

Fundamental constant measurements with ANDES

Insights from HARPS and ESPRESSO

Cosmology

The Friedmann Equations

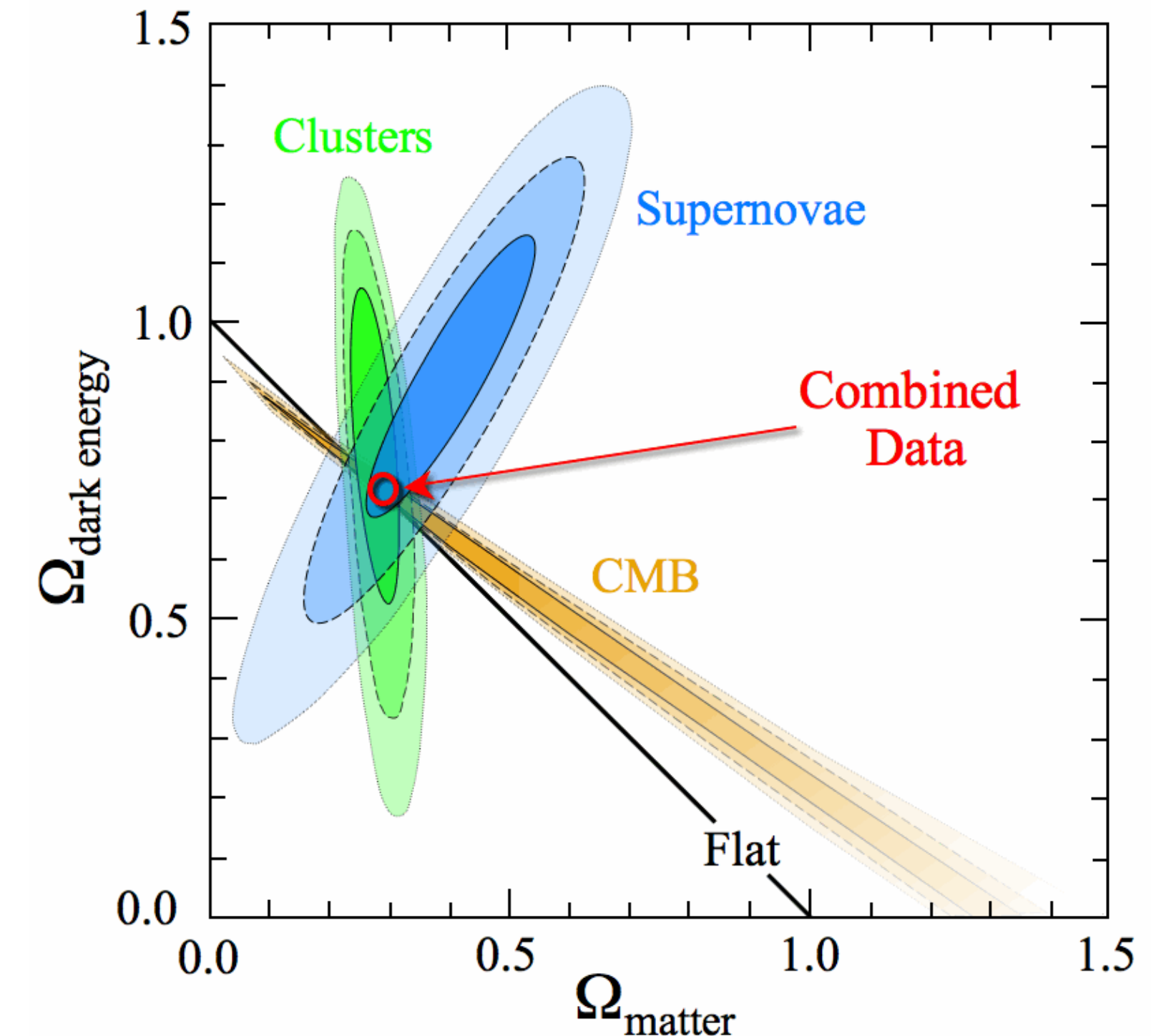
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4\pi G}{3}(\rho + 3p)$$

We want to measure equation's parameters as accurately as possible (in red)

$$H^2(z) = \color{red}{H_0^2} \left[\color{red}{\Omega_{de}} a^{-3(1+\color{red}{w})} + \color{red}{\Omega_m} a^{-3} + \color{red}{\Omega_r} a^{-4} + \color{red}{\Omega_k} a^{-2} \right]$$

From: <https://ncatlab.org/nlab/show/standard+model+of+cosmology>



Since ~2015, our most precise measurements of cosmological parameters increasingly disagree

