Lecture 3

Jean-Philippe UZAN
Generalities
Observables and primary constraints

A given physical system gives us an observable quantity

\[ O(G_k, X) \]

External parameters: \textit{temperature, \ldots:} 
Primary physical parameters

From a physical model of our system we can deduce the sensitivities to the primary physical parameters

\[ \kappa_{G_k} = \frac{\partial \ln O}{\partial \ln G_k} \]

The primary physical parameters are usually not fundamental constants.

\[ \Delta \ln G_k = \sum_i d_{ki} \Delta \ln c_i \]
Physical systems

- Atomic clocks
- Oklo phenomenon
- Meteorite dating
- Quasar absorption spectra
- Local obs
- QSO obs
- CMB obs
- Z = 0
- Z = 0.14
- Z = 0.43
- Z = 10^3
- Z = 10^8
- CMB
- BBN
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Hubble constant</td>
<td>$h$</td>
<td>0.73(3)</td>
</tr>
<tr>
<td>Baryon-to-photon ratio</td>
<td>$\eta = n_b/n_\gamma$</td>
<td>6.12(19) $\times 10^{-10}$</td>
</tr>
<tr>
<td>Photon density</td>
<td>$\Omega_\gamma h^2$</td>
<td>$2.471 \times 10^{-5}$</td>
</tr>
<tr>
<td>Dark matter density</td>
<td>$\Omega_{CDM} h^2$</td>
<td>0.105(8)</td>
</tr>
<tr>
<td>Cosmological constant</td>
<td>$\Omega_m$</td>
<td>0.73(3)</td>
</tr>
<tr>
<td>Spatial curvature</td>
<td>$\Omega_K$</td>
<td>0.011(12)</td>
</tr>
<tr>
<td>Scalar modes amplitude</td>
<td>$Q$</td>
<td>$(2.0 \pm 0.2) \times 10^{-5}$</td>
</tr>
<tr>
<td>Scalar spectral index</td>
<td>$n_S$</td>
<td>0.955(16)</td>
</tr>
<tr>
<td>Neutrino density</td>
<td>$\Omega_\nu h^2$</td>
<td>$(0.0005 - 0.023)$</td>
</tr>
<tr>
<td>Dark energy equation of state</td>
<td>$w$</td>
<td>-0.97(7)</td>
</tr>
<tr>
<td>Scalar running spectral index</td>
<td>$\alpha_S$</td>
<td>$-0.05 \pm 0.03$</td>
</tr>
<tr>
<td>Tensor-to-scalar ratio</td>
<td>$T/S$</td>
<td>$&lt; 0.36$</td>
</tr>
<tr>
<td>Tensor spectral index</td>
<td>$n_T$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Tensor running spectral index</td>
<td>$\alpha_T$</td>
<td>?</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.0223(7)</td>
</tr>
</tbody>
</table>

**Time-redshift relation**

![Time-redshift relation graph](image)
<table>
<thead>
<tr>
<th>System</th>
<th>Observable</th>
<th>Primary constraint</th>
<th>Other hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic clocks</td>
<td>Clock rates</td>
<td>$\alpha, \mu, g_i$</td>
<td>-</td>
</tr>
<tr>
<td>Quasar spectra</td>
<td>Atomic spectra</td>
<td>$\alpha, \mu, g_p$</td>
<td>Cloud physical properties</td>
</tr>
<tr>
<td>Oklo</td>
<td>Isotopic ratio</td>
<td>$E_r$</td>
<td>Geophysical model</td>
</tr>
<tr>
<td>Meteorite dating</td>
<td>Isotopic ratio</td>
<td>$\lambda$</td>
<td>Solar system formation</td>
</tr>
<tr>
<td>CMB</td>
<td>Temperature anisotropies</td>
<td>$\alpha, \mu$</td>
<td>Cosmological model</td>
</tr>
<tr>
<td>BBN</td>
<td>Light element abundances</td>
<td>$Q, \tau_n, m_e, m_N, \alpha, B_d$</td>
<td>Cosmological model</td>
</tr>
</tbody>
</table>
Atomic clocks
FIG. 3. Hyperfine structure of the $n=1$ level of the hydrogen atom. The fine-structure Hamiltonian induces a shift of $-mc^2 \alpha_{EM}^4/8$ of the level $1s$. $J$ can only take the value $+1/2$. The hyperfine Hamiltonian (74) induces a splitting of the level $1s_{1/2}$ into the two hyperfine levels $F=0$ and $F=+1$. The transition between these two levels corresponds to the 21-cm ray with $Ah^2 = 1420.405751.768 \pm 0.001$ Hz and is of first importance in astronomy.
### Atomic clocks

