# Chapter 1

# INTRODUCTION

The architecture of the universe is put in perspective by starlight. This light is perpetuating through time and space revealing the intricate, yet wonderful, but ever elusive design of the universe. And here we are with our telescopes, our observations, our models and theories, our questions and answers chasing after more whys and hows, striving for the beatitude of understanding how it all came to be. In the end, however, we settle with the answer to a hand full of our questions acknowledging that in its greatness the universe seems to always be one question ahead.

Nice!

We believe that the universe begun with a violent explosion: The Big Bang. In just one second from the time of the Big Bang the universe went through the Planck Epoch and the Particle Cosmology Epoch. The beginnings of the Planck Epoch were governed by the laws of quantum gravity and little is understood about this time period. However as the temperature of the universe dropped down to $10^{28}$ K, the quarks formed, and soon after the universe went through a period of rapid inflation. A bit of a second later still in the Planck Epoch, the Electro Magnetic and Weak Nuclear forces became differentiated. As the universe took another step down in temperature the Particle Cosmology Epoch set in, where new fundamental particles such as leptons formed and quarks combined to form baryons and mesons. As the temperature continued dropping ($10^9$ K) the universe entered the Nucleosynthesis phase, where in a few minutes ~~old universe~~ the light atomic nuclei formed: hydrogen (one proton), deuterium (one proton and one neutron), tritium (one proton and two neutrons), and helium (two protons and two neutrons). The universe lit up.

After four minutes from its birth, the universe stopped creating atomic nuclei and it took another drop in temperature (to $10^5$ K) and 3000 years until the universe switched from being radiation dominated into being matter dominated. The universe continued to cool and expand, but because the electrons roamed freely, still too energetic to be bound to nuclei, the light particles, the photons could not reach through making the universe opaque to light and radiation. So, the light that existed then cannot be seen by our telescopes. Only when the universe was at the age of 380,000 years and a temperature of 3000 K the electrons could no longer overcome the attractive force of atomic nuclei and as they became bound to atoms, the light was set free. This "recombination" process gave way to the "first light", that reached us in the form of the Cosmic Microwave Background Radiation. Our observations of the Cosmic Microwave Background (CMB) radiation complement our cosmological view of the universe, with a picture of the young universe, one that supports the current standard model of cosmology, the Λ Cold Dark Matter (ΛCDM) model. (Springel et al., 2006).

Ironically enough, the "first light" set the beginning of the Dark Ages, the period between the time of the emission of the cosmic microwave back–ground radiation and the time when the first stars formed and the evolution of structure based on gravitational collapse of objects started. During the Dark Ages, the atomic gas was still close to homogeneous, and as the temperature dropped down, only a small fraction of it formed the first molecules of $H_2$, HD, and LiH (Miralda-Escudé, 2003). During the Dark Ages most of the existing matter got organised into small dark halos (White & Rees, 1978) and it was inside these halos that the first stars at a redshift of 50 formed and started giving light (Springel et al., 2006). By redshift 15 there were enough first stars to begin a new phase in the life of our universe: the reionization. The reionization is marking the turnover from a mostly neutral universe to an ionized one, but also encloses a world of information about the first sources of light in our universe and the star formation mechanisms of its early history. Unfortunately, our observations have difficulties reaching this epoch in time, an epoch known to finish around ~~the~~ redshift of 6.

Theoretically, it is believed that the first stars formed from zero metallicity gas and acted as catalysts in further star formation episodes inside the halo that was hosting them, but also in neighbouring halos (Ricotti et al., 2008). This explains why the first galaxies formed preferentially in chain–like structures, similar to the young star clusters at ~~the~~ low redshift. In the centre of the dark matter haloes, the gas condensed and cooled and when it reached a sufficiently high density it started to fragment into stars and further gave birth to the first galaxies. The first galaxies ~~will be~~ were low mass systems, $10^6$ times smaller than the Milky Way. Most of their haloes ~~would have~~ had disappeared by now in the larger scale build up, leaving them as

The dark matter haloes disappeared?, Not sure I fully understand the intent of this sentence.

identifiable stellar systems (White & Rees, 1978). As the haloes ~~get~~ became organised into larger systems and started populating the “cosmic web”, the groups and clusters of galaxies ~~are~~ were also created. According to White & Rees (1978), as the haloes of the first galaxies ~~get~~ became disrupted and merged into larger structure~~ units~~s, the residual gas ~~may~~ cooled and collapsed forming large central galaxies, in this way making possible the existence of small satellites around big galaxies.

Excellent motivation for why dwarfs.

In this scheme of things at least some of the small satellite galaxies (dwarf galaxies) that we see today, sitting inside their cold dark matter haloes may in fact be primordial galaxies. Our knowledge of the history of our universe brings forth the topic of dwarf galaxies as holding essential information not only in confirming ~~our current beliefs and results~~ our understanding of the present, but also in increasing our knowledge of the past ~~without having~~ OK to look any further than our own back yard. Dwarfs are the most common type of galaxies, apparently simple, yet with complex star formation histories and even more exotic star formation mechanisms (Mateo, 1998). Their importance goes beyond solving the dark matter problem. They are able to provide clues on mechanisms acting in low metallicity environments, on new constraints on the relationship and interaction models between dwarfs and giants and none the least evidence on the structural evolution that enabled the variety of dwarf galaxies we observe today and the possible evolutionary links between them.

## 1.1 Dwarf Irregular Galaxies

This doesn't include more massive dIrr, like the LMC. Maybe give upper limits?

Dwarf galaxies with a mass around $10^6$ solar masses and about 1 Kpc in size can be classified just like the giant galaxies, into ellipticals, spirals and irregulars (Mateo, 1998). Because the dwarf ellipticals do not have the same properties as their giant counterparts, they are also known as dwarf spheroidal galaxies. Gnedin & Kravtsov (2006) suggest that all luminous satellites ~~have~~ formed a few stars before ~~the~~ reionization, but only the galaxies massive enough (dwarf irregular and dwarf spheroidal types) managed to keep their gas and continue to form stars, while others (fossil dwarf spheroidal galaxies) lost their gas during the reionization epoch and kept only their, by now old, stellar populations. Other authors, however, suggest that according to observations and theoretical calculations there should be two groups of dwarf galaxies: primordial and tidal dwarf galaxies, easily distinguishable based

There are dSph + dE systems.

on their cold dark matter content (Kroupa, 2012). In a follow-up paper (Dabringhausen & Kroupa, 2013) find that even for a group such as dwarf spheroidals, their properties are best explained as ancient tidal dwarf galaxies rather than primordial dwarfs, raising a question mark to the validity of the ΛCDM model itself. In truth, the ΛCDM model does predict more satellite galaxies than we observe, however there are strong indications that besides the low-mass luminous satellites, dark satellites may also exist even in our Local Group (Simon et al., 2004).

