Unveiling Dark Energy with large astronomical datasets

XIX Roma Tre Topical Seminar on Subnuclear Physics: Gravitational waves and Cosmology

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Universita' Roma TRE, INFN-RM3

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Summary

<u>The big picture</u>: The dark energy problem in context.

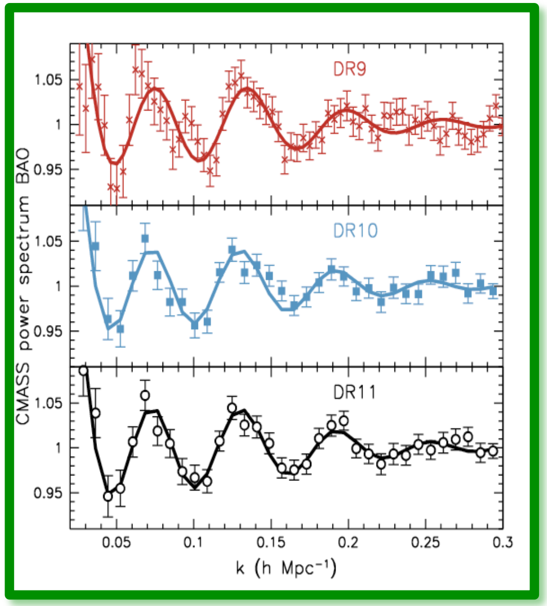
<u>The strategy</u>: galaxy surveys as dark energy experiments.

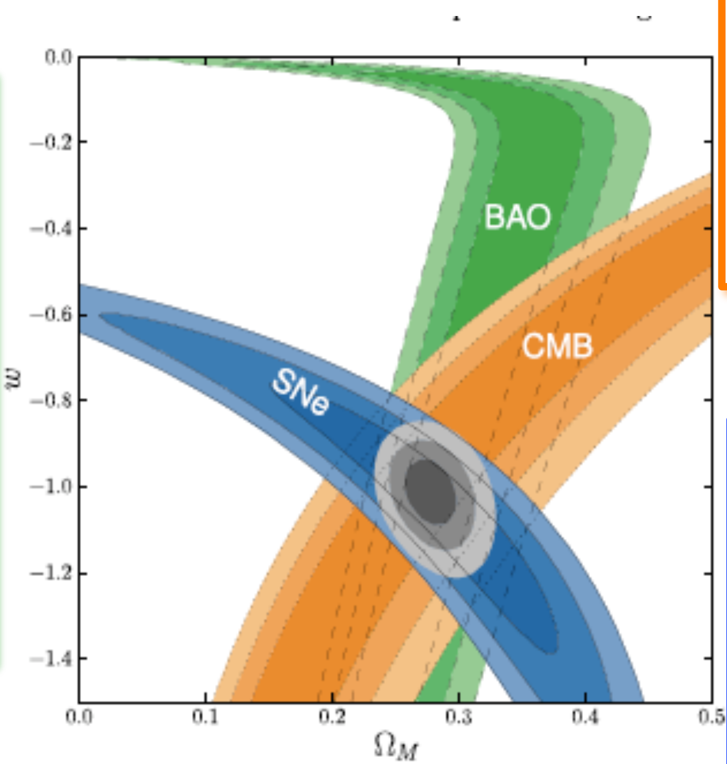
<u>The weapons</u>: observational strategies and statistical tools.

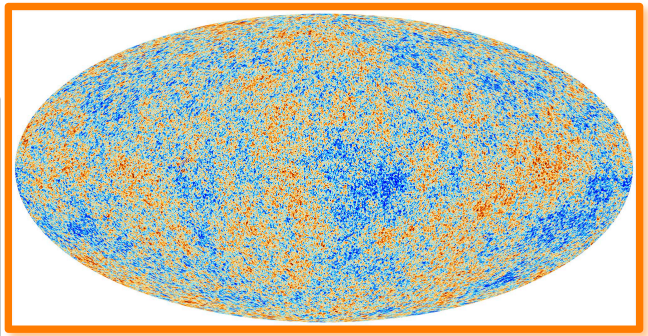
<u>The (near) future</u>: upcoming surveys and the Euclid space mission.

The Dark Energy Problem

Observations are well described by a Λ-dominated "concordance" model of an accelerated Universe. The model is simple but implies "New Physics".







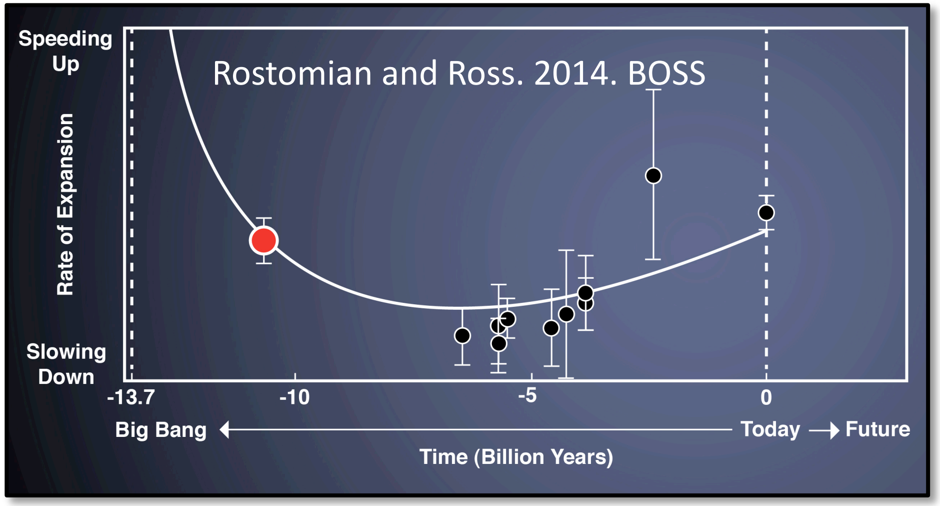
Amanullah et al. 2010 (Union supernovae)

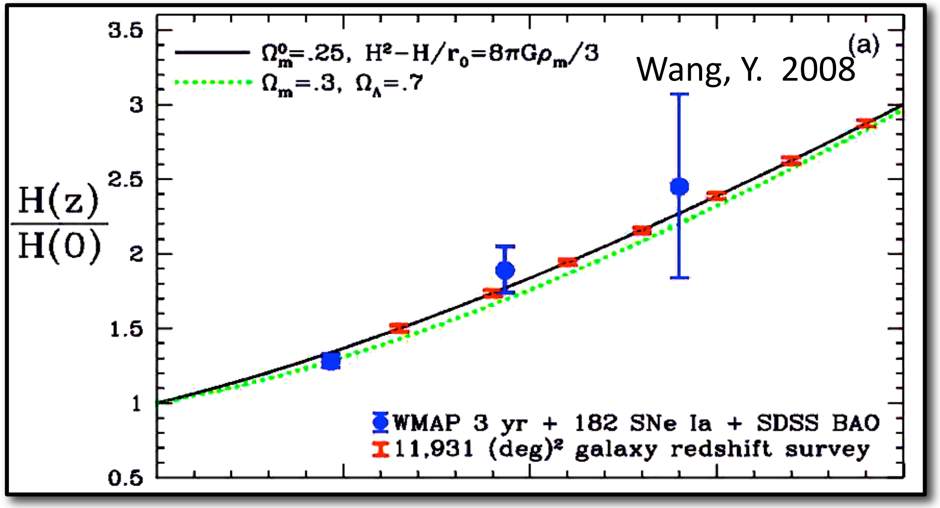
Open issues

What drives the cosmic acceleration ?
Is it a “simple” Cosmological constant ?
Or is it driven by a fundamental, evolving scalar field ?
Or is general relativity that is to be modified on cosmological scales ?
Can we tell the difference between a Dark Energy [DE] and a Modified Gravity [MG] scenario ?

Expansion History

Using Supernovae Ia and baryonic acoustic oscillations [BAOs] in the CMB and in the galaxy spatial distribution to probe the mean curvature or, equivalently, the expansion history it is not sufficient to distinguish between DE and MG options.





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

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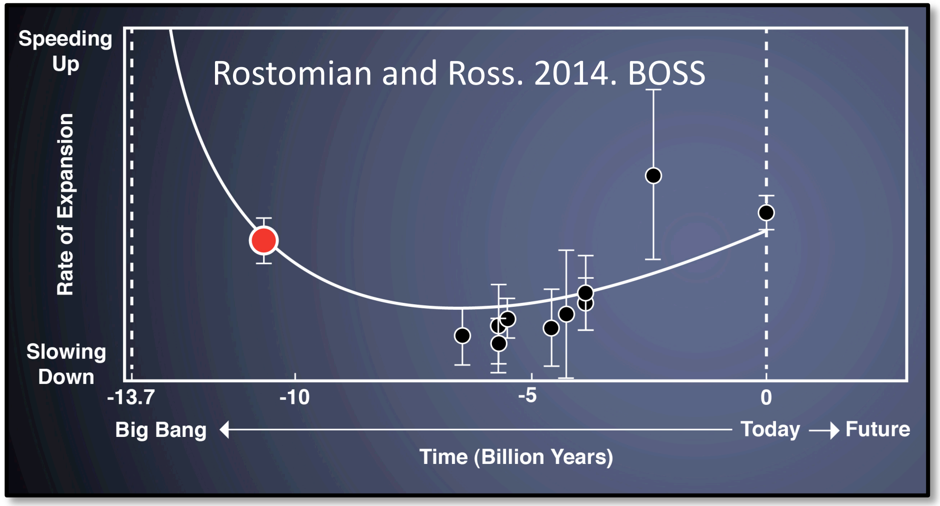

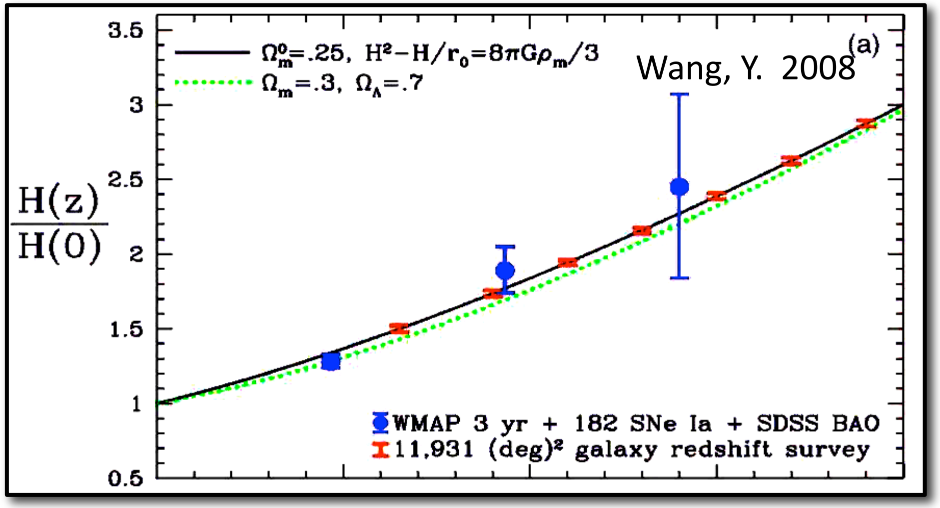

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2}\left(T_{\mu\nu} + \tilde{T}_{\mu\nu}\right)$$

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Beyond background cosmology: Cosmological Perturbations

This degeneracy can, at least partially, be lifted by considering perturbation in the cosmic density and velocity fields and their evolution. A linearly perturbed FRW metric in the Newtonian gauge can be expressed as

$$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)d\vec{x}^2$$

A general phenomenological characterization of deviations from GR (in which $\Phi = \Psi =$ Newtonian potential) leads to two modified Poisson equations:

$$k^2\tilde{\Psi} = 4\pi G a^2[1+\mu(k,a)]\langle\rho\rangle\tilde{\delta}(k,a)$$

$$k^2(\tilde{\Psi}+\tilde{\Phi}) = 4\pi G a^2[1+\Sigma(k,a)]\langle\rho\rangle\tilde{\delta}(k,a)$$

Non-relativistic particles

Relativistic particles

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$$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)d\vec{x}^2$$

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

Expansion History Probed e.g. by BAO

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

Galaxy surveys can measure these three quantities in a single experiment

What is a galaxy redshift survey ?

