# The cosmological model under pressure

AnimaSciences - 28 mars 2025

# The cosmological model

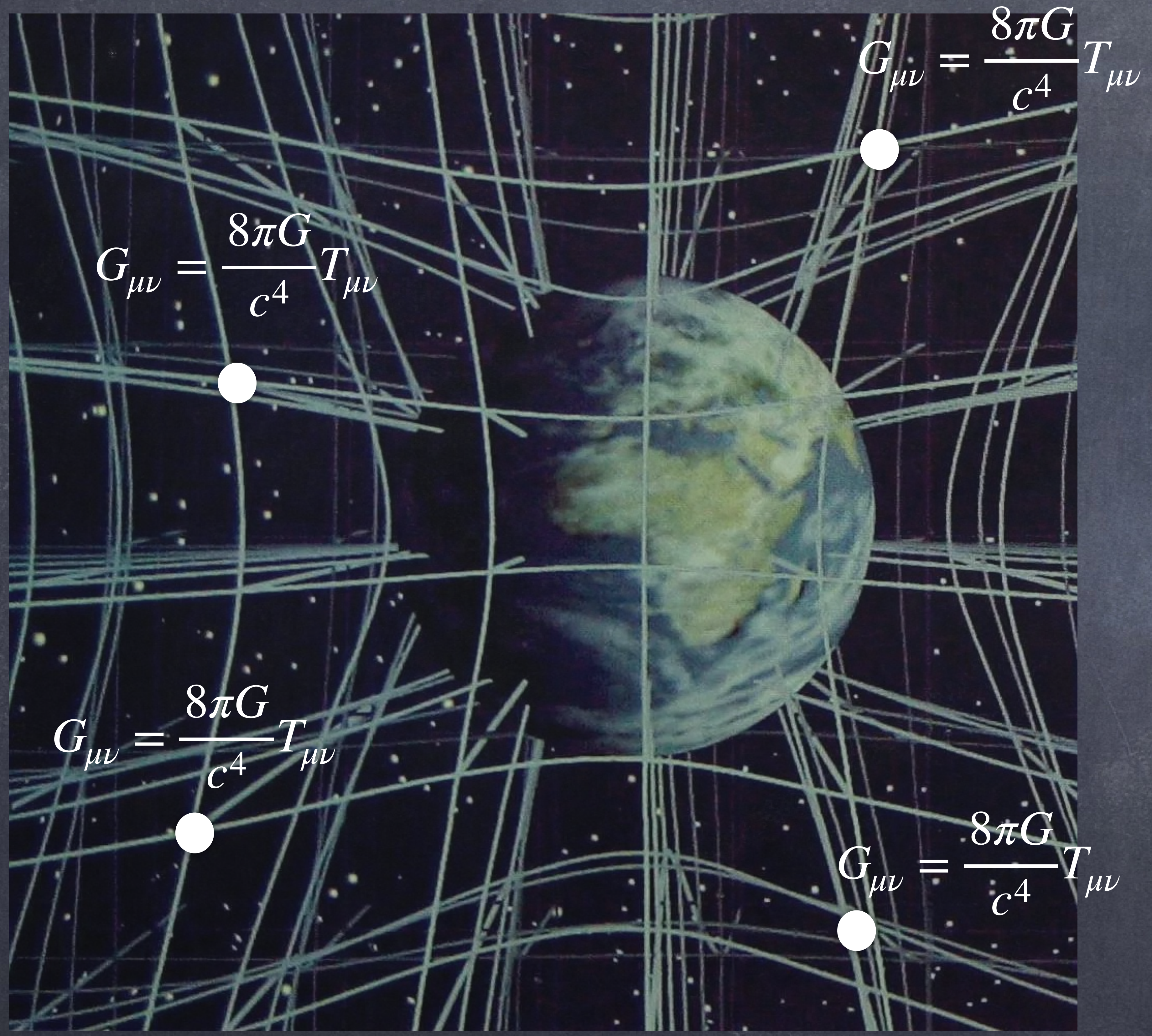
- Comes from General Relativity

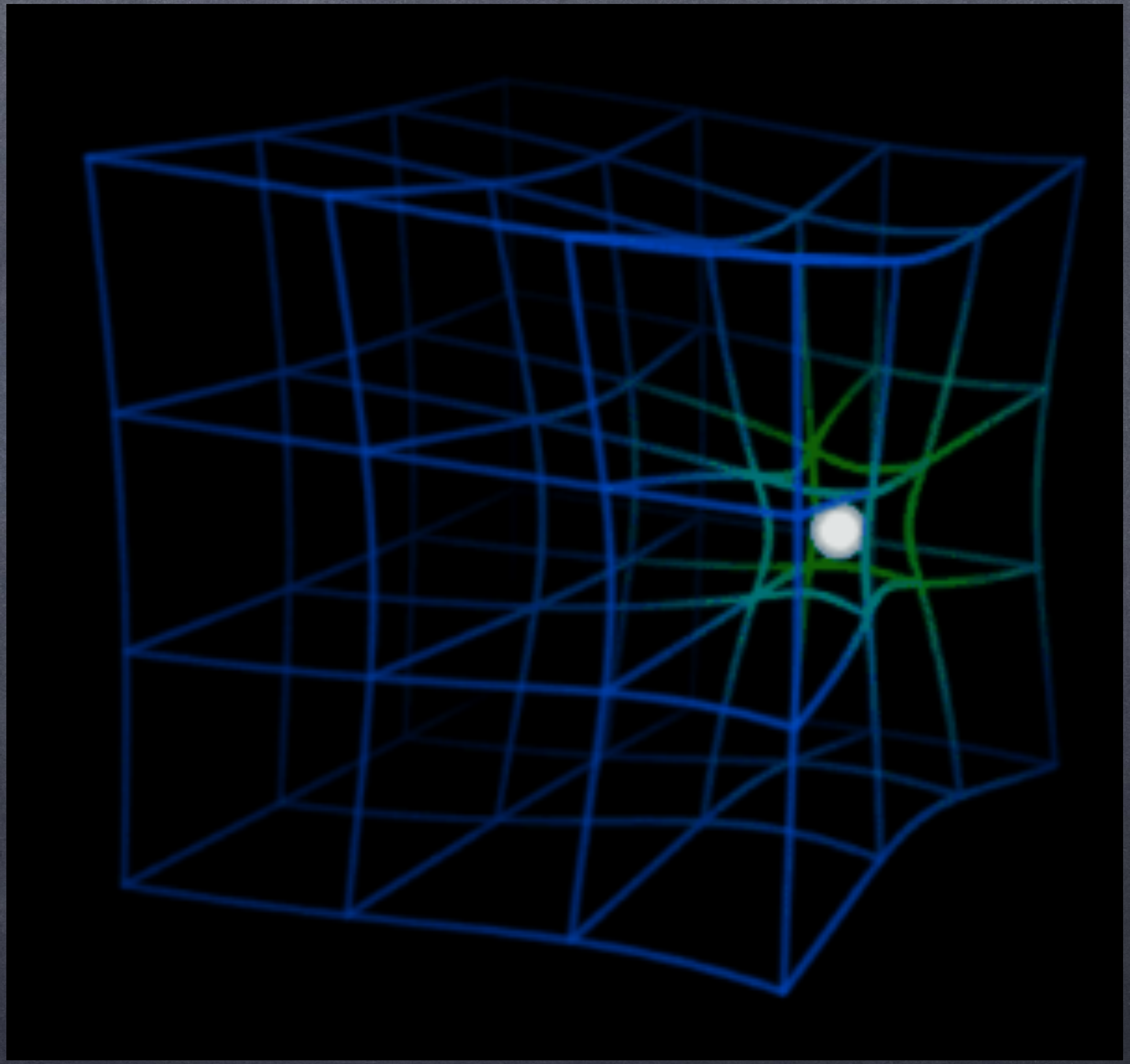
space grid                                                        matter/energy

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Local equation !

# Local deformation of space-time



# Universe global description ?

- Cosmological principle : uniform and isotropic

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

perfect fluid

$$T^{\mu}_{\ \nu} = \begin{bmatrix} -\rho & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{bmatrix}$$

# Universe global description ?

- Cosmological principle : uniform and isotropic

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

space 3D

$$G_{\mu\nu} = \begin{pmatrix} -c^2 & 0 \\ 0 & a^2(t)\gamma_{ij}(k) \end{pmatrix}$$

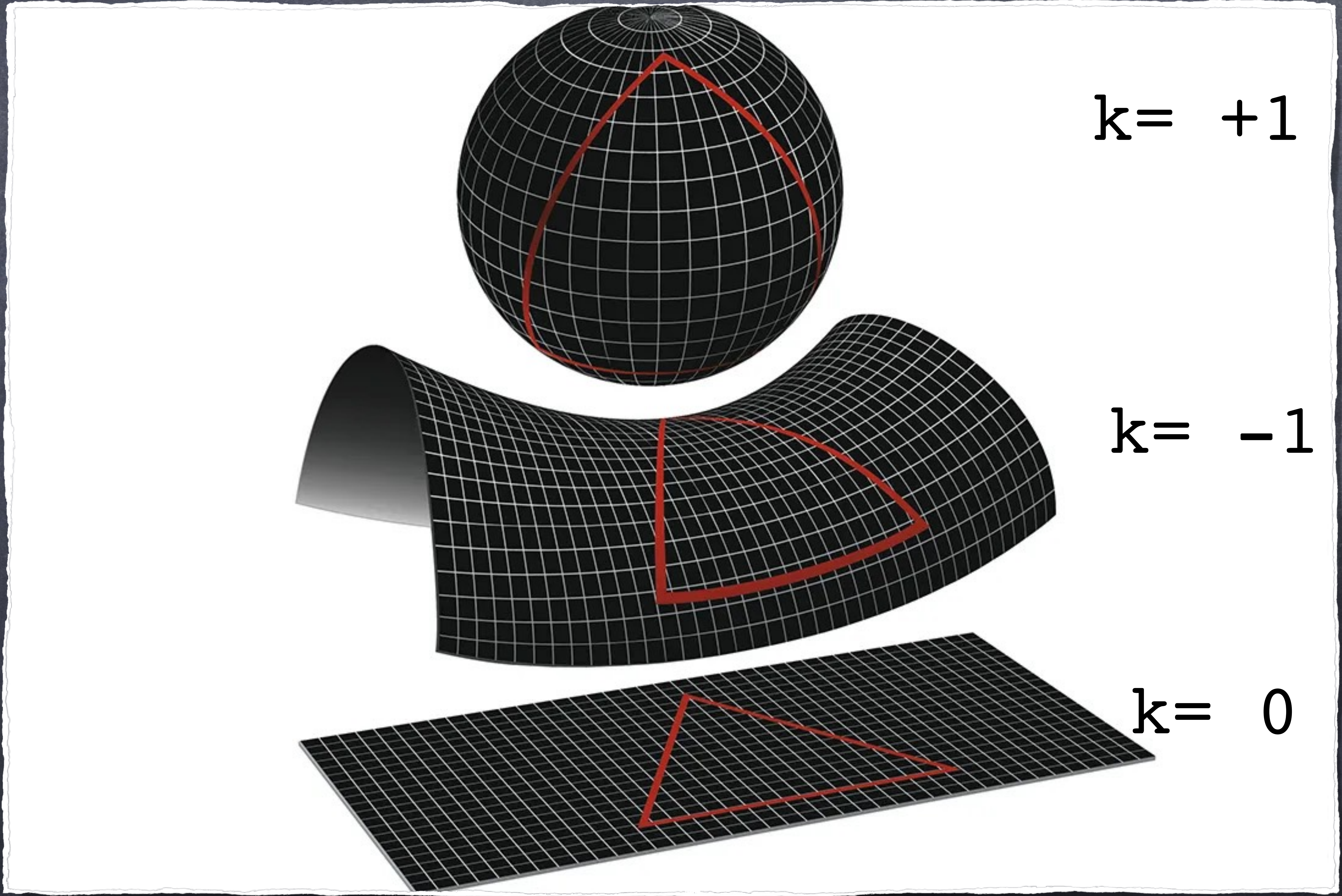
scale factor space curvature

perfect fluid

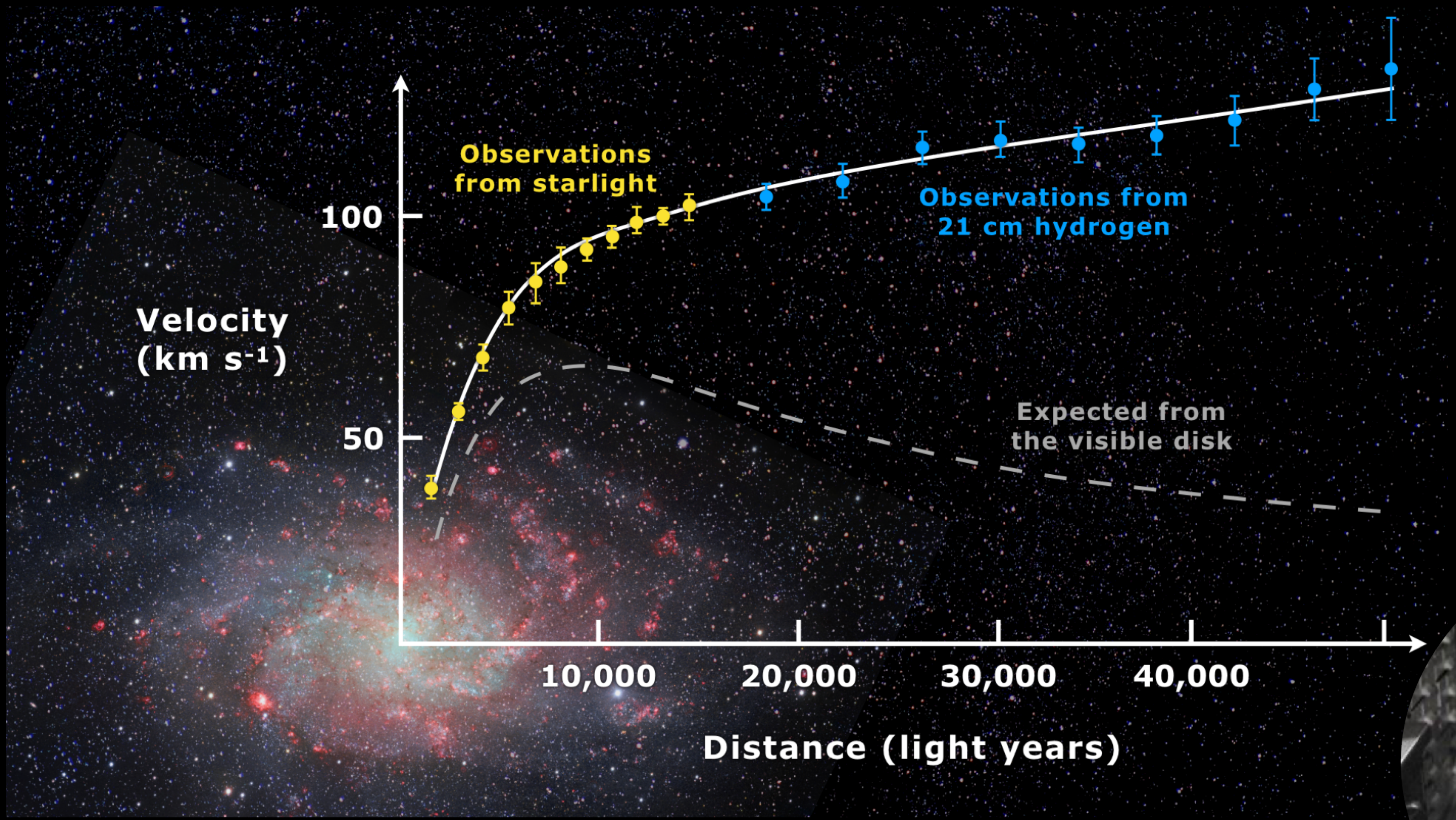
$$T^{\mu}_{\ \nu} = \begin{bmatrix} -\rho & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{bmatrix}$$

# Space-time curvature k

- Assumption -> flat universe



# Perfect Fluids: Dark matter




About 5 times more “dark matter” than normal matter

*Vera Rubin*

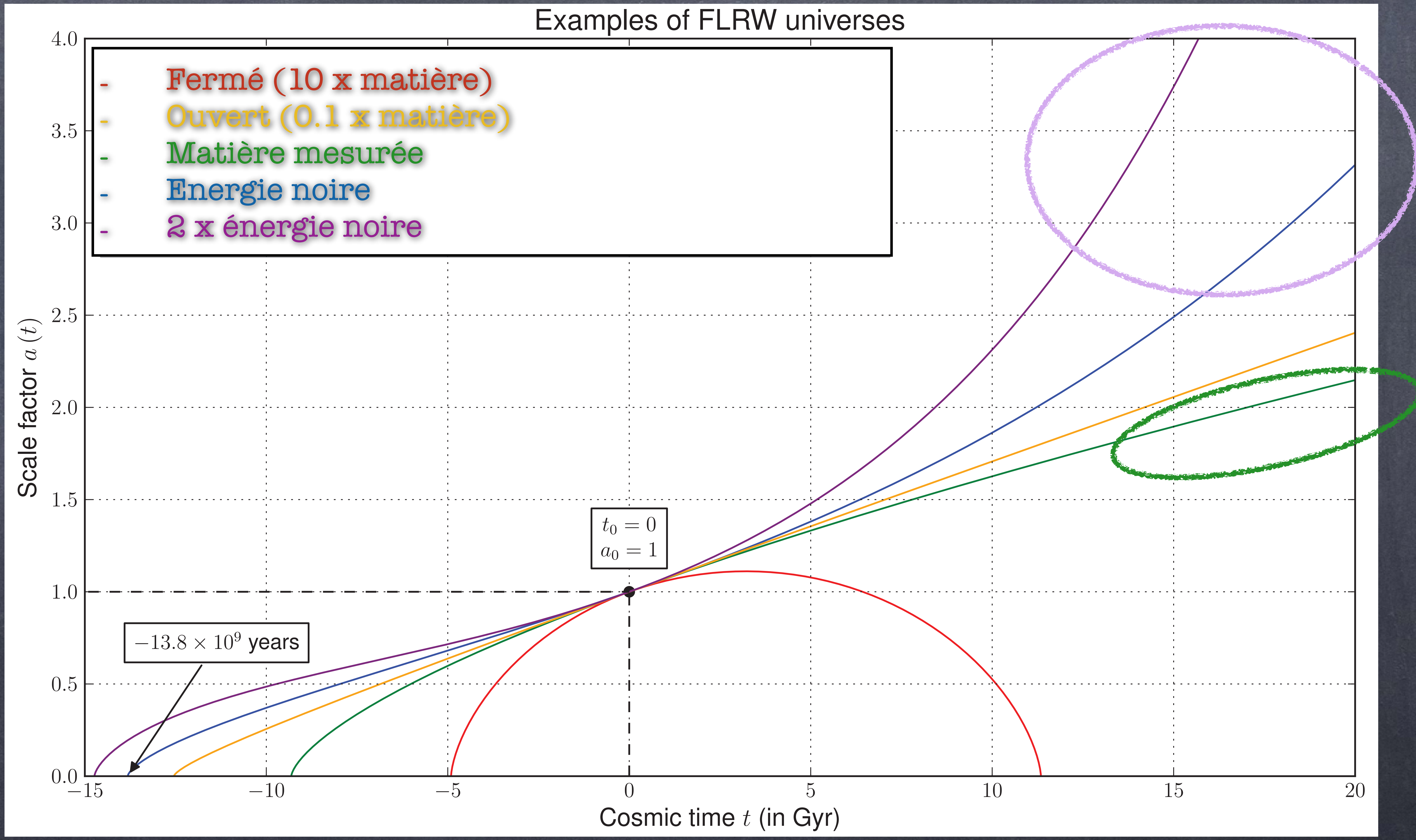
Assumption : Cold Dark Matter (CDM)