If ~~instead of following the structural evolution or the dark matter problem related questions,~~ we concentrate our attention ~~towards,~~ on star formation mechanisms in low metallicity, “simple” environments, th~~a~~en we should ~~also~~ focus our interest on dwarf irregular galaxies. They share properties such as low or no spiral arms, no shear motions, slow rotations, low metallicity and large H I content with their giant counterparts, however they are less luminous, less massive and with a lower surface brightness than giant irregular galaxies (Hunter et al., 1982; Hunter & Gallagher, 1985b).

Irregular galaxies in general, and implicitly dwarf irregulars, are bluer than spirals (Hunter et al., 1982). Morphological peculiarities indicative of past interactions are observed in about one third of them, while 23% of them host stellar bars, which tend to be larger than in spiral galaxies, at times off–centre and occupying most of the optical disk (de Vaucouleurs & Freeman, 1972; Hunter & Elmegreen, 2006). Dark matter contributes ~~with~~ a higher fraction of the total disk mass in irregular galaxies than in spirals, enhancing in this way the disk instability and allowing the formation of cool H I (Hunter et al., 1998). The lack of spiral arms or any other large-scale collision enhancer does not hinder the effectiveness of star formation, hence the wide range of star formation rates observed in these galaxies (Hunter et al., 1982). Due to the low level of shear motions, holes created by massive stars will persist longer and implicitly the smoothing of gas will take longer than in spirals (Hunter et al., 1998).

Reference cite papers for high fraction of DM.

?

wide range is open puzzle you mean dIrrs form ☆ happily w/o spiral arms

Hunter & Gallagher (1985b) finds that dwarf irregulars, optically tiny galaxies, show features such as “disconnected botches of light or plum like features”, some show no rotational motion making any inclination estimation very difficult and have distinct H II regions smaller than those in giant irregulars suggesting the existence of fewer O stars. They also find that the process of star formation takes longer in dwarf irregular galaxies (10 Hubble times). In a follow up paper Hunter et al. (1998) suggest that the slowness of the star formation process in dwarf irregulars could be linked to stellar feedback, in other words injecting energy in the interstellar medium ~~is~~ enabl~~ing~~es cloud formation for future star formation events. The Longer the star formation cycles, the more pristine and abundant their gas reservoir destined to contribute to future generations of stars, which allows us to observe the star formation mechanisms today in low metallicity environments.

## 1.2 Star Formation

It took 400 million years until the birth of the first stars, and for billions of years since the universe has been continuously forming stars. The neutral gas turns molecular, out of the molecular gas stars form, then stars die and release back into the interstellar medium gas and metals destined to contribute to the life of the following generations of stars. Looking at the small scale ~~S~~tar ~~F~~formation mechanisms, one gets the impression that star formation is a complex but very exact process, yet when looking at larger scales no universal law seems to explain the amazing structural diversity of our universe. Star formation happens everywhere in the universe, in big spiral galaxies and in small irregular dwarf galaxies, in high and low metallicity gas, in the centre and the outskirts of galaxies. What regulates the star formation process? What law dictates what fraction of the neutral gas will become molecular? Why do stars form where they do? Is star formation self-propagating or does it need an external trigger? Is there a universal star formation law? How does metallicity influence this law? And these are just a few of the multitude of star formation related questions still left for us to answer.

Nice!

### 1.2.1 How do stars form?

In a large mass of atomic hydrogen there naturally coexist two components of very different properties: the warm neutral medium and the cold neutral medium. The warm neutral medium (WNM) with a density of about 0.5 cm$^{-3}$ and a temperature of $8 \times 10^3\,K$ is not confined to individual clouds and it has a scale height twice that of the cold neutral medium (CNM) component (Burton et al., 1992). This cold component of the atomic hydrogen is manifested in H I clouds with densities between 10 and 100 cm$^{-3}$, diameters between 1 and 100 pc and a representative temperature of 80 K. These H I clouds are long lived due to the pressure balance between the confining effect of the warm neutral medium surrounding the cloud and the dispersion by internal thermal motions inside the cloud (Cox & Smith, 1974; McKee & Ostriker, 1977). These cold H I clouds are the parents of molecular clouds.

Ever since the first molecules were observed in diffuse clouds, it has been ~~quite~~ a challenge to explain the chemistry involved in turning atoms into molecules. ~~Assuming that~~ If the temperature and density are high enough and the neutral gas is ionized enough to contain some free electrons, the combination of neutral atoms with available electrons, or protons for that matter, can lead to molecular hydrogen formation (Hartquist & Williams, 1995; van Dishoeck & Blake, 1998). A small fraction of the first stars have indeed formed from low temperature, zero metallicity gas clouds, where the molecular hydrogen formation is catalysed by the $H^-$ ion, (Ricotti et al., 2008). This mechanism must have played a key role in the formation of the first stars, but presently a different mechanism is at play. With the perpetuation of star formation through the life of the universe, the proliferation of metals has opened up a new avenue for molecular hydrogen formation, an avenue where two neutral hydrogen atoms can combine if on the surface of a dust grain which absorbs the atoms released energy without a significant rise in temperature (Hollenbach & Salpeter, 1971). The $H_2$ molecule is the only ~~one forming~~ one that forms in this way; the formation of other molecules is based on a different reaction. The dipole moment induced by a charged ion when encountering a neutral molecule (or atom) acts as an electrostatic attraction between the two, a process known as the ion–molecule reaction (Hartquist & Williams, 1995; van Dishoeck & Blake, 1998).

Cold H I clouds become molecular from the inside out (Goldsmith, 2007). Nicely put. Therefore, inside the cold H I cloud $H_2$ molecule formation begins first using the $H^-$ ion as a catalyst until all available electrons are exhausted and then using dust as a catalyst. However no pure $H_2$ cloud can exist, because all the molecules near the surface are dissociated by ultraviolet photons of 11.2 eV or higher. Therefore even when the whole cloud would have left the neutral phase and joined the molecular phase, where it is known as a Giant Molecular Cloud (GMC), it will still have an atomic envelope. The transition from cold neutral gas to molecular gas implies a drop in temperature from 80 K to 10 K, which can only be achieved through a balance between the heating and cooling mechanisms at play in the molecular environment. The main heating contributors are interstellar cosmic rays and photons (coming from both the diffuse stellar background and the X–rays from pre–main sequence stars). Cooling on the other hand is achieved mainly through CO trapping, but also through emission of infrared photons mainly from the 63 $\mu$m line of O I and the

158 $\mu$m line of C II (Neufeld et al., 1995) and collisional energy transfers from the gas to the dust grains.

