Fundamental Physics with Stellar Twins

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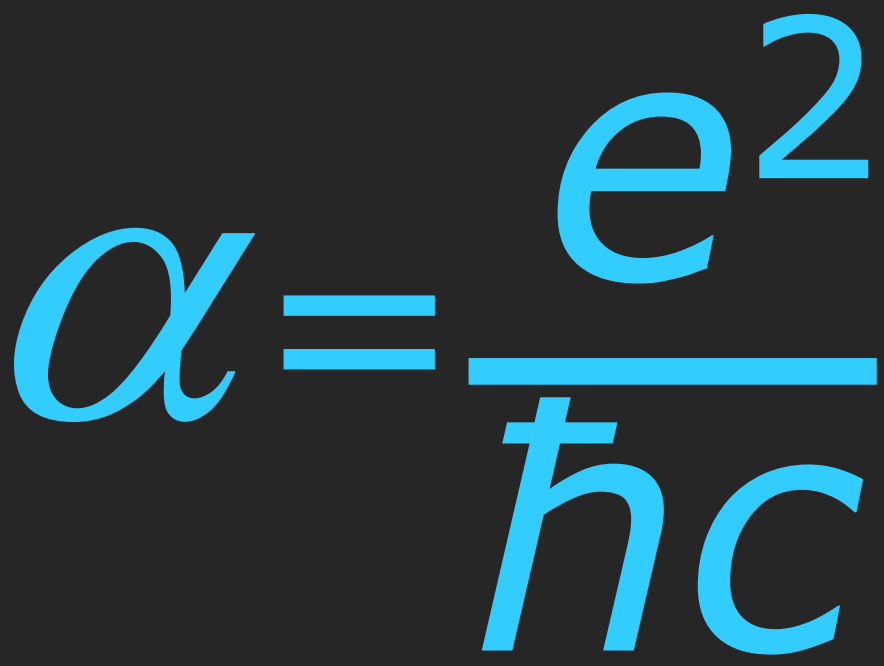
Image: NASA/SDO & the AIA, EVE, and HMI teams

Overview

- Why “varying constants”?
- Are electromagnetism & Dark Matter deeply connected?
- New project:
  Map EM strength with DM density across our Galaxy with stars
  - Solar twin results from HARPS
  - Red giants work!
  - Ready for ESPRESSO & KPF


$\alpha = \frac{e^2}{\hbar c}$

Fundamental? Constant?

- Why fundamental?
  - Theory doesn't explain them
- Why constant?
  - 'Merely' observed to be
  - Exquisite lab experiments:
    α stable within 10^{-18} yr^{-1} (e.g. Lange+21)
- Feynman on α (1985, *QED*)

  It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man…

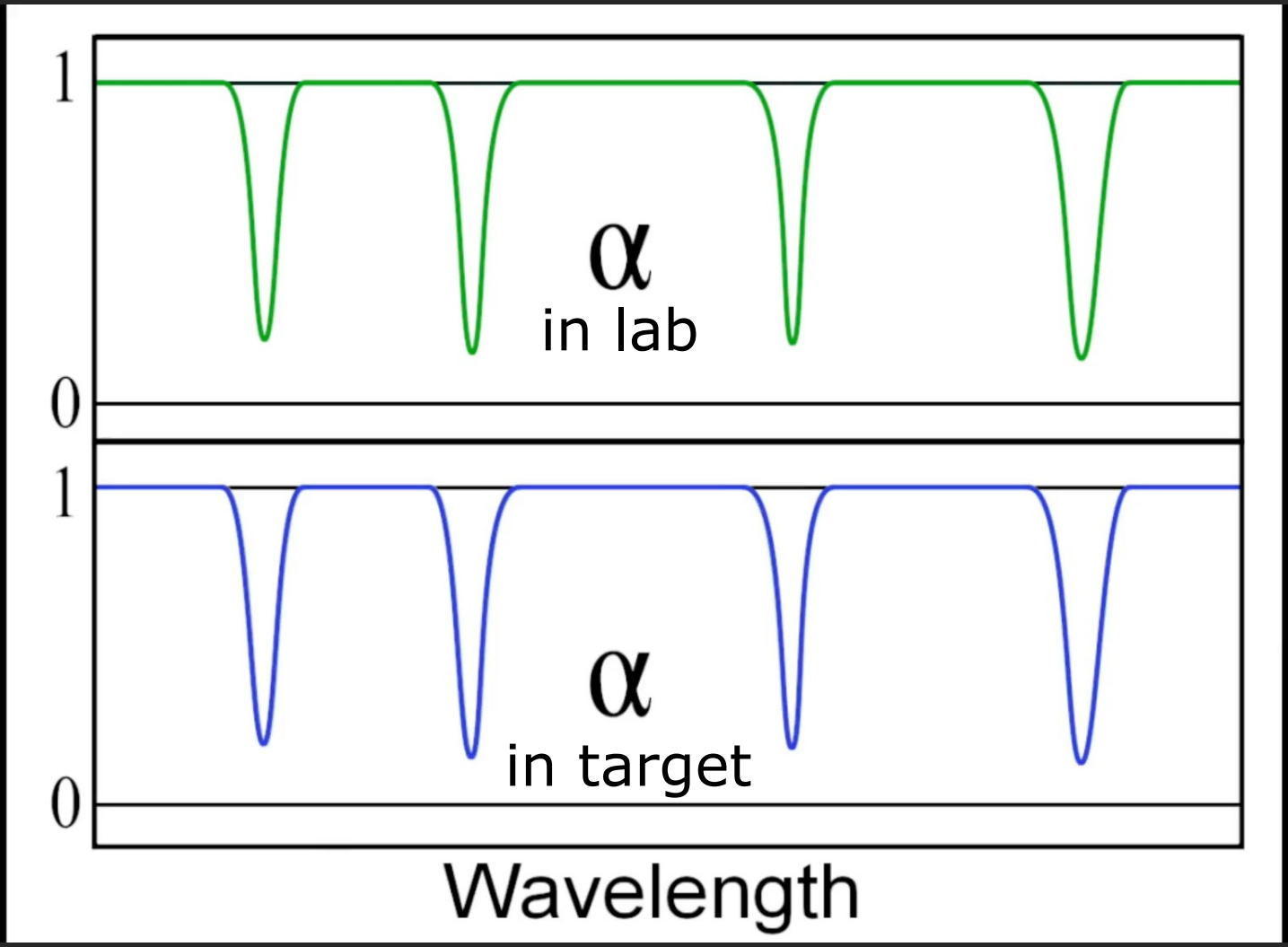
  … all good theoretical physicists put this number up on their wall and worry about it.
- Hint that Standard Model is incomplete

Many Multiplet method:

$$\frac{\Delta v}{c} \approx -2Q \frac{\Delta \alpha}{\alpha}$$

- Calculate Q from quantum mechanics
- Measure Δv in spectrum

Line shifts with varying α

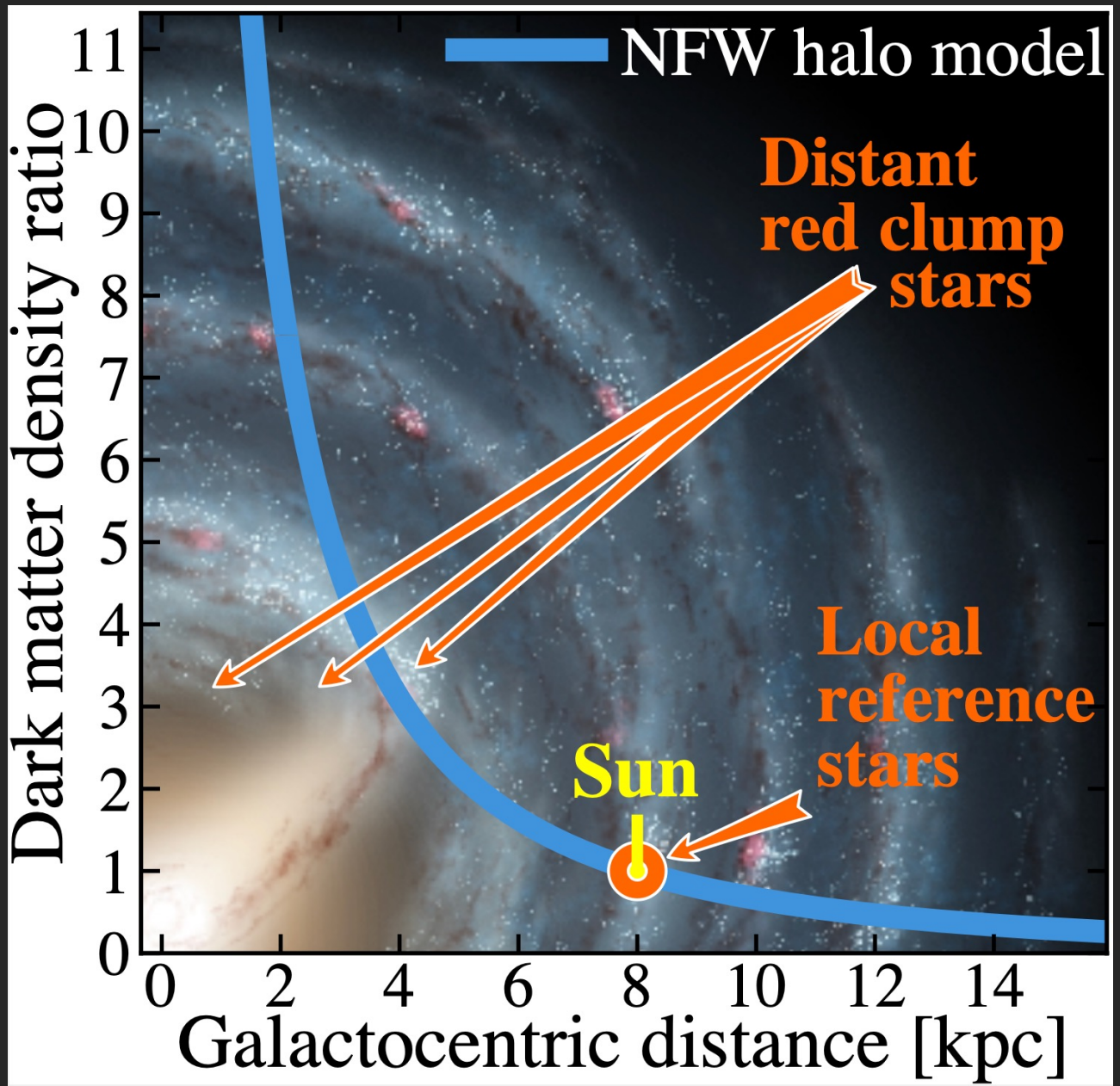


Credit: Daniel Berke

Previous measurements

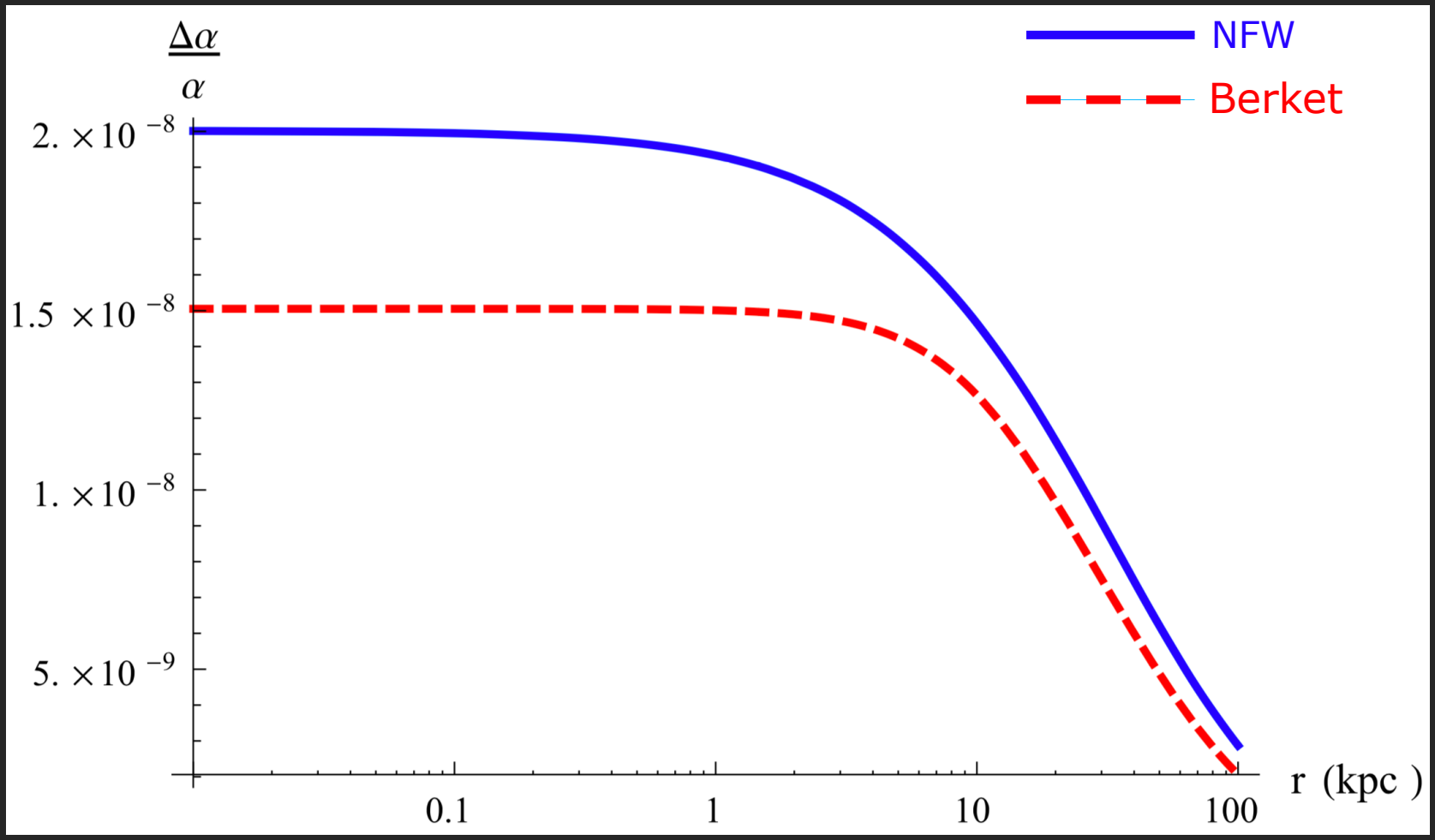
- Goal:
  - Measure α in different places, times, environments…
- Status:
  - Quasar absorption: $\Delta\alpha/\alpha \lesssim 2$ ppm over ~12 billion years (Murphy+22)
  - Quasar absorption: $\Delta\alpha/\alpha \lesssim 4$ ppm across universe (Murphy+22)
  - White dwarfs: $\Delta\alpha/\alpha \lesssim 6$ ppm at $10^4\times$ Earth's grav. potential (Berengut+13, Bainbridge+17, Hu+21)
- Dark Matter?
  - Cosmological & laboratory constraints (e.g. Stadnik & Flambaum 15) are indirect & model-dependent

α–Dark Matter connection?



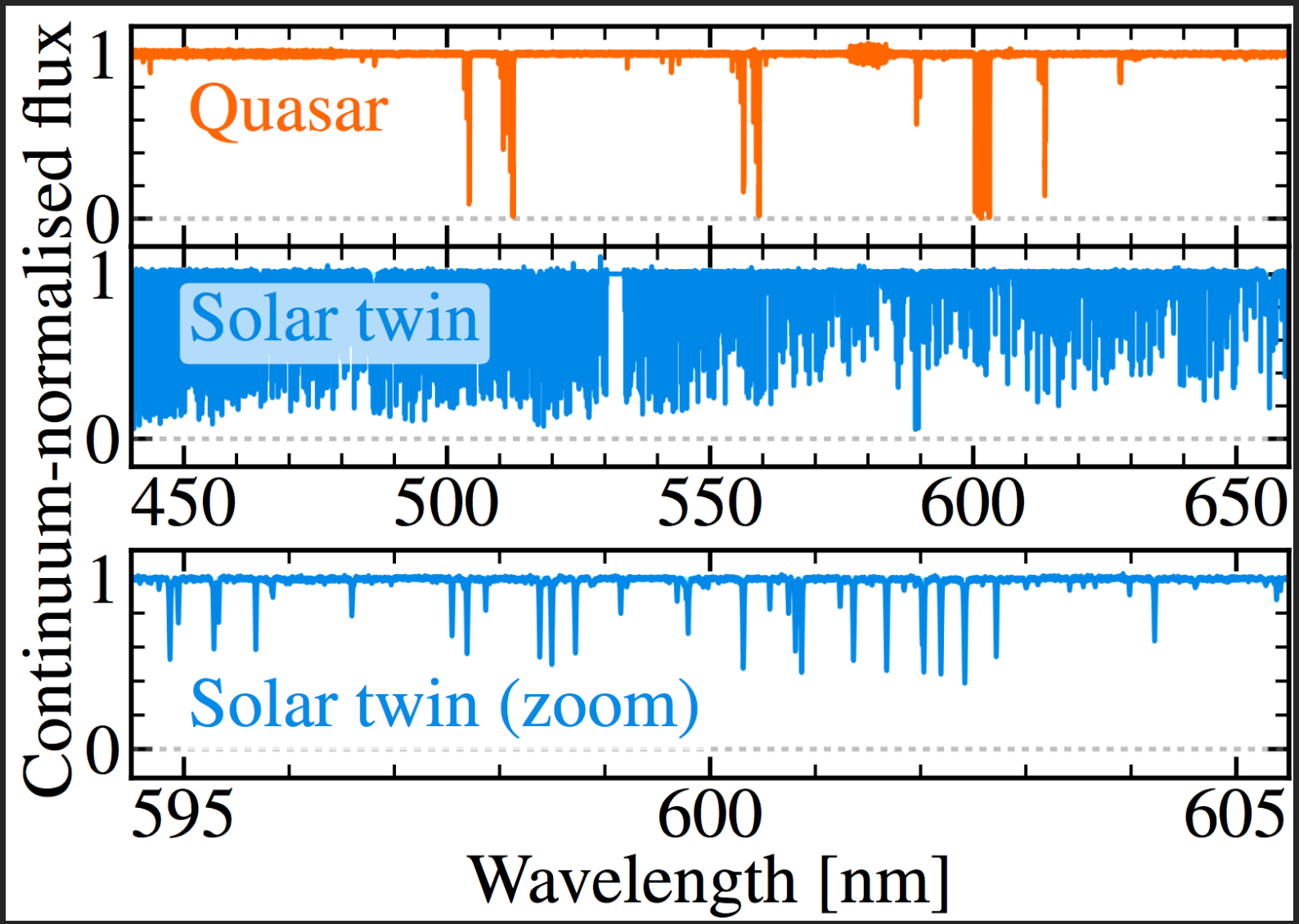
Scalar field example

- Scalar field couples DM & charged fermions (e.g. muons)
- DM changes fermion mass ⟹ changes screening effect for α



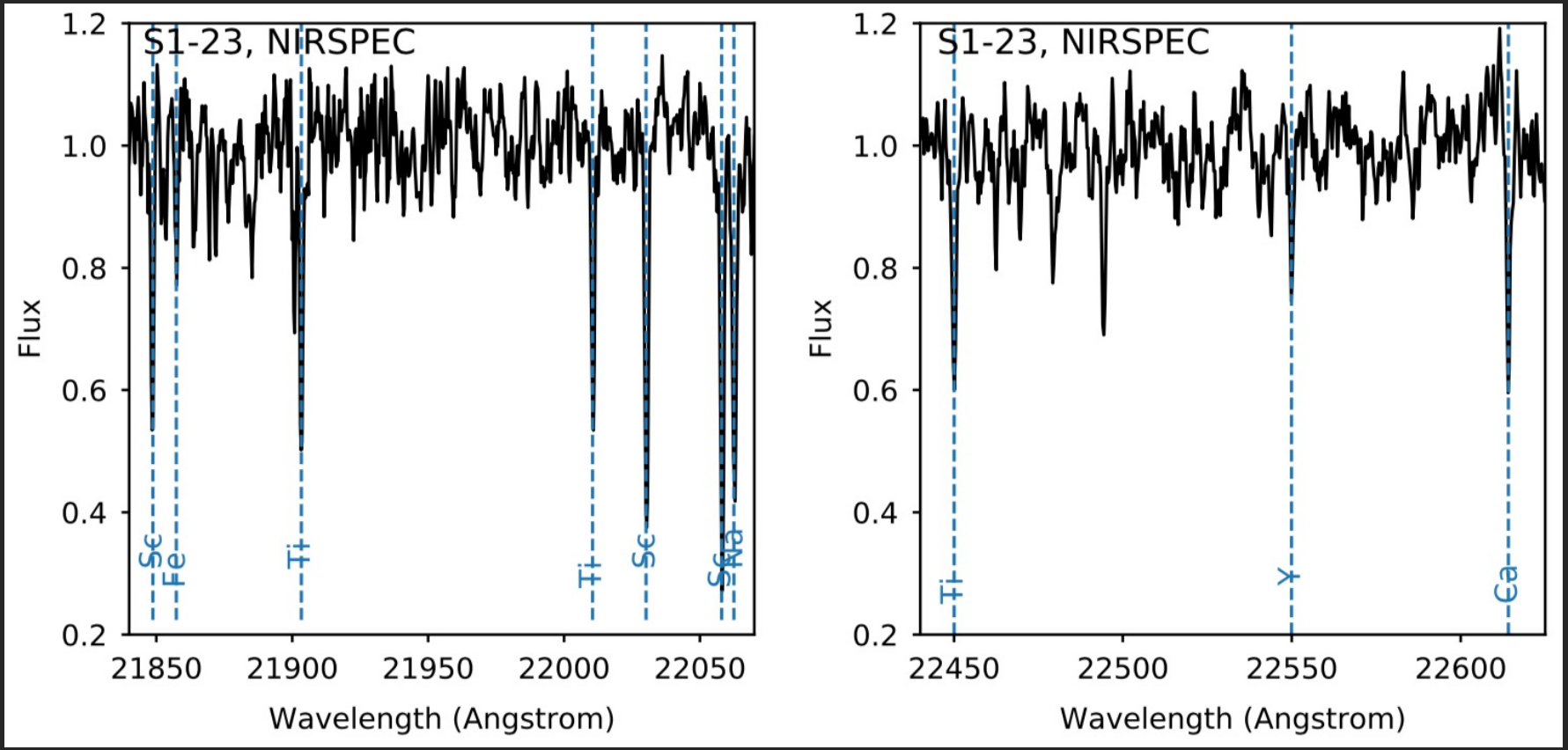
Davoudiasl & Giardino 19

Can we probe α with stars?



