Physics of galaxies: some basis

I: Galactic (Chemical) Evolution; introduction, examples, abundance measurements, definitions, IMF, SFR, returned fraction.

II: Star Formation Laws; threshold, resolution effects, star formation laws, state of the art of observations, gas measurements.

III: Outskirts of galaxies: truncations, anti-truncations, XUV disks, HI, CGM, shells, ...

Samuel Boissier,
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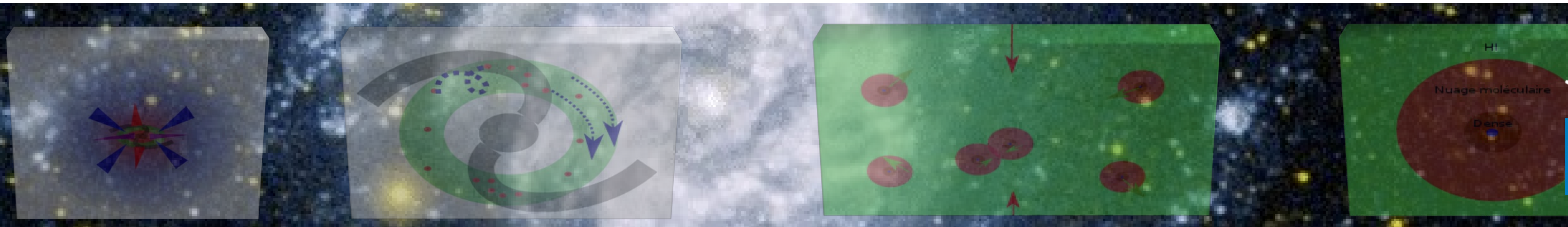
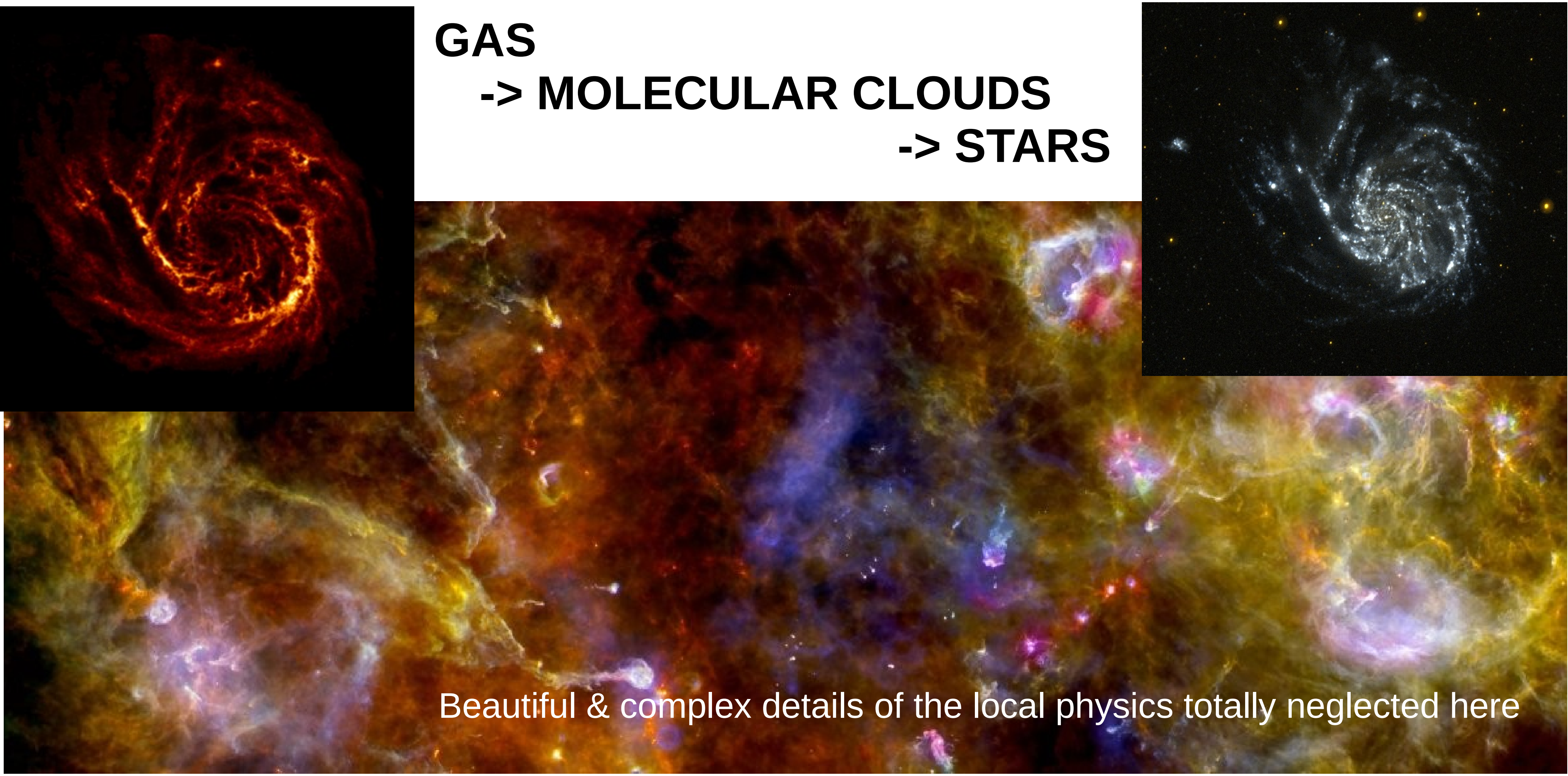
Galaxies, Etoiles et Cosmologie group



GAS
-> MOLECULAR CLOUDS
-> STARS



Beautiful & complex details of the local physics totally neglected here

1) Are there conditions to start the process ?

2) What determine the Star Formation Rate on galactic scales?

STAR FORMATION LAWS

a) Threshold theories
b) Influences on SF
c) The scales
d) Observational state of the art
e) Measurements : gas
f) SFR – Z – M* relation

Some References

- Kennicutt (1998): ARAA
- Leroy et al. (2008), Bigiel et al. (2008)
- Kennicutt, Evans (2011)
- Boissier (2013): “Star Formation in Galaxies”
  http://adsabs.harvard.edu/abs/2013pss6.book..141B
  Preprint (not to be distributed) : ask me
- Book: “A panchromatic view of Galaxies”, Boselli
- Review Krumholz (2014) : arxiv:1402.0867

STAR FORMATION LAWS

a) Threshold theories

The Toomre (1964) parameter

Stability of a stellar disk

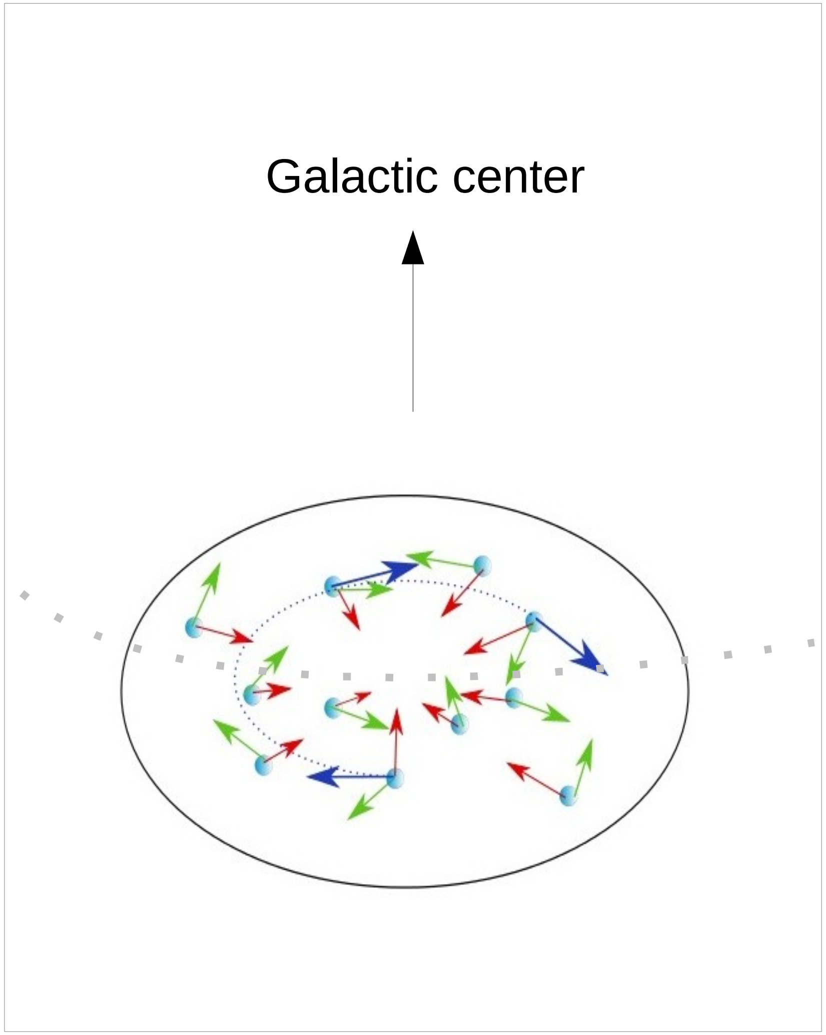
$$Q_* = \frac{\sigma_* \kappa}{3.36 G \Sigma_*}.$$

Stability of a gaseous disk

$$Q = \frac{\sigma_{gas} \kappa}{\pi G \Sigma_{gas}}.$$

Gaseous + stellar disk

$$Q \simeq \frac{\sigma_{gas} \kappa}{\pi G \Sigma_{gas}} \left(1 + \frac{\Sigma_* \sigma_{gas}}{\Sigma_{gas} \sigma_*}\right)^{-1}.$$

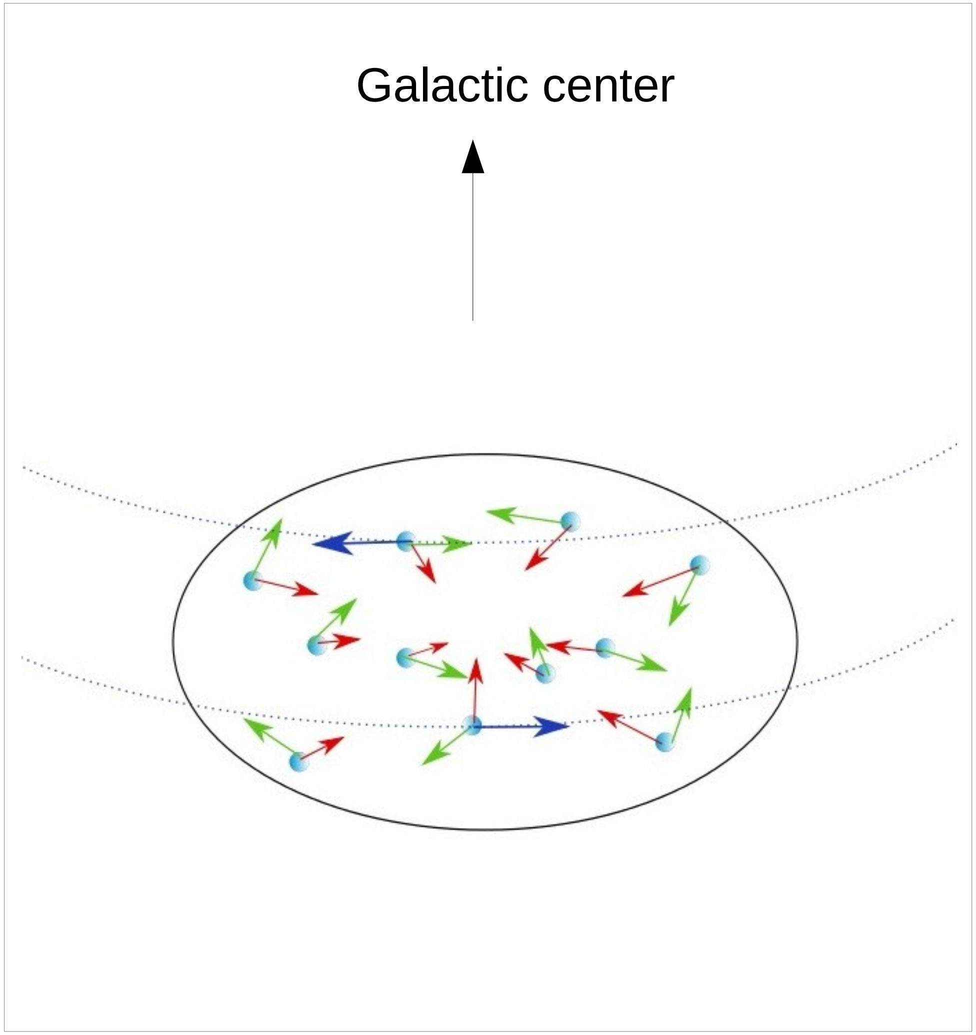


Q=1 defines
a “**critical density**”
Σcrit

Shear threshold

$$Q_A = \frac{2.5\sigma_{gas} A}{\pi G \Sigma_{gas}},$$

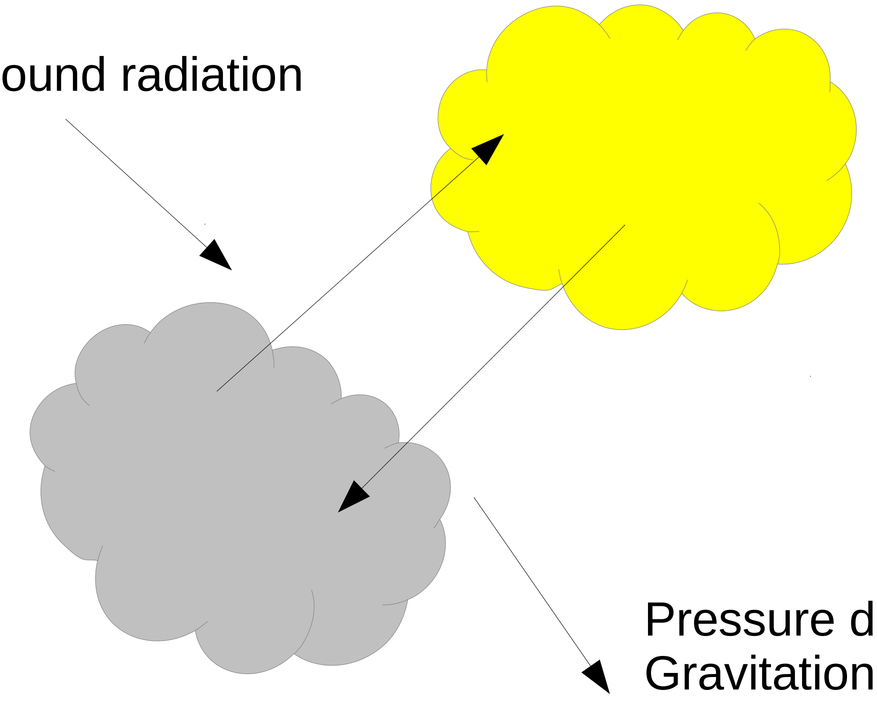
$$A = 0.5R\frac{d\Omega}{dR}.$$



Hunter et al., (1998)
Seigar (2005)

Phase transition threshold

`Schaye (2004)`



WARM PHASE

UV background radiation

Pressure drops
Gravitational instability

COLD PHASE

Minimum density
Is needed to form
a cold-phase → Threshold in surface density for the outer edge of star formation

$$\begin{aligned}\log N_{\rm H}(T=500\ {\rm K}) \approx\ & 20.75 + 0.29\log(f) + 0.0052\log^2(f)\\ & - 0.32\log(Z/0.1\ Z_\odot) - 0.047\log^2(Z/0.1\ Z_\odot)\\ & + 0.23\log(I/10^6\ {\rm cm^{-2}\ s^{-1}})\\ & + 0.027\log^2(I/10^6\ {\rm cm^{-2}\ s^{-1}}). \qquad (23)\end{aligned}$$

STAR FORMATION LAWS

a) Threshold theories

b) Influences on SF

SF influences: theories

$$\Sigma_\psi = \epsilon \frac{\Sigma_{gas}}{\tau}$$

Madore : **free fall** time prop to rho**-0.5
Constant scale height ΣGAS**1.5

Hydrostatic Equilibrium

$$h = \frac{\sigma_{gas}}{\pi G}\left(\frac{\Sigma_{gas}}{\sigma_{gas}} + \frac{\Sigma_*}{\sigma_*}\right)^{-1}.$$

$\tau \propto \rho_{gas}^{-0.5}$ with $\rho_{gas} = \Sigma_{gas}/2h$, leading to

$$\Sigma_\psi \propto \frac{\Sigma_{gas}^2}{\sigma_{gas}}\left(1 + \frac{\Sigma_*}{\Sigma_{gas}}\frac{\sigma_{gas}}{\sigma_{*,z}}\right)^{0.5}$$

Possible influence of Stellar density
(Dopita & Rider, 2004; Abramova & Zasov 2008)

Larson 92: timescale set by
Equilibrium between
dispersion & gravitation

$$\tau \propto \frac{\sigma_{gas}}{\pi G \Sigma_{gas}}.$$

nstant, the star f

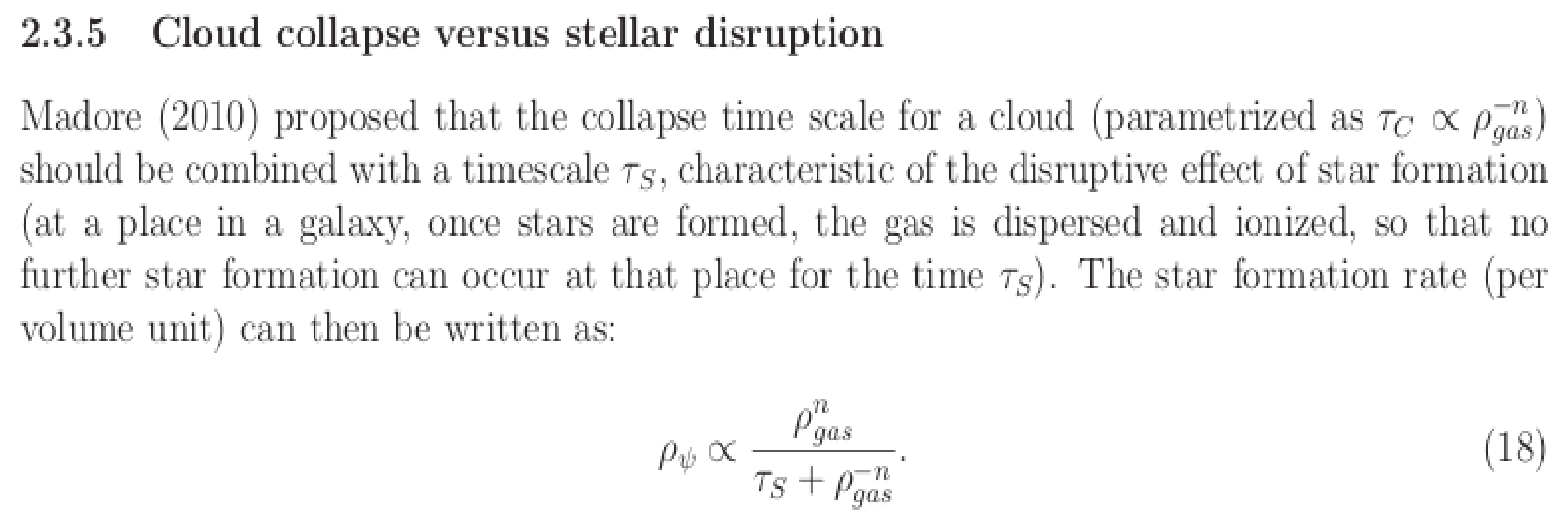
$$\Sigma_\psi \propto \Sigma_{gas}^2.$$

SELF REGULATION
Q=1

$$\Sigma_\psi \propto \Sigma_{gas}\kappa.$$

$$\kappa = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)^{0.5}.$$

Note: For flat R.C.:
κ -> Ω
Same as for Qshear!

