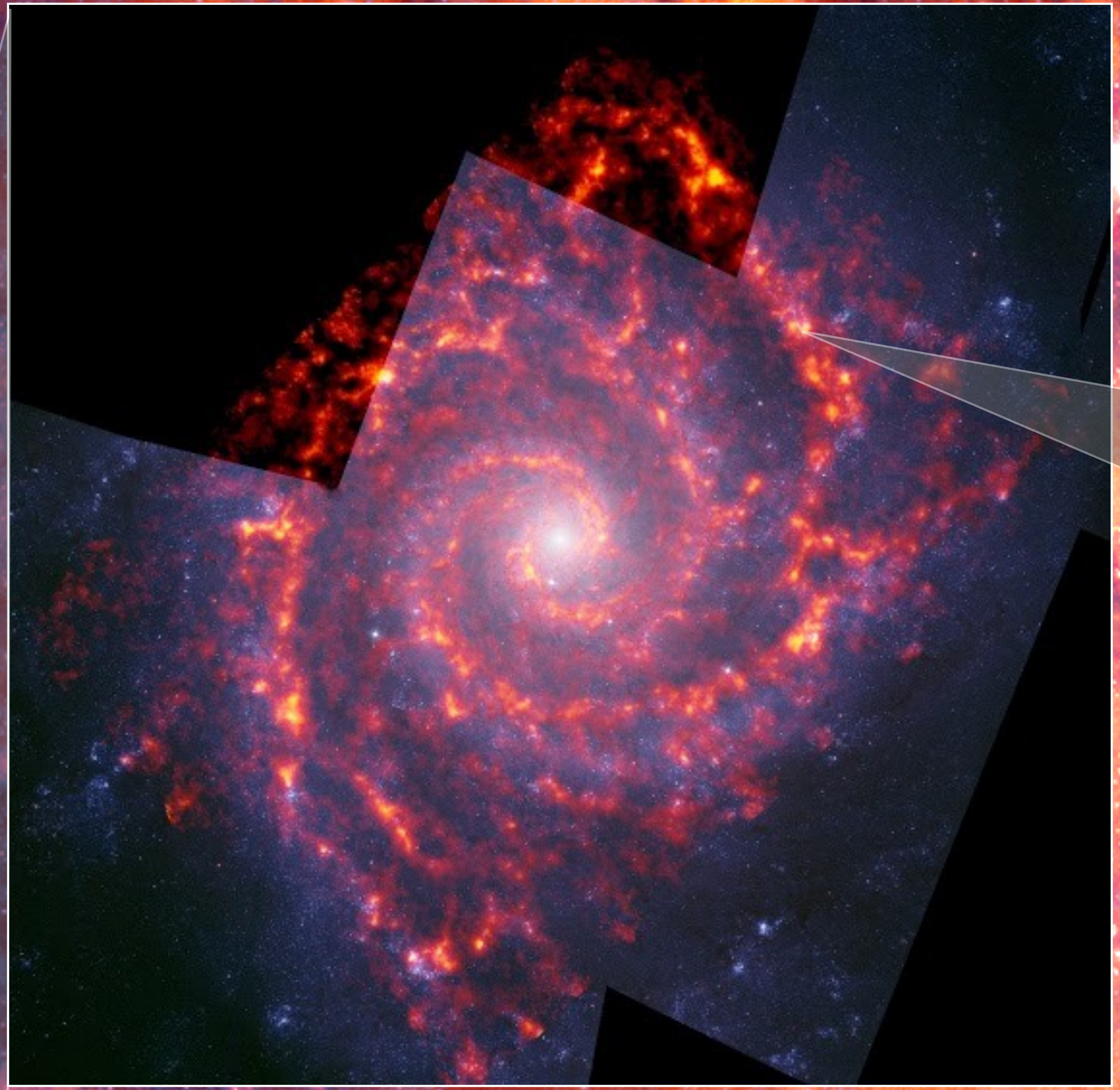


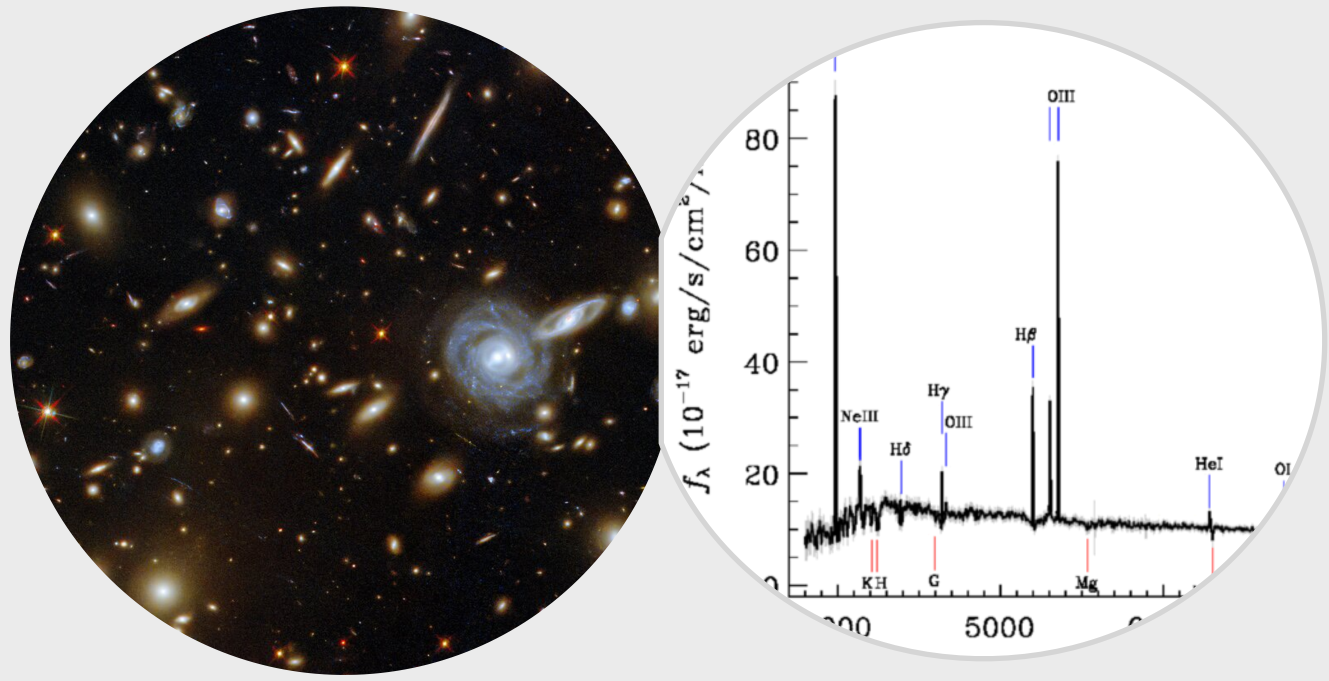
The cold interstellar medium of galaxies in the local universe

Based on Saintonge & Catinella, 2022, ARA&A, 60, 319

Professor Amélie Saintonge (University College London)

Observing galaxy evolution (the “traditional” way)

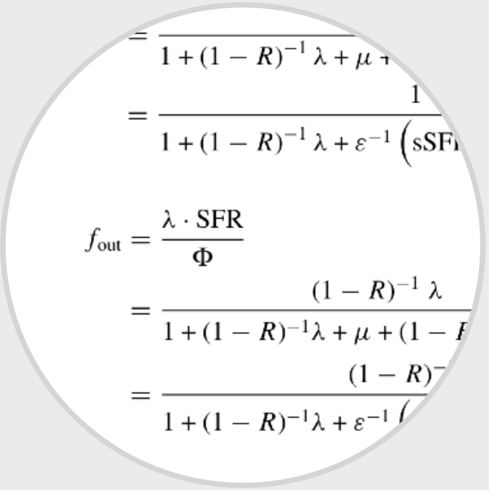
UV/optical/IR photometry & spectroscopy



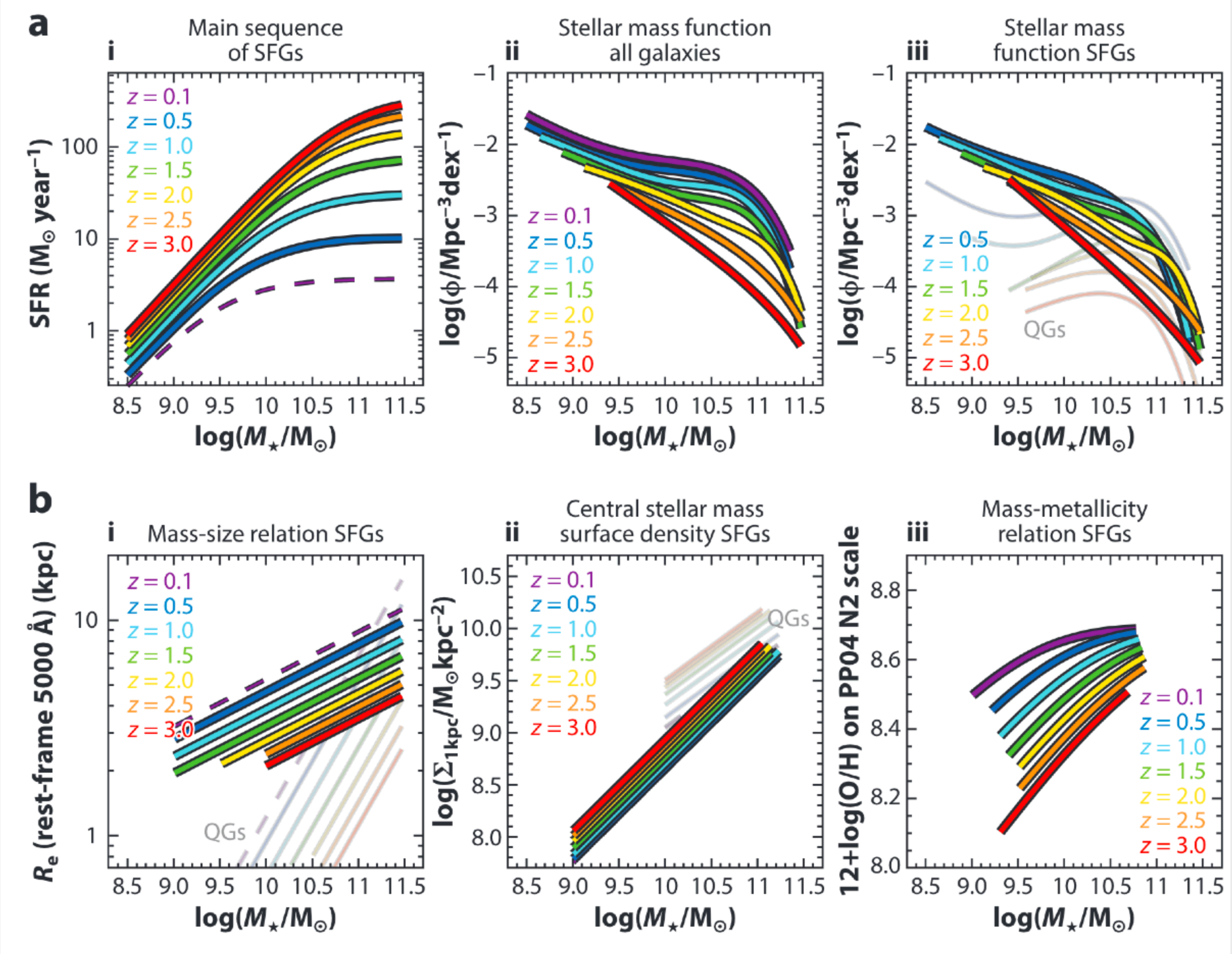
Physical properties

- stellar mass
- size
- star formation rate
- gas-phase metallicity
- stellar metallicity
- morphology
- AGN activity
- rotation velocity
- central velocity dispersion
- environment
- dark halo mass
- angular momentum
- magnetic field

Simulations & theory



Empirical scaling relations



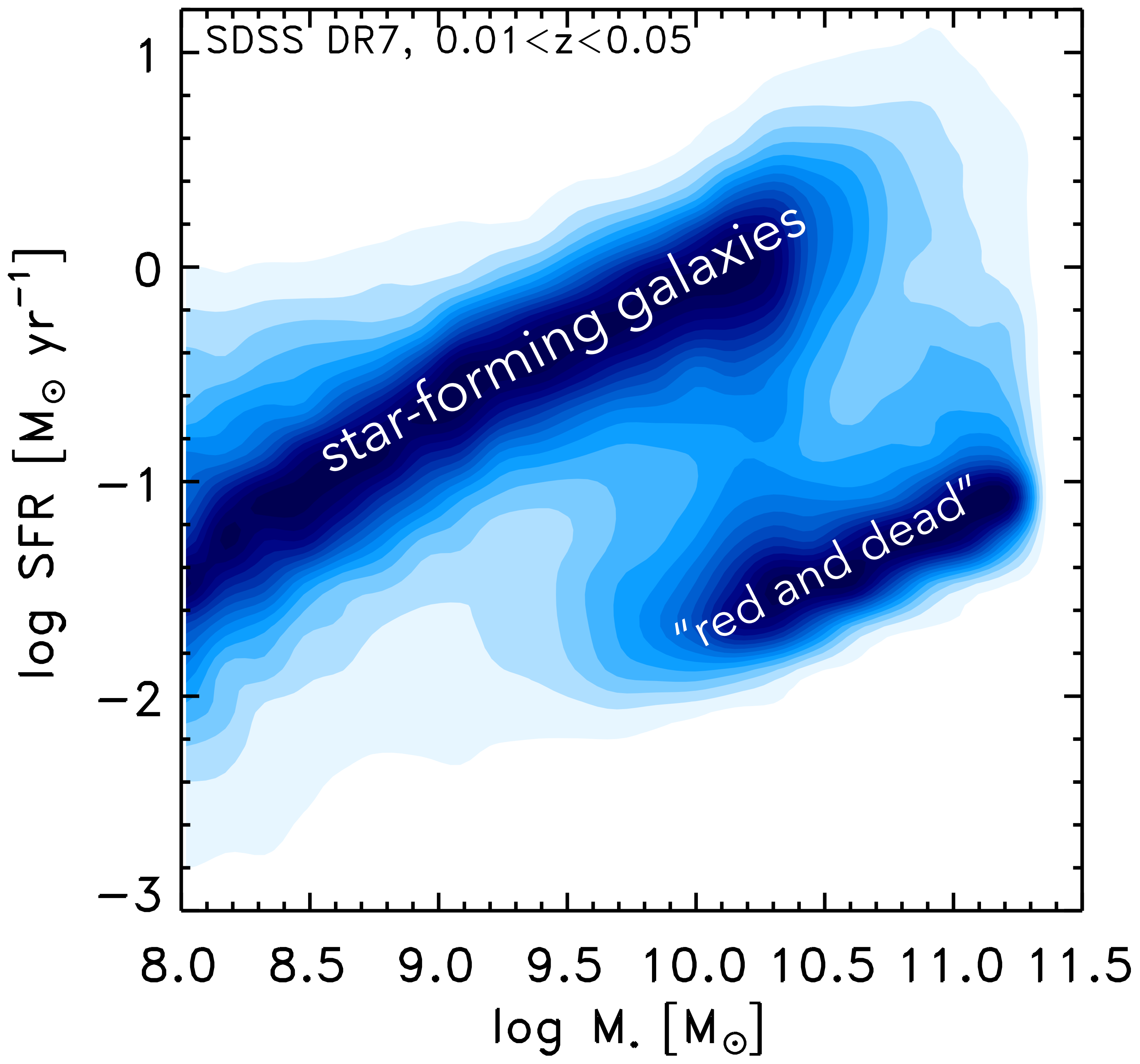
Constraints on evolutionary mechanisms

- minor/major mergers
- star formation triggering/ quenching
- AGN feedback
- environmental stripping
- gas accretion
- bulge formation
- disc growth
- morphological transformation

