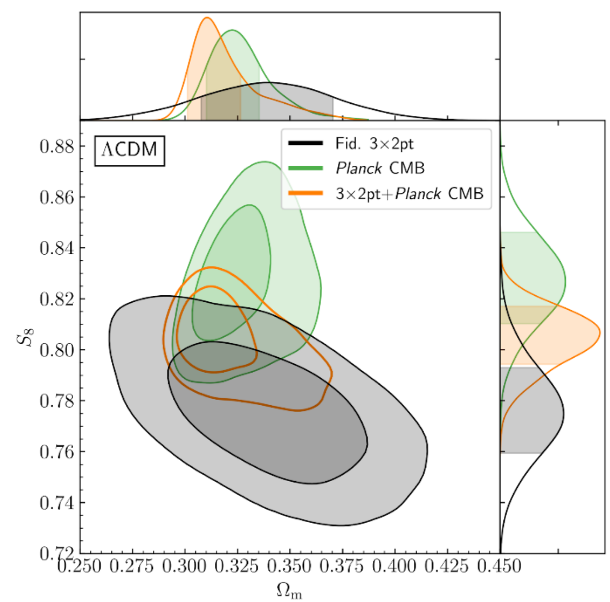
Hubble Parameter: Tensión is 3-4 σ



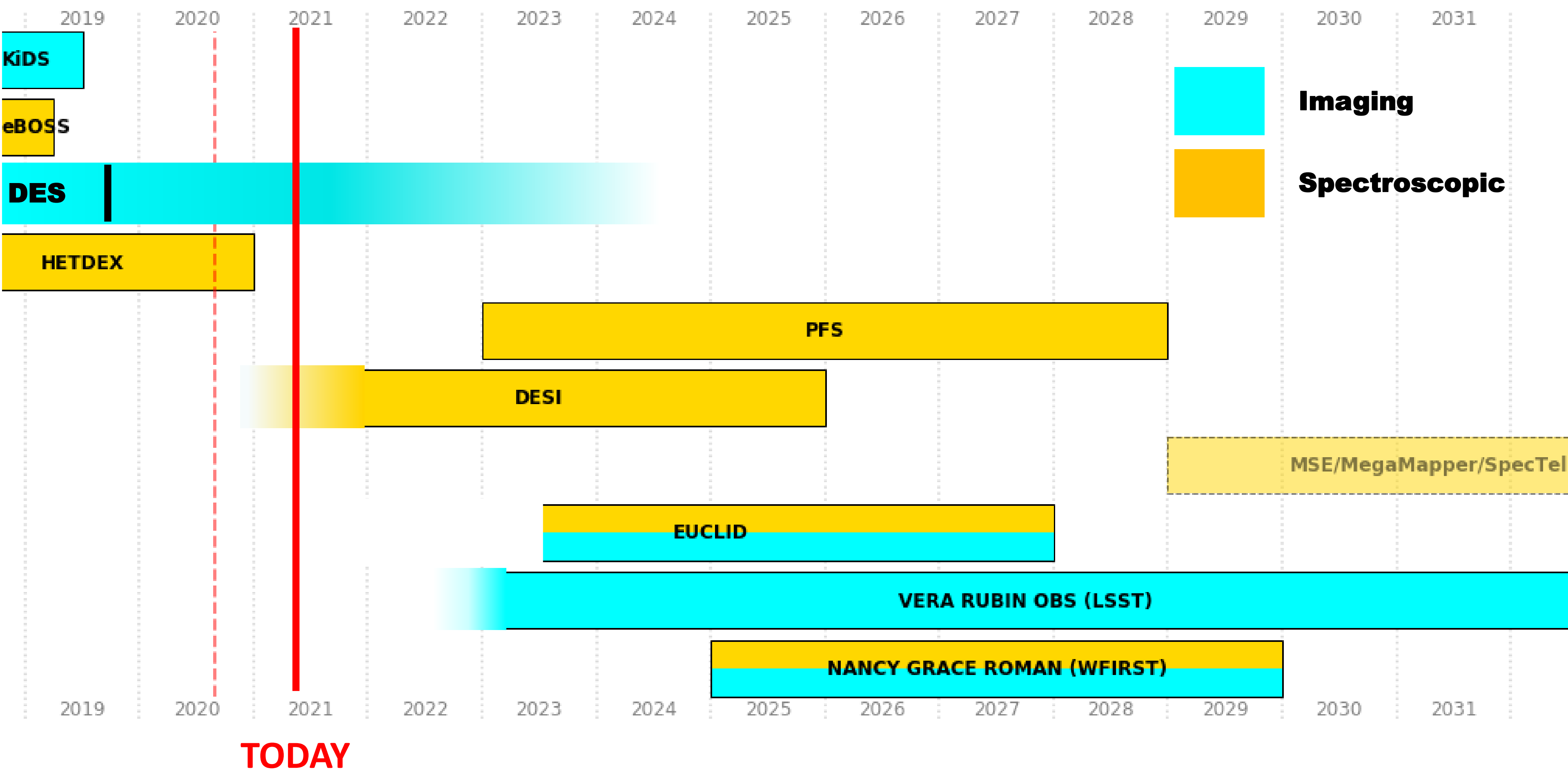


σ_8 Parameter: Tensión is 2-3 σ





CURRENT AND FUTURE PROJECTS



eBOSS: SDSS-IV, Apache Point , New Mexico
HETDEX: Hobby-Eberly Telescope Dark Energy Experiment (Mc Donald observatory, Texas)
PFS: Prime Focus Spectrograph at Subaru Telescope (Mauna Kea, Hawaii)

DES

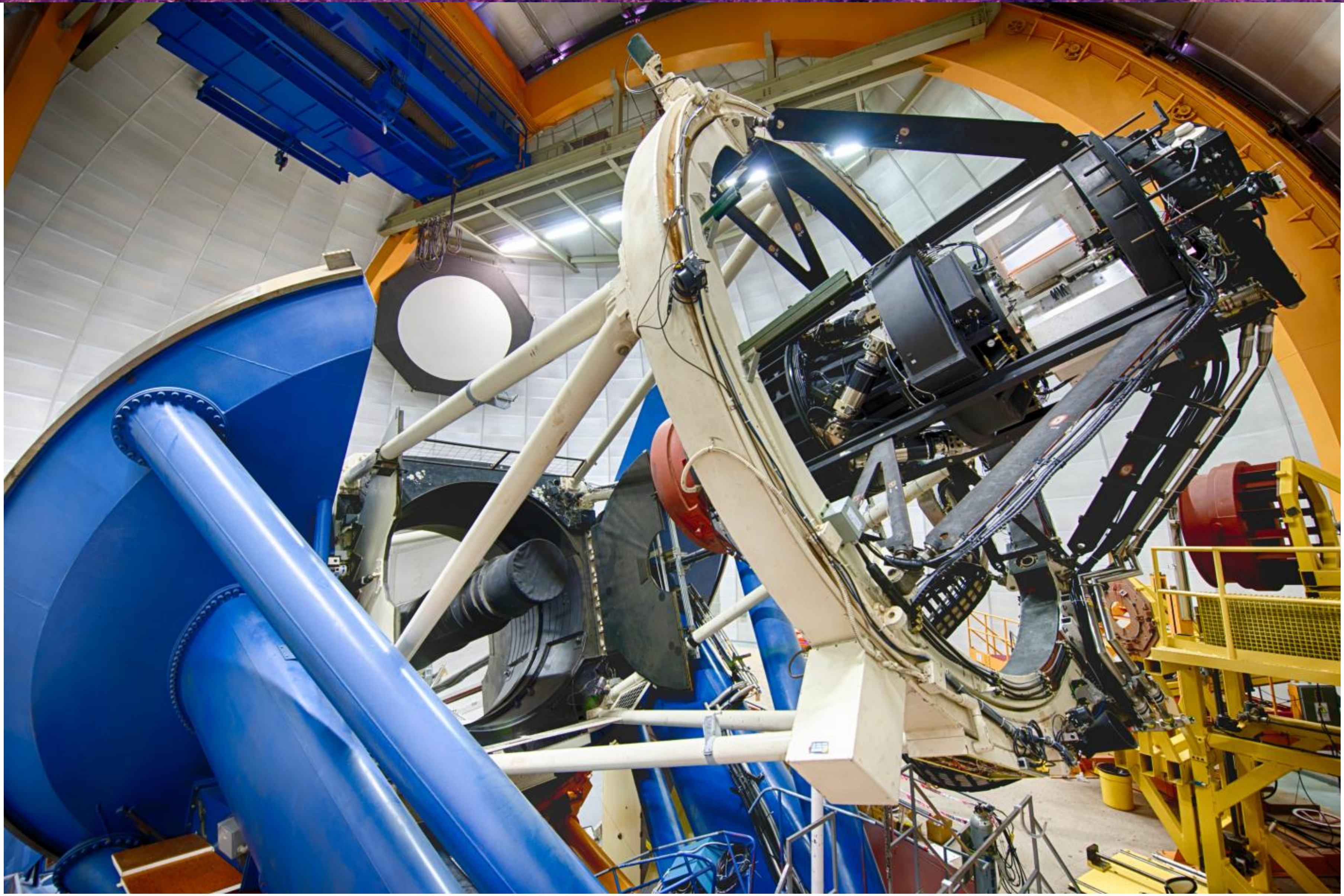
Optical/IR imaging survey with the Blanco 4m telescope at Cerro Tololo Inter-American Observatory(CTIO) in Chile

5000 sq-deg (1/8 of the sky) in grizY bands (2500 sq-deg overlapping with SPT survey) + 30 sq-deg time-domain griz (SNe)

Up to i_{AB} ~ 24th magnitude at 10 σ (z~1.5)

570 Mpx camera with 3 sq-deg FoV, DECam

DES



DES

NGC 1365 (the Great Barred Spiral Galaxy) is a barred spiral galaxy about 56 million light-years away in the constellation Fornax. (DECam, DES Collaboration)

