Dark energy and modified gravity theories: current status and prospects with the Euclid satellite.

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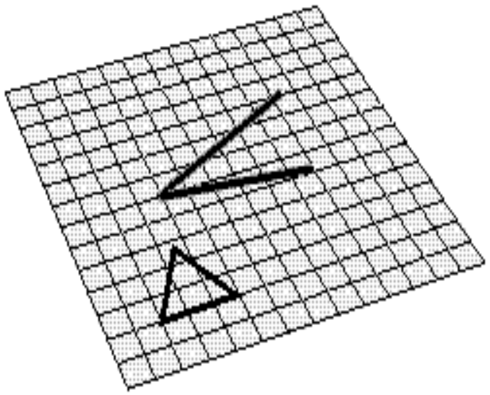
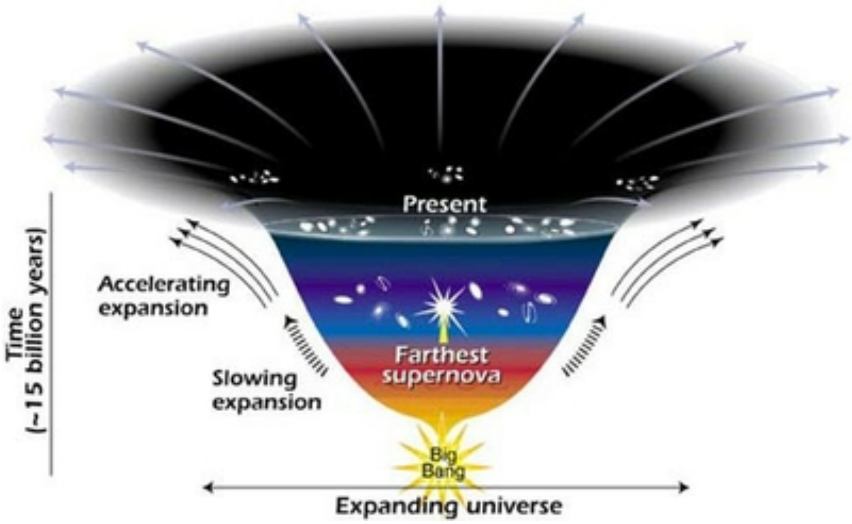
Accelerating Universe in the Dark, Kyoto, 4-8 March

What drives cosmic acceleration?

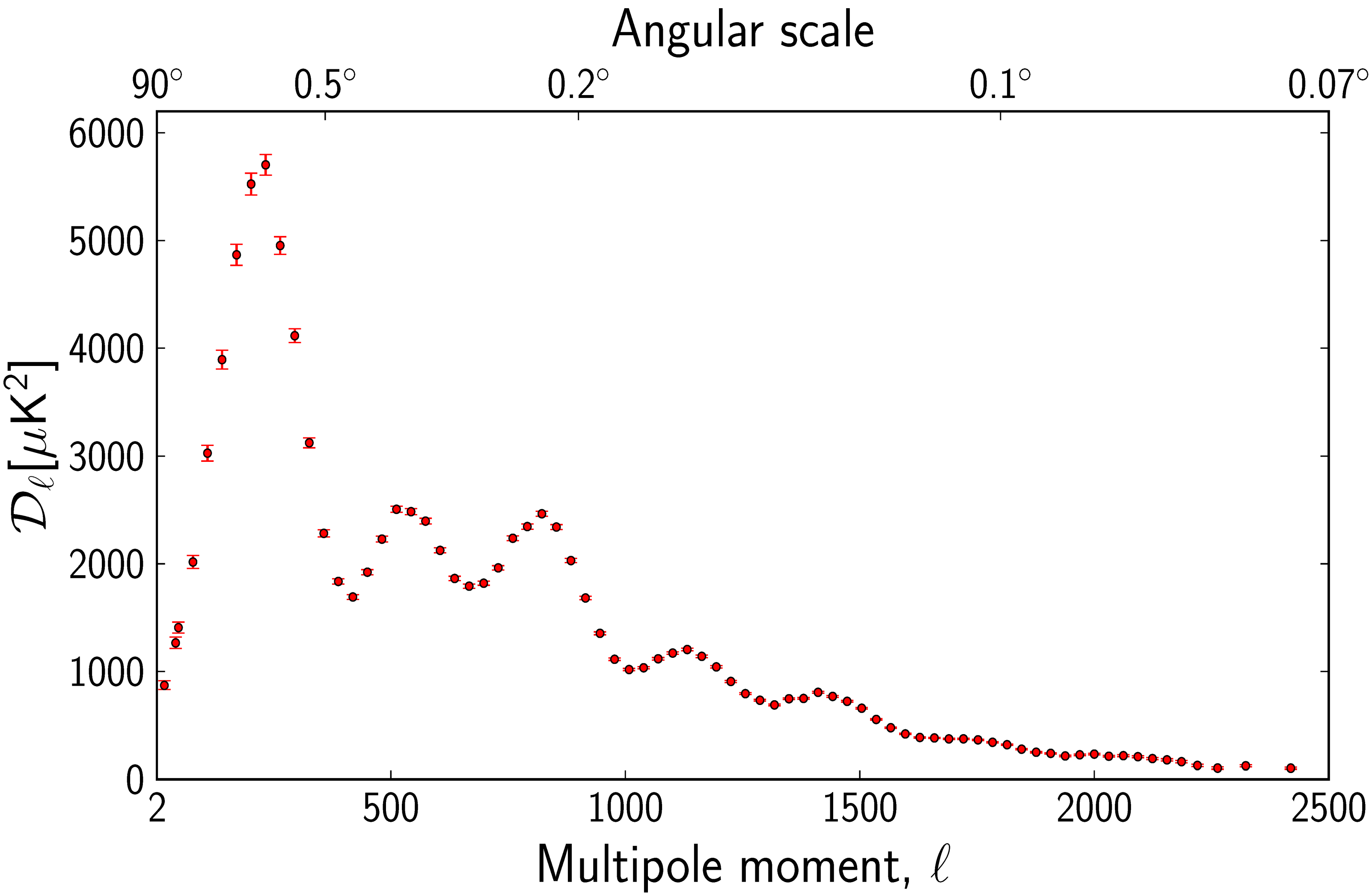
Independent probes point towards a similar picture



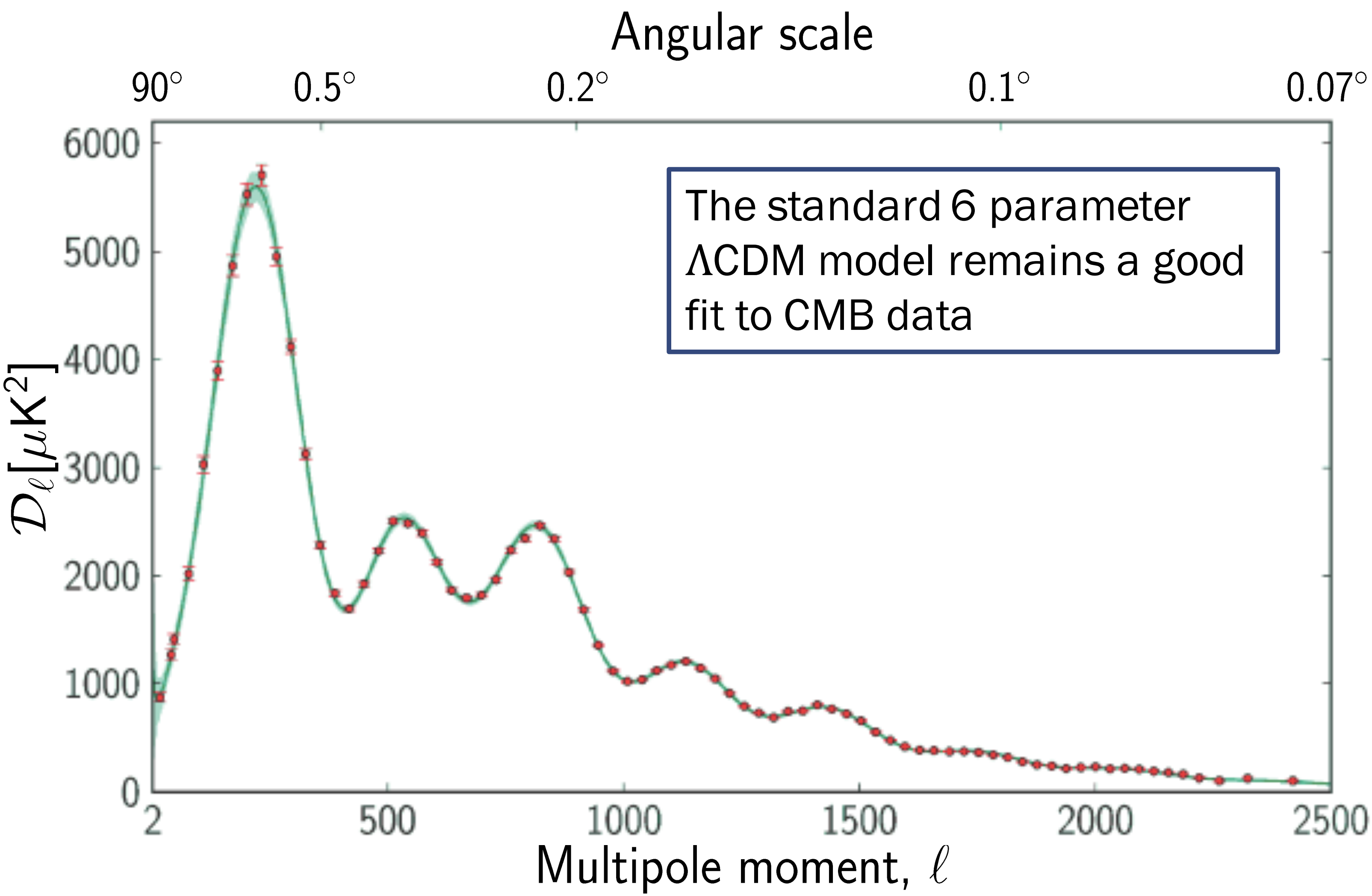


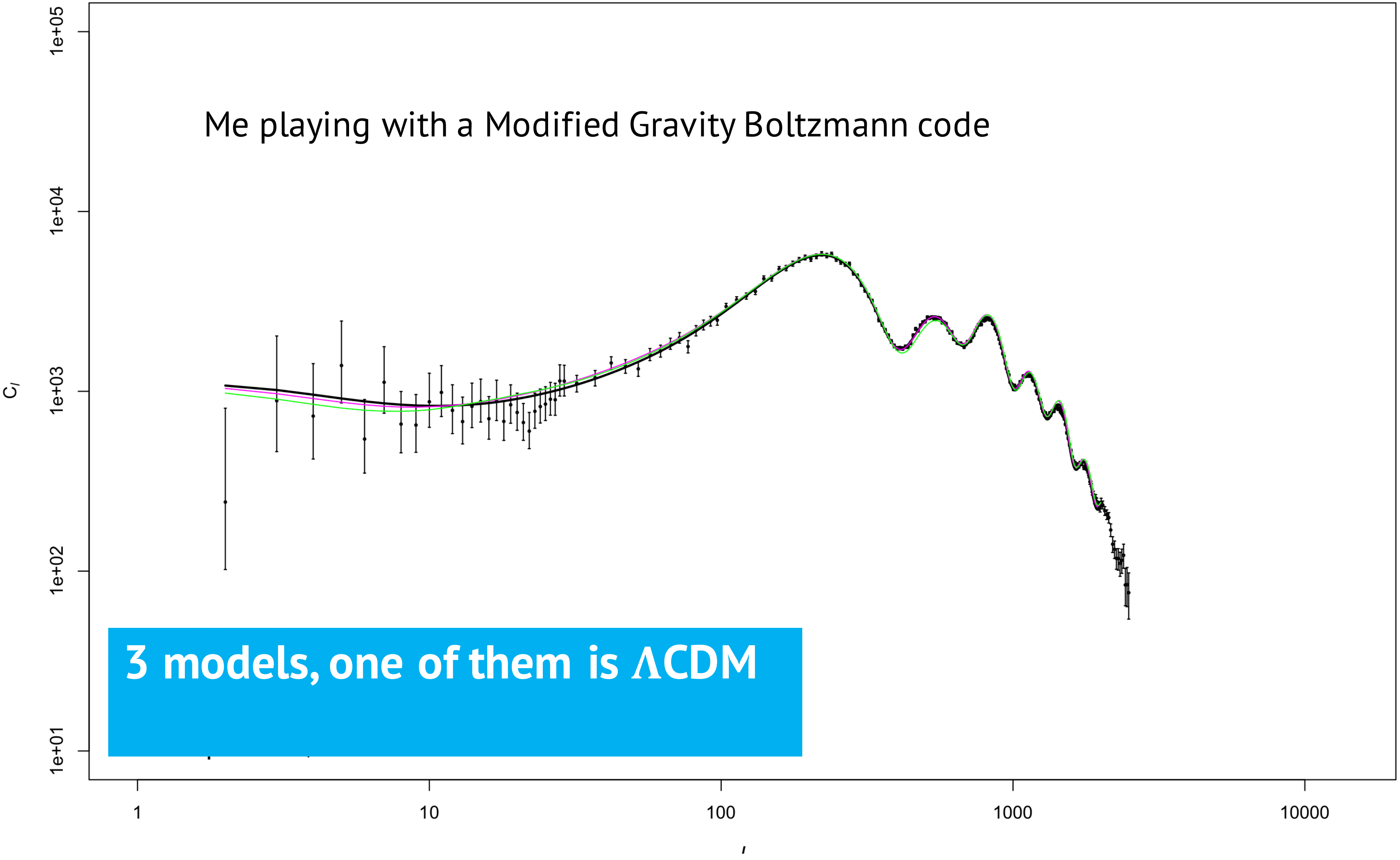
A new fluid or a new force at cosmological scales?

Planck Paper XVI

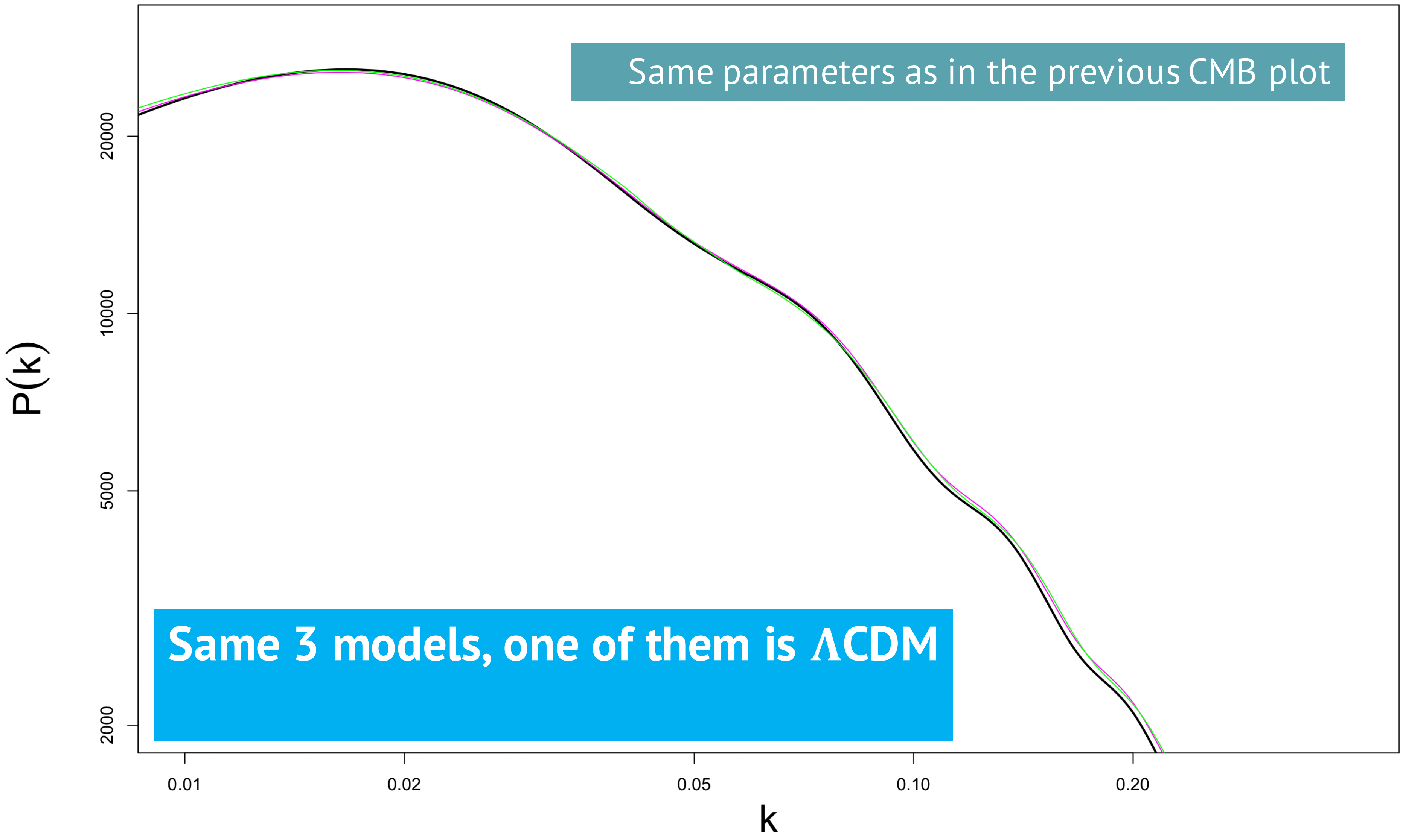


Planck Paper XVI





Me playing with a Modified Gravity Boltzmann code
3 models, one of them is ΛCDM
C_l
1e+05
1e+04
1e+03
1e+02
1e+01
1
10
100
1000
10000
l



