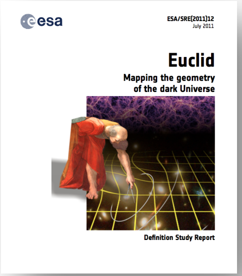


Euclid: the ultimate cosmological experiment

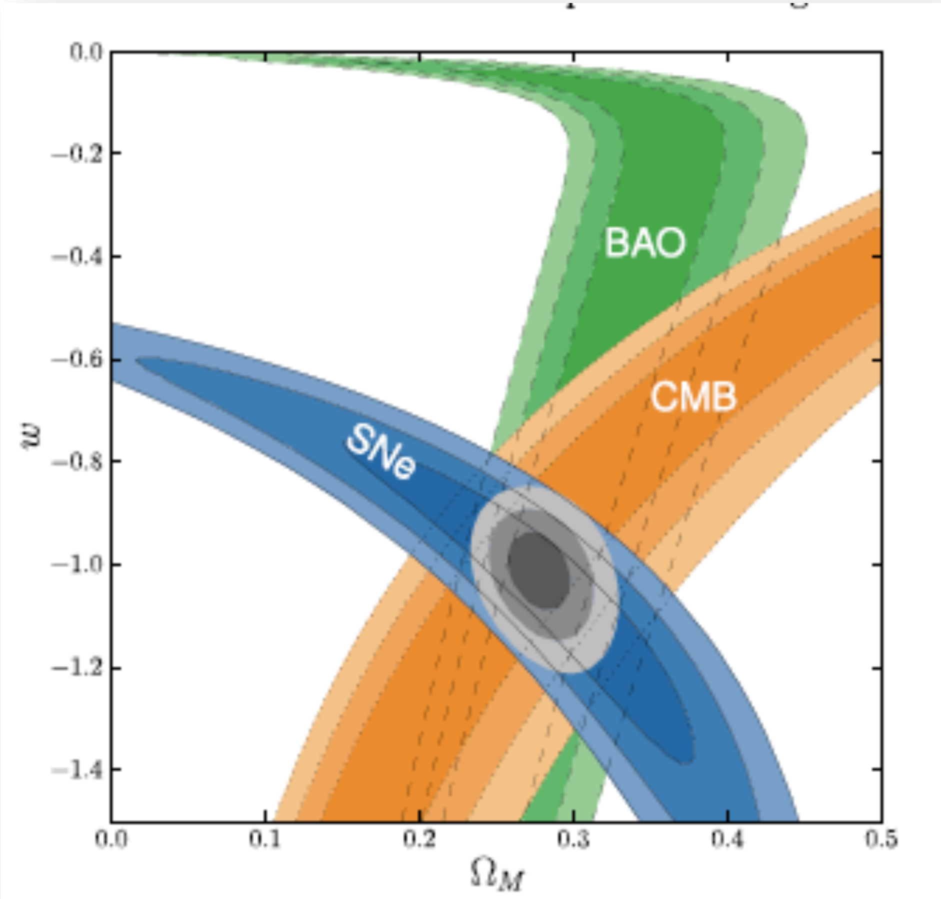
Luigi (Gigi) Guzzo
Osservatorio di Brera – INAF - Italy

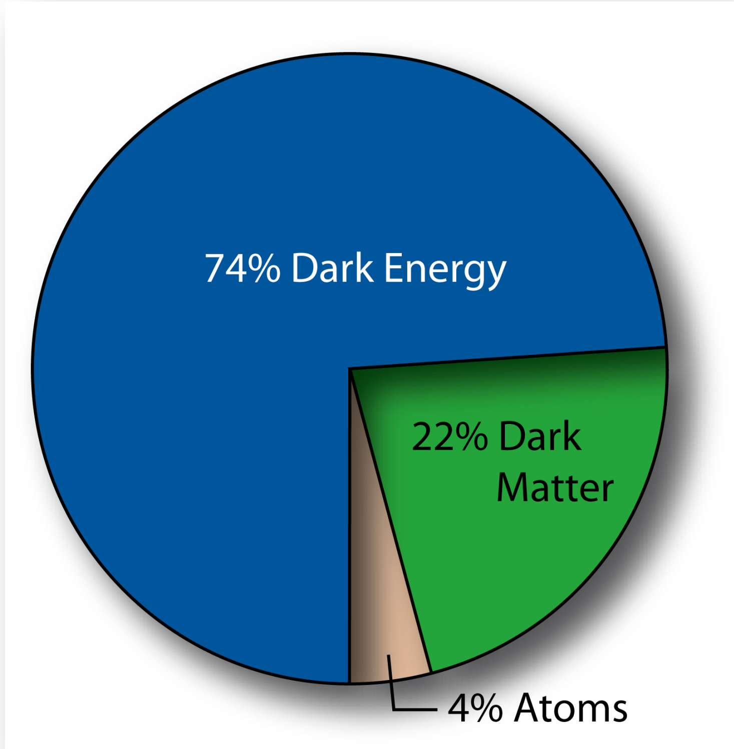
on behalf of the EUCLID Consortium

Euclid cosmological motivation

Euclid Consortium

The standard model: cosmic concordance, but many open questions…





Amanullah et al. 2010 (Union supernovae)

Euclid key question 1

1. Is cosmic acceleration produced by a cosmological constant or by an evolving scalar field?

Euclid key question 1

Euclid Consortium

Parameterizing our ignorance

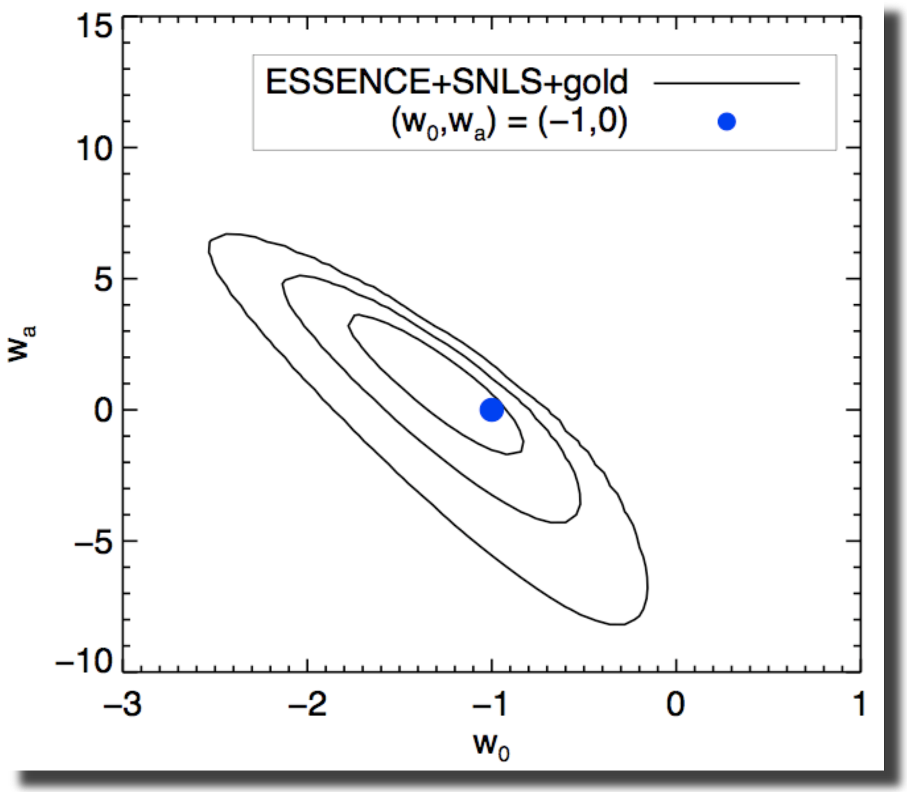
e.g. $w(a) = w_0 + w_a(1-a)$

It has become customary to characterize future surveys through a Figure of Merit in this or similar plane:

$$\mathrm{FoM} = 1/(\Delta w_0 \times \Delta w_a)$$

But this reflects chosen parameterization

→ FoMs should be taken with grain of salt (e.g. NASA/DOE/ESA FoMSWG report, Albrecht et al. 2009)



Wood-Vasey et al. 2007

“Dark Gravity” instead of Dark Energy…?

Euclid Consortium

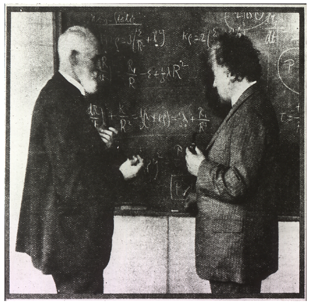
A story with two sides…

?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Modify gravity theory [e.g. ***R → f(R)***]

Add dark energy



→ Distinguish by measuring both background expansion H(z) and growth rate of structure f(z)

Euclid key question 2

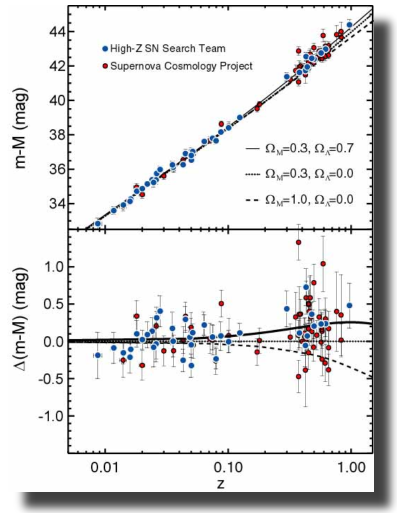
Euclid Consortium

1. Is cosmic acceleration produced by a cosmological constant or by an evolving scalar field?

2. Does General Relativity need to be modified on cosmological scales?

Euclid answers both questions

Euclid Consortium



1. Measure expansion history H(z) to high accuracy, as to detect percent variations of DE *equation of state* w(z) with robust control of systematics.

Achieve this through **two probes**:

A. Measurement of geometry through Weak Gravitational Lensing

B. Baryonic Acoustic Oscillations (BAO) in the clustering pattern of galaxies as standard rod

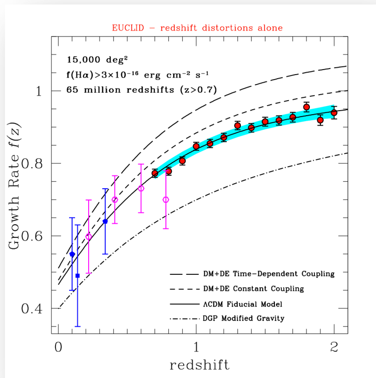
Euclid answers both questions

1. Measure expansion history H(z) to high accuracy, as to detect percent variations of DE *equation of state* w(z) with robust control of systematics.