$$\kappa_\alpha \equiv \frac{\partial \ln F}{\partial \ln \alpha_{\text{EM}}}$$

<table>
<thead>
<tr>
<th>Atom</th>
<th>Transition</th>
<th>sensitivity $\kappa_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>$1s - 2s$</td>
<td>0.00</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>hf</td>
<td>0.34</td>
</tr>
<tr>
<td>$^{133}\text{Cs}$</td>
<td>$^2S_{1/2}(F = 2) - (F = 3)$</td>
<td>0.83</td>
</tr>
<tr>
<td>$^{171}\text{Yb}^+$</td>
<td>$^2S_{1/2} - ^2D_{3/2}$</td>
<td>0.9</td>
</tr>
<tr>
<td>$^{199}\text{Hg}^+$</td>
<td>$^2S_{1/2} - ^2D_{5/2}$</td>
<td>-3.2</td>
</tr>
<tr>
<td>$^{87}\text{Sr}$</td>
<td>$^1S_0 - ^3P_0$</td>
<td>0.06</td>
</tr>
<tr>
<td>$^{27}\text{Al}^+$</td>
<td>$^1S_0 - ^3P_0$</td>
<td>0.008</td>
</tr>
</tbody>
</table>
## Atomic clocks

<table>
<thead>
<tr>
<th>Clock 1</th>
<th>Clock 2</th>
<th>Constraint (yr(^{-1}))</th>
<th>Constants dependence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{87}\text{Rb})</td>
<td>(^{133}\text{Cs})</td>
<td>((0.2 \pm 7.0) \times 10^{-16})</td>
<td>(g_{\text{Cs}} \mu \alpha_{\text{EM}}^{0.49})</td>
<td>Marion (2003)</td>
</tr>
<tr>
<td>(^{87}\text{Rb})</td>
<td>(^{133}\text{Cs})</td>
<td>((-0.5 \pm 5.3) \times 10^{-16})</td>
<td>(g_{\text{Rb}} \alpha_{\text{EM}}^{0.49})</td>
<td>Bize (2003)</td>
</tr>
<tr>
<td>(^{1}\text{H})</td>
<td>(^{133}\text{Cs})</td>
<td>((-32 \pm 63) \times 10^{-16})</td>
<td>(g_{\text{Cs}} \mu \alpha_{\text{EM}}^{2.83})</td>
<td>Fischer (2004)</td>
</tr>
<tr>
<td>(^{199}\text{Hg}^+)</td>
<td>(^{133}\text{Cs})</td>
<td>((0.2 \pm 7) \times 10^{-15})</td>
<td>(g_{\text{Cs}} \mu \alpha_{\text{EM}}^{6.05})</td>
<td>Bize (2005)</td>
</tr>
<tr>
<td>(^{199}\text{Hg}^+)</td>
<td>(^{133}\text{Cs})</td>
<td>((3.7 \pm 3.9) \times 10^{-16})</td>
<td>(g_{\text{Cs}} \mu \alpha_{\text{EM}}^{1.93})</td>
<td>Fortier (2007)</td>
</tr>
<tr>
<td>(^{171}\text{Yb}^+)</td>
<td>(^{133}\text{Cs})</td>
<td>((-1.2 \pm 4.4) \times 10^{-15})</td>
<td>(g_{\text{Cs}} \mu \alpha_{\text{EM}}^{2.77})</td>
<td>Peik (2004)</td>
</tr>
<tr>
<td>(^{171}\text{Yb}^+)</td>
<td>(^{133}\text{Cs})</td>
<td>((-0.78 \pm 1.40) \times 10^{-15})</td>
<td>(\alpha_{\text{EM}}^{-3.208})</td>
<td>Peik (2006)</td>
</tr>
<tr>
<td>(^{87}\text{Sr})</td>
<td>(^{87}\text{Dy})</td>
<td>((-1.0 \pm 1.8) \times 10^{-15})</td>
<td></td>
<td>Blatt (2008)</td>
</tr>
<tr>
<td>(^{27}\text{Al}^+)</td>
<td>(^{199}\text{Hg}^+)</td>
<td>((-5.3 \pm 7.9) \times 10^{-17})</td>
<td></td>
<td>Cingöz (2008)</td>
</tr>
</tbody>
</table>