Both the newly formed $H_2$ molecules and the dust grains present in the cloud will absorb the incoming ultraviolet photons, shielding the cloud from further dissociation. Consequently these $H_2$ molecules will dissociate and the dust will emit at far–infrared (FIR) wavelengths. It is at this depth into the cloud, where the $H_2$ self-shielding (Hollenbach et al., 1971) mechanism is activated, that the atomic envelope ends and the molecular interior begins. Throughout the Giant Molecular Cloud, the incoming photon energy will be spent on turning both hydrogen and carbon atoms into molecules. When most of the available hydrogen will have become molecular the incoming energy from photons will be used to turn C I into C II, which in turn will be used to form CO via the ion–molecule reactions (van Dishoeck & Black, 1987). Similarly to $H_2$, CO will also self–shield. Deeper inside the cloud atomic oxygen ~~is prevailing~~ prevails, because its small dissociation energy makes it weak against even the remnants of the incident ultraviolet flux.

The self-shielding mechanism active inside the condensing medium of a Giant Molecular Cloud could have induced a degree of clumping inside the gas, where certain regions with higher density ($10^3$ cm$^{-3}$) and lower temperatures are surrounded by lower density gas partly molecular and partly atomic. Morphologically mainly from CO isotope~~s~~ observations we know that a ~~giant molecular cloud~~ GMC can have either one or more molecular clumps in its composition. One molecular clump is known as an Individual Dark Cloud, while the distribution of multiple molecular clumps ~~distribution~~ is known as a Dark Cloud complex. Both structures have the same temperature of 10 K, however the individual dark cloud has a higher density and a lower mass and size (Blitz, 1993). Inside the dark clouds we have ten times denser regions called the dense cores (Myers, 1995). It is within these dense cores that the star formation actually takes place. Some of the dense cores we observe via the radio lines of molecules such as $NH_3$, $^{12}C^{18}O$ and CS and they do have point like infrared sources in their centres, representing their optical counterparts. stellar?

At the centre of a gravitationally collapsing (Ebert, 1955; Bonnor, 1956) dense core a protostar is formed (Bodenheimer & Sweigart, 1968; Shu, 1977) and its mass accretion rate is set by the parent cloud temperature (Boss, 1987). The accretion luminosity while high enough to be optically observed is obstructed by the dust envelope and re–emitted in the infrared. The shock generated by the cloud matter impacting the protostar surface, indirectly ignites deuterium (Stahler, 1988) and turns on convection. In an intermediate–mass protostar the convection will stop, while the deuterium will continue to burn in an inner shell and if accretion continues eventually the ordinary hydrogen will ignite as well (Palla & Stahler, 1991). A massive star, such as an O or B star~~s~~ cannot form in this manner, but rather arises from the merger of dense cores and previously formed stars.

### 1.2.2 Star Formation at larger scales

~~Stars do not form individually but rather in groups.~~ Star formation is ~~itself acts~~ also ~~as~~ a global galactic process. Therefore when talking about star formation, apart from understanding how one Individual Dark Cloud or a Dark Cloud complex forms stars, we also need to understand how global the star formation process really is: how many stars form, where do they form, why do they form there and not at some other location and in which way is this star formation process imprinted in the very fabric of our universe. Suddenly the perspective changes and we find ourselves looking at ~~individual star forming regions in our own Galaxy or at a larger scale still,~~ star formation on ~~at~~ an individual galaxy level.

#### 1.2.2.1 Neutral Gas and its transition towards the molecular phase

Abundance of neutral hydrogen is necessary when it comes to star formation, as suggested by the spatial correlation between H I and FUV emissions (Bigiel et al., 2010a). Bigiel et al ~~Following, the authors~~ also find that the large H I reservoir in the outskirts of M 83 has such a long depletion time, that star formation is not able to exhaust it, implying that this reservoir is also available for the inner disk of the galaxy. To trace the neutral hydrogen gas we make use of the hydrogen line transition at 21.1 cm (van de Hulst, 1945; Ewen & Purcell, 1951), which is directly proportional to the H I column density. By collision with a neighbouring atom, the hydrogen atom is ~~gets~~ excited and later, also through collision, it is ~~gets~~ deexcited, emitting a photon at 21.1 cm in the process. Although an average of $1 \times 10^7$ yr passes between emission events, the large number of available hydrogen atoms produce enough radio signal at 21.1 cm to be detectable (Burton et al., 1992).

Part of the available atomic gas turns molecular. What determines ~~How it is decided~~ the amount of atomic gas to be turned molecular and what mechanism regulates it are all questions wrapped up under the subject of ~~entitled~~ molecular gas fraction. In a comprehensive study of the relation between star formation rate and molecular hydrogen surface densities as a function of stellar mass Rahman et al. (2012) find that the molecular gas fraction is affected by the stellar potential well, although it cannot influence in any way the rate at which the molecular gas is converted into stars. Pelupessy & Papadopoulos (2009) have incorporated the molecular gas phase in their numerical simulations and were able to reproduce molecular fractions ranging from 0.001 to 0.3 for low metallicity galaxies and from 0.17 to 0.4 for solar metallicity galaxies. They also find that the molecular fraction depends on metallicity, a result that naturally derives from the molecular hydrogen formation mechanism which uses dust as a catalyst. Gnedin & Kravtsov (2011) using cosmological simulations conclude that the molecular gas fraction depends on the dust to gas ratio and far ultraviolet (FUV) radiation flux. Leroy et al. (2006) argue that the molecular gas fraction is better predicted by pressure, important in enabling the $H_2$ formation from H I. In the spiral galaxy M 51, Schuster et al. (2007) finds that the ratio between the molecular and the atomic gas surface densities are related with the galactic radius through a power law of index number N=1.5. This relationship breaks at large radii, beyond 6 Kpc. Thus the mechanism involved in turning neutral gas into molecular gas differs based on environment type and implicitly on galaxy type. For more details see Section 1.2.3.

#### 1.2.2.2 Molecular Gas Phase

An in depth knowledge of the properties of ~~Giant Molecular Clouds~~ GMCs is essential in order to be able to observe star formation at large scales. Bolatto et al. (2008) found GMCs from a wide range of environments are very similar to the ones in our Galaxy: gravitationally bound structures with typical sizes of around 40 pc and a mean density of $\approx 1.5 \times 10^{22}\,\mathrm{cm}^{-2}$. Resolution allows us to observe individual GMCs only in our own Galaxy or in very nearby objects. So, to investigate how star formation proceeds in other galaxies we extract from the knowledge we gained from our own Galaxy the ~~very~~ signatures that can be seen ~~despite the loss in~~ at low resolution.