Galaxy redshift surveys are observational campaigns to measure angular and radial positions of extragalactic objects (galaxies). Under the assumption that galaxies are fair tracers of the underlying density field, redshift surveys ***can be used to probe cosmological perturbations and their evolutions and, simultaneously, the exapnsion history of the Universe.***

Redshifts are used as proxy to galaxy distances. They are measured with different techniques. In a **spectroscopic survey** the redshift is measured with high precision from lines emission/absorption in the galaxy spectra. In a **photometric survey** the redshift is measured by comparing the flux measured in different energy bands**.** **Photometric redshifts** are significantly less precise (~30x) than **spectroscopic redshifts** but can be measured for a much larger (~100x) number of objects

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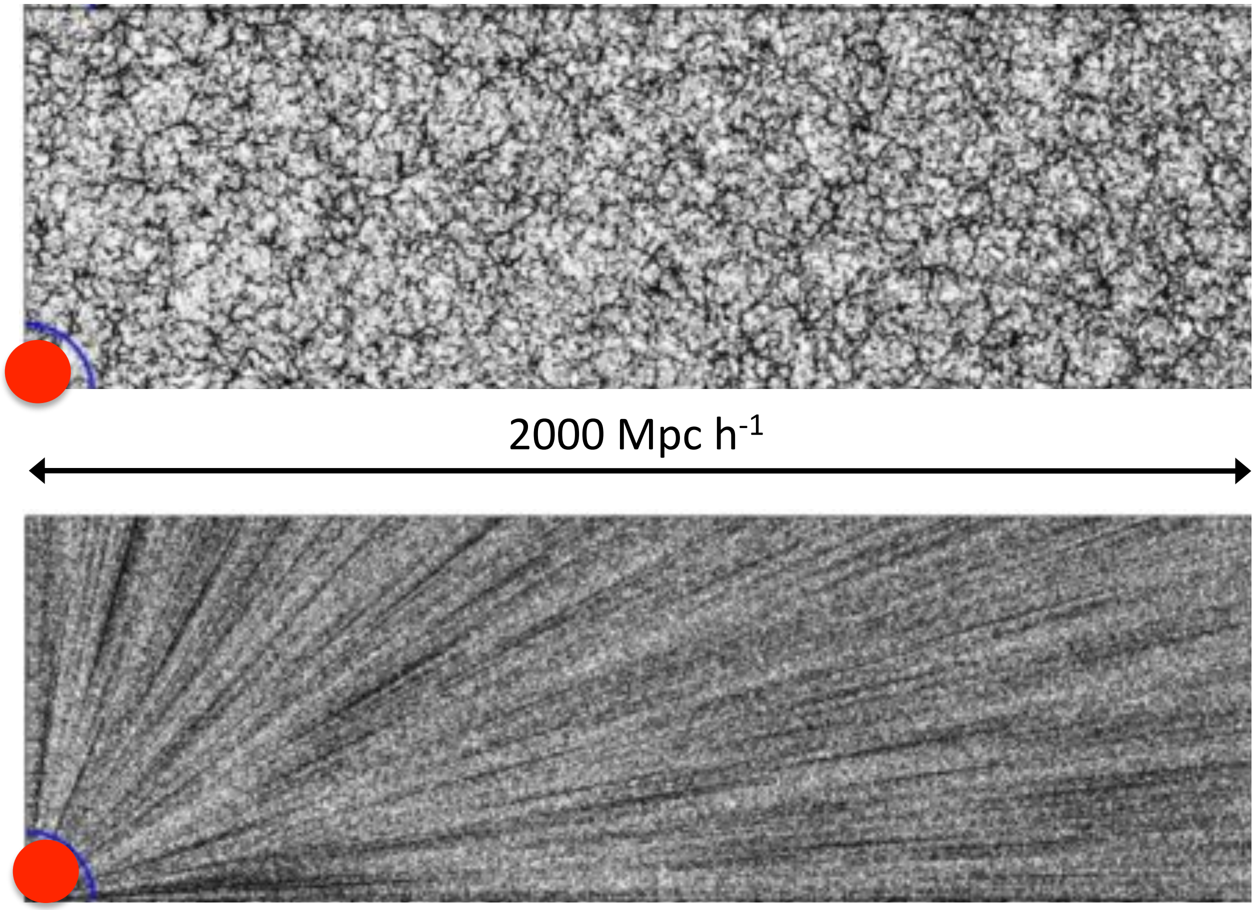
What is a galaxy redshift survey ?



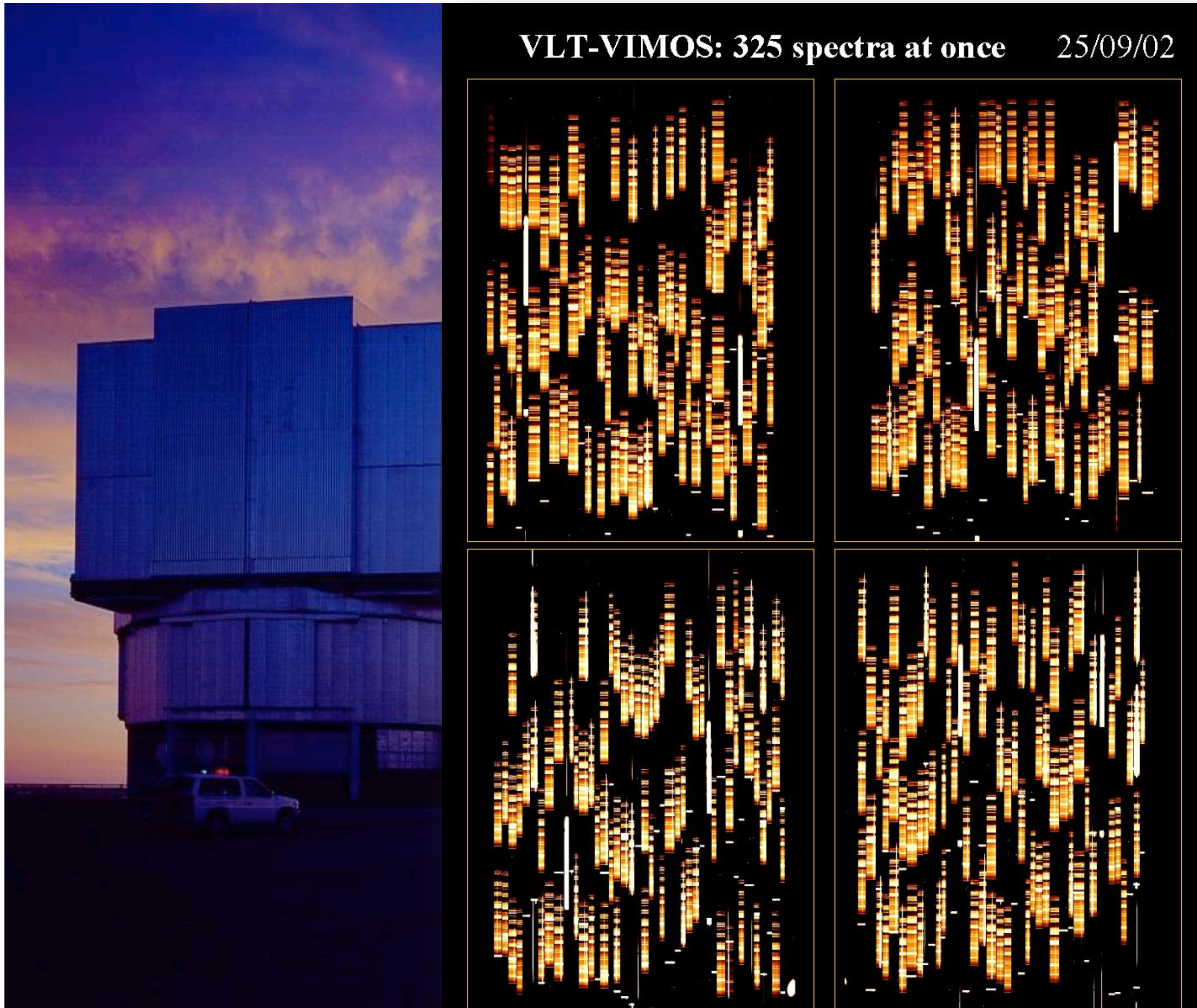
Spectroscopic surveys can probe the 3D distribution of objects.

Photometric surveys can probe the 2D distribution of objects and their mean radial distribution N(z)

Galaxy redshift surveys: Italian expertise and the VIPERS experience.

100,000 galaxies at $z\sim0.8$ in 24 deg^2. Capability of taking hundreds of spectra simultaneously.

What is a galaxy redshift survey ?
The VIPERS experience



100,000 galaxies at $z\sim0.8$ in 24 deg^2. Capability of taking hundreds of spectra simultaneously.

Next generation surveys will push it to $O(10^7)$ objects with spectra and $O(10^9)$ objects with photometric redshift…

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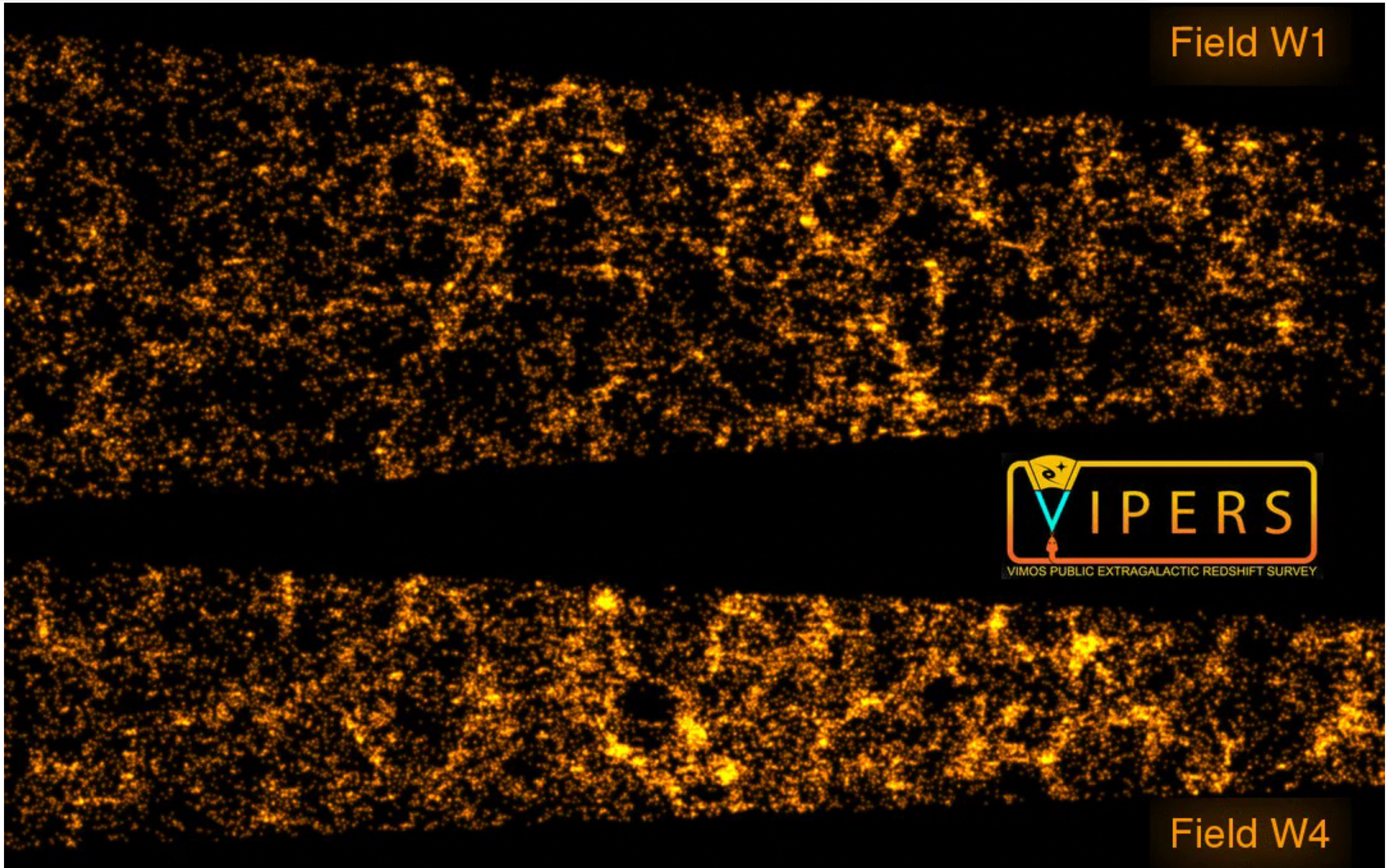
What is a galaxy redshift survey ?
The VIPERS experience