Questions that may be resolved by 2036 and some interesting recent studies

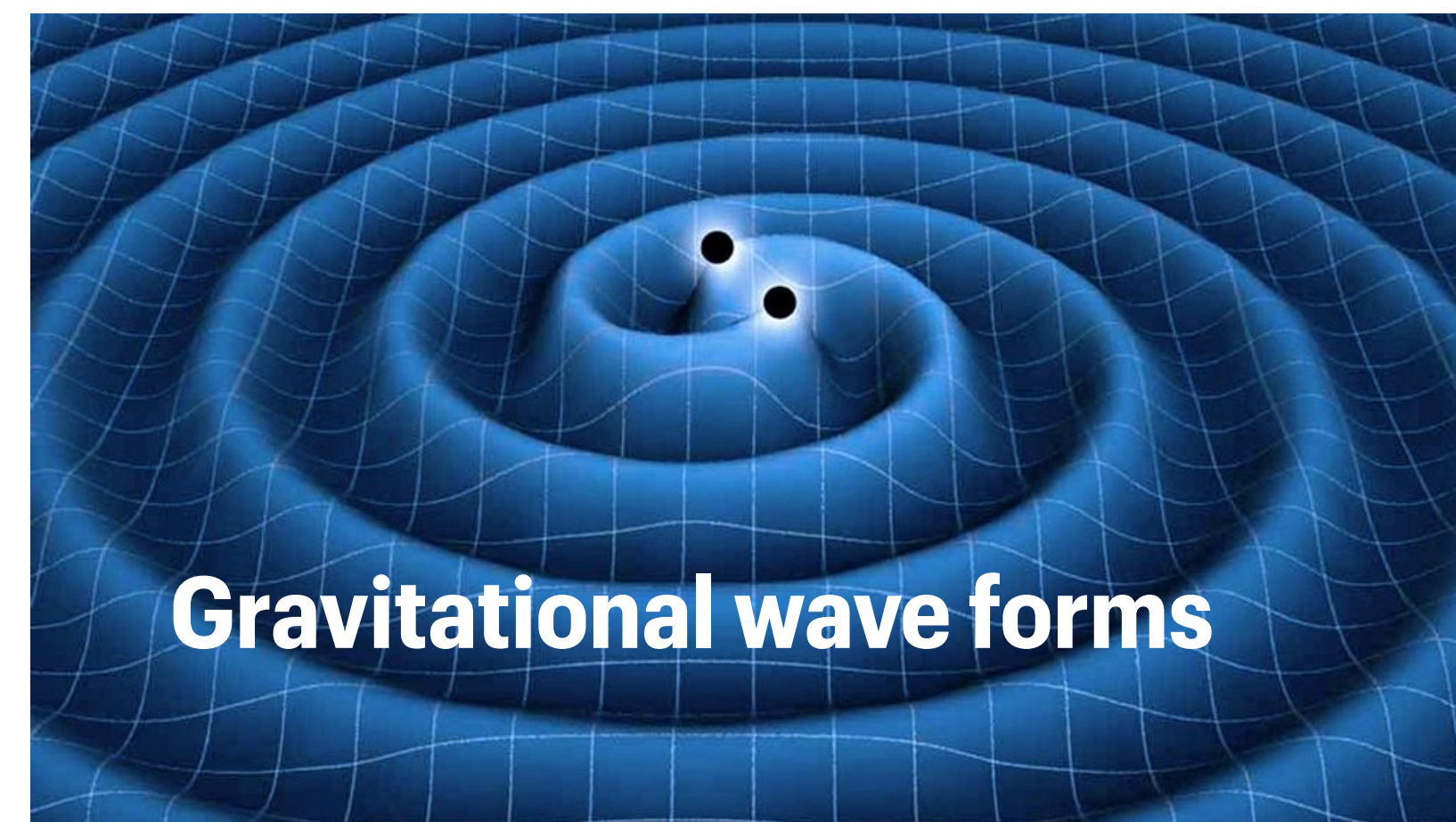
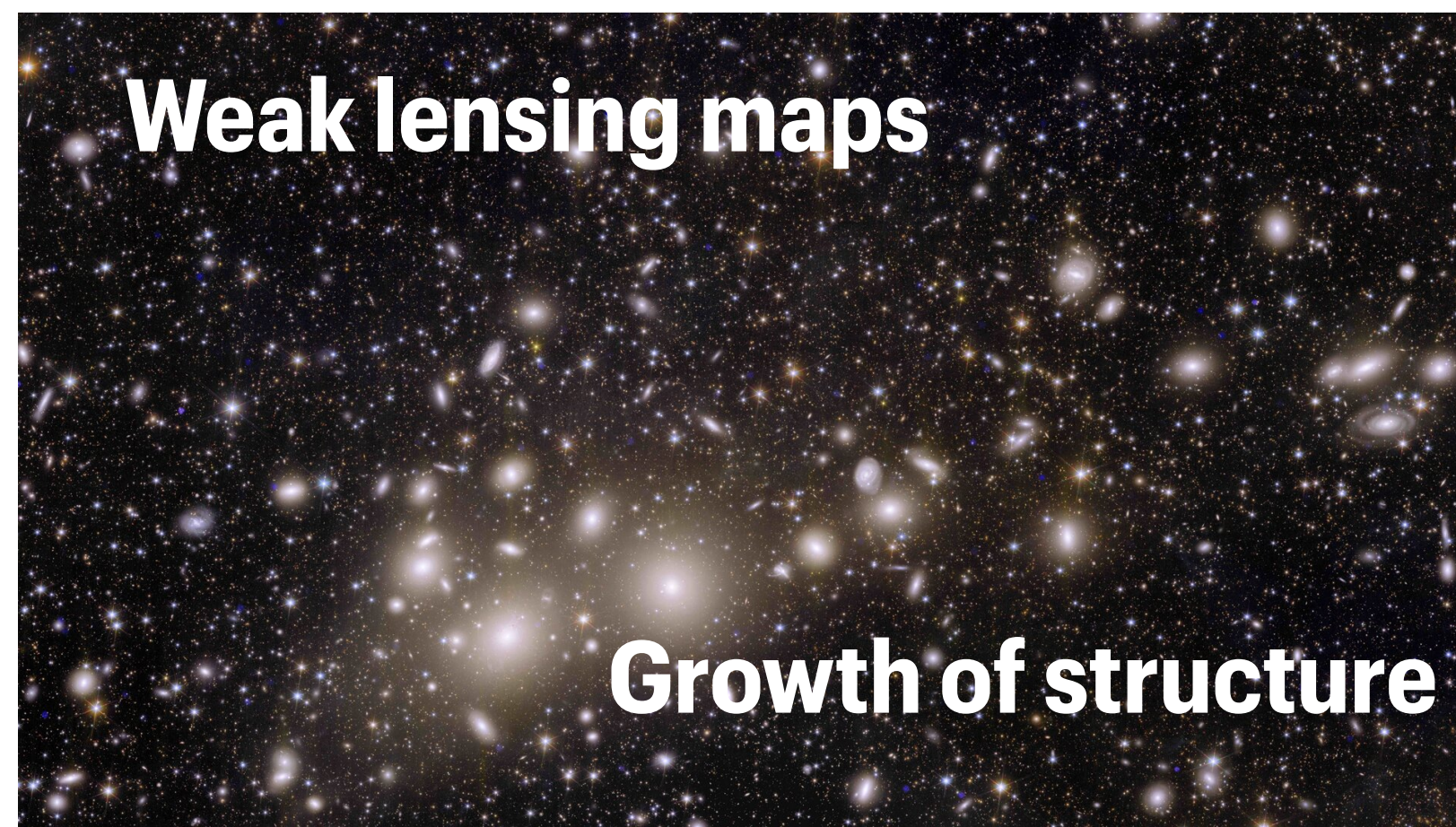
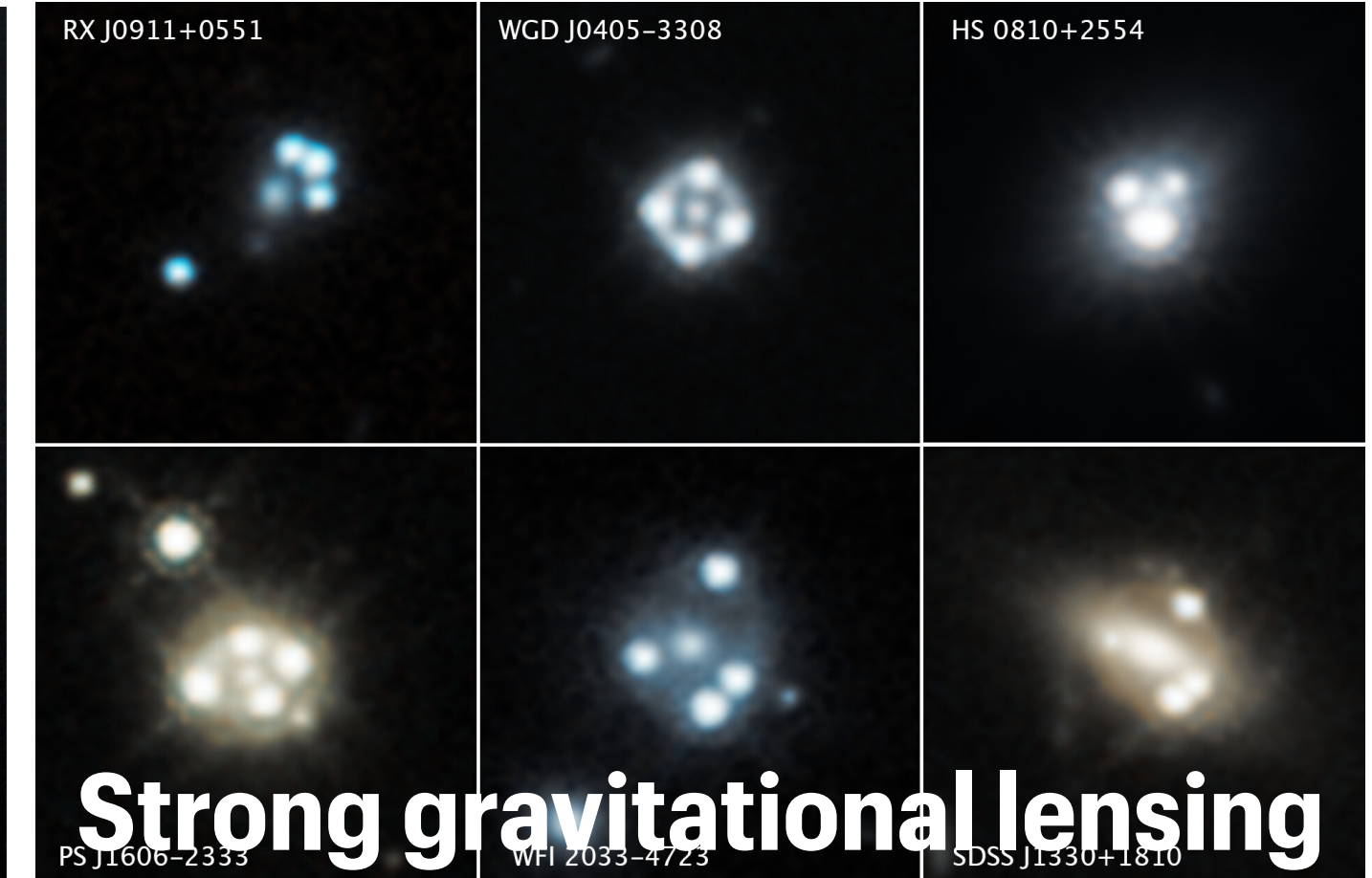
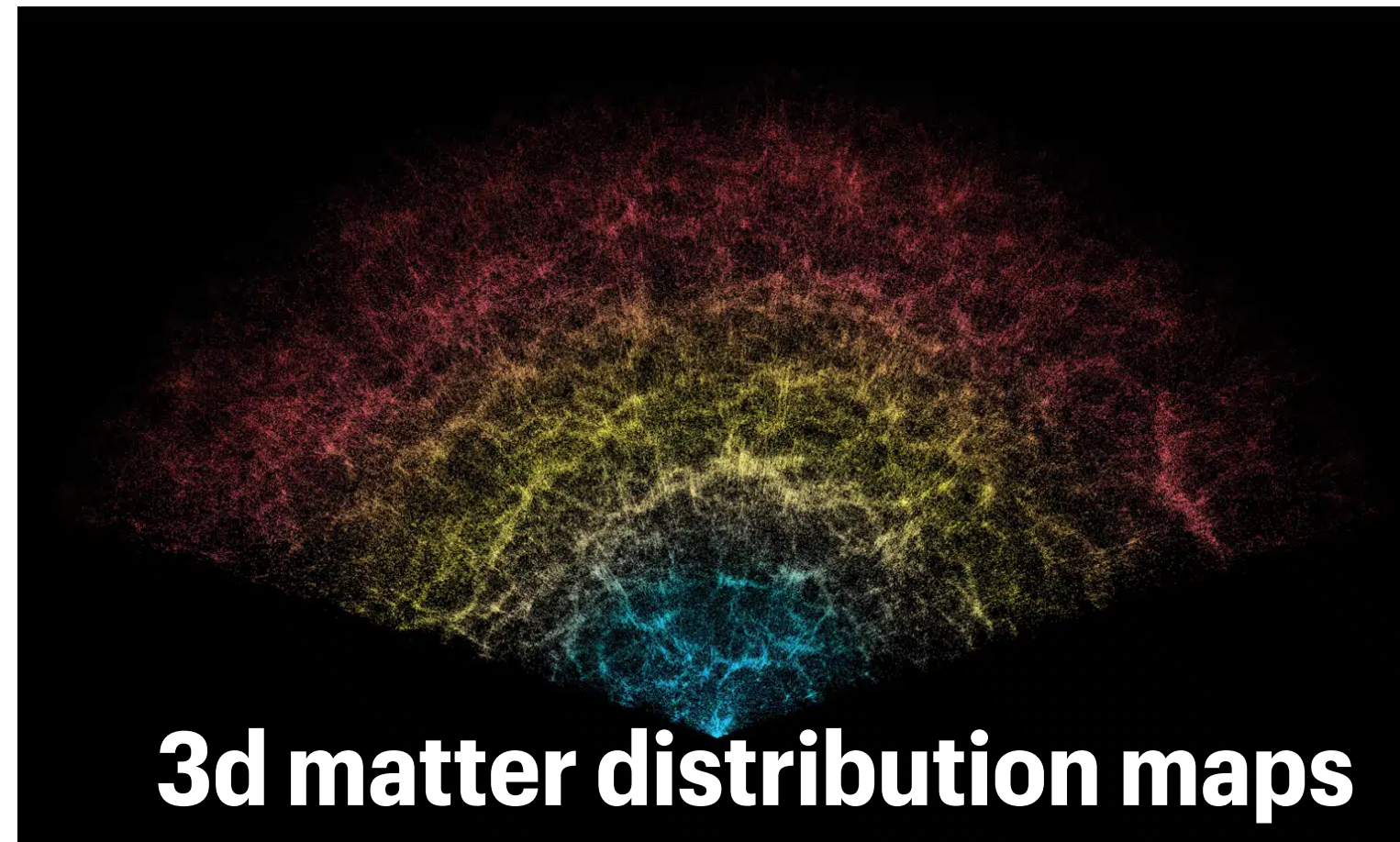
- Is the “Hubble tension” caused by systematics or by unknown physics?
- Is dark energy a cosmological constant?
- What is the nature of dark matter?
- Are there deviations from General Relativity on cosmological scales or in gravitational wave signatures?
- Are neutrino mass measurements consistent between astronomical and terrestrial experiments?
- Did inflation occur and what was its energy scale?
- H0 dipole from galaxy clusters (X-ray and Sunyaev-Zeldovich datasets, Pandya et al. 2024, countered by Stiskalek et al. 2026, Salzano et al 2025)
- Preference for time-evolving dark energy (DESI 2024 VI)
- Evidence for birefringence in the CMB datasets (WMAP, Planck, Atacama Cosmology Telescope, see Diego-Palazuelos & Komatsu 2025, Komatsu 2022)
- Neutrino mass tension, bulk flows, quasar dipoles, etc... (Cosmoverse white paper 2025)

A new paradigm to succeed Λ CDM?