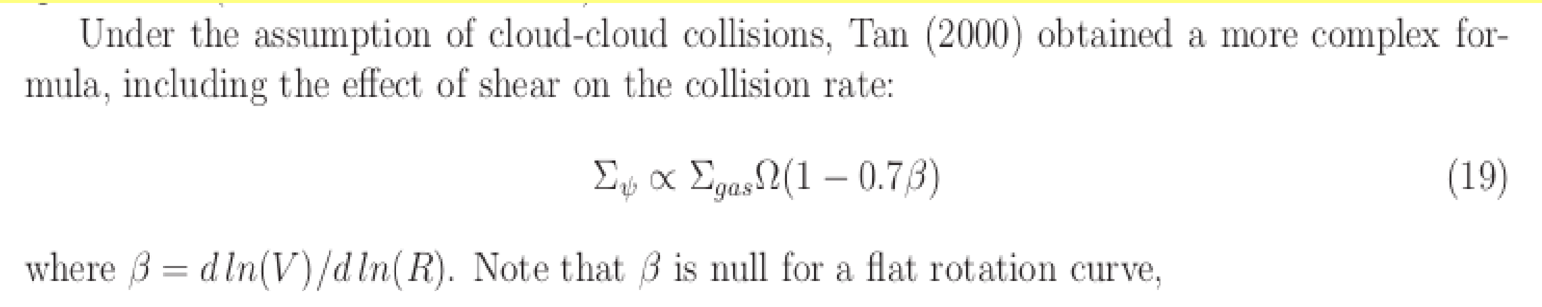


2.3.5 Cloud collapse versus stellar disruption

Madore (2010) proposed that the collapse time scale for a cloud (parametrized as $\tau_C \propto \rho_{gas}^{-n}$) should be combined with a timescale τ_S, characteristic of the disruptive effect of star formation (at a place in a galaxy, once stars are formed, the gas is dispersed and ionized, so that no further star formation can occur at that place for the time τ_S). The star formation rate (per volume unit) can then be written as:

$$\rho_\psi \propto \frac{\rho_{gas}^n}{\tau_S + \rho_{gas}^{-n}}. \tag{18}$$

Cloud-cloud collisions



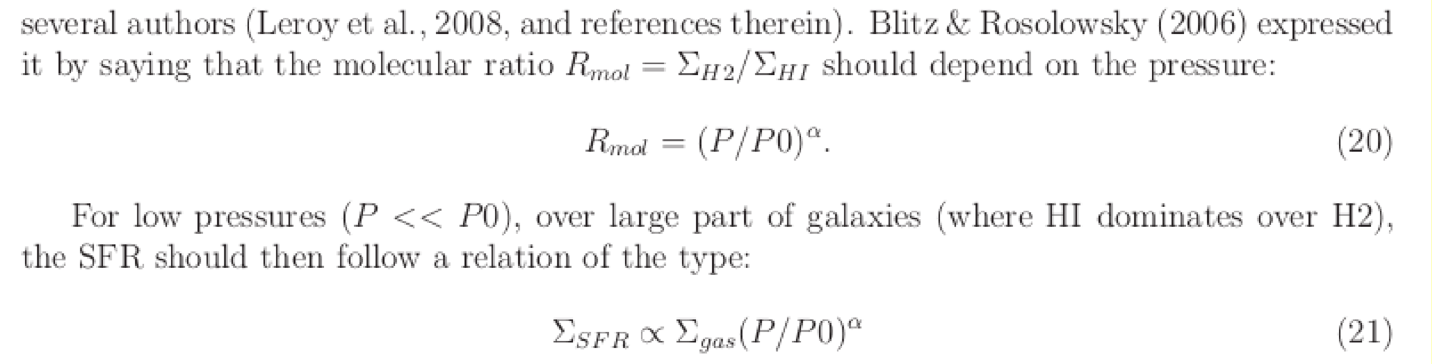
Under the assumption of cloud-cloud collisions, Tan (2000) obtained a more complex formula, including the effect of shear on the collision rate:

$$\Sigma_\psi \propto \Sigma_{gas}\Omega(1 - 0.7\beta) \tag{19}$$

where $\beta = d\,ln(V)/d\,ln(R)$. Note that β is null for a flat rotation curve,

Or
ΣGAS**2

Role of the molecular fraction



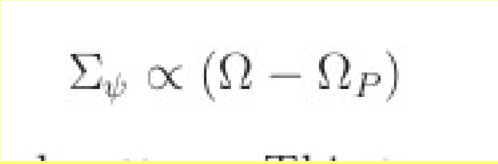
several authors (Leroy et al., 2008, and references therein). Blitz & Rosolowsky (2006) expressed it by saying that the molecular ratio $R_{mol} = \Sigma_{H2}/\Sigma_{HI}$ should depend on the pressure:

$$R_{mol} = (P/P0)^{\alpha}. \tag{20}$$

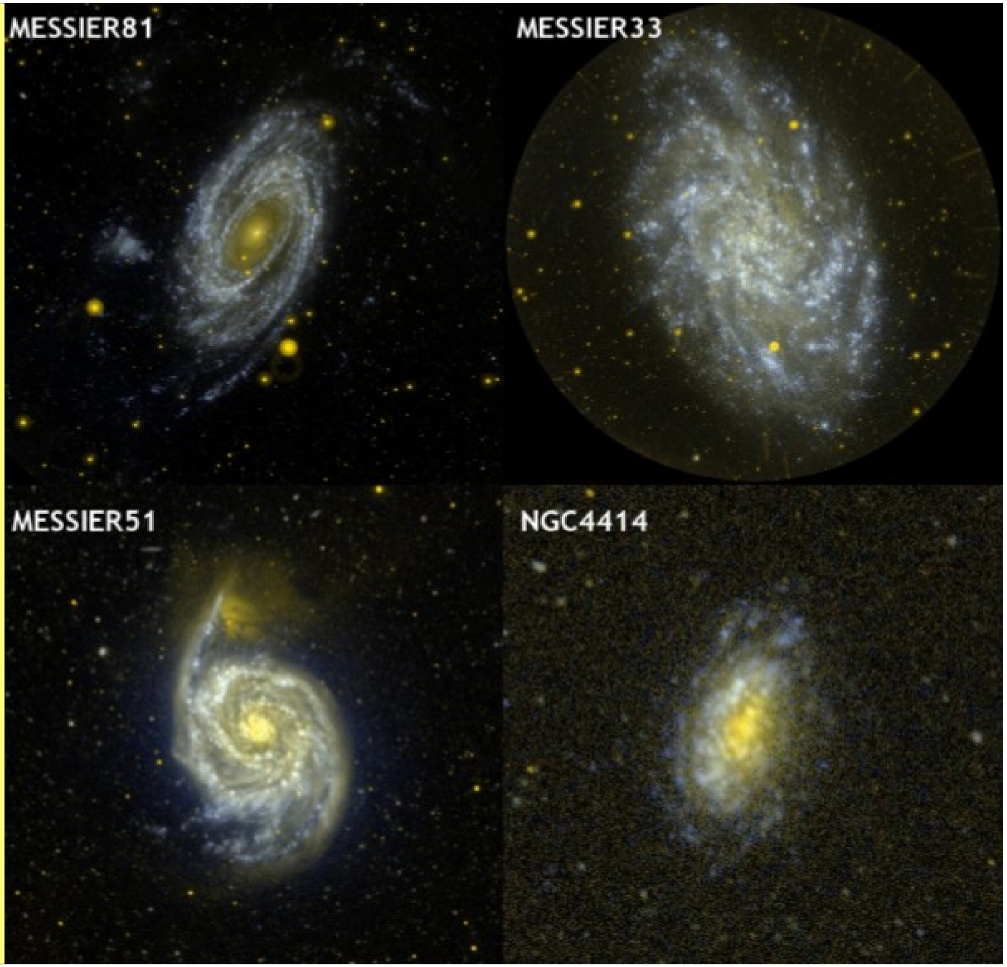
For low pressures ($P << P0$), over large part of galaxies (where HI dominates over H2), the SFR should then follow a relation of the type:

$$\Sigma_{SFR} \propto \Sigma_{gas}(P/P0)^{\alpha} \tag{21}$$

Role of spiral arms



$$\Sigma_{\psi} \propto (\Omega - \Omega_P)$$

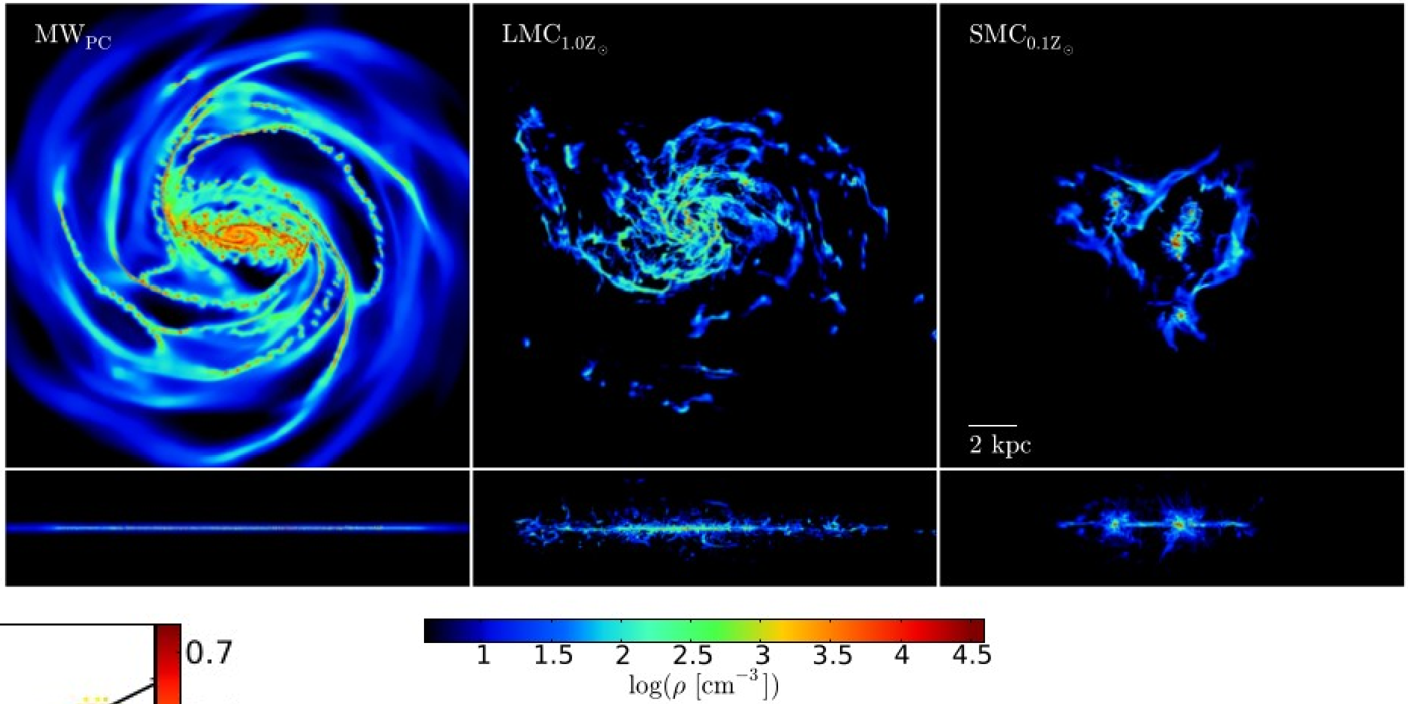


GALEX UV images of nearby spirals

The role of turbulence ?

- Kraljic, Renaud, Bournaud et al. 2014
- Renaud, Kraljic, Bournaud 2012

A simple simulation with a local SL law + threshold due to the onset of supersonic turbulence reproduces the observations.



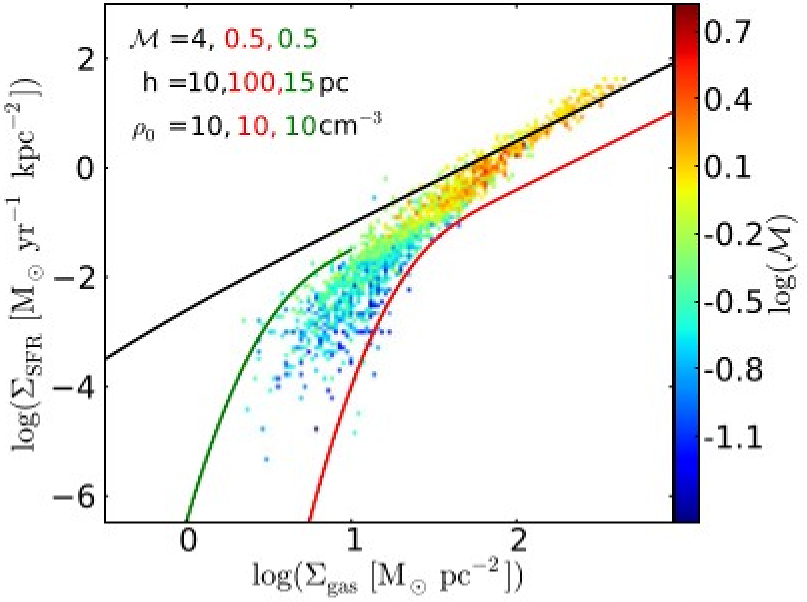


Figure 18. MW$_{\rm PC}$: comparison with the Renaud et al. (2012) model. As in Figure 17, the supersonic regime is compared to the model prediction and similarly, the subsonic regime at low $\Sigma_{\rm gas}$ is situated between the curves characterized by the Mach number lower than unity for the measured thickness.

“Our results suggest that together with the collapse of clouds under self-gravity, turbulence (injected at galactic scale) can induce the compression of gas and regulate star formation.”

A “general” formula

$$\Sigma_{\psi} \propto \Sigma_{gas}^{\alpha} \Omega^{\beta} P^{\gamma}$$

Theories are not definitively predictive.

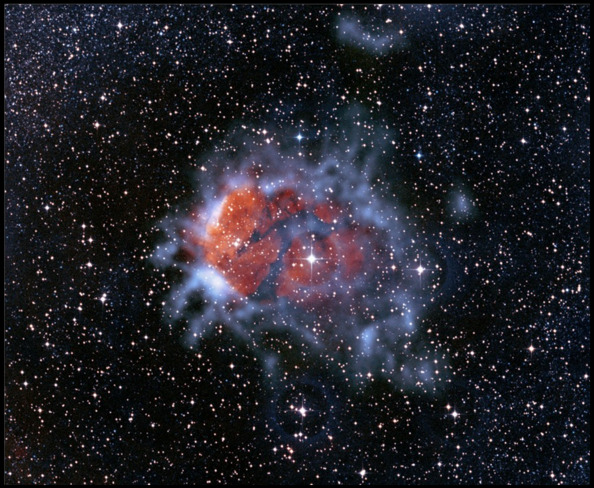
Importance of empirical studies

STAR FORMATION LAWS

a) Threshold theories
b) Influences on SF
c) The scales

Which scale is right ?

RCW120 :
a star formation region in the Milky Way

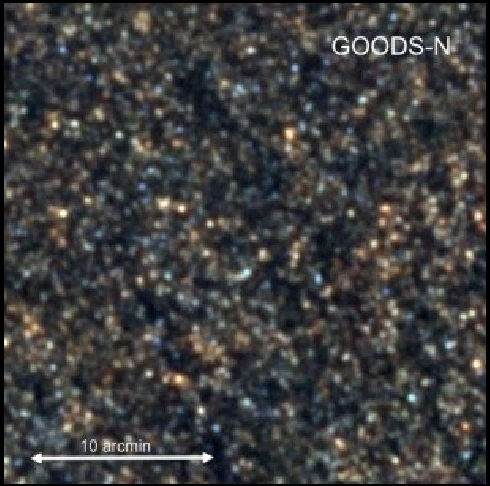


ESO/APEX/DSS2/SuperCosmos/
Deharveng/Zavagno

MESSIER33 :
a nearby star forming galaxy

GALEX + Spitzer
(NASA/JPL-Caltech)

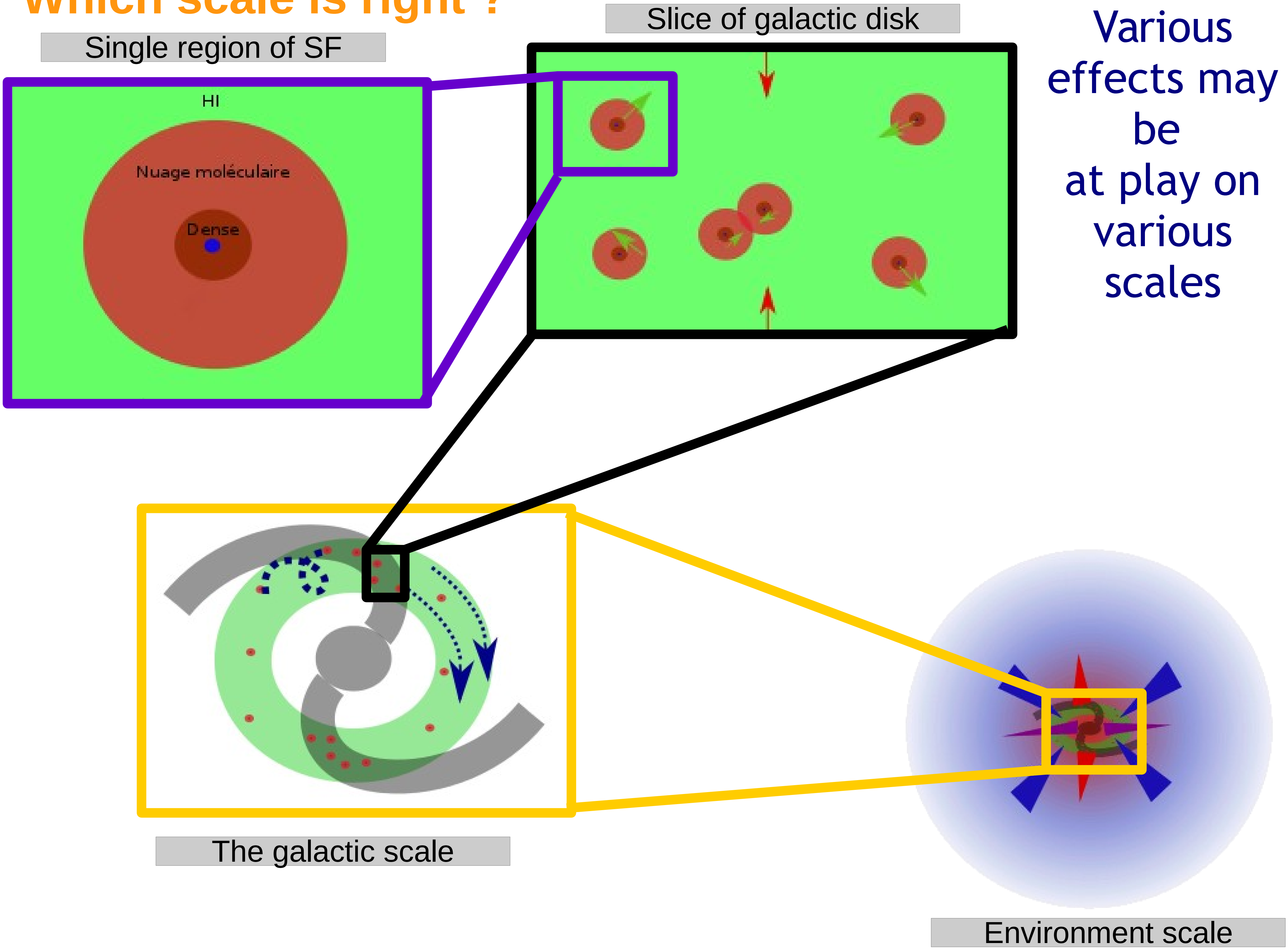
Herschel Deep Field: far far away galaxies



ESA/SPIRE
Consortium/HerMES

What is "Star Formation"
lies in the eye of the beholder...

Which scale is right ?



Single region of SF

Slice of galactic disk

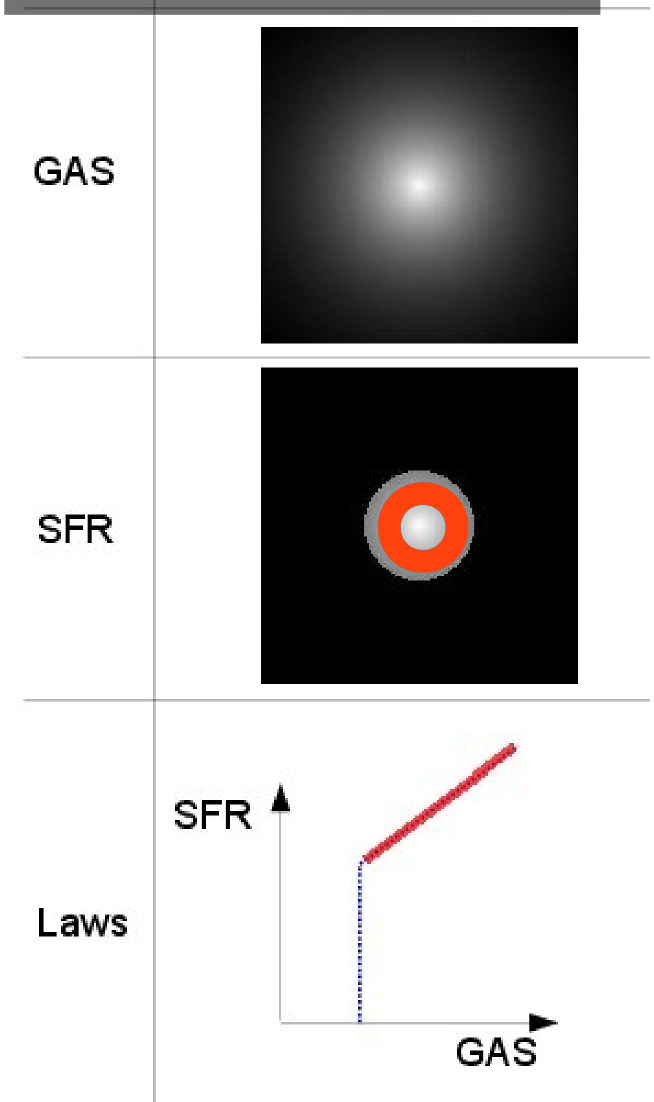
The galactic scale

Environment scale

Various effects may be at play on various scales

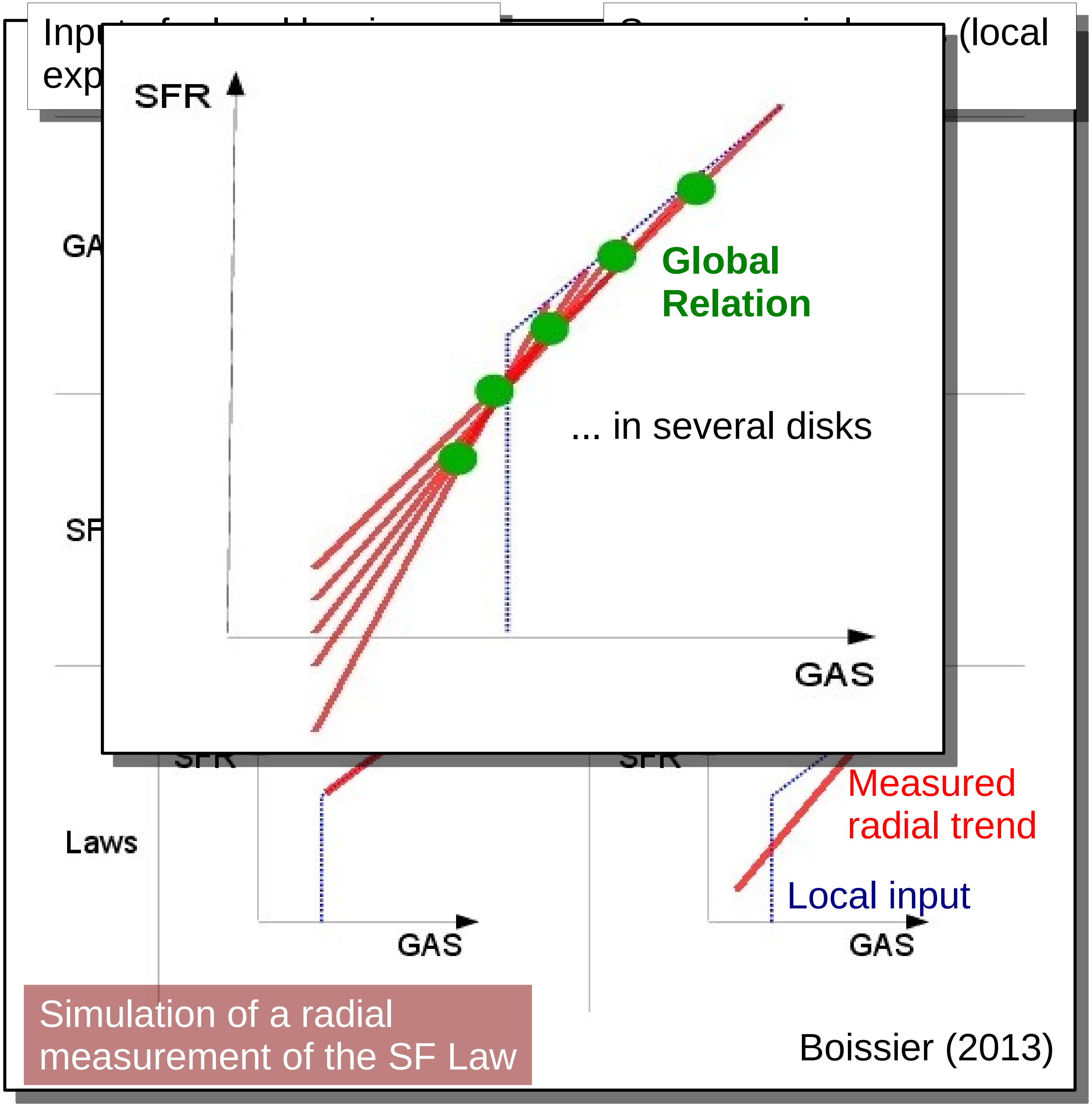
Which scale is right ?

