The Intergalactic Medium as a Cosmological Probe

Stefano Cristiani
INAF-Trieste Observatory
A meeting in March 1999 – Chile – VLT inauguration

C.R. – You spent billions for your telescopes, if you don’t win a couple of Nobel prizes in the next few years, you’ll have failed...

Be bold, and attack the fundamental questions of Physics (e.g. the observations of SN Ia for the discovery of the accelerating expansion of the Universe).
IGM Cosmology

- Cosmological parameters
- Particles and Dark Matter
- Testing General Relativity
- The Fundamental Constants of Physics

Special thanks to M.Murphy, P.Molaro, M.Viel, J.Liske, R.Maiolino and the HIRES team

[Usual Disclaimer: the science of 2022+ will not be the science that we would do today with the facilities of 2022]
The (simple) physics of the Cosmic Web

~90% of the baryons at z=3 are in the IGM (Lyman-α forest)

Neutral hydrogen (HI) is determined by ionization balance between recombination of e and p and HI ionization from UV photons

Recombination coefficient depends on T(gas)

Neutral hydrogen traces overall gas distribution, which traces dark matter on large scales, with additional pressure effects on small scales

Density and temperature are correlated, modeled as a power law with slope γ and amplitude T₀

$$\rho_{HI} \propto \rho_{gas}^2$$

$$T = T_0 (1 + \delta)^\gamma$$
\[ \Omega_m = 0.26 \quad \Omega_\Lambda = 0.74 \quad \Omega_b = 0.0463 \quad H = 72 \text{ km/sec/Mpc} \quad - 60 \text{ Mpc/h} \]

COSMOS computer – DAMTP (Cambridge)

\[ \delta_{\rm IGM} \sim \delta_{\rm DM} \text{ at scales larger than the Jeans length} \sim 1 \text{ com Mpc} \]

\[ \text{flux} = \exp(-\tau) \sim \exp[-(\delta_{\rm IGM})^{1.6} T^{-0.7}] \]

Courtesy M. Viel
cosmoIGM: science

COSMOLOGY

IGM as a tracer of the large scale structure of the universe: tomography of IGM structures; systematic/statistical errors; synergies with other probes – IGM unique in redshift and scales

cosmoIGM

PARTICLE PHYSICS

IGM as a probe of fundamental physics: dark matter at small scale; neutrinos; coldness of dark matter; fundamental constants; cosmic expansion

GALAXY FORMATION

Galaxy/IGM interplay: metal enrichment and galactic feedback; impact on the cosmic web and metal species; the UV background; the temperature of the IGM
The primordial dark matter power spectrum

Tegmark & Zaldarriaga 2002

CMB physics
$z = 1100$
dynamics

Lyα physics
$z < 6$
dynamics
+ termodynamics

Temperature, metals, noise

CMB + Lyman $\alpha$  Long lever arm
Constrain spectral index and shape

Relation: $P_{\text{FLUX}}(k) - P_{\text{MATTER}}(k)$
e.g. Kim, Viel, Haehnelt, Carswell, Cristiani 2004
Cosmological implications: combining the forest data with CMB

\begin{align*}
n &= 1.01 \pm 0.02 \pm 0.06 \\
\sigma_8 &= 0.93 \pm 0.03 \pm 0.09
\end{align*}

\( M(\nu) \) now in the range 0.05 – 0.3 eV
Cosmological implications: Warm Dark Matter particles

$\Lambda$CDM

30 comoving Mpc/h \(z=3\)

In general

\[m(\text{sterile neutrino}) > 28 \text{ keV} \,(2\sigma)\]

if light gravitinos

\[m(\text{WDM}) > 4 \text{ keV} \,(2\sigma)\]

