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ESO Santiago  
March 23<sup>rd</sup>, 2015

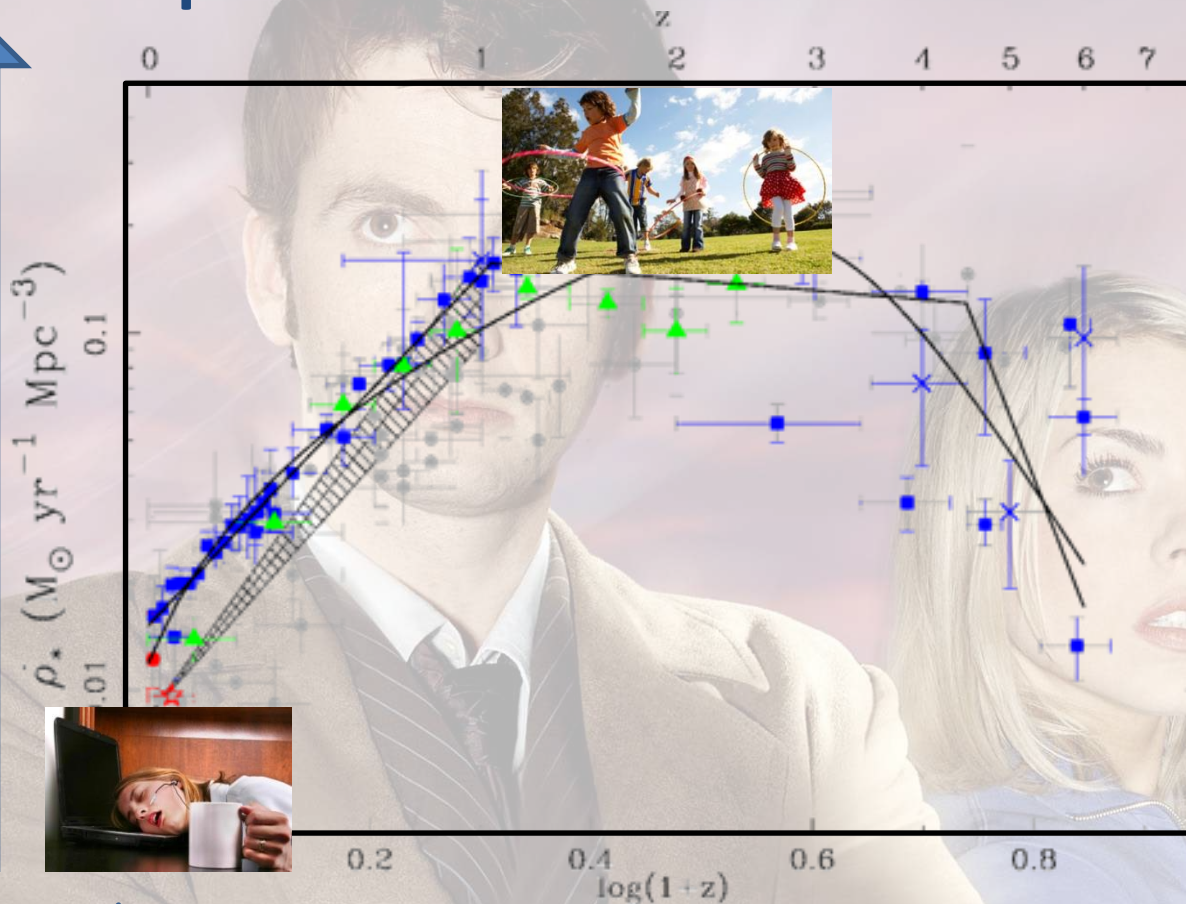
# Stirring Up the Gas: Star Formation and Powering High Pressures in galaxies 10 Billion Years Ago





# An epoch of intense activity

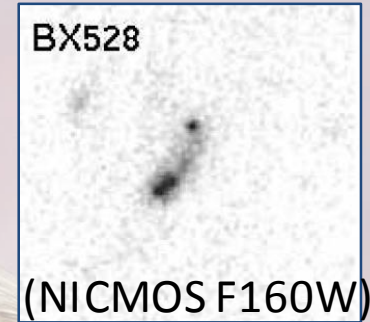
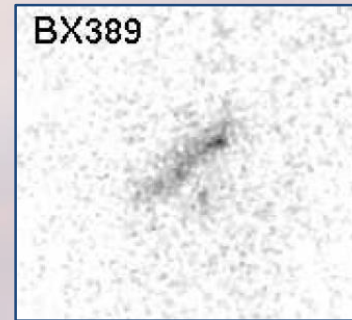
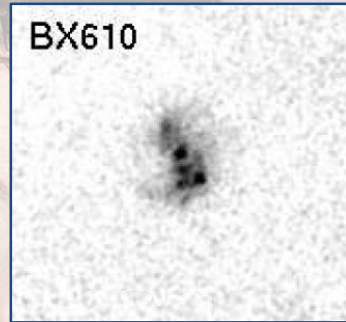
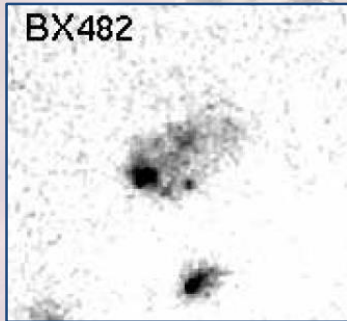
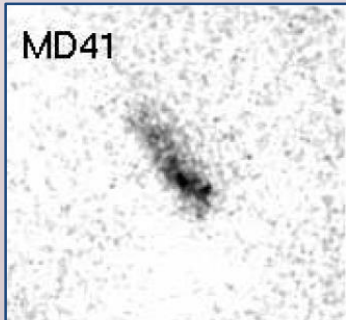
More stars created



Time

*Hopkins & Beacom, 2006*

# Irregular morphologies



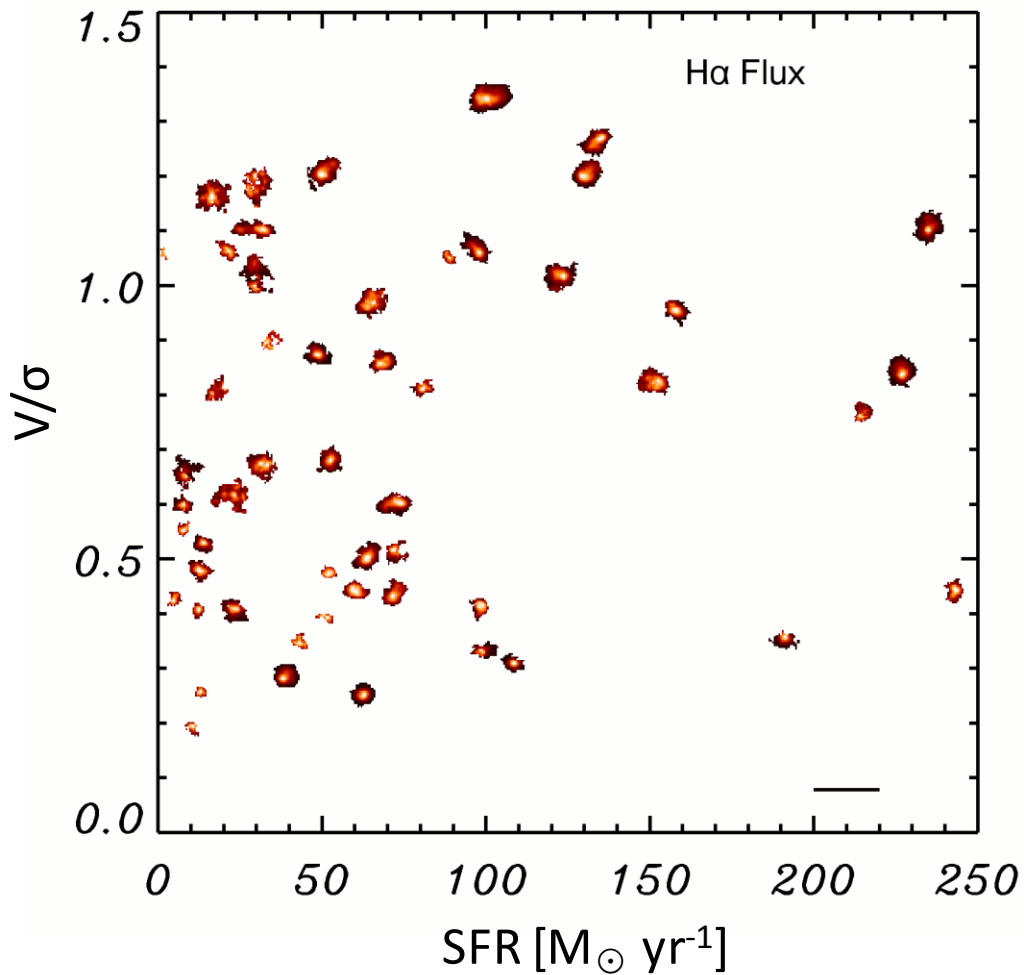
- Morphologies are increasingly irregular towards higher redshifts.
- The covering fraction of star forming regions appears to be high in intensely star forming galaxies.



Put your glasses on Rose,  
we're doing  
**3D spectroscopy!**



# The sample used for this work



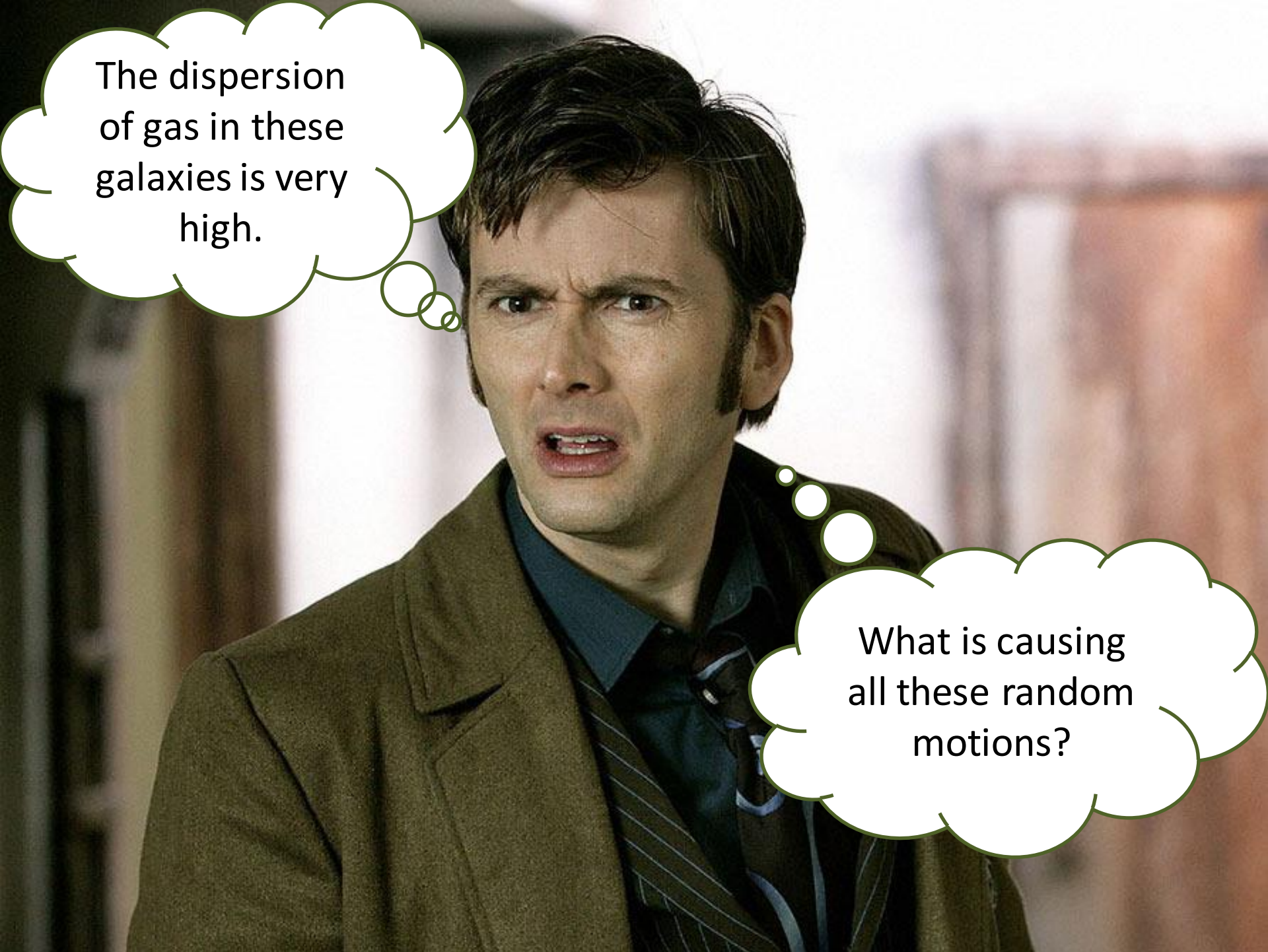
53 galaxies

$1.3 < z < 2.7$

$\langle \text{Area} \rangle \approx 200 \text{ kpc}^2$

$\langle \text{SFR} \rangle \approx 70 M_{\odot} \text{ yr}^{-1}$

$\langle v/\sigma \rangle \approx 1$

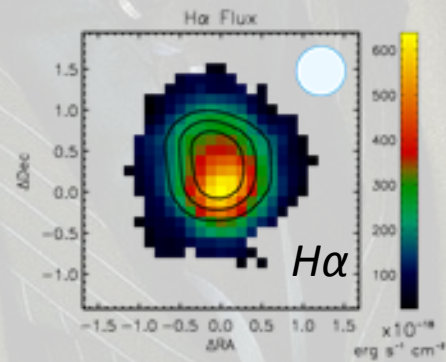
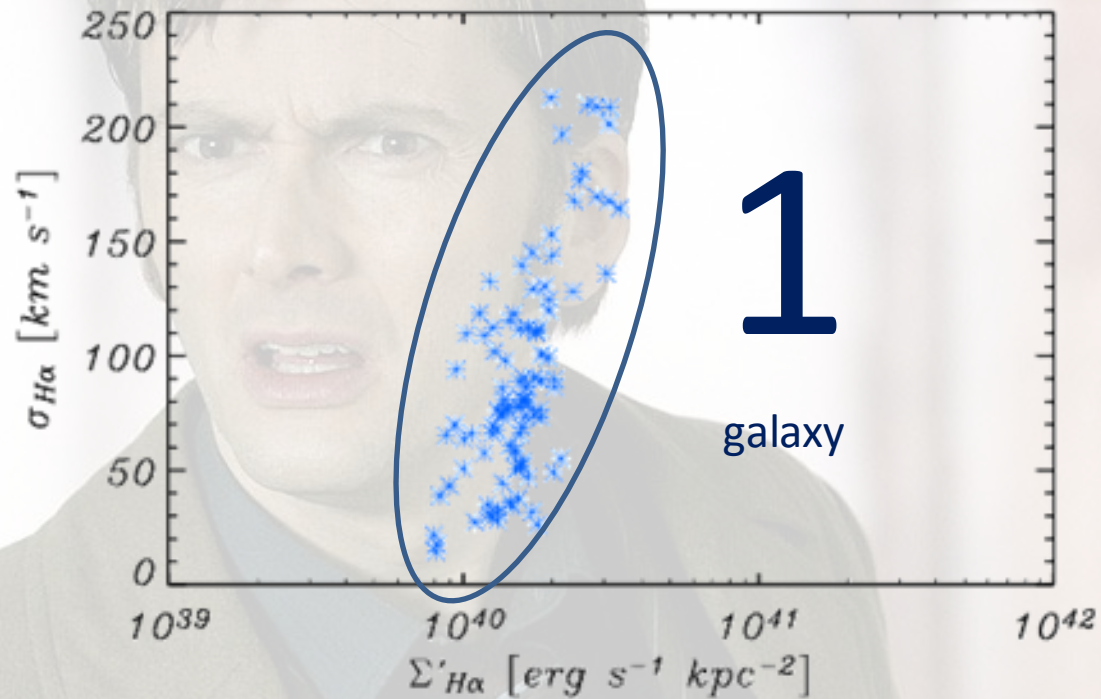
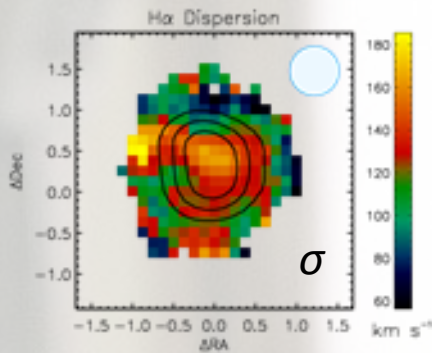
A man with dark hair, wearing a brown coat over a dark blue shirt and a striped tie, has a confused expression. He is looking slightly to the right. Two thought bubbles are overlaid on the image. The first bubble is in the top left, and the second is in the bottom right. The background is a blurred indoor setting with wooden paneling.

The dispersion  
of gas in these  
galaxies is very  
high.

