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# Lyman Continuum Radiation from Intermediate-Mass Black Holes

## An Estimation of the Contribution of LyC Radiation from IMBHs in z~3 Galaxies

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# Abstract

This thesis concerns the cosmic reionization of the intergalactic medium in the high redshift universe and, in particular, is a first approach to examine what role intermediate mass black holes (IMBHs) play in this cosmic age. Unexpectedly high values of hydrogen ionizing radiation, compared to current models, have been reported from galaxies at redshift $\simeq$3 (used as stand-ins for galaxies at the age of reionization), and thus these models need revision, potentially by adding effects of IMBH content in the galaxies.

The thesis consist of two parts: a literature study of the cosmic reionization, galaxies at high redshift and accreting black holes, and a research part where spectral colours of observed galaxies at redshift $\simeq$3, modelled IMBH accretion discs and a stacked quasar spectrum are compared, to examine if black hole physics might play a part in producing the extra radiation observed, and if so, how many IMBHs (of varying mass and accretion rate) would be needed to produce this radiation.

Results show that the IMBH model spectra have colours that agree with them being possible sources of the ionizing radiation from the observed galaxies. However, the colours of the quasar spectrum were found to be too red for a typical quasar to be a plausible such source. We find that for several combinations of the parameters mass and accretion rate, our model leads to reasonable numbers of IMBHs, whereas there are cases in which parameters lead to non-physical numbers (e.g. $<$1).

However, the model for IMBH spectra used is simplified and does not incorporate emission lines, feedback effects or viewing angle dependency of the observed luminosity.

Despite this, our results are consistent with galaxies hosting one or several IMBHs, and further research should be conducted with more precision to establish the exact way they should be accounted for in models.

The thesis is conducted at the Division of Astronomy and Space Physics at Uppsala University.

# Sammanfattning

Uppsatsen berör den kosmiska återjoniseringen av det intergalaktiska mediet och är en undersökning av vilken roll svarta hål med intermediär massa (IMBHs) spelar i forskningen kring denna era. Oväntat höga värden av vätejoniserande strålning har rapporterats från galaxer vid redshift $\simeq$3, vilka används som utgångspunkt för galaxerna vid tiden för återjoniseringen, och alltså behöver modellerna för dessa galaxer revideras, eventuellt genom inklusion av strålning från IMBHs.

Uppsatsen består av två delar: dels en litteraturstudie om den kosmiska återjoniseringen, galaxer vid högt redshift samt svarta hål, och en försöksdel där spektralfärger hos observerade galaxer, modellerade IMBHs och ett "genomsnittligt" kvasarspektrum jämförs för att uppskatta huruvida svarta hål kan spela en roll i de höga strålningsvärdena och om så, hur många IMBHs (av olika massa och ackretionshastighet) som skulle behövas för att producera dessa värden.

Resultaten visar att modellspektrumen för IMBHs har rätt färger för att kunna vara upphovet till den extra strålningen. Kvasarspektrumet hade dock för röda färger. Vi fann att flera av kombinationerna av massa-ackretionshastighet resulterade i rimliga värden på antal IMBHs som behövdes, medan extremfallen gav upphov till ofysikaliska värden (t.ex. antal $<$1).

I undersökningen användes dock en förenklad modell för ackretionsskivor, som till exempel inte räknar med emmisionslinjer, feedback-effekter eller observationsvinkel.

Trots detta är resultaten positiva till möjligt innehåll av IMBHs i de observerade galaxerna och vidare forskning bör förfina de använda modellerna för att mer exakt kunna ta dessa effekter med i beräkning.

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# Contents

# 1 Introduction

One of modern cosmology's great unsolved mysteries is the cosmic reionization. The hydrogen in the intergalactic medium (IGM) is now ionized, even though it is known to have recombined to neutral particles in the early stages of the universe. Hence, hydrogen ionizing radiation (Lyman continuum, LyC) must have been emitted in large quantities at some point after the recombination, reionizing the IGM. The sources of this radiation are still unknown, although several different candidates, such as quasars and early star-forming galaxies, have been proposed.

For several reasons, such high redshift galaxies as those at the time of reionization (z∼6) are hard to study directly, and therefore the method to studying them is based on looking at galaxies at lower redshift and assuming they behave alike.

Results from [1] show an unexpectedly high amount of LyC from z∼3 galaxies, suggesting they might contain sources of LyC not yet accounted for.

The research part is based on the work of I. Iwata and A. K. Inoue et al. 2009 [1], who developed a method for searching for ionizing radiation from galaxies using a specially developed filter. Using this method they found a higher fraction of hydrogen ionizing radiation from galaxies at $z \simeq 3$ than expected from models. To account for this, one could change parameters in the existing model (e.g., change the initial mass function, IMF, used), or one could examine the inclusion of other potential sources to the radiation, such as, in this thesis, intermediate mass black holes.

This work investigates the possibility of this LyC radiation to have been produced by black holes of intermediate masses. It is not yet known if these types of black holes existed at the time of the cosmic reionization; we do not even know if they exist today (although there are indications, see section 2.3.2). However, intermediate mass black holes (IMBHs) cannot be disregarded from the list of potential LyC sources until they have been thoroughly examined, and any indicative results from such a study might speak both for the existence of IMBHs, and for black hole physics to have had some kind of impact on the cosmic reionization.

This work is only a first peek at the possibility that IMBHs might have played such a role. The methods are simplified and the goal of this work is not to work out the details of any intermediate mass black hole effect on cosmic reionization, but to try a simple approach to the hypothesis and see if the results are consistent with IMBH involvement in the cosmic reionization or not.

