Title: Mapping the Universe with Euclid

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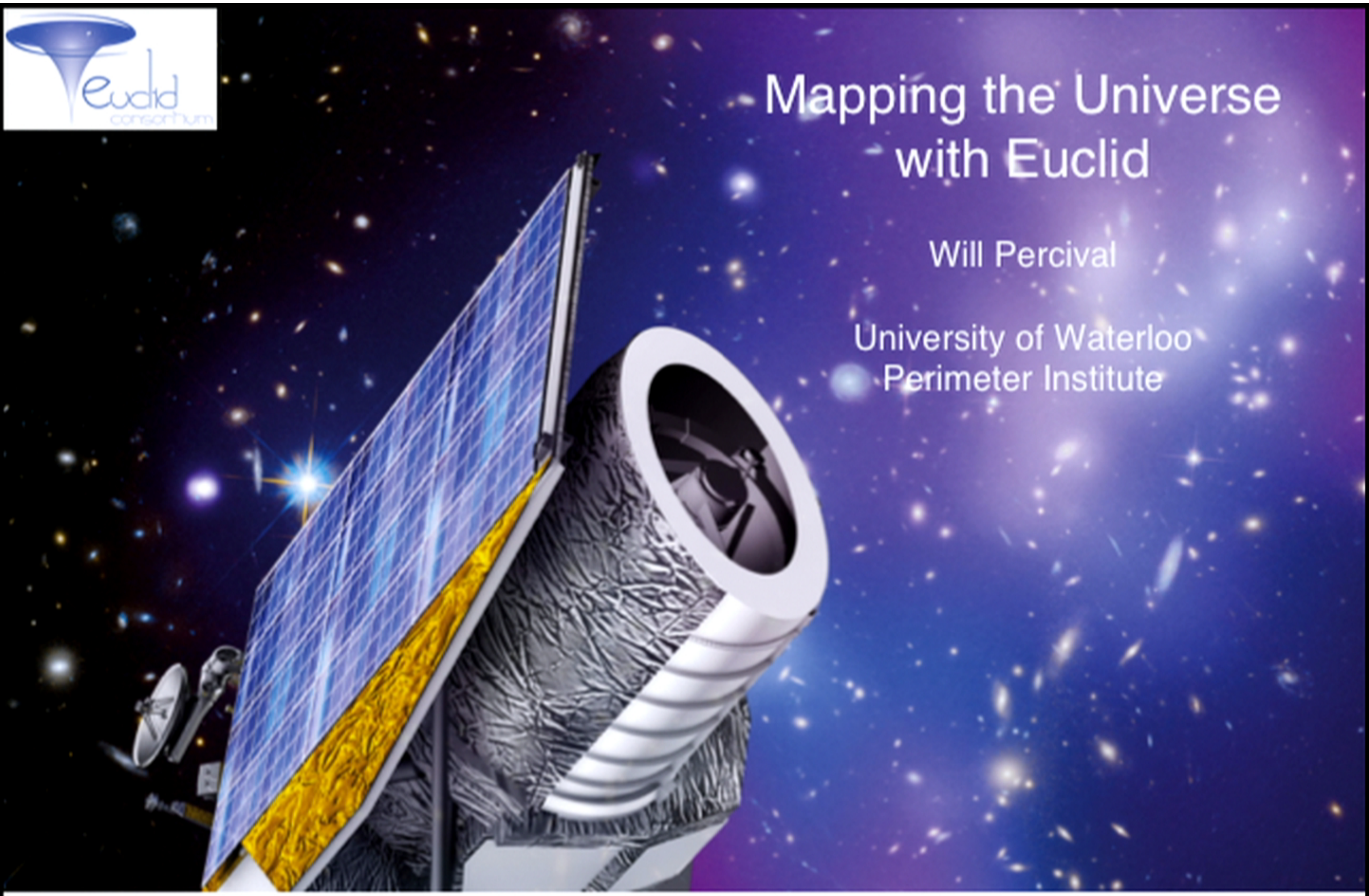
URL: http://pirsa.org/18030079

Abstract: <p>In 2020 the European Space Agency (ESA) will launch the Euclid satellite mission. Euclid is an ESA medium class astronomy and astrophysics space mission, and will undertake a galaxy redshift survey over the redshift range 0.9 < z < 1.8, while simultaneously performing an imaging survey in both visible and near infrared bands. The complete survey will provide hundreds of thousands images and several tens of Petabytes of data. About 10 billion sources will be observed by Euclid out of which several tens of million galaxy redshifts will be measured and used to make galaxy clustering measurements. These observations will be used to help to understand Dark Energy, the physical mechanism causing the current acceleration in the expansion of the Universe.</p>



Mapping the Universe with Euclid

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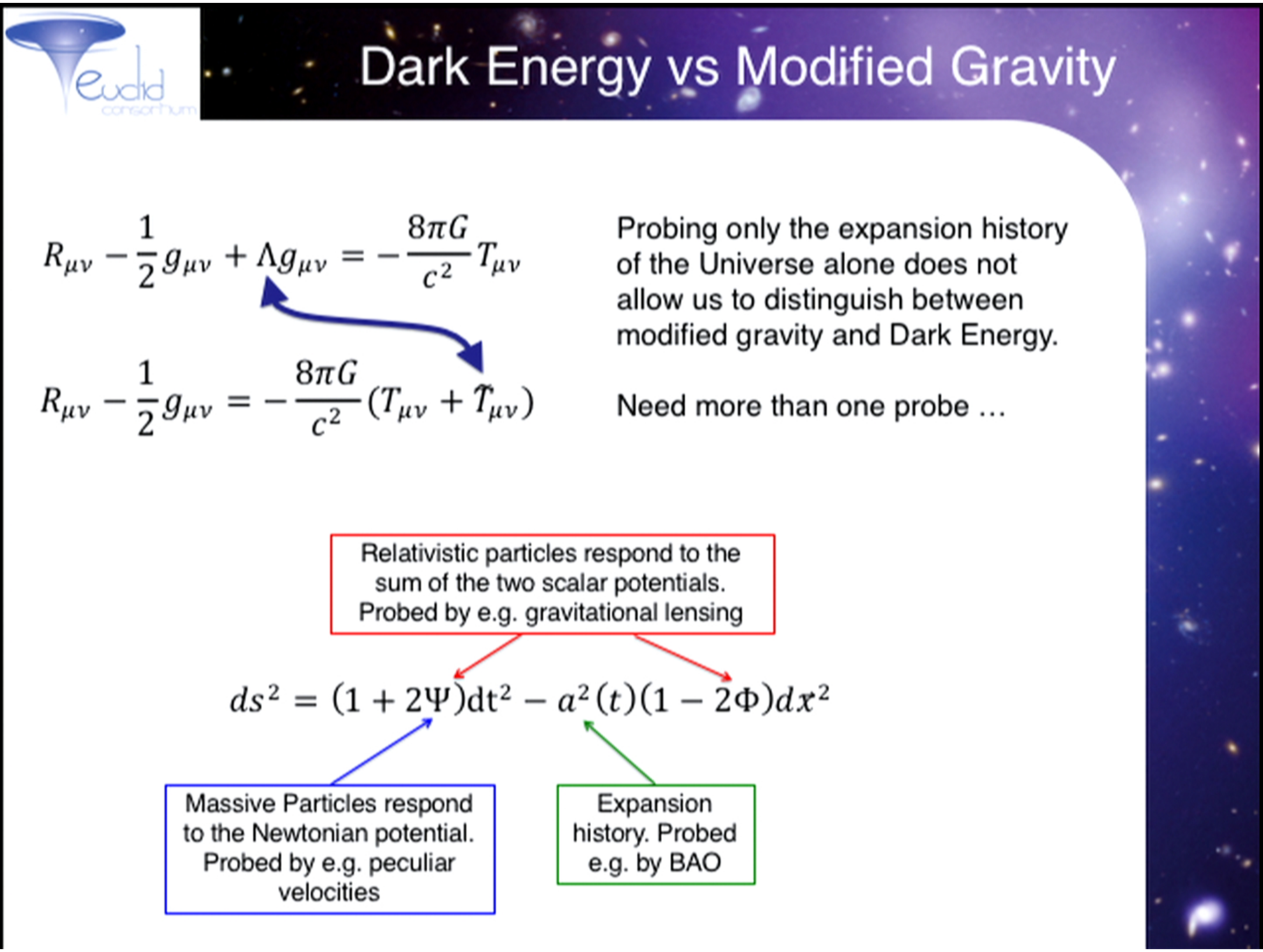
esa

CSA ASC



Dark Energy vs Modified Gravity

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

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} = -\frac{8\pi G}{c^2} (T_{\mu\nu} + \tilde{T}_{\mu\nu})$$

Probing only the expansion history of the Universe alone does not allow us to distinguish between modified gravity and Dark Energy.

Need more than one probe …

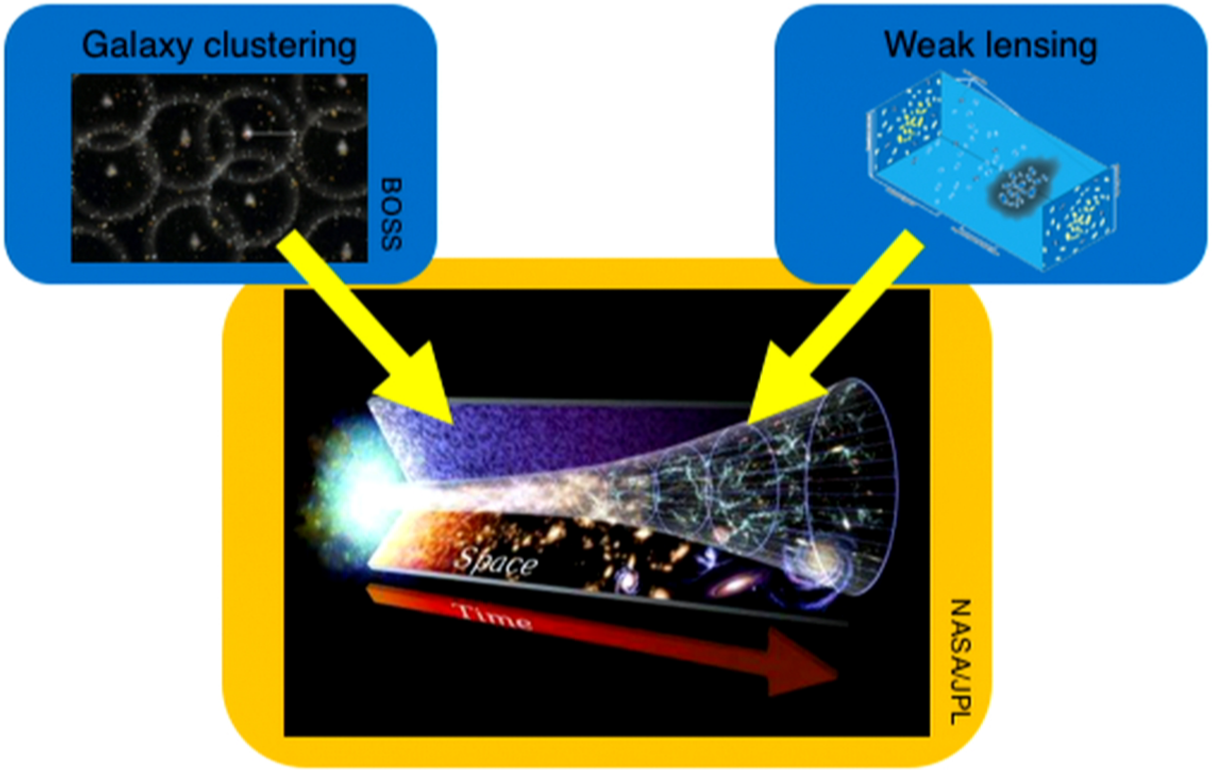
Relativistic particles respond to the sum of the two scalar potentials. Probed by e.g. gravitational lensing

$$ds^2 = (1 + 2\Psi)\mathrm{d}t^2 - a^2(t)(1 - 2\Phi)dx^2$$

Massive Particles respond to the Newtonian potential. Probed by e.g. peculiar velocities

Expansion history. Probed e.g. by BAO

Euclid: a cosmology-survey machine

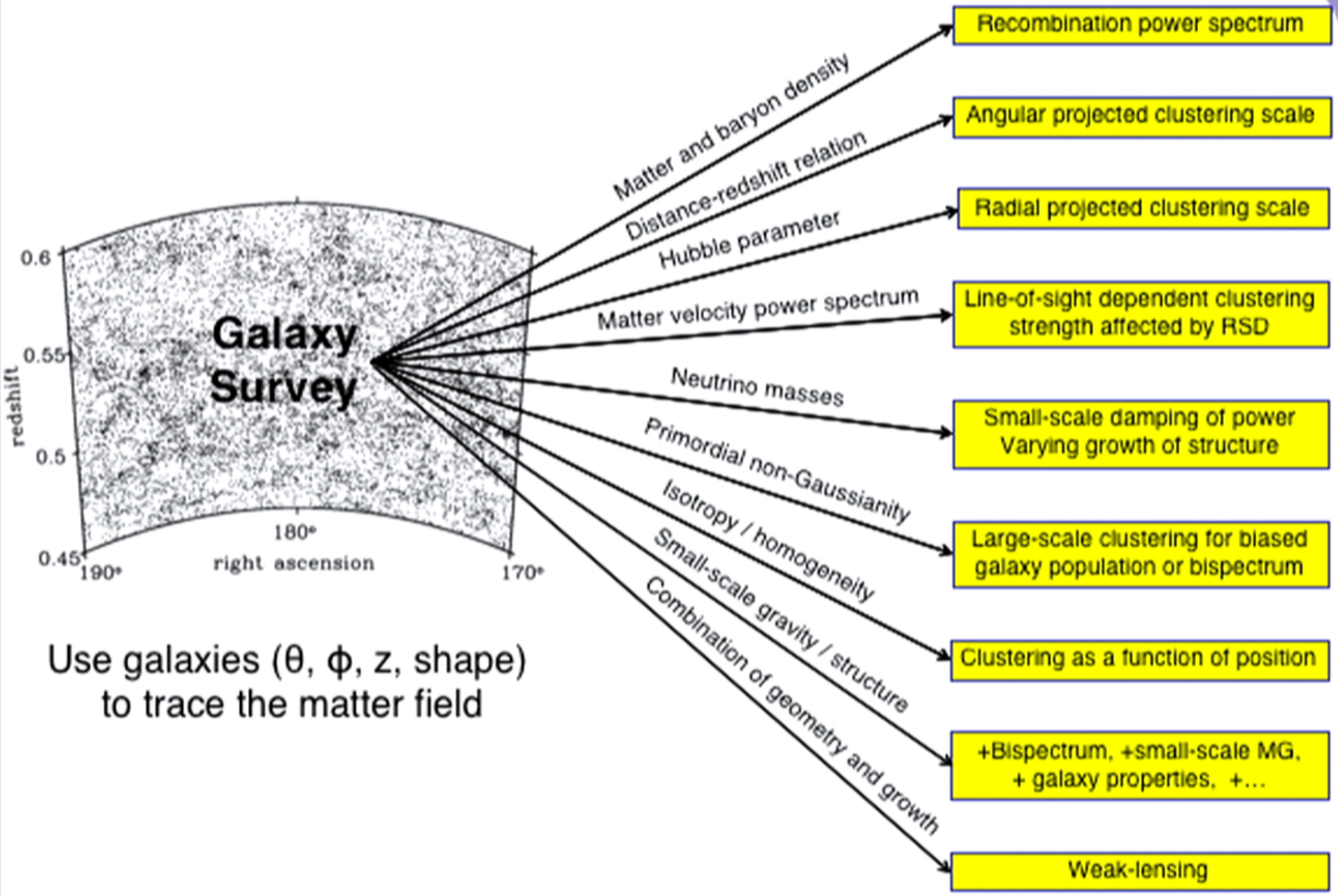


Type 1a supernovae

Cluster counts

CMB cross correlations

Science from a galaxy survey



Matter and baryon density → Recombination power spectrum

Distance-redshift relation → Angular projected clustering scale

Hubble parameter → Radial projected clustering scale

Matter velocity power spectrum → Line-of-sight dependent clustering strength affected by RSD

Neutrino masses → Small-scale damping of power Varying growth of structure

Primordial non-Gaussianity → Large-scale clustering for biased galaxy population or bispectrum

