

AREA

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**THEME**

Title

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**Henrik Andrews**

Norwegian university of Science and Technology

November 24, 2023

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## Abstract

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## Summary

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## Acknowledgments

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# Contents

<b>1</b>	<b>Introduction</b>	<b>6</b>
<b>2</b>	<b>Cosmological distances</b>	<b>6</b>
2.1	cosmographic parameters . . . . .	6
2.2	Components of the universe . . . . .	6
2.3	Redshift . . . . .	7
2.4	Comoving distance . . . . .	7
2.5	Comoving distance part 2 . . . . .	8
2.6	Angular distance . . . . .	8
2.7	Luminosity distance . . . . .	8
<b>3</b>	<b>Particle theory</b>	<b>9</b>
3.1	Emission lines . . . . .	9
3.1.1	Broad emission lines . . . . .	9
3.1.2	Narrow emission lines . . . . .	9
<b>4</b>	<b>Neutrino production</b>	<b>9</b>
<b>5</b>	<b>Types of AGNs</b>	<b>9</b>
5.1	Active galactic nuclei . . . . .	9
5.2	AGN structure and classification . . . . .	10
5.2.1	Accretion disk . . . . .	10
5.3	Corona . . . . .	12
5.3.1	dust torus . . . . .	12
5.3.2	Broad line region . . . . .	12
5.3.3	Jets . . . . .	12
5.4	Types of AGNs . . . . .	12
5.4.1	Type I and II AGNs . . . . .	12
5.4.2	Blazars . . . . .	12
5.4.3	Radio galaxies . . . . .	13
5.4.4	Seyfert galaxies . . . . .	13

<b>6</b>	<b>luminosity functions</b>	<b>13</b>
6.1	X-ray LF . . . . .	14
6.2	Luminosity density . . . . .	15
<b>7</b>	<b>Evolution</b>	<b>15</b>
7.1	Galaxy evoluion . . . . .	15
7.2	AGN evolution . . . . .	15
7.2.1	Luminosity distribution . . . . .	15
7.2.2	Density distribution . . . . .	15

## List of Figures

1	AGN unification . . . . .	11
2	Luminosity density for the four different classes of AGNs. The different classes are defined in the title as well as the chosen LF model. The luminosity density is given in units of $\text{erg/s/Hz/Mpc}^3$ . .	16

## List of Tables

1	X-ray LF parameters . . . . .	14
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-abstract -sammendrag -acknowledgments -list of figure -list of tables

## 1 Introduction

## 2 Cosmological distances

In order to investigate sources very far away from an observer it is important to understand the influence this distance has on your desired observable. Therefore in astrophysics and astronomy in general there are distances created to take into account the effects of an expanding universe.

### 2.1 cosmographic parameters

The most notorious parameter is the Hubble constant  $H_0$ . This parameter sets the recession speed of a point at proper distance  $d$  and our current position via this equation.

$$v = H_0 d \quad (1)$$

The subscript 0 refers to the present epoch since in general  $H_0$  changes with time. The value of  $H_0$  is quite debated so I will follow the nomenclature of D. Hogg and write it as a parameterized equation.

$$H_0 = 100 \frac{\text{km}}{\text{s}} \frac{1}{\text{Mpc}} h$$

where  $h$  is a dimensionless number that according to current knowledge can take the value between 0.5 to 0.8

The Hubble constant has units of inverse time and therefore one can define the Hubble time as

$$t_H = \frac{1}{H_0}$$

The constant also has units of speed, and therefore we can define the Hubble distance.

$$D_H = \frac{c}{H_0}$$

### 2.2 Components of the universe

In this paper and in most articles one refers to the flat lambda CDM model to parameterize the contents of the universe and by extension the properties of its expansion. Here two important parameters to define are the mass

density of the universe  $\rho_0$  and the cosmological constant  $\Lambda$ . These variables which change with time also define the metric tensor in general relativity and allow us to model the curvature of the universe given an initial configuration. njaaa, skriv på nytt.

