The MW as a distant galaxy: turbulence, mixing, and quenching

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with Misha Haywood, Paola Di Matteo, Owain Snaith, David Katz, Anita Gomez ...

NGC 1627 Hubble Heritage image

Global problems in galaxy evolution

Galaxy formation is a balance between accretion, SF, and outflows. Is over-cooling still a problem.

However, the balance is based on understanding what regulates each and they are on different scales.

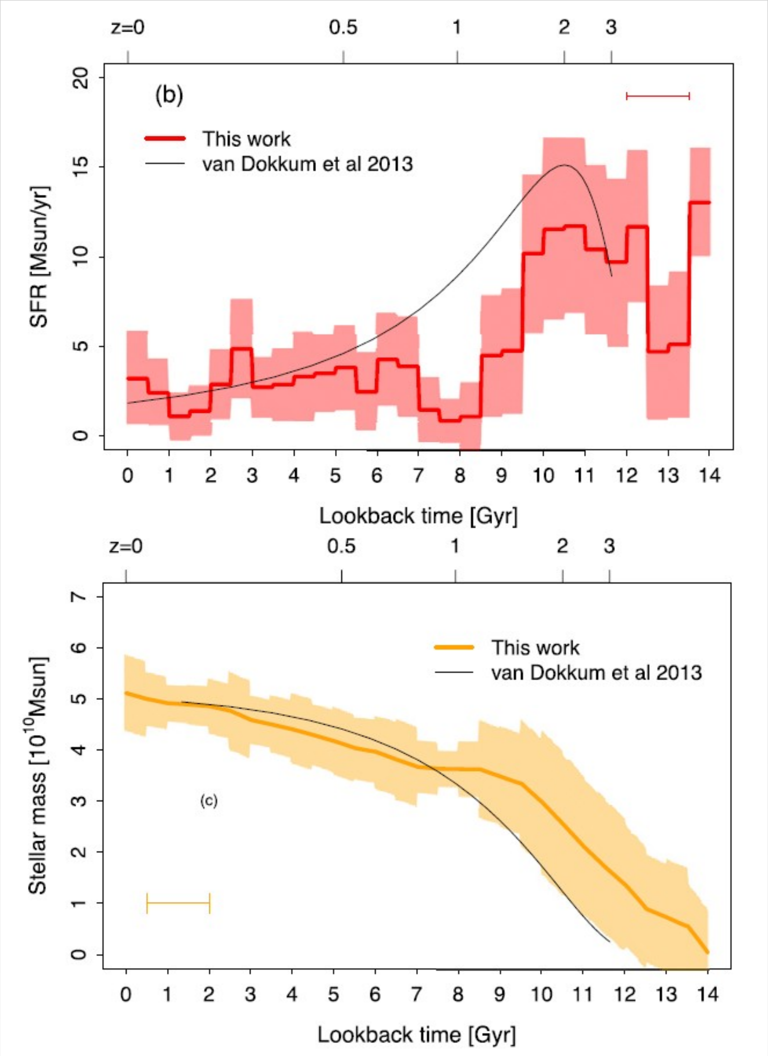
Turbulence has a role over many scales. For example, turbulent injection on large scales can increase the cooling time and could perhaps play a role in regulating the gas content, changing this balance.

Turbulence connects phases through a mass, momentum, and energy flow.

Thermal instabilities naturally generates turbulence.

Issues between global heating and local cooling through entropy fluctuations.

