Ionization of Atoms by Axions and Dark Matter Particles

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Some popular non-baryonic DM candidates

- **WIMP** (e,g. neutralino), **M > 1 GeV**
- **Super-WIMP**

a) **fermionic** (sterile neutrino, gravitino) – undetectable

b) **bosonic**, M: 10-100 KeV (scalar, pseudoscalar, vector, pseudovector) – might be detectable.

- **Axions**, **M: 10^{-6} – 1 eV.**

Bosonic super-WIMPs and **Axions** may be detected through ionization of atoms.

Pseudoscalar super-WIMPs interaction with electrons

Hamiltonian:

$$H_a = \frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$$

Ionization cross section:

$$\sigma_a(\varepsilon_a) = \pi \left(\frac{\varepsilon_a}{f_a} \right)^2 \frac{c}{v} K(\varepsilon_a) a_0^2$$

K is dimensionless function of energy

Dimensionless function

$$K(\varepsilon_a) = \pi \left(\frac{\varepsilon_a}{\varepsilon_0} \right)^2 \varepsilon_a \sum_c R_{c\varepsilon}^2 (2 j_c + 1)$$

(similar to photoionization)

In non-relativistic limit (Pospelov, Ritz, Voloshin)

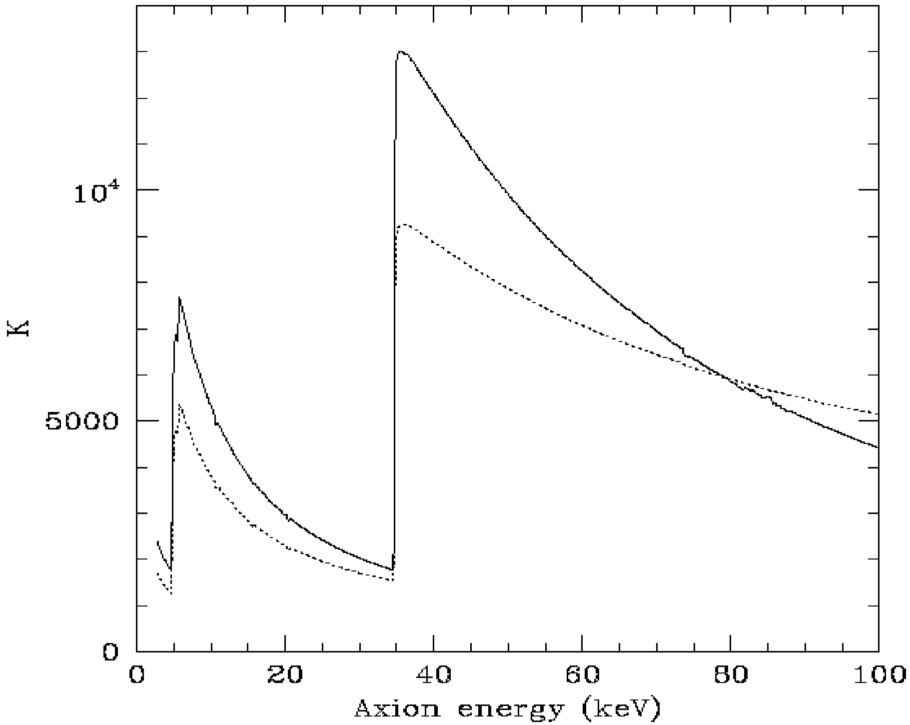
$$\frac{\sigma_a}{\sigma_\gamma} = \frac{c}{v} \frac{3\varepsilon_a^2}{4\pi\alpha f_a^2}$$

$$\frac{\sigma(m_a = 0)}{\sigma(m_a c^2 = \varepsilon_a)} = \frac{2}{3}$$

Calculations by the relativistic Hartree-Fock method. Agreement with experiment for photoionization of Kr and Xe is within 10%.

