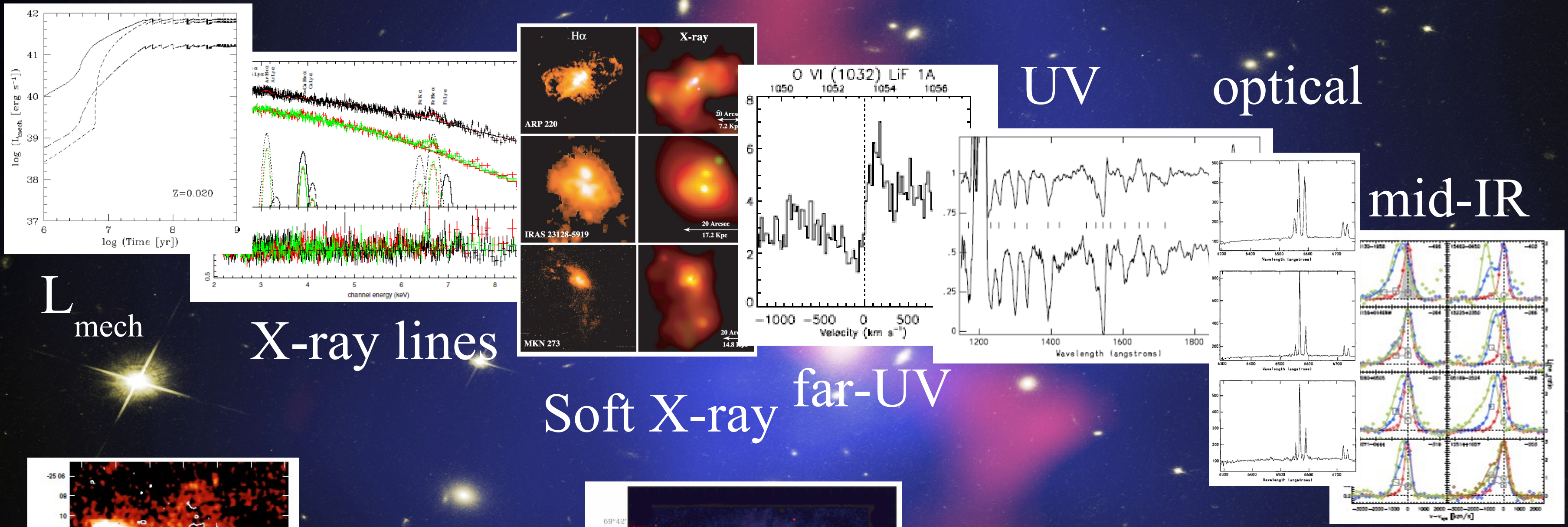
A Broad View of Galaxy Evolution: MW and Galaxy Evolution



L_{mech}

X-ray lines

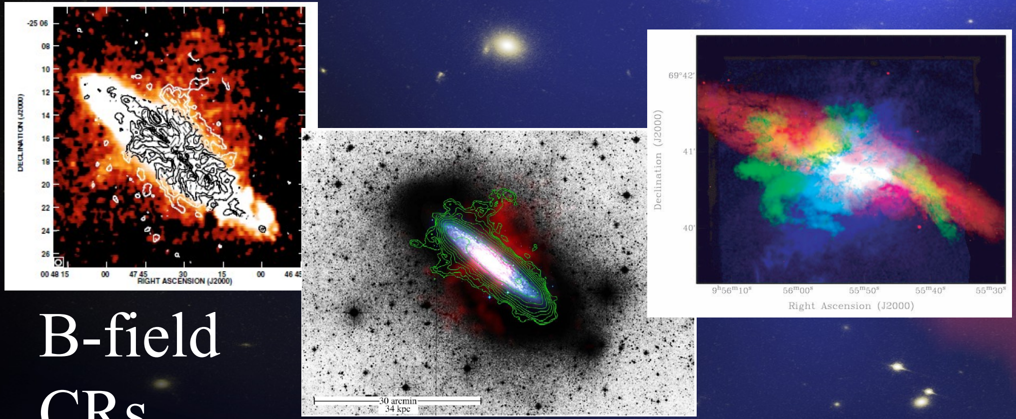
Soft X-ray

far-UV

UV

optical

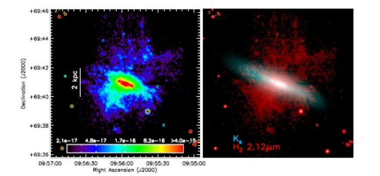
mid-IR



B-field
CRs

HI

CO



Dust/H_2

Matt Lehnert
IAP

Galaxy Formation: Why so Difficult?

Developing a coherent model for the growth of baryons in galaxies is inherently difficult. Why?

- Highly non-linear problem
- Wide range of physical scales (LSS to Galaxies to Stars)
- Lots of marginally constrained physics like AGN- and starburst-driven feedback, star-formation efficiency, gas accretion/infall, merging, etc. − all highly stochastic.

Yet little direct predictive power – need observational constraints
Need to trace the physical nature of all components of the gas

Galactic and Extra-Galactic Cycles

Big bang cooling to nucleosynthesis

First objects and galaxies form
Reionization

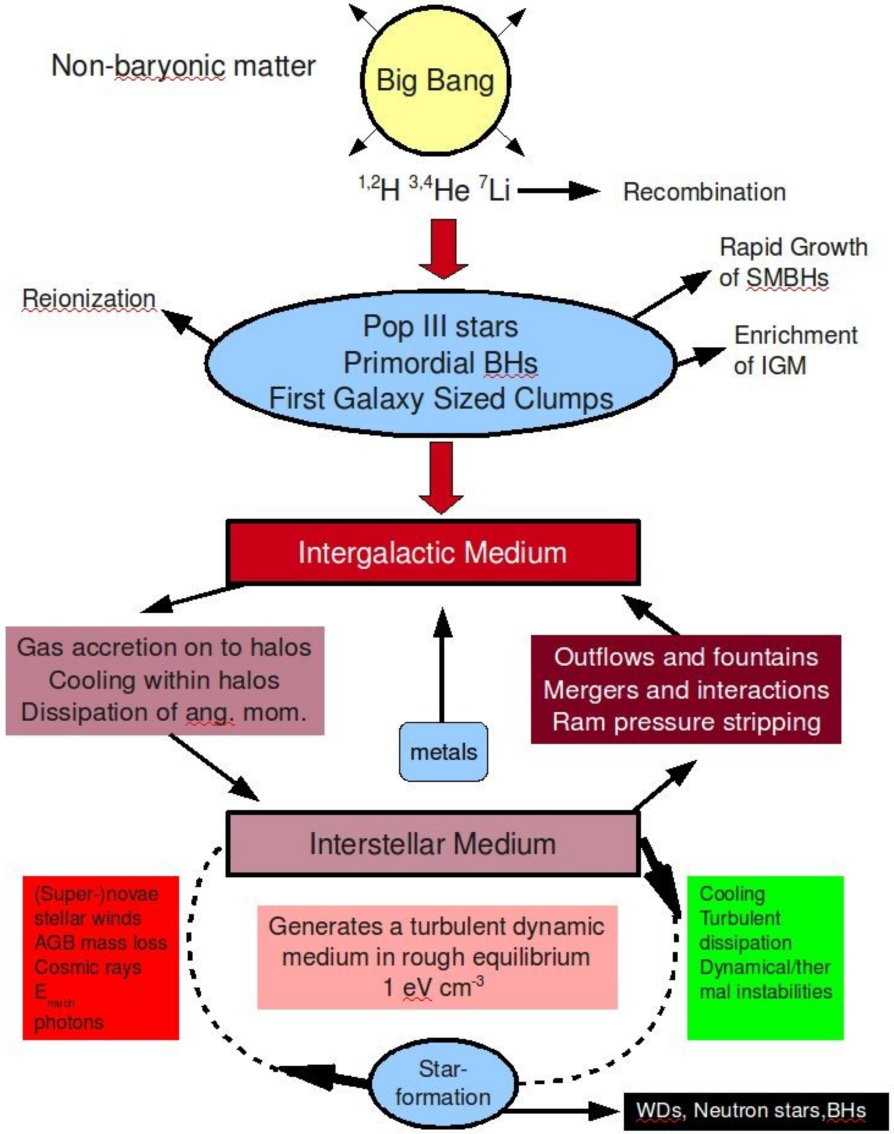
Cosmic web formation driven by gravity

Infall and outflow into and out of halos plus star formation regulates gas supply

Angular moment controls where the gas is and its mass surface density

Complex cycle of cooling and heating controls the ISM

Galaxies become stellar dominated



Non-baryonic matter

Big Bang

^{1,2}H ^{3,4}He ^{7}Li → Recombination

Reionization

Pop III stars
Primordial BHs
First Galaxy Sized Clumps

Rapid Growth of SMBHs

Enrichment of IGM

Intergalactic Medium

Gas accretion on to halos
Cooling within halos
Dissipation of ang. mom.