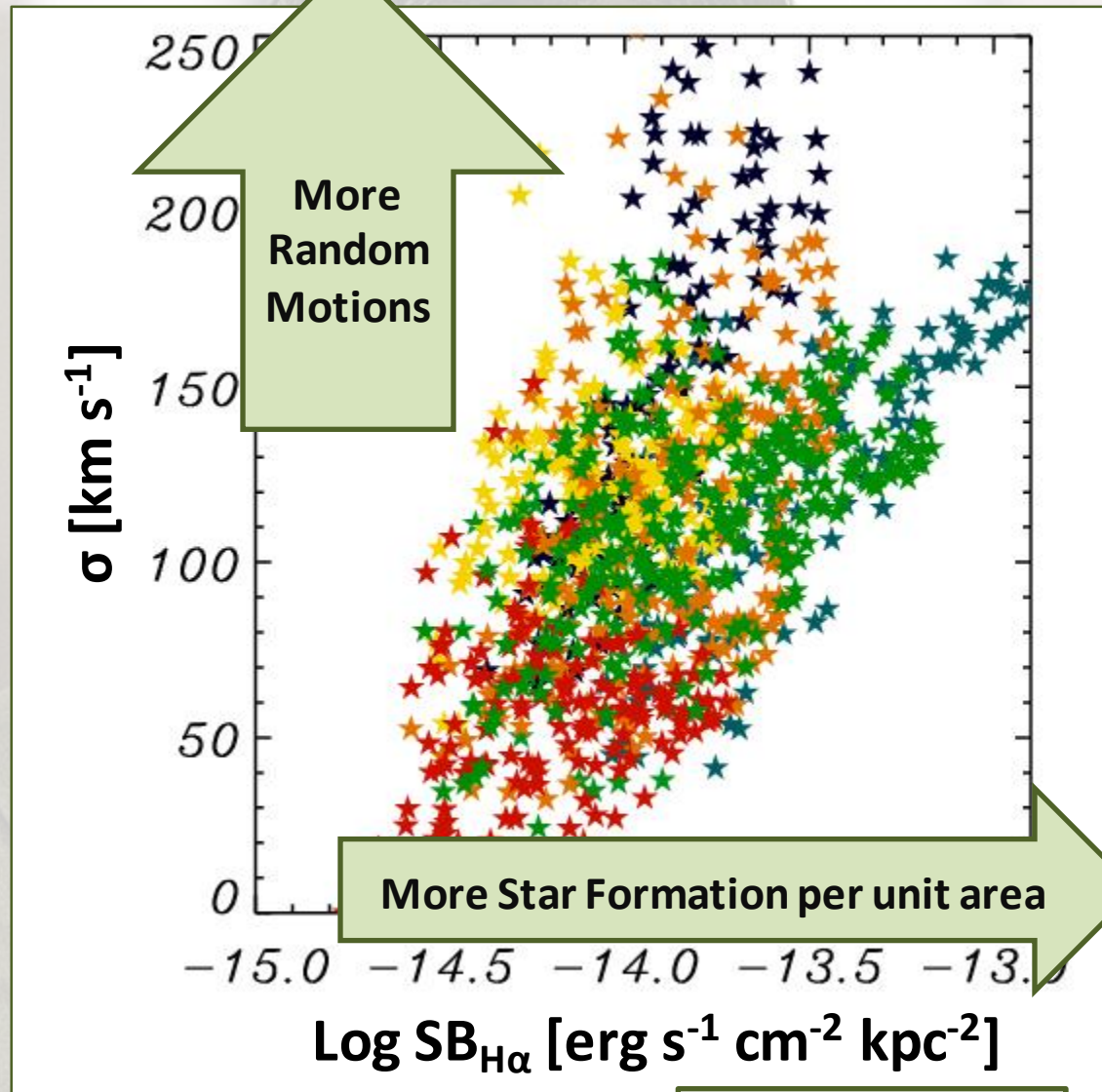
What is causing  
all these random  
motions?



# Random motions VS H $\alpha$ luminosity



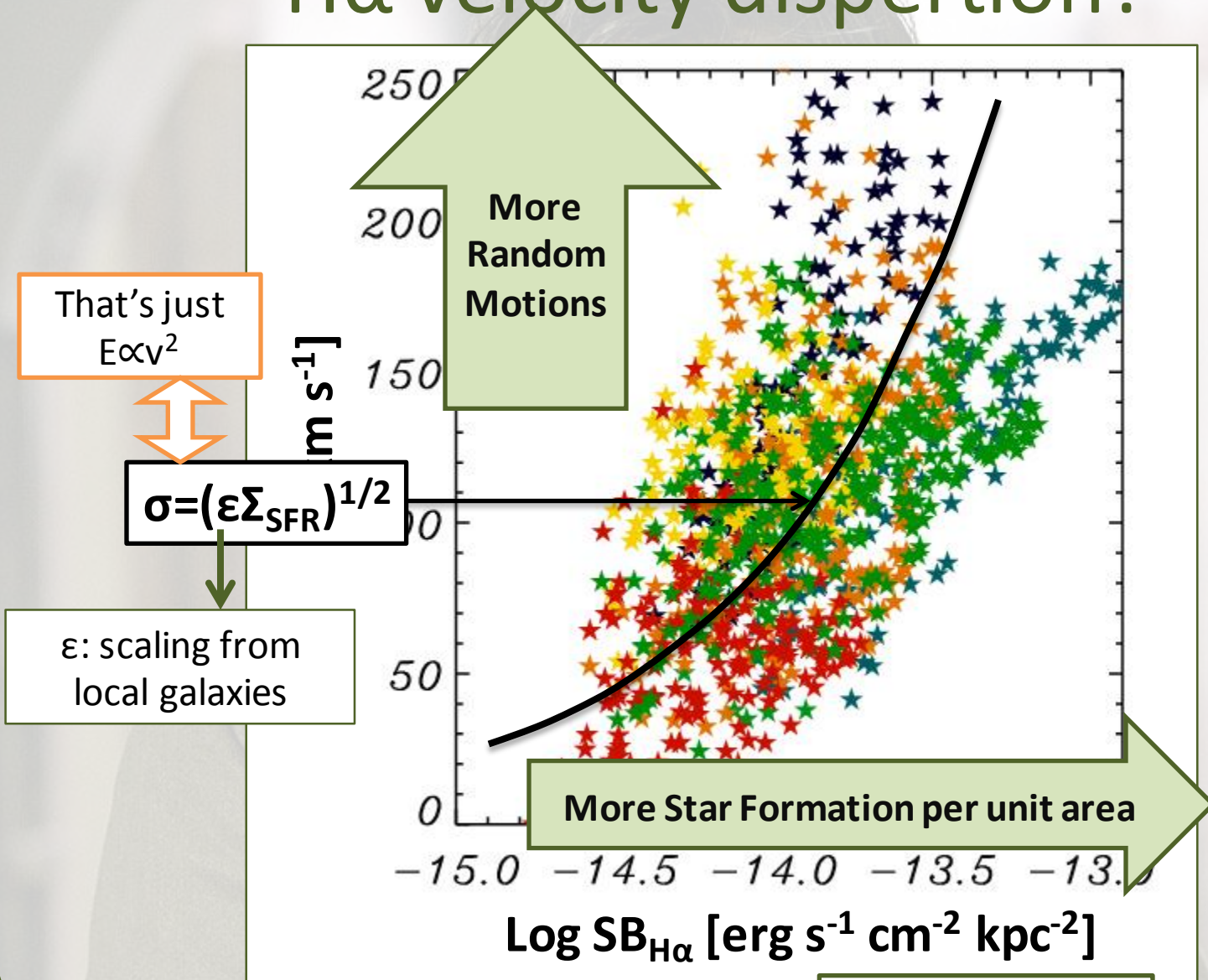
# Is there a trend between SFR and H $\alpha$ velocity dispersion?




*Lehnert et al. (2009)*



# Is there a trend between SFR and H $\alpha$ velocity dispersion?



A man and a woman are standing in profile, facing each other in a museum or gallery. The woman is on the left, wearing a light blue sweater and black pants. The man is on the right, wearing a dark suit. They are looking at a large, vibrant projection on the wall behind them, which depicts a star formation with bright yellow and orange colors. A speech bubble is positioned above the woman, containing text. The overall scene is dimly lit, with the projection being the primary light source.

So do you think these  
random motions are  
produced by the intense  
star formation?

*All your praying moments amount to just one breath*



What else?



Lehnert+2009,2013, Le Tiran+2011ab




Maybe gas accretion produces these random motions?

Let's check!



What quantity of gas infall do we need to fuel the H $\alpha$  luminosities?

50 000  $M_{\odot} \text{ yr}^{-1}$



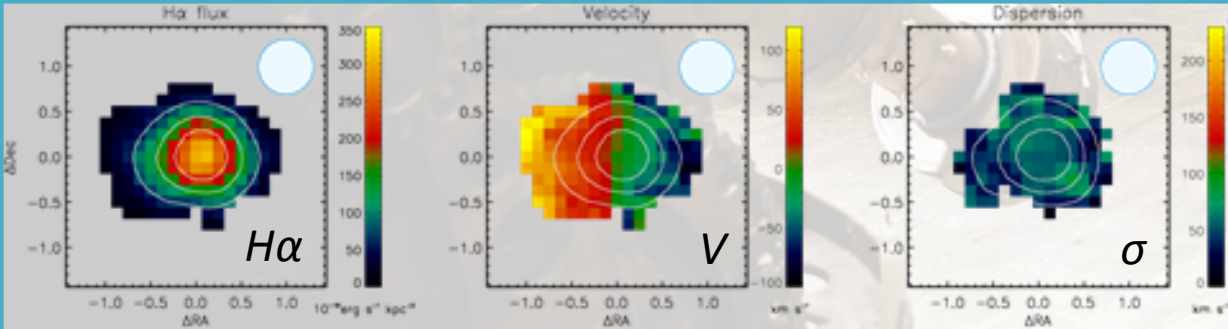
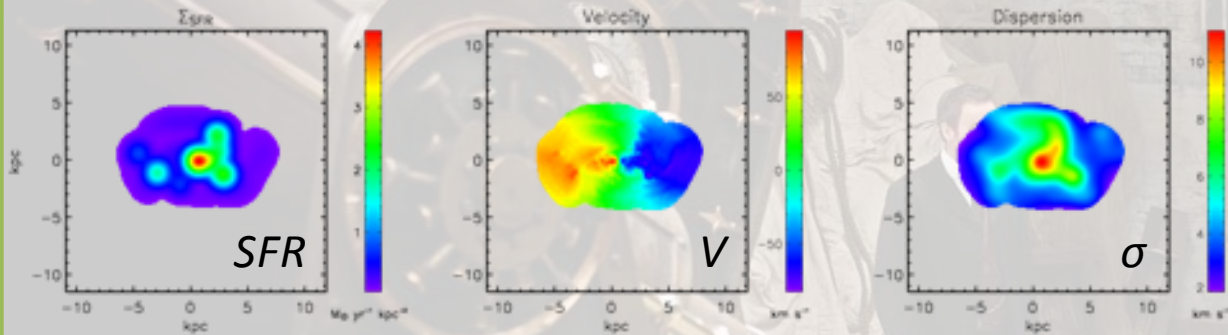
Maybe the large  $H\alpha$  linewidths are just an instrumental effect?

Beam smearing? I don't think so. Here's why...



# Quantifying the Effects of Beam Smearing

N-body/SPH Simulation (Di Matteo, Bournaud et al. 2008)

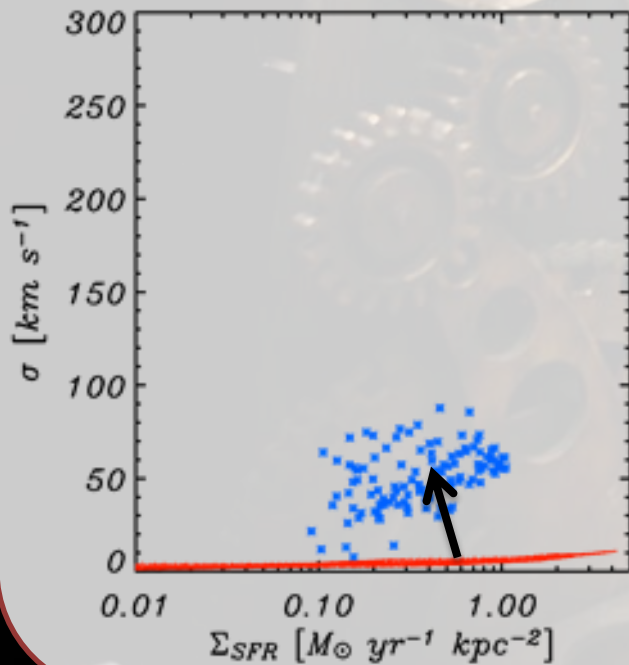
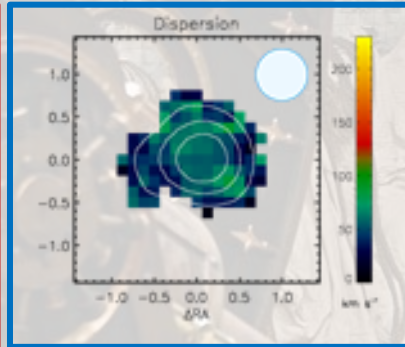
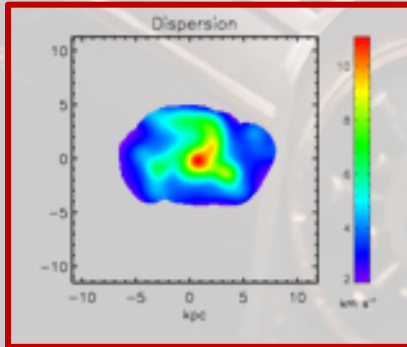


Virtual observation

We can use simulated “clumpy disks” and analog them to a virtual SINFONI observation, in order to study the importance of beam smearing

# Quantifying the Effects of Beam Smearing

gravitational dispersion

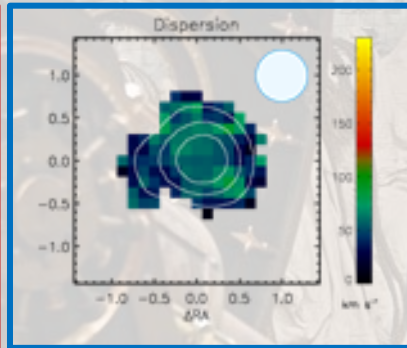
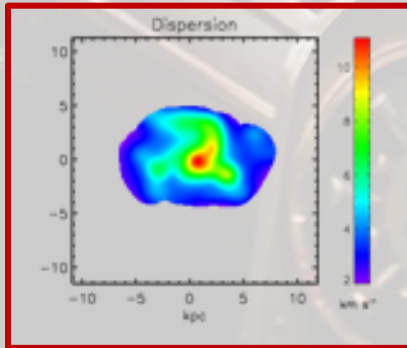


We can use simulated “clumpy disks” and analog them to a virtual SINFONI observation, in order to study the importance of beam smearing

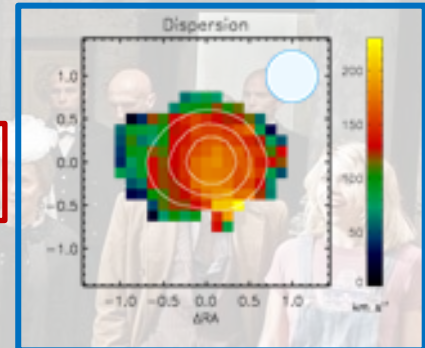


# Quantifying the Effects of Beam Smearing

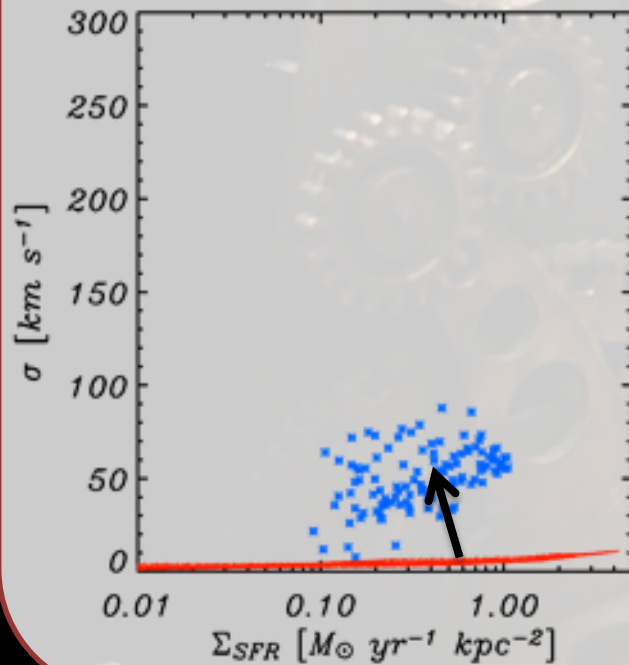
gravitational dispersion



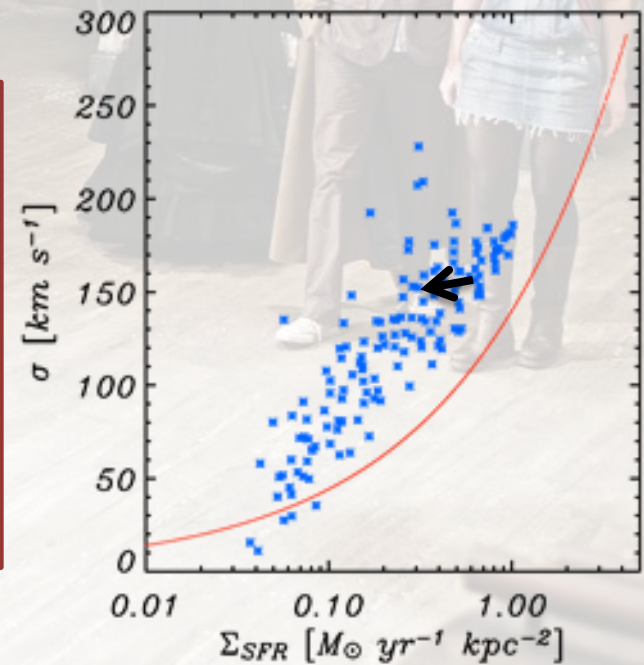
analytic dispersion



$$\sigma = (\epsilon \Sigma_{\text{SFR}})^{1/2}$$



We can use simulated “clumpy disks” and analog them to a virtual SINFONI observation, in order to study the importance of beam smearing





\$1 Million



What is stirring up the gas?


A: Gas accretion

B: An instrumental effect

C: Star formation

D: The moon





You know M82, the starburst,  
right? Well, it's a bit the same  
thing that in M82...

...but different.



The image is a composite of the painting 'The Starry Night' by J.M.W. Turner. The scene depicts a coastal town at night, with a prominent church spire in the center. The sky is filled with vibrant, swirling patterns of blue and yellow, representing stars and a full moon. A TARDIS, a blue police box from the British science fiction series Doctor Who, is superimposed on the right side of the painting, appearing to fly through the turbulent sky. In the center, a white rounded rectangle with a dark blue border contains the word 'Thanks!' written in a black, cursive font.

*Thanks!*





## Mensageiro Sideral

De onde viemos, onde estamos e para onde vamos



Perfil

Salvador Nogueira é jornalista de ciência e autor de oito livros.

