Shedding light on fundamental physics with Planck

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$\Lambda$CDM: The most boring universe?
Outline

• Introduction

• What is the nature of Dark Matter?
  • Dark Matter Searches
  • Dark Matter Annihilation in the CMB
    • Simplified constraints
    • Refined constraints
    • Latest results on the study of energy propagation

• Is currently known physics sufficient to describe our universe?
  • Testing Variation of Fundamental Constants
    • CMB
    • Clusters of galaxies
Dark Matter Searches

- **Collider searches**: LHC.
- **Direct detection**: CoGeNT, DAMA/LIBRA, XMASS, CRESST-II, EDELWEISS, CDMSII, XENON, PICASSO, COUPP
- **Indirect detection**
  - High energy photons: Fermi-LAT, ACTs (HESS, Veritas, Magic)
  - Electrons/positrons: PAMELA, AMS02, ATIC, Fermi-LAT, HESS, MAGIC.
  - Antiprotons: PAMELA, AMS.
  - Neutrinos: ANTARES, IceCube.

- CMB, 21 cm, BBN etc.
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Planck Collaboration/ Su et al./Dobler et al./ Finkbeiner et al.
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Anomalies in Cosmic Rays

- **Anomalies:** excess in the positron electron fraction and in the energy spectrum of electrons.
- Several explanations: pulsar emission, supernovae, **dark matter annihilation** etc...

**Positron Electron Fraction**

- Expected from solar modulation
- Unexpected!

**Electron Spectrum**

- Conventional diffusive model

Adriani et al. 2009

Fermi Lat-collaboration 2010
Anomalies in Cosmic Rays

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Ams02 confirms Pamela!

Fermi Lat-collaboration 2010
Anomalies in Cosmic Rays

→ Thermal production of DM:

\[ \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}. \] (WIMP)

→ Annihilation rate:

\[ \Gamma \sim n^2 \langle \sigma v \rangle. \] n from dm simulations, models, observations

Astrophysical or Particle Physics **BOOST** to explain the data.

Profumo, S. 2005, PRD, 72, 103521

Motivations

→ Thermal production of DM:
  \[ <\sigma v> \sim 10^{-2.6} \text{ cm}^3/\text{s}. \] (WIMP)

→ Annihilation rate:
  \[ \Gamma = n^2 <\sigma v> \] (n from dm simulations, models, observations)

**BOOST** of the cross section to explain the data, depends on mass of DM and annihilation channel.

Dark Matter annihilation should leave a *signature in CMB*:

- At (z~1000), when CMB forms, the homogeneous dark matter density is
  \[ n(z=1000) = n_{\text{today}} (1+z)^3 \sim n_{\text{today}} \times 10^9 \]

- DM mean velocity \( \beta \sim 10^{-8} \). Favours Sommerfeld Enhancement.
CMB

Angular Power Spectra

$T = 3000K$

$z = 1000$

$\theta \sim \pi / l$

Last Scattering Surface

Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu
Changing recombination model changes position and thickness of the visibility function.

The visibility function represents the probability density that a photon is last scattered at redshift $z$. 

![Graph showing visibility function with redshift $z$ on the x-axis and visibility on the y-axis.](image)
DM annihilation in the recombination epoch

\[ \frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \left( f(z) \frac{\langle \sigma v \rangle}{m_\chi} \right) \]

\[ \chi_i \frac{dE}{dt} \]  \text{IONIZATIONS}

\[ \chi_\alpha \frac{dE}{dt} \]  \text{LYMAN-\(\alpha\)}

\[ \chi_h \frac{dE}{dt} \]  \text{HEATING}
DM annihilation in the recombination epoch

\[ \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \left\{ f(z) \frac{<\sigma v>}{m_\chi} \right\} \]

- \( f(z) \) is the fraction of energy that from the annihilation is absorbed by the plasma at each \( z \). Depends on DM mass and annihilation channel.

\[ \chi_i \frac{dE}{dt} \]  
IONIZATIONS

\[ \chi_\alpha \frac{dE}{dt} \]  
LYMAN-\( \alpha \)

\[ \chi_h \frac{dE}{dt} \]  
HEATING
DM annihilation in the recombination epoch

\[ \frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \left[ f(z) \frac{<\sigma v>}{m_\chi} \right] \]

- \( \chi_i \) are the fractions going into heating, ionization and excitation (Lyman alpha) of the medium!
Energy Deposition History

Primaries: $W^\pm, b\bar{b}, Z, h, \tau^\pm, e^\pm, \ldots$

Decay

Final Products: $p\bar{p}, \nu\bar{\nu}, e^\pm, \gamma$

Protons penetrating, poor at transferring energy

Neutrinos escape away

Positrons at high energy behave like electrons, then form positronium and annihilate

Electrons at high energy IC with CMB photons producing gamma ray.