![Graph](image)

*Note: The graph shows the change in the constraint over time.*
The gyromagnetic factors can be expressed in terms of $g_p$ and $g_n$ (shell model).

$$\frac{\delta g_{Cs}}{g_{Cs}} \sim -1.266 \frac{\delta g_p}{g_p} \quad \frac{\delta g_{Rb}}{g_{Rb}} \sim 0.736 \frac{\delta g_p}{g_p}$$

All atomic clock constraints take the form

$$\frac{\dot{\nu}_{AB}}{\nu_{AB}} = \lambda_{g_p} \frac{\dot{g}_p}{g_p} + \lambda_{\mu} \frac{\dot{\mu}}{\mu} + \lambda_\alpha \frac{\dot{\alpha}}{\alpha}$$

Using Al-Hg to constrain $\alpha$, the combination of other clocks allows to constraint $\{\mu, g_p\}$.

Note: one actually needs to include the effects of the polarization of the non-valence nucleons and spin-spin interaction.

[Flambaum, 0302015, …]

[Luo, Olive, JPU, 2011]
Atomic clocks: from observations to constraints

One then needs to express $m_p$ and $g_p$ in terms of the quark masses and $\Lambda_{QCD}$ as

$$\frac{\delta g_p}{g_p} = \kappa_u \frac{\delta m_u}{m_u} + \kappa_d \frac{\delta m_d}{m_d} + \kappa_s \frac{\delta m_s}{m_s} + \kappa_{QCD} \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}},$$

$$\frac{\delta m_p}{m_p} = f_{T_u} \frac{\delta m_u}{m_u} + f_{T_d} \frac{\delta m_d}{m_d} + f_{T_s} \frac{\delta m_s}{m_s} + f_{T_g} \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}}.$$ 

$$m_i = h_i \nu$$

Assuming unification.

$$\frac{\dot{\nu}_{AB}}{\nu_{AB}} = \lambda_{g_p} \frac{\dot{g}_p}{g_p} + \lambda_{\mu} \frac{\dot{\mu}}{\mu} + \lambda_{\alpha} \frac{\dot{\alpha}}{\alpha},$$

$$\frac{\dot{\nu}_{AB}}{\nu_{AB}} = C_{AB} \frac{\dot{\alpha}}{\alpha}.$$ 

$C_{AB}$ coefficients range from 70 to 0.6 typically.

Model-dependence remains quite large.

[ Luo, Olive, JPU, 2011]
Radioactive decay
### alpha-decay

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>A</th>
<th>Lifetime (yr)</th>
<th>$Q$ (MeV)</th>
<th>$s_\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sm</td>
<td>62</td>
<td>147</td>
<td>$1.06 \times 10^{11}$</td>
<td>2.310</td>
<td>774</td>
</tr>
<tr>
<td>Gd</td>
<td>64</td>
<td>152</td>
<td>$1.08 \times 10^{14}$</td>
<td>2.204</td>
<td>890</td>
</tr>
<tr>
<td>Dy</td>
<td>66</td>
<td>154</td>
<td>$3 \times 10^{6}$</td>
<td>2.947</td>
<td>575</td>
</tr>
<tr>
<td>Pt</td>
<td>78</td>
<td>190</td>
<td>$6.5 \times 10^{11}$</td>
<td>3.249</td>
<td>659</td>
</tr>
<tr>
<td>Th</td>
<td>90</td>
<td>232</td>
<td>$1.41 \times 10^{10}$</td>
<td>4.082</td>
<td>571</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>235</td>
<td>$7.04 \times 10^{8}$</td>
<td>4.678</td>
<td>466</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>238</td>
<td>$4.47 \times 10^{9}$</td>
<td>4.270</td>
<td>548</td>
</tr>
</tbody>
</table>
Wilkinson [539] considered the most favorable case, that is the decay of $^{238}\text{U}$ for which $s_\alpha = 548$ (see Table 9). By comparing the geological dating of the Earth by different methods, he concluded that the decay constant $\lambda$ of $^{238}\text{U}$, $^{235}\text{U}$ and $^{232}\text{Th}$ have not changed by more than a factor 3 or 4 during the last $3-4 \times 10^9$ years from which it follows

$$|\Delta \alpha_{EM}/\alpha_{EM}| < 8 \times 10^{-3}. \quad (62)$$

This constraint was revised by Dyson [168] who claimed that the decay rate has not changed by more than 20%, during the past $2 \times 10^9$ years, which implies

