Observational Cosmology

A review for the XLIV International Meeting of Fundamental Physics 2016

Nacho Sevilla Noarbe (CIEMAT)

Observational Cosmology

1) Goals for Observational Cosmology
2) Tools for Observational Cosmology
3) Current observations in Cosmology

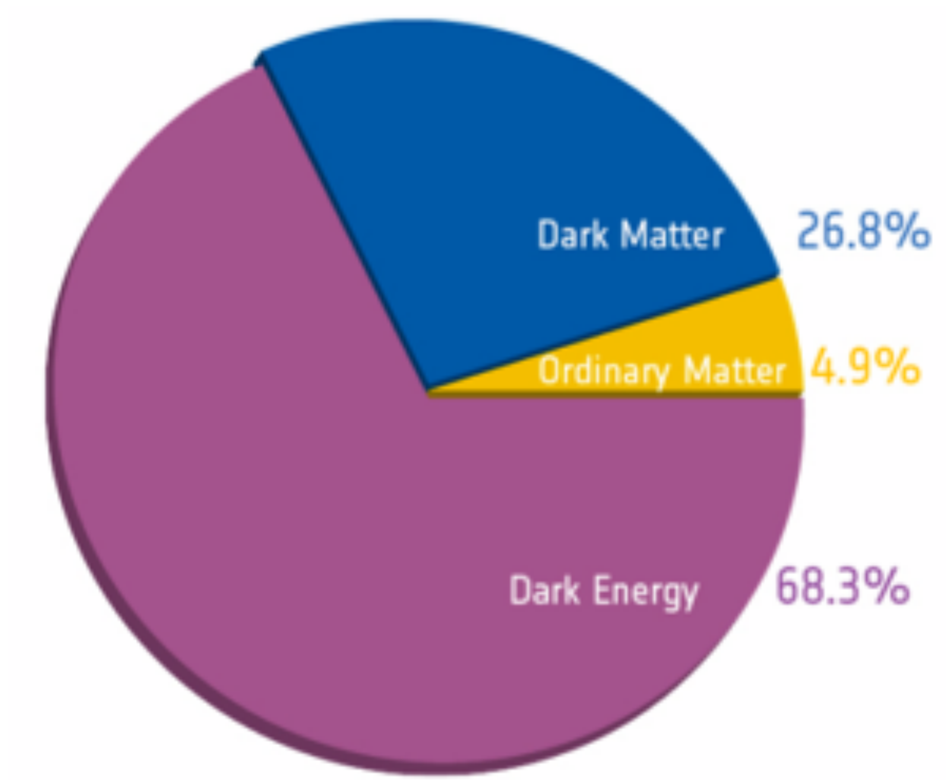
Cosmology became a data-driven science ~20 years ago

- Breakthroughs coming from instrumentation and data processing.

- Coming of age of several observational channels.

- We have arrived at a data-driven cosmological 'standard' model (ΛCDM).

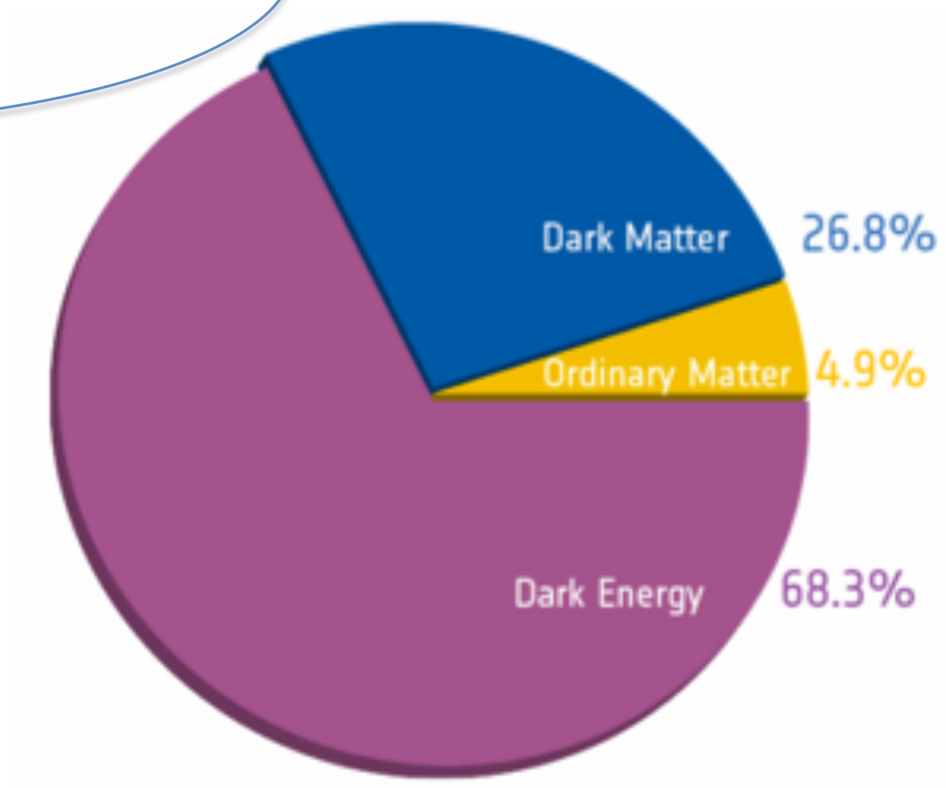
- This paradigm contains some of the strongest indications of physics BSM and/or challenges to GR.



Cosmology provides an astonishing picture of the contents of the Universe

If I had been present at the moment of Creation, I would have given some useful indications

Alfonso X el Sabio



The quest for observational cosmology is to **quantify the** characteristics of the **Universe** in order **to understand** its origin, structure, evolution and **its fundamental rules** (nature of its constituents), through the **detection of particles** reaching the Earth from **beyond the atmosphere.**

~~EXPERIMENTAL~~ OBSERVATIONAL COSMOLOGY

The quest for observational cosmology is to determine values for the model parameters

- Dynamics: expansion rate H

- Mass-energy budget: Ω_X (X= matter; dark energy; radiation; neutrinos …)

- Characteristics of primordial fluctuations: r; n_S; Δ_R

- Physical state of the Universe: τ

Concordance model can be detailed with 6-7 parameters

Others: sum of neutrino mass, equation of state for DE, helium fraction

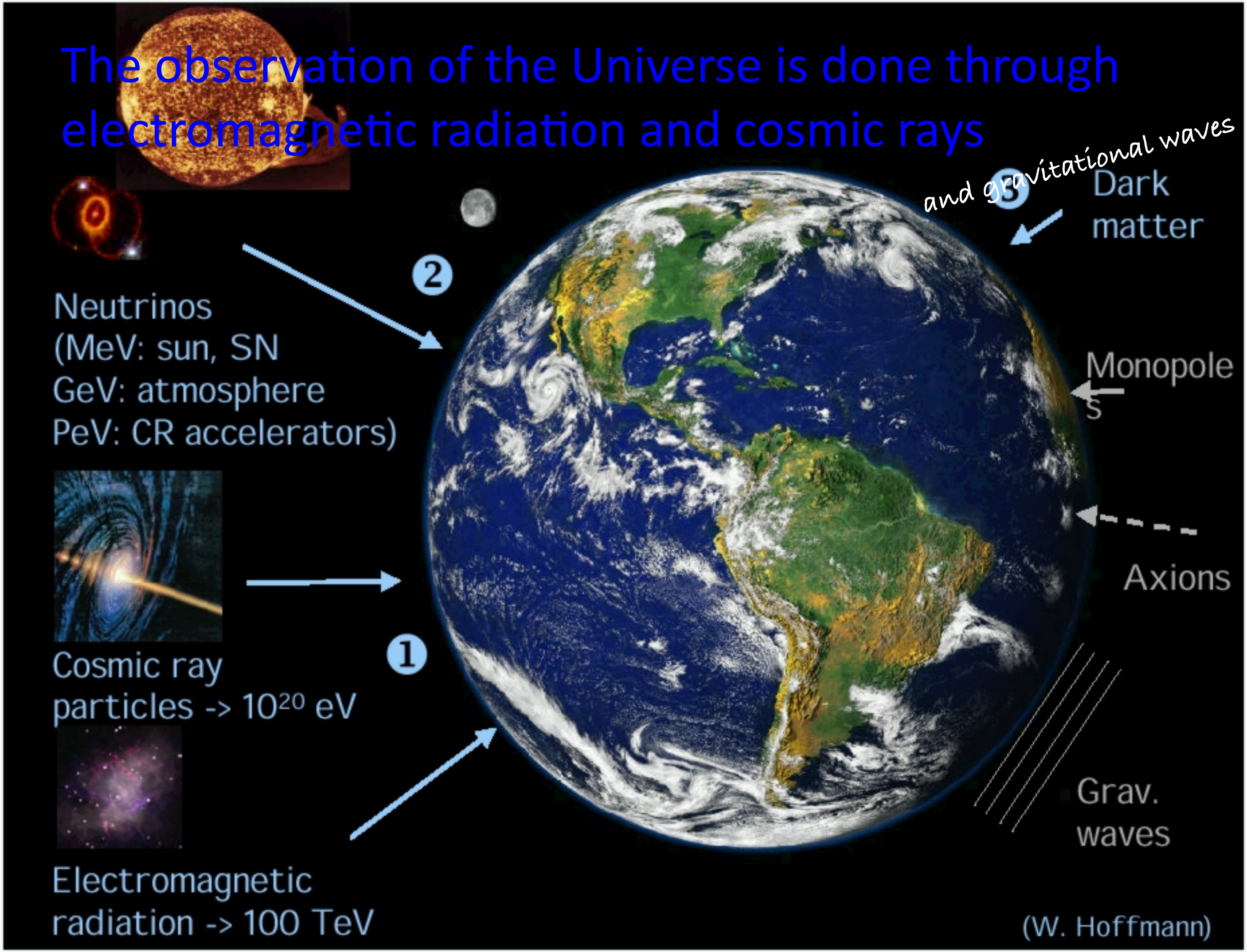
The quest for observational cosmology is to challenge the current paradigm

- Is the ΛCDM standard model the final word from the Universe?

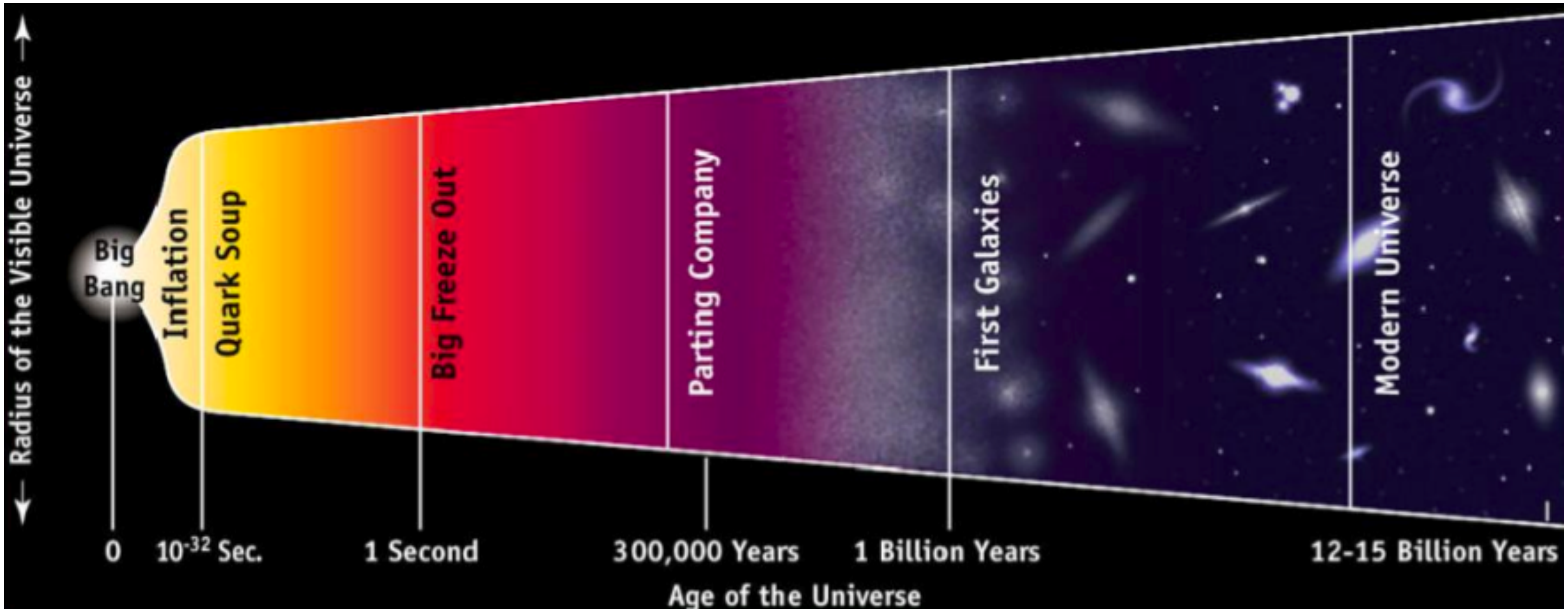
…and other questions:

- ~~What is the description of the Universe?~~
- Are all measurements consistent?
- What is dark energy? ~~What is dark matter?~~
- What is total neutrino mass?
- What can we learn from inflation? (see M.Bastero's talk)

The observation of the Universe is done through electromagnetic radiation and cosmic rays



Each of these probes has its own reach



CMB

(leaves imprint in CMB)

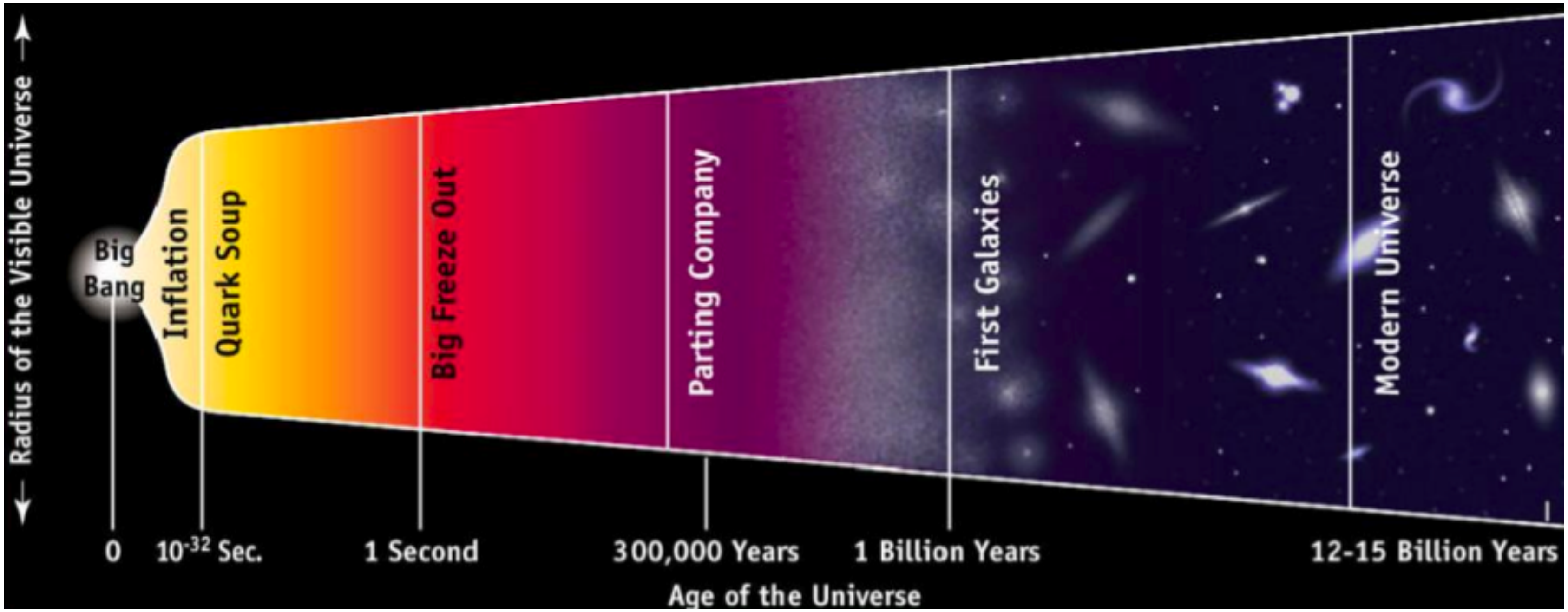
CMB

(leaves imprint in CMB)

Infrared

Optical

Each of these probes has its own reach



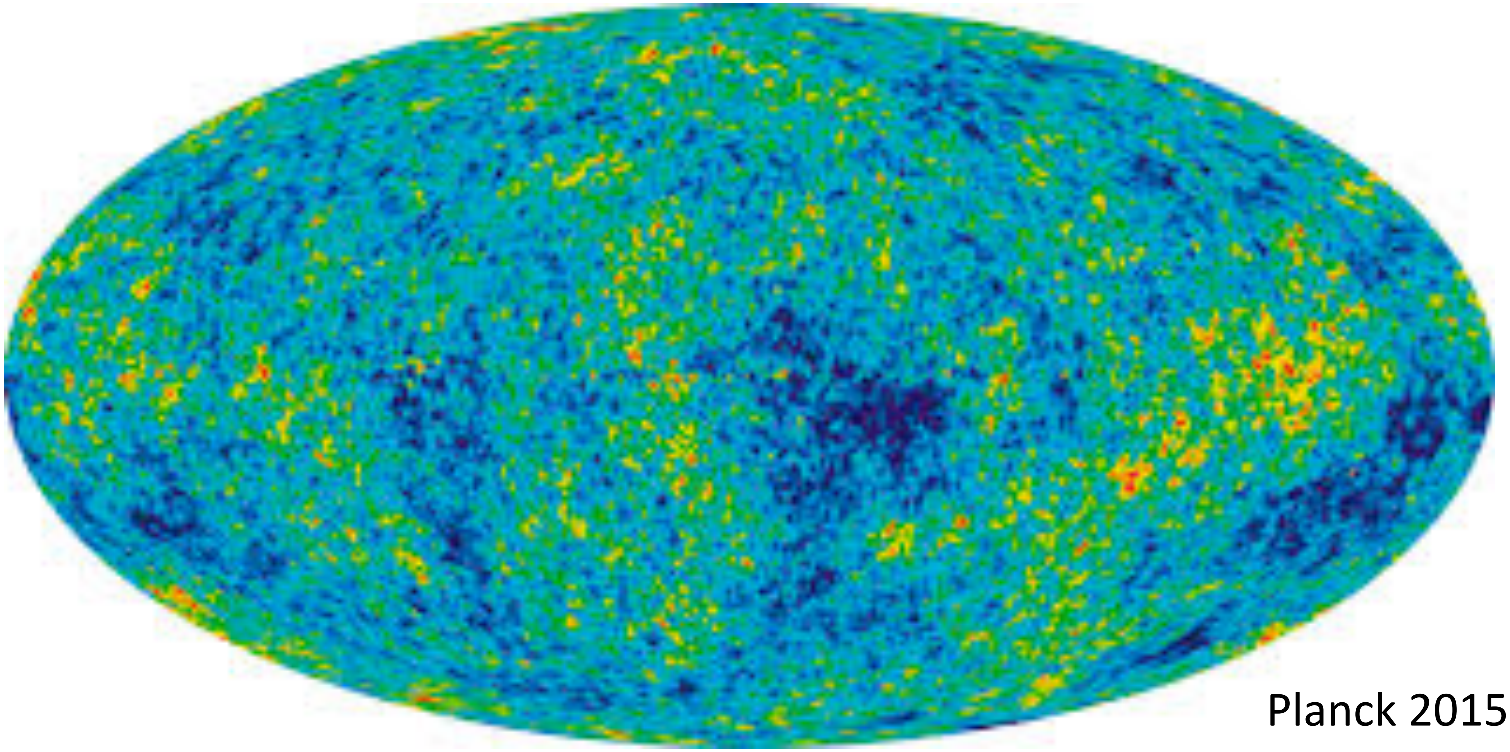
Cosmic rays (incl. gamma)

Dark Matter

Grav. Waves

Neutrinos

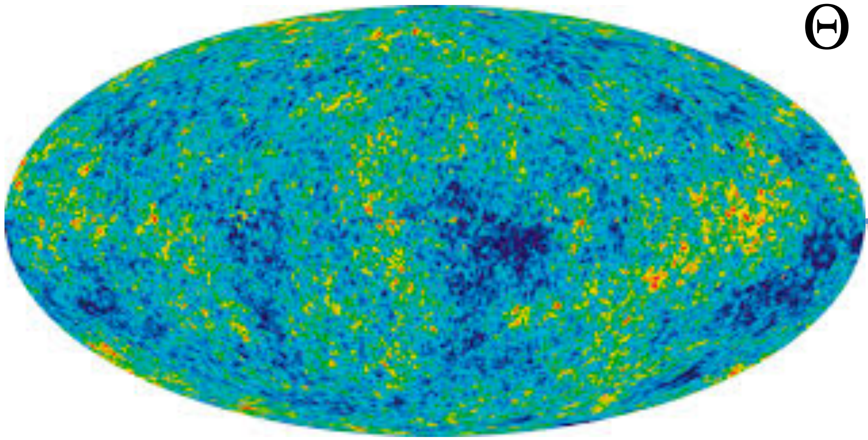
Our most precise tool is the measurement of the cosmic microwave background



Planck 2015

Radiation 'liberated' at the epoch of decoupling contains information in its power spectrum map (and also from other epochs).

Our most precise tool is the measurement of the cosmic microwave background

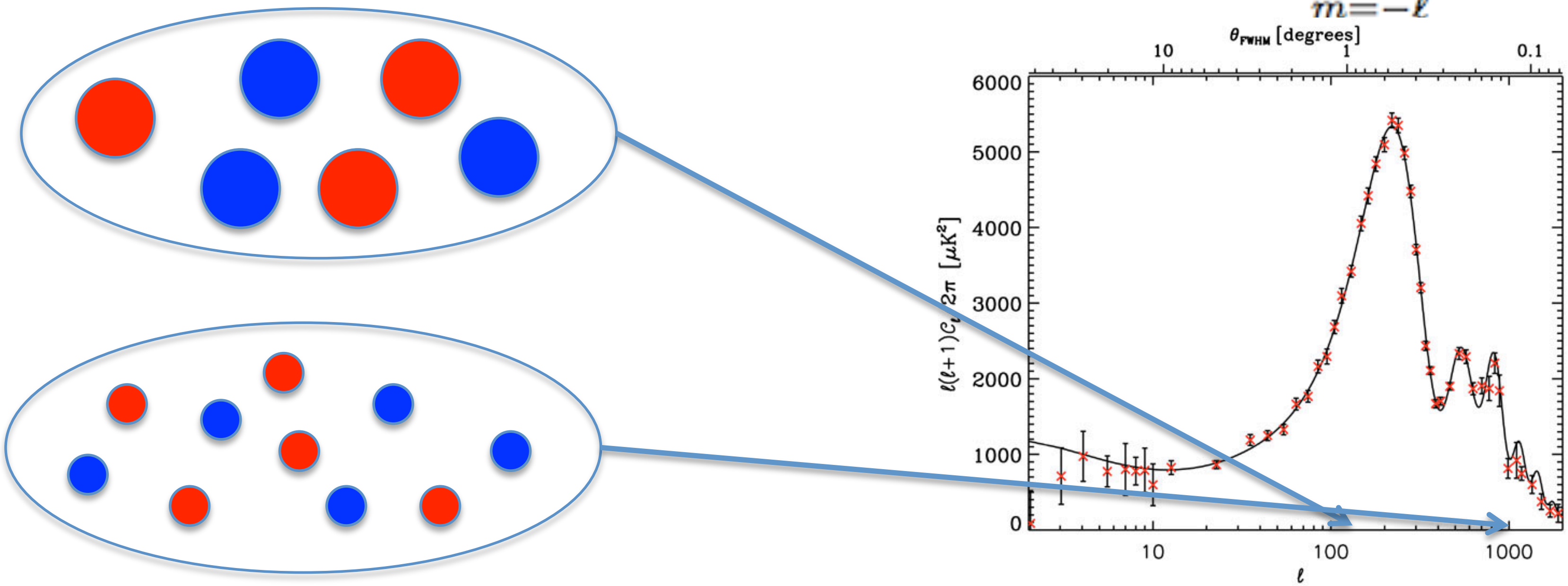


$\Theta \sim 10^{-5}$

Temperature fluctuations

$$\Theta(\hat{\mathbf{n}}) = \sum_{\ell=0}^{\ell=\infty} \sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\hat{\mathbf{n}})$$

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{lm}|^2 \rangle$$



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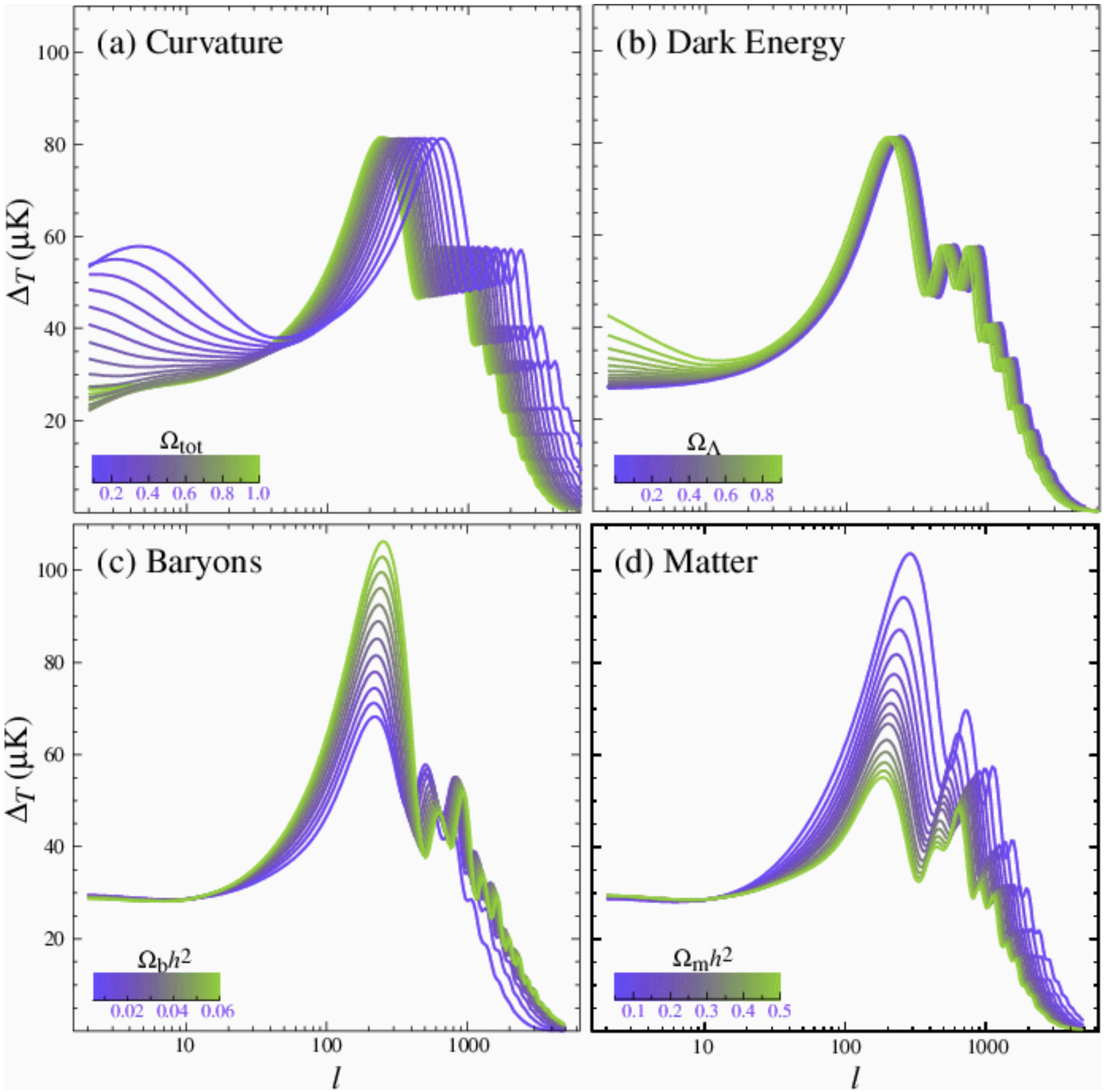


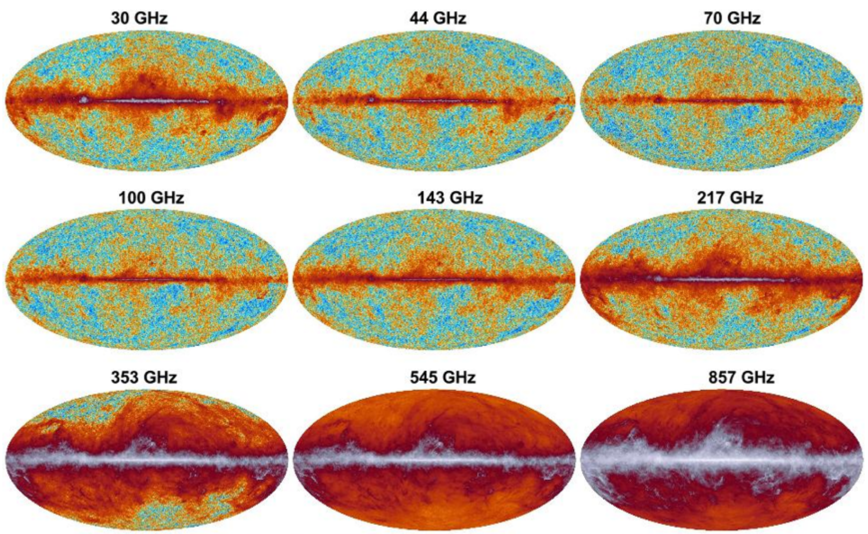
This probe is very sensitive to the curvature, matter content and baryon content of the Universe.