One can write these into dimensionless variables as such

$$\Omega_m = \frac{8\pi G\rho_0}{3H_0^2}$$

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

In general one has a third density parameter  $\Omega_k$  which defines the curvature of spacetime and is defined from

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

The flat lambda CDM has three components, the dark energy density, the dark matter density, and the ordinary matter parameter. In the rest of this paper and other articles used by this dissertation the values of these components are represented by their  $\Omega$  parameter and one has a universe with  $\Omega_\Lambda = 0.7$ , and  $\Omega_m = 0.3$  also known as the flat lambda since the curvature parameter is 0

## 2.3 Redshift

Redshift is defined as the fractional Doppler shift of emitting light. The Doppler effect is a known effect on different observables in our universe where the relative motion of sources to observers will impact the observable. The redshift is quantified for a light source as

$$z = \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1 \quad (2)$$

Here  $o$  refers to the observed quantity and  $e$  the emitted. If one want to connect this redshift to the velocity of the observed object one needs to go to general relativity. There is an analog in special but one omits it here since one does not use it. The important factor is that redshift is an observable and can help us determine distances of objects. especially if they are far away the relative velocity becomes negligible and only the effect of the expansion of the universe become important.

## 2.4 Comoving distance

The comoving distance or more clearly the line of sight distance for an observer locted here at earth is a foundational distance measure in cosmography. All other distance measures can be derived from it. One derives it by defining the small co-moving distance  $\delta D_c$ . This quantity defines the distance between two objects that remains constant when both objects expand with the Hubble flow. One can think of it as a proper distance from relativity since it is constant in all "time-frames". If one wants the total comoving distance one integrates all  $\delta D_c$  in the line of sight from  $z = 0$  to the object. In order to do this one need to take into account the different densities in the universe, from Hogg (2000) one defines the function

$$E(z) = \sqrt{\Omega_m(z+1)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \quad (3)$$

This function is defined by the density parameters defined above and also the redshift  $z$ . One can also relate this to the measured Hubble constant as measured by an hypothetical observer at redshift  $z$  via  $H(z) = H_0 E(z)$ .



One then receives the comoving distance  $D_c$  from

$$D_c = D_H \int_0^z \frac{dz}{E(z)} \quad (4)$$

## 2.5 Comoving distance part 2

$D_c$  is the line of sight of an object and its observer but given different space-time geometry that line is distorted. If one looks at two objects, both at redshift  $z$  the distance between them will be given as a function of the angle between them. If they are separated by an angle  $d\theta$  then the distance between them will be  $d\theta D_m$  where  $D_m$  is the comoving distance

$$D_m = \begin{cases} D_H \frac{1}{\sqrt{\Omega_k}} \sinh\left(\frac{\sqrt{\Omega_k} D_c}{D_H}\right) & \text{if } \Omega_k > 0 \\ D_c & \text{if } \Omega_k = 0 \\ D_H \frac{1}{\sqrt{|\Omega_k|}} \sin\left(\frac{\sqrt{|\Omega_k|} D_c}{D_H}\right) & \text{if } \Omega_k < 0 \end{cases}$$

The different cases are dependent on the curvature of the universe, and one can see that one enters hyperbolic geometry or spherical geometry based on the different curvatures. The true curvature of the universe is still a mystery but recent studies suggest that it is flat, as expected.

## 2.6 Angular distance

The angular

## 2.7 Luminosity distance

The luminosity distance  $D_l$  is defined through the relation between the bolometric flux  $F$  of a source and its bolometric luminosity  $L$ . The flux is the amount of energy per unit time per unit area and the luminosity is the total amount of energy per unit time. The luminosity distance is defined as

$$D_l = \sqrt{\frac{L}{4\pi F}} \quad (5)$$

In more clearer words it describes the total loss in energy due to light's travel across an expanding universe. The total observed flux an observer will see will be different from different distances. The intrinsic luminosity emitted at the source

It is related to the transverse comoving distance via

$$D_l = (1+z)D_m \quad (6)$$

This of course is for bolometric quantities, but if one wants to calculate the spectral flux/differential flux one needs to take into account a correction. This correction comes from the fact that one is viewing a redshifted object. The object is emitting in a different band than observed. The spectrum of the differential flux  $F_\nu$  is related to the spectral luminosity via

$$F_\nu = (1+z) \frac{L_{(1+z)\nu}}{L_\nu} \frac{L_\nu}{4\pi D_l^2} \quad (7)$$

If one wishes to translate an observed spectral flux of particles to a density distribution one needs to take into account this redshift effect

## 3 Particle theory

### 3.1 Emmision lines

When a particle is photionized by the continuum radiation of a source it will emit a photon when it returns to its ground state. This photon will have a specific wavelength that is determined by the energy difference between the two states. This wavelength is called the emmision line of the particle. When looking a dynamical systems with high velocities the doppler shift of these emmision lines becomes important since it will affect the observed spectra of the source.

