On the high-resolution spectroscopic requirements for the studies of the cosmological variation of fundamental constants

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WHY FUNDAMENTAL CONSTANT IMPORTANT ?

FUNDAMENTAL?

1. They are not predictable, we do not know where from their value come?

CONSTANT?

1. They have same value irrespective of time and space (e.g experiment in low energy limits).
2. Theory also do not predict variation, until the unification theory like existence of extra-dimension .

Q: Shell we extend above constancy is from terrestrial scale to cosmological time scale?

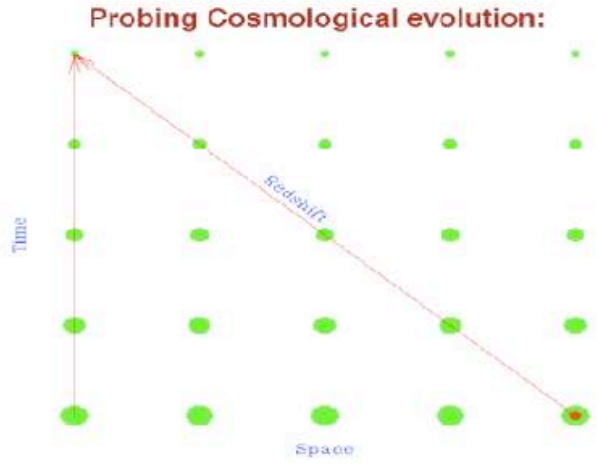
A: QSOs absorption lines, can probe look back time of billion years, to test constancy of fundamental constant like :

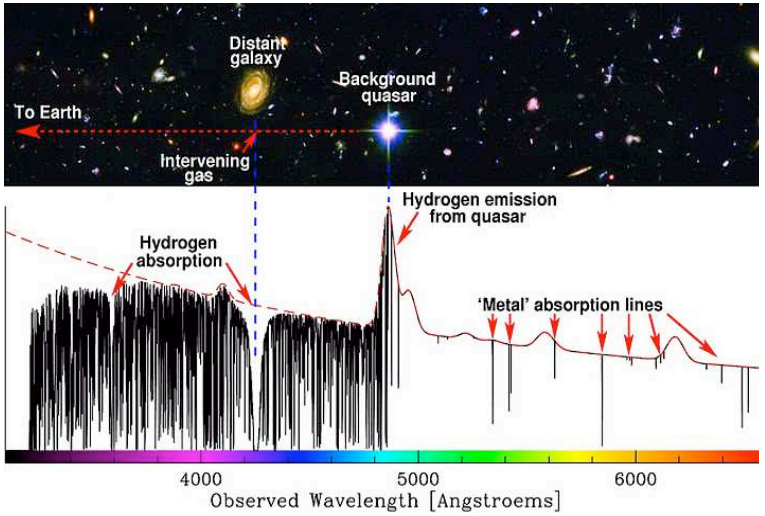
1. **Fine-structure constant $\alpha=e^2/\hbar c$**
2. **Electron-proton mass ratio $\mu=m_e/m_p$**

FROM 10M CLASS TO TMT ERA

How QSOs and its absorption lines act as tool to prob our Universe evolution

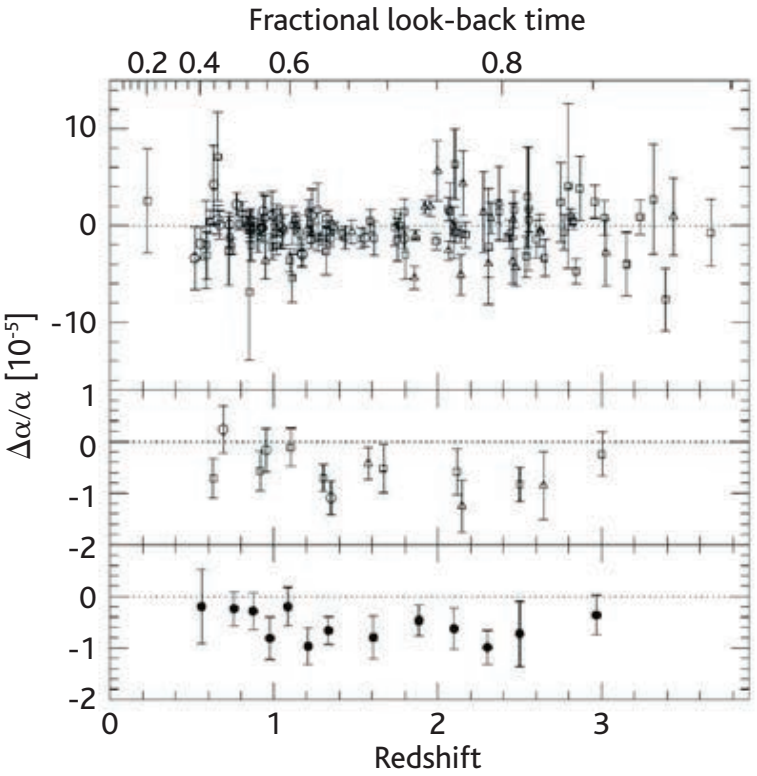
- The finite speed of light, imply observation of farther the object will give older its history.
- To see far away, need luminous sources, the Active Galactic Nuclei (AGN) perfectly fit in here.





RECENT COMUNITY INTEREST: KECK/VLT RESULTS

HIRES result, Murphy et al (2003)

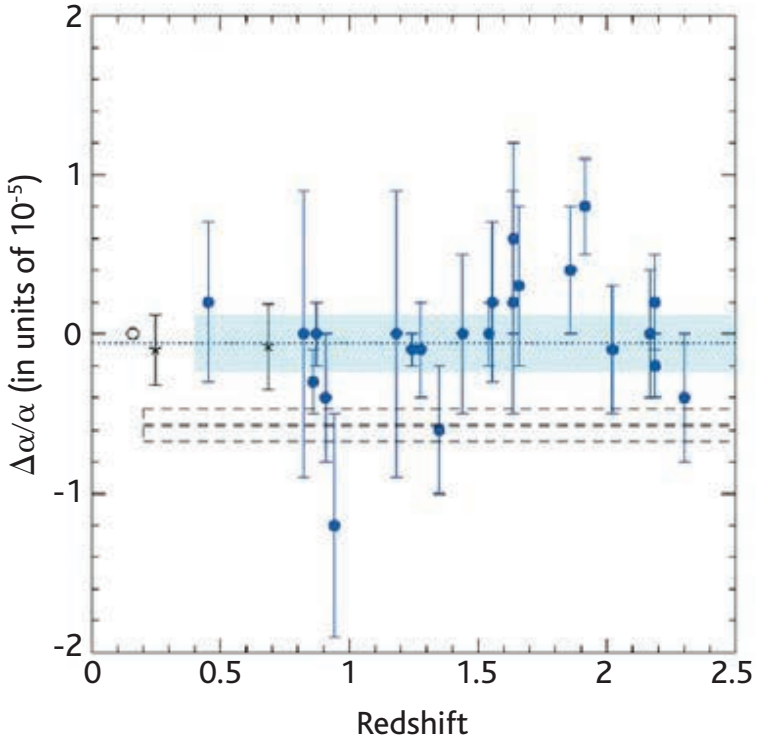


For $\alpha(t)$: HIRES/Keck

- Results: $\langle \Delta\alpha/\alpha \rangle_w = (-0.57 \pm 0.10) \times 10^{-5}$,

Latest update: UVES/VLT re-analysis, shows $\langle \Delta\alpha/\alpha \rangle_w = (-0.06 \pm 0.16) \times 10^{-5}$ [Webb et al 2011

