Future perspectives in cosmology

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A biased view

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Beyond ΛCDM?

- H_0 tension, σ_8 tension, evolving dark energy
- We work on them: new models, new measurements

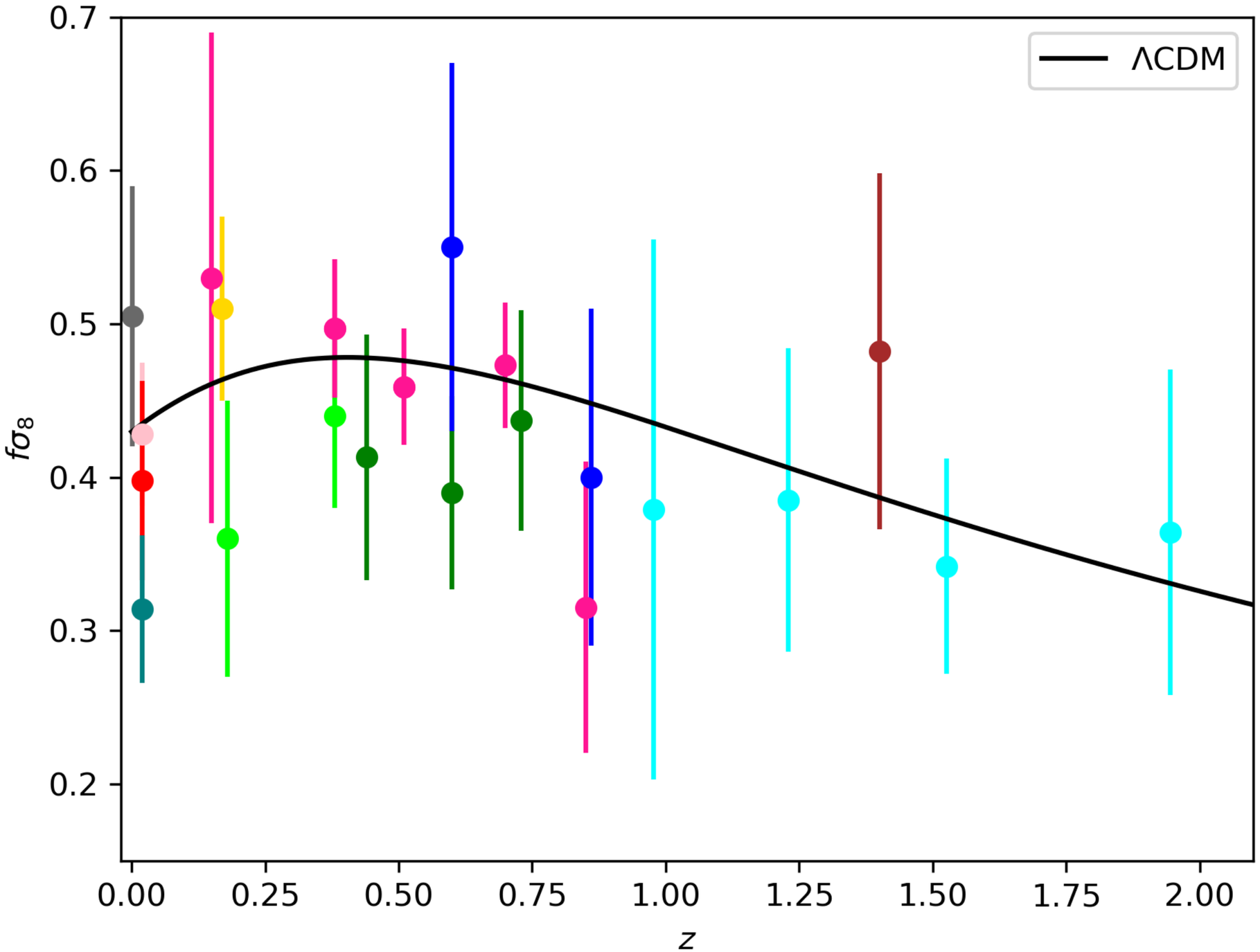
  Back of our mind → **systematics**?
- What would it take to truly **convince** us?
  - Seeing the same tensions in **different data** sets?
  - Seeing deviations at the level of the **background** and the **perturbations** pointing towards the same theory?

  → Can we hope for it?

Beyond ΛCDM?