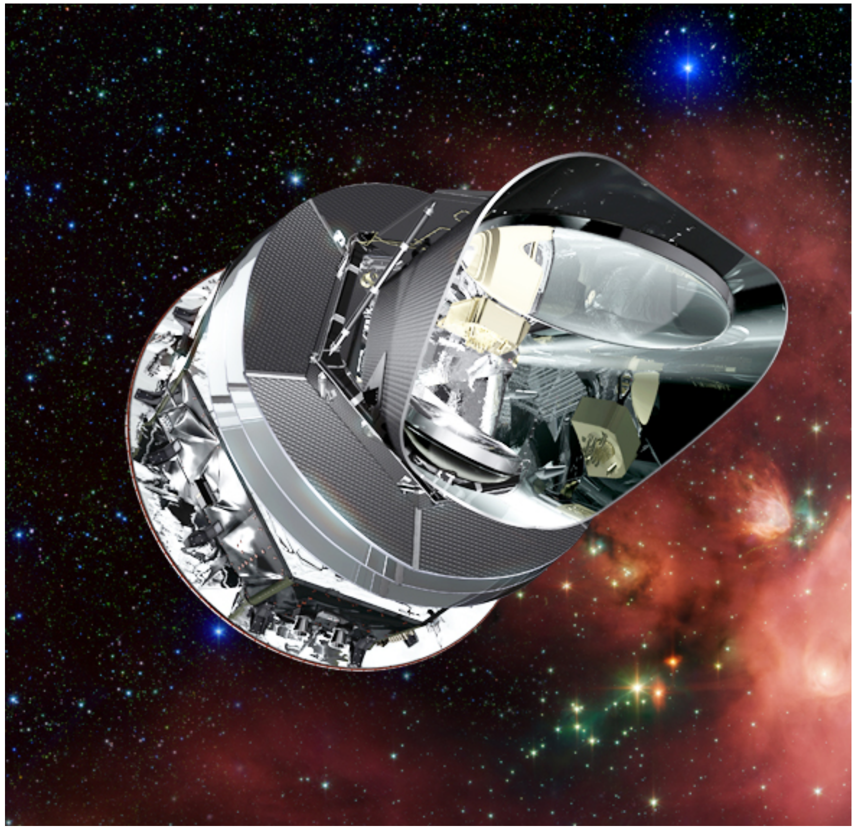
Hu & Dodelson 2002

ESA's Planck satellite is the state of the art in the measurement of cosmological parameters

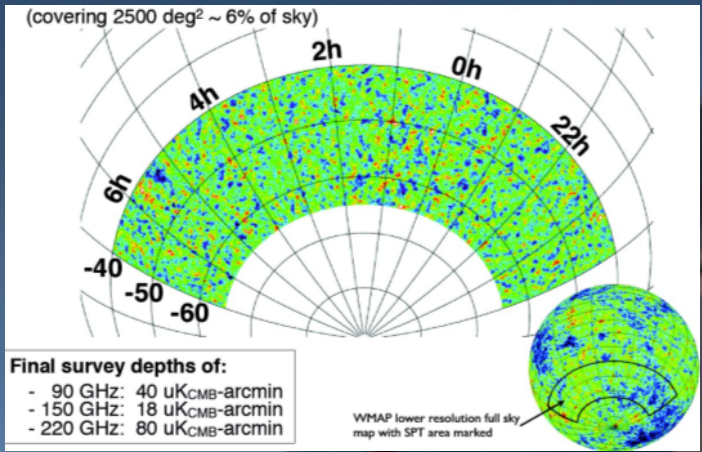
Temperature and polarization

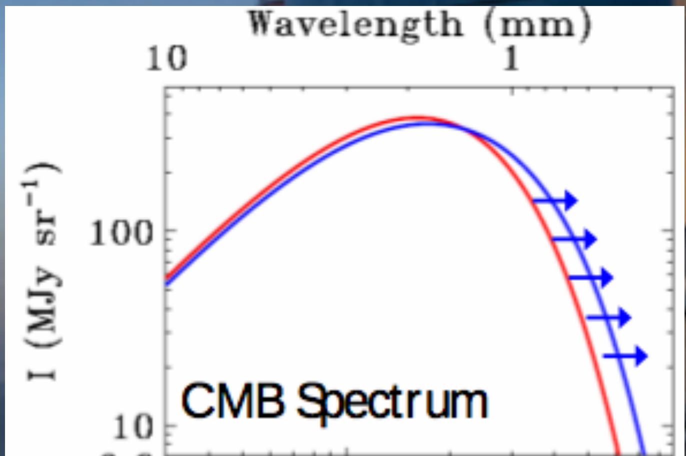
9 maps in different bands





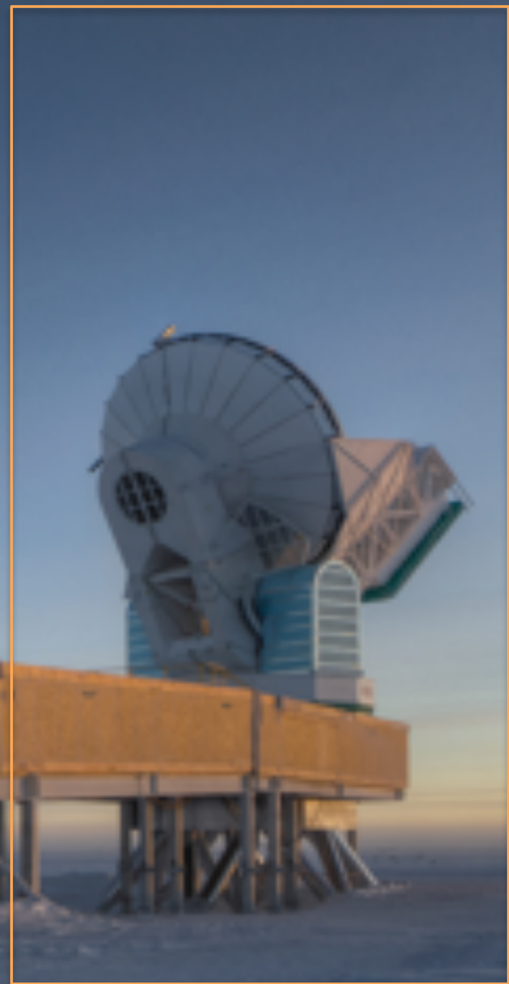
CMB observations from ground complement those from Planck (high angular resolution)





The South Pole Telescope measures the CMB with high angular resolution.

Galaxy clusters are measured through distortions in the CMB spectrum.



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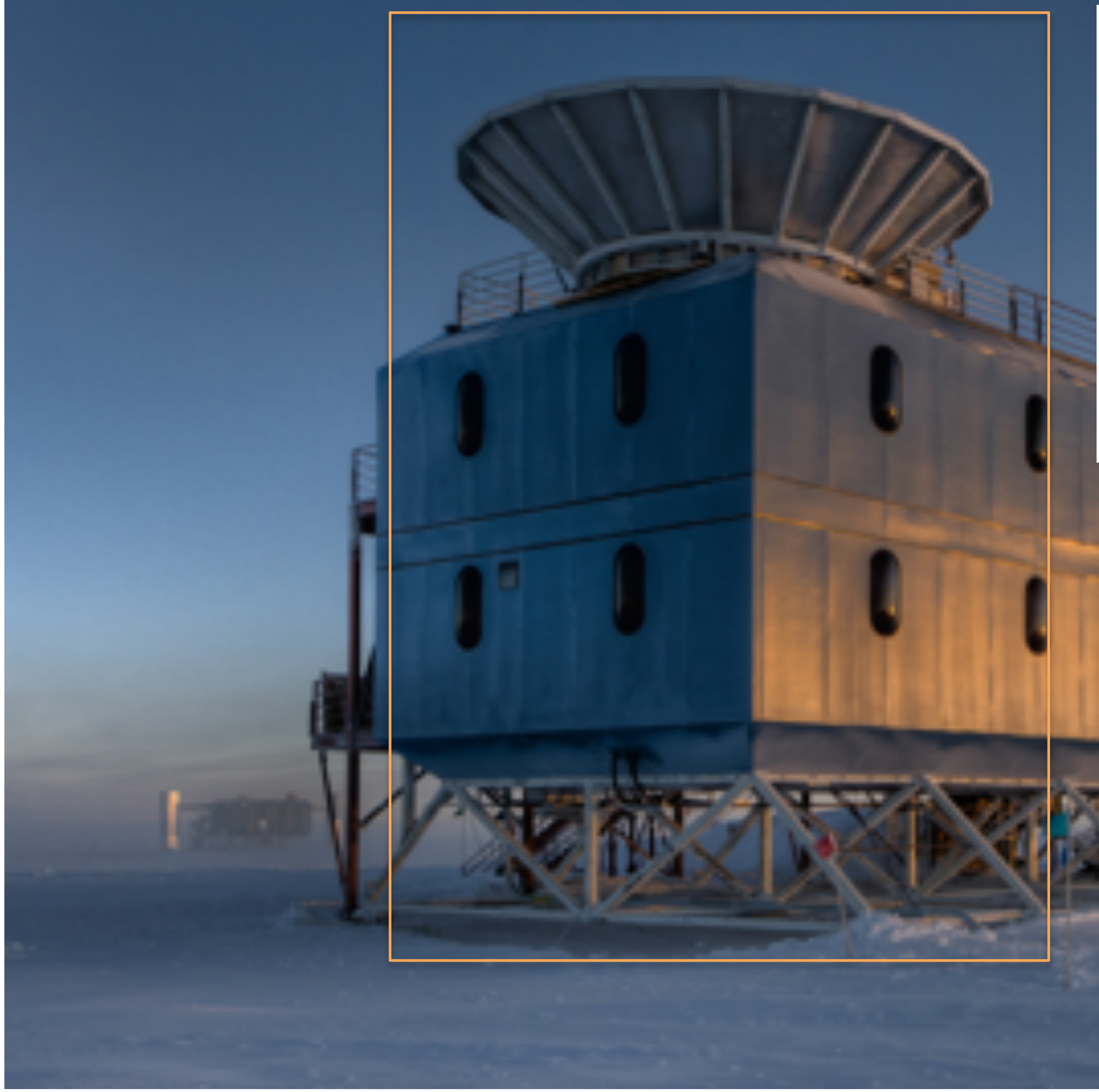
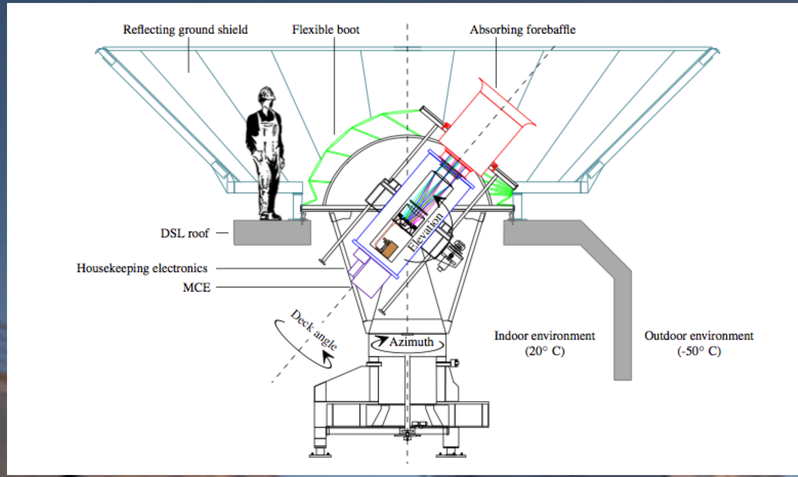
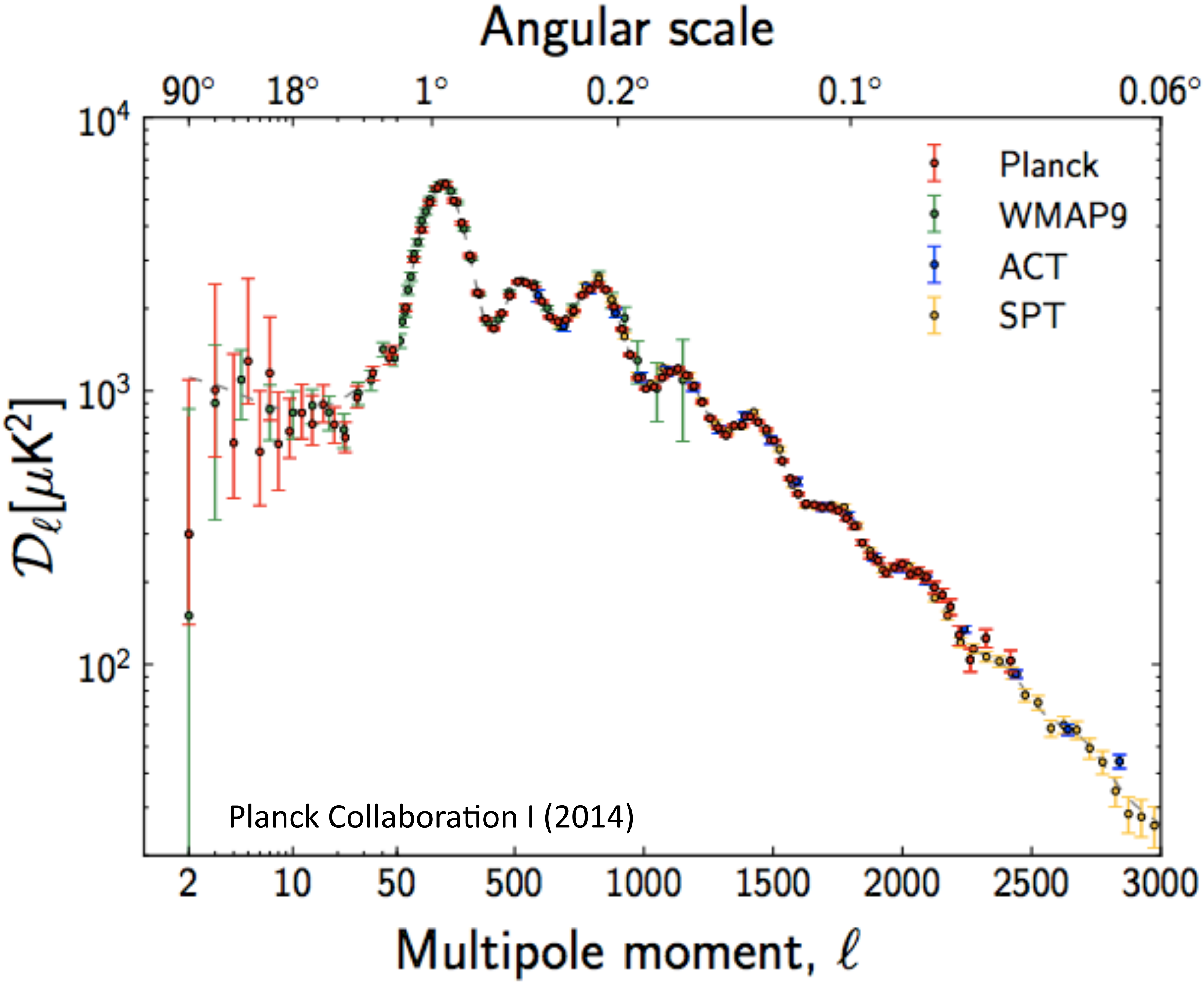
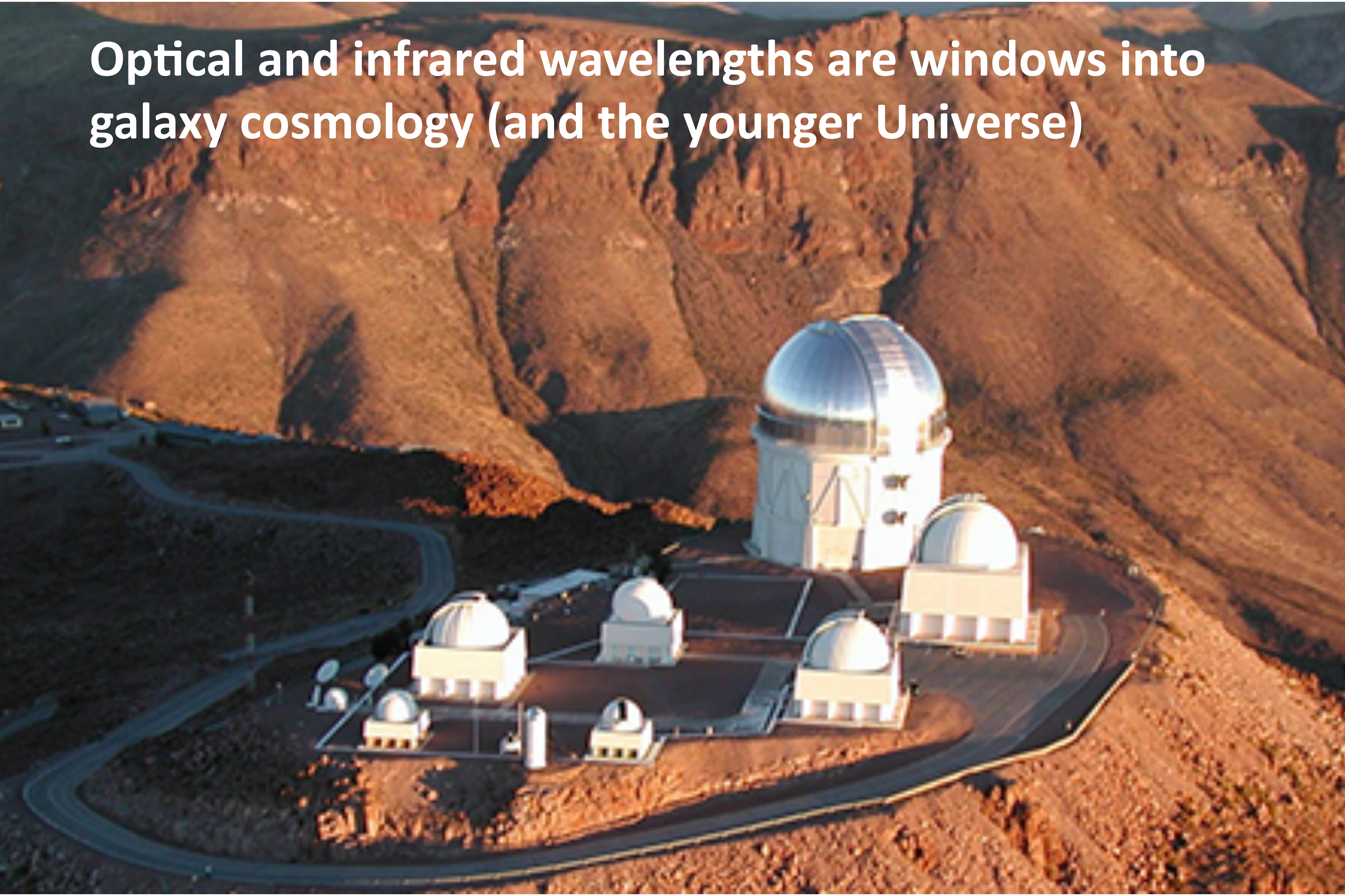




The BICEP telescopes and Keck arrays are designed to measure polarization through specialized bolometer. The goal is to try to measure primordial B-mode distortions in the CMB.


Angular scale
90°
18°
1°
0.2°
0.1°
0.06°
10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
Planck
WMAP9
ACT
SPT
Planck Collaboration I (2014)
2
10
50
500
1000
1500
2000
2500
3000
Multipole moment, ℓ

Optical and infrared wavelengths are windows into galaxy cosmology (and the younger Universe)



Determine distances or matter clustering as a function of redshift to probe dark energy.

$$H(z) = H_0 \left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)} e^{-3w_a \frac{z}{1+z}}\right]$$

$$d_L \equiv \sqrt{\frac{L}{4\pi f}} \qquad d_L = (1+z)\, c \int_0^z \frac{dz'}{H(z')} \qquad \kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_H} \mathrm{d}\chi W_{(i)}(\chi)\delta_m[\chi, \chi\boldsymbol{\theta}]$$

$$d_A \equiv \frac{s}{\Delta\theta} \qquad d_A = \frac{1}{1+z}\, c \int_0^z \frac{dz'}{H(z')} \qquad W_{(i)}(\chi) = \frac{3}{2}\Omega_M H_0^2 a^{-1}(\chi)\chi \frac{1}{\bar{n}_{(i)}} \int_\chi^{\chi_H} \mathrm{d}\chi_s n_{(i)}(z) \frac{\mathrm{d}z}{\mathrm{d}\chi_s} \frac{\chi_s - \chi}{\chi_s}$$

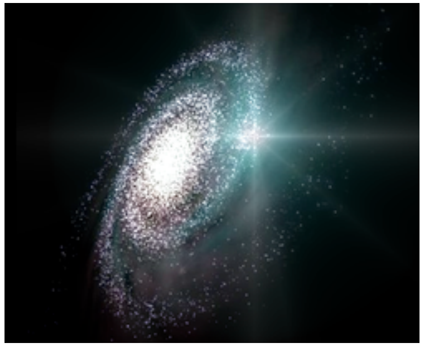
Equation of state $w = p/\rho$ can help us determine the nature of dark energy.

$w = -1$	A cosmological constant-like phenomenon
$w = w(z)$	Quintessence, k-essence models
$w < -1$	Phantom energy

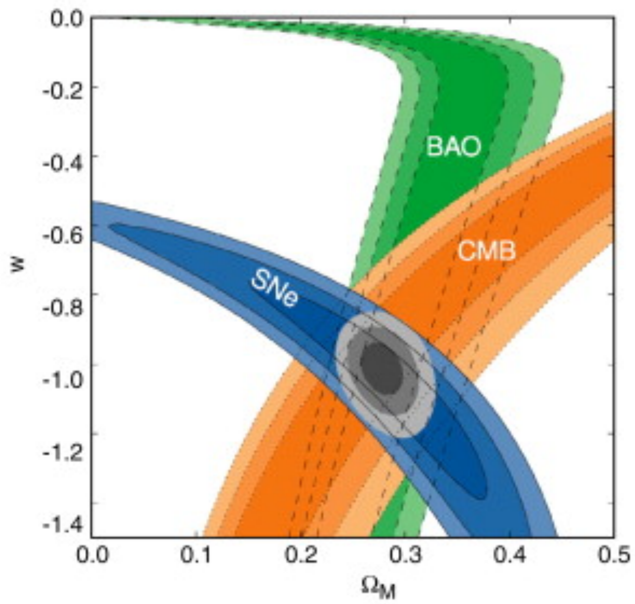
Look for inconsistent measurements between expansion rate (H() derived *w* and structure formation derived *w*.

Dark Energy can be approached through several observational channels.