Agrees with Abundance matched MWs

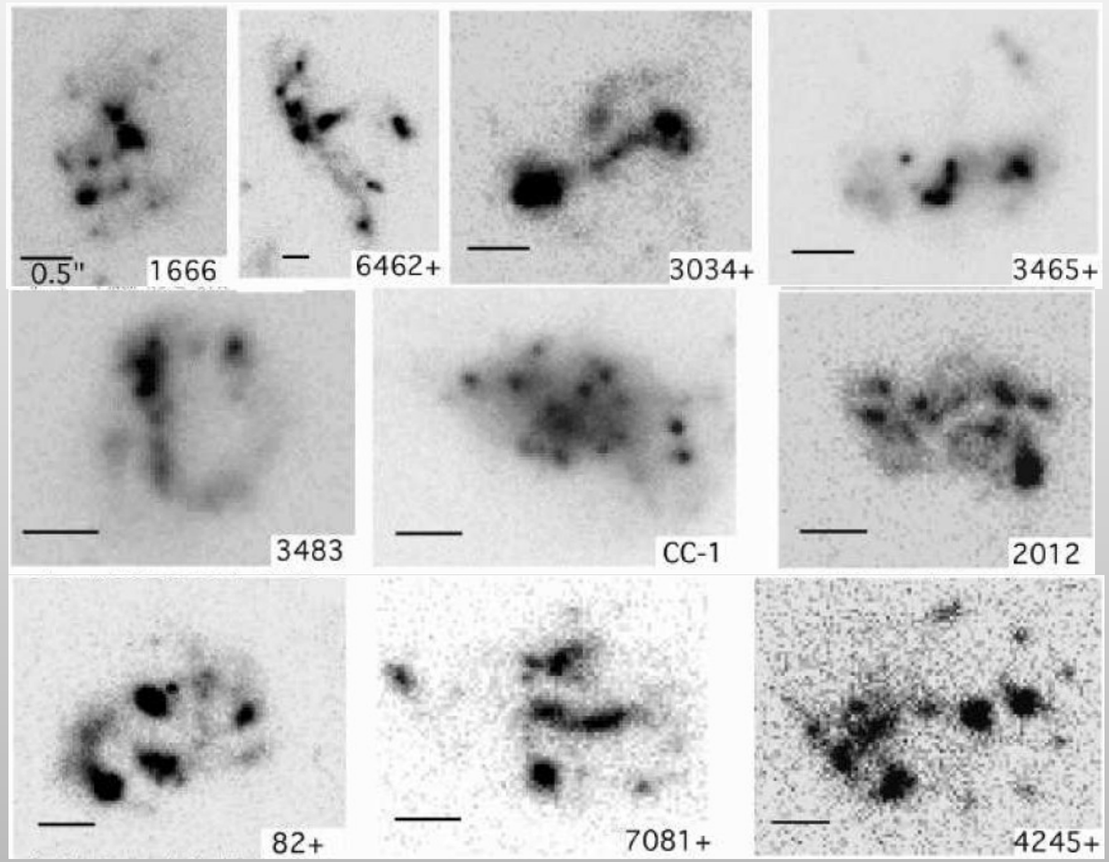


The MW falls within the range of SFH determined through abundance matching. So it appears OK with in situ formation.

Snaith et al. (2014)

Disk formation – clumpy, thick disks at high redshift

Clumpy thick galaxies in the UDF …1 kpc, clumps, 1 kpc, 10^9 solar masses



Elmegreen & Elmegreen (2005)

Galaxies at high redshift are increasingly dominated by their gas.
Locally, 10%, about 10 Gyrs ago, 50% of galaxy mass is molecular.

High-z disks form stars intensely

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

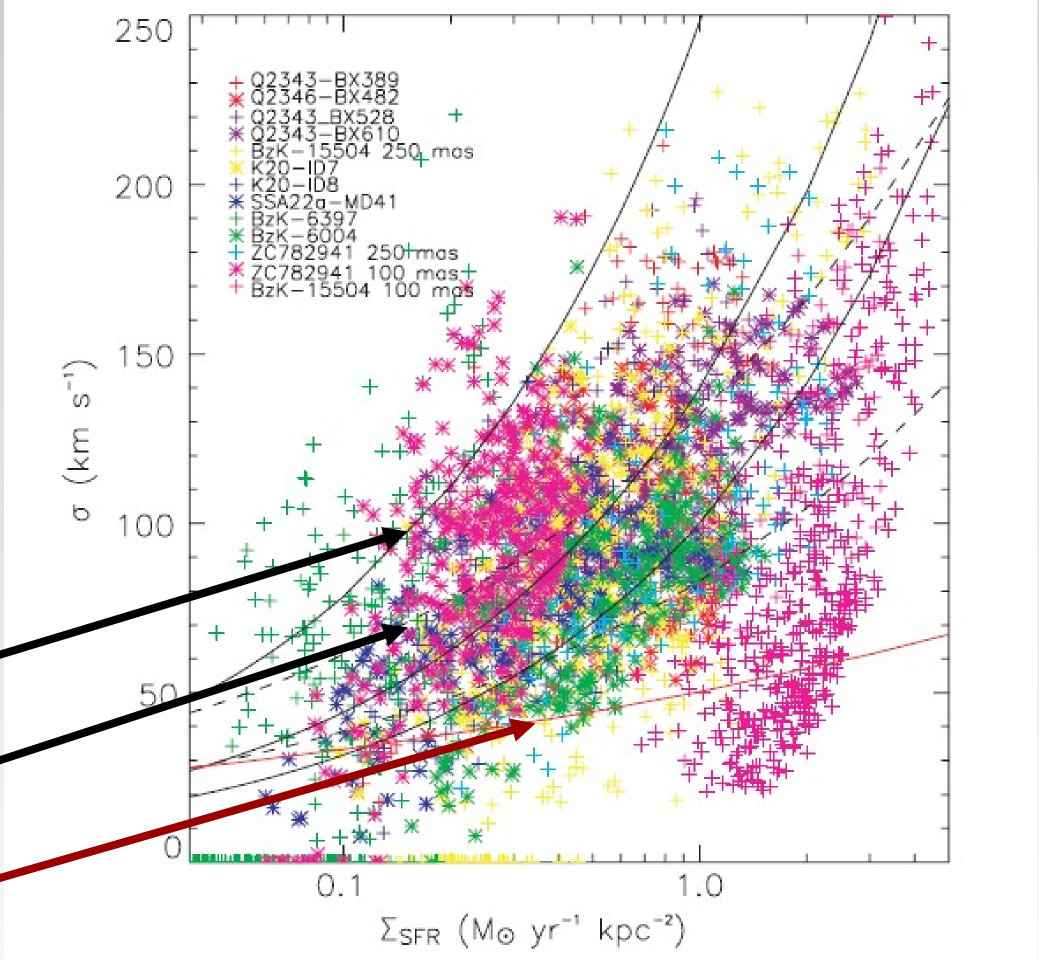
$\Sigma_{SFR} \approx 5\text{x}10^{-2}\ M_{\odot}\ yr^{-1}\ kpc^{-2}$ drive outflows; Lehnert & Heckman (1996), Heckman (2001)