Ionization cross section
(*K*-function for Xe)

(There are also numerical calculations for Ar, Ge, etc. and numerical fit for 18<Z<60 and 10<ε_a<50 keV).



solid line: $m_a c^2 = \varepsilon_a$

dotted line: $m_a = 0$

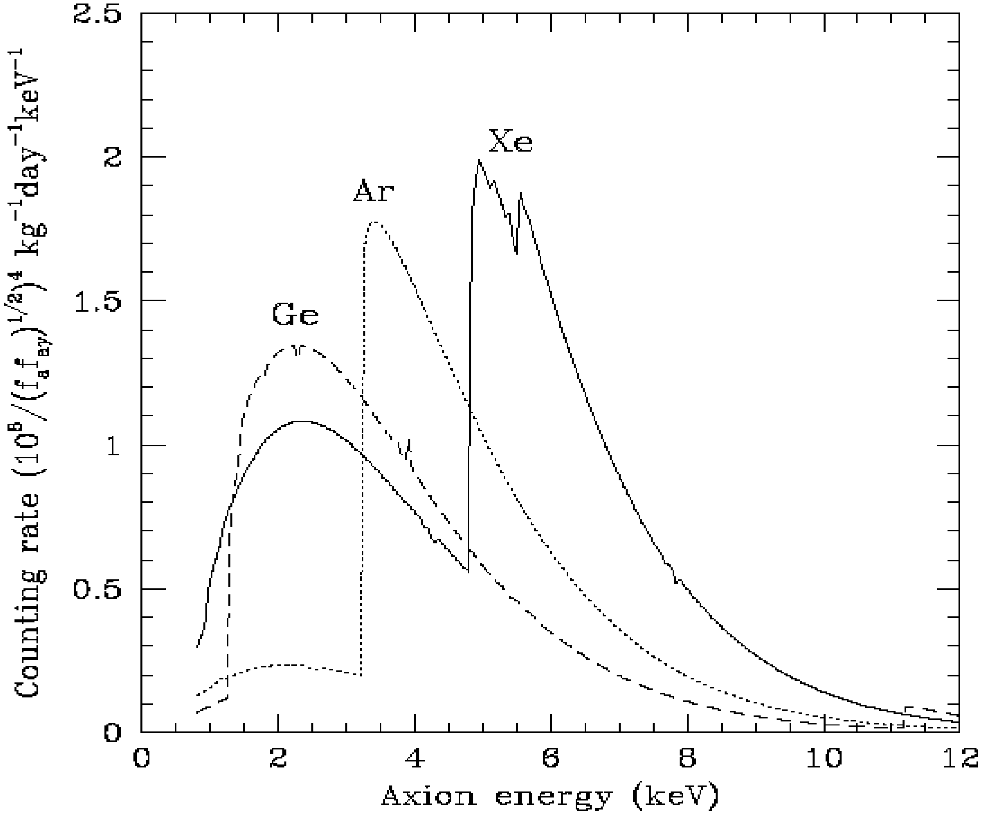
$$\frac{\sigma(m_a = 0)}{\sigma(m_a c^2 = \varepsilon_a)} = \frac{2}{3} + aZ^2 + b\frac{\varepsilon_a + \varepsilon_{1s}}{\varepsilon_0}$$

$a = 1.4 \times 10^{-5}$ $b = 2 \times 10^{-4}$

Solar axion

a) γγ-production

Axion flux from the sun: $\frac{d\Phi}{d\varepsilon} = 6\times10^{30}\left(\frac{GeV}{f_{a\gamma}}\right)^2 \varepsilon^{2.481} e^{-\frac{\varepsilon}{1.205}} cm^{-2}s^{-1}keV^{-1}$



Total counting rate:

$$R_{Ar} = 5.0\left(\frac{10^8\,GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

$$R_{Ge} = 5.2\left(\frac{10^8\,GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

$$R_{Xe} = 8.2\left(\frac{10^8\,GeV}{(f_a f_{a\gamma})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

Solar axion

b) nuclear–γ production

Axion flux from the sun at ε_a=14.4 keV:

$$\Phi_a = 4.5\times 10^{23}\left(\frac{GeV}{f_{aN}}\right)^2 cm^{-2}s^{-1}$$

Total counting rate:

$$R_{Ar} = 4\left(\frac{10^6\,GeV}{(f_a f_{aN})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

$$R_{Ge} = 18\left(\frac{10^6\,GeV}{(f_a f_{aN})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

$$R_{Xe} = 11\left(\frac{10^6\,GeV}{(f_a f_{aN})^{1/2}}\right)^4 kg^{-1}day^{-1}$$

Conclusion

- **We have:**

  Absorption cross section for pseudo-scalar super-WIMPs (including axions).

