Emerging Age of Precision Spectroscopy in Astronomy using Laser Frequency Combs

National Institute of Advanced Industrial Science and Technology
AIST

Malte Schramm AIST

Kavli IPMU Sep 2015

ERATO
MINOSHIMA IOS PROJECT

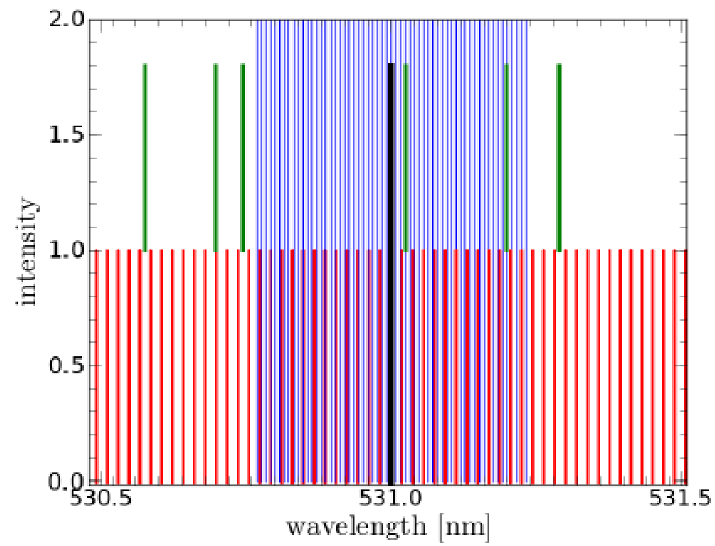
Team: H. Inaba, S. Okubo, K. Nakamura, A. Onae, K. Hosaka, , T. Kobayashi (AIST)
K. Minoshima (UEC), F.L. Hong (YNU),Hiroki Yamamoto (YNU)
Collaborators: H. Izumiura, E. Kambe (OAO)

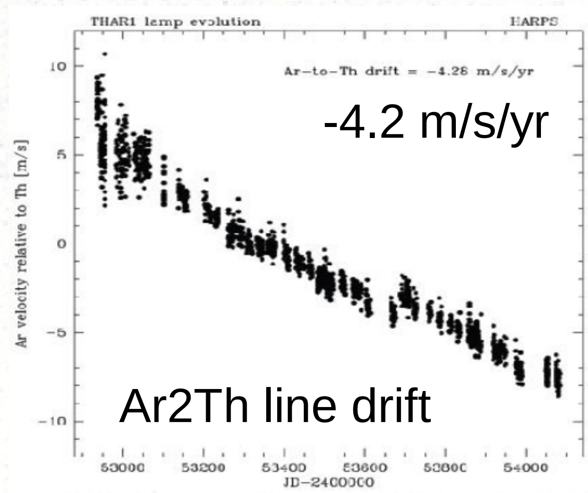
Astro-comb facilities

Why Astro-comb?

The “comb” cosnists of evenly spaced lines who’s frequencies are known *a priori* to better than 1 in 10^{15}

- Homogenous wavelength coverage
- High intensity lines over the whole range
- Simultaneous reference but no overlap spectrum (e.g. Iodine Cell)
- Ultra stable (Repeatability)

