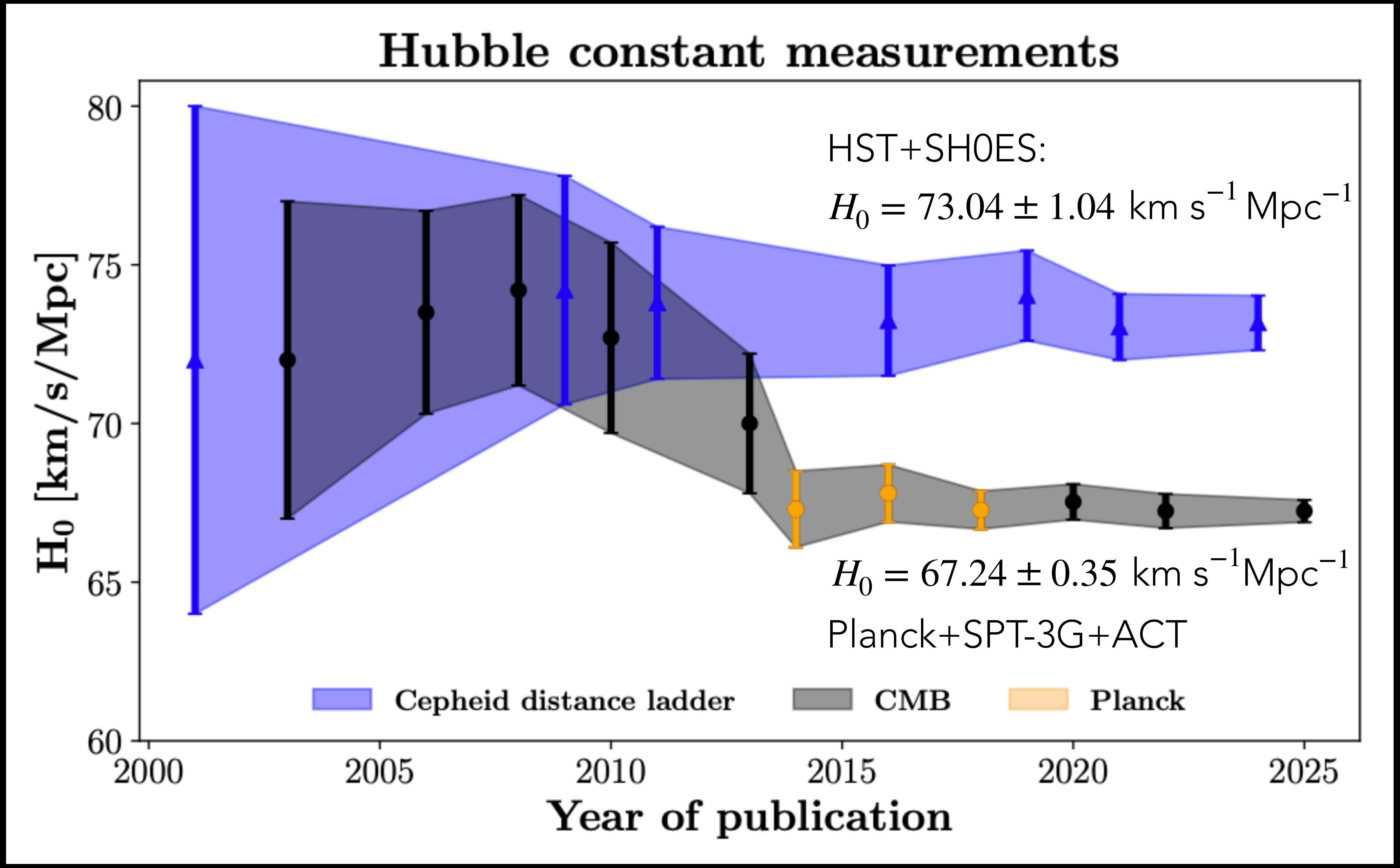
MASSIMO MENEGHETTI (INAF-OAS BOLOGNA)

THE COSMOLOGICAL MODEL, DARK MATTER AND DARK ENERGY

INSIGHTS ON COSMOLOGICAL TENSIONS FROM GALAXIES AND GALAXY CLUSTERS

H0 TENSION

- **What is the precise value of the Hubble constant?**
- **Directly measured** by fitting a cosmological model to distance (i.e. in the late universe)
- **Indirectly measured** from angular scales that characterize the early universe (sound horizon at recombination/drag epoch), assuming a cosmological model (from the acoustic peaks in the CMB power-spectrum or from BAO)
- The two methods disagree at $\sim 5\sigma$! Local ladder demands faster expansion today!



N. Schöneberg, Corfù 2025

$$\theta_\star = \frac{H_0 r_\star}{\int_0^{z_\star} 1/E(z)dz}$$

↘ Pre-recombination

↘ Late expansion

$$E(z) = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{DE}(z) + \dots}$$

$w_0 - w_a$ TENSION

- **Is dark energy a cosmological constant?**
- Recently, DESI+CMB+SN combinations hint at w(a) not equal to -1 (>3σ evidence):

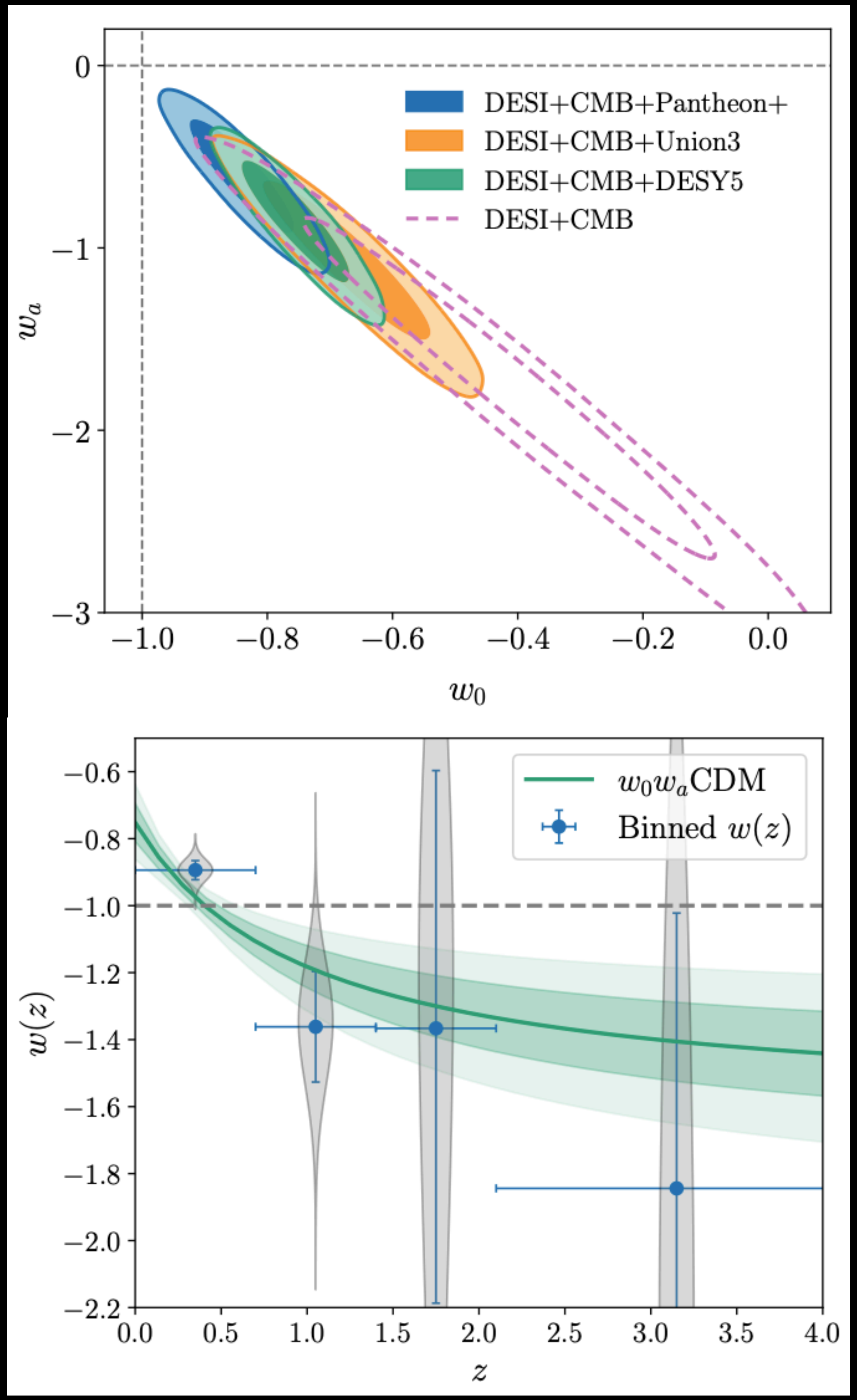
$$w(a) = w_0 + w_a(1 - a) \text{ (CPL)}$$

$$w_0 > -1, w_a < 0$$

This implies that DE is weaker than a cosmological constant at $z \lesssim 0.5$

- $H_0 = 67.51 \pm 0.59$ km s^{-1} Mpc^{-1} (w0waCDM, DESI+CMB+Pantheon+)
- Less freedom to solve the H0 tension with late-time physics (e.g. phantom dark energy)!

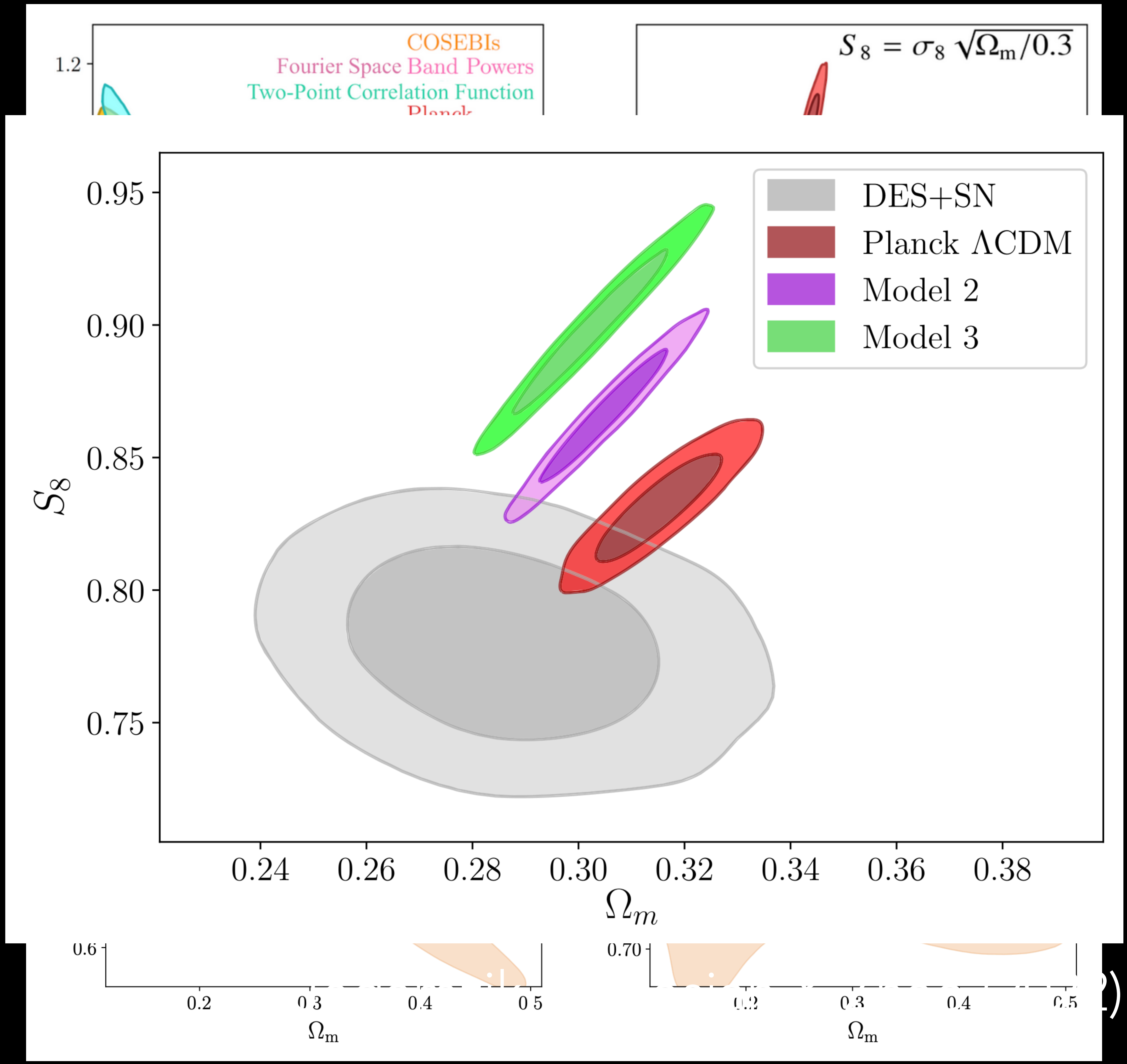
DESI DR2 BAO (DESI coll. 2025)



THE S8 TENSION

- **Does the clustering amplitude agree with LCDM predictions?**
- $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
- CMB observations support higher values of S8 compare to later-time probes of structure formation (cosmic shear from KiDS, DES, HSC)
- Milder tension (at $\sim 2\sigma$) compared to the previous tension on H0 and DE
- Could get worse when trying to solve the H0 tension with early-time physics!

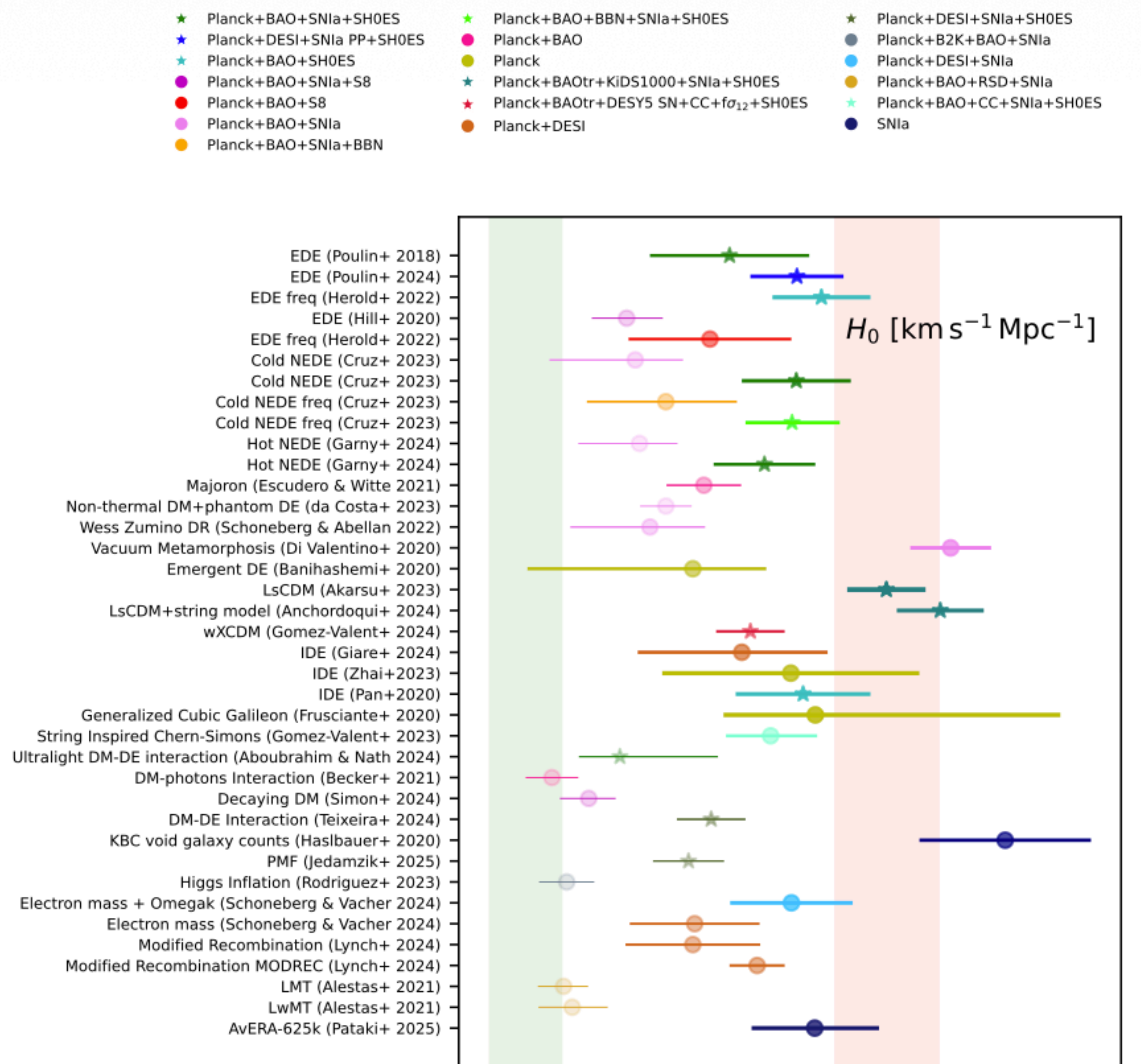
Asgari et al. (2020)



DESY3+KiDS1000 (2023)

INVESTIGATING THE ISSUES: COSMIC EXPANSION

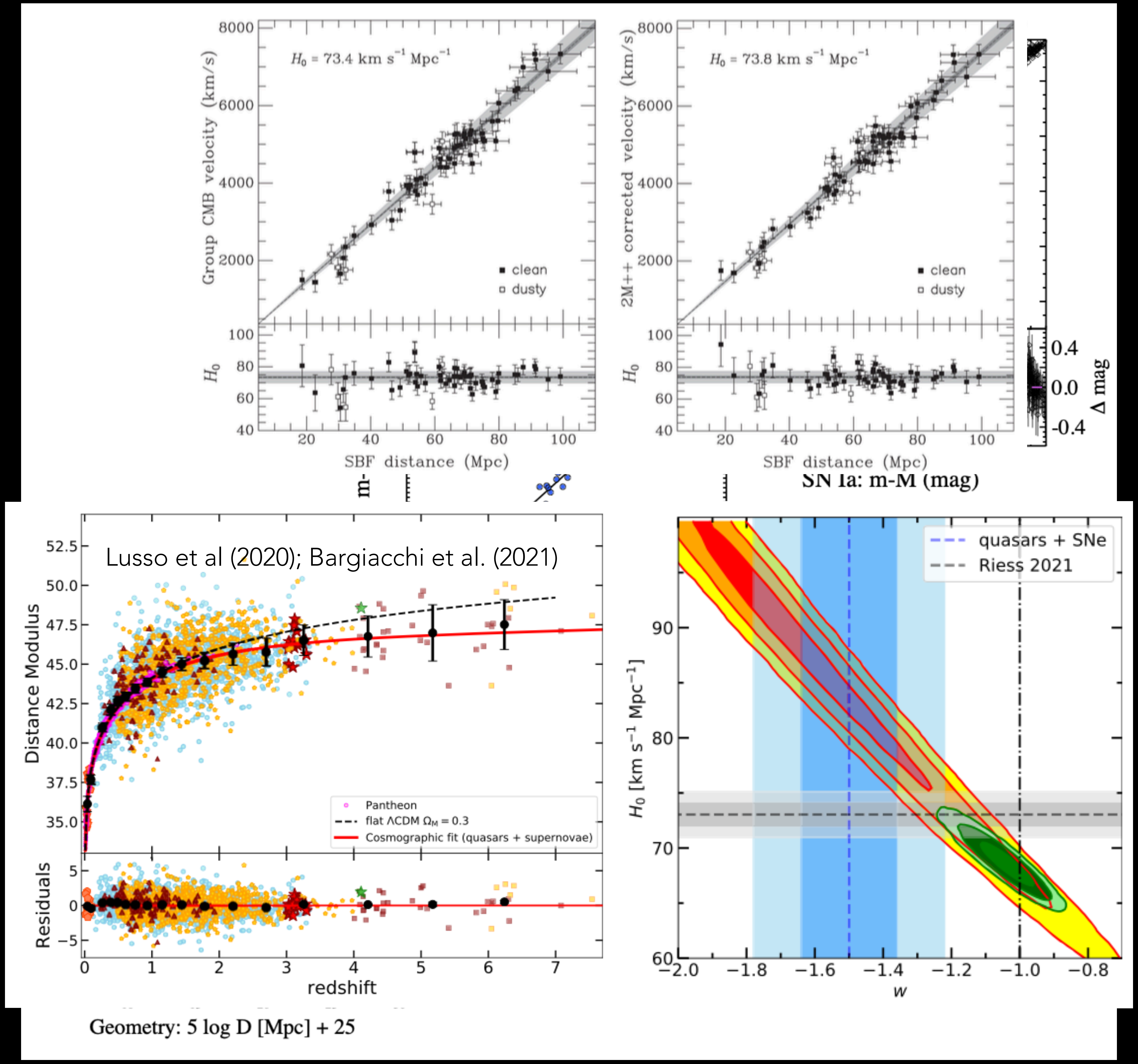
- These tensions may signal **unknown systematics** or **new physics beyond ΛCDM**
- **Theoretical work is ongoing.** For example: decaying DM, interacting DM-DE, early modified gravity, phantom dark energy, dark radiation (Viel et al.@Trieste, Finelli et al@Bologna, Menci@Rome)
- **Need to find a models that solve current tensions without creating new ones.**
- Using multiple independent probes of cosmic expansion is essential to cross-check assumptions, control systematics, disentangle solutions linked to early- vs late-time physics



Di Valentino et al. (2025)