PERFIL COMPLETO

## Câmara aprova Brasil no ESO

POR SALVADOR NOGUEIRA

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Compartilhar

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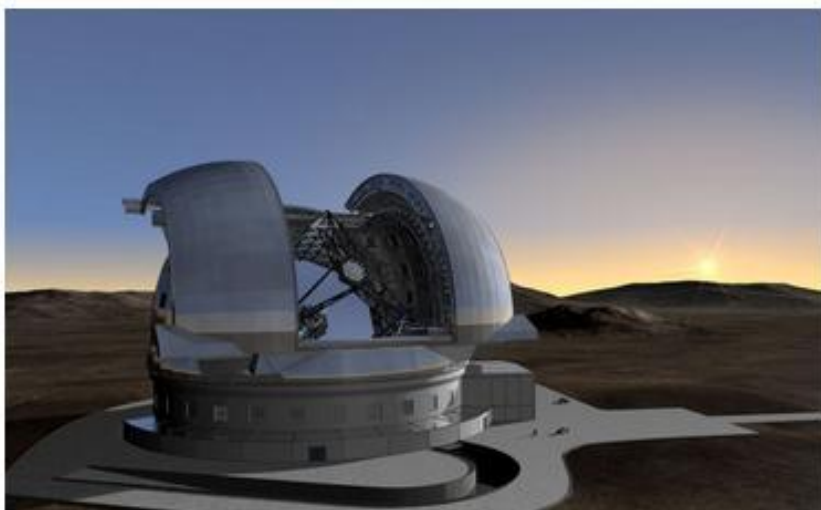
Twitter

68

3

OUVR O TEXTO

Depois de algumas **idas** e **vindas** que causaram comoção na comunidade astronômica, o acordo de adesão do Brasil ao ESO (Observatório Europeu do Sul) foi aprovado nesta quinta-feira (19) pelo Plenário da Câmara dos Deputados.



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The background of the slide is a reproduction of the painting 'The Starry Night' by Vincent van Gogh. It features a turbulent, swirling night sky with a bright yellow sun or moon in the upper right, a small lighthouse on a rocky outcrop, and a village with a church spire in the foreground. The sky is filled with numerous bright, glowing stars and a prominent crescent moon, all set against a deep blue background with swirling patterns.

## What's stirring-up the gas?

- Not an instrumental effect
- Not due to gas accretion
- Star formation!






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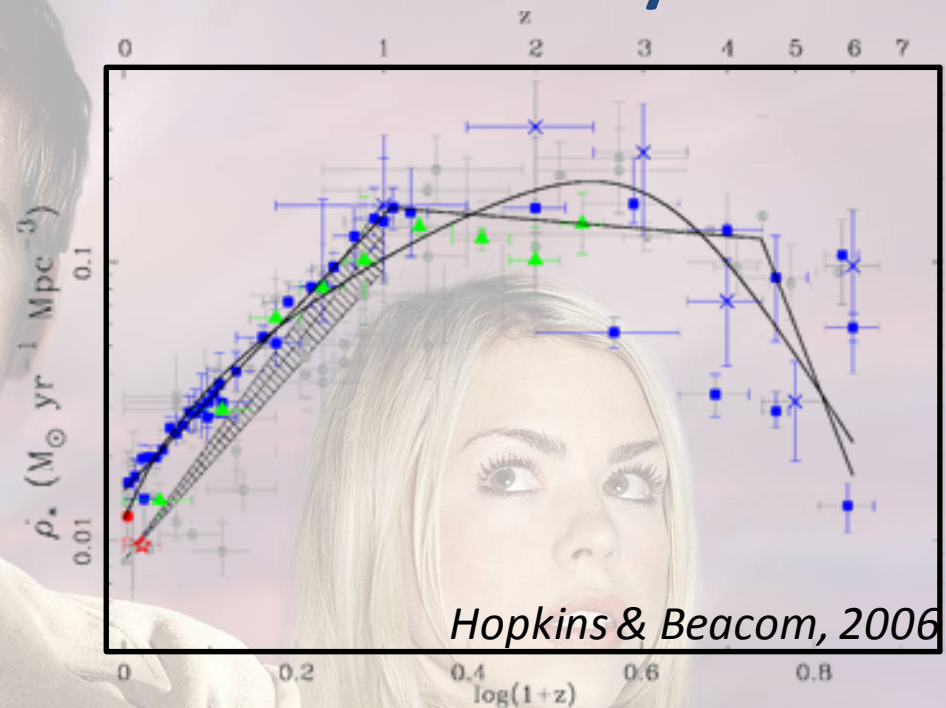
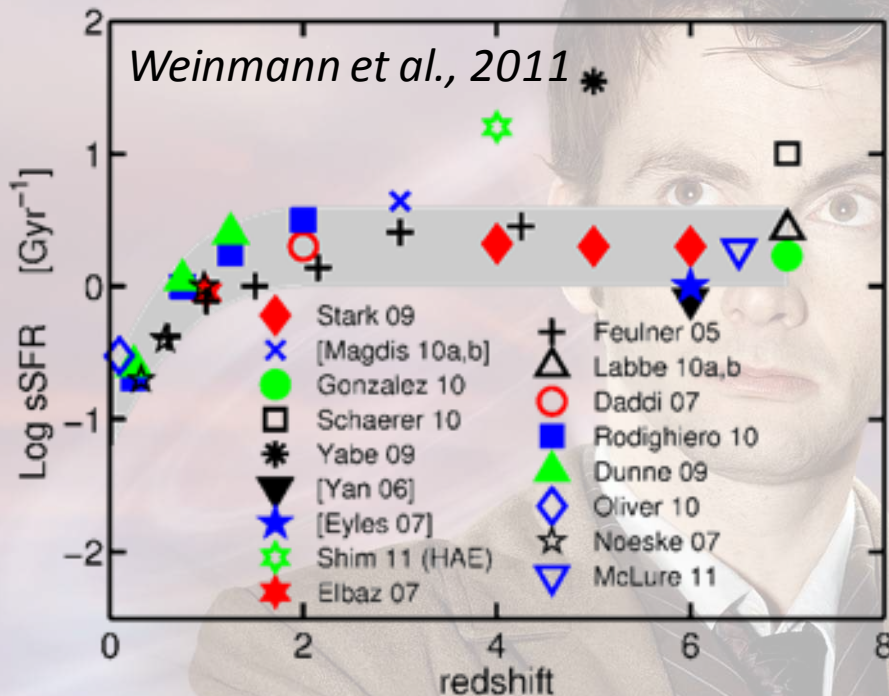


Where are we travelling  
today Doctor?

3 billion years after the  
Big Bang Rose...



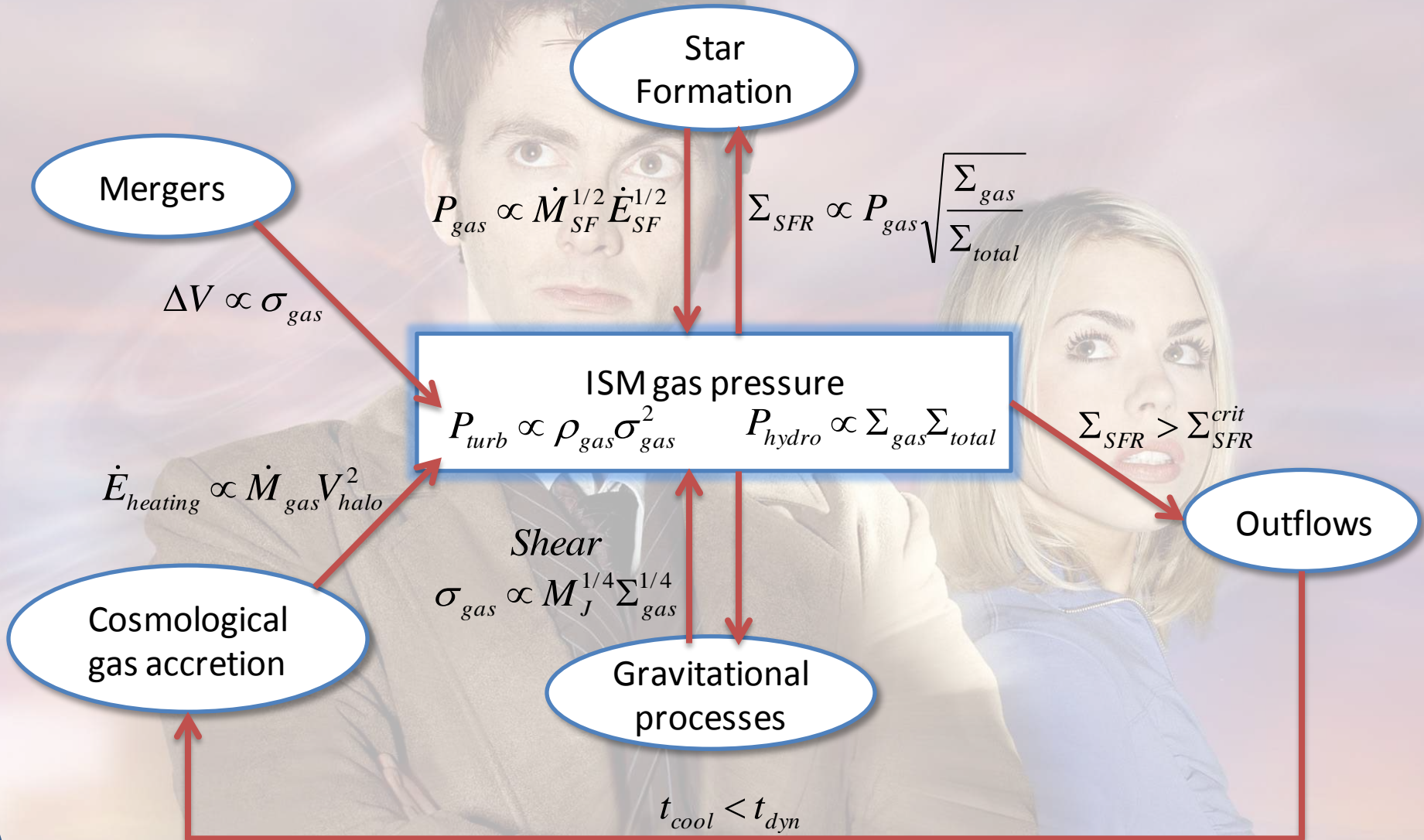
# An epoch of intense activity



Hopkins & Beacom, 2006

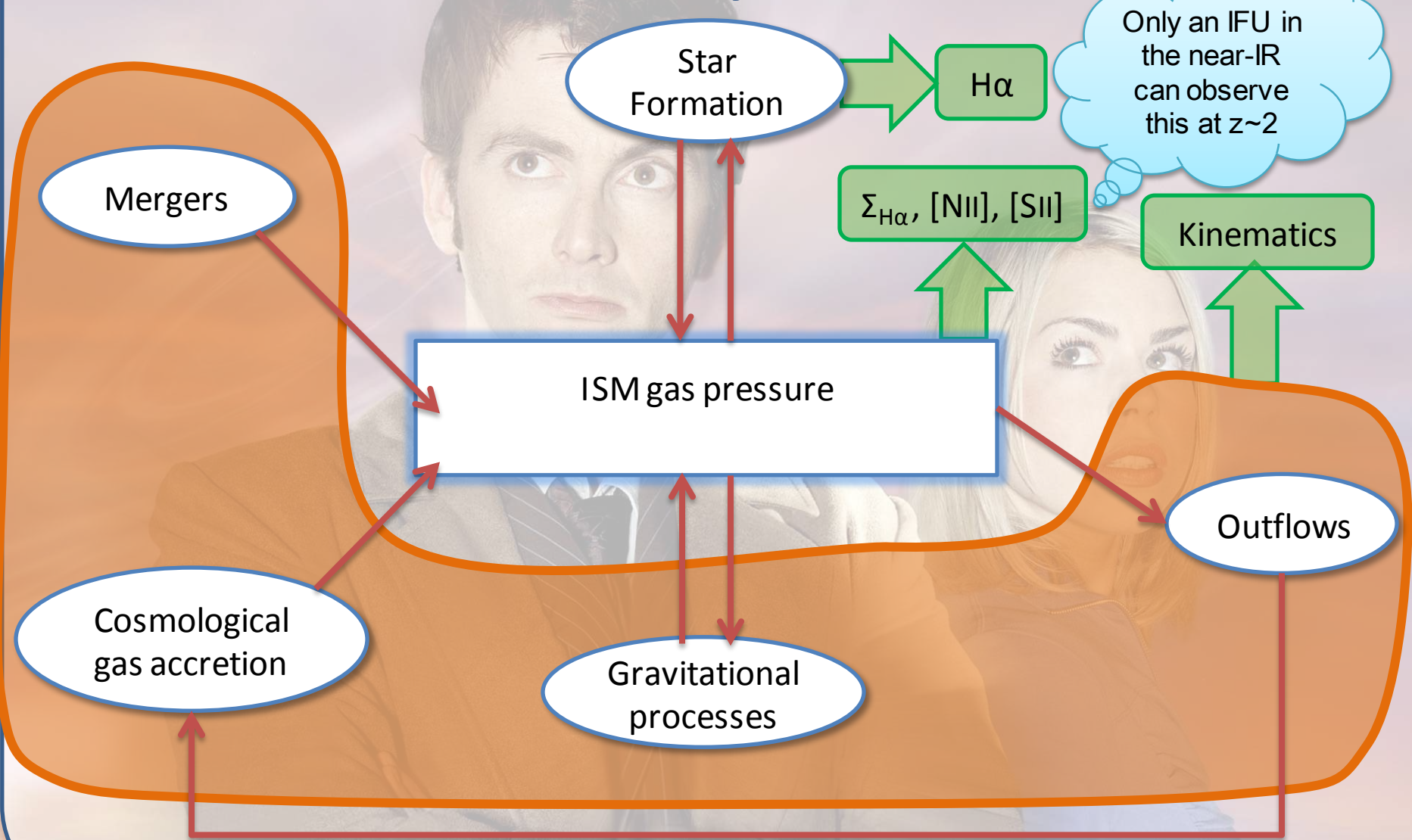
The relative growth rate of individual galaxies, and of the ensemble of galaxies, reaches a maximum at  $z=1-3$

# Galaxies: a variety of processes

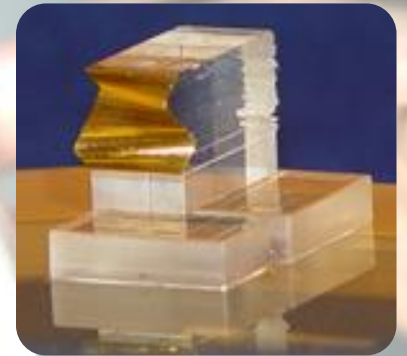
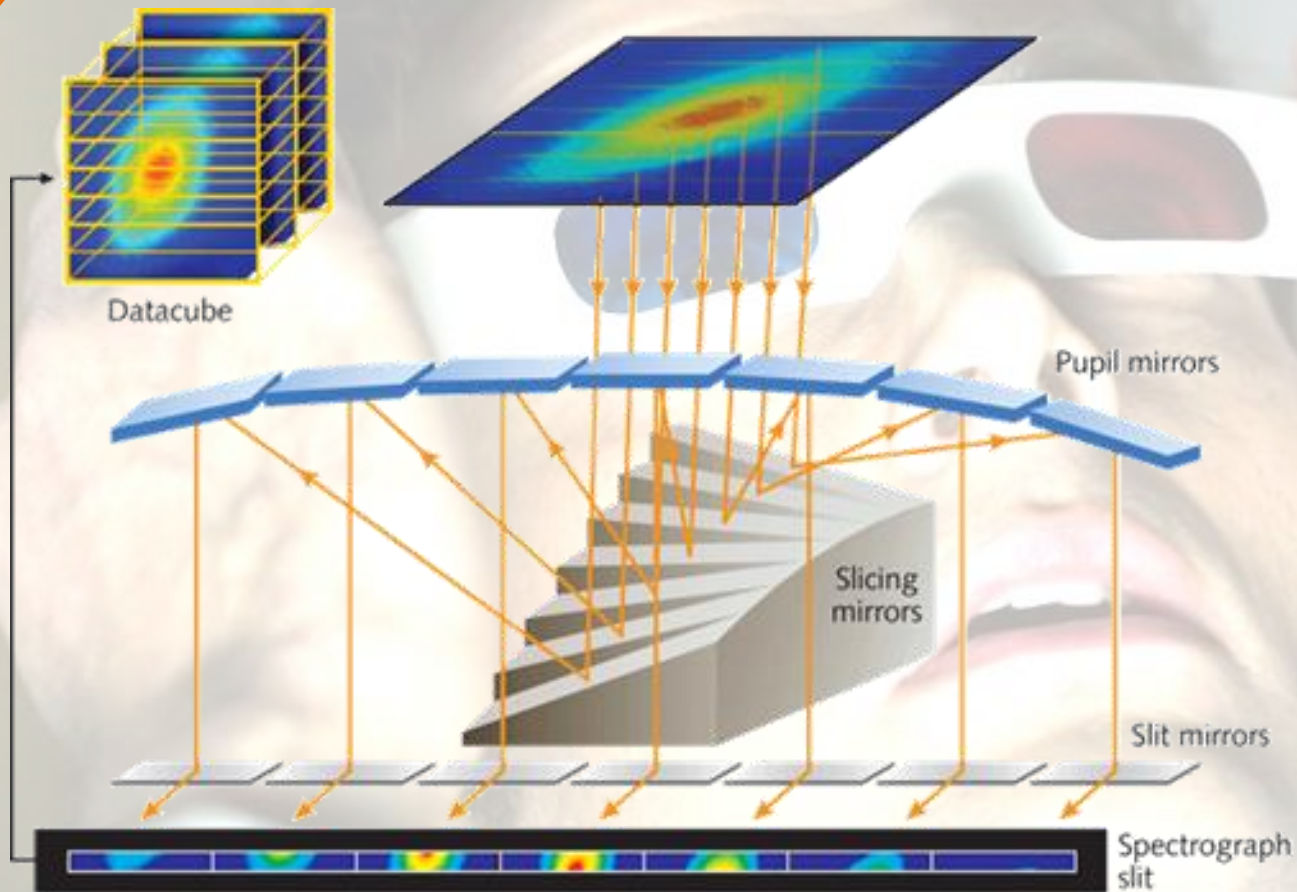




# Galaxies: a variety of observables



# Integral Field Spectroscopy with SINFONI

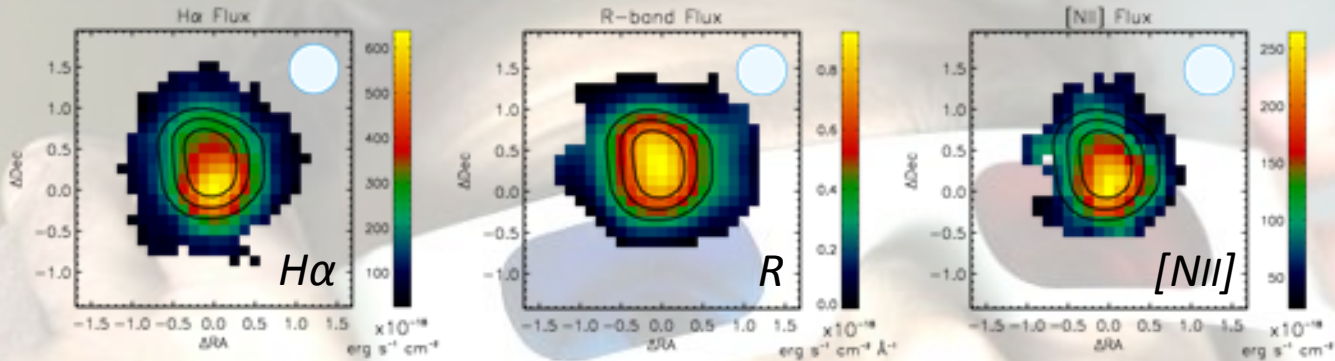


SINFONI uses an image slicer to produce spatially resolved spectroscopic data.