$$|\Delta \alpha_{EM}/\alpha_{EM}| < 4 \times 10^{-4}. \quad (63)$$

Uranium has a short lifetime so that it cannot be used to set constraints on longer time scales. It is also used to calibrate the age of the meteorites. Therefore, it was suggested [400] to consider $^{147}\text{Sm}$. Assuming that $\Delta \lambda_{147}/\lambda_{147}$ is smaller than the fractional uncertainty of $7.5 \times 10^{-3}$ of its half-life

$$|\Delta \alpha_{EM}/\alpha_{EM}| \lesssim 10^{-5}. \quad (64)$$
first considered by Peebles and Dicke [407]. They noted that the very small value of its decay energy $Q = 2.6$ keV makes it a very sensitive probe of the variation of $\alpha_{EM}$. In that case $p \approx 2.8$ so that $s_\alpha \approx -18000$; a change of $10^{-2}\%$ of $\alpha_{EM}$ will induce a change in the decay energy of order of the keV, that is of the order of the decay energy itself. Peebles and Dicke [407] did not have reliable laboratory determination of the decay rate to put any constraint. Dyson [167] compared the isotopic analysis of molybdenite ores ($\lambda_{187} = (1.6 \pm 0.2) \times 10^{-11}$ yr$^{-1}$), the isotopic analysis of 14 iron meteorites ($\lambda_{187} = (1.4 \pm 0.3) \times 10^{-11}$ yr$^{-1}$) and laboratory measurements of the decay rate ($\lambda_{187} = (1.1 \pm 0.1) \times 10^{-11}$ yr$^{-1}$). Assuming that the variation of the decay energy comes entirely from the variation of $\alpha_{EM}$, he concluded that $|\Delta \alpha_{EM}/\alpha_{EM}| < 9 \times 10^{-4}$ during the past $3 \times 10^9$ years. Note that the discrepancy between meteorite and lab data could have been interpreted as a time-variation of $\alpha_{EM}$, but the laboratory measurement were complicated by many technical issues so that Dyson only considered a conservative upper limit.

\[
\frac{\Delta \lambda_{187}}{\lambda_{187}} = p \frac{\Delta Q}{Q} \approx p \left( \frac{20 \text{ MeV}}{Q} \right) \frac{\Delta \alpha_{EM}}{\alpha_{EM}} \approx -2.2 \times 10^4 \frac{\Delta \alpha_{EM}}{\alpha_{EM}}
\]
\[ \left| \frac{\Delta \lambda_{187}}{\lambda_{187}} \right| = -0.016 \pm 0.016. \]

\[ \Delta \alpha_{EM}/\alpha_{EM} = (-8 \pm 16) \times 10^{-7}. \]
Oklo
Oklo- a natural nuclear reactor

It operated 2 billion years ago, during 200 000 years!!
Oklo: why?

4 conditions:
1- Naturally high in $^{235}\text{U}$,
2- moderator: water,
3- low abundance of neutron absorber,
4- size of the room.
Oklo-constraints

Natural nuclear reactor in Gabon, operating 1.8 Gyr ago \( (z \approx 0.14) \)

Abundance of Samarium isotopes

\[ {}^{149}\text{Sm} + n \rightarrow {}^{150}\text{Sm} + \gamma \quad E_r = 0.0973 \text{ eV} \]

Damour, Dyson, NPB 480 (1996) 37
Fujii et al., NPB 573 (2000) 377
Lamoreaux, torgerson, nucl-th/0309048
Flambaum, shuryak, PRD 67 (2002) 083507
First, the cross section $\sigma_{(n,\gamma)}$ strongly depends on the energy of a resonance at $E_r = 97.3$ meV.

Geochemical data allow to determine the isotopic composition of various elements, such as uranium, neodymium, gadolinium, and samarium. Gadolinium and neodymium allow to determine the fluence (integrated flux over time) of the neutron while both gadolinium and samarium are strong neutron absorbers.

From these data, one deduces the value of the averaged value of the cross section on the neutron flux, $\hat{\sigma}_{149}$. This value depends on hypothesis on the geometry of the reactor zone.

The range of allowed value of $\hat{\sigma}_{149}$ was translated into a constraint on $E_r$. This step involves an assumption on the form and temperature of the neutron spectrum.