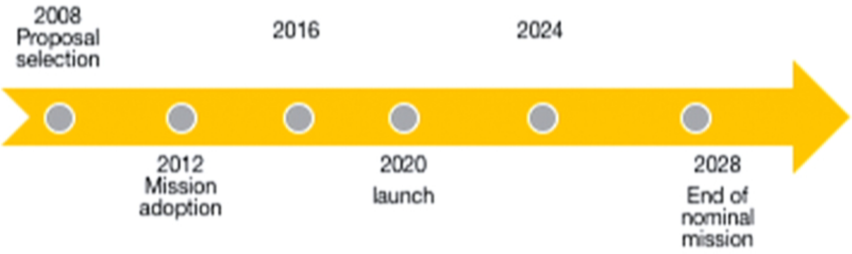
Isotropy / homogeneity → Clustering as a function of position

Small-scale gravity / structure → +Bispectrum, +small-scale MG, + galaxy properties, +…

Combination of geometry and growth → Weak-lensing

Use galaxies (θ, ϕ, z, shape) to trace the matter field

The Euclid mission



European Space Agency led mission

- Second medium mission in Cosmic Visions program
- Dark Energy experiment with great auxiliary science opportunities
- 3 years from launch
- 6 year mission
- Incremental public data releases

http://www.euclid-ec.org/

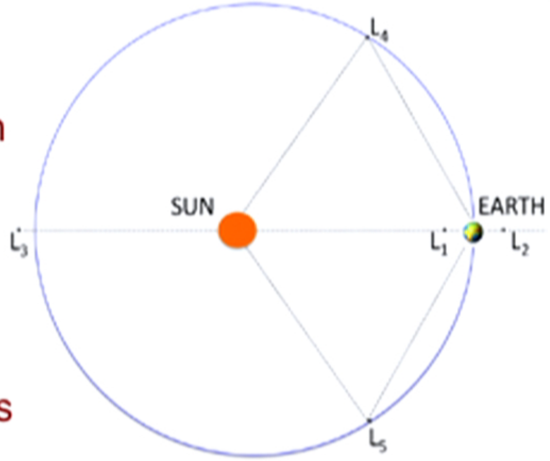
Libration points

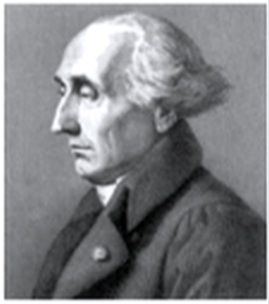
Libration points

- 5 Lagrange points in earth-sun system
- Euclid will go to L2

Satellite at L2

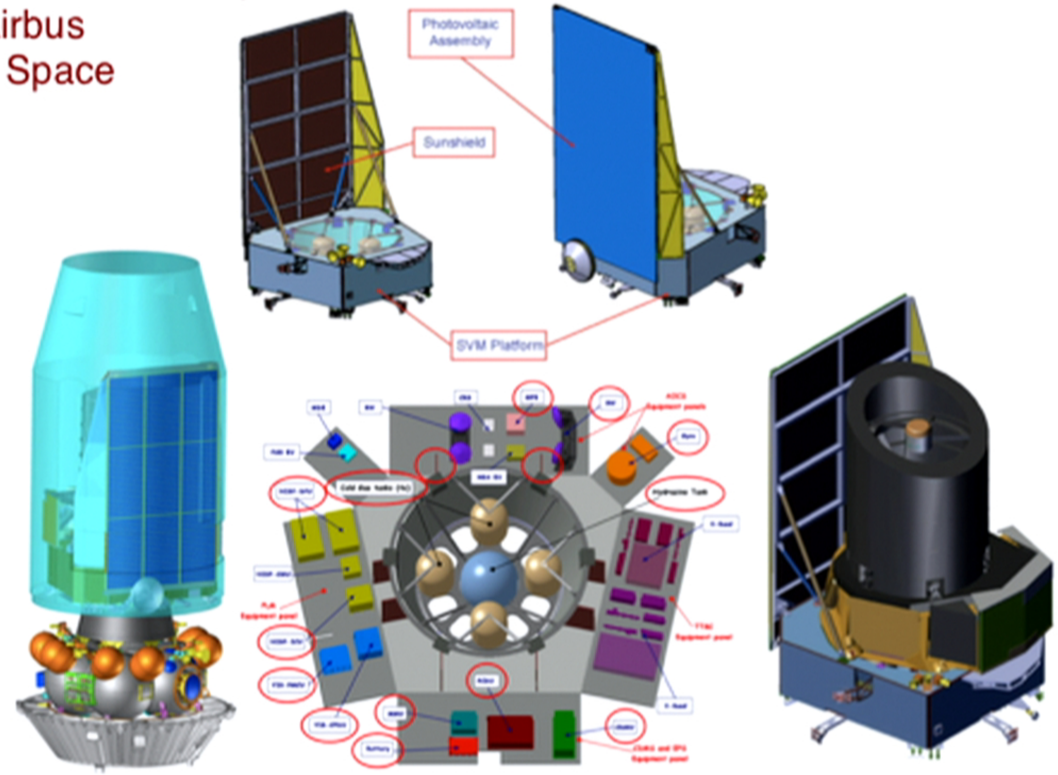
- Centrifugal force (R=1.01AU) balances central force (Earth+Sun)
    - 1 year orbit at 1.01AU with Sun+Earth attracting
    - Semi-stable position
- Formal theory relies on circular orbits and Earth+moon in 1 point
    - Hence, will orbit L2



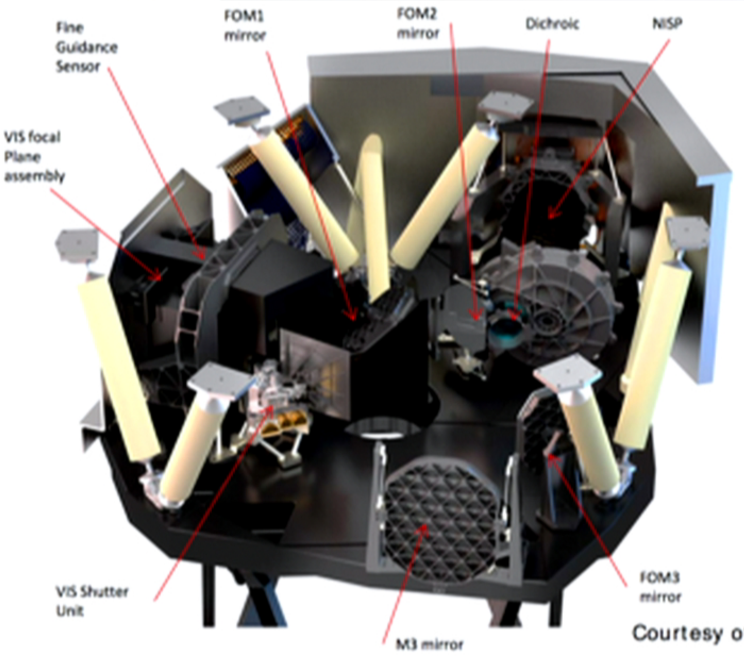

Lagrange 1736-1813

The spacecraft + payload

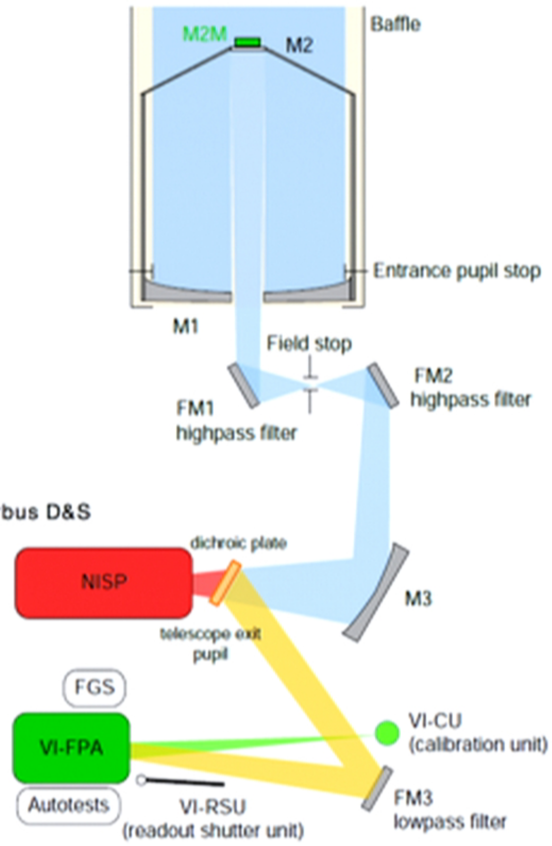
Total mass: 2200kg
Dimensions: 4.5m x 3m
Sunshield: Thales Alenia Space
Telescope: Airbus Defence and Space



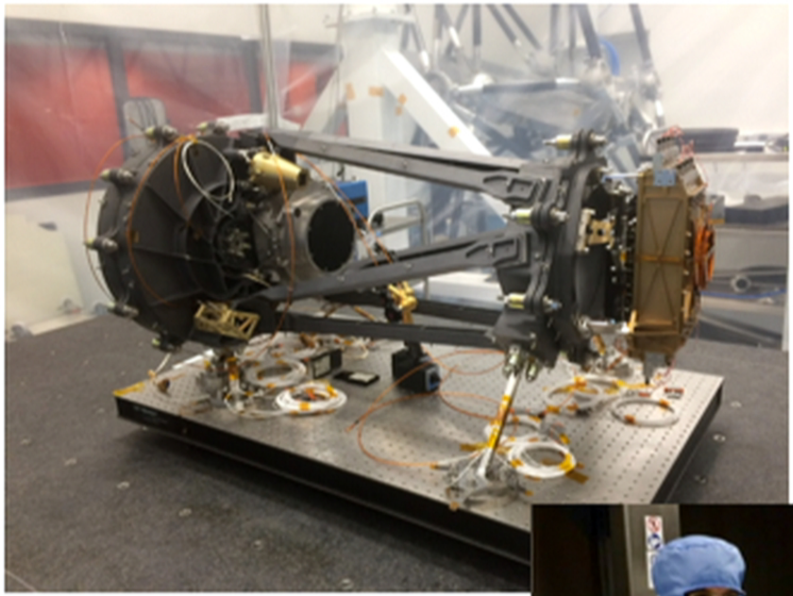
Payload module



Courtesy of Airbus D&S



Two channels: Visible and NIR

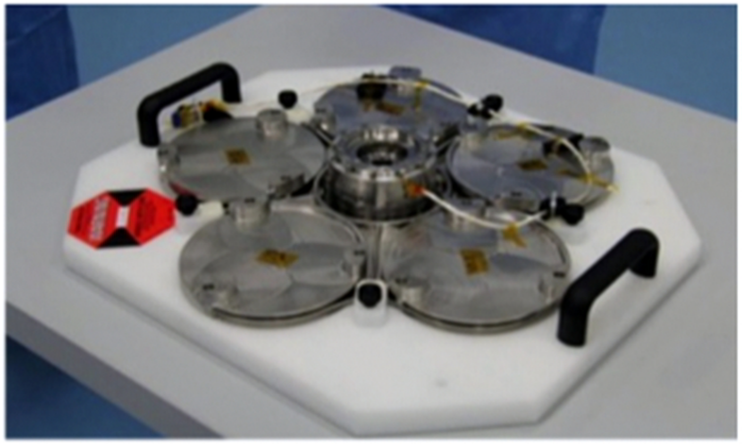


Structure and Thermal Model (STM) for NISP and VIS delivered and tested

NISP

Filter wheel: Y, J, H

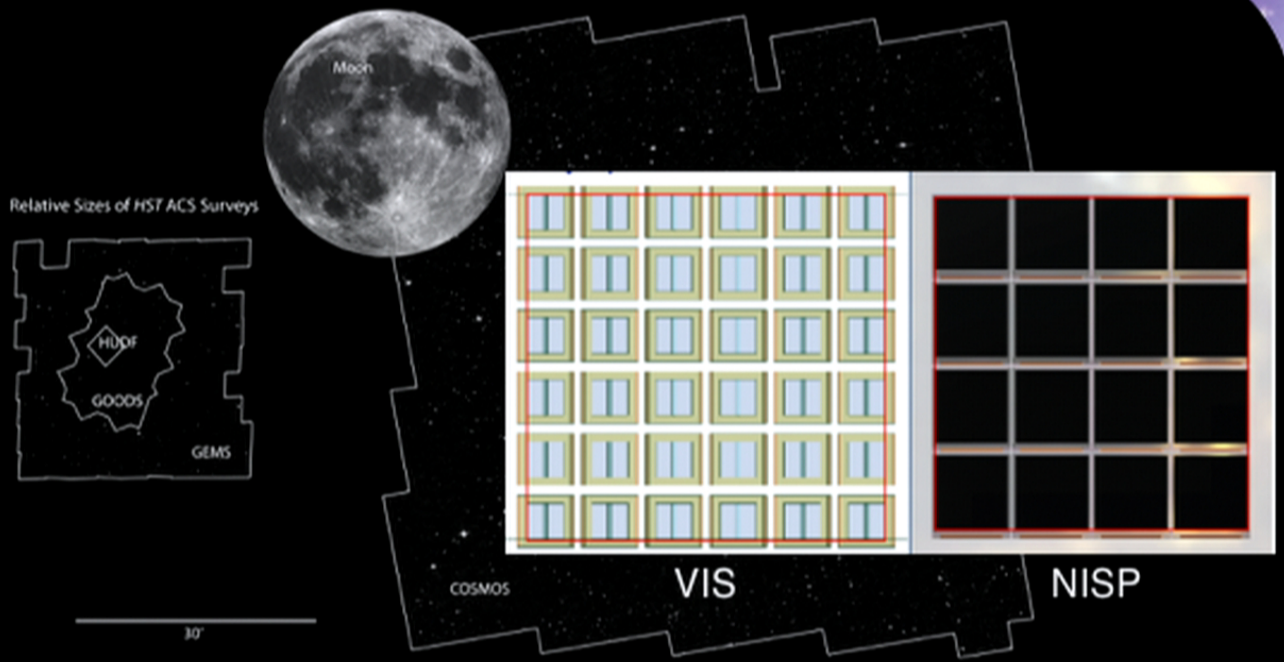
grism wheel: red 0, 90, 180, blue 0



NISP instrument will perform photometry in Y, J, H and slitless spectroscopy:

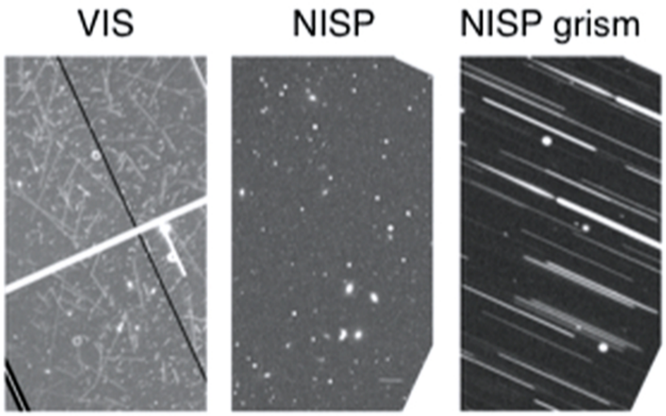
Red grism 1.25-1.85 μm
Blue grism 0.93-1.3 μm

Dual wide-field imagers

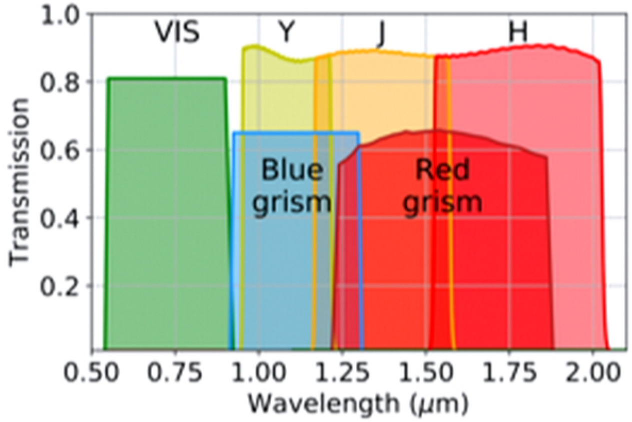


	VIS	NISP
Detectors	36 4096×4132	16 2040x2040
Pixel size	0.1”	0.3”
Dispersion	-	13.4 A/pixel