# Too fast expansion of universe

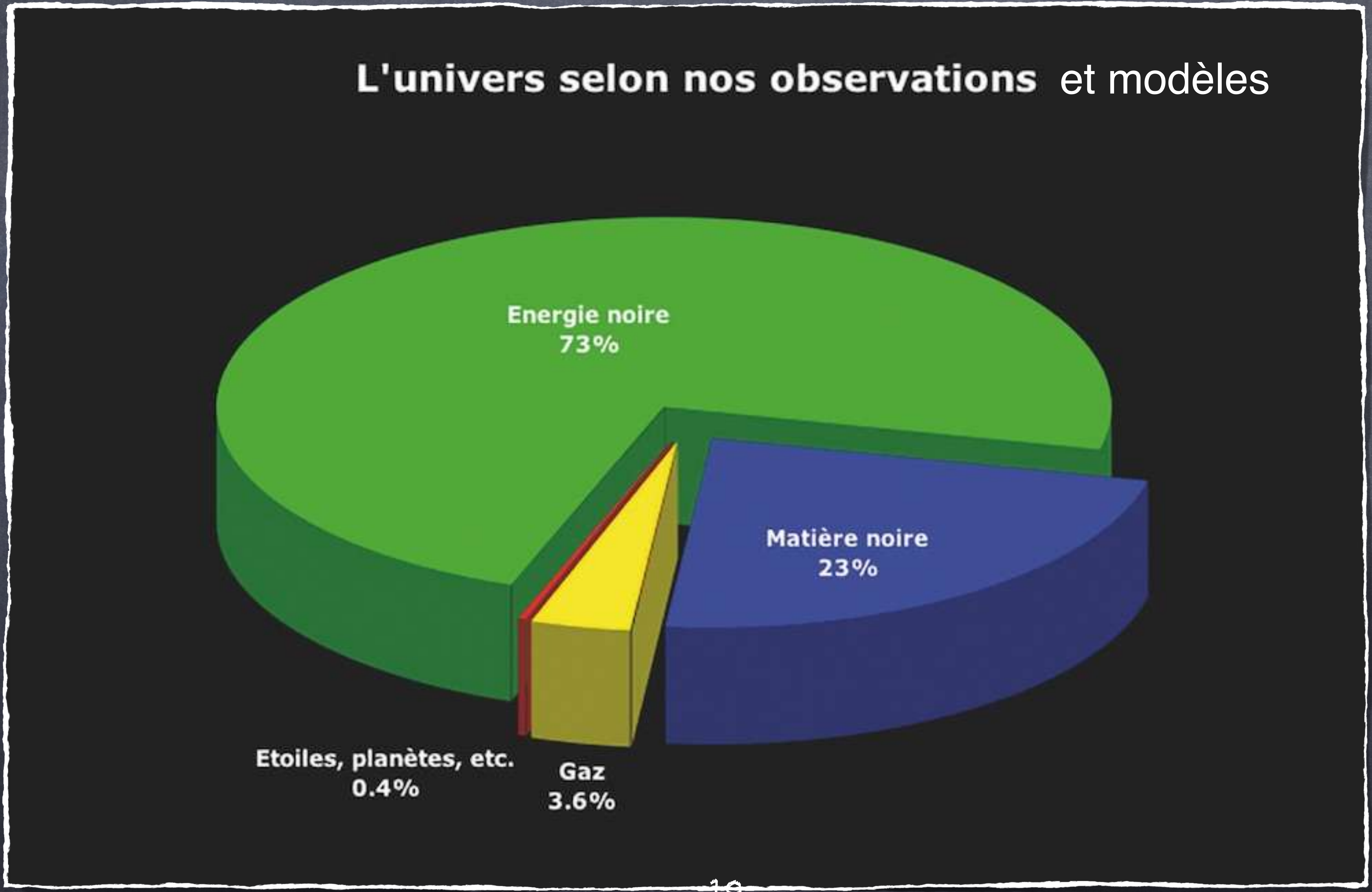
- Assumption : additional cosmological constant $\Lambda$ (or dark dark energy)

$$G_{\mu\nu}+\Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

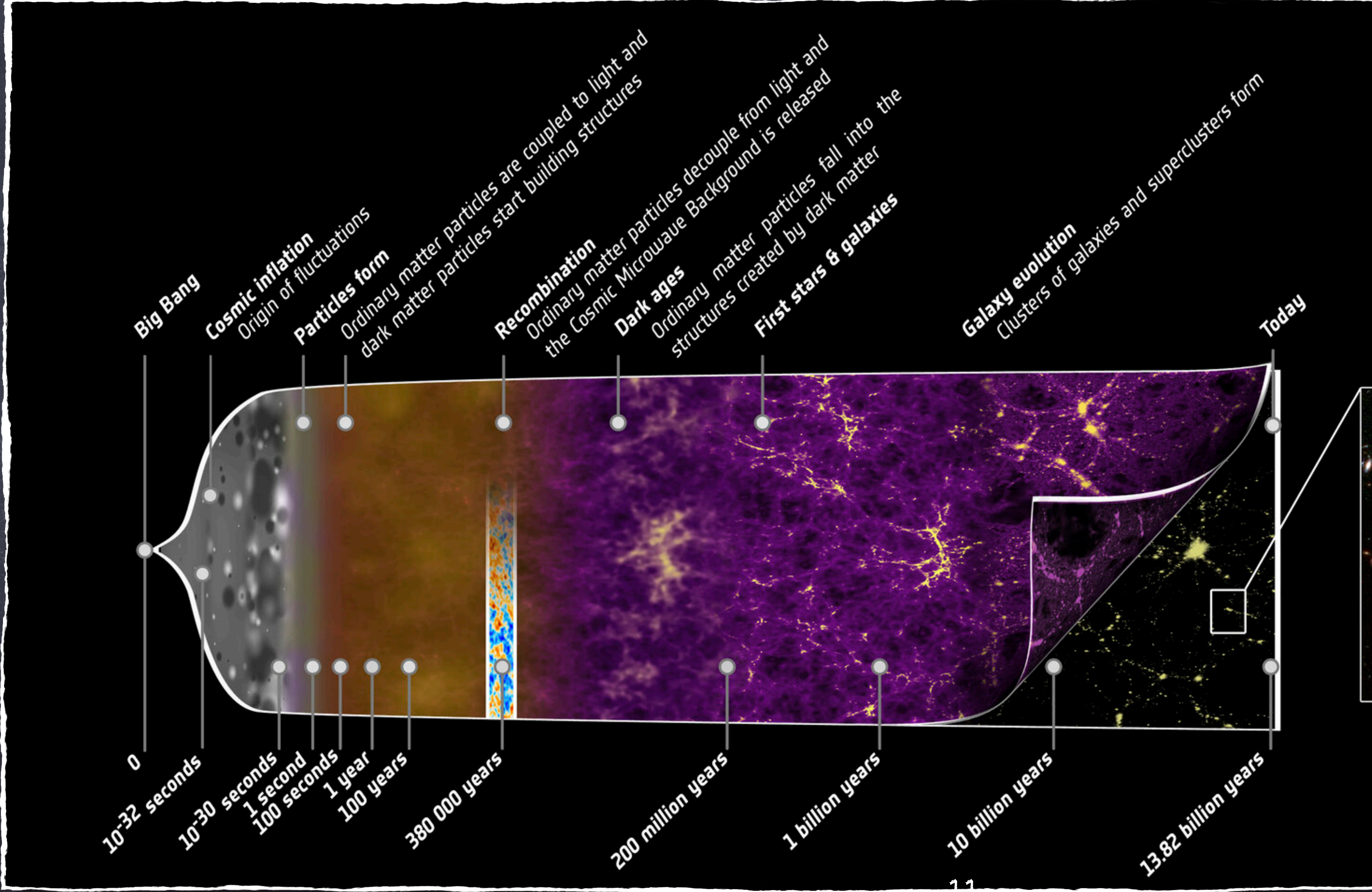
allowed from Lovelock theorem

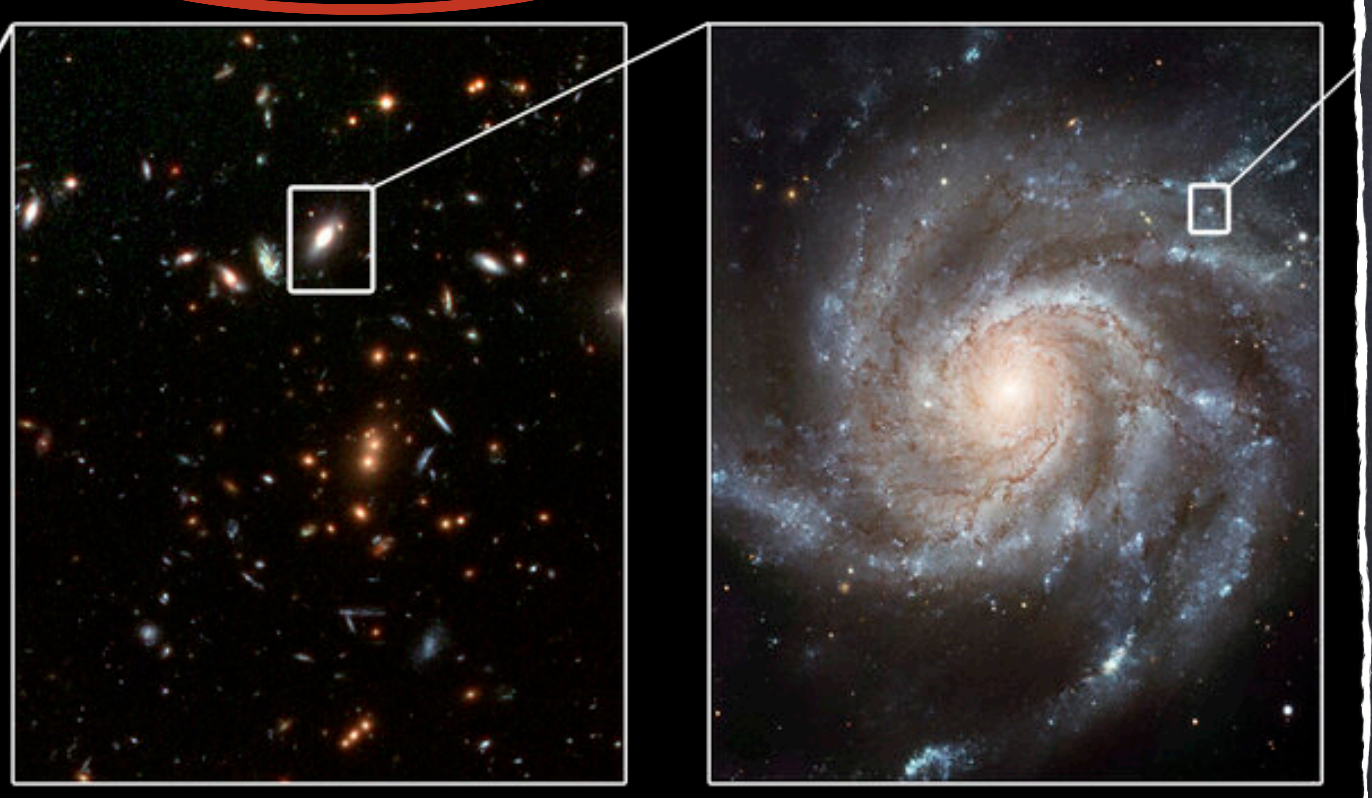


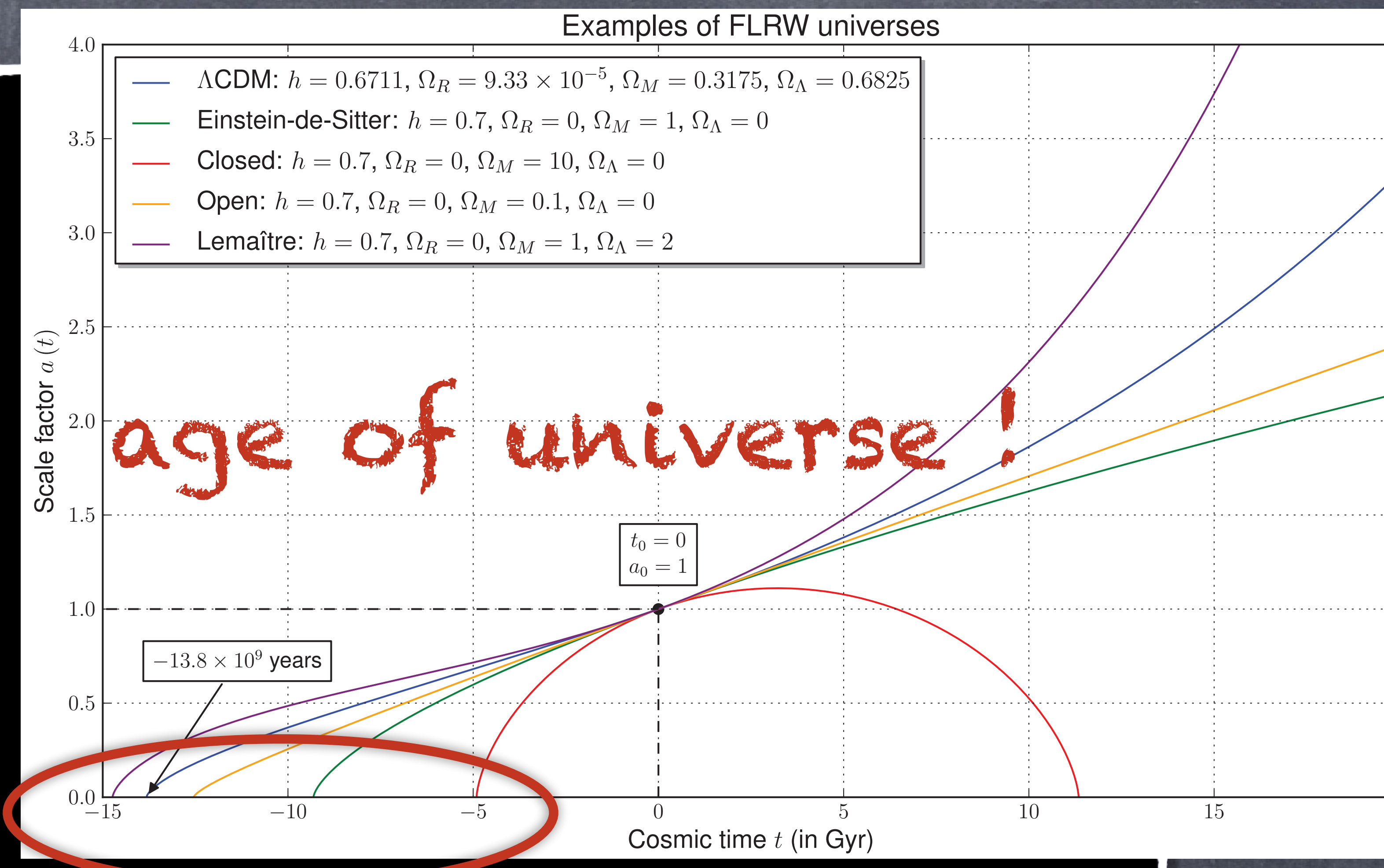
# Flat $\Lambda$CDM : Dark Energy and Dark matter in a flat universe