The current empirical picture for galaxy evolution

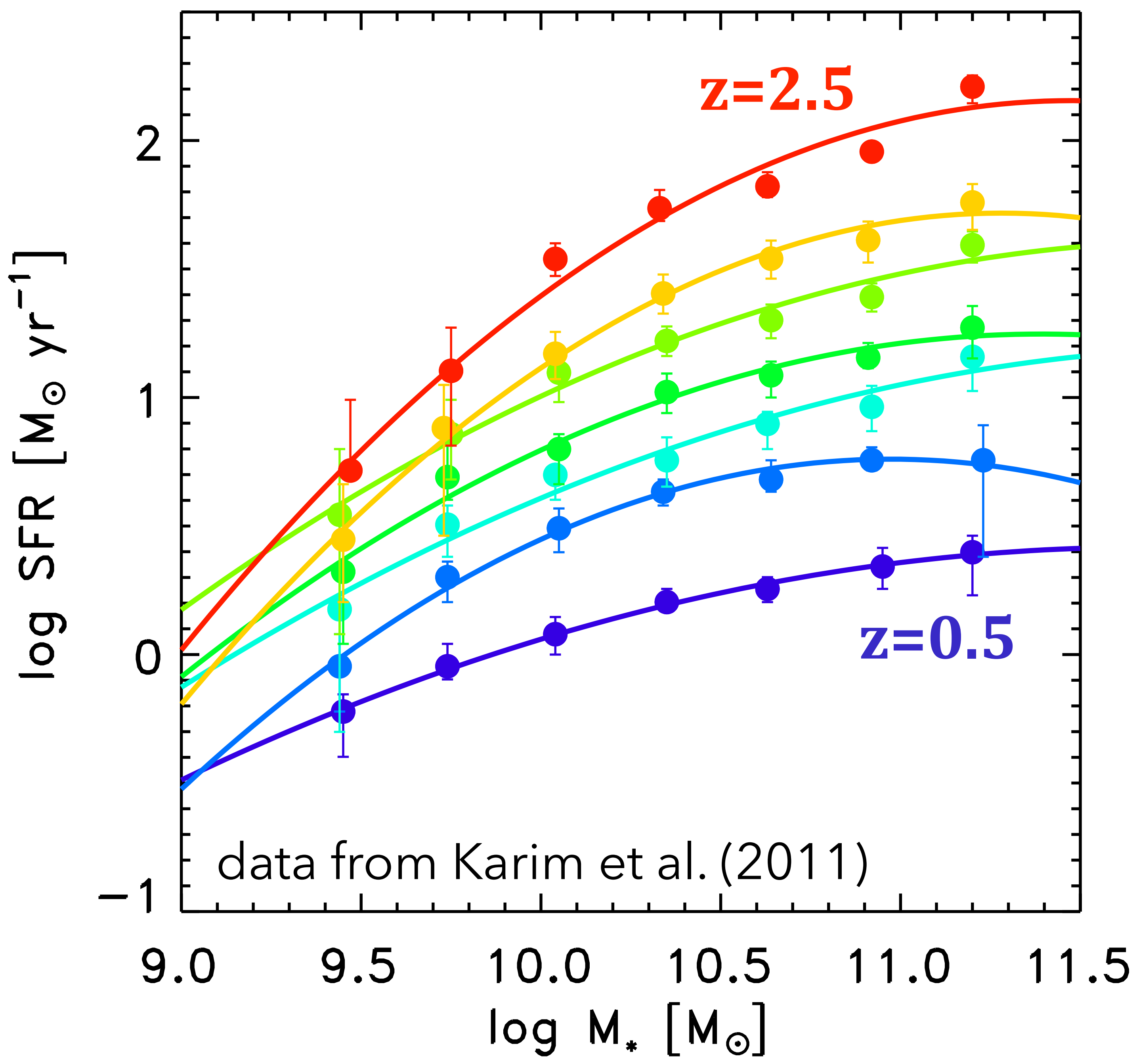
the star formation "main sequence"

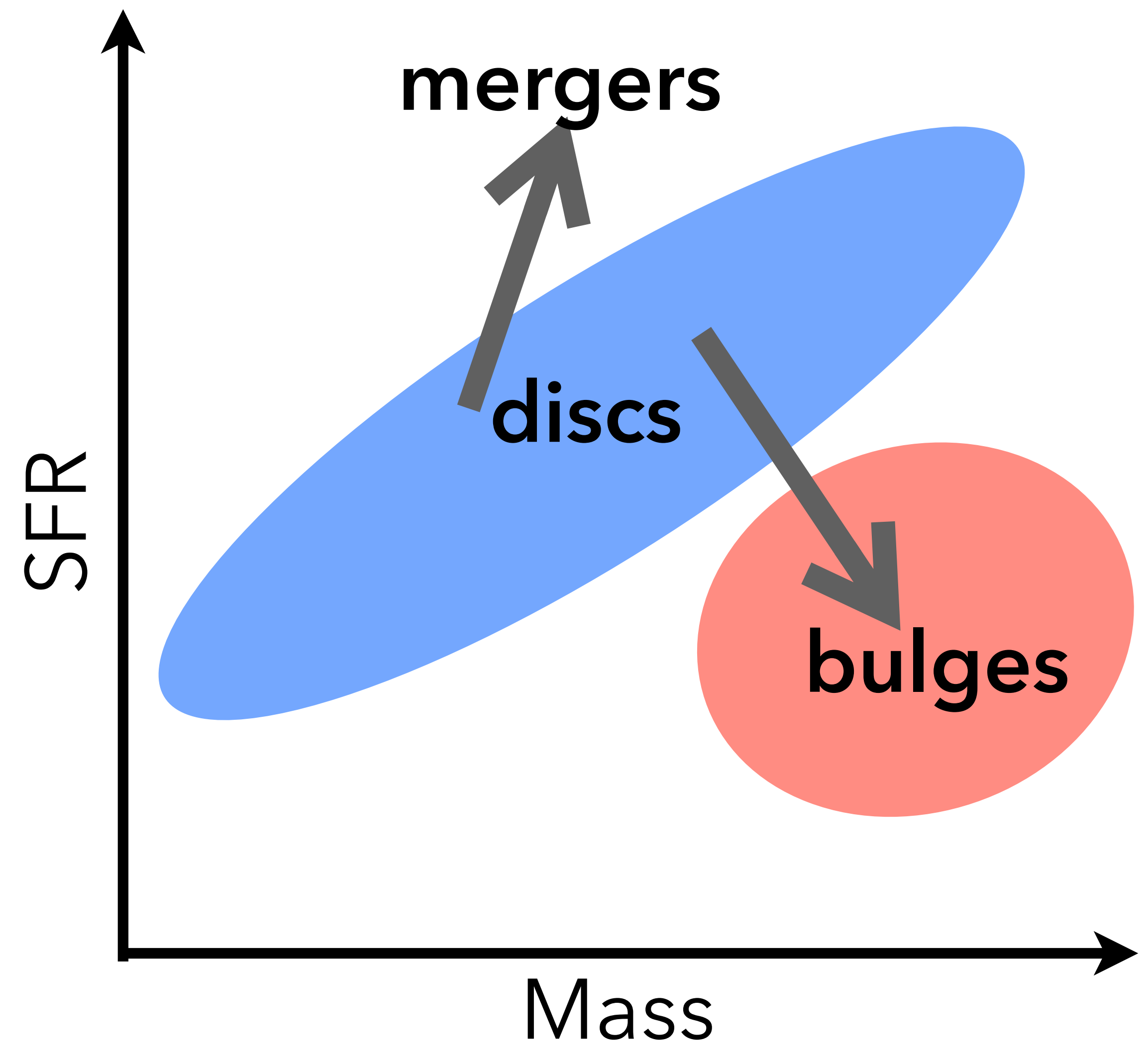
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)



the redshift evolution of the main sequence

see e.g.: Whitaker et al. (2014), Tomczak et al. (2016), Speagle et al. (2014), Leslie et al. (2020),….

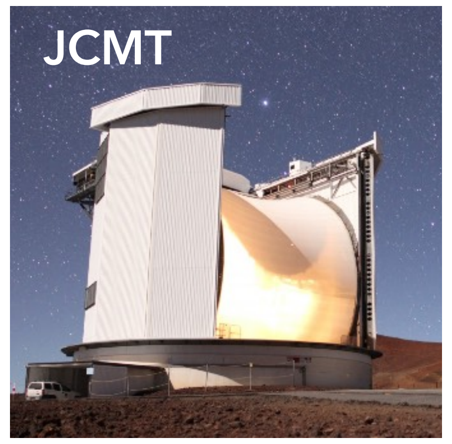


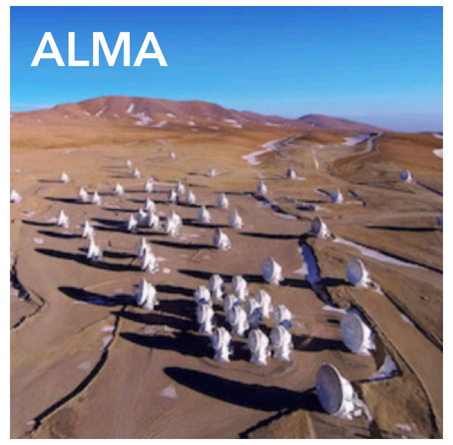


$$SFR \sim M_*^a (1+z)^b, \text{ where } a \sim 0.8,\ b \sim 2.5$$

- Galaxies on the main sequence (MS) contribute ~90% of the star formation.
- Duty cycles on the MS are high at 40-70% implying that "catastrophic" events like major mergers cannot be the main agent responsible for regulating star formation.

Legacy surveys to quantify the ISM properties of galaxies at low-z





Global measurements (targeted surveys for CO, HI, or dust):

x(COLD) GASS (PIs A. Saintonge, B. Catinella)

950h IRAM 30-m Large Programmes +1500h Arecibo Programme

Integrated M_{HI} and M_{H2} measurements for 532 SDSS-selected galaxies with $0.01<z<0.05$, $M^*>10^9$ Msun

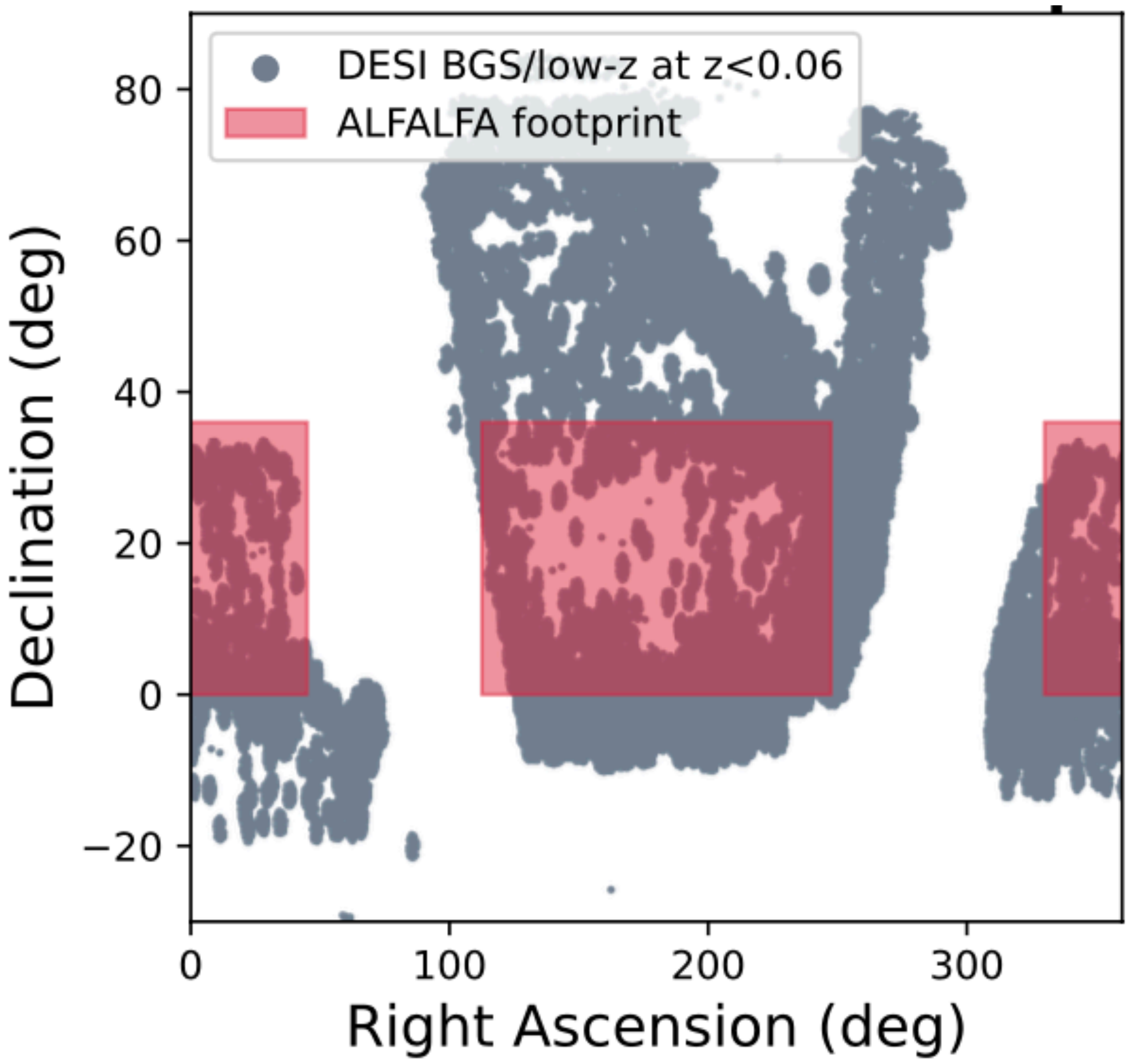
Saintonge et al. 2011a, 2011b, 2012, 2016, 2017, Catinella et al. 2010, 2013, 2018, Lutz et al. 2021, Accurso et al. 2017, Tiley et al 2016, Huang & Kauffmann 2014, Saintonge & Catinella 2022,…

see also: FCRAO (Young et al. 1995), HRS (Boselli et al. 2010), ALLSMOG (Bothwell et al. 2014, Cicone et al. 2017), MASCOT (Wylezalek et al. 2022), JINGLE (Saintonge et al. 2018) …

Global measurements (blind surveys for HI):

Rather than targeting specific galaxies one by one, with radio telescopes it is possible to map out large areas of sky to pick up many galaxies, without a priori information

Examples of such surveys include: HIPASS (Barnes et al. 2001), ALFALFA (Giovanelli et al. 2005),…



Resolved measurements:

~kpc scale CO and/or HI maps

Samples of ~50-100 galaxies, mostly massive star-forming spirals

HERACLES (Leroy et al. 2009), THINGS (Walter et al. 2008), EDGE (Bolatto et al. 2017), ALMaQUEST (Lin et al. 2020)

~kpc scale dense gas maps

Samples of ~10-20 galaxies, CO-bright and massive

EMPIRE (Jimenez-Donaire et al. 2019), MALATANG (Tan et al. 2018)