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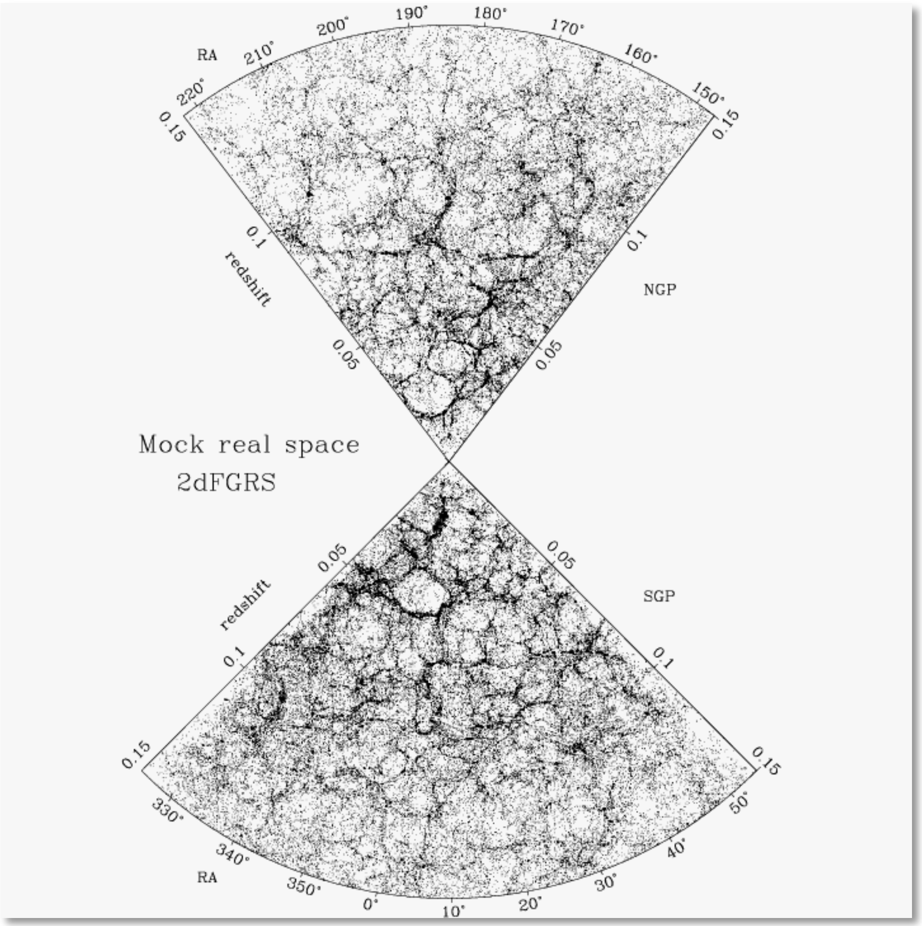
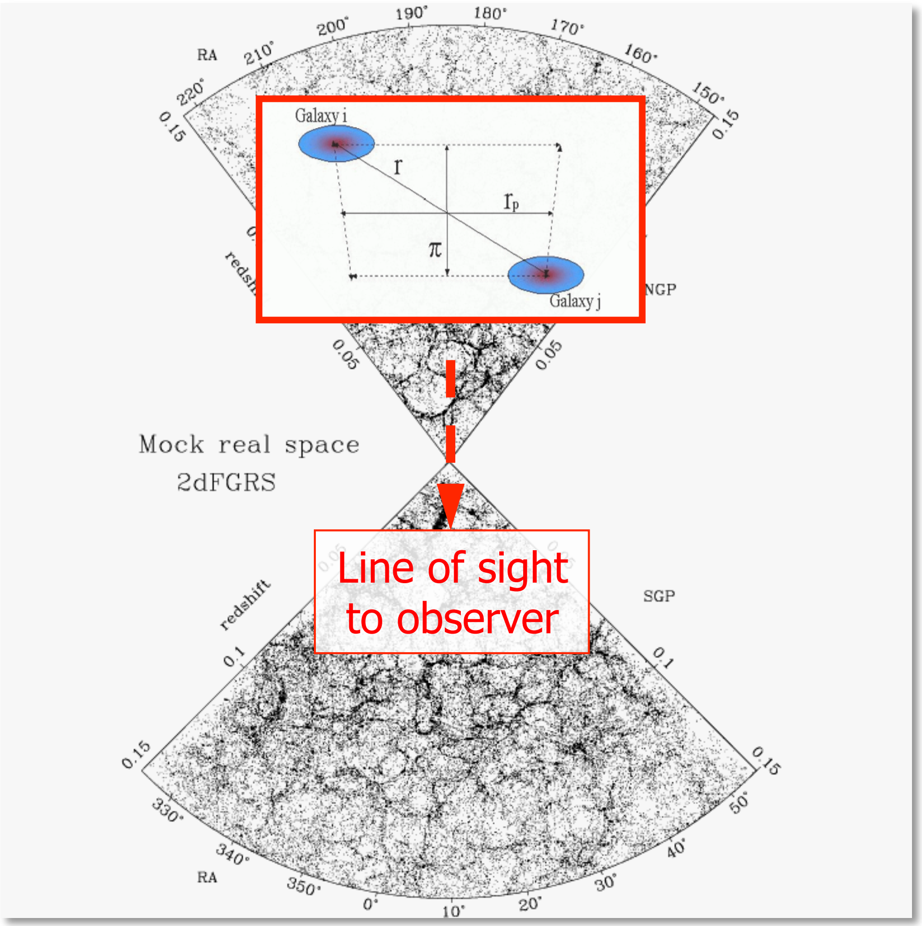
BAO as cosmological ruler



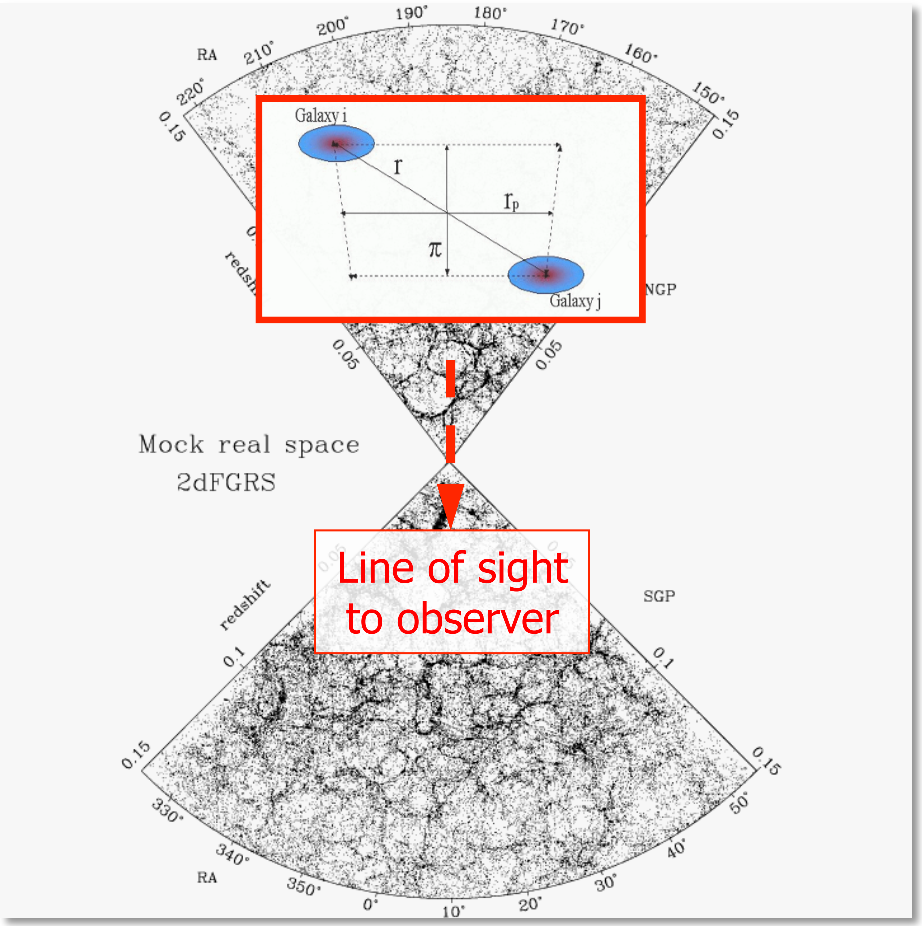
Galaxy 3D distribution can be conveniently characterized through two-point statistics, either in real or in Fourier space.

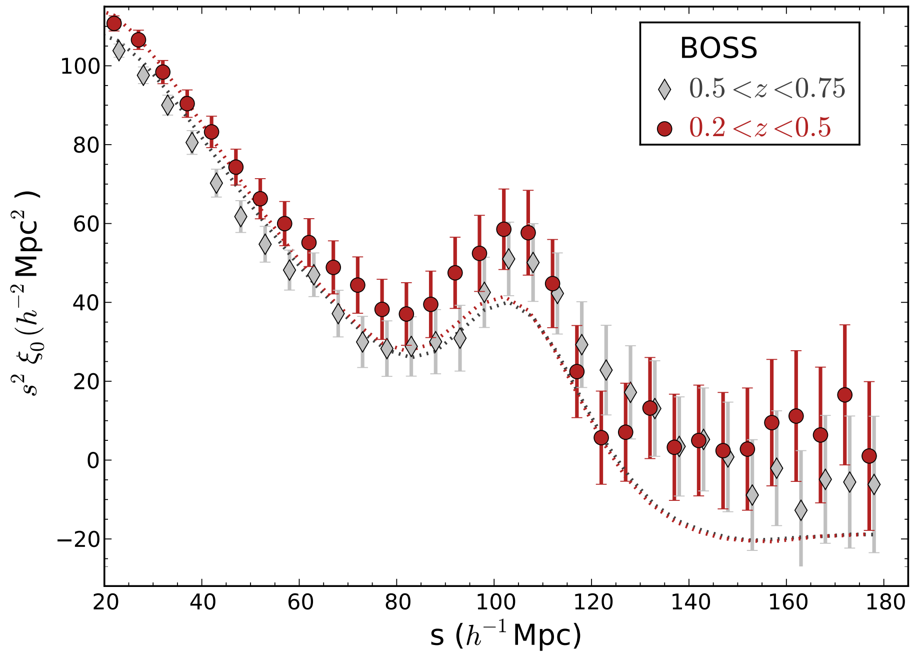
BAO as cosmological ruler



In real space one can measure the galaxy-galaxy correlation function by counting galaxy pairs at different separations.