# Can deduce universe history



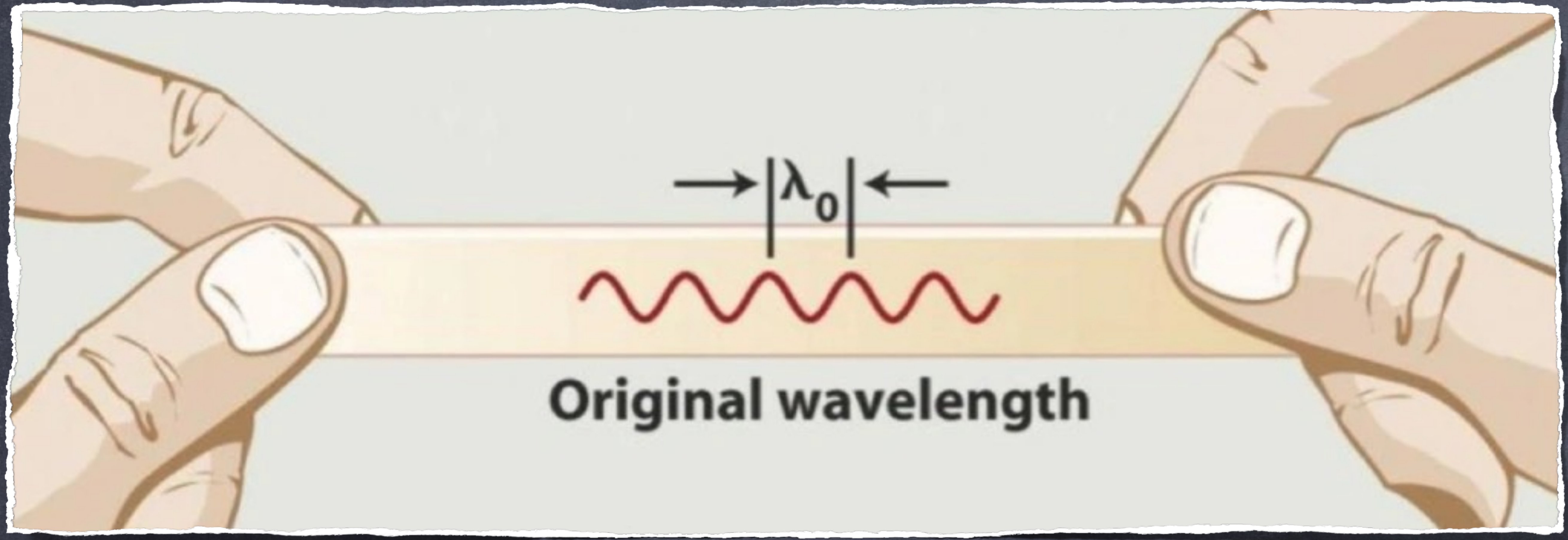



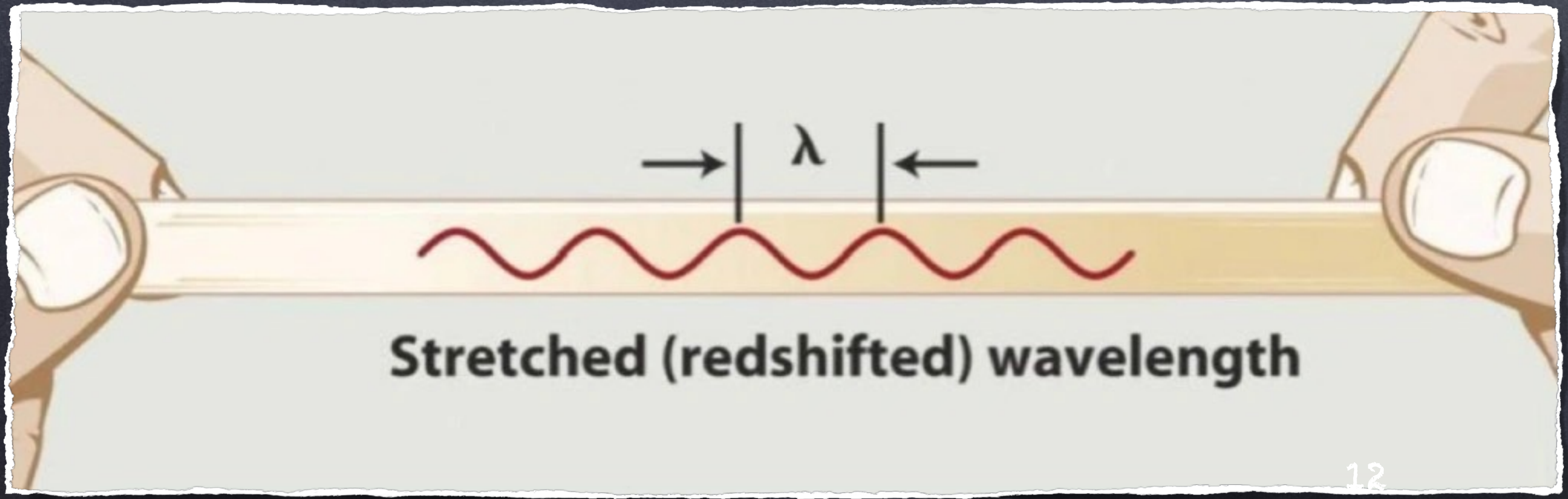


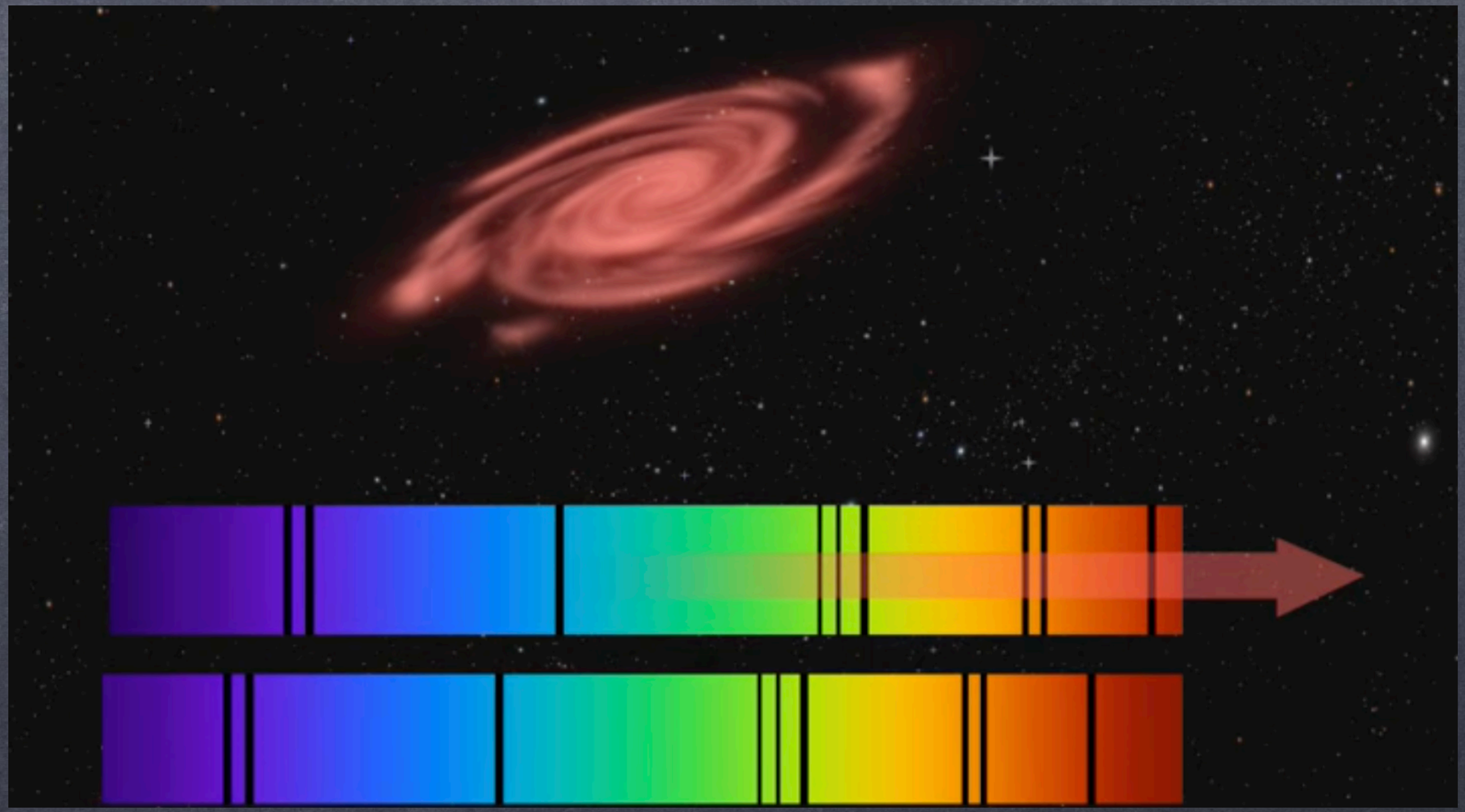

credits: ESA

# Is this really ΛCDM ?

- Measure universe expansion -> redshift

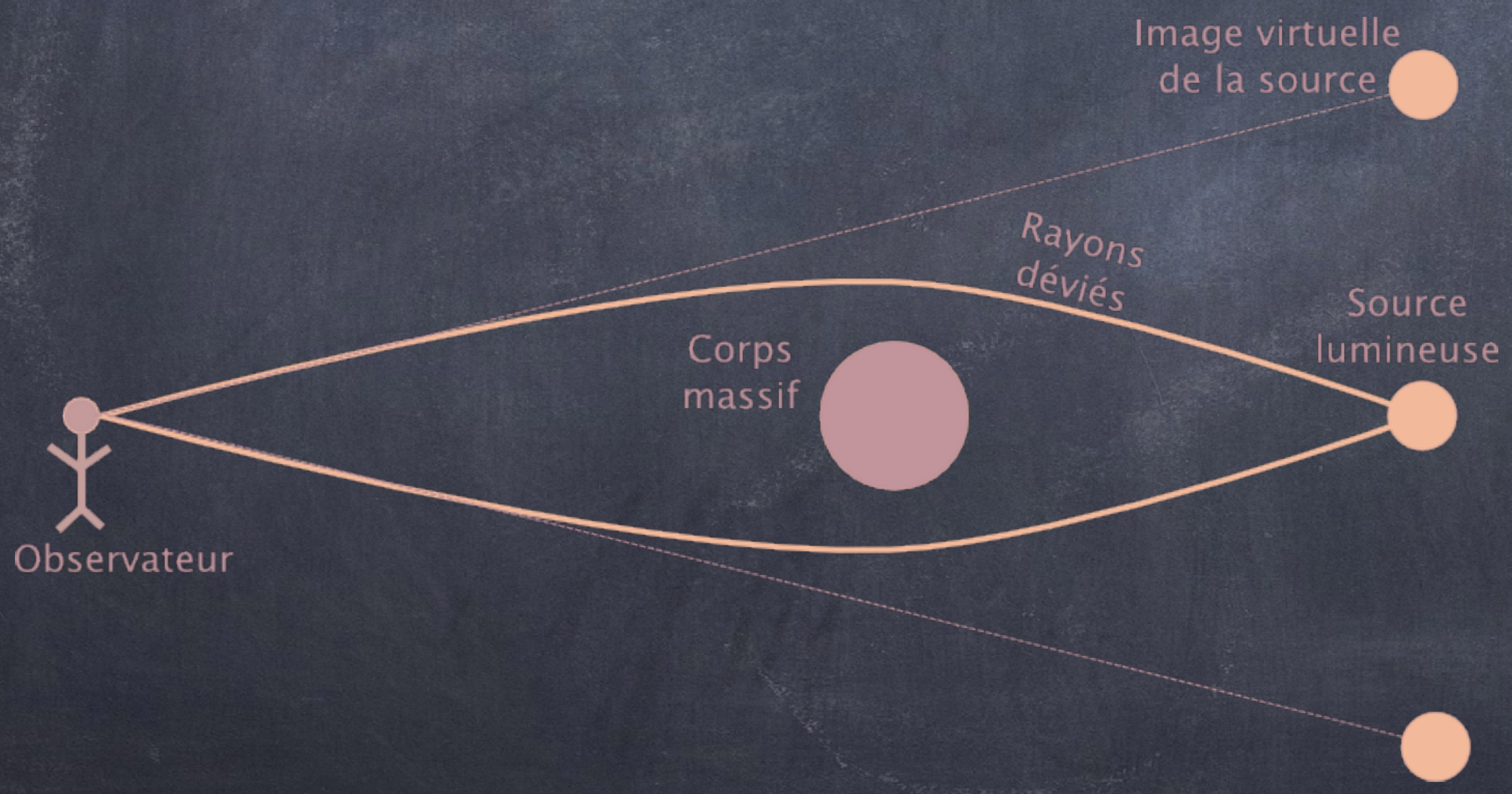


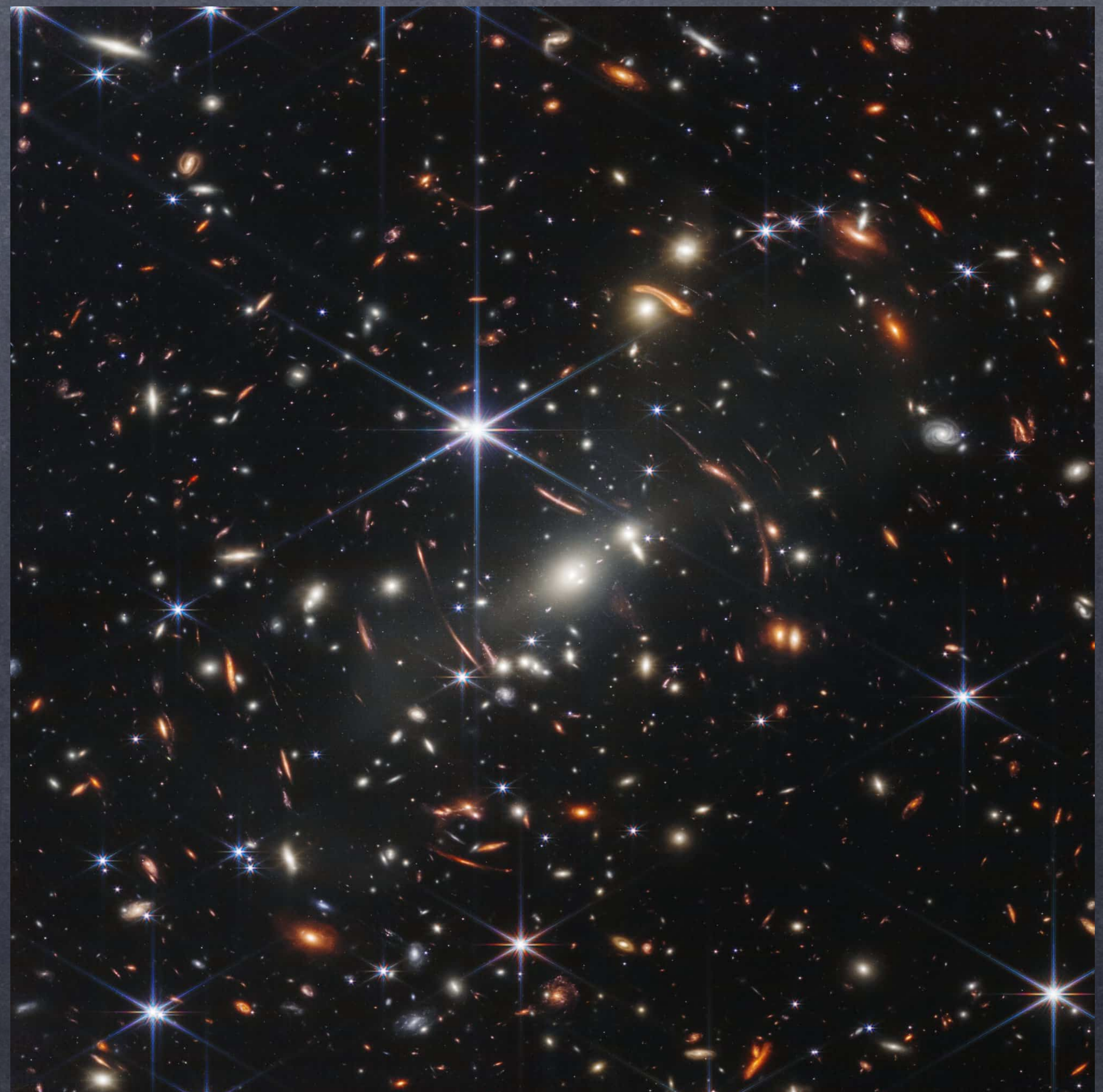



# Is this really ΛCDM ?

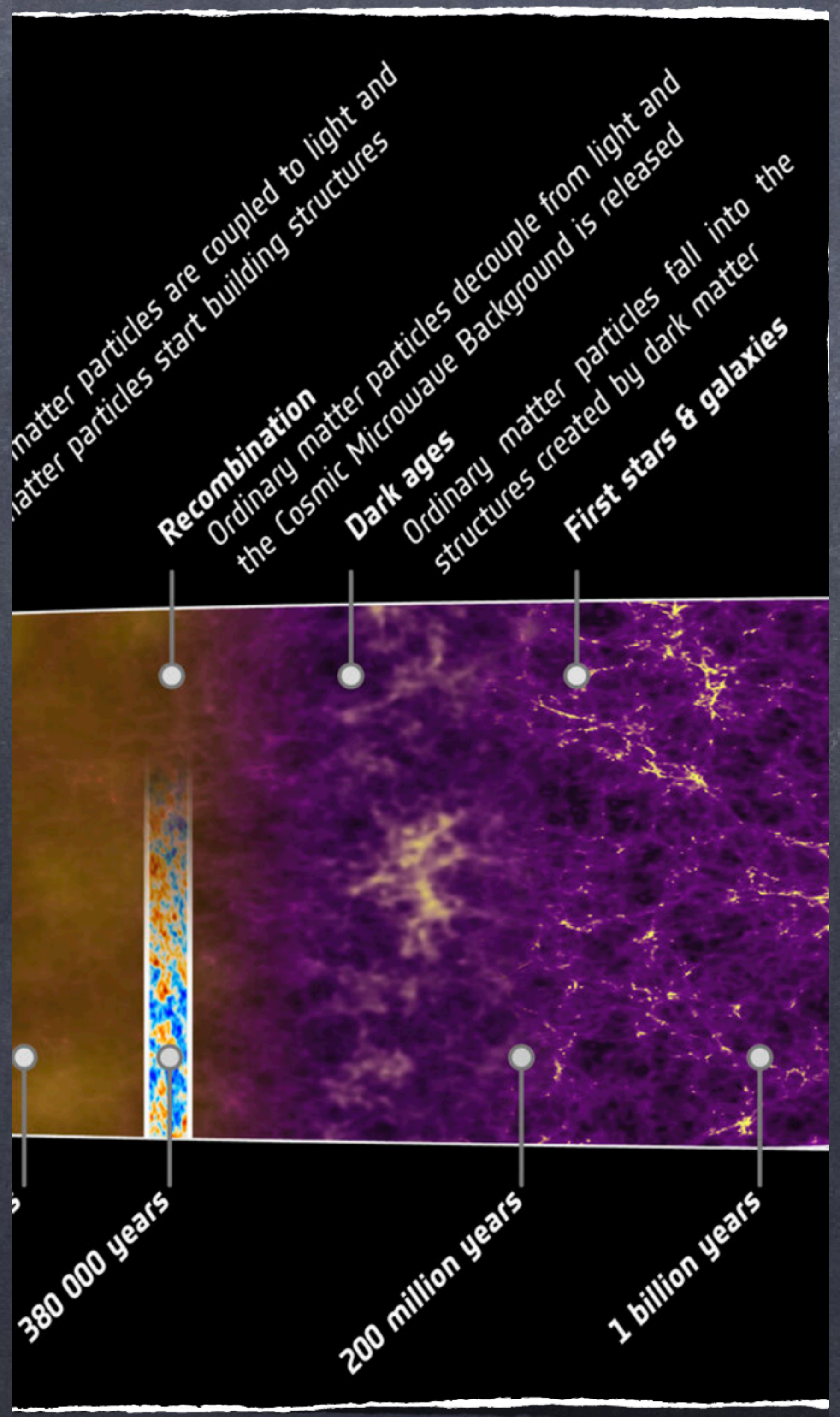
- Measure universe expansion -> redshift
- Use gravitational lensing to measure mass of structures

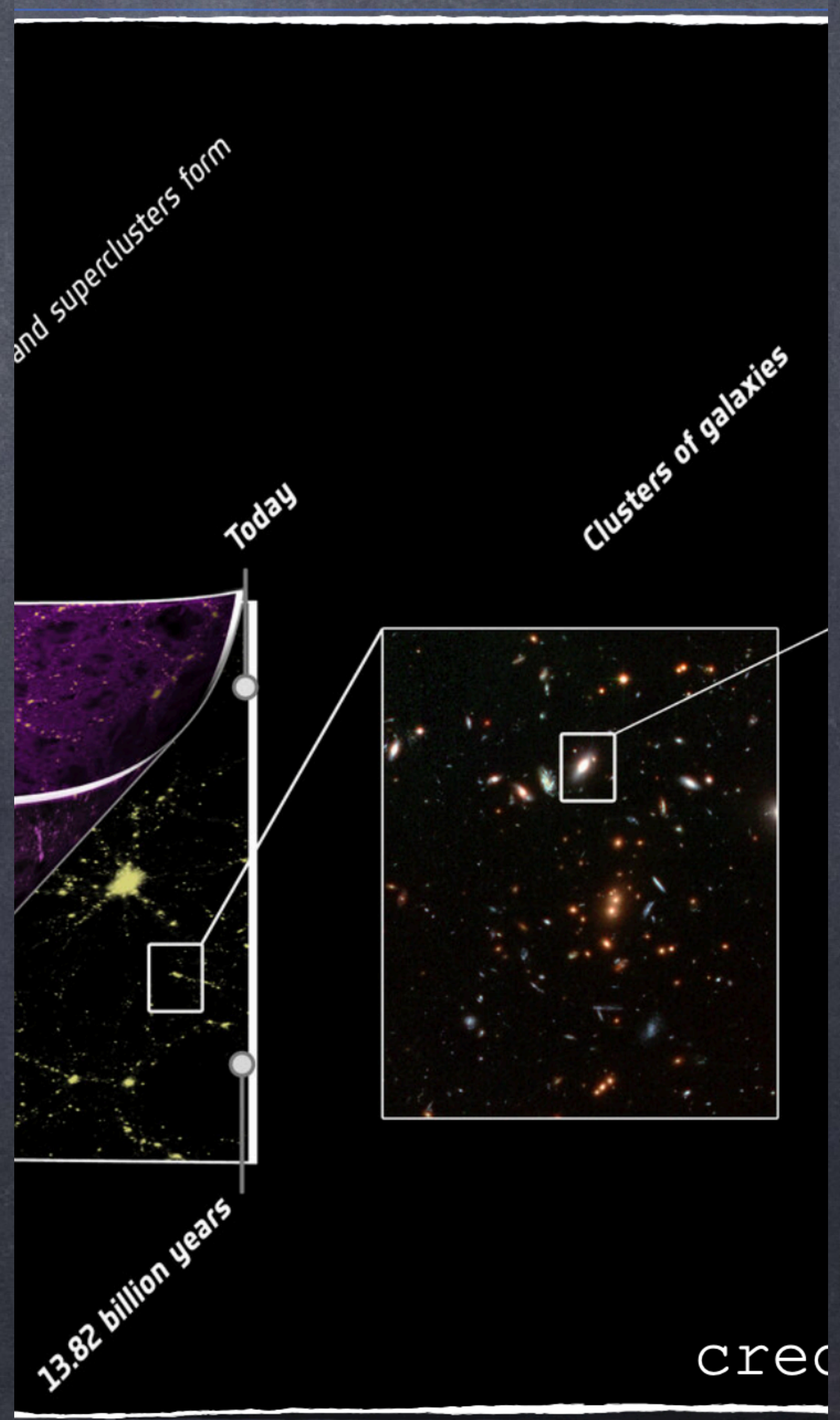


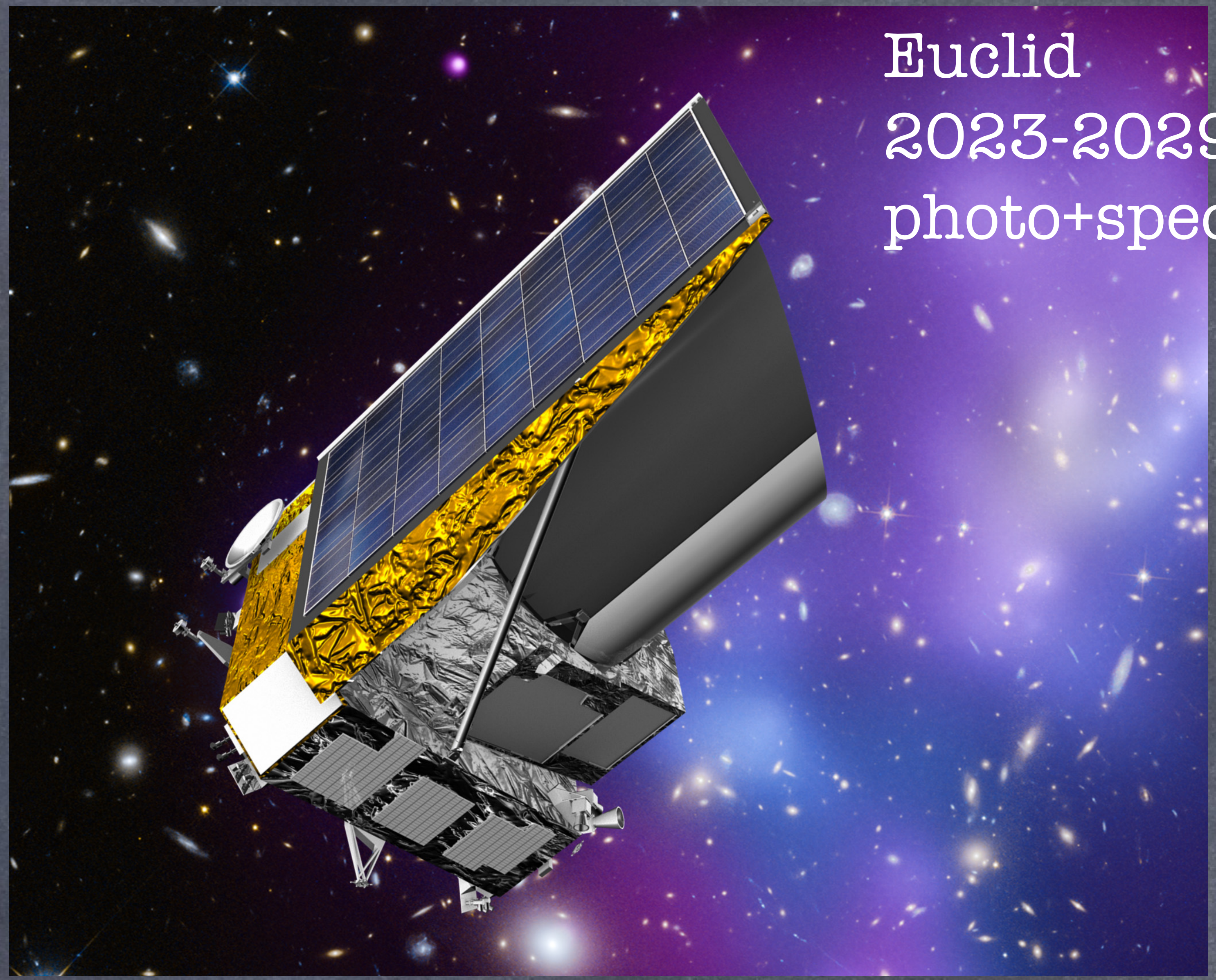
# Is this really ΛCDM ?