~ 100pc scale CO maps

Total of <100 galaxies, all star-forming spirals

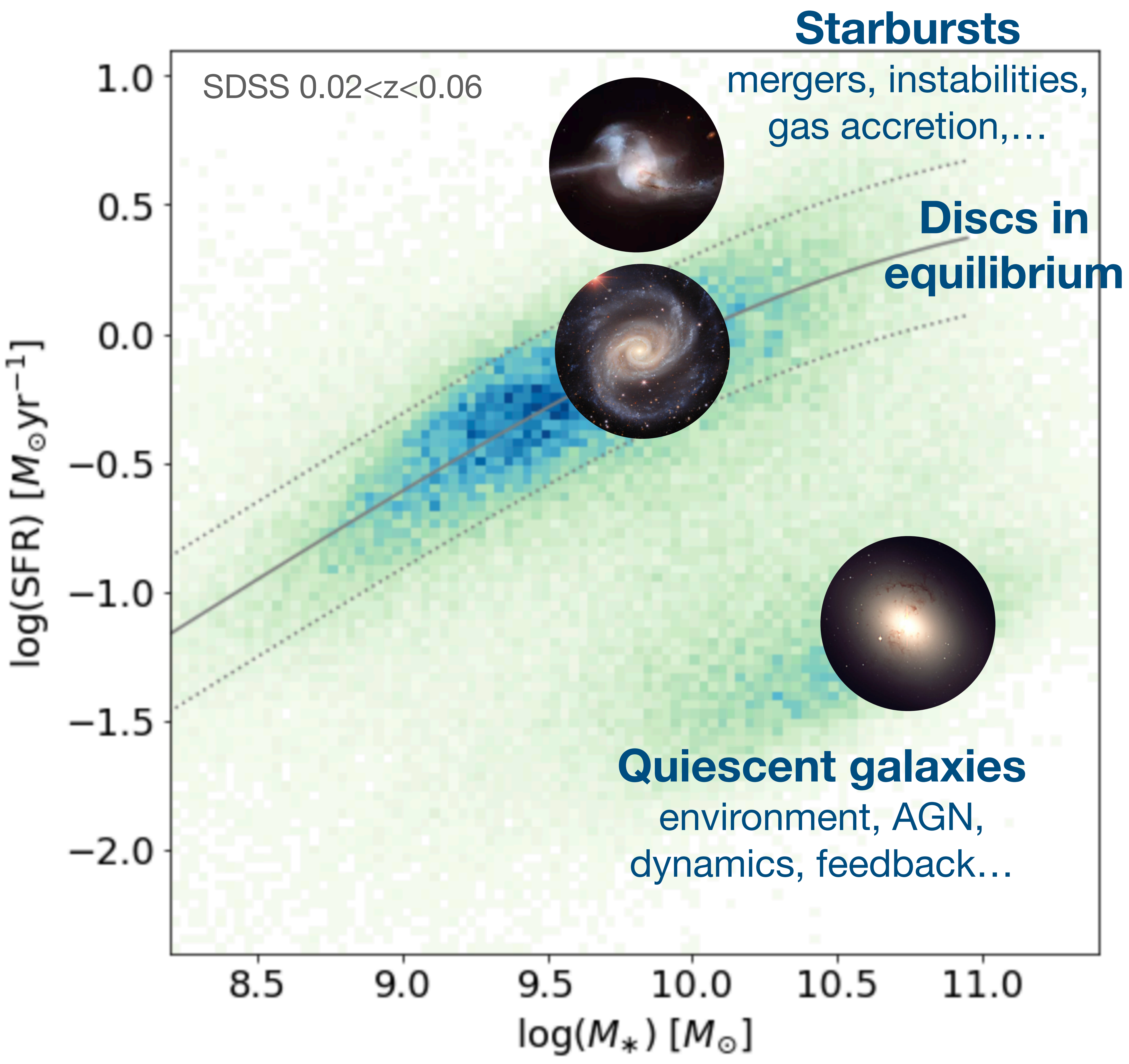
PHANGS-ALMA (Leroy et al. 2021), WISDOM (Davis et al. 2017), PAWS (Schinnerer et al. 2013

Gas and star formation as the drivers of galaxy evolution

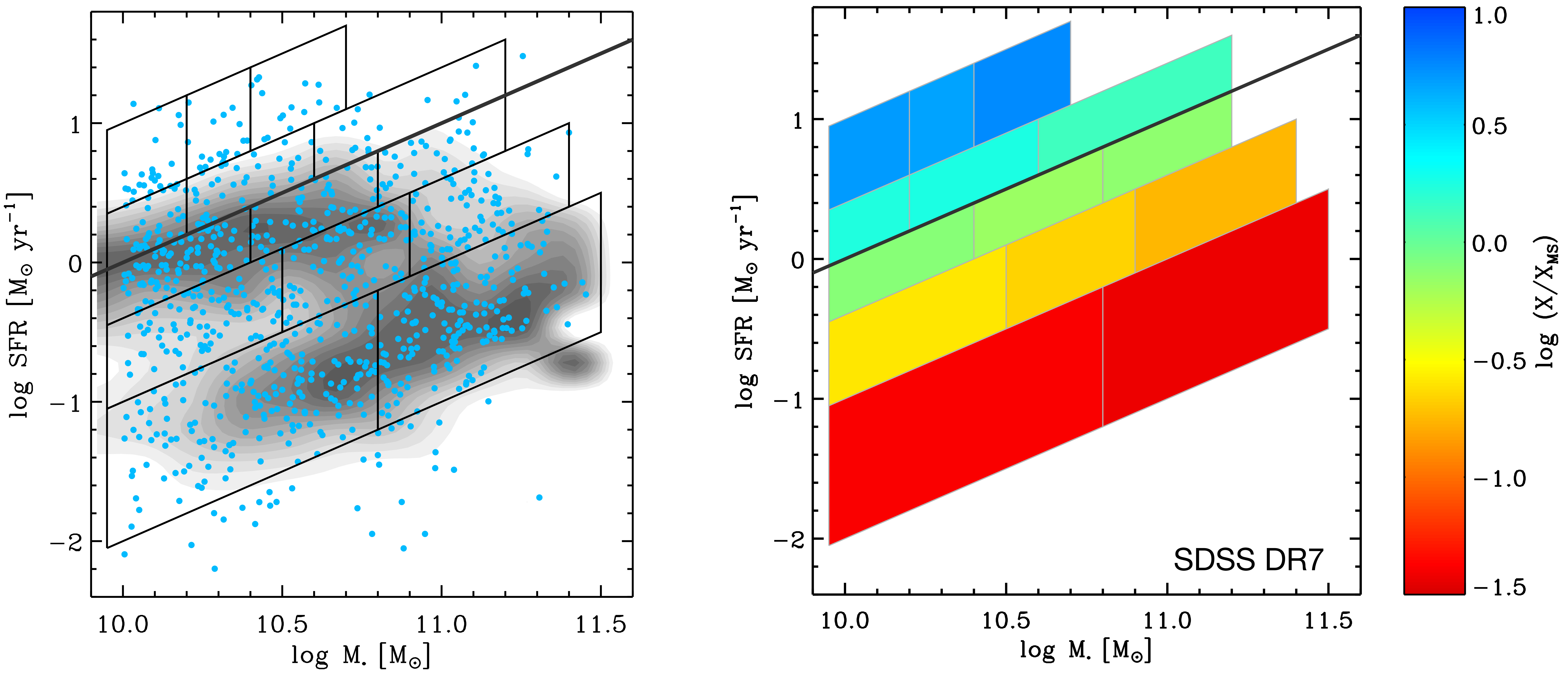
What sets the star formation activity of galaxies?
When/where/how is it triggered/suppressed?

$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = \frac{M_{HI}}{M_*}\,\frac{M_{H2}}{M_{HI}}\,\frac{\mathrm{SFR}}{M_{H2}}$$

$$= f_{HI}\; R_{mol}\; \mathrm{SFE}$$



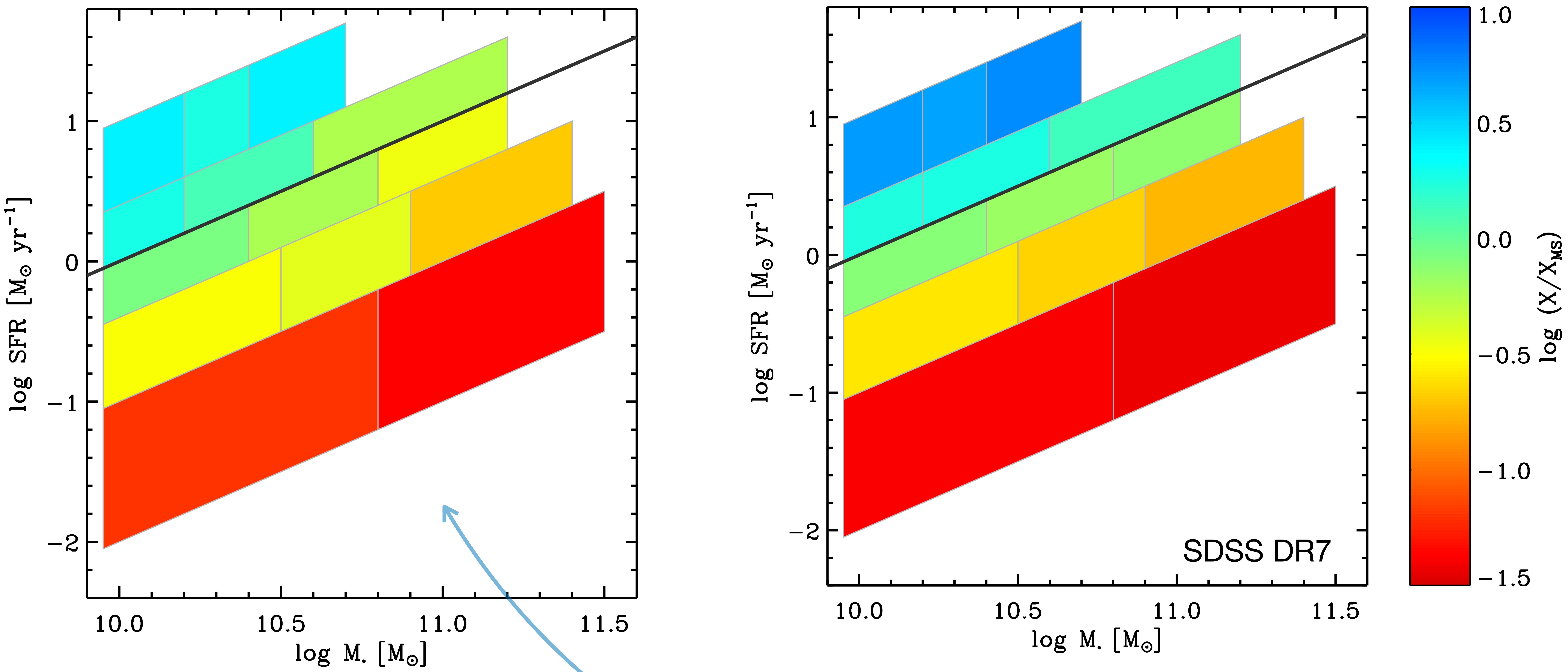
Gas and star formation as the drivers of galaxy evolution



$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = f_{HI}\ R_{mol}\ \mathrm{SFE}$$

Saintonge et al. (2016)

Gas and star formation as the drivers of galaxy evolution



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Saintonge et al. (2016)

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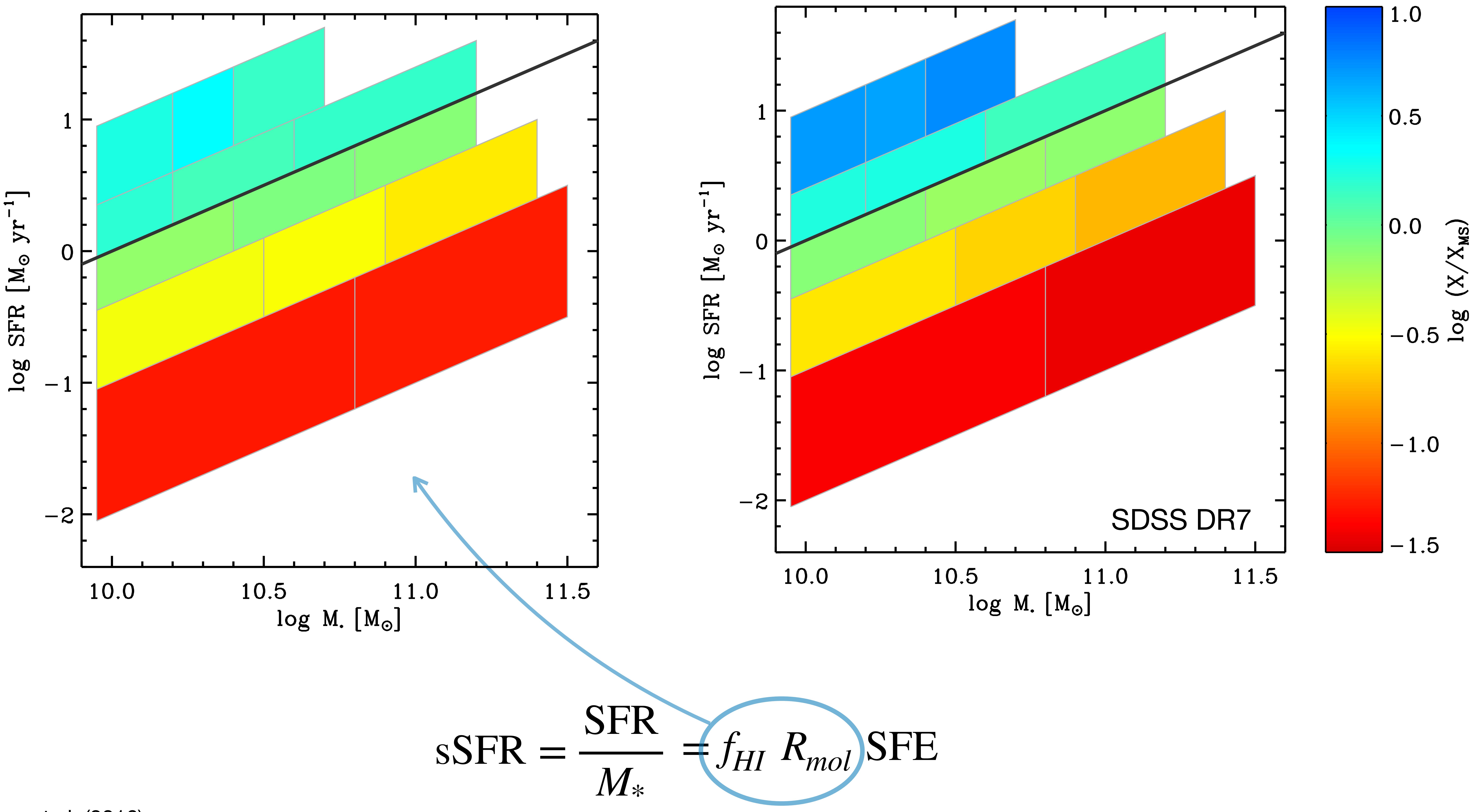

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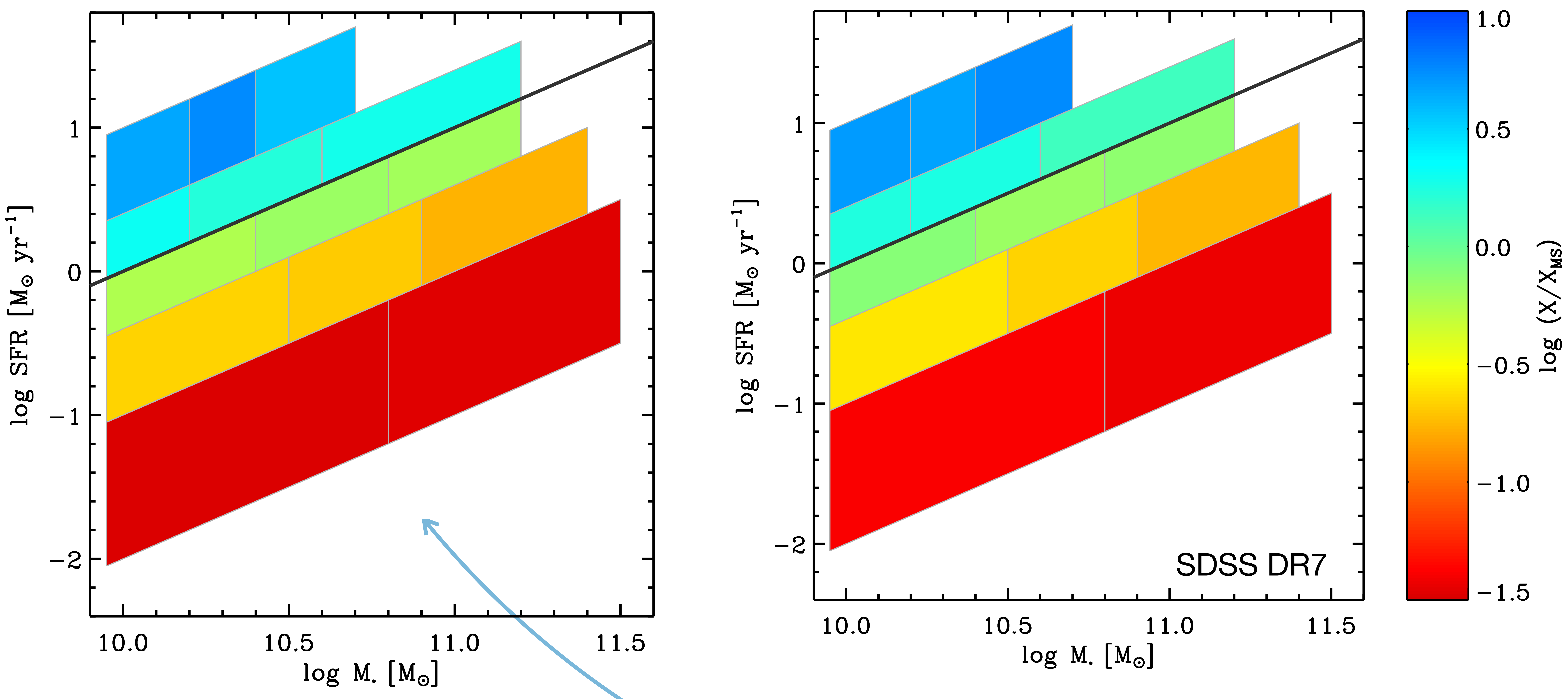
Saintonge et al. (2016)