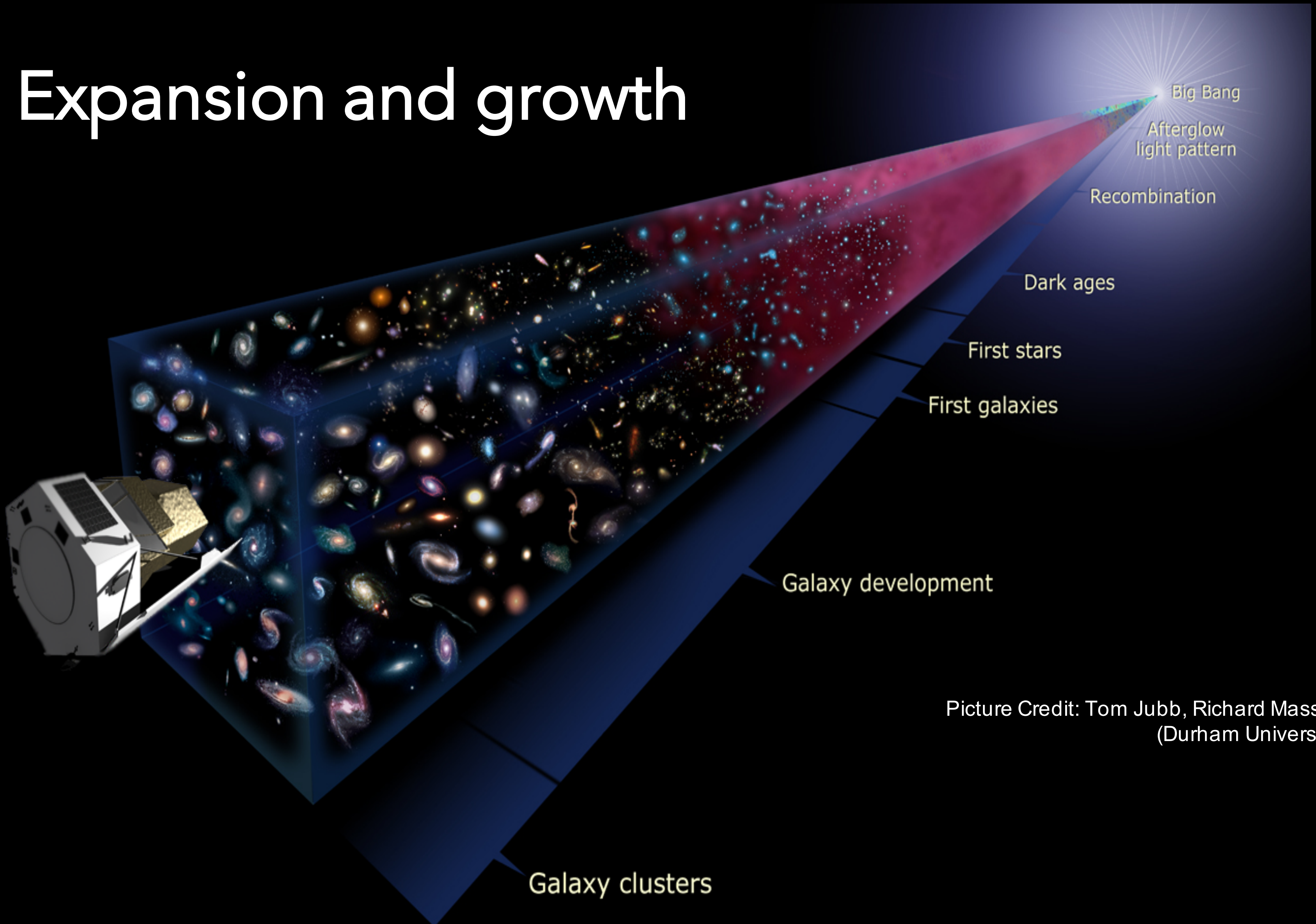
Same parameters as in the previous CMB plot
Same 3 models, one of them is ΛCDM
P(k)
20000
10000
5000
2000
0.01
0.02
0.05
0.10
0.20
k

$$\Lambda$$

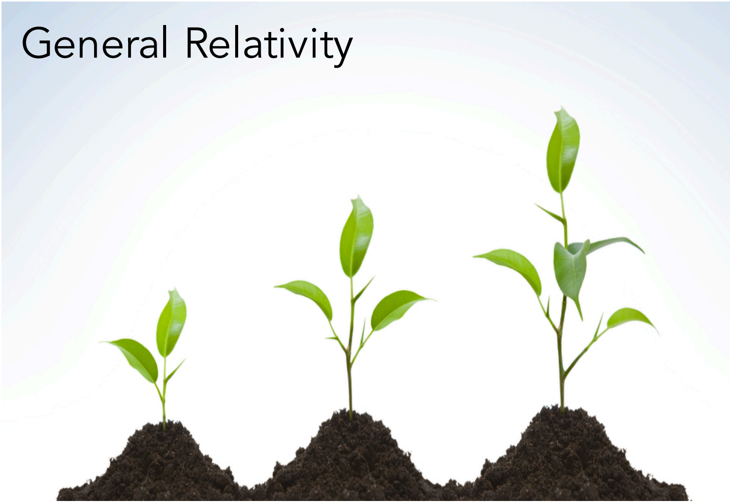
Can we falsify a cosmological constant?

Can we distinguish among the models present in literature?

Expansion and growth



Picture Credit: Tom Jubb, Richard Massey (Durham University)

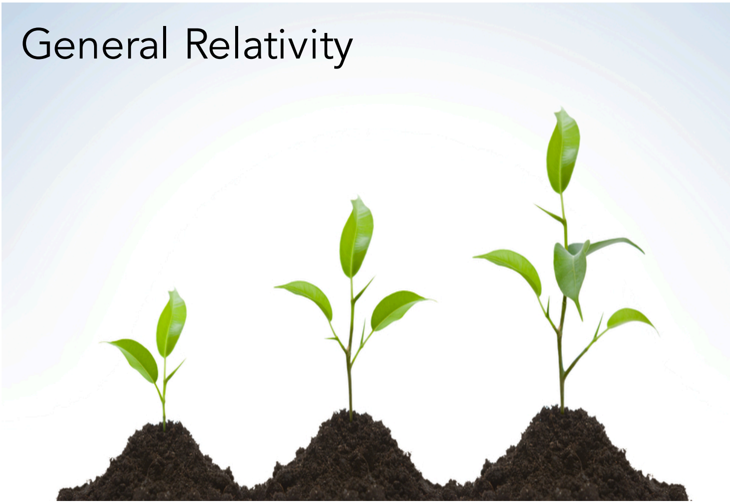


Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

$$f \equiv \frac{d\ln\delta}{d\ln a}$$

$$\mathrm{d}s^2 = -(1+2\Psi)\mathrm{d}t^2 + a^2(1+2\Phi)\mathrm{d}x^i\mathrm{d}x^i$$



Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

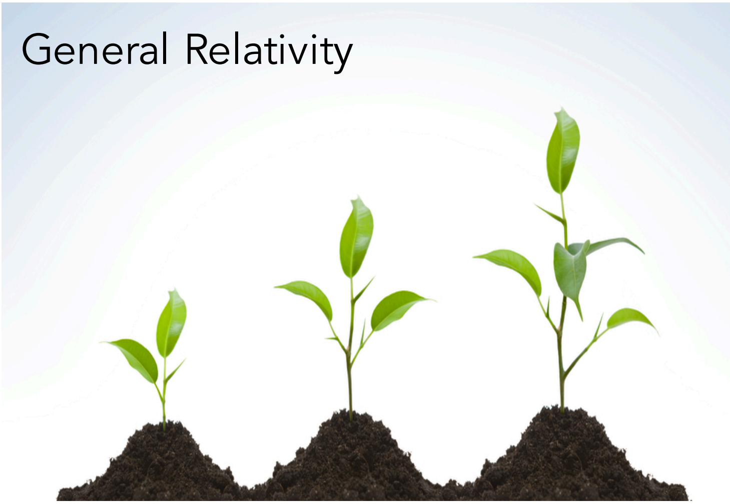
$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(1 + 2\Phi)dx^i dx^i$$

(conservation/Euler equation)

$$f\delta = -\frac{\nabla \cdot v}{aH}$$

(Poisson equation)

$$-k^2\Psi \equiv 4\pi G a^2 \rho\Delta$$



Modified Gravity

Growth ⟷ Density Velocities ⟷ Geometry (gravitational potentials)

(conservation/Euler equation)

$$f\delta = -\frac{\nabla\cdot v}{aH}$$

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^i dx^i$$

(Poisson equation)

$$\eta(a,k) \equiv \Phi/\Psi$$

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,k)\rho\Delta$$

VP for Planck 2015, 2018

Casas, VP et al 2017

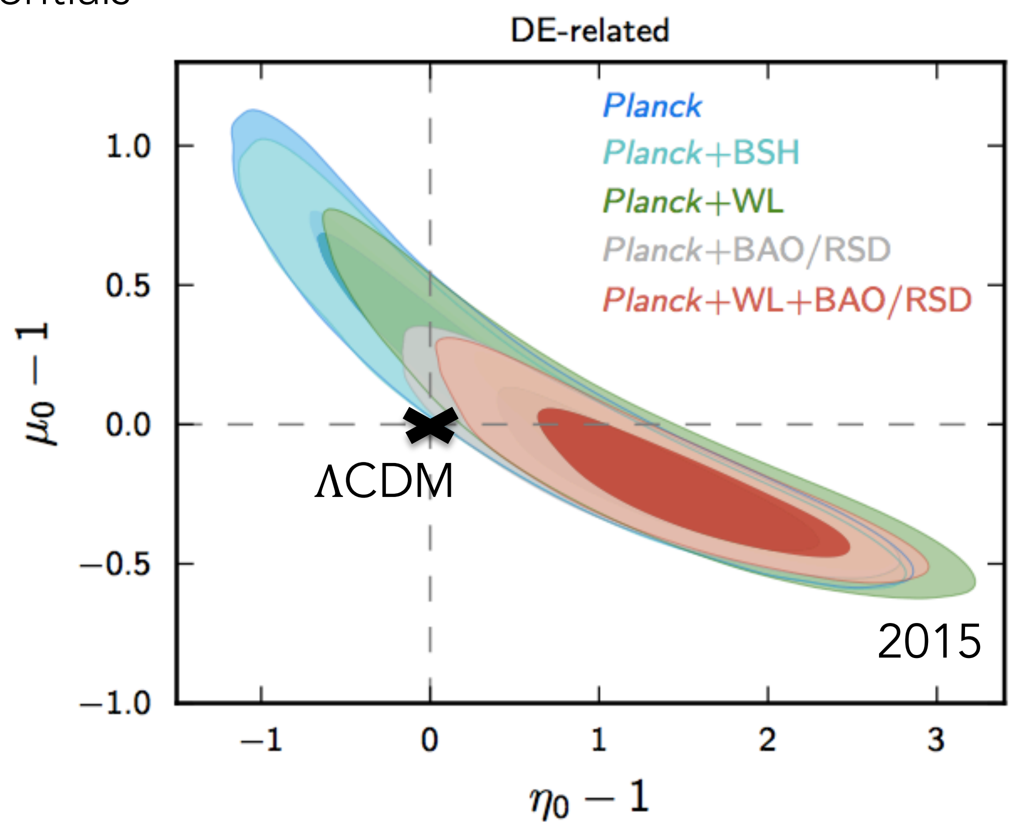
Planck Dark Energy & Modified Gravity paper
astro-ph 1502.01590
V.P. for the Planck collaboration

μ modifies the growth

η is the ratio of the gravitational potentials

Planck alone lies at the 2 σ limit
Tension with ΛCDM at 3σ when combining RSD+WL

	Planck+WL+RSD (present)
μ	~ 17%
η	~ 25%



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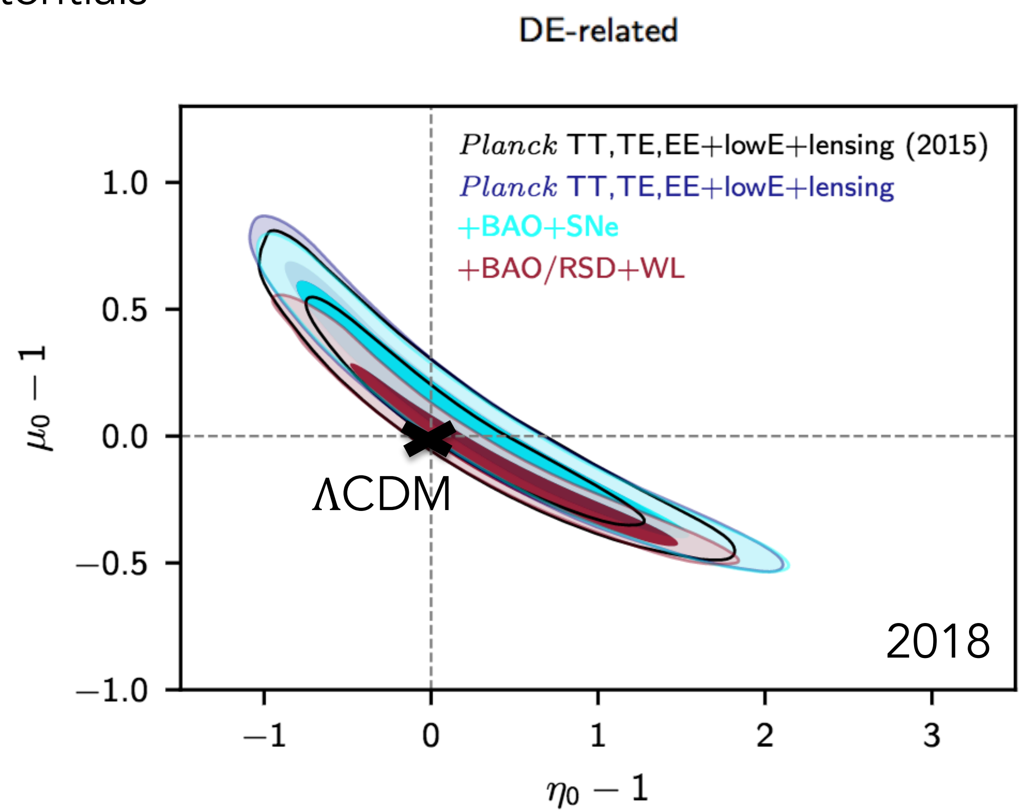
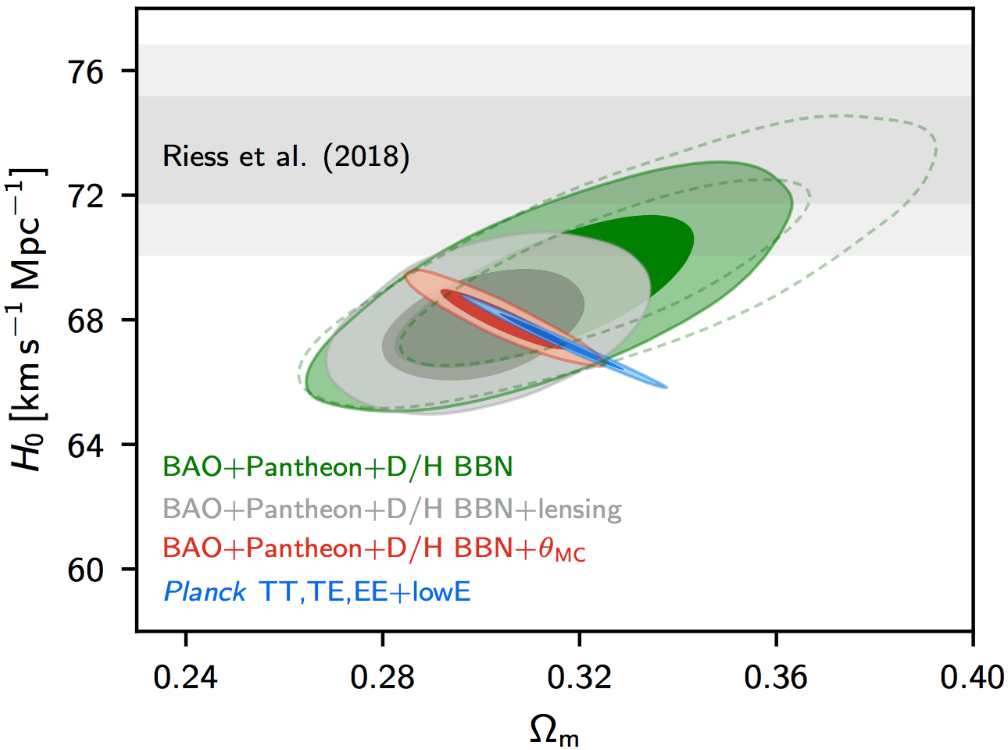