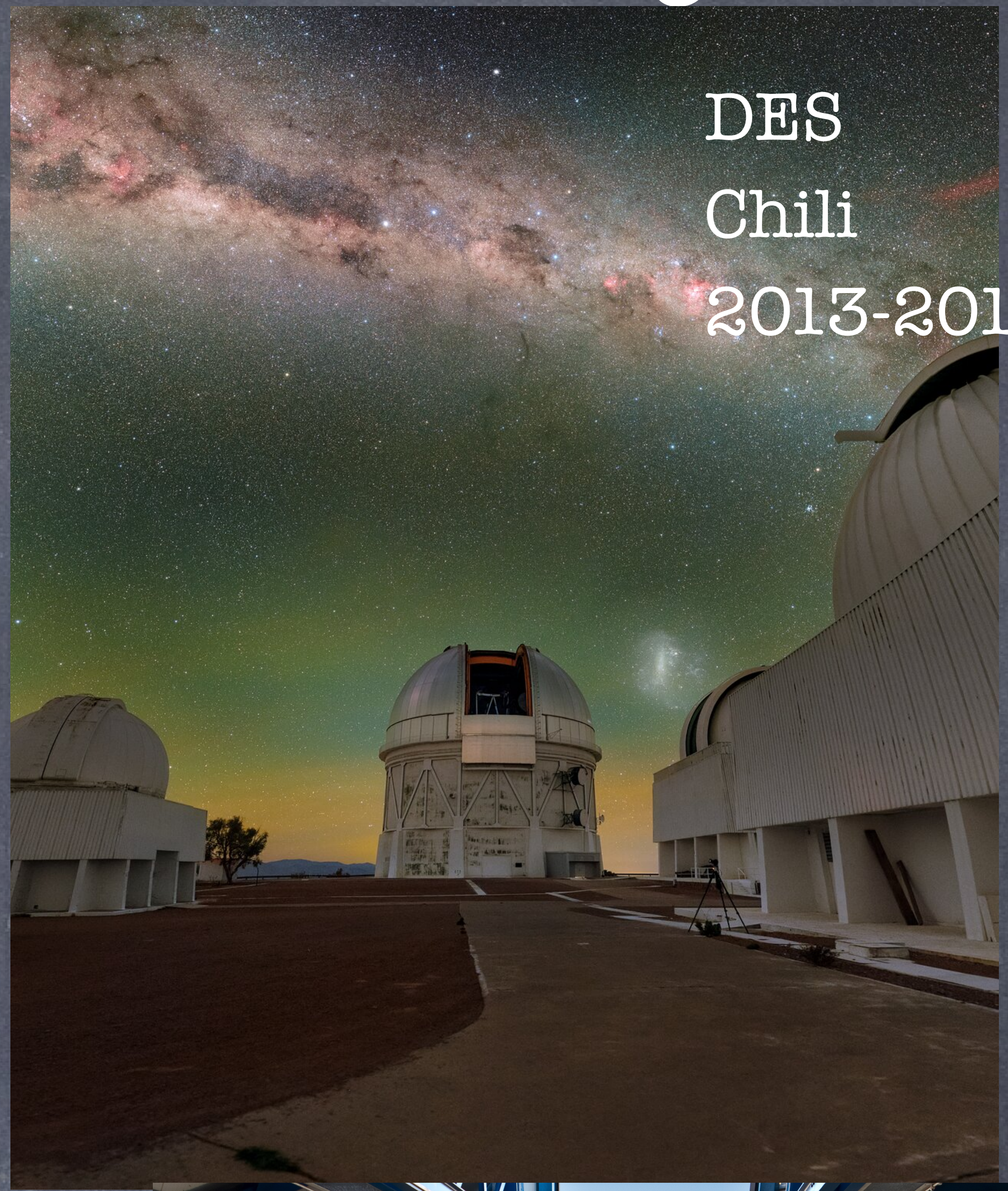
- Measure universe expansion -> redshift
- Use gravitational lensing to measure mass of structures
- Measure universe at different ages
    - CMB
    - First galaxies
    - More recent galaxy clusters

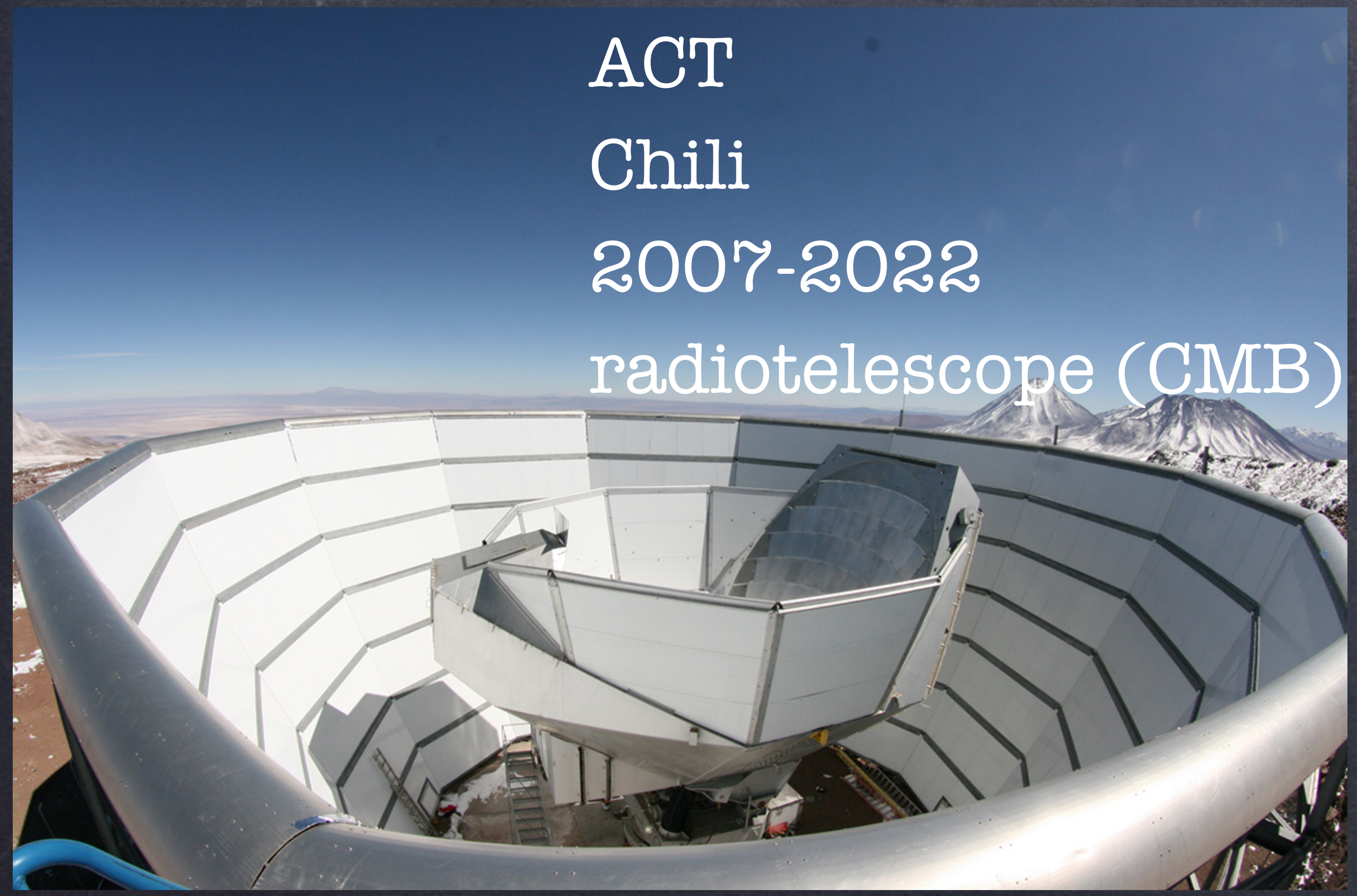


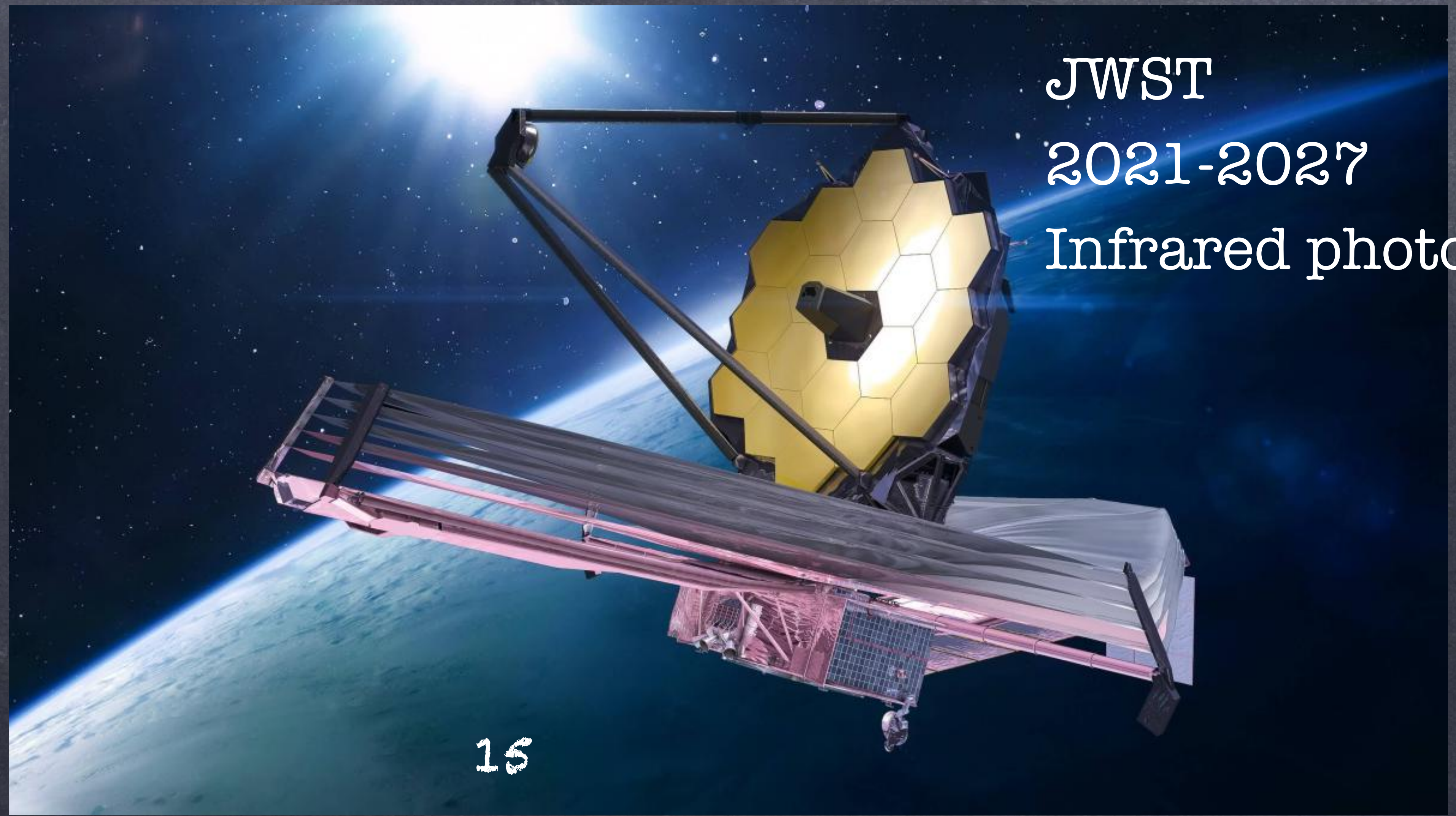



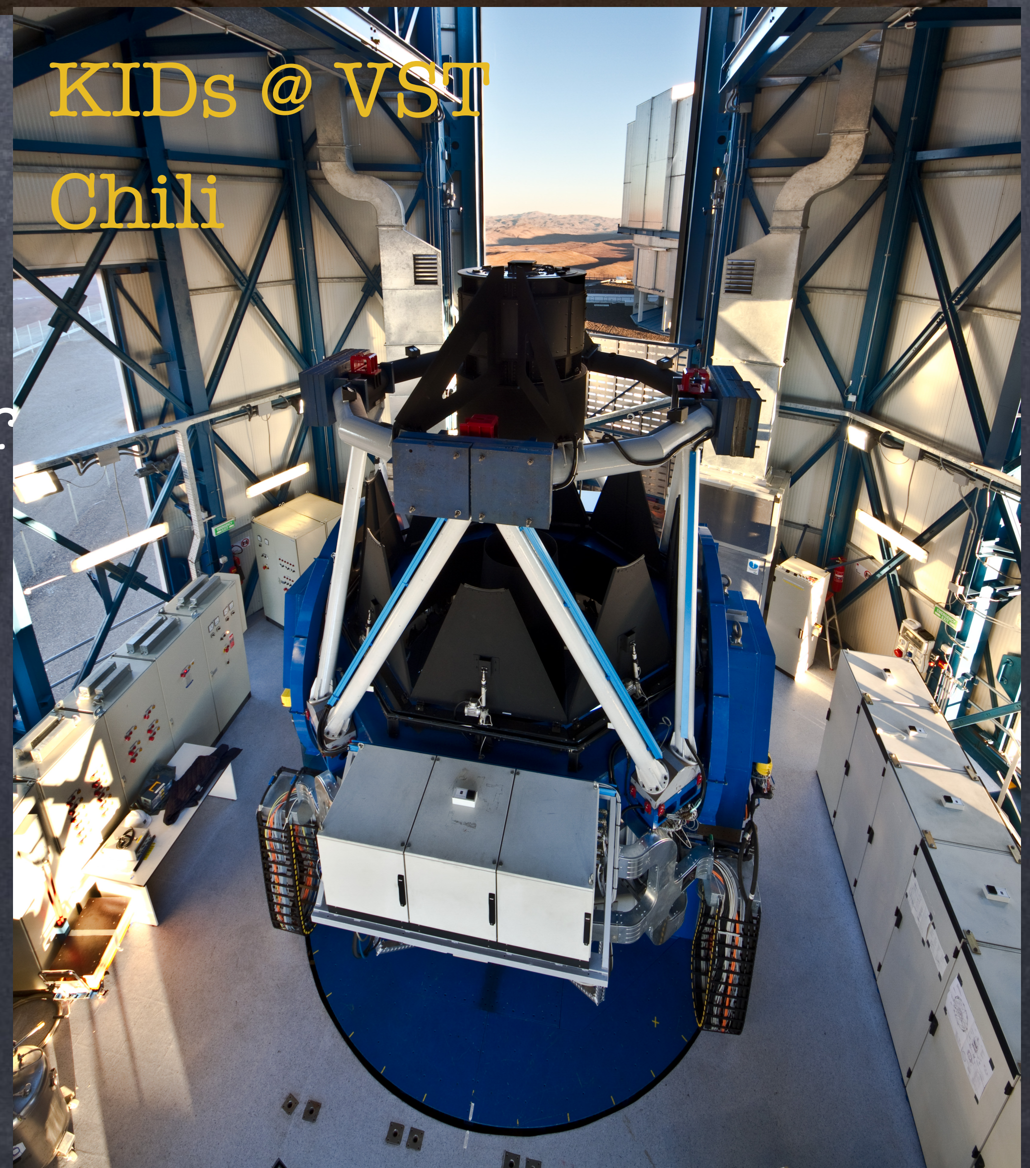
# Huge set of data collected an published recently

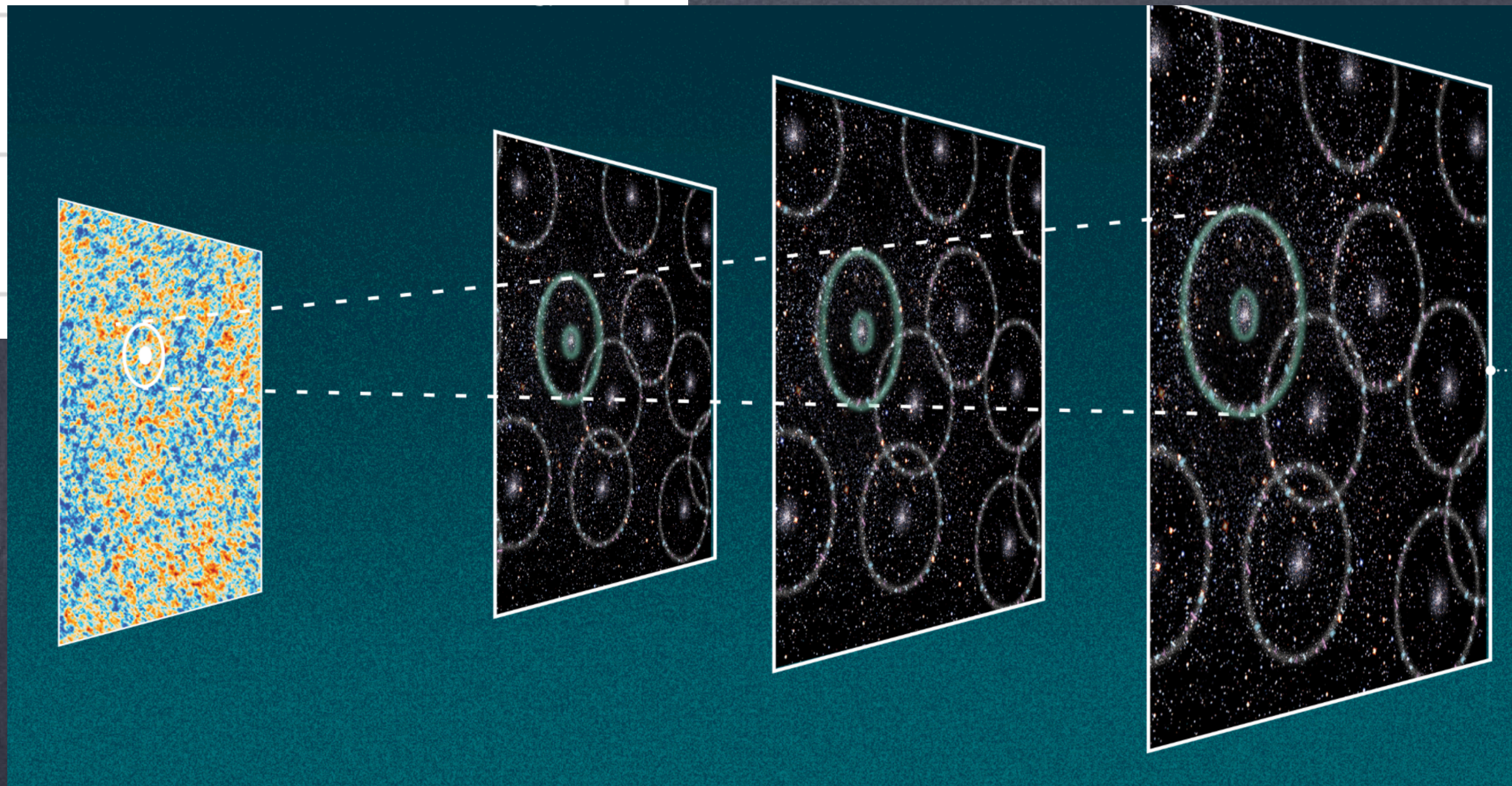



# Cosmological probes

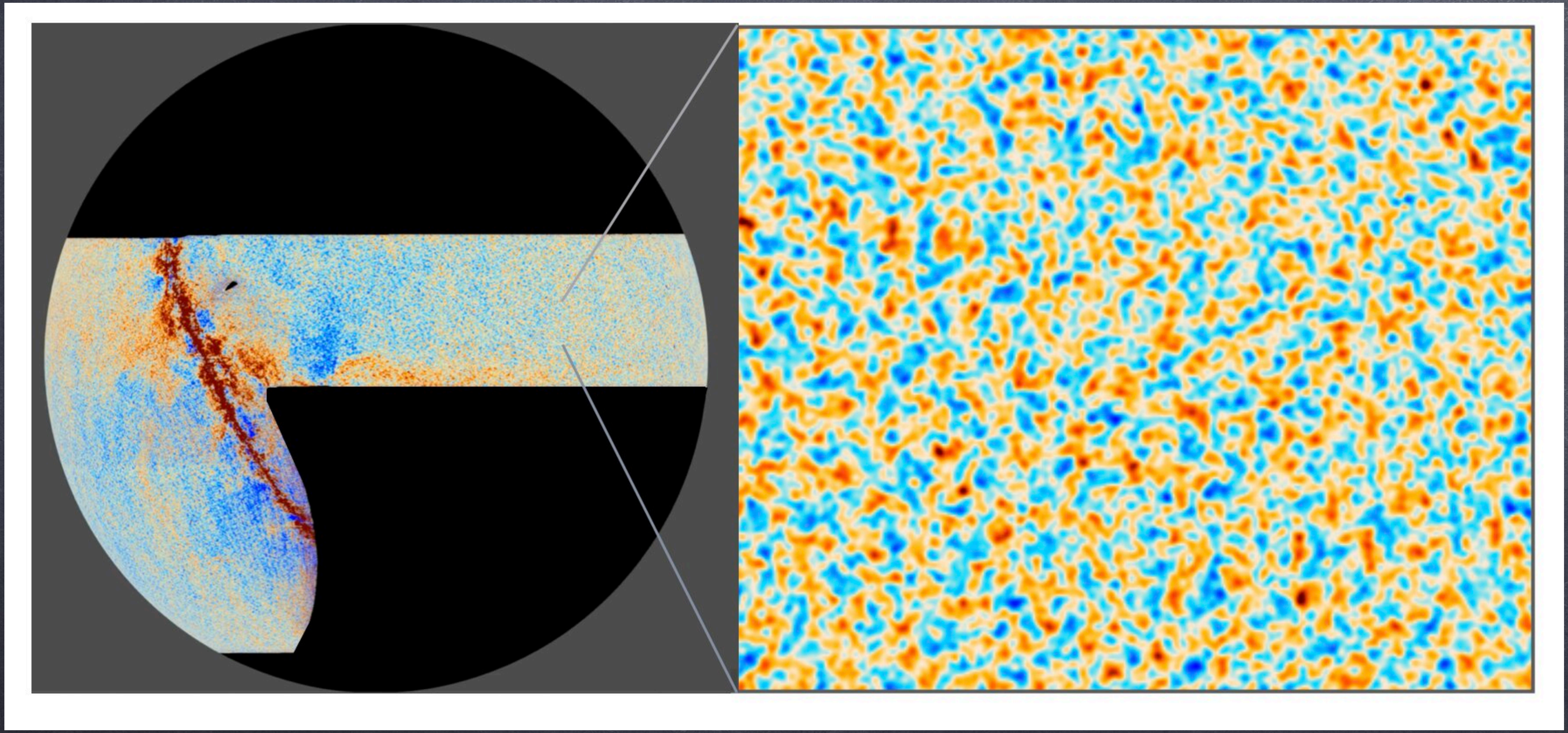
| Probe | | Epoch Probed |
|---|---|---|
| Cosmic Microwave Background (CMB) | ACT, Planck | ~380,000 years (recombination era) |
| Baryon Acoustic Oscillations (BAO) | DESI, DES | ~300,000 years to present |
| High-Redshift Galaxies | JWST | ~500 million years to ~1 billion years |
| X-ray/Radio (Early Universe) | | ~100 million years to ~1 billion years |
| Large Scale Structure (LSS) | | ~1 billion years to present |
| Galaxy Clusters | Euclid | ~1 billion years to present |
| Gravitational Lensing | KIDs | ~1 billion years to present |
| Cosmic Voids | | ~1 billion years to present |
| Type Ia Supernovae | DES | ~9 billion years to present |