$E_r$ was related to some fundamental constant, which involve a model of the nucleus.
Oklo-constraints

\[
\frac{dN_{147}}{\phi dt} = -\hat{\sigma}_{147} N_{147} + \hat{\sigma}_{f235} y_{147} N_{235}
\]

\[
\frac{dN_{148}}{\phi dt} = \hat{\sigma}_{147} N_{147}
\]

\[
\frac{dN_{149}}{\phi dt} = -\hat{\sigma}_{149} N_{149} + \hat{\sigma}_{f235} y_{149} N_{235}
\]

\[
\frac{dN_{235}}{\phi dt} = -\sigma_5 N_{235},
\]
<table>
<thead>
<tr>
<th>Ore</th>
<th>neutron spectrum</th>
<th>Temperature (°C)</th>
<th>$\dot{\sigma}_{149}$ (kb)</th>
<th>$\Delta E_r$ (meV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>?</td>
<td>Maxwell</td>
<td>20</td>
<td>55 ± 8</td>
<td>0 ± 20</td>
<td>[466]</td>
</tr>
<tr>
<td>RZ2 (15)</td>
<td>Maxwell</td>
<td>180–700</td>
<td>75 ± 18</td>
<td>−1.5 ± 10.5</td>
<td>[123]</td>
</tr>
<tr>
<td>RZ10</td>
<td>Maxwell</td>
<td>200–400</td>
<td>91 ± 6</td>
<td>4 ± 16</td>
<td>[220]</td>
</tr>
<tr>
<td>RZ10</td>
<td>Maxwell + epithermal</td>
<td>327</td>
<td>91 ± 6</td>
<td>−97 ± 8</td>
<td>[220]</td>
</tr>
<tr>
<td>RZ2</td>
<td>Maxwell + epithermal</td>
<td>73.2 ± 9.4</td>
<td>45^{+7}_{-15}</td>
<td>[306]</td>
<td></td>
</tr>
<tr>
<td>RZ2</td>
<td>Maxwell + epithermal</td>
<td>200–300</td>
<td>71.5 ± 10.0</td>
<td>−5.5 ± 67.5</td>
<td>[417]</td>
</tr>
<tr>
<td>RZ10</td>
<td>Maxwell + epithermal</td>
<td>85.0 ± 6.8</td>
<td>85.0 ± 6.8</td>
<td>−</td>
<td>[234]</td>
</tr>
<tr>
<td>RZ2+RZ10</td>
<td>Maxwell + epithermal</td>
<td>7.2 ± 18.8</td>
<td>7.2 ± 18.8</td>
<td>−</td>
<td>[234]</td>
</tr>
<tr>
<td>RZ2+RZ10</td>
<td></td>
<td></td>
<td>90.75 ± 11.15</td>
<td>−</td>
<td>[234]</td>
</tr>
</tbody>
</table>
Oklo-constraints

Natural nuclear reactor in Gabon, operating 1.8 Gyr ago \((z \sim 0.14)\)

Abundance of Samarium isotopes

\[
^{149}\text{Sm} + n \rightarrow ^{150}\text{Sm} + \gamma \quad E_r = 0.0973 \text{ eV}
\]

From isotopic abundances of Sm, U and Gd, one can measure the cross section averaged on the thermal neutron flux

\[
\hat{\sigma}_{149}(T, E_r) = 91 \pm 6 \text{ kb}
\]

From a model of Sm nuclei, one can infer

\[
s = \Delta E_r / \Delta \ln \alpha
\]

\(s \sim 1\text{MeV}\) so that

\[
\Delta \alpha / \alpha \sim 1\text{MeV}/0.1\text{eV} \sim 10^{-7}
\]

\[
\Delta \alpha / \alpha = (0.5 \pm 1.05) \times 10^{-7}
\]

Damour, Dyson, NPB 480 (1996) 37
Fujii et al., NPB 573 (2000) 377
Lamoreaux, torgerson, nucl-th/0309048
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Damour, Dyson, NPB 480 (1996) 37
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2 branches.
Quasar absorption spectra
Paleo-spectra

Quasar emission spectrum

Absorption spectrum

Observed spectrum

Reference spectrum
Absorption spectra

Cosmic expansion redshift all spectra (achromatic)

We look for achromatic effects
The method was introduced by Savedoff in 1956, using Alkali doublet

Most studies are based on optical techniques due to the profusion of strong UV transitions that are redshifted into the optical band

\( \text{e.g. SiIV} @ z>1.3, \ Fe\text{II} \lambda 1608 \at z>1 \)