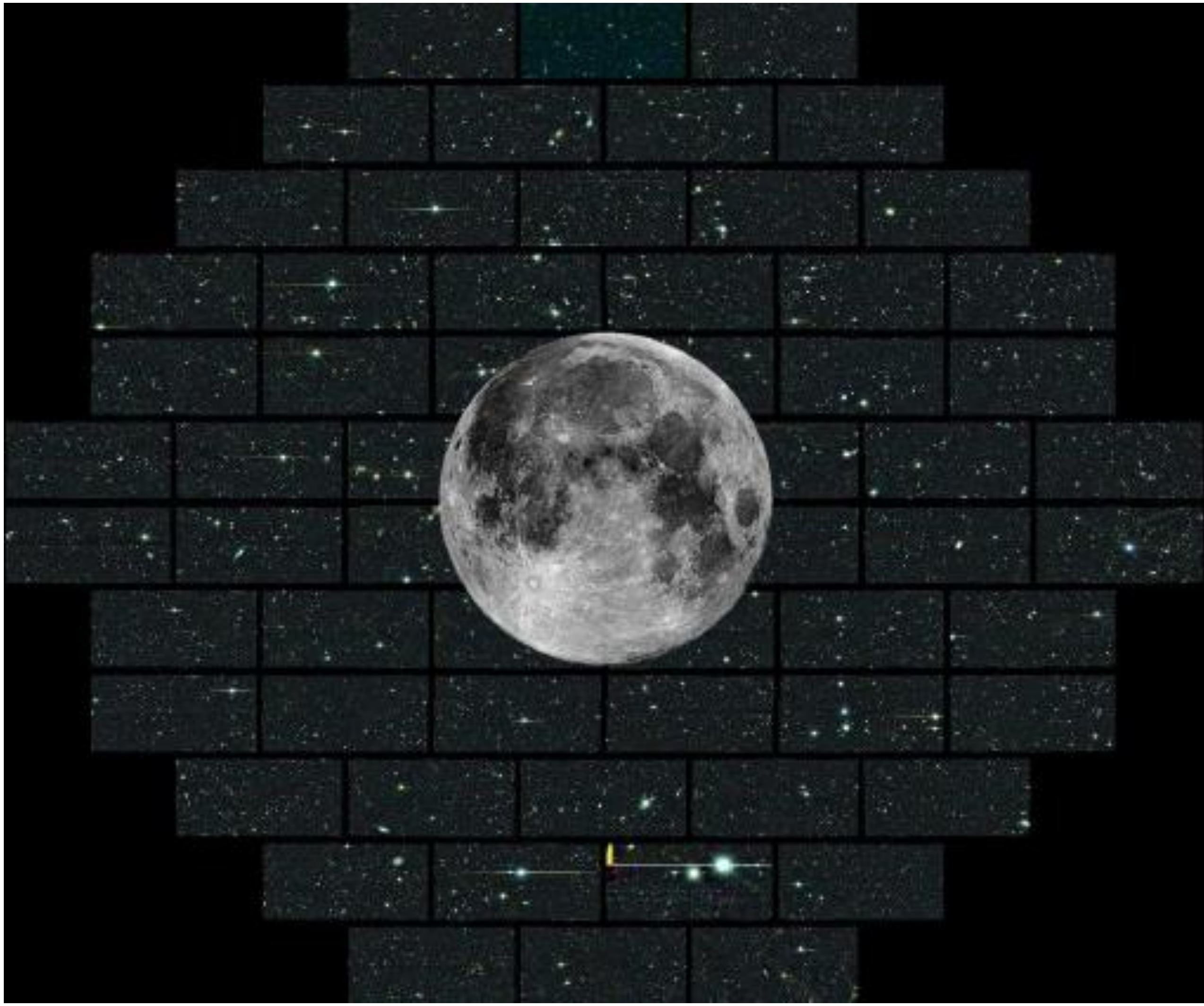
DES

74 CCD chips (570 Mpx/image) (62 2kx4k image, 8 2kx2k alignment/focus, 4 2kx2k guiding)

Red Sensitive CCDs
QE>50% @ 1000 nm
250 microns thick

3 sq-deg FoV
Excellent image quality
0.27´´/pixel

Low noise electronics (<15 e @ 250 kpx/s)



DES Collaboration

~500 scientists from
25 institutions in 7 countries
darkenergysurvey.org
Facebook.com/darkenergysurvey

USA: Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of pennsylvania, Argonne National Laboratory, Ohio State University, Santa Cruz/SLAC Consortium, Texas A&M University , CTIO (in Chile)

UK Consortium: UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

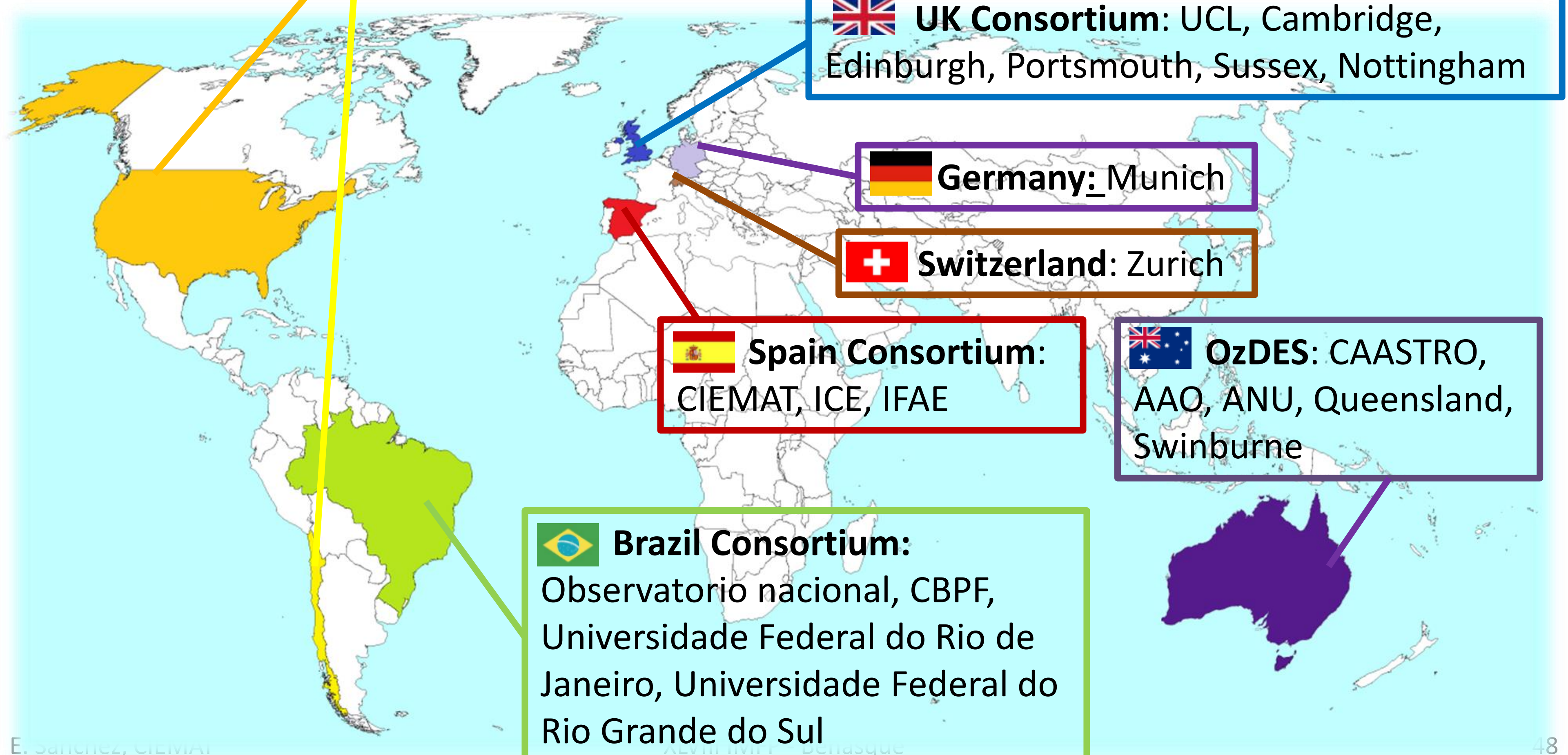
Germany: Munich

Switzerland: Zurich

Spain Consortium: CIEMAT, ICE, IFAE

OzDES: CAASTRO, AAO, ANU, Queensland, Swinburne

Brazil Consortium: Observatorio nacional, CBPF, Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande do Sul



DES

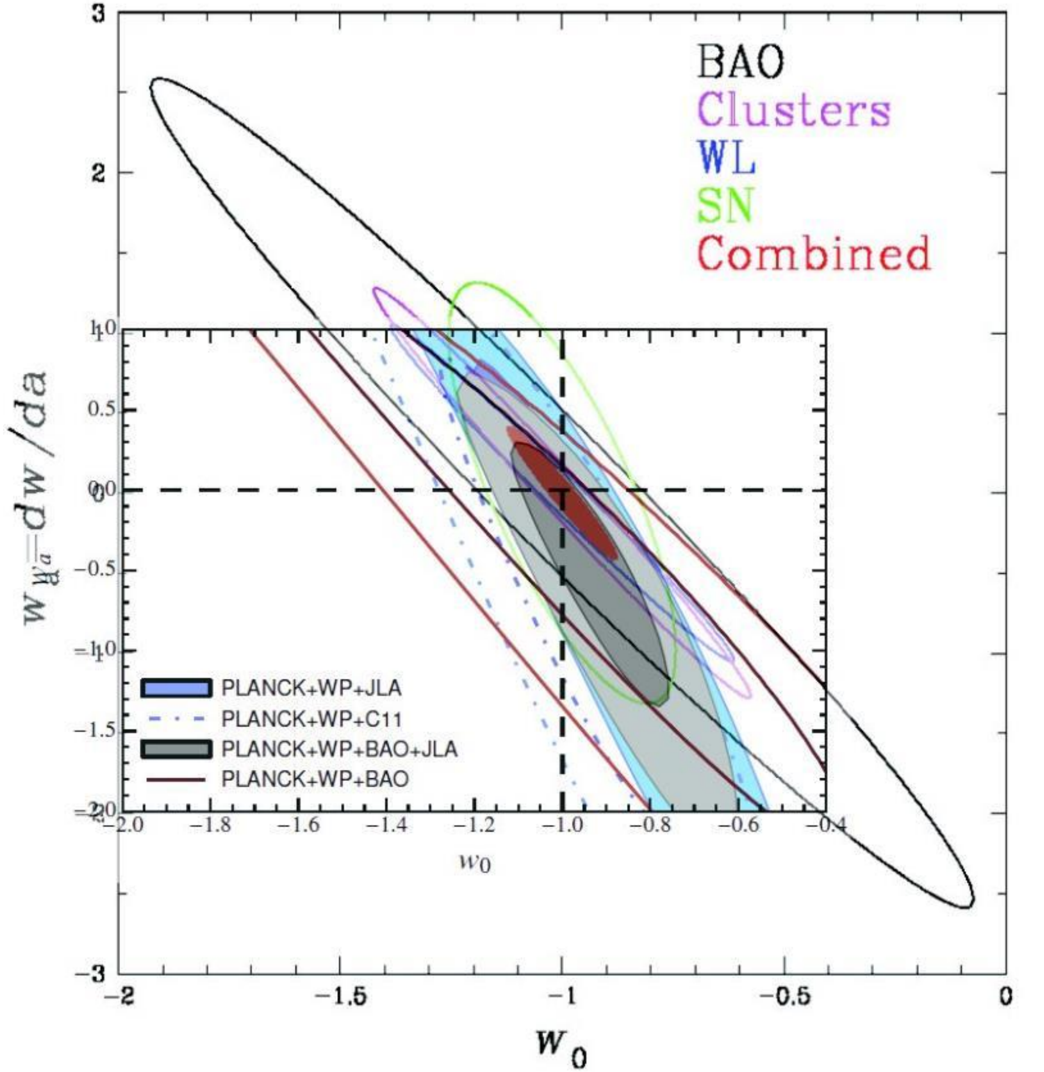
4 Probes of Dark Energy

Galaxy Clusters (dist & struct)
Tens of thousands of clusters to z~1
Synergy with SPT, VHS