This work includes a literature study of different aspects of the underlying fields of cosmic reionization, high redshift galaxies and accreting black holes, all of which are covered in the Background section. It also contains a research part where colours of modelled IMBH spectra, observed galaxy spectra and a mean quasar spectrum were plotted to see if they have the colours required for them to be potential sources of LyC.

The method of comparing spectral colours used in this project is done as in [1], including use of their nb359 filter (constructed to represent the LyC part of spectra), and the model for black hole accretion disc spectra is constructed and provided by A. Inoue [2].

Apart from the colours of the three above mentioned sources, the results also include the number of black holes of varying masses and mass accretion rates that is needed to produce the desired magnitude in the nb359 filter, giving an indication on the probability of this black hole content.

# 2 Background/Review

## 2.1 Cosmic reionization

After the assumed beginning of time and space in the Big Bang, the universe underwent rapid expansion known as the inflation. As a consequence of this, matter in the form of ionized baryons was fairly homogeneously distributed throughout the universe. However, the electromagnetic force keeping the baryonic gas hot and ionized did not affect the dark matter, which could assemble into denser regions. The universe kept expanding and cooling, until at one point 0.37 million years after the Big Bang, the baryonic matter was cool enough to recombine and become neutral, forming a medium mostly consisting of hydrogen [3]. The photons emitted in this process are what we call the cosmic microwave background radiation [4].

Gravitational forces now caused the baryonic matter to fall into the regions of dense dark matter, where it grew denser until it was hot enough to ignite fusion processes. The first stars were born, soon to gather into the first galaxies [4].

These stars would emit highly energetic photons able to ionize the neutral IGM. First the regions around the galaxies were ionized, then they grew and merged until all of the intergalactic gas was ionized, at a time when the universe was about 1 Gyr old (z $\sim$ 6-7) [5].

The above described scenario is a plausible one - if we can find enough galaxies producing enough ionizing radiation, and a large enough fraction of this radiation reaching the IGM and ionizing it.

Until then, we must assume other sources could have contributed to the reionization as well. For example, the first generation of stars (PopulationIII; PopIII), could have collapsed into intermediate mass black holes (or these could form through other processes, see section 2.3.2), and the possible contribution of these in the reionization is what we are investigating in this thesis.

To study the origin of the cosmic reionization one needs to survey these high redshift galaxies. One interesting feature of the galaxies is the escape fraction $f_{esc}$, which denotes the fraction of hydrogen ionizing radiation (LyC) produced in a galaxy that manages to escape the interstellar medium (ISM) of the galaxy (see section 2.2.1). This is the amount of radiation reaching the IGM and thus, roughly speaking, the radiation being able to ionize it.

Progress with the Hubble Space Telescope and in technology for near-IR astronomy has recently enabled this field of research to grow, and the cosmic reionization to be studied more carefully [6].

In spite of this progress, it is not possible to study the galaxies responsible for the ionizing radiation, at z $\sim$ 6-12, directly. This is due to the increasing number of Lyman limit systems at z $>$ 4 [1]. Lyman limit systems are regions with high enough density for radiation not to reach their interior, hence to still contain neutral hydrogen [7]. Instead, we must observe and make models for galaxies at lower readshifts and extrapolate backwards assuming these lower-redshift and higher-redshift galaxies behave alike.

## 2.2 Galaxies at high redshift

We will start discussing properties of galaxies of interest to the cosmic reionization, and then move on to means of studying such galaxies, both theoretically and observationally.

### 2.2.1 Lyman leakage and the escape fraction

The term Lyman continuum leakage refers to the phenomenon of hydrogen ionizing radiation produced in the galaxies to escape out of the ISM inside the galaxy to the IGM outside of it. This radiation can potentially ionize the IGM and hence contribute to the cosmic ionization. The escape fraction quantifies the Lyman continuum leakage [4].

The processes through which Lyman continuum leakage is possible are poorly understood. However, this ability seems to have changed with time, with larger leakage from galaxies in the young universe than later ones [4].

There are two types of escape fractions that are used at different times. There is the *absolute escape fraction*, used for local galaxies, and the *relative escape fraction*, for galaxies at redshifts z $>$ 0.4 [4]. Both types of escape fractions depend on an estimate of the total amount of radiation produced by the stars in the galaxy, and the amount we measure. The latter needs to be corrected for absorbtion by the IGM and the ISM in the Milky Way galaxy [4].

Naturally, due to the large tendency of dust to absorb LyC, the dust content of galaxies (or at least the star-forming parts of them) is a key feature in determining the escape fraction. Thus, a leaking galaxy should contain little gas and dust (along the line of sight) and its spectrum would exhibit weak emission lines [4].

Models have shown that high star formation rate (SFR) is connected to a high escape fraction, not only when it comes to forming the stars that emit the ionizing radiation, but also by the amount of stellar winds and supernovae explosions that come with a high SFR (since massive stars have short, dramatic lives), making way for the radiation to escape through tunnels and channels created by these effects [4].

For LyC photons to escape the galaxies and not be absorbed by the gas and dust inside them, this ISM needs to be very thin (as in the outer areas of arms in spiral galaxies), or inhomogeneously distributed, so that "pathways" of little or ionized ISM are made that the radiation can escape through [4].

Such pathways can be an effect of radiative pressure and mechanical feedback from massive pop III stars and supernovae, which soon follow from star formation as the deaths of massive stars with short lifetimes. Even less extreme scenarios can cause this disruption of the ISM, if the star formation is spread out instead of concentrated [4].

Models that do not include these "secondary" effects of star formation do not show a connection between high SFR and high escape fraction [4].

Assuming radiation escape is dependent on these feedback effects, and because these effects do not affect the ISM equally in all directions, the Lyman leakage should be dependent on the viewing angle.

Another parameter that seems to be important for the LyC escape is the mass of the galaxies, most models showing lower halo mass connected to higher escape fractions [4].