Photon and Electron Cooling

Heating, excitation and ionization
Photon cooling

Ionization

Compton Scattering

Pair production

Photon Scattering

Slatyer 2009

Hubble time / Cooling time

$\frac{t_H}{t_{cool}}$

$E$ (eV)

$\gamma e^- \rightarrow \gamma e^-$

$\gamma \rightarrow e^+ e^-$

Ionized IGM

Neutral IGM

CMB

$z=1000$

$z=1000$

$\sim 10$ KeV

$\sim 100$ MeV

$\sim 10$ GeV

$H_{ub}b_{lm}/C_{ol}ing\_ime$
Propagation of the shower

- **DM**
- **Secondary shower**

**E~TeV/GeV**

- **Photon cooling:**
  - Through IC
  - Through absorption in plasma

- **Electron cooling:**
  - Through IC
  - Through absorption in plasma

\[ f(z) \]

- **H, He, Hel ionization**
- **H, He excitation**
- **Collisions with thermal electrons**
- **Free-free interactions with ionized atoms**
- **Recombinations**

\[ \chi_i(x_e) \]

\[ t_{\text{cool}} \sim t_H \rightarrow \text{redshifting need to be taken into account, NO on the SPOT!} \]

\[ E \sim \text{KeV} \]

Many very rapid processes,
\[ t_{\text{cool}} \ll t_H. \]
OK on the SPOT OK.
MCMC approach.
Propagation of the shower

DM

Secondary shower

E~TeV/GeV

High energy Code (Slatyer et al.)

- Analytical
- $t_{\text{cool}} \sim t_H$, redshifting need to be taken into account
- Electron and photon spectra calculated at each time step.
- NO on the SPOT!

Low energy Code (Valdes et al.)

- MCMC from 1 injected electron at energy ~KeV.
- $t_{\text{cool}} \ll t_H$, no redshifting taken into account

ON THE SPOT.

Galli, Slatyer, Valdes, Iocco 2013
\[ \frac{dE}{dt} = \rho_c c^2 \Omega_{dm} (1+z)^6 f(z) \frac{<\sigma v>}{m_\chi} \]

f(z) depends on the mass, model and annihilation channel of the DM particle considered.

Slatyer et al. 2009
\[ \frac{dE}{dt} = \rho_c^2 c^2 \Omega_{dm}(1+z)^6 f(z) \frac{\langle \sigma \, v \rangle}{m_\chi} \]

\textit{f(z) depends on the mass, model and annihilation channel of the DM particle considered.}

Galli, Slatyer, Valdes, Iocco 2013

\[ 10 \text{ GeV DM} \rightarrow e^+ + e^- \]
Correct vs Approximate $\chi$ fractions

Dashed: Approximate fractions used in the literature.

Solid: our accurate new fractions. We calculate for the first time the correct amount of energy going into Lyman $\alpha$ radiation.

We checked our fractions again a very large number of possible systematics, none of them affects the constraints.

Galli, Slatyer, Valdes, Iocco, 2013
EFFECT ON THE CMB
DM annihilation in the recombination epoch

\[
p_{\text{ann}}
\]

\[
\frac{dE}{dt} = \rho_c c^2 \Omega_{DM}^2 (1+z)^6 \left[ f(z) \frac{\langle \sigma v \rangle}{m_\chi} \right]
\]

\begin{itemize}
  \item At first, we assume \( f(z) = \text{CONSTANT} \)
\end{itemize}

\[ p_{\text{ann}} \text{[m}^3\text{/s/Kg]} \]

\begin{itemize}
  \item The energy injected \text{ionizes, excites and heats} the medium. This affects the evolution of the free electron fraction.
\end{itemize}
DM annihilation in the recombination epoch

\[ \frac{dE}{dt} = \rho_c c^2 \Omega_{DM}^2 (1+z)^6 \left[ f(z) \frac{\langle \sigma v \rangle}{m_\chi} \right] \]

- At first, we assume \( f(z) = \text{CONSTANT} \)

- A larger amount of free electrons after recombination makes the width of the visibility function larger.
CMB Angular Power Spectra

Temperature TT

Polarization EE

Cross Temp-Pol TE
CMB Angular Power Spectra

\[ \frac{((l+1)/2\pi)^2C_{ll}}{\bar{C}_{ll}[\mu K]^2} \]

- \( p_{ann} = 1 \times 10^{-6} \)
- \( p_{ann} = 5 \times 10^{-6} \)
- \( p_{ann} = 1 \times 10^{-6} \)
- \( p_{ann} = 0 \)
Constraints....