Weak Lensing (dist & struct)
Shape and magnification measurements of 200 million galaxies

Baryon Acoustic Oscillations (dist)
Millions of galaxies to z~1.4

Supernovae (dist)
3500 well-sampled Sne Ia to z~1



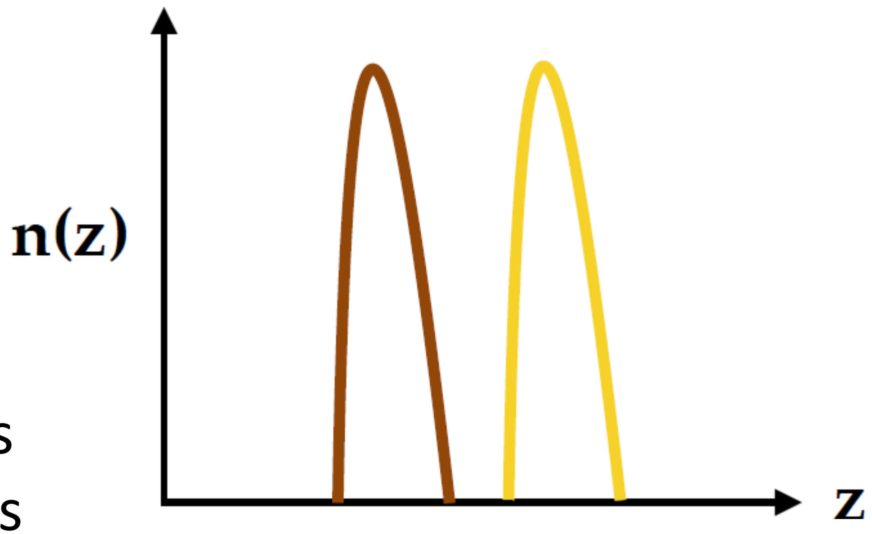
DES Y3: 3x2pt Results

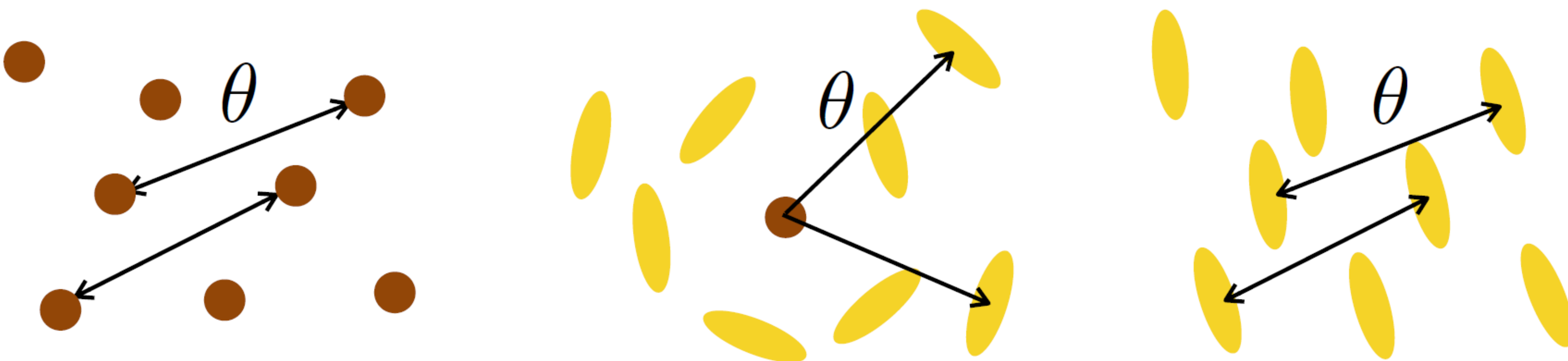
DES Y3 3x2pt Cosmology

2 samples of galaxies: **“lens”** and **“sources”**

Combine the auto and cross-correlation of

1. **positions** of the lens galaxies
2. **shapes** of the source galaxies



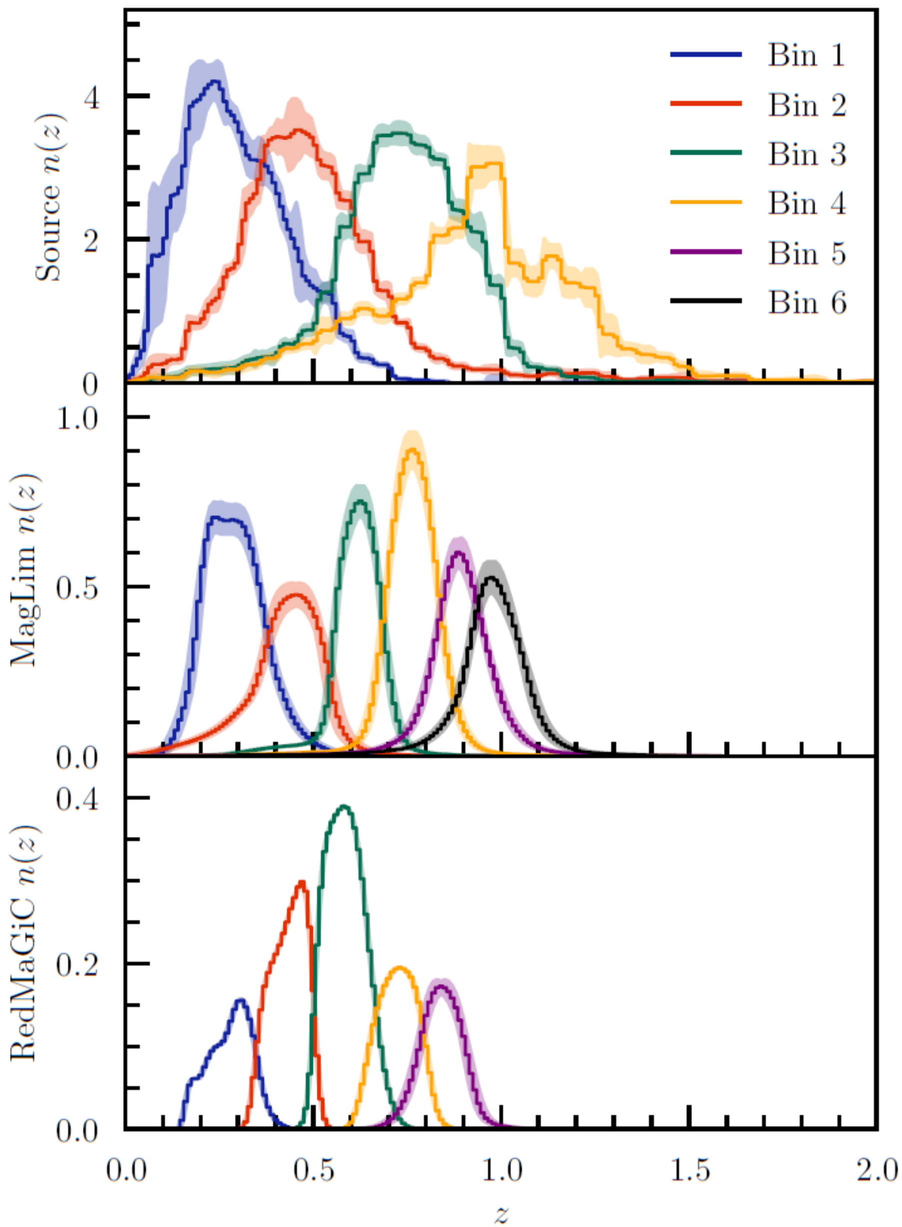


Galaxy clustering　　Galaxy-galaxy lensing　　Cosmic shear

DES Y3: 3x2pt Results

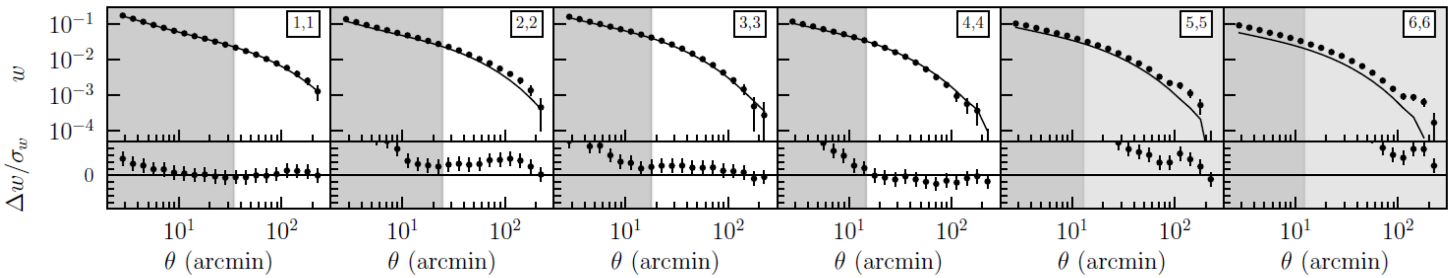
This is a very demanding measurement:

- Manage a large dataset
- Compute correlation functions (3 types)
- These measurements are not independent → Compute and verify the covariance matrix