  Absorption cross section and counting rate for solar axions.

Convenient analytical fits of numerical calculations:

Cross sections and counting rates as functions of nuclear charge Z

- **The results are to be used in the analysis of the data from the underground detectors.**

- **Similar calculations are to be done for scalar, vector, pseudo-vector super-WIMPs.**

Constraint on axion-like particles from atomic physics

Exchange by axion-like particle produces

Yukawa-type interaction between electron and nuclear spin in Hydrogen, Deuterium and Muonium and leads to corrections to 1s hyperfine splittings which are very accurately measured. Contrary to astrophysics we do not assume that particles are stable or long lived.

Karshenboim, Flambaum Phys. Rev. A 2011

Effects of moving 300 km/s axion Bose condensate

- Lorentz invariance violation. Effect on electron and nuclear spins similar to that of oscillating magnetic field, the frequency is equal to axion energy/h. Direction of the effective field is along the average axion momentum k, strength of the interaction

  V=1 nHz cos(mt) , m=2 GHz if axions saturate dark matter energy density.

$V= 2. \times 10^{-24}$ eV=0.5 nHz (10^{12} Gev/f)

$m= 0.6 \times 10^{-5}$ eV =1.5 GHz (10^{12} Gev/f)

Effects of axion Bose condensate

- Graham,Rajendran: Oscillating electric dipole moments of elementary particles, nuclei and atoms due to axion-induced QCD theta-term (source of strong CP invariance violation). 10^{-24} eV = nHz ?
- Similar effects in paramagnetic atoms and molecules due to electron-axion condensate iteraction.

Evidence for spatial variation of the fine structure constant α

Quasar spectra

Webb, King, Murphy, Flambaum, Carswell, Bainbridge, PRL2011,MNRAS2012

$$\alpha(x) = \alpha(0) + \alpha'(0)\,x + \ldots$$

$x = r\cos(\phi)$, $r = ct$ – distance (t - light travel time, c - speed of light)

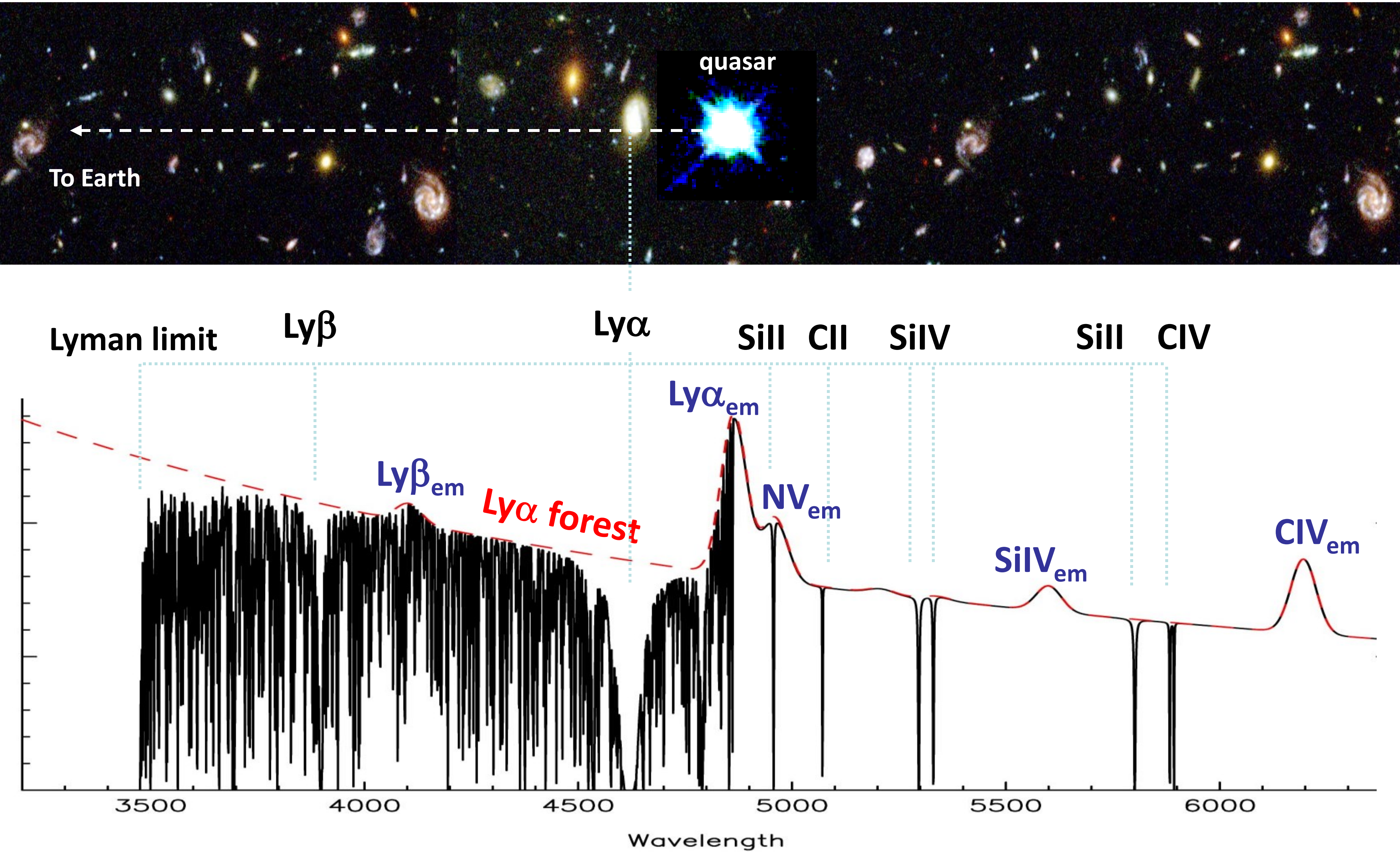
Reconciles all measurements of the variation