metals

Outflows and fountains
Mergers and interactions
Ram pressure stripping

Interstellar Medium

(Super-)novae
stellar winds
AGB mass loss
Cosmic rays
E$_{mech}$
photons

Generates a turbulent dynamic medium in rough equilibrium
1 eV cm^{-3}

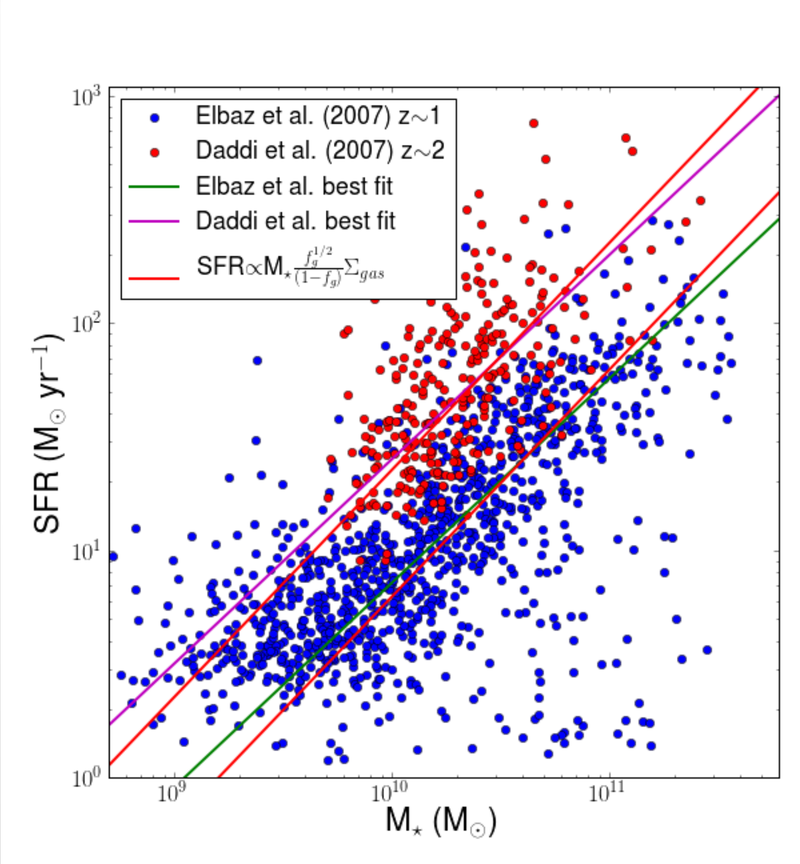
Cooling
Turbulent dissipation
Dynamical/thermal instabilities

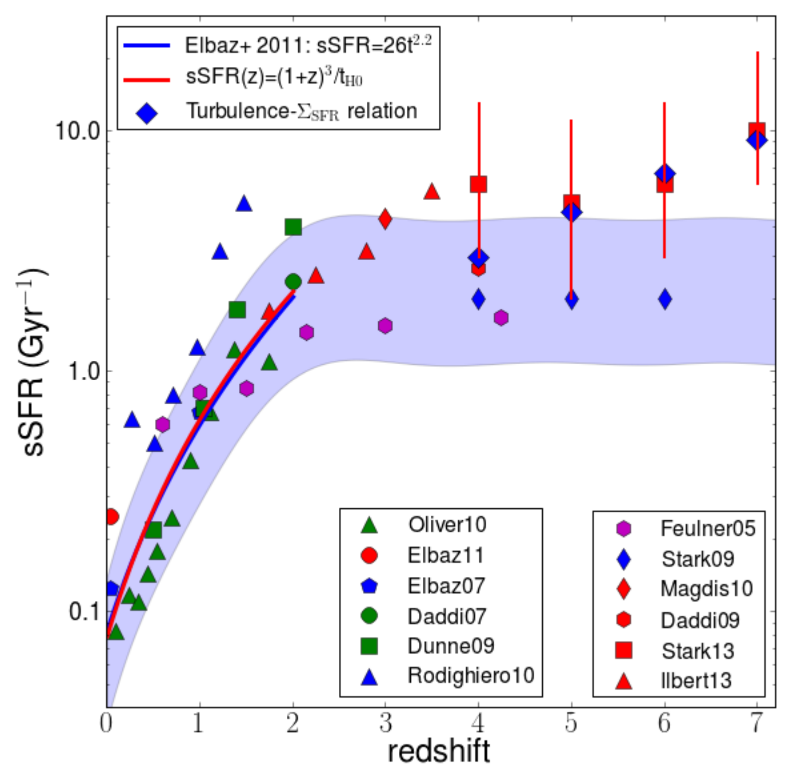
Star-formation

WDs, Neutron stars,BHs

Main Sequence of Star formation

Evolution of the main sequence of star formation



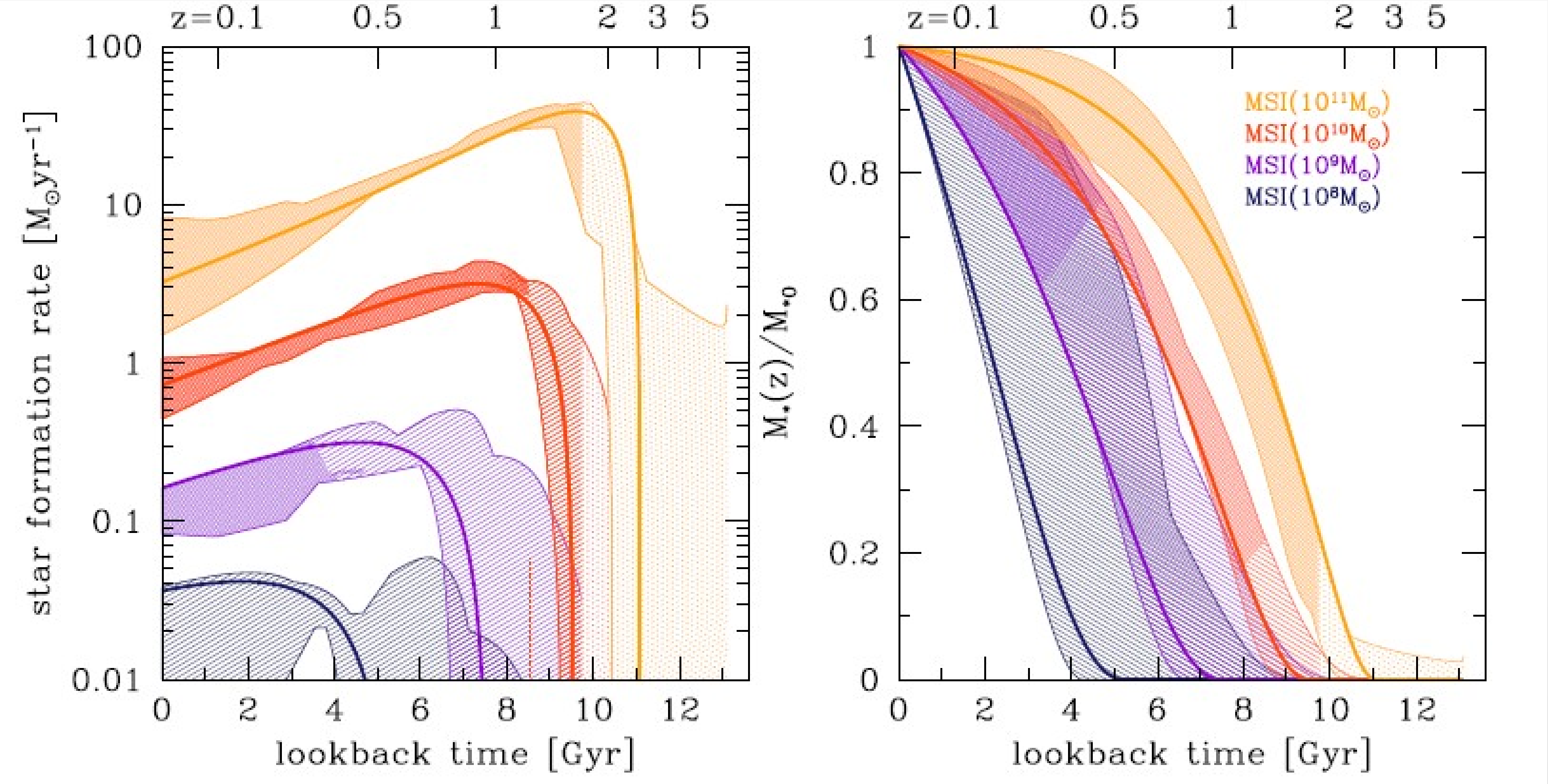


Fundamental question: Do galaxies simply move along MS or move on & off?

Elbaz et al. (2011); Lehnert et al. (2013, A&A submitted)

Running the Clock Backwards

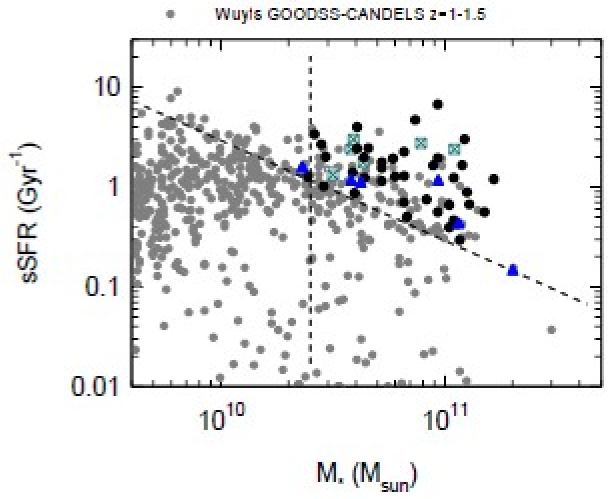
MSI – assumes that forming galaxies always live on the main sequence of star formation



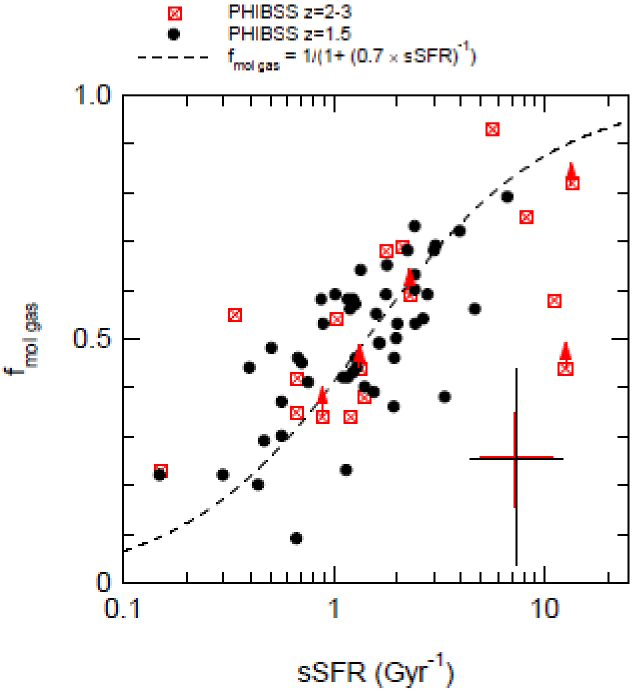
Doubtful that galaxy formation is continuous. Perhaps two populations ...