Supernovae Ia

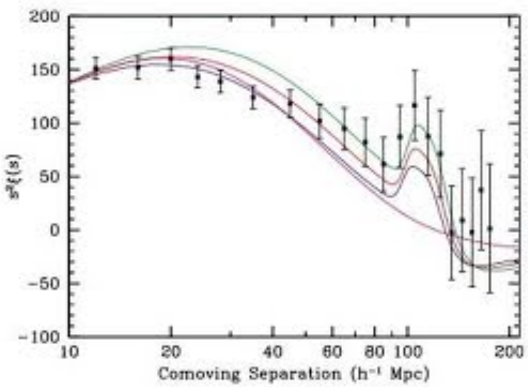


Cluster density

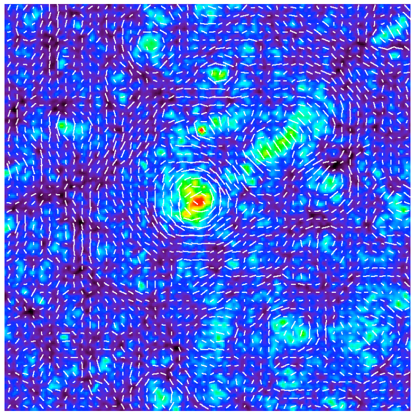


Kerschaggl et al. 2011

Baryon Acoustic Oscillations



Weak lensing



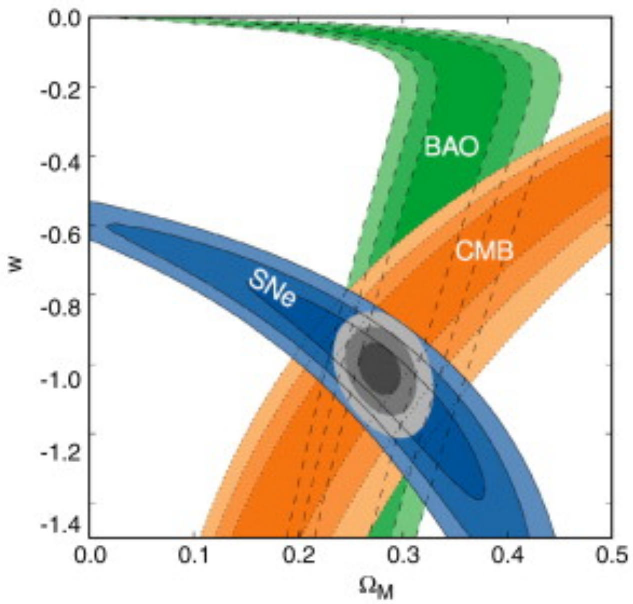
In 2000's, Dark Energy Task Force determined the most promising probes.

Dark Energy can be approached through several observational channels.

Supernovae Ia

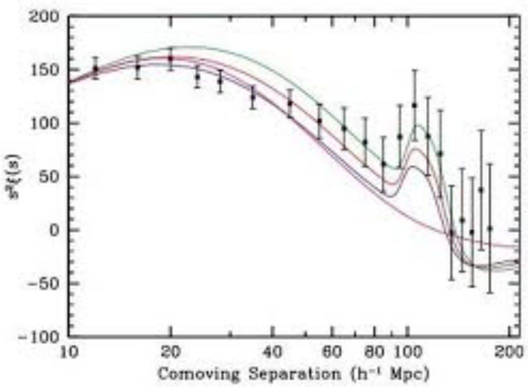
Observe **objects of known absolute brightness** to measure distances → expansion rate as function of time H(z)

Cluster density

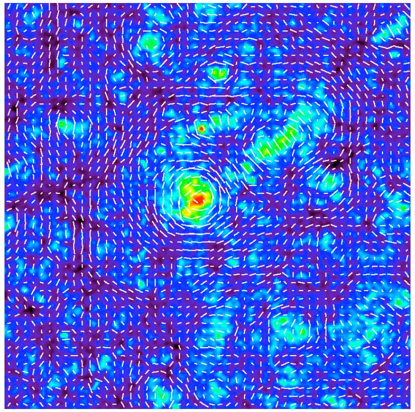


Kerschaggl et al. 2011

Baryon Acoustic Oscillations

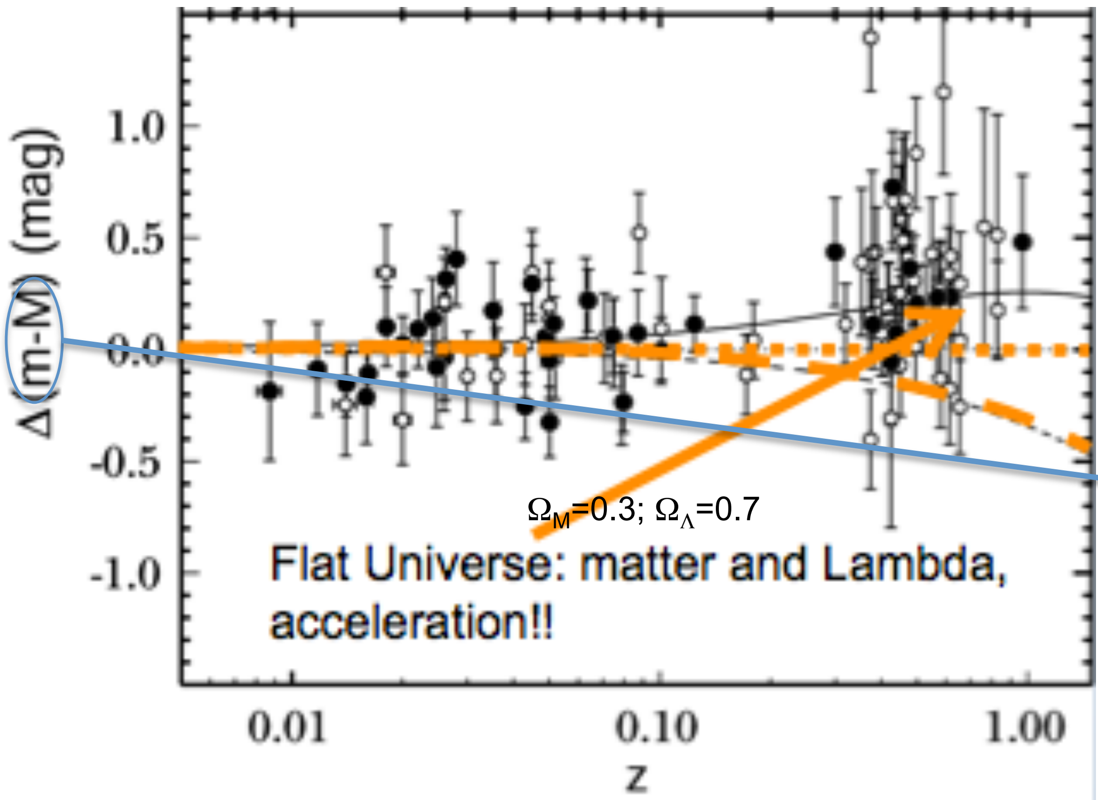


Weak lensing



In 2000's, Dark Energy Task Force determined the most promising probes.

Observe objects of known absolute brightness to measure expansion rate at different epochs



A.Riess et al. 1998; S.Perlmutter et al. 1999

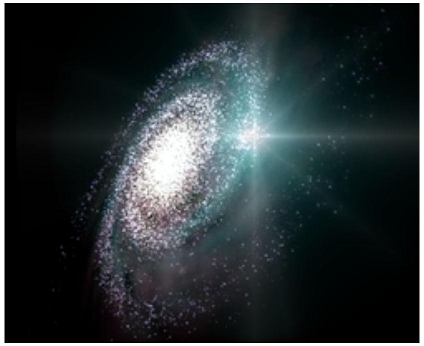
Apparent brightness of supernovae (distance) versus scale of the Universe

$$\chi^2 = \sum_{objects} \frac{(\mu - 5\log(d_L(z;\Omega_M,\Omega_{DE},w))/10pc)^2}{\sigma^2}$$

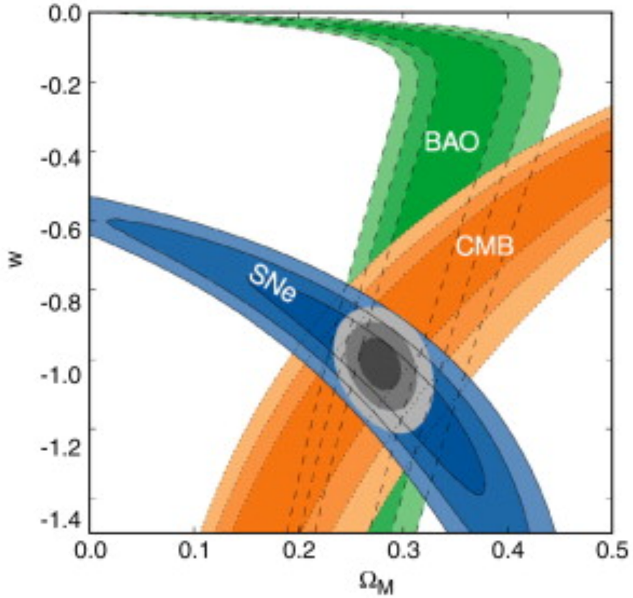
$$d_L = (1+z)\, c \int_0^z \frac{dz'}{H(z')}$$

Dark Energy can be approached through several observational channels.

Supernovae Ia



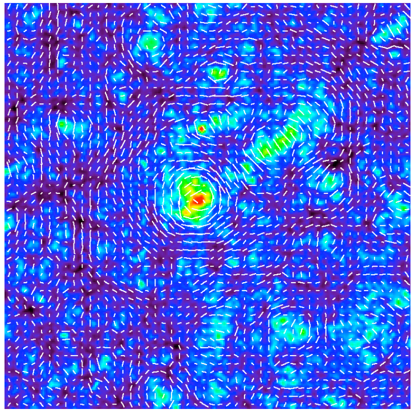
Cluster density



Kerschaggl et al. 2011

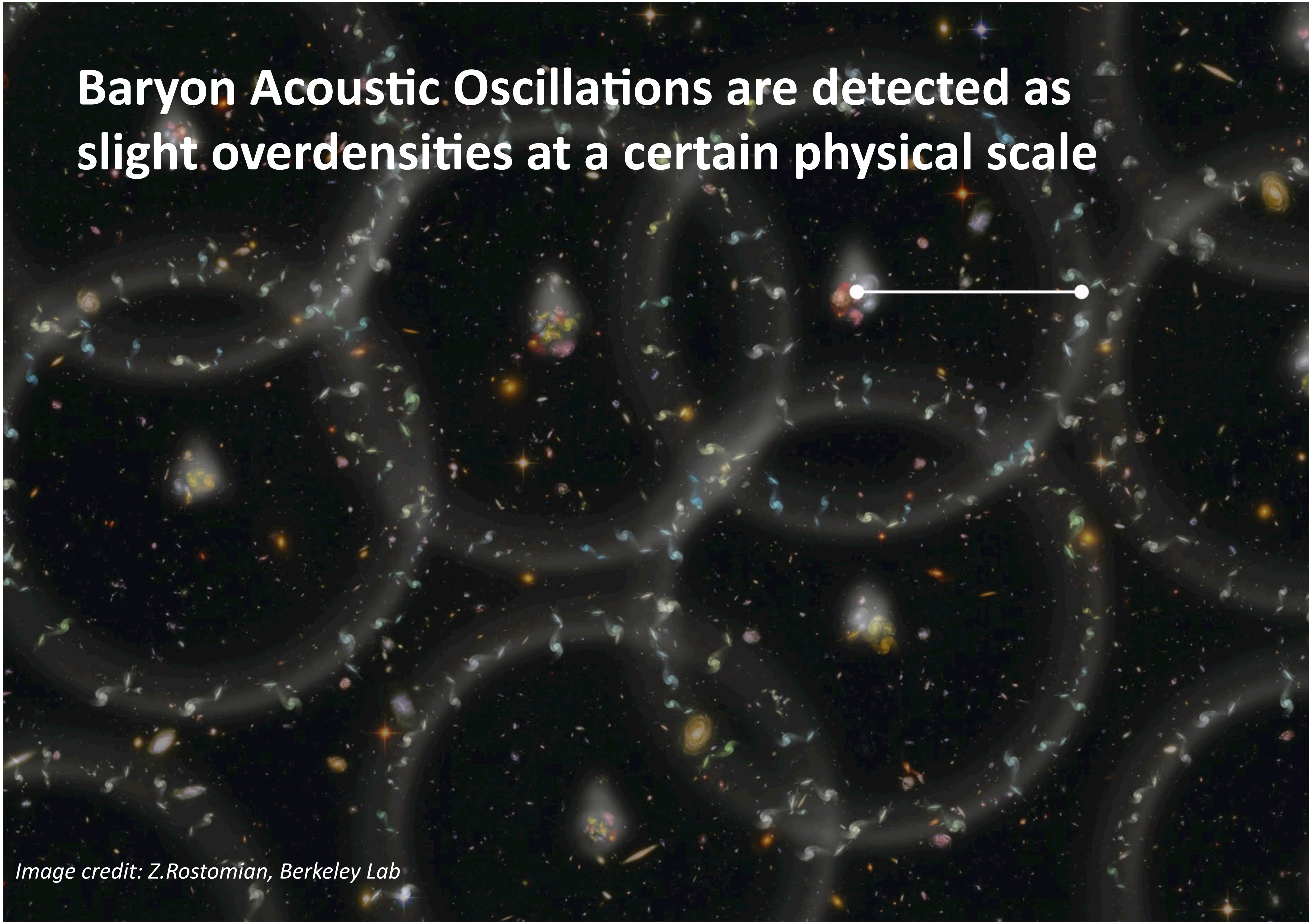
Baryon Acoustic Oscillations

Weak lensing

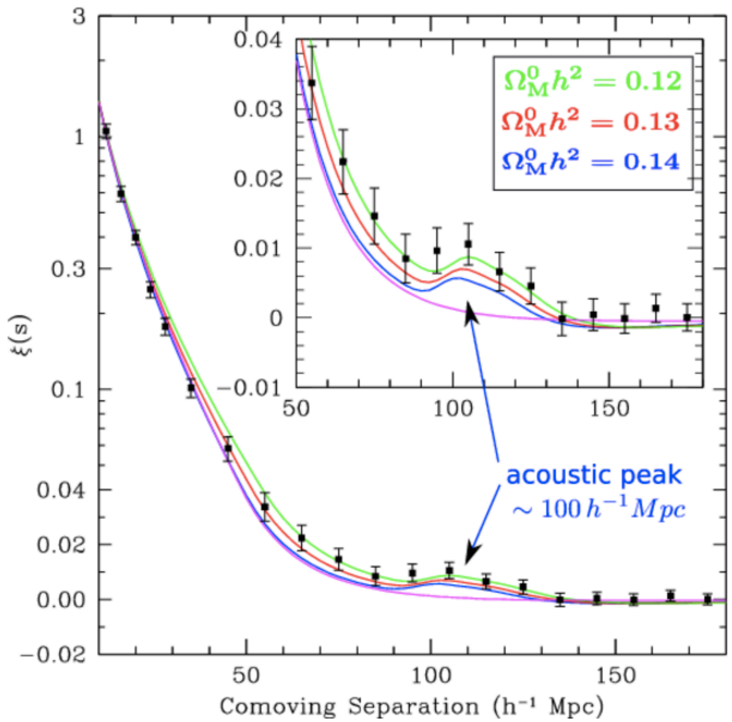


Observe **'objects' of known absolute size** to measure distances → expansion rate as function of time H(z)

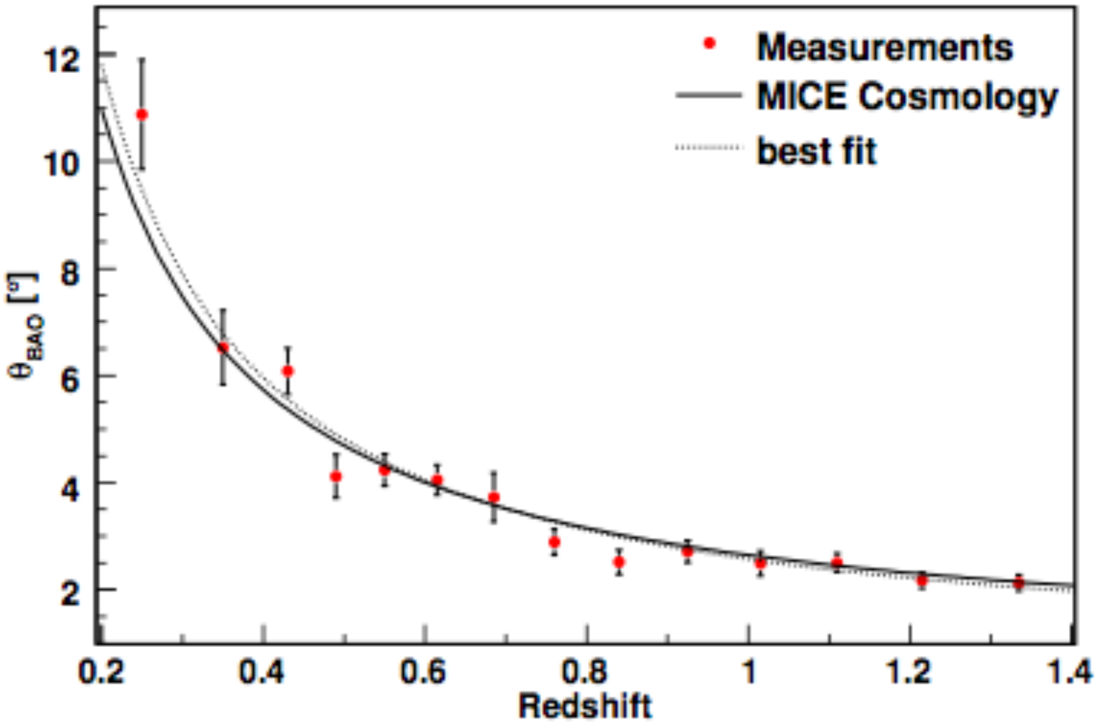
In 2000's, Dark Energy Task Force determined the most promising probes.


Baryon Acoustic Oscillations are detected as slight overdensities at a certain physical scale
Image credit: Z.Rostomian, Berkeley Lab

Observe objects of known absolute size (BAO) to measure variation of expansion rate



D.Eisenstein et al. 2005



E.Sánchez et al. 2011

$$d_A \equiv \frac{s}{\Delta\theta} \qquad d_A = \frac{1}{1+z}\, c \int_0^z \frac{dz'}{H(z')}$$

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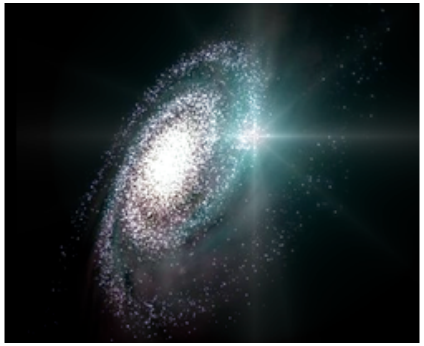
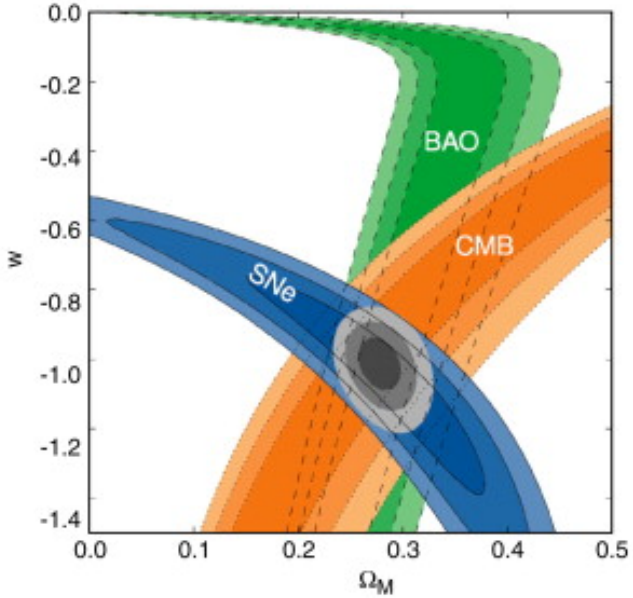
Supernovae Ia



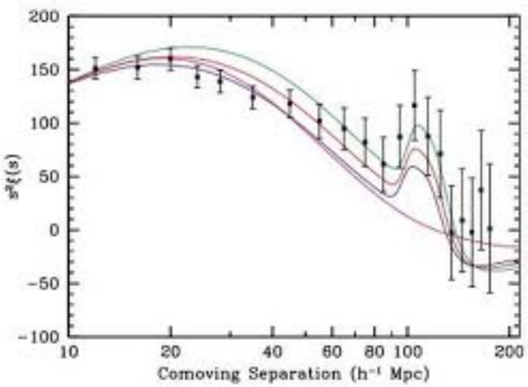
Cluster density

Count clusters of galaxies at different distances → expansion rate and growth of structure as function of time dV(z), f(z)

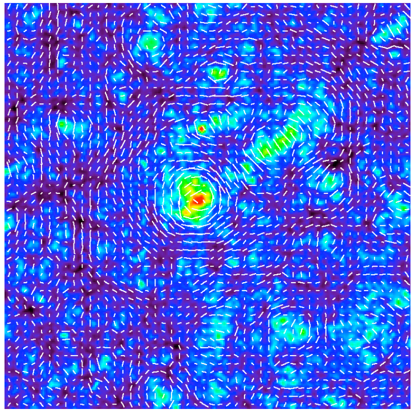


Kerschaggl et al. 2011

Baryon Acoustic Oscillations



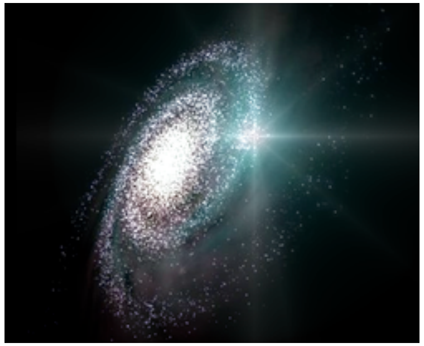
Weak lensing



In 2000's, Dark Energy Task Force determined the most promising probes.

Dark Energy can be approached through several observational channels.

Supernovae Ia



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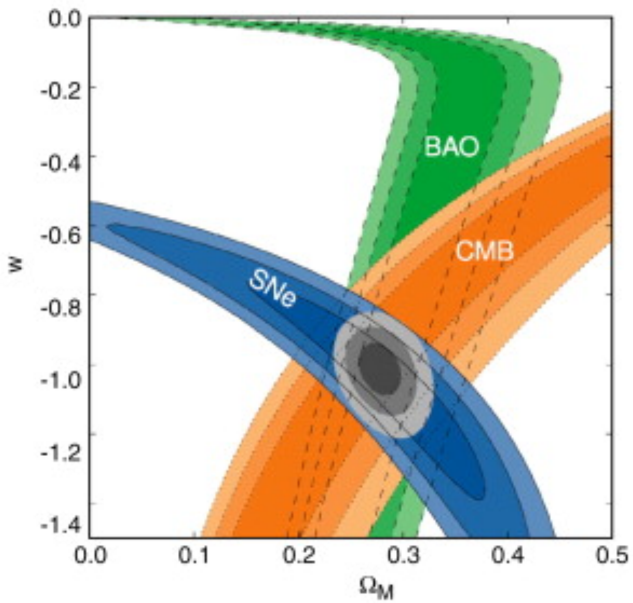
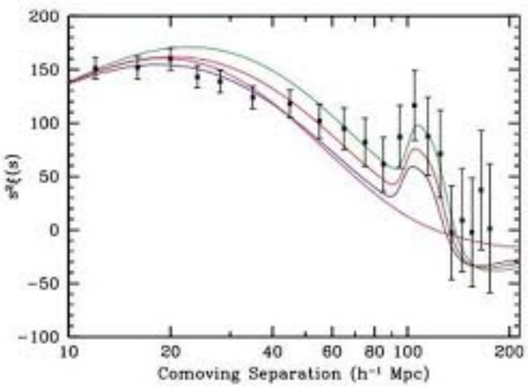


Kerschaggl et al. 2011

Baryon Acoustic Oscillations

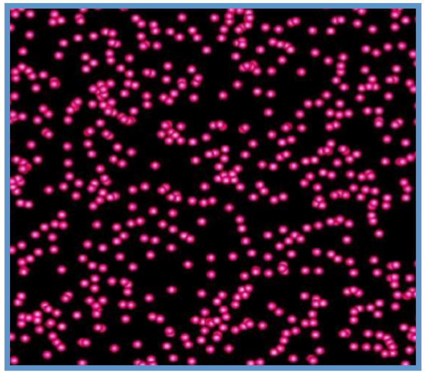


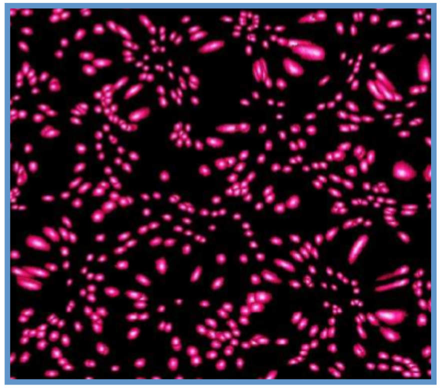
Weak lensing

Measure **background light distortions due to foreground mass** at different distances → expansion rate and growth of structure as function of time

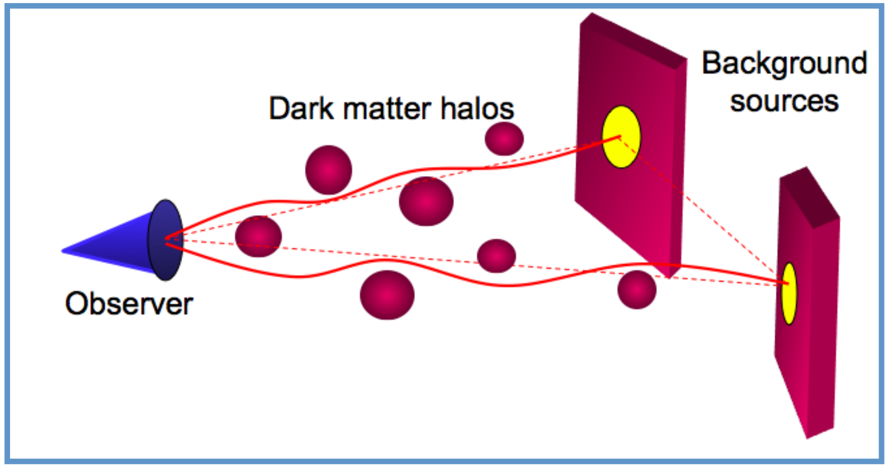
In 2000's, Dark Energy Task Force determined the most promising probes.

Growth of structure in cosmic time can be used to probe acceleration (weak lensing)





A.Amara



- Use far away objects to study clustering of objects in line of sight.

