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A limit on Planck-scale froth with ESPRESSO

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ABSTRACT

Some models of quantum gravity predict that the very structure of space–time is 'frothy' due to quantum fluctuations. Although the effect is expected to be tiny, if these space–time fluctuations grow over a large distance, the initial state of a photon, such as its energy, is gradually washed out as the photon propagates. Thus, in these models, even the most monochromatic light source would gradually disperse in energy due to space–time fluctuations over large distances. In this paper, we use science verification observations obtained with ESPRESSO at the Very Large Telescope to place a novel bound on the growth of space–time fluctuations. To achieve this, we directly measure the width of a narrow Fe II absorption line produced by a quiescent gas cloud at redshift $z \simeq 2.34$, corresponding to a comoving distance of $\simeq$5.8 Gpc. Using a heuristic model where the energy fluctuations grow as $\sigma_E/E = (E/E_{\rm P})^{\alpha}$, where $E_{\rm P} \simeq 1.22 \times 10^{28}$ eV is the Planck energy, we rule out models with $\alpha \le 0.634$, including models where the quantum fluctuations grow as a random walk process ($\alpha = 0.5$). Finally, we present a new formalism where the uncertainty accrued at discrete space–time steps is drawn from a continuous distribution. We conclude, if photons take discrete steps through space–time and accumulate Planck-scale uncertainties at each step, then our ESPRESSO observations require that the step size must be at least $\gtrsim 10^{13.2} l_{\rm P}$, where $l_{\rm P}$ is the Planck length.

Key words: elementary particles – gravitation – line: profiles – quasars: absorption lines – cosmology: theory.

1 INTRODUCTION

At microscopic distance scales comparable to the Planck length, $l_{\rm P} = \sqrt{\hbar G/c^3} \simeq 1.62 \times 10^{-35}$ m, it is thought that space–time itself is subject to quantum fluctuations. If true, space–time should appear 'fuzzy' or 'frothy', an effect that was termed 'quantum foam' (also referred to as space–time foam) by Wheeler (1963). A foamy space–time would cause minute uncertainties in the propagation of waves, such as the distance traversed by a photon, or its energy. If found, it would demonstrate that the nature of space–time is probabilistic, rather than deterministic, and provide strong clues towards finding a unified description of gravity and quantum mechanics (for an overview, see Amelino-Camelia 2013).

A variety of cosmological experiments have been conducted to place limits on models of quantum gravity. The most stringent constraint currently available is based on timing observations of distant gamma-ray bursts (GRBs; Abdo et al. 2009; Vasileiou et al. 2013), which can be used to limit the in-vacuo dispersion of photons. Some models of quantum gravity predict that the photon speed depends on its energy (Amelino-Camelia et al. 1998; Mattingly 2005; Jacobson, Liberati & Mattingly 2006; Kostelecký & Mewes 2008), with the highest energy photons being the most affected. Over the immense cosmological distances to high-redshift GRBs, the tiny shift of the propagation speed accumulates, and may produce a detectable difference in the arrival times of photons of different energy. The current GRB data disfavour quantum gravity theories that predict a variable speed of light at length-scales, $l < l_{\rm P}/1.2$ (Abdo et al. 2009).

Currently, the most popular astrophysical probes of space–time 'fuzziness' are the phase delay and spatial blurring of cosmological sources. The first of these approaches was proposed by Lieu & Hillman (2003), building off a related proposal to search for quantum foam using gravitational wave interferometers (Amelino-Camelia 1999). The idea is relatively simple: some quantum gravity models predict that the period and wavelength of monochromatic photons gradually disperse as the wave propagates due to Planck-scale uncertainties. As the waveform travels further, its period and wavelength will increasingly deviate from the initial (i.e. emitted) values. When the waveform enters the aperture of a telescope (or interferometer), it will no longer represent a plane wave that uniformly illuminates the telescope aperture. As a result, if quantum

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foam scrambles the wavefront, an Airy disc diffraction pattern will not appear at the focus.

Lieu & Hillman (2003) used the observation of an Airy disc in an image of PKS 1413+135 (at a distance of 1.2 Gpc), to suggest that first-order fluctuations down to the Planck scale are ruled out. Shortly after their study, Ragazzoni, Valente & Marchetti (2003) extended this idea, and proposed that high-redshift cosmological point sources should experience spatial blurring due to the effects of quantum foam, and placed comparably strong limits on Planck-scale phenomena. However, the above results were contested soon after by Ng, Christiansen & van Dam (2003), who highlighted that the cumulative effects of quantum foam depend on the choice of quantum gravity model (see also Coule 2003).