Molecular hydrogen, $H_2$, although it constitutes the largest component of the total molecular gas mass, it cannot be traced directly. The $H_2$ molecule has the smallest moment of inertia, lacks a permanent electric dipole moment and its lowest excited energy levels corresponding to molecular rotation are very difficult to populate. For direct detection, $H_2$ has to be observed in hot environments such as clouds shocked by stellar wind. In order to estimate the molecular gas, observations rel~~a~~y on the detection of CO (Wilson et al., 1970), always present in the molecular interior of the cloud as cores inside an $H_2$ envelope. Because the CO molecule moment of inertia is greater and ~~faster~~ electric dipole transitions occur faster, the CO molecule can be excited to the following isotopes: $^{12}C^{16}O$, $^{13}C^{16}O$, $^{12}C^{17}O$ and $^{13}C^{18}O$. Among these the most abundant one is the CO(1–0) transition of the $^{12}C^{16}O$ isotope which corresponds to a emitted photon wavelength of 2.60 mm. To trace molecular gas associated with star formation on kiloparsec~~s~~ scales it is best to use the CO(1–0) transition instead of the CO(2–1) transition, because of the reduced radial gradient of the former (Crosthwaite & Turner, 2007). A large variation in the intensity ratio of the two transitions indicates the presence of widespread optically thin gas. ?

In a spiral galaxy such as NGC 6946, in the central part of the galaxy the total gas surface density is dominated by molecular gas (Crosthwaite & Turner, 2007). Further, the CO emission peaks ~~are~~ coincid~~ing~~e with high density peaks in H I, $H\alpha$ and FIR outside the nuclear region. The correlation between CO and FIR luminosities is a consequence of the fact that the FIR luminosity is dust-reprocessed light coming from young stars that have recently formed out of the molecular gas traced by CO (Leroy et al., 2005).

Unlike the 21 cm emission with respect to the H I column density, the CO luminosity is not directly proportional to the molecular gas surface density, hence the need for a conversion factor, also known as the $X_{CO}$ factor to estimate the molecular $H_2$ gas mass based on the CO emission. The Galactic $X_{CO}$ factor is $2 \times 10^{20}$ cm$^{-2}$ (K Km s$^{-1}$). However, the Galactic conversion factor will give correct results only for galaxies which have the same size CO cores as our own galaxy (Bolatto et al., 2008).

On the other hand, the $^{12}C^{16}O$ isotope, can only provide information on the conditions in the less dense~~r~~ outer regions of the molecular cloud because the cloud becomes optically thick. To peek into even higher–density molecular regions we need a different flavour molecule, the polyatomic ammonia molecule ($NH_3$). The inversion transition of ammonia produces microwave photons at a wavelength of 1.27 mm (Ho & Townes, 1983), which can be used to trace the dense molecular cloud regions.

Because the dust surface density is spatially correlated with the atomic and molecular gas (Roman-Duval et al., 2010), dust can also be used as a molecular gas tracer. Leroy et al. (2007a) mention among the advantages of using dust as a molecular gas tracer, the dust emission being optically thin, the dust abundance relative to atomic gas being directly measurable outside the GMC cloud and the $H_2$ molecule and the dust itself in the outer parts of molecular clouds being destroyed in similar quantities (Maloney & Black, 1988). Since, dust will be mixed also with the $H_2$ molecules surrounding the CO cores, it will be able to trace better the extent of the molecular gas disk, beyond the observed edge of the CO disk, which seems rather a detection limit than an actual threshold at least in NGC 6946 (Crosthwaite & Turner, 2007).

Dame et al. (2001) proved that the molecular gas estimation from dust and CO emissions agree well within our own Galaxy. The method (Israel, 1997; Dame et al., 2001; Leroy et al., 2007a) employed in obtaining the molecular gas map based on dust emission makes use of a FIR map, at 160 $\mu$m. At this wavelength, large dust grains in relative equilibrium with the interstellar radiation field achieve temperatures of several tens of degrees kelvin and emit in the far–infrared (Bolatto et al., 2007). The observed dust map combined with a fixed dust–to–gas ratio (which scales almost linearly with metallicity) measured nearby, but outside the molecular gas region of interest will yield the total gas map. Then subtracting from the total gas map, the atomic gas and the helium contributions we end up with a molecular gas map (Leroy et al., 2007a, 2011). One of the challenges of this method, though, is obtaining based on the 160 $\mu$m map a molecular map with a resolution comparable to the one derived from CO observations (Leroy et al., 2007a).

Another good tracer of molecular gas has proved to be the [C II] line. The available carbon atoms ionised by the ultraviolet photons and turned into C II, through fine structure splitting on impact with ambient hydrogen atoms radiate energy at the 158 $\mu$m wavelength, contributing in this way to the gas cooling process. The most important gas coolant however is CO trapping, because only the carbon atoms not locked in CO molecules can participate in the [C II] line emission. This line was first observed by NASA airborne platforms. The first time this line was observed outside our own Galaxy was in NGC 6946 by Madden et al. (1993) using NASA's Kuiper Airborne Observatory (KAO). They found that the [C II] emission peaks in the centre and follows the spiral arms of the galaxy. In a follow up article, Madden et al. (1997) confirm that the [C II] emission extends beyond the optical disk and the molecular disk traced by CO, while still correlating with high density H I. They conclude that although resolution only allows for global averages and although the [C II] line originating from both neutral and diffuse, partially ionised gas, this emission line has great potential in shedding some light into the mechanisms responsible for enhancing star formation. Significant improvements in resolution are already available through the coming online of the Stratospheric Observatory For Infrared Astronomy (SOFIA).

### 1.2.2.3 ~~From molecular phase to stars:~~ Star Formation Tracers

Although only part of the neutral gas turns molecular, once molecular the gas turns into stars at the same depletion time no matter the environment (Krumholz & McKee, 2005). Moreover, Rahman et al. (2012) find that the molecular gas depletion time is independent of both molecular and stellar surface densities and it does not correlate with either the effective Jeans time or the free fall time in the molecular regions. Their results confirm once more that GMCs turn their masses into stars at a constant rate irrespective of their local environments (Krumholz & McKee, 2005). Both dwarf and spiral galaxies exhibit the same relationship between star formation rate and molecular gas surface densities (Leroy et al., 2005).

Part of our star formation at larger scales investigation is also estimating the number of stars resulting in the star formation process, a quantity directly related to the neutral and molecular gas reservoirs available. To asses the rate at which different galaxies form stars we use star formation tracers, at wavelengths where young stars emit.

The $H\alpha$ emission was the first to be used for such a purpose and it traces massive, ionising stars, mainly grouped in OB associations (Kennicutt, 1983, 1988). The conversion from $H\alpha$ flux to star formation rate (SFR) was further developed by Kennicutt (1998) and more recently by Calzetti et al. (2007). The main caveat of this SF tracer lies in the fact that its luminosity is partly obstructed from our view by internal extinction (Cardelli et al., 1989). Some of the photons that would have otherwise travelled to us as $H\alpha$ carriers are absorbed by the dust particles along their way out of the galaxy being observed.

