Euclid: a mission to unravel the Dark Side of the Universe

Stéphane Ilić
(IJCLab, France)

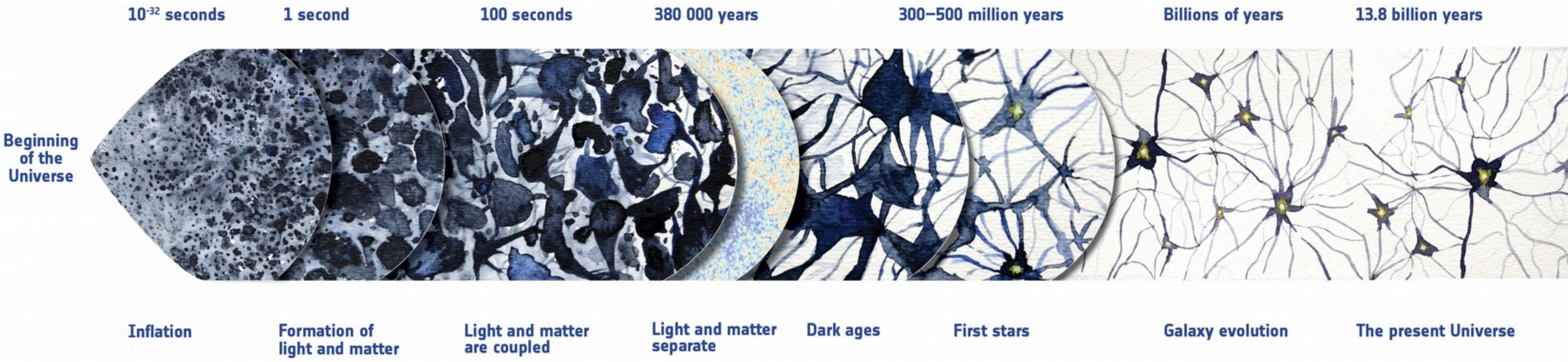
Based on the work and efforts of
many members of the Euclid Consortium

euclid consortium

CosPT Workshop @ IJCLab, Orsay, 12/05/2023

The standard model of cosmology

- The ΛCDM paradigm: a (relatively) simple model, with many successes…



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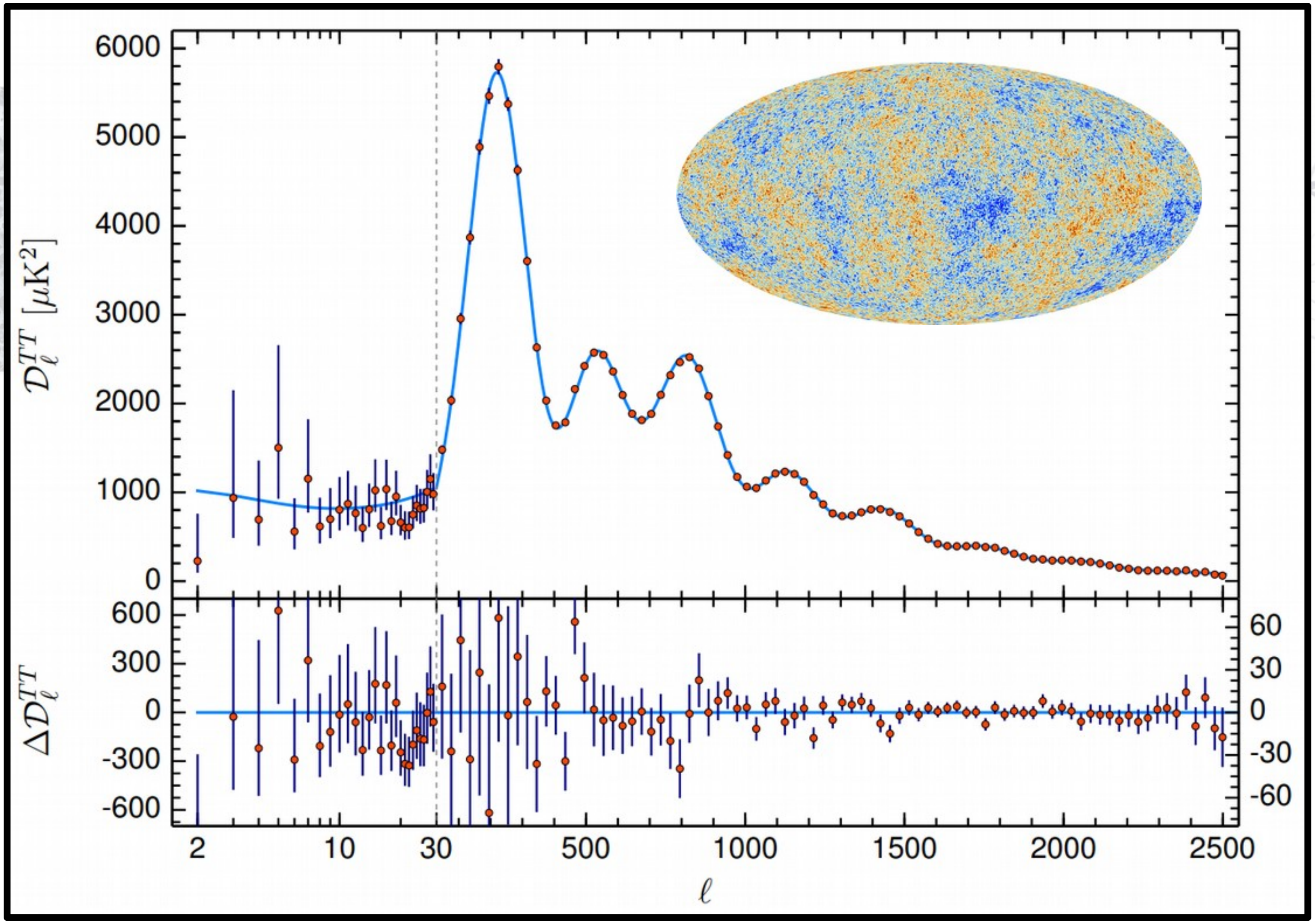

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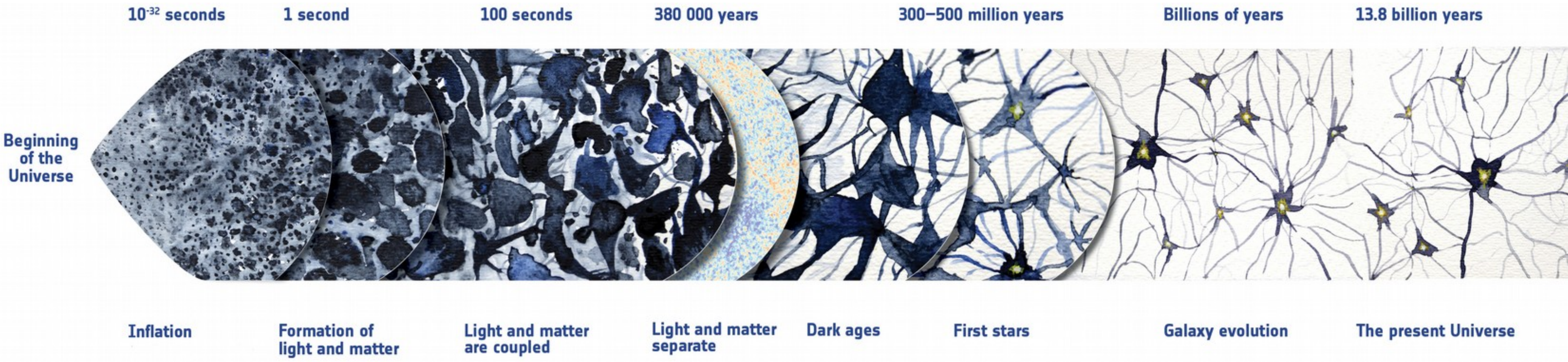
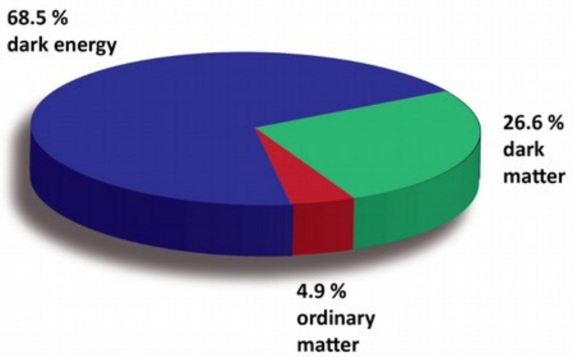
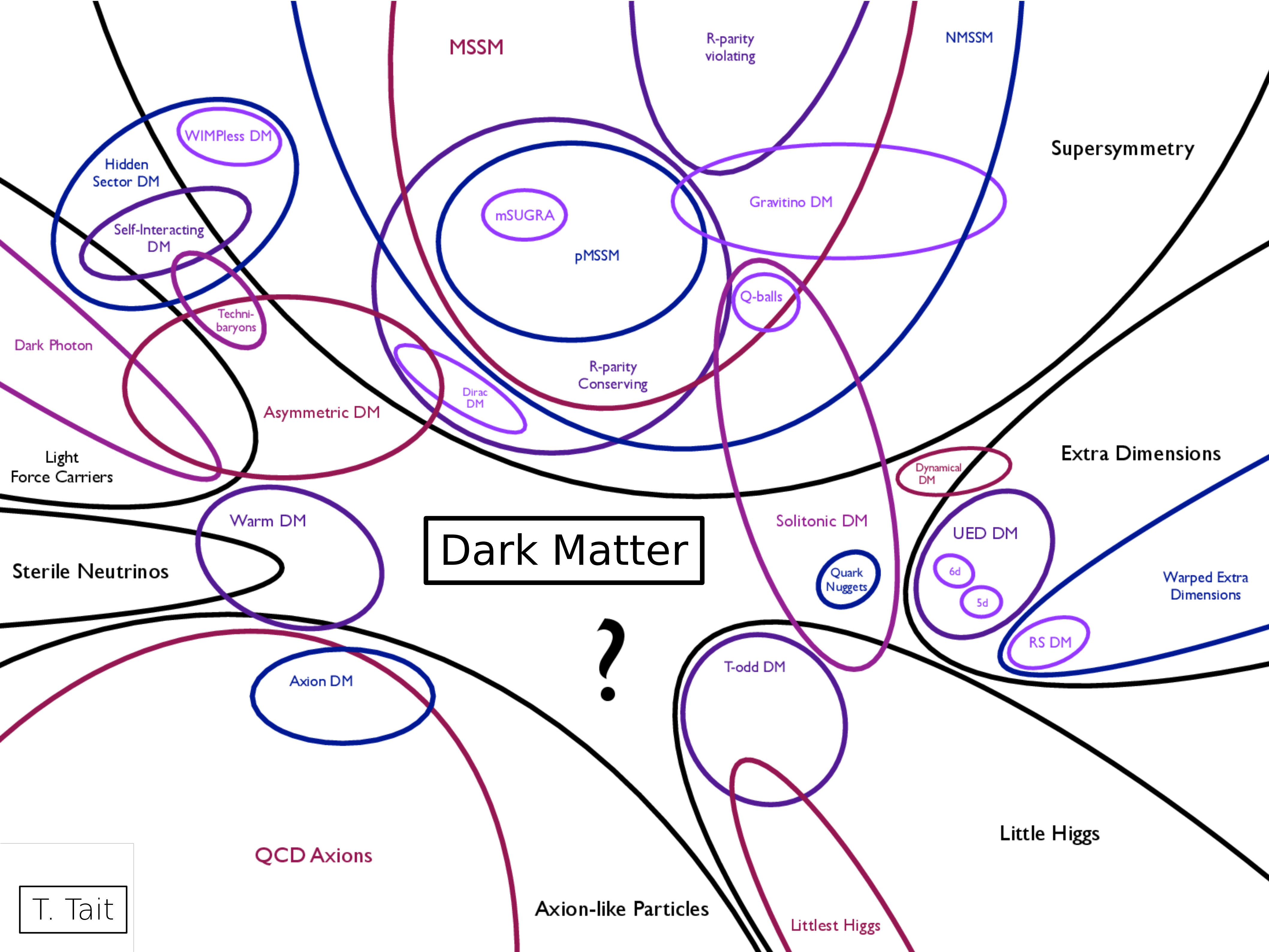
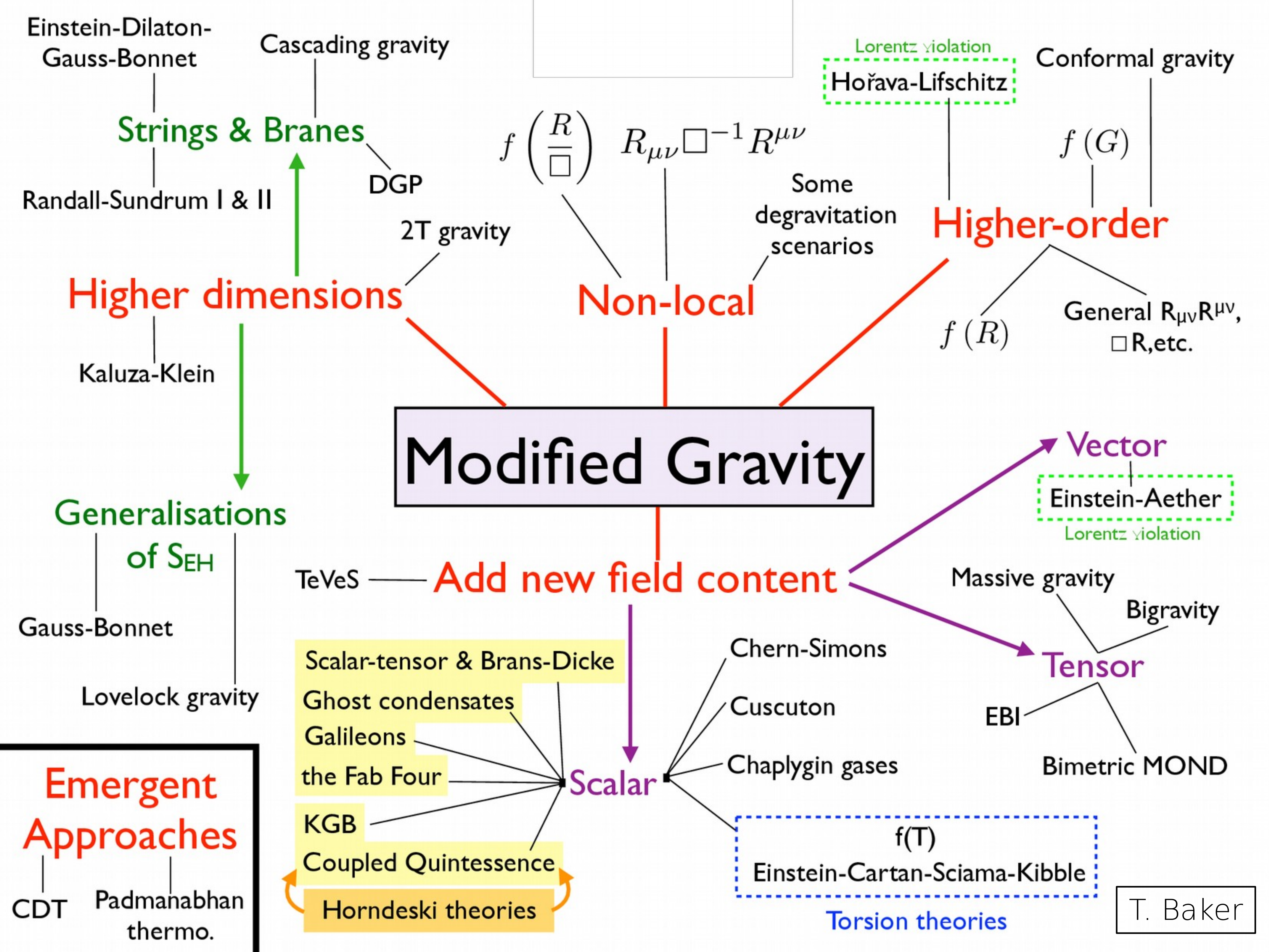