<https://lweb.cfa.harvard.edu/~pberlind/whipple/agn.html>

#### 3.1.1 Broad emmision lines

Broad emission lines in the case of AGN are formed from the high density gas clouds located close the the central black hole. The high density parameter is innferred from the fact that one only sees broad emission from permitted line transitions (f.ex hydrogen Lyman and Balmer, iron II, and magnesium II). High densities allow for collisional de-exitation. And the boradaning is an indictation that these gas clouds are moving are moving at huge velocities around the massive objects. This implies that they are located close to the black hole

#### 3.1.2 Narrow emmision lines

Narrow emission lines are on the other hand formed in low density gas clouds. The low densities are inferred from the fact that one sees both permitted and forbbidden line transitions. They are narrow lines due to their velocities being substantially lower than the inner most gas clouds.

## 4 Neutrino production

We will be discussing two types of neutrino generation. The pp chain and  $p\gamma$  production

## 5 Types of AGNs

### 5.1 Active galactic nuclei

Active Galactic Nuclei (AGNs) is an interesting field in astrophysical studies. Since their discovery, there has been rapid advancement in understanding these phenomena. Today, AGNs are known to be among the brightest entities in the night sky, but they only gained significant attention in the 1950s. This shift occurred with the arrival of new radio observations, which revealed a new type of quasi stellar object through the discovery of Quasars.

Initially, these luminous objects, characterized by broad, unidentifiable spectral lines, were enigmatic to scientists in the early 1960s. However, with the identification of more sources and their optical parts, it became clear that these were not stars but a distinct class of celestial objects. Research done by M. Schmidt on of the emission lines from the Quasar 3C 273 opened the interpretation of these celestial objects. He found that the emmision lines of quasars were similar to hydrogen, but were redshifted by a factor of 0.158, an exceptionally high value at the time Shields (1999). Observations at the same time also revealed significant variability in quasar luminosity, suggesting that these objects were no larger than one light year across.

These observations lead to the speculation of super luminous objects located very far away from earth. The problem

was that such objects had no reasonable explanation at the time. It was not until the mid 1960 early 1970s when modern cosmology was afoot that more of these issues were resolved.

Observation of the surrounding galaxy of AGNs with matching redshift and observation of gravitational lensing cemented the distances of these objects. In addition the modern view of black holes which had only been a theory in the 1950s came to fruition and the modern model of a AGN was born. This modern perspective views AGNs as supermassive black holes that accrete matter from surrounding accretion disks. This accretion releases large amounts of energy and has also according to processes such as the Blandford-Znajek process (1977), been shown to produce relativistic jets, when the black hole is rotating.

In the most recent times a landmark achievement was achieved in March 2021, when scientists associated with the Event Horizon Telescope project presented the first image of the supermassive black hole at the center of the Messier 87 galaxy, located 55 million light-years away. This image, showing a bright ring surrounding a dark central region, aligns with predictions for an accreting supermassive black hole, reinforcing our understanding of these powerful cosmic sources.

## 5.2 AGN structure and classification

The modern view of AGNs is unified model that combined different categories of powerful luminous objects visible in the night sky. These distinctions that astronomers made still have value, but to understand an AGN it is important to get a picture of the modern structure of an AGN

An active galactic nucleus is defined as a galaxy containing a massive accreting black hole. This mass according to Netzer (2015) is defined as  $M_{BH} > 10^5 M_{\odot}$ . AGNs also contain an Eddington ratio exceeding the limit of  $\frac{L_{AGN}}{L_{Edd}} = 10^{-5}$ , where  $L_{AGN}$  is the bolometric luminosity, and  $L_{Edd}$  is the Eddington luminosity for a solar composition gas. These definitions help constrain what galaxies might contain an AGN, for example it excludes the Milky Way by these criteria, but it fails to capture the full structure definition of an AGN. Therefore the structure of most AGNs will include several of the following components.