Theoretical advancement	Examples
Dark energy is due to one or more new scalar fields of nature	Quintessence, early dark energy, chameleon / symmetron fields
A new theory of gravity	$f(R)$ gravity, (beyond) Horndeski theories, massive gravity
There are extra dimensions in the Universe	Braneworld, Kaluza-Klein theory, string theory
Dark matter and/or dark energy are exotic fluids	Chaplyn gas, coupled DM/DE

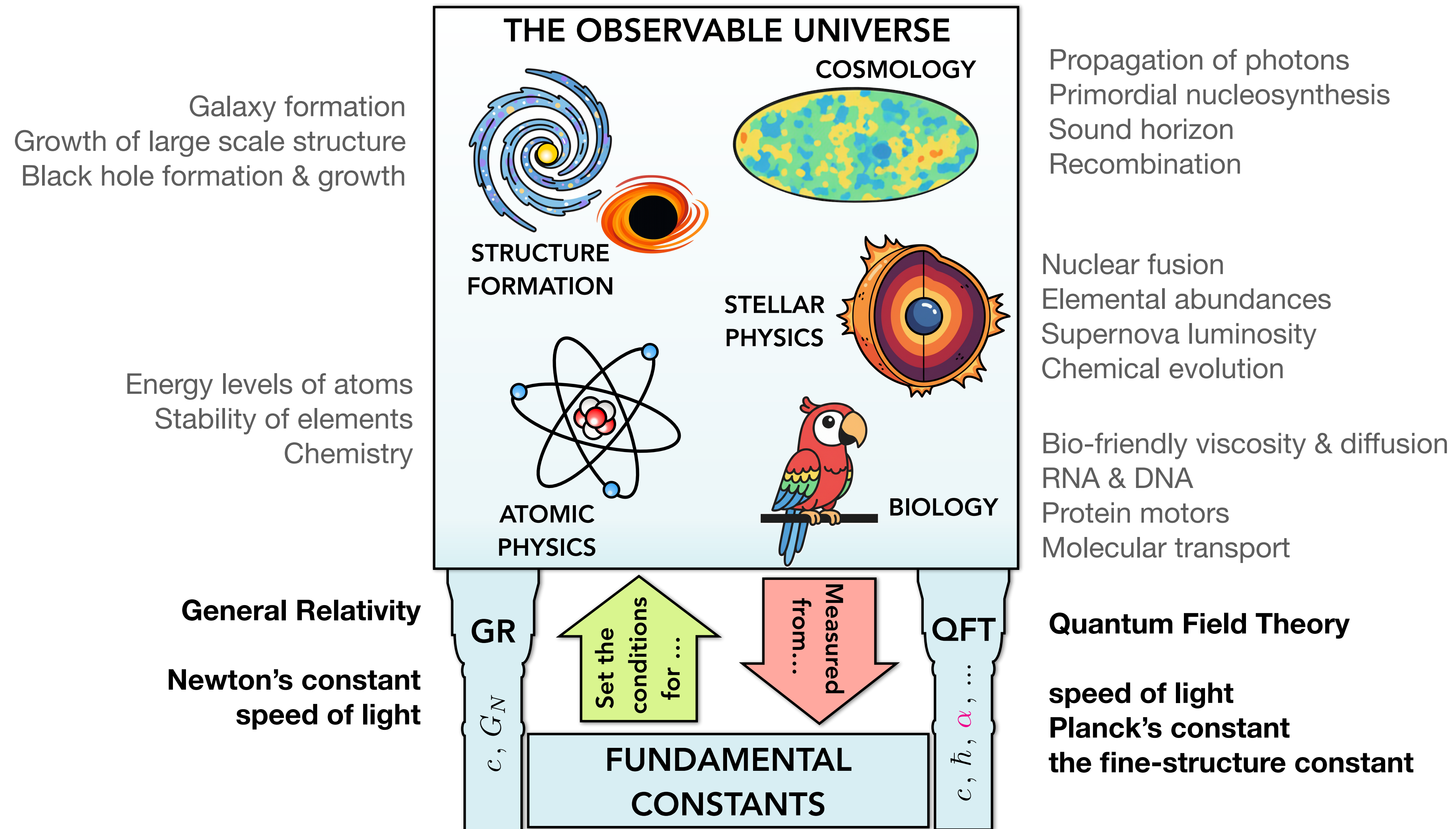
Cosmological probes

Overwhelmingly probe gravitational physics



Different models may have similar predictions on expansion history, growth of structure, lensing potentials (degeneracies between competing models)

Spectroscopy can provide crucial information on non-gravitational physics



When are constants expected to vary?

Framework	Cosmological motivation
If a dynamical scalar field couples to the matter metric	Dark energy
In scalar-tensor and modified gravity theories	Dark matter and dark energy
When extra dimensions expand/contract	Grand unification theories
In string theory, if vacuum moduli fields evolve in time	Grand unification theories and dark energy
Varying speed of light theories	Alternative to inflation

What if constants do not vary?

We learn that:

- dark energy is almost certainly not a scalar field (eliminates quintessence)
- the structure of quantum physics is decoupled from cosmology
- our interpretation of other datasets is robust (because we rely on the “constancy of constants” when using supernovae, CMB, BAO, growth of structure)

The fine structure constant

the “fine structure constant”

electromagnetism

$$\alpha \equiv \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

quantum mechanics

general relativity

IF $\Delta\alpha \rightarrow \Delta E \rightarrow \Delta\lambda$

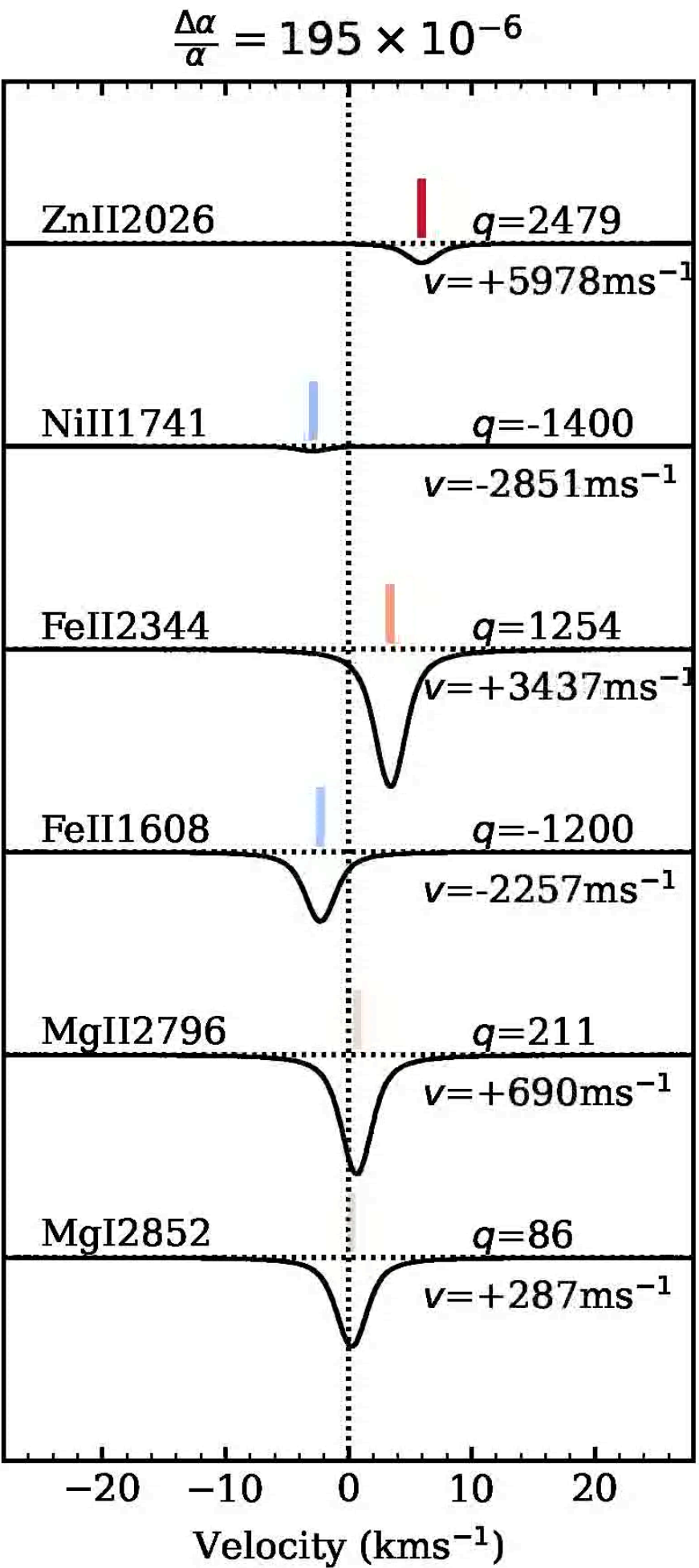
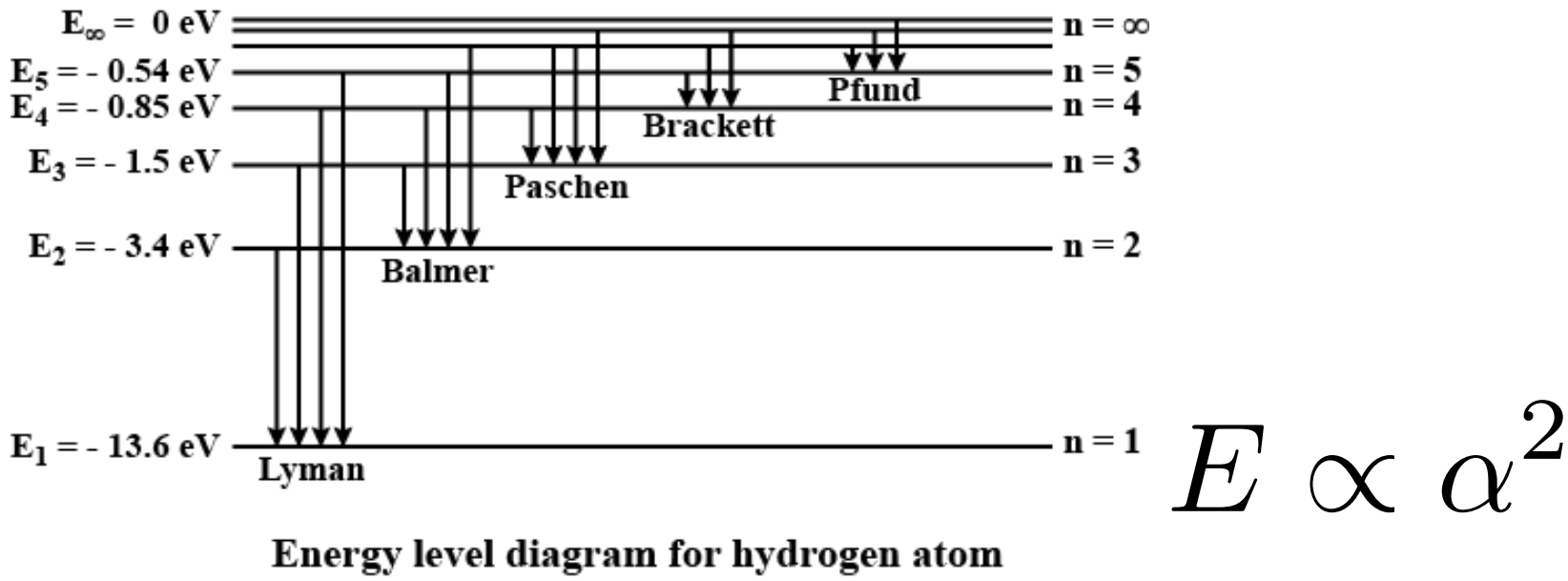
Measurable