Source: ESA and the Planck Collaboration / Gabriela Secara / Perimeter Institute

# CMB (ACT)

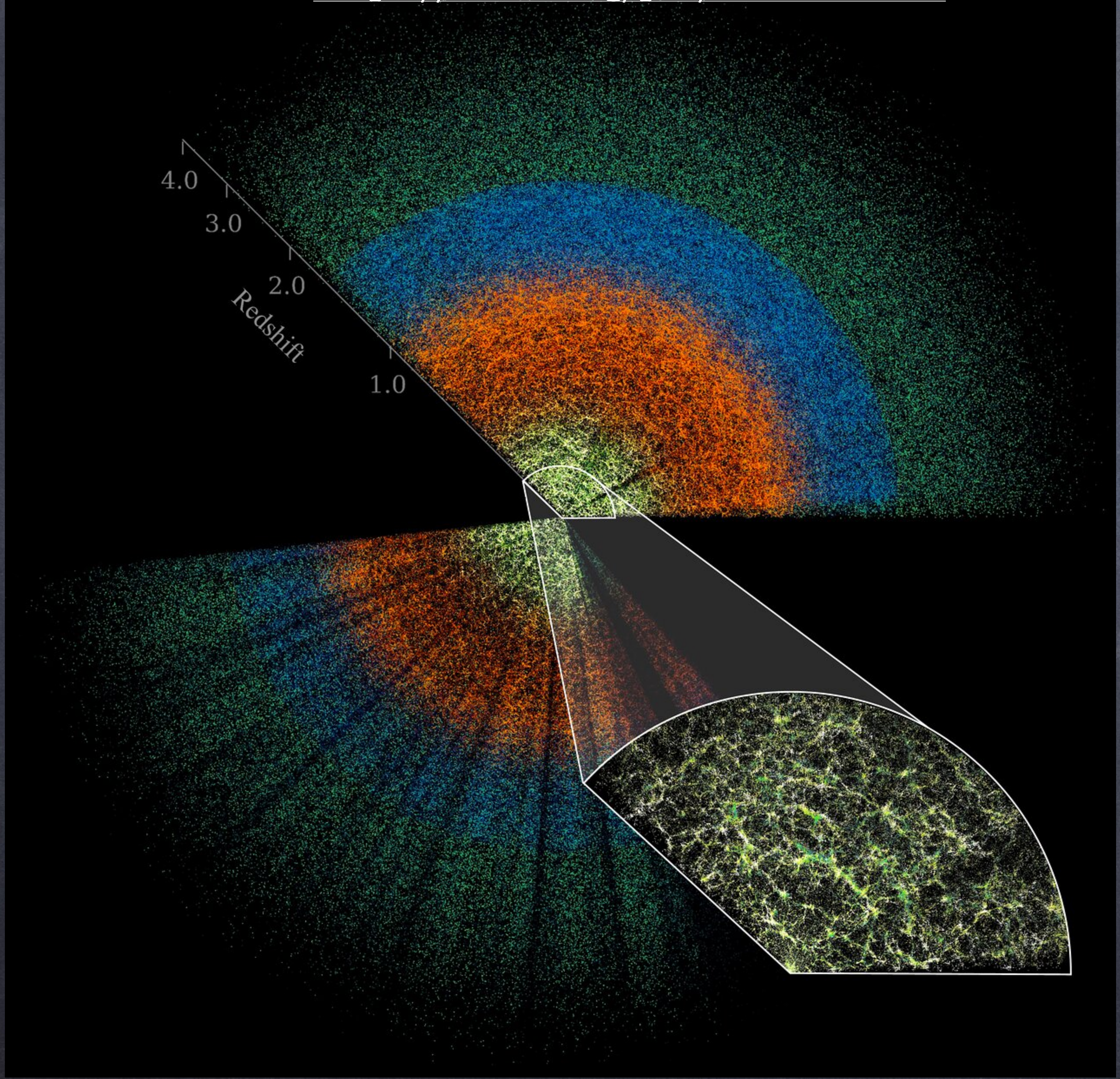
- bolometric millimetric instrument

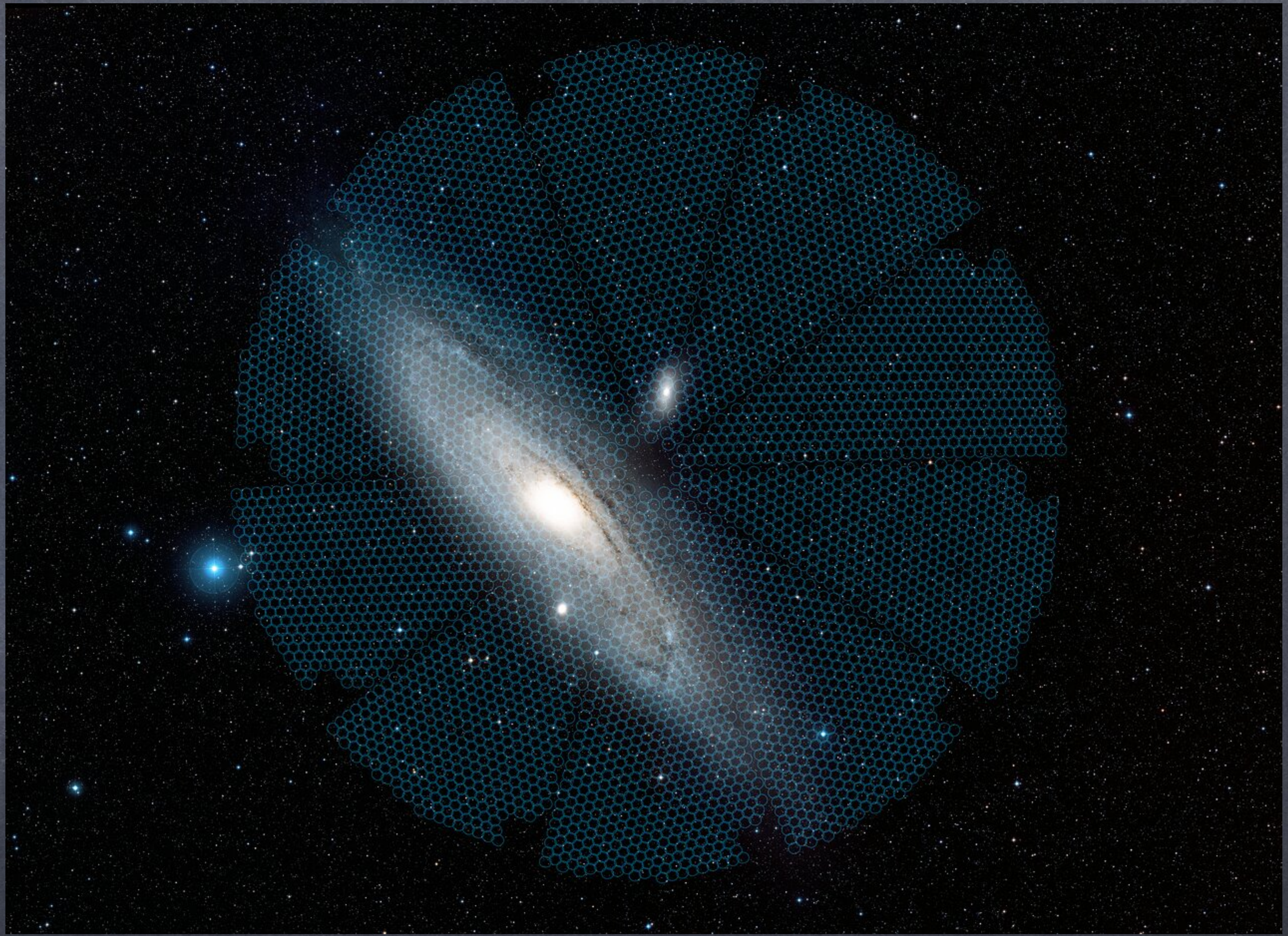


# BAO (DESI)

https://noirlab.edu/public/images/archive/search/page/2/?adv=&subject_name=DESI

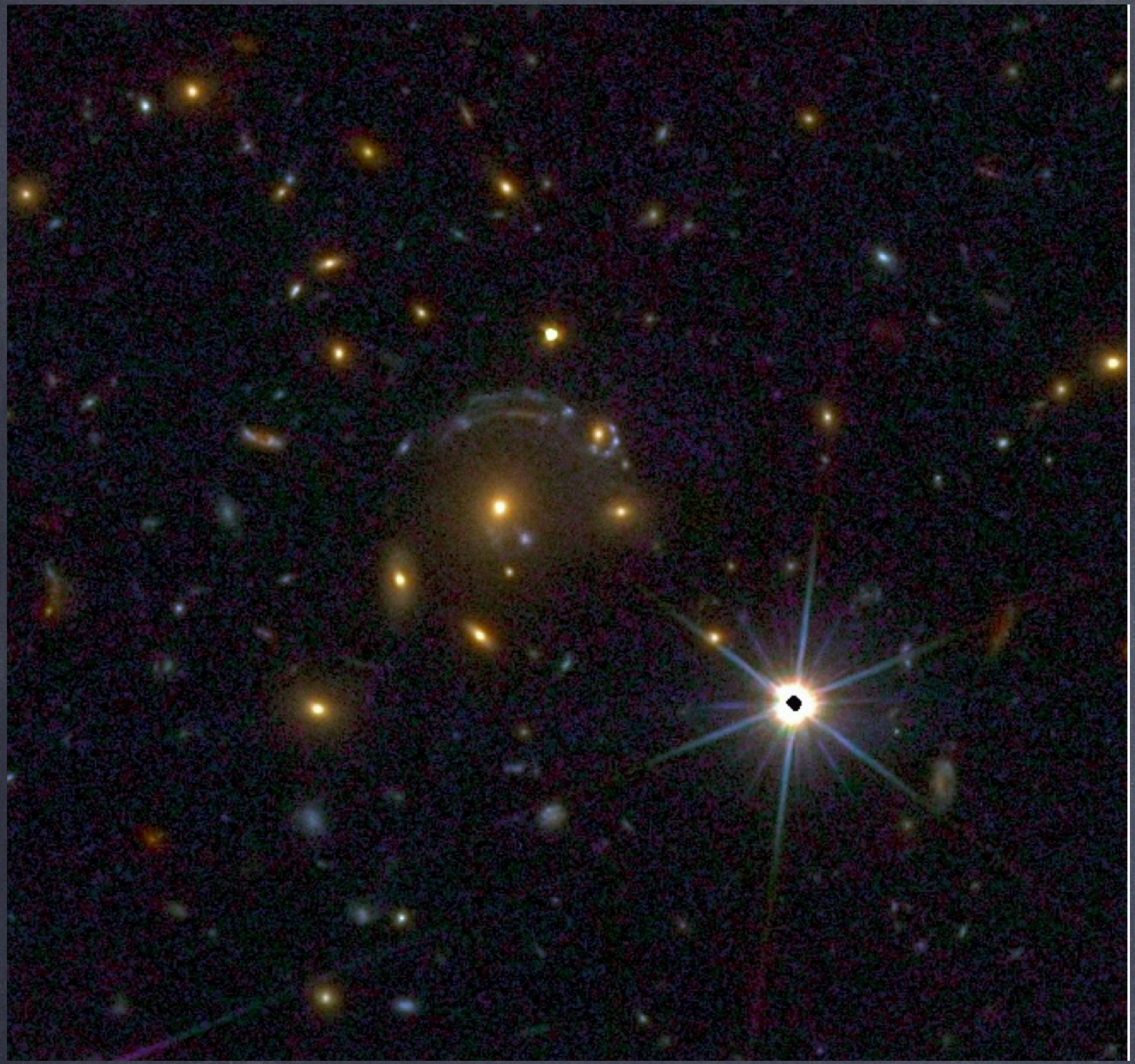
https://arxiv.org/pdf/2503.14738



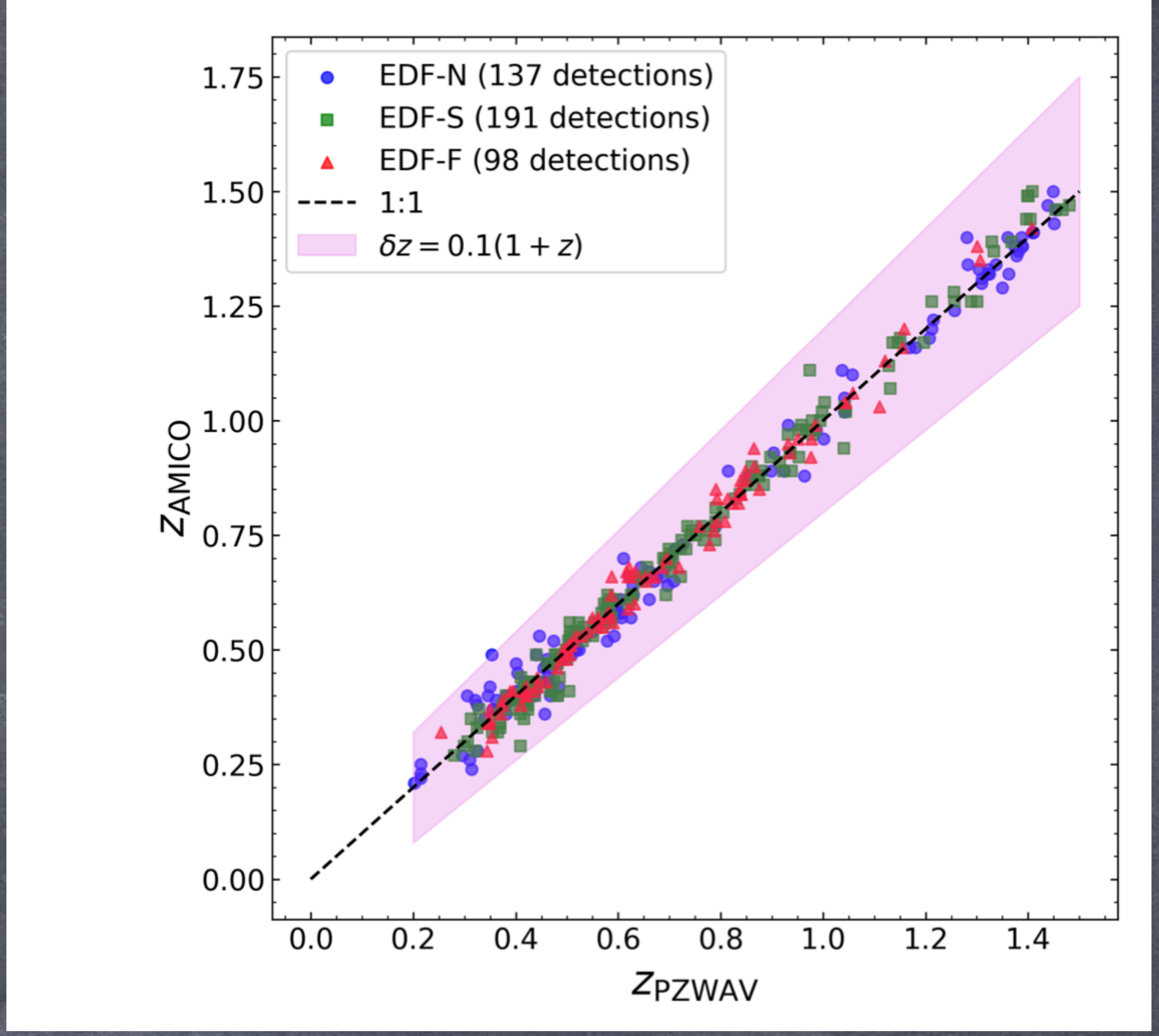



- 5000 fiber-positioning robots
- Baryonic Acoustic Oscillations

# Clusters (Euclid)



https://arxiv.org/pdf/2503.19196




- Detection of clusters
- photometric redshift

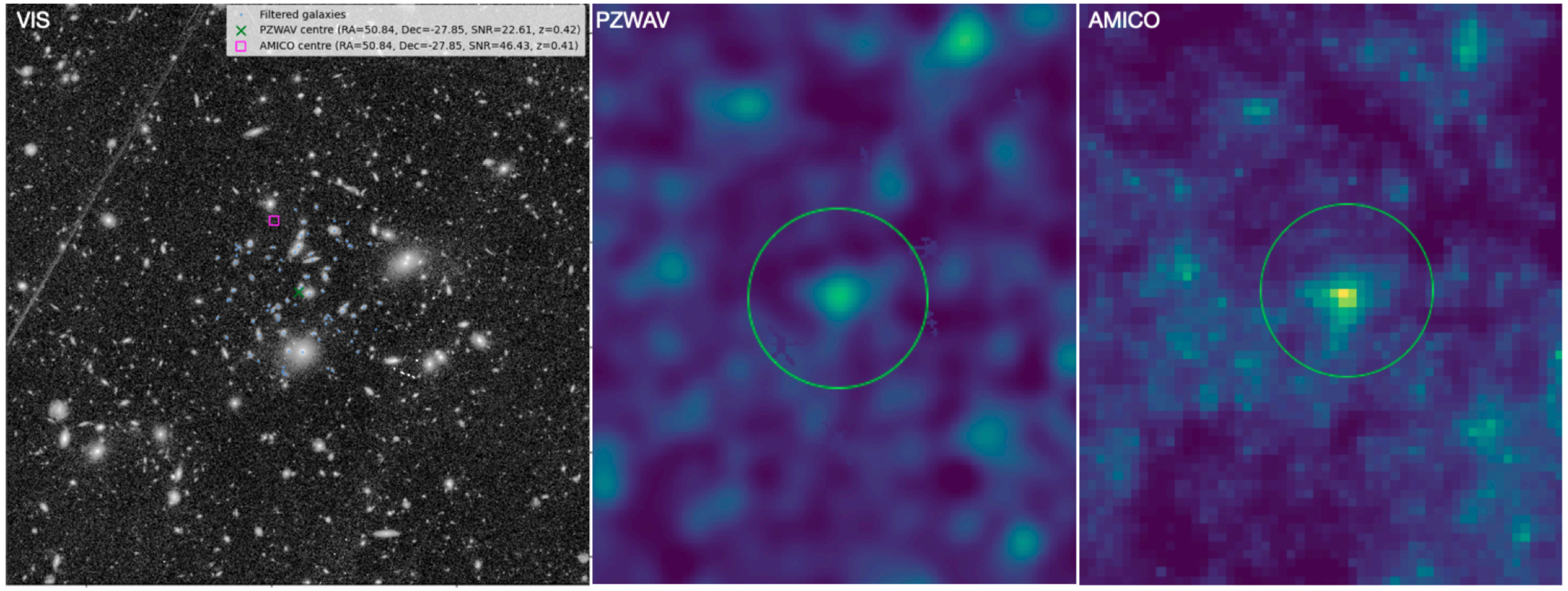
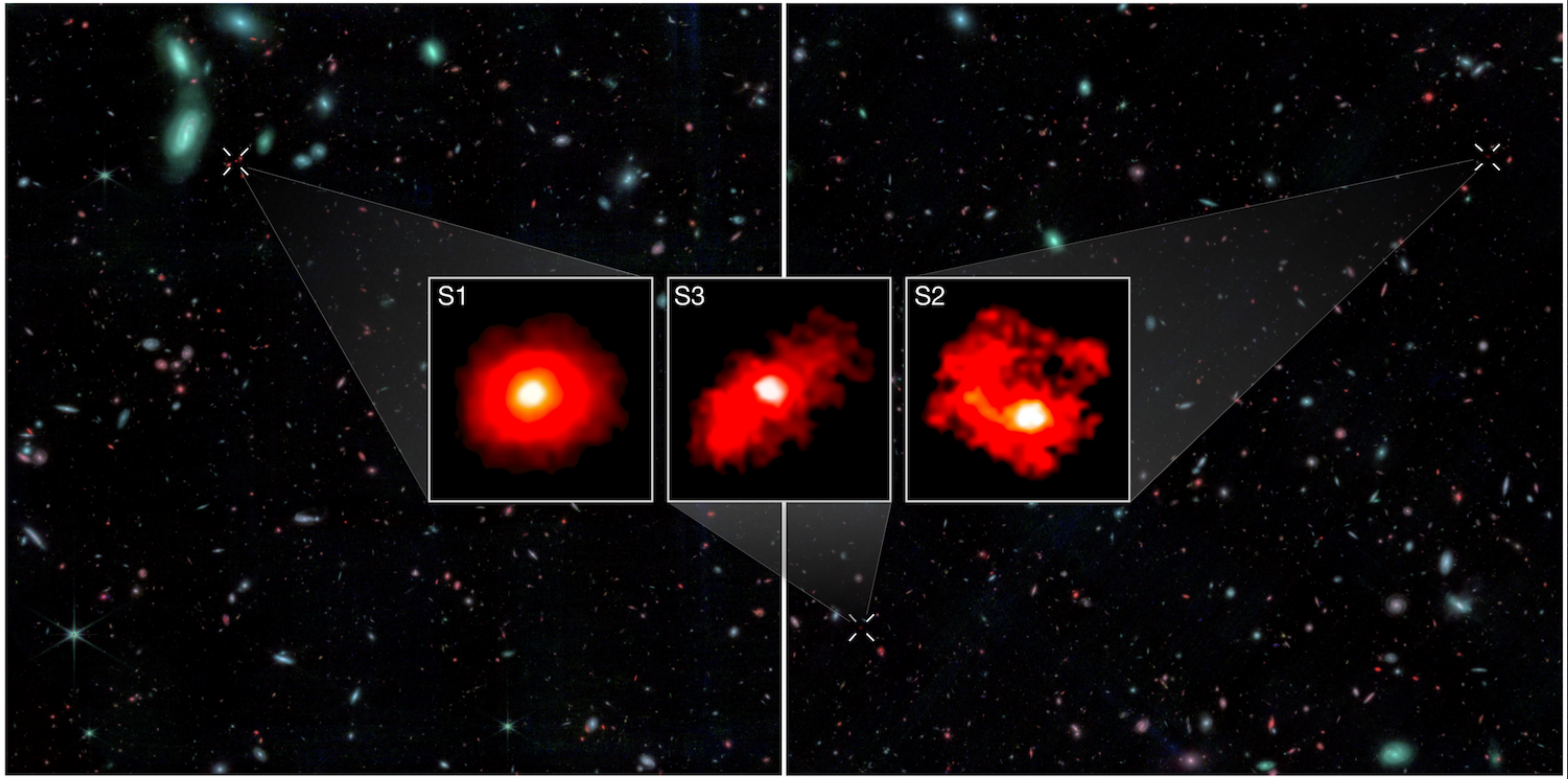