“ Fine tuning” of fundamental constants is needed for life to exist. If fundamental constants would be even slightly different, life could not appear!

Variation of coupling constants in space provide natural explanation of the “fine tuning”: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

There are theories which suggest variation of the fundamental constants in expanding Universe due to variation of the scalar field (dark energy)

Quasars: physics laboratories in the early universe



Use atomic calculations to find $\omega(\alpha)$.

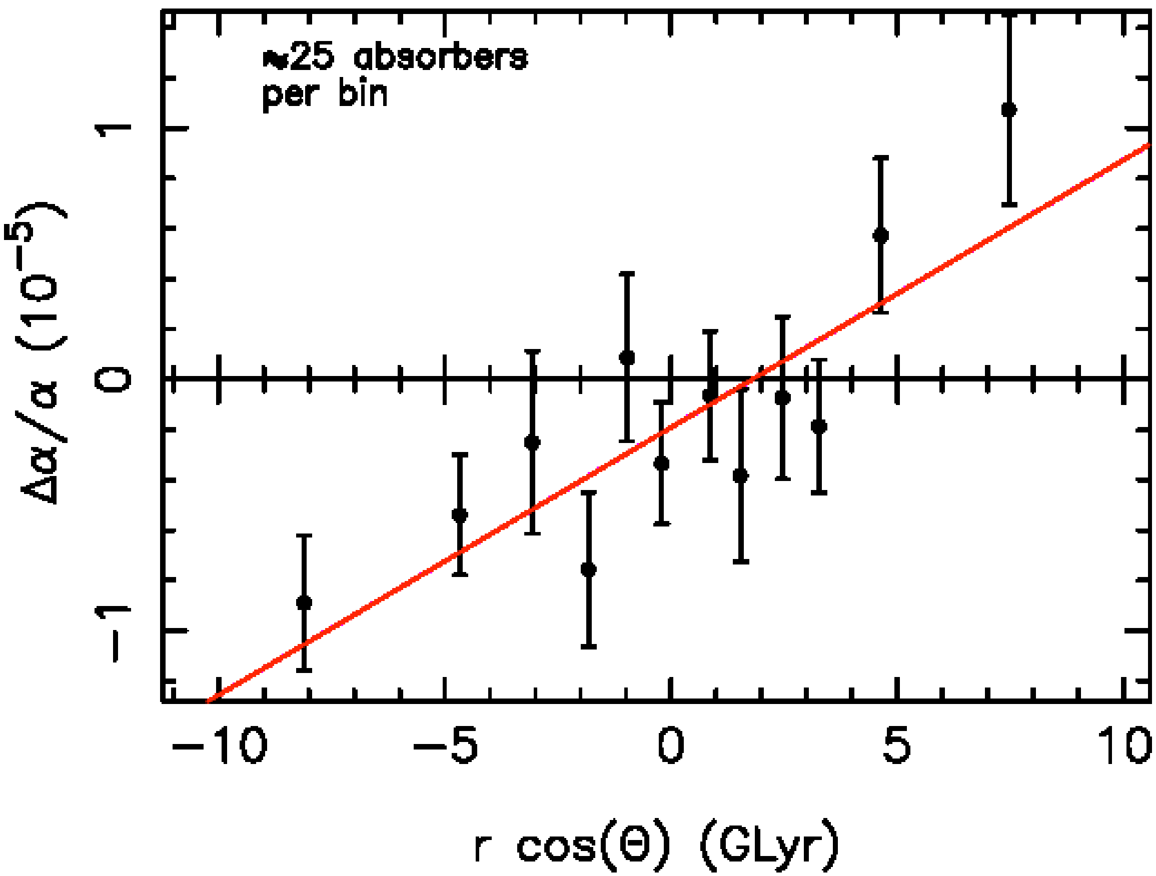
For α close to α_0 $\quad \omega = \omega_0 + q(\alpha^2/\alpha_0^2 - 1)$