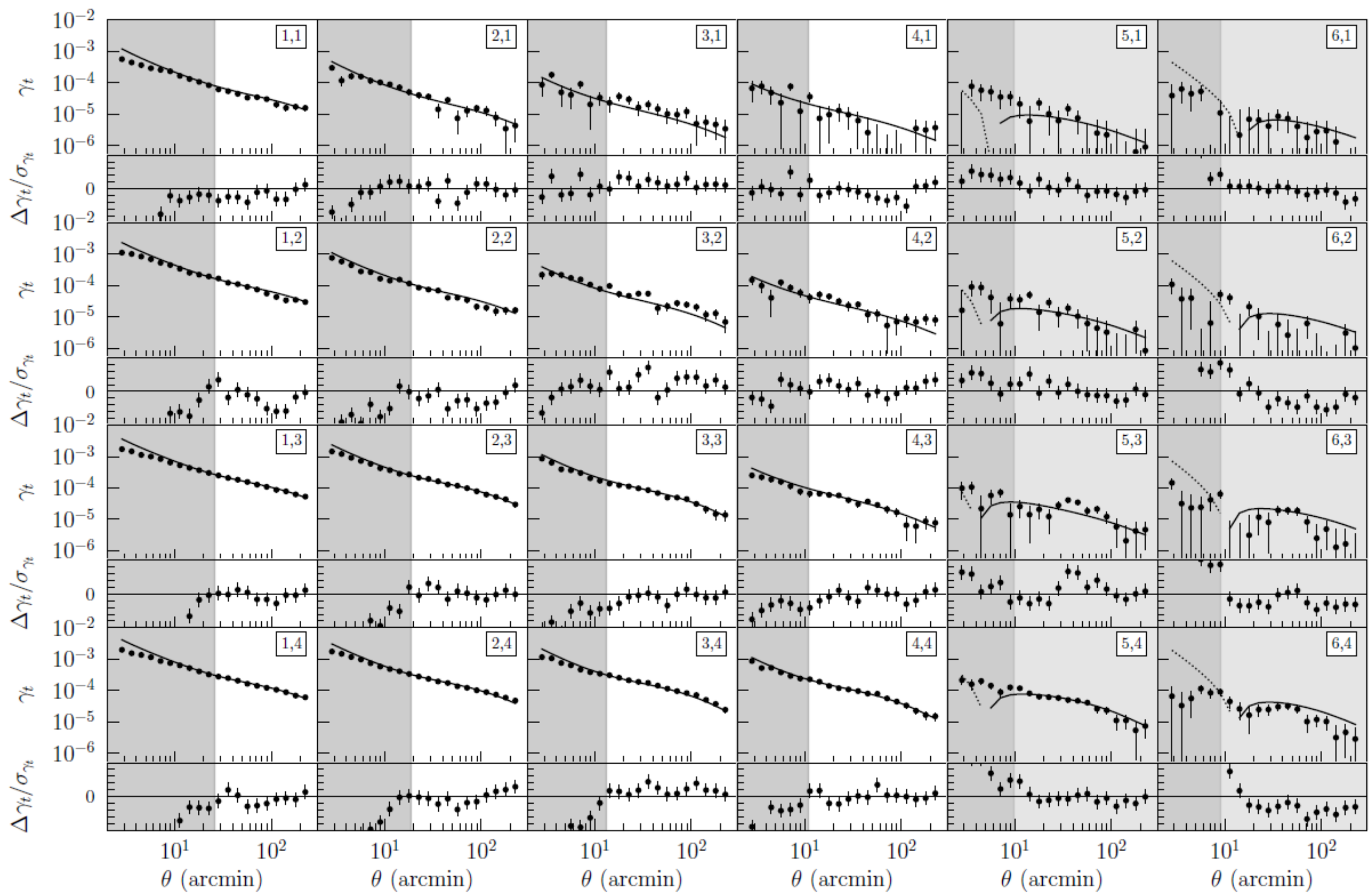


DES Y3: 3x2pt Results

Galaxy-Galaxy correlations (lens – lens)

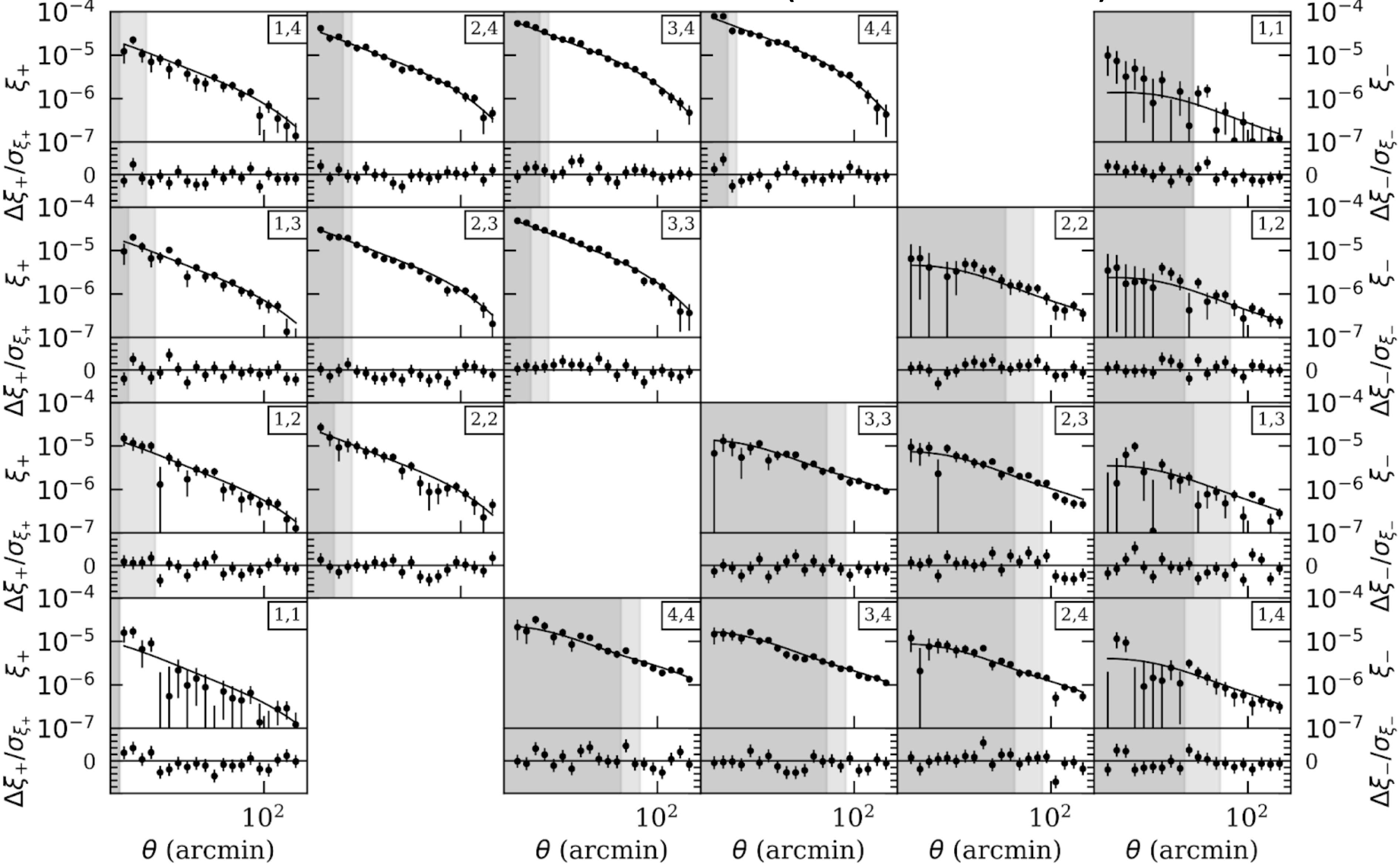


Galaxy-Shear correlations (lens – source)



DES Y3: 3x2pt Results

Shear-Shear correlations (source – source)



DES Y3: 3x2pt Results

$$w^i(\theta) = (b^i)^2 \int \frac{dl\, l}{2\pi} J_0(l\theta) \int d\chi \times \frac{\left[n_1^i(z(\chi)\right]^2}{\chi^2 H(z)} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

Galaxy Clustering
Correlation position-position

$$\gamma_{\rm t}^{ij}(\theta) = b^i(1+m^j) \int \frac{dl\, l}{2\pi} J_2(l\theta) \int d\chi n_1^i(z(\chi)) \times \frac{q_s^j(\chi)}{H(z)\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right),$$

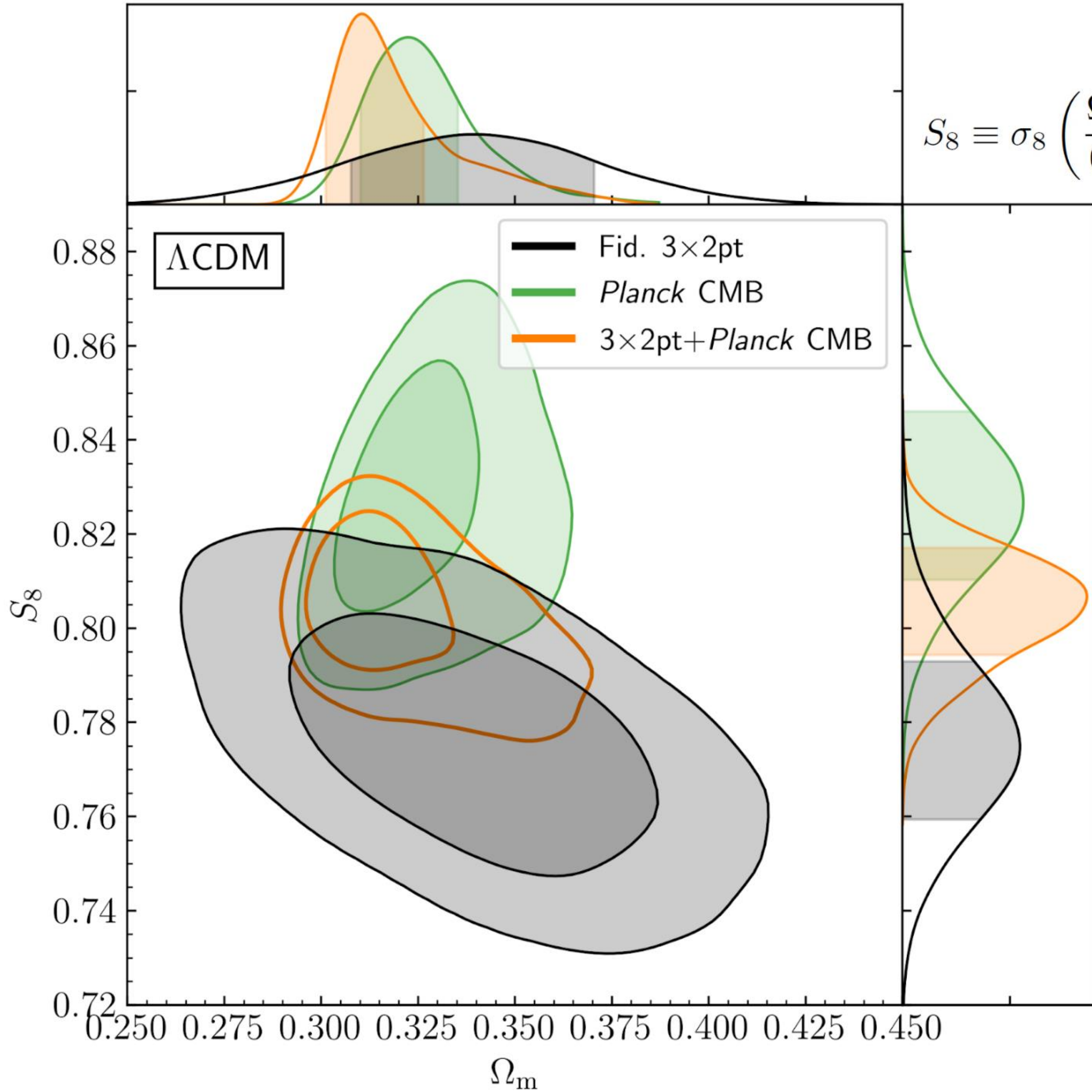
Galaxy-Glaxy Lensing
Correlation position-shape

$$q_s^i(\chi) = \frac{3\Omega_m H_0^2}{2} \frac{\chi}{a(\chi)} \int_\chi^{\chi(z=\infty)} {\rm d}\chi' n_s^i(z(\chi')) \frac{dz}{d\chi'} \frac{\chi'-\chi}{\chi'} \tag{IV.3}$$

$$\xi_{+/-}^{ij}(\theta) = (1+m^i)(1+m^j) \int \frac{dl\, l}{2\pi} J_{0/4}(l\theta) \int d\chi \times \frac{q_s^i(\chi) q_s^j(\chi)}{\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

