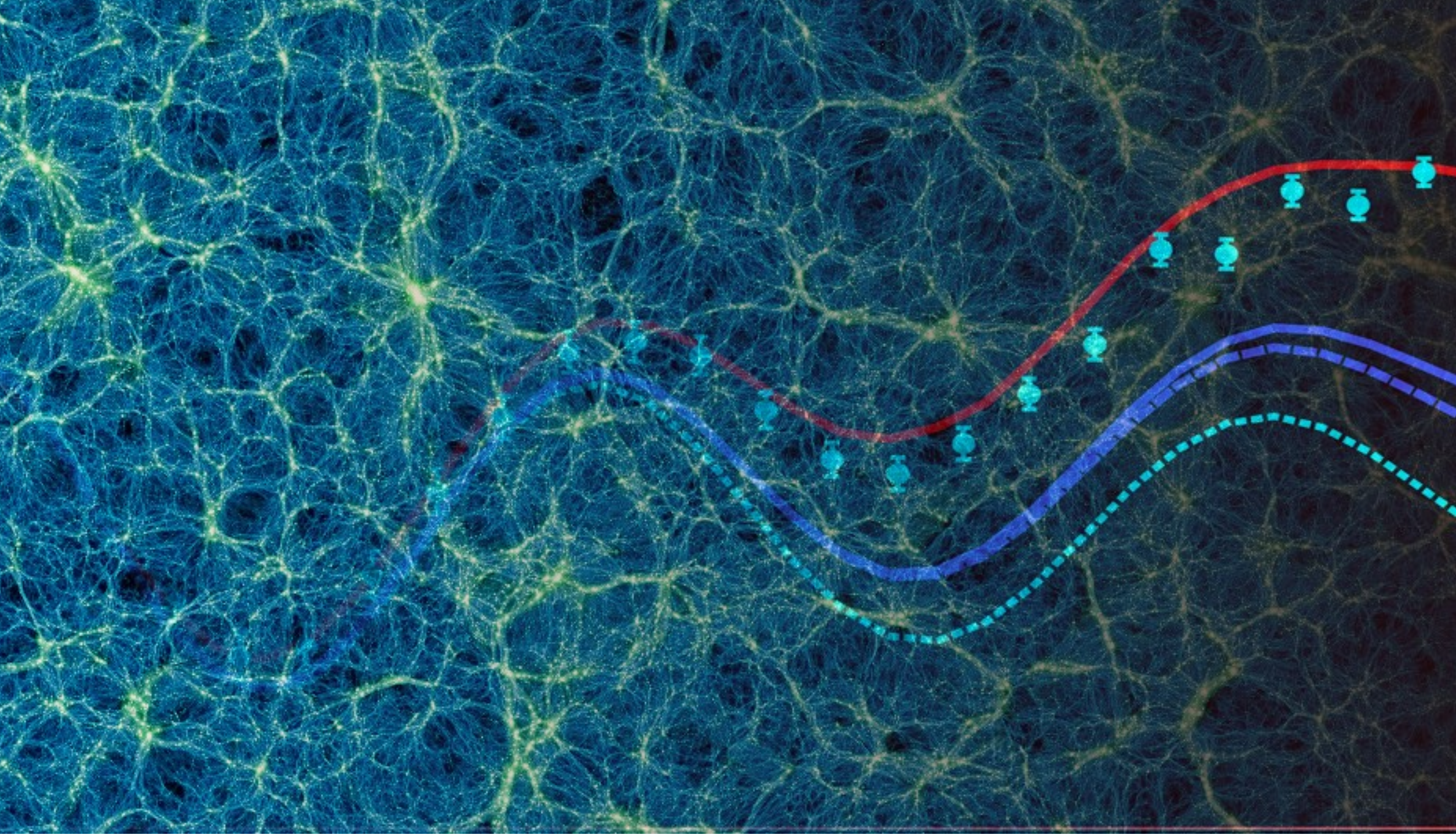


Cosmology: open problems & perspectives

Emiliano Sefusatti, Osservatorio Astronomico di Trieste

Let’s start from the beginning …

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8 \pi G \, T_{\mu\nu}$$

General Relativity

$$v = H_0 D$$

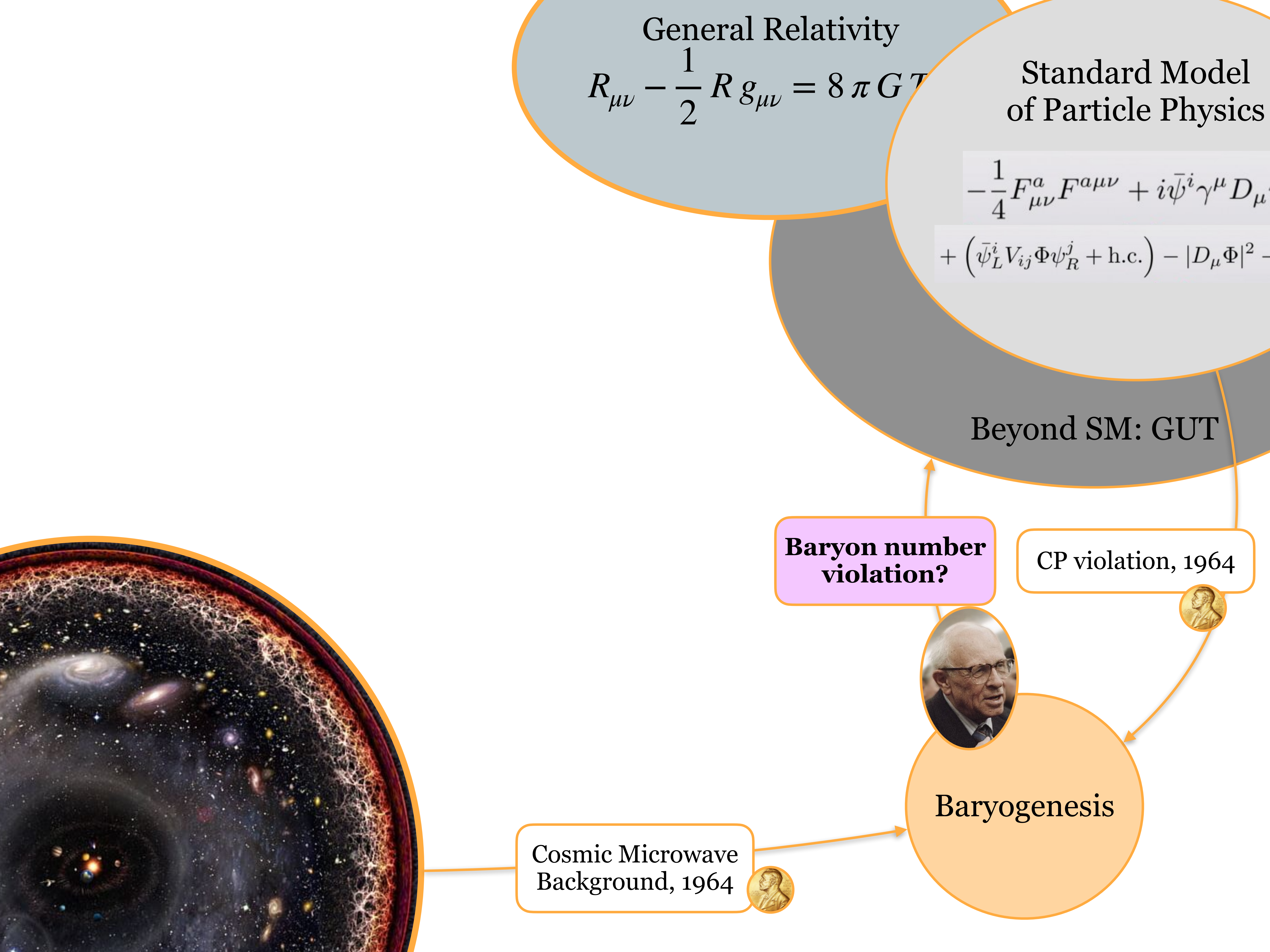
General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\,\pi\, G\, T$$

Standard Model of Particle Physics

$$-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}^i\gamma^\mu D_\mu$$

$$+\left(\bar{\psi}^i_L V_{ij}\Phi\psi^j_R + \text{h.c.}\right) - |D_\mu\Phi|^2 -$$


General Relativity
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Standard Model
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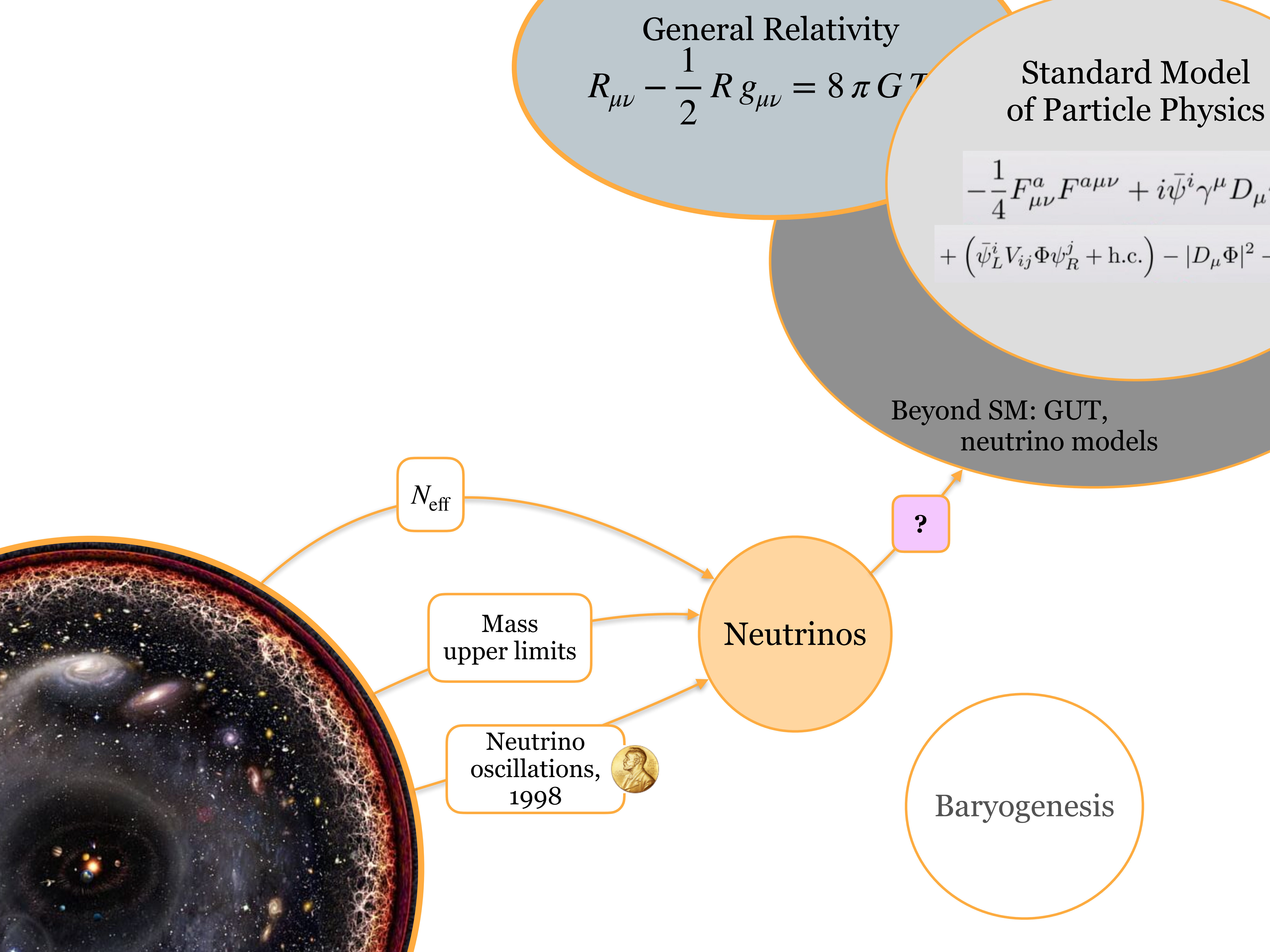
$+ \left(\bar{\psi}^{i}_{L} V_{ij} \Phi \psi^{j}_{R} + \mathrm{h.c.}\right) - |D_{\mu}\Phi|^{2}$
Beyond SM: GUT
Baryon number violation?
CP violation, 1964
Baryogenesis
Cosmic Microwave Background, 1964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$+ \left(\bar{\psi}^i_L V_{ij} \Phi \psi^j_R + \mathrm{h.c.} \right) - |D_\mu \Phi|^2 -$
Beyond SM: GUT,
neutrino models
?
N_{eff}
Mass
upper limits
Neutrino
oscillations,
1998
Neutrinos
Baryogenesis

General Relativity

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\,\pi\, G\, T$$

Standard Model
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$$-\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{\psi}^{i}\gamma^{\mu} D_{\mu}$$

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Beyond SM: GUT,
neutrino models,
WIMPs, axions

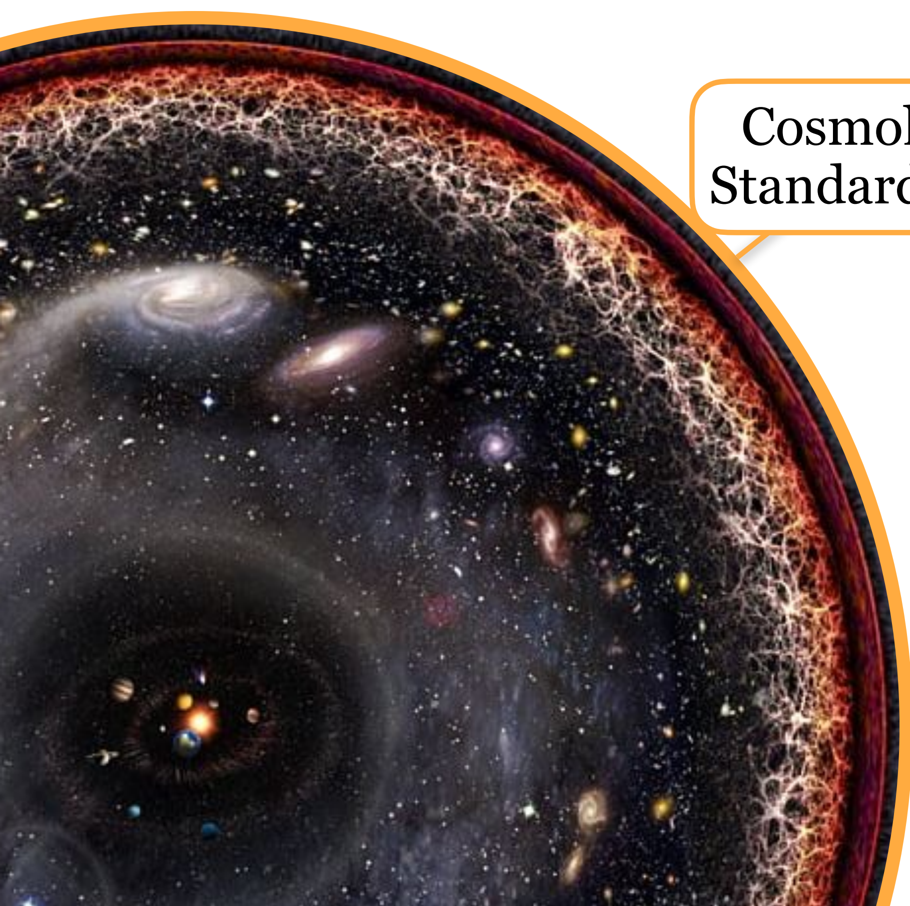
?

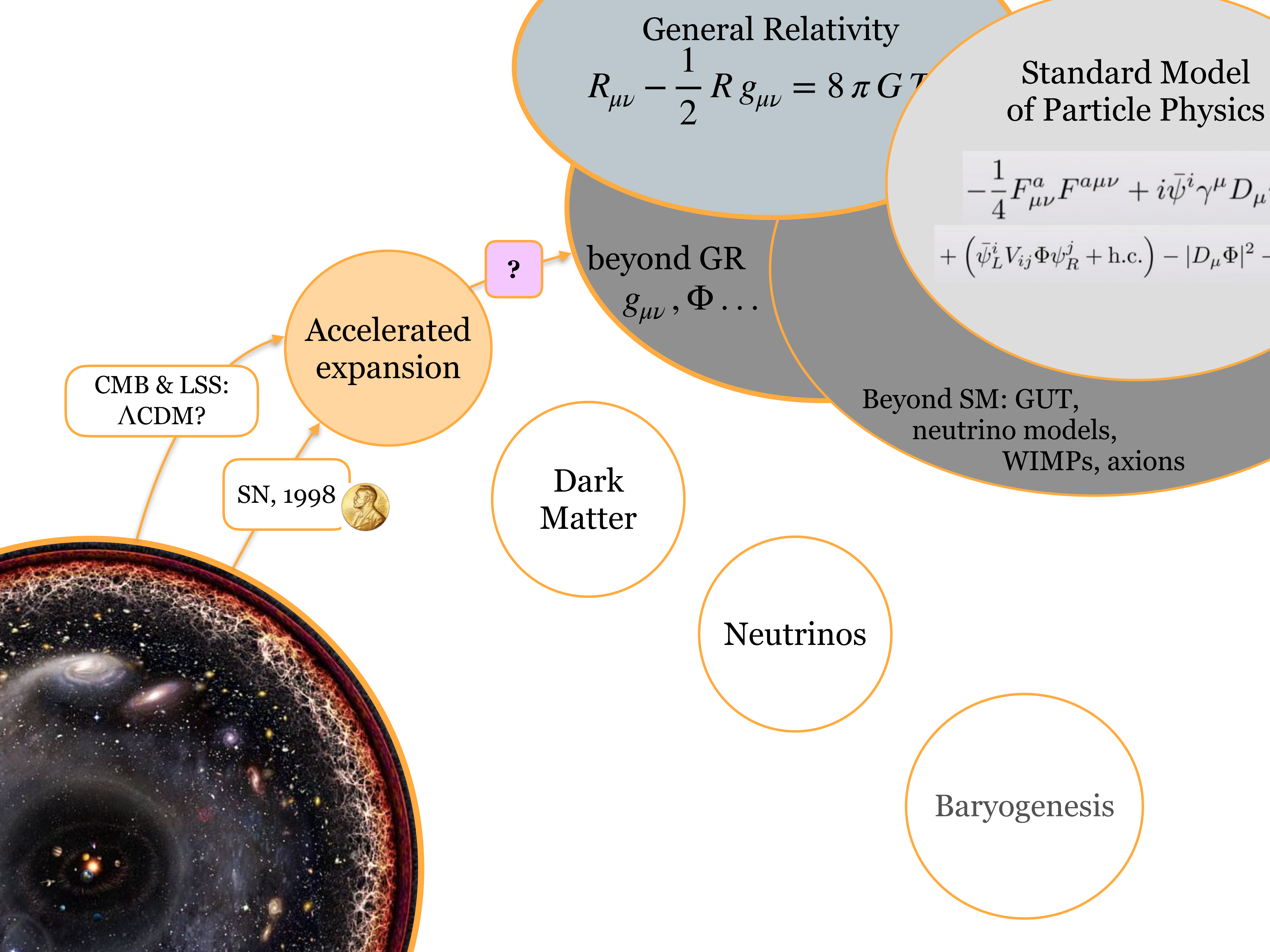
Dark
Matter

Cosmological
Standard Model

Neutrinos

Baryogenesis





General Relativity
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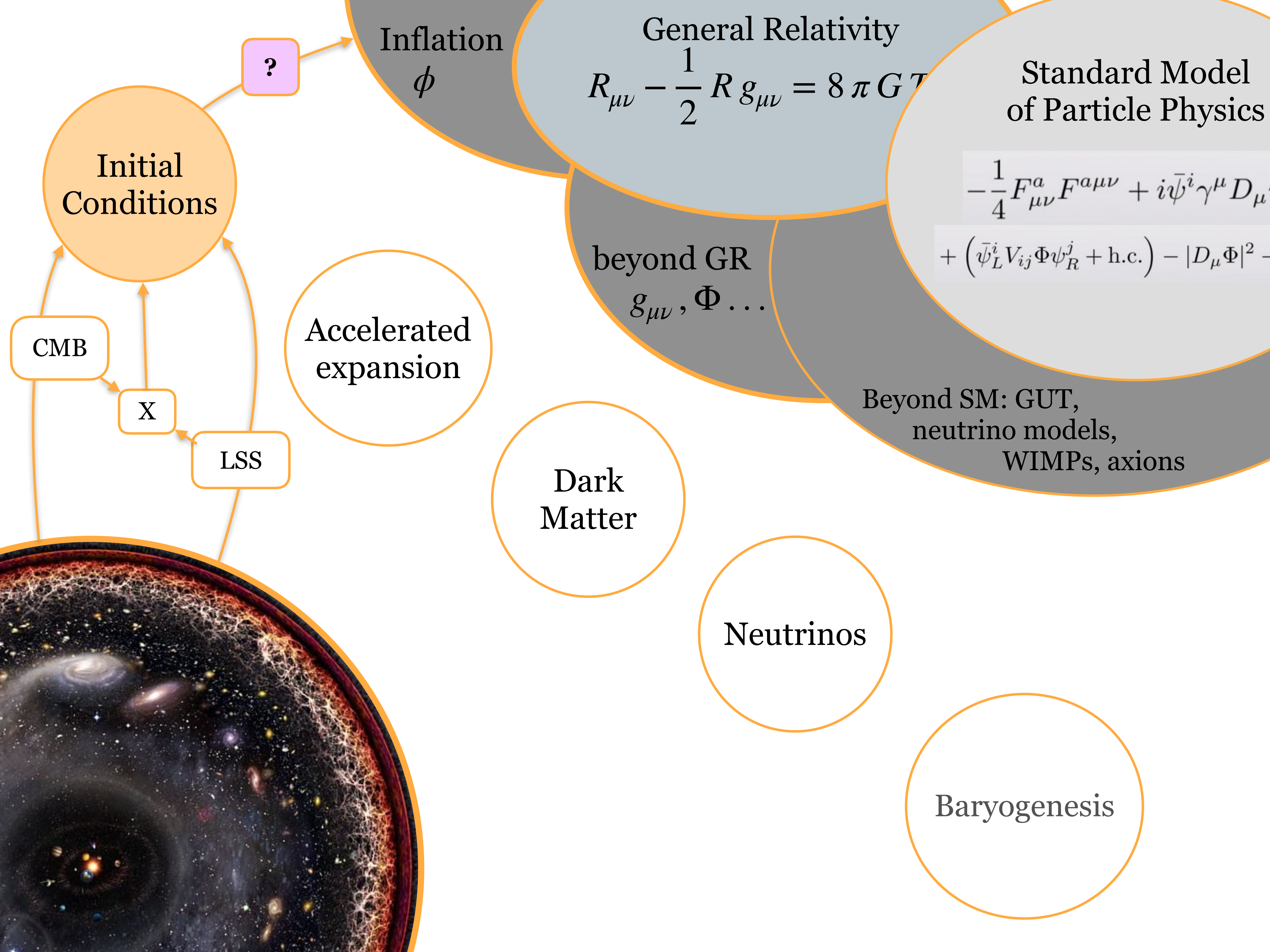
beyond GR
$g_{\mu\nu}\,, \Phi \ldots$
?
Accelerated expansion
CMB & LSS: ΛCDM?
SN, 1998
Beyond SM: GUT, neutrino models, WIMPs, axions
Dark Matter
Neutrinos
Baryogenesis


Inflation
ϕ
General Relativity
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?
Initial
Conditions
beyond GR
$g_{\mu\nu}\,, \Phi \ldots$
Accelerated
expansion
CMB
X
LSS
Beyond SM: GUT,
neutrino models,
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Dark
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Inflation
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General Relativity
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beyond GR
$g_{\mu\nu}\,,\Phi\ldots$