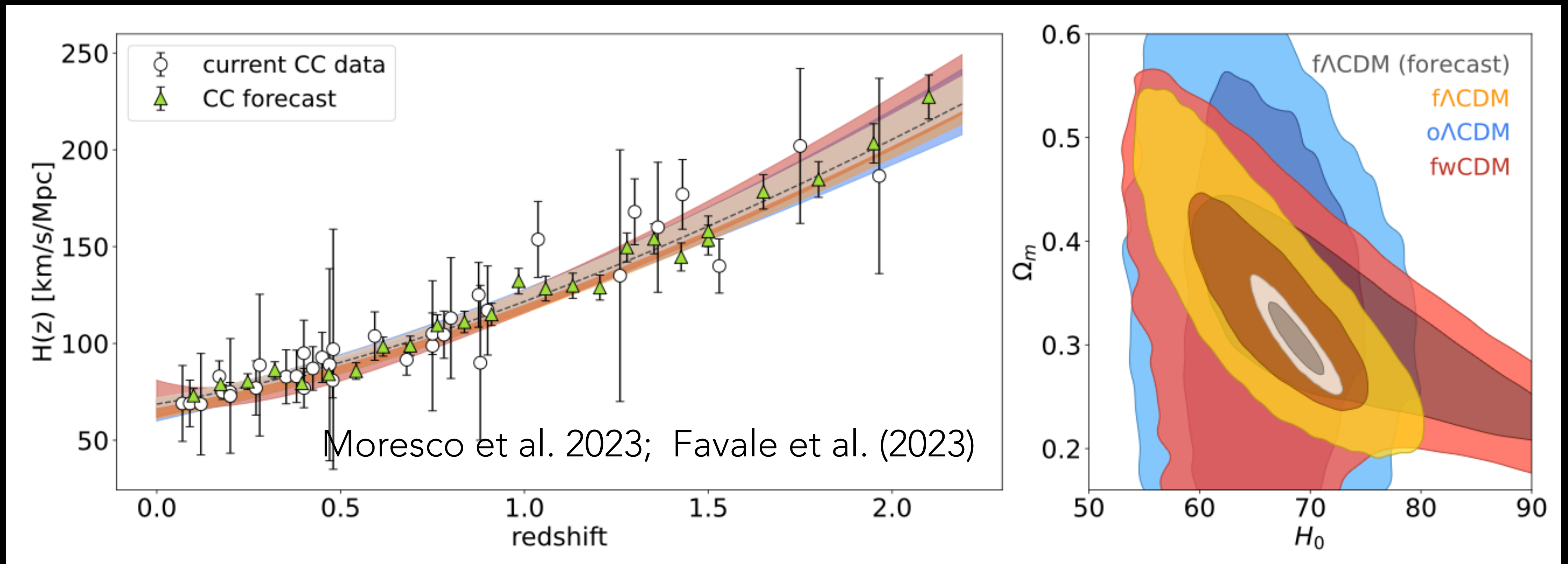
DIRECT PROBES OF COSMIC EXPANSION

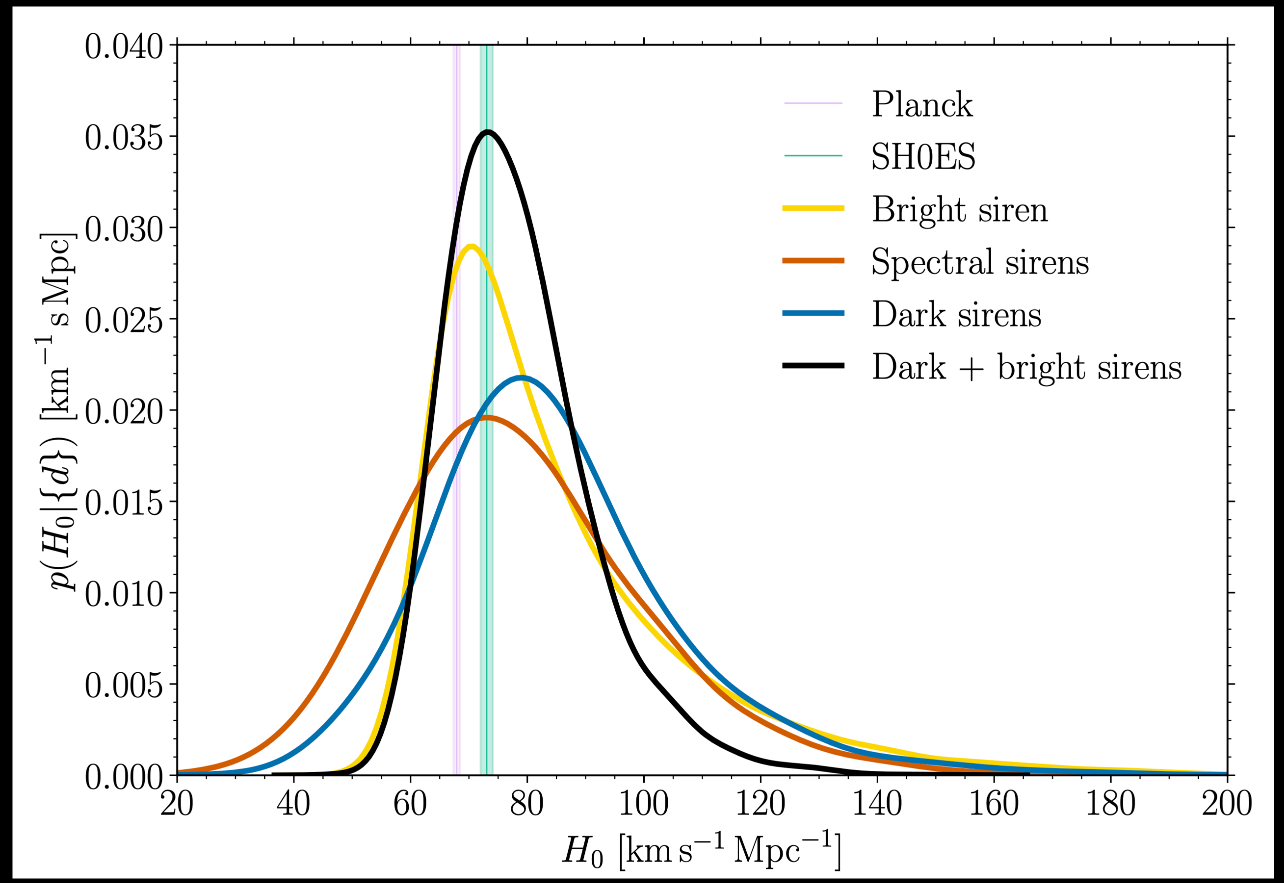
- Naturally transversal science case within INAF (e.g., RSN2: local cosmology, calibration of distance indicators — Cepheids, MIRAS, TRGB, JAGB, SNII; ⇒ Ilaria Musella's talk at RSN2; RSN4 — GWs, GRBs)
- Several galaxy based methods (e.g. Tully-Fischer relation, fundamental plane, …)
- Surface-brightness fluctuations: using SB fluctuations in unresolved old stellar populations as distance indicator, also used to calibrate SNIa (Cantiello et al@Teramo)
- Quasars: based on L_{UV}-L_X relation (Risaliti-Lusso relation); extending the Hubble diagram to high redshift; $z \lesssim 7$ (Firenze)



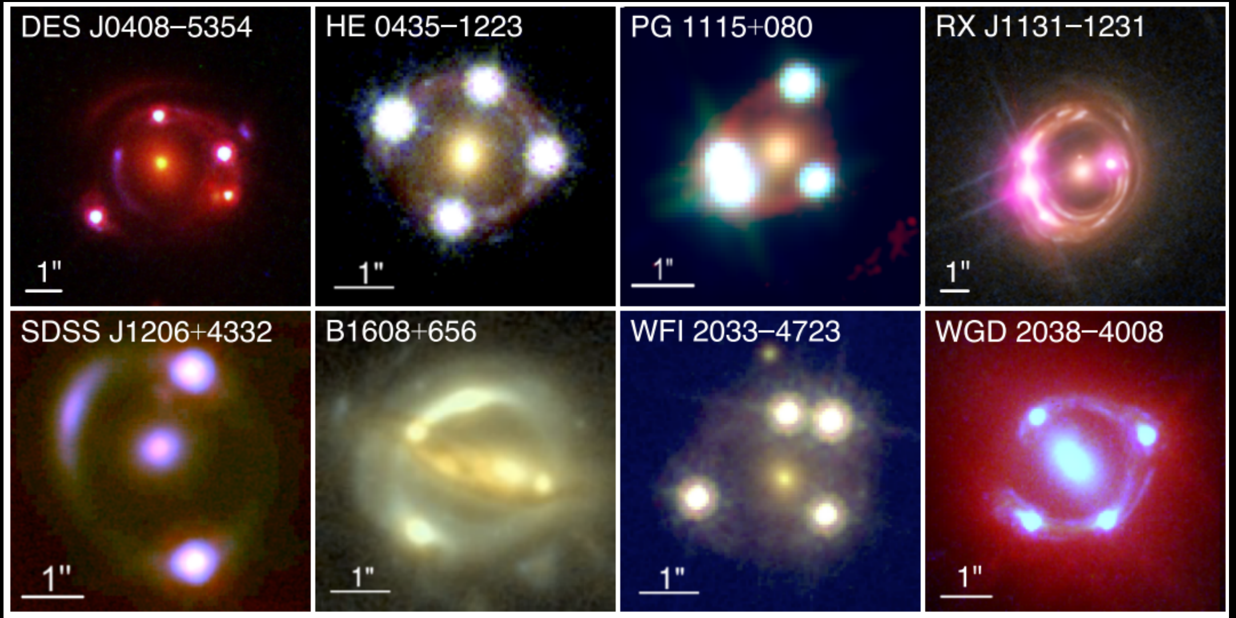
INDIRECT PROBES

- **Modeling phenomena to infer H0 or w**:
  - Cosmic chronometers: using differential ages of passively evolving galaxies. Dating stellar pops (Moresco, Cimatti, Pozzetti, et al@Bologna OAS+UniBO)
  - Cosmic sirens: modeling GW signals with EM counterparts (e.g. GW170817) or with galaxy catalogs (dark sirens) → GRAWITA ($\gtrsim 100$ INAF members + associates)
  - Time delay cosmography: using time delays between multiple images of QSOs and SNs lensed by galaxies and **galaxy clusters** [Grillo, Annunziatella@Milano (IASF+UniMI), Rosati et al.@Ferrara, Bergamini, Meneghetti et al.@Bologna OAS, Angora, Mercurio et al.@Capodimonte]

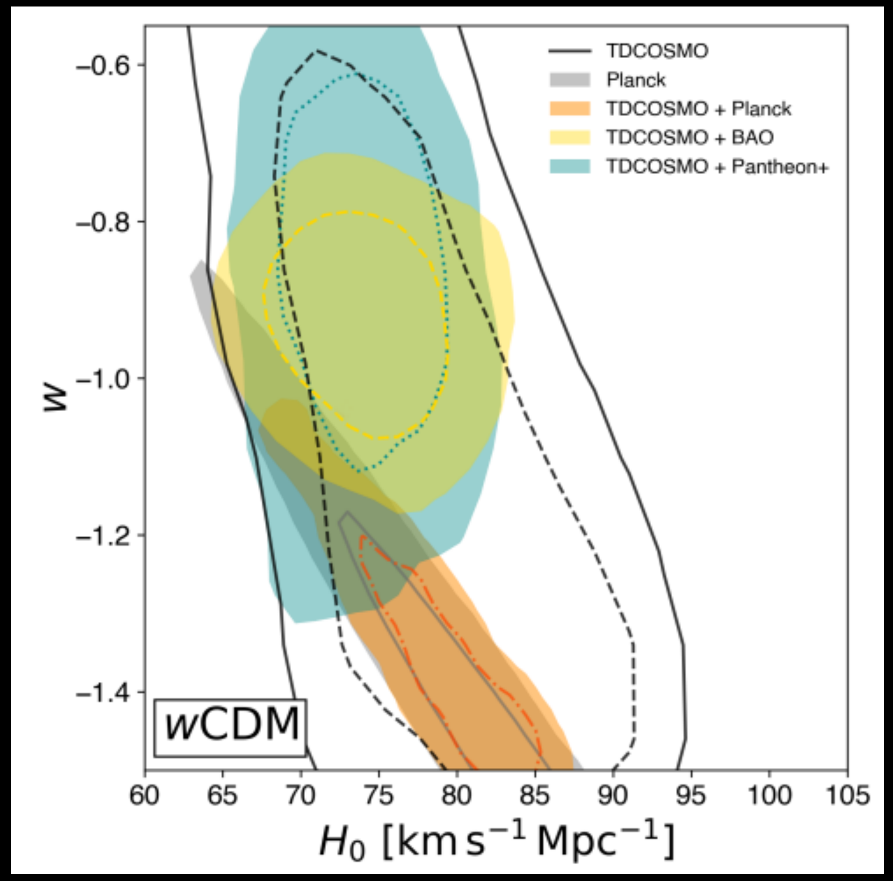




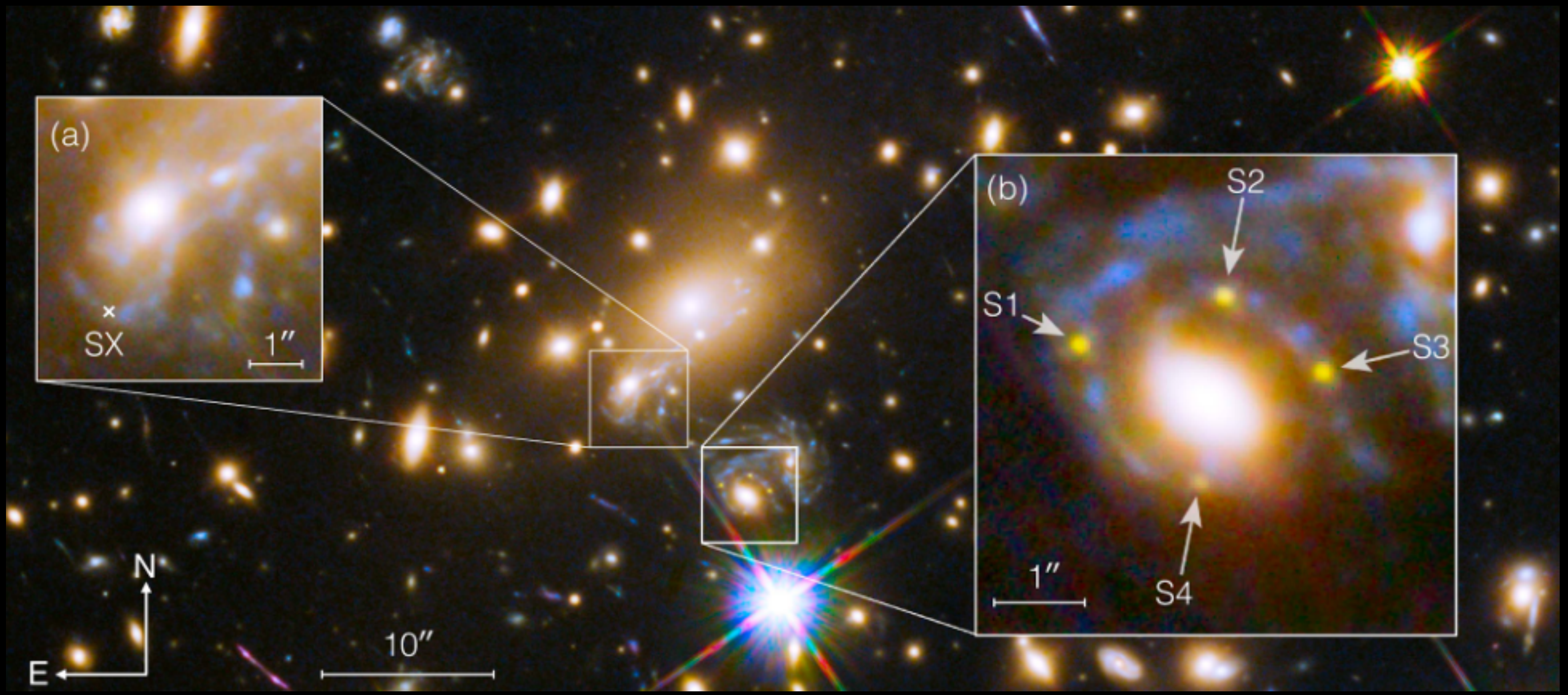
Cantiello et al. 2018, LIGO, Virgo, KAGRA collabs. (2025)

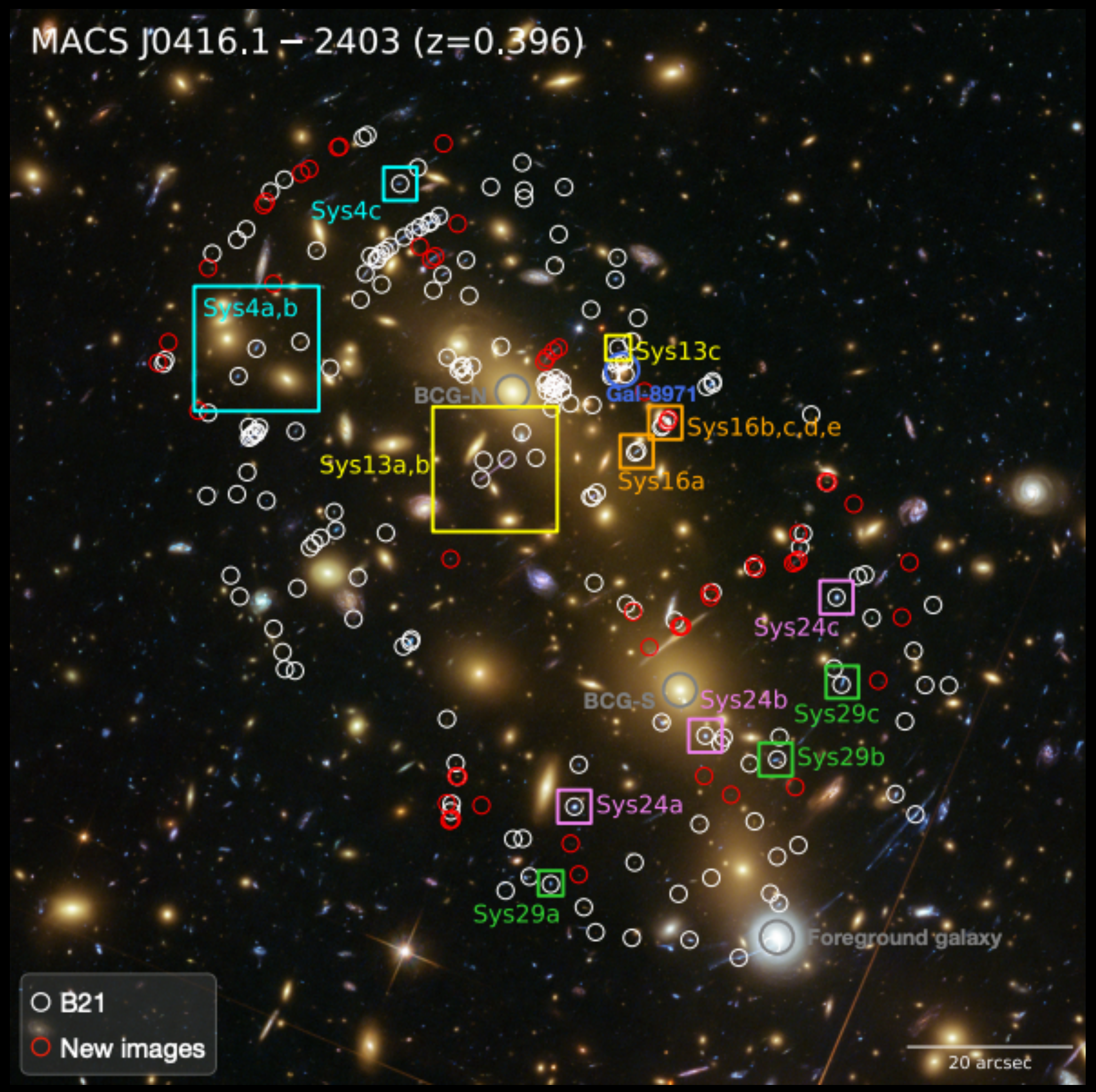


TDCOSMO: Birrer et al. (2025)

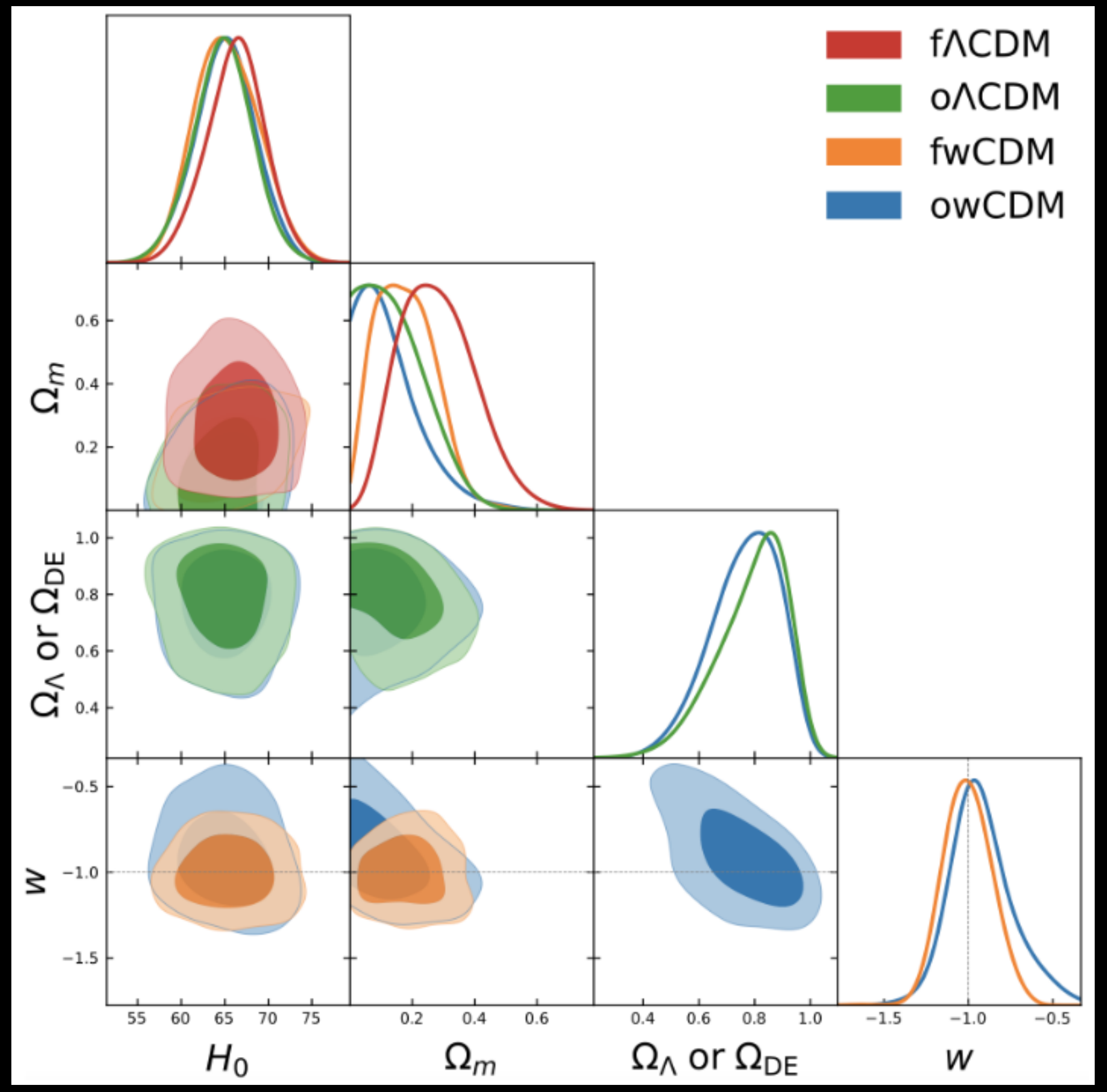


- Few SNs and QSOs (~10, few with time monitoring) observed in galaxy clusters, but very interesting results.
- Examples: SN Refsdal in MACSJ1149 (observed in 2014, reappeared in 2015)
- Strong lensing cosmography: using distance ratios of lensed sources at different redshifts. Deep HST and JWST imaging + MUSE@VLT spectroscopy: up to 300 multiple images/cluster
- Increasing number of lensed SNae and QSOs (JWST, Euclid, Rubin-LSST, …)
- In-kind Rubin-LSST project (PI Grillo): VST monitoring of lensed QSOs in galaxies and clusters (4620 hrs over 7 years). Goal: ~30 new systems, ~2% TD precision, ~1% uncertainty on H0.

