# Challenges in Cosmology in the ‘40s

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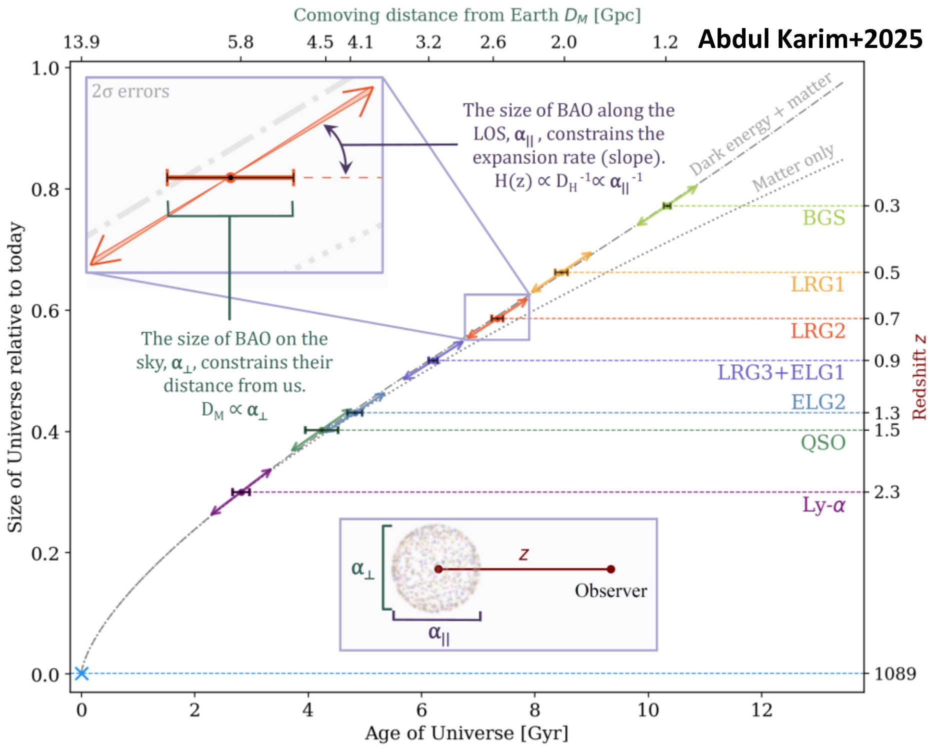
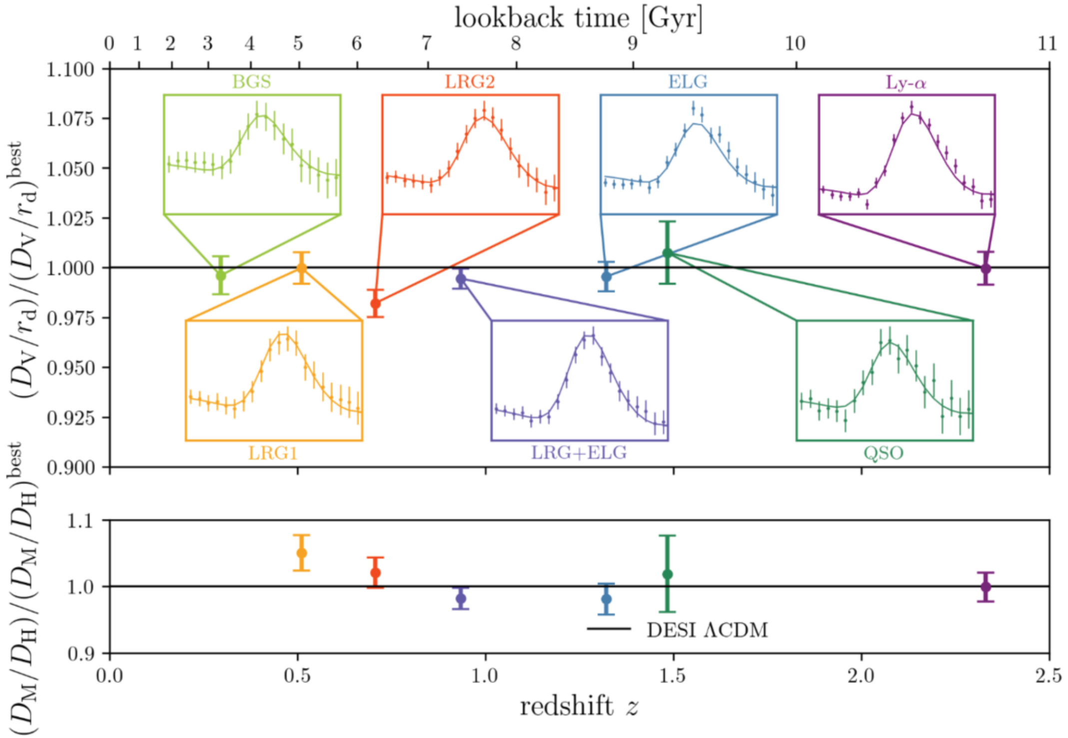
# The state of play in Cosmology: a list of questions

In the last decades observed data drove to the **standard $\Lambda$CDM model of Cosmology**, composed by Cosmological Constant and Cold Dark Matter… but:

- Is Dark Energy a Cosmological Constant?
- What is the nature of Dark Energy?
- Is there Early Dark Energy ?
- What is the nature of Cold Dark Matter?
- How many massive neutrinos are there?
- What is the sum of neutrino masses?
- Has there been an inflationary phase in the primordial universe?
- Is there a consensus on the model of Inflation?
- What is the value of $H_0$?
- What is the value of $\sigma_8$?
- Is this really a *golden* age for Cosmology?

# The state of play: DR2 BAO from DESI
## (first blinded analysis)




Overall size

Anisotropy

Credit: A. de Mattia/DESI collaboration

$$r_{||} = \frac{c\Delta z}{H(z)}$$

$$r_\perp = (1+z)D_A(z)\Delta\theta$$

$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z)}{1+z}dz\right]}$$

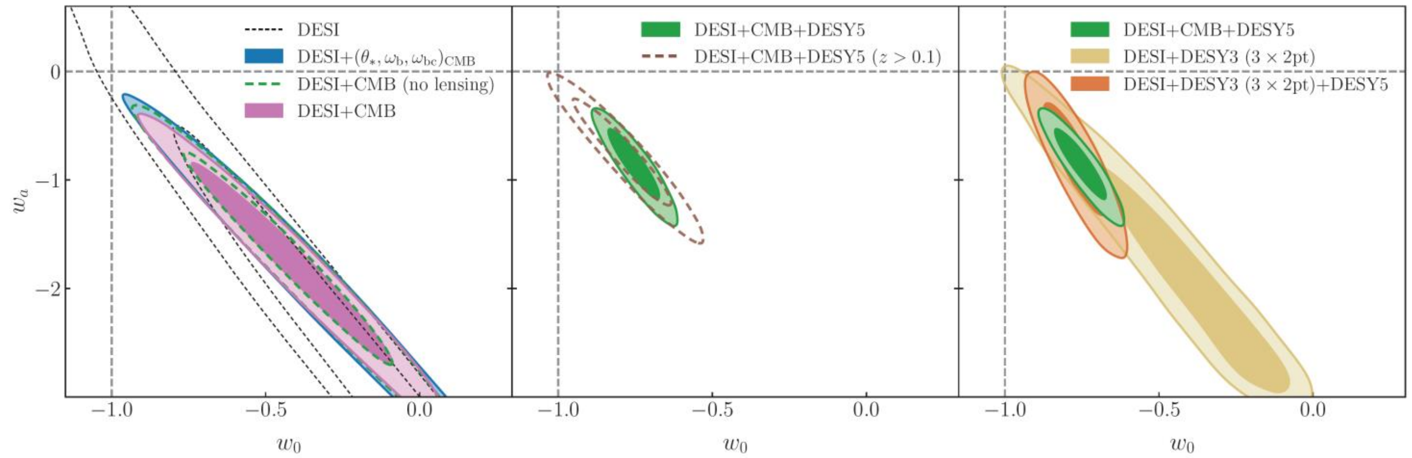
$$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz}{H(z)}$$

$$D_M(z) = (1+z)D_A(z) \qquad D_H(z) = c/H(z)$$

$$D_V(z) = \left[czD_M^2(z)/H(z)\right]^{1/3}$$

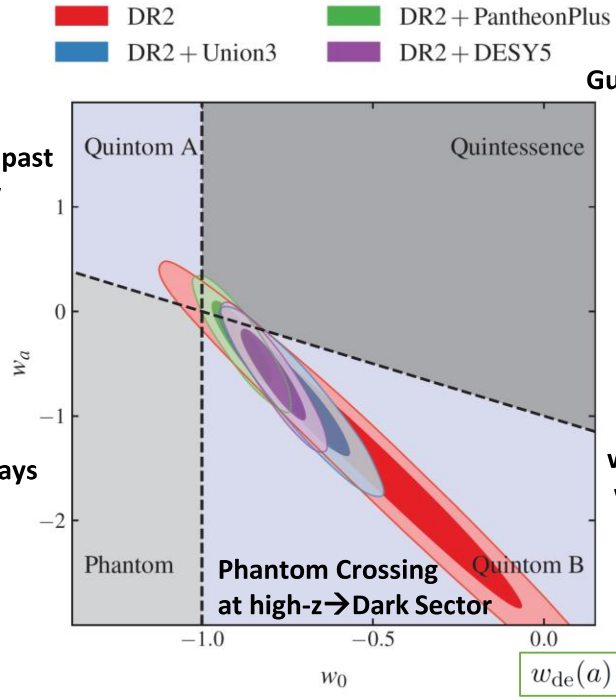
# The state of play: $\Lambda$ tension from DESI