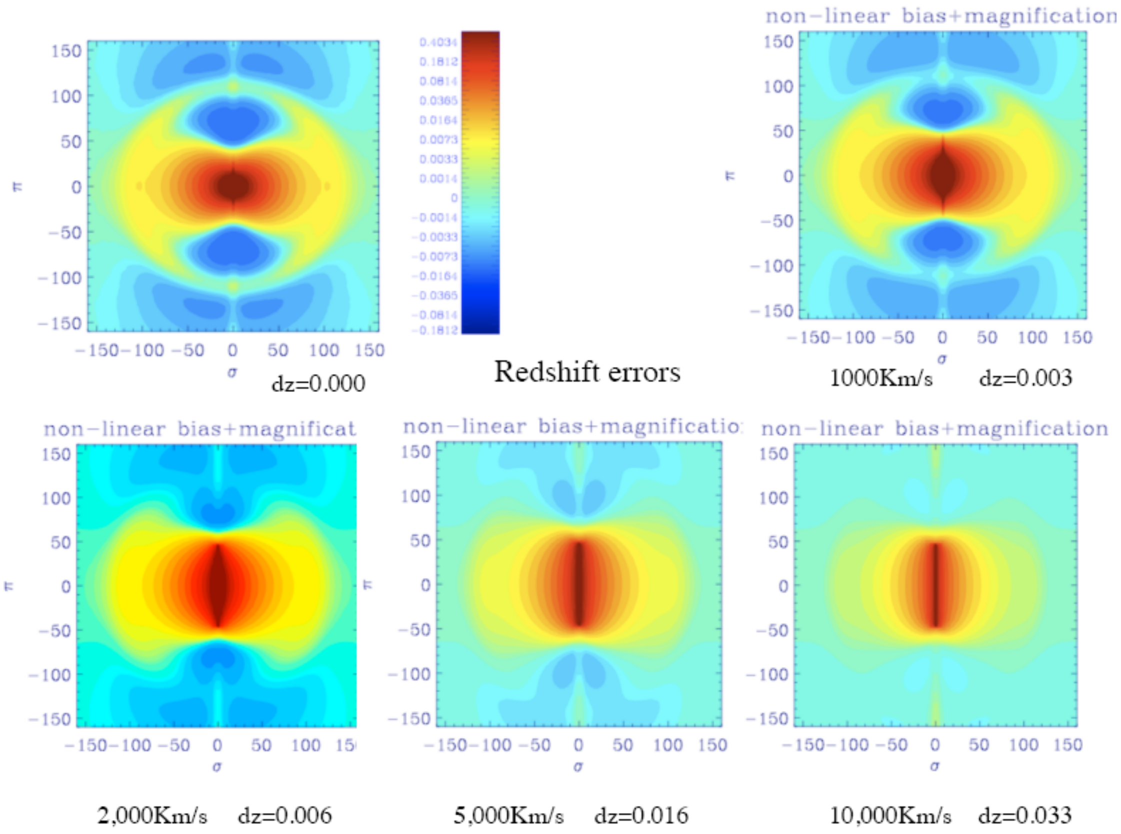
- This is done through the effect of gravity on light (lensing).

- Effect is tiny (<1%), it is studied statistically.

- Systematic effects are dominant (shape, orientation).

$$\kappa_{(i)}(\boldsymbol{\theta}) = \int_0^{\chi_H} \mathrm{d}\chi W_{(i)}(\chi)\delta_m[\chi, \chi\boldsymbol{\theta}]$$

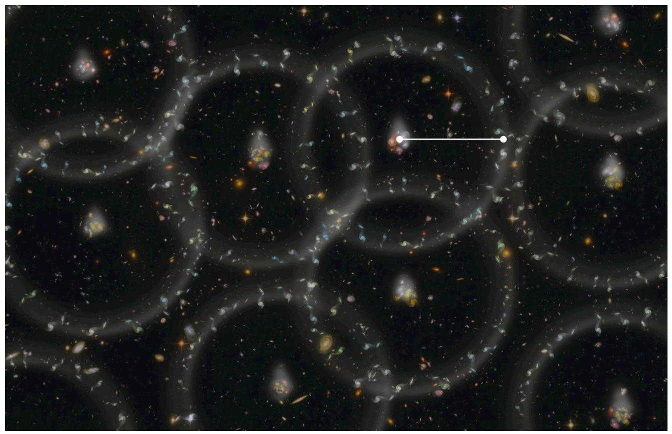
Sometimes you don’t need to have very precise redshifts



E.Gaztañaga et al. 2012

Redshift space distortions measurement is an interesting probe of matter is clustering as a function of redshift.

Need precise spectra, not necessarily spectroscopic!



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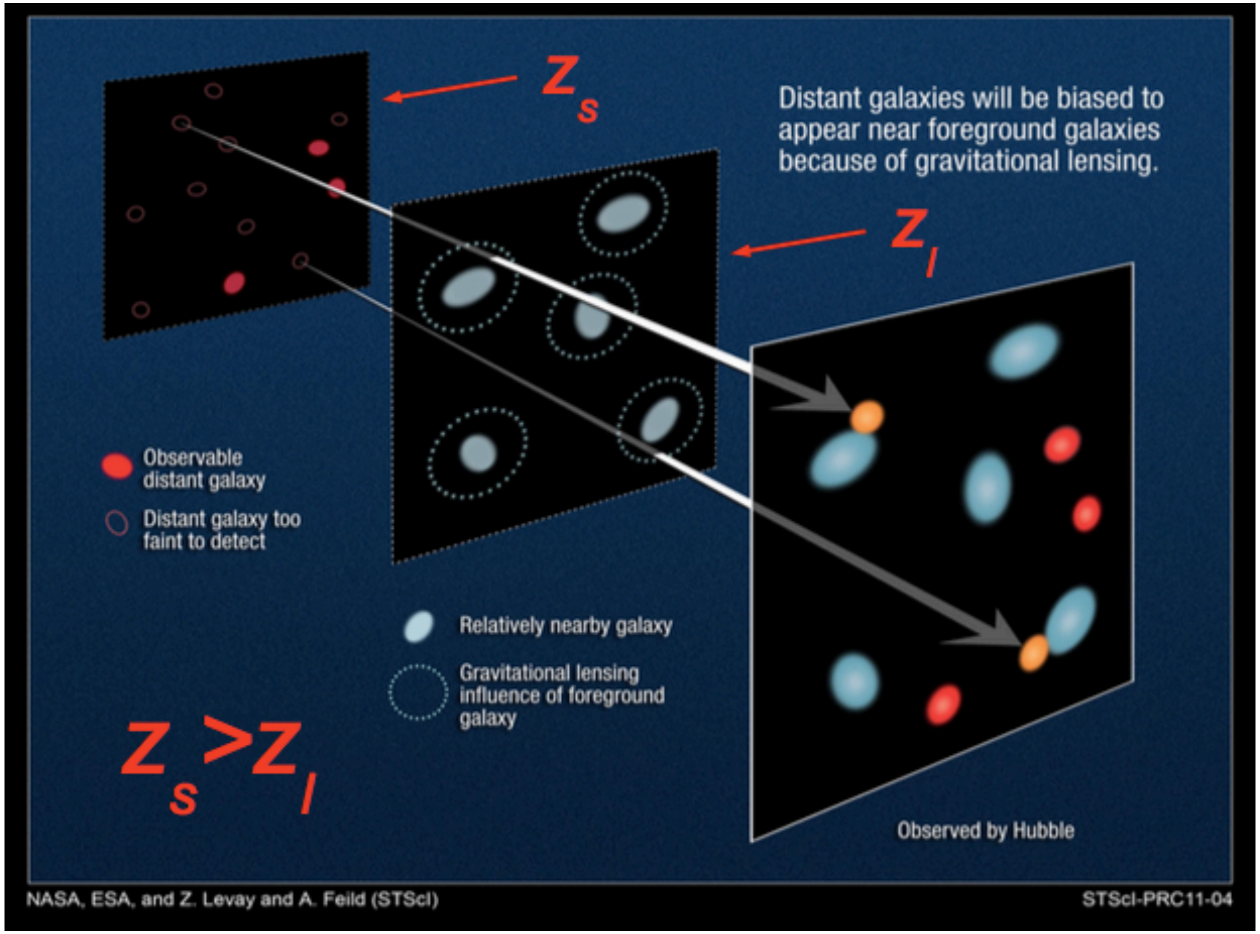
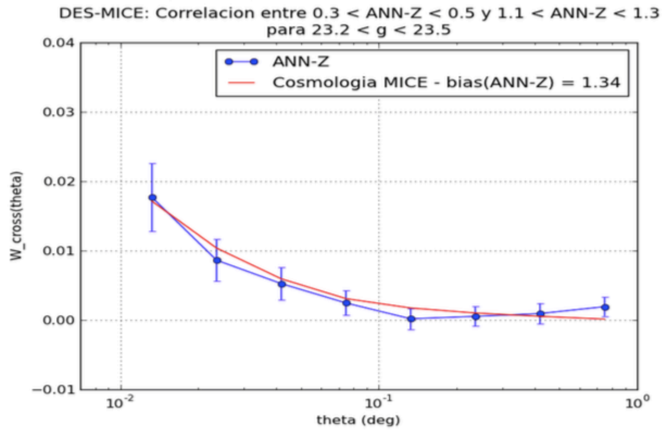




R.Ponce PhD 2015

Correlations of objects in two redshift bins, count appearing and disappearing objects.

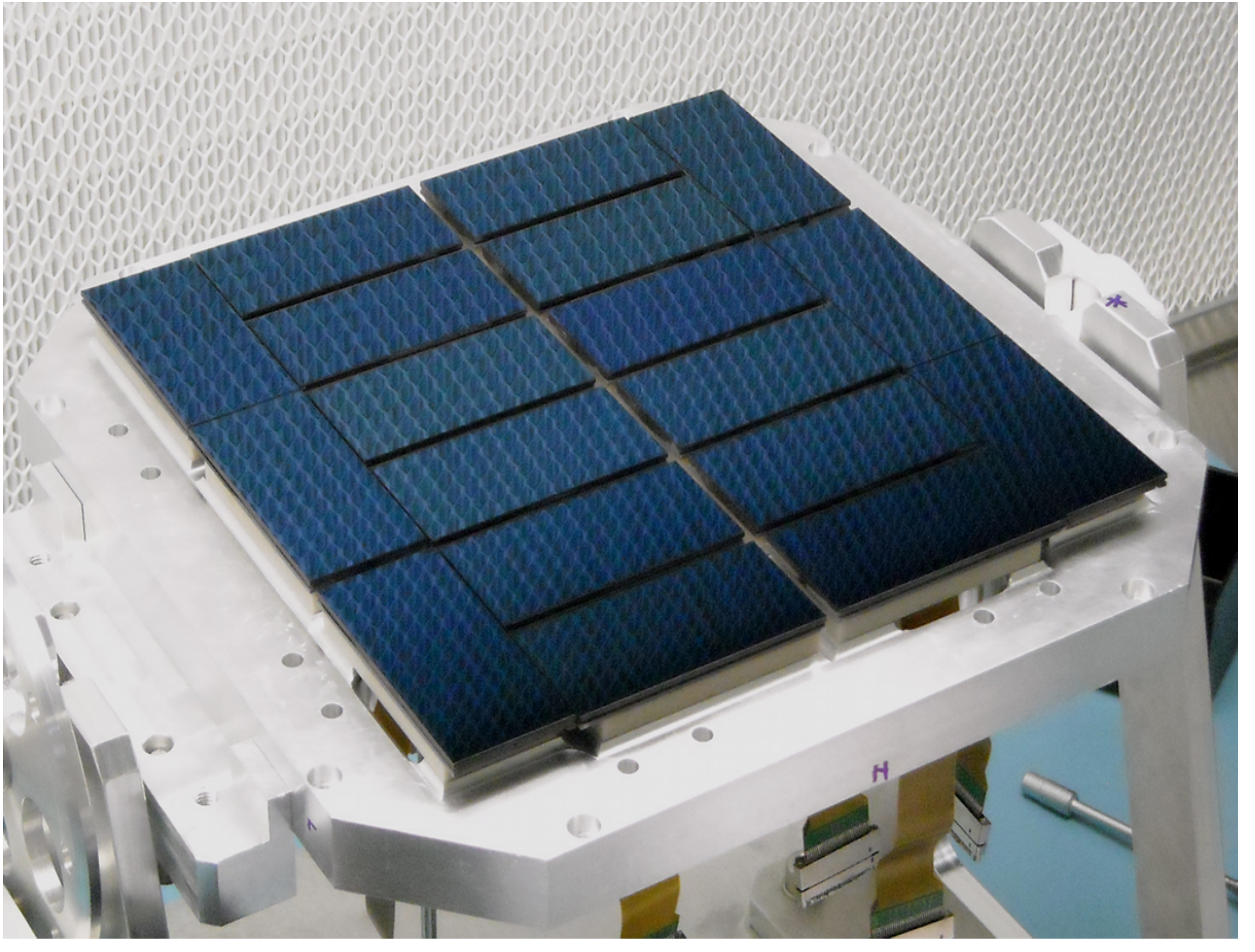
And there is where PAUCam comes in!

PI : E. Fernández (UAB/IFAE)
Co-Is: E. Sánchez (CIEMAT), E. Gaztañaga(IEEC/CSIC), R. Miquel (IFAE), J. García-Bellido (IFT/UAM), M. Delfino (PIC)

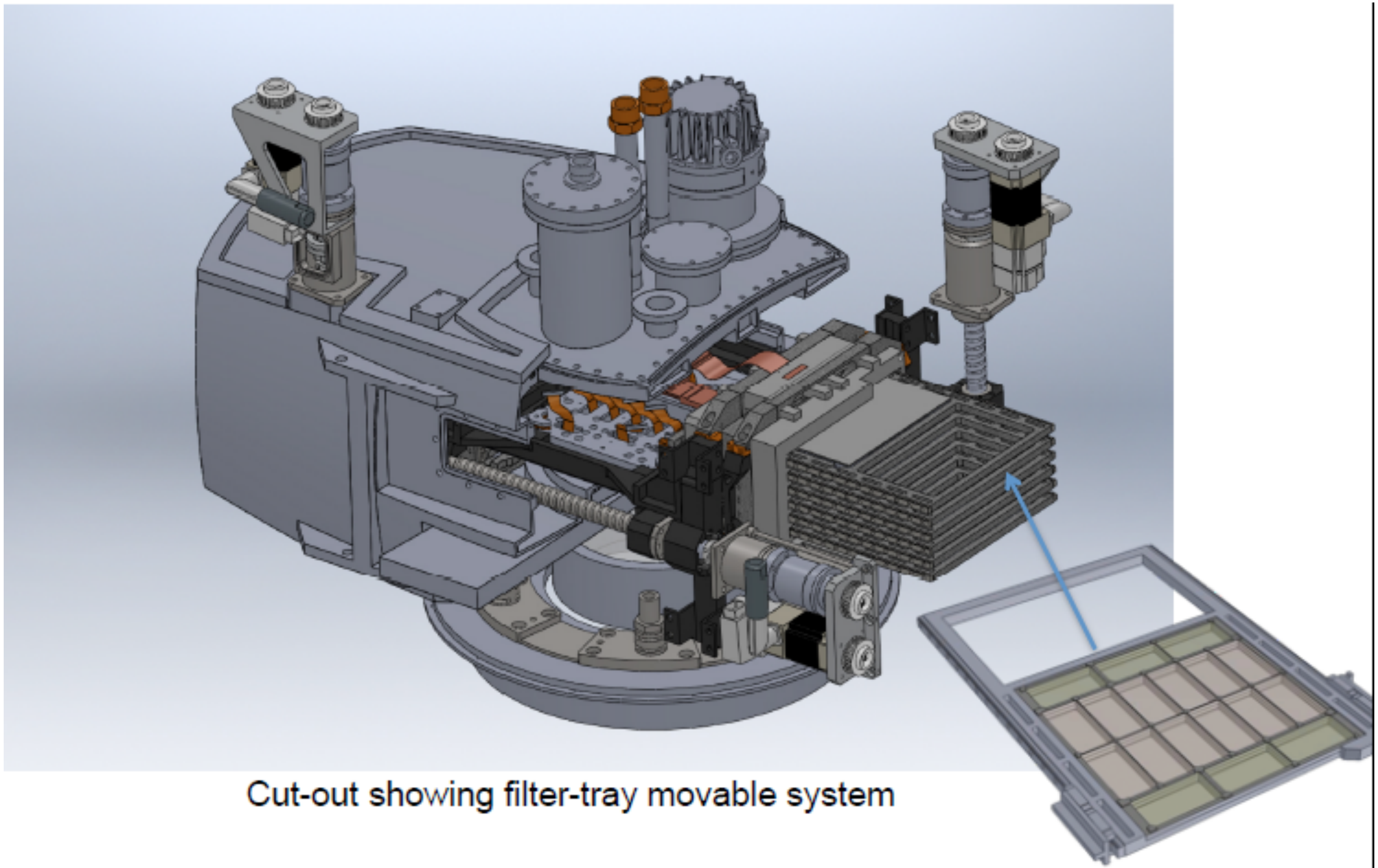
PAUCam PI: F. J. Castander
Project Manager: C. Padilla; System Engineer: L. Cardiel; DAQ: J. de Vicente; Mechanics: F. Grañena; Control: O. Ballester; Optics and integration: R. Casas, J. Jiménez.

PAUDM & Science PI: E. Gaztañaga
Simulations: F.J. Castander; Operation: N. Tonello; Data Reduction: S. Serrano; QA&Validation: I. Sevilla.

PAUCam focal plane



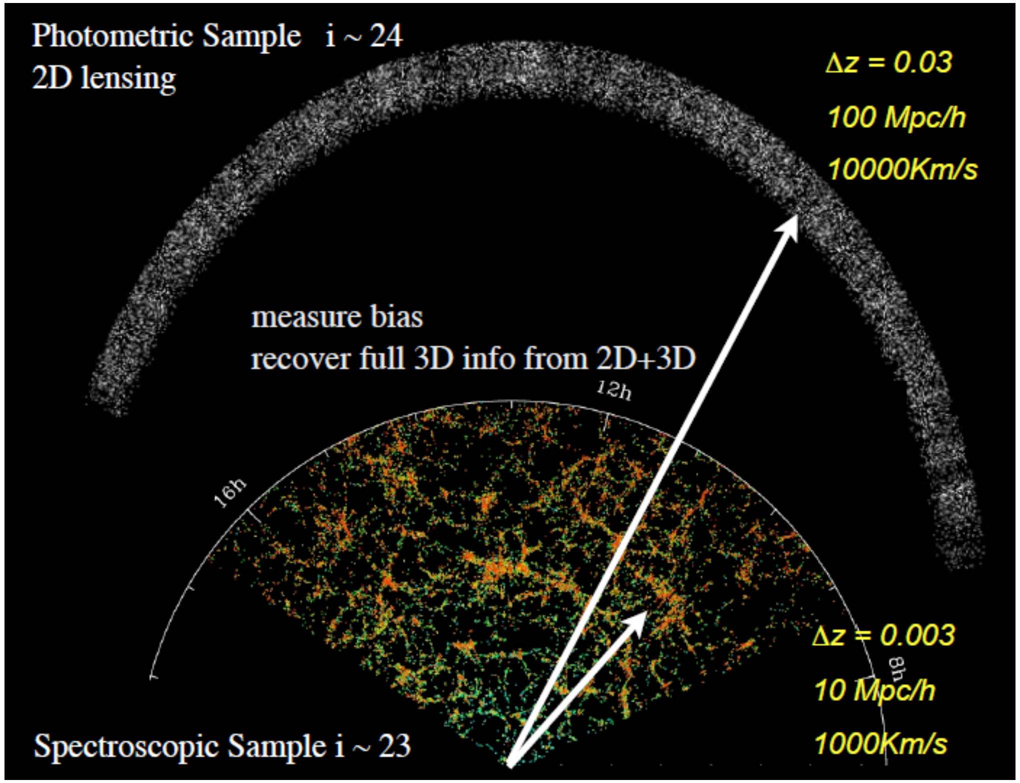
PAUCam filter tray



Cut-out showing filter-tray movable system

F.J.Castander et al. 2014

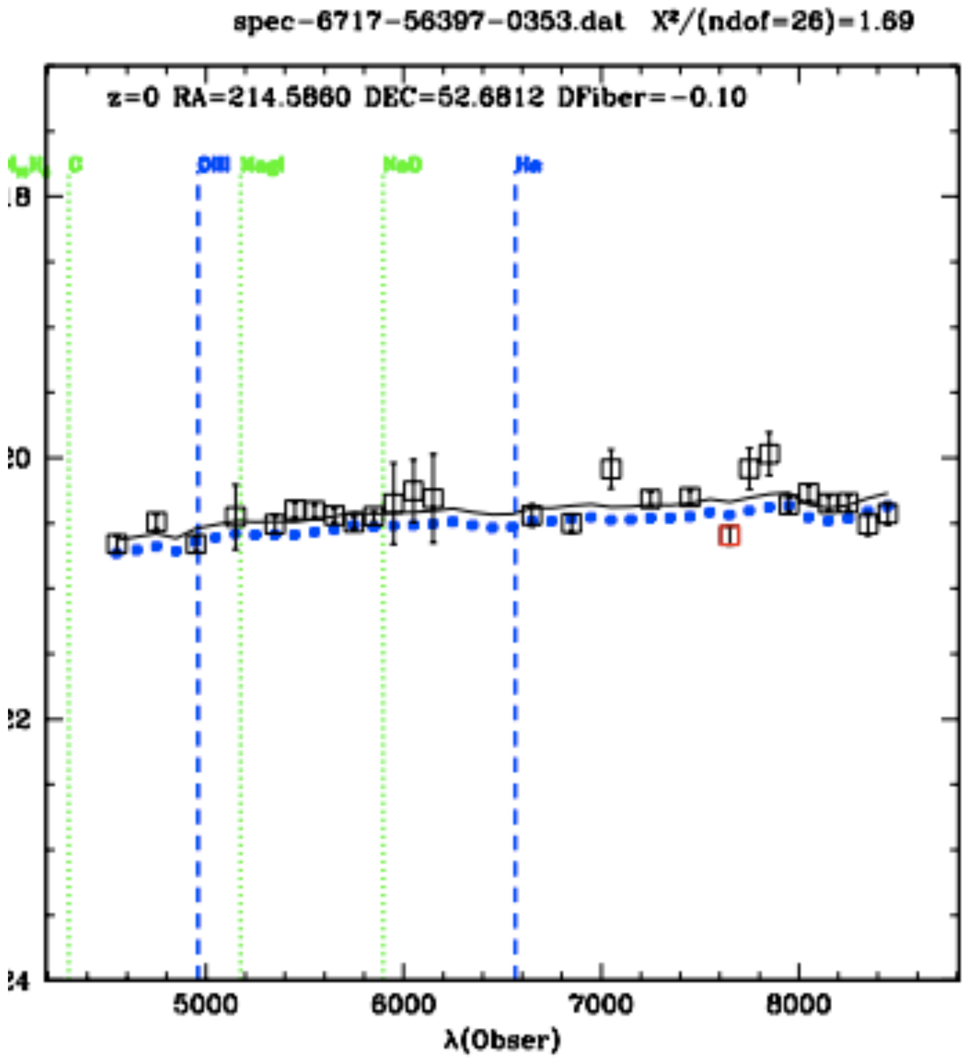
The PAU Survey will combine both probes for extra efficiency



Using a faint sample 22.5 < i <24
Using a bright sample i < 22.5
100 square degrees (2015-~2018)

Combination of RSD and WL in the same dataset:
→ powerful in breaking degeneracies between galaxy bias and growth of structure
→ a unique advantage of PAU.
Systematics beating: understand intrinsic alignments of galaxies (→ Euclid)
Systematics beating: photo-z calibration (→ Euclid)

The PAU Survey is happening now



- PAUCam builders + ETH + Durham University + Leiden Observatory
- ~10 nights of data (including commissioning)
- Several ~tens of nights expected in the next 2-3 years.