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

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

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

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

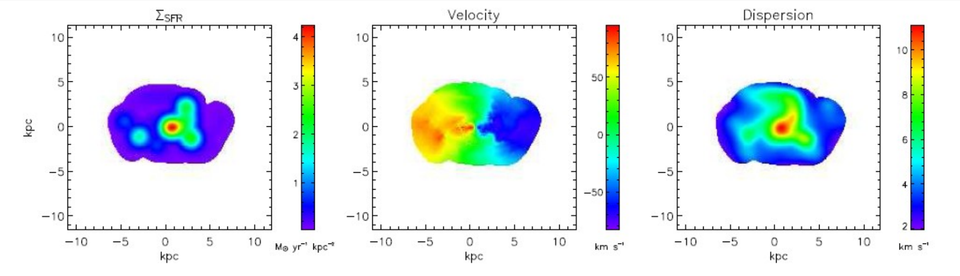


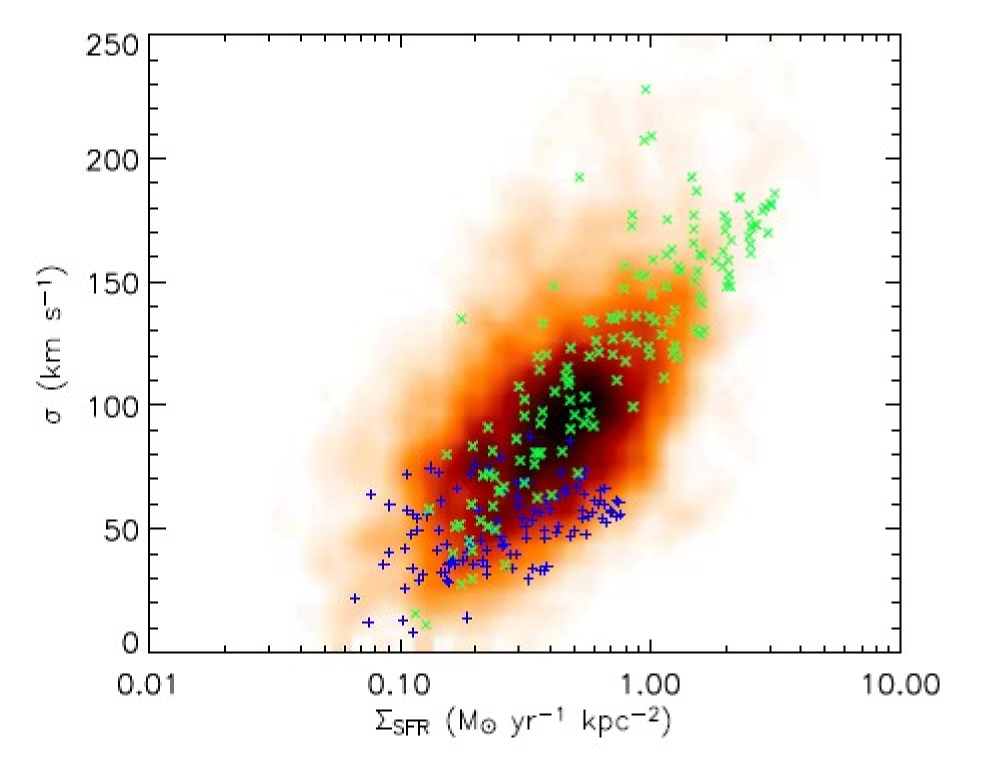
Lehnert et al. (2009)

Disks at high-z are intense SFers

Comparison to SPH/N-body simulations...