Abdul Karim+2025




Tests of the robustness of dark energy results to different data selections

Gu+2025




w > −1 in the past
w < −1 today

w > −1 always

w < −1 always

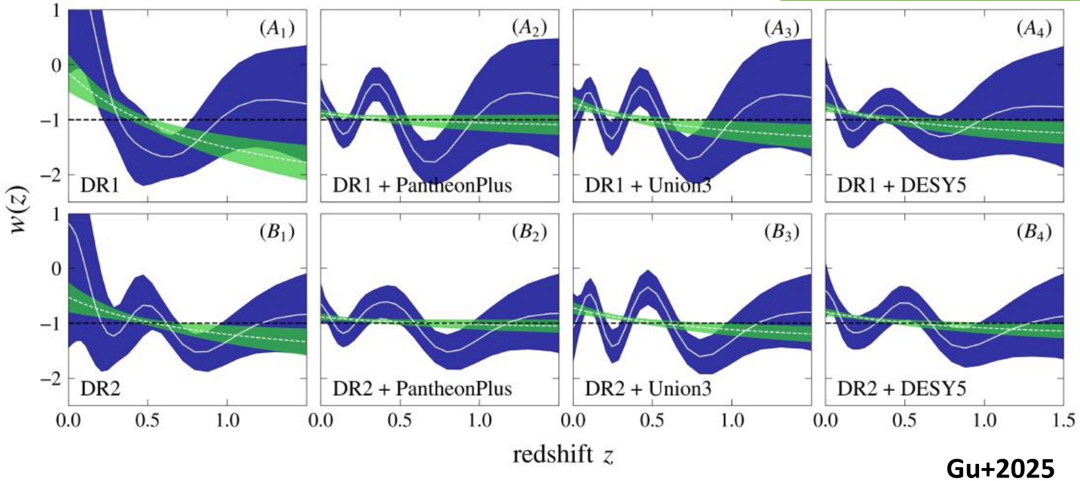
w < −1 in the past
w > −1 today

CPL

$$w_{de}(a) = w_0 + w_a(1 - a)$$

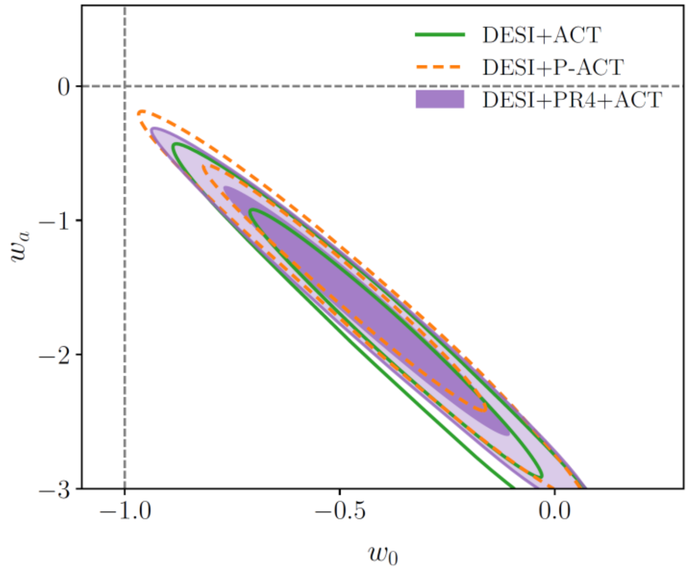
**Dark Sector:** Phantom dark energy possesses negative kinetic energy and predicts expansion of the universe in excess wrt to $\Lambda$. Phantom energy would suggest that the vacuum is unstable with ***negative mass*** particles bursting into existence.

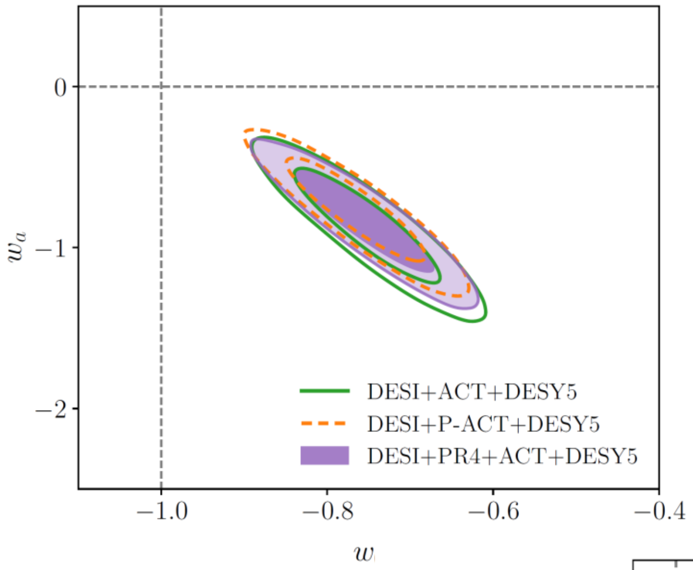
**An unexpected challenge for the next decades**




Gu+2025

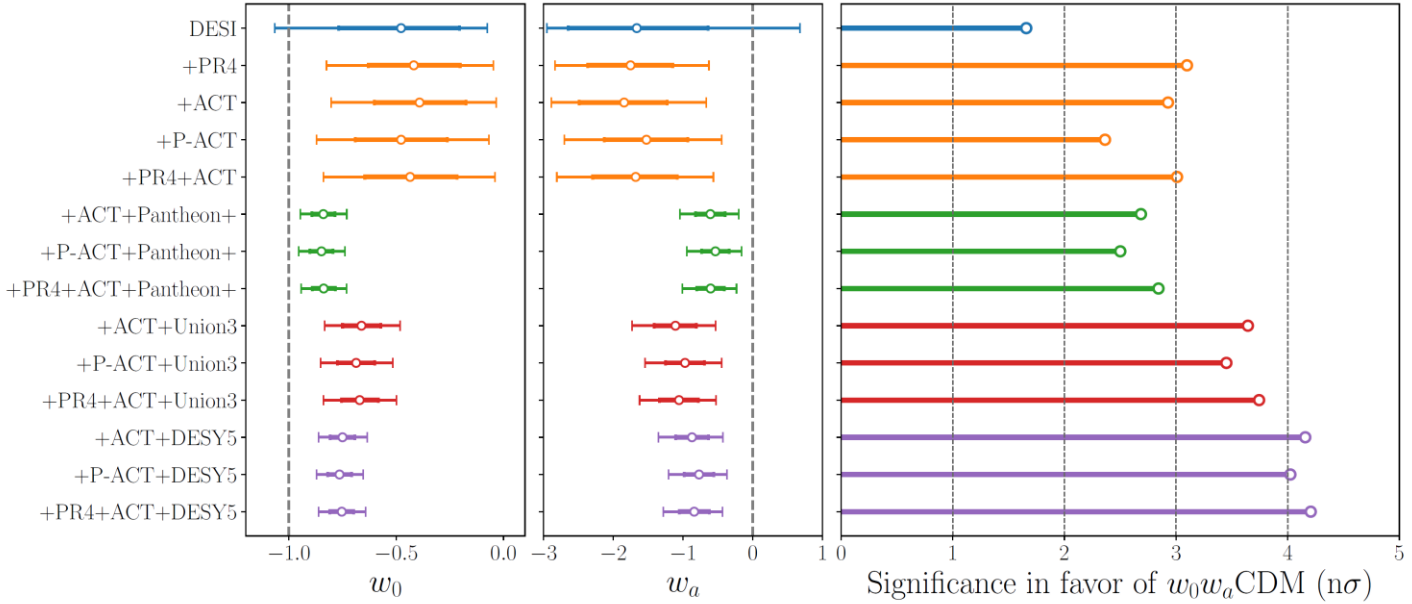
# The state of play: $\Lambda$ tension from DESI when combined with ACT




Constraints on $w_0$ and $w_a$, highlighting the robustness of the results against variations in the CMB dataset chosen for the analysis. Thick bars represent 68% errors and thin bars 95% errors.

Significance in favour of the $w_0\,w_a$CDM model.




**ACT DR6 data predict higher values for the physical densities of both baryons and cold dark matter, compared to Planck.** Within the ΛCDM model, this results in a discrepancy with DESI at a level exceeding 3σ, which is larger than the 2σ discrepancy observed with Planck PR4 (without CMB-lensing).

**DESI+ACT shows a 2.9σ evidence in favour of the $w_0w_a$CDM model.**

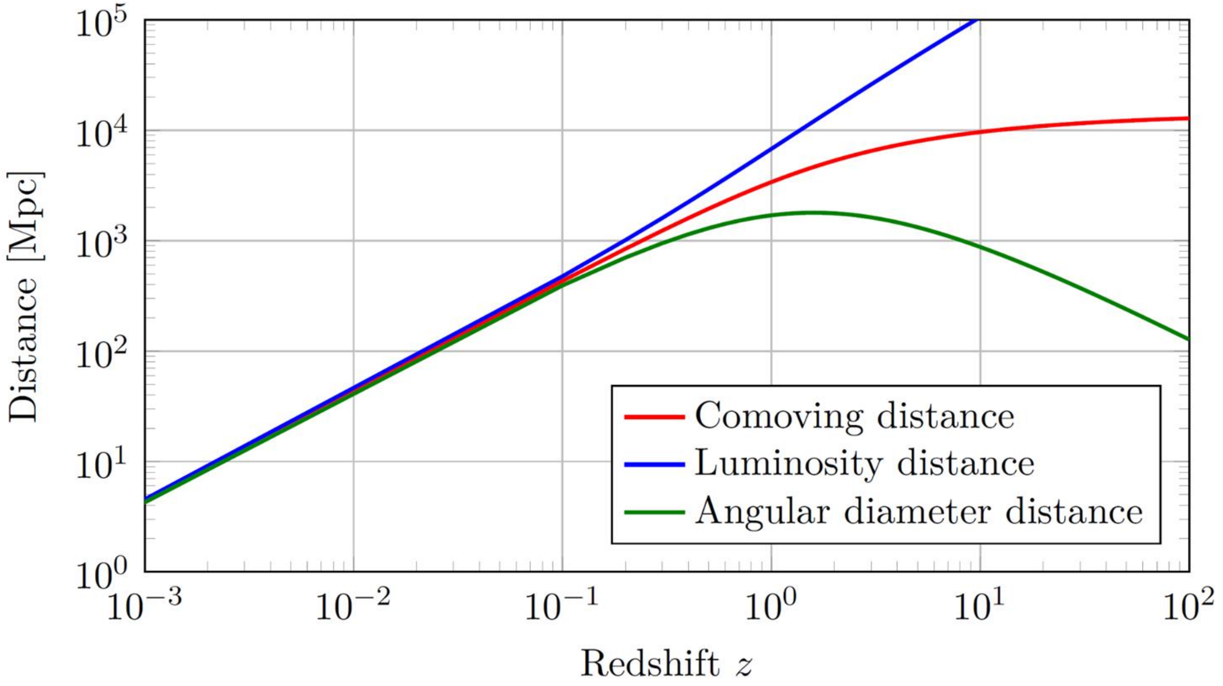
# Independent probes of Dark Energy: GW Luminosity Distance