Chen & Kamionkowski 2004 (decay)

Padmanabhan & Finkbeiner 2005;

Zhang et al. 2006 (WMAP3+others, constant f)

Galli et al. 2009 (WMAP5+others, constant f)

Kim & Naselsky (WMAP5+others, constant f)

Galli et al 2011 (Future constraints, constant f)

Galli et al. 2011 (WMAP7+ACT, constant f and f for ee, mm channels)

Huetsi et al. 2011 (WMAP7, empirical parametrization of f )

Natarajan 2012 (WMAP7+SPT+other, f for bbar)

Finkbeiner, SG, et al. (Principal components approach for f)

Giesen et al. 2012 (WMAP7+SPT, f constant and variable)

Results on DM annihilation with constant f

\[ p_{ann} = \frac{f \langle \sigma v \rangle}{m_\chi} \]

- Wmap5 data already puts stringent constraints on the cross section/mass, i.e. on the properties of dark matter particles.
- WMAP7 improves of a factor 1.4, thanks to better measurements at higher l in TT, TE.
- Dark Matter models favoured by Pamela almost excluded by WMAP.
- Planck will improve results thanks to polarization data.

\[ p_{ann}[m^3/s/Kg] \text{ at } 95\% \text{ c.l.} \]

- WMAP5 < $2.0 \times 10^{-6}$
- WMAP7 < $1.4 \times 10^{-6}$
- WMAP7 + ACT < $1.2 \times 10^{-6}$

- Planck < $1.7 \times 10^{-7}$
- CVI < $5.9 \times 10^{-8}$

Forecasts!

Planck constraints (from TT only)

WMAP9                    <1.2x10^{-6}
Planck+WP              <5.4x10^{-6}
Planck+WP+CMB lensing <3.1x10^{-6}
Polarization (not used in this release)

**FORECAST!**
Wmap (Blue)
Planck simulated (Red)
A second approach: constraints with variable f(z)

For each specific f(z) one can set constraints on the cross-section.

Constraints on $<\sigma v>$ [cm$^3$/s] using WMAP7+ACT

<table>
<thead>
<tr>
<th>$m_\chi$</th>
<th>channel</th>
<th>Variable $f(z)$</th>
<th>Constant $f$</th>
<th>$f(z=600)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GeV</td>
<td>$e^+e^-$</td>
<td>$&lt;2.41 \times 10^{-27}$</td>
<td>$&lt;2.41 \times 10^{-27}$</td>
<td>0.87</td>
</tr>
<tr>
<td>100 GeV</td>
<td>$e^+e^-$</td>
<td>$&lt;3.55 \times 10^{-25}$</td>
<td>$&lt;3.35 \times 10^{-25}$</td>
<td>0.63</td>
</tr>
<tr>
<td>1 TeV</td>
<td>$e^+e^-$</td>
<td>$&lt;3.80 \times 10^{-24}$</td>
<td>$&lt;3.48 \times 10^{-24}$</td>
<td>0.60</td>
</tr>
</tbody>
</table>

\[
\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{dm} (1+z)^6 f(z) \frac{<\sigma \, v>}{m_\chi} <\sigma \, v> = \frac{p_{\text{ann}}^{\text{const}} m_\chi}{f(z=600)}
\]

For WMAP7 and WMAP7+ACT, knowing the overall normalization $f(z=600)$ is sufficient. This might not be the case for Planck!

Comparison of constraints

CMB constraints from Galli et al. 2011
Fermi constraints from dwarf spheroidal galaxies (Fermi-LAT Collaboration 2011).
AMS constraints from feature searches in positron spectrum. (Bergstrom 2013)
Conclusions

- CMB is a very good DM annihilation probe, independent from the knowledge of DM distribution.
- WMAP already puts strong constraints, that are already used to rule out DM models that fit Pamela data.
- We provided a general accurate approach to model different injection histories.
- Planck will need this accurate approach. Polarization is essential to have improvements.
Variation of the fine structure constant
The short version
Clusters can be observed through:

**SZ effect:** Clusters leave an imprint in the CMB spectrum as the hot gas inverse Compton scatter CMB photons.

**X-rays:** Clusters at T>2 KeV mainly emit through Bremsstrahlung effect.

From both, one can estimate quantities proportional to the thermal energy of the cluster.
New probe of variation of fine structure constant

SZ effect $\rightarrow$ Inverse Compton scattering $\rightarrow Y_{sz}$ $\alpha^2$

X-ray emission $\rightarrow$ Bremsstrahlung effect $\rightarrow Y_X$ $\alpha^{-1.5}$

$$\left( \frac{Y_{sz}D_A^2}{Y_X} \right)_i = \left( \frac{\alpha_i}{\alpha_0} \right)^{3.5} \left( \frac{Y_{sz}D_A^2}{Y_X} \right)_0$$

With 62 clusters observed by Planck in SZ and XMM-Newton in Xrays,

0.8% constraint on $\alpha$

Comparable to CMB constraints today (but completely different redshift range) and are robust!