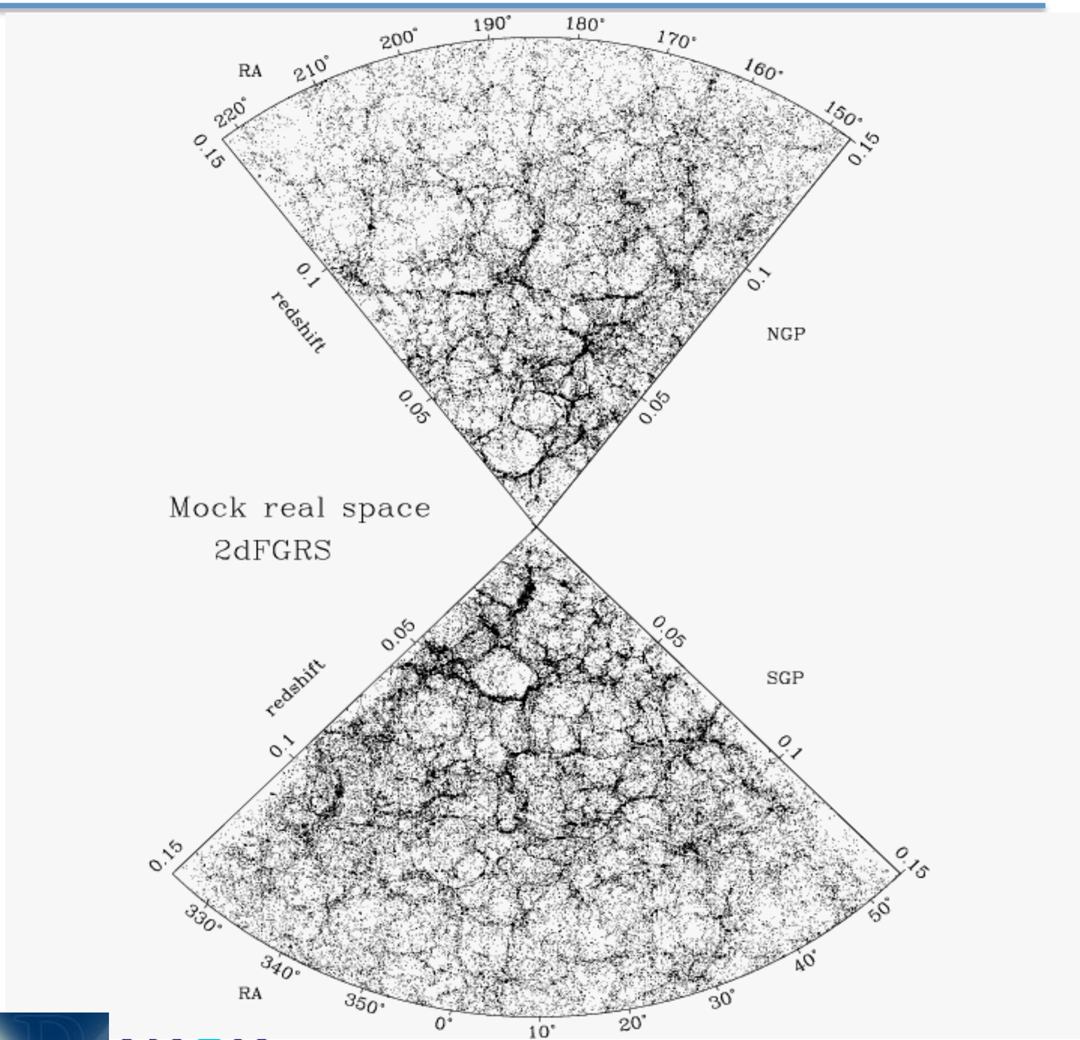
BAO as cosmological ruler



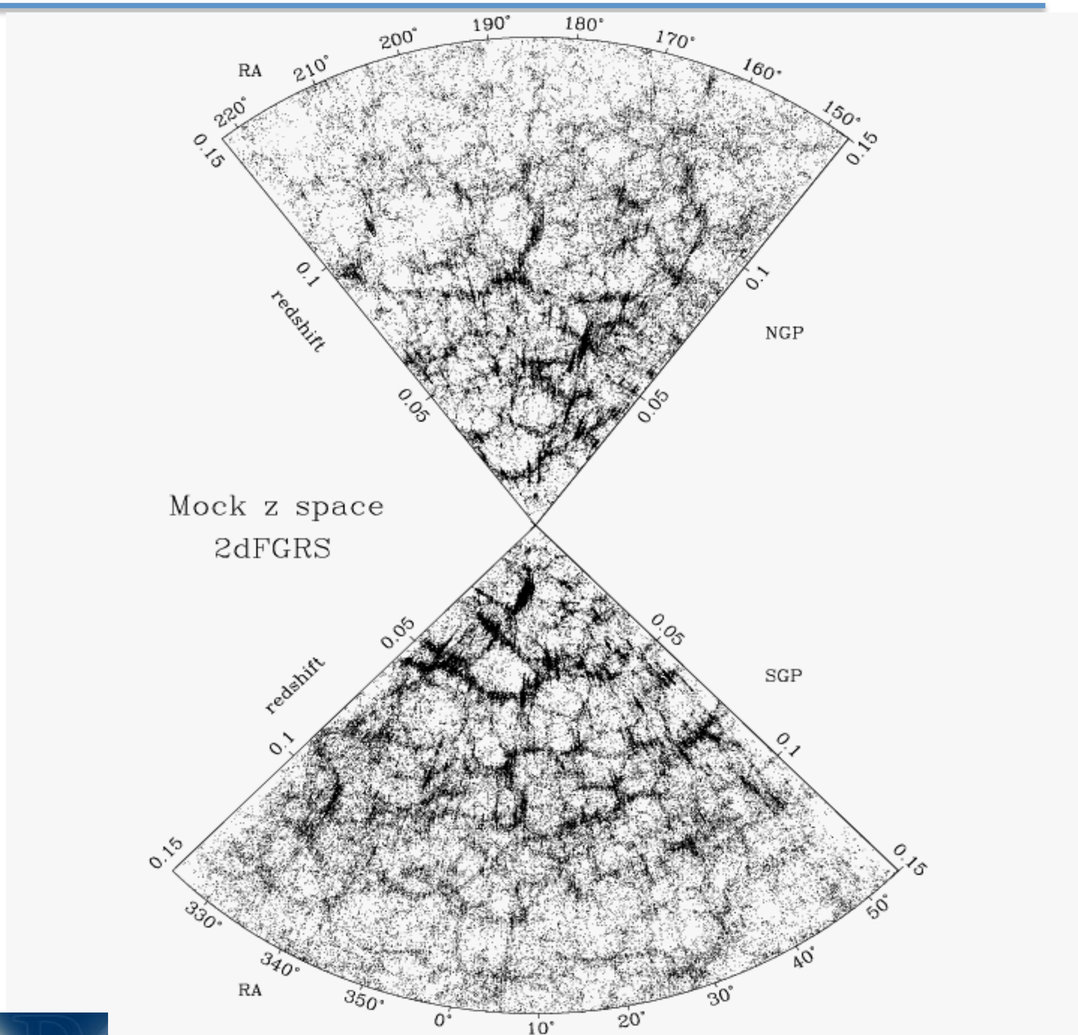


Ross+ 2016 SDSS DR12

Inferring velocities from galaxy clustering



Inferring velocities from galaxy clustering



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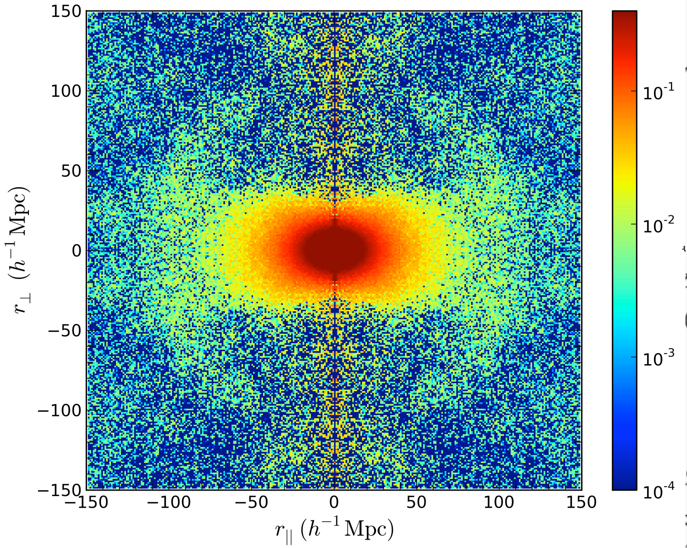
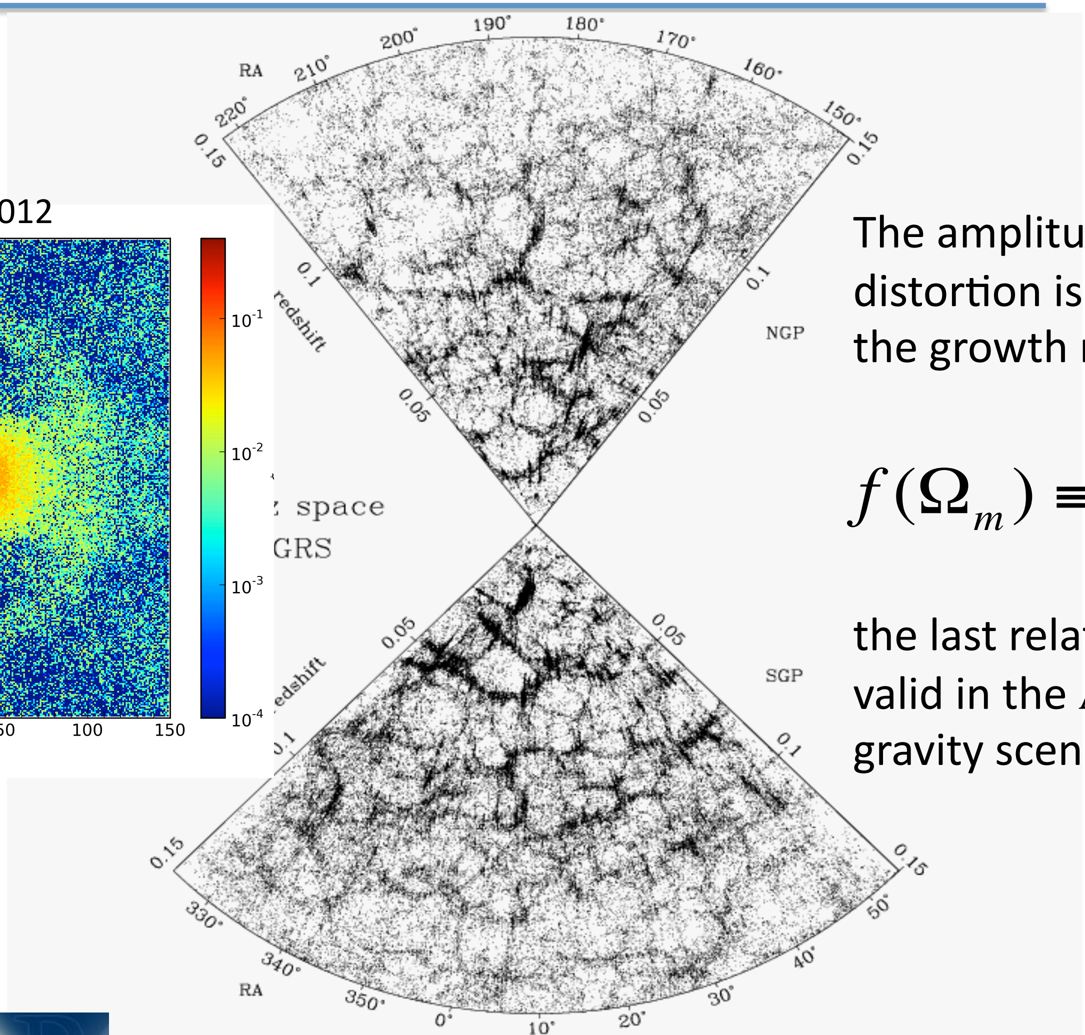
Inferring velocities from galaxy clustering