Planck alone lies at the 2 σ limit
Tension with RSD+WL reduced
(but some choice in data)

	Planck+WL+RSD (present)
μ	~ 17%
η	~ 25%

Some tensions remain: H_0 3.6 σ tension

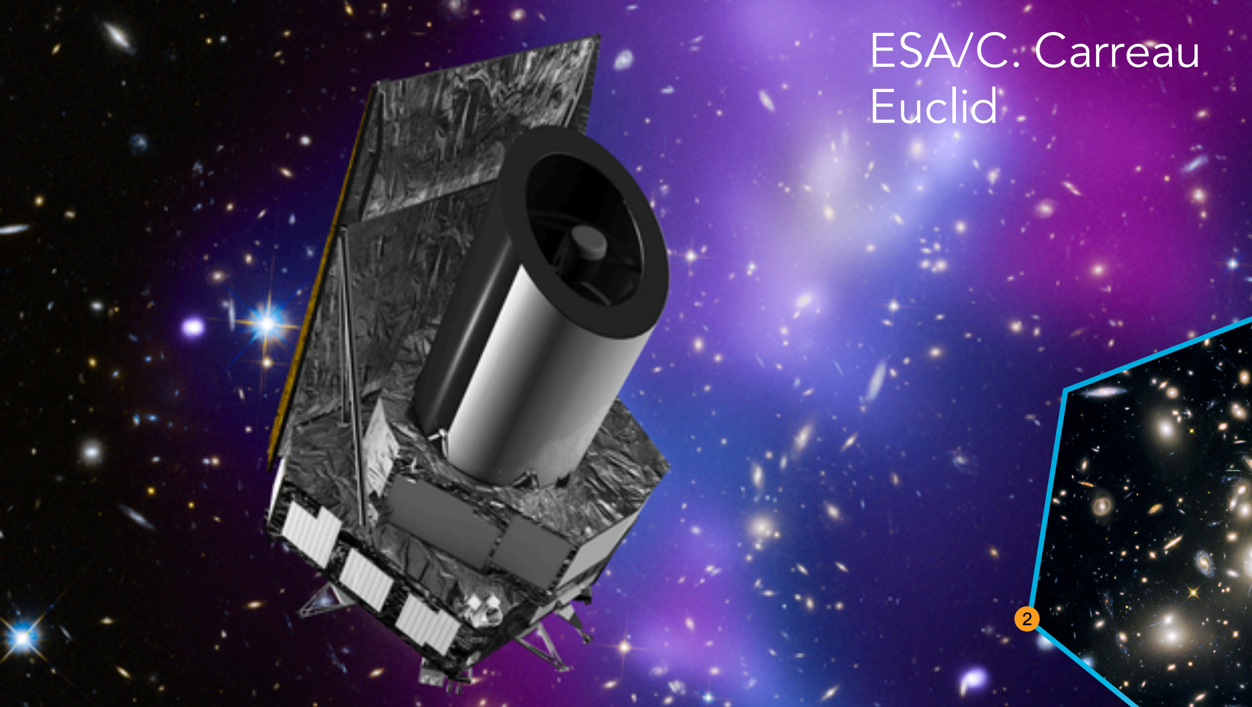


Planck TTTEEE+lowE+lensing 2018

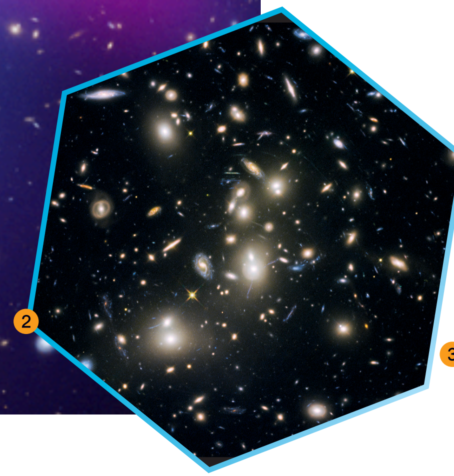
$$H_0 = (67.27 \pm 0.60)\ \mathrm{km\ s^{-1}Mpc^{-1}} \quad \text{LCDM}$$
$$H_0 = (68.35 \pm 0.82)\ \mathrm{km\ s^{-1}Mpc^{-1}}, \quad (w_0\ \text{varying}),$$
$$H_0 = (68.34 \pm 0.83)\ \mathrm{km\ s^{-1}Mpc^{-1}}, \quad (w_0, w_a\ \text{varying}).$$

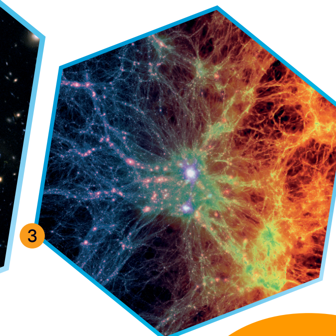
Riess et al 2018

$$H_0 = (73.48 \pm 1.66)\ \mathrm{km\ s^{-1}Mpc^{-1}}$$



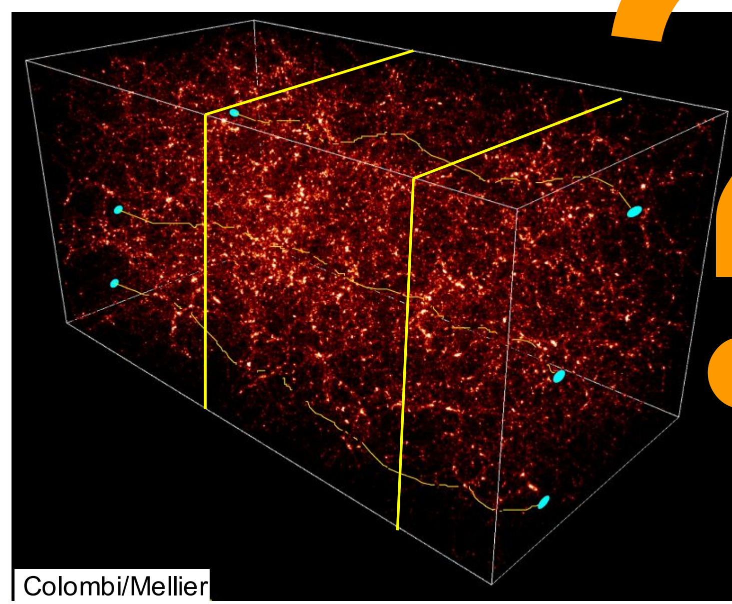
New generation of experiments

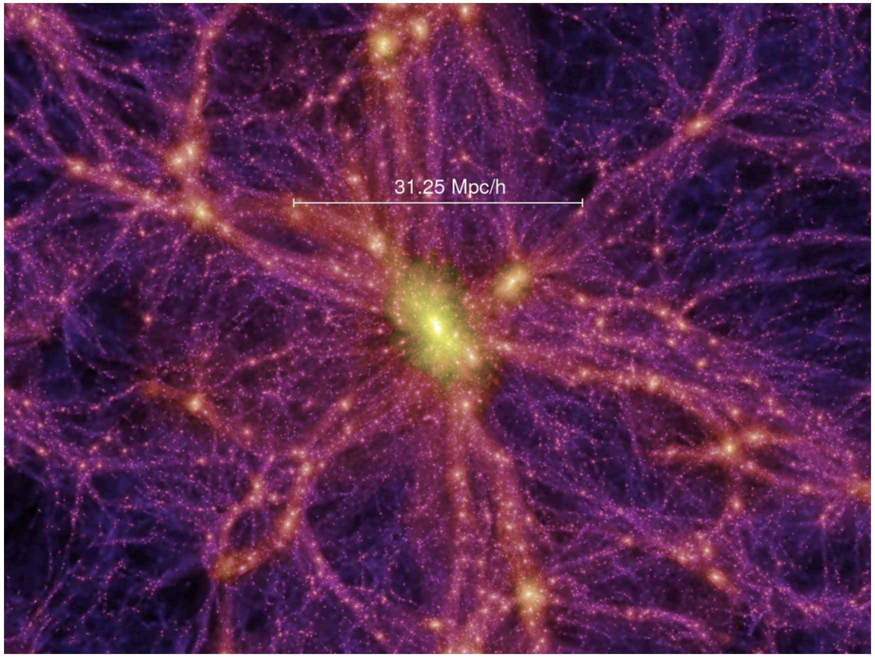




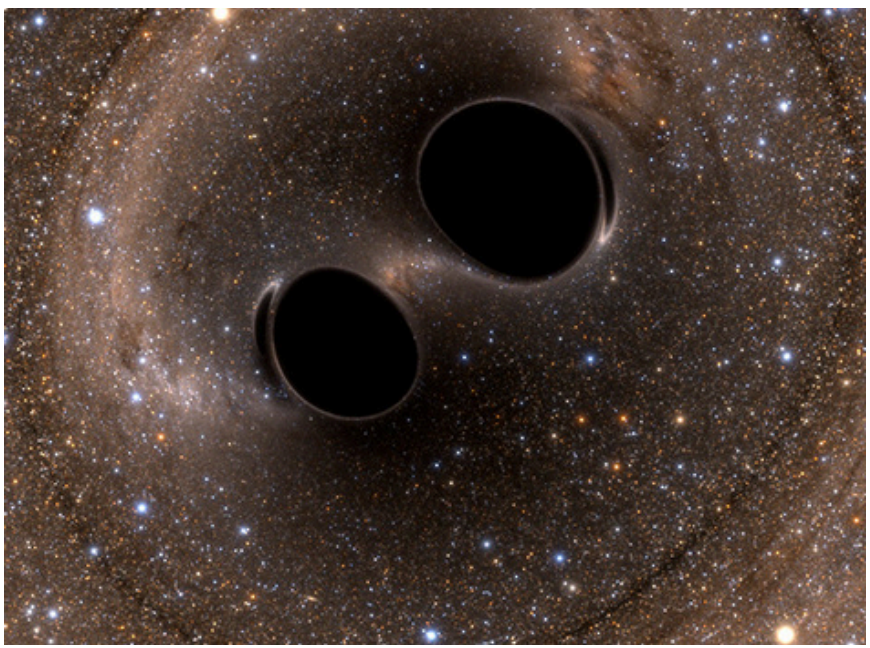
using different probes scanning the sky in slices

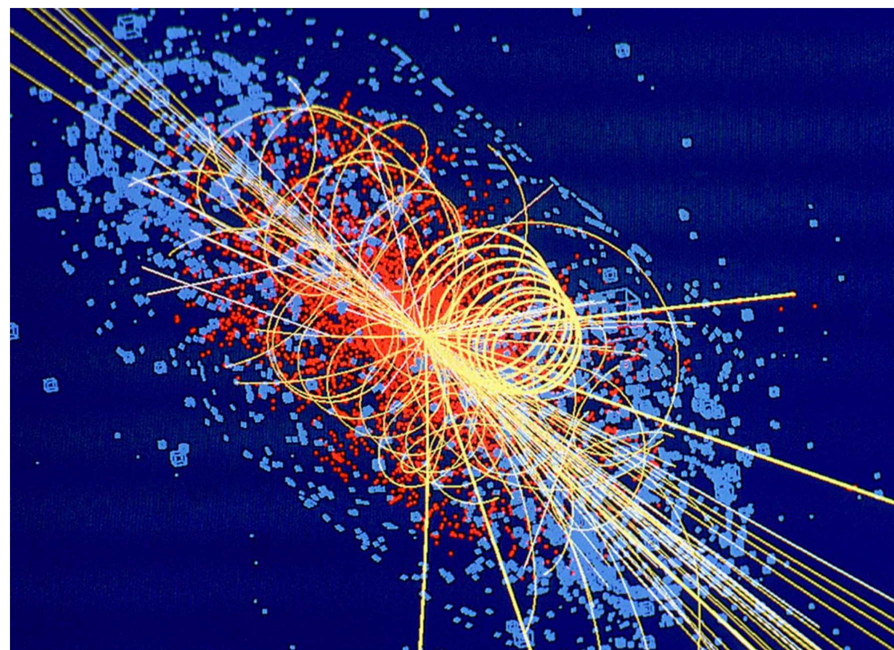
To confirm or disprove the standard picture





We want to test interactions at cosmological scales as in particle physics and value complementarity of probes





Laureijs etal 2011,Refregier 2009,Cimatti etal 2009

Satellite
Mass 2200 kg
Size: 4,5 m x 3m x 3m

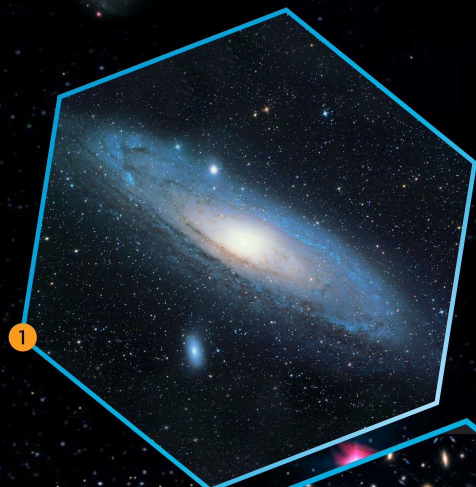
Telescope
Primary mirror diameter 1,20 m

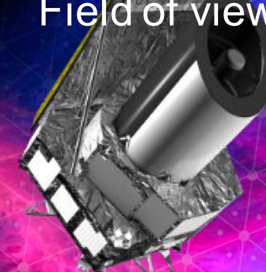
Instruments
VIS the visible photometer
NISP, the infra red spectro photometer