Geometrically thick ~1 kpc
Highly turbulent, σ~100 km s^{-1}
t_{diss}~100pc/10 km s^{-1}~1 kpc/100 km s^{-1}





Two types of simulations:

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

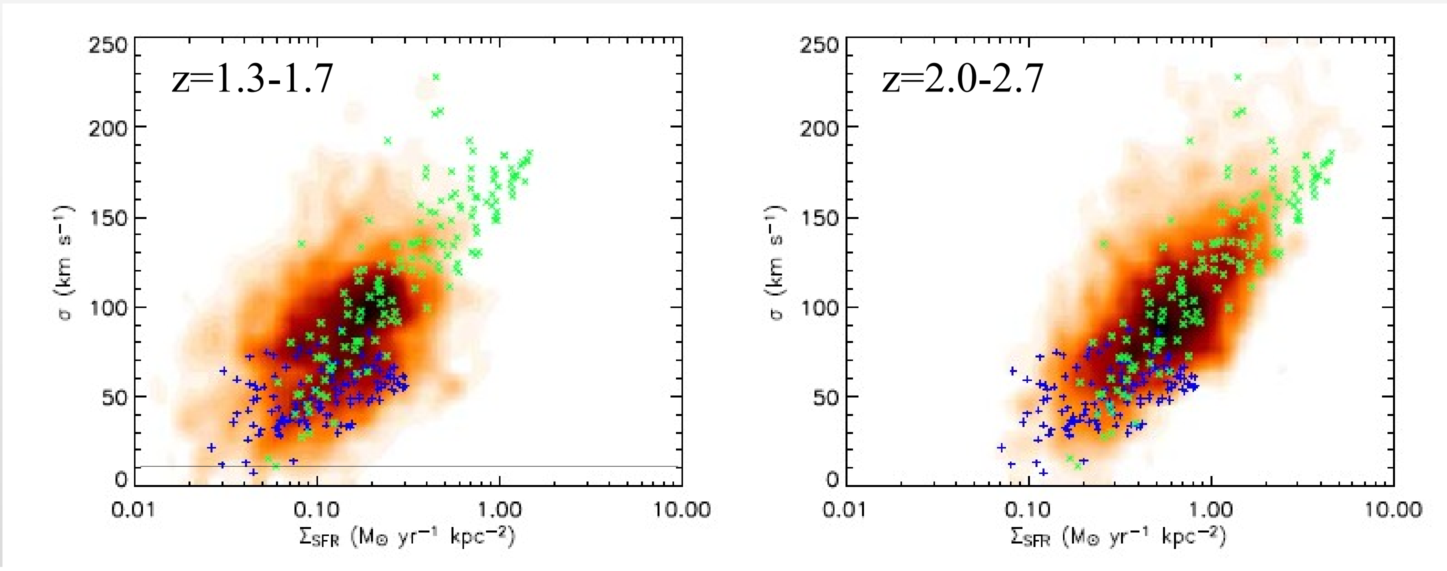
Same, except now σ proportional to $\Sigma_{SFR}^{1/2}$

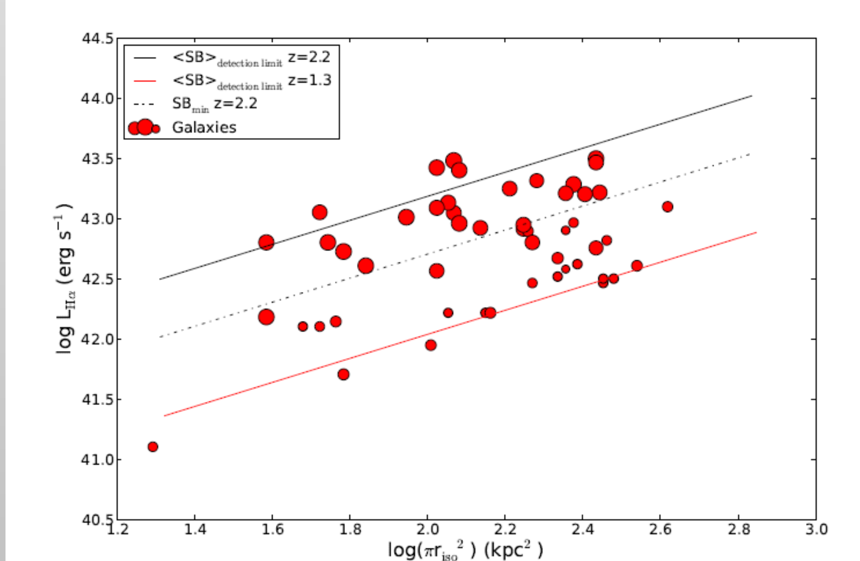
All galaxies shifted to common average Σ_{SFR} for ~50 galaxies over z=1.3 to 2.7

Lehnert et al. (2013)

High Surface Brightnesses

Disk settling … velocity dispersion decreasing with redshift ...





At lower redshifts can probe lower SB.