- … but rests on some pillars that are "shrouded in darkness":
  - Primordial Universe, inflation
  - Dark ages & reionisation
  - **Dark matter** ("CDM")
  - **Dark energy** ("Λ")

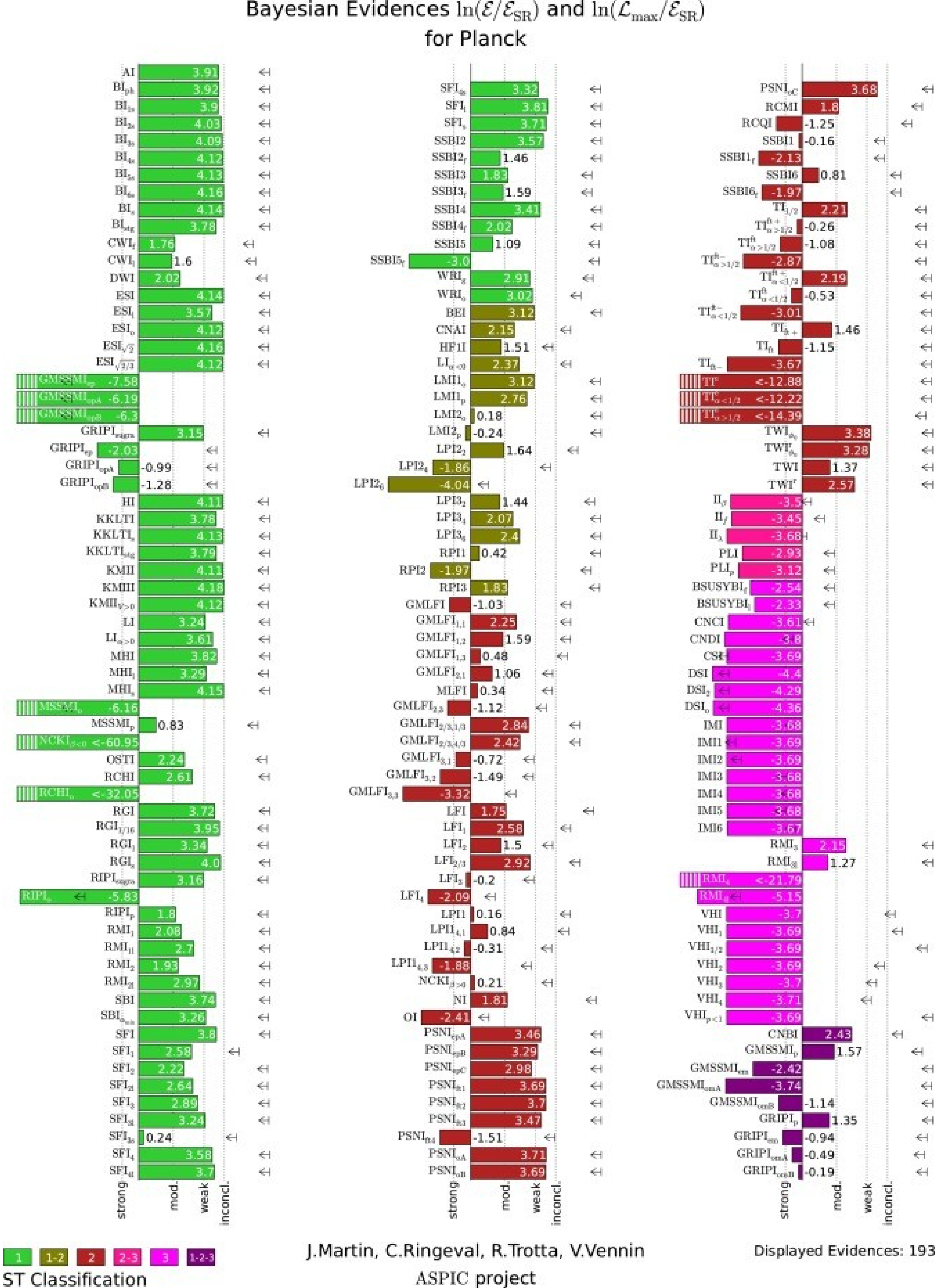



MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-
baryons
Dark Photon
R-parity
Conserving
Dirac
DM
Asymmetric DM
Light
Force Carriers
Dynamical
DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Dark Matter
Sterile Neutrinos
Quark
Nuggets
6d
5d
Warped Extra
Dimensions
?
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T. Tait



Modified Gravity
Higher dimensions
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
DGP
Randall-Sundrum I & II
2T gravity
Kaluza-Klein
Non-local
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Higher-order
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Add new field content
TeVeS
Vector
Einstein-Aether
Lorentz violation
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Emergent Approaches
CDT
Padmanabhan thermo.
T. Baker

Inflation models



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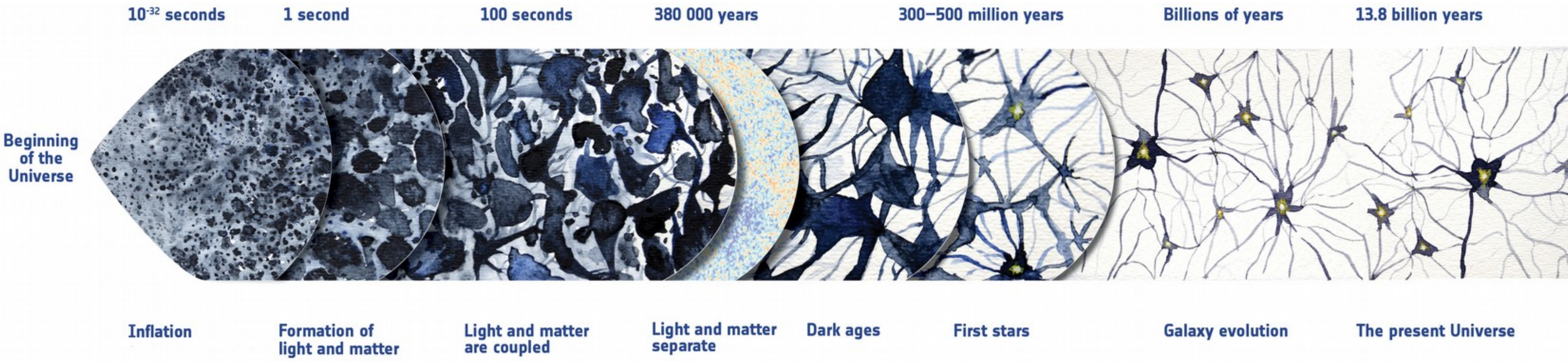

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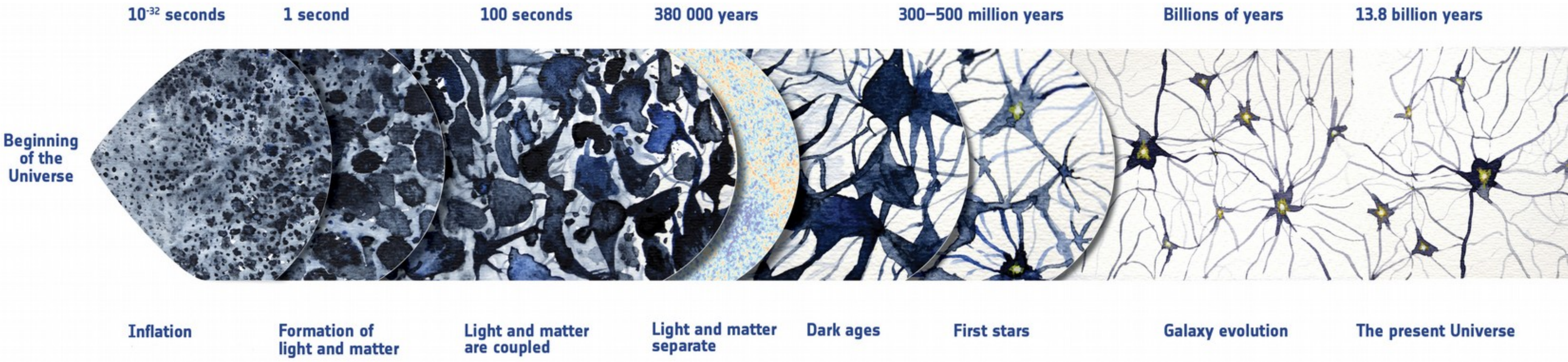
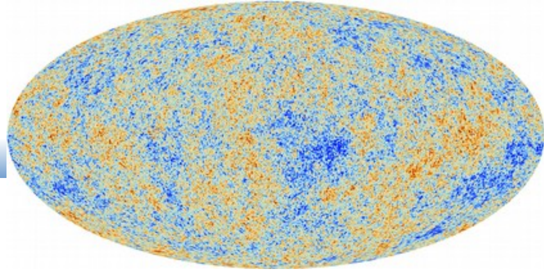
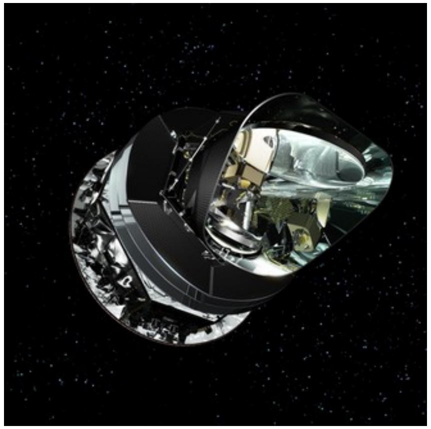
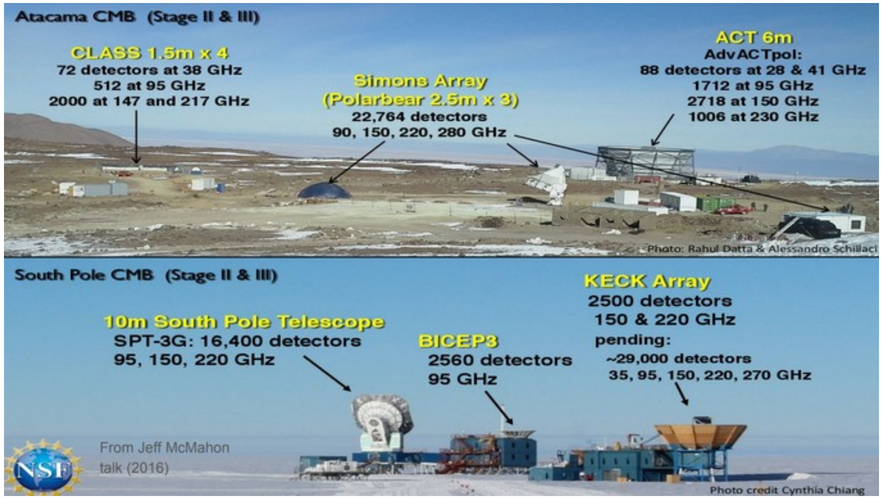