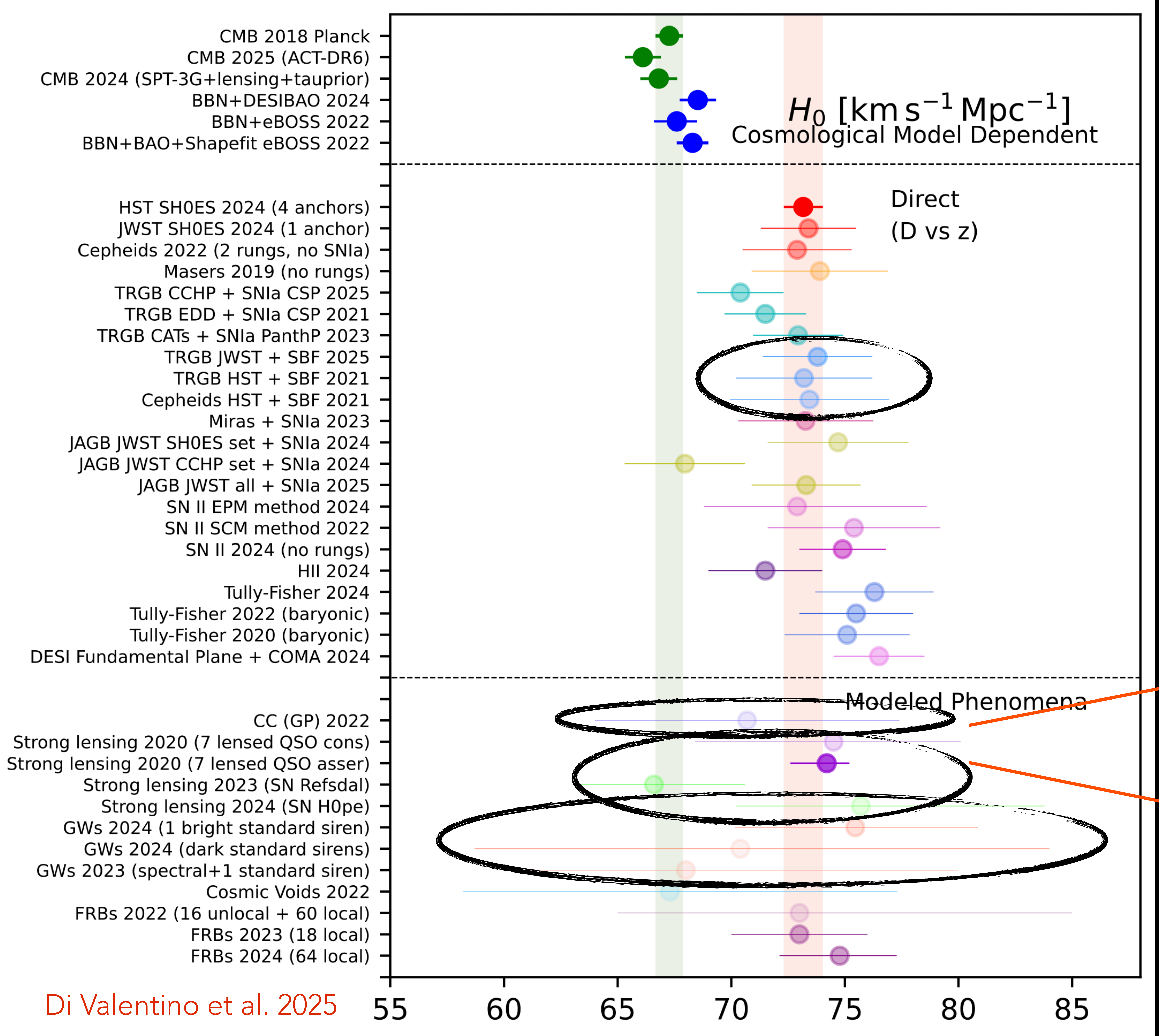




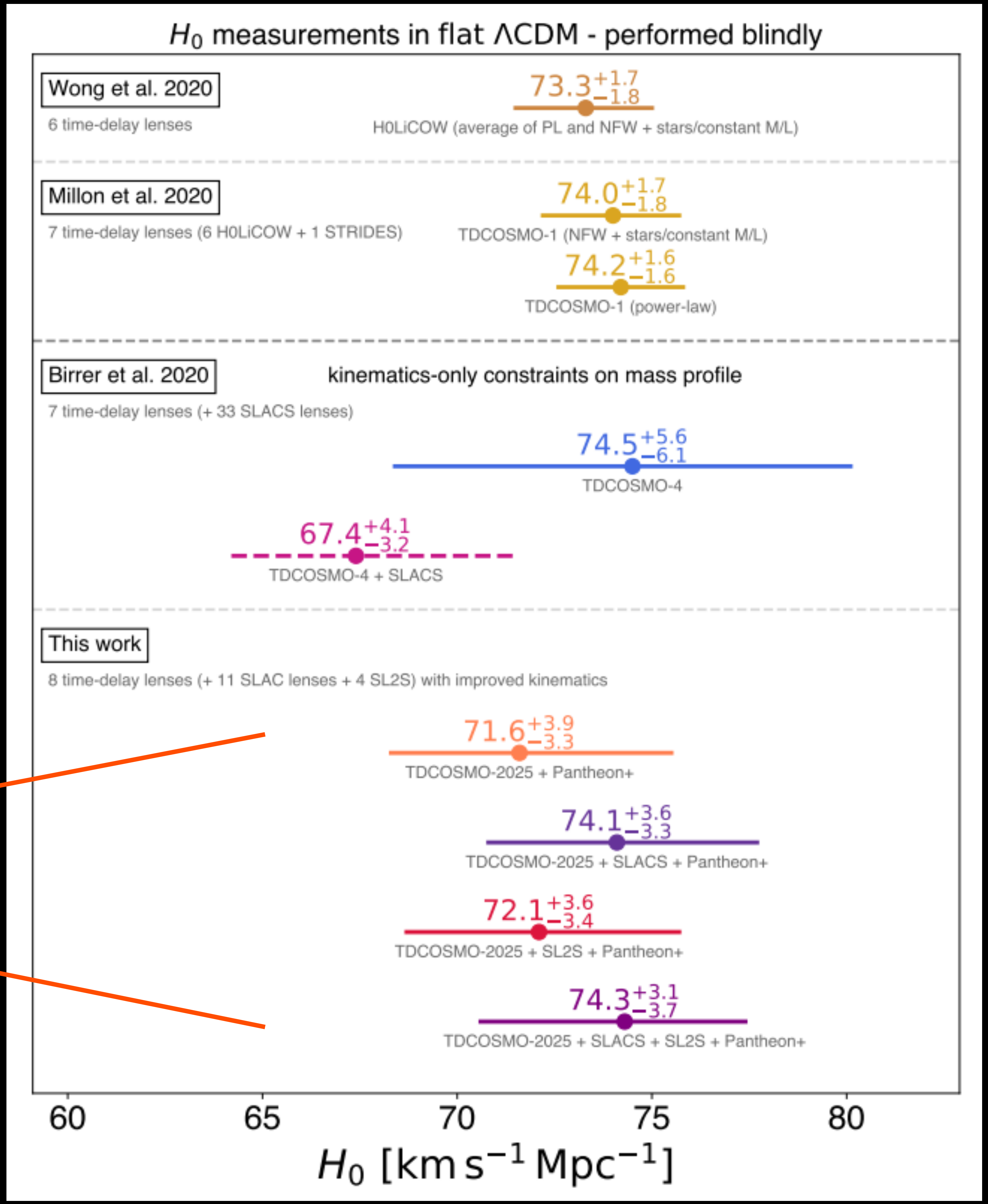
Bergamini et al. (2024)



Grillo et al. (2024)



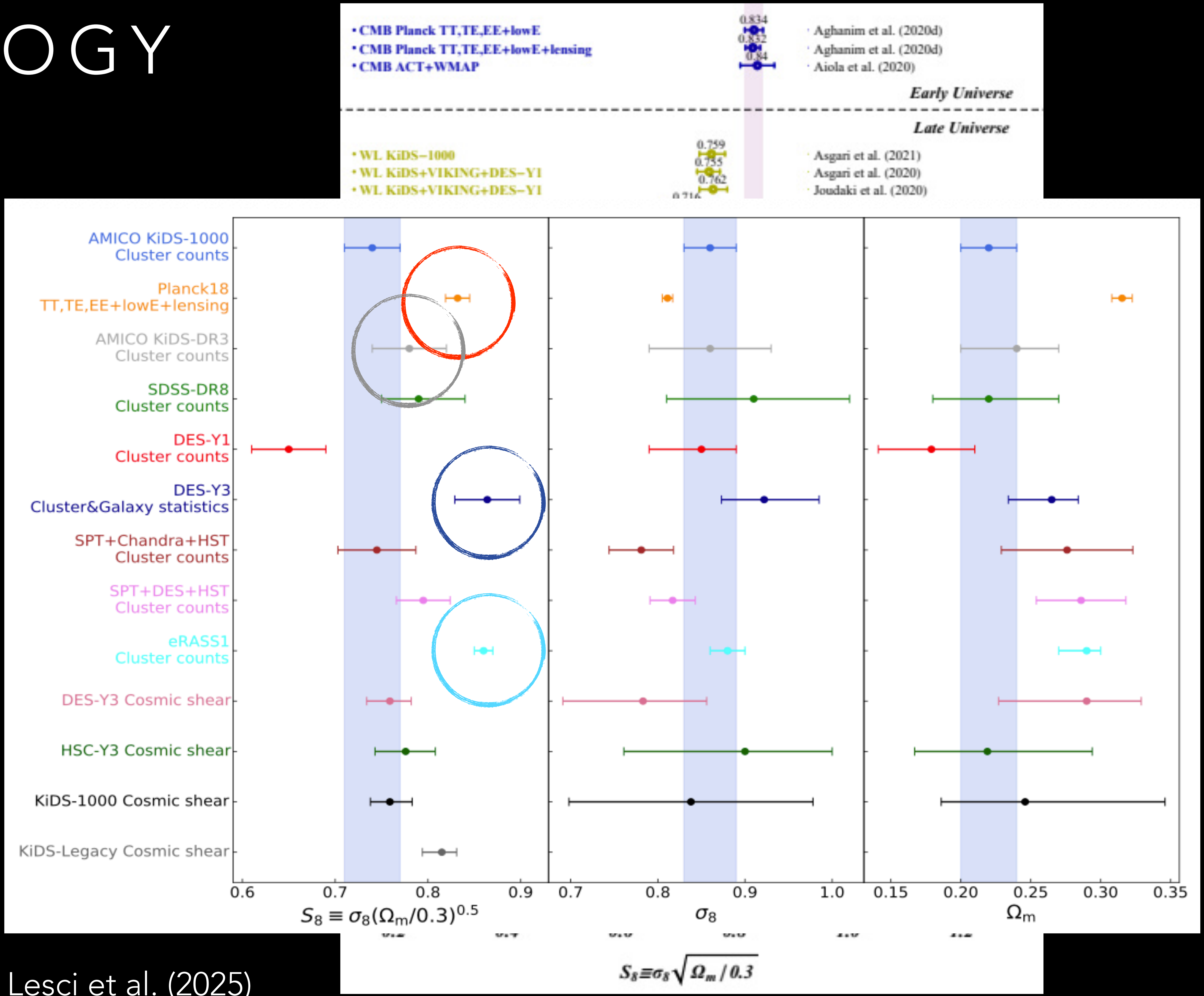
Di Valentino et al. 2025



Birrer et al. (2025)

CLUSTER COSMOLOGY

- Large cluster community (see talks by P. Tozzi and S. Molendi)
- Involvement in many cluster cosmology projects SPT (A. Saro, V. Strazzullo, …), eRosita (Ghirardini, …), DES (M. Costanzi, …), KiDS (Lesci, Giocoli, Moscardini, Radovich, …), Euclid (Giocoli, Sartoris, Munari, Moscardini, Sereno, and many more)
- Cluster counts, mass function and its evolution is a powerful probe of cosmology (including σ_8, Ω_M, DE)
- Latest results from KiDS, DES (and also eRosita) support no S8 tension (e.g. Lesci et al. 2025, Ghirardini et al. 2024)
- Why? Better understood selection function, source contamination, mass calibration, etc.

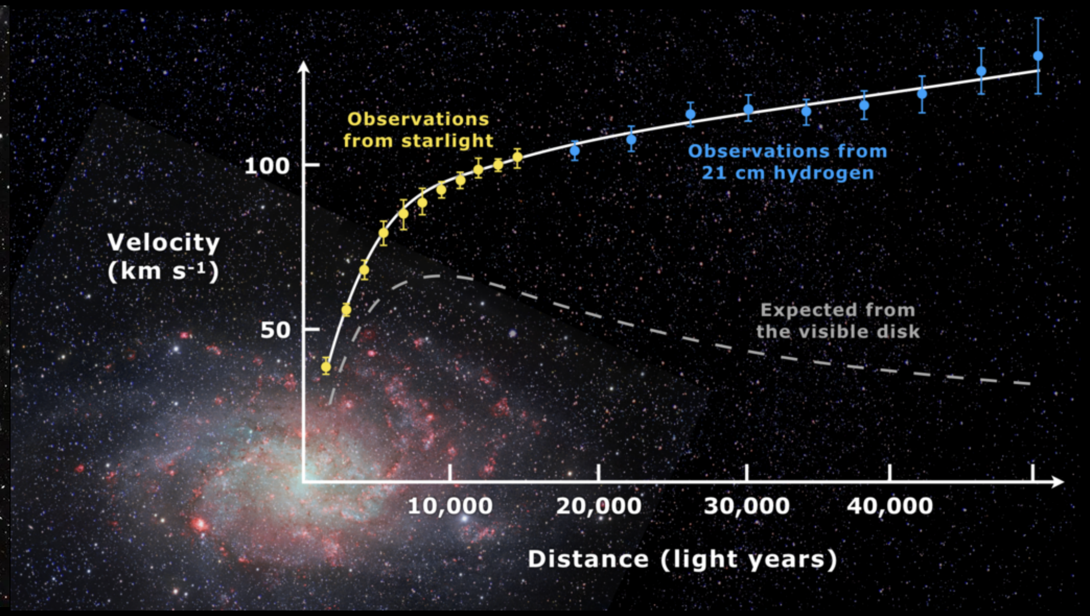


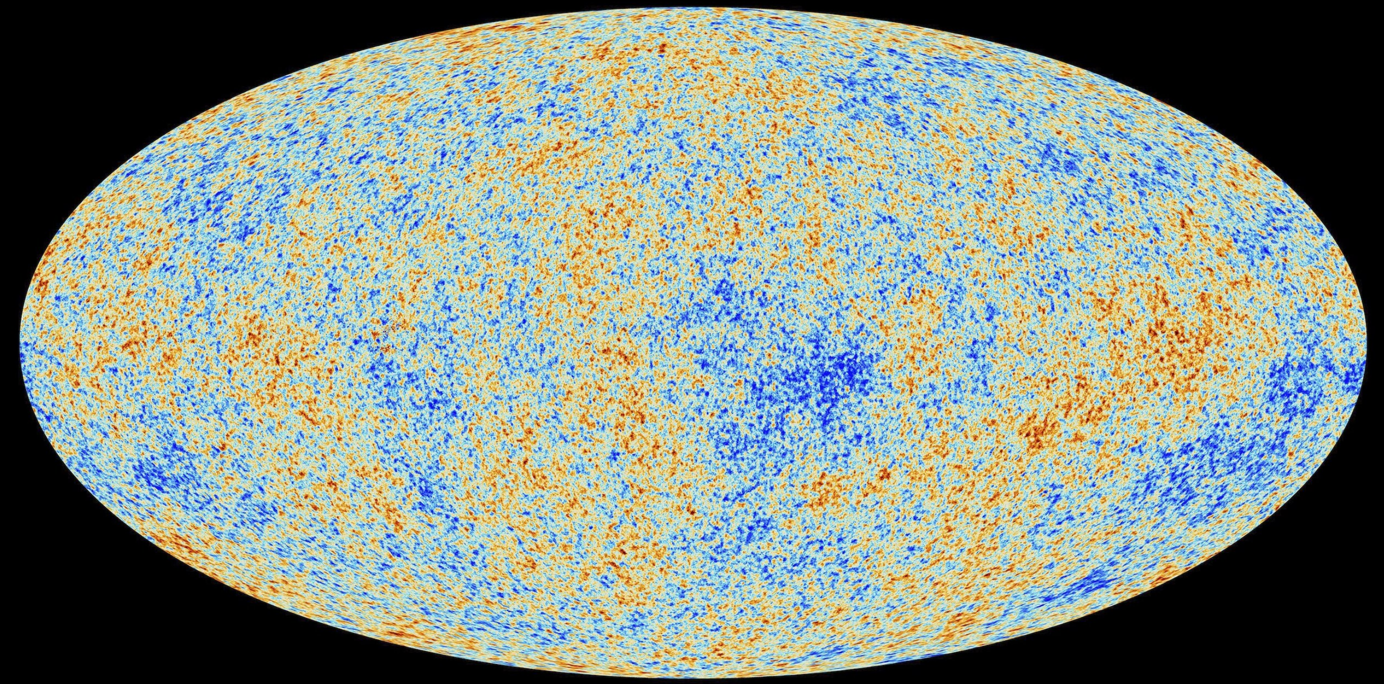
Lesci et al. (2025)

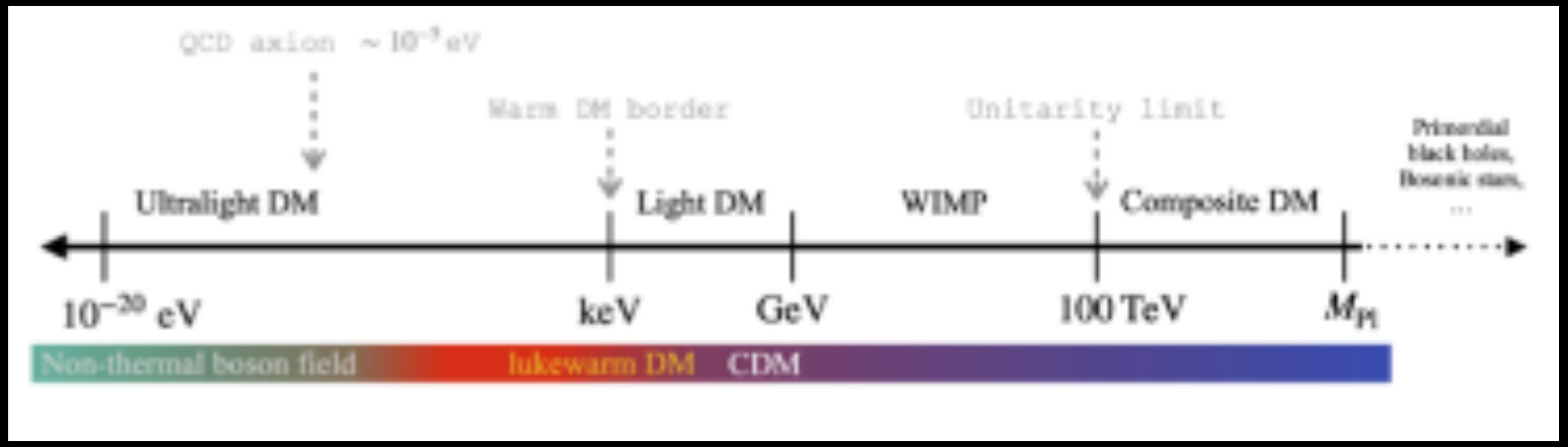
Snowmass 2022

WHAT IS THE NATURE OF DARK MATTER?

- In the Cold Dark Matter (CDM) paradigm, DM consists of **massive** and **weakly interacting** (collision-less) particles
- Their velocities in the early universe were too low to erase **small-scale density fluctuations** on galactic and sub-galactic scales
- Particle candidate: **WIMP** (thermal relics)
- Consistent with observations of the universe on large scales, but…
- …despite a host of particle physics experiments, no direct detection yet…

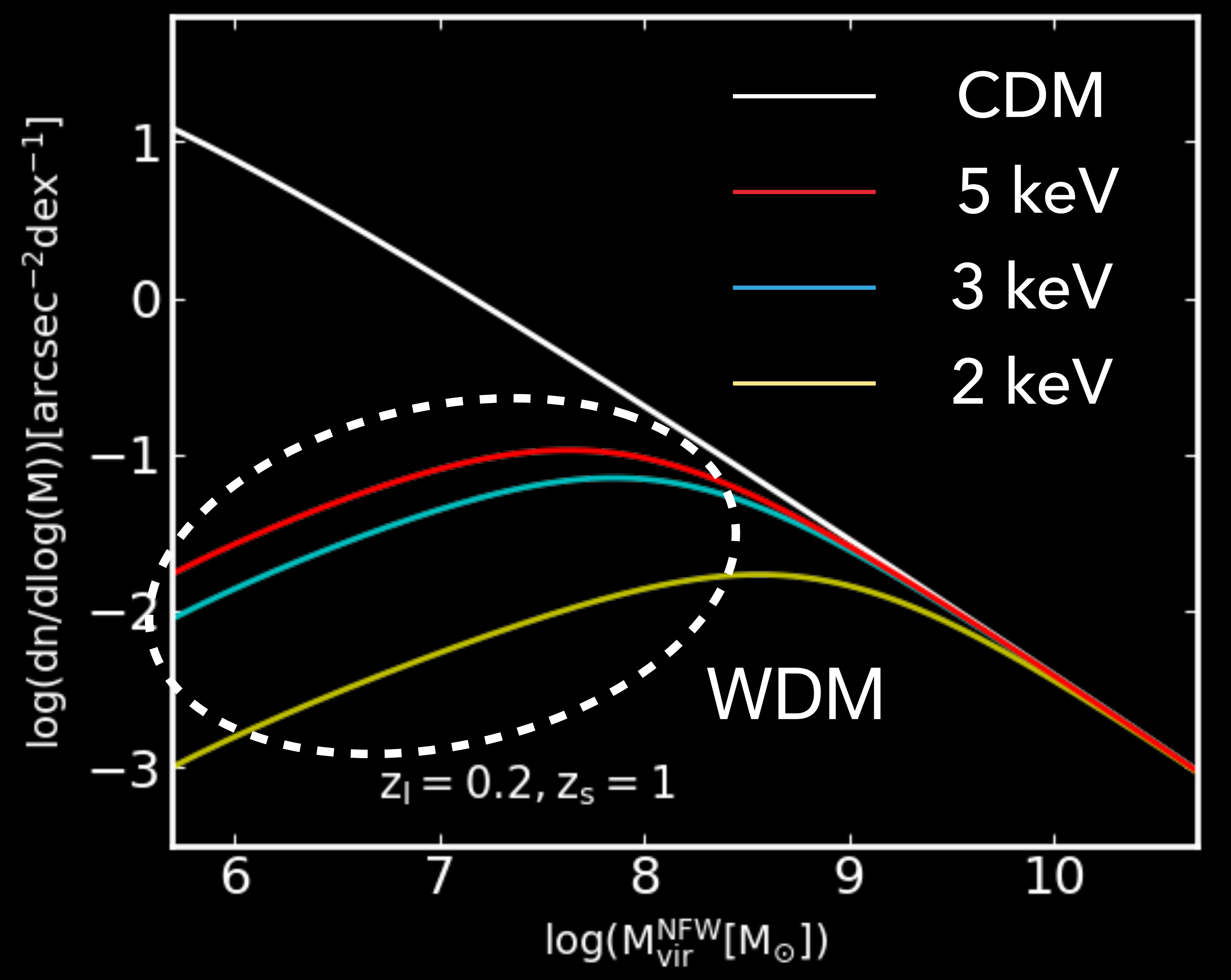




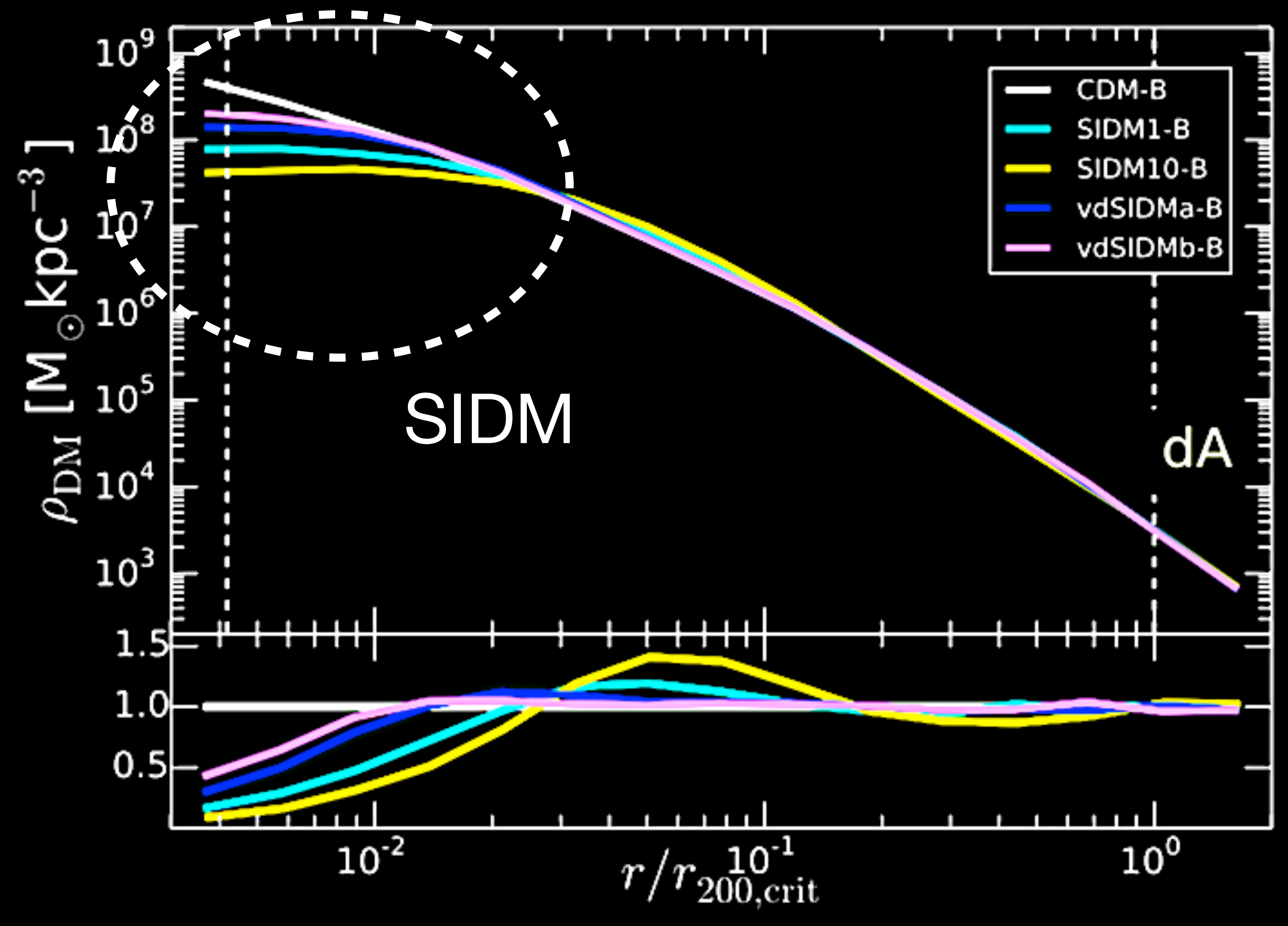


DOES CDM WORK ON SMALL SCALES?