UVES results, Chand et al 2004, Srianand et al 2004



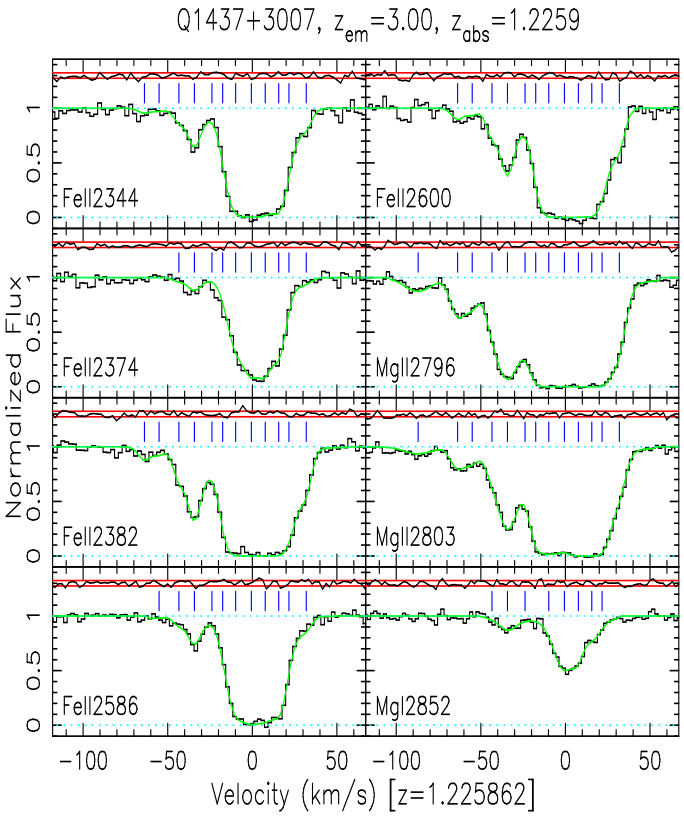
Against $\alpha(t)$: UVES/VLT

- Results: $\langle \Delta\alpha/\alpha \rangle_w = (-0.06 \pm 0.06) \times 10^{-5}$

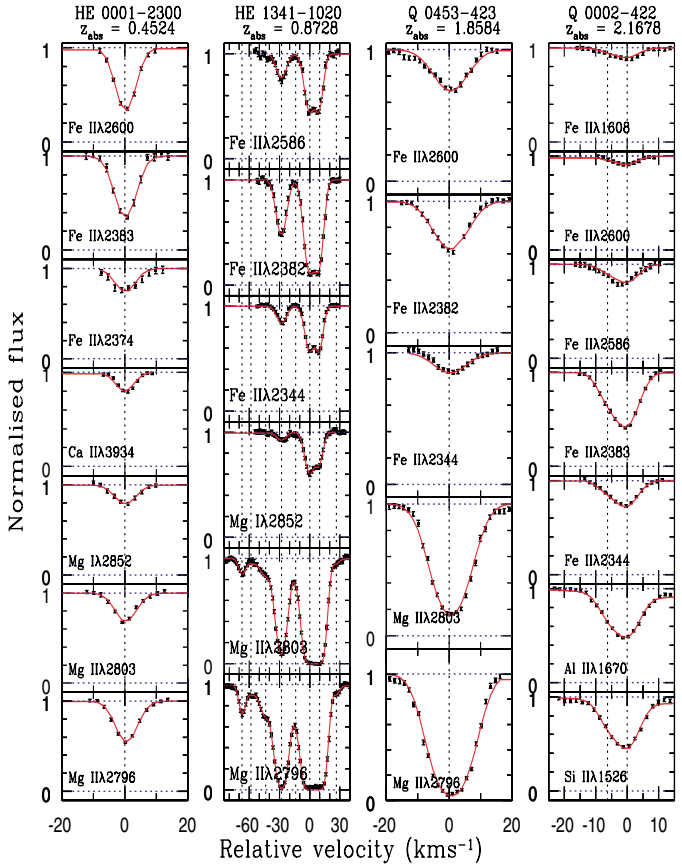
Revised statistical error: $\langle \Delta\alpha/\alpha \rangle_w = (0.01 \pm 0.15) \times 10^{-5}$
(Srianand et al 2007)

RECENT COMUNITY INTEREST: KECK/VLT RESULTS

HIRES result, Murphy et al 2003

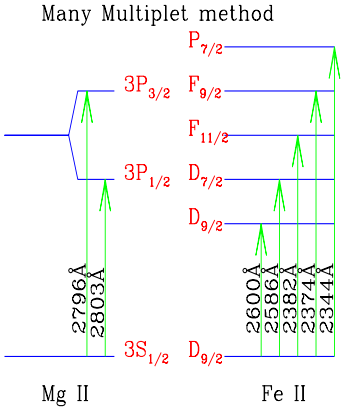


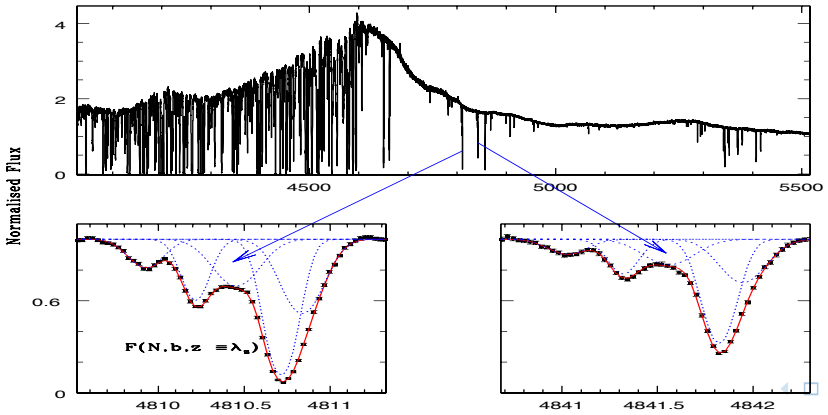
UVES results, Chand et al 2004, Srianand et al 2004

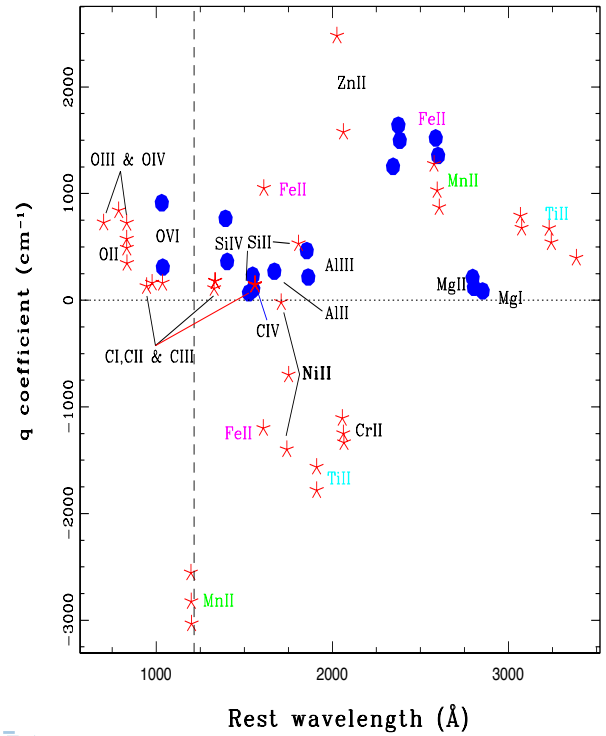


MAIN PRINCIPLE

$$\omega_z = \omega_0 \left[1 + \frac{q}{\omega_0} \left((\frac{\alpha_z}{\alpha_0})^2 - 1 \right) \right] \quad \text{(Dzuba et al. 1999)}$$