### 2.2.2 Starburst galaxies

Star-forming galaxies is the most popular candidate as producers of the radiation that started and kept the cosmic reionization going. Starburst galaxies are galaxies with very high star-formation rates ranging up to several hundred solar masses per year. These high star-formation rates are presumably the result of interactions with other galaxies [6].

Young stars emit hydrogen ionizing radiation into the ISM within the galaxy. The hydrogen that has been ionized by this radiation can recombine to excited states, and produces recombination lines when the hydrogen returns to the ground state (among these lines is the Lyman-alpha line). Hence these lines are indicators of star formation, since they suggest young stars exist in the area [4].

When the radiation from these stars does not ionize the ISM and instead leaks out of the galaxy, it can serve as fuel for the ionization of the IGM [4]. Therefore, early galaxies with high star formation rates are popular candidates for initializing and fuelling the cosmic reionization.

Lyman break galaxies (see section 2.2.4) are thought to have active star formation, since photons at the Lyman limit are only emitted by young, hot stars [6]. The UV luminosity of galaxies depends on the star-formation rate [6]. Thus, to measure star formation rates of galaxies in the distant universe, one common method is to measure the UV luminosity of the galaxies, since this type of radiation should primarily be coming from young, massive stars [4]. Radiation from the hot stars heat the dust in the regions of active star-formation, making it radiate in the far infra-red (FIR). Thus starburst galaxies are usually strong FIR emitters [6].

When searching for potential reionization sources, star-forming galaxies are of great interest. The first PopIII stars formed from clouds of gas before the first galaxies. The light elements existing at that time had low ability to radiate away energy (due to the few atomic transitions they provided), which helped these stars grow massive. The pop III stars thus emitted highly energetic, ionizing radiation, since stars radiate in a way similar to the Planck curve. Large mass means higher temperature which causes more energetic photons to be produced [4]. Within galaxies, PopIII stars can form in pockets of neutral gas within the galaxy. These early, massive stars would have met a dramatic death including stellar winds and supernovae. These effects might have torn the ISM and made it porous, making way for the ionizing radiation to escape into the IGM and ionize it [4].

While star-forming galaxies have many of the properties required to drive the cosmic reionization, there is one significant problem with galaxy-driven reionization: stars are formed from neutral gas clouds. Due to the large absorptivity of LyC in neutral hydrogen, these clouds might absorb the radiation before it reaches the IGM.

Thus, depending on the amount of dust and HI regions in these galaxies, high star formation rate does not directly correspond to a large escape fraction of LyC radiation.

When studying galaxies in the distant universe, it is common to use submillimeter lines. However, to get even better data it is common to instead look at local starburst galaxies, and estimate how such galaxies in the distant universe might have behaved. These are not perfect analogues, due to the fact that local galaxies have higher metallicity and the rate of their evolution is slower than that of galaxies in the younger universe, including fewer encounters with other galaxies and a lower star formation rate [4].

The differences aside, studying local star forming galaxies might give us clues about some processes that allow Lyman continuum production and escape.

### 2.2.3 Population synthesis

Population synthesis assumes the light from a galaxy may be modelled as a superposition of stellar spectra. Since the spectral energy distribution of the stars in a galaxy changes as the galaxy ages (with more massive, blue stars leaving the main sequence faster than less massive ones and hence giving rise to a redder spectra), the galaxy spectrum tells the history of a galaxy, and a population synthesis that reproduces this correctly will help in understanding the evolution of galaxies [8].

When modelling a stellar population an IMF needs to be assumed. This describes the mass distribution of the stars at the time of their birth. A common assumption is that of a Salpeter IMF (which is used in this work), where the mass distribution $\phi(m)$ is proportional to the mass to the power of -2.35, $\phi(m) \propto m^{-2.35}$ [8].

Other features that determine the SED of a galaxy are the star-formation rate (amount of mass of gas that is bound into stars per unit time) and the metallicity Z of the interstellar medium that will become the metallicity of the stars born from it. The latter will increase with time due to the cosmic chemical evolution which results in the colour of the galaxy being shifted to the red. The colours of the galaxies also need to be corrected for dust absorption and nebular emission [8].

### 2.2.4 The lyman break method

Finding high-redshift galaxies can be challenging due to difficulty of distinguishing between real high-redshift galaxies and low-redshift objects. Since high-redshift galaxies are faint, spectroscopic redshift determination of each candidate is very time-consuming. The preferred method of study is instead the Lyman break method, providing a quick way to sort out the high redshift galaxies from the low redshift ones.

Photons emitted at energies higher than the Lyman limit (at 912 Å) make up the so called Lyman continuum (LyC). Photons at the Lyman limit have the minimum ionization energy for neutral hydrogen, and hence all LyC photons have high enough energies to ionize neutral hydrogen, forming a continuous absorption energy spectrum.

The Lyman break is a feature in spectra of galaxies that arises when the LyC emitted from galaxies has been absorbed by the neutral hydrogen in the ISM and IGM. Since the ionization cross section of neutral hydrogen is very large, this absorption gives rise to a distinct drop in flux at energies above the Lyman limit, producing a 'break' in the spectrum [6].

For galaxies at high redshifts, not only must the LyC emitted from a galaxy escape from the ISM in the galaxy itself, but the amount of IGM that the LyC photons have to pass through before reaching Earth is high enough for a distinct Lyman break to form in the spectra of essentially all redshift ($z \gtrsim 3$) galaxies, providing an ingenious way for identifying such objects [6], avoiding the expenses of spectroscopy.

The Lyman break method consists of taking images of faint galaxies in three non-overlapping filters, with at least one filter above and one below the Lyman break of the redshifted spectrum [6]. Galaxies suitable for studying the high-redshift universe are then those that appear in the filters at larger wavelengths than the redshifted Lyman limit, but disappear in the filters at smaller wavelengths. Having found one such candidate with the Lyman break method, this galaxy can then be studied with spectroscopy for more detailed results [6].