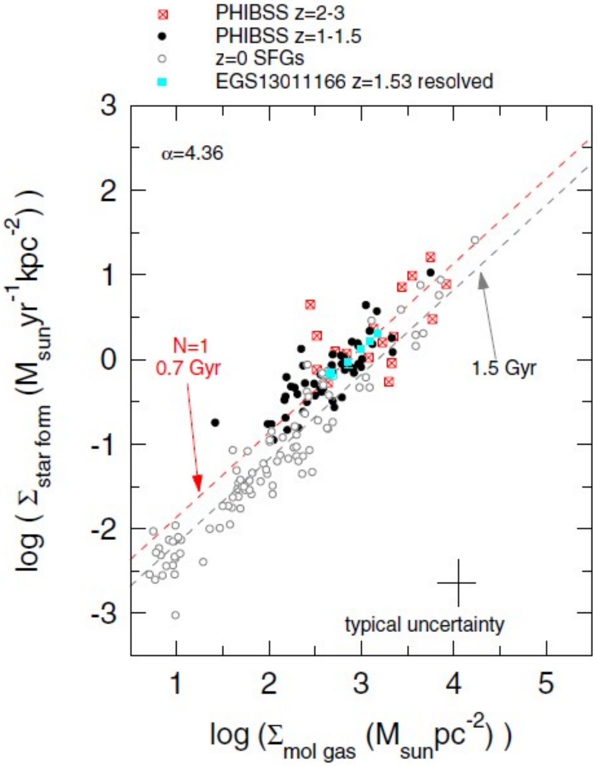
Leitner et al. (2012)

Gas Content of distant galaxies



Are high sSFR simply driven by the gas supply?

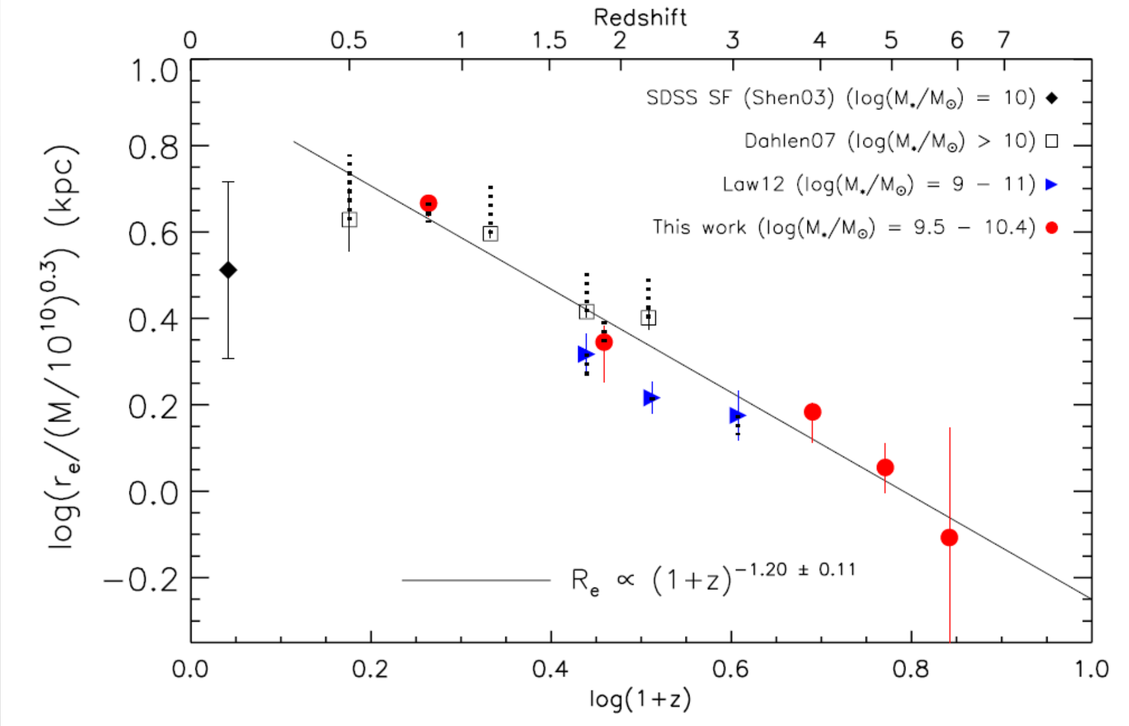




What does the gas depletion time scale mean? Does short imply constant refueling?

Tacconi et al. (2013)

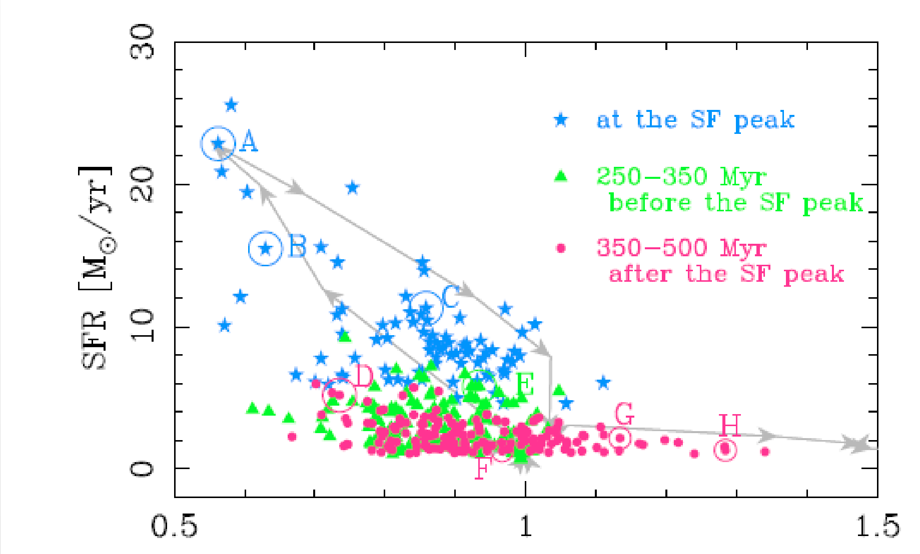
Size Evolution of LBGs

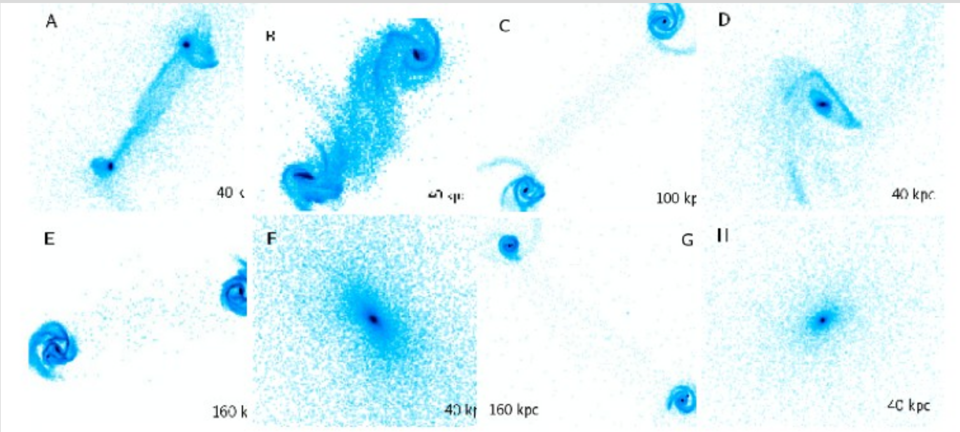


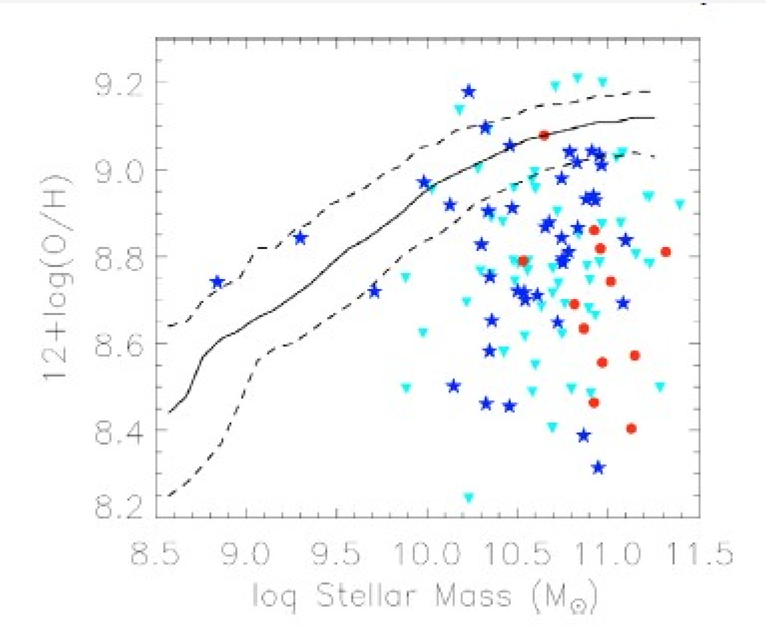
Mosleh et al. (2012)

Mergers and metallicities

Mergers and metallicity evolution ...