Subsequent studies of spatial blurring (Christiansen, Ng & van Dam 2006; Steinbring 2007; Christiansen et al. 2011; Perlman et al. 2011; Tamburini et al. 2011; Steinbring 2015) have narrowed the allowed model space by employing sources that emit high-energy photons and are at larger cosmological distances. More recently, Perlman et al. (2015) pointed out that when the distortions due to quantum foam become comparable to the wavelength of the photon, the intensity of a source decays to the point that the very *detection* of a high-redshift cosmological source places a strong bound on models of quantum gravity. Their work offers the tightest constraints yet, effectively ruling out the holographic model (see Section 2).

In this work, we present a novel limit on space–time foam using the widths of narrow spectral lines that are seen in absorption against the light of a more distant background quasar. In Section 2, we present an overview of the cosmological fluctuation models that appear in the literature. We then extend this formalism to generalize the step size and the amount of uncertainty accumulated at each step. In Section 3, we report a new bound on space–time foam using the Ly α forest, before offering an improved bound using state-of-the-art observations with the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) instrument (Pepe et al. 2010) on the Very Large Telescope (VLT). We describe the future opportunities of this approach in Section 4 before summarizing our main conclusions in Section 5. Throughout, we assume a flat cosmology with $H_0 = 67.8\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\mathrm{B},0} = 0.04825$, and $\Omega_{\mathrm{M},0} = 0.307$ (Planck Collaboration VI 2018).

2 THE COSMOLOGICAL FLUCTUATION MODEL

Consider a precisely monochromatic laser placed at a cosmological distance. As the photons propagate towards our telescope, some models of quantum gravity predict that the photons gradually disperse in energy, leading to a measurable energy width of the photon ensemble. In this section, we derive the observed energy width of a cosmological laser.

2.1 Literature models

The fundamental idea behind the following model is that space–time fluctuations accumulate over large cosmological distances. Most of the studies described in Section 1 adopt the following one parameter model to describe the uncertainty (σ_l) of a distance measurement (l), relative to the Planck length: $\sigma_l/l = (l_\mathrm{P}/l)^\alpha$, where α describes how the quantum fluctuations grow as a wave propagates (herein, we refer to α as the 'growth factor'; note $0.5 \le \alpha \le 1.0$). One can show that this parametrization leads to similar uncertainties on the energy (Ng & van Dam 2000; Lieu & Hillman 2003), $\sigma_E/E = (E/E_\mathrm{P})^\alpha$, where $E_\mathrm{P} = \hbar c/l_\mathrm{P} \simeq 1.22 \times 10^{28}$ eV is the Planck energy.

There are two proposals for how the accumulation of Planck-scale effects should grow over distance (see Lieu & Hillman 2003; Ng et al. 2003, and papers thereafter by these groups). According to Ng et al. (2003), Planck-scale effects accumulate once every wavelength. Therefore, the fluctuations over distance, L, grow by a multiplicative factor $C_\alpha = N^{1-\alpha}$, where $N = L/\lambda$ is the integer number of wavelengths traversed by a photon (i.e. the number of times that quantum foam affects the photon). In this case, the fluctuation model becomes $\sigma_l/l = (l_\mathrm{P}/l)^\alpha\, C_\alpha$. In an expanding universe, we have

$$N = \int \frac{\mathrm{d}r}{\lambda(z)} = \frac{c}{H_0\,\lambda_0}\int_0^z \frac{\mathrm{d}z}{E(z)} = \frac{D_\mathrm{C}}{\lambda_0}, \tag{1}$$

where r is the proper distance, λ_0 is the observed wavelength of a photon emitted at redshift z, and D_C is the comoving distance. Thus, if $C_\alpha = N^{1-\alpha}$, a collection of precisely monochromatic photons emitted at redshift z with wavelength λ_em would gradually disperse in energy, leading to an observed energy width (or, equivalently, a velocity width, Δv_q)

$$\sigma_E/E \equiv \Delta\lambda/\lambda \equiv \Delta v_\mathrm{q}/c = \frac{(l_\mathrm{P}/\lambda_\mathrm{em})^\alpha\,(D_\mathrm{C}/\lambda_\mathrm{em})^{1-\alpha}}{1+z}. \tag{2}$$

It follows that one of the predictions of this formalism is that the relative widths of any two atomic transitions intrinsically dispersed by quantum foam should vary as

$$\Delta v_{\mathrm{q},1}/\Delta v_{\mathrm{q},2} = \lambda_2/\lambda_1, \tag{3}$$

completely independent of: (1) the growth factor; (2) the distance travelled by the photon; and (3) cosmology.