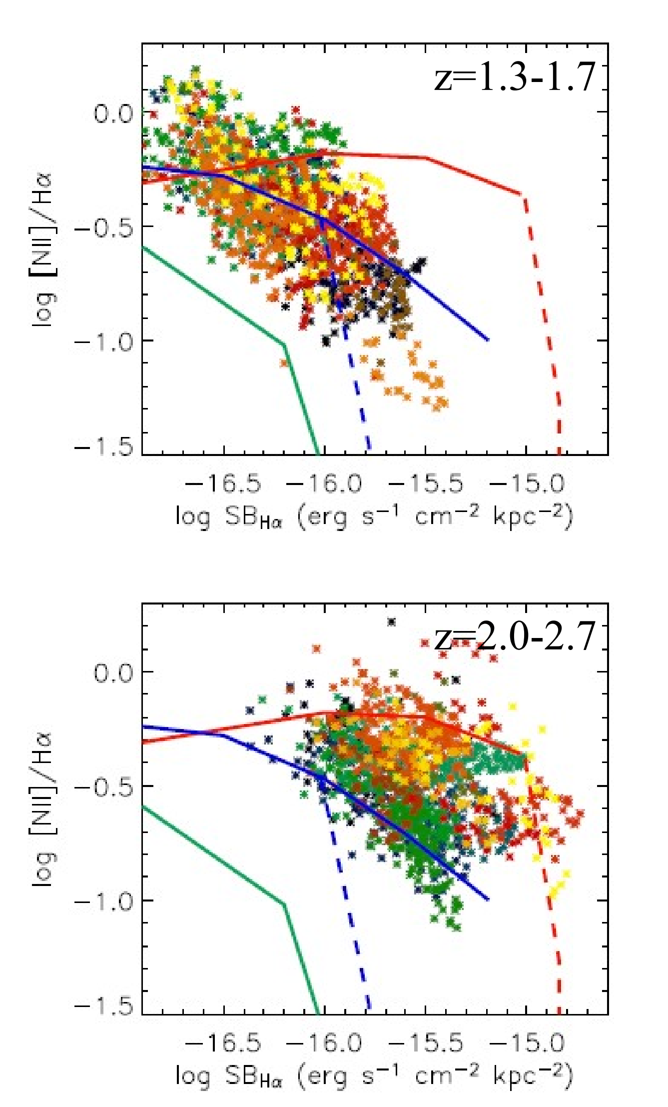
SB limited by cosmological surface brightness dimming $(1+z)^4$

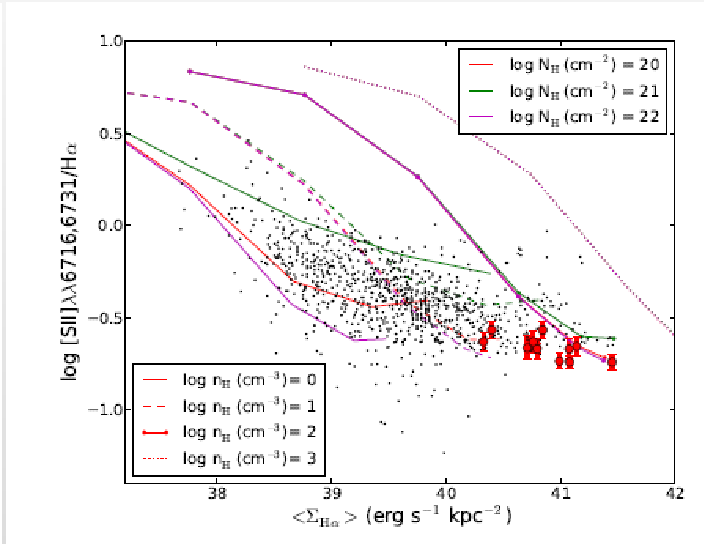
Starting to probe low Σ_{SFR} at lower z and hence lower energy injection rates and perhaps constant dispersions