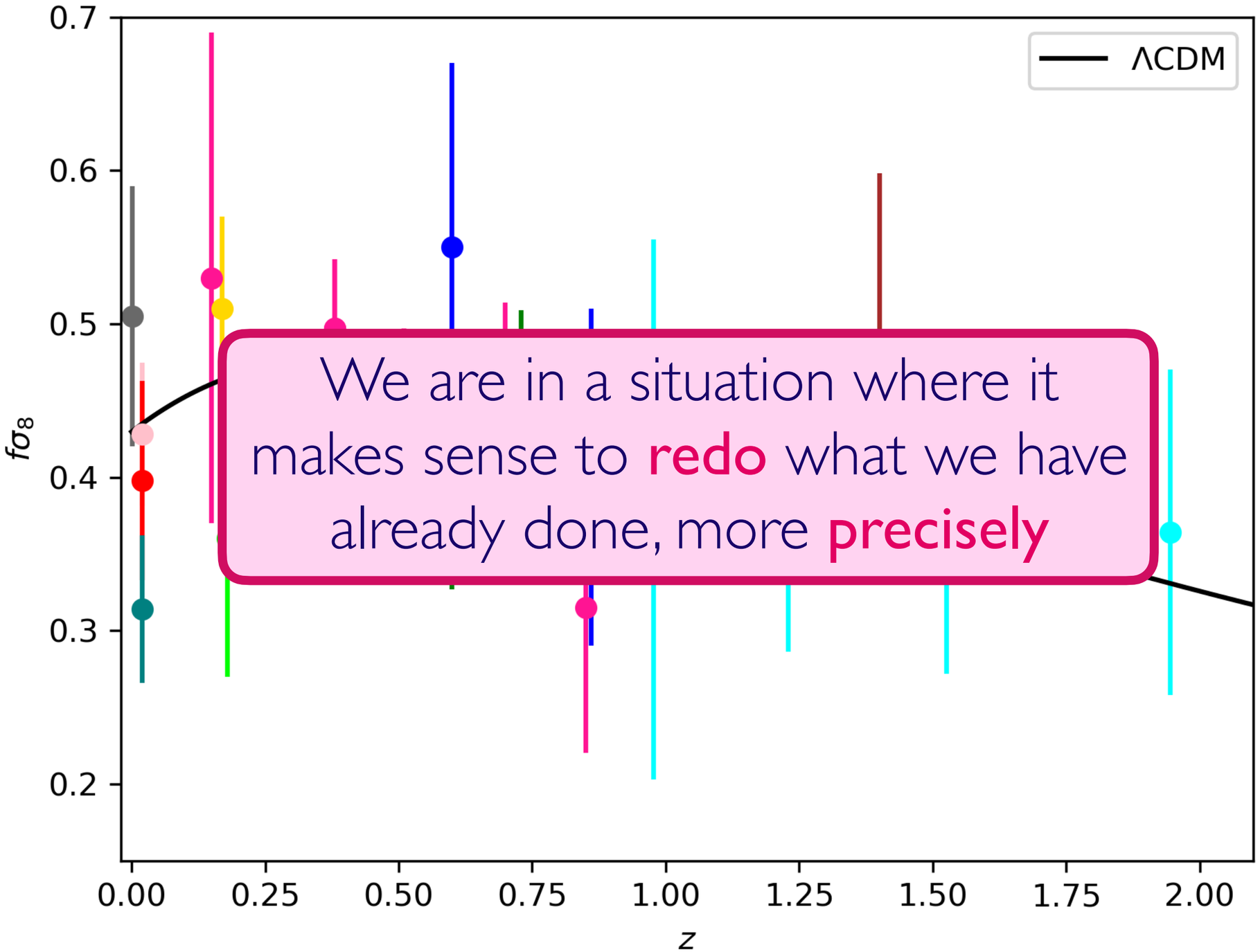
- In **modified gravity** we could have
  - Deviations in the background
  - Change in the growth of structure → $f\sigma_8$
  - Change in potentials → gravitational lensing
- Can we realistically **hope** for this?
- Are we right to build **new** expensive **missions** with that goal?