This must go back further than 1983.

And that it becomes hard/impossible to detect in outer disks because the disk puffs up and the Emission Measure of the HII region drops.

To overcome the internal extinction difficulties, a hybrid SF tracer was developed by Kennicutt et al. (2007). This hybrid uses $H\alpha$ luminosity to account for the young stars light and correct it for internal extinction by adding to it the mid infrared 24 $\mu$m emission representing the obscured light of the young stars re–radiated in the infrared bands.

Another ~~nowadays~~ common star formation tracer used today is the FUV emission. The advantage of this tracer over the traditional $H\alpha$ one and its hybrid flavours resides in the fact that, because it is emitted by lower mass young stars, a greater population than that of O,B stars, it ~~is~~ sampl~~ing~~es star formation ~~more extensively~~ over a longer time scale. GALEX UV data extends as far as the outskirts of big galaxies and inside the low density regimes, suggesting that SF is active in those environments as well (Boissier, 2008). This result encourages the ~~preferential~~ use of FUV rather than $H\alpha$ as a star formation tracer. The UV luminosity is dominated by the UV photons originating in the young star atmospheres, thus the star formation rate (SFR) in proportional to the UV flux, as long as the SFR is constant over a timescale of 100 Myr (Iglesias-Páramo et al., 2006).

Why? Since extinction increases with decreasing λ.

Similar, but not as severly as $H_\alpha$, the FUV emission also suffers from internal extinction. Leroy et al. (2008) came up with a hybrid as well, one where FUV emission is combined with the mid infrared 24 $\mu$m emission such that both the obscured and unobscured emission from the young stars are accounted for.

The discovery that obscured light from young stars is traced by infrared emission, set the stage for a new category of star formation tracers, one entirely based on mid–infrared band~~s~~ emission. Star formation rate (SFR) correlates with 24 $\mu$m emission representing re–processed light from young stars (Calzetti et al., 2005; Pérez-González et al., 2006). On the other hand, 8 $\mu$m emission comes from polycyclic aromatic hydrocarbons (PAHs), very small dust grains ~~which~~ that when heated by single UV and optical photons, emit in the mid–infrared. In a more in depth study Calzetti et al. (2007) investigate the accuracy of the mid–infrared bands 24 $\mu$m and 8 $\mu$m in tracing the star formation rate (SFR) in a sample of 33 nearby galaxies and find that in high metallicity galaxies the 24 $\mu$m emission alone is a robust SF tracer even though its correlation with $Pa_\alpha$ is not linear, however the 8 $\mu$m emission depends strongly on environment, metallicity and star formation history.

Explain that $Pa_\alpha$ is a tracer of HII but is in NIR so not has heavily affected by extinction as $H\alpha$. Otherwise point here is lost.

The source of radio emission in normal galaxies is mostly ~~originating from~~ the synchrotron emission of supernova remnants and the radio thermal (free–free) emission of H II regions. According to Condon (1992) and Murphy et al. (2011), both supernova remnants and H II regions are related to massive stars that turn into supernovae or ionise the H II regions. Therefore, the radio emission in itself traces massive star formation and implicitly recent star formation activity. The advantages of radio observations are the pointing accuracy, the resolution, the transparency to the "burst" type events when flux intensities are proportional to luminosities and last but not least the fact that they are not contaminated by the contribution of older populations of stars (Condon, 1992). Adding ~~to the above~~ that radio observations do not suffer from the complications of extinction, the radio emission is one of the most promising SFR tracers. When observing below 30 MHz in frequency, the free–free emission from the H II regions, where massive stars are still ionising their surrounding, is very weak. The radio emission is dominated by synchrotron radiation coming

Reference Volker paper.

from electrons that have outlived the supernova remnants that they originated from. Yet the tight correlation between the FIR and the radio luminosities (de Jong et al., 1985; Helou et al., 1985) provides the necessary constraints for relating radio emission to massive star formation. When observing at higher frequencies, above 30 MHz, the radio emission becomes dominated by free-free emission from H II regions which can be directly related to the ionised photon~~s~~ rate coming from young massive stars (Condon, 1992). Radio emission as a SFR tracer is a recent development in the field, and is being explored for dwarfs by Volker + Zed. ~~an avenue worth exploring a direction where more refinement will bring interesting results.~~

Another method of determining the SFR without uncertainties due to internal extinction is by measuring the X–ray emission of a galaxy, which according to Fabbiano (2006), ~~prevalently~~ preferentially comes from X–ray binaries (XRBs). Within the X–ray binary population, the low mass X–ray binaries (LMBXs) represent the old star population while the high mass X–ray binaries, with lifetimes of ≈ $10^7\,yr$, represent the young stellar population~~,~~ and thus can be used as a SF tracer. The correlation between SFR and X–ray luminosity of a galaxy has been established by Grimm et al. (2003), then Persic & Rephaeli (2007) and further refined by Mineo et al. (2011, 2012). Today's attainable resolution allows the study of X–ray source populations of luminosities comparable to the Galactic X–ray binaries and up to a distance of 30–40 Mpc (Fabbiano, 2006; Mineo et al., 2011). Apart from resolution, using X–ray sources, more precisely HMXBs as a SF tracer, poses the problem of differentiating between the HMXBs contribution to the X–ray luminosity and the LMXBs contribution, since the latter is unrelated to the star formation activity (Mineo et al., 2011, 2012).

How do you deconvolve?

### 1.2.3 Star Formation in Dwarfs vs. Spirals

Does star formation proceed in the same way in all galaxies, no matter their size and type? Spiral galaxies for example, have spiral arms which dictate where most of the star formation sites will be and also ~~help~~ re–shuffl~~ing~~es gas, in this way increasing the star formation efficiency (SFE). Once it became established that massive star formation rates in irregular galaxies are comparable to those in spirals (Hunter et al., 1982) and spiral density waves are not necessary for forming massive stars (Elmegreen & Elmegreen, 1986), dwarf irregulars came to be seen as interesting environments for investigating star formation mechanisms and triggers. Consequently,

There is some stuff here, especially sections 1.2.3.2 + 1.2.3.3, that is repetitive with previous sections. I would make these sections, which are dwarf-specific, tighter so the reader can see where you are going. Put non-dwarf specific stuff back in those earlier sections.

a multitude of questions arose such as how giant cloud complexes and stars form at all in ~~sub-critical~~ low density gas of dwarfs and to what extent ~~turbulence~~ different processes ~~contributes~~ contribute to SF in these environments (Struck & Smith, 1999; Boissier, 2008; Ostriker et al., 2010; Walch et al., 2011).