observed
wavelength shift

$$\frac{\Delta\lambda}{\lambda} \propto q \frac{\Delta\alpha}{\alpha}$$

sensitivity
coefficient

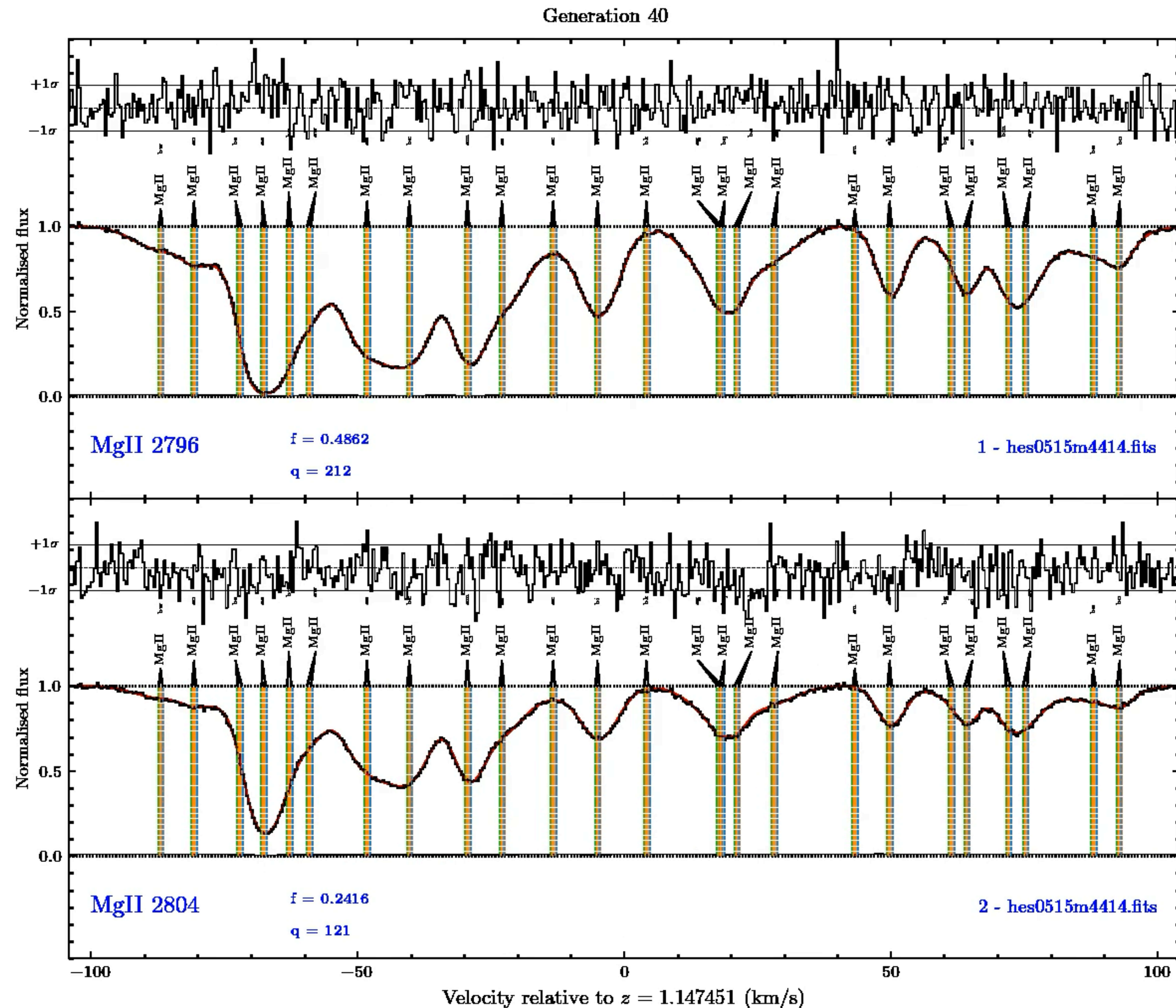
Every transition has a
different sensitivity to $\Delta\alpha$



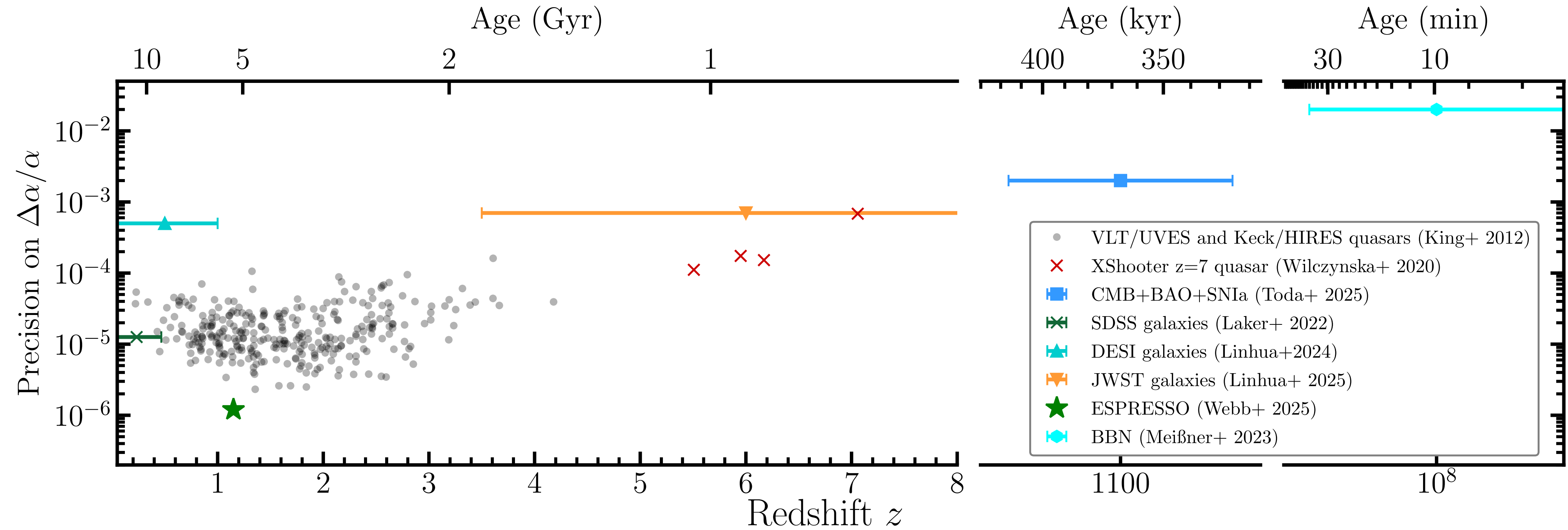
AI-VPFIT: data modelling is a solved problem

Lee et al. 2021a, 2021b; Webb et al. 2021;
Webb et al. 2022; Milaković et al. 2021;