Can we probe α with stars?

- Hees+20 (PRL):
  - Keck IR spectra of (effectively) 1 star near Galactic Centre
  - 10 lines compared to lab wavelengths
  - $\Delta\alpha/\alpha$ = 0.9 ± 5.8 ppm



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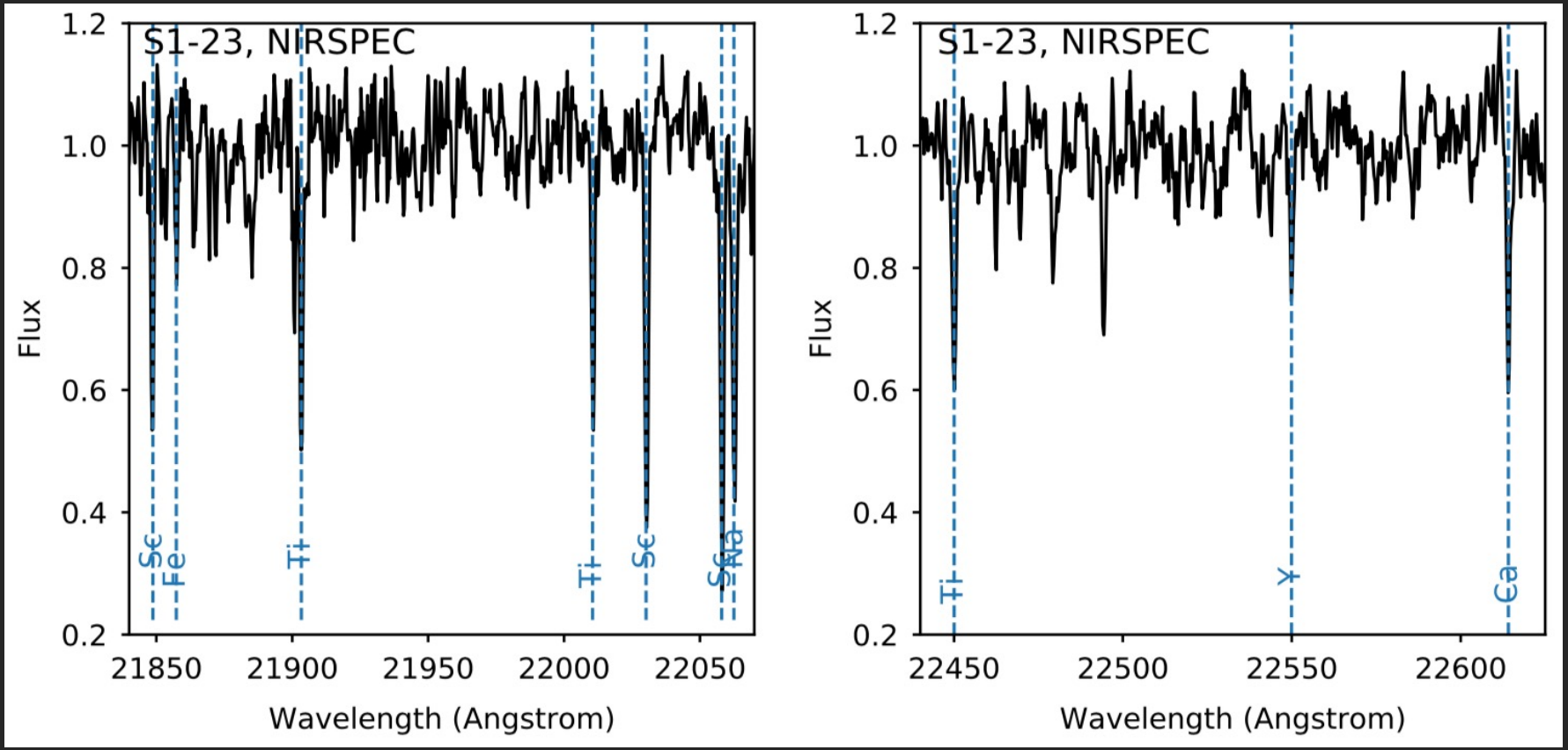

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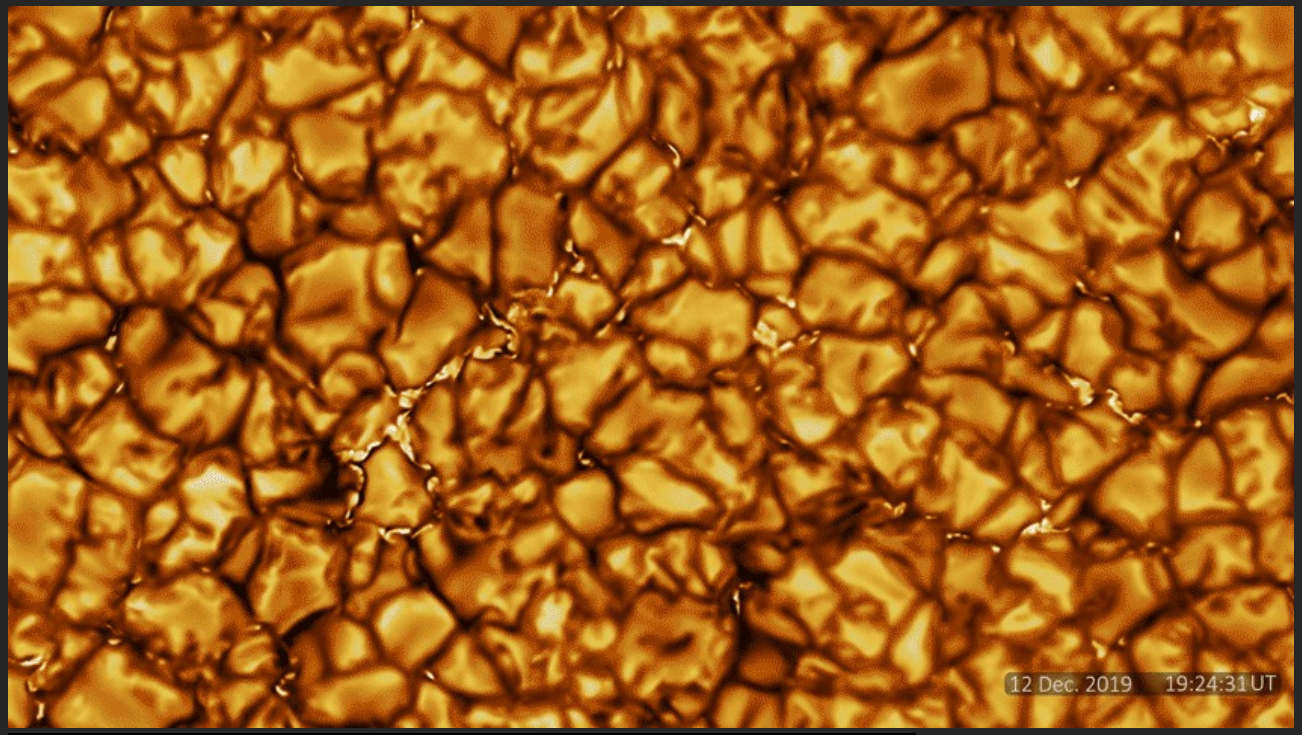

NSO/NSF/AURA

NASA

NASA/SDO

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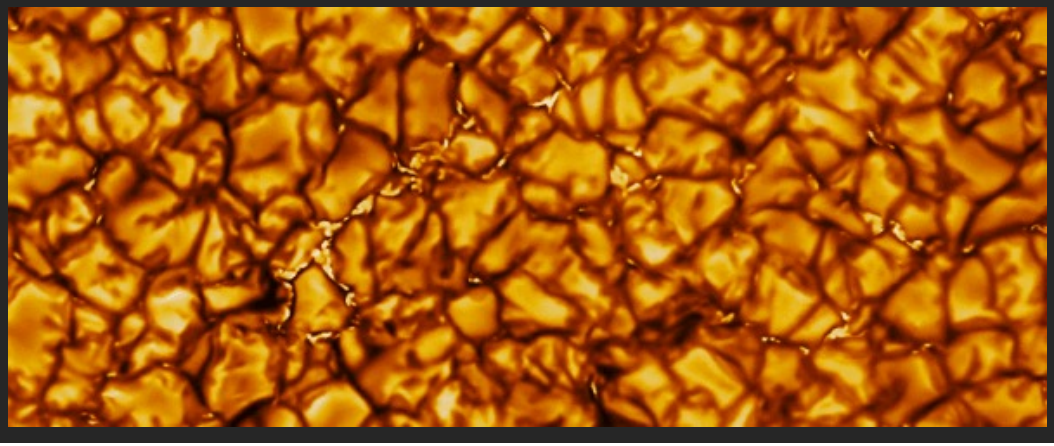

