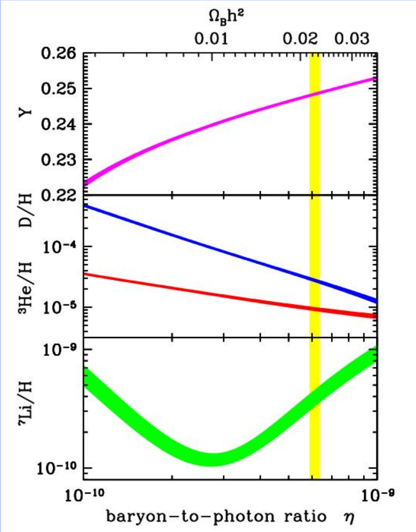
Cosmology with ESPRESSO & CODEX

Paolo Molaro
INAF-OAT

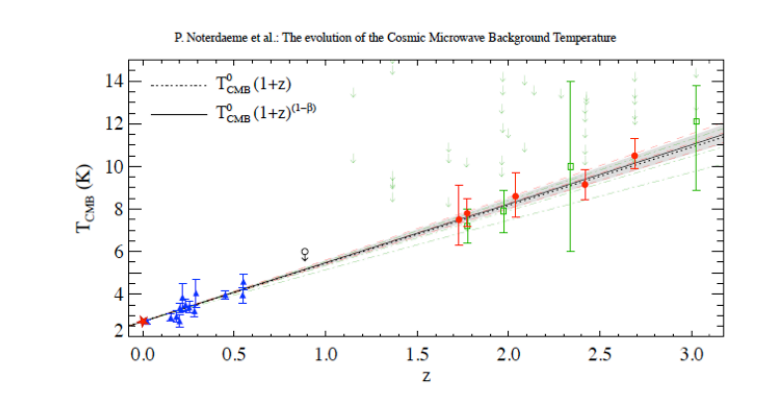
CONTRIBUTION OF H.R. SPECTROSCOPY TO COSMOLOGY

- Abundances of primordial elements He, D/H, Li/H

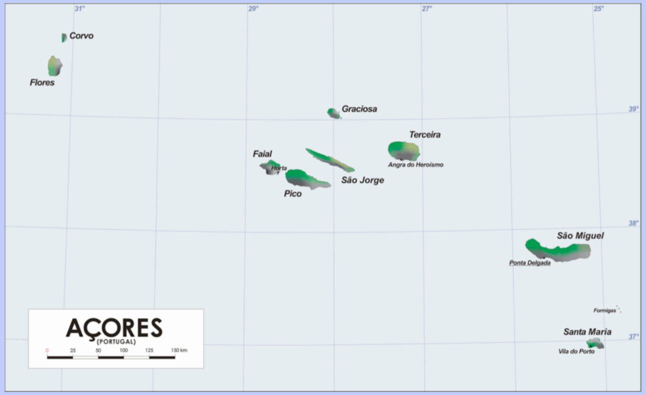


- Measure of the T of the CMB in the past

- Chemical characterization of sources throughout the universe (Universal chemical evolution)



OUTLINE



- The most metal poor star
- Fundamental constants (an observer's point of view)
- ESPRESSO @ VLT & CODEX @ E-ELT
- Measurement of the expansion drift

LETTER

An extremely primit

Elisabetta Caffau[1,2], Piercarlo Bonifacio[2], Patrick Fr… …çois Spite[2],
Hans-G. Ludwig[1,2], Roger Cayrel[2], Simone Zaggia[6]

nature10377

O GLOBO

ASTROFÍSICA

Estrela que não dever… conhecida

Plantão | Publicada em **31/08/2011** às 14h31m

Cesar Baima (cesar.baima@oglob…

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издание Rambler Media Group

пятница, 02.09.2011, 10:03:54

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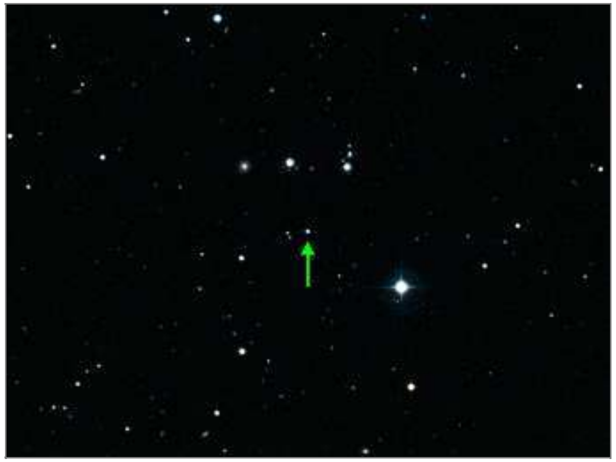
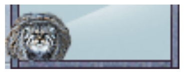


Стрелка указывает на звезду SDSS J102915+172927. Изображение ESO

В космосе нашли невозможную звезду

Астрономы описали "невозможную" звезду в созвездии Льва. Статья ученых появилась в журнале *Nature*, а ее краткое описание приведено в пресс-релизе Европейской южной обсерватории (ESO).

Исследователи наблюдали светило SDSS J102915+172927 при помощи массива телескопов



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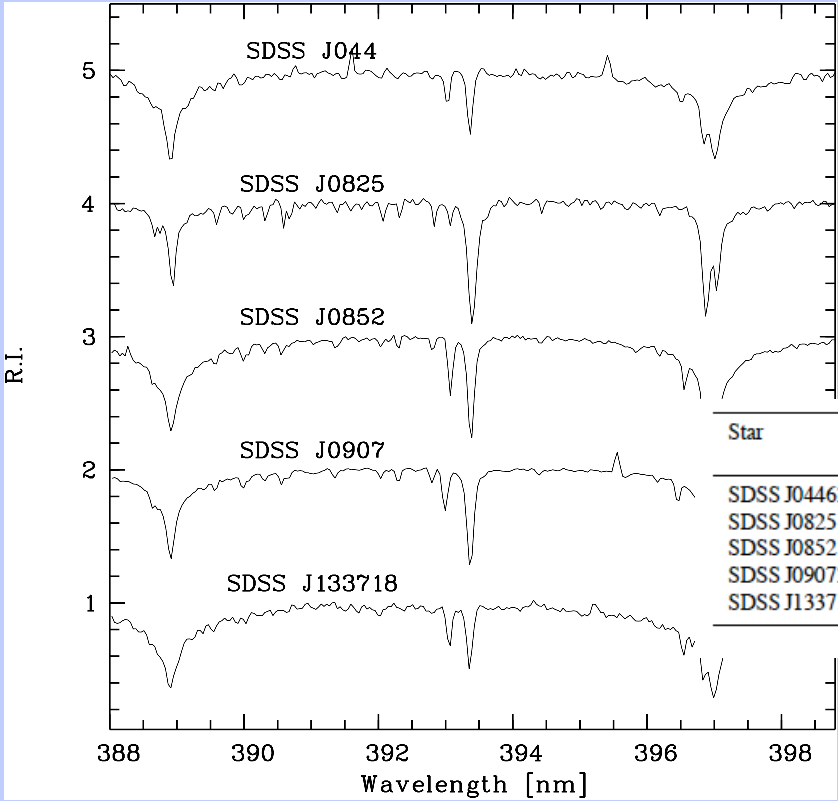
SDSS SURVEY

- From SDSS pre-selection. From (g-z) => 125000 stars. From spectra R~2000 => ~2899 candidates with [Fe/H]<-2.0; 750 with Fe/H<-3.5



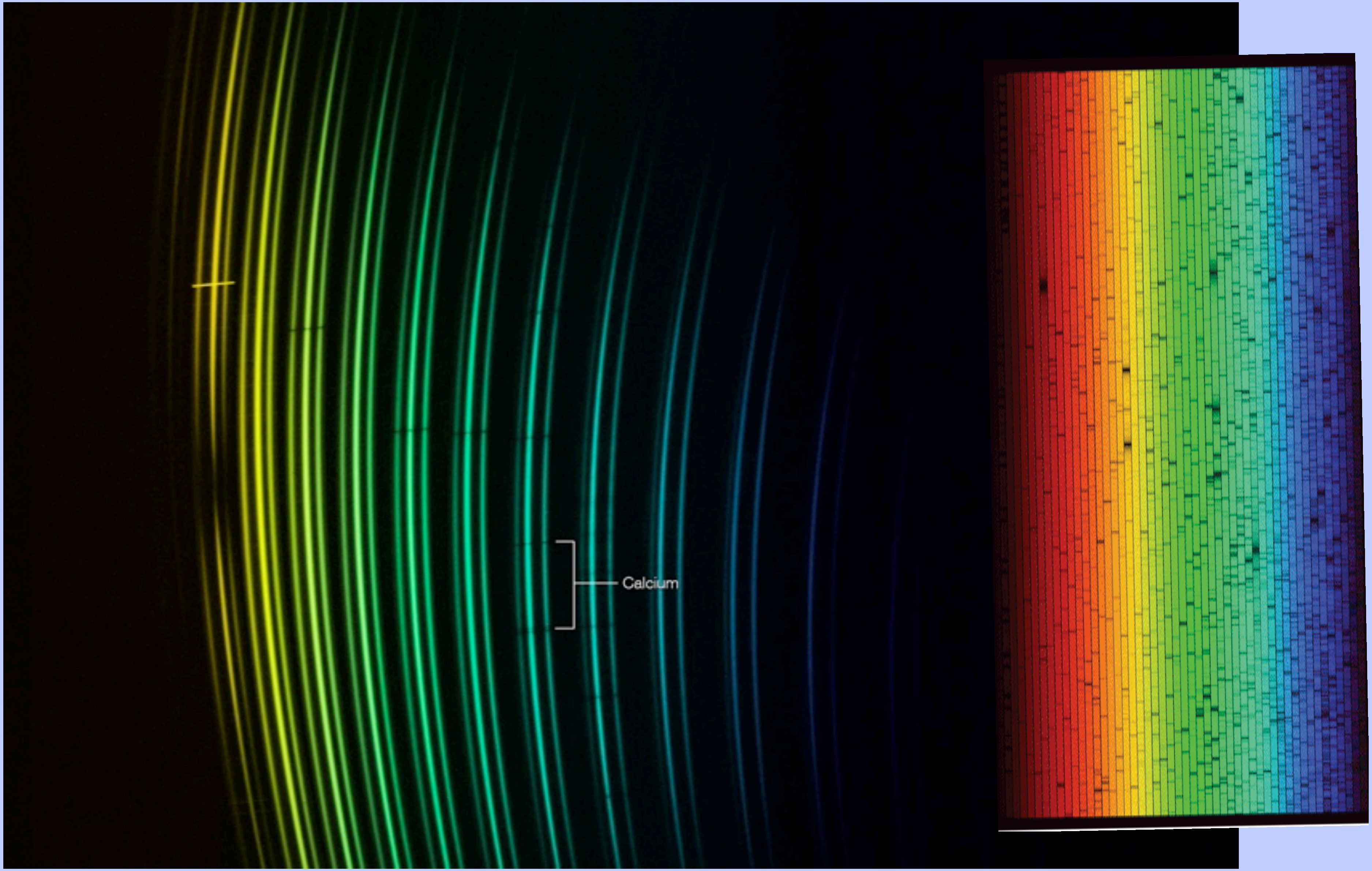
CaII H & K

- 30% SDSS area accessible to VLT

- XShooter @ VLT

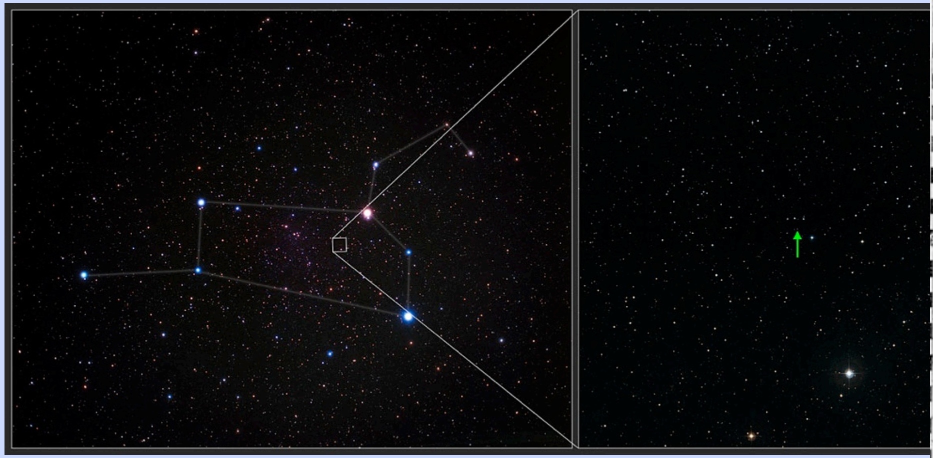
Star	V_{rad} km s^{-1}	T_{eff} km s^{-1}	log g K	ξ km s^{-1}	S/N @ 400 nm	$[Fe/H]_{SDSS}$	[Fe/H]	[α/H]
SDSS J044638-065528	242	6194	4.0	2.0	45	−3.38	-3.71 ± 0.27	-3.12 ± 0.11
SDSS J082511+163500	24	5463	4.0	1.5	90	−3.58	-3.22 ± 0.24	-3.18 ± 0.16
SDSS J085211+033945	228	6343	4.0	2.0	90	−3.15	-3.24 ± 0.24	-2.86 ± 0.22
SDSS J090733+024608	304	5934	4.0	1.8	100	−3.37	-3.52 ± 0.14	-3.11 ± 0.13
SDSS J133718+074536	212	6377	4.0	2.0	40	−4.40	-3.49 ± 0.32	-3.27 ± 0.14

X-shooter IFU spectrum of SDSS J102915+172927

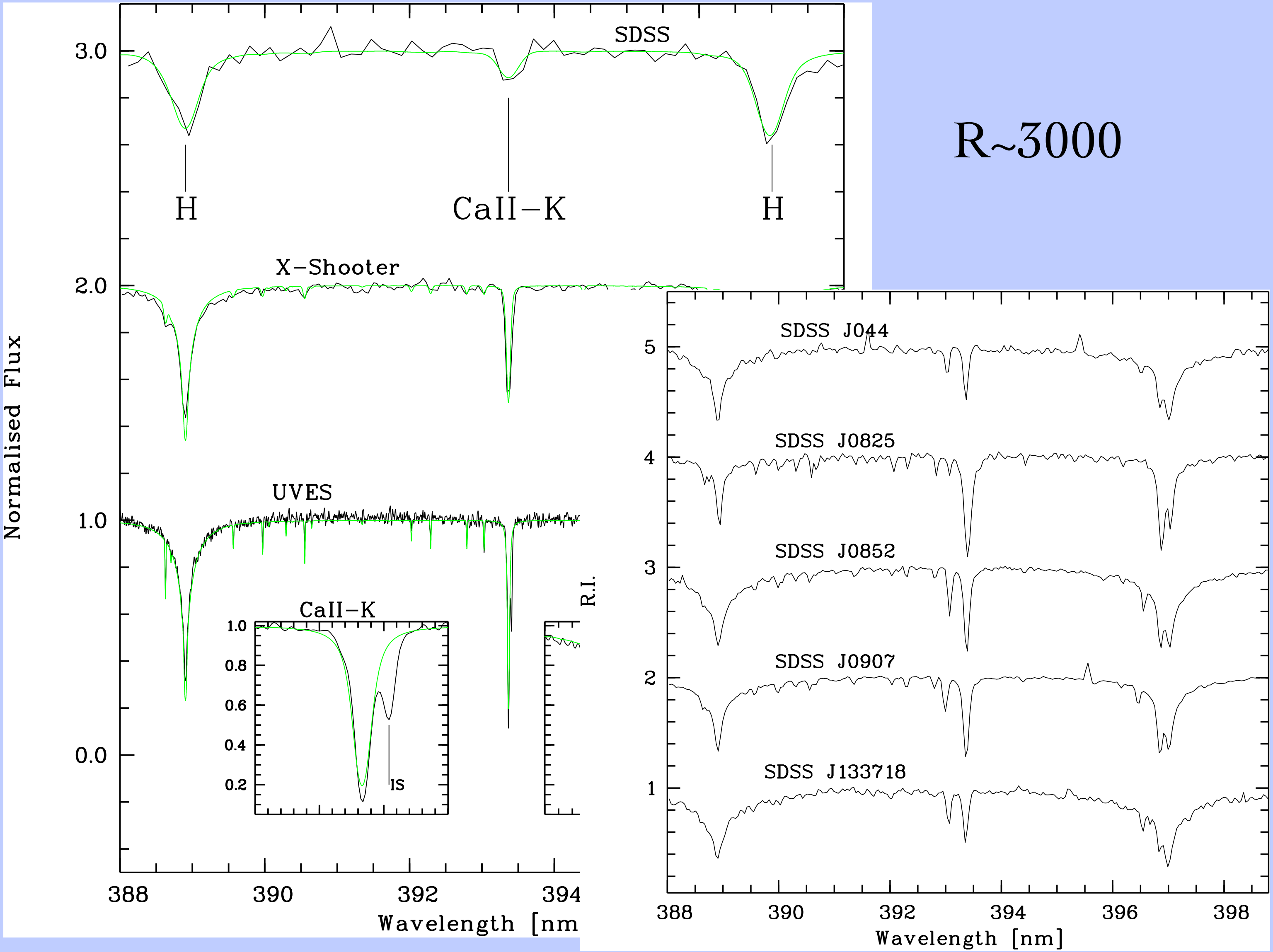


SDSS J102915+172927

- T_{eff}=5811 K From (g-z)=0.53 mag, & fitting of Hα
- log g = 4.0± 0.2 (from Balmer Jump (u-g), CaII-CaI
- d= 1.27 ± 0.15 Kpc from photometry



CaII region



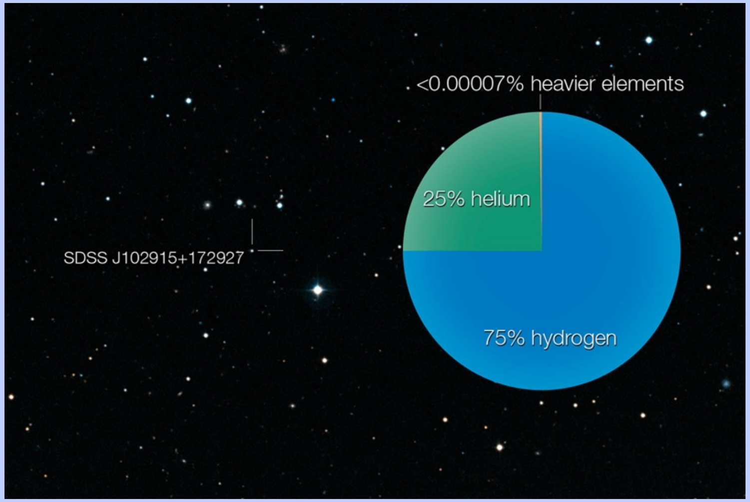
R~3000

Abundances

Element	A(X), 3D	[X/H], 3D	[X/Fe], 3D	[X/H], 1D	Number of lines
C	≤4.2	≤−4.3	≤+0.7	≤−3.8	G band
N	≤3.1	≤−4.8	≤+0.2	≤−4.1	NH band
Mg I	2.95	−4.59 ± 0.10	+0.40	−4.68 ± 0.08	4
Si I	3.25	−4.27 ± 0.10	+0.72	−4.27 ± 0.10	1
Ca I	1.53	−4.80 ± 0.10	+0.19	−4.72 ± 0.10	1
Ca II	1.48	−4.85 ± 0.11	+0.14	−4.71 ± 0.11	3
Ti II	0.14	−4.76 ± 0.11	+0.23	−4.75 ± 0.11	6
Fe I	2.53	−4.99 ± 0.12	+0.00	−4.73 ± 0.13	44
Ni I	1.35	−4.88 ± 0.11	+0.11	−4.55 ± 0.14	10
Sr II	≤−2.28	≤−5.2	≤−0.21	≤−5.1	1

[Fe/H]~ -5.0 !

[X/H]= log(X/H)-log(X/H)

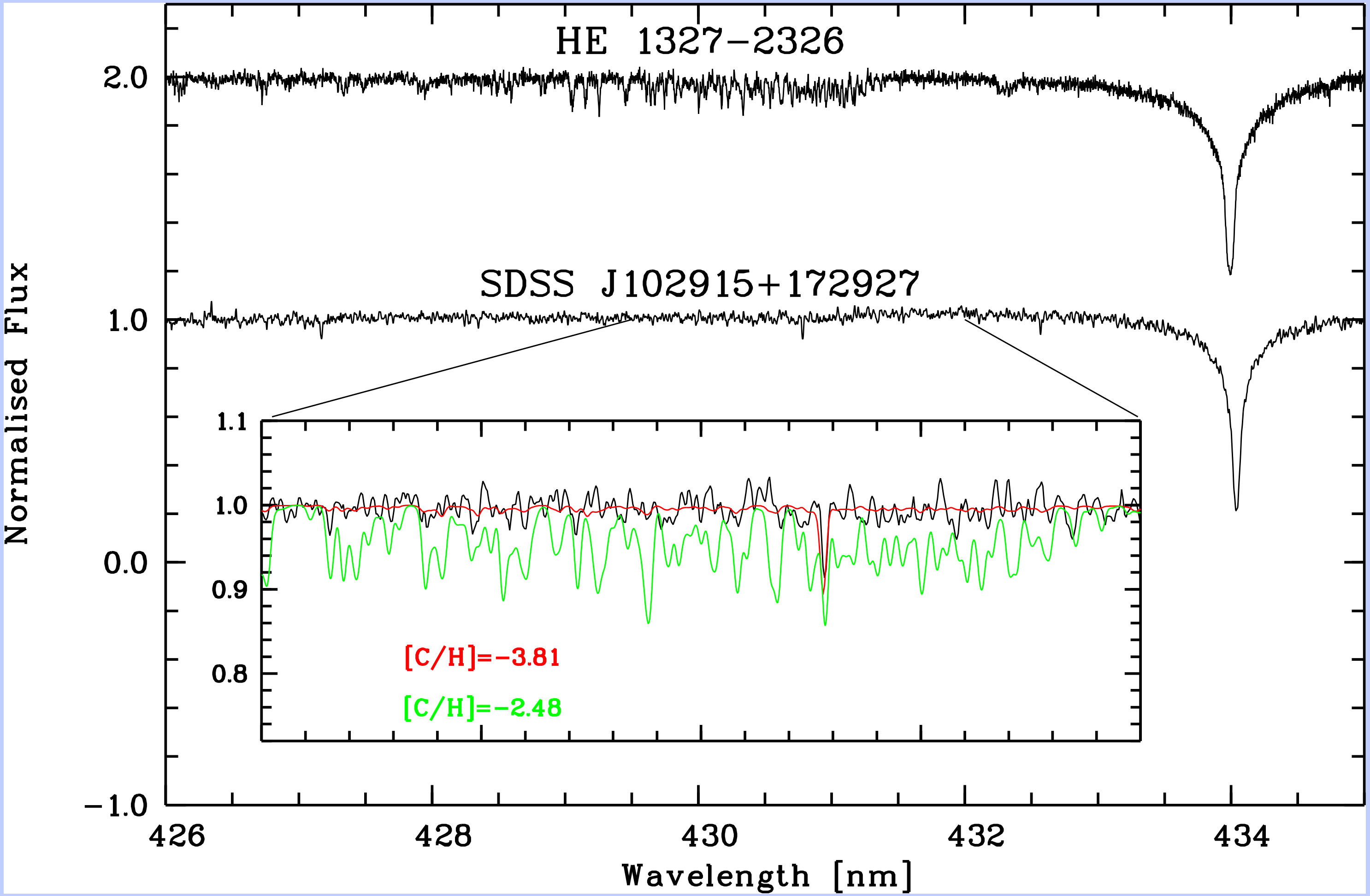


The most metal poor object

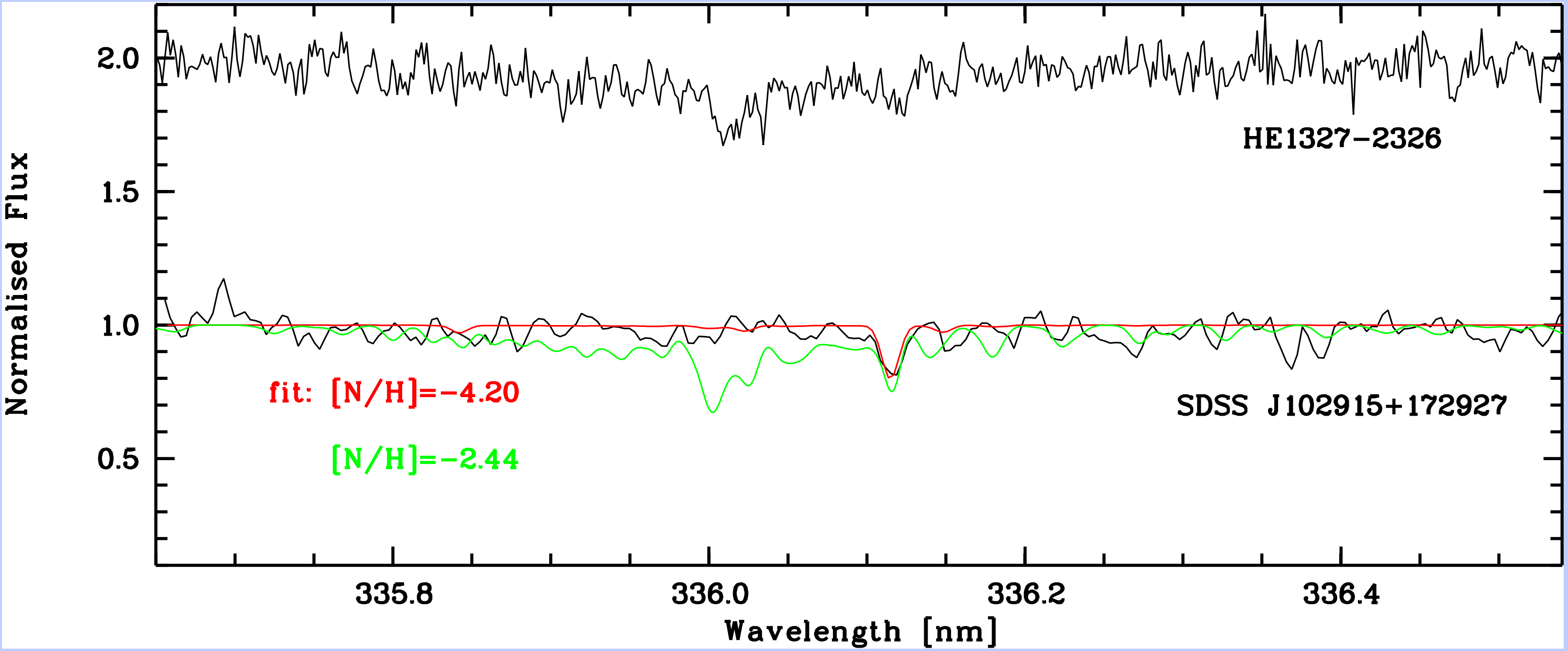
C, N ~ Fe

CARBON

CH: G-band at 430 nm



NITROGEN



- NH band at 336 nm, [N/H]<-4.8 (3D)
- Oxygen??

“THE STAR THAT SHOULD NOT EXIST”

- PopIII formed in DM minihalos of mass ~ 10^6 Msun at z~20-30. Primordial gas cooling is from H2.

- Transition to small masses: CII and OI are the most important coolants (Hollenbach & Mc Kee 1989).

  - IP CI is 11.26 eV ionized before HI by UV photons of SN

- Radiative Cooling rate > free-fall compressional heating

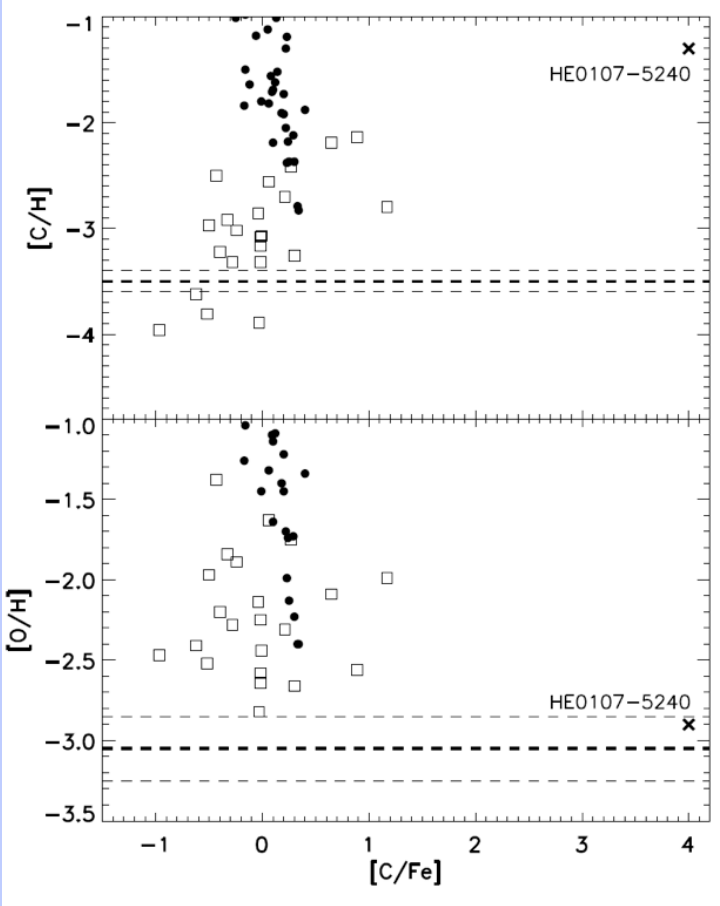
  ➡ [C/H]c ~ -3.5 ± 0.1

  ➡ [O/H]c ~ -3.05 ± 0.2

- Observations:

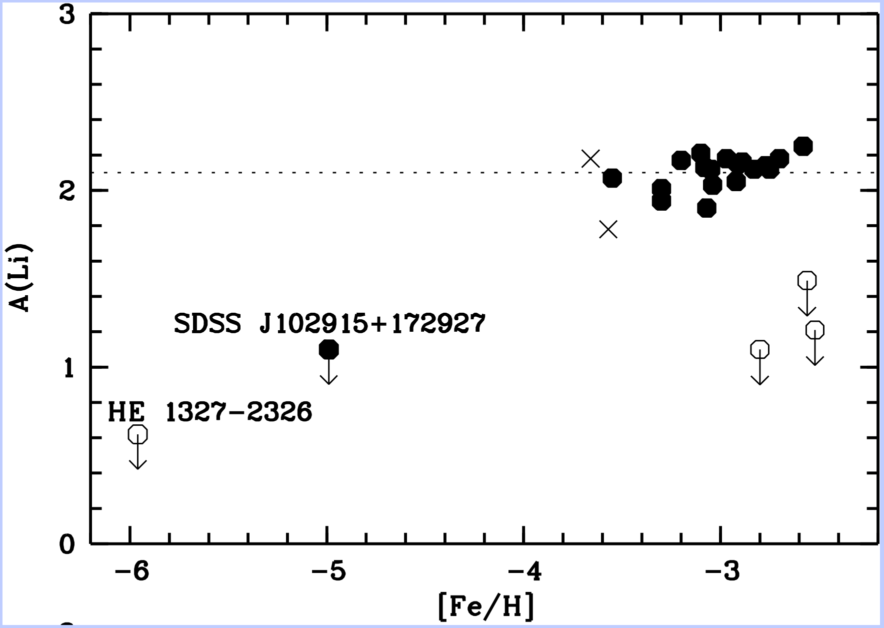
  - HE 0107-5240 [Fe/H]-5.3 but [C/H]=-1

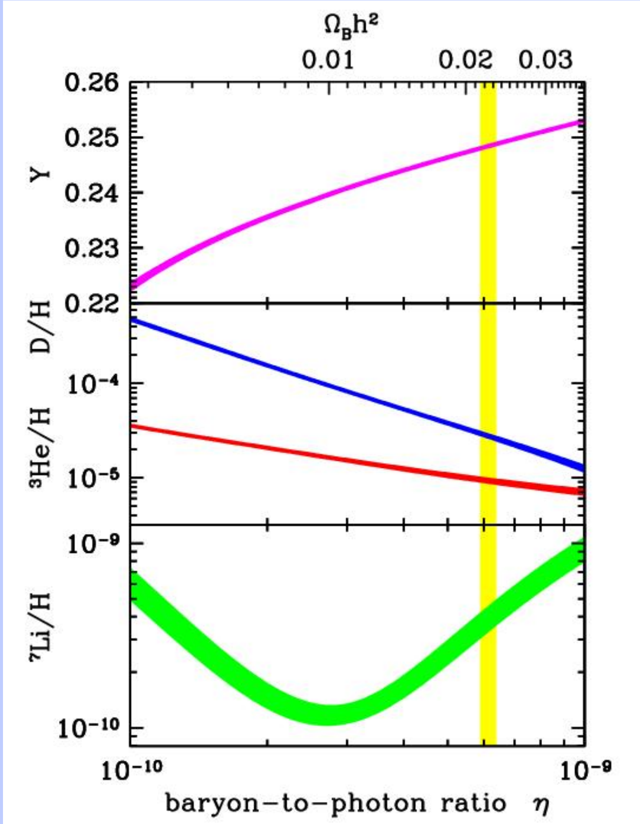
  - HE 1327-2326 [Fe/H]=-6, [C/H]=-2.2



Where is lithium?

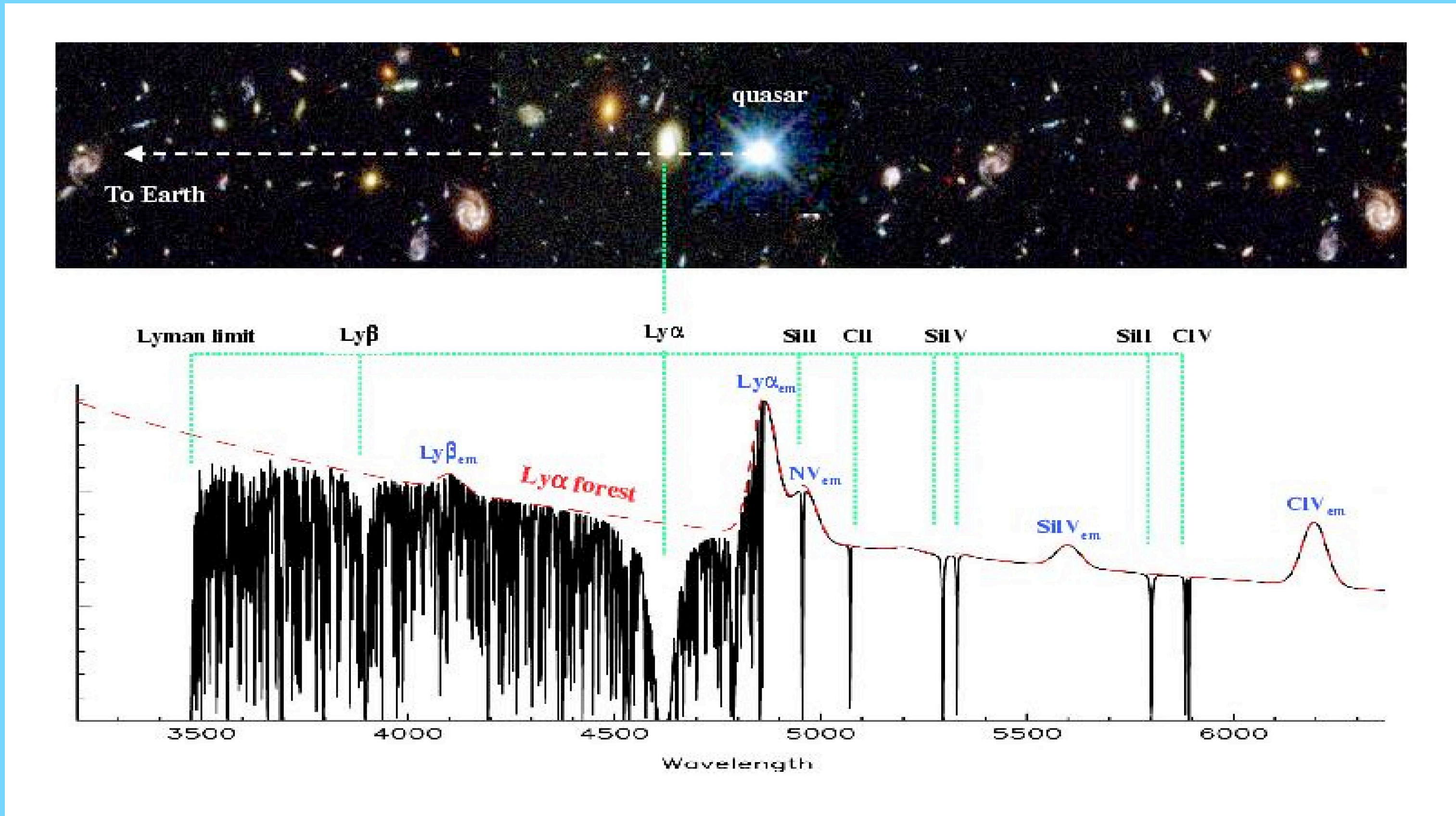
The star should be on the Spite and Spite plateau





- A(Li)<1.1
- must" be destroyed in the stellar formation (??)

Fundamental Constants & QSOs absorption lines



POWERED BY DAMAGE INC.

BARCODE with atomic structure
at time t(z)

What is a FC?

Fundamental constant = any parameter that cannot be calculated(free parameter)

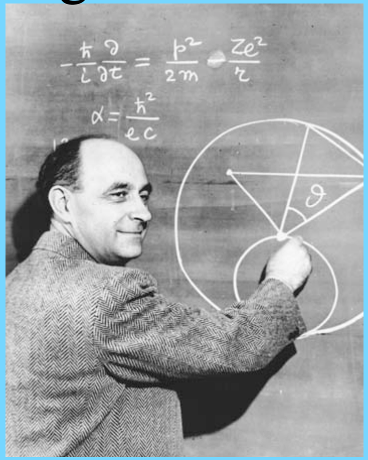
In the Standard Model the interactions depend on 28 fundamental constants.
These are:
the constant of gravitiy G,
the finestructure constant α,
the coupling constant g_w of the weak interactions,
the coupling constant g_s of the strong interactions,
the mass of the W-boson,
the mass of the "Higgs"–boson,
the masses of the three charged leptons, m_e, m_μ, m_τ,
the neutrino masses $m(\nu_1), m(\nu_2), m(\nu_3)$,
the masses of the six quarks $m_u, m_d, m_c, m_s, m_t, m_b$,
the four parameters, describing the flavor mixing of the quarks,
and the six parameters, describing the flavor mixing of the leptons, measured by the neutrino oscillations.

from H. Fritzsch 2009

Which can be measured?

1. The fine-structure constant ➡ Electromagnetic force

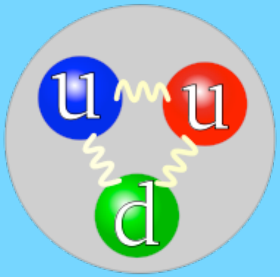
$$\alpha_{\rm EM} = \frac{e^2}{\hbar c} \approx \frac{1}{137.035999679}$$



2. The electron-to-proton mass ratio (μ)

- m_e= 0. 5 Mev ∝ the vacuum expectation value of the Higgs field ➡ The weak scale (223 Mev)

- m_p = 938 Mev = $(862_{QCD} + 74_q + 2_{QED})$ Mev ∝ Λ_{QCD} ➡ strong forces



➡ μ ratio of strong to weak forces.

➡In general a particle mass depends on all the coupling costants

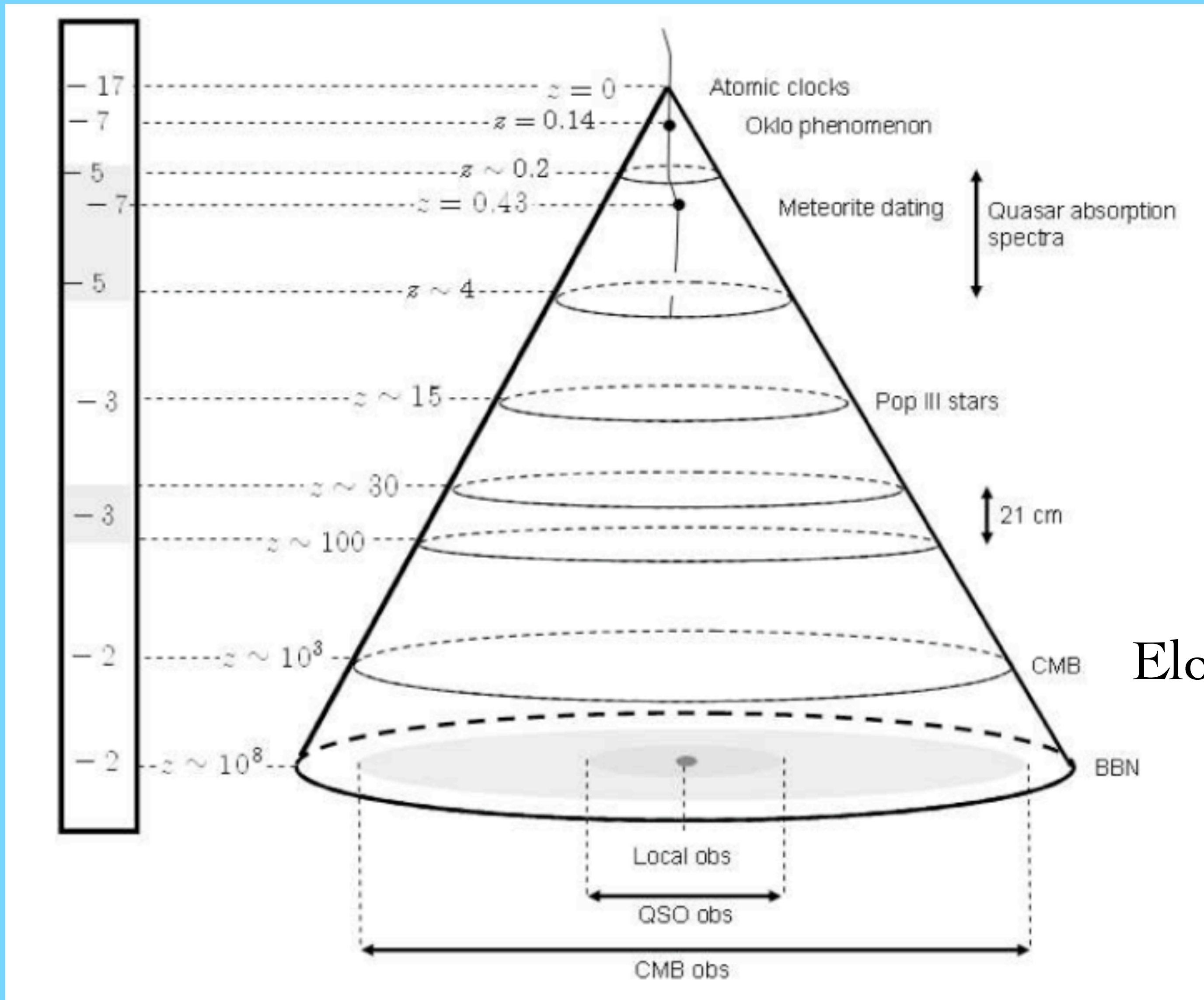
Why FC should vary?

- We do not have a theory of constant variation (cfr Carlos' lecture)
  - if there is a coupling of a scalar field with one or more terms of the Lagrangian matter-radiation then the physical constants may vary

- Scalar fields:
  - GUTs
  - Strings: moduli fields (extra-dimensions theories)
  - f(R) theories modifications of gravity
  - Quintessence as DE

➡ searching for variation of fundamental constants is a way to search for massless fields which couple with matter

Various methods



Eloisa's talk

Uzan 2010

A BIT OF HISTORY

α

- Savedoff (1956)
- Bahcall, Sargent, Schmidt (1967) in 3C191 < 5%

μ

- Thompson (1975) method :
  - H_2: electron-vibro-rotational transitions have different dependence from the reduced molecular mass
- Varshalovich Levshakov (1993)
  - first detection of extragalactic H_2
- New method based on Ammonia

(Flambaum Kozlov 2007

THE ASTROPHYSICAL JOURNAL, Vol. 149, July 1967

AN ANALYSIS OF THE ABSORPTION SPECTRUM OF 3C 191

JOHN N. BAHCALL, WALLACE L. W. SARGENT, AND MAARTEN SCHMIDT
California Institute of Technology and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, and California Institute of Technology
Received May 12, 1967

We report on an analysis of a 193 Å/mm spectrum of 3C 191, a quasi-stellar source whose rich absorption spectrum has been described by Burbidge, Lynds, and Burbidge (1966) and by Stockton and Lynds (1966) (hereinafter these papers will be referred to as "BLB" and "SL," respectively). This relatively high dispersion for such a faint object (m_v = 18.4) was sought in order to investigate the relative intensity of different fine-structure lines in absorption (Bahcall 1967). The principal results of our analysis are: (1) most of the absorption lines are resolved and have widths of the order of 3 Å in the rest frame of the source; (2) either the electron density is of the order of 10^3 cm^{-3} or the distance between the continuum source and the absorbing region is of the order of $10^{2\pm1}$ pc; (3) the value of the fine structure constant at $z = 2$ equals the laboratory value to within measuring errors (about 5 per cent); (4) the carbon-to-silicon abundance ratio by number is 2.5 to 1 with an uncertainty that is probably less than a factor of 3; (5) there is no evidence for a dependence of absorption redshift, z_{abs}, on ionization potential; and (6) there is no significant evidence for absorption lines from metastable states of C III and S II.

Astrophysical Letters 1975, Vol. 16, pp. 3–4
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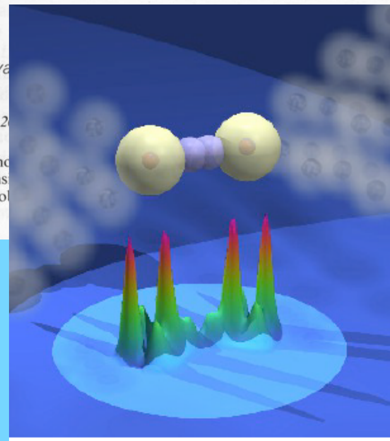
The Determination of the Electron to Proton Inertial Mass Ratio via Molecular Transitions

RODGER I. THOMPSON Steward Observa
University of Arizona

(Received August 2

It is demonstrated that the wavelengths of mo … to proton inertial mass. Observation of molecular trans … f this ratio in distant objects. If confirmed, the recent ol … ld allow a determination of m_e/m_p for these objects.



transitions depend on different combinations of dimensionless constants.

Rydberg constant $\mathrm{Ry} = \frac{\alpha^2 m_e c^2}{2}$

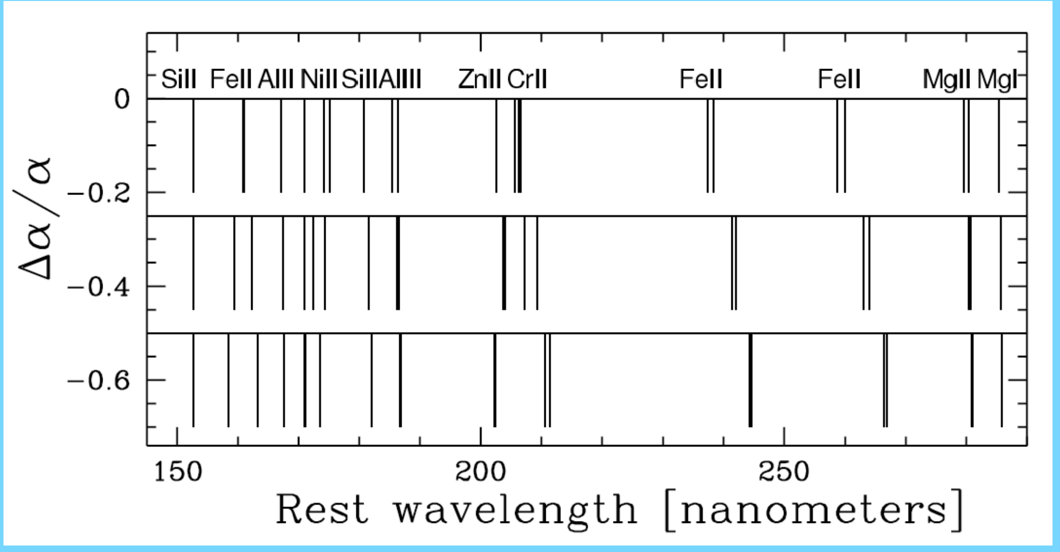
Transition		Scaling
Atomic	Gross Structure	Ry
	Fine Structure	$\alpha^2\ \mathrm{Ry}$
	Hyperfine Structure	$\alpha^2\ (g_p\mu)\ \mathrm{Ry}$
Molecular	Electronic Structure	Ry
	Vibrational Structure	$\mu^{1/2}\ \mathrm{Ry}$
	Rotational Structure	$\mu\ \mathrm{Ry}$
Relativistic Corrections		α^2

Atomic calculations are required to compute ω (α)

$$\omega = \omega_0 + q_1 Z^2 \left[\left(\frac{\alpha}{\alpha_0} \right)^2 - 1 \right] + q_2 Z^4 \left[\left(\frac{\alpha}{\alpha_0} \right)^4 - 1 \right]$$

Sensitivity coefficients q are found by varying α in computer codes (Dzuba et al 1999)

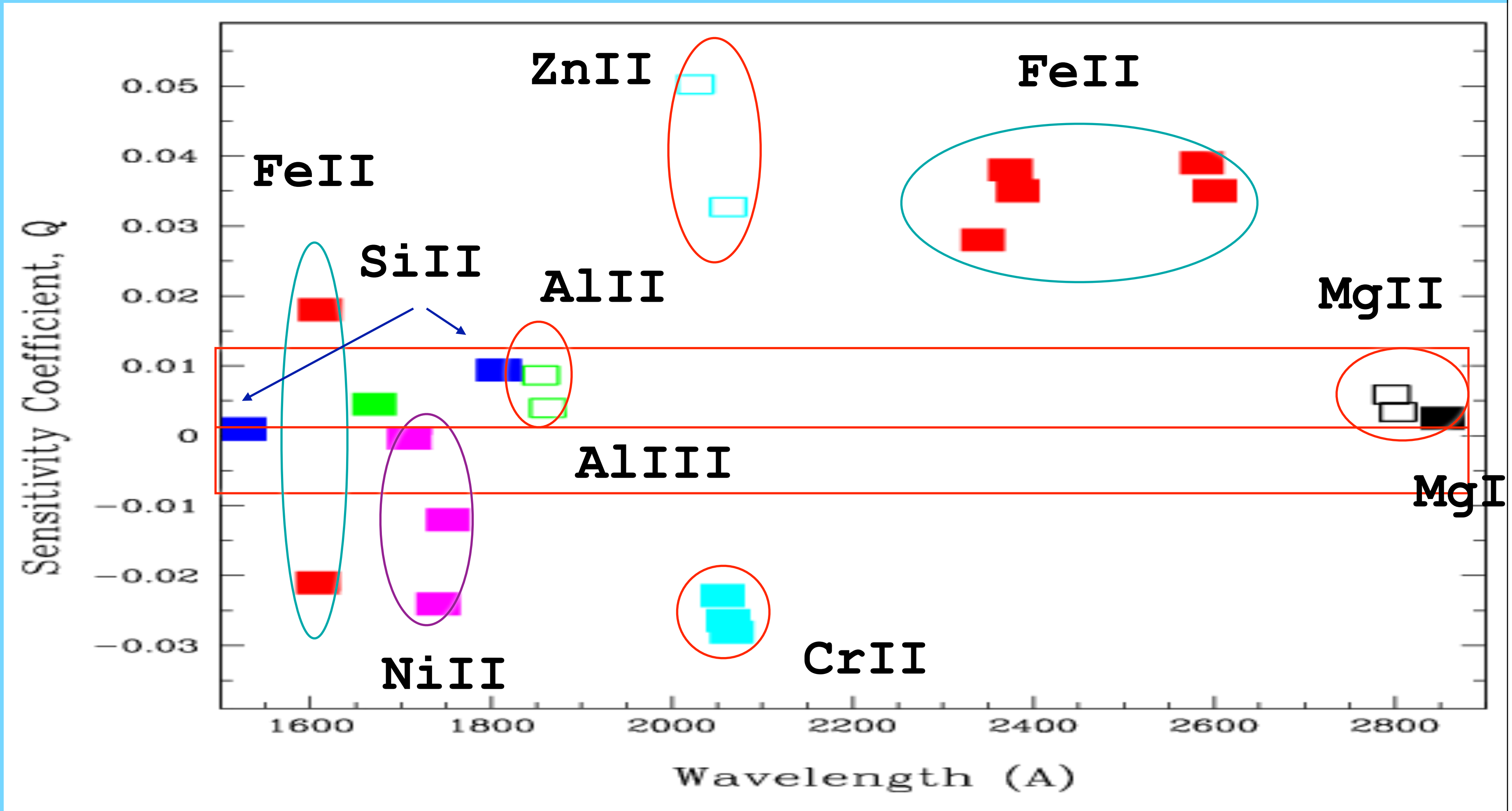
N_{ve}	Relativistic Hartree-Fock +	Accuracy
1	All-orders sum of dominating diagrams	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%



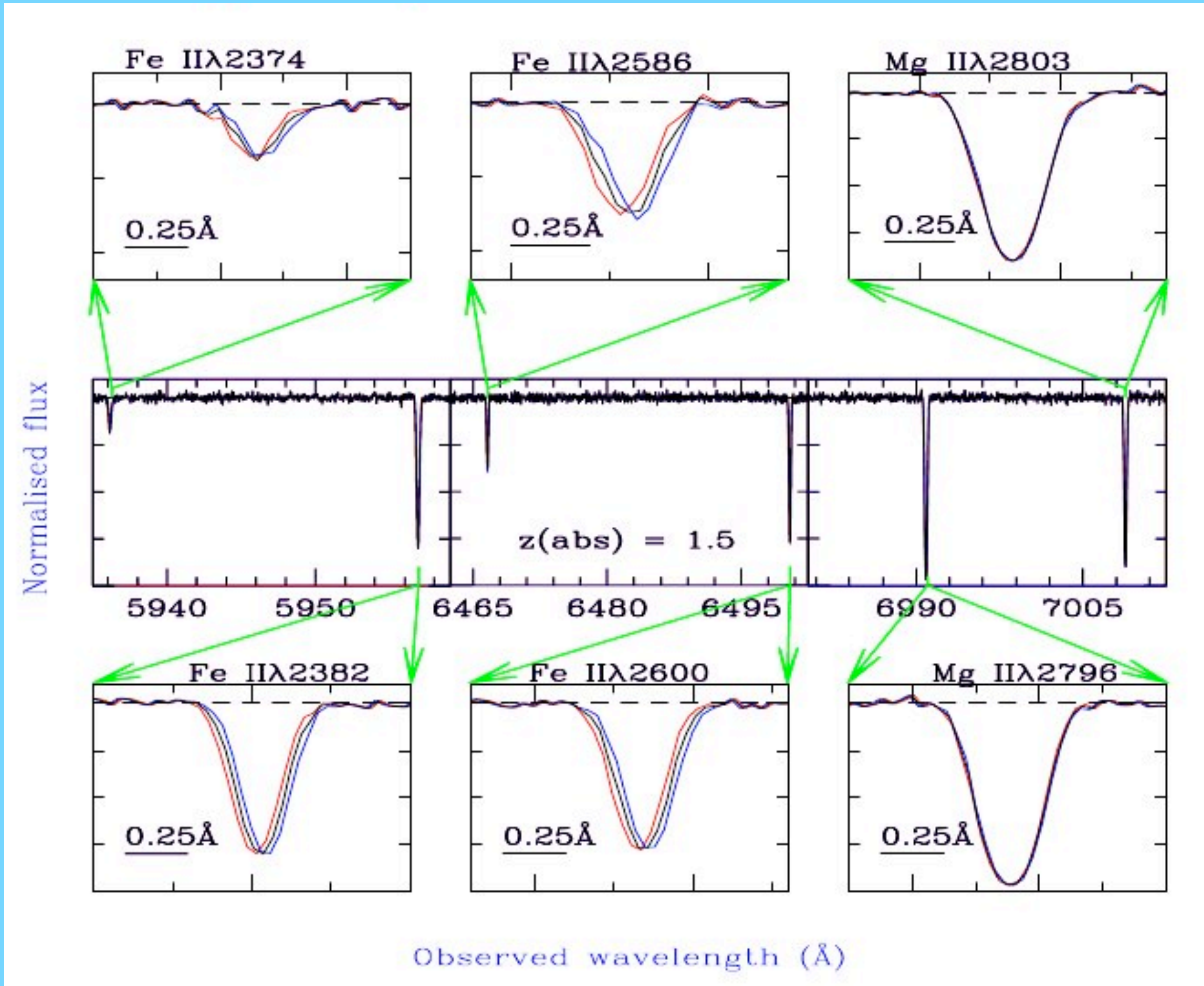
The Many-Multiplet method

High-z (>1.8)

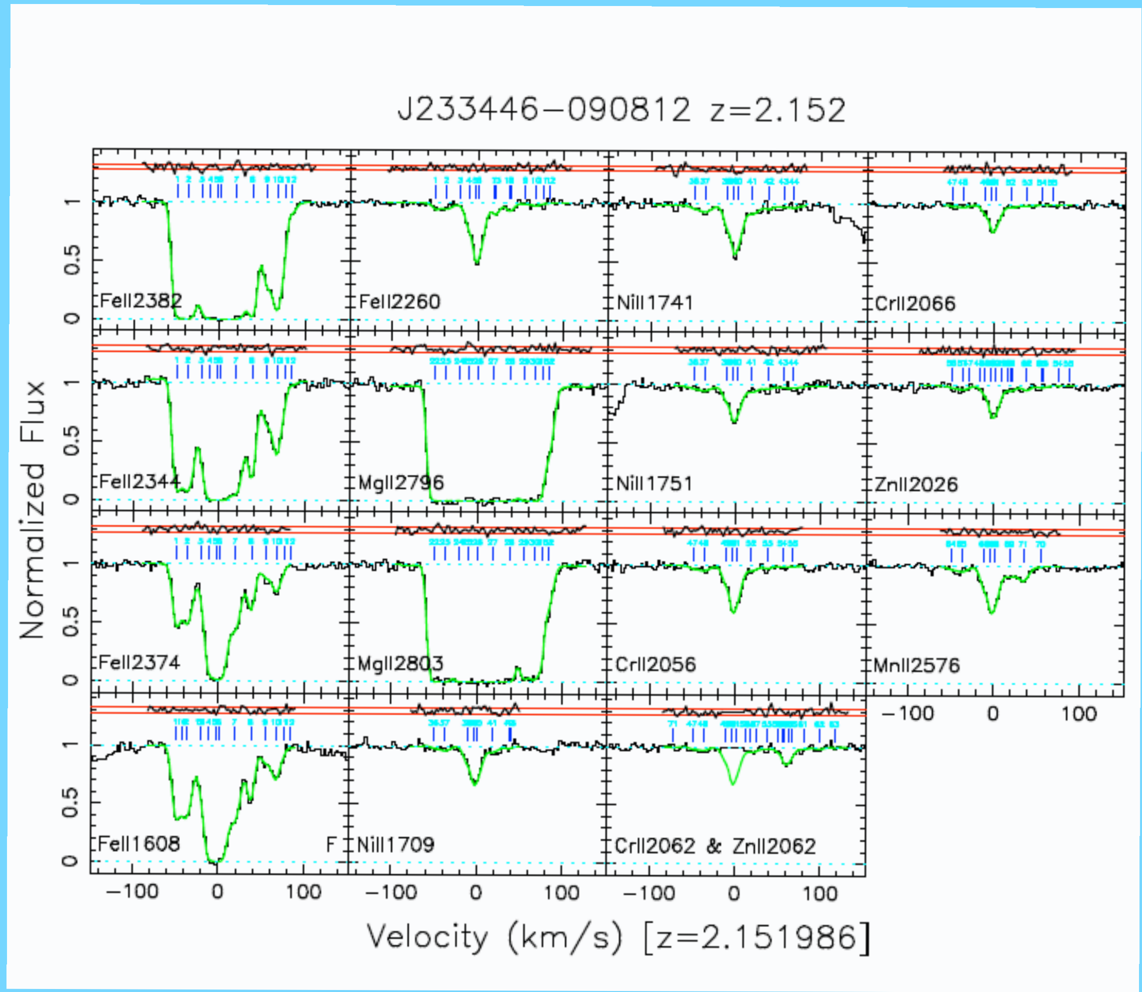
Low-z (0.5 – 1.8)



$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(\mathcal{Q}_1 - \mathcal{Q}_2)} = \frac{\Delta v}{2\,c\,\Delta\mathcal{Q}}$$

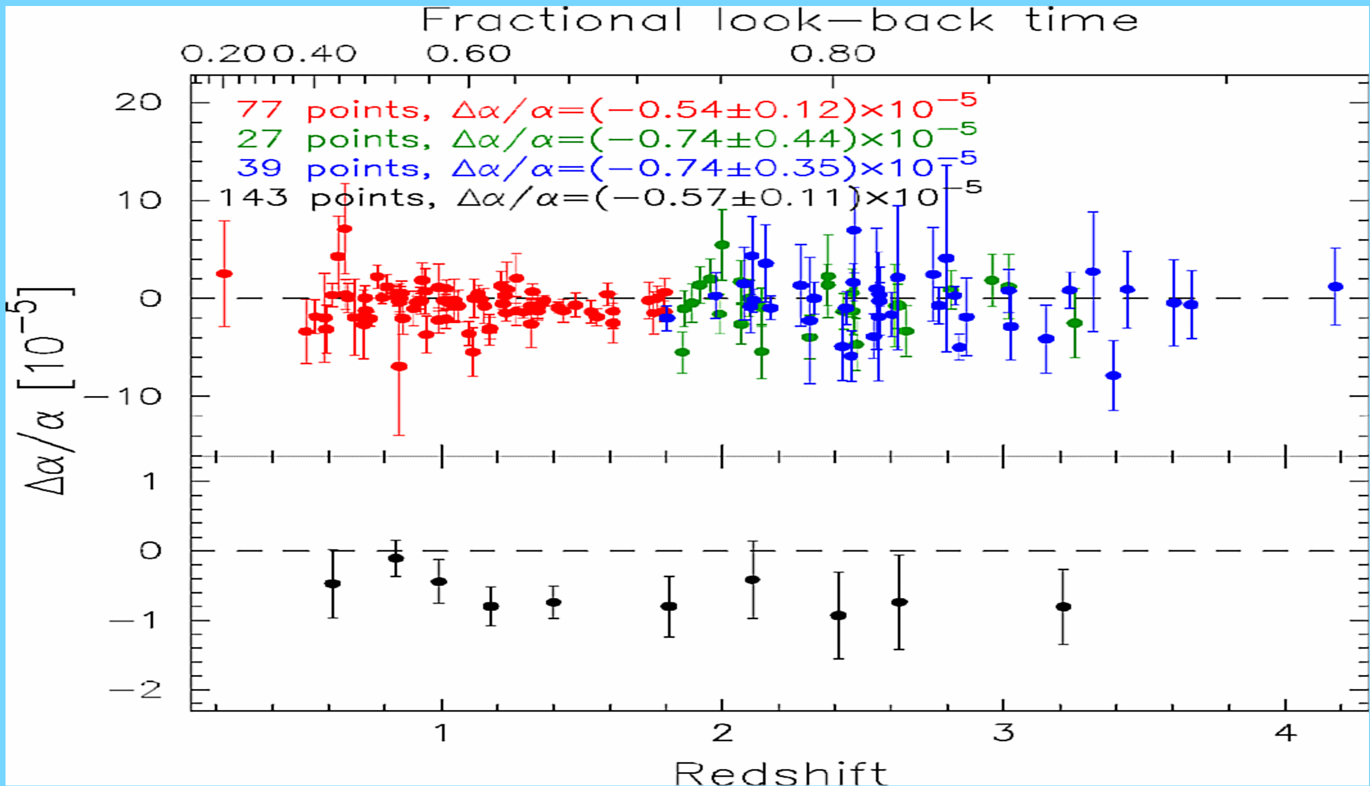


Simulation with $\Delta\alpha/\alpha = 10^{-4}$; or 1.8 km/s



VPFIT alpha as an additional variable

Murphy Webb Flambaum (2004)



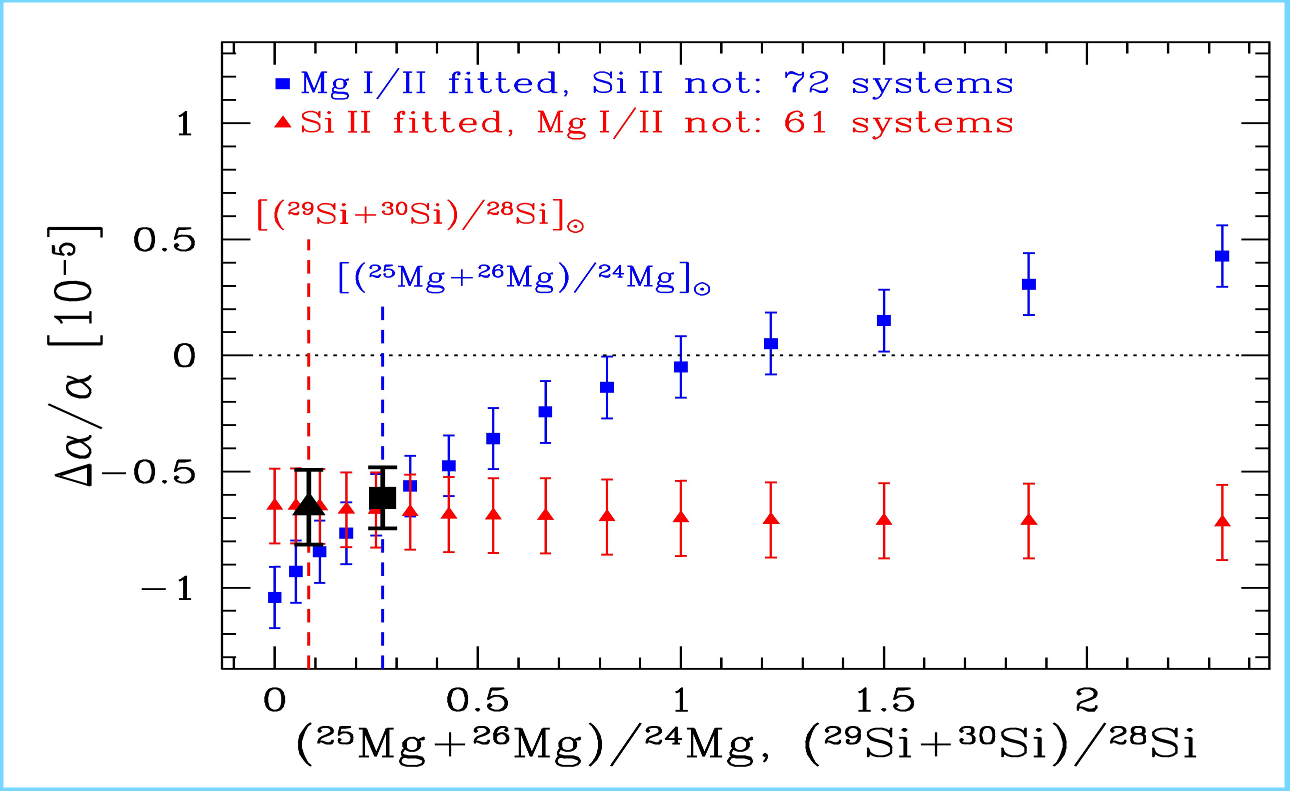
MgII

SiII

$\Delta\alpha/\alpha$ = (-5.7 ± 1.1) ppm (parts per million)

ISOTOPES

- Assumed solar ratios. For Mg is critical (OK for SiII and FeII)
- ^{25,26}Mg are contributed by Intermediate Mass Stars (4-8 M_{sun}) . Little information on isotopic behaviour.



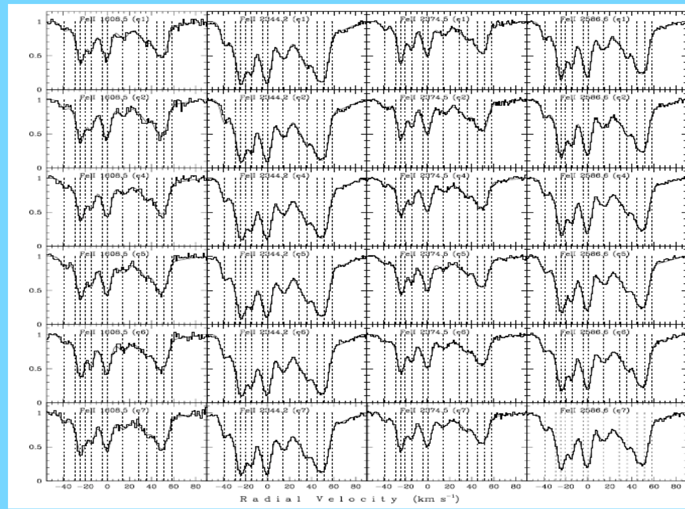
From Murphy et al 2003

Supersolar ^{25,26}Mg/^{24}Mg
no need for a variation
Undersolar:
variation even more significant

However, unlikely explain the signal of Webb et al

Individual L. O. S.

- Only FeII lines. Independent from non-solar isotopic composition of Mg

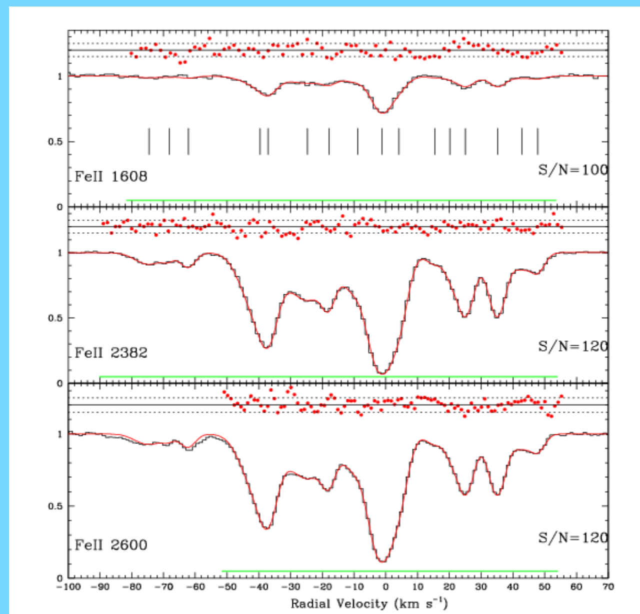


• HE 0515-4414 V=14.9, z_{abs}=1.1, Only FeII
(Molaro et al 2008)

$\Delta\alpha/\alpha$ = (-0.07 ± 1.8) ppm

• QSO 1101-264 V=16, z_{abs}=1.84, Only FeII
Levshakov et al 2007

$\Delta\alpha/\alpha$ = (5.4 ± 2.5) ppm



• HE 0001-2340, z_{abs}=1.58 SiII+FeII
(Agafonova et al 2011)

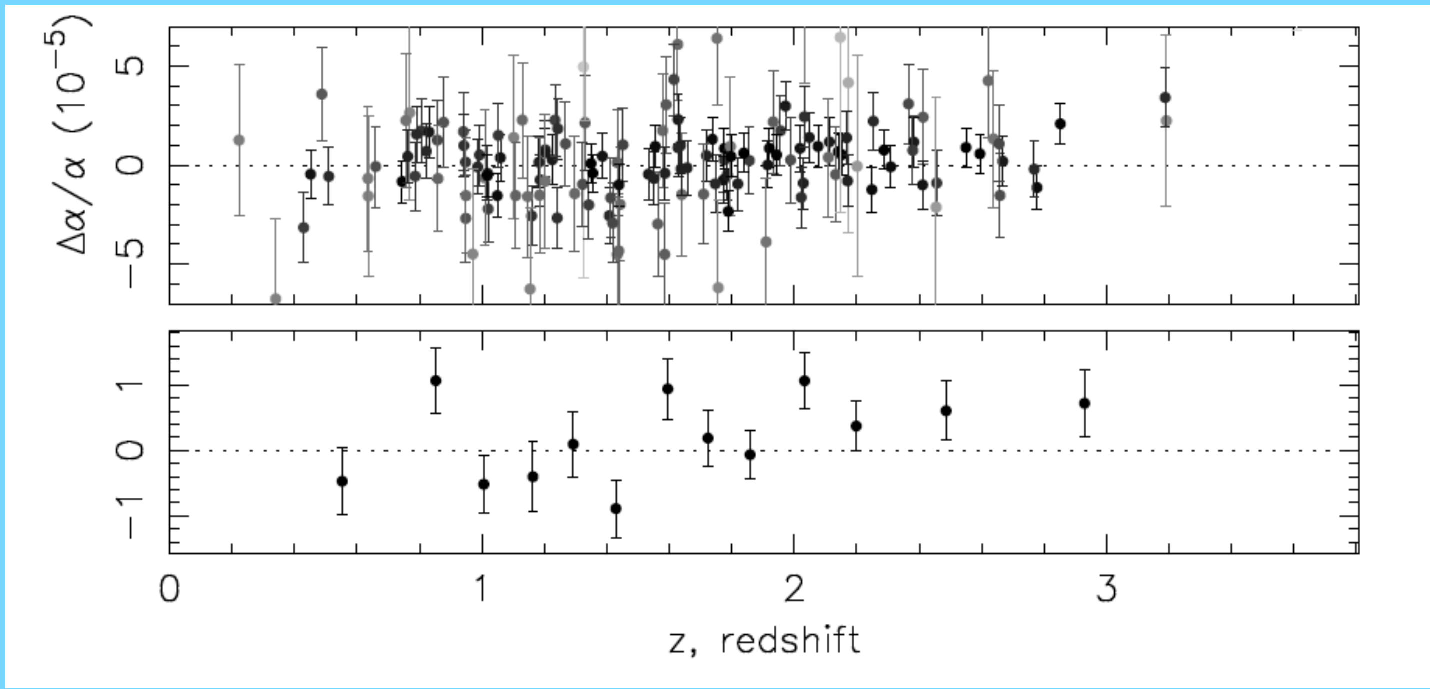
$\Delta\alpha/\alpha$ = (-1.5 ± 2.6) ppm

Only systems with errors < 3ppm (Error ~ large surveys!)

VLT survey

Webb, King Murphy et al 2010 arXiv:1008.3907

King, Webb, Murphy, Flambaum Carswell Bainbridge Koch 2011 submitted



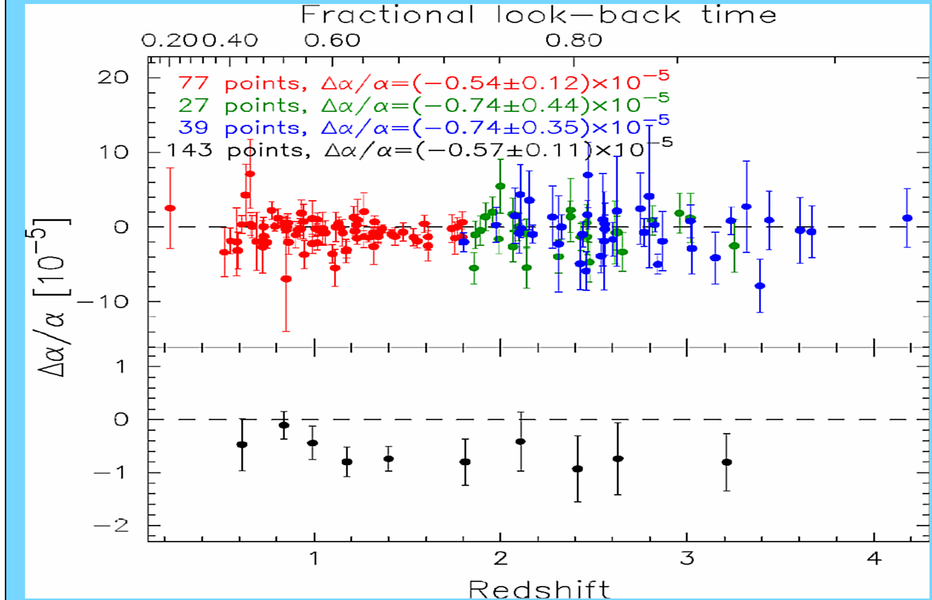
153 absorbers

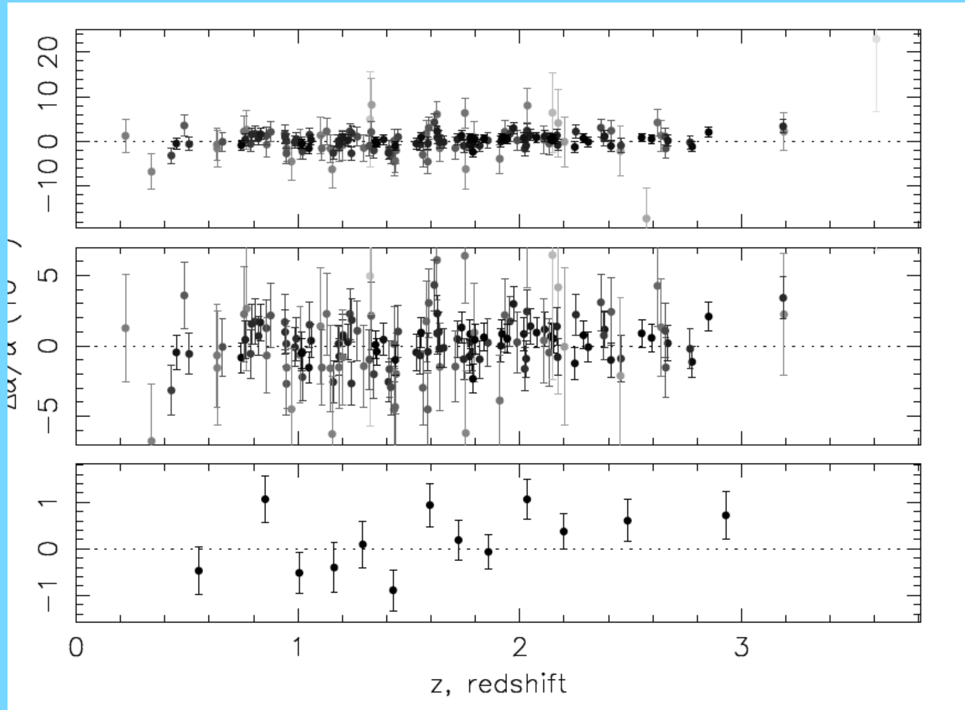
~200 nights VLT

$\Delta\alpha/\alpha$ = (2.08 ± 1.24) ppm

Keck

VLT





$\Delta\alpha/\alpha$ = (-5.7 ± 1.1) ppm

$\Delta\alpha/\alpha$ = (2.08 ± 1.24) ppm

End of the story?

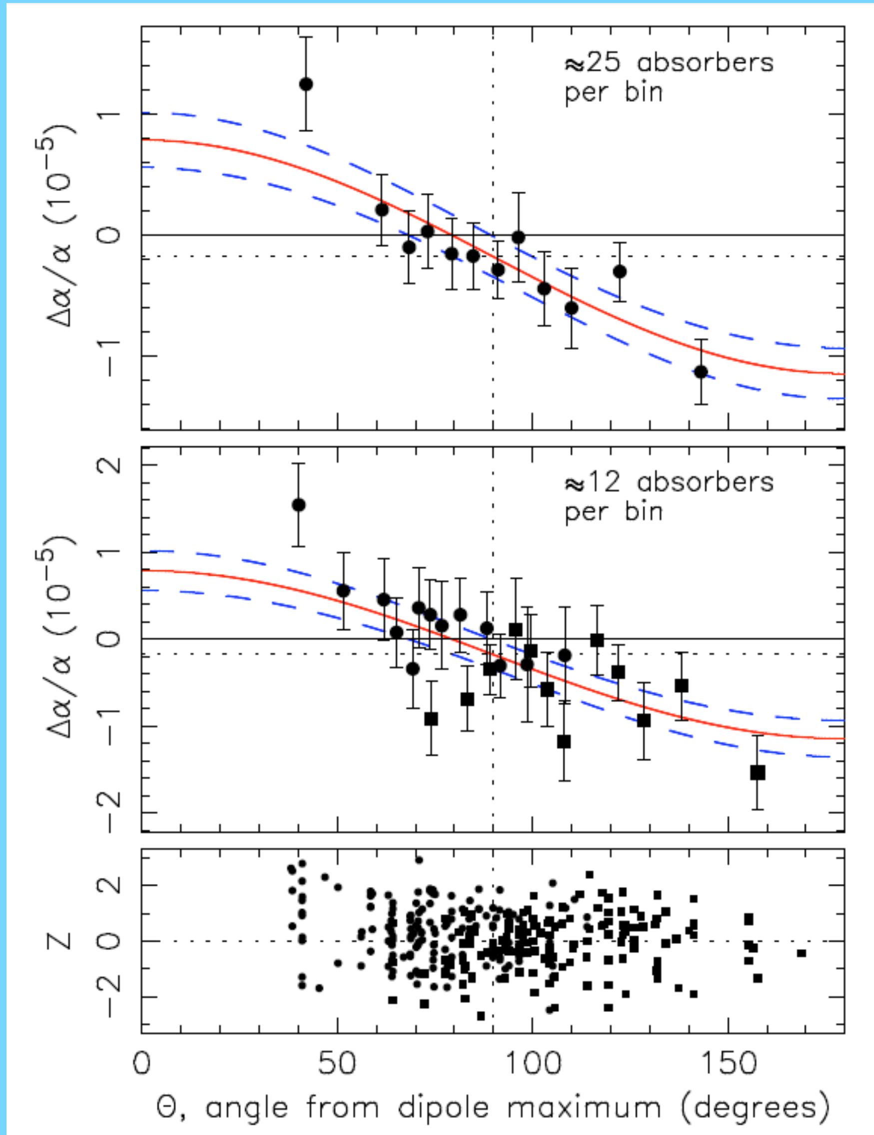
An angular (spatial) dipole?

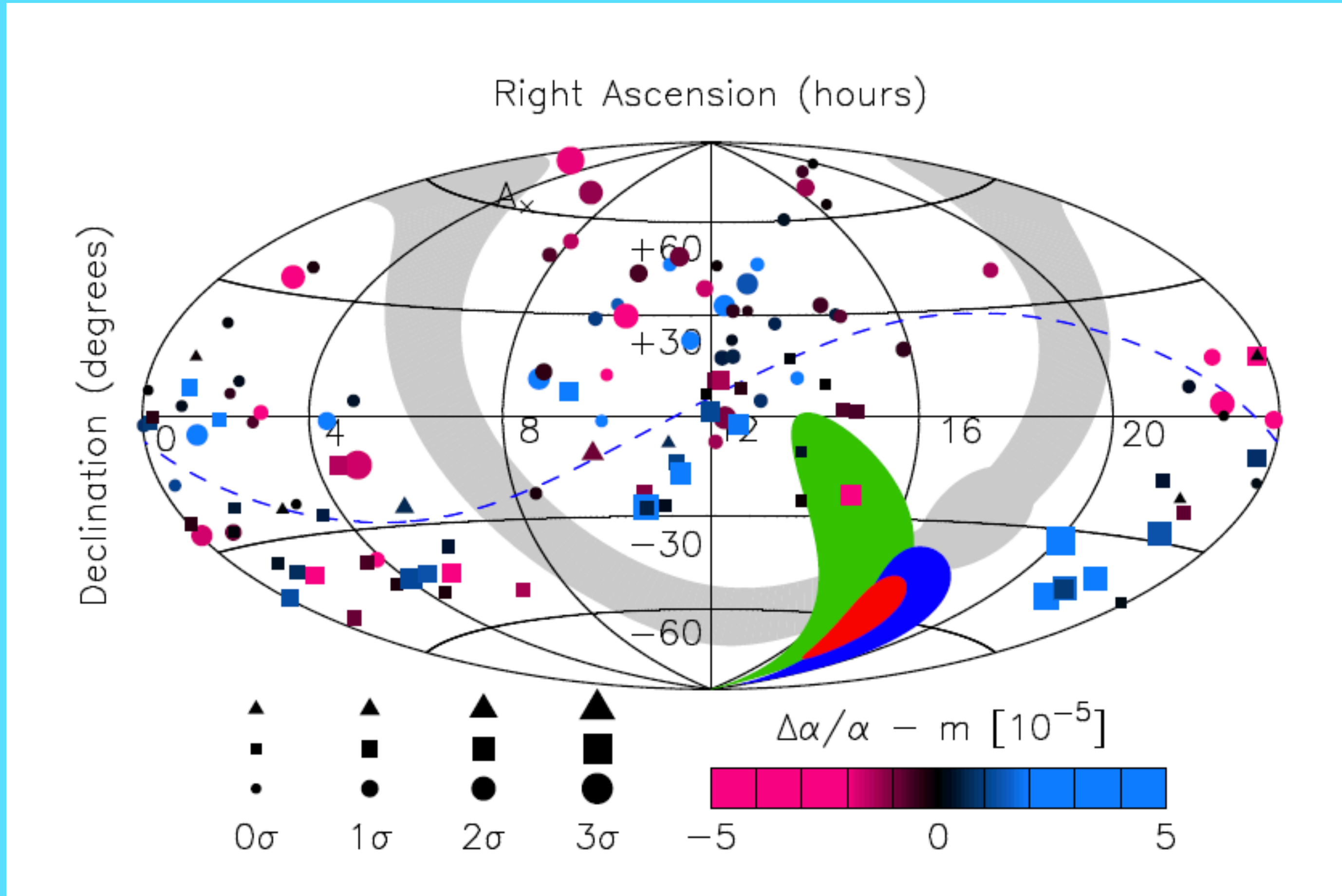
Direction:
RA = 17.4 ± 1.0 h
DEC = -61 ± 10

VLT+Keck

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
- In the equatorial region of the dipole consistency between Keck and VLT (6 QSOs in common)

COMPARISON WITH INDIVIDUAL LOS

$\Delta\alpha/\alpha$	measured	predicted
HE 0515	-0.07 ±1.8	-1.9 ±1.5
QSO 1101-264	+5.4 ±2.5	+3.8 ±2.0

- a 4 σ result need to be studied.
- spatial dipole: no existing theories predict a dipole in α.

➡ implications for the fine-tuning: constants can take different values!

- no more temporal variation!

M_P/M_E

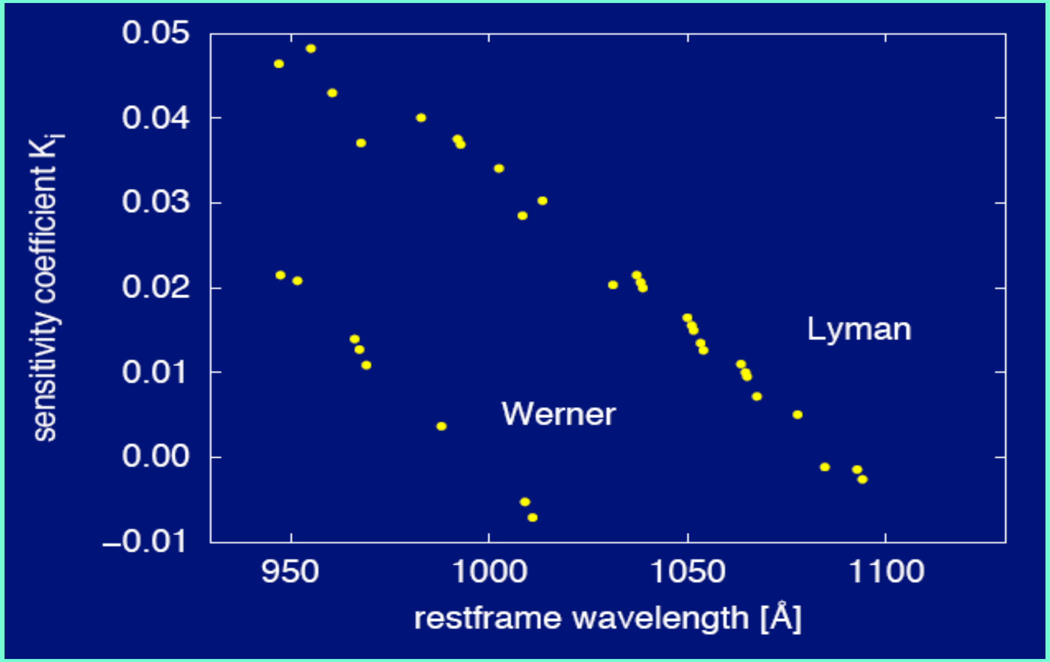
- Werner and Lyman transitions

$$\Delta\mu/\mu \equiv (\mu_z - \mu_0)/\mu_0$$

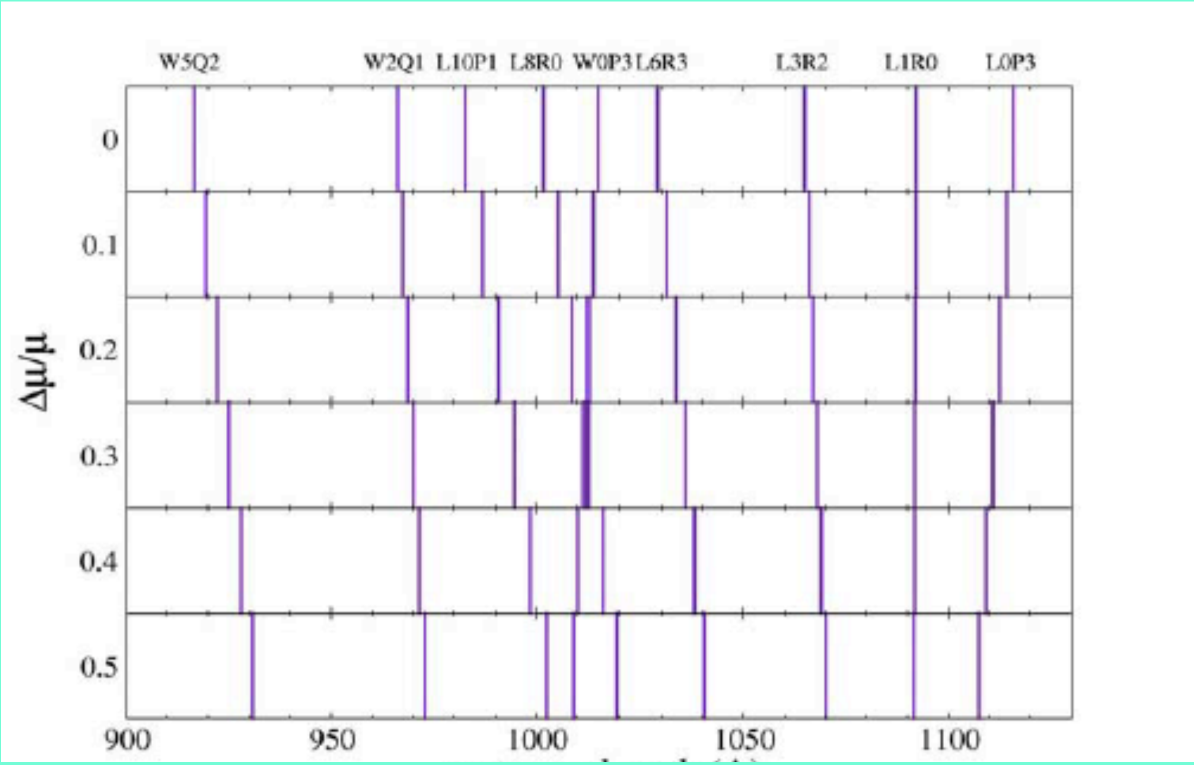
$$\nu \simeq E_I\,(c_{\rm elec} + c_{\rm vib}/\sqrt{\mu} + c_{\rm rot}/\mu)$$

$$\lambda_{obs} = \lambda_{rest}\,(1+z_{abs})(1+K_i\,\Delta\mu/\mu)$$

$$K_i = -\frac{\mu_n}{\lambda_i}\frac{d\lambda_i}{d\mu_n}$$



- Werner and Lyman transitions wavelength accuracy $\sim 4 \times 10^{-8}$ (Ubachs et al 2007)
- K coefficients 0.00-0.05 (accuracy 1-2%)

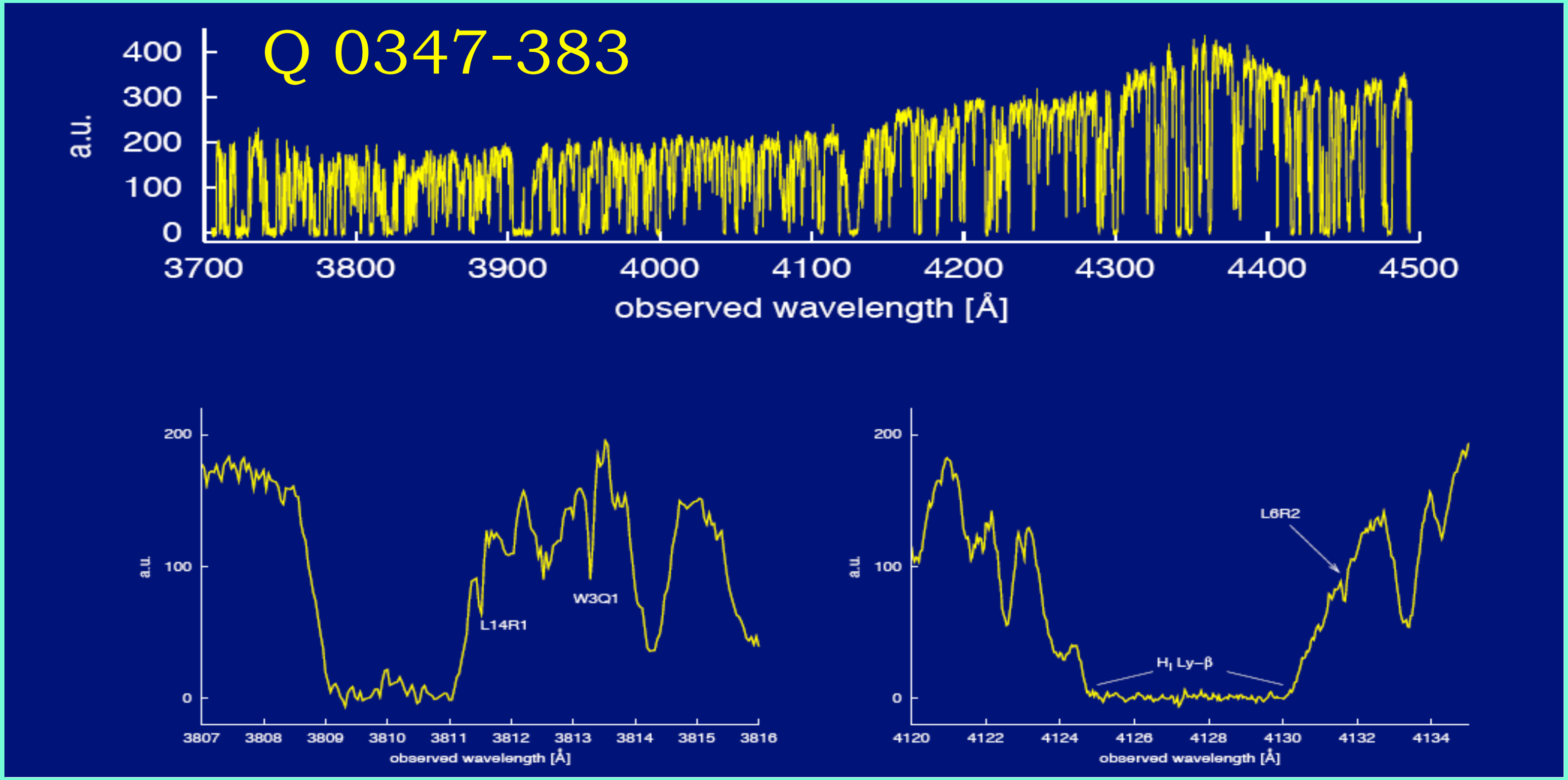


Reduced redshift:

$$\frac{\Delta v_i}{c} \approx \zeta_i \equiv \frac{z_i - z}{1+z} = K_i \frac{\Delta\mu}{\mu}$$

~150 m/s => ~10 ppm

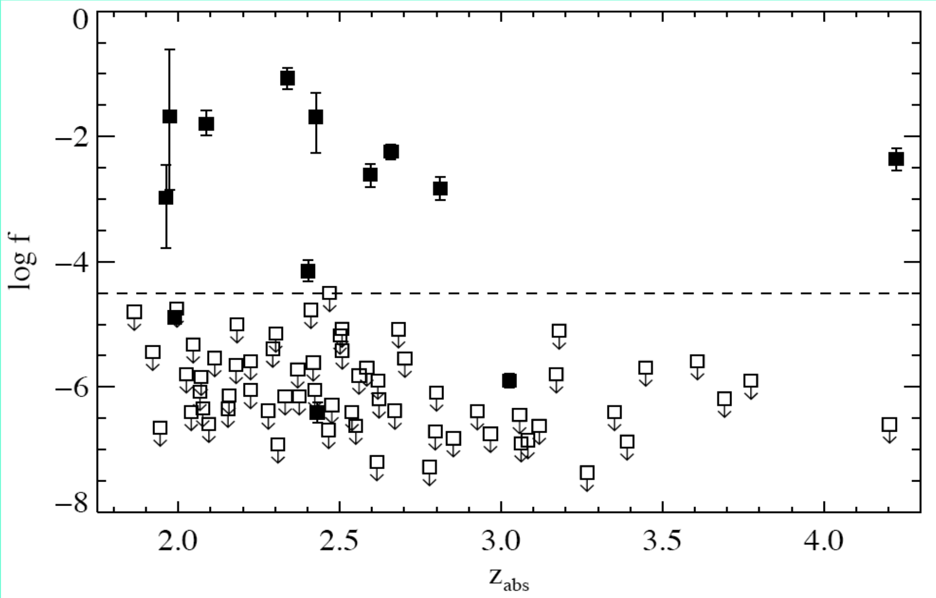
DIFFICULT TO MEASURE



- H_2 in DLA: few systems,
- lines in the UV ~ 950-1050 A ➡ z_{abs}>2.5 .

- UVES-VLT first analysis of μ (88 lines detected, 15 used) Levshakov, Dessauges-Zavadsky, D'Odorico, Molaro (2002): $\Delta\mu/\mu=(2.1\pm 3.6)\times10^{-5}$

H_2 AT HIGH Z

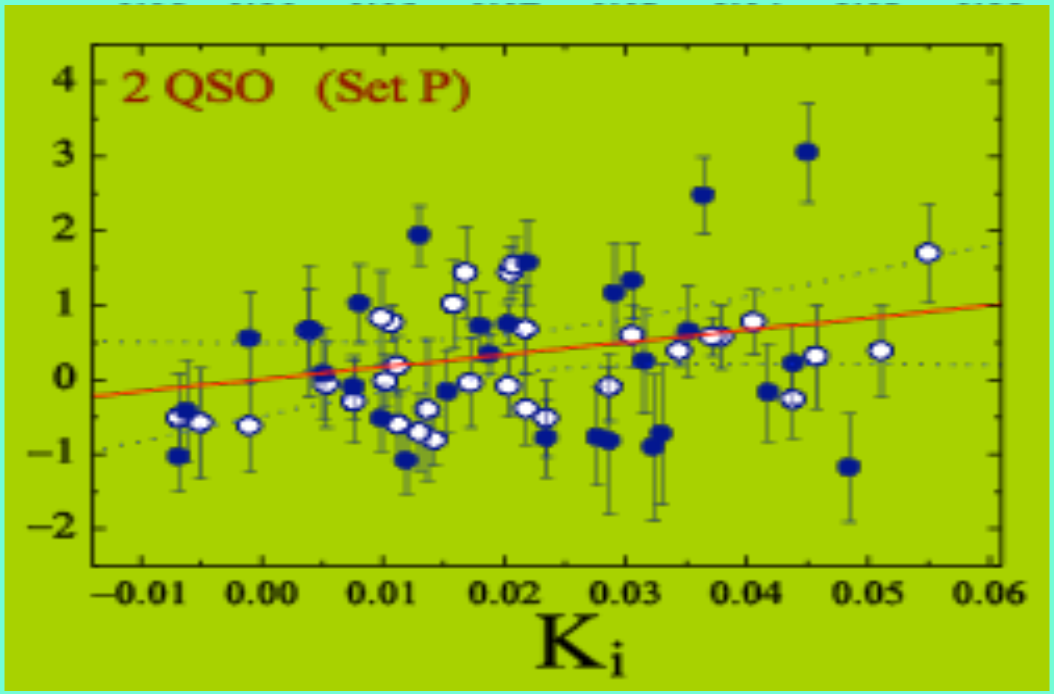


Noterdaeme et al 2008

- Only 4 QSOs
  - PKS 0528 z=2.8 Varshalovich Levshakov (1993) Cowie Songaila 1995, Potekhin 1998, King et al 2011
  - Q 0347-383 Levshakov et al 2002, Thompson et al (2009) King et al (2010) Wendt& Molaro (2011)
  - Q 0405-443 Ivanchick et al 2005, Reinhold et al 2006
  - Q 2123-0050 Malec et al 2010 but at z= 2, very bright QSO

VARIATION?

QSO 0347-383 & QSO 0405-443



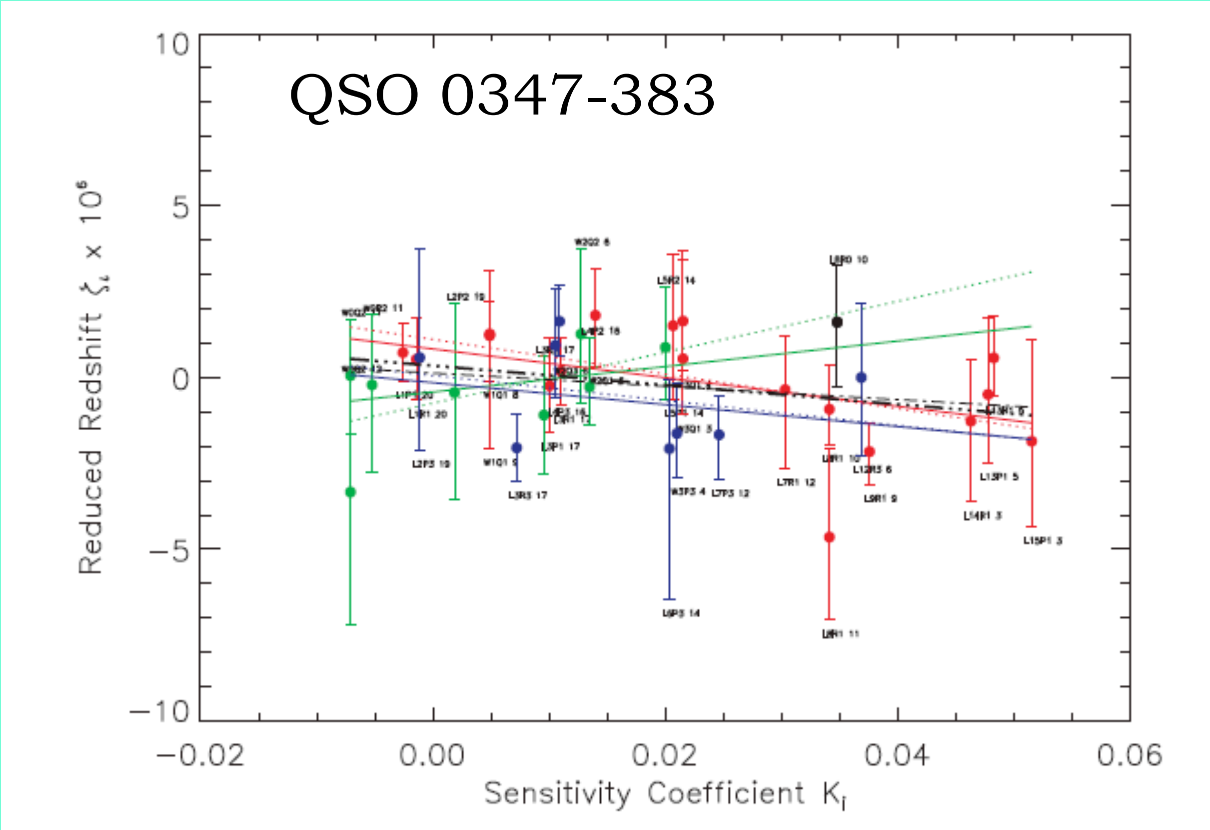
Ivanchik et al 2005
Reinhold et al 2006
Ubach et al 2007

Q 0347-383: $\Delta\mu/\mu$ = (+20.6 ± 7.9) ppm

Q 0405-443: $\Delta\mu/\mu$ = (+27.8 ± 8.8) ppm

combined value: **$\Delta\mu/\mu$ = (+24 ± 6) ppm**

Thompson et al 2009 (yes, the same Thompson 1975!)

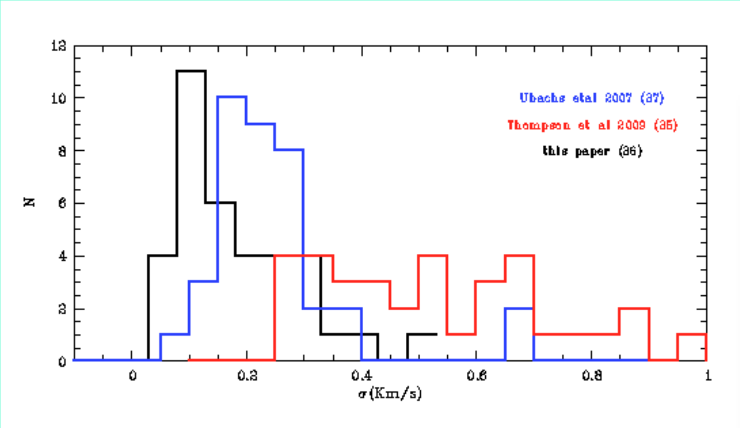


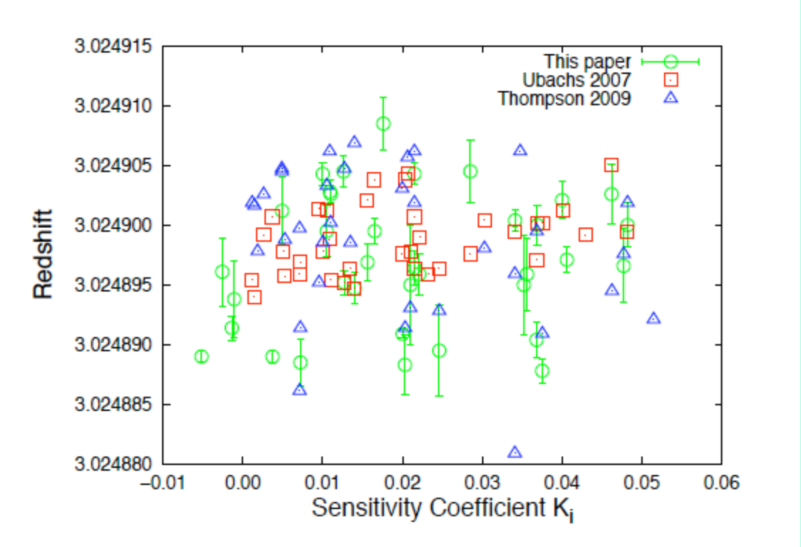
$\Delta\mu/\mu$ = (-28 ± 16) ppm

QSO 0405-443 $\Delta\mu/\mu$ = (0.55 ± 10) ppm

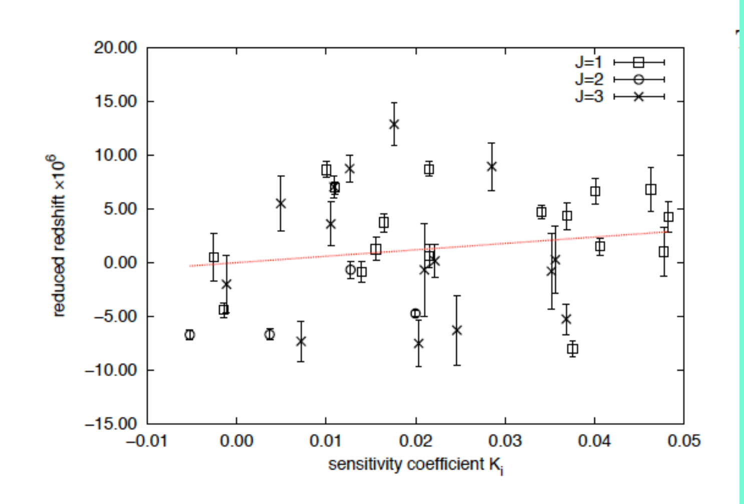
QSO 0347 again

- 8 new spectra (~ x2) Wendt & Molaro (2010)
- Higher S/N => smaller positioning error





analysis performed on individual spectra
Result: more dispersion => systematic errors dominate

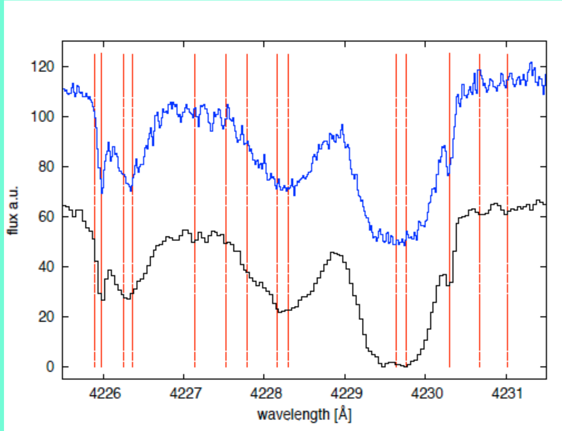


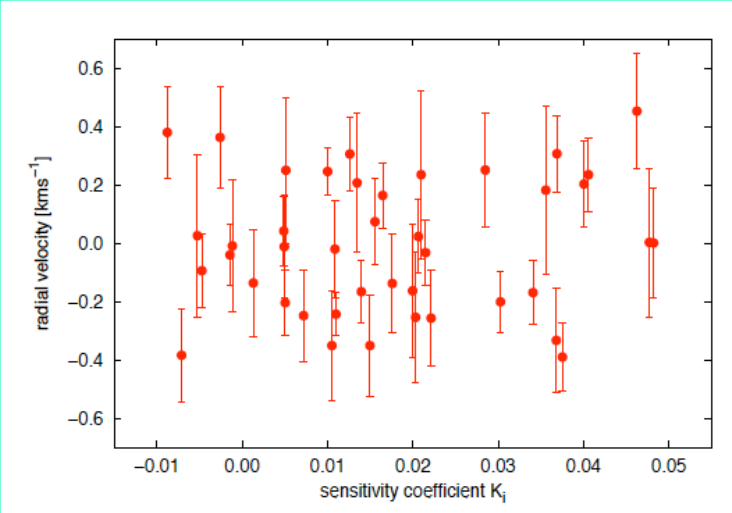
$\Delta\mu/\mu$ = (15 ± 9 stat ± 6 sys) ppm

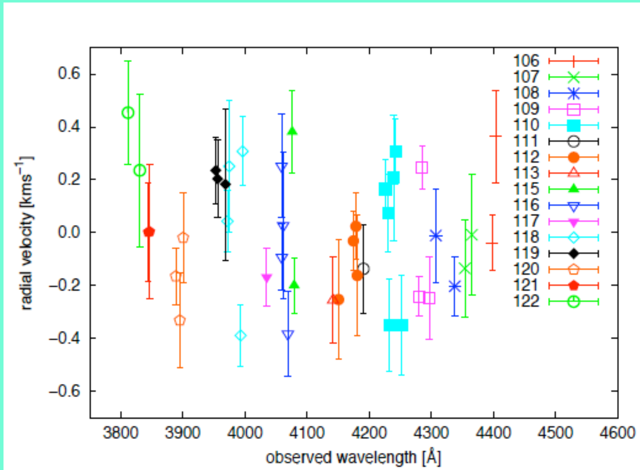
....AND AGAIN

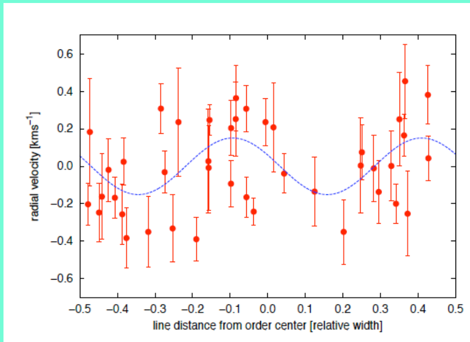
11 new spectra
- higher resolution (R~70000)
- no CCD binning
- attached calibration Th-Ar
- correction for global shifts

Wendt et al 2011 in prep



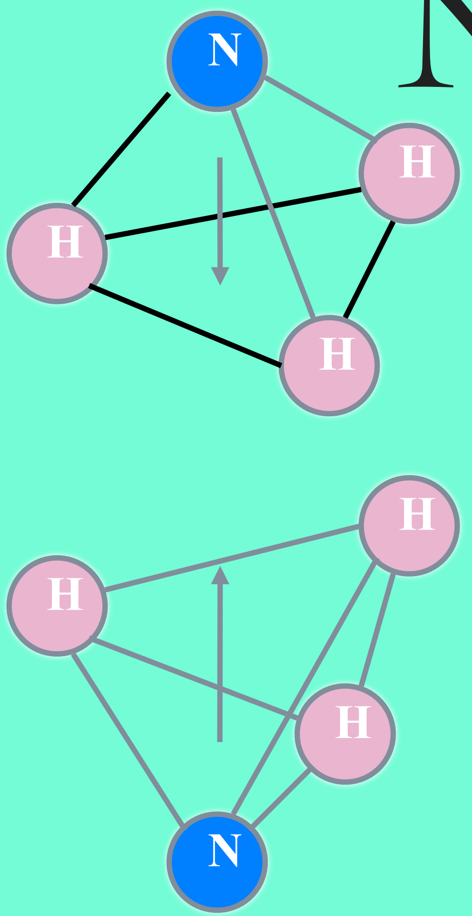


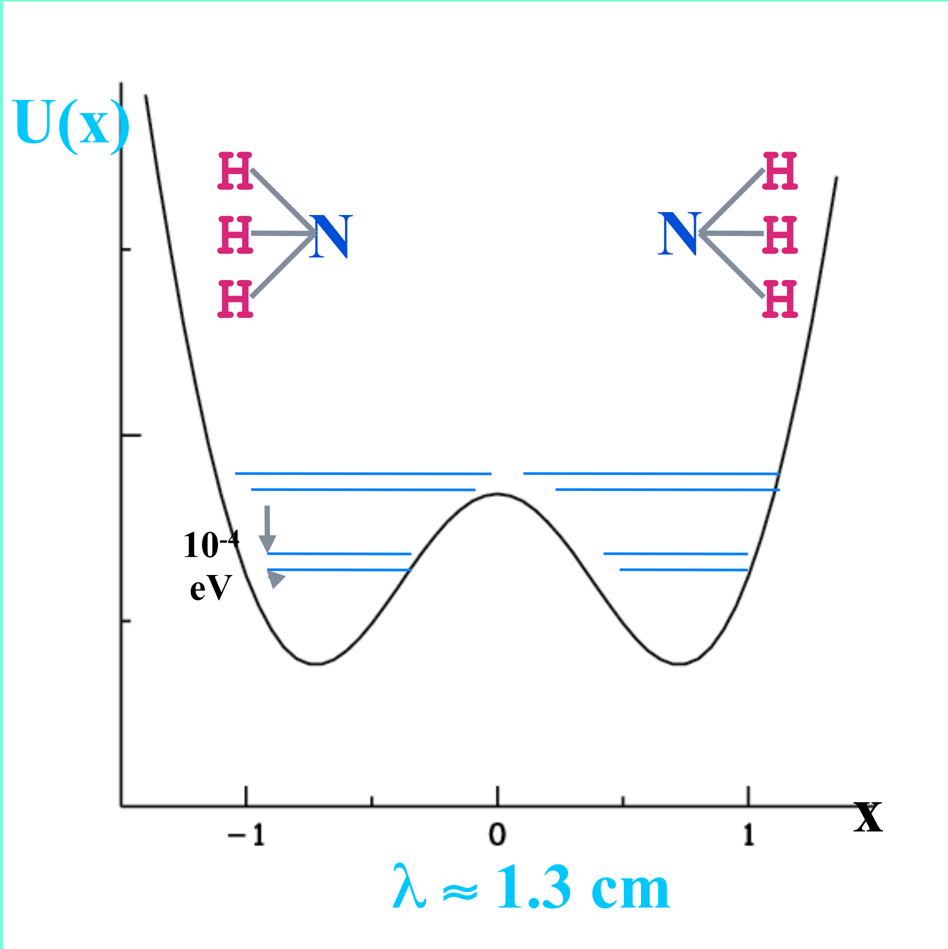




$\Delta\mu/\mu$ = (4.3 ± 7.2) ppm

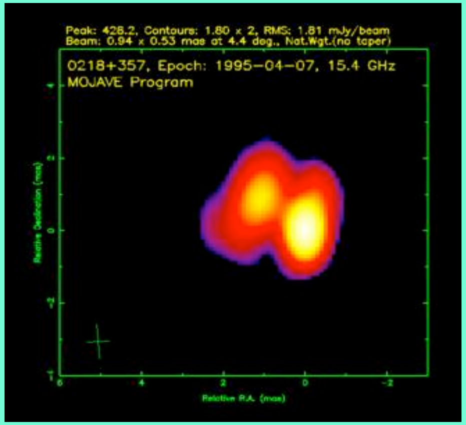
NH3

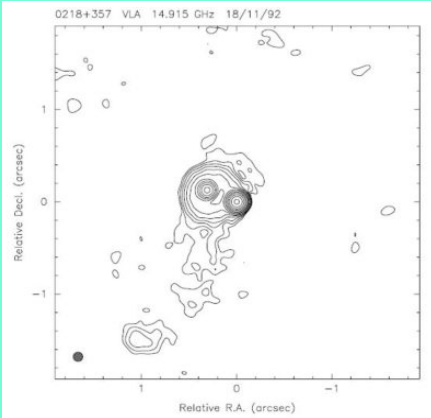


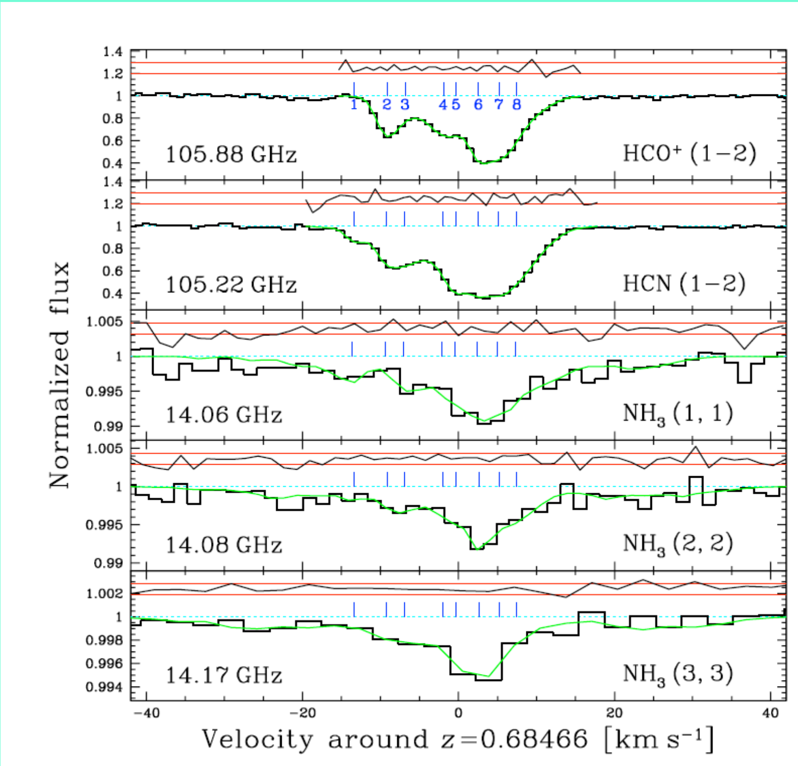


- Due to the tunneling the two levels are split into inversion doublets at 23 GHz
- Flambaum & Kozlov (2007) $\Delta\omega/\omega = -4.46\ \Delta\mu/\mu$

B 0218+357







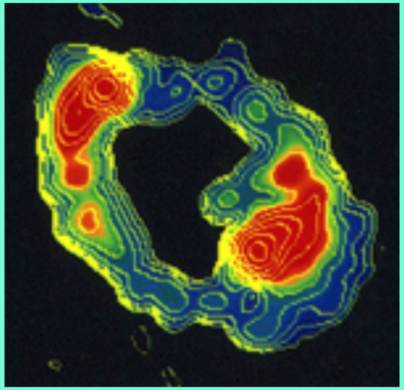
gravitational lens, z=0.68

NH_3 versus CO, HCN, HCO^+

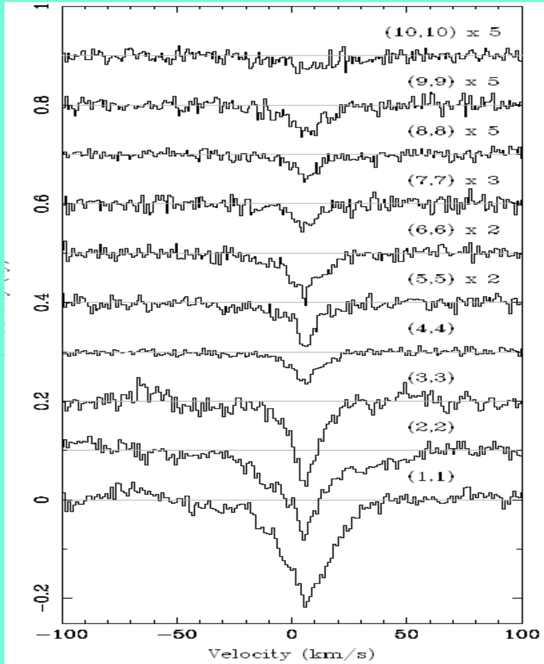
$\Delta\mu/\mu$=(0.74±0.47stat±0.76sys) ppm

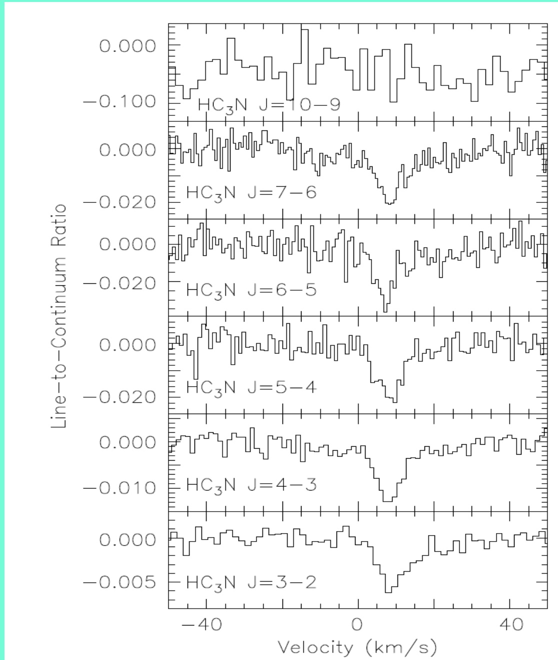
Flambaum & Kozlov (2007) Murphy et al 2008

PKS 1830-211

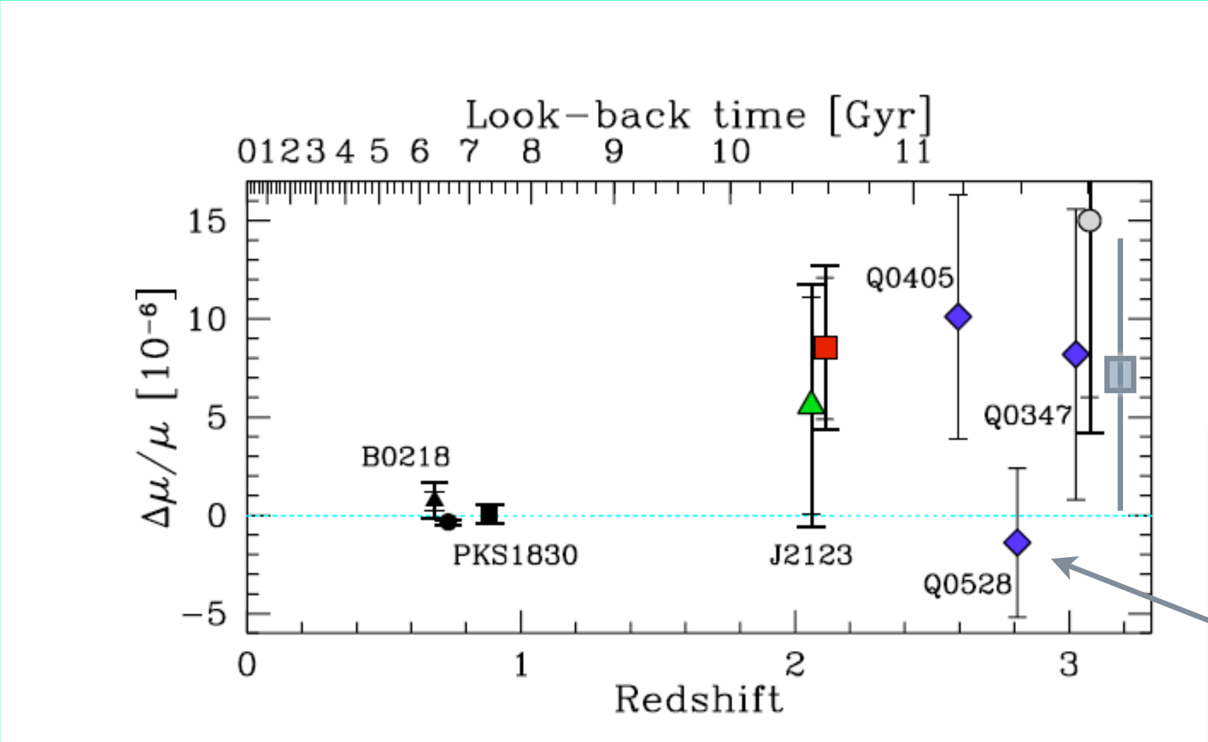


- radio source (z=2.5), lensing face-on spiral galaxy at
- z_{abs} =0.89 => 3 main components + Einstein ring
- Effelsberg 100-m: 10 NH_3 inv. lines 5 rot. transition of HC_3N





$\Delta\mu/\mu$ = (0.08 ±0.47) ppm Henkel et al 2009



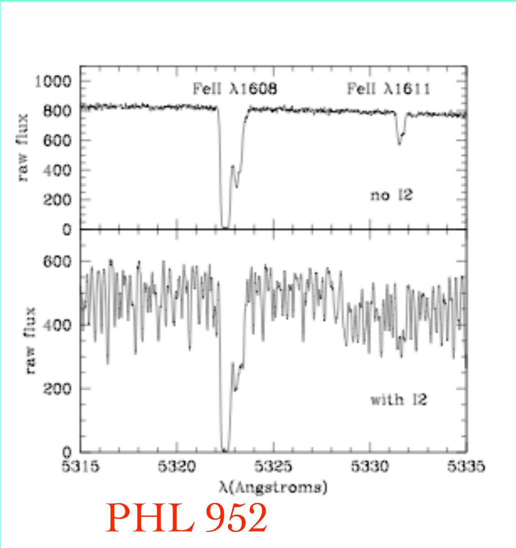
King et al 2011, complex system 3 comp. saturated

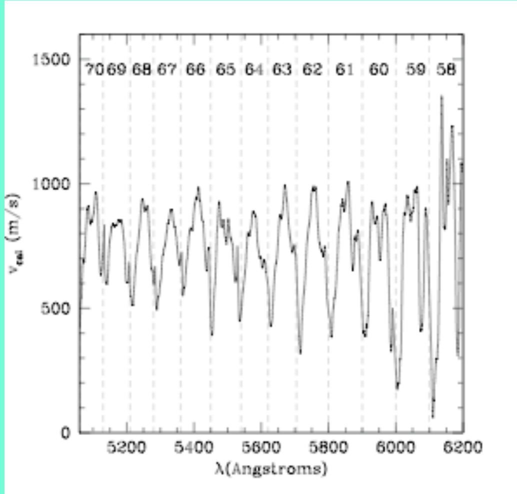
- z=3.0 QSO 0347-383 Reinhold 2006, King 2008); z=2.8 PKS 0528-25 King et al (2008) (see also king et al 2011; z=2.5 QSO 0405-443 (Reinhold et al 2006) ; z=2.059 Malec et al 2010 QSO 2123-0050 van Verderburg e al 2011; z=0.68 Murphy et al 2008 B0218+357; z=0.89 Henkel et al 2009 PKS 1830-201

Are calibration errors an issue?

Keck-HIRES

Iodine- ThAr comparison



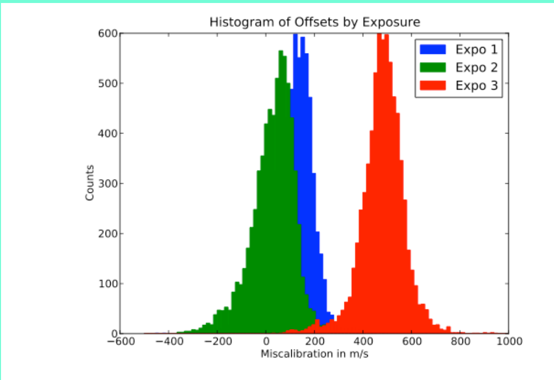


Griest et al 2009

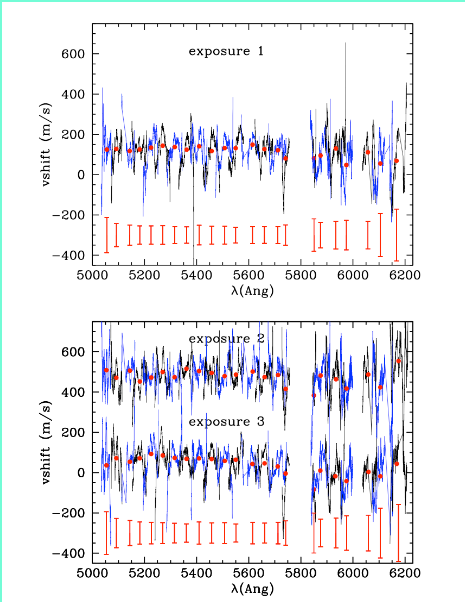
order modulation:

saw-tooth

UVES-VLT



global shift slit effect

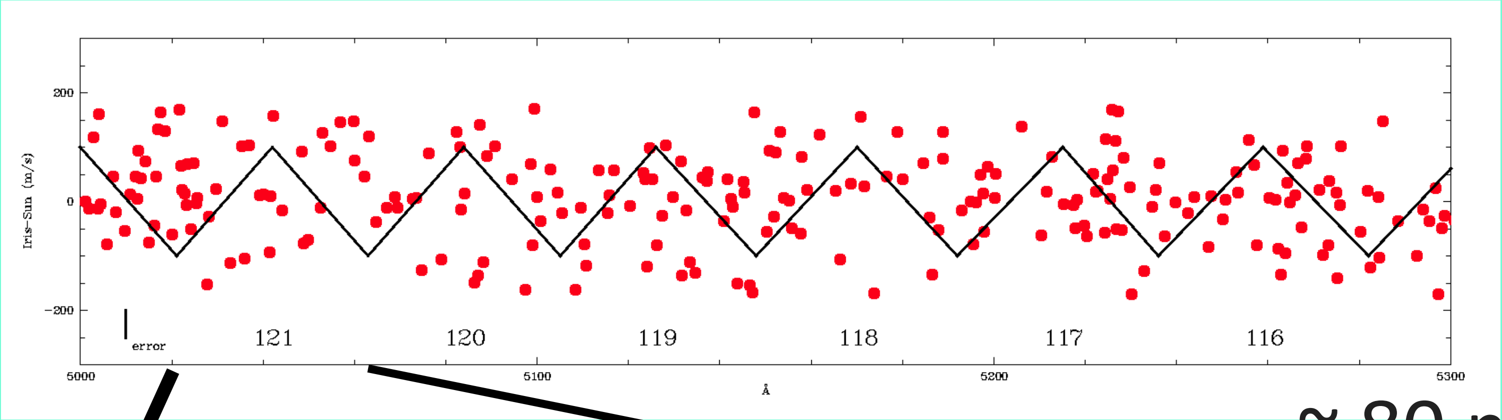


intraorder: +/- 100 m/s

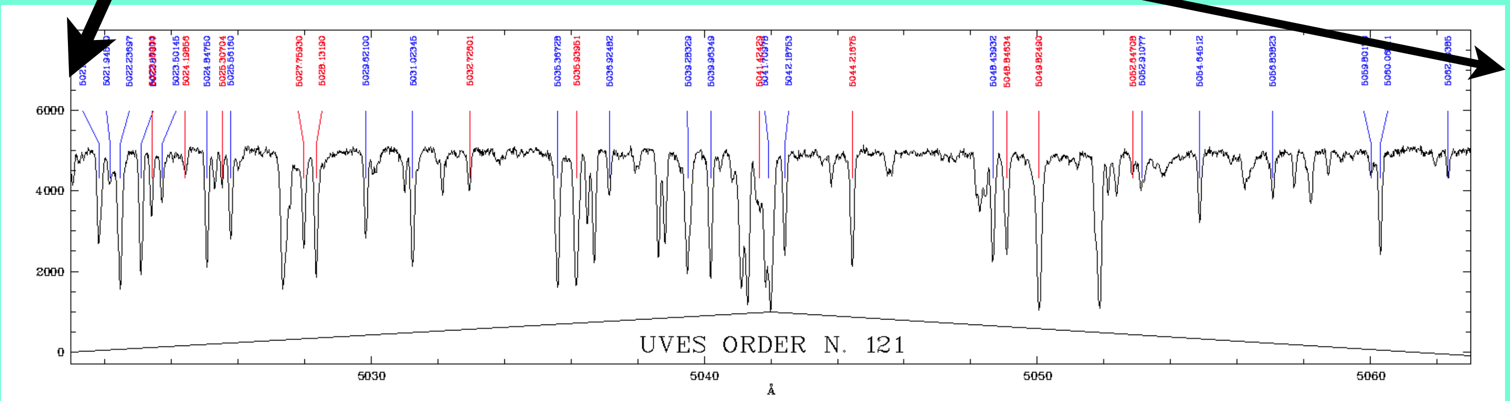
Whitmore et al 2010

ASTEROIDS

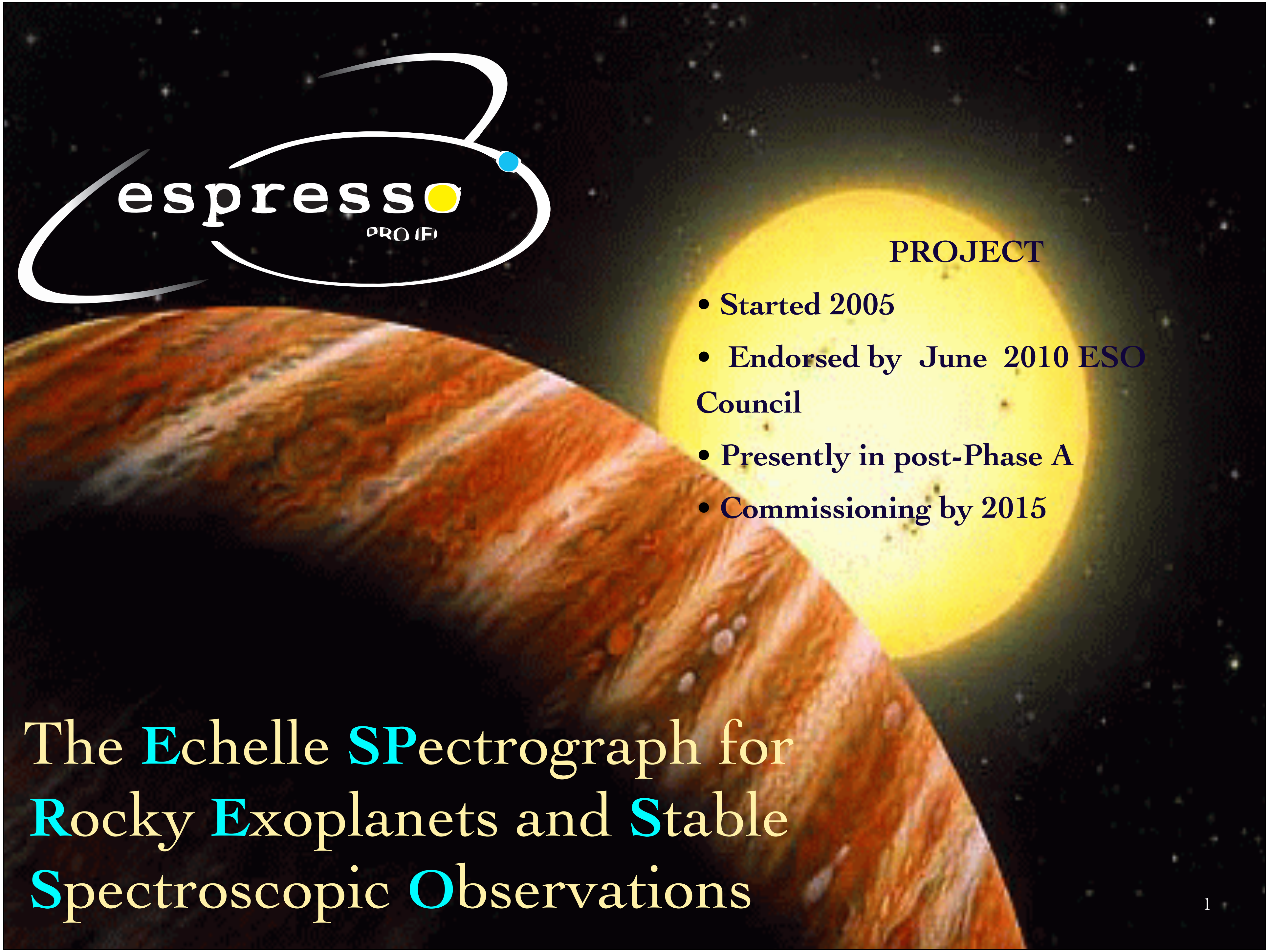
UVES observations of solar spectrum to look for shifts of line positions compared to "absolute" solar line positions:



σ_v ~ 80 m/s



➡ no evidence for a saw-tooth but distorsions at the level of 80 m/s with a length of 10-15 A

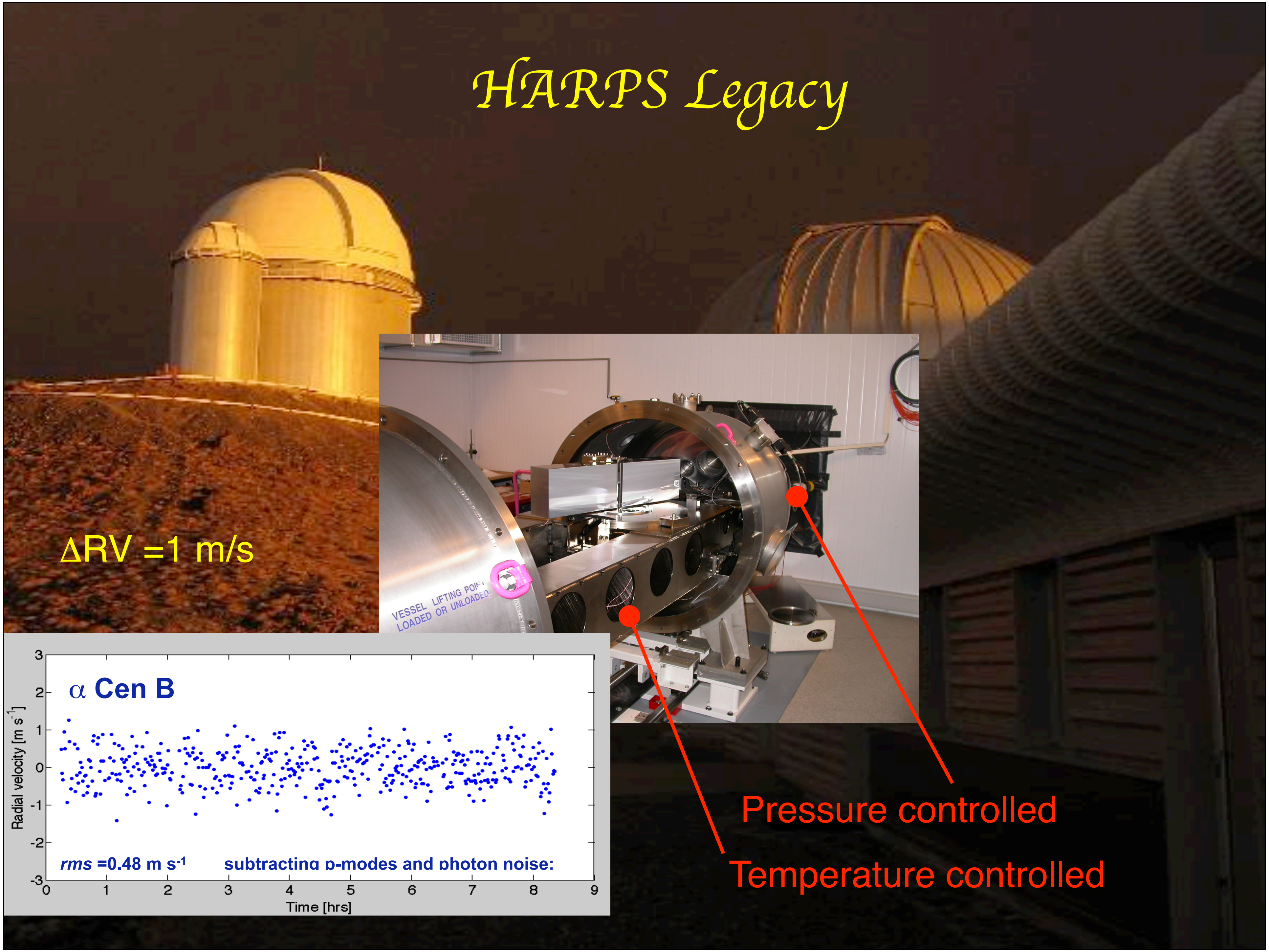


espresso PROJECT

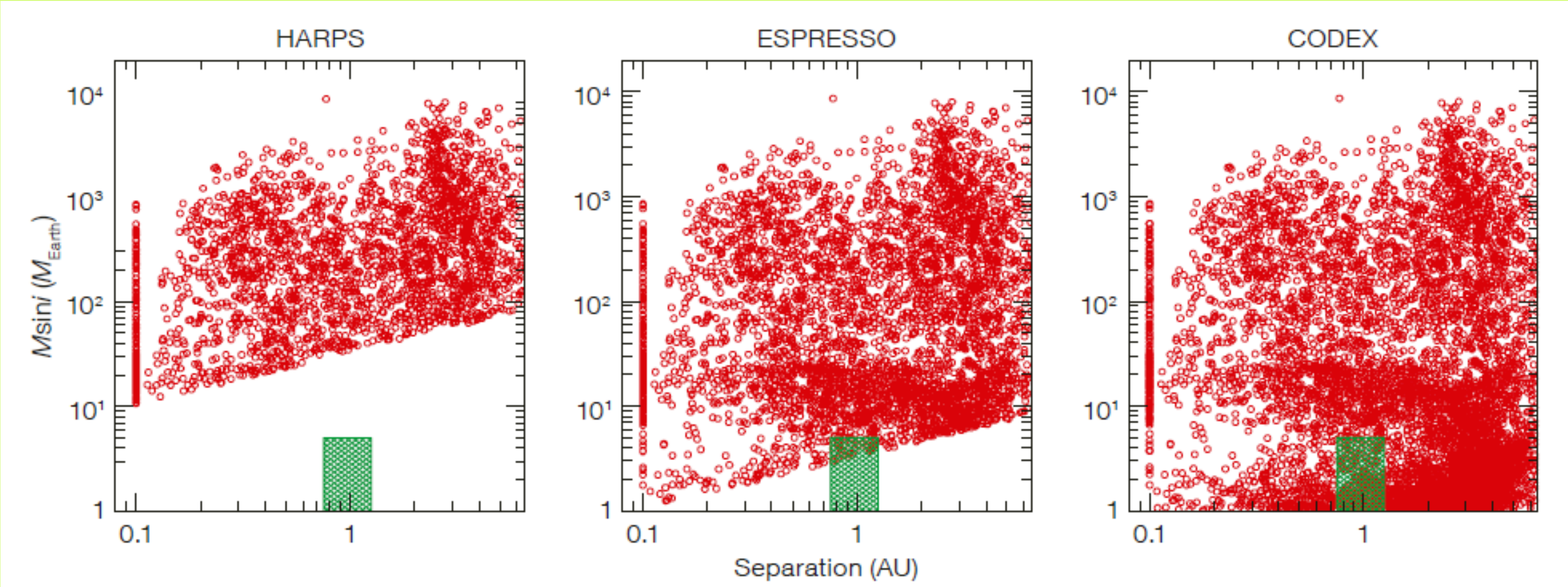
PROJECT

- Started 2005
- Endorsed by June 2010 ESO Council
- Presently in post-Phase A
- Commissioning by 2015

The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations


HARPS Legacy
ΔRV =1 m/s
α Cen B
Radial velocity [m s-1]
rms =0.48 m s-1
subtracting p-modes and photon noise:
Time [hrs]
VESSEL LIFTING POINT
LOADED OR UNLOADED
Pressure controlled
Temperature controlled

ESO Roadmap



1 m/s 0.10 m/s 0.01 m/s

reduction of systematics + photon collection

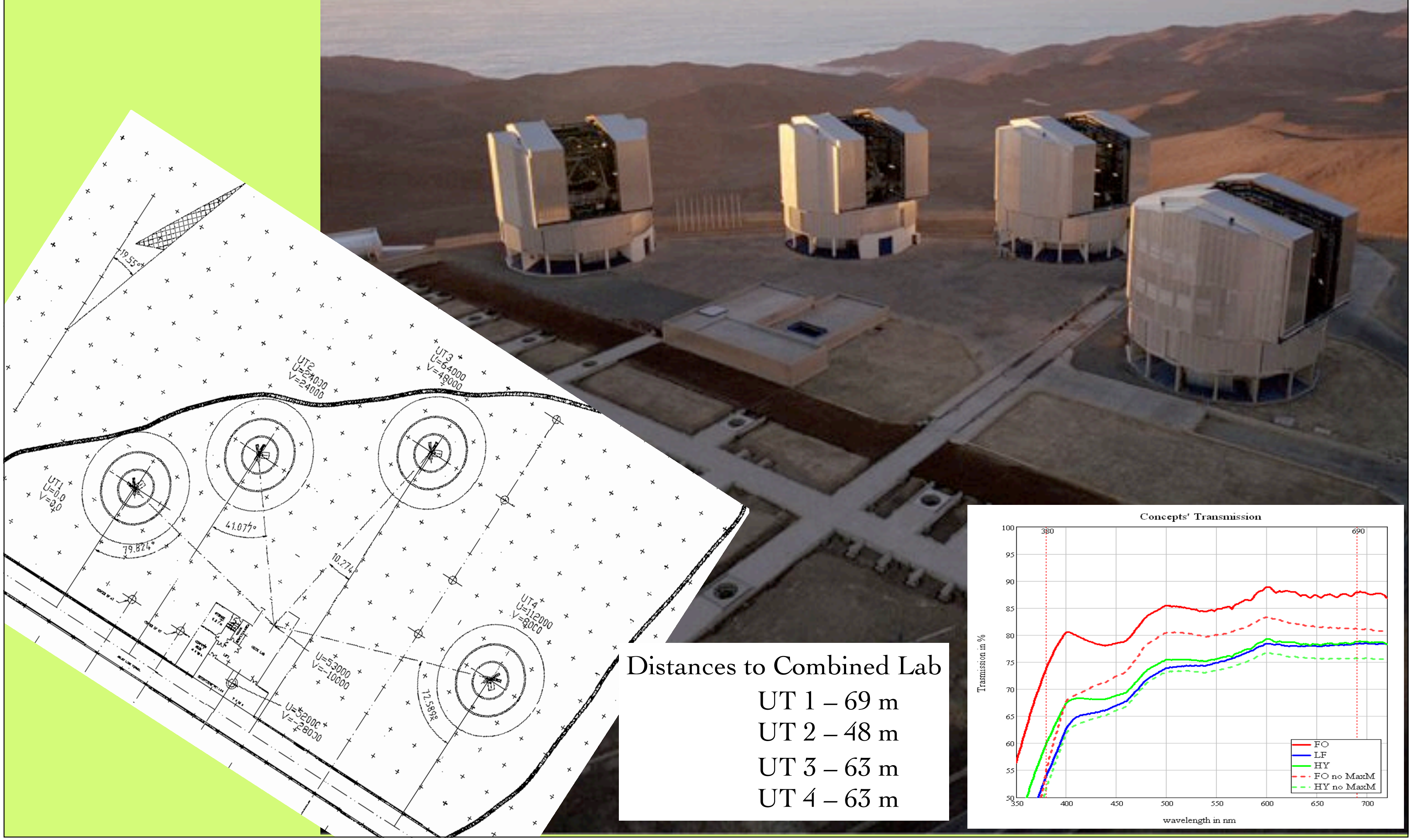
CONSORTIUM

- Geneva Observatory, Bern University (Switzerland)
- CAUP, Porto and Universidade de Lisboa (Portugal)
- IAC (Spain)
- Milan and Trieste Observatories (INAF, Italy)
- ESO

Francesco A. Pepe, Stefano Cristiani, Rafael Rebolo Lopez, Nuno C. Santos, Antonio Amorim, Gerardo Avila, Willy Benz, Piercarlo Bonifacio, Alexandre Cabral, Pedro Carvas, Roberto Cirami, João Coelho, Maurizio Comari, Igor Coretti, Vincenzo De Caprio, Hans Dekker, Bernard Delabre, Paolo Di Marcantonio, Valentina D'Odorico, Michel Fleury, Ramòn Garcia Lòpez,

José Miguel Herreros Linares, Ian Hughes, Olaf Iwert, Jorge Lima, Iocken Liske, Jean-Louis Lizon, Gaspare Lo Curto, Christophe Lovis, Antonio Manescau, Carlos Martins, Denis Mégevand, André Moitinho, Paolo Molaro, Mario Monteiro, Manuel Monteiro, Christoph Mordasini, Luca Pasquini, Didier Queloz, José Luis Rasilla, Jose Manuel Rebordão, Samuel Santana Tschudi, Paolo Santin, Danuta Sosnowska, Paolo Spanò, Fabio Tenegi, Stéphane Udry, Eros Vanzella, Matteo Viel, Maria Rosa Zapatero Osorio, Filippo Zerbi

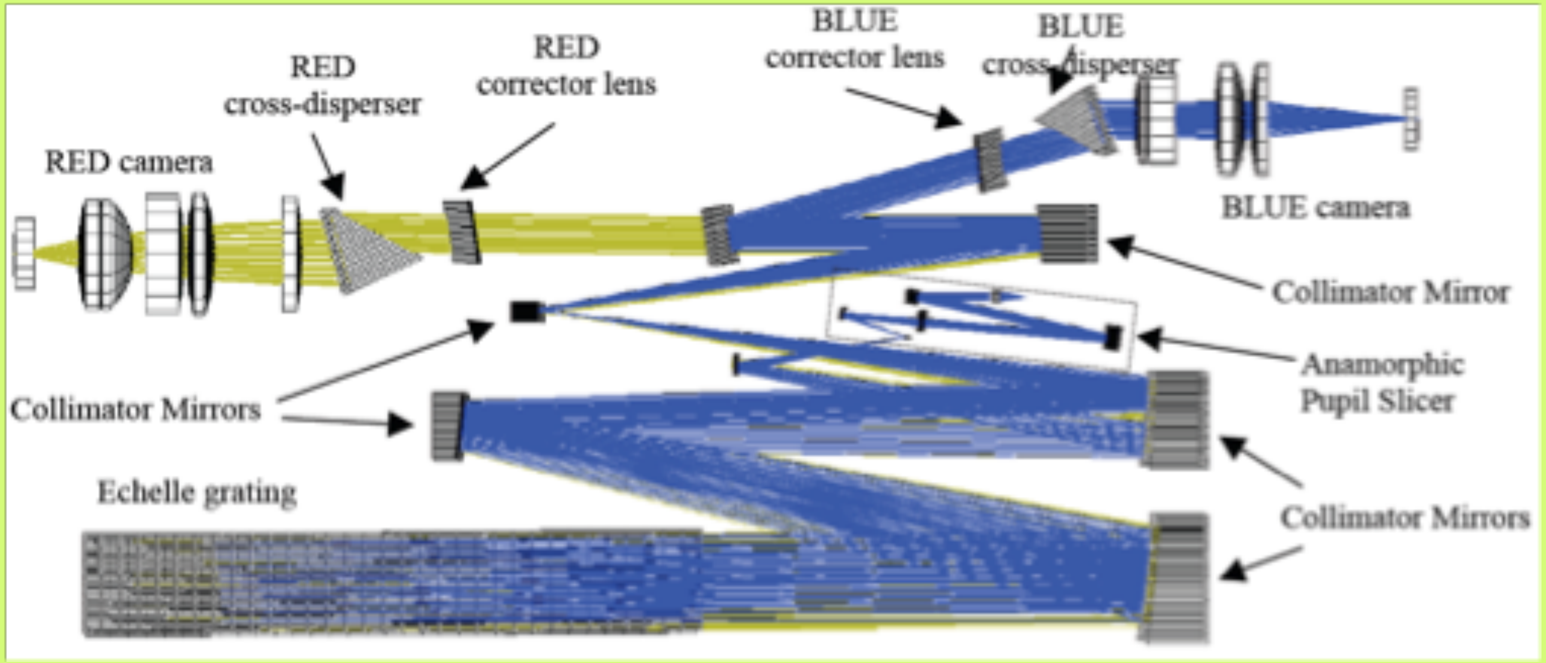
- A spectrograph on a 16 m telescope (foreseen since 1977)
- the largest visible photon-collector until ELTs will be available



Distances to Combined Lab

UT 1 – 69 m
UT 2 – 48 m
UT 3 – 63 m
UT 4 – 63 m

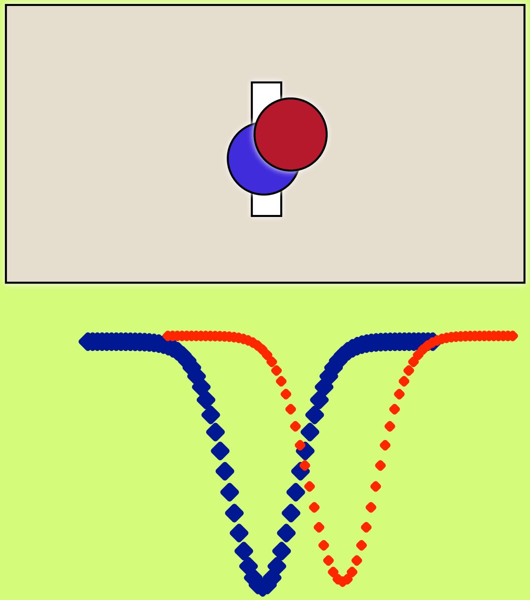
espresso
PROJECT



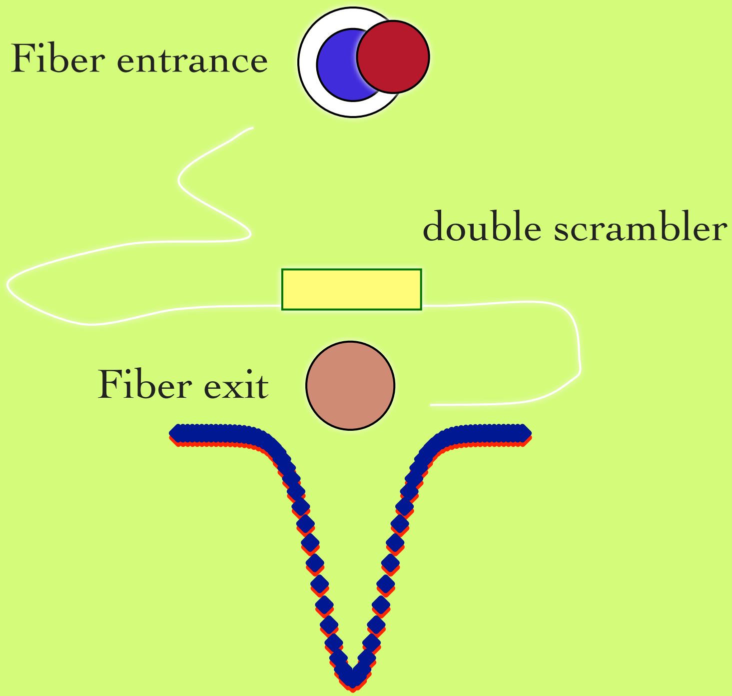
- Fiber-fed, cross-dispersed Echelle spectrograph with pupil slicing
- High stability spectrograph (vacuum, thermal, mechanical)
- FOV = 1.0 arcsec
- R = 70’000 (4 UT), 140’000 (1 UT) or 225’000 (1UT, high-resolution)
- Sampling = 3.5 pixels/RE @ R=140‘000

Improving the spectrograph feeding

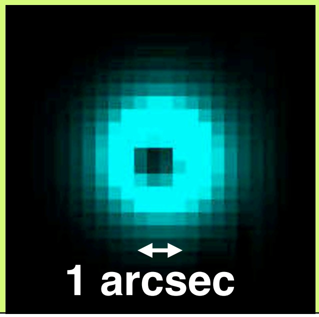
Slit spectrograph



Fiber-fed spectrograph



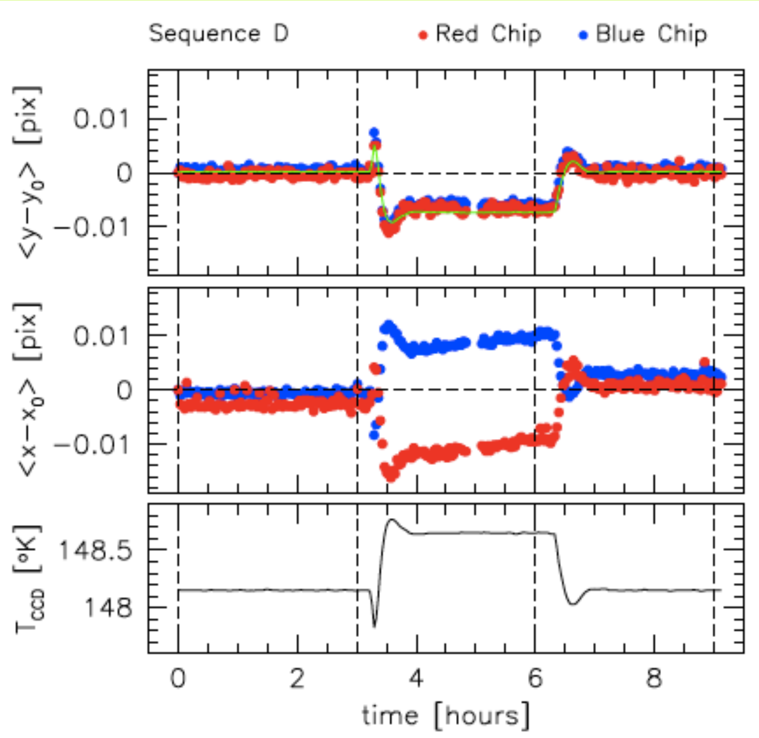
RV

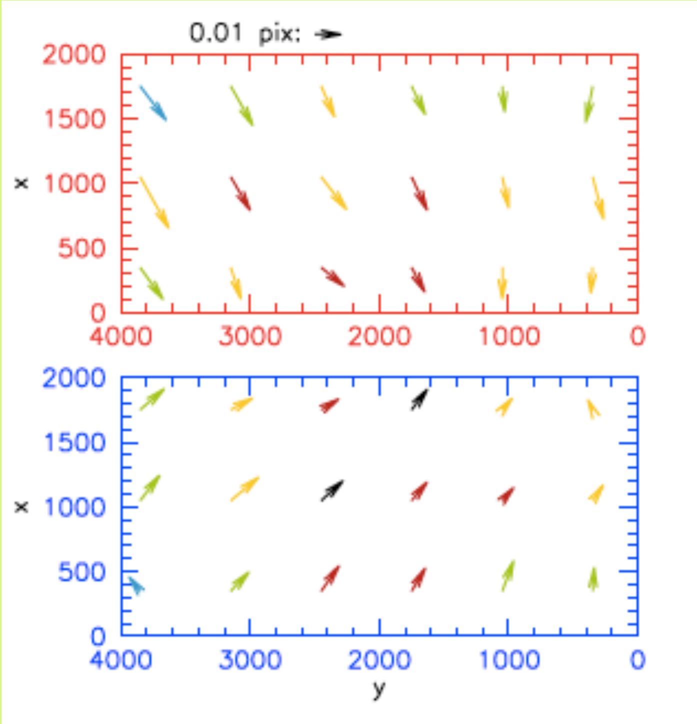


Δ RV

"Good" guiding, 0.1" RMS,
~30 cm/s contribution to RV

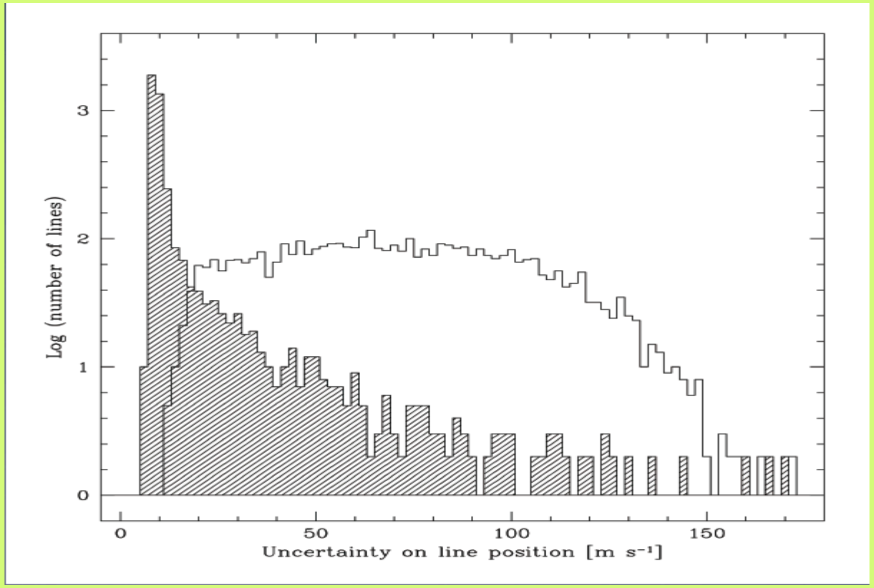
Surprise: the detector is alive



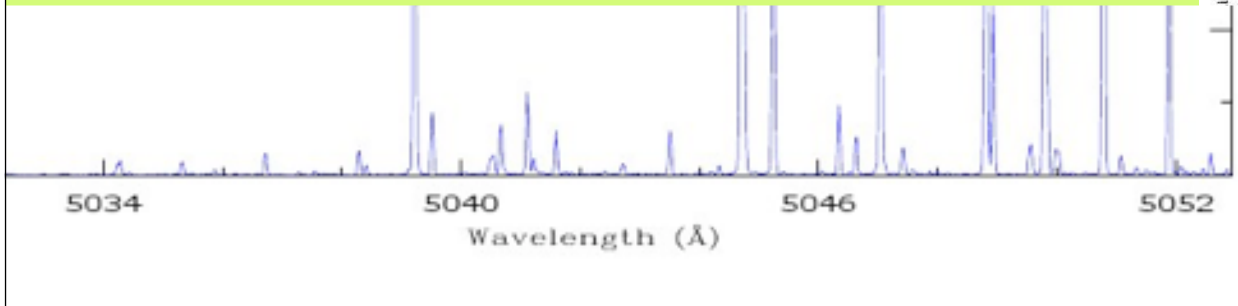


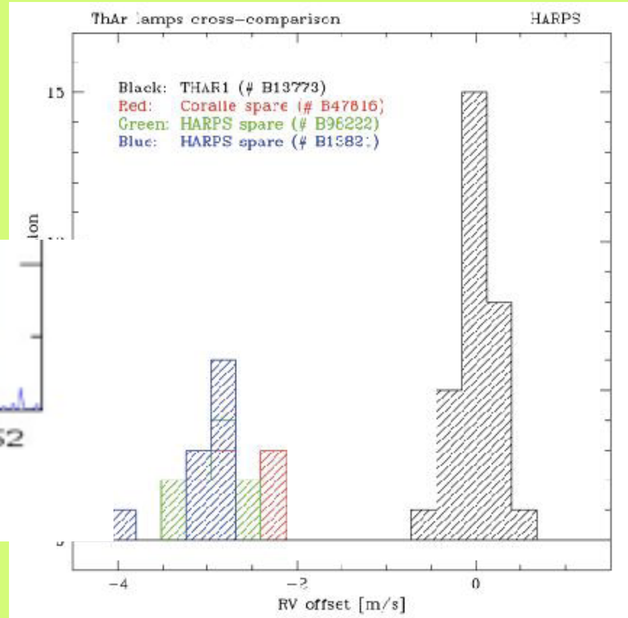
- Movements in the CCD: ~0.01 pixel/K (1 cm/s mK)
- CCD expands around the attachments of the mosaic to the support
- Development of super stable cryostat (FP7)

The wavelength calibration Bottle-neck

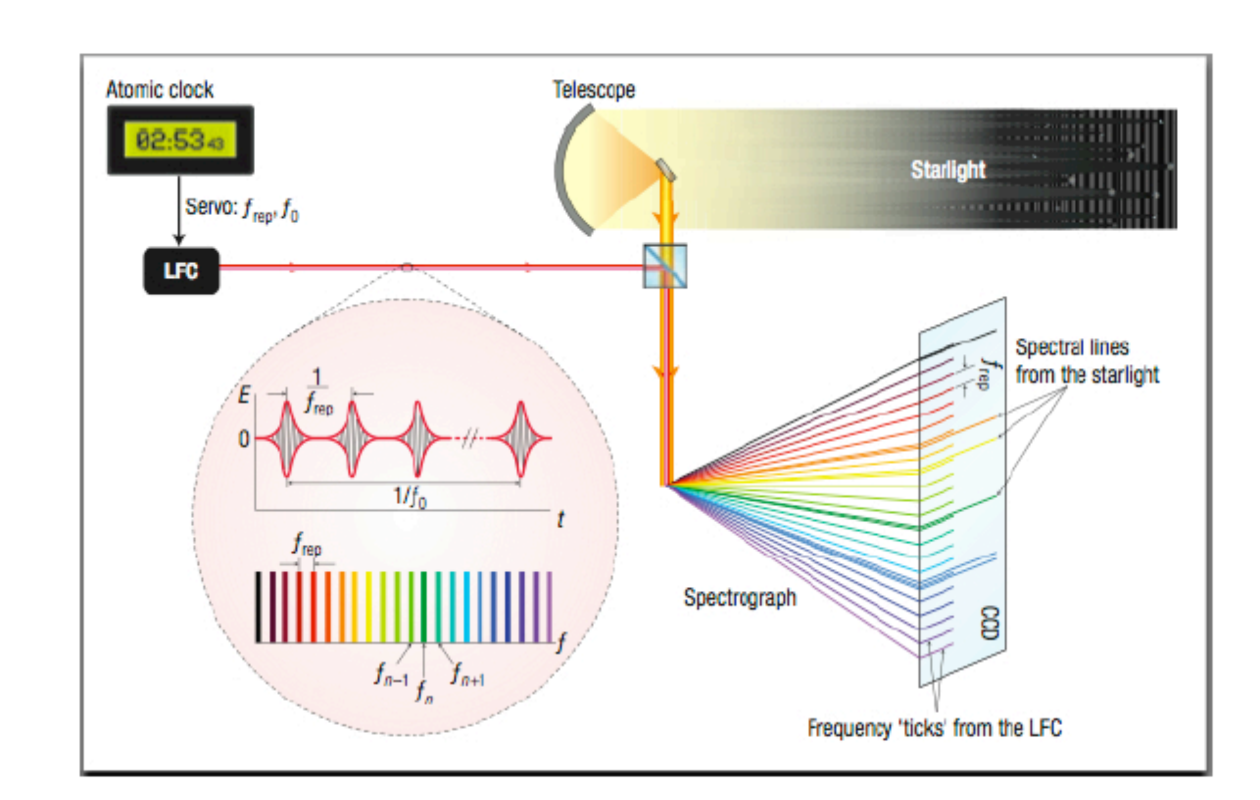


4000 ThAr lines,
precision 15-150 m/s





Laser Comb

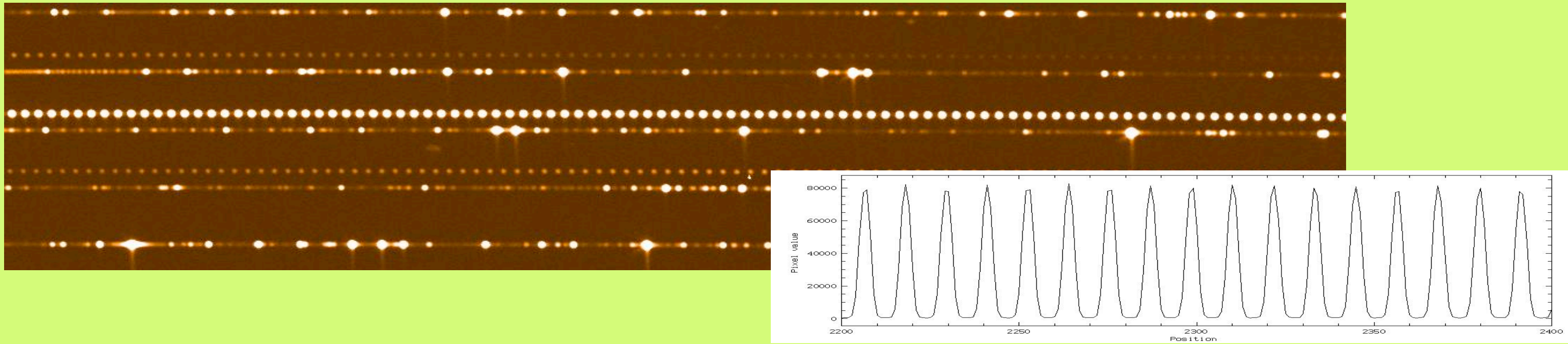


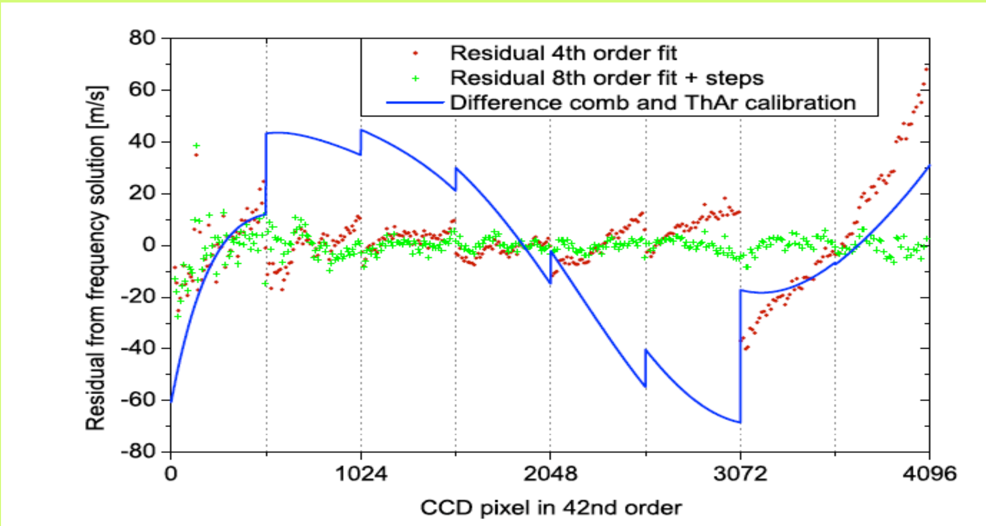
- Optical or NIR laser producing a train of femptoseconds pulses (controlled by an atomic clock)

- Produces a spectrum of evenly spaces delta-functions whose positions are known very precisely

- Prototype tested at HARPS Jan 2009

Comb spectra @ HARPS





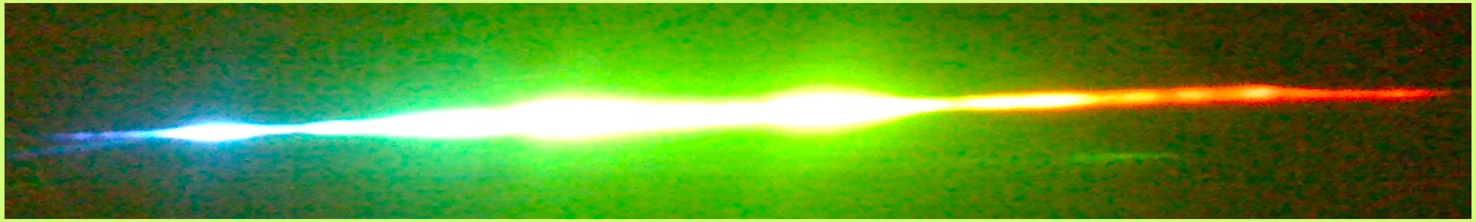
Wilken et al 2009

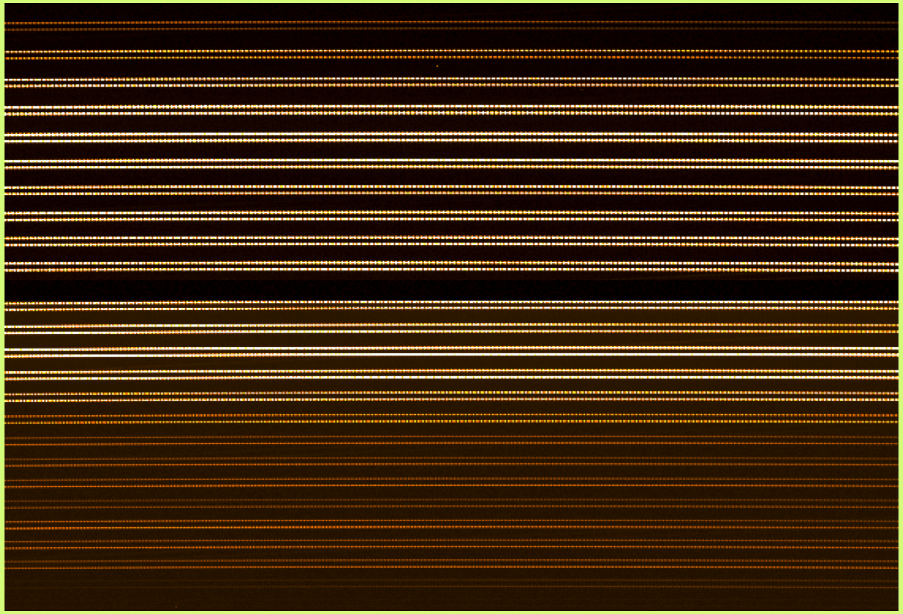
- Comb-ThAr up to ~100 m/s (but ~ 0 in the mean)

- UVES? and HIRES?

II TEST: MARCH 2010

The comb after broadening





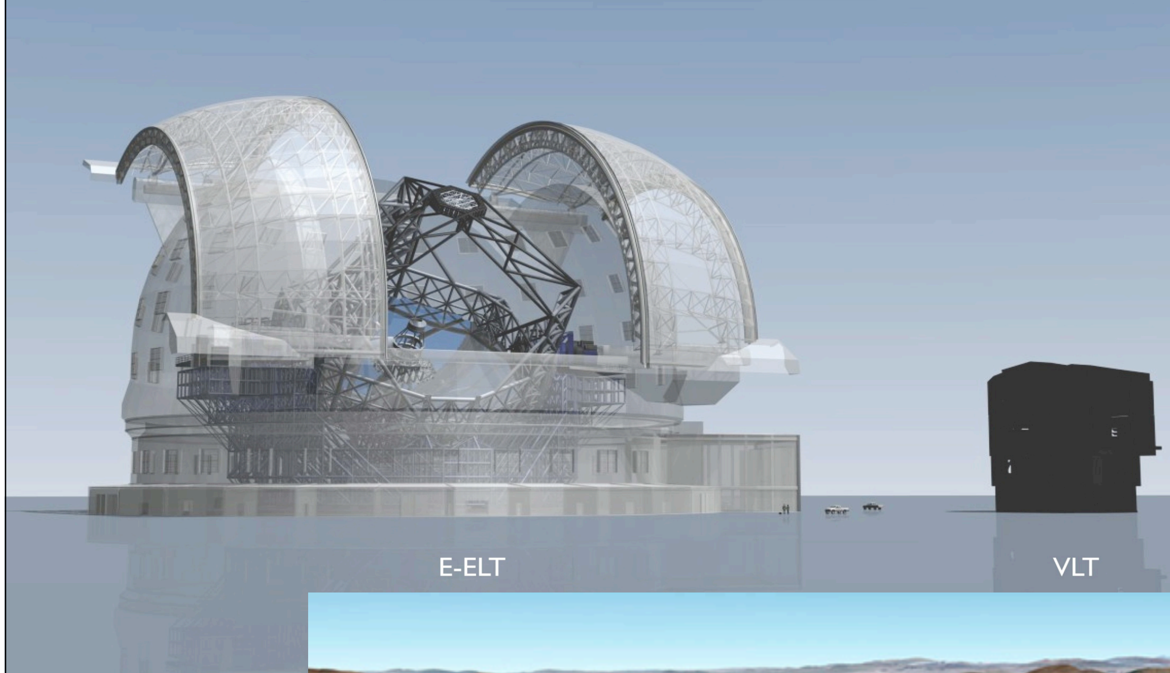
- Range: 470 - 580 nm
- 23 orders with 11000 lines

with the Th we use ~ 1000 lines!!

~450 lines/ord 6 times more flux than ThAr
photon noise: 4 cm/s !

Laser comb will change High Resolution spectroscopy

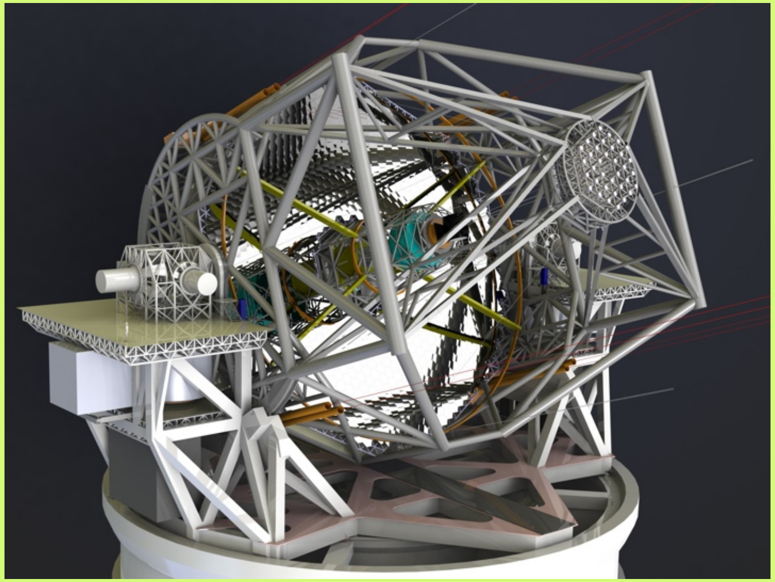
The World's Biggest Eye on the Sky

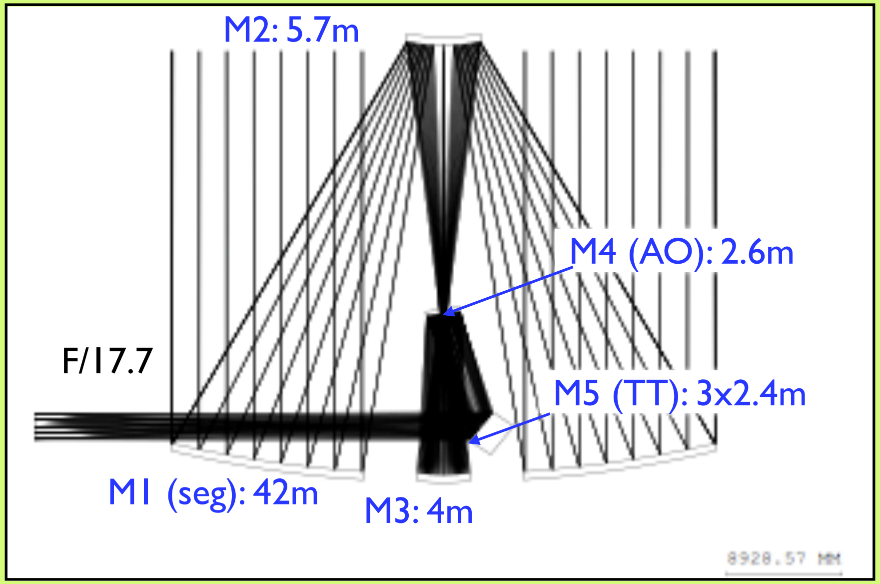


- Start construction in 2012, first light 7 years later (1 billion Euro)
- June 2011 rescaled to 39.3m
- The size of a football stadium

The Telescope

- Nasmyth telescope with a segmented primary mirror of 39.3 m diameter
- Nearly 5000 tons of structure
- Two instrument platforms of the size of tennis courts
- Six laser guide stars

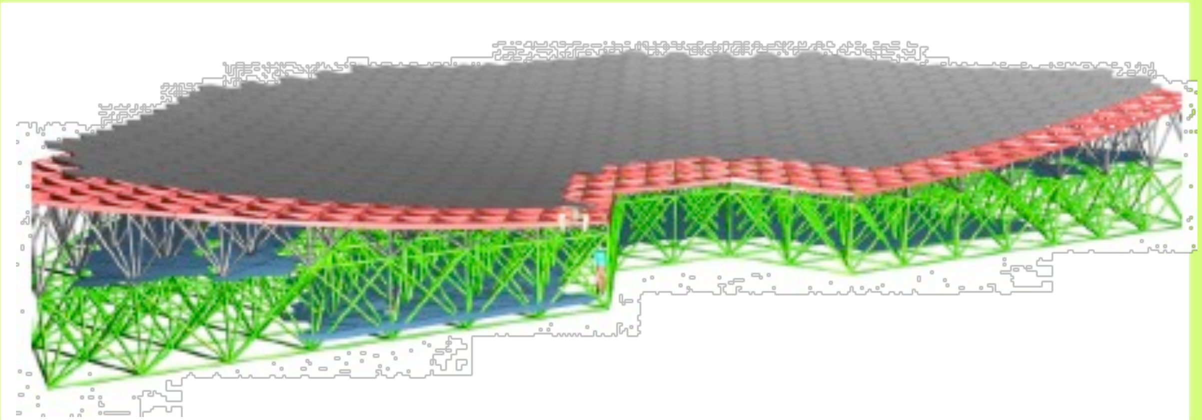


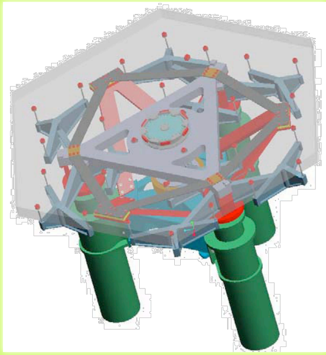


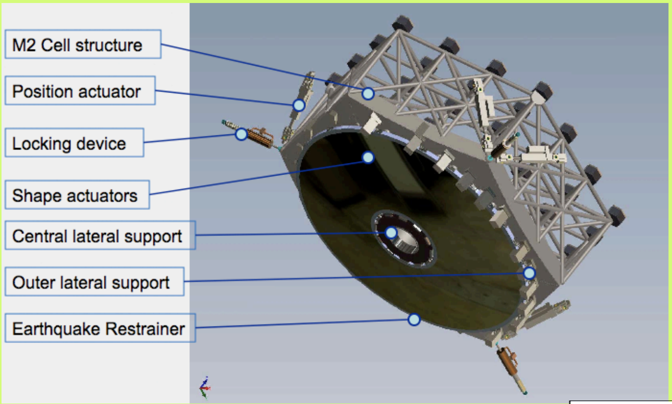
- 5 mirror design to include adaptive optics in the telescope
- Classical 3-mirror anastigmat + 2 flat fold mirrors [M4,M5]
- Outstanding image quality

The Mirrors

- Primary mirror: 39.3 m ∅, (984 segments of 1.4m, 1200 m^2

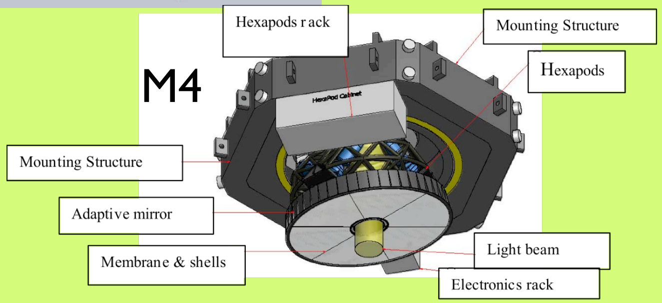






M2

- Secondary: 4.2m ∅, (156 axial supports)
- Tertiary: 4m ∅, controls f-ratio ?

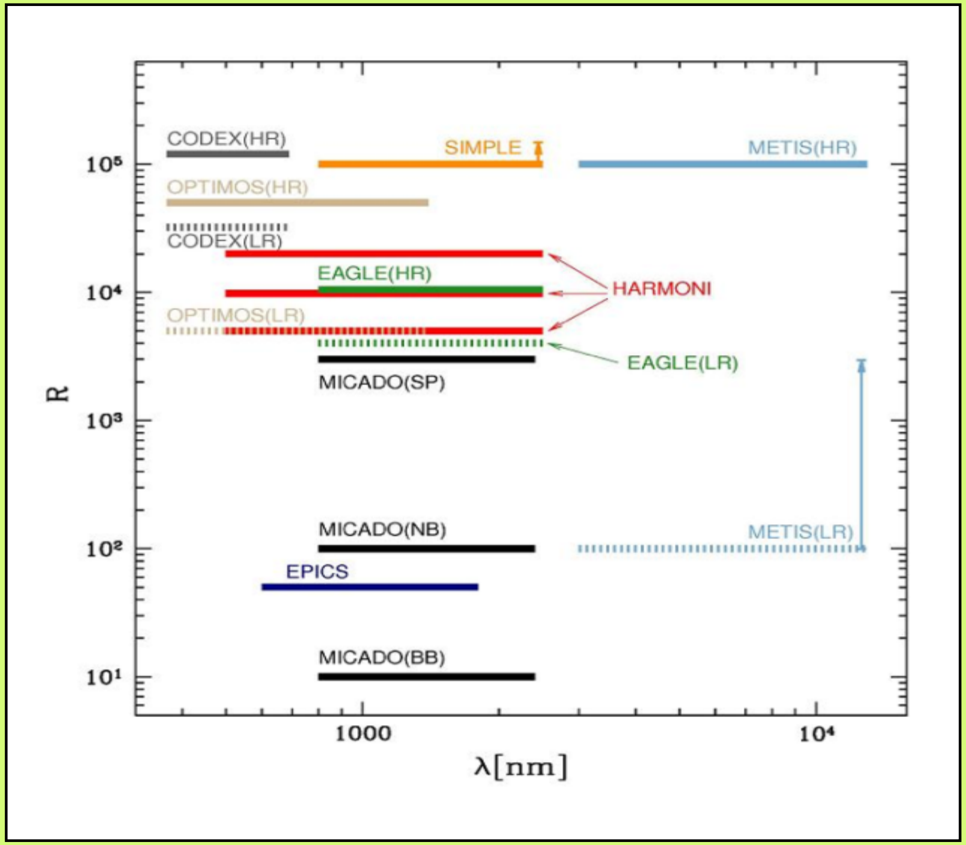


- M4: 2.6m ∅ flat, adaptive with 6000-8000 actuators
- M5: 3x2.4m, flat, tip-tilt

CODEX

COsmic Dynamical EXperiment

- E-ELT can host up to 10 instruments
- FOV 10 arcminutes
- from 300nm to 24 microns
- 9 stations for fixed instruments (2 gravity invariant)



- Eight instrument concepts & two post-focal adaptive optics modules
- 2 first inst. CODEX unlikely first light instrument

Codex Requirements

	Espresso (1UT)	CODEX
Telescope	VLT (8m)	E-ELT (42m)
Scope	Rocky Planets	Earth-Like
Sky Aperture	1 arcsec	0.80 arcsec
R	150000	150000
λ Coverage	350-730 nm	380-680 nm
λ Precision	5 m/sec	1 m/sec
RV Stability	< 10 cm/sec (1/5000 pixel)	< 2 cm/sec

similar technical solutions

CODEX Consortium

Team

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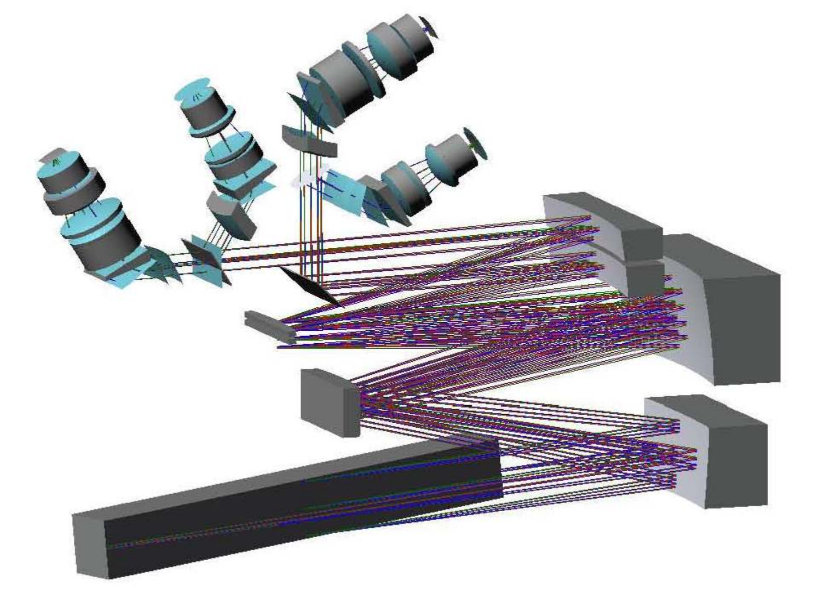
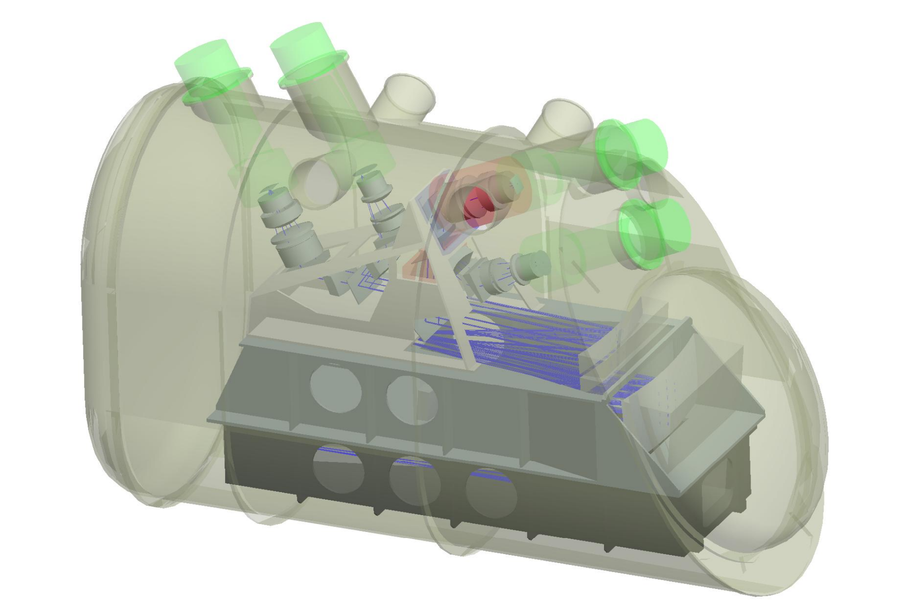
Optical Design

High Resolution at Large telescopes very challenging

Dimensions vacuum vessel:
3x2.4x4.2 (m) [height x width x length]





Anamorphism (12X) plus Pupil Slicer (8X) → 1 echelle (1.6 x 0.2m)
Dychroic → 4 Spectra (2 Red + 2 Blue)
Slanted VPHG compress each of the spectra to 45x706 microns on 2 blue and 2 red cameras
Object + sky (or simultaneous calibration) recorded simultaneously

Concept study for the

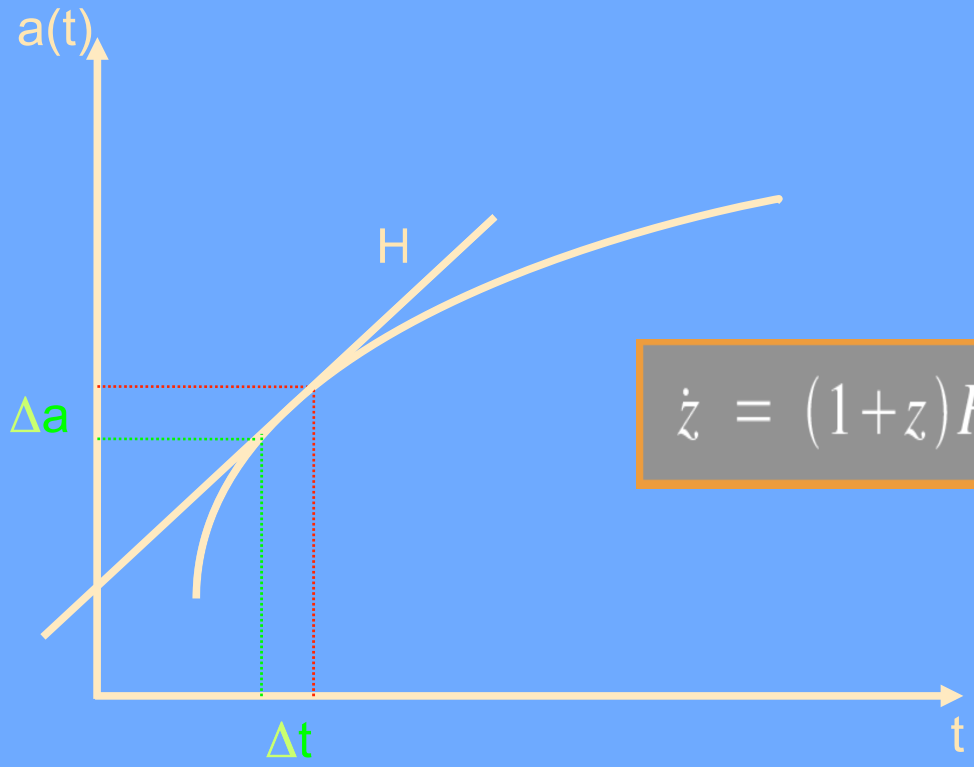
<u>**COsmic**</u>
<u>**Dynamics**</u>
<u>**EXperiment**</u>

"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"

Allan Sandage 1962 ApJ 136,319

The concept

measuring H(z)

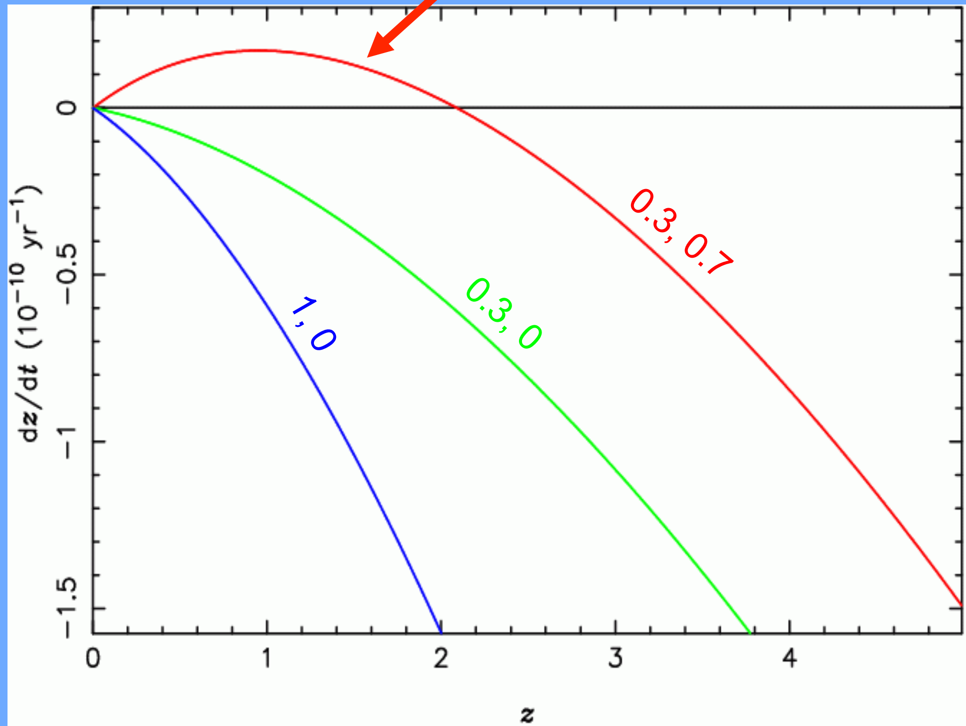


$$\dot{z} = (1+z)H_0 - H(z)$$

$$H = H_o\left[\Omega_{mat}\left(\frac{a_o}{a}\right)^3 + \Omega_R\left(\frac{a_o}{a}\right)^4 + \Omega_{de}\left(\frac{a_o}{a}\right)^{3(1+w)} + \left(1-\Omega_{tot}\right)\left(\frac{a_o}{a}\right)^2\right]^{1/2}$$

Tiny signal!

Signature of $\Omega_\lambda >$



$\Delta t = 10$ years:

➡ $\Delta z \sim 3 \times 10^{-10}$

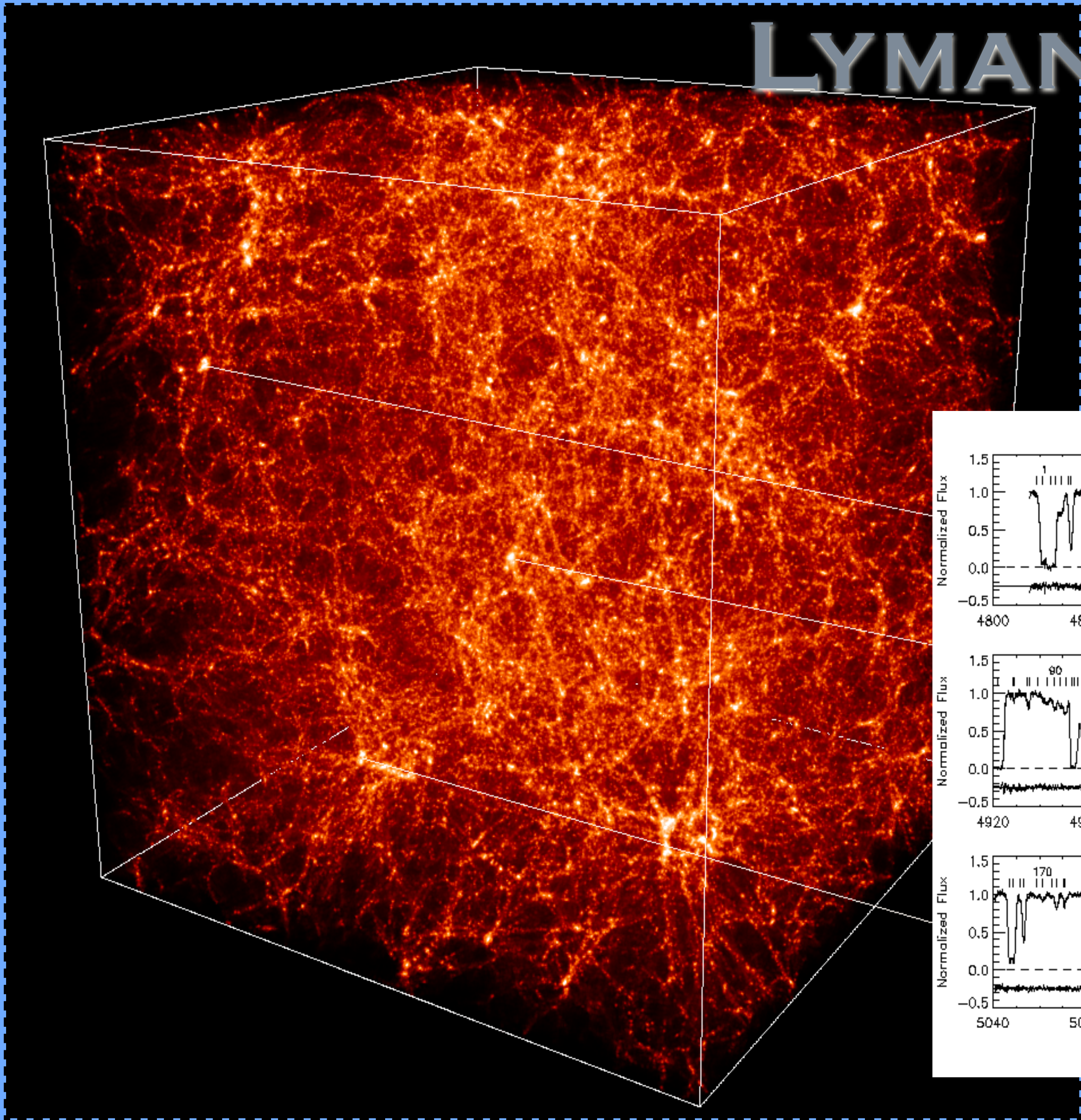
➡ $\Delta \lambda = \lambda \Delta z/(1+z) \sim 3 \times 10^{-7}$ Å

➡ $\Delta v = c \Delta z/(1+z) \sim 2\text{-}10$ cm/s

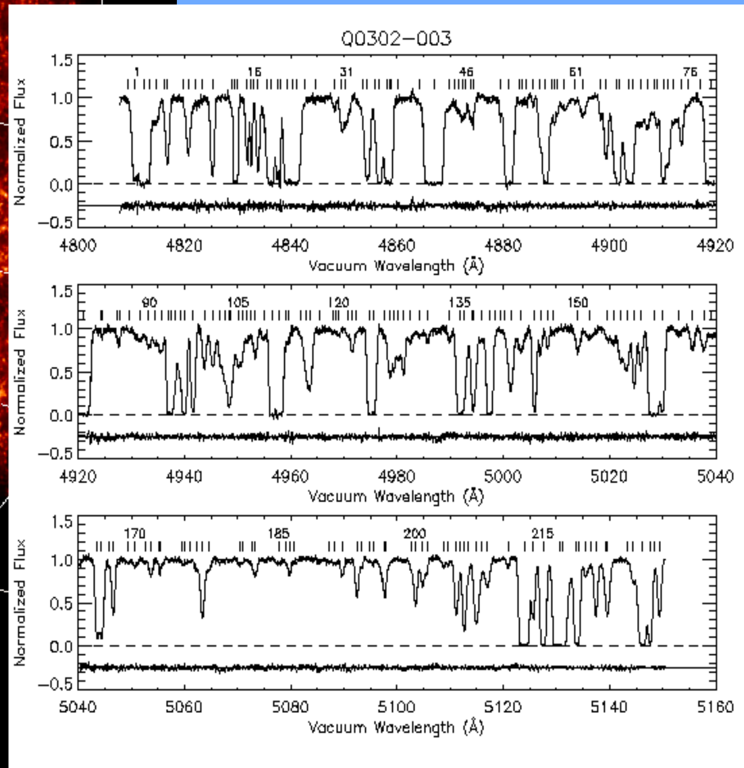
Sandage predictions:

z=0.4,	k=+1	dz/dt =	-0.73 cm /sec/y
	k= -1		-0.3
	k= 0		-0.59
	Steady state		+0.92

Lyman forest



Loeb 1998

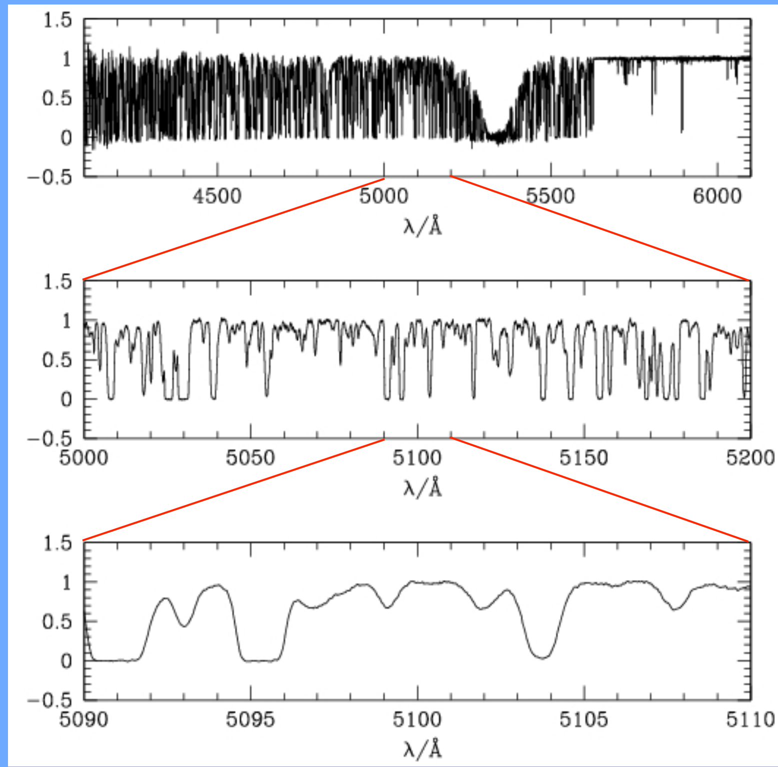


• Each line of sight to a background QSO shows ~10² Ly lines.

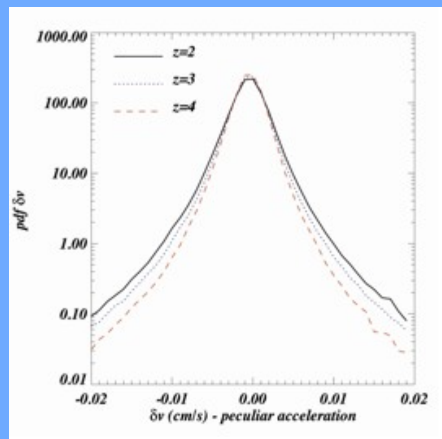
•intergalactic nature imply shallow potential wells.

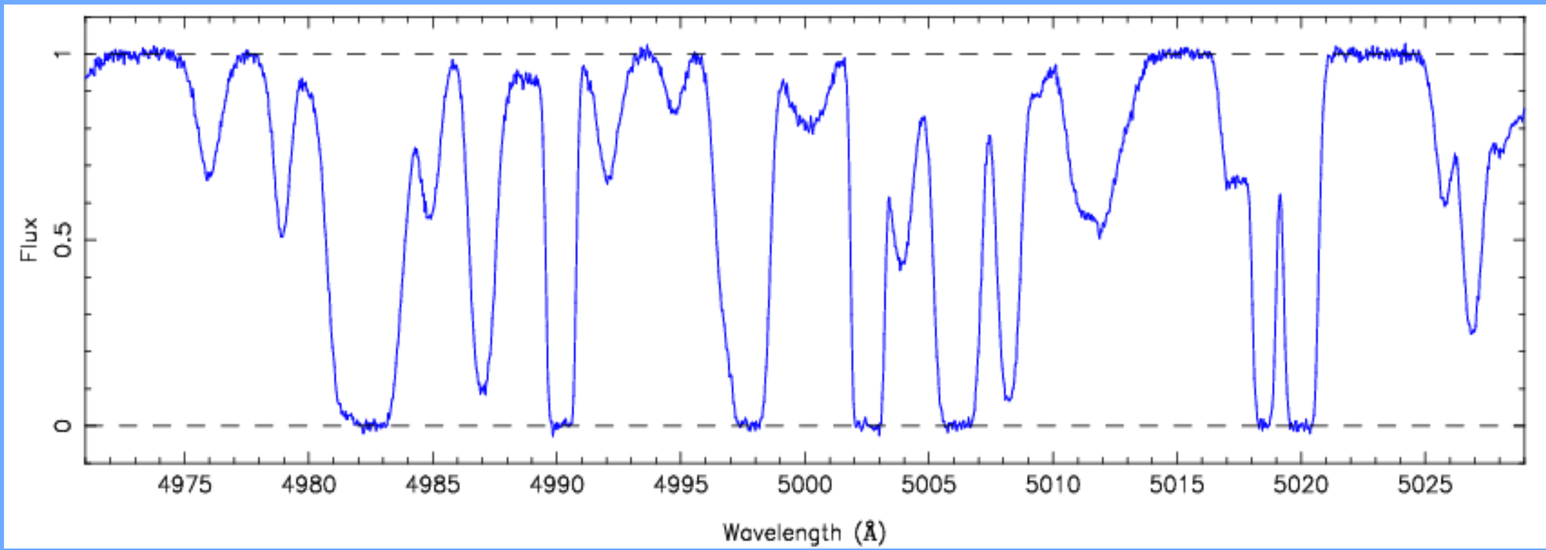
•The Ly forest traces the Hubble flow!

•Line widths are 15-50 km/s.Metal line widths are of order 1 km/s (but reside in deeper potential wells)

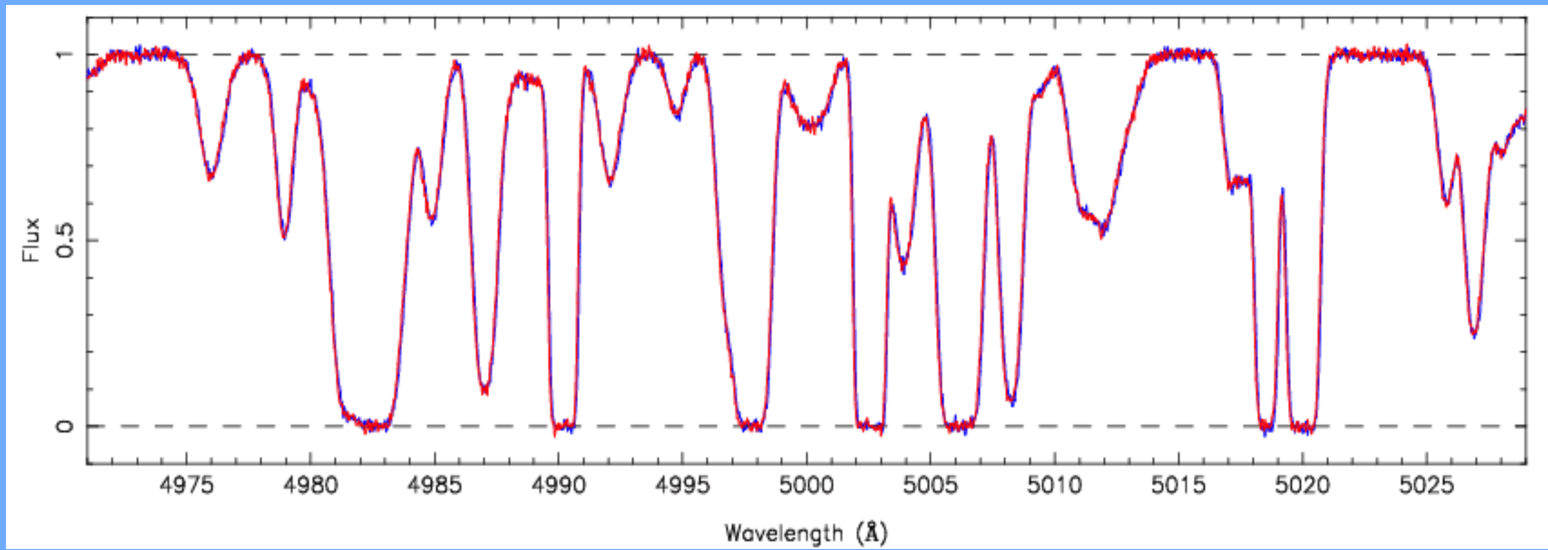


•Simulations yield peculiar accelerations ~x10 below the cosmic signal.

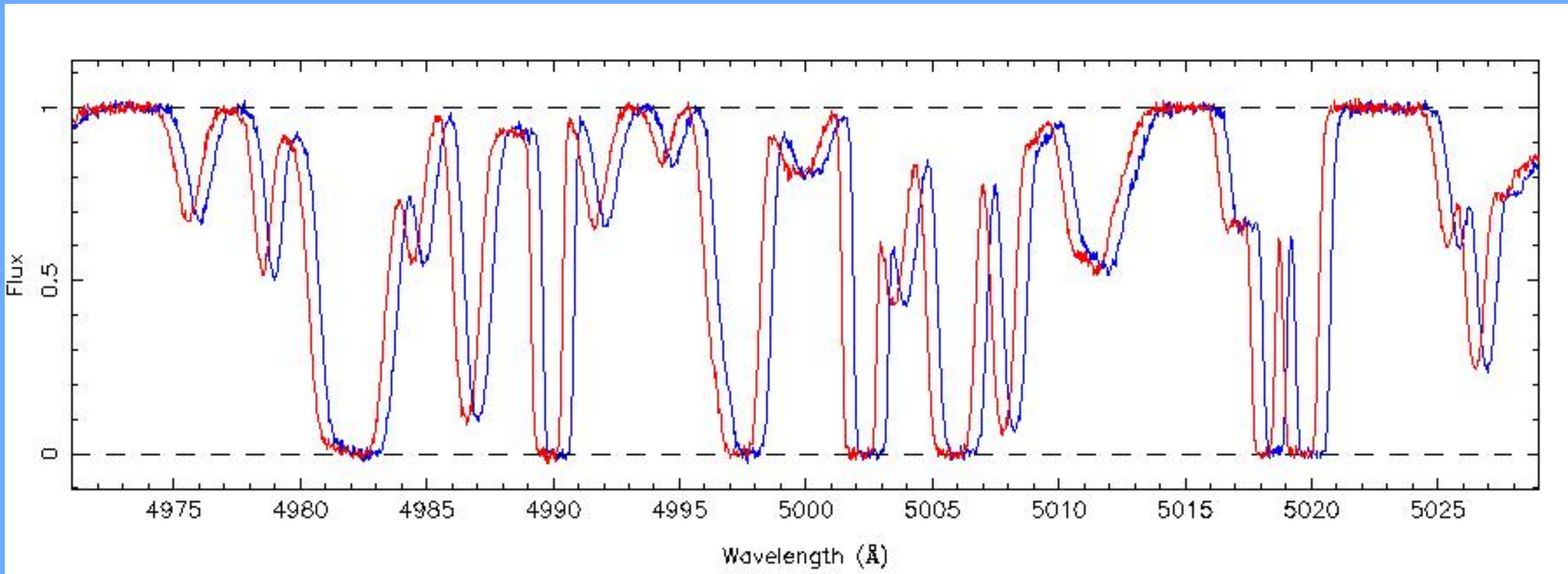




Flux
1
0.5
0
4975
4980
4985
4990
4995
5000
5005
5010
5015
5020
5025
Wavelength (Å)



$\Delta t = 10^6$ years!



for 10^7 years…!!

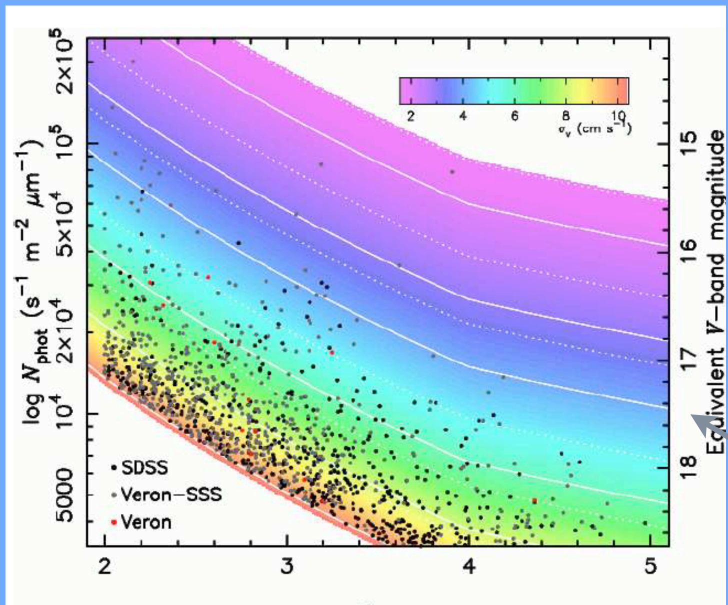
Is detectable?

- Only photon noise:

$$\sigma_v = 1.4*(2350/(S/N))(30/N_{QSO})^{0.5}\,(5/(1+Z))^{1.8}\ \mathrm{cm/sec}$$

σ_v total uncertainty in difference between 2 epochs. Liske et al 2008

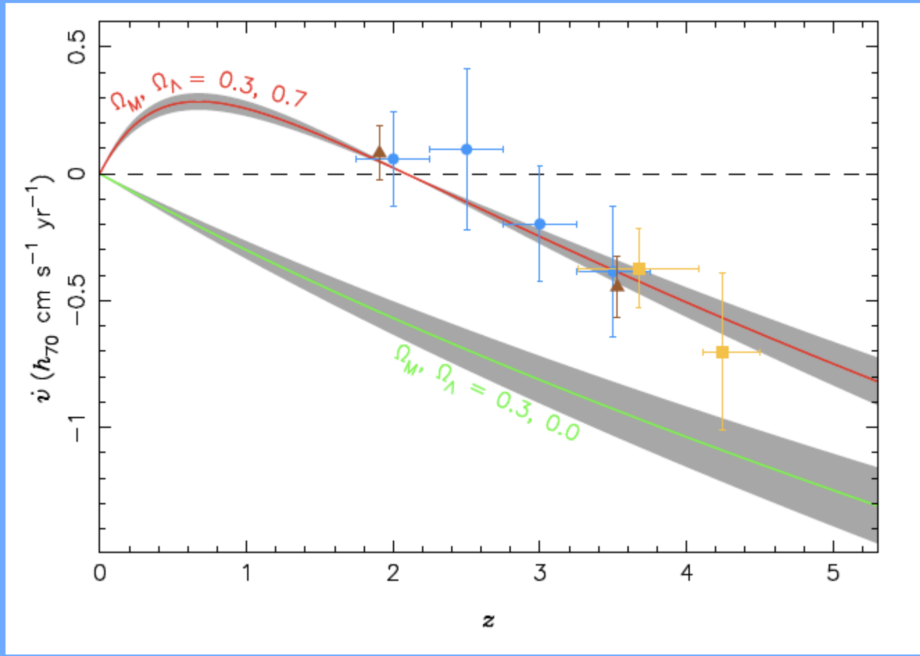
Are there the targets?



QSO selected from existing catalogues: Veron, SDSS

with T=2000h

After that few bright QSOs discovered....

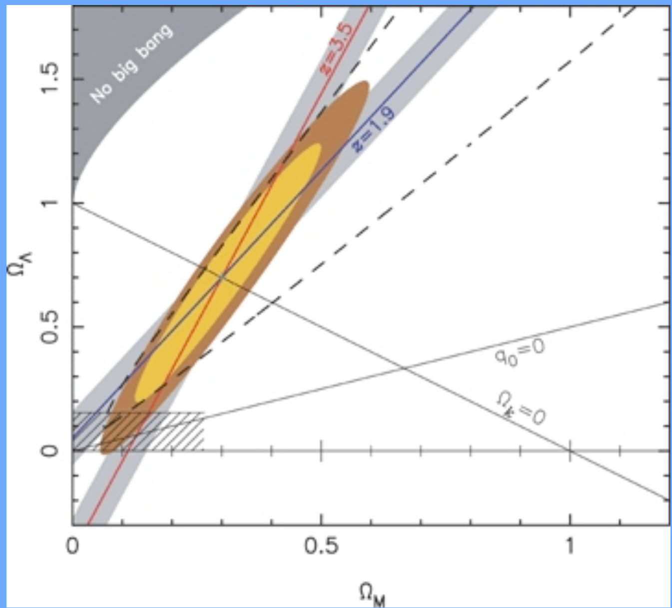


Different colors for different implementation of the experiment

shadow for Ho=70+/- 8 km/s/Mpc

$$O = \left(\frac{D}{42\,\mathrm{m}}\right)^2 \frac{\epsilon}{0.25} \frac{t_{\mathrm{int}}}{2000\,\mathrm{h}}$$

precision & accuracy for 400 nights of the E-ELT over 20 years (conservative)




Thank you