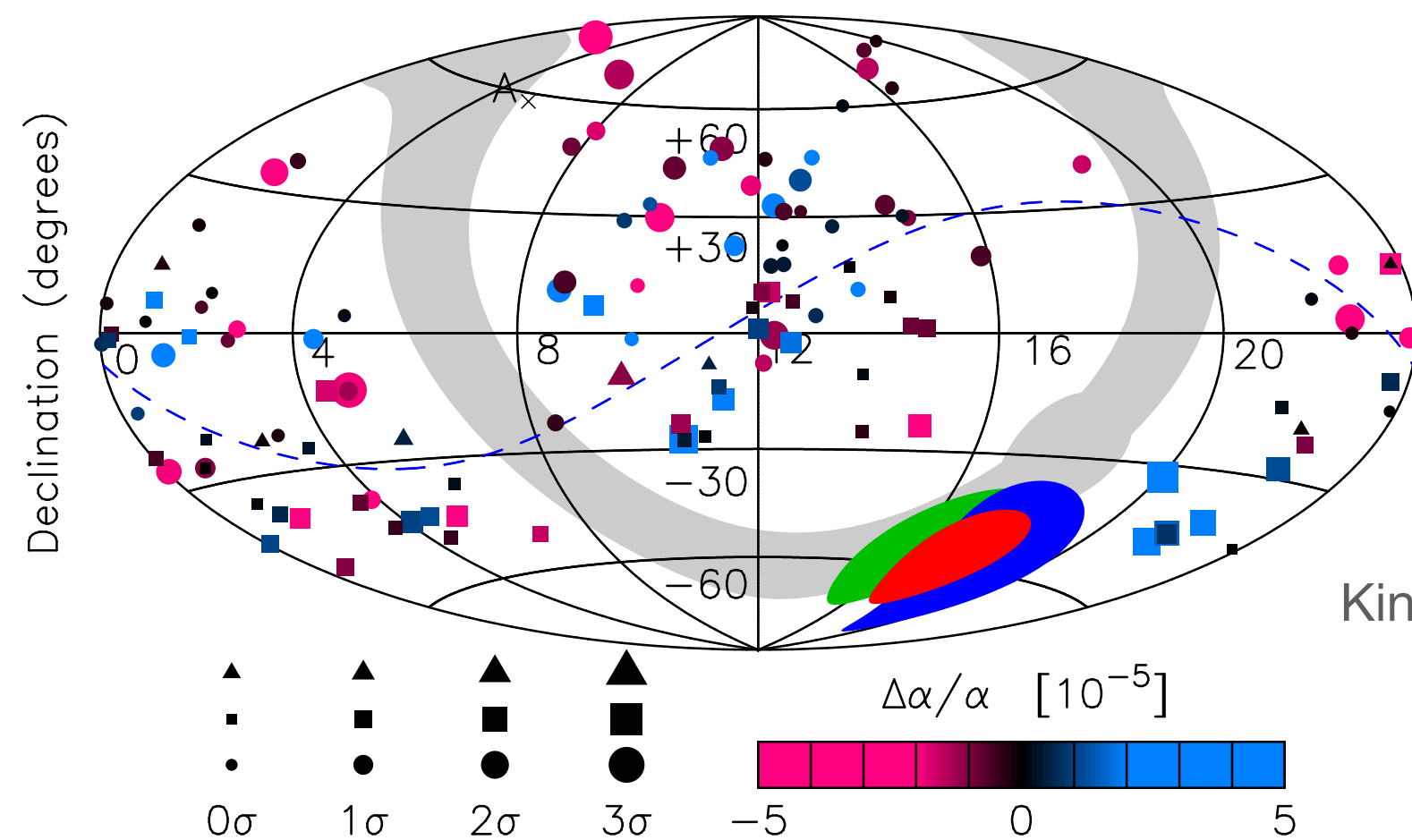
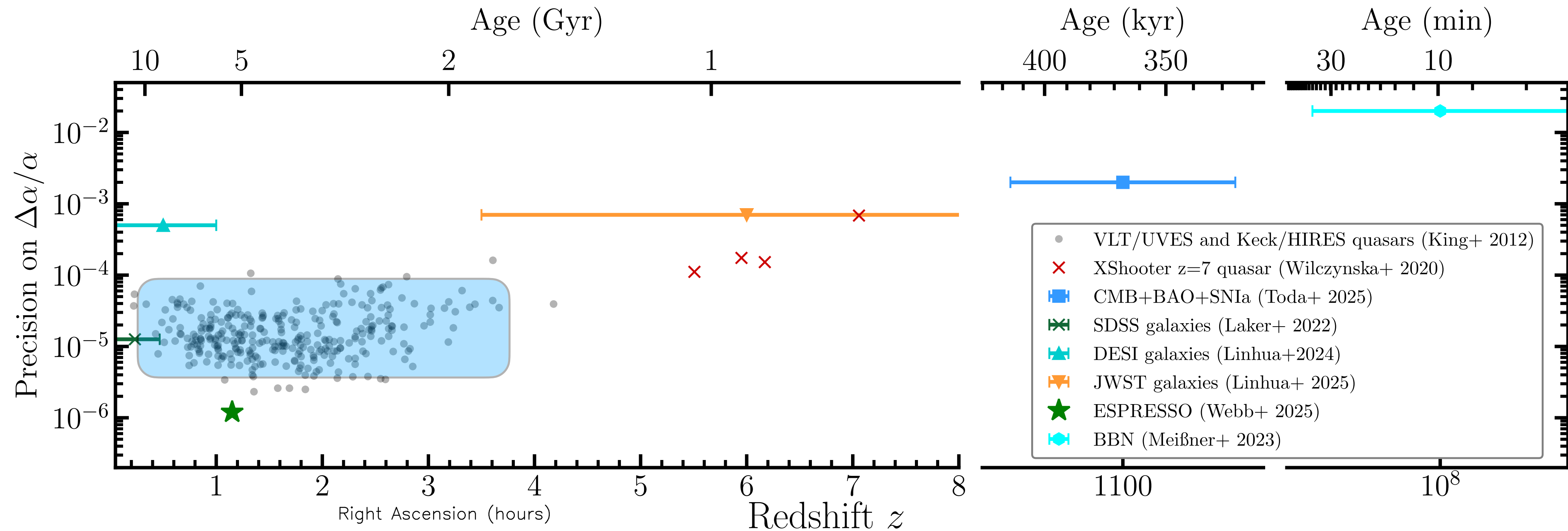
- Made in 41h
(a human expert took >1 month)
- **Ability to process huge datasets in a short time**
- Applicable to ELT/ANDES in the future
- No human input = no human bias
- **Requires assumptions on instrument profile — currently a Gaussian**



Constraints on the fine structure constant



Constraints on the fine structure constant



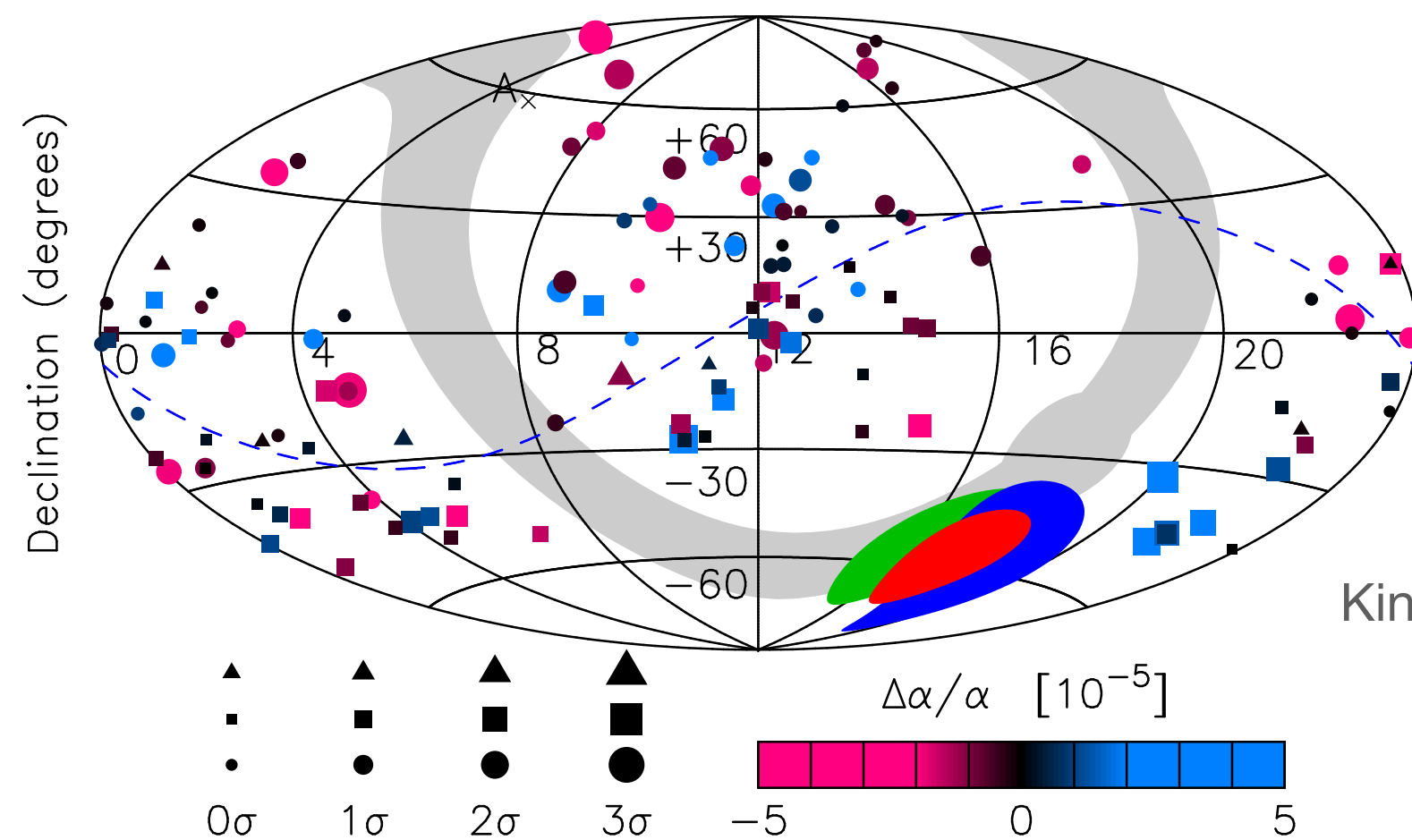
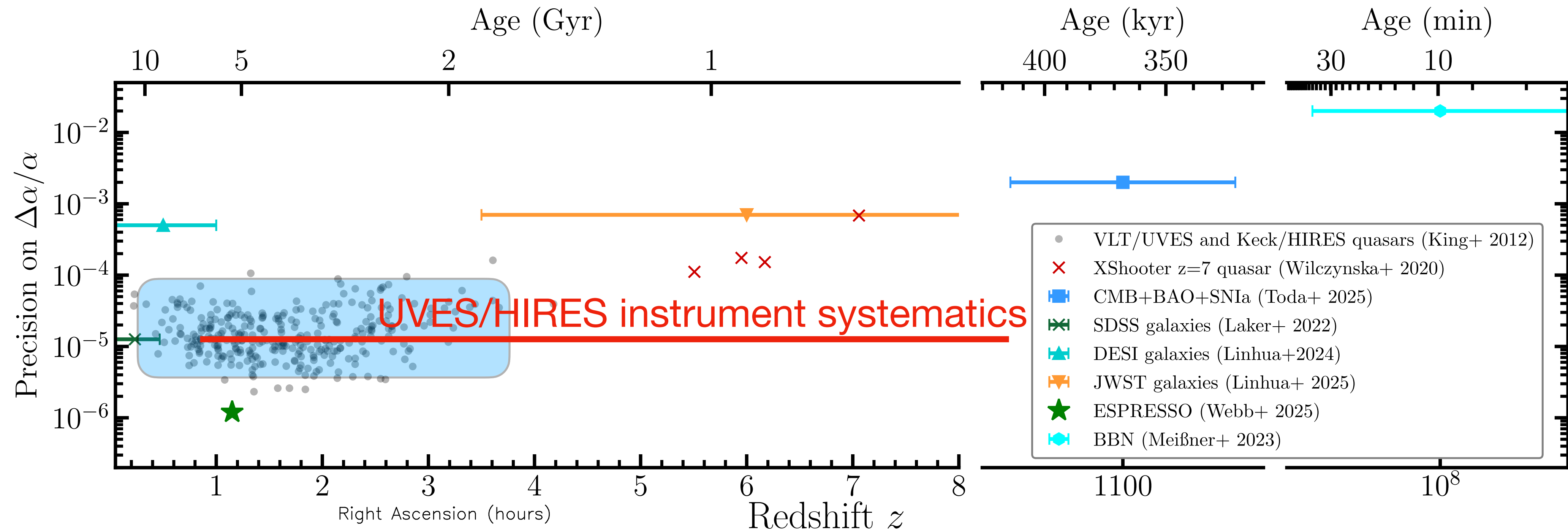
King et al. 2012

