Solar spectrum as a radial velocity reference

Paolo Molaro

OATS-INAF

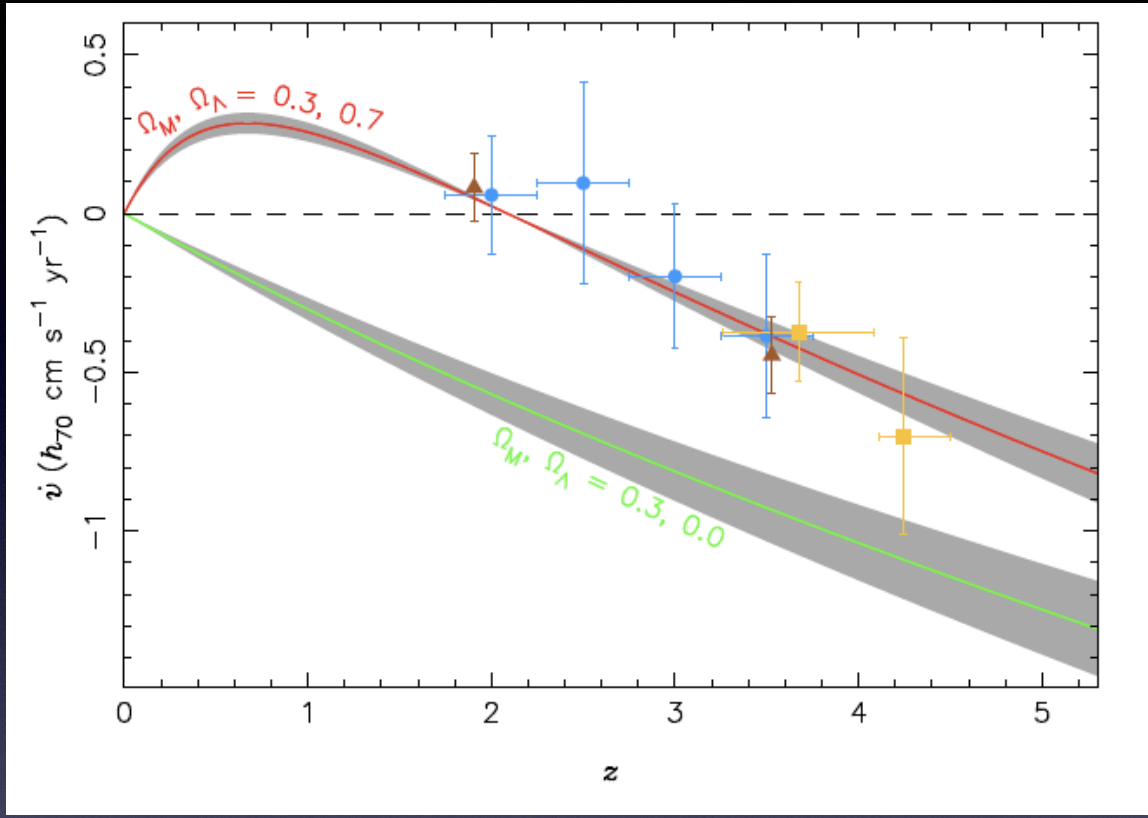
Outline

- Precise and accurate RV in cosmology and fundamental physics
- What in spectrographs UVES, HIRES & HARPS
- Tools to check for accuracies: solar spectrum

Allan Sandage Test

Allan Sandage 1962 ApJ 136,319

"*It should be possible to choose between various models of the expanding universe if the deceleration of a given galaxy could be measured. Precise predictions of the expected change in* $z=d\lambda/\lambda_0$ *for reasonable observing times (say 100 years) is exceedingly small. Nevertheless, the predictions are interesting, since they form part of the available theory for the evolution of the universe*"

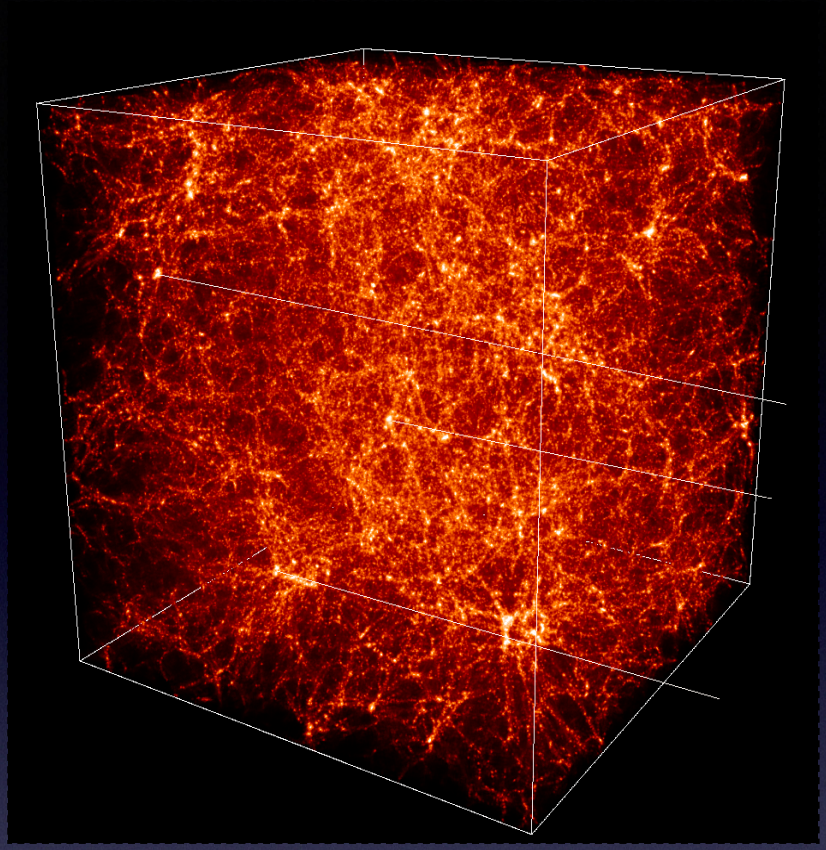


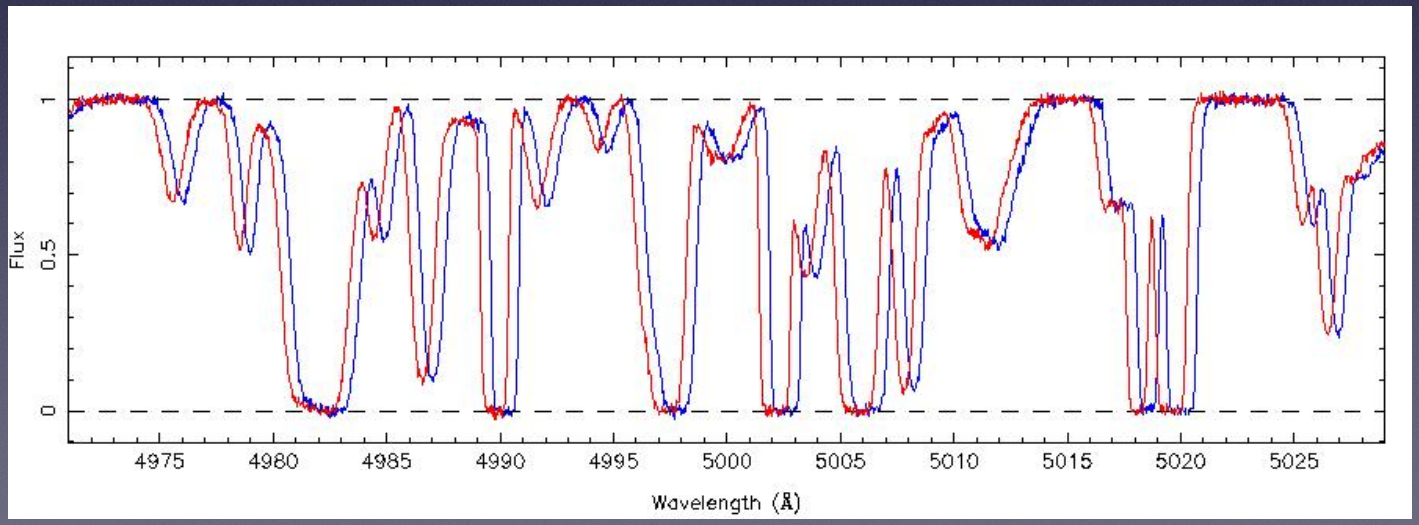
Liske et al 2008

400 nights of the E-ELT
over 20 years
no systematic considered
(conservative)

z=0.4	K	cm/s/y
	+1	-0.73
	-1	-0.30
	0	-0.59
	Seady state	+0.92

Sandage 1962





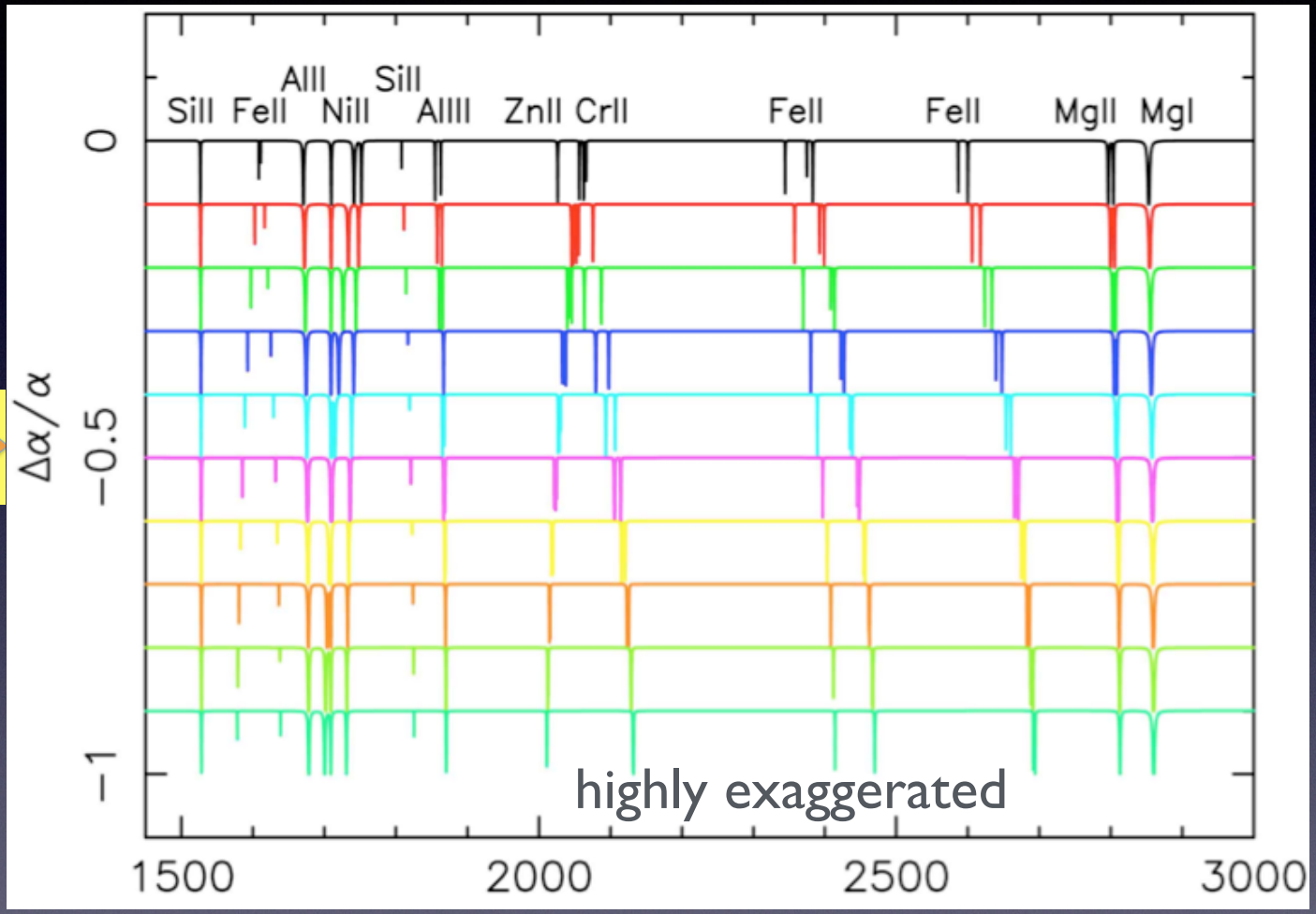
for 10^7 years…!!

Fundamental physical constants

All atomic transitions depend on α

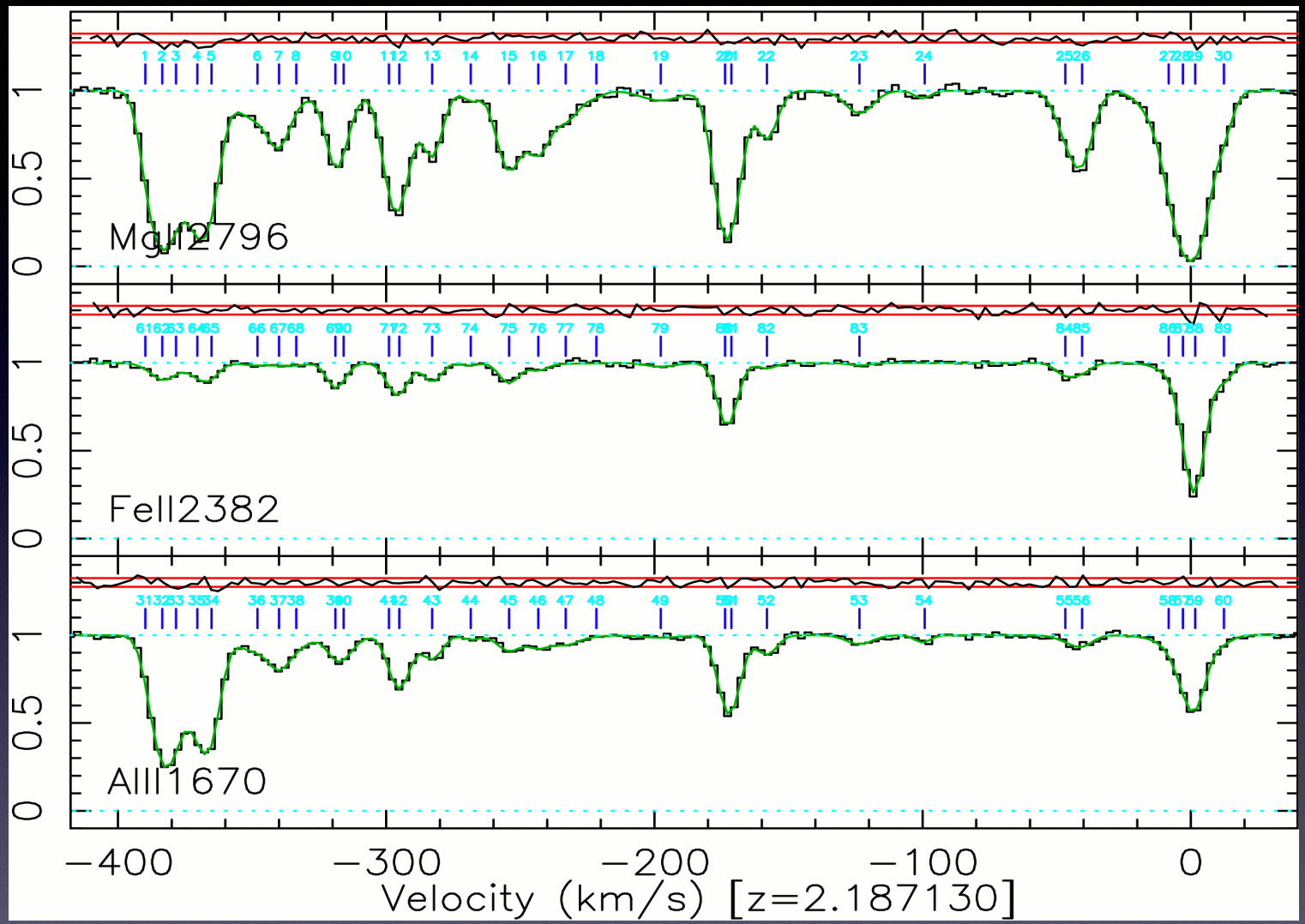
$$\alpha = \frac{e^2}{\hbar c}$$

a decreases

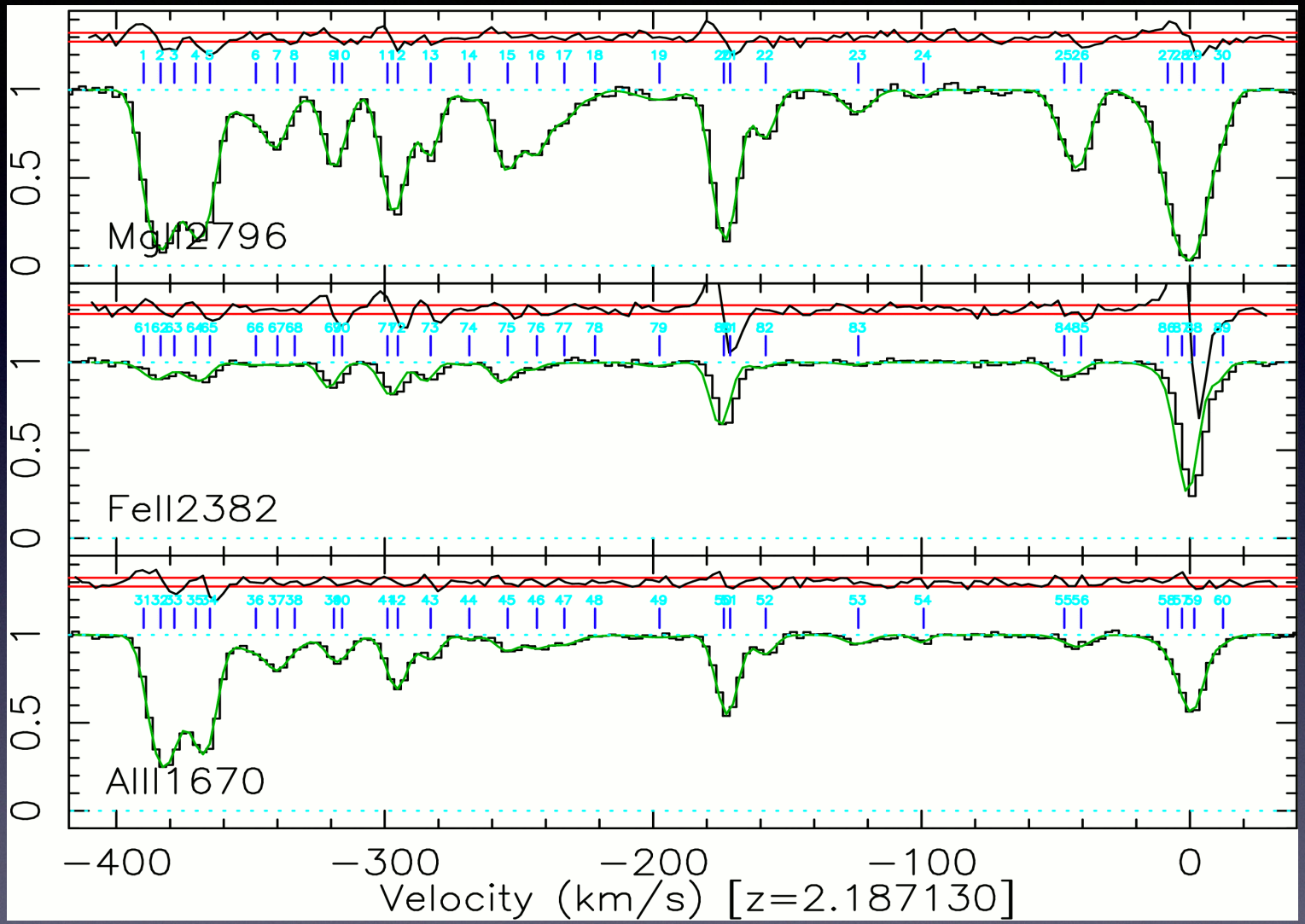


$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(Q_1 - Q_2)} = \frac{\Delta v}{2\,c\,\Delta Q}$$

Shifts ~2 km/s => $\Delta\alpha/\alpha$ ~10^{-4}

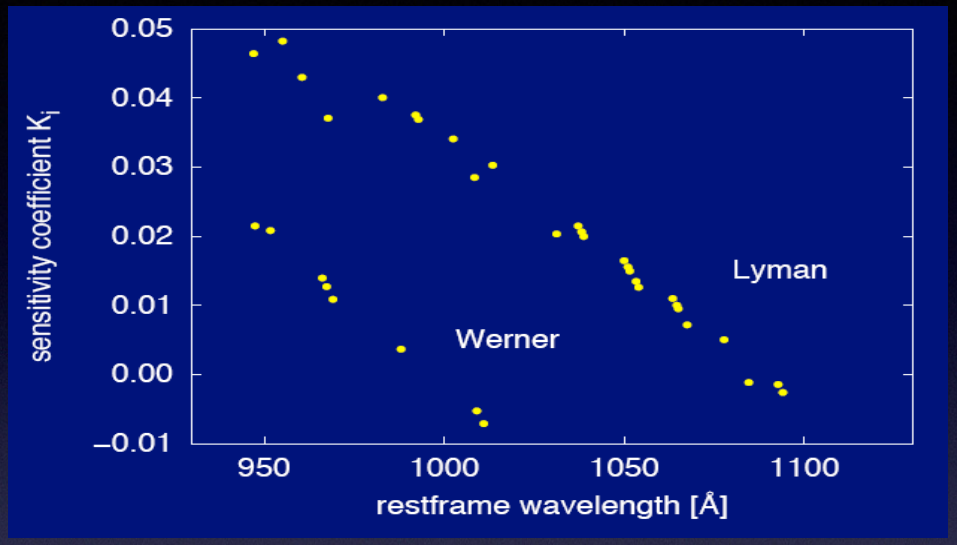


$\Delta\alpha/\alpha = 0$



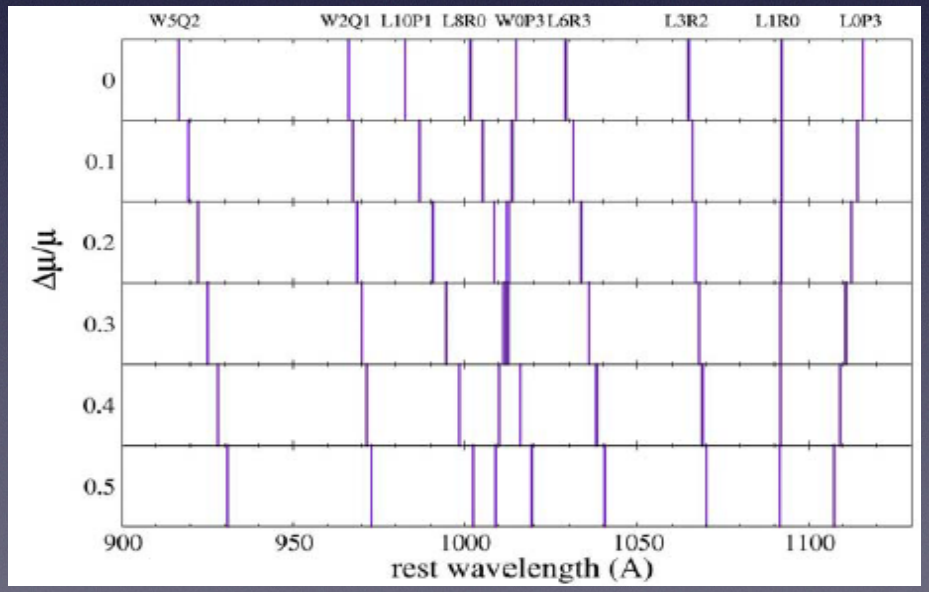
Shifts ~2 km/s => $\Delta\alpha/\alpha = 10^{-4}$

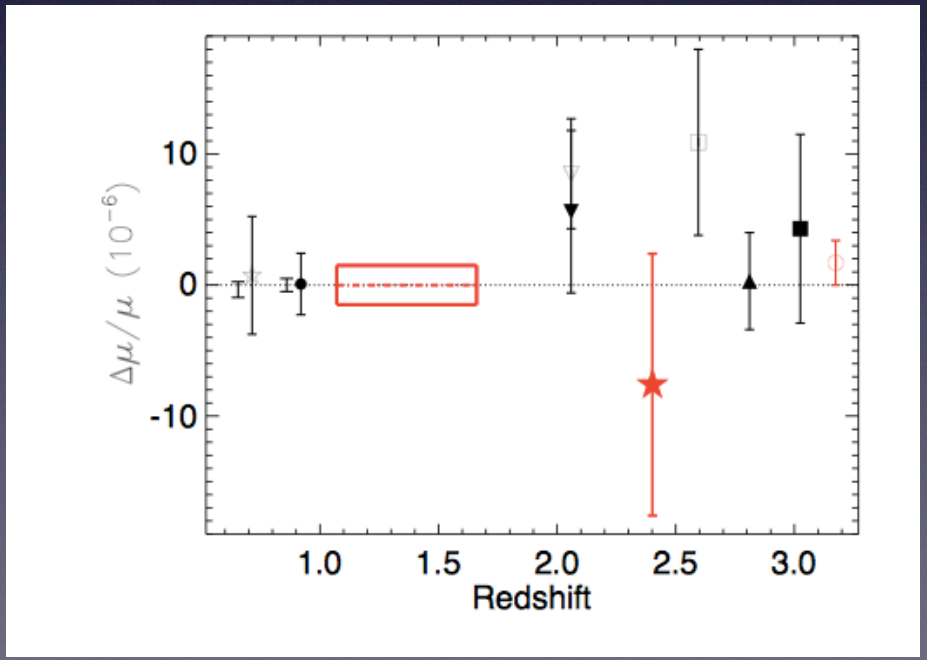
$\mu = m_e/m_p$



$$\frac{\Delta\nu}{\nu} = K_\mu \frac{\Delta\mu}{\mu}$$

Measure — Calculate — Determine



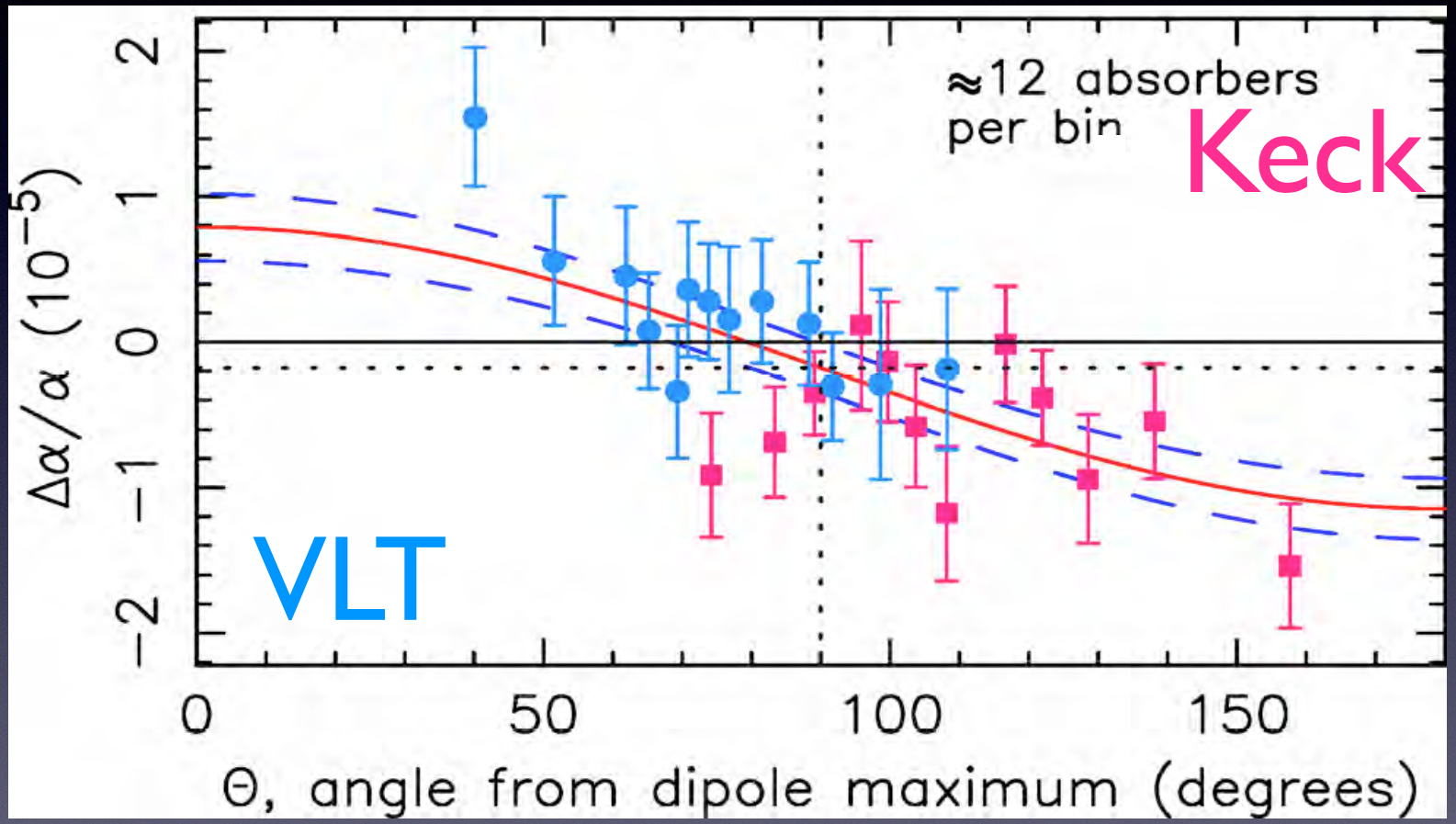


An angular dipole

$\Delta\alpha/\alpha = A \cos\theta + m$

Webb et al 2012

King et al 2012

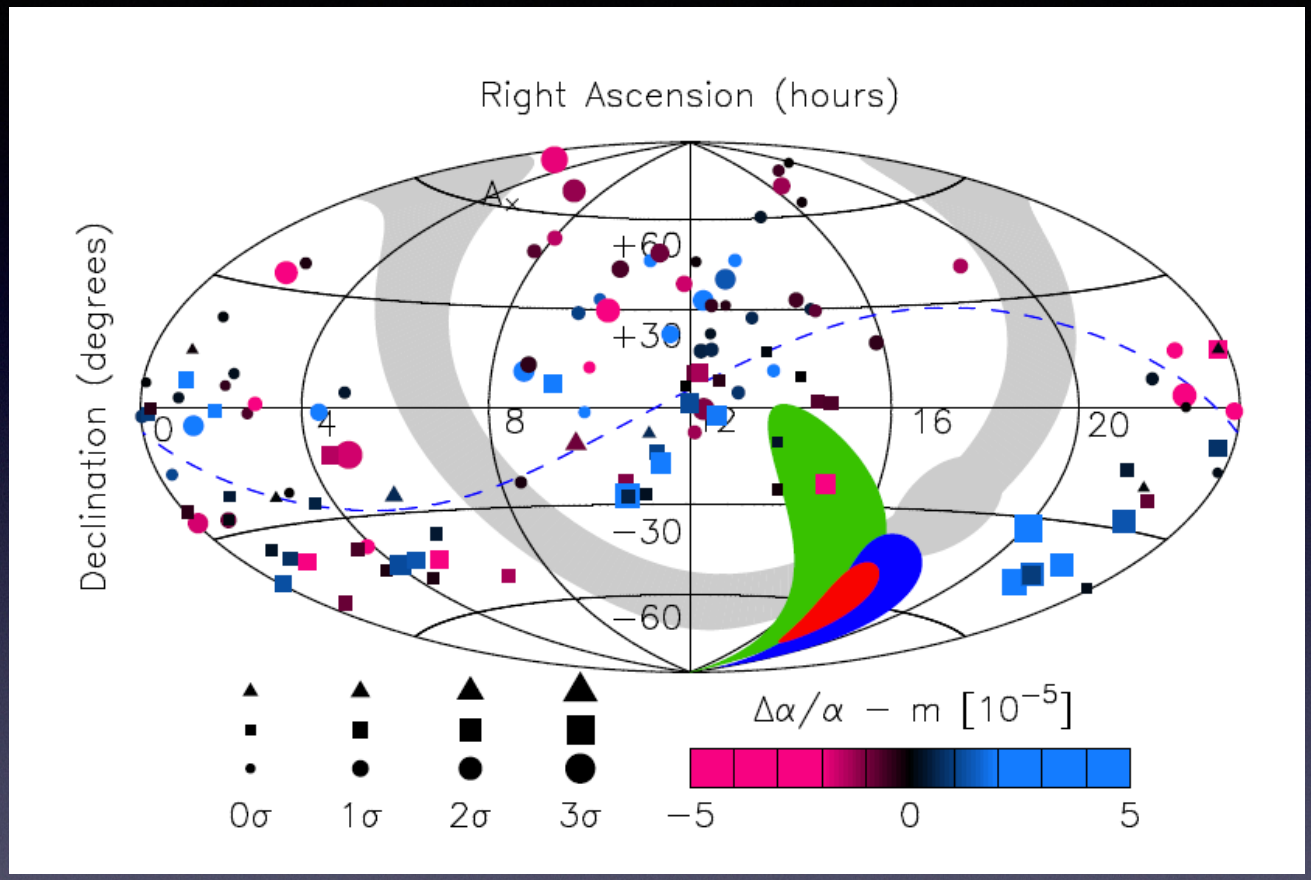


$\Delta\alpha/\alpha$ = 9.7± 2.1 ppm

4.1-σ dipole

pole direction:
RA: 17.4±1.0 hr
DEC: -61 ±10 deg

VLT



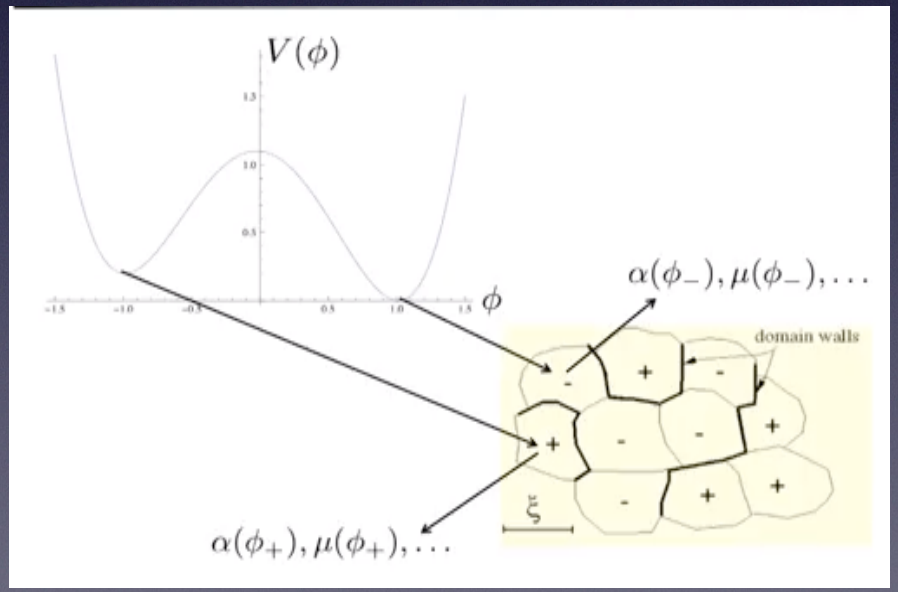
Keck

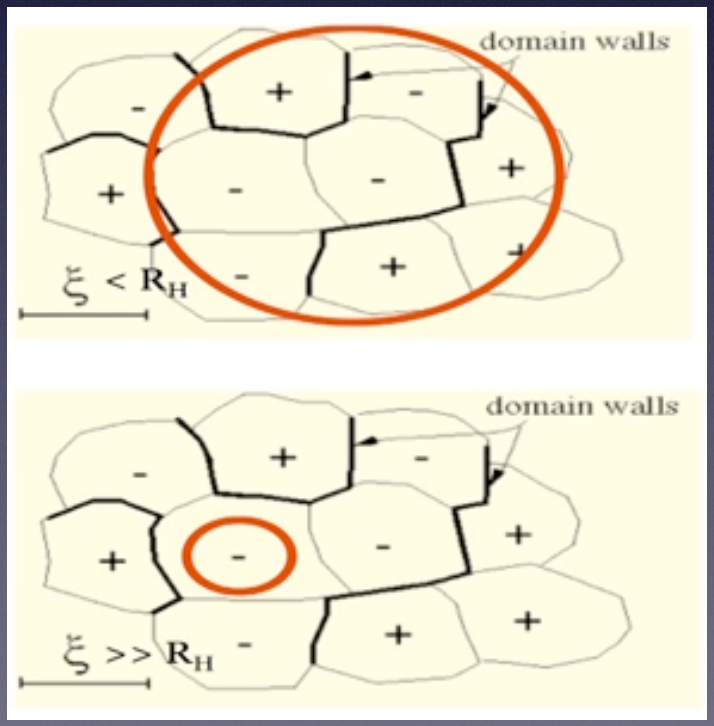
- Directions of dipole of VLT and Keck samples separately agree
- Directions of dipole for $z < 1.6$ and $z > 1.6$ cuts of the combined VLT+Keck data agree (low and high redshifts involve different set of lines)
- In the equatorial region of the dipole consistency between Keck and VLT

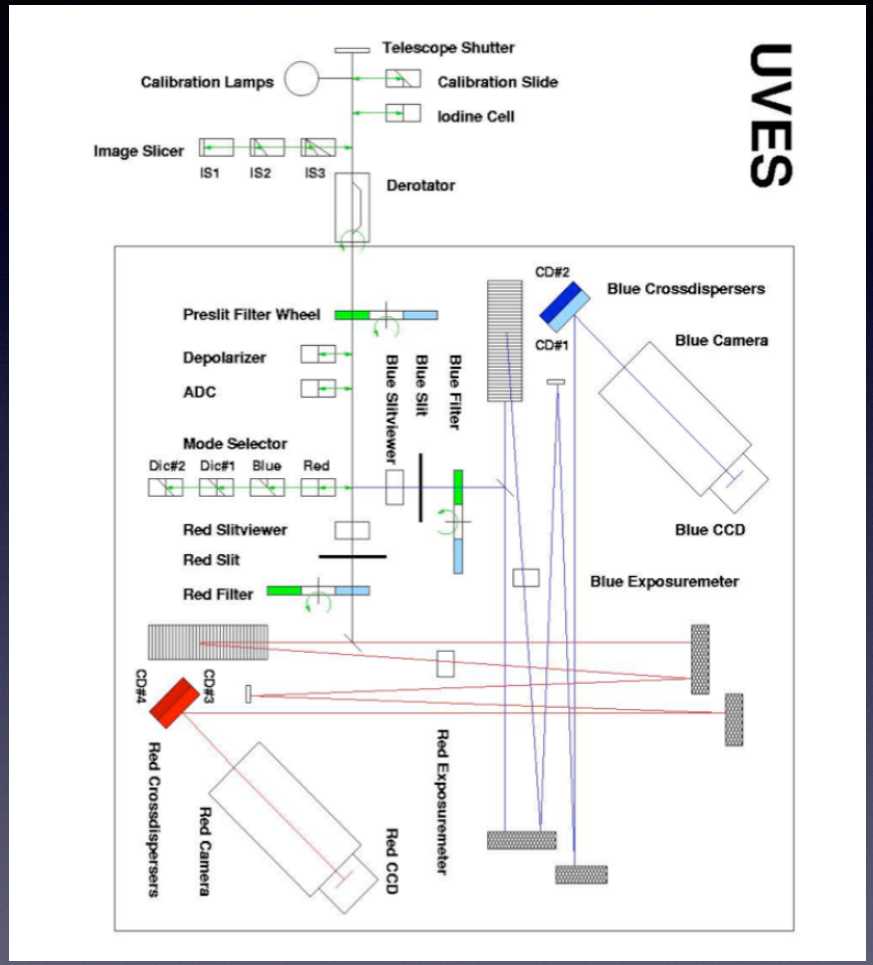
Origin?

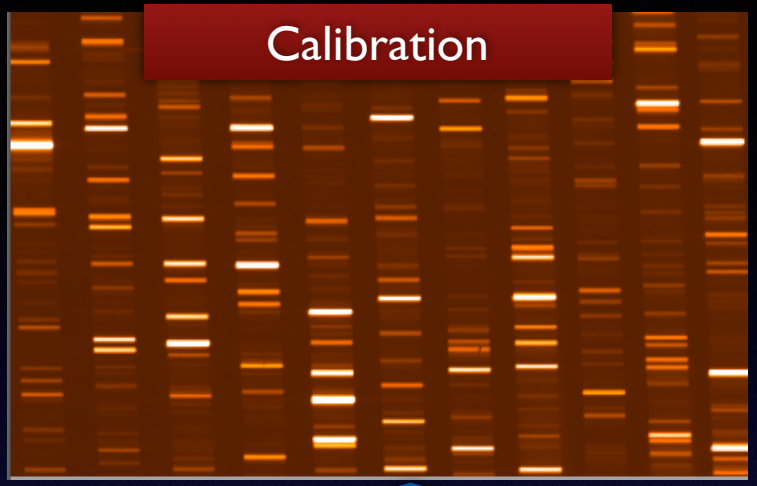
Olive, Peloso Uzan 2011, Olive Peloso Peterson 2012

Micro-Landscape theory:
spatial discontinuity due to a domain wall crossing our Hubble volume
spontaneous symmetry breaking of a dilaton scalar field coupled to electromagnetisms

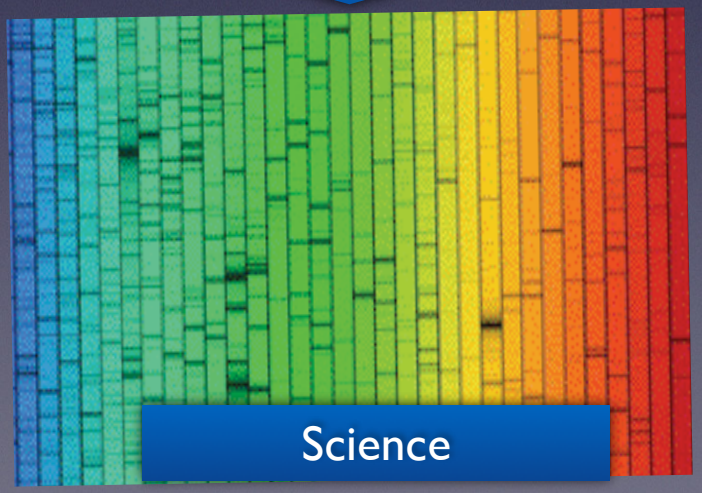








Map the wavelength solution
to the science exposure



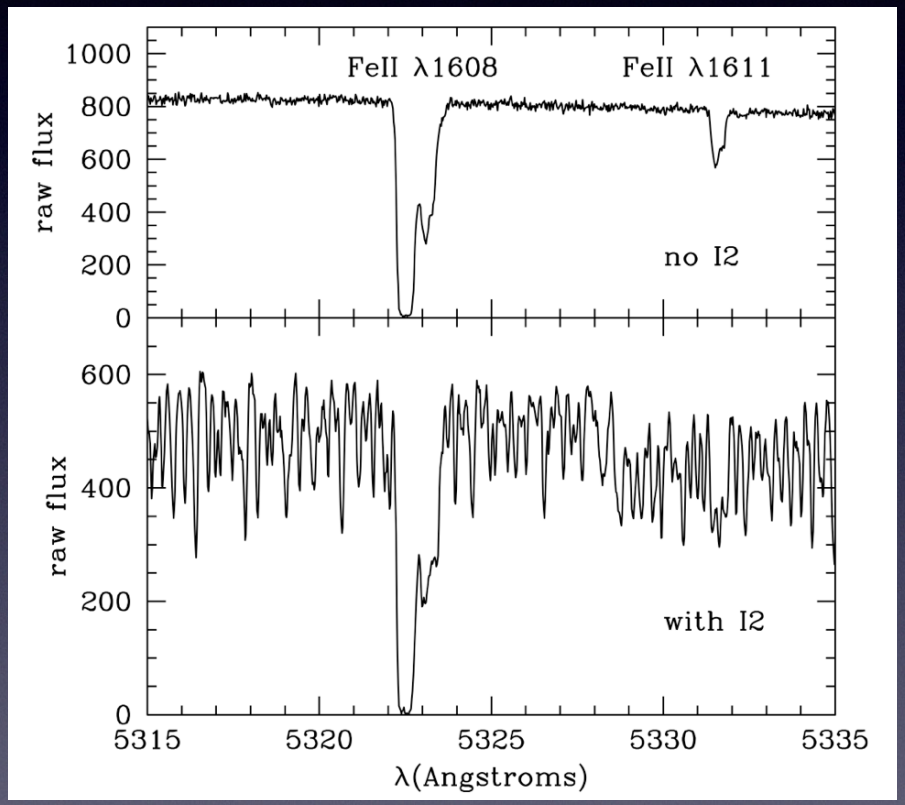
Different paths!

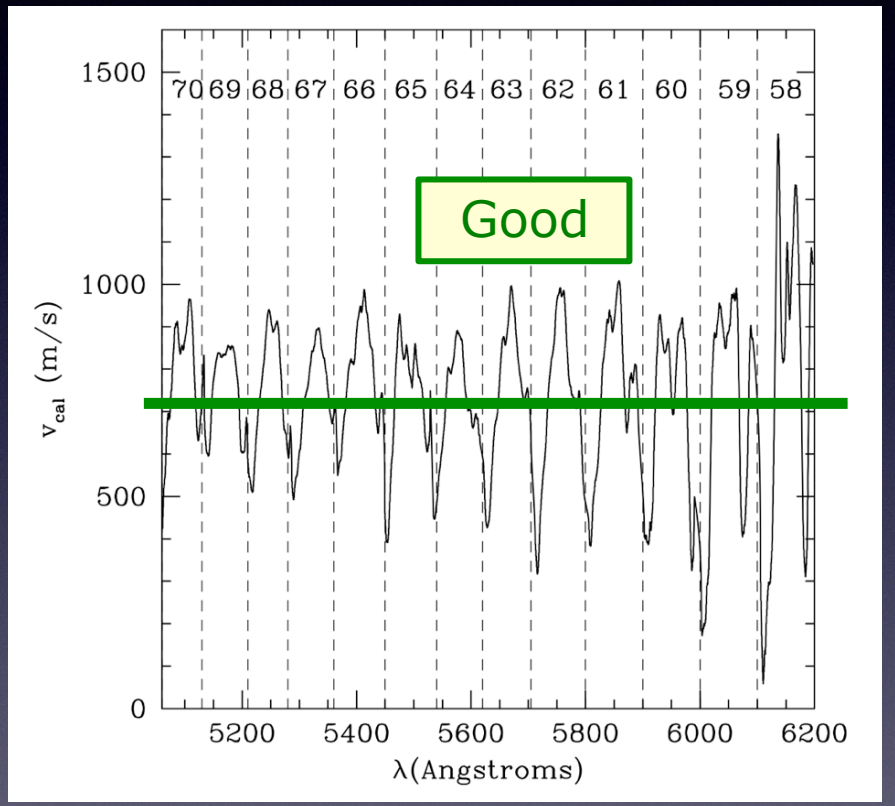
ThAr- Iodine comparison

HIRES- KECK

Griest et al 2010

PHL 952



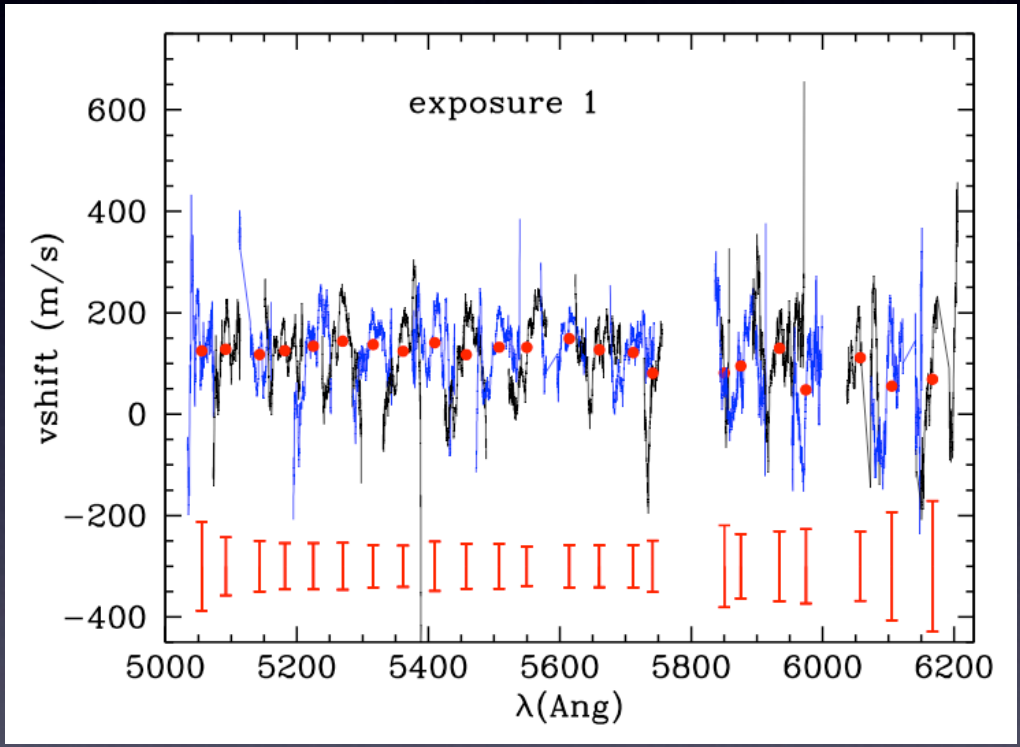


Iodine: 5075-6300 A

Order saw-tooth modulation amplitude σ_v ~ 200 m/s

UVES-VLT

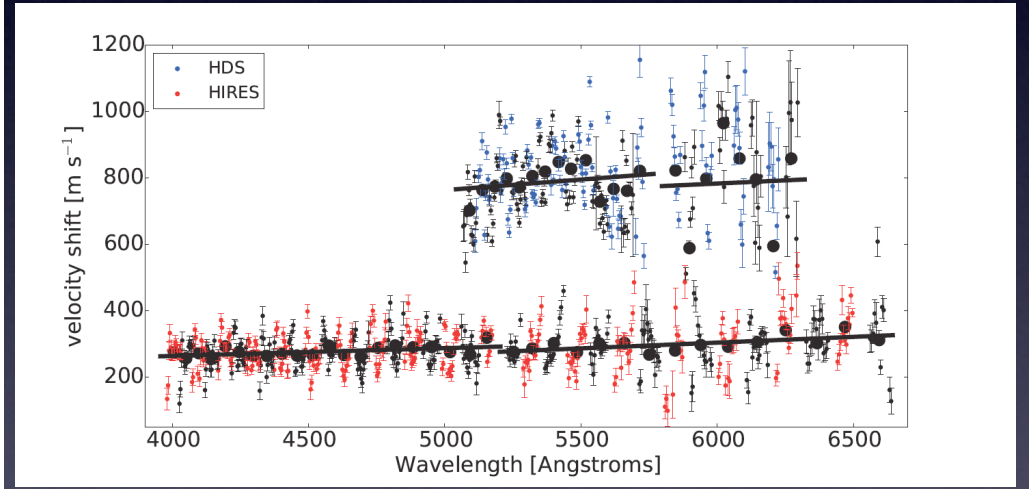
Whitmore et al 2010



Modulation amplitude σ_v ~ 100 m/s
Not constant!

HDS-Subaru

Evans et al 2014

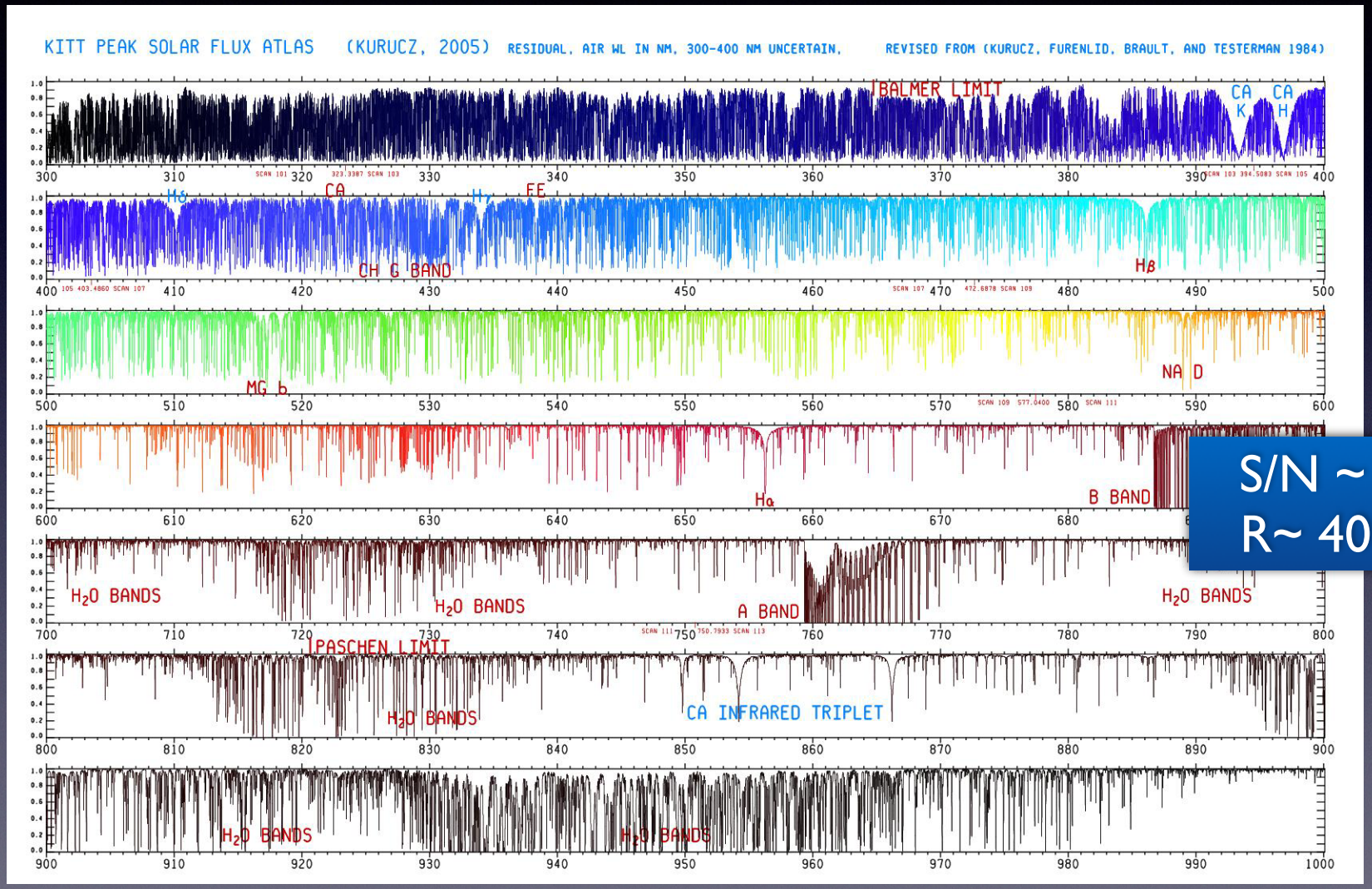


~ 300 m/s

Solar spectrum

(Kurucz et al 1984, 2006, 2010)

FTS McMath-Pierce Solar Telescope Kitt Peak National Observatory



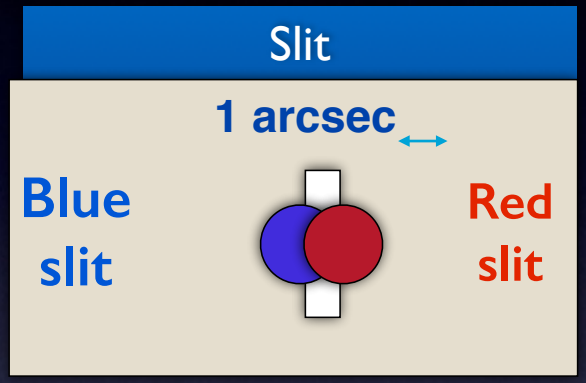
S/N ~ 2500,
R~ 400 000

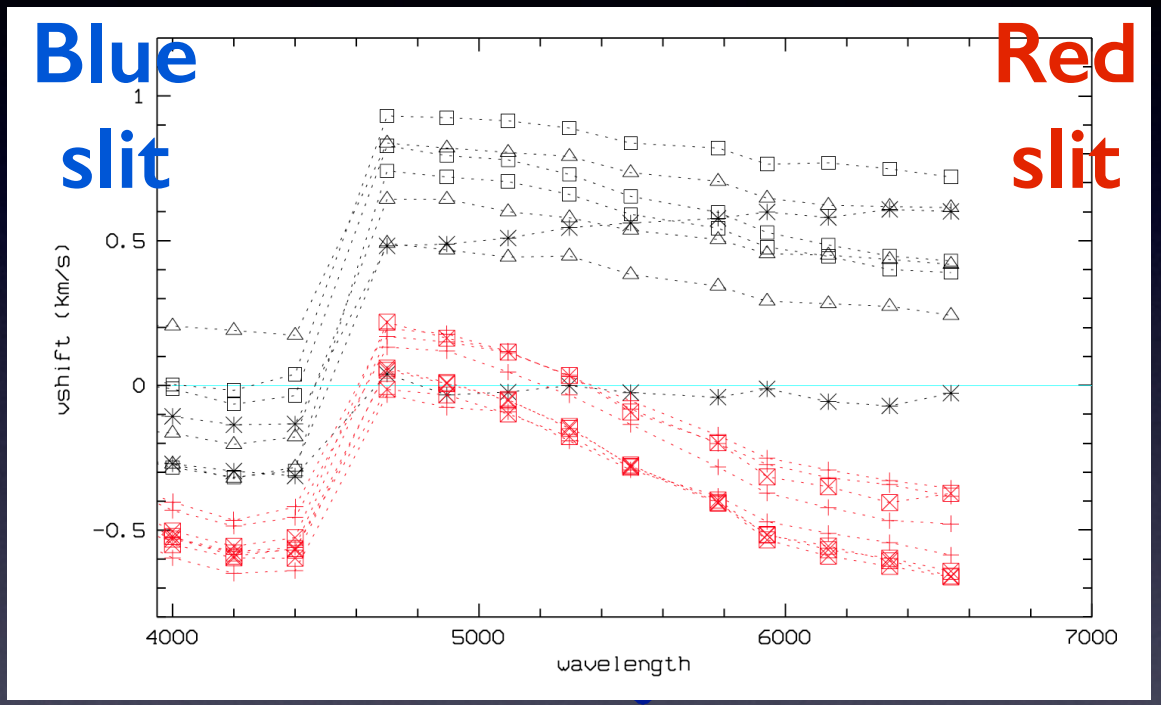
integrated solar spectrum: merger of several observations on the solar disk taken in 1980-1981

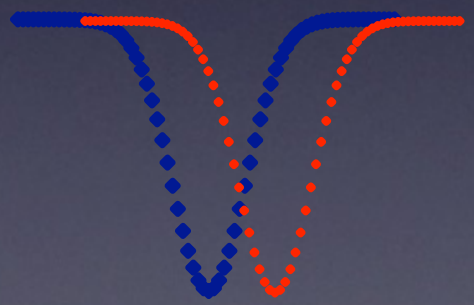
Alternative: HARPS Solar Atlas calibrated with the LFC

asteroids have known kinematics at cm/s level => "*absolute*" radial velocity.

UVES







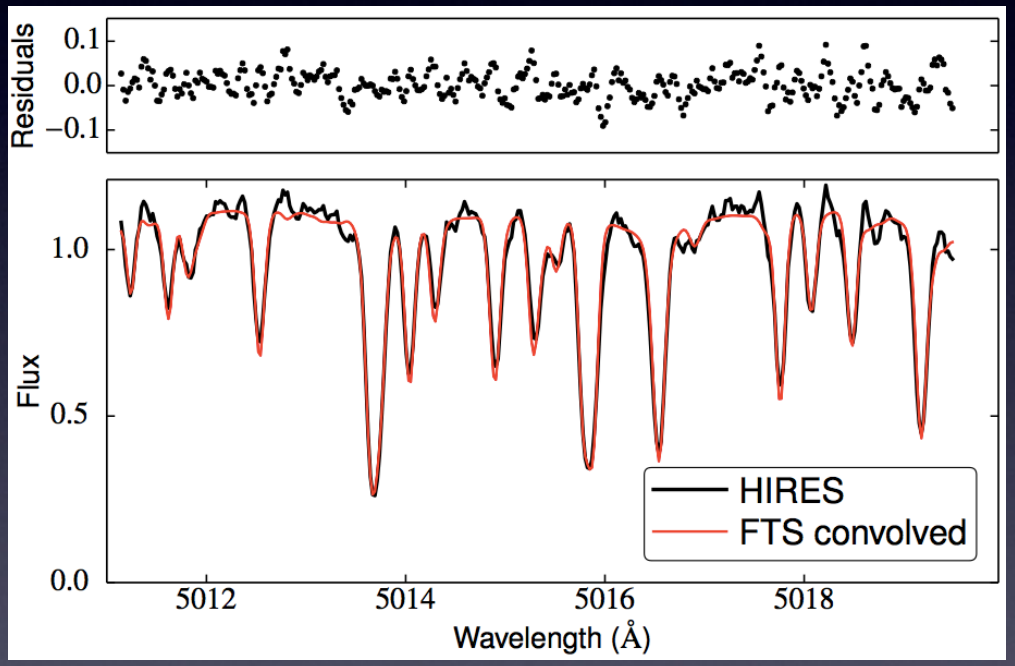
Δ RV
up to 1 km/s

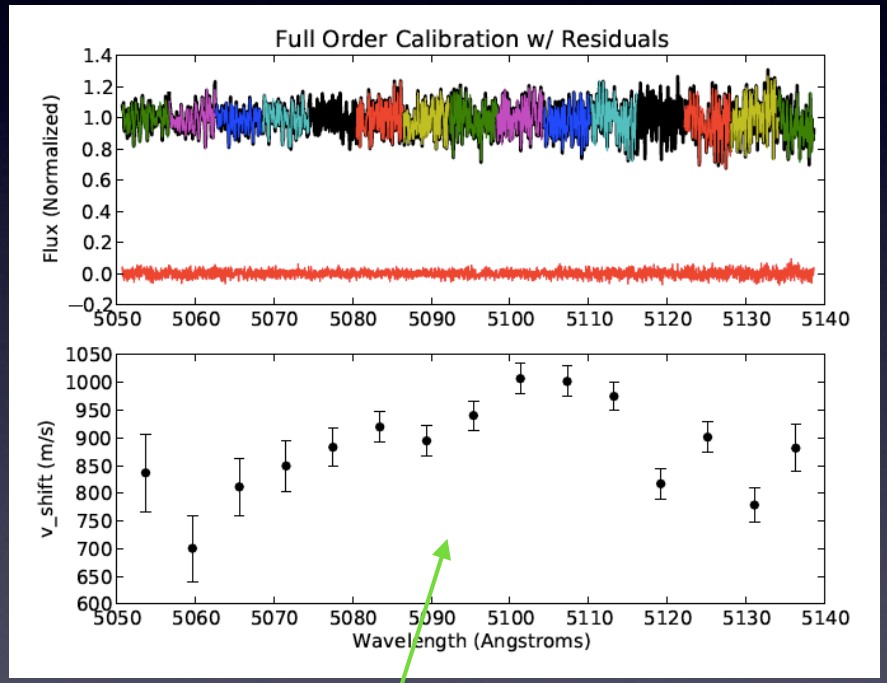
in UVES BLUE and RED arms may differ
UVES miss absolute RV by up to 1 km/s (slit illumination)

PM et al 2008

the Sun-as-a-star

Asteroids or solar twins
RV from spectral bins: ~ 5 A



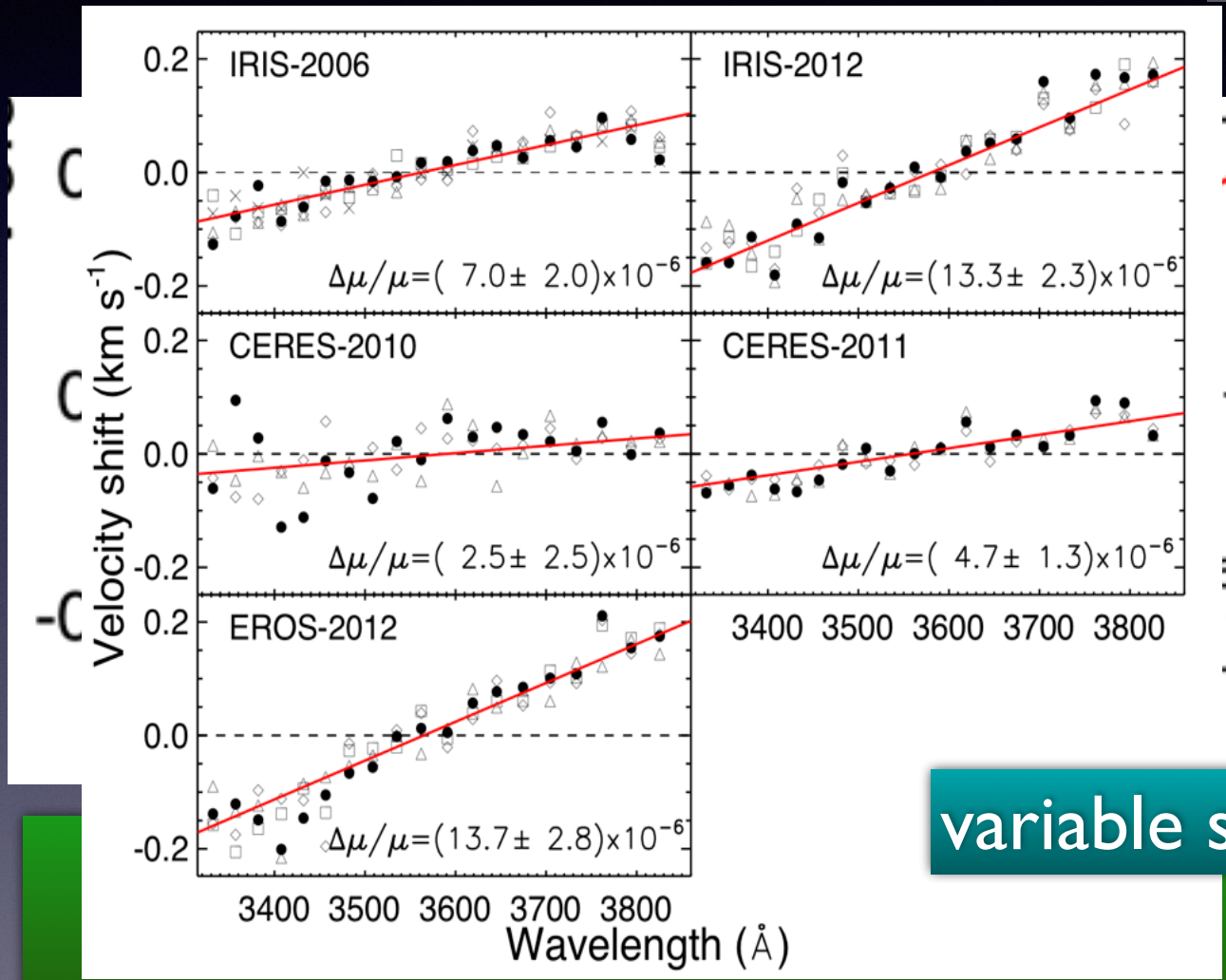


~ distortions revealed by I2

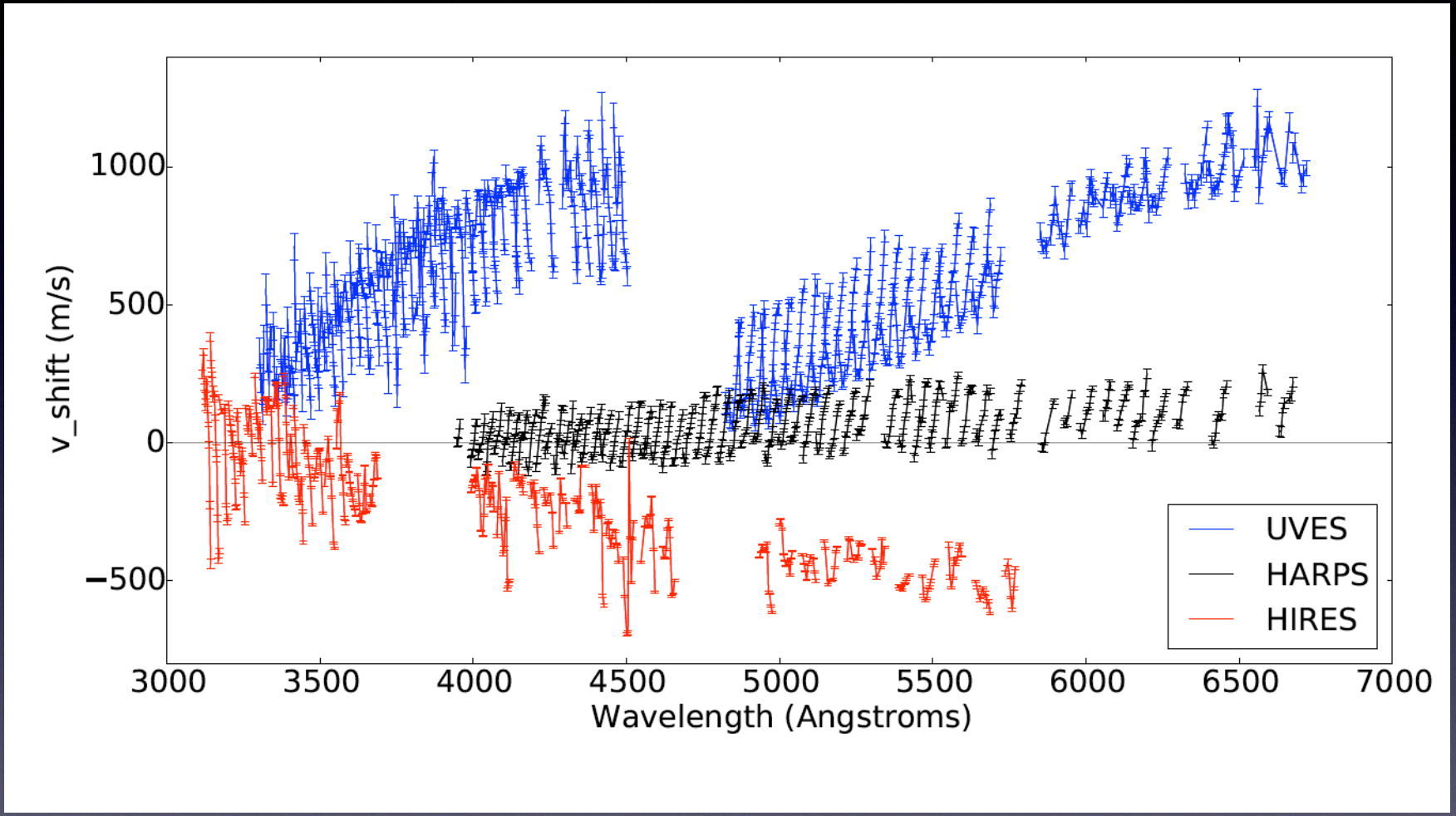
Spectral Drifts

RV: UVES/asteroid - FTS/solar spectrum

Rahmani et al 2013



variable slope



possible impact on the α- dipole

Whitmore & Murphy 2014 arxiv1409.4467

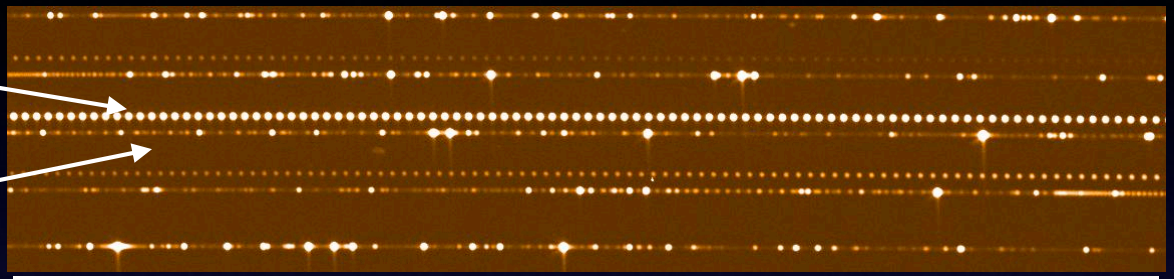
LFC HARPS

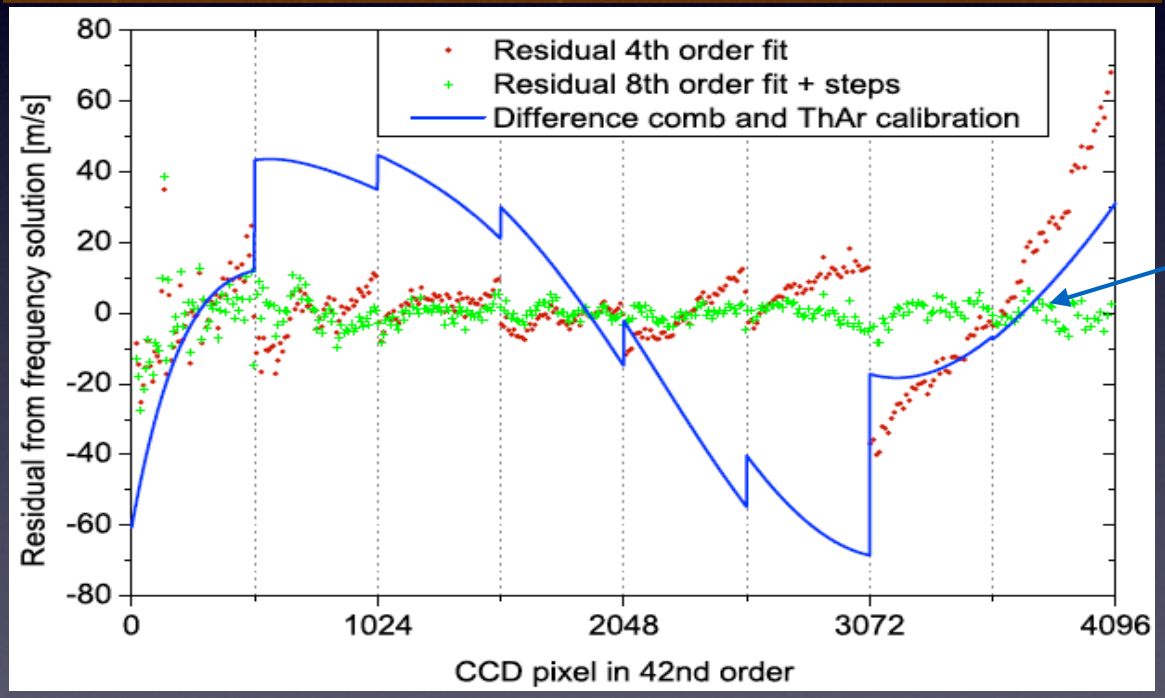
ESO-MPQ prototype Laser Frequency Comb

Wilken et al 2010

LFC

ThAr





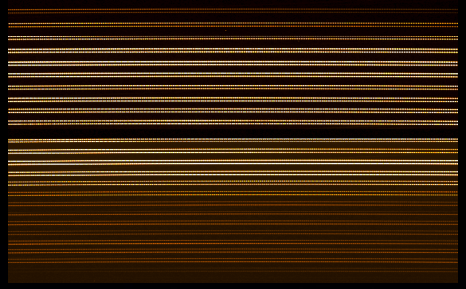
DIFFERENCE COMB and ThAr

512 pixel pattern

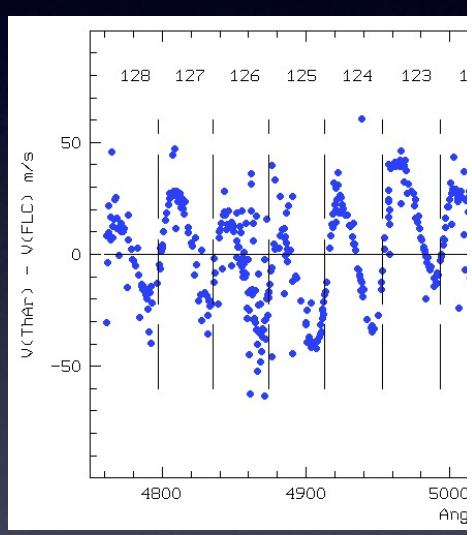
Intra-order distortions, amplitude ~100 m/s (but ~ 0 in the mean)

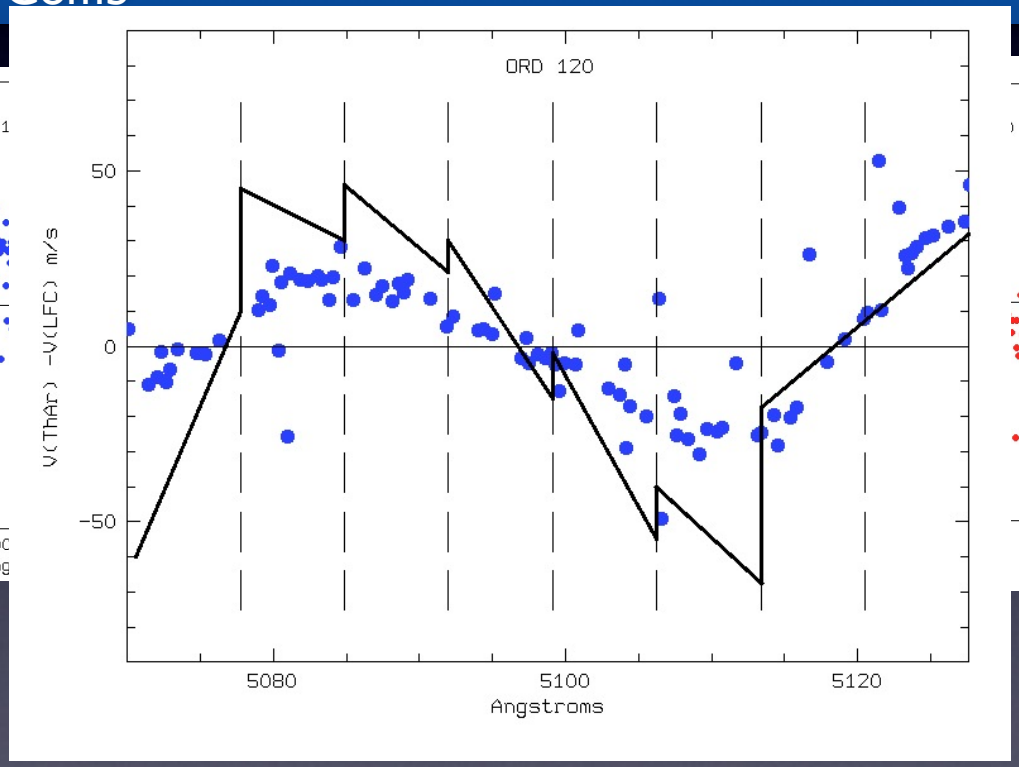
From two lines peak-to-peak ➡ $d\alpha/\alpha \sim 5 \times 10^{-6}$

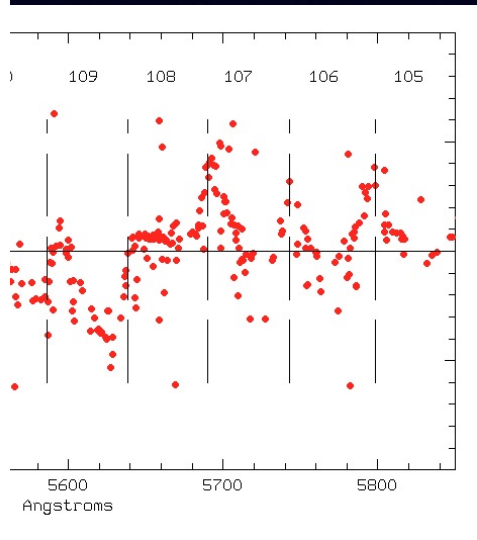
LFC prototype Nov 2010:
23 orders, 110 nm range
Few observations of the Moon



Difference in positions between lines measured in the solar spectrum calibrated with the ThAr and with the LF Comb

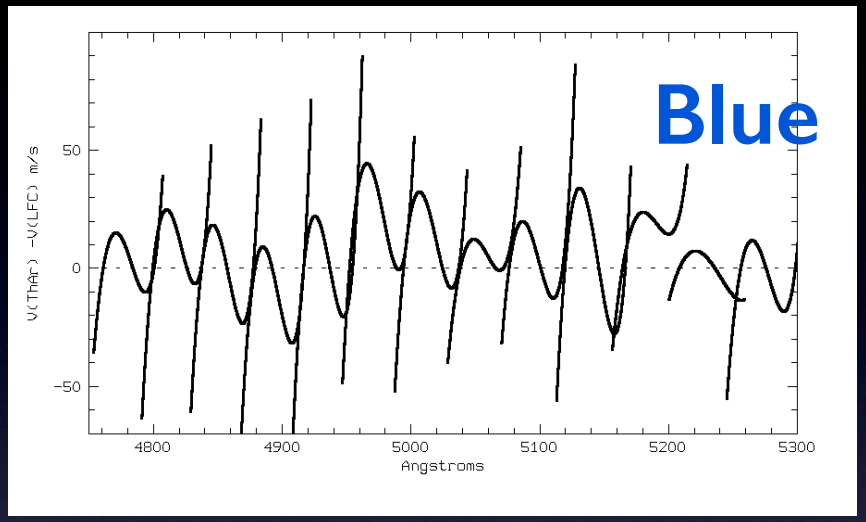


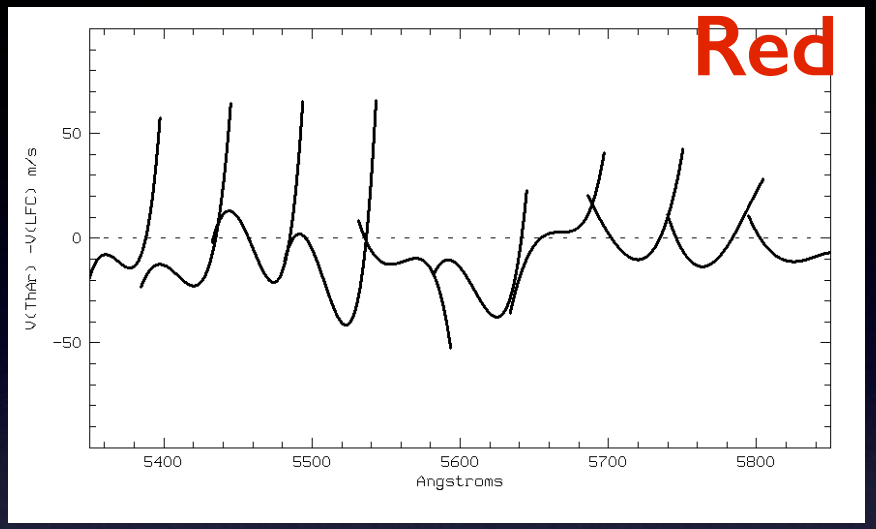


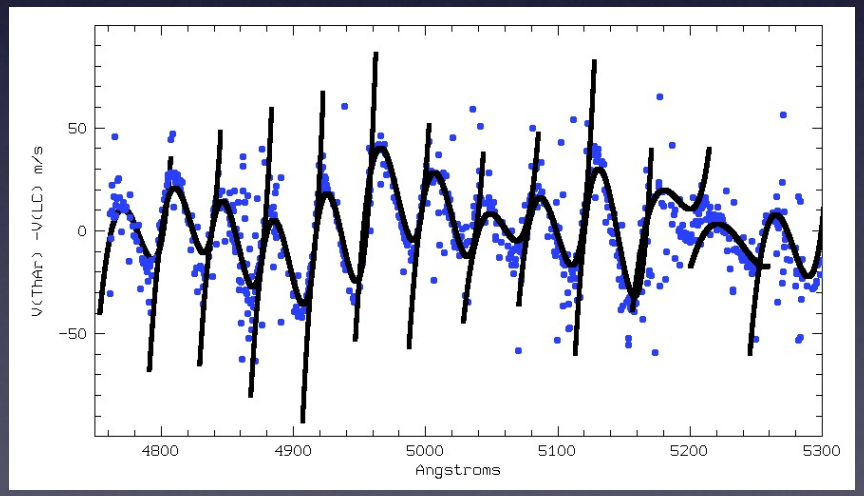


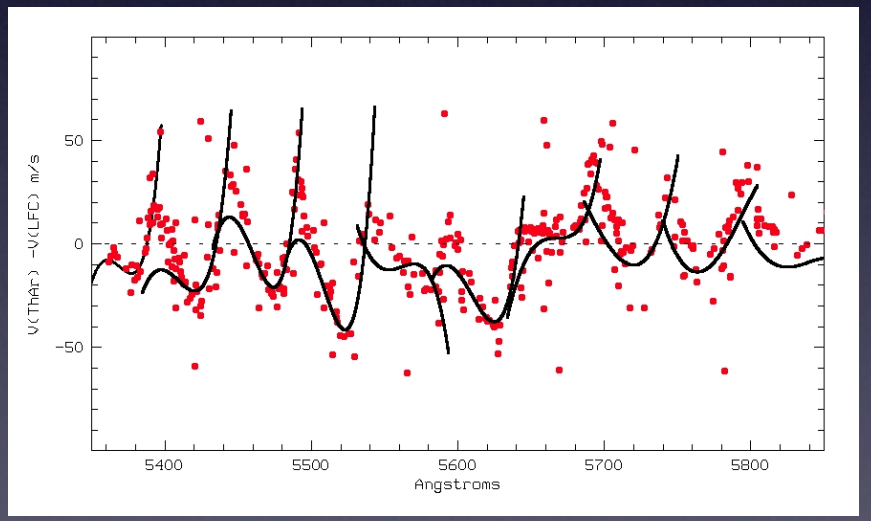
- intra-order shifts are in all orders of ~ 100 m/s
- slightly different from order to order
- same 2009 ~ 2010

difference between the FLC -ThAr and FLC-FLC





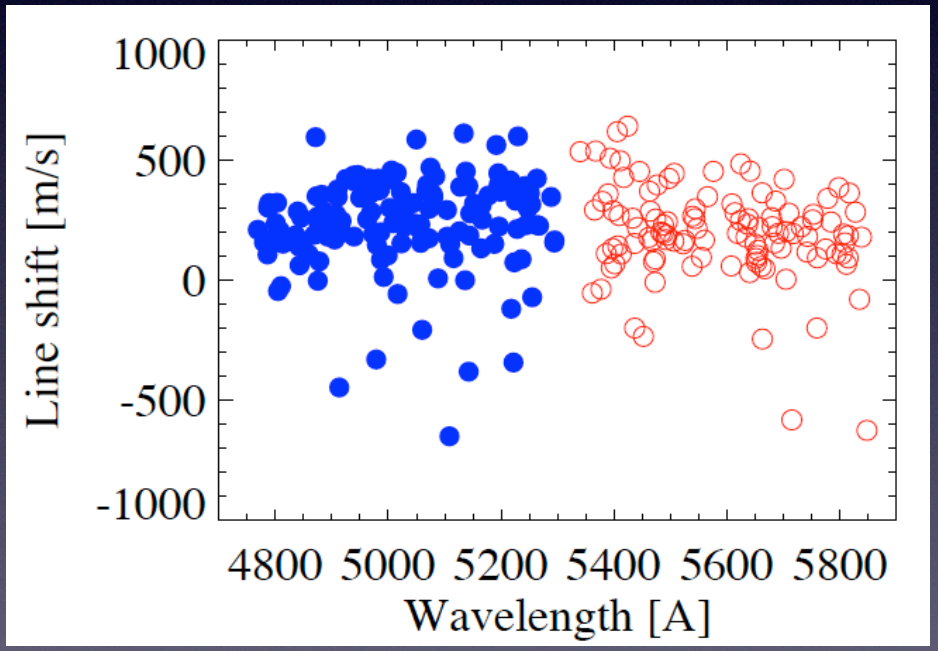




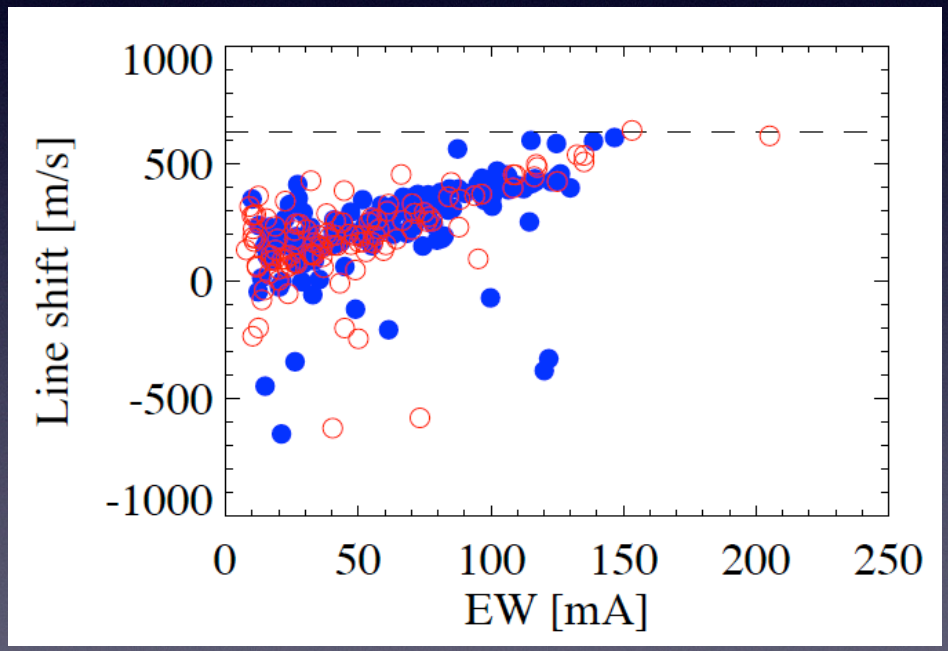
positions of solar atlas accurate within few m/s

New solar Atlas calibrated with the LFC (PM et al 2013)

Fe I line shift = Obs - Lab



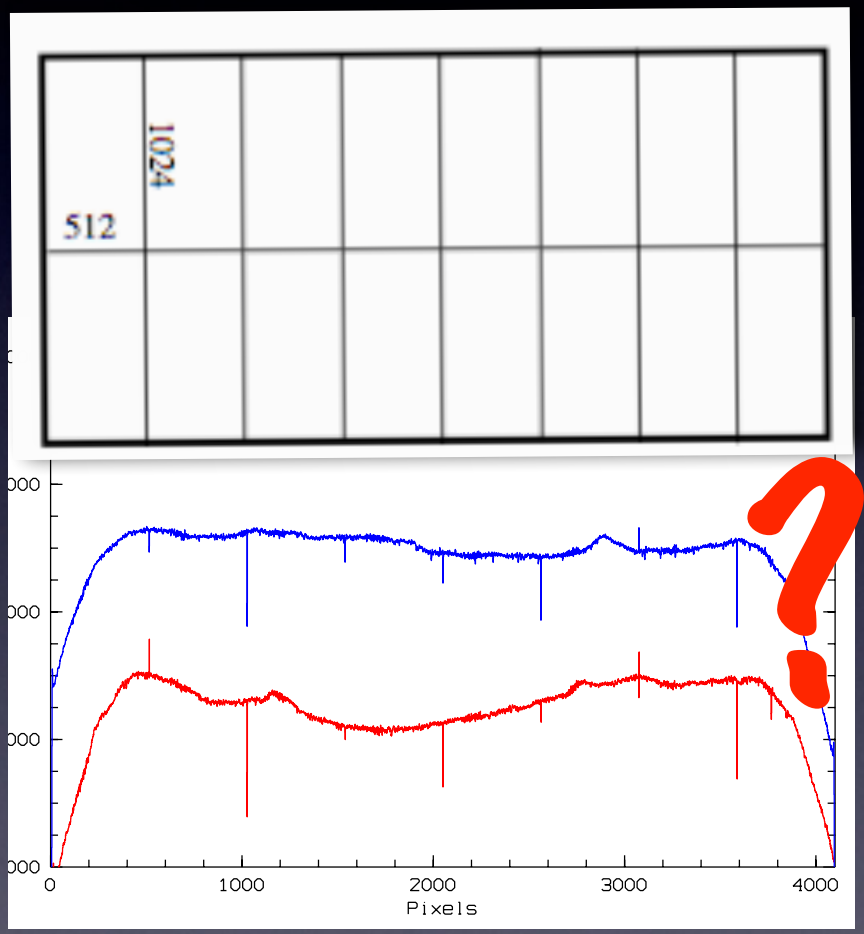
Grav Red: 636.5 m/s



Gonzalez-Hernandez et al 2014 in prep

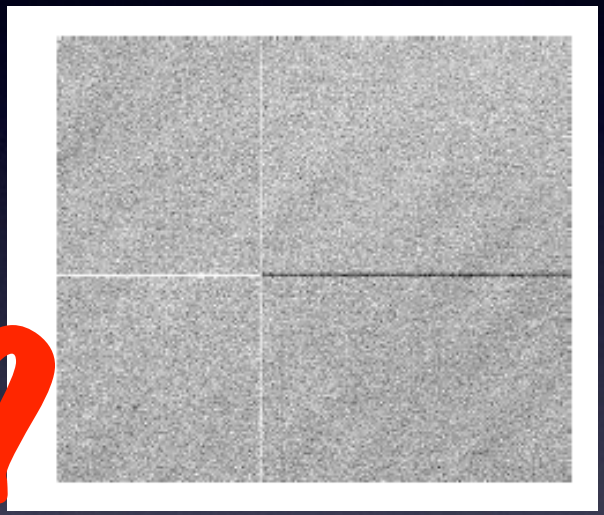
The Origin

CCD Stitching



???

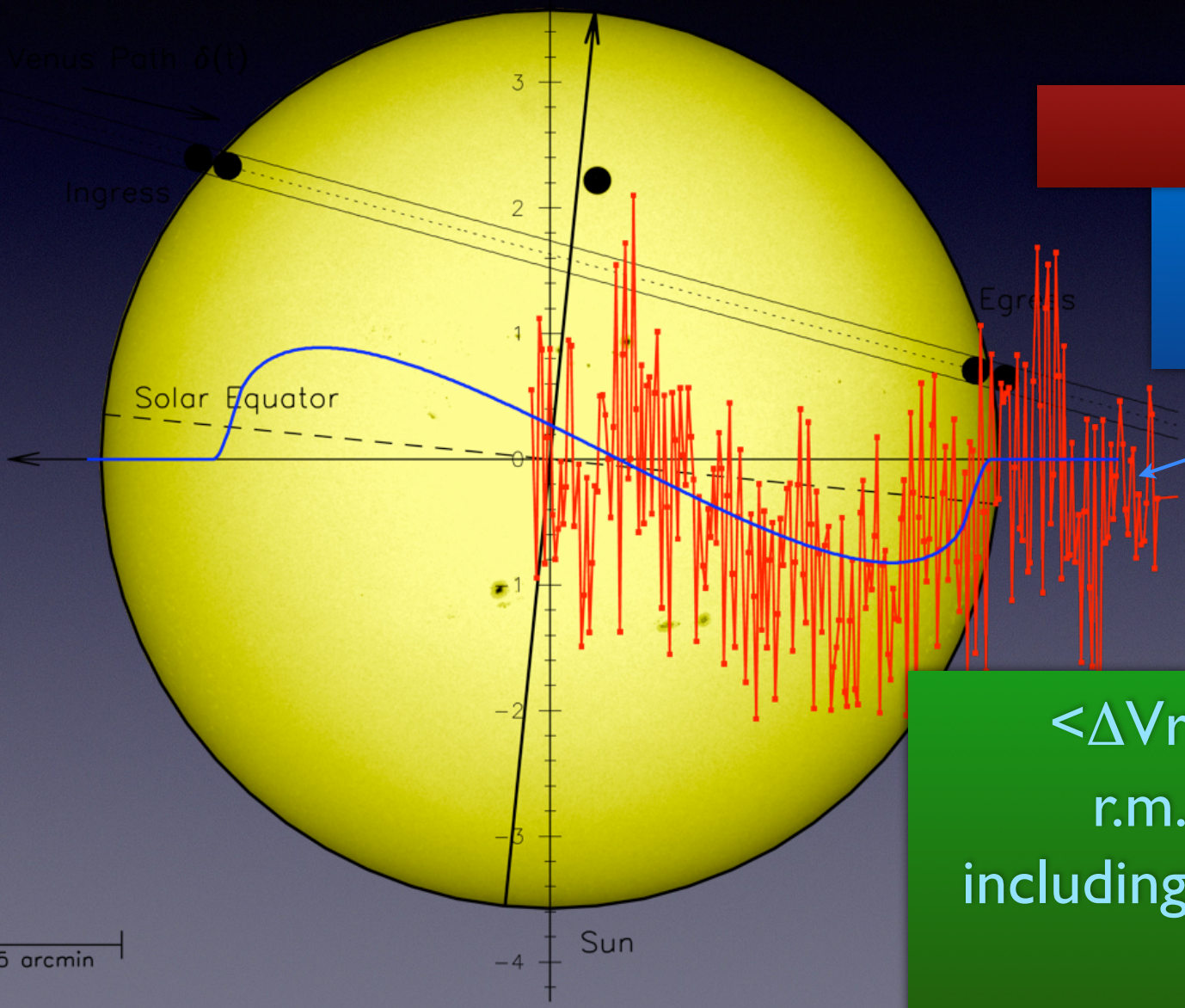
Flat



Pixels are not all of the same size

Are the distortions stable?

The 2012 Venus Transit



247 spectra of the Sun

Model NOT a Fit!

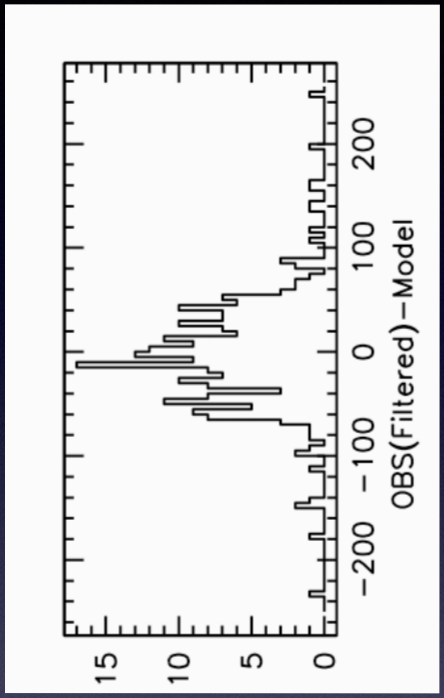
PM et al 2013

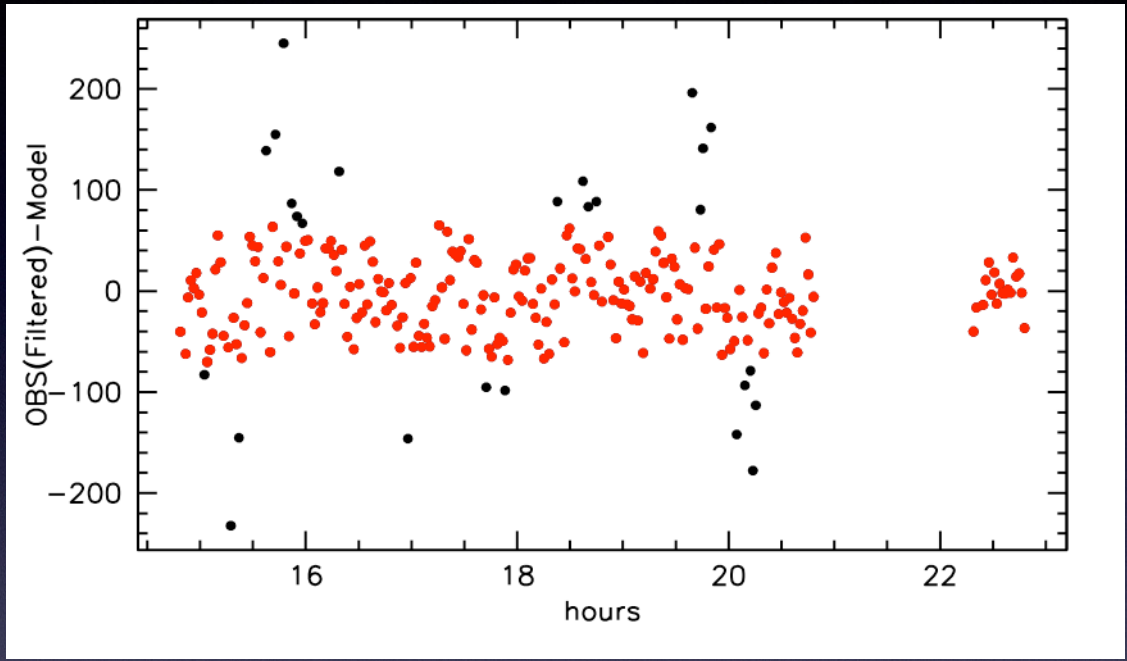
$\langle \Delta V_r \rangle$ = -1.7 cm s^{-1}

r.m.s =0.68 cm s^{-1},

including solar oscillation

Observations-Model





2 sigma clip: r.m.s = 35 cm s^{-1}

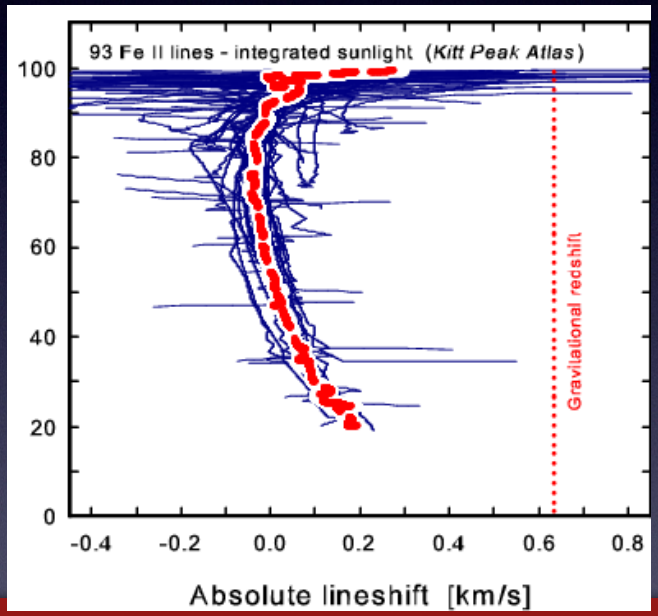
$<\Delta Vr(O-M)>$= -4 cm s^{-1}

Normalization error ± 5 cm s^{-1}

HARPS distortions need to be constant

Is the solar spectrum stable?

Dravins 2008

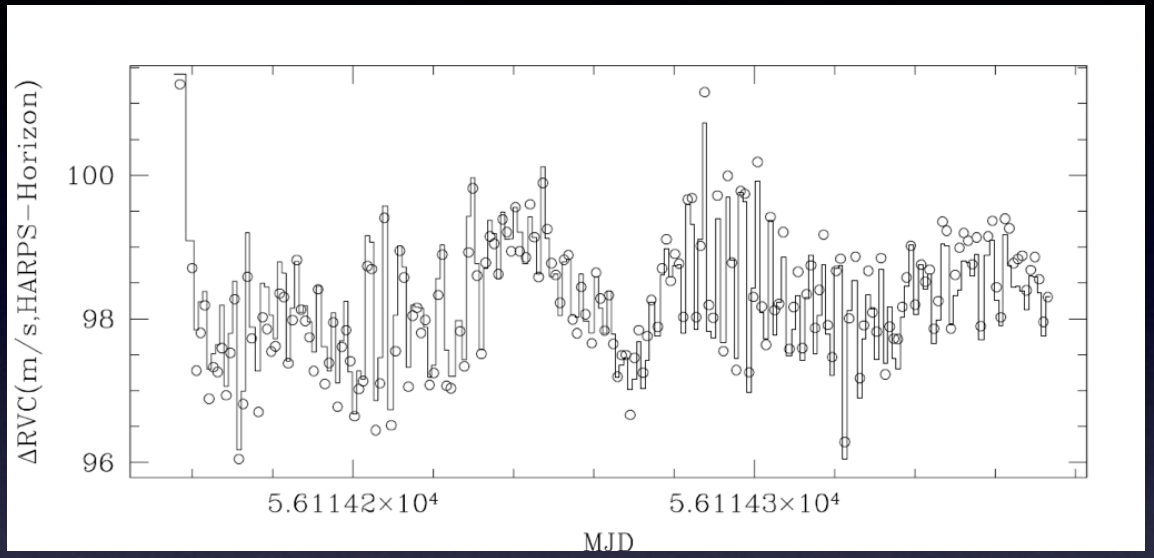


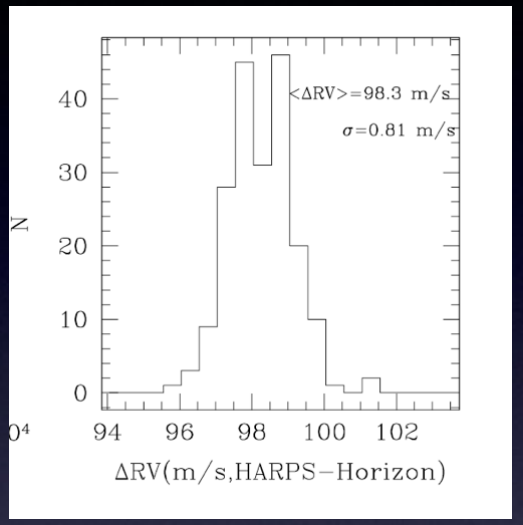
- Gravitational Redshift: +636.5 m/s
- Convection, Granulation: up to ~ 1 km/s, differ for line (move?)
- Magnetic activity Spots, Plages ~ few m/s)
- 5m solar oscillation: RV ~ 1 m/s

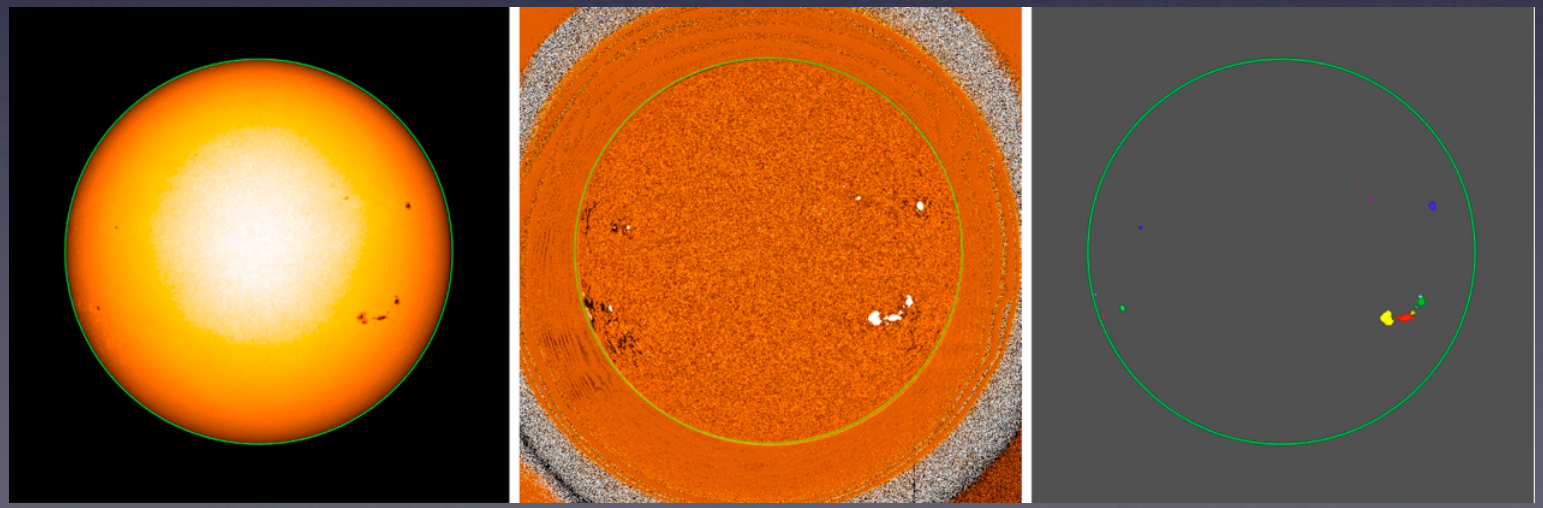
RV & solar spots

5 Luglio 2012

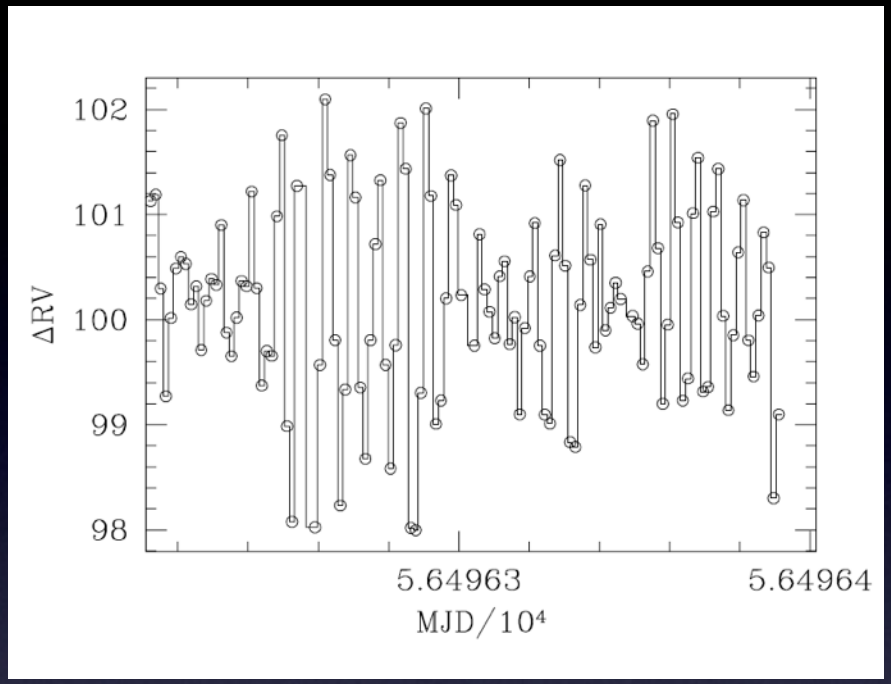
inclusive 5m solar oscillation

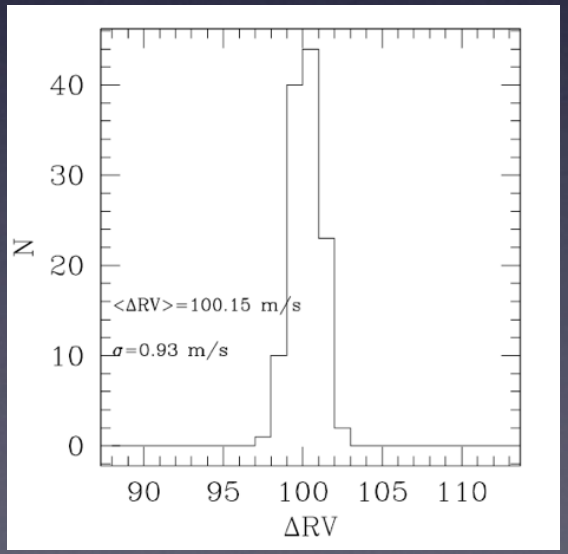




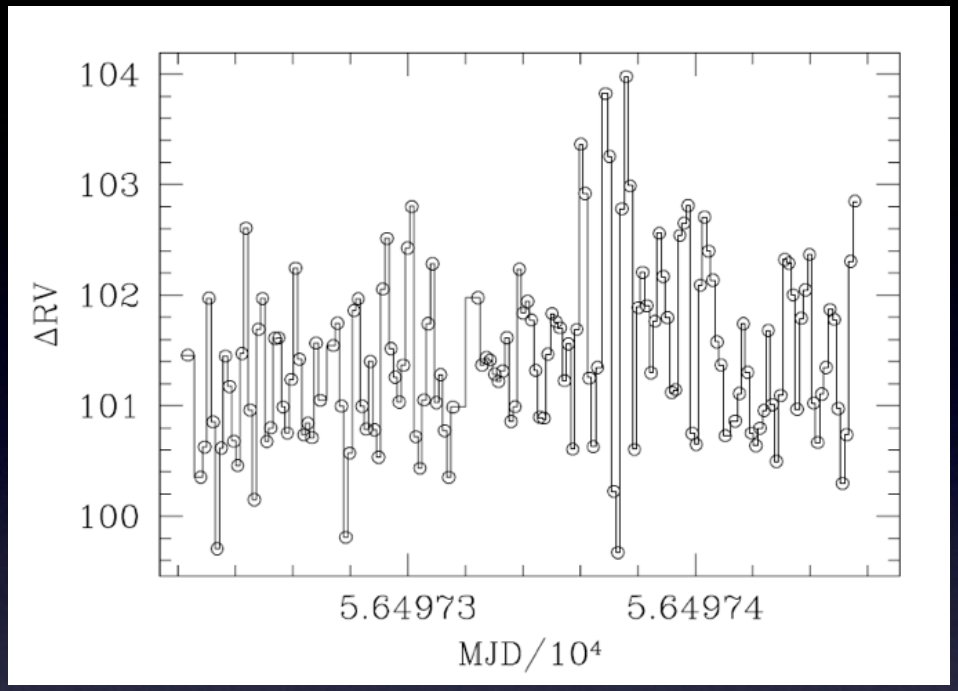


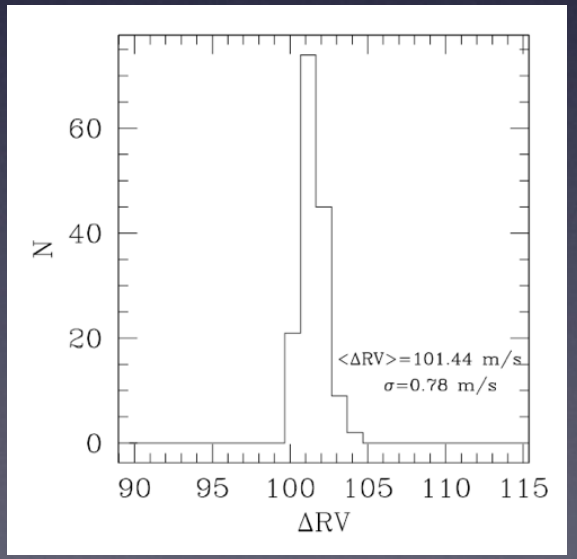
22 Luglio 2013

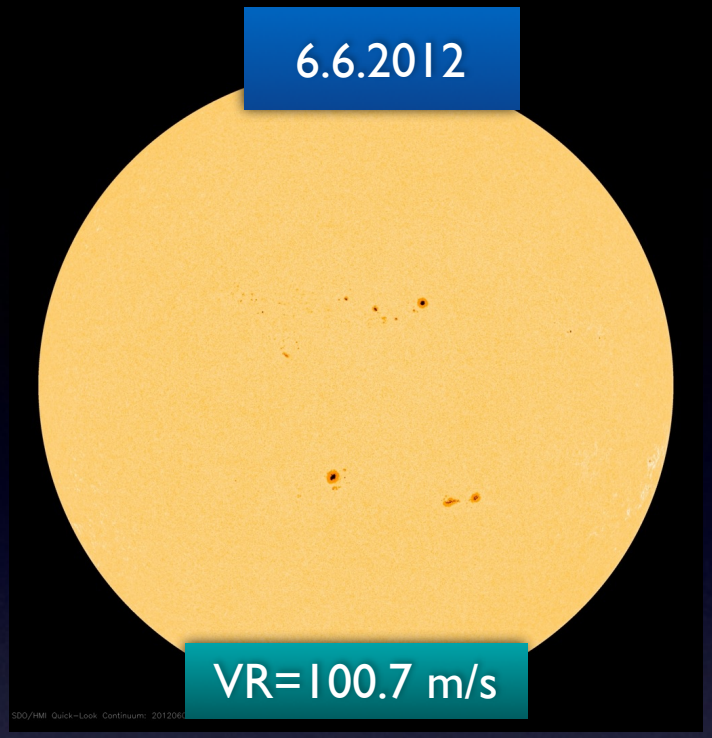


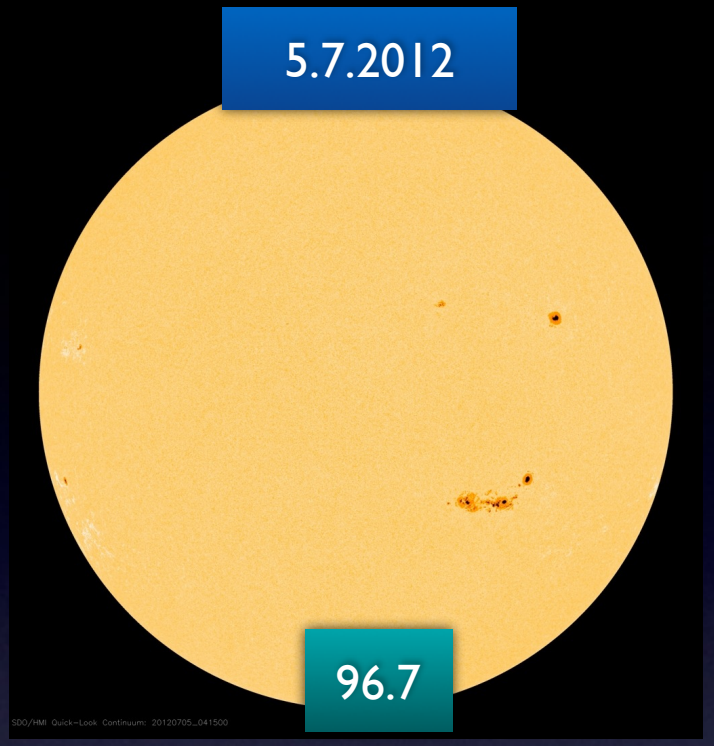


23 Luglio 2013



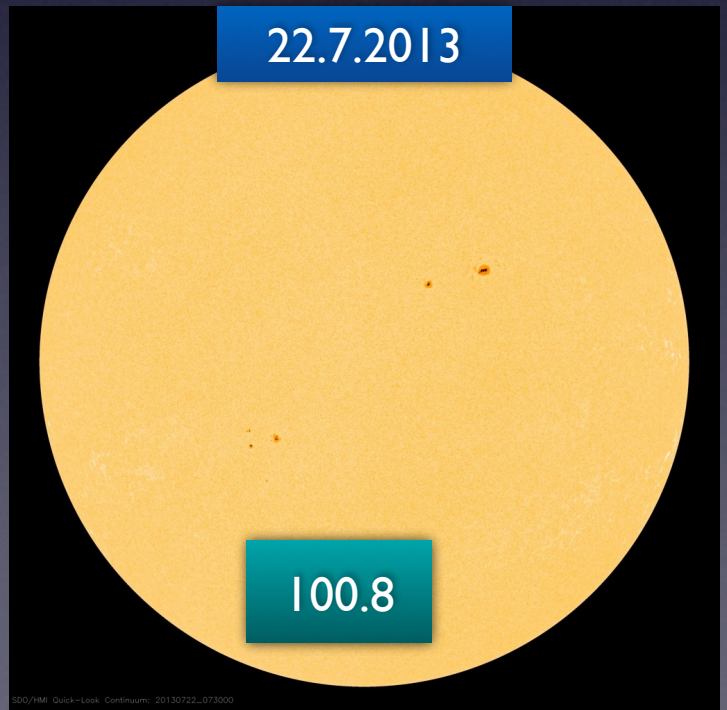


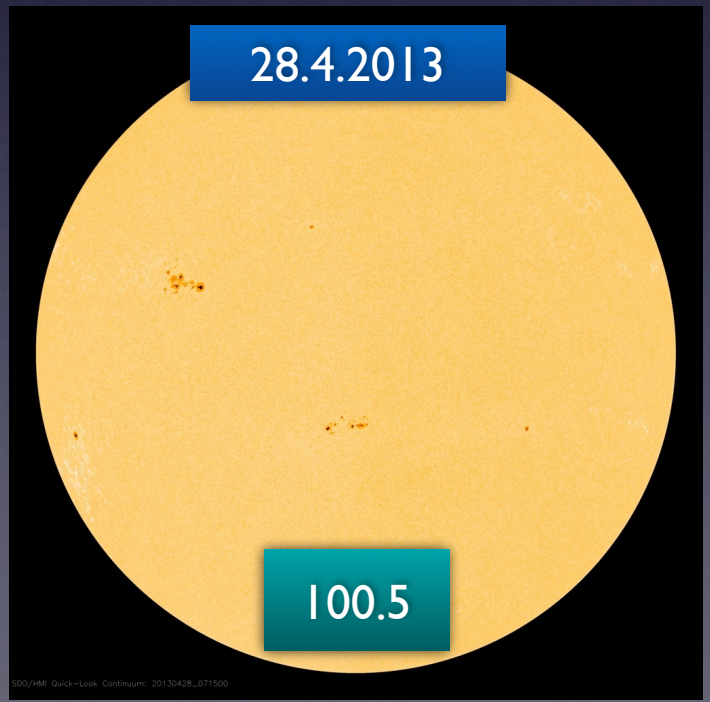




DVR < 0.3 m/s

DVR ~ 4 m/s



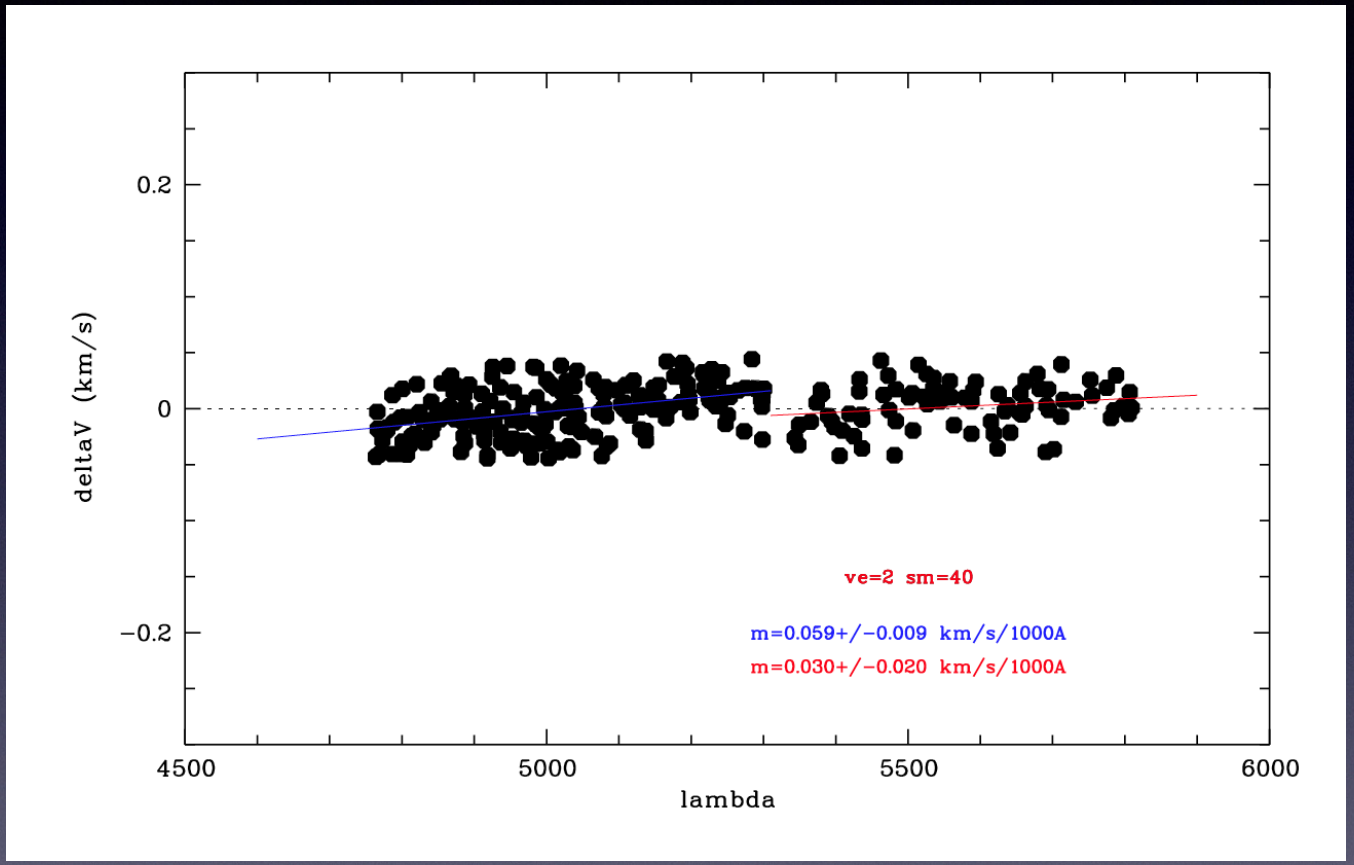


Lanza et al
in prep

Summary

- Precise and accurate RV important for cosmology and fundamental physics
- New tests reveal spectral (short and long) distortions with possible impact on the α- dipole
- Origin?
- Call for accurate calibration of spectrographs
- Need for an RV reference, Sun ok for ~ m/s. We need better
- … and, no distortions, please!

L. F. COMB versus FTS Solar spectrum



rms 40 m/s

they ~ agree

which is the right one?

Peter Paul Ruben's copy of the lost Battle of Anghiari made by Leonardo da Vinci for the stanza dei 500
in Palazzo Vecchio

Pisa - Florence battle Giorgio Vasari