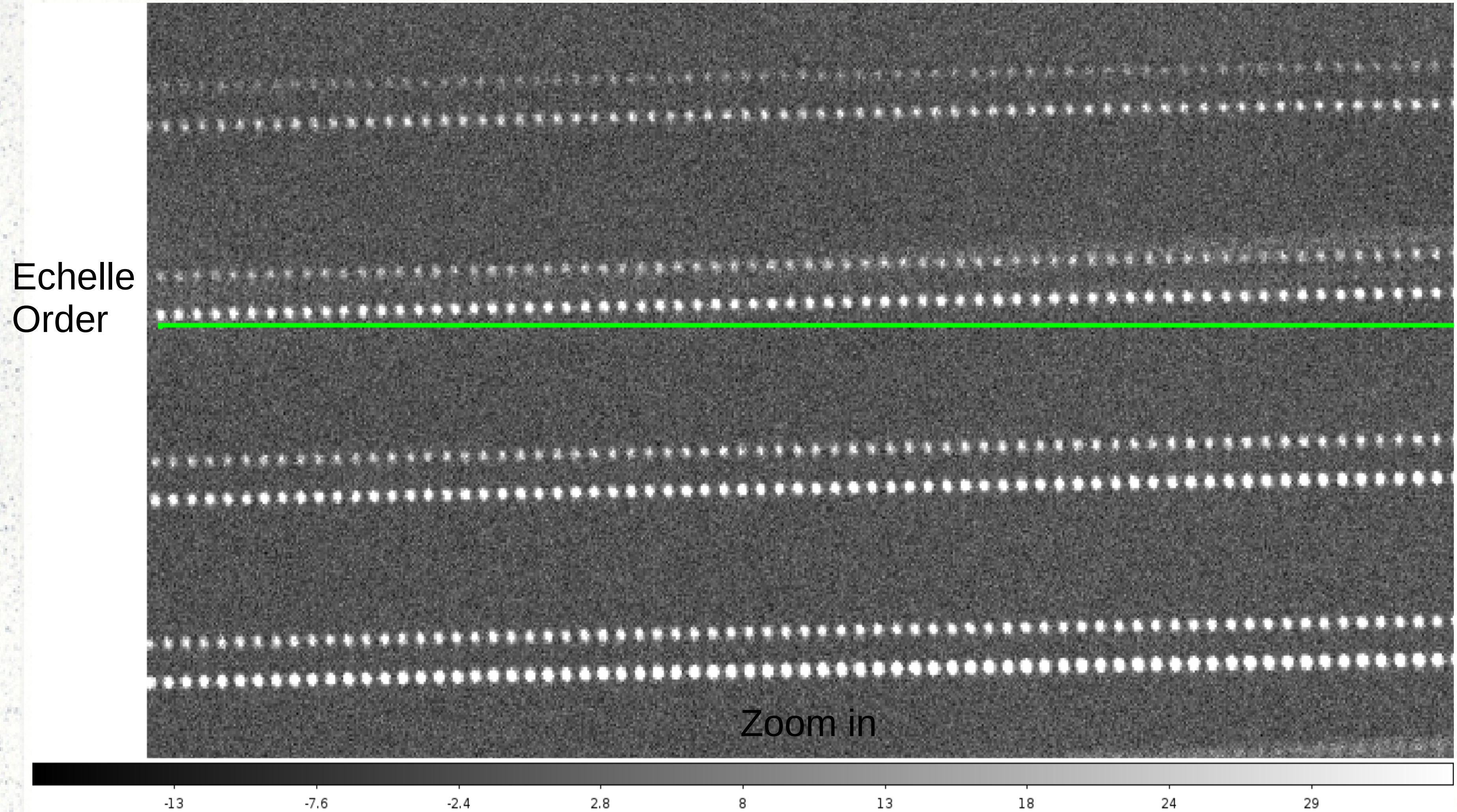




OAO/HIDES Comb Character Sheet

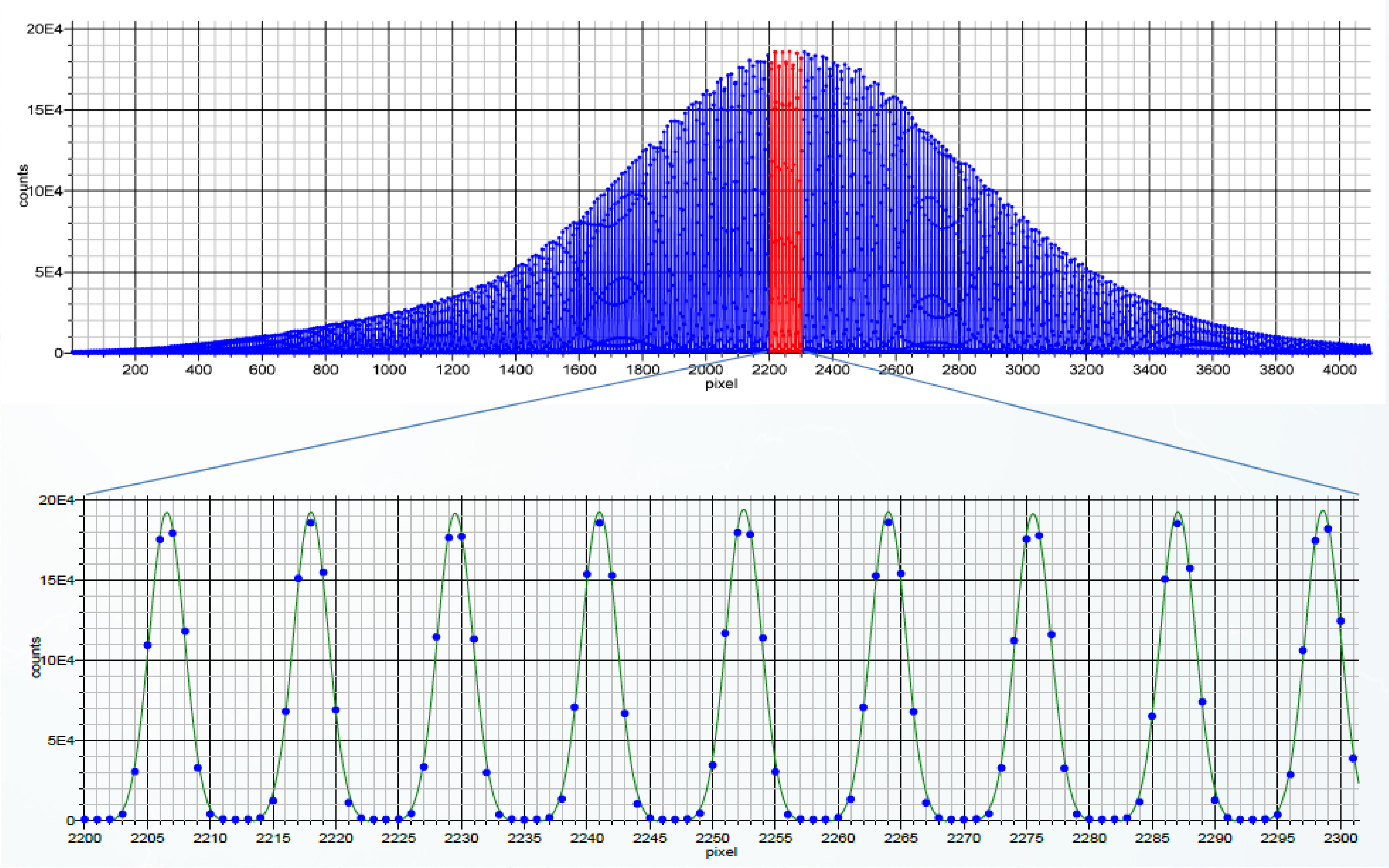
- Optical Comb 380-540 nm (300-2500 nm possible)
- homogenous line spacing 100 Mhz → 20 Ghz
- narrow comb lines with a FWHM of few kHz (determined by the reference laser)
- Extremely low frequency (wavelength) uncertainty of the comb itself at the sub-mm/s level in case of using Rb-based reference
- Final accuracy ~<m/s level (current level 30 m/s with Th-Ar)