Survey of 15000 deg²
Field of view 0.5 deg²

Euclid satellite

ESA medium class space mission
selected in the program
Cosmic Vision 2015-2025





france for euclid

euclid consortium

The Euclid mission

Launch foreseen in 2022 from Kourou space base, by a Soyouz rocket

T0: start nominal mission

Year 1 — Q1 : ~ 50 deg^2

Year 2 — DR1 : ~ 2500 deg^2

Year 3 — Q2 : + ~ 50 deg^2

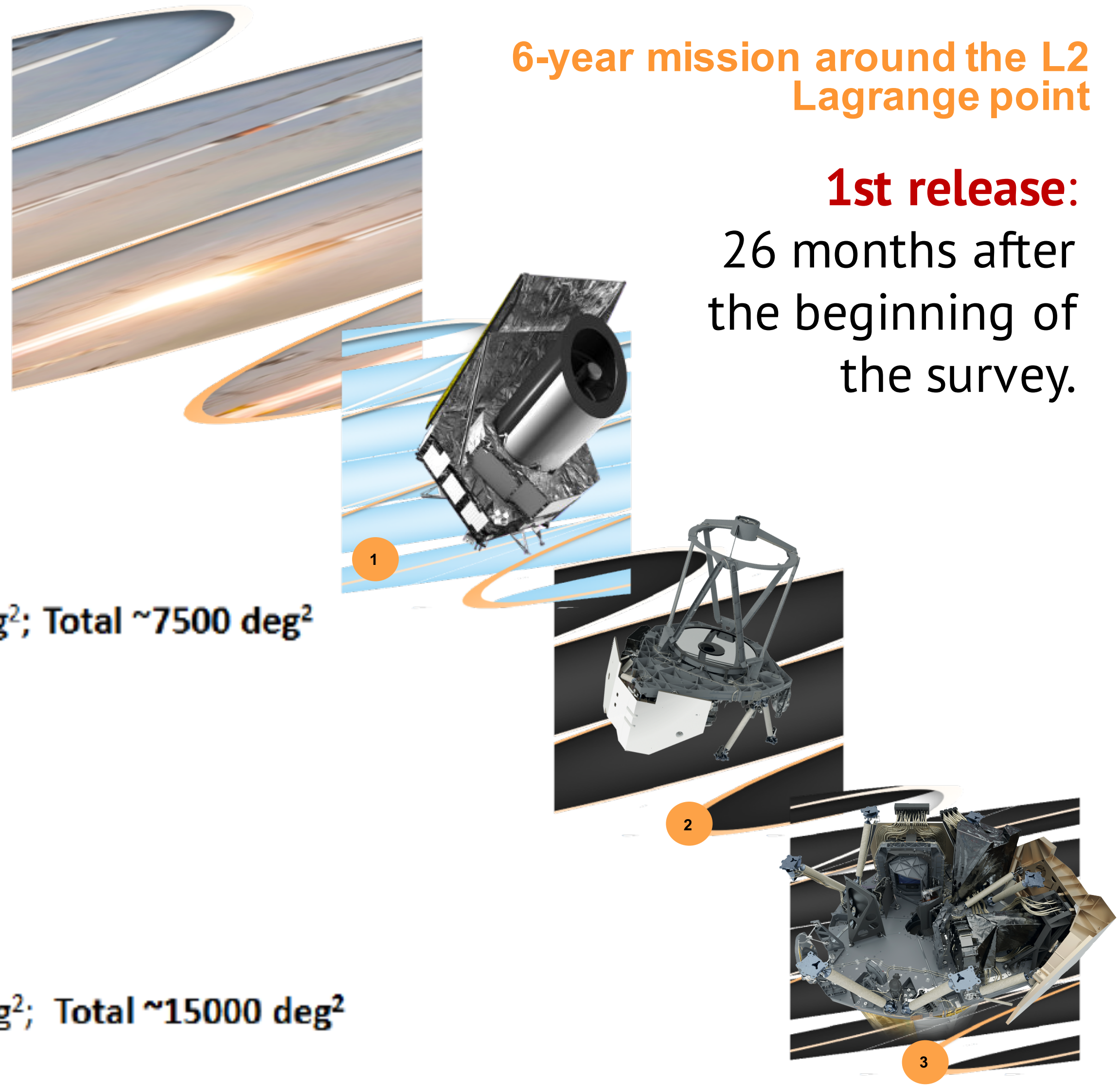
Year 4 — DR2 : + ~ 5000 deg^2; Total ~7500 deg^2

Year 5 — Q3 : + ~ 50 deg^2

Year 6 — Q4 : + ~ 50 deg^2

DR3 : + ~ 7500 deg^2; Total ~15000 deg^2

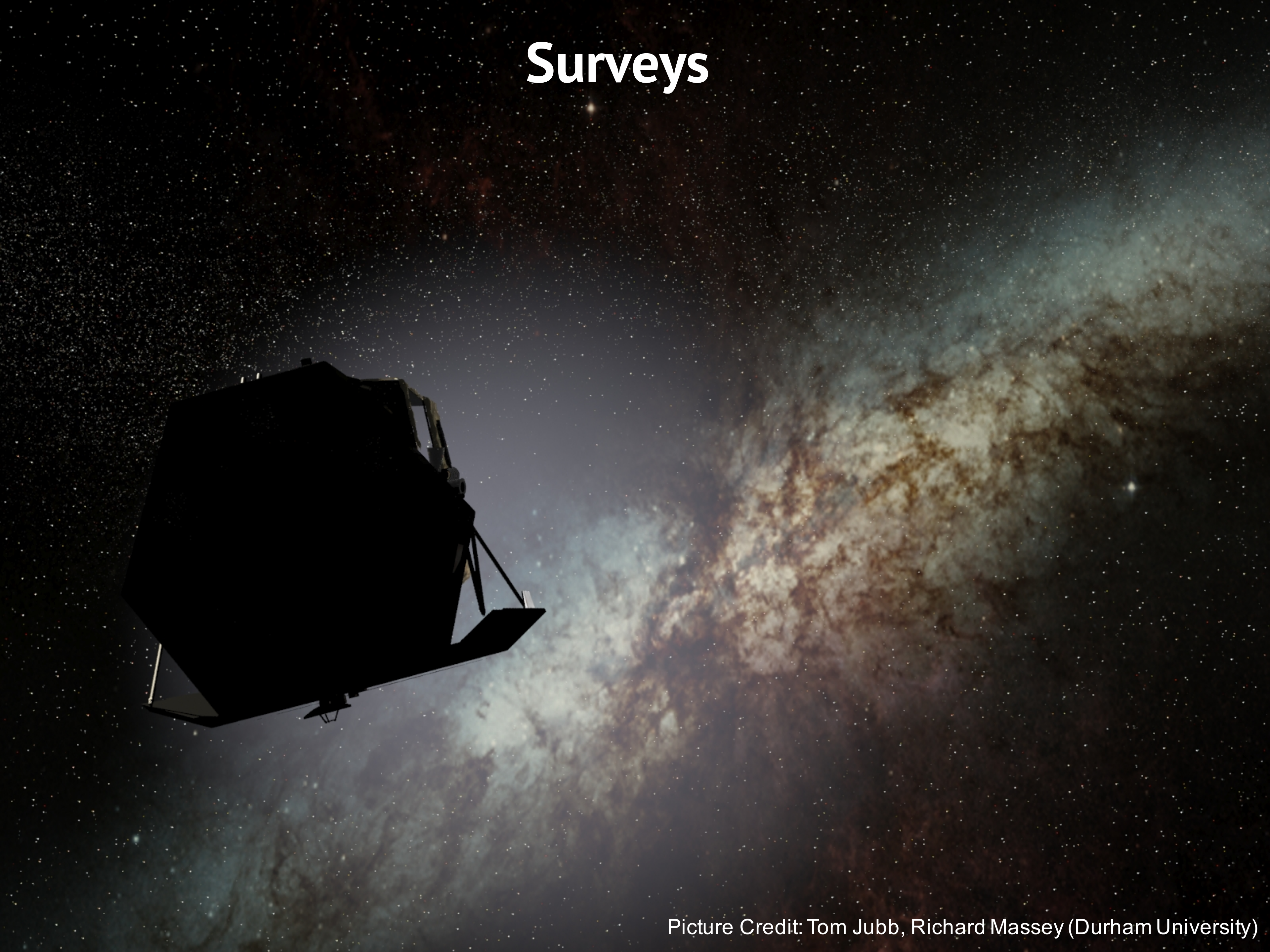
Mission Timeline



6-year mission around the L2 Lagrange point

1st release: 26 months after the beginning of the survey.

Surveys



Picture Credit: Tom Jubb, Richard Massey (Durham University)

Surveys

1.2 m telescope

WIDE SURVEY	DEEP SURVEY
will cover about 1/3 of the entire sky outside the Galactic plane (15000 deg^2); it will achieve galaxy shear measurements for 30-40 galaxies/$arcmin^2$ and spectroscopic measurements for 3500-5000 galaxies/deg^2 with redshift accuracy of $z < 0.001(1+z)$	will be 2 magnitudes deeper than the Wide Survey, cover nearly 40 deg^2 in patches greater than 10 deg^2

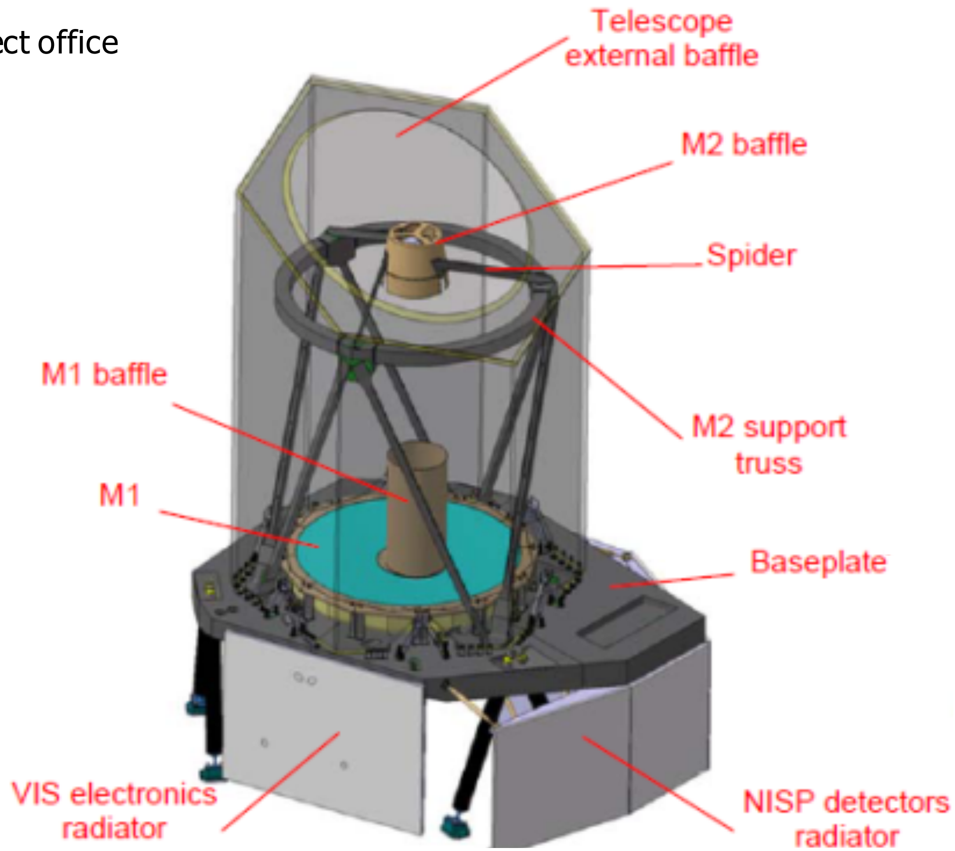
IMAGING	SPECTROSCOPY
Measure shapes and distances (photometric redshift) of 1.5 billions galaxies	Measures the tridimentional distribution of galaxies as a function of z, measuring 30 millions of redshifts between z ~ 0.7 and 2.

Picture Credit: Tom Jubb, Richard Massey (Durham University)

Telescope and instruments

The telescope feeds two instruments via a beam splitter.
Reflected light to VIS, transmitted light to NISP

Courtesy:
Astrium and ESA Project office



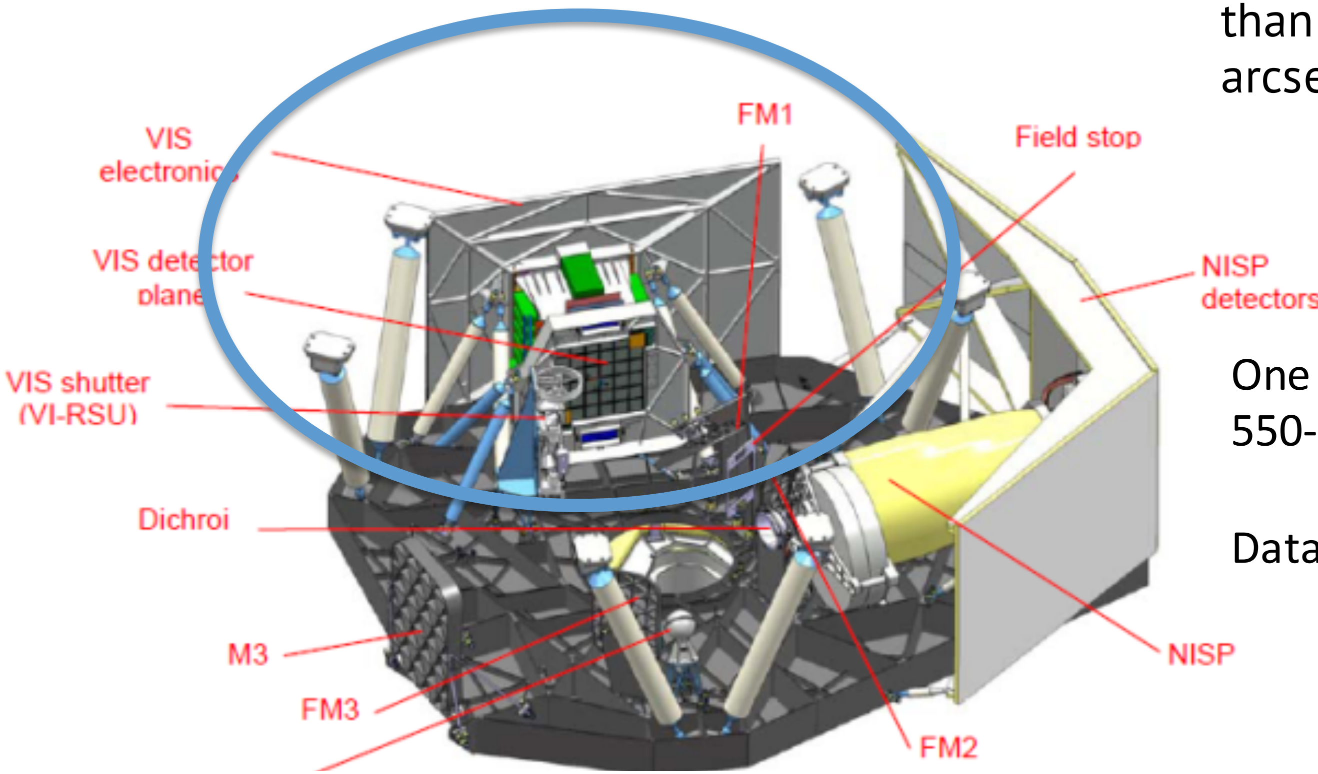
Same field of views, they will operate simultaneously in step-and-stare mode

VIS instrument

The VIS (visible band imager) instrument **measures shapes with high resolution**

Courtesy:
Astrium and ESA Project office

The VIS is equipped with 36 (4kx4k) CCDs, covering more than 0.5 deg^2 field with 0.1 arcsec pixels.



One wide visible band 550-900 nm

Data volume: 520Gbit/day

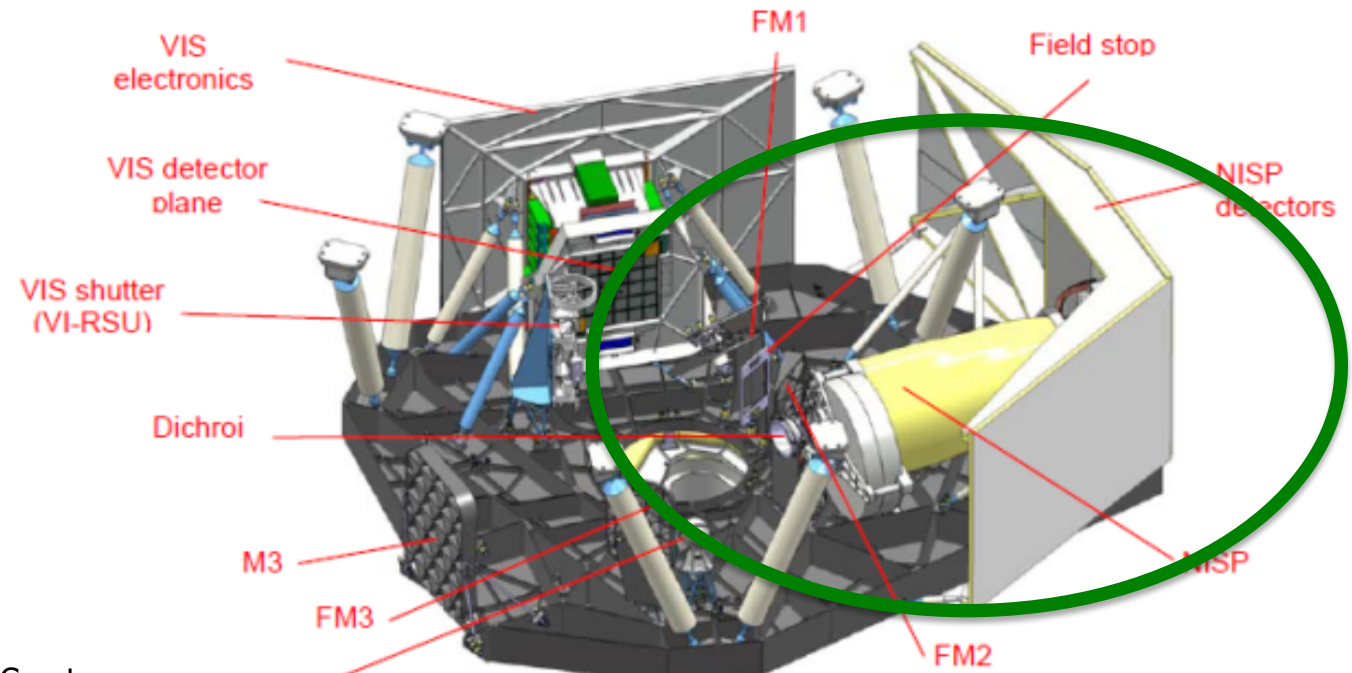
Courtesy:
Astrium and ESA Project office

NISP instrument

The NISP instrument provides both **imaging and spectroscopy**

It has 16 infrared detectors, covering more than 0.5 deg^2 with 0.3 arcsec pixels.
Data volume: 180 Gbit/day
NISP performs photometry or spectroscopy in sequence selecting a filter or grism wheel respectively

The NISP **imaging photometer** mode contains 3 filters (Y,J,H) in the 1-2 micron wavelength range.