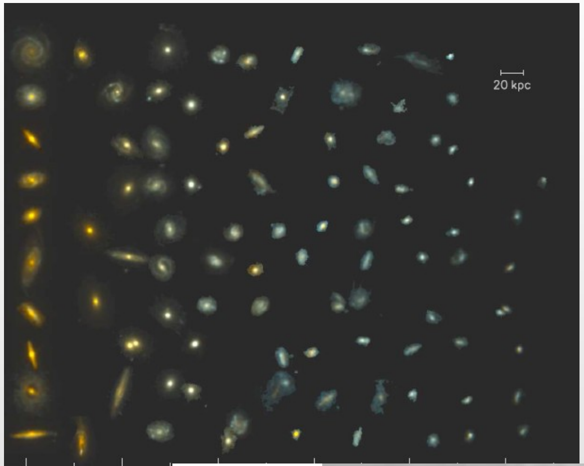




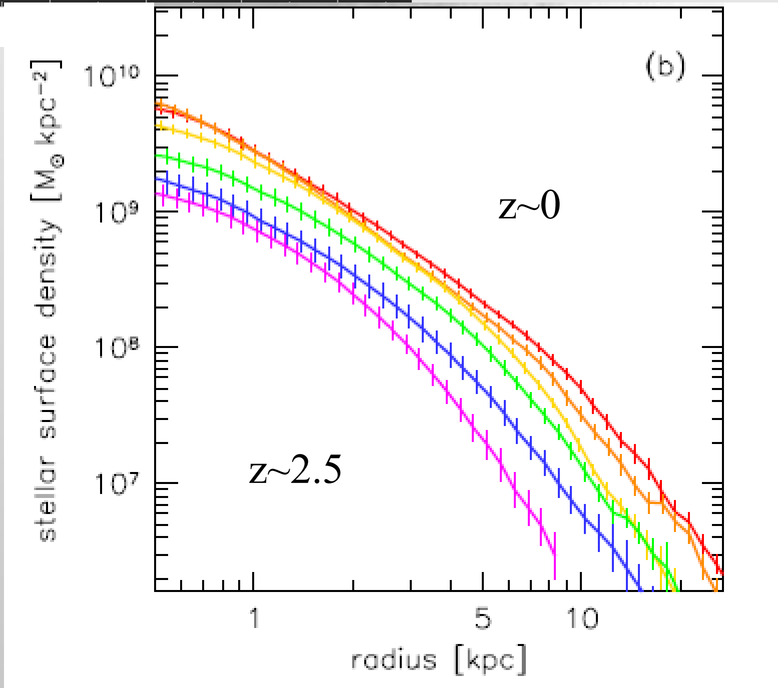
… can form positive metallicity gradients … implications for massive GRB hosts?

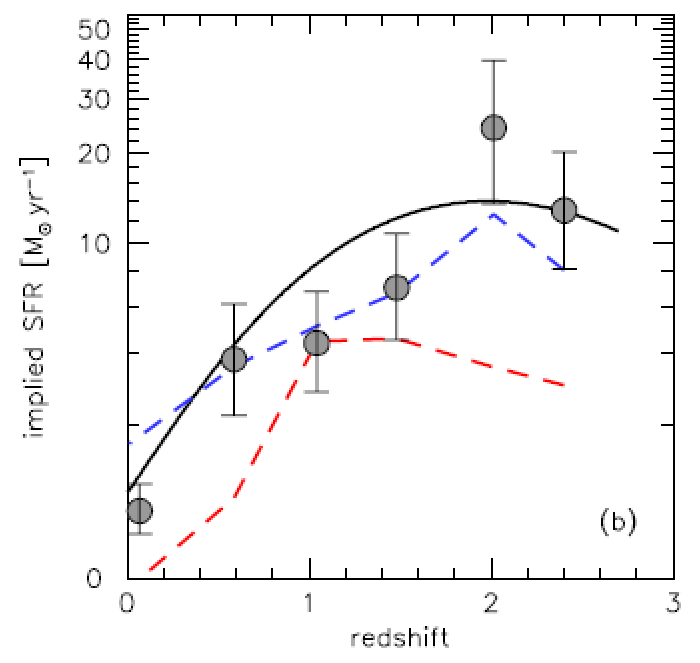
Montuori et al. (2010)

Build-up of MW Analogs



Abundance-matched sample: constant co-moving density





May suffer from bias due to halo evolution

van Dokkum et al. (2013)

The MW as a fossil of distant galaxy

Planet Searching – good for the MW structure

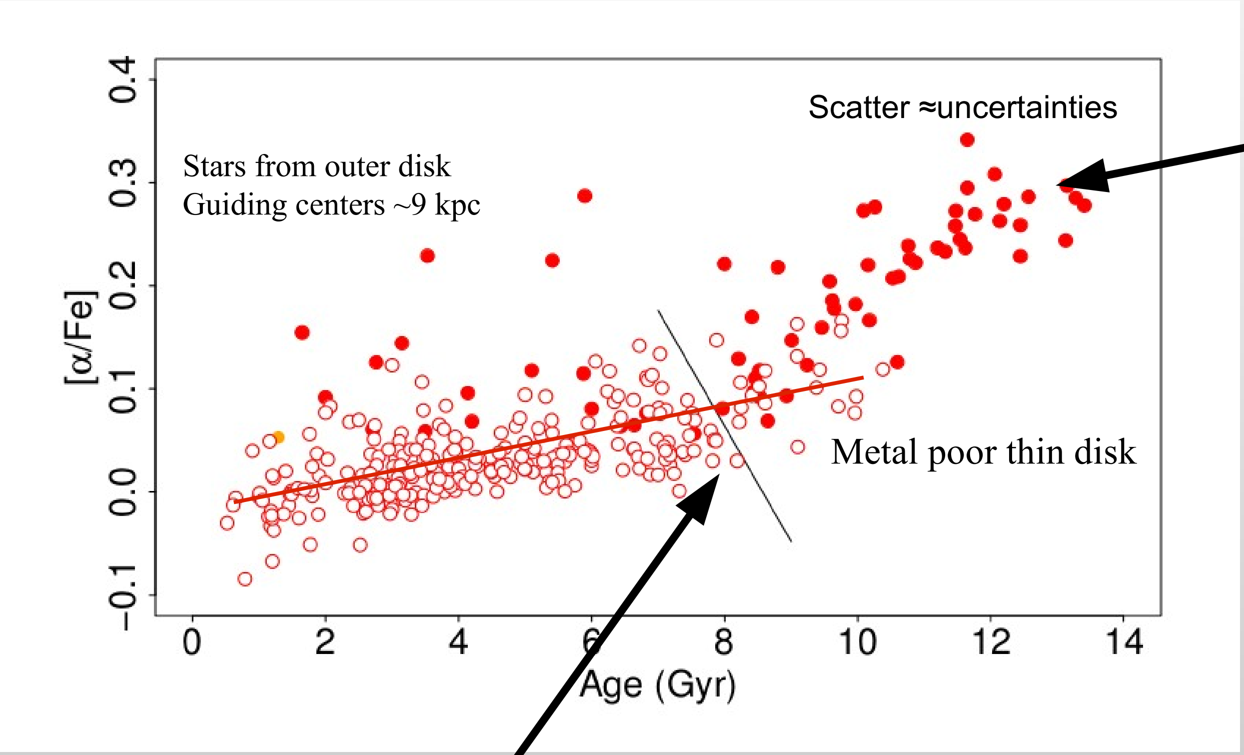
Used Adibekyan etal. (2012) analysis of 1111 FGK stars …

- R=110000
- S/N > 200 for 55% of sample
- Low rotational velocity
- Limiting distance subsample
- Low atmospheric activity
- Some mild selection: 97 stars with photo metalicities -0.5 to -1.5, b-y > 0.33
- Atmospheric parameters Teff, [Fe/H], [alpha/Fe] (alpha excludes Ca)
- parallaxes

Haywood et al. (2013)

Evolution of the disk of the MW

Divided the thick and thin disk using [α/Fe] vs. age plane. This division indicates several interesting features of the disk … Δ[α/Fe]/Δt changes



Stars from outer disk
Guiding centers ~9 kpc

Scatter ≈uncertainties

Metal poor thin disk

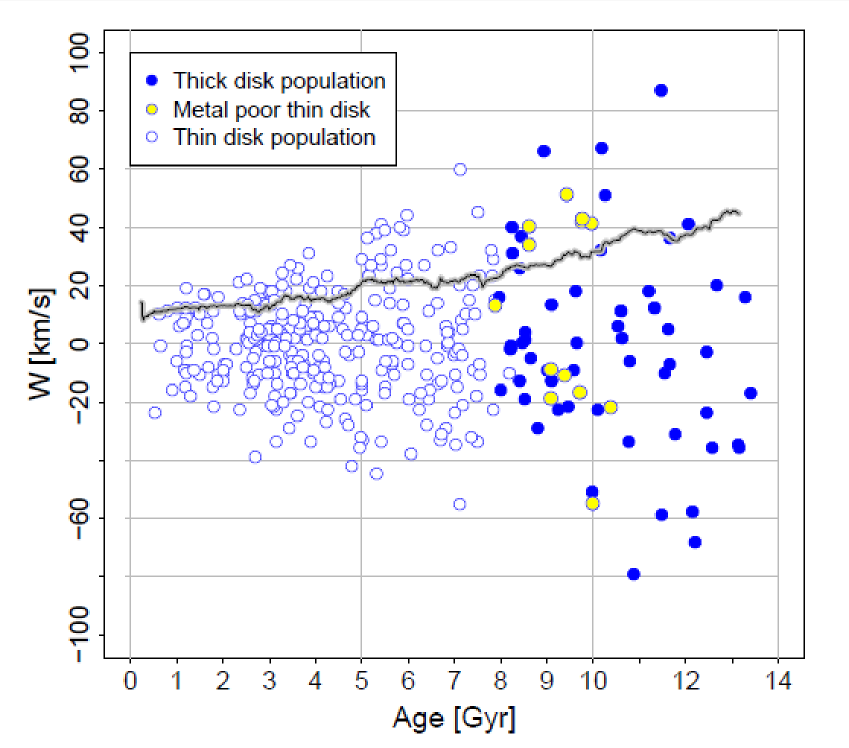
Chemical
homogeneous
rapid
enrichment

≈8 Gyr

Haywood et al. (2013)

Evolution of the disk of the MW

Vertical dispersion decreases with time ...