Alternatively, Planck-scale effects may accumulate linearly with distance (i.e. $C_\alpha = N$); this is the original proposal put forward by Lieu & Hillman (2003). In this case, the observed velocity width (cf. equation 2)

$$\Delta v_\mathrm{q}/c = \frac{(l_\mathrm{P}/\lambda_\mathrm{em})^\alpha\,(D_\mathrm{C}/\lambda_\mathrm{em})}{(1+z)^{1+\alpha}}. \tag{4}$$

In this work, we report limits on α based on the former approach (i.e. equation 2), since it offers a more conservative limit on the growth of fluctuations. It is important to note that the above heuristic formalism was developed to experimentally search for potential quantum effects on the structure of space–time. Only recently, have these models been placed into a more robust theoretical description of quantum gravity (Amelino-Camelia, Calcagni & Ronco 2017; Calcagni & Ronco 2017). In particular, the parameter α is related to the Hausdorff dimension of effective space–time, $d_\mathrm{H} = (1-\alpha)\,D$, where D corresponds to a D-cube with a side of length l.

Since there is not a universally accepted theory of quantum gravity, different space–time foam models in the family described above are parametrized by different values of the growth factor, α. The three most prominent models of quantum foam that are discussed in the literature are

(i) The random walk model (Diósi & Lukács 1989; Amelino-Camelia 1999), whereby the growth of quantum fluctuations is modelled as a random walk process, and is parametrized by $\alpha = 1/2$.

(ii) The holographic model of fluctuations (Ng & van Dam 1994), which is motivated by the holographic principle ('t Hooft 1993; Susskind 1995). In this model, the information in a three-dimensional volume can be encoded on a two-dimensional surface, resulting in $\alpha = 2/3$.

(iii) The so-called standard version of quantum foam, with $\alpha = 1$, corresponding to the original proposal by Wheeler (1963). In this model, the quantum fluctuations are not accumulated over distance, and there is therefore no obvious benefit in appealing to cosmological sources to test this model.

Note, the fluctuation formalism discussed above requires that α is in the range $0.5 \leq \alpha \leq 1$. In closing this section, we note that the derivation of the accumulation factor, C_α, makes the following two assumptions: (1) uncertainties are accumulated at each step, where the step size is assumed to be equal to the wavelength of a photon; and (2) each step accumulates an uncertainty of $\pm l_\mathrm{P}(\lambda/l_\mathrm{P})^{1-\alpha}$ (i.e. only two possibilities), with equal probability. In the following subsection, we describe an alternative approach that makes different assumptions about the step size and the accumulation of uncertainty at each step.

2.2 Convolutional fluctuation model

We now describe a simple extension to the above formalism that allows us to generalize the step size taken by a particle, and the amount of uncertainty that is accumulated at each step. This simple model is primarily motivated by the aforementioned assumption that the uncertainty accumulated at each step is drawn from a two-point distribution, instead of a continuous distribution. One would naively expect that the two-point assumption exacerbates the effects of quantum foam. Instead, a more conservative approach is that the accumulated uncertainty is drawn from a continuous distribution.

Suppose a particle makes a step of size λ, and accumulates an uncertainty that is drawn from a uniform distribution between $\pm l_\mathrm{P}/2$. We are interested in deriving the dispersion accumulated over a distance L. We note that the above variables, λ and l_P, may be interpreted by the reader as the wavelength and Planck length, respectively. However, this is just for ease of comparison with previous work, and we stress that the following formalism is general to different choices of these length-scales.

If at each step, the uncertainty of the step size is independent of the previous step, we can model this process as a rectangle (i.e. 'tophat') function of width l_P, repeatedly convolved with itself at each step. Assuming that the step size $\lambda \gg l_\mathrm{P}$, then the wave will take $N = L/\lambda$ steps, corresponding to N convolutions of a rectangle function with itself. The resulting form of the space–time foam-induced broadening function, Φ_q, can be calculated with Fourier transforms, assuming $N \gg 1$,

$$\begin{aligned}\Phi_\mathrm{q} &= \mathcal{F}^{-1}[\mathcal{F}[\mathrm{rect}(l/l_\mathrm{P})]^N] \\ \Phi_\mathrm{q} &\simeq \mathcal{F}^{-1}[(1-(\pi\, l_\mathrm{P}\, x)^2/6)^N] \\ \Phi_\mathrm{q} &\simeq \mathcal{F}^{-1}[\exp(-N\,(\pi\, l_\mathrm{P}\, x)^2/6)].\end{aligned} \tag{5}$$