➡ <u>in CDM</u>: number density of haloes increasing with decreasing halo mass

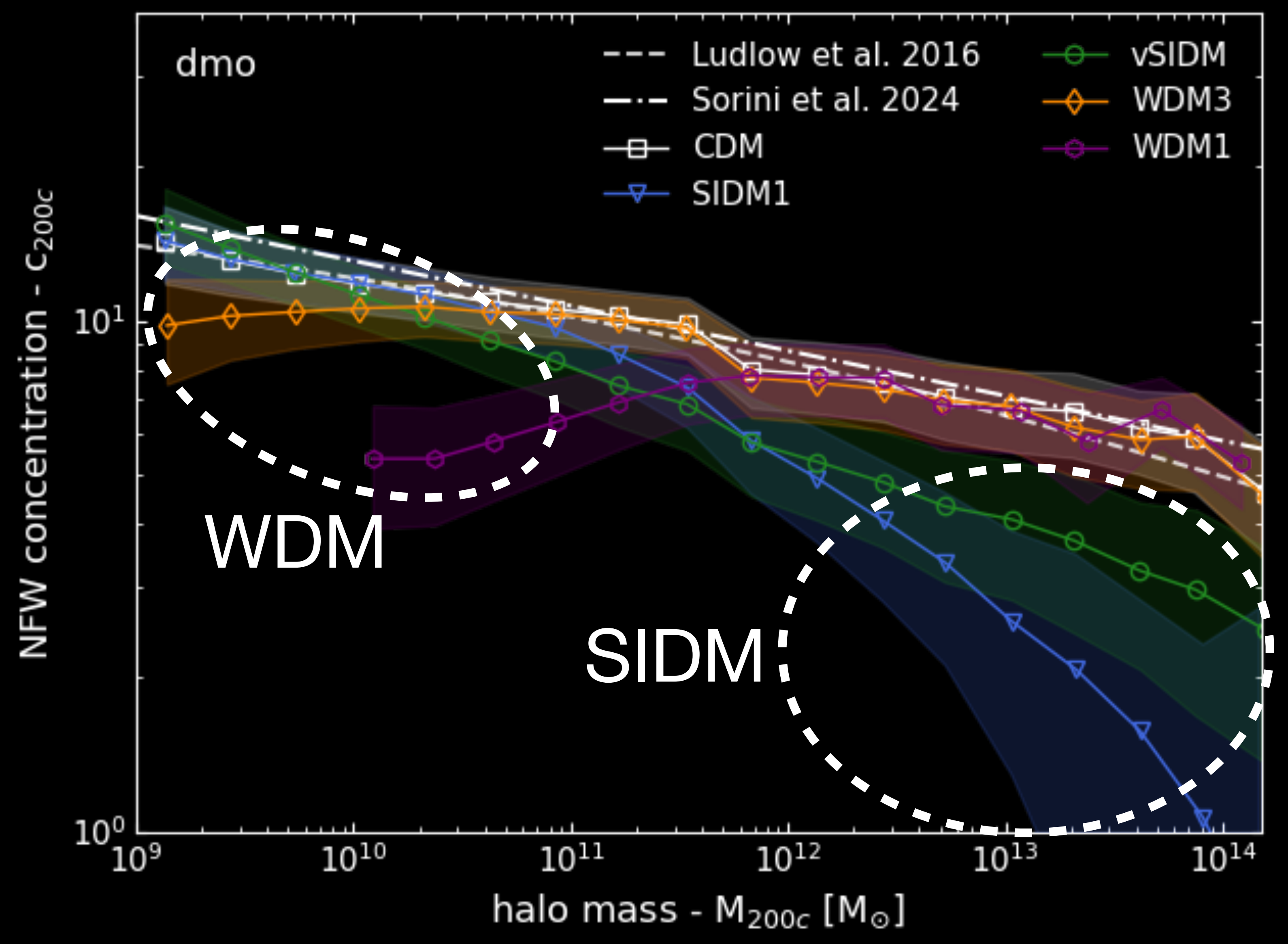


➡ <u>in CDM</u>: structure of haloes well described by the NFW profile



(*Vogelsberger et al. 2016*)

➡ CDM: low mass haloes are more concentrated

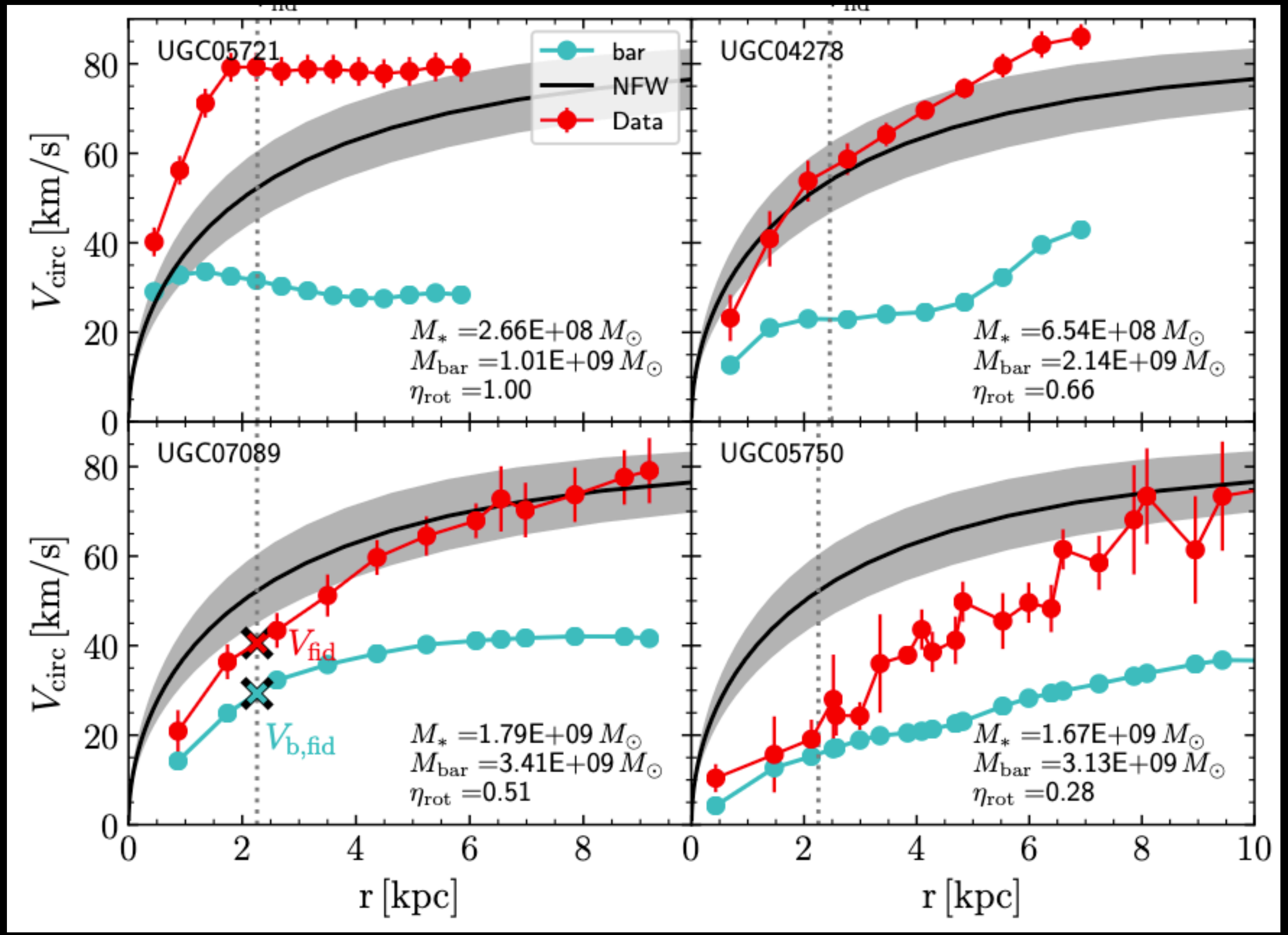


(*Despali et al. 2025*)

PROBES OF DARK MATTER

Santos-Santos et al. (2020)

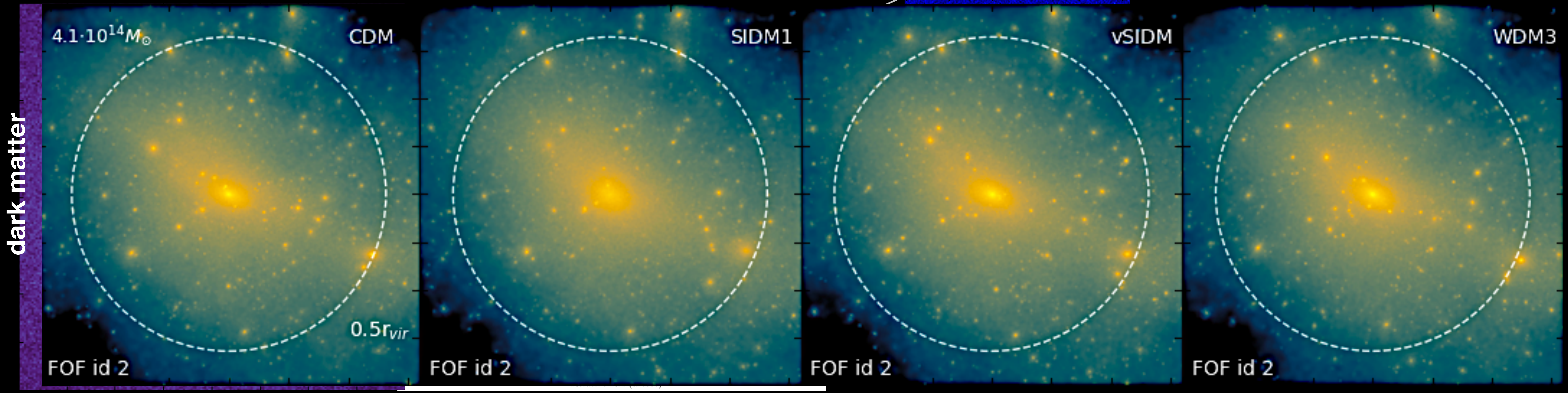
- This topic is transversal to RSN2 (e.g. stellar streams, probing hierarchical structure formation in the MW, globular clusters as tracers of early DM subhalos, etc) and RSN4 (direct and indirect detection, gravitation) → talk by C. Spingola at RSN4.
- How to measure the DM distributions in galaxies and clusters?
  - Galaxy and clusters internal dynamics: dwarf spheroidal galaxies (Tortora et al.@Capodimonte) , but also late type galaxies (e.g. GALDYN project, funded by MUR via FIS2 grant, PI: Lelli, to test DM vs modified gravity); Biviano et al.@Trieste
  - X-ray, SZ modeling: fitting temperature, surface brightness, pressure profiles of galaxy clusters assuming hydrostatic equilibrium (Ettori, Ghirardini, et al.@Bologna OAS, Gastaldello, Molendi et al.@Milano, Tozzi et al.@Arcetri)
  - Gravitational lensing: weak and strong lensing mass mapping in clusters; gravitational imaging, flux ratio anomalies (e.g., DARKER project, also funded by MUR via FIS2 grant; PI: Spingola)



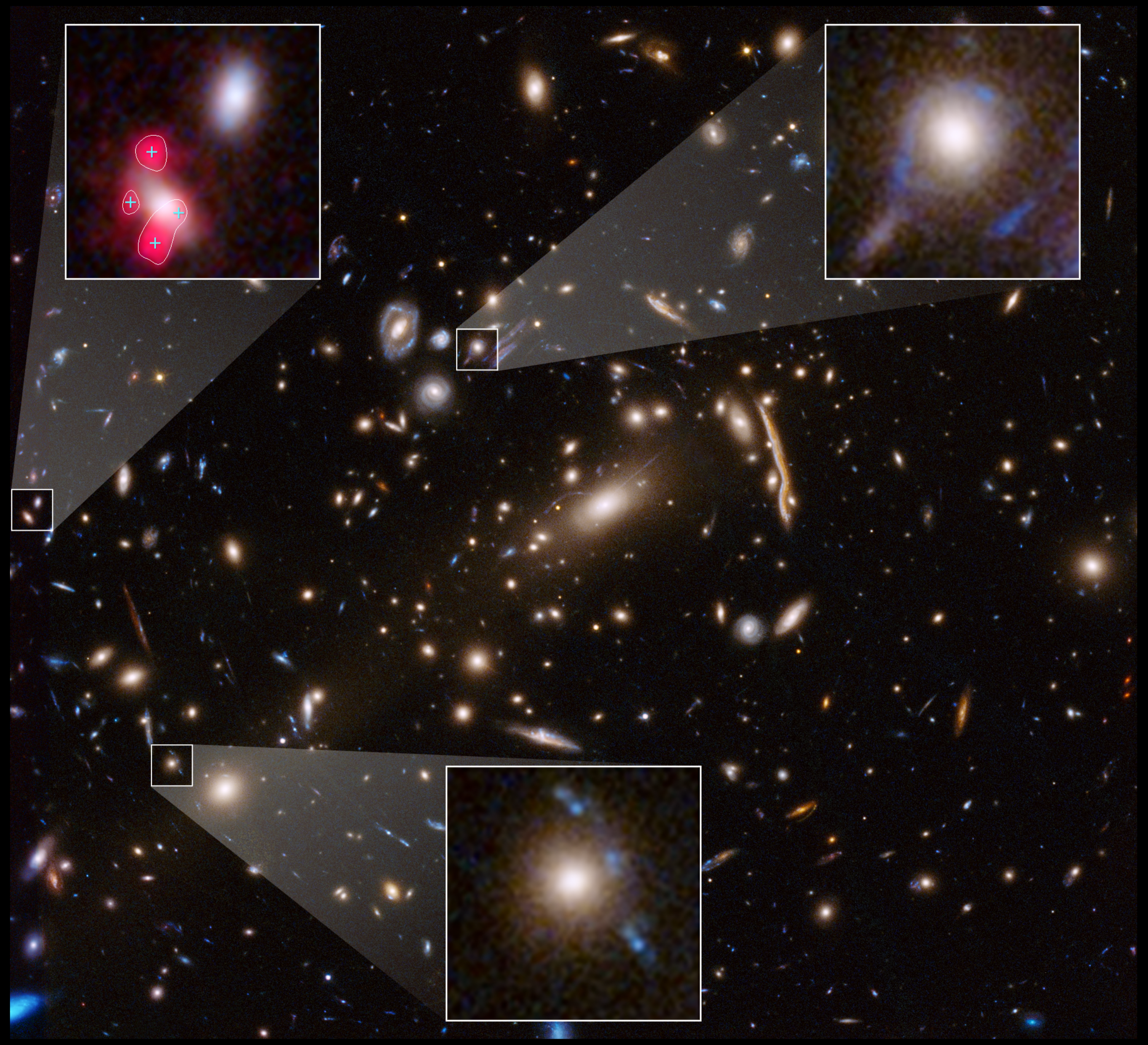
A diversity problem from rotation curves of dwarf spheroidal galaxies?

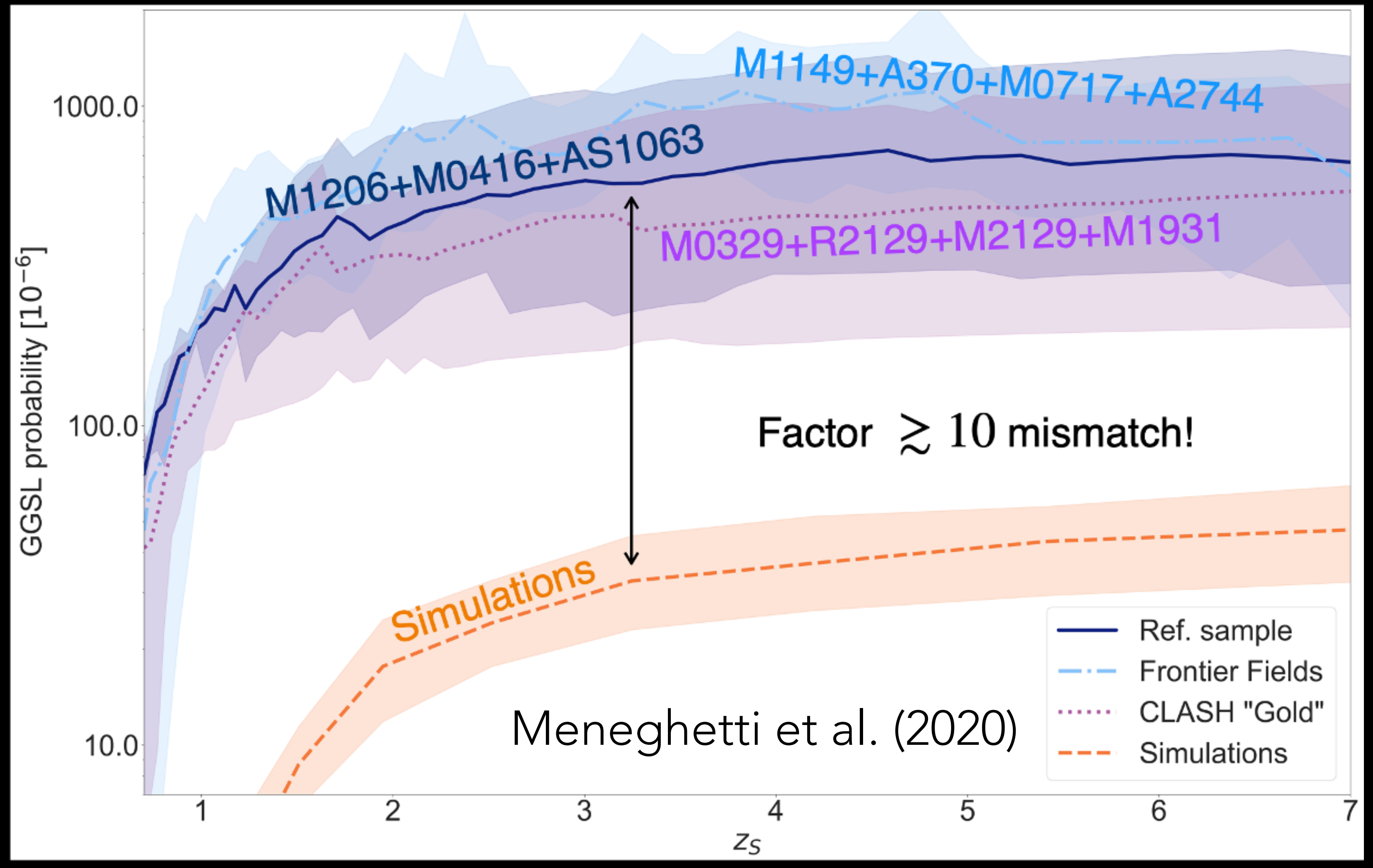
In LCDM, galaxies with similar "baryonic" (visible) properties should be embedded in similar dark matter halos, leading to similar internal dynamics.

Powell et al. (2025), Nat. Ast., McKean et al. (2025), Vegetti et al. (2026), Nat. Ast. With substantial contribution from C. Spingola & G. Despali



Dark halo perturbation? Ultra-compact dwarf? Globular cluster?

