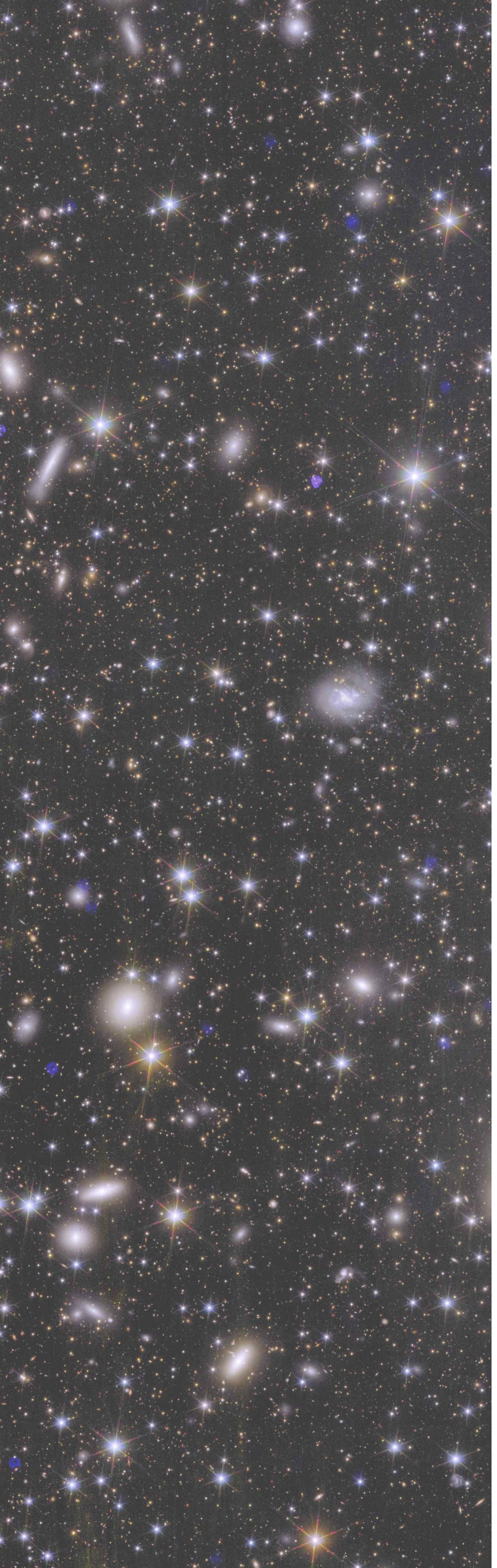


FROM THEORY TO TELESCOPE

Galaxy Surveys to Unveil the Dark Universe

Dr. GUADALUPE CAÑAS-HERRERA

9th January 2026

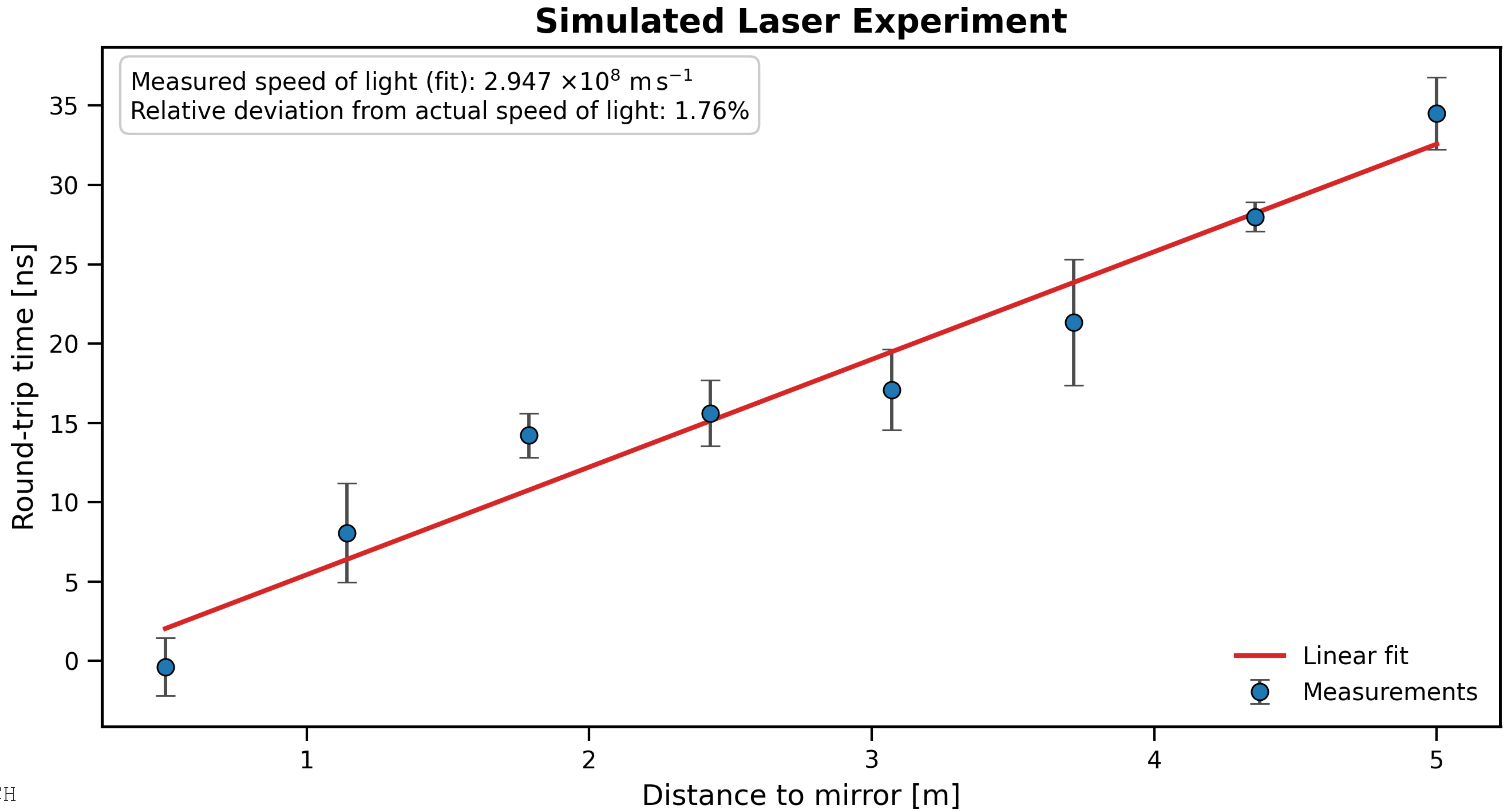
New Directions in Theoretical Physics

WHAT MAKES A THEORETICAL PHYSICIST … A THEORETICAL PHYSICIST?

I’m not sure I have a definitive answer, but one thing I do know: we are all researchers

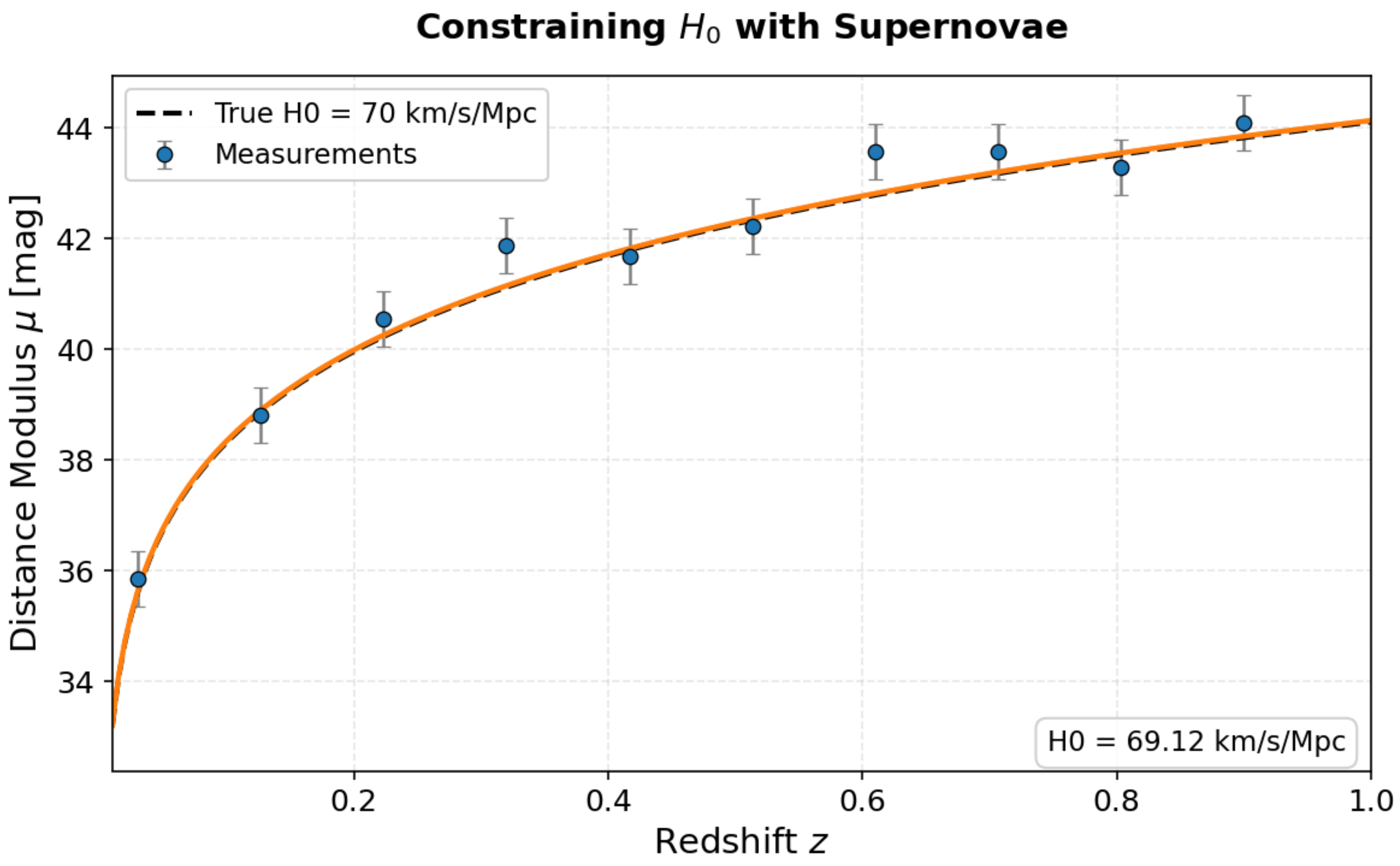
IT'S ALL ABOUT FITTING

About 10 years ago, I was characterizing photon counters' performance for particle physics



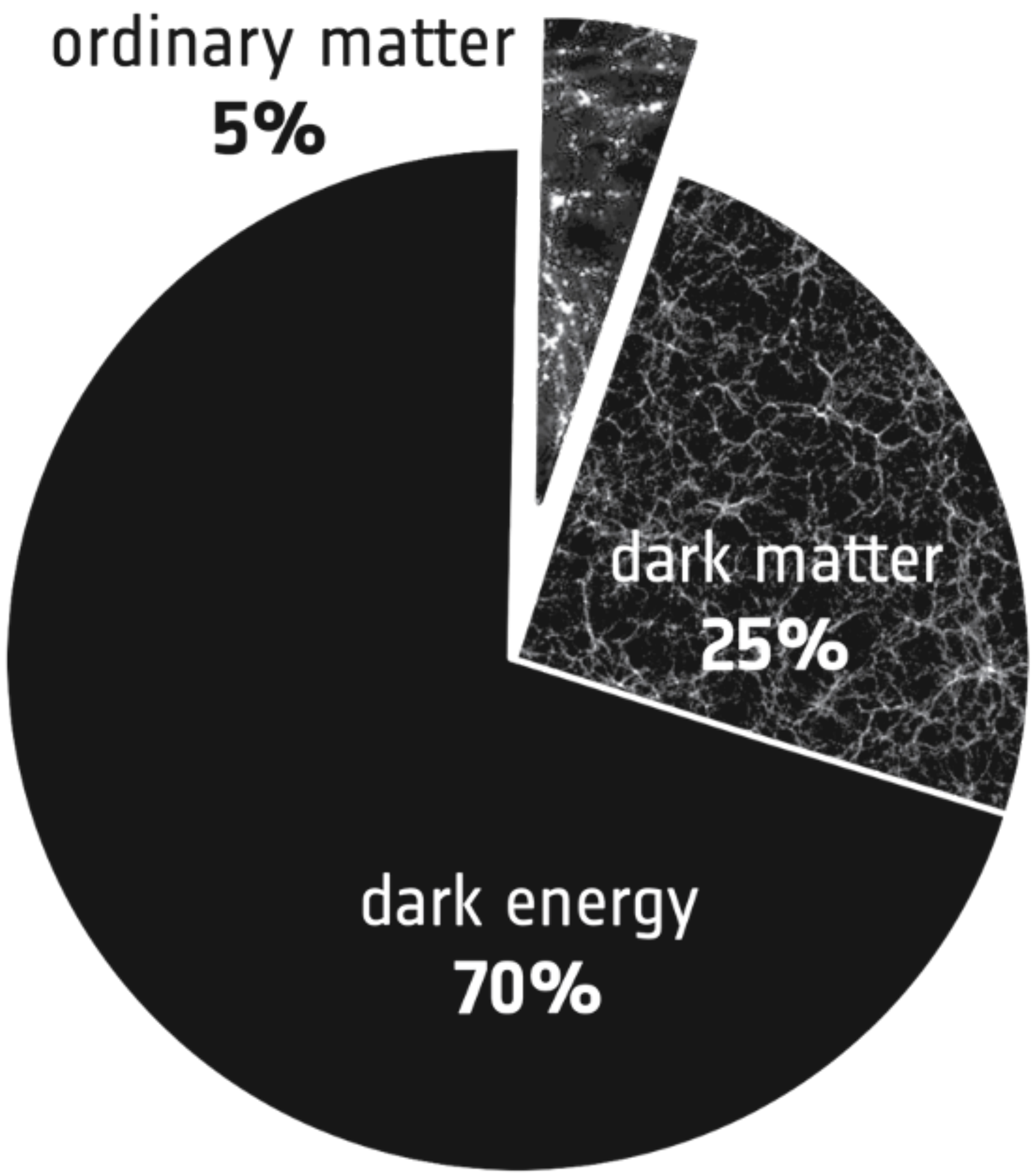
Credit: GCH

DIFFERENT SCOPE… *SAME* APPROACH



Credit: GCH

95% OF OUR UNIVERSE IS *UNKNOWN*



Credit: European Space Agency

What is the nature of the agent driving the accelerated expansion?

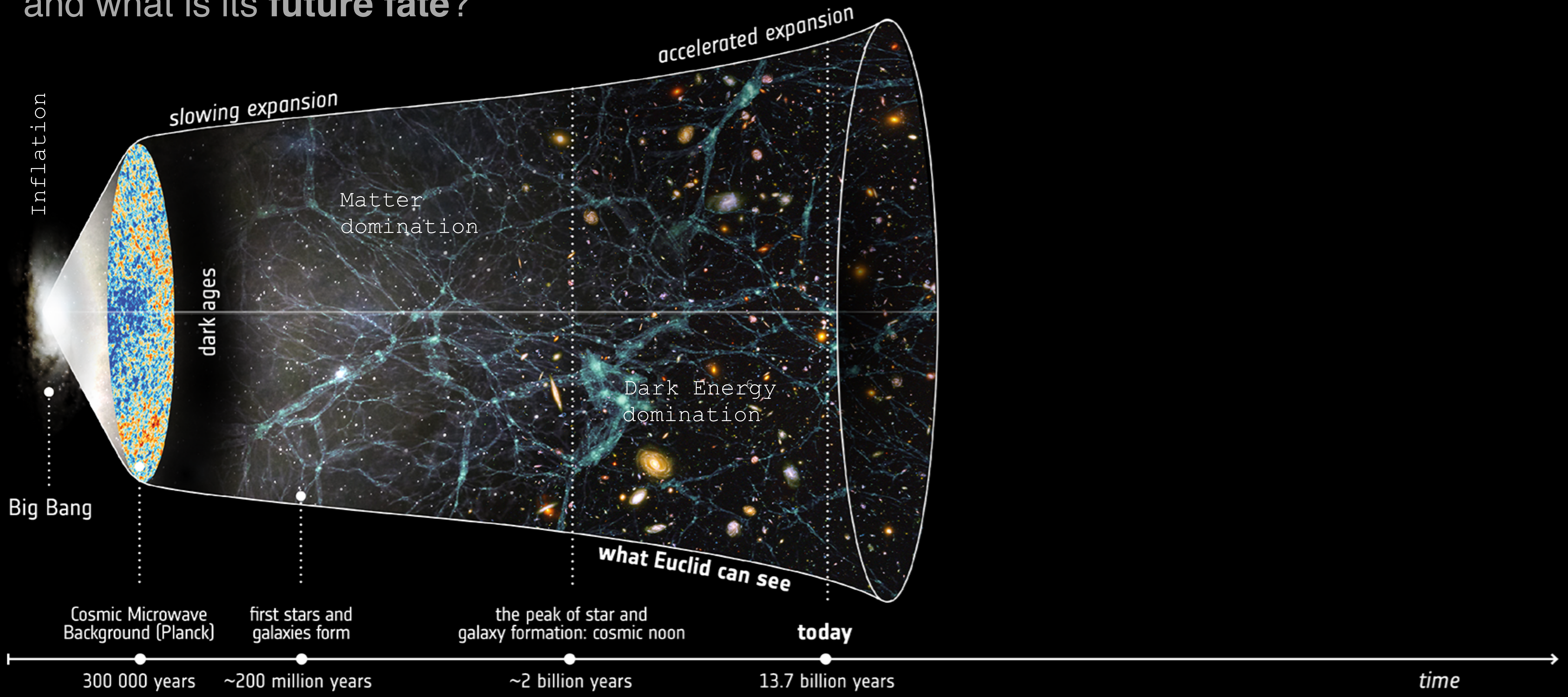
What is the nature of dark matter? And what about neutrinos?

How did our Universe begin?

Credit: European Space Agency/ATG, with contributions from **Cañas-Herrera**

CHASING FOR NEW PHYSICS

We root our Universe's understanding in unknowns: How did the Universe begin, evolve and what is its **future fate**?



Credit: European Space Agency/ATG, with contributions from **Cañas-Herrera**

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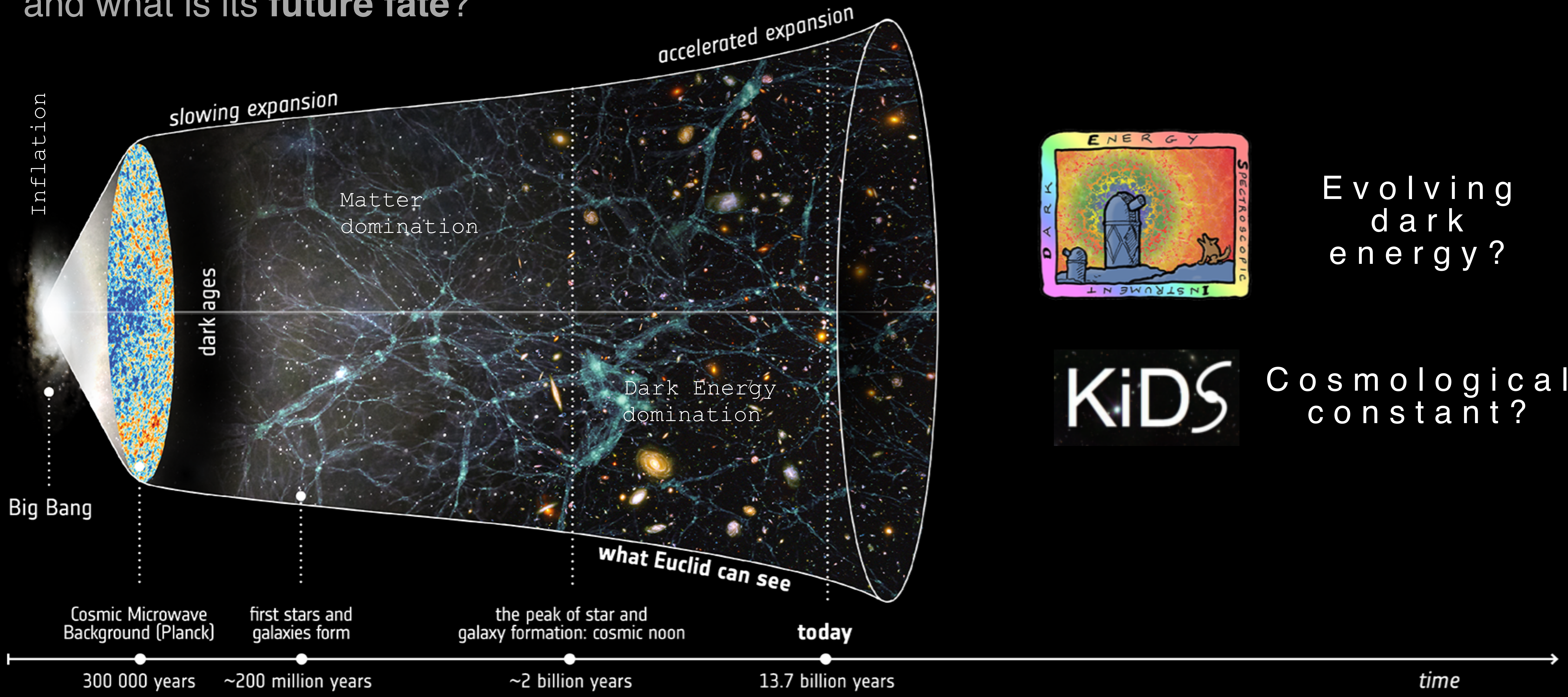
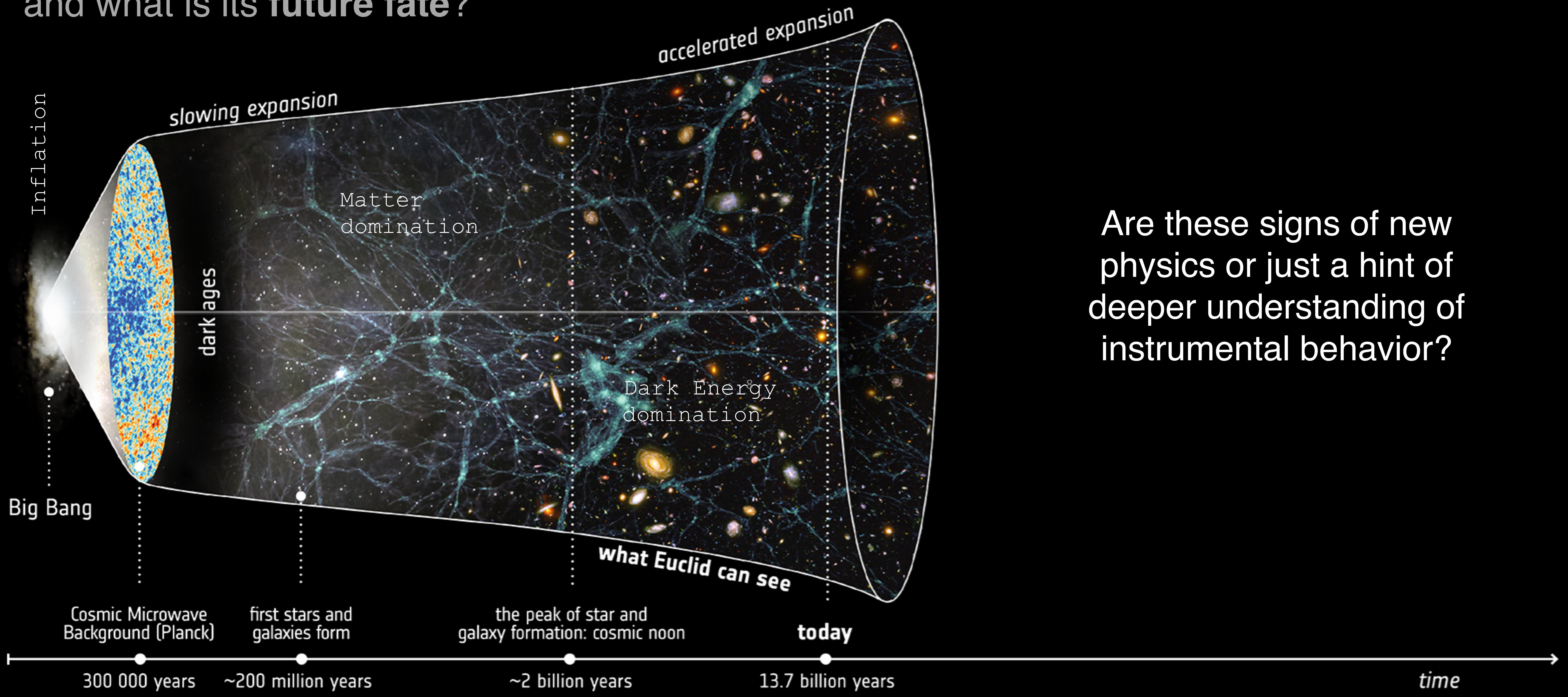


Evolving dark energy?

Cosmological constant?

CHASING FOR NEW PHYSICS

We root our Universe's understanding in unknowns: How did the Universe begin, evolve and what is its **future fate**?



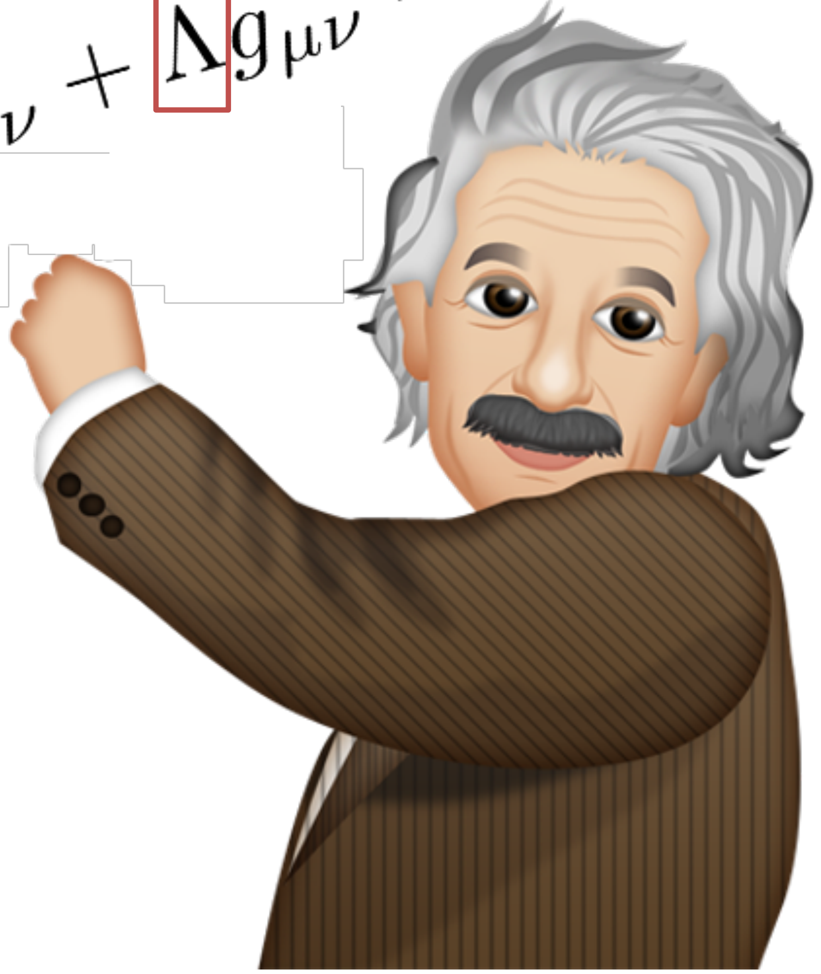
Are these signs of new physics or just a hint of deeper understanding of instrumental behavior?

CHASING EINSTEIN AND Λ

The accelerated expansion of the Universe can be explained assuming a new substance

Using a cosmological constant

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \boxed{\Lambda}g_{\mu\nu} = 8\pi G\boxed{T_{\mu\nu}}$$



Assuming an unknown substance
(i.e: dark energy)
with a time-dependent
equation-of-state*

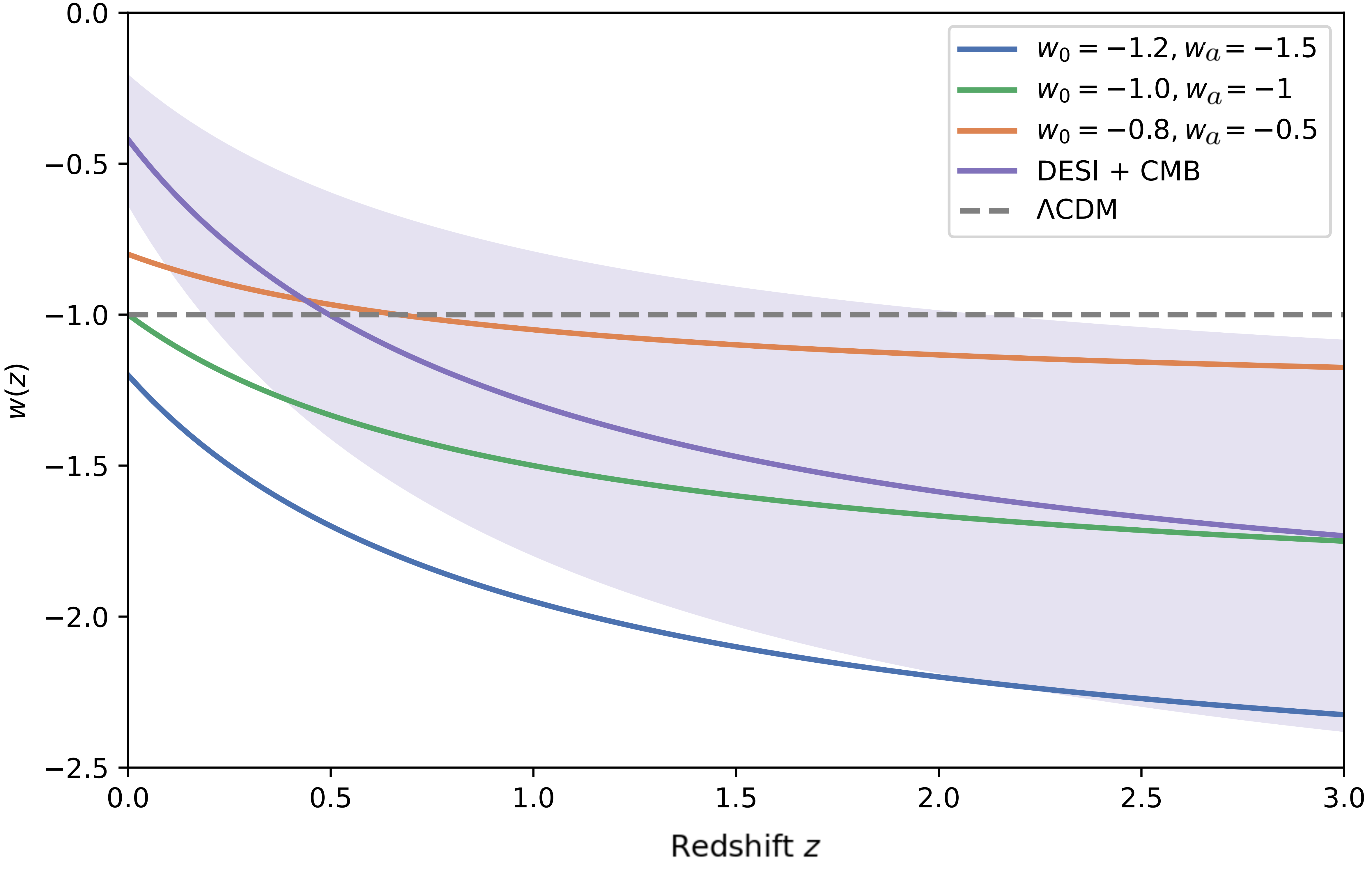
$$w(z) = \boxed{w_0} + \boxed{w_a}\frac{z}{1+z}$$

*: We call it dark energy because we have no clue what it is—proof that bad marketing exists even in science.

Credit: EinsteinMoji

UNDERSTANDING DARK ENERGY

Constraining w(z) gives us hints about potential new physics beyond ΛCDM



Credit: Jip de Buck

But, unfortunately, we do not measure directly the equation of state of dark energy…

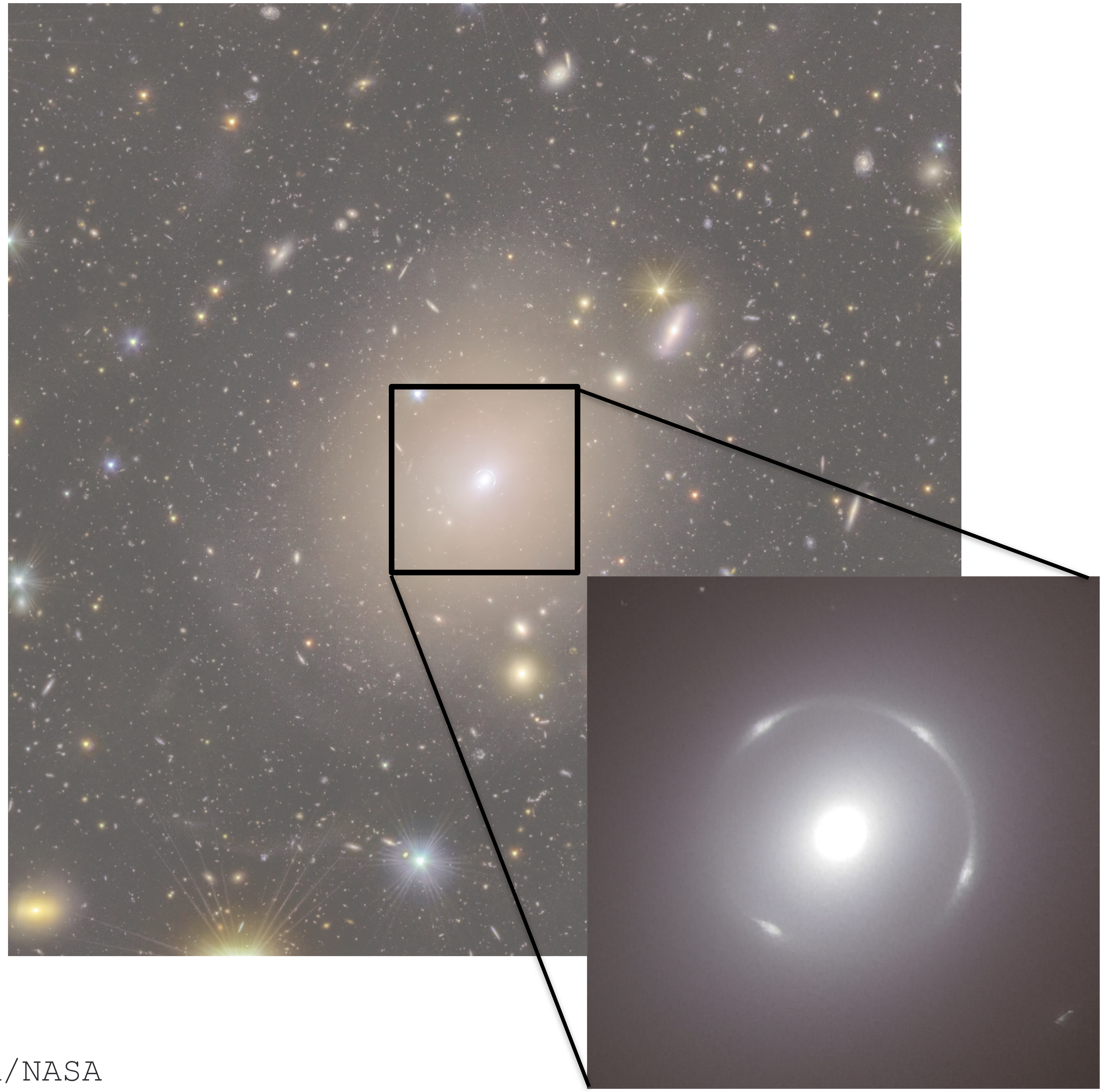
…We infer it.

LARGE-SCALE STRUCTURE OBSERVABLES

Weak Lensing and Galaxy Clustering are sensitive to the underlying cosmological model

WEAK LENSING

Distortion of the apparent shape of galaxies due to the bending of light by foreground cosmic structures

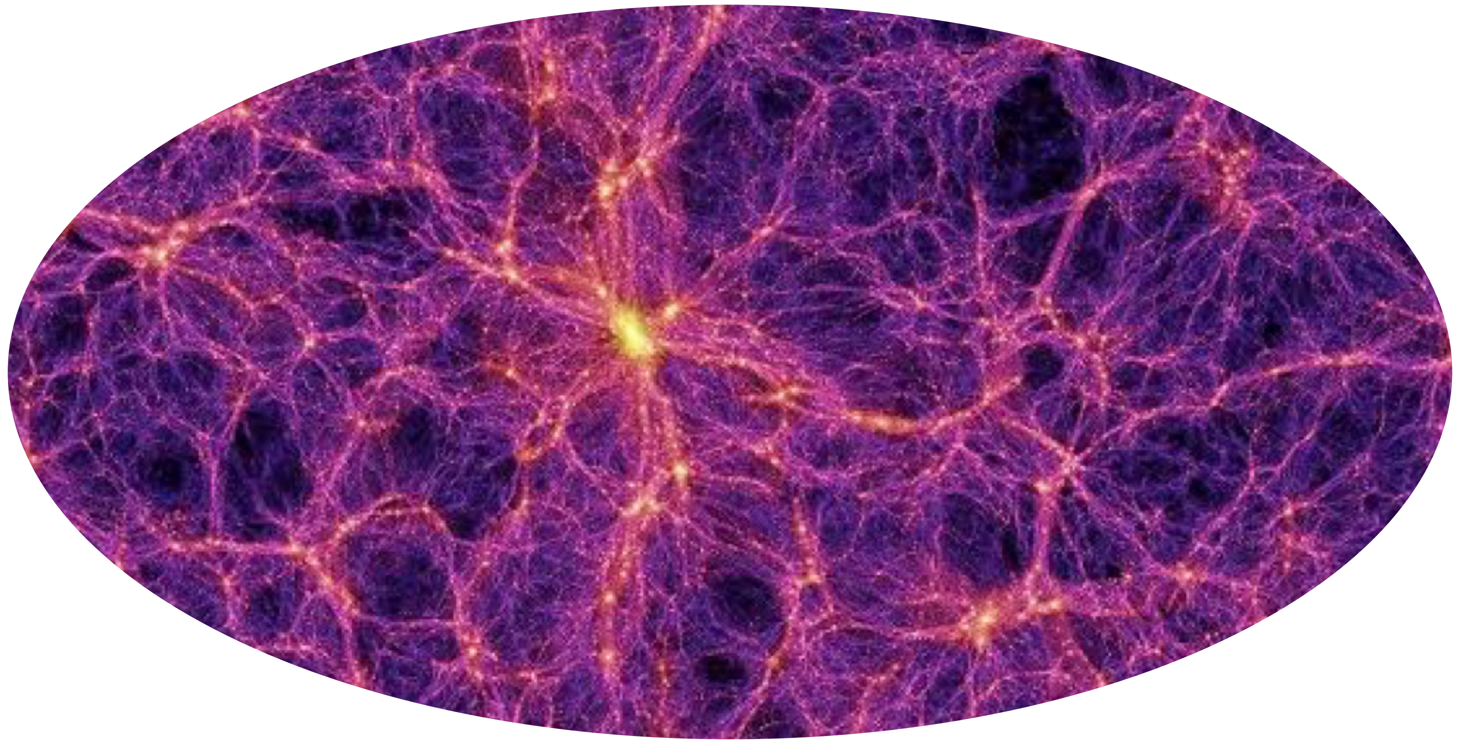


Credit: Perseus Cluster & Altieri lens. ESA/Euclid/Euclid Consortium/NASA

LARGE-SCALE STRUCTURE OBSERVABLES

Weak Lensing and Galaxy Clustering are sensitive to the underlying cosmological model

GALAXY CLUSTERING



Galaxies are biased tracers of the underlying matter distribution

Credit: National Geographic & FLAMINGO simulations

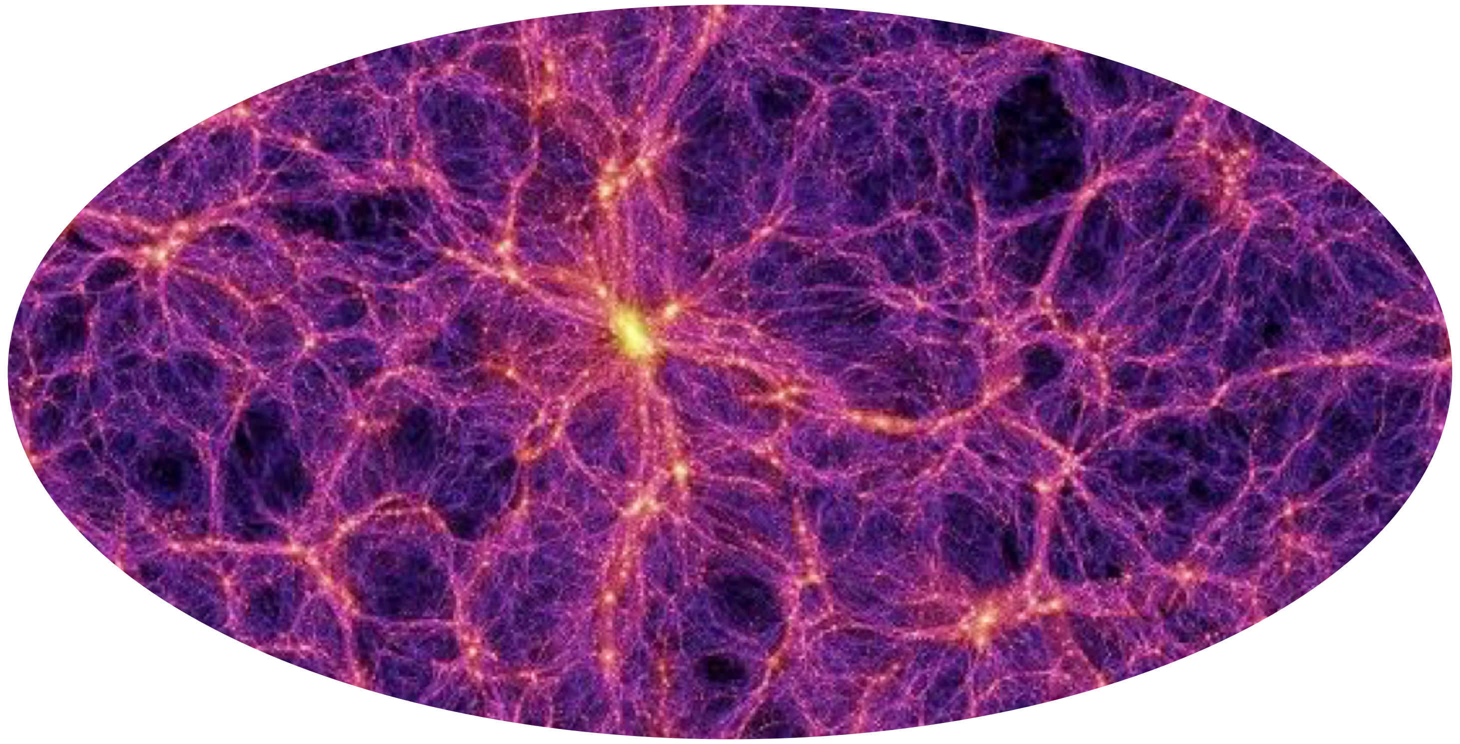
LARGE-SCALE STRUCTURE OBSERVABLES

Weak Lensing and Galaxy Clustering are sensitive to the underlying cosmological model

WEAK LENSING

Constrain the overall matter distribution and quantify its level of clumpiness

GALAXY CLUSTERING



Constrain visible matter and expansion rate

Credit: Perseus Cluster. ESA/Euclid/Euclid Consortium/NASA

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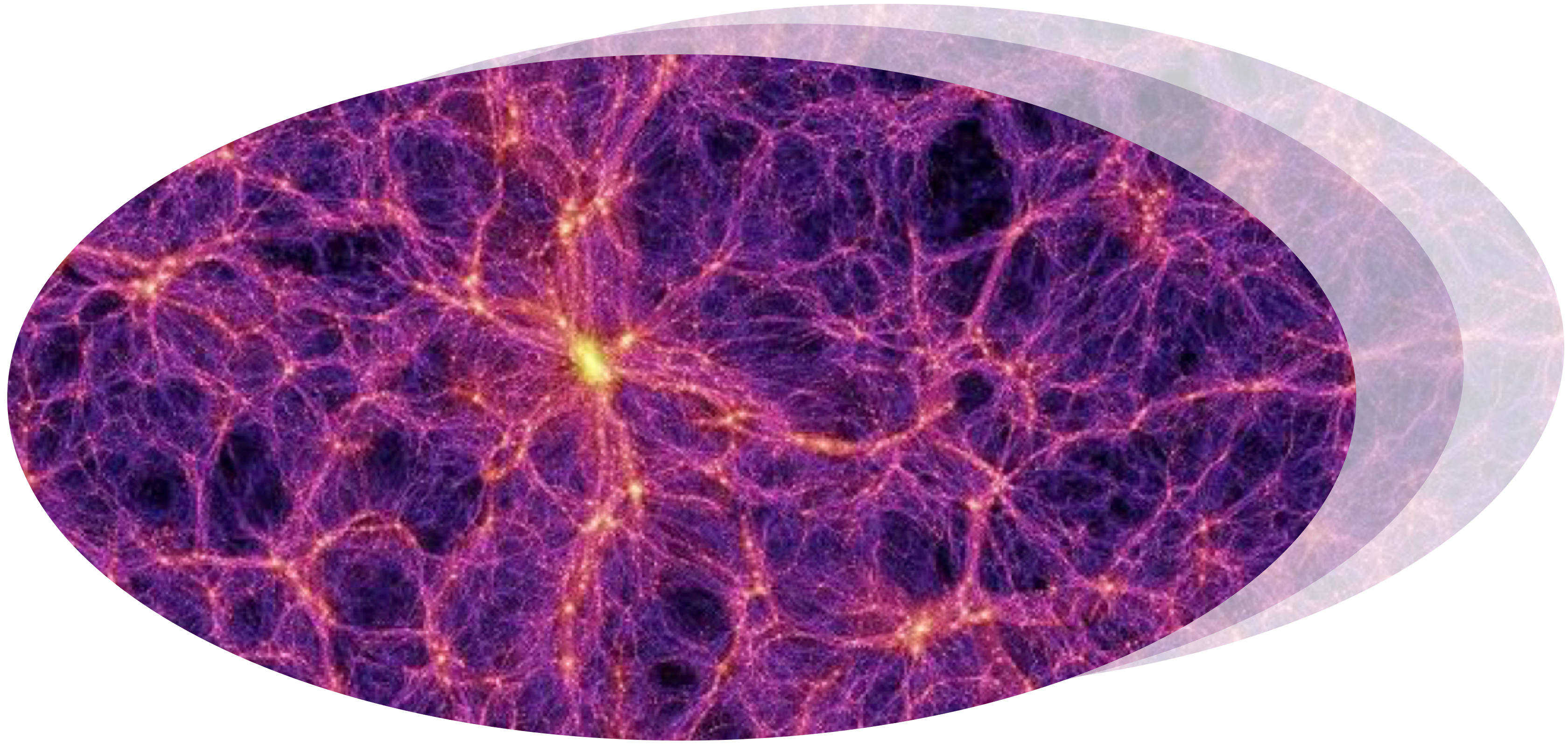
WEAK LENSING

GALAXY CLUSTERING



Tomography: Classifying galaxies as a function of distance to obtain different time snapshots

Credit: Perseus Cluster. ESA/Euclid/Euclid Consortium/NASA

LARGE-SCALE STRUCTURE OBSERVABLES

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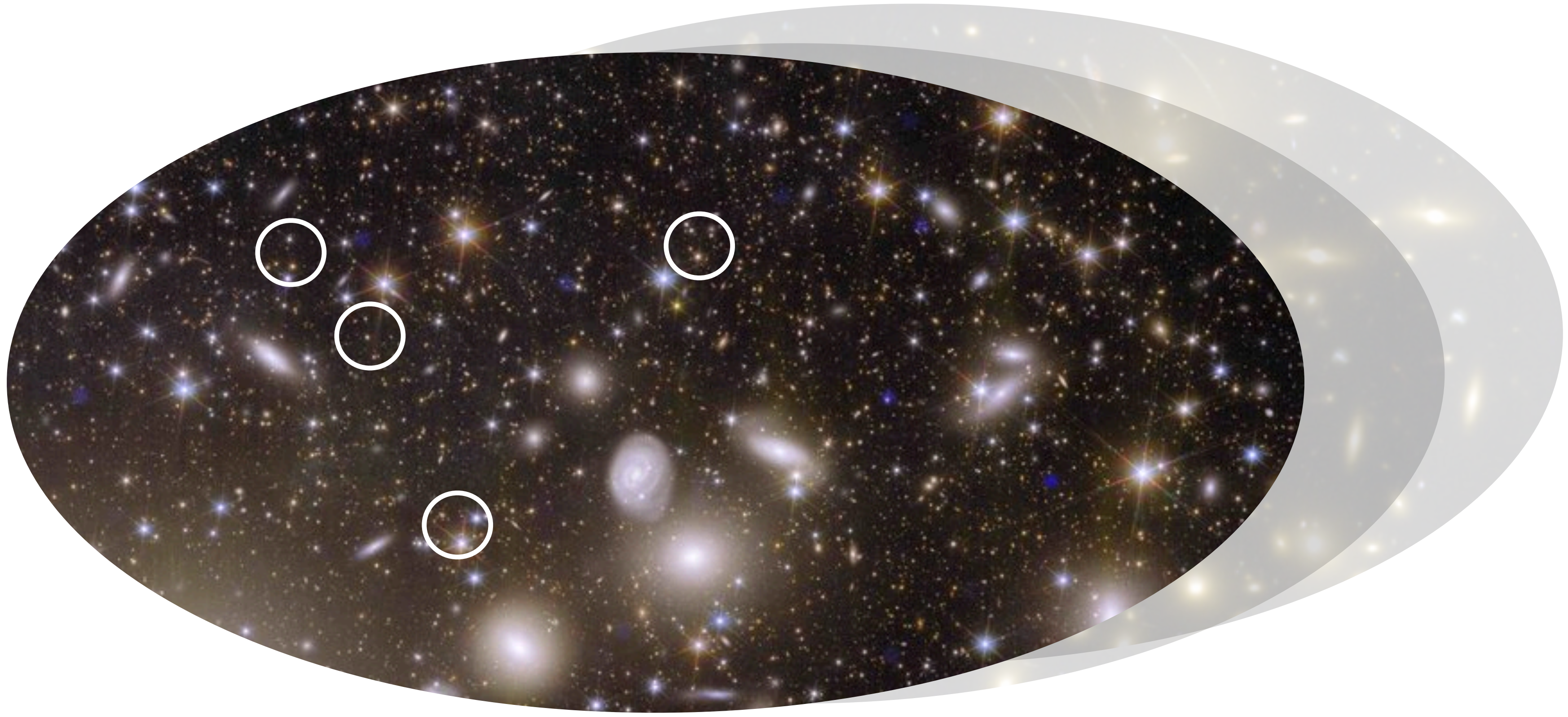
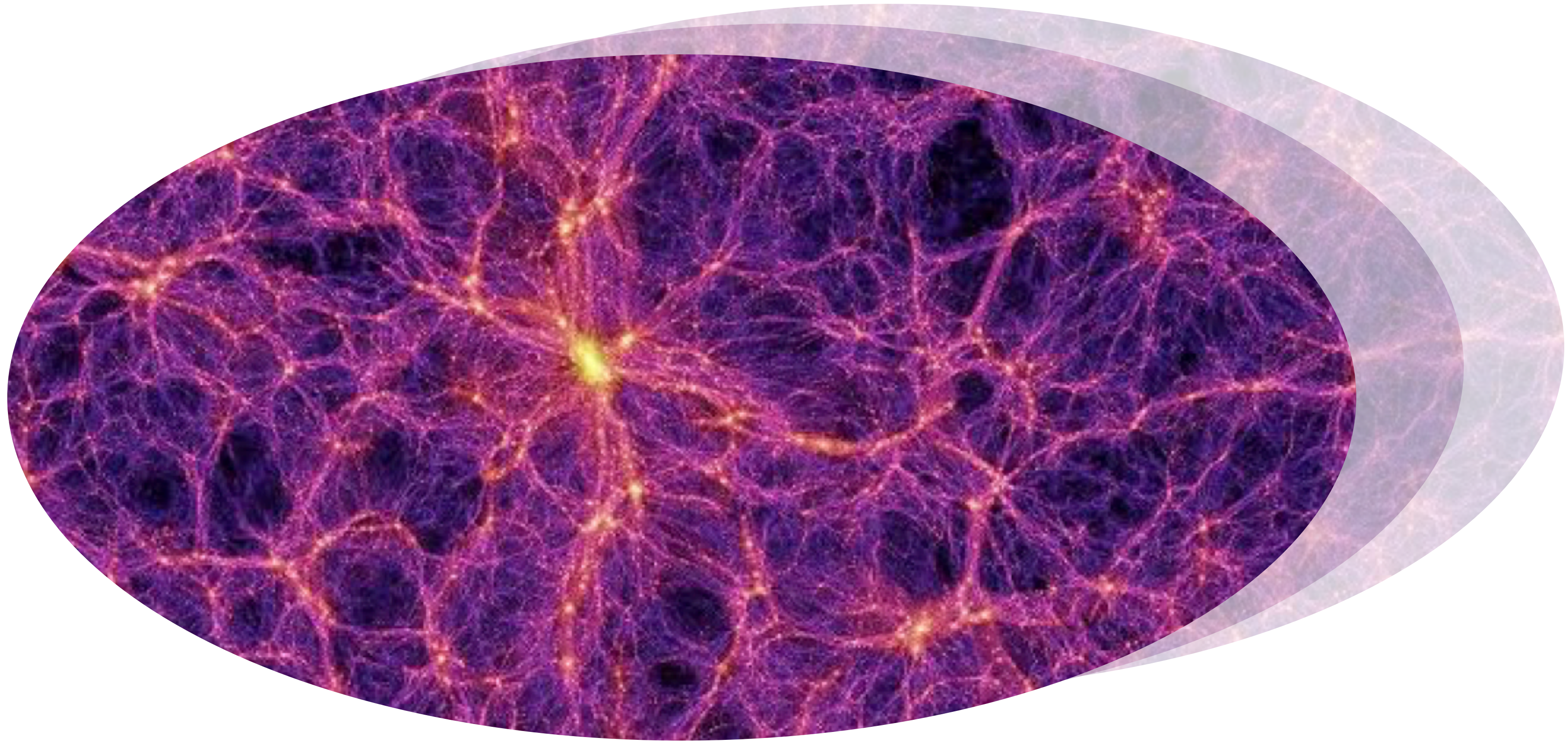
WEAK LENSING



GALAXY CLUSTERING

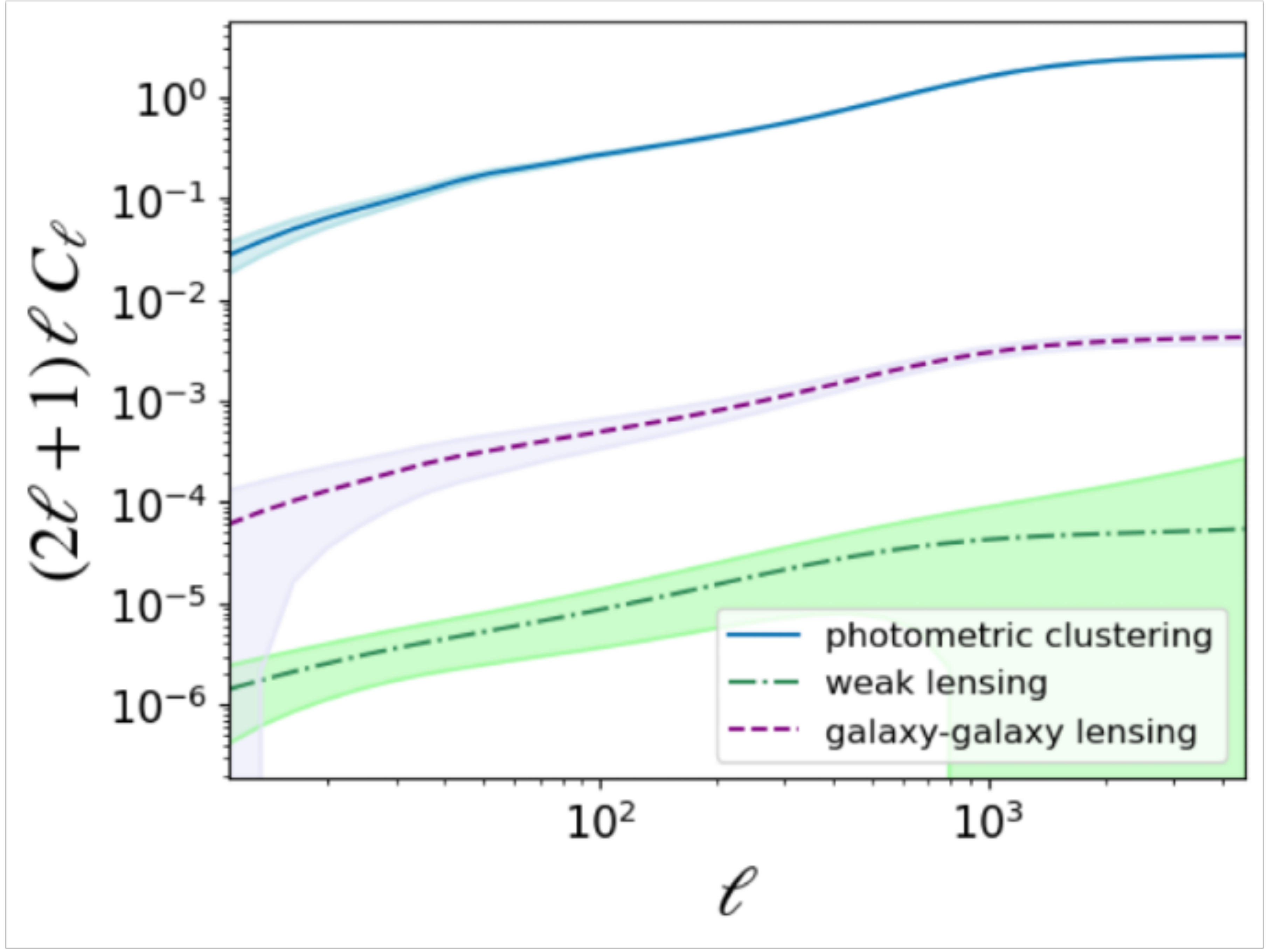


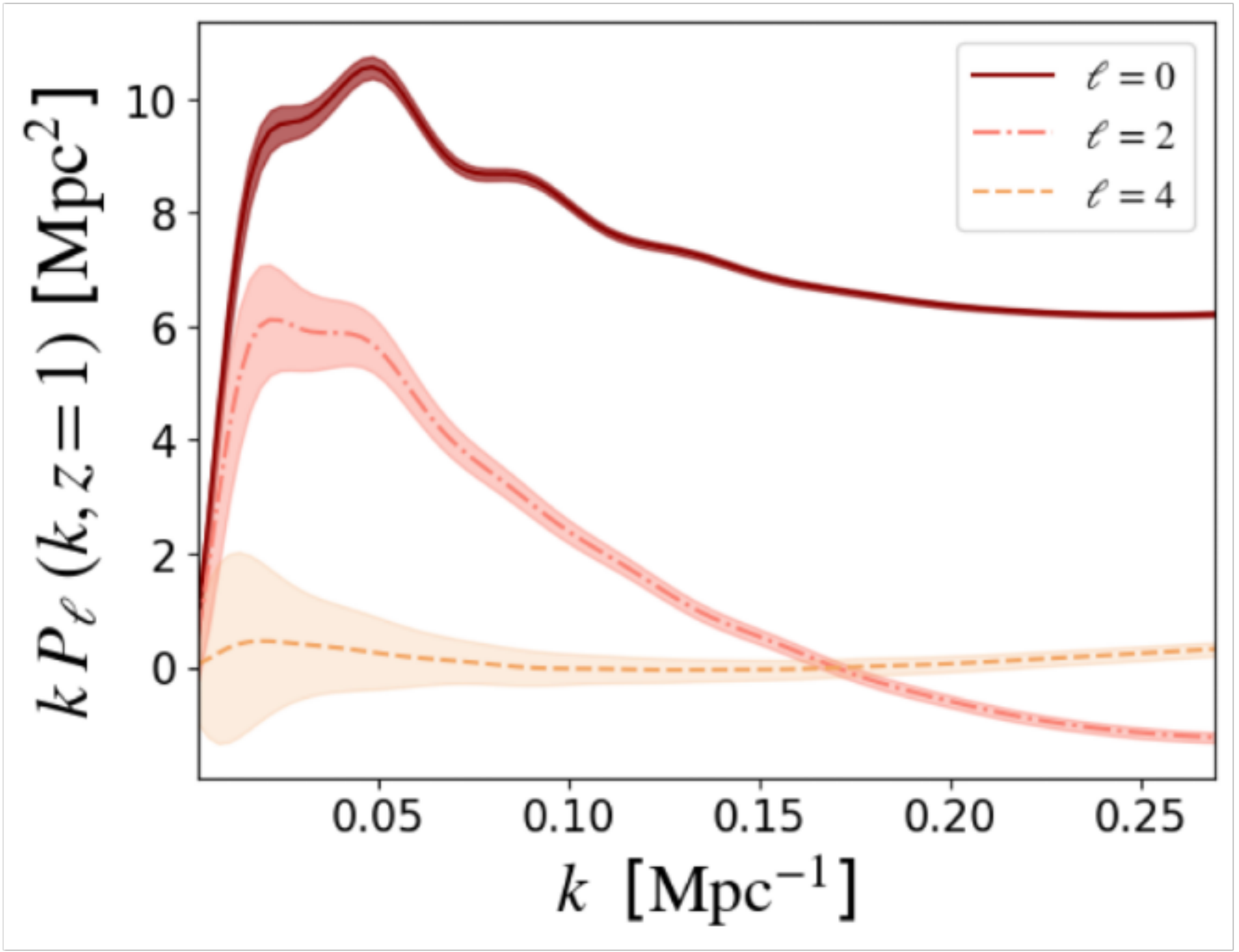
Compress information in summary statistics such as power spectra or correlation functions

Credit: Perseus Cluster. ESA/Euclid/Euclid Consortium/NASA

COSMOLOGY WITH LSS

Aiming to fit summary statistics to infer cosmological parameters





Credit: Euclid I. Mellier et al. (GCH)

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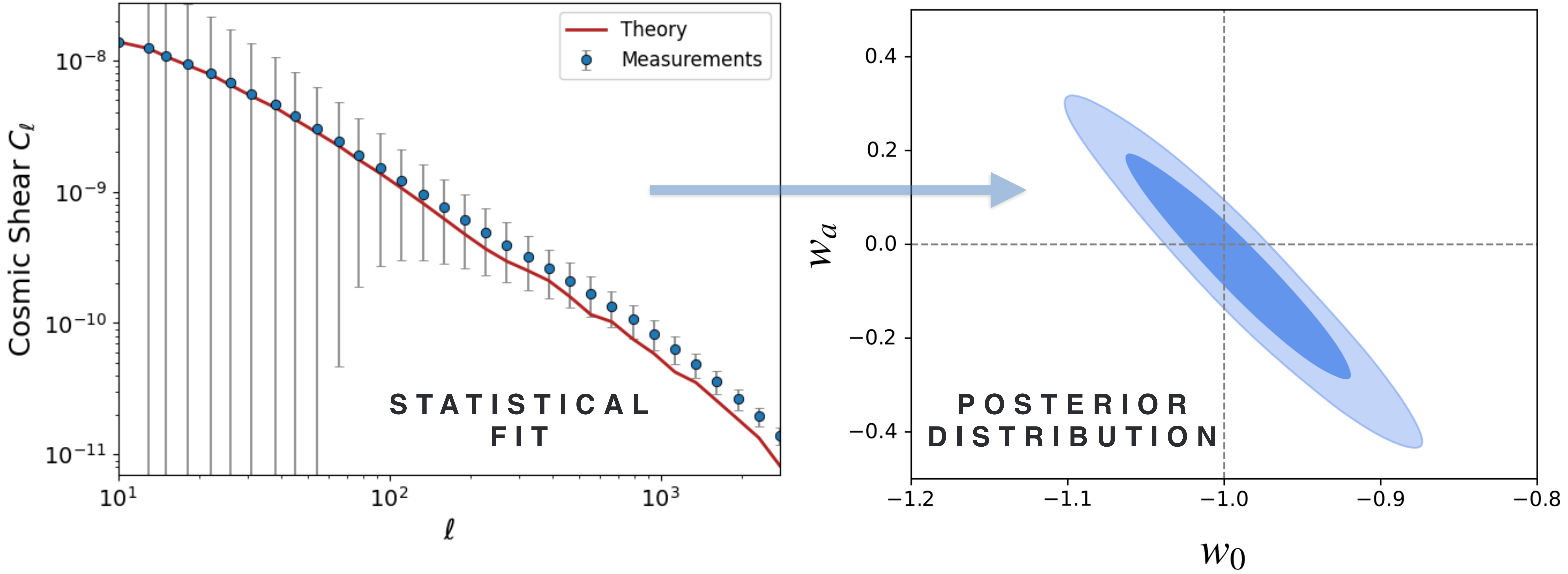


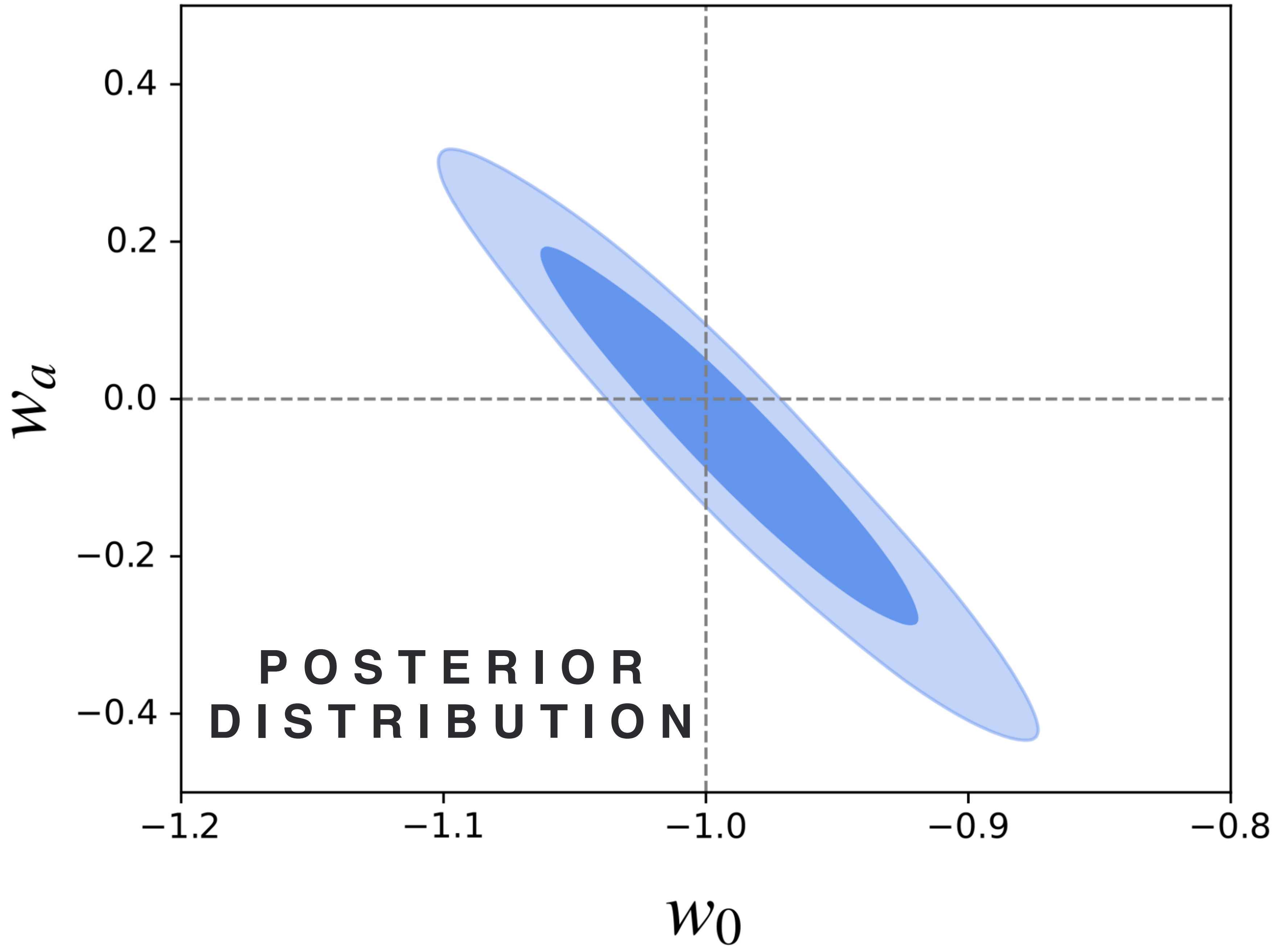
Credit: GCH

COSMOLOGY WITH LSS

Aiming to fit summary statistics to infer cosmological parameters

BAYES' THEOREM

$$P(\theta \,|\, d, M) = \frac{\mathcal{L}(d \,|\, \theta, M)\, \Pi(\theta \,|\, M)}{\mathcal{Z}(d \,|\, M)}$$



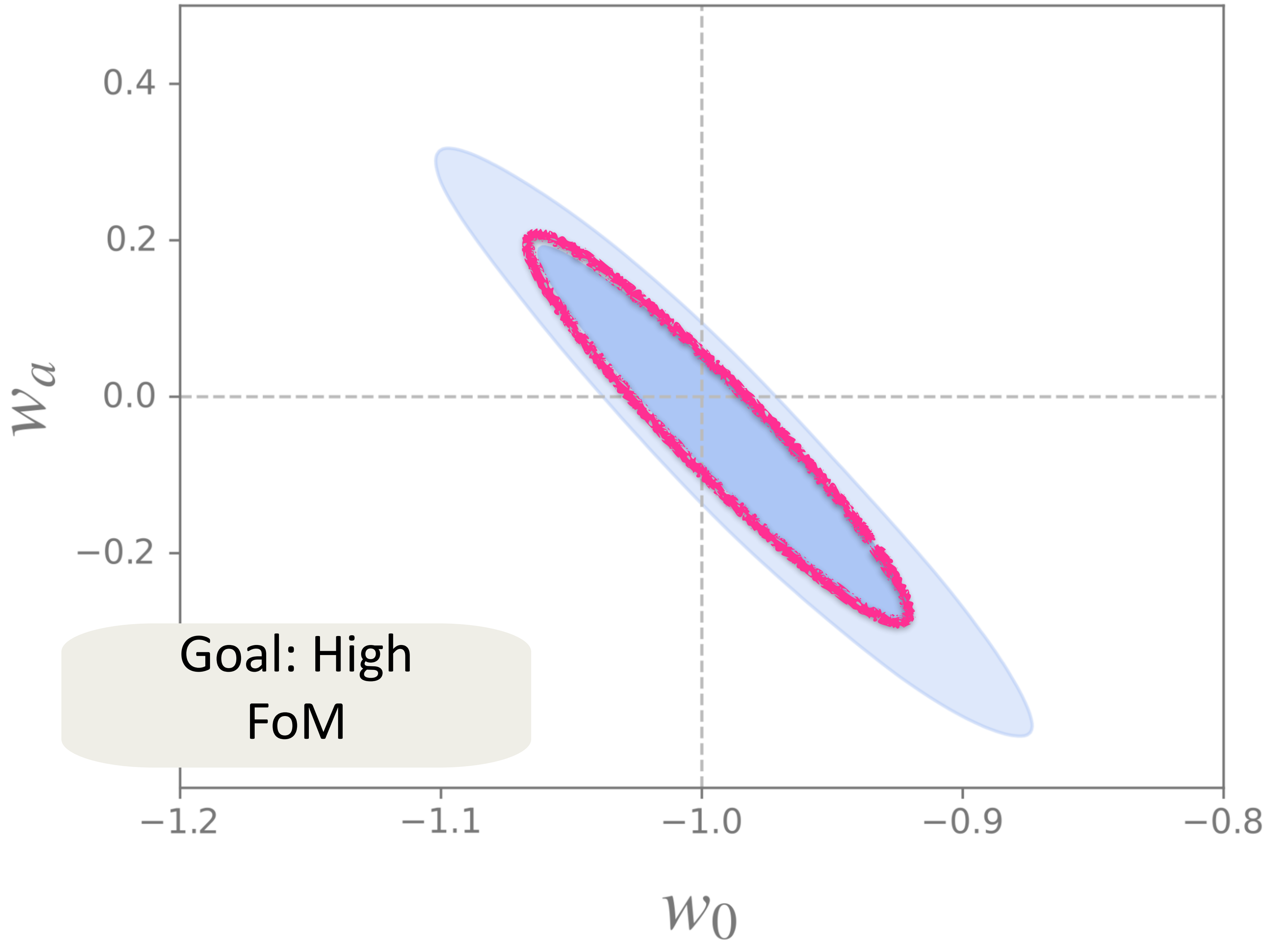
COSMOLOGY WITH LSS

Figures of Merit: quantifying the improvement

BAYES' THEOREM

$$P(\theta \,|\, d, M) = \frac{\mathcal{L}(d \,|\, \theta, M)\, \Pi(\theta \,|\, M)}{\mathcal{Z}(d \,|\, M)}$$

$$\mathrm{FoM} = \frac{1}{\sqrt{\det \mathrm{Cov}(w_0, w_a)}}$$



Goal: High FoM

COSMOLOGY WITH LSS

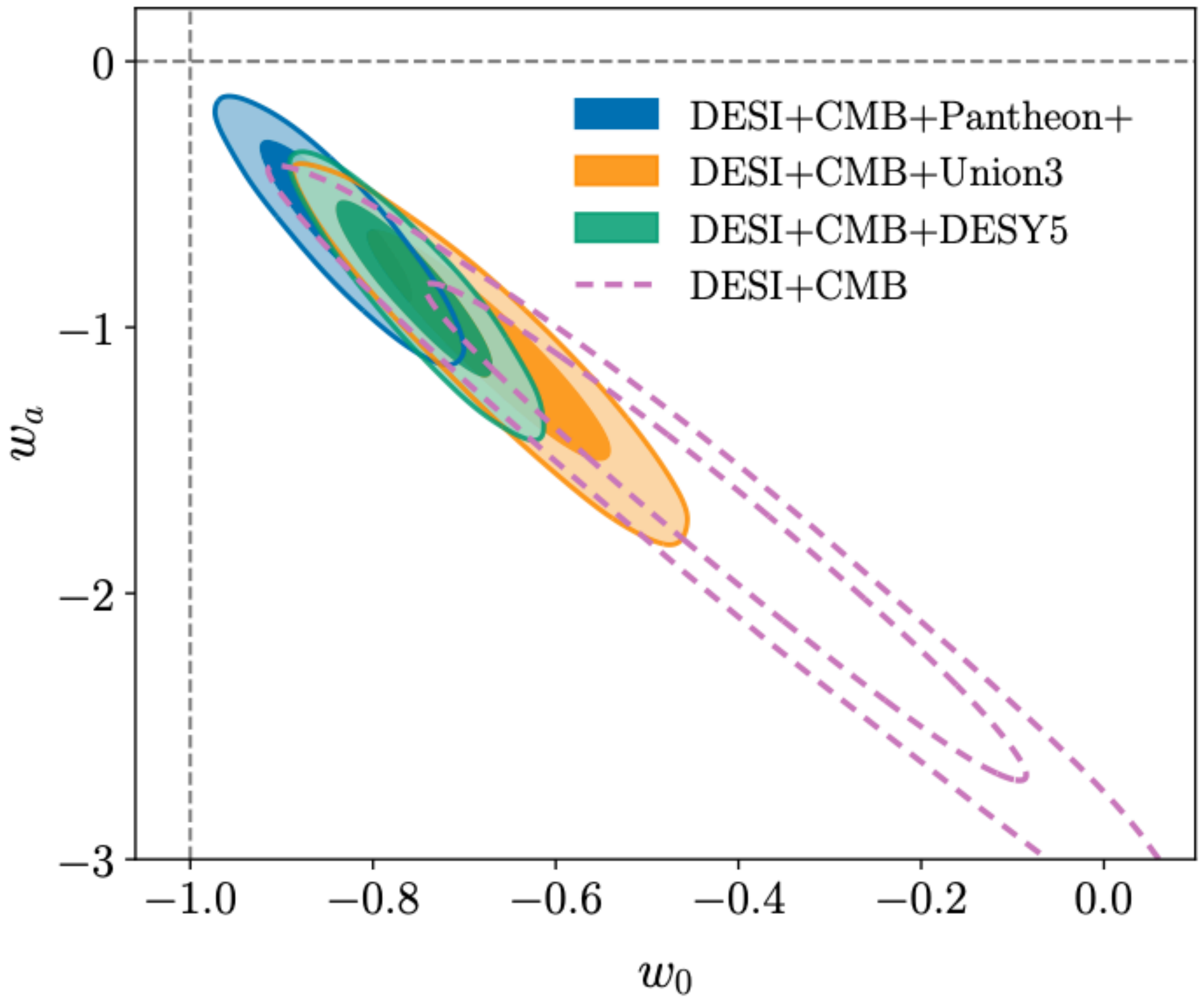
Figures of Merit: quantifying the improvement

BAYES' THEOREM

$$P(\theta \,|\, d, M) = \frac{\mathcal{L}(d \,|\, \theta, M)\, \Pi(\theta \,|\, M)}{\mathcal{Z}(d \,|\, M)}$$

DESI

SPECTROSCOPIC BAOs



Credit: **DESI Collaboration, 25**

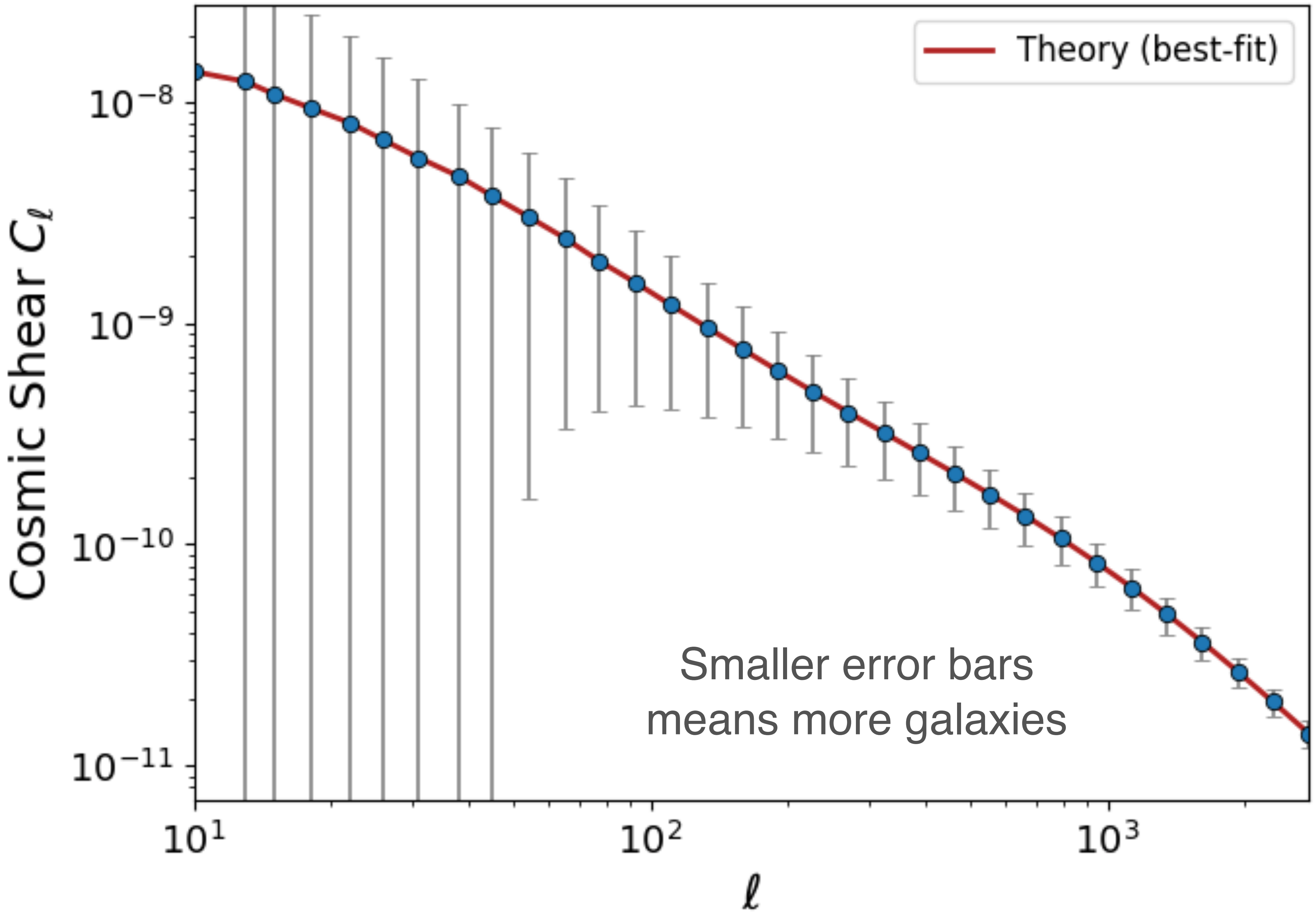
PRECISION COSMOLOGY WITH LSS

Aiming to fit summary statistics to infer cosmological parameters

COVARIANCE MATRIX

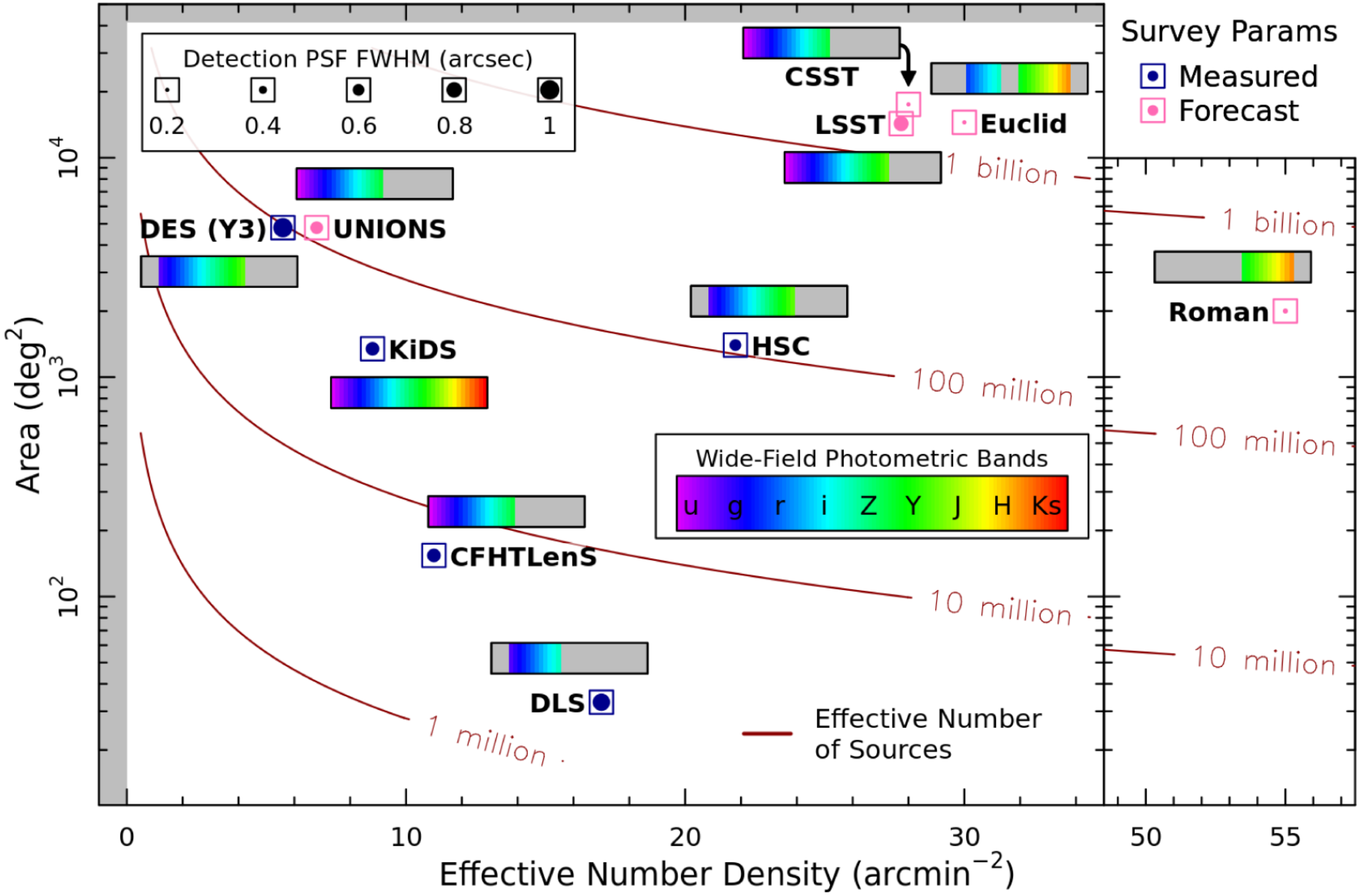
$$\mathrm{Cov}\left(C_\ell^{ij}, C_{\ell'}^{mn}\right) =$$

$$= \frac{\delta_{\ell\ell'}}{(2\ell+1)\boxed{f_{\rm sky}}}\left[\left(C_\ell^{im} + \frac{\delta_{im}}{\bar{n}_i}\right)\left(C_\ell^{jn} + \frac{\delta_{jn}}{\bar{n}_j}\right) + \left(C_\ell^{in} + \frac{\delta_{in}}{\boxed{\bar{n}_i}}\right)\left(C_\ell^{jm} + \frac{\delta_{jm}}{\bar{n}_j}\right)\right].$$



IN THE ERA OF LSS COSMOLOGY

Surveying the sky with a purpose: understanding the dark universe



Credit: A. Wright

IN THE ERA OF LSS COSMOLOGY

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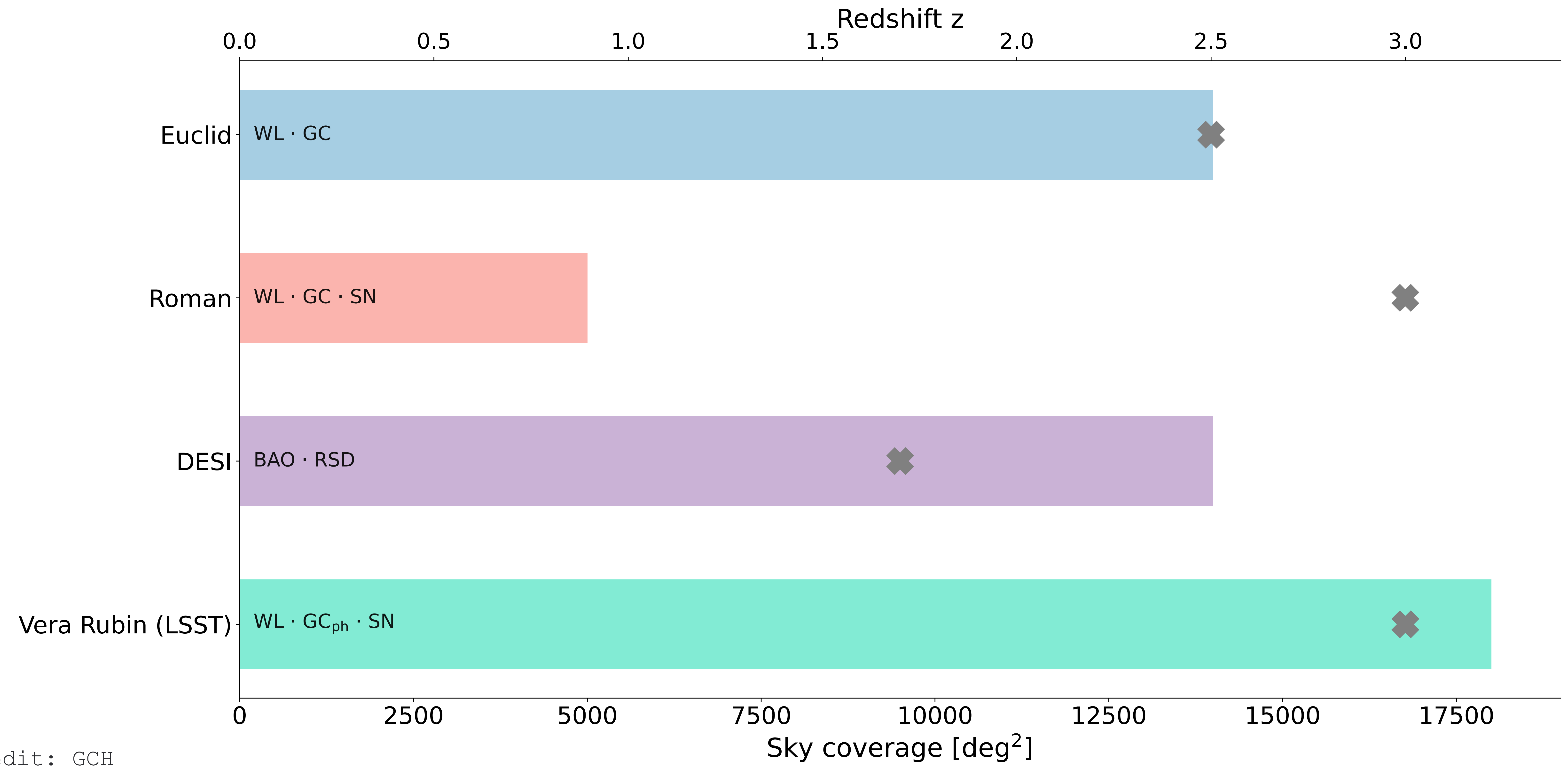

Credit: GCH

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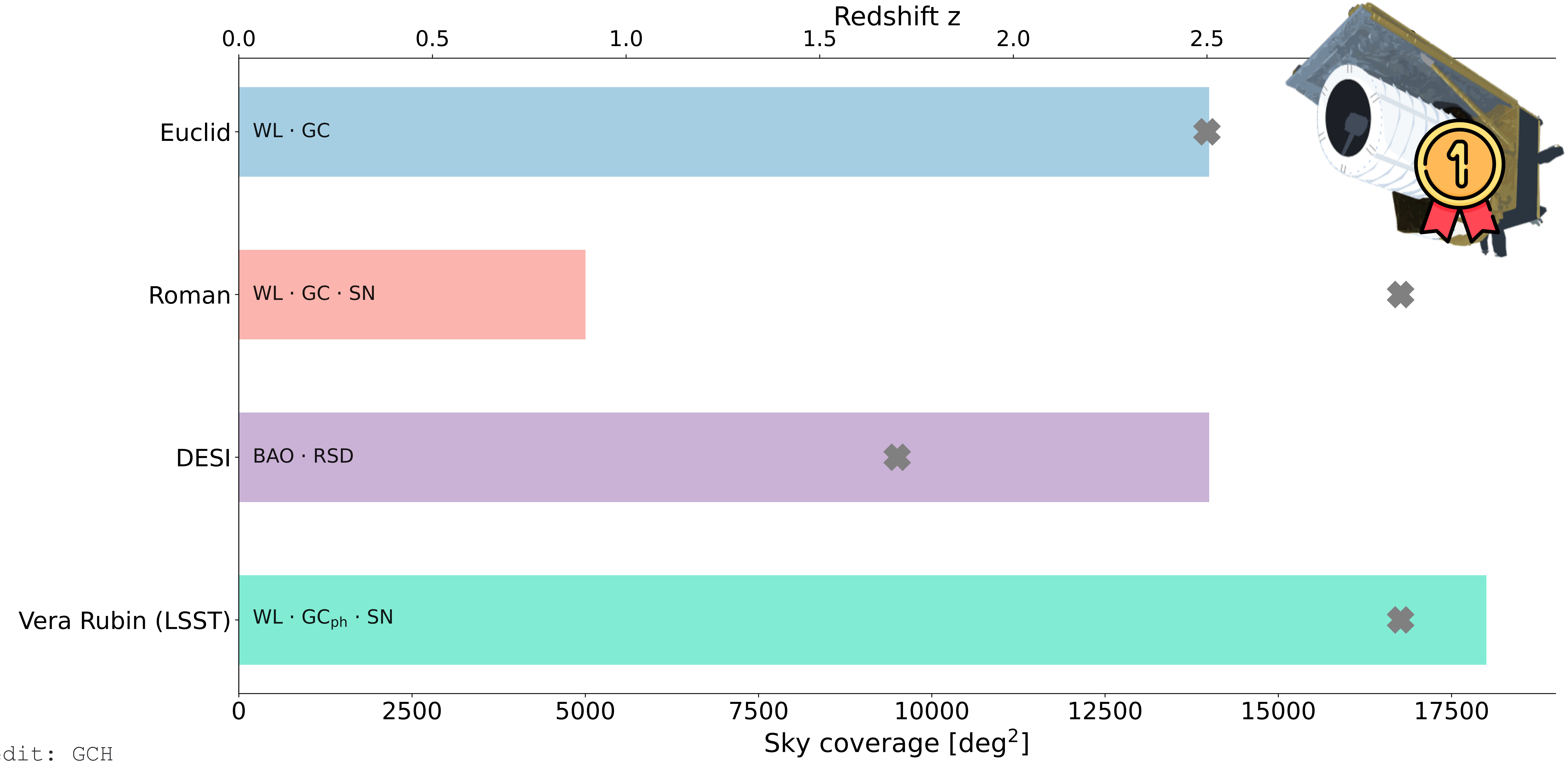


Credit: GCH

EUCLID: A MISSION TO MAP THE UNIVERSE

Led by ESA, currently surveying billions of galaxies from space

Credit: GCH,
Euclid spacecraft in Cannes, 2023

Launched in 2023, Euclid is conducting a **six-year survey** of one-third of the sky (successful first quick data release accomplished!)

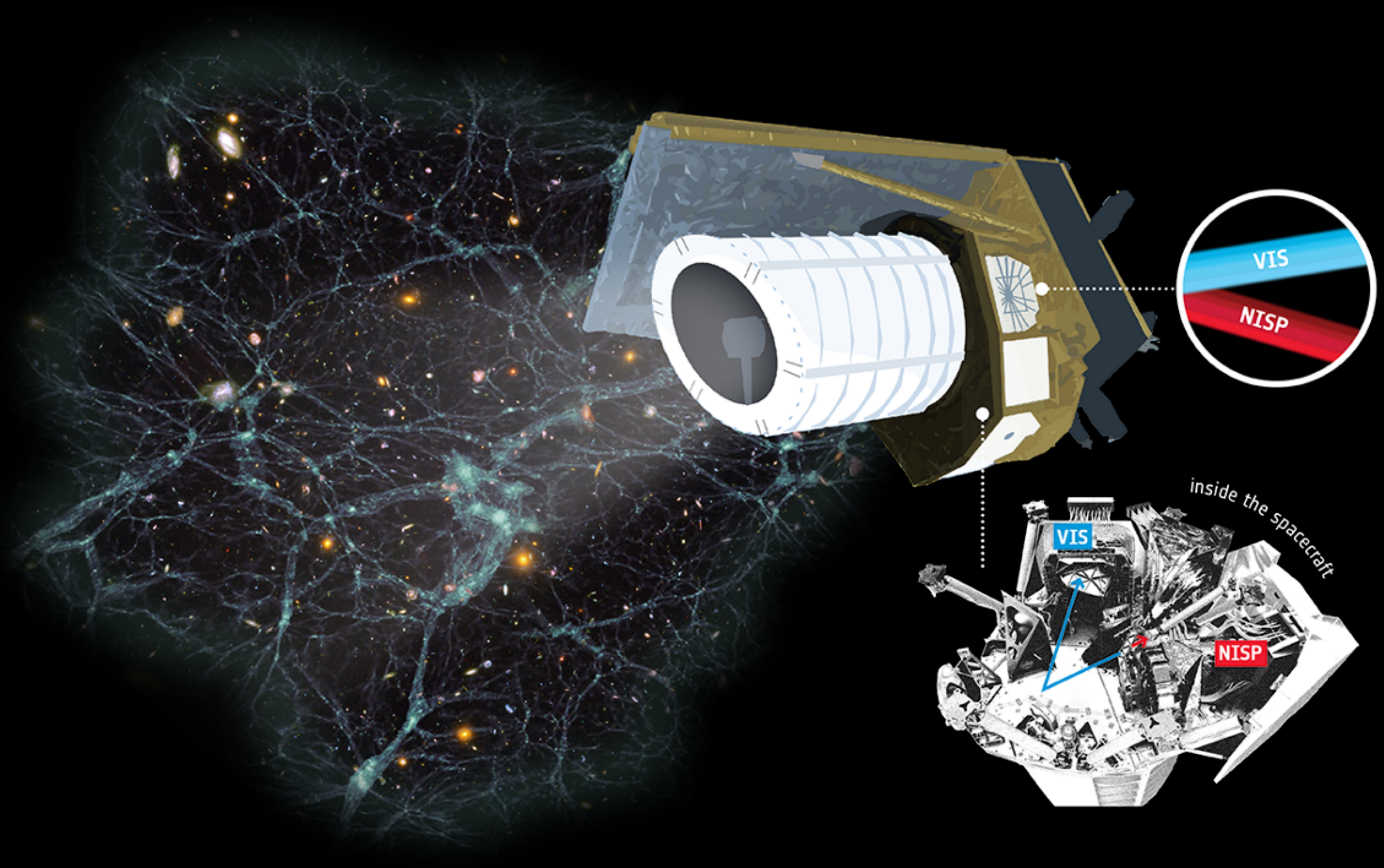
Two instruments onboard to photograph galaxies and measure their distances

+3000 workforce behind, + $1.5 B+ total cost**, 6 years in operations, 9 data centers, +170 petabytes** of data


esa
esa
STRONGBACK RETRACT
STARTUP
LIFTOFF
MAX-Q
MECO
FAIRING
T - 00:00:13
EUCLID
STARTUP
THE FALCON 9 FLIGHT COMPUTERS HAVE
TAKEN CONTROL OF THE COUNTDOWN

EUCLID INSTRUMENTS: VIS AND NISP

Euclid instruments are designed to fulfill the objectives of the Euclid mission



VIS: Visible imager

Produce high-resolution images

NISP: Near-Infrared Spectrometer and Photometer

Gather galaxy photometric and spectroscopic redshifts

Credit: ESA/ATG

EUCLID INSTRUMENTS: VIS AND NISP

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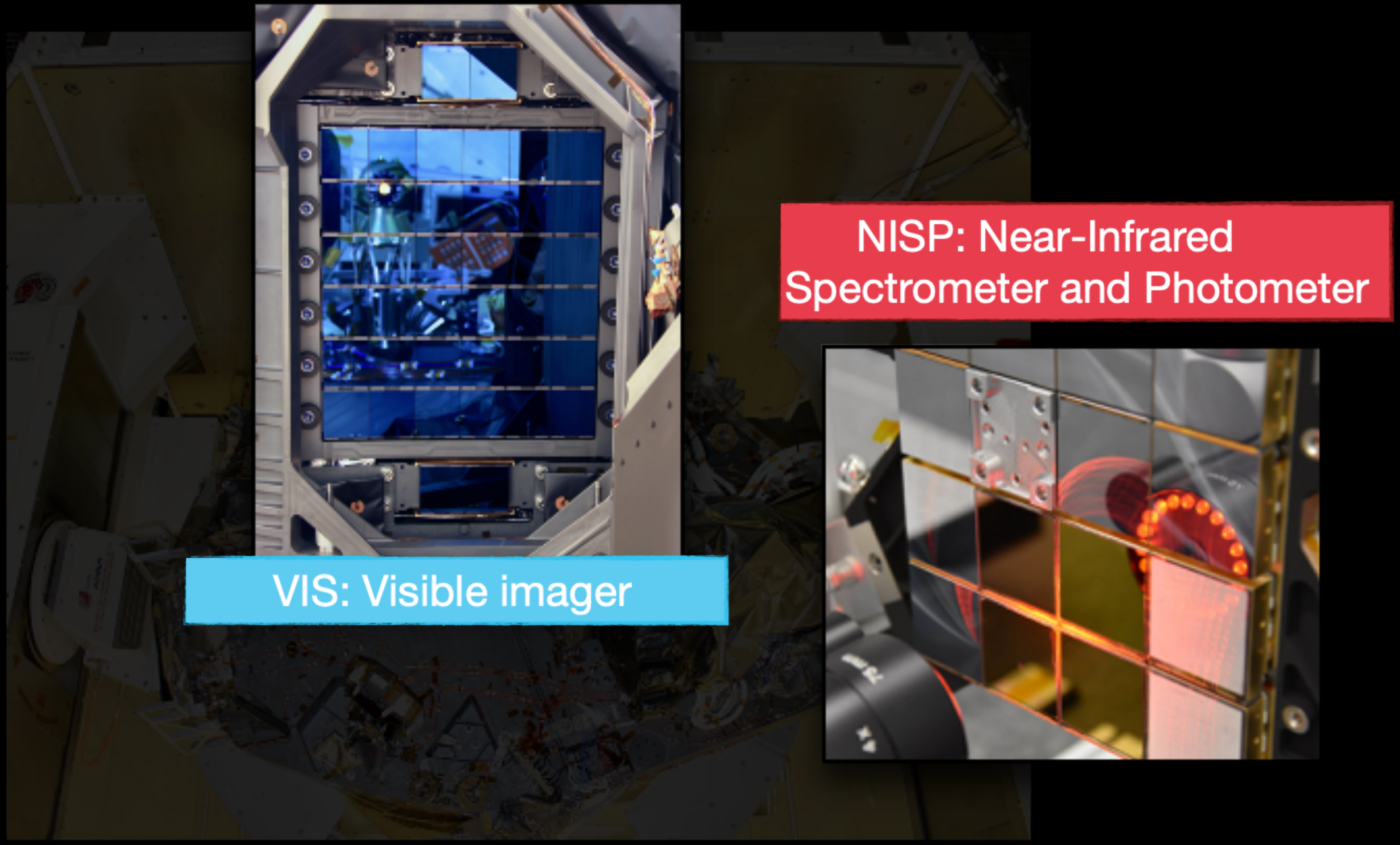

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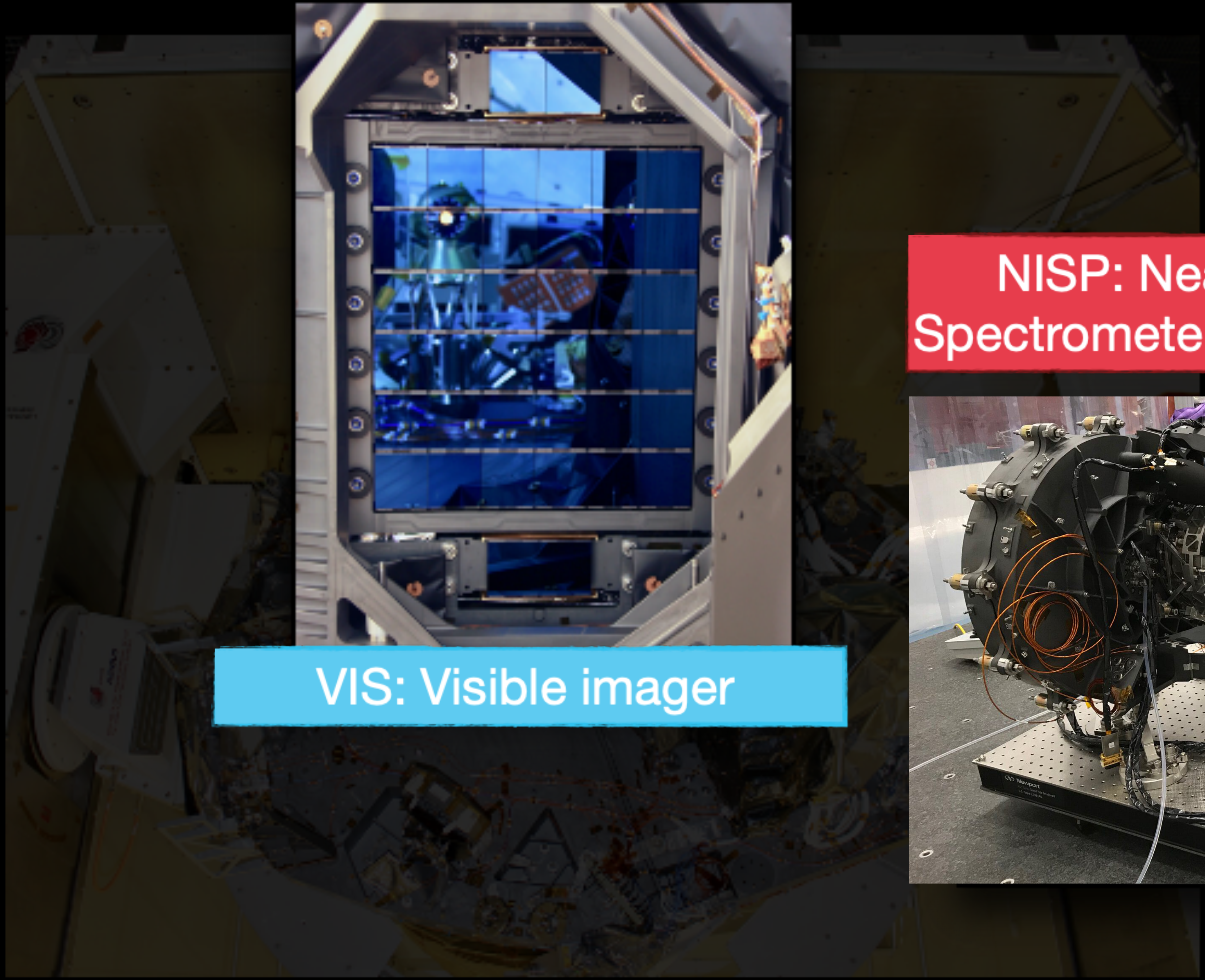
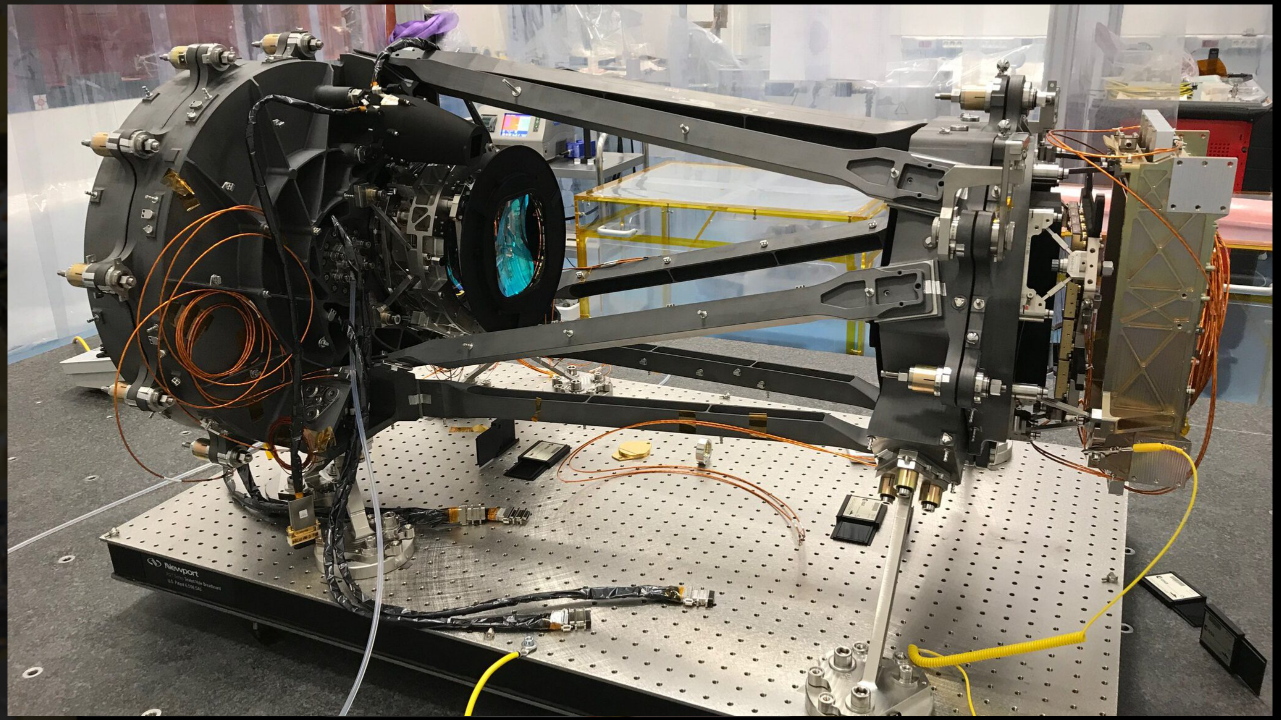
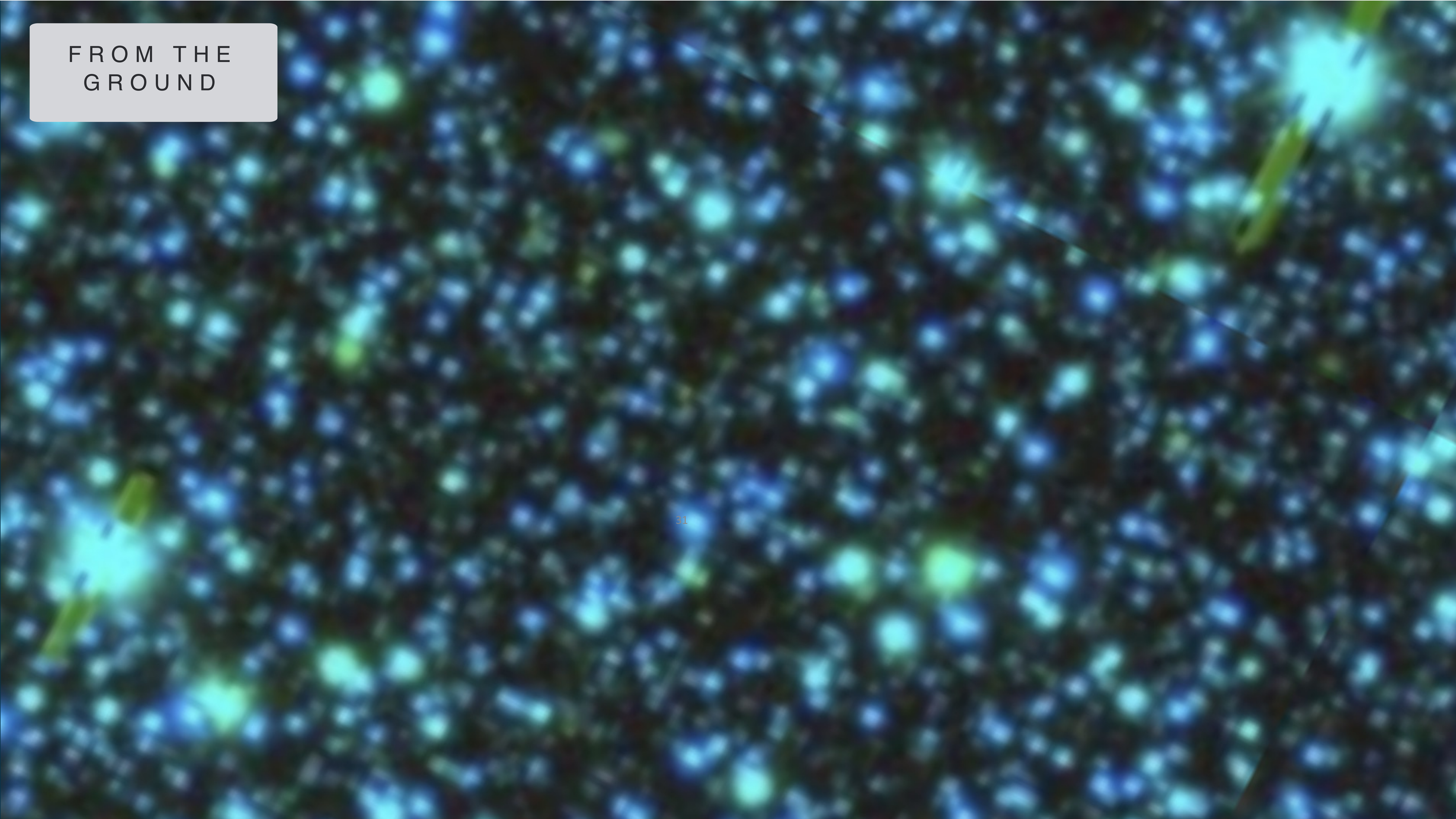


VIS: Visible imager

NISP: Near-Infrared Spectrometer and Photometer

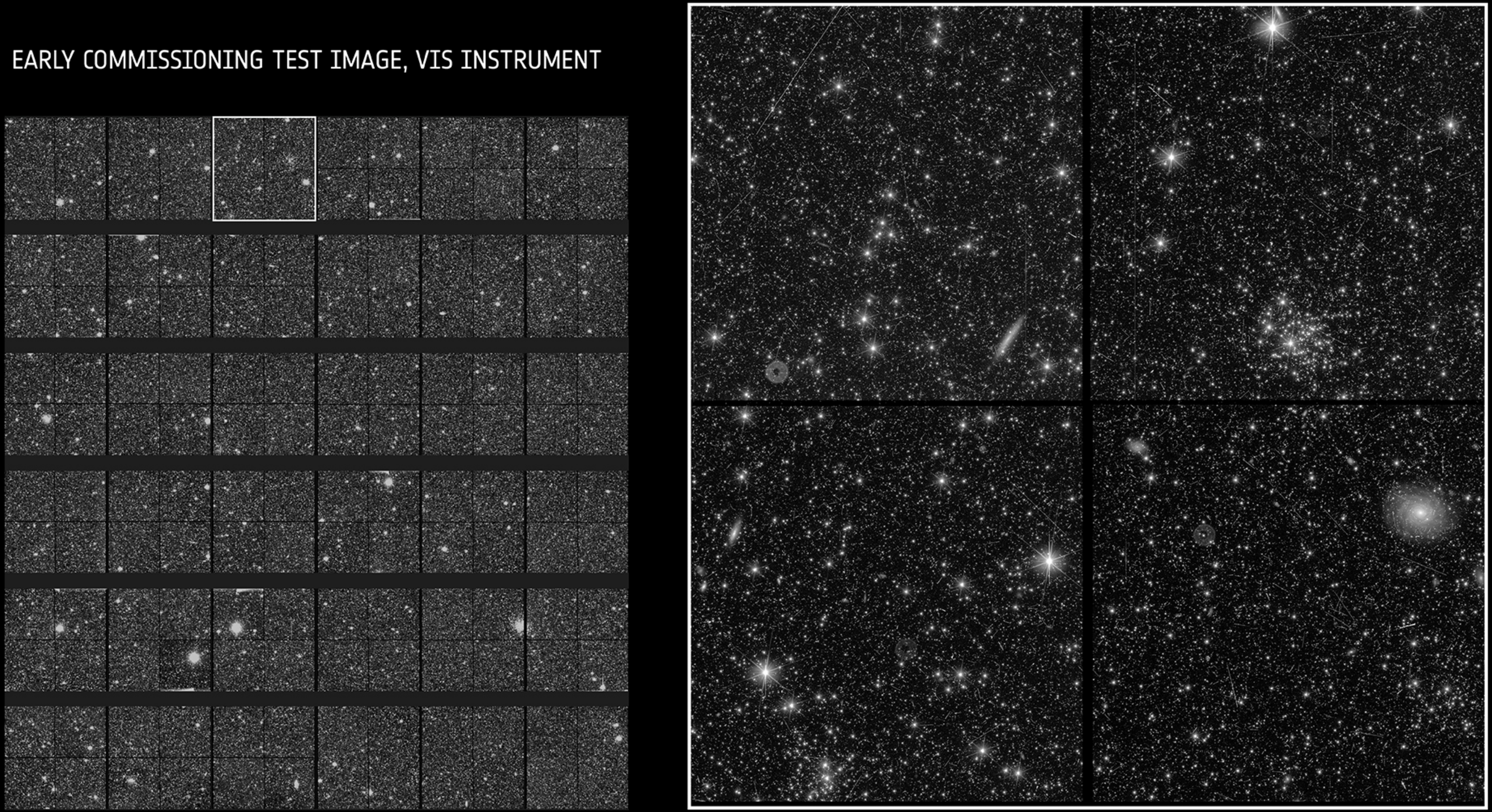


FROM THE GROUND



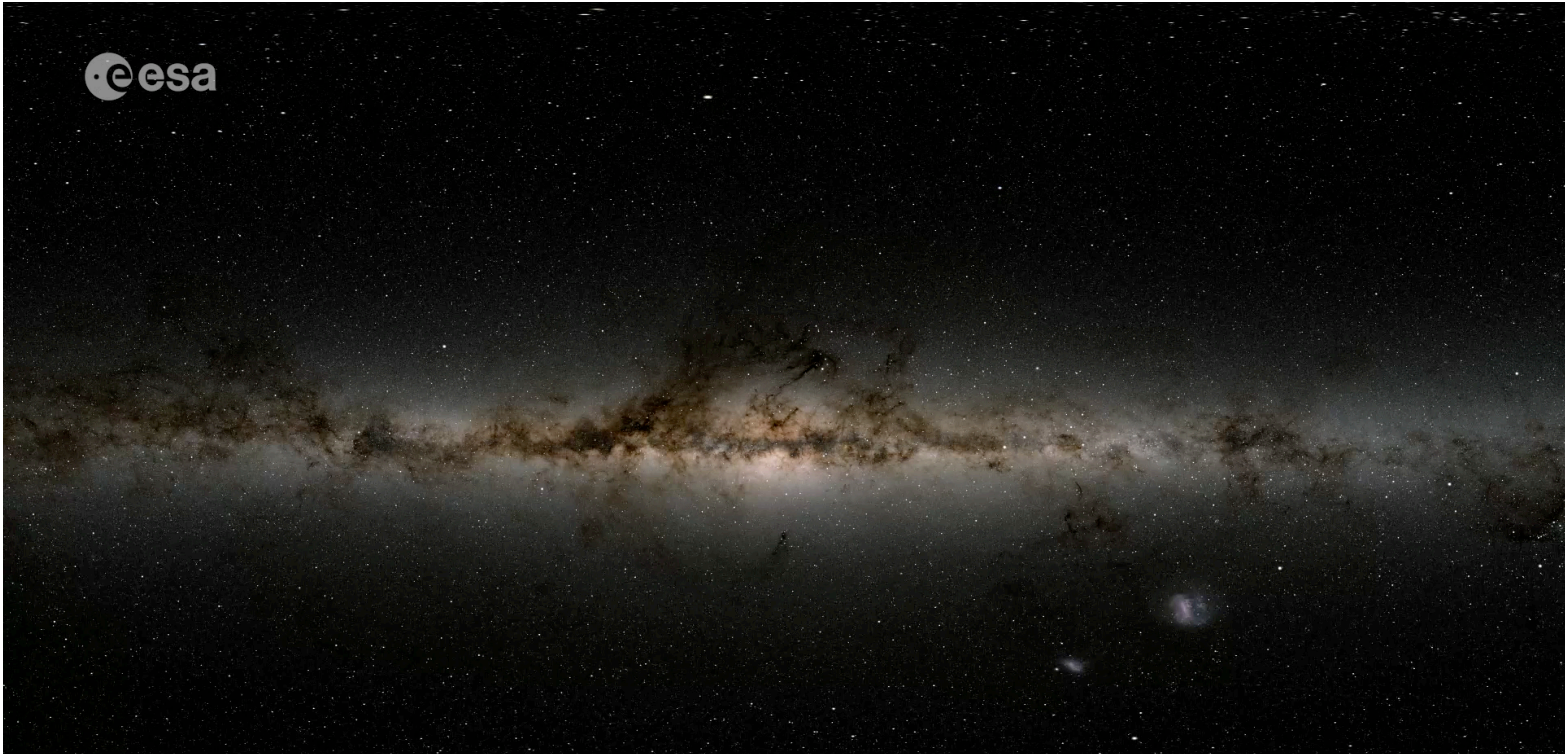

FROM
SPACE

EARLY COMMISSIONING TEST IMAGE, VIS INSTRUMENT



FROM OBSERVATIONS TO CONSTRAINTS

Processing Euclid data is the duty of the Science Ground Segment: the gem of the mission



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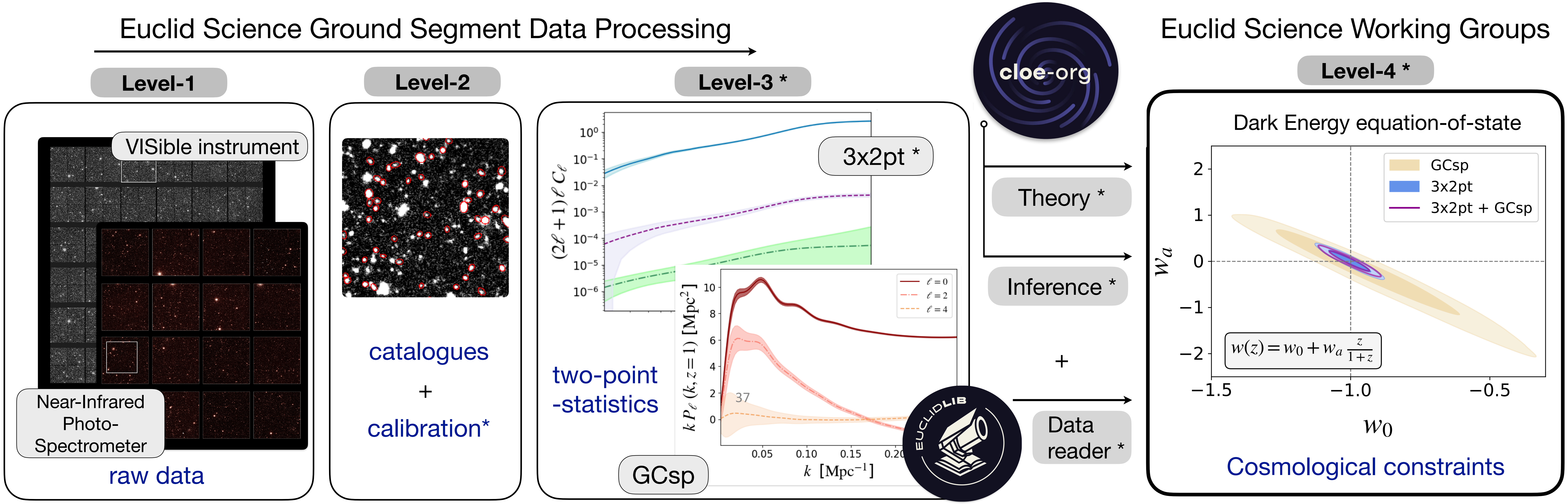


IMAGES AND DISTANCES TO GALAXIES ARE PROCESSED IN CATALOGUES → TO COMPUTE SUMMARY STATISTICS → AND TO BE COMPARED WITH ALTERNATIVE MODELS

OPERATING THE INSTRUMENTS IN REAL CONDITIONS

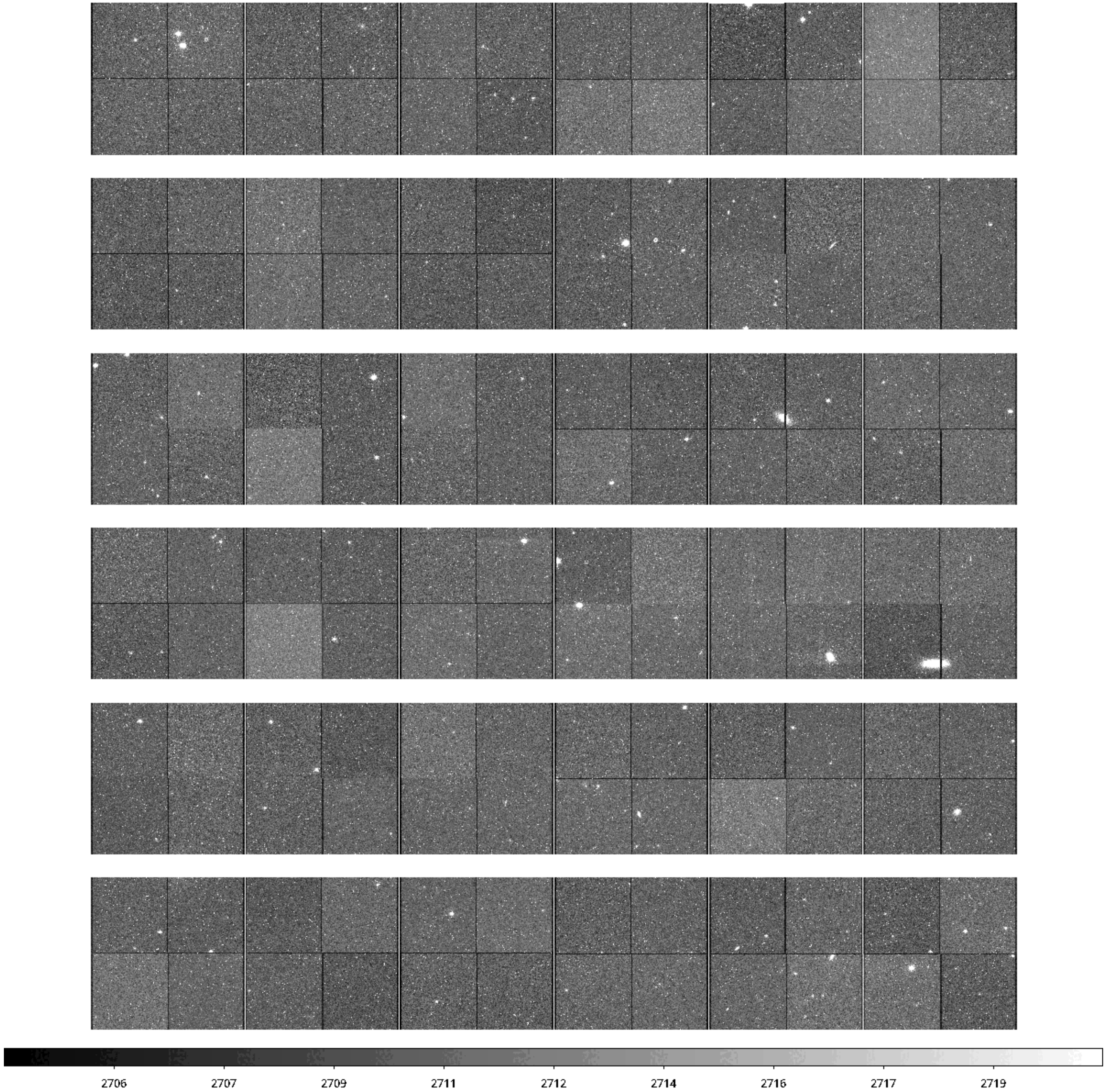
Since its launch, Euclid faced:

❄️ **Ice formation** – ice can accumulate on the optics or instruments, affecting observations.

☢️ **X-ray hits** – cosmic X-rays can impact detectors and create noise in data.

🌟 **Stray light** – unwanted light entering the telescope can reduce image quality.

Credit: Koen Kuijken

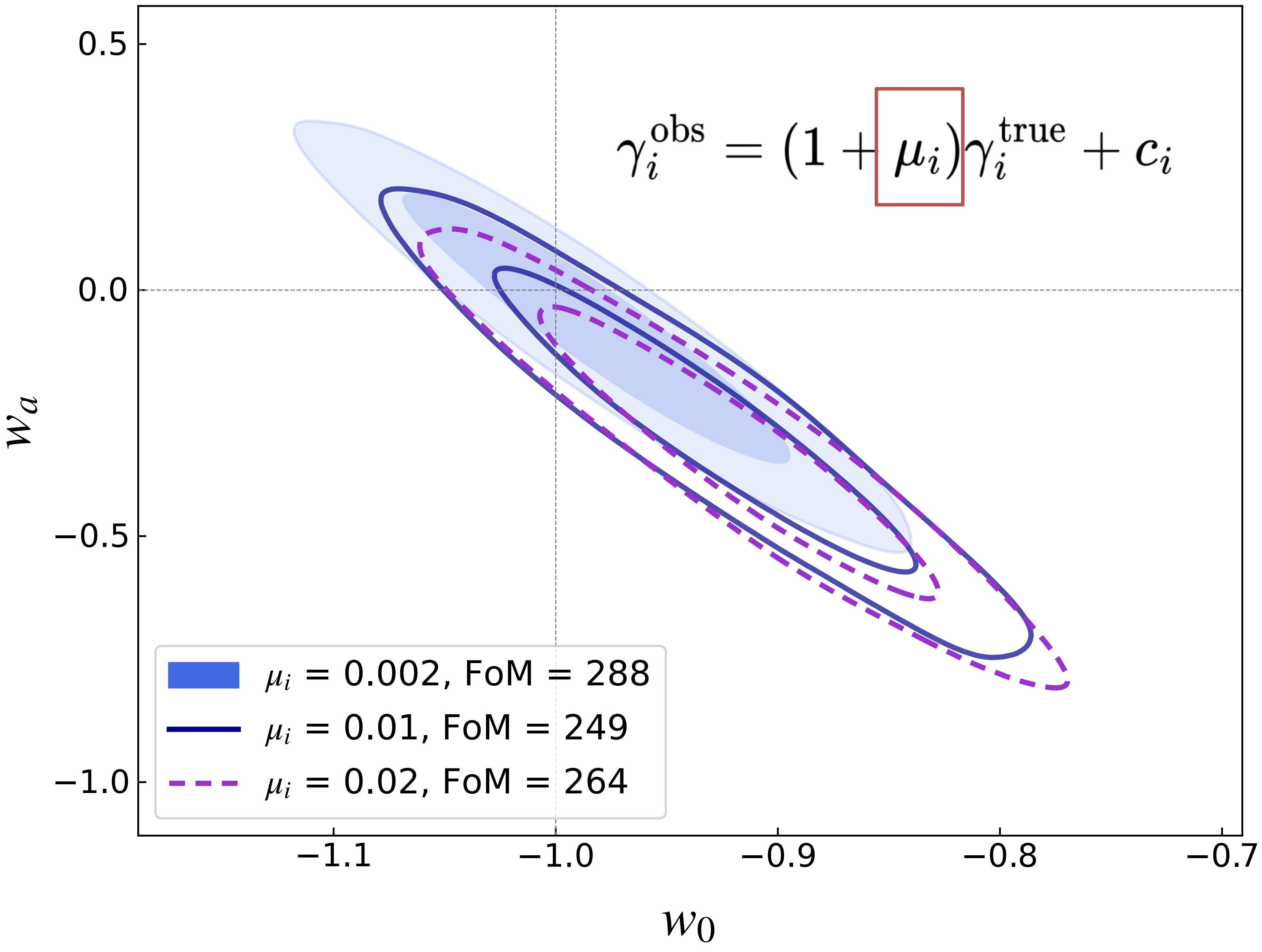


OPERATING THE INSTRUMENTS IN REAL CONDITIONS

On top, we must calibrate:

Galaxy shapes – accurate shape measurements are essential for weak lensing studies (i.e: we rely on simulations)

Redshifts – accurate distance measurements are key to unbiased cosmological results (i.e: using Earth-based observations)



Credit: GCH

BETTER DATA MEANS BETTER ANALYSIS

But it comes with a cost: **the parameter space becomes high-dimensional**

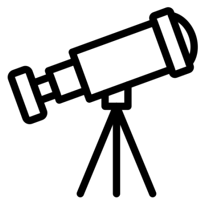
LIKELIHOOD

COVARIANCE MATRIX

$$-\log \mathcal{L} \propto [d - T(\theta)]^t \,\mathrm{Cov}^{-1}\, [d - T(\theta)]$$

DATA

THEORY



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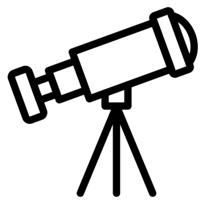
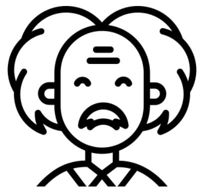
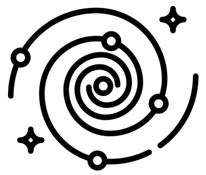
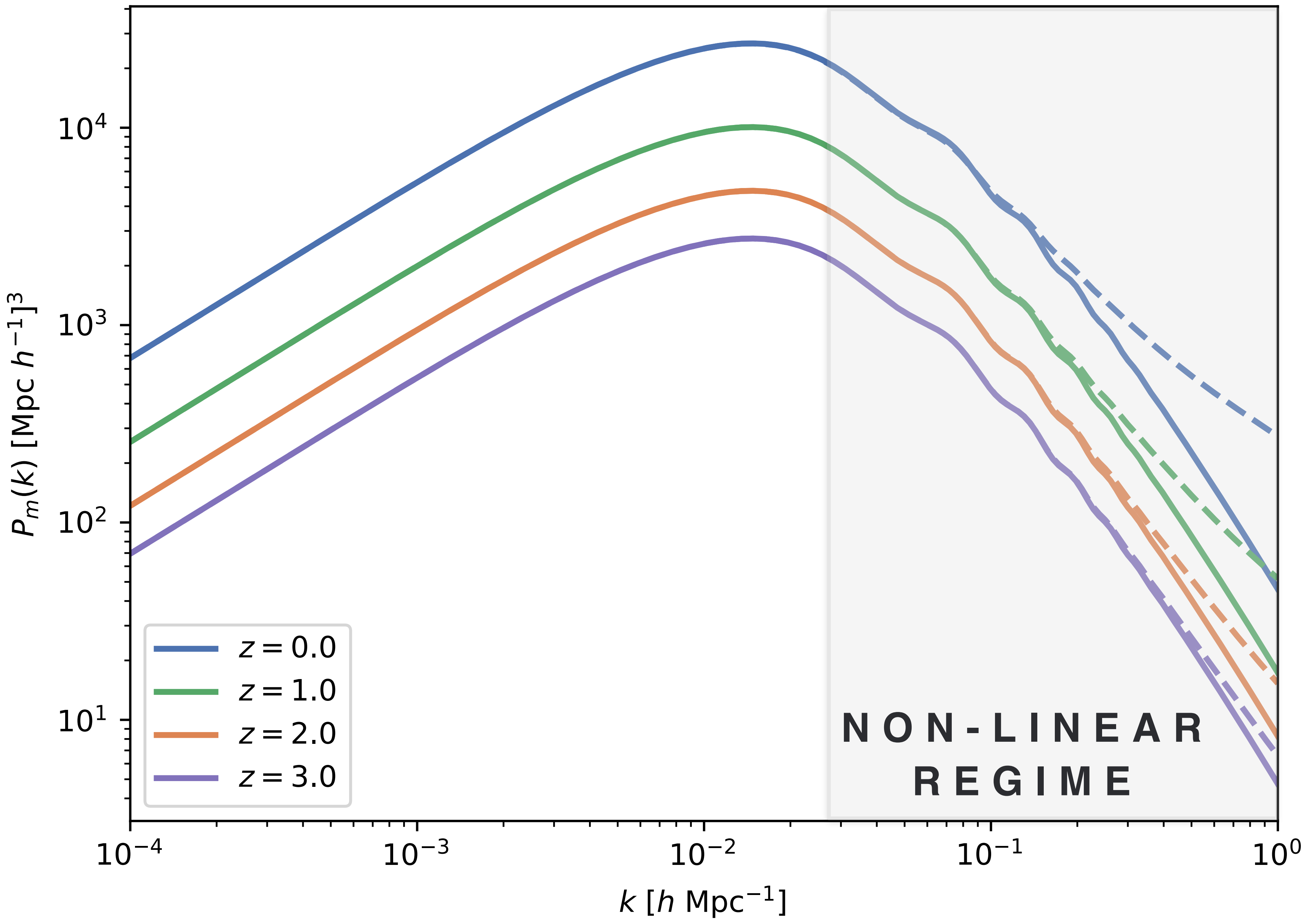






MODELLING LSS OBSERVABLES

At late times, the Universe's evolution is dominated by non-linear gravitational effects

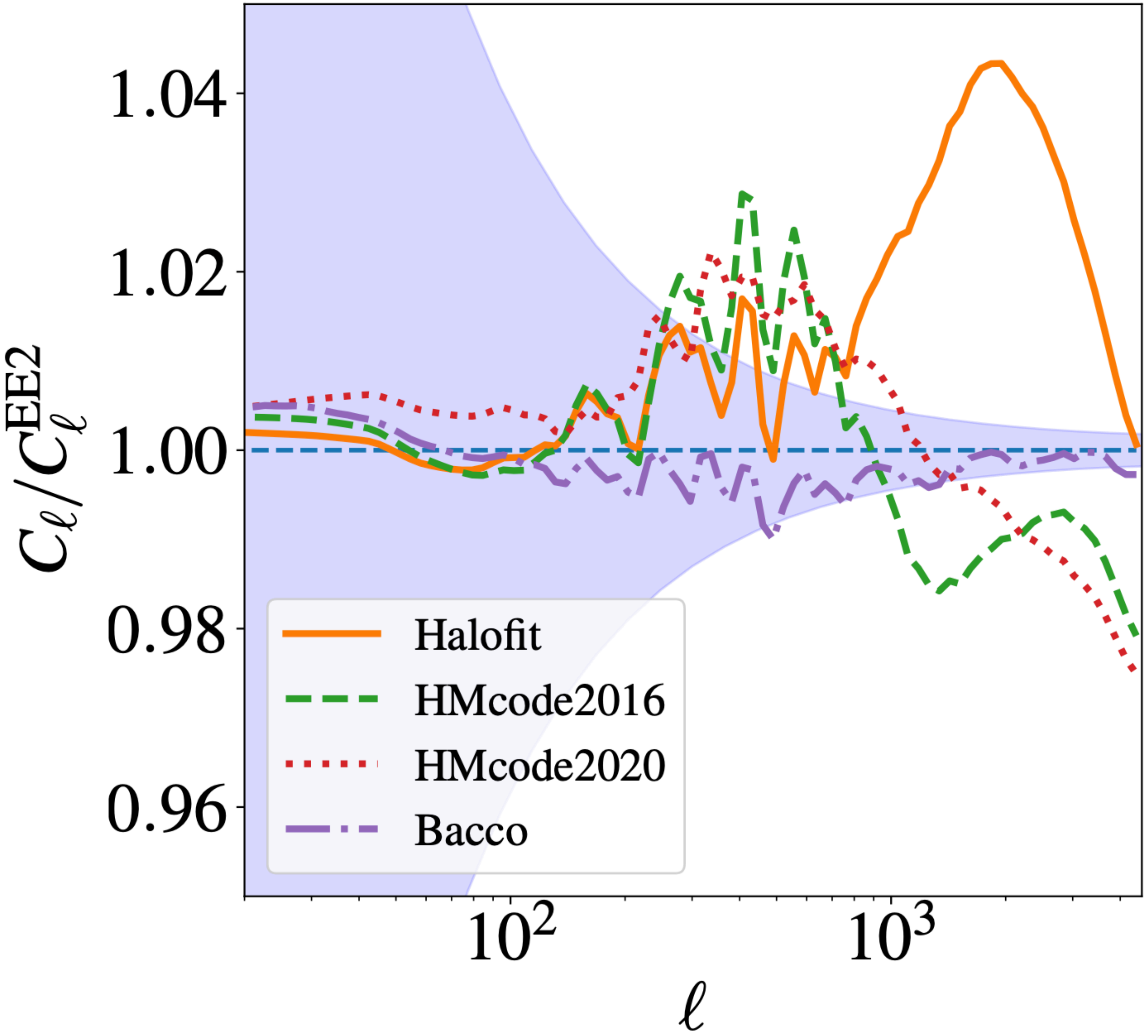


The notorious non-linear regime –
Accurately modeling the so-called non-linear regime requires running N-body simulations, as the simple linear approximations of structure growth break down in this regime

Credit: Jip de Buck

MODELLING LSS OBSERVABLES

At late times, the Universe's evolution is dominated by non-linear gravitational effects



Credit: P. Carrilho

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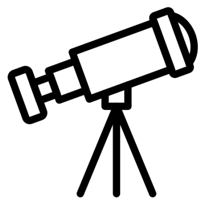
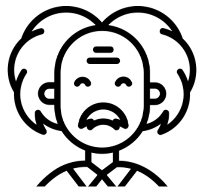
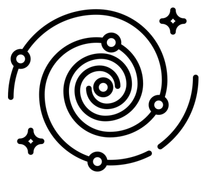
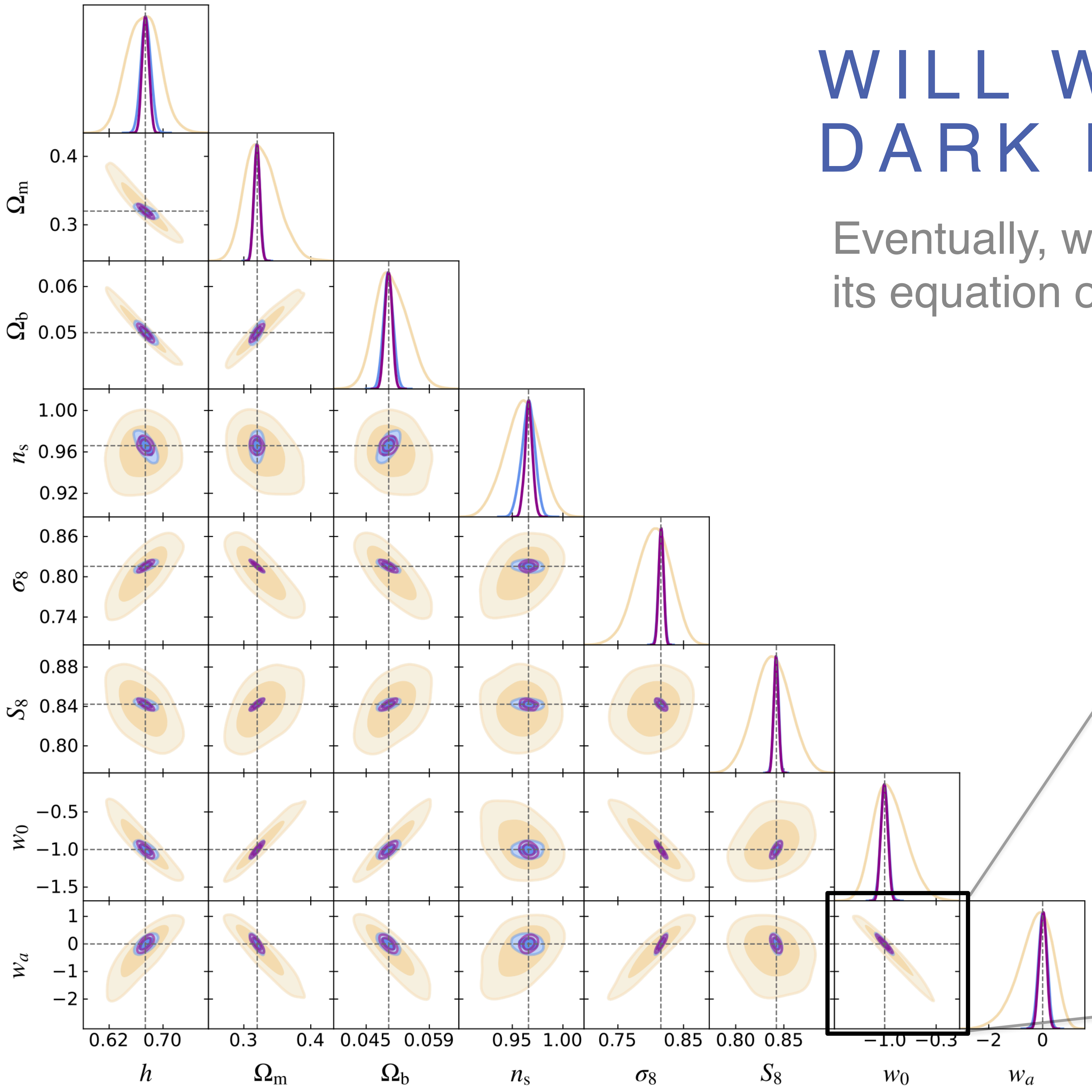


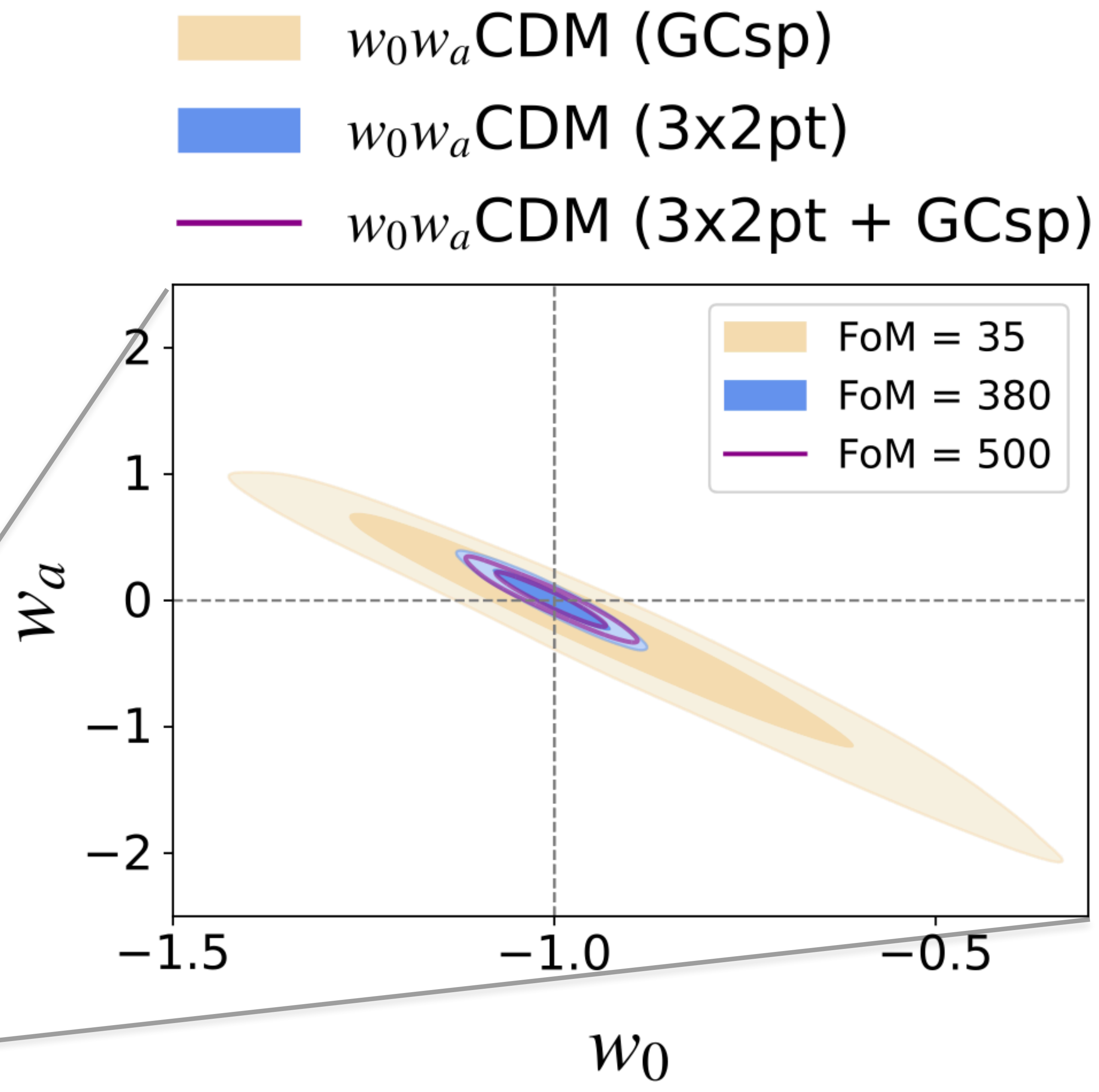




WILL WE CONSTRAIN DARK ENERGY?

Eventually, we should be able to reconstruct its equation of state





Credit: GCH

NEW STATISTICAL TECHNIQUES

Rethinking cosmological inference for the challenges of tomorrow

HOW DO WE PERFORM THE STATISTICAL ANALYSIS SUCCESSFULLY?

BY ENCOURAGING OPEN SCIENCE DEVELOPMENT OF INFERENCE PIPELINES FOLLOWING FAIR PRINCIPLES AND ADOPTING XXI TECHNIQUES

GPU

cloe-org

Repositories People 141

Our main repositories:

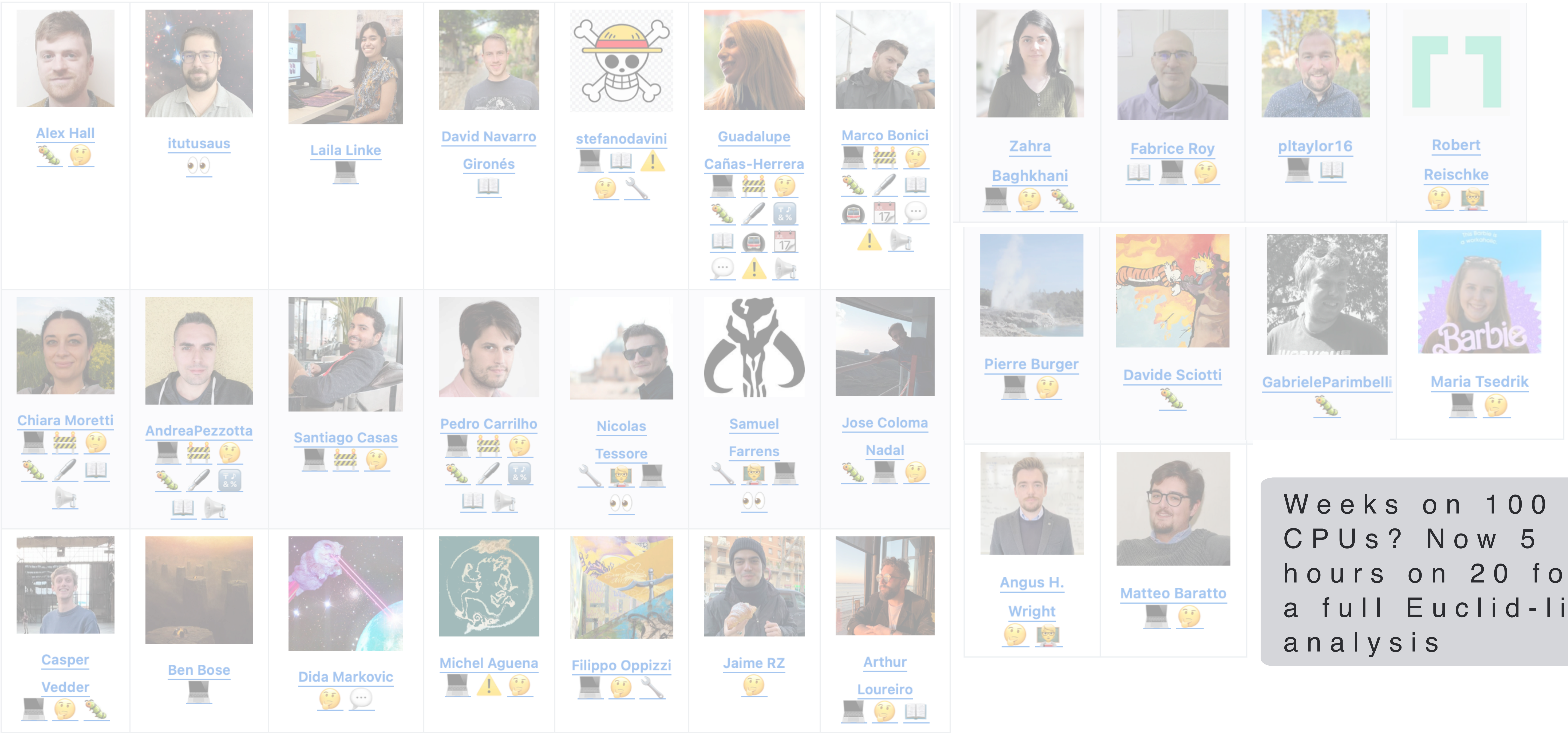
Repository Name	Description
cloelib	Computation of the theoretical predictions for Euclid primary observables
cloelike	Euclid likelihood module for photometric and spectroscopic primary observables
playground	Tutorials, examples and DEMO notebooks
darkflipper	Computation of Figure of Merit and Figure of Bias measurements

EuroHPC
Joint Undertaking

R E S

USING AI TO TRACK CONTRIBUTIONS

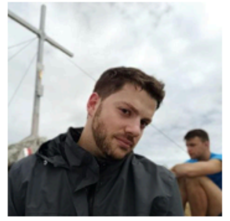
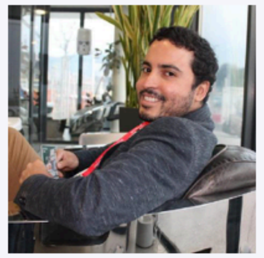
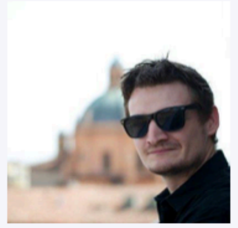
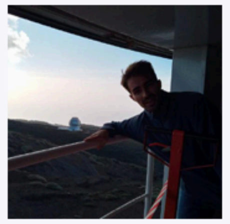
Our amazing hall of fame is automatically updated to boost visibility



Weeks on 100 CPUs? Now 5 hours on 20 for a full Euclid-like analysis

USING AI TO TRACK CONTRIBUTIONS

Our amazing hall of fame is automatically updated to boost visibility

 Alex Hall 🐛 🤔	 itutusaus 👀	 Laila Linke 💻	 David Navarro Gironés 📖	 stefanodavini 💻 📖 ⚠️ 🤔 🔧	 Guadalupe Cañas-Herrera 💻 🚧 🤔 🐛 🖋 🔣 📖 🚇 📆 💬 ⚠️ 📢	 Marco Bonici 💻 🚧 🤔 🐛 🖋 📖 🚇 📆 💬 ⚠️ 📢
 Chiara Moretti 💻 🚧 🤔 🐛 🖋 📖 📢	 AndreaPezzotta 💻 🚧 🤔 🐛 🖋 🔣 📖 📢	 Santiago Casas 💻 🚧 🤔	 Pedro Carrilho 💻 🚧 🤔 🐛 🖋 🔣 📖 📢	 Nicolas Tessore 🔧 🧑‍🏫 💻 👀	 Samuel Farrens 🔧 🧑‍🏫 💻 👀	 Jose Coloma Nadal 🐛 💻 🤔
 Casper Vedder 💻 🤔 🐛	 Ben Bose 💻	 Dida Markovic 🤔 💬	 Michel Aguena 💻 ⚠️ 🤔	 Filippo Oppizzi 💻 🤔 🔧	 Jaime RZ 🤔	 Arthur Loureiro 💻 🤔 📖

 Zahra Baghkhani 💻 🤔 🐛	 Fabrice Roy 📖 💻 🤔	 pltaylor16 💻 📖	 Robert Reischke 🤔 🧑‍🏫
 Pierre Burger 💻 🤔	 Davide Sciotti 🐛	 GabrieleParimbelli 🐛	 Maria Tsedrik 💻 🤔
 Angus H. Wright 🤔 🧑‍🏫	 Matteo Baratto 💻 🤔		

THE UNIVERSE MIGHT BE DARK

But these are truly thrilling times for cosmology

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But these are truly thrilling times for cosmology

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Data of the large-scale structure of the Universe will take center stage in shaping the cosmological landscape

DELIVERABLES OF THIS EFFORT HOLD HIGH IMPACT FOR THE COMMUNITY

Both software and theoretical development will play a crucial role in advancing cosmology on the next years

PS: EUCLID EXISTS!