- A close rotational dominated accretion disc around the SMBH. The thickness defining this accretion flow will distinguish different AGNs. One example is an optically thin accretion disk that sometimes becomes advection dominated. These flows will be referred to as radiation inefficient accretion flows (RIAF) due to the special nature of the disk.
- high density gas clouds that are said to be dust free moving at high velocities close to the black hole, in the so called broad line region (BLR)
- Low density gas clouds that move at lower velocities further away from the black hole in the so called narrow line region (NLR)
- A axisymmetric structure of dust that is responsible for the obscuration of the central region of the AGN. This is called the torus. It lies at a luminosity dependent distance from the SMBH, but according to Netzer (2015) this is around 0.1 - 10 pc depending on the luminosity.
- A relativistic jet that is powered by the accretion disk. This is not always present but is a common feature of AGNs.

The reader is directed to image 1 for a visual representation of the different components.

### 5.2.1 Accretion disk

An accretion disk is a natural consequence of the conservation of angular momentum. In the case for infalling matter coming close to a super massive black hole, the matter will have some angular momentum. This angular momentum would in an ideal fluid orbit the black hole at some stable distance. Due to radiative processes and

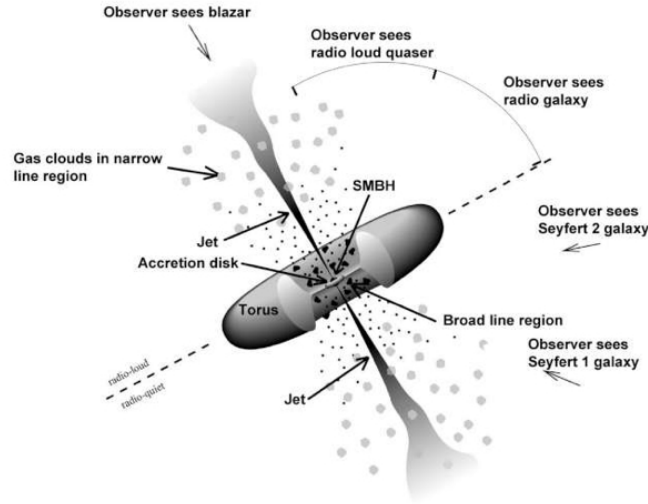


Figure 1: AGN unification

some fluid viscosity in this high density matter the matter will lose angular momentum and spiral inwards. This inward spiral will eventually allow the matter to fall onto the black hole. This process of inspiral is what is called accretion and the forces acting on the matter to cause the inspiral will also in the same process heat it up to high energies causing it to radiate. This radiation is closely linked to the infalling matter that is accreted onto the black hole and one can express the total luminosity of the accretion disk as

$$L_{acc} = \eta \dot{M} c^2 \quad (8)$$

Here  $\eta$  is the efficiency of the accretion disk,  $\dot{M}$  is the mass accretion rate and  $c$  is the speed of light.

The efficiency of the accretion disk is a function of the spin of the black hole and the radius of the innermost stable circular orbit (ISCO). The ISCO is a counter intuitive term in classical mechanics but in general relativity the maximum speed of a particle in addition to a energy term in the calculation of the orbit set bounds for how close a particle can be to a black hole without spiraling in. without going into too much detail the ISCO will be a solution of this equation based on the black holes mass and spin  $a$

$$6\frac{M}{r} - 8\frac{aM^{(1/2)}}{r^{3/2}} + 3\frac{a^2}{r^2} = 1 \quad (9)$$

The accretion disk also has a bound for its maximum luminosity. As calculated for stars the Eddington luminosity sets a maximum strength for the radiation pressure of the accretion disk. This is given as

Get sources!

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} \quad (10)$$

write about BB radiation from accretion disk which give rise to x-rays.

## 5.3 Corona

### 5.3.1 dust torus

maybe write about thermal radiation from dust torus

### 5.3.2 Broad line region

maybe write about BLR

### 5.3.3 Jets

Write about shock structure write about non thermal radiation Jet acceleration?, acceleration before jet, cooling effects

section radiation

## 5.4 Types of AGNs

<https://astrobites.org/guides/galaxy-and-agn-types/>

Before the unification of the AGNs astronomers named the puzzling objects based on their observational properties. These names are still used to this day and are somewhat useful since their observational properties are important parameters for further study. The different classification are important in understanding which objects could have the potential to produce the different observables one looks for in the night sky. There is a lot of talk around AGNs being possible sources for ultra high energy cosmic rays (UHECRs) and neutrinos. This is yet to be confirmed, but the theoretical framework for the necessary particle acceleration is there. therefore it seems appropriate to discuss the different types of AGNs and their observational properties.