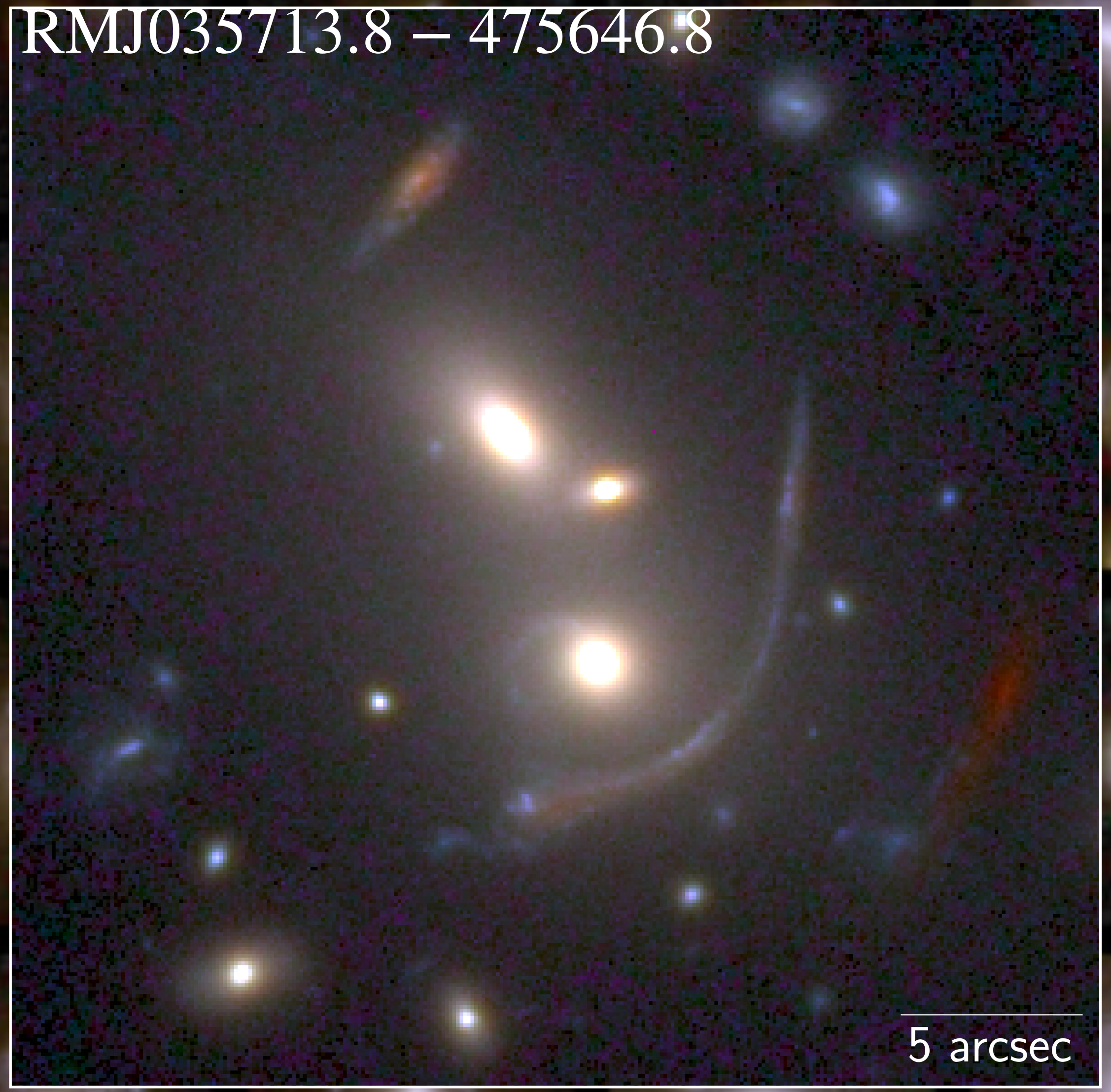


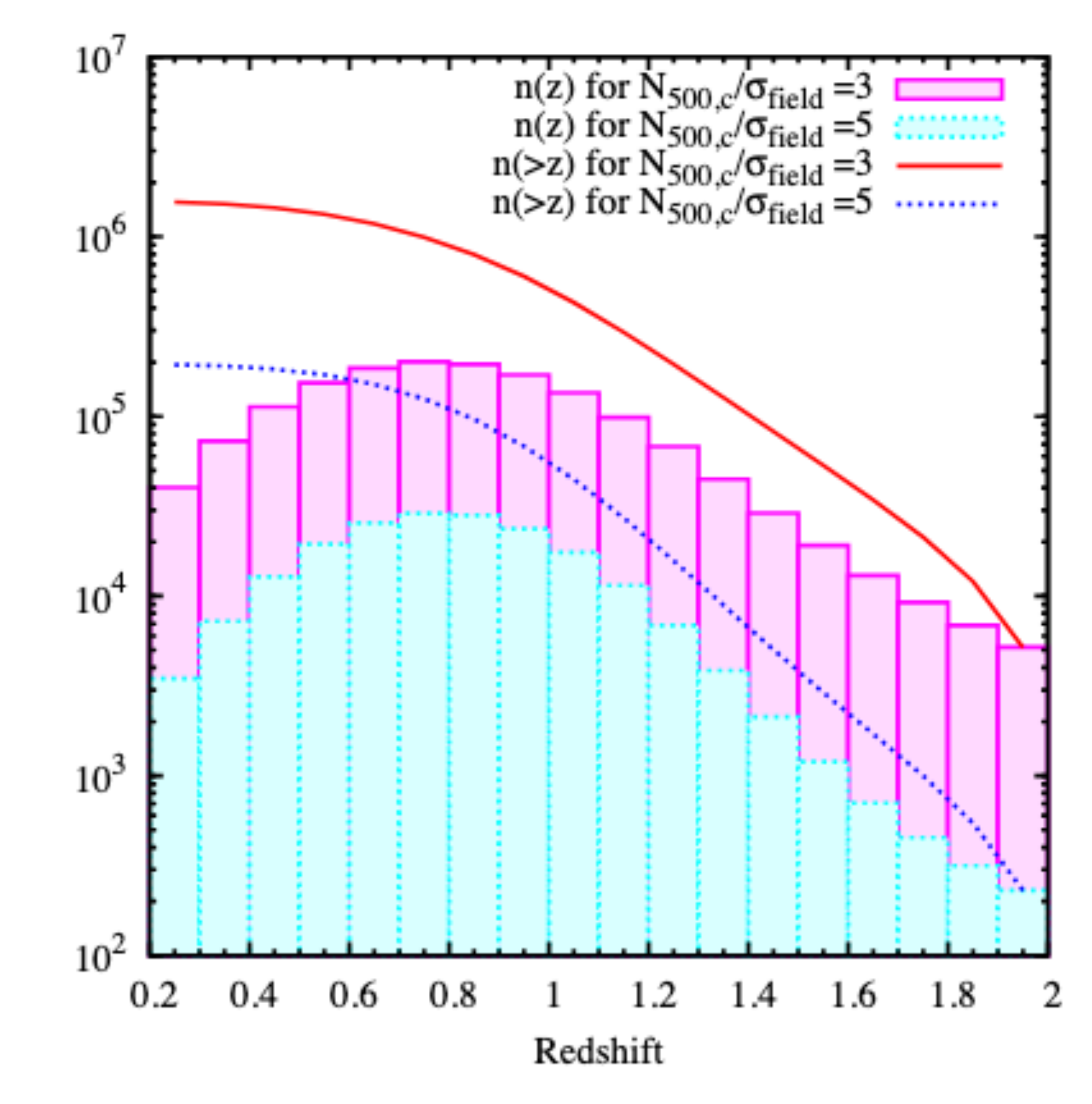


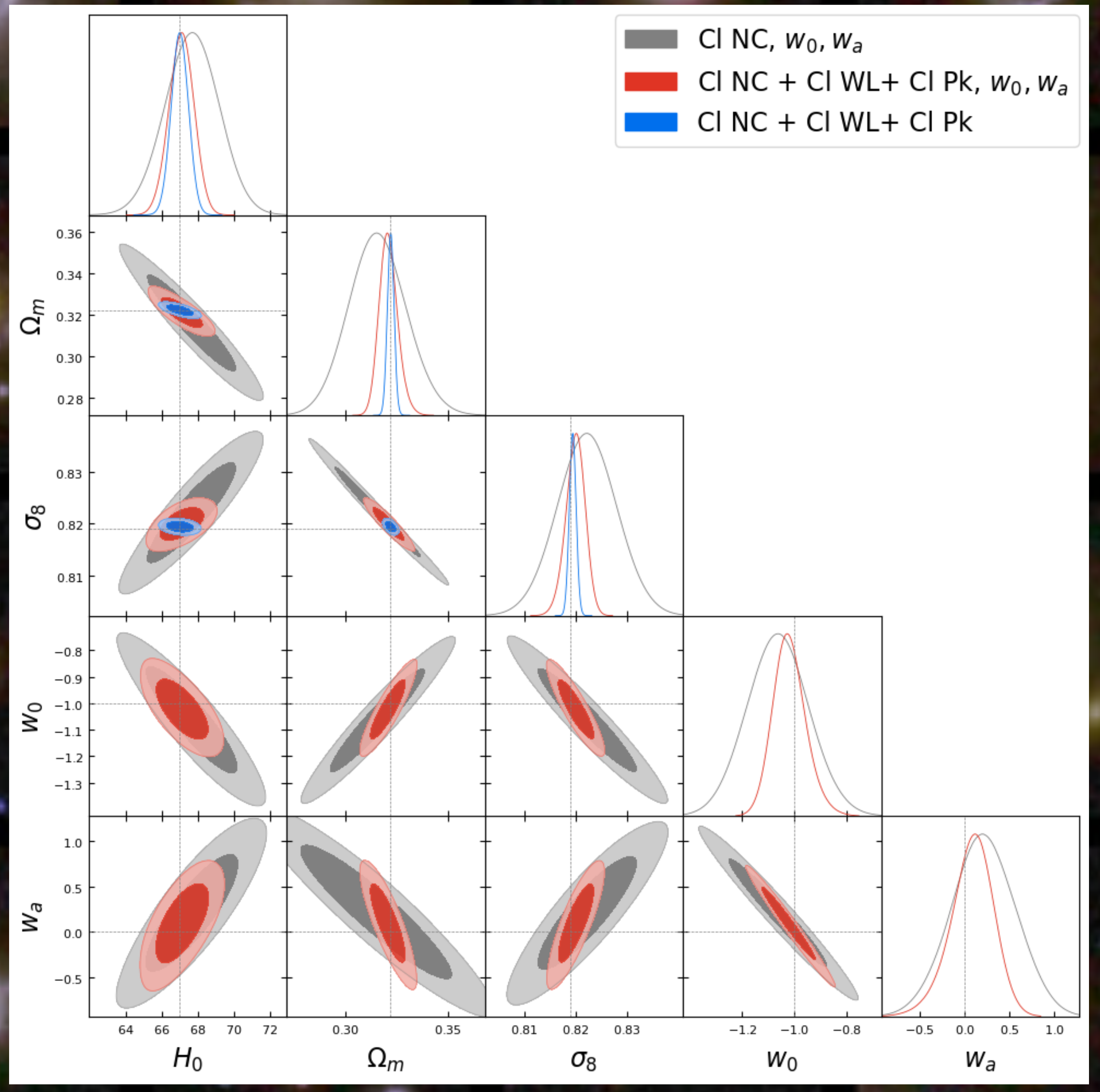
Hydro-sims by Trieste's group

Needed: **high-resolution cosmological hydro simulations**, also in alternative DM models (WDM, SIDM)! E.g. AIDA-TNG (Despali et al. 2025), DIANOGA-SIDM (Ragagnin et al. 2024)

WHAT NEXT?







An RSN1 opportunity:

- Galaxies and clusters are central to all major tensions
- We will have access to an impressive amount of data:
  - **Euclid:** Among 241 members of RSN1, 118 are also members of the Euclid Consortium (total INAF Euclid members=298)
  - **Rubin-LSST:** at least 5 in-kind contributions (Cantiello, Grillo, Rosati, Botticella, Saro,…)
  - In the future: E-ELT, SKA, Athena
- Challenges: follow-up observations? better understanding of systematics? Automatizing workflows? More simulations?
- Strong INAF positioning:
  - Leading roles in Euclid, Rubin, SKA
  - Expertise spanning theory, simulations, observations
- **We can play a crucial role in assessing whether LCDM remains a consistent description of the universe or whether a paradigm shift is needed!**

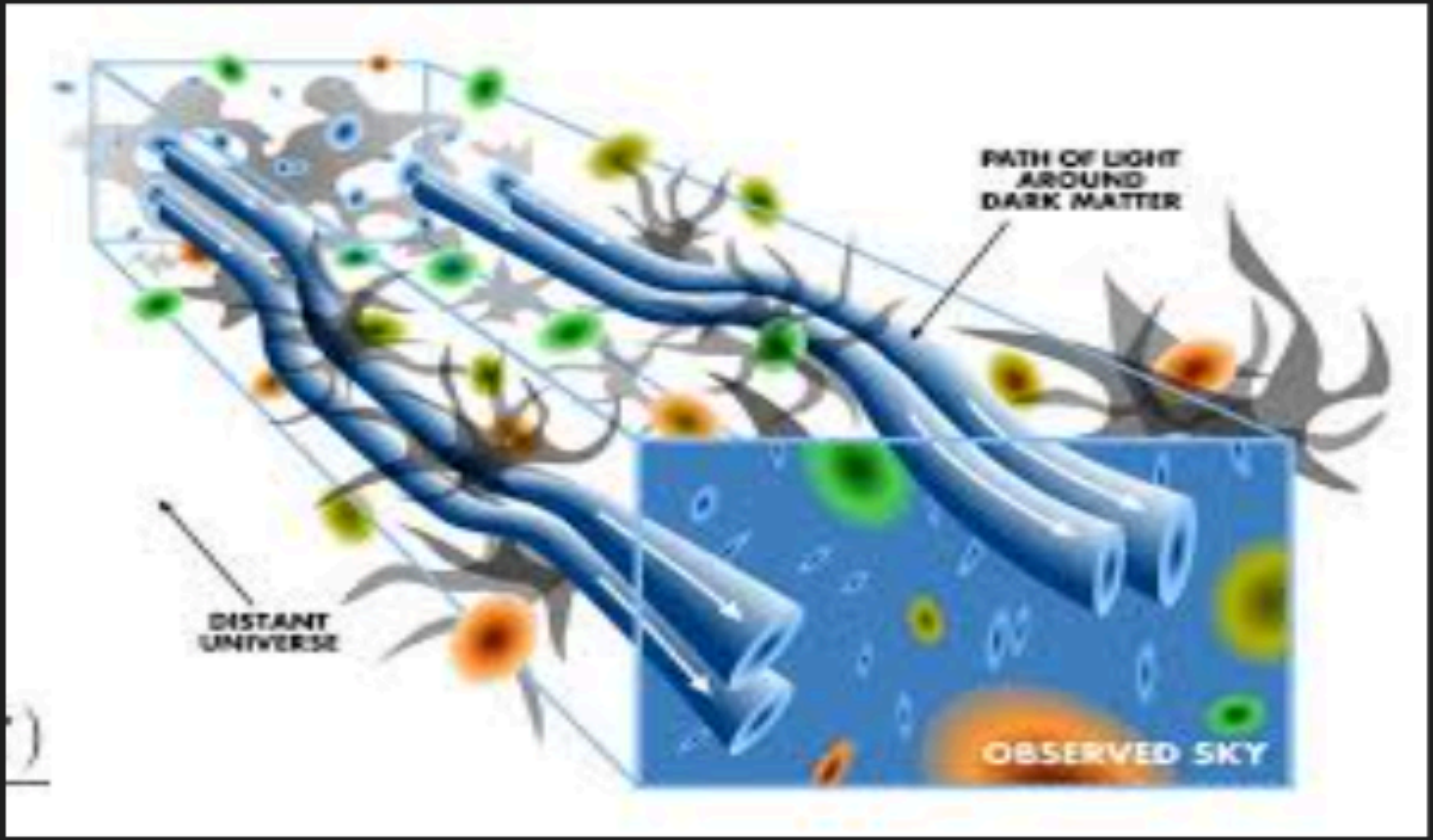
VINCENZO F. CARDONE (INAF-OA ROMA)

THE COSMOLOGICAL MODEL, DARK MATTER AND DARK ENERGY

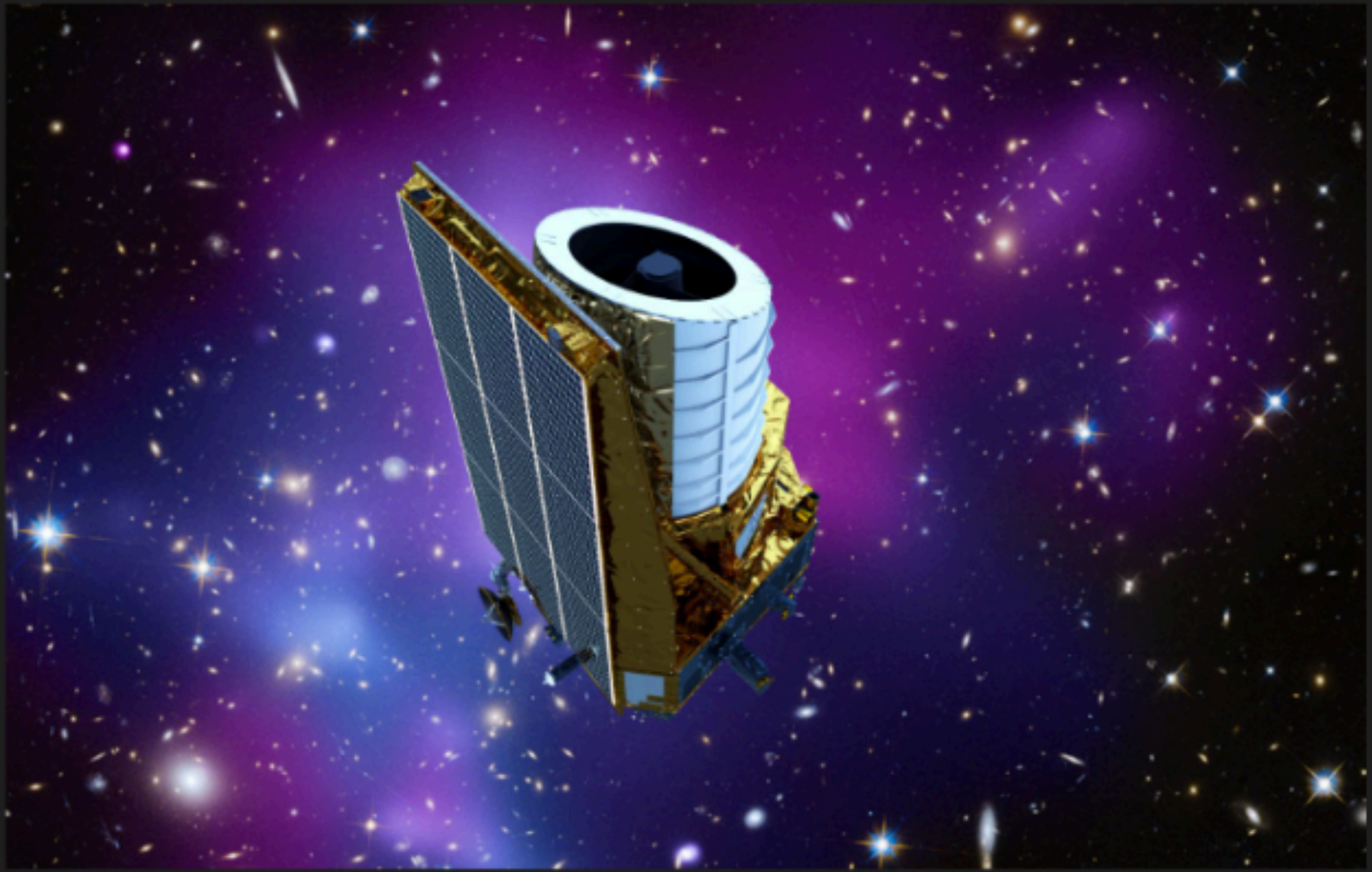
DARK ENERGY OR MODIFIED GRAVITY? DIFFERENT SCALES FOR ONE QUESTION

Galaxy Surveys vs Dark Energy

- ***Cosmic Shear***
  - shape measurement
  - light propagation
  - growth of structures
- ***Galaxy clustering***
  - overdensity field
  - photometric
    - 2D clustering
    - galaxy bias
    - growth of structures
  - spectroscopic
    - 3D clustering
    - BAO



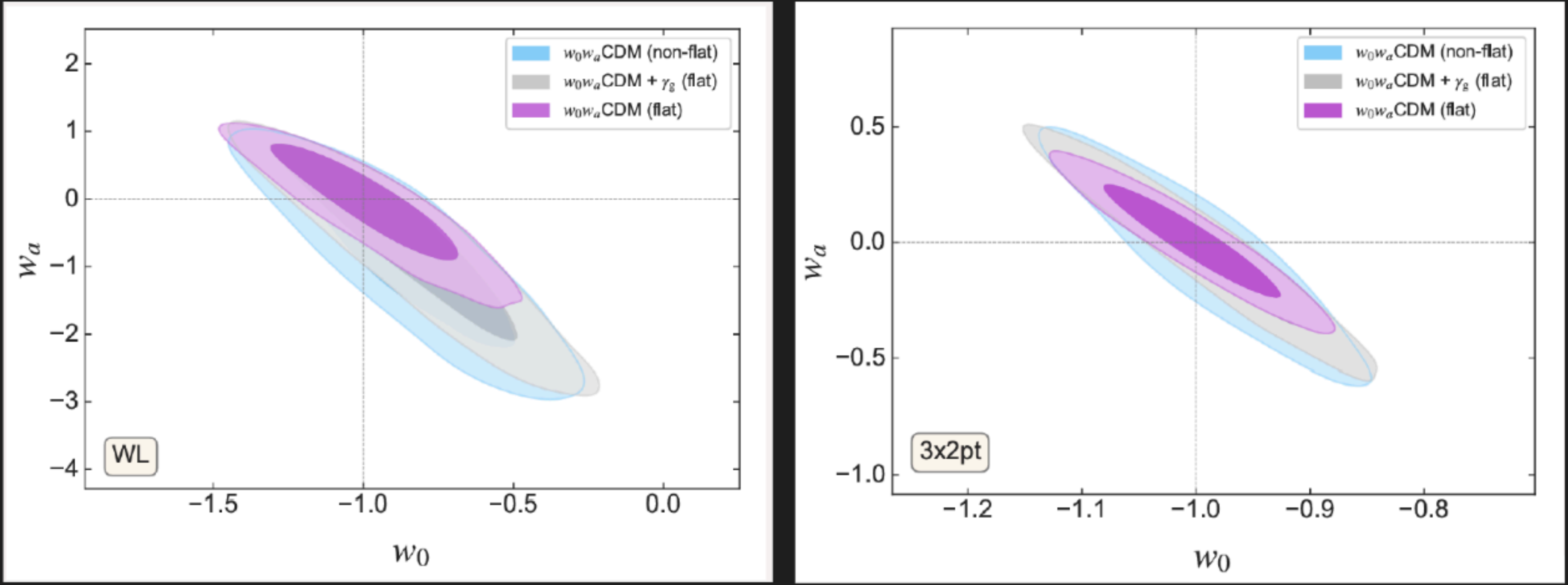
Looking into the Dark Universe: Euclid and LSST



- space based survey
- photometry and spectroscopy
- cosmic shear and 2D photo clustering
- BAO and 3D power spectra

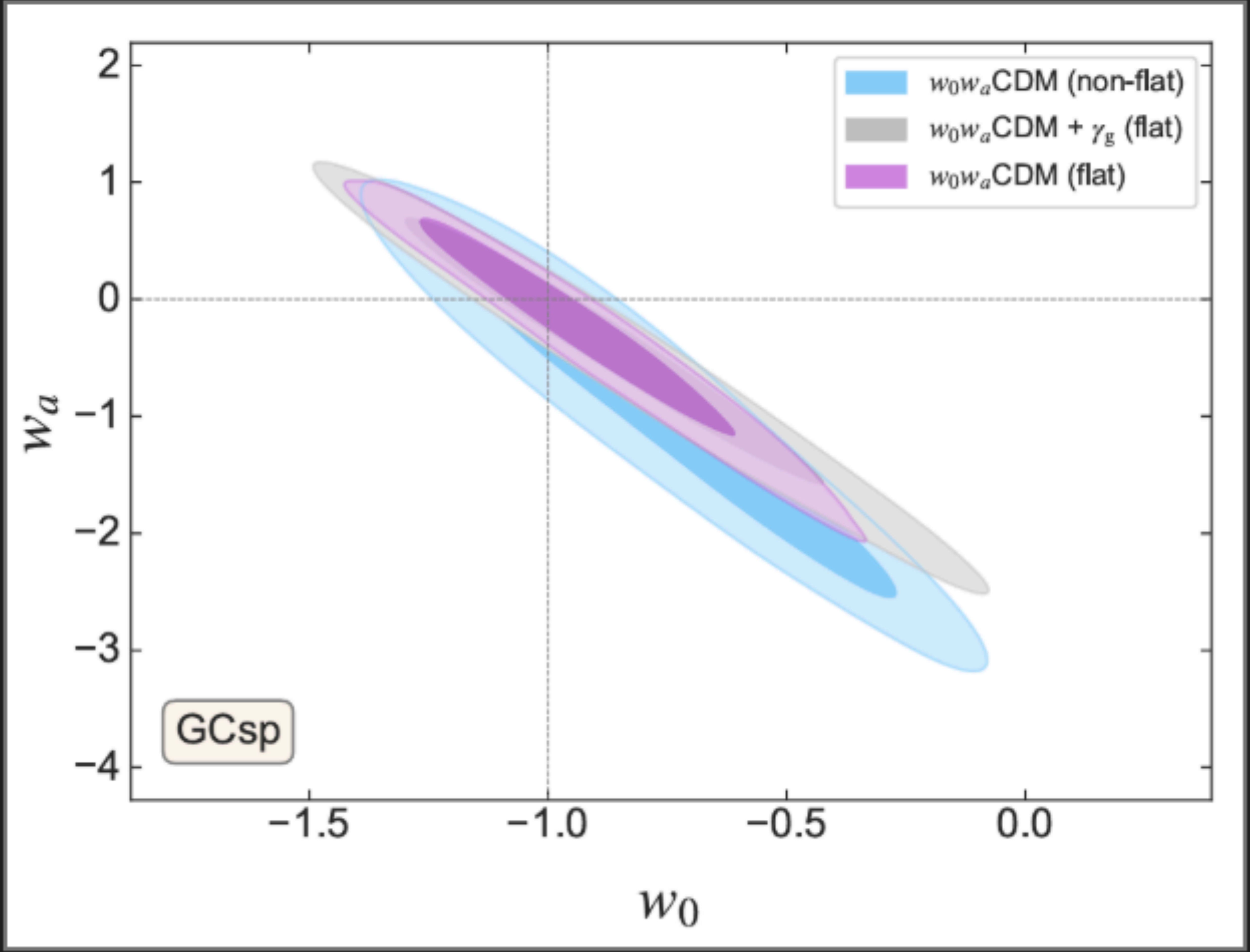
- ground based survey
- photometry and time domain
- cosmic shear and 2D photo clustering
- SNeIa and transients