2. Measure at the same time growth rate of structure from the same probes:

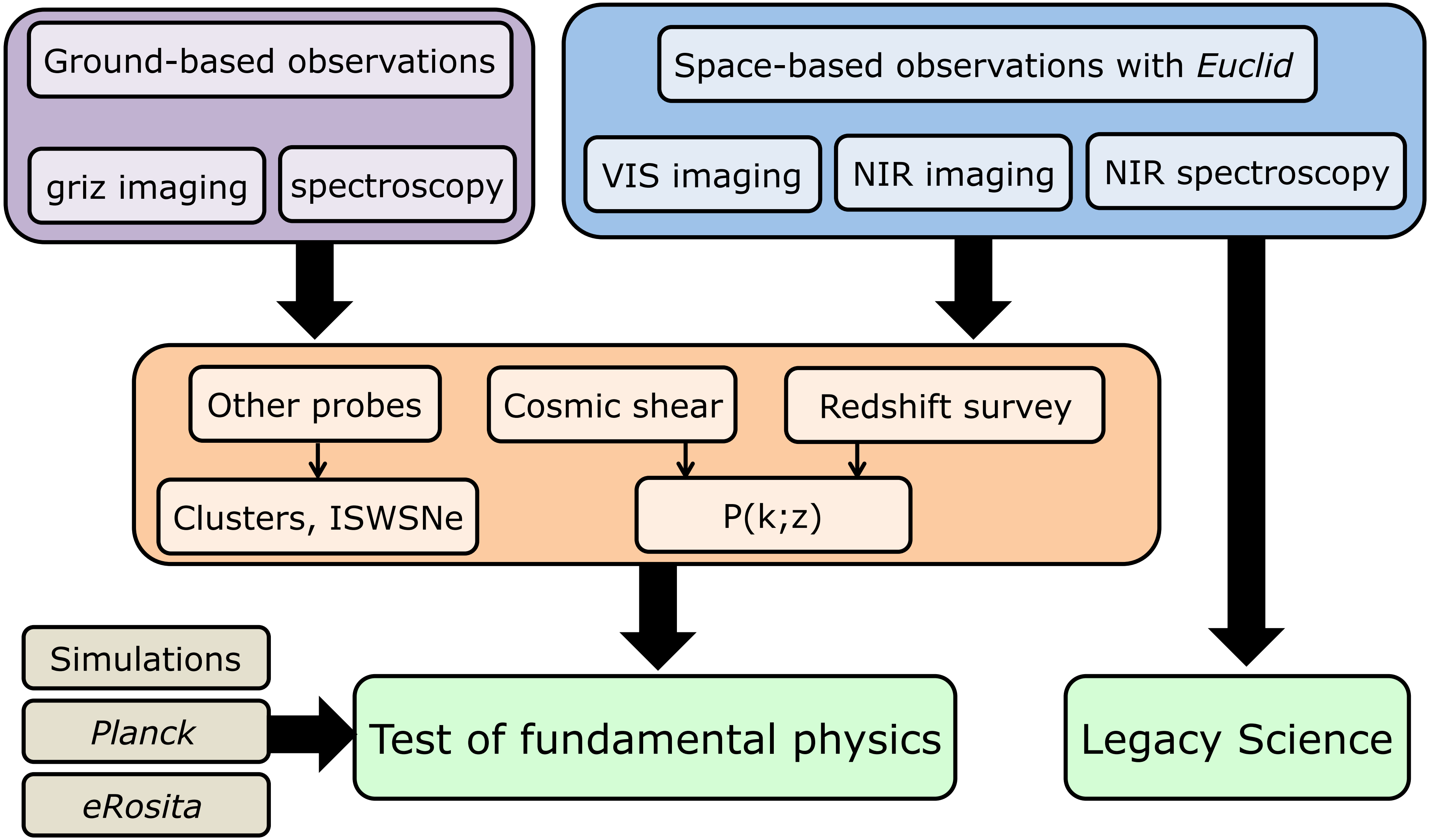
   A. Weak Lensing Tomography

   B. Redshift-space distortion of clustering (RSD)



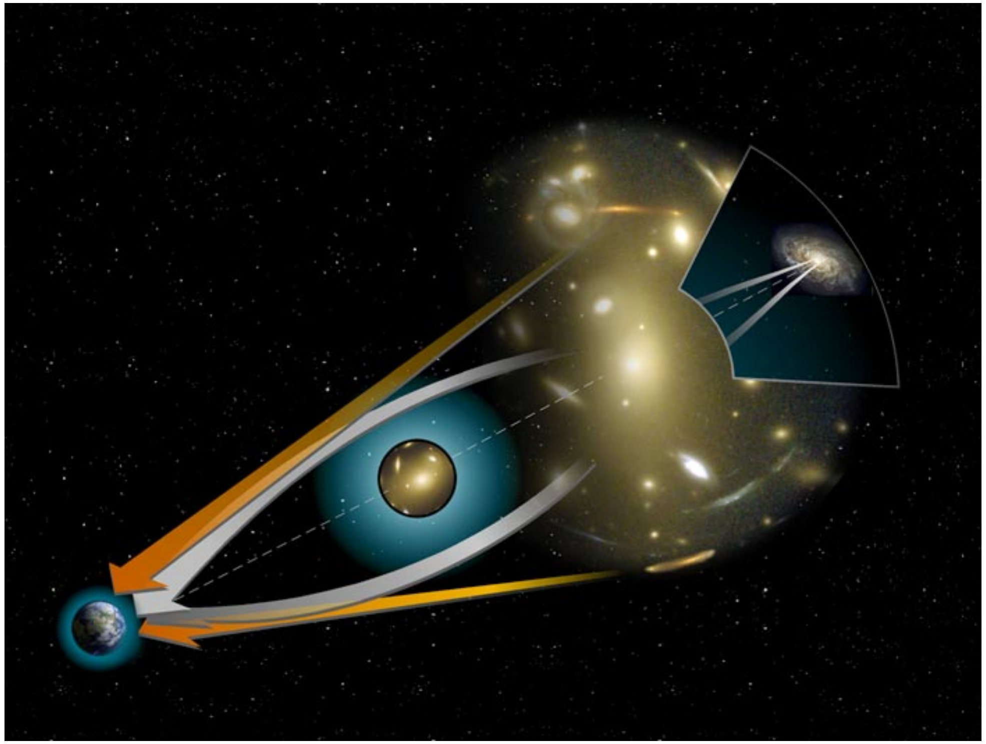
How to do this with Euclid

Euclid Consortium



Probe 1: Weak gravitational lensing

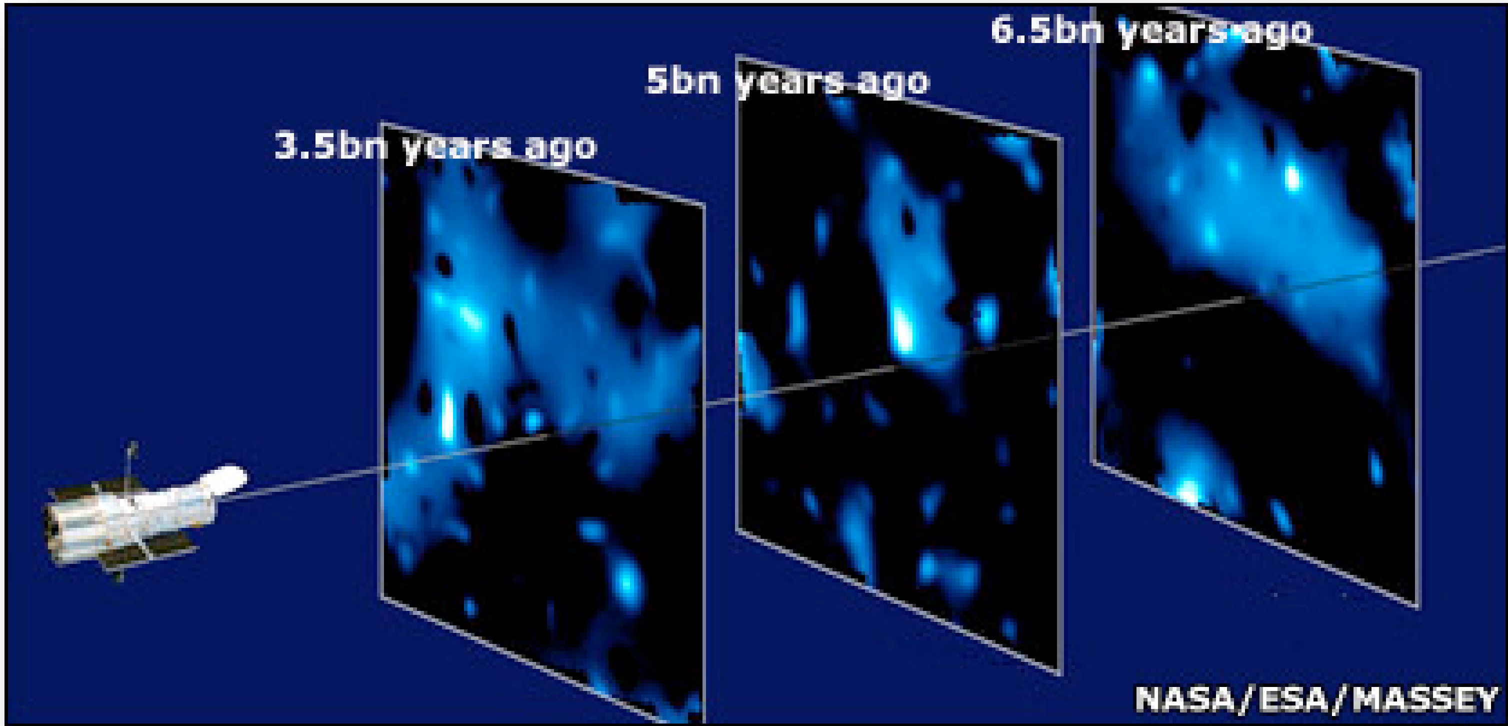
Euclid Consortium



Density fluctuations in the universe affect the propagation of light rays, leading to correlations in the their *observable* shapes.

The statistics of shape correlations as a function of angular scale and redshift can be used to *directly* infer the statistics of the density fluctuations and consequently cosmology.

Weak lensing tomography

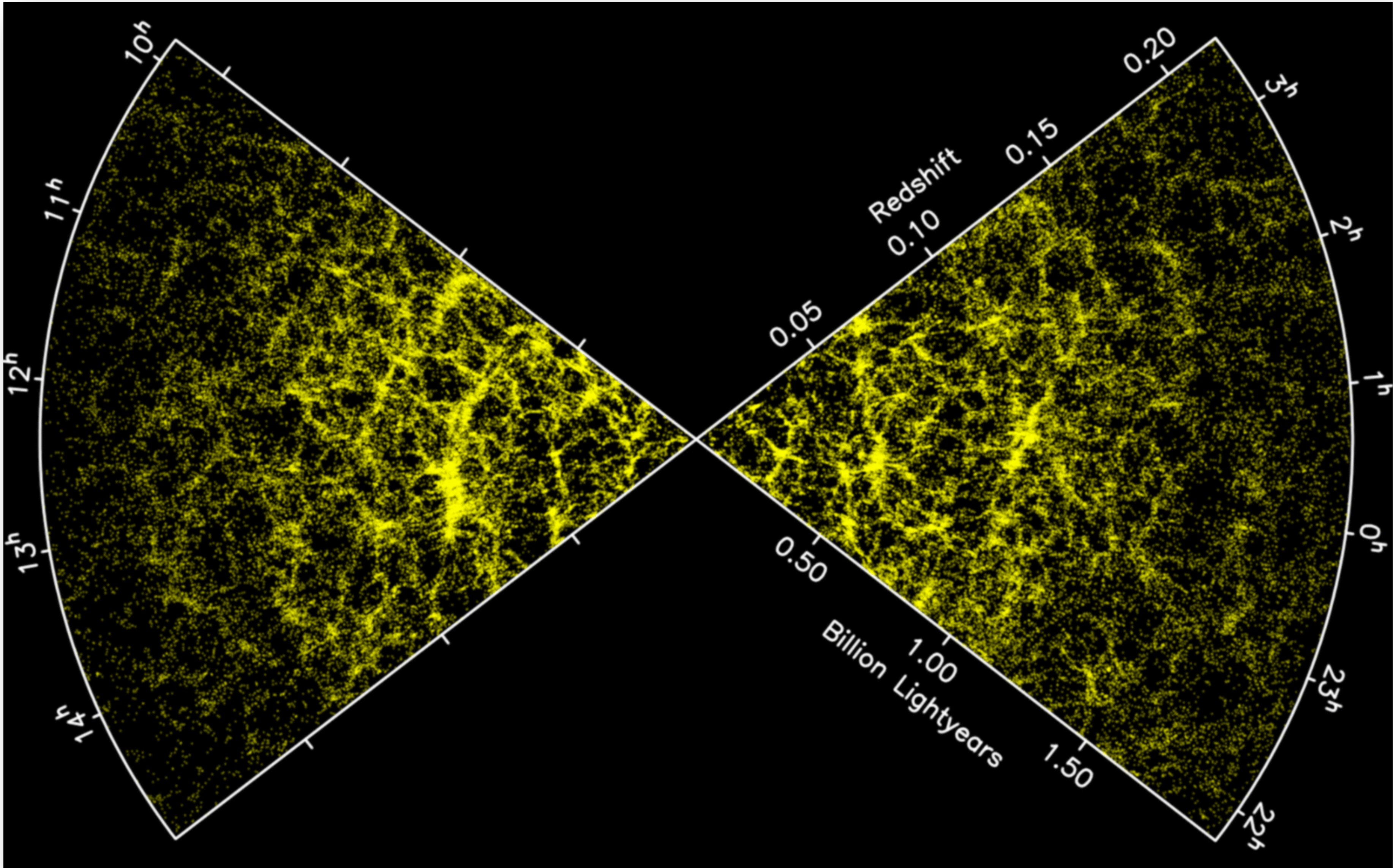


- Measures a combination of geometry (thus H(z)) and growth

- To achieve the science goals we need to measure the matter distribution as a function of redshift: weak lensing tomography requires redshifts for the sources.

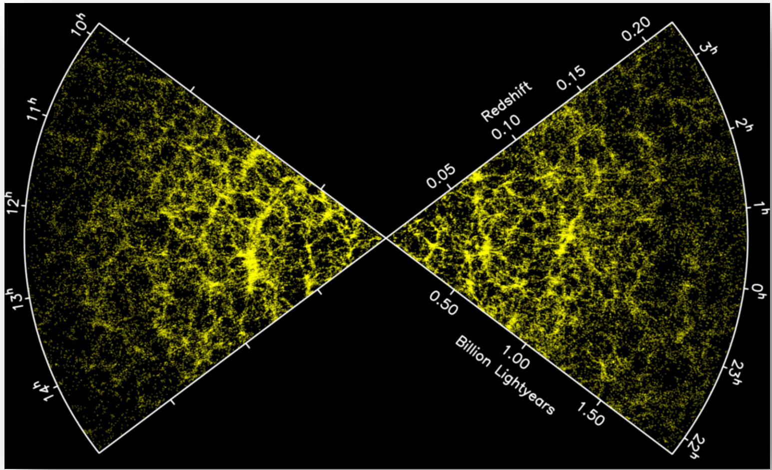
Probe 2: Galaxy Clustering

Euclid
Consortium

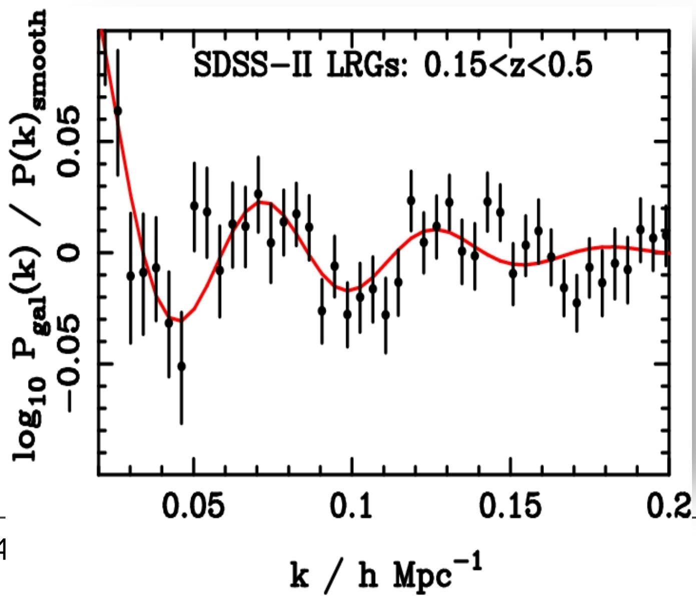


Baryonic Acoustic Oscillations

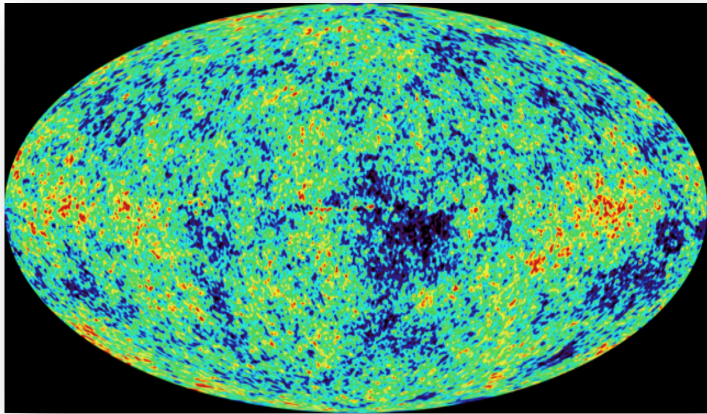
Galaxies



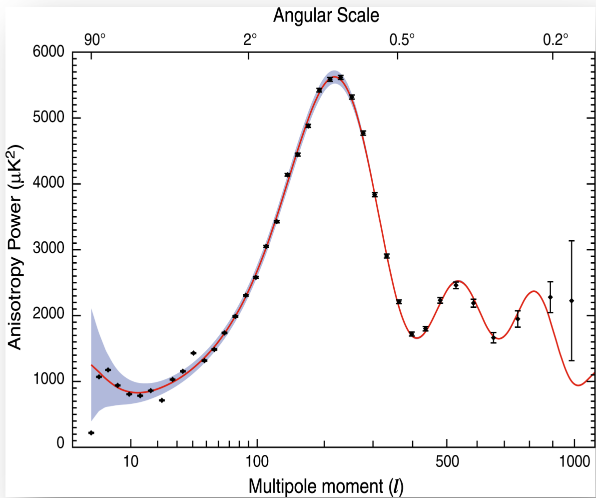
Percival et al. (2007, 2009, 2010); Anderson et al 2012