### 1.2.3.1 Star Formation ~~Scenarios~~ Histories

According to Martín-Manjón et al. (2012) three fundamental star formation history scenarios can be formulated for dwarf galaxies: **bursting SF**, where stars form in short but intense episodes separated by long quiescent periods of time (Tosi et al., 1991; Bradamante et al., 1998), **gasping SF**, where stars form in long but moderate in intensity episodes separated by short quiescent times (Tosi et al., 1991; Recchi & Hensler, 2004) and finally **continuous SF**, where SF takes place continuously, at low intensity with sporadic small bursts (Legrand et al., 2000). Among these three, dwarf irregular galaxies are best described as having gasping or bursting SF (Tosi et al., 1991; Gallagher et al., 1996), the main difference between these two scenarios being that chemical enrichment of the interstellar medium takes place gradually for the gasping SF scenario and on a time scale of a few tens of millions of years for the ~~gasping~~ bursting SF scenario. Boissier (2008) find evidence of a lower star formation efficiency in low surface brightness (LSB) galaxies and favour the idea that the star formation history of these galaxies is most probably characterised by periods of intense bursts in SF followed by longer quiescent phases. Distinguishing between SF scenarios has the additional difficulty that our observations sample different phases/ times in the SF cycle of the targeted galaxies. Martín-Manjón et al. (2012) find evidence that different star formation scenarios correspond in fact to different phases of the star formation cycle.

Need to explain what LSB galaxies are, ≠ dwarfs.

Don't understan

~~No need to say that~~ In galaxies like dwarf irregulars, where there ~~is~~ are no spiral ~~structure~~ density waves, it is very difficult to pinpoint ~~how exactly~~ the regulatory process ~~takes place~~. The degree of regulation in the global SFR of dwarf irregulars ~~will~~ can not be due to environment (Hunter & Elmegreen, 2004), so could only be due to one or more of the following: gas ~~content~~ kinematics and distribution, structural properties or ~~internal~~ feedback processes ~~such as feedback from massive stars~~ (Lee et al., 2007). On the other hand, McQuinn et al. (2009) entertains the possibility that star formation propagates through the galaxy independently.

Independent of what?

#### 1.2.3.2 Molecular Gas Phase in Dwarfs

Some of this is repetitive with an earlier section.

Whether in a dwarf or a spiral, a molecular gas cloud is bound to collapse and form stars at an approximately constant rate, regardless of their host environment (Krumholz & McKee, 2005). In a study of the molecular gas in the low metallicity dwarf galaxy IC 10, Leroy et al. (2006) finds that the GMCs in this galaxy are undistinguishable from the GMCs from spiral galaxies such as M 31 and M 33. They also find that the GMCs in IC 10 are always associated with high density atomic gas. In this way, H I is necessary, but not sufficient for molecular clouds formation.

After adjusting $X_{CO}$ for metallicity?

Not following this.

Although irregular dwarf galaxies have impressive H I reservoirs, this does not drive the SFRs higher than in spiral galaxies. In other words, the H I emission it is not a tracer of the molecular gas fraction (Leroy et al., 2006). The molecular gas fraction (as inferred from CO luminosity) in a dwarf irregular galaxy is ten times lower than in spirals. Pelupessy et al. (2006) find that in these systems, where CO is often not detected, the upper limit of the molecular hydrogen fraction is 1%. They also note that in such systems the neutral to molecular gas transition takes place at higher densities (n= $100\,\mathrm{cm^{-3}}$), which consequently increases the molecular fraction by a factor of 2-5. In a follow up paper Pelupessy & Papadopoulos (2009) argue that in metal poor systems where the higher density of the gas deep within the CNM cloud makes up for the diminished dust quantity employed as a catalyst in the molecular gas formation, the star formation is more efficient per CO-rich $H_2$ mass.

According to Walch et al. (2011), gas metallicity has a dominant influence on the formation and survival of stable molecular cloud cores, without which star formation would effectively be inhibited. In other words, Walch et al. (2011) model the effects of metallicity on SFR and find that in the low metallicity regime of dwarfs star formation can only proceed if a strong turbulence driver is also present. Moreover in dwarf galaxies, the compact cold cores of the GMCs are surrounded by a large fraction of $H_2$ gas which self-shields meanwhile the CO molecule dissociates (Maloney & Wolfire, 1997). As metallicity decreases, the molecular clump does not change its size, but the CO emitting core does (Bolatto et al., 2008). Wong et al. (2009) found in the LMC, bright H I emission either adjacent or coincident to CO emission. This certainly seems to be the case of IZw18 a galaxy with active star formation, but low CO content (Leroy et al., 2007b). In other words if in spiral galaxies CO can be used as a tracer for molecular gas, in dwarf galaxies this becomes a difficult matter. Not only the CO molecule dearth (as a direct consequence of low metallicity) poses a problem for its detection, but also if observed the conversion of the CO luminosity into a molecular gas mass becomes uncertain as it will inevitably depend on metallicity.

In a study of the LMC, Wong et al. (2009) discuss the reasons behind a poor correlation between H I and CO emissions: (1) partial depletion of H I ~~as is currently converted~~ by conversion into $H_2$; (2) flaws in the assumption that CO and H I trace molecular and atomic column densities faithfully and (3) volume density ~~and~~ not being represented by column densities ~~of H I are decoupled~~ of HI. According to Leroy et al. (2005), in dwarf galaxies the CO luminosity is most strongly correlated with the K–band and the far–infrared luminosities most probably due to the fact that the stellar component drives the pressure and density of the atomic gas, controlling in this way the molecular hydrogen formation.

In this context, CO becomes a poor and non linear tracer of the molecular hydrogen gas distribution suggesting that in dwarf galaxy environments certain epochs of their evolution such as immediately after a burst of star formation, are "CO dark" (Pelupessy & Papadopoulos, 2009). Leroy et al. (2011) found that CO dark gas becomes an important component of the gas mass, in the metallicity range 12+log(O/H) $\approx 8.2 - 8.4$. Dust extinction is the main parameter influencing the fraction of CO dark gas (Wolfire, 2010). This missing CO dark component might solve the discrepancy between the molecular gas mass inferred from the CO luminosity and the one inferred from dust mass estimations. The CO dark component can be inferred from the difference between the molecular gas mass from dust and the one estimated based on the CO luminosity. Such a procedure however brings us back to the problem of a metallicity dependent CO conversion factor.