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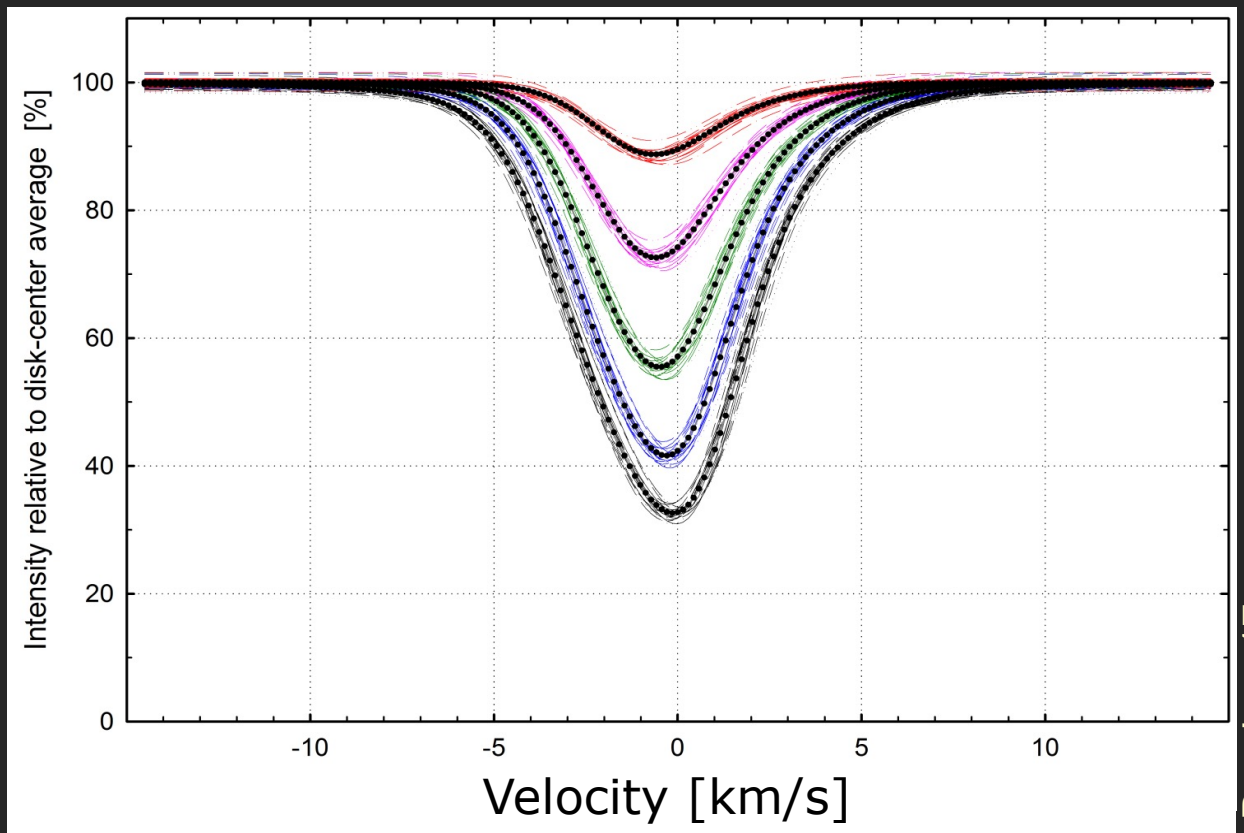


Dravins+17

- Blueshifts up to ~900 m s^{-1}
- Asymmetries up to ~400 m s^{-1}

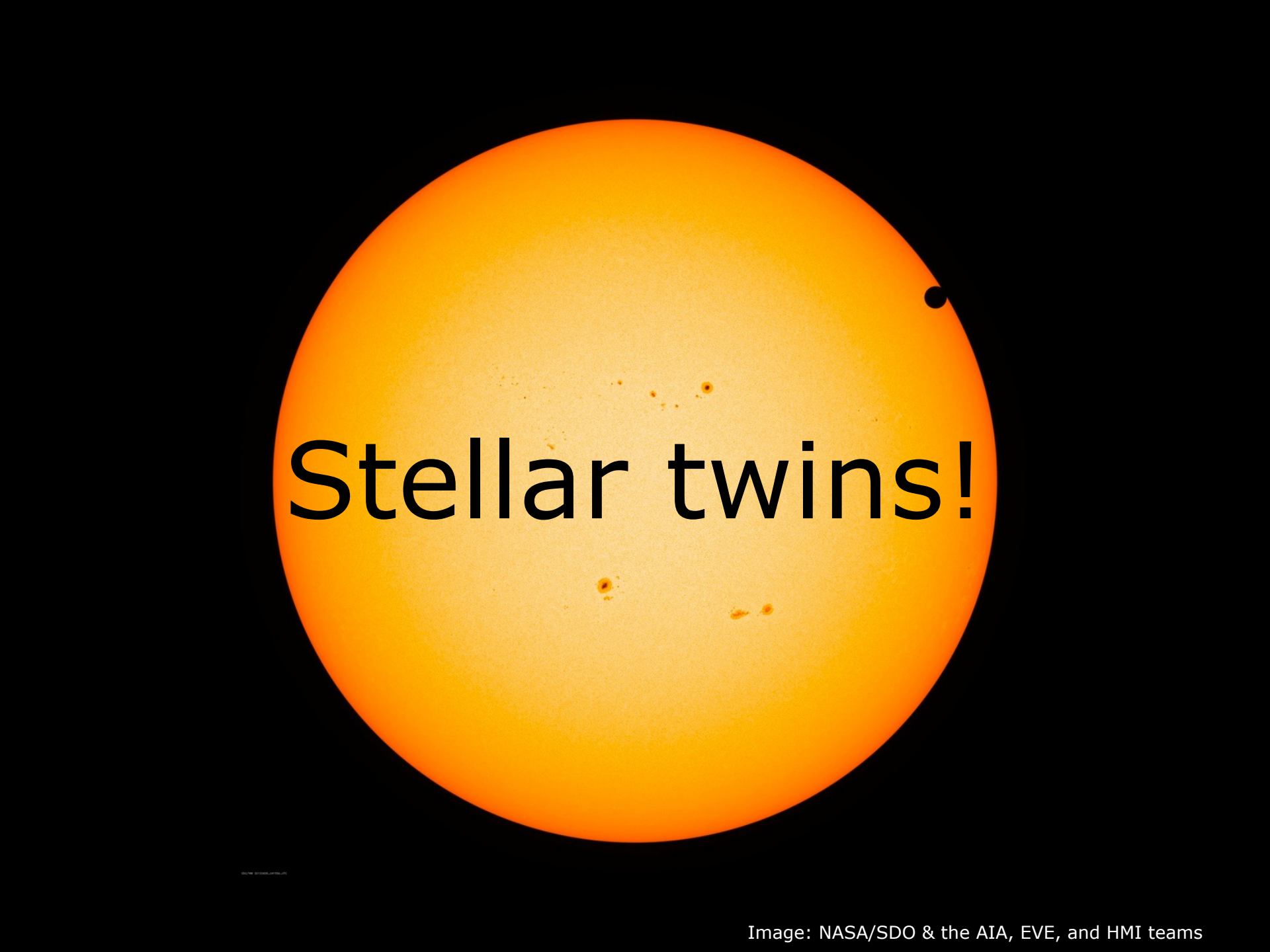
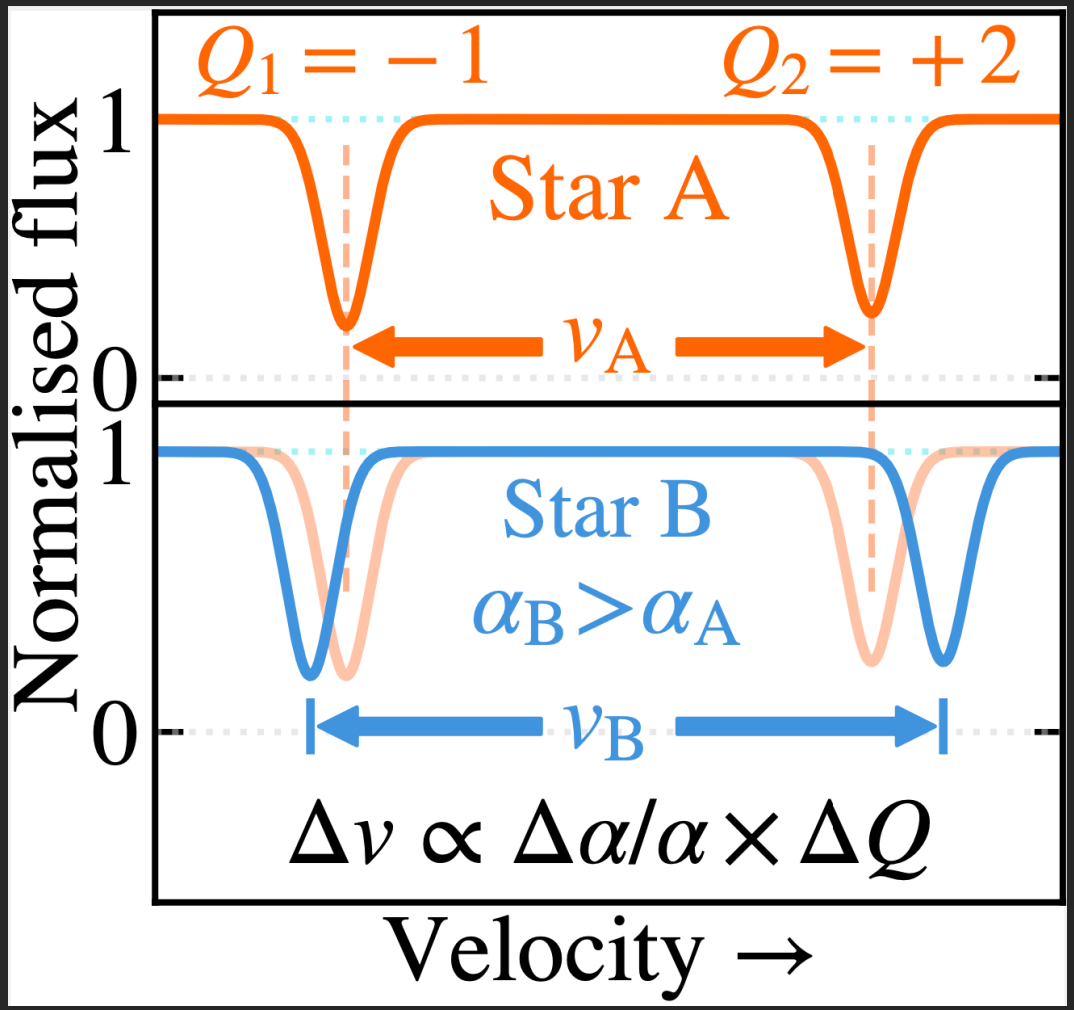


Image: NASA/SDO & the AIA, EVE, and HMI teams

Differential approach:

- Compare separations of the same pairs of lines in very similar stars



HARPS local reference:

- Vacuum, highly stable, high-*R*
- Best-characterized astro spectrograph?
- Huge database of local, Sun-like stars ($\lesssim$ 100 pc)
  - >10^4 exposures of Sun-like stars with S/N > 200 pix^{-1}
  - Time series on single stars ➔ tests for systematics
  - Non-uniform pixel size corrections (Coffinet+19)
  - Laser frequency comb calibration corrections (Milakovic+20)