Microwave background

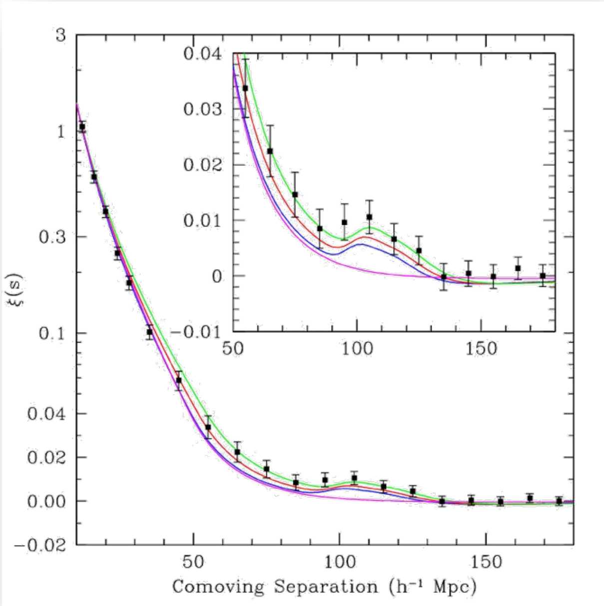


WMAP, e.g. Komatsu et al. 2009

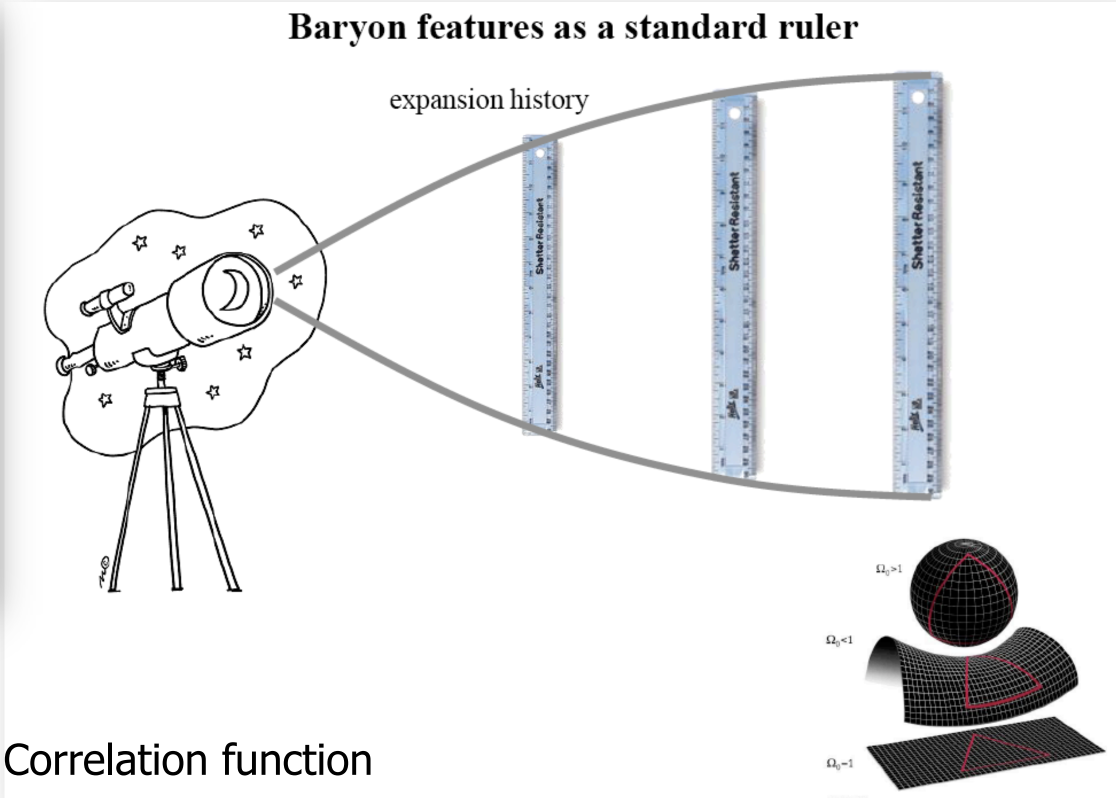


Baryonic Acoustic Oscillations

- Measure H(z) from redshift surveys



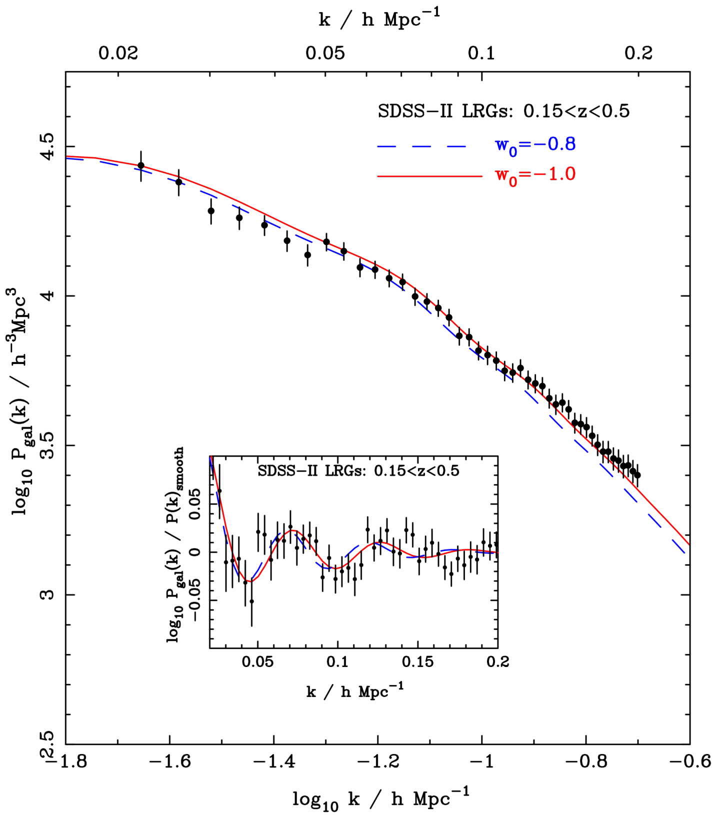
SDSS: Eisenstein et al 2005



BAO: a broad feature in the Correlation function

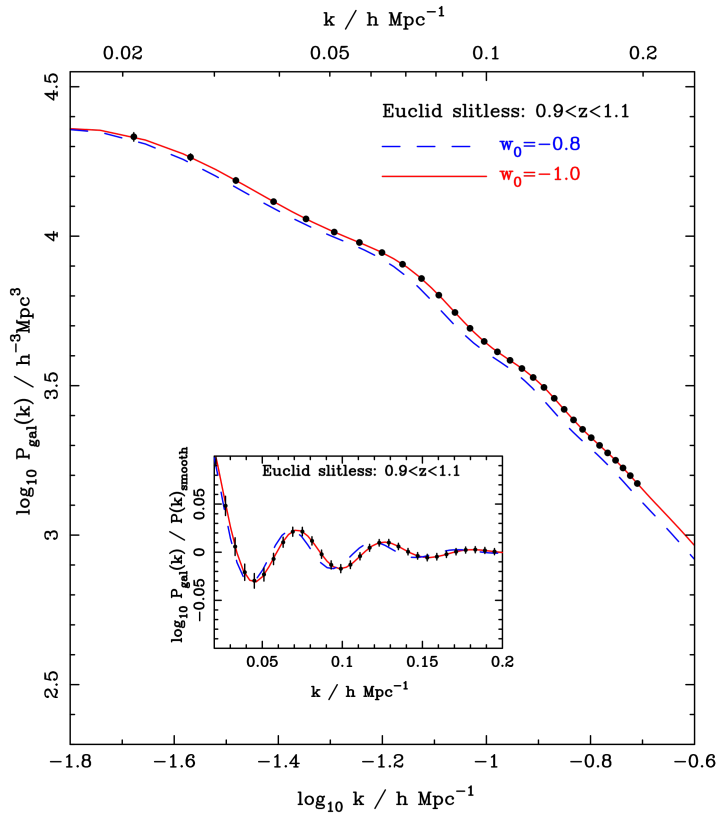
w(z) from Baryonic Acoustic Oscillations