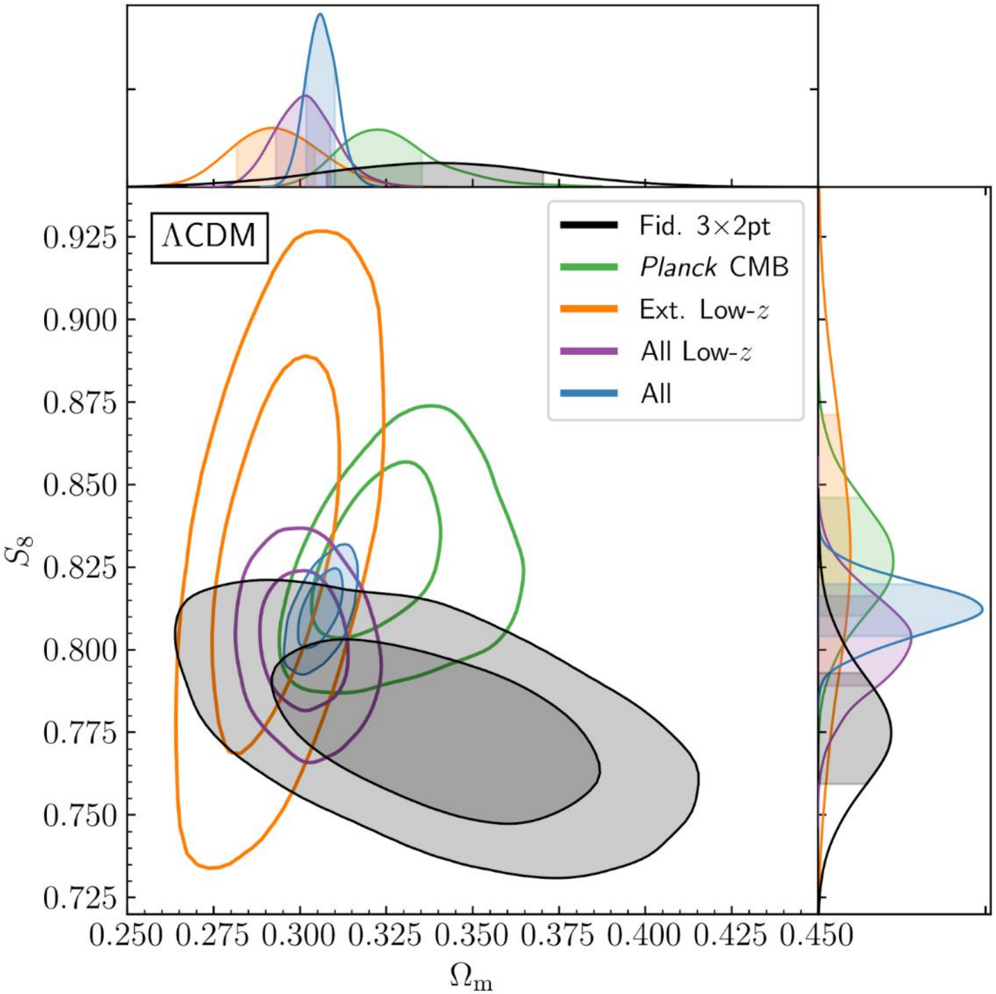
Cosmic Shear
Correlation shape-shape

DES Y3: 3x2pt Results



$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

DES Y3: 3x2pt Results



Combining all these data sets we find:

In ΛCDM:

$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$
$$\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)$$
$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)$$
$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$
$$\sum m_\nu < 0.13 \text{ eV } (95\% \text{ CL})$$

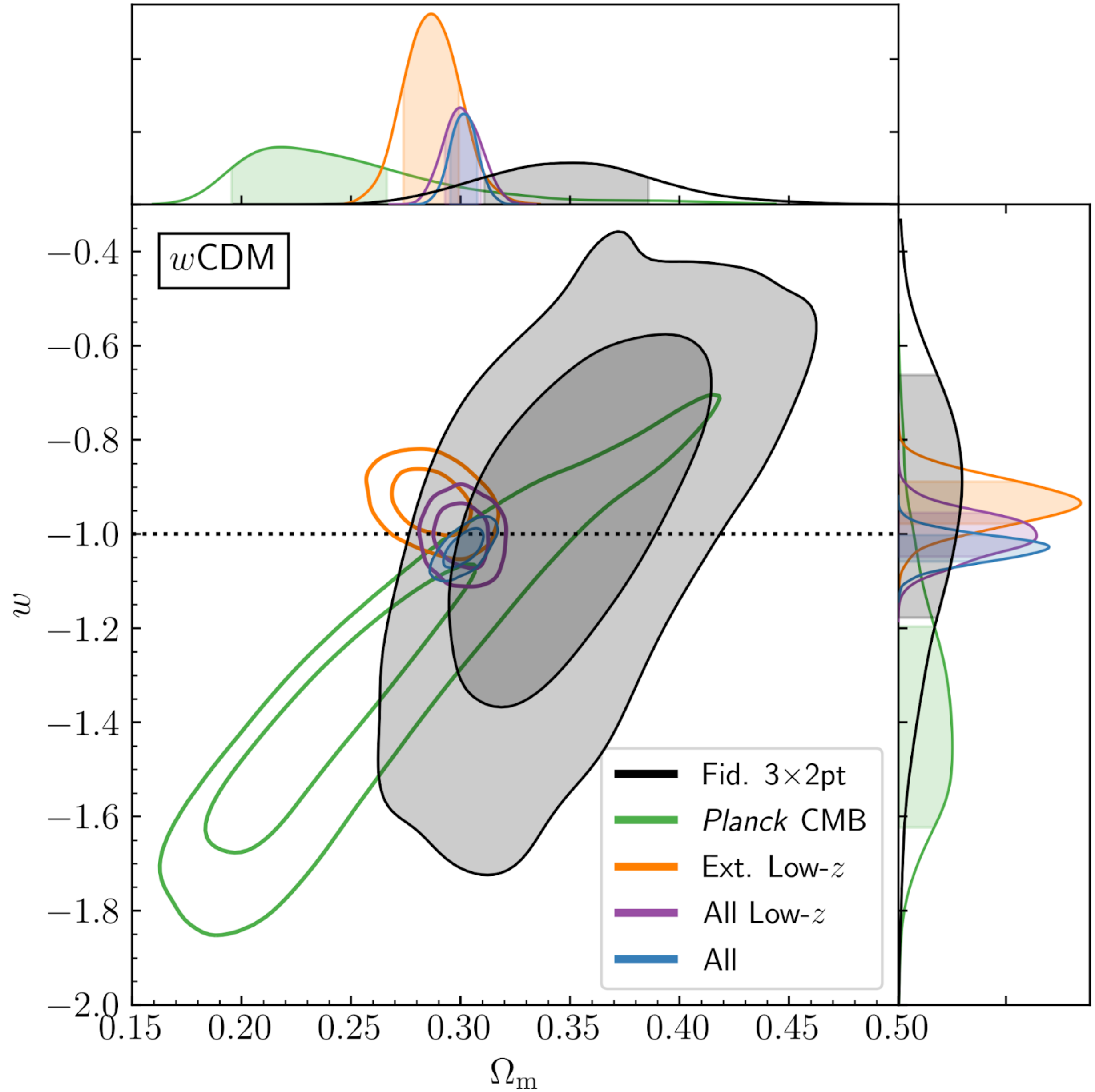
In wCDM:

$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804),$$
$$\Omega_m = 0.302^{+0.006}_{-0.006} \quad (0.298),$$
$$w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$$

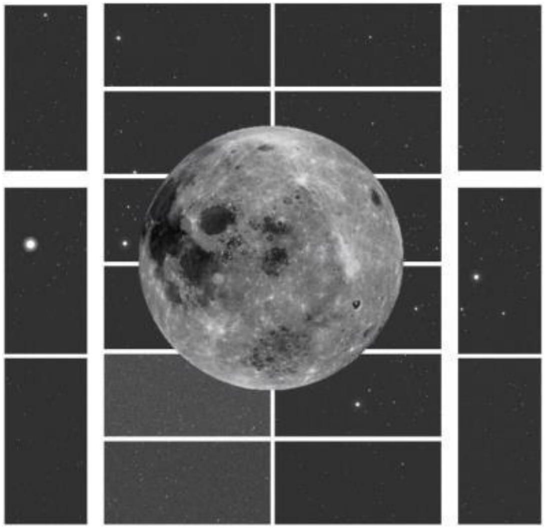
Early (CMB, Planck) and late (DES) Universe constraints are compatible, a strong test of ΛCDM

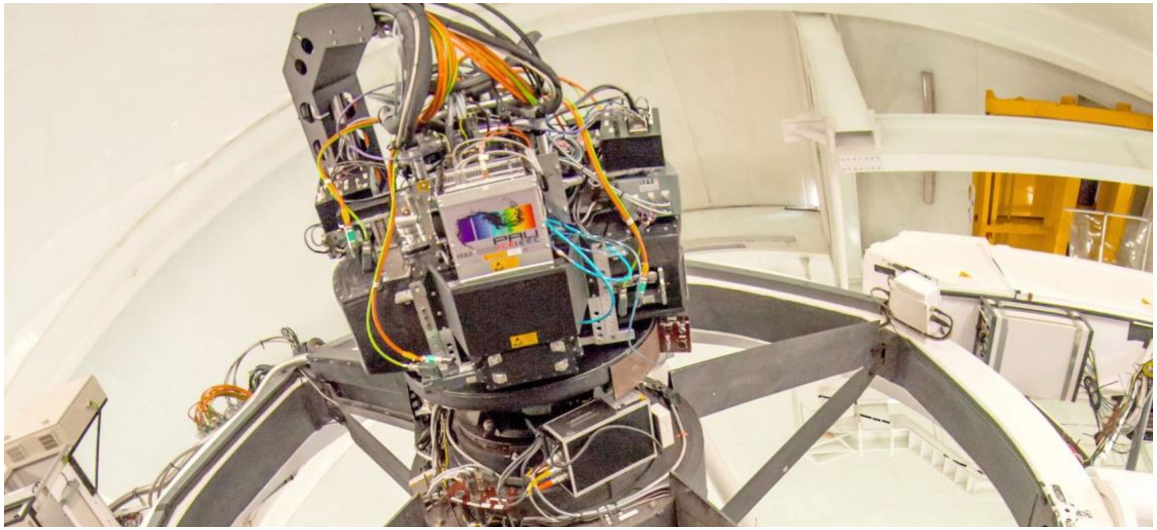
DES Y3: 3x2pt Results

The dark energy is compatible with being the cosmological constant, now with better precision