q is found by varying α in computer codes:

$q = d\omega/dx = [\omega(0.1) - \omega(-0.1)]/0.2, \quad x = \alpha^2/\alpha_0^2 - 1$

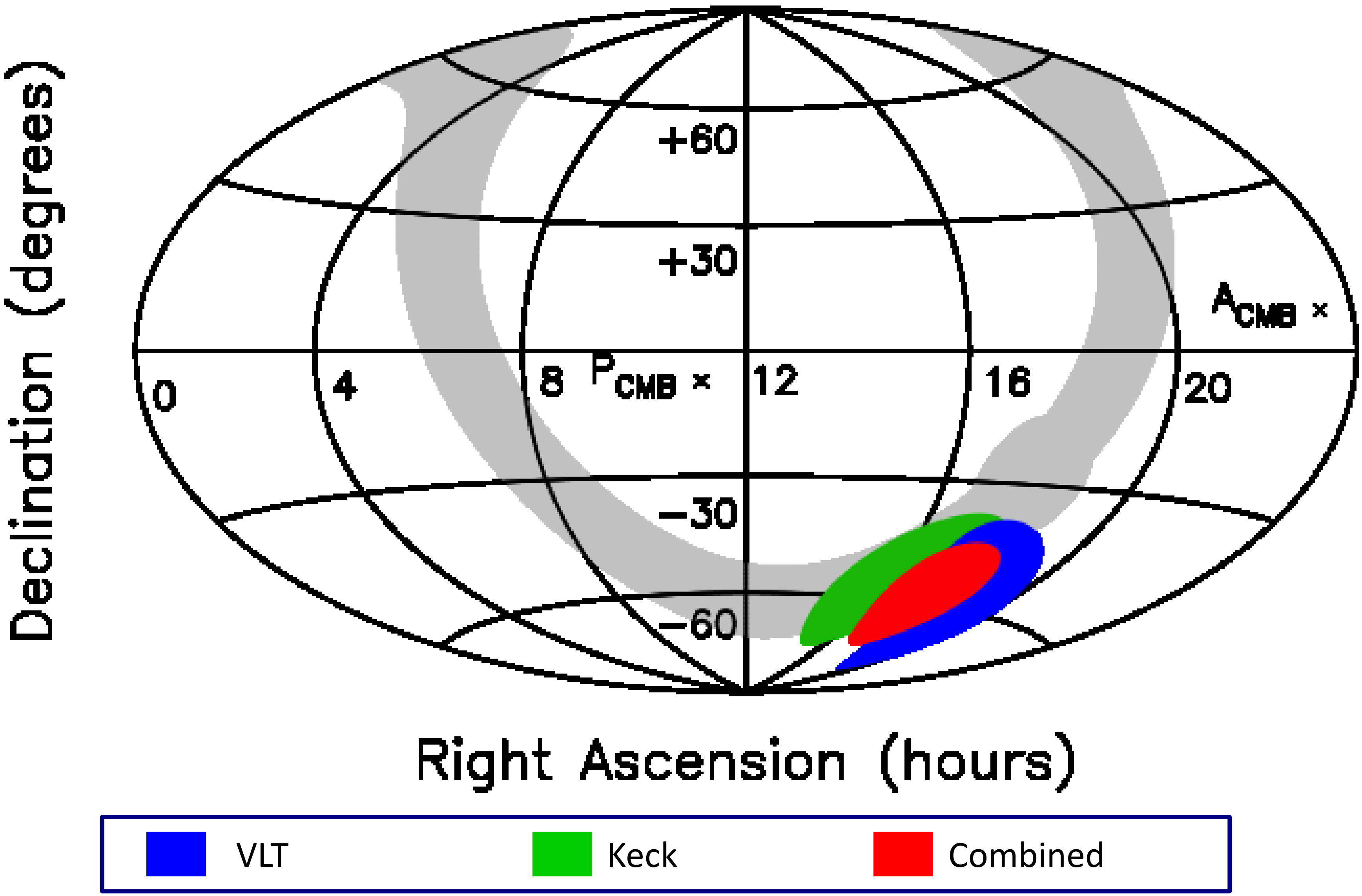
$\alpha = e^2/2\,\varepsilon_0 hc = 0$ corresponds to non-relativistic limit (infinite c). Dependence on α is due to relativistic corrections.