By knowing the Lyman limit in the rest frame of the galaxy (912 Å), and comparing this to the wavelength at which the Lyman break appears in a galaxy spectrum, one can calculate the redshift of the galaxy using $\frac{\lambda_{obs}}{\lambda_{emit}} = 1 + z$ .

The flux at energies above the Lyman limit disappears almost completely at z $\gtrsim$ 6, assumed to represent the end of the cosmic reionization [9].

## 2.3 Accreting black holes

Accretion of matter onto black holes is one of the most powerful sources of radiation known in the universe. This radiation is the result of several energy transformations within the matter in the disc. Gas surrounding a black hole will have gravitational potential energy, converting to kinetic energy when the gas falls towards the black hole. If the gas could fall straight into the black hole it would do so without converting this energy to radiation. Since the gas cloud that is the origin of the accretion disc generally has some angular momentum, this is not the case. The angular momentum transfer within the gas together with the frictional forces between the gas particles makes the disc rotate differentially in a Kepler disc [10]. The same frictional forces slow down the angular velocity, making gas move to orbits closer to the black hole and converting the kinetic energy to heat, raising the temperature of the gas and thus leading to the emission of radiation.

A geometrically thin, optically thick disc will have a local luminosity emission corresponding to a black body spectrum. The energy of the radiation depends on the temperature in the disc, which varies with the radius according to

$$T(r) = \left(\frac{3c^6}{64\pi\sigma_{SB}G^2}\right)^{1/4} \dot{m}^{1/4} M_{BH}^{-1/2} \left(\frac{r}{r_S}\right)^{-3/4} \tag{1}$$

[10]. Since the temperature increases inward (proportional to $r^{-3/4}$), the accretion disc can be approximated as a superposition of black body rings with higher temperatures for smaller radii, which as a result has a more broad energy distribution than a Planck spectrum [10]. From the equation we also see that, for a fixed ratio $r/r_S$ ($r_S$ being the Schwarzchild radius), a larger accretion rate $\dot{m}$ will increase the temperature, and a larger black hole mass $M_{BH}$ will decrease the temperature. This means that the thermal radiation emitted from discs around stellar mass black holes have higher energies than that from supermassive black holes [10].

The nature of the radiation depends on the properties of the black hole, the most important parameters being the mass M of the black hole and the

Kerr spin parameter a/M (where the specific angular momentum of the black hole a = J/M and $0 \leq a/M \leq 1$) [11]. The black hole mass determines the spacetime geometry close to the event horizon and the Kerr spin parameter determines the efficiency and, to a certain extent, the form (the way energy is converted to produce different types of radiation) of energy release [11]. This efficiency of accretion is determined at a point called the *innermost stable circular orbit*, ISCO, marking the radius inside which matter that fall into the black hole ideally does so without losing any additional energy [11].

These properties make up the inner boundary conditions for the accretion, and naturally, outer boundary conditions also come into play. These are provided by the environment from which the black hole is accreting matter. This might be stars and dust in the center of a galaxy for a super massive black hole (SMBH) and matter from a companion star in an X-ray binary system or ejected star material in a supernova explosion for stellar mass black holes. The accretion flow is also regulated by several properties of the accretion disk itself. Radiation pressure forces, a variety of magnetic forces and interactions between gas and these forces among other things give rise to complex flow dynamics with corresponding radiation signatures. These signatures can be observed by astronomers and provide a means to study the regions surrounding black holes.

### 2.3.1 Eddington accretion flows

Most of the energy produced in an accretion disc is produced close to the Schwarzschild radius and propagates outwards, exerting a radiation pressure on the infalling matter via absorption or scattering of photons on electrons. This radiation pressure force on an electron at radius r is given by

$$F_{rad} = \sigma_T \frac{L}{4\pi r^2 c} \tag{2}$$

where $\sigma_T$ is the Thomson cross-section [10]. The gravitational force from the black hole hence needs to be larger than this radiation force for accretion to take place at all. As can be seen from the equation above, the radiation force decreases with the radius squared. As does the gravitational force, and hence the ratio of the radiation force to the gravitational force is constant throughout the disc (independent of the radius) [10].

For matter to accrete this ratio needs to be less than 1, translating to a maximum luminosity L for a black hole of a given mass. This is the Eddington luminosity $L_{Edd}$, and we compute its value by assuming an equal amount of protons and electrons in the accreting matter and that these are electromagnetically bound in couples. Neglecting the electron mass, the gravitational force opposing the radiation force on an electron is then the gravitational force on the proton, yielding

$$\frac{\sigma_T L}{4\pi r^2 c} < \frac{G M_{BH} m_p}{r^2} \tag{3}$$

for accretion [10], and hence

$$L_{Edd} \equiv \frac{4\pi G c m_p}{\sigma_T} M_{BH} \approx 1.3 \cdot 10^{38} \left( \frac{M_{BH}}{M_\odot} \right) erg/s \tag{4}$$

[10]. Hence, if a luminosity L of a black hole is observed, a lower limit on the black hole mass can be determined.

For the results in this thesis the unit of $\dot{M}/\dot{M_{crit}}$ is used, where $\dot{M_{crit}} = L_{Edd}/c^2$ is the critical accretion rate, i.e. the accretion rate at which the radiative force is balanced by the gravitational force [12].

The above reasoning is valid under the assumption of an isotropic emission of luminosity. If the emission is not isotropic, luminosities above the Eddington luminosity can be obtained. This could for example be due to jets emanating from the black hole along the axis of rotation. It also means the observed flux might be very different from the actually emitted one, if the largest part of the radiation is emitted in another direction than the observer's [10].