PAU





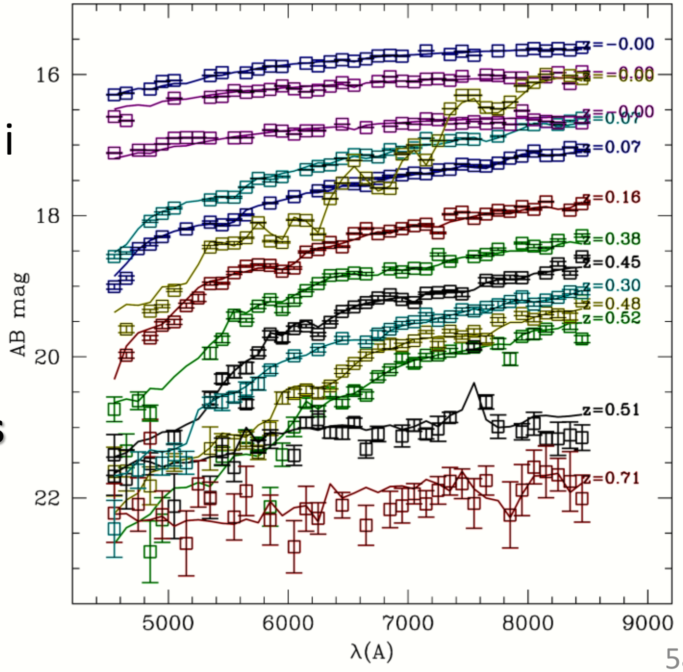
PAUCam at WHT with 18 CCDs covering a **1 degree diameter field of view**

40 Narrow band filters (100 A width) and wide band (u, g. r, i , z, Y) in movable trays

Provide low resolution spectra, with a redshift resolution ~0.003(1+z)

Data from 2015 to 2019: 50 sq-deg covered with 40 narrow band filters. Up to 100 sq-deg with smaller number of filters

Collaboration: CIEMAT, Durham (UK), ETH Zurich (Switzerland), ICE, IFAE, IFT, Leiden Observatory (Netherlands), PIC, UCL (UK)



PAU: Redshift Precision

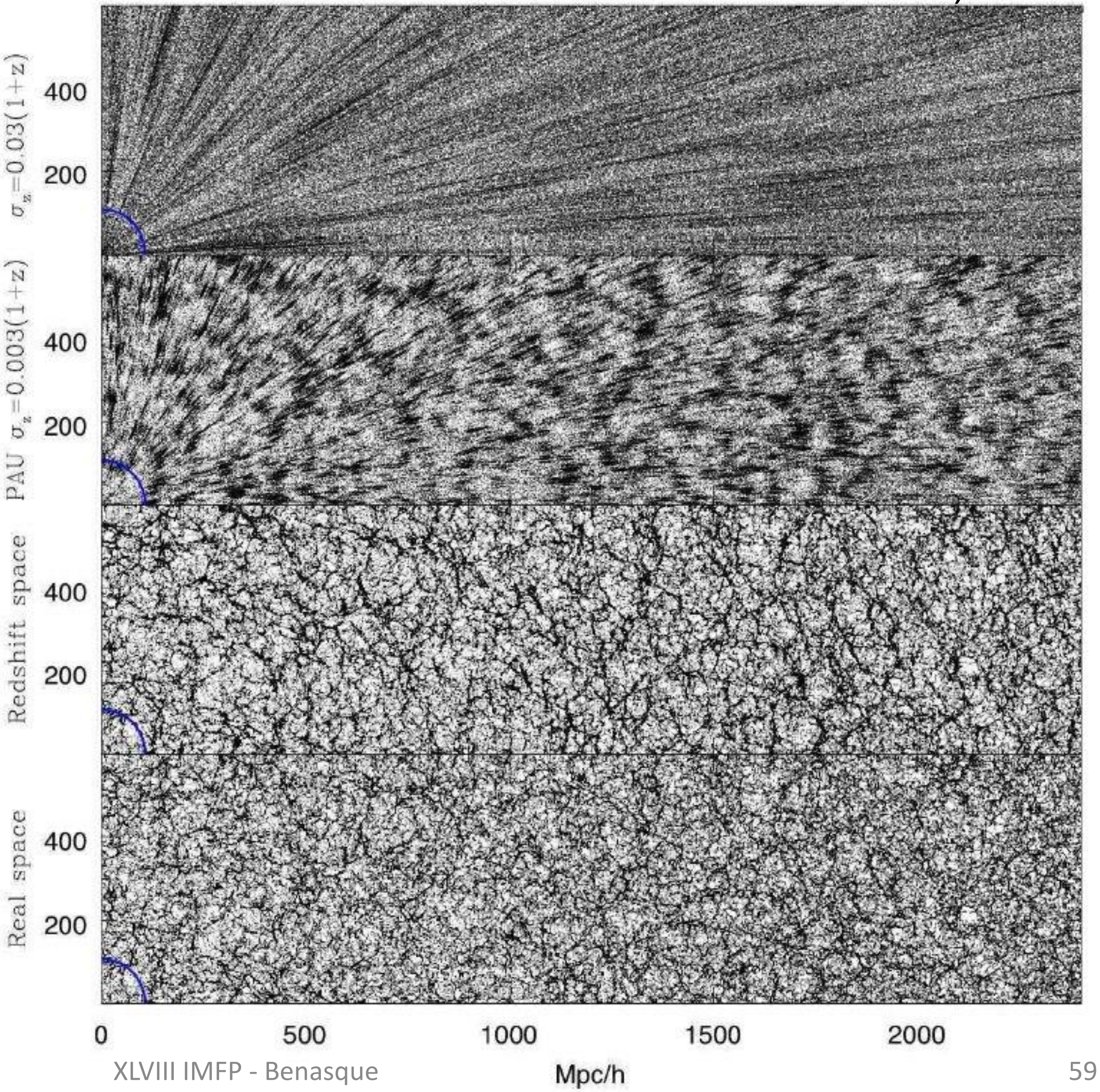
Benitez et al, 2009

z-space, Δz=0.03(1+z) + peculiar velocities (DES)

z-space, Δz=0.003(1+z) + peculiar velocities (PAU)

z-space, perfect resolution + peculiar velocities (BOSS)

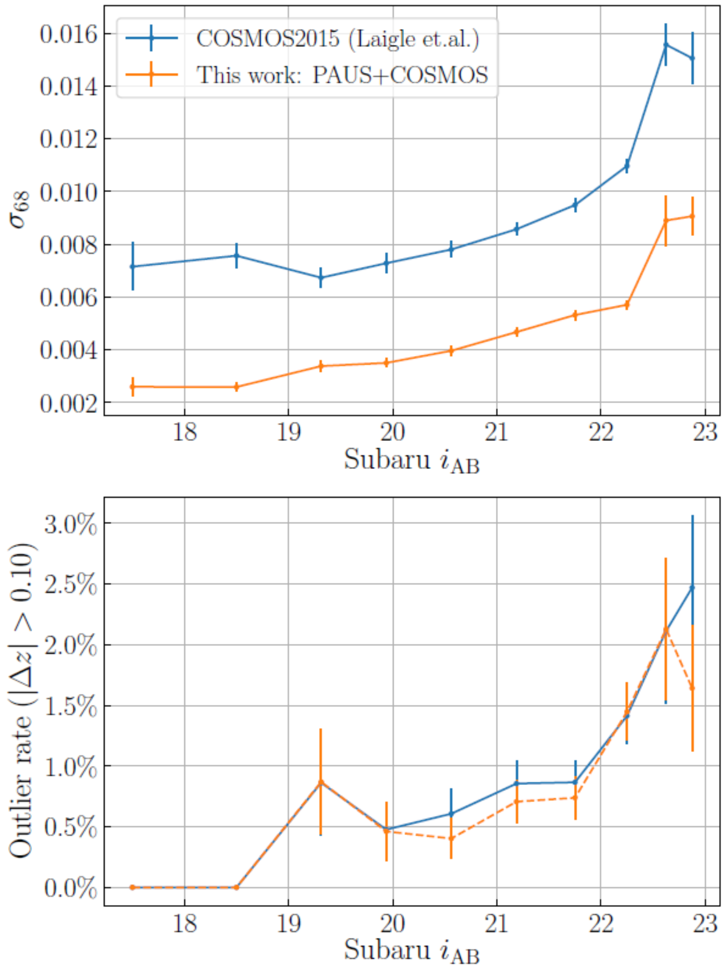
Real space

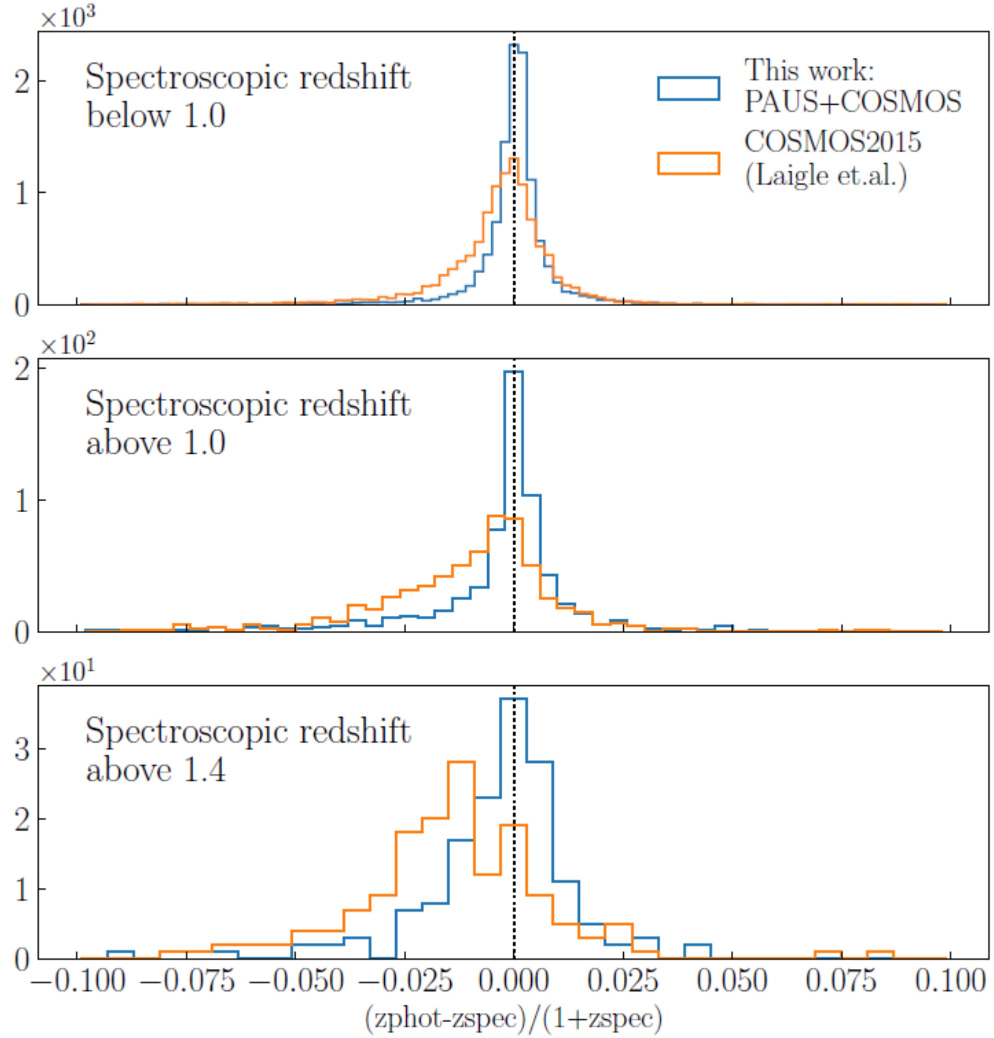


PAU: Science

The power of narrow band filters: Improved redshift catalog in cosmos field. Already used for better calibration in other surveys like DES. Will be used in Euclid, LSST.