- … but rests on some pillars that are "shrouded in darkness":
  - Primordial Universe, inflation
  - Dark matter (''CDM'')
  - Dark ages & reionisation
  - Dark energy (''Λ'')
- … and is shaken by some persistent tensions :
  - H_0 discrepancies
  - σ_8 tensions
  - ISW excesses
  - CMB "anomalies"

Current/upcoming CMB surveys



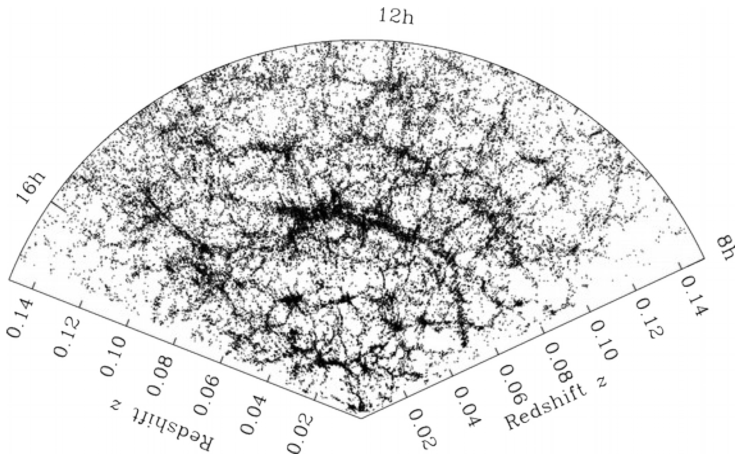




Future:

- Simons Observatory
- LiteBIRD
- CMB Stage-4

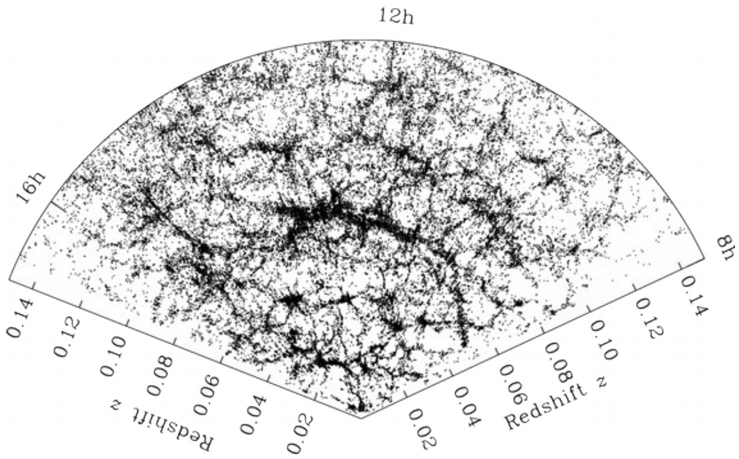
Current/upcoming LSS surveys



DETF classification:

- Stage II: SDSS, KiDS, ...
- Stage III: DES, ...
- Stage IV: DESI, LSST, ...

Current/upcoming LSS surveys



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The ESA Euclid space telescope mission

→ map the distribution and evolution of galaxies/matter across a large fraction of the observable universe

→ investigate the nature of dark matter and dark energy

"A space mission to map the Dark Universe"

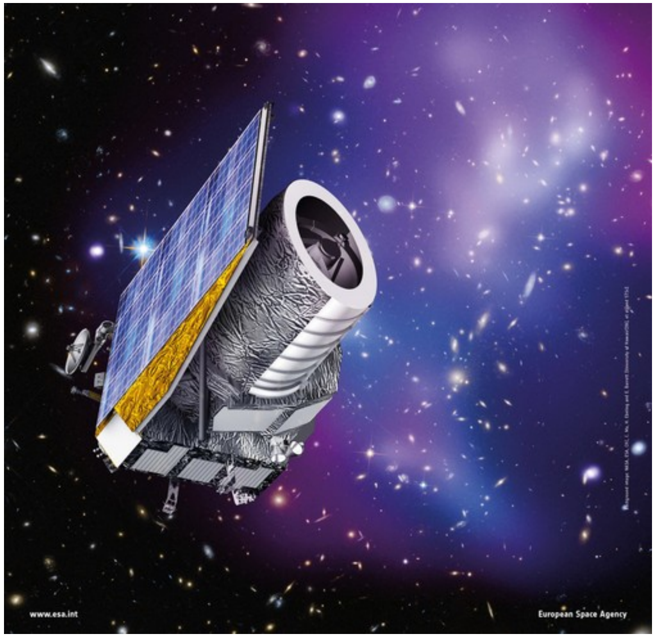
Euclid fact sheet

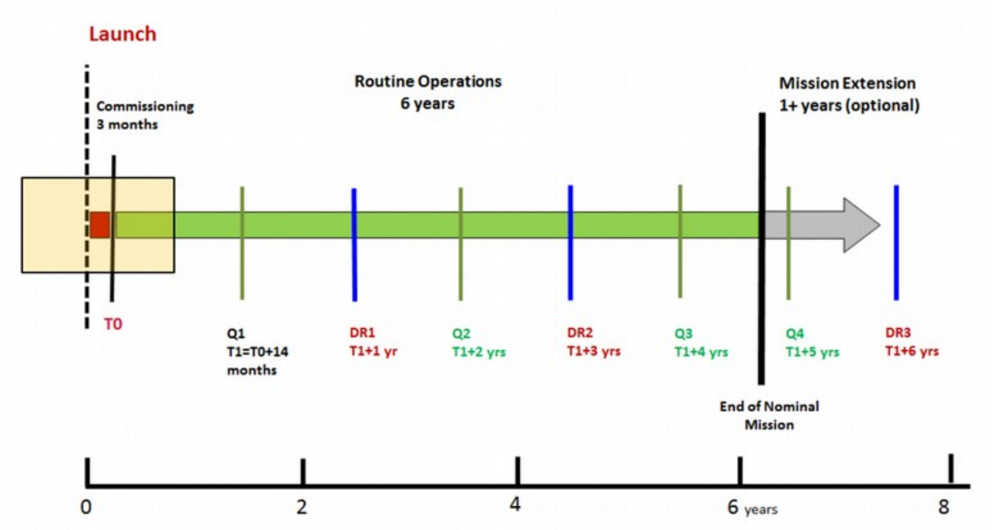
Technical parameters:

- 1.2 m mirror telescope
- 2 instruments:
  - panoramic visible imager (VIS)
  - near infrared photometer (NISP-P) and slitless spectrograph (NISP-S)

Mission parameters:

- Orbit around L2
- ~15,000 sq. deg., up to z~2.5
- Spectro + photo (1.5 B gal) survey
- ~6 years of mission
- Q1 after 17 months, DR1 at 29
- Launch ~~with Soyuz from Kourou~~
  ~~with Ariane 6 from Kourou~~
  with Falcon 9 from Cape Canaveral
- Launch date: ...





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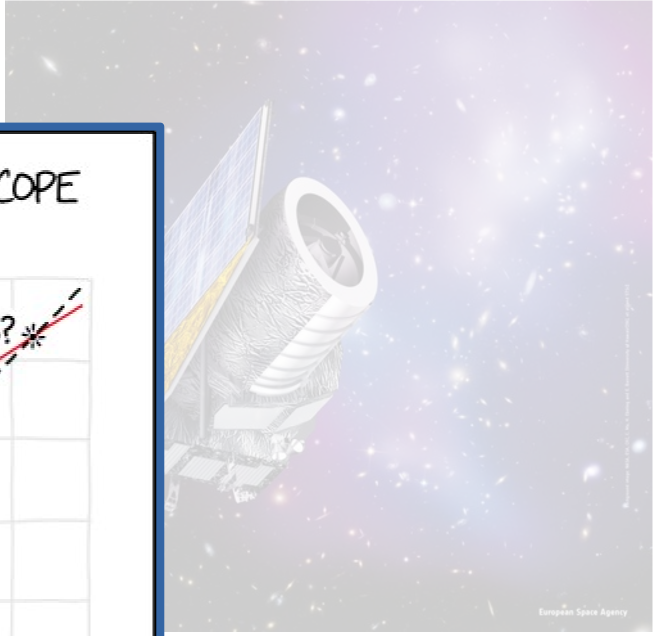