Samushia+ 2012





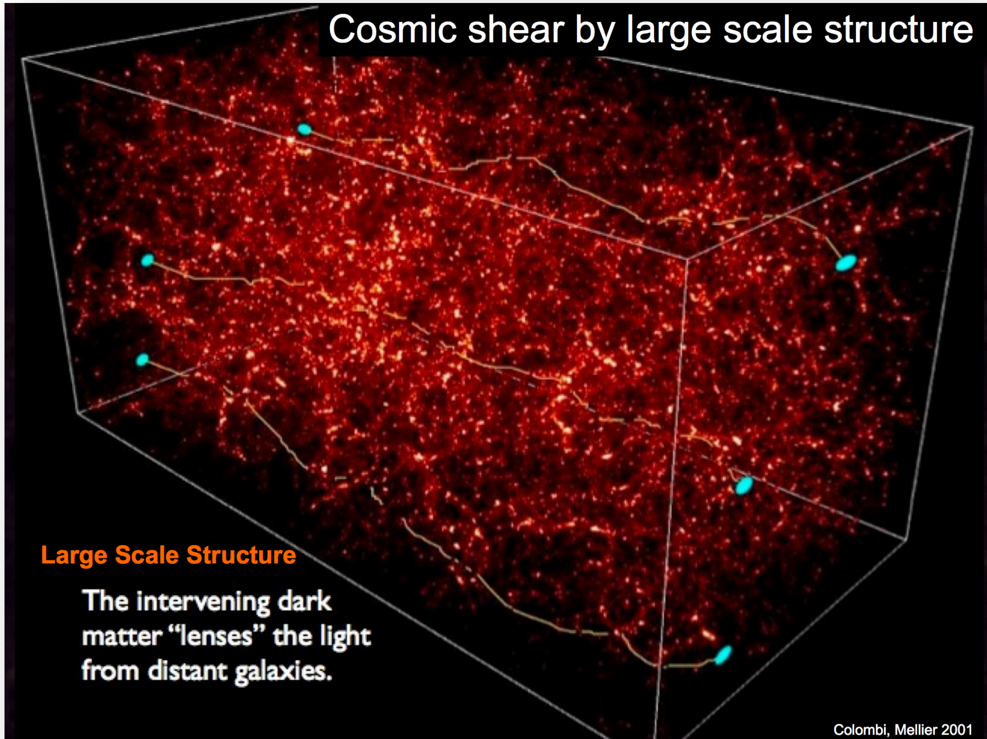
The amplitude of the distortion is proportional to the growth rate of structures.

$$f(\Omega_m) \equiv \frac{d\ln D_+}{d\ln a} \approx \Omega_m^\gamma$$

the last relation with γ~6/11 is valid in the ΛCDM, standard gravity scenario.

Weak gravitational lensing by large scale structures

Measure the ***gravitational-lensing-induced*** distortions in galaxy shapes and luminosities (e.g. ***shear maps***) to constrain the sum of the two scalar potentials $\Phi+\Psi$.



Dataset required: a ***photometric sample*** to perform a tomographic analysis of the lensing signal.

Weak gravitational lensing by large scale structures

Measure the ***gravitational-lensing-induced*** distortions in galaxy shapes and luminosities (e.g. ***shear maps***) to constrain the sum of the two scalar potentials Φ+Ψ.

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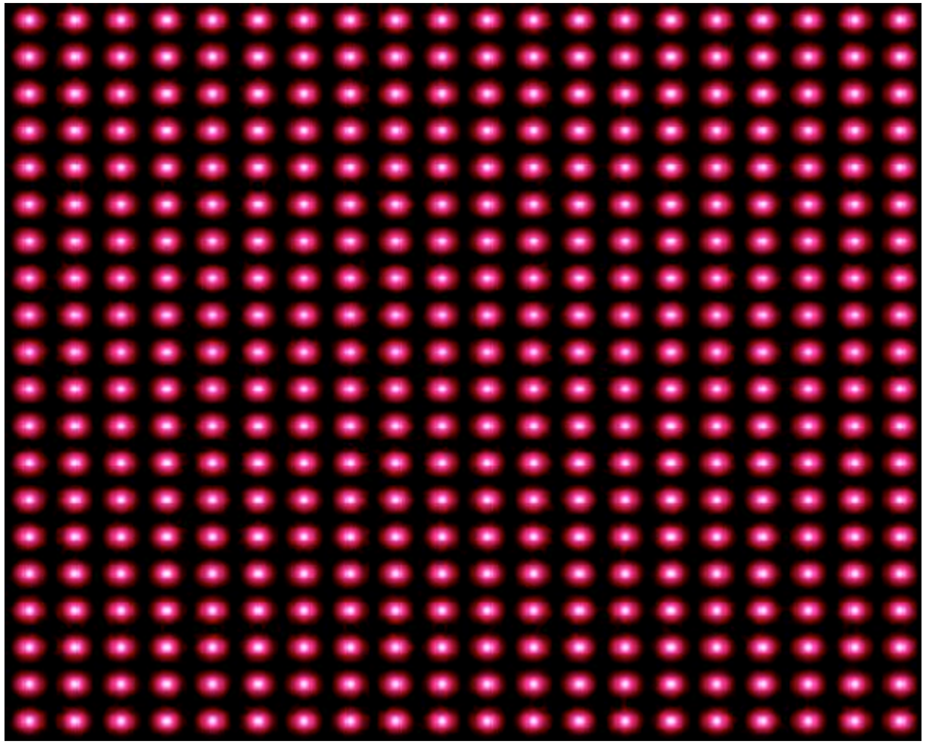

Weak gravitational lensing by large scale structures

3. Measure the ***gravitational-lensing-induced*** distortions in galaxy shapes and luminosities (e.g. ***shear maps***) to constrain the sum of the two scalar potentials $\Phi+\Psi$.

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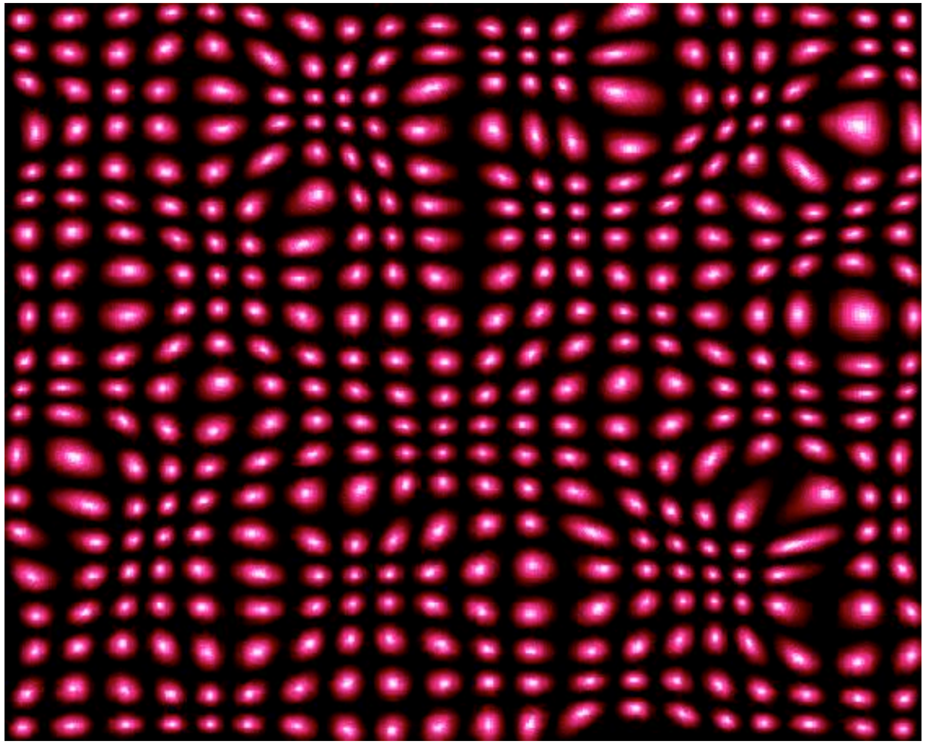


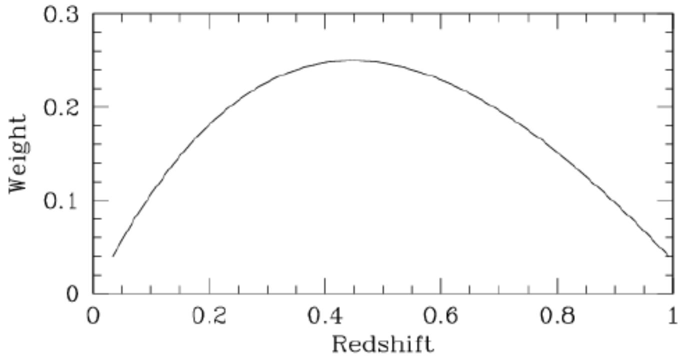
Weak Lensing tomography: inferring the matter power spectrum $P_{\delta\delta}$

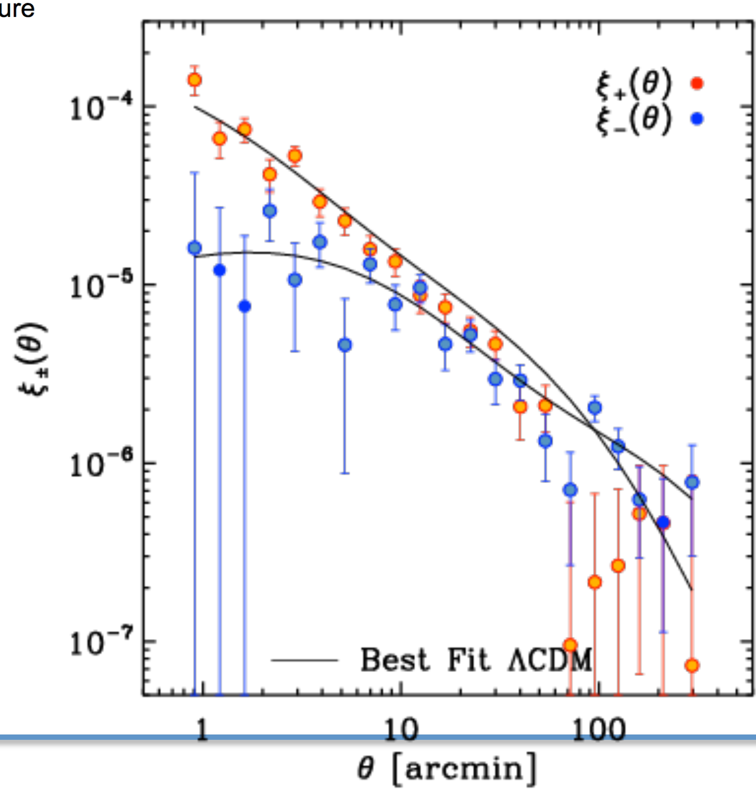
- The lensing kernel is most sensitive to structure halfway between the observer and the source. But the kernel is broad: we do not need precise redshifts for the sources: photometric redshifts are fine
- Also, since the kernel is broad the tomographic bins are very correlated. The gain saturates quickly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

Geometry Large Scale Structure

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

Lensing Power Spectrum





All in one go

To effectively constrain MD/DE models one needs to estimate these observational quantities at the % precision level. Systematics are likely to dominate the error budget.