### 2.3.2 Intermediate mass black holes

Today, the existence of both stellar mass black holes (masses between 5 and 100 $M_\odot$) and supermassive black holes (masses larger than $10^6$ $M_\odot$) is strongly supported by both theory and observation. This is not the case for black holes of intermediate masses. However, there are indications of the existence of intermediate mass black holes (IMBHs), from microlensing events, ultra luminous X-ray sources [13] and globular clusters, among other things [14].

The existence of IMBHs is interesting for many reasons. For example, they could provide a key to understanding the formation process of supermassive black holes [14].

One reason for the lack of direct observation of IMBHs might be that the environments they reside in do not support the production of detectable signals to the same extent as for stellar mass or supermassive black holes [14]. This makes it hard to know what to look for and where to look, but formation theories for IMBHs might provide some clues.

Three popular theories for formation of IMBHs are as remnants of PopIII stars (sufficiently massive to produce a black hole of intermediate mass when collapsing), as an effect of the high central density in star clusters, or as one step in the formation of a supermassive black hole [14].

IMBHs formed from PopulationIII would have a mass of either below 140 $M_{\odot}$ or above 260 $M_{\odot}$ (stars with masses in between would not form any remnant due to the explosion yielded by the electron-positron pair instability) and are believed to have formed at redshift z $\sim$ 10-20 [14]. IMBHs can arise in the central regions of dense clusters of normal stars or compact objects such as neutron stars or stellar mass black holes, most likely through runaway merging [14].

Many of the plausible scenarios of SMBH formation involve IMBHs at some point. These processes often include merging or accretion, possibly with a BH formed in one of the above scenarios. For example, an IMBH formed from a collapsing PopIII star which then moves to the galaxy center through dynamical friction could there build up to typical SMBHs masses by merging and/or accretion [14].

The effects that IMBHs would cause by interacting gravitationally with other objects are used to constrain their numerosity. For example, IMBHs increase the velocity dispersion of stars in galaxy disks and hence the observed stellar velocity dispersions constrain the BH masses in the halos of the galaxies. One can also look for disruption of star clusters, which can be due to IMBHs [14]. Studies of microlensing events from IMBHs in halos on background stars can also be used to put limits to the fraction of the halo that can possibly be made up of MACHOs (massive compact halo objects), part of which can be IMBHs [14].No stringent constraints have yet been put on the cosmic mass density of IMBHs from PopIII stars [14].

### 2.3.3 Quasars

Quasars are a type of active galactic nuclei which are extremely luminous [10]. They emit at all wavelengths but are strong emitters of ultraviolet radiation [15], which makes them relevant as potential sources of LyC radiation.

Quasars were first discovered in the 1960s when astronomers identified newly found radio loud sources with known optical sources. Later, when the understanding of quasars increased, radio-quiet quasars were found as well (in fact, the majority of quasars are radio-quiet) [15].

In a study by James S Dunlop, Ross J McLure and colleagues in 2003, surveying 33 quasars (both radio-loud and radio-quiet) and radiogalaxies, it was found that both the radio-loud and the radio-quiet quasars hosted a massive black hole in their centers [15]. For the radio-loud quasars the black holes were supermassive on the order of $10^9 M_\odot$, whereas the radio-quiet quasars had black holes of masses on the order of $10^8 M_\odot$.

Historically, quasars have been among the most distant objects observed and several quasars have been detected at redshifts of the cosmic reionization (e.g. Mortlock et al 2011 [16]). Hence, they are of interest as a potential source of LyC powering the cosmic reionization.

## 2.4 Setup

The 8.2 m Subaru telescope at Mauna Kea Observatory, Hawaii was used for obtaining the observational data, provided by Micheva et al [17].

The filters used are V, R and i as well as the narrow band NB359 filter with central wavelength 359 nm and FWHM (full width at half maximum) 15 nm, constructed by Iwata et al [1] especially for the purpose of measuring LyC radiation, see Figure 1.

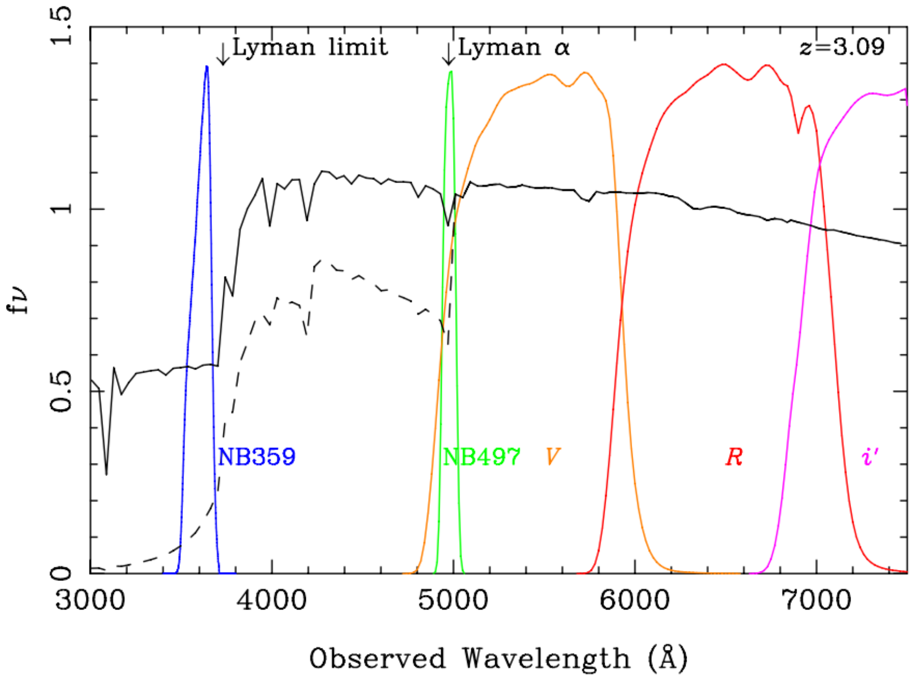

Figure 1: The ranges of the four filters used to calculate the colour differences of the objects in this survey: V, R, i and NB359. As can be seen, the NB359 filter is situated right below the Lyman limit, and the V, R, and i filters are at larger wavelengths. The filter NB497, at the Lyman $\alpha$-line, is not used in this survey. The figure is taken from [18].