The BOSS/SDSS-III perspective: 3D flux power

Slosar et al. 2011 (BOSS collaboration)
Present perspectives: BAO

**Importance of transverse direction:**
Viel et al. 2002;
White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2009

about < 20 QSOs per square degree with BOSS

\[ z(\text{eff}) = 2.4 \]
The small-scale Structure of the IGM

Multiple LOS
expansion-collapse in the cosmic web
winds

Rauch, Becker, Viel et al. 2005
Testing General Relativity Dynamics: measuring $a(t) \leftarrow H(z)$

$$
\frac{z(t_0 + \Delta t_0) - z(t_0)}{\Delta t_0} = \frac{\Delta z}{\Delta t_o} \simeq \frac{dz}{dt_o} = (1 + z) H_o - H(z)
$$
A small signal..

this is for $10^7$ years… Having much less time at our disposal the shift is much smaller.. Why can we conceive to detect it NOW?

Fig. 2: The redshift drift in a simulated Lyα forest spectrum for $\Delta t = 10^7$ yr.

Fig. 3: The difference of two simulated noiseless Lyα forest spectra taken $\Delta t = 10$ yr apart.
Feasibility Test with a $R_s \sim 10^5$ spectrograph

Different coloured points reflect different targeting strategies

- 4000 hrs on 39-m E-ELT over 21.5 years, or
- 1200 hrs on 39-m E-ELT over 40 years


Not observable from the ground!
Fundamental? Constants?:

[Note: Only low-energy limits of constants discussed here]

Why “fundamental”? 
- Cannot be calculated within Standard Model

Why “constant”? 
- Because we don’t see them changing
- No theoretical reason – see above

Best of physics: Relative stability of $\alpha \sim 10^{-17}\text{ yr}^{-1}$ (Rosenband et al. 2008)

Worst of physics: Sign of incomplete theory?

Constancy based on Earth-bound, human time-scale experiments

Extension to Universe seems a big assumption
The Many Multiplet (MM) method:

\[ \frac{\Delta \alpha}{\alpha} = 1 \times 10^{-5} \implies \Delta v = 200 \text{ms}^{-1} \]
143 Keck/HIRES absorbers:

MTM et al. (MNRAS 3003; LNP, 2004)

Time since Big Bang [Gyrs]

\[ \Delta \alpha / \alpha = (-0.57 \pm 0.11) \times 10^{-6} \]
153 VLT/UVES absorbers:

Webb et al. (PRL, 2011), King et al. (MNRAS, 2012)

Time since Big Bang [Gyrs]

\[ \Delta\alpha/\alpha = (+0.21 \pm 0.12) \times 10^{-5} \]
Dipoles from Keck & VLT agree:

Right Ascension (hours)
Update

Absorbers toward QSO HE2217-2818 reveal no evidence for variation in $\alpha$ at the 3 ppm level ($1\sigma$) (the expectation from the dipole being 3.2-5.4 $\pm 1.7$ ppm)

Molaro et al 2013
What if it’s correct?:

- **ELTs MUST confirm it!**

- **ELTs MUST characterize variation accurately:**
  - Does $\alpha$ depend on redshift, density, [other]?
  - What are the astrophysical systematics?

What if it’s incorrect?:

- **VLT/ESPRESSO refutes it**

- **Motivation for new measurements same as now**

- **E-ELT obtains best possible constraints**

- **E-ELT finds new, real effect?**
H$_2$ constraints on $\Delta \mu/\mu$:
Extragalactic values of $\Delta \mu / \mu$:

**Look–back time [Gyr]**

4 5 6 7 8 9 10 11

**$\Delta \mu / \mu [10^{-6}]$**

-20 -10 0 10 20


Can more be found???
Precision from future instruments:

*VLT/UVES* ($\varepsilon=17\%$)

*GMT*

*VLT/ESPRESSO* ($\varepsilon=20\%$)

*TMT*

*E-ELT*

Calibration is key!
## Sandage test requirements:

<table>
<thead>
<tr>
<th>Aspect/parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral resolution</td>
<td>$R \geq 100k$, mainly for precise $\lambda$ calibration</td>
</tr>
<tr>
<td>Spectral coverage</td>
<td>$350\text{nm (important)} &lt; \lambda &lt; 670\text{nm}$</td>
</tr>
<tr>
<td>Spectral sampling</td>
<td>$\geq 3$ pix per FWHM</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>1</td>
</tr>
<tr>
<td>Wavelength calibration</td>
<td>Freq. comb.; $2 \text{ cm s}^{-1}$ absolute</td>
</tr>
<tr>
<td>Stability</td>
<td>$2 \text{ cm s}^{-1}$ night$^{-1}$ if absolutely calibrated</td>
</tr>
<tr>
<td>Entrance interface</td>
<td>Fibre (crucial), scrambling $\epsilon &gt; 2000$</td>
</tr>
<tr>
<td>Exposure time</td>
<td>$15 \text{ min} &lt; T_{exp} &lt; 120 \text{ min}$</td>
</tr>
<tr>
<td>Total throughput</td>
<td>$\epsilon \geq 20%$</td>
</tr>
<tr>
<td>Source size</td>
<td>Point source</td>
</tr>
<tr>
<td>Typical object magnitudes</td>
<td>15–17</td>
</tr>
<tr>
<td>Sky subtraction</td>
<td>Yes</td>
</tr>
<tr>
<td>Background</td>
<td>Dark time</td>
</tr>
<tr>
<td>Target density</td>
<td>Very low ($\sim 50$ over hemisphere)</td>
</tr>
<tr>
<td>Adaptive optics</td>
<td>Not essential</td>
</tr>
<tr>
<td>Field of view</td>
<td>$\sim$few arcseconds</td>
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## $\Delta \alpha/\alpha$ requirements:

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<tr>
<td>Spectral resolution</td>
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<tr>
<td>Spectral coverage</td>
<td>$370\text{nm} &lt; \lambda &lt; 800\text{nm}$ (680nm is OK)</td>
</tr>
<tr>
<td>Spectral sampling</td>
<td>$\geq 4$ pix per FWHM</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>1</td>
</tr>
<tr>
<td>Wavelength calibration</td>
<td>Freq. comb preferred; $2 \text{ cm s}^{-1}$ relative</td>
</tr>
<tr>
<td>Stability</td>
<td>$1 \text{ m s}^{-1} \text{ night}^{-1}$</td>
</tr>
<tr>
<td>Entrance interface</td>
<td>Fibre (crucial), scrambling $\varepsilon &gt; 100$</td>
</tr>
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<td>Exposure time</td>
<td>$15 \text{ min} &lt; T_{\text{exp}} &lt; 120 \text{ min}$</td>
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<tr>
<td>Total throughput</td>
<td></td>
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<tr>
<td>Source size</td>
<td>Point source</td>
</tr>
<tr>
<td>Typical object magnitudes</td>
<td>15–18</td>
</tr>
<tr>
<td>Sky subtraction</td>
<td>Preferred</td>
</tr>
<tr>
<td>Background</td>
<td>Bright is OK (then need sky subtraction)</td>
</tr>
<tr>
<td>Target density</td>
<td>Low ($\sim 500$ over hemisphere)</td>
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<tr>
<td>Typical object magnitudes</td>
<td>$16$–$19$</td>
</tr>
<tr>
<td>Sky subtraction</td>
<td>Yes</td>
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<td>Background</td>
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VLT papers use data generated by VLT instruments, including visitor instruments for which observing time is recommended by the ESO OPC (Observing Programmes Committee), e.g., VLT Ultracam. Instrument-level data for the VLT are available since the beginning of operations, i.e., from publication year 1999 onwards.

**Fig. 4:** Refereed publications using data from VLT instruments

FLAMES = FLAMES/UVES + FLAMES/GIRAFFE  
NACO = NAOS + CONICA  
SINFONI = SPIFFI + MACAO  

Grothkopf & Meakins 2013