### 5.4.1 Type I and II AGNs

One distinguishes type I and type II AGNs based on the presence of broad emission lines. In other words this distinction is a matter of a visible nucleus or not. Type I refers to sources whose nucleus is exposed to the observer and whose spectrum has both narrow and broad emission lines. Type II refers to sources whose nucleus is obscured by a torus and therefore only has narrow emission lines.

### 5.4.2 Blazars

The most extreme class of AGN. These sources are distinguished by their relativistic jets that are pointed towards the observer. This jet produces both synchrotron and Inverse Compton gamma rays and are extremely variable over short timescales. The emission is also highly polarized. Often and including in this paper one divides blazars into subgroups based on the emission lines. The two most common are BL Lacs and Flat spectrum radio quasars (FSRQs). The difference between these two is the presence of broad emission lines. BL Lacs have no broad emission lines while FSRQs do.

### 5.4.3 Radio galaxies

As the name suggest these sources are very bright in the radio band. They usually refer to AGN viewed edge on, where the torus might block the emissions from the accretion disk. The orientation of Radio galaxies give way for strong synchrotron radiation, and they are often used to study the jet structure of AGNs.

### 5.4.4 Seyfert galaxies

Spiral galaxies that have a bright nucleus. They are bright in the optical band and have a smaller active region than radio galaxies. They are often divided into two groups Seyfert I and Seyfert II where the distinction comes from type I and II. They also show quite high variability indicating a small emitting region.

All these different distinctions are a help in understanding what processes one might be observing. The different dominant bands indicate different processes being in our line of sight, and by considering the modern structure of AGNs one can then try to determine the underlying dynamics.

## 6 luminosity functions

A luminosity function is a function that describes the distribution of objects per luminosity and per comoving volume for a population of celestial sources, such as galaxies or quasars. It is a powerful tool for understanding the properties and evolution of these objects, as well as the larger-scale structure of the universe. We usually talk about the differential luminosity function given as

$$\frac{d\Psi(L, z)}{dL} = \frac{d^2 N(L, V_c(z))}{dL dV_c(z)} \quad (11)$$

We also can change the differential of the comoving volume into a term only depending on the redshift assuming it is isotropic.

$$\frac{d^2 N(L, V_c(z))}{dL dV_c(z)} \frac{dV_c(z)}{dz} = \frac{N(L, z)}{dL dz} \quad (12)$$

Several articles express the luminosity function in base 10 logarithm and we note the conversion between the two.

$$\frac{d\Psi(L, z)}{d\log(L)} = \ln(10) L x \frac{d\Psi(L, z)}{d(L)} \quad (13)$$

The luminosity function (LF) is a theoretical tool, but in order to determine the luminosity functions one usually separate the function into two terms. One takes the local luminosity function at  $z = 0$  and then multiply it with a redshift evolution function. These evolution functions are varying from survey to survey, but in general one has two main classes. The different classes are separated on how the evolution term is added to the local LF and is determined on what fits the evolution the best. The pure density evolution (PDE) model evolves the local density function while the pure luminosity evolution (PLE) model evolves the local luminosity. The evolution is better represented by its equations and is given as

$$\frac{d\Psi(L, z)}{d(L)} = \begin{cases} \frac{d\Psi(L/e(z), z=0)}{d(L)} & (PLE) \\ \frac{d\Psi(L, z=0)}{d(L)} e(z) & (PDE) \end{cases} \quad (14)$$

The PLE and PDE models sometimes fails to capture the evolution of the luminosity function. Therefore modern LF might use a modified version. This will be more clear in the next section.

Model	A	$L_{star}$	$\gamma_1$	$\gamma_2$	$v_1$	$v_2$	$z_c$	$L_c$	$\alpha$
RG-SLDDE	8.375	2.138	2.15	1.10	4.00	-1.50	1.90	3.981	0.317
AMPLE-Blazar	1.379	1.810	-0.87	2.73	3.45	-0.25			
AMPLE-FSRQ	0.175	2.420	-50.00	2.49	3.67	-0.30			
APLE-BLlac	0.830	1.000	2.61	-0.79					

Table 1: X-ray LF parameters

## 6.1 X-ray LF

For a given type of AGN, different bands will be more important than others. And for populations such as blazars seyfert I or the sub population of blazars where the X-ray factory close to the central engine is visible the x-ray luminosity from these sources will be important. Therefore several studies attempt to describe the luminosity functions of these sources through the use of the x-ray band.