Beyond SM: GUT,
neutrino models,
WIMPs, axions

Initial Conditions

Accelerated expansion

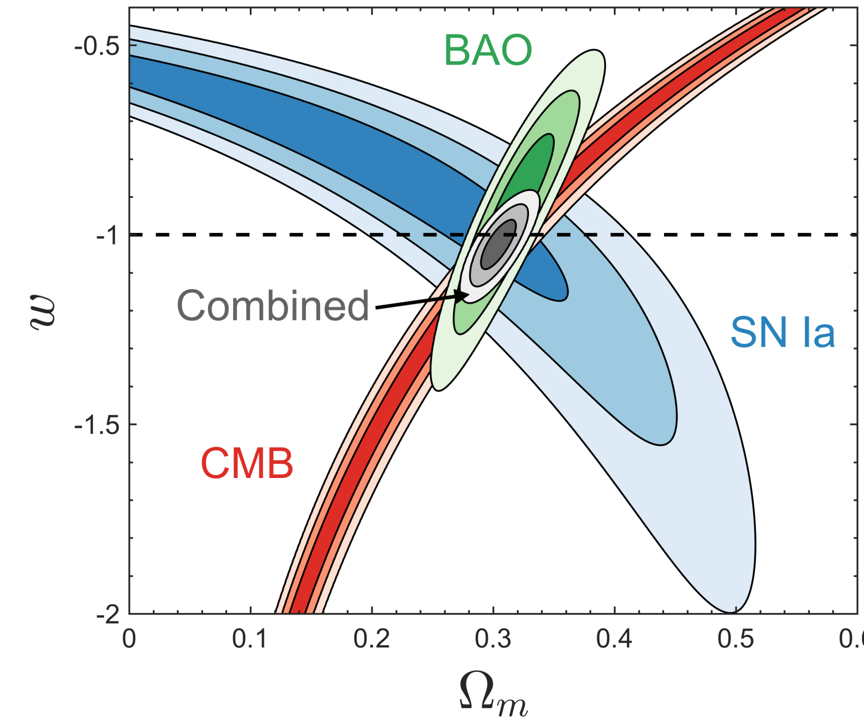
Dark Matter

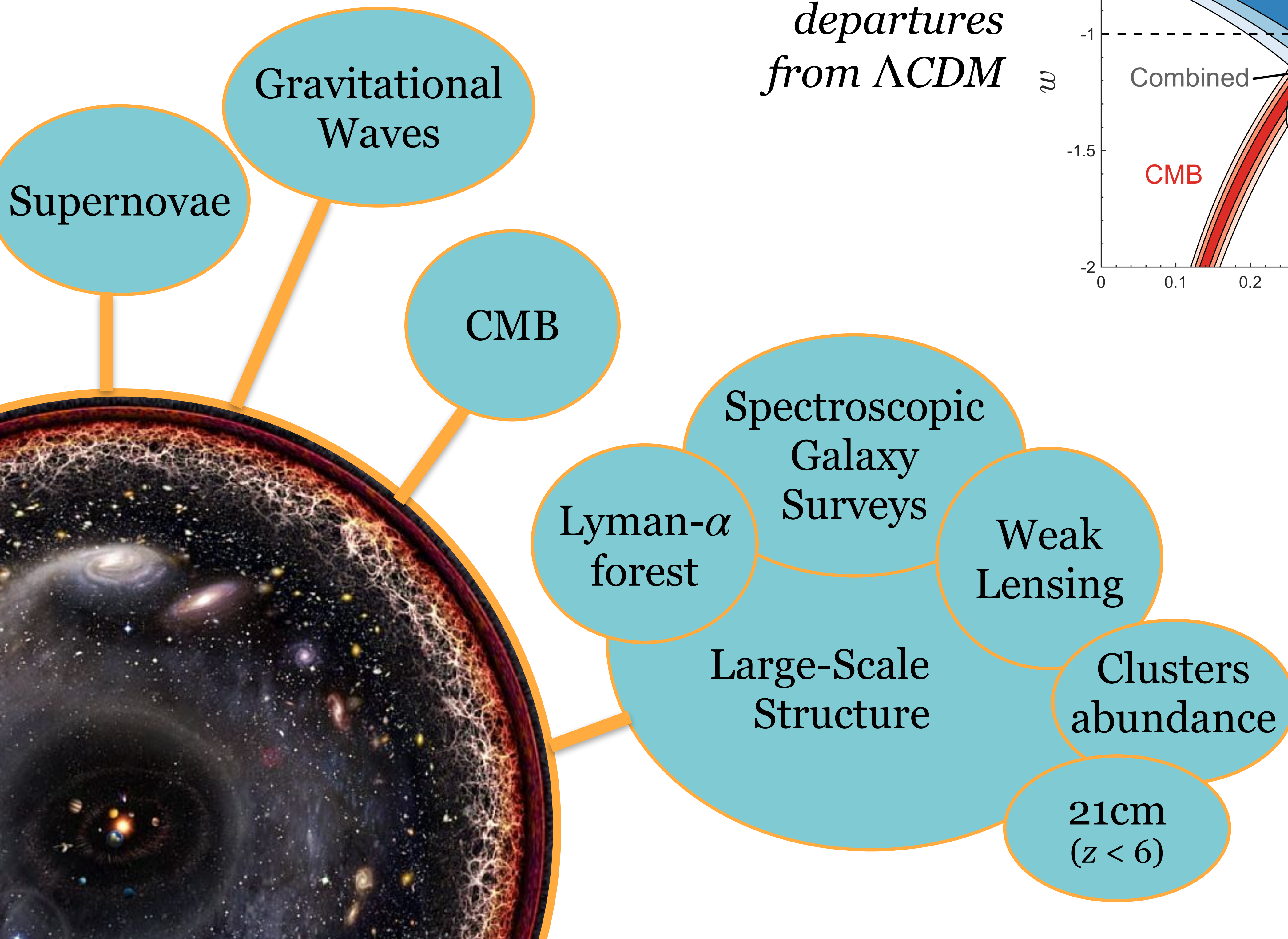
Neutrinos

Baryogenesis

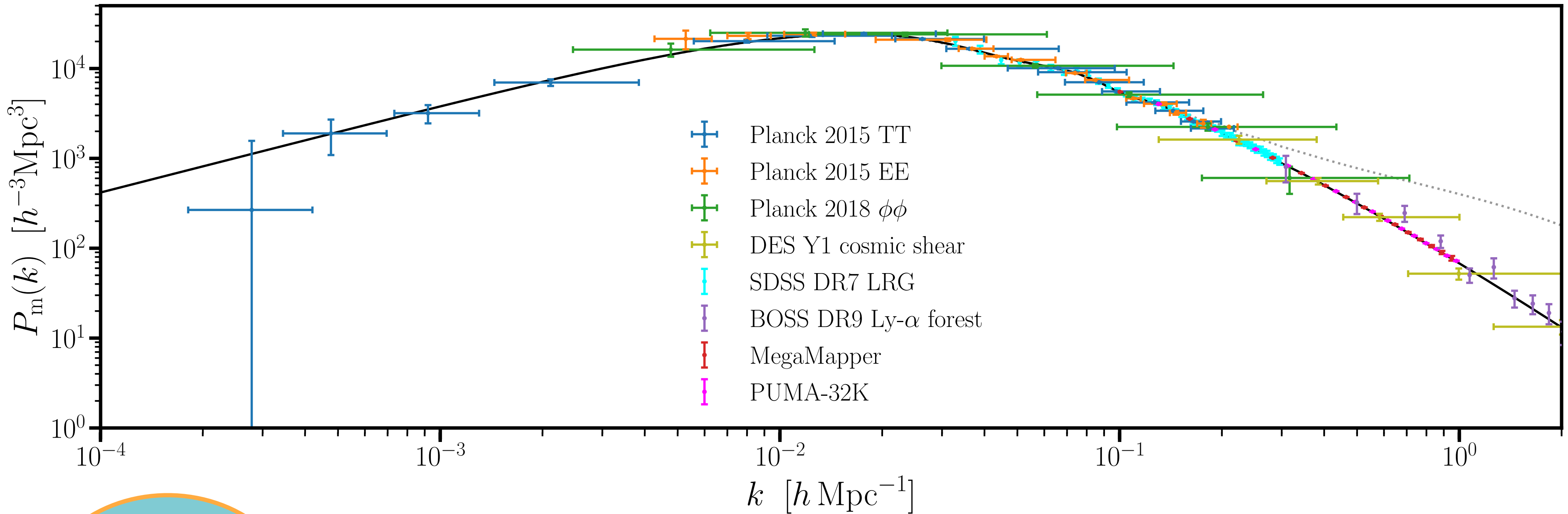
Cosmological Probes

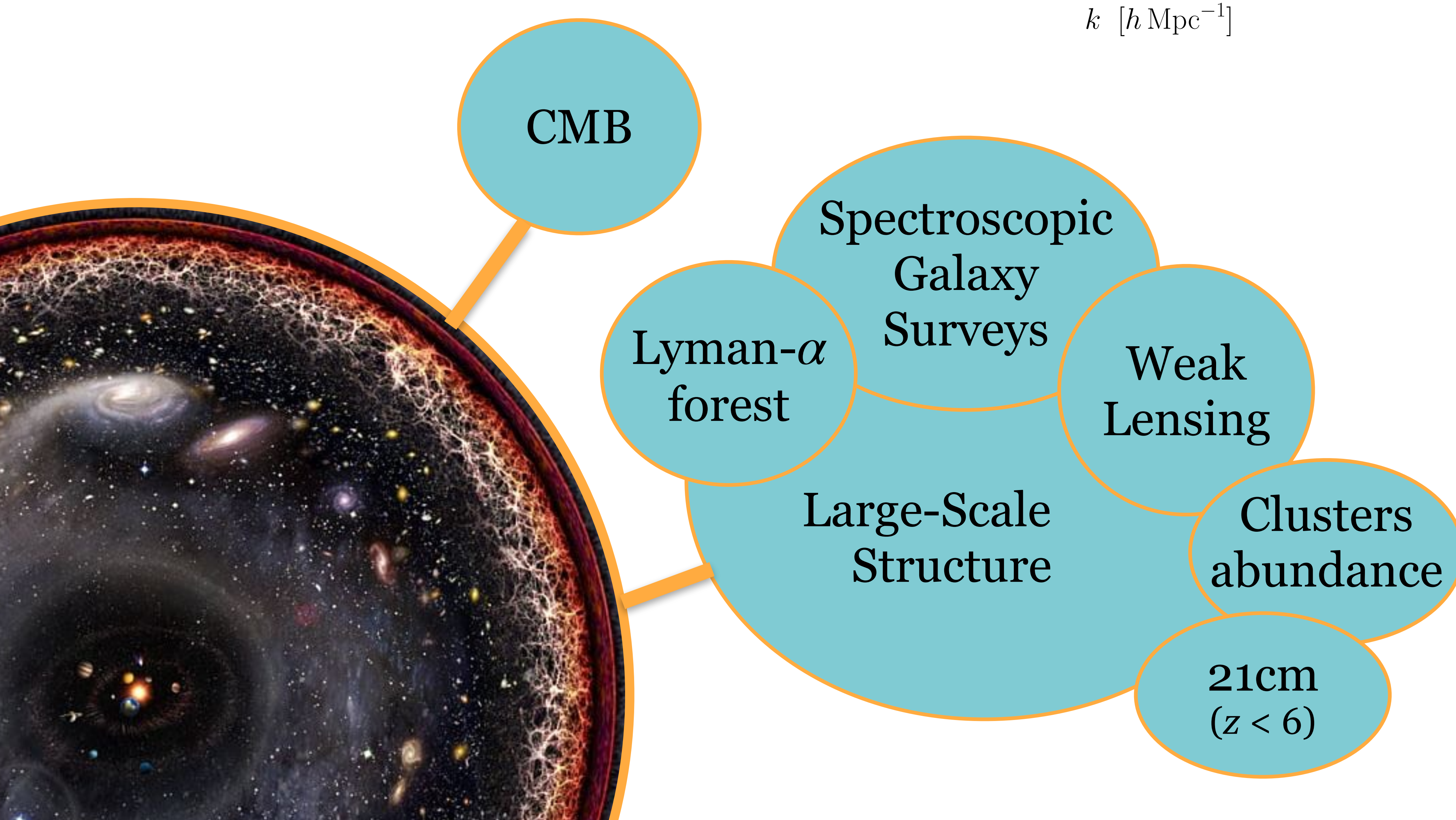
Combination of probes is crucial to test departures from ΛCDM





A great advancement is expected from probes of ***perturbations***





Volume is key

$$N_{\text{modes}} \sim V k_{\max}^3$$

Cosmological Tensions

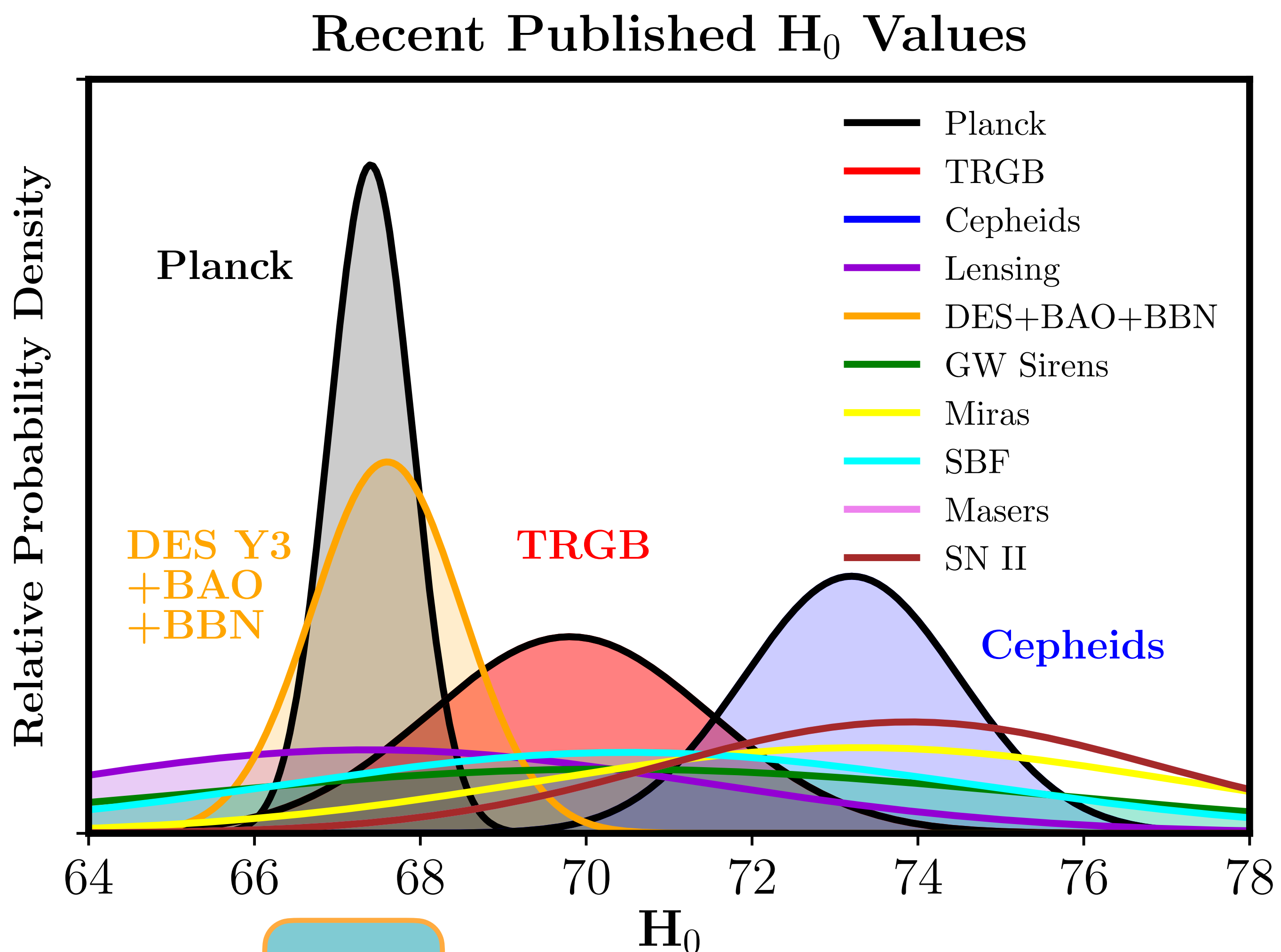
An example:
Hubble constant measurements

Is this real?

If it is, then it is an extremely exciting **challenge to theory**

If not, then we need to work a lot on systematics, since the **error bars are getting very small** …

Other tensions are there, as the one on σ_8:
a “dynamical” one



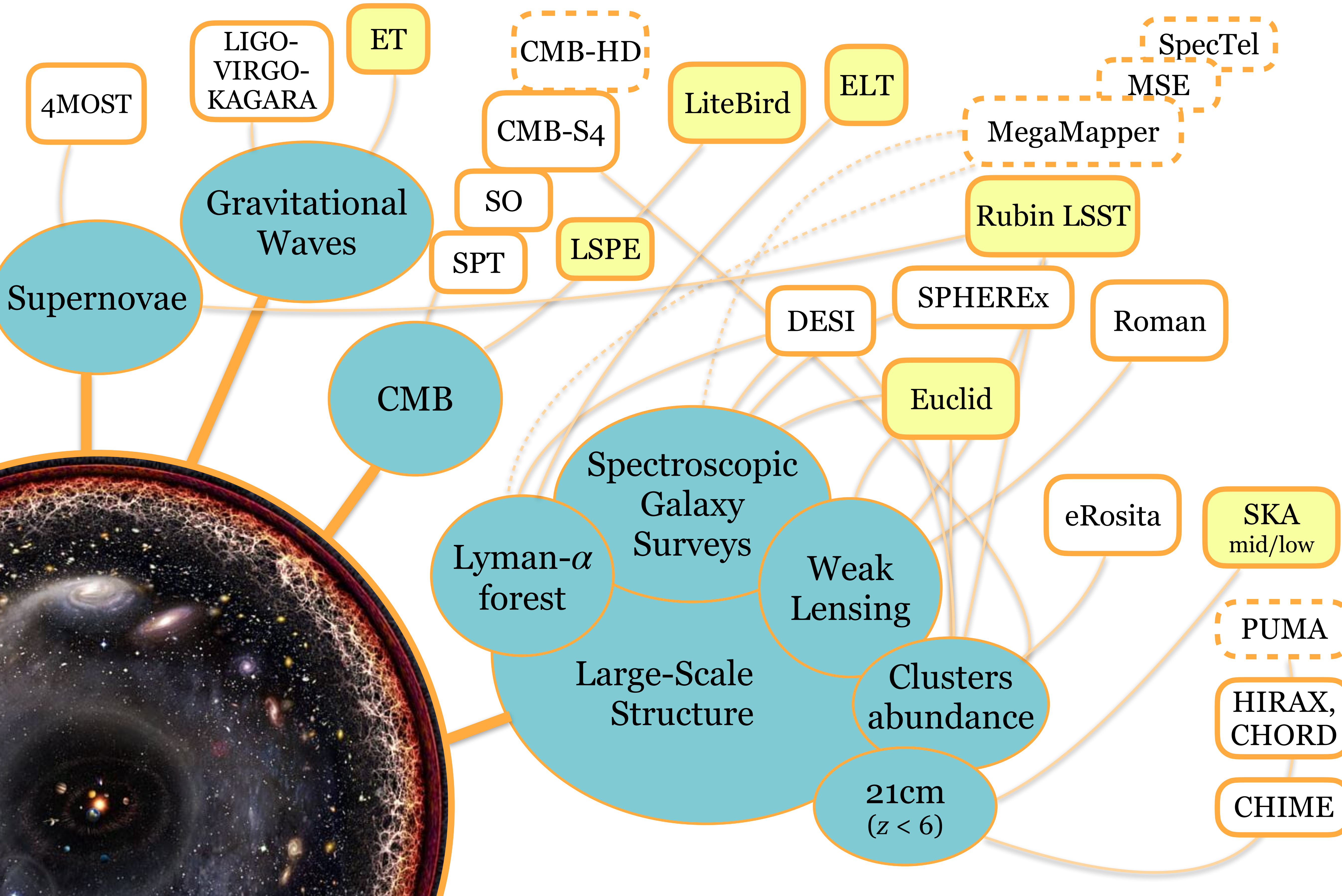
CMB

Galaxy Clustering

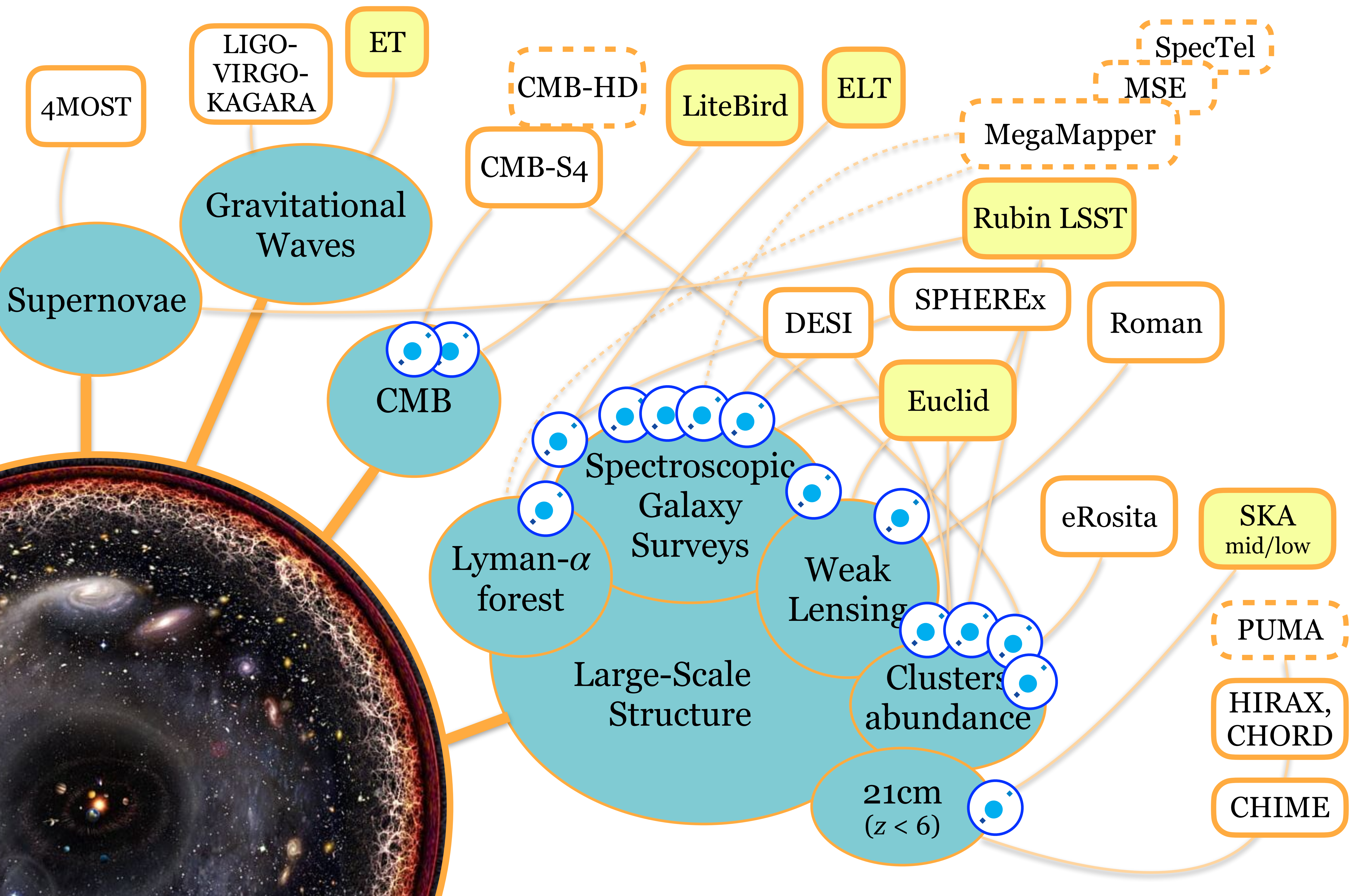
CMB lensing

Supernovae

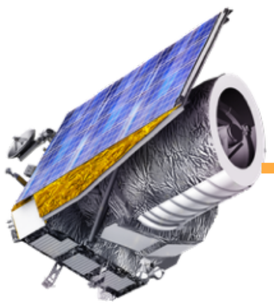
Gravitational Waves


4MOST
LIGO-VIRGO-KAGARA
ET
CMB-HD
CMB-S4
SO
SPT
LSPE
LiteBird
ELT
SpecTel
MSE
MegaMapper
Rubin LSST
SPHEREx
DESI
Roman
Euclid
eRosita
SKA mid/low
PUMA
HIRAX, CHORD
CHIME
Supernovae
Gravitational Waves
CMB
Spectroscopic Galaxy Surveys
Lyman-α forest
Weak Lensing
Large-Scale Structure
Clusters abundance
21cm (z < 6)

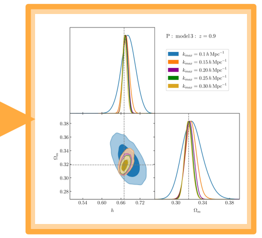
INAF is “sparse-sampling” this huge effort



A variety of tasks, expertises & backgrounds



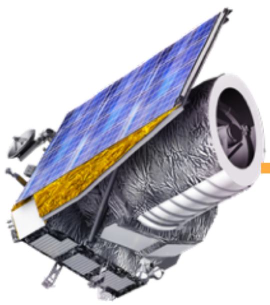
Cosmological parameters

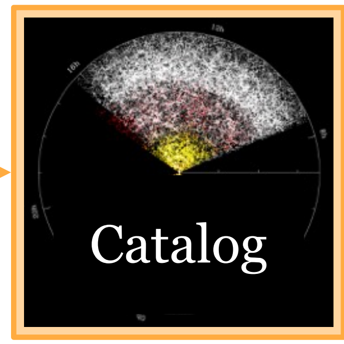


For each of these probes the variety in the expertise required has been steadily growing over the past years ...

A variety of tasks, expertises & backgrounds

A variety of tasks, expertises & backgrounds



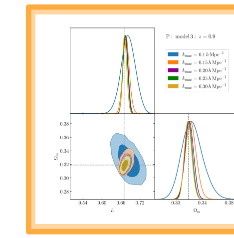


P&P

Estimators

$\hat{P}_{obs}(k)$

Cosmological parameters

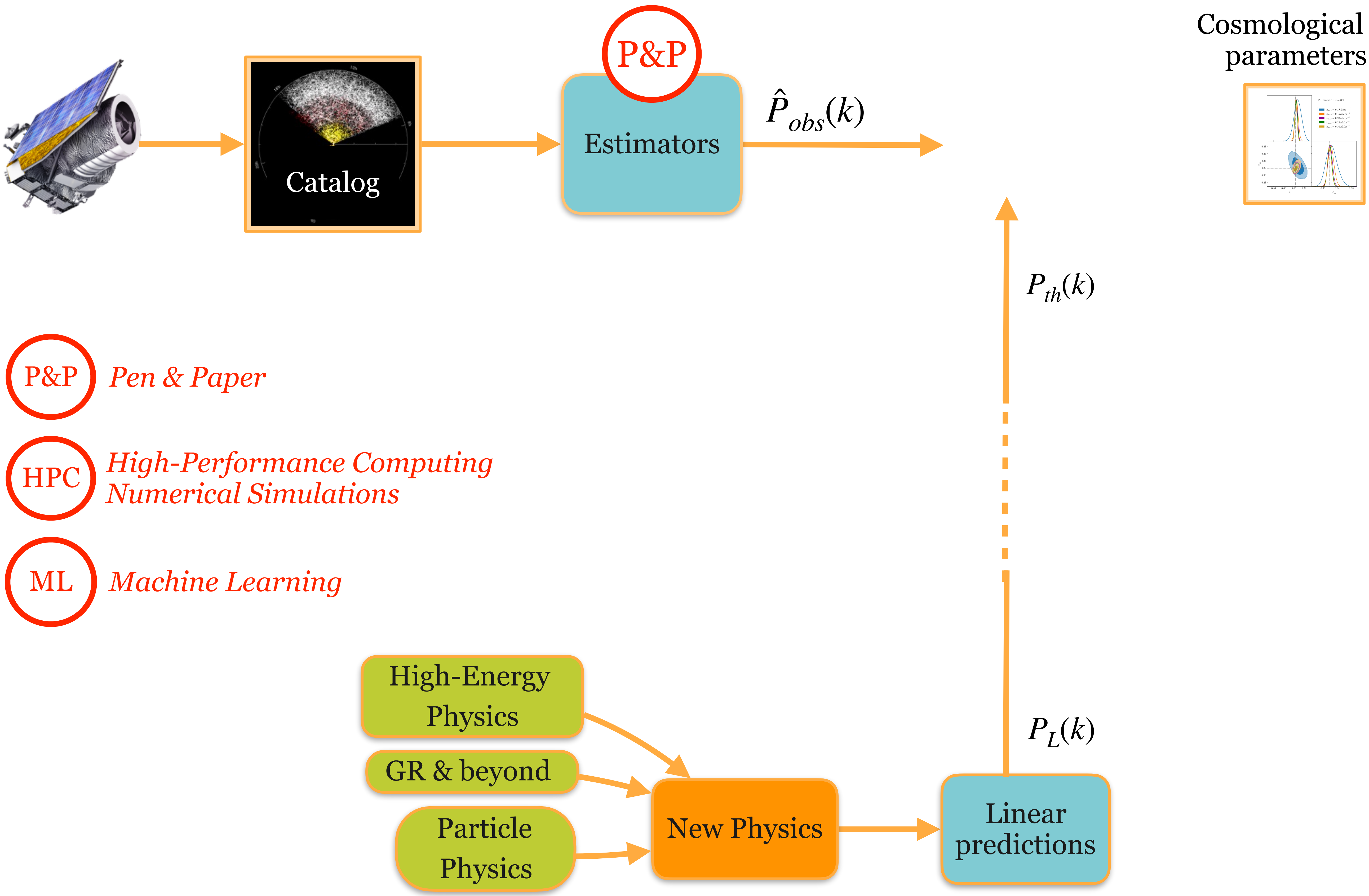


P&P *Pen & Paper*

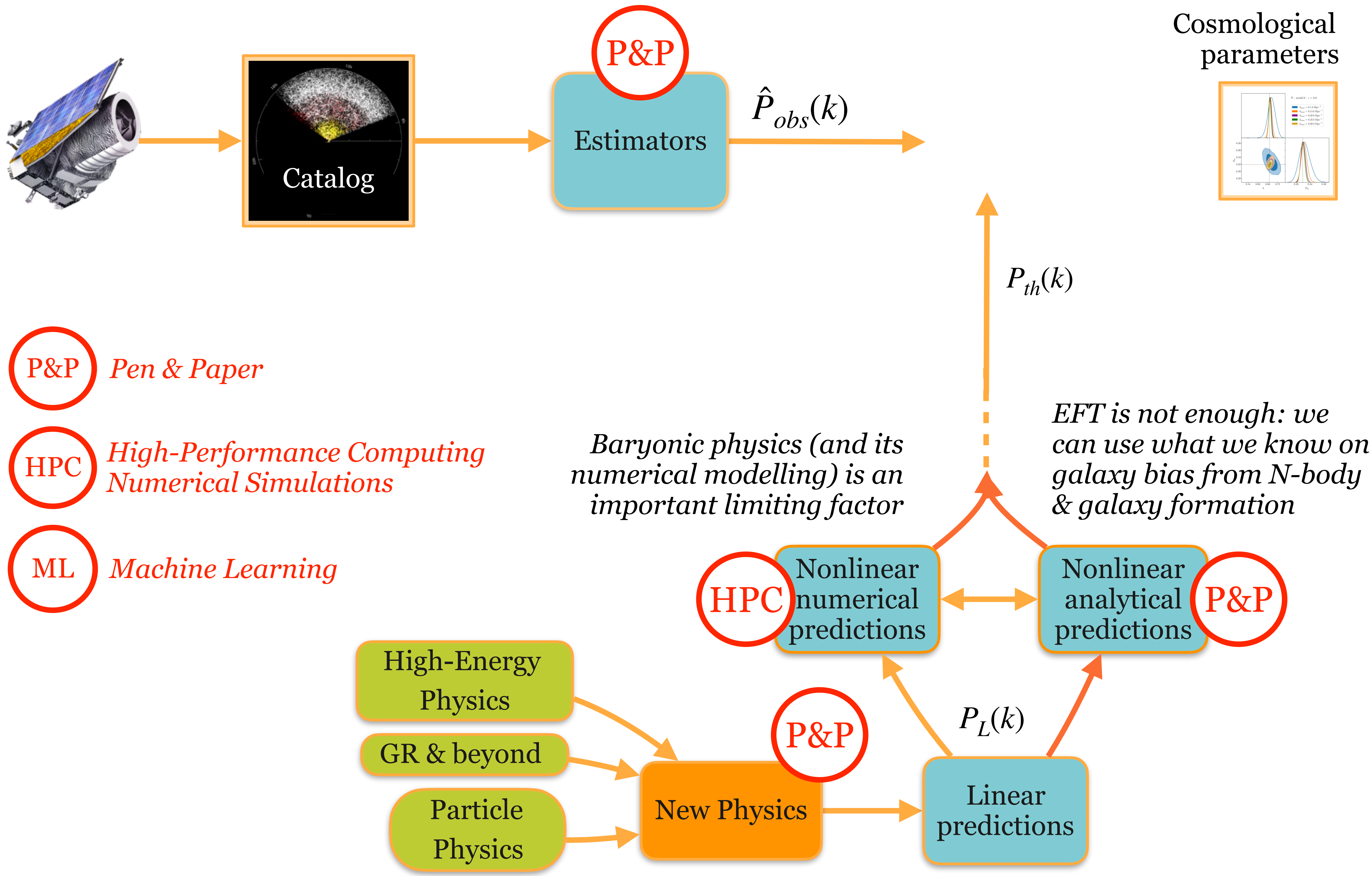
HPC *High-Performance Computing*
Numerical Simulations

ML *Machine Learning*

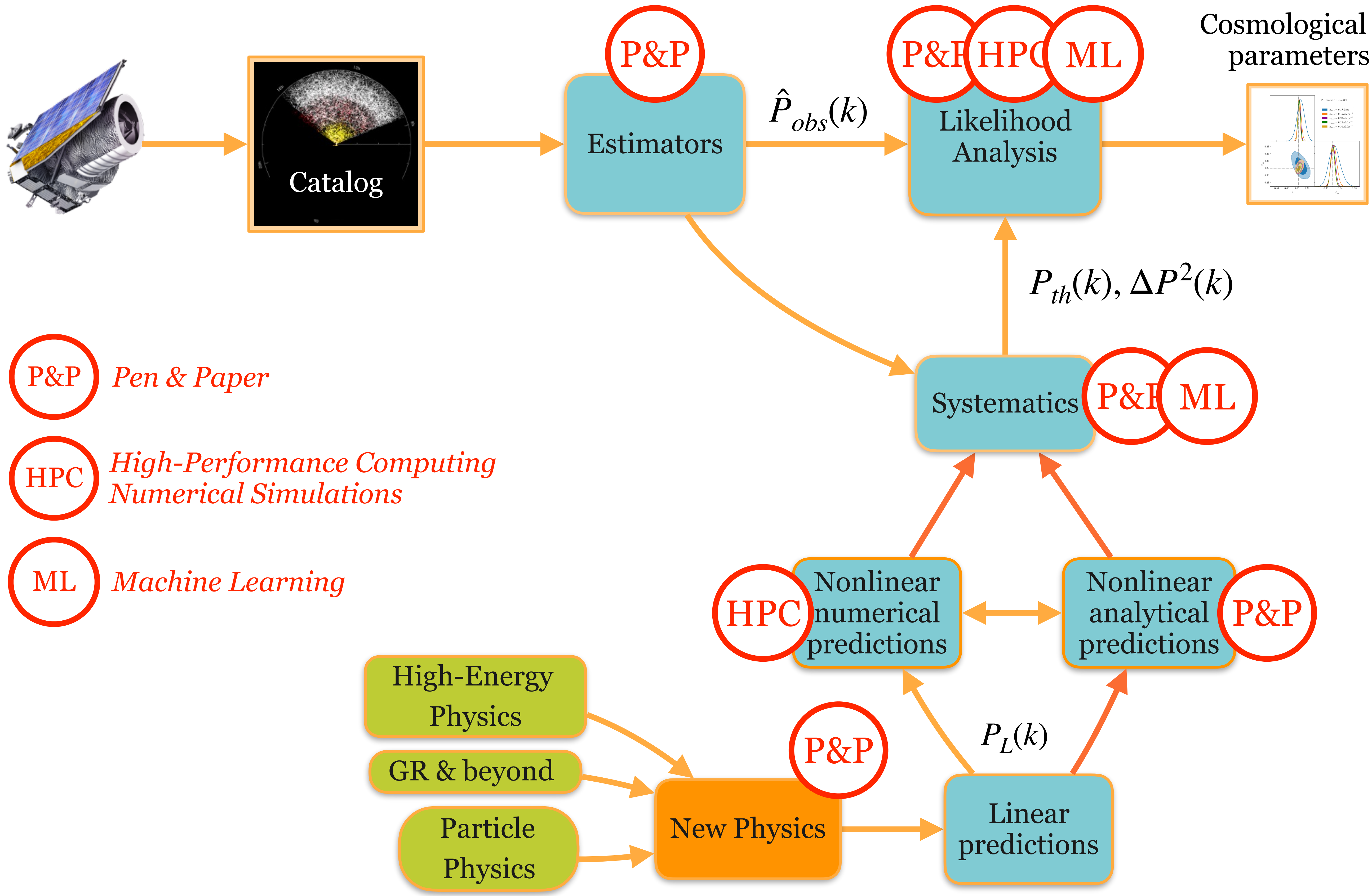
A variety of tasks, expertises & backgrounds



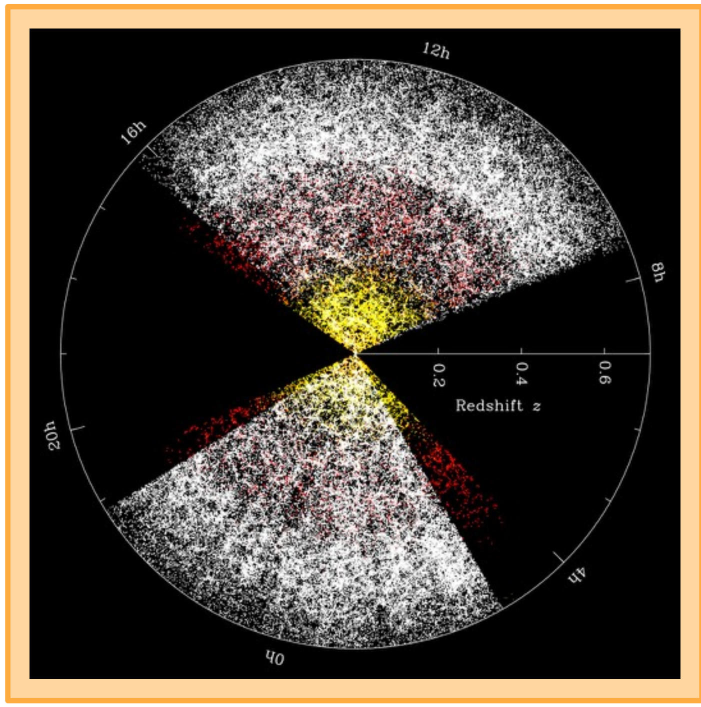
A variety of tasks, expertises & backgrounds



A variety of tasks, expertises & backgrounds

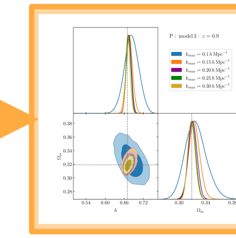


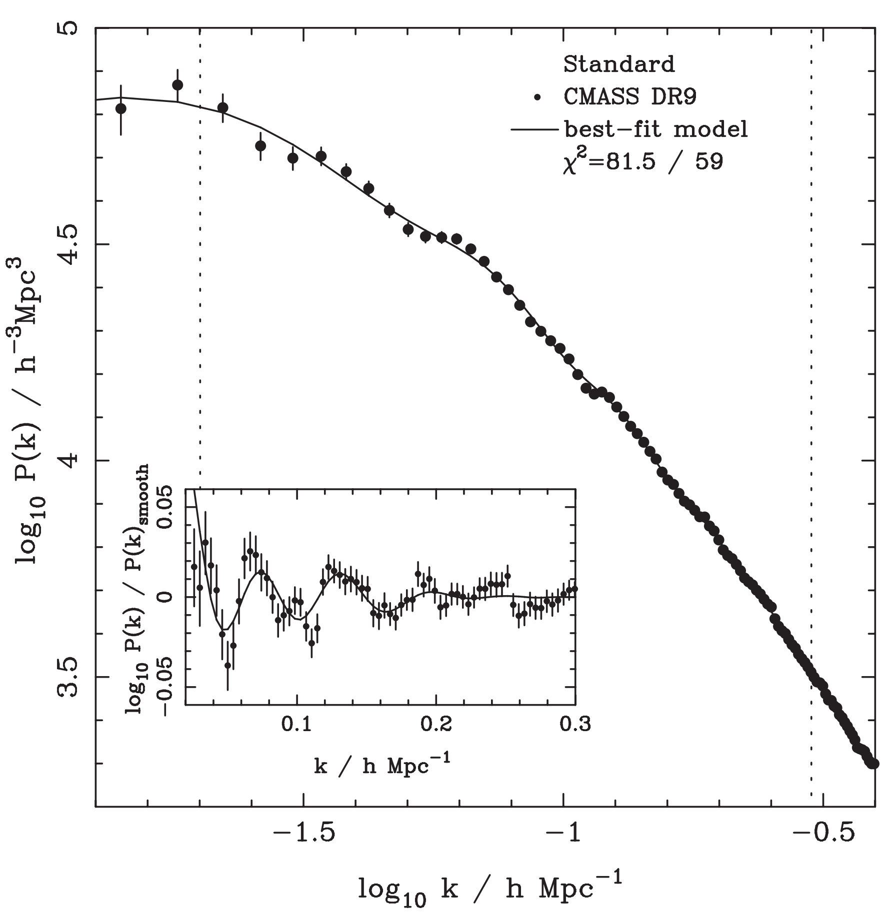
Several new methods are being proposed and explored



Power Spectrum, $P(k)$ / 2-Point Function, $\xi(r)$

Cosmological parameters





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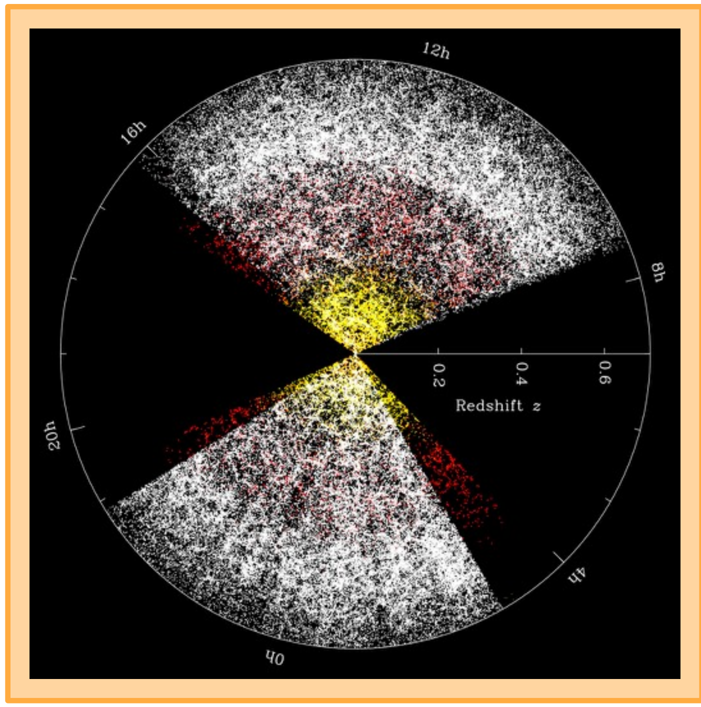
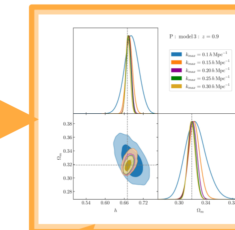
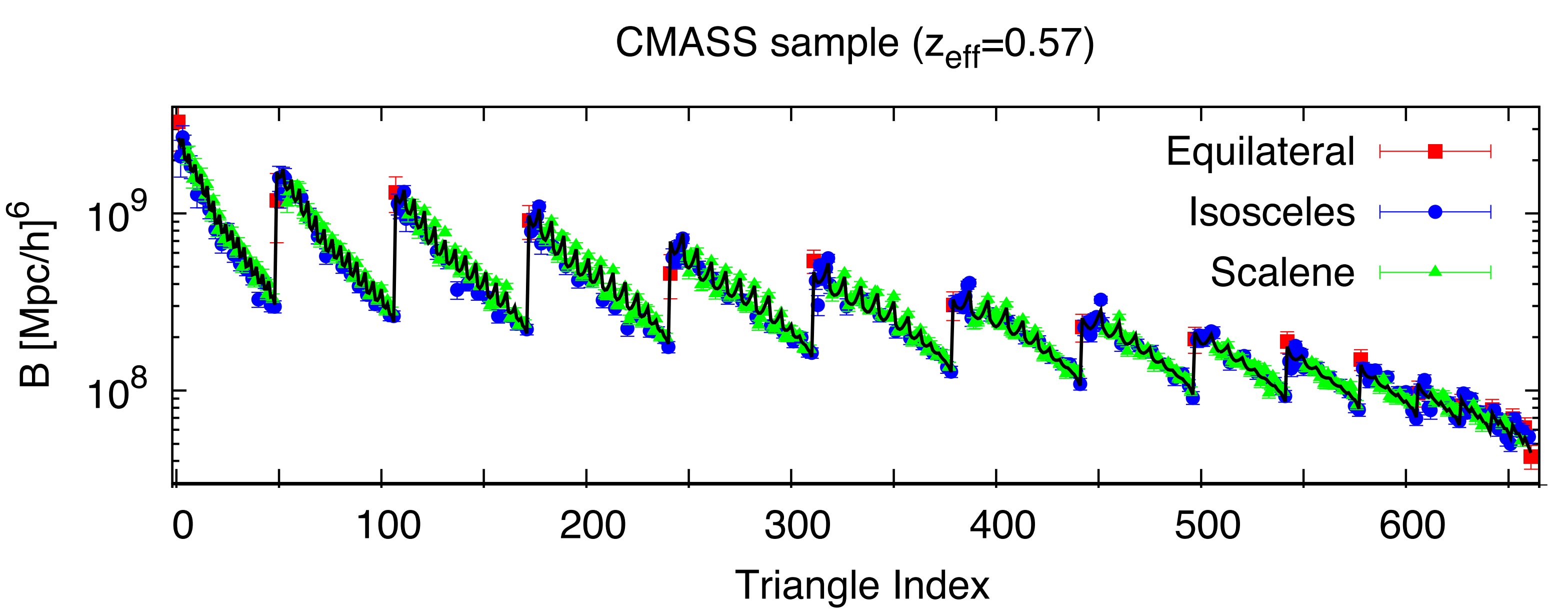


Power Spectrum, $P(k)$ / 2-Point Function, $\xi(r)$

Higher-Order Correlations, e.g. $B(k_1, k_2, k_3)$

Cosmological parameters





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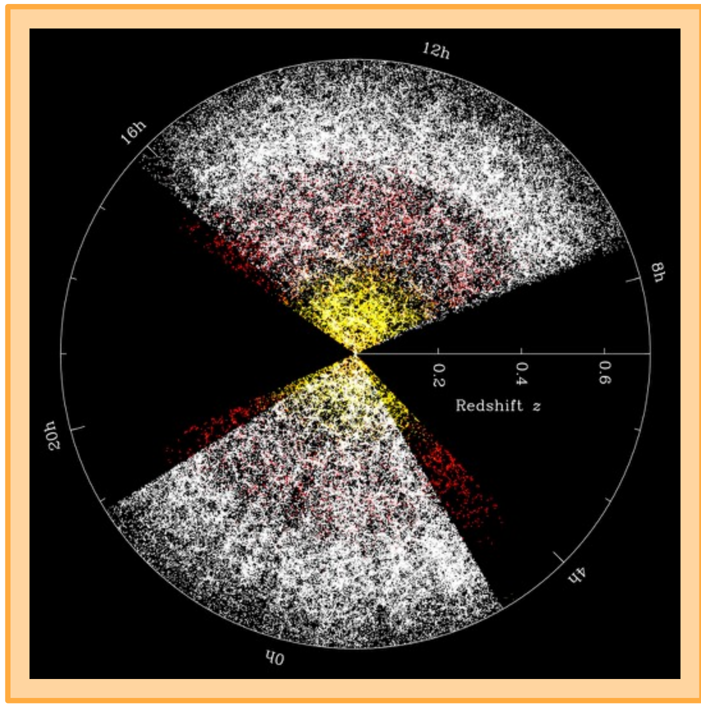
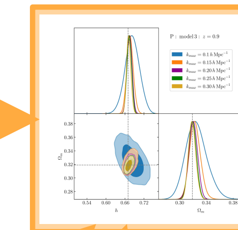


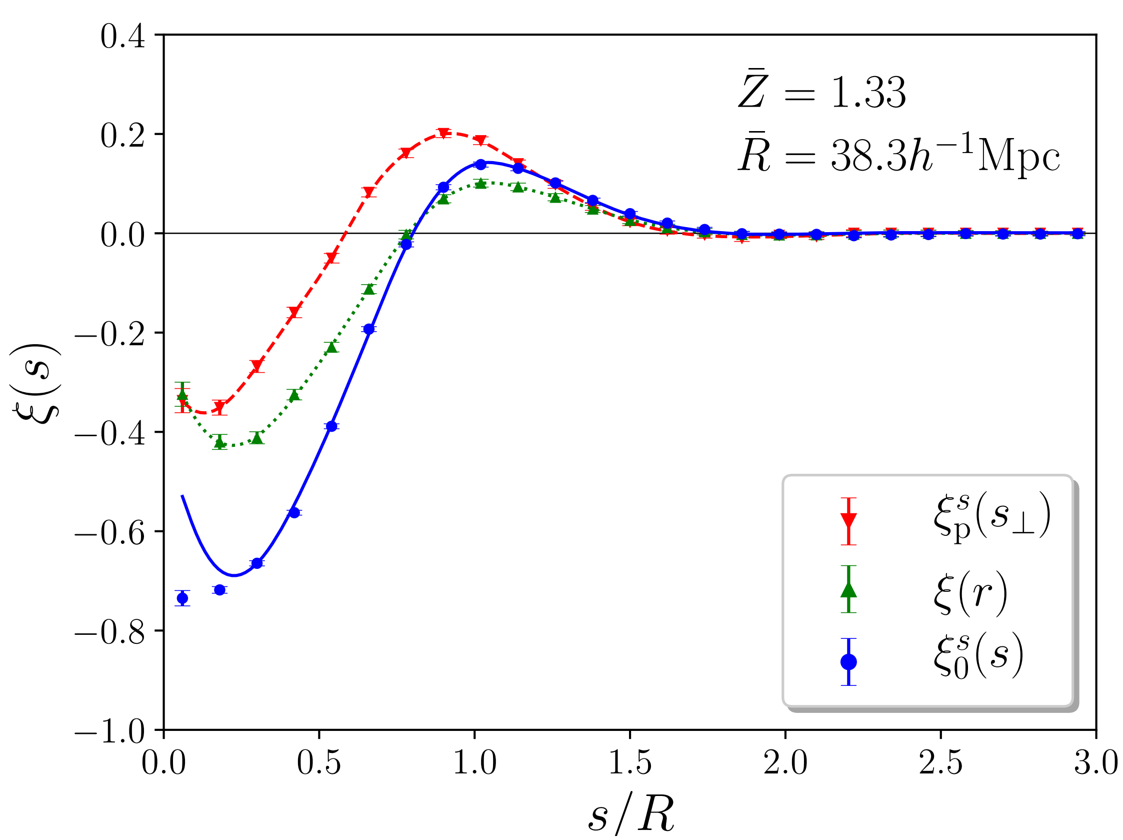
Power Spectrum, $P(k)$ / 2-Point Function, $\xi(r)$

Higher-Order Correlations, e.g. $B(k_1, k_2, k_3)$

Voids

Cosmological parameters





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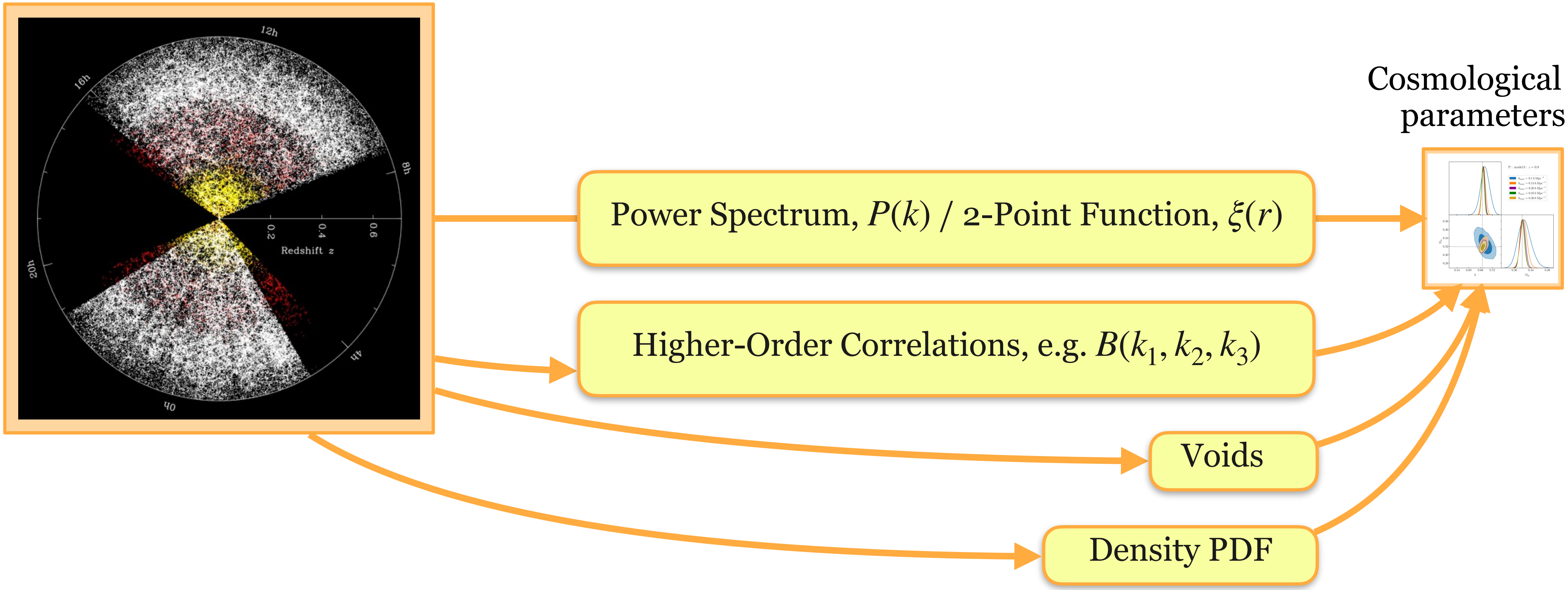

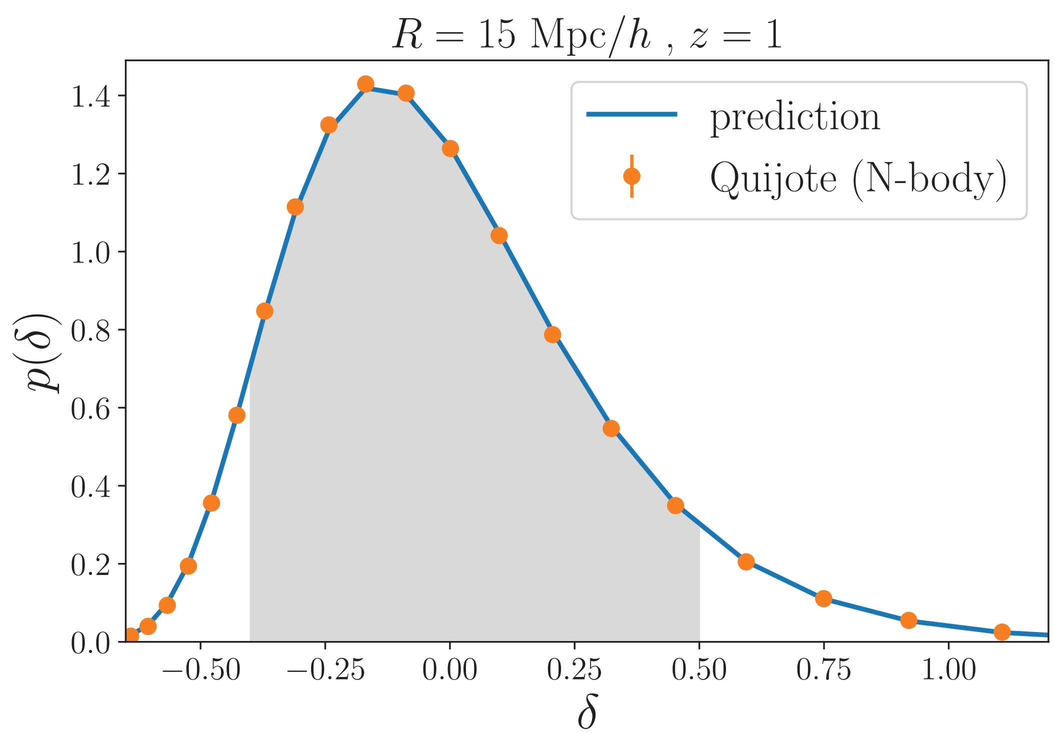

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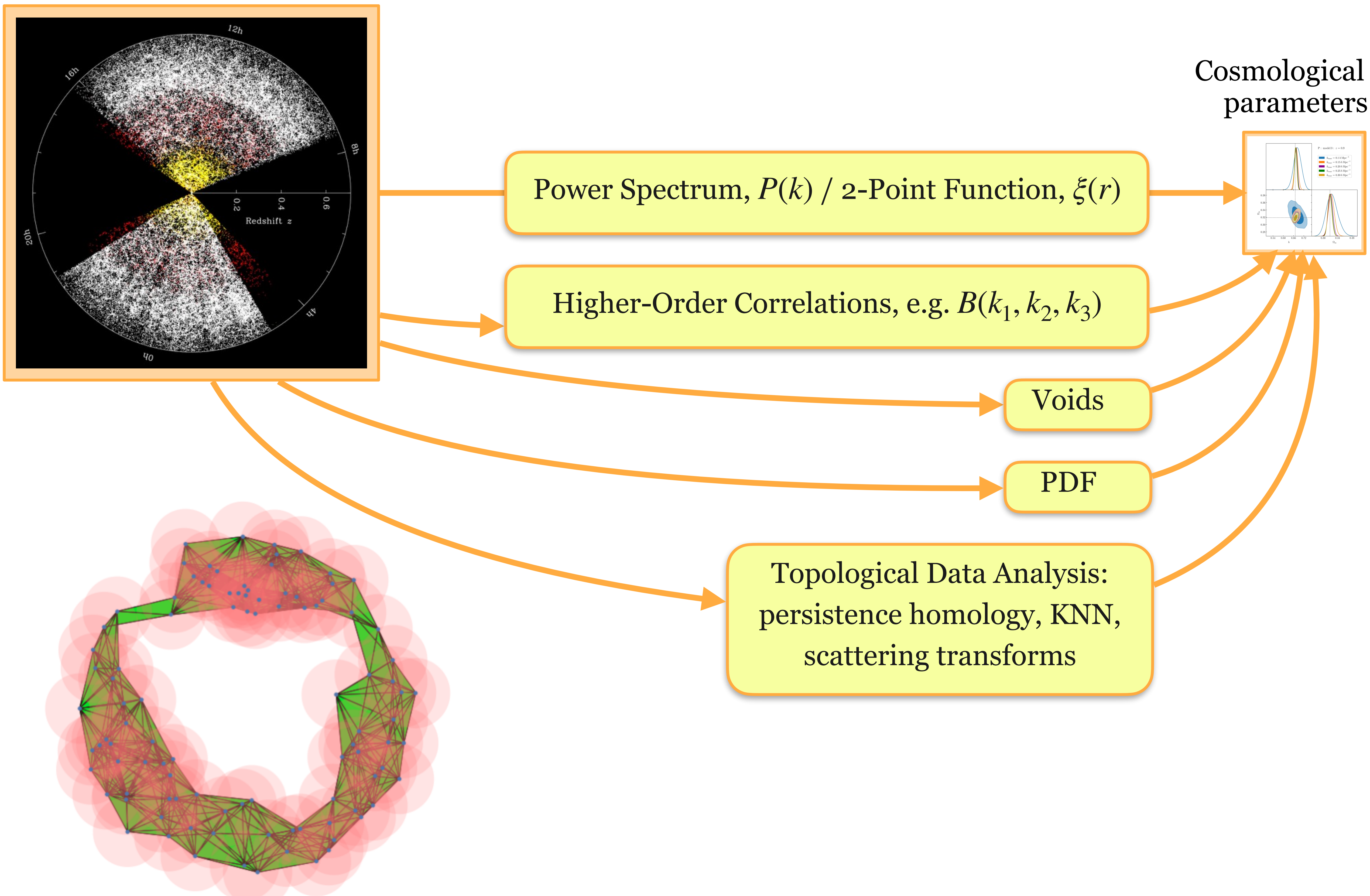

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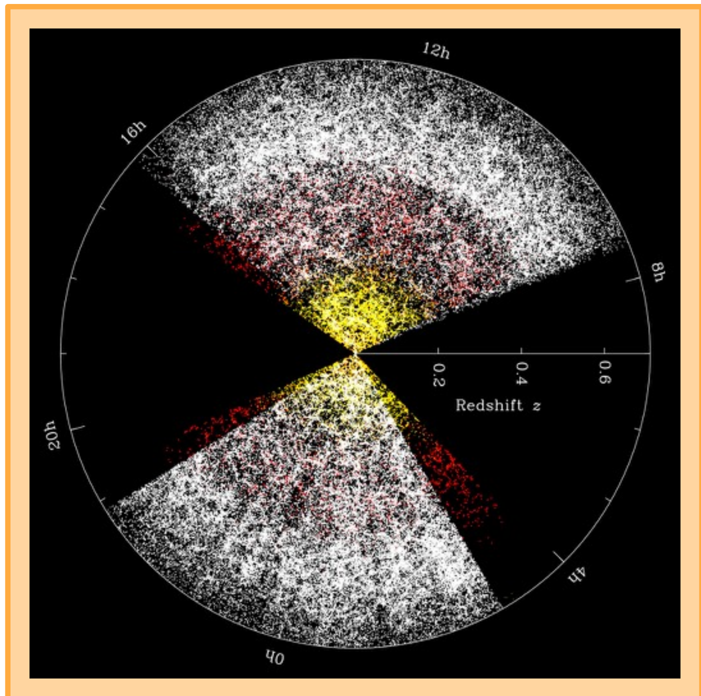


Power Spectrum, $P(k)$ / 2-Point Function, $\xi(r)$

Higher-Order Correlations, e.g. $B(k_1, k_2, k_3)$

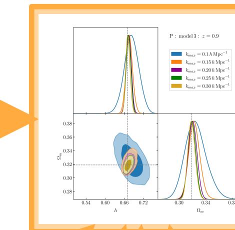
Voids

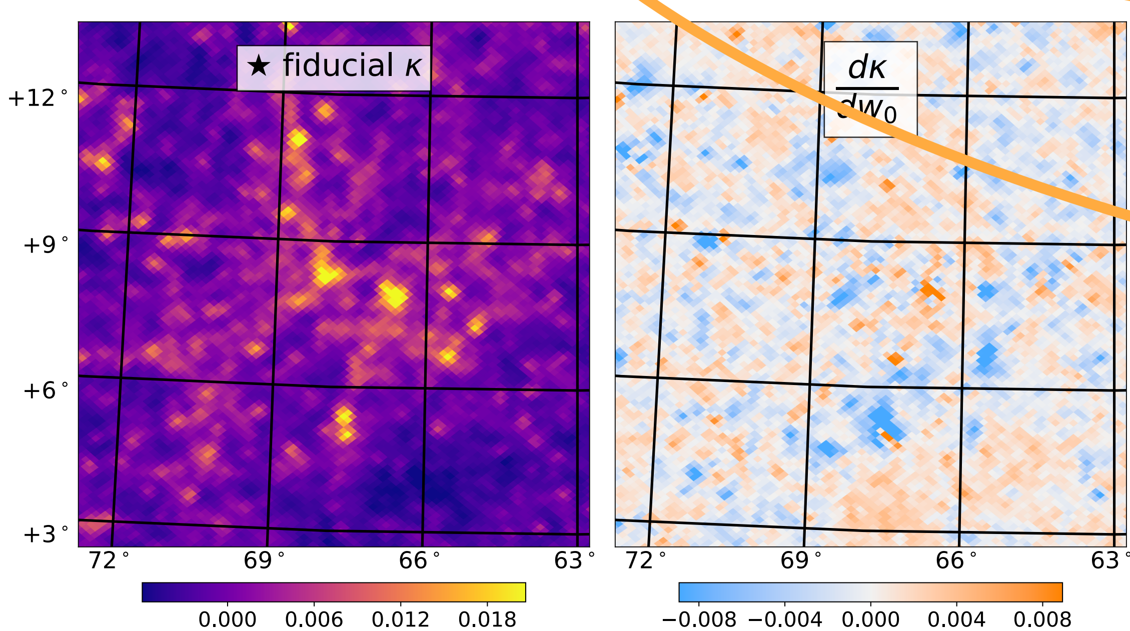
PDF

Topological Data Analysis: persistence homology, KNN, scattering transforms

Forward modelling / Field-level inference

Cosmological parameters



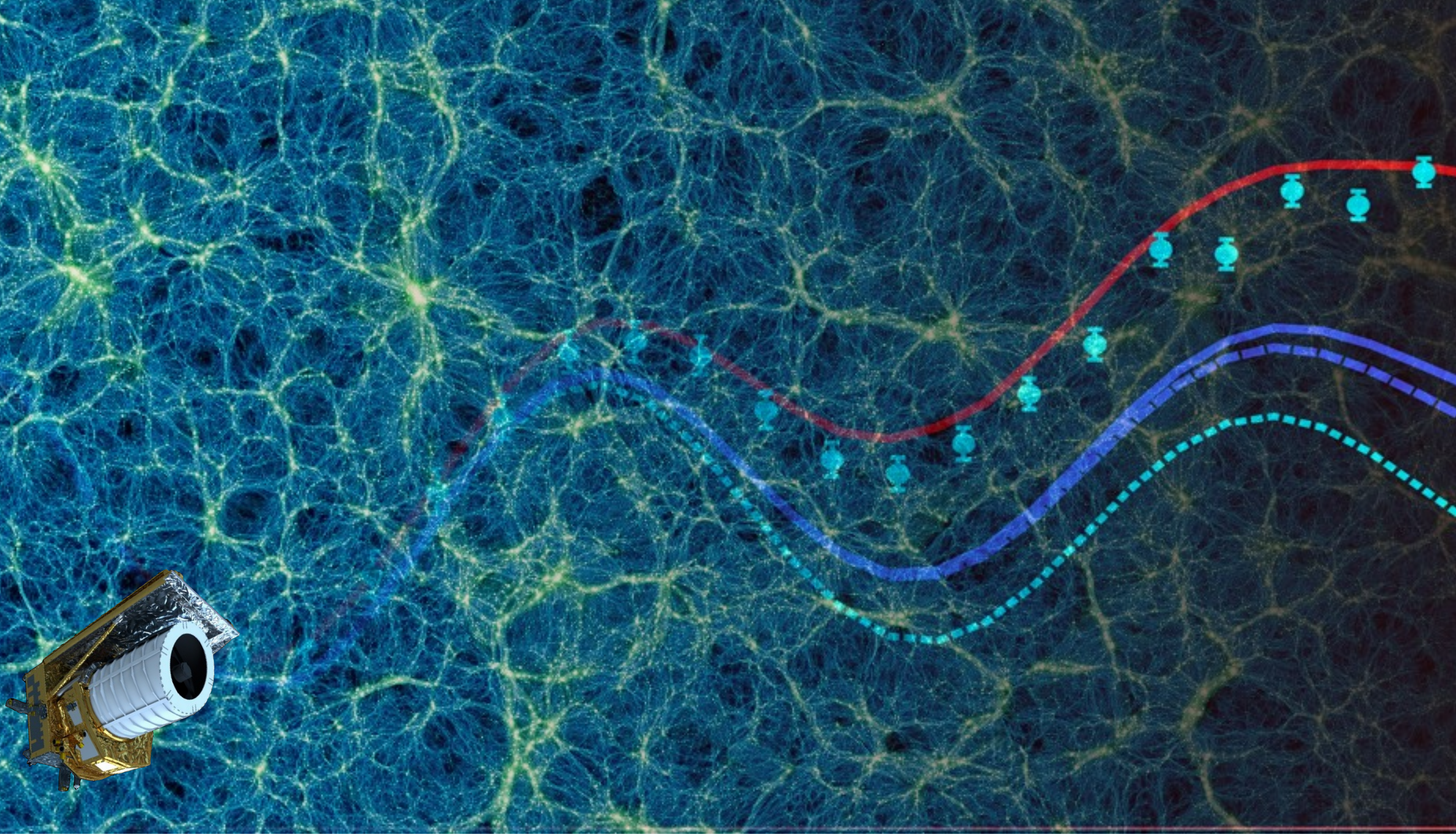


(An incomplete list)

P&P

HPC

ML



Cosmology with next-generation galaxy surveys

Luigi Guzzo
Dipartimento di Fisica "Aldo Pontremoli", Universita` di Milano
& INAF Osservatorio Astronomico di Brera

Preliminary remarks

- ★ Many thanks to all collaborators in Euclid and other projects. Special thanks to B. Granett, C. Carbone, D. Bianchi, M. Archidiacono, F. Tosone, M. Cagliari, E. Castorina

- ★ <u>All Euclid material and forecasts shown on behalf of (and approved by) the *Euclid Consortium*</u>

- ★ CAVEAT: inevitably, a biased review

Outline

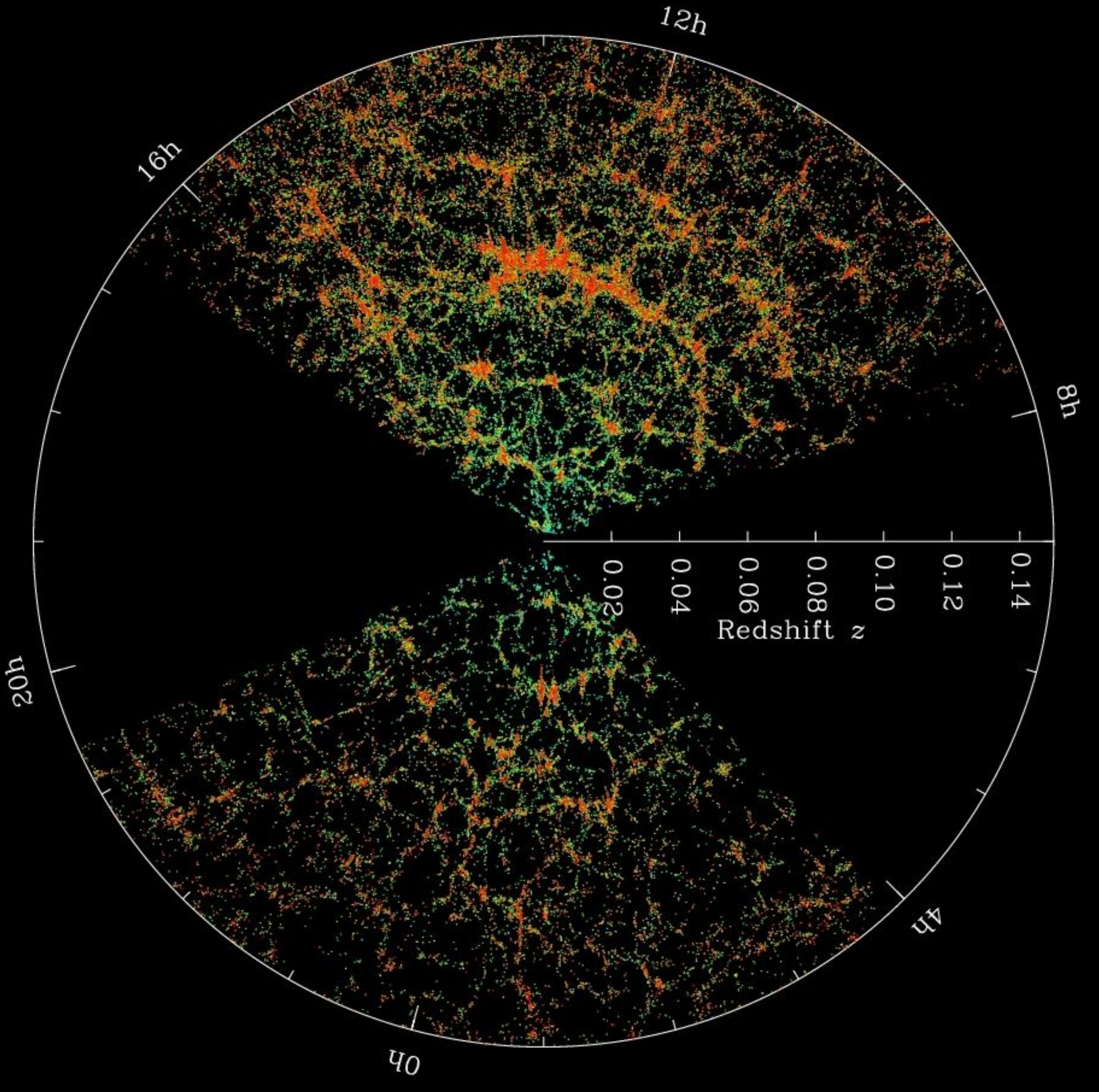
★ The golden era of galaxy surveys

★ Data complexity: "…*with great power comes great responsibility*"

★ Data richness: how do we extract all cosmological information?

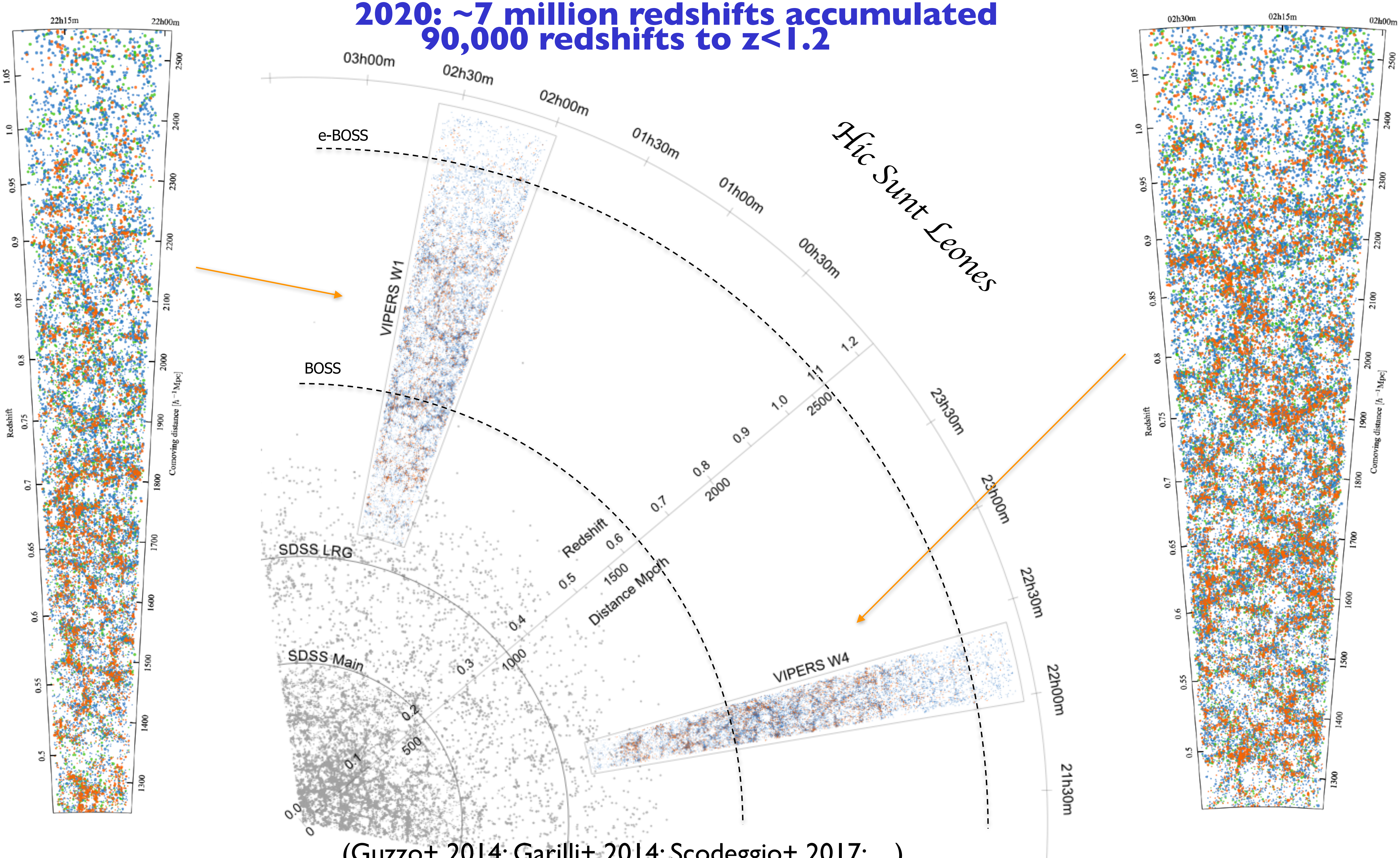
Galaxy redshift surveys: a pillar of the standard model of cosmology

2001: Sloan Digital Sky Survey + 2dFGRS   ~1 million redshifts to z~0.15



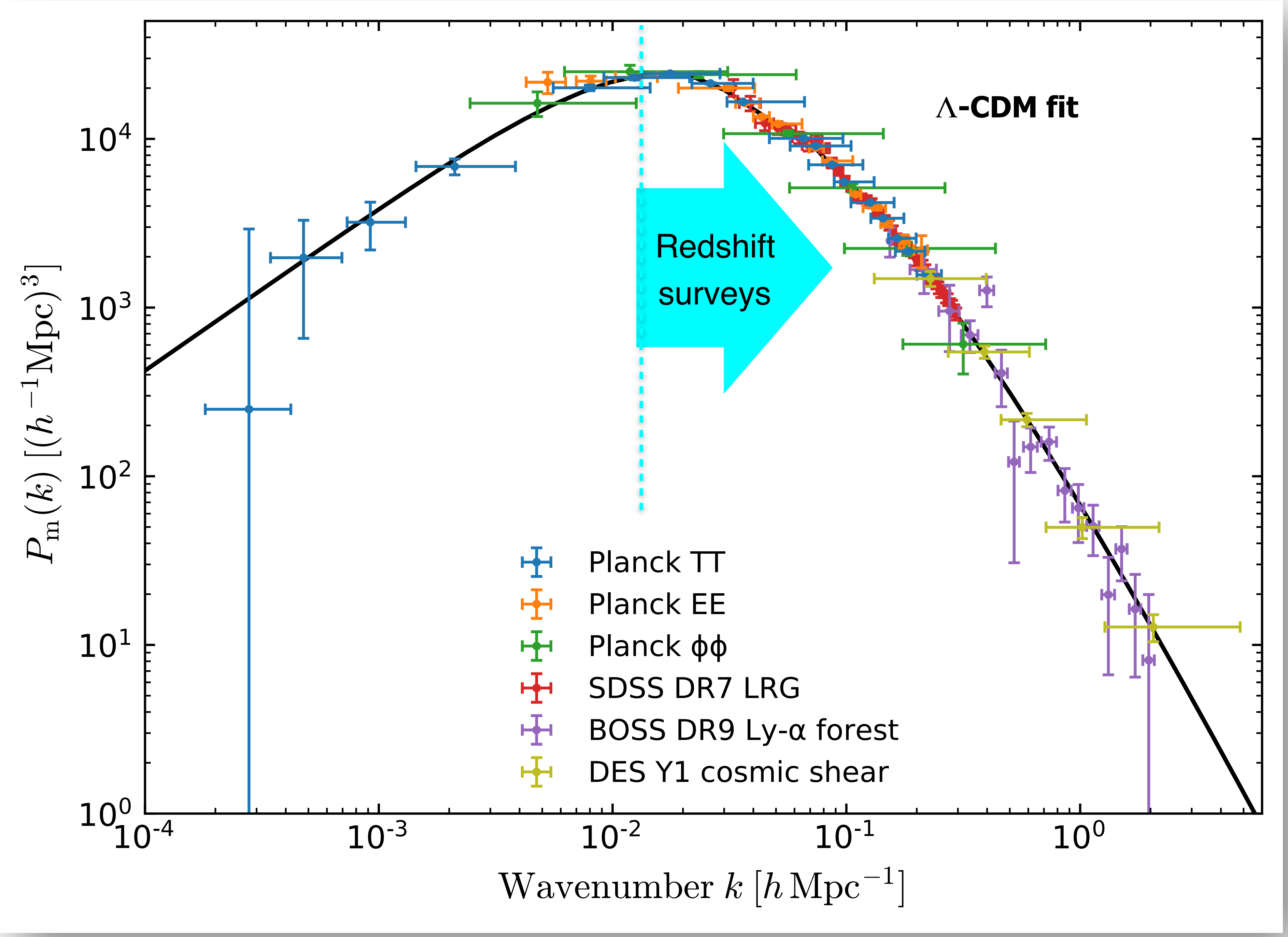
Galaxy redshift surveys: a pillar of the standard model of cosmology

2020: ~7 million redshifts accumulated
90,000 redshifts to z<1.2



(Guzzo+ 2014; Garilli+ 2014; Scodeggio+ 2017;…)

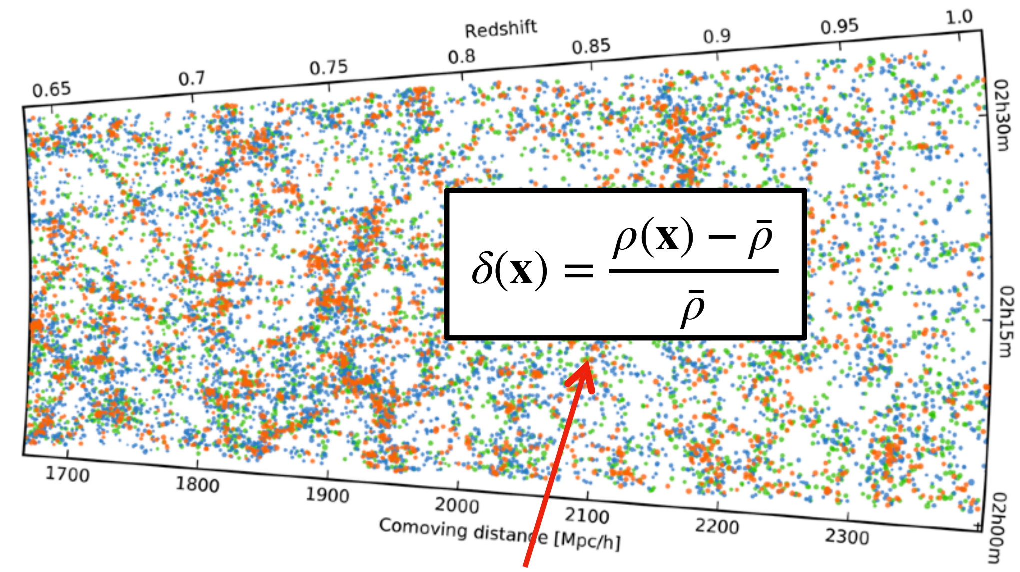
What we want to get from galaxy surveys, first of all



Planck 2018 - I

What does this mean, in practice…

- **Science comes from overdensities $\delta(\mathbf{x})$**
  - Need galaxy catalogue
  - Need survey mask (shape, hoes, sensitivity…):
    - angular completeness
    - radial completeness
    - radial/angular fluctuations



Need to know where we **could** have seen galaxies in the Universe, had they existed

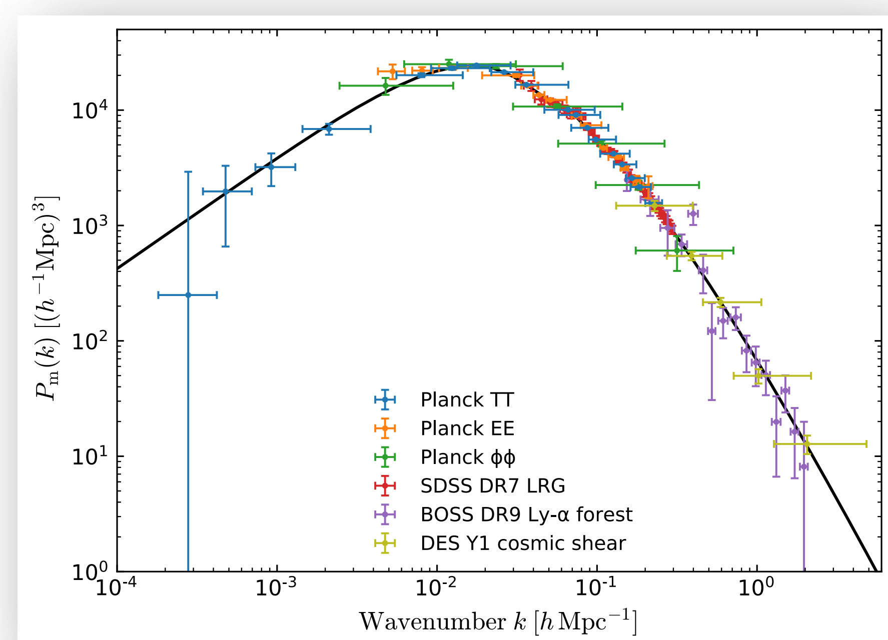
- **2-point statistics of δ field** contain most (<u>yet not all</u>), information:

- **power spectrum**

$$\langle \delta(\mathbf{k_1}) \delta(\mathbf{k_2}) \rangle = (2\pi)^3 \delta_D(\mathbf{k_1} - \mathbf{k_2}) P(k_1)$$

- **correlation function**

$$\begin{aligned} \xi(\mathbf{x_1}, \mathbf{x_2}) &= \langle \delta(\mathbf{x_1}) \delta(\mathbf{x_2}) \rangle \\ &= \xi(\mathbf{x_1} - \mathbf{x_2}) \\ &= \xi(|\mathbf{x_1} - \mathbf{x_2}|) \end{aligned}$$



The name of the game: go big

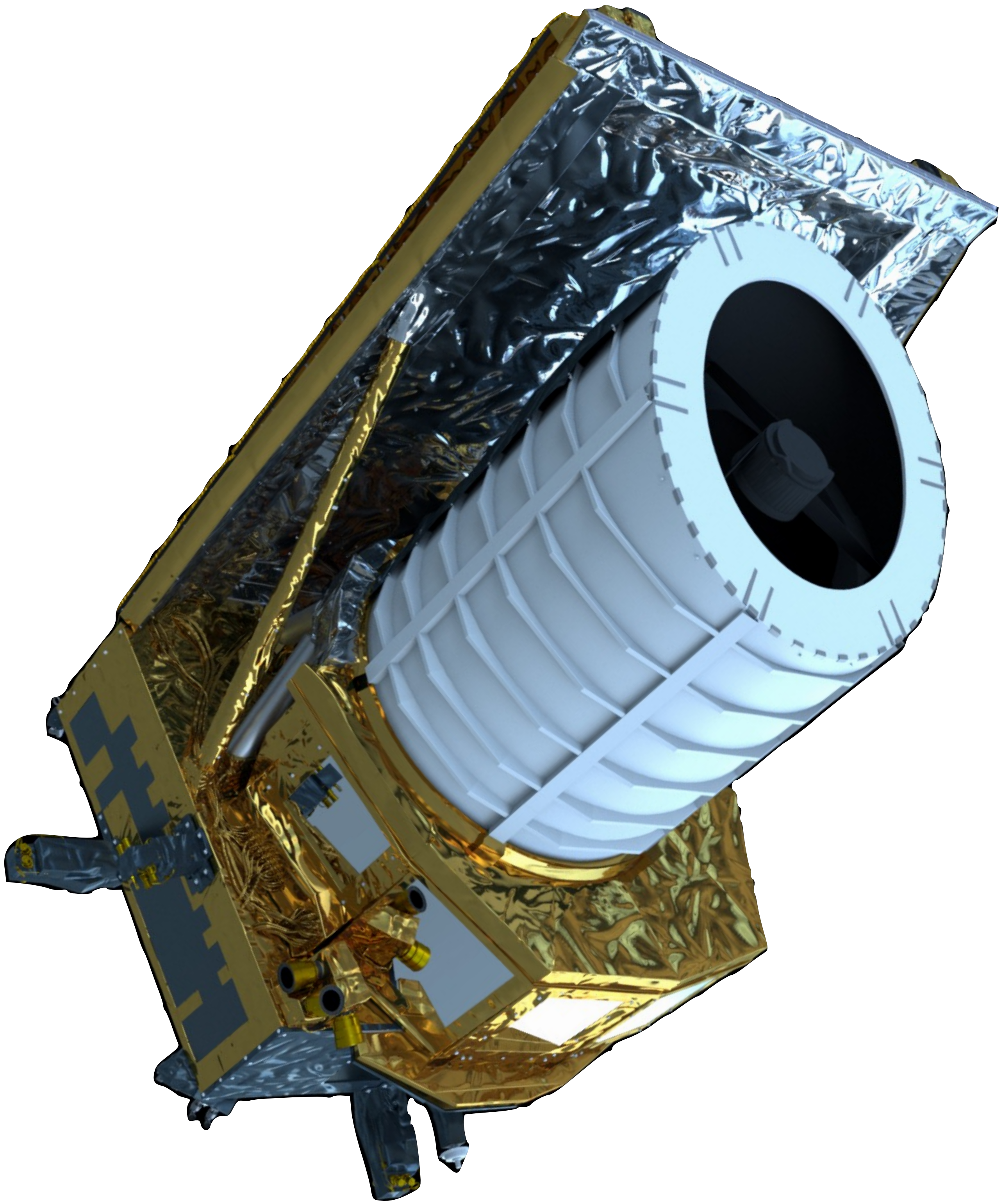
1. If we measure P(k) - or ξ(r) - in the linear regime (large scales), we are directly probing primordial fluctuations

2. If these were Gaussian, two-point statistics is all we need to fully characterise the primordial density field

3. This is why we want larger and larger surveys, to map fluctuations as linear as possible

4. Various effects complicate the picture: nonlinear evolution, galaxy biasing, redshift-space distortions

2023: The next milestone cosmology mission



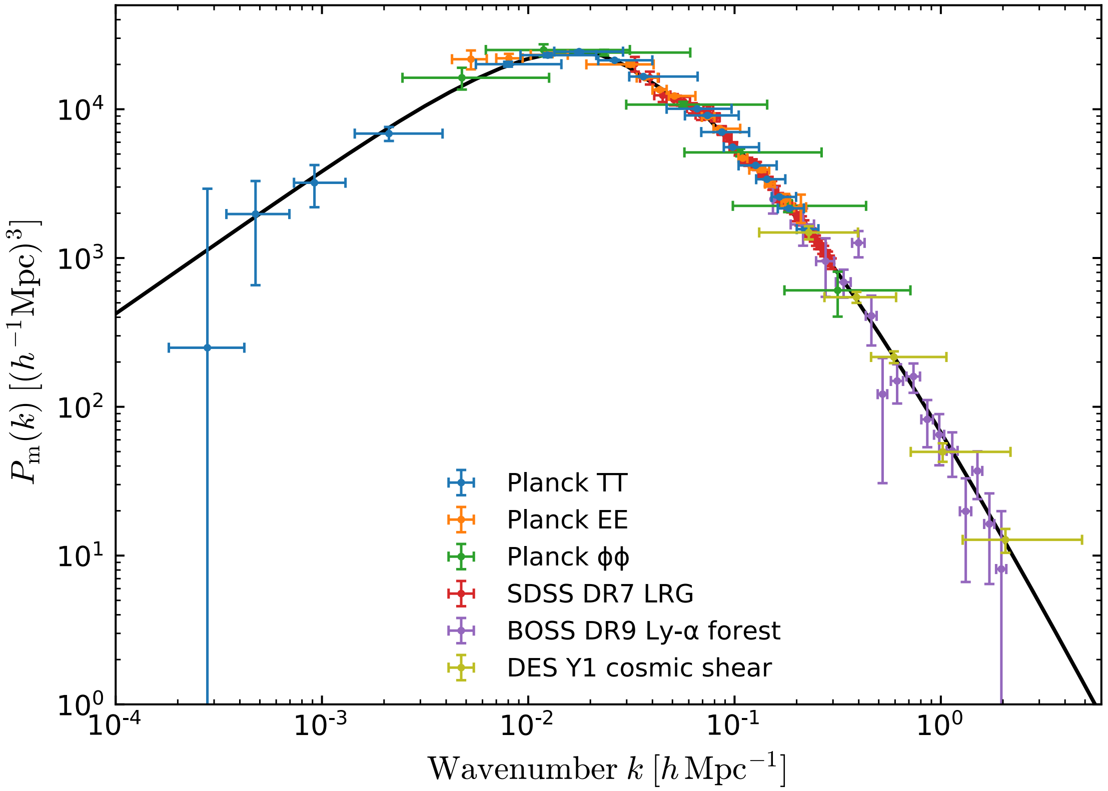
SPACE (Italy-led, Cimatti et al.)

strong FTE contribution by Italy and INAF in particular

galaxy redshifts

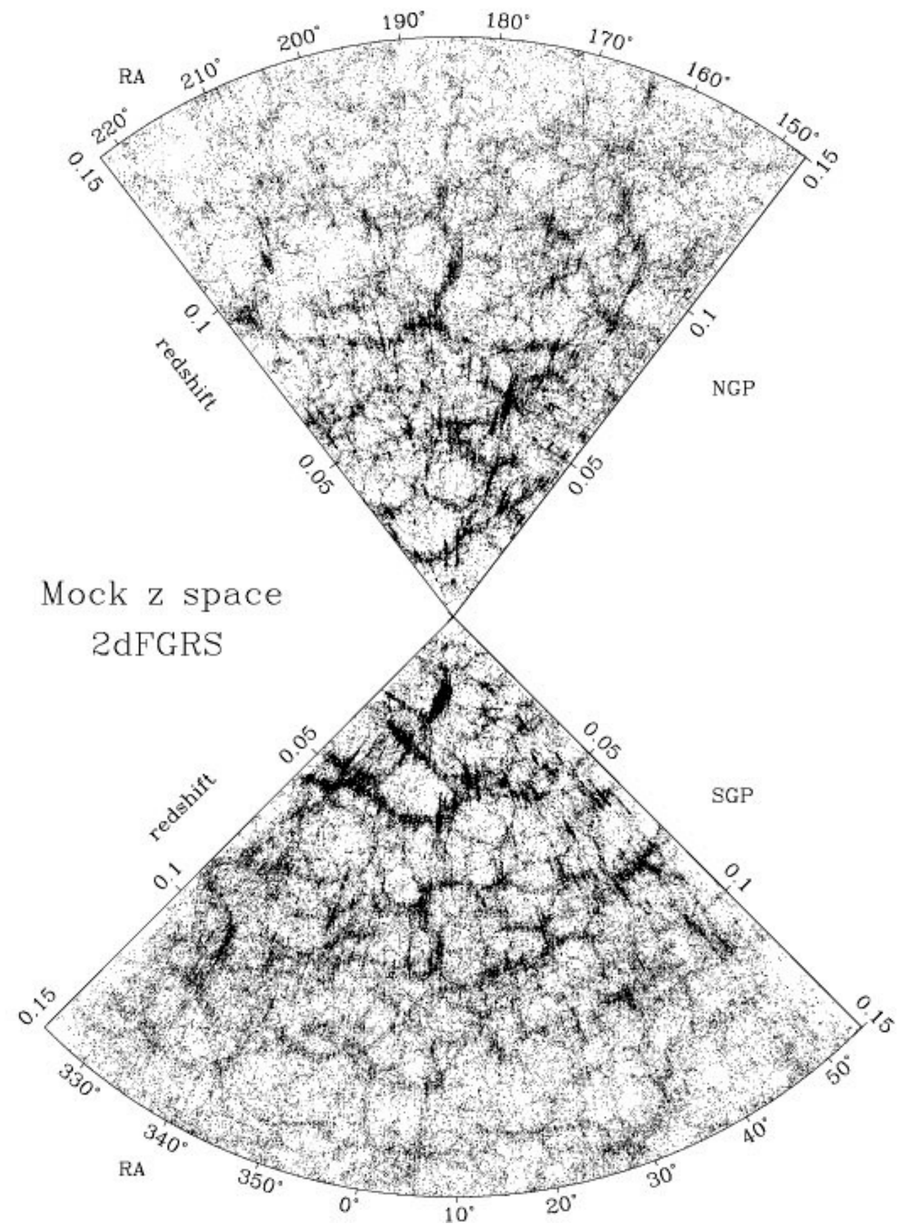
weak gravitational lensing

Galaxy clustering probe



★ **Baryon acoustic oscillations (BAO)** provide a cosmic standard ruler

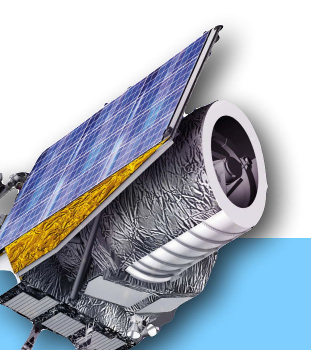
★ Measure the **expansion history** *H(z)* and angular diameter distance relation $d_A(z)$



★ **Redshift-space distortions (RSD)** measure the **growth rate** of structure *f(z)*

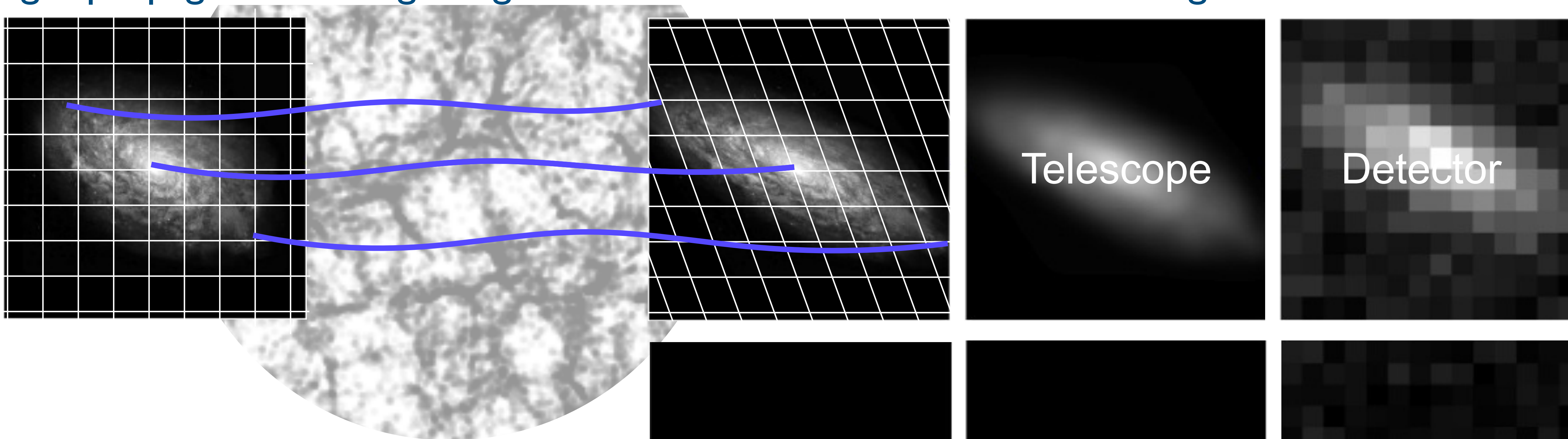
★ Test "beyond Einstein" scenario, as alternative to Λ

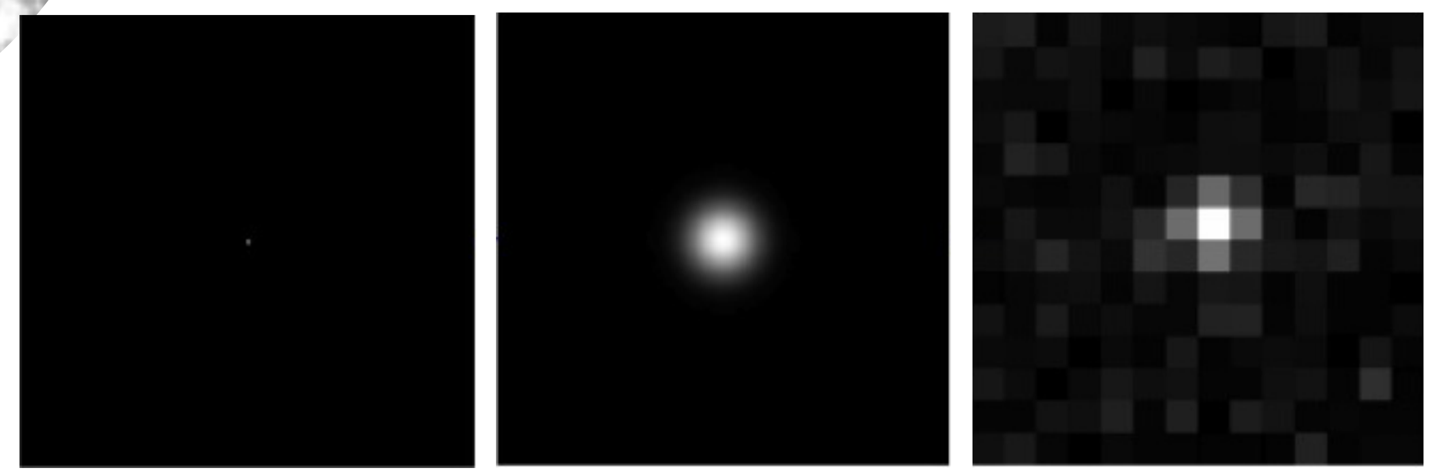
★ A key original feature in the SPACE/Euclid proposal (LG+ 2008, Nature, 451, 541)



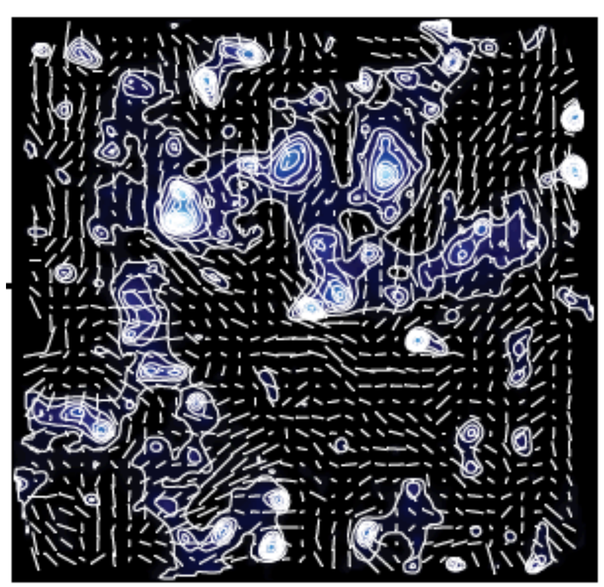
Weak lensing probe

Light propagation through large-scale structure results in a lensed image

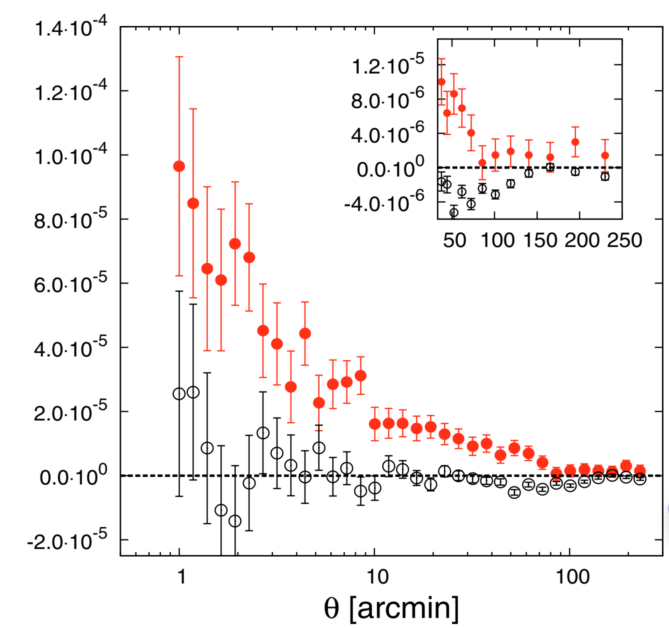




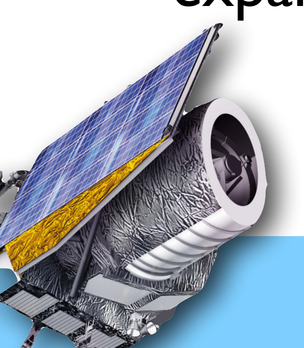
- ★ Correlate shapes of millions of galaxies to measure the cosmological signal at 10^{-3} in ellipticity
- ★ **Measure clustering in the full mass distribution**
- ★ Trace combined growth and expansion histories



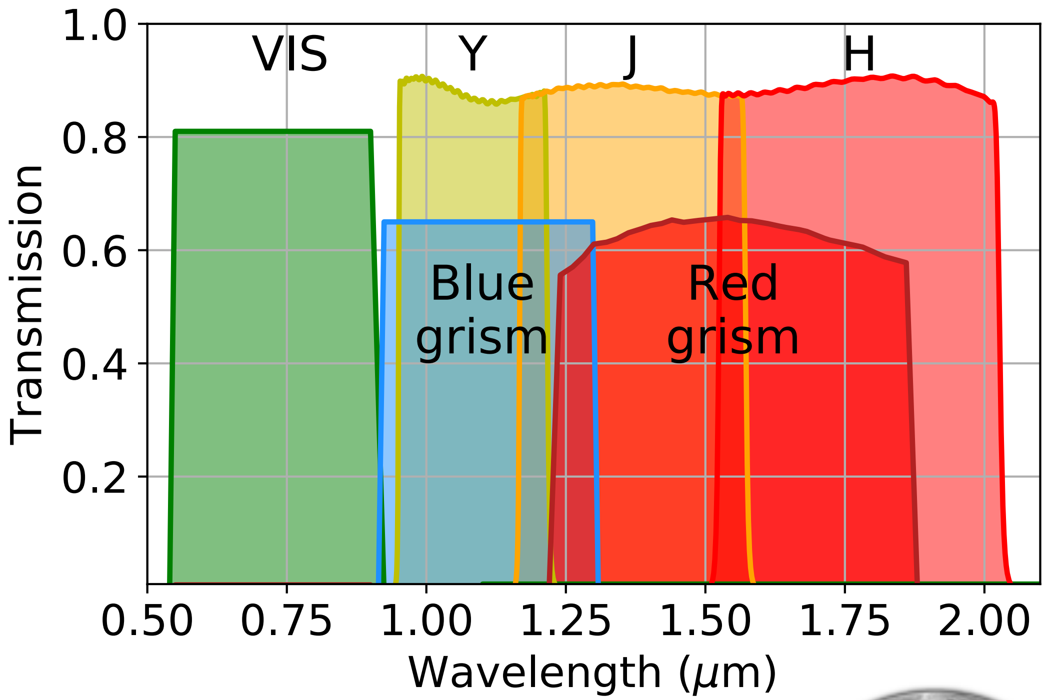
Massey+

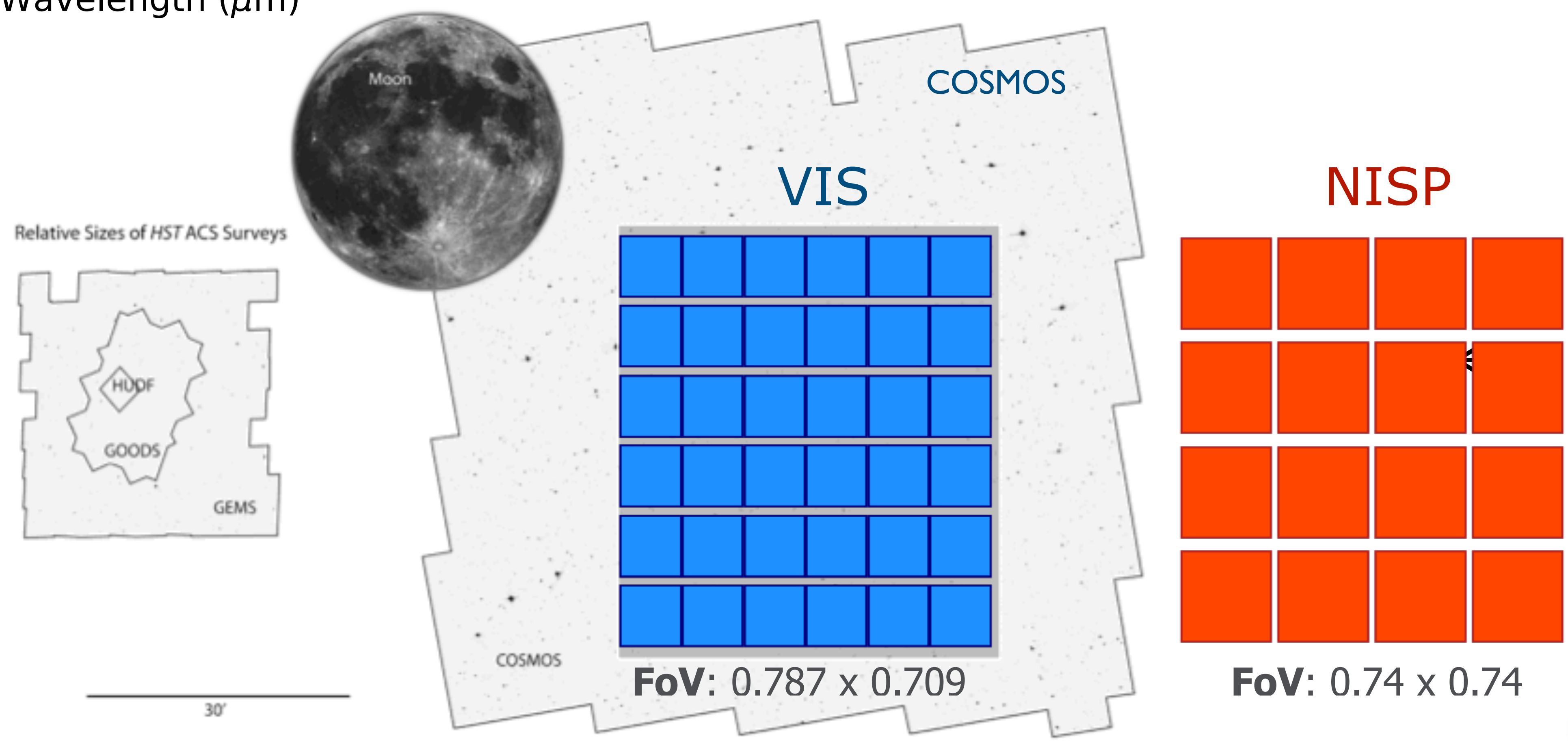


Fu+2008

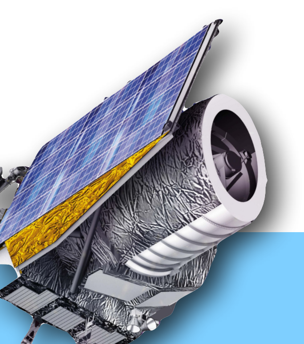


Euclid: dual wide-field imager and NIR spectrograph





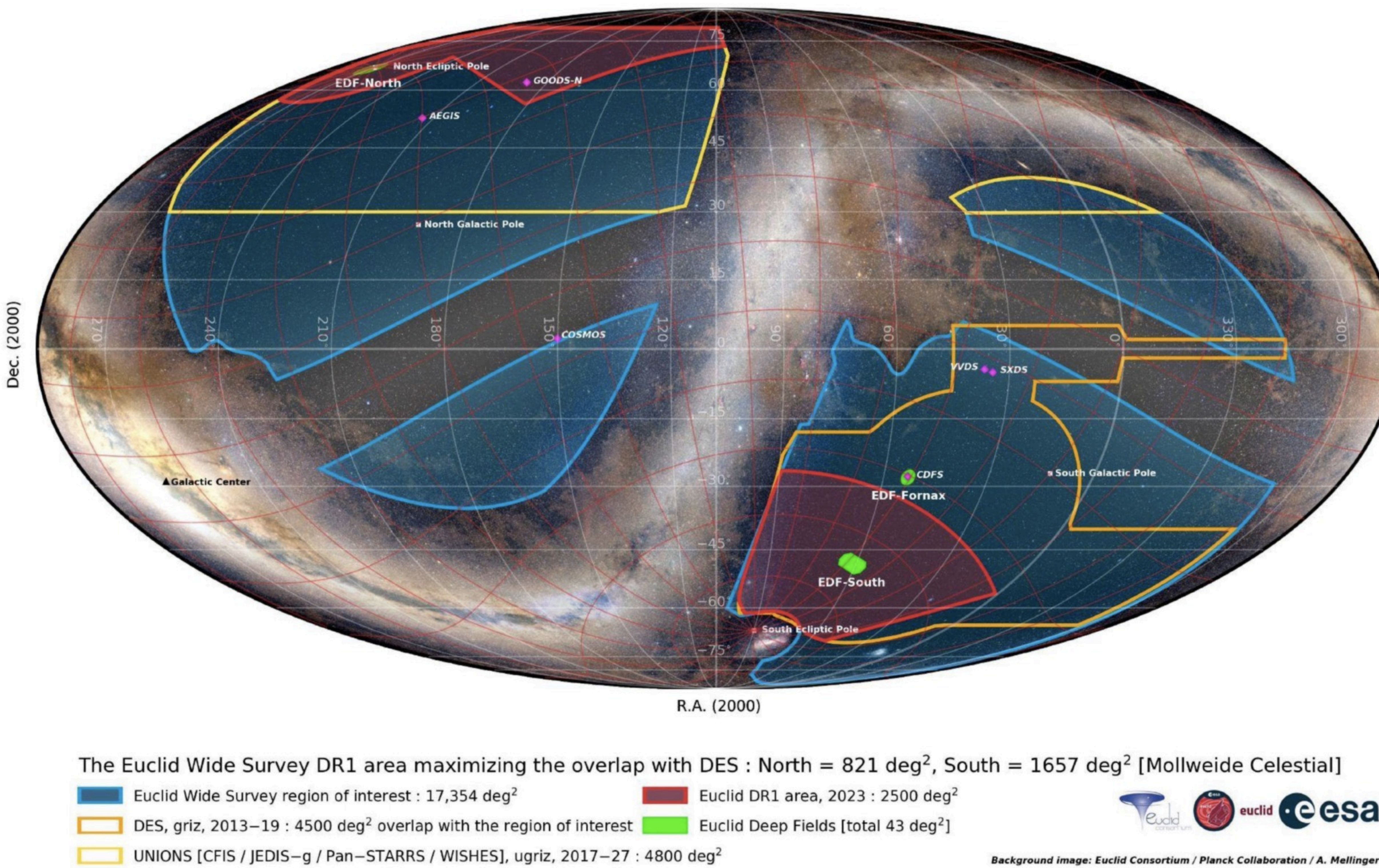
Spec: R~380, 13.4 A/pixel



Euclid surveys

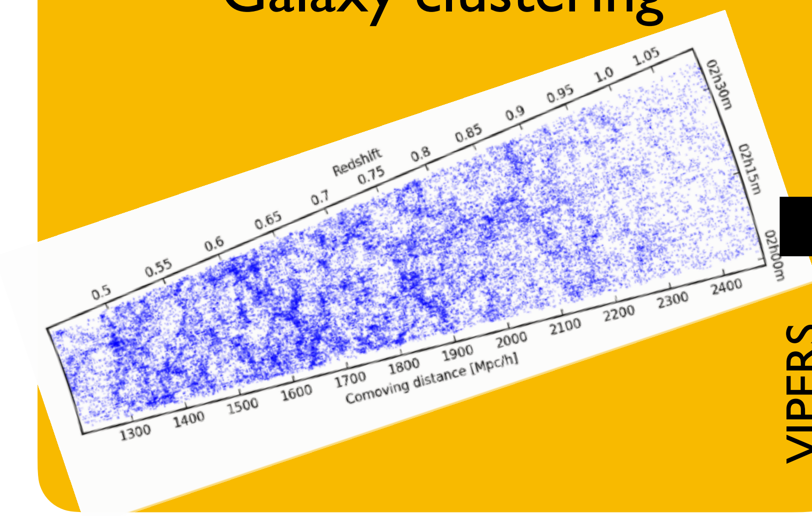
(Scaramella & EC 2022)

- **Wide survey: 15,000 deg^2 (VIS, Y, J, H, spec)**
- **~2 billion galaxy images**
- **~30 million redshifts**
- **Deep Fields: 43 deg^2 (calibration + science)**



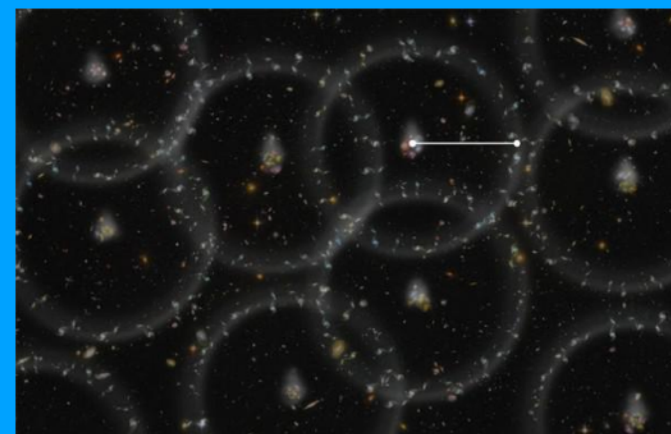
Euclid: much more than a redshift survey

Galaxy clustering



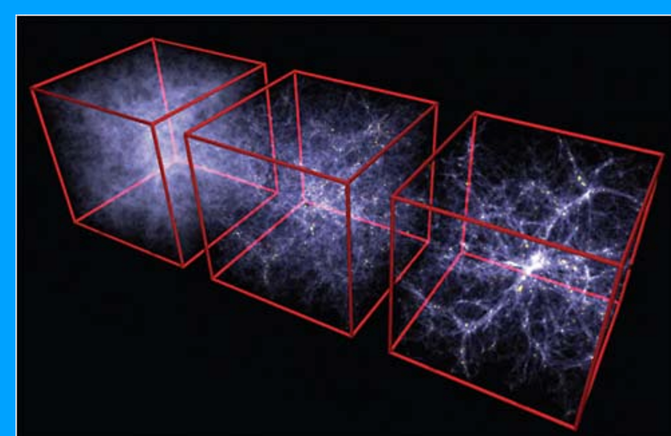
VIPERS

Expansion history



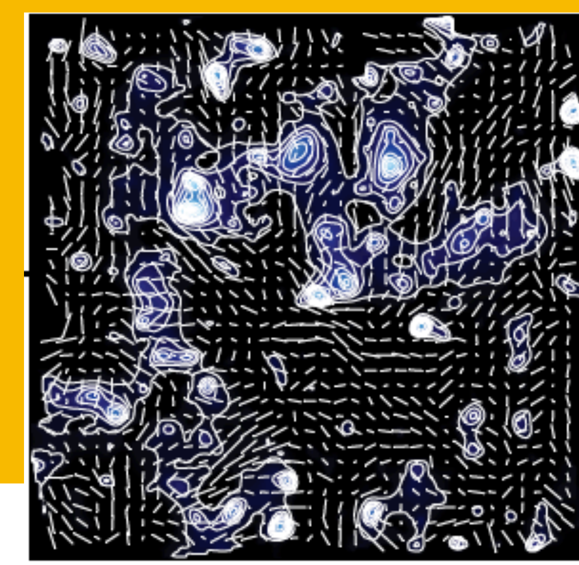
SDSSIII BOSS

Growth of structure



MPA/Millennium

Weak lensing



COSMOS

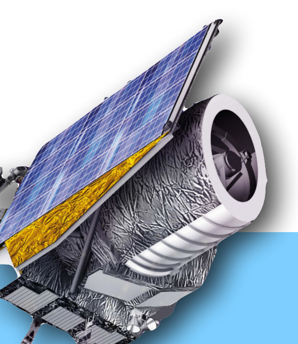
…plus

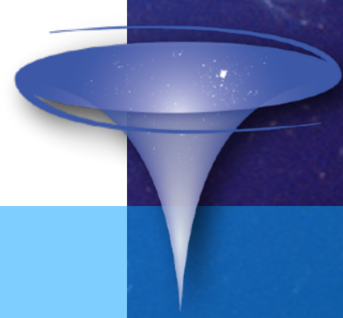
Clusters

CMB cross-correlations

Strong lensing

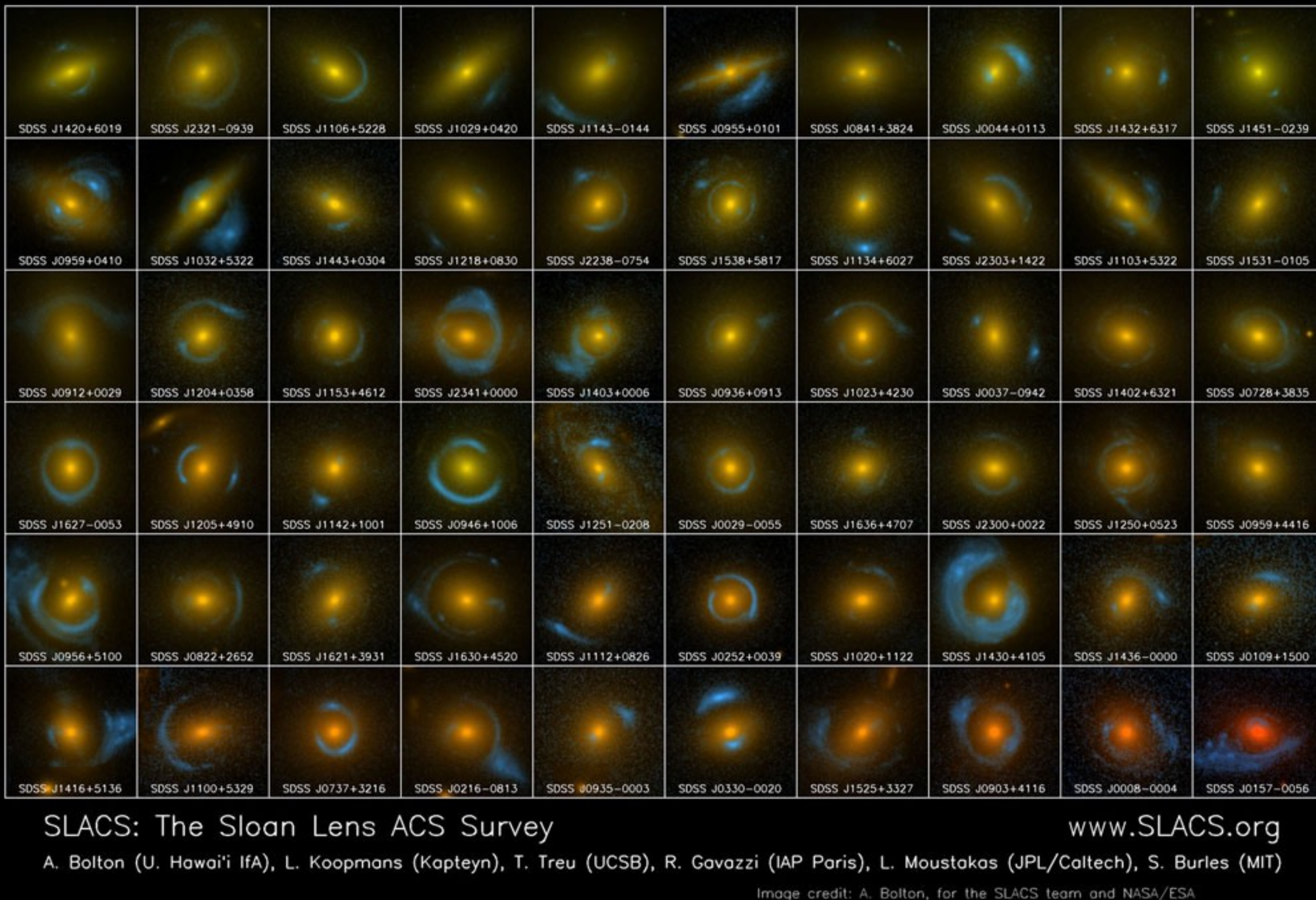
Galaxy evolution





Just an example: strong gravitational lensing by galaxies

Euclid: 3300 in two months, 200,000 in total (Boldrin, Giocoli, Meneghetti 2016)



Euclid is ready for launch (2023)

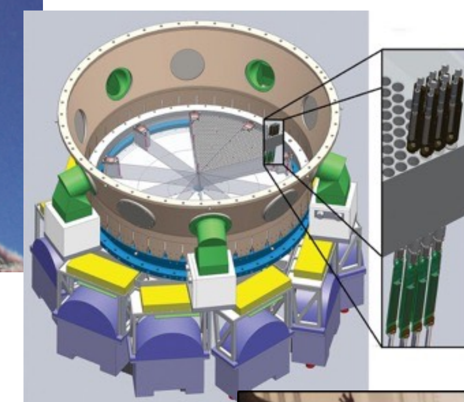
- July 1st, 2022 @ Thales-AleniaSpace in Turin

- Flight model fully assembled, now in Cannes for final environmental tests

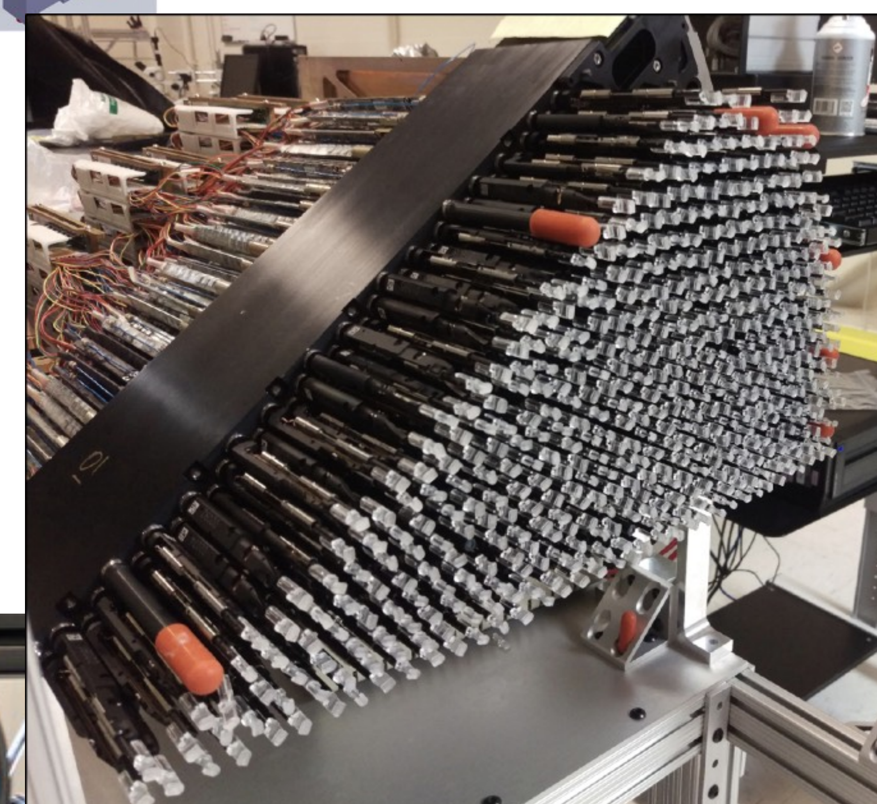
The competition: Dark Energy Spectroscopic Instrument (DESI)

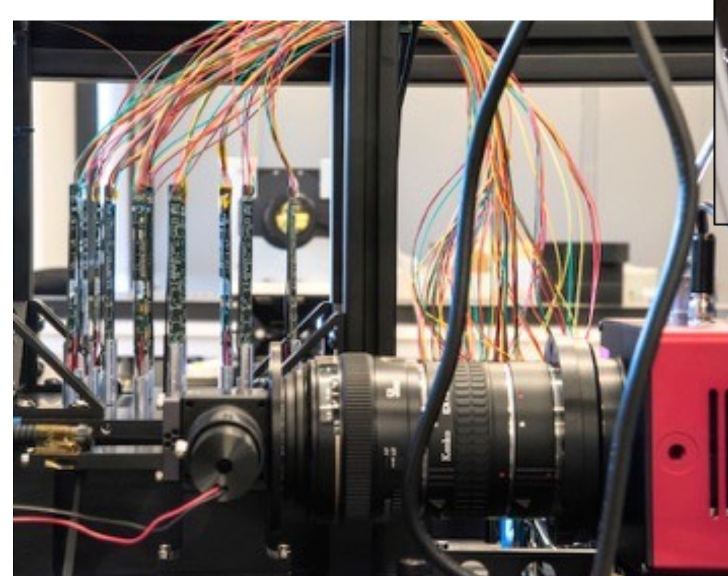
- **5000 fibres** MOS @ Kitt Peak 4.2m Mayall Telescope
- **Ω =14,000deg^2**
- **~30 million galaxies z<1.4**
- **~600,000 quasars**
- Complementary to Euclid spectroscopic survey in many respects
- **No Italian participation (unlike virtually all other Euclid major countries)**

- (Other forthcoming fibre couplers, as WEAVE (WHT) and 4MOST (VISTA) but not comparable in terms of cosmological application/power)

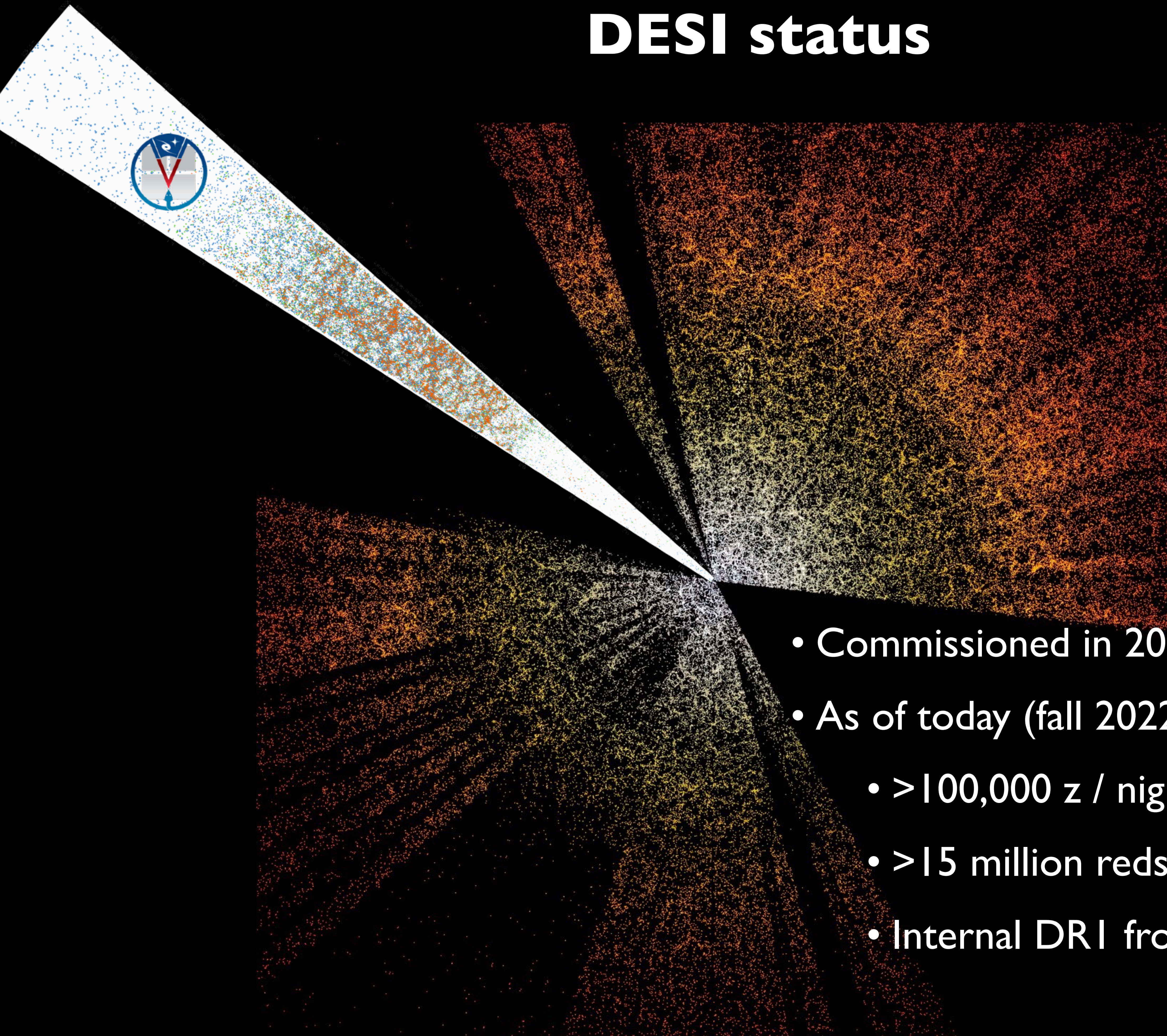


A "petal" with a subset of the 5000 automatic fibre positioners





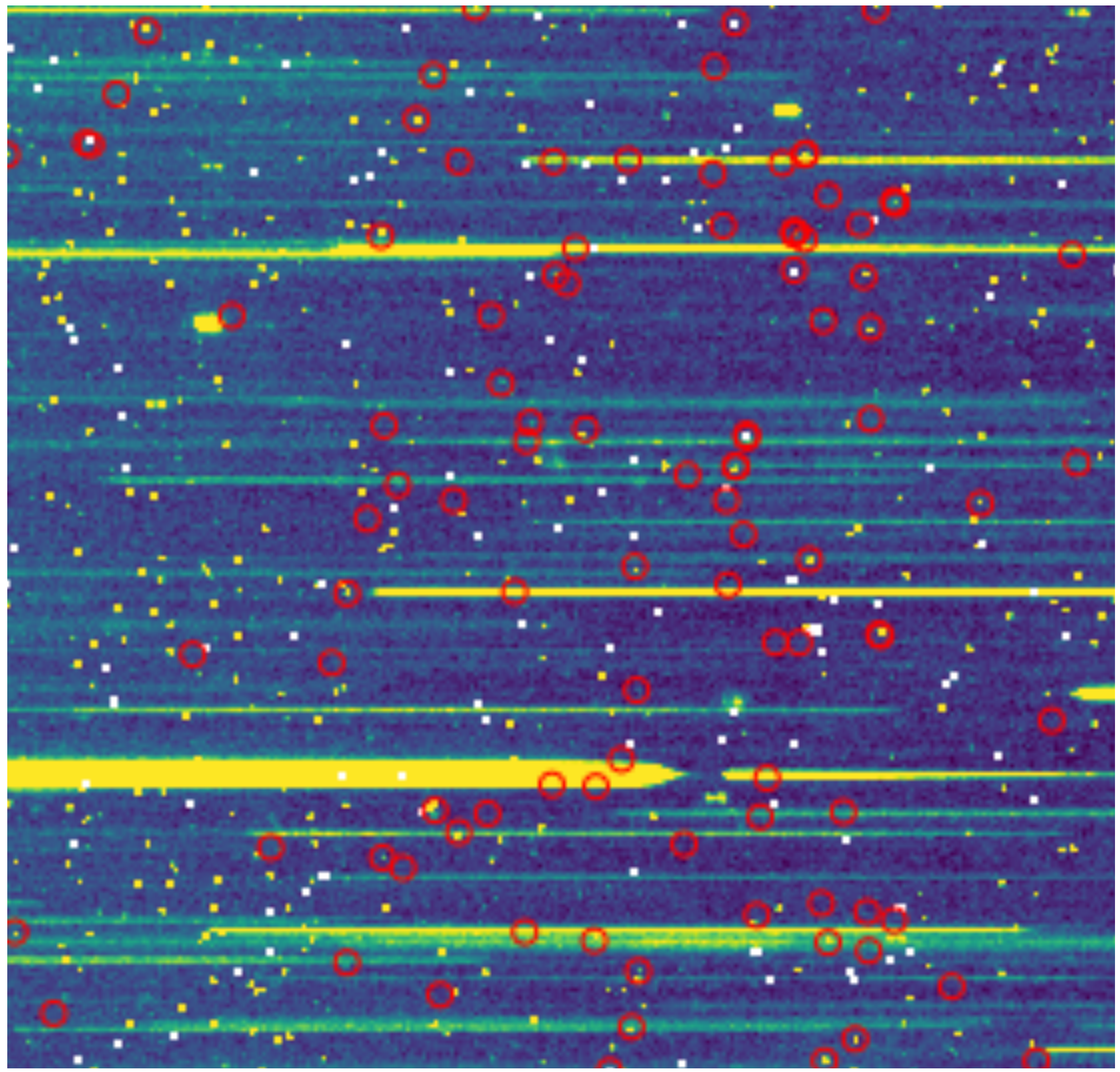
DESI status



- Commissioned in 2019
- As of today (fall 2022):
  - >100,000 z / night (!)
  - >15 million redshifts observed
  - Internal DR1 frozen

High precision requires high control of systematics (high accuracy)

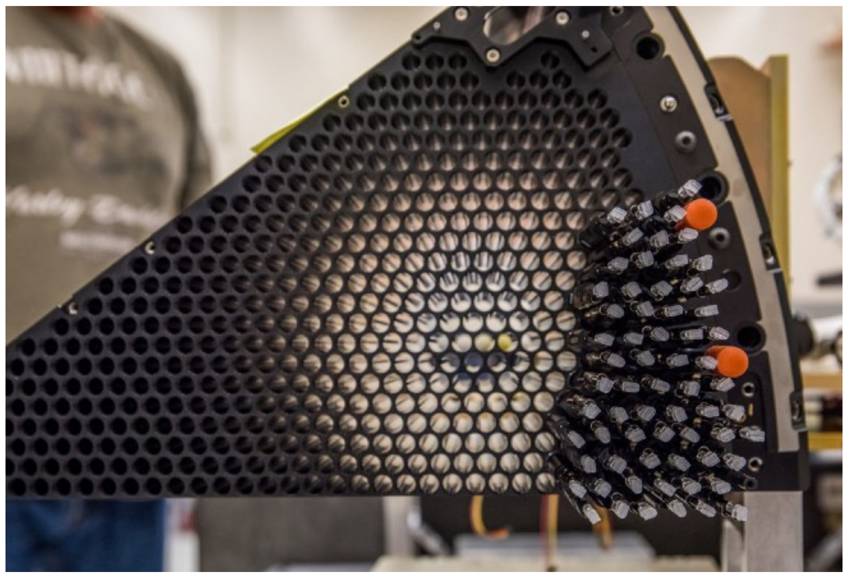
Euclid data are complex: slitless spectroscopy



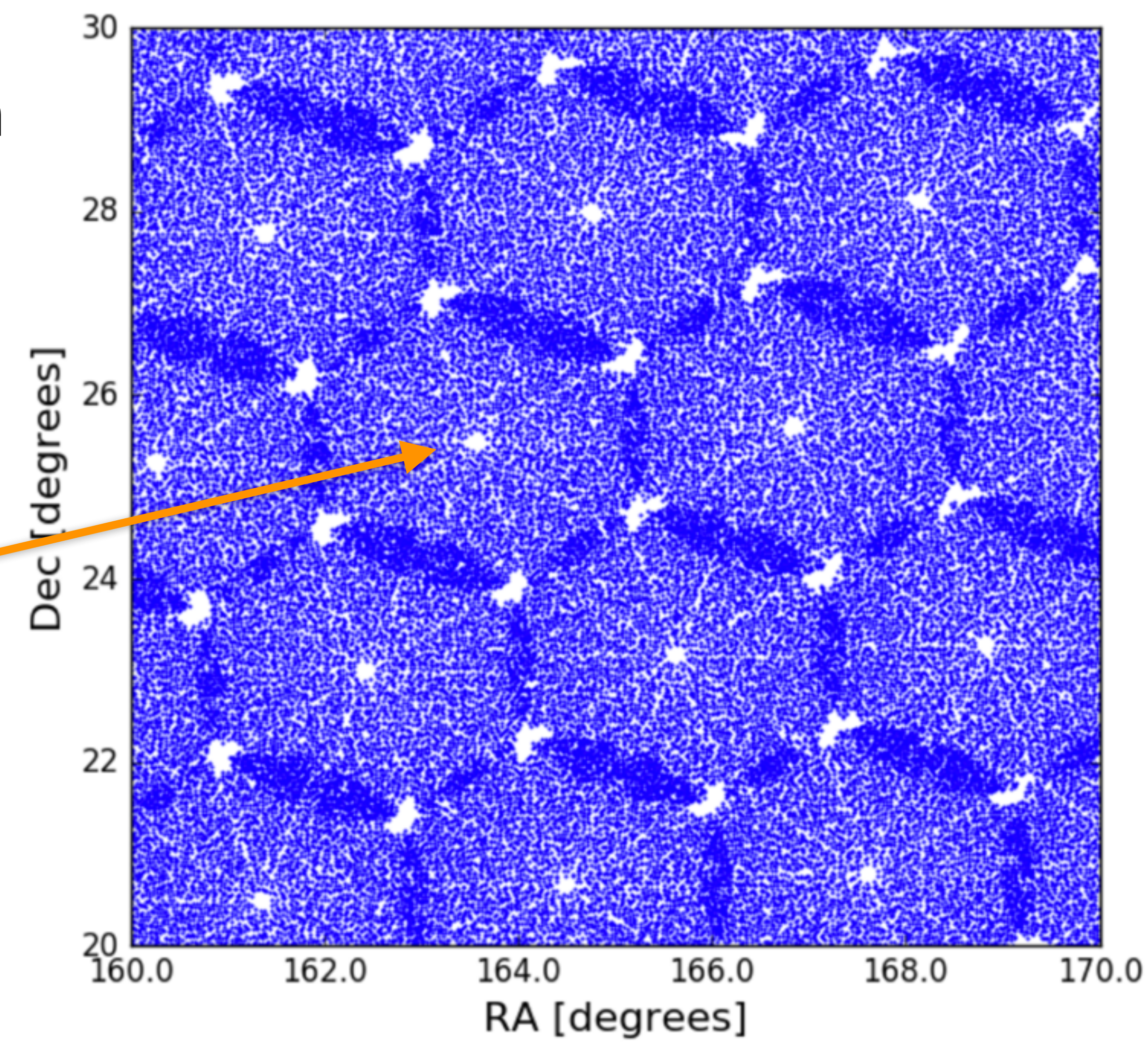
Euclid NISP-S simulated exposure, with H_α lines marked (B. Granett & e2e group)

Slitless mode critically different from traditional redshift surveys…

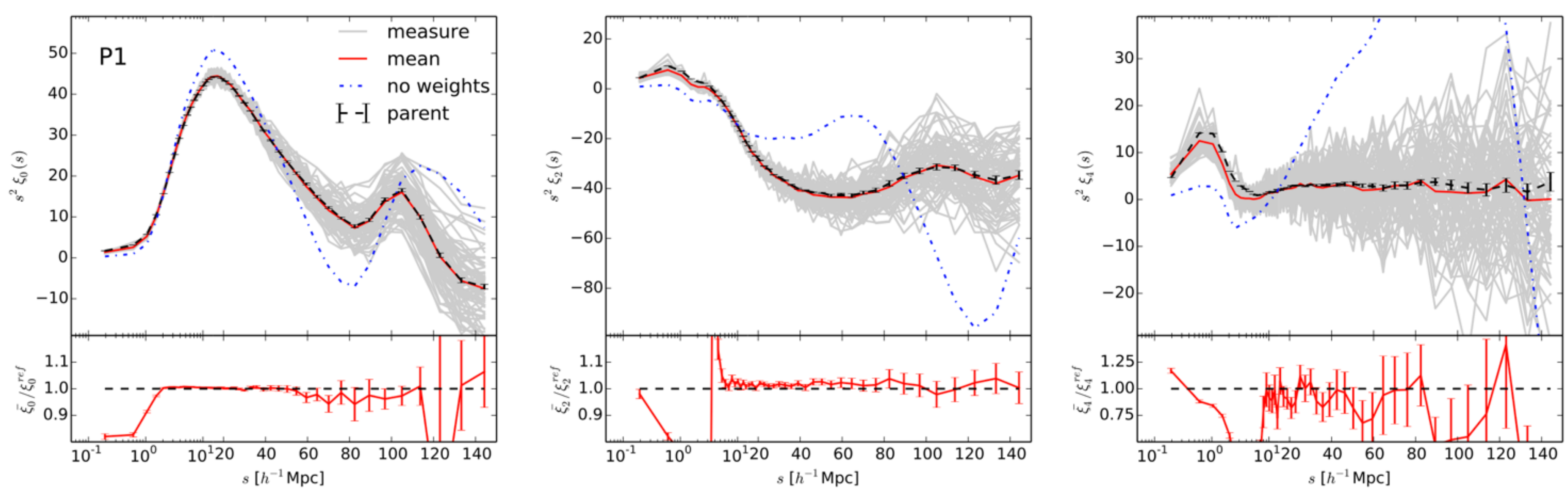
as, e.g., **DESI** multi-fibre spectrograph



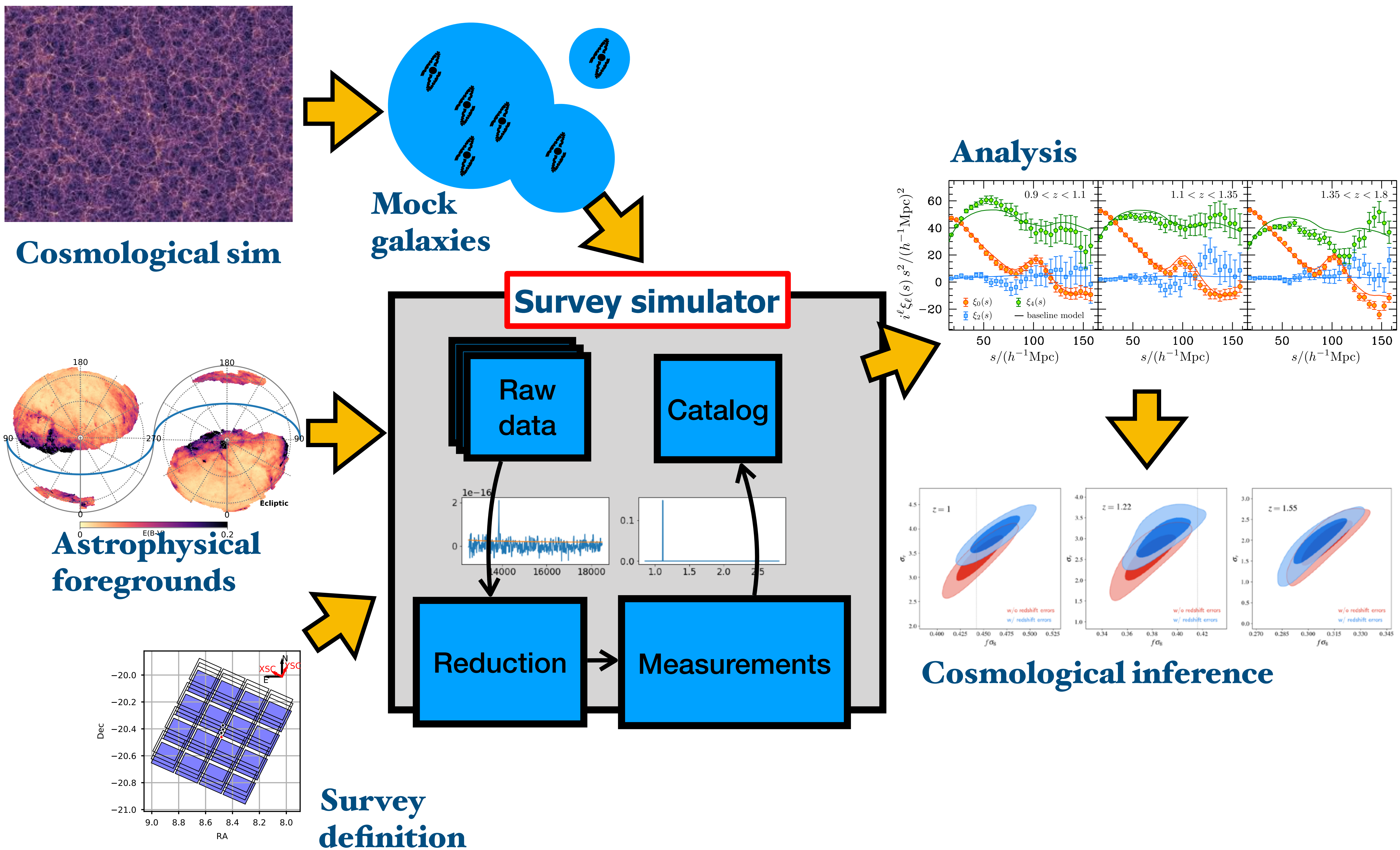
x 10



Bianchi & Percival 2017; arXiv:1703.02070



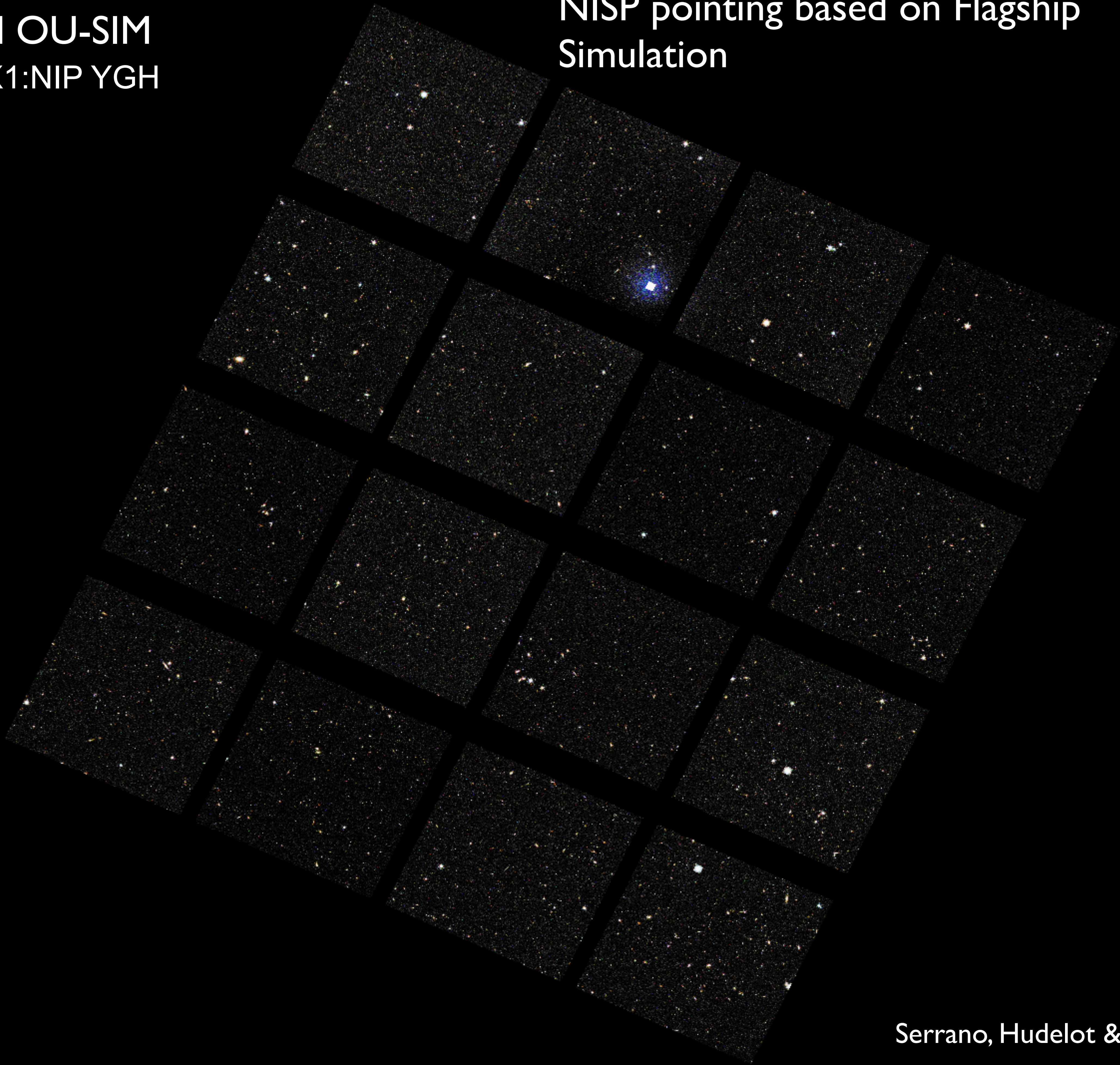
End-to-end simulations are key in this game…



(Ben Granett & Euclid end-to-end group)

Euclid OU-SIM
Field X1:NIP YGH

NISP pointing based on Flagship Simulation

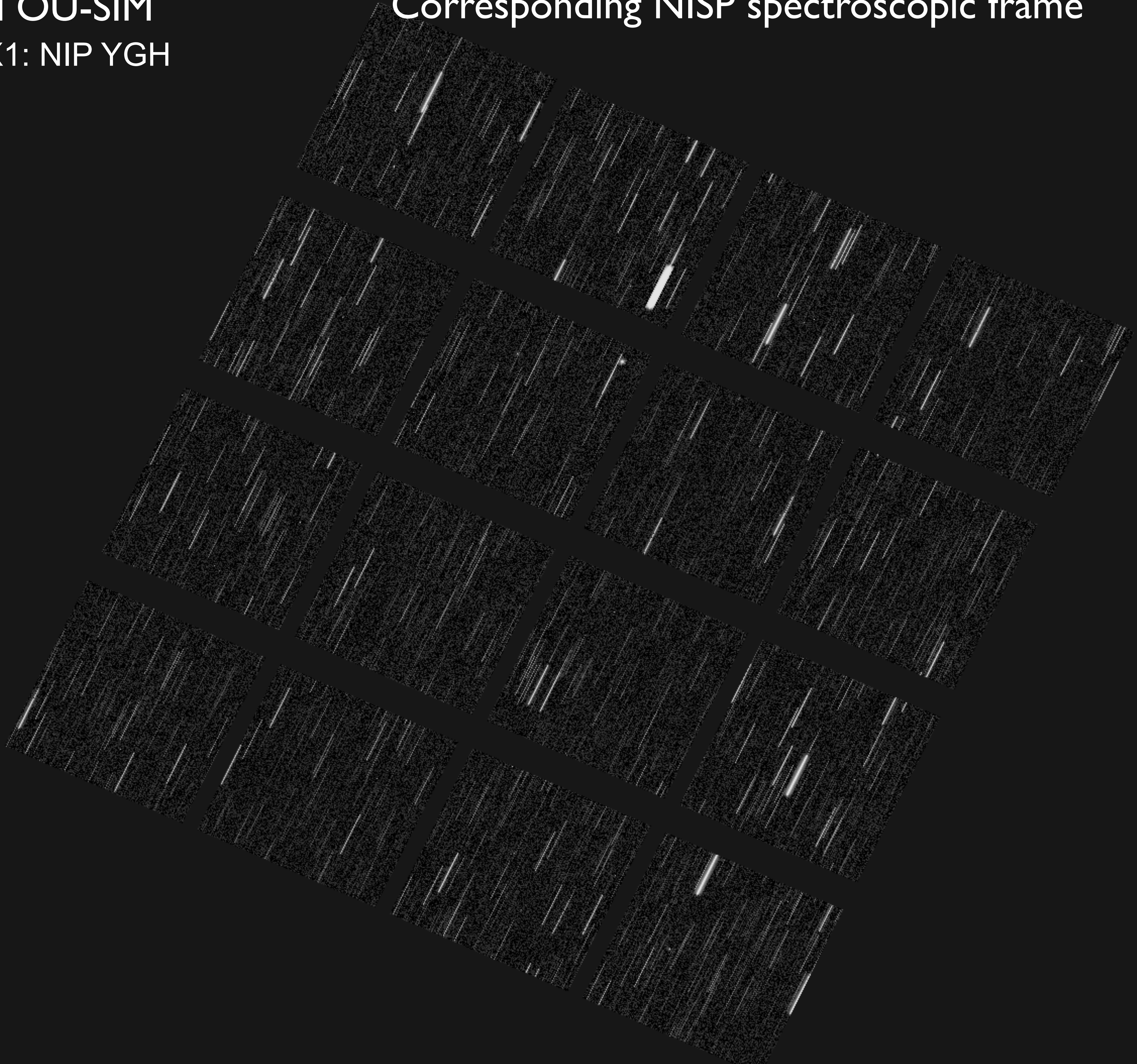


Serrano, Hudelot & OU-SIM

Euclid OU-SIM

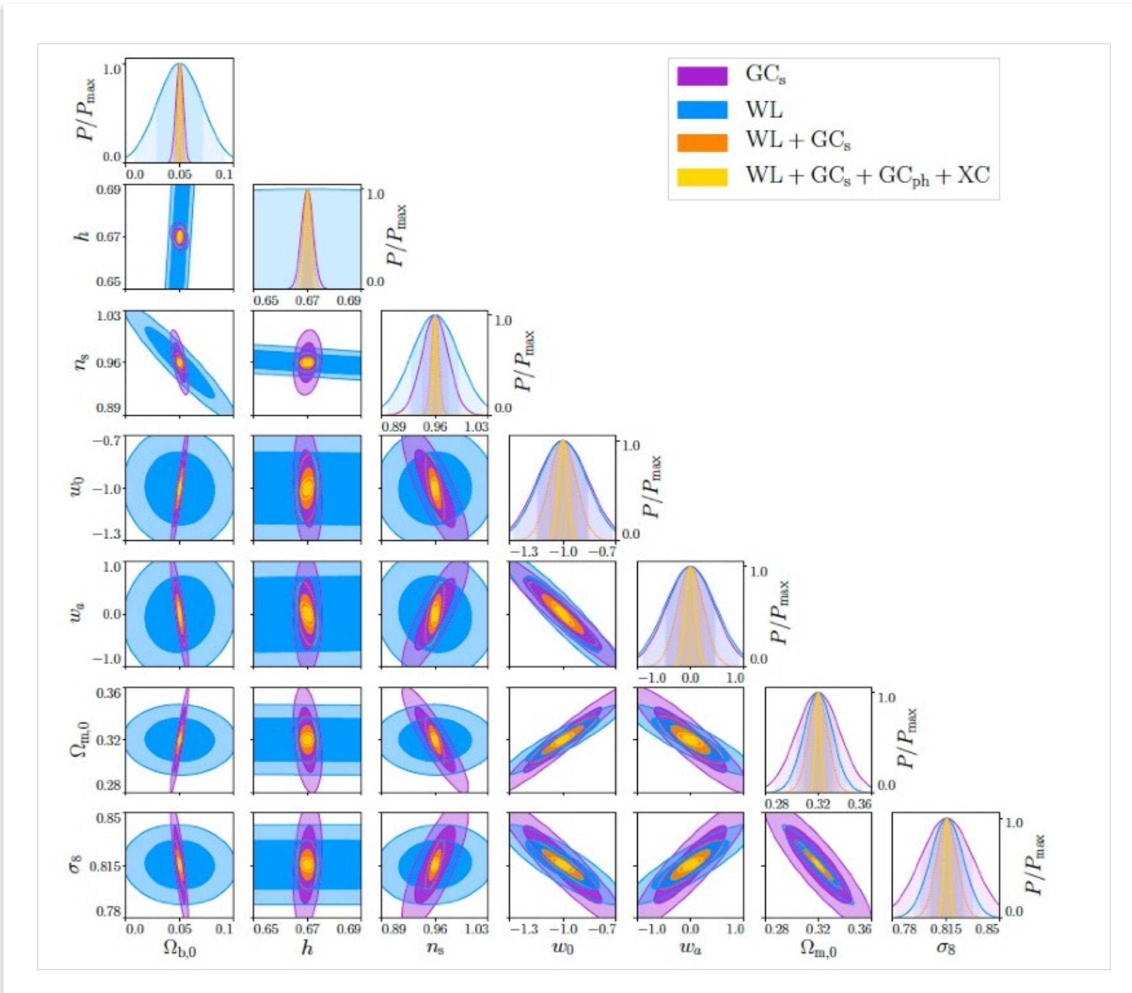
Field X1: NIP YGH

Corresponding NISP spectroscopic frame

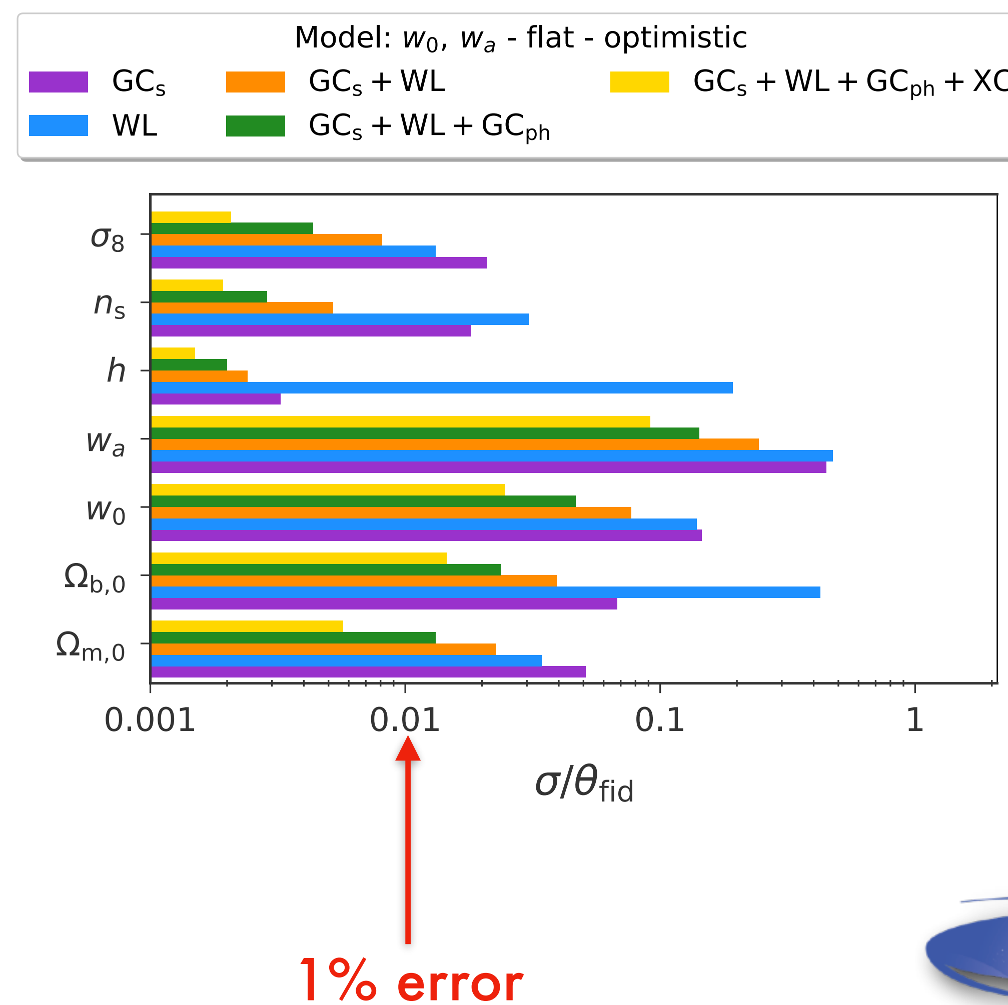


… to derive informed forecasts of scientific performances

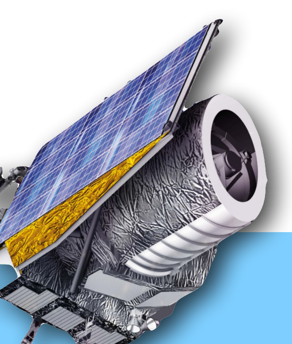
REFERENCE PAPER: IST:F & Euclid Consortium, arXiv:1910.09273

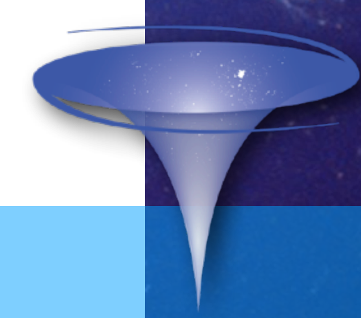


The power of probe combination



Work no progressing with
IST:Likelihood
IST:NonLinear

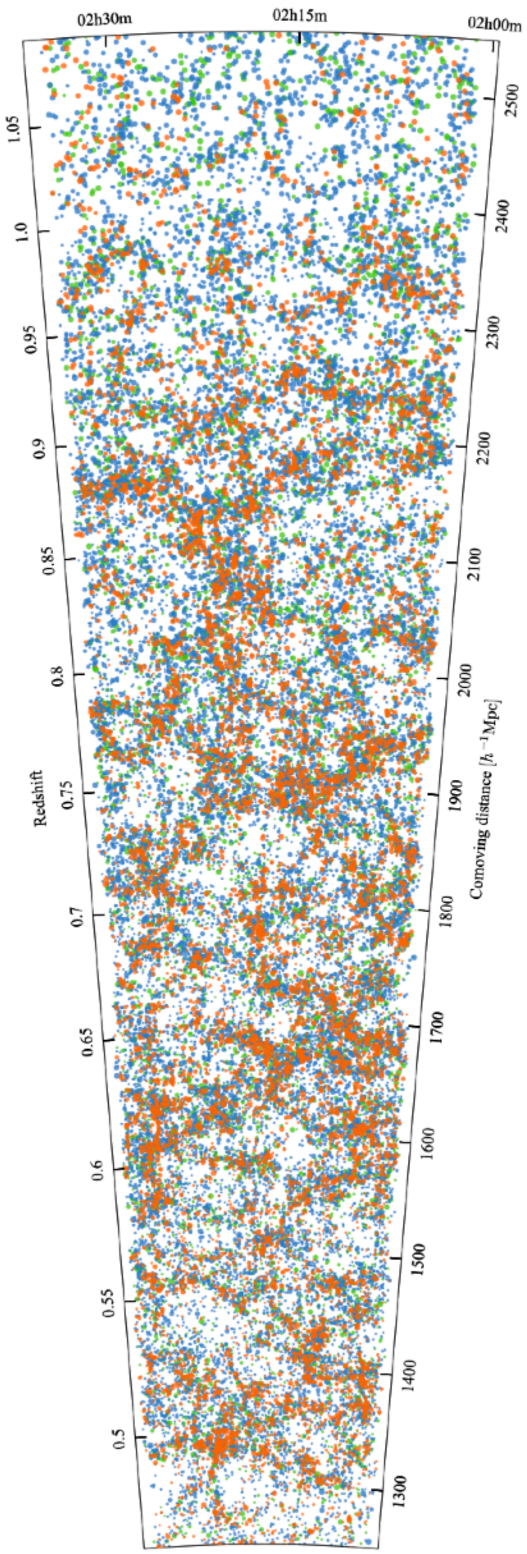


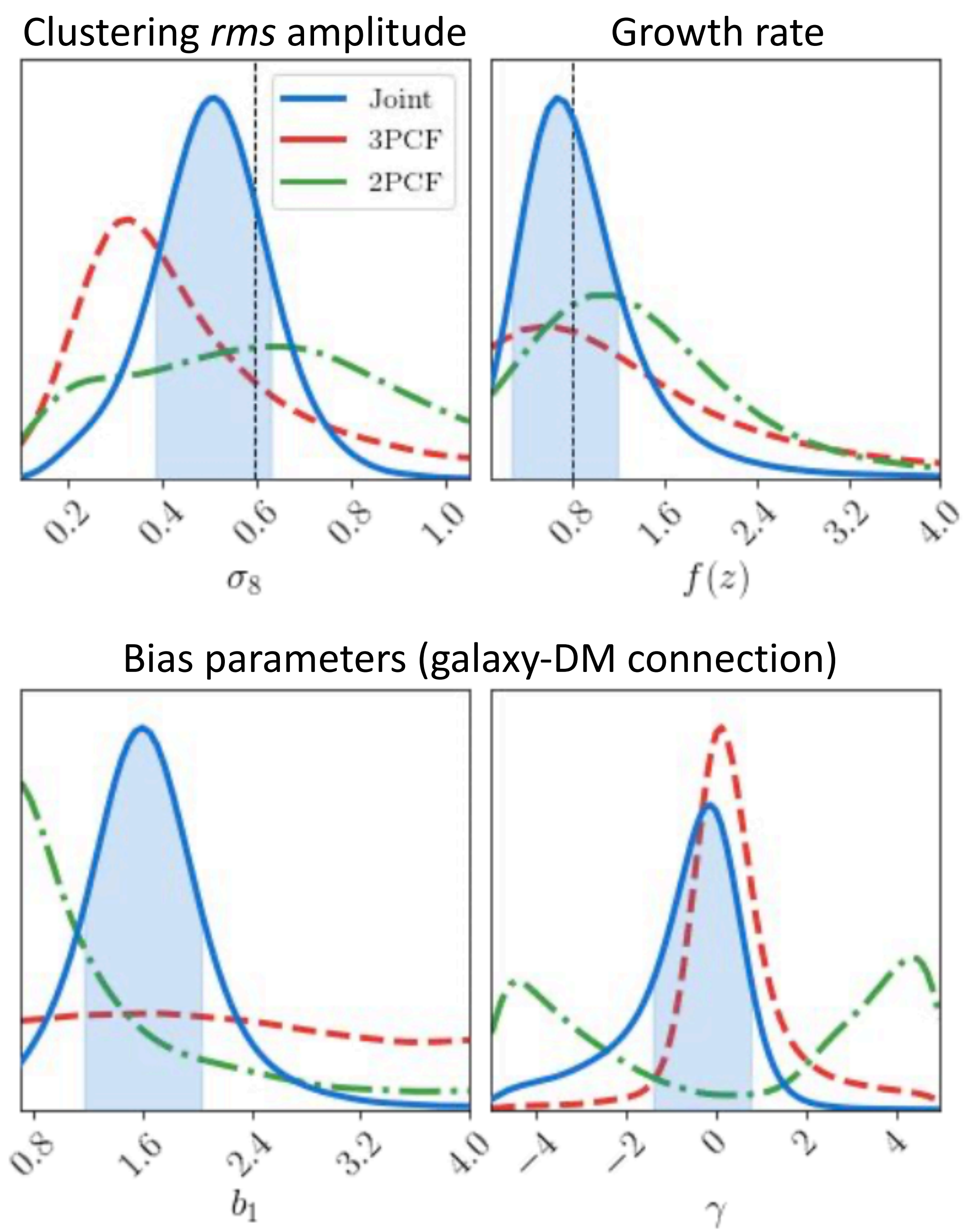


There is more in the data beyond two-point statistics

Add higher-order information: VIPERS joint 2-point + 3-point constraints

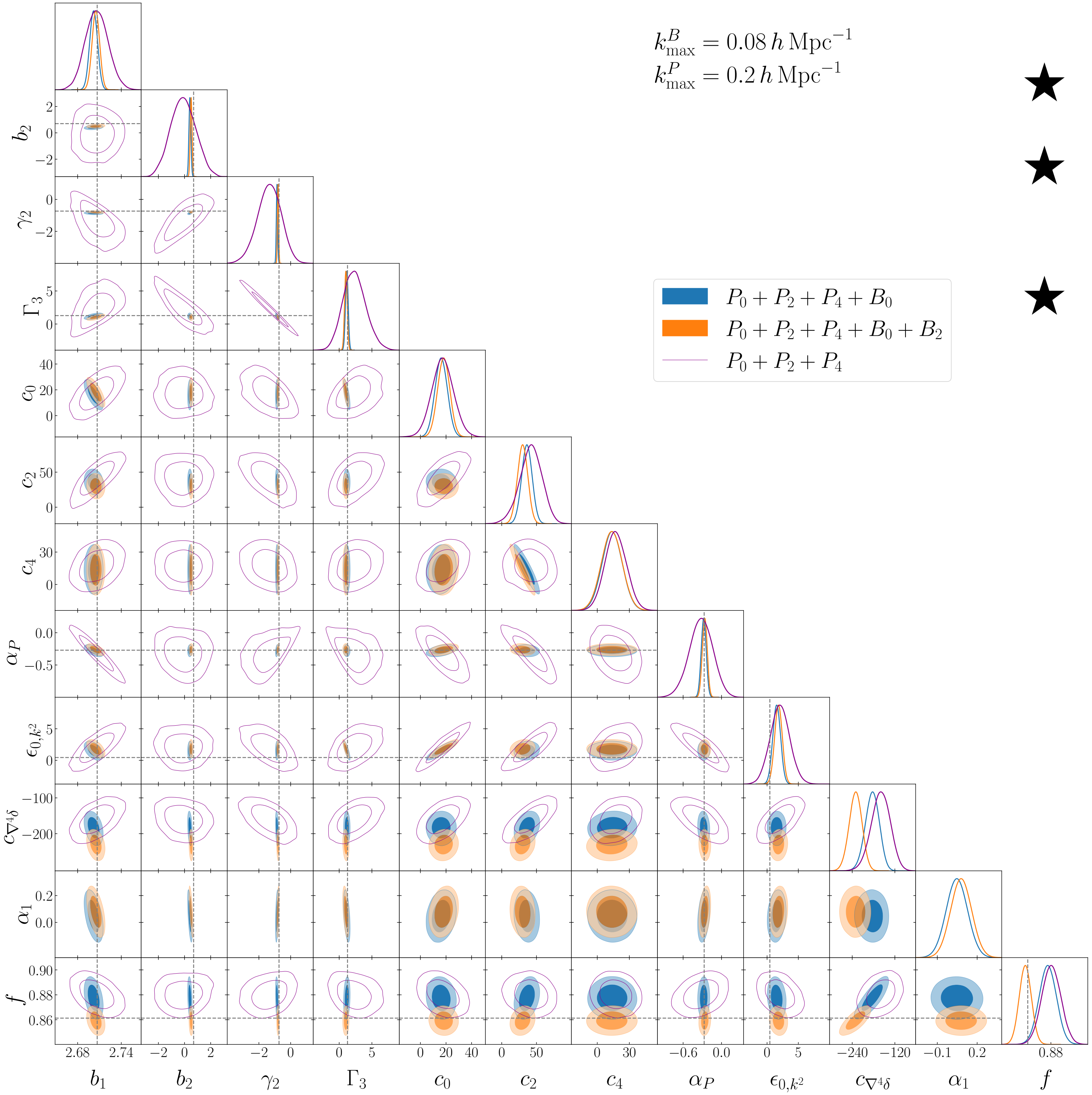
(Veropalumbo, w/ Branchini, LG et al.+ 2021, MNRAS, 507, 1184)





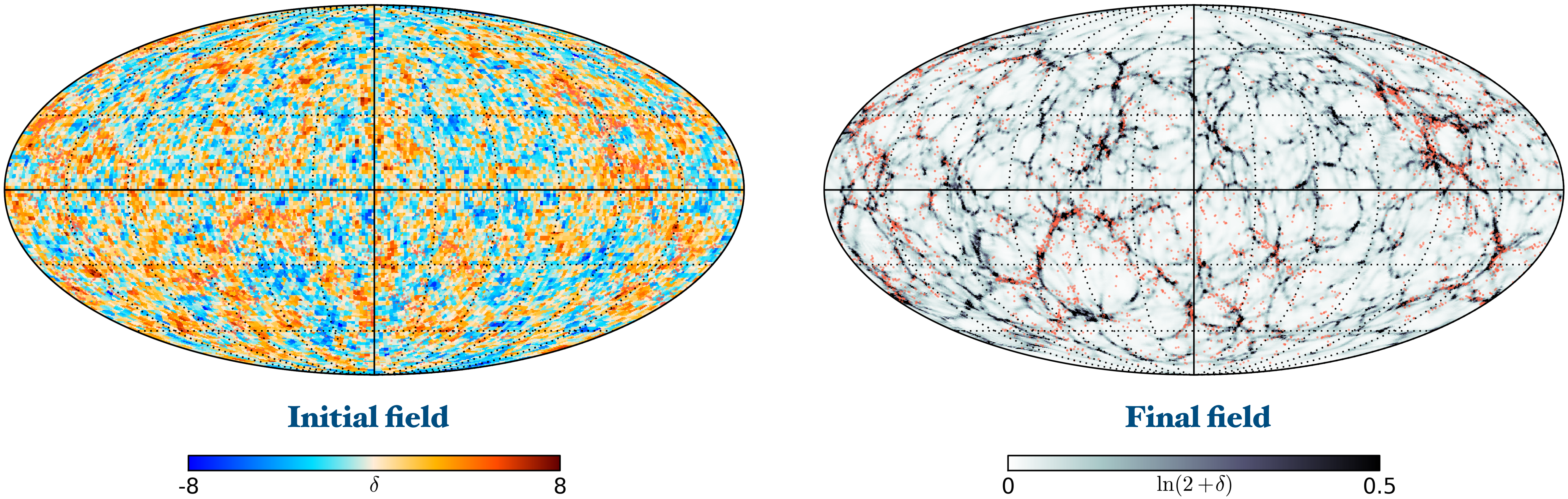
Add higher-order information: Euclid Fourier-space forecasts

(Moretti, Sefusatti+, in prep.)



- ★ Combine P(k) and B(k)
- ★ Include redshift-space distortion constraints (multipoles)
- ★ Dedicated work package inside Euclid Galaxy Clustering SWG (led by Sefusatti & Porciani)

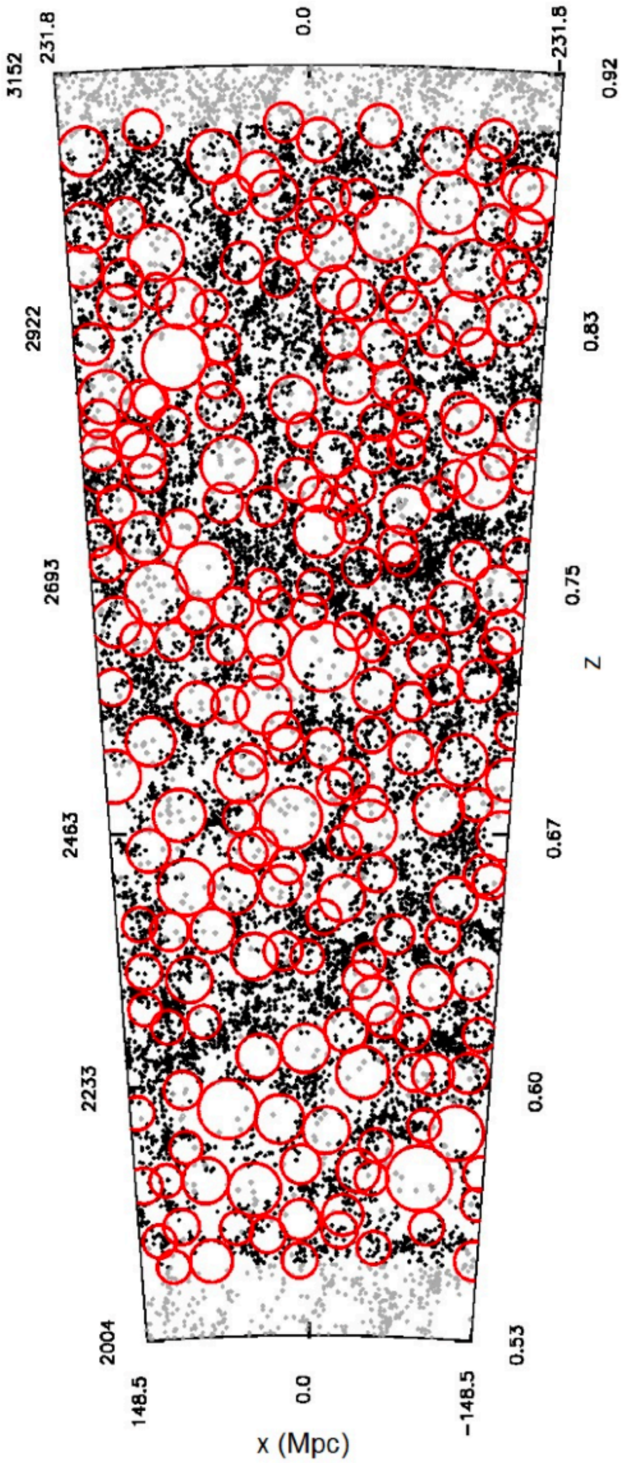
Forward-modelling cosmological Inference



Constrained particle-mesh simulation of real 2Mass++ survey: single realisation (Lavaux & Jasche 2018)

- ★ Generate realisations of the initial conditions (density field) sampling model parameters
- ★ Evolve these to current epoch
- ★ Apply appropriate *bias* recipe and data model to compare directly to data
- ★ Pioneered by B. Wandelt group ( )
- ★ Simplified version: Wiener filtering (e.g., Granett & VIPERS Team 2015; Estrada+ 2022)

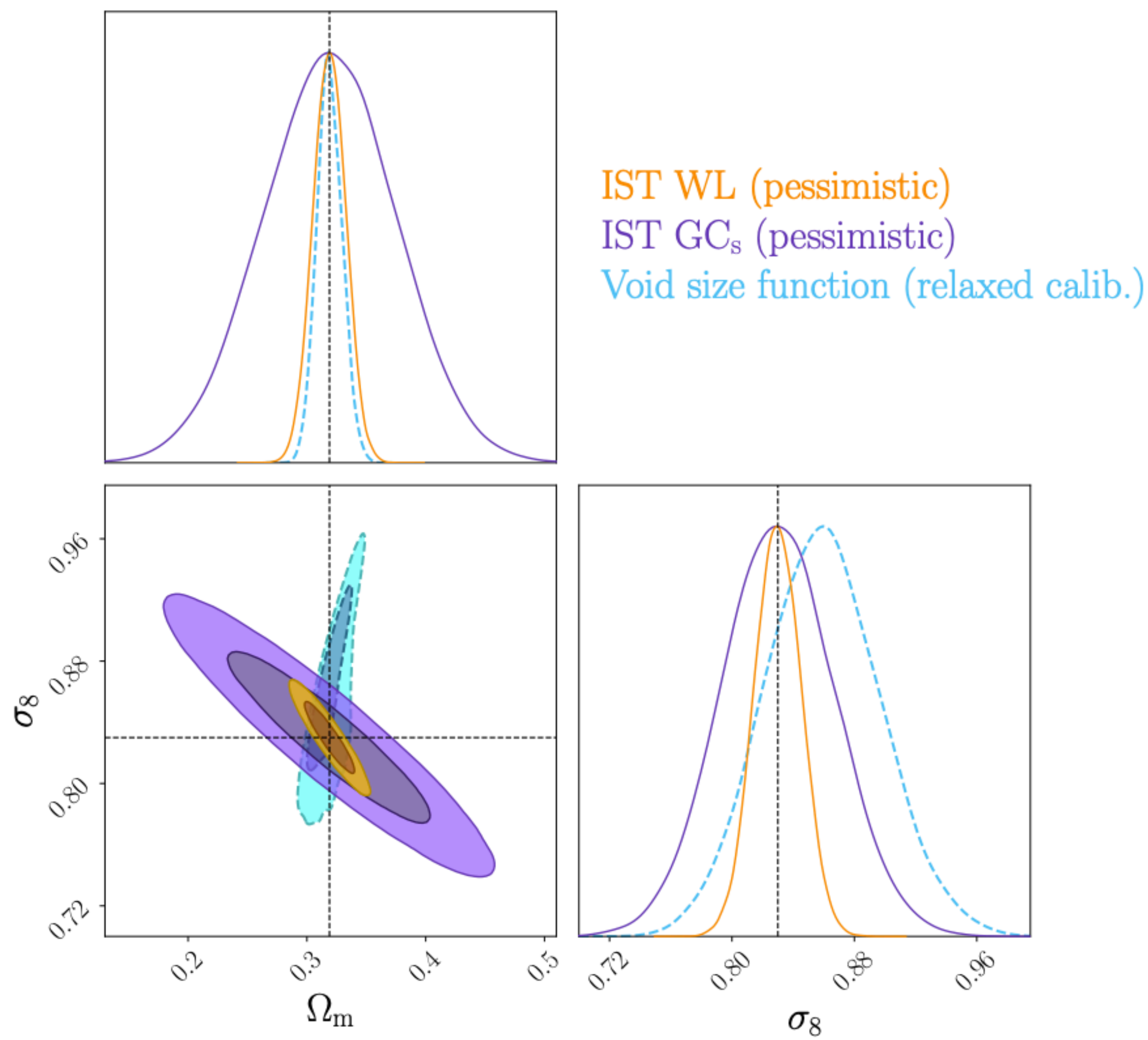
Cosmic voids statistics capture n-point information



VIPERS example
(Micheletti, Iovino & VIPERS, 2015)

Void size distribution function

(e.g., Verza, Pisani, Carbone et al. 2019)

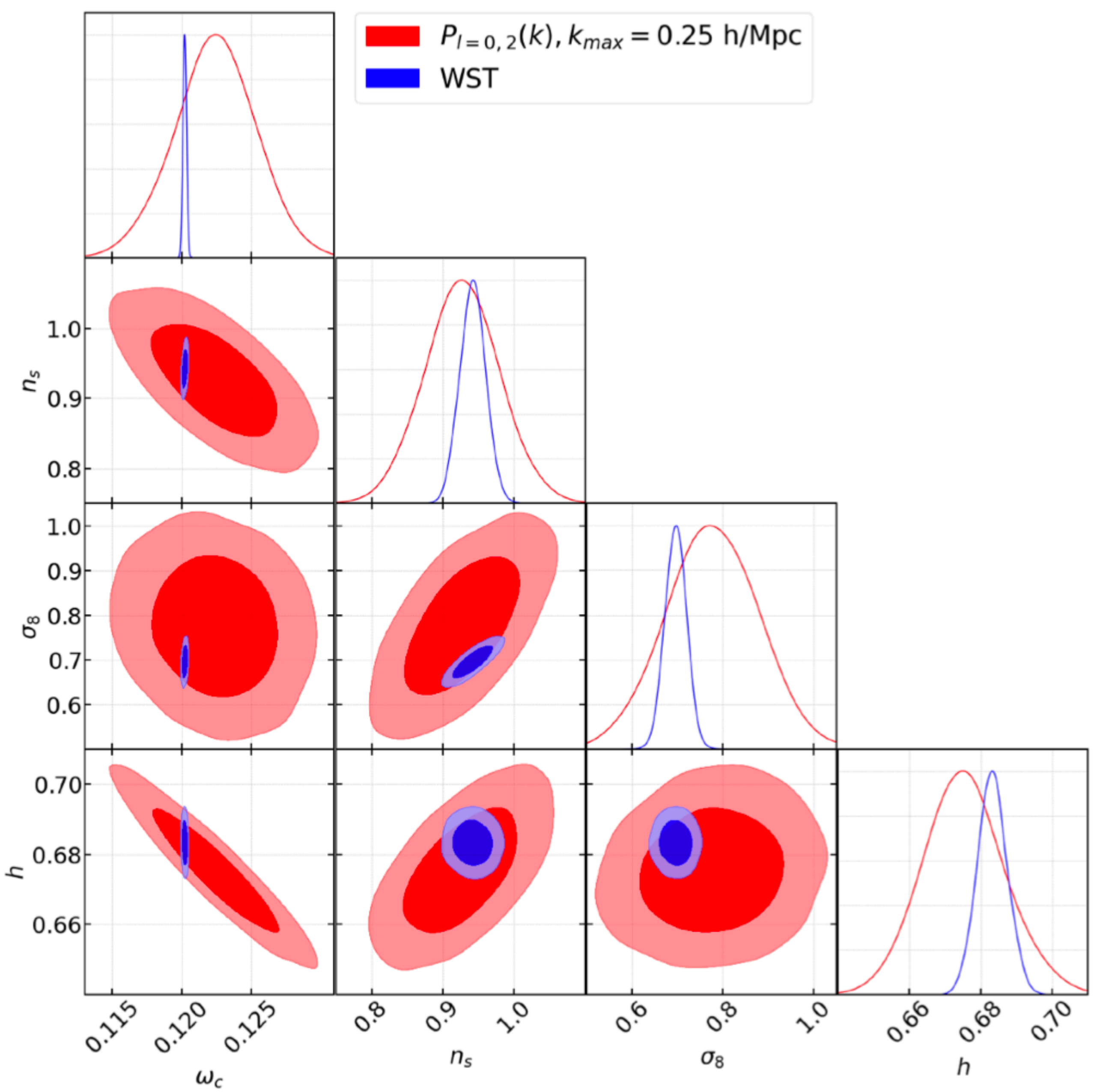


Euclid forecasts

(Contarini, Verza & Euclid Consortium, 2021)

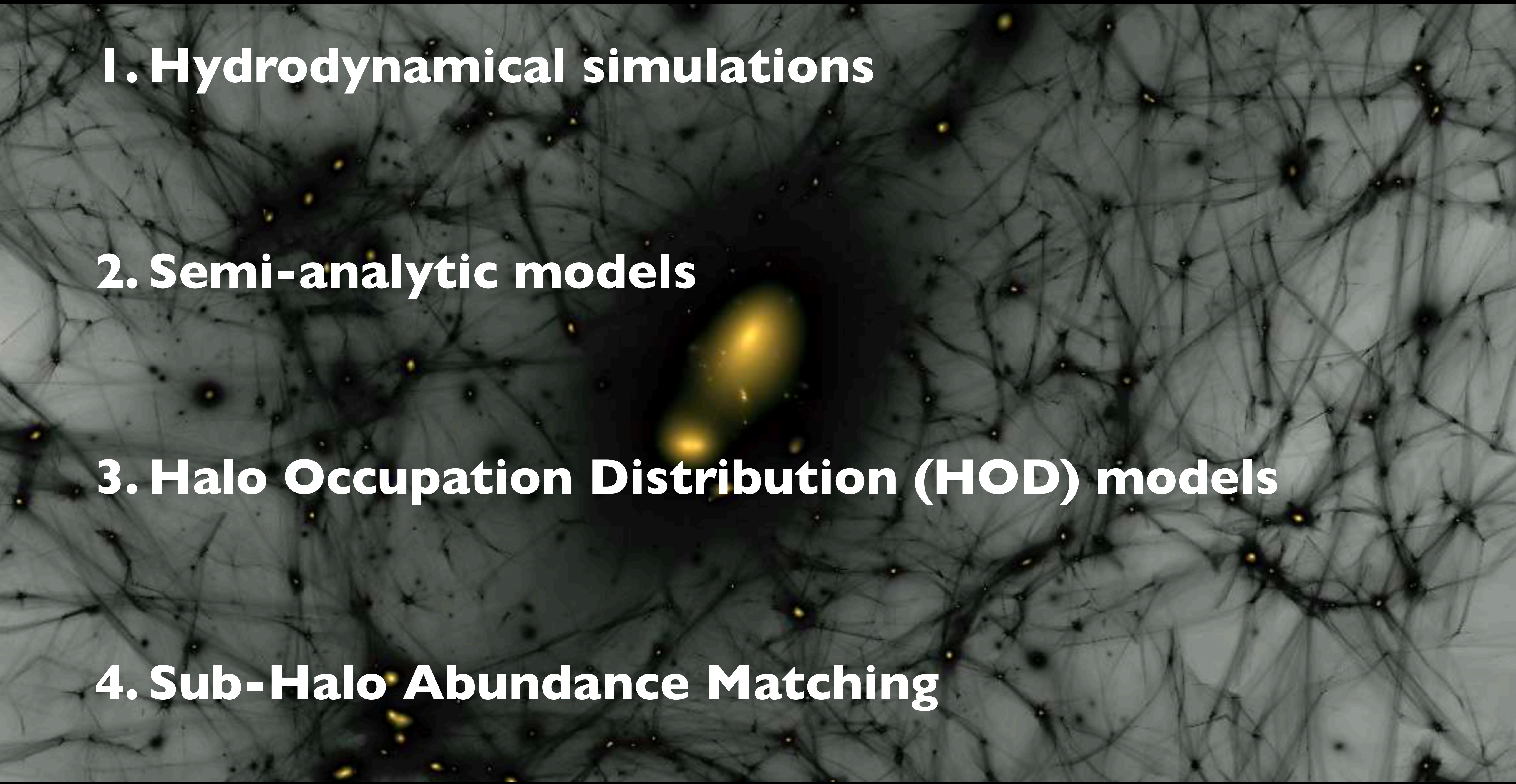
Alternative "compression" statistics, e.g., the Wavelet Scattering Transform

(Valogiannis & Dvorkin 2021, 2022; see Cheng & Menard 2021 for pedagogical introduction)



- ★ Filter the galaxy field with appropriate wavelet kernel, compare to numerical simulations
- ★ Applied to real data (BOSS)
- ★ "Field transformation" techniques (Neyrinck+ 2009; Carron & Szapudi 2013, see also Biagetti+ arXiv:2009.04819)
- ★ Caveat 1: require large suites of numerical simulations, covering variety of cosmologies
- ★ Caveat 2: require comparing to simulated "galaxies" (e.g., marginalise over HOD parameters)

Making galaxies into (simulated) dark matter haloes

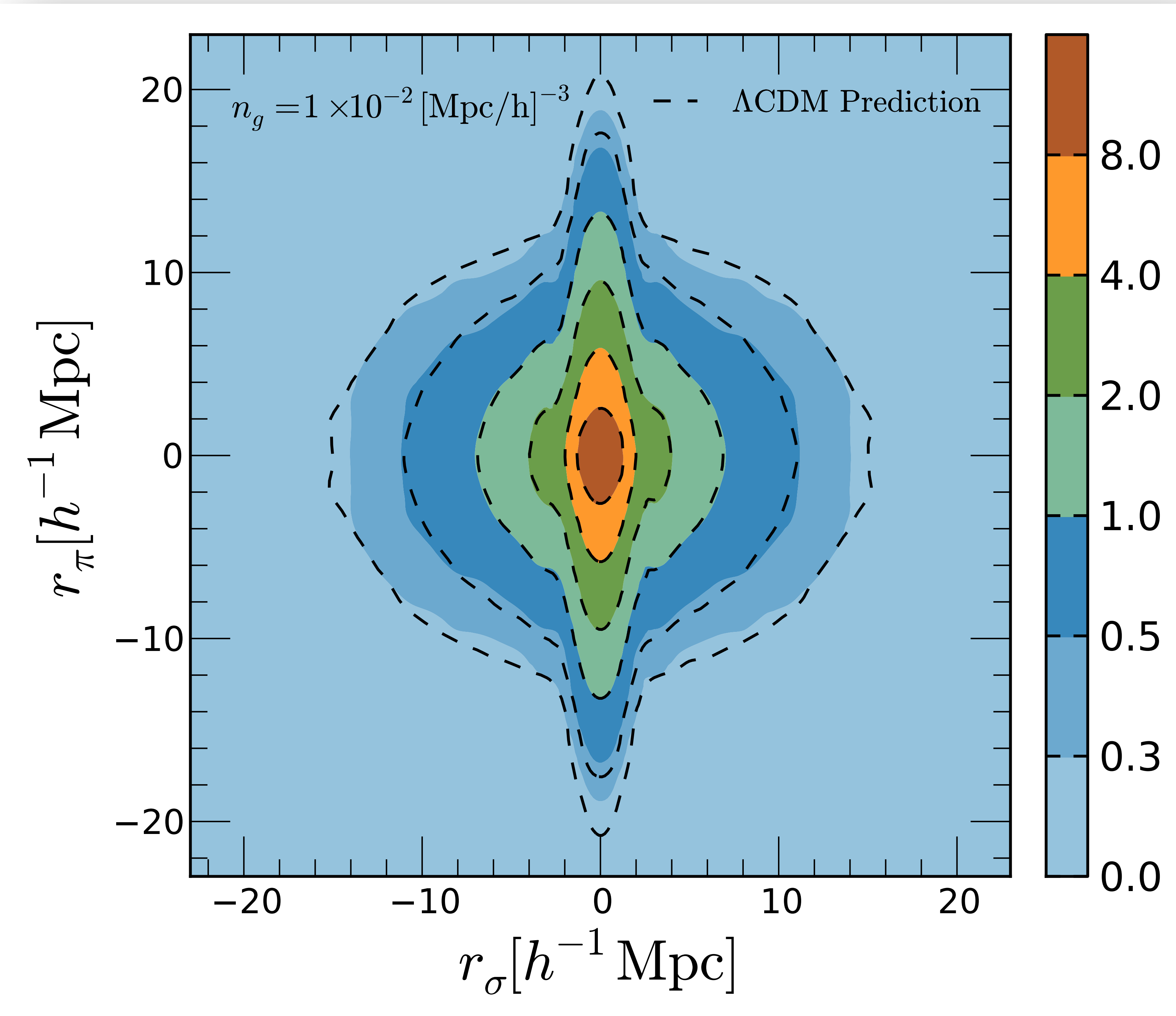


1. **Hydrodynamical simulations**
2. **Semi-analytic models**
3. **Halo Occupation Distribution (HOD) models**
4. **Sub-Halo Abundance Matching**

(Image credit: R. Kaehler)

Using SHAM to match SDSS clustering to ΛCDM down to fully nonlinear scales

(He, Guzzo, Li & Baugh 2018)



(also, e.g., Granett+ 2019; Girelli+2020; Carella+2022 for similar applications)

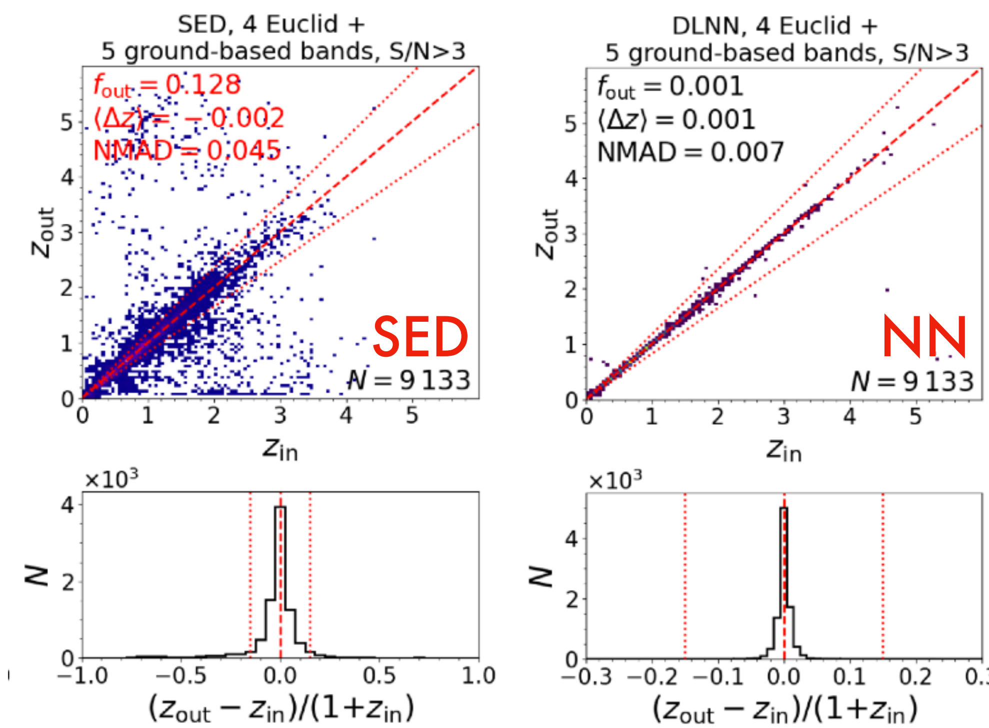
The importance of understanding galaxies to do cosmology

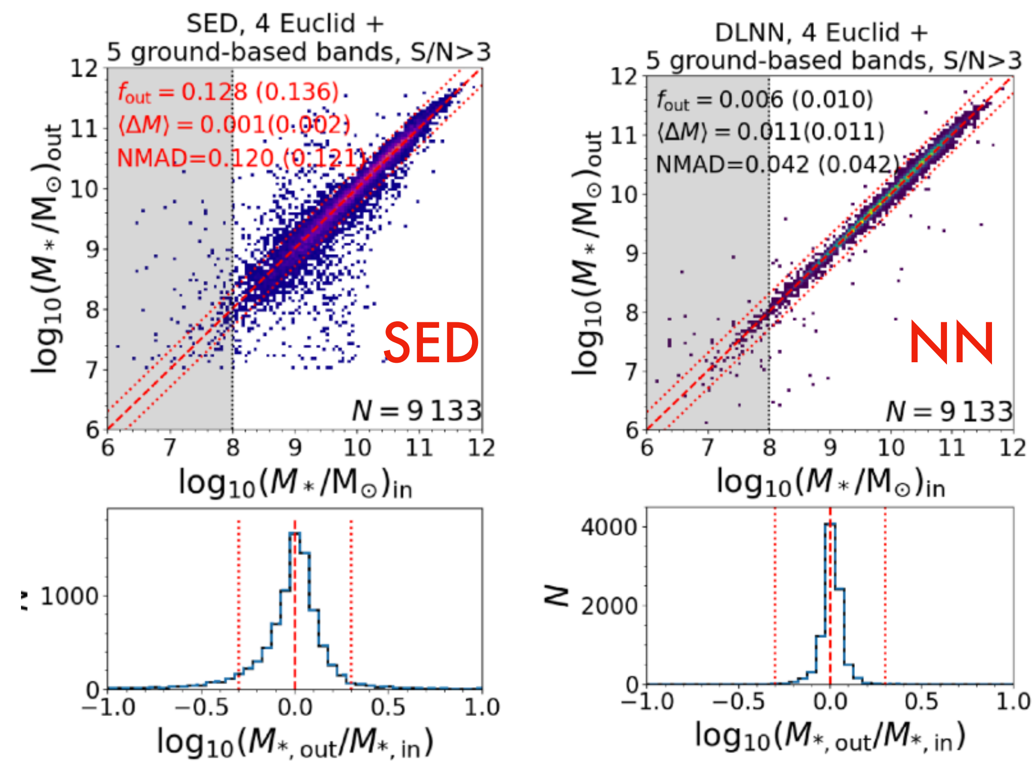
Capture the full scale / order clustering information altogether, through a Machine Learning approach?

Importance of developing ML expertise: e.g., (I) data mining, classification / regression

Estimate galaxy meta-properties, as **photometric redshifts** and **stellar masses**

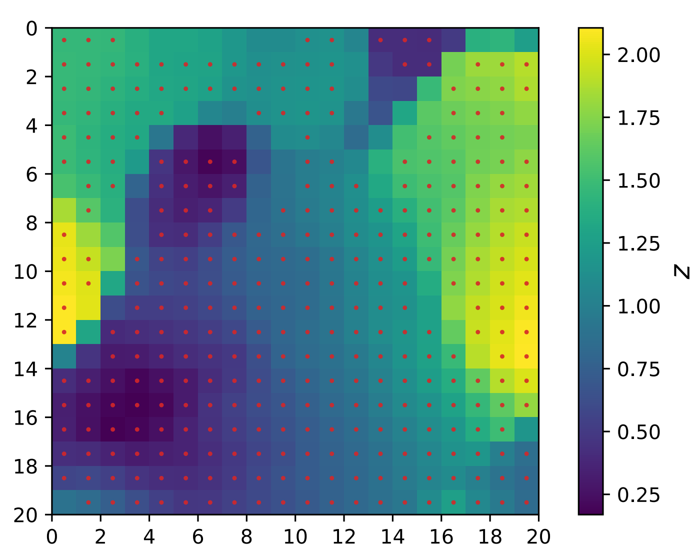
(Bisigello & Euclid Consortium, 2022, submitted)



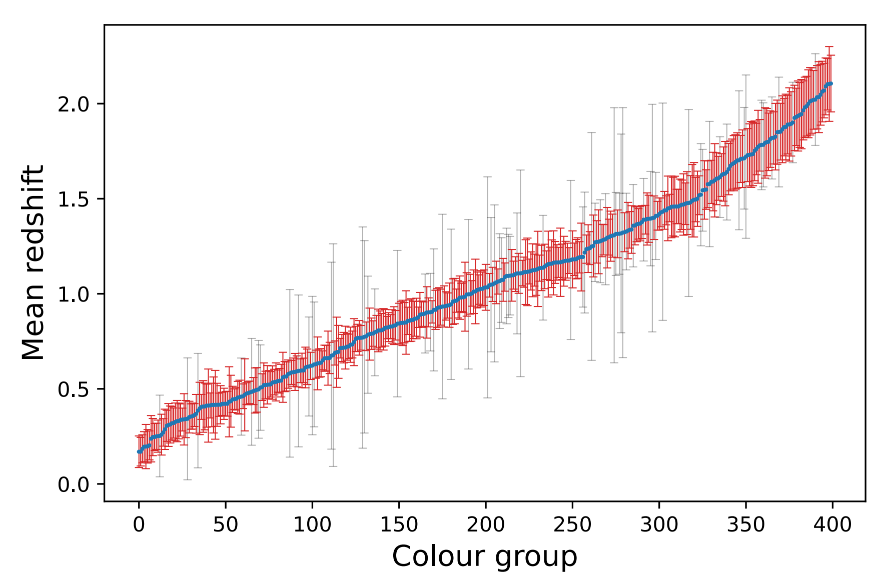


…or **redshift distributions** by stacking low SNR spectra, matched through photometric colours…

(Cagliari, Granett & Euclid Consortium 2021)



Self-Organising Maps (SOM)



Importance of developing ML expertise: (ii) *emulators* to accelerate cosmological inference

(**Bonici**, Biggio, Carbone & Guzzo, 2022, MNRAS, submitted)

We do inference applying **Bayes Theorem**:

$$P(\theta \mid D) = \frac{\mathcal{L}(D|\theta) P(\theta)}{P(D)}$$

Our goal: posterior on data

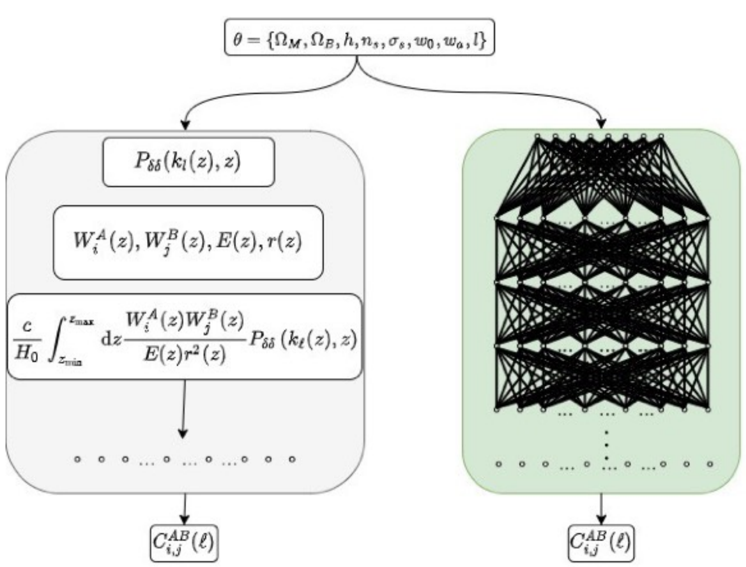
Likelihood function, connecting theory and data

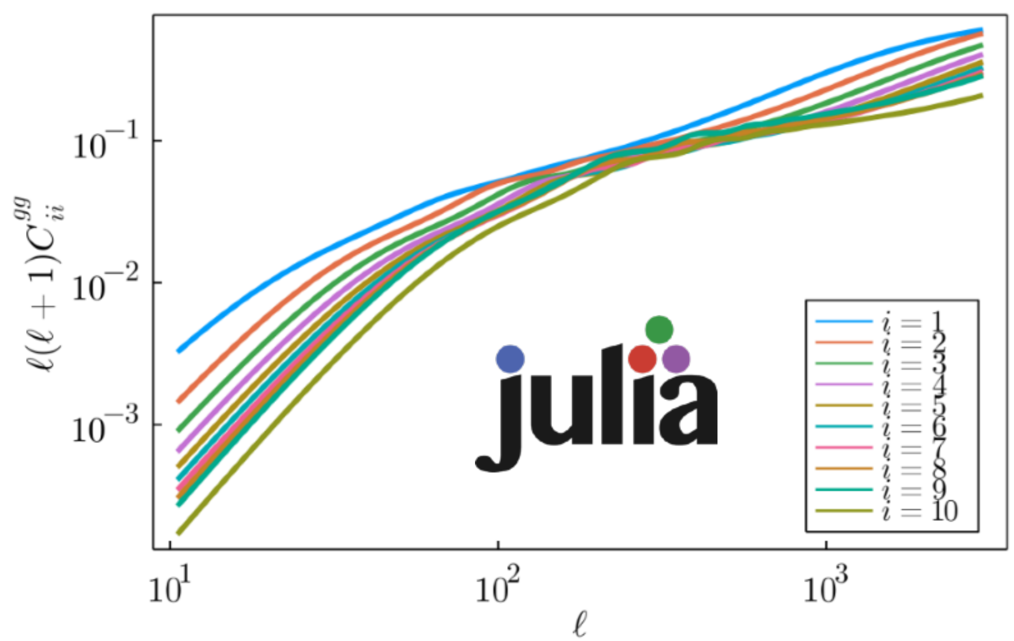
Prior on model parameters

Need **repetitive expensive computations** of model power spectra to explore the Likelihood

$$\mathcal{L}(\boldsymbol{D} \mid \boldsymbol{\theta}) \propto \exp\left(-\frac{1}{2}\left[(\boldsymbol{D} - \boldsymbol{C}(\boldsymbol{\theta}))^{\mathrm{T}} \boldsymbol{Cov}^{-1} (\boldsymbol{D} - \boldsymbol{C}(\boldsymbol{\theta}))\right]\right)$$

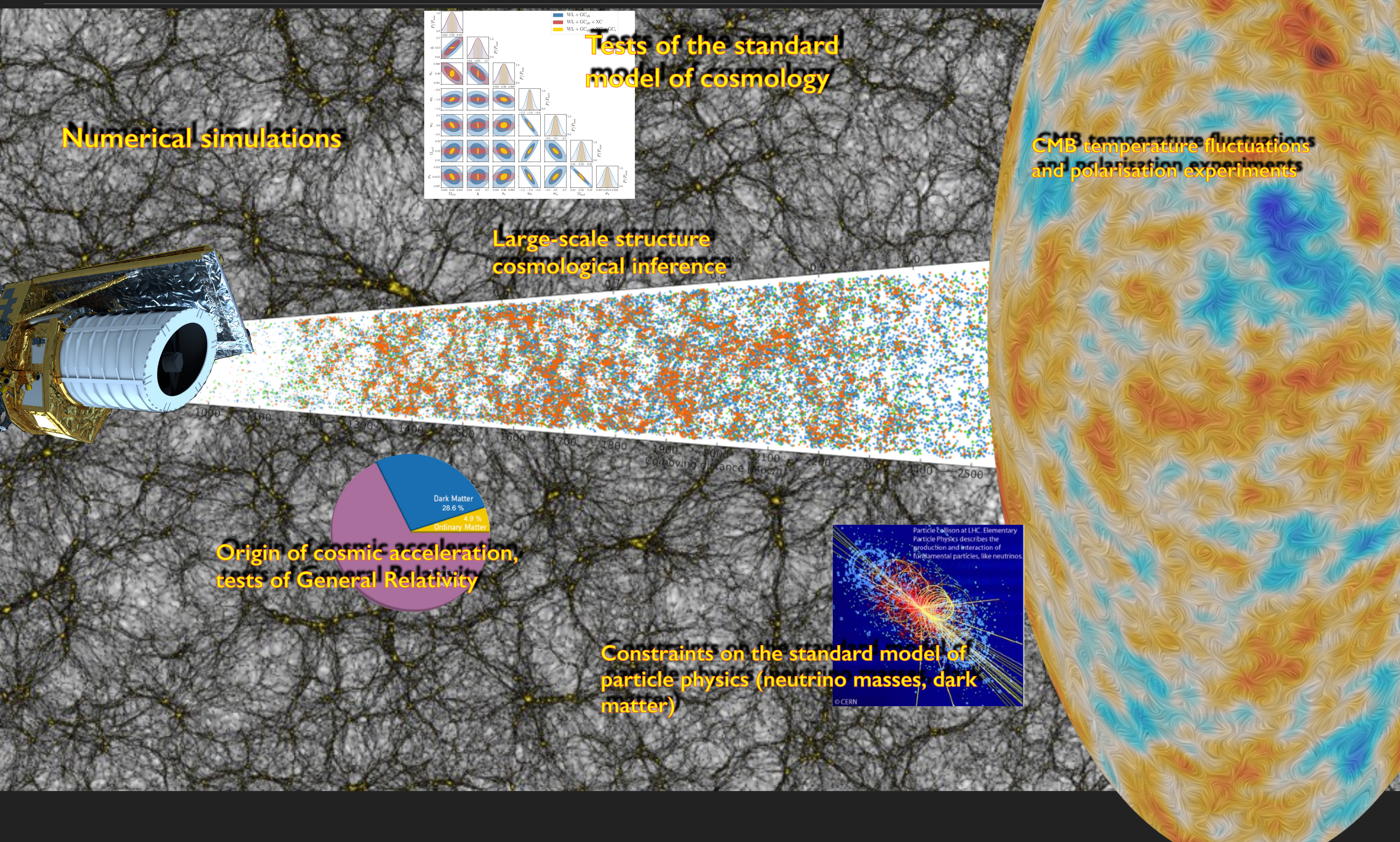
Solution: replace expensive Boltzmann solvers with a trained **neural network**





- **Speed-up ~10³**
- **Accuracy <0.2% on all scales**

LSS COSMOLOGY IN THE NEXT 20 YEARS



- We do have a **Standard Cosmological Model**, which however poses several challenges to fundamental physics
- Future observations will directly tackle these problems and may indicate **failures in the ΛCDM paradigm**
- Such expectations call for **unprecedented accuracy in both measurements and model predictions** (a different mindset, actually)
- At the same time, **new methods and techniques** are important to fully harvest all cosmological information
- The expertise required is present in INAF and covers different probes, but barely so: **we are a few, stretched across different fields**
- In some fields such **expertise in Italy is relatively recent**, which may lead to a limited perception of its role and value
- **Data is coming tomorrow!**

The end