**Two polarization modes**

$$\tilde{h}_+(f) = A\, e^{i\Psi_+(f)} \frac{c}{D_L} \left(\frac{G\mathcal{M}}{c^3}\right)^{5/6} \frac{1}{f_d^{7/6}} \left(\frac{1+\cos^2\iota}{2}\right)$$

$$\tilde{h}_\times(f) = A\, e^{i\Psi_\times(f)} \frac{c}{D_L} \left(\frac{G\mathcal{M}}{c^3}\right)^{5/6} \frac{1}{f_d^{7/6}} \cos\iota$$

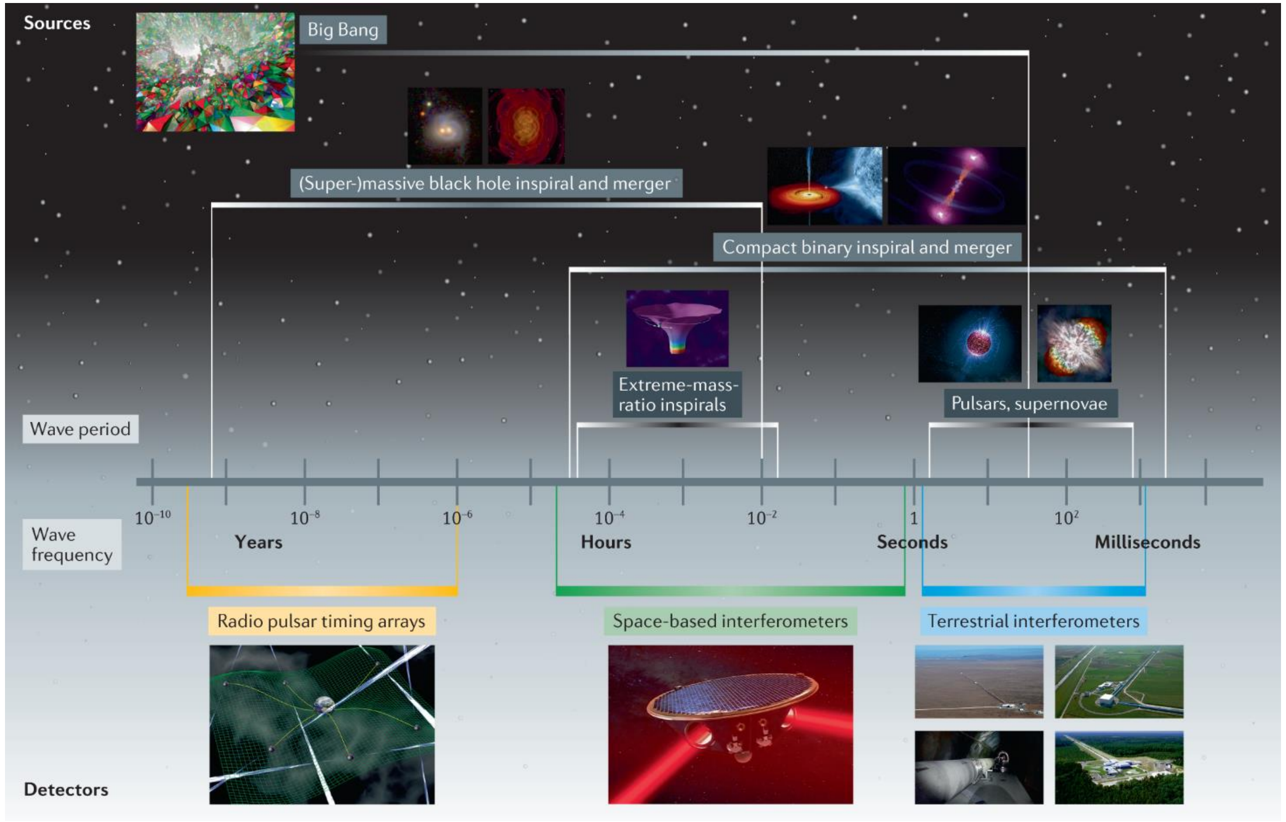
$$\mathcal{M} = M_c(1+z) \qquad M_c \stackrel{\text{def}}{=} \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \qquad f_d = \frac{f}{1+z}$$

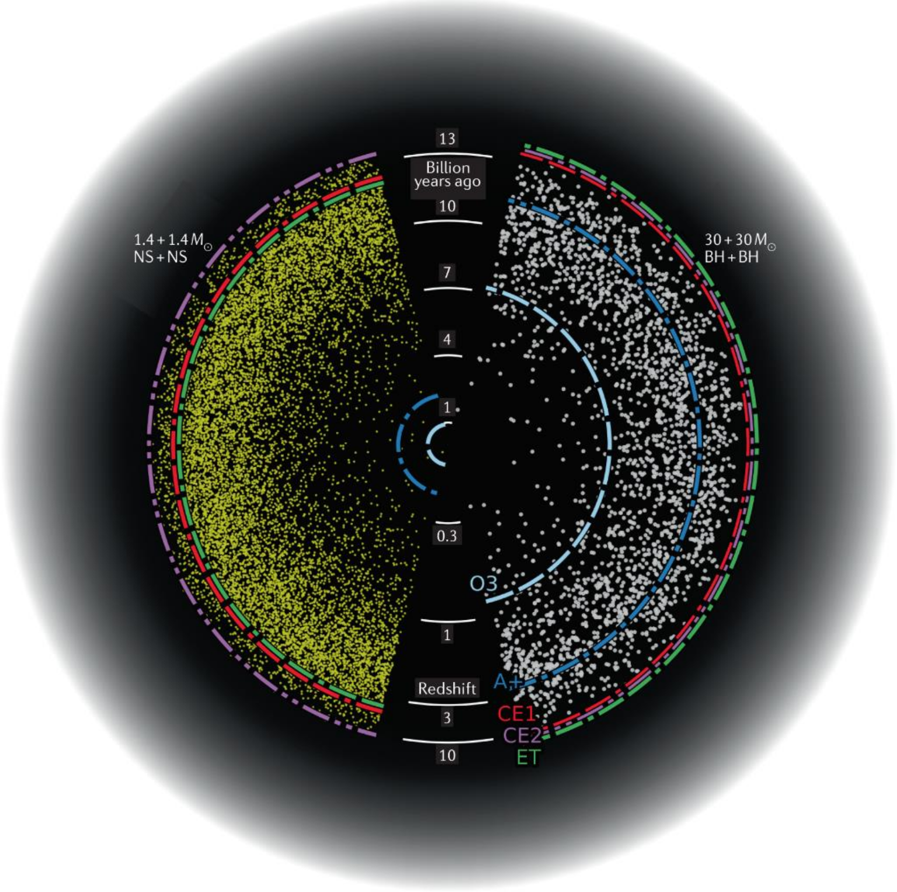



$$D_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H_0\sqrt{\Omega_m(1+z')^3 + \Omega_r(1+z')^4 + \Omega_{\rm DE}\exp\left(3\int_0^{z'} \frac{1+w(z'')}{1+z''}\,dz''\right)}}$$