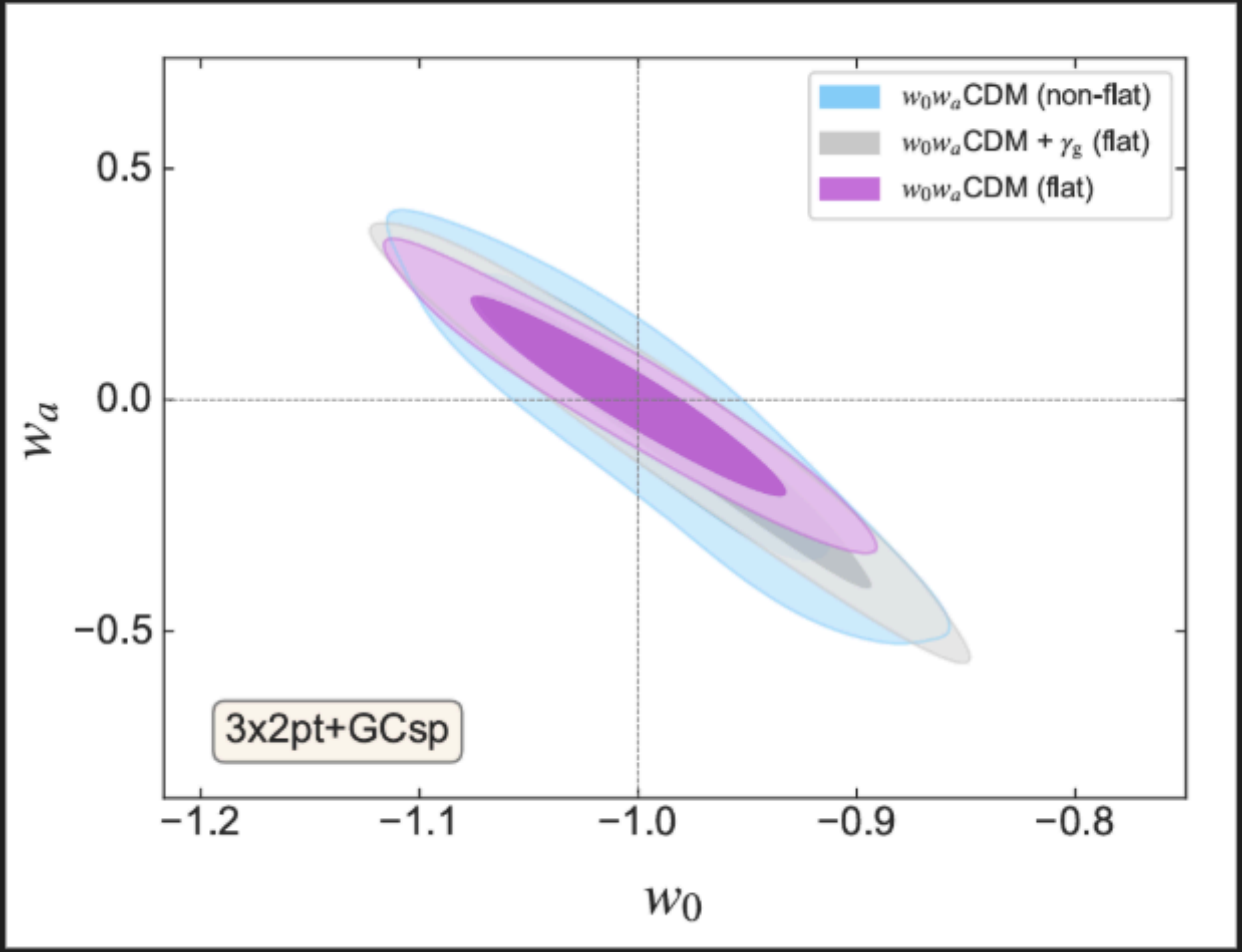
Constraining Dark Energy with Euclid Photometry



- cosmic shear only vs 3x2pt (cosmic shear + photo clustering + galaxy galaxy lensing)
- *the total is more than the sum of the parts*

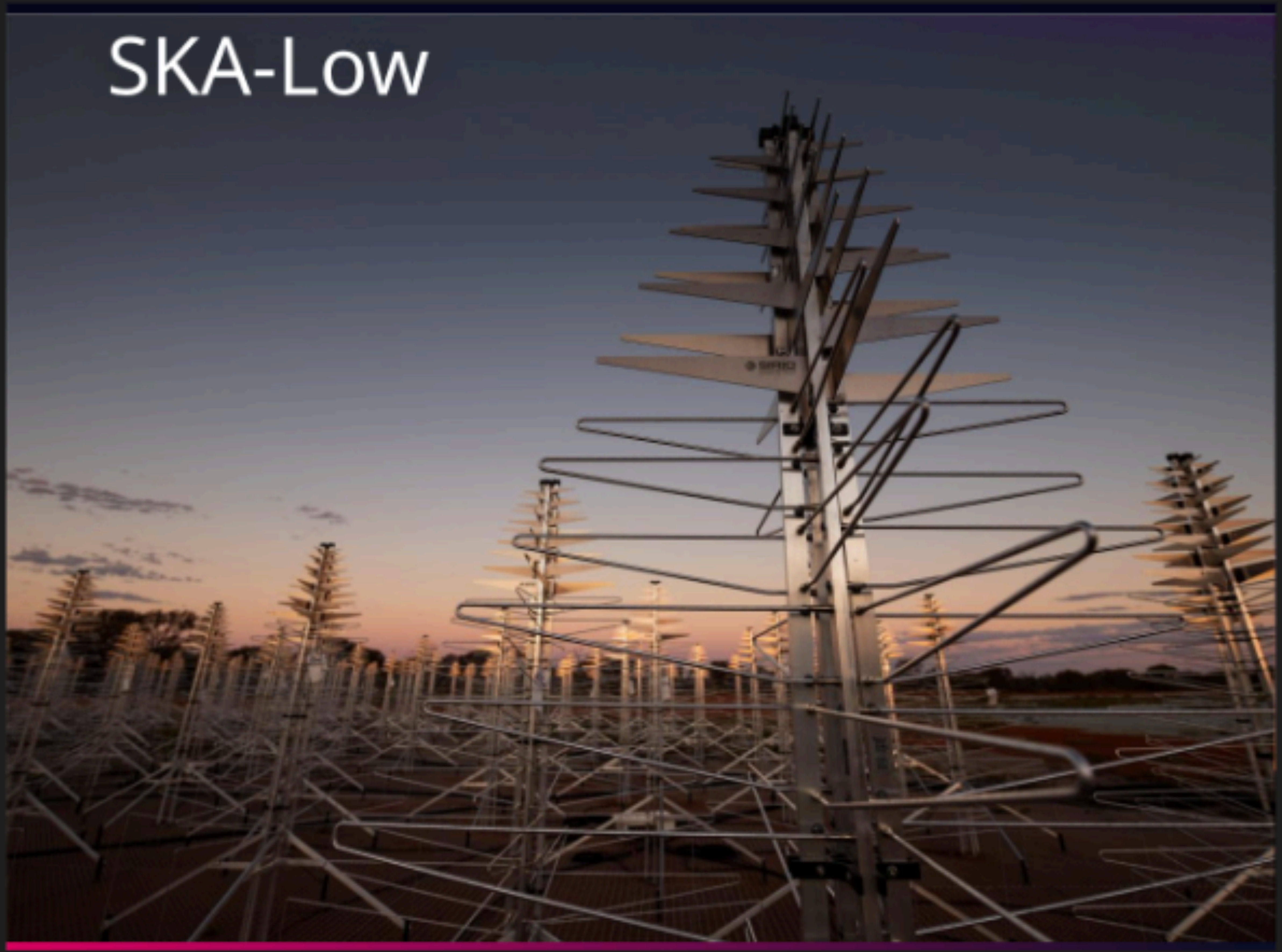
Constraining Dark Energy with Euclid Full Dataset





- 3D clustering only vs 3x2pt + GCsp (full set of Euclid main probes)
- *Figure of Merit: 21 for WL, 35 for GCsp, 380 for 3x2pt, 500 for 3x2pt + GCsp*

Cosmology Beyond the Optical: SKAO



- 512 stations with 256 antennas each
- 2m tall over a central 1 km core
- spiral arms structure 74 km large
- 50 - 350 MHz

- 197 15m parabolic dishes
- 1 km core with MeerKat 13.5 m dishes
- spiral arms structure 150 km large
- 350 MHz - 15.4 GHz (goal 24 GHz)

Cosmology in the Radio Domain: Surveys and Obs Probes

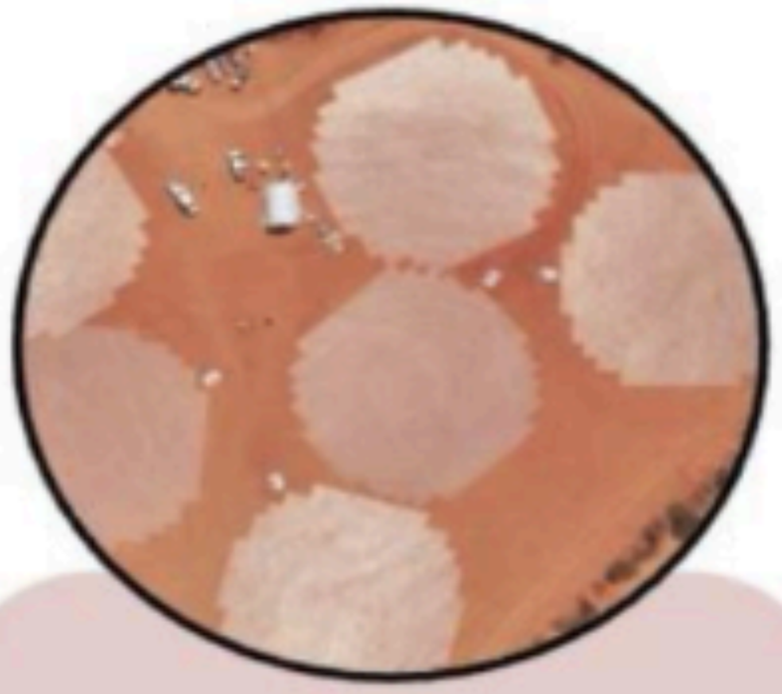
- HI line (spectroscopic - like)
- Radio continuum (photometric - like)
- HI intensity mapping

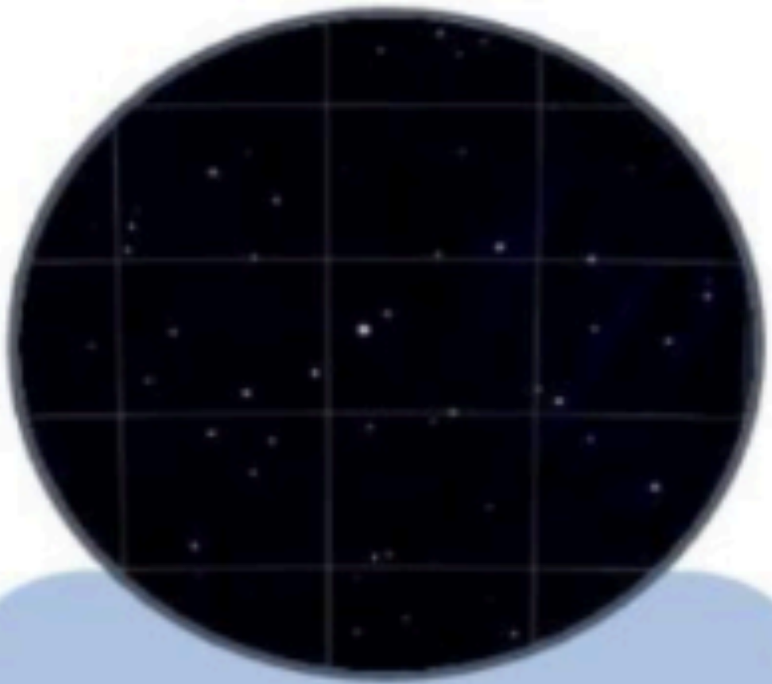
- 3D power spectrum and BAO
- 3x2pt at radio wavelengths
- constraining DE, MG and PNG

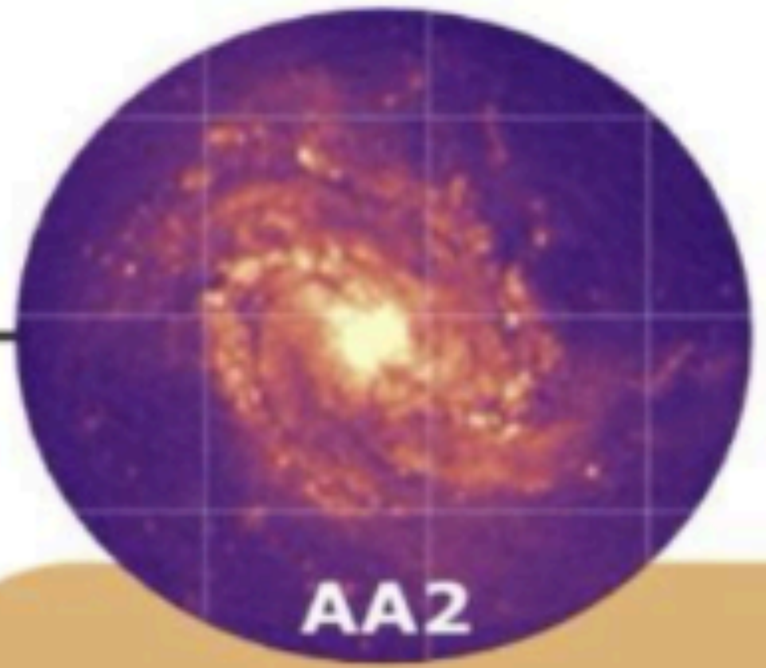
Evolution of SKAO operational modes

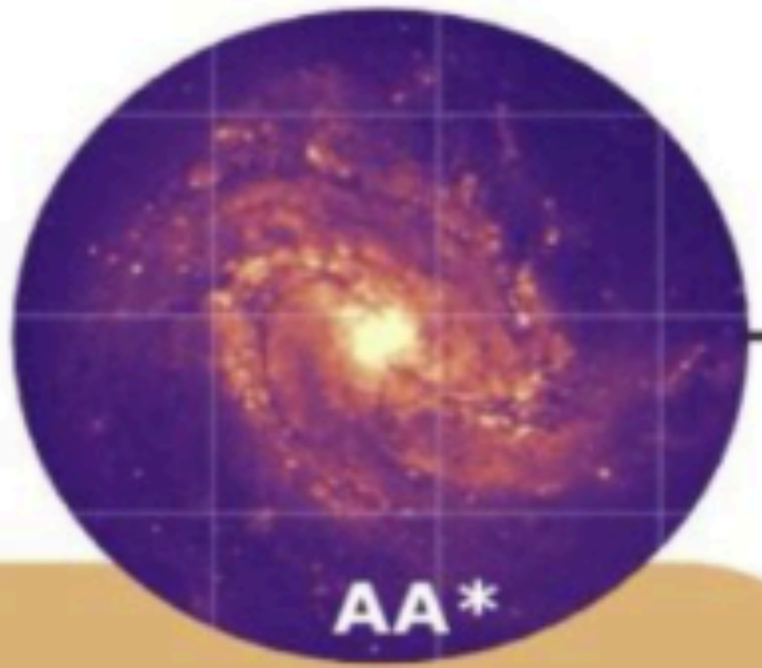
Community involvement starts

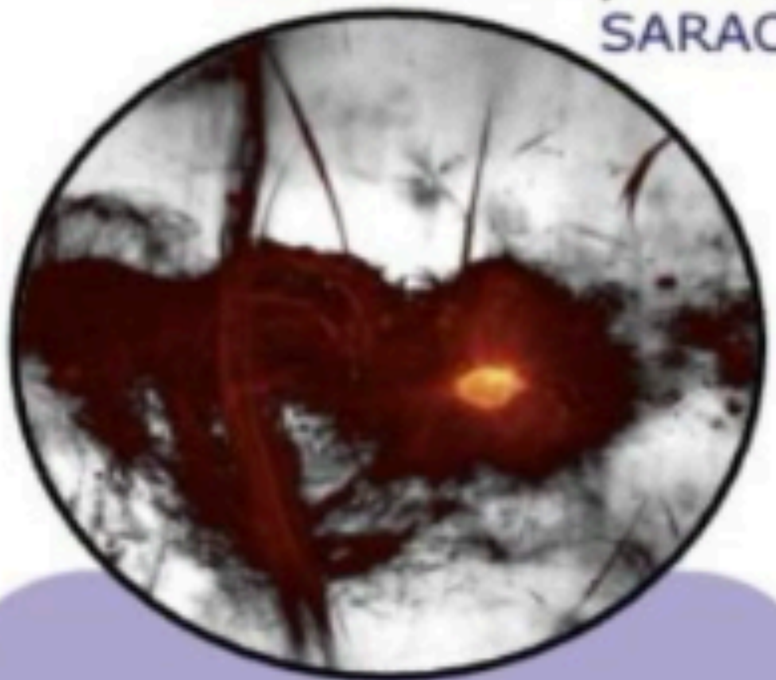
Credit: I. Heywood, SARAO











Construction

- Building antennas, dishes, roads etc!
- Followed by Assembly, Integration and Verification

Commissioning

- SKAO activity
- Collaborative across system verification and science commissioning

Science Verification

- A full dress rehearsal of the end-to-end system for every mode of operation
- Once modes and pipelines are working, the community can submit target ideas
- Data will be publicly available for scrutiny
- Build trust and fostering an early science return

Cycle 0

- Shared-risk PI projects
- SRCNet resources ready for user
- proprietary periods

Now	Now	First half 2027	First half 2029	2030
Now	Soon	First half 2029	First half 2031	2032

SKA-Low: Delivery of observing modes and ODPs to the astronomy community

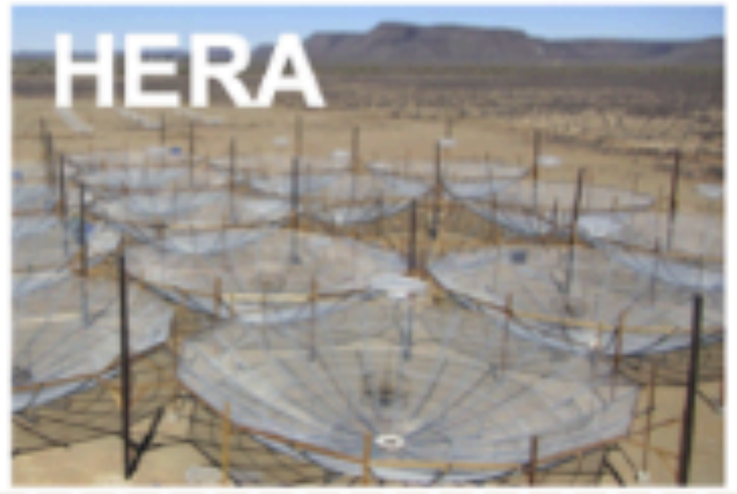
SKA-Mid: Delivery of observing modes and ODPs to the astronomy community

Towards the SKAO

[Courtesy of A. Bonaldi]

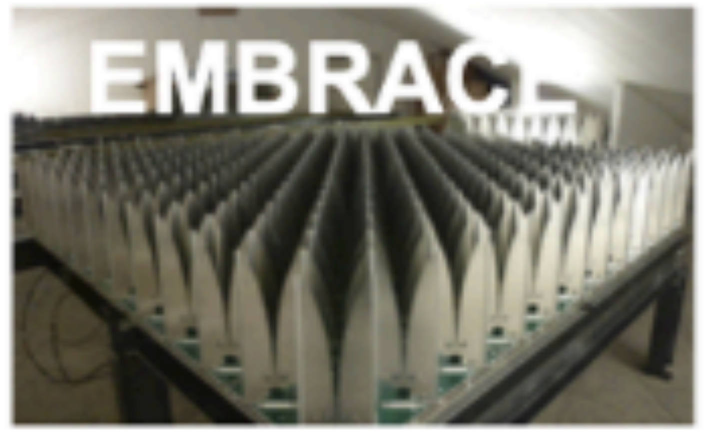
Precursors

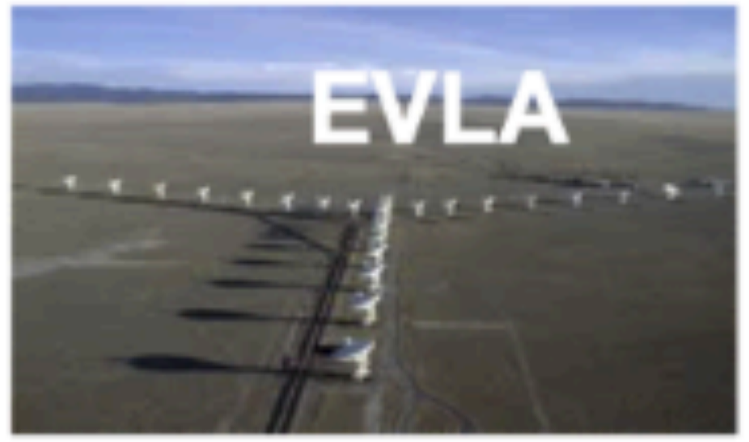
Located at future SKA sites (South Africa and Australia)