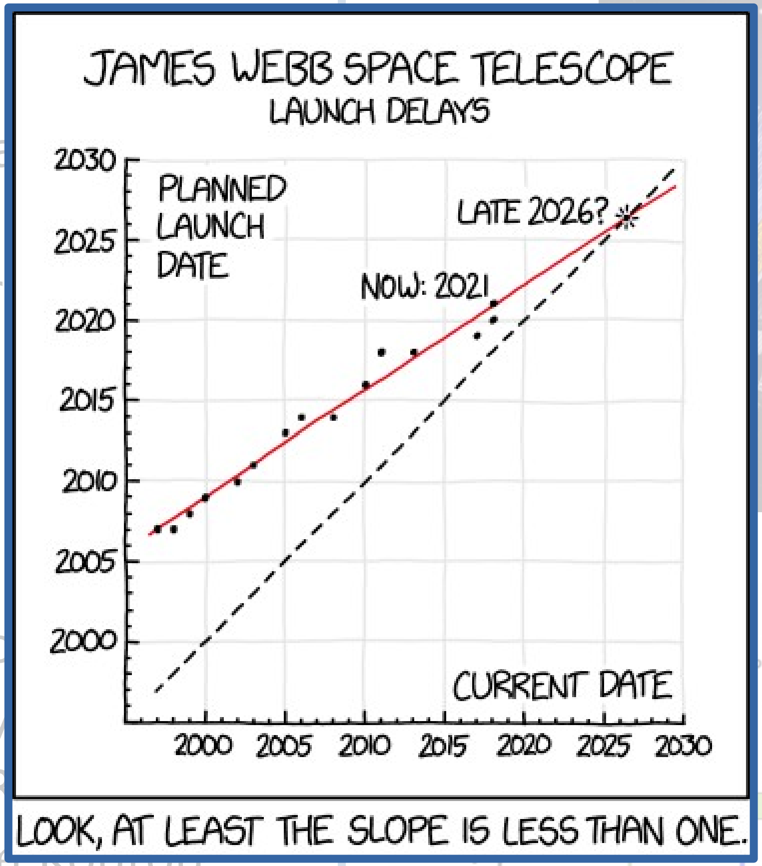

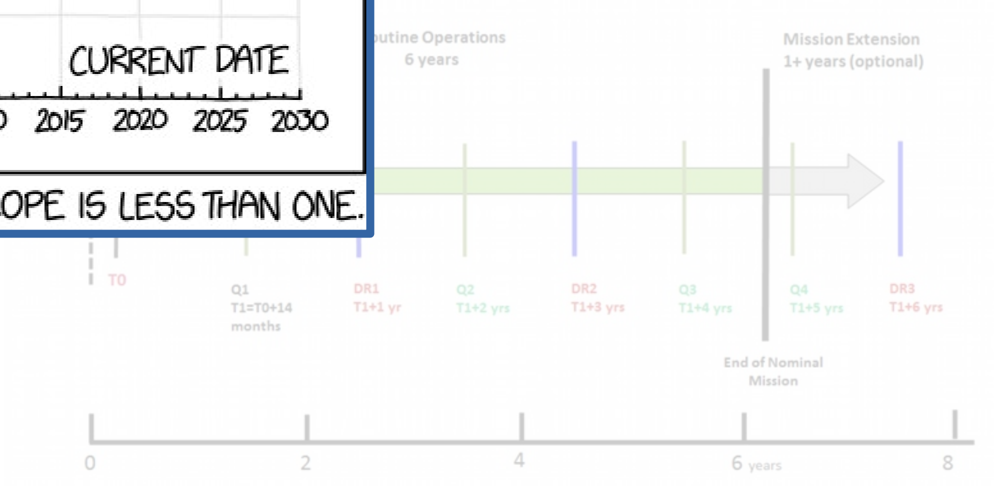

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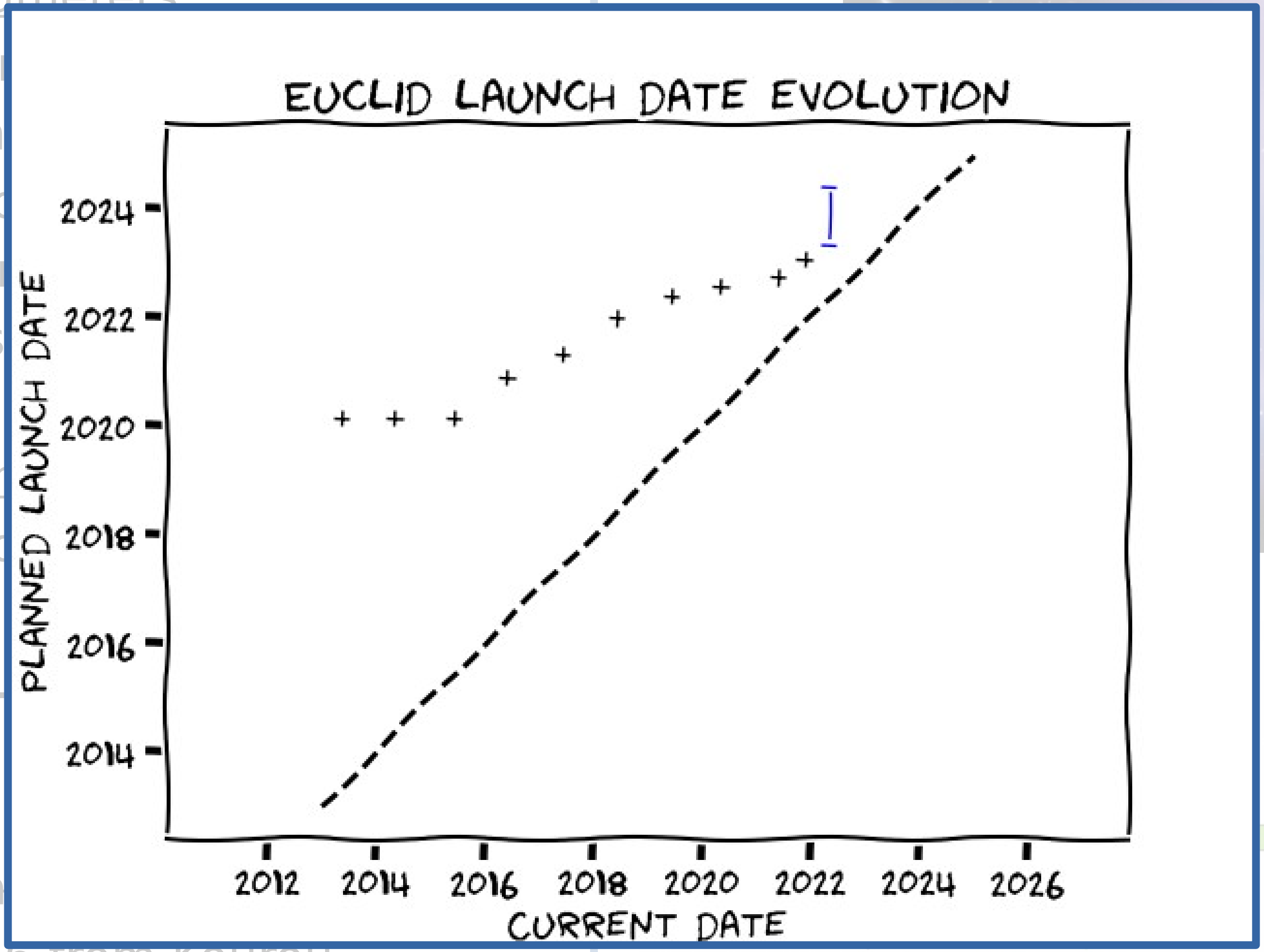

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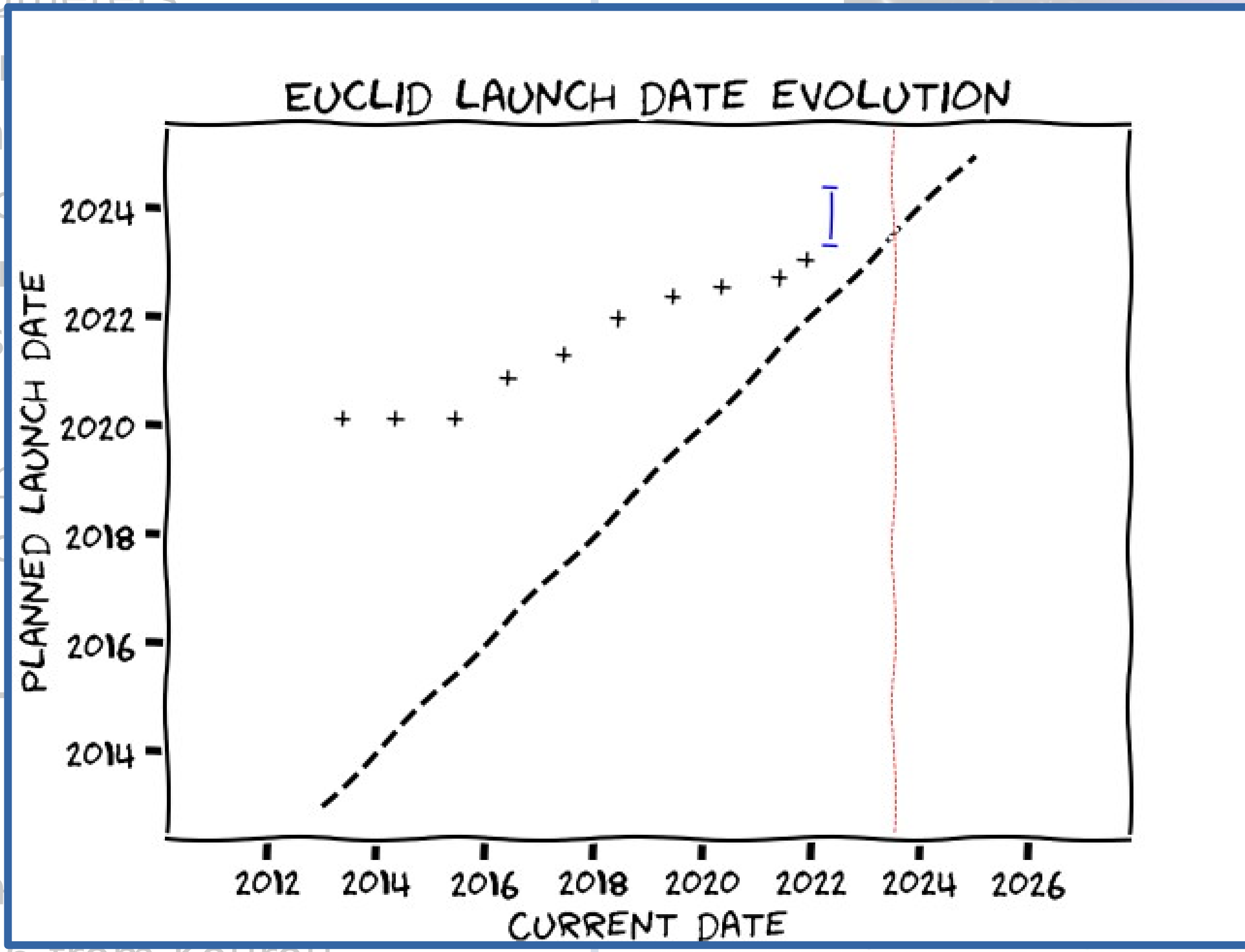

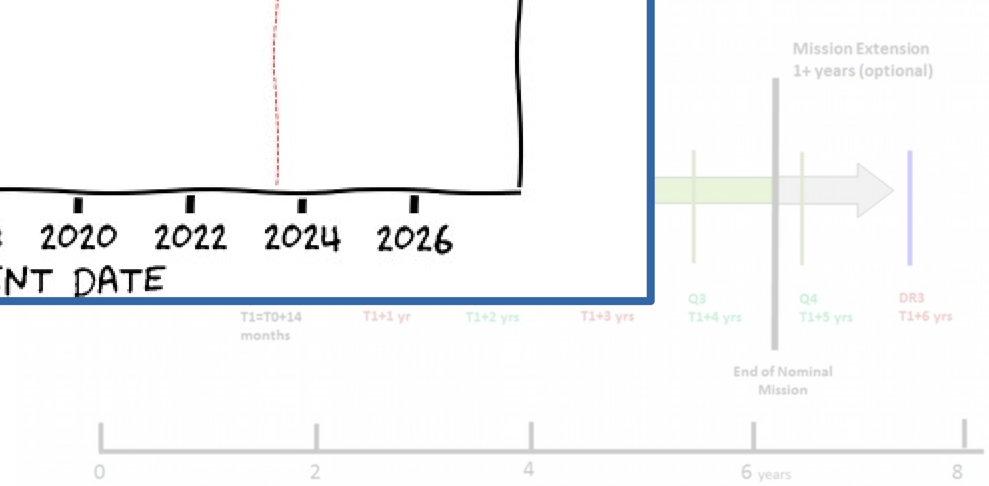

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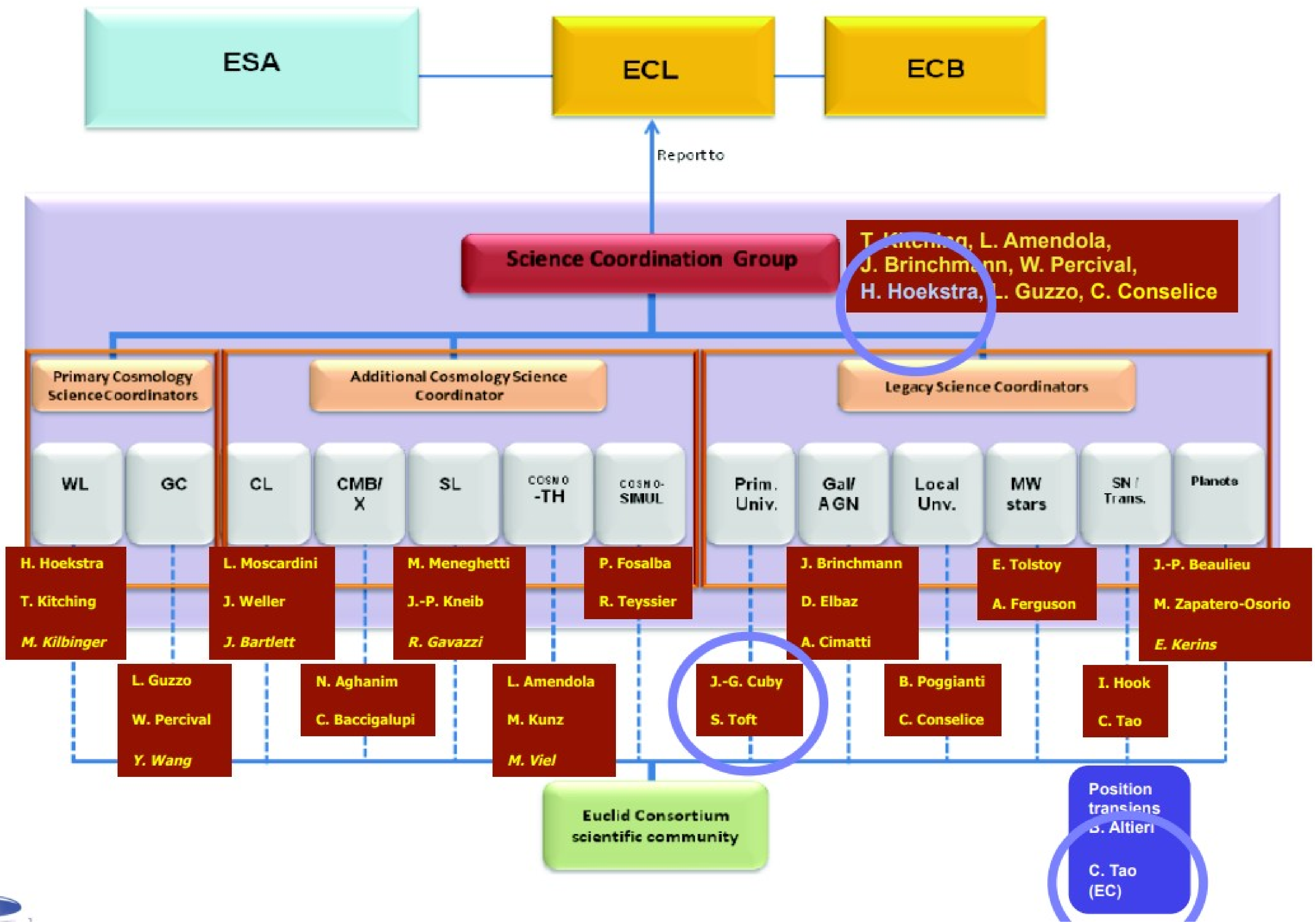
The Euclid Consortium