# Gravitational-wave physics and astronomy in the 2020s and 2030s

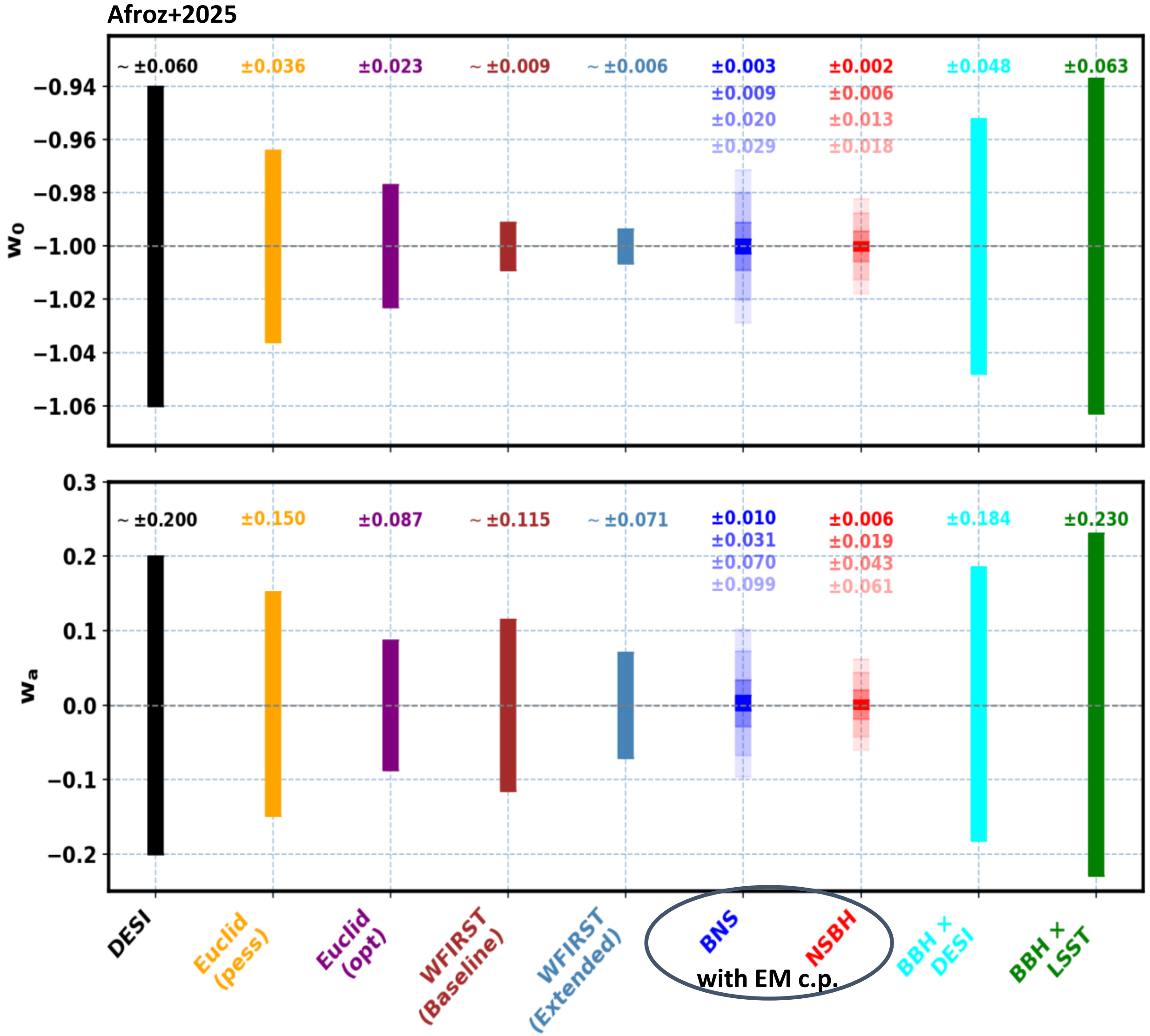
Bailes+2021




Yellow (white) circles represent populations of BNS (BBH) mergers as a function of redshift or lookback time.

# The future of Dark Energy: multi-messenger & *precision* cosmology




Projected constraints on the dark energy equation of state parameters, $w_0$ and $w_a$, from Euclid, DESI, WFIRST, and the upcoming GW observatories, **Cosmic Explorer** and **Einstein Telescope**.

For BNS and NSBH scenarios, the constraints depend upon the fraction of EM counterpart detections associated with these events. The figure shows four different cases of EM detections: the lightest corresponds to 1% detection, followed by 10% detection, 50% detection, and the darkest represents 100% detection of EM counterparts

**What about LISA?**

LISA's MBHs have low mass, therefore the counterparts will be faint sources: ELT will be crucial for taking spectra

There is rich multimessenger science with LISA waiting for us.

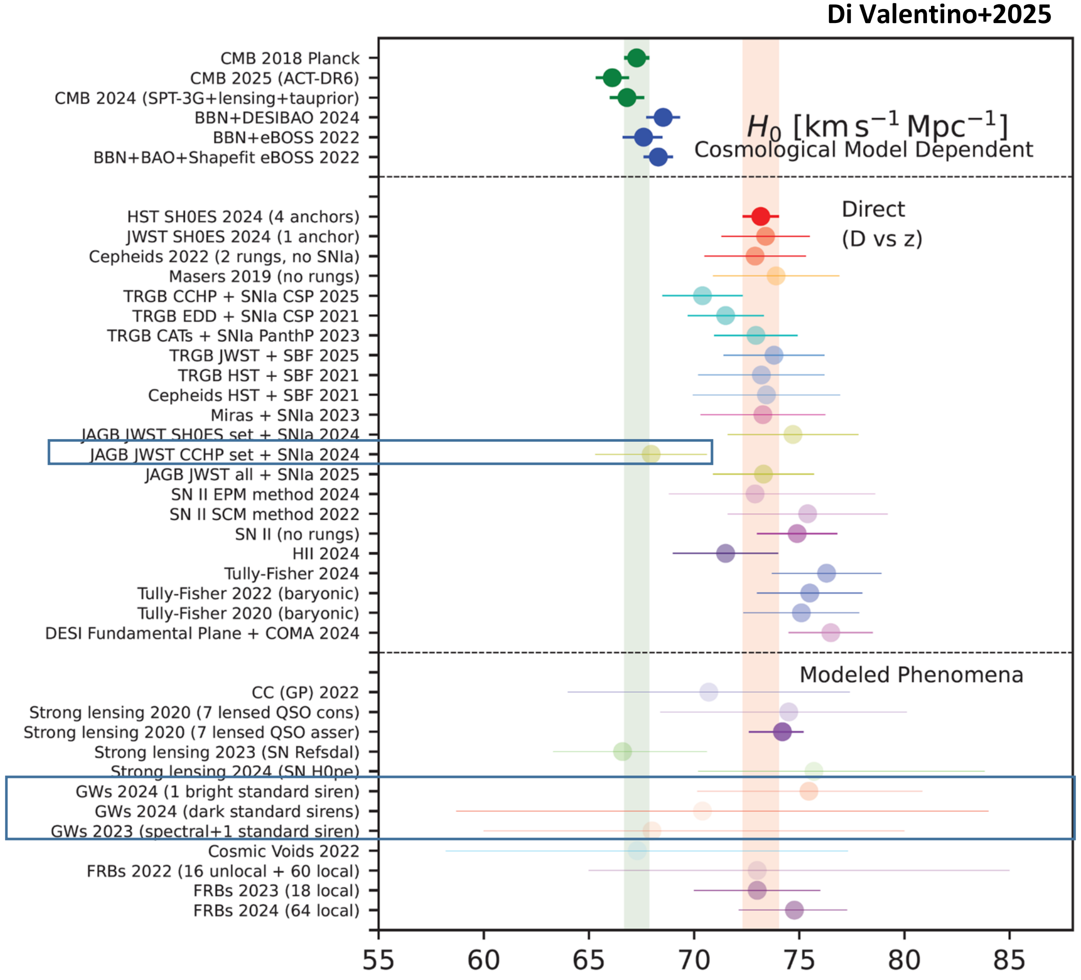
Extragalactic sources are expected to be faint: $10^4 - 10^7$ $M_{sun}$ BH in $10^8 - 10^{10}$ $M_{sun}$ galaxies out to z >> 3.

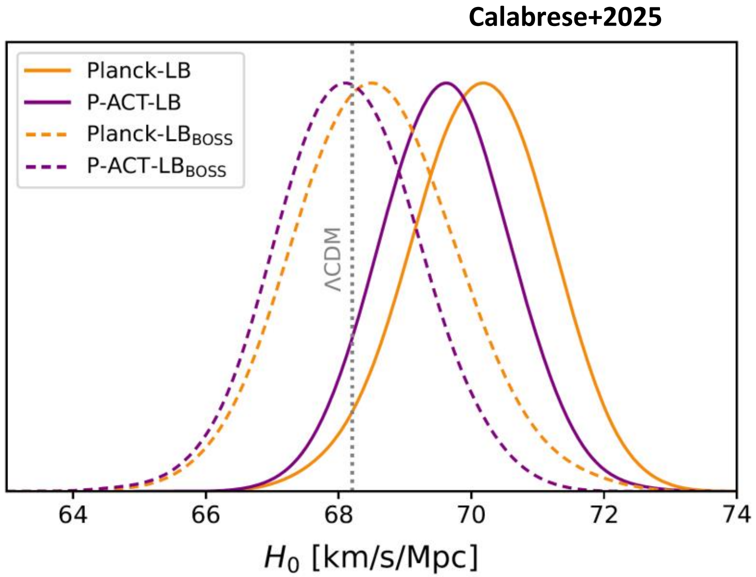
**We need to measure redshift and properties of the sources: ELT is the best (if not only) telescope for the high-z sources.**

**Synergies also with ATHENA, LSST, SKA are envisaged**

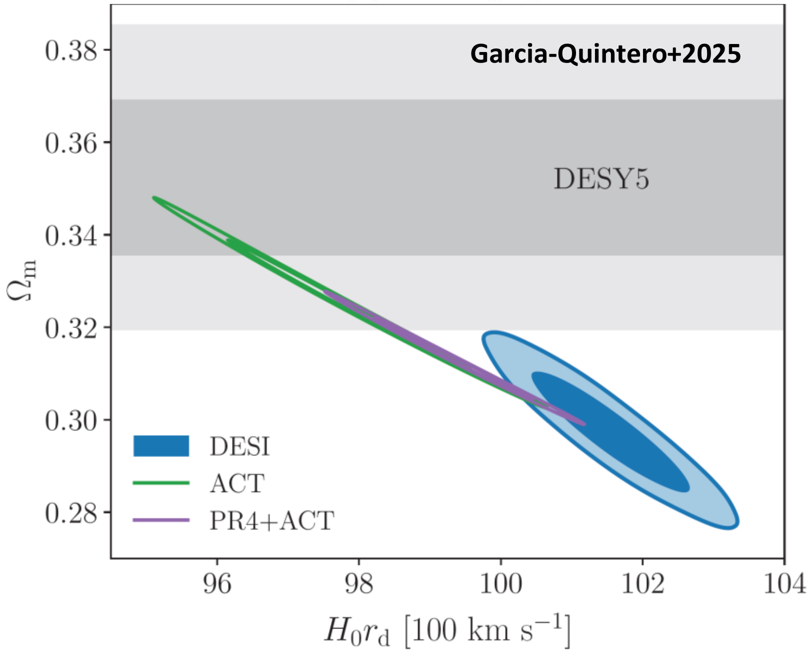
(Volonteri, SF2A 2021)