A. Alarcon et al., MNRAS 501 (2021) 6103

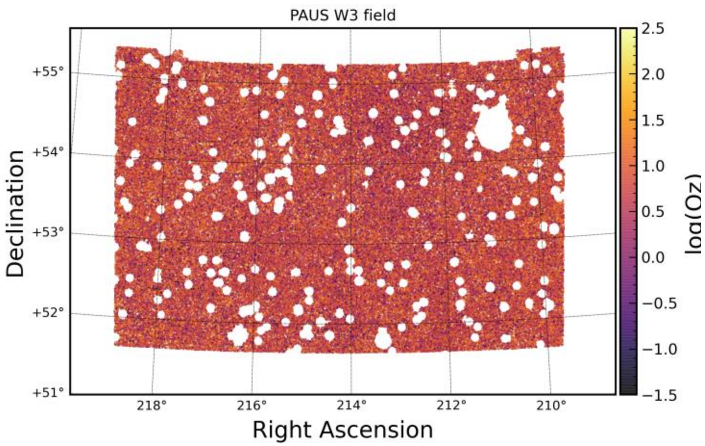


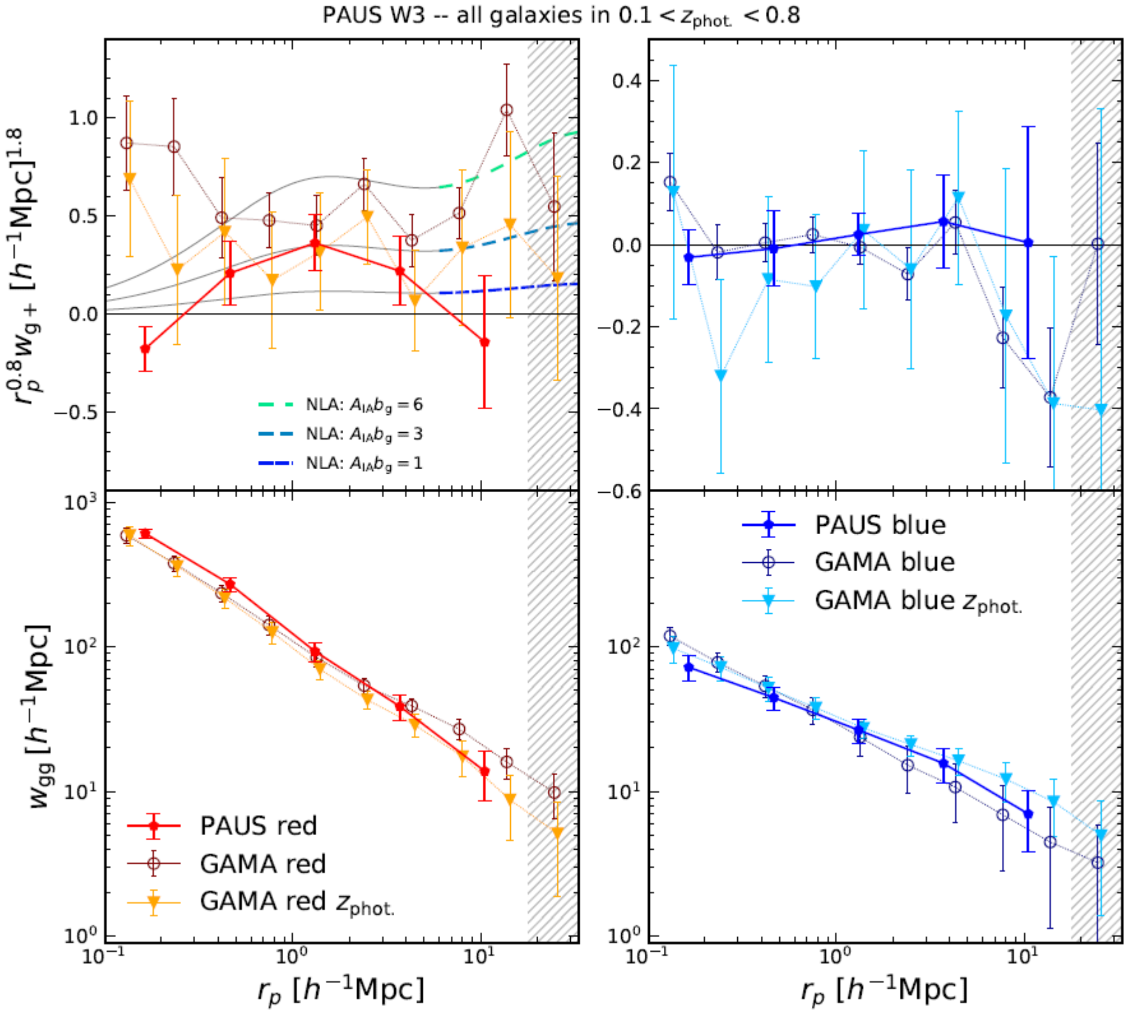


PAU: Science

First measurement of clustering of galaxies and intrinsic alignment. Very useful measurement for weak lensing calibration (Euclid, LSST). Only a survey like PAU can do this kind of mesurement

H. Johnston et al., A&A 645, A147 (2021)





DESI

DESI (Dark Energy Spectroscopic Instrument)

The DESI collaboration has built and installed:

A new corrector for the Mayall telescope at Kitt Peak (8 deg^2 FOV)

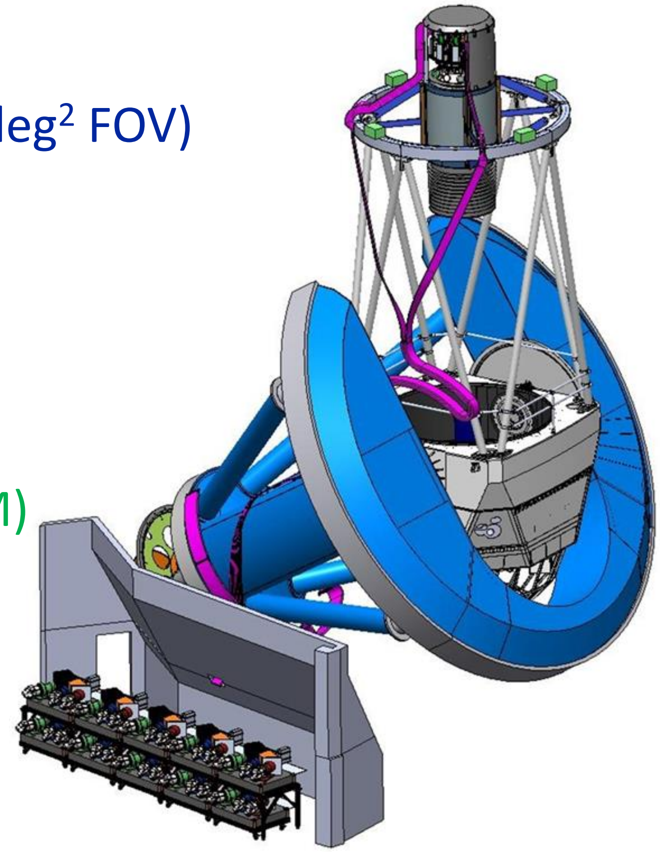
A new top ring, barrel and hexapod

A focal plane with 5000 robots fiber positioner

10 espectrographs, following the BOSS design

Instrument control and data proccess systems

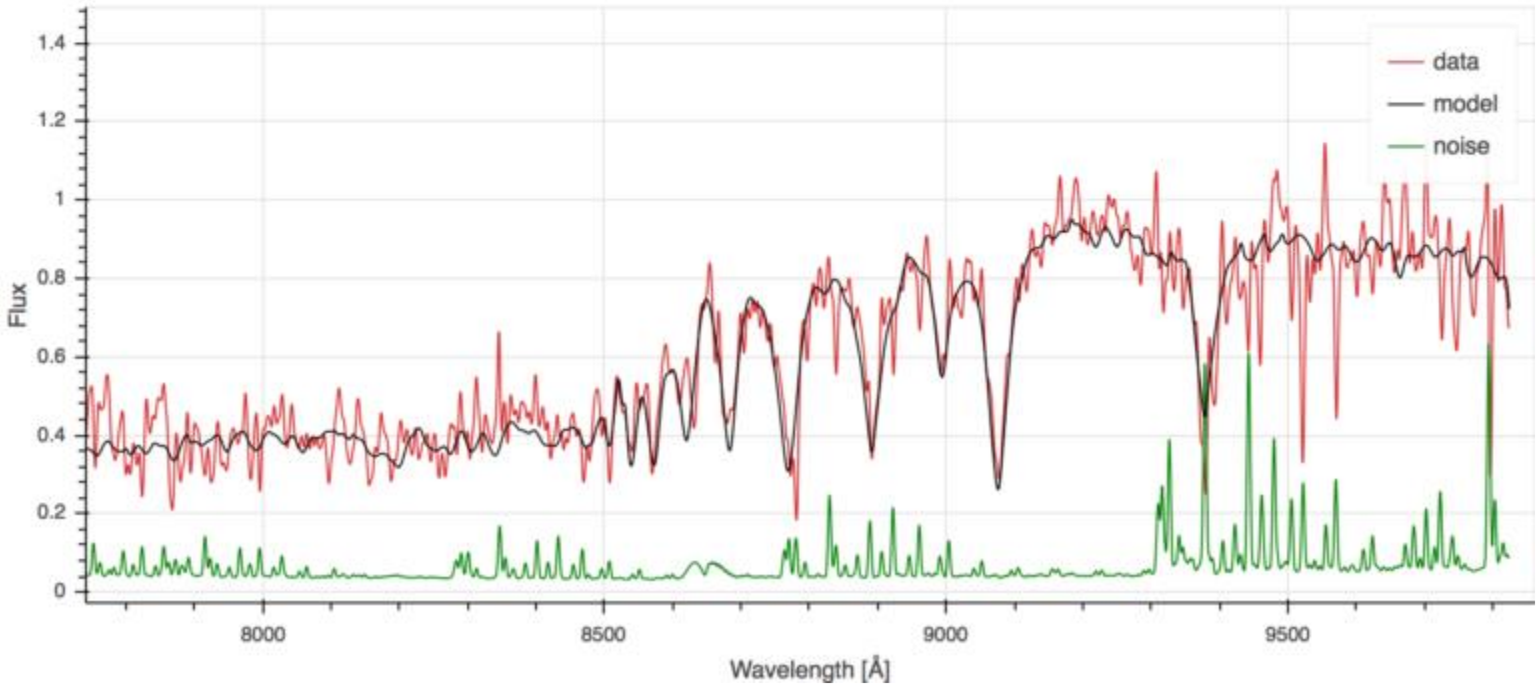
Spain: Guiding and Focus System (IFAE, CIEMAT, ICE, UAM)