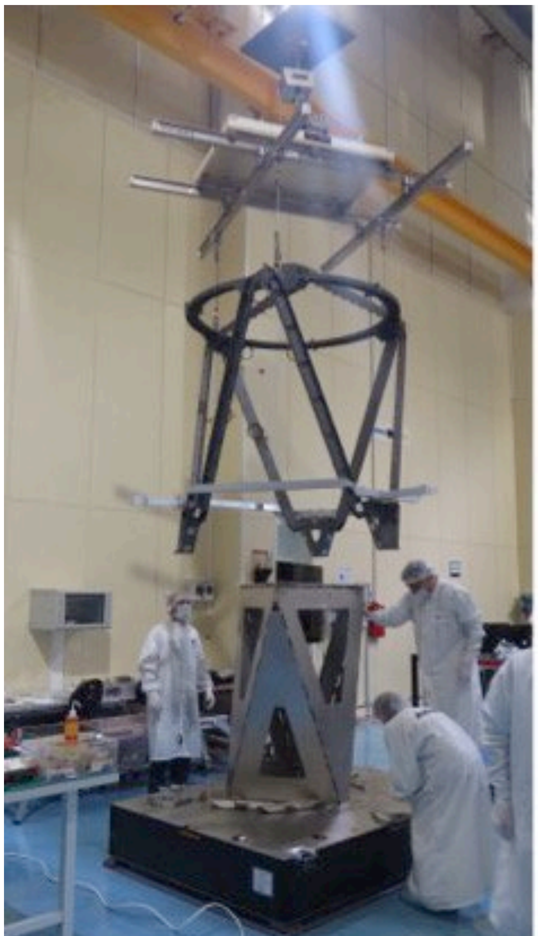
The NISP **slitless spectrometer** mode contains 4 grisms to provide spectra in two bands with orthogonal directions.

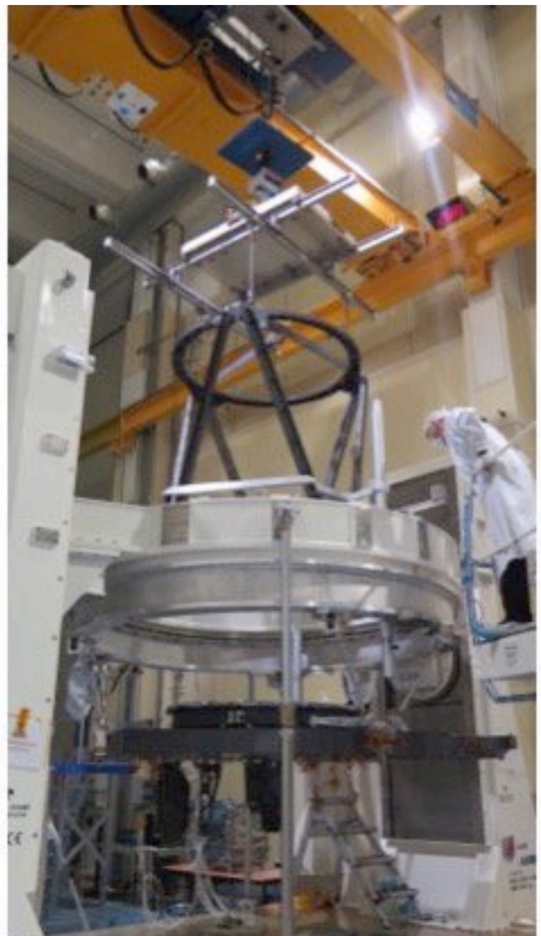
Courtesy:
Astrium and ESA Project office

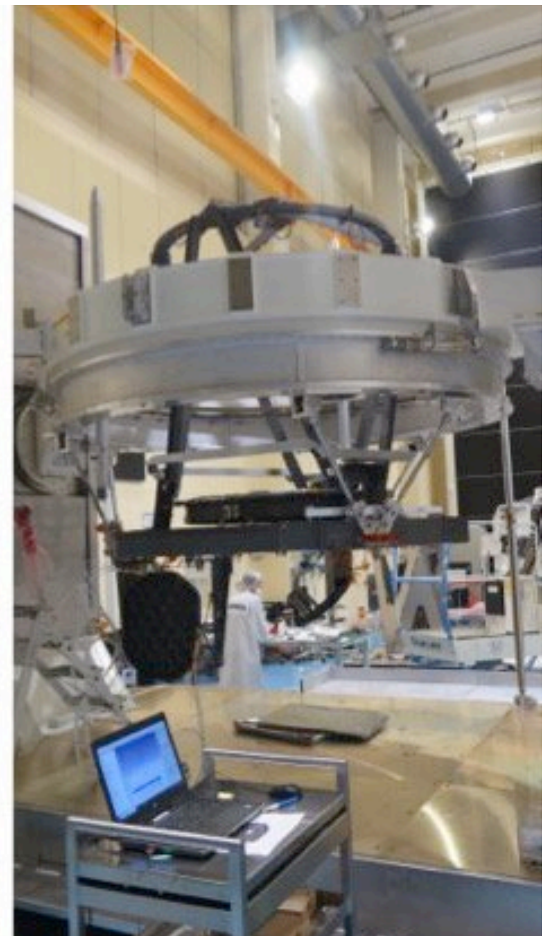
Euclid is currently being assembled

(pict. from Dec 2018)

@Euclid_FR

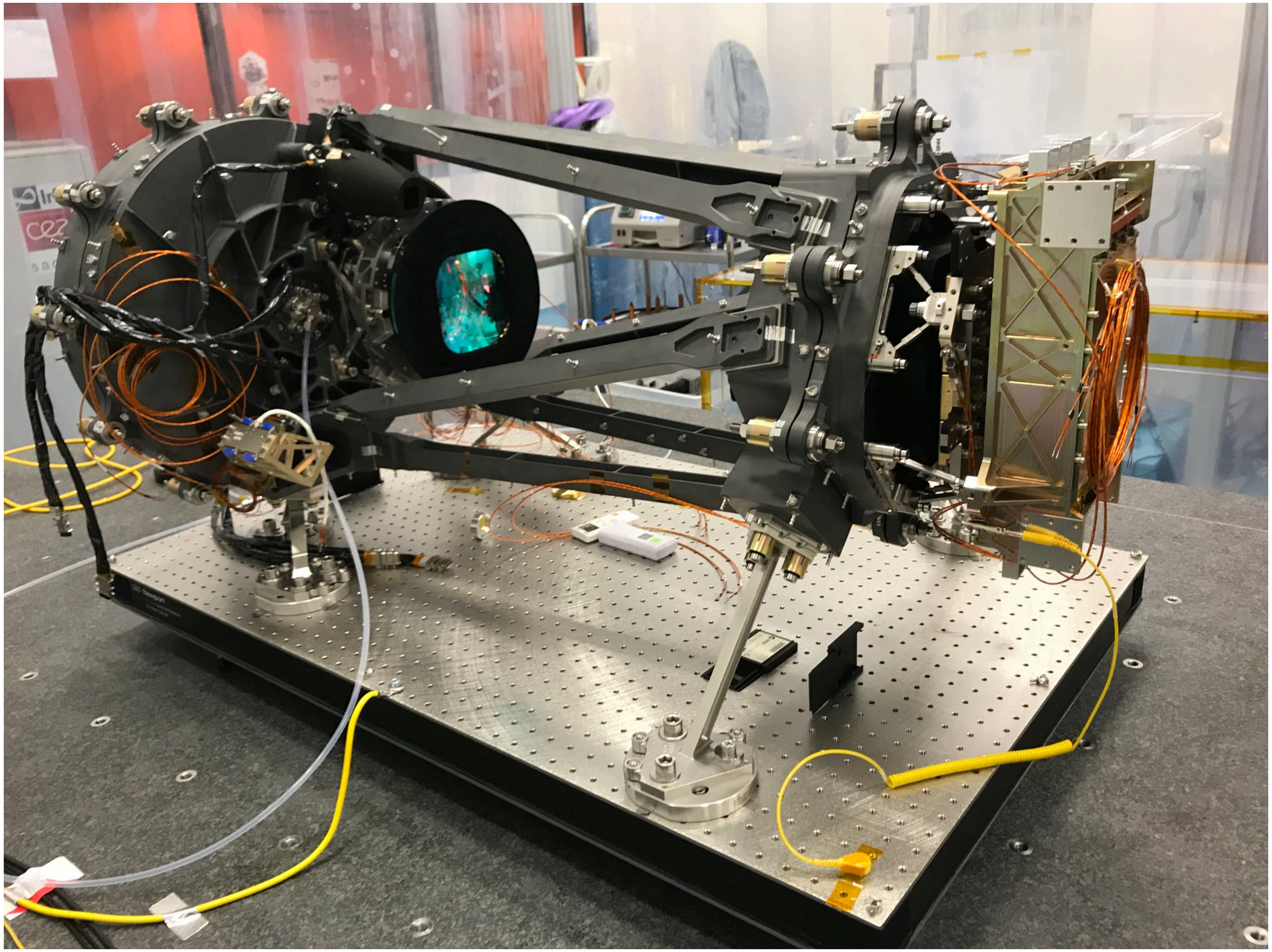






@Euclid_NISP

Euclid NISP



Focal plane

Based on H2RG Teledyne detectors
2048 x 2048 pixels
Pixel size: 18 µm
Spectral bandwidth: 0,9 µm – 2 µm
The focal plane contains 16 H2RG which corresponds roughly to 64 millions pixels

Characteristics

160 kg
1 m x 0,5 m x 0,5 m
Field of view : 0,78 x 0,73 deg^2
Focal plane cooled to 90K

Infra red camera, the biggest ever launched in space

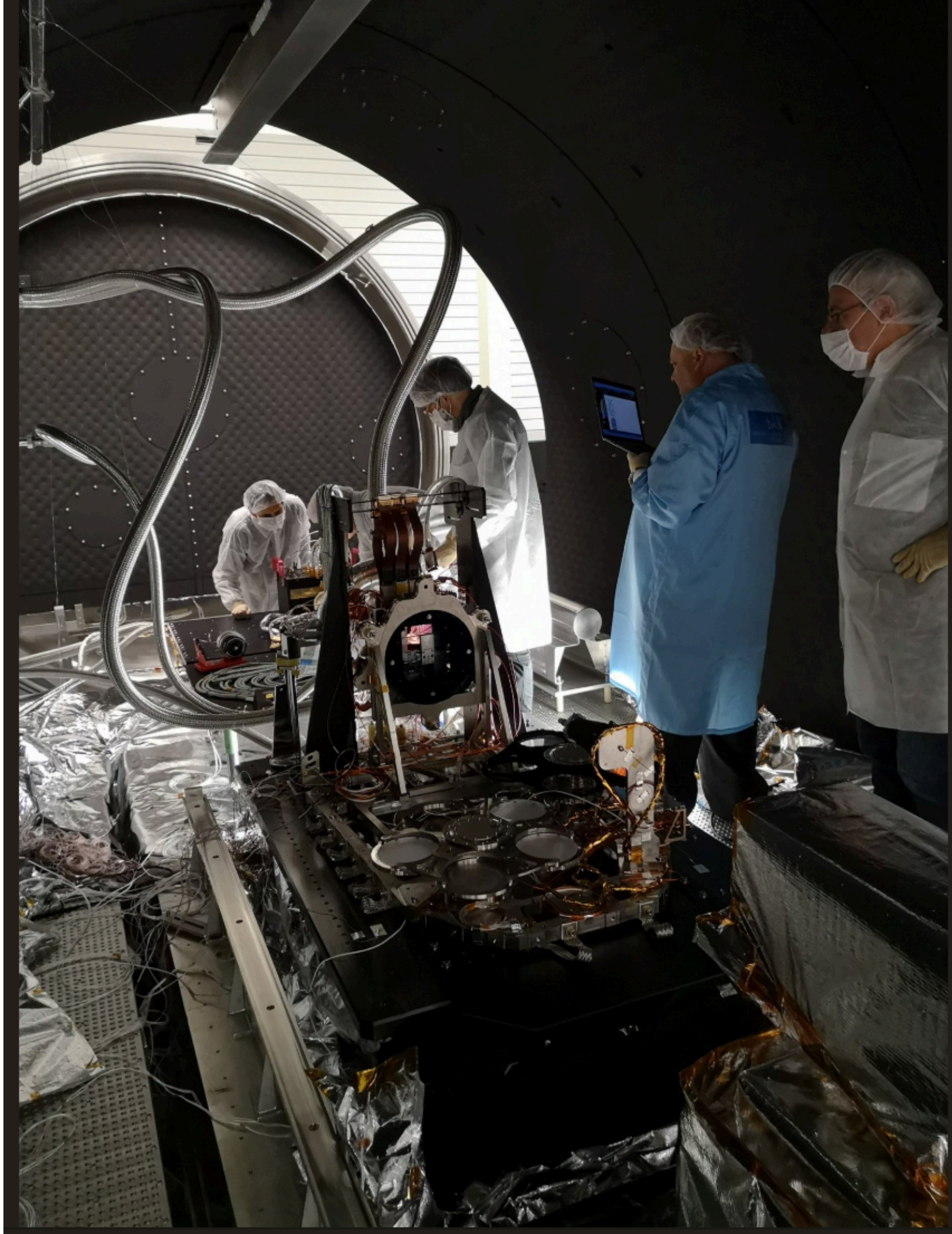
the grism wheel assembly (GWA) is integrated with the NISP structure (27 Sept 2018)

Euclid NISP

Building of the NISP instrument
is done under the leadership of the Laboratoire d'Astrophysique de Marseille (LAM, France).