By performing the inverse transform, we conclude that the repeated convolution of an initially monochromatic wave that propagates with a uniform uncertainty between $\pm l_\mathrm{P}/2$ is a Gaussian of width $\sigma_\mathrm{L} = a_0\, l_\mathrm{P}\sqrt{L/\lambda}$, where $a_0 = 1/\sqrt{12}$ for a rectangle step probability.[1] If we adopt a step size that corresponds to the wavelength of the wave, as assumed in Section 2.1, the accumulated fuzziness is diminished by a factor of $\sqrt{l_\mathrm{P}/\lambda}$ (i.e. ~14 orders of magnitude for far-ultraviolet light) in the case of the $\alpha = 0.5$ model. In other words, by allowing the accumulated fuzziness to be drawn from a uniform distribution rather than a two-point distribution with values $\pm l_\mathrm{P}(\lambda/l_\mathrm{P})^{1-\alpha}$, the effects of quantum foam are considerably diminished.

Finally, we note that the above formalism is not valid when the step size is of order $\sim l_\mathrm{P}$; this is satisfactory, since the accumulated effects of quantum foam would be *substantial* in this case. Therefore, in what follows, we have chosen to model the step size $\lambda = \beta\, l_\mathrm{P}$. In this case, the accumulated energy spread of an initially monochromatic beam is given by

$$\Delta v_\mathrm{q}/c = \frac{a_0\sqrt{l_\mathrm{P}\, D_\mathrm{C}/\beta}}{\lambda_\mathrm{em}\,(1+z)}. \tag{6}$$

Note that the relative velocity width of any two atomic transitions, in this case, is identical to that described by equation (3).

3 BOUNDS ON SPACE–TIME FOAM

Transitions between atomic and molecular energy levels offer the best approximation to a monochromatic laser at high redshift. For the purpose of this work, we will use narrow absorption lines that are imprinted on the spectrum of a background quasar. This absorption line technique offers a fine, one-dimensional view of the gas that lies between us and the quasar. The atoms residing in the intervening gas cloud absorb the quasar light at discrete values corresponding to the energy levels of the atoms. The velocity width of the observed absorption lines includes contributions from natural broadening (a Lorentzian function), as well as the turbulent and thermal motions of the atoms (a Maxwellian distribution).

An absorption line is therefore characterized by a Voigt profile with a Doppler width, b, which is simply related to the one-dimensional 1σ velocity interval along the line of sight, $\Delta v \equiv b/\sqrt{2}$. In the case of weak absorption lines, the natural broadening contribution to the line profile is undetectable, and only becomes apparent in the wings of the strongest absorption lines. In general, all atoms in a cloud experience the same amount of turbulent broadening (b_t), while the thermal broadening (b_th) depends on the gas kinetic temperature (T_kin) and the atomic mass (m)

$$b_\mathrm{th}^2 = 2\, k_\mathrm{B}\, T_\mathrm{kin}/m, \tag{7}$$

where k_B is the Boltzmann constant. The total Doppler width of an absorption line is then given by $b^2 = b_\mathrm{t}^2 + b_\mathrm{th}^2$. Therefore, the heaviest ions produce the narrowest absorption features; furthermore, absorption lines of the same ion that arise from the ground state are expected to exhibit the same broadening. Using this guidance, one could in principle identify quantum foam by measuring the relative widths of several absorption lines from a heavy atom, such as Fe II, and searching for a wavelength-dependent velocity width of the form given by equation (3).

There are also wavelength-dependent contributions to the line broadening that one must consider due to the spectrograph that is used to record the data. The main contribution to the line broadening of a narrow absorption line is the instrument spectral resolution. For reference, the world's premier optical Echelle spectrographs have a full width at half-maximum (FWHM) spectral resolution as low as a few km s^{-1}.

Finally, we note that quantum foam would broaden an absorption line in a similar fashion to the instrument broadening function. Specifically, the intrinsic (Voigt) profile of the absorption line generated by a gas cloud would be convolved with a Gaussian

[1]We did not have to choose a rectangle function for the step probability; provided that the uncertainty associated with each step is independent of the previous step, the central limit theorem ensures that the only change to this functional form is to the value of the coefficient, a_0. For example, a Gaussian step probability of width $\sigma = l_\mathrm{P}$ will result in the same functional form, but with $a_0 = 1$.