Radio observations are also very important

\( \text{e.g. hyperfine splitting (HI21cm), molecular rotation, lambda doubling, ...} \)
- offer high spectral resolution (<1km/s)
- higher sensitivity to variation of constants
- isotopic lines observed separately (while blending in optical observations)

Shift to be detected are small

\( \text{e.g. a change of } \alpha \text{ of } 10^{-5} \text{ corresponds to} \)
  - a shift of 20 mÅ (i.e. of 0.5 km/s) at \( z \sim 2 \)
  - \( \frac{1}{3} \) of a pixel at \( R=40000 \) (Keck/HIRES, VLT/UVES)

Many sources of uncertainty

- absorption lines have complex profiles (inhomogeneous cloud)
- fitted by Voigt profile (usually not unique: require lines not to be saturated)
- each component depends on \( z \), column density, width
QSO: sensitivity

Dzuba et al. 1999-2005
QSO absorption spectra

3 main methods:

**Alkali doublet (AD)**  
Savedoff 1956

- Fine structure doublet, $\Delta \lambda / \lambda \propto \alpha^2$
- Single atom
- Rather weak limit

**Many multiplet (MM)**  
Webb et al. 1999

- Compares transitions from multiplet and/or atoms
- s-p vs d-p transitions in heavy elements
- Better sensitivity

**Single Ion Differential $\alpha$ Measurement (SIDAM)**  
Levshakov et al. 1999

- Analog to MM but with a single atom / FeII

VLT/UVES: Si IV in 15 systems, $1.6<z<3$
\[
\frac{\Delta \alpha}{\alpha} = (0.15 \pm 0.43) \times 10^{-5}
\]
Chand et al. 2004

HIRES/Keck: Si IV in 21 systems, $2<z<3$
\[
\frac{\Delta \alpha}{\alpha} = (-0.5 \pm 1.3) \times 10^{-5}
\]
Murphy et al. 2001
The many-multiplet method is based on the correlation of the shifts of different lines of different atoms.

Relativistic N-body with varying $\alpha$:

$$\omega = \omega_0 + 2 q \frac{\Delta \alpha}{\alpha}$$

First implemented on 30 systems with MgII and FeII

$$\text{HIRES-Keck, 143 systems, } 0.2 < z < 4.2$$

$$\frac{\Delta \alpha}{\alpha} = (-0.57 \pm 0.11) \times 10^{-5}$$

$5\sigma$ detection!
QSO: uncertainty

- Error in the determination of laboratory spectra
- Different atoms may not be located in the same part of the cloud (relative Doppler)
- Lines may be blended by transitions in another system
- Variation of velocity of the Earth during integration can induce a differential Doppler shift
- Atmospheric dispersion
- Magnetic fields in the clouds
- Temperature variation during the integration
- Instrumental effects (e.g. variation of the intrinsic profile of the instrument)

Isotopic abundance of MgII (used as an anchor)
- affects the value of the effective rest-wavelengths
- assumed to be close to terrestrial $^{24}\text{Mg} : ^{25}\text{Mg} : ^{26}\text{Mg} = 79:10:11$
- $r = (26+25)/24$ cannot be measured directly
- from molecular absorption of MgH: $r$ decreases with metallicity
- But $r$ found to be high in giant stars in NGC6752
- Ashenfelter et al proposed an enhancement of $r$ from stars in (2-8)$M_\odot$ in their asymptotic giant branch phase
- If $r=0.62$ instead of $r=0.27$, then no variation of $\alpha$
- But overproduction of P, Si, Al
QSO: VLT/UVES analysis

Selection of the absorption spectra:
- lines with similar ionization potentials
  most likely to originate from similar regions in the cloud
- avoid lines contaminated by atmospheric lines
- at least one anchor line is not saturated
  redshift measurement is robust
- reject strongly saturated systems

Only 23 systems
lower statistics / better controlled systematics
R>44000, S/N per pixel between 50 & 80

VLT/UVES

\[
\frac{\Delta \alpha}{\alpha} = (-0.01 \pm 0.15) \times 10^{-5}
\]

Srianand et al. 2007

DOES NOT CONFIRM HIRES/Keck DETECTION
Going further

Other transitions:

- HI21cm vs UV of heavy element transitions: $\alpha^2 g_p / \mu$

- HI vs molecular transitions (CO, HCO+, HCN): $g_p \alpha^2$

- OH18cm: ground state $^2\Pi_{3/2} J=3/2$ of OH is split in 2 levels further split in 2 hyperfine states,
  It constrains $g_p (\alpha^2 \mu)^{1.57}$