@Euclid_NISP
@LAM_Marseille
@INFNPadova

Integrating the Electrical Model

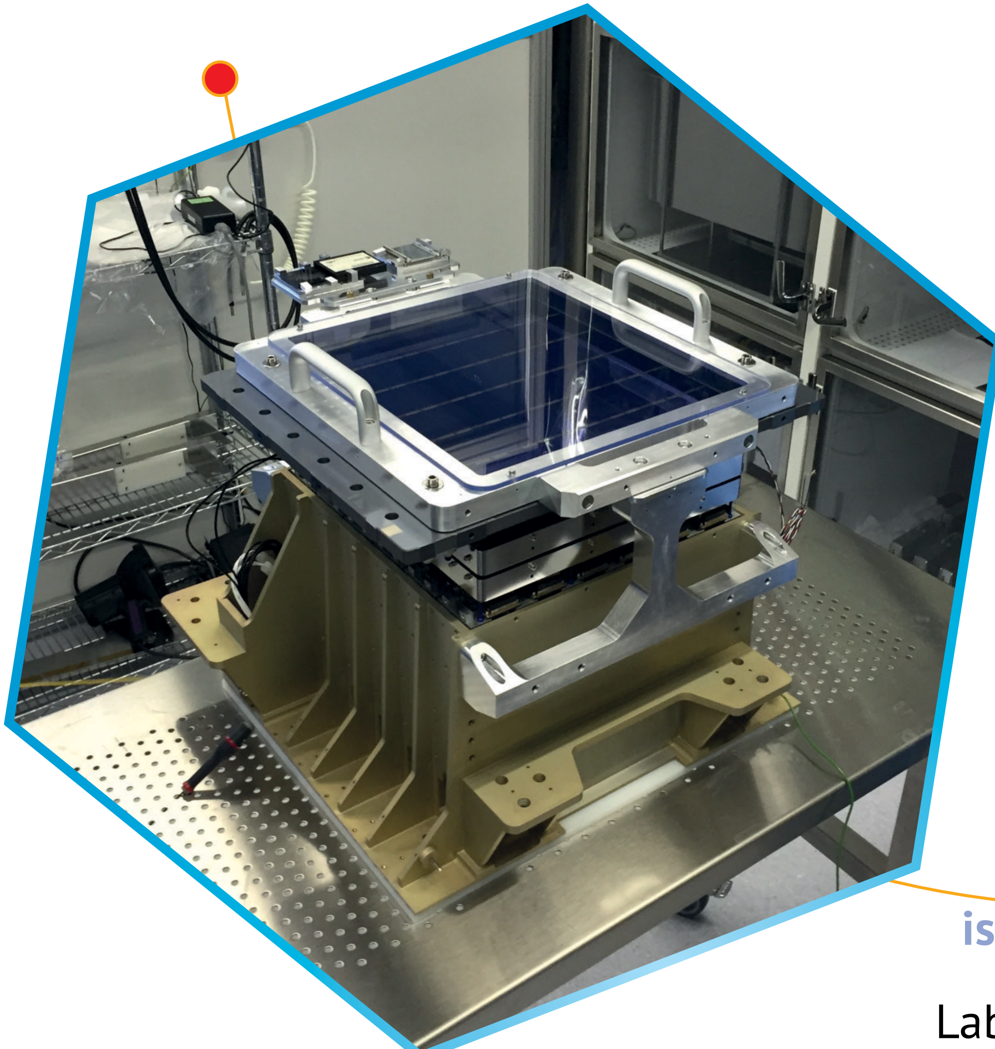


@Euclid_NISP

Euclid NISP (7 Feb 19)

NISP in its black multi-layer insolation

VIS instrument



Base on CCD detectors from e2V
4056 x 4056 pixels
Pixel size: 12 µm
The focal plane contains 36 CCD
which corresponds roughly to 600 millions pixels
Focal plane cooled to 140K

Building of the VIS instrument is done under the leadership of the Mullard Space Science Laboratory (MSSL, United Kingdom).

Ground-based
Observatories

The third instrument

Two types of measurements are required:

- A "large field" photometric survey based on 800 observation nights.
(telescopes : CFHT, JST, Pan-Starrs, LSST, Blanco)

- A spectrometric survey from which data are used to calibrate the photometric redshifts:
Telescopes Keck (45 nights, North hemisphere) and VLT (40 nights, South hemisphere)

Present and upcoming wide–field imagers relevant to Euclid

Etendue

Facility	Year	Aper.	FOV	IQ	CCD class	Type	Hemisphere
LSST	2021	6.6m	9.6 sq.deg.	0.8"	Deep depletion	Surveyor	South
Subaru	2013	8.2m	1.8 sq.deg.	0.6"	Fully depleted	Observatory	North
Blanco	2013	4.0m	3.0 sq.deg.	0.9"	Fully depleted	Observatory	South
JST	2018	2.5m	4.8 sq.deg.	0.7"	Deep depletion	Surveyor	North
CFHT	2003	3.6m	1.0 sq.deg.	0.6"	EPI	Observatory	North
PS1	2008	1.5m	7.0 sq.deg.	1.0"	Fully depleted	Surveyor	North

Euclid Consortium organization

18 countries
285 institutes
1913 members
75 members “at large“
286 Alumni
(October 2018)

esa

EST
Euclid Science Team
10 members

France leads the consortium (33% of members) with Italy (25%)
The other big contributors are Germany & United Kingdom (~10%), NASA, Japan (Subaru), Canada (CFHT)

Euclid Consortium Board (ECB)
22 members

ECL
Yannick Mellier
(IAP)

ECL Support

- *Support Office*
- *Coordination support*
- *Mission System*
- *Mission survey WG*
- *Calibration WG*
- *Science Performance Verification*
- *Tracking Team*
- *Communication*
- *Complementary data group*
- *Coordination Group*
- *Editorial Board*

SWG (Science Working Groups)

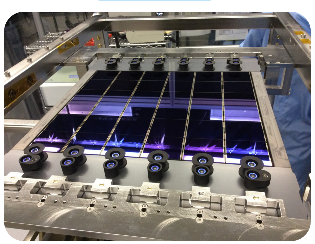
Cosmology

- *Weak Lensing*
- *Galaxy Clustering*
- *Clusters*
- *CMB Cross Correlation*
- *Strong Lensing*
- *Cosmology theory*
- *Cosmological simulations*

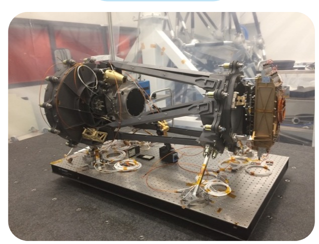
Legacy

- *Primeval Universe*
- *Galaxy & AGN evolution*
- *Local Universe*
- *Planets*
- *Supernovae & transients*
- *Solar System Objects*
- *Milky Way & resolved stellar population*

VIS



NISP



SGS

OBS

Consortium Meeting in May 2018, Bonn.

Euclid primary probes

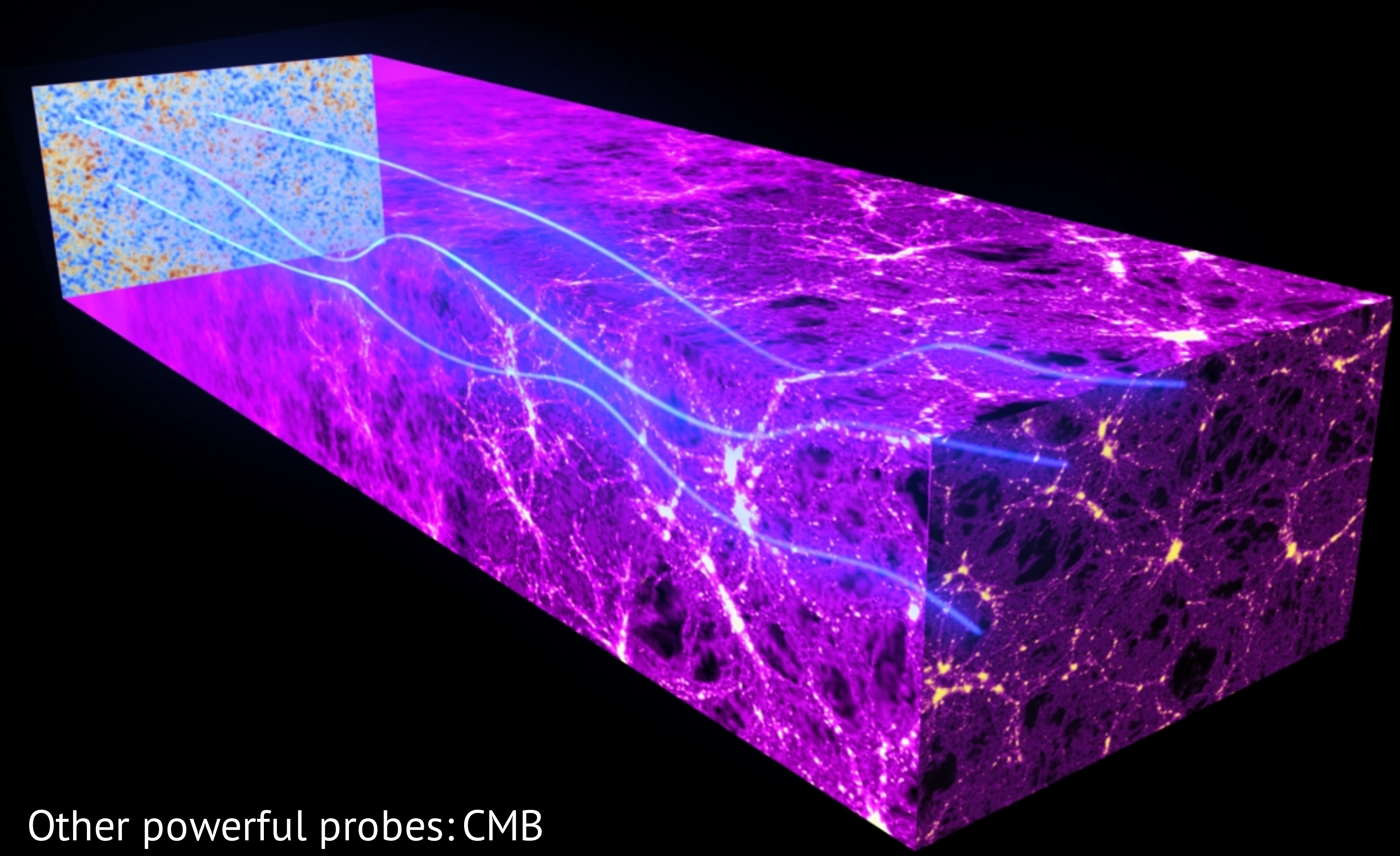
Galaxy clustering

The power spectrum shape in several z-bins.

BAO in the radial and transverse directions measure $H(z)$ and $D_A(z)$ respectively (and therefore sensitive to modifications in the growth (sensitive to μ)

Weak Lensing

Related to both gravitational potentials, which may not be equal beyond LCDM (sensitive to η).



Other powerful probes: CMB
cross correlation with LSS,
abundance of clusters,
strong lensing

Joined in 2007

My contribution in the Euclid Consortium at present (2019):

Inter Science Taskforces

Respond to the need of addressing joint goals that require an interface among different SWGs.

co-coordinator (2017-2019) for IST:Forecast

to validate forecasts for GC, WL and XC

co-coordinator (2019 -) IST:Likelihood

to implement the likelihood for GC, WL and XC

Theory WG

Cosmology Review with Euclid
https://arxiv.org/abs/1606.00180

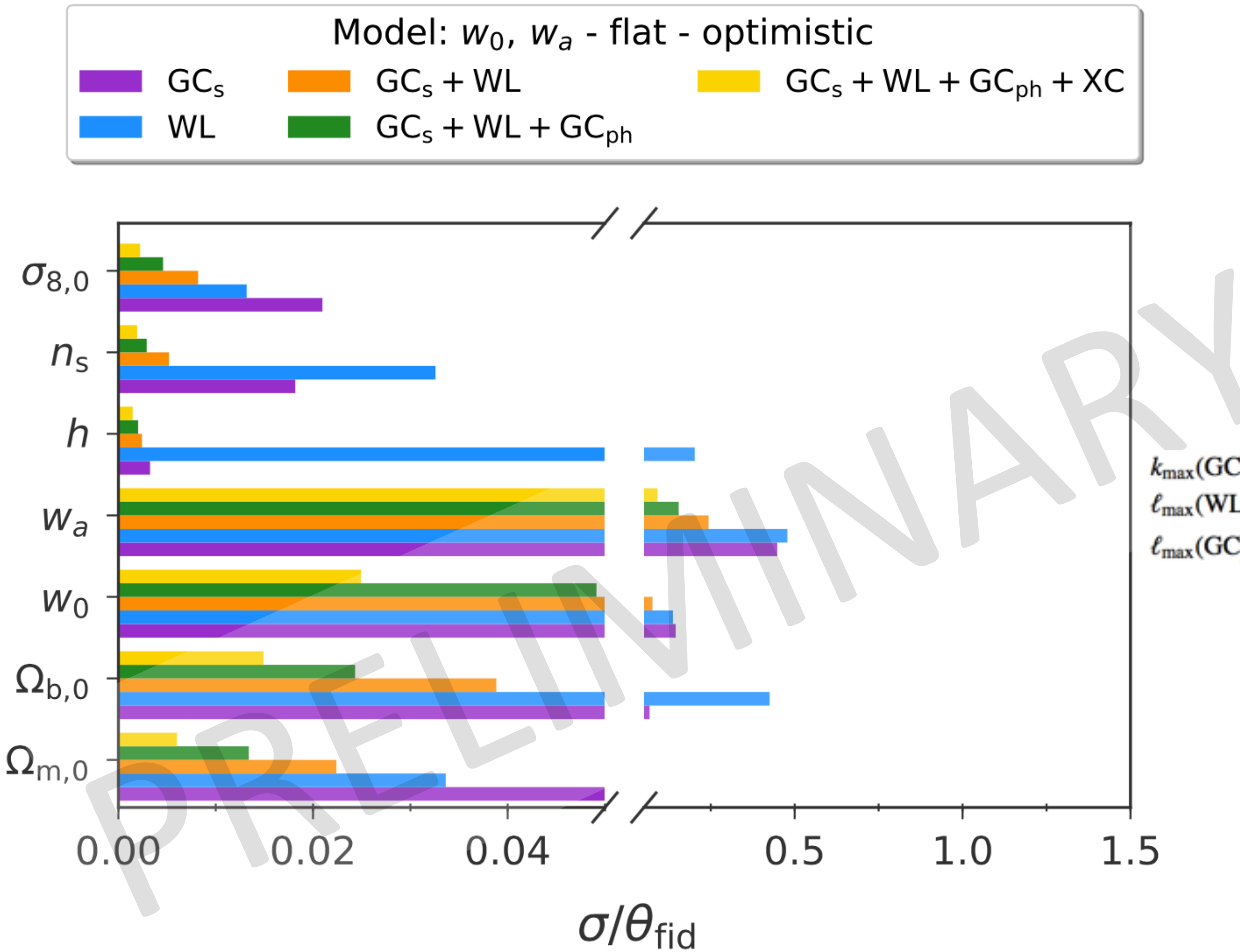
(Editor in chief)

Communication

CEA representative for
Euclid France COMM
(2017 -)

Euclid Inter-Science Taskforce: Forecasts

V.Pettorino with T.Kitching & A.Sanchez and main contributors: GC: D.Sapone, C.Carbone, S.Casas, D.Markovic, V.Yankelevich, A.Pourtsidou, ...
WL: V.F.Cardone, S.Camera, M.Kilbinger, ... ; XC: M.Martinelli, I.Tutusaus, S.Ilic, A.Blanchard, ...

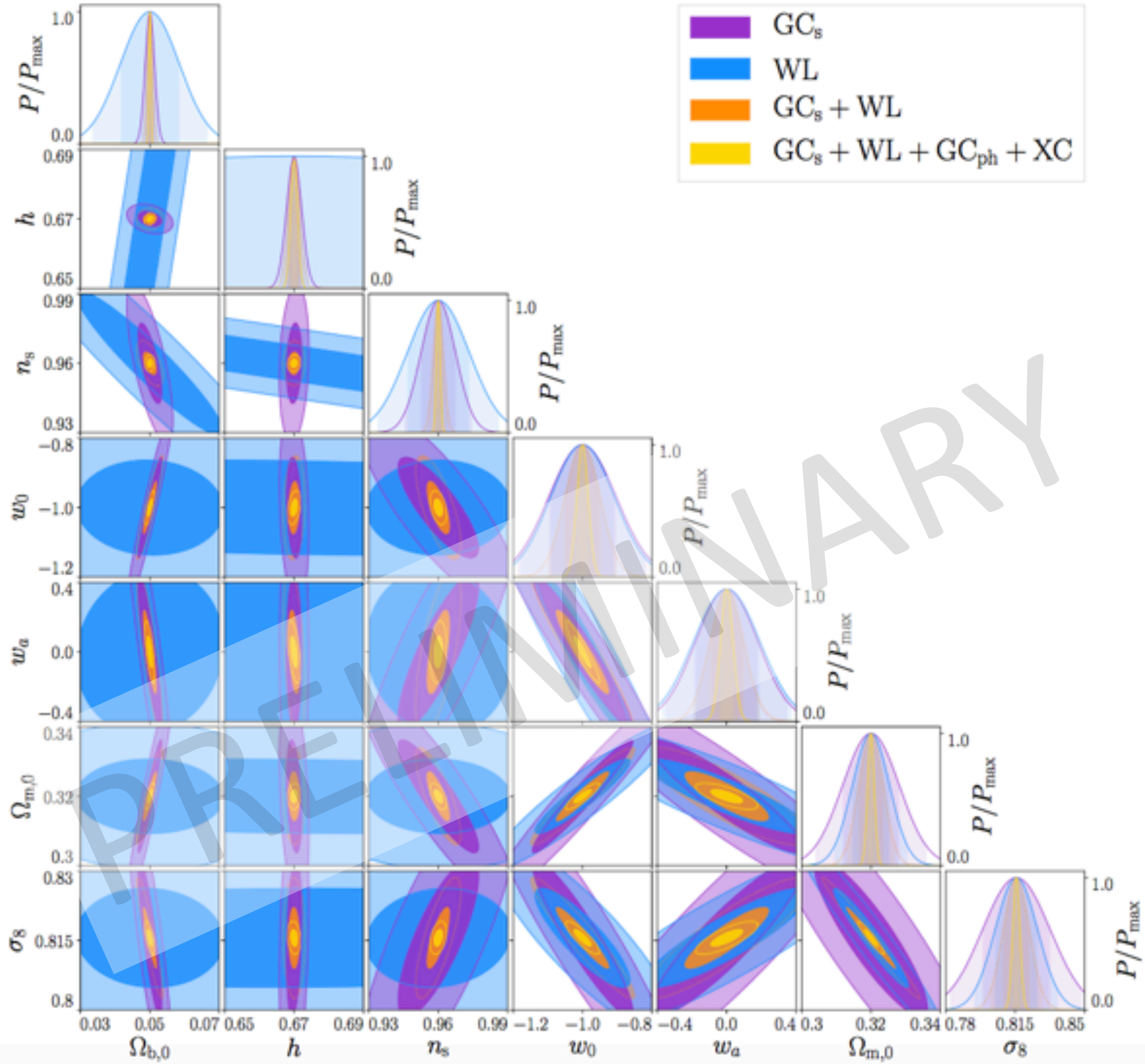


$k_{\max}(\mathrm{GC_s}) = 0.3\ h\ \mathrm{Mpc}^{-1}$, with fixed σ_p and σ_v ,
$\ell_{\max}(\mathrm{WL}) = 5000$,
$\ell_{\max}(\mathrm{GC_{ph}}) = \ell_{\max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 3000$.