The Dark Energy Survey is …

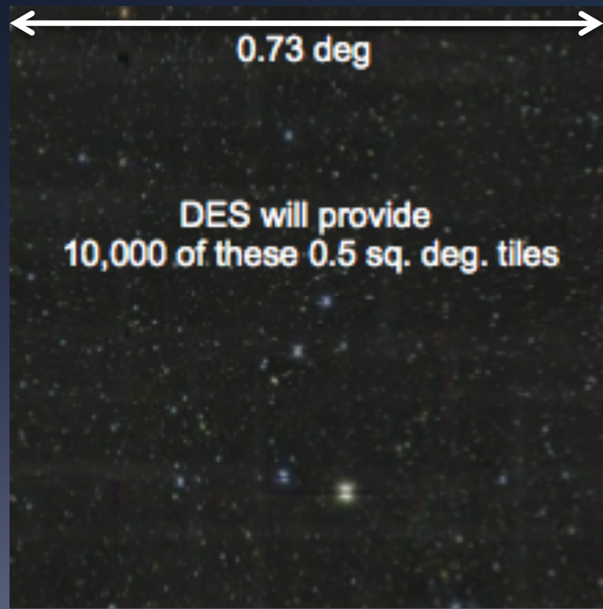
… a 1” resolution map of 1/8 of the southern sky

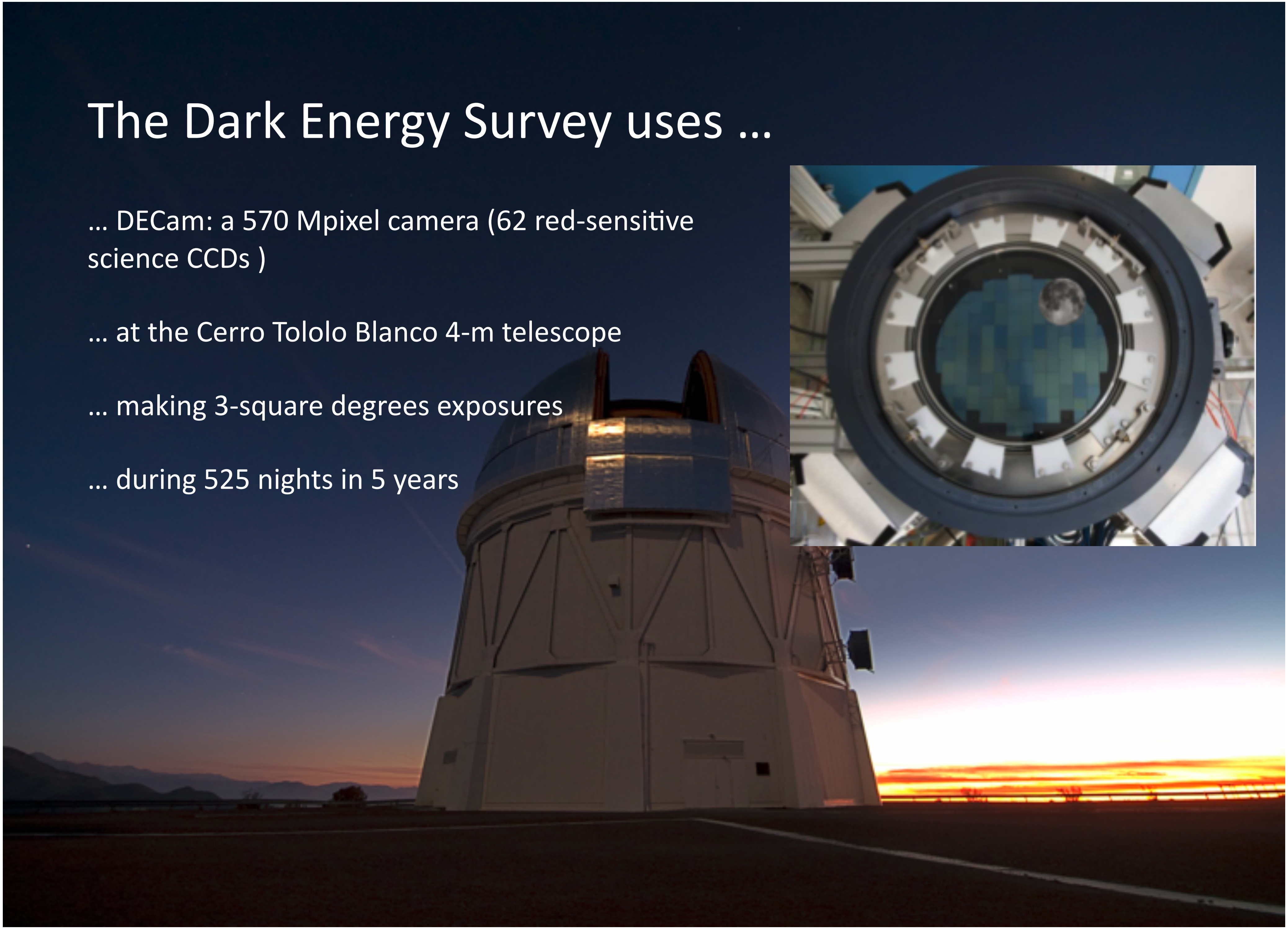
… up to depths of i_AB = 24

… in 5 photometric bands (g, r ,i , z , Y)

… to explore dark energy using four probes:

- Cluster counts
- Large Scale Structure (BAOs)
- Supernovae
- Weak Lensing





The Dark Energy Survey uses …

… DECam: a 570 Mpixel camera (62 red-sensitive science CCDs)

… at the Cerro Tololo Blanco 4-m telescope

… making 3-square degrees exposures

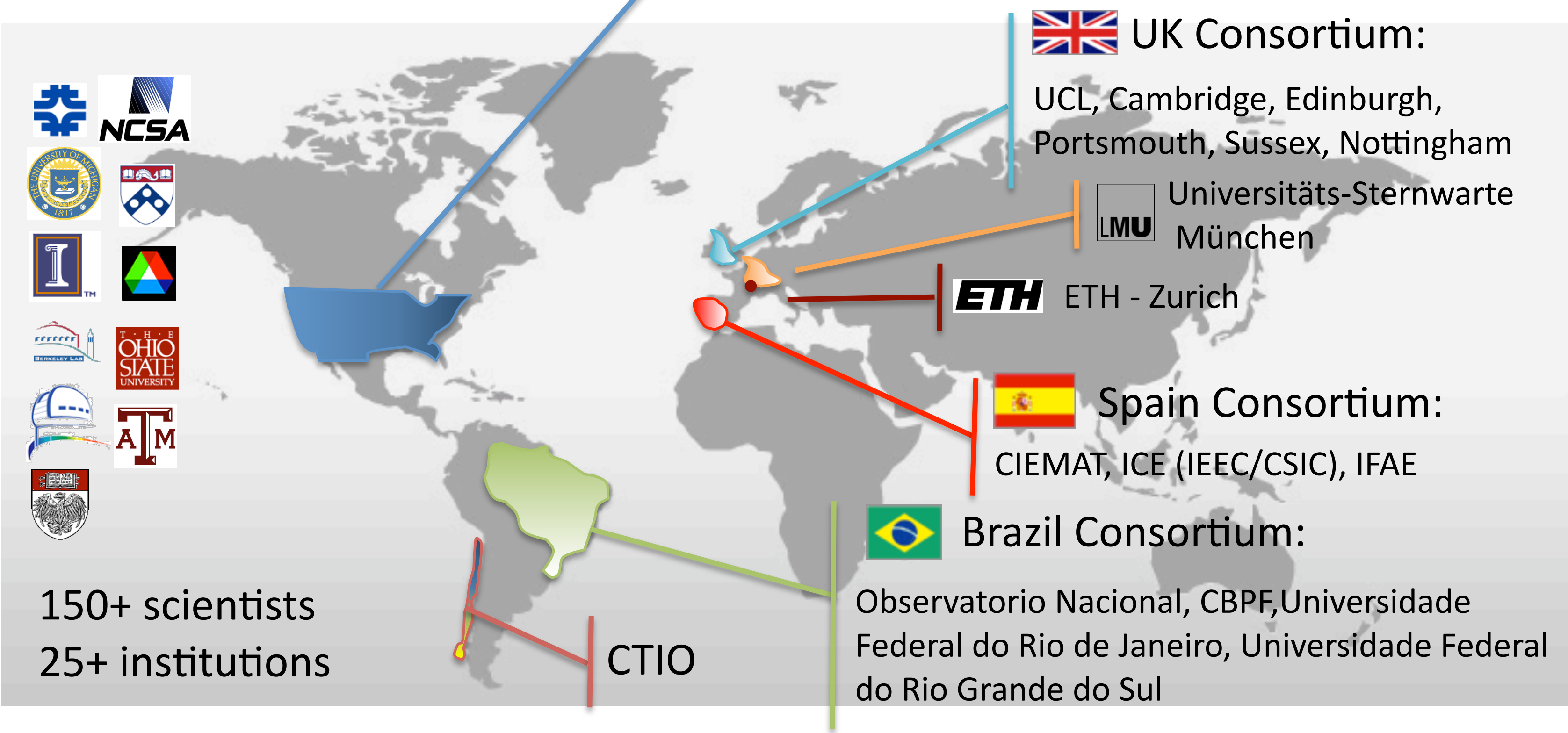
… during 525 nights in 5 years

The mandatory collaboration slide

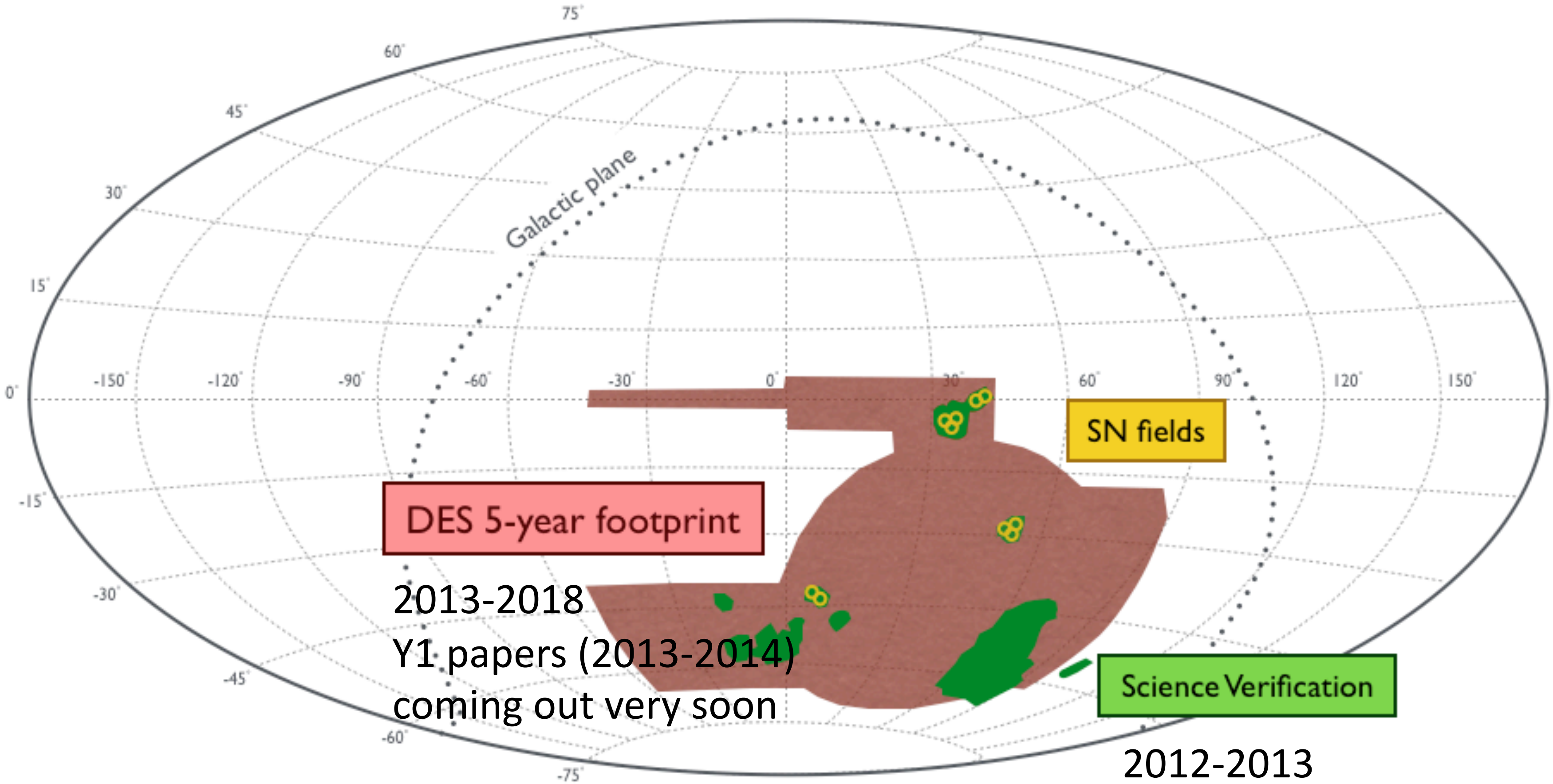
Dark Energy Survey

… is an international project to measure the dark energy equation of state (nature). This effort is led by Joshua Frieman (Fermilab).

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa-Cruz/SLAC/Stanford Consortium, Texas A&M University



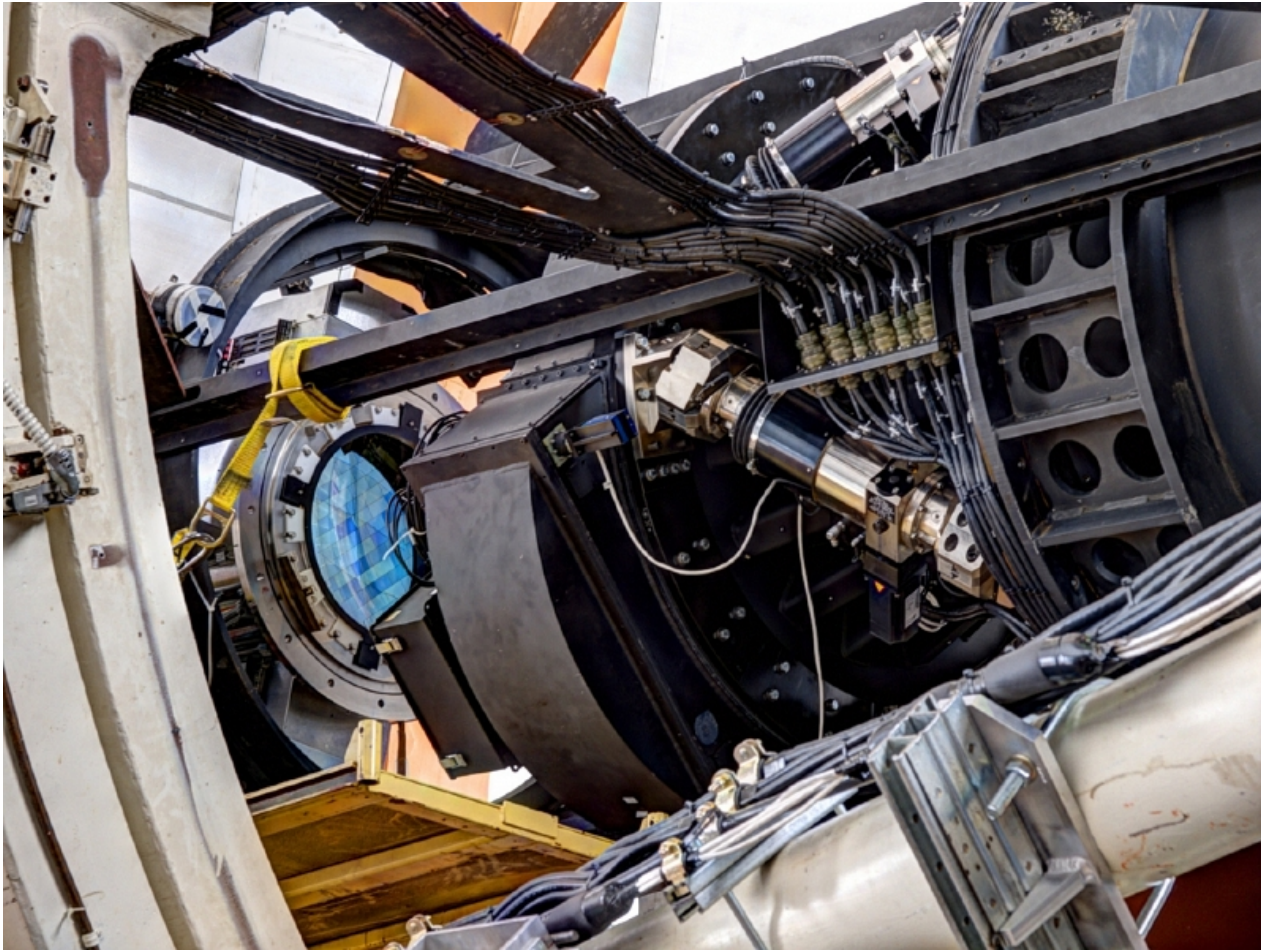
The largest volume in the Universe surveyed to date



2013-2018
Y1 papers (2013-2014)
coming out very soon

2012-2013
Papers and catalogs out
1st cosmology results


© JFS • JOSEFRANCISCO.ORG



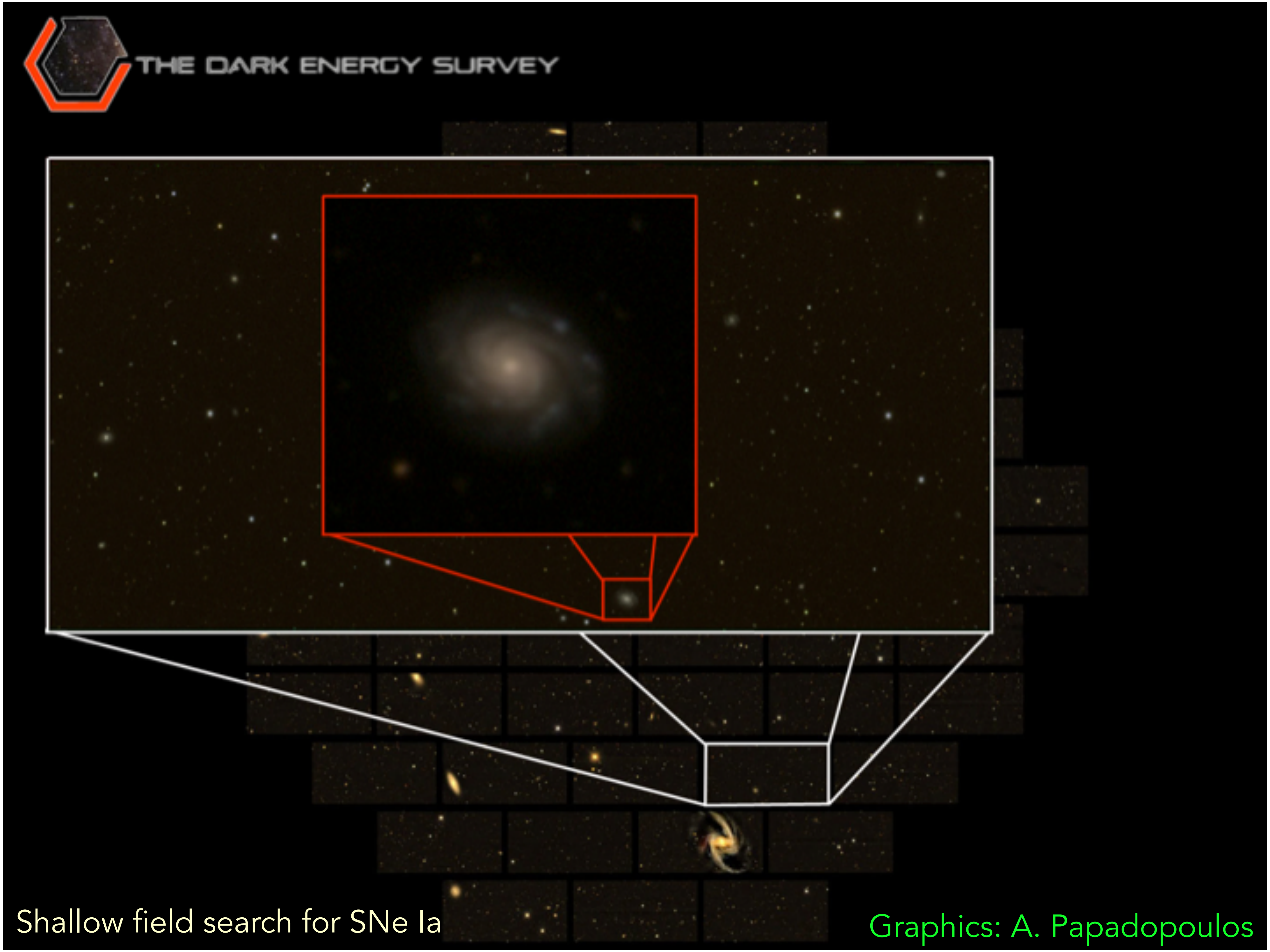
THE DARK ENERGY SURVEY

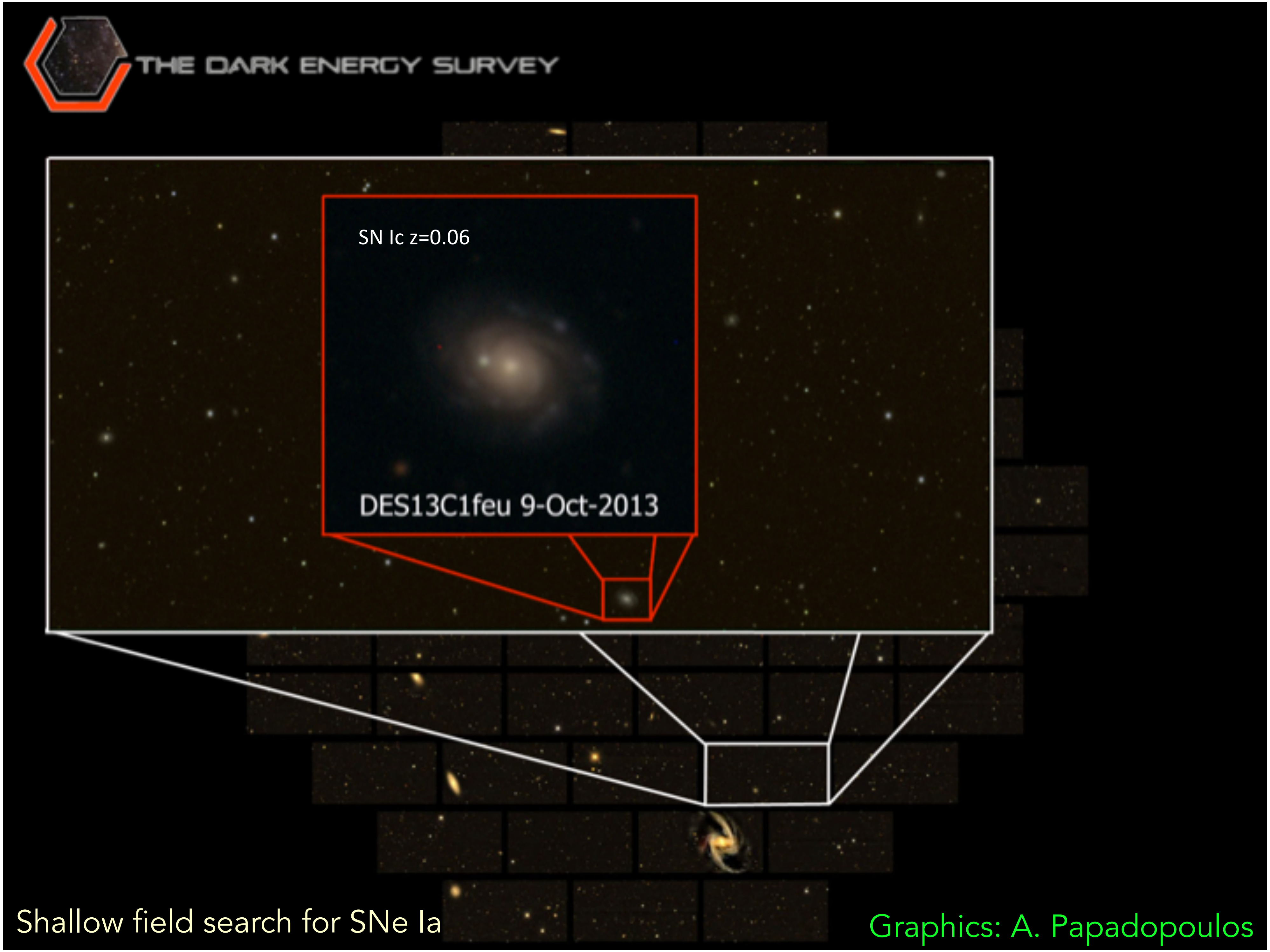
Shallow field search for SNe Ia

Graphics: A. Papadopoulos

Shallow field search for SNe Ia

Graphics: A. Papadopoulos


THE DARK ENERGY SURVEY
Shallow field search for SNe Ia
Graphics: A. Papadopoulos


THE DARK ENERGY SURVEY
SN Ic z=0.06
DES13C1feu 9-Oct-2013
Shallow field search for SNe Ia
Graphics: A. Papadopoulos

Clusters in Science Verification

SPT-CL J2332-5358

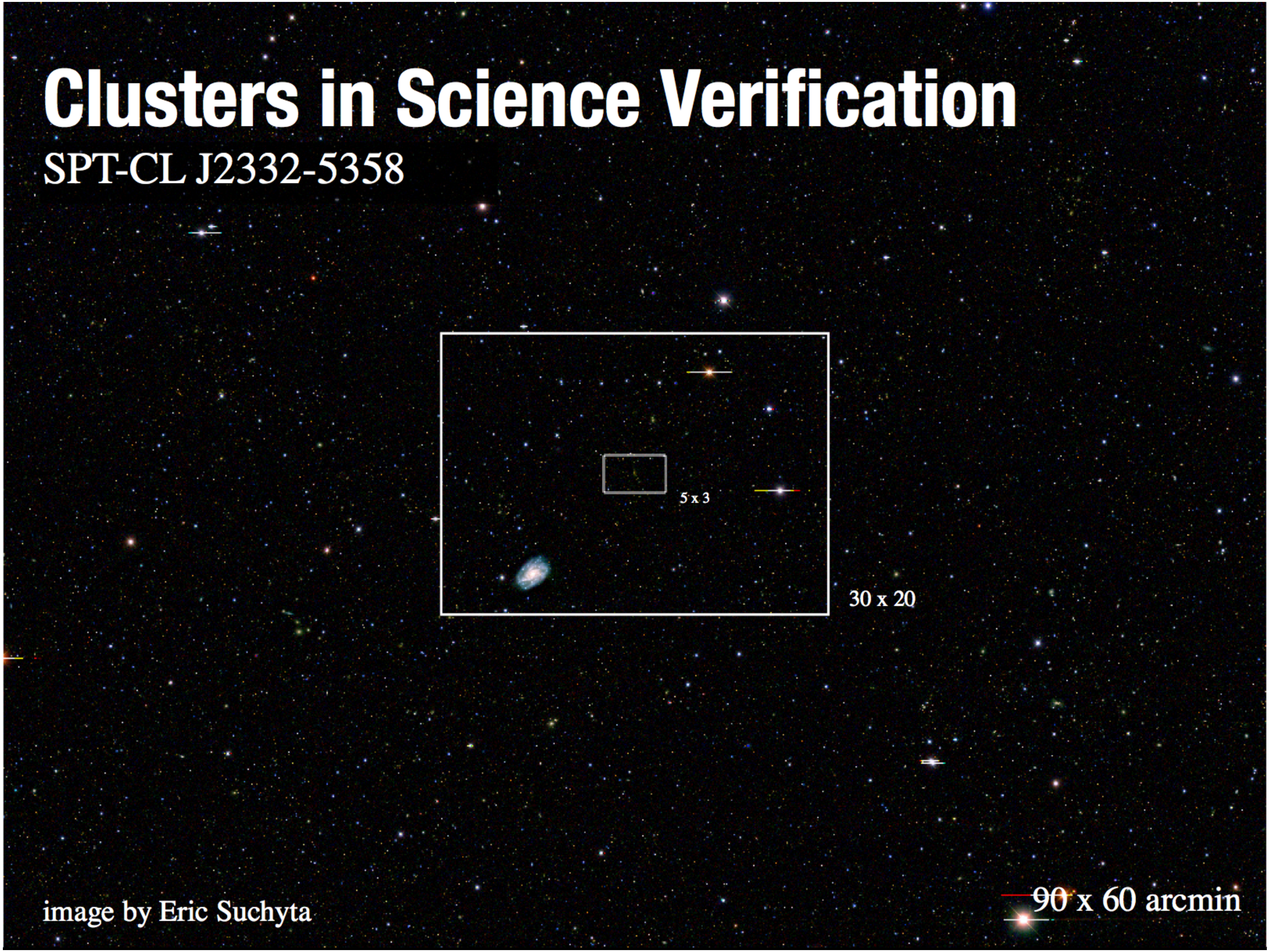
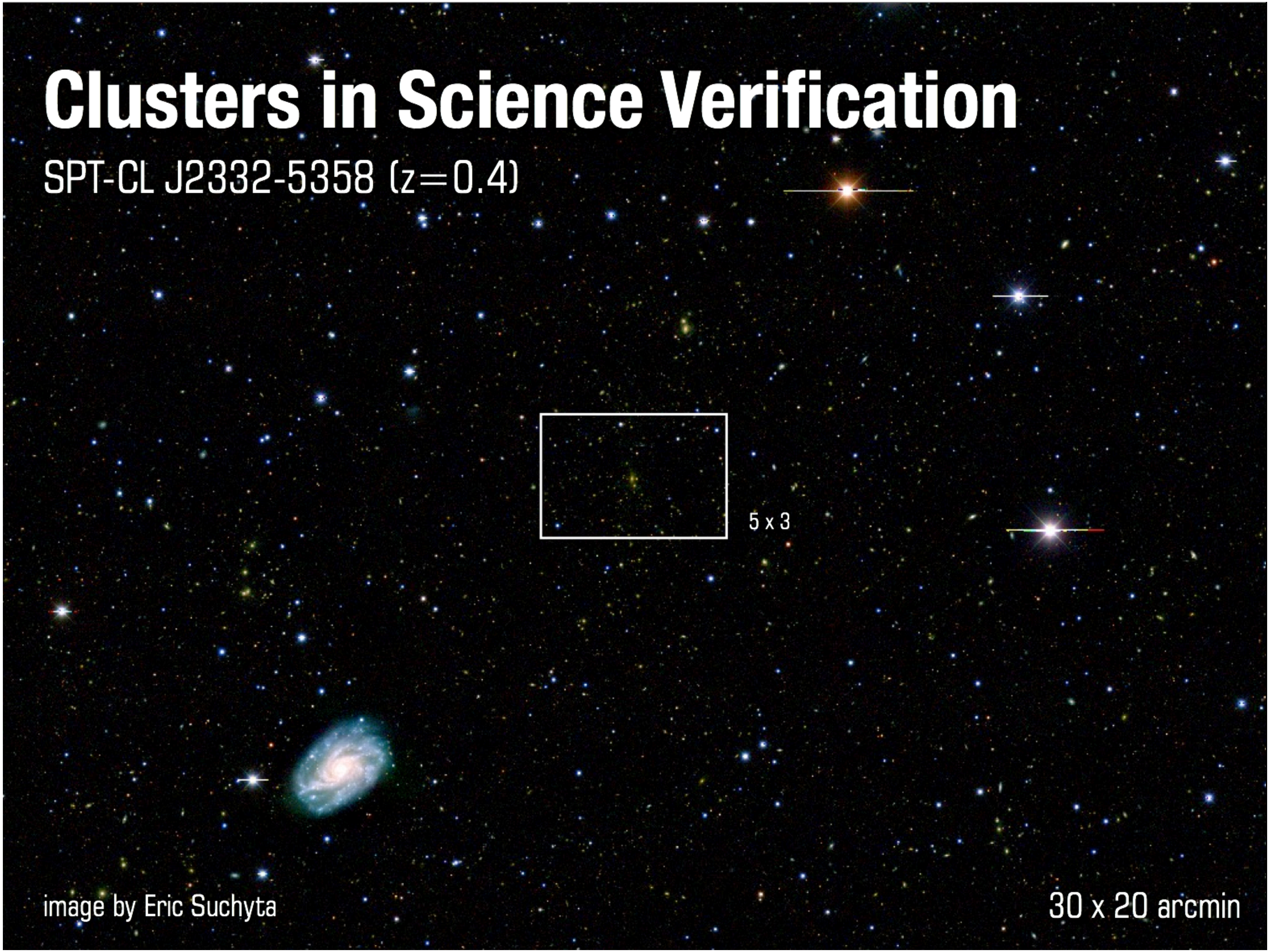


image by Eric Suchyta

Clusters in Science Verification

SPT-CL J2332-5358 (z=0.4)



Clusters in Science Verification

More than 50 papers have been submitted already with DES data

- Produced the largest contiguous mass map of the Universe;
- Discovered 17 new Milky Way companions (with implications for DM signal searches, no significant gamma ray signal detected);
- Measured scores of supernovae, weak lensing, galaxy clustering, correlations with the CMB in the small Science Verification area (5% of total);
- High redshift QSOs and super-luminous supernovae;
- Follow-up of gravitational wave signals.