Results were compared to the models used in [1], based on the Starburst99 code of Leitherer et al [19]. The model is based on a Salpeter IMF with the bluest SED, the gray area in Figure 2 representing the colours that can be explained by dust and IGM attenuation on this SED.

### 2.4.1 The model for accretion disks of IMBHs

A model constructed by Inoue A in 2008 [2] was used for modelling spectra of accretion disks around intermediate mass black holes. It is based on the analytical solutions of Watarai 2006 [20], and integration of black body spectra using Planck's law, with Wien's approximation for sufficiently high frequencies, is done over the radius of the disk.

# 3 Method

This work is partly an extension to the research by Iwata et al 2009 [1]. All results are compared in the same way as those in this research, which is represented in Figure 2:

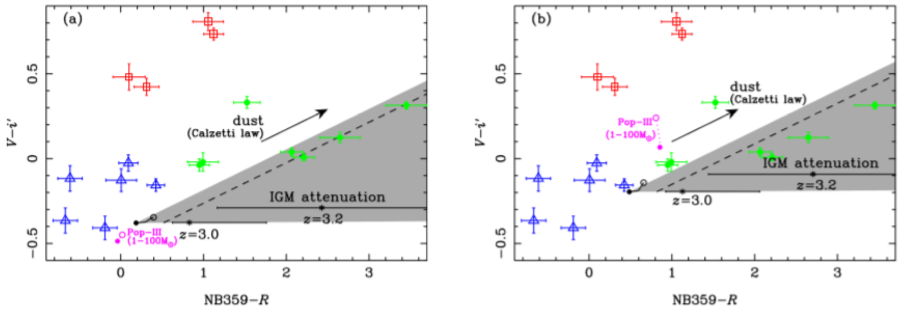

Fig. 5.— (a) NB359$-R$ and $V-i'$ colors of objects detected in NB359. LBGs detected in NB359 are shown with circles, and two LAE sub-groups divided by their UV slopes are shown with open squares and triangles. Filled and open circles connected with a olid line are the color tracks of a model galaxy with the bluest SED with the Salpeter IMF from $z = 3.0$ and 3.3, respectively. The shaded area indicates a color range which can be explained with attenuation by dust and IGM on this model SED. The arrow indicates the direction of dust attenuation following a prescription by Calzetti et al. (2000) and changes in colors with $E(B-V) = 0.1$ attenuation. Two filled circles with horizontal error bars show the colors of the bluest model SED with the median IGM attenuation at $z = 3.0$ and $z = 3.2$. The error bars represent the ranges of IGM opacity with 68% probability. The expected colors with the stellar population at zero metallicity based on the SED by Schaerer (2003) from $z = 3.0$ to $z = 3.3$ are also shown (labeled with "Pop-III"). The model galaxy SEDs do not include nebular continuum emission. (b) same as (a) for observed colors of the objects detected in NB359, but model galaxy SEDs include nebular continuum emission.

Figure 2: Results from Iwata et al 2009 [18], description included.

## 3.1 The observed galaxies

As an introduction to the research methods, observational data from the Subaru telescope, provided by Micheva G et al [17] is analyzed using the provided models for calculating and plotting differences in colour between filters NB359, R, i and V. The treated data set consists of flux measurements and errors from 34 LyC candidates including LAEs, LBGs and AGNs. Fluxes and errors are converted from Jansky to AB magnitudes and a NB359-R to V-i diagram is plotted. The positions of these objects in this diagram are then compared to the modelled values used in [1], the gray area in figure 2.

## 3.2 The quasar spectrum

Quasars are a type of very luminous active galactic nuclei. The galaxies studied may contain quasars, and hence a comparison of the galaxy spectra to that of a quasar is needed. This will help draw conclusions of how quasars affect positions of galaxy spectra in the diagram and might imply the role of black hole physics in LyC emission.

The stacked quasar spectrum from Lusso et al. 2015 [21] (L15 hereafter) is used as quasar reference as it provides an 'average' quasar spectrum suitable for comparisons. Data is extracted from figure 1 ($1290 \lesssim \lambda \lesssim 2550$ Å) and 4 ($600 \lesssim \lambda \lesssim 1290$ Å) in L15 and put together to account for the IGM correction needed at shorter wavelengths. AB magnitudes in N359, R, V and i filters are calculated and the NB359-R to V-i position is plotted. From the position of the quasar in this diagram compared to that of the galaxies, conclusions are drawn on how the galaxies are affected by potential quasar content.

## 3.3 The intermediate mass black holes

Spectra of black holes with varying mass and mass accretion rates are produced using the Inoue 2008 model [2]. Spectra are produced with black hole masses between $10^2$-$10^6$ $M_\odot$, and mass accretion rates ranging from 1-$10^3$ $\dot{M}/\dot{M}_{crit}$, with steps of $10^{0.5}$ in both cases.

The black hole spectra are then converted into AB magnitudes for the four prescribed filters, and colour-colour diagrams are plotted as above. The positions of the model black holes in the diagram are then compared to those of the model galaxies from [1], the observed galaxies and the quasar.