# The state of play: $H_0$ tension

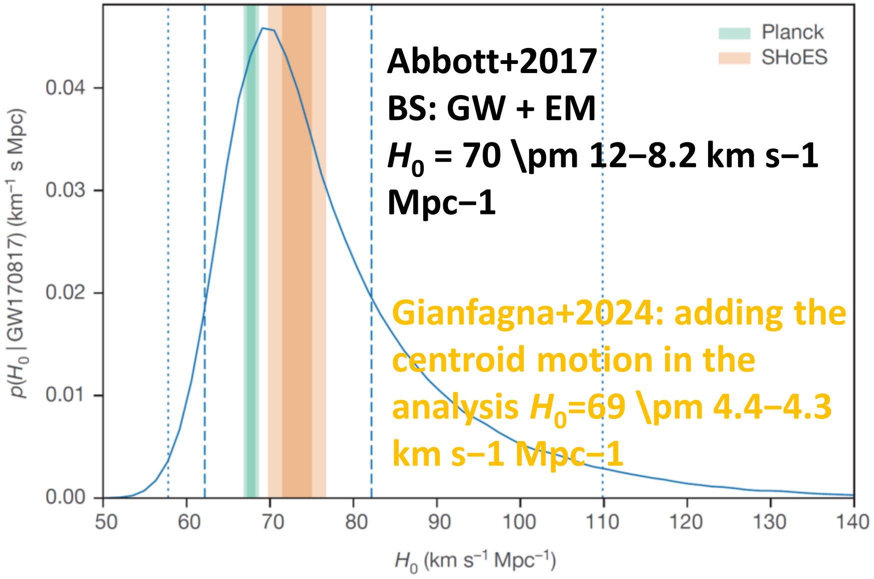



ACT shows a **2.7σ tension** with DESI (**3.2σ** if CMB lensing is excluded), while the combination of PR4+ACT shows a **2σ tension** with DESI, once CMB lensing and low-ℓ TT data are included



# Promising $H_0$ measurements from Dark Sirens and galaxy catalogues

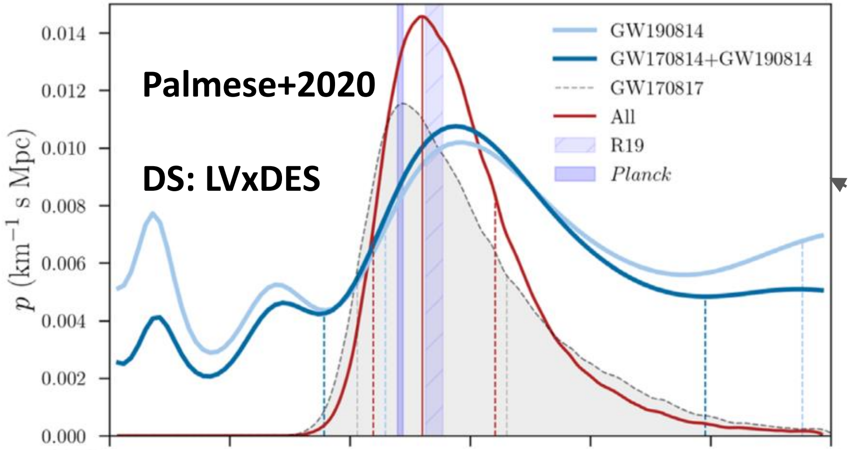



**Abbott+2017**

**BS: GW + EM**

**$H_0$ = 70 \pm 12–8.2 km s−1 Mpc−1**

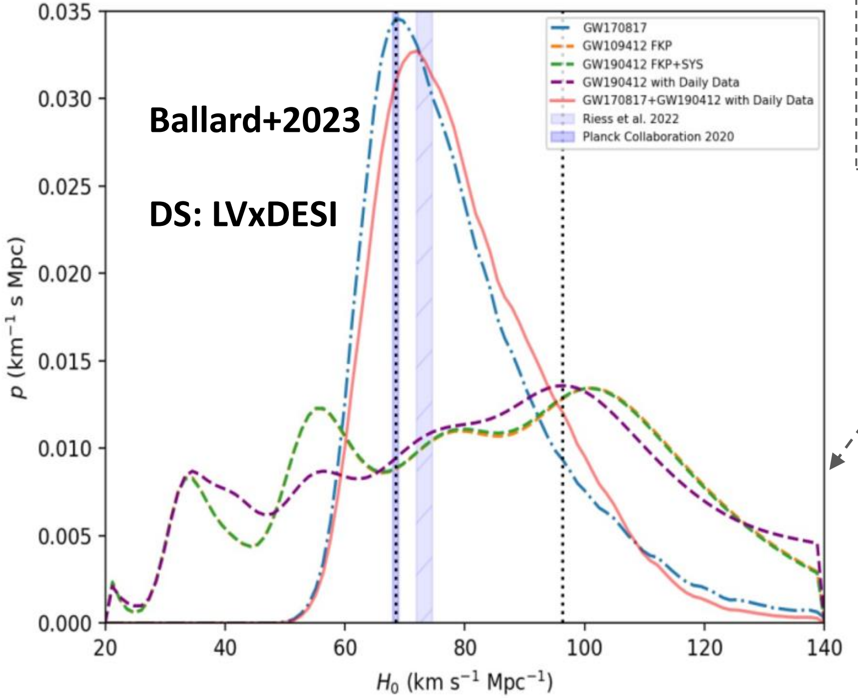
**Gianfagna+2024: adding the centroid motion in the analysis $H_0$=69 \pm 4.4–4.3 km s−1 Mpc−1**




**Palmese+2020**

**DS: LVxDES**

**$H_0$ = 72 \pm 12–8.2 km s−1 Mpc−1**



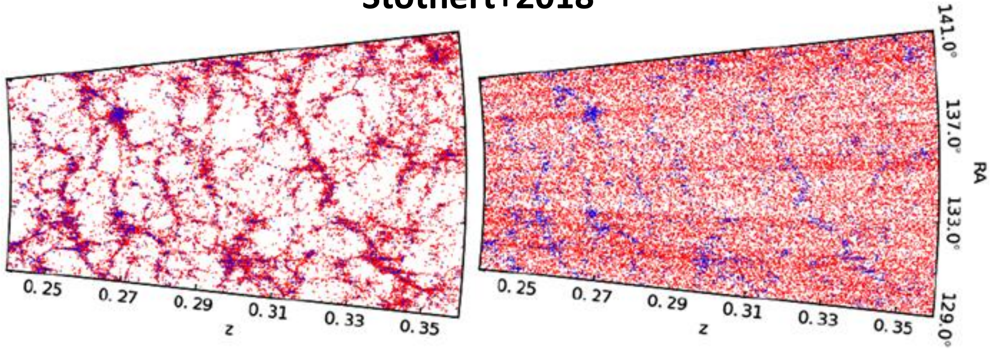

**Ballard+2023**

**DS: LVxDESI**

**$H_0$ = 77.96 \pm 23.0–5.03 km s−1 Mpc−1**

If we are unable to find an EM counterpart, we can use a statistical approach taking advantage of measurements of the redshift distribution of populations of potential host galaxies

**Stothert+2018**



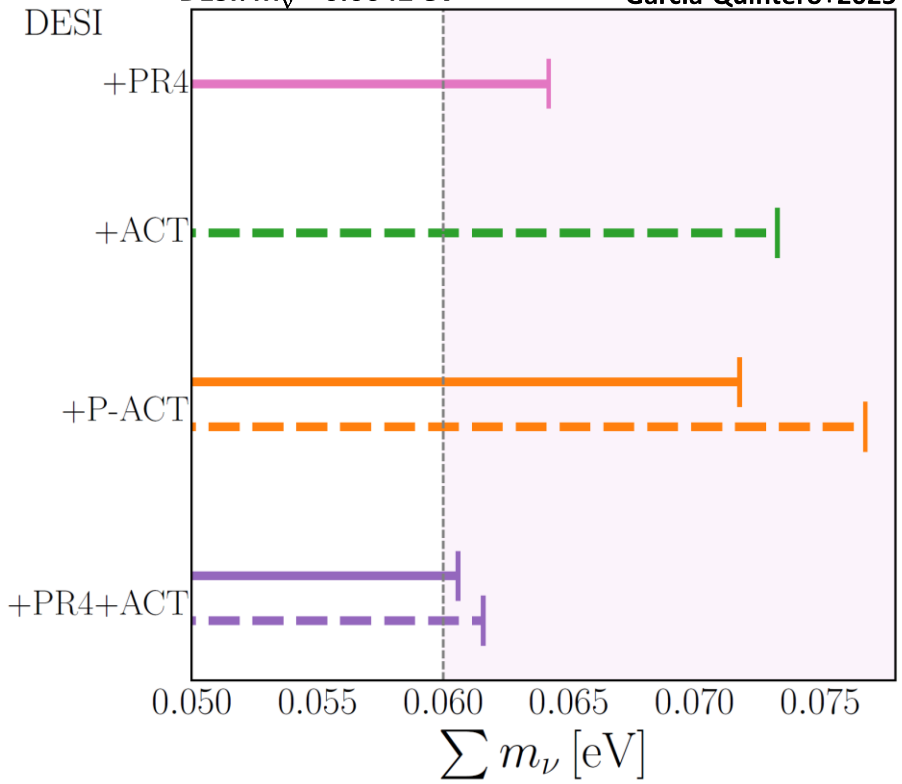

**spectro-z** **photo-z**

# Current situation

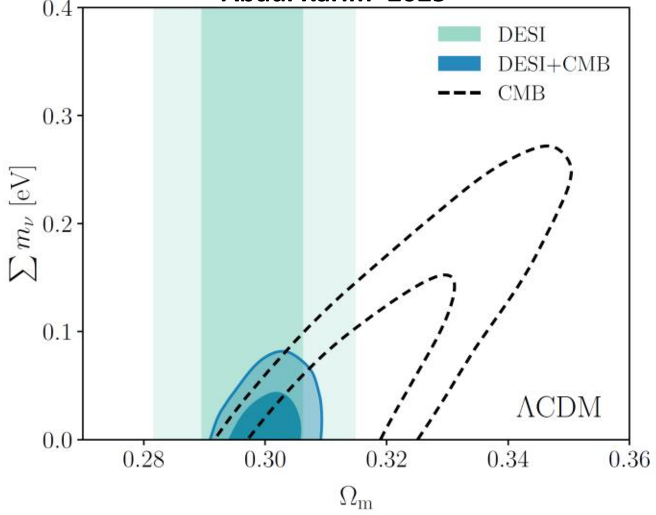
- ACT and Planck are in tension on matter and baryon energy densities
- DESI is in tension with Planck and ACT if we fit the $\Lambda$CDM model
- DESI and CMB experiments point toward a weird dynamical dark energy with phantom crossing at high-z
- Gravitational waves are independent DE probes and could provide very stringent constraints if we have the E.M. counterpart for BS
- BOSS+CMB is in tension with DESI+CMB on $H_0$
- More to come…