A panchromatic survey

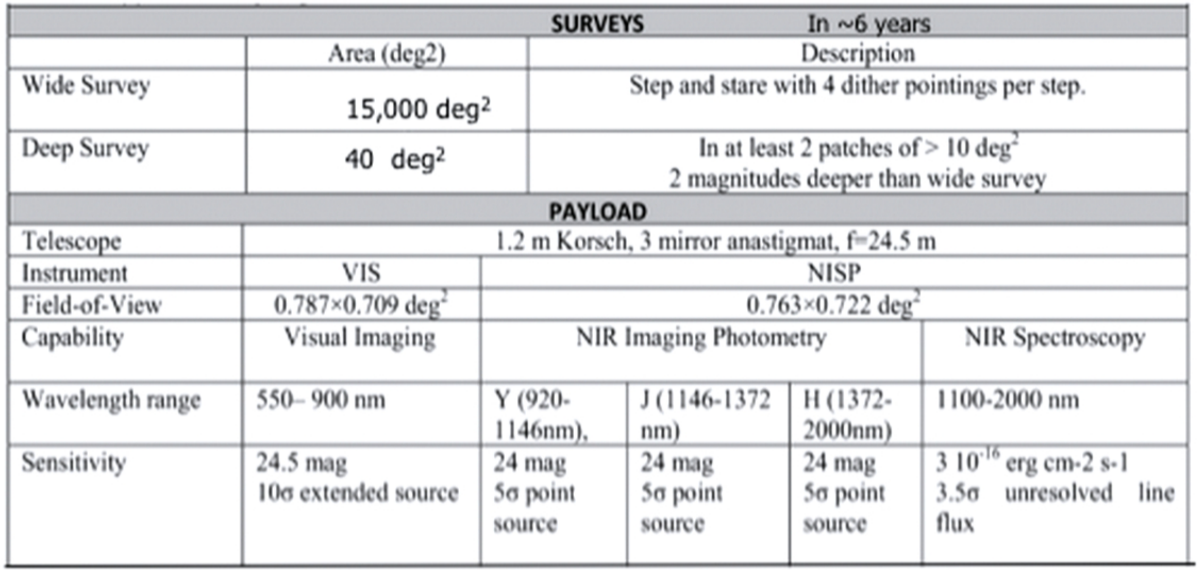


* NISP simulation does not include cosmic rays



	VIS	Y	J	H	GRISM
Wide	24.5	24	24	24	2x10^{-16} erg/s/cm^2
Deep	26.5	26	26	26	2x10^{-17} erg/s/cm^2

Euclid targets



		SURVEYS		In ~6 years	
	Area (deg2)	Description			
Wide Survey	15,000 deg^2	Step and stare with 4 dither pointings per step.			
Deep Survey	40 deg^2	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey			
		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

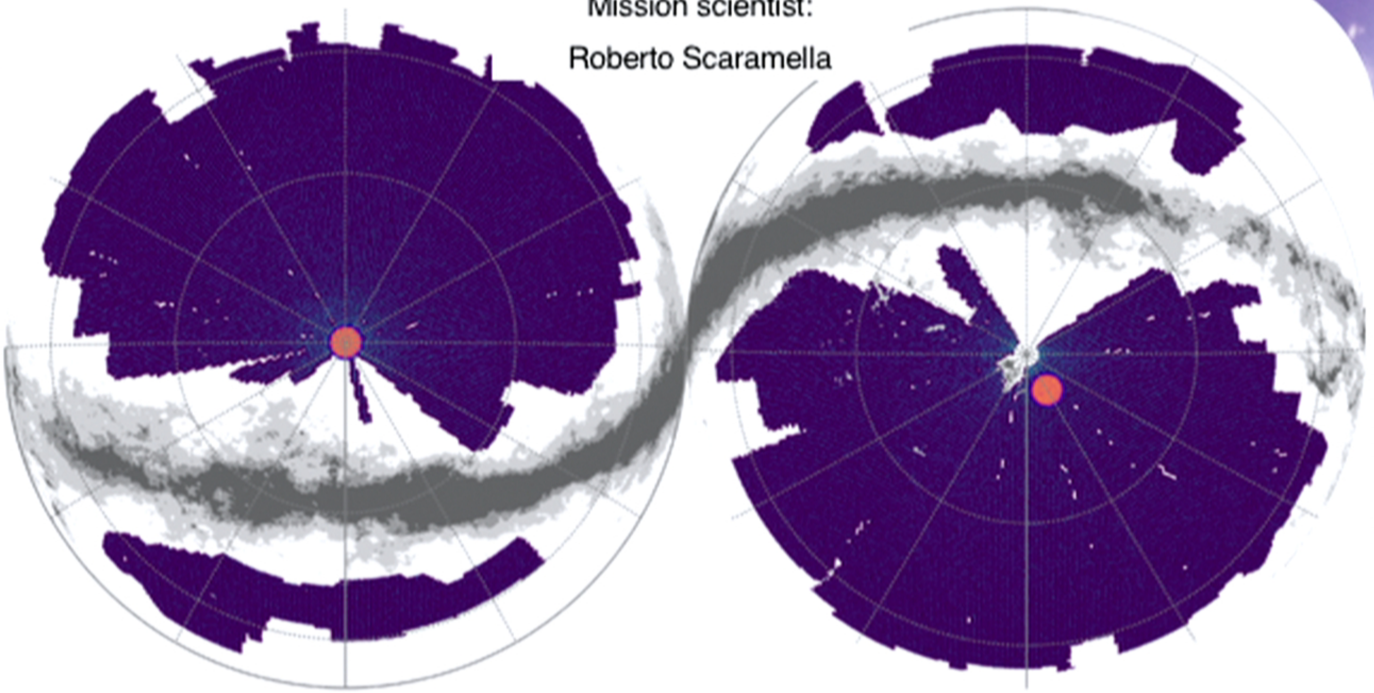
Shapes + Photo-z of n = 1.5 x10^9 galaxies,
Spectroscopic redshifts for n = 2.6x10^7 galaxies

Euclid Definition Study Report: Laureijs et al arXiv:1110.3193

Euclid reference surveys

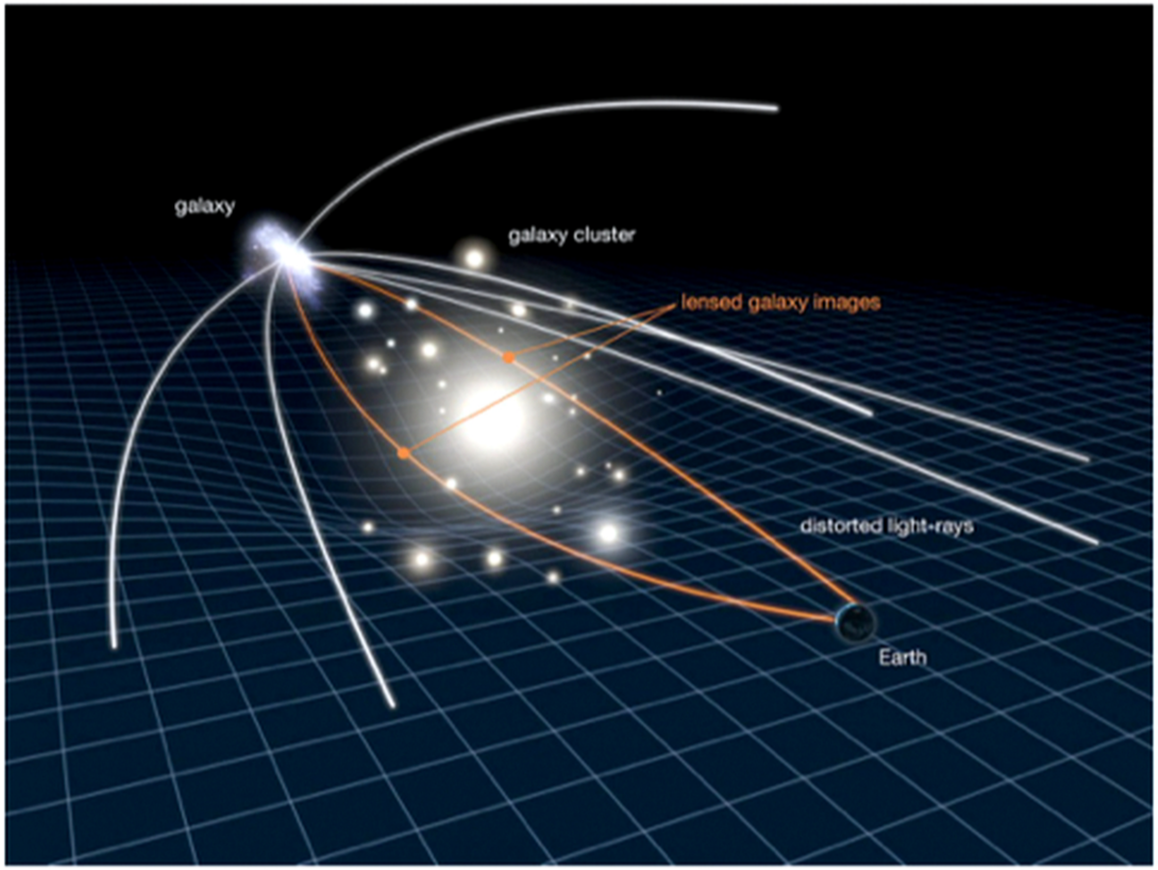
Mission scientist:

Roberto Scaramella



Wide	15000 deg^2
Deep	40 deg^2 - EDF-N (NEP) - EDF-S (SEP) - EDF-Fornax (CDF-S)

Lensing



Light propagation through large-scale structure gives a lensed image

Image credit: NASA/JPL

Weak-lensing

Assumptions

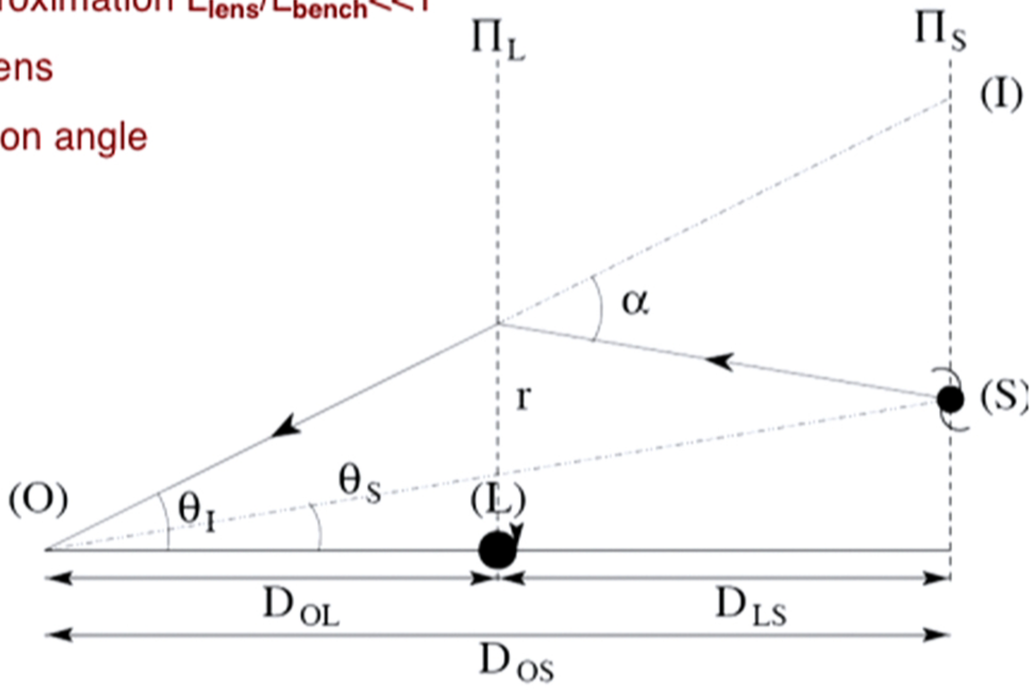
weak field limit $v^2/c^2 << 1$

stationary field $t_{dyn}/t_{cross} << 1$

thin lens approximation $L_{lens}/L_{bench} << 1$

transparent lens

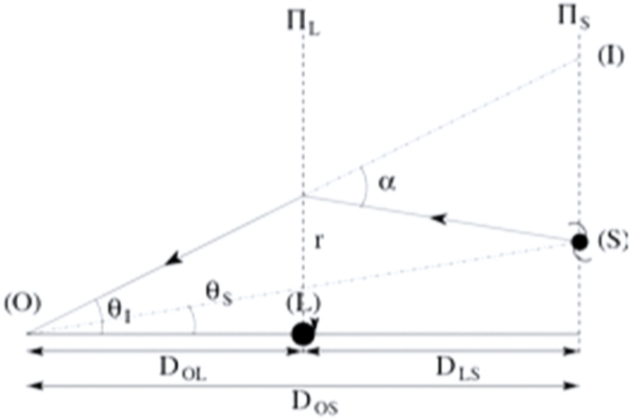
small deflection angle



Weak-lensing

The bend angle depends on the gravitational potential through

$$\alpha = \frac{2}{c}\int \nabla_{\perp}\Phi d\ell$$

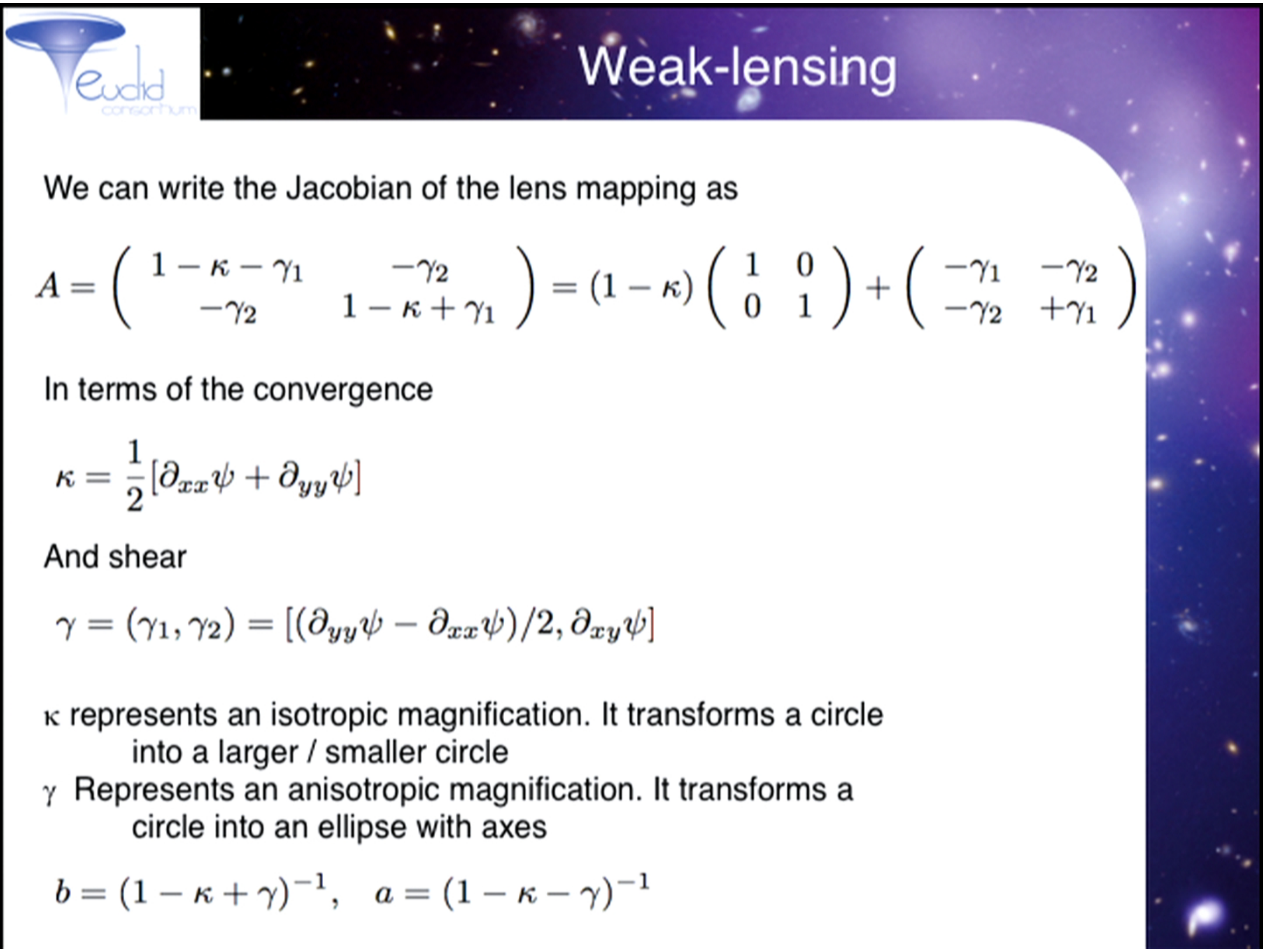


So the lens equation can be written in terms of a lensing potential

$$\theta_I - \theta_S = \frac{D_{LS}}{D_{OS}}\alpha \equiv \nabla_\theta \psi(\theta_I)$$