Euclid Consortium



SDSS LRGs at z~0.35

Total effective volume
V_{eff} = 0.26 Gpc^{3}h^{-3}

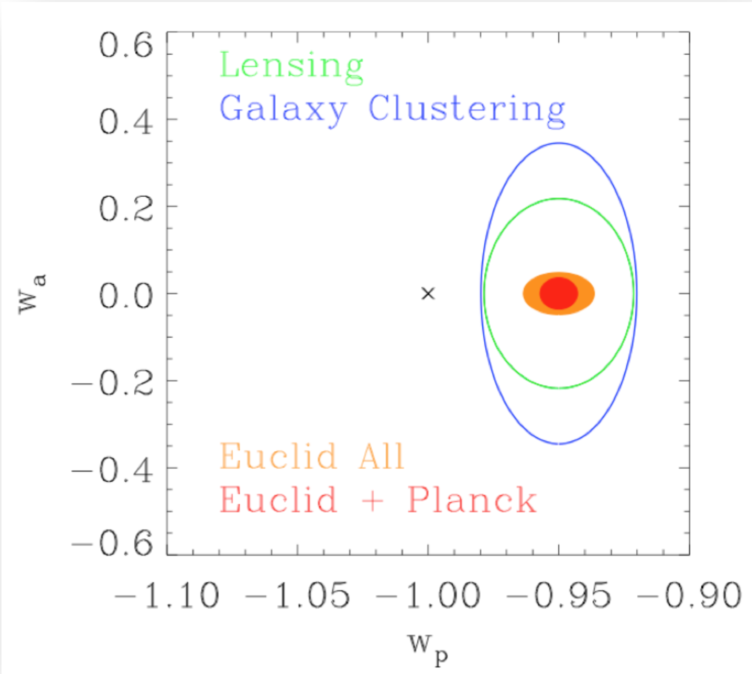


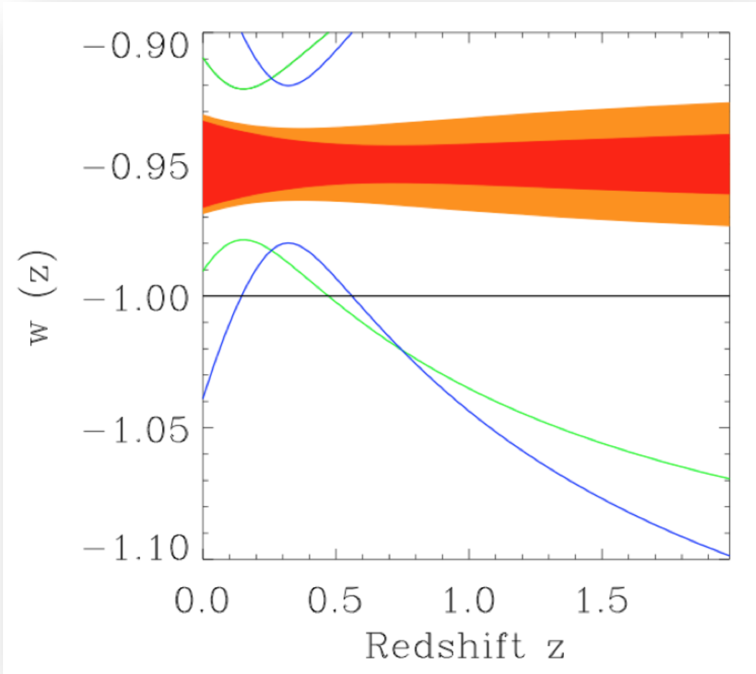
20% of the Euclid slitless data at z~1

Total effective volume (of Euclid)
V_{eff} = 19.7 Gpc^{3}h^{-3}

The full power of EUCLID

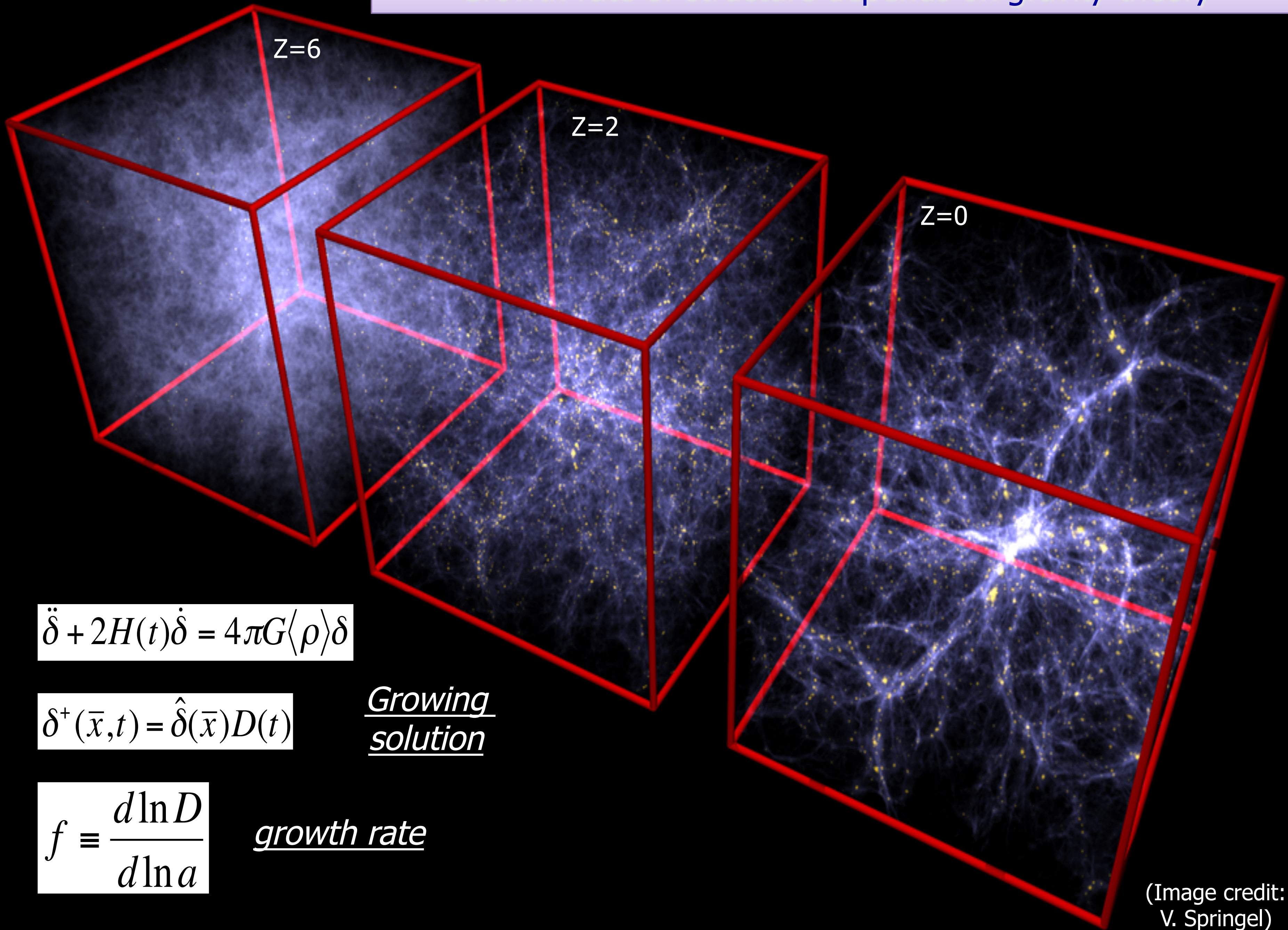
1. Dark Energy equation of state from combined Weak Lensing and Galaxy Clustering (BAO)





Answering Euclid key science question 1: Is dark energy simply a cosmological constant, or is it a field that evolves dynamically with the expansion of the Universe?

Growth rate of structure depends on gravity theory



$$\ddot{\delta} + 2H(t)\dot{\delta} = 4\pi G\langle\rho\rangle\delta$$

$$\delta^{+}(\bar{x},t) = \hat{\delta}(\bar{x})D(t)$$ *Growing solution*

$$f \equiv \frac{d\ln D}{d\ln a}$$ *growth rate*

(Image credit: V. Springel)

Growth produces motions: galaxy peculiar velocities

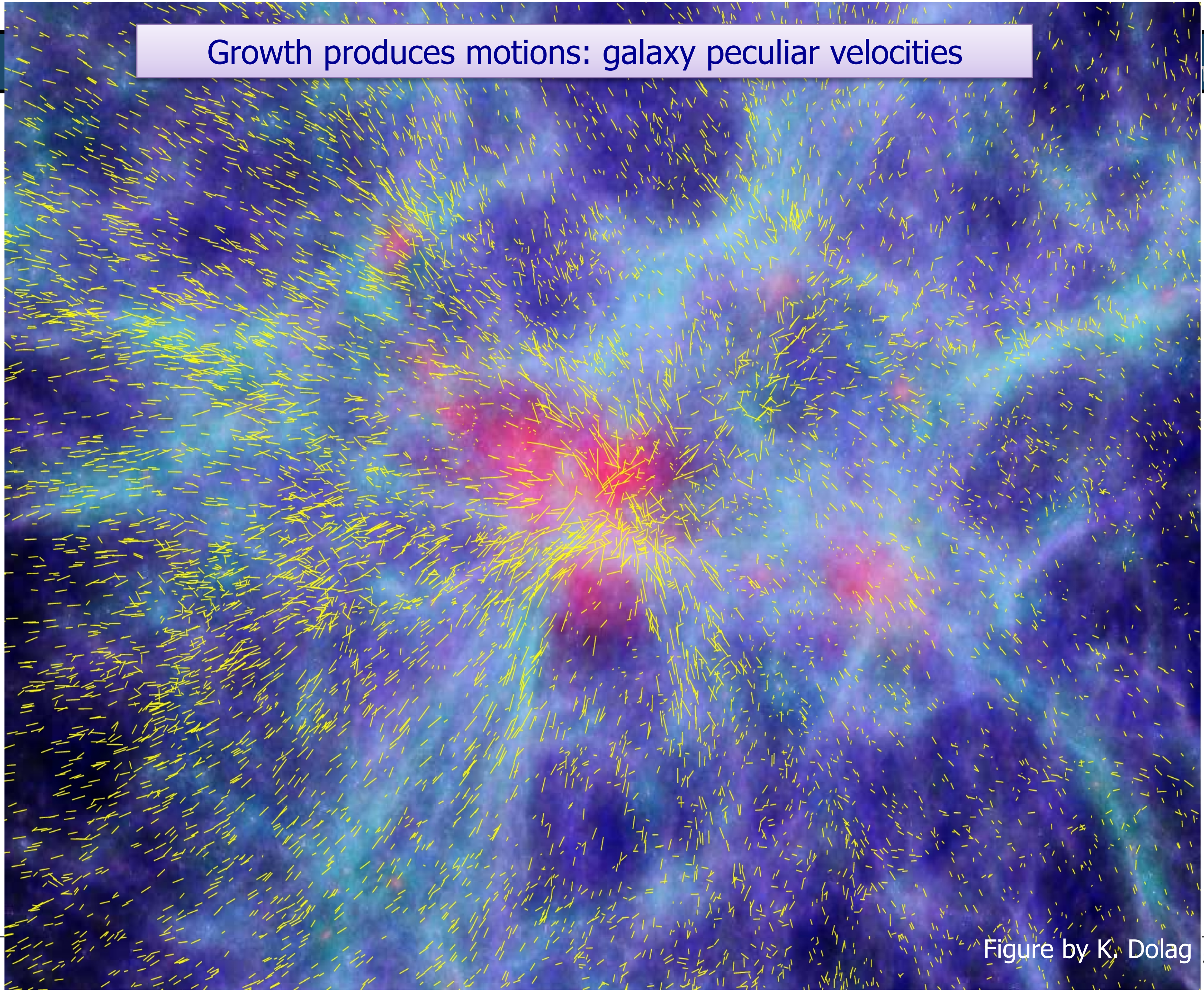
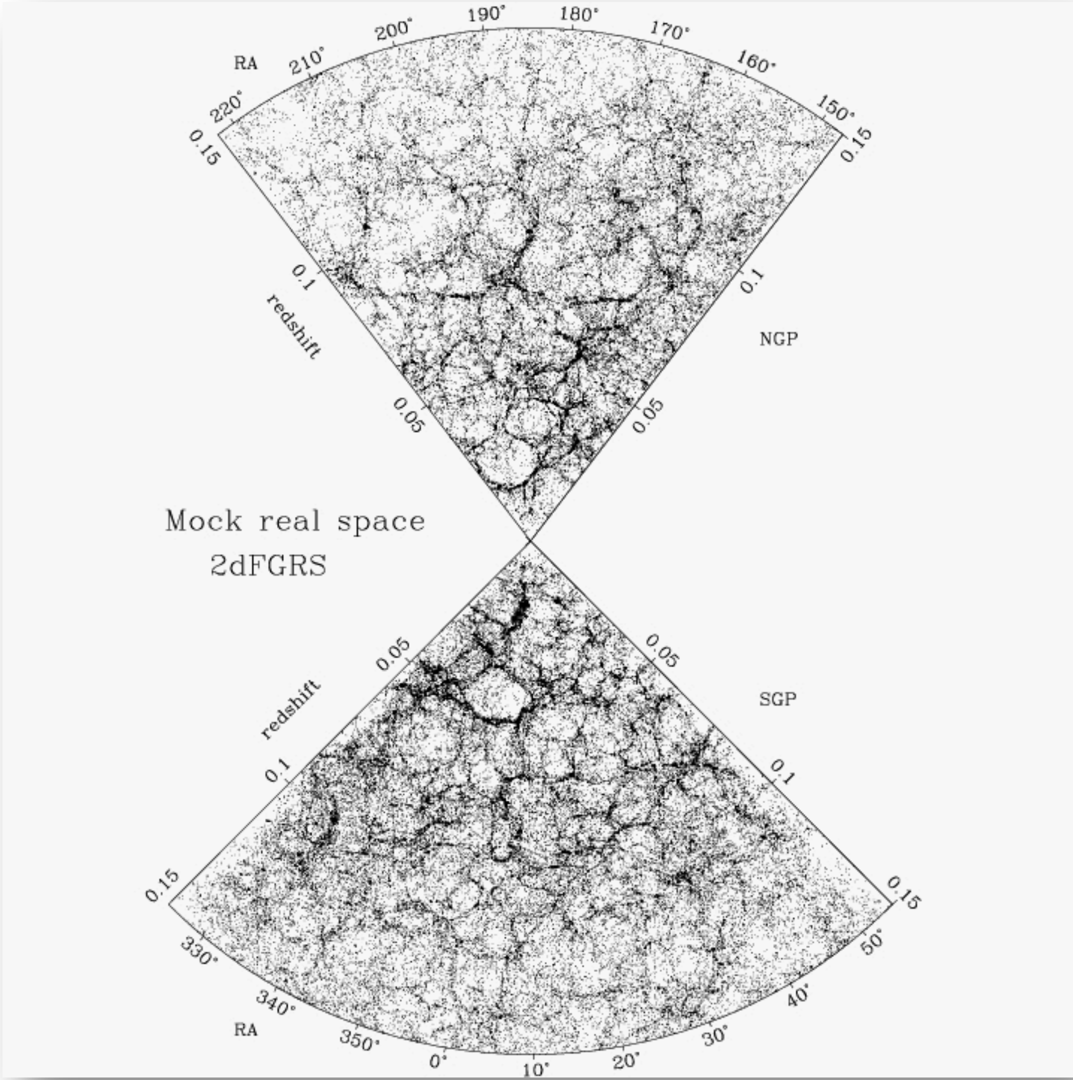


Figure by K. Dolag

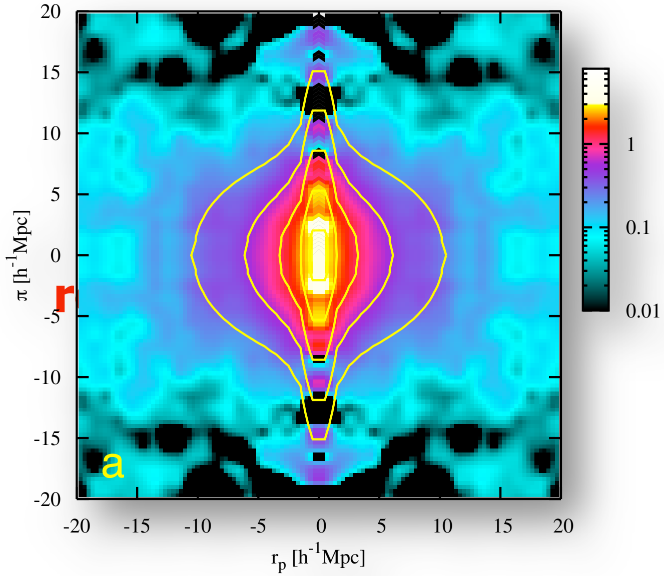
In galaxy redshift surveys peculiar velocities manifest themselves as *redshift-space distortions* (Kaiser 1987)

real space

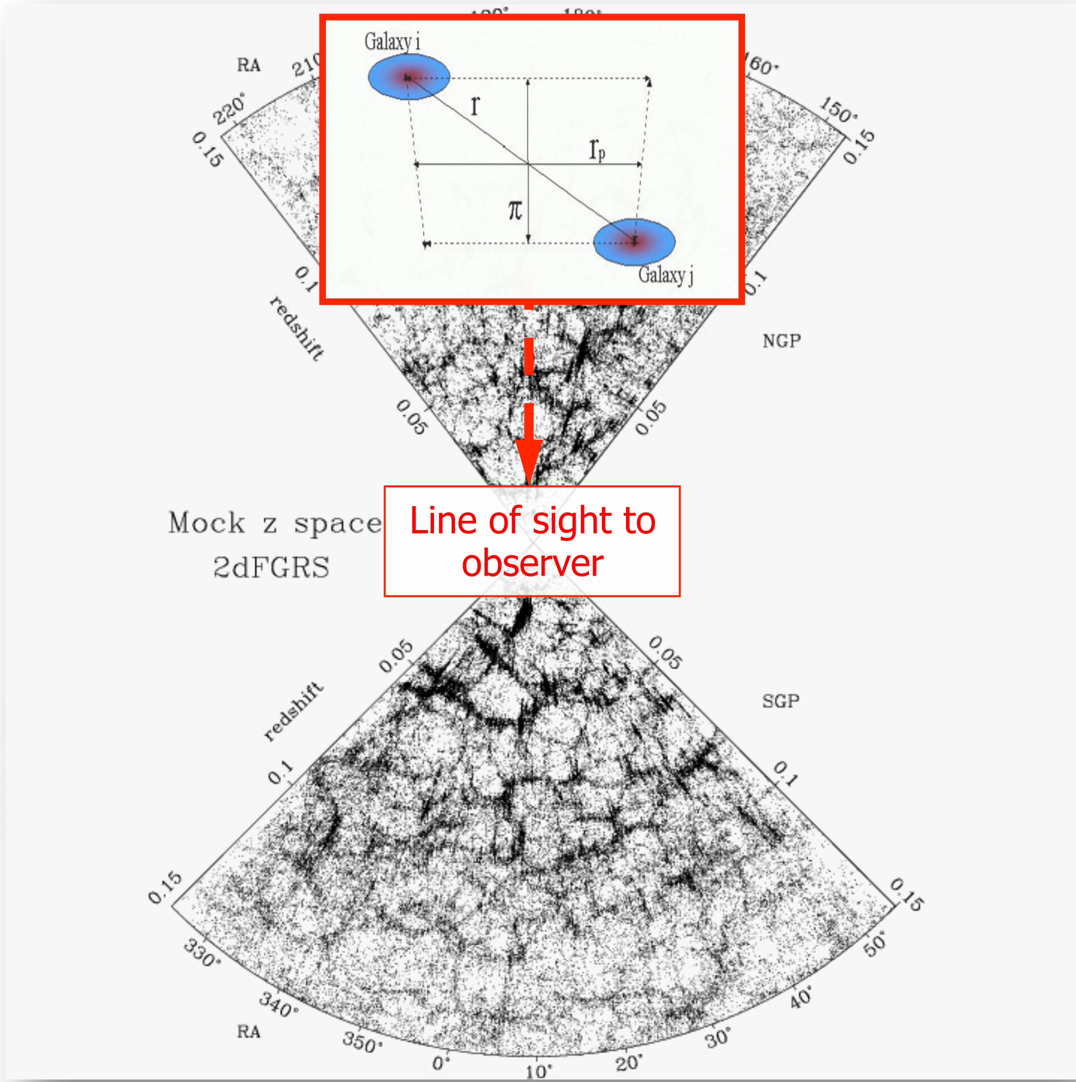


Eke & 2dFGRS

In galaxy redshift surveys peculiar velocities manifest themselves as *redshift-space distortions* (Kaiser 1987)