# The state of play: $M_\nu$ from DESI & ACT

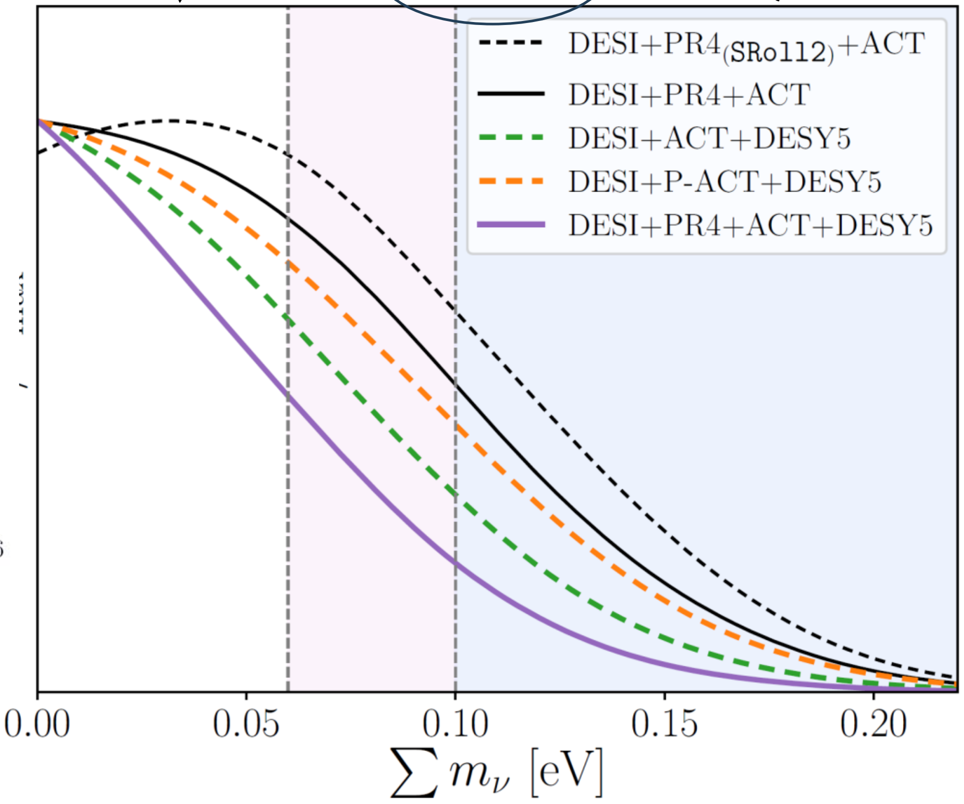
DESI: $M_\nu$ < 0.0642 eV $\Lambda$CDM Garcia-Quintero+2025




Abdul Karim+2025



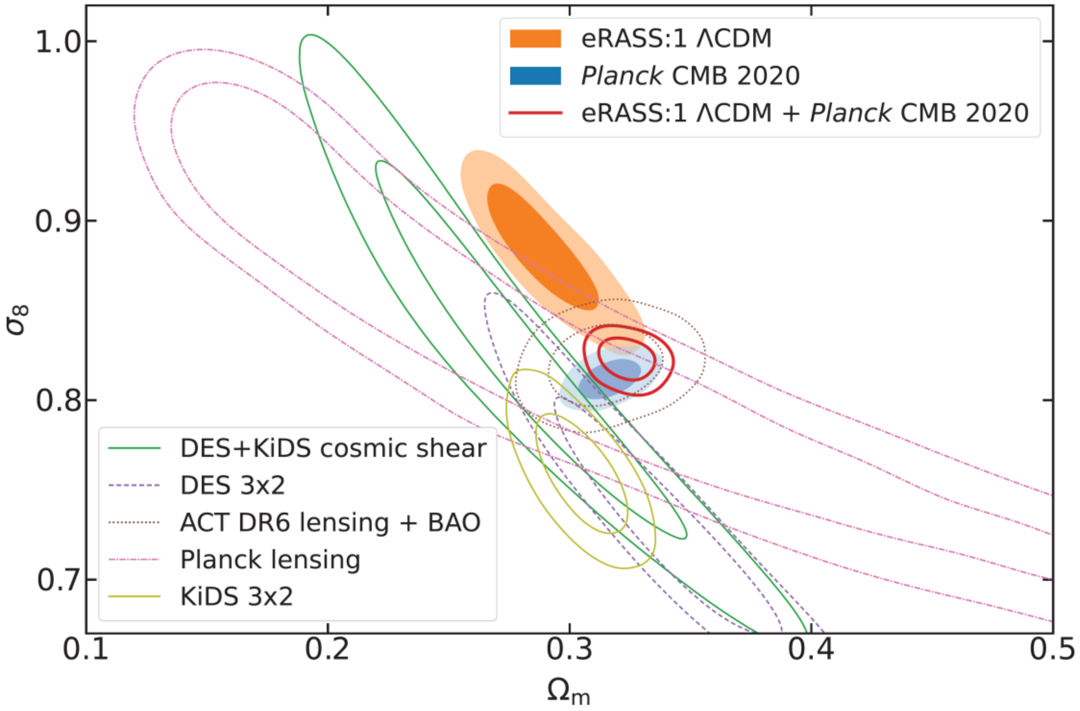

DESI: $M_\nu$ < 0.163 eV $w_0w_a$CDM Garcia-Quintero+2025




Extending the background to an evolving dark energy component parameterized by $w_0$ and $w_a$ gives an upper mass limit of $M_\nu$ < 0.17 eV and $M_\nu$ < 0.15 eV at 95% c.l., for DESI+ACT and DESI+PR4+ACT, respectively. **Combining DESI BAO with CMB data yields a preference for positive neutrino masses**. This preference vanishes when SNe data are included in the analysis

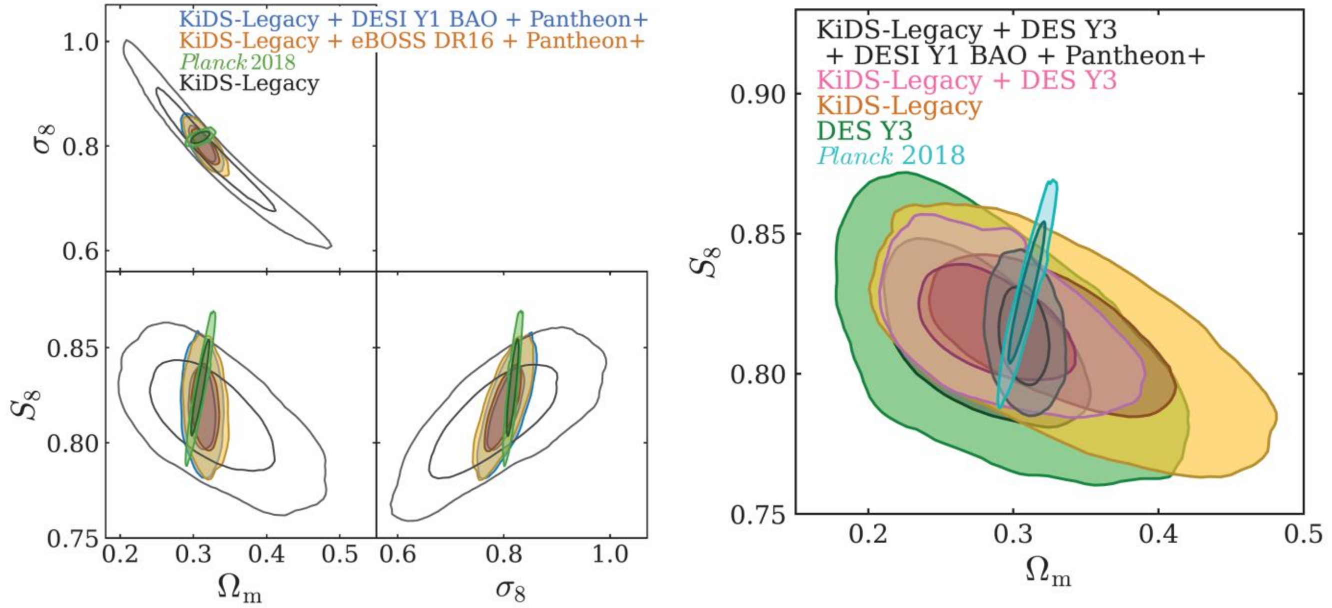
# The state of play: $\sigma_8$ tension vanished!