The number of black holes needed to produce the amount of ionizing radiation observed in galaxies [17], $N_{BH}$, is calculated by

$$N_{BH} = 10^{\frac{m_{obs} - m_{model}}{-2.5}}$$

where the magnitude in the NB359 filter is taken to represent the magnitude of ionizing radiation. This is done directly for the different black holes from the model, and a mean of the NB359 magnitudes for all observed galaxies is taken as an estimate to compare with the black hole magnitudes.

# 4 Results

## 4.1 The colours

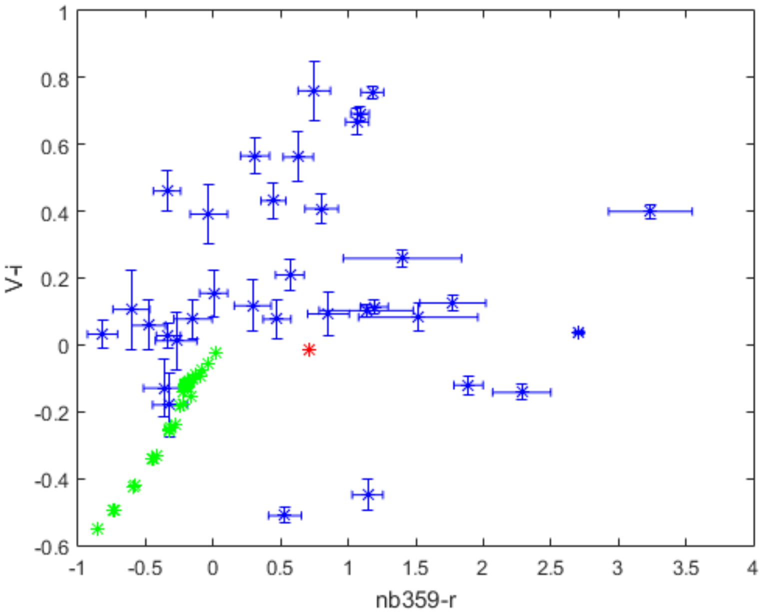

Figure 3: NB359-R to V-i colours of galaxies at z > 3 observed with the Subaru 8.2m telescope (blue), the stacked quasar spectrum from Lusso et al [21] for its magnitudes at z=3.1 (red) and model intermediate mass black hole colours at z=3.1 for the different masses and mass accretion rates (green).

## 4.2 Number of black holes

The number of black holes needed to produce the mean observed magnitude in the NB359 filter, for each respective black hole with a certain mass and accretion rate, is seen in Table 1 in Appendix A.

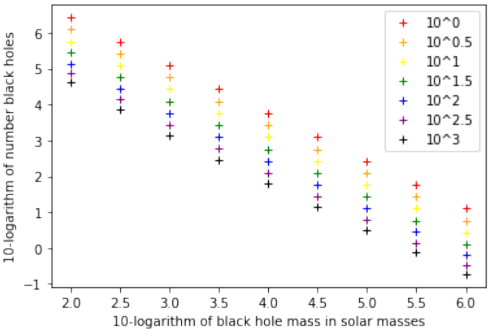

Figure 4: 10-logarithm of the number of black holes needed to produce the mean observed magnitude in the NB359 filter, by given mass varying between $100M_\odot$ and $1{,}000{,}000M_\odot$. The data is colour labeled by its mass accretion rate, given in $\dot{M}/\dot{M}_{crit}$.

# 5 Discussion

Comparing the positions of the observational data points with the position of the gray area in figure 2, one sees that the majority of the observed galaxies are found outside this area of colours that can be produced by the models. This is consistent with the galaxies observed in [1].

The observed galaxies are generally to the left of those provided by the galaxy model, meaning an addition to the models of a source of bluer radiation is needed for them to better coincide with the observed galaxy colours.

As can be seen in the diagram, this source could potentially be intermediate mass black holes, since these have a spectrum situated to the left of the gray area, indicating they would move the gray area to the left in the diagram if included in the galaxy models, making it to a greater extent intersect with the observed galaxy colours.

The calculated number of black holes of varying mass and mass accretion rates show a clear trend. Lower BH mass generally yields a higher number of required black holes, and so does lower mass accretion rates. For some values the numbers are non-physical; e.g. for black holes of $10^6 M_\odot$ and $10^3 \dot{M}/\dot{M_{crit}}$, a number of 0.18 such black holes would have to be present in a galaxy to produce the desired NB359 magnitude which is clearly not physical. On the other hand, it would take a content of 2.65 million black holes of $100M_\odot$ and $1\dot{M}/\dot{M_{crit}}$ in a galaxy to produce the same radiation, which is clearly improbable.

However, many of the numbers are physical, ranging between one or a couple of more massive IMBHs, and a few tens of less massive ones. Altogether, the results indicate IMBHs might have played a role in creating the LyC ionizing the intergalactic medium during the epoch of reionization. The fact that IMBHs could be a source of the excess LyC radiation might also be an implication of the existence of intermediate mass black holes.

The colour of the quasar does not lie along line of the black hole model. This approximate linearity continues when modelling for larger black hole masses in the regime of typical quasar masses. That the quasar does not lie along this line is not surprising since quasars host complex accretion disks, potentially giving rise to features not modelled by the simple black body based accretion disk model used in this work.

Looking at the positions of the galaxies' and the quasar's colours in the diagram, one can conclude that it is improbable that quasars are the main contributor to the blue colours of the galaxies.

Despite the reputation of quasars as among the bluest objects in the universe, the observed galaxies are bluer than the stacked quasar spectrum along the nb359-r axis. (On the V-i axis however, the quasar colour is bluer).