It is quite possible that in low metallicity galaxies [C II] or far–infrared emission trace molecular gas better than CO (Madden et al., 1997). Observing the [C II] line in the dwarf irregular IC 10, Madden et al. (1997) find that the [C II] surface density correlates with the H I and CO peaks and that the [C II]/ CO intensity ratio is higher than in normal metallicity galaxies. This higher [C II]/CO intensity ratio has also been observed in the LMC (Poglitsch et al., 1995), SMC (Israel et al., 1996) and a number of other irregular galaxies (Jones et al., 1997). In a low metallicity environment, the dust quantity necessary to ensure the availability of enough carbon atoms to form CO cores, and the dust necessary to maintain the shielding of such cores will control the [C II]–to–CO ratio. Since the CO cores are small, the free carbon atoms will prevail, amounting to a higher contribution in the gas cooling process and also shining at the 158 $\mu$m wavelength in the process. The resolution available for [C II] line observations remains an issue, especially in these low surface brightness galaxies. Why?

I found this section harder to follow than previous ones. It would help to begin with a statement that we know stars form from molecular clouds, so what about molecular gas in dwarfs. Then ~~[illegible]~~ end this section with ~~something about~~ what you have but maybe explicitly say you cant count on knowing about molecular gas ~~to~~ in dwarfs.

We already know that the molecular hydrogen is more extended than CO, and the dust is mixed in with both the molecular hydrogen and CO dominating regions. Therefore if the dust is warm enough to emit in the far–infrared it will trace molecular gas better than CO (Leroy et al., 2007a). Moreover, Roman-Duval et al. (2010) interpret the excess of FIR emission with respect to the total gas surface density traced by CO and H I as indicating the presence of molecular hydrogen not traced by CO in the envelope of the molecular cloud. However, they also find that at low surface densities the dust to gas ratios are less certain because of the offset between the dust and H I surface densities maps. ?

I don't know if you referenced them earlier, but Bolatto et al have shown FIR as tracer of CO in LMC + Verdugo (Celia) has done the SMC (but not published yet, I think).

In other words, observing molecular gas in low metallicity environments becomes very difficult, when we loose confidence in both CO as a tracer and dust–to–gas ratios as means of converting the dust map into a total gas map. Moreover Leroy et al. (2007a) found that the SMC, for example, emits more at submillimeter and millimeter wavelengths than would be inferred from the FIR emission assuming Galactic dust, suggesting that the most probable cause for this long–wavelength emission is a different grain emissivity law than the Galactic one. In such a context, extending our knowledge from the solar metallicity to the low metallicity regime implies weighing our assumptions very carefully.

belongs earlier

other ideas, not yet resolved

The submm excess? Reference Madden papers. See, for example, the APEX LABOCCA proposals or JCMT.

### 1.2.3.3 The Star Formation Tracers in Dwarfs

When it comes to star formation tracers, dwarf irregular galaxies stand out once more. Lee et al. (2009) find that in low luminosity dwarf galaxies, the total SFR based on $H\alpha$ as a star formation tracer is lower than the total SFR based on FUV. The authors discuss different possible causes, ruling out metallicity as acting in the opposite direction than the observed trend, photon leakage as inhibited by the big H I envelopes of dwarf galaxies and stochasticity in the high mass star formation at low star formation rates as having an effect not large enough to match observations. They conclude that the following two causes are more likely to explain the discrepancy. As dwarf galaxies go through bursty episodes of star formation, one could imagine that the high mass stars will disappear a lot earlier than the low mass ones, so if observed in this post-starburst period of time a dwarf galaxy would be deficient in $H\alpha$ compared to FUV. Therefore, for lower than 0.01 $M_{\odot}\,yr^{-1}$ SFR, FUV is recommended as a SF tracer rather than $H\alpha$ ~~is recommended~~ (Lee et al., 2009). At the same time $H\alpha$ as a star formation indicator relies on highly luminous massive stars, which

Issue of IMF as cause of FUV/Hα: Wherever we can count stars, the IMF is the same. There are other reasons, more likely, to cause loss of Hα. See ~~[illegible]~~ Hunter et al, in prep (I'll send it to you) + Thilker et al 2005, 2007; Boissier et al 2007; Melena, et al (2009, AJ, 138, 1203).

Only in absolute #, not relative.

are rarer in dwarf galaxies than in big galaxies and in such a case the form of the IMF may also play an important role. Also Boissier et al. (2008) claims a steeper IMF favouring the formation of less massive stars, in low mass surface brightness galaxies would explained the observed redder FUV–NUV.

When turning from star formation tracers such as FUV and $H_\alpha$, we find that decreasing metallicity poses problems also to infrared emission tracers. Dust properties in dwarf galaxies are distinct from those of spiral galaxies resulting from a combination of factors such as harder radiation fields, more compact structure, different composition, different heating mechanism and different distribution of dust in the interstellar medium (Rosenberg et al., 2008). Further, these authors show that these properties combined with the difference in the shape of the Mid–Infrared continua in dwarfs with respect to spirals result in a true difficulty in using infrared measurements as star formation tracers for measuring the SFR in dwarf galaxies. Also, Calzetti et al. (2010) find indications that the 160 $\mu$m maps are contaminated with dust heated by stellar populations that do not currently participate in the SF process, which confirms the general expectations that as metallicity goes down and galaxies become more transparent, the infrared becomes a poor star formation tracer.

### 1.2.4 Star Formation Laws

To describe how efficiently gas is turned into stars, Schmidt (1959) used a power law to relate the volume density of the interstellar neutral gas in a region of the Galaxy with the number of stars formed there per unit time and volume. Estimating total gas volume densities wasn't in any way trivial, therefore only when Buat et al. (1989) suggested using surface densities instead of volume densities did this direction of research start flourishing. This relation, $\Sigma_{SFR} \propto (\Sigma_{gas})^N$ was called the Star Formation law (SF law) or the Kennicutt-Schmidt law (K-S law), acknowledging the extensive work done by Kennicutt in this field (Kennicutt, 1983, 1988, 1998; Kennicutt et al., 2007).

Although the power law form of the SF law originated from a logical association between the number of stars observed and the gas, the fuel available for forming them, there are physical reasons to expect such a relationship. Coming back to the mathematical formula of the SF law above lets consider different possibilities to express the gas surface density term and see how the power law index changes. For an individual ~~giant molecular cloud~~ ~~(~~GMC~~)~~ the power law index is $N \approx 0.75$, whereas for a uniform population of GMCs $N \approx 1$ (Krumholz & McKee, 2005). Theoretically we expect that, if the determining SF process is gravitational instability in the total gas with a constant scale height, then $N \approx 1.4$, whereas if it is fundamentally collisional $N \approx 2$ (Bigiel et al., 2008). These theoretical expectations are in the range of the observationally derived values.

Early on, the gas density was represented by atomic gas only. Later, Kennicutt (1989), using a sample of disk galaxies, quantified the ~~star formation rate~~ (SFR) using $H\alpha$ as a tracer and related it to a gas density that for the first time also included molecular gas. In their extensive work, Kennicutt (1989, 1998), computed a power law index $N \approx 2.47 \pm 0.39$ for normal spiral galaxies and $N \approx 1.40 \pm 0.15$ for a mixed sample of galaxies. As the technical advances allowed more and more accurate molecular gas observations, it became obvious that SFR and molecular gas surface densities were more closely correlated than SFR and total gas surface densities and that there was no strong correlation between SFR and atomic gas surface densities (Kennicutt et al., 2007; Bigiel et al., 2008). By then, this area of research had evolved considerably from the traditional study of the SF law as a globally averaged relationship (Kennicutt, 1989, 1998), to a more recent direction, the investigation of this relationship on a spatially resolved basis investigating the SF law in kpc-size regions within galaxies. (Leroy et al., 2008; Bigiel et al., 2008, 2010b; Leroy et al., 2012).

Bigiel et al. (2008), using a large sample of THINGS spiral galaxies, concluded that there is a one to one relationship between the SFR surface density and the molecular gas surface density in other words. This relationship is now known as the molecular star formation law. In a follow up work, ??, extends his sample to 30 disk galaxies and confirms his previous results ~~which relate the SFR surface density with the molecular gas surface density~~ through a power law with index number $N \approx 1.0$. Using the $24\,\mu$m emission in a sample of nearby infrared–bright galaxies as a star formation indicator, Rahman et al. (2012) also confirm previous results by computing a power law index for the molecular SF law of $N \approx 0.96 \pm 0.16$. The linearity of molecular SF law confirms the theoretical scenario of Krumholz & McKee (2005): no matter the environmental parameters the GMCs will turn their masses into stars. Blanc et al. (2009), employs an innovative method of creating a SFR map based on integral field unit (IFU) spectroscopy in NGC 5194 and find that while SFR surface density correlates well with molecular gas surface density, the SFR and atomic gas surface densities are uncorrelated, confirming once more the Bigiel et al. (2008) results, ~~In which regards the SF slopes they find agreement with Bigiel et al. (2008);~~ but disagree ing with Kennicutt et al. (2007). However, Crosthwaite & Turner (2007) find

I found this page through middle of next page a little hard to follow — molecular + HI law and global + resolved studies are intertwined. Maybe you could discuss global 1st + then resolved + how those are different. Or HI + then just one paragraph on molecular law.

total = HI + $H_2$
This is also back to global quantities?

evidence in the spiral galaxy NGC6946, for a more closer relationship between SFR and total gas surface densities, rather than a simple confirmation of the molecular star formation law. A similar situation is described by Schuster et al. (2007) in M 51 (NGC 5194), where the correlation between SFR and total gas surface densities is strongest and it follows a Schmidt law with an index of $N \approx 1.4 \pm 0.6$.

Because star formation occurs almost everywhere H I is observed (Bigiel et al., 2010a), the search for a star formation law ~~has also~~ been extended to THINGS dwarfs and the outskirts of spiral galaxies. In these environments, (Bigiel et al., 2010b) finds a clear relationship between atomic gas and star formation surface densities and compute for this relationship a power law index close to 1.7. They also find that dwarf galaxies tend to have higher H I column densities than spirals. In a study of star formation in extreme dwarfs, Roychowdhury et al. (2011) also find a clear relation between SFR and atomic gas surface densities. According to Bigiel et al. (2011), the $\Sigma_{SFR} - \Sigma_{gas}$ parameter space is populated differently depending on the host environment. The strength of the correlation between star formation rate and molecular gas surface densities holds throughout the inner and outer parts of big galaxies (Schruba et al., 2011) as well as in dwarfs such as the SMC (Bolatto et al., 2011). However the correlation between SFR and atomic gas surface densities switches on in low metallicity regimes only, suggesting that H I surface density plays an important role in driving star formation at large radii (Bigiel et al., 2011). Consequently, there is no wonder that the K-S law shows a strong dependence on the dust–to–gas ratio and a less strong dependence on FUV flux (Gnedin & Kravtsov, 2011).

Specifically what is seen concerning the dust/gas + K-S?

In Section 1.2.3, we have already mentioned the result of Leroy et al. (2006) who find that the GMCs in IC 10 are associated with high density H I clouds mostly above 10 $M_\odot$ pc$^{-2}$. Also, Bigiel et al. (2008) find that for spiral galaxies in their sample the transition point where atomic hydrogen turns molecular is always 10 $M_\odot$ pc$^{-2}$. In dwarfs however this turnover has a higher value (Roychowdhury et al., 2011; Leroy et al., 2011). This difference between spirals and dwarfs is directly linked to the metals availability, which dwarfs have to compensate for by achieving higher atomic gas densities in order to protect the molecule formation from photodissociation (Krumholz et al., 2009, 2011).

Roychowdhury et al. (2011) discuss the possible causes of the discrepancies between the $H\alpha$ based and FUV based SFR surface densities, in a sample of 23 dwarf galaxies, and although they are not able to explain such discrepancies they do find evidence which correlates them to high neutral gas surface densities. High H I column densities, higher than $10\,M_{\odot}\,pc^{-2}$, occur in galaxies where the ratio between the $H\alpha$ based and FUV based SFR surface densities is greater than one, suggesting that massive SF takes place in high column density gas (Roychowdhury et al., 2011).

What turnover?

A low metallicity regime automatically implies a low dust column regime. Therefore, if the turnover is correlated with metallicity as found by Krumholz et al. (2009, 2011), it is not very surprising that the turnover in the K–S law relating SFR and total gas surface densities is dominated by the dust–to–gas ratio (Gnedin & Kravtsov, 2011).

Another interesting aspect of the K–S relation is its correlation with the stellar mass. In a comprehensive study of the relationship between SFR and gas surface densities as a function of stellar mass at sub–Kpc and Kpc scales, Rahman et al. (2012) find that there are no strong correlations between the stellar masses and either the molecular SF law power–law index or the molecular SF law normalization. On the other hand, Shi et al. (2011) find a tight correlation between SFE and stellar mass surface density, name it the Extended Schmidt Law and interpret it as proof for the important role existing stars play in the SF activity continuity.

Are existing stars a more efficient predictor for star formation (SF) than H I column density thresholds? The mechanism through which stars intervene in the SF scenario is not well understood. Whether they are driving the mid–plane pressure (Leroy et al., 2005), increasing the turbulence to compensate for decreasing metallicity (Walch et al., 2011), inducing star formation by controlling the local gas density and the gas re-shuffling mechanism (Dopita et al., 1985; Brinks et al., 1990; Dolphin & Hunter, 1998) or an environment dependent combination of the above, a clear link between the existing stars and the future generations of stars is still elusive. We do know that previous neutral hydrogen (H I) and optical observations of dwarf irregulars showed a better correlation between the star formation rate (SFR) and the *V*–band surface brightness than any other measure (Hunter et al., 1998; Hunter & Elmegreen, 2004; Shi et al., 2011).

## 1.3 Motivation