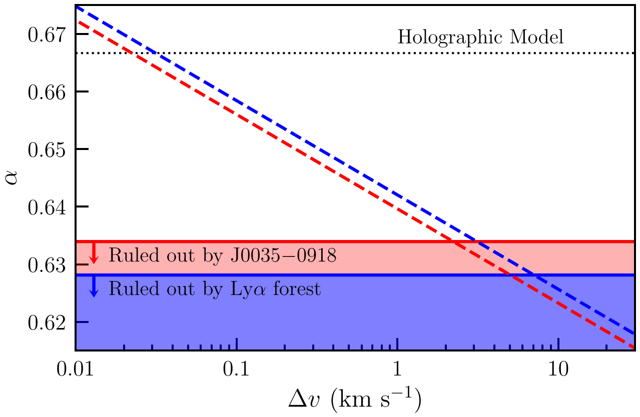

Figure 1. The dashed diagonal lines show how the velocity width of a spectral line depends on the accumulated effects of quantum foam, parametrized by the growth factor, α. The red dashed line represents an Fe II λ1608 Å absorber at redshift $z = 2.34$ (i.e. the case of J0035−0918), while the blue dashed line represents an Ly α absorber (H I λ1215 Å) at redshift $z = 2.5$. The blue and red shaded bands indicate the range of α models that are ruled out by the measured widths of the Ly α forest and J0035−0918, respectively. The black horizontal dotted line labelled 'holographic model' indicates a model with $\alpha = 2/3$.

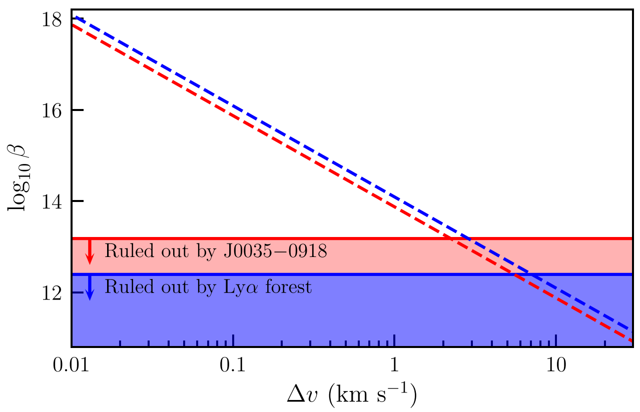

Figure 2. Same as Fig. 1, but shows the limits on the growth factor, β, for the convolution fluctuation model (see Section 2.2). This model suggests that, if photons take discrete steps through space–time and accumulate a Planck-scale uncertainty at each step, then the step size must be at least $\beta l_{\rm P}$.

of width $\Delta v_{\rm q}$ due to the cumulative effects of quantum foam. Then, as the light passes through the spectrograph, it would be further convolved by the instrument broadening function (usually approximated by a Gaussian).[2] Thus, if quantum foam broadens the line profile, it will appear as an 'effective' instrument FWHM profile of width $\sqrt{v_{\rm FWHM}^2 + \Delta v_{\rm q}^2}$ (i.e. slightly broader than the actual instrumental FWHM).

In the presence of quantum foam, the equivalent widths of absorption lines would be preserved. It is therefore important to *directly* resolve the width of a narrow absorption line to place a limit on quantum foam using this approach. In other words, a curve-of-growth analysis is insufficient to infer quantum foam-induced broadening. This is unfortunate, because the existence of intrinsically narrow (unresolved) spectral features has been inferred in several quasar absorption line systems (see e.g. Jorgenson et al. 2009; Jorgenson, Wolfe & Prochaska 2010). We must therefore resort to systems with simple kinematics, but with lines that are not too narrow compared to the instrument resolution. In the case of absorption line profiles that are marginally resolved, we need to accurately determine the instrumental FWHM.

We now consider two lines of evidence that place strong limits on the accumulation properties of quantum foam.

3.1 Ly α forest absorption

First, we consider the multitude of absorption lines that comprise the H I Ly α forest (Lynds 1971). Cosmological hydrodynamic simulations of the Ly α forest indicate that these gas clouds predominantly arise from low-density gas in the intergalactic medium (see Meiksin 2009, and references therein). Observations of either multiply imaged or multiple nearby quasar sightlines (Smette et al. 1992; Bechtold et al. 1994; Smette et al. 1995; Fang et al. 1996; D'Odorico et al. 2006) indicate that these lines-of-sight predominantly intersect large-scale structures whose motions mainly contain contributions from the Hubble flow (Rauch et al. 2005) and the thermal motions of the intersected gas. Since the broadening of the Ly α forest lines is dominated by both the thermal motions of the gas and Hubble broadening, we adopt the conservative assumption that the minimum velocity width of the lines comprising the Ly α forest provides an upper limit on the possible broadening due to quantum foam, and a corresponding lower limit on the growth factor.