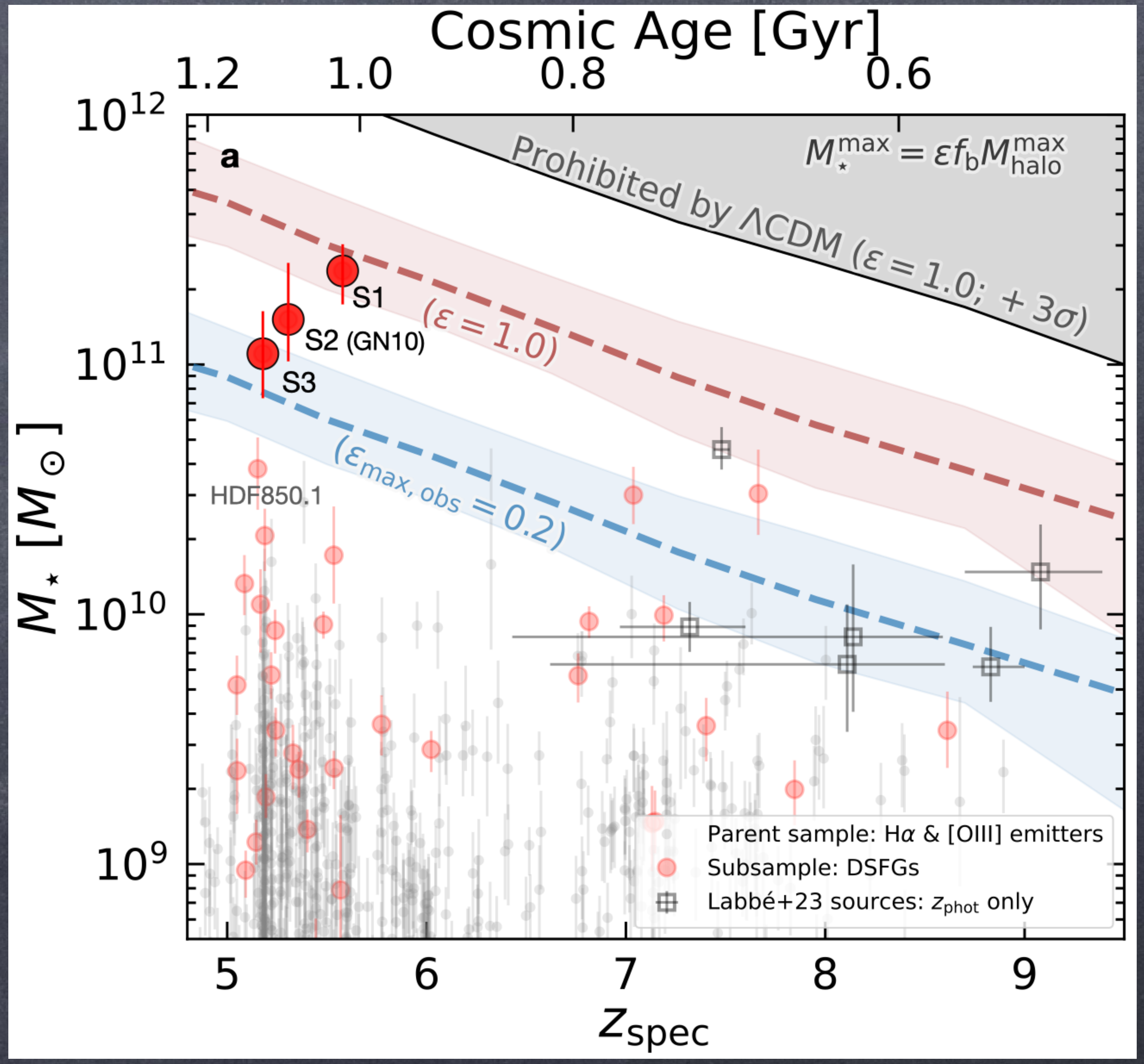

**Fig. 4.** Left: VIS zoom-in of $2' \times 2'$ at the location of a PZWav and AMICO-detected cluster, at redshift $z_p = 0.42$, located in the EDF-F. The cluster has a *Euclid* richness of $\lambda = 56.1$. The middle and right panels show PZWav and AMICO amplitude maps, respectively centred at the cluster position. The radius of the green circle is 6 arcminutes.

# Results

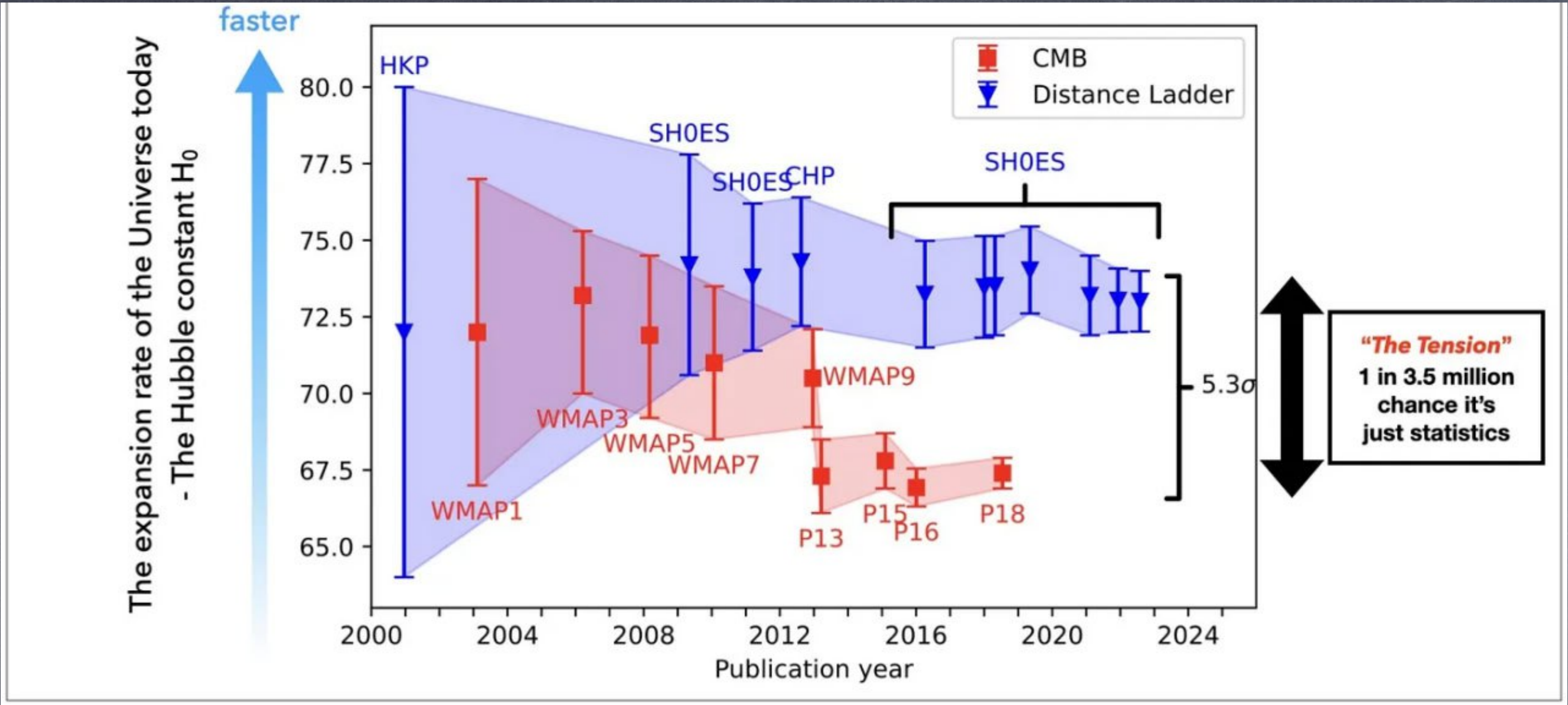
# Wrong Age of universe ?

- JWST



# Expansion rate: nobody agrees ?



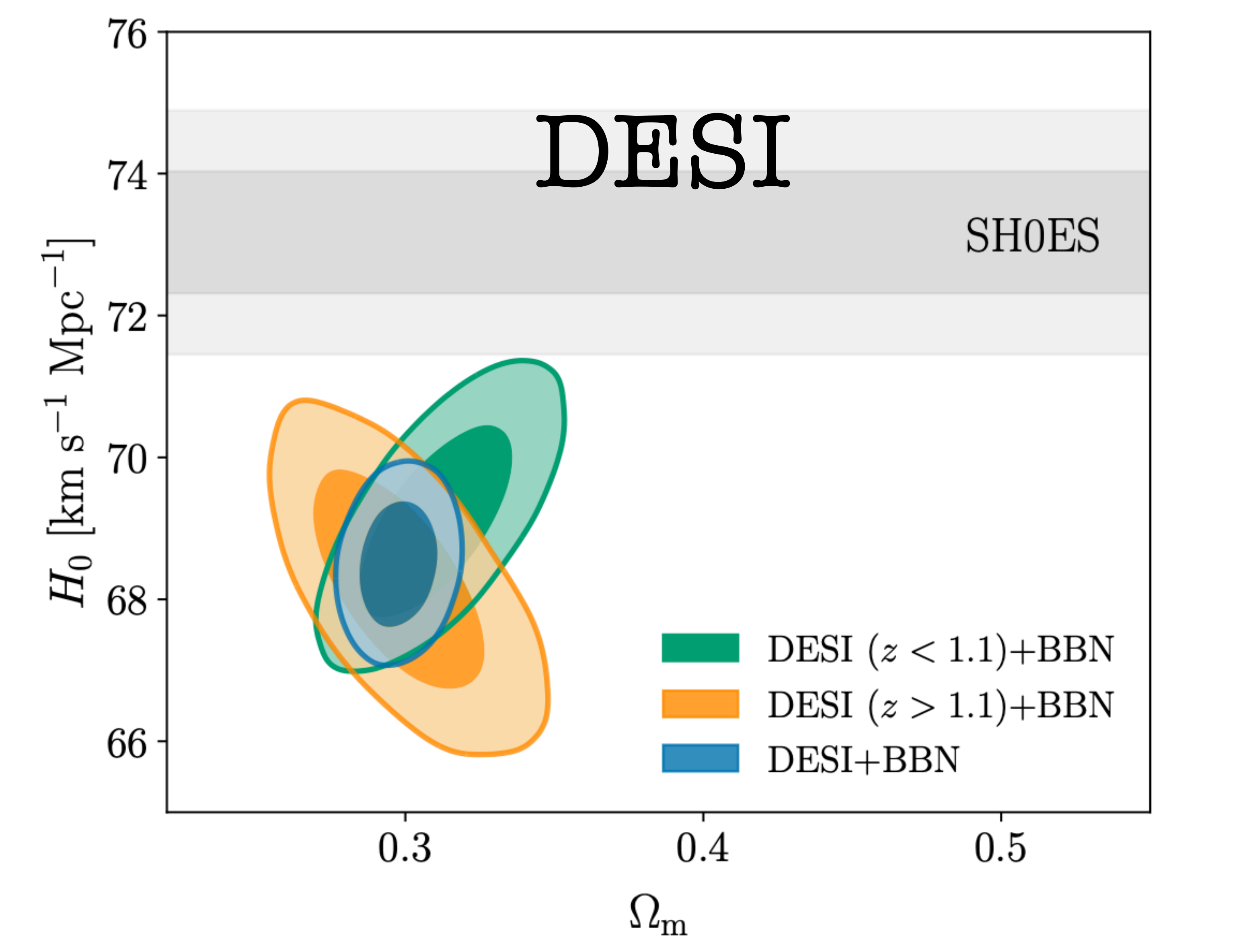
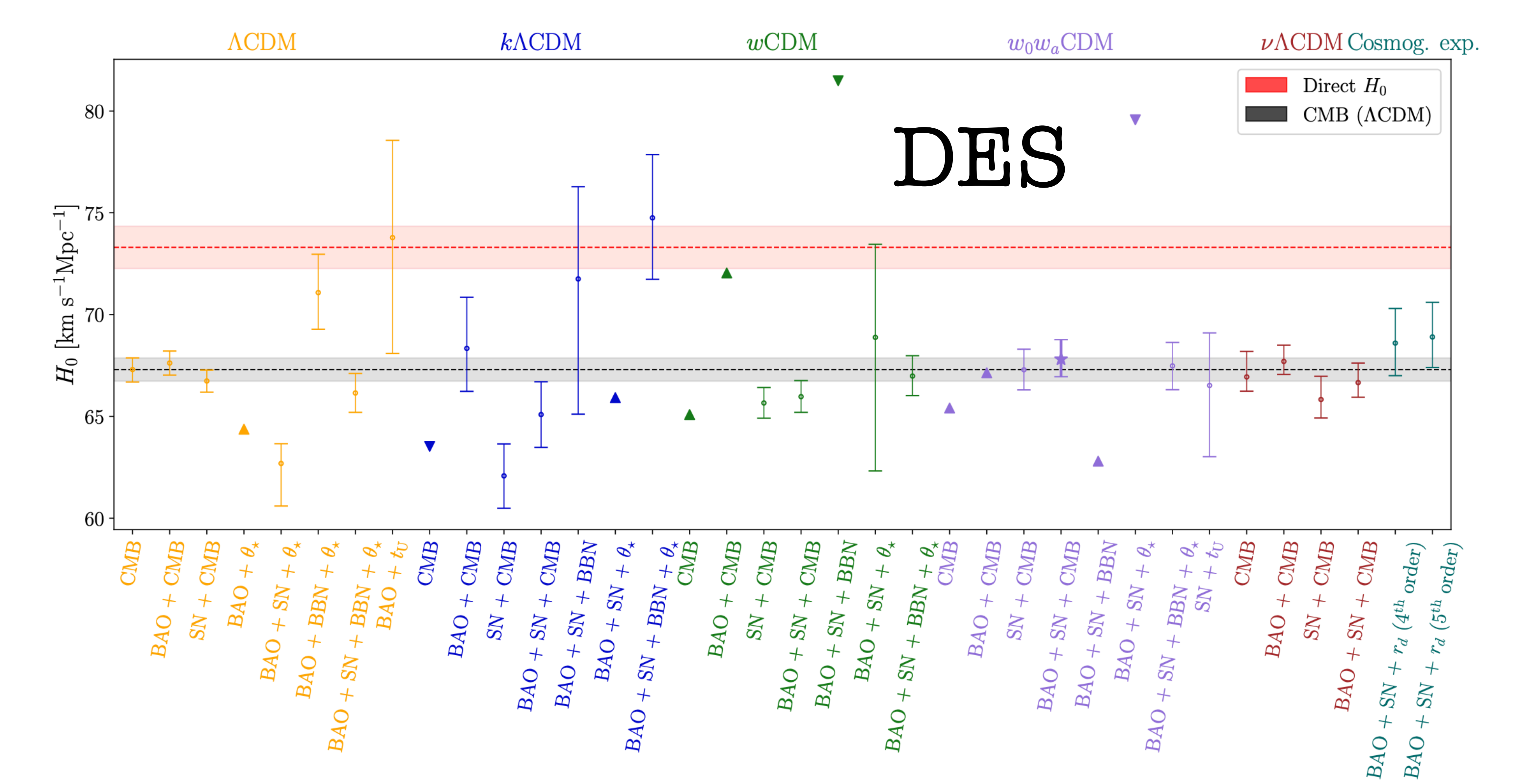
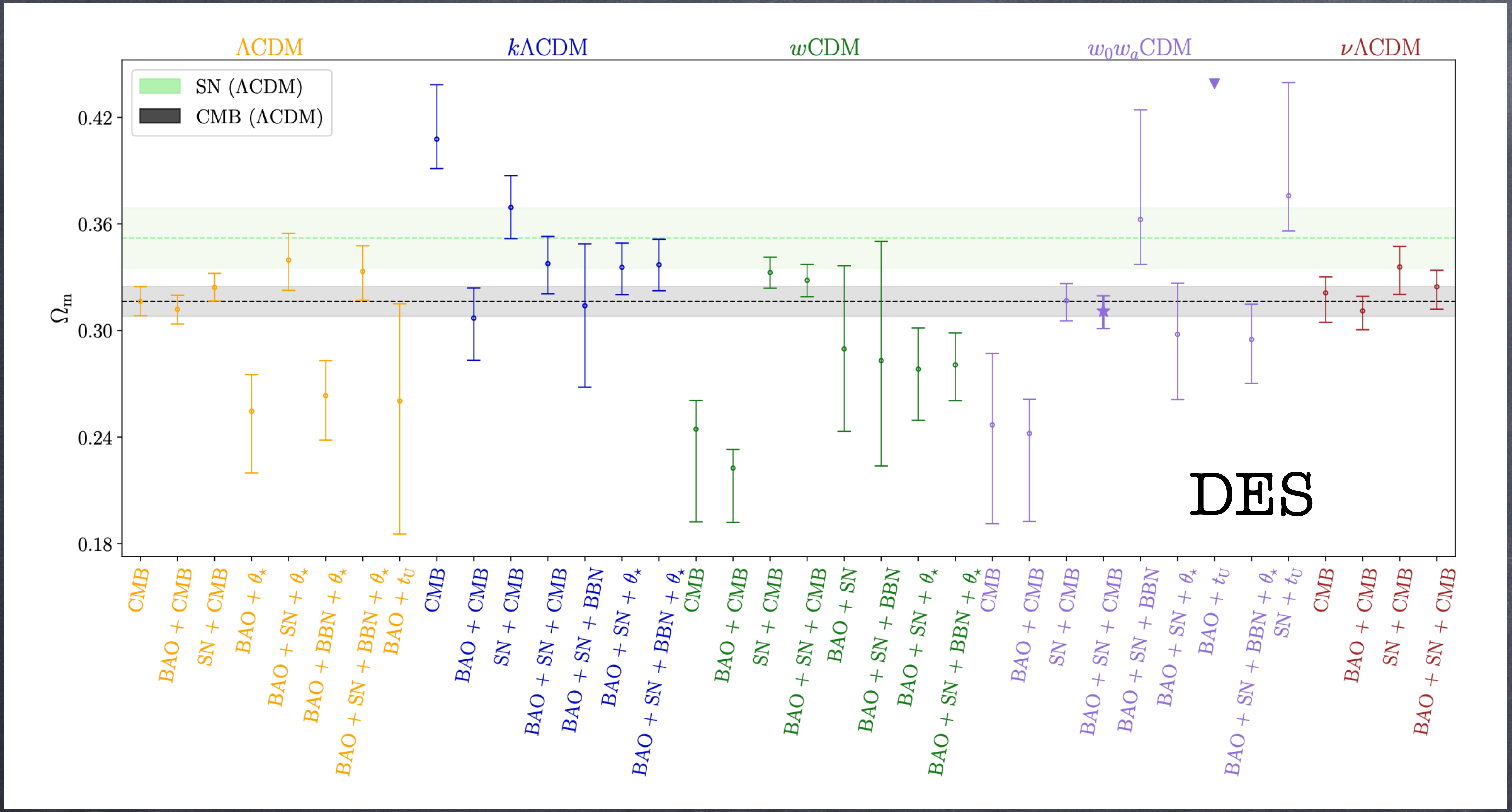
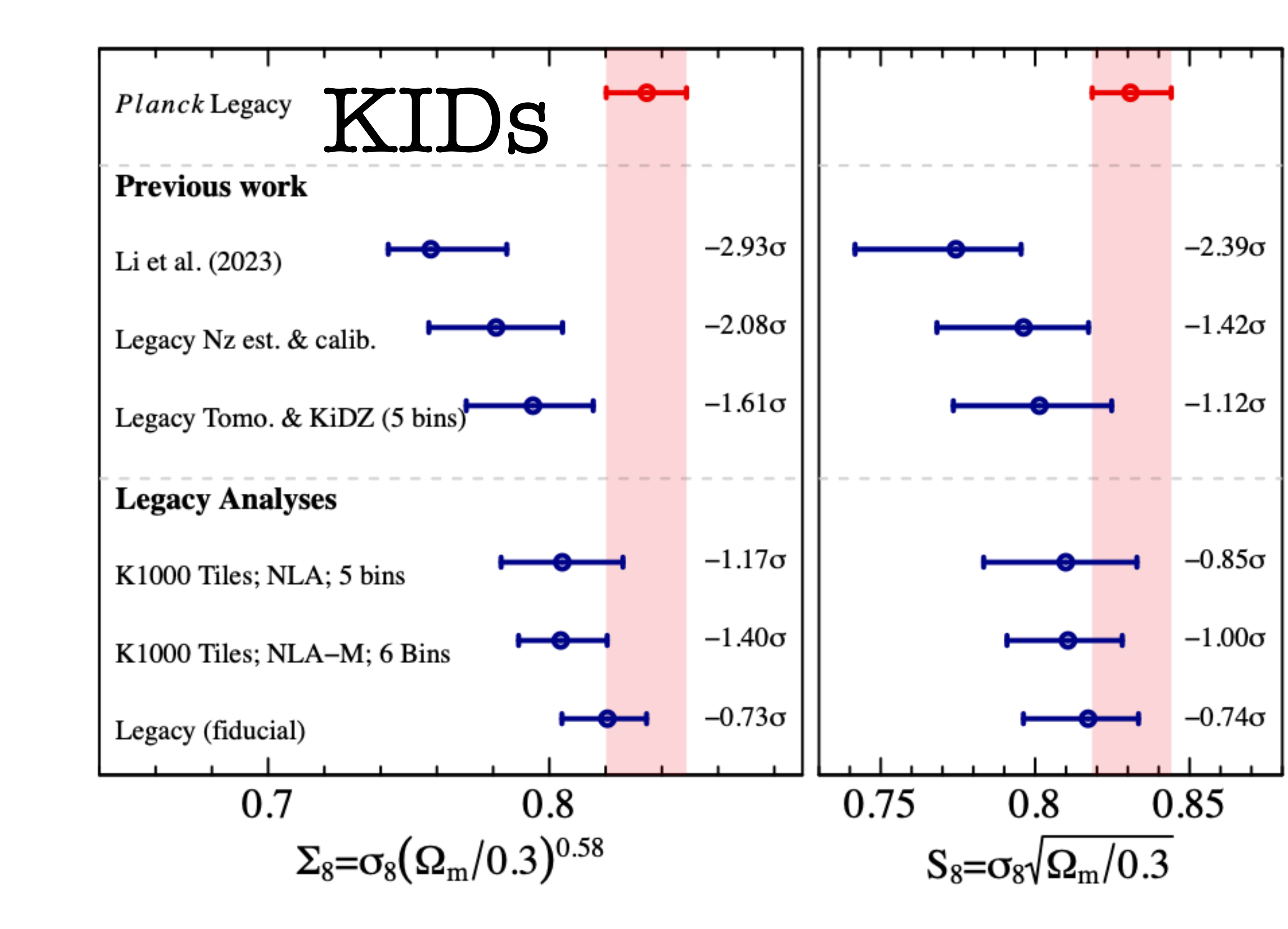




FIG. 9. Comparison of our $H_0$ constraints with respect to SH0ES, assuming a ΛCDM model (Section VI). We show the combination DESI+BBN for our low redshift and high redshift samples. For $z > 1.1$, only the **ELG2**, **QSO**, and Ly$\alpha$ tracers are included, while DESI($z < 1.1$) includes **BGS**, **LRGs** and the **LRG3+ELG1** tracer combinations. Both subsets are individually in $> 3\sigma$ tension with SH0ES measurements.