A ΛCDM model fits the CMB data very well

	Planck TT+lowP+lensing	*Planck* TT+lowP+lensing+ext
$\Omega_{\mathrm{b}}h^2$	0.02226 ± 0.00023	0.02227 ± 0.00020
$\Omega_{\mathrm{c}}h^2$	0.1186 ± 0.0020	0.1184 ± 0.0012
$100\,\theta_{\mathrm{MC}}$	1.0410 ± 0.0005	1.0411 ± 0.0004
n_{s}	0.968 ± 0.006	0.968 ± 0.004
τ	0.066 ± 0.016	0.067 ± 0.013
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.062 ± 0.029	3.064 ± 0.024
h	0.678 ± 0.009	0.679 ± 0.006
σ_8	0.815 ± 0.009	0.815 ± 0.009
Ω_{m}	0.308 ± 0.012	0.306 ± 0.007
Ω_{Λ}	0.692 ± 0.012	0.694 ± 0.007

Planck Collaboration XIII (2015)

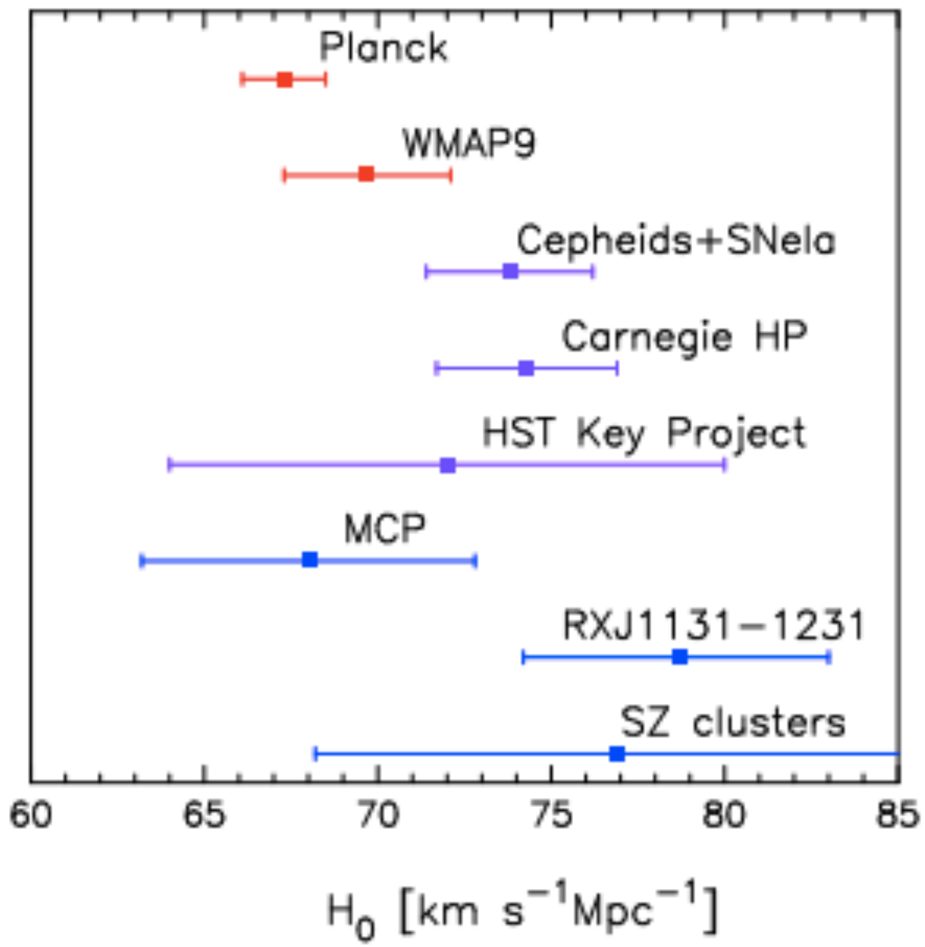
The Hubble constant shows some discrepancy between CMB and direct measurements

- Measure angle; calculate rs

$$D_A = \frac{r_s}{\theta_s} \qquad D_A = \frac{1}{1+z^*}\int_0^{z^*}\frac{dz}{H(z)}$$

- 1) Direct distance measurements to Cepheids; 2) Use calibrated Cepheids to determine luminosity of supernovae in galaxies containing them.

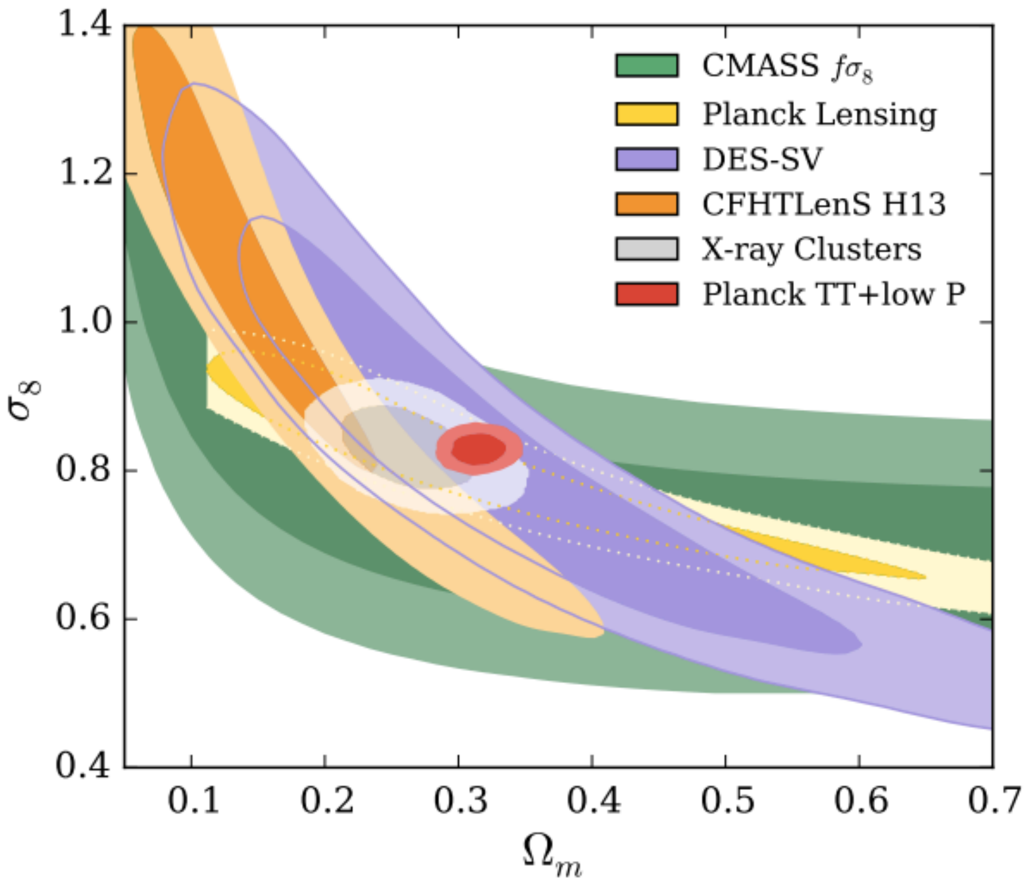
- Direct impact in allowed dark energy models!



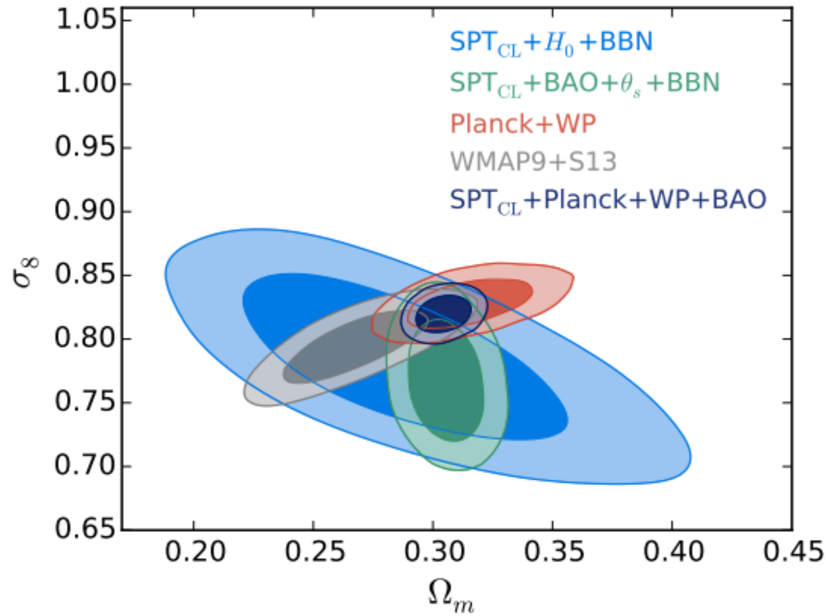
Planck Collaboration XVI (2014)

Direct vs indirect H0…

Matter fluctuations from cluster measurements and weak lensing in broad agreement/slight disagreement



The Dark Energy Survey Collaboration (2015)



de Haan et al. (2016)

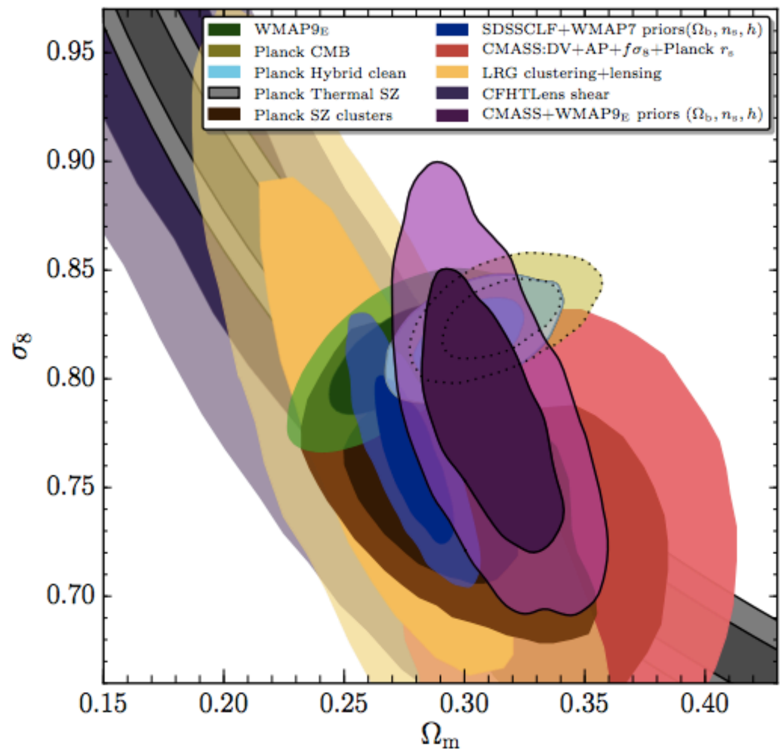
σ_8= RMS fluctuation of matter for spheres of a certain size

Weak lensing and cluster counts vs CMB…

Matter fluctuations from cluster measurements and weak lensing in broad agreement/slight disagreement

A month too soon…

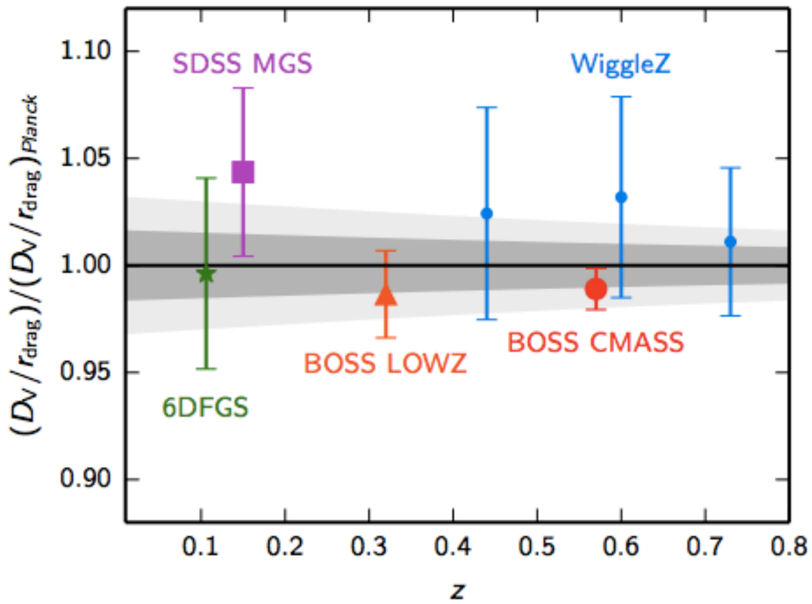
DES clustering + lensing results to be released in the coming weeks

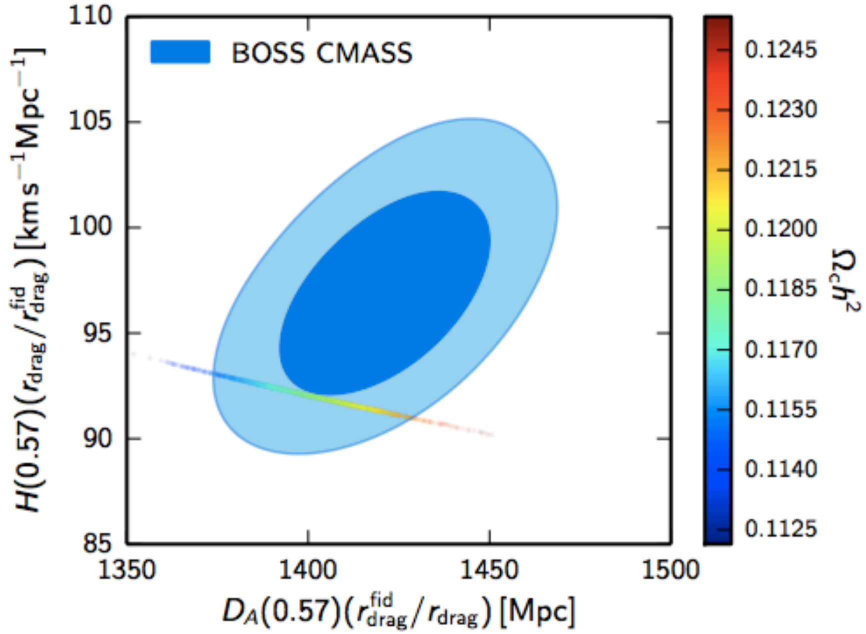


S. More et al. (2015)

Combining weak lensing and large scale structure in the same analysis…

There is agreement at low redshift between BAO and CMB measurements.



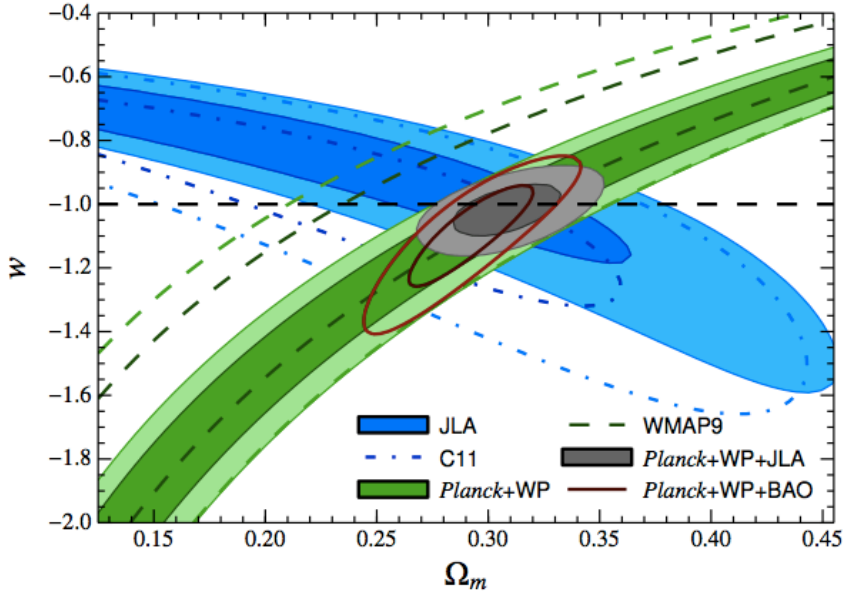


Planck Collaboration XIII (2015)

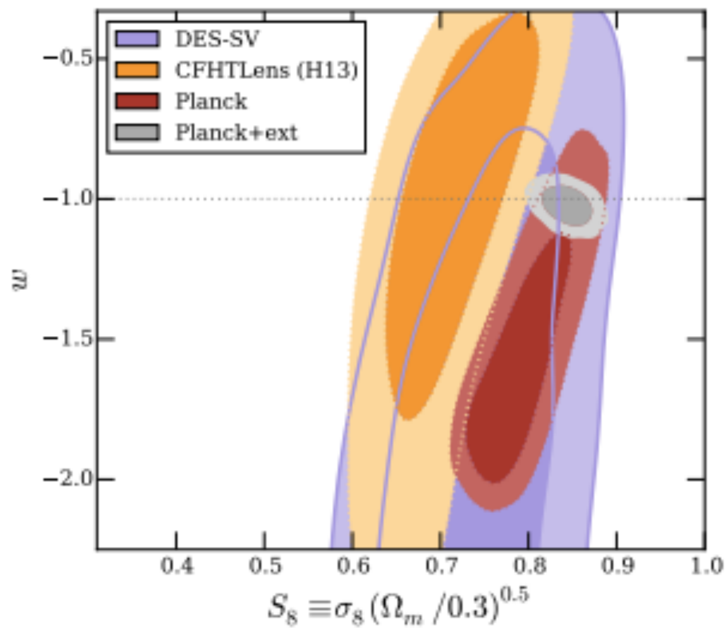
However, ~3σ discrepancy with higher redshift BAO measurements from Ly-α forest.
Other geometric probes (SN) in agreement too.

Geometric distances BAO vs CMB…

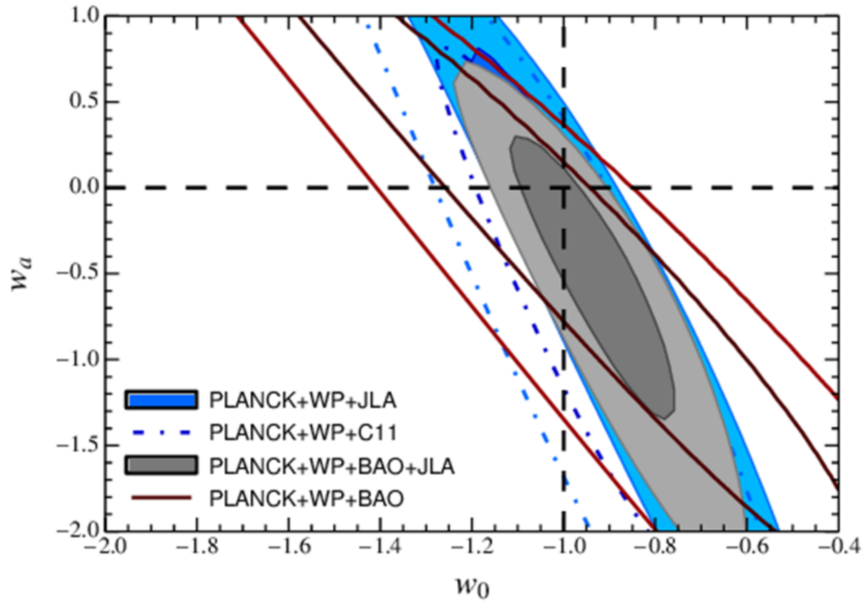
Possible evolution of *w* is largely unconstrained



M. Betoule et al. 2014



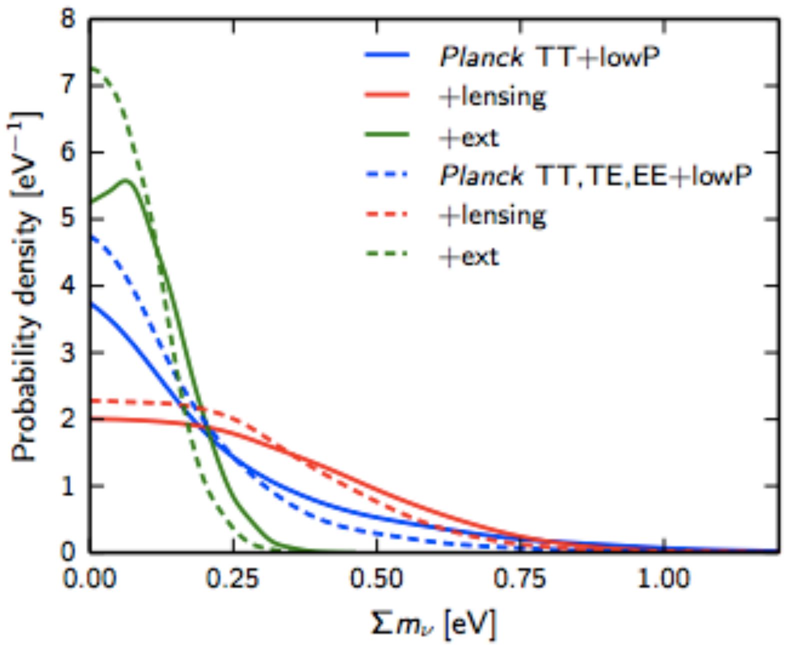
The Dark Energy Survey Collaboration (2015)



$$w(a) = w_0 + (1 - a)w_a$$

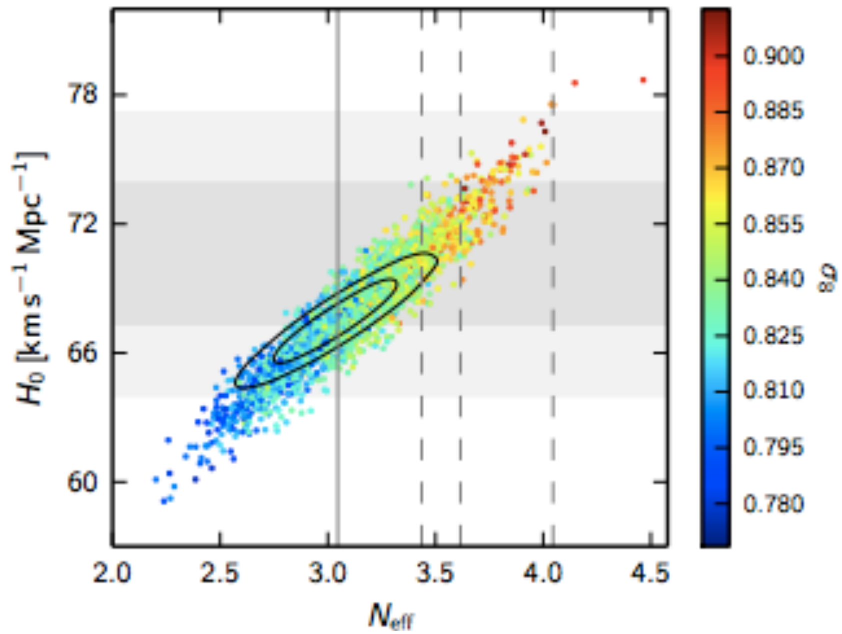
A fixed w is close to -1, w(a) is undetermined.