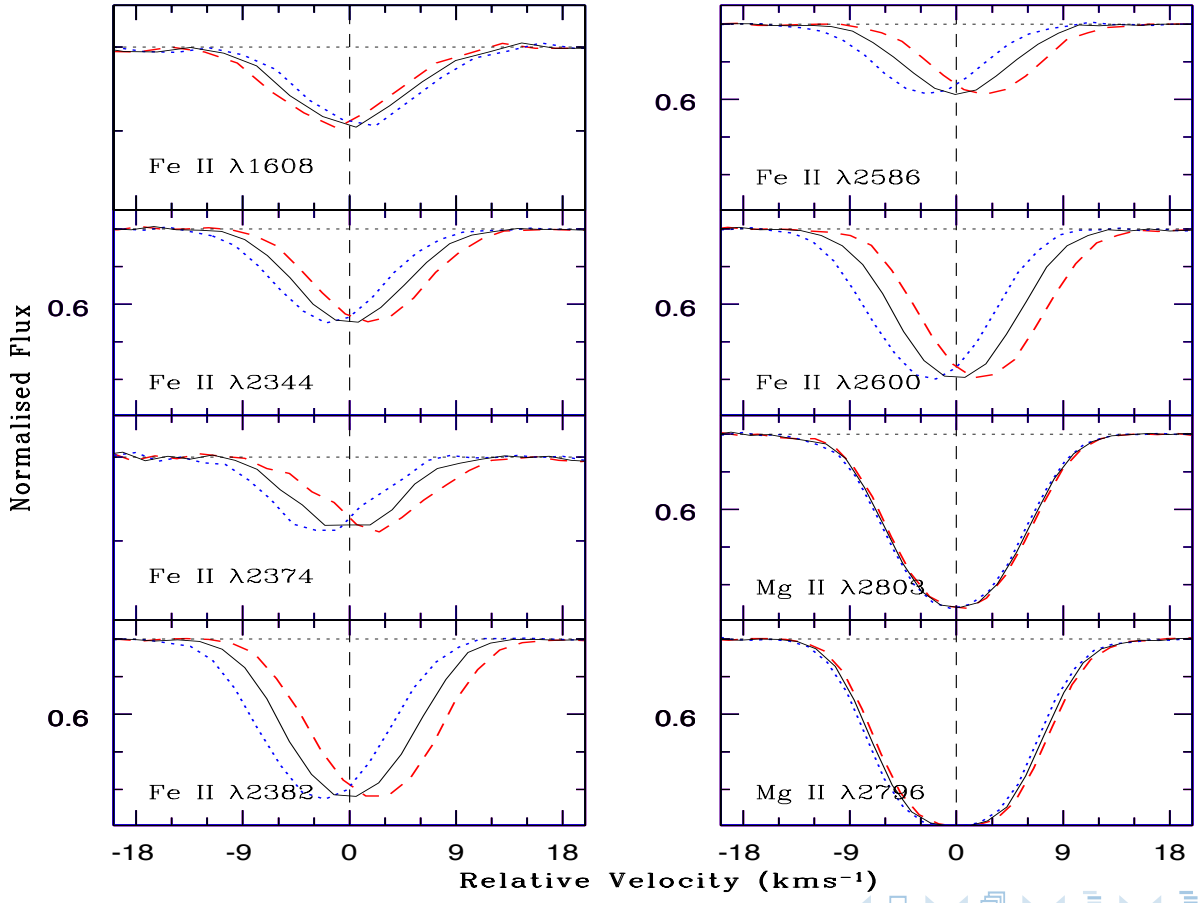




SHIFT WILL BE IS TOO SMALL EVEN FOR CHANGE OF 100 PART PER MILLION (PPM)

Illustration of lines shift due to $\alpha(t)$: at $\Delta\alpha/\alpha = \pm 10^{-4}$

(i.e 100-1000 time the accuracy we are looking for!)



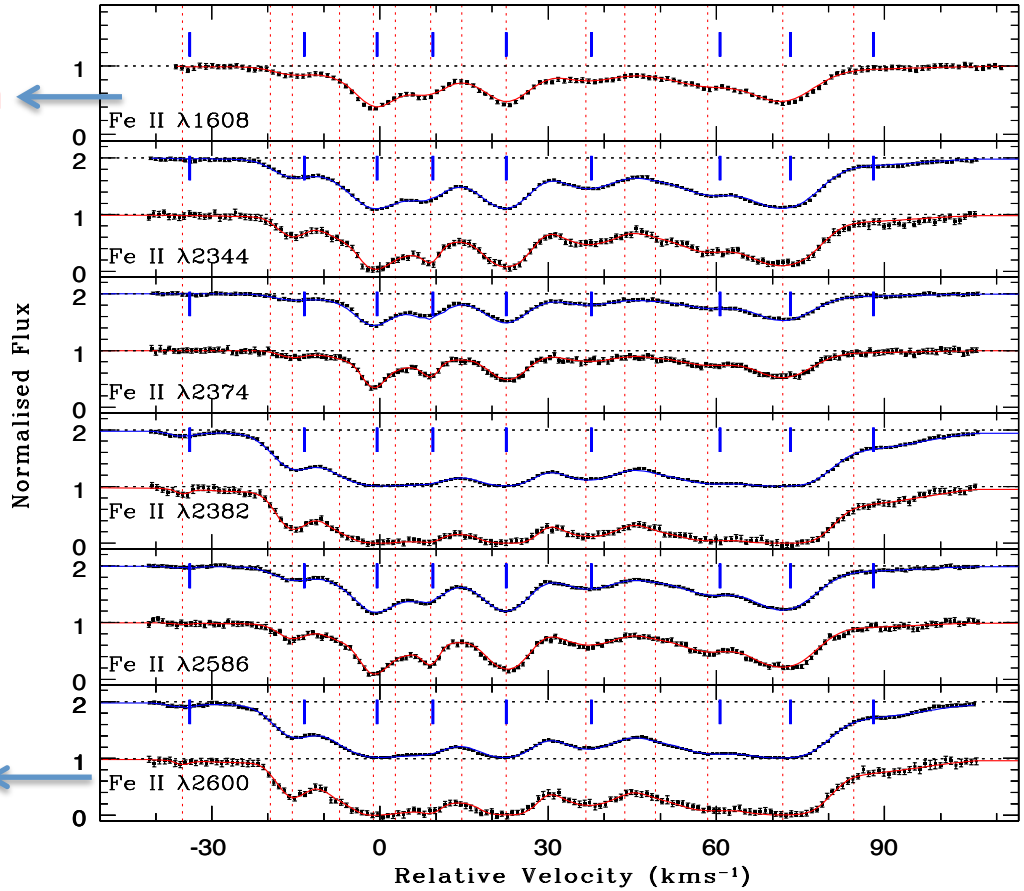
DO WE HAVE CONTROL OVER SYSTEMATICS TO BE THAT ACCURATE?

WAVELENTH CALIBRATION ?

DO WE HAVE CONTROLL OVER SYSTEMATICS: Component fitting uncertainty ?

