ESPRESSO - no limits

Prequel & Science
Universal Expansion

The original Hubble diagram (Hubble 1929):

All distant galaxies are found to recede from us. Hubble's Law: \( v = H_0 d \) → **The universe expands!**
Relativistic Big Bang Cosmology

Expansion
Relativistic Big Bang

Cosmology

Expansion

Cosmic Microwave Background

Abundance of light elements

Structure formation
Which of the solutions of the Friedmann equation corresponds to reality?

Or in other words:
What is the stress-energy tensor of the universe?
For each mass/energy component i, what is $\Omega_i$, $w_i$?

How can these be measured?
- Dynamics
- Geometry
- Clustering (the universe is not homogeneous on small scales!)

Density parameter
Equation of state parameter

Both determined by gravity in GR
Which of the solutions of the Friedmann equation corresponds to reality?

Answers have already been provided by:

- Cosmic Microwave Background
- Supernovae type Ia
- Large scale structure of galaxies and intergalactic medium
- BAOs
- Galaxy clusters
- Weak lensing

Tegmark et al. (2004)
With the assumptions of homogeneity and isotropy, the concordance model finds a FRW metric with a non zero cosmological constant.

$$H^2 = \frac{8 \pi G}{3} \rho - \frac{k c^2}{a^2}$$

$$H(z)^2 = \frac{8 \pi G}{3} [\rho_\gamma(0)(1+z)^4 + \rho_m(0)(1+z)^3 + \rho_k(0)(1+z)^2 + \rho_\Lambda]$$

$$\rho_k \sim 0 \; \text{(flat space)} \quad \Omega_m \sim 0.30 \quad \Omega_\Lambda \sim 0.70$$

We do not know what $\rho_\Lambda$ is and how it evolves. **Dynamics has never been measured.**

All other experiments, extremely successful such as **High Z SNae search and WMAP** measure geometry: dimming of magnitudes and scattering at the recombination surface and **clustering** (growth of structure).
If we do not measure we do not know

But.. Geometry tells us that the Universe is Expanding, so why bother to measure dynamics?

Measurement of the dynamics of the Universe can be compared to basic experiments such as the test of the principle of equivalence between Inertial and Gravitational mass…

Without it, it is like measuring the geometrical orbits of planets w/o measuring their accelerations… (Copernicus without Kepler)
Can we measure the history of the expansion directly?

Goal is to measure or reconstruct the unknown function $a(t)$. 
Can we measure the history of the expansion directly?

Yes: Measure $a(z)$, $\frac{da}{dt}(z) \rightarrow a(t)$
Need to measure $H(z)$ using the dynamics!
Can we measure the history of the expansion directly?

Yes: Measure $a(z)$, $\frac{da}{dt}(z) \rightarrow a(t)$

Need to measure $H(z)$ using the dynamics!
Can we measure the history of the expansion directly?

Yes: Measure $a(z)$, $da/dt(z) \rightarrow a(t)$
Need to measure $H(z)$ using the **dynamics**!
Direct Dynamical Measurement of the Expansion

One way to implement this experiment is to monitor the redshifts of cosmological sources. The change of these redshifts as a function of time is a direct signal of the de/acceleration of the universe's expansion and hence of its dynamics.
Measuring $H(z)$

\[
\frac{z(t_0 + \Delta t_0) - z(t_0)}{\Delta t_0} = \frac{\Delta z}{\Delta t_0} \approx \frac{dz}{dt}_0 = (1 + z) H_0 - H(z)
\]
~1985 – Garching

Radio lines? (P. Shaver)
Cosmic Signal

\[ 1 + z(t_0, t_e) = \frac{a(t_0)}{a(t_e)} \]

t_e = \text{emission epoch}

\[ t_0 = \text{actual epoch} \]

\[ dz = \frac{\partial z}{\partial t_0} dt_0 + \frac{\partial z}{\partial t_e} dt_e; \]

\[ \dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e} \frac{dt_e}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{\dot{a}(t_e)}{a(t_e)} \frac{a(t_0)}{a(t_e)} \frac{1}{1 + z} \]

\[ \dot{z} = (1 + z)H_0 - H(t_e) \]

\[ H = H_0 \left[ \Omega_M (1 + z)^3 + \Omega_R (1 + z)^4 + \Omega_\Lambda + (1 - \Omega_{tot}) (1 + z)^2 \right] \]

where \( \Omega_{tot} = \Omega_M + \Omega_R + \Omega_\Lambda \approx 1 \)
The change in sign is the signature of the non zero cosmological constant.
Direct Dynamical Measurement of the Expansion


“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 $z = \frac{d \Delta l}{l_0}$ 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”

Since then:

How to Measure this signal?

**Masers**: in principle very good candidates: lines are very narrow and measurements accurate: however they sit at the center of huge potential wells: large peculiar motions, larger than the Cosmic Signal are expected.

**Molecular Lines with ALMA**: as for Masers, local motions of the emitters are real killers. Few radio galaxies so far observed show variability at a level much higher than the signal we should like to detect.