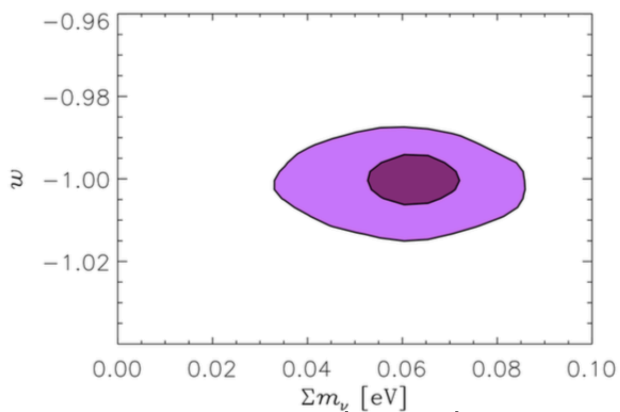
Cosmology is starting to put some strong constraints in the neutrino sector too



$$\sum m_\nu < 0.17 \text{ eV}$$ (95%) including BAO

Planck Collaboration XIII (2015)

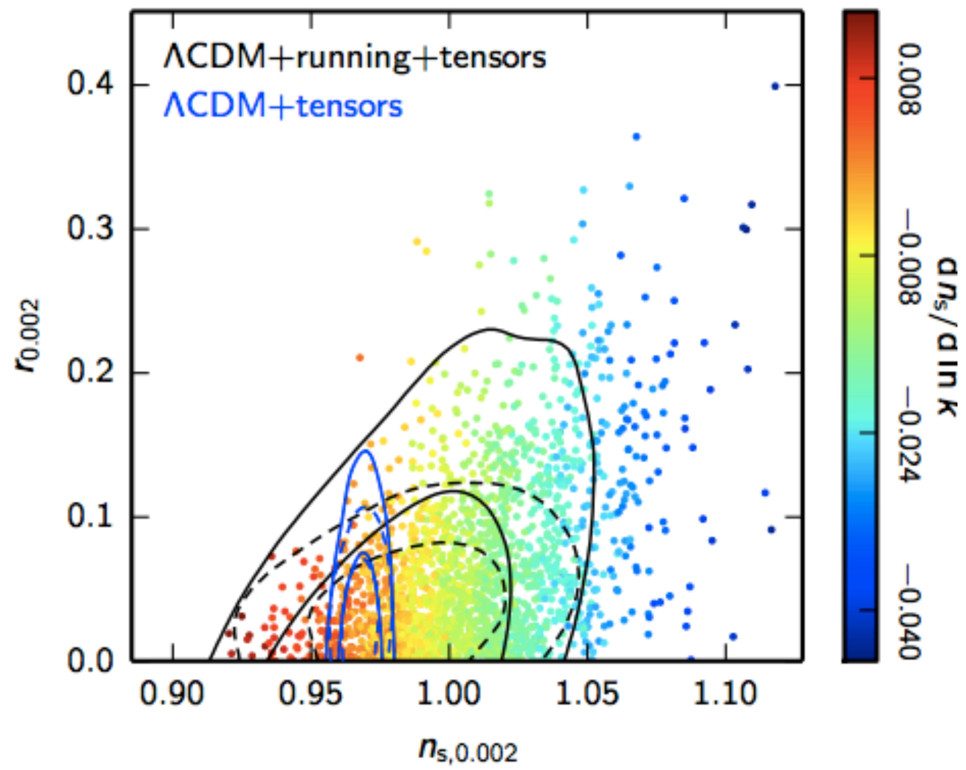




Hannestad (2014)

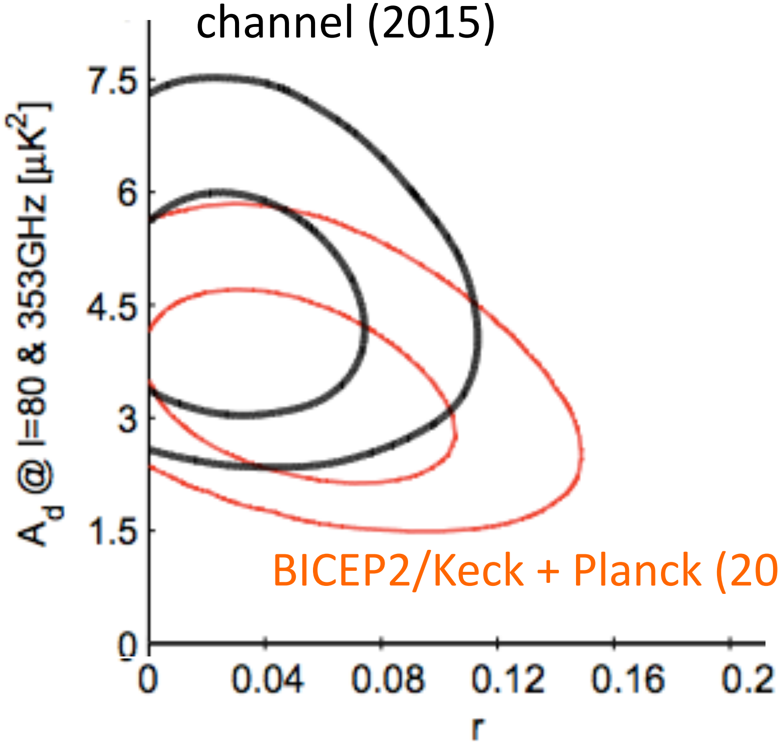
Planck + Euclid
±0.02 eV error!

No measurement of tensor component or running of the scalar index in CMB yet



Planck Collaboration XIII (2015)

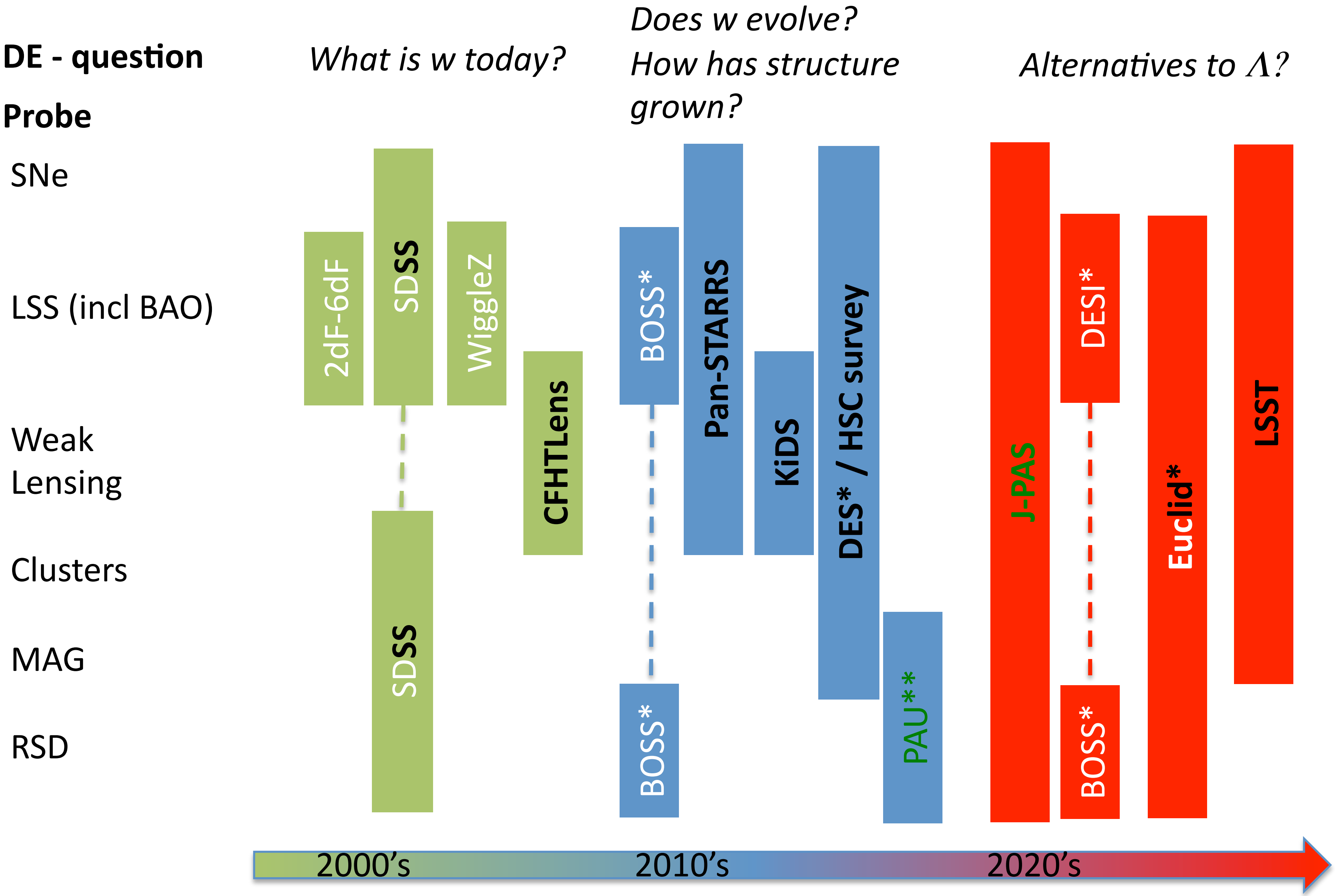
BICEP2/Keck update w/95 GHz channel (2015)



BICEP2/Keck + Planck (2015)

$r_{0.05}$ < 0.07 (95%CL) using all datasets

Galaxy Survey (very partial) Landscape



Disclaimer: CMB projects not included. Not exhaustive.

* Contribution from Spanish Institutions.

** PAU is integrally funded by Spain

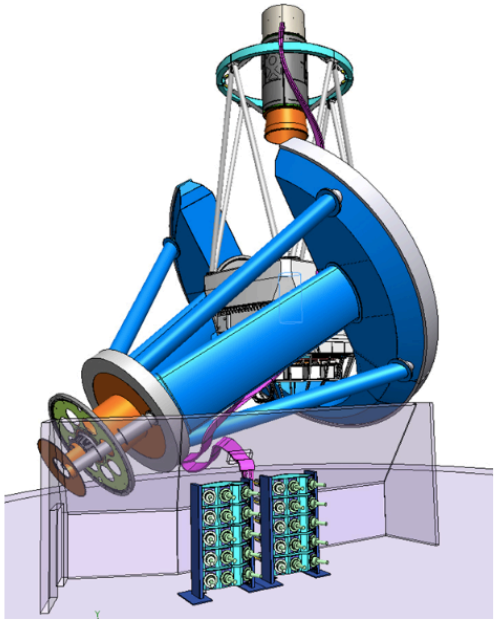
Black: photometric

White: spectroscopic

Green: spectro-photometric

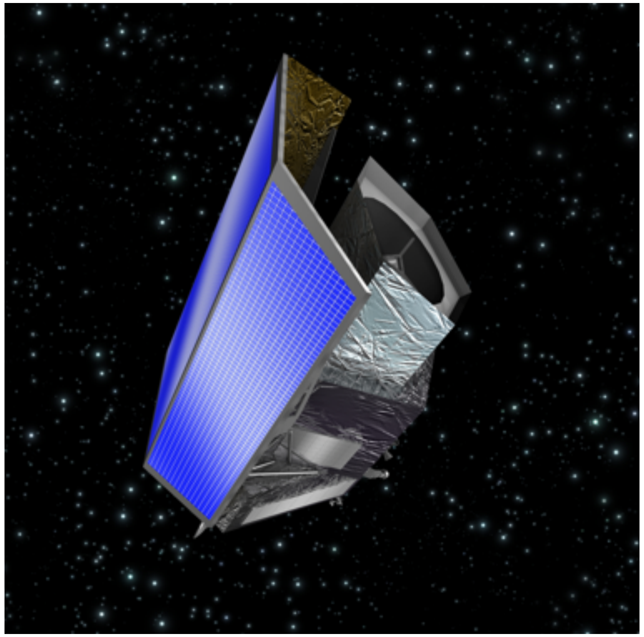
Several projects to provide definitive observations in optical/IR wavelengths

DESI (2019+)



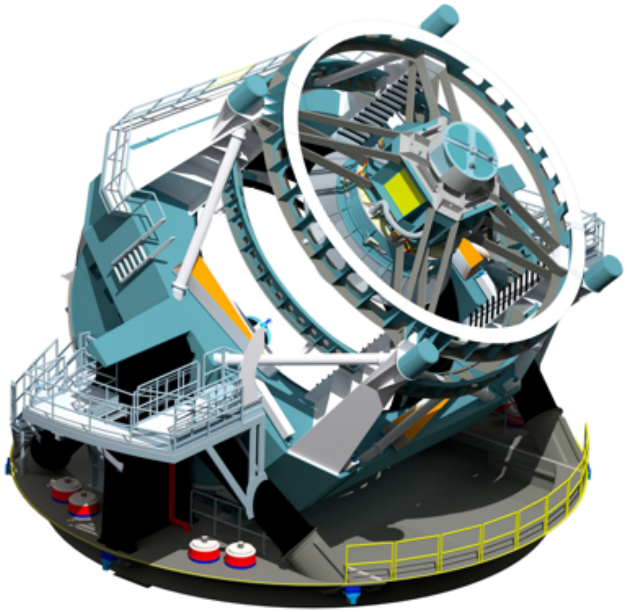
- Deep spectroscopic survey.
- Definitive BAO measurement.

Euclid (2020+)



- Photometry and spectroscopy from space.
- Definitive weak lensing measurement.

LSST (2022+)



- Billions of galaxies
- Hundreds of thousands of SNe
- Whole sky every 3 days

Several projects to look at polarization from ground in the short term

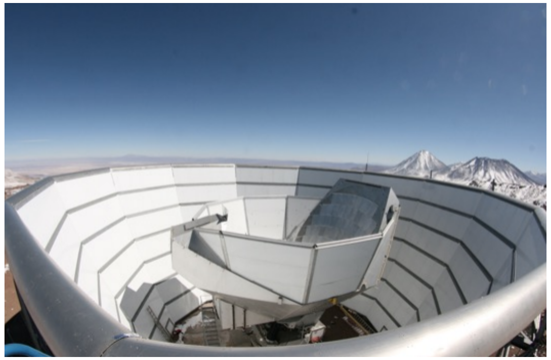
BICEP 3 + Keck

- Very fast data-taking.
- New measurements at 95 Ghz with higher angular resolution.

QUIJOTE

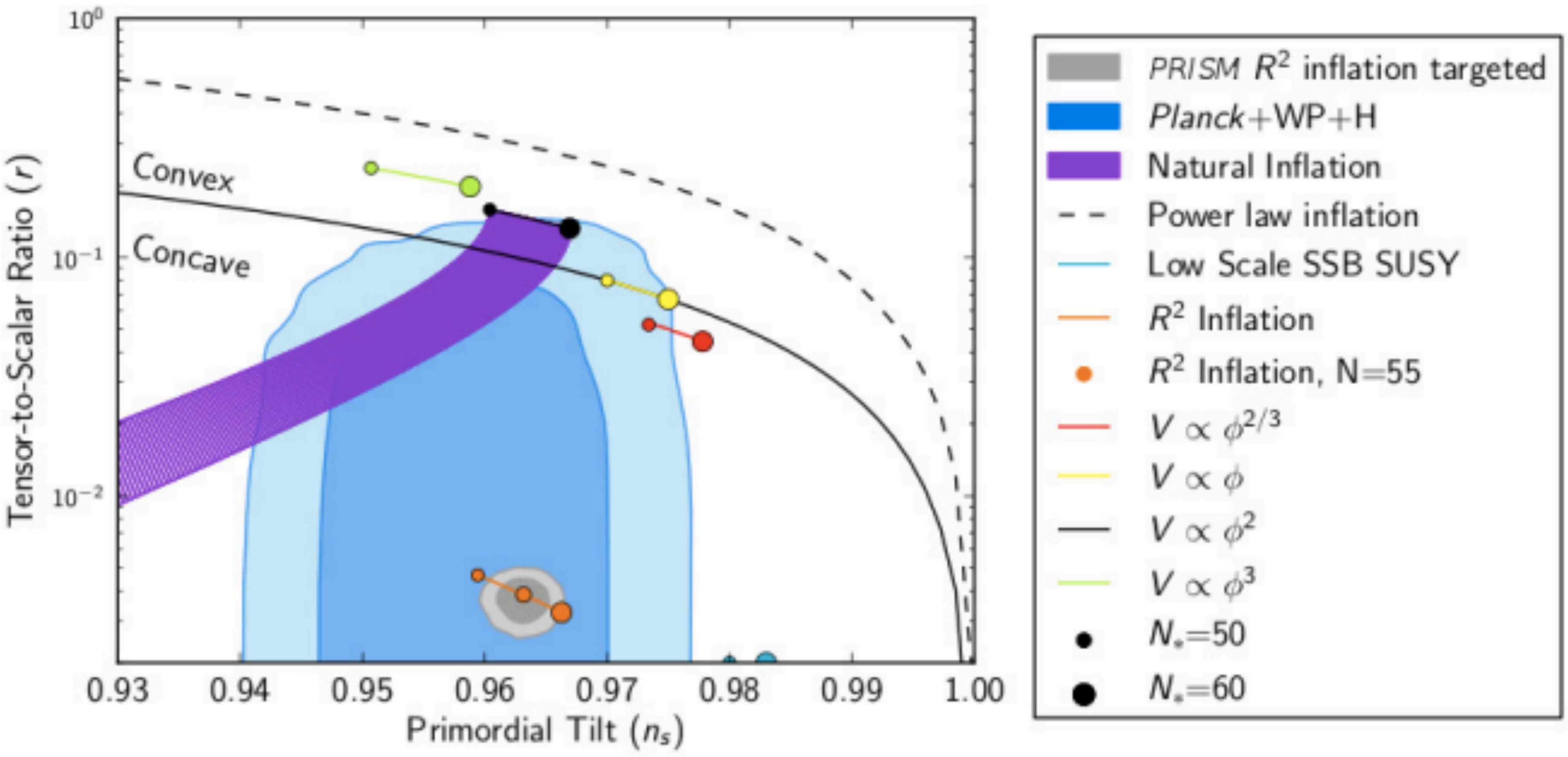
- Large survey.
- Unique low frequency range.

ACTPol



- Large survey.
- High angular resolution, will reach $\sigma(r) = 0.003$.

The PRISM mission could be the next big milestone for CMB cosmology



PRISM Collaboration White Paper (2013)

Final words

Next 10-15 years will see the maturity of **several techniques** (polarization, weak lensing).

Start **hammering down systematics** (we have to understand the astrophysics, not marginalize over them).

New windows: gravitational waves, neutrino astronomy, 21 cm

Definitive measurements in several channels (BAO, CMB temperature, galaxy clusters, planned for the **next 10-20 years**). Statistical limits.

ΛCDM in good shape but some annoying/exciting 2σ inconsistencies (CMB vs low redshift probes).

The quest for observational cosmology is to challenge the current paradigm

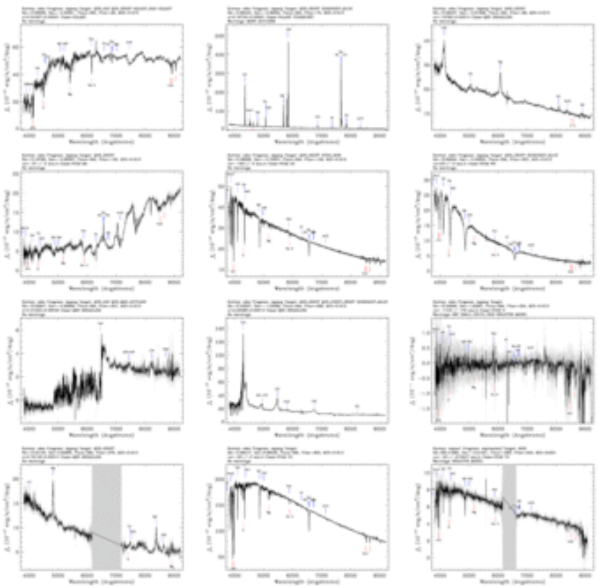
- Is the ΛCDM standard model the final word from the Universe?

…and other questions:

- ~~What is the description of the Universe?~~
- Are all measurements consistent?
- What is dark energy? ~~What is dark matter?~~
- What is total neutrino mass?
- What can we learn from inflation?

Extra balls

Observations are carried out through imaging or spectra



Type	Pros	Cons	Examples
Photometric	Statistics Weak Lensing	$\sigma(z) \sim 10$ % Galaxy type	DES, LSST
Spectroscopic	$\sigma(z) \sim 0.01$ % RSD	Lower statistics Selection bias	BOSS,DESI
Spectro-phot	Statistics, $\sigma(z) \sim 0.35$ %		PAU, J-PAS

Cluster density

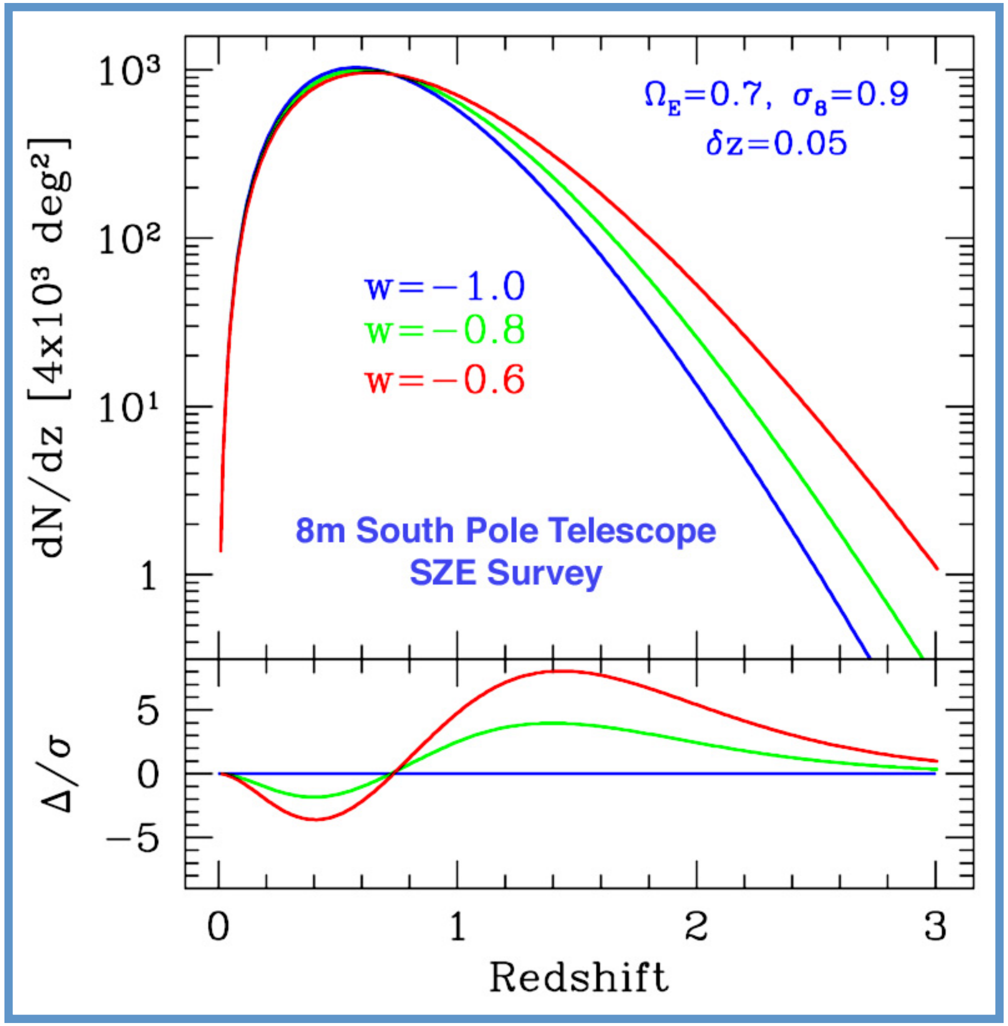
Strategy: structure probe

• Obtain number count of galaxy clusters per unit volume.
• counts + cluster mass + redshift:

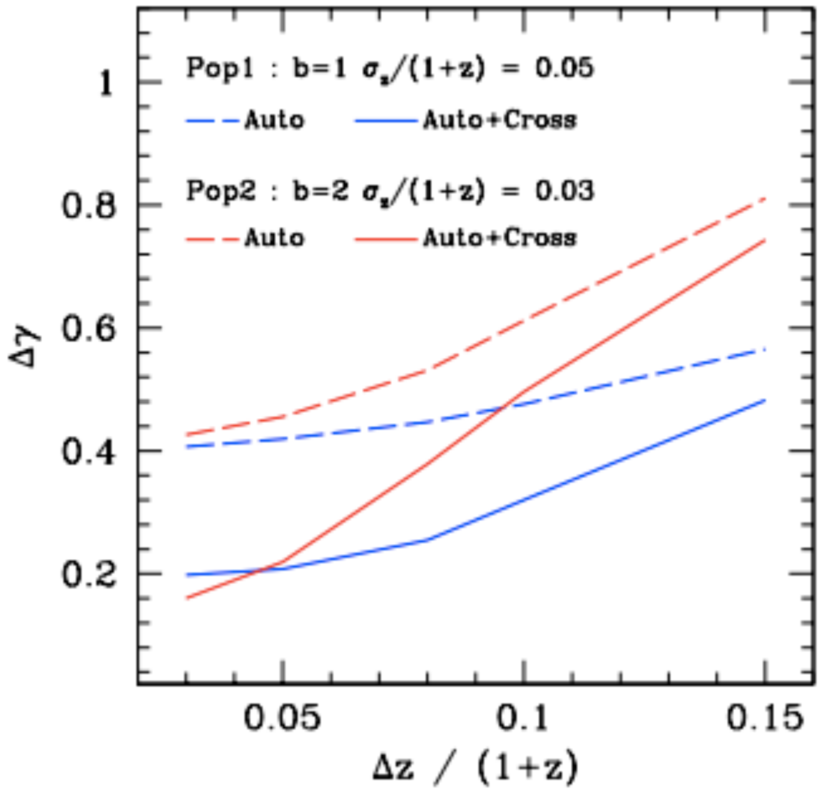
$$\frac{d^2N}{dz d\Omega} = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_0^\infty f(M,z) \frac{dn}{dM}(z) dM$$

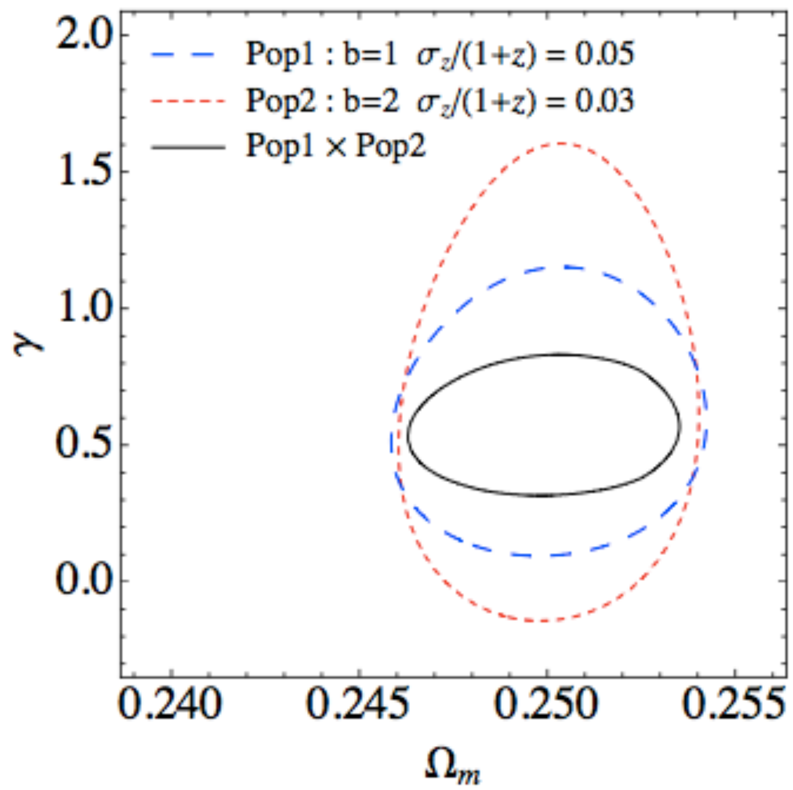
DES:
• Measure ~20000 clusters up to z~1.3
• Identification using partnership with South Polar Telescope (using Sunyaev-Zeldovich effect).