The narrowness of the [alpha/Fe]-age relation implied efficient mixing which agrees with the high dispersions … the gas was well mixed both vertically and in radius

Evolution of the disk of the MW

Summary:

- alpha enhanced disk formed over ~4-5 Gyrs
- It was chemically homogeneous as it increased in metallicity (short crossing times)
- Self-enrichment coupled to declining v-dispersion – grew thinner
- Thin disk formation “feeds” the composition of the thin disk and push α enhanced gas into the outer disk – re-cycling of the gas was important
- Inside-out? low r_e homogeneous thick disk + high r_e thin disk
- Using scale length of thick disk, mass and t_{sf} implies $\sum_{SFR} > 0.1\ M_{sun}\ yr^{-1}\ kpc^{-2}$ and SFR~30 $M_{sun}\ yr^{-1}$ (outflow limit) – follows analogs

Next: distant galaxies – phenomenological relationship?

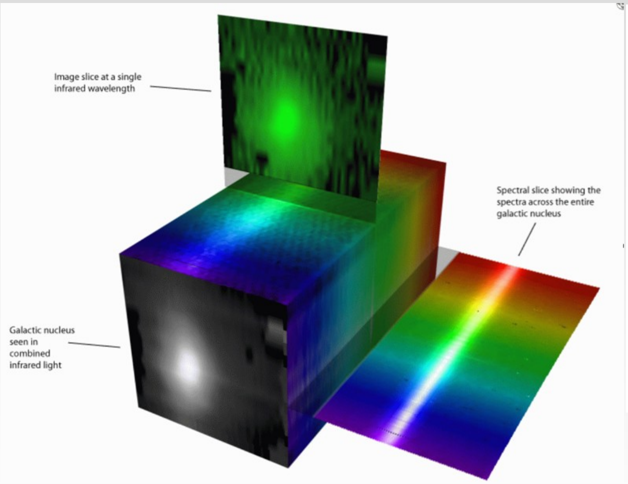
High SB high redshift galaxies

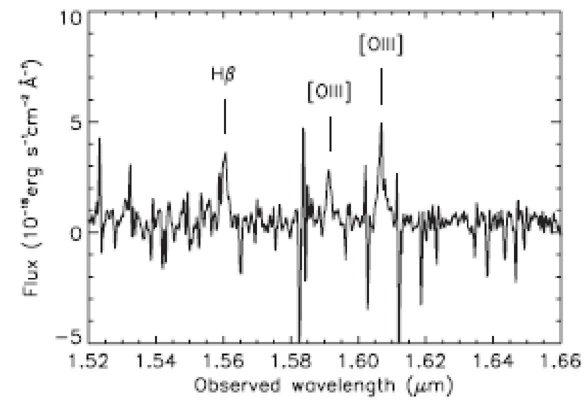
The nature of the warm ionized media in distant galaxies

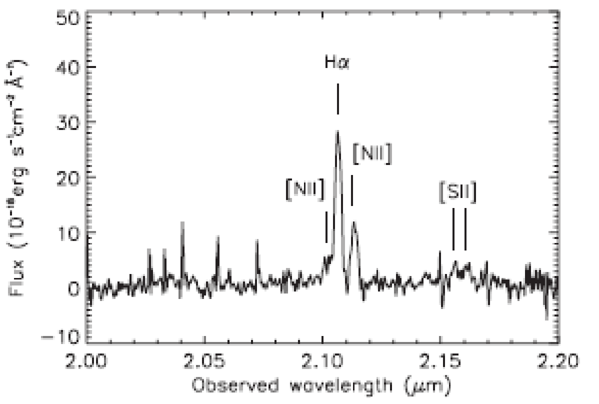
Large sample, 53 star-forming high redshift, z=1.3-2.7, galaxies observed with SINFONI – a near-IR IFU on the ESO-VLT (partly SINS sample)

Selection inhomogeneous … all intensely star forming and have rates of ~10s to 200 M_{sun} yr^{-1}

Typically have rest-frame optical lines, Hα, [NII]λλ6548,6583, [SII]λλ6716,6731, sometimes [OI]λ6300, and a few spectra in the blue optical with [OIII]λλ4959, 5007 and Hβ.







Star-formation regulates the ISM?

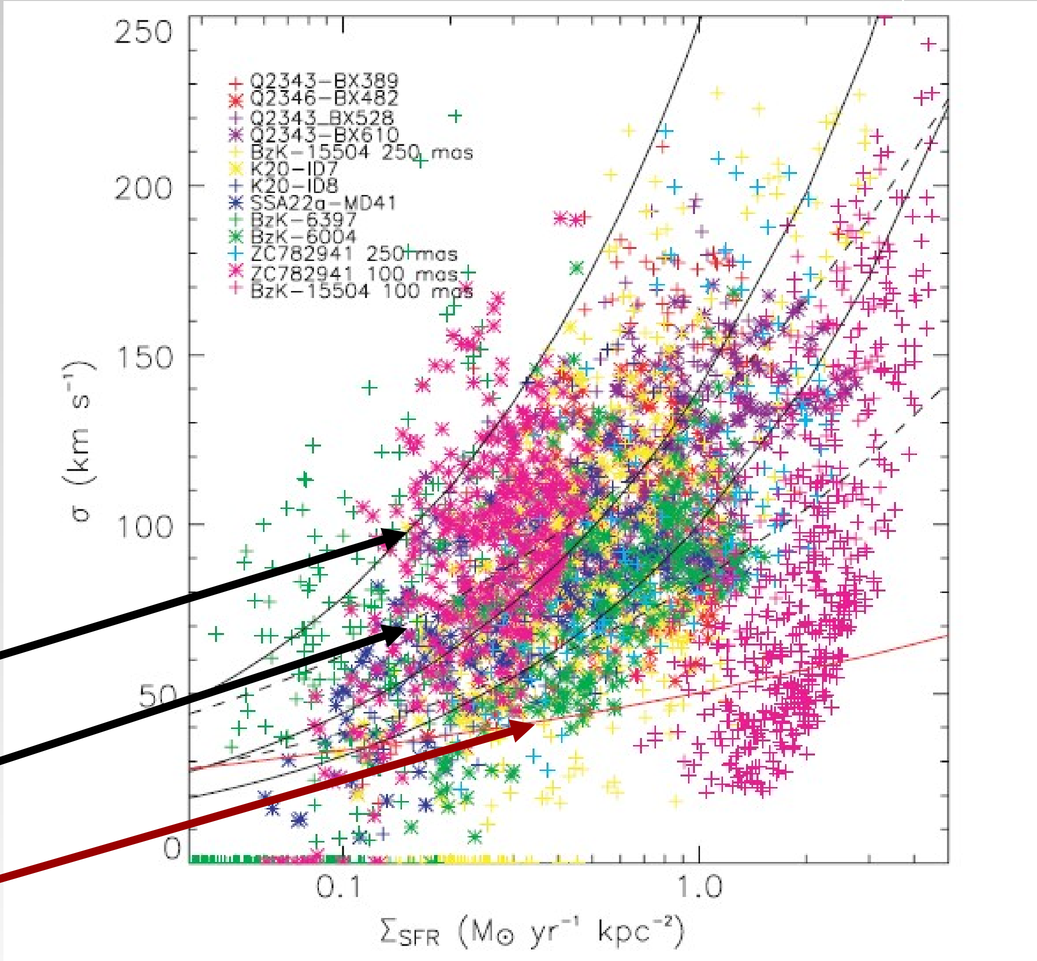
Many distant galaxies have H-alpha surface brightness well above nearby galaxies. M82-like over 10-20 kpc

Self regulation:

- shocks
- cloud-cloud collisions
- pressure and turbulence regulated ISM
- rate of formation of molecular gas

Likely not completely explained by gravitational instabilities

$\Sigma_{SFR} \approx 5 \times 10^{-2}\ M_{\odot}\ yr^{-1}\ kpc^{-2}$ drive outflows; Lehnert & Heckman (1996), Heckman (2001)



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

$$\sigma = (\epsilon \Sigma_{SFR})^{1/3}$$

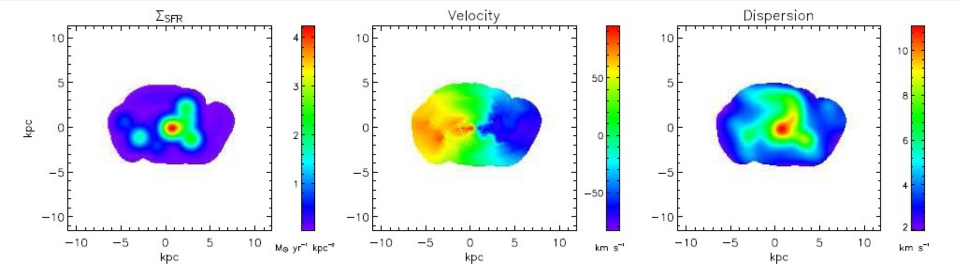
Jeans Instability for $10^9\ M_{\odot}$ clump