DESI started the data taking in may 17th, 2021

DESI

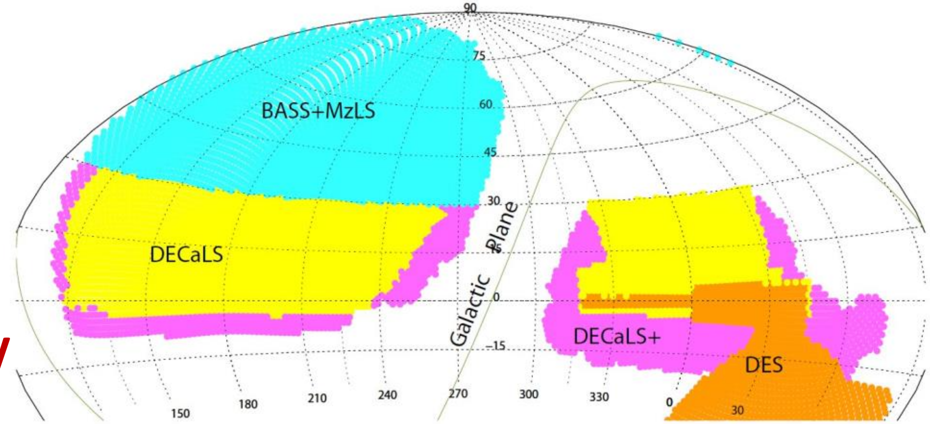
Example of DESI already existing data
~10^6 spectra already stored



Infrared spectrum of one luminous red galaxy target, easily revealing the distinctive Balmer-line signature of a post-starburst galaxy at an impressive redshift z= 1.286. This galaxy is magnitude 19.9 (AB) in the z-band, about a factor of 2 brighter than our planned flux limit. DESI observed this target for 45 minutes on March 15, 2020.

DESI

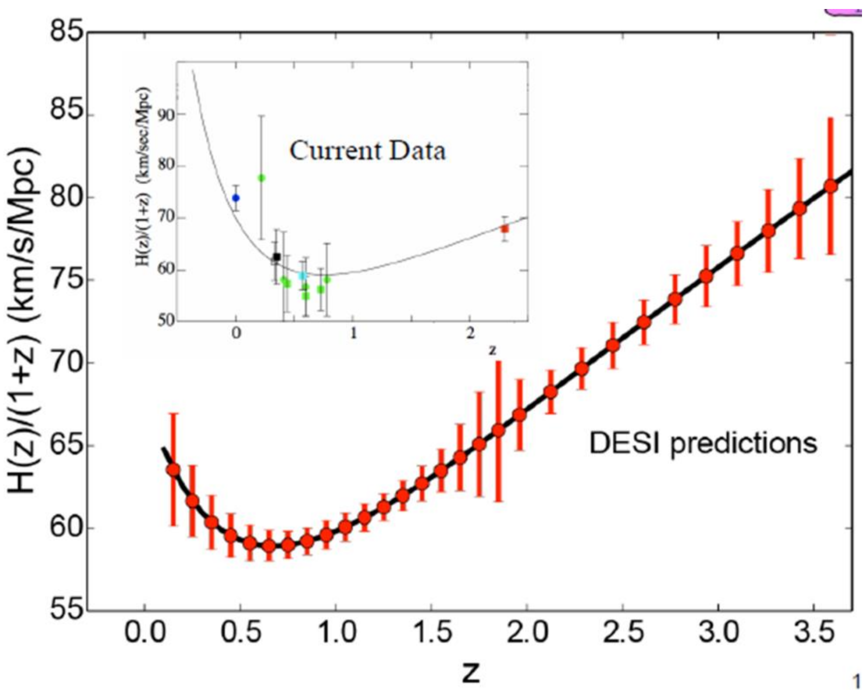
Scientific potential

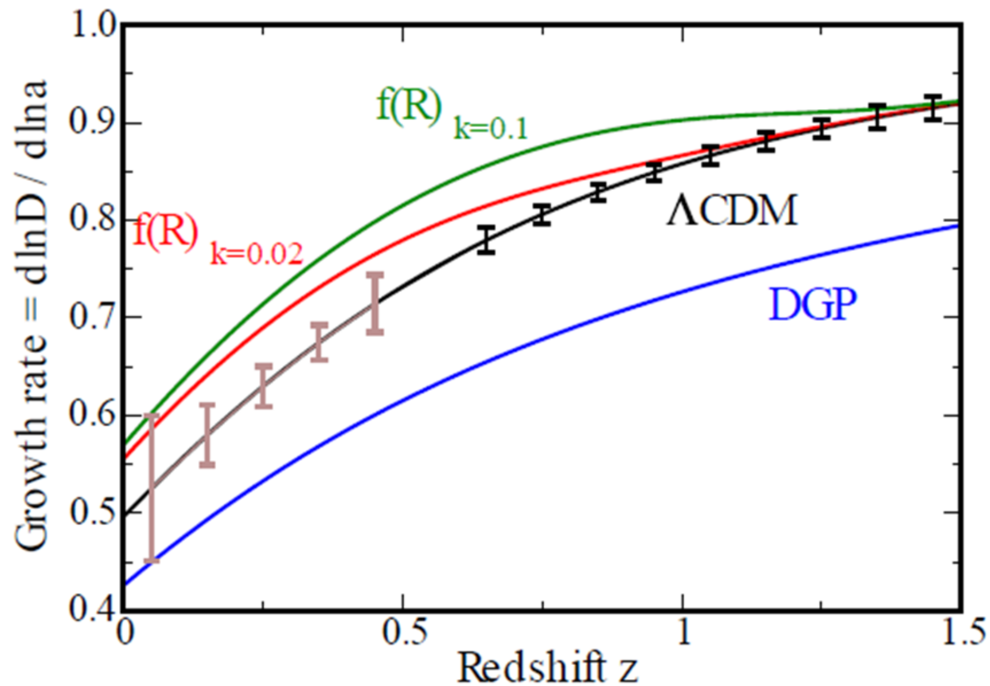


Distances with BAO better than 0.3%

Growth factor better than 1% → GR test

Sum of neutrino masses better than 20 meV





LSST/DESC AND EUCLID

Euclid Consortium

FoM ~ 1500 , -4000 (all)

Main probes: WL & Galaxie clustering (BAO,RSD) (spectro))

European lead project / ESA

Participation of NASA

~ 1000 members

Space telescope / 1.2 m mirror

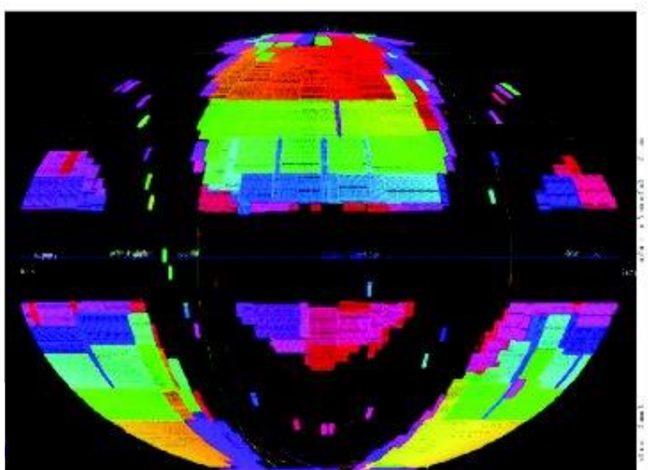
Launch : **Q4 2023**

Mission length : 6 years

1 exposure depth : 24 mag

Survey Area : 15 000 sq deg (.36 sky)

Filters : 1 Visible(550-900nm)+ 3 IR (920-2000 nm) + NIR spectroscopy (1100 – 2000 nm)



LSST Large Synoptic Survey Telescope

FoM > 800

Main probes : **WL, CL, SN, BAO (photo)…**

US lead project / NSF-DOE

Participation of France/In2P3

~ 450 Core members + 450 to come

Ground Telescope / 6.5 m effective mirror

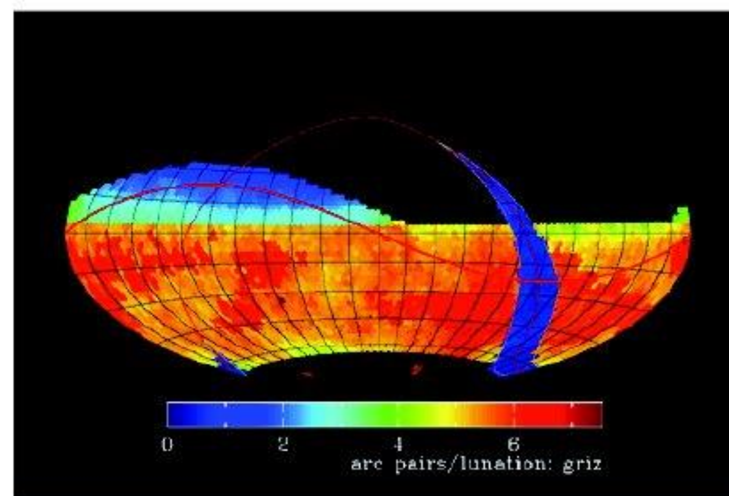
1st light : **2023**

Observation length : 10 years

1 exposure depth : 24 mag (i)

Survey Area : 20 000 sq dg (.48 sky)

Filters : 6 filters (320-1070 nm)



CONCLUSIONS

Cosmology is in a golden era

All current data are consistent with ΛCDM: 70% cosmological constant, 25% of dark matter (of unknown nature) and 5% of ordinary matter

Some open problems that affect the whole picture: dark energy, dark matter, inflation, baryogenesis → Require new physics

Probing the expansión history of the Universe and the growth of structure with much better precisión can provide a strong boost to the current knowledge

A number of large projects are under way or planned for the future, and hopefully, will bring significant progress

Dark matter, dark energy, baryogenesis and inflation are very important questions both for cosmology and for particle physics, since the unveiling of their physical nature can bring us to a revolution in our understanding of the cosmos