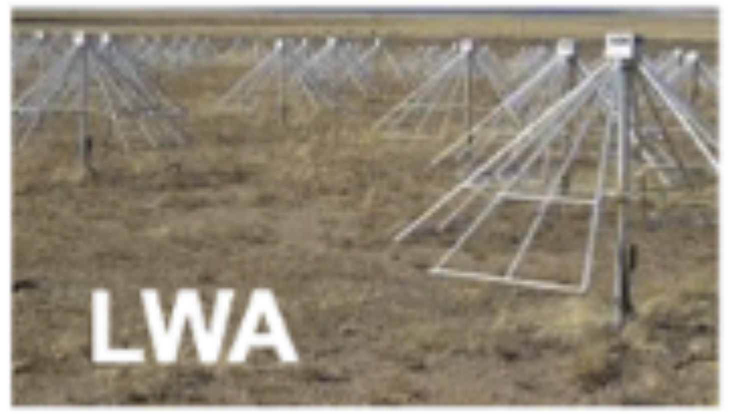


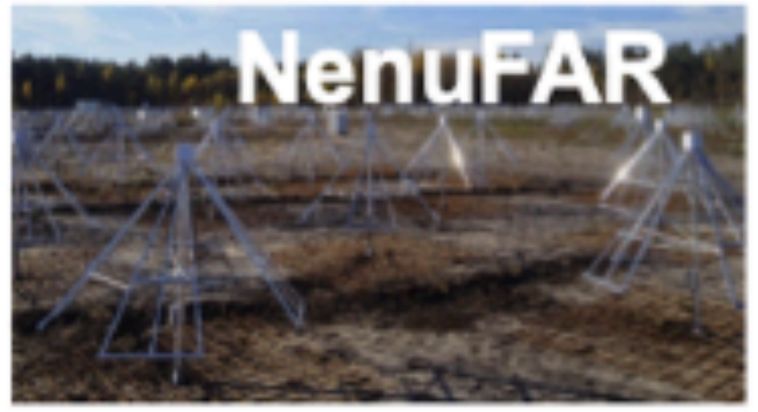
Pathfinders

Engaged in SKA related technology and science studies



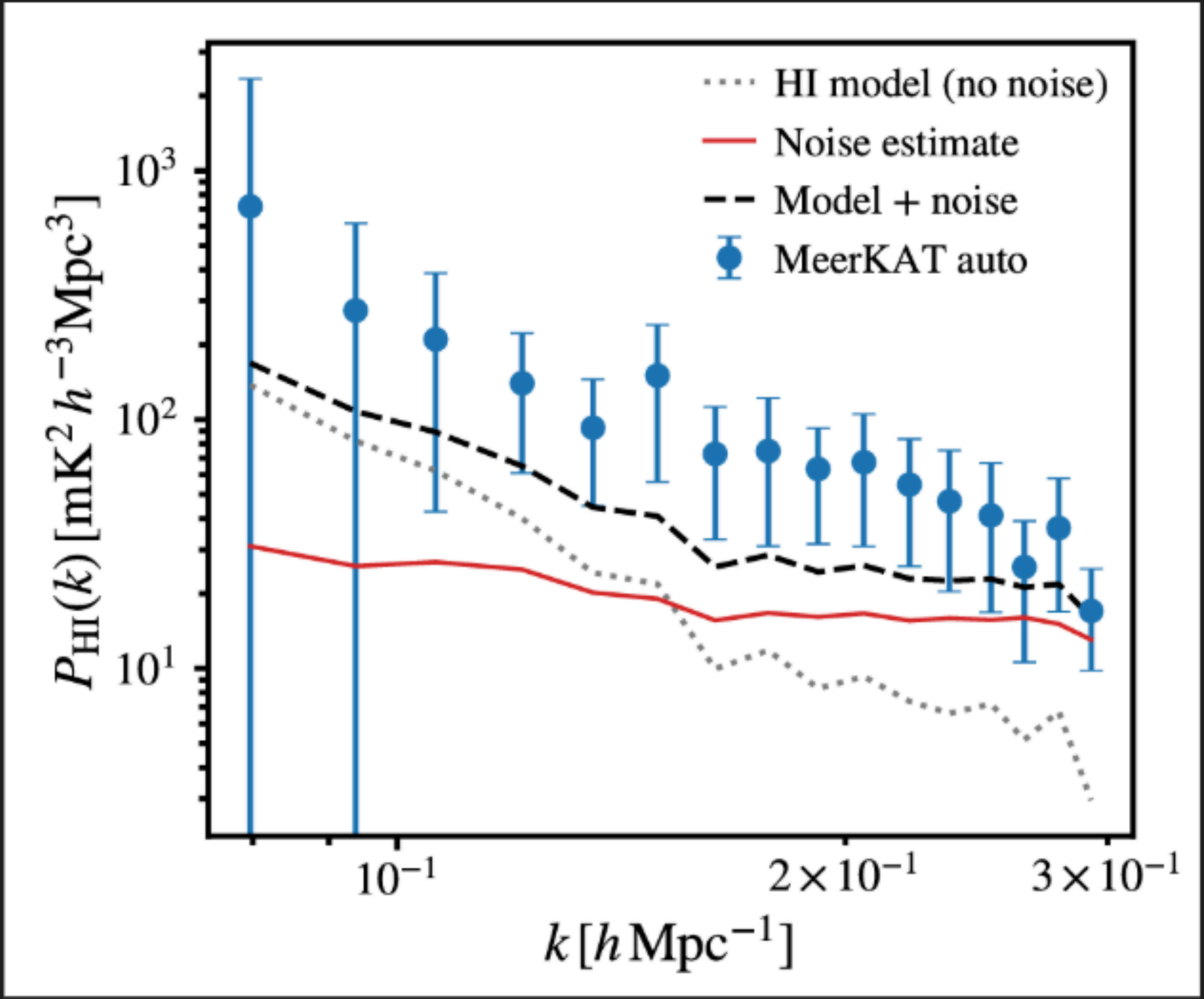


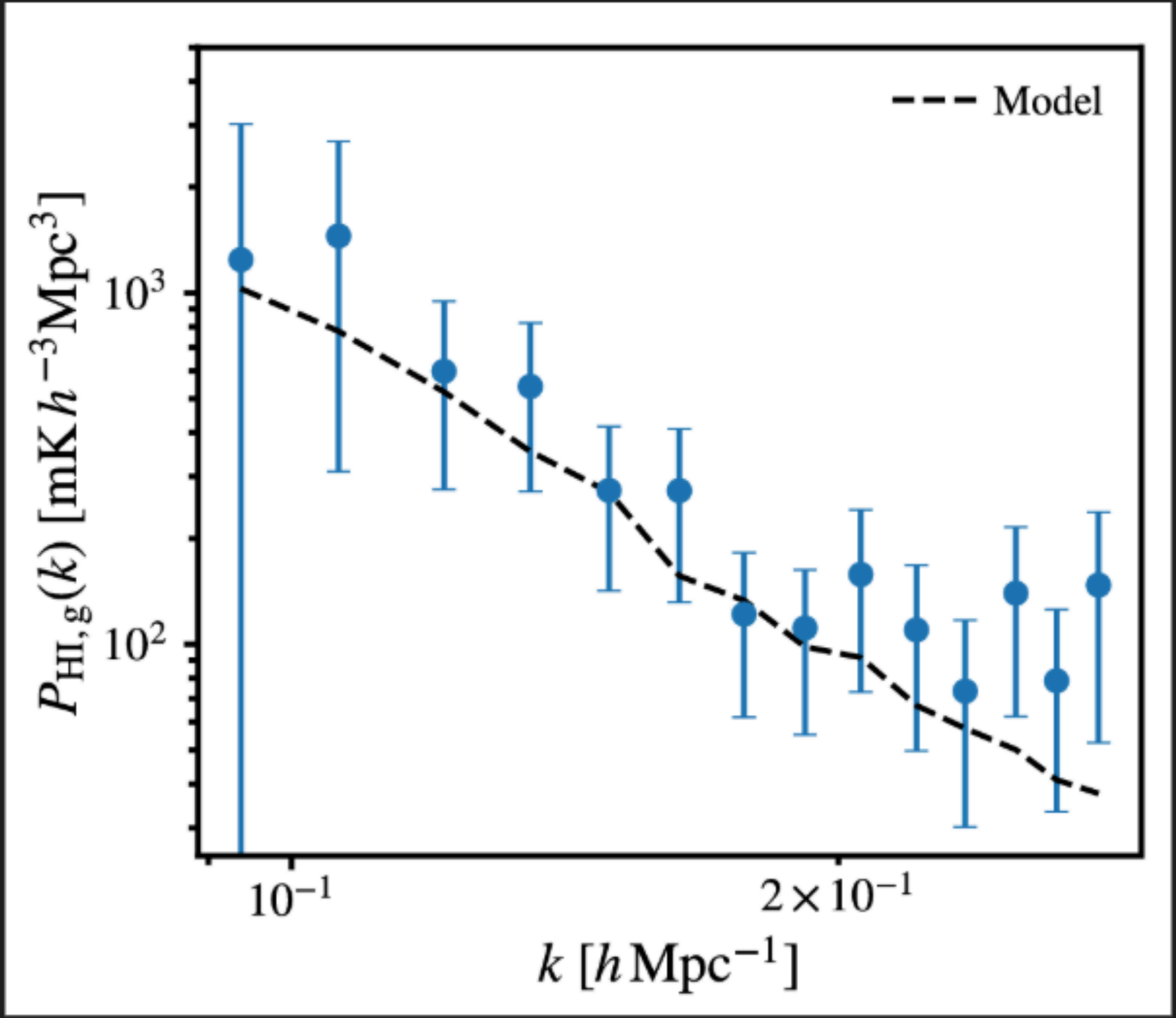




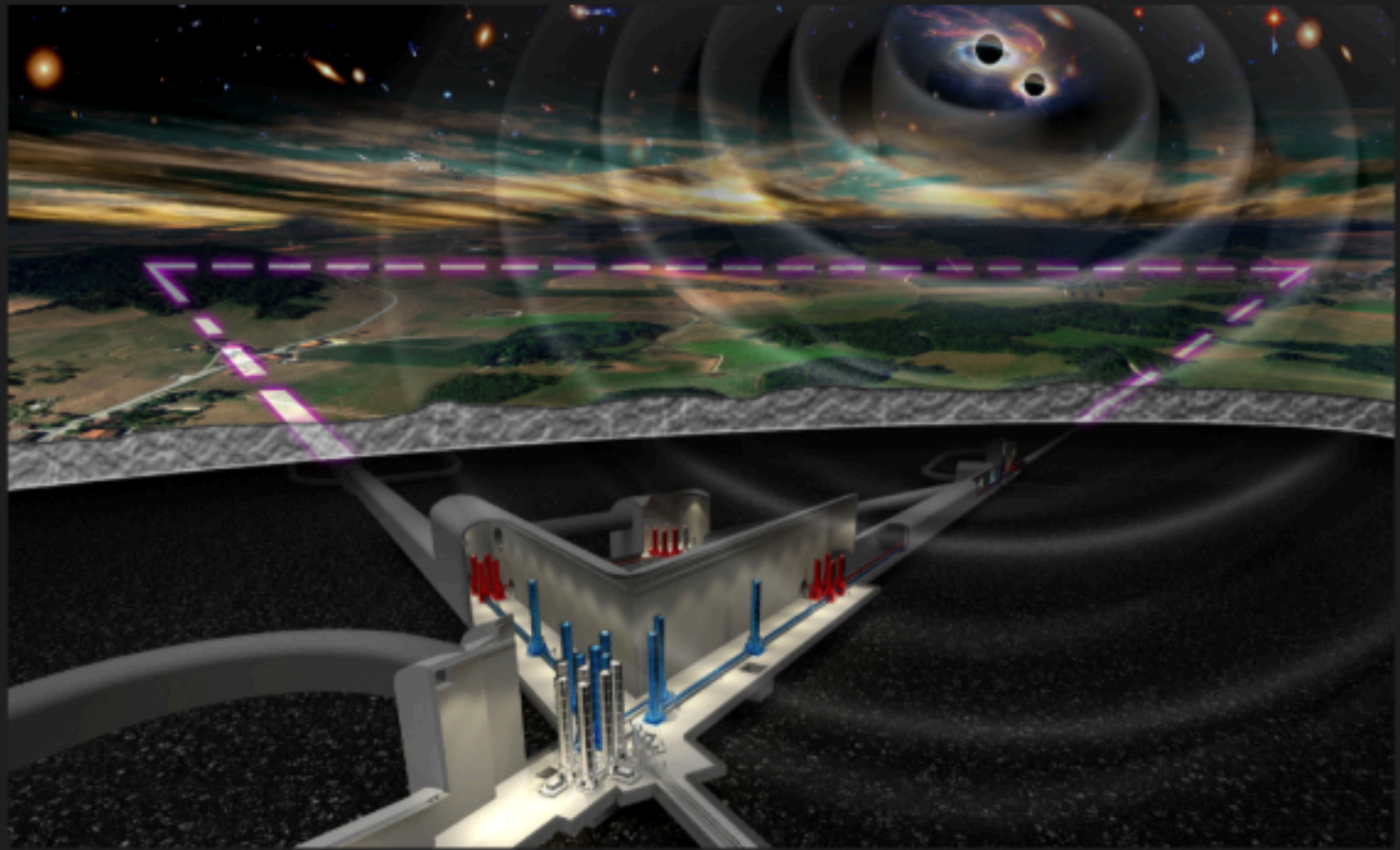
MeerKLASS

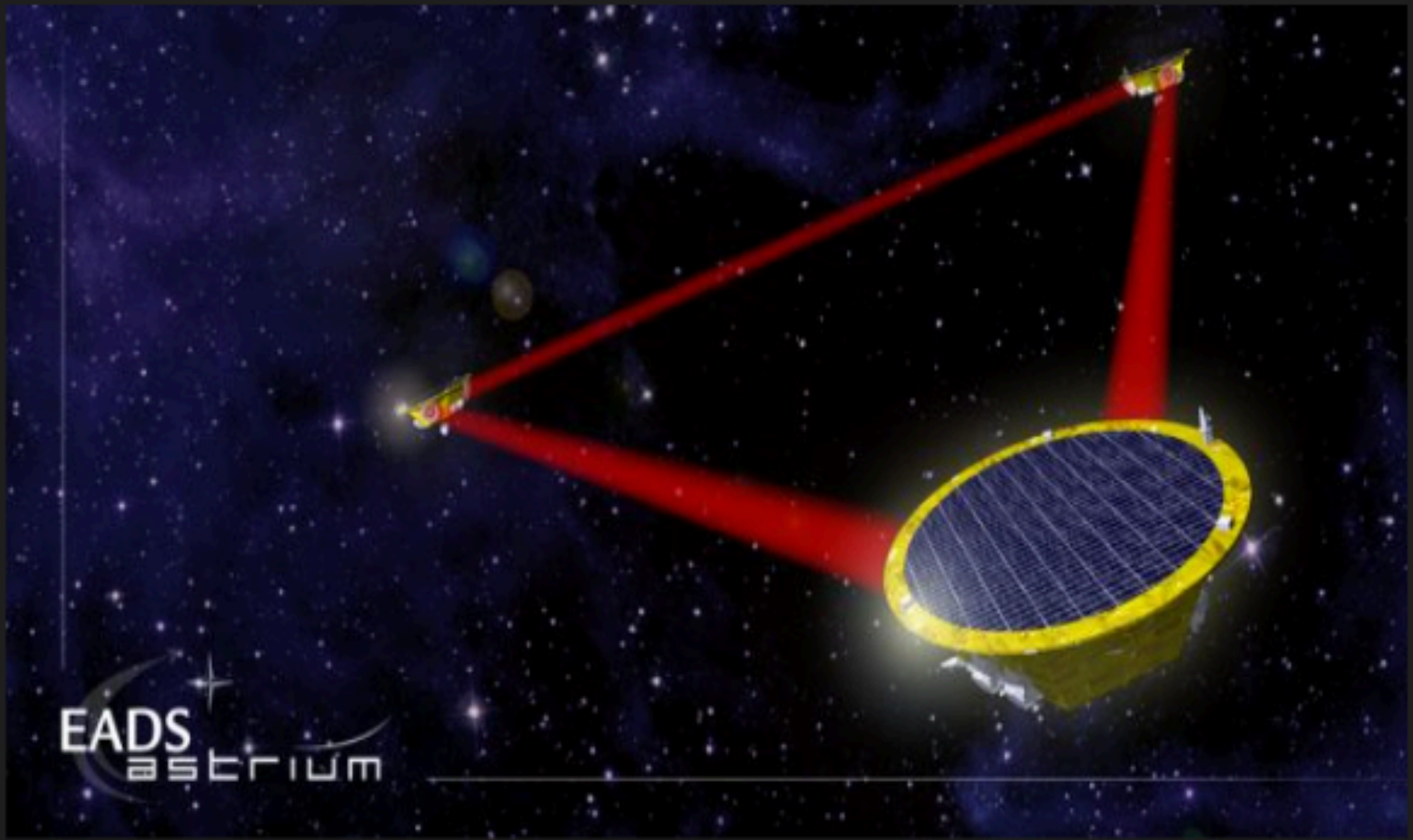
- 10000 sq deg at 580 - 1015 MHz (UHF)
- 500 sq deg at 856 - 1712 MHz (L)
- HI auto and cross spectra at z = 0.44





Cosmology in the Gravitational Waves Era





Einstein Telescope

- ground based interferometer
- planned for completion in 2035
- frequency range: 1 Hz - 10 kHz

LISA

- space based interferometer
- planned for launch in 2035
- frequency range: 0.1mHz - 1 Hz

Cosmology with Gravitational Waves

Stochastic GW Background

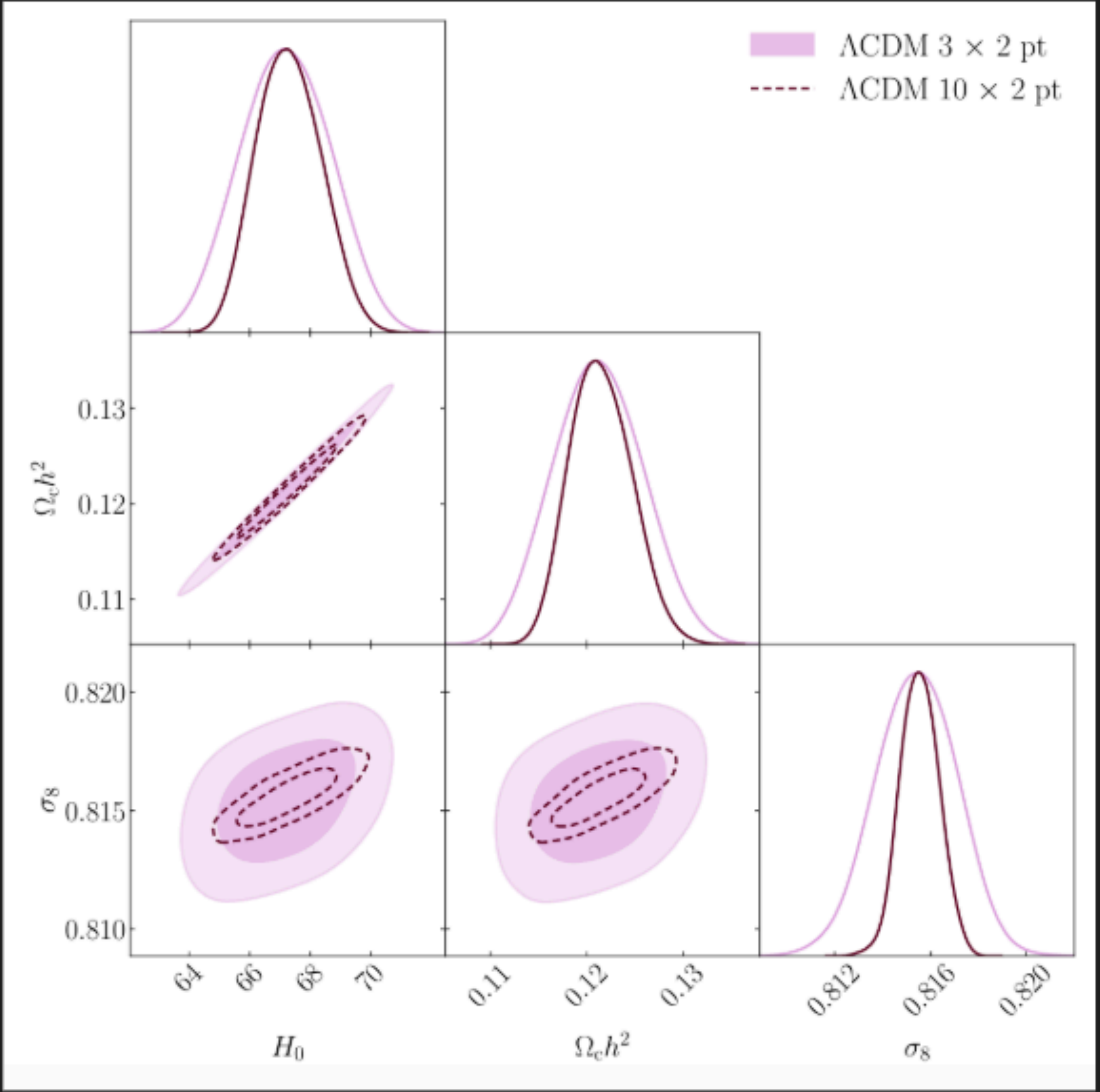
- anisotropy
- polarization

Early Universe

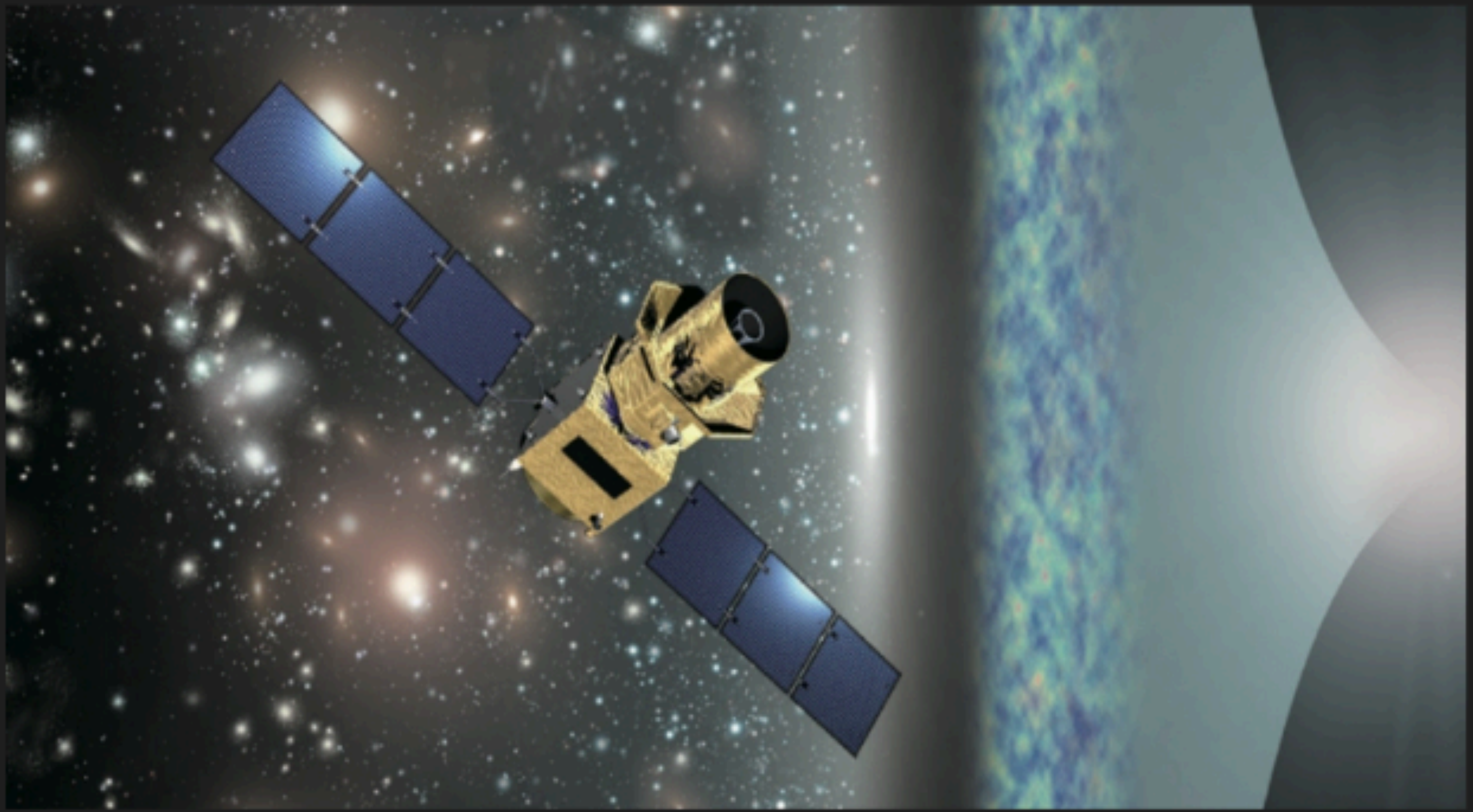
- inflation / domain walls
- primordial black holes