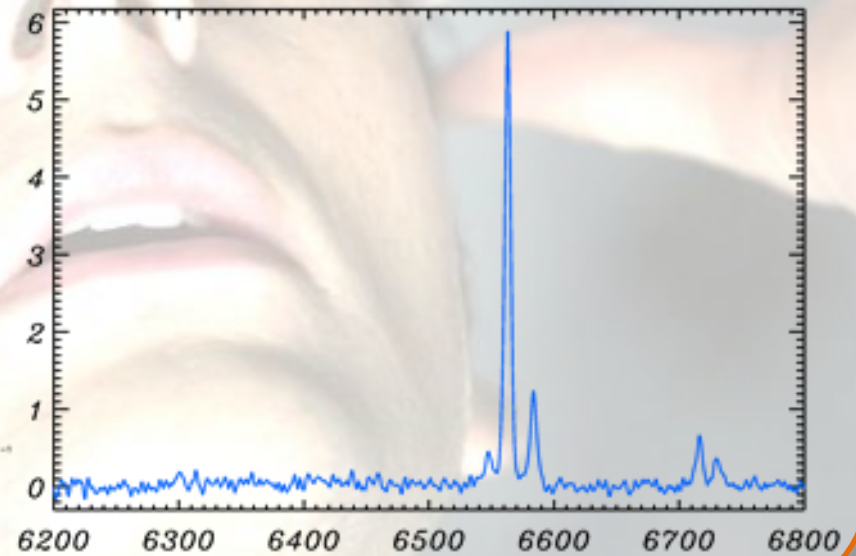
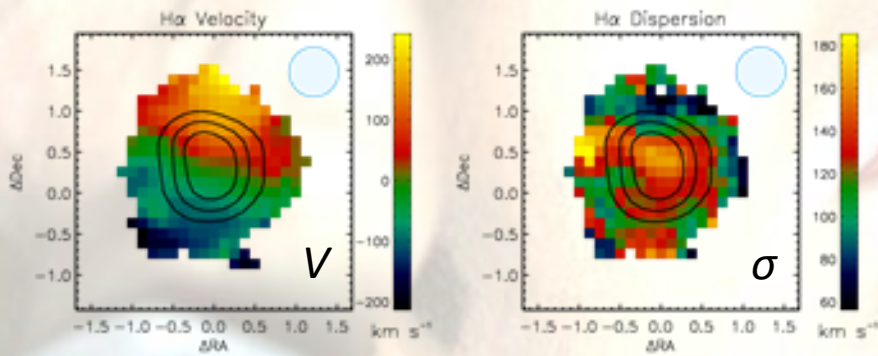


# The observables

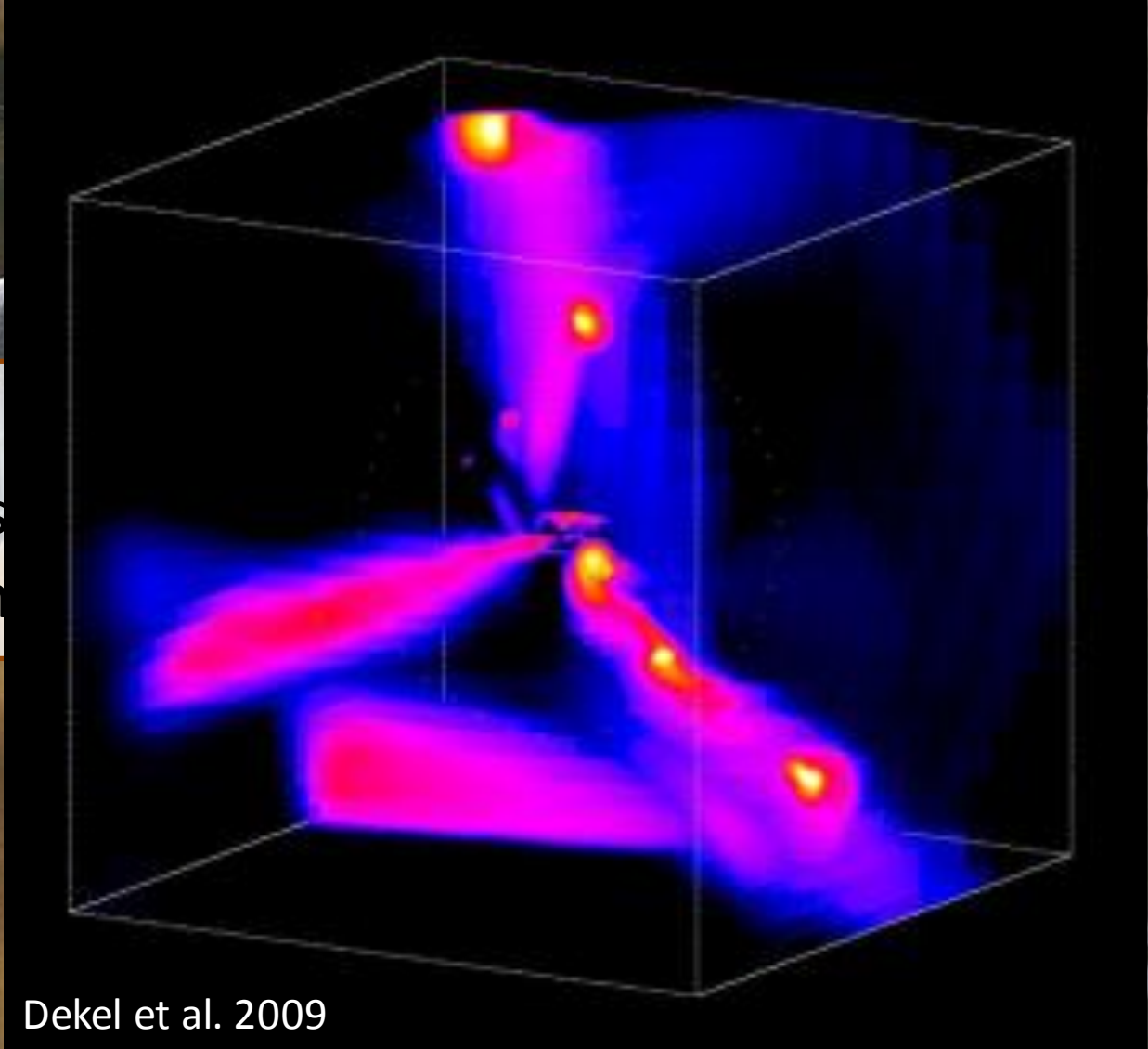
Morphology



Dynamics



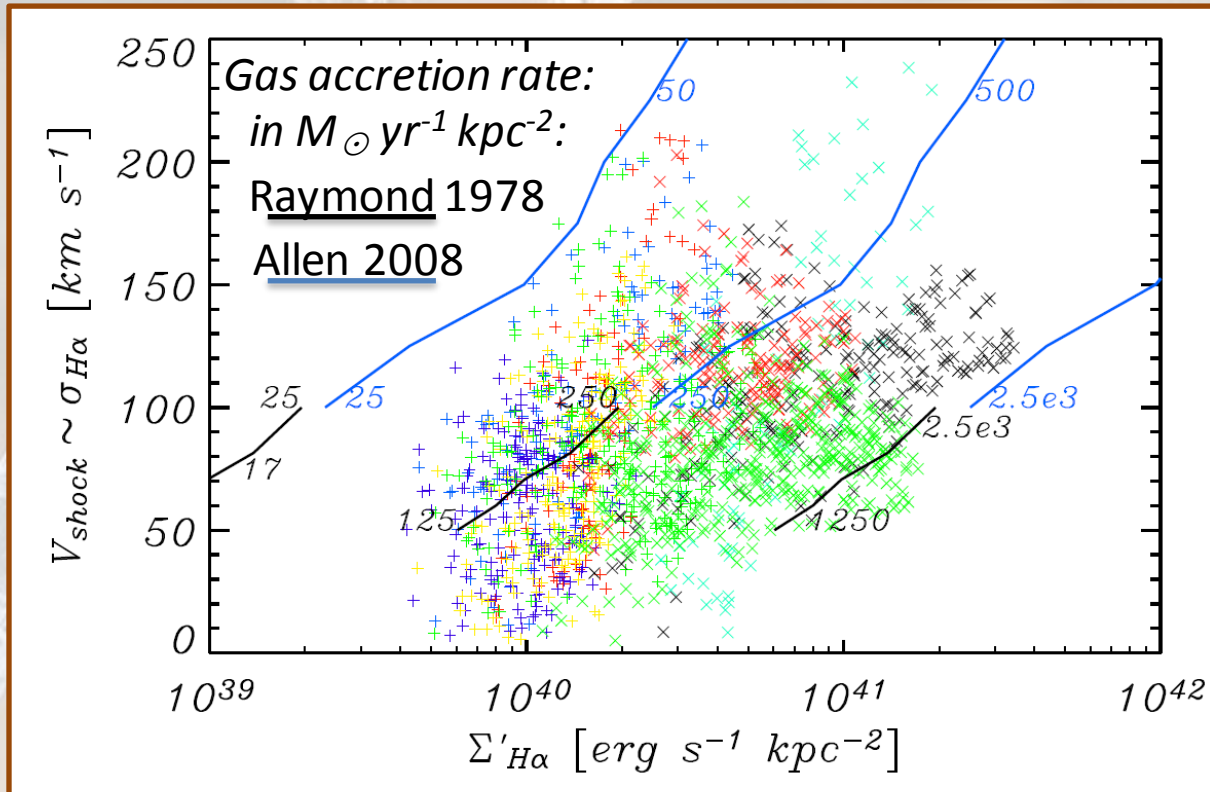
Maybe  
produces  
m



Dekel et al. 2009

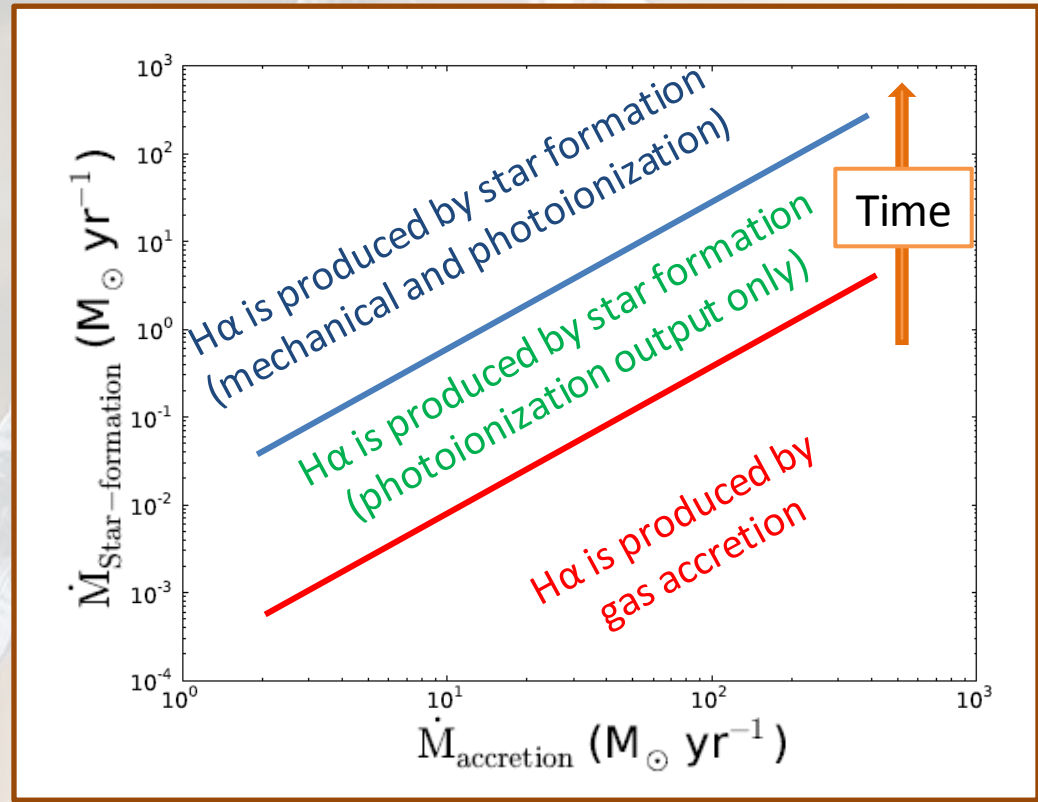


# What quantity of gas do we need to fuel the H $\alpha$ luminosities?



From shock models, we can show that an unrealistic gas accretion rate is needed to power the H $\alpha$  velocity dispersions and luminosities.

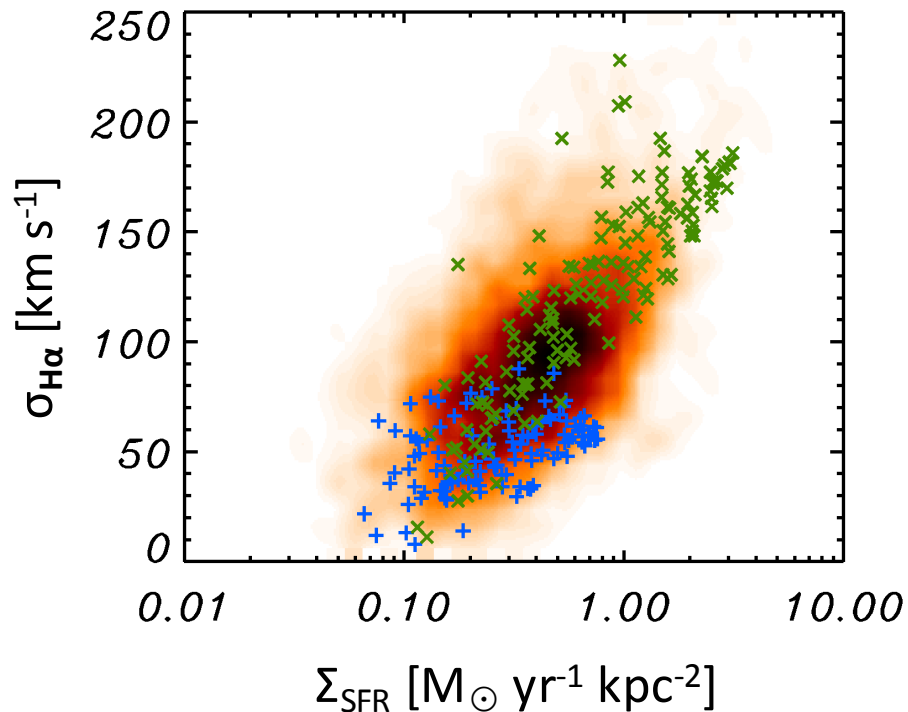
# Distinguishing between the different contributions of H $\alpha$ luminosity



We can model the different contributions from accretion and star formation. Observing the effect of gas accretion in H $\alpha$  will be difficult.



# Quantifying the Effects of Beam Smearing




Normalized distribution for the whole sample of galaxies

analytic dispersion  $\sigma = (\epsilon \Sigma_{\text{SFR}})^{1/2}$

gravitational dispersion

Even when taking account of the effects of beam smearing and spectral resolution, the range of dispersions in our sample of galaxies are best explained with energy output from star formation  $\sigma = (\epsilon \Sigma_{\text{SFR}})^{1/2}$



You know M82, the starburst,  
right? Well, it's a bit the same  
thing that in M82...

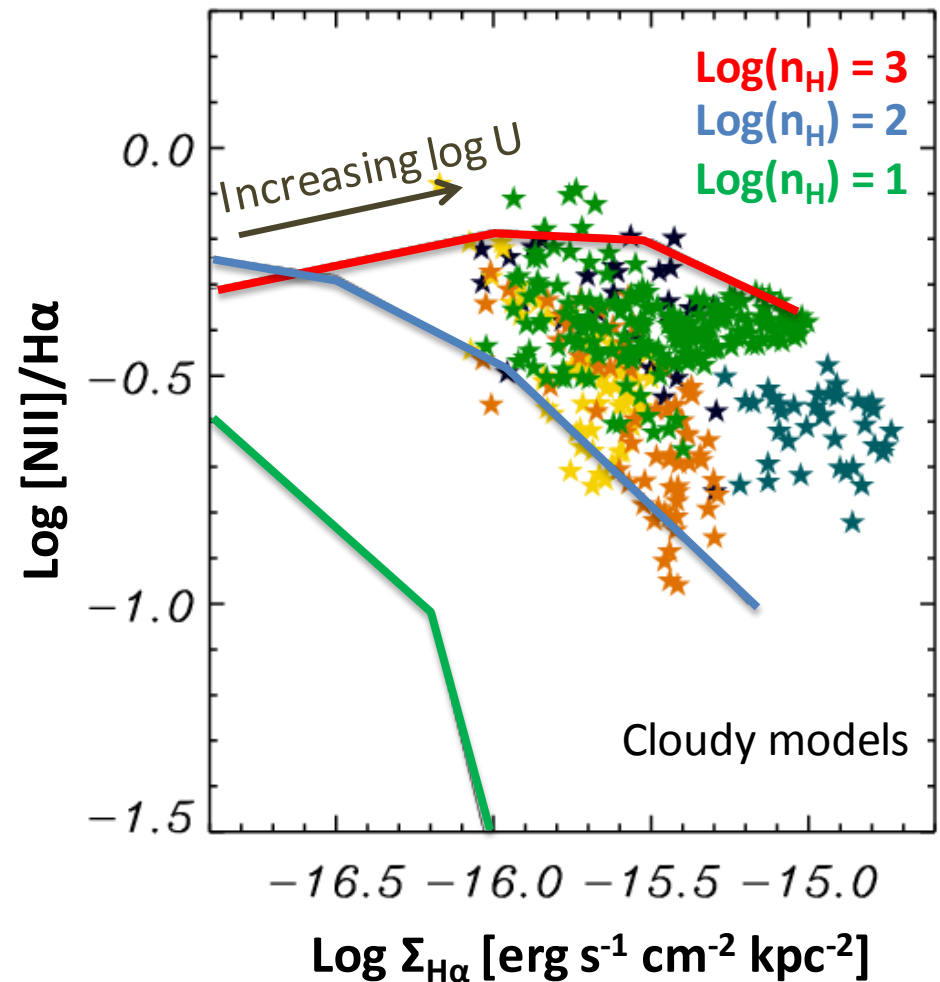
...but different.