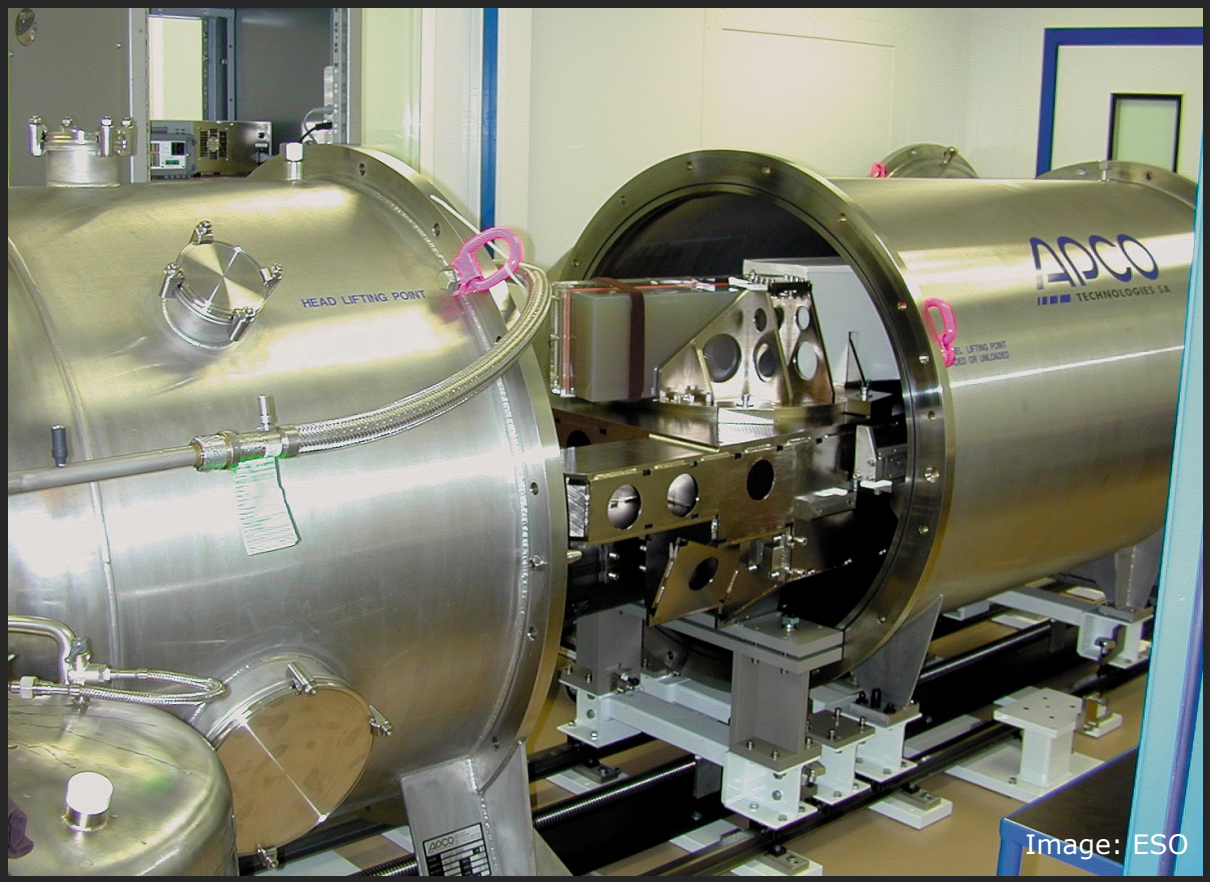
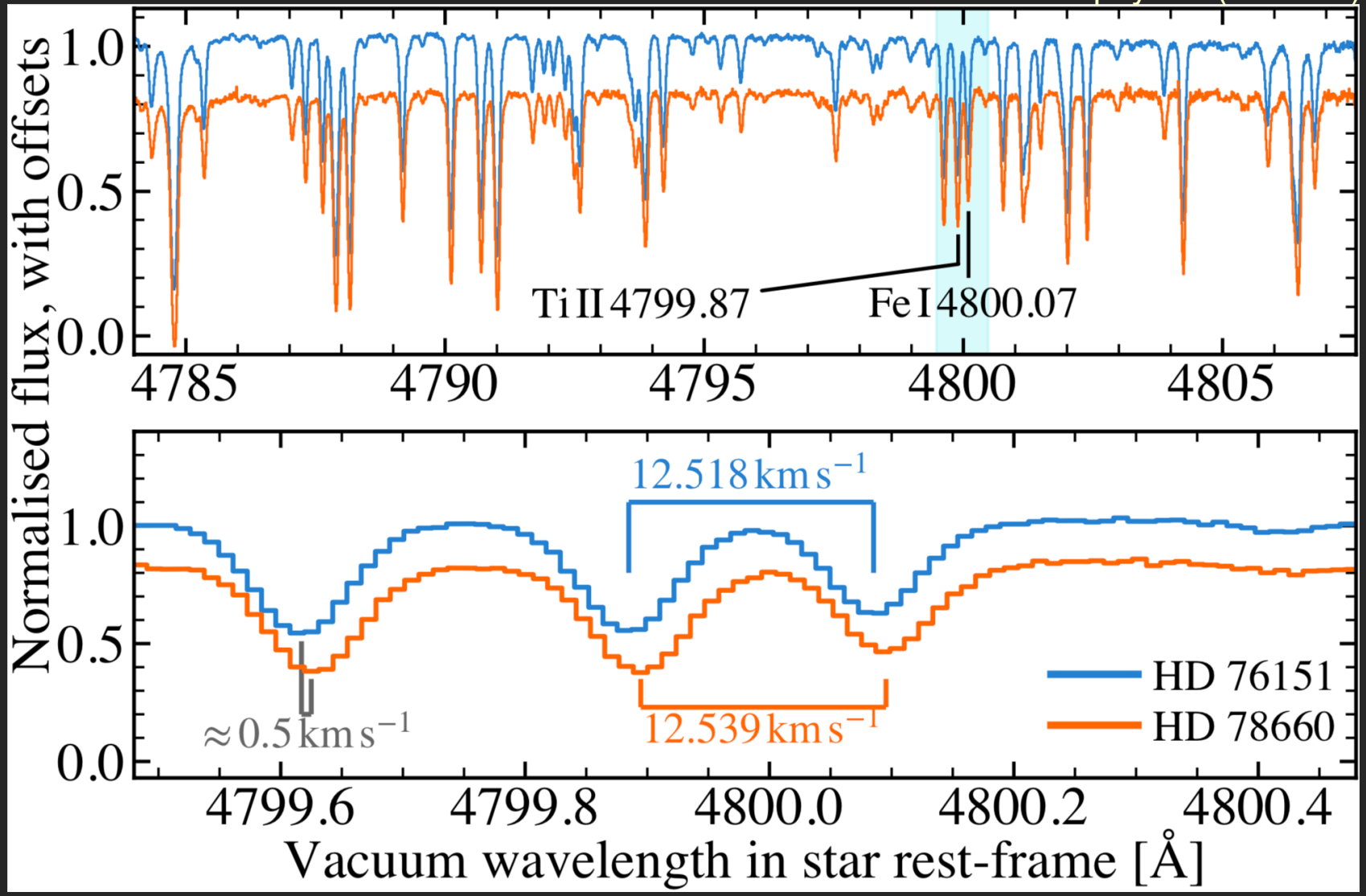


Image: ESO

HARPS solar twins

Murphy+22 (Science)

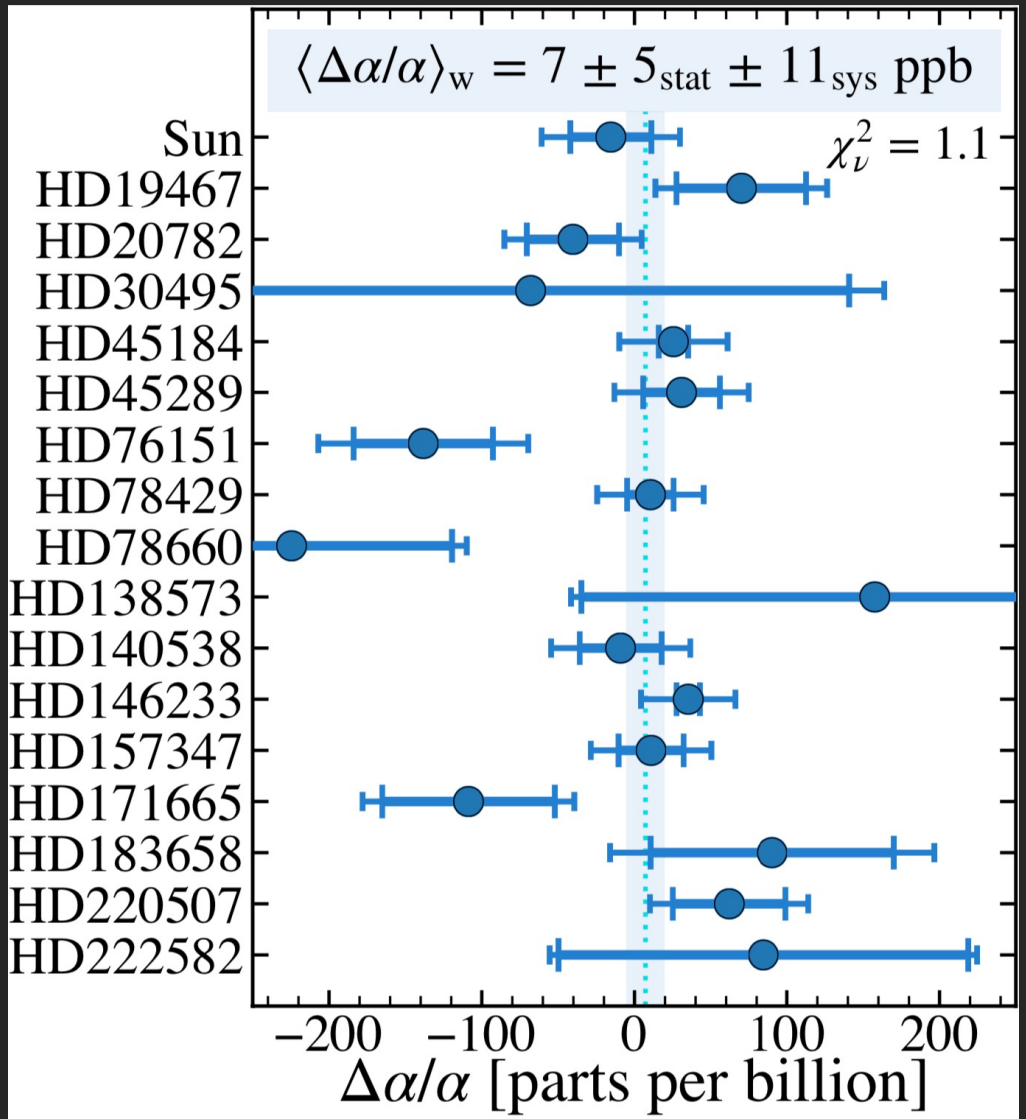


Solar twin results

- 17 solar twins
- 17 transition pairs with known α-sensitivities ("*Q*")
- 423 exposures, ≈10 per star