The growth rate



2dFGRS
6dFGS
WiggleZ
SDSS
Gamma
2MASS
2MTF
Vipers
FastSound
IRAS

The growth rate



2dFGRS
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New observables

- Until now, we have measurements of
  - Change in **spectrum** → velocities $f\sigma_8$
  - Change in **light propagation:** cosmic shear, CMB lensing, magnification in galaxy clustering

→ Weyl potential $\Phi + \Psi$

- Can we measure something else?
  - **Relativistic effects** → gravitational redshift → Ψ

Yoo, Fitzpatrick & Zaldarriaga (2009)
Challinor & Lewis (2011)
CB & Durrer (2011)
Jeong, Schmidt & Hirata (2011)

McDonald (2009)
Croft (2013)
CB, Hui and Gaztanaga (2014)

Gravitational redshift

- Already measured in **clusters** with SDSS/eBOSS

Wojtak, Hansen & Hjorth (2011), Sadeh, Feng, Lahav (2015), Mpetha et al (2021), Rosselli et al (2023)

→ DESI Lahav Euclid Project: Castello & Mpetha

Alam, Zhu, Croft et al. (2017)

- 2.7 sigma detection in the **non-linear regime** with BOSS

→ Euclid Project: Lepori

- DESI should measure it in the **linear regime**

Beutler & Di Dio (2020), CB, Lepori, Schulz, Tutusaus, Adamek & Fosalba (2023)

WG: Beutler

- Why **interesting**?
  - In ΛCDM: no interest Lorenz, Alonso & Ferreira (2018)
  - Can be used to test **gravity** and **dark forces**

CB & Fleury (2018), Saga, Taruya, Rasera & Breton (2021), Castello, Grimm & CB (2022), CB & Pogosian (2023), Castello, Zheng, CB & Amendola (2025)

Gravitational redshift

- Current **tests** of **gravity**

  - Measure $\Phi + \Psi$ from lensing
  - Measure V from RSD → Ψ

  } → gravitational slip

What if **Euler's** equation is **not valid**? → Wrong Ψ

- Adding Ψ allows us to **discriminate** between theories

  - Compare $\Phi + \Psi$ with Ψ : test of **gravity** Tutusaus, Sobral-Blanco & CB (2023)
  - Compare V with Ψ : test of **dark forces** CB & Fleury (2018)

Other LSS observables

Rubart & Schwarz (2013); Bengaly, Maartens & Santos (2018);
Secrest, von Hausegger, Rameez, Mohayaee & Sarkar (2022)

- **Kinetic dipole**: 5 sigma tension (quasars and radio sources)
  - Truly a shift in paradigm: **no isotropic** background
  - Measure it with other **sources**: galaxies (Euclid), SNe, GWs Sorrenti, Durrer & Kunz (2023); Grimm, Pijnenburg, Mastrogiovanni, CB, Foffa & Cusin (2023)
  - Measure $\ell - (\ell + 1)$ cross-correlations in galaxy clustering
    Lacasa, CB, Dalang & Durrer (2024)
- 21cm:
  - HIRAX: BAO up to $z = 2.5$ and new tracer of the LSS
  - SKA: large scales (non-gaussianities), high redshift (first stars), high density (relativistic effects)

Synergies between GWs and LSS

- **Hubble diagram** combining d_L from GWs and z from galaxies

  Schutz (1986); Holz & Hughes (2005); Dalal et al. (2006); MacLeod & Hogan (2008); Del Pozzo (2012); Nissanke et al. (2013); Finke et al. (2021); Cousins et al (2025)...

- **Lensing** of GWs

  Cutler & Holz (2009); Camera & Nishizawa (2013); Balaudo, Garoffolo, Martinelli, Mukherjee & Silvestri (2023); Beltrame, Bonici & Carbone (2024), ...

- Impact of peculiar **velocities** on GWs

  CB, Caprini, Sturani & Tamanini (2016); Inayoshi, Tamanini, Caprini & Haiman (2017); Tamanini, Klein, CB, Barausse & Caprini (2019); CB, Cusin, Pitrou, Mastrogiovanni, Congedo & Gair (2023)

CMB

- **Primordial GWs** through B-modes
  - Delensing will give us a factor 3 improvement for BICEP/Keck
  - Simon Observatory $\sigma(r) \leq 0.003$
  - CMB-S4 $\sigma(r) = 5 \times 10^{-4}$

- **Neutrino masses** through gravitational lensing

  → Synergy with LSS: DESI and Euclid