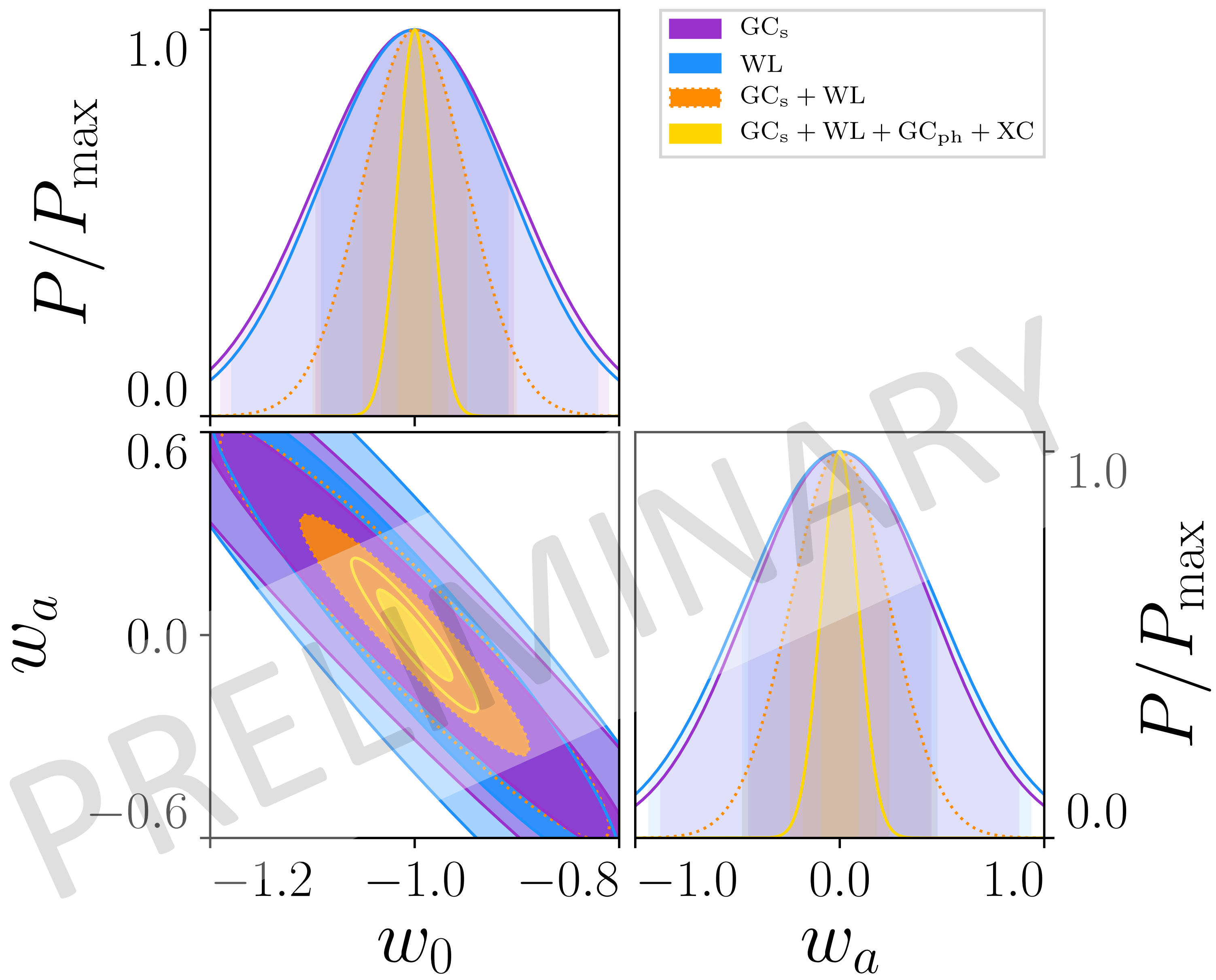
Euclid Inter-Science Taskforce: Forecasts

V.Pettorino with T.Kitching & A.Sanchez and main contributors: GC: D.Sapone, C.Carbone, S.Casas, D.Markovic, V.Yankelevich, A.Pourtsidou, …
WL: V.F.Cardone, S.Camera, M.Kilbinger, … ; XC: M.Martinelli, I.Tutusaus, S.Ilic, A.Blanchard, …

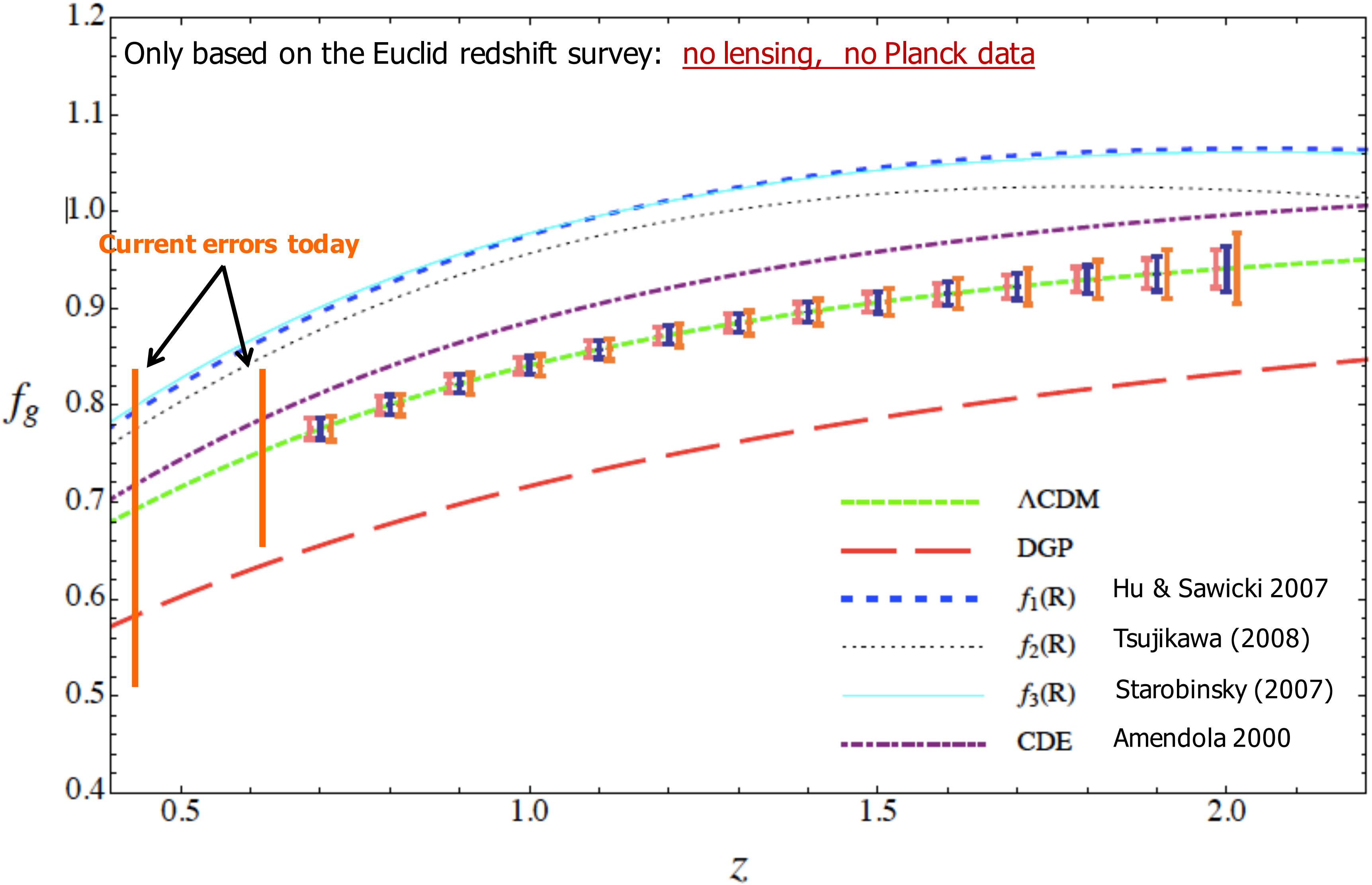
w_0, w_a flat							
	$\Omega_{m,0}$	$\Omega_{b,0}$	w_0	w_a	h	n_s	$\sigma_{8,0}$
Linear setting							
GC_s	0.080	0.10	0.20	0.66	0.0063	0.030	0.024
Pessimistic setting							
GC_s	0.17	0.26	0.39	1.4	0.020	0.063	0.045
WL	0.043	0.48	0.16	0.59	0.21	0.036	0.019
GC_s+WL	0.031	0.062	0.096	0.32	0.0066	0.0089	0.012
GC_s+WL+GC_{ph}	0.025	0.053	0.085	0.27	0.0058	0.0068	0.0096
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	0.011	0.035	0.036	0.15	0.0053	0.0053	0.0049
Optimistic setting							
GC_s	0.051	0.068	0.15	0.45	0.0032	0.018	0.021
WL	0.034	0.43	0.14	0.48	0.20	0.033	0.013
GC_s+WL	0.022	0.039	0.077	0.24	0.0024	0.0052	0.0082
GC_s+WL+GC_{ph}	0.014	0.025	0.050	0.15	0.0020	0.0030	0.0047
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	0.0060	0.015	0.025	0.092	0.0015	0.0019	0.0022



GC_s
WL
$GC_s + WL$
$GC_s + WL + GC_{ph} + XC$
PRELIMINARY
P/P_{max}
$\Omega_{b,0}$
h
n_s
w_0
w_a
$\Omega_{m,0}$
σ_8



$\mathrm{GC_s}$
WL
$\mathrm{GC_s + WL}$
$\mathrm{GC_s + WL + GC_{ph} + XC}$
P/P_{max}
1.0
0.0
w_a
0.6
0.0
−0.6
−1.2
−1.0
−0.8
w_0
−1.0
0.0
1.0
w_a
PRELIMINARY



Cosmology and fundamental physics with the Euclid satellite
Living Reviews in Relativity & https://arxiv.org/abs/1606.00180

Euclid and coupled dark energy

$$\mathcal{L} = -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - U(\phi) - m(\phi)\bar{\psi}\psi + \mathcal{L}_{kin}[\psi]$$

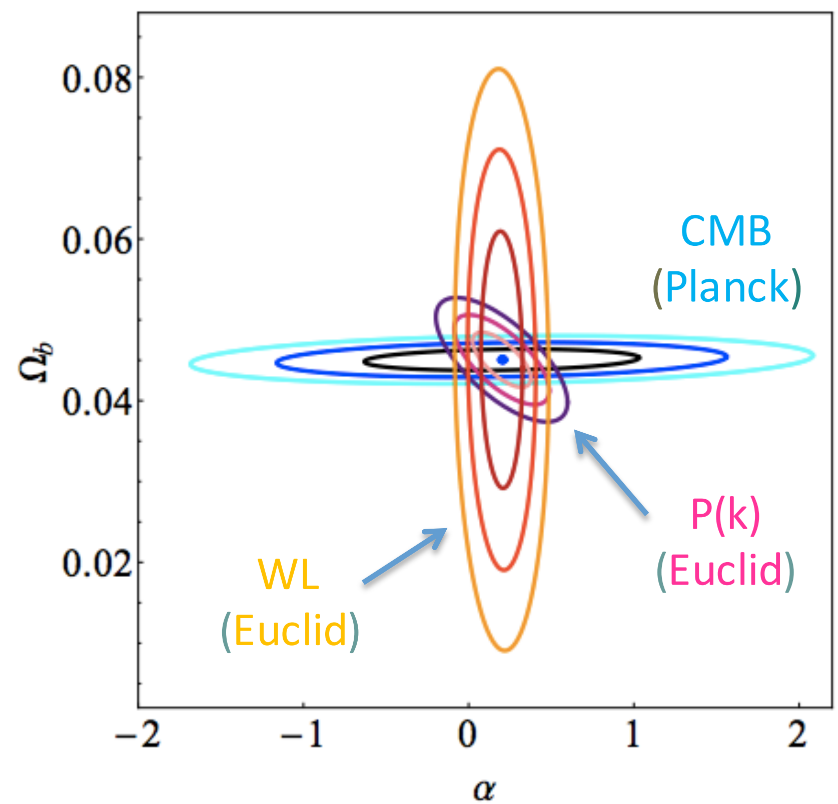
$$G_{eff} = G(1 + \beta^2)$$

Still in agreement with observations

Can alleviate tensions in H_0

Tested with Planck (β^2~2.5 – 2.8 σ *from* 0)
(priors?)

Euclid forecasts
β at 2%
Comparable to interactions among atoms



Amendola, Pettorino, Quercellini, Vollmer 2011,
Pettorino etal 2012, Pettorino 2013

Testing μ and η with Euclid

Euclid can reach a precision of 1-2% after marginalizing over nonlinear prescription

Casas etal 2017

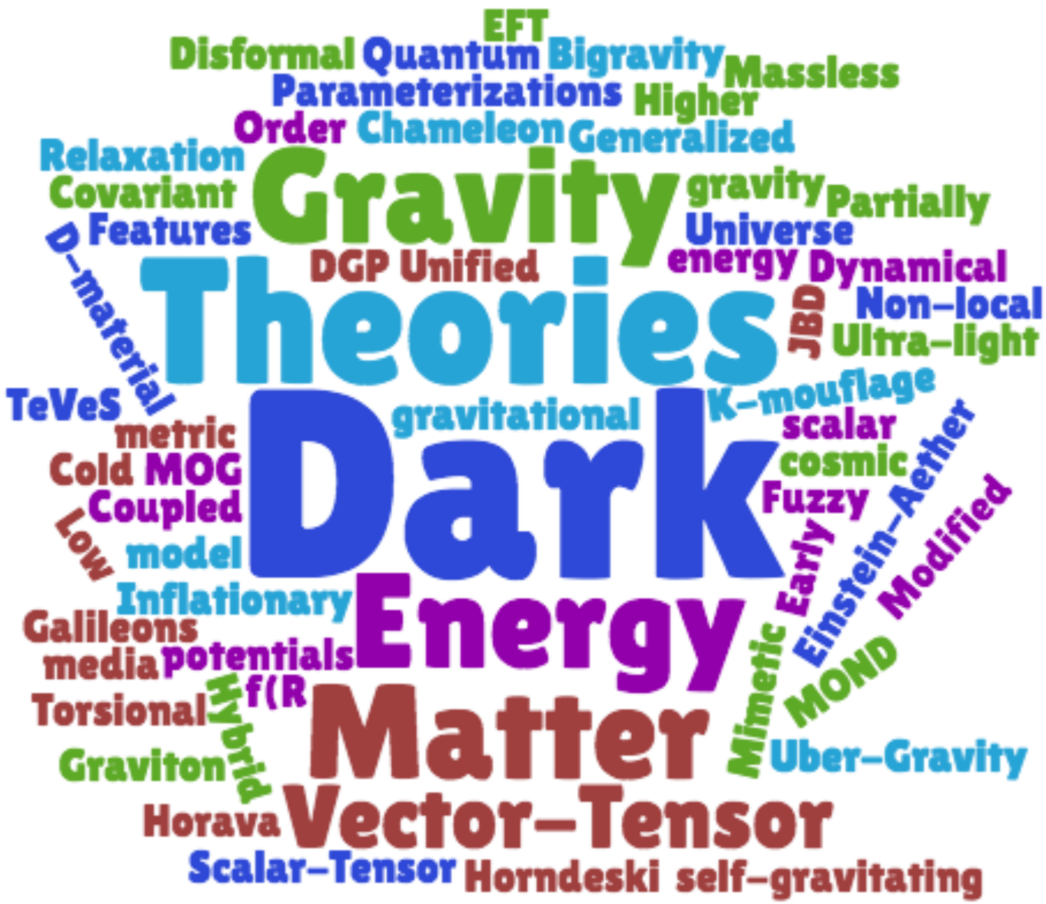
Modified expressions for cosmic shear, galaxy-galaxy lensing and galaxy clustering (applied to KiDS + GAMA)