- FIR fine-structure lines (CO) $\alpha^2 \mu$

- Conjugate OH lines (emission+absorption lines with same shape): $g_p (\alpha \mu)^{1.85}$

- Molecular lines (H2, NH3, HD): $\mu$
QSO: ways out

High $r$ for some giant stars in globular cluster NGC 6752

Yong et al. 2003

**Hypothesis:** polluted by asymptotic giant branch stars (AGB)

**What $r$ to reconcile observations with no variation?**

$r \sim 0.6$ instead of 0.27 for Solar system abundances to explain HIRES/Keck

But, overproduce N, Si, Al and P: can be tested!
Table 10: Summary of the latest constraints on the variation of fundamental constants obtained from the analysis of quasar absorption spectra. We recall that $y \equiv g_p \alpha_{EM}^2$, $F \equiv g_p (\alpha_{EM}^2 \mu)^{1.57}$, $x \equiv \alpha_{EM}^2 g_p \mu$, $F' \equiv \alpha_{EM}^2 \mu$ and $\mu \equiv m_p/m_o$, $G = g_p (\alpha \mu)^{1.85}$.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Method</th>
<th>System</th>
<th>Constraint ($\times 10^{-5}$)</th>
<th>Redshift</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{EM}$</td>
<td>AD</td>
<td>21</td>
<td>$(-0.5 \pm 1.3)$</td>
<td>2.33–3.08</td>
<td>[366]</td>
</tr>
<tr>
<td></td>
<td>AD</td>
<td>15</td>
<td>$(-0.15 \pm 0.43)$</td>
<td>1.59–2.92</td>
<td>[87]</td>
</tr>
<tr>
<td></td>
<td>AD</td>
<td>9</td>
<td>$(-3.09 \pm 8.46)$</td>
<td>1.19–1.84</td>
<td>[339]</td>
</tr>
<tr>
<td></td>
<td>MM</td>
<td>143</td>
<td>$(-0.57 \pm 0.11)$</td>
<td>0.2–4.2</td>
<td>[356]</td>
</tr>
<tr>
<td></td>
<td>MM</td>
<td>21</td>
<td>$(0.01 \pm 0.15)$</td>
<td>0.4–2.3</td>
<td>[86]</td>
</tr>
<tr>
<td></td>
<td>SIDAM</td>
<td>1</td>
<td>$(-0.012 \pm 0.179)$</td>
<td>1.15</td>
<td>[351]</td>
</tr>
<tr>
<td></td>
<td>SIDAM</td>
<td>1</td>
<td>$(0.566 \pm 0.267)$</td>
<td>1.84</td>
<td>[351]</td>
</tr>
<tr>
<td>$y$</td>
<td>H1 - mol</td>
<td>1</td>
<td>$(-0.16 \pm 0.54)$</td>
<td>0.6847</td>
<td>[364]</td>
</tr>
<tr>
<td></td>
<td>H1 - mol</td>
<td>1</td>
<td>$(-0.2 \pm 0.44)$</td>
<td>0.247</td>
<td>[364]</td>
</tr>
<tr>
<td></td>
<td>CO, CHO+</td>
<td></td>
<td>$(4 \pm 6)$</td>
<td>0.247</td>
<td>[519]</td>
</tr>
<tr>
<td>$F$</td>
<td>OH - H1</td>
<td>1</td>
<td>$(-0.44 \pm 0.36 \pm 1.0_{syst})$</td>
<td>0.765</td>
<td>[266]</td>
</tr>
<tr>
<td></td>
<td>OH - H1</td>
<td>1</td>
<td>$(0.51 \pm 1.26)$</td>
<td>0.2467</td>
<td>[134]</td>
</tr>
<tr>
<td>$x$</td>
<td>H1 - UV</td>
<td>9</td>
<td>$(-0.63 \pm 0.99)$</td>
<td>0.23–2.35</td>
<td>[479]</td>
</tr>
<tr>
<td></td>
<td>H1 - UV</td>
<td>2</td>
<td>$(-0.17 \pm 0.17)$</td>
<td>3.174</td>
<td>[457]</td>
</tr>
<tr>
<td>$F'$</td>
<td>CH1 - CO</td>
<td>1</td>
<td>$(1 \pm 10)$</td>
<td>4.69</td>
<td>[316]</td>
</tr>
<tr>
<td></td>
<td>CH1 - CO</td>
<td>1</td>
<td>$(14 \pm 15)$</td>
<td>6.42</td>
<td>[316]</td>
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<tr>
<td>$G$</td>
<td>OH</td>
<td>1</td>
<td>$&lt; 1.1$</td>
<td>0.247, 0.765</td>
<td>[91]</td>
</tr>
<tr>
<td></td>
<td>OH</td>
<td>1</td>
<td>$&lt; 1.16$</td>
<td>0.0018</td>
<td>[91]</td>
</tr>
<tr>
<td></td>
<td>OH</td>
<td>1</td>
<td>$(-1.18 \pm 0.46)$</td>
<td>0.247</td>
<td>[268]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>H2</td>
<td>1</td>
<td>$(2.78 \pm 0.88)$</td>
<td>2.59</td>
<td>[417]</td>
</tr>
<tr>
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<td>H2</td>
<td>1</td>
<td>$(2.06 \pm 0.79)$</td>
<td>3.02</td>
<td>[417]</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>1</td>
<td>$(1.01 \pm 0.62)$</td>
<td>2.59</td>
<td>[281]</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>1</td>
<td>$(0.82 \pm 0.74)$</td>
<td>2.8</td>
<td>[281]</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>1</td>
<td>$(0.26 \pm 0.30)$</td>
<td>3.02</td>
<td>[281]</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>1</td>
<td>$(0.7 \pm 0.8)$</td>
<td>3.02, 2.59</td>
<td>[475]</td>
</tr>
<tr>
<td></td>
<td>NH3</td>
<td>1</td>
<td>$&lt; 0.18$</td>
<td>0.685</td>
<td>[355]</td>
</tr>
<tr>
<td></td>
<td>NH3</td>
<td>1</td>
<td>$&lt; 0.38$</td>
<td>0.685</td>
<td>[343]</td>
</tr>
<tr>
<td></td>
<td>HC3N</td>
<td>1</td>
<td>$&lt; 0.14$</td>
<td>0.89</td>
<td>[243]</td>
</tr>
<tr>
<td></td>
<td>HD</td>
<td>1</td>
<td>$&lt; 9$</td>
<td>2.418</td>
<td>[398]</td>
</tr>
<tr>
<td></td>
<td>HD</td>
<td>1</td>
<td>$(0.56 \pm 0.55_{stat} \pm 0.27_{syst})$</td>
<td>2.059</td>
<td>[332]</td>
</tr>
</tbody>
</table>
A word on $\mu$