Gas and star formation as the drivers of galaxy evolution



$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = f_{HI}\ R_{mol}\ \mathrm{SFE}$$

Saintonge et al. (2016)

Gas contents and star formation activity across the galaxy population

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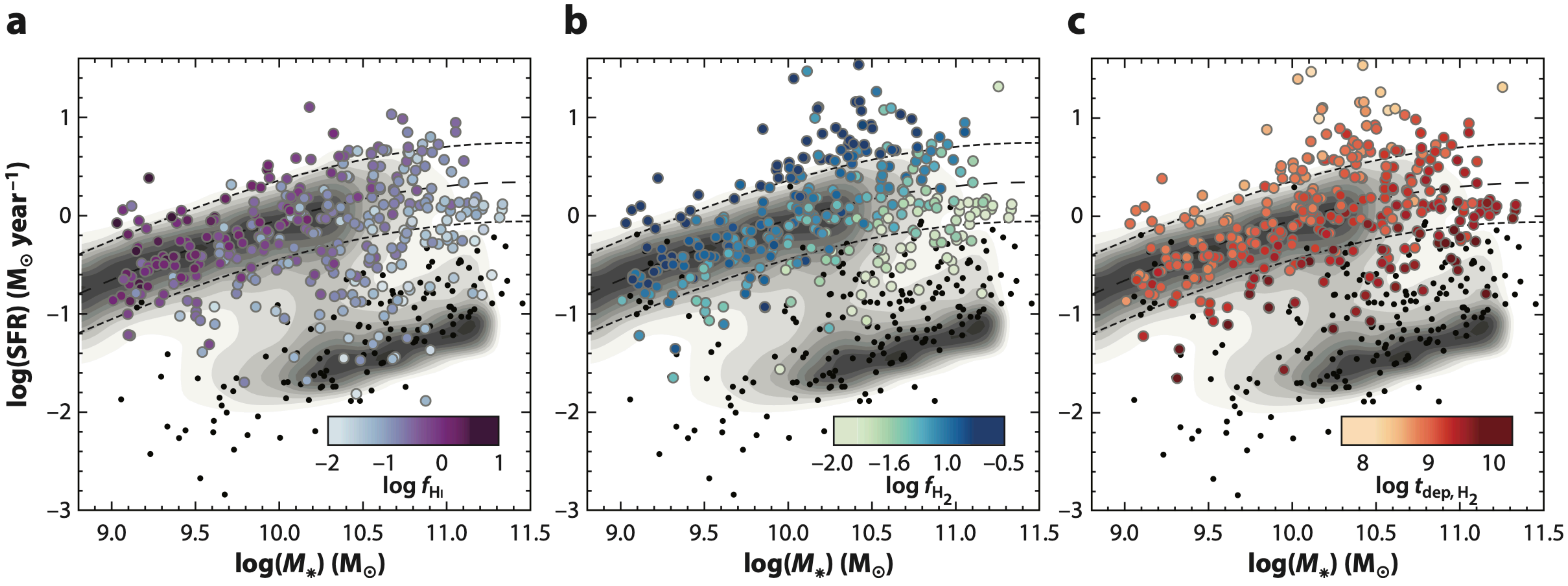

Saintonge et al. (2017), Saintonge & Catinella (2022, ARA&A)

Gas contents and star formation activity across the galaxy population

What sets the star formation activity of galaxies?
When/where/how is it triggered/suppressed?

$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = \frac{M_{HI}}{M_*}\,\frac{M_{H2}}{M_{HI}}\,\frac{\mathrm{SFR}}{M_{H2}}$$

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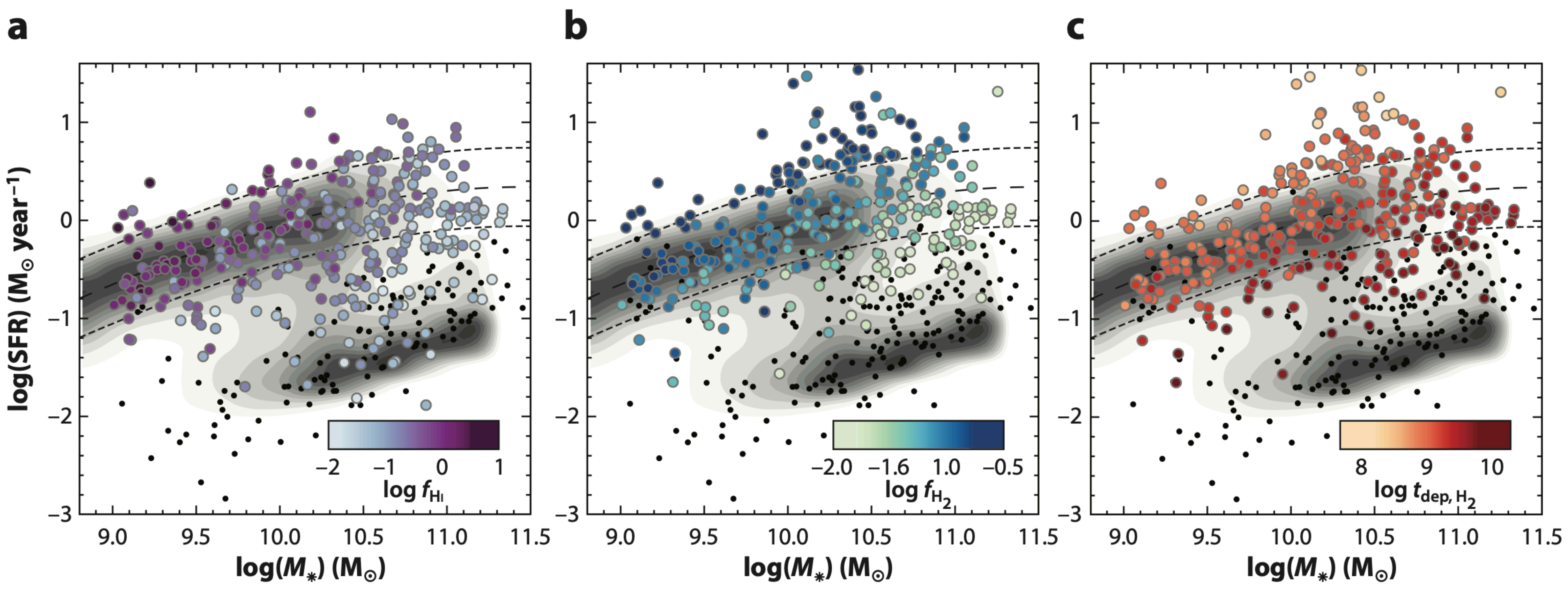
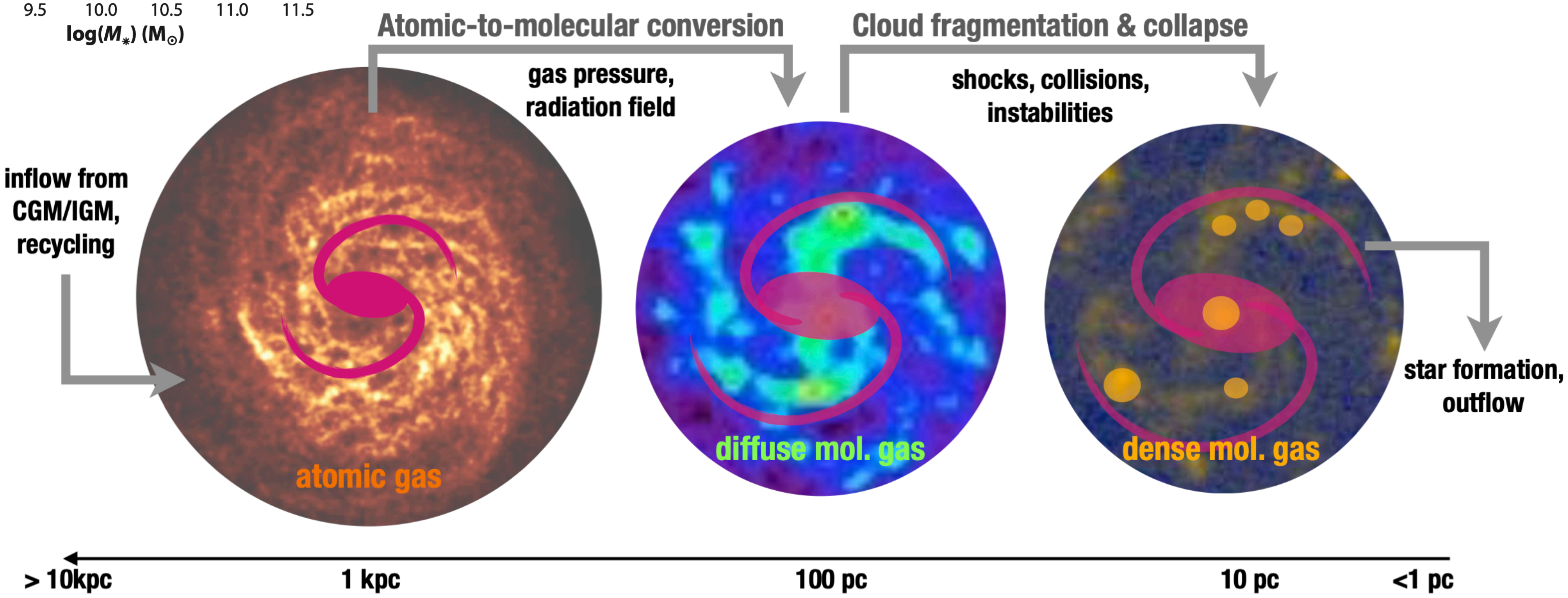


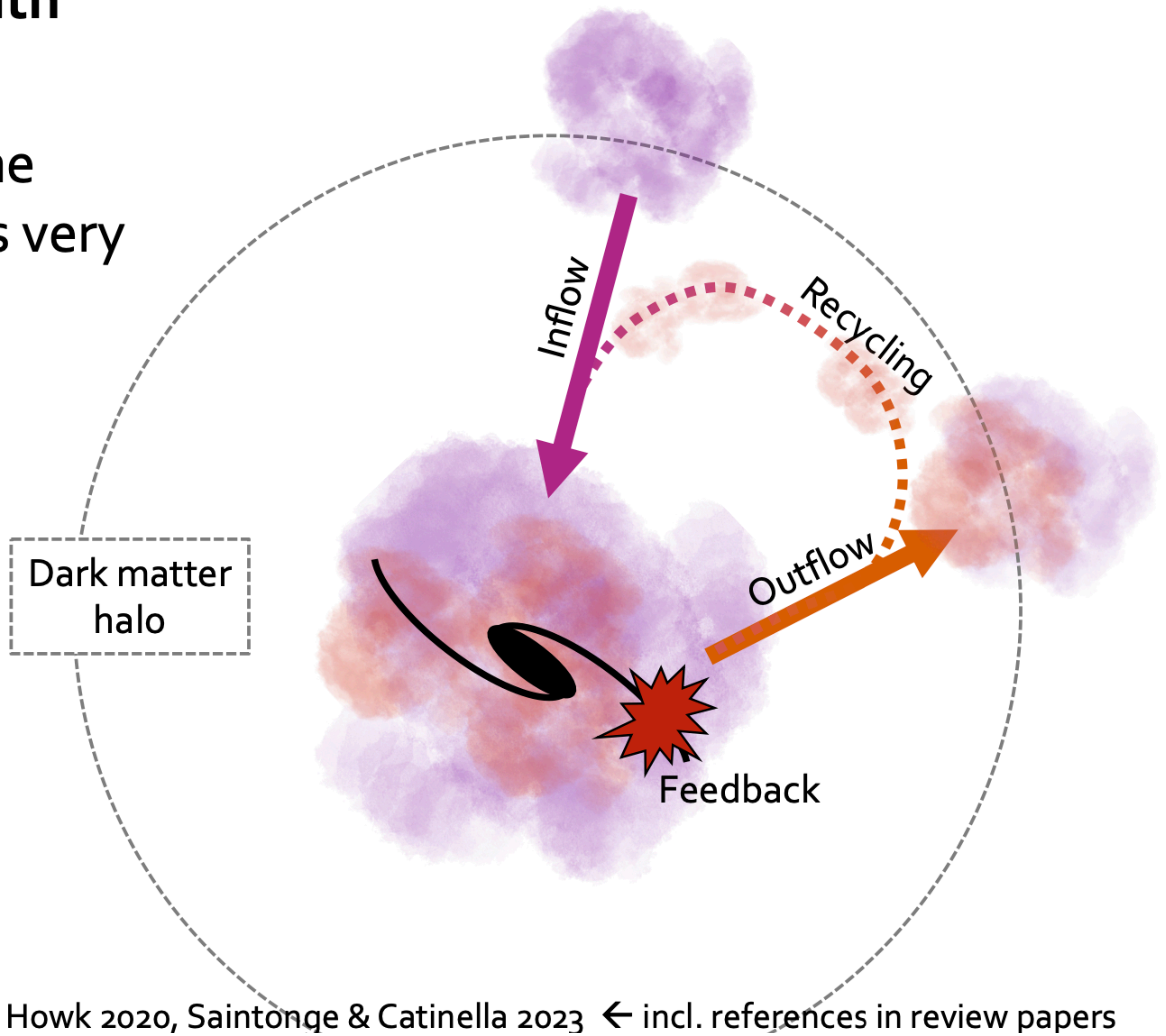


Gas-driven galaxy evolution — observations & theory

slide courtesy of D. Scholte

Galaxies are complex systems with many interacting components

Directly measuring the effect of the processes driving their evolution is very challenging.



See also: Tinsley 1980, Tumlinson, Peeples & Werk 2017, Peroux & Howk 2020, Saintonge & Catinella 2023 ← incl. references in review papers

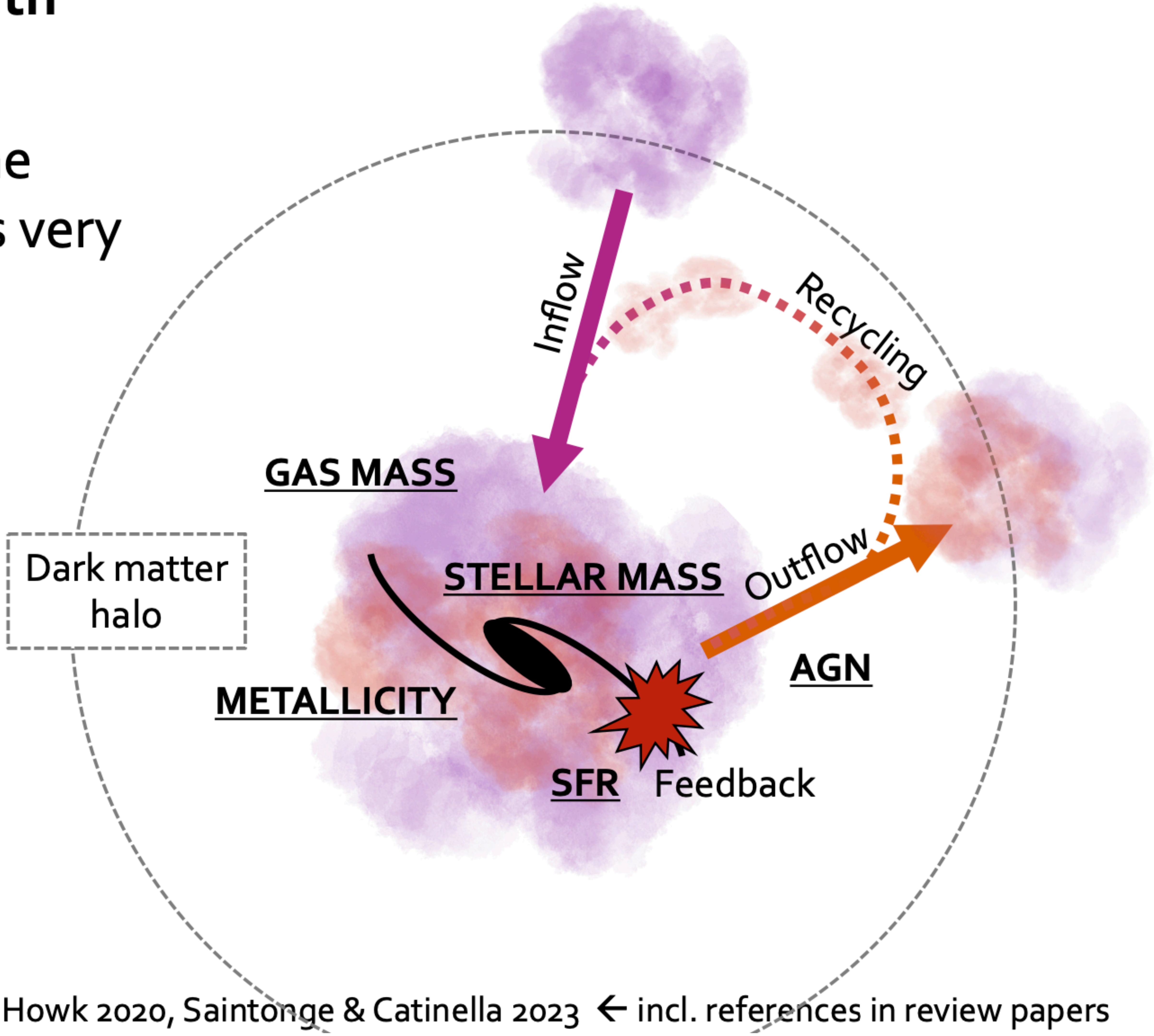
Gas-driven galaxy evolution — observations & theory

slide courtesy of D. Scholte

Galaxies are complex systems with many interacting components

Directly measuring the effect of the processes driving their evolution is very challenging.