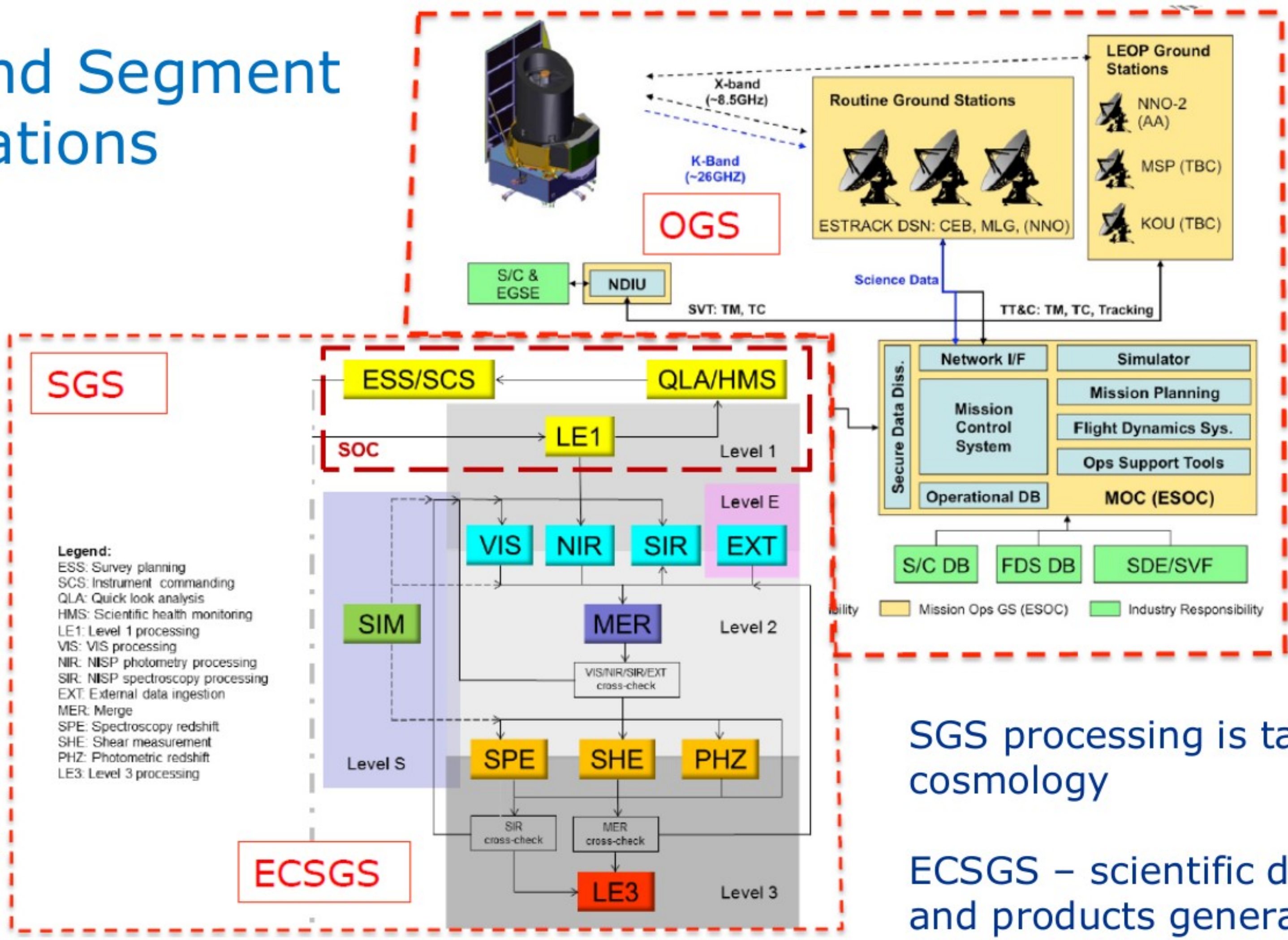
1500+ members, 200+ institutes, 14+ countries

Science Working Groups (Jan 2016 - update)



The Euclid Consortium

Ground Segment Operations



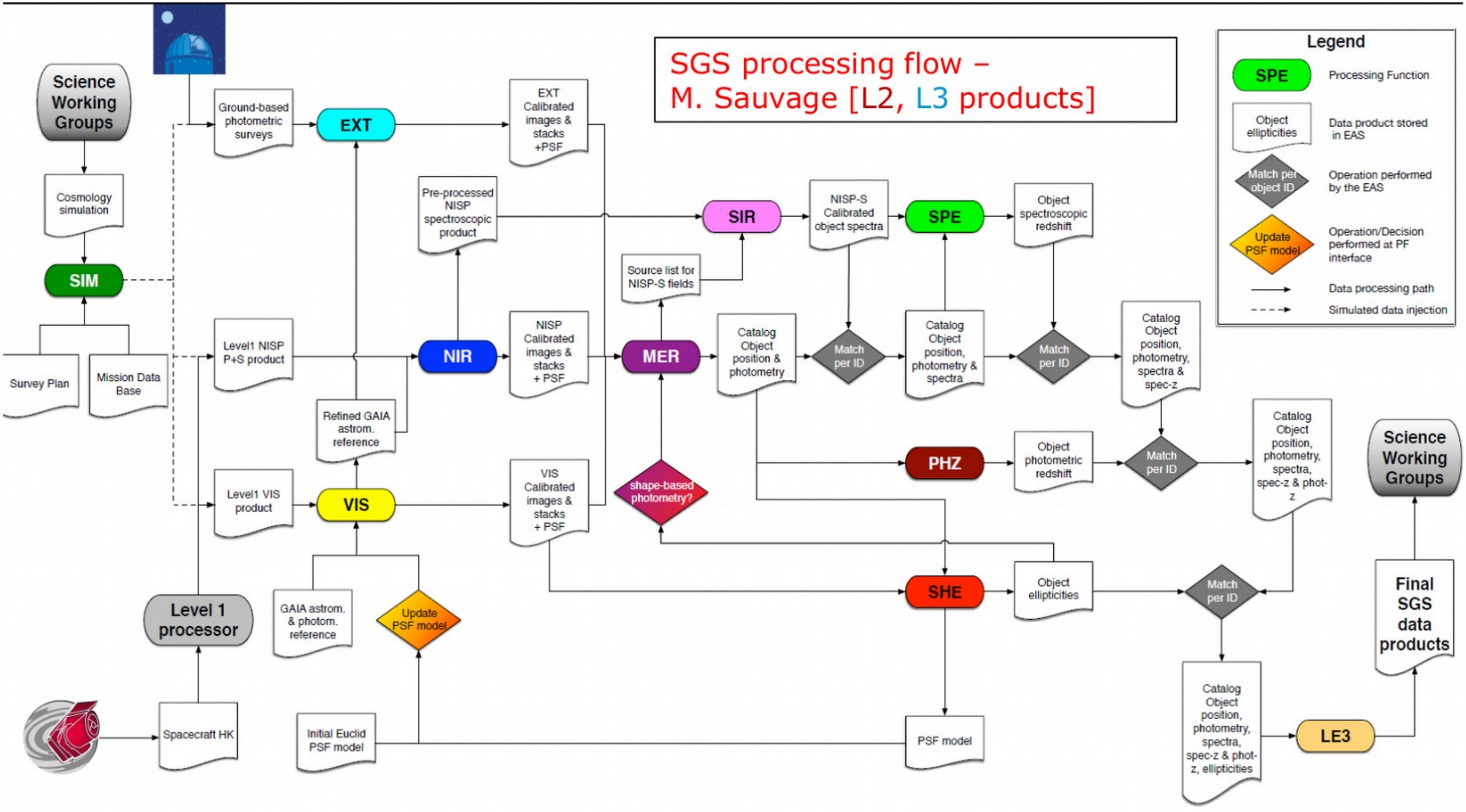
Operations Ground Segment

Science Ground Segment

SGS processing is tailored for cosmology

ECSGS – scientific data processing and products generation are provided by the Euclid Consortium

The Euclid Consortium



Euclid publications

Paterson et al.:
Euclid preparation. XXVII. A UV-NIR spectral atlas of compact planetary nebulae for wavelength calibration

Merlin et al.:
Euclid preparation. XXV. The Euclid Morphology Challenge. Towards model-fitting photometry for billions of galaxies

Bretonnière et al.:
Euclid preparation. XXVI. The Euclid Morphology Challenge. Towards structural parameters for billions of galaxies

Camarena et al.:
Euclid: Testing the Copernican principle with next-generation surveys

Cabayol-Garcia et al.:
The PAU Survey & Euclid: Improving broadband photometric redshifts with multi-task learning

Moriya et al.:
Euclid: Discovering pair-instability supernovae with the Deep Survey

Saglia et al.:
Euclid preparation: XX. The Complete Calibration of the Colour–Redshift Relation survey: LBT observations and data release

Keihanen et al.:
Euclid: Fast two-point correlation function covariance through linear construction

Humphrey et al.:
Euclid preparation. XXII. Selection of Quiescent Galaxies from Mock Photometry using Machine Learning

Nesseris et al.:
Euclid: Forecast constraints on consistency tests of the ΛCDM model

Loureiro et al.:
KiDS & Euclid: Cosmological implications of a pseudo angular power spectrum analysis of KiDS-1000 cosmic shear tomography

Martinelli et al.:
Euclid: constraining dark energy coupled to electromagnetism using astrophysical and laboratory data

Scaramella et al.:
Euclid preparation: I. The Euclid Wide Survey

Serrano Borlaff et al.:
Euclid preparation: XVI. Exploring the ultra low-surface brightness Universe with Euclid/VIS

Ilic et al.:
Euclid preparation: XV. Forecasting cosmological constraints for the Euclid and CMB joint analysis

Stanford et al.:
Euclid preparation: XIV. The complete calibration of the colour-redshift calibration (C3R2) survey: data release 3

Martinelli et al.:
Euclid: impact of nonlinear prescriptions on cosmological parameter estimation from weak lensing cosmic shear

Martinelli et al.:
Euclid: Forecast constraints on the cosmic distance duality relation with complementary external probes

Knabenhans et al.:
Euclid preparation: IX. EuclidEmulator2 -- Power spectrum emulation with massive neutrinos and self-consistent dark energy perturbations

Tutusaus et al.:
Euclid: The importance of galaxy clustering and weak lensing cross-correlations within the photometric Euclid survey

Guglielmo et al.:
Euclid preparation: VIII. The Complete Calibration of the Colour-Redshift Relation (C3R2) Survey: VLT/KMOS Observations and Data Release

Pöntinen et al.:
Euclid: Identification of asteroid streaks in simulated images using StreakDet software

Deshpande et al.:
Euclid: On the Reduced Shear Approximation and Magnification Bias for Stage IV Cosmic Shear Experiments

Adam et al.:
Euclid preparation. III. Galaxy cluster detection in the wide photometric survey -- performance and algorithms selection

Inserra et al.:
Euclid: Superluminous supernovae in the Deep Survey

Knabenhans et al.:
Euclid preparation: II. The EuclidEmulator -- A tool to compute the cosmology dependence of the nonlinear matter power spectrum

The science of Euclid

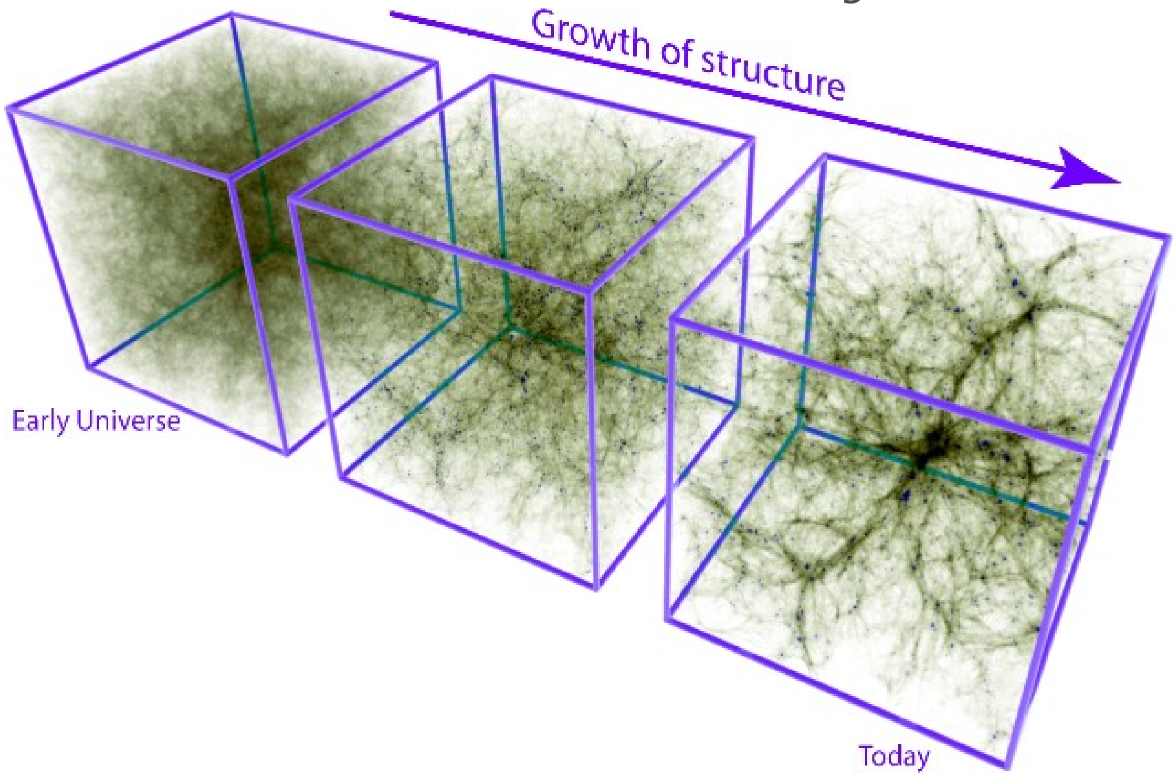
The dark matter and energy can be studied by looking at:

1. **The geometry of the universe**

   → Measure of position of galaxies as a function of redshift

2. **Growth of density perturbations**

   → Evolution of structure as a function of cosmic time, *growth rate*



- Structure follows the expansion of the Universe
- Gravity causes structure to evolve