Resolution effect on $\Delta\alpha/\alpha$: *comparing* $R = 112\,000$ *(HARPS) with* $R = 55\,000$ *(UVES)*

Blue Arm

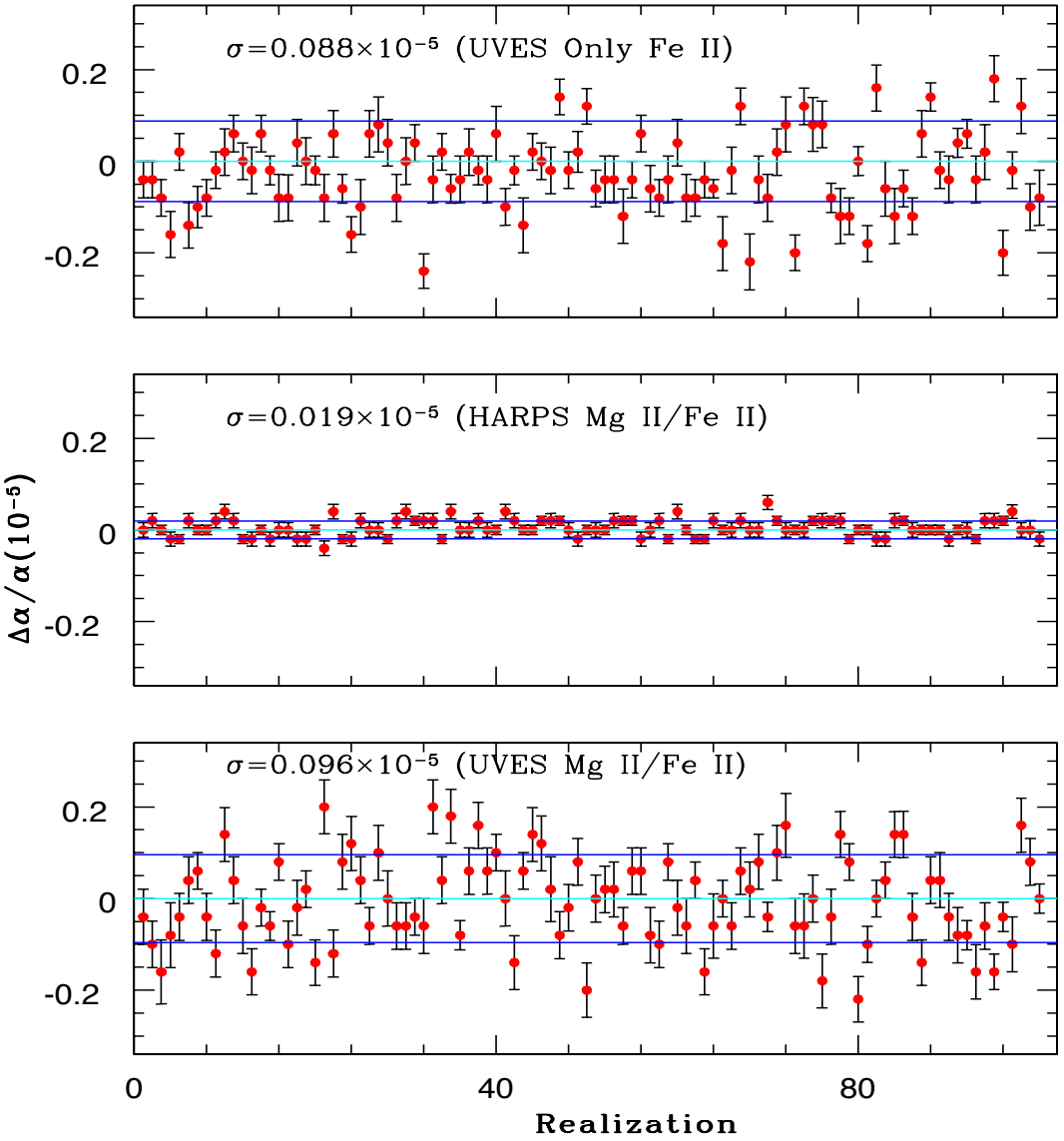


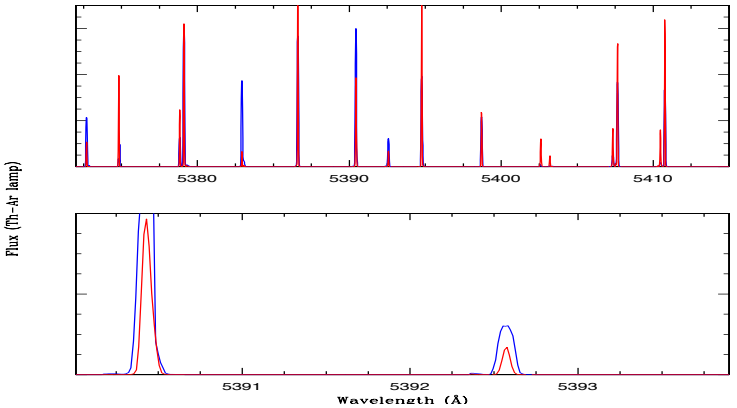
Red Arm

1. 15 component in high resolution compare to 9 in lower resolution.
2. The component problem is random, and can be avoided by many high SNR, simple profile system.
3. WHAT ABOUT THE SYSTEMATICS IN WAVELENGTH CALIBRATION?

$\Delta\alpha/\alpha=(0.05 \pm 0.24) \times 10^{-5}$ (Chand, H. et al. 2006, A&A 451, 45).

DO WE HAVE CONTROL ON WAVELENGTH CALIBRATION: TH-AR LAMP CALIBRATION?





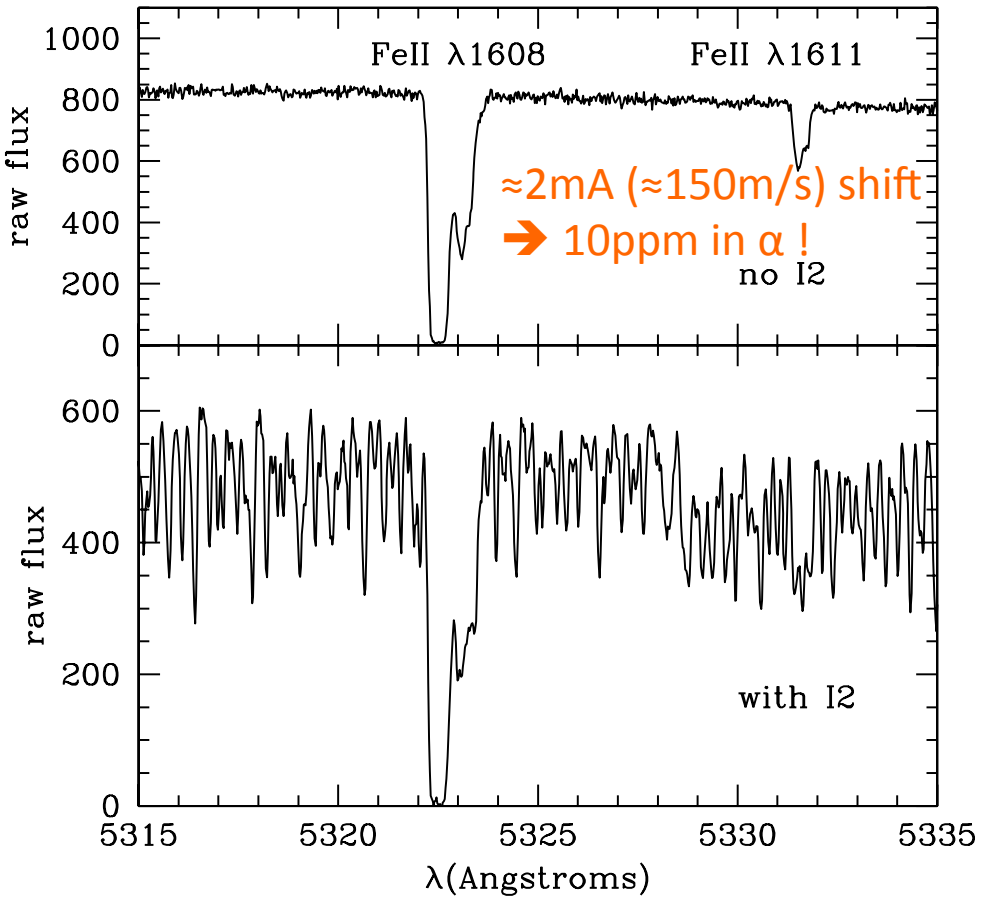
1. SCATTER:
   1. Non-uniformity of lines
   2. Line blending
   3. Accuracy of Th-Ar wavelength

2. Replacing **Th-Ar** by **LASER COMB** scatter can be overcome.

3. QUESTION IS: **DOES PIXEL TO WAVELNGTH SCALE OF TH-AR/ COMB HOLD FOR SCIENCE EXPOSURE ?**

DOES Th-Ar PIXEL-LAMBDA MAPPING HOLD FOR SKY-OBJECT: HIRES/KECK?

Griest et al 2010 (for HIRES/Keck)



1. Normal calibration:
   1. Th-Ar calibration without I_2 cell
2. Super calibration:
   1. With I_2 cell in sky-object path
   2. Take I_2 spectrum with absolute calibration using Fourier transform spectrometer(FTS)
3. Shift using Super calibration: Chunk of spectrum to match the I_2 in FTS with the I_2-skyobject using Th-Ar calibration?

IS THE CALIBRATION ERRORS STABLE: HIRES/KECK ?

Griest et al 2010 (for HIRES/Keck)

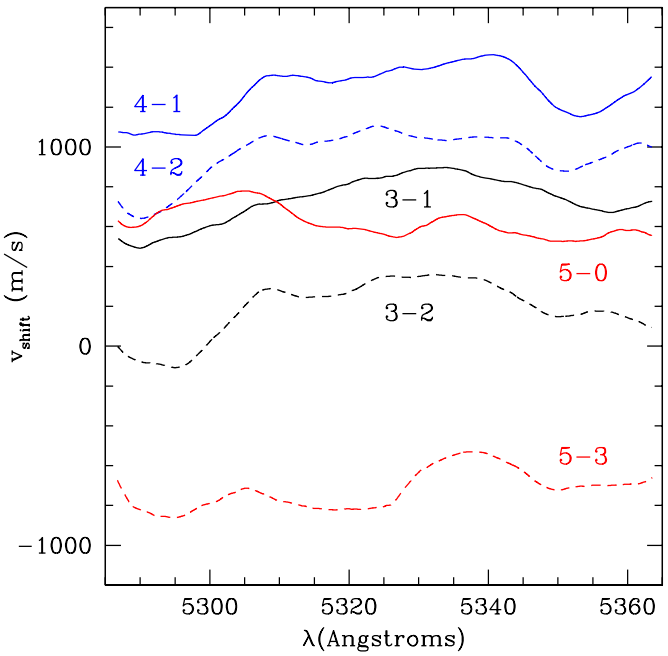


Fig: Time evolution of calibration shift between (blue,black,red) and within night (solid-dashed).

➔**Spectrograph stability over time required.**

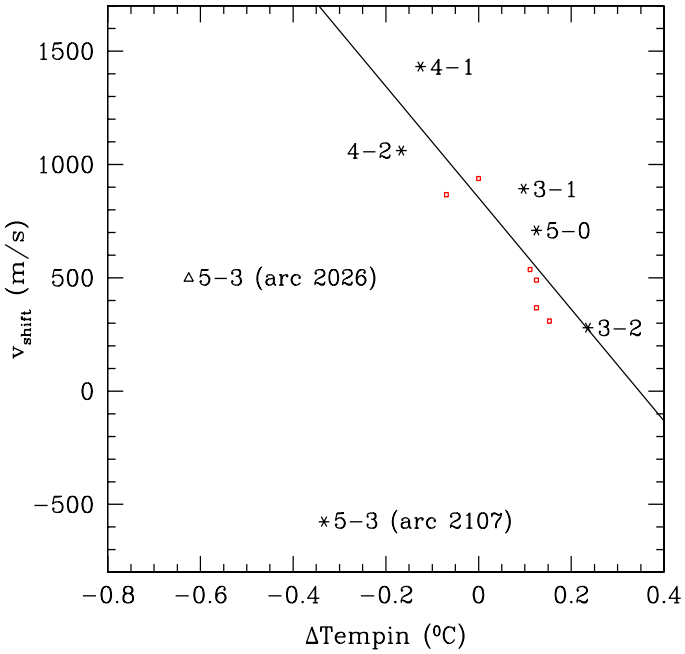


Fig: Average calibration shift of an order vs Temp difference of HIRES between calibration and science exposure

➔**Constant temperature, low/stable pressure of spectrograph required.**

CALIBRATION ERROR ON SCIENCE EXPOSURE: HIRES/KECK ?

Griest et al 2010 (for HIRES/Keck)

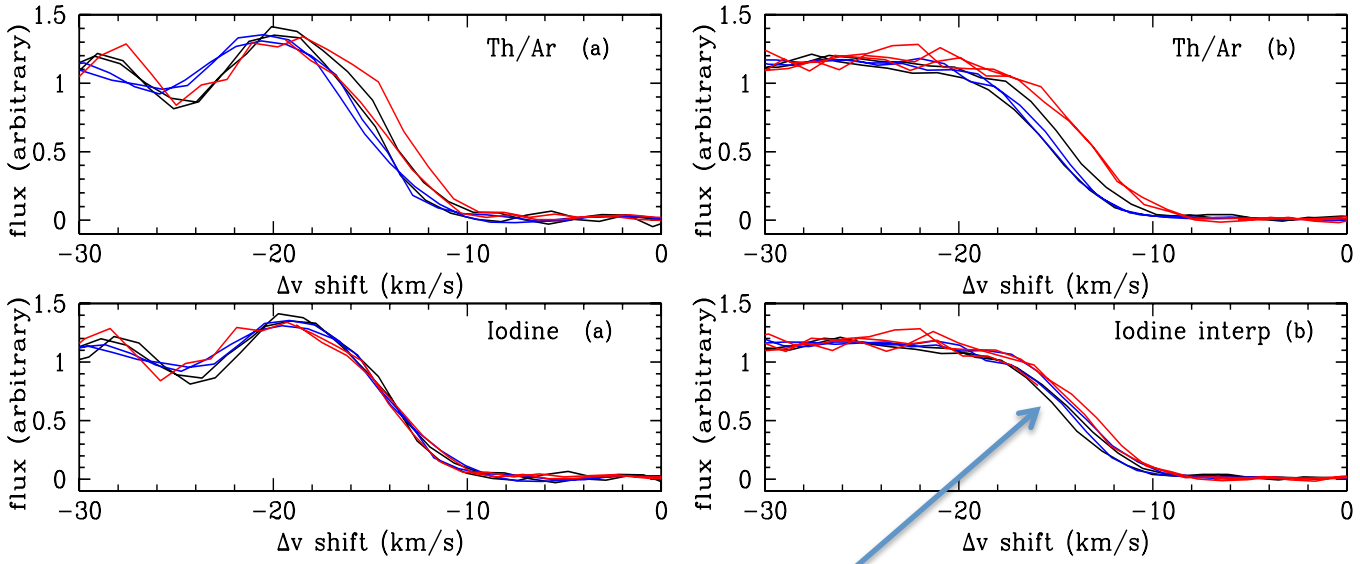
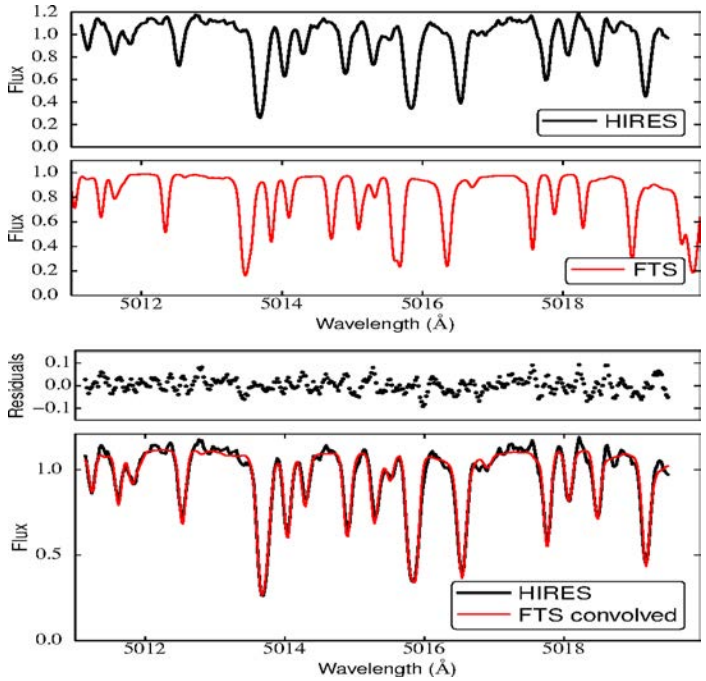


Fig: Close up of Fe1608 exposures. The shift in individual spectrum even after interpolation of I_2 calibrated shift propagate to the combined spectrum!

➔**Ability to model the calibration shift to align the science exposure is needed, i.e. we should be able to model these shifts.**

LONG RANG CALIBRATION ERROR: HIRES/KECK, UVES/VLT, HARPS ?

Whitmore et al 2015 (for HIRES/Keck, UVES/VLT, HARPS)



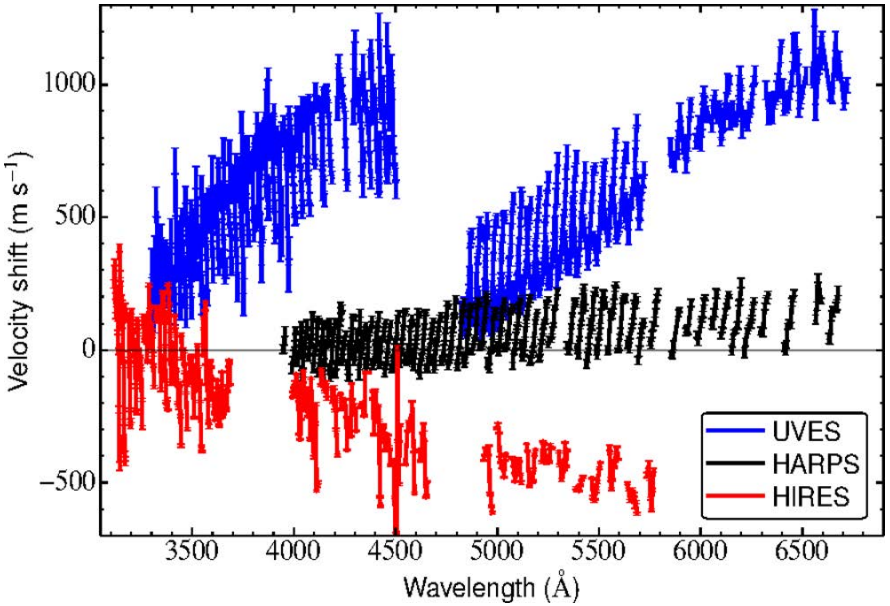


Fig: Calibration shift based on solar twin spectrum comparison with solar FTS spectrum. Calibration shift averaged over chunk of 8A, to get inter-order shifts

➔**Long range distortion can be as large as** ±200m/s per 1000A.

➔**Stability as in HARPS/3.6m desirable which can also be model easily.**

INTRA-ORDER AND SLIT POSITIONING EFFECT (I_2 in fast rotating star) : HIRES/KECK, UVES/VLT

Whitmore et al 2015 (for HIRES/Keck, UVES/VLT)

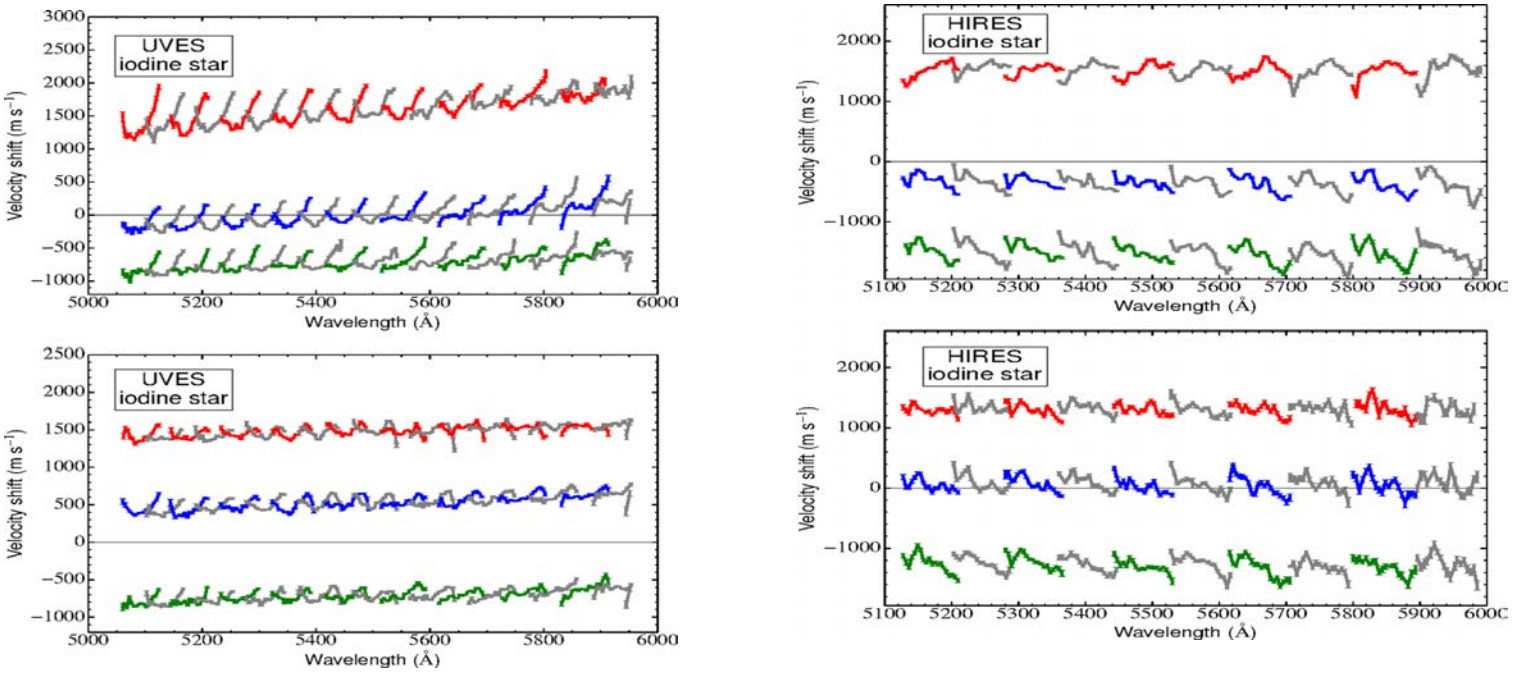


Fig: Calibration shift based on 1/3 shift across the slit position. Apart from constant shift in both UVES and HIRES, there is change in slop within order in HIRES (difficult to model !).

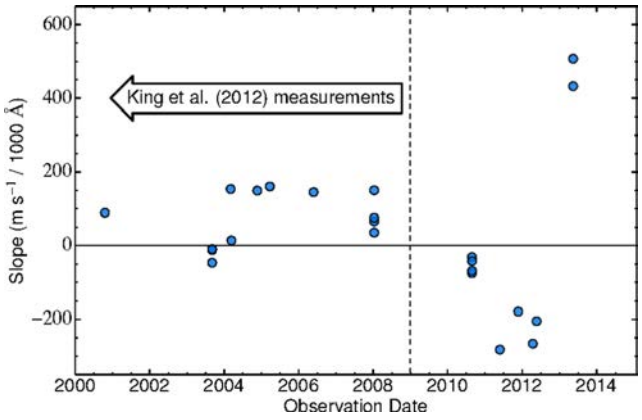
➔**Intra order shift variation up to 500m/s; LASER COMB may be useful.**

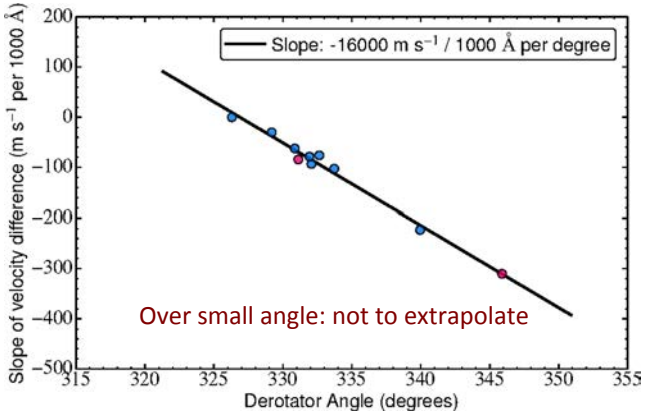
➔**Fiber based spectrograph (like HARP) to avoid slit effect on science target will be needed.**

LONG TERM STABILITY (physical): HIRES/KECK, UVES/VLT

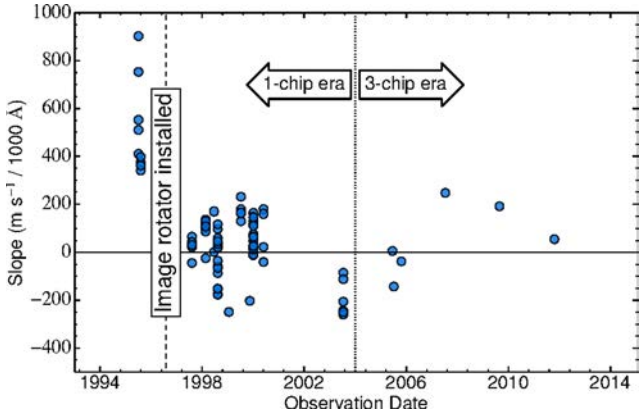
Whitmore et al (2015)

UVES/VLT





HIRES/Keck



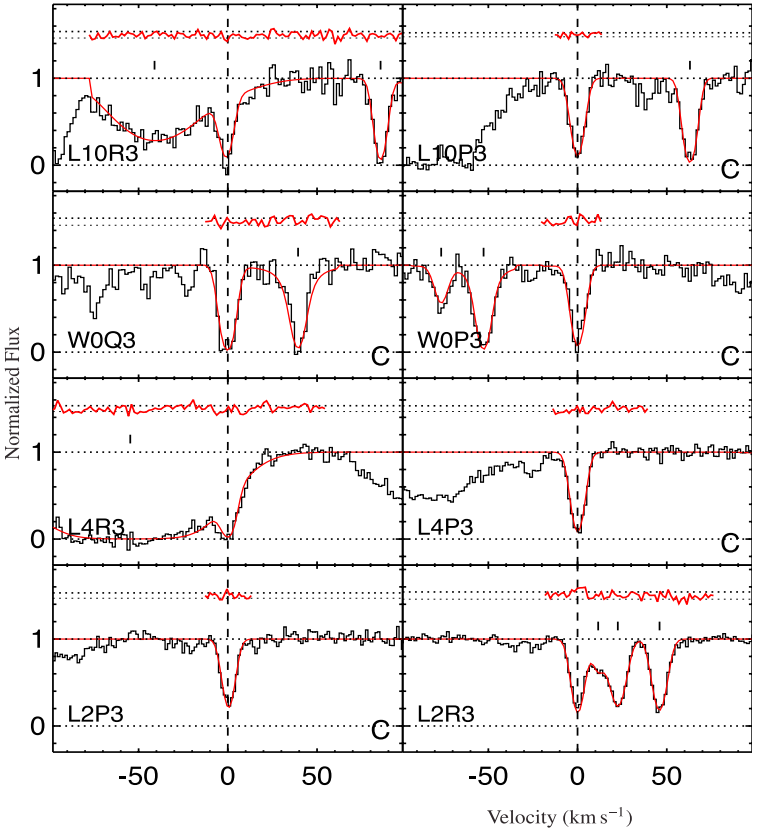
1. Calibration for $\alpha=e^2/\hbar c$ measurement:
   1. Found in both the spectrograph
   2. UVES, mostly +ve slop over time (<2008), and perhaps could be model.
   3. HIRES, fluctuate both in +ve/-ve, perhaps difficult to correct.

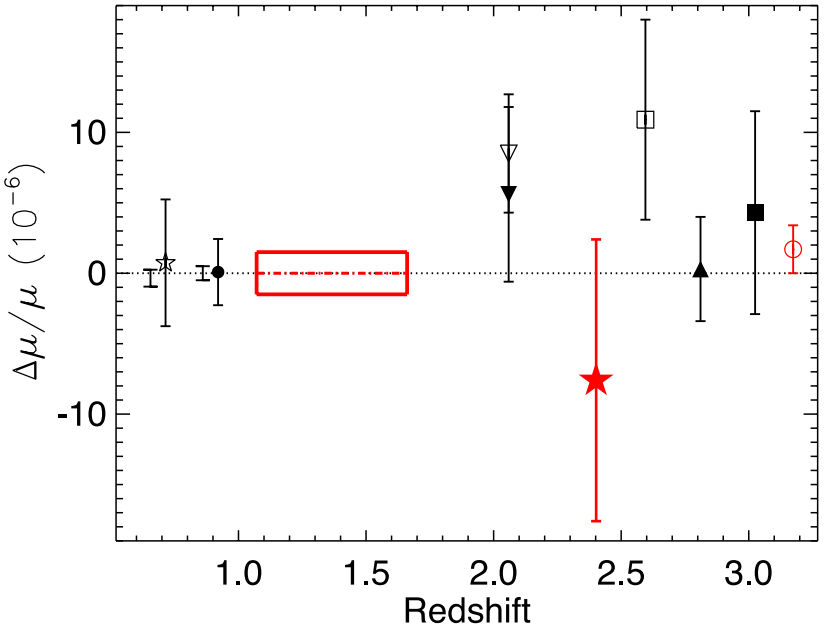
2. Certainly it weaken the α variation HIRES/KECK claim?

➔HOPE now on new TMT-spectrograph!

CALIBRATON ERROR for VARIATION OF $\mu=m_e/m_p$

$$\lambda_i = \lambda_0(1+z_{abs})(1+K_i\frac{\Delta\mu}{\mu})$$





Rahmani et al 2013 (filled star, after super calibration, UVES/VLT)

CALIBRATION EFFECT VARIATION OF $\mu=m_e/m_p$: UVES/VLT

Rahmani et al 2013 (UVES/VLT)

Relative calibration error

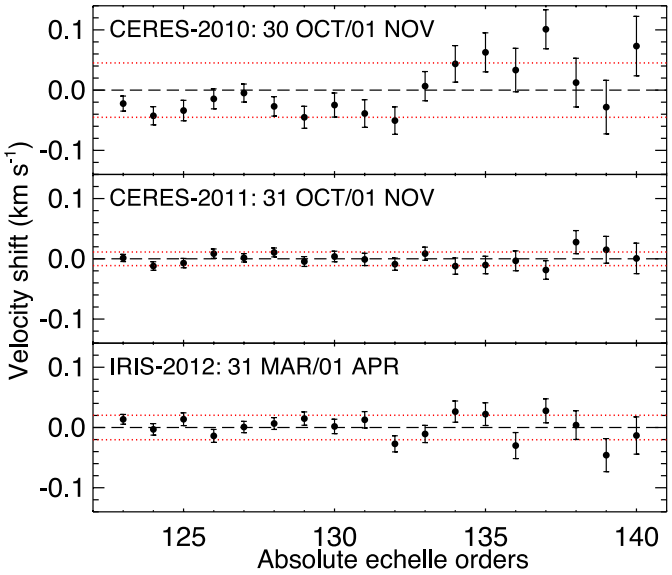


Fig: Velocity shifts between asteroid exposures (after subtracting mean shift).

Absolute calibration error

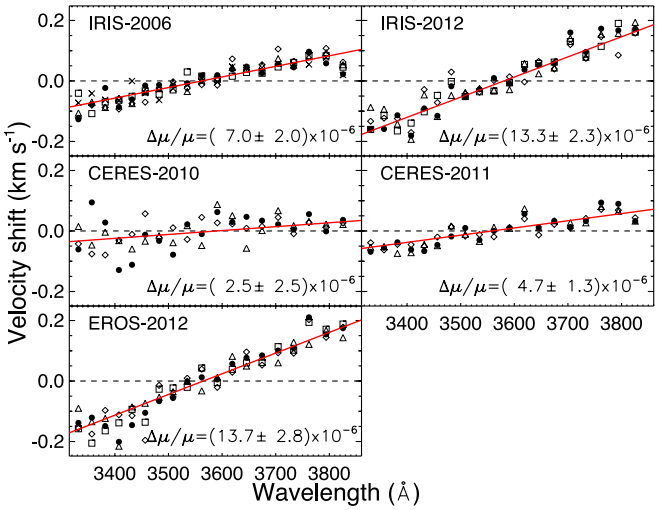
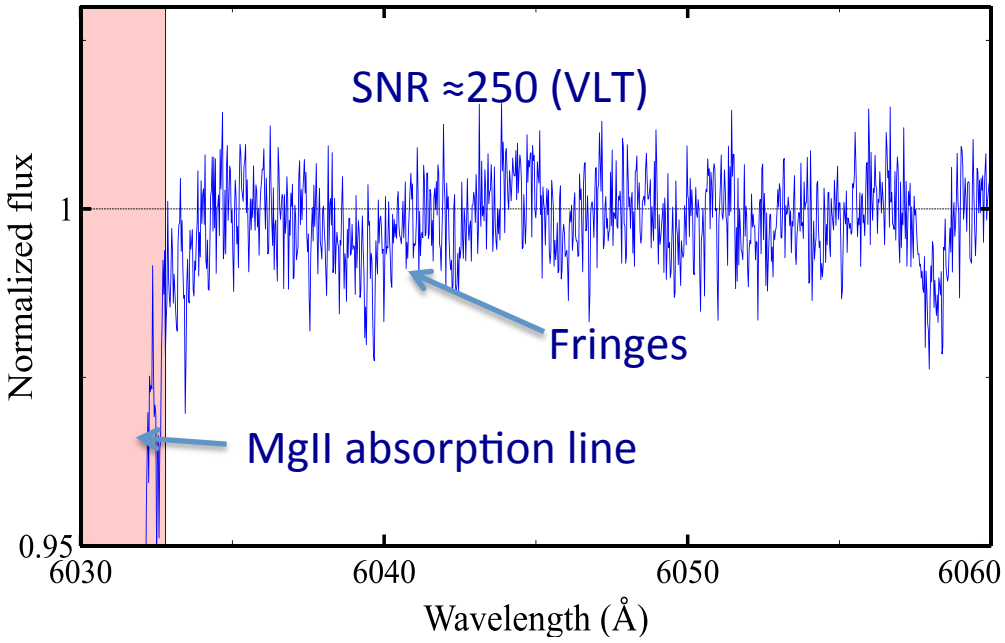


Fig: Velocity shifts after cross-correlating observed asteroid with solar spectra.

➔ **Like for $\alpha=e^2/\hbar c$ variation, calibration error equally important for $\mu=m_e/m_p$ variation.**

OTHER EFFECT: FRINGING

Kotus et al 2017



1. At high-SNR, many fringes are significant.
2. Will also be in line fitting region?

➔**Wish list: Detector with material avoiding/mitigate effects of fringing and artifact of sky-subtraction and flat-fielding etc.**

SUMMARY & WISH LIST for HROS@TMT

Wavelength calibration accuracy is crucial:

1. Uncertainty in $\Delta\alpha/\alpha \approx \sigma_{\Delta\lambda/\lambda}/(Q_i - Q_j)$; Q_i being sensitive coefficient
2. At R≈40000 accuracy of about 1 mÅ (i.e. 60m/s e.g. at 5000A)
    1. ➔ $\Delta\lambda/\lambda \approx 2\times10^{-7}$
    2. ➔ Uncertainty in $\Delta\alpha/\alpha \approx 2\times10^{-6}$ (for $Q_i - Q_j \approx 0.1$)

Existing wavelength calibration systematics:

1. Intra-order (short range distortion).
    1. Can be as large as 500m/s within a Echelle order
        ➔ LASER COMB instead of Th-Ar
2. Inter-order (long range distortion): Evidence exist in archival data of UVES/VLT and HIRES/KECK for such distortion varying ±200m/s per 1000A.
    ➔ Fiber fed spectrograph @constant temperature, @low and stable pressure

Spectral coverage and resolutions:

1. Longer the better (to take advantage of lines varying sensitive coefficient), but not at the cost of long range distortions➔ **Coverage** ≈0.4-0.7µm minimum.
2. QSOs line, few km/s, rarely of less than 1 km/s . ➔**Resolutions** ≈100000-150000 (also not at the cost of SNR).
3. The typical 100 systems with SNR≈500 ➔ **Δα/α accuracy** $\approx10^{-7}$ -10^{-8} , provided we controlled systematics (cf. long wavelength distortion) at the level of few m/s (cf. HARPS).

SUMMARY & WISH LIST for HROS@TMT ..Cnt

Accuracy @TMT: With these wish list, about two order of improvement in accuracy is expected

1. **Detection of variation:** Will give first proof/support for extra dimension theory if any.

2. **Non-detection of variation:** Will also put strong constraint on unification theories

TMT Key advantage:

1. As TMT will be the largest telescope in northern sky so will be crucial to immediately test the variation detected by HIRES/KECK, hence the proposed spatial variation (cf. as existing HIRES/KECK calibration still not understood)

Synergy with other facilities (e.g SKA) : TMT constrain on $\alpha=e^2/\hbar c$, $\mu=m_e/m_p$ will be crucial to complement with radio measurements sensitive to combinations of constants

1. General strategy 2. Science case: constant variation

Thanking You.

ARIES pics.