The lensing will produce a first order mapping distortion (Jacobian of the lens mapping)

$$\frac{d\theta_S}{d\theta_I} = A = \begin{pmatrix} 1-\partial_{xx}\psi & -\partial_{xy}\psi \\ -\partial_{xy}\psi & 1-\partial_{yy}\psi \end{pmatrix}$$



Weak-lensing

We can write the Jacobian of the lens mapping as

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & +\gamma_1 \end{pmatrix}$$

In terms of the convergence

$$\kappa = \frac{1}{2}[\partial_{xx}\psi + \partial_{yy}\psi]$$

And shear

$$\gamma = (\gamma_1, \gamma_2) = [(\partial_{yy}\psi - \partial_{xx}\psi)/2, \partial_{xy}\psi]$$

κ represents an isotropic magnification. It transforms a circle into a larger / smaller circle

γ Represents an anisotropic magnification. It transforms a circle into an ellipse with axes

$$b = (1-\kappa+\gamma)^{-1}, \quad a = (1-\kappa-\gamma)^{-1}$$

Weak-lensing

Galaxy ellipticities provide a direct measurement of the shear field (in the weak lensing limit)

Need an expression relating the lensing field to the matter field, which will be an integral over galaxy distances χ

$$P_\kappa(\ell) = \frac{9\pi}{4\ell}\Omega_m^2 H_0^4 \int_0^{\chi_\infty} d\chi \frac{g^2(\chi)}{\chi^2 a^2(\chi)} P_m(\ell/\chi)$$

The weight function, which depends on the galaxy distribution is

$$g(\chi) \equiv 2\chi \int_\chi^{\chi_\infty} d\chi' \left(1 - \frac{\chi}{\chi'}\right) W(\chi')$$

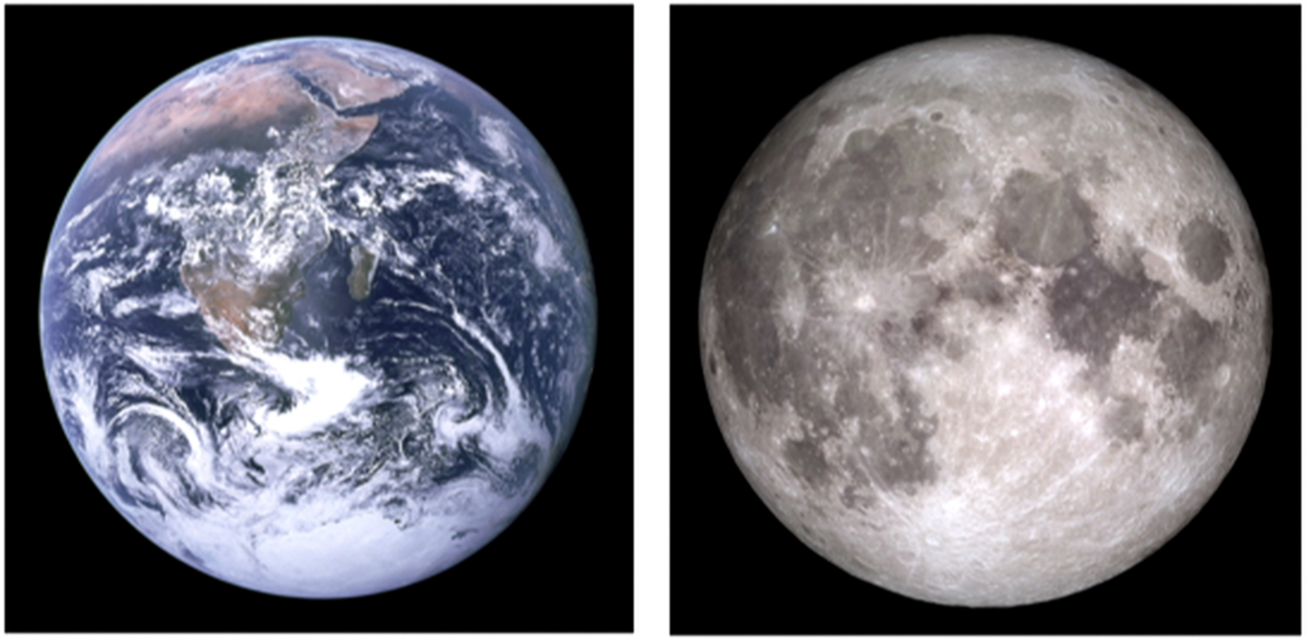
The shear power spectra are related to the convergence power spectrum by

$$P_{\gamma_1}(\ell, \phi_\ell) = \cos^2(2\phi_\ell) P_\kappa(\ell)$$

$$P_{\gamma_2}(\ell, \phi_\ell) = \sin^2(2\phi_\ell) P_\kappa(\ell)$$

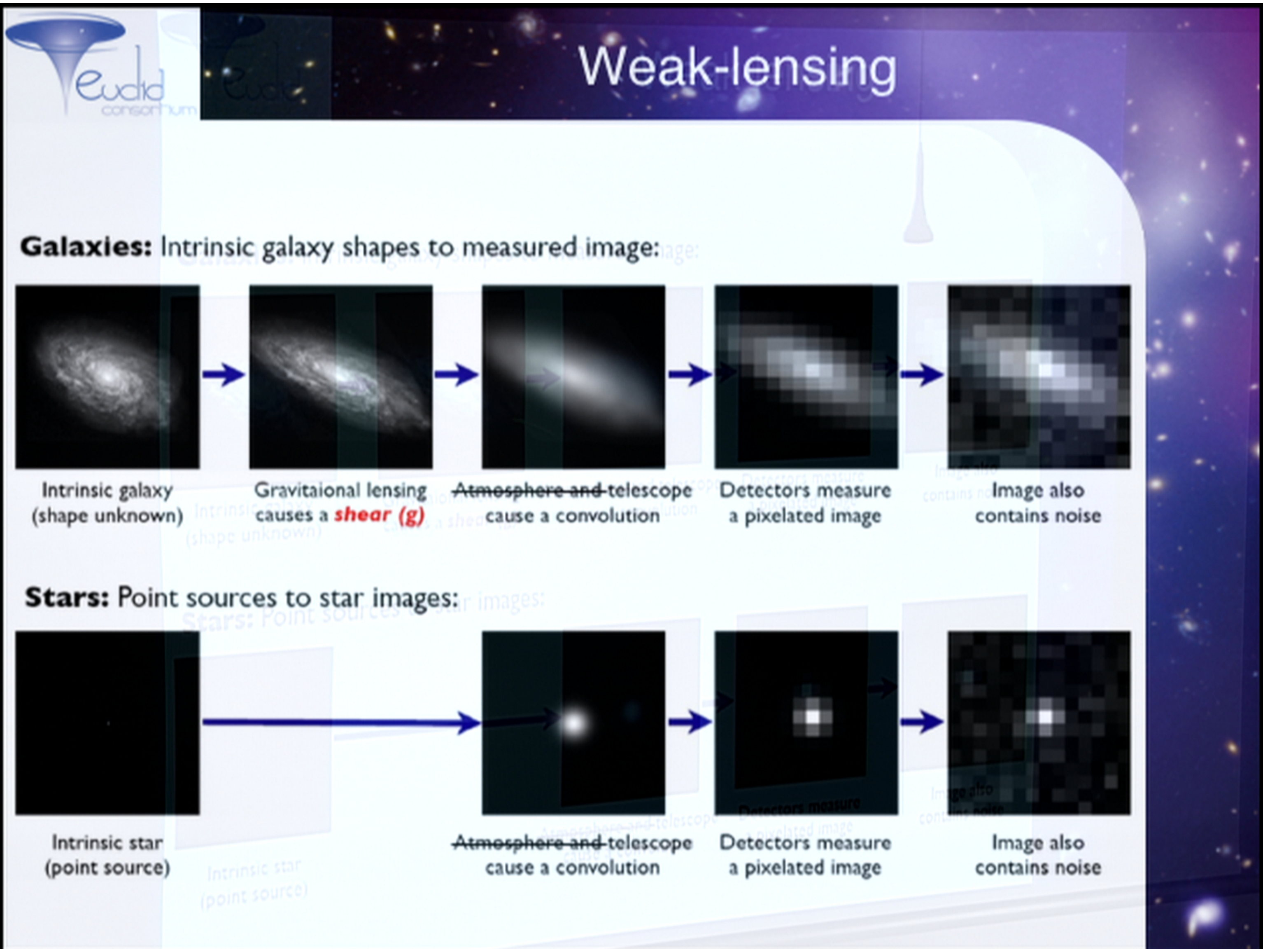
As expected, from a measurement of the convergence power spectrum we can constrain the matter power spectrum (mainly amplitude) and geometry

Weak-lensing



Average shear distortion equivalent to
difference in ellipticity between Earth and Moon

VIS imaging allows shape measurements for 30-40 galaxies/sqr arcmin



Weak-lensing

Galaxies: Intrinsic galaxy shapes to measured image:

Intrinsic galaxy
(shape unknown)

Gravitaional 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

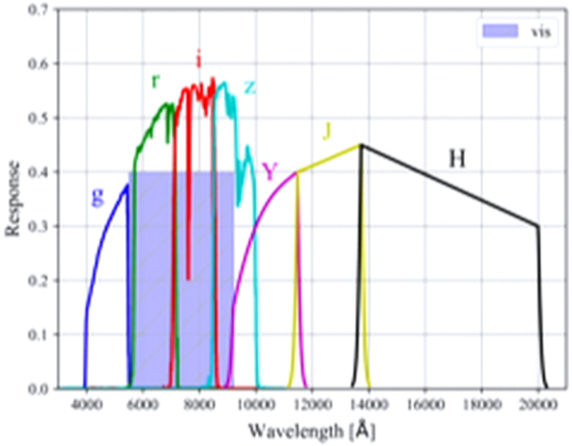
Detectors measure
a pixelated image

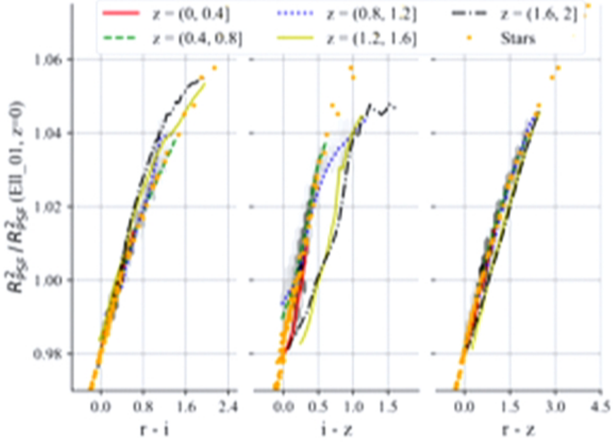
Image also
contains noise

Weak-lensing

- A sharp PSF is not enough: need to correlate shapes of millions of galaxies at ~10^{-3} in ellipticity, so need to know the PSF variation across survey

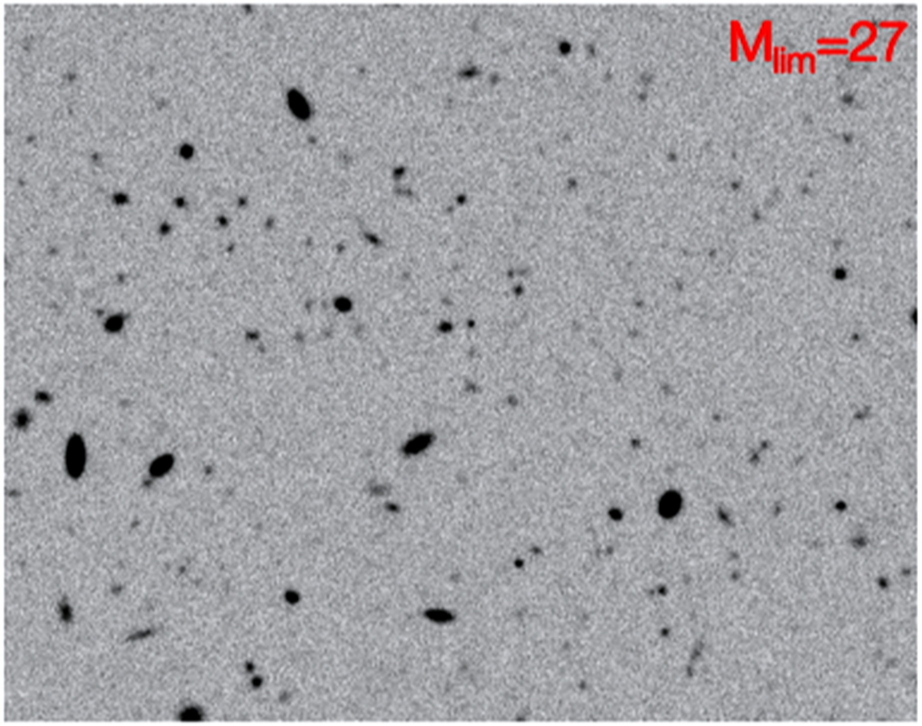
- PSF is colour-dependent. Even colour gradients in galaxies can bias results: we cannot ignore this, but we can correct for it, just like for the overall PSF.



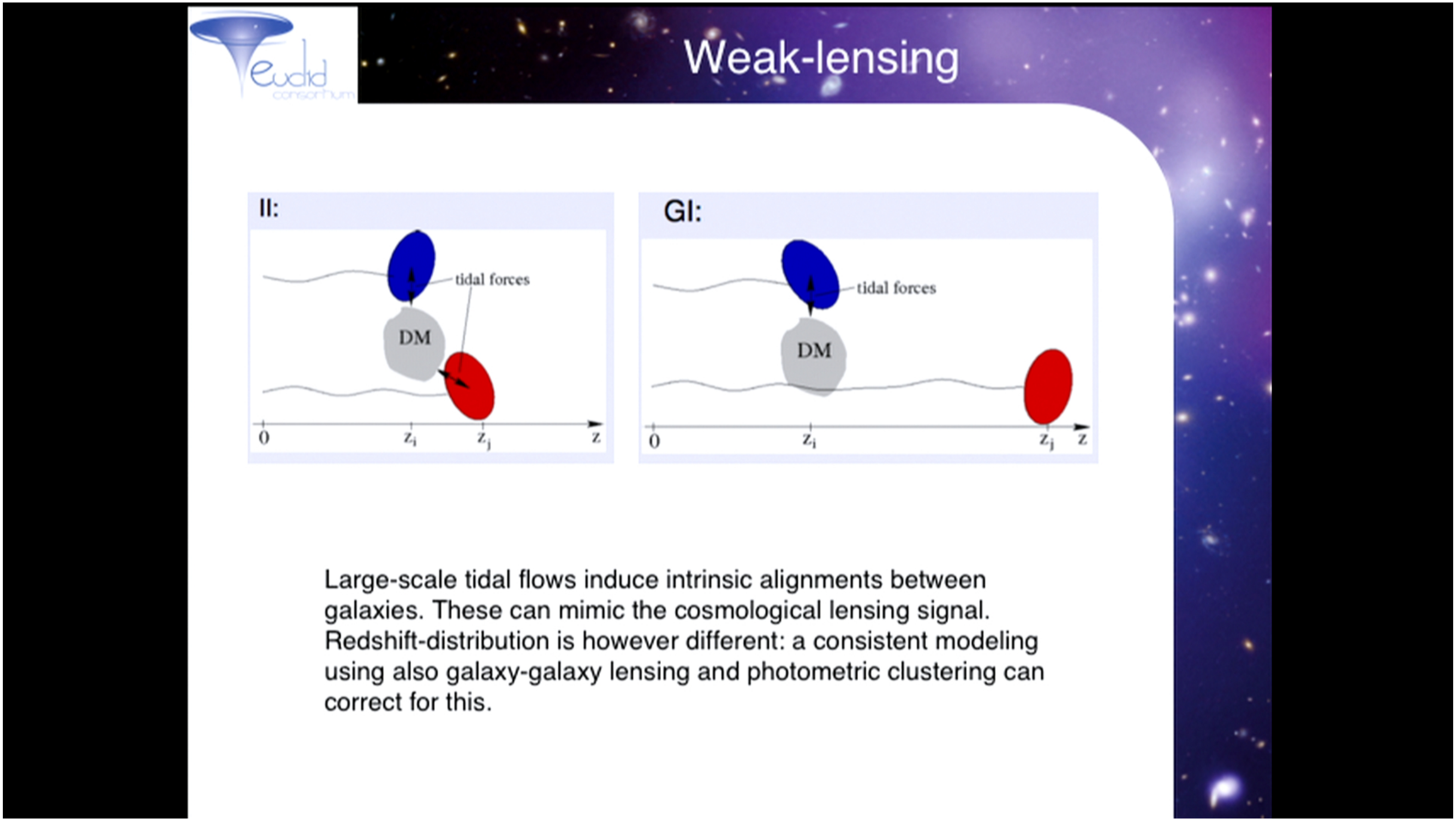


Eriksen & Hoekstra 2017; arXiv:1707.04334

Weak-lensing



Faint unresolved galaxies impact the shapes of brighter source galaxies through blending