1990s – 2010s

VLT/UVES + Keck/HIRES
spatial dipole,
4.2 σ statistical significance

The result that motivated
the inclusion of fundamental constant
as science cases for ESPRESSO and ANDES

Constraints on the fine structure constant



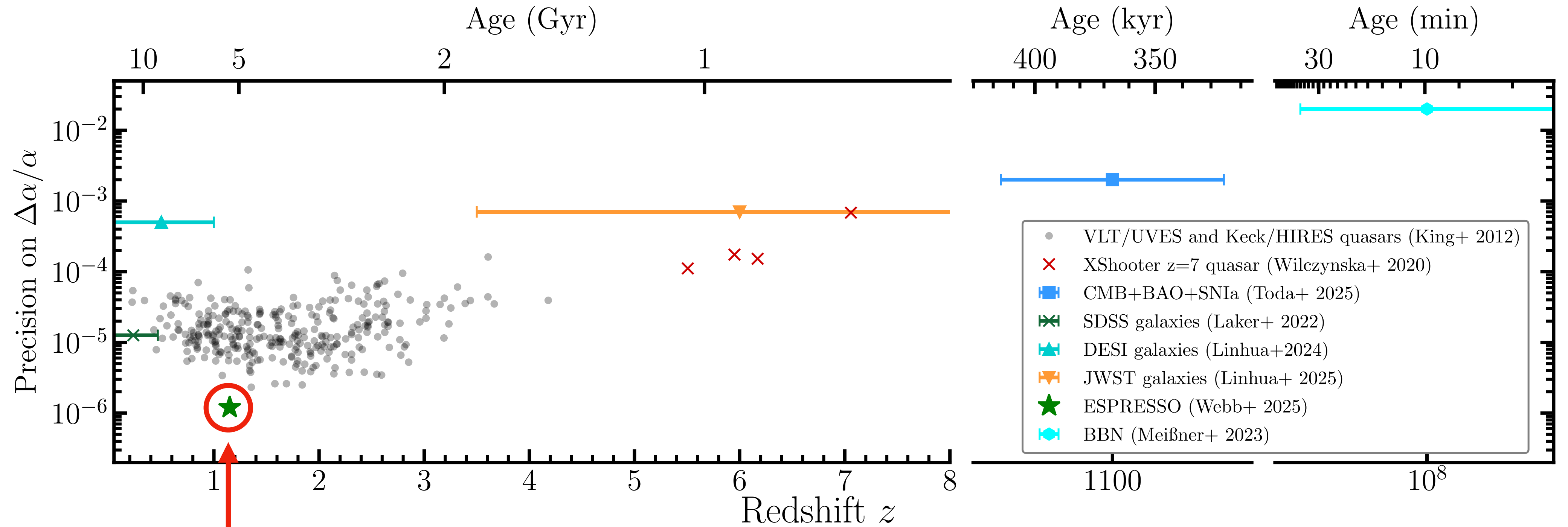
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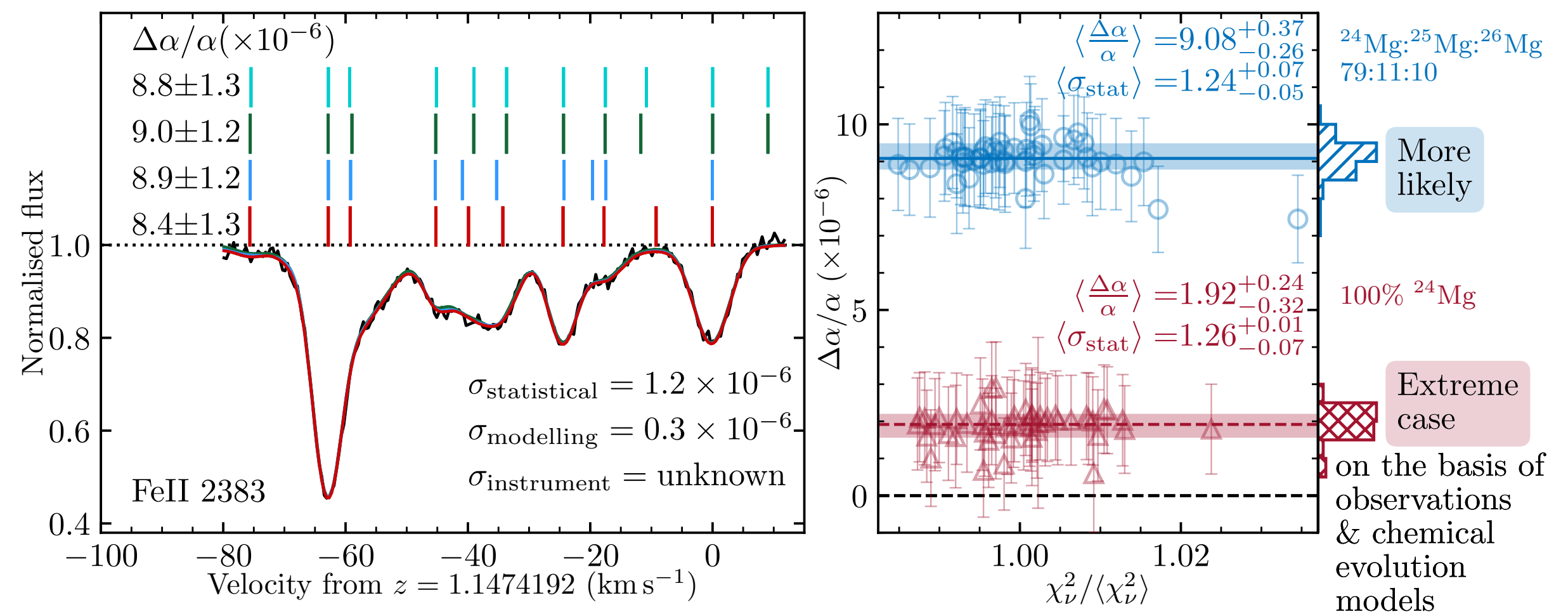
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Constraints on the fine structure constant

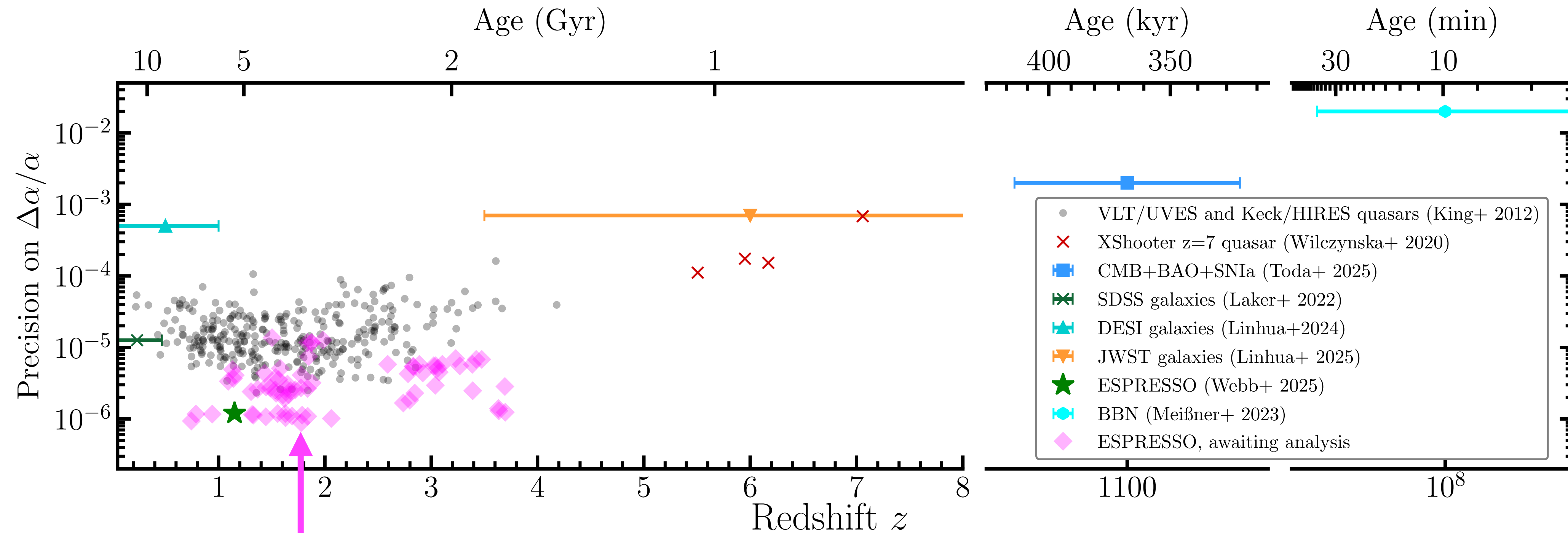


A 7σ variation signal with ESPRESSO,
the only made with AI-VPFIT (Webb et al. 2025)

The full picture is complicated...