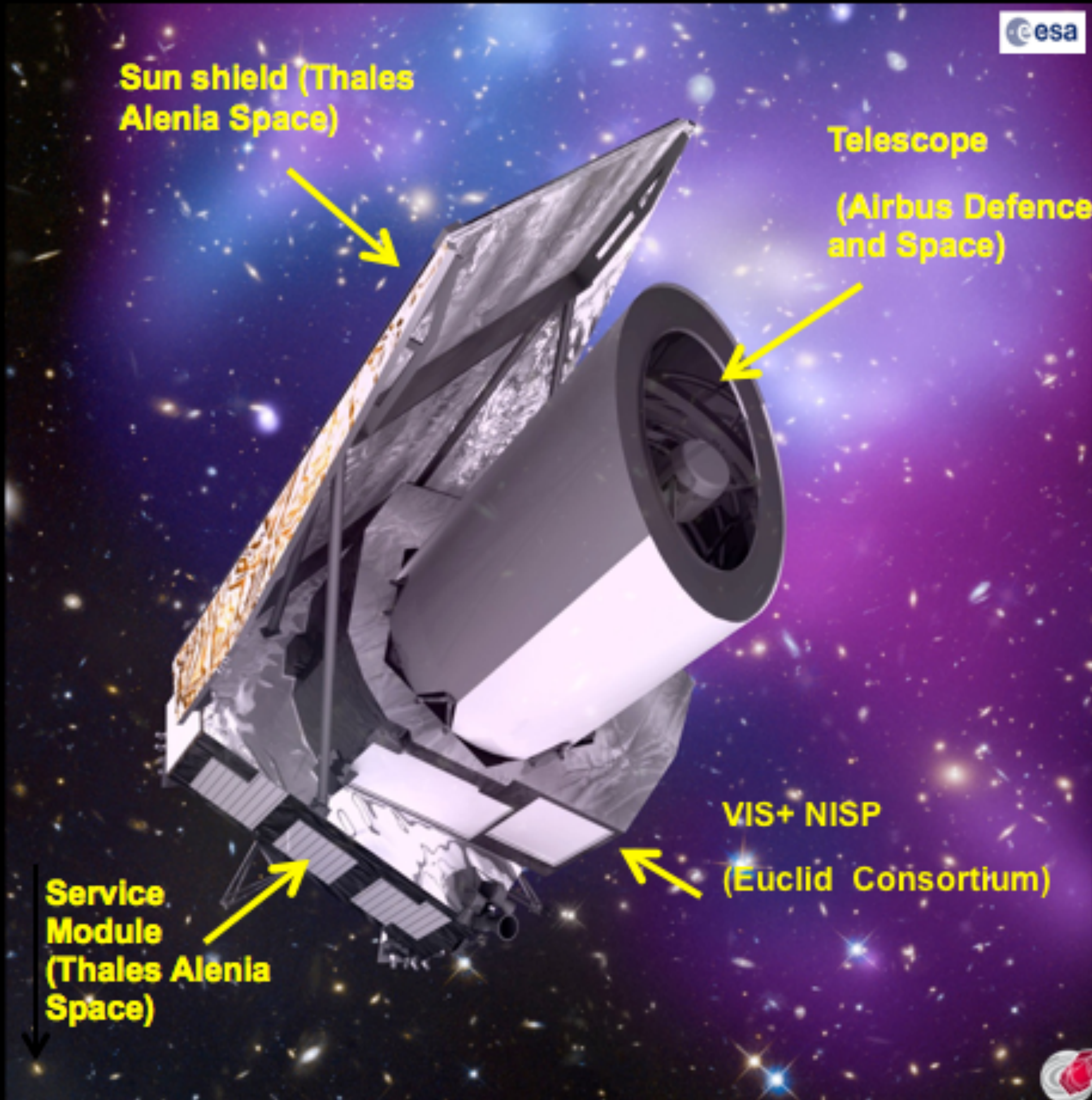
Hence the switch from *Precision Cosmology* to *Accurate Cosmology*.

The best strategy is to measure all relevant quantities from a single survey using different and complementary cosmological probes.

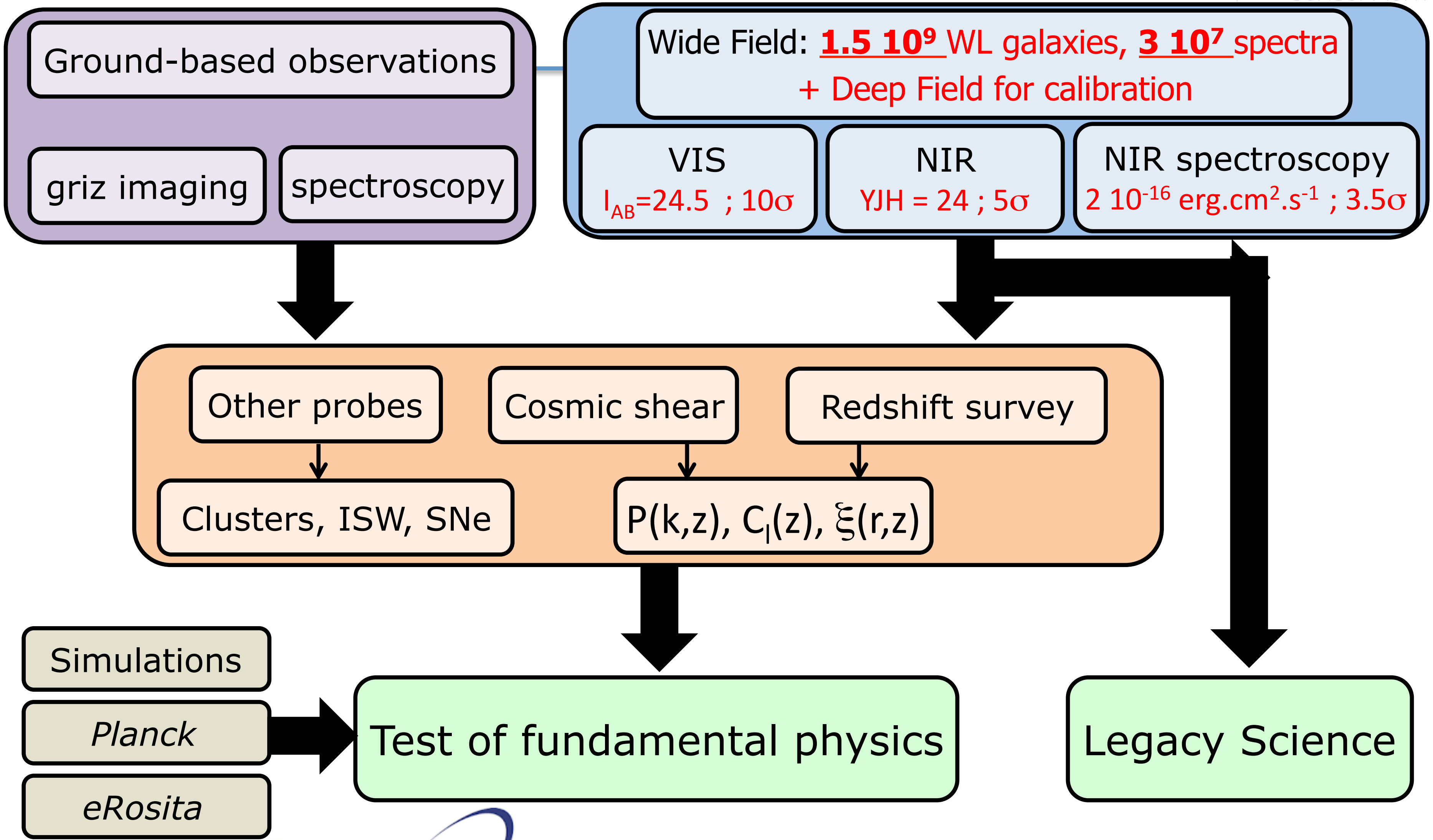
ESA Euclid mission

The legacy of SPACE (Italy-led, PI Cimatti) and DUNE (France-led, PI Refregier) Cosmic Vision proposals: →France and Italy main contributors to Euclid

- - Mirror size: 1.2 m Korsch
- - Total mass satellite : 2 200 kg
- - Dimensions: 4,5 m x 3 m
- - Launch: end 2020 by a Soyuz rocket from the Kourou space port
- - Placed in L2
- - Survey: 6 years,



How to do this (and more) with Euclid ?



Mission Requirements

WL and systematics

$$\gamma^{obs} = (1+m)\times\gamma^{true} + c$$

$$C_l^{true} \approx \left[1+2\langle m\rangle\right]\times C_l^{obs} + \langle c^2\rangle$$

- Small PSF, Knowledge of the PSF size
- Knowledge of distortion
- Stability in time → cryogenic space telescope
- Visible photom photo-z accurary: 0.05x(1+z)
- Additional ground-based photo surveys (g,r,i,z)
- 0<z<2.0

GC and systematics

- Understand selection→Deep field (photo+spectro)
  - Completeness
  - Purity
- dz/(z+1)< 0.001
- 0.7 < z < 2.05
- > 3500 redshift/sq deg

	Wide survey	**Deep survey**
Survey: 6 years		
Area	15, 000 deg ^{2}	40 deg^2 N/S
VIS imaging		
Depth	n_{gal} >30 arcmin-^{2} M_{AB} =24.5, 10σ for gal size 0.3 » → <z> ~0.9	M_{AB} = 26.5
PSF size knowledge	$\sigma[R^2]/R^2<10^{-3}$	
Multiplicative bias in shape	$\sigma[m]<2\ .10^{-3}$	
Additive bias in shape	$\sigma[c]<2\ .10^{-4}$	
Ellipticity RMS	$\sigma[e]<2\ .\ 10^{-4}$	
NIP photometry: YJH		
Depth	24 M_{AB}	26 M_{AB}
NIS spectroscopy: 4 R exp., 3 R orientations		
Flux limit (erg/ cm^2/s)	2 10^{-16}	5 10^{-17}
Completness	> 45 %	>99%
Purity	>80%	>99%
Confusion	3 rotations	>12 rotations