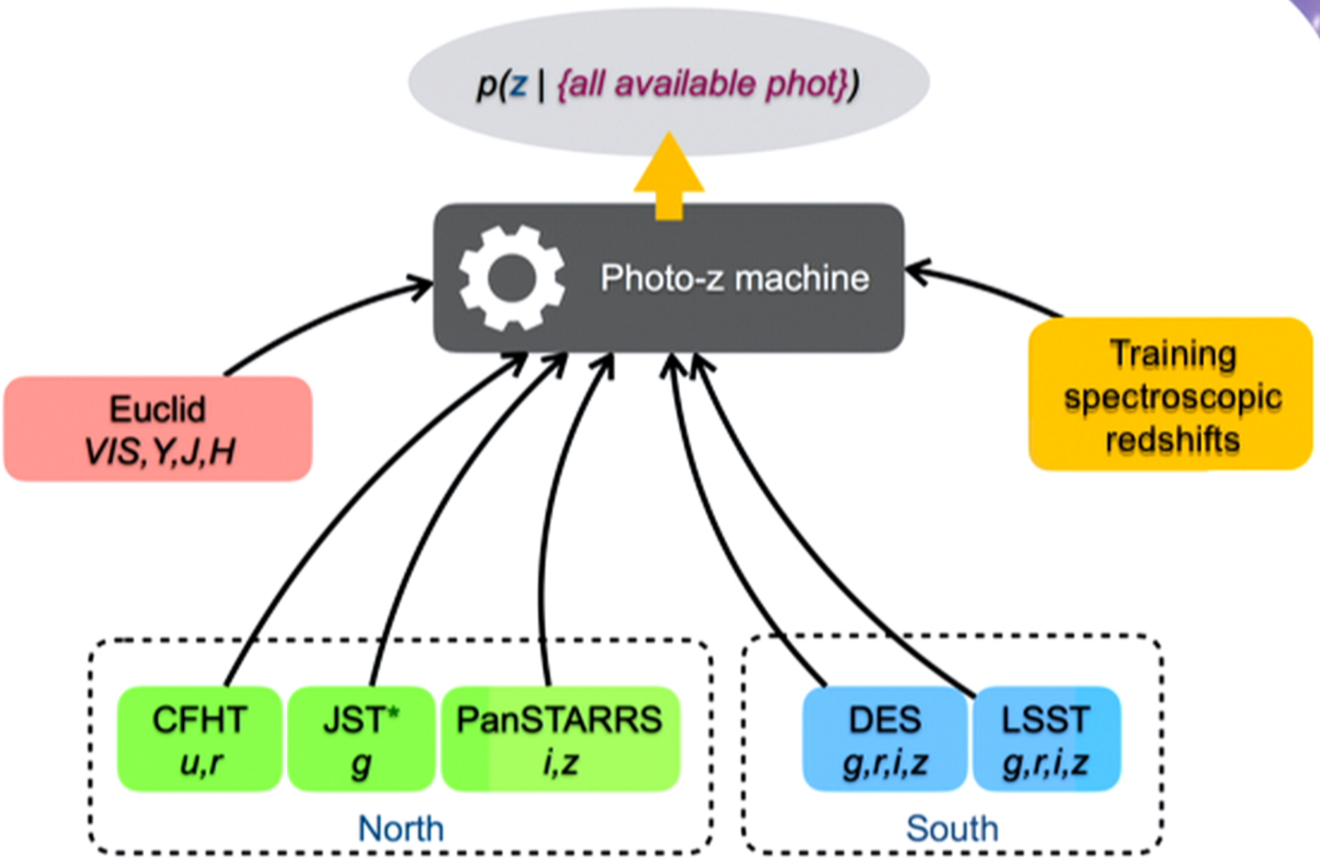
Weak-lensing

II:

GI:

Large-scale tidal flows induce intrinsic alignments between galaxies. These can mimic the cosmological lensing signal. Redshift-distribution is however different: a consistent modeling using also galaxy-galaxy lensing and photometric clustering can correct for this.

Photometric redshift factory



$p(z \mid \{\text{all available phot}\})$

Photo-z machine

Euclid
VIS,Y,J,H

Training spectroscopic redshifts

CFHT
u,r

JST*
g

PanSTARRS
i,z

North

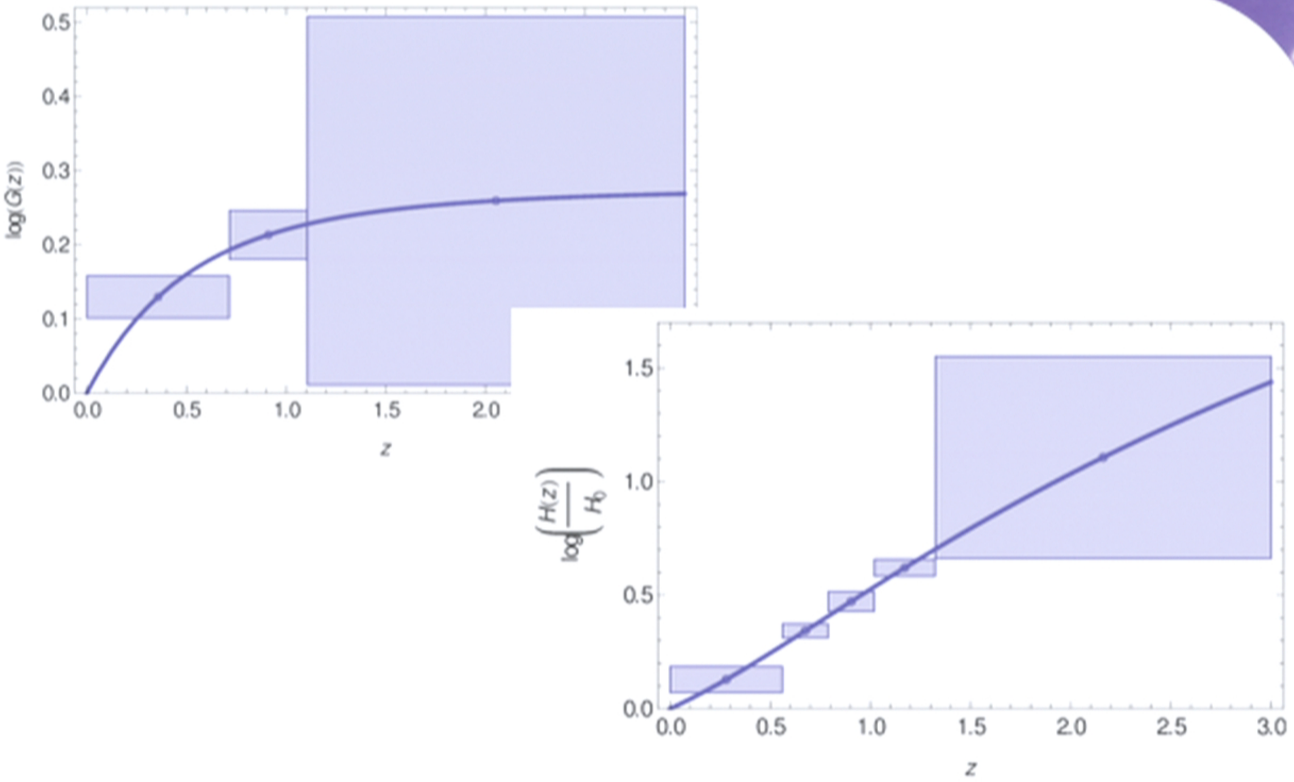
DES
g,r,i,z

LSST
g,r,i,z

South

* Javalambre Observatory, Teruel, Spain

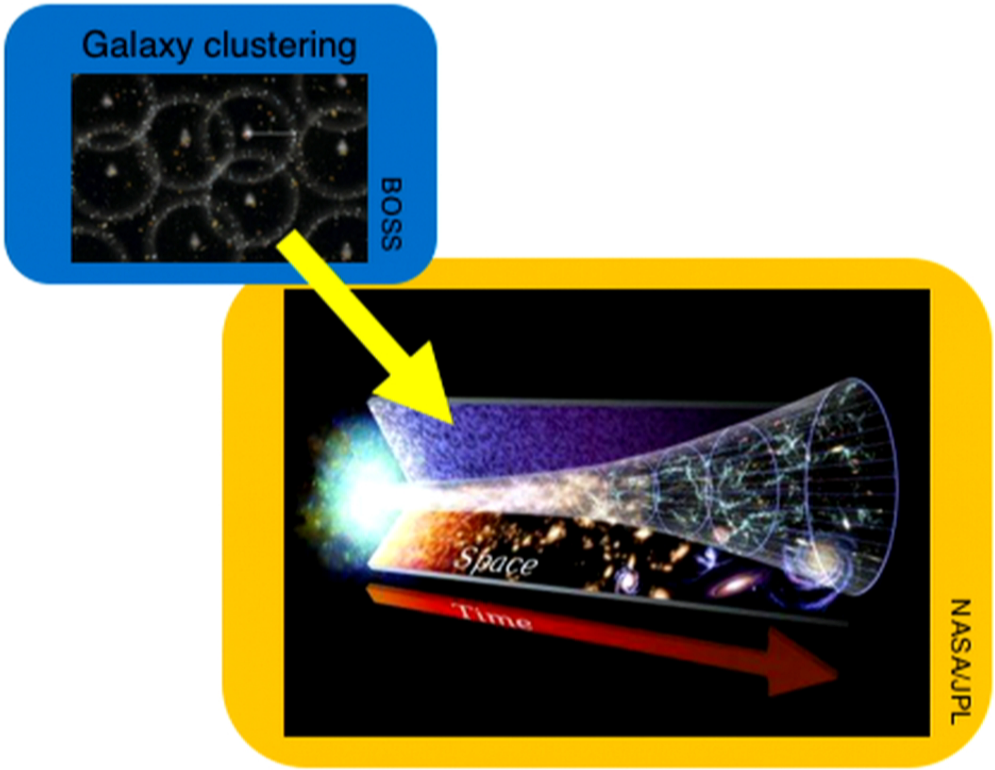
Euclid weak-lensing predictions



Shown are model-independent constraints on growth and expansion

Amendola et al. 2016; arXiv:1606.00180

Euclid: a cosmology-survey machine



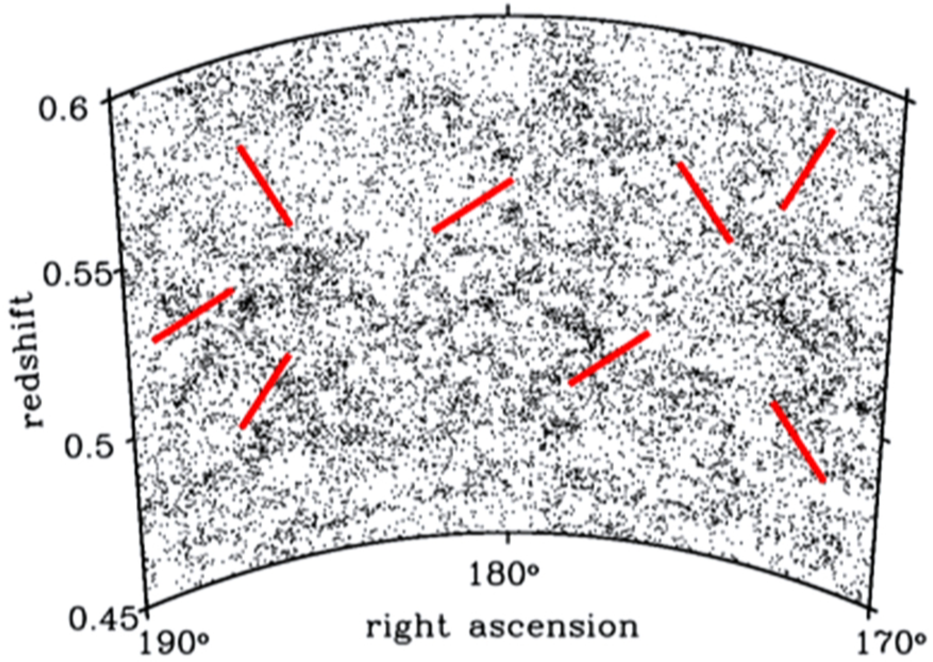
Type 1a supernovae

Cluster counts

CMB cross correlations

Galaxy clustering

Clustering strength = number of galaxy pairs beyond random



$$\delta = \frac{\rho - \rho_0}{\rho_0}$$

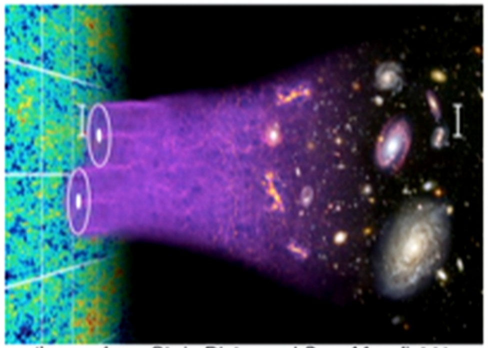
$$P(k) = \langle \delta_k(k)^2 \rangle$$

$$\xi(d) = \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

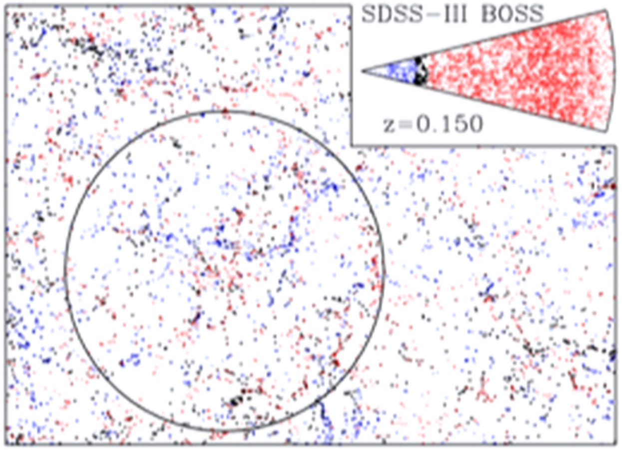
SDSS

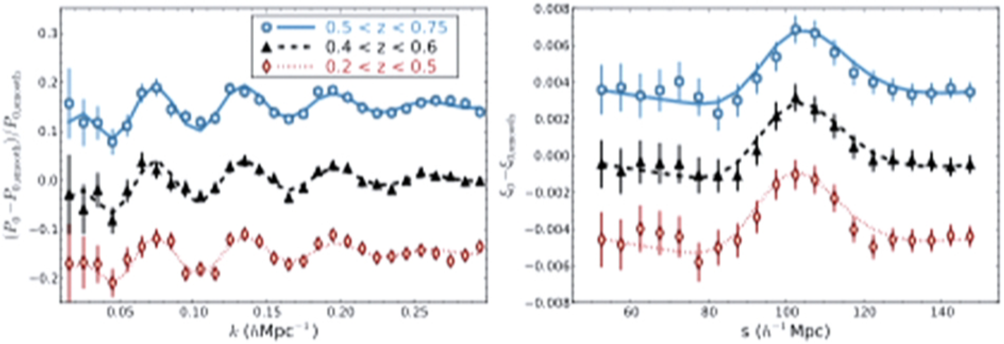
Baryon Acoustic Oscillations (BAO)

(images from Martin White)



(image from Chris Blake and Sam Moorfield)

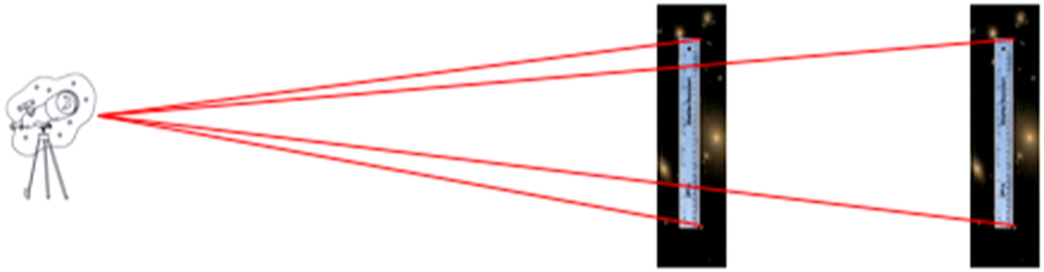




Alam et al. 2016, arXiv:1607.03155

BAO as a standard ruler

Surveys measure angles and redshifts, and we use a fiducial model (denoted “fid”) to translate to comoving coordinates



Changes in apparent BAO position ($\Delta d_{\mathbf{comov}}$) depend on:

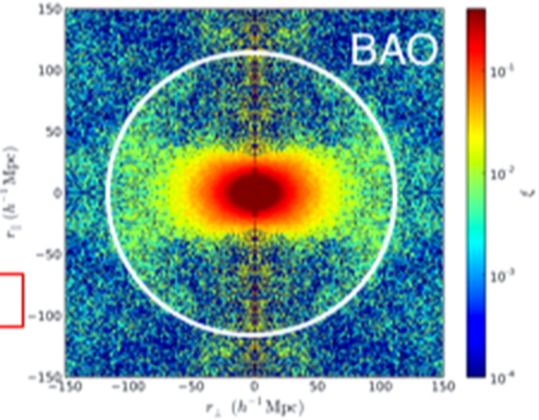
Radial direction

$$\alpha_{\parallel} = \frac{H(z)_{\rm fid}\, r_{d,\rm fid}}{H(z)\, r_d}$$

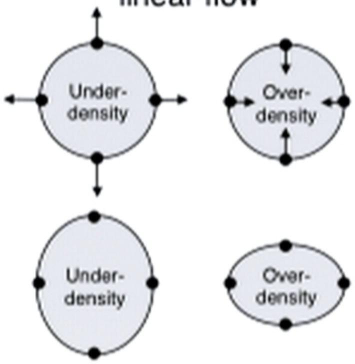
Angular direction

$$\alpha_{\perp} = \frac{D_A(z)\, r_{d,\rm fid}}{D_A(z)_{\rm fid}\, r_d}$$

r_d is the sound horizon at recombination



Redshift Space Distortions (RSD)

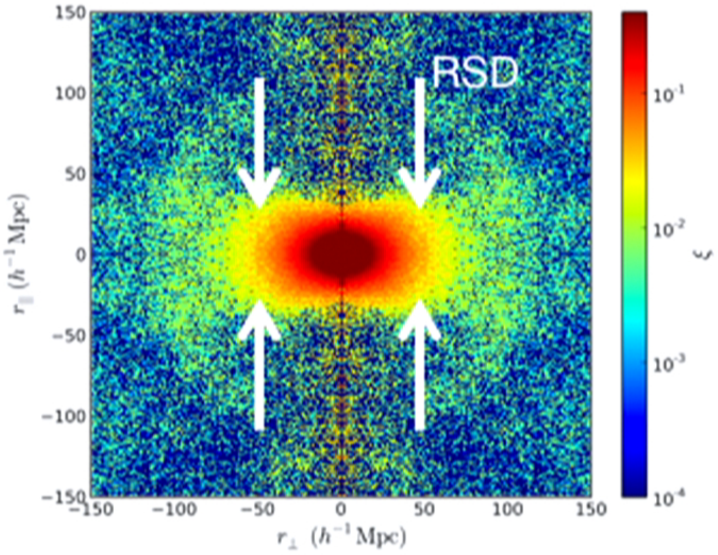


linear flow

Actual shape

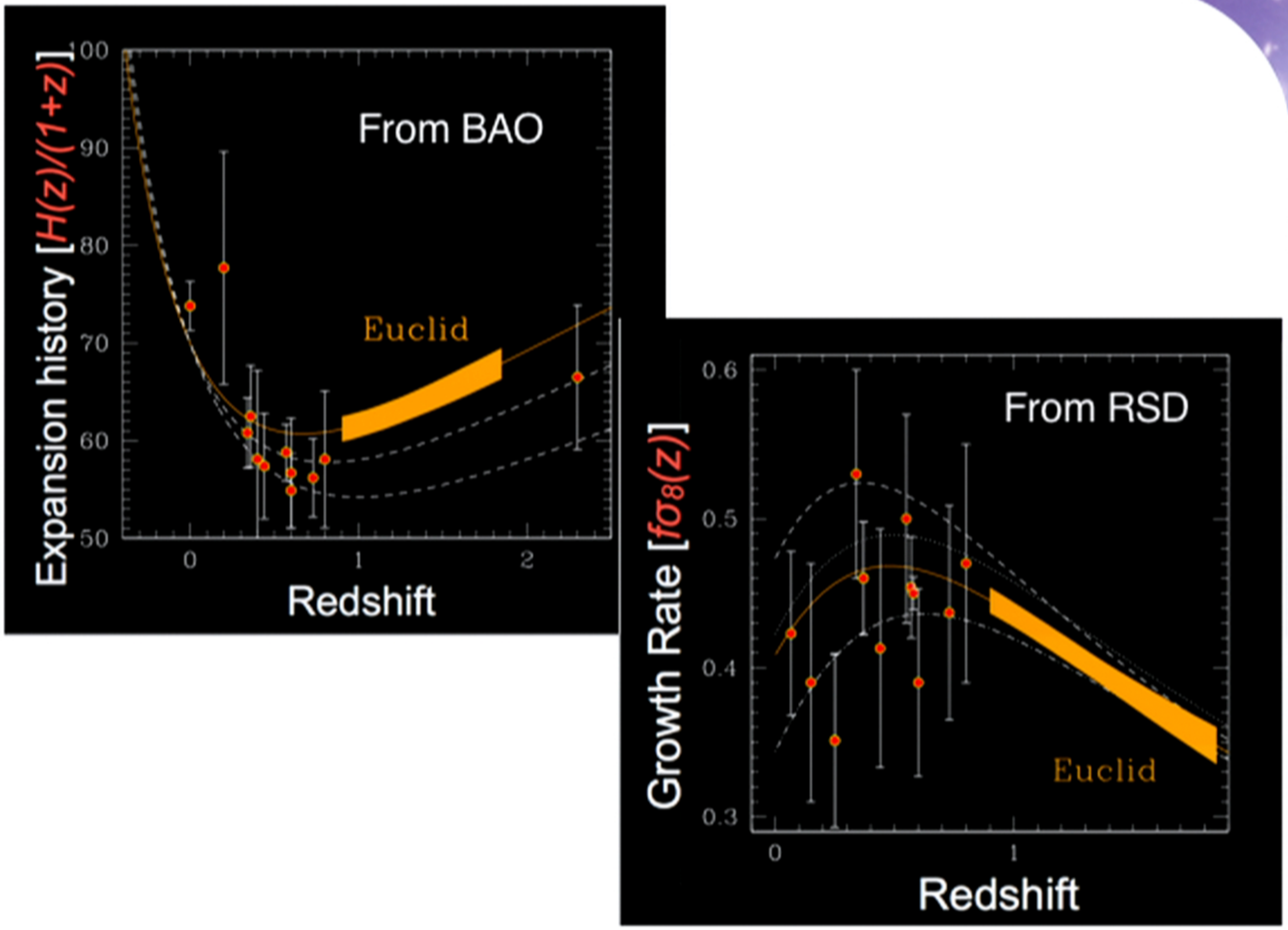
Apparent shape (viewed from below)