However, we can infer the effect of these processes through spectroscopic observables.



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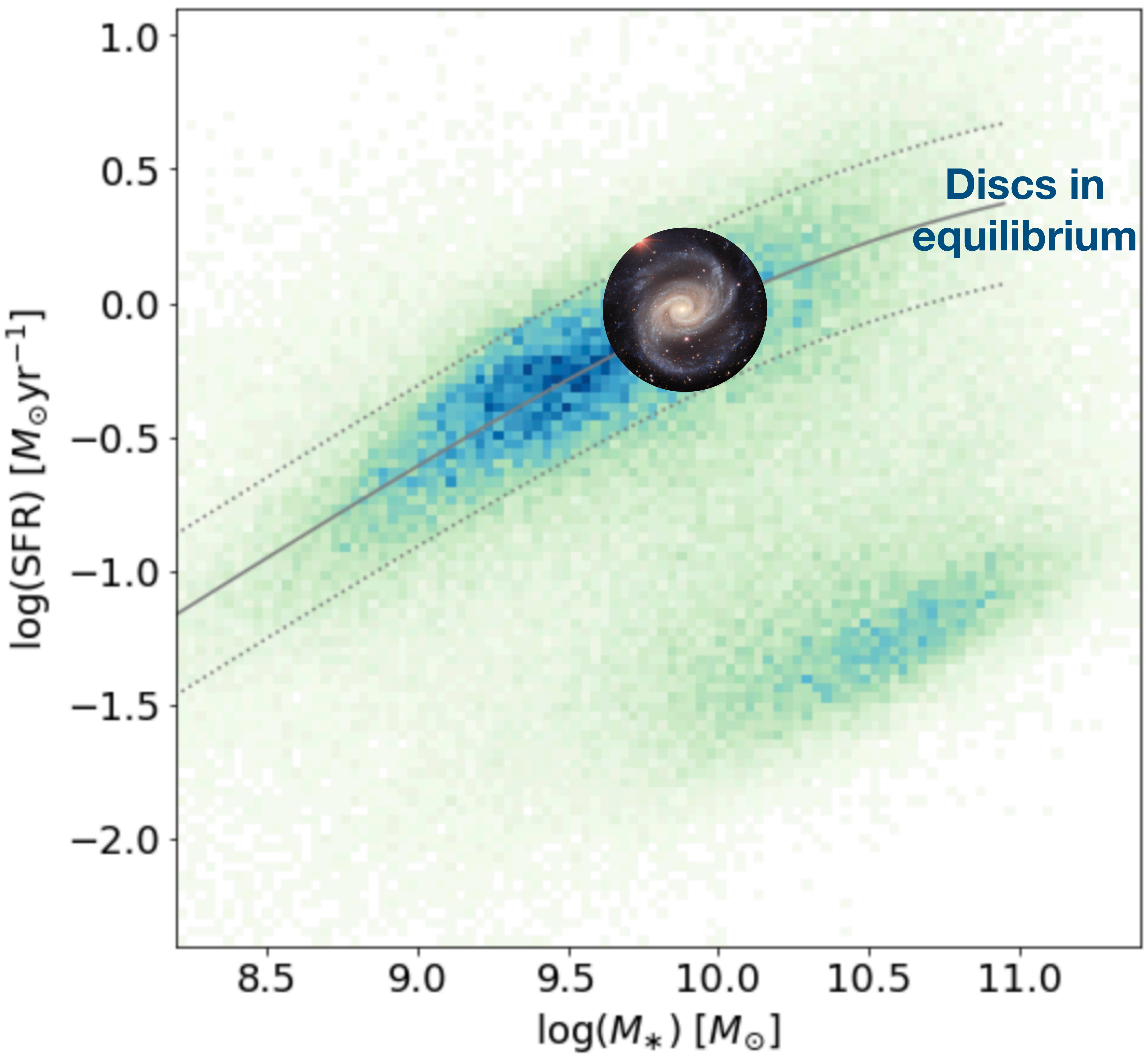
Gas-driven galaxy evolution — observations & theory

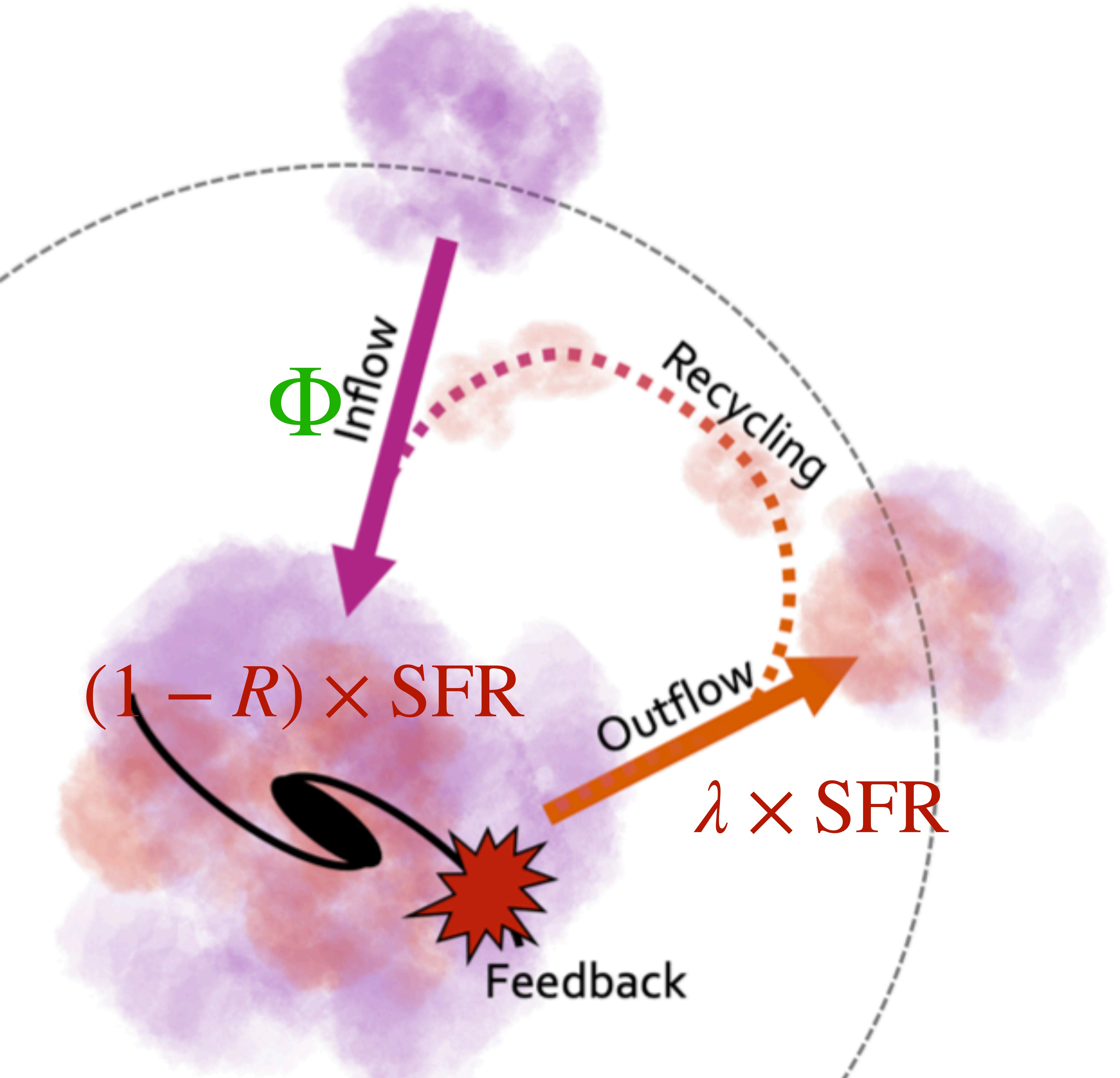


Star-forming (i.e. "main sequence") galaxies

— Galaxies on the main sequence (MS) contribute ~90% of the star formation.

— Can we explain the shape and scatter of the MS through the gas contents and star formation efficiency?

Gas-driven galaxy evolution — observations & theory



Star-forming (i.e. "main sequence") galaxies

– Equilibrium models suggest that galaxies are "gas conversion engines", regulated by mass conservation principles

$$\Phi = (1 - R + \lambda)\mathrm{SFR} + \frac{\mathrm{d}M_{gas}}{\mathrm{d}t}$$

accretion rate — stellar mass buildup — outflows — time evolution of the gas reservoir

accretion rate: $\propto M_{halo}^{\alpha}(1+z)^{\beta}$

outflows: $\propto M_{gas}\ \mathrm{SFE}$

assuming that SFE and λ are constant, then the model predicts:

$$\mathrm{SFR} \propto M_*^a\ (1+z)^b \quad (a \sim 0.8,\ b \sim 2.5)$$

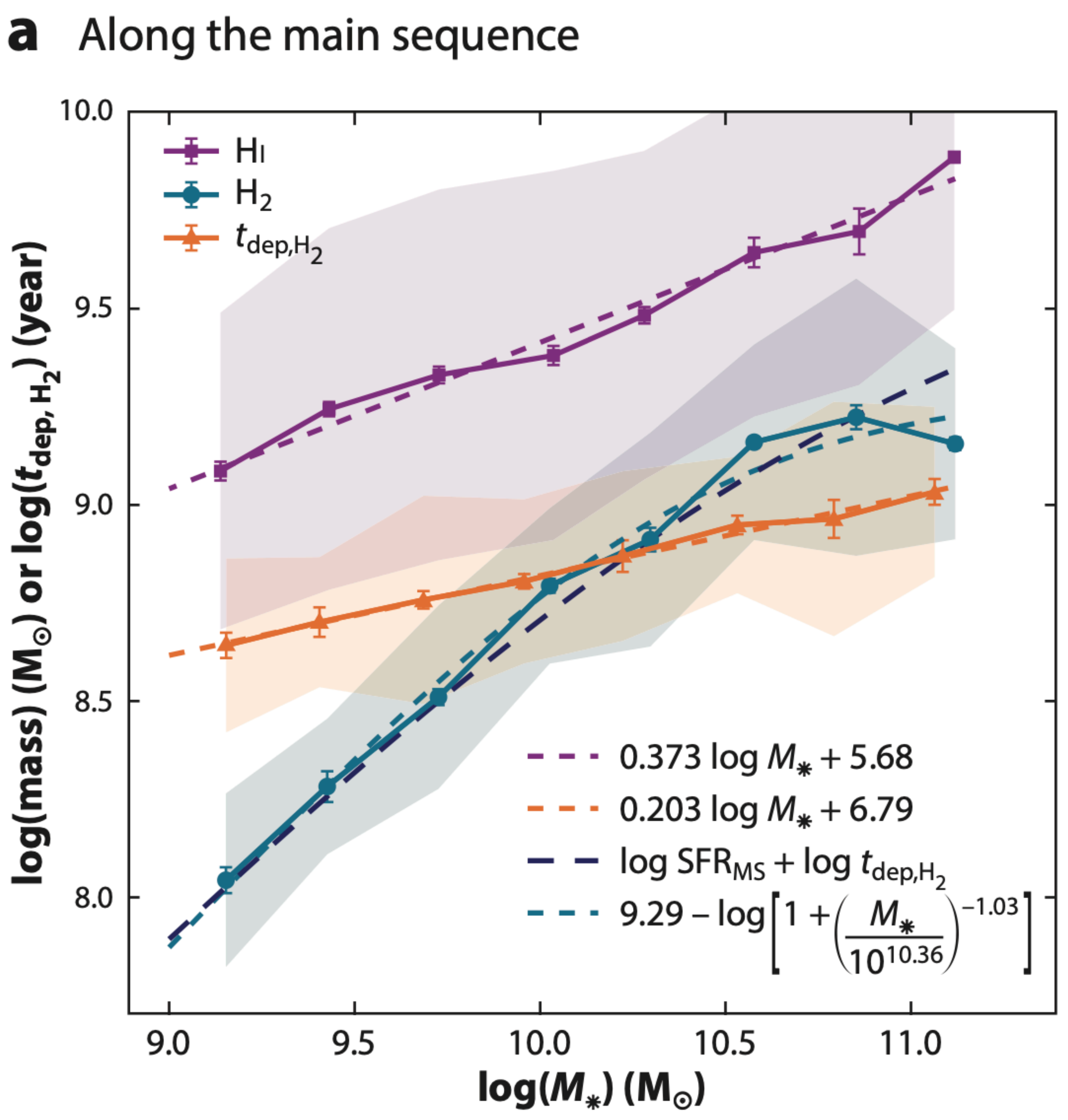
Let's check this against our observations of the shape and redshift evolution of the main sequence…

Bouché et al. (2010), Davé et al. (2012), Lilly et al. (2013), Dekel & Mandelker (2014), Tacchella et al. (2016), …