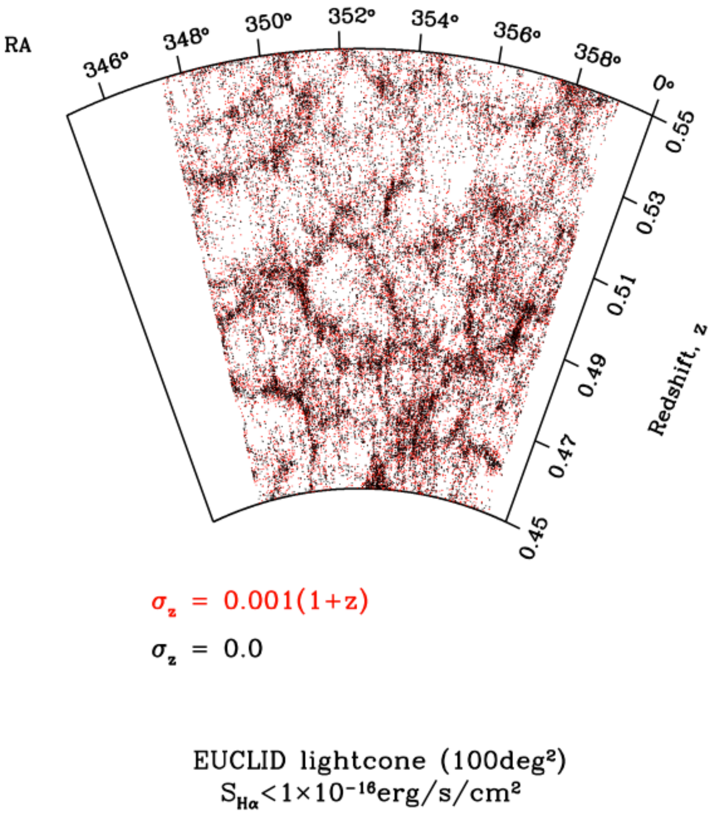
Guzzo et al., Nature 451, 541 (2008)

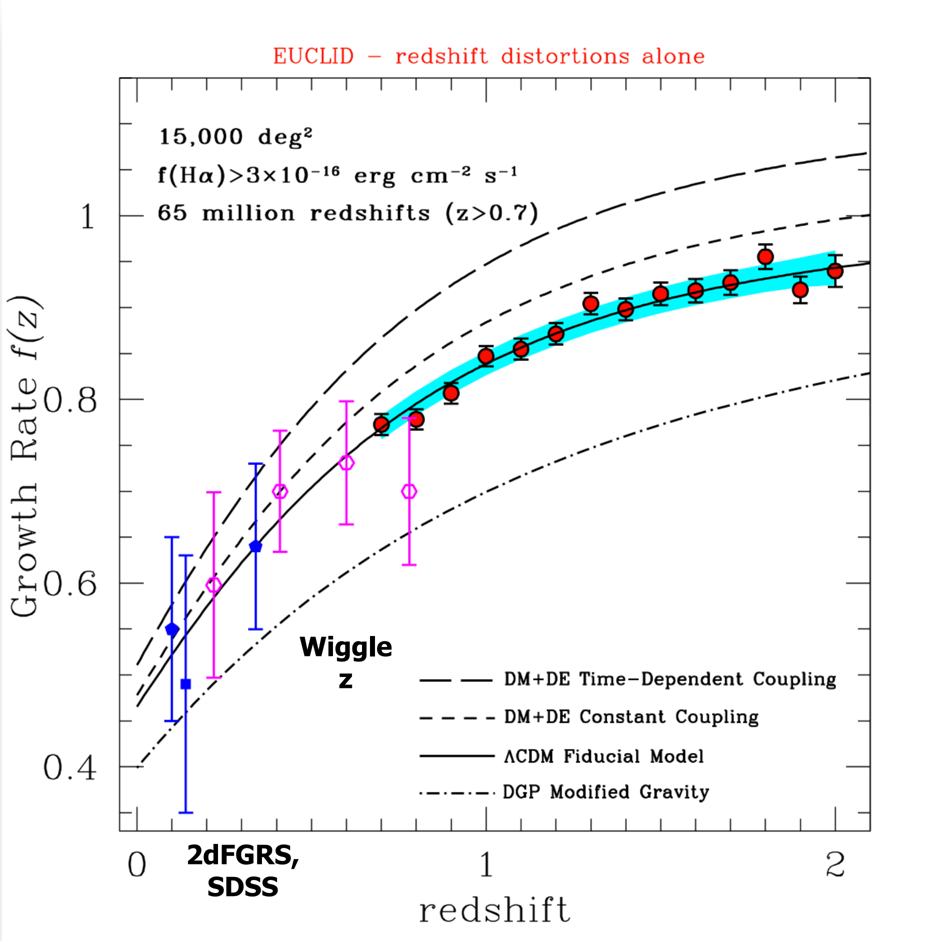


Growth with Euclid: RSD

Euclid Consortium

- Redshift-space distortions map motions due to structure growth





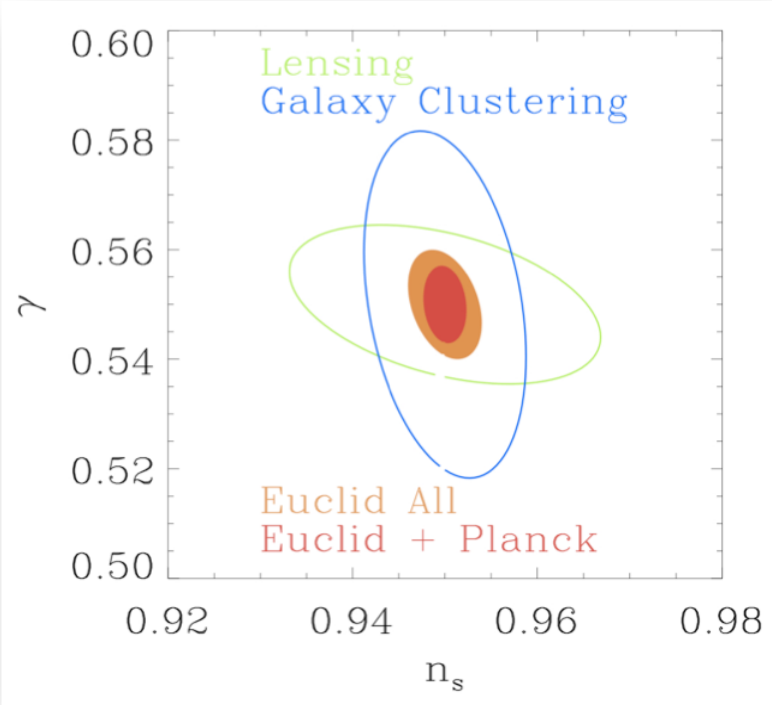
sims by Bianchi et al. (2011)

(sims from Durham group)

The full power of EUCLID

2. Growth rate of structure from combined Weak Lensing (tomography) and Galaxy Clustering (redshift-space distortions)

$f(z)=[\Omega_m(z)]^\gamma$

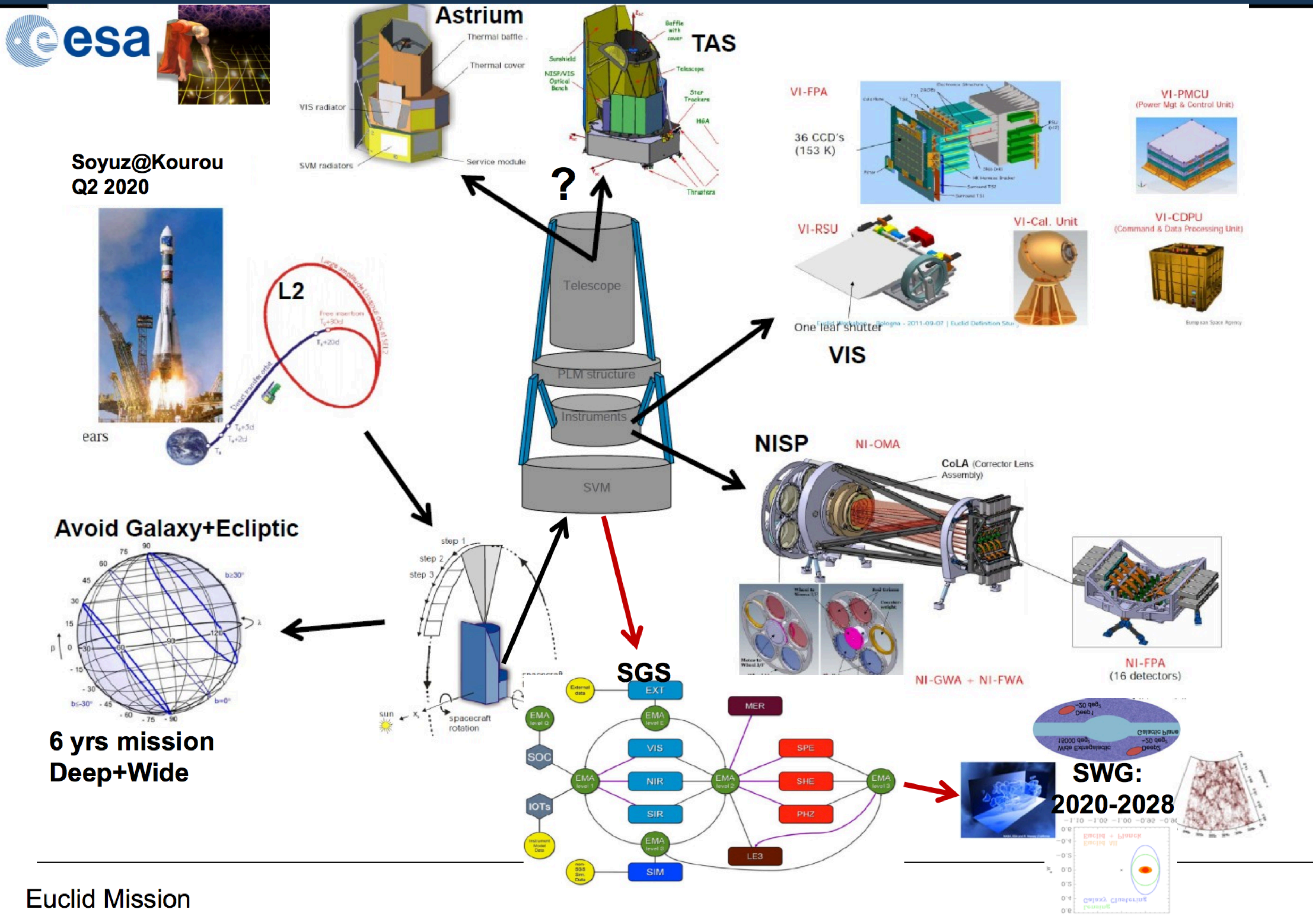


$P_o(k)=Ak^n$

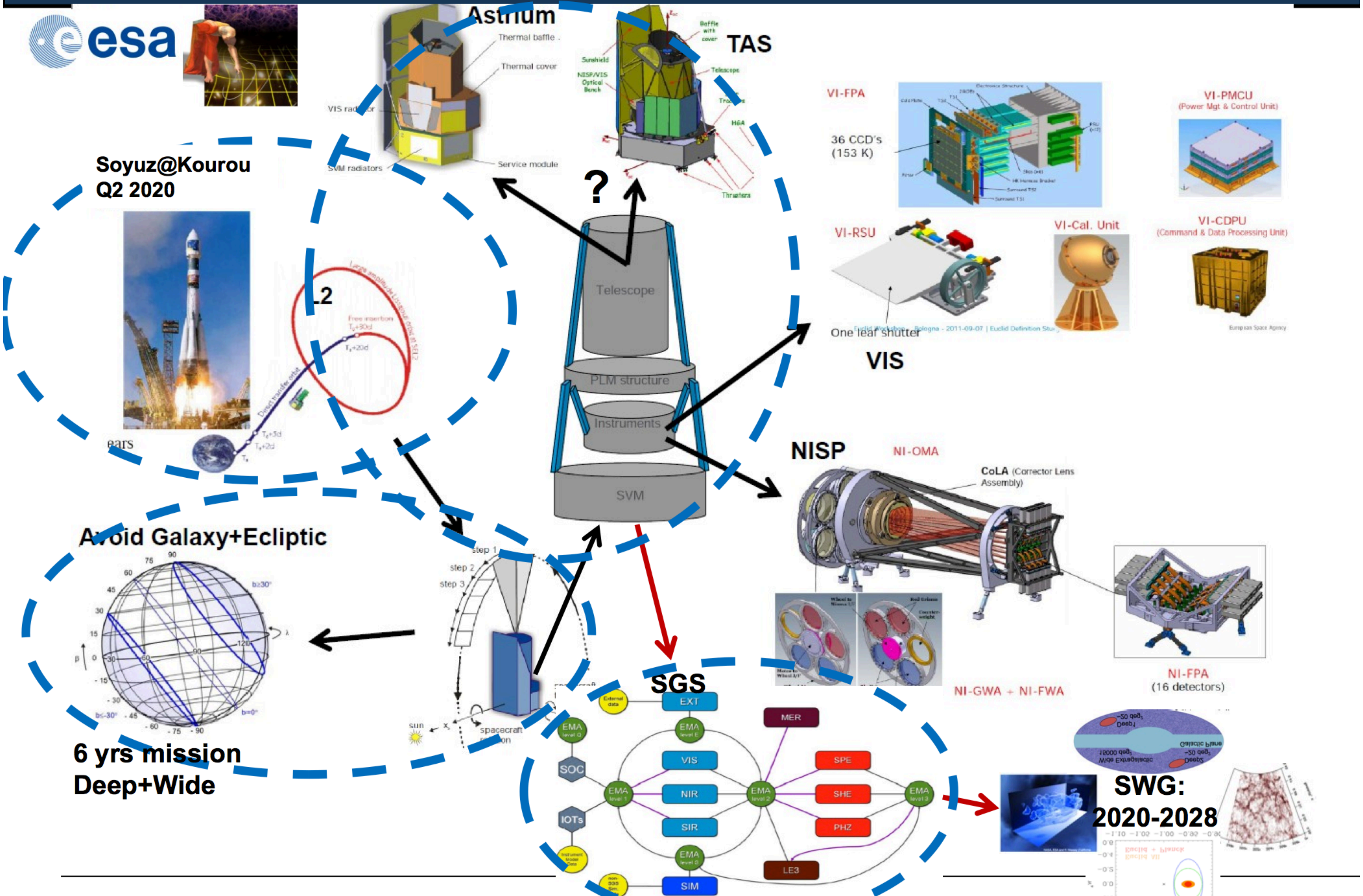
Answering Euclid key science question 2: Is is the apparent acceleration instead a manifestation of a breakdown of General Relativity on the largest scales?