Input of a local law in an exponential disk of gas



Simulation of a radial measurement of the SF Law

Which scale is right ?



Simulation of a radial measurement of the SF Law

Boissier (2013)

The presence of spiral arms imply differences between local and radial “star formation laws”.

And the global one !

STAR FORMATION LAWS

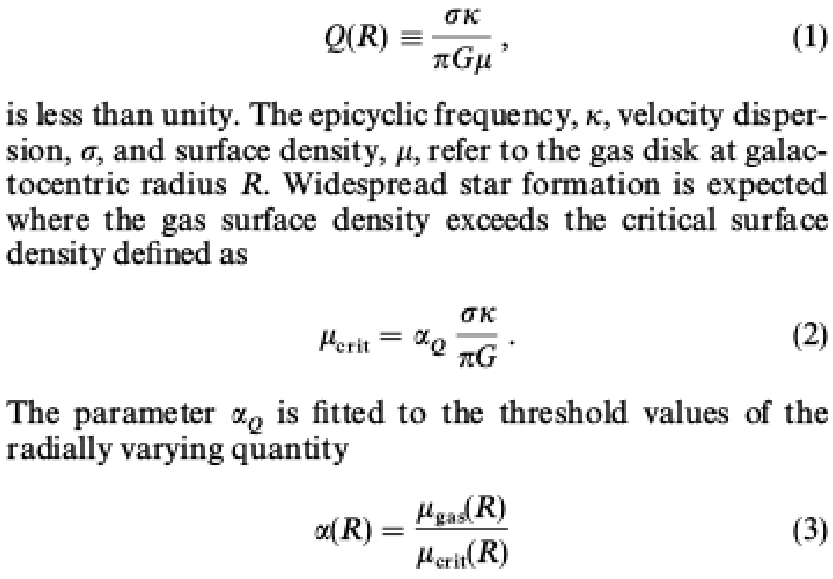
a) Threshold theories
b) Influences on SF
c) The scales
d) State of the art on various scales

Threshold (or not)

The “classical” idea of threshold:

Martin & Kennicutt (2001)

NOTE : IT IS A RADIAL THRESHOLD



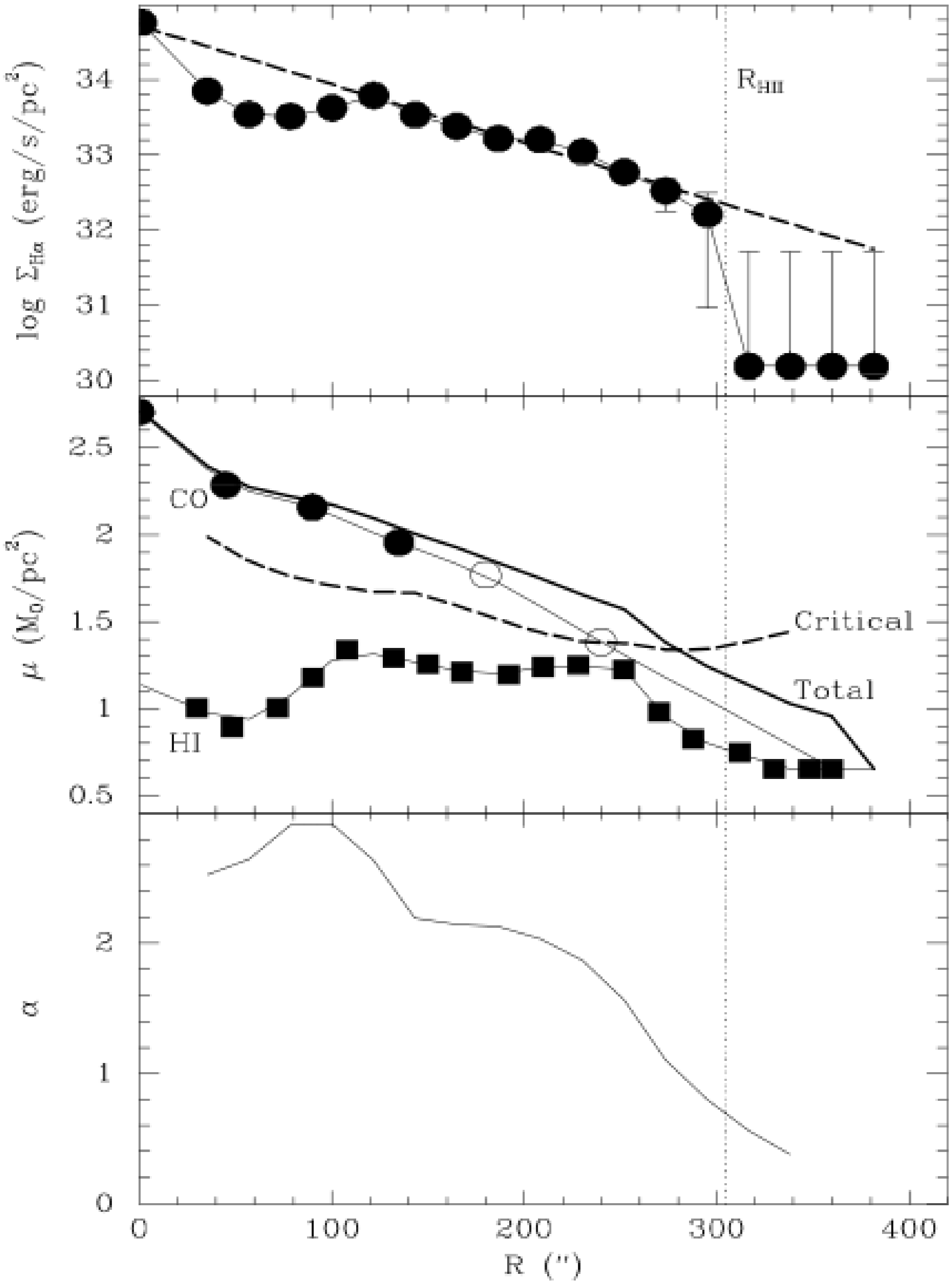
$$Q(R) \equiv \frac{\sigma\kappa}{\pi G\mu}, \quad (1)$$

is less than unity. The epicyclic frequency, κ, velocity dispersion, σ, and surface density, μ, refer to the gas disk at galactocentric radius R. Widespread star formation is expected where the gas surface density exceeds the critical surface density defined as

$$\mu_{\mathrm{crit}} = \alpha_Q \frac{\sigma\kappa}{\pi G}. \quad (2)$$

The parameter α_Q is fitted to the threshold values of the radially varying quantity

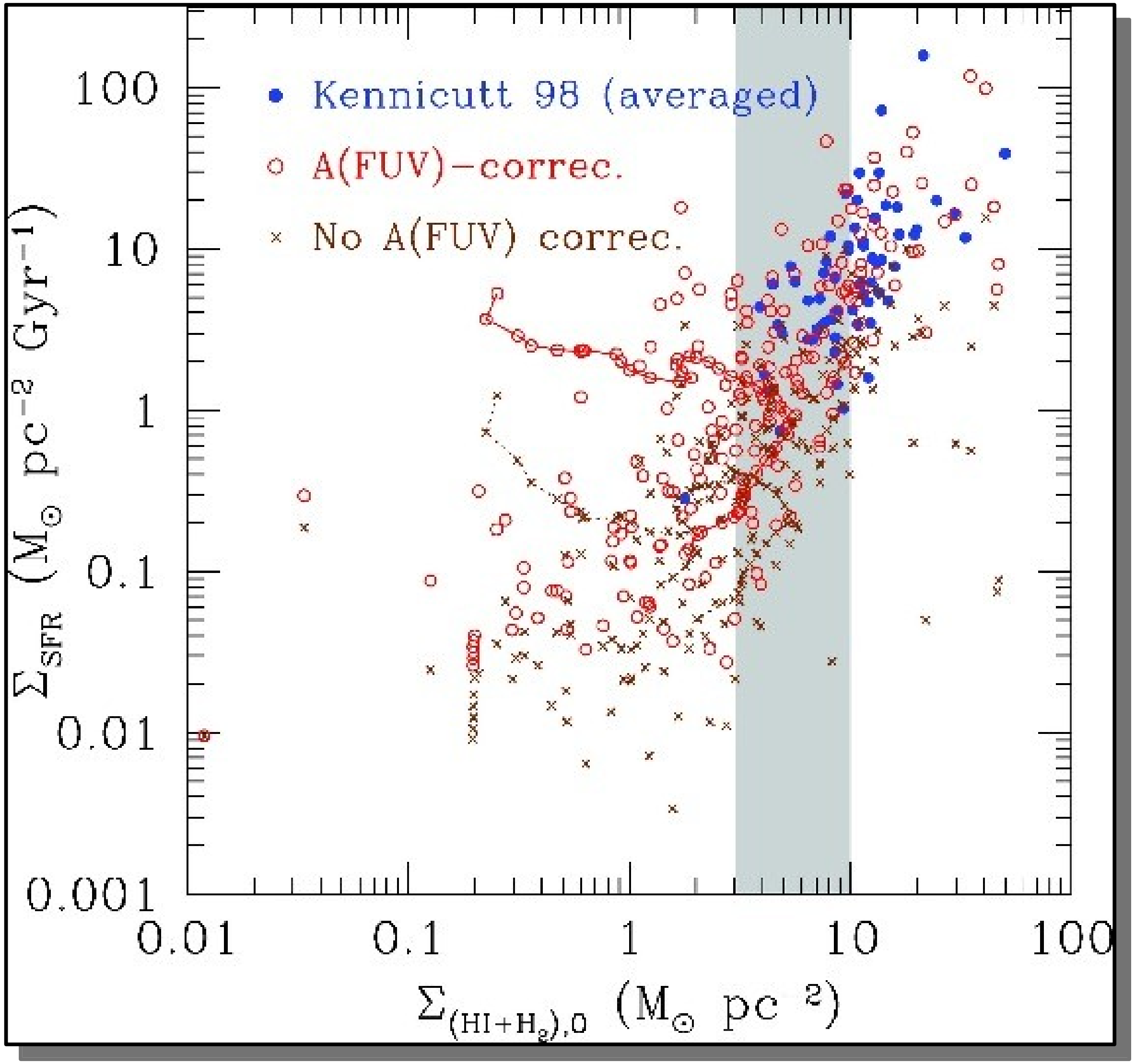
$$\alpha(R) = \frac{\mu_{\mathrm{gas}}(R)}{\mu_{\mathrm{crit}}(R)} \quad (3)$$



Threshold (or not)

A sample of large galaxies observed with UV+FIR profiles (GALEX + IRAS):

The profiles extend below the previously called “threshold” for star formation !



Boissier et al. (2007)

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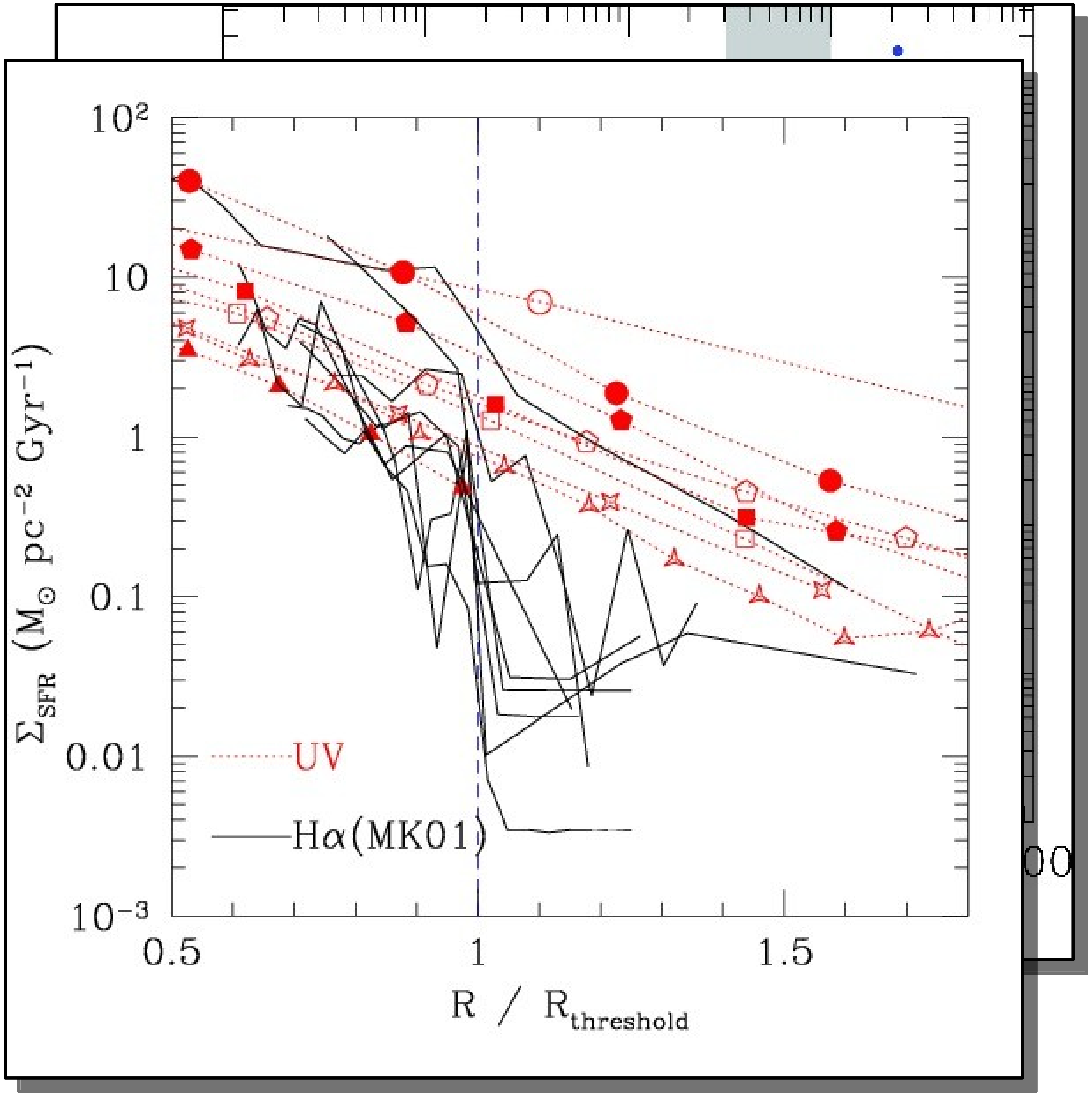


Boissier et al. (2007)

Threshold (or not)

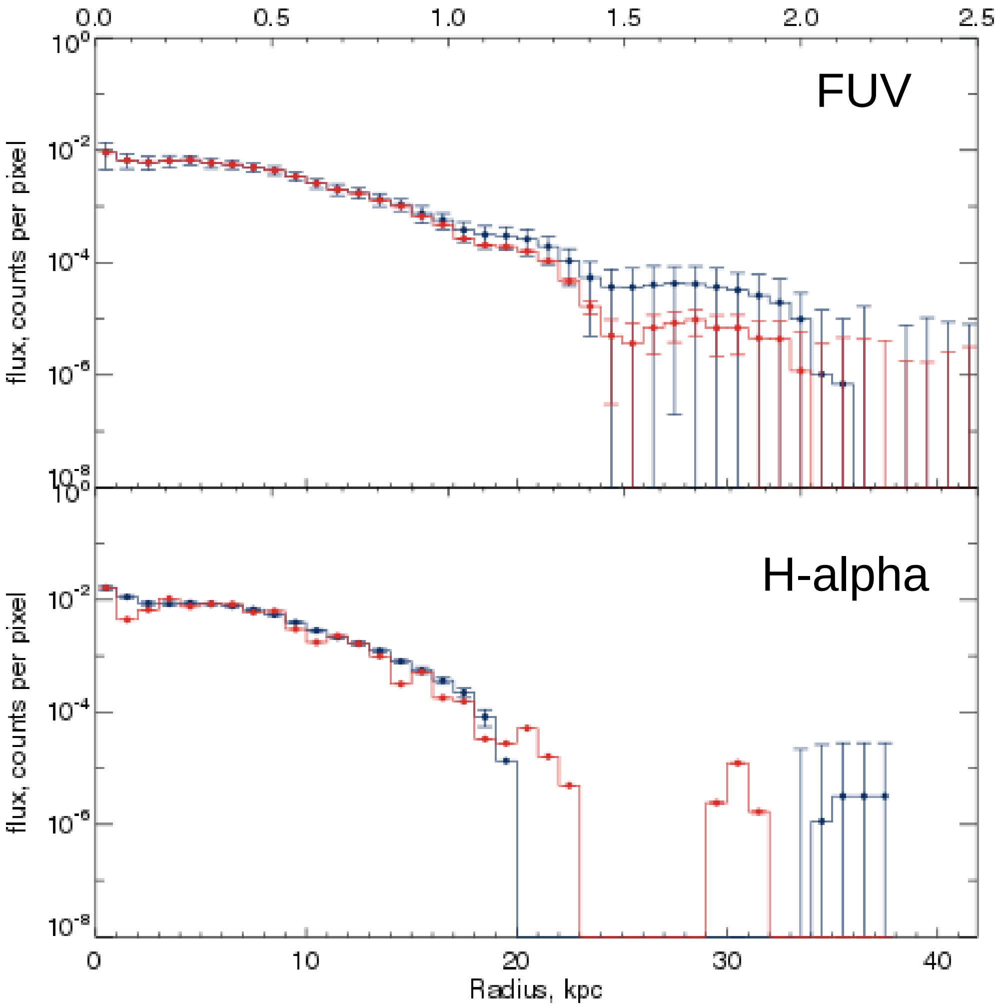


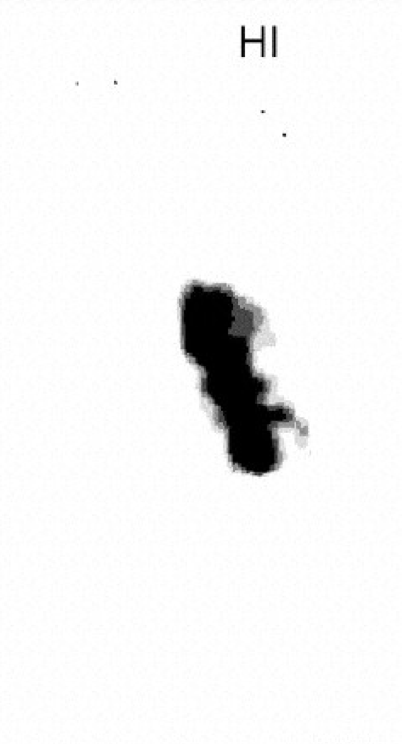
Figure 2. Surface photometry plots for the galaxy NGC 628. The top panel shows the FUV emission in units of counts per second per pixel whilst the bottom panel shows the Hα emission. Dark grey (blue) lines show profiles derived using full annular area surface photometry, and light grey (red) lines show profiles measured from the addition of object fluxes for distinct radial bins. The top axis shows the radius in units of R_{25}.