Boost to radial clustering depends on the amplitude of bulk-flow velocities

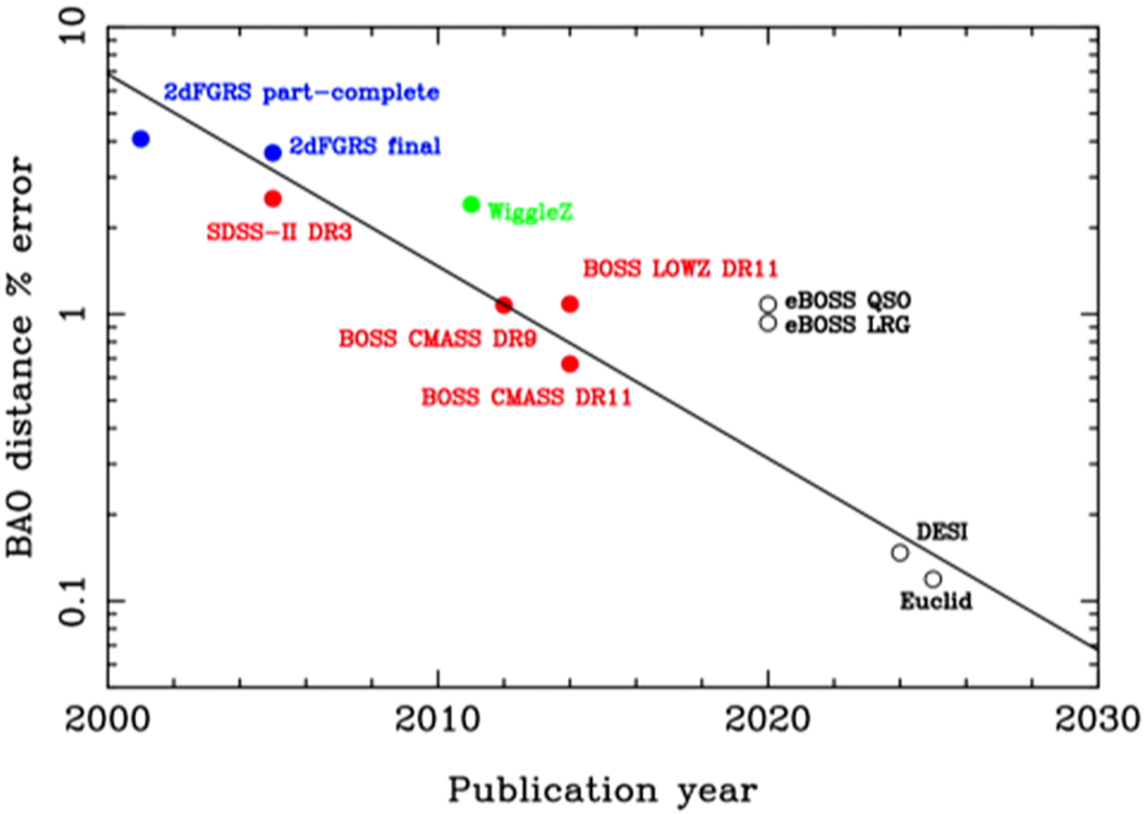


Samushia et al. 2013; MNRAS, 439, 3504

Euclid galaxy clustering predictions



BAO errors from past / future surveys

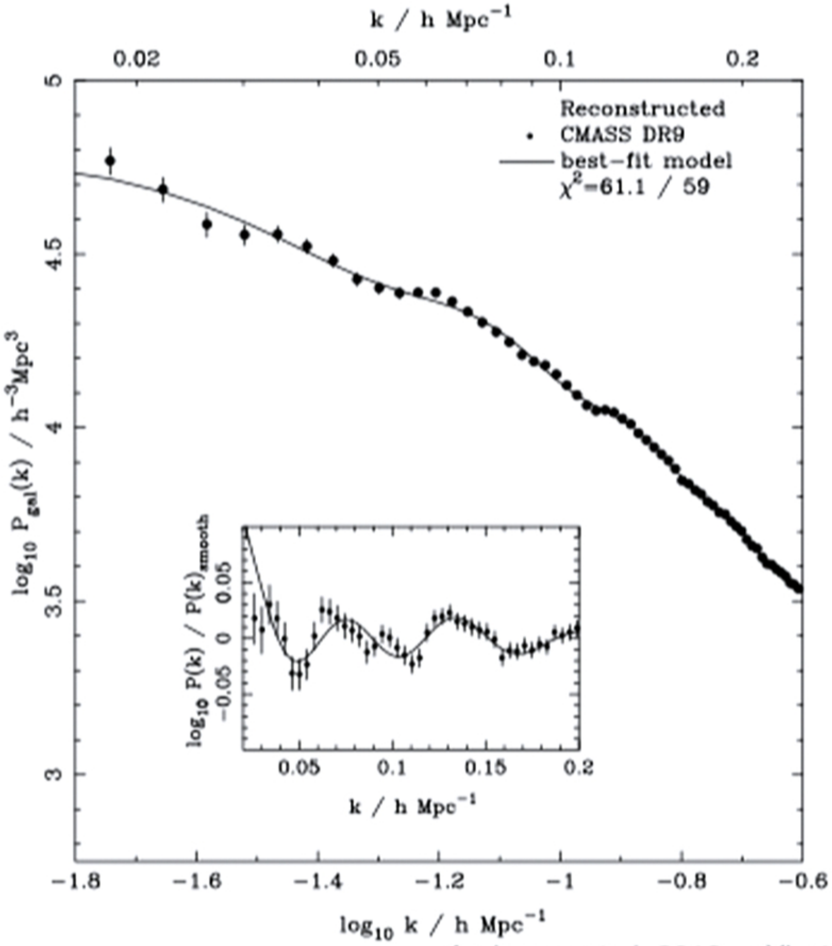


Reid et al. 2015, arXiv:1509.06529

BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

Total effective volume
$V_{\mathrm{eff}} = 2.2\ \mathrm{Gpc}^3$

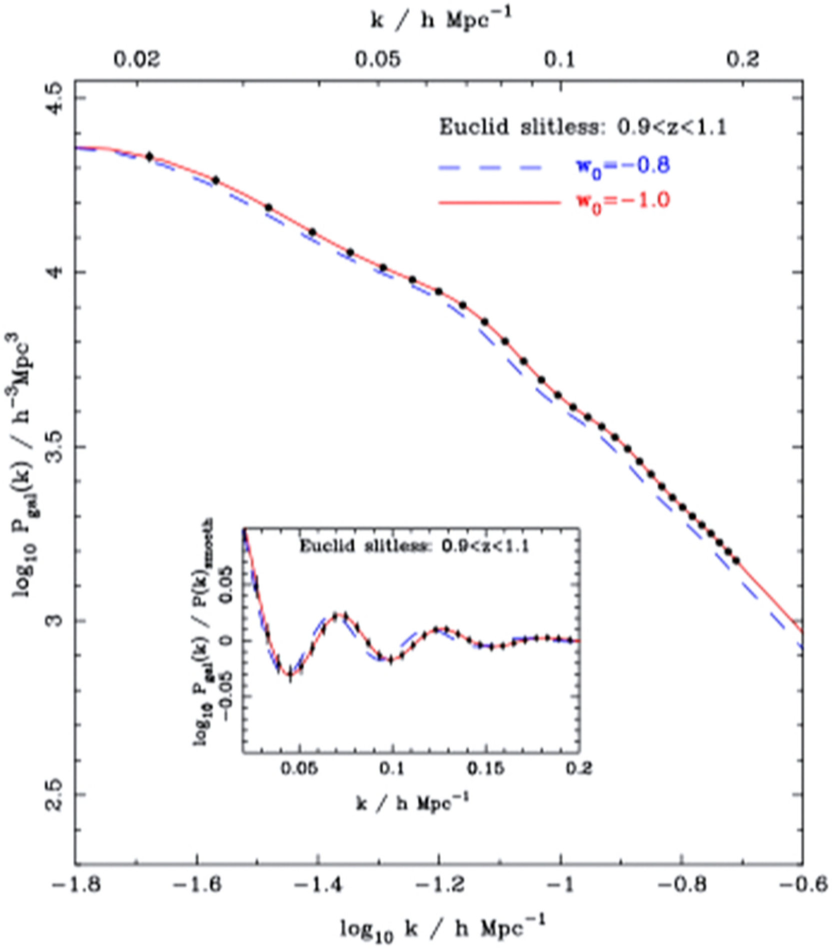


Anderson et al. 2012; arXiv:1203.6565

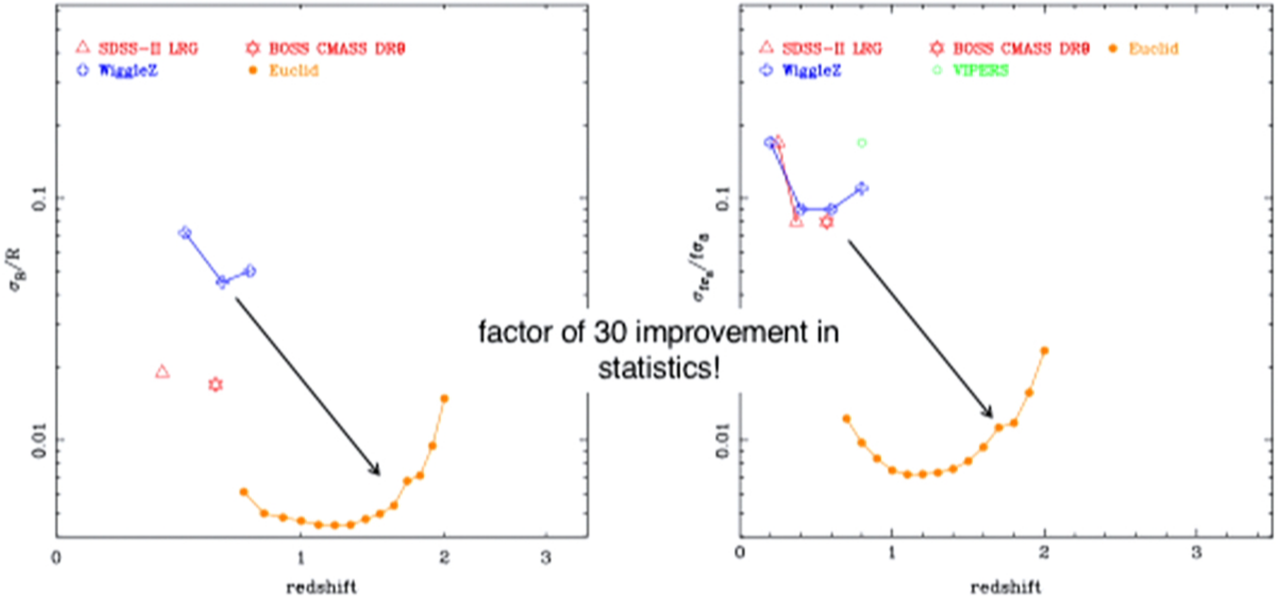
Predicted Euclid galaxy clustering

Redshift slice
$0.9 < z < 1.1$

Total effective volume (of Euclid)
$V_{\mathrm{eff}} = 57.4\ \mathrm{Gpc}^3$



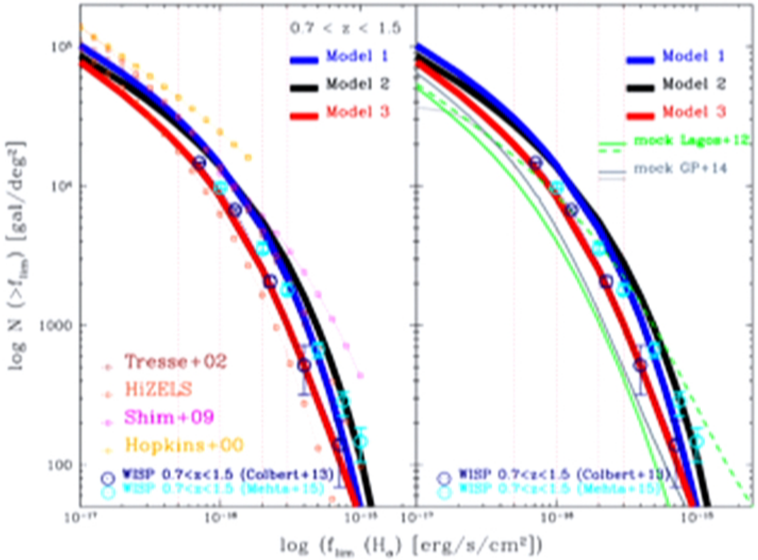
Improvement in precision



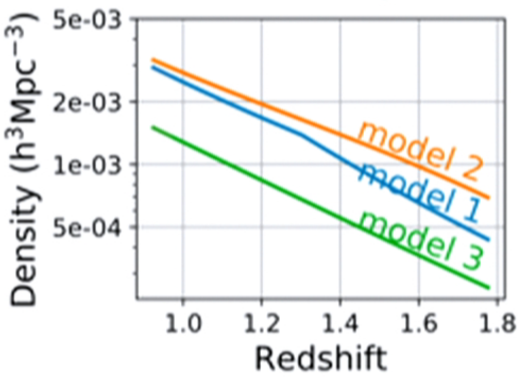
factor of 30 improvement in statistics!

Good control of systematic errors will be critical

Hα emitters at z>1



Hα > 2x10^{-16} erg/s/cm^2



- Factor of 2 uncertainty in the populations of emission line galaxies at z>1
- Expectations based upon WISP+3D HST (Claudia Scarlata, Micaela Bagley+) and Lucia Pozzetti+16
- Hα gives ~4000 sources/deg^2 at $0.9 < z < 1.8$ (Pozzetti+16 Model 1)
- Blending with [NII] can boost signal

Hα emitter distribution

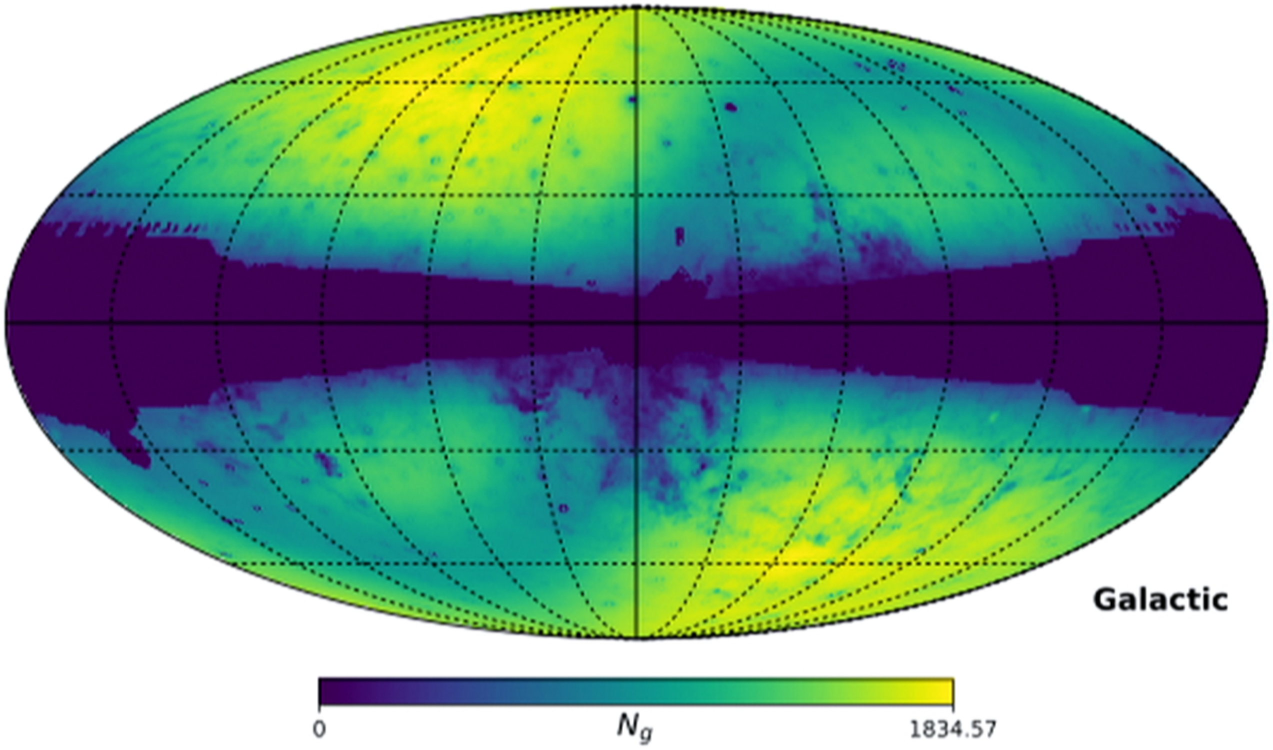
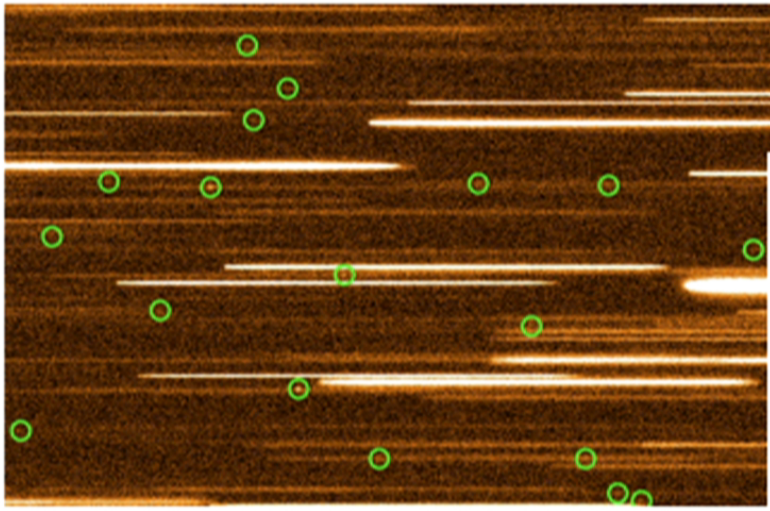
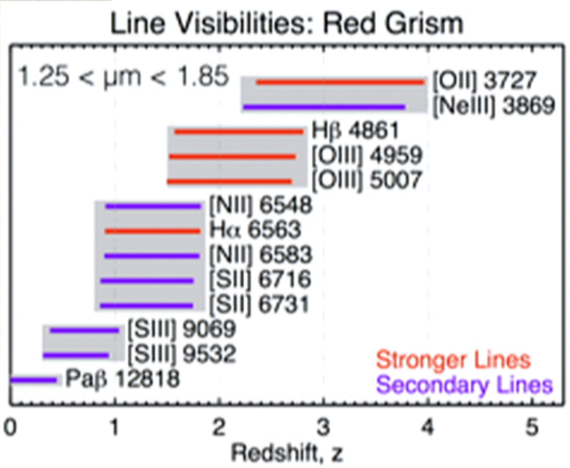


Image credit: Bianca Garilli, Dida Markovic

The redshift challenge

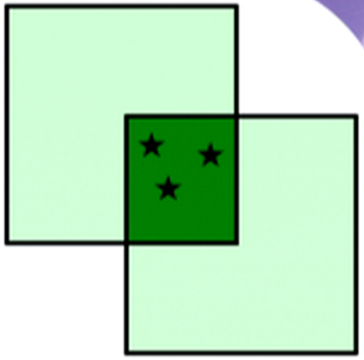

B. Garilli



G. Addison

- Slitless spectroscopy is difficult!
  - Zodiacal background and straylight are the dominant noise terms
  - Line misidentification
  - Spectra confusion
  - Detector persistence

The calibration challenge



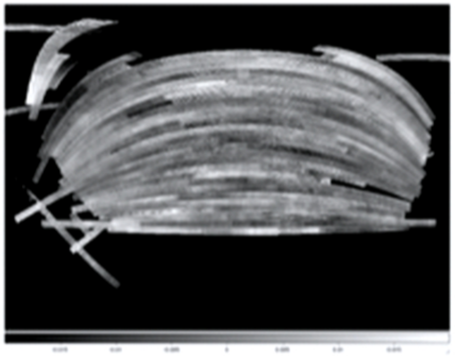
Ubercal procedure

- find stars in overlaps between exposures and compare ADUs measured for same star in different exposures
- Worked well for the SDSS imaging data
- But cannot correct for large-scale trends

For Euclid, we have a 4-dither pattern covering 15,000deg2. The pattern can still be tweaked to optimize calibration (many other competing demands)

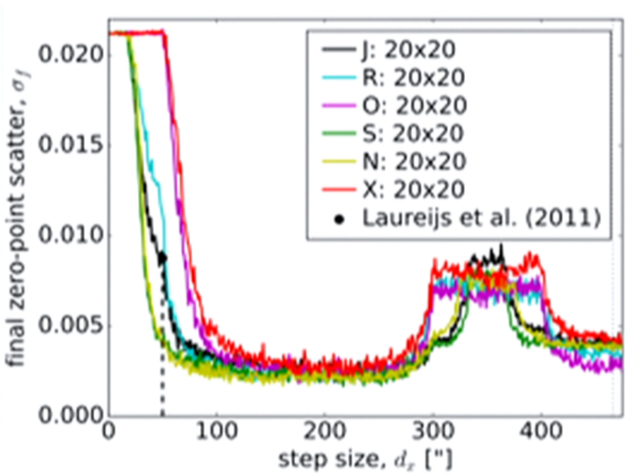
- Set up a toy model for Euclid, performing Ubercal over a simplified survey

$$\chi^2_{\mathrm{eff}}(\{k_i\}|m_{li}) = \underbrace{\sum_{l}^{N_\mathrm{o}}\sum_{i}^{N_l}\left[\frac{\overline{m^{\mathrm{c}}}_l - m^{\mathrm{c}}_{il}}{\sigma^{\mathrm{c}}_l}\right]^2}_{\text{likelihood part}} + \underbrace{\sum_{i}^{N_{\mathrm{exp}}}\left[\frac{k_i}{\sigma^{\mathrm{k}}}\right]^2}_{\text{prior part}}$$

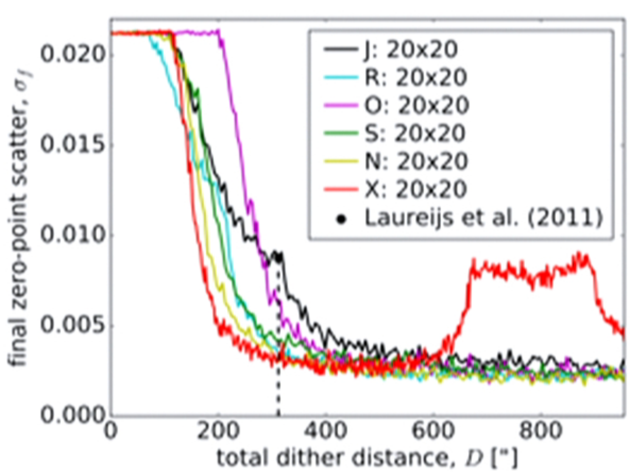


Markovic et al. 2016, arXiv:1606.07061; Padmanabhan et al. 2008, astro-ph/0703454

The calibration challenge



Exposure-to-exposure variations



Detector-to-detector variations

Baseline dither pattern for Euclid now changed to the “S” pattern

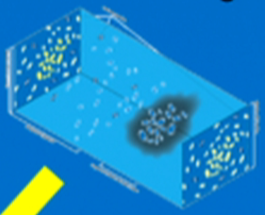
Markovic et al. 2016, arXiv:1606.07061

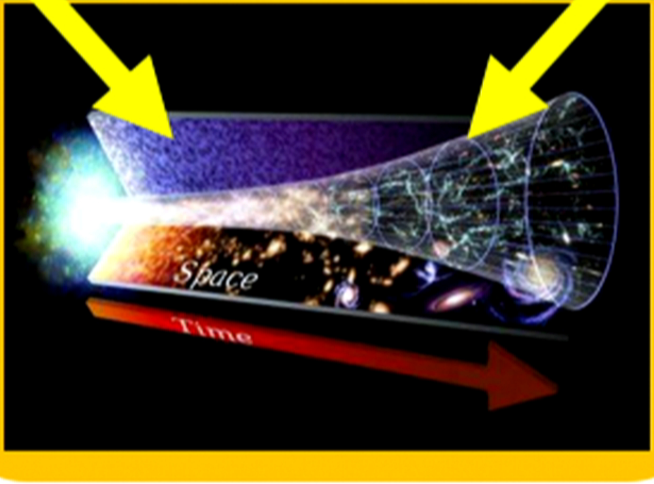
Euclid: a cosmology-survey machine

Galaxy clustering

BOSS

Weak lensing





NASA/JPL

Type 1a supernovae

Cluster counts

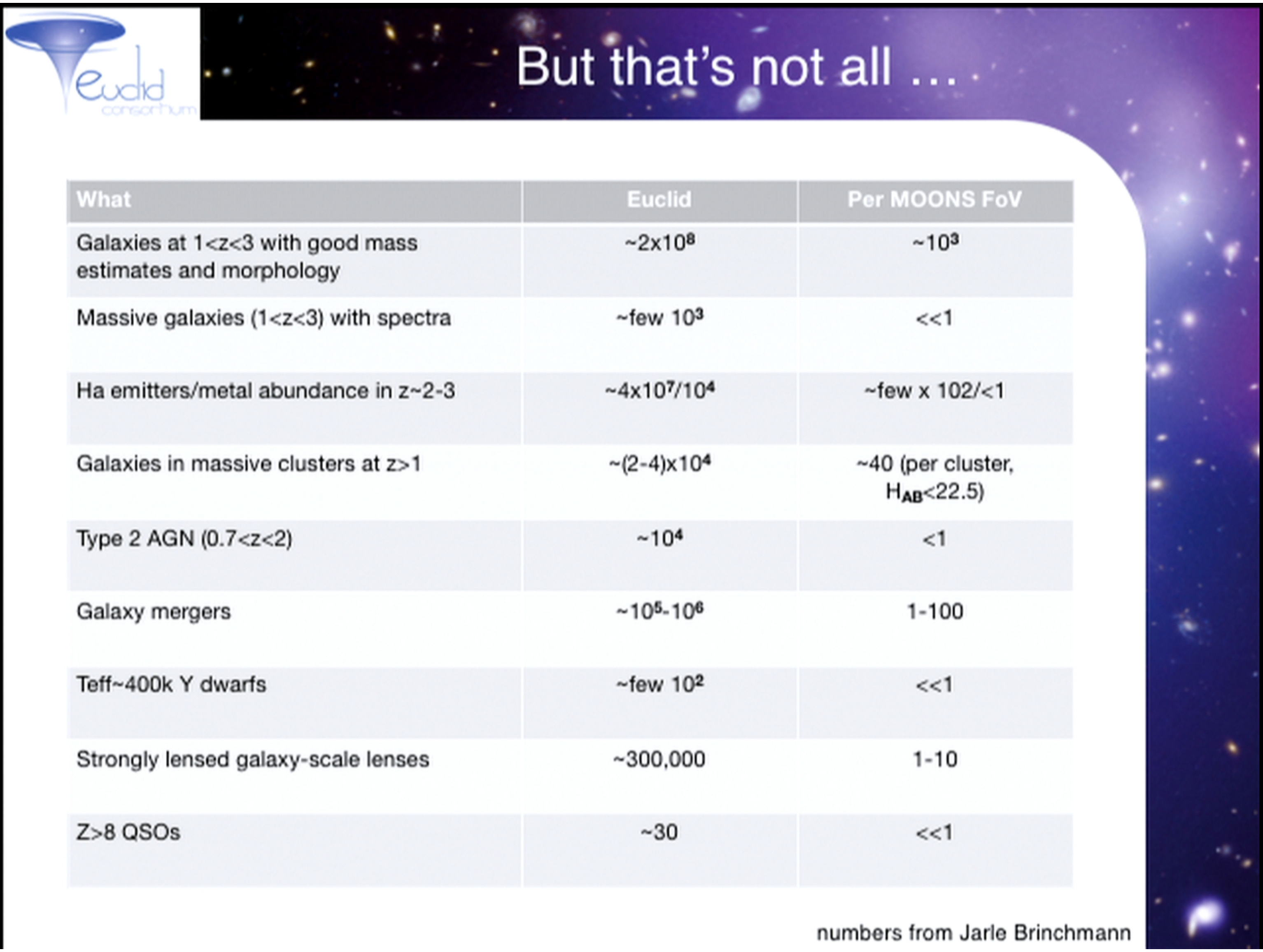
CMB cross correlations

But that’s not all …

The primary cosmology probes drive the design of the survey, but the resulting data set enables an enormous amount of legacy science, which cannot be done otherwise:

Euclid will image 15000 deg^2 in YJHAB=24, which would take 680 years to complete with VISTA.

The deep survey of 40 deg^2 down to YJHAB=26 would take 72 years with VISTA.

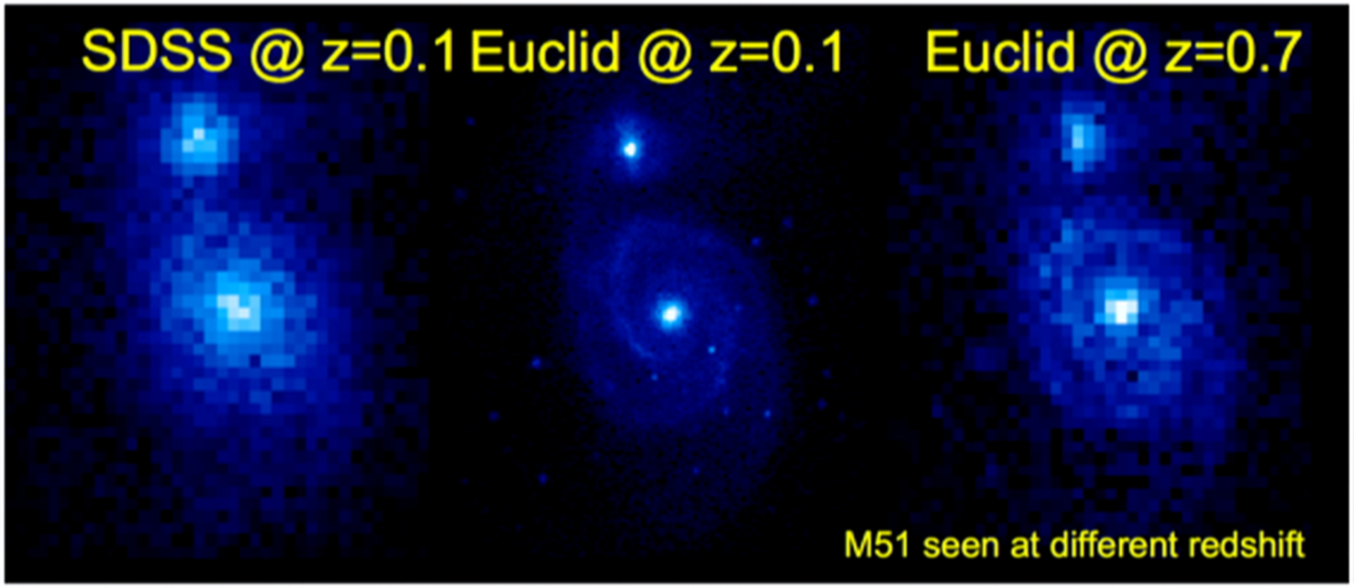


But that's not all …

What	Euclid	Per MOONS FoV
Galaxies at 1<z<3 with good mass estimates and morphology	~2x10^8	~10^3
Massive galaxies (1<z<3) with spectra	~few 10^3	<<1
Ha emitters/metal abundance in z~2-3	~4x10^7/10^4	~few x 102/<1
Galaxies in massive clusters at z>1	~(2-4)x10^4	~40 (per cluster, H_{AB}<22.5)
Type 2 AGN (0.7<z<2)	~10^4	<1
Galaxy mergers	~10^5-10^6	1-100
Teff~400k Y dwarfs	~few 10^2	<<1
Strongly lensed galaxy-scale lenses	~300,000	1-10
Z>8 QSOs	~30	<<1

numbers from Jarle Brinchmann

But that’s not all …



Euclid images of z~1 galaxies will have the same resolution as SDSS images at z~0.05 and will be at least 3 magnitudes deeper.

What's happening at the moment … SPV

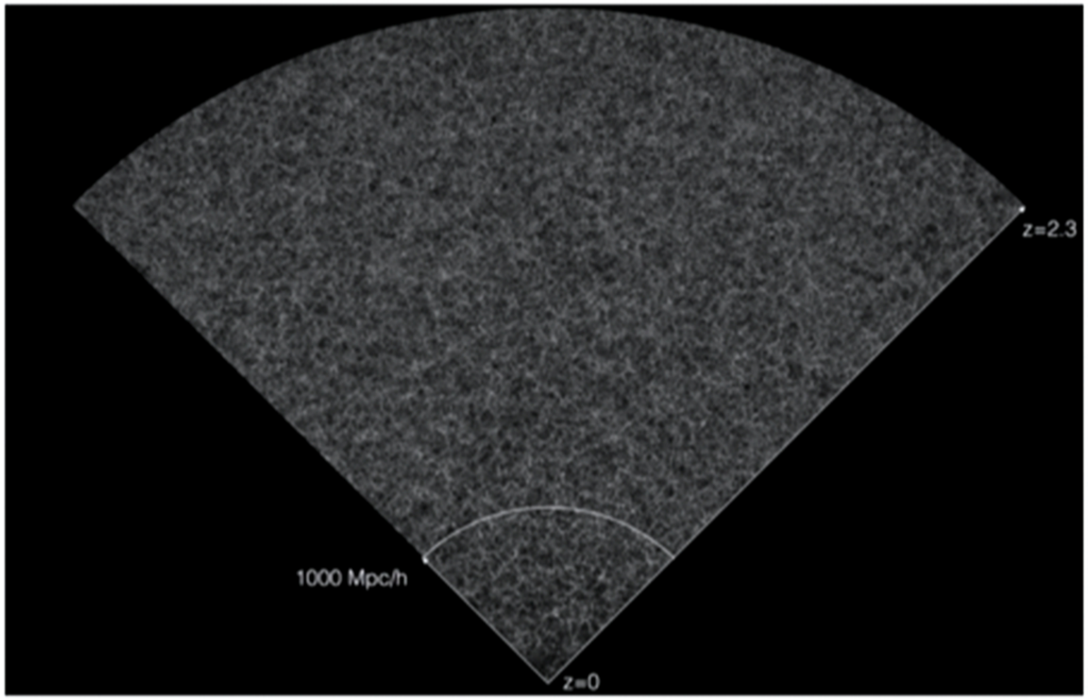
Making a new detailed study of the performance of Euclid, resulting in an update of the Mission Performance Document

This exercise is called SPV (Science Performance Verification), and will be used to test many things within Euclid (sample selection, masks, analysis software, redshifting, …)

During these exercises, the expected performance of the Euclid Mission with respect to its two main science goal is evaluated and compared to the requirements

We will also consider further survey optimisation

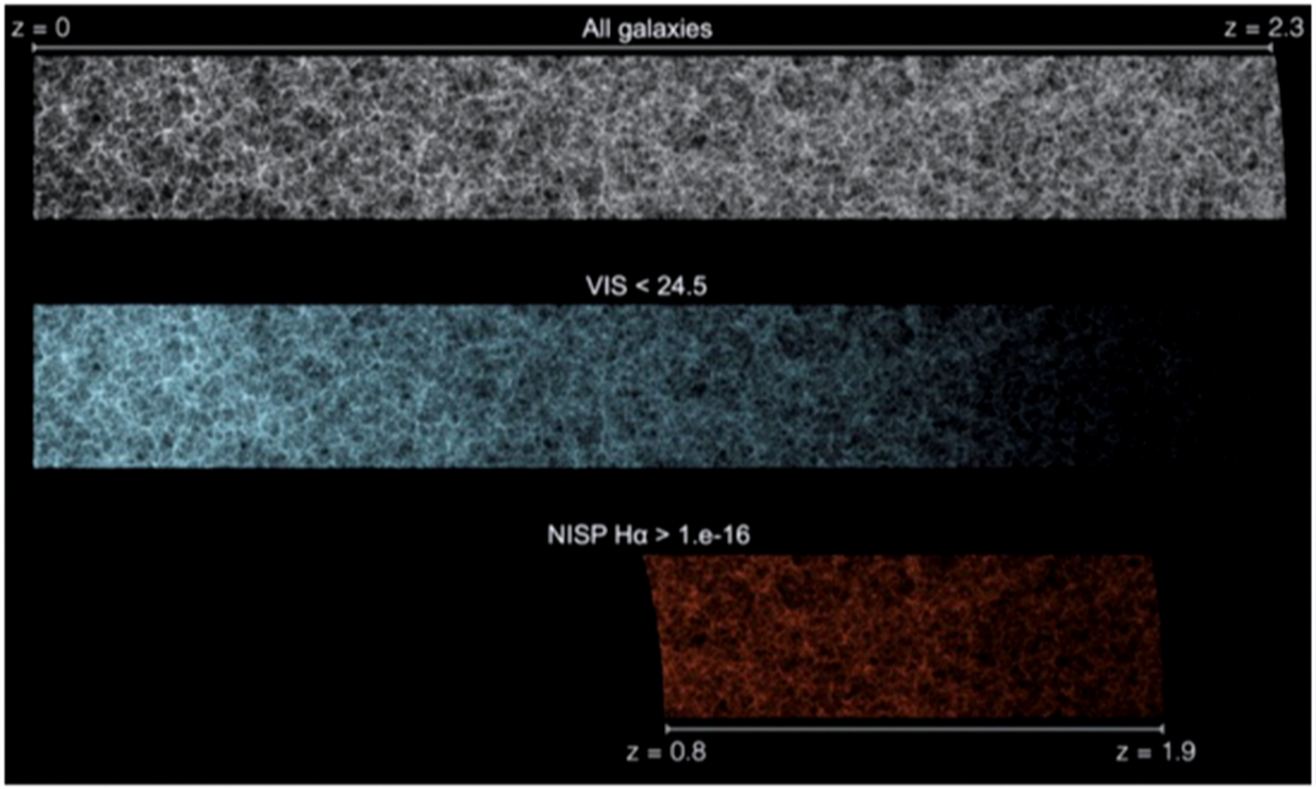
A mock Euclid survey



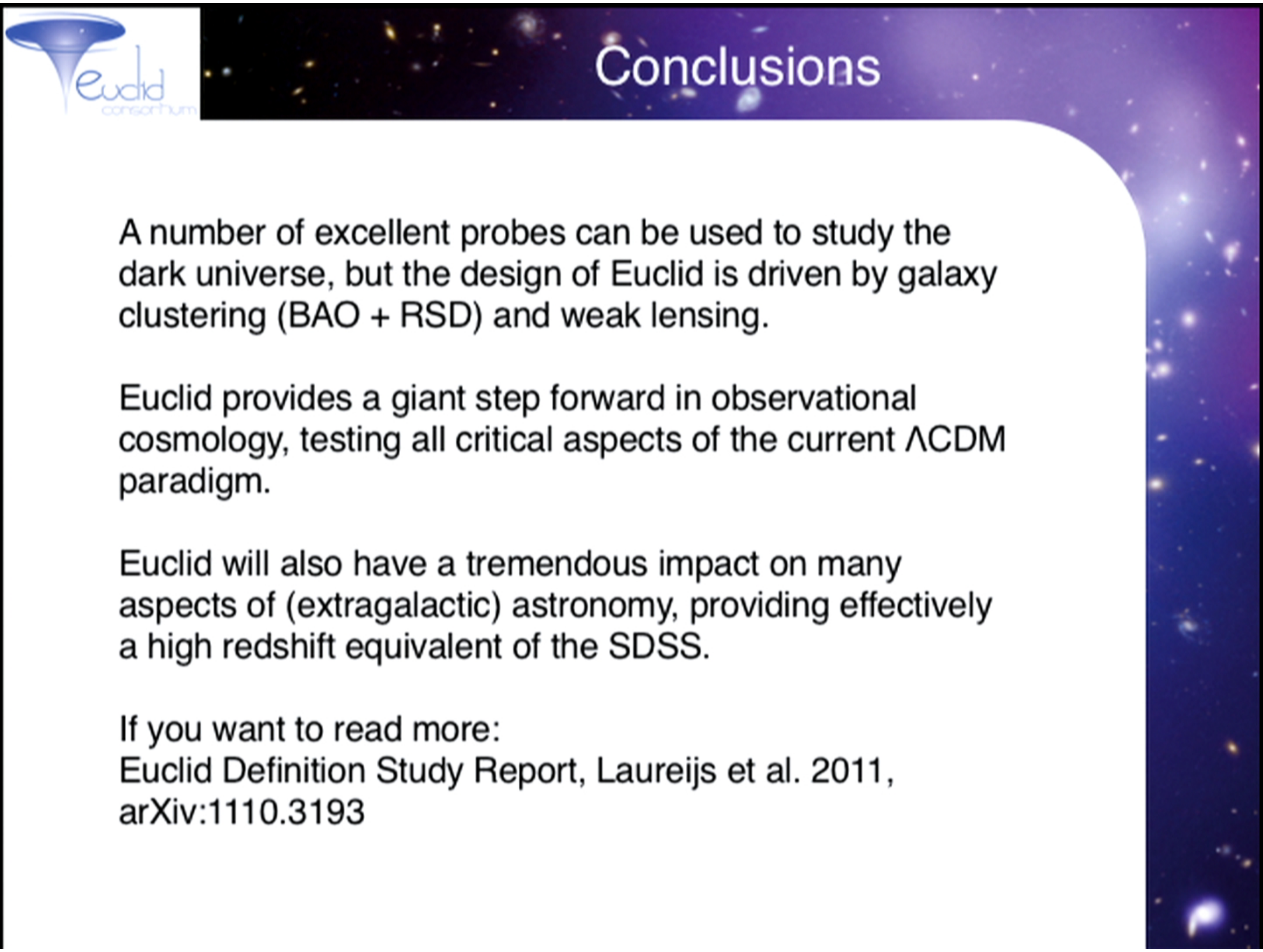
- Full-scale mock: Euclid Flagship simulation
- Sim box: L=3 h^{-1}Gpc, , N=2 trillion dark matter particles
- Light cone: $0 < z < 2.3$
- Raytraced lensing maps
- Galaxy properties by HOD
- U. Zurich / Barcelona ICE/IEEC-CSIC

Leads of simulation working group: P. Fosalba, R. Teyssier

A mock Euclid survey



Leads of simulation working group: P. Fosalba, R. Teyssier



Conclusions

A number of excellent probes can be used to study the dark universe, but the design of Euclid is driven by galaxy clustering (BAO + RSD) and weak lensing.

Euclid provides a giant step forward in observational cosmology, testing all critical aspects of the current ΛCDM paradigm.

Euclid will also have a tremendous impact on many aspects of (extragalactic) astronomy, providing effectively a high redshift equivalent of the SDSS.

If you want to read more:
Euclid Definition Study Report, Laureijs et al. 2011,
arXiv:1110.3193