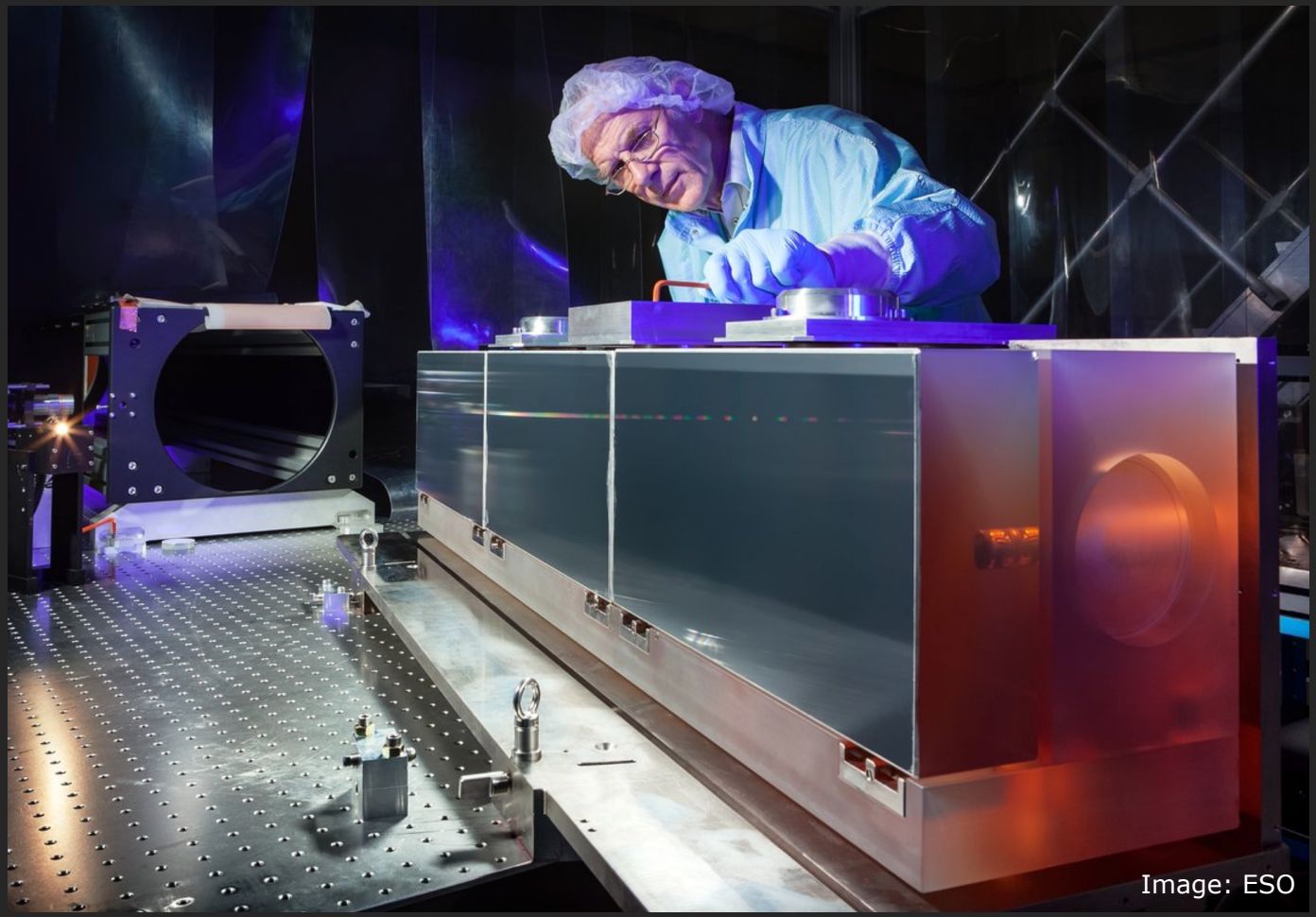
- **Variations in α < 50 ppb in local 50 pc ⟹ Best astro measurement so far**
- **Local reference defined with 12 ppb precision**

Murphy+22 (Science)



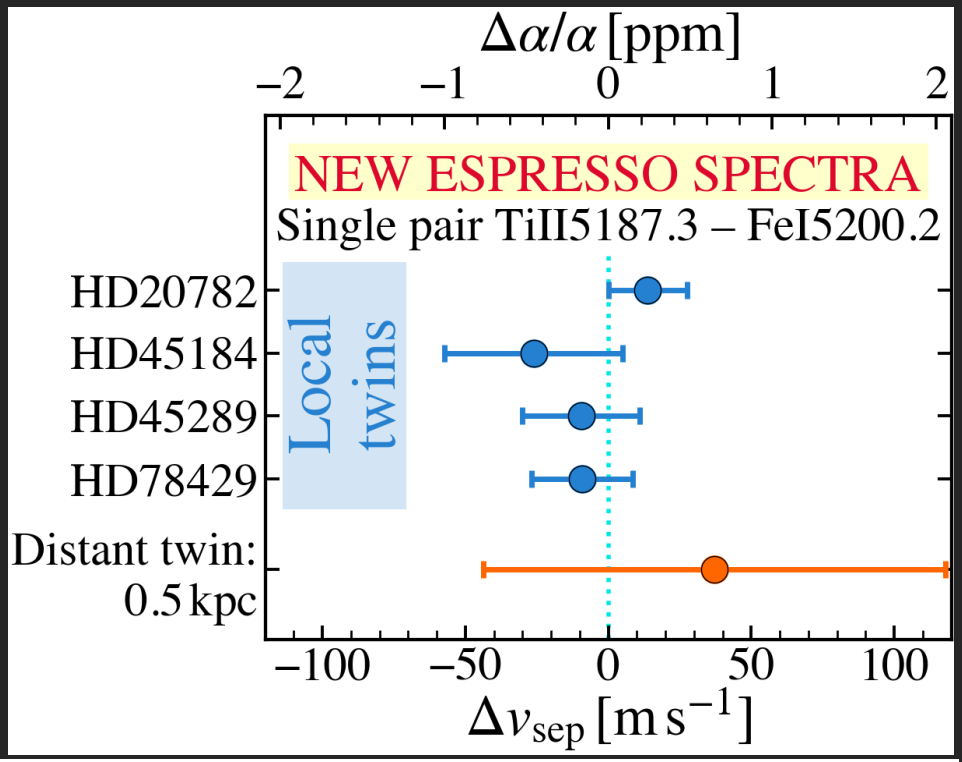
ESPRESSO @ VLT

- "Super HARPS":
  - Fibre fed, 'astrocomb' calibrated, super-stable, vacuum, *R*=140,000

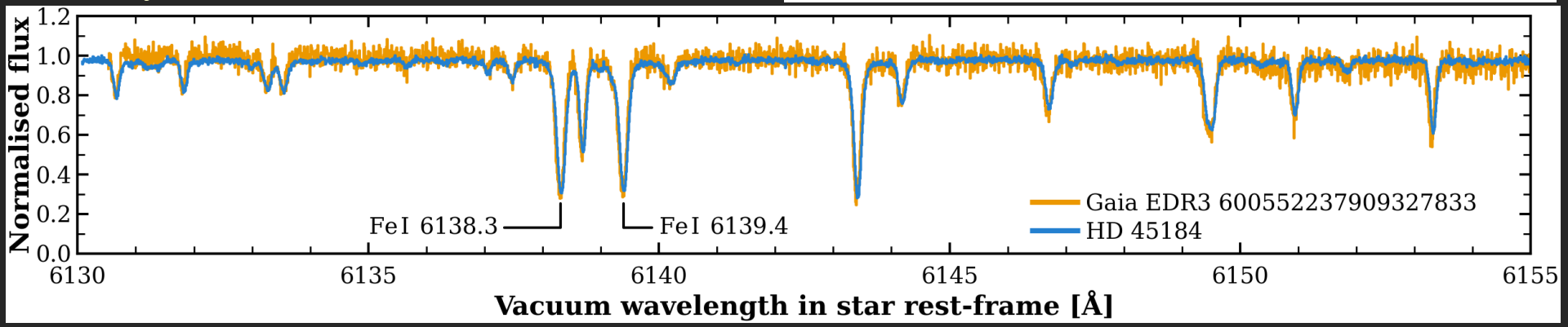


Towards the Centre with ESPRESSO

- 5 solar twins up to 1 kpc towards GC
  - SNR ~ 70 per pix
- 10 local twins
  - SNR ~ 250 per pix
  - Transfer HARPS calibration of method to ESPRESSO



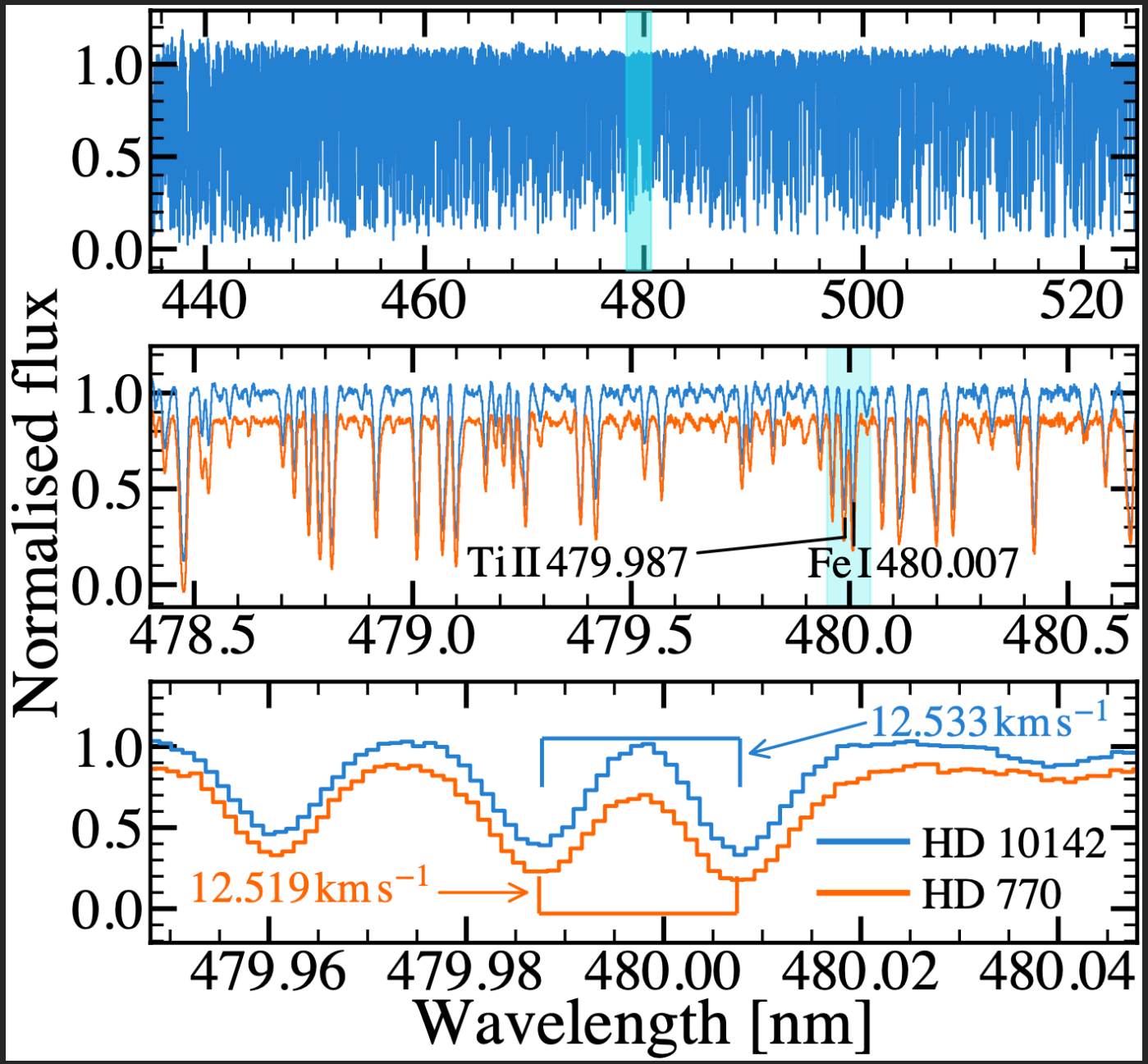
Courtesy of Ben Scott



Towards the Centre with ESPRESSO

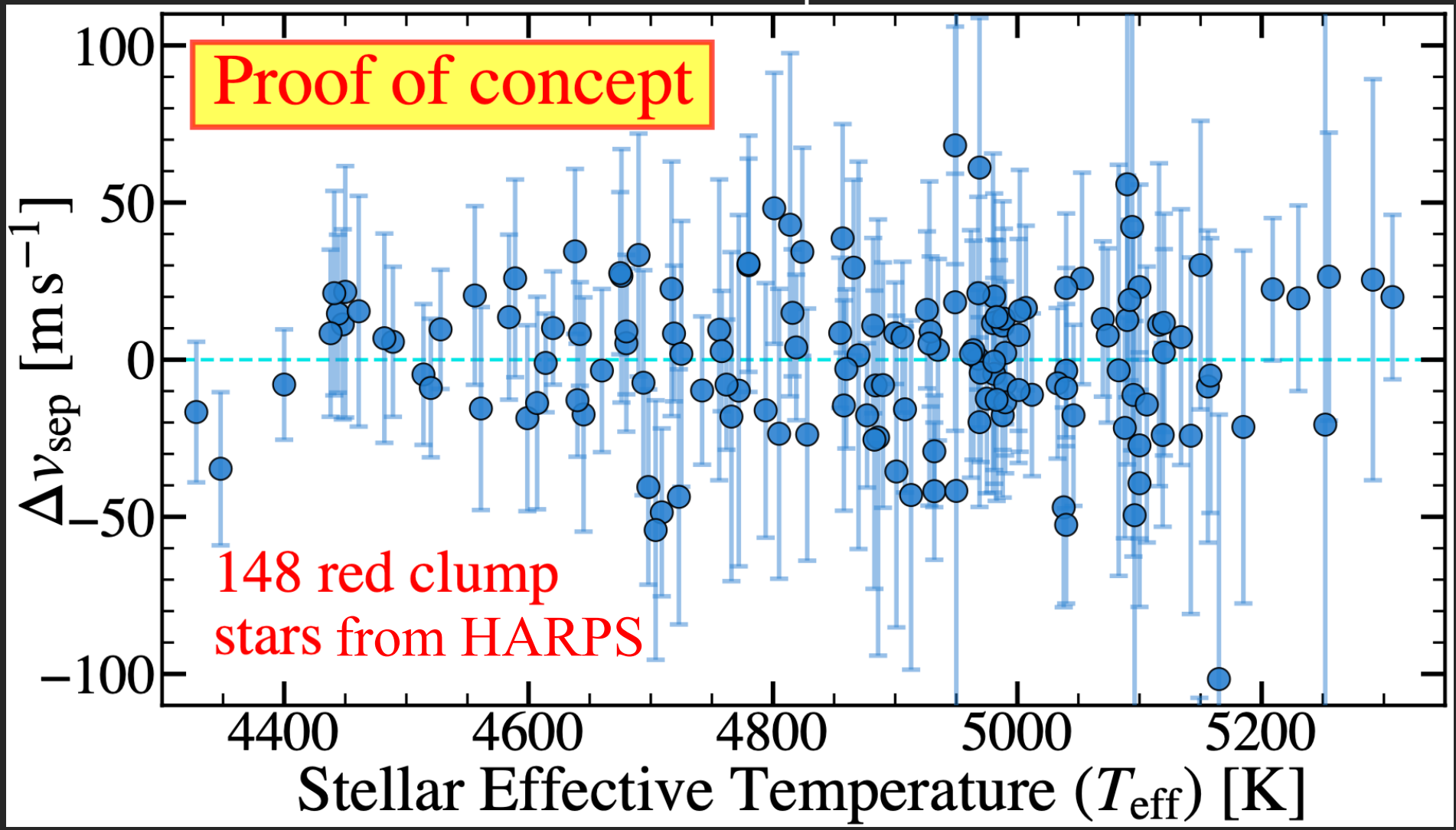
- … but solar twins are too faint near GC, ~8 kpc away
- Enter “red clump” stars:
  - Helium-core burning red giants
  - ≳***50*** *brighter* than Sun-like stars
- Can they be used to measure α?

Red clump stars ***can*** probe α



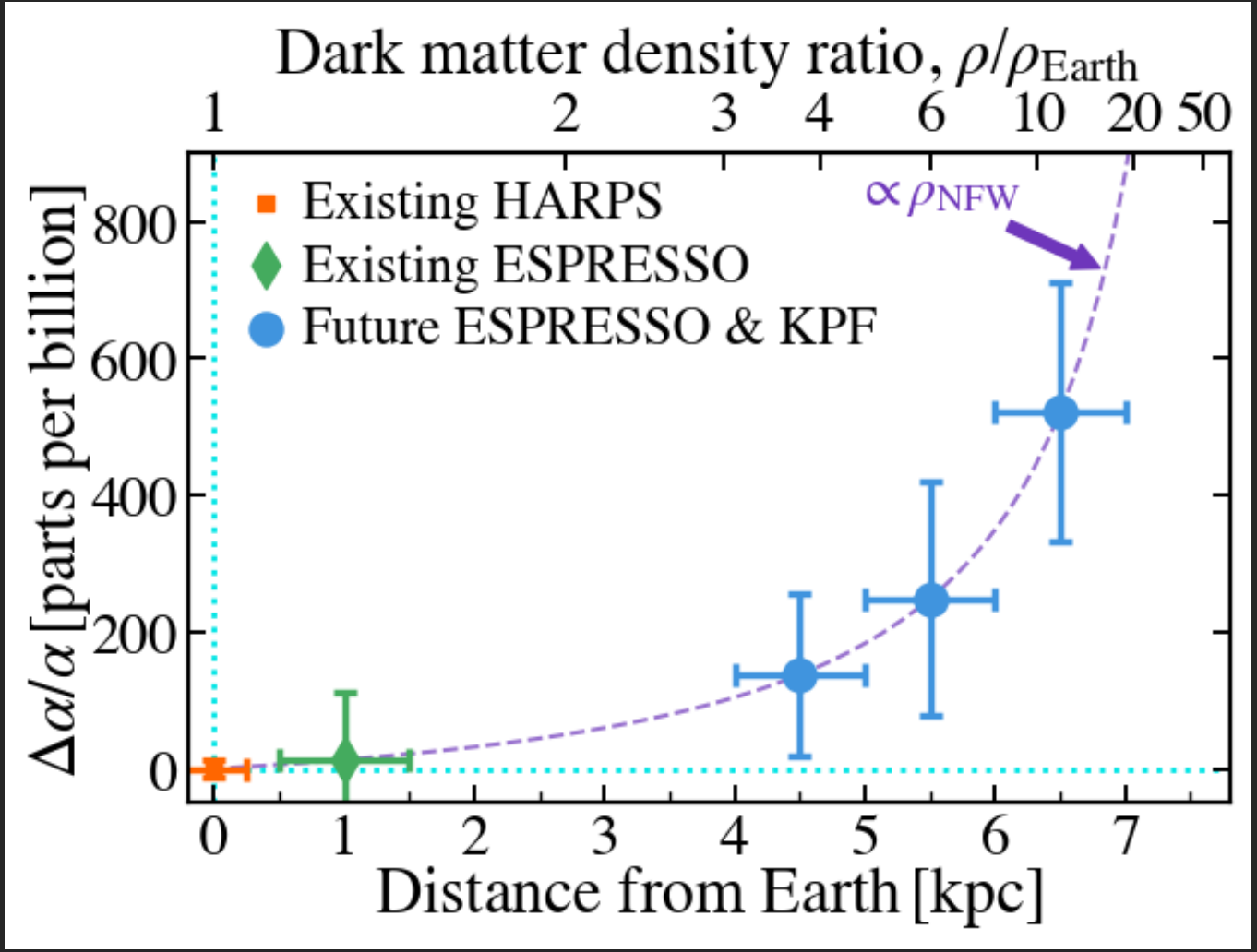
Red clump stars ***can*** probe α

One transition pair: NaI6162.45 & CaI6168.15



ESPRESSO & KPF projections

- Projected VLT & Keck uncertainties
  - 35 known red clump stars at 4–8 kpc
  - ~50 hours telescope time



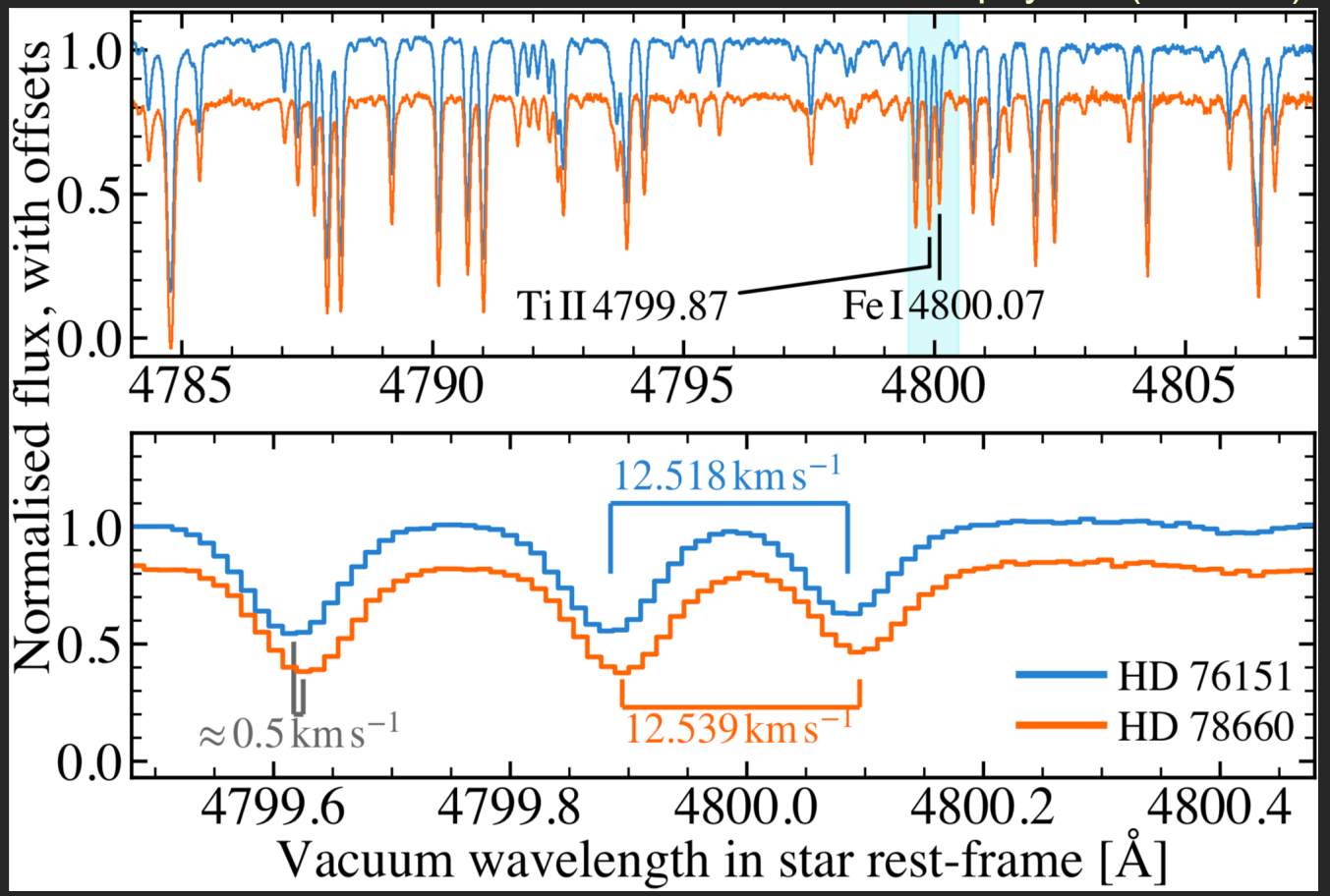
Conclusions

- Stellar twins can test α–Dark Matter connection
- Local twins with HARPS:
  - Solar twins: No local variations >50 ppb
  - Red clump stars work!
- Time for ESPRESSO & KPF:
  - Already: 5 solar twins @ 0.5–1 kpc
    ~5 red clump stars @ ~0.5–1.5 kpc
  - ~35 red clump stars @ 4–8 kpc
    - 100 ppb precision possible!
    - Only ~50 hours needed, split between VLT & Keck

Line selection

- **Close pairs** (within 800 km s^{-1})
- Moderate depth (10–85%)
- Similar depth (<20% different)
- No tellurics (<0.1%)

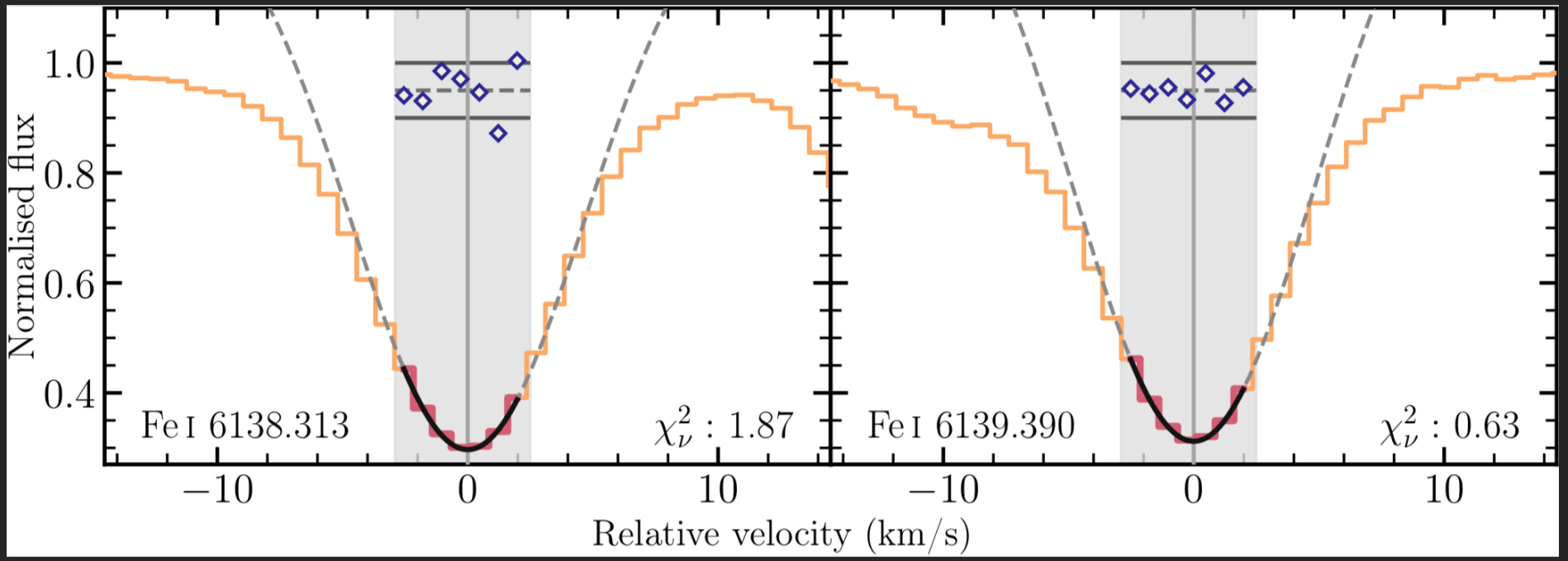
Murphy+22 (Science)



Line centroiding

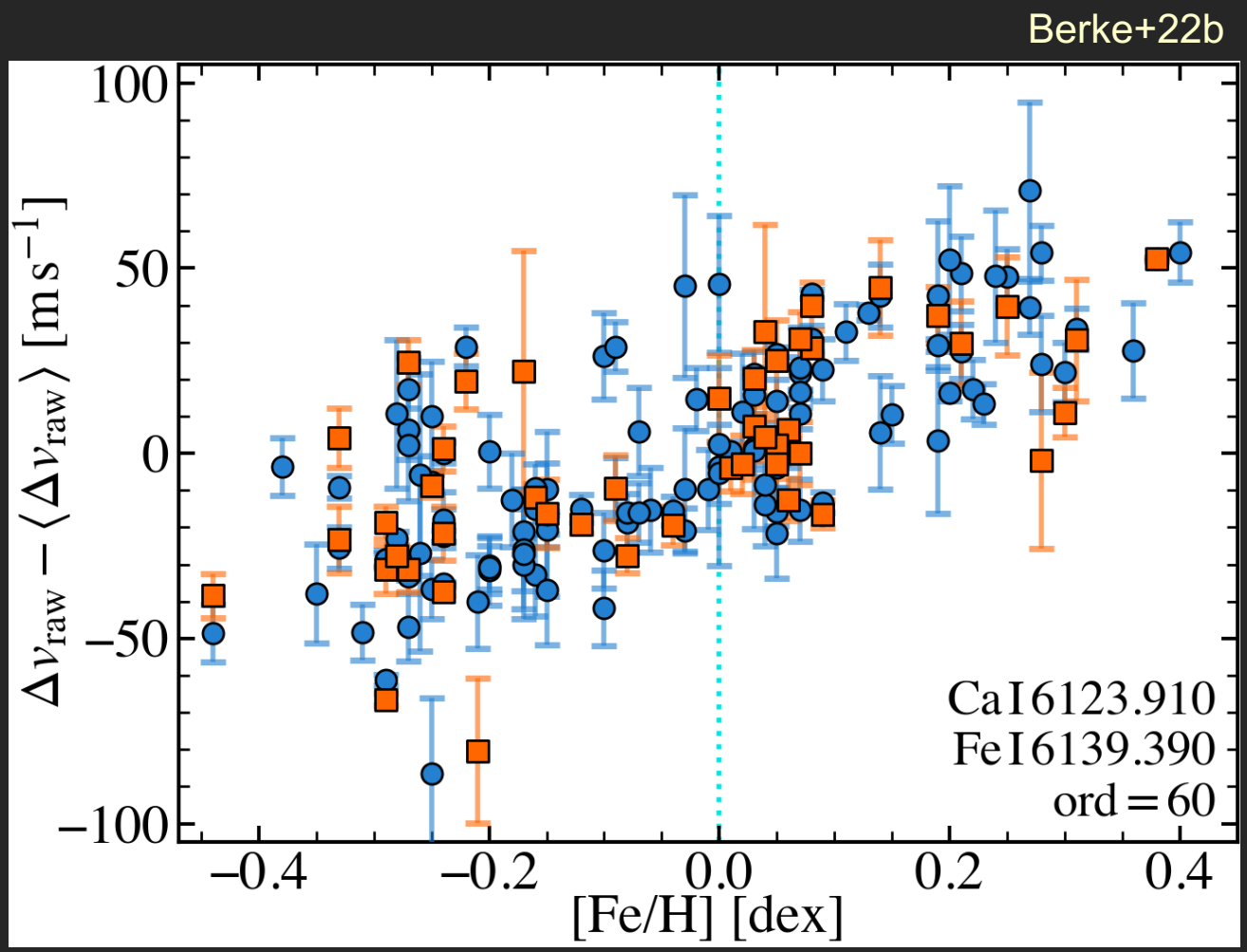
- Gaussian fits to core only
- Outlier rejection (~10^4 exposures)
- Entirely automatic (~1.6 million measurements)

Berke+22a



Line separation varies!

- … weakly, with stellar parameters
- Quadratic model in $T_{\rm eff}$, [Fe/H] & log(g)



Line separation varies!

- … weakly, with stellar parameters
- Quadratic model in $T_{\rm eff}$, [Fe/H] & log(g)
- Residual star-to-star scatter σ_{**} = 0–15 m s^{-1}

Berke+22b