Distance dependence

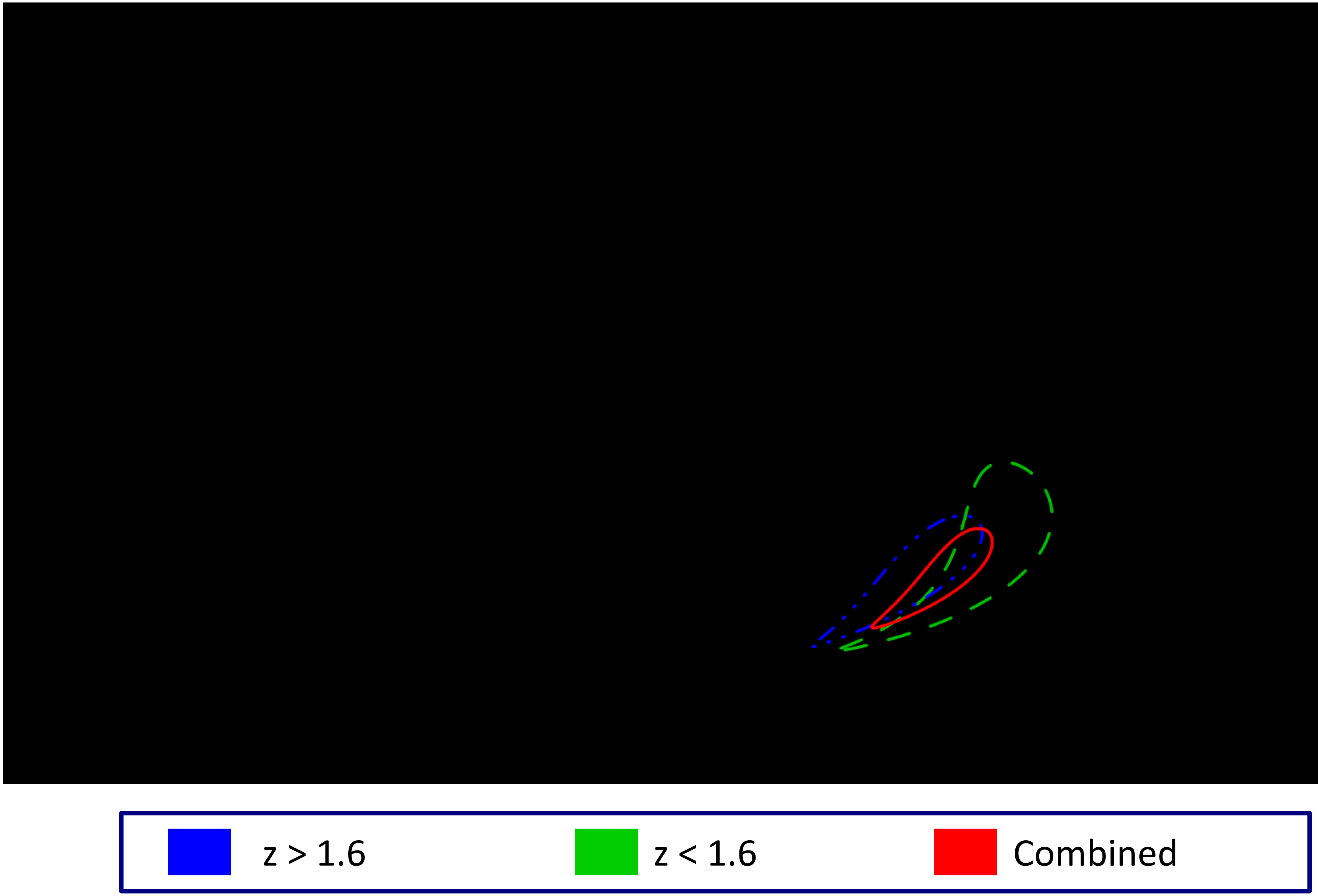


Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} $GLyr^{-1}$ and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.1σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

Keck & VLT dipoles independently agree, p=4%



Low and high redshift cuts are consistent in direction. Effect is larger at high redshift.



Hints that this result might be real

Two internal consistencies:

1 Keck and VLT dipoles agree. Independent samples, different data reduction procedures, different instruments and telescopes.

2 High and low redshift dipoles also agree - different species used at low and high redshift – and different transitions respond differently to the same change in α.

300 absorption systems, 30 atomic lines

Plank satellite Cosmic Microwave Background data 2013:
Universe is not symmetric!
CMB fluctuations are different in different directions.

Limits on dependence of alpha on gravity from white dwarf spectra
Fe^{4+},Ni^{4+} 4.2(1.6) 10^{-5}. Accurate laboratory spectra needed.

Consequences for atomic clocks

- Sun moves 369 km/s relative to CMB
  $\cos(\phi) = 0.1$
  This gives average laboratory variation
  $\Delta\alpha/\alpha = 1.5\ 10^{-18}\ \cos(\phi)$ per year

- Earth moves 30 km/s relative to Sun-
  $1.6\ 10^{-20}\ \cos(\omega t)$ annual modulation

Neutrino speed and variation of the fundamental constants

- Limiting speed c may be different deep underground (neutrino experiments)