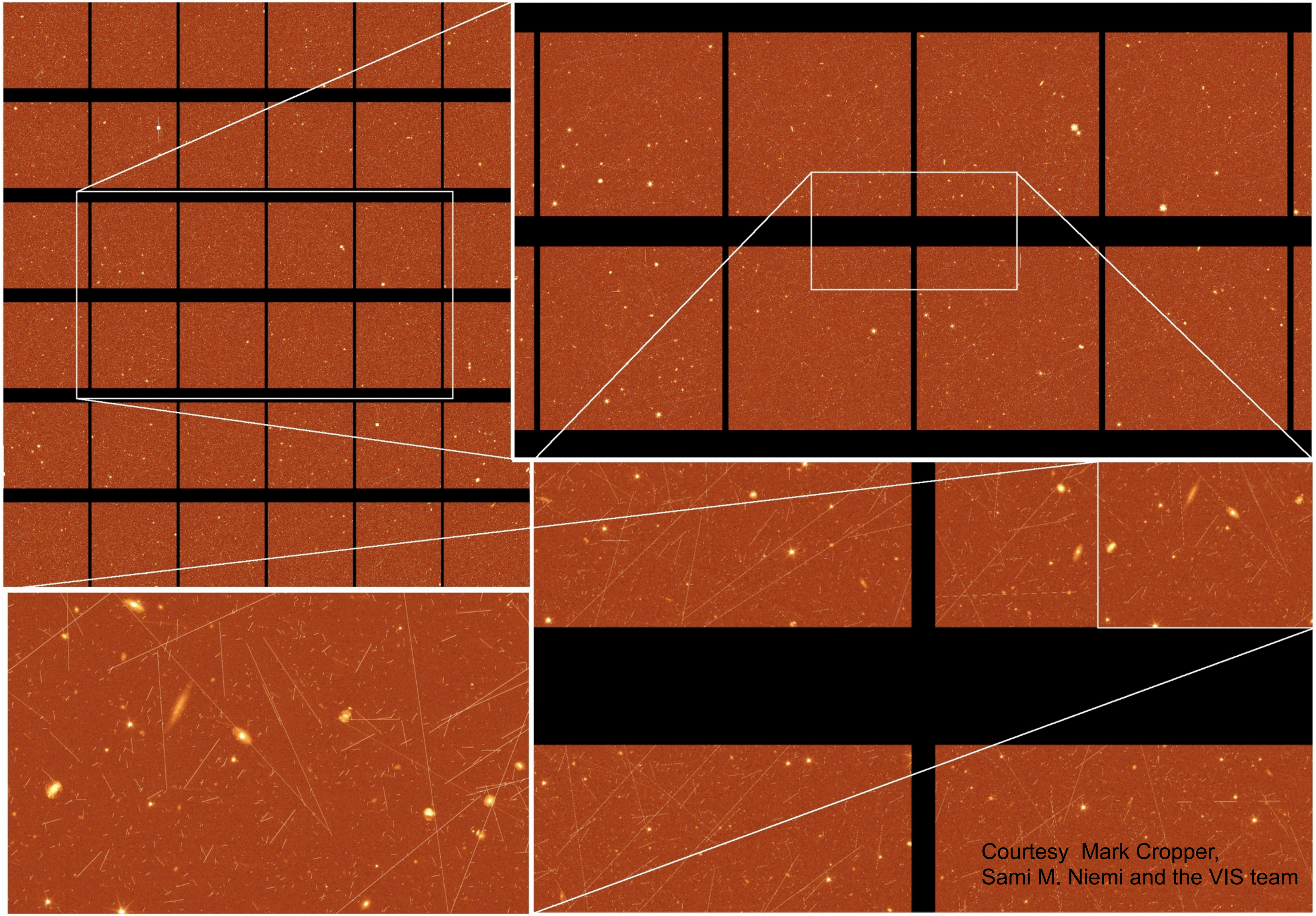
Euclid Imaging

M51

Courtesy J. Brinchmann, Steve Warren

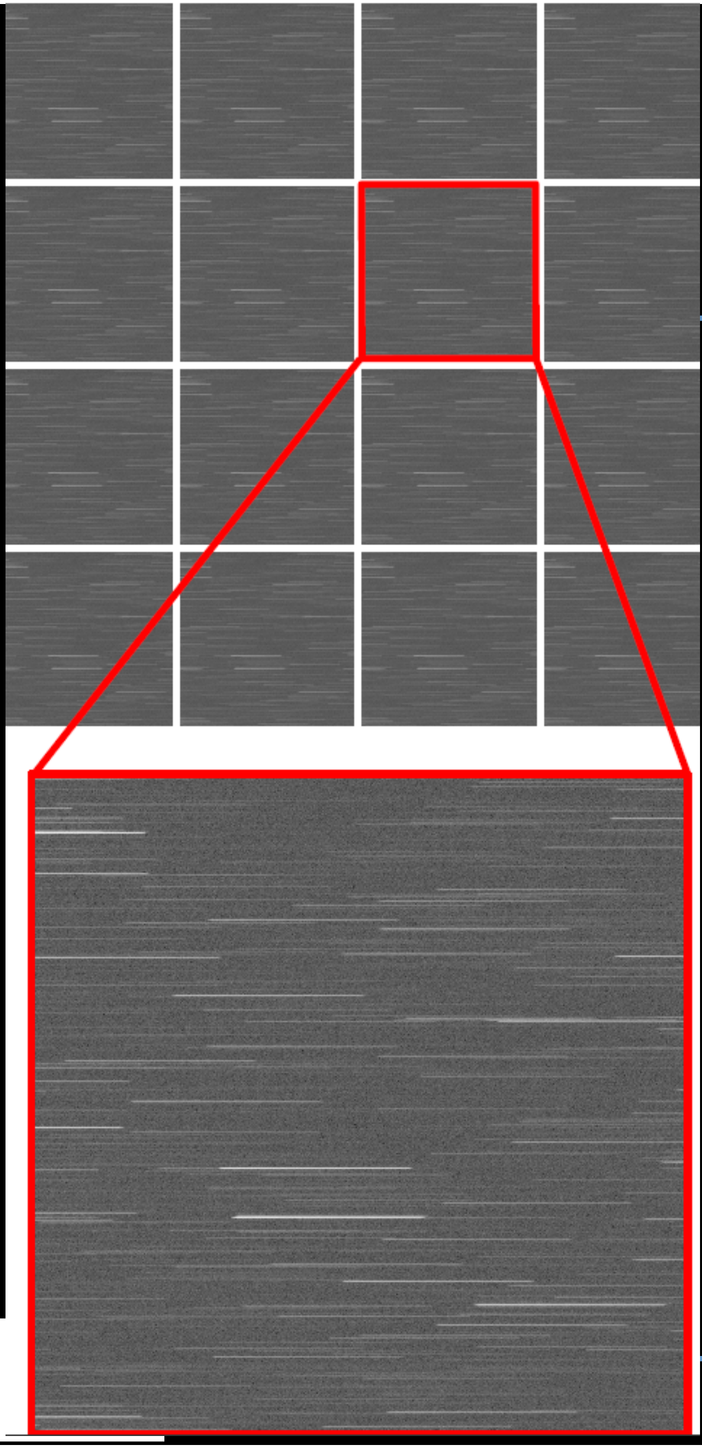
SDSS @ z=0.1 | Euclid @ z=0.1 | Euclid @ z=0.7

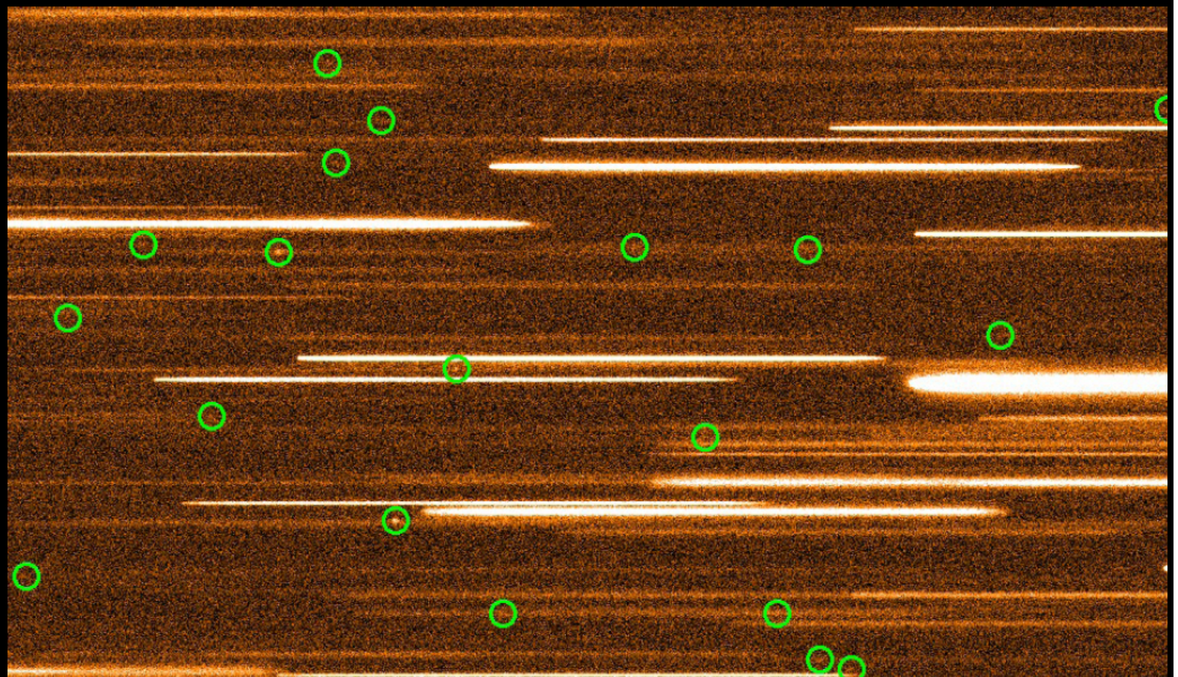
Euclid : VIS imaging instrument



Courtesy Mark Cropper,
Sami M. Niemi and the VIS team

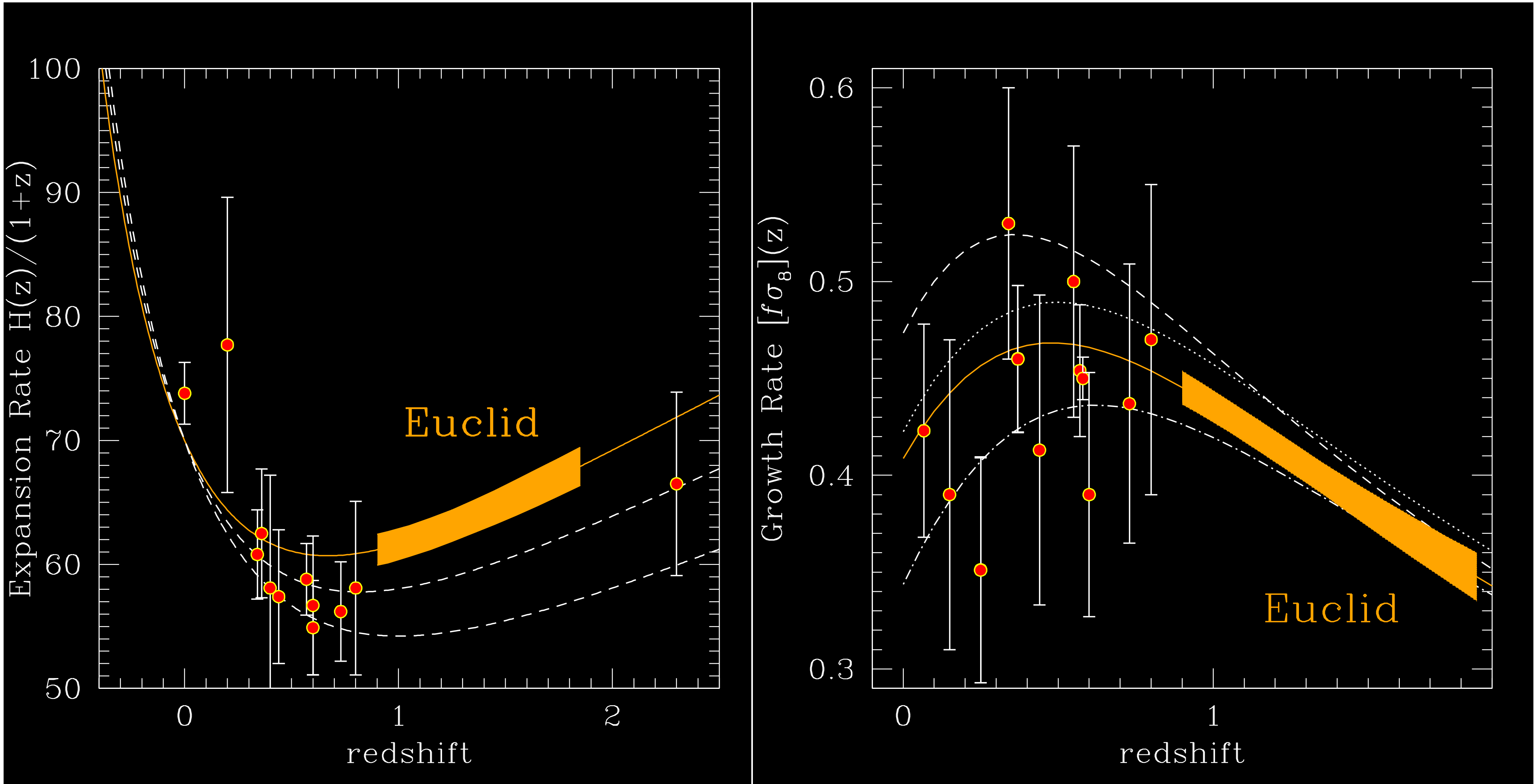
NISP-spectroscopy for Euclid (2016)





Sims by P. Franzetti, B. Garilli, A. Ealet, N. Fourmanoit & J. Zoubian

Euclid Forecast



Expected scientific performances

Ref: Euclid RB arXiv:1110.3193

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν /eV	f_{NL}	w_p	w_a	*FoM*
Euclid primary (WL+GC)	0.010	0.027	5.5	0.015	0.150	$= 1/(\Delta w_0 \times \Delta w_a)$ 430
EuclidAll (clusters,ISW)	**0.009**	**0.020**	**2.0**	**0.013**	**0.048**	**1540**
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020 → **6000**
Reference (2011)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>40**	**>400**

ASSUMPTION: ALL SYSTEMATIC ERRORS ARE UNDER CONTROL !!!