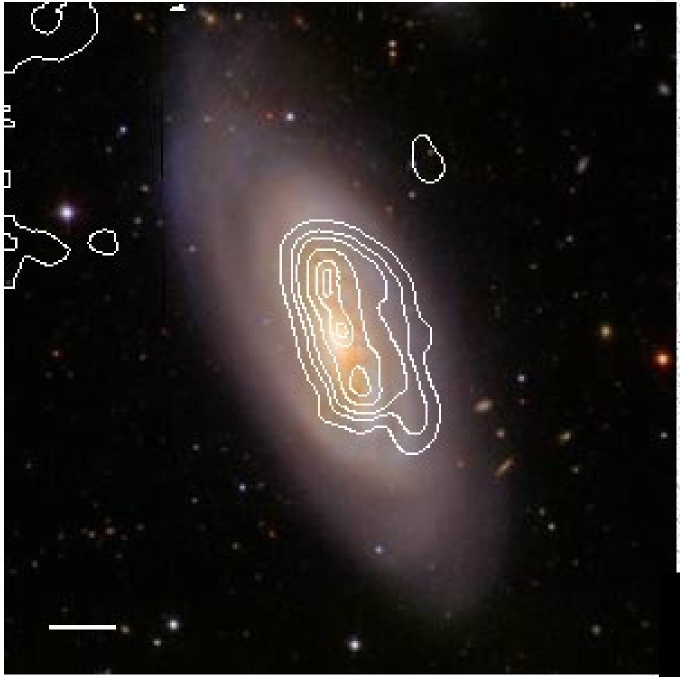
Threshold revisited by Goddard et al. 2010 in 21 galaxies:

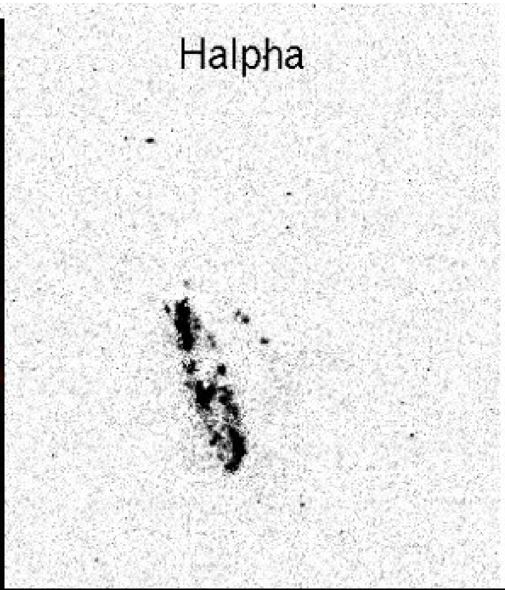
- 50% : “normal” disks (a break is observed in both UV and Hα close to the optical radius.
  Note however that it is more a break (change of slope) than a sharp truncation (threshold).
- 50%: UV extended galaxies.
  - Of these, 6 out of 10 galaxies are also extended in Hα
  - only 4 out of 10 galaxies only have a UV smooth profile and a sharp truncation in Hα.

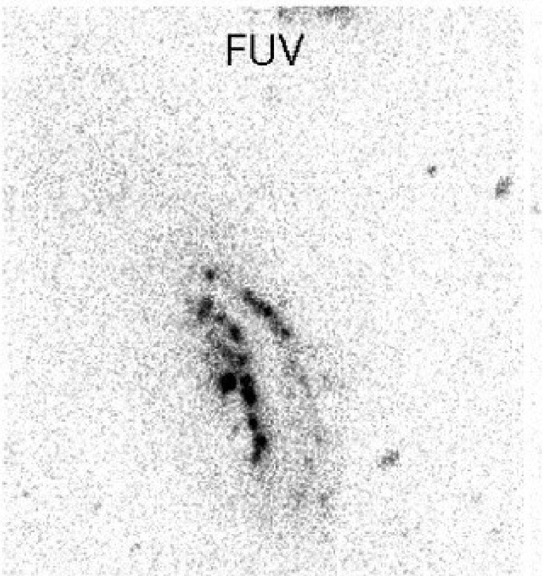
`Goddard et al. (2010)`

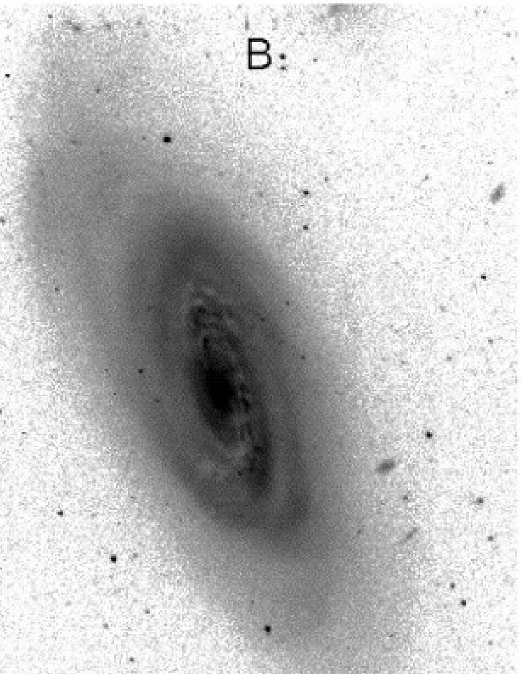
How to make a threshold in H-alpha but not UV ?

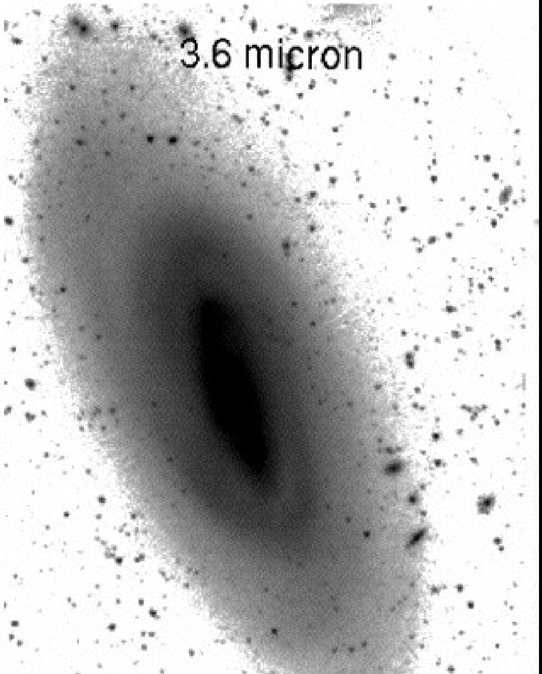


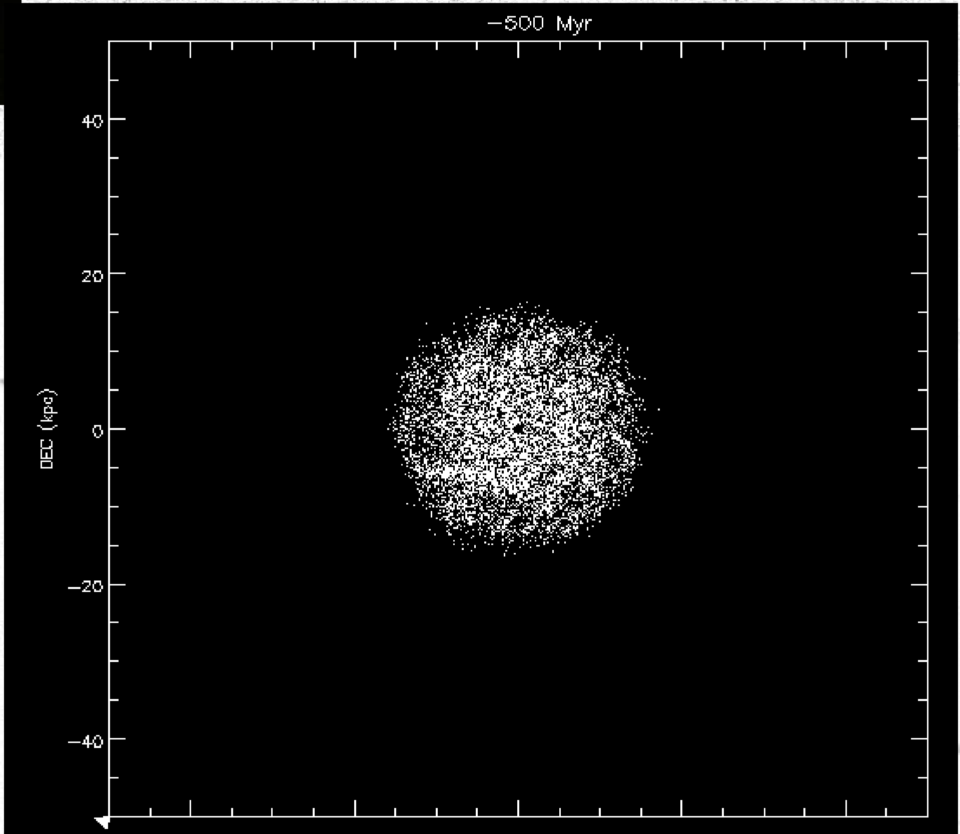




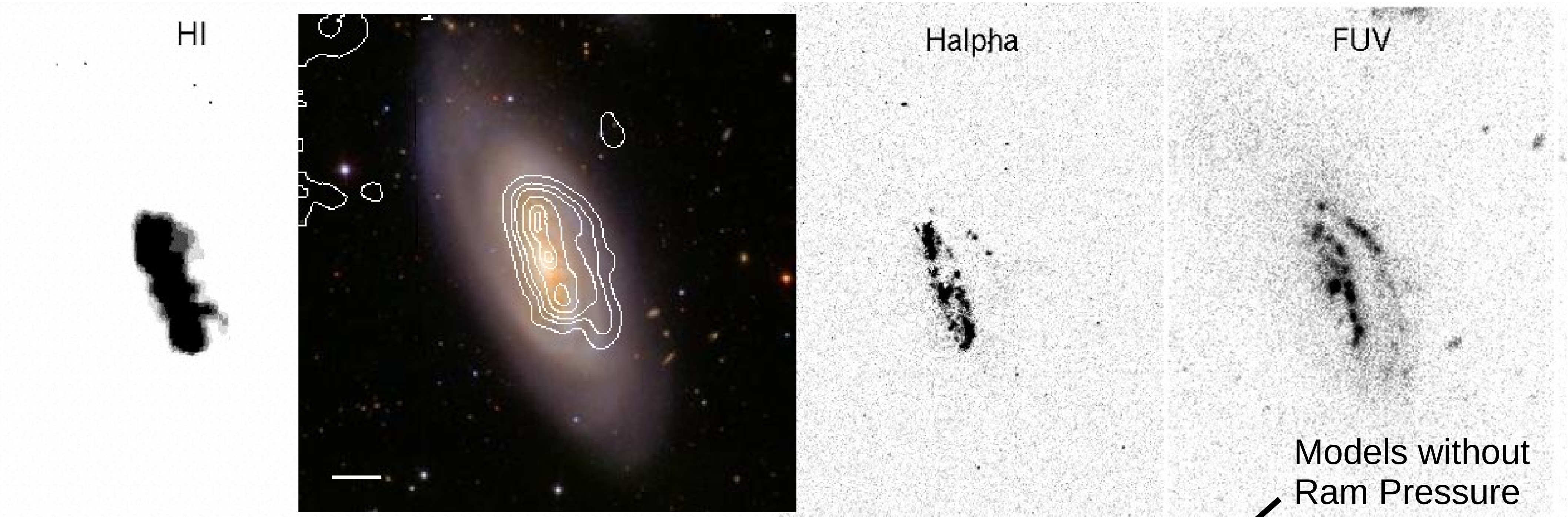








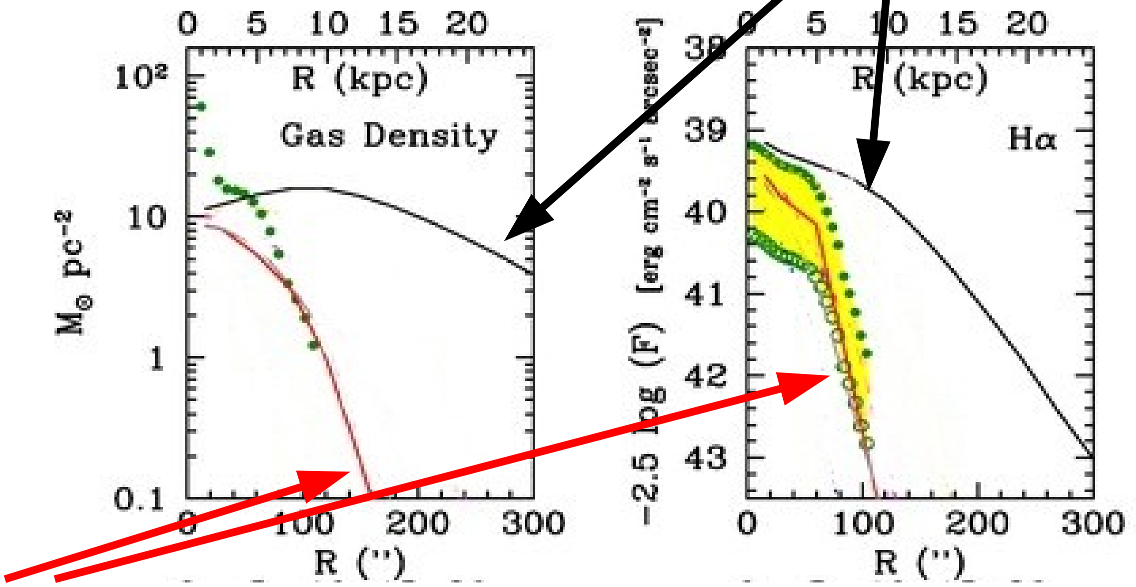
How to make a threshold in H-alpha but not UV ?



Models without Ram Pressure

NGC5469:

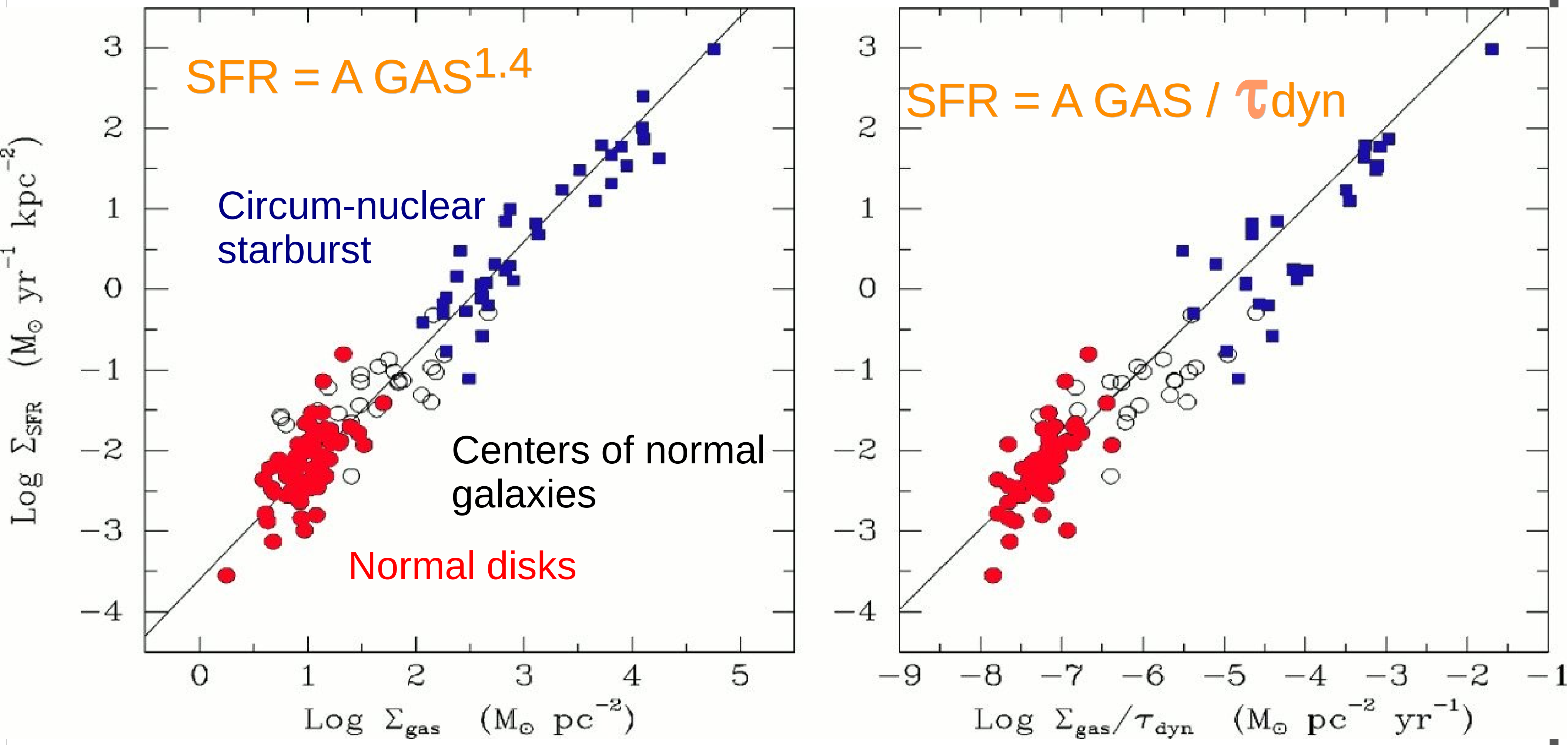
Ram-pressure stripping: Truncation of gas + star forming disk -> fake threshold + lower star formation activity



Boselli et al. (2006)

Model including ram-pressure stripping

Star Formation “Law” (Schmidt law, Schmidt-Kennicutt law)



SFR = A GAS$^{1.4}$

SFR = A GAS / τ_{dyn}

Circum-nuclear starburst

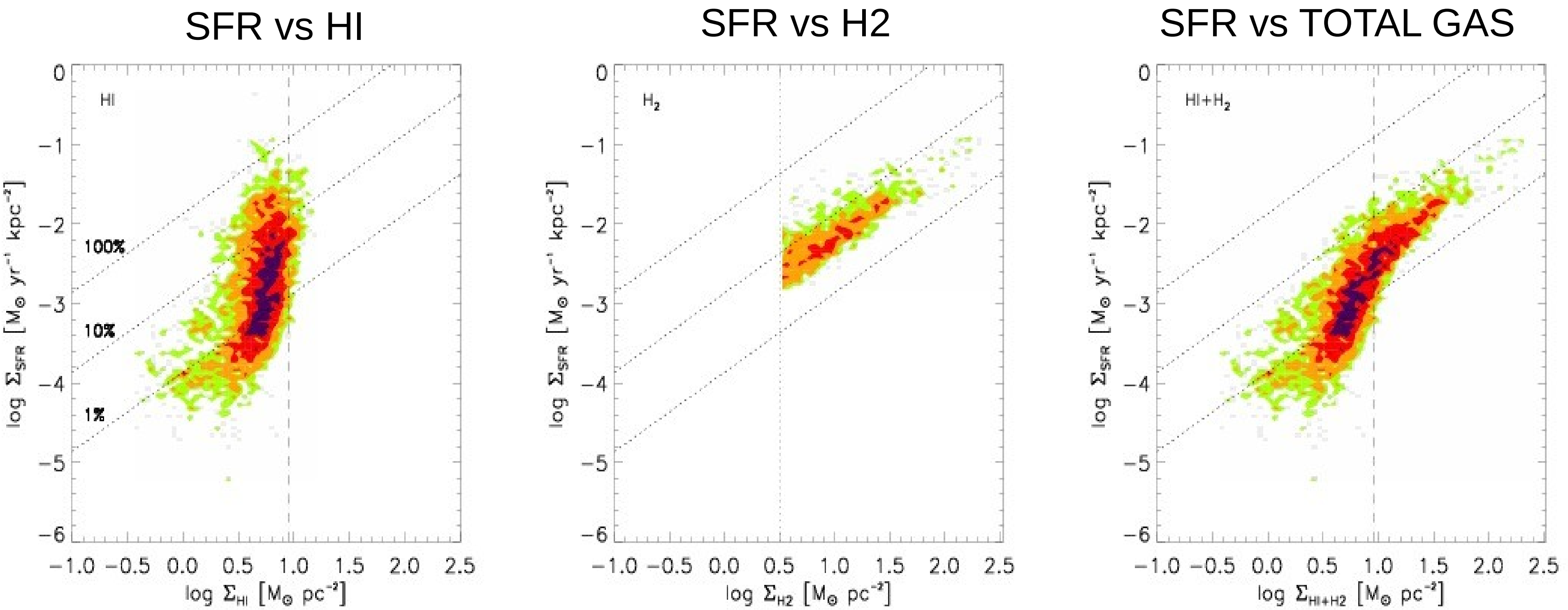
Centers of normal galaxies

Normal disks

Kennicutt (1998)

Global Star Formation Law in nearby galaxies

Star Formation “Law” (Schmidt law, Schmidt-Kennicutt law)

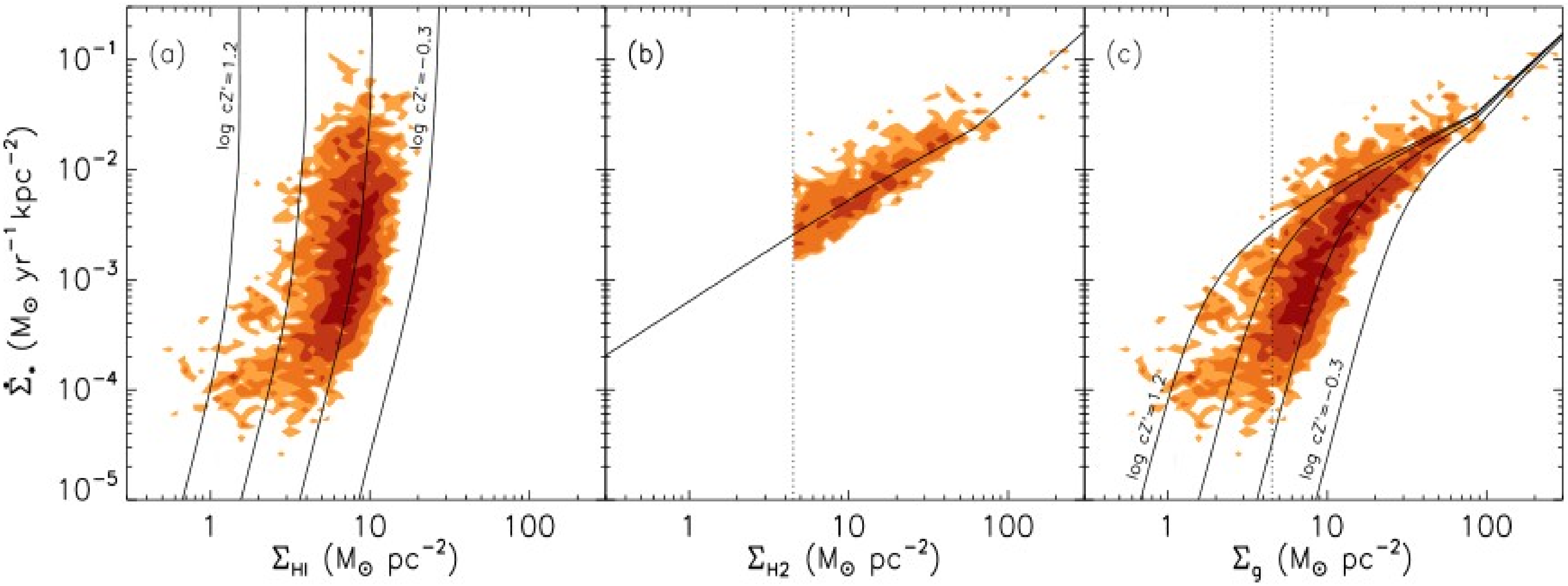


Bigiel et al. (2008)

Local *(few 100 pc)* Star Formation studies suggest:

- a slope 1 for SFR vs H2,
- a broken law with total gas,
- no relation with HI (saturation at ~ 10 Msol/pc^2).