The Ly α forest absorption lines have been found to exhibit Doppler widths as low as $b \simeq 10$ km s^{-1} at redshift $z \simeq 2.5$ (Rudie, Steidel & Pettini 2012). Such absorption features are well resolved by current Echelle spectrographs, which leads to a direct measure of the line width. Given the assumed cosmology (Planck Collaboration VI 2018), the comoving distance to these H I Ly α absorbers ($\lambda_{\rm em}$ = 1216 Å) is $D_{\rm C} \simeq 6$ Gpc. We use the relation $v_{\rm q} = b/\sqrt{2}$, we infer a bound on the growth factor, $\alpha \geq 0.628$. This limit, together with the growth curve (equation 2), is presented in Fig. 1 (blue solid and dashed lines, respectively).

The Ly α forest therefore rules out quantum gravity models that require a growth factor of $\alpha = 0.5$, including the random walk model. Said differently, if quantum fluctuations accumulate over distance with $\alpha = 0.5$, the velocity width of Ly α absorbers at $z \simeq 3$ would be $\Delta v_{\rm q} \simeq 5.6 \times 10^8$ km s^{-1} (refer to equation 2).[3] Thus, the very existence of absorption features associated with the Ly α forest is incompatible with models that predict a growth factor $\alpha = 0.5$.

If we instead consider the convolutional fluctuation model proposed in Section 2.2, the Ly α forest requires that $\beta \geq 10^{12.4}$, implying that if photons accumulate a Planck-scale uncertainty at discrete steps in space–time, then the step size must be $\beta\, l_{\rm P} \geq 4 \times 10^{-23}$ m to be consistent with the Ly α forest. The blue shaded band in Fig. 2 indicates the values of β that are ruled out by observations of the Ly α forest.

[2]In reality, the functional form of the instrument broadening function is not a Gaussian. The instrumental profile typically exhibits non-Gaussian wings and an asymmetry, both of which depend on wavelength and spectral order.

[3]Such a large number results from the exponential terms in equation (2), combined with the large numbers involved; a relative small change in α leads to a large change to the bound on the velocity width. Conversely, in order to make a significant improvement on the α limit, one requires a much stronger bound on the velocity width.

3.2 Damped Ly α systems

To place a tighter bound on the growth of quantum fluctuations, we need to identify absorption line systems that: (1) contain quiescent gas; (2) are decoupled from the Hubble flow; and (3) contain gas that is sufficiently cold to minimize the effects of thermal broadening. These properties are generally satisfied by damped Ly α systems (DLAs), which are clouds of mostly neutral gas intersected by lines of sight to unrelated, background quasars. DLAs are defined to have H I column densities that exceed $N(\mathrm{H\,I}) \geq 10^{20.3}$ cm^{-2} (Wolfe et al. 1986), and appear to be associated with a range of galaxy types (Pontzen et al. 2008; Fumagalli et al. 2015; Krogager et al. 2017; for a general review of DLAs, see Wolfe, Gawiser & Prochaska 2005). The metallicity distribution function of DLAs evolves slowly with redshift (Rafelski et al. 2012; Jorgenson, Murphy & Thompson 2013), and is peaked at a metallicity ∼1/30 of solar (Pettini et al. 1997; Prochaska et al. 2003; Rafelski et al. 2012; Jorgenson et al. 2013). The DLA population also displays a metallicity–velocity width relation (Ledoux et al. 2006; Murphy et al. 2007; Prochaska et al. 2008; Jorgenson et al. 2013; Cooke, Pettini & Jorgenson 2015), which is thought to be tied to an underlying mass–metallicity relation. Taken together, the above characteristics fall on a 'fundamental plane' between metallicity, redshift, and velocity (Neeleman et al. 2013); the DLAs with the simplest kinematics are those that have the lowest metallicity.

The most metal-poor DLAs are clouds of gas that have been enriched by at most a few generations of stars (Welsh, Cooke & Fumagalli 2019), and in some cases, exhibit just a single absorption component of kinematically quiescent gas (see e.g. the line profiles of the systems reported by Pettini et al. 2008; Cooke et al. 2011a,b). Of the metal-poor DLAs currently known, the most quiescent gas is exhibited by the absorber at $z_{\mathrm{DLA}} \simeq 2.34$ towards the quasar J0035−0918, first reported by Cooke et al. (2011a). Dutta et al. (2014) collected and analysed new data of this system that covered several strong Fe II lines, thereby allowing the kinematics and chemistry of this gas cloud to be pinned down (see also Cooke et al. 2015).