Ghirardini+2024



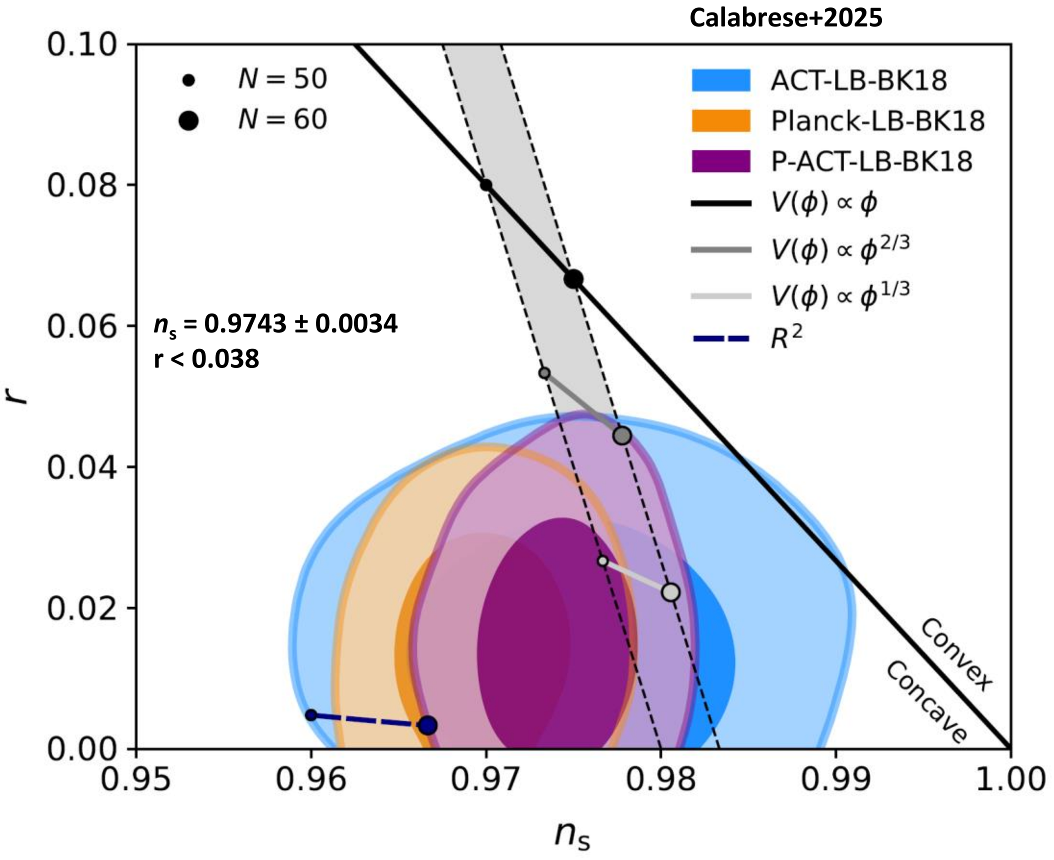

The origin of the $S_8$ tension previously reported in the literature likely lies in systematic or statistical noise in the weak lensing results and not in the theoretical extension of the ΛCDM cosmological model.

Stolzner+2025




In a joint cosmological analysis of KiDS-Legacy and DES-Y3 cosmic shear, combined with data from the Pantheon+ Type Ia supernovae compilation and BAO from DESI-Y1, the constraints are consistent with Planck measurements of the CMB with $S_8$ = 0.814\pm 0.011 − 0.012 and $\sigma_8$ = 0.802 \pm 0.022 − 0.018.

# The state of play: Inflation tension from ACT




**Even more fun!! ☺**

The ACT data show an enhancement wrt Planck in the value of the scalar spectral index $\boldsymbol{n_s}$, leading to disfavoring many inflationary models, including the $R^2$ Starobinsky model preferred by Planck.

# The state of play: Dark Matter
## (from Rocky Kolb colloquium in March 2025 @UniPD)

## Dark Matter particle mass range (mere 41 orders of magnitude)

$10^{-22}$ eV ◀ non-thermal | thermal freeze-out | non-thermal ▶ $10^{19}$ GeV

$m_{\text{electron}}$ $m_{\text{proton}}$ $m_Z$ 100 TeV

Plancktons: $m \sim m_{\text{Planck}} = 10^{19}$ GeV

WIMPzillas: $m \sim m_{\text{inflaton}} = 10^{10} - 10^{13}$ GeV

Supermassive: $m > 100$ TeV

WIMP range (e.g., neutralino): $m_{\text{proton}} < m < 1$ TeV

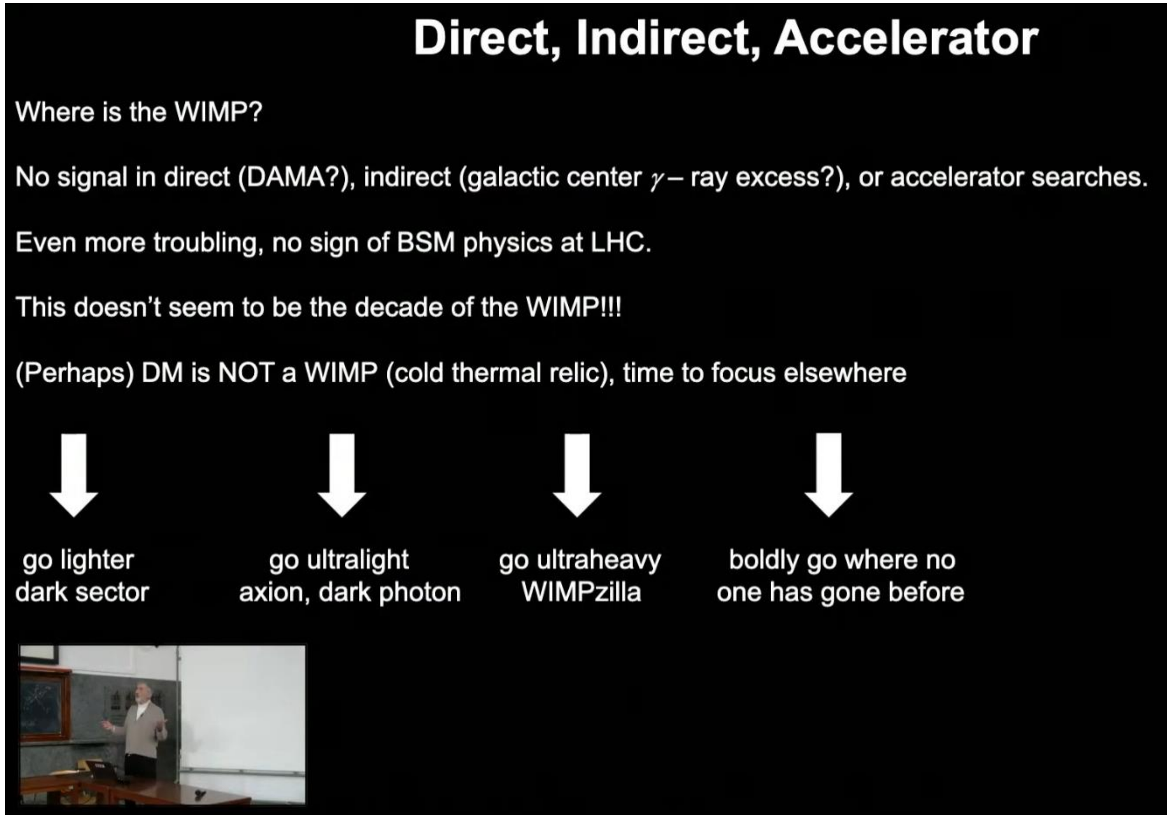
Light dark matter (e.g., dark photon): $m_{\text{electron}} < m < m_{\text{proton}}$

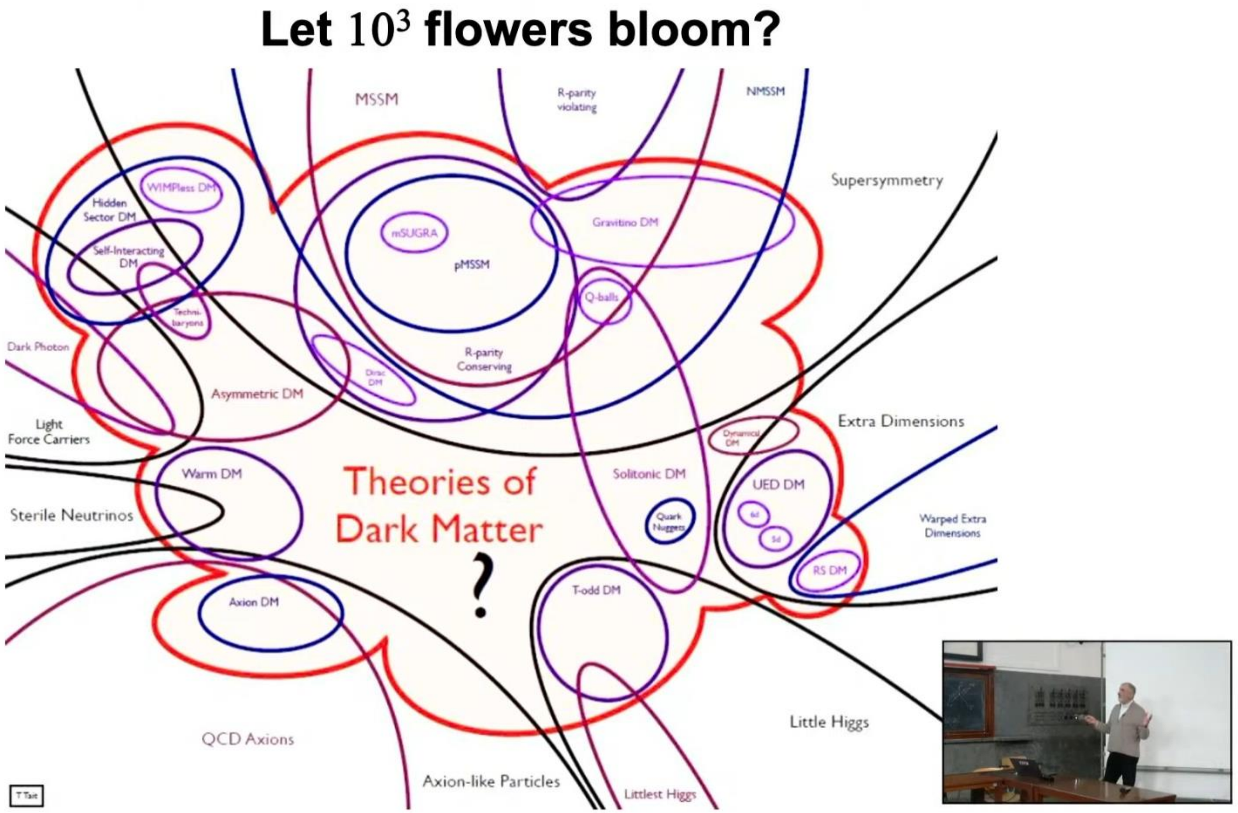
Ultralight dark matter (e.g., axion): $m < 1$ eV