The most simplest form of the local luminsoty function is expressed in Ajello et al. (2009) and is given as a power law.

$$\frac{d\Psi(L, z=0)}{dL} = \frac{A}{L_x} \left( \frac{L_x}{L_*} \right)^{1-\gamma_2} \quad (15)$$

This simpler power law fails to capture all details for all population evolution and therefore a more complex model is needed. For some sources Ajello et al. (2009) and Ueda et al. (2003) use a double power law to better fit the data.

$$\frac{d\Psi(L, z=0)}{dL} = \frac{A}{\log(10)} \frac{1}{L_x} \left( \left( \frac{L_x}{L_*} \right)^{\gamma_1} + \left( \frac{L_x}{L_*} \right)^{\gamma_2} \right)^{-1} \quad (16)$$

Which has the effect of splitting the luminosity function at the break luminosity  $L_*$ . In addition to the local LF one also considers the evolution factor denoted  $e(z)$ .

Again for the simplest evolution a power law is used.

$$e(z) = (1+z)^{v_1+v_2z}$$

where  $v_2 = 0$  gives the simple power law. In for some cases a more complex evolution is needed. As described in Ajello et al. (2009) A modiiied evolution is often required transformin the usuall PLE and PDE into so called Modified PLE and PDE (MPLE, MPDE) and is where the dependenci on  $z$  in the exponent arrives.

As described in Ueda et al. (2003) the evolution of the luminosity function is not always a simple as a power law. And for some sources a more complex evolution is needed. In Ueda et al. (2003) they use a double power law to better fit the data where the evolutions is now not only dependent on the redshift but also on the luminosity. This then recvies the apt name as a luminsoty dependent density evolution (LDDE)

$$e_z(z, L) = \begin{cases} (1+z)^{v_1} & \text{if } z \leq z_*(L) \\ e_z(z_*(L), L) \times \left( \frac{1+z}{1+z_*(L)} \right)^{v_2} & \text{if } z > z_*(L) \end{cases} \quad (17)$$

with  $z(L)$  being defined as

$$z_*(L) = \begin{cases} z_c \left( \frac{L}{L_c} \right)^\alpha & \text{if } L \leq L_c \\ z_c & \text{if } L > L_c \end{cases} \quad (18)$$

The expansion of the parameter space allows for easier fitting to the observed data, but comes of course with an increase in complexity.

## 6.2 Luminosity density

For the different classes discussed one can integrate the differential luminosity function to retrieve the Luminosity distribution of each object. This distribution highlightst the difference over emmitting power and therefore are important for us to be able to distinguish the most powerfull sources and their prevelance. One calculates the Luminosity density by mulitplying the class specific luminosity function with the differential comoving volume and integrating over the relevant redshift bin. By seperating it into bins of redshift one will illuminate the number evolution of these objects.

$$\frac{dN(L)}{dL} = \int_{z_{\min}}^{z_{\max}} \frac{\Psi(L, V(z))}{dL} \frac{dV(z)}{dz} dz \quad (19)$$

In both Ajello et al. (2009) and Ueda et al. (2003) they calculate the luminsity function for different types of AGNs.

This is over a particular band of wavelengths

This equation does not have a simple equation to describe all types of light sources, but for different intervals of wavelengths and redshifts ( $z$ ) one can observe different trends for different light sources.

In the paper Jacobsen et al. (2015) the author uses the xray luminosity function. The X-ray luminosity function is used to describe the distribution of X-ray luminosities of objects in a specific population, such as galaxies, galaxy clusters, or active galactic nuclei (AGNs). It provides information about the number density of objects at various X-ray luminosity levels within a given volume of the universe.

In Jacobsen et al. (2015) there is a mention of several different models for different populations of AGNs. There she highlights two, Ajello et al. (2009) and Ueda et al. (2003). They are used for different populations.