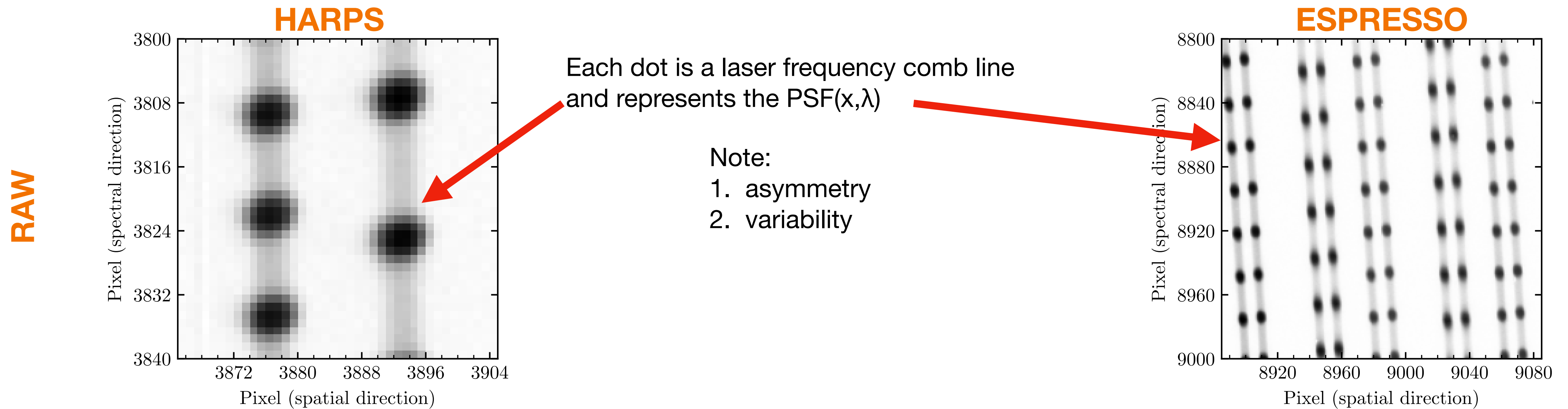
Constraints on the fine structure constant



70 new systems
await analysis, of which
15 promise 10^{-6} statistical precision

What is needed to deliver the best possible constraints with ANDES?

More advanced spectral extraction procedures

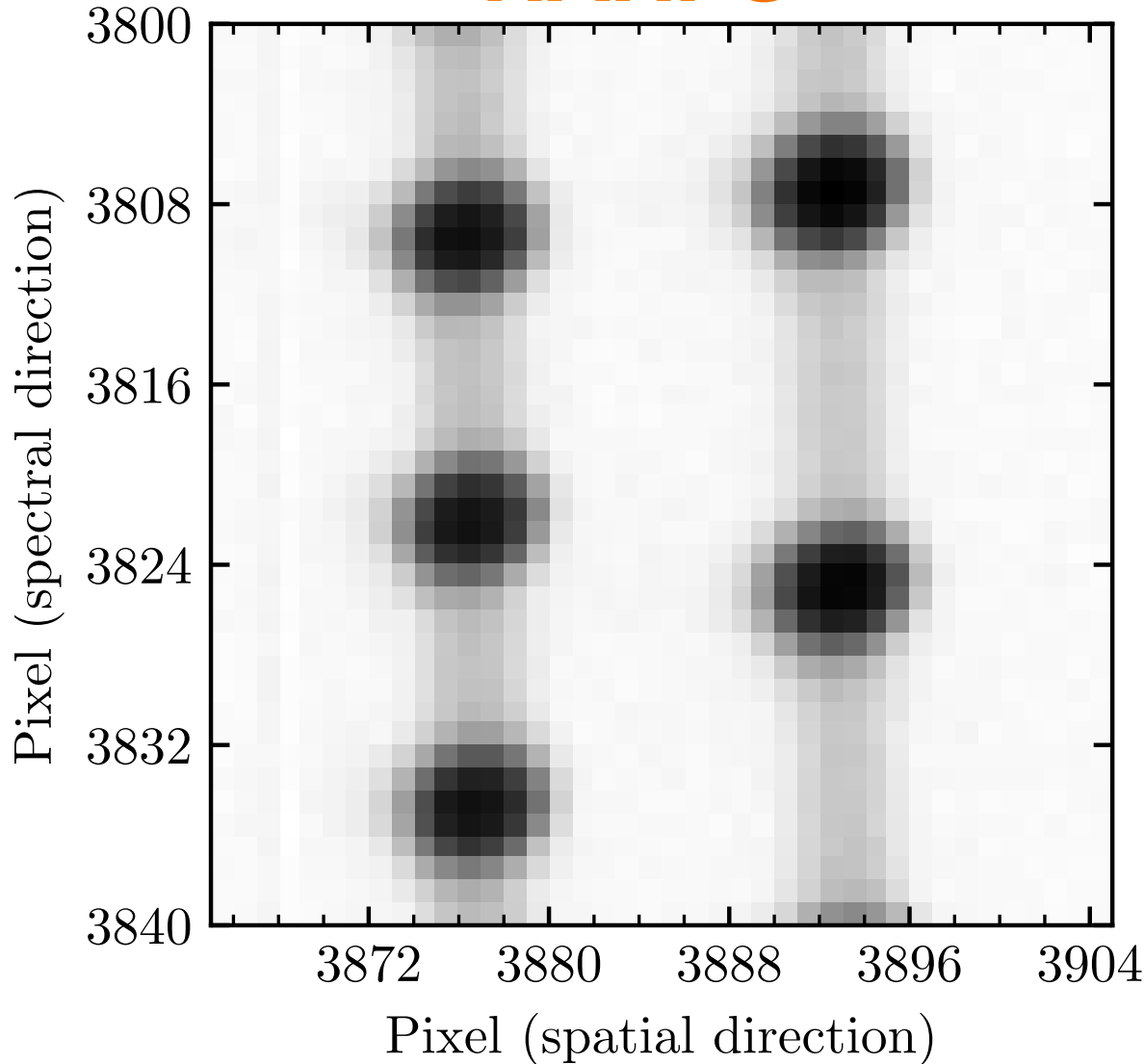


What is needed to deliver the best possible constraints with ANDES?

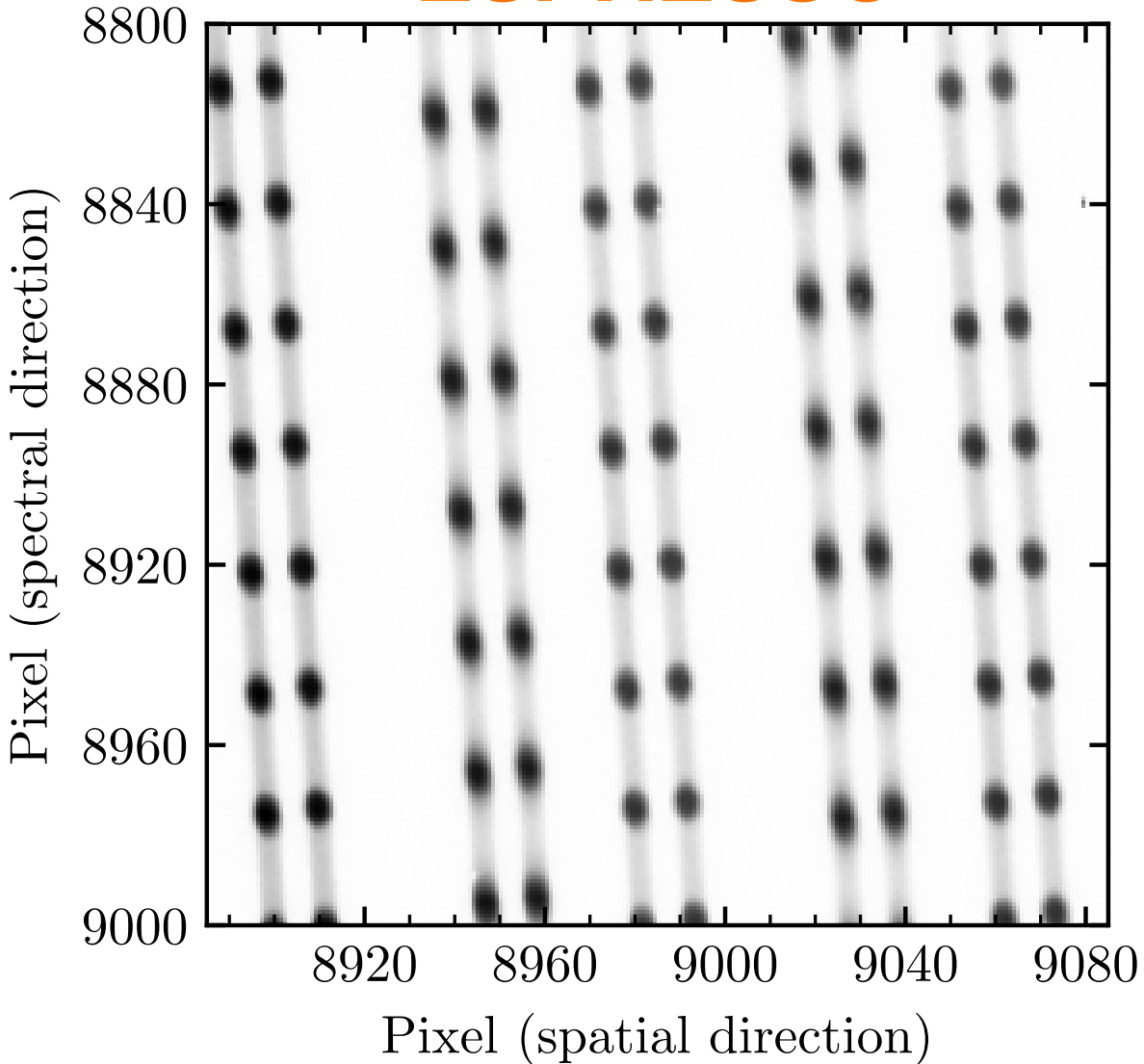
More advanced spectral extraction procedures