# Matter and density fluctuation, a tension ?



# Flat universe ?

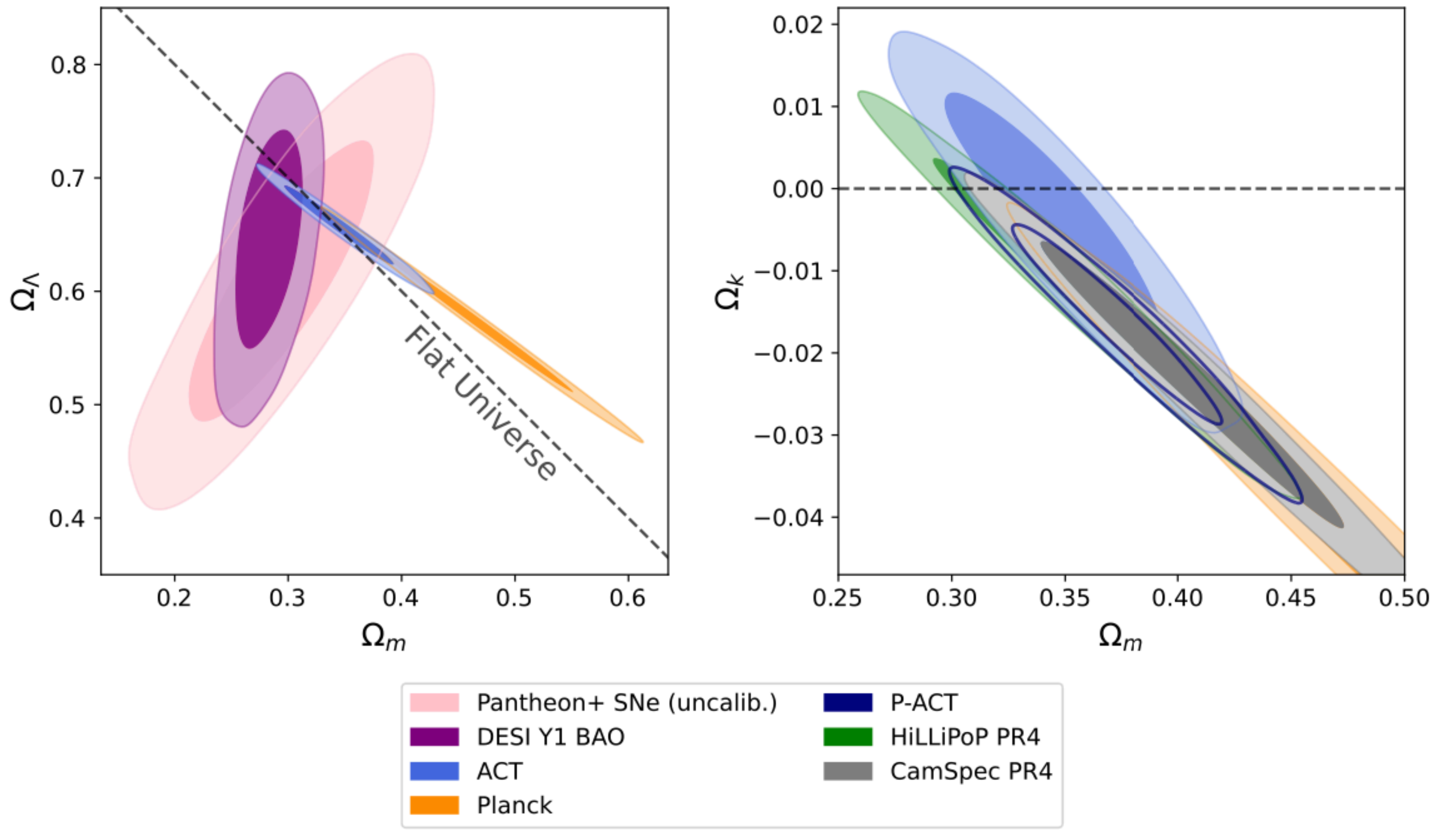



**Figure 20.** (Left) Measurements of background cosmological parameters, including possible non-zero spatial curvature, from DESI Y1 BAO, uncalibrated Pantheon+ supernovae (SNe), ACT, and *Planck* PR3. Increased concordance between the BAO, SNe, and CMB results is observed with the ACT data. (Right) Results from ACT, P-ACT, and the *Planck* NPIPE CamSpec (Rosenberg et al. 2022) and HiLLiPoP likelihoods (Tristram et al. 2024) are consistent with ΛCDM (zero curvature).

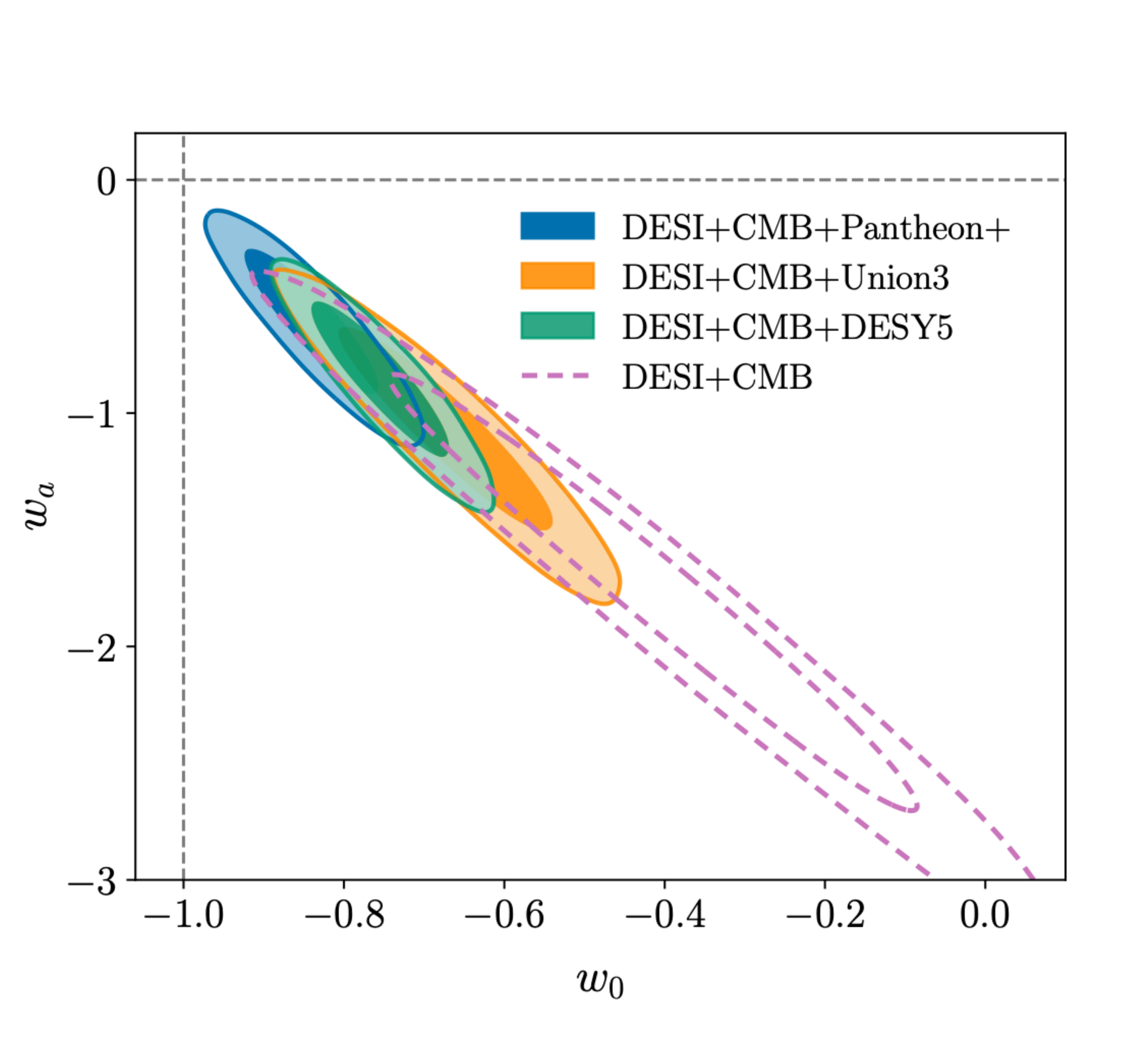
# Dark Energy: a constant or not ?

DES

$$\left.\begin{aligned} w_0 &= -0.673^{+0.098}_{-0.097} \\ w_a &= -1.37^{+0.51}_{-0.50} \end{aligned}\right\} \text{BAO+SN+CMB.}$$

| Datasets | $\Delta\chi^2_{\rm MAP}$ | Significance | $\Delta$(DIC) |
|---|---|---|---|
| DESI | −4.7 | 1.7σ | −0.8 |
| DESI+$(\theta_*, \omega_b, \omega_{bc})_{\rm CMB}$ | −8.0 | 2.4σ | −4.4 |
| DESI+CMB (no lensing) | −9.7 | 2.7σ | −5.9 |
| DESI+CMB | −12.5 | 3.1σ | −8.7 |
| DESI+Pantheon+ | −4.9 | 1.7σ | −0.7 |
| DESI+Union3 | −10.1 | 2.7σ | −6.0 |
| DESI+DESY5 | −13.6 | 3.3σ | −9.3 |
| DESI+DESY3 (3×2pt) | −7.3 | 2.2σ | −2.8 |
| DESI+DESY3 (3×2pt)+DESY5 | −13.8 | 3.3σ | −9.1 |
| DESI+CMB+Pantheon+ | −10.7 | 2.8σ | −6.8 |
| DESI+CMB+Union3 | −17.4 | 3.8σ | −13.5 |
| DESI+CMB+DESY5 | −21.0 | 4.2σ | −17.2 |

TABLE VI. Summary of the difference in the effective $\chi^2_{\rm MAP}$ value (defined as twice the negative log posterior at the maximum posterior point) for the best-fit $w_0w_a$CDM model relative to the best ΛCDM model with $w_0 = -1$, $w_a = 0$, for fits to different combinations of datasets as indicated. The third column lists the corresponding (frequentist) significance levels given 2 extra free parameters, and the final column shows the results for $\Delta(\rm DIC) = DIC_{w_0w_a CDM} - DIC_{\Lambda CDM}$. As a rule of thumb, Δ(DIC) values < −5 indicate a ‘strong’ preference for $w_0w_a$CDM and values < −10 a ‘decisive’ preference [144].



# Other models tested (DES)

$$\frac{H(a)^2}{H_0^2} = \begin{cases} \Omega_m a^{-3} + (1-\Omega_m) & \text{for } \Lambda\text{CDM} \\ \Omega_m a^{-3} + (1-\Omega_m) a^{-3(1+w)} & \text{for } w\text{CDM} \\ \Omega_m a^{-3} + (1-\Omega_m) a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} & \\ & \text{for } w_0 w_a\text{CDM} \\ \Omega_m a^{-3} + (1-\Omega_m-\Omega_k) + \Omega_k a^{-2} & \\ & \text{for } k\Lambda\text{CDM} \end{cases} \quad (11)$$

| | Tension ($\sigma$) | | | | |
|---|---|---|---|---|---|
| Datasets | **ΛCDM** | ***k*ΛCDM** | ***w*CDM** | **$w_0 w_a$CDM** | ***ν*ΛCDM** |
| BAO vs SN | 0.5 | 0.0 | 0.0 | 0.3 | 0.2 |
| CMB vs SN | 1.7 | 1.5 | 1.3 | 1.1 | 1.2 |
| CMB vs BAO | 2.0 | 3.2 | 0.6 | 0.1 | 2.0 |
| SN vs BAO + $\theta_\star$ | 2.4 | - | - | - | - |
| CMB vs BAO + SN + BBN | 2.2 | 3.3 | 2.2 | 1.2 | - |
| SN vs BAO + BBN | 0.4 | - | - | - | - |
| SN vs BAO + BBN + $\theta_\star$ | 2.9 | 0.5 | 0.0 | 0.9 | 2.6 |
| BAO + CMB vs SN | 2.1 | 1.5 | 2.5 | 1.6 | 2.1 |
| CMB vs BAO + SN + BBN + $t_U$ | 1.5 (0.8) | - | - | 0.9 (0.9) | - |

| | Deviations from **ΛCDM** ($\sigma$) | | |
|---|---|---|---|
| Dataset | ***k*ΛCDM** | ***w*CDM** | **$w_0 w_a$CDM** |
| BAO + SN + BBN | 1.4 | 1.4 | 1.8 |
| BAO + SN + BBN + $t_U$ | – | – | 2.0 (2.7) |
| BAO + SN + $\theta_\star$ | 2.5 | 2.7 | 2.3 |
| BAO + SN + $\theta_\star$ + BBN | 2.8 | 3.1 | 2.8 |
| BAO + SN + $\theta_\star$ + BBN + $t_U$ | – | – | 2.9 (2.8) |
| SN | 1.3 | 1.6 | 2.0 |
| CMB | 3.0 | 1.7 | 2.5 |
| SN + CMB | 2.9 | 2.0 | 2.2 |
| BAO + CMB | 0.6 | 2.8 | 3.4 |
| **BAO + SN + CMB** | 1.2 | 1.8 | **3.2** |

# Conclusions

## DES

of data characterization and analysis methodology. Additionally, a physical model of cosmic acceleration that is more well motivated from first principles would help establish a viable alternative to ΛCDM.

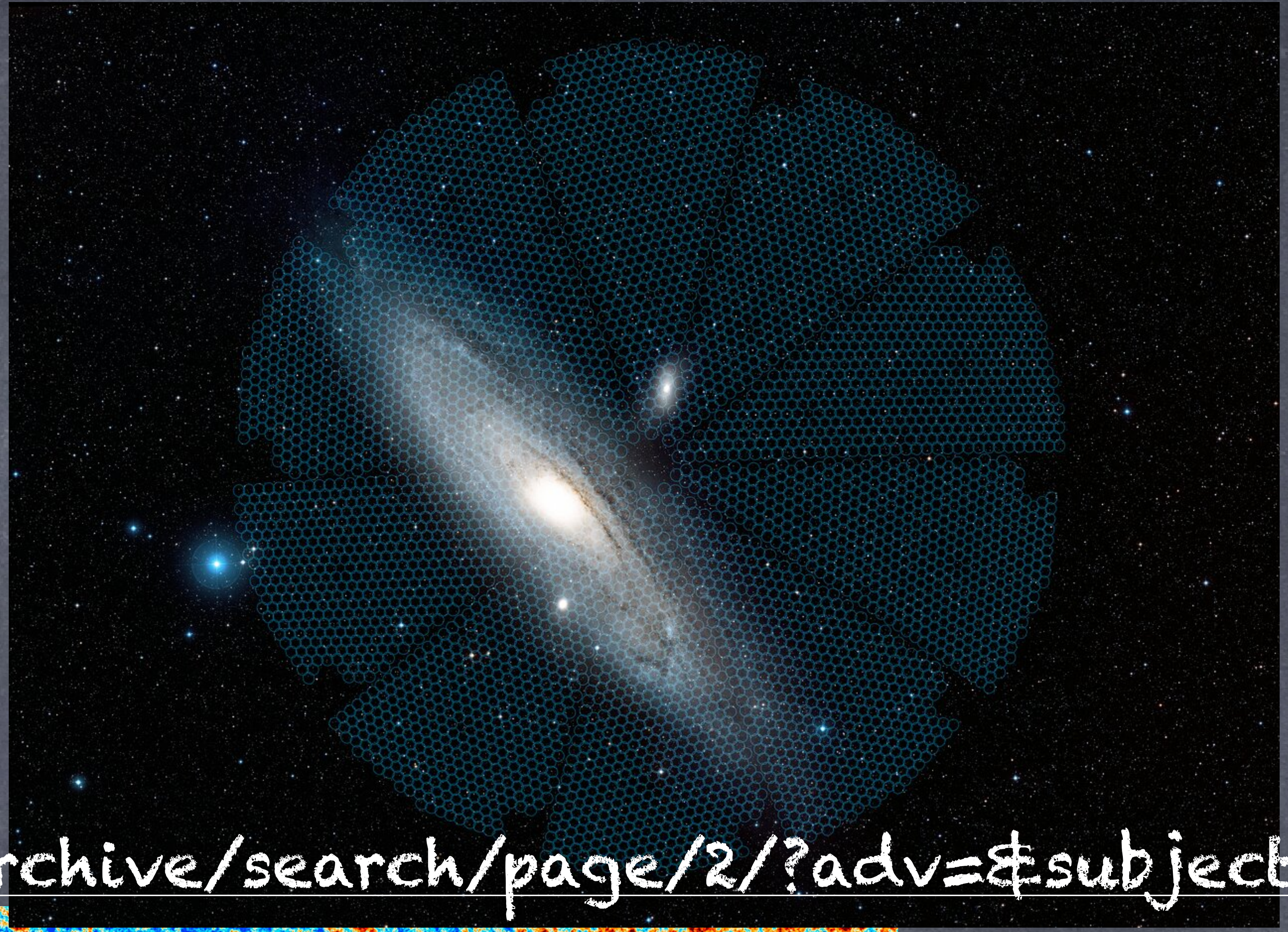
DES will soon be releasing analyses that additionally probe the growth of structure and the density perturbations in the late-time Universe. These include studies of weak gravitational lensing, galaxy clustering, cluster counts, cross-correlations among those probes and also with external datasets, such as the CMB. These upcoming results will both provide better constraints on the properties of our cosmological models and provide crucial cross-checks of whether the emerging paradigm shift is self-consistent across probes. Certainly, the legacy of DES will be a rich source of insight for state-of-the art cosmological analyses in the coming years.