Bolstered by the quiescence of this metal-poor DLA, we requested 3×2100 s exposures with ESPRESSO in 4UT mode during the science verification phase. We collected an exquisite, high-resolution spectrum of the absorption lines associated with this DLA, allowing us to measure the detailed isotopic chemistry of the gas cloud and derive the gas kinematics (see Welsh et al. 2020, for the detailed analysis of these new data, including the updated chemistry of this system). The final combined signal-to-noise ratio of the data near Fe II λ1608Å is S/N $\simeq$ 20 per wavelength bin. Even at the resolution of ESPRESSO in 4UT mode (FWHM velocity resolution of 4.28 km s^{-1}), the absorption profile of this DLA is well represented by a single, narrow component (see Welsh et al. 2020).

To model the absorption lines, we use the ABSORPTION LINE SOFTWARE (ALIS;[4] see Cooke et al. 2014 for details about this software). To place a limit on the velocity width due to quantum foam, we need to first measure the widths of the absorption line profiles, and remove the instrumental contributions to the line widths. We account for the instrumental FWHM of the line profiles by measuring the widths of the ThAr calibration lines at the measured wavelengths of the DLA absorption features (see Welsh et al. 2020 for further details).

After accounting for the measured instrumental broadening, Welsh et al. (2020) find that the line profiles are entirely dominated by thermal broadening, with a temperature $T_{\mathrm{kin}} = 9100 \pm 500$ K. The absorption line that is most sensitive to quantum foam-induced broadening is Fe II λ1608 Å, since this is the shortest wavelength line of the highest atomic mass element detected. The Doppler parameter of the Fe II absorption, $b_{\mathrm{th}} = 2.70 \pm 0.15$, makes it the narrowest line directly measured with the available ESPRESSO data. We adopt the conservative assumption that this line width provides an upper limit on quantum foam-induced broadening. Using the relation $\Delta v_{\mathrm{q}} = b_{\mathrm{th}}/\sqrt{2}$, we place a 3$\sigma$ lower limit on the allowed values of the growth factor $\alpha \geq 0.634$, which is represented by the red shaded band in Fig. 1. Using instead the convolutional fluctuation model described in Section 2.2, our ESPRESSO observations require $\beta \geq 10^{13.2}$ (3σ), leading to a limit on the step size, $\beta\, l_{\mathrm{P}} \geq 2.4 \times 10^{-22}$ m (see red shaded band in Fig. 2).

Our reported limit on the allowed range of α using J0035−0918 is almost as competitive as the best available limits using the image blurring of cosmological point sources ($\alpha \geq 0.65$; Christiansen et al. 2011; Perlman et al. 2011; Tamburini et al. 2011). The most competitive bound on the accumulation power of quantum foam is based on the mere detection of distant point sources at GeV energies ($\alpha \gtrsim 0.72$ Perlman et al. 2015). Nevertheless, the narrow spectral line observations that we present here offer a complementary and independent limit on quantum foam.

3.3 Blazars

For completeness, we also report a limit on β using the Perlman et al. (2015) approach, which is based on the detection of very high energy (VHE) sources. In this regime, when the accumulated uncertainty becomes comparable to the wavelength, the simple detection of a source can rule out models of quantum foam. The most distant cosmological source[5] that has been detected in VHE emission, with a secure redshift, is the flat-spectrum radio quasar PKS 1441+25, at a redshift $z = 0.939$ (Abeysekara et al. 2015; Ahnen et al. 2015). This source has been detected in gamma-ray emission >100 GeV, which corresponds to a limit $\beta \geq 10^{23.3}$, or equivalently a step size of $\beta\, l_{\mathrm{P}} \geq 3.8 \times 10^{-12}$ m $\equiv 3 \times 10^{5}\, \lambda$, where λ is the wavelength of a 100 GeV photon. In other words, the effects of quantum foam – if present – are being accumulated over a distance that is at least 300 000 times larger than the wavelength of a 100 GeV photon.

4 FUTURE OPPORTUNITIES

There are two obvious possibilities to improve upon the current limit using spectral line observations: (1) acquire higher spectral resolution observations of intrinsically narrow absorption line profiles; or (2) search for spectral lines or abrupt changes to the spectral shape at higher energies. We briefly explore each of these possibilities below.