The Euclid mission

Euclid Consortium

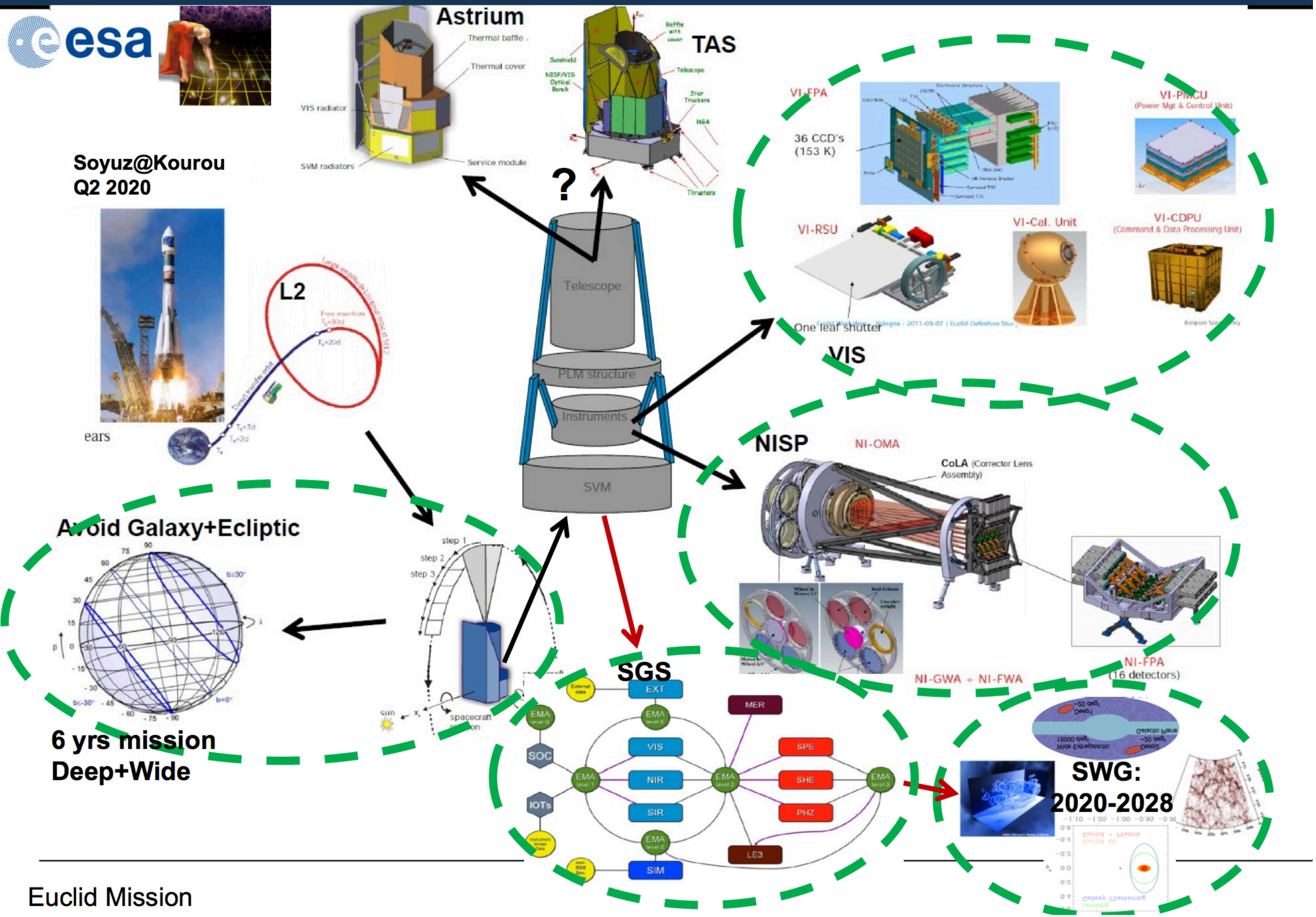


Contributions of ESA/industry



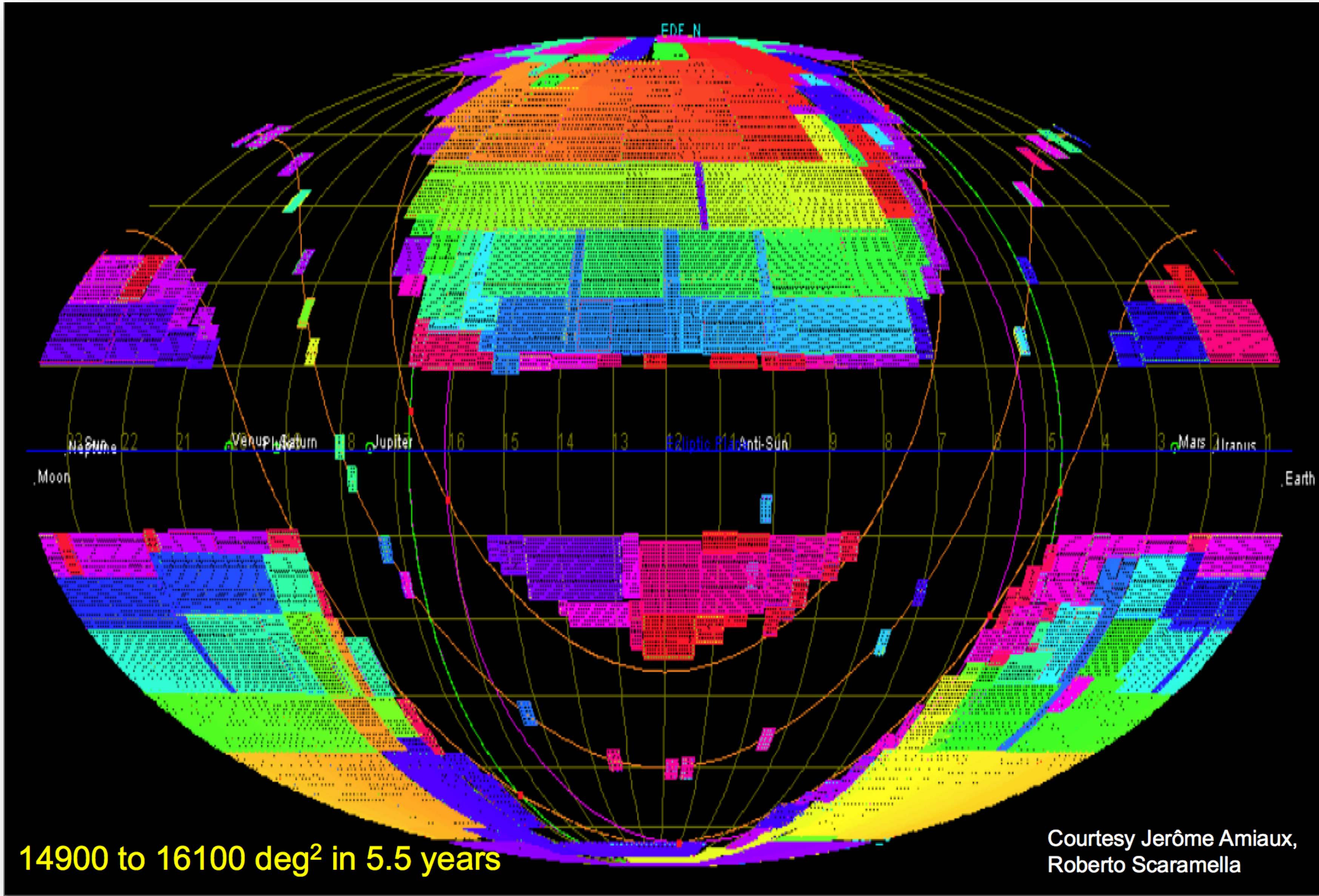
Contributions of the Euclid Consortium

Euclid Consortium



Euclid Wide+Deep Surveys feasible in 5.5 years

Euclid Consortium



LINKS TO GROUND-BASED SPECTROSCOPY

Weak lensing requirements

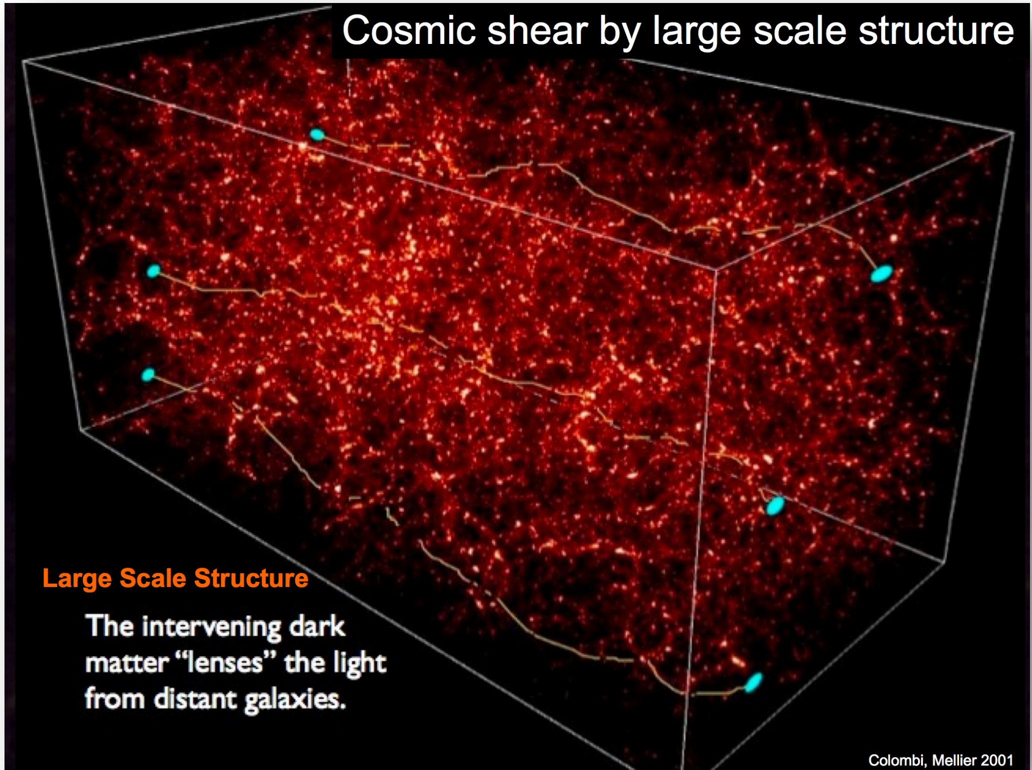
- Required to reach dark energy and modified gravity objectives

- Accurate Shape Measurement
  - Achieved through stable satellite and space environment
  - Small diffraction limited PSF
  - Resolved galaxies (small pixels 0.1'')
  - Broad optical filter RIZ to achieve required S/N

- Redshift Estimate
  - Necessarily photometric redshifts (too many for spec-z)

Weak Lensing requirements

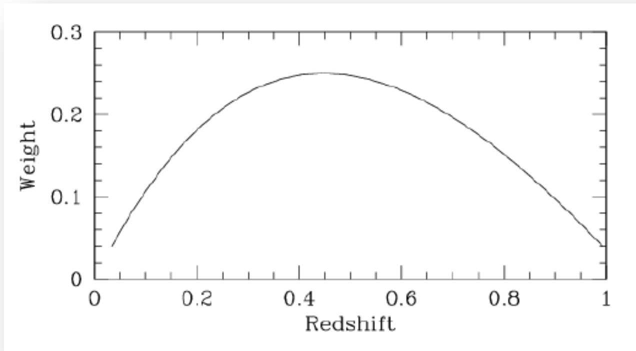
- The lensing kernel is most sensitive to structure halfway between the observer and the source. But the kernel is broad: we do not need precise redshifts for the sources: photometric redshifts are fine
- Also, since the kernel is broad the tomographic bins are very correlated. The gain saturates quickly with the number of bins: not many z bins



Geometry   Large Scale Structure

$$C_{ij}(\ell) = \int_0^{r_H} \mathrm{d}r\, W_{ij}^{\mathrm{GG}}(r) P_{\delta\delta}\left(\frac{\ell}{S_k(r)}; r\right)$$