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 …



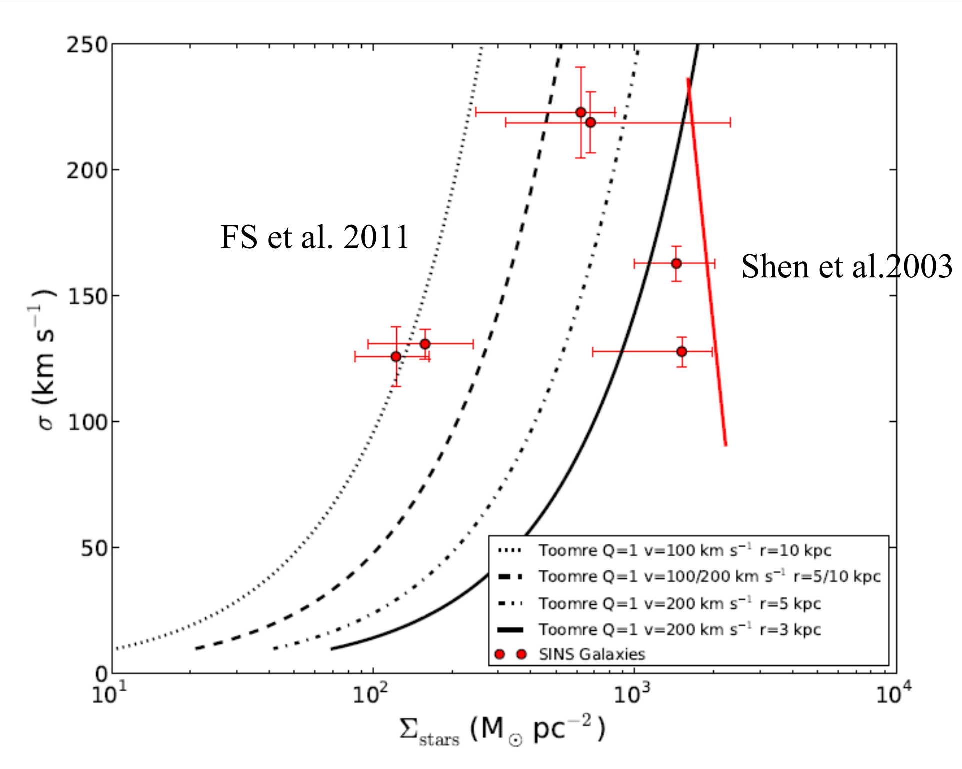


- [SII]λ6716/[SII]λ6731 suggests $P/k=10^{6\text{-}7}$ K cm^{-3}
- Single parameter family with nearby galaxies
- Lower redshift galaxies have lower pressures … surface brightness effect
- $P_{\text{gas, turb}} \sim P_{\text{hydrostatic}} > P_{\text{thermal}}$

Lehnert et al. (2009; 2013); 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).

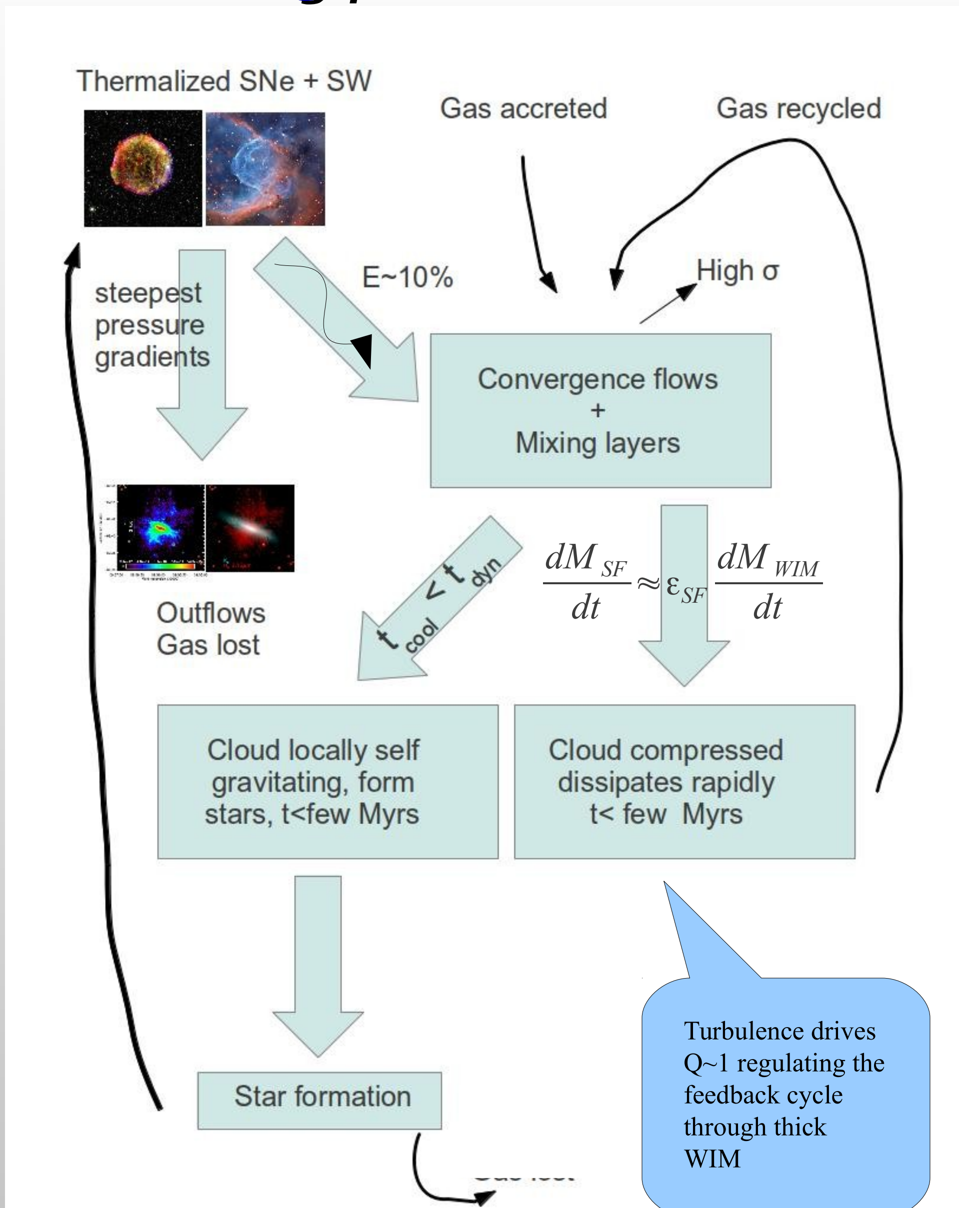
Estimating Σ_{gas} by inverting the Schmidt-Kennicutt relation gives similar results.