**Diatomic molecule**

vibrorotational transitions:

$$\nu = E_I(c_1 + c_2/ \sqrt{\mu} + c_2/\mu)$$

so that

$$\lambda_i = \lambda_i^0 (1 + z_{abs}) \left(1 + K_i \frac{\Delta \mu}{\mu}\right) \rightarrow z_i = z_{abs} + b K_i$$

$H_2$ lines of Lyman and Werner Band from 2 systems at $z=2.597$ and $z=3.0249$ (resp. 42 and 40 lines) + 2 sets of laboratory spectra:

$$\frac{\Delta \mu}{\mu} = (3.05 \pm 0.75) \times 10^{-5} \quad \text{or} \quad \frac{\Delta \mu}{\mu} = (1.65 \pm 0.74) \times 10^{-5}$$

Ivanchik et al. 2005

**Improvement of laboratory spectra**

$$\frac{\Delta \mu}{\mu} = (2.4 \pm 0.6) \times 10^{-5}$$

Reinhold et al. 2006

But, only 7 lines in both spectra: intercalibration difficult.
Spatial variation?

[Webb et al., 2010]

Claim: Dipole in the fine structure constant [« Australian dipole »]

Indeed, this is a logical possibility to reconcile VLT constraints and Keck claims of a variation.
CODEX: COsmic Dynamics EXperiment

Time drift of the redshifts

\[ \Delta \lambda = \frac{\Delta t}{1 + z} \left[ H_0 (1 + z) - H(z) \right] \lambda_0 \]

Given the cosmological parameters:
shift of $10^{-6}$/an

CODEX:
spectral domain: 400-680 nm
R=150000
10-20 times HARPS on 10 years!
long term calibration (atomic clocks...)

Constants

The accuracy of a variability measurement is determined by the precision of measurement of the line positions.

Precision on $\alpha$ et $\mu$: $10^{-8}$
2 order of magnitude better than VLT/UVES