Lensing Power Spectrum



How Euclid does it

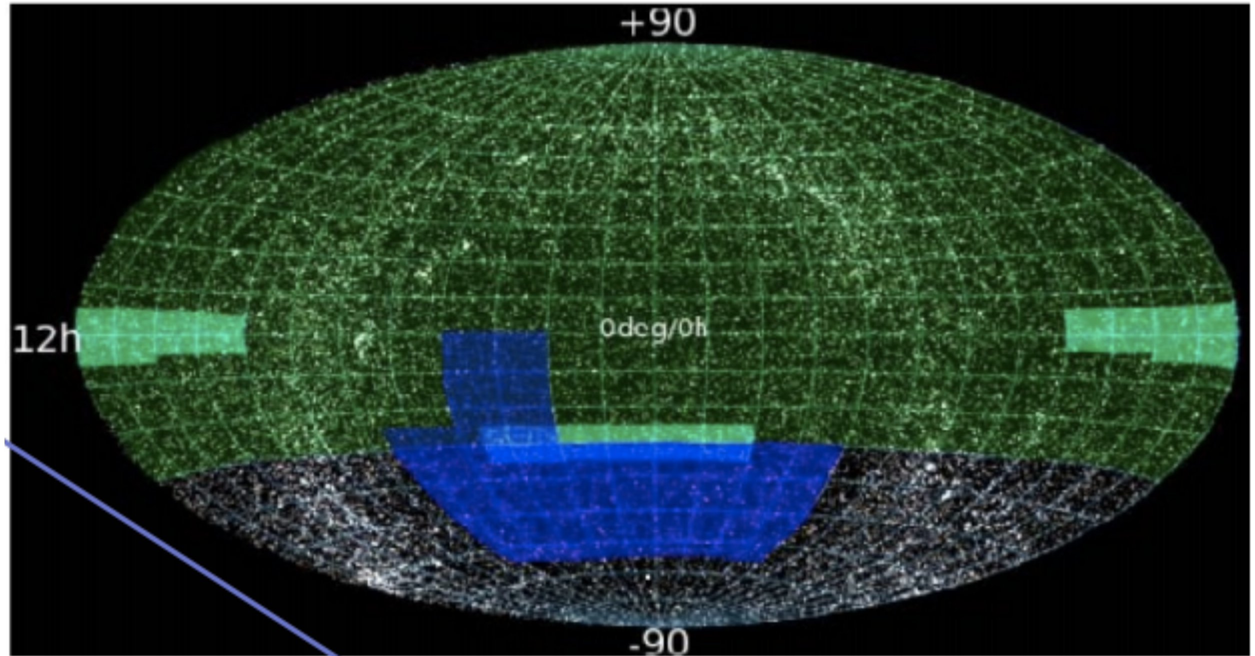
Euclid Consortium

- 1) On board NIR bands (JHK)
- 2) Ground-based optical photometry (griz)

PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Ground surveys: imaging/photometry for photo-z

Euclid Consortium

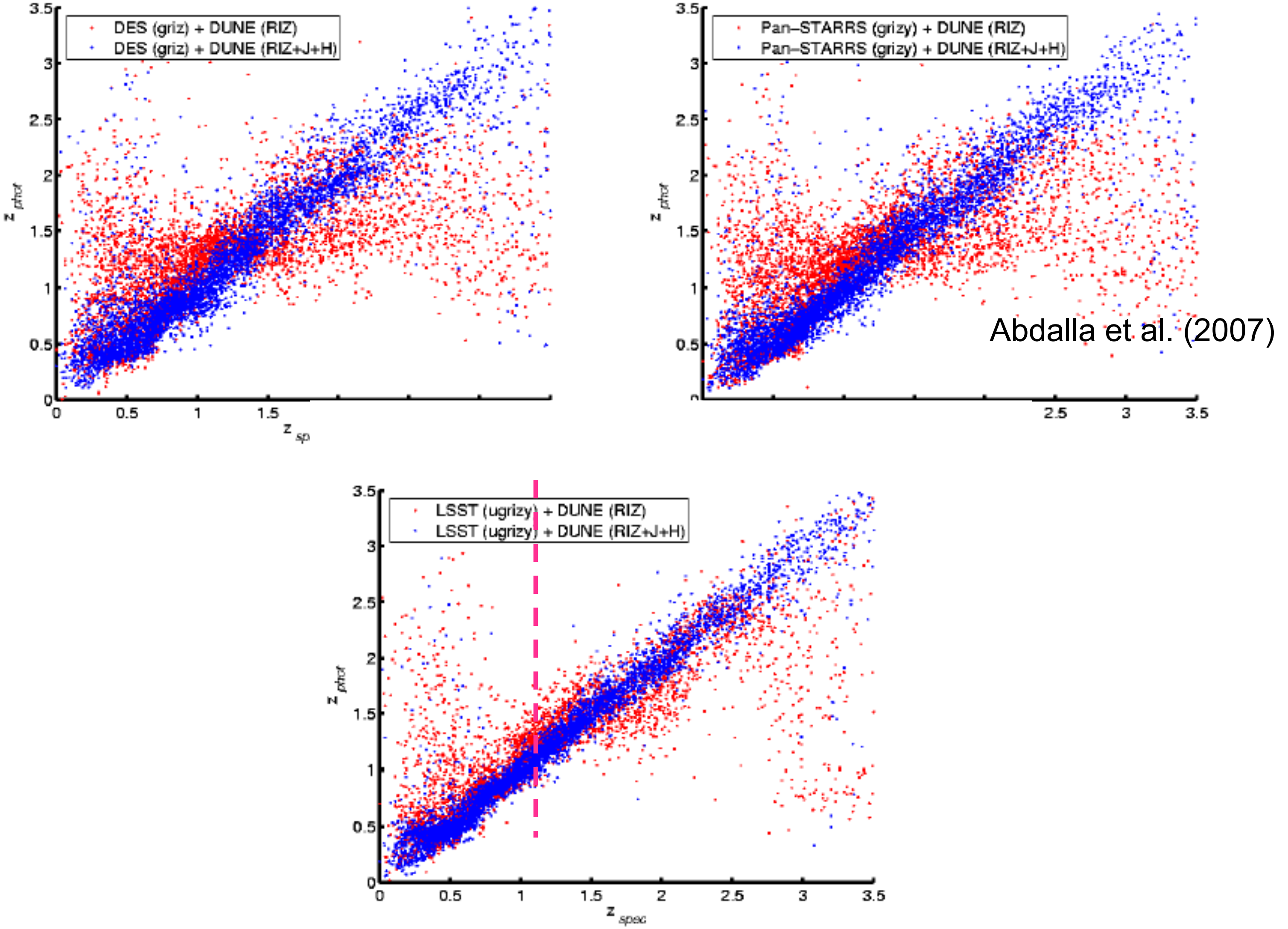


External survey timelines	2011	2012	2013	2014	2015	2016	2017	2018
KiDS-VIKING	Survey underway		VIKING completed	KiDS completed, VIKING final release	, KiDS final release			
Pan-STARRS1	Survey underway		Survey completed		PS1 final release			
Pan-STARRS2				Survey start				
DES		Survey start		1st data release		Survey end	Final data release	
LSST								2020?
GAIA		Launch						

Survey	Area (sq deg)	U	G	r	i	z	Y	J	H	K
KiDS+VIKING	1500 Eq+SGC	24,8	25,4	25,2	24,2	23,1	22,3	22.0	21,5	21,2
Pan-STARRS1	15000 NGC+½ SGC		23,4	23,0	22,7	22,0	20,9			
PS2	15000 NGC+½ SGC		24,8	24,4	24,1	23,4	22,3			
DES	5000 ½ SGC		25,4	24,9	24,8	24,7	22,3			

Slide from Y. Mellier

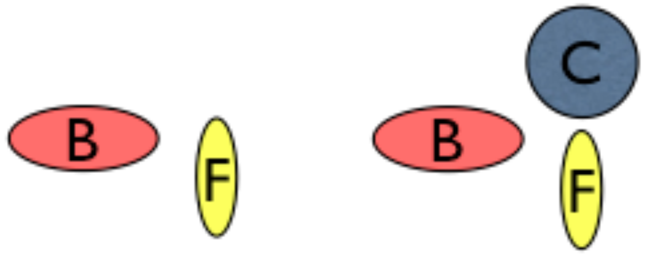
- Optical griz+Euclid(YJH) meets requirements on photo-z errors



Intrinsic alignments

(T. Kitching, H. Hoekstra, B. Joachimi, et al.)

Gravitational lensing is not the only source of shape alignments. The local gravitational tidal field generates torques and shear forces.



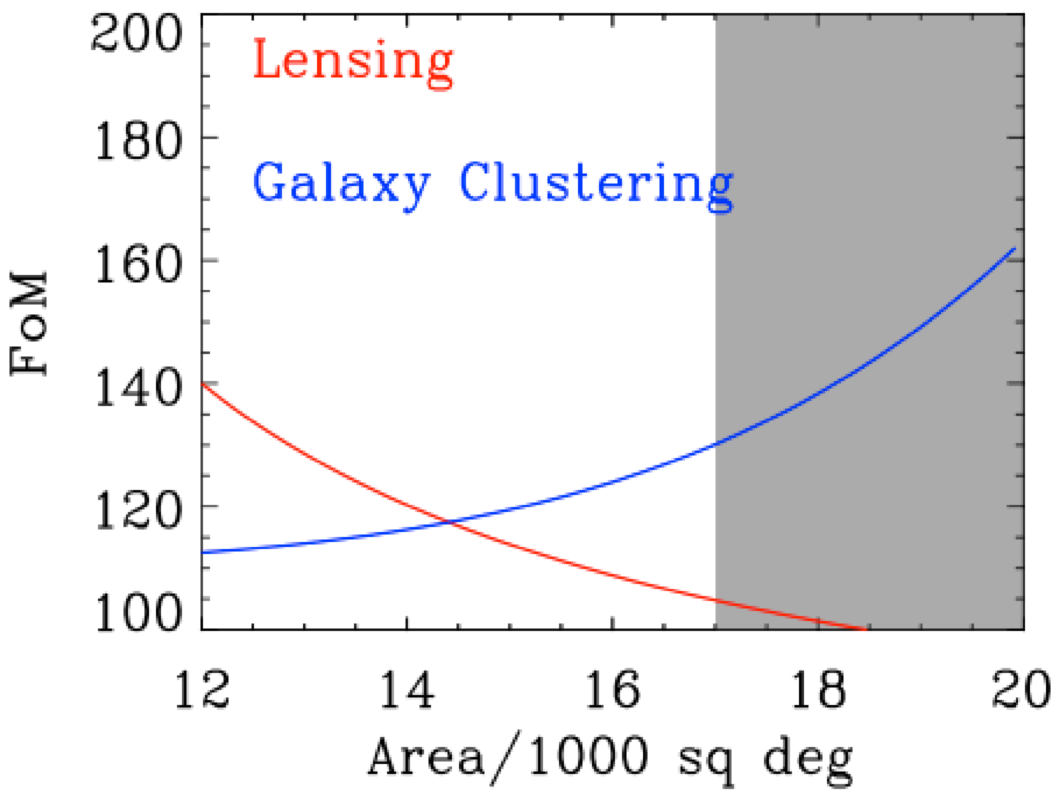
- Shapes and angular momenta of galaxies are intrinsically aligned
- Leads to additional contributions to the ellipticity correlation function:

$$\varepsilon_{\mathrm{observed}} = \gamma + \varepsilon_{\mathrm{intrinsic}} + \mathrm{noise}$$

$$\langle \epsilon_i \epsilon_j \rangle = \underbrace{\langle \gamma_i \gamma_j \rangle}_{\mathrm{GG}} + \underbrace{\langle \epsilon_i^s \epsilon_j^s \rangle}_{\mathrm{II}} + \underbrace{\langle \gamma_i \epsilon_j^s \rangle + \langle \epsilon_i^s \gamma_j \rangle}_{\mathrm{GI}}$$

Intrinsic alignments

We currently know little about intrinsic alignments. We therefore have to model the signal using a generic (flexible) approach. This leads to a preference of a deeper, but smaller survey for a given survey duration.



Intrinsic alignments

The intrinsic alignments signal can be measured by correlating the shapes of galaxies that are physically associated, i.e. close in redshift. The required ground-based imaging data allow us to do this: Euclid survey “sweet spot” at 15,000 deg^2

The few observational constraints (supported by results from numerical simulations) suggest that early type galaxies may show stronger alignments. As they tend to be associated with more massive structures, they also contribute most to the GL signal.

A spectroscopic survey of early type galaxies would be extremely useful to improve the measurement of the IA signal, and thus improve the precision of the cosmic shear results.

But we need to know n(z) well

Euclid Consortium

R-WL.1-7: The mean of the redshift distribution n(z) in each tomographic redshift bin shall be known to a precision of $\sigma(<z>)/(1+z)<0.002$

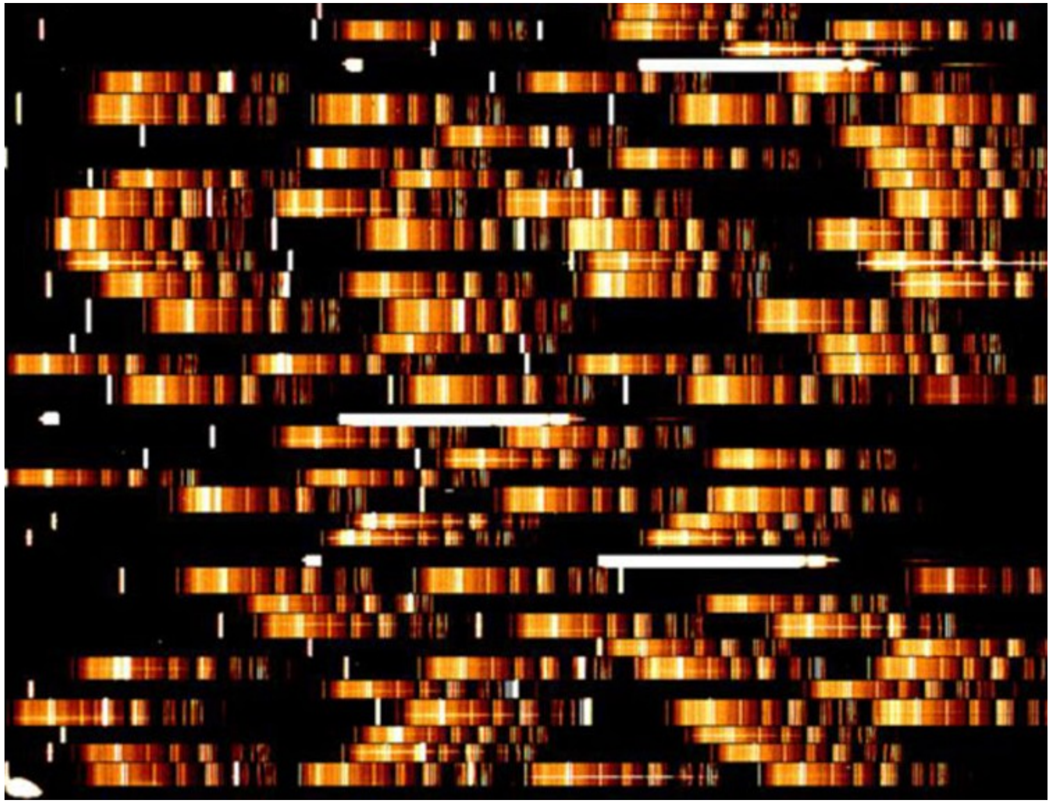
R-EXT.2-1: Spectroscopic redshifts for more than 10^5 galaxies shall be available. The properties of these galaxies should be representative of the full population of galaxies used in the weak lensing analysis. The fraction of galaxies for which redshifts could not be determined should be $<4\times10^{-4}$.