Star Formation “Law” (Schmidt law, Schmidt-Kennicutt law)

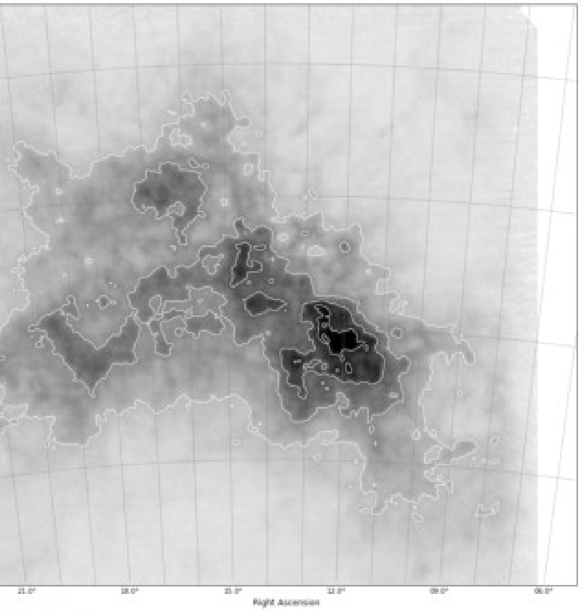


Same data + model by Krumholtz 2009:

- Molecular fraction = f(interstellar radiation, self-shielding)
- Inside molecular cloud: internal feedback determine properties
- Small fraction of star formation within molecular clouds (turbulence)

This allows to “predict” the SFR density from the local gas density but does not predict the distribution of gas/sfr

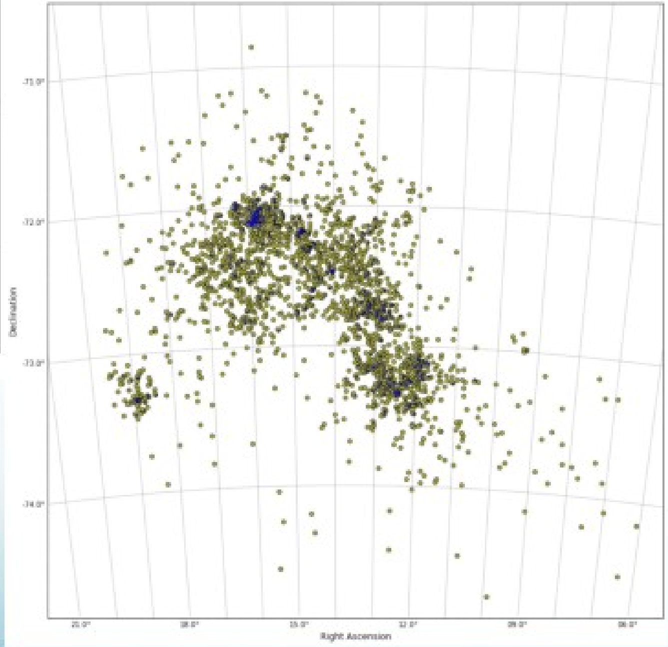
- Madore proposes to take into account the timescales (stellar lifetime, timescales to form stars from the gas as a function of density.

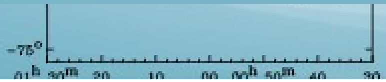


HI

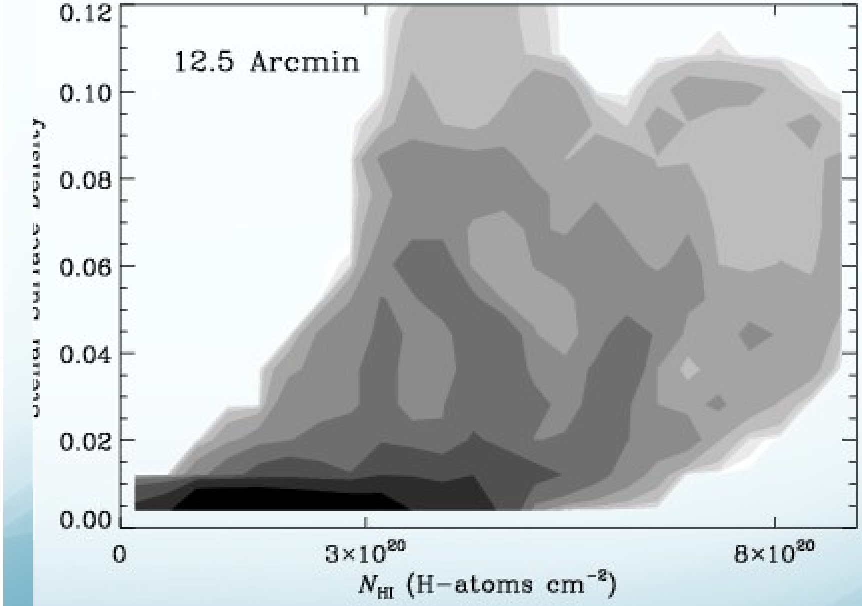
Small Magellanic Cloud

OB Stars



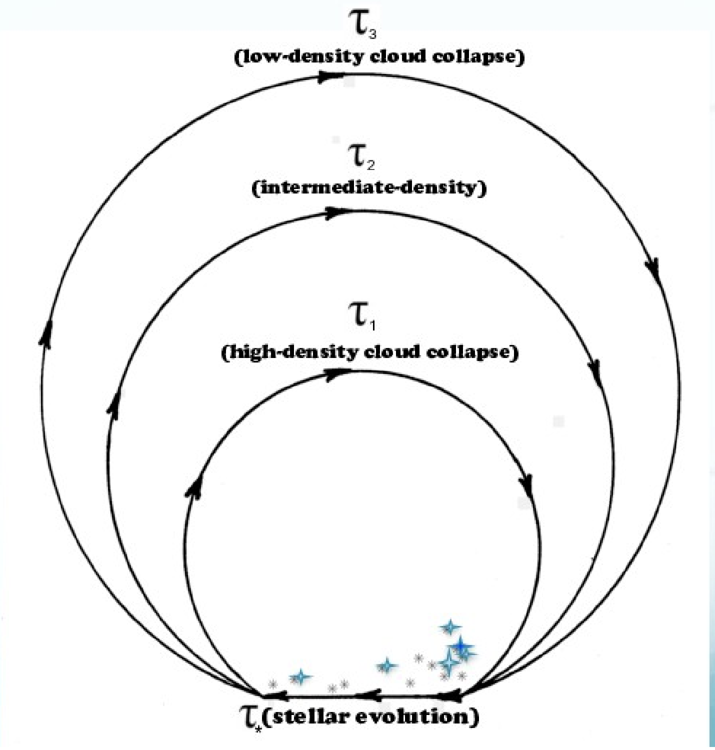


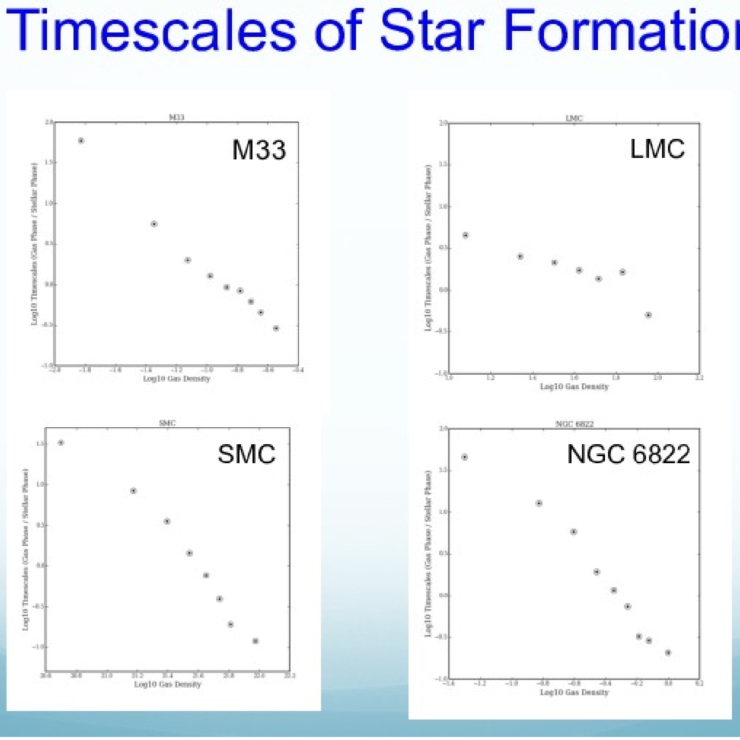
The Hess Diagram for Star Formation



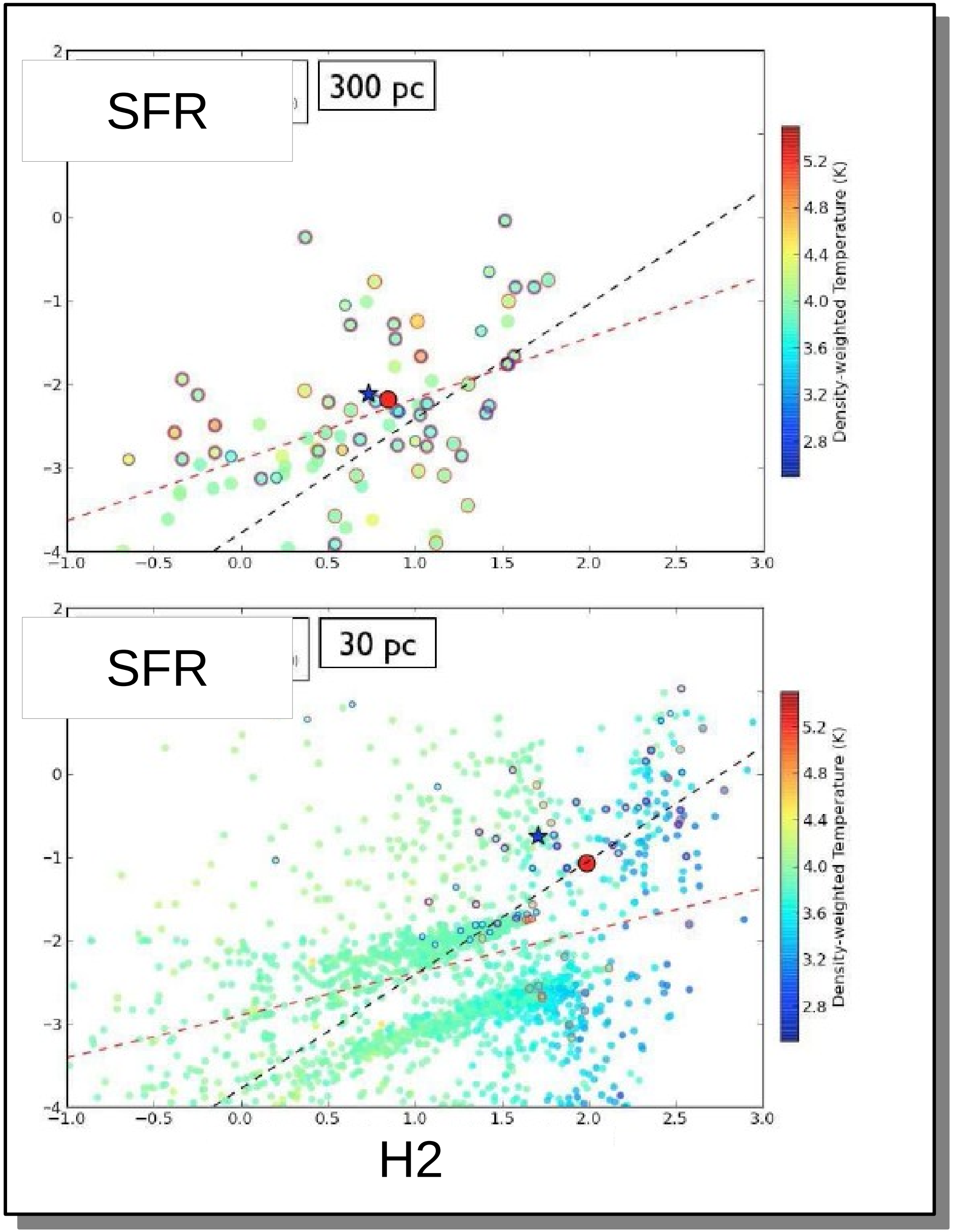
Areal frequencies=
Relative time-scales

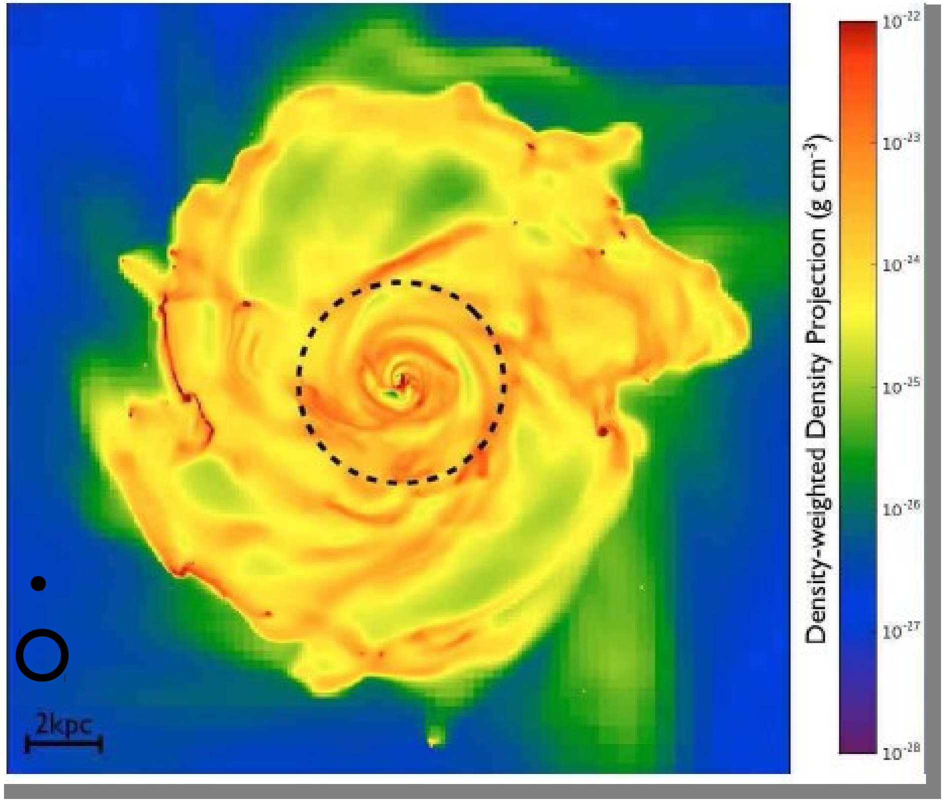
- Madore proposes to take into account the timescales (stellar lifetime, timescales to form stars from the gas as a function of density.




Timescales of Star Formation

Local law as a function of scale!

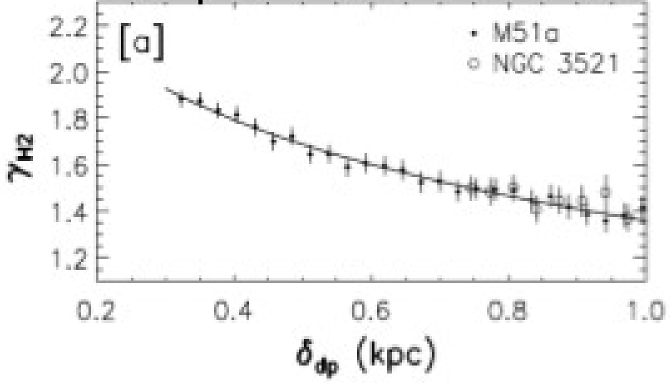




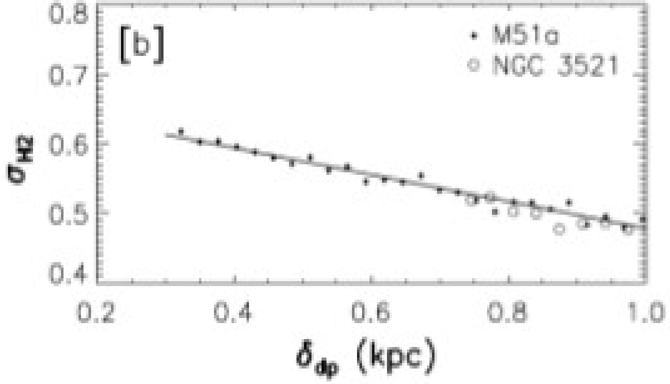
Kim et al. (2012)

Local law as a function of scale!

Slope of the SF Law



Dispersion of the SF Law



`Liu et al. (2011)`

Scales:

<~ 100 pc
    Within Molecular clouds:
    Interest for
    Star Formation detailed physics,
    Efficiency of H2 -> Stars

A few 100 pc:
    Average over several clouds
    Larger than “drift” scale during the
    timescales of SF tracers

Larger scales:
    Incorporate other aspects
    (e.g. Mix arm/interarm)

Radial distribution

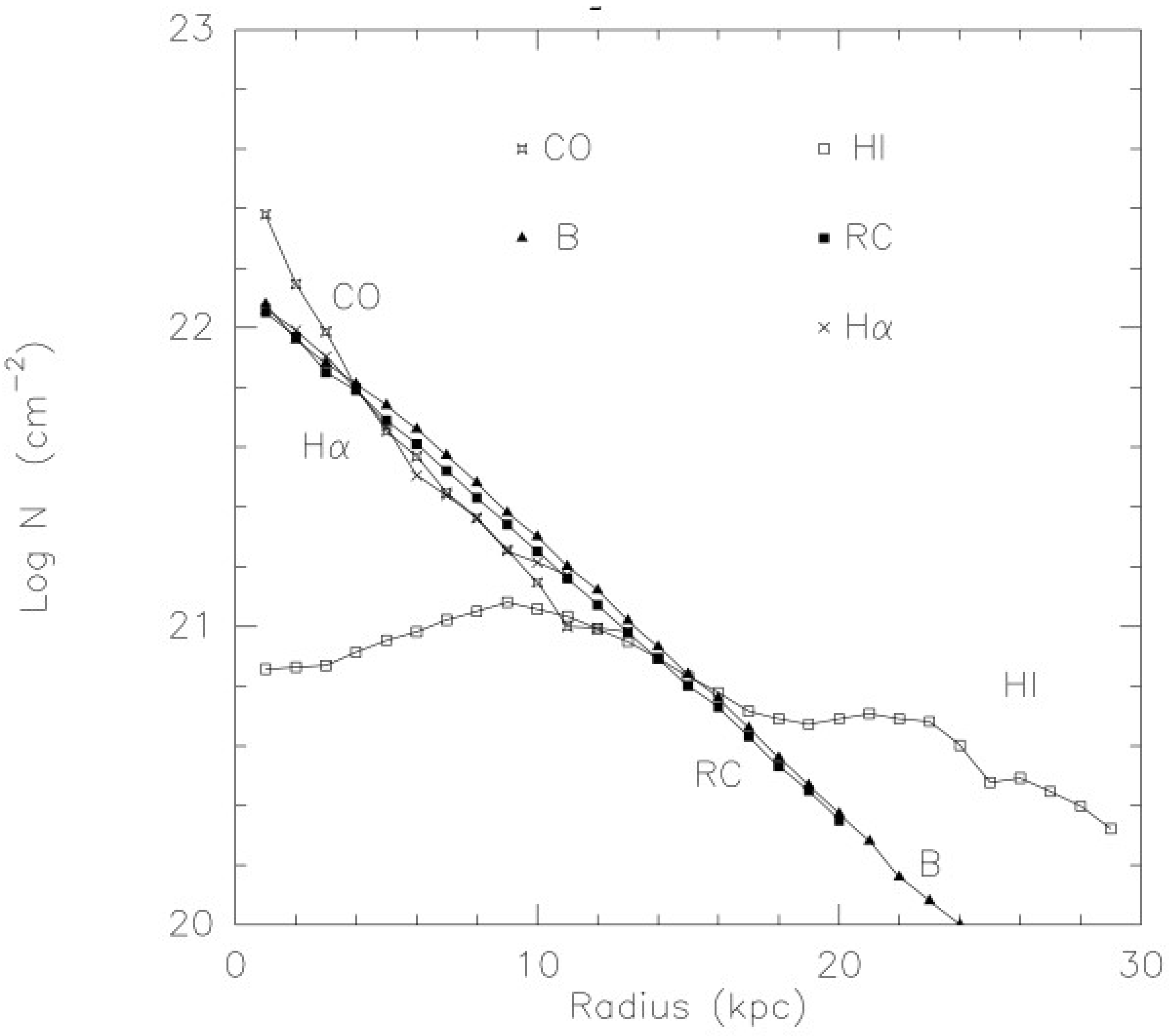


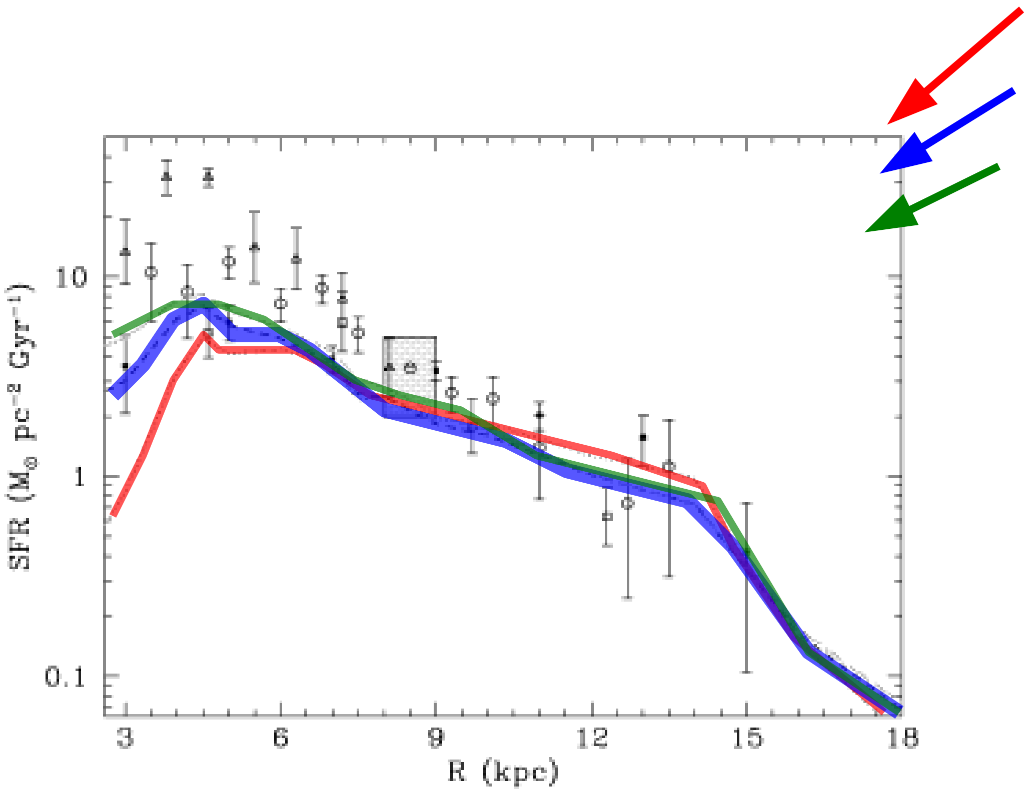
FIGURE 2. Radial distributions of various surface densities in a typical spiral galaxy NGC 6946: H_2(CO) and HI column densities, Blue, Radio-continuum and Hα surface densities (adapted from Tacconi & Young, 1986).