How does a comb signal look like
Test data from ESO 3.6m/HARPS (2010)

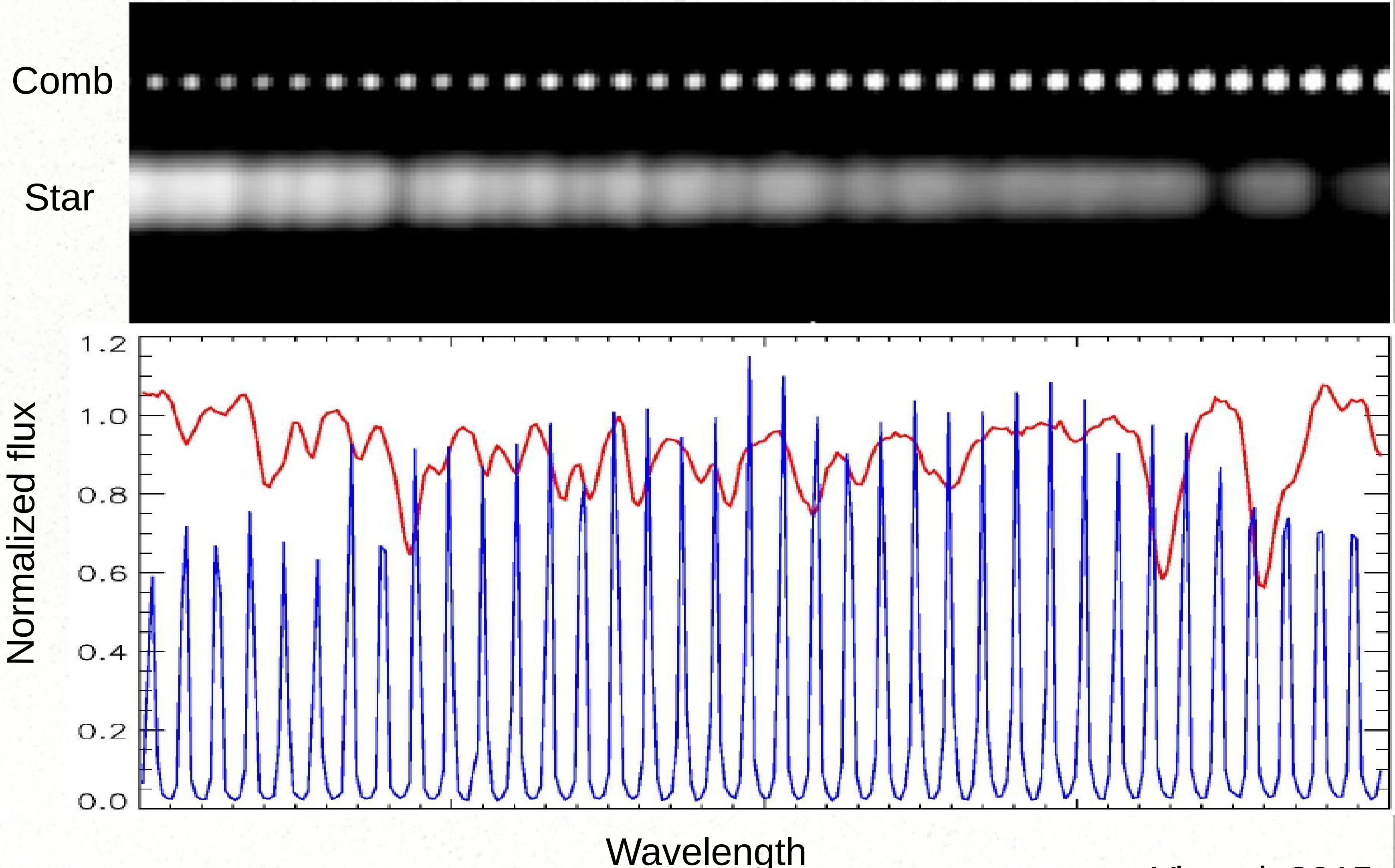


from ESO archive

The Comb Spectrum

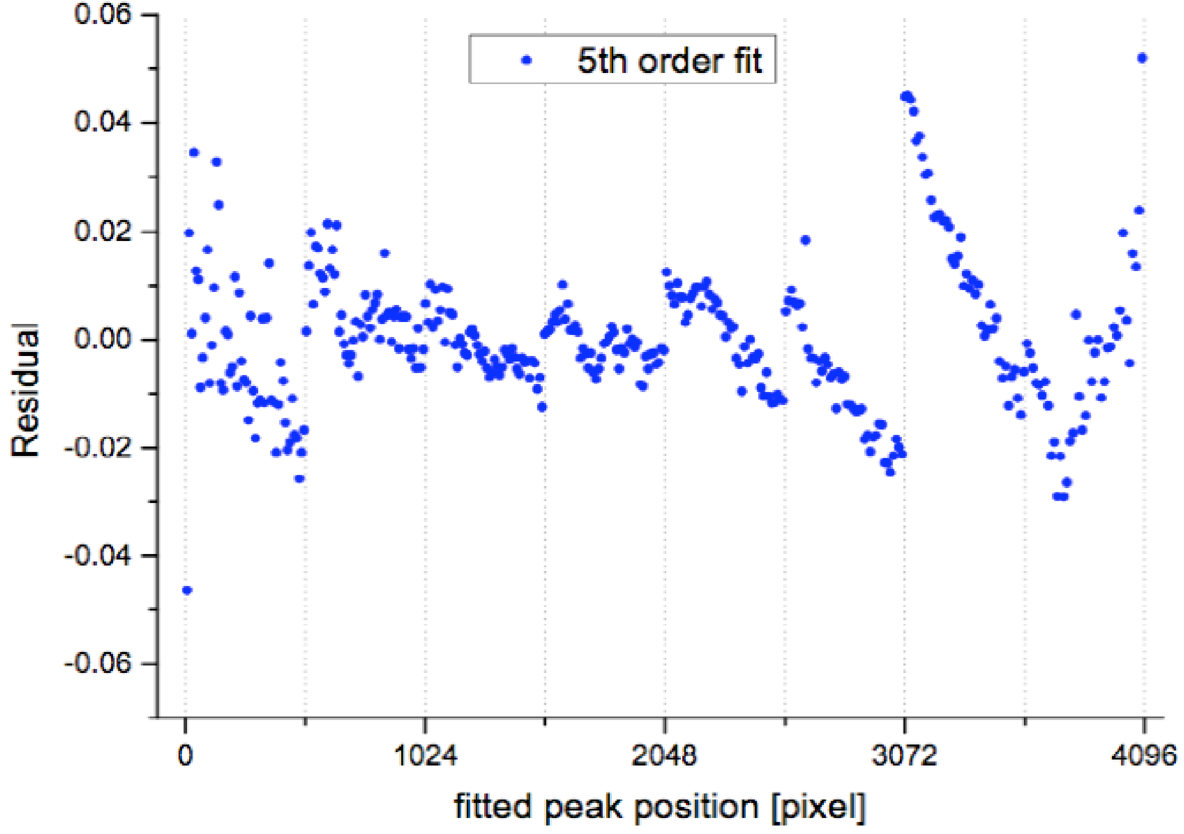


Example of LFC calibrated stellar spectrum



Yi et al. 2015