This might be explained if the observed galaxies were chosen based on high nb359 flux. Then, instead of representing average galaxies (as the mean quasar spectrum can be assumed to represent the average quasar), they would represent blue galaxies and their place in the diagram could be explained. This is in fact the case, since the galaxies are chosen on the fact that they are all LyC candidates. None of the modelled black hole masses are between 140-260 $M_\odot$, and so they do not contradict the range of masses possible for IMBHs formed by population III stars.

Errors might come from the fact that the IGM is inhomogeneously distributed and although all spectra are corrected for dust, one can not be sure that the corrections corresponds to the actual attenuation. The fact that the mean of the NB359 magnutides of all the galaxies is used in the calculations may have contributed with some error, which can be prevented by using the exact magnitude of each galaxy instead.

Finally, one should keep in mind that this study is based on simplified models and is to be considered a first, sketchy approach to the hypothesis that IMBHs might be responsible for some part of the excess LyC produced by these galaxies. This simplification is most probably a source of errors and future research should use more realistic models to improve the quality of results. For example, IMBH environments should host massive feedback effects, LyC absorption by dust and HI regions, and viewing angle radiation escape, and not conform to the assumption of isotropic black body radiation.

# 6 Recommendation/Outlook

Since the model for making black hole spectra is a first approximation to an accretion disk around intermediate mass black holes, a more carefully constructed model of black hole spectra needs to be developed. For example, emission and absorption lines, feedback effects and viewing angle dependency needs to be accounted for.

Another modification that could be done to analyze the situation more carefully, is plotting the galaxies in different colours depending on their type (LAEs/LBGs/AGNs) to be able to discuss how this affects the galaxies and draw conclusions from the different roles of these galaxy types in the early universe.

As the research on both cosmic reionization, high redshift galaxies and IMBHs continues, more details and conditions will make future research on the role of black holes in cosmic reionization more exact.

# 7 Conclusions

A literature study was conducted to gain background in the area of subject. Colours from observational data of $z \simeq 3$ galaxies were plotted together with those from a stacked quasar spectrum and modelled accretion disc colours of intermediate mass black holes.

Results show that, for some values of black hole mass and mass accretion rate, intermediate mass black holes might be a source of LyC radiation from $z \simeq 3$ galaxies, and models would probably agree more with observation if intermediate mass black holes were taken into account when modelling.

# A Table: Number of black holes for varying mass and accretion rate

| Mass | Mass accretion rate | Number of black holes |
|---|---|---|
| 2,00 | 0,00 | 6,42 |
| 2,00 | 0,50 | 6,09 |
| 2,00 | 1,00 | 5,76 |
| 2,00 | 1,50 | 5,44 |
| 2,00 | 2,00 | 5,14 |
| 2,00 | 2,50 | 4,87 |
| 2,00 | 3,00 | 4,63 |
| 2,50 | 0,00 | 5,76 |
| 2,50 | 0,50 | 5,42 |
| 2,50 | 1,00 | 5,09 |
| 2,50 | 1,50 | 4,76 |
| 2,50 | 2,00 | 4,44 |
| 2,50 | 2,50 | 4,14 |
| 2,50 | 3,00 | 3,88 |
| 3,00 | 0,00 | 5,09 |
| 3,00 | 0,50 | 4,76 |
| 3,00 | 1,00 | 4,42 |
| 3,00 | 1,50 | 4,09 |
| 3,00 | 2,00 | 3,76 |
| 3,00 | 2,50 | 3,45 |
| 3,00 | 3,00 | 3,16 |
| 3,50 | 0,00 | 4,43 |
| 3,50 | 0,50 | 4,09 |
| 3,50 | 1,00 | 3,76 |
| 3,50 | 1,50 | 3,43 |
| 3,50 | 2,00 | 3,10 |
| 3,50 | 2,50 | 2,77 |
| 3,50 | 3,00 | 2,47 |
| 4,00 | 0,00 | 3,76 |
| 4,00 | 0,50 | 3,43 |
| 4,00 | 1,00 | 3,09 |
| 4,00 | 1,50 | 2,76 |
| 4,00 | 2,00 | 2,43 |
| 4,00 | 2,50 | 2,11 |
| 4,00 | 3,00 | 1,80 |

| Mass | Mass accretion rate | Number of black holes |
|---|---|---|
| 4,50 | 0,00 | 3,095 |
| 4,50 | 0,50 | 2,76 |
| 4,50 | 1,00 | 2,43 |
| 4,50 | 1,50 | 2,10 |
| 4,50 | 2,00 | 1,77 |
| 4,50 | 2,50 | 1,45 |
| 4,50 | 3,00 | 1,15 |
| 5,00 | 0,00 | 2,43 |
| 5,00 | 0,50 | 2,10 |
| 5,00 | 1,00 | 1,76 |
| 5,00 | 1,50 | 1,43 |
| 5,00 | 2,00 | 1,11 |
| 5,00 | 2,50 | 0,80 |
| 5,00 | 3,00 | 0,51 |
| 5,50 | 0,00 | 1,77 |
| 5,50 | 0,50 | 1,43 |
| 5,50 | 1,00 | 1,10 |
| 5,50 | 1,50 | 0,77 |
| 5,50 | 2,00 | 0,45 |
| 5,50 | 2,50 | 0,15 |
| 5,50 | 3,00 | -0,12 |
| 6,00 | 0,00 | 1,11 |
| 6,00 | 0,50 | 0,77 |
| 6,00 | 1,00 | 0,44 |
| 6,00 | 1,50 | 0,11 |
| 6,00 | 2,00 | -0,20 |
| 6,00 | 2,50 | -0,49 |
| 6,00 | 3,00 | -0,73 |

Table 1: Mass (10-logarithm of black hole mass in solar masses), accretion rate (in $\dot{M}/\dot{M_{crit}}$) and the 10-logarithm of the number of black holes needed to produce the mean observed magnitude in the NB359 filter.

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