The completeness needs to be confirmed.

So, Euclid WL does need ground-based redshifts …

What is / will be available?

ESO PR, Le Fèvre et al 2006



- **CFHTLS : VVDS** with VMOS,
  - 32,000 redshifts to I=22.5 over ~15 deg^2, (Garilli et al 2008)
  - 15,000 to I=24 over ~1 deg^2 (Le Fèvre et al 2005)
  - 1000 redshifts 23<I<24.75 over 0.15 deg^2 (Le Fèvre et al 2012)

- **CFHTLS : VIPERS** with VMOS: ~100,000 redshifts to I=22.5 over 25 deg^2 (Guzzo et al 2012)

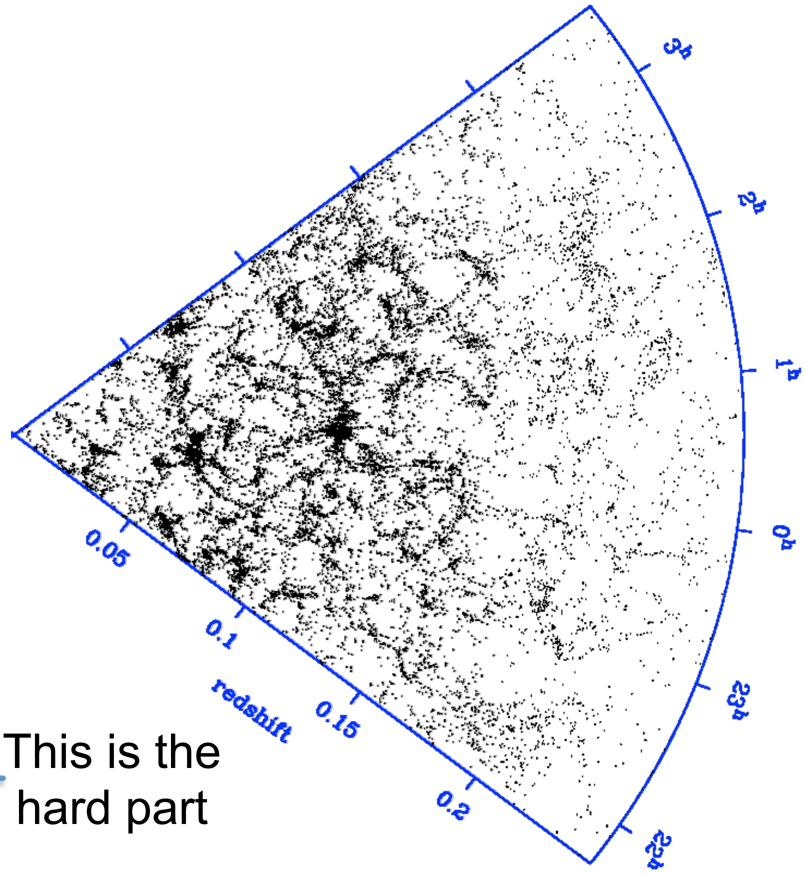
- **COSMOS : z-Cosmos** with VMOS:
  - ~ 20,000 redshifts to I=22.5 over 1.7 deg^2 (Lilly et al 2009)
  - ~10,000 redshiifts B<25.25 color selected, over 0.9 deg^2

… How can we get 10^5 redshifts for I=24.5 + subsamples to I>24.5??

Clustering of galaxies: Requirements

Euclid Consortium

- Need angular galaxy positions
- Need galaxy redshifts



- Need to understand population
  - angular completeness
  - radial completeness
  - radial/angular fluctuations

This is the hard part

- Then we can go from a density field to an overdensity field, and measure statistically the amplitude and anisotropy of clustering (correlation function, power spectrum)

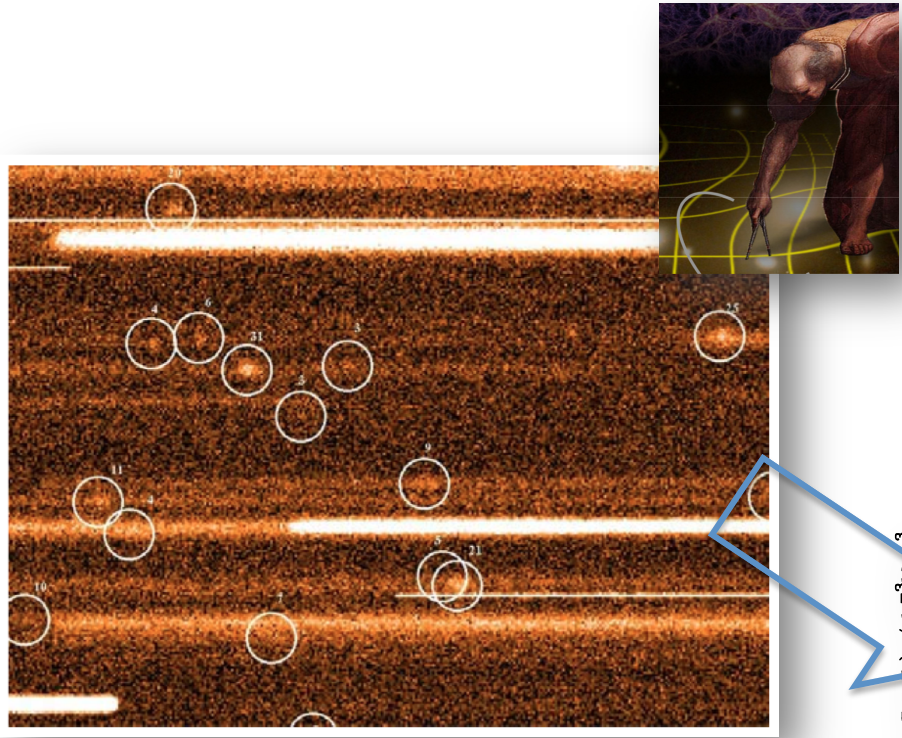
How we do it: slitless spectroscopy from space. Why?

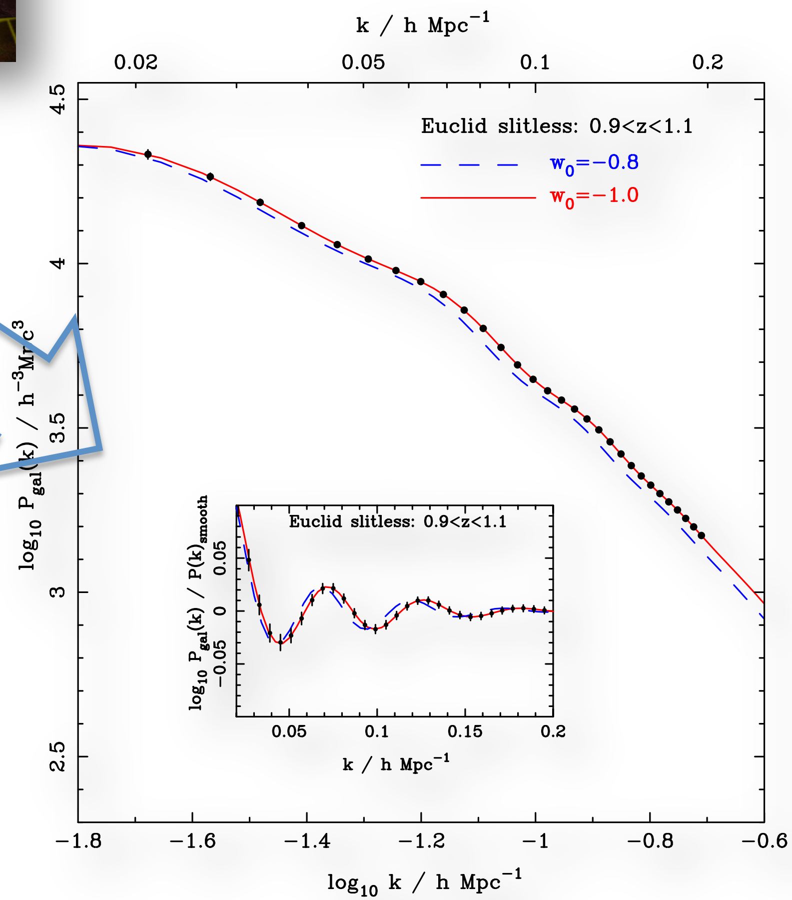
- Near-IR spectroscopy targets rest-frame optical for z>0.7: best complementary with low-z ground-based optical (e.g. SDSS)
- Very high-multiplexing NIR spectroscopy not feasible from the ground: sky-line forest needs higher dispersion (long spectra, low packing)
- H-alpha is a primary tracer of the star formation rate: abundant at early epochs → enough galaxy density at high redshift to achieve cosmology statistical goals
- The most important emission lines are in the rest-frame optical (i.e. redshifted in the near-IR for z>0.7)
- H-alpha is less affected by galaxy internal dust extinction than other lines in the blue (e.g. a factor of about 2 less than [OII]3727)

- Slitless technique provides an *a priori* uniform sample, with no need to specify a target sample
- There is no free lunch, however. Simpler to do, more complex to understand

The long way from raw data to cosmology

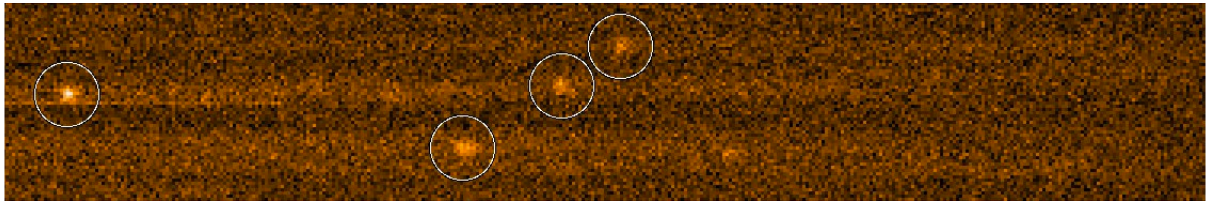
Euclid Consortium





Sources of bias for spectroscopy

Slitless spectroscopy is technically simpler, but the resulting selection function is complex: confusion of adjacent spectra makes measuring redshifts more difficult in crowded areas:



- **Completeness:** what fraction of all galaxies expected to a given limit (in Hα flux) will not have a redshift because of confusion?
- **Purity:** what fraction of the measured redshifts is correct (within statistical errors) I.e. how many catastrophic errors do we expect? And which is their redshift distribution?

The main problem is that for these observations there is no such a thing as a parent sample: we know the flux of our objects only *after* performing the spectroscopic observations (no "a priori" mag-limited sample, as in standard slit-based redshift surveys)

Spectroscopic requirements on systematic errors

- Well understood sample of galaxies ($0.7<z<2.0$) with accurate redshifts $\sigma_z<0.001(1+z)$
- We want:
  - High and controlled redshift measurement success rate:
    - Angular position (density dependence → control spectral confusion)
    - Redshift (wavelength dependence → control flux limit)
  - Control catastrophic redshifts (<20% from L1):
    - Accurately know their fraction (error <1%)
    - Accurately know mean in redshift shell (systematic << statistical)
- **Need control sample of ~2 x 10^5 redshifts, with purity > 99% at the depth of the Euclid survey: Deep Field**
- Shall we need a ground-based spectroscopic follow-up of the Deep field?
- This is not a requirement, but might be desirable at some point, given the accuracies we are aiming at…

Take home 1 (for ground-based fans)

Euclid Consortium

GENERAL:

1. Euclid will perform an unprecedented redshift survey of the $0.7<z<2.1$ Universe, building a sample of ~6 10^8 galaxies with measured distances (and much more)

2. Results combined with WL companion survey may well revolutionize our understanding of physics

GALAXY CLUSTERING PROBE:

1. Slitless spectroscopy targeting H-alpha: simpler to do for the engineers, complex to understand for astronomers, limited spectral information for legacy

2. Simulations fundamental to understand systematics

3. Deep calibration field will provide the crucial "real thing" to believe the simulations and provide final calibration

4. Any follow-up spectroscopy may clean important aspect and lead to "gold" samples to verify broader cosmological results: worth having, given the potential of the Euclid data

5. Of course, spectroscopic follow-up of specific objects will be interesting per se from the galaxy evolution point of view

Take home 2 (for ground-based fans)

Euclid Consortium

WEAK LENSING:

1. Euclid will perform an unprecedented imaging survey of ~ 10^9 galaxies with measured shapes
2. Support ground-based spectroscopy is an important part of the photometric-redshift calibration
3. Also crucial to disentangle intrinsic alignments
4. Spectroscopy of ~10^5 galaxies at z~1-3 down to I~24.5 needed, with proper coverage of SED types

More about Euclid

To date the Euclid Consortium (EC) includes members from 14 European countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Romania, Spain, Switzerland and the United Kingdom), with additional contributions from a few US laboratories.

In total, nearly 1000 scientists are registered in the EC, which makes it the largest astronomy consortium to date. More than 100 European laboratories covering all fields in cosmology, theoretical physics, high energy, particle physics and space science contribute to Euclid.

For more information:

- Consortium website at: http://www.euclid-ec.org/
- Euclid "Red Book"

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#

Euclid performance

Euclid Consortium

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current (09/2011)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

Euclid addresses most aspects of the current cosmological paradigm