# Similarity with the nuclei of intense starbursts: high pressures and densities

Modeling the line ratio of  $[\text{NII}]/\text{H}\alpha$  and  $\Sigma_{\text{H}\alpha}$  suggests the need to have high pressures and ionization parameter.





# Similarity with the nuclei of intense starbursts: high pressures and densities

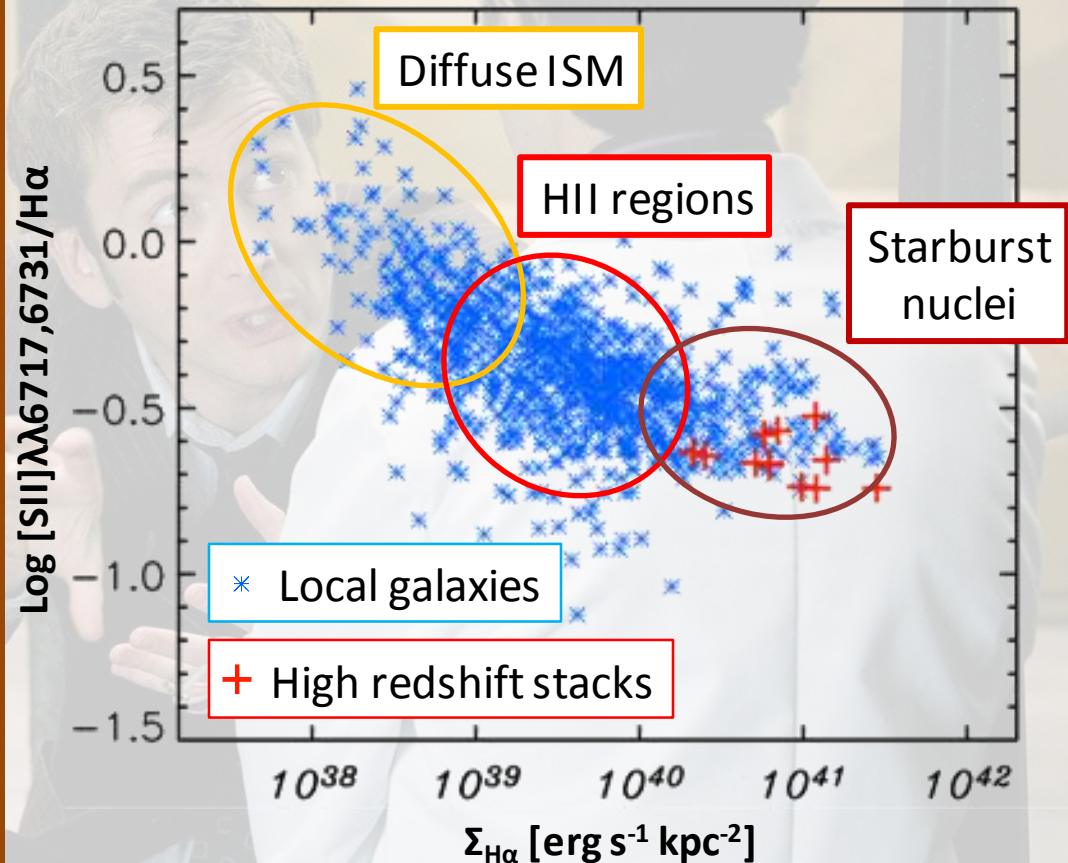
- High pressures
- High densities
- SII/H $\alpha$  ratio

# Similarity with the nuclei of intense starbursts: high pressures and densities

The diffuse ISM, HII regions, and starburst nuclei in nearby galaxies form a single parameter family (Wang *et al.* 1998).

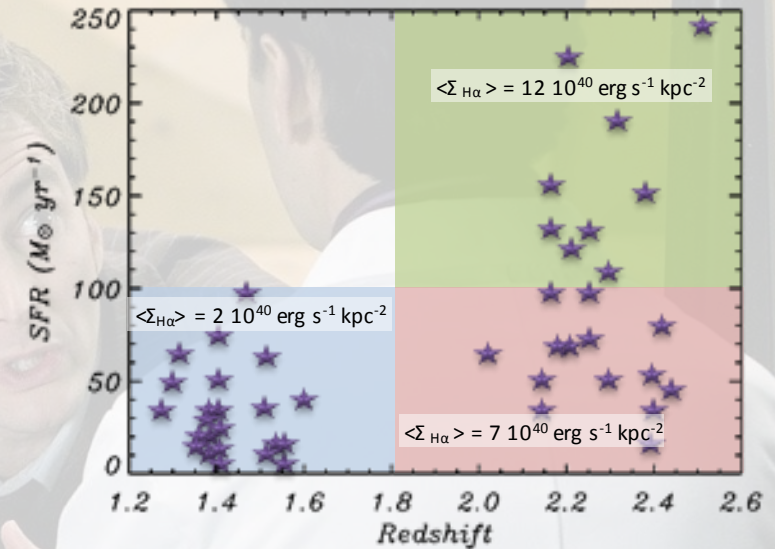
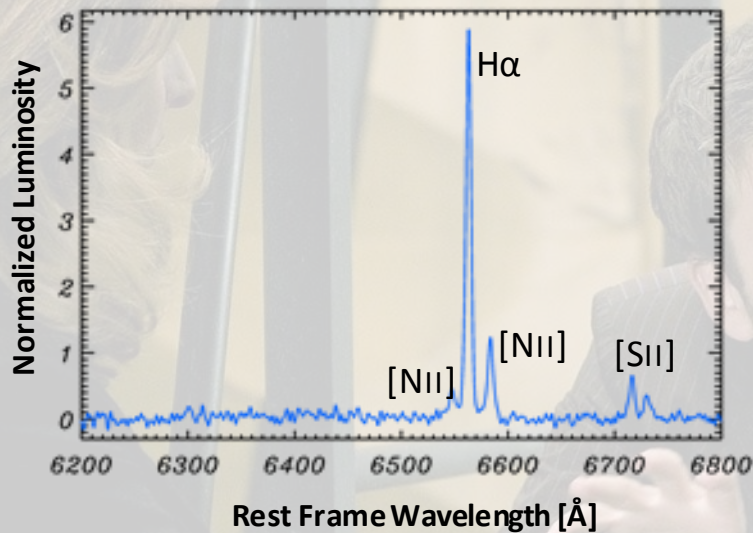
Our data from high redshift stacks are coherent with the physical conditions in nearby starburst nuclei (high densities and high ionization parameter).

This is showing the same overall trend as the spatially resolved  $[\text{NII}]/\text{H}\alpha$  versus  $\Sigma_{\text{H}\alpha}$  plot confirming the high ionization parameters and pressures in these galaxies.





# Extracting the precious signal: stacking analysis

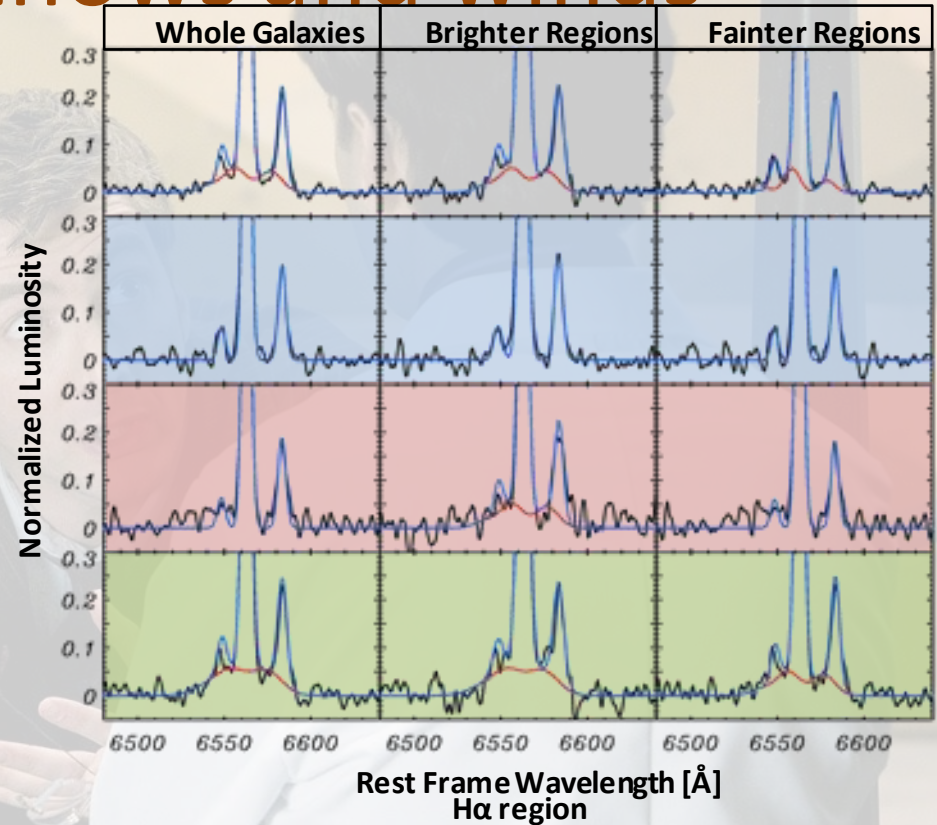
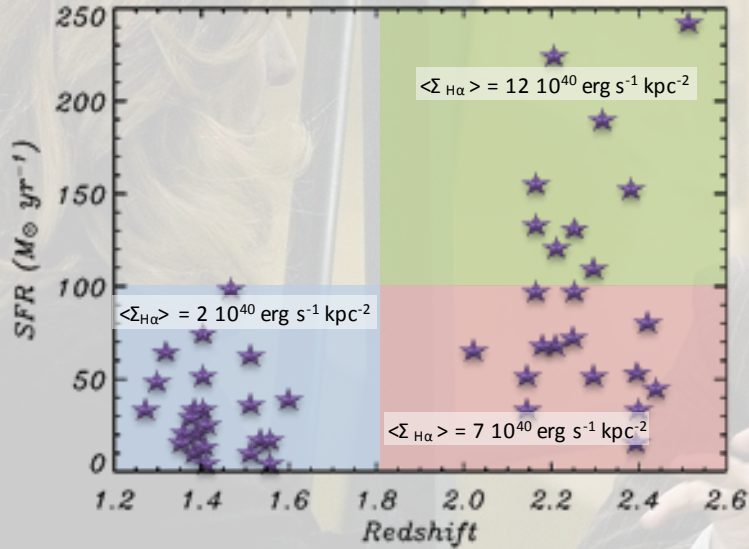


We use a stacking analysis to detect the average contributions of weak components in the observed spectra.

Spectra from each galaxy are summed according to:

- The position in the  $z$  – SFR diagram of the galaxy
- The H $\alpha$  brightness in the spectrum compared to the rest of the galaxy

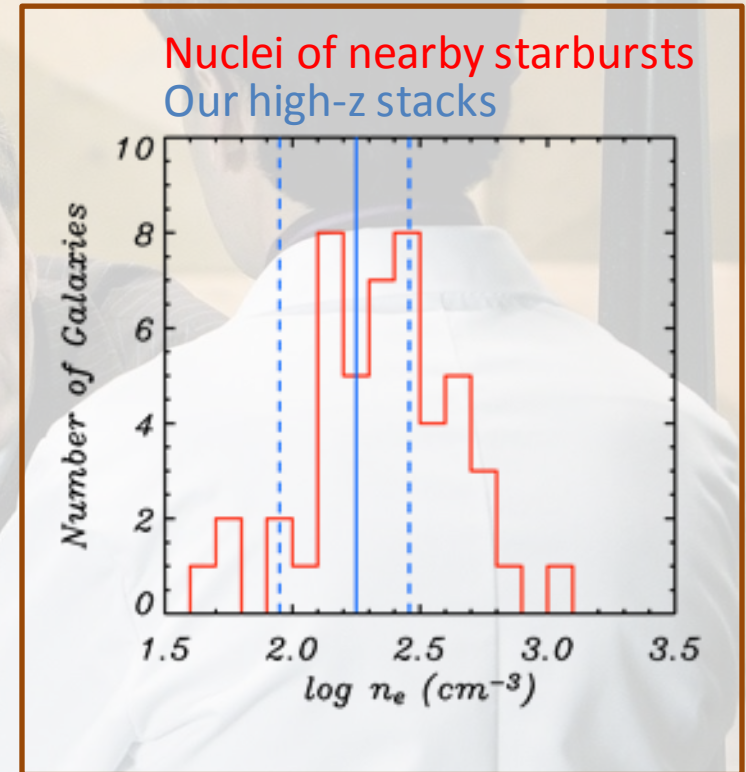
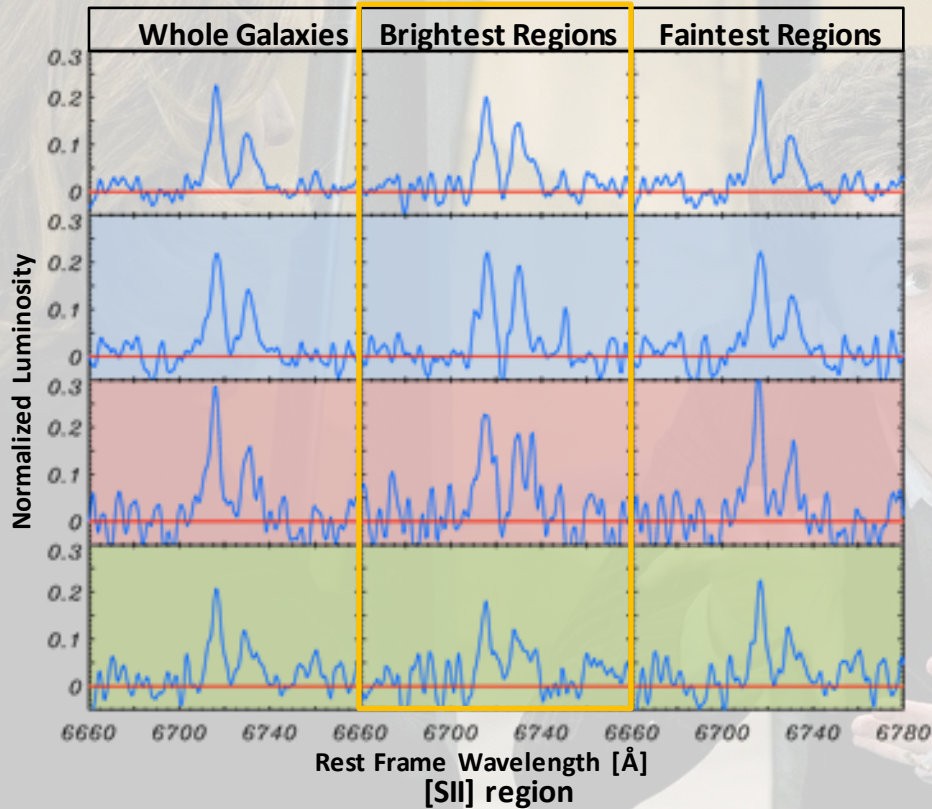
# Similarity with the nuclei of intense starbursts: Outflows and winds



The stacks composed of the galaxies or areas with the highest  $\langle \Sigma_{\text{H}\alpha} \rangle$  show the best evidence for a broad component. This is consistent with intense star formation driving outflows in these galaxies.



# Similarity with the nuclei of intense starbursts: Electron densities



The electron densities in the brightest regions of the galaxies are comparable to those observed in the nuclei of intense starbursts.

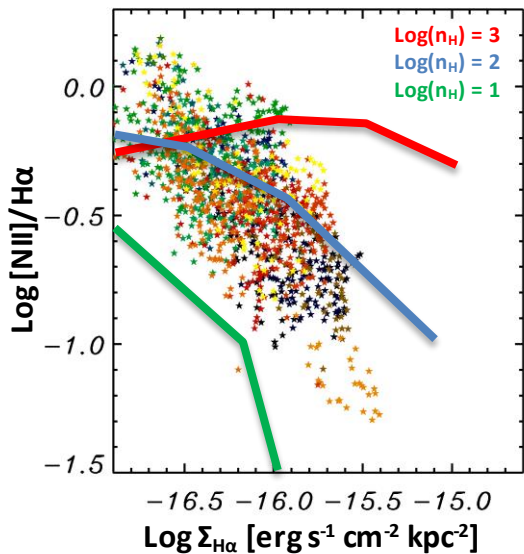
Is it always the same for all  
your sample?

Let's have a look!





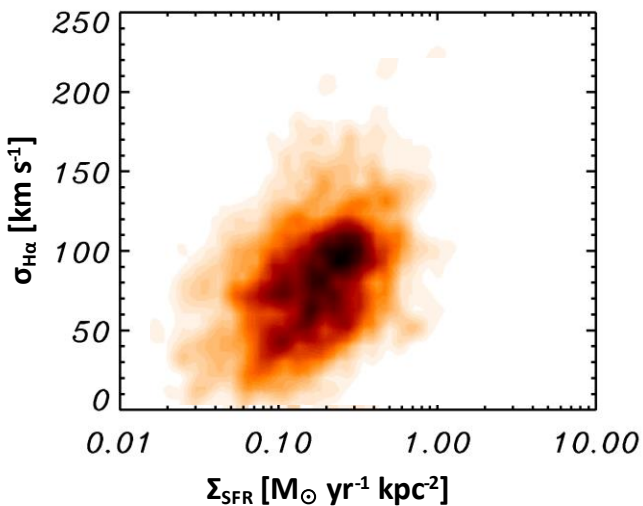
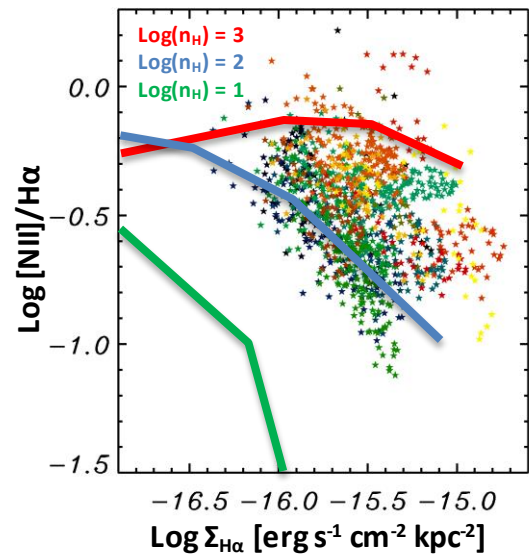
# A different regime probed at lower redshift?