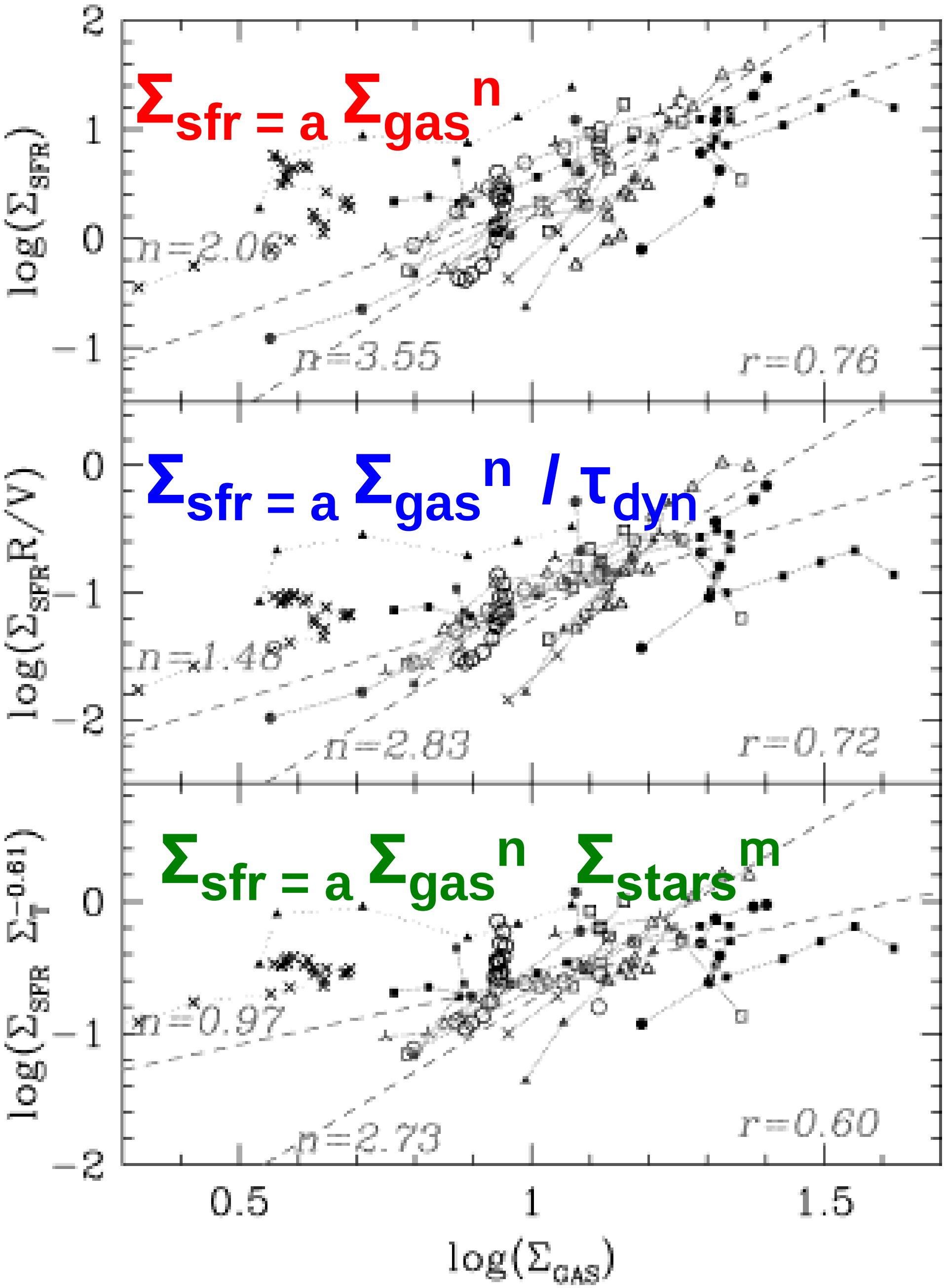
Star Formation “Law” (Schmidt law, Schmidt-Kennicutt law)

Radial averages in nearby galaxies:

Temporal average over the rotation time-scale > time for chemical evolution / mixing

And in the Milky Way:





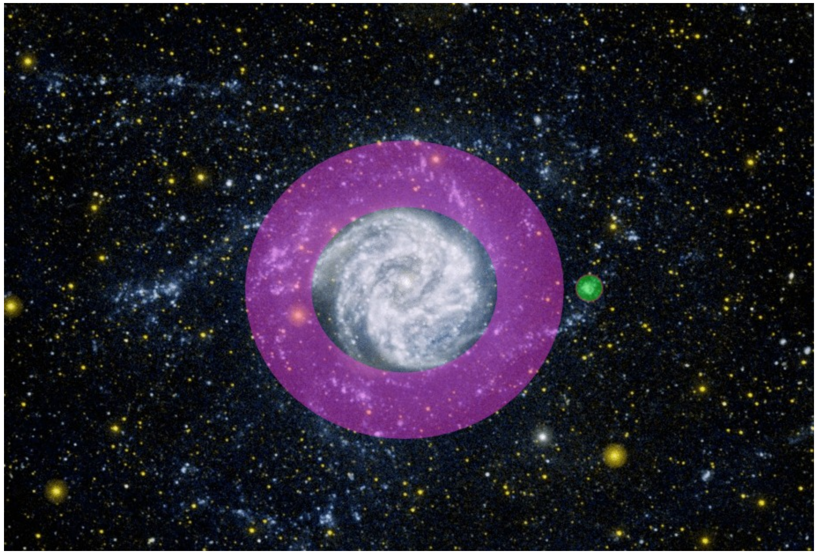
$\Sigma_{sfr} = a\ \Sigma_{gas}^{n}$

$\Sigma_{sfr} = a\ \Sigma_{gas}^{n}\ /\ \tau_{dyn}$

$\Sigma_{sfr} = a\ \Sigma_{gas}^{n}\ \ \Sigma_{stars}^{m}$

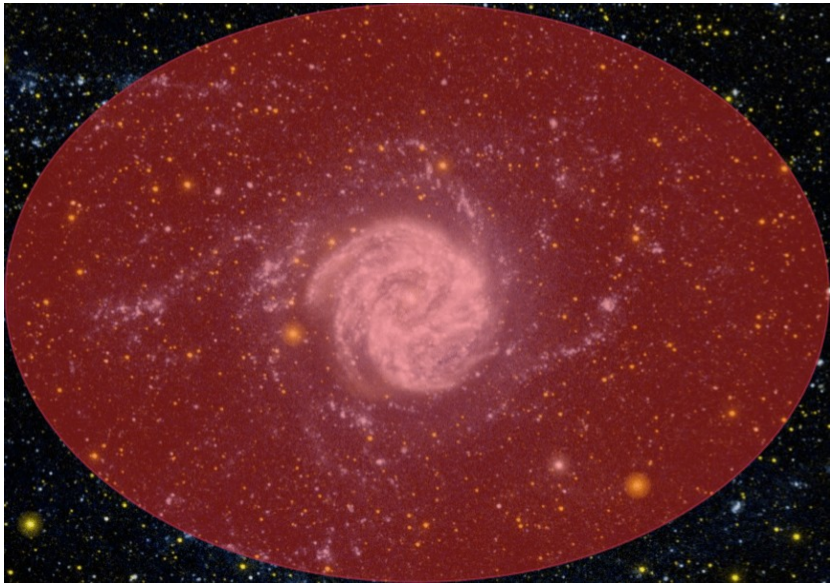
Boissier et al. (2003)

State of the art on various scales



LOCAL:
- Universality of SF on small scales (good H2-SFR relationship)
- Scatter varies with resolution

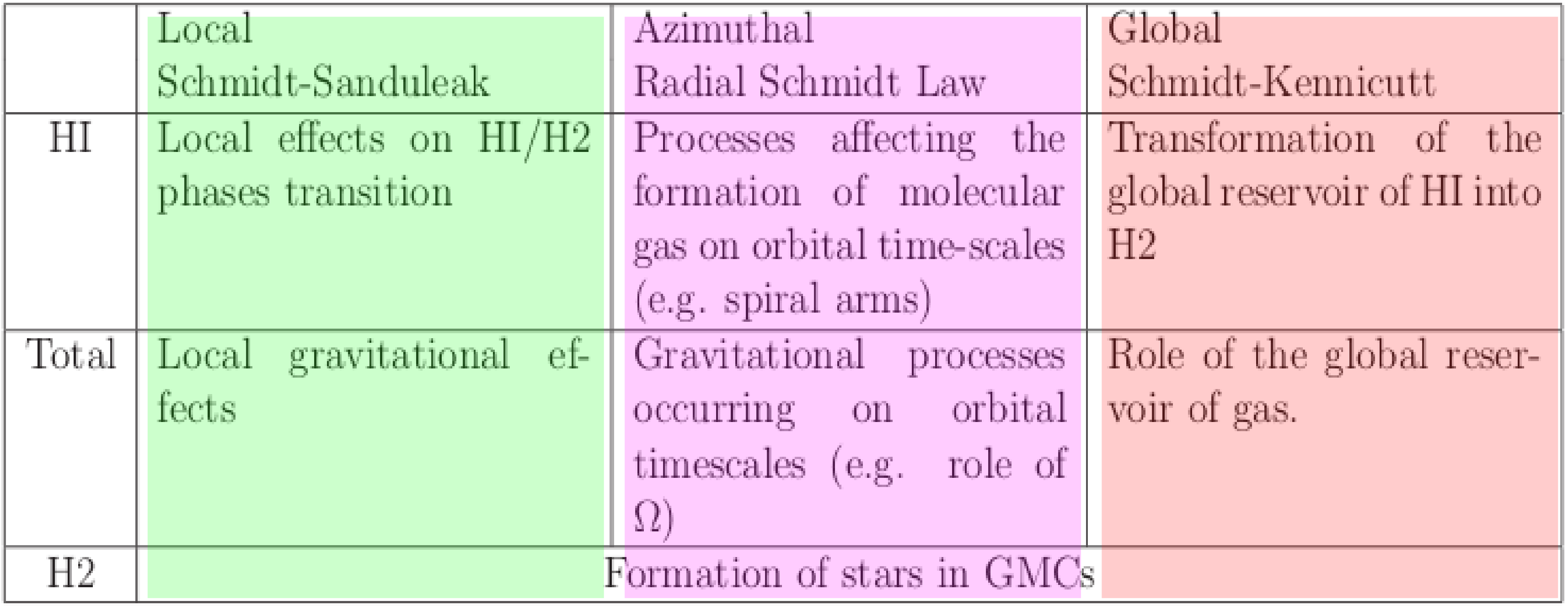
RADIAL:
- Smooth over the lifetime of molecular gas/mixing
- Relations with the total gas
- Effects on orbital time-scale (e.g. spiral arms)



GLOBAL:
Relations are also found with HI/total gas, stressing the role of the global reservoir.

The SF law as a function of scale and phase...

(or: which law is right ?)



	Local Schmidt-Sanduleak	Azimuthal Radial Schmidt Law	Global Schmidt-Kennicutt
HI	Local effects on HI/H2 phases transition	Processes affecting the formation of molecular gas on orbital time-scales (e.g. spiral arms)	Transformation of the global reservoir of HI into H2
Total	Local gravitational effects	Gravitational processes occurring on orbital timescales (e.g. role of Ω)	Role of the global reservoir of gas.
H2	Formation of stars in GMCs		

Table 6: *Proposed relevance of the various Schmidt Laws. Secondary factors not included!*

Schmidt Law at high redshift

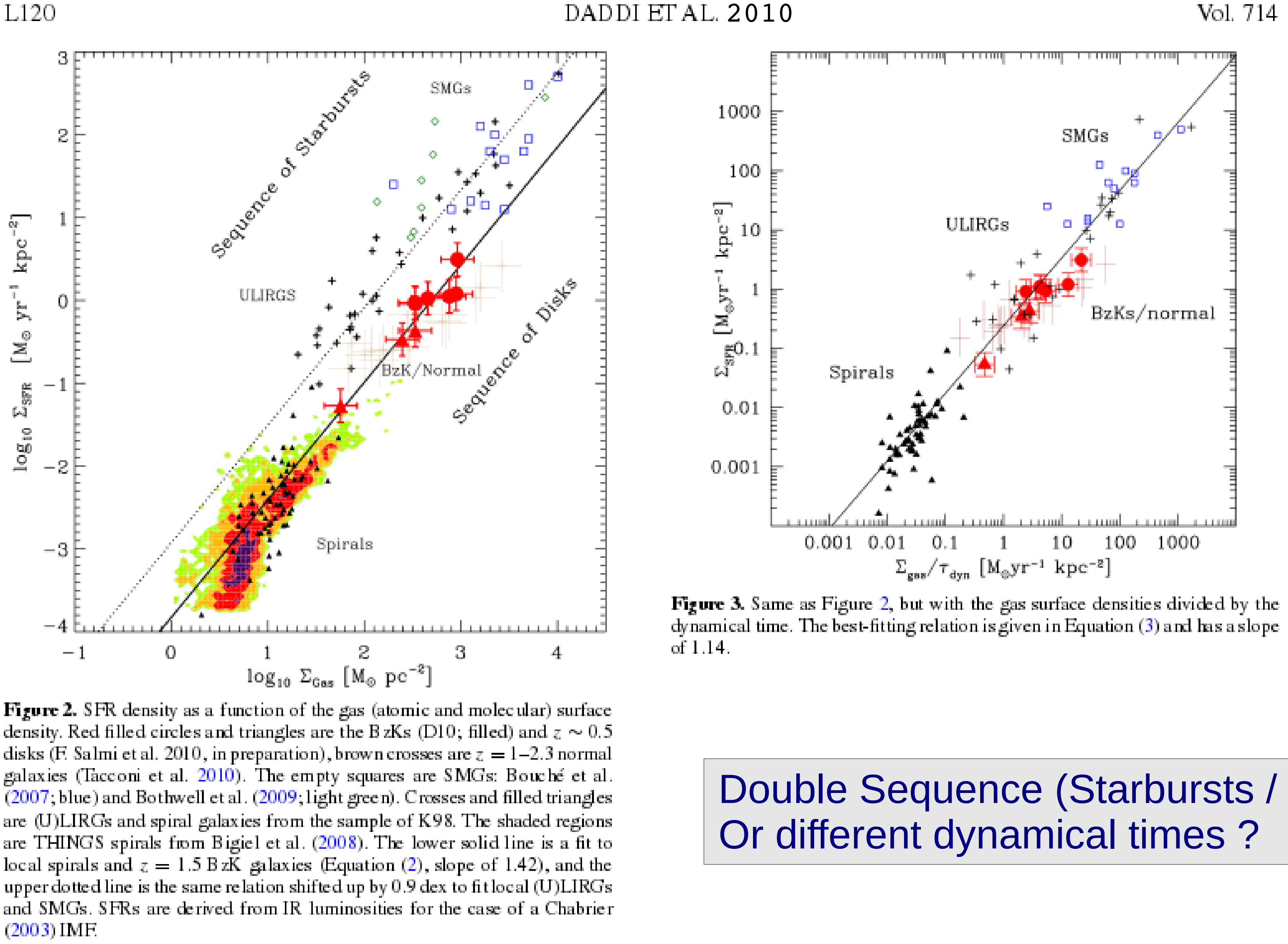


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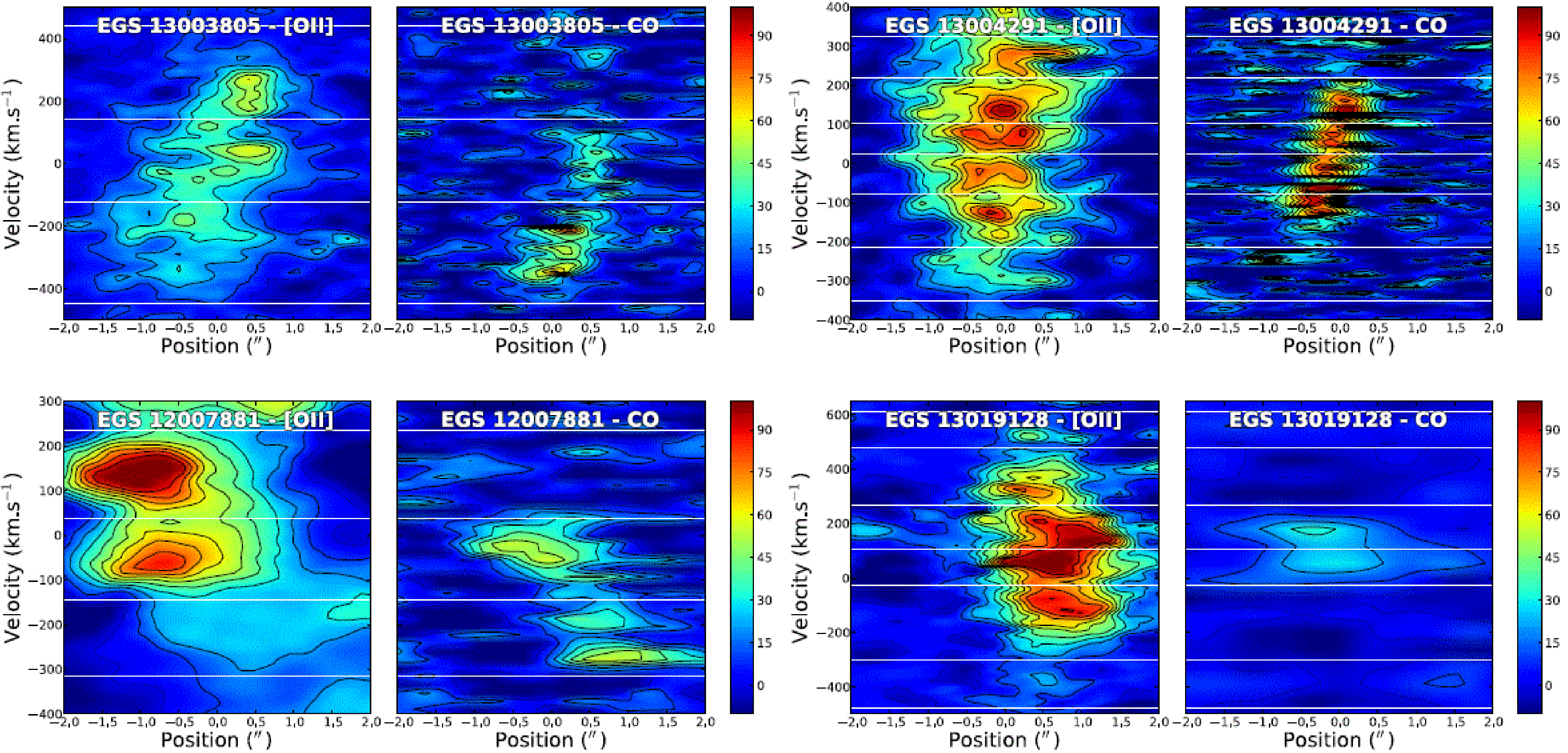
Figure 2. SFR density as a function of the gas (atomic and molecular) surface density. Red filled circles and triangles are the BzKs (D10; filled) and $z \sim 0.5$ disks (F. Salmi et al. 2010, in preparation), brown crosses are $z = 1$–2.3 normal galaxies (Tacconi et al. 2010). The empty squares are SMGs: Bouché et al. (2007; blue) and Bothwell et al. (2009; light green). Crosses and filled triangles are (U)LIRGs and spiral galaxies from the sample of K98. The shaded regions are THINGS spirals from Bigiel et al. (2008). The lower solid line is a fit to local spirals and $z = 1.5$ BzK galaxies (Equation (2), slope of 1.42), and the upper dotted line is the same relation shifted up by 0.9 dex to fit local (U)LIRGs and SMGs. SFRs are derived from IR luminosities for the case of a Chabrier (2003) IMF.