- Fine structure constant $\alpha = e^2/2\varepsilon_0 hc$ ***contains c and may be different***
- ***Accuracy of atomic clocks is 10 orders of magnitude better – compare ratio of clock frequencies deep underground***

Neutrino speed and variation of the fundamental constants

Flambaum, Pospelov 2012

QED Lagrangian with additional term describing modification of limiting speed c by depth-dependent tensor $h_{\iota\kappa}$ different from the general relativity metric tensor $g_{\iota\kappa}$

Relations between neutrino speed experiments and atomic clock experiments placed deep underground, e.g. Sudbury mine 2 km, Mariana Trench 11 km, deeper than neutrino

Conclusions

- Spatial gradient of alpha from quasar data, 4.2 sigma, Keck and VLT data agree, low and high red shift data agree, no contradictions with other groups.
- It provides alpha variation for atomic clocks due to Earth motion at the level 10^{-19} . Two orders of magnitude improvement in the measurement accuracy is needed.
- Very weak indications for the spatial variation in H_2 quasar spectra. The same direction of the gradient!
- Many systems with relative enhancement due to transition between close levels: Dy atom and molecules with narrow close levels.

New systems with higher absolute sensitivity include highly charged ions and ^{229}Th nucleus.

- Search for anisotropy in primordial deuterium distribution, CMB, expansion of the Universe, structure formation.
- Search for dependence of alpha on environment (deep underground or near white dwarfs)