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

Self-regulated star formation?

Lehnert et al. (2013)

Hypothesis: Schematic Presentation



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

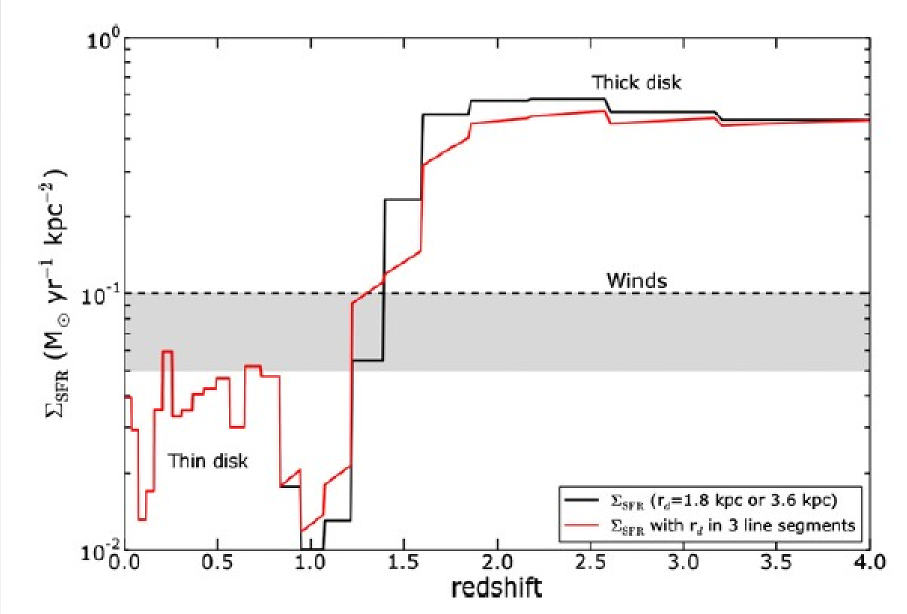
Results in $P_{turb} \sim P_{hydro} > P_{thermal}$

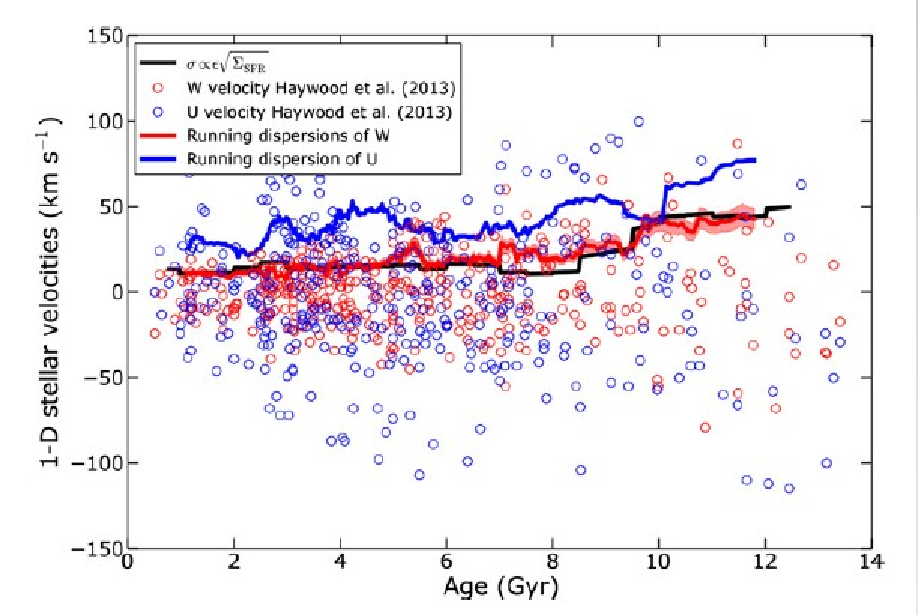
$P_{turb} \sim \sum_{i=ISM\ phases} (ff_V \langle\rho\rangle \sigma^2)_i$ note: $P_{turb,WIM}$ small

Q~1 and star formation is self regulating

Formation of the thick disks

We need to explain the homogeneity of the thick disk … no specific radial variation