Figure 3. Same as Figure 2, but with the gas surface densities divided by the dynamical time. The best-fitting relation is given in Equation (3) and has a slope of 1.14.

Double Sequence (Starbursts / Disks) ?
Or different dynamical times ?

Schmidt Law at high redshift

Freundlich et al. 2013



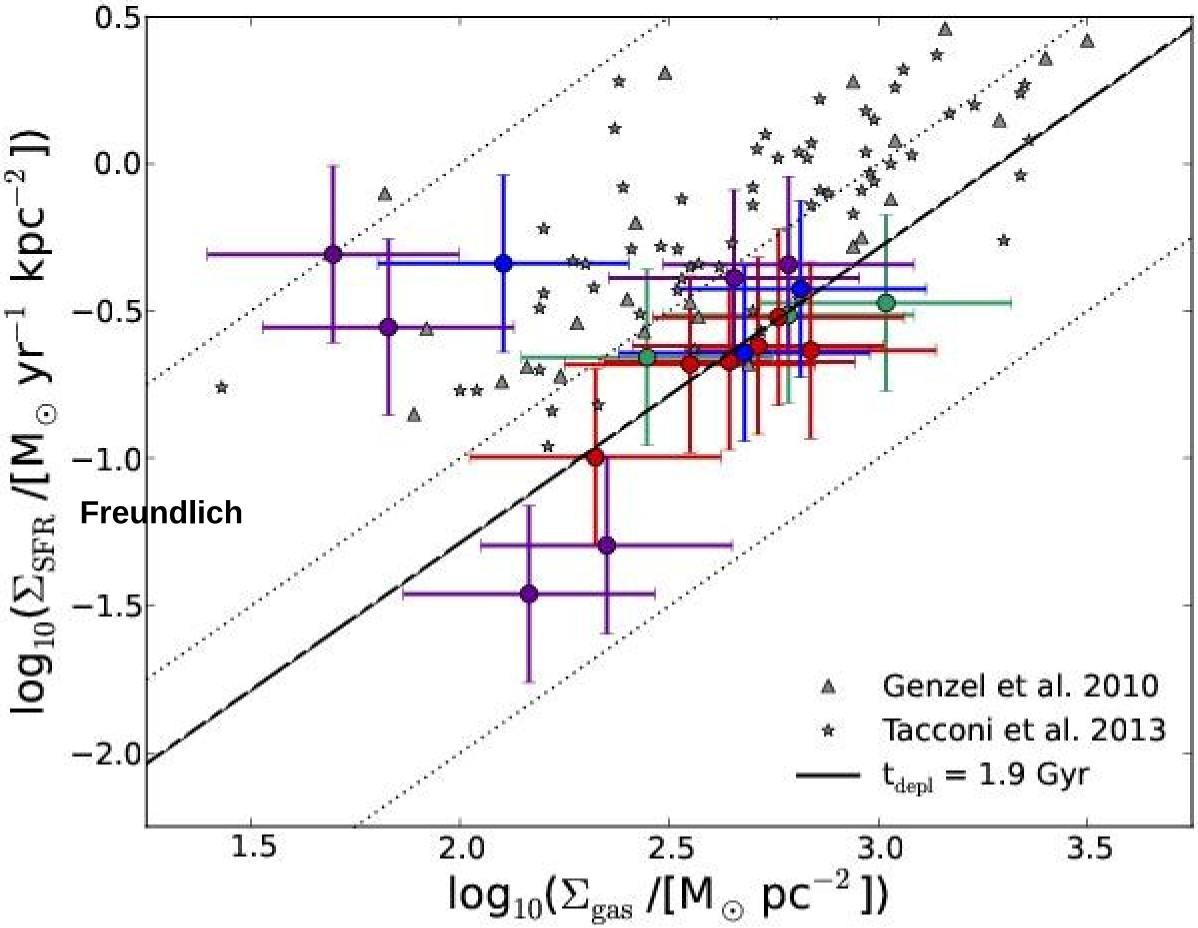
“spatially resolved” Schmidr law at high redshift

(using the position-velocity diagram to isolate clumps!)

Schmidt Law at high redshift

Freundlich et al. 2013

“the star formation scaling law between SFR and gas surface densities is not significantly different at high redshift than in the local Universe. Our limited sample of ~8 kpc-scale ensembles of clumps of distant galaxies is compatible with a constant depletion time of 1.9 Gyr, which is of the same order of magnitude as measurements at lower redshift.”



Schmidt Law at high redshift

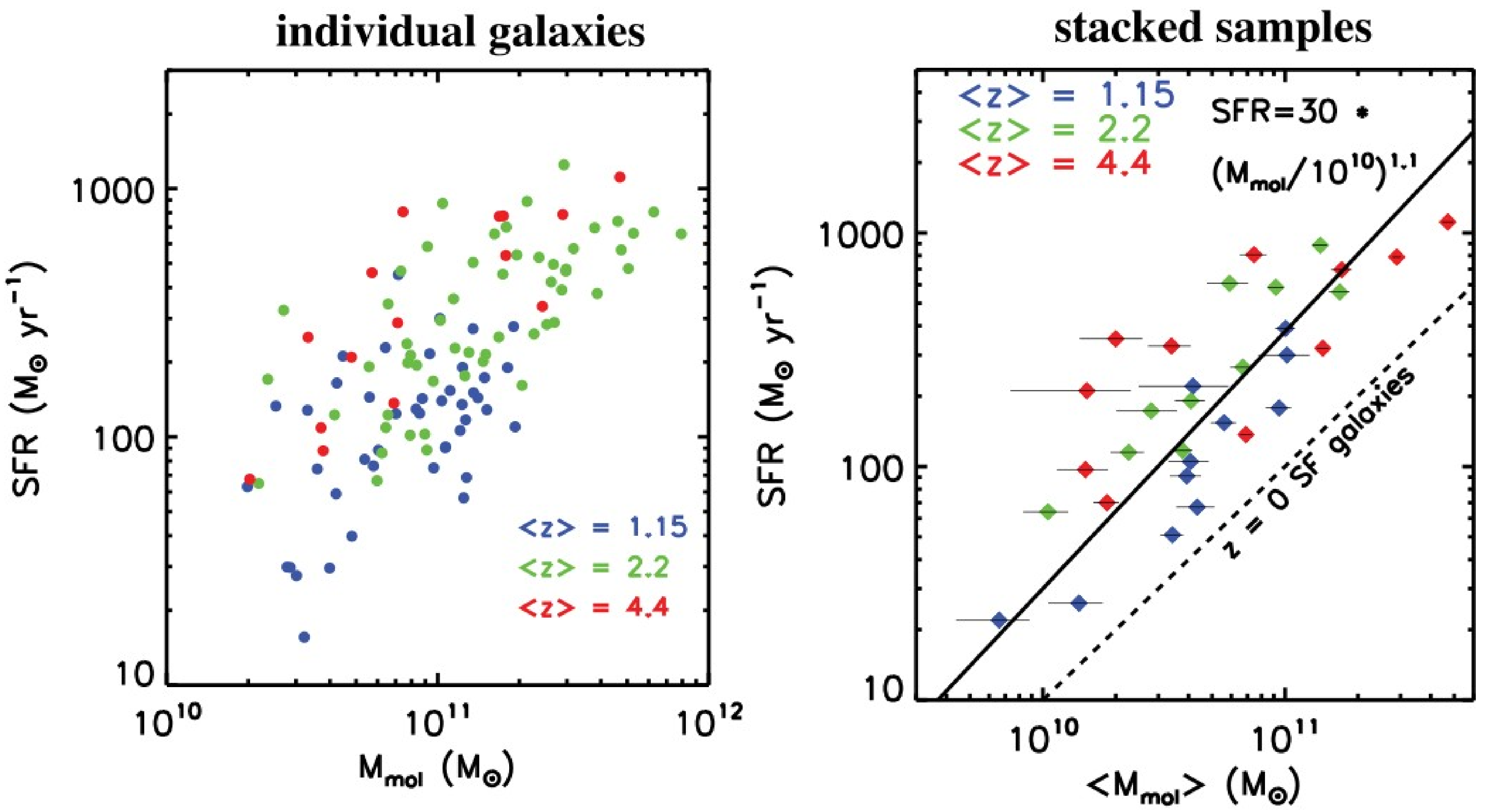


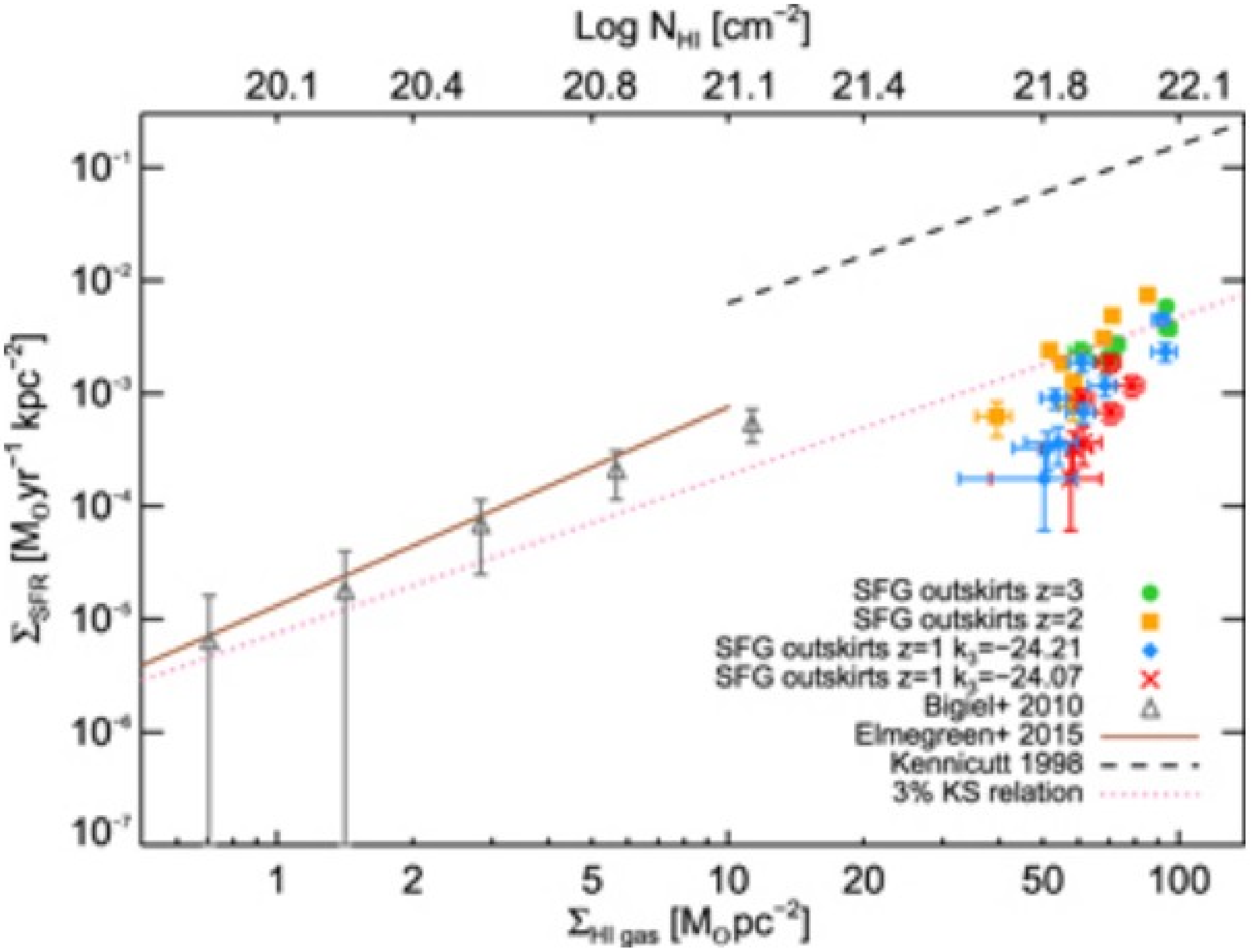
Figure 8. Left: the SFRs as a function of M_{mol} are shown for the individual galaxies. Right: same as on the left, but for the stacked galaxy samples. The best-fit SF law, given by Equation (2) and evaluated at $z = 2$, is shown in the right panel.

COSMOS field: UV + IR → SFR ; ALMA dust mass → gas mass through empirical calibrations

A higher efficiency at high redshift (increased interactions, …).

Schmidt Law at high redshift

Raffelski et al. (2016)



Stacked Star Forming Galaxies → SFR

Damped lyman Alpha systems → atomic gas

The efficiency in low density atomic gas does not depend on redshift...

STAR FORMATION LAWS

a) Threshold theories
b) Influences on SF
c) The scales
d) State of the art on various scales
e) Measurements : gas

The gas in galaxies

X: factor 1.3-1.4 to account for metallicity

Mgas=Mneutral + Mmolecular (+ Mionized)

$M(\text{Hydrogen}) \sim M(\text{HI}) + \boxed{M(\text{H2})}$

$$M_{HI} = 2.36 \times 10^5 D^2 \boxed{\int F \, dV} M_\odot$$

where D is the distance in Mpc.

Total HI line flux
In Jy km/s

Distance (Mpc)

Roberts 1962, AJ 67, 437

Wild, 1952 ApJ 115, 206

(from alfalfa web site)

The gas in galaxies

X: factor 1.3-1.4 to account for metallicity

Mgas=Mneutral + Mmolecular (+ Mionized)

$M(Hydrogen) \sim M(HI) + \boxed{M(H2)}$

- H2 at a few 10K does not radiate : only indirect measurements.
- CO : most abundance molecule after H2. CO1-0 (2.6mm) is easily excited.
- Calibration factor X=N(H2)/I(CO) ?
- For galaxies of size ~ < beam

$$M(H2) = 2.96\ 10^{-19}\ D^2\ I(CO)\ X\ \Theta^2$$

Solar masses

Distance Mpc

K km s^{-1}

Beam (arcsec2)

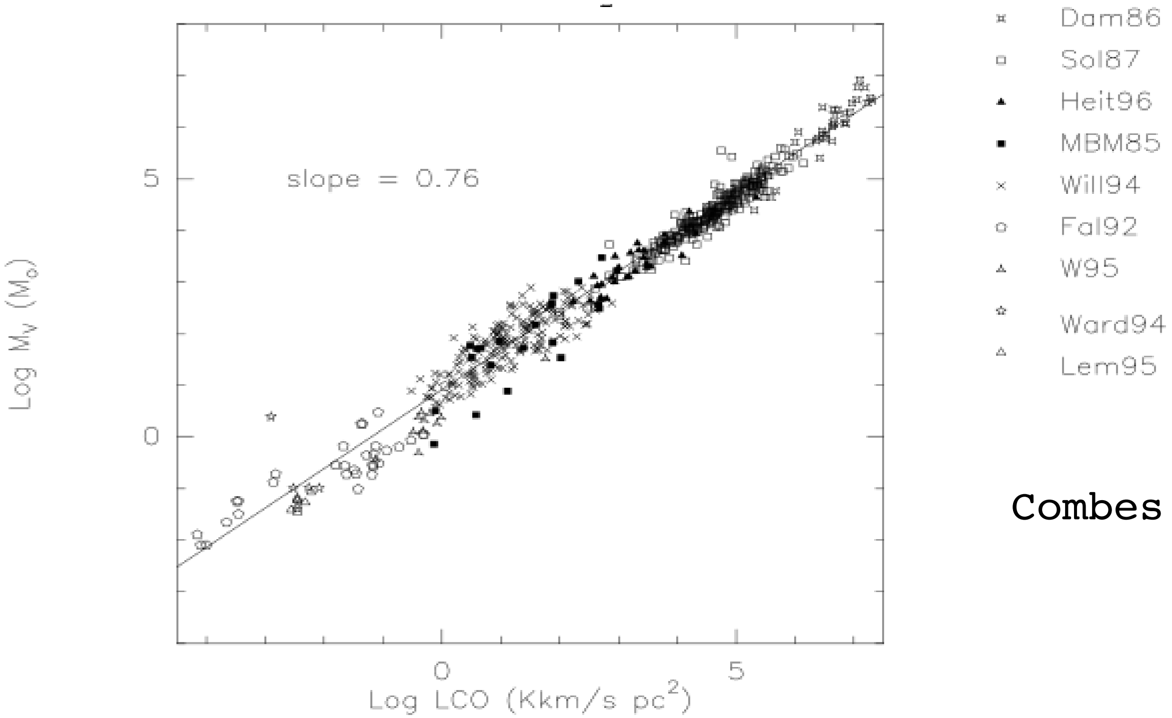
The gas in galaxies

Calibration of X=N(H2)/I(CO):

Measuring the size of molecular clouds (R) + ΔV from the line

=> Deriving virial mass Mv.

Empirical correlation with L(CO)

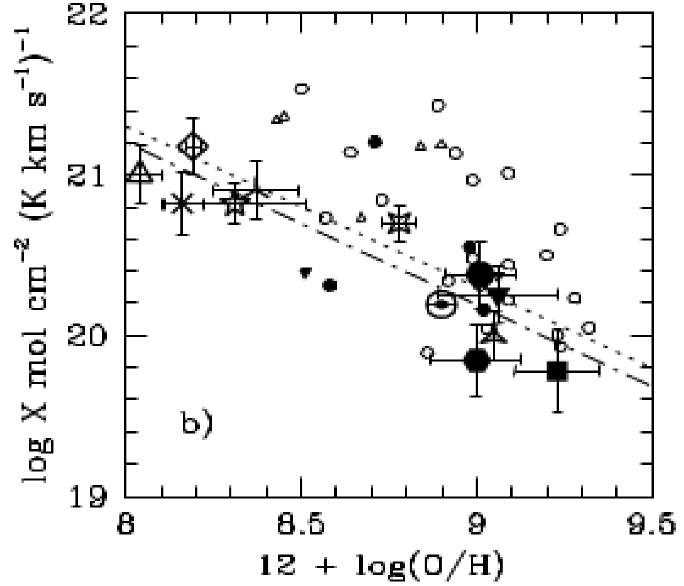


Combes 1999

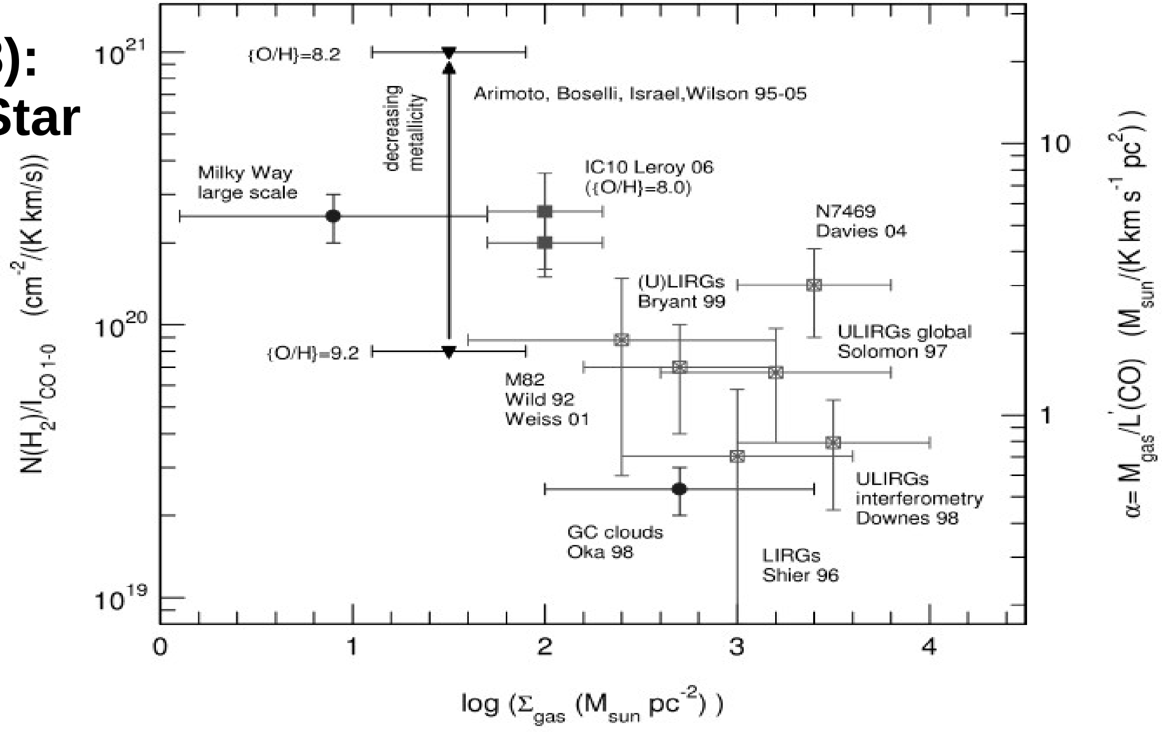
The gas in galaxies Factor affecting the conversion factor

The Role of Metallicity ?

Boselli 2002



"Local" ULIRGs (bursting galaxies): Standard X overestimates the mass by a factor 3 (Solomon 1997). Also at high z (tacconi et al. 2008): Role of large densities of gas & Star formation



The gas in galaxies

Other methods to calibrate X or measure H2:
- Assume a Mdust / M(H2) (eventually with a metallicity correction)

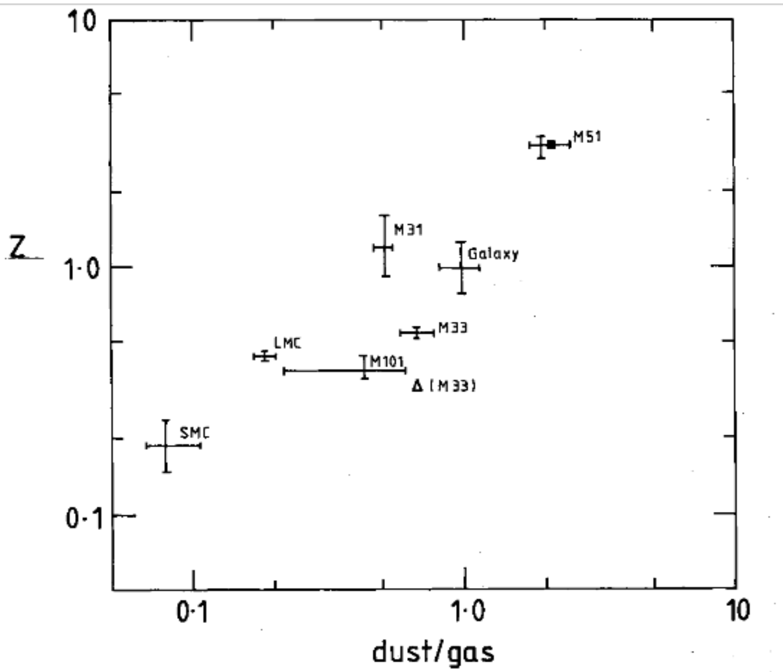


Fig. 3. Metallicity values at $R/R_{dV} = 0.7$ for local galaxies, plotted against the dust-to-gas ratio at the same radius. The values are all normalised to our Galaxy (dust-to-gas ratio from Bohlin et al., 1978). The open triangle shows the metallicity value derived by Kwitter and Aller for M33, which is suspected of being too low (see text). The solid square is the M51 data without correction for H_2

Dust to gas ratio
(Issa et al. 1990):

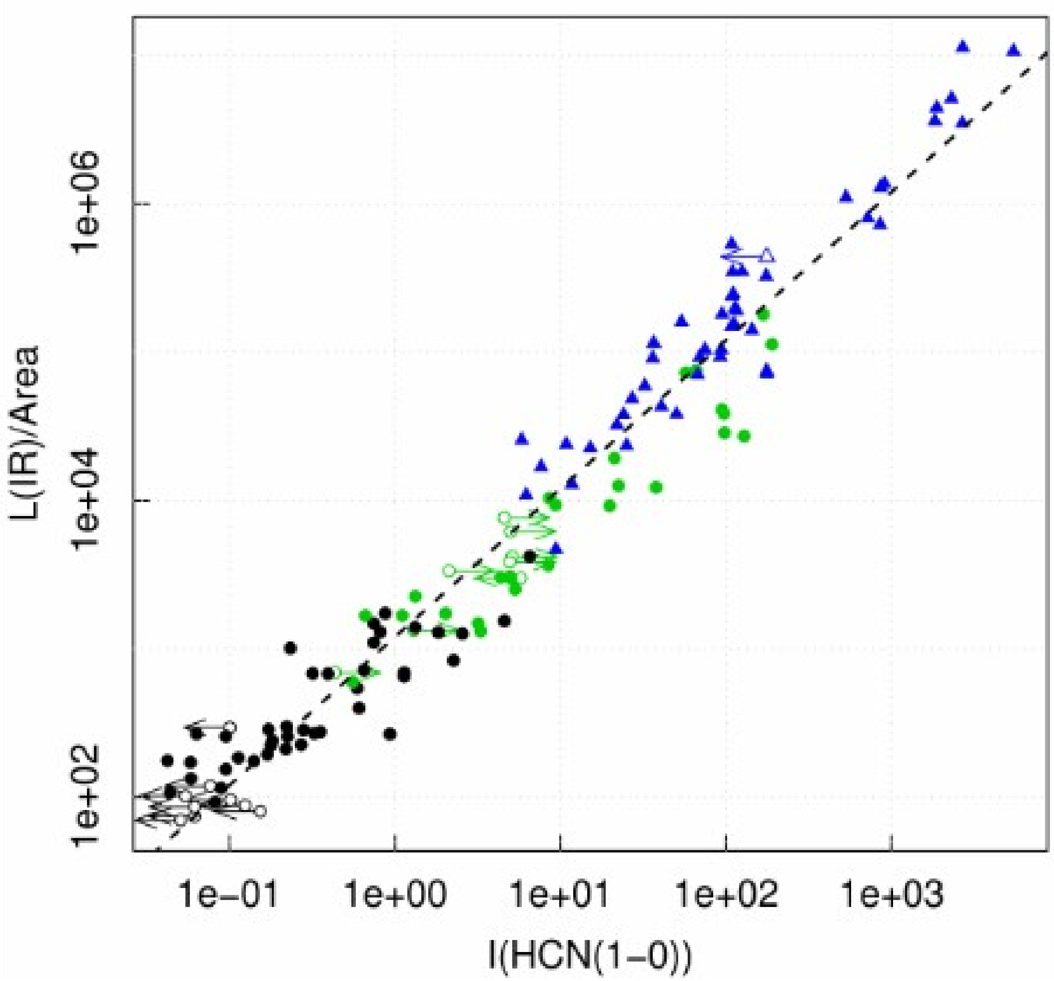
From Mdust, we can
Derive M(HI)+M(H2)

(with a metallicity effect)

- Gamma Rays (prop. To cosmic ray density x gas density)

- H2 absorption lines in the UV (at low column densities)

The gas in galaxies



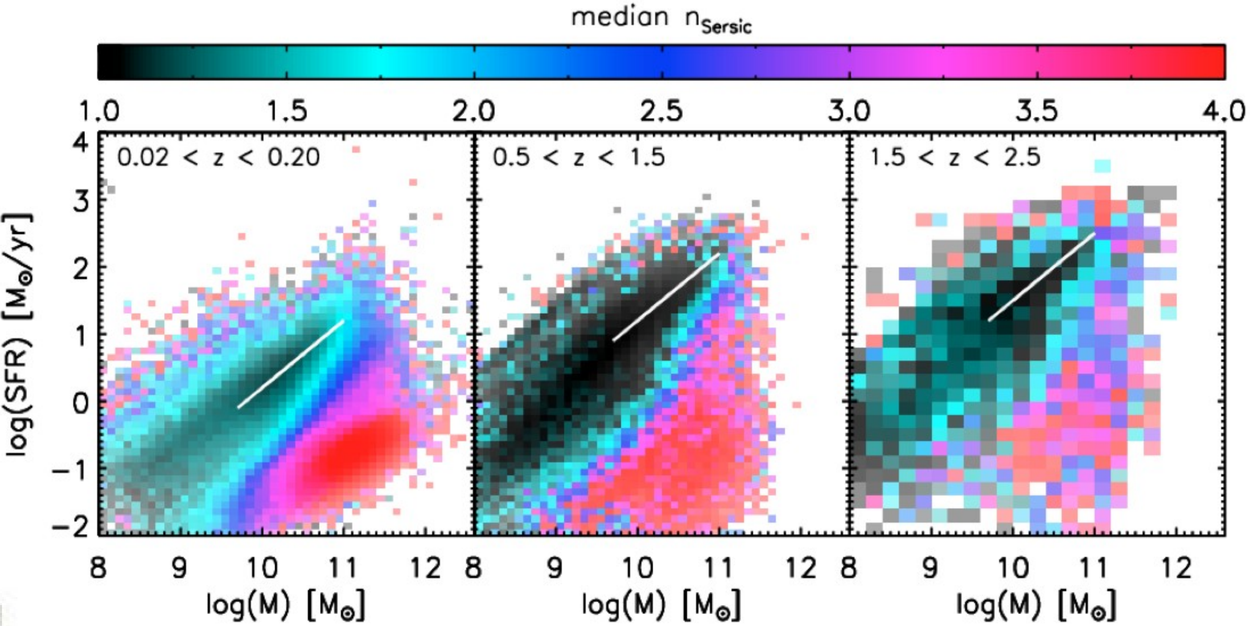
Use of other molecules:
HCN traces the DENSE molecular gas

STAR FORMATION LAWS

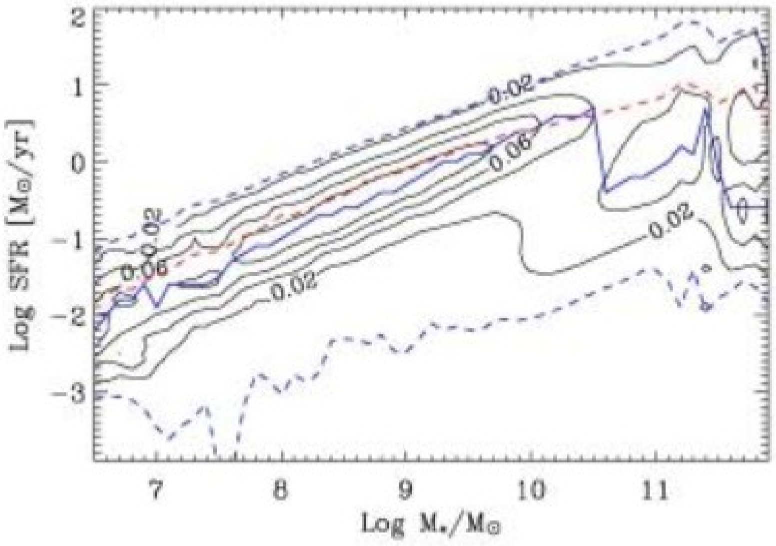
a) Threshold theories
b) Influences on SF
c) The scales
d) State of the art on various scales
e) Measurements : gas
f) SFR – Z – M* relation

SFR – STELLAR MASS RELATION

A relation exist between SFR and stellar mass at various redshift. It is often called the galaxies “main sequence” (after Noeske et al. 2007, I believe) but a very confusing nickname).



e.g. Wuyts et al. 2011



e.g. Brinchmann et al. 2004 in SDSS

SFR – METALS – STARS RELATIONSHIP

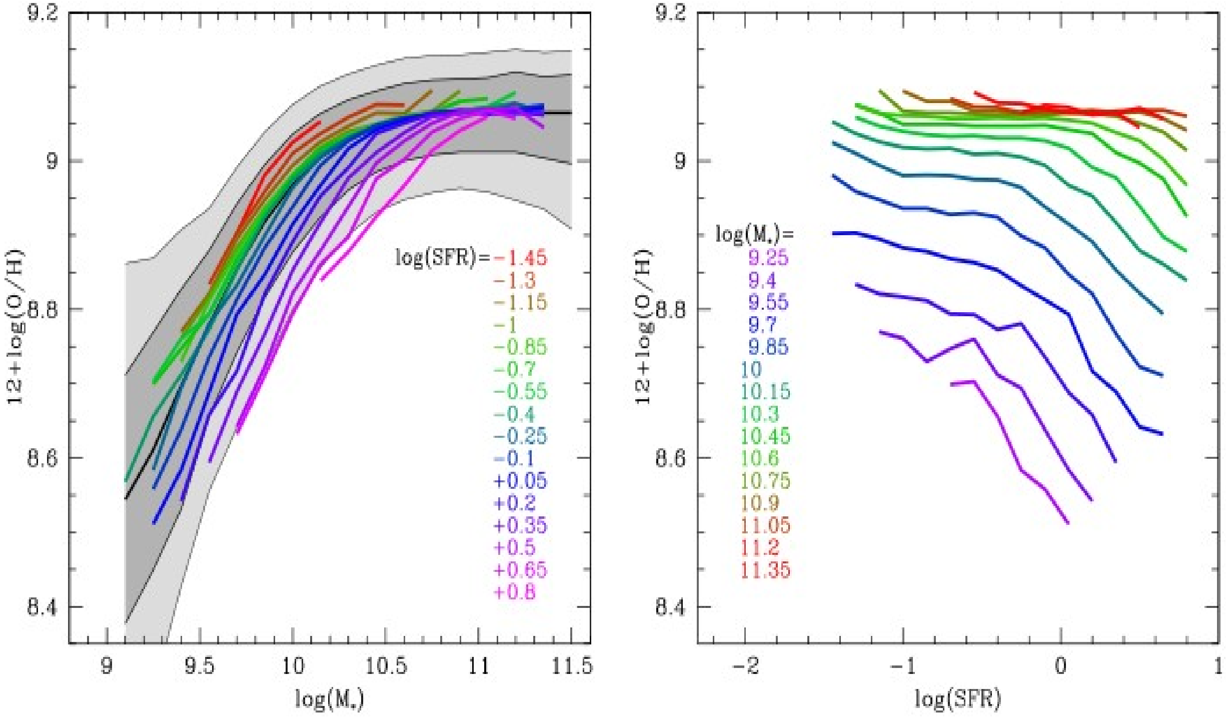
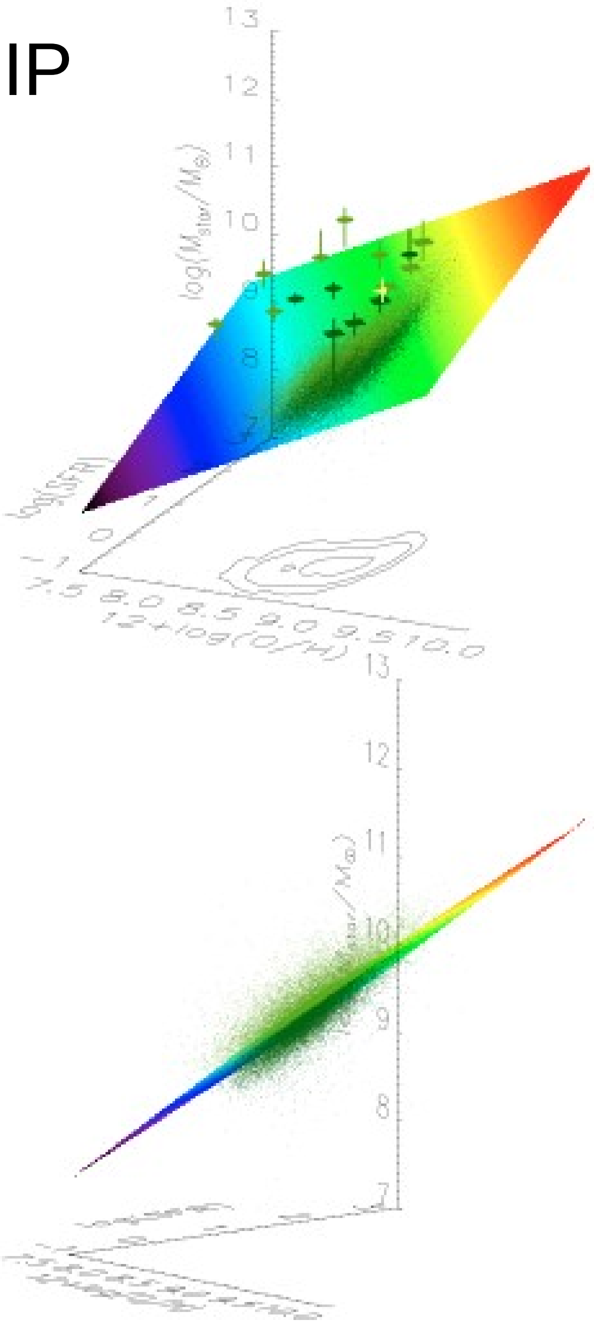


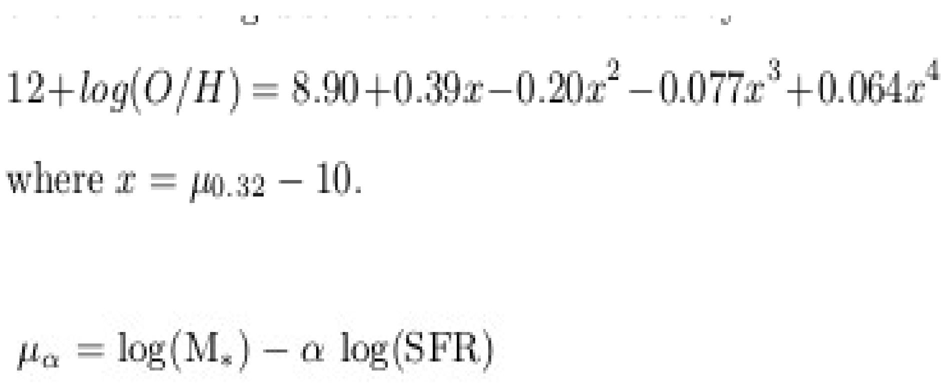
Figure 1. *Left panel:* The mass-metallicity relation of local SDSS galaxies. The grey-shaded areas contain 64% and 90% of all SDSS galaxies, with the thick central line showing the median relation. The colored lines show the median metallicities, as a function of $M_\star$, of SDSS galaxies with different values of SFR. *Right panel:* median metallicity as a function of SFR for galaxies of different $M_\star$. At all $M_\star$ with $\log(M_\star)<10.7$, metallicity decreases with increasing SFR at constant mass .

Mannucci et al. 2010



Lara-Lopez et al. 2010

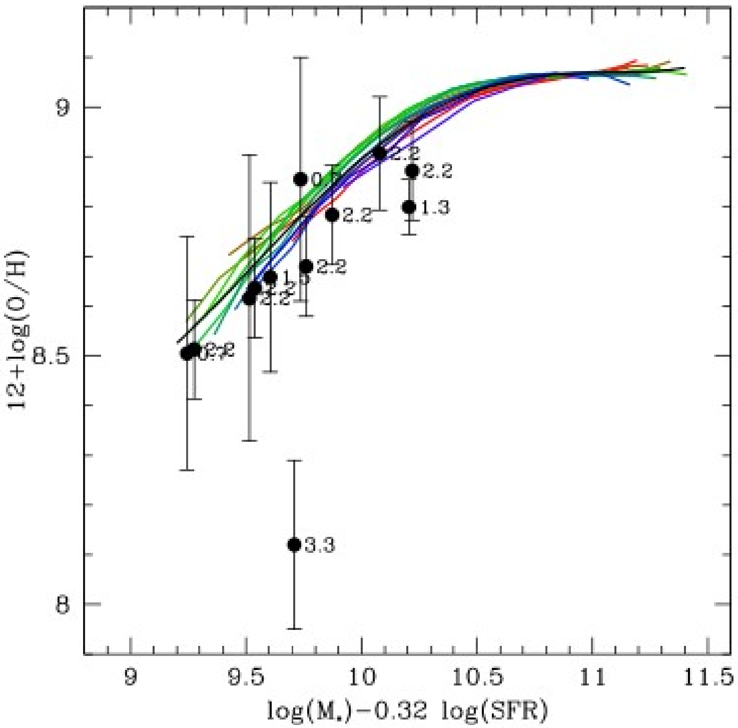
SFR – METALS – STARS RELATIONSHIP



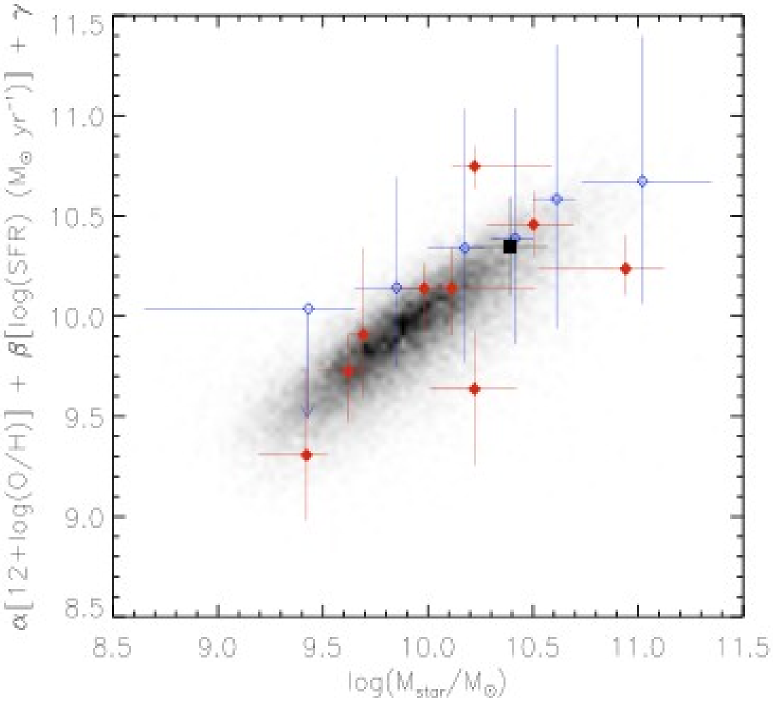
$$12+log(O/H) = 8.90+0.39x-0.20x^2-0.077x^3+0.064x^4$$

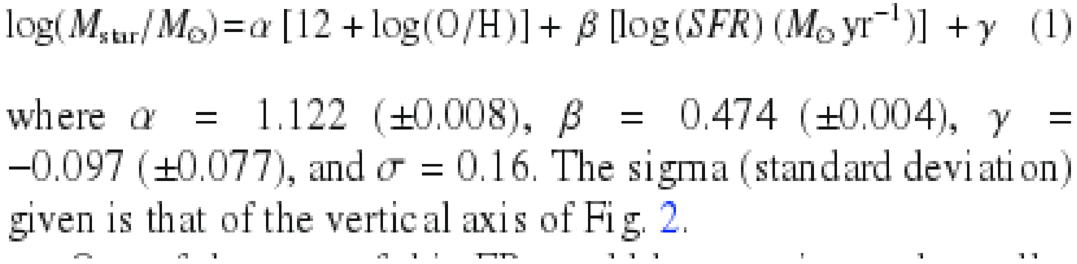
where $x = \mu_{0.32} - 10$.

$$\mu_\alpha = \log(M_*) - \alpha \log(SFR)$$



Mannucci et al. 2010





$$\log(M_{\rm star}/M_\odot) = \alpha\,[12+\log({\rm O/H})] + \beta\,[\log(SFR)\,(M_\odot\,{\rm yr}^{-1})] + \gamma \quad (1)$$

where α = 1.122 (±0.008), β = 0.474 (±0.004), γ = −0.097 (±0.077), and σ = 0.16. The sigma (standard deviation) given is that of the vertical axis of Fig. 2.

Lara-Lopez et al. 2010

Simple analytical models in Dayal et al. 2013