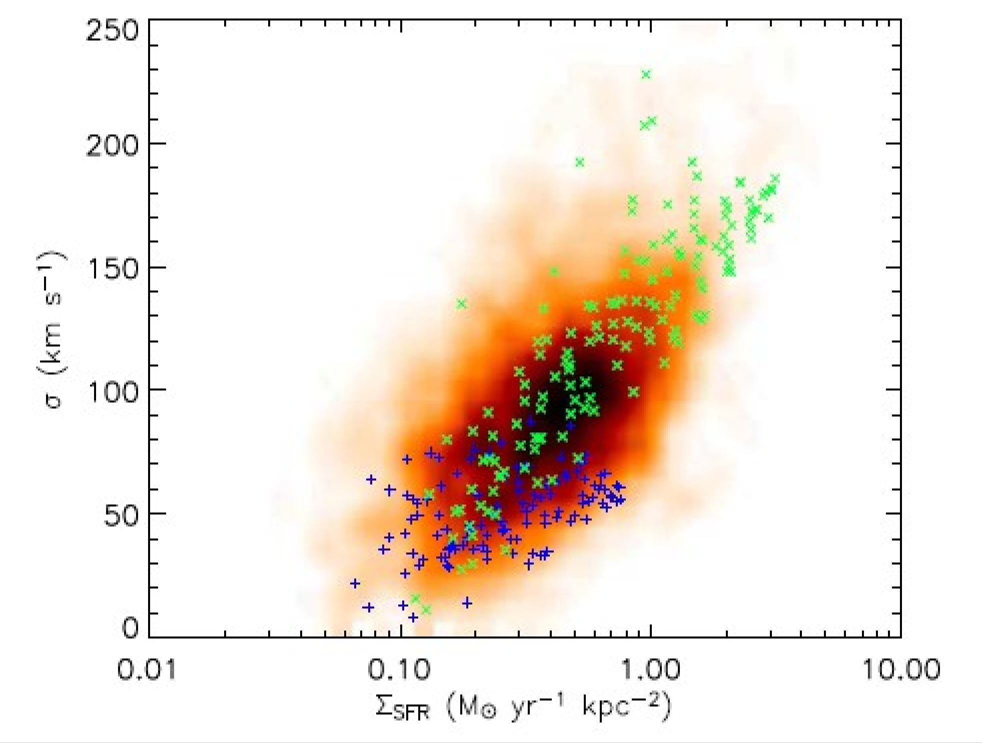
$$\sigma_{gas} \sim M_J^{1/4} G^{1/2} \Sigma_{gas}^{1/4} = 54 M_{J,9}^{1/4} \Sigma_{SFR}^{0.18}\ \mathrm{km\ s^{-1}}$$

Lehnert et al. (2009)

Comparison with Simulations

Comparison to SPH/N-body simulations...





Two types of simulations:

50% gas fraction, evolved in isolation
$\sigma(r)$~10 km s^{-1}, & V_{rot}~200 km s^{-1}

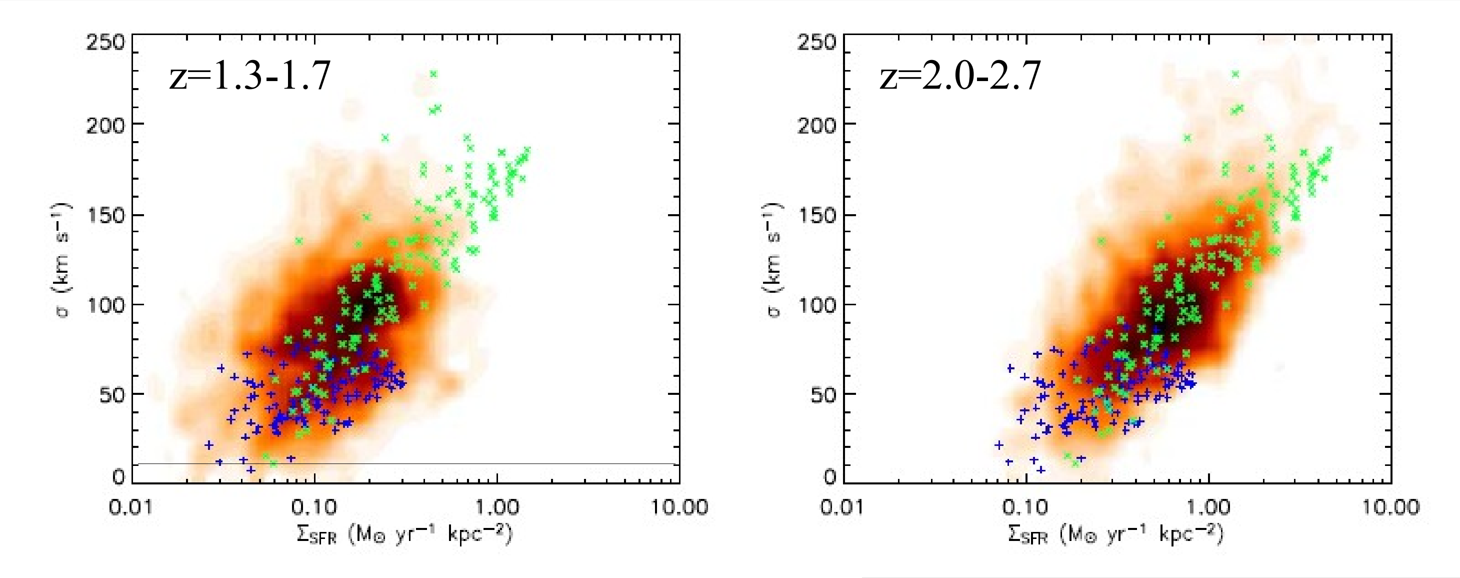
Same, except now σ proportional to $\Sigma_{SFR}^{1/2}$

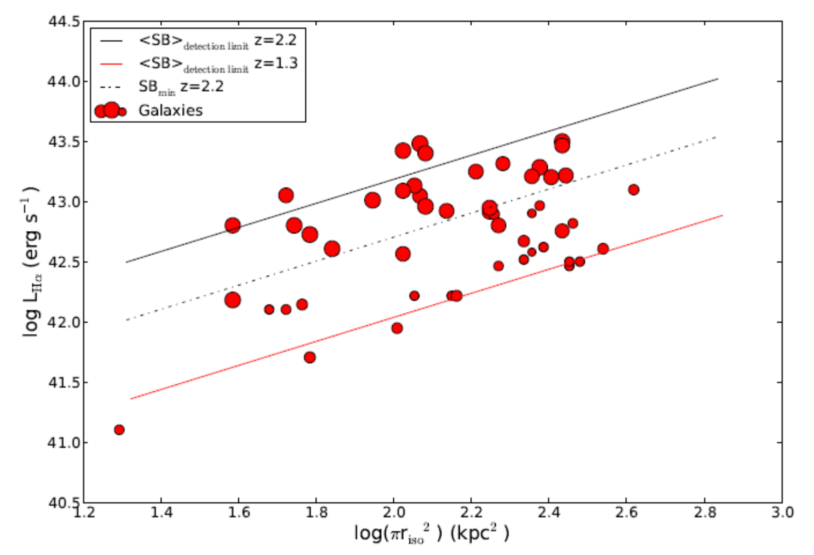
All galaxies shifted to common average Σ_{SFR}

Lehnert et al. (2013)

High Surface Brightnesses

Surface brightnesses are related to line widths ...





At lower redshifts can probe lower SB.

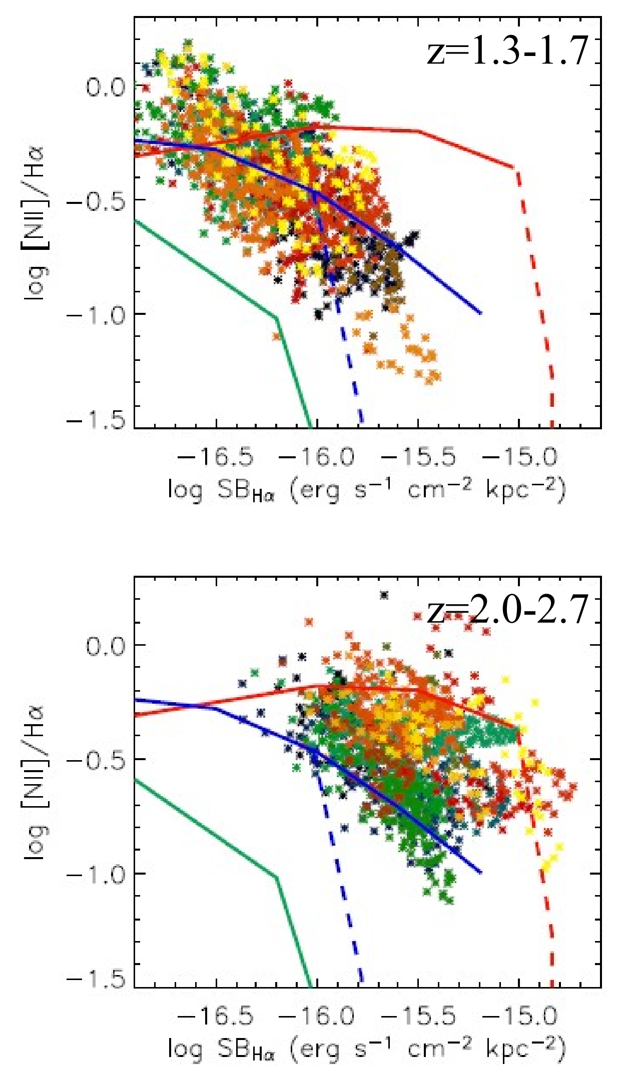
SB limited by cosmological surface brightness dimming $(1+z)^4$