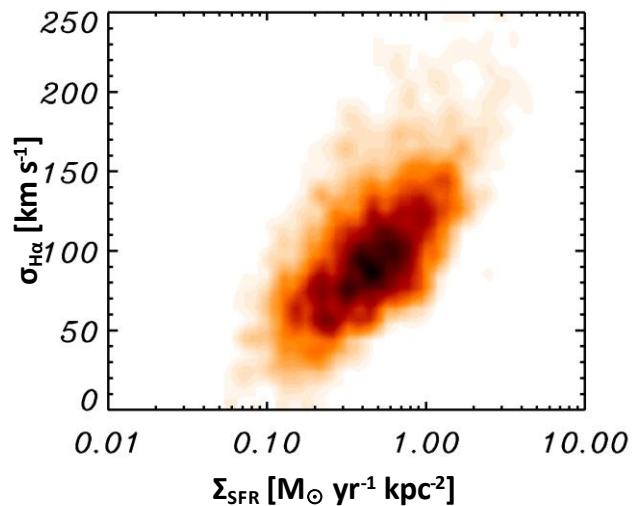
1.3 < z < 1.8

1.8 < z < 2.7

Increasing surface brightness dimming



At lower redshifts, we can spatially resolve galaxies with lower  $\langle \Sigma_{H\alpha} \rangle$ , perhaps starting to probe a regime that is not completely dominated by the star formation.



# Conclusions

- Star formation dominates the ISM pressure in the most star-forming galaxies at high redshift.
- Gas accretion cannot explain these H $\alpha$  luminosities and velocity dispersions.
- The self regulation of star formation through the pressure occurs at high redshift just as it does in intense starbursts at low redshift.



The image is a composite of the painting 'The Starry Night' by J.M.W. Turner and a TARDIS from the television series 'Doctor Who'. The TARDIS is depicted as a dark blue, boxy object with glowing windows, flying through the swirling, vibrant blue and yellow sky of the painting. The background shows the characteristic elements of the painting: a dark, turbulent sea in the foreground, a small town with a church spire in the middle ground, and a large, dark, jagged rock formation on the left side. The overall style is that of a classic oil painting with visible brushstrokes.

*Thanks!*

+++



# Todo:

- Find image with SF in bow shock
- Red Há SF image
- Morphologies



# The future...

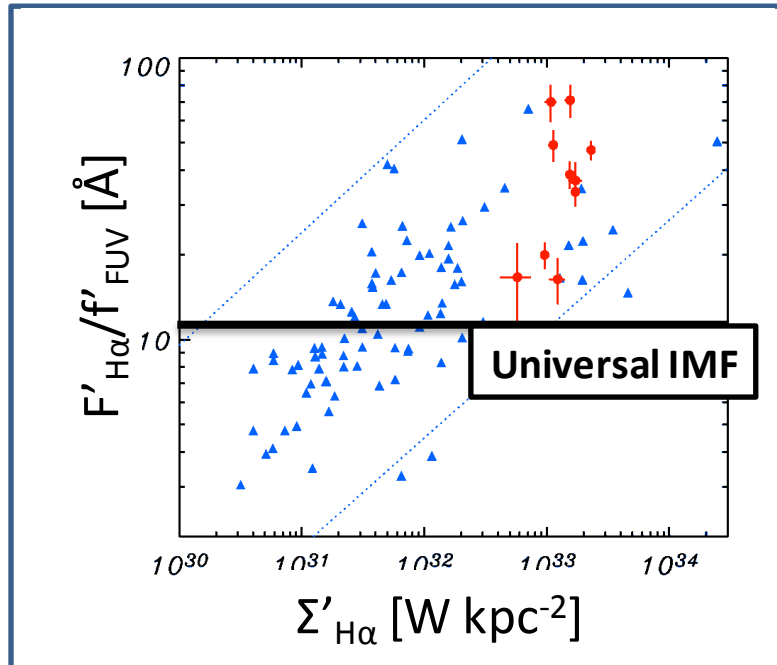
Projeto de pesquisa de pós-doutorado  
UM PASSEIO NO VALE VERDE:  
RUMO A UMA MELHOR COMPREENSÃO DA  
EVOLUÇÃO DAS GALÁXIAS COM J-PAS

Candidato à bolsa: Loïc Le Tiran  
Supervisor: Laerte Sodré Jr

Instituição:  
Instituto de Astronomia, Geofísica e Ciências Atmosféricas,  
Universidade de São Paulo



# The ISM at $z \approx 1.4$ : IMF variations, bursts of star formation, high pressures?

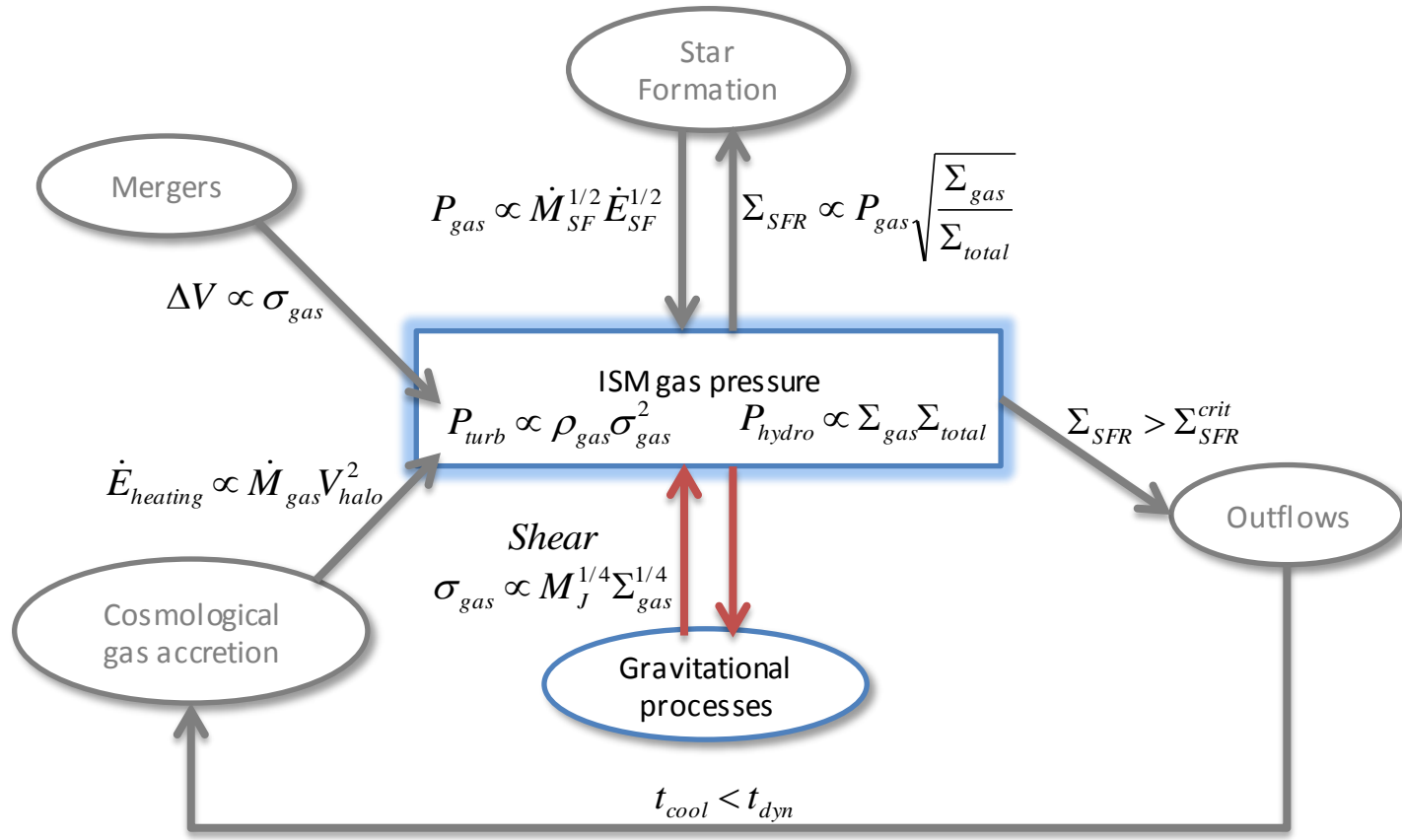


- ▲ Local galaxies, *Meurer et al. 2009*
- $z \approx 1.4$

➤ Examine the relationship between  $F_{\text{H}\alpha}/f_{\text{FUV}}$  and  $\Sigma_{\text{H}\alpha}$  or  $\Sigma_{\text{R}}$ : does it extend to higher redshift and higher surface brightnesses? Linearly? Is there a relationship between the position of the galaxies on these plots and their dynamics?

➤ Explore galaxies at  $z \approx 1 - 1.5$  and lower mass galaxies at  $z > 2$ , in order to study an ISM less dominated by intense star formation and more by gravitational processes.

➤ Probe higher density medium using molecular lines observations and compare its distribution to ionized gas.



# GRAVITATIONAL PROCESSES



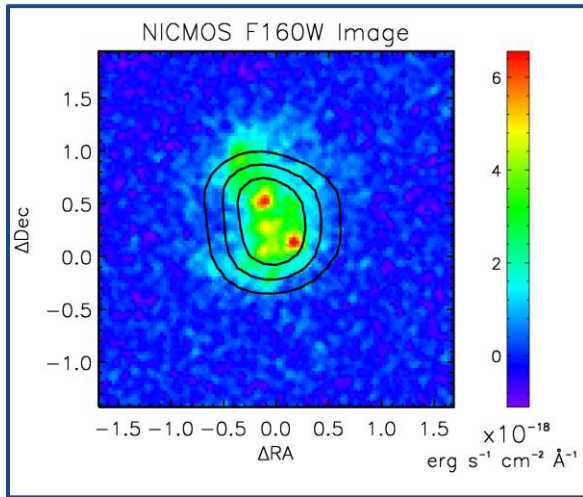




# CONCLUSIONS AND PERSPECTIVES



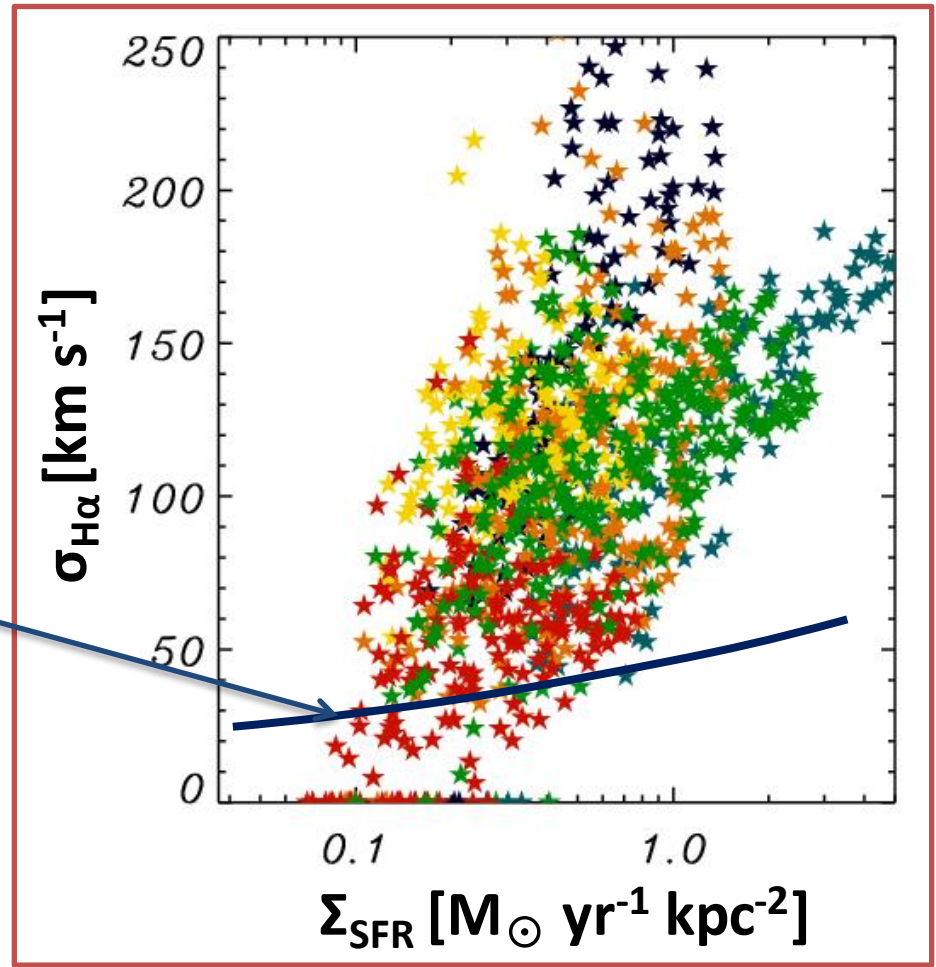
# Dispersion due to clumps



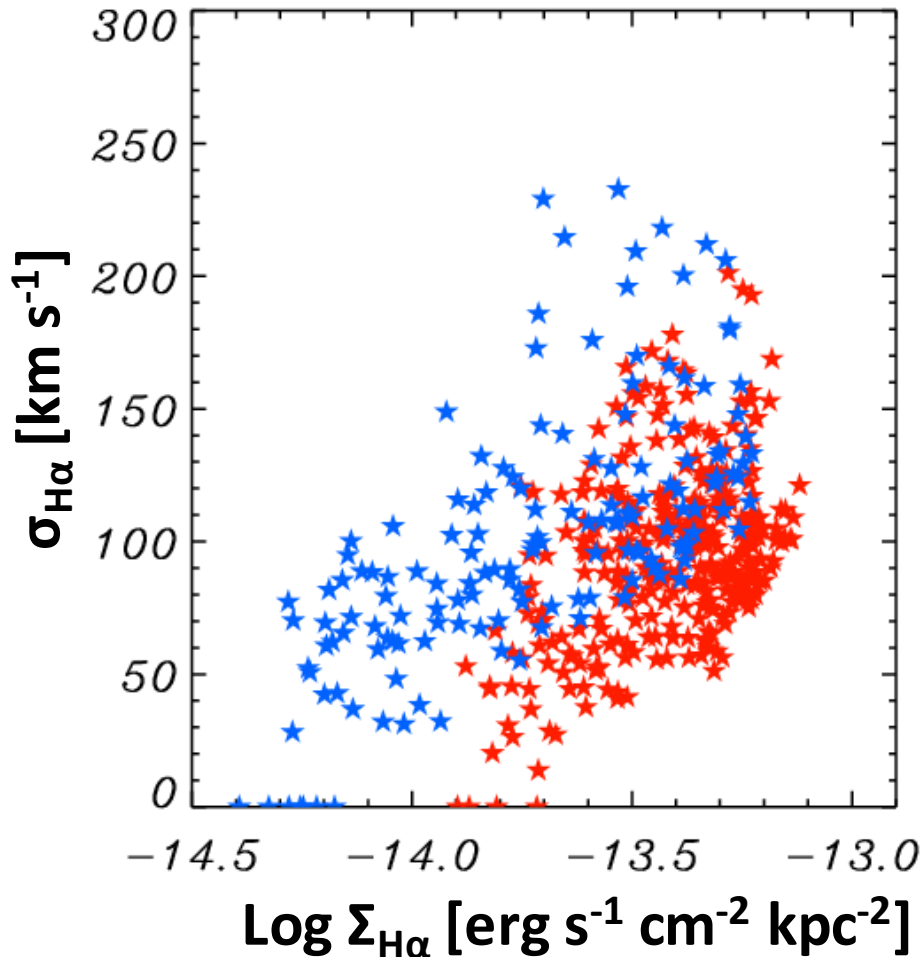
Jeans instability:

$$\sigma_{\text{gas}} \sim M_J^{1/4} G^{1/2} \Sigma_{\text{gas}}^{1/4} = 54 M_{J,9}^{1/4} \Sigma_{\text{SFR}}^{0.18} \text{ km s}^{-1}$$

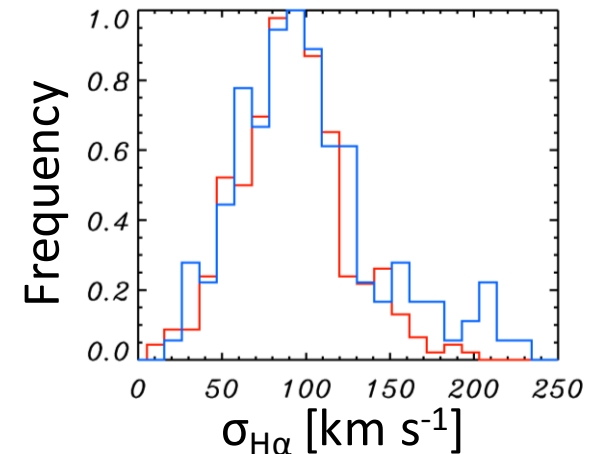
The velocity dispersions estimated from the effect of Jeans unstable clumps are not consistent with the data.