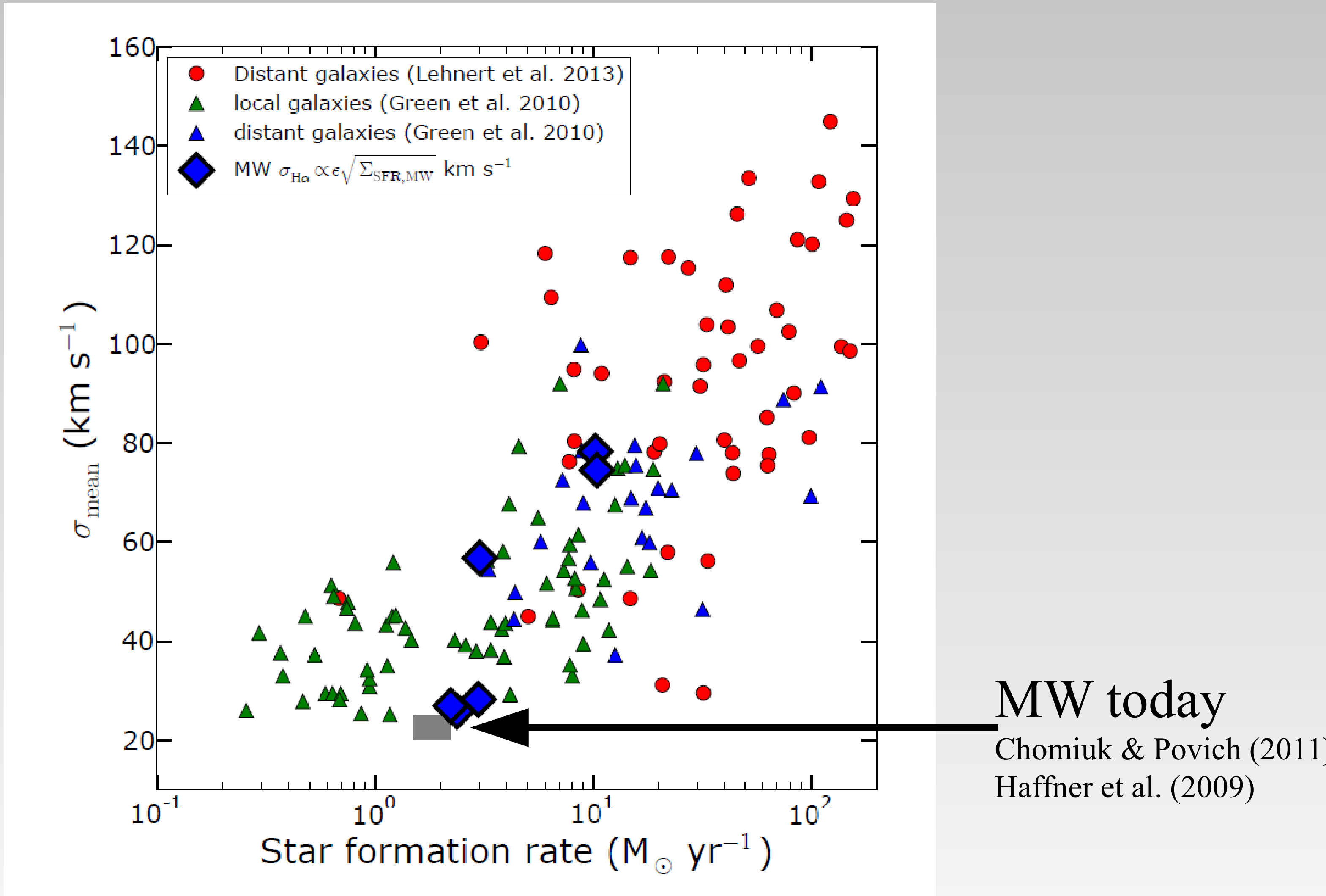




Can be understood as a strong coupling between the mechanical and radiative energy into the gas and a momentum exchange between phases … need to invoke a cascade of energy, momentum, and phase

Lehnert et al. (2014), see the first arguments for thick turbulent disks at high redshift in Lehnert et al. (2009) and Lehnert et al. (2013)

Turbulent disks



Even agrees with the integrated star formation rate of disks …

for z=0.1, 0.3, 0.8, 1.3, 2, and 3.

Lehnert et al. (2014)

Seeing the formation of thick disks

Disks were very turbulent at high redshift. Perhaps several different causes …

Energy arguments are almost useless as by definition, there is plenty of energy. Key: determining the dissipation time scale.

Favoring SF for generating turbulence – self-regulation:

The turbulent turnover time is ~evolutionary timescale of massive stars. Uniform metallicity in the thick disk.

Accreted gas has high angular momentum – outer disk (e.g., Danovich et al. 2015). Use other processes to redistribute it. I favor viscosity.