The first possibility could be readily realized with dedicated observations of known C I absorbers (e.g. Jorgenson et al. 2010; Noterdaeme et al. 2018) or CO molecular absorption lines (e.g. Noterdaeme et al. 2011) towards high-redshift quasars. Both C I and CO molecular absorption lines probe the cold neutral medium of galaxies, where the thermal contribution to the line width is minimal. Most of the known C I and CO absorbers are relatively metal rich with tens of absorption components; the overall kinematics of these

[4] ALIS is publicly available from https://github.com/rcooke-ast/ALIS.

[5] For a list of VHE sources, see: http://tevcat.uchicago.edu/.

absorbers can exceed several hundred km s^{-1}, but in some cases, the *individual* C I and CO lines are apparently not blended with other features. The highest spectral resolution observations with ESPRESSO in 1UT mode (FWHM $\simeq 1.5$ km s^{-1}) might permit a measure of quantum foam-induced broadening down to a level of a few hundred m s^{-1}, provided that the amount of broadening due to the instrument is well determined. Such a measure would deliver a limit $\beta \geq 10^{15}$ or an equivalent limit on the growth factor of $\alpha \sim 0.66$, which is approaching the value expected for the holographic model.

Looking forward, in order to be competitive with the Perlman et al. (2015) approach, the best opportunity is to use VHE sources at cosmological distances. To give an illustrative example, if the spectral shape changes by just ∼10 per cent (i.e. $\Delta E/E \sim 0.1$) at an energy of ∼10 TeV, then a source at redshift $z \sim 1$ would provide a limit $\alpha \gtrsim 0.76$, or $\beta \gtrsim 10^{30}$. Such an experiment may become possible with the Cherenkov Telescope Array, which is expected to be online in the next 5 yr.

5 SUMMARY AND CONCLUSIONS

Using data acquired with the recently commissioned ESPRESSO spectrograph at the European Southern Observatory Very Large Telescope, we have placed a novel limit on the existence of space–time foam based on the intrinsic widths of measured spectral lines. The main conclusions of this paper can be summarized as follows:

(i) We describe a novel approach to place a bound on quantum foam-induced fluctuations, based on the measured energy widths of rest-frame ultraviolet absorption lines. We employ a commonly used heuristic model, which contains a single parameter α that characterizes how the quantum fluctuations grow as a wave propagates.

(ii) We also present a new formalism to model the accumulated energy fluctuations in the event that photons take discrete space–time steps as they propagate. This simple model is characterized by a single parameter, β, where the step size is given by $\beta\, l_{\rm P}$, and $l_{\rm P}$ is the Planck length.

(iii) We first apply the above models to observations of the Ly α forest, which already place a strong limit on the growth factors, $\alpha \geq 0.628$ and $\beta \geq 10^{12.4}$. Indeed, the very existence of the Ly α forest indicates that the random walk model (corresponding to $\alpha = 0.5$) is ruled out.

(iv) Currently, our strongest bound on space–time foam-induced fluctuations is derived from the narrow Fe II λ1608 absorption line of the near-pristine DLA at $z_{\rm DLA} \simeq 2.34$ towards the quasar J0035−0918. Here, we report a conservative 3σ limit on the growth factors, $\alpha \geq 0.634$ and $\beta \geq 10^{13.2}$. The latter corresponds to a photon step size of $\beta\, l_{\rm P} \geq 2.4 \times 10^{-22}$ m.

(v) We suggest future opportunities to use narrow spectral line observations to place more stringent limits on models of space–time foam. In the immediate future, perhaps the best opportunity is to directly measure the widths of C I or CO absorption lines towards known metal-rich DLAs with an ultra-high resolution Echelle spectrograph, such as ESPRESSO on the Very Large Telescope. Such observations may just be able to test the holographic model of space–time foam, independent of the phase and image blurring approaches that have previously been used.

(vi) Previous work by Perlman et al. (2015) has shown that gamma-ray detections of high-redshift blazars offer the tightest current bounds on α. Using this approach, we place a strong limit on the growth factor $\beta \geq 10^{23.3}$, which is equivalent to a step size of $3 \times 10^5\, \lambda$, where λ is the wavelength of a 100 GeV photon.

We find that our reported limits on quantum foam-induced fluctuations are competitive with the blurring of cosmological point sources, and provide complementary evidence to support the current limits on α using that approach. Owing to the extra sensitivity of the fluctuation models at higher energy, spectral line/shape observations at TeV energies may further narrow the range of allowed models, and provide strong clues towards finding a unified description of gravity and quantum mechanics.

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