# The beam smearing effect



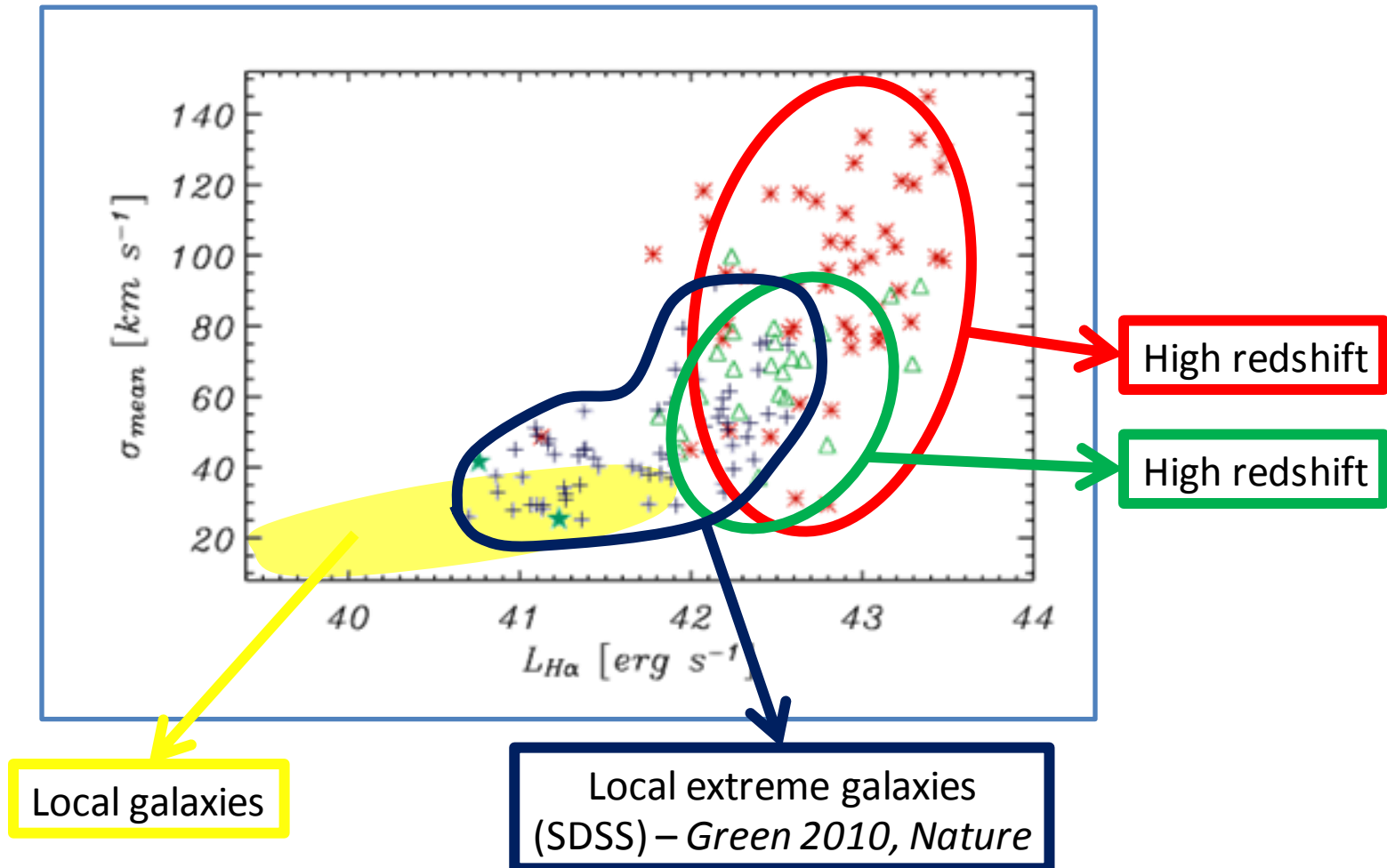
★ Non-AO (.6 arcsec)  
★ AO (.2 arcsec)



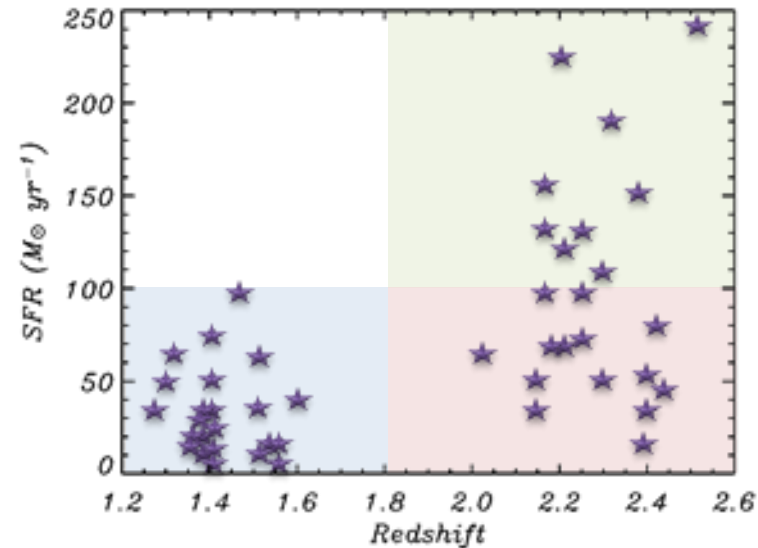
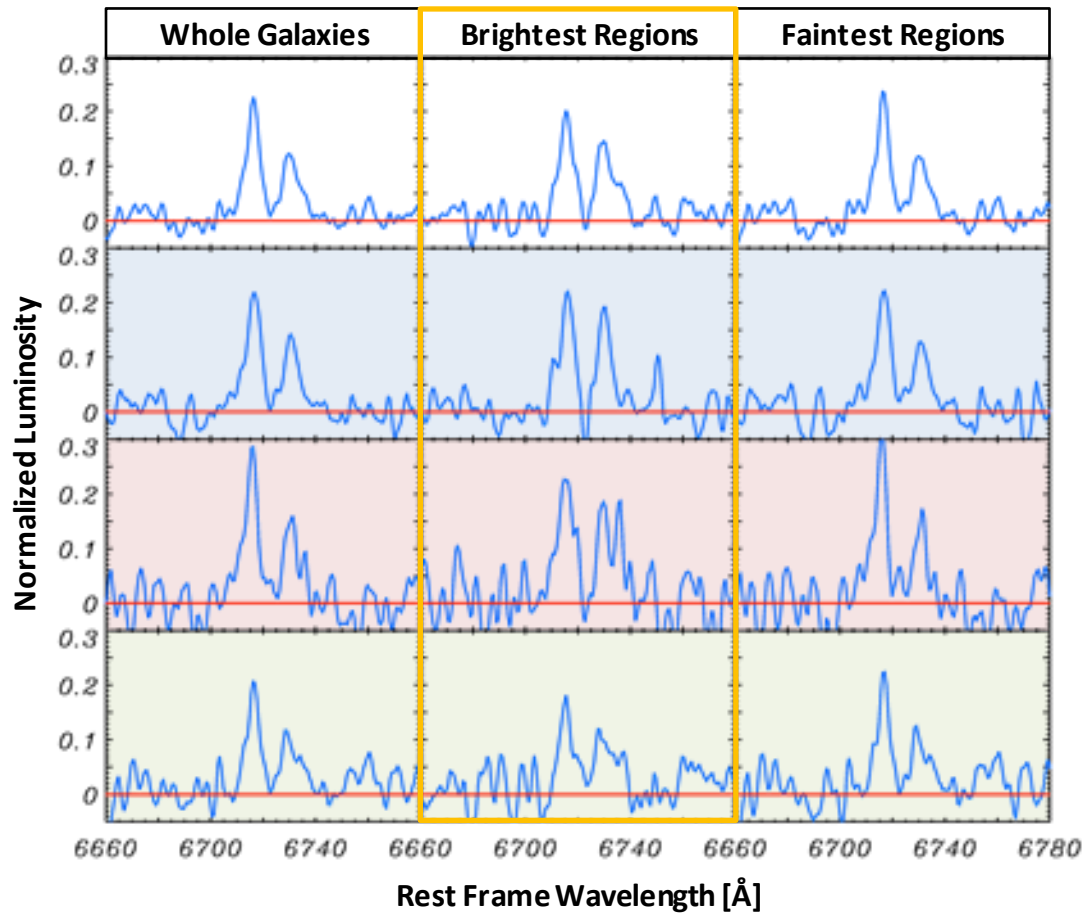
AO and non-AO observations of the same galaxy have the same range of velocity dispersions, which suggests that the effect of beam smearing is small.



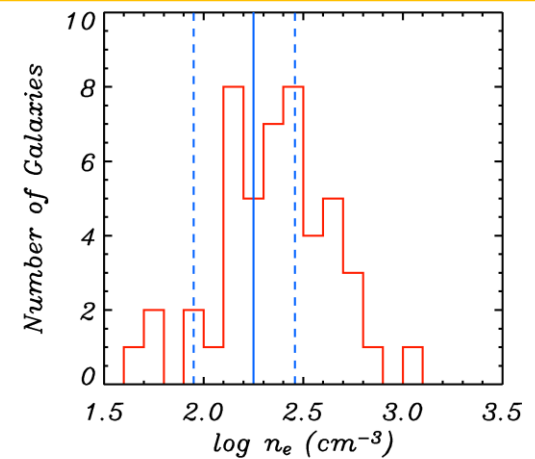
# Integrated measurements



# Electron densities in the brightest regions



High electronic densities in the brightest regions

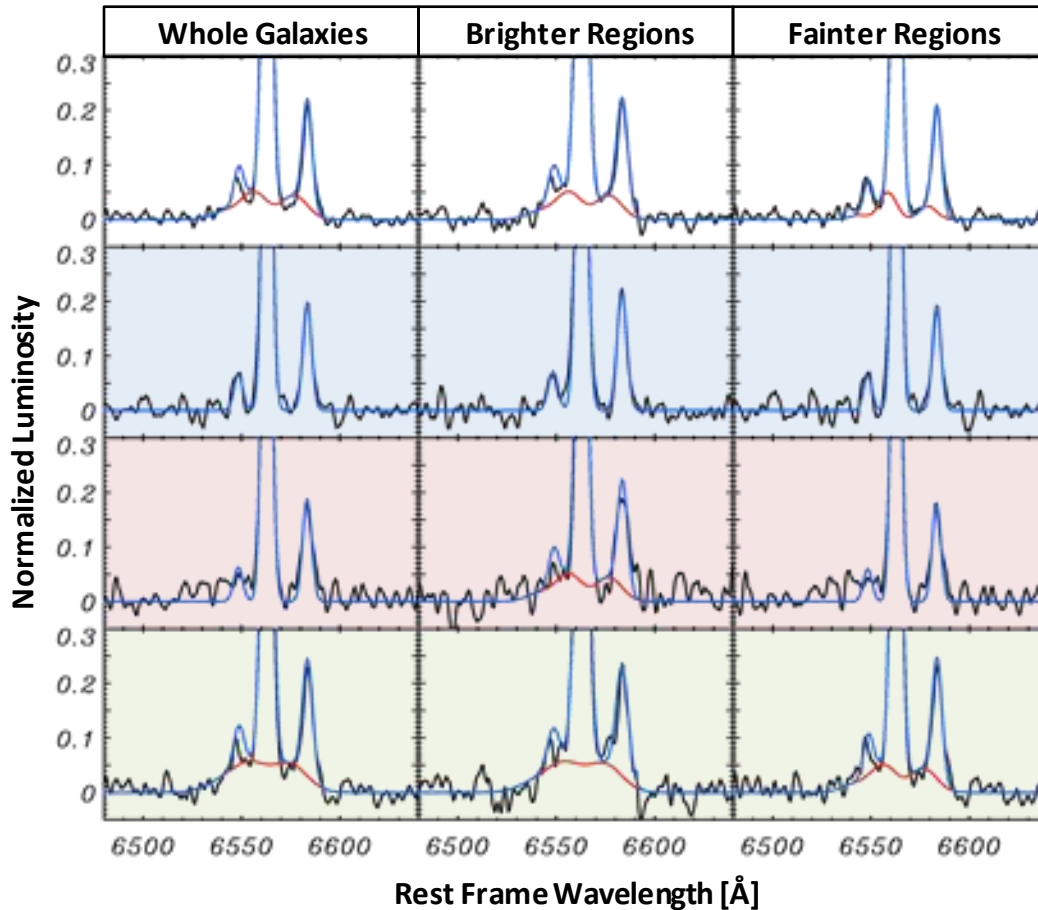


From the line ratio of the [SII] doublet, we find high

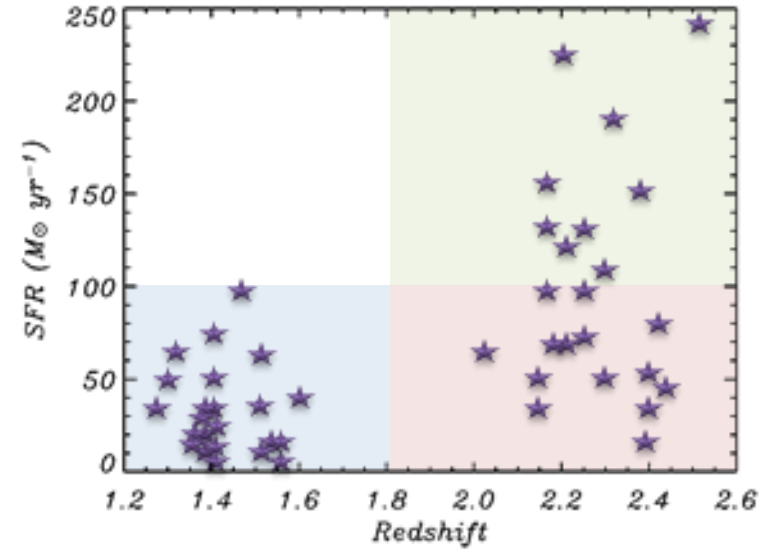
*Le Tiran et al. (2011b)* nsities in the brightest regions.



# Outflows and winds



*Le Tiran et al. (2011b)*



In red: Simple Broad Lines Model  
for H $\alpha$  & NII]:

$$V_{\text{offset}} = \sigma_{\text{H}\alpha} = \sigma_{[\text{NII}]}$$

$$= [\text{NII}]/\text{H}\alpha \text{ constraint}$$

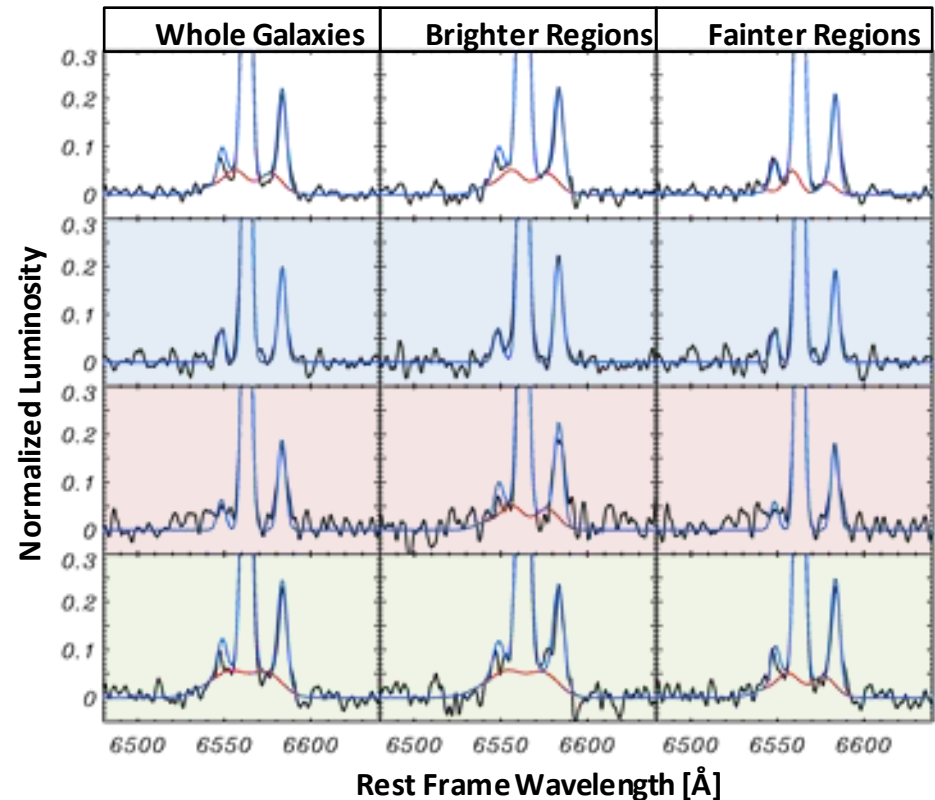
Similar conditions that extended  
emission in nearby starbursts

# Outflows and winds

We can mimic the broad component (in red) with a very simple model:

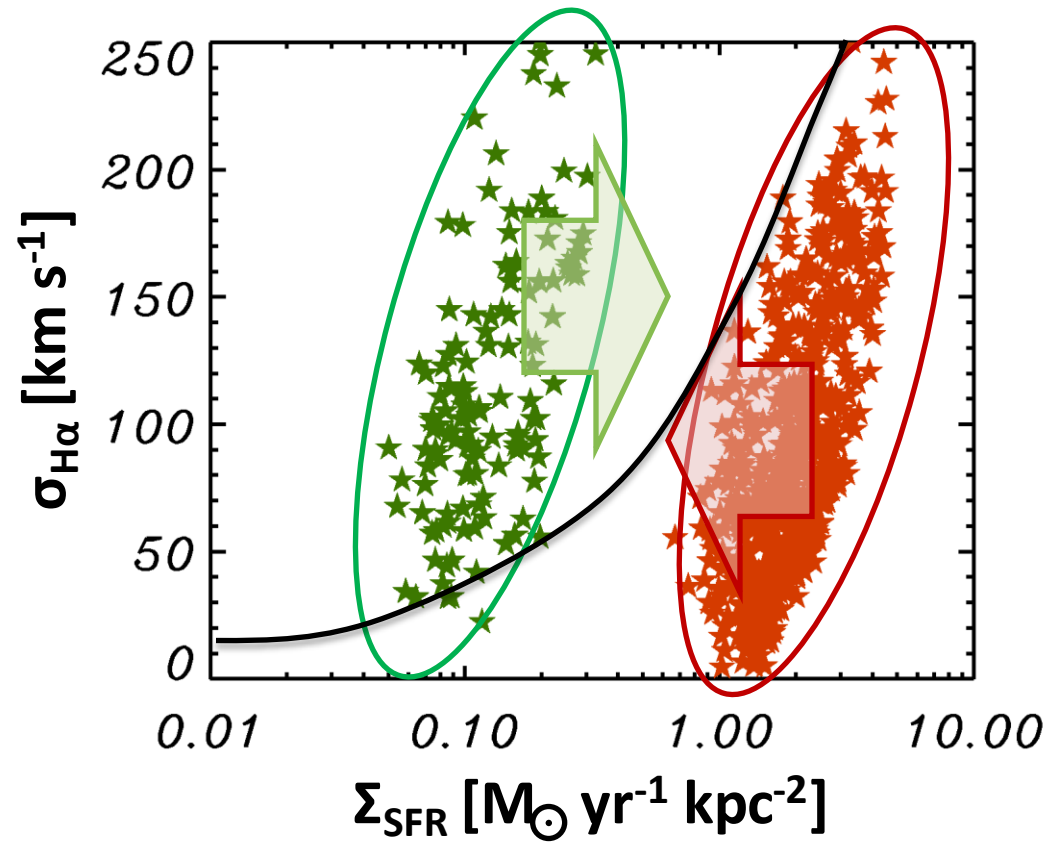
- 3 broad lines for H $\alpha$  & [NII]
- $V_{\text{offset}} = \sigma_{\text{H}\alpha} = \sigma_{[\text{NII}]}$  and the line ratio [NII]/H $\alpha$  is constrained from shock models.
- $F_{\text{H}\alpha, \text{broad}} = 0.05 \times F_{\text{H}\alpha, \text{narrow}}$

Those conditions are similar to the extended emission in nearby starbursts .

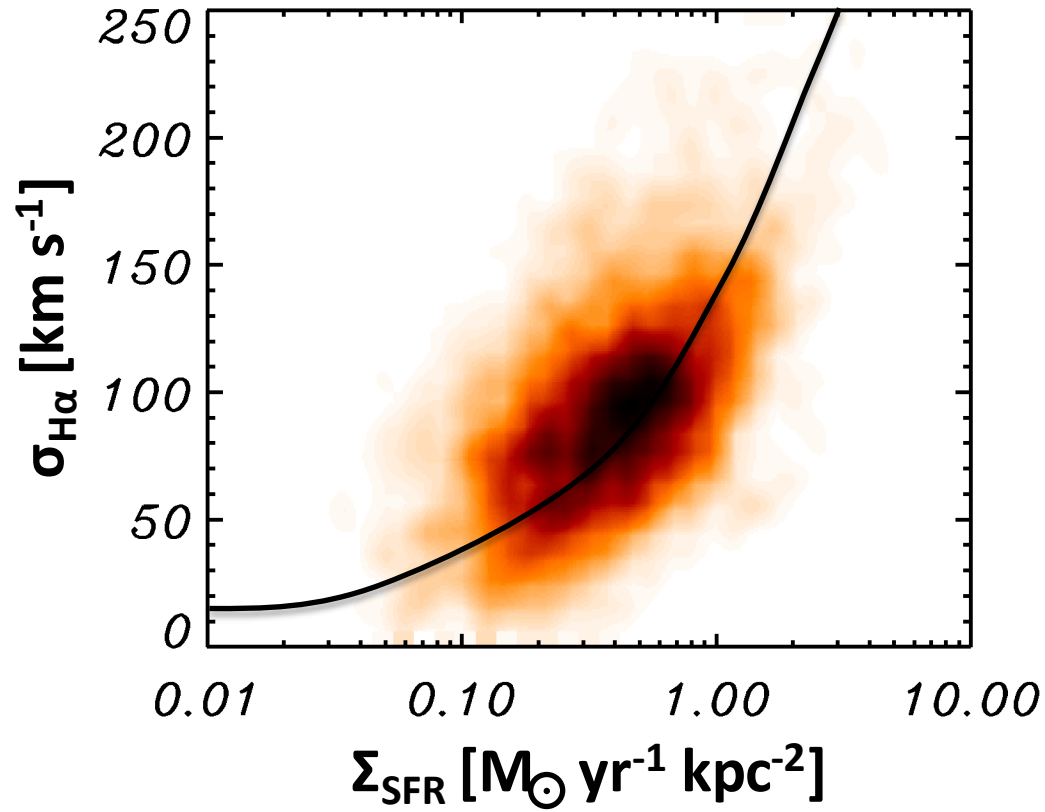




# Making a normalized relation

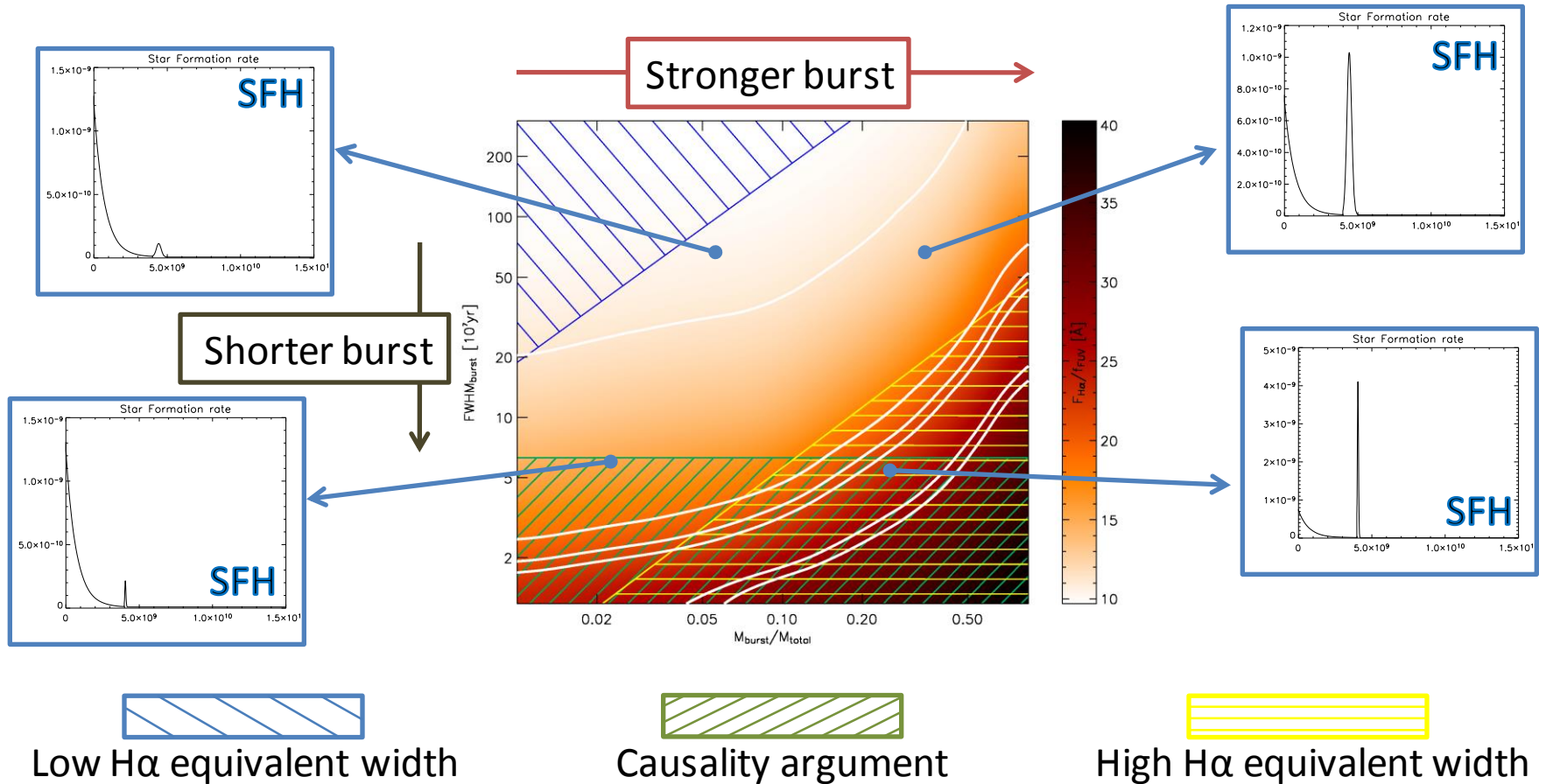


# Making a normalized relation



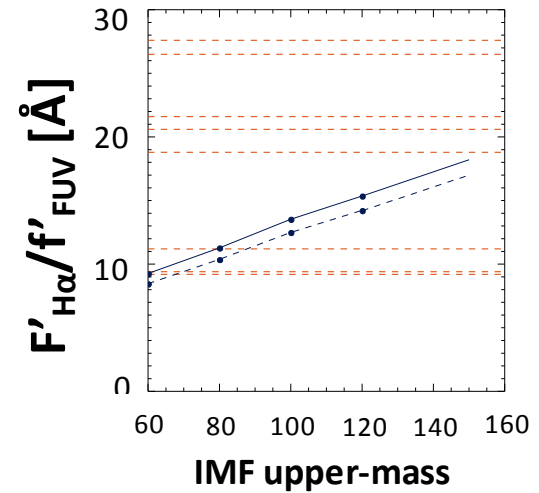
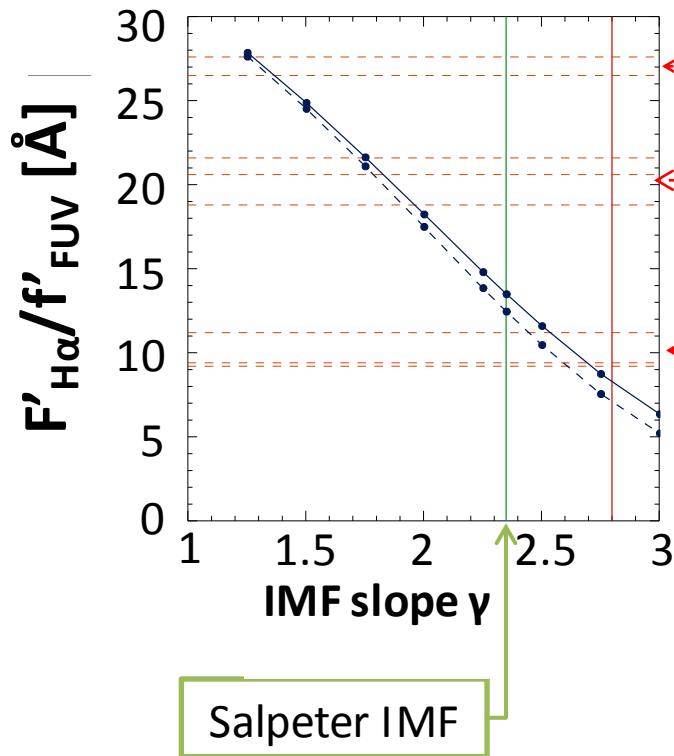


# Bursts of Star Formation



A burst of star formation that could explain such high values of  $F_{H\alpha}/f_{FUV}$  would be unrealistic.

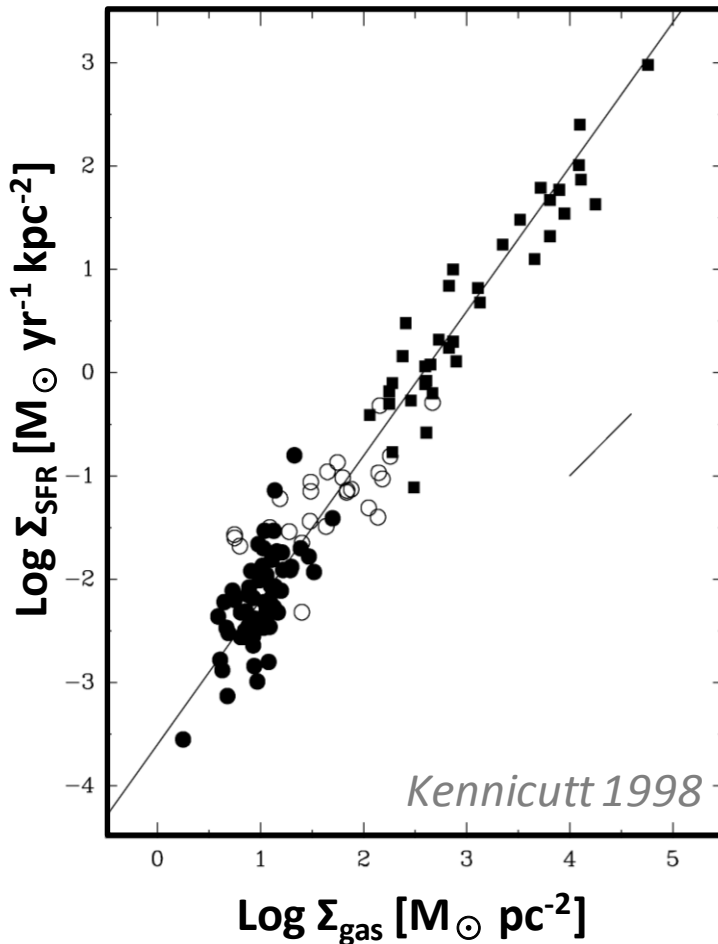
# Variation of the IMF?



Variations of the **slope** (or upper-mass) of the IMF could explain our observations



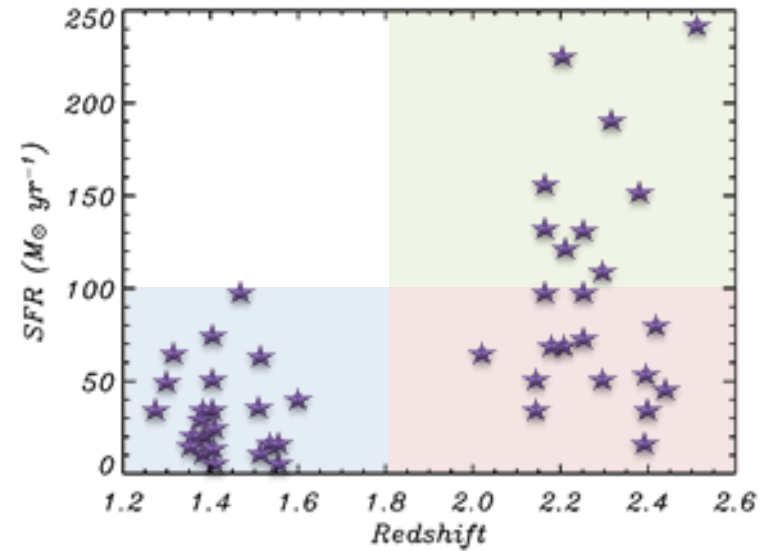
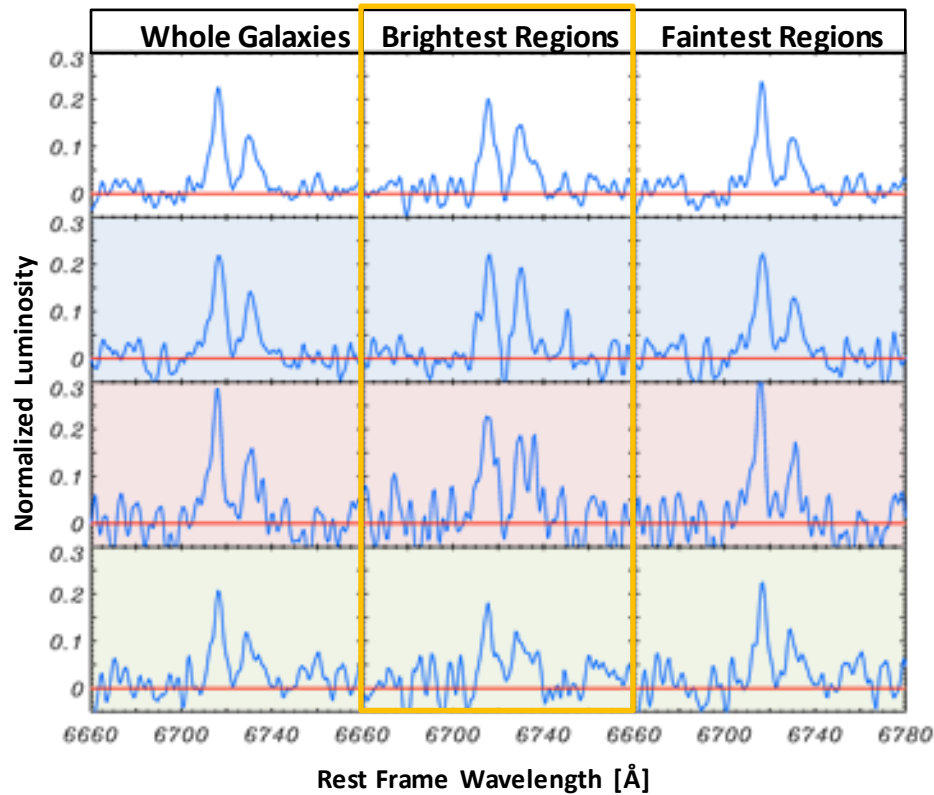
# Self regulation of star formation



The Schmidt-Kennicutt law tells us that there is a simple relationship between pressure and star-formation rate over many orders of magnitudes.

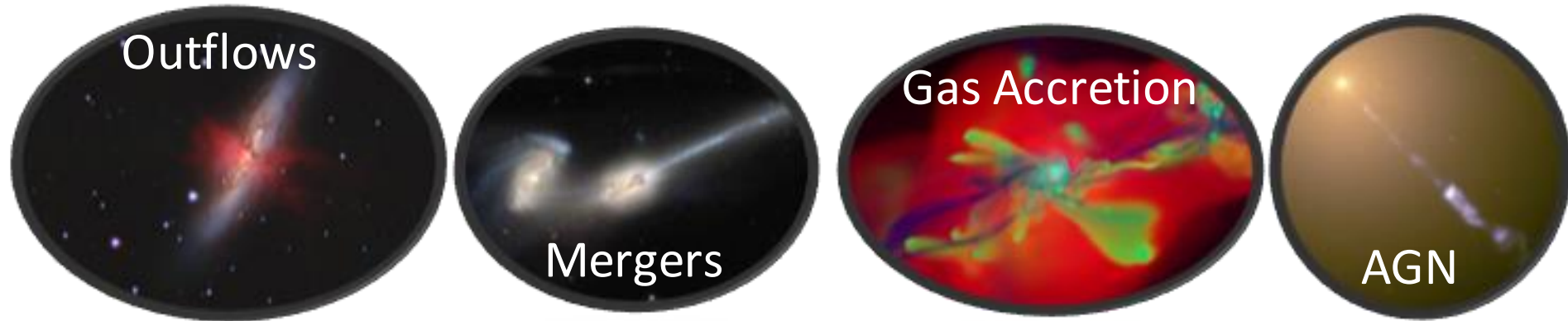
Self regulation of star formation:  
Star formation increases the pressure in the ISM and higher pressures increase the star formation rate.  
It has been proposed for the regulation of star formation in nearby galaxies (*Silk 1997, 2001; Wang+1998*).

# Electron densities in the brightest region





# Diversity of phenomena



However, galaxy evolution might not be dominated by these large scale mechanisms!

# **PURPOSE OF THIS THESIS**



# Main questions to answer



What is the primary driver of the large spatially resolved line widths observed in the optical emission line gas in galaxies at  $z \approx 2$ ?

- Turbulence generated by gravity in a collapsing disk?
- Cosmological accretion of gas?
- Intense star formation?



How do gas densities, pressures, intensity of the radiation fields, and/or shocks compare to local galaxies?

**How?** Investigate the physical processes that shape the warm ionized media in galaxies from  $z=1-3$  by carefully analyzing the properties of their optical emission lines. Get insight into the physics underlying the dynamics and excitation of the warm ionized gas and to compare this with the properties of nearby galaxies.