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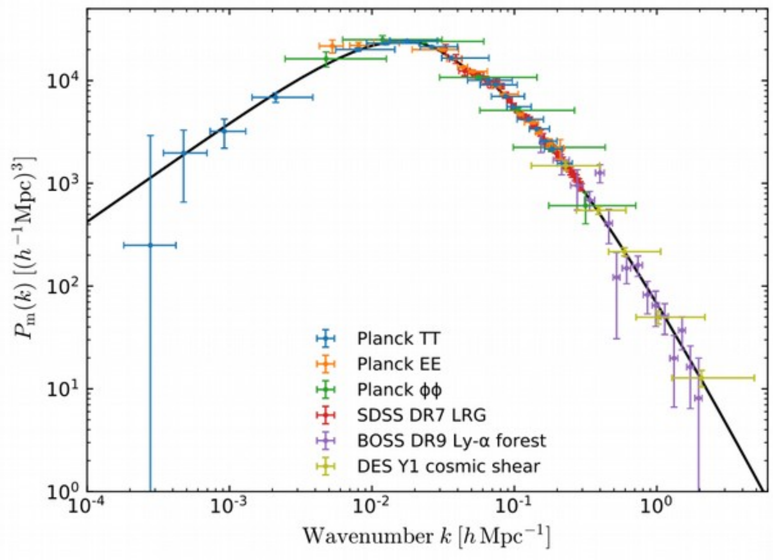
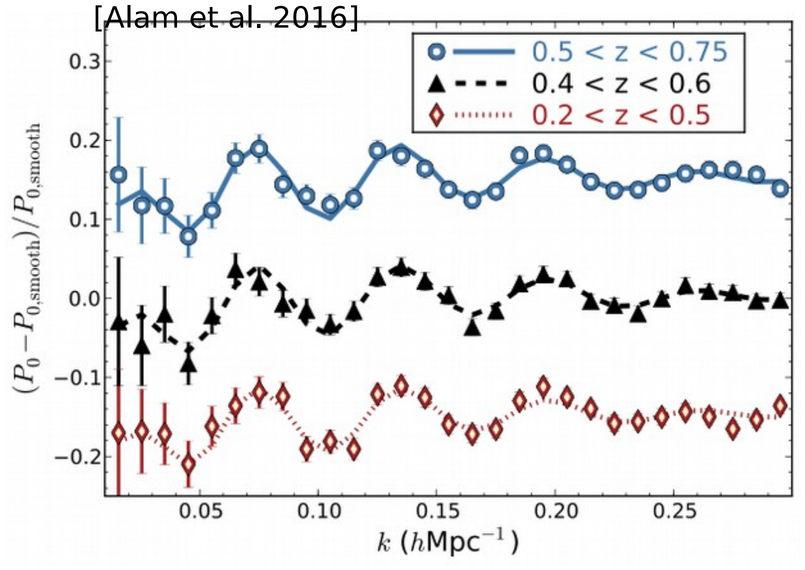
Euclid *cosmological probes:*

- **Galaxy Clustering**
  - **Baryon Acoustic Oscillations (power spectrum at large scales)**
  - **redshift-space distortions**

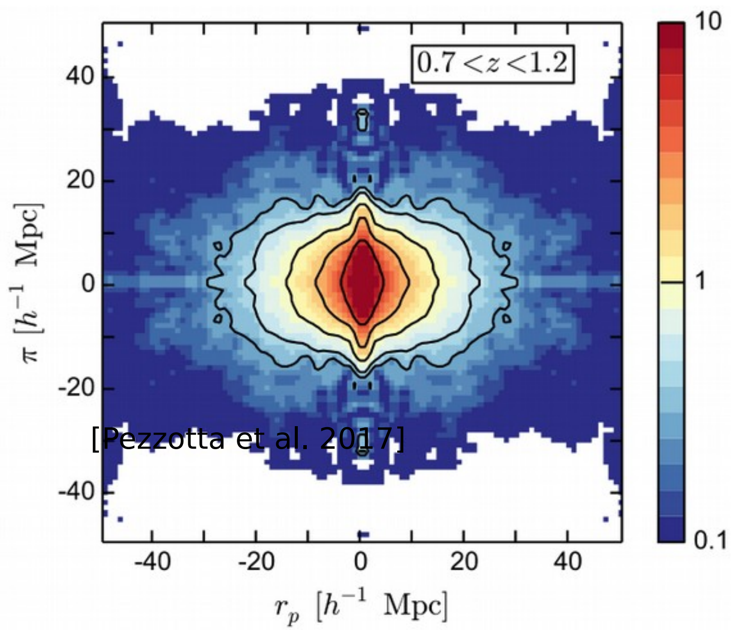


The science of Euclid – galaxy clustering

- **Baryon acoustic oscillations** (BAO):
  - provide a **cosmic ruler**
  - sensitive to the **expansion** history and the angular-diameter **distance**
- **Redshift-space distortions** (RSDs):
  - sensitive to the **growth rate** of structures
  - tests of **modified gravity**



[Alam et al. 2016]



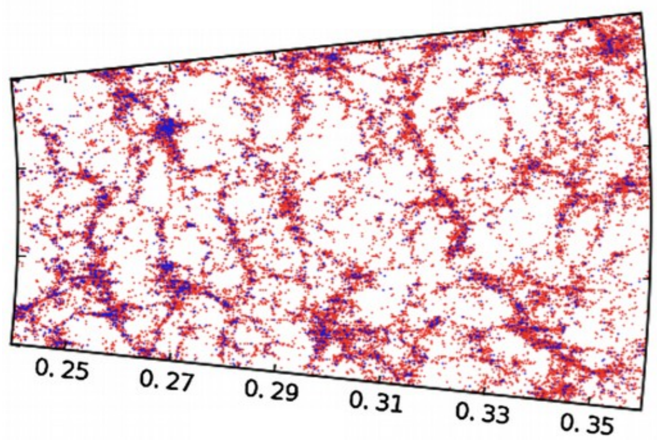
[Pezzotta et al. 2017]

The science of Euclid – galaxy clustering

- Spectroscopic vs **photometric** galaxy clustering:
  - loss of radial information
  - higher number density & different systematic uncertainties
  - **source** of cosmological information

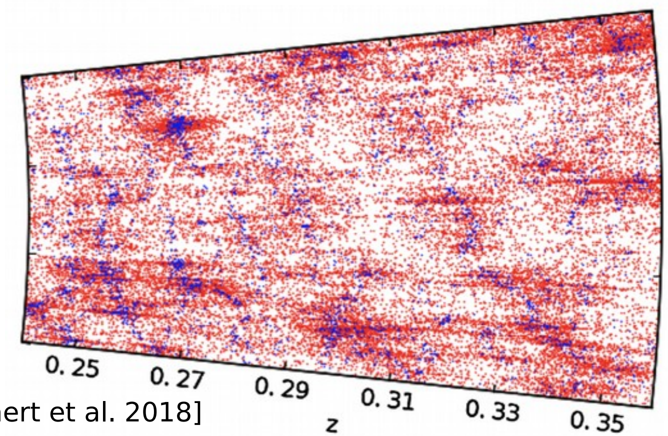
spectroscopic (GCs)

galaxies position on the sky



redshift

photometric (GCp)



[Stothert et al. 2018]

redshift

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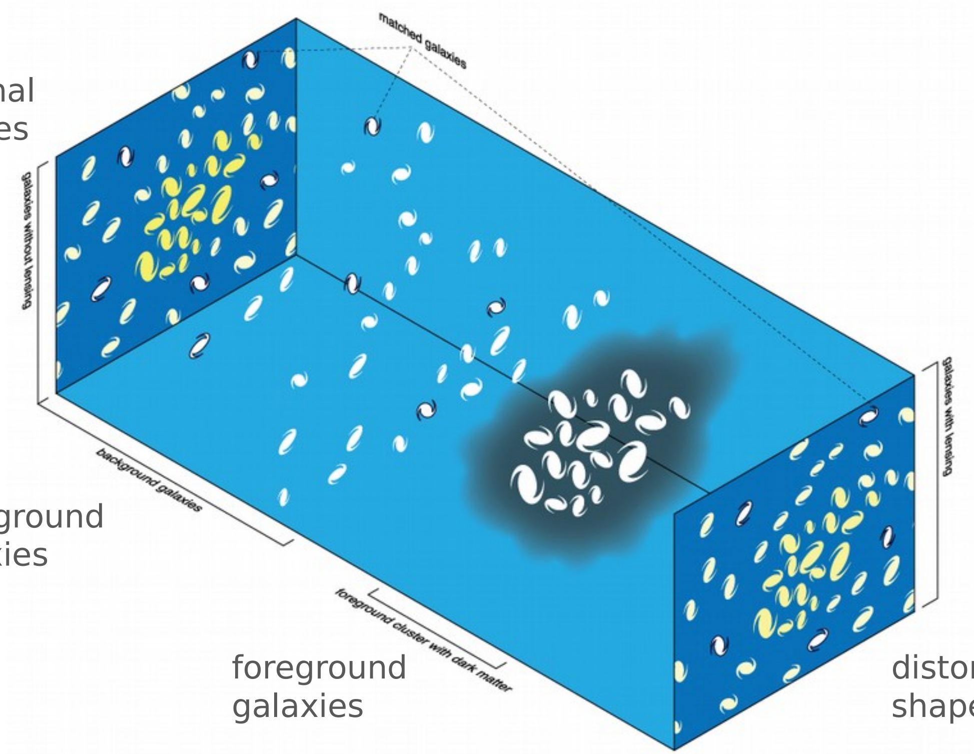
- **Galaxy Clustering**
  - **Baryon Acoustic Oscillations (power spectrum at large scale)**
  - **redshift-space distortions**

- **Weak Gravitational Lensing of galaxies by matter**

The science of Euclid – weak lensing

- **Weak lensing** (WL):
  - information about **mass distribution** imprinted on galaxy images
  - sensitive to **matter density**, initial conditions, and **growth of structures**



original shapes

background galaxies

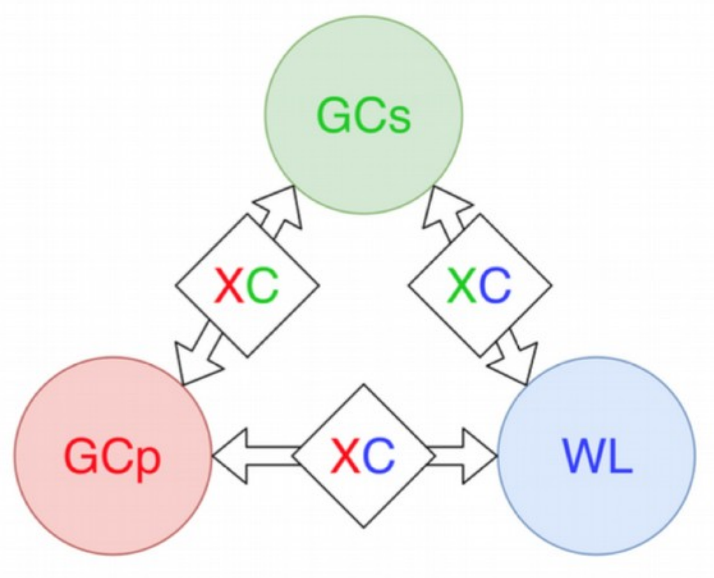
foreground galaxies

distorted shapes

The science of Euclid – combination

- *Euclid* is the ideal survey for a combined analysis:

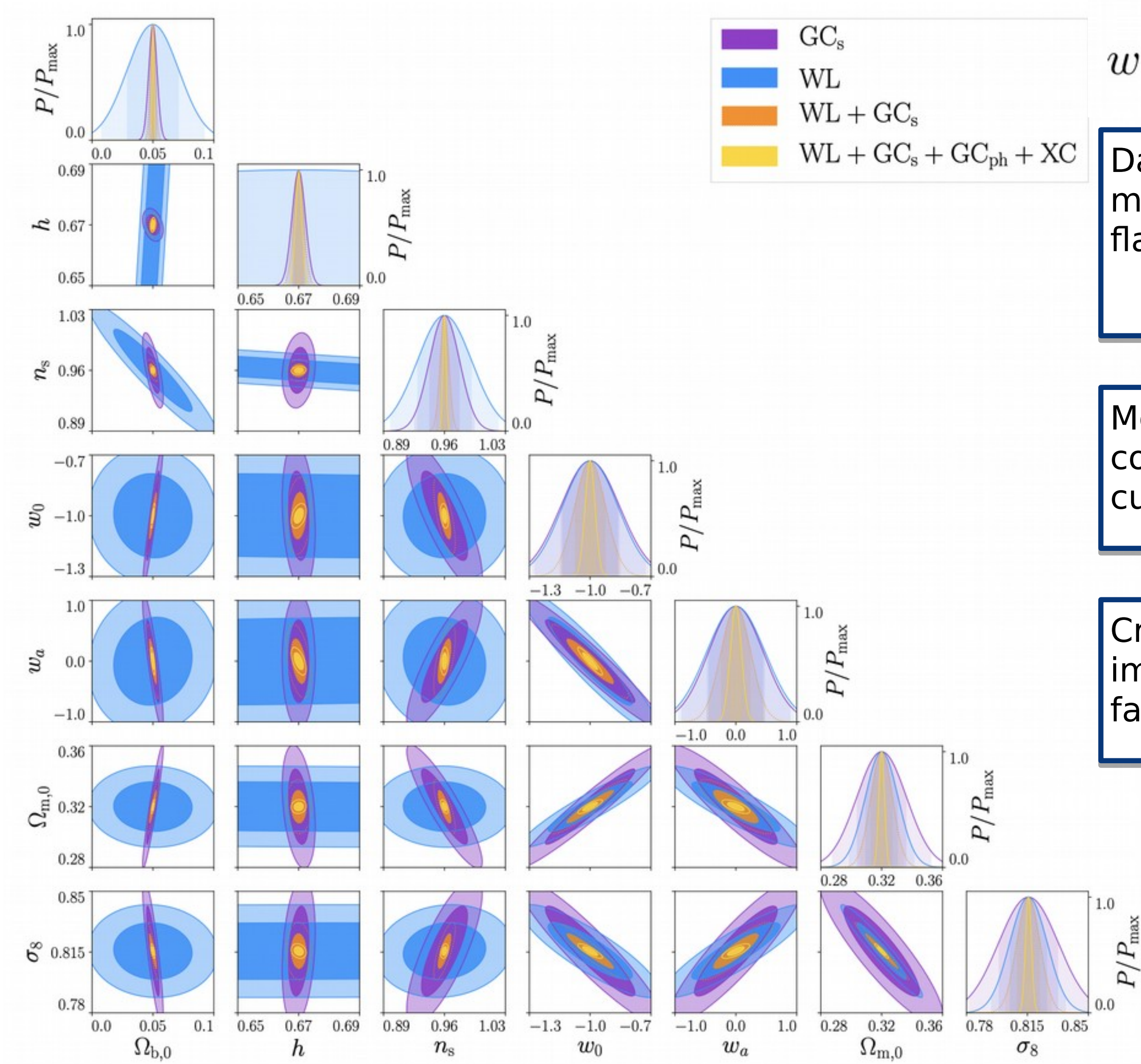
  GCs, GCp, WL, and 3 **cross-correlations** (XC)