**Ly$\alpha$ forest**: Absorption from the many intervening lines in front of high-z QSOs are the most promising candidates. Simulations, observations and analysis all concur in indicating that Ly$\alpha$ forest and associated metal lines are produced by systems sitting in a warm IGM following beautifully the Hubble flow!
The Lyman Forest
Today and ... ... years after
Observing $dz/dt$ in the Ly-$\alpha$ Forest
Observing $dz/dt$ in the Ly-$\alpha$ Forest
Observing $dz/dt$ in the Ly-α Forest

$\Delta t = 10^6$ years!
Observing $dz/dt$ in the Ly-α Forest

$\Delta t = 10$ years:
$\Delta$flux $\sim 10^{-6}$
The E-ELT

E-ELT concept:
- 42m aperture (↓ 39? – 20%)
- ~1000 1.4m mirror exagonal segments (↓ -2 circles)
- NIR/optical
- First light 2018? (↑)

See ESO's web pages for details
The HARPS Experience

**Th-Th < 10 cm/sec**

**O-C < 80 cm/sec**

---

**Graph 1:**
- Measured rms: 30 cm/s (thermal dilatation of CCD)
- Measured rms: 10.8 cm/s
- Photon noise: 10.6 cm/s

**Graph 2:**
- Radial Velocity (km s⁻¹)
- "Velocity Curve" of mu Arae

---

**Source:** ESO PR Photo 25d/04 (25 August 2004) © European Southern Observatory
HARPS: it is possible!

- Exoplanets (HARPS)
  long term accuracy 1m/s, short term (hours) 0.1m/s (and largely understood)

- ELT !! LOT OF PHOTONS (we need them!!)
COsmic Dynamics & EXoplanets
A simulated measurement

30 pairs of Ly$\alpha$ forest spectra randomly distributed in range $2 < z_{\text{QSO}} < 4.5$

S/N = 2000

$\Delta t = 30$ yr

2000+2000 hours

Not observable from the ground!

Liske et al. 2008
One giant leap from HARPS (3.6m)?

Need for a prototype
Better… a precursor
**ESPResso**
Echelle **S**Pectrograph for **R**ocky **E**xoplanets and per **S**table **S**pectroscopic **O**bservations
@ the ESO VLT – possibly @ the incoherently combined focus of the 4 UTs
ESPRESSO Science

**Terrestrial extra-solar planets**

- search and characterization of rocky exoplanets in the habitable zone of quiet, nearby G to M-dwarfs.
- Radial velocity follow-up of earth-mass planet candidates discovered through other techniques (astrometry, transits).
- Different environments and formation histories (GCs, DGs)
- Difficulty: “seeing” the planet through the noise of stellar activity
Espresso Science

- Cosmological variation of the fine structure constant, $m_e/m_p$ ratio
  - Accuracy in $\Delta \alpha/\alpha \sim 10^{-7}$

See Molaro+ 09
QSO absorption lines:

A Keck/HIRES doublet

Separation $\propto \alpha^2$

C IV 1548Å

C IV 1550Å
Multiple LOS expansion-collapse in the cosmic web winds

Rauch, Becker, Viel et al. 2006
ESPRESSO - Science

+ stellar oscillations

Precision Doppler measurements of asteroids

Abundances in Local Galaxies, MW, GCs, isotopic abundances

Molecular hydrogen and chemical elements at high-$z$, primordial D SNe, GRBs and DLAs
ESPRESSO – The Instrument

Radial velocity accuracy: 10 cm/s at any time scale from 20 s up to 10 yr
Spectral coverage: (350) 380-686 (760) nm corresponding to z (1.9) 2.1 - 4.6 (5.2) in the Lyα forest
Spectral Resolution: 1-UT mode R > 120,000 (goal >150,000)
1-UT mode hi-res R>220,000
4-UT mode R > 30,000
Spectral sampling: >3 pixels/FWHM (>2 pixels/FWHM in hi-res)
>2 pixels/FWHM spatial
Feed: 1 object fiber, 1 reference and/or sky fiber (Δ>7’’)

Total aperture on the sky: 1.2 > FOV > 0.9 arcsec

Total detection efficiency: at least 10%, goal >14% (at peak) and not less than 7% (0.65 arsec DIMM) all modes

Performance at faint mags: 1-UT mode: SNR=10 per pix @ 550nm in 1h for a G2V star of V=17.2
4-UT mode: SNR=10 @ 550nm in 1h for V=20.1
The ESPRESSO Team

ESO:

IAC/Spain

INAF-Trieste/Brera:

Observatoire Geneve/Phinst Bern:
F.Pepe, W.Benz, M. Fleury, I.Hughes, Ch. Lovis, M. Mayor, D.Megevand, M.Pichard, D. Queloz, D.Sosnowska, S. Udry

Portugal (CAUP/FCUL Porto-Lisboa) :
N.Santos, M.Abreu, A.Armorim, A.Cabral, P.Figueira, J.Lima, A.Moitinho, M.Monteiro, J.Pinto Coelho
The ESPRESSO Resources

Estimated

~125 FTE

~12.5 MEu
(capital investment)