Fuzzy dark matter: $m \sim 10^{-22}$ eV

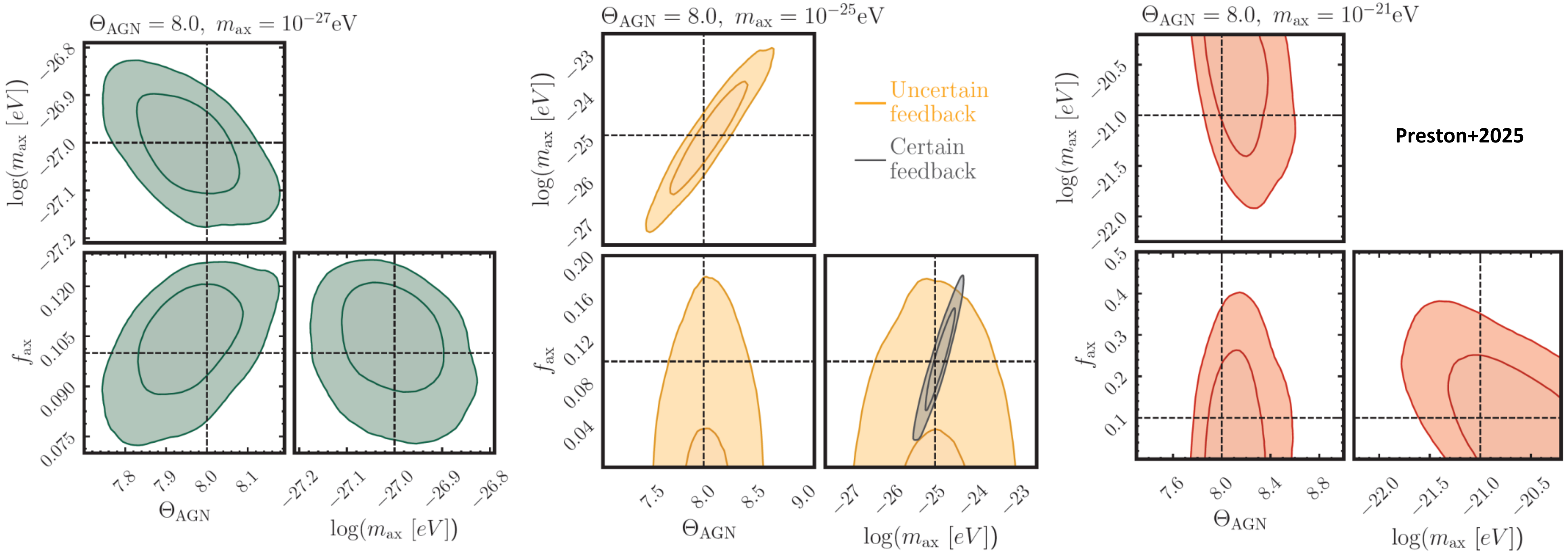
# The state of play: Dark Matter

**(from Rocky Kolb colloquium in March 2025 @UniPD)**



# Disentangling Dark Matter with galaxy surveys?




Posterior distributions from a simulated **LSST Y1-like shear** correlation function, where the axion mass, axion fraction and baryonic feedback parameters are varied.

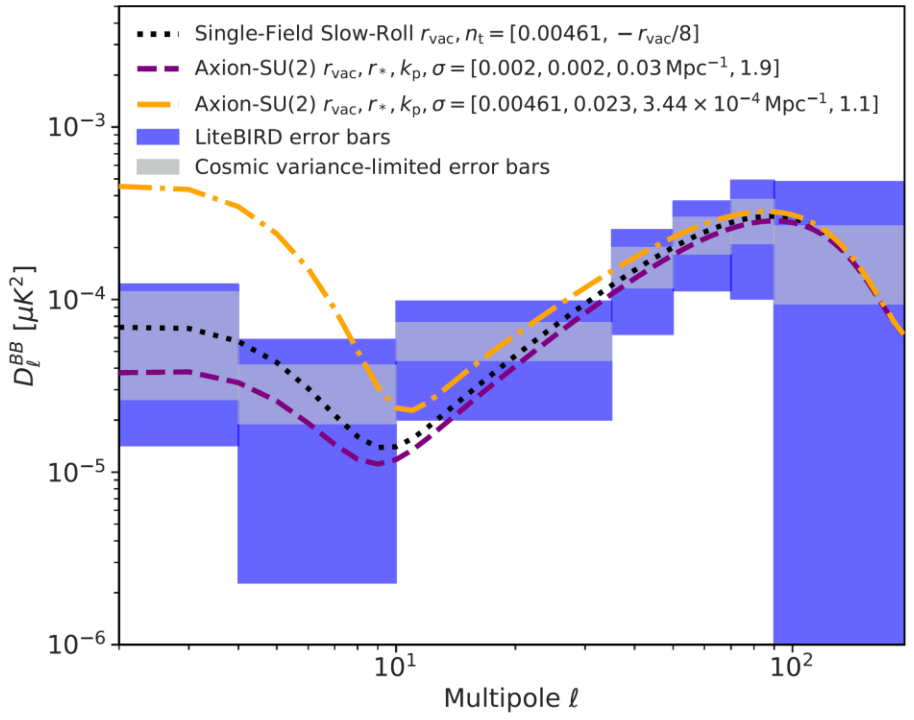
**For the lightest axion (max = $10^{-27}$ eV) the truth and a non-zero preference for axions is recovered**

The heaviest axion (max = $10^{-21}$ eV) has a weaker effect on the matter power spectrum for k < 10 hMpc−1

**For the intermediate-mass axion (max = $10^{-25}$ eV), the scales at which baryonic feedback and axions suppress the matter power spectrum are the same**. It is therefore hard to disentangle the two effects without external information on feedback, although a competitive limit on the axion fraction is still feasible.

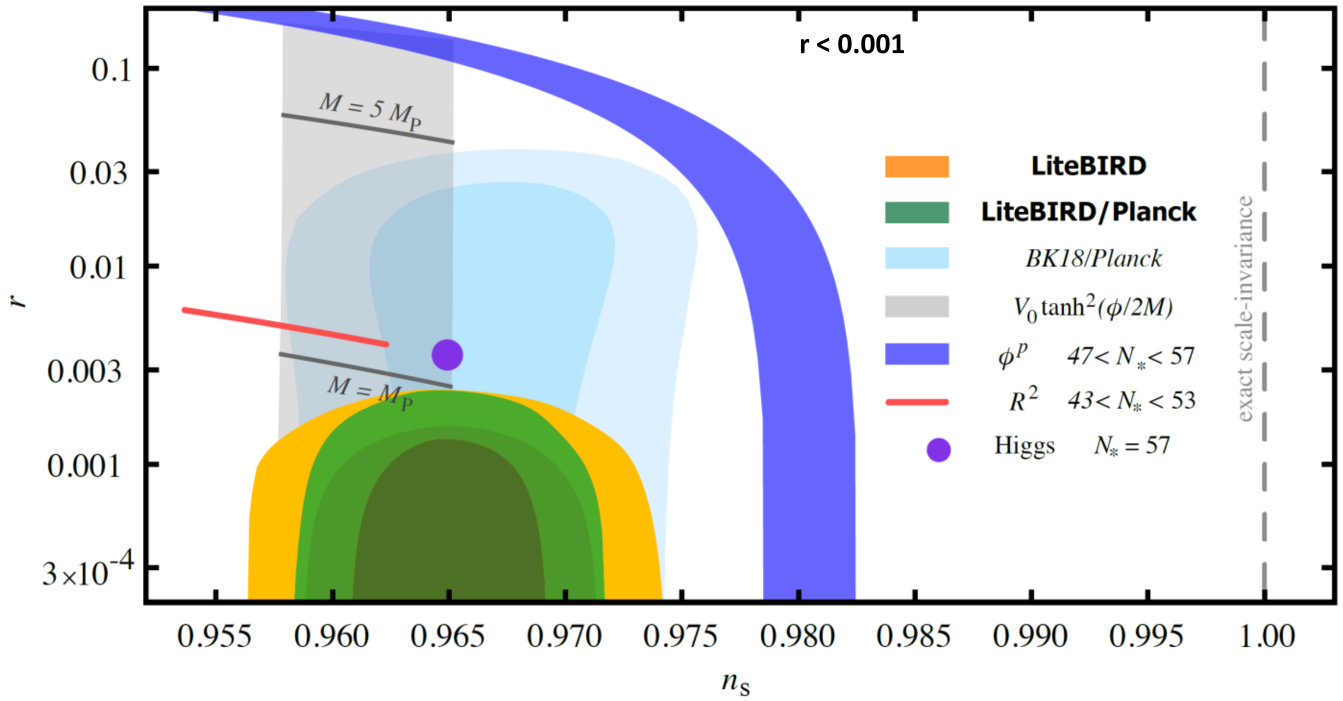
# Inflation and Dark Matter from future CMB B-mode experiments?

Campeti+2024




Understand the origin of the primordial gravitational wave signal and distinguish among two production mechanisms: quantum vacuum fluctuations of spacetime and matter sources (eg axions) during inflation.

Allys+2023




In the absence of a primordial GW detection, LiteBIRD (2032) will exclude the Starobinsky model and models that invoke the Higgs field as the inflaton, shown as the red line and the purple dot.

# An *intriguing* unknown future…

We are in the era of *precision* Cosmology, but what about Cosmology in the '40s?

- will we achieve the era of *accuracy* Cosmology in 2040?
- probably the $H_0$ tension will be solved with the help of independent probes such as *redshifts drift* measurements (SKA, ELT) and *luminosity distance* measurements from GWs (LSSxET-DS, ELTxLISA-BS)
- probably the total neutrino mass will be measured via CMB-lensing and galaxy-surveys
- probably no *early* Dark Energy but still huge uncertainty on the *nature* of Dark Energy
- probably no new ideas about Dark Matter unless a surprising discovery (GW from primordial black holes??)
- still uncertainty on the model of primordial Inflation if cosmological primordial GWs won't be detected from CMB experiments (there's no limit on *r*, the tensor-to-scalar ratio of primordial perturbations) or from upcoming GW observatories

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