Forecasts on cosmological constraints

IST:F: Task-force to produce homogenised and validated forecasts:

→ Great complementarity between probes: breaking of degeneracies



$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Dark energy figure-of-merit of 1257 (500) for a flat (non-flat) cosmology

Modified gravity constrained at 5% and curvature at 1%

Cross-correlations improve constraints by a factor 4

[Euclid Collaboration VII. A&A 642, A191 (2020); I. Tutusaus *et al.* A&A 643, A70 (2020)]

Forecasts on cosmological constraints

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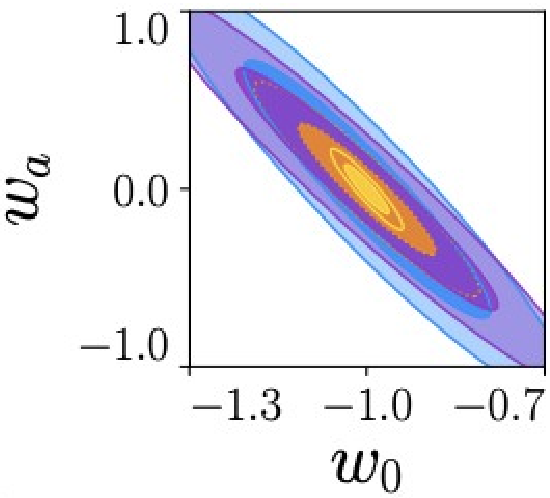

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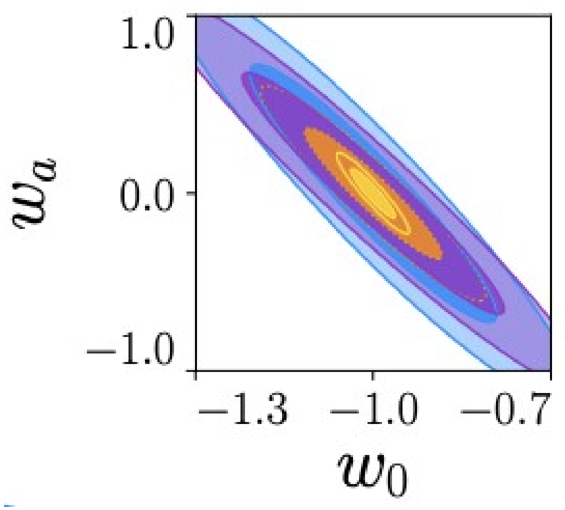
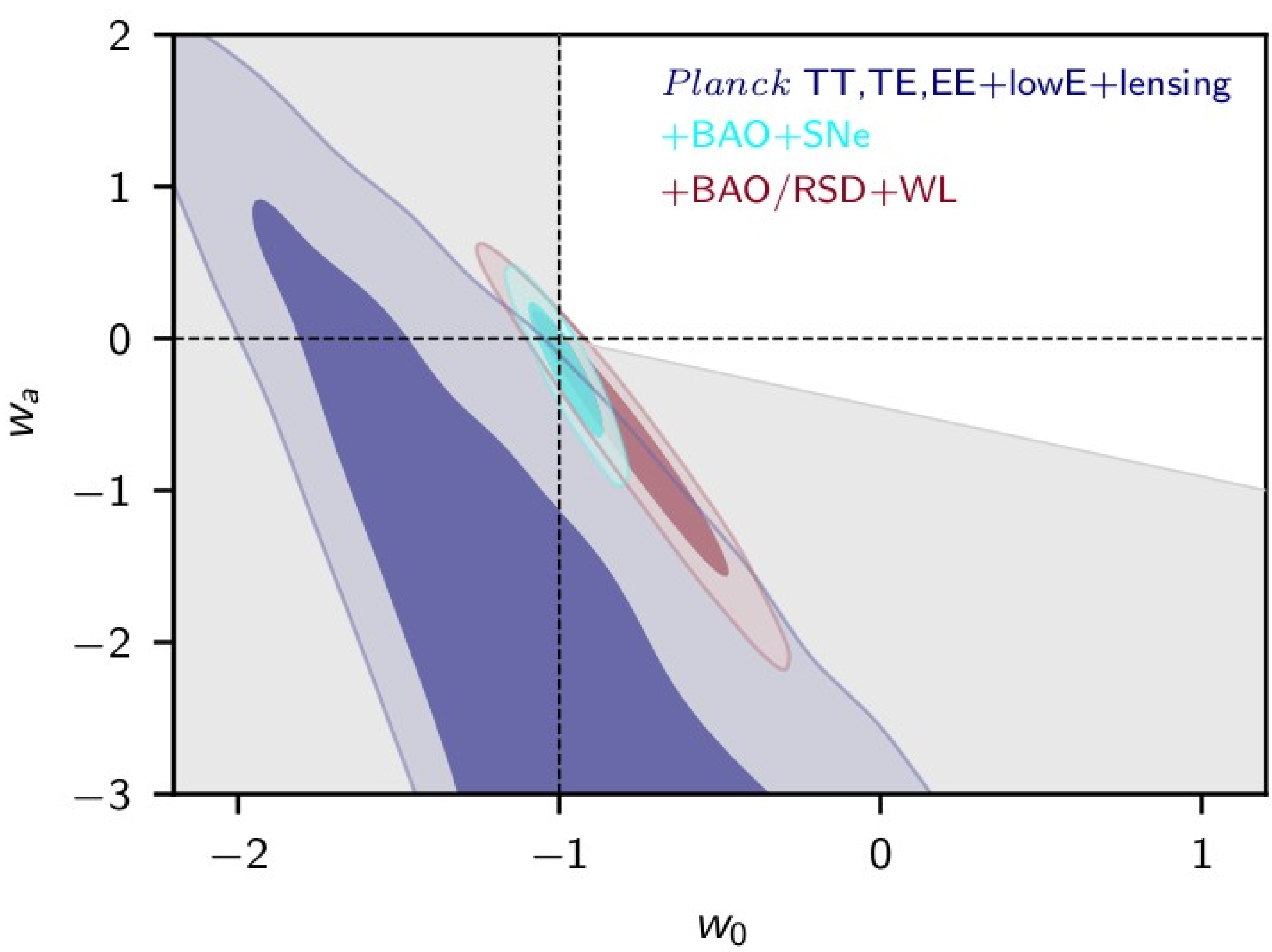
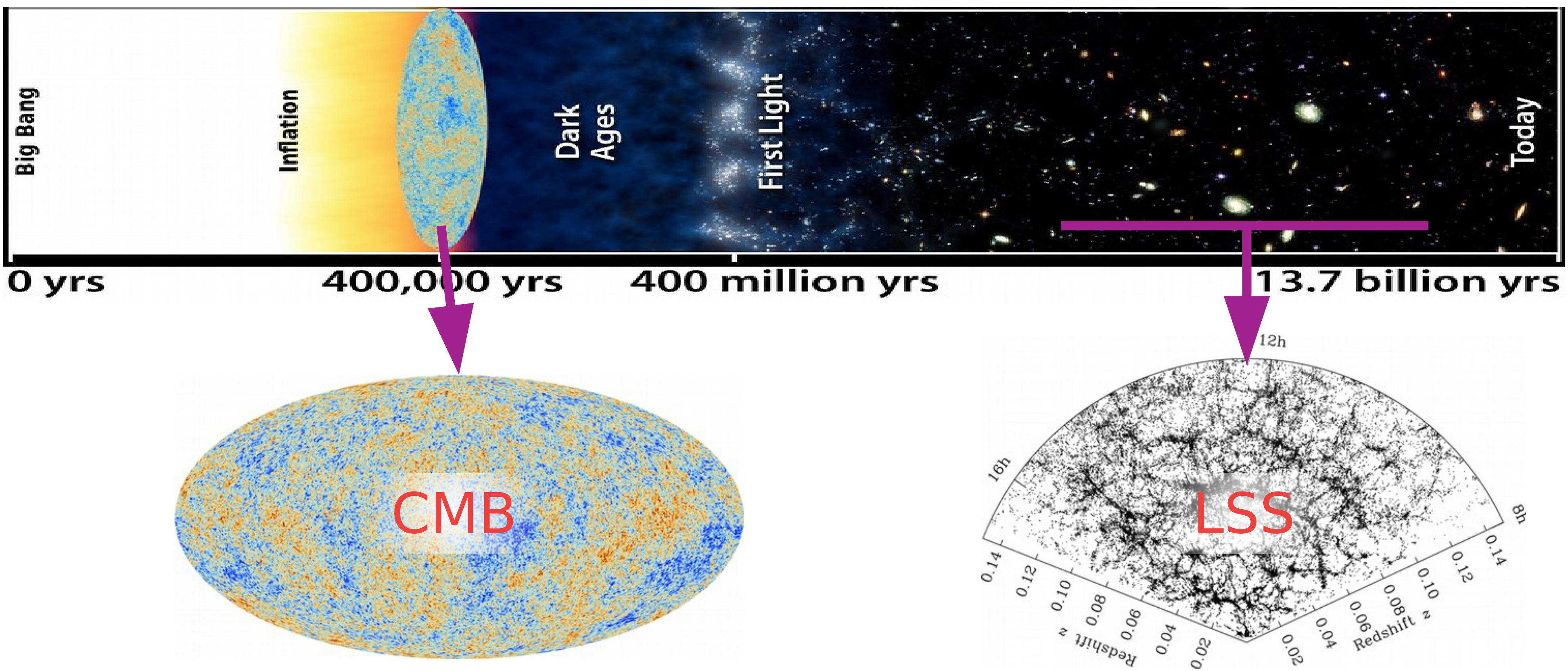




Joint analysis with external probes

Joint analysis with external probes

- Probes of different “sectors”:
  - Background evolution: all standard rulers/candles
  - Perturbations: probes of structure growth
- Probes of different epochs:

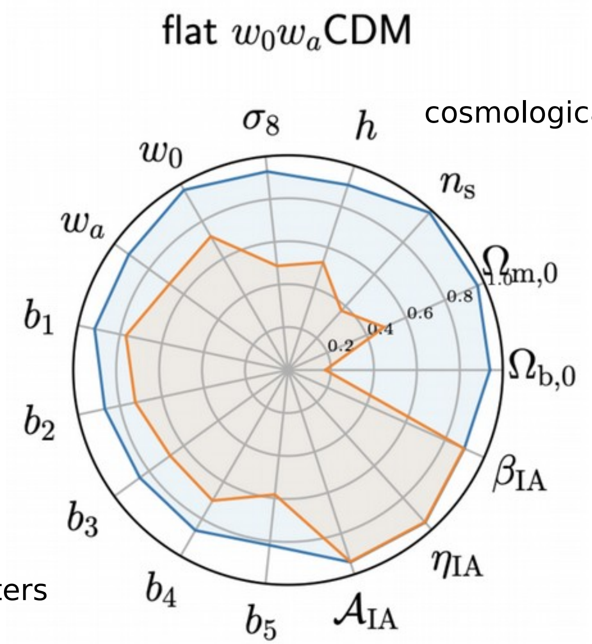


Joint analysis with external probes

Example with CMB data

CMB cross-correlations working group produce their own set of forecasts

- Euclid main probes + Simons Observatory CMB lensing (blue)
- Euclid main probes + all Simons Observatory CMB probes (orange)



cosmological parameters

nuisance parameters

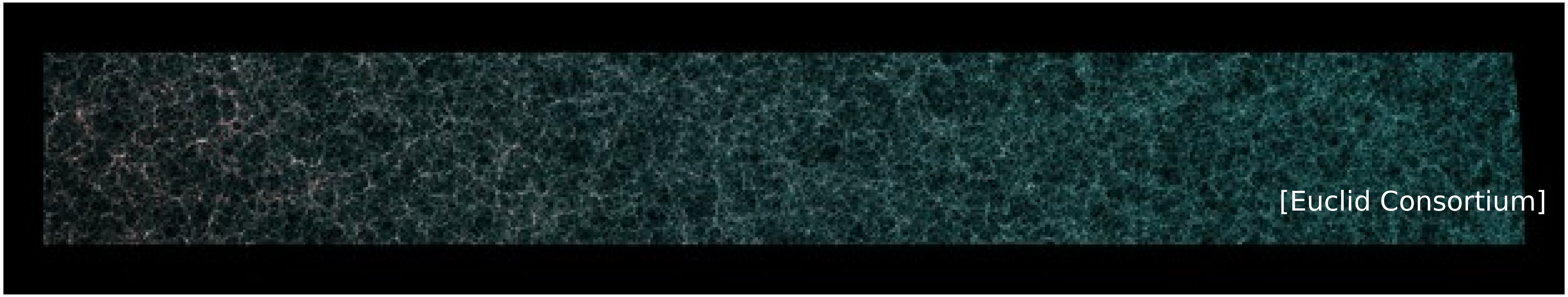
Improvements up to a factor of 10

[Euclid Collaboration XV., Ilic et al, A&A 657, A91 (2022)]