S. Galli, PRD 2013, accepted for publication
The long version
Testing the validity of known physics

- Fundamental Constants characterize theories, only measured and not theoretically predictable.

- Testing for variation of constants corresponds to testing validity of known physics.

**Fine Structure Constant** (strength e.m. force)

- Claim of a space-time variation of $\alpha$ in quasars. (Webb et al. 2004, 2011)

- From Pre-Planck CMB constraints at 2% (0.5% in combination) (Menegoni, SG, et al 2009, 2010 2012; Galli et al 2009, Martins, SG et al 2010)

  - Planck alone CMB constraint at 0.4%

CMB constraints test physics at redshift ~1000. Time-space scales different from laboratory constraints.
Evidence for spatial variation of the fine structure constant

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(Dated: August 25, 2010)

We previously reported observations of quasar spectra from the Keck telescope suggesting a smaller value of the fine structure constant, $\alpha$, at high redshift. A new sample of 153 measurements from the ESO Very Large Telescope (VLT), probing a different direction in the universe, also depends on redshift, but in the opposite sense, that is, $\alpha$ appears on average to be larger in the past. The combined dataset is well represented by a spatial dipole, significant at the 4.1$\sigma$ level, in the direction right ascension $17.3 \pm 0.6$ hours, declination $-61 \pm 9$ degrees. A detailed analysis for systematics, using observations duplicated at both telescopes, reveals none which are likely to emulate this result.

PACS numbers: 06.20.Jr, 95.30.Dr, 95.30.Sf, 98.62.Ra, 98.80.-k, 98.80.Es, 98.80.Jk

The Fine Structure Constant?

The UVES Large Program for Testing Fundamental Physics: I
Bound on a change in $\alpha$ towards quasar HE 2217–2818


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ABSTRACT

Context. Absorption-line systems detected in quasar spectra can be used to compare the value of the fine-structure constant, $\alpha$, measured today on Earth with its value in distant galaxies. In recent years, some evidence has emerged of small temporal and also spatial variations of $\alpha$ on cosmological scales which may reach a fractional level of $\approx 10$ ppm (parts per million).

Aims. To test these claims we are conducting a “Large Program” of observations with the Very Large Telescope’s Ultraviolet and Visual Echelle Spectrograph (UVES). We are obtaining high-resolution ($R \approx 60000$) and high-signal-to-noise ratio ($S/N \approx 100$) UVES spectra calibrated specifically for this purpose. Here we analyse the first complete quasar spectrum from this Program, that of HE 2217–2818.

Methods. We apply the Many Multiplet method to measure $\alpha$ in 5 absorption systems towards this quasar: $z_{\text{abs}} = 0.7866, 0.9424, 1.5558, 1.6279$ and 1.6919.

Results. The most precise result is obtained for the absorber at $z_{\text{abs}} = 1.6919$ where 3 Fe II transitions and Al II $\lambda 1670$ have high $S/N$ and provide a wide range of sensitivities to $\alpha$. The absorption profile is complex, with several very narrow features, and requires 32 velocity components to be fitted to the data. We also conducted a range of tests to estimate the systematic error budget. Our final result for the relative variation in $\alpha$ in this system is $\Delta \alpha/\alpha = +1.3 \pm 2.4_{\text{stat}} \pm 1.0_{\text{syst}}$ ppm. This is one of the tightest current bounds on $\alpha$-variation from an individual absorber. A second, separate approach to the data-reduction, calibration and analysis of this system yielded a slightly different result of $-3.8 \pm 2.1_{\text{stat}}$ ppm, possibly suggesting a larger systematic error component than our tests indicated. This approach used an additional 3 Fe II transitions, parts of which were masked due to contamination by telluric features. Restricting this analysis to the Fe II transitions only and using a modified absorption profile model, gave a result consistent with the first approach, $\Delta \alpha/\alpha = +1.1 \pm 2.6_{\text{stat}}$ ppm. The other 4 absorbers have simpler absorption profiles, with fewer and broader features, and offer transitions with a smaller range of sensitivities to $\alpha$. Therefore, they provide loose bounds on $\Delta \alpha/\alpha$ at the $\approx 10$ ppm precision level.

