Benasque - 7 August 2012

EUCLID *(a few whys and hows)*

R. Scaramella (on behalf of E. Consortium)

**(Euclid Consortium, old timer,
Mission Survey Scientist,
member of the EC Board and EST)**

Lots of figures and material courtesy of other EC members
(Amendola, Amiaux, Cropper, Guzzo, Nichol ... many people!)

Red Book released in July 2011 (ESA web pages)

• Gigastructures...

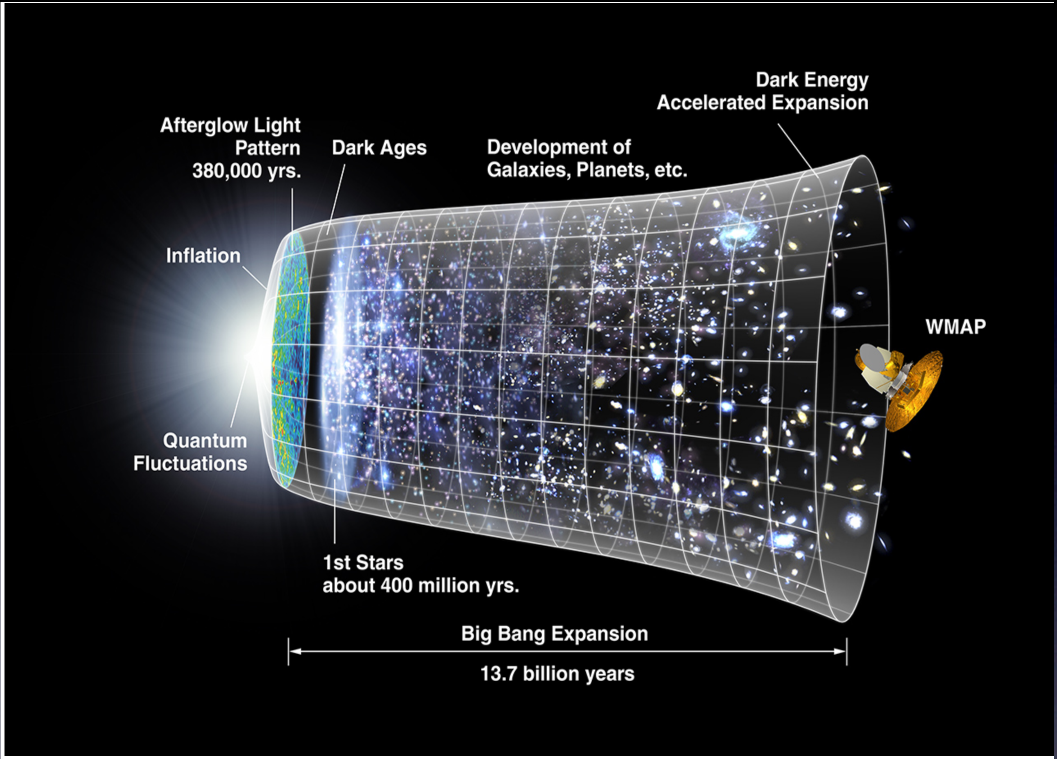
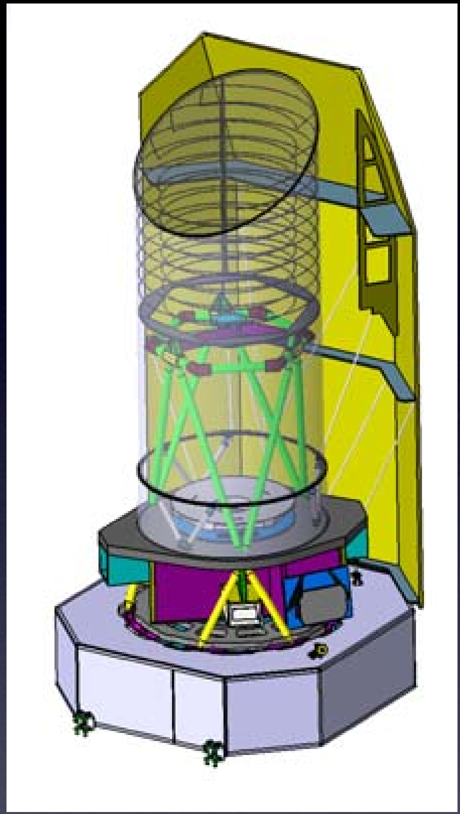


FIGURE 2-5 The cosmic timeline, from inflation to the first stars and galaxies to the current universe. The change in the vertical width represents the change in the rate of the expansion of the universe, from exponential expansion during the epoch of inflation followed by long period of a slowing expansion during which the galaxies and large scale structures formed through the force of gravity, to a recent acceleration of the expansion over the last roughly billion years due to the mysterious dark energy. Credit: NASA Wilkinson Microwave Anisotropy Probe Science Team.



- Observed with a **mini** structure: mirror ~1 m ∅

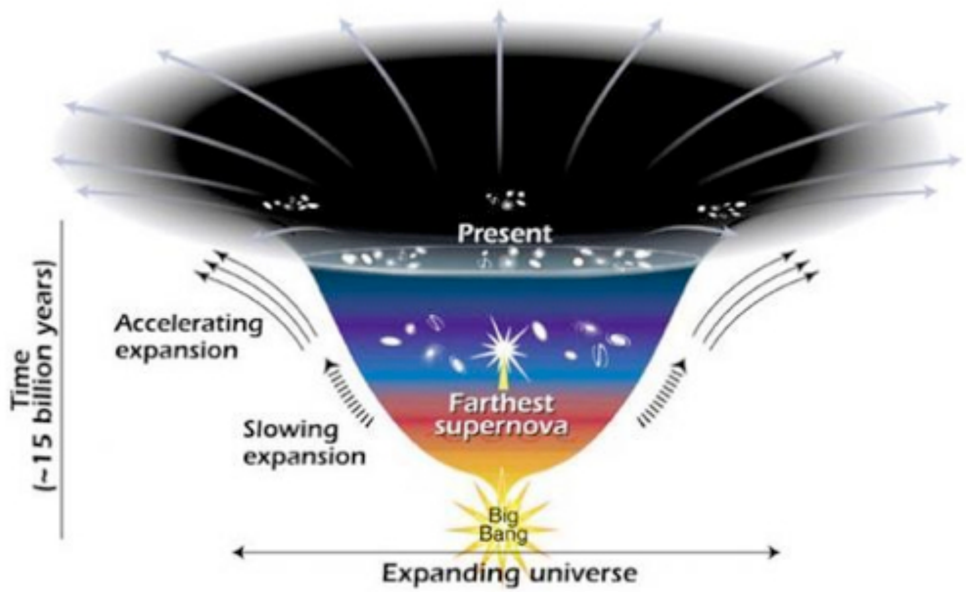
Giants need dwarfs too....

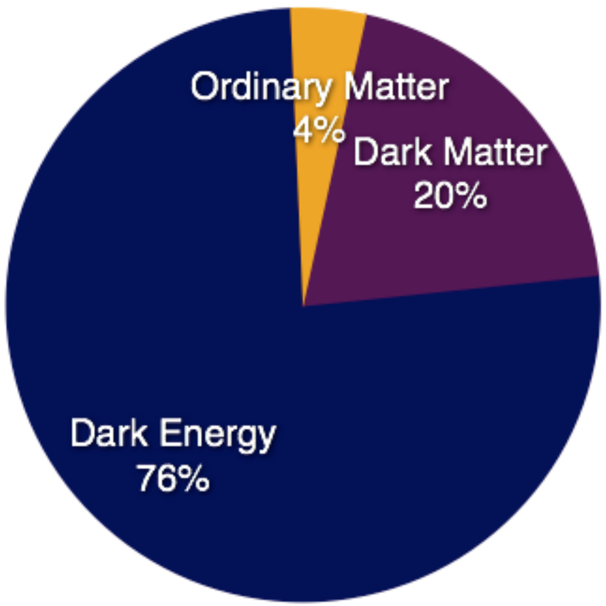
Open Questions in Cosmology

- Nature of the Dark Energy
- Nature of the Dark Matter
- Initial conditions (Inflation Physics)
- Modifications to Gravity
- Formation and Evolution of Galaxies

Large ignorance on > 95% of Universe content !!

“precise” ignorance





Current status of Dark Energy

Dark Energy:

- Affects cosmic geometry and structure growth
- Parameterized by equation of state parameter:

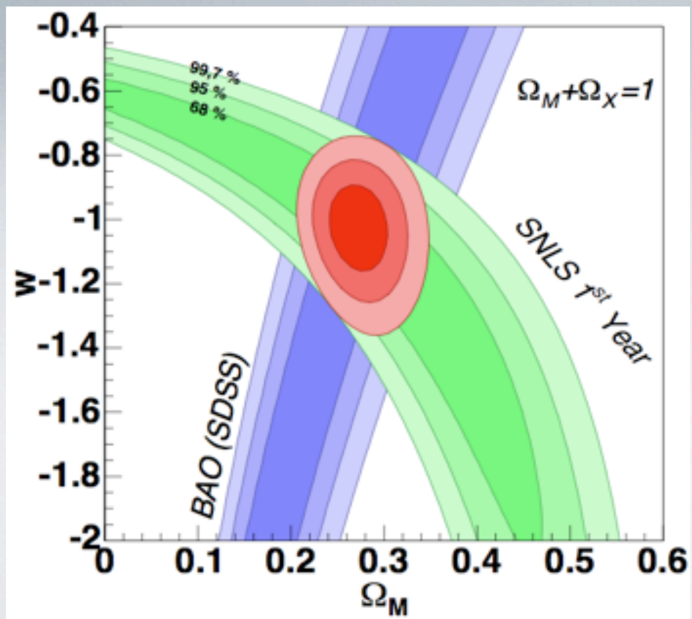
$w(z)=p/\varrho$, constant $w=-1$ for cosmological constant

Not necessarily DE!!!
could be non std GR

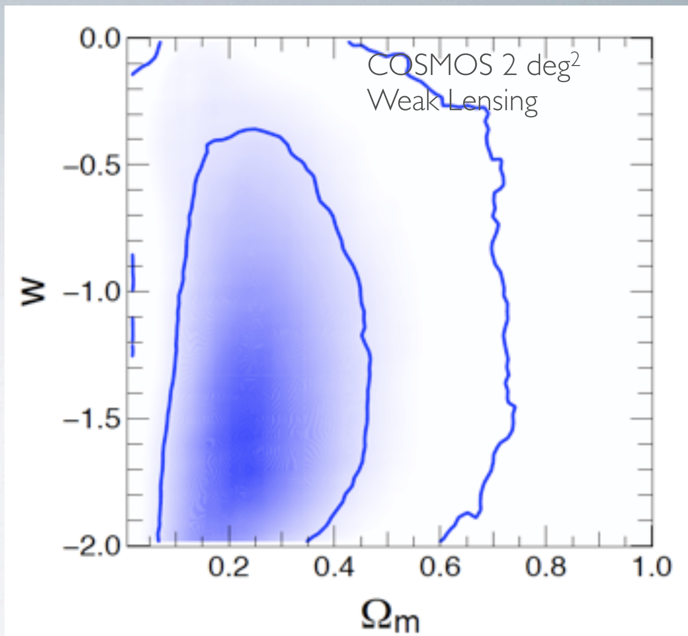
Current constraints: 10% error on constant w

For "definite" answers on DE: need to reach a precision of 1% on (varying) w and 10% on $w_a=dw/da$ → Objective for Euclid alone (FoM ~4-500)

Astier et al. 2005



Schrabback et al 2009



Recall a few basics

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

Evolution governed by components: $H(z) \Leftrightarrow \Omega_X, w$

$$H^2(a) = H_0^2\left[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE}\exp\left\{3\int_a^1 \frac{da'}{a'}[1+w(a')]\right\}\right]$$

Ellipses: uncertainty in parameters via Fisher matrix. An useful approximation (curse of dimensionality; also different definitions). *Priors*

Usually use Figure of Merit= 1/Area

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

$a=(1+z)^{-1}$ expansion factor

δ = density fluctuation

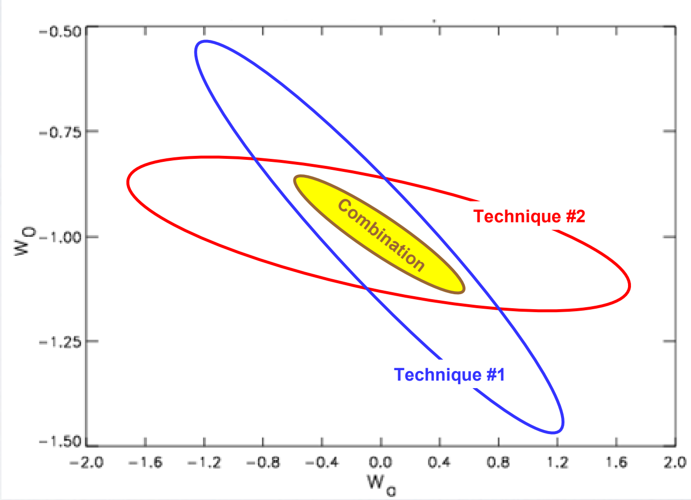
$P(k)$ = power spectrum of $\delta(\mathbf{x},z)$

$w = p/\varrho$, γ=growth index

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

$$f_{GR}(z) \equiv \frac{d\ln G_{GR}}{d\ln a} \approx [\Omega_m(z)]^\gamma$$

Λ: $w_0= -1$, $w_a =0$, $\gamma \sim 0.55$



to get a small uncertainty on power spectrum need:

$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\text{modes}}}}\left(1 + \frac{1}{P\bar{n}}\right)$$

accurate/adequate sampling in number of objects

large volumes to accomodate several Fourier modes

Cosmic Variance ⇔ Volume

Poisson ⇔ Number

EUCLID

1. Why
2. How
3. When

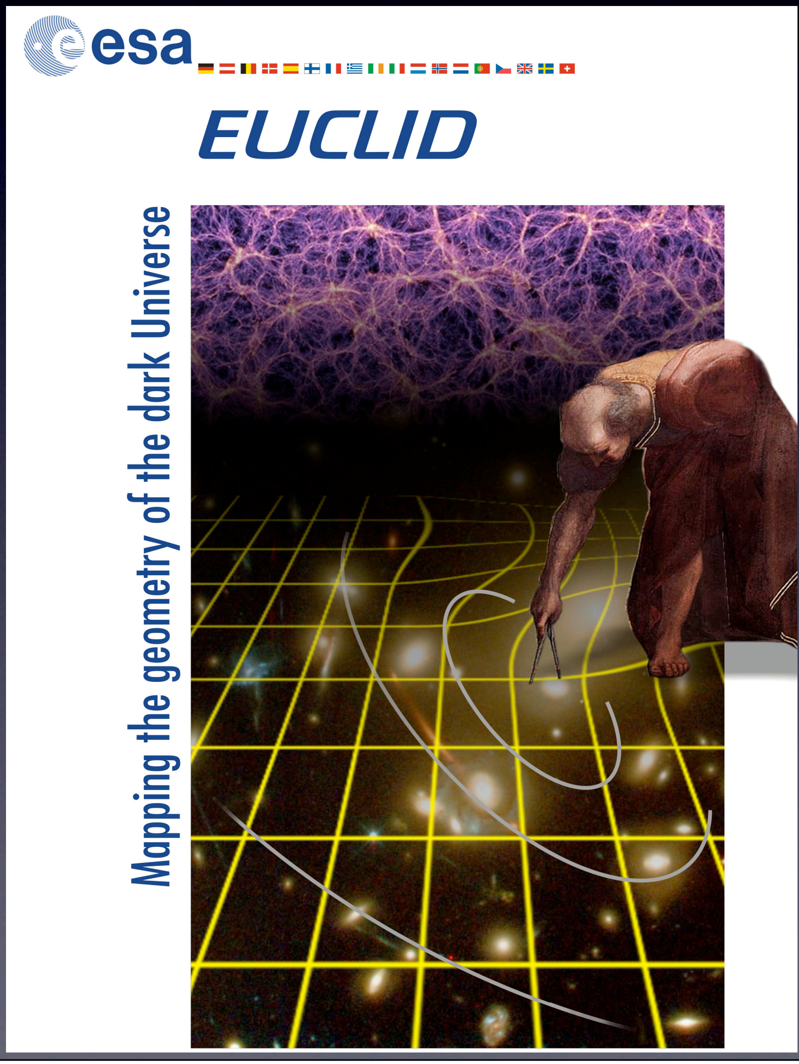
1. Dark Energy & Dark Matter (Cosmology) ; Legacy
2. Space imaging (morphology & NIR) + Spectra: Grav. Lensing & BAO
3. 2020-2025+

2006 ESA Cosmic Vision Proposals

DUNE: all-sky imaging for lensing

SPACE: all-sky spectra

Joined in a single mission: **Euclid**



Test Space-Time Geometry & Growth of Structure

Two phase A instrument consortia:

EIC for imaging (P.I. A. Refregier) and

wide visible red band (R+I+Z, 0.55-0.92μ) resolution of 0.18 arcsec
NIR bands (Y, J, H+, spanning 1.0-2.0μ) with a resolution of 0.3 arcsec

ENIS for spectroscopy (P.I. A. Cimatti)

1.0-2.0 micron in slitless mode at a spectral resolution R ~ 500

In early 2010 merged in a single consortium EC
[most of EU nations, spokesperson A. Refegier ⇒ Y. Mellier]

STATUS: Phase A completed, selected f... Phase B1 (extended A). Ranked fi... interest among t... ar Orbit...

Fina... ...ion selection in sum... 2 slots for 3 candidates....

fall

Not only selected: now it's adopted !!

New Worlds, New Horizons in Astronomy and Astrophysics (Decadal Survey 2010)

Ground Projects – Large – in Rank Order

Large Synoptic Survey Telescope (LSST)

LSST is a multipurpose observatory that will explore the nature of dark energy and the behavior of dark matter, and will robustly explore aspects of the time-variable universe that will certainly lead to new discoveries. LSST addresses a large number of the science questions highlighted in this report. An 8.4-meter optical telescope to be sited in Chile, LSST will image the entire available sky every 3 nights.

TABLE ES.3 Ground: Recommended Activities—Large Scale (Priority Order)

Recommendation[b]	Science	Technical Risk[c]	Appraisal of Costs Through Construction[a] (U.S. Federal Share 2012-2021)	Appraisal of Annual Operations Costs[d] (U.S. Federal Share)	Page Reference
1. LSST - Science late 2010s - NSF/DOE	Dark energy, dark matter, time-variable phenomena, supernovas, Kuiper belt and near-Earth objects	Medium low	$465M ($421M)	$42M ($28M)	7-29

Space Projects – Large – in Rank Order

Wide Field Infrared Survey Telescope (WFIRST)

A 1.5-meter wide-field-of-view near-infrared-imaging and low-resolution-spectroscopy telescope, WFIRST will settle fundamental questions about the nature of dark energy, the discovery of which was one of the greatest achievements of U.S. telescopes in recent years. It will employ three distinct techniques—measurements of weak gravitational lensing, supernova distances, and baryon acoustic oscillations—to determine the effect of dark energy on the evolution of the universe. An equally

TABLE ES.5 Space: Recommended Activities—Large-Scale (Priority Order)

Recommendation	Launch Date[b]	Science	Technical Risk[c]	Appraisal of Costs[a]: Total (U.S. share)	Appraisal of Costs[a]: U.S. share 2012-2021	Page Reference
1. WFIRST - NASA/DOE collaboration	2020	Dark energy, exoplanets, and infrared survey-science	Medium low	$1.6B	$1.6B	7-17

DE as TOP priority both for Ground and Space also across the Atlantic

Main Scientific Objectives

Understand the nature of Dark Energy and Dark Matter by:

- Reach a dark energy *FoM* > 400 using only weak lensing and galaxy clustering; this roughly corresponds to 1 sigma errors on w_p and w_a of 0.02 and 0.1, respectively.
- Measure γ, the exponent of the growth factor, with a 1 sigma precision of < 0.02, sufficient to distinguish General Relativity and a wide range of modified-gravity theories
- Test the Cold Dark Matter paradigm for hierachical structure formation, and measure the sum of the neutrino masses with a 1 sigma precision better than 0.03eV.
- Constrain n_s, the spectral index of primordial power spectrum, to percent accuracy when combined with Planck, and to probe inflation models by measuring the non-Gaussianity of initial conditions parameterised by f_{NL} to a 1 sigma precision of ~2.

SURVEYS

	Area (deg2)	Description
Wide Survey	15,000 (required) 20,000 (goal)	Step and stare with 4 dither pointings per step.
Deep Survey	40	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
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

SPACECRAFT

Launcher	Soyuz ST-2.1 B from Kourou
Orbit	Large Sun-Earth Lagrange point 2 (SEL2), free insertion orbit
Pointing	25 mas relative pointing error over one dither duration 30 arcsec absolute pointing error
Observation mode	Step and stare, 4 dither frames per field, VIS and NISP common FoV = 0.54 deg^2
Lifetime	7 years
Operations	4 hours per day contact, more than one groundstation to cope with seasonal visibility variations;
Communications	maximum science data rate of 850 Gbit/day downlink in K band (26GHz), steerable HGA

Budgets and Performance

	Mass (kg)		*Nominal Power (W)*	
industry	TAS	Astrium	TAS	Astrium
Payload Module	897	696	410	496
Service Module	786	835	647	692
Propellant	148	232		
Adapter mass/ Harness and PDCU losses power	70	90	65	108
Total (including margin)	**2160**		**1368**	**1690**

All data you need to know (Red Book)

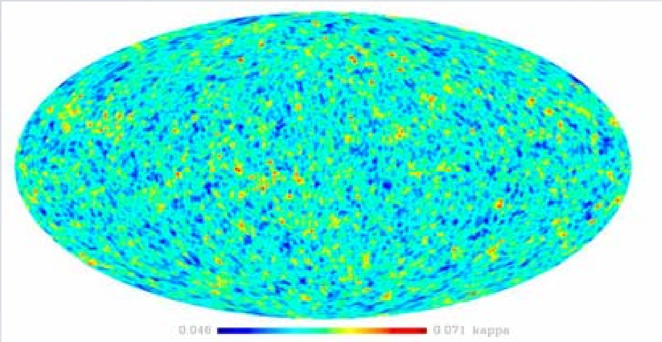
- **Wide Area** (>10^4 sq deg)
- **Wide Field** (FoV > 0.5 sq deg)
- **Opt. imaging**
- **NIR photom**
- **NIR slitless**

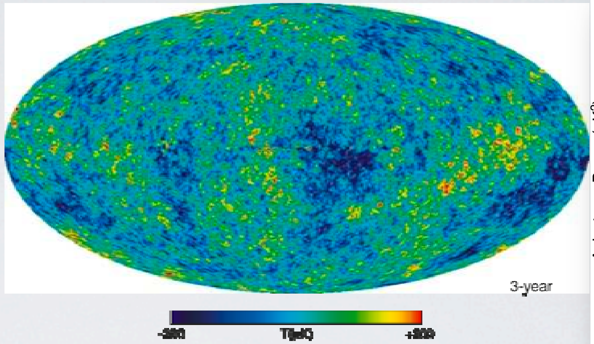
Two instruments:

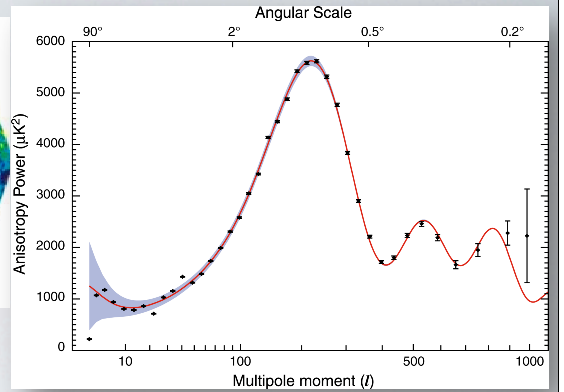
VIS: optical imager &

NISP: NIR imager + grisms

Synergy with Planck: Universe @ z~1000 vs z~1-3







Weak Lensing Dark Matter Maps

CMB Temperature Maps (5y WMAP)

Figure 2.15: a. (left) Simulated all sky mass map from weak lensing (Teyssier et al., 2008) for a Euclid survey. This was produced using a 70 billion particle N-Body simulation. This can be compared with the all sky temperature maps of the CMB, such as the WMAP 5 Year all sky temperature map (Hinshaw et al., 2008). b. (right) The Planck CMB map will produce an all sky temperature map at an even higher resolution of approximately 0.2 degrees at a redshift of ~1100. Euclid will produce a 3D map between a redshift of 0 and 2 down to arcminute scales.

shear
shear

Most of the effects happen at z < 3

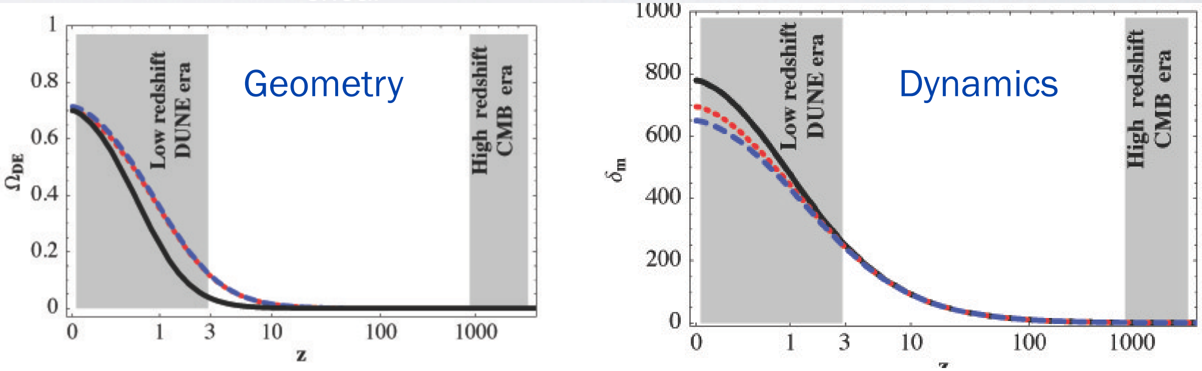


Figure C.1: *Effect of dark energy on the evolution of the Universe.* ***Left:*** *Fraction of the density of the Universe in the form of dark energy as a function of redshift z., for a model with a cosmological constant (w=-1, black solid line), dark energy with a different equation of state (w=-0.7, red dotted line), and a modified gravity model (blue dashed line). In all cases, dark energy becomes dominant in the low redshift Universe era probed by DUNE, while the early Universe is probed by the CMB.* ***Right:*** *Growth factor of cosmic structures for the same three models. Only by measuring the geometry (left panel) and the growth of structure (right panel) at low redshifts can a modification of dark energy be distinguished from that of gravity. Weak lensing measures both effects.*

Need also dynamics to further disentagle

Want, NEED! several probes for synergies and Xchecks

Observational Input	Probe	Description
Weak Lensing Survey	Weak Lensing (WL)	Measure the expansion history and the growth factor of structure
Galaxy Redshift Survey: Analysis of *P(k)*	Baryonic Acoustic Oscillations (BAO)	Measure the expansion history through D_A(z) and H(z) using the “wiggles-only”.
	Redshift-Space distortions	Determine the growth *rate* of cosmic structures from the redshift distortions due to peculiar motions
	Galaxy Clustering	Measures the expansion history and the growth factor using all available information in the amplitude and shape of P(k)
Weak Lensing plus Galaxy redshift survey combined with cluster mass surveys	Number density of clusters	Measures a combination of growth factor (from number of clusters) and expansion history (from volume evolution).
Weak lensing survey plus galaxy redshift survey combined with CMB surveys	Integrated Sachs Wolfe effect	Measures the expansion history and the growth

Want to measure expansion factor H(z) - *geometry* -
and growth of density perturbations - *dynamics* -

Legacy

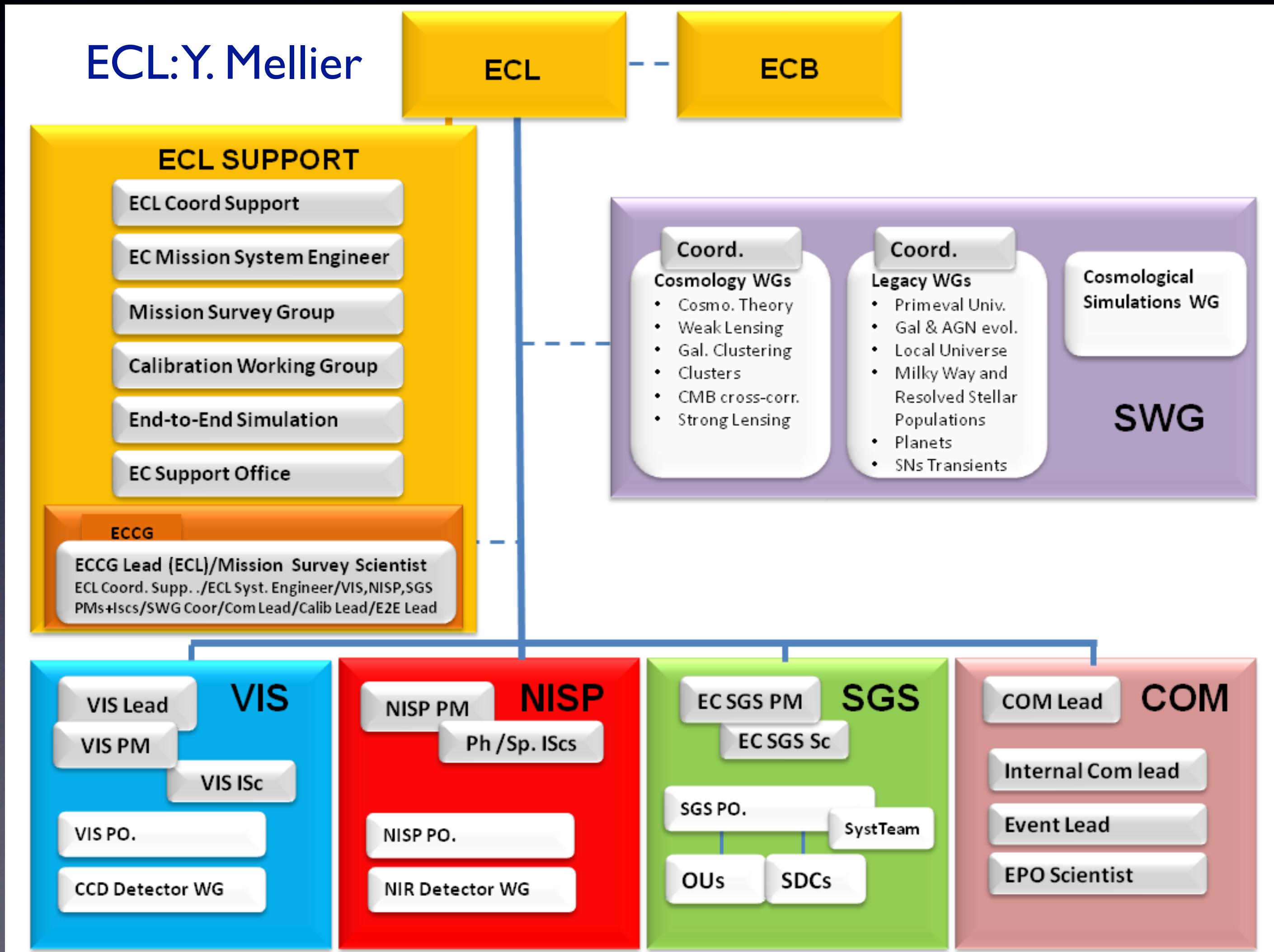
Wide survey: >15,000 sq. deg (visible: 24.5th ABmag 10σ extended; NIR: 24th ABmag 5σ; spectra: Hα line flux > 4×10^{-16} erg s^{-1} cm^{-2}, rate ~35%)

Deep Survey: ~40 sq. deg ~ 2 mags deeper (~40 visits)

EC organization

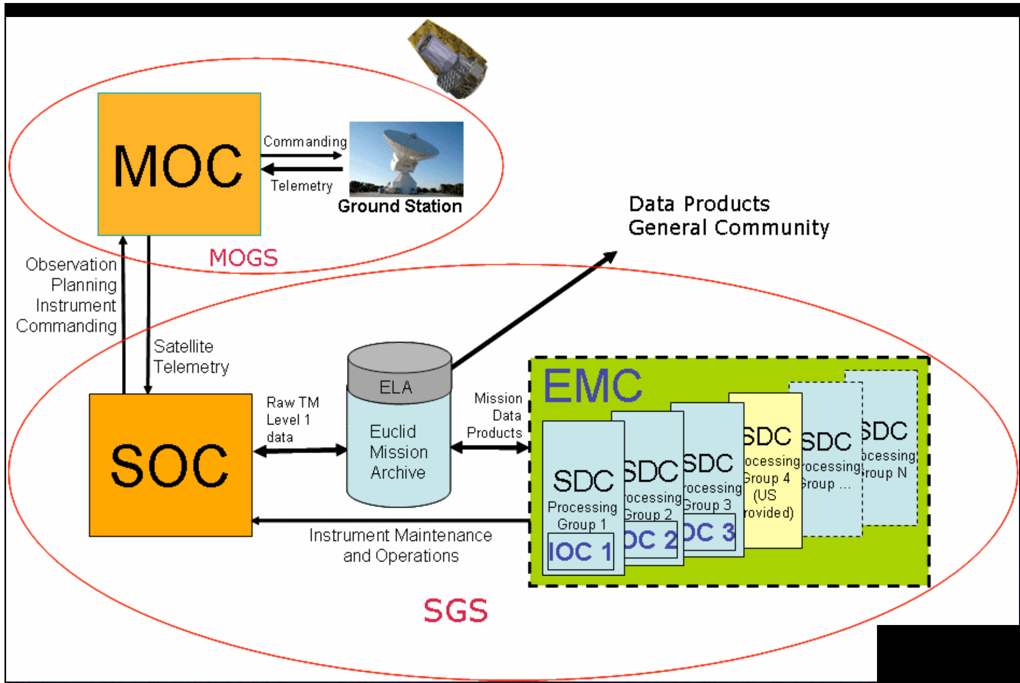
EC is responsible of instruments and parts of Ground Segment (telescope, MOC, SOC and archive are provided and managed by ESA)

ESA Euclid Science Team [EST]



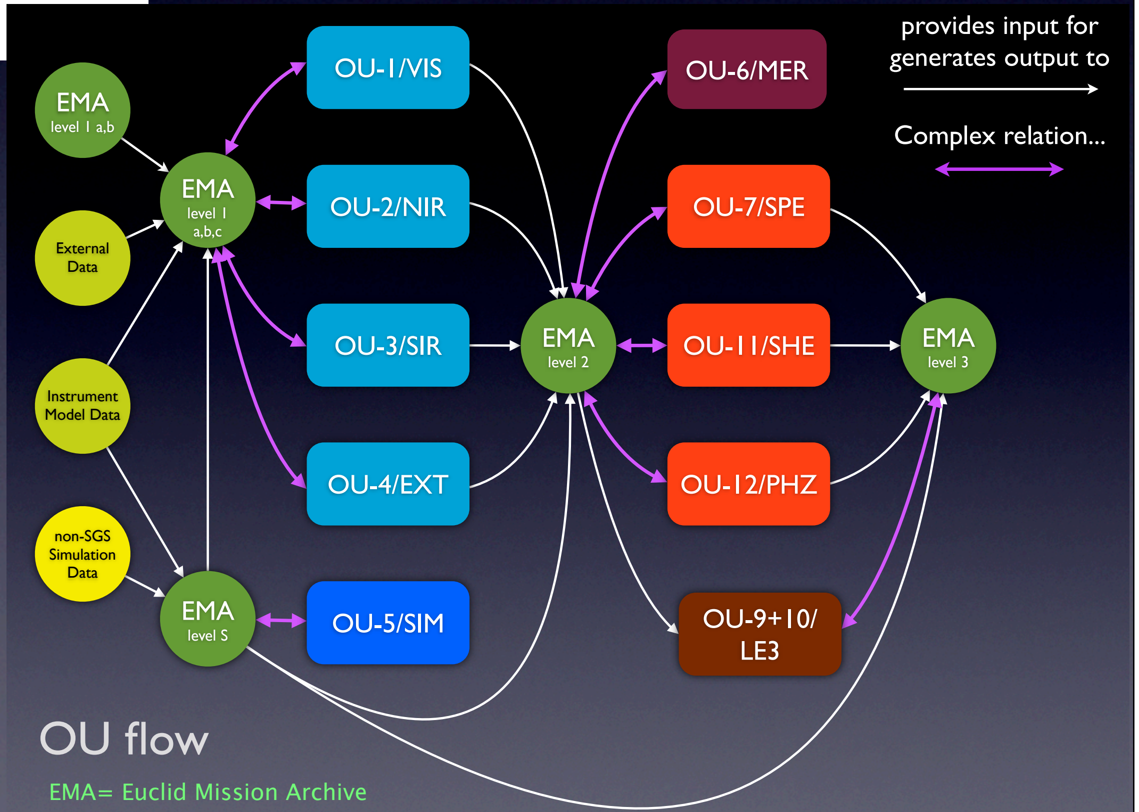
Many European Countries,
~900 aficionados,
~450+ M€ (ESA)
~100 M€ Payload
~100 M€ Ground

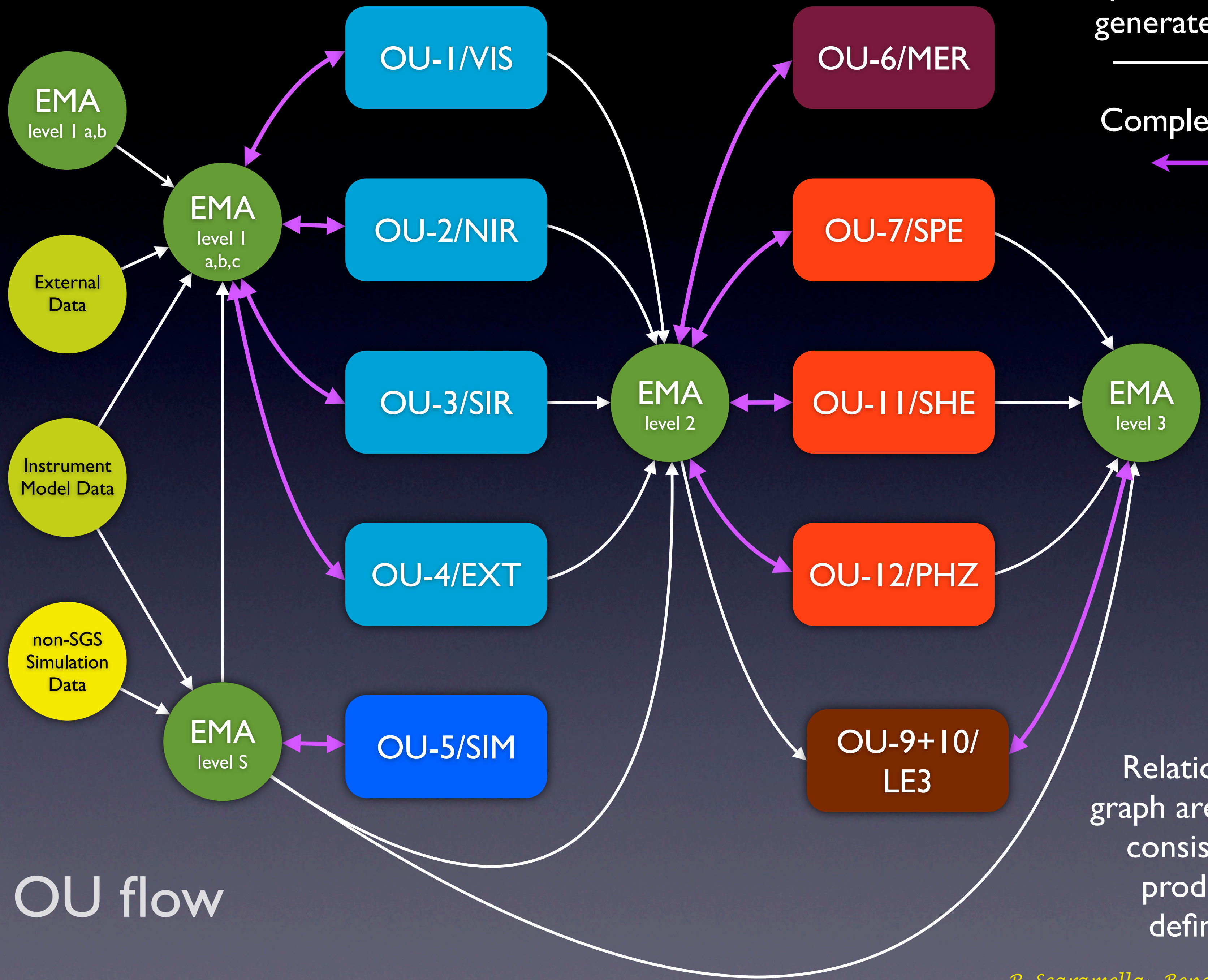
Ground Segment



A few Petabytes...

instruments costs ≈ GS costs





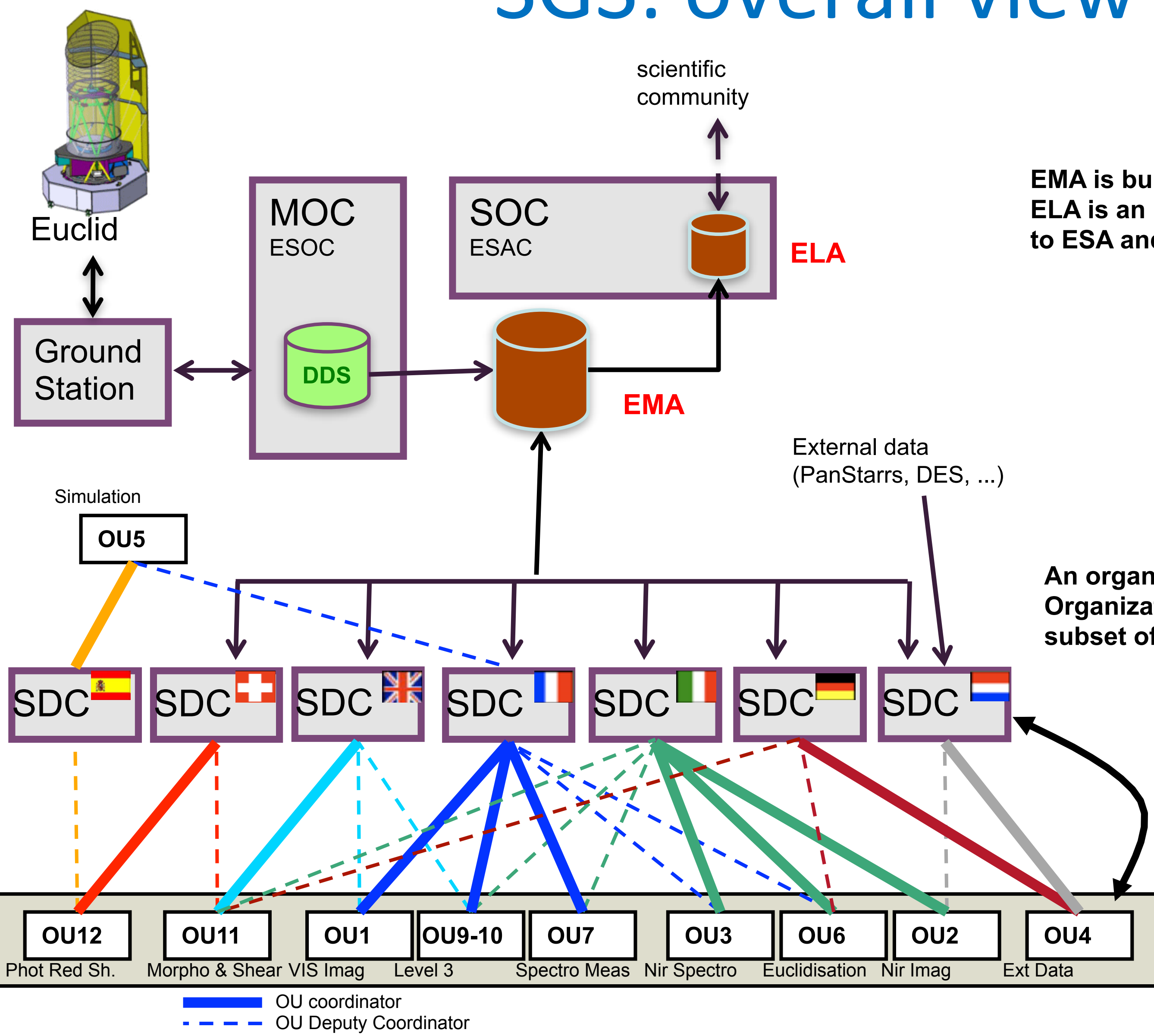
provides input for
generates output to

Complex relation...

OU flow

Relations in this graph are not always consistent with product level definitions...

SGS: overall view



EMA is built by EC and managed by SOC
ELA is an EMA subset, is a formal EC delivery to ESA and is distributed by SOC

An organization based on the decomposition in Organization Units (OU) corresponding to a subset of overall EUCLID Data Processing

Each OU produces algorithms which are integrated and executed in an SDC (Science Data Center)

OUs are transnational

According to people, Euclid Surveys need to have just *"a few"* features.....


Commissioning
First Light
Strategy
Calibrations
VIS
NIP
NIS
Additional Surveys
Planet microlensing
How long
Cadence
Milky Way
When
End of the mission
Dedicated time spans during mission
Supernovae
Wide Survey
Goal
Minimum required
Number of galaxies (Poisson)
Spatial sampling: Area/Volume (cosmic variance, char scales)
Global [N(M,D,etc)]
Number of useful dithers, Bright stars etc
Effective S
Shear
Spectra
Limiting magnitude
Useful size
Good photoz
Limiting line flux
Crowding
Halpha detected
Deep Survey
When
Interleaved
End of the mission
Dedicated time spans during mission
Depth
How
Size
Sequences
Need to fix priorities !!!

Some Inputs/Constraints

1. FoV, exposure times, number of ditherings

2. Possible orbits: Solar Aspect Angle max Δ range & area visibility, overheads & overall efficiency

3. max # of slews (-if- limited amount of gas for manouvers), mission lifetime (extensions are extremely welcome for general astronomy)

4. Targeted Calibrations: VIS, NIP, NIS (angles!)

Some Desires

1. Have a southern deep field with (max) observability from ground large facilities (ESO, ALMA, LSST, EELT, SKA,CTA etc). It is highly desirable to take advantage of existing data

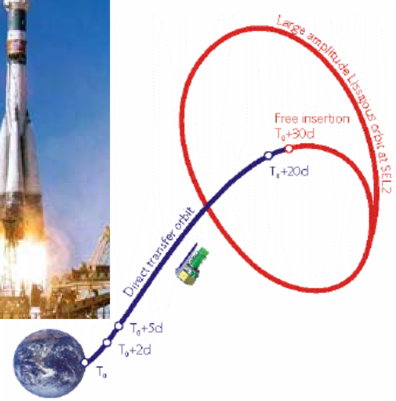
2. Adequate time sampling for SN

3. Additional Surveys (e.g. MW, microlensing)

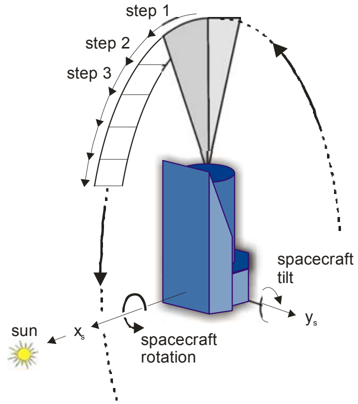
EUCLID Mission

in part OLD

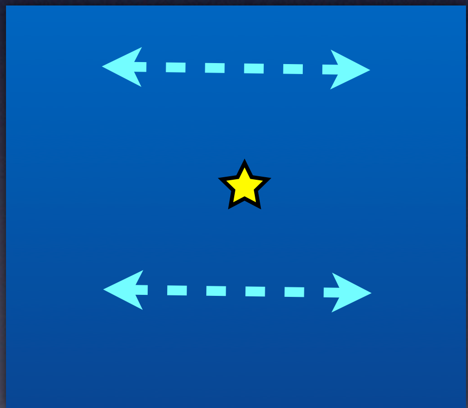
- Launcher: Soyuz ST2-1B from Kourou
- Direct injection into tranfer orbit
  - Transfer time: 30 days
  - Transfer orbit inclination: 5.3 deg
- Launch vehicle capacity:
  - 2160 kg (incl. adapter)
  - 3.86 m diameter fairing
- Launch ≈ 2020
- Mission duration 6 years



Advanced Studies and Technology Preparation Division

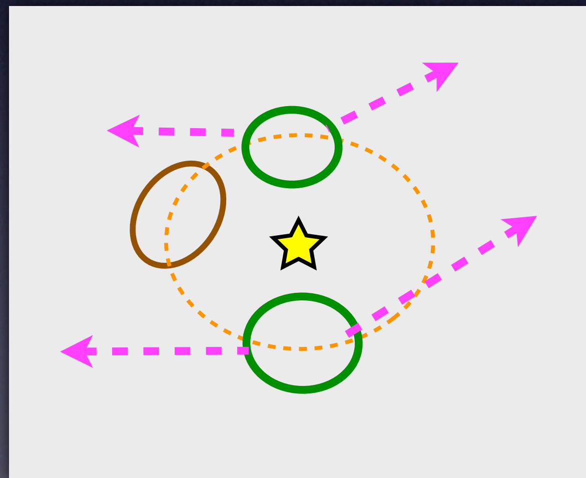


Looks like CMB satellites but with step & stare



For stability need to always observe orthogonally to the sun

< 5 deg variation, i.e. observe on a circle



region visibility twice/yr at ecliptic plane, max at ecliptic poles *(spin 2)*

Gas supply for manouvers is limited

The core: ~0.5 sq/degs, VIS & NIR Focal Planes, lots of pixels !!!

The geometrical Field of View is the sky area limited by the contour of the focal plane array of a given instrument (VIS or NISP) projected onto the sky. The contour is defined by the first pixel line or columns of the detectors on the edge of the FPA as indicated on the next figure.

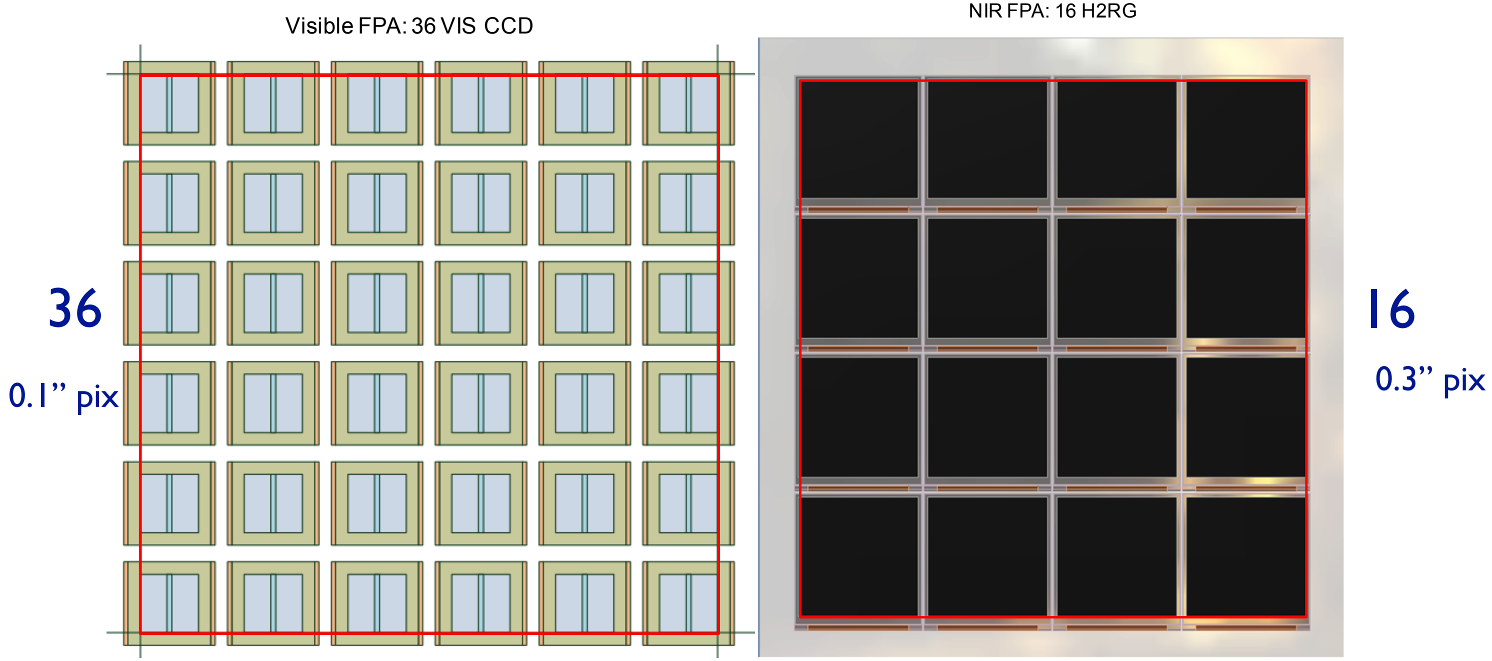


Figure 6-1: VIS (left red ensquared area) and NISP (right red ensquared area) Geometrical FoV.

With the current definition of the instruments, the joint VIS/NISP Survey Geometrical Field of View is:

- JOINT_FOV_x= 0.763°
- JOINT_FOV_y= 0.709°

The x and y field orientations are defined in the figure 6-2.

4 dithers ~1 full Field -0.5 sq deg- / 1.25 hr (≈10 sq deg/day)

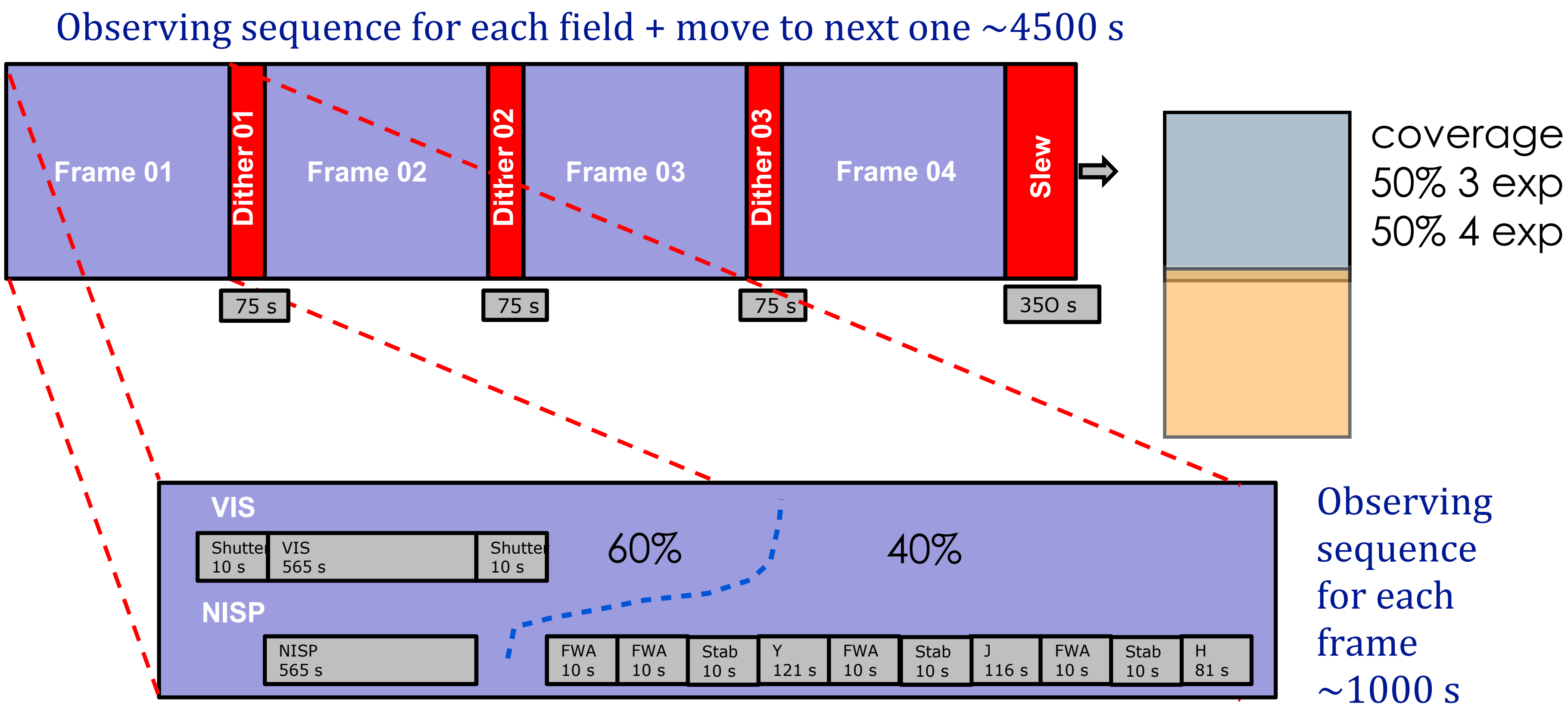
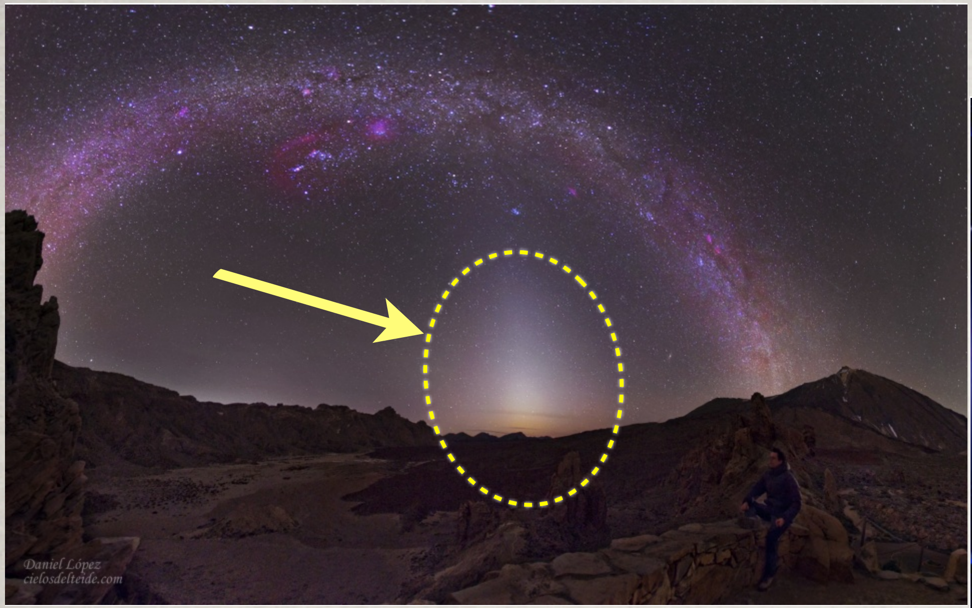


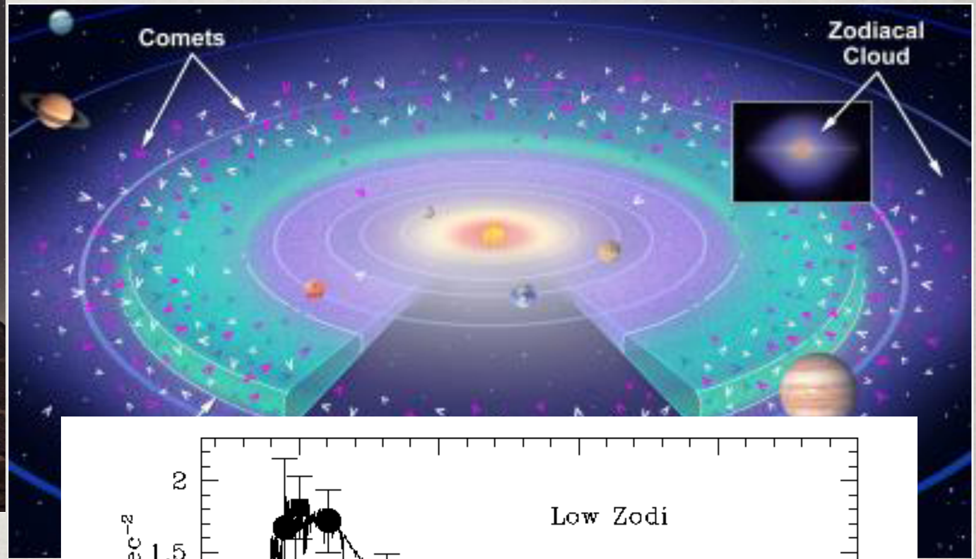
Figure 5-4: Nominal Field Observation Sequence.

NIR: first spectroscopy contemporarily to VIS, then imaging (filter wheels motion perturbs VIS)

Slitless: Blue, then Red grism, then again at 90 degs

Zodiacal Light





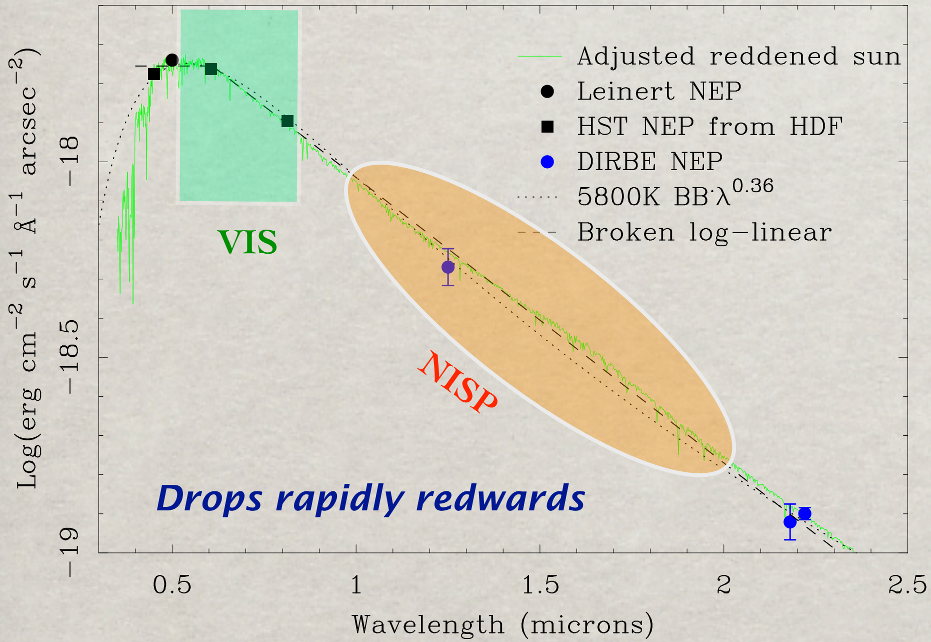


Figure 7: The solar spectrum, adjusted to match the observed zodiacal background (solid green). Simplified characterization - a 5800° K blackbody scaled by $\lambda^{0.36}$ (dotted black). Broken power-law parameterization (dashed black).

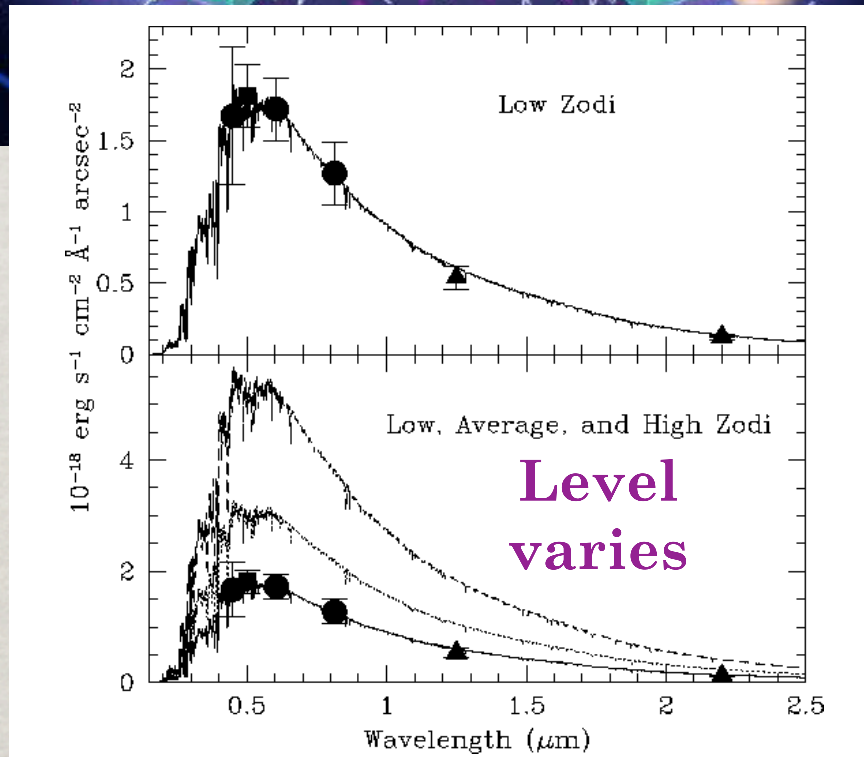
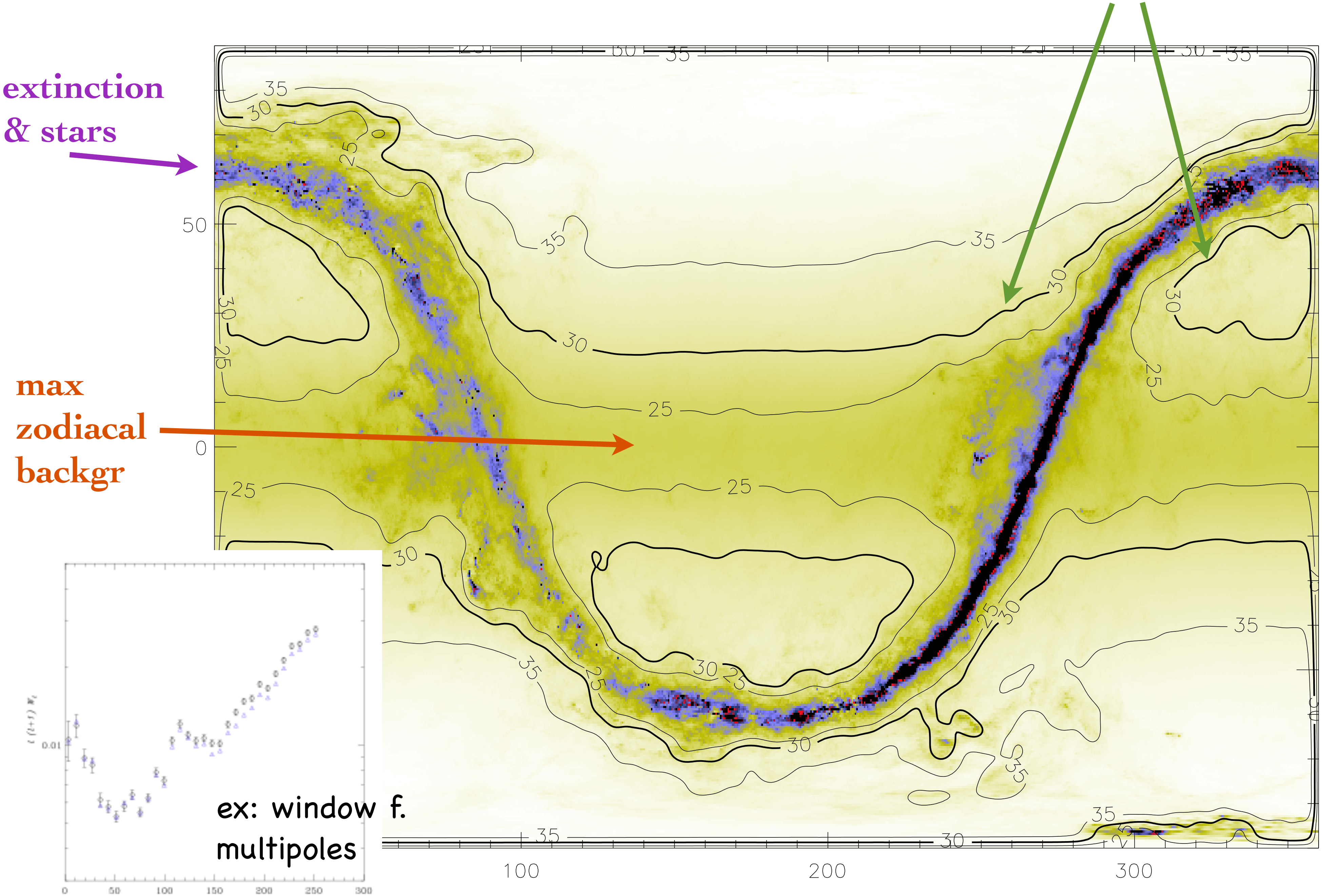
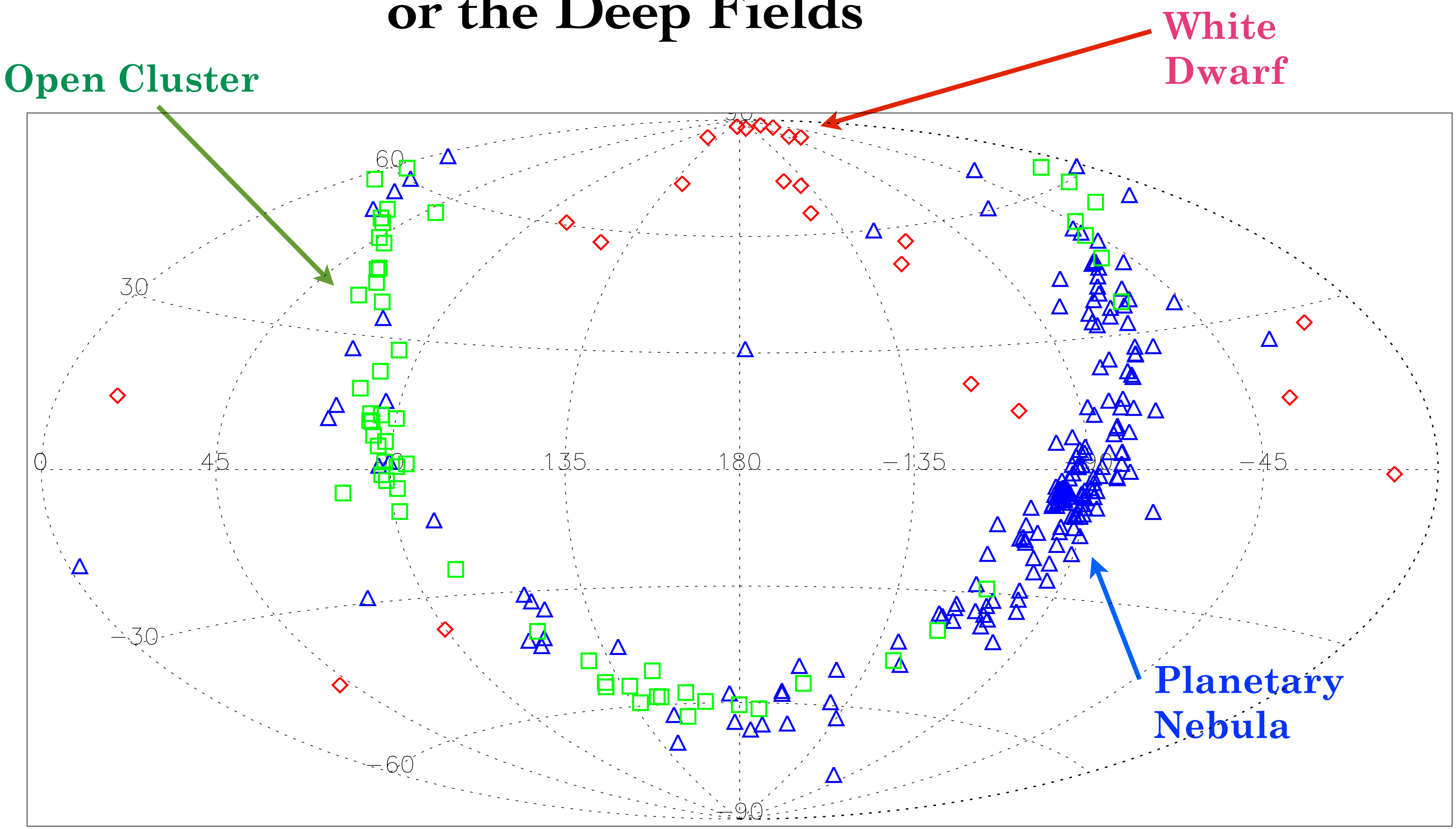


Figure 1. Upper panel. The spectrum of the zodiacal background light at the NEP compared to broad-band observations from the ground and HST observations. The circles are data at 0.450, 0.606 and 0.814 μm, respectively from the HDF; the square is Leinert et al. (1998) measure at 0.5 μm, and the triangles are measures from COBE/DIRBE at 1.25 and 2.2 μm. **Lower panel.** The comparison between the intensity of the three adopted normalizations of the zodiacal backgroud light. The lowest normalization is the one relative to the NEP, and it is shown together with the broad-band data points discussed above.

Galaxy density for WL: want the overall average > 30 /sq arc min



For calibrations use specific targets or the Deep Fields



NISP calibrators above, for WL need dense star regions
(in the galaxy plane)

Example
(ecliptic coords)

Wide Survey
1st year

Zodiacal light max
in the ecliptic plane

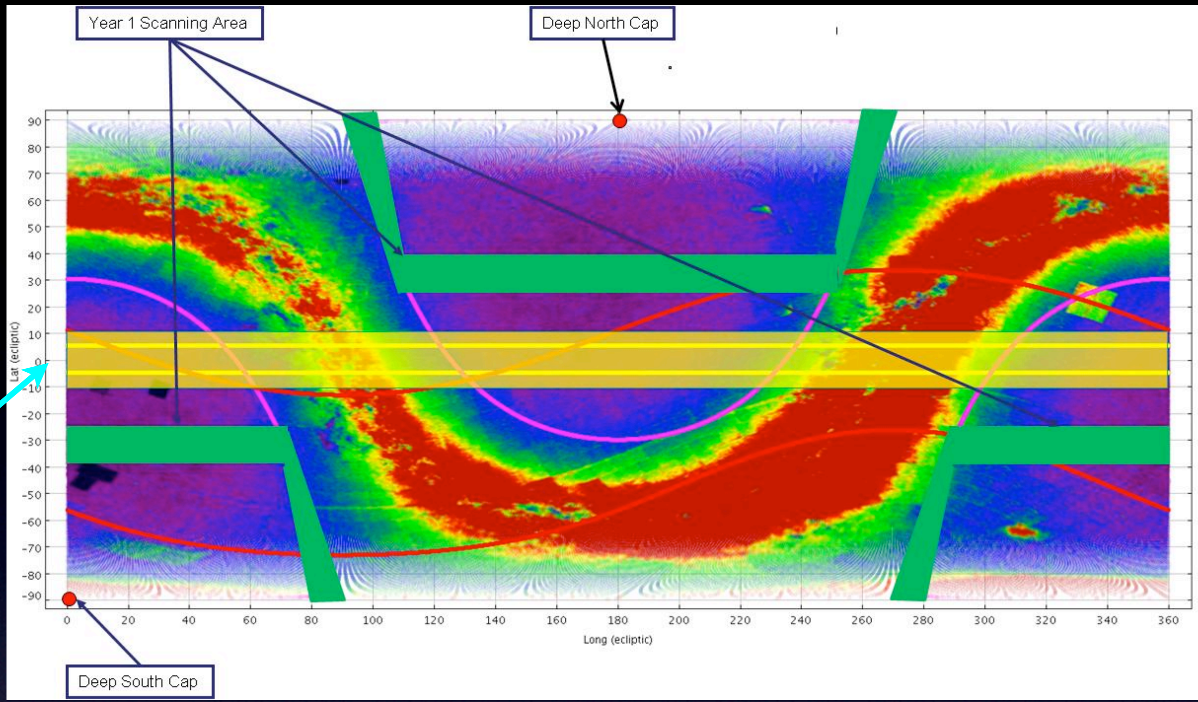


Figure 6-5: Targeted area for year 1.

Wide Survey
5th year

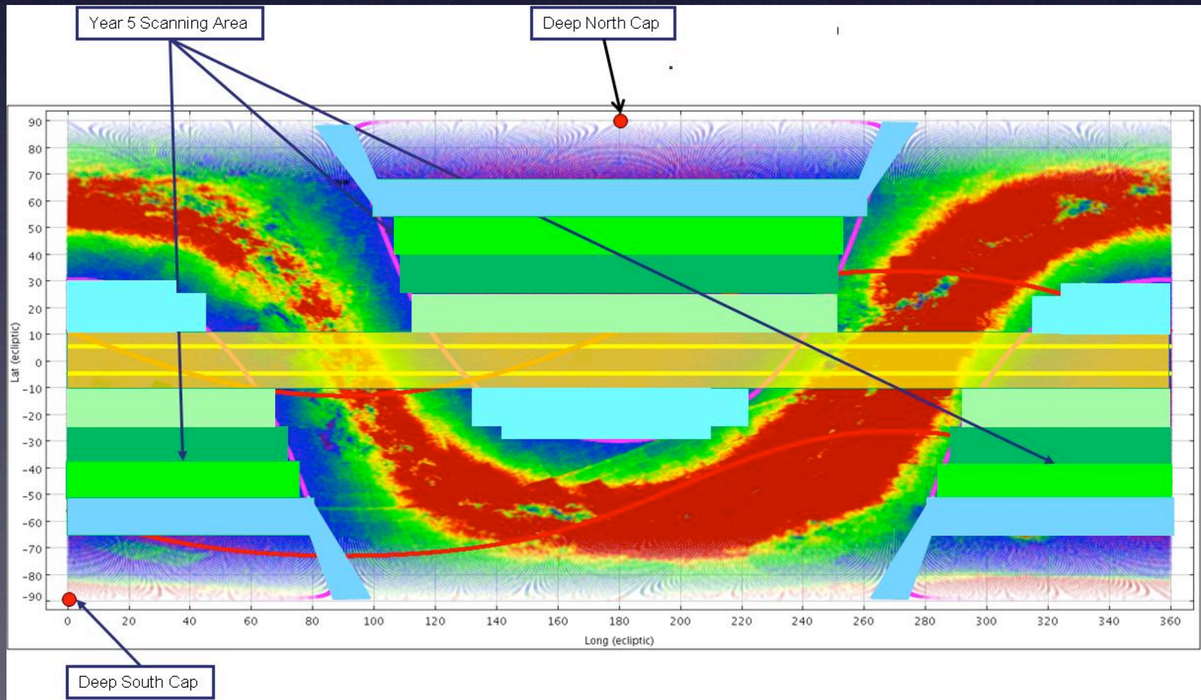


Figure 6-9: Targeted area for year 5.

Deep Field(s): calibration reqs (*being revised*) + science

Need high ecliptic latitude for observability (want low extinction too)

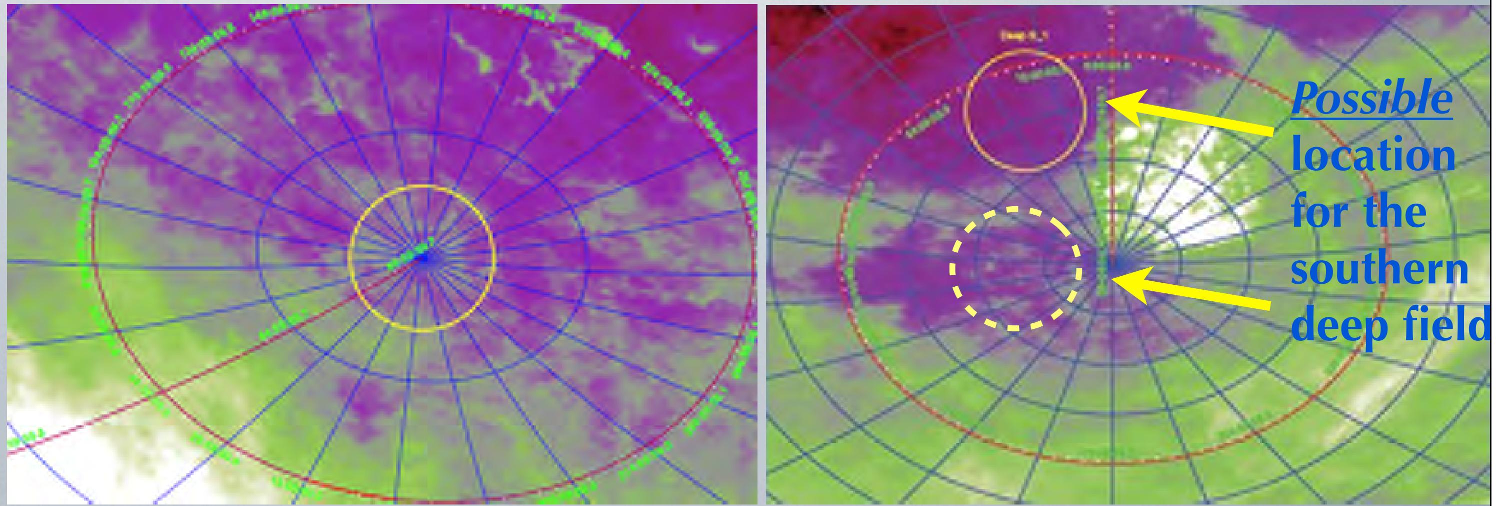
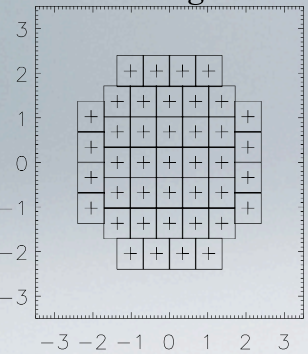
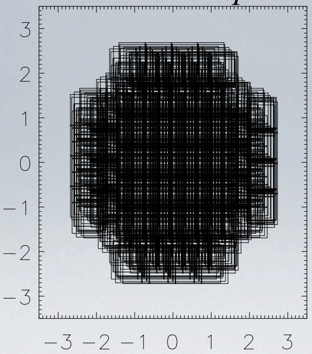


Figure 5.6: Left panel: Northern Deep Field projected on a sky extinction map. Right panel: Southern Deep Fi

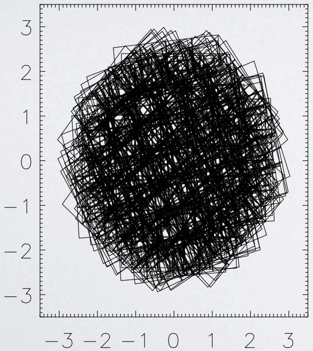
Basic pattern



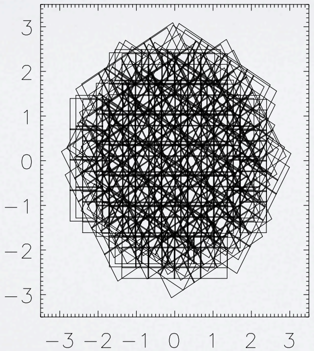
Staggered centers



Staggered 2 months continuous



Staggered one year, one per month



Deep Field example: 41 FoVs

Want 40 passes in total

solutions can change after optimization

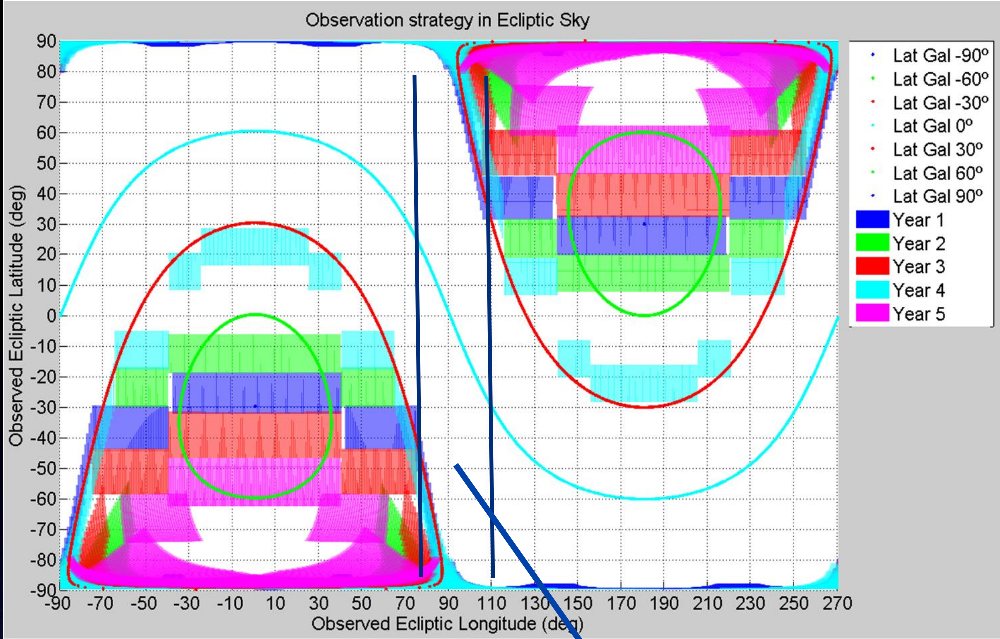


Figure 6-17: Observed area after year 7 (Ecliptic Coordinates)

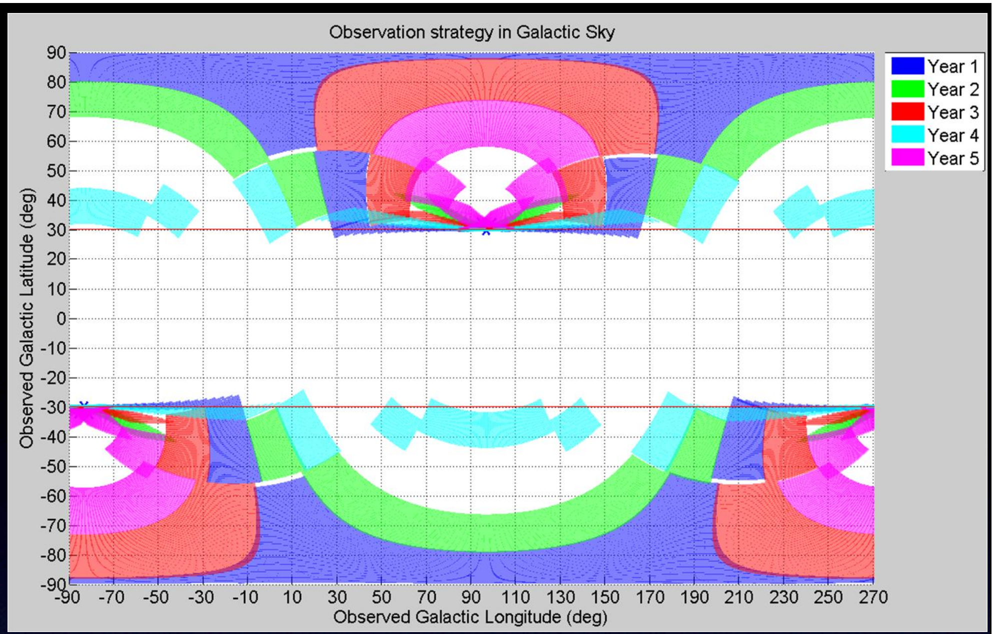


Figure 6-18: Observed area after year 7 (Galactic Coordinates).

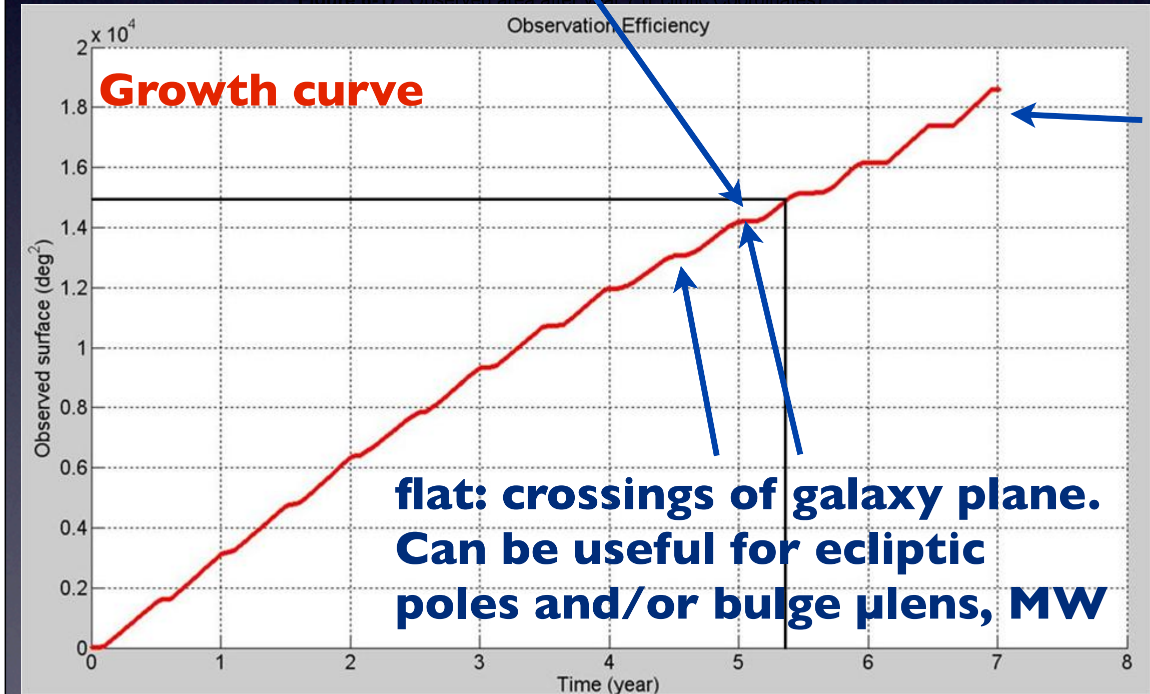


Figure 6-30: Observed as a function of time

Number of unobserved areas that can be pointed at within SAA constraints drops with time

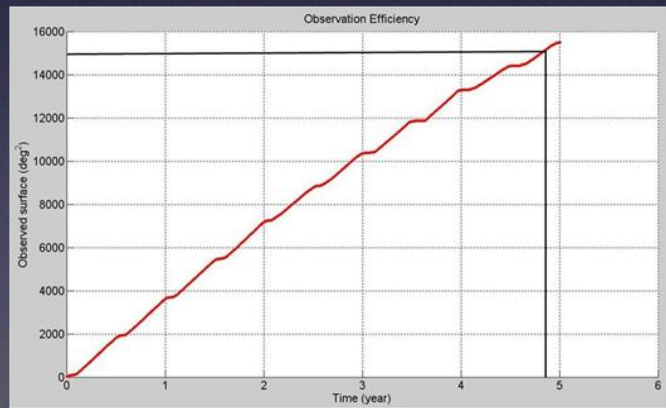
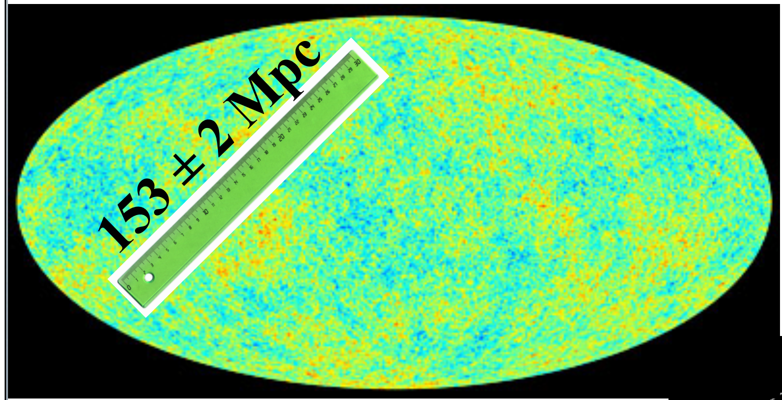


Figure 6-19: Observed as a function of time

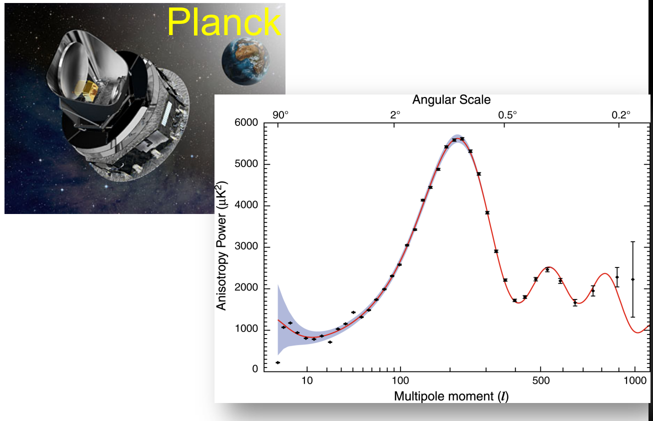
currently under revision with new tool

With nominal values (no margins) go faster

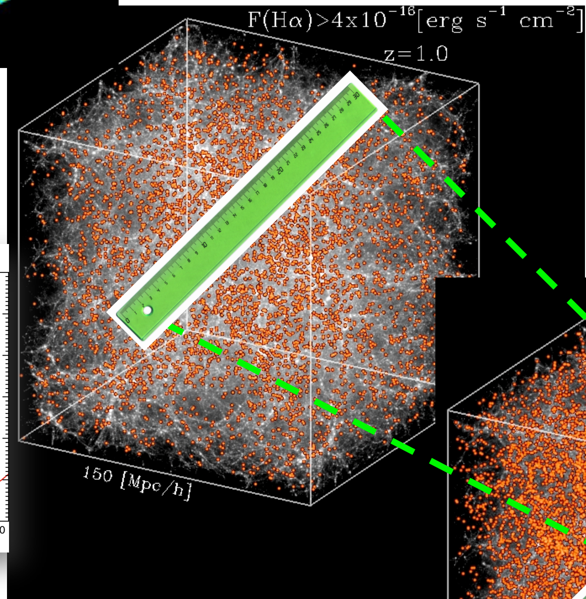
BAO as standard ruler



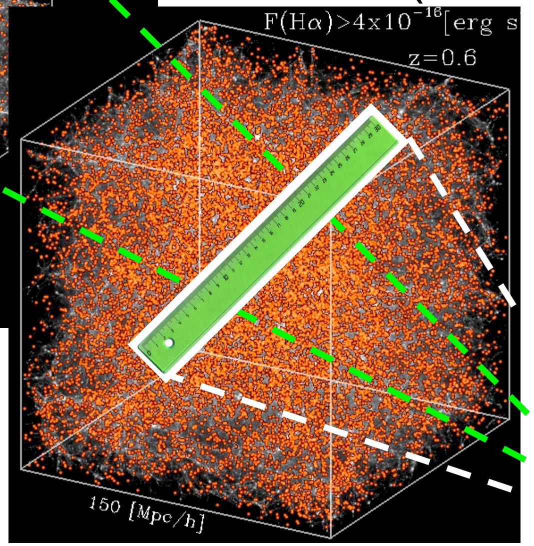
CMB (z≈1000)

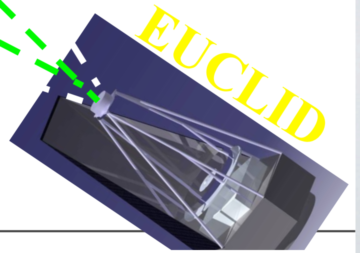


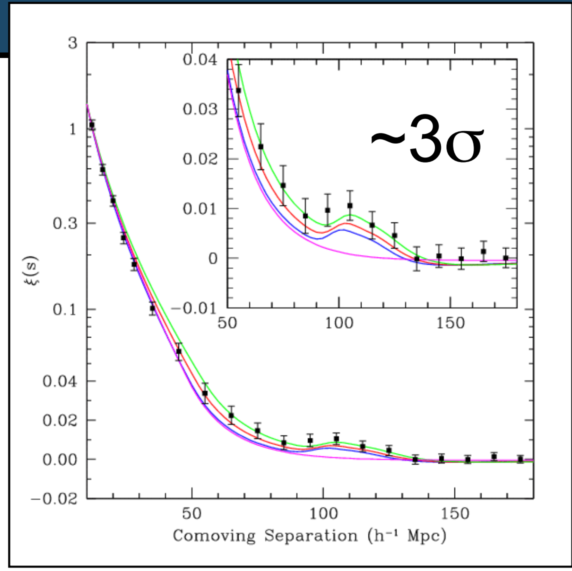
Galaxies (z>1)



Galaxies (z≈0.35)

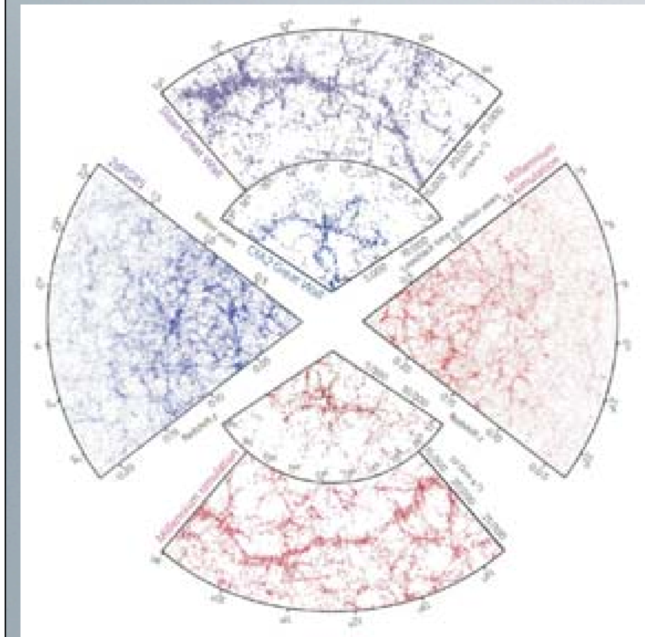






- H(z) (radial)
- $D_A(z)$ (tangential)
- H(z) & $D_A(z)$ depend on w(z)

Expansion and Growth Histories through Galaxy Clustering



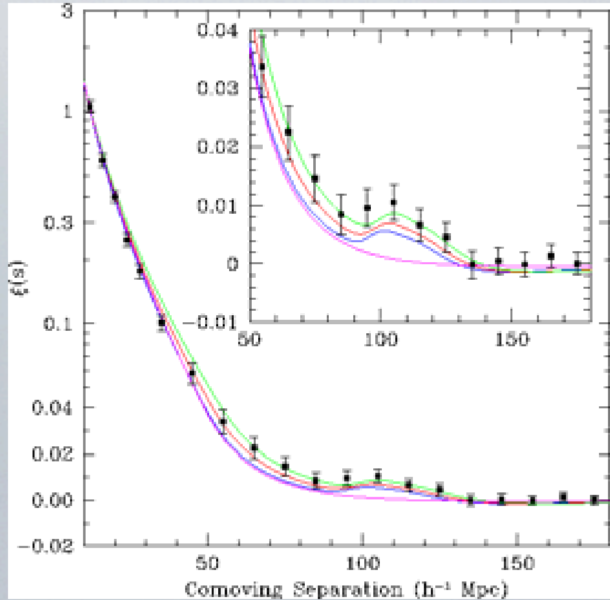
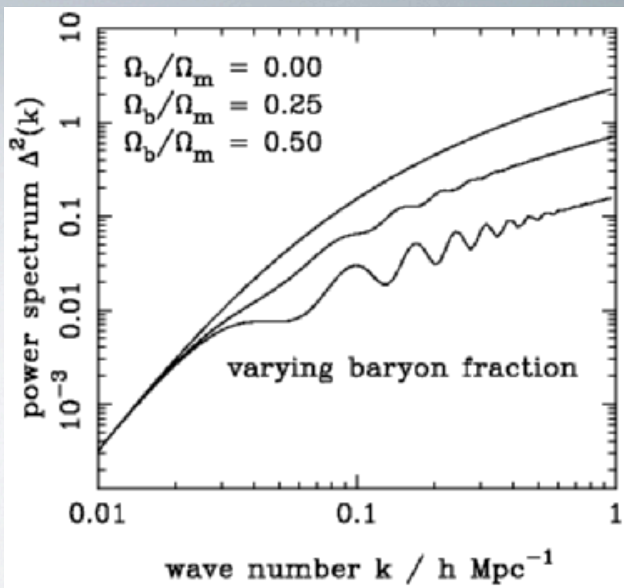


Figure 2.10: a. (Left panel) The galaxy distribution in the largest surveys of the local Universe, compared to simulated distributions from the Millennium Run (Springel et al. 2005); b. (Right panel) The two-point correlation function of SDSS "luminous red galaxies", in which the BAO peak at ~105 h^{-1} Mpc has been clearly detected (Eisenstein et al. 2005).

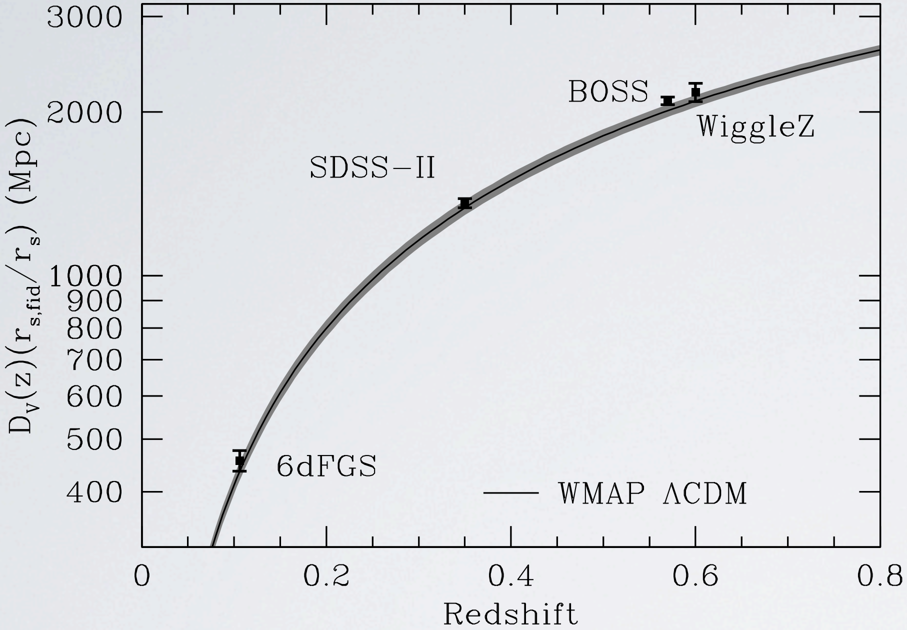


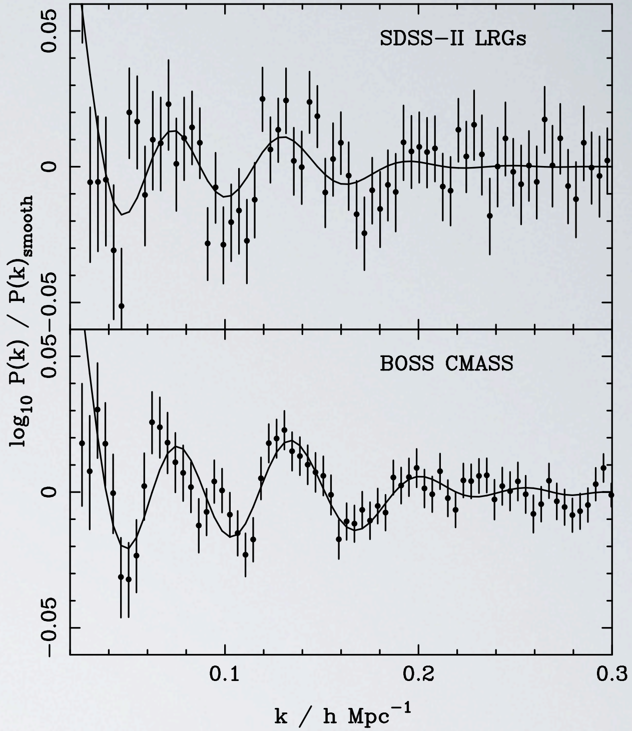
Clustering reveals features in the power spectrum of density perturbations

K. Mehta et al. 2012

L. Anderson et al. 2012

So far, so good..





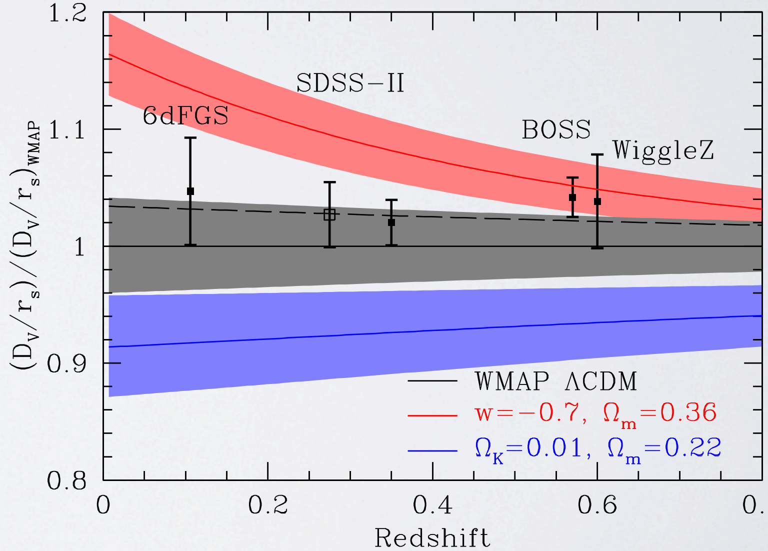


Figure 19. A plot of the distance-redshift relation from various BAO measurements from spectroscopic data sets. We plot $D_V(z)/r_s$ times the fiducial r_s to restore a distance. Included here are this CMASS measurement, the 6dF Galaxy Survey measurement at $z = 0.1$ (Beutler et al. 2011), the SDSS-II LRG measurement at $z = 0.35$ (Padmanabhan et al. 2012a; Xu et al. 2012; Mehta et al. 2012), and the WiggleZ measurement at $z = 0.6$ (Blake et al. 2011a). The latter is a combination of 3 partially covariant data sets. The grey region is the 1 σ prediction from WMAP under the assumption of a flat Universe with a cosmological constant (Komatsu et al. 2011). The agreement between the various BAO measurements and this prediction is excellent.

What happens at higher z?

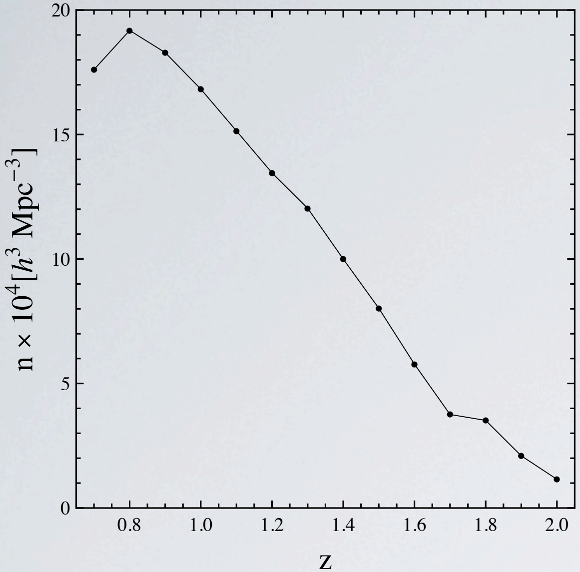
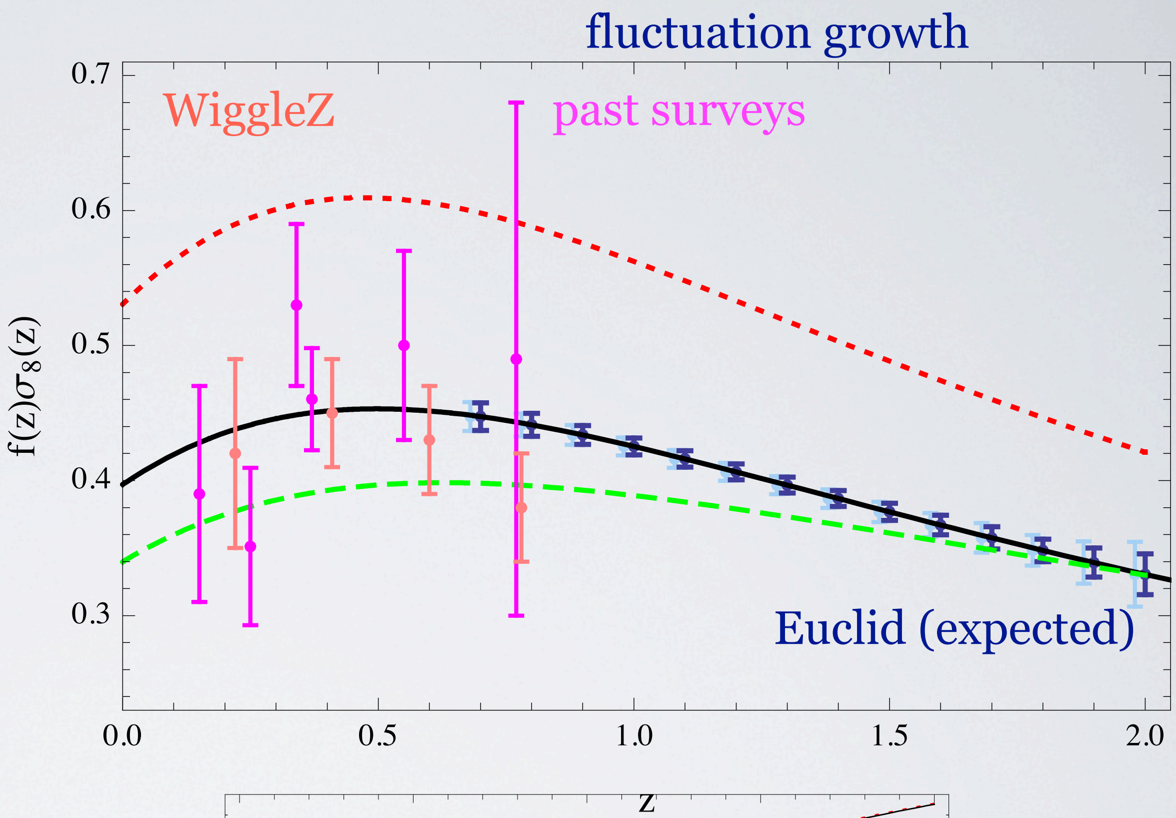


Figure 1. Predicted mean number density of galaxies in each redshift bin centred in z, expected from the baseline Euclid wide spectroscopic survey, given the instrumental and survey configurations and the estimated efficiency.

Elisabetta Majerotto et al. 2012



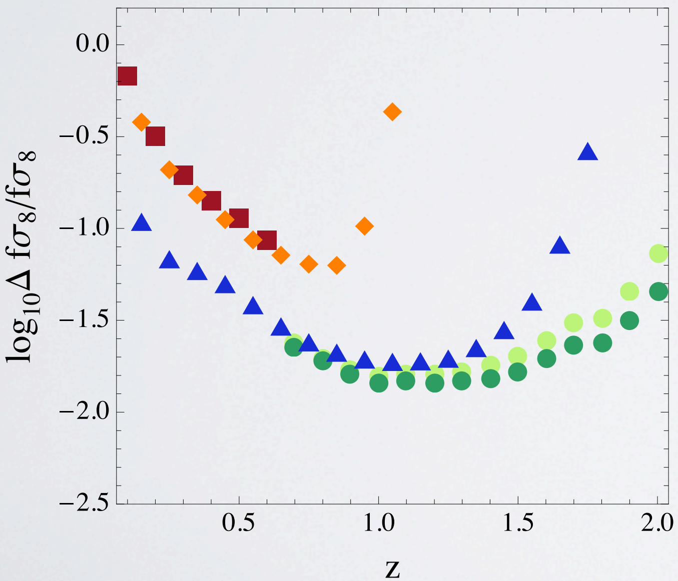
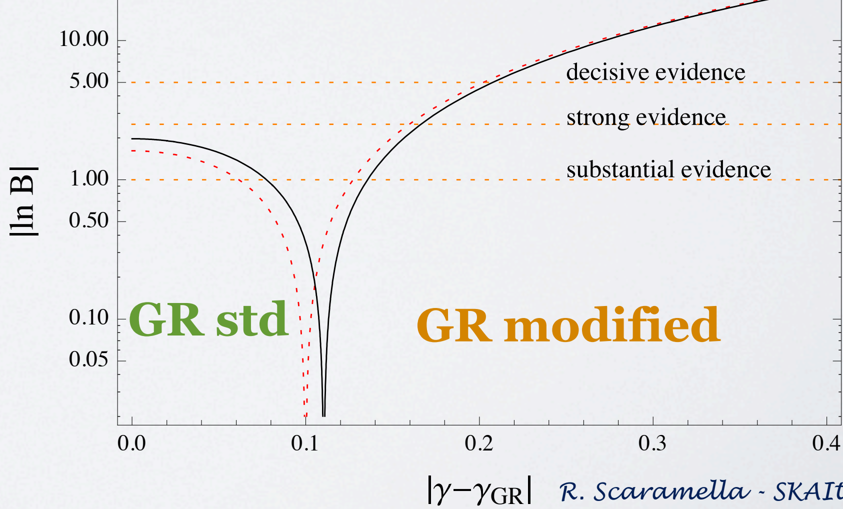
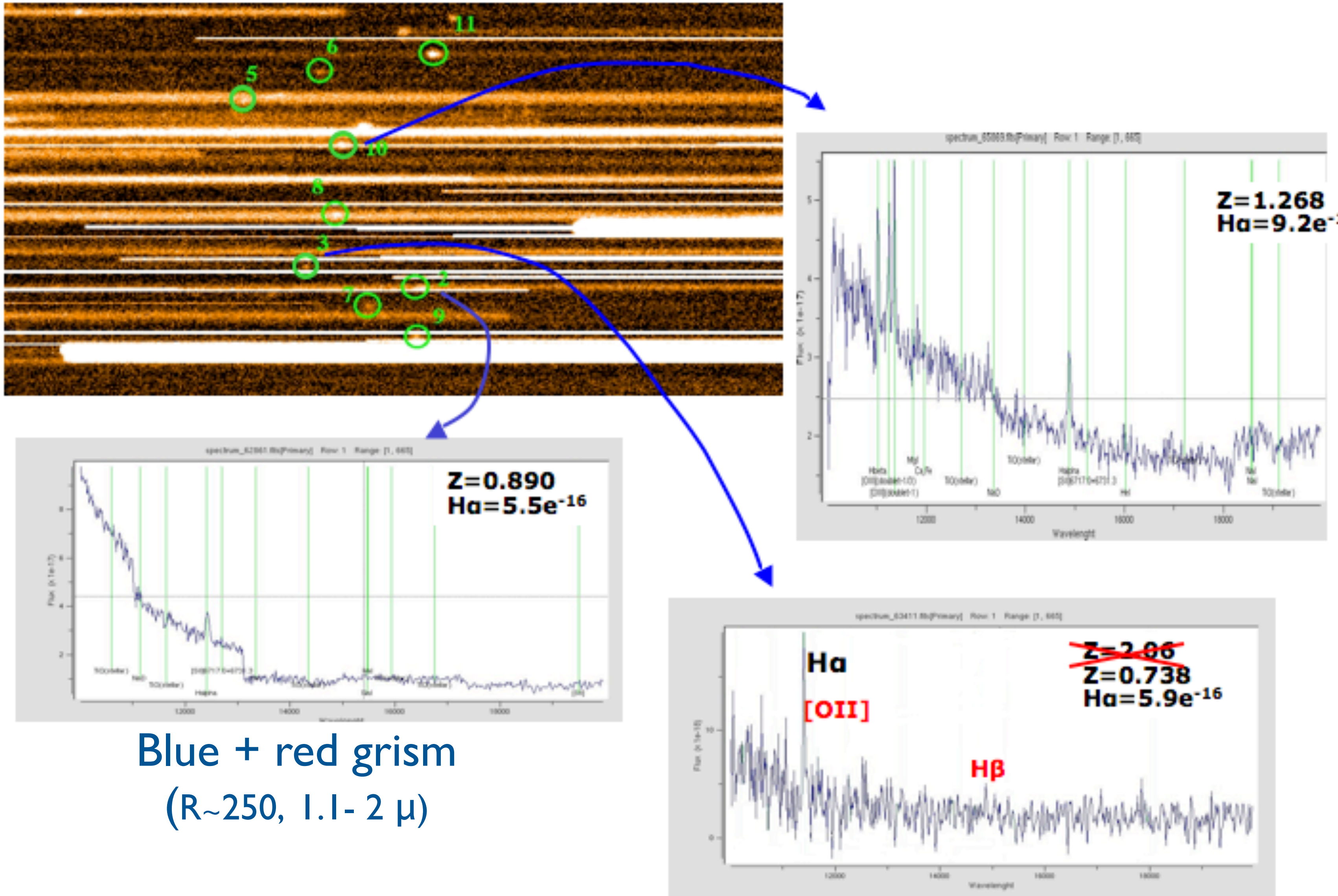


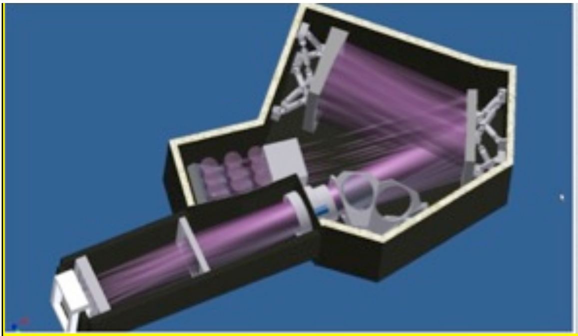
Figure 3. Relative error on $f\,\sigma_8$ of Euclid (dark-green circles, light-green circles for the pessimistic case of half the galaxy number density), BOSS (dark-red squares), BigBOSS ELGs (blue triangles) and LRGs (orange diamonds).



For clustering need spectroscopic redshifts (slitless is not easy)



Blue + red grism
(R~250, 1.1- 2 μ)

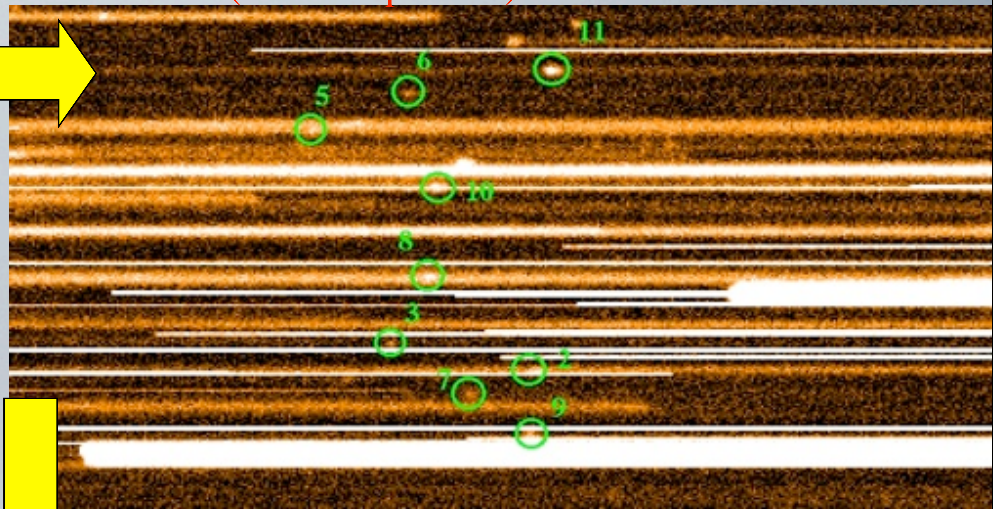


$\lambda/\Delta\lambda=300$
1-2 μm
FoV=0.5 deg²

Slitless spectroscopy

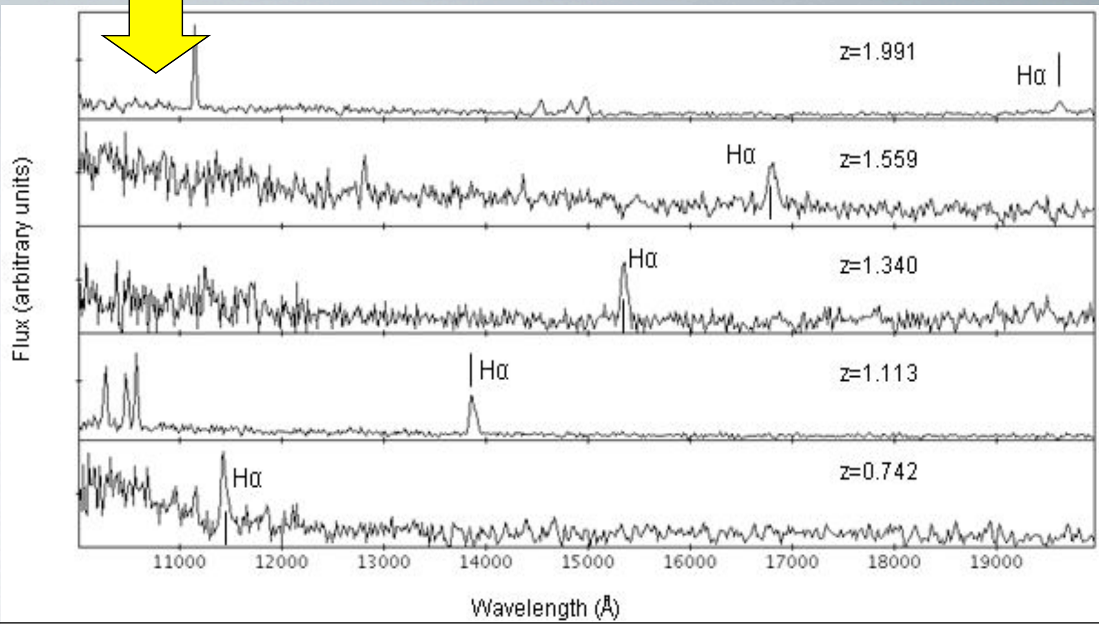
Simulated spectroscopic data

Main Problems:
- mostly emission lines (bias wrt matter? antib clusters)
- confusion (rotate spectra)

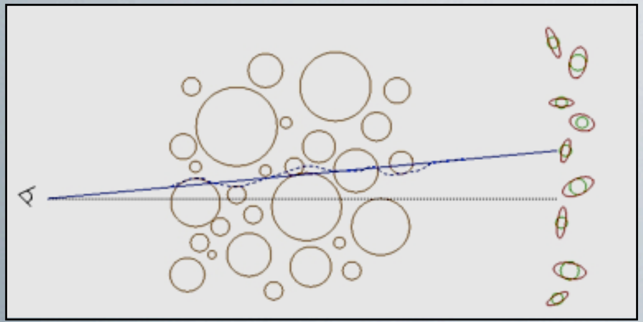


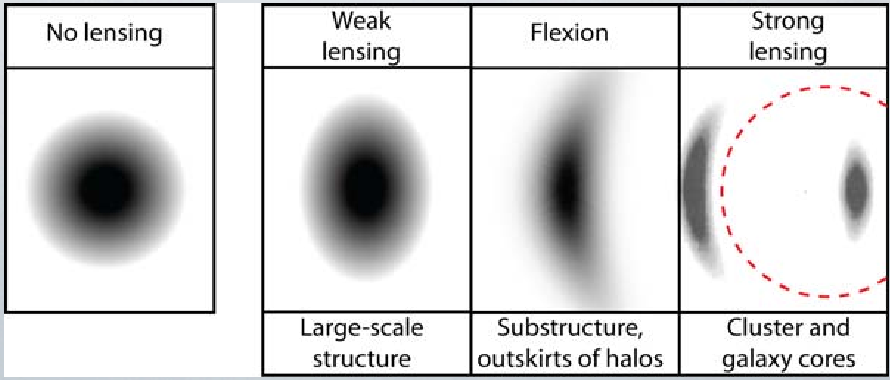
- Star-forming galaxies
- $0.9<z<2$ (Hα)
- $F_{line} > 4\times10^{-16}$ erg/s/cm² (H<19.5)
- $\sigma_z \leq 0.001(1+z)$
- Redshift success rate ≥ 50%
- N(gal) ≈ 5×10^7
- Sky coverage >15,000 deg²
- Mission duration ≥ 6 years

slitless main problems:
high(er) background
&
spectra overlaps



Expansion and Growth Histories through Gravitational Lensing





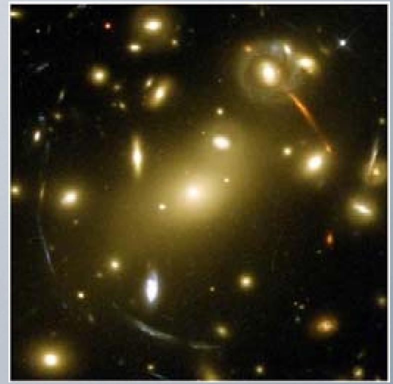


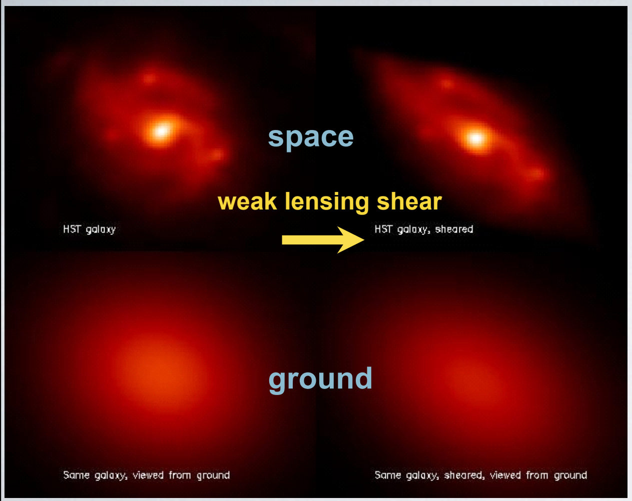
Figure 2.8: a. (Left) Illustrations of the effect of a lensing mass on a circularly symmetric image. Weak lensing elliptically distorts the image, flexion provides an arc-ness and strong lensing creates large arcs

$$\kappa = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_s} d\chi \frac{D(\chi)D(\chi_s-\chi)}{\chi_s}(1+z)\delta(\chi),$$

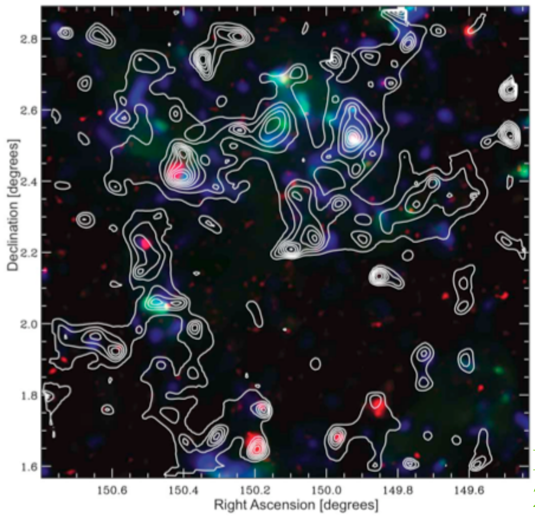
observable

distances

density perturbation

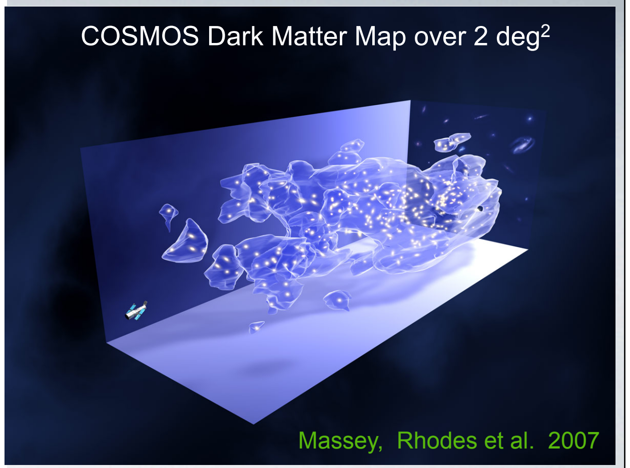


COSMOS Dark Matter Map over 2 deg^2



Massey et al. 2007a, Nature

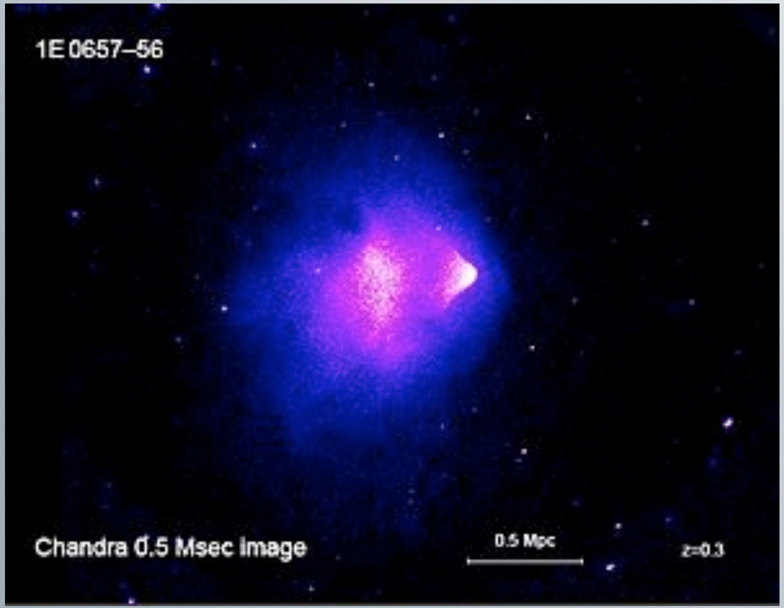
photoz →

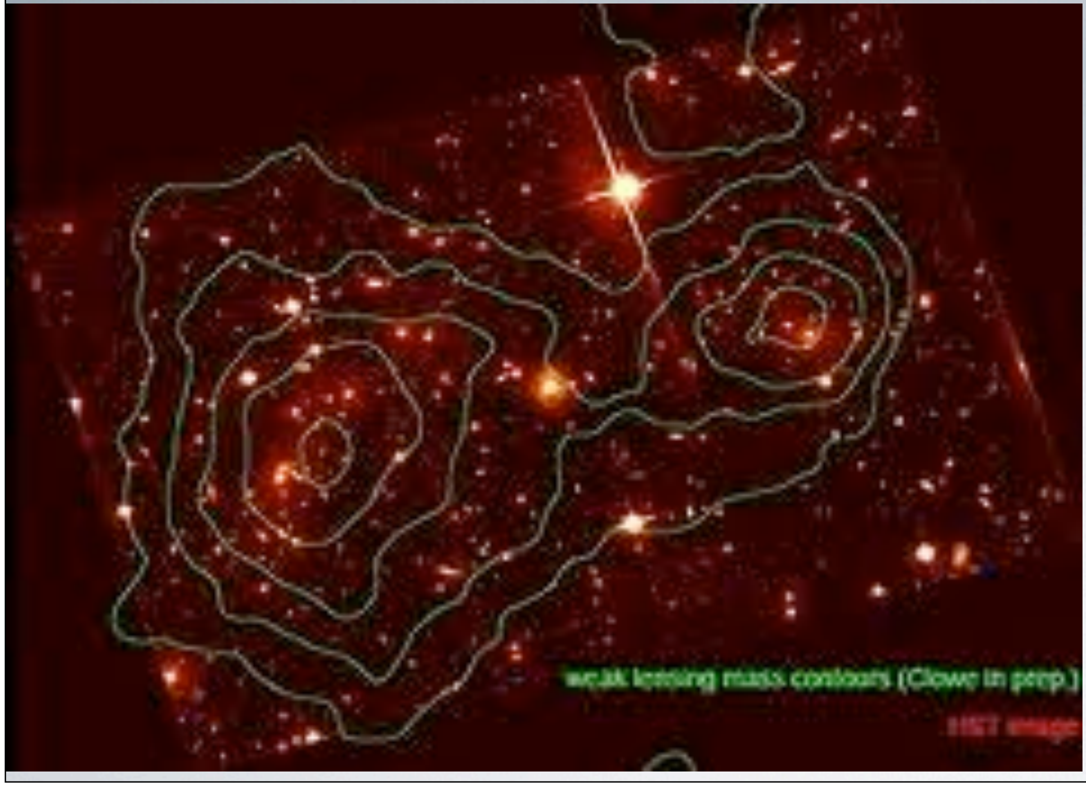


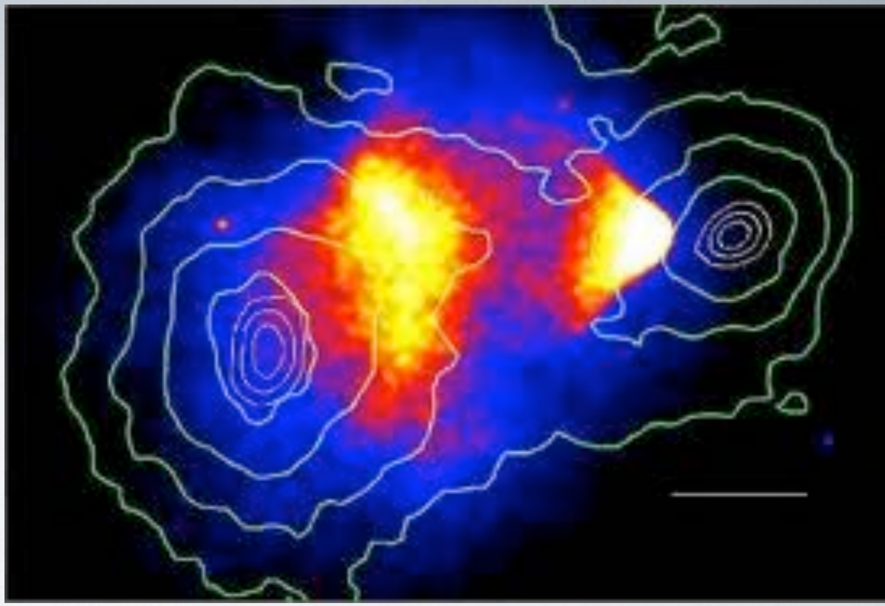
A370 ACS

will loose a factor of 2 in resolution, but get all sky!

Bullet Cluster: Dark Matter!







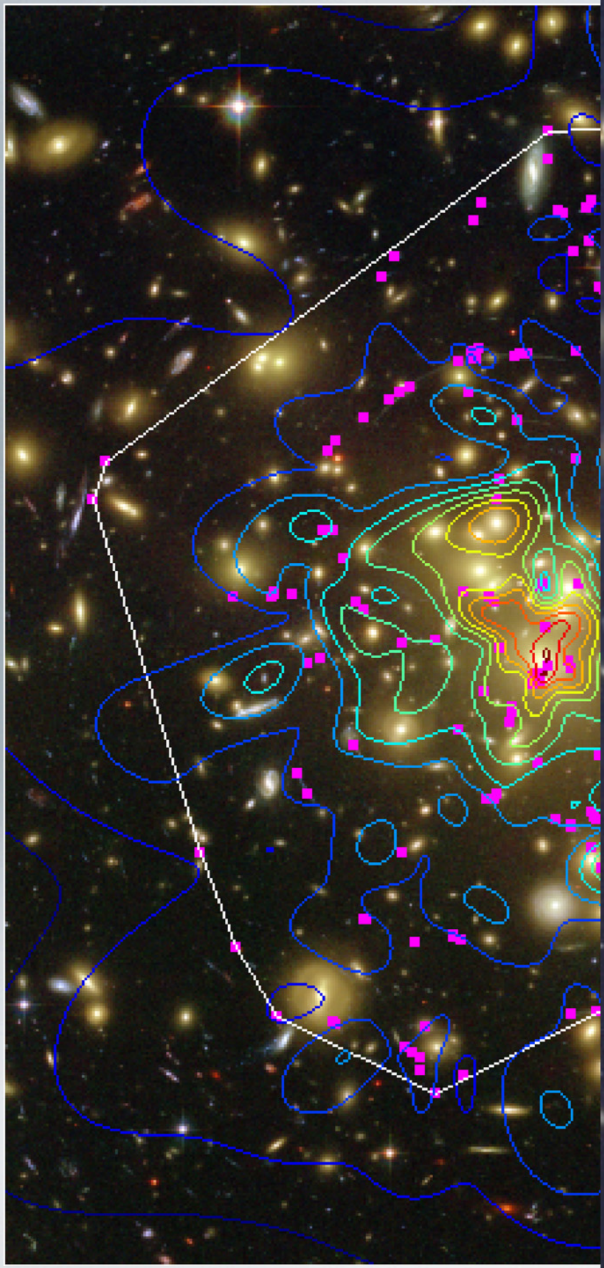


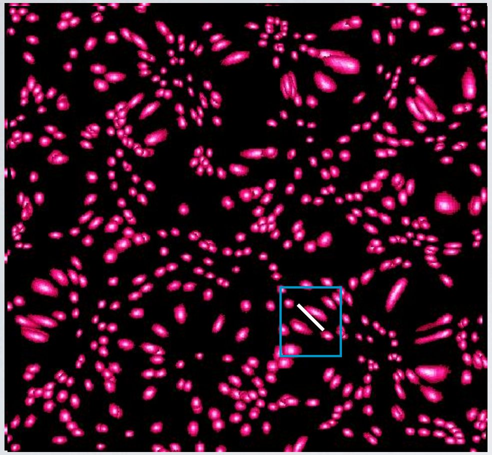
Figure 5. Mass map contours in units of $\kappa_\infty = 1/3$ laid over the $3.'2 \times 3.'3$ STS
previous figure. Pink squares indicate the 135 multiple image positions all perfectly reproduced by our model, and the white line indicates the convex hull. Outside this region, our solution should be disregarded. This solution is not unique but was the "most physical" we found.

(A color version of this figure is available in the online journal.)

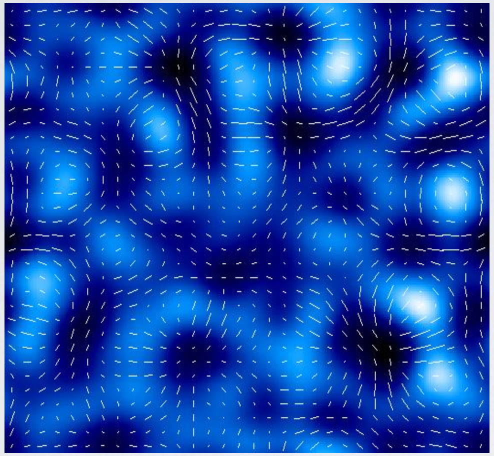
Details on Dark Matter clustering!

Weak Lensing Shear Measurement — Euclid

Distortion matrix: $\Psi_{ij} = \frac{\partial \delta\theta_i}{\partial \theta_j} = \int dz\, g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j}$



lensed background galaxies



mass and shear distribution

⇒ correlated image distortions on sky produce WL power spectrum $C_l(\theta,z)$

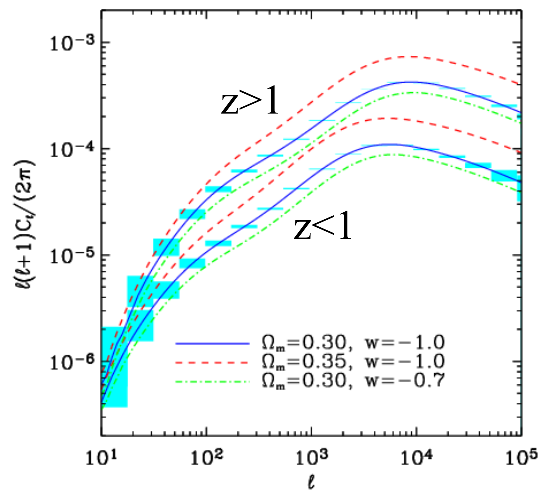
Weak Lensing Tomography **Slices in z** Euclid

Lensing signal $C_l(\theta,z)$ depends on:

- shape of total matter density fluctuation spectrum
- angular diameter distance in lensing equation for lensing amplitude
- angular diameter distance for angular scale of density spectrum
- growth factor *g(z)* of dark matter density fluctuations

WL tomography addresses all sectors of Dark Cosmology

from photoz need accurate <z> for bins



Example: WL power spectrum for each of two *z*-bins

Ground based lensing is limited by ***systematics***

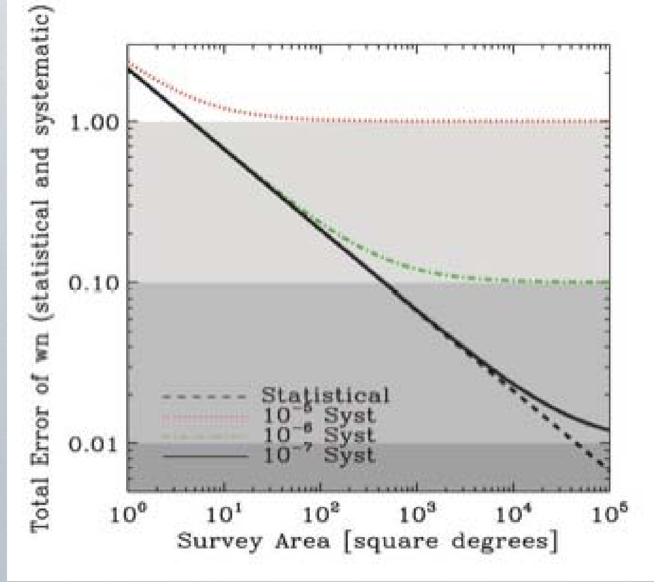


Figure 2.17: Advantages of space based observations in order to reach Euclid's cosmological objectives. The total error on the equation of state decreases statistically as the area of a survey is increased. However systematic effects limit the achievable dark energy constraint. For Euclid to achieve 2% on the dark energy equation of state requires an area of 20,000 square degrees and shape systematic levels with a variance of 10^{-7} (Cf. Amara & Réfrégier 2008). Such a systematic precision can only be achieved with the stability and accuracy of space-based observations.

For photo-z need optical colors from ground based surveys (more systematics)

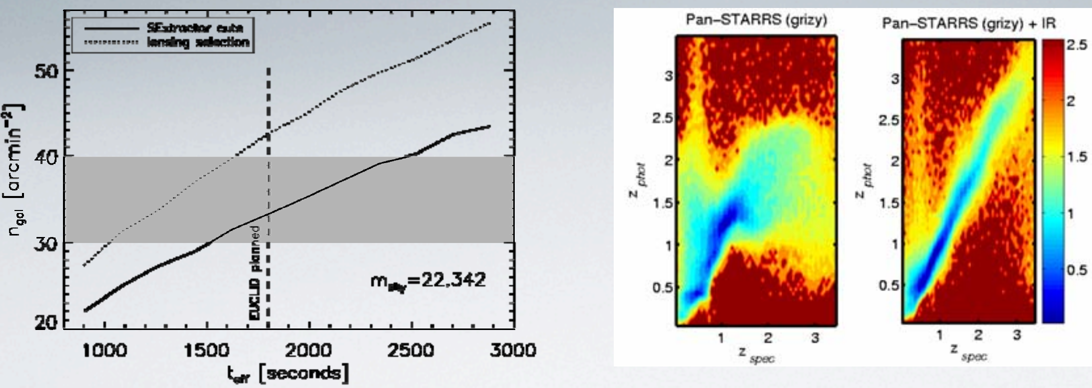


Figure 2.18: a. (Left) The expected number counts of galaxies useful for lensing as a function of exposure time. The solid line is made using a simple cut on SExtractor detection with S/N>10 and FHWM[gal]>1.25FWHM[PSF], the dashed line is from the shape measurement pipelines that sum the lensing weight assigned to each galaxy, with a cut in ellipticity error of 0.1. We see that we are able to reach our requirements of 30-40 gal/amin^2. b. (Right) Shows the redshift measurement for PanSTARRS with and without the Euclid NIR bands (c.f. Abdalla et al 2007). We find that with DES, PanSTARRS-2 and a fortiori PanSTARRS-4 and LSST we will be able to meet out requirements of $\delta z = 0.05(1+z)$.

NIR <u>is mandatory</u> for accurate photoz for 1<z<3

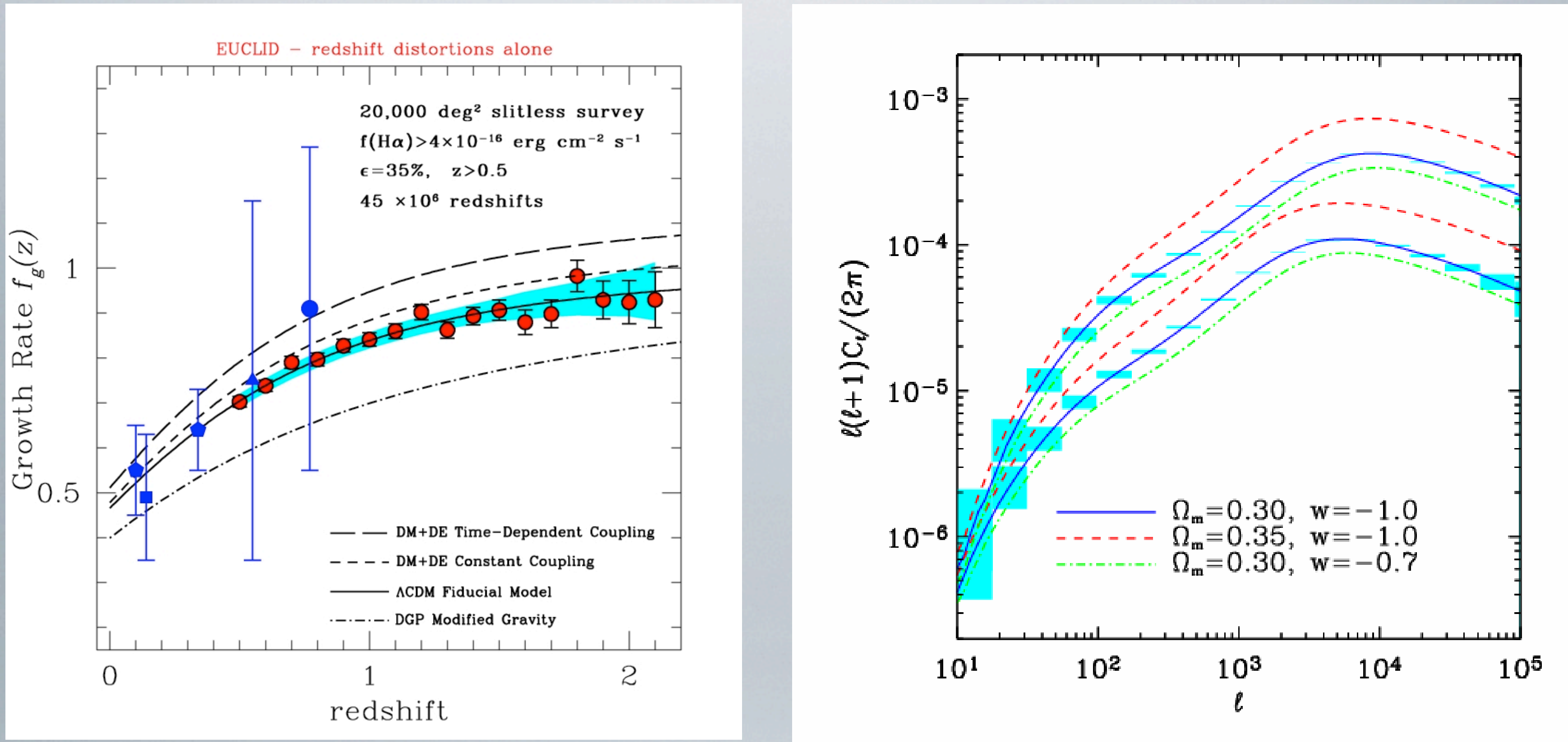


Figure 2.14: a. (left) The growth rate of matter perturbations as a function of redshift. Data points and errors are from a simulation of the spectroscopic redshift survey. The assumed ΛCDM model, coupled dark matter/dark energy modes and DGP are also shown. b. (right): The predicted cosmic shear angular power spectrum at z=0.5 and z=1 for a number of cosmological models

Can discriminate cosmology

[Dark Energy, Dark matter, non std GR]

Does gravity follow standard G.R.?

Weak limit

Need experiments with high sensitivity/precision....

$$w \equiv p/\rho \qquad w(a) = w_p + (a_p - a)w_a \qquad \frac{d\log\delta_m}{d\log a} \equiv f(a) \cong \Omega_m(a)^\gamma$$

$$ds^2 = a(\tau)^2\left[-(1+2\psi)d\tau^2 + (1-2\phi)dr^2\right]$$

e.g. f(R) in Lagrangian

$$R = g^{\mu\nu}R_{\mu\nu}$$

$$S[g] = \int \frac{1}{2\kappa} R\sqrt{-g}\, \mathrm{d}^4x$$

$$S[g] = \int \frac{1}{2\kappa} f(R)\sqrt{-g}\, \mathrm{d}^4x$$

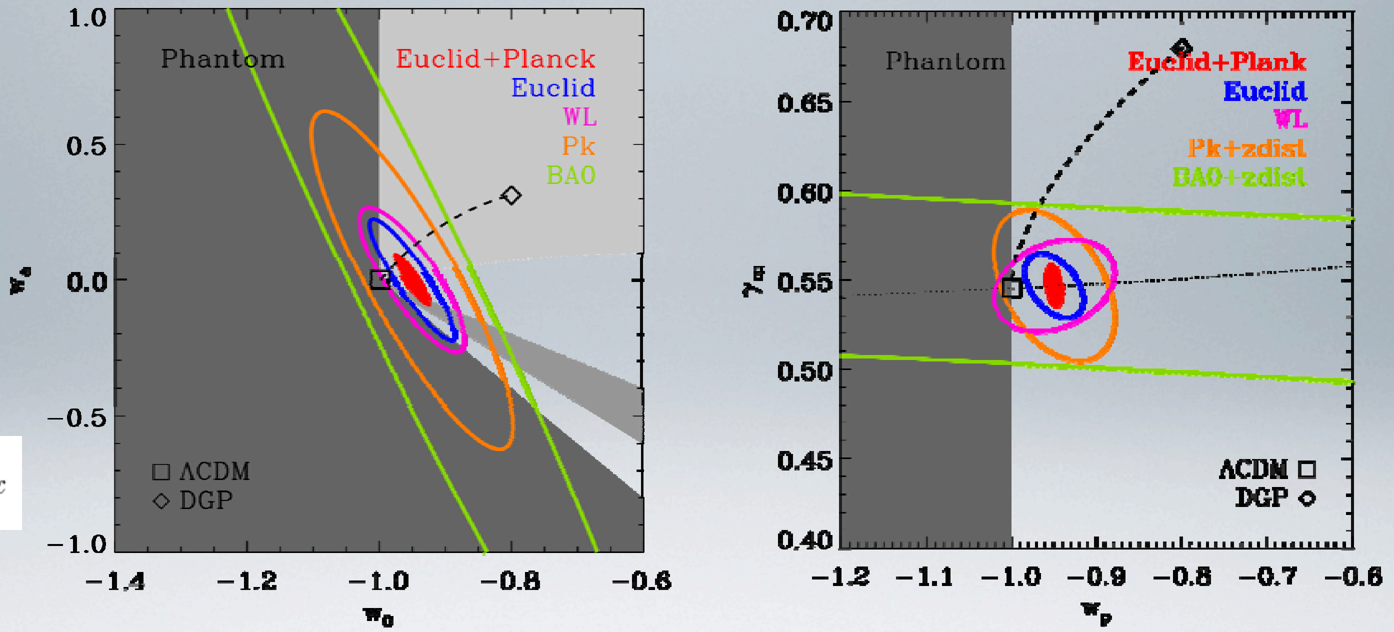


Figure 2.13: a. (left) Predicted constraints from Euclid on the dark energy w_0-w_a plane. The grey areas show different region relevant for DE theory. The darkest grey region w_0 <-1 is the Phantom zone, while the others show 'thaw' and 'freeze' models (middle grey and lightest grey). The outer (green) ellipses show the constraints from BAO, orange shows the galaxy power spectrum, P(k), purple weak lensing alone, and inner blue ellipse the combined Euclid probes. The inner red ellipse is the combined Eulcid and Planck constraints. The square denotes ΛCDM and diamond DGP in parameter space, with the dotted line connecting them showing where extended DGP models lie. b. (right) Similar constraints in the growth index, γ_m, and w_p.

(cf. L. Amendola, M. Kuntz)

The most general (linear, scalar) metric at first-order

$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2+dy^2+dz^2)]$$

At the linear perturbation level and sub-horizon scales

Full metric reclarstruction at first order requires 3 functions

$$H(z) \quad \Phi(k,z) \quad \Psi(k,z)$$

- modified Poisson's equation $\quad k^2\Psi = -4\pi G a^2 Q(k,a)\rho_m\delta_m$
- non-zero anisotropic stress $\quad \eta(k,a) = \frac{\Phi+\Psi}{\Psi}$

New gravity,
same matter

$$X_{\mu\nu} = -8\pi G T_{\mu\nu}$$

$$T^{\nu}_{\mu\,;\nu} = 0.$$

$$Y_{\mu\nu} = X_{\mu\nu} - G_{\mu\nu}$$

$$G_{\mu\nu} = -8\pi G T_{\mu\nu} - Y_{\mu\nu}.$$

Same gravity,
new matter

Modified Gravity at linear level

▪ standard gravity	$Q(k,a)=1$ $\eta(k,a)=0$	
▪ scalar-tensor models	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$ $\eta(a)=\frac{F'^2}{F+F'^2}$	Boisseau et al. 2000 Acquaviva et al. 2004 Schimd et al. 2004 L.A., Kunz &Sapone 2007
▪ f(R)	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}}, \quad \eta(a)=\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$	Bean et al. 2006 Hu et al. 2006 Tsujikawa 2007
▪ DGP	$Q(a)=1-\frac{1}{3\beta}; \quad \beta=1+2Hr_c w_{DE}$ $\eta(a)=\frac{2}{3\beta-1}$	Lue et al. 2004; Koyama et al. 2006
▪ coupled Gauss-Bonnet	$Q(a)=...$ $\eta(a)=...$	see L. A., C. Charmousis, S. Davis 2006

Need to break degeneracy

Galaxies, BAO **COMPLEMENTARITY** Photons, WL

massive particles respond to Ψ

$$\delta'' + (1 + \frac{H'}{H})\delta = \frac{k^2}{a^2}\Psi$$

massless particles respond to Φ-Ψ

$$\alpha = \int \nabla_{perp} (\Psi - \Phi) dz$$

Correlation of galaxy ellipticities:
galaxy weak lensing

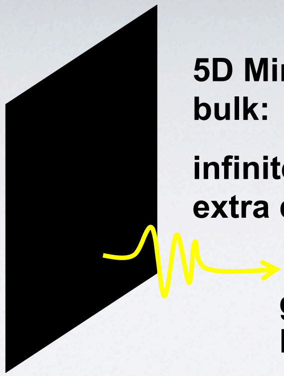
$$P_{ellipt}(k,z) \propto (\Phi - \Psi)^2$$

DG

(Dvali, Gabadadze, Porrati 2000)

$$S = \int d^5x\sqrt{-g^{(5)}}\ R^{(5)}\ +\ L\int d^4x\sqrt{-g}\,R$$

$$H^2 - \frac{H}{L} = \frac{8\pi G}{3}\rho$$



L = crossover scale:

$$r << L \Rightarrow V \propto \frac{1}{r}$$

$$r >> L \Rightarrow V \propto \frac{1}{r^2}$$

- **5D gravity dominates at low energy/late times/large scales**
- **4D gravity recovered at high energy/early times/small scales**

γ: perturbation growth indexunder gravity

$$\frac{d\log\delta}{d\log a} = \Omega_m(a)^\gamma$$

$$\gamma_s = \frac{3(1-w)}{6w-5} \approx 0.55$$ Standard

DG

$$\gamma \approx \gamma_s\left(1 + \frac{1-Q}{(1-w)(1-\Omega_m)}\right) \approx 0.65 - 0.70$$

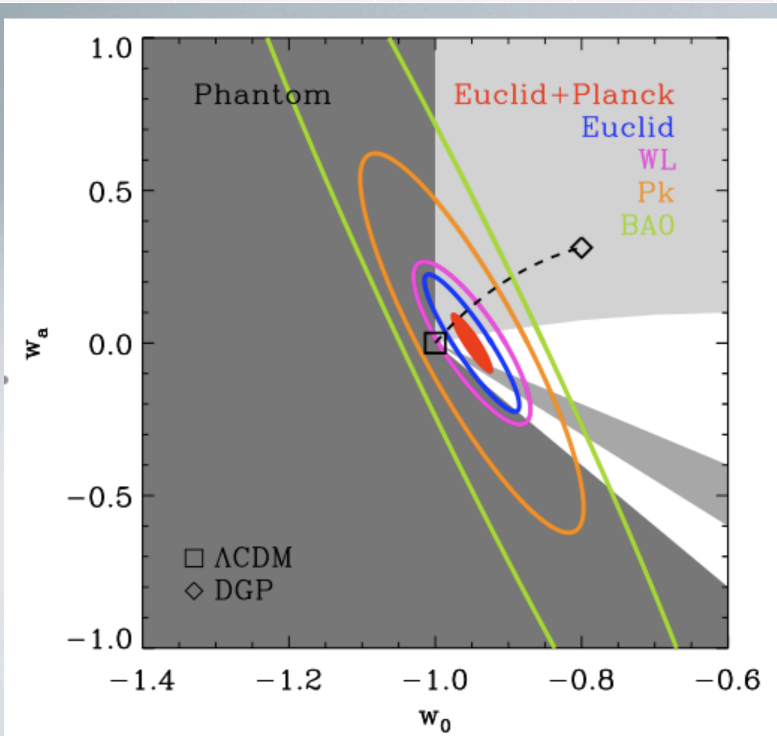
f(R)

$$\gamma \approx \gamma_s\left(1 + \frac{k^2a^2}{M(f)^2 + k^2a^2}\right) \approx 0.40 - 0.55$$

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.01	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.02	2	0.013	0.048	1540
Euclid +Planck	0.007	0.019	2	0.007	0.035	4020
Current	0.2	0.58	100	0.1	1.5	~10
Improv. Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

$$\text{FoM} = 1/(\Delta w_p \times \Delta w_a)$$

IMPROVE ~
× 10 ON W
× 20 ON γ



Euclid will challenge all sectors of the cosmological model:

- **Dark Energy**: w_p and w_a with an error of 2% and 13% respectively (no prior)
- **Dark Matter**: test of CDM paradigm, precision of 0.04eV on sum of neutrino masses (with Planck)
- **Initial Conditions**: constrain shape of primordial power spectrum, primordial non-gaussianity
- **Gravity**: test GR by reaching a precision of 2% on the growth exponent γ ($d\ln\delta_m/d\ln a \propto \Omega_m^\gamma$)

Uncover new physics and map LSS at 0<z<2: Low redshift counterpart to CMB surveys

Integrated Sachs Wolfe

(will use Planck)

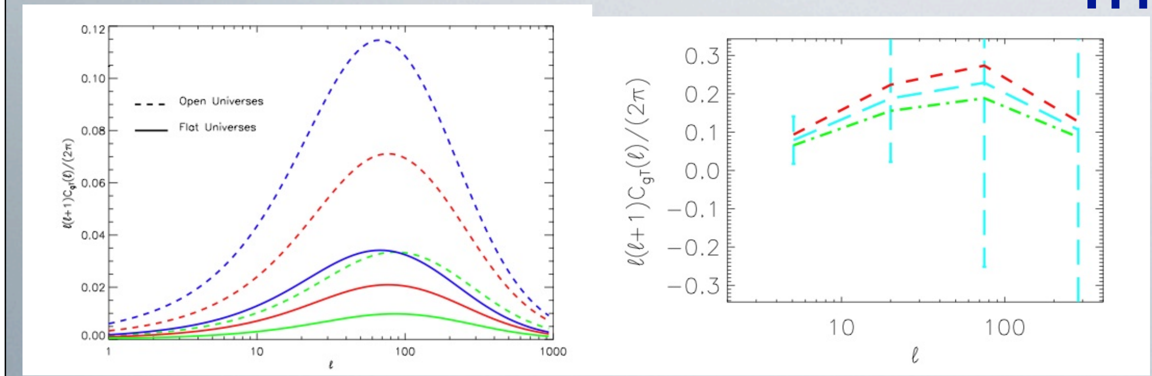
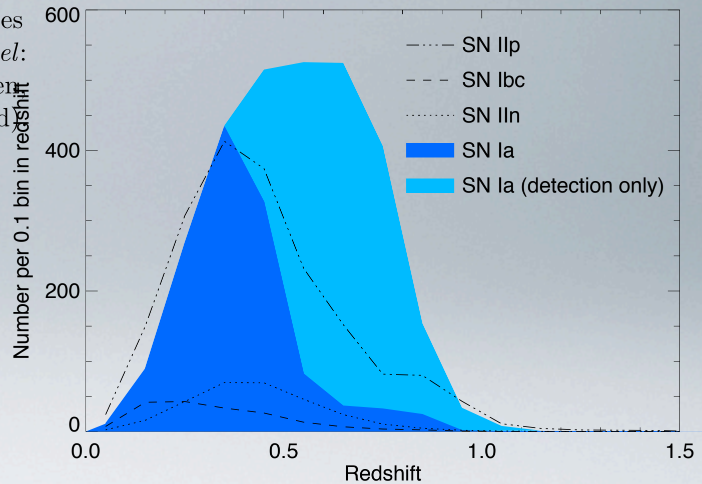


Figure 12.1: *Left Panel*: Prediction of the ISW cross-correlation signal for different values of the dark energy density ($\Omega_{DE} = 0.10$, green line; $\Omega_{DE} = 0.20$, red line; $\Omega_{DE} = 0.30$, blue line) for universes with flat geometry (solid lines) and universes with open geometry and no dark energy. The ISW signal for universes with the same matter density is larger in open universes than in flat universes. The signal is calculated for a Euclid-like photometric survey. *Right panel*: The ISW cross-correlation signal for different values of the growth parameter ($\gamma = 0.44$, green dash-dotted line; $\gamma = 0.55$, blue dashed line; $\gamma = 0.68$, e.g. a DGP model, red short dashed). *Both figures are taken from Rassat (2007).*



Physics and cosmology from SN

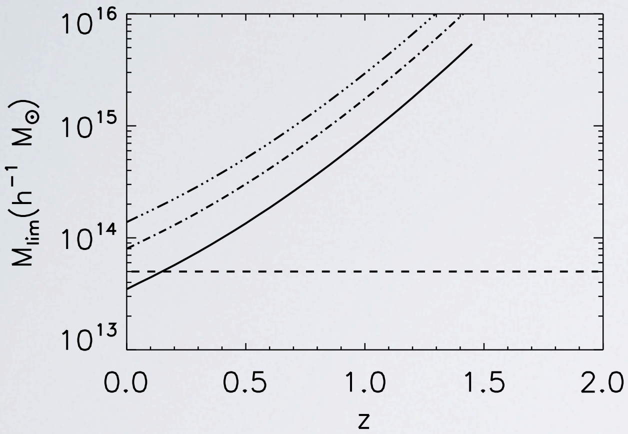
Figure 16.2: Number of SNe of various types that are expected to be detected by Euclid in the J band, as a function of redshift. Estimates for SNe of type Ia (dark blue shaded region), Ibc, IIn and IIp were provided by A. Goobar based on assumptions in Goobar *et al.* (2008), using SNe Ia rates from Dahlen *et al.* (2004) and assuming a 5 year survey that monitors a patch of 10sq deg at any time. These histograms represent the $N(z)$ for SNe with sufficient sampling to measure their lightcurve shapes (i.e. reaching 1 magnitude fainter than the peak brightness). The light-blue shaded region shows an independent estimate of the total number of SNe Ia detections including those only detected at peak luminosity, i.e. without full lightcurve measurements.

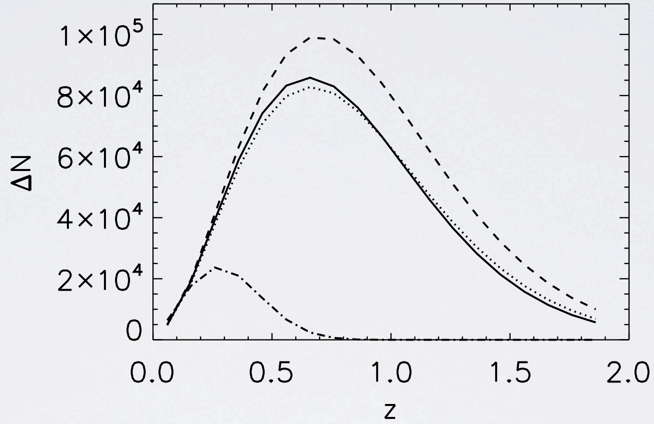
Counts & **mass function** ***(calibrate!!)***

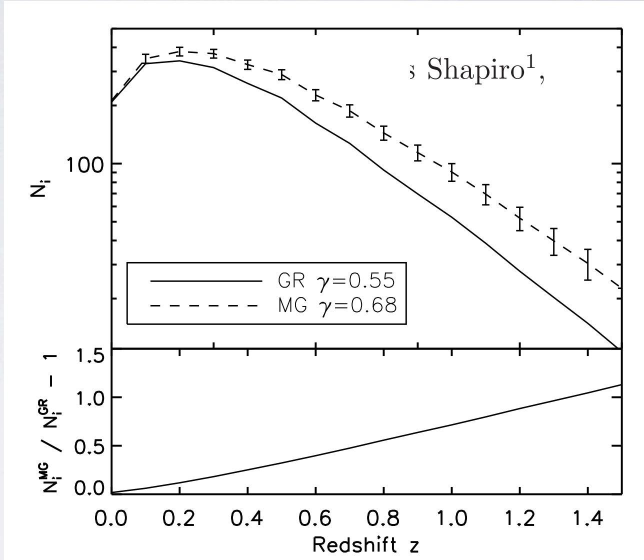
NIR photom (24.5), WL, (vel disp.)

expect N ~ few x 10^5

Clusters of galaxies: interesting and powerful

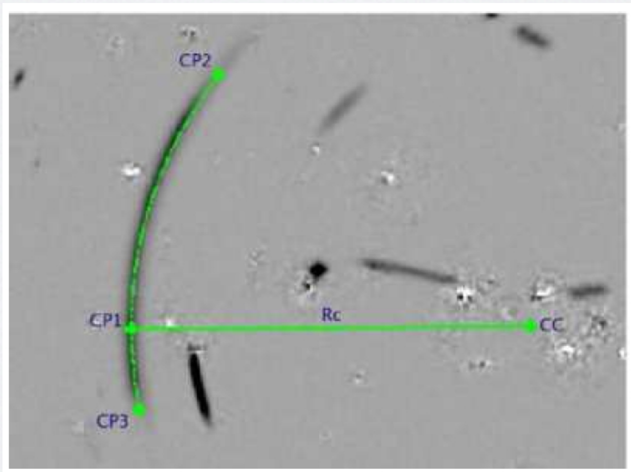


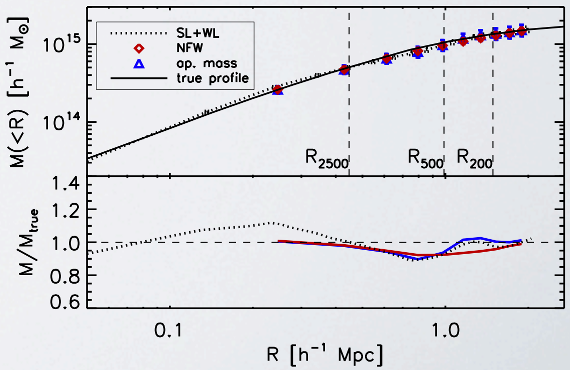




Strong lensing

Mass profile in inner regions; frequency of arcs

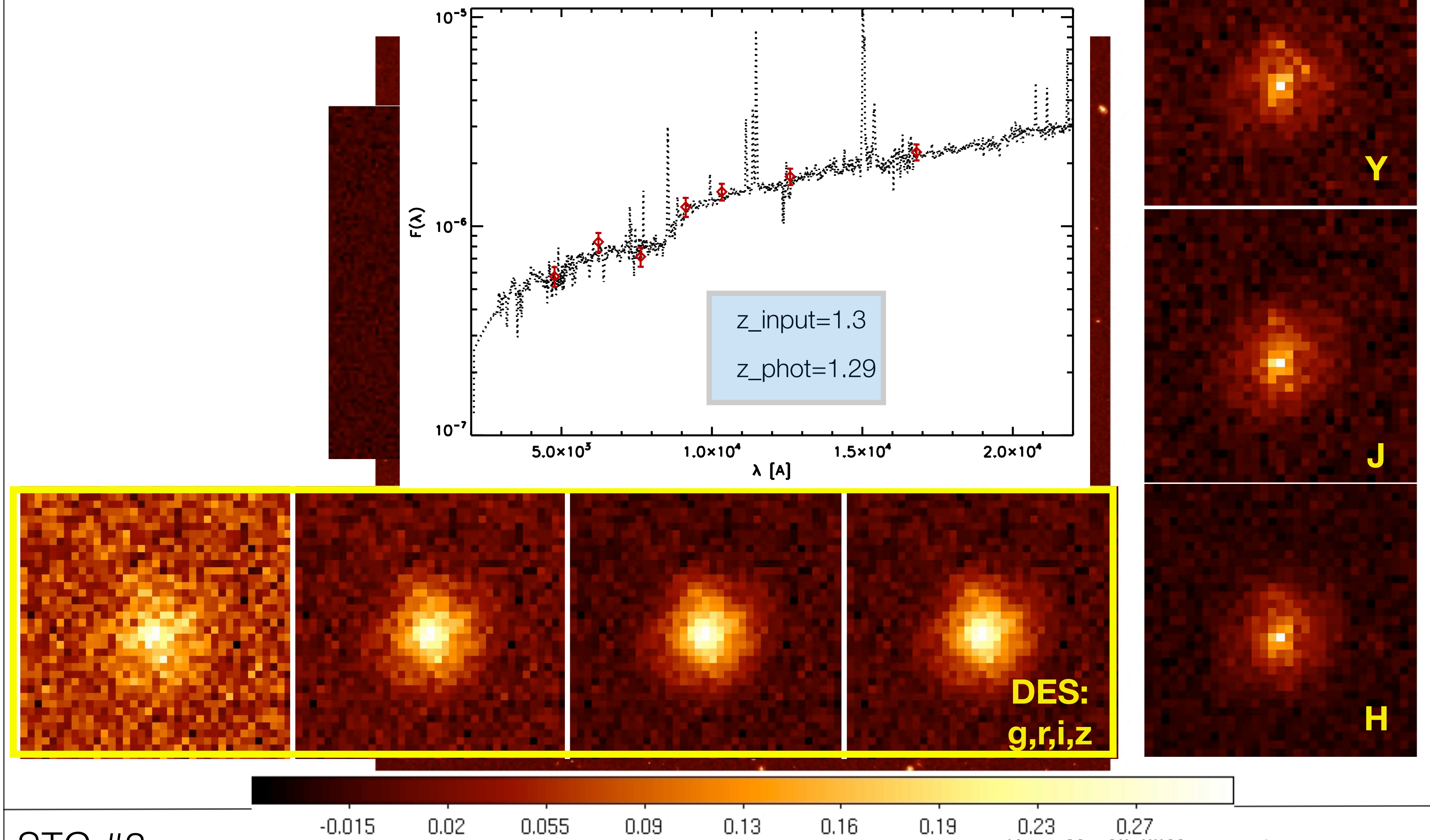




High redshift (z~1) cluster as seen from Euclid

(Meneghetti et al.)

Image simulations:
Euclid + ground based data



Cosmological Sims NISP High z cluster

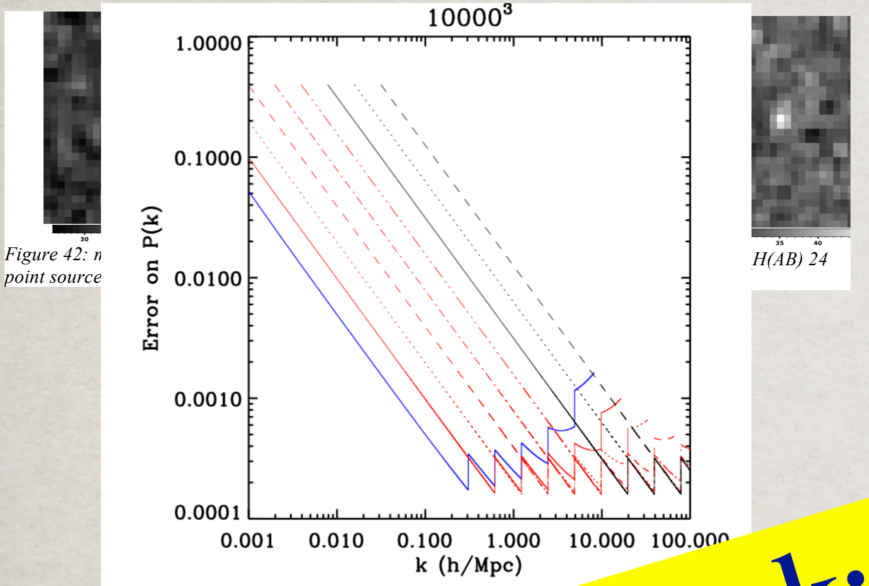
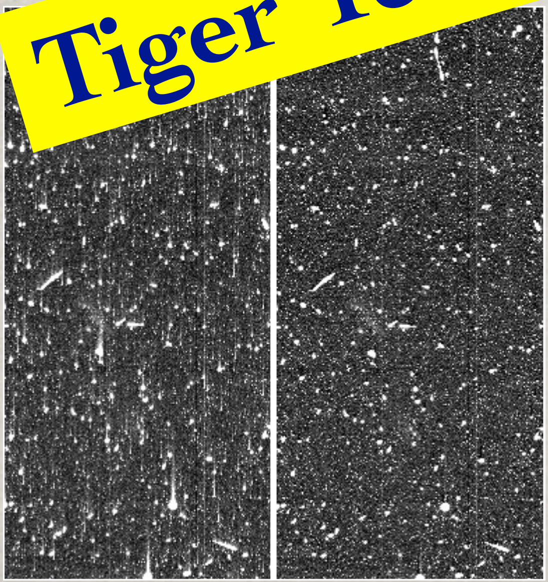


Figure 15: Estimated error on the measured power spectrum for N… and various box sizes. Starting with a box size of 200 Mpc/… box size 2 times larger. The blue curve is for a b… for k>0.1 h/Mpc. Below this scale, ana… 0.001 h/Mpc < k < 0.1 h/Mpc.

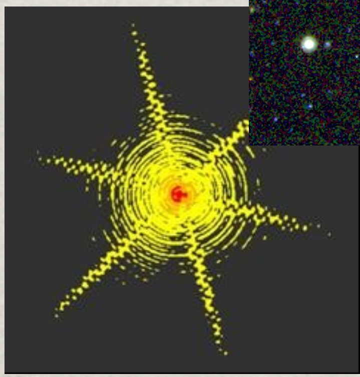
Figure 8: Combined Euclid images of a high redshift cluster

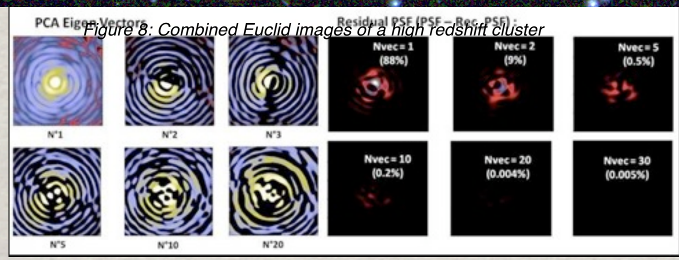
Tiger Team work: no show stoppers !!

VIS

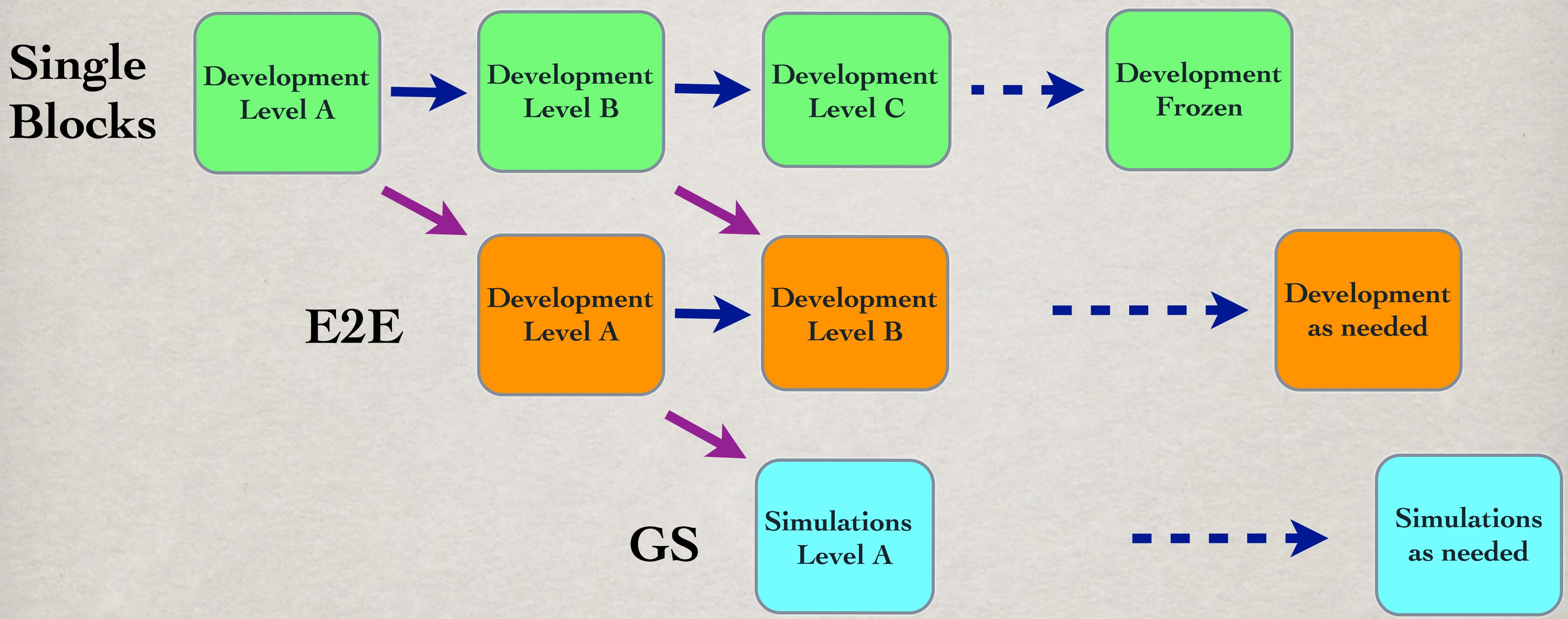


PSF





≈ 6 months steps



A first sketch of goals... increase size and complexity/accuracy

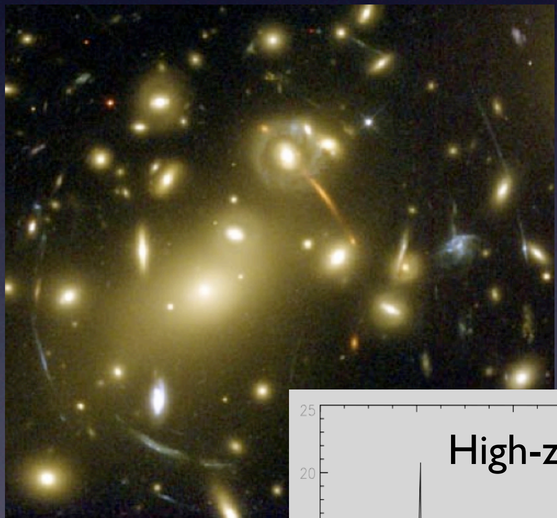
- 2 hrs of full data ~1 sq deg
- 1 day of full data ~10 sq deg — Cluster: SL & localized WL
- 1 week of full data ~100 sq deg — large k
- ~100 sq deg with different params and systematics — blind systematics
- few 100 sq deg with different cosmology — Wow!!
- ~1 deep field — High z, SN, calibs
- ~1000 sq deg — small k

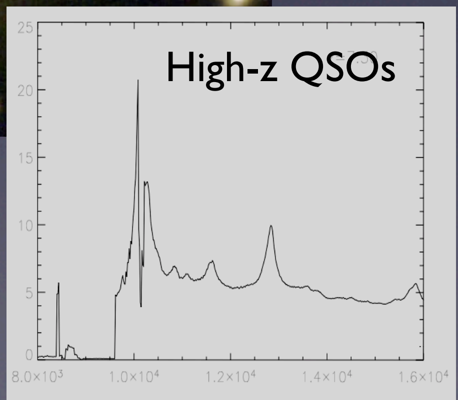
Unique legacy survey: 2 billion galaxies imaged in optical/NIR to mag >24

Million NIR galaxy spectra, full extragalactic sky coverage, Galactic sources

Unique datase for various fields in astronomy: galaxy evolution, search for high-z objects, clusters, strong lensing, brown dwarfs, exo-planets, etc

- Synergies with other facilities: JWST, Planck, Erosita, GAIA, DES, Pan-STARSS, LSST, E-ELT etc (e.g. to do NIR from the ground would take several x 10^3 yr)
- All data publicly available through a legacy archive





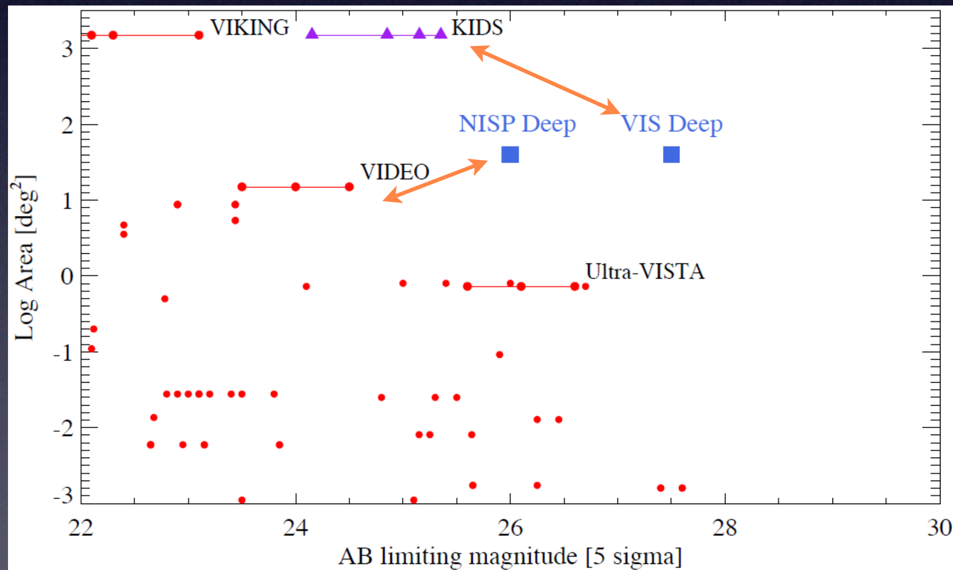


***Figure 3.5:** The depth of current and on-going NIR surveys (red points), and the optical KIDS survey (blue triangles) compared to the Euclid deep surveys in visible and NIR wavelengths (blue squares).*

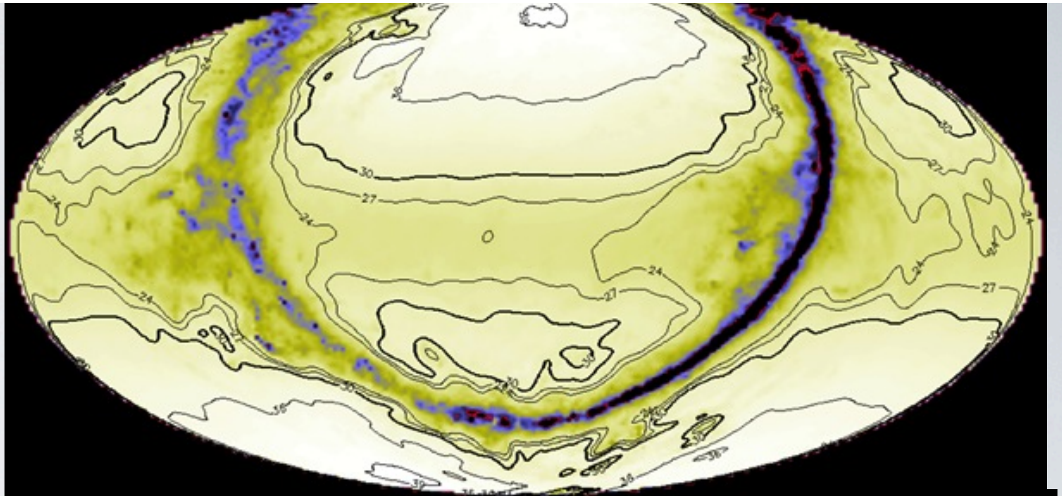
Competition / Complementarity

- **Ground-based lensing surveys now (DES, PanSTARRS, KIDS/VIKING, HSC)**
  - Hard to get PSF stability and IR imaging data to gain higher-z photo-z's
  - Patchy overlap with spectroscopic survey (photo-z's, testing gravity)
  - Help develop techniques further and needed by Euclid
- **Ground-based spectroscopic surveys (BOSS, BigBOSS, DESpec, + many more!)**
  - Only BOSS underway (z<0.7 and passive galaxies) %-level distances from BAO
  - Other surveys may not be on-sky before Euclid!
  - Hard to compete on volume & redshift coverage
  - Potentially lacking high quality photometric input catalogues
  - Inefficiencies because of weather and over-crowding
- **WFIRST & LSST**
  - WFIRST likely launch date is next decade → ***W2LATE (?)***
  - Expensive ($1.6 billion with JWST beforehand)
  - Much competition for probes
  - LSST will be an awesome complement to Euclid (but only one hemisphere)

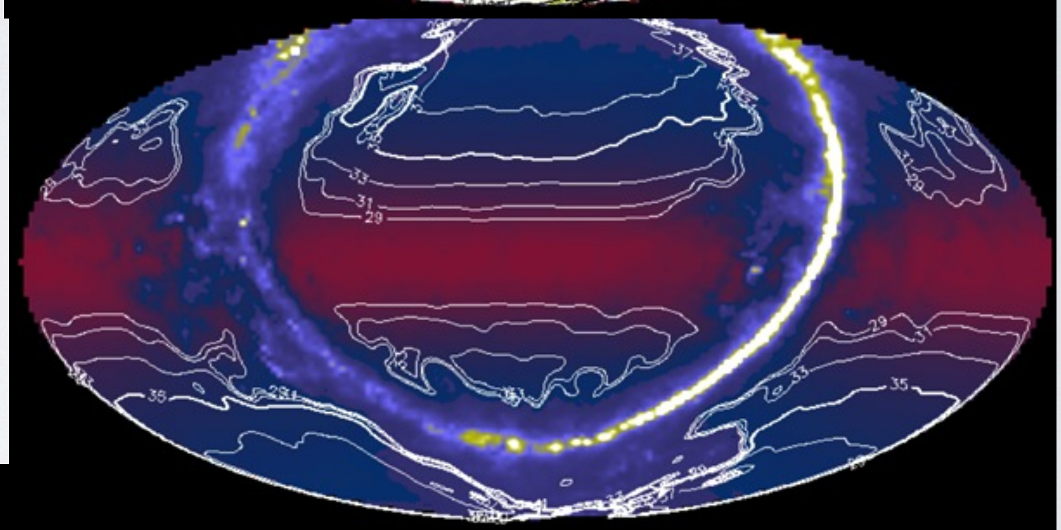
Euclid remains the right mission at the right time for cosmology
Also get all that legacy science

Euclid Survey Areas,
(~few weeks ago)

$N \sim 1.5\text{-}2\ 10^{9}$ Weak Lensing sampling



$N \sim 5\text{-}6\ 10^{7}$ ditto for Clustering



R.S & J. Amiaux (ESAC tool)

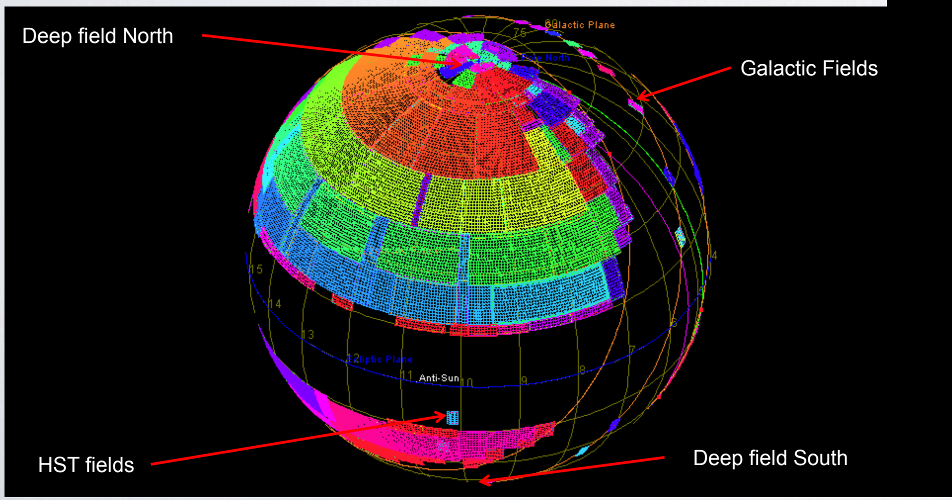


Figure 3.11.4-2: Assumption for locations of main calibrators for building the reference survey and implementation of the fields on the reference survey.

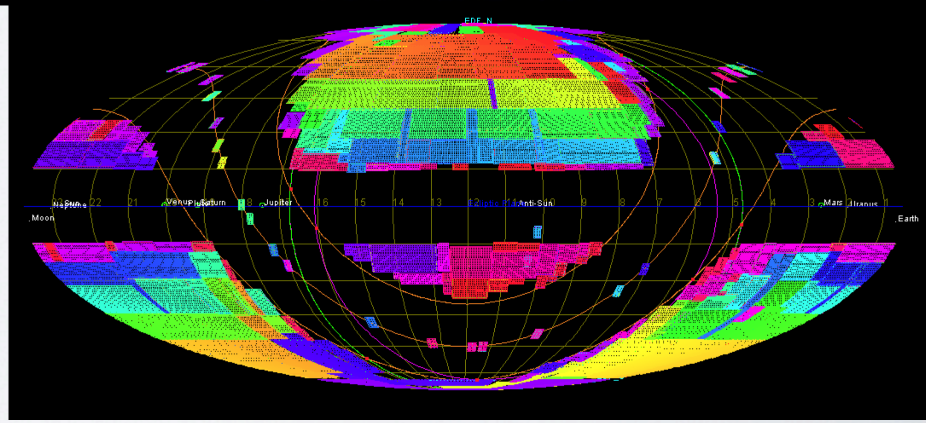
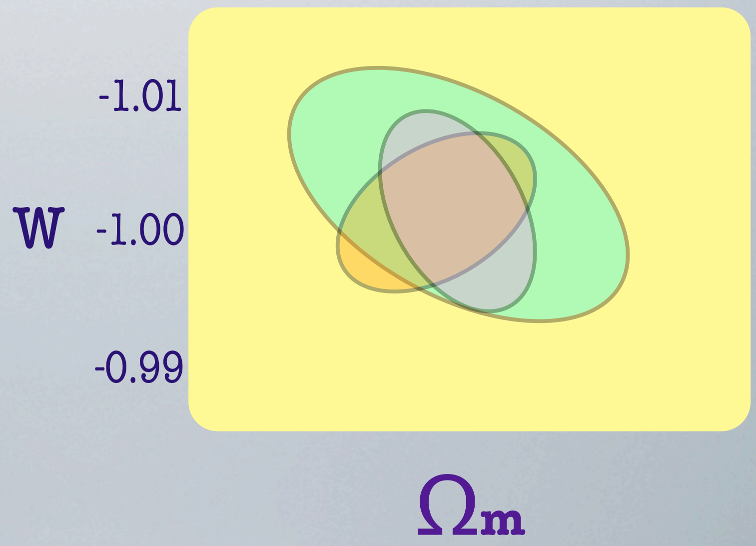


Figure 3.11.4-3: Mollweide representation of the full reference survey (including location of calibration fields).

Possible outcomes.....

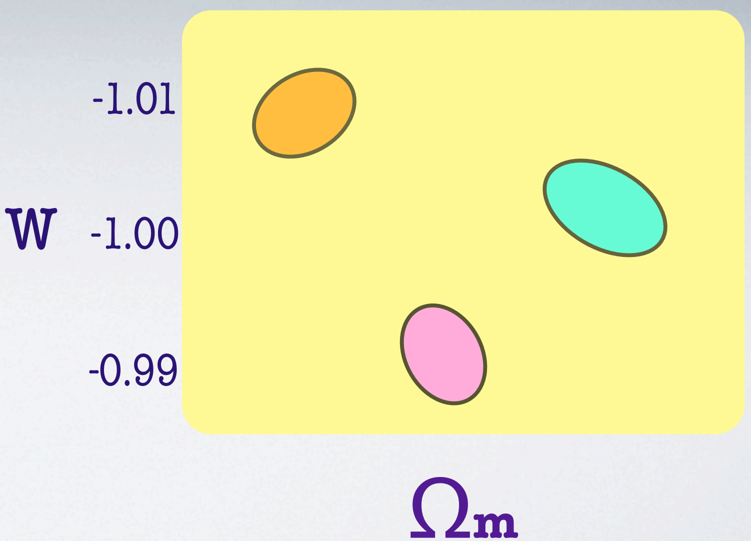
Different probes

Quite useful but a bit dull....



Λ=const

Much more interesting!!



?!?!?

Summary:

- ★ ***Best*** science (cf Decadal)
- ★ Enormous Legacy
- ★ Tough but feasible

Stay tuned!

THE

END