## DESI

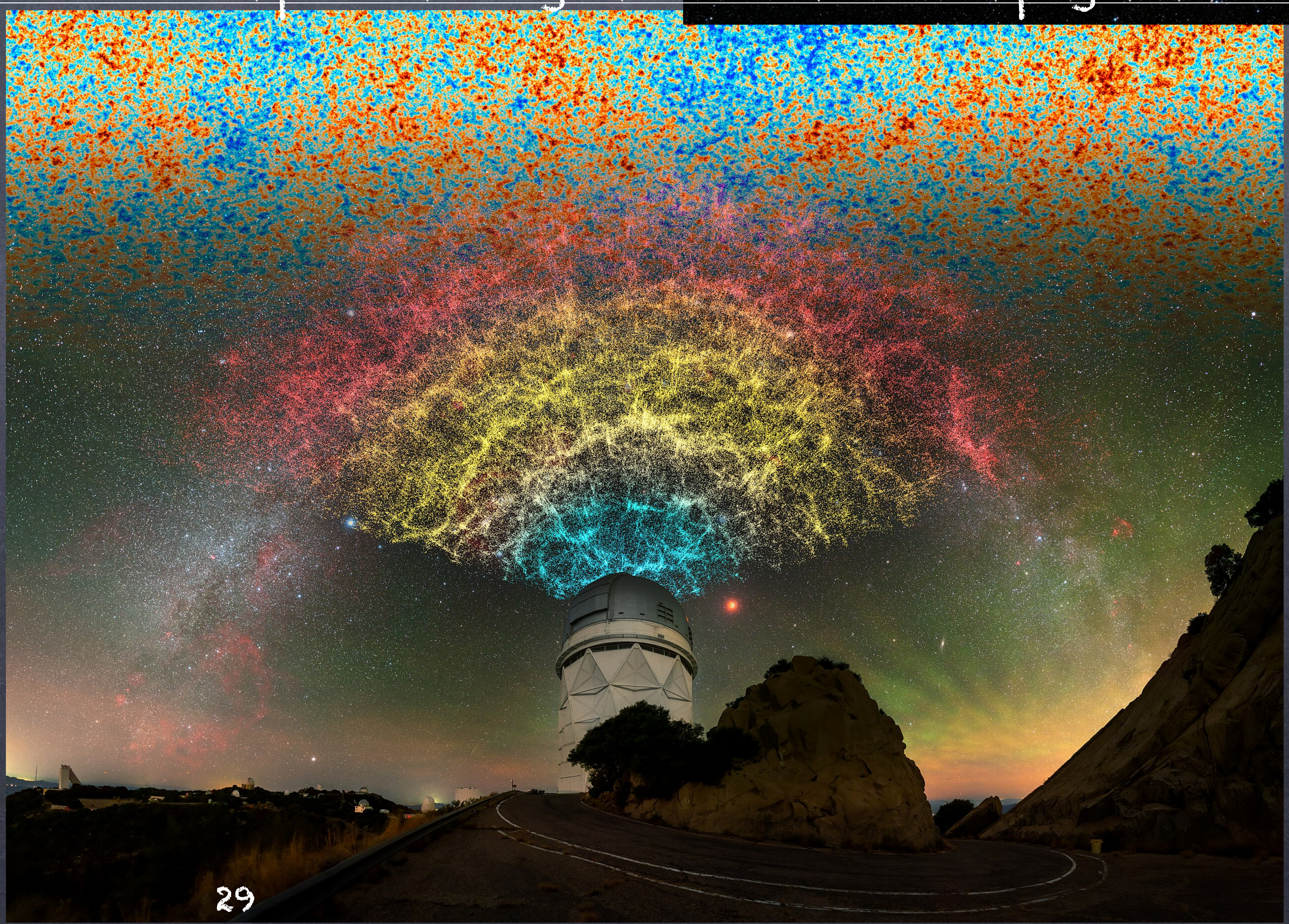
Nevertheless, it is becoming clear that unless some unidentified systematic error affects one or several of the different cosmological datasets used, the challenge to the ΛCDM model has increased. Sharper measurements from future DESI analyses and from other experiments will show whether these challenges to the standard cosmological model herald yet another radical transformation in our understanding of the evolution and energy content of the Universe.

# Back-up

# DESI

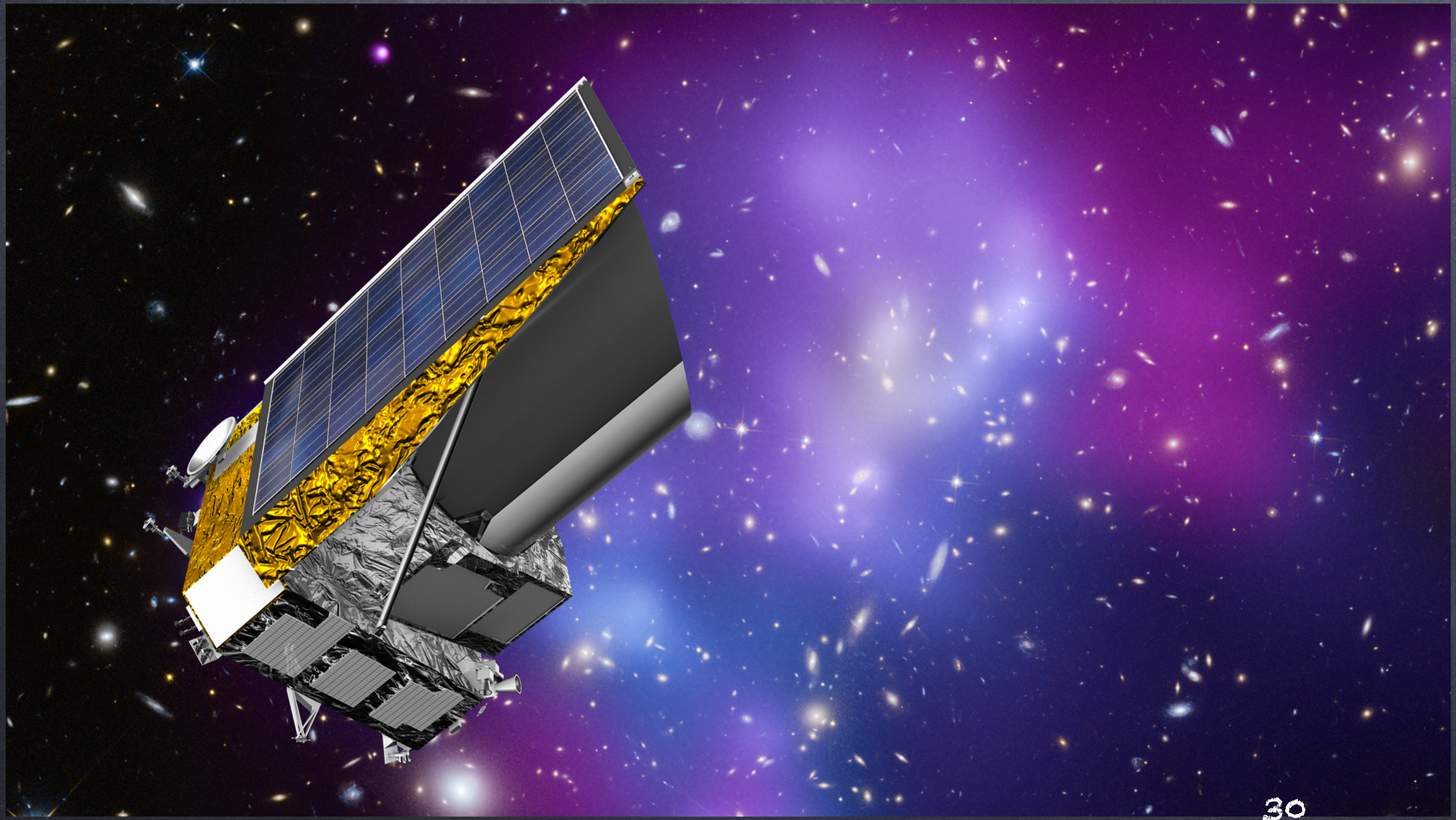


- Dark Energy Spectroscopic Instrument
  - 5,000 fiber-positioning robots / 4m telescope / Arizona
  - 3D map of galaxies/quasars / May 2021- 5 years
  - 900 persons
  - https://noirlab.edu/public/images/archive/search/page/2/?adv=&subject_n



# Euclid

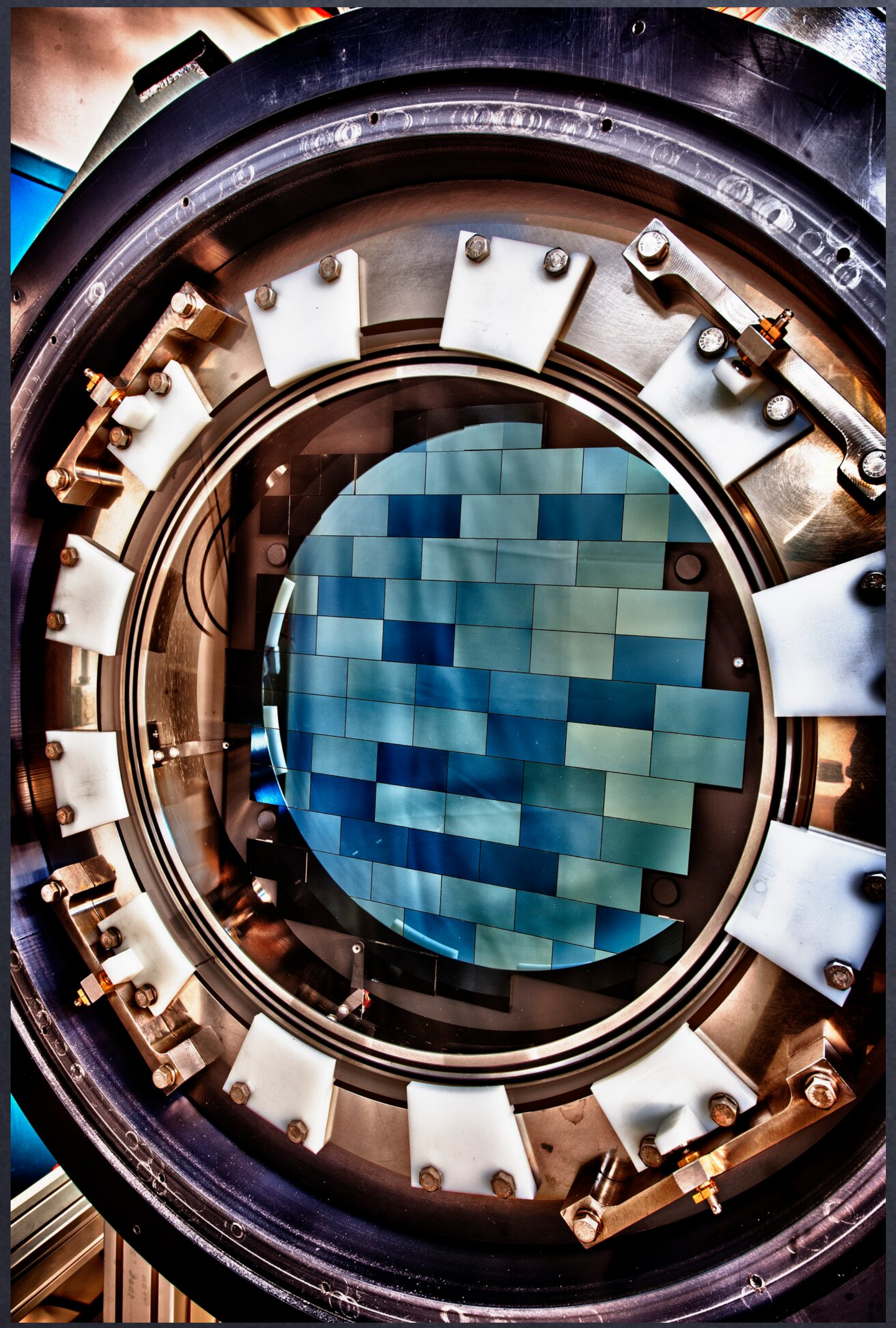
- 1.2m mirror , imager VIS et spectro-imageur NISP. observations des galaxies (juillet 2023), point L2

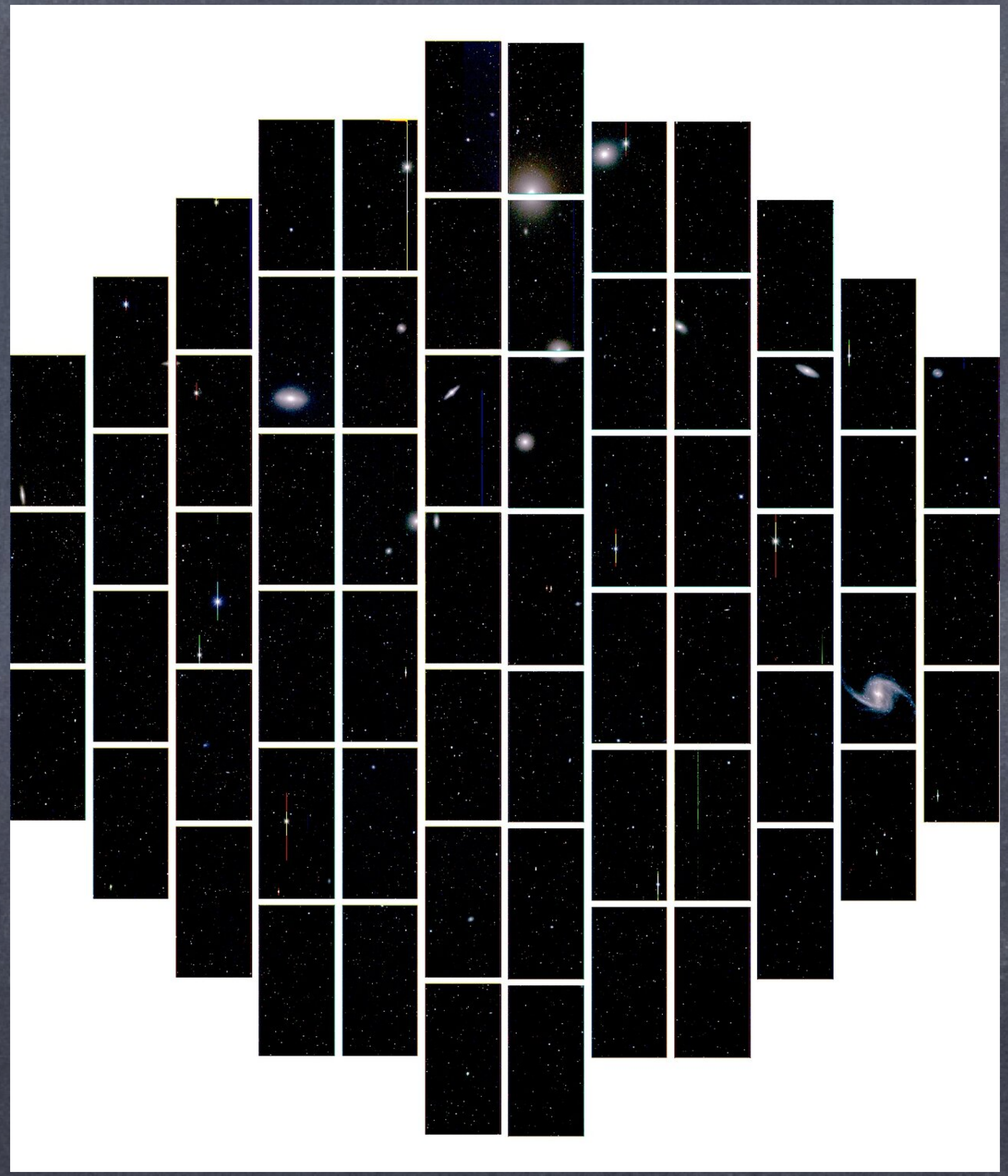


# DES

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21

- 400 scientists
- Chili
- 2013-2019



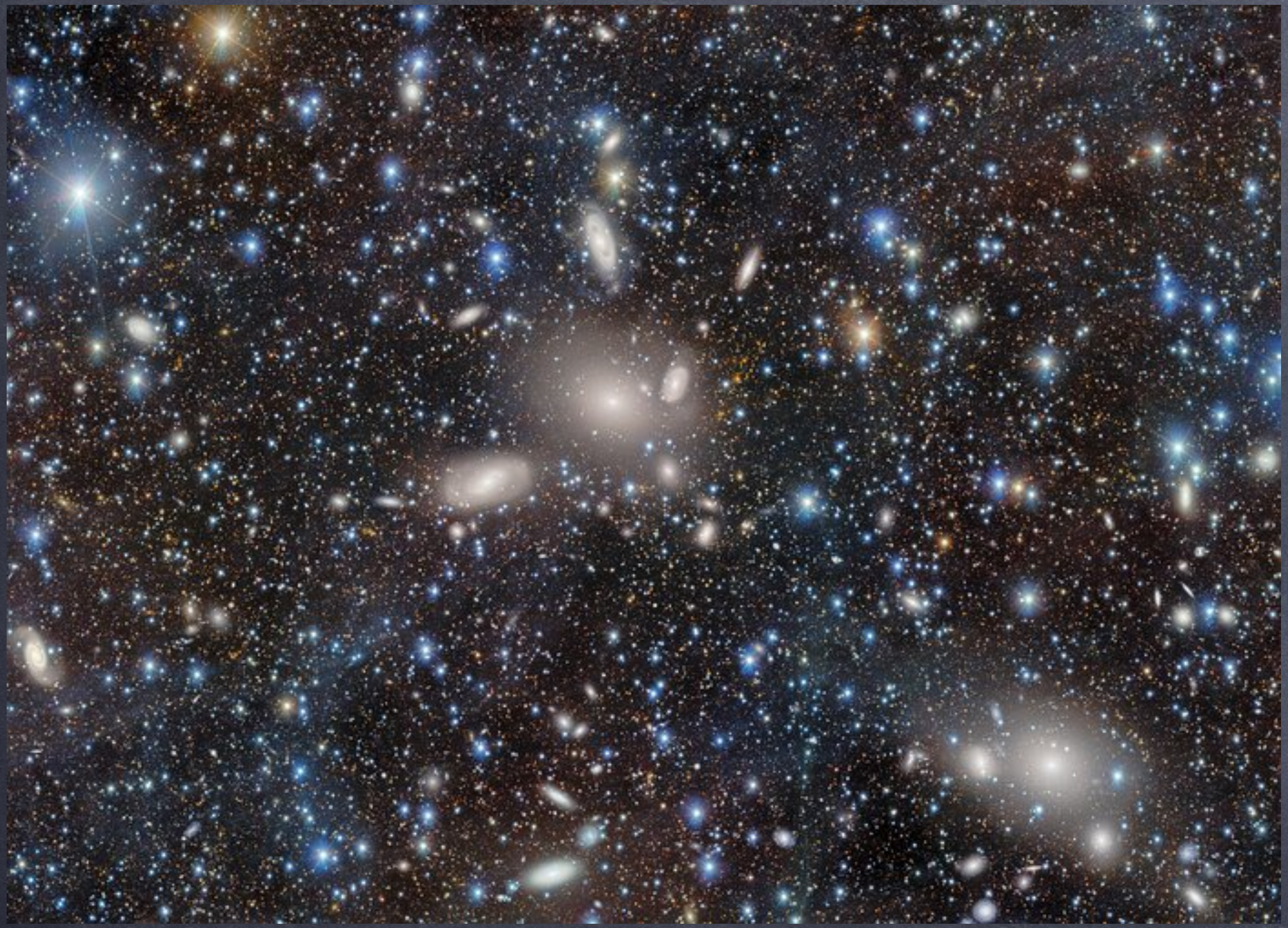


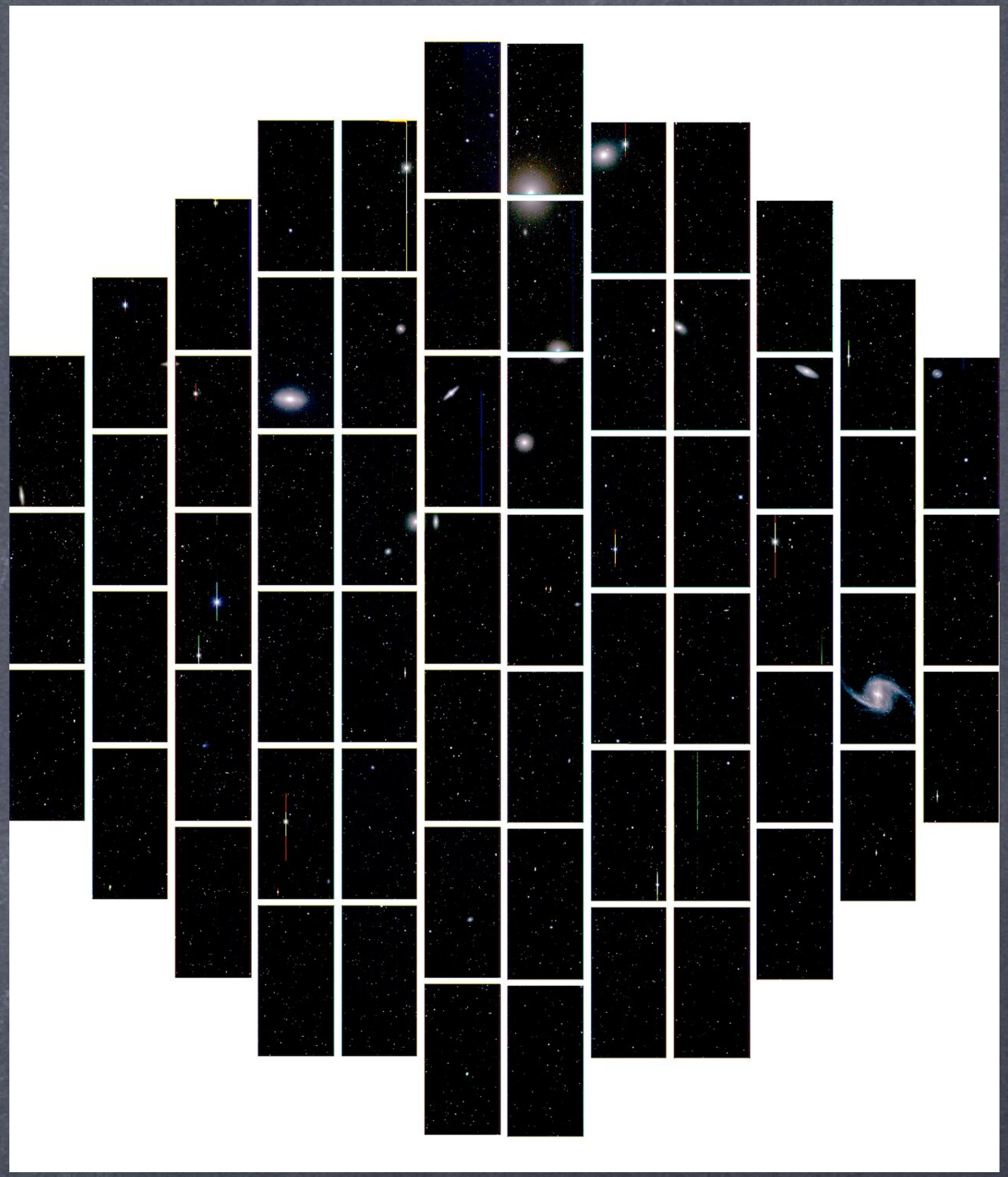

# KIDS

# DES

https://noirlab.edu/public/images/archive/search/?adv=&instrument=21

- https://arxiv.org/pdf/2503.06712





- 16 millions galaxies + >1600 SN Type 1
- 5,000 deg of the southern sky, with 5 filters (*grizY*) to a depth of $i$ = 23.8

# JSWT