Conclusions. The absorbers towards quasar HE 2217–2818 reveal no evidence for variation in $\alpha$ at the 3-ppm precision level (1-$\sigma$ confidence). If the recently-reported 10-ppm dipolar variation of $\alpha$ across the sky were correct, the expectation at this sky position is $(3.2-5.4) \pm 1.7$ ppm depending on dipole model used. Our constraint of $\Delta \alpha/\alpha = +1.3 \pm 2.4_{\text{stat}} \pm 1.0_{\text{syst}}$ ppm is not inconsistent with this expectation.
New probe of variation of fine structure constant

Clusters can be observed through:

**SZ effect:** Clusters leave an imprint in the CMB spectrum as the hot gas inverse Compton scatter CMB photons.

**X-rays:** Clusters at T>2 KeV mainly emit through Bremsstrahlung effect.

From both, one can estimate quantities proportional to the thermal energy of the cluster.
The spectral distortion due to the SZ effect is proportional to the $y$ parameter. This is proportional to the thermal pressure integrated along the line of sight.

$$y = \frac{\sigma T}{m_e c^2} \int n_e(r)T(r)dl$$

Thomson scattering cross section
The spherical $Y_{sz} D_A^2$ is the estimate of the thermal energy of the cluster from SZ.

$$Y_{SZ}^{sp}(R) D_A^2 = \frac{\sigma_T}{m_e c^2} \int_0^R n(r) T(r) 4\pi r^2 \, dr$$

$$\sigma_T = \frac{8\pi}{3} \frac{\hbar^2}{m_e^2 c^2} \alpha^2$$

$Y_{SZ} \propto \alpha^2$
X-ray and the fine structure constant

\( Y_X \) is the estimate of the thermal energy from X-rays.

\[ Y_X = M_g(R)T_X \]

Gas mass determined from density profile, which is inferred from observed surface brightness of the galaxy. Surface brightness depends on the Bremsstrahlung emissivity, the \( \alpha \).

\[ \epsilon_{\nu} = \alpha^3 \frac{2^5 \pi \hbar^3}{3m_e} \left( \frac{2\pi}{3m_e k} \right)^{1/2} Z^2 g_{ff} n_e n_i T^{-1/2} e^{-h\nu/kT} \]
$Y_X$ is the estimate of the thermal energy from X-rays.

$$Y_X = M_g(R)T_X$$

Gas mass determined from density profile, which is inferred from observed surface brightness of the galaxy. Surface brightness depends on the Bremsstrahlung emissivity, the DEPENDS ON $\alpha$.

$$M_g(R) \propto \sqrt{\alpha^{-3} I_\nu D_A^{5/2}}$$

$$Y_X \propto \alpha^{-1.5}$$
Ysz/Yx and the fine structure constant

If thermal profile of clusters is universal, because scaling relation are self-similar (evolution of the cluster only determined by gravitational physics-mass), then the ratio is expected to be CONSTANT.

\[
\left( \frac{Y_{SZ} D_A^2}{Y_X} \right)_i = \left( \frac{\alpha_i}{\alpha_0} \right)^{3.5} \left( \frac{Y_{SZ} D_A^2}{Y_X} \right)_0
\]

\[
\frac{Y_{SZ} D_A^2}{Y_X} = C_{SZ} \frac{\int n_e(r) T(r) dV}{T_X(R) \int n_e(r) dV} \sim \text{const}
\]

S. Galli, PRD 2013
Universal Profiles

Rescaled density profile

Rescaled temperature profile

Arnaud et al. 2010
A new probe for the variation of the fine structure constant

Clusters Thermal Energy
To the error budget, we quadratically add a constant term representative of the unaccounted intrinsic scatter. This scattering term is estimated directly from the data, imposing that the reduced $\chi^2$ of the fit must be 1.
New probe of variation of fine structure constant

With 62 clusters observed by Planck in SZ and XMM-Newton in Xrays,

$$\sigma(\alpha/\alpha_0) = 0.8\%$$

Comparable to CMB constraints today (but at completely different redshift range)
Future improvements

Current constraints are not limited by the uncertainty on cosmological parameters. However, with an arbitrarily large sample of clusters, the constraint on $\alpha$ attainable would be (assuming cosmology constrained by pre-Planck data):

$$\sigma(\alpha/\alpha_0) = 0.3\%$$

Using future Planck+Euclid data, a constraint using 2000 cluster could be:

$$\sigma(\alpha/\alpha_0) = 0.34\%$$