The present day XLF is presented in Ajello et al. (2009) and is given by a simple power law.

$$\frac{d\Psi(Lx, 0)}{d\text{Log}(Lx)} = A \ln(10) \left(\frac{Lx}{Lc}\right)^{(1-\gamma_2)} \quad (20)$$

However there is a break with high enough score count and this break can be better fitted with a double power law

## 7 Evolution

### 7.1 Galaxy evoltuion

### 7.2 AGN evolution

#### 7.2.1 Luminosity distribution

#### 7.2.2 Density distribution



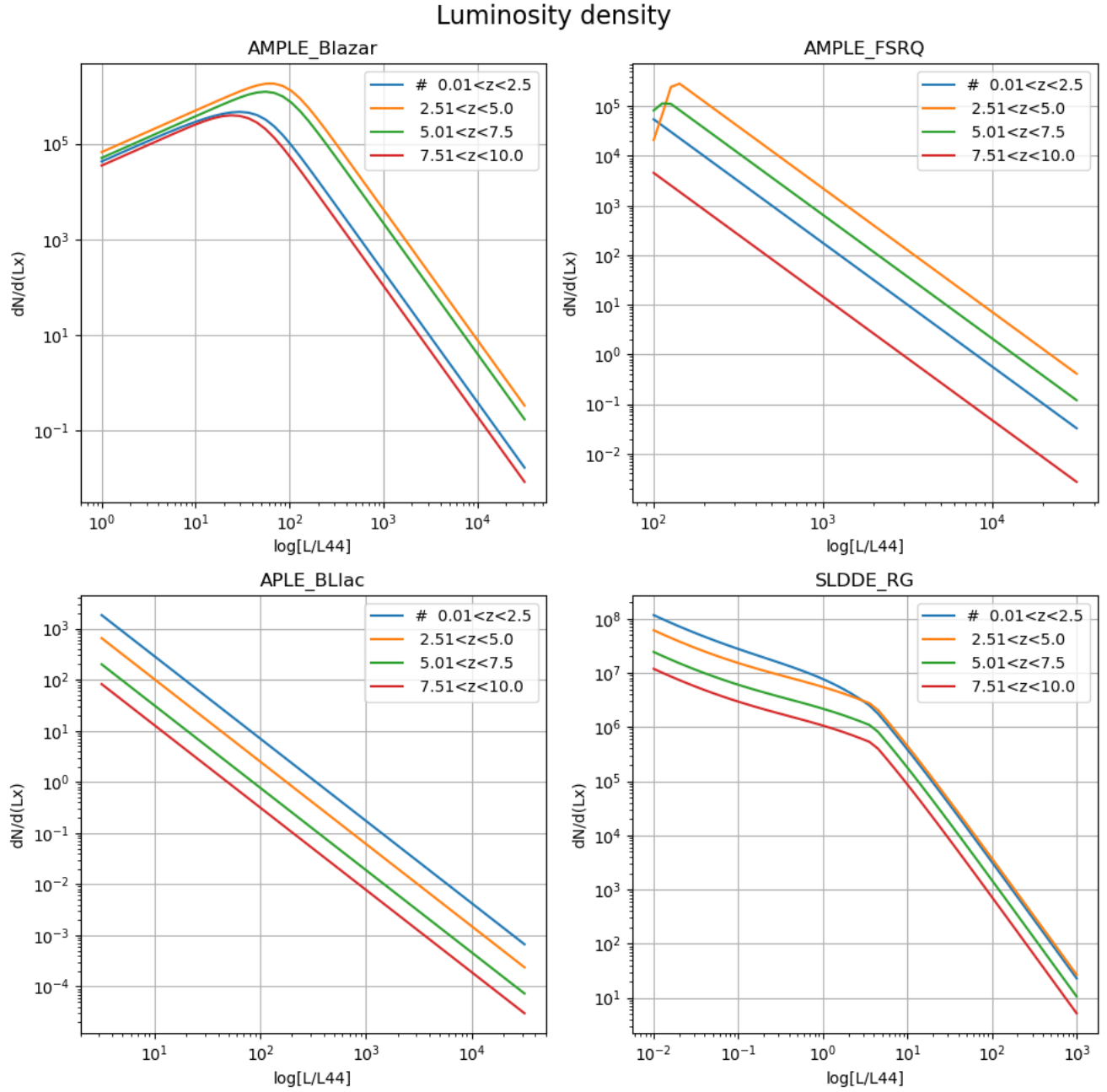


Figure 2: Luminosity density for the four different classes of AGNs. The different classes are defined in the title as well as the chosen LF model. The luminosity density is given in units of  $\text{erg/s/Hz/Mpc}^3$