Alessio Spurio-Mancini, etal 2019

$$P_{ij}^{E}(\ell) = \left(\frac{3H_0^2\Omega_m}{2c^2}\right)^2 \int_0^{\chi_H} \mathrm{d}\chi \, \frac{g_i(\chi)g_j(\chi)}{a(\chi)^2} \, P_\delta\left(\frac{\ell+1/2}{\chi};\chi\right)$$
$$\times \mu\left(\frac{\ell+1/2}{\chi},\chi\right)^2 \left(\frac{1+\eta\left(\frac{\ell+1/2}{\chi},\chi\right)}{2}\right)^2,$$

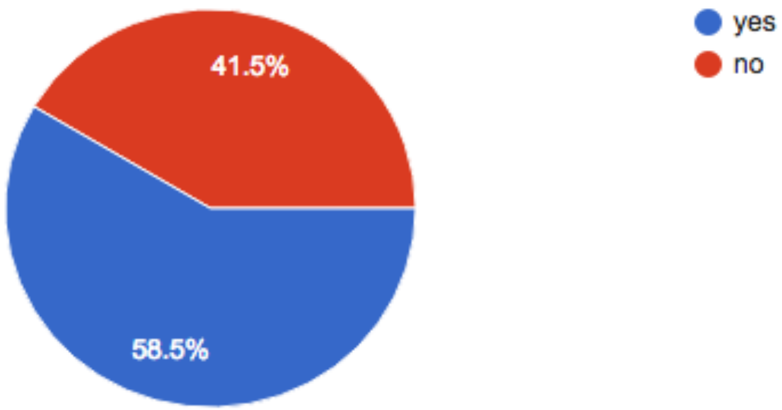
Extra terms to account for generic deviations from GR

Survey I did for Euclid Theory WG: 41 classes of models suggested



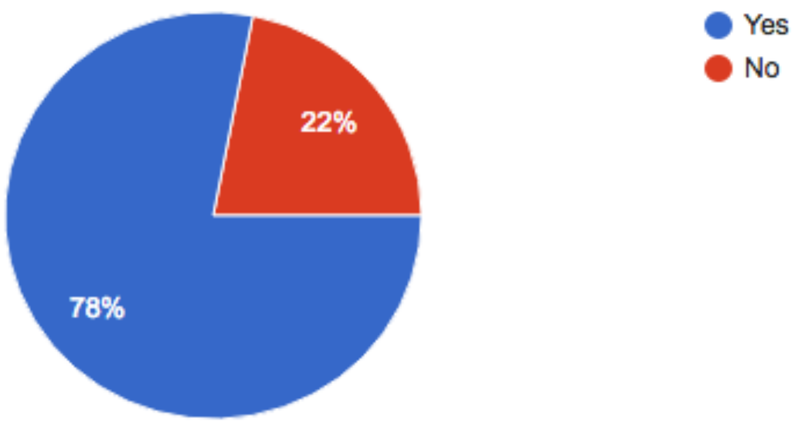
Has the model ever been tested against any WL or GC data?

41 responses



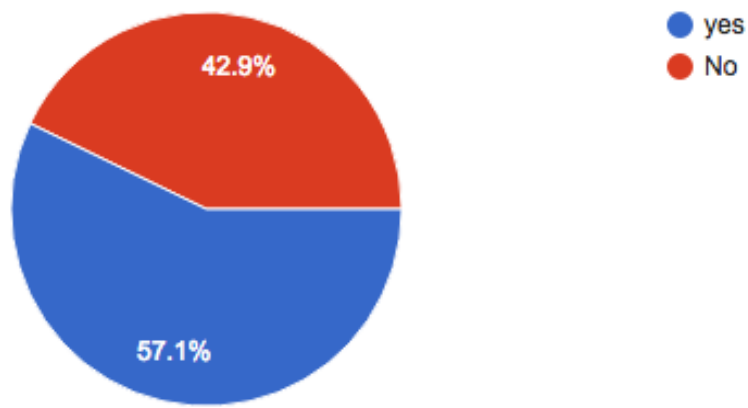
Does a linear Boltzmann code exist for this scenario?

41 responses



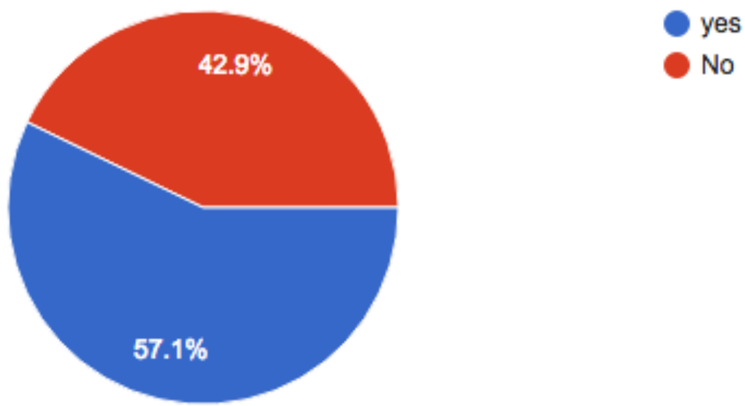
If yes, has this Boltzmann code been compared and validated with other codes?

35 responses



If yes, has this Boltzmann code been compared and validated with other codes?

35 responses



Several valuable models, urgent challenge:
work needed to build reliable codes and predictions for non linear scales

[Galileons could have been excluded before GWs (Leloup etal 2019)]

Several known degeneracies

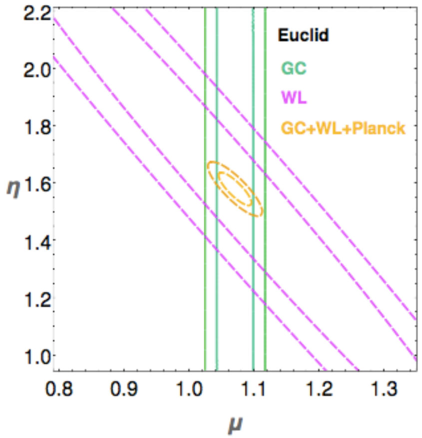
Ω_M σ_8 m_ν Ω_{EDE} ●●●

massive neutrinos vs **fifth force**

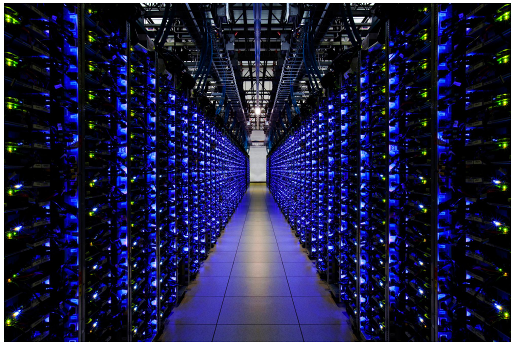
Suppresses the growth

Can enhance the growth

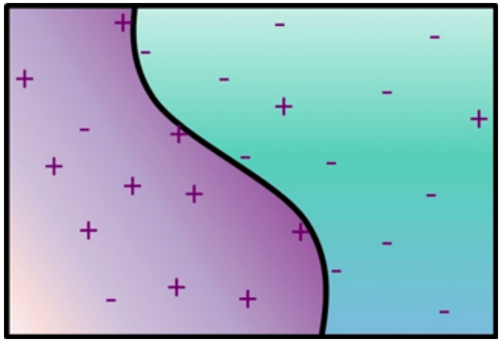
Strategies to break degeneracies



Combining different probes



Getting more data



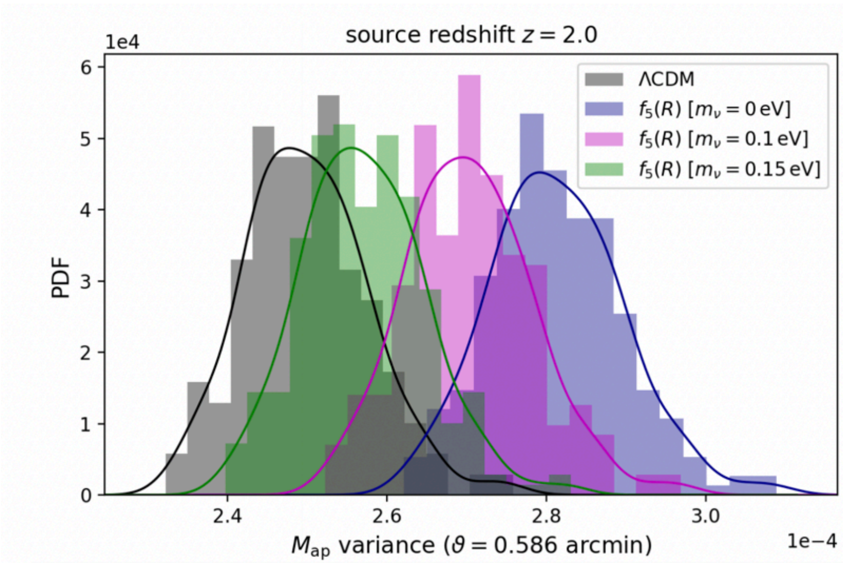
Changing the statistics

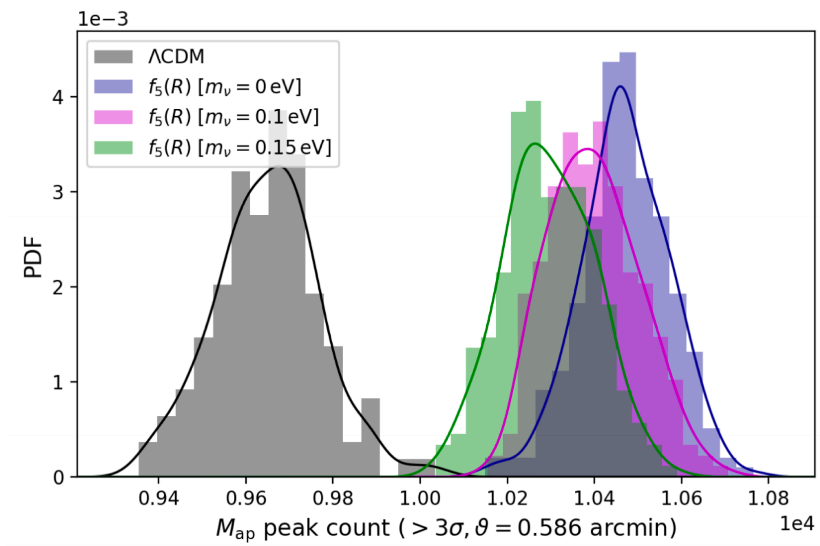
Austin Peel, Valeria Pettorino, JL Starck 2018

ΛCDM or MG+neutrinos?

Austin Peel, V.Pettorino, J-L Starck et al 2018

astro-ph: 1805.05146



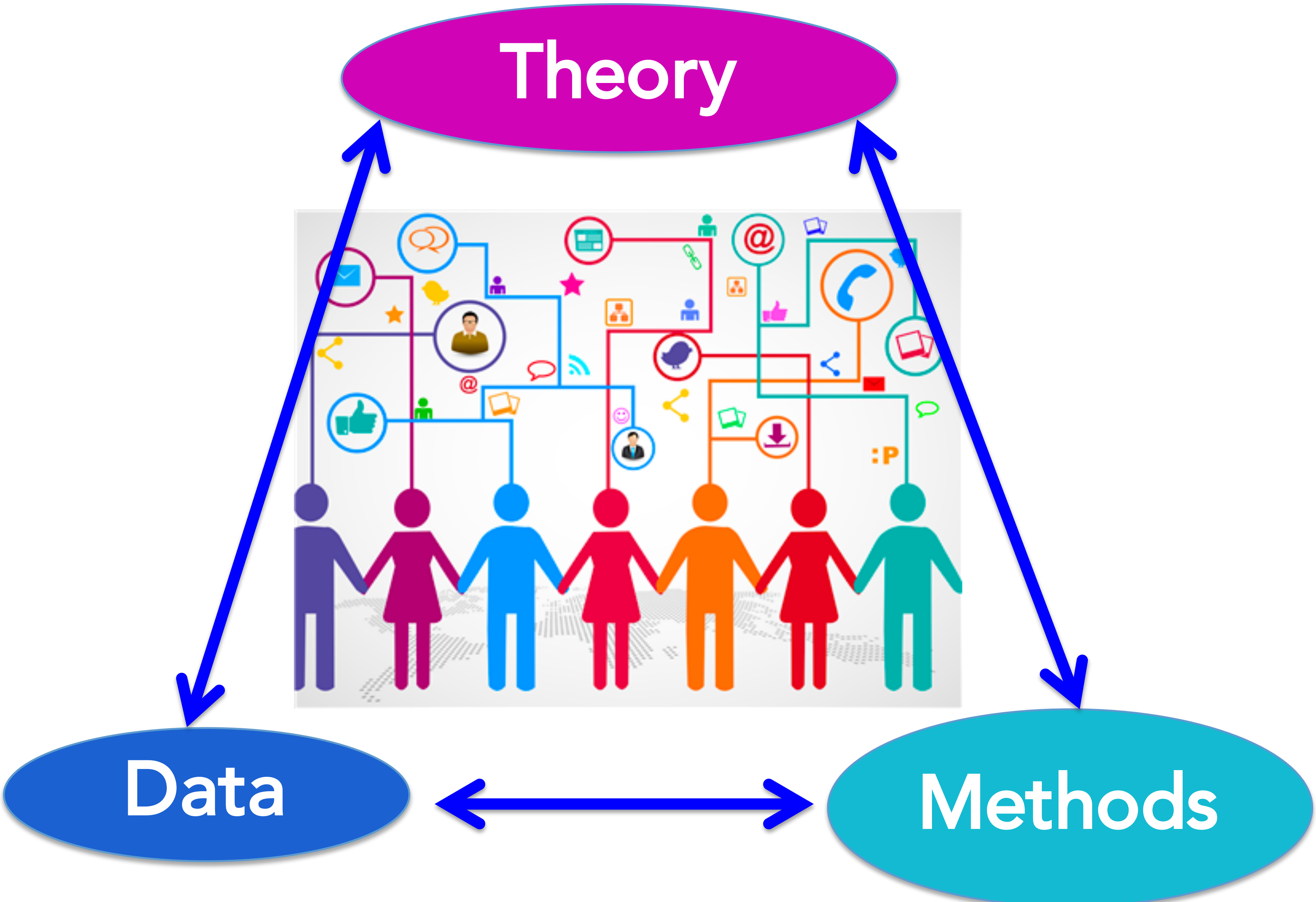


Standard analysis

New results (Peel etal 2018)

Results:
Peak count is the weak lensing statistics that best discriminates modified gravity from a constant

Follow up: machine learning improves the discrimination efficiency even more: 1810.11030 A.Peel, F. Lalande, Pettorino, JL Starck, etal 2019


Theory
Data
Methods

Summary

- There are several valuable scenarios of dynamical Dark Energy and Modified Gravity which are in agreement with current data or yet to be tested

- Euclid: ESA space mission designed to test the dark universe through structure formation: combination of Weak Lensing and Galaxy Clustering. Launch 2022, assemblage is ongoing. Huge potential to test several dark energy and modified gravity scenarios.

- Challenges for Dark Energy and Modified Gravity tests:
  - reliable numerical codes -> LCDM is also the model for which we ~ trust codes
  - predictions at nonlinear scales -> often discard data or assume LCDM
  - degeneracies -> ex. fifth forces & neutrino masses

- Combining probes, large datasets and advanced statistics are three complementary strategies.

Strengthen synergy between theory and data, processing and interpretation, all the way to the Dark Universe.