RAW

HARPS



ESPRESSO

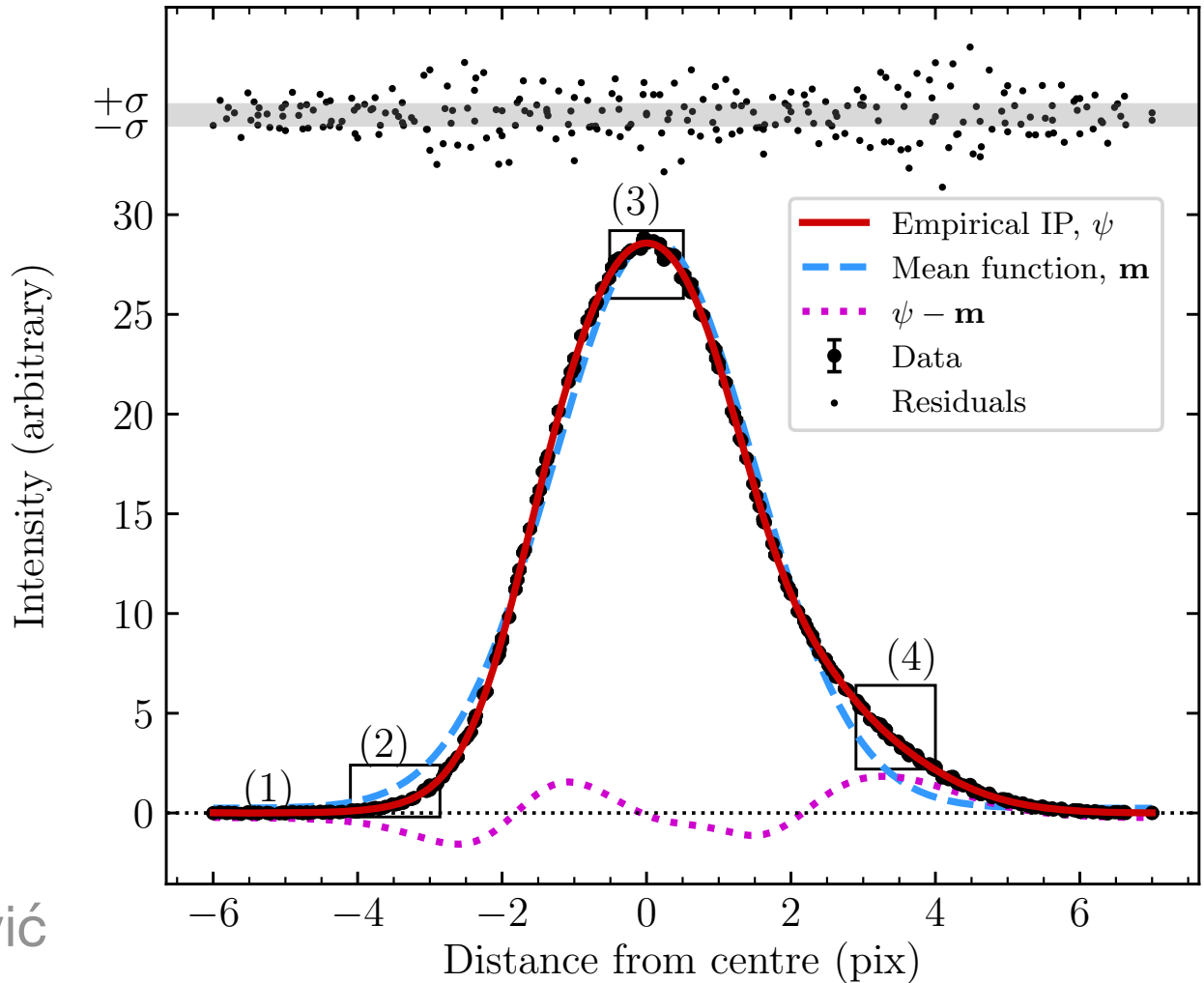


Each dot is a laser frequency comb line
and represents the PSF(x,λ)

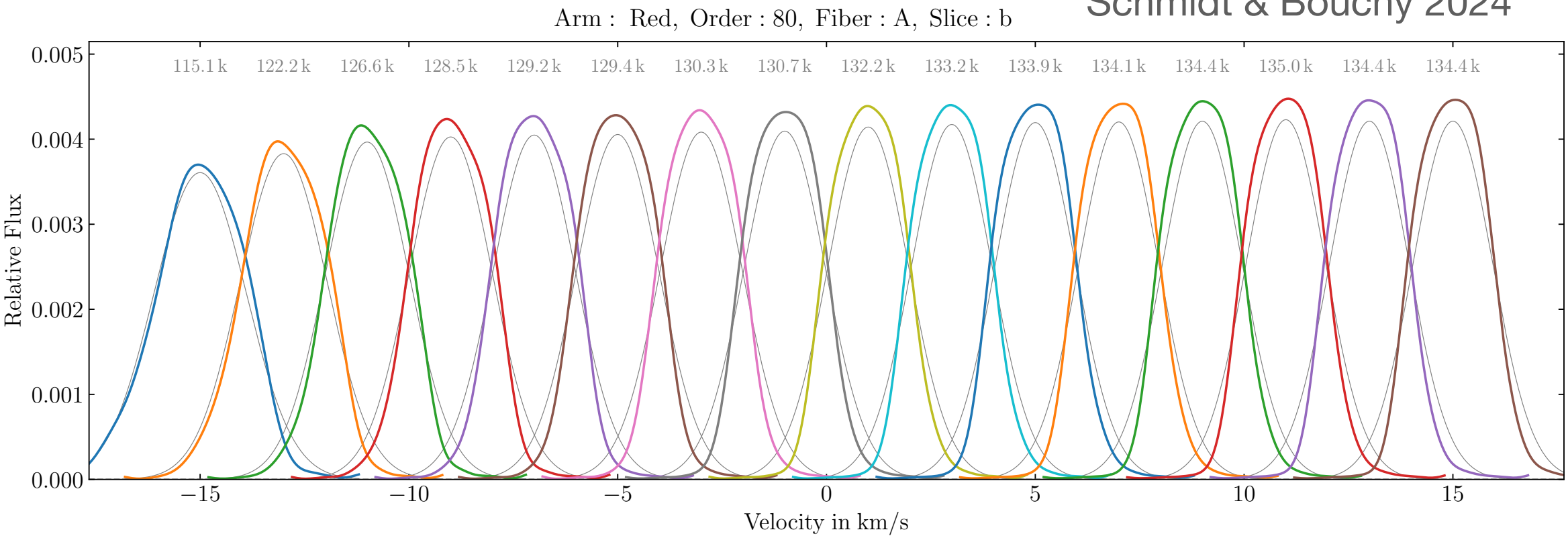
- Note:
- 1. asymmetry
 - 2. variability

EXTRACTED

Milaković & Jethwa 2024



Schmidt & Bouchy 2024



What is needed to deliver the best possible constraints with ANDES?

More advanced spectral extraction procedures

RAW

EXTRACTED

HARPS

ESPRESSO

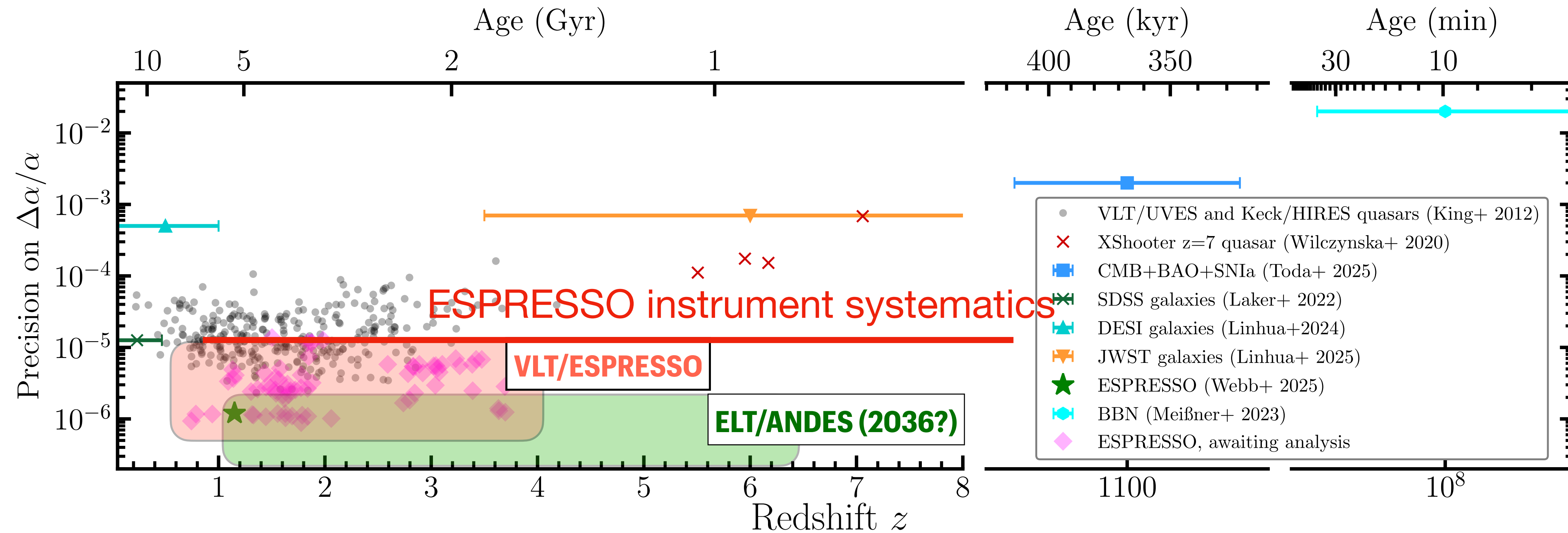
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ANDES

(Weber et al. 2024)

nidt & Bouchy 2024

Constraints on the fine structure constant



100 times more precise at $z>4$

Conclusions

- Fundamental constants as a complementary probe of physics beyond Λ CDM, now and in the future
- AI-VPFIT can deal with astrophysics but we are limited by not having precise, publicly available, measurements of the instrument profile for modelling
- ESPRESSO has observed ~40 quasars, 70 systems await analysis: potentially interesting results
- ANDES will be even more complicated
 - instrument profile as community product? Benefits also RV / isotope studies.
 - a tunable high-finesse FP or a tunable LFC for PSF reconstruction?
 - spectral perfectionism as the base data reduction procedure?