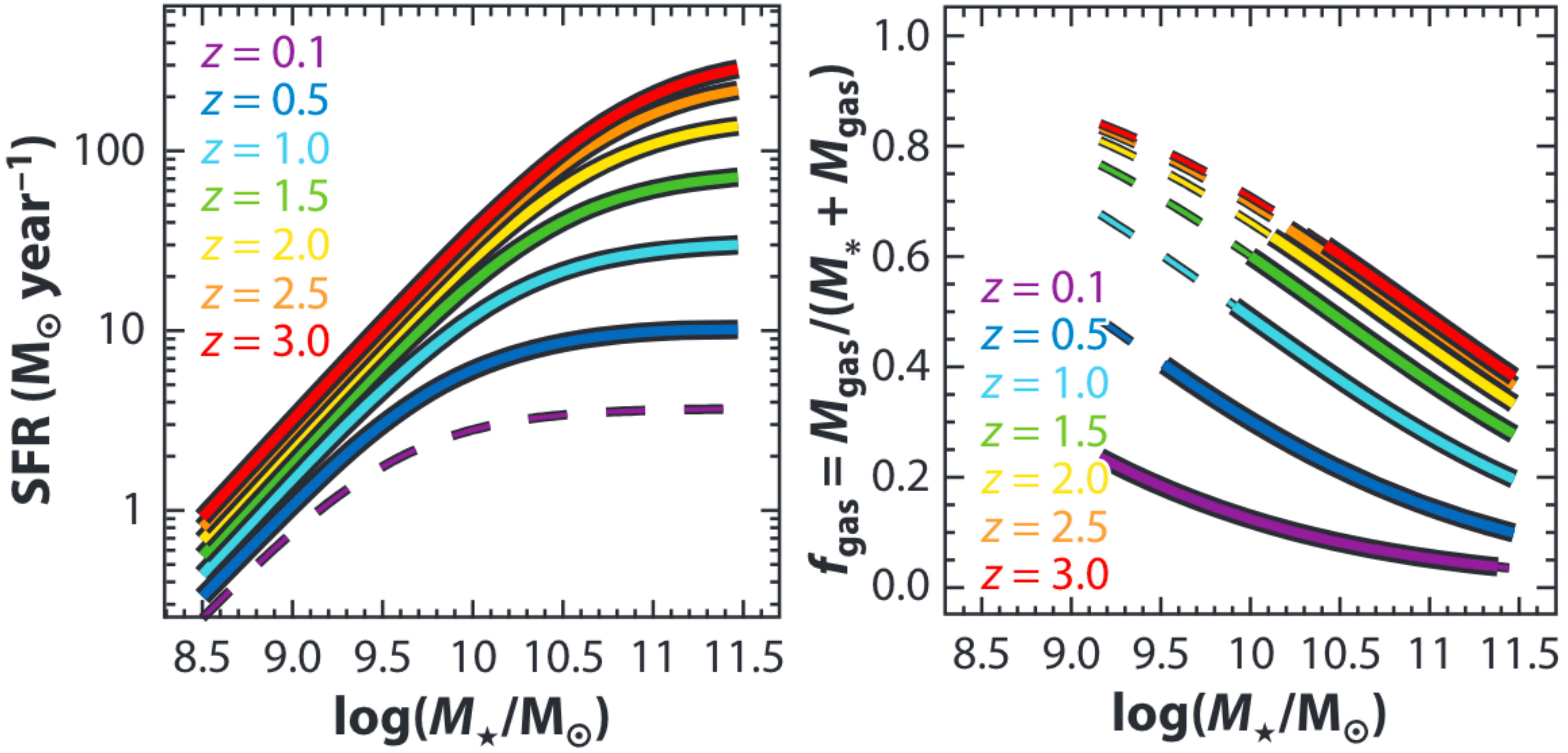
Gas-driven galaxy evolution — observations & theory

Let's check this against our observations of the shape and redshift evolution of the main sequence…

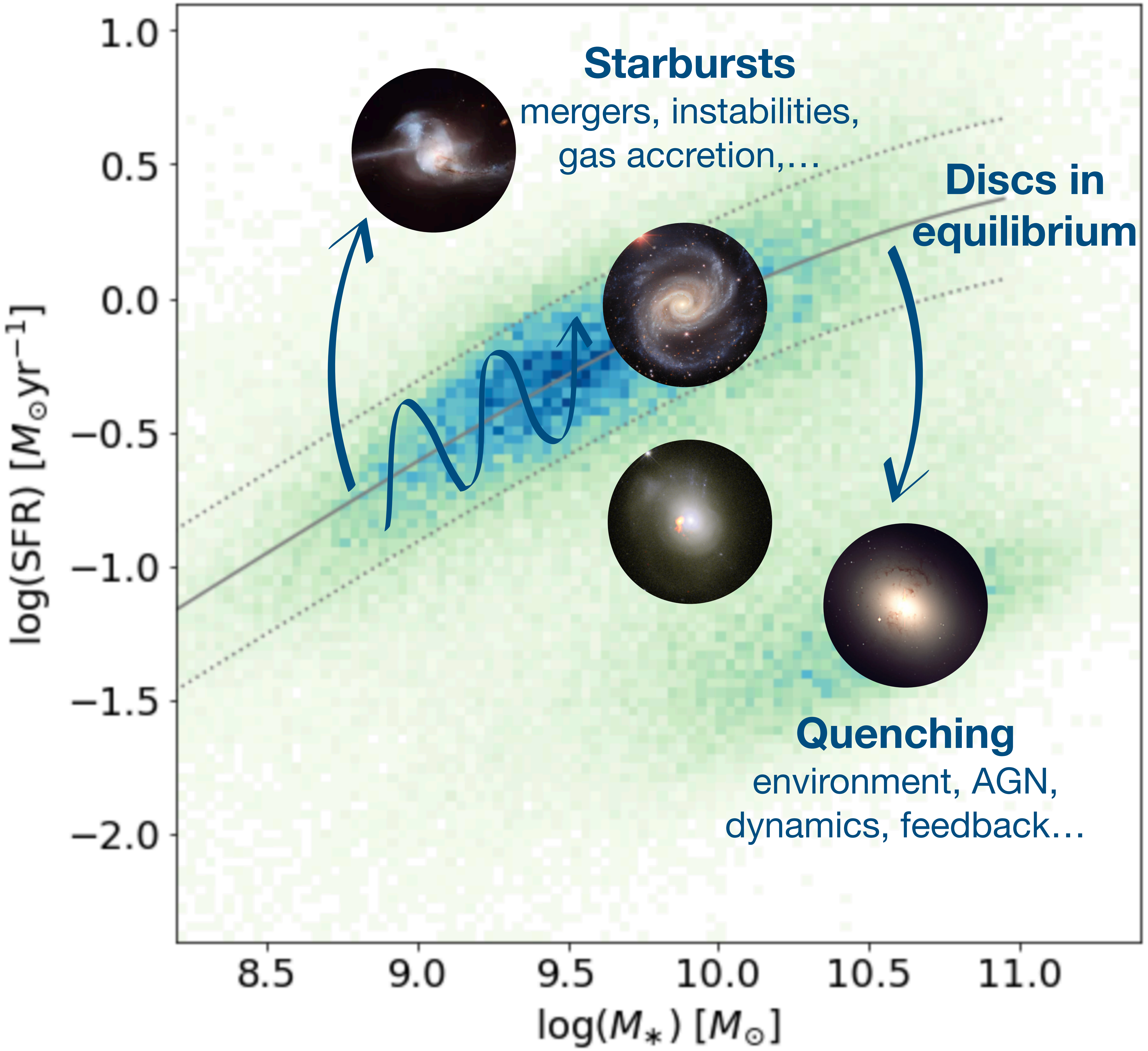
$$\mathrm{SFR} \equiv M_{gas}\ \mathrm{SFE} \propto M_*^{\alpha}\ (1+z)^{\beta}$$



Forster-Schreiber & Wuyts (2020)

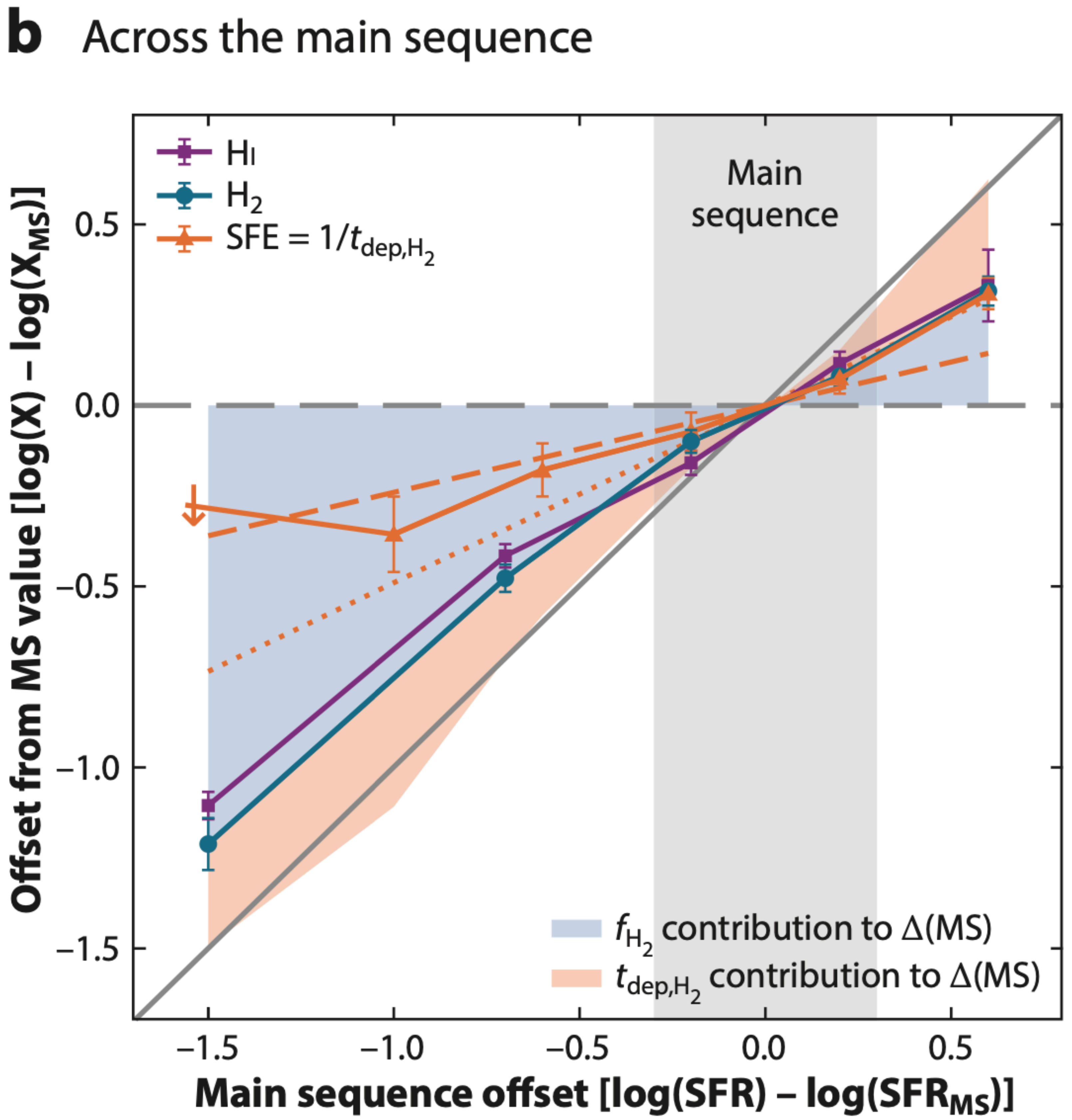


Gas-driven galaxy evolution — observations & theory



Off-main sequence galaxies

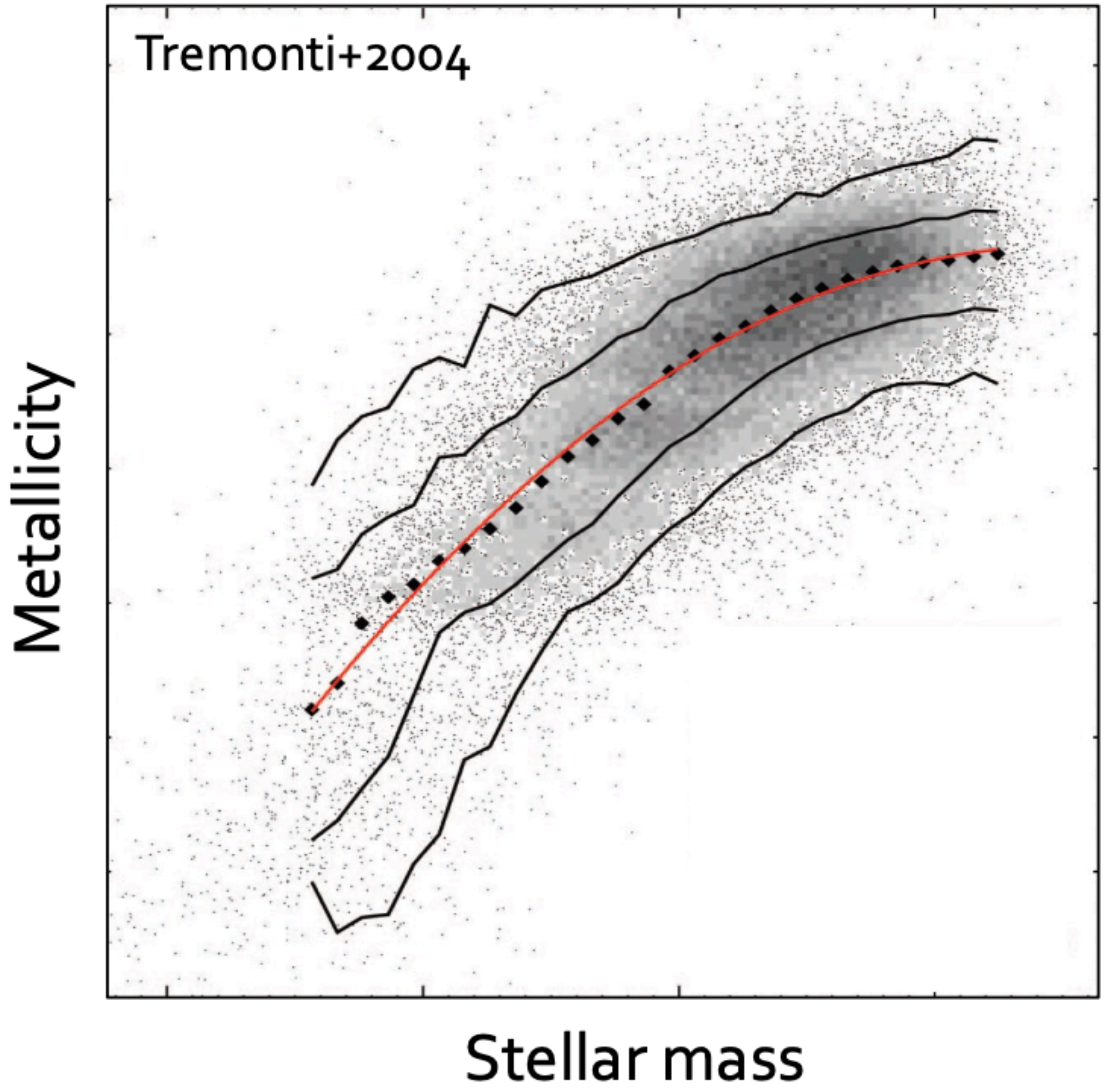
– Wide range of processes can disrupt the equilibrium state, affecting both gas contents ***and star formation efficiency***



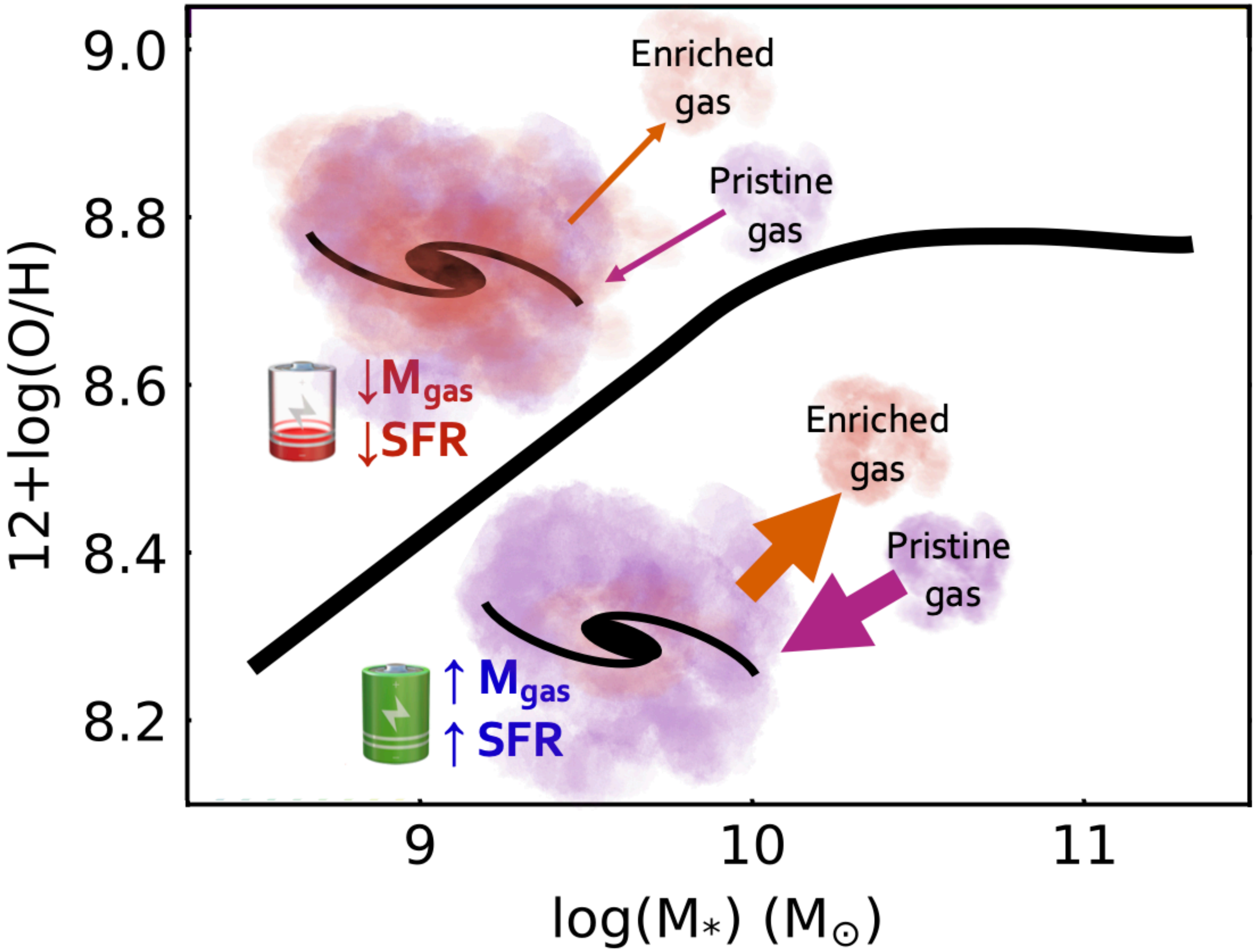
Saintonge et al. (2012), Saintonge & Catinella (2022)
see also e.g. Magdis et al. (2012), Sargent et al. (2014), Saintonge et al. (2012, 2016), Tacconi et al. (2018, 2020), Scoville et al. (2017), Colombo et al. (2020), …