Systematics: observable-mass relation, photometric redshift, completeness and purity of cluster sample…



A ‘quasi-spectroscopic’ survey can do that, while maintaining good sampling



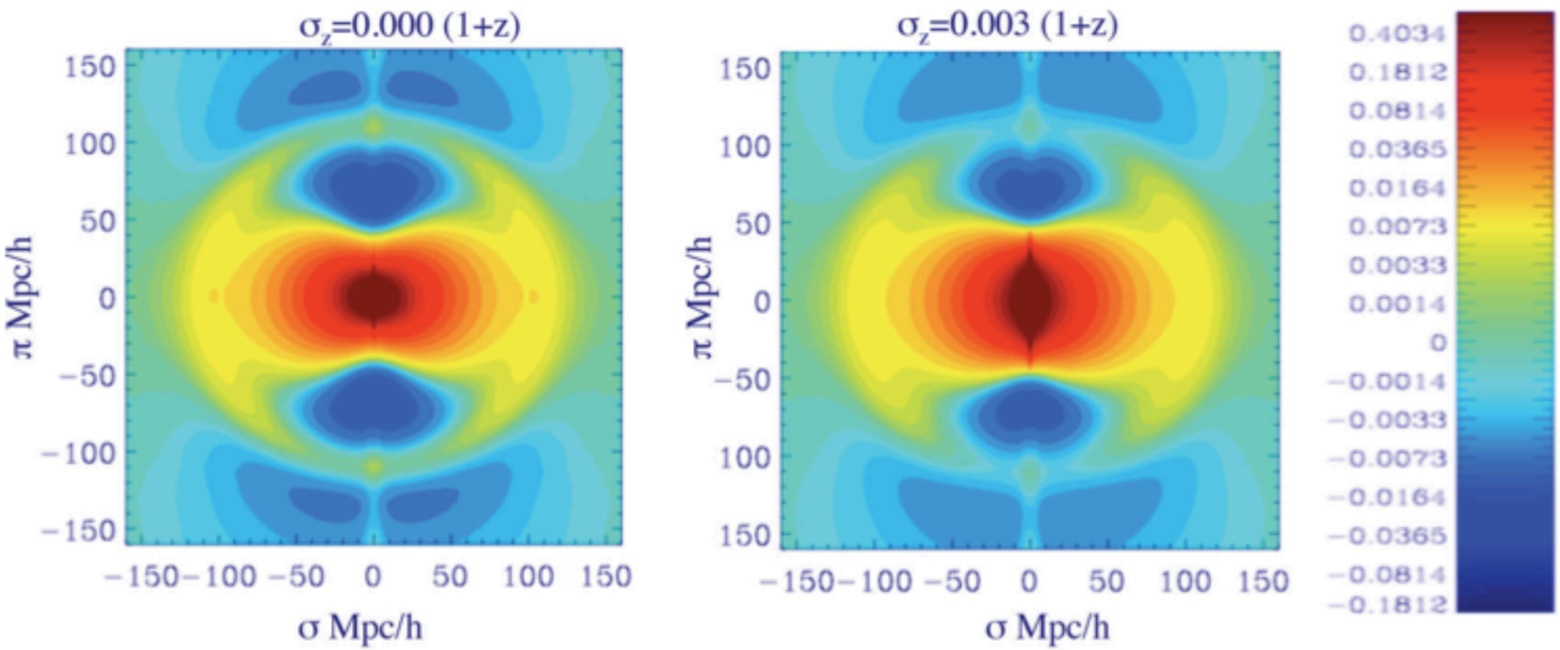


J.Asorey, E.Gaztañaga, M.Crocce 2014

PAU photo-z resolution is able to measure redshift space distortions

Bulk motions in radial direction → effective redshift variations

Radial correlation function



Angular correlation function

E.Gaztañaga et al. 2012

$$\delta_g(k, \mu) = (b + f\mu^2)\delta(k)$$

Constrain $b\sigma$ and $f\sigma$

Magnification can be observed cross-correlating bright and faint samples

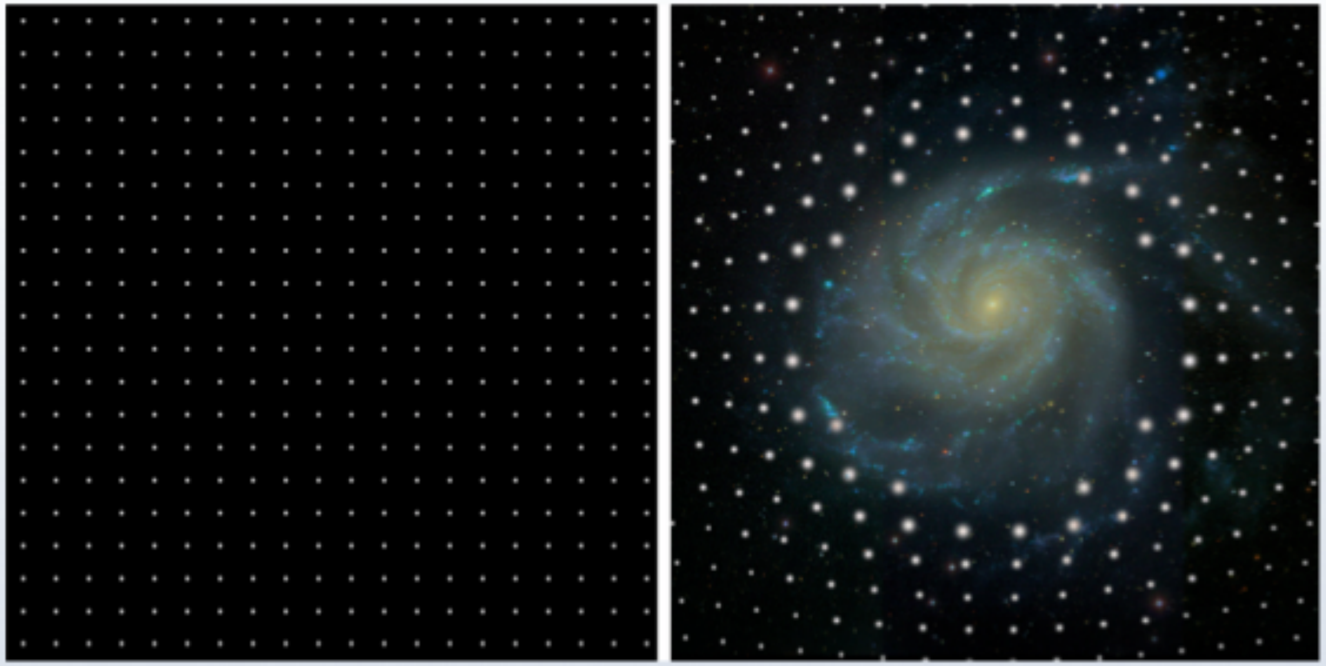


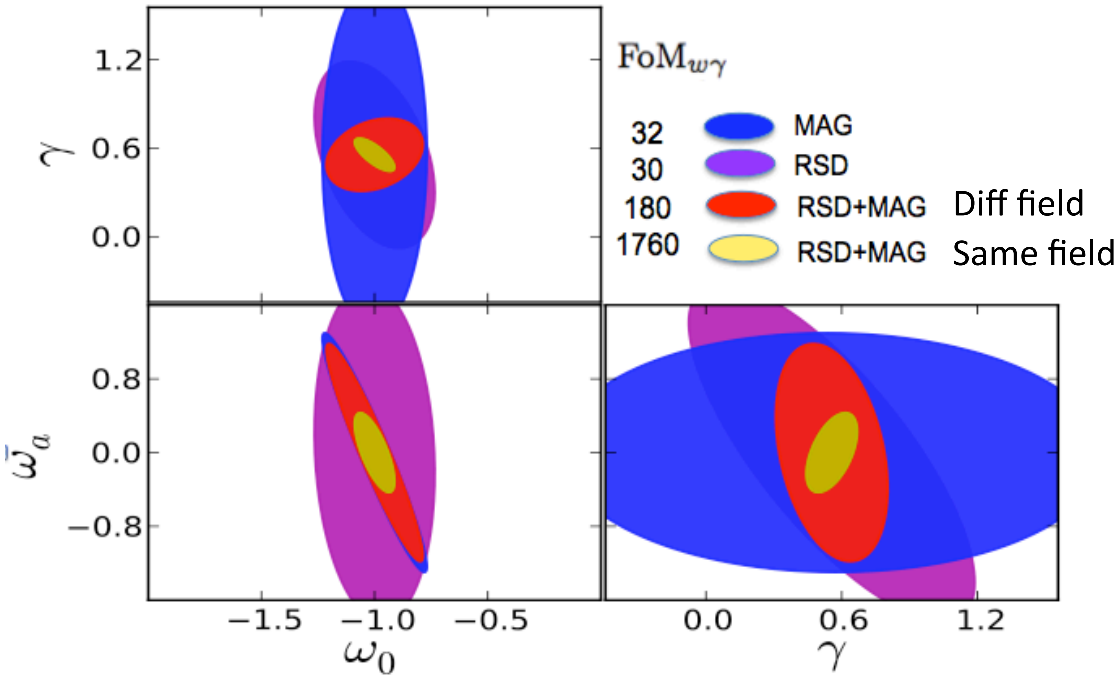
Image credit: Joerg Colberg, Ryan Scranton, Robert Lupton, SDSS

$$\langle \hat{\delta}_{g_i} \hat{\delta}_{g_i} \rangle \simeq b_i^2 \langle \delta_{m_i} \delta_{m_i} \rangle$$

$$\langle \hat{\delta}_{g_i} \hat{\delta}_{g_j} \rangle \simeq b_i \, p_{ij} \langle \delta_{m_i} \delta_{m_i} \rangle \qquad i < j$$

Obtain galaxy bias, weak-lensing kernel and mass fluctuations

PAU will combine both probes for extra efficiency

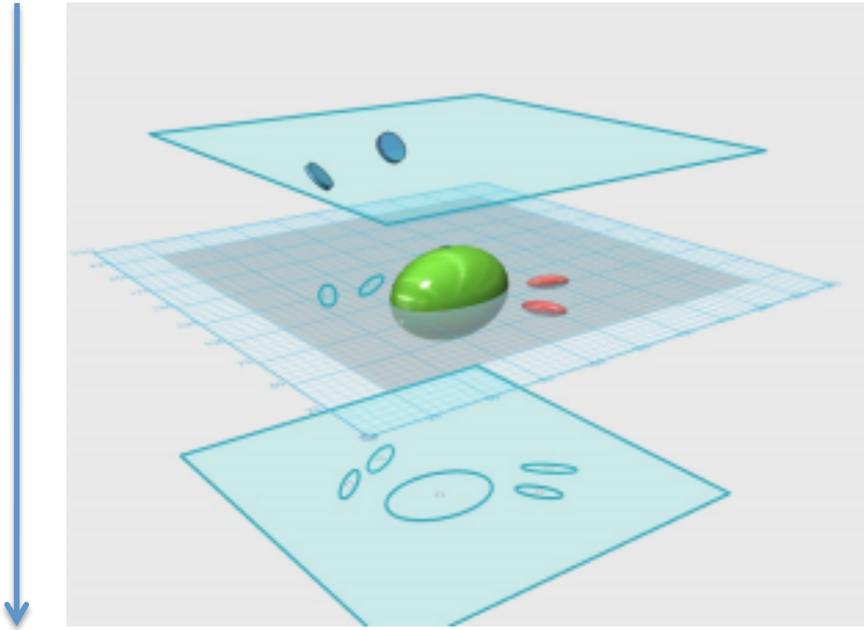


Using a faint sample 22.5 < i <24
Using a bright sample i < 22.5
200 square degrees

E.Gaztañaga et al. 2012

Combination of RSD and WL in the same dataset:
→ powerful in breaking degeneracies between galaxy bias and growth of structure
→ a unique advantage of PAU.

Galaxy intrinsic alignments can be disentangled with precise redshifts



B.Joachimi et al. 2015

Intrinsic alignments of galaxies coming from cluster tidal forces are the most important astrophysical systematic for shear measurement.

Observe regions with well measured shapes (HST, CFHT, KIDS) to obtain high resolution photo-zs.

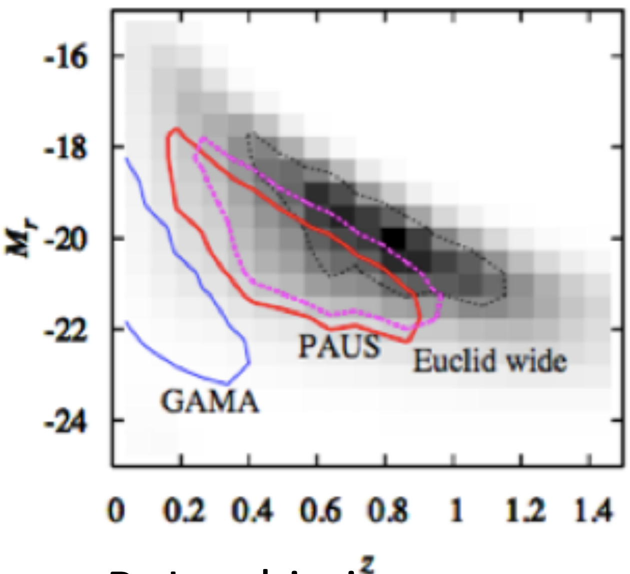
$$
\begin{aligned}
C_{\epsilon\epsilon}^{(ij)}(\ell) &= C_{\mathrm{GG}}^{(ij)}(\ell) + C_{\mathrm{IG}}^{(ij)}(\ell) + C_{\mathrm{IG}}^{(ji)}(\ell) + C_{\mathrm{II}}^{(ij)}(\ell) \\
C_{nn}^{(ij)}(\ell) &= C_{\mathrm{gg}}^{(ij)}(\ell) + C_{\mathrm{gm}}^{(ij)}(\ell) + C_{\mathrm{gm}}^{(ji)}(\ell) + C_{\mathrm{mm}}^{(ij)}(\ell) \\
C_{n\epsilon}^{(ij)}(\ell) &= C_{\mathrm{gG}}^{(ij)}(\ell) + C_{\mathrm{gI}}^{(ij)}(\ell) + C_{\mathrm{mG}}^{(ij)}(\ell) + C_{\mathrm{mI}}^{(ij)}(\ell),
\end{aligned}
$$

G.Bernstein 2009
B.Joachimi, S.Bridle 2010

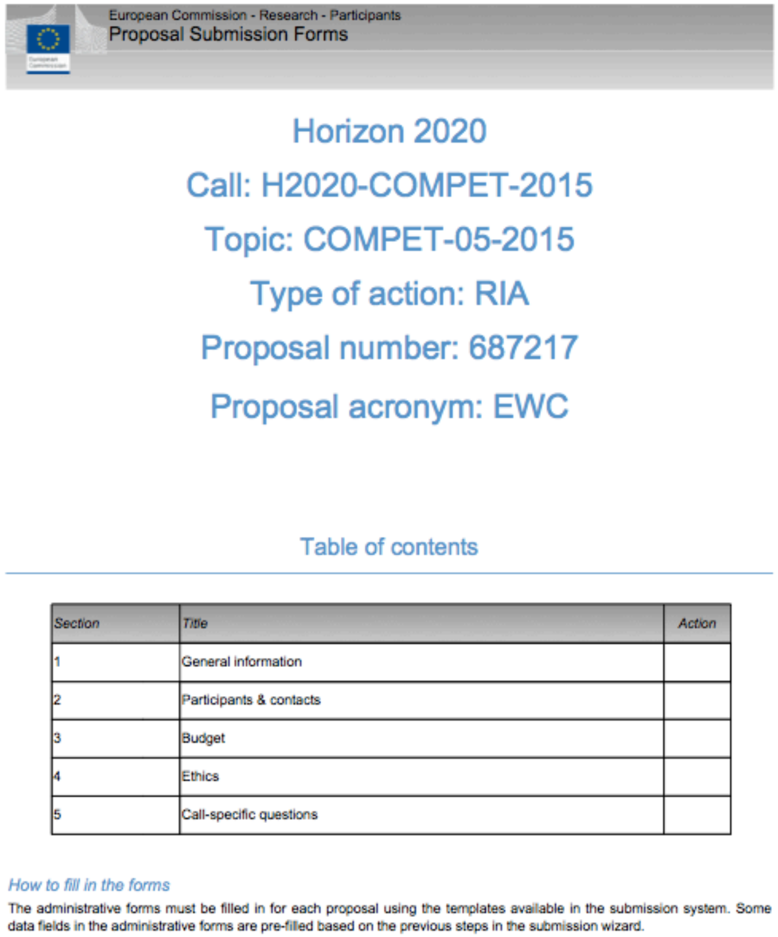
PAUCam can be employed to provide unique calibration for the Euclid mission

Submitted a European grant request, to pursue these goals in the context of the Euclid mission, endorsed by the Euclid consortium.

Leads: T.Kitching, H.Hoekstra, FJ.Castander and other 8 European institutions.



B. Joachimi



European Commission - Research - Participants
Proposal Submission Forms

Horizon 2020

Call: H2020-COMPET-2015

Topic: COMPET-05-2015

Type of action: RIA

Proposal number: 687217

Proposal acronym: EWC

Table of contents

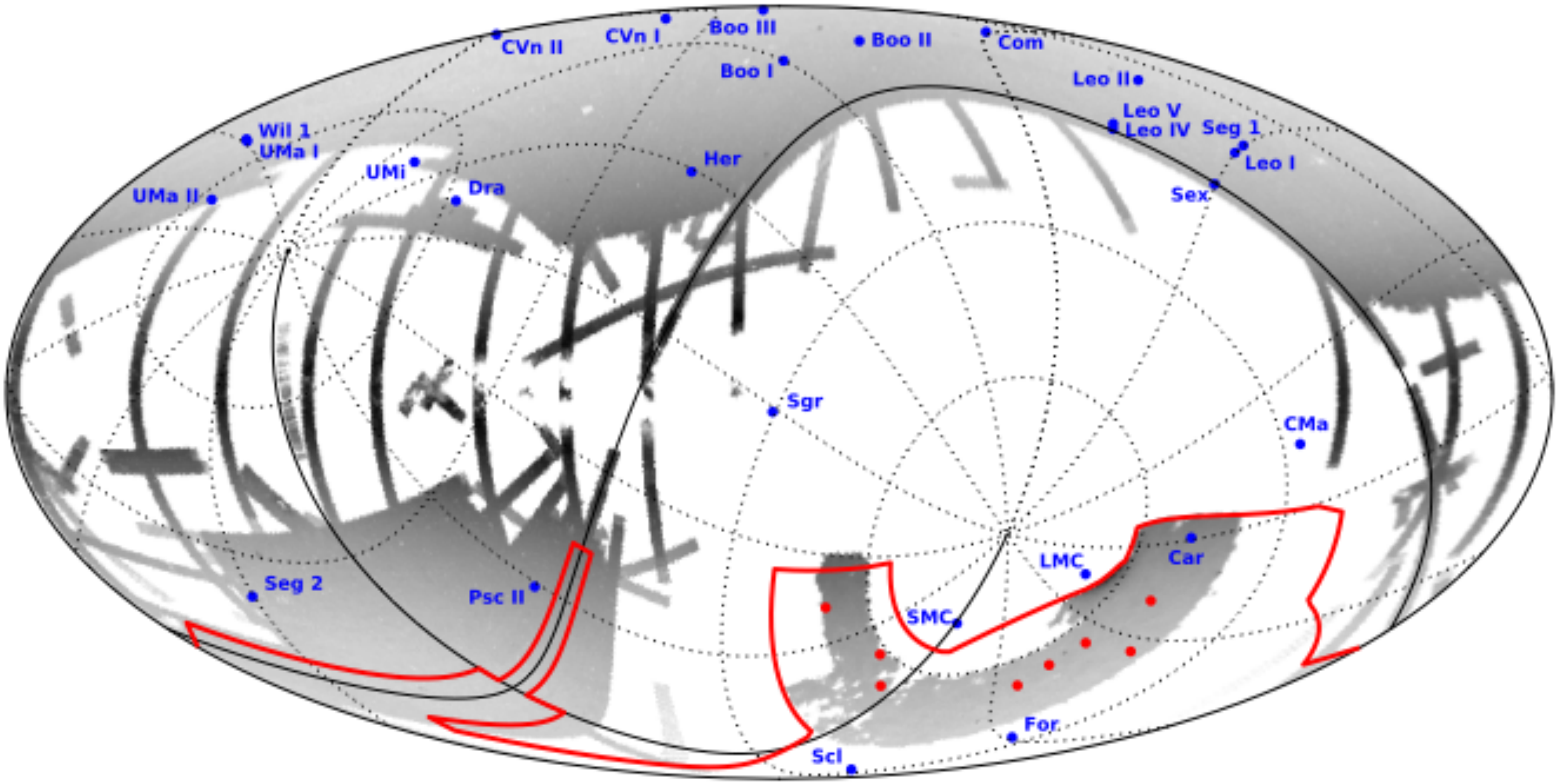
Section	Title	Action
1	General information	
2	Participants & contacts	
3	Budget	
4	Ethics	
5	Call-specific questions	

How to fill in the forms

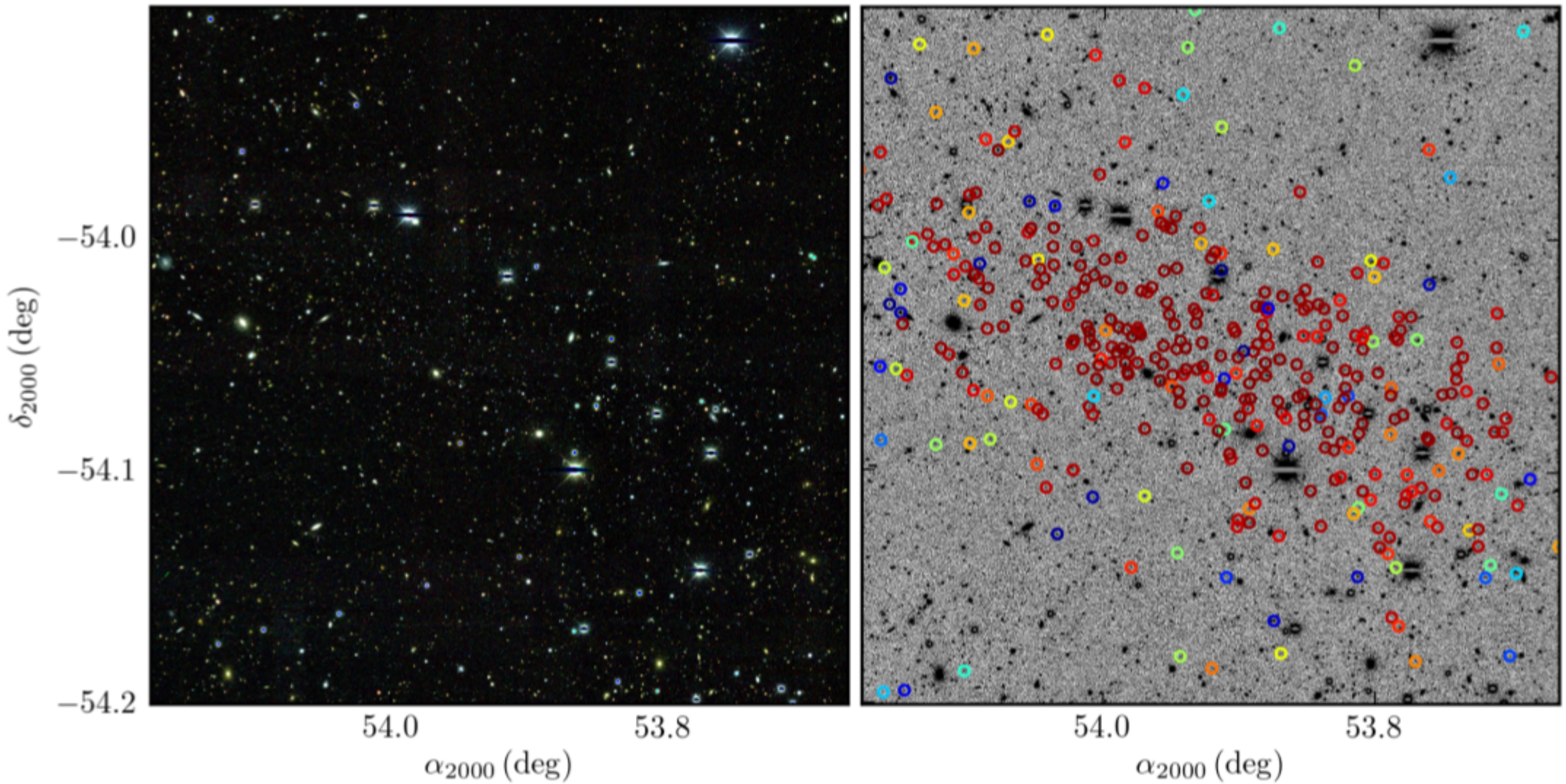
The administrative forms must be filled in for each proposal using the templates available in the submission system. Some data fields in the administrative forms are pre-filled based on the previous steps in the submission wizard.

Eight new dSph candidates in the Southern sky

arXiv:1503.02584 (K.Bechtol, DES Collaboration)



A closer look at (candidate) Reticulum II



No significant excess observed in gamma rays (LAT)

arXiv:1503.02632 (A. Drlica-Wagner, DES+LAT Collaborations)