Towards data analysis

Towards data analysis

- Development of cosmological simulations to develop the analysis pipelines:
  - Flagship galaxy catalog [Carretero, Castander, Fosalba, Neissner, Pozzetti, Stadel, Tallada++]:

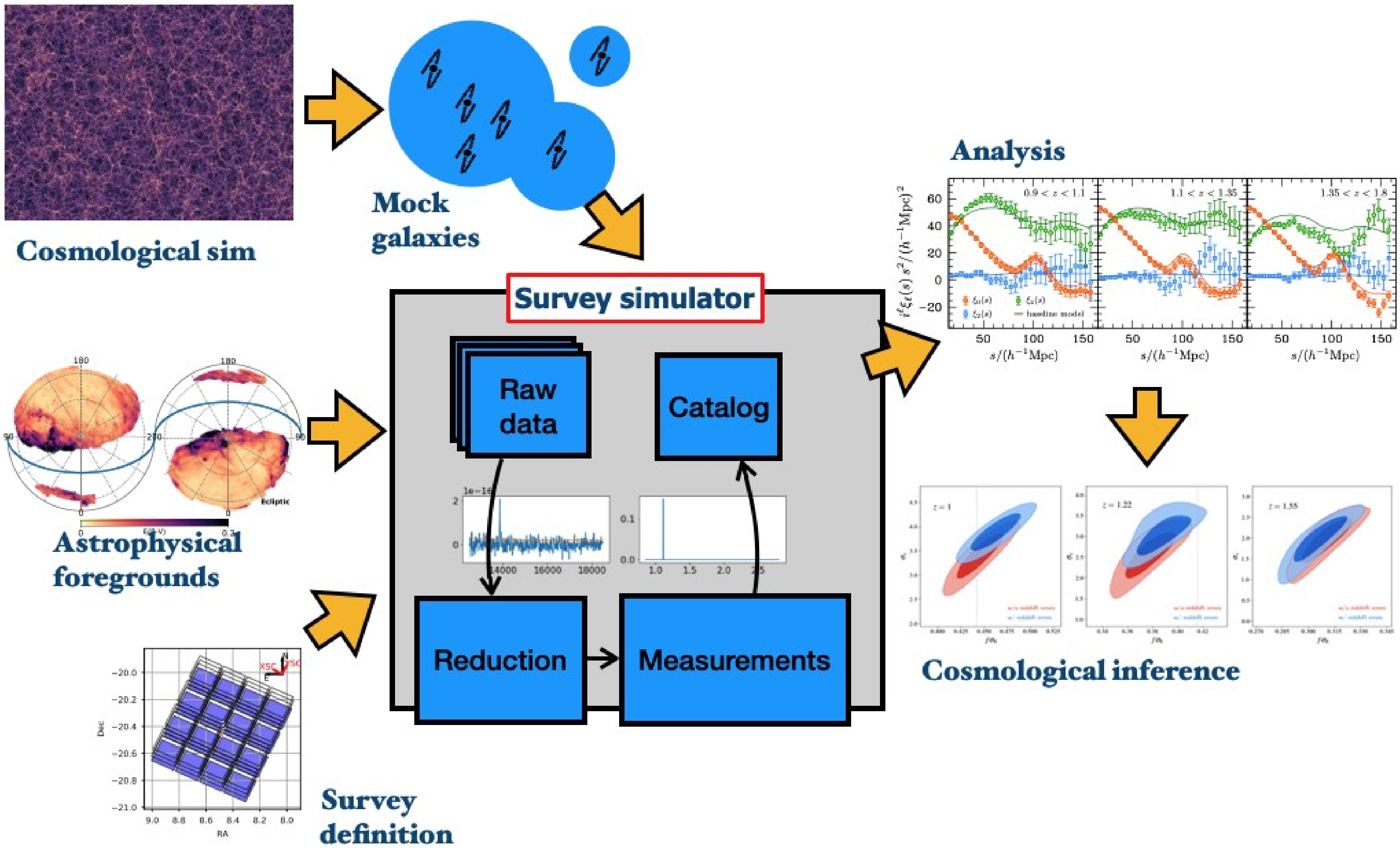


- WIDE: 10^9 M_{sun} resolution (4.1 trillion particles, 3600 Mpc/h box)

- DEEP: 10^8 M_{sun} resolution (0.9 trillion particles, 1000 Mpc/h box)

Towards data analysis

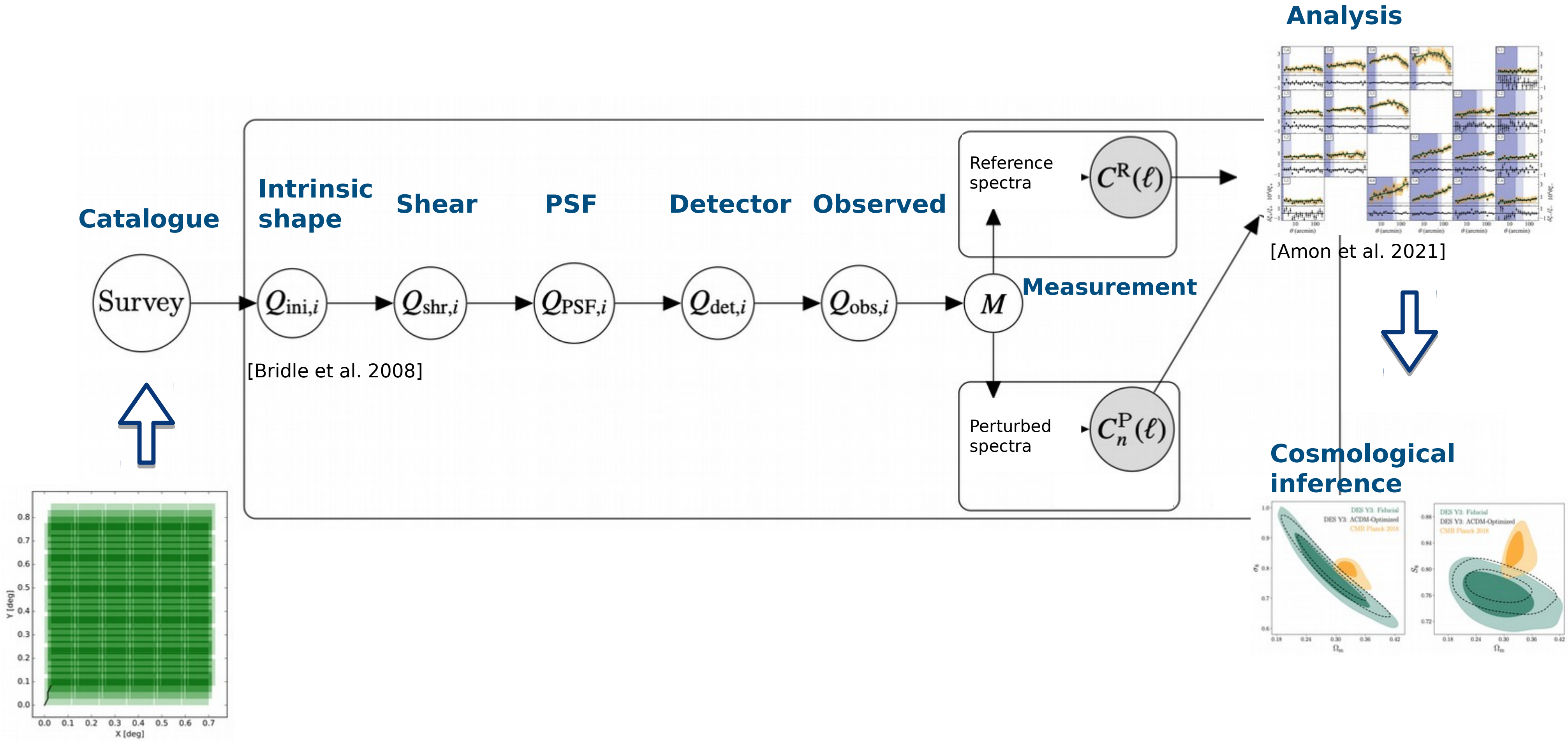
- Complex measurements: End-to-end simulations — spectroscopic galaxy clustering



[Slide courtesy of B. Granett and GC end-to-end group]

Towards data analysis

- Complex measurements: End-to-end simulations — weak lensing & photometric galaxy clustering

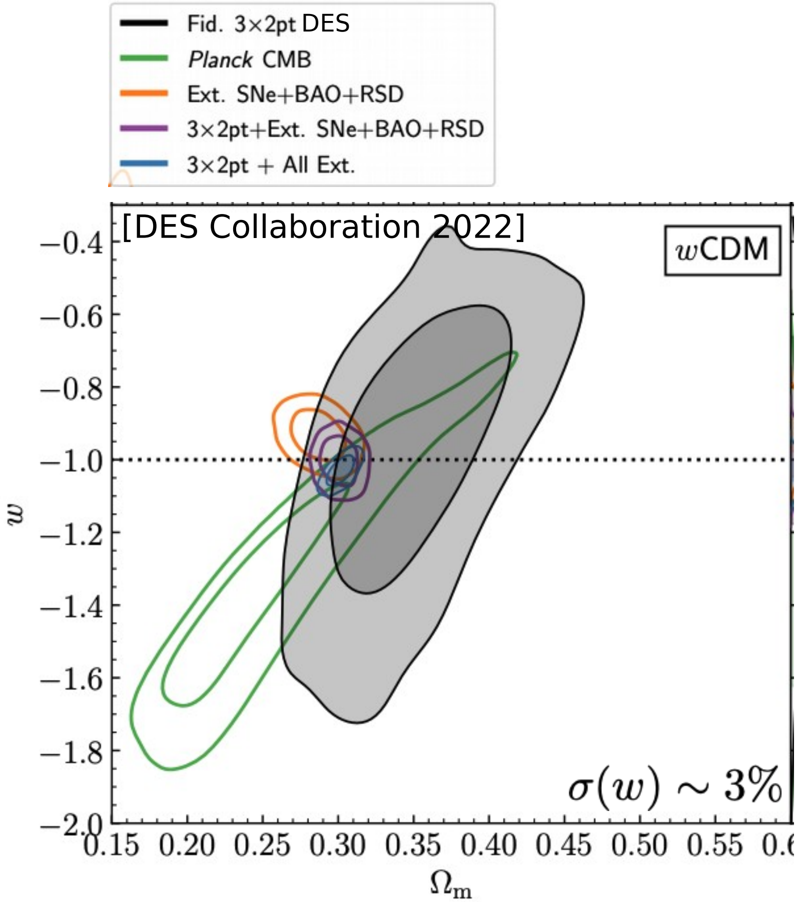


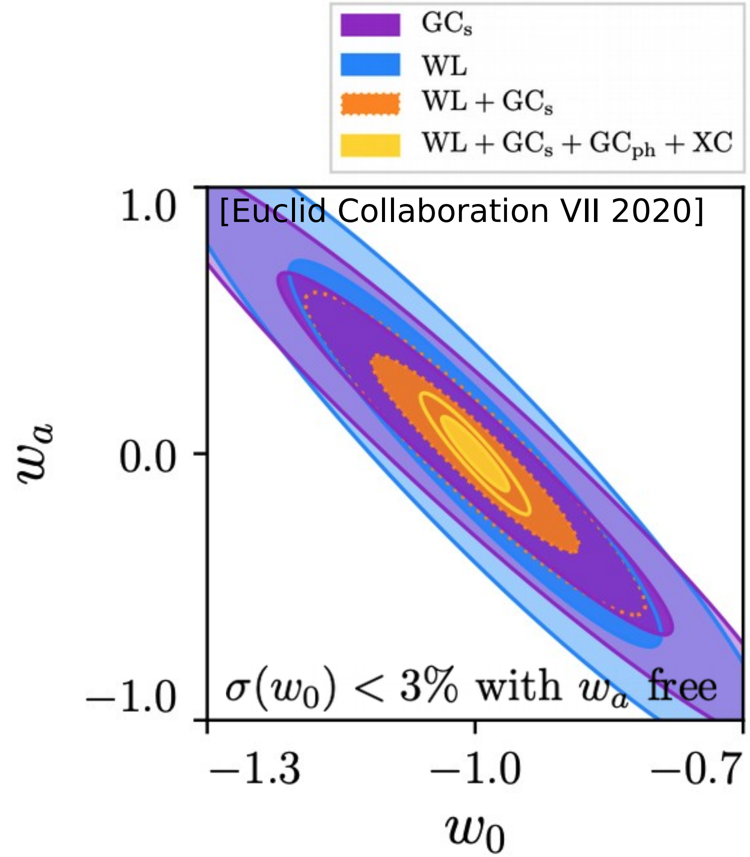
Towards data analysis

- **Simulations**:
  - more volume and resolution, emulators
  - end-to-end pipelines
- **Modelling** of the observables:
  - nonlinear modelling of the matter and galaxy power spectra, including RSDs
  - magnification and other relativistic contributions
- Towards the **coming data**:
  - addition of systematic uncertainties and mitigation techniques

Conclusions

- *Euclid* will provide unprecedented constraints on **dark matter**, **gravity** at cosmological scales and will constrain **dark energy better than all current observations together**:





The end (for now!)

Thank you for
your attention !