Chemical composition of the ISM: the mass-metallicity relation

The more massive the galaxy, the more enriched in metals (here measured as the relative abundance of O compared to H) the ISM is. This relation is known as the mass-metallicity relation (MZR)

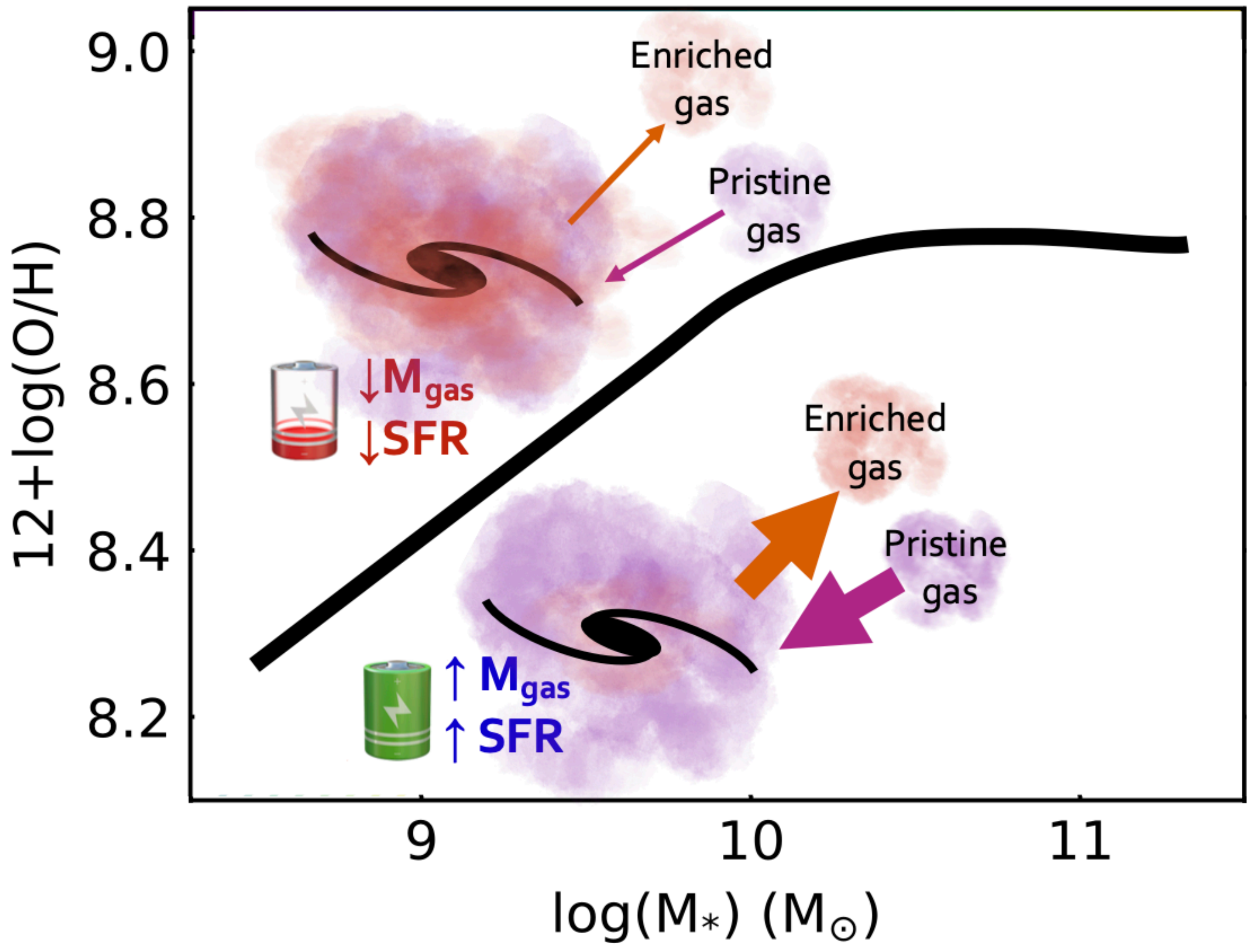


Within our gas-centric galaxy evolution model, there should be a correlation between the shape and scatter of the MZR and the cold gas contents of the galaxies:

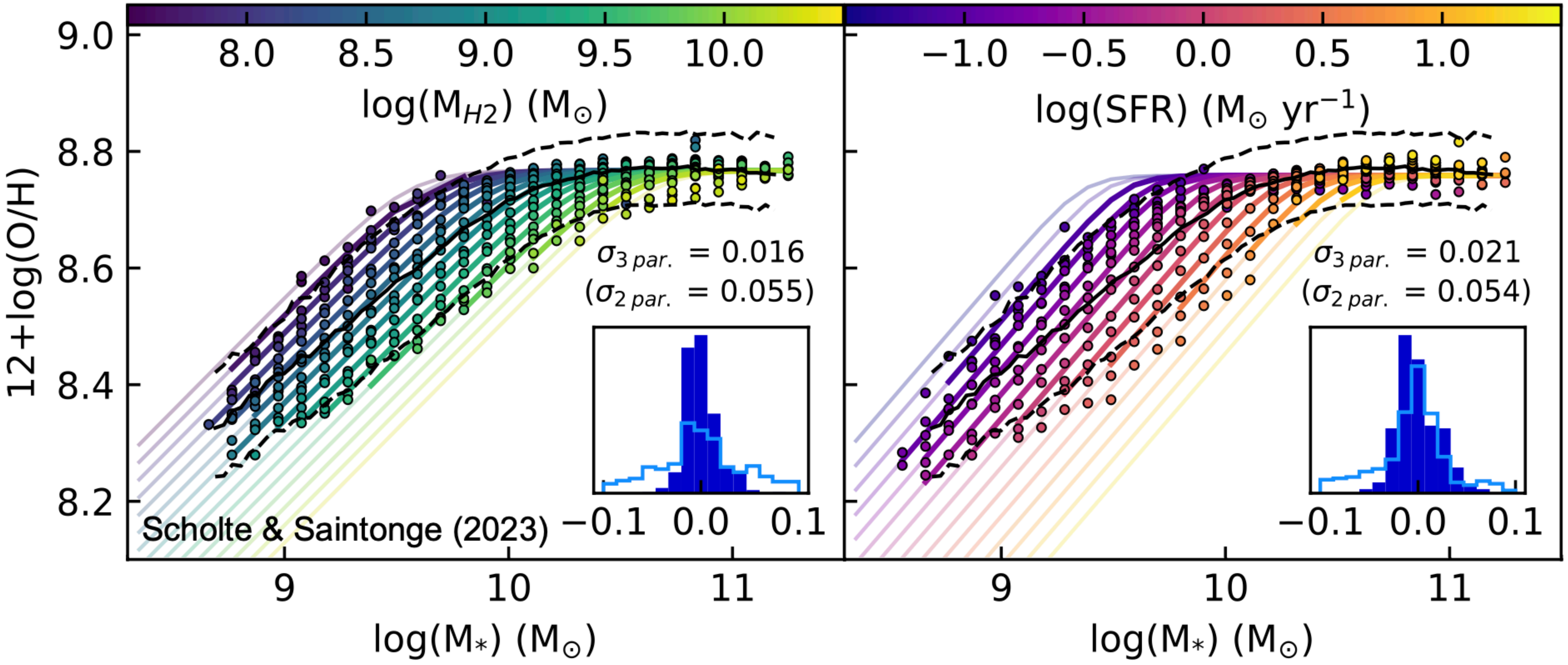


Gas and the mass-metallicity relation

As predicted by the simple equilibrium models, both gas mass and SFR are directly linked with the scatter of the MZR. Of the two, **gas appears to be the more fundamental parameter driving the scatter**



Fundamental Metallicity relation



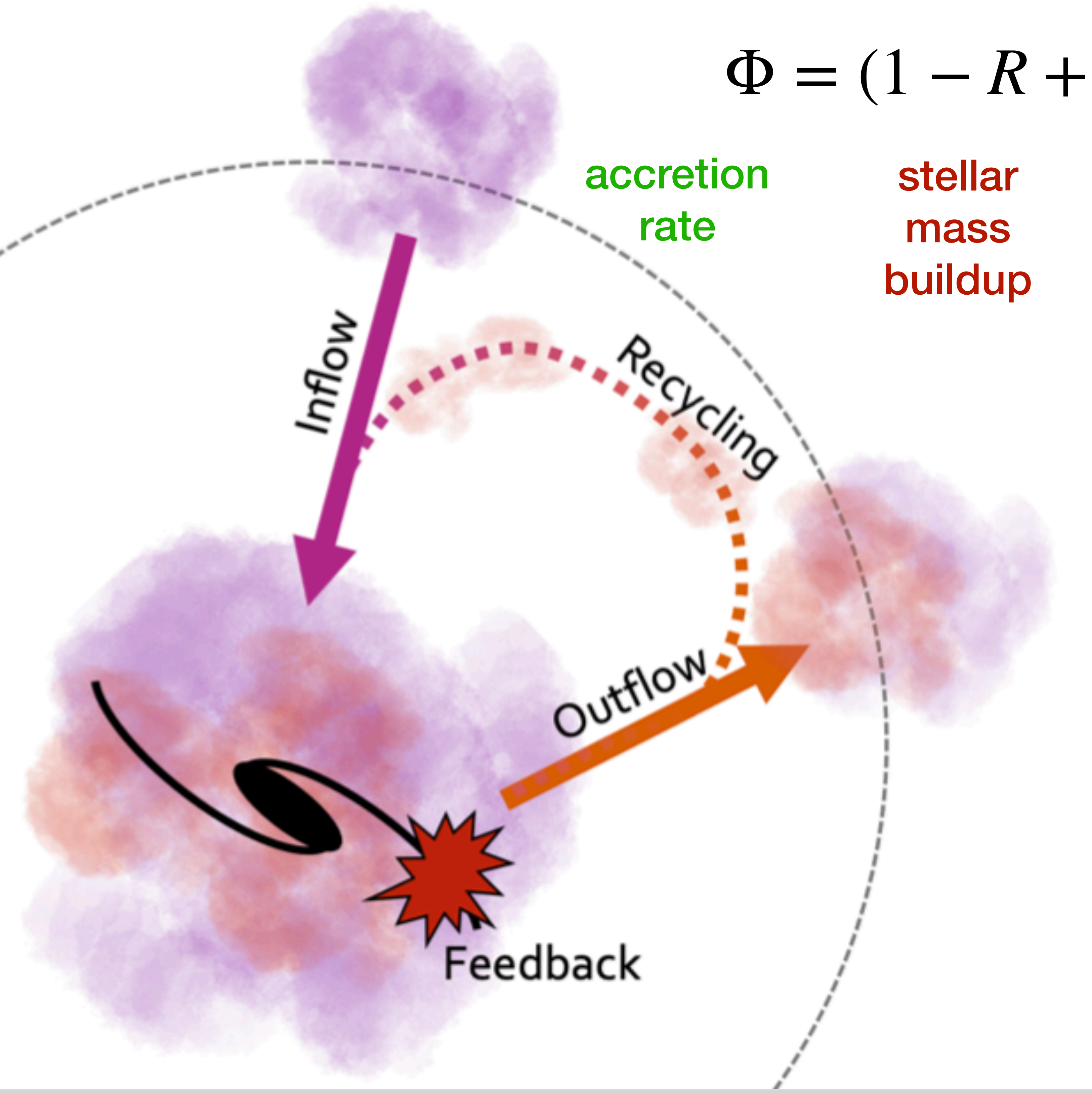
See also: Brown et al. 2018, Ellison et al. 2008, Mannucci et al. 2010, Lara-Lopez et al. 2010

Gas-driven galaxy evolution — summary

The shape, scatter and redshift evolution of key galaxy scaling relations (in particular the star formation main sequence and the mass-metallicity relation) can be to first order explained by the principle of a simple equilibrium model

$$\Phi = (1 - R + \lambda)\mathrm{SFR} + \frac{\mathrm{d}M_{gas}}{\mathrm{d}t}$$

accretion rate | stellar mass buildup | outflows | time evolution of the gas reservoir

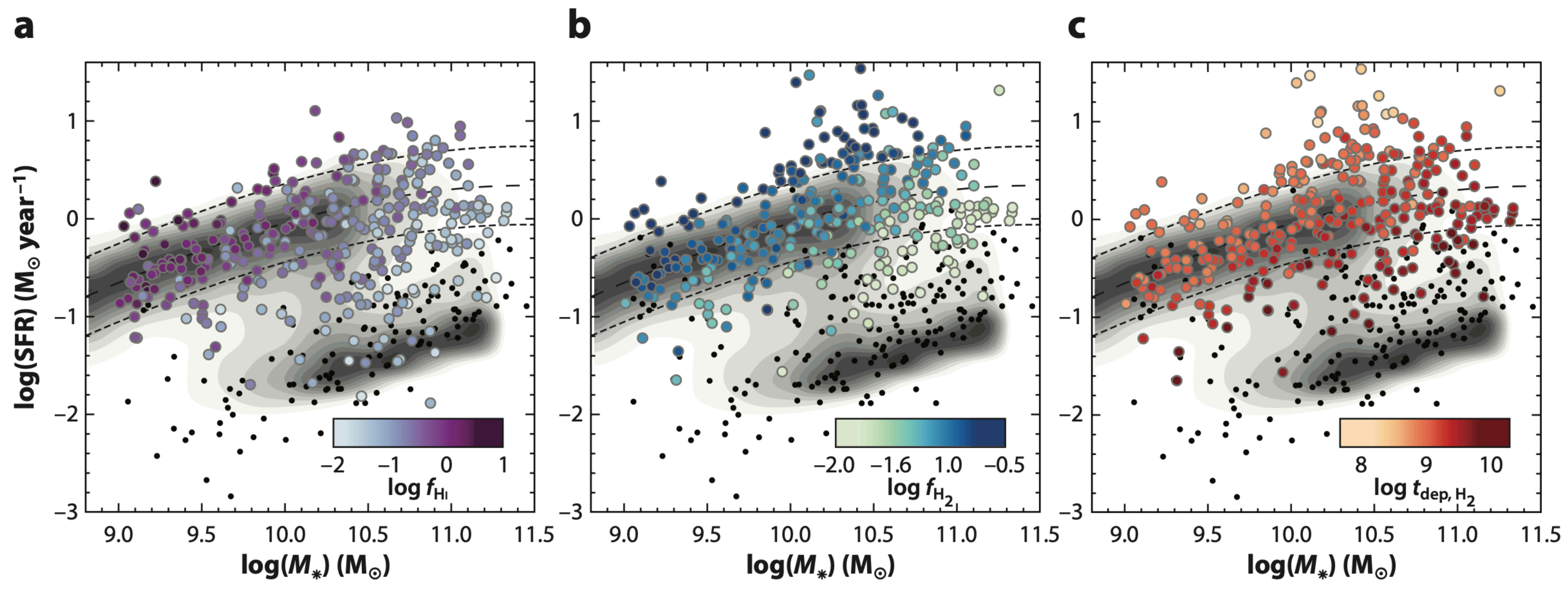


The global **star formation activity of a galaxy** (i.e. its position in the SFR-M* plane) depends on:

(1) how much fuel it has (HI)

(2) how much of it is available for star formation (H_2)

(3) the efficiency of the conversion of this gas into stars

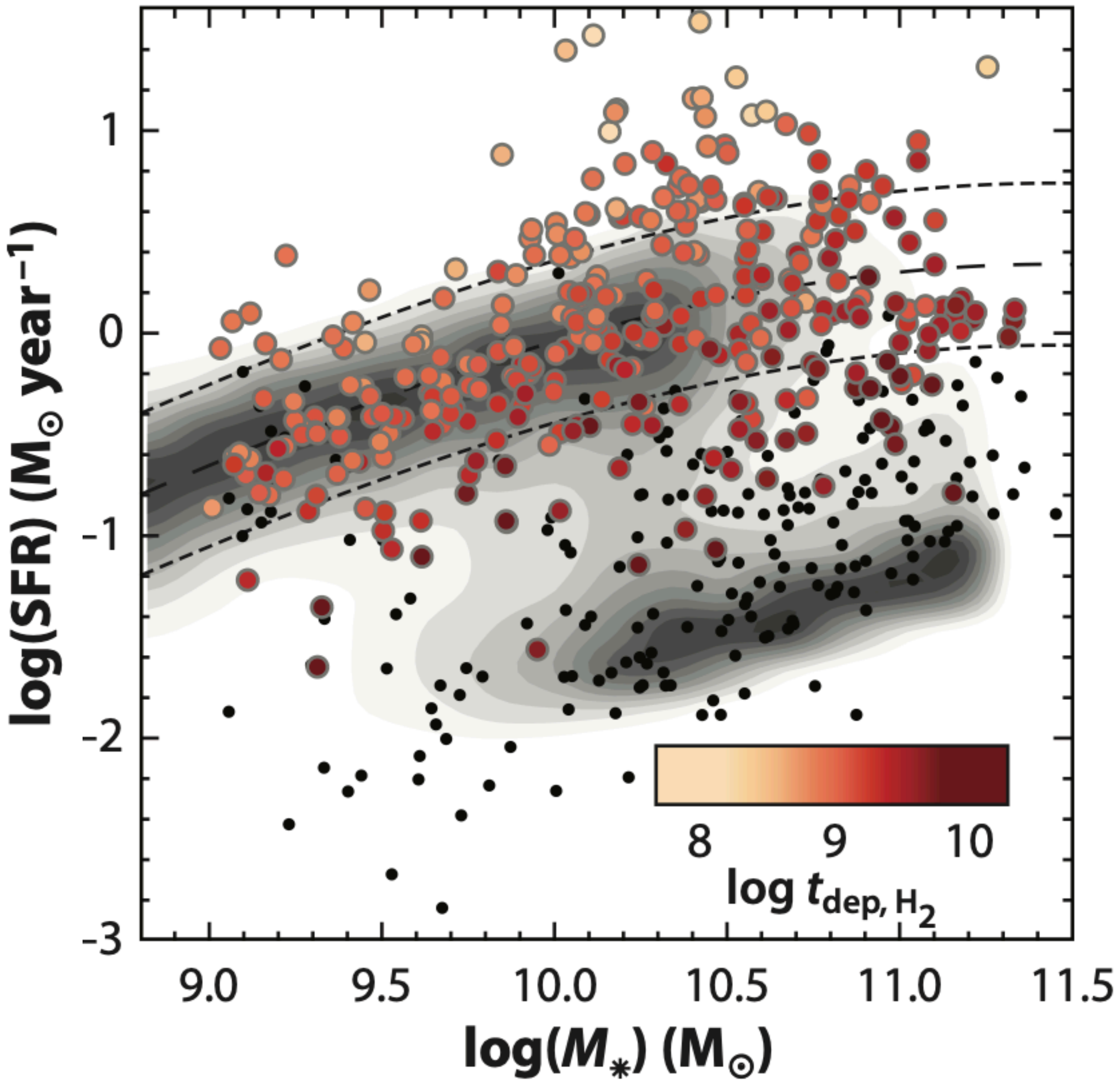


Gas availability and star formation efficiency are the two fundamental quantities that determine the growth of galaxies.

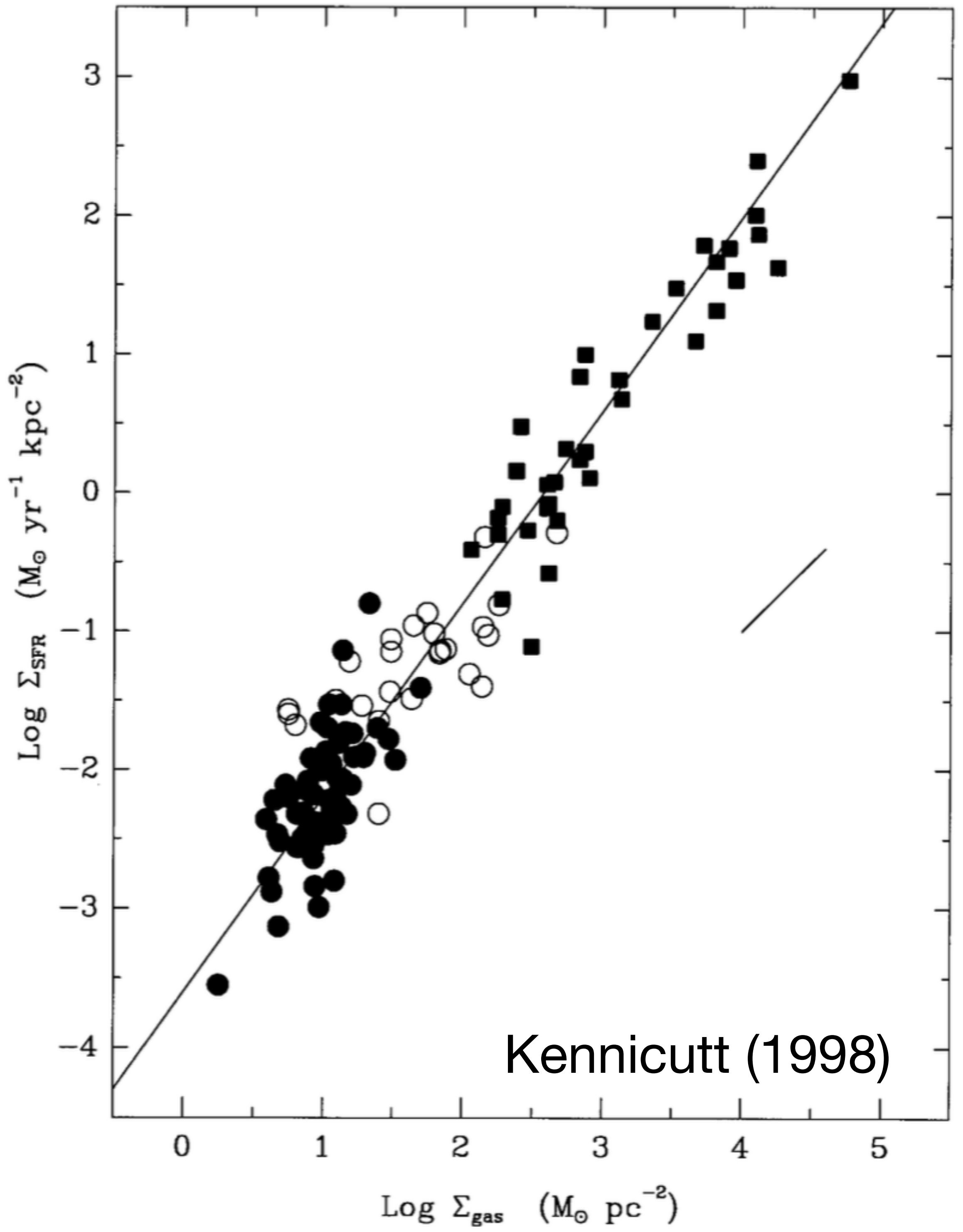
see also Bouché et al. (2010), Davé et al. (2012), Lilly et al. (2013), Dekel & Mandelker (2014), Tacchella et al. (2016), Saintonge et al. (2016), Lin et al. (2019), Feldmann (2020), Ellison et al. (2020), Baker et al. (2022),…

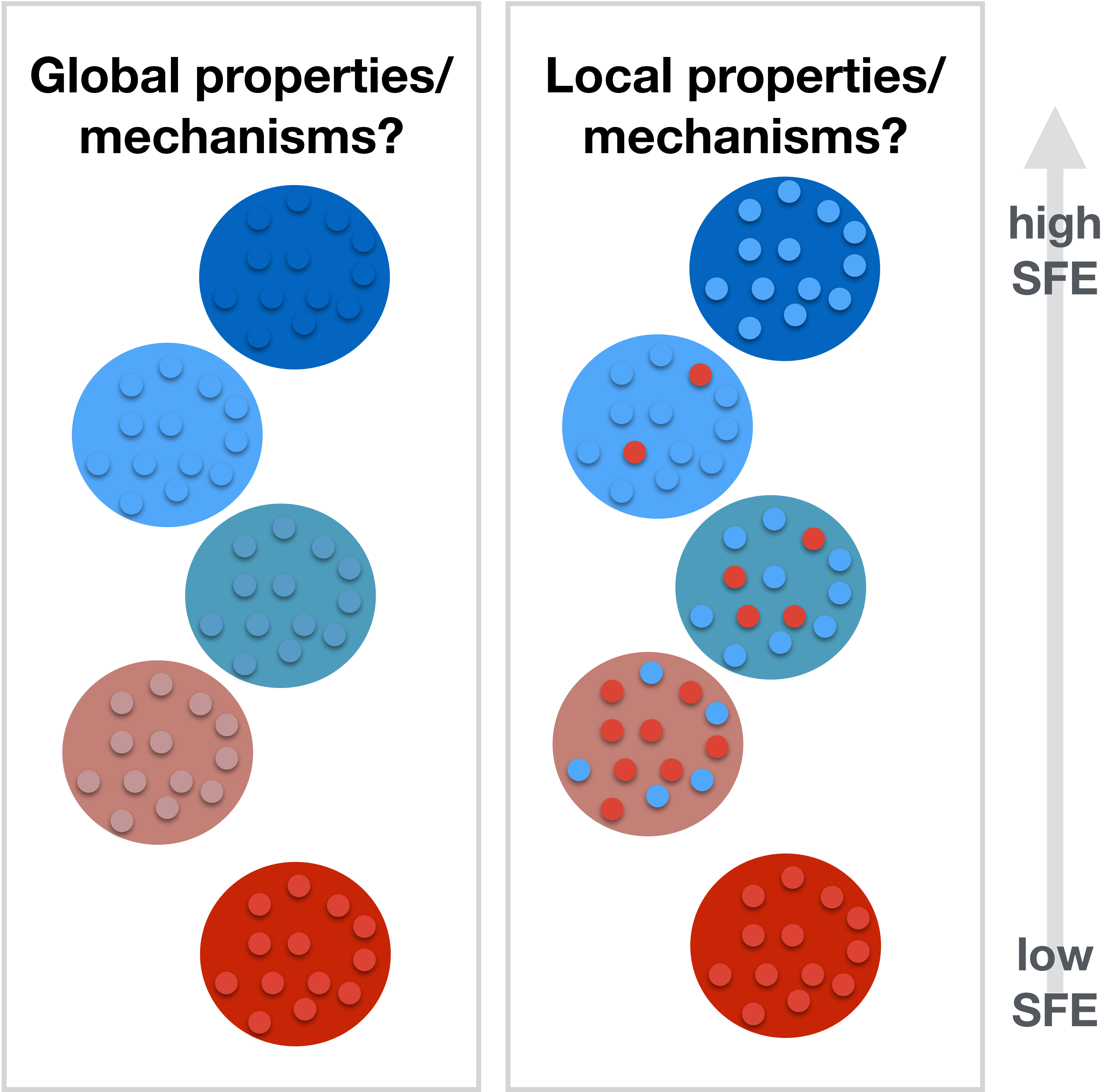
What is driving the systematic star formation efficiency variations?

Star formation efficiency varies systematically across the galaxy population: why??



this is a departure from the view of a "universal" M_{H2}->SFR relation





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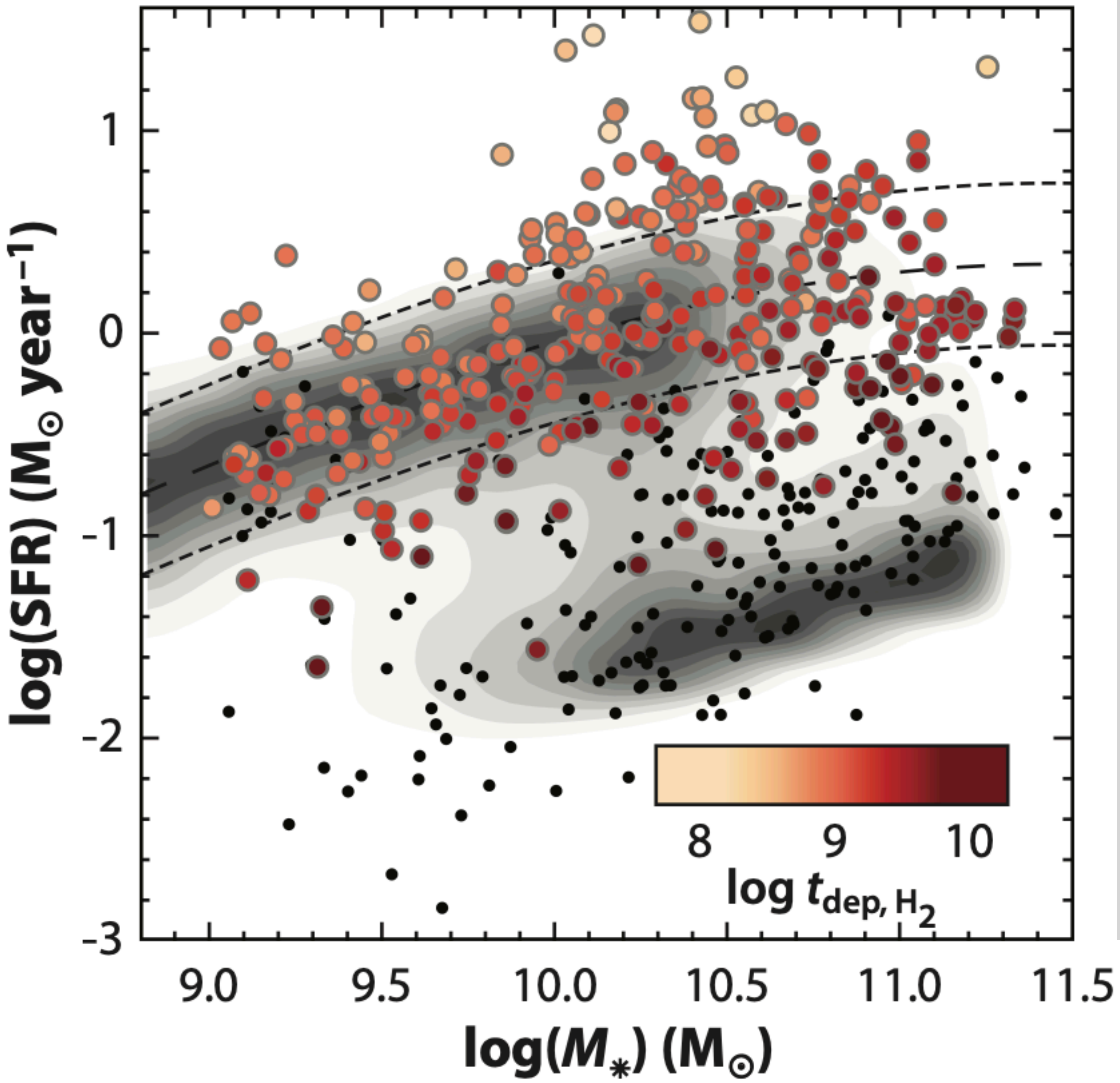