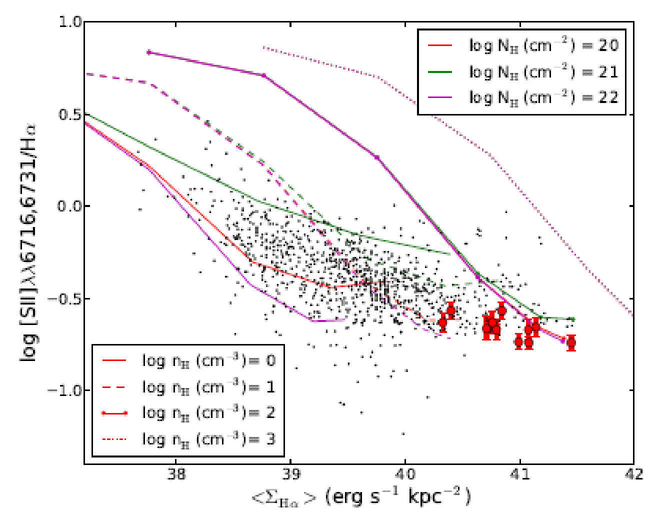
Starting to probe low Σ_{SFR} at lower z and hence lower energy injection rates and perhaps constant dispersions

Le Tiran et al. (2011); Lehnert et al. (2013)

WIM Properties

High densities and moderate-high ionization parameters or lower densities and low ionization but thicker disks …



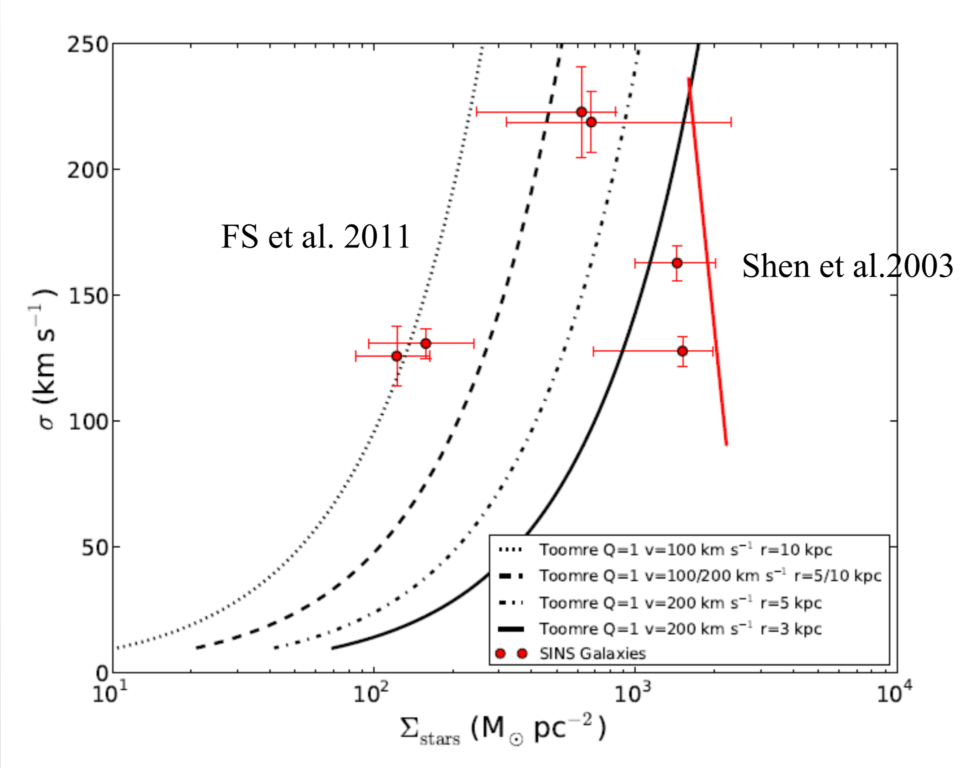


- [SII]λ6716/[SII]λ6731 suggests $P/k=10^{6-7}$ K cm^{-3}
- Single parameter family with nearby galaxies
- Lower redshift galaxies have lower pressures … surface brightness effect
- $P_{\text{gas, turb}} \sim P_{\text{hydrostatic}} > P_{\text{thermal}}$

Lehnert et al. (2009; 2012); Le Tiran et al. (2011)

Driving to the line of stability

Interestingly, galaxies appear close to Q~1 … perhaps coincidental … but certainly suggestive ….



Toomre criteria, $Q_{stars}=\kappa\sigma/\pi G\Sigma_{stars}$

Formally,

$$\frac{1}{Q}=\frac{1}{Q_{stars}}+\frac{1}{Q_{gas}}$$

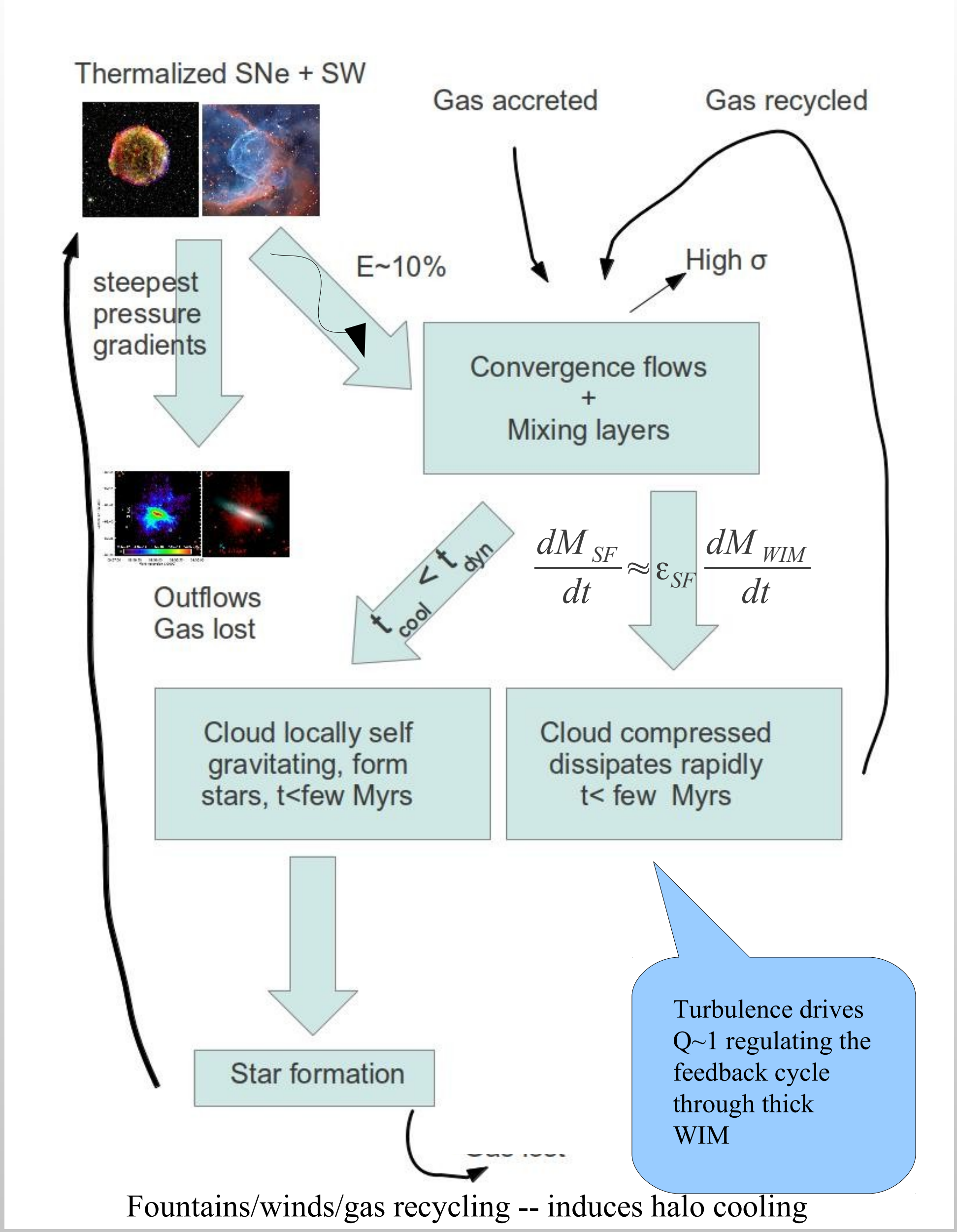
Must assume that $\sigma_{gas} \sim f\sigma_{stars}$ where f is not far from 1 (0.2 to 1 is probably OK).

Estimating Σ_{gas} by inverting the Schmidt-Kennicutt relation gives similar results.

It appears that dispersions are what is necessary to keep the gas near the line of instability.

