Fundamental Physics with Stellar Twins

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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
Why fundamental?
- Theory doesn’t explain them

Why constant?
- ‘Merely’ observed to be
- Exquisite lab experiments: $\alpha$ stable within $10^{-18}\text{ yr}^{-1}$ (e.g. Lange+21)

Feynman on $\alpha$ (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:

\[
\frac{\Delta \nu}{c} \approx -2Q \frac{\Delta \alpha}{\alpha}
\]

- Calculate \( Q \) from quantum mechanics
- Measure \( \Delta \nu \) in spectrum
Line shifts with varying $\alpha$

Credit: Daniel Berke
Previous measurements

Goal:

- Measure $\alpha$ in different places, times, environments...

Status:

- Quasar absorption: $\Delta \alpha/\alpha \lesssim 2$ ppm over $\sim 12$ 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 $\Rightarrow$ changes screening effect for $\alpha$

![Graph showing $\Delta \alpha / \alpha$ vs. $r$ (kpc)]

Davoudiasl & Giardino 19
Can we probe $\alpha$ with stars?
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Hees+20 (PRL):
- Keck IR spectra of (effectively) 1 star near Galactic Centre
- 10 lines compared to lab wavelengths
- $\Delta\alpha/\alpha = 0.9 \pm 5.8$ ppm
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- Blueshifts up to $\sim 900 \text{ m s}^{-1}$
- Asymmetries up to $\sim 400 \text{ m s}^{-1}$
Stellar twins!
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 ($\approx 100$ pc)
  - $>10^4$ exposures of Sun-like stars with S/N > 200 pix$^{-1}$
  - Time series on single stars $\rightarrow$ tests for systematics
  - Non-uniform pixel size corrections (Coffinet+19)
  - Laser frequency comb calibration corrections (Milakovic+20)
HARPS solar twins

Murphy+22 (Science)
Solar twin results

- 17 solar twins
- 17 transition pairs with known $\alpha$-sensitivities ("$Q$")
- 423 exposures, $\approx 10$ per star

- Variations in $\alpha < 50$ ppb in local 50 pc
  $\Rightarrow$ Best astro measurement so far

- Local reference defined with 12 ppb precision

\[ \langle \Delta \alpha / \alpha \rangle_w = 7 \pm 5_{\text{stat}} \pm 11_{\text{sys}} \text{ ppb} \]
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 $\sim$ 70 per pix

- 10 local twins
  - SNR $\sim$ 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, $\sim 8$ kpc away

Enter “red clump” stars:
- Helium-core burning red giants
- $\geq 50\times$ brighter than Sun-like stars

Can they be used to measure $\alpha$?
Red clump stars can probe $\alpha$
Red clump stars *can* probe $\alpha$

One transition pair: NaI6162.45 & CaI6168.15

**Proof of concept**

148 red clump stars from HARPS
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 $\alpha$–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
    $\sim$5 red clump stars @ $\sim$0.5–1.5 kpc
  - $\sim$35 red clump stars @ 4–8 kpc
    - 100 ppb precision possible!
    - Only $\sim$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 (\(\sim 10^4\) exposures)
- Entirely automatic (\(\sim 1.6\) million measurements)

Berke+22a
Line separation varies!

... weakly, with stellar parameters

Quadratic model in $T_{\text{eff}}$, [Fe/H] & log$(g)$

Berke+22b
Line separation varies!

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

Berke+22b