A comb can reveal CCD inhomogeneities



Most important application for now: Exoplanets

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

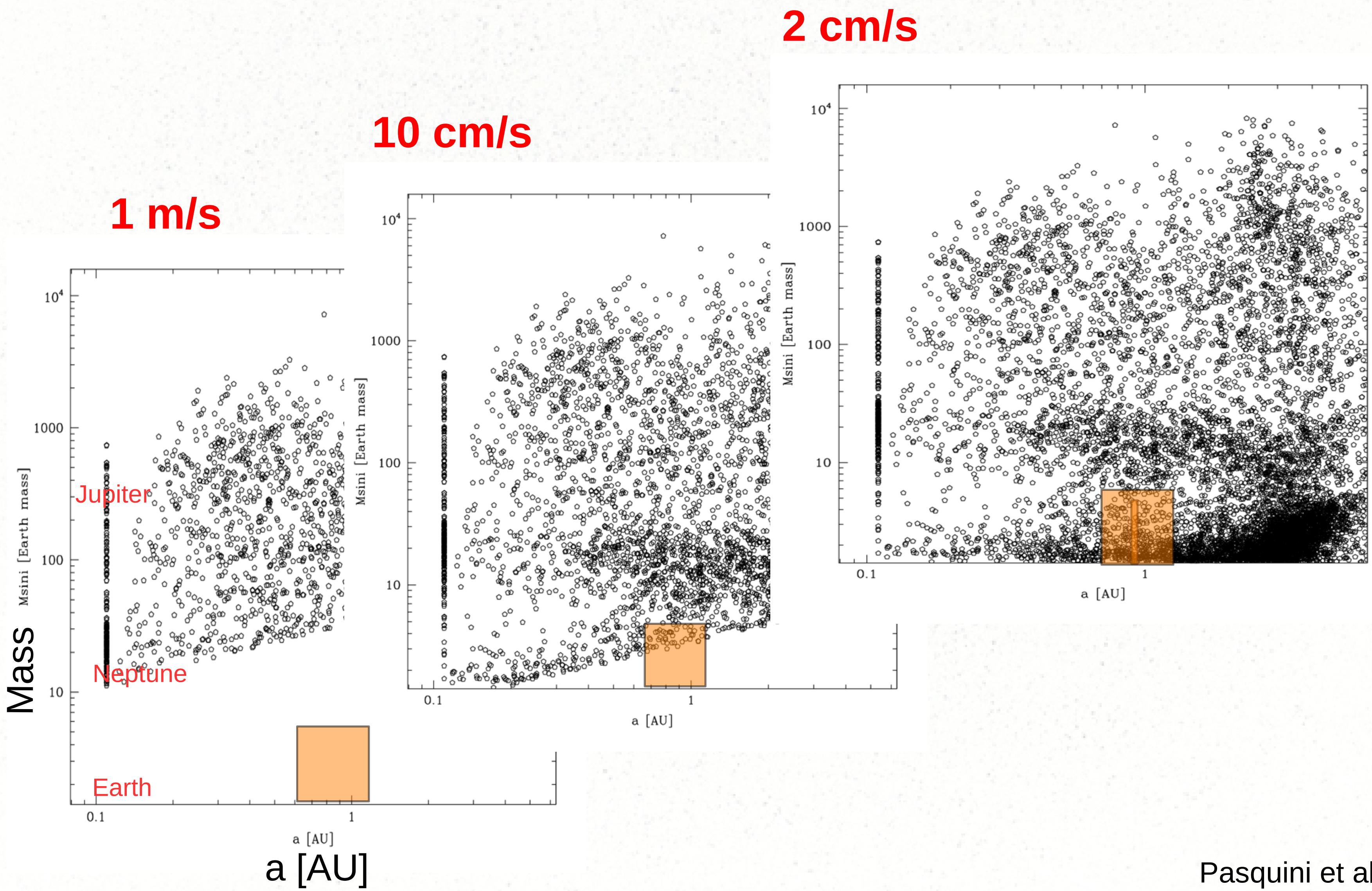
Possible targets for HIDES

RV Stability

Planet Detectability with radial velocities

- Typical issues:
  - Telescope guiding (30 cm/s)
  - Detector instabilities and wavelength reference precision

Detecting low-mass planets

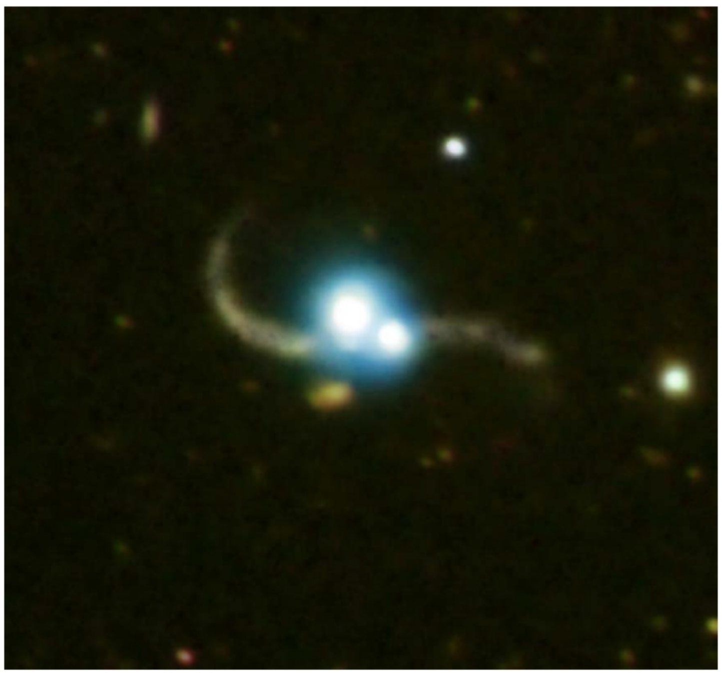


Pasquini et al.

Binary Supermassive BHs

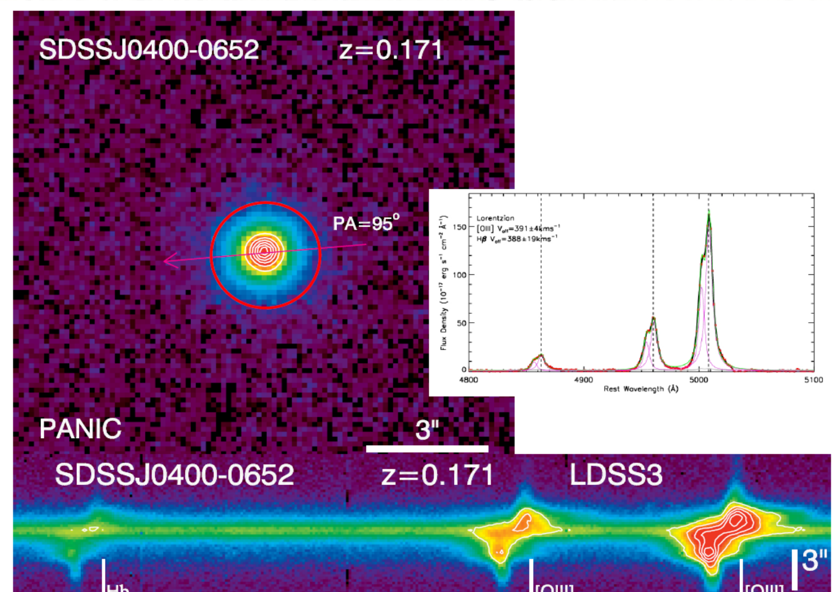
- Why are they interesting?

  - Provide constraints for gravitational wave detections and galaxy formation models



* Example of a ~20 kpc binary AGN (Greene et al. 2010)
* We know 100s of binary AGN on larger scales hundreds of kpc ~ tens of kpc
*Easy to resolve with imaging or spectroscopy

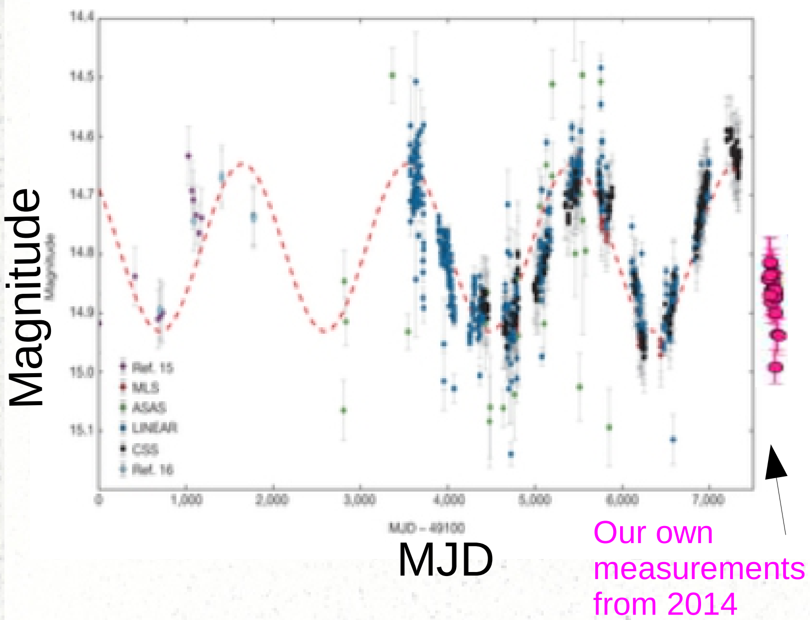
The Challenge: sub-pc binary BHs



- Not all DP emitters are binary AGN
- Beware of kinematics origin: smooth stellar distribution but two spatially offset [OIII] components

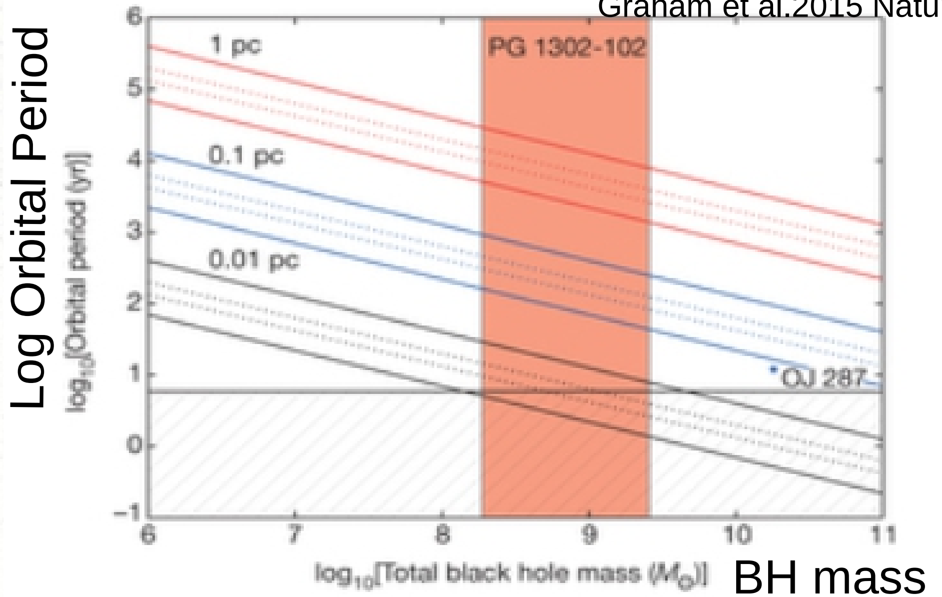
Binary BHs on sub pc – pc scales

- Here SUBARU (HSC+PFS) can contribute: Only very few candidates known



We need spectroscopic monitoring with accurate wavelength solution to confirm the binary nature and provide targets for gravitational wave detections

Graham et al.2015 Nature

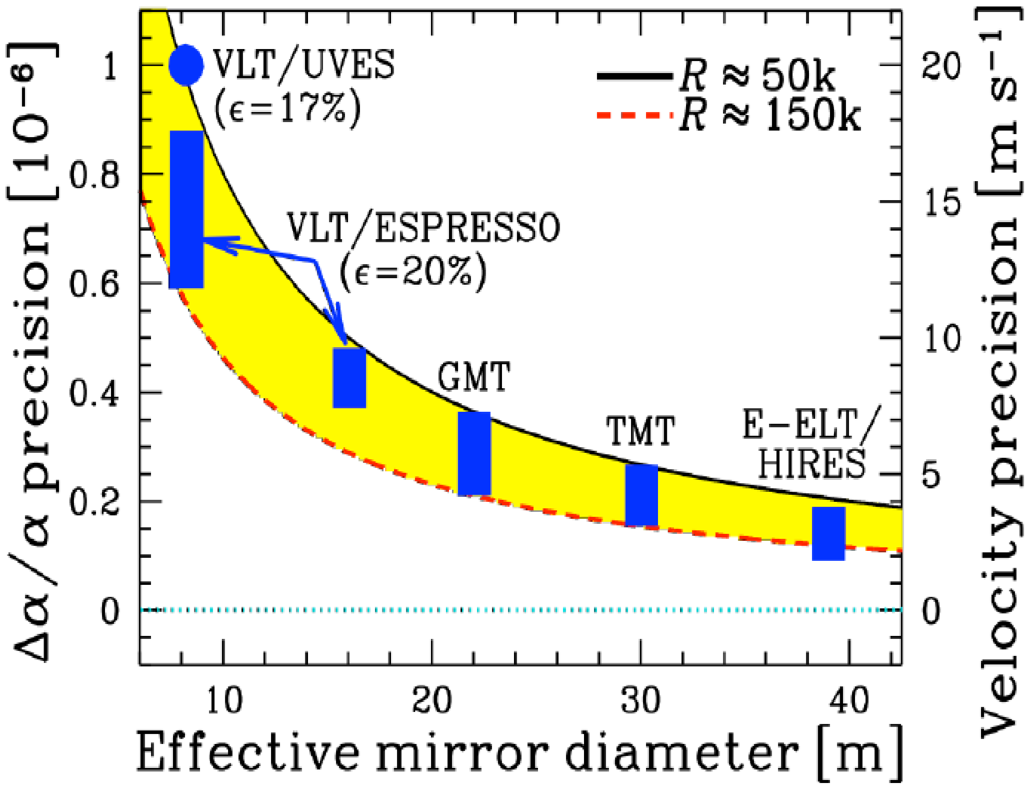


Monitoring AGN to identify potential candidates

Cosmological variation of the fine structure constant

Variation of 1 ppm in α or μ leads to a velocity shift of 20 m/s

- Typically use Quasar absorption line systems e.g. Lya forest
- Currently extremely challenging task
- Good test for next generation telescopes
- Precision can finally compete with clock measurements

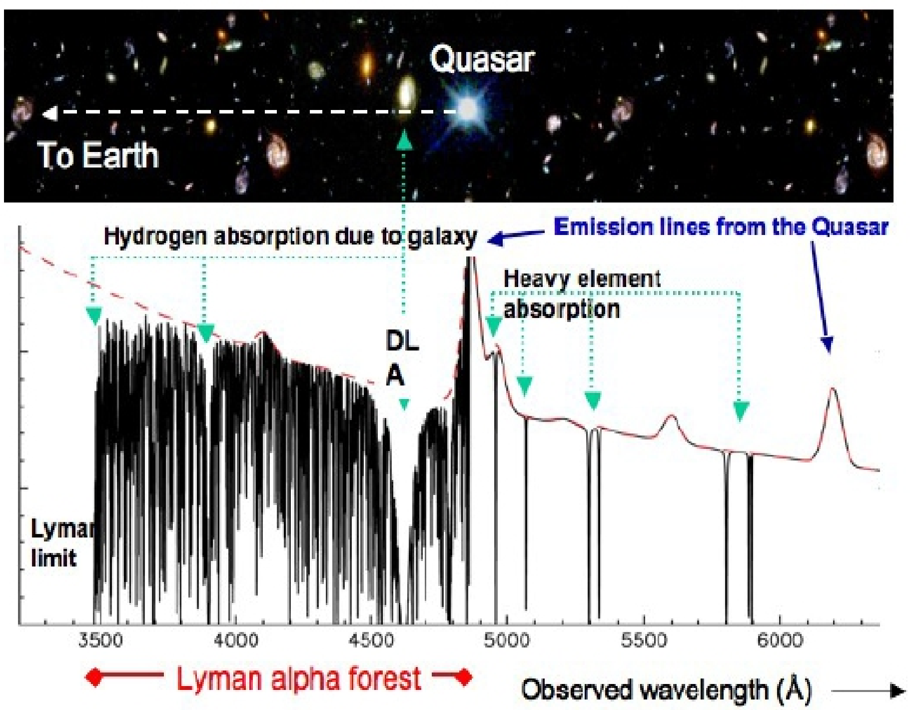


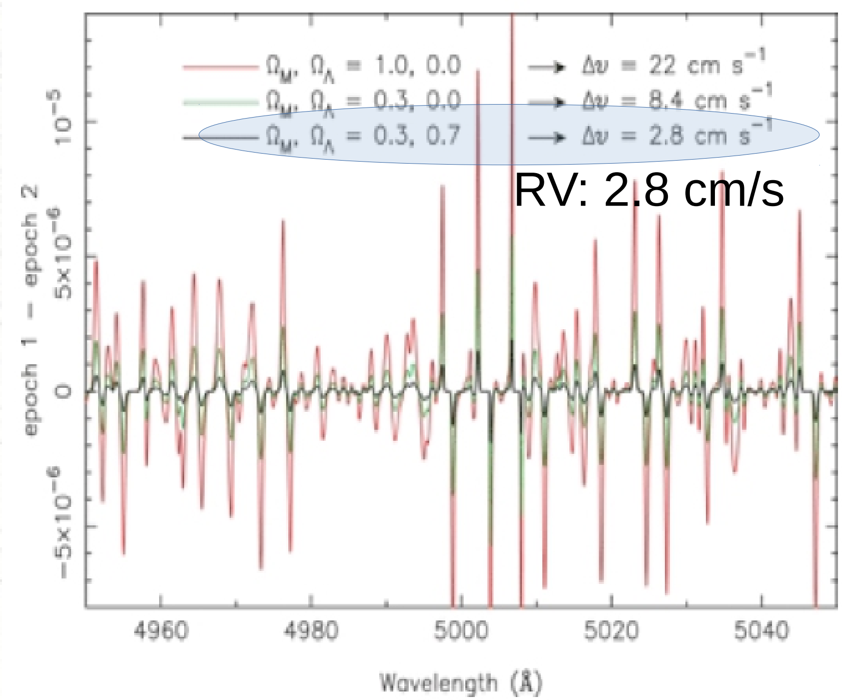
CODEX like instruments aim at even better presicion

Most challenging task:

Direct measurements of the dynamics of the universe

"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" **Sandage 1962 ApJ 136,319**





Most challenging task:

Direct measurements of the dynamics of the universe

"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" **Sandage 1962 ApJ 136,319**

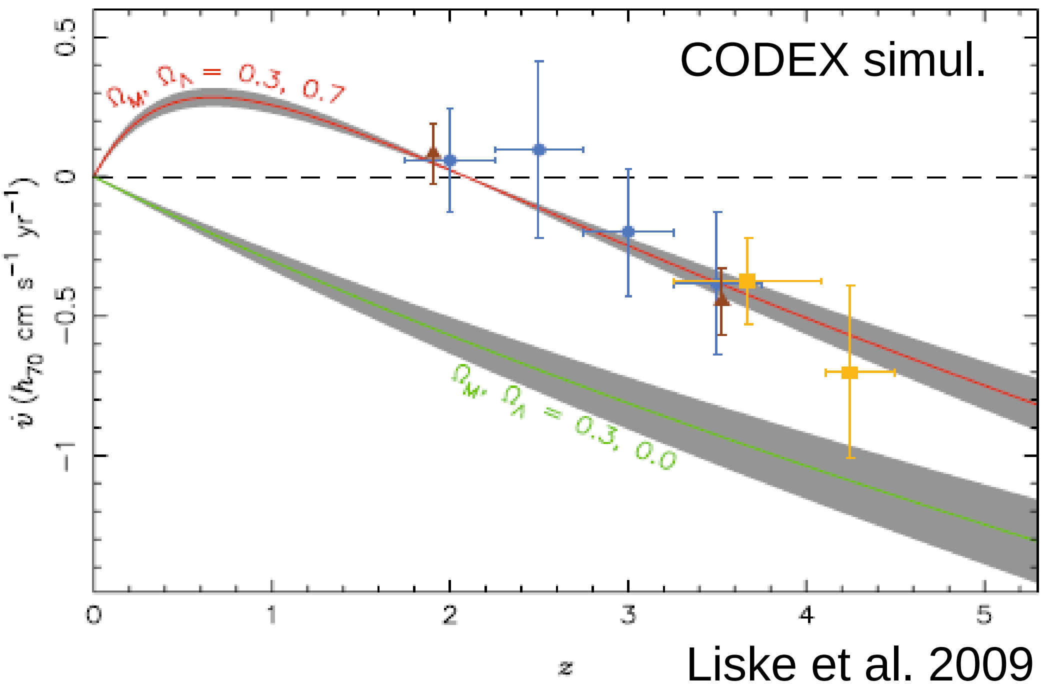
Requirements:

*** TMT or E-ELT class telescope**

***Absolute wavelength accuracy at 1-2 cm/s (~25 kHz) given 20 yr time scale**

***Stability 1-2 cm/s/night**

LONG TERM STABILITY IS CRUCIAL



Science Requirements or the need for LFCs

	expansion	planets	stars	metals	constants
FOV	few arcsec	few arcsec	few arcsec	few arcsec	few arcsec
tot. energy in fibre	$\geq$ 80%	$\geq$ 80%	$\geq$ 80%	$\geq$ 80%	$\geq$ 80%
spectral resolution	$\geq$100 000	150 000	120 000	$\geq$ 100 000	$\geq$ 150 000
spectral sampling	$\geq$ 3	$\geq$ 4	$\geq$ 4	$\geq$ 3	$\geq$ 4
wavelength range (μ)	0.35-0.67	0.38-0.68	0.38-0.68	0.37-0.75	0.37-0.68
wavelength accuracy					$\leq$ 1m/s
RV stability	2 cm/s (20yr)	2-5 cm/s (10 yr)			
throughput	$\geq$0.2				
typical magnitude	15-17	$<$11	15	17-21	16-18
source size	point sources	point sources	point sources	point sources	point sources
minimum exposure time	photon noise limit (typically 15min)	typically 15min	phot. noise lim. (typically 15min)	phot. noise lim. (typically 15min)	phot. noise lim. (typically 15min)
maximum cumulative exposure time	few hundreds of hours	few tens of hours	few tens of hours	few hundreds of hours	few tens of hours
target density	low	low	low	$\leq$ 0.01-1 arcmin^{-2}	low
background	dark time	grey-dark time		dark time	dark time
sky subtraction	?	?		yes	yes
sky coverage	$\geq$ 90%	$\geq$ 90%	$\geq$ 90%	$\geq$ 90%	$\geq$ 90%

Haehnelt 2010

Summary

- Astro-combs provide a reproducible, (long-term) stable wavelength calibrator of evenly spaced lines with known frequencies at 1 in 10^{15}
- Currently main application for exoplanet detection (even with small telescopes)
- TMT and E-ELT will enable new science ()
  - Variation of fine structure constant comparable to atomic clocks
  - Sandage test (Cosmological probe)
  - Primordial nucleosynthesis