Lehnert et al. (2013)

Hypothesis: Schematic Presentation



Thermalized SNe + SW

Gas accreted

Gas recycled

steepest pressure gradients

E~10%

High σ

Convergence flows
+
Mixing layers

Outflows
Gas lost

$t_{cool} < t_{dyn}$

$$\frac{dM_{SF}}{dt} \approx \varepsilon_{SF} \frac{dM_{WIM}}{dt}$$

Cloud locally self gravitating, form stars, t<few Myrs

Cloud compressed dissipates rapidly t< few Myrs

Star formation

Turbulence drives Q~1 regulating the feedback cycle through thick WIM

Fountains/winds/gas recycling -- induces halo cooling

$P_{thermal,hot} \sim P_{thermal,WIM}$

Allows for efficient energy and mass coupling. Hot gas to WIM to CNM because of high pressures (Wolfire et al. 1995)

If energy and mass transfer cycle is efficient, postulate $\sigma_{WIM} \sim f\sigma_{CNM}$

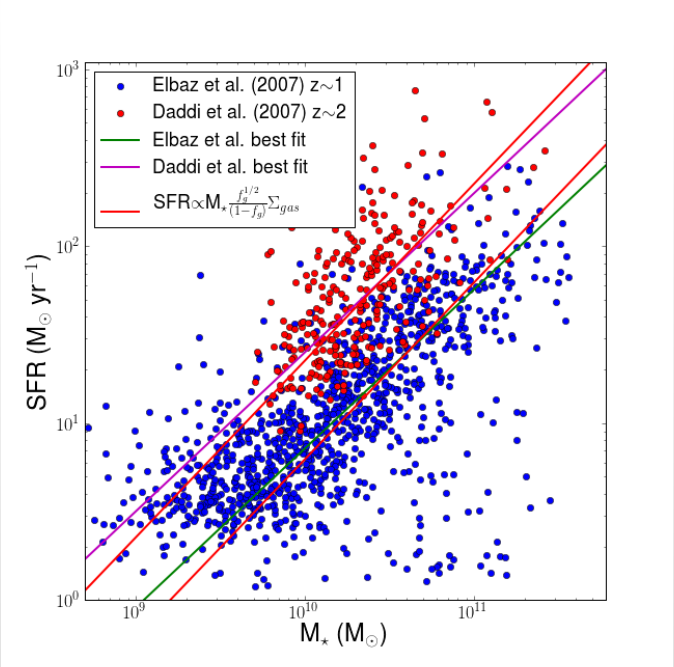
$t_{dissipation}$~10s Myrs < t_{dyn} < SF age (~500 Myrs; Erb et al. 2006; Forster Schreiber et al. 2011, others)

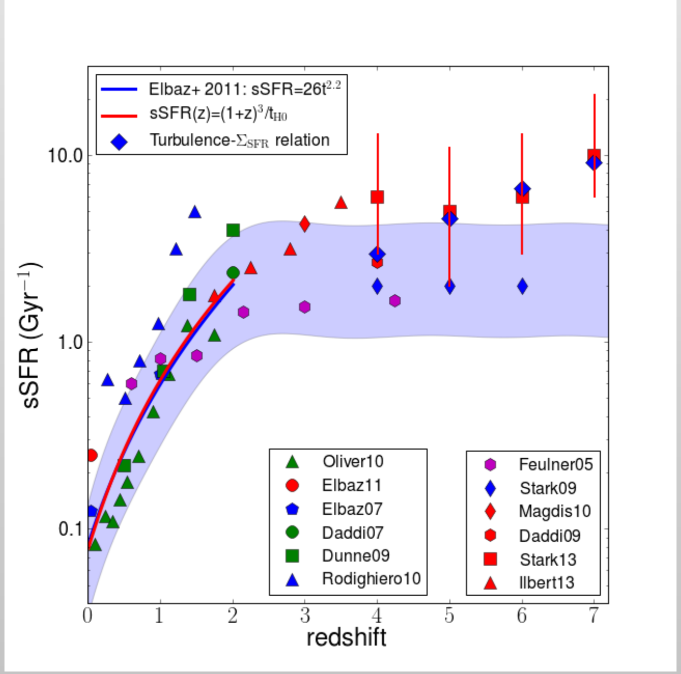
Cooling time to CMM short
Implication: very little CNM

Results in $P_{turb} \sim P_{hydro} > P_{thermal}$

$P_{turb} \sim \sum_{i=\mathrm{ISM\ phases}} (ff_V \langle\rho\rangle \sigma^2)_i$ – $P_{turb,WIM}$ small

Q~1 and star formation is self regulating





Generalized Schmidt law and gas pressure,

$$\Sigma_{SFR} \propto \Sigma_{gas}^{3/2}\Sigma_{total}^{1/2} \qquad P_{gas} = \rho\sigma^2 = \pi/2\,\Sigma_{gas}\Sigma_{total}$$

Pressure regulated star formation,

$$SFR \propto M_\star \frac{f_g^{1/2}}{(1-f_g)}\Sigma_{gas},$$ surface density important,

Angular momentum regulated star formation,

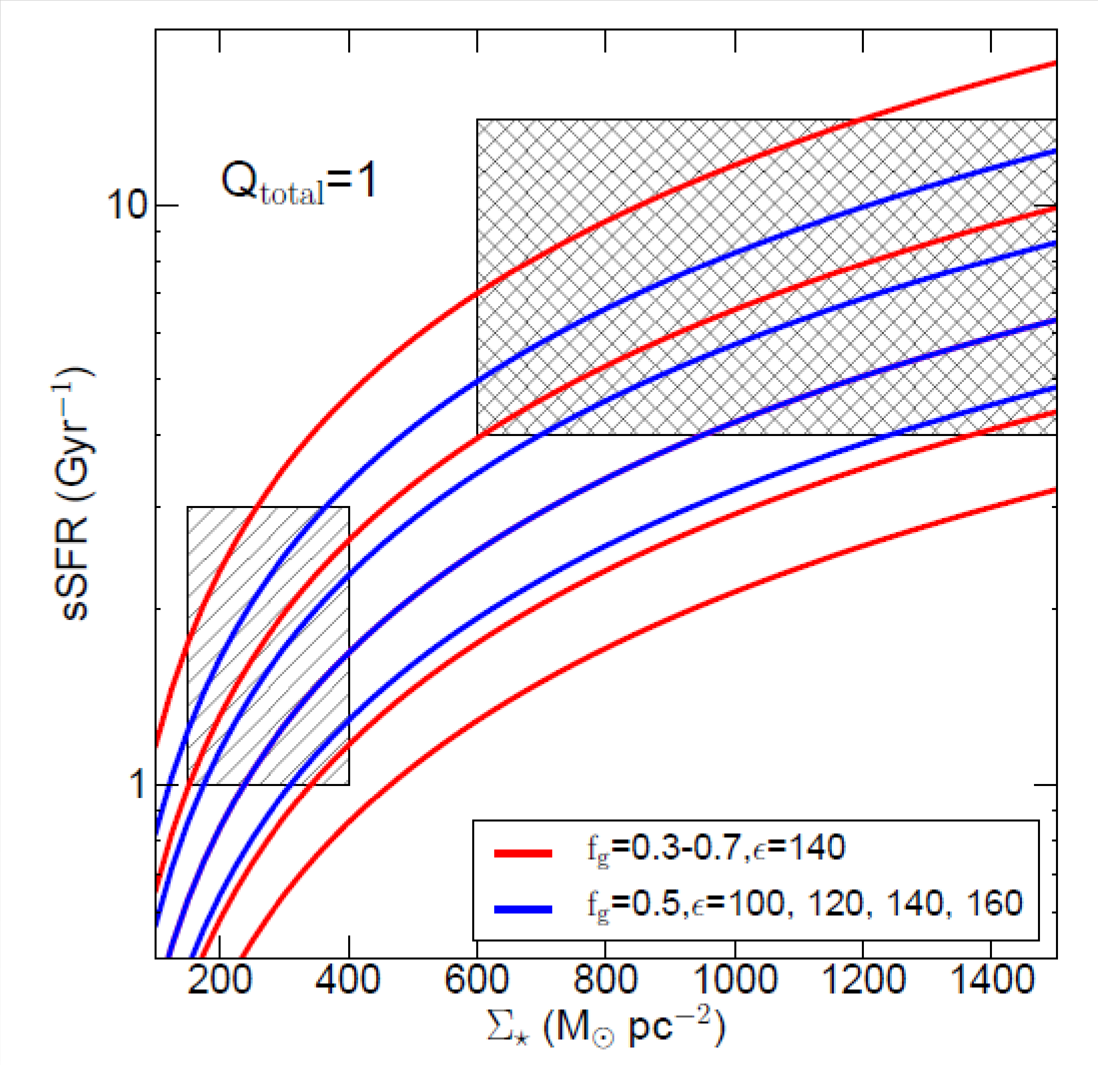
$$sSFR = (1+z)^3/t_{H0}$$

Angular momentum controls gas mass surface density … z<2

z>2: Colliding streams, dense small halos leads to compact high density objects … feedback decisive … truncates sSFR ...

Lehnert et al. (2013, A&A submitted)

Feedback model



Disk stability plus turbulence

$$\frac{1}{Q} = \frac{1}{Q_{stars}} + \frac{1}{Q_{gas}} \qquad \sigma_{gas} = \epsilon\, \Sigma_{SFR}^{1/2}$$

… a form of self-regulation

$$\mathrm{sSFR} = \left(\frac{\Sigma_{\mathrm{SFR}}}{\Sigma_\star}\right) = \left(\frac{\pi G Q_{\mathrm{total}}}{\kappa\epsilon}\right)^2 \Sigma_\star \left(\frac{\mathrm{f_g}}{1-\mathrm{f_g}} + \frac{\sigma_{\mathrm{gas}}}{\sigma_\star}\right)^2$$

Conclusions

Understanding galaxy formation and evolution is difficult.

Holism vs. reductionism.

There is no perfect approach … but following the gas is probably good...

Lots of years of difficult research ahead …

Don't believe everything you hear in a talk or read in a paper!