Late Universe and LSS

- GW propagation
- weak lensing of GW
- GW counts vs halo abundance
- cross correlation with other probes



(Old School yet Evergreen) Cosmology: CMB

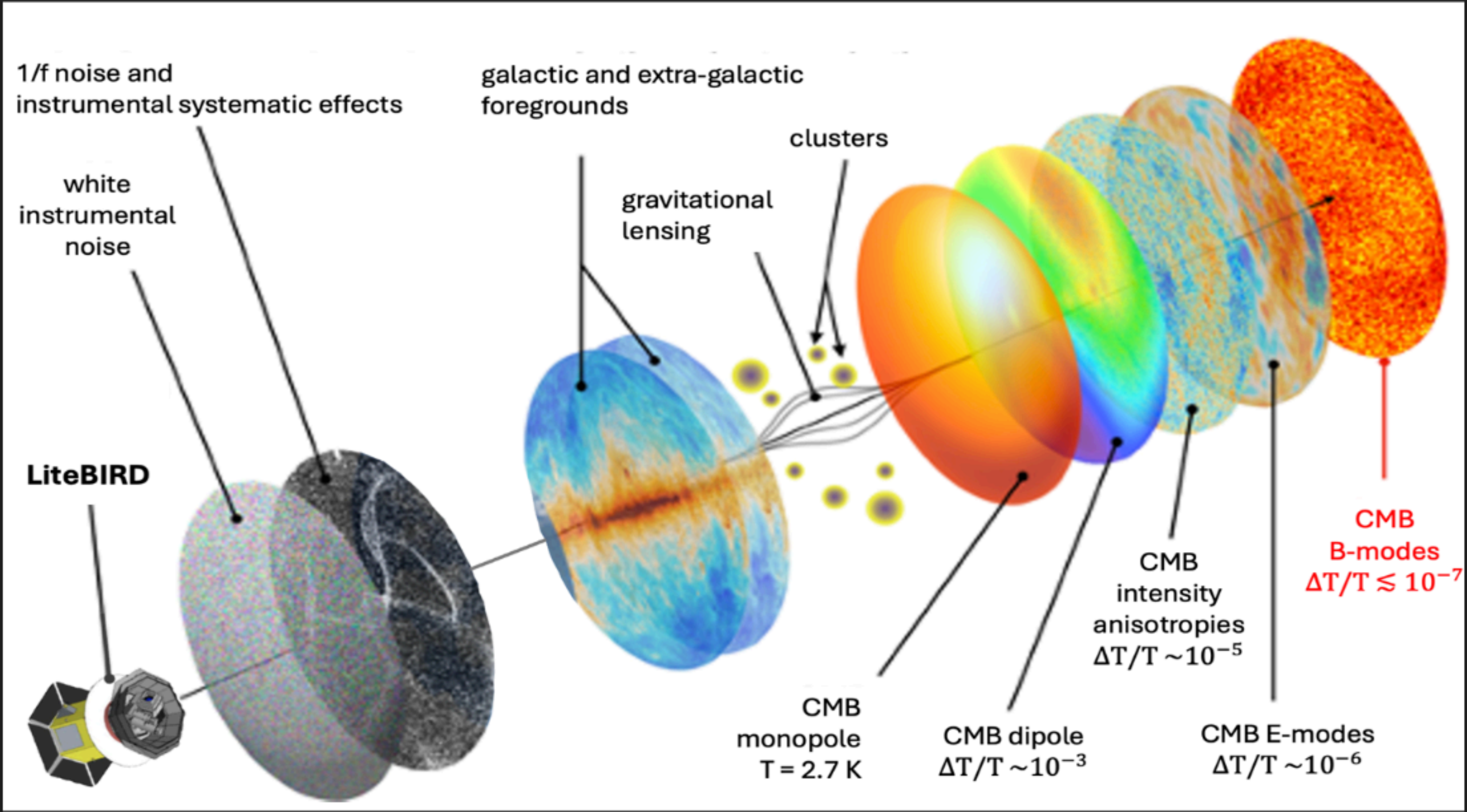


Simons Observatory

- now: 3x0.5mt SAT + 1x6mt LAT
- goal: 6x0.5mt SAT+ upgrade LAT
- in operation / commissioning

LiteBIRD

- 15 bands over the range 34 - 448 GHz
- 2.2 μK - arcmin with 0.5 deg res at 100 GHz
- planned for launch in 2032

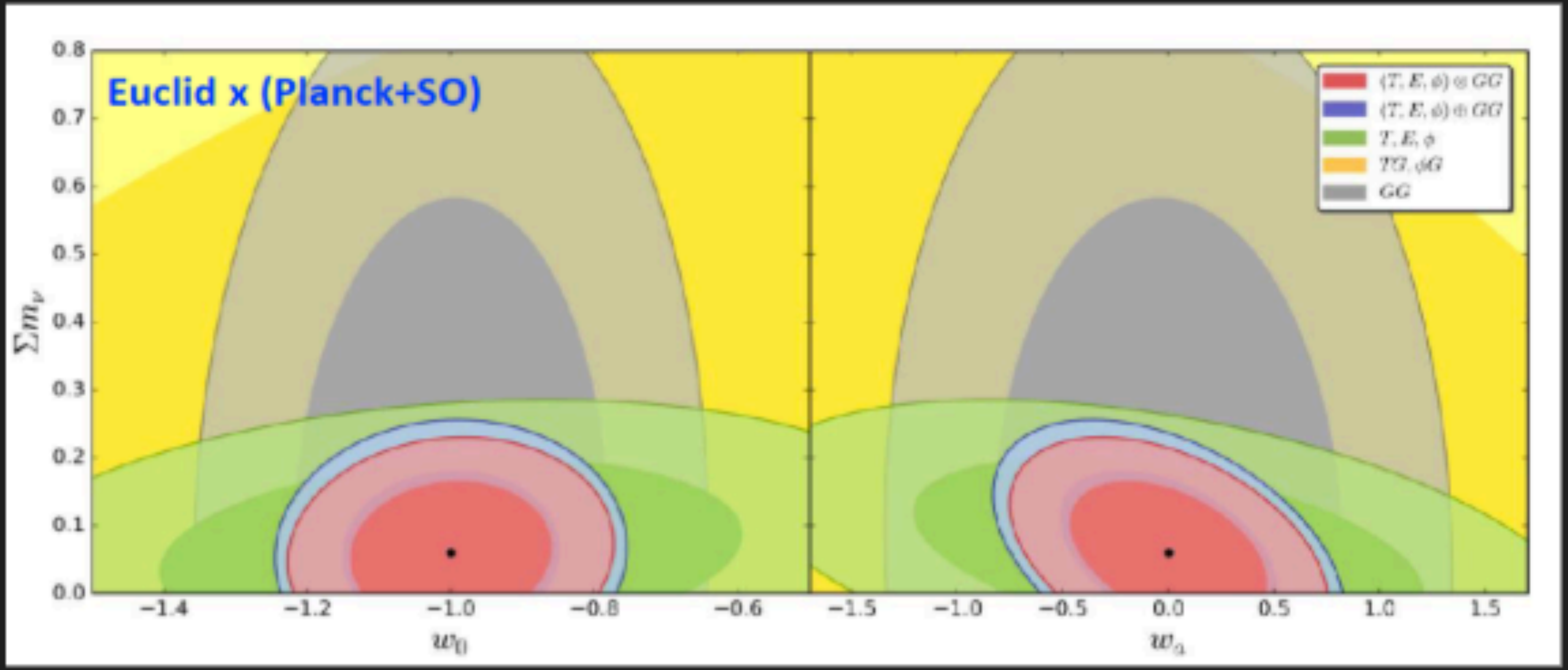


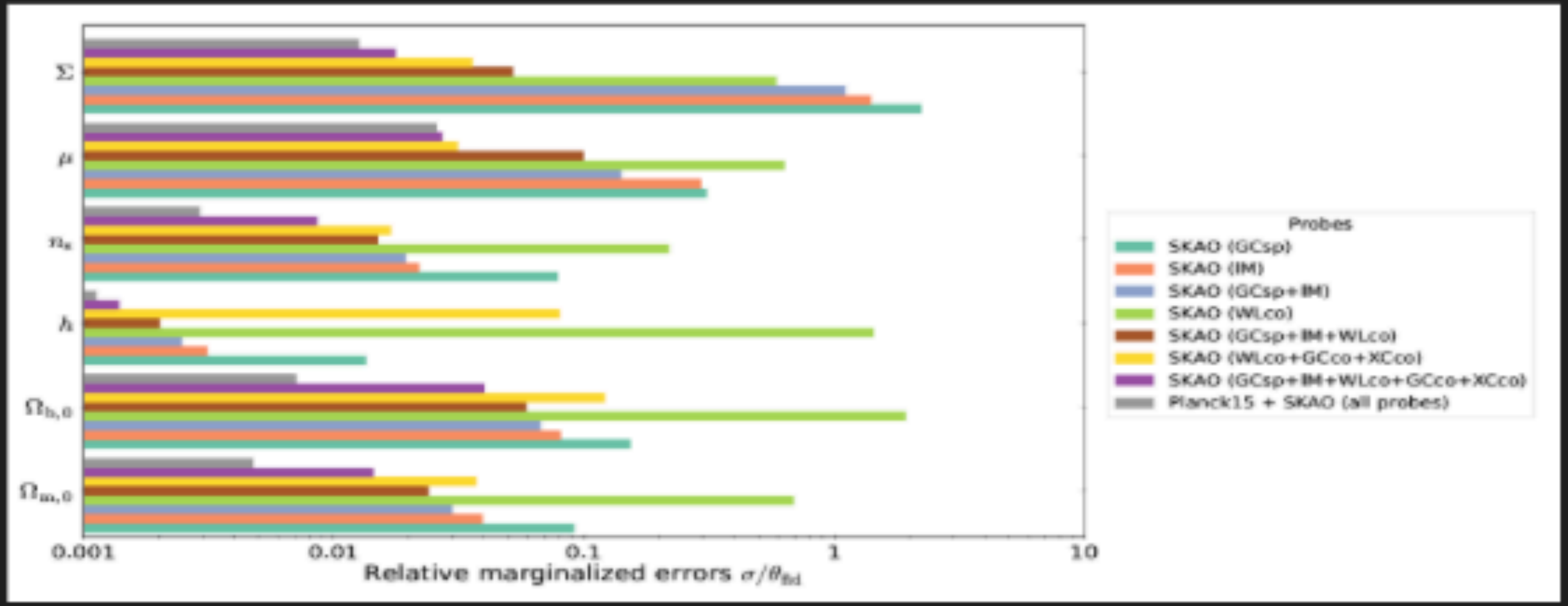
1/f noise and instrumental systematic effects
galactic and extra-galactic foregrounds
clusters
white instrumental noise
gravitational lensing
LiteBIRD
CMB monopole T = 2.7 K
CMB dipole ΔT/T ~10⁻³
CMB intensity anisotropies ΔT/T ~10⁻⁵
CMB E-modes ΔT/T ~10⁻⁶
CMB B-modes ΔT/T ≲ 10⁻⁷

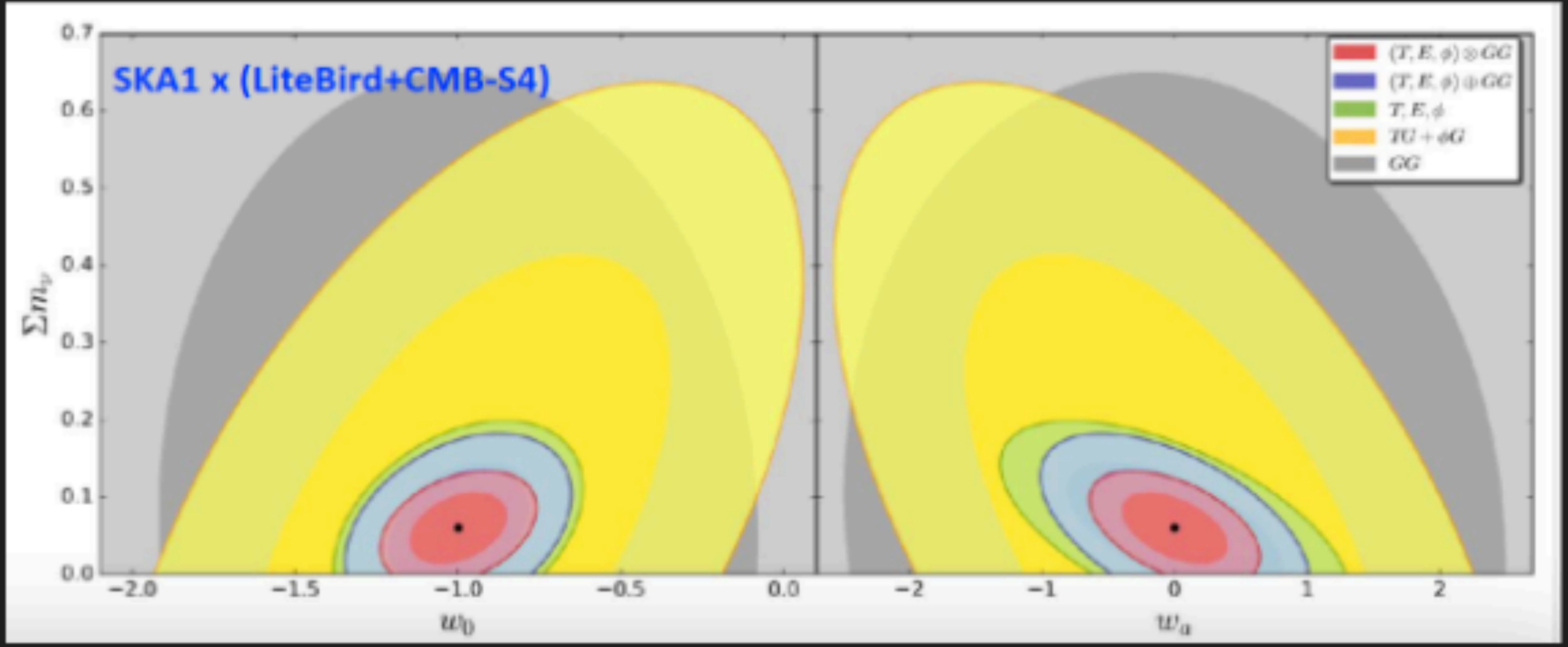
With all due respect to Tolkien and its masterpiece

- *One ring to rule them all. One ring to find them. One ring to bring them all, and in the darkness bind them*

- *Many rings to rule it all. Many rings to find the one. Many rings to bright the dark, and in the light take it all.*







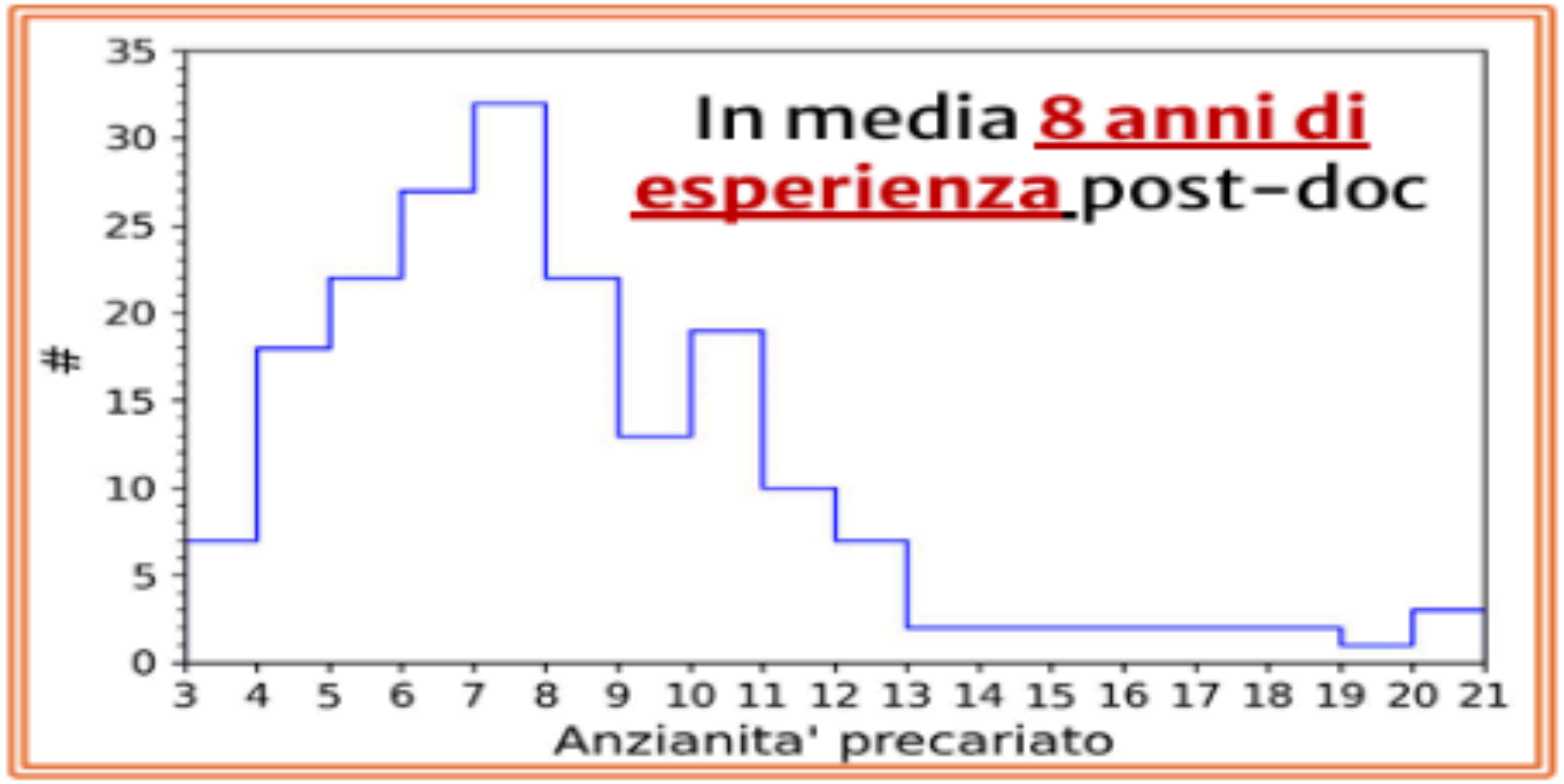
- Optical x Radio (Euclid x SKAO) or Old x New Astronomy (Euclid x GW) or CMB x LSS
- *Everything Everywhere All at Once*: cross correlation among all probes at all wavelengths

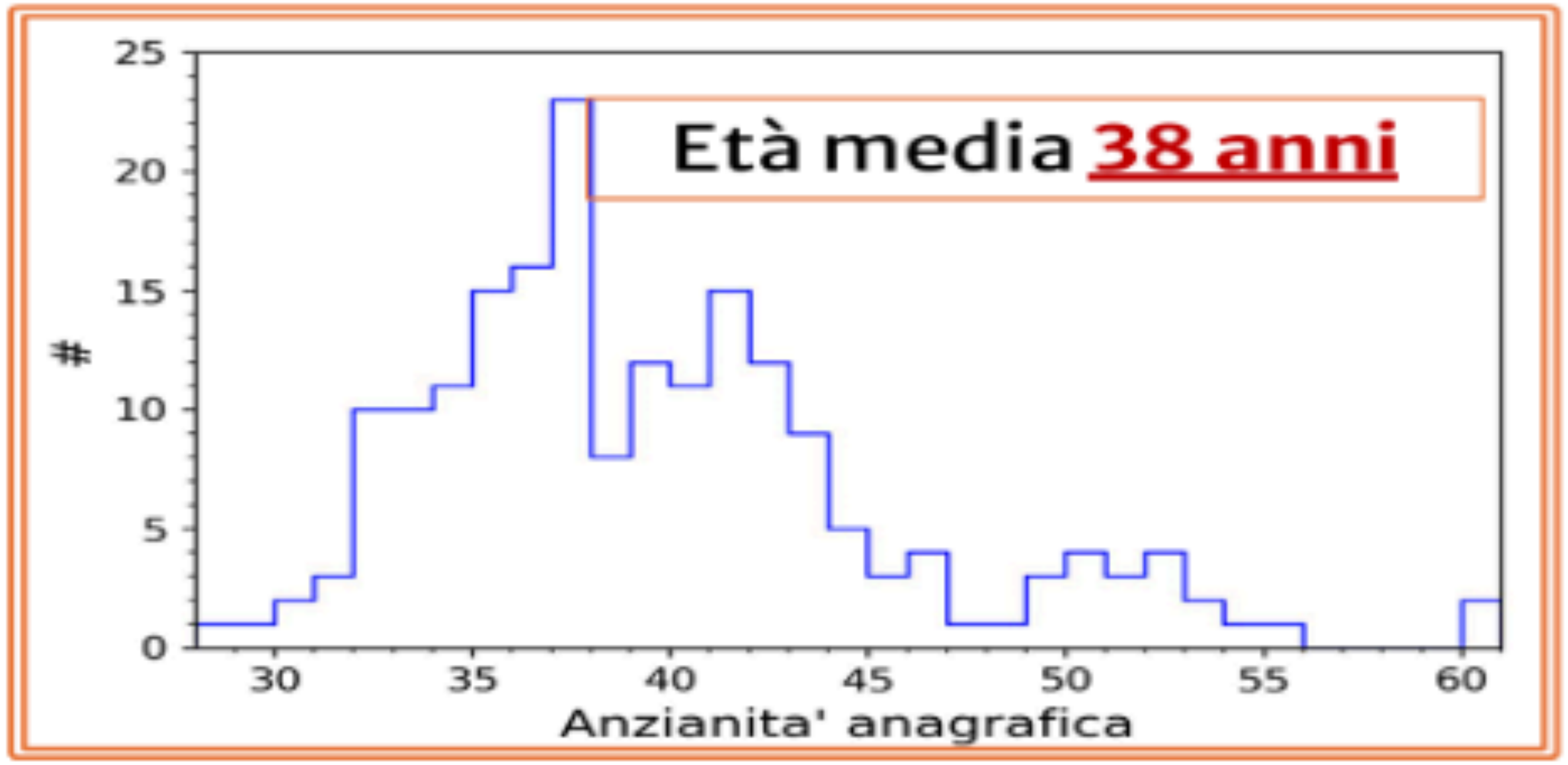
INAF and Cosmology in the Multiwavelength Era

- massive involvement in all main ground and space based missions
- leading roles in Euclid, LSST, SKAO, LiteBIRD, Einstein Telescope
- strong synergies with universities and INFN
- good investment in computational facilities

La situazione del personale precario in INAF è **INSOSTENIBILE**!

1.200 TI Vs 650 precari: più di 1 precario ogni 2 persone di ruolo





Plot di un campione rappresentativo dei precari INAF al 31/12/2024

Entro l'anno, l'attuale situazione determinerà l'esodo di > 100 lavoratori altamente qualificati

È URGENTE che INAF RIVENDICHI con fermezza, presso il MUR, finanziamenti svincolati dal turnover ed etichettati per le STABILIZZAZIONI MADIA: unica soluzione per questa emergenza

Rete Stabilizzandi INAF

Per aspera ad astra

Per sostenerci, inquadra il QRcode e firma