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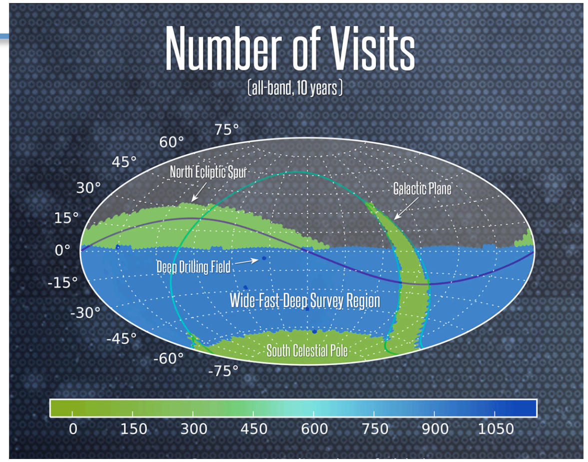
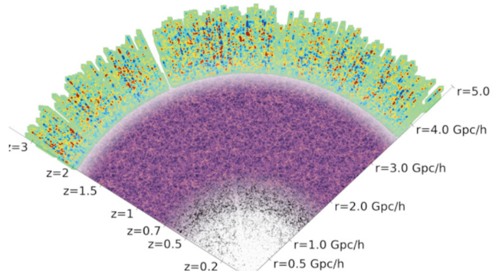
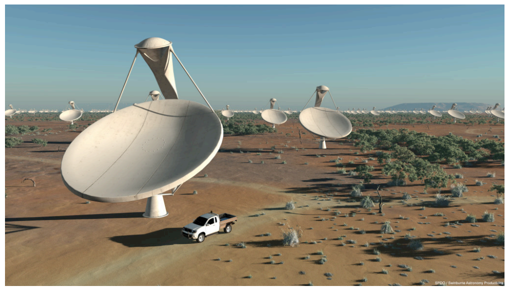
Euclid competitors



LSST: ground based survey. 8.5 mt telescope. 3.5 deg f.o.v.
20,000 deg^2 . 6 bands (+2). Short exposures. 1000 visits.
O(10^{10}) gals. Out to z+2 with photo-z. (3x10^9 with small errors)
Goals (cosmology): WL and BAO. Timeline: 2020-2030



DESI: ground based survey. 4 mt telescope. Multiple spectra.
14,000 deg^2 . 2.5x10^7 gals + 2x10^6 QSOs. z-range [0.2,3.5].
Goals (cosmology): BAO, Redshift distortions. Timeline: 2018-2022



SKA: ground based radio survey. Radio interferometer. 21 cm line.
30,000 deg^2 . 10^9 gals. Z<2 + HI intensity mapping.
Goals (cosmology): BAO, Redshift distortions. Timeline: 2023-?

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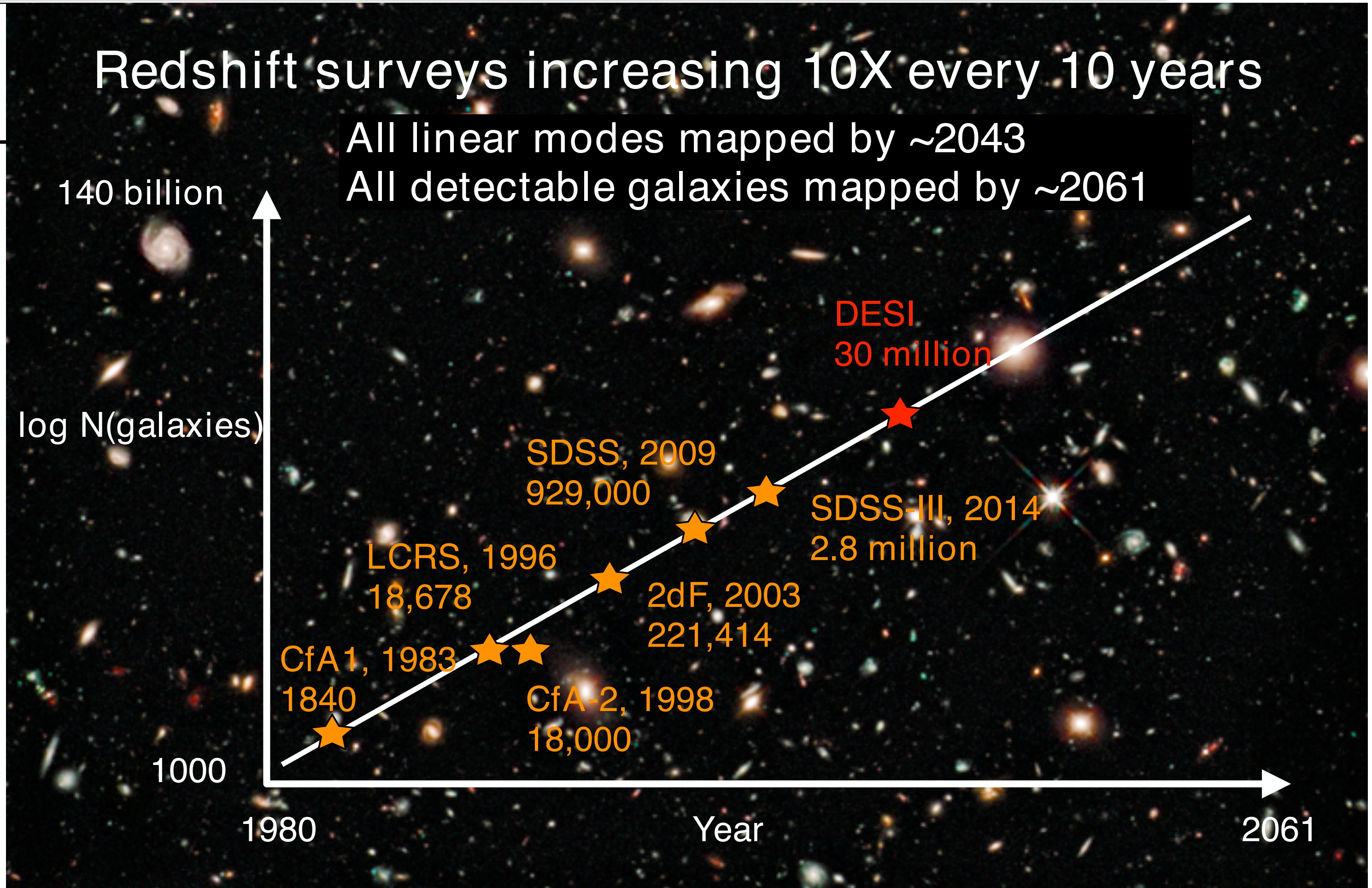
Golden Age or Gold Rush ?



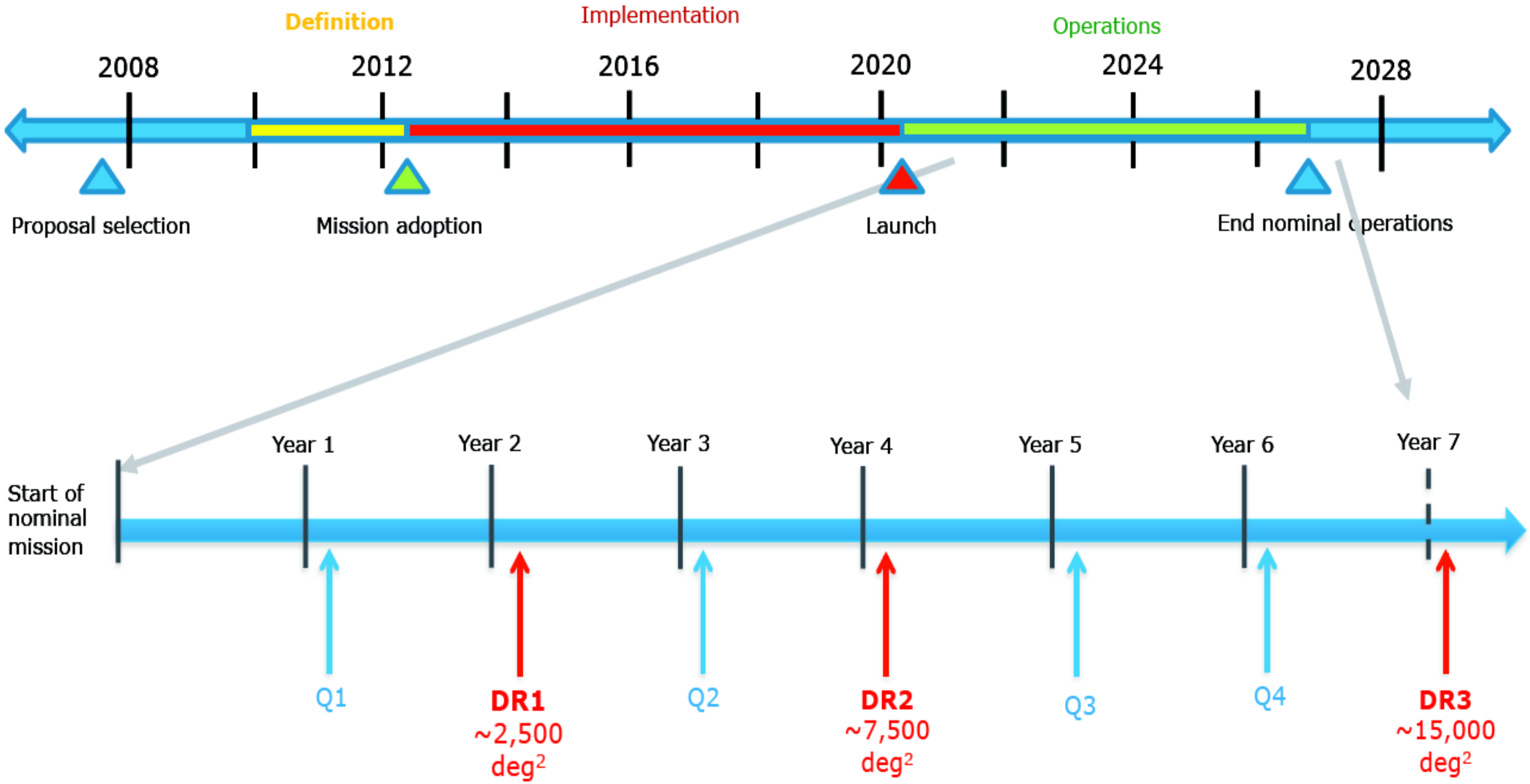
Courtesy: D. Schlegel

To wrap up…

- **Galaxy Redshift Surveys will be the primary tool to investigate the origin of the accelerated cosmic expansion.**
- **The Euclid survey will play a leading role:**
  - Explore the dark universe: **DE/MG**, DM, Neutrinos, inflation
  - Use no less than 5 cosmological probes, with at least 2 independent
  - Support/complement and benefit from current and next generaton wide field surveys: GAIA, DES, LSST, e-ROSITA, SKA.
  - Huge Legacy Science added value: 12 billion sources, 35 million redshifts, 1.5 billion shapes/photo-z of galaxies. A reservoir of targets for JWST, E-ELT, ALMA, VLT. A set of astronomical catalogues useful until 2040+.

- **National involvement:**
  - The national community is playing a major role in the Euclid consortium (Many leading roles in Science Working Groups and Ground Segment activities, instrument building).
  - Thanks to past/ongoing experiences in observational campaigns (e.g. VIPERS) and space mission (e.g. Planck).
  - INFN is actively involved both directly (on-board HW/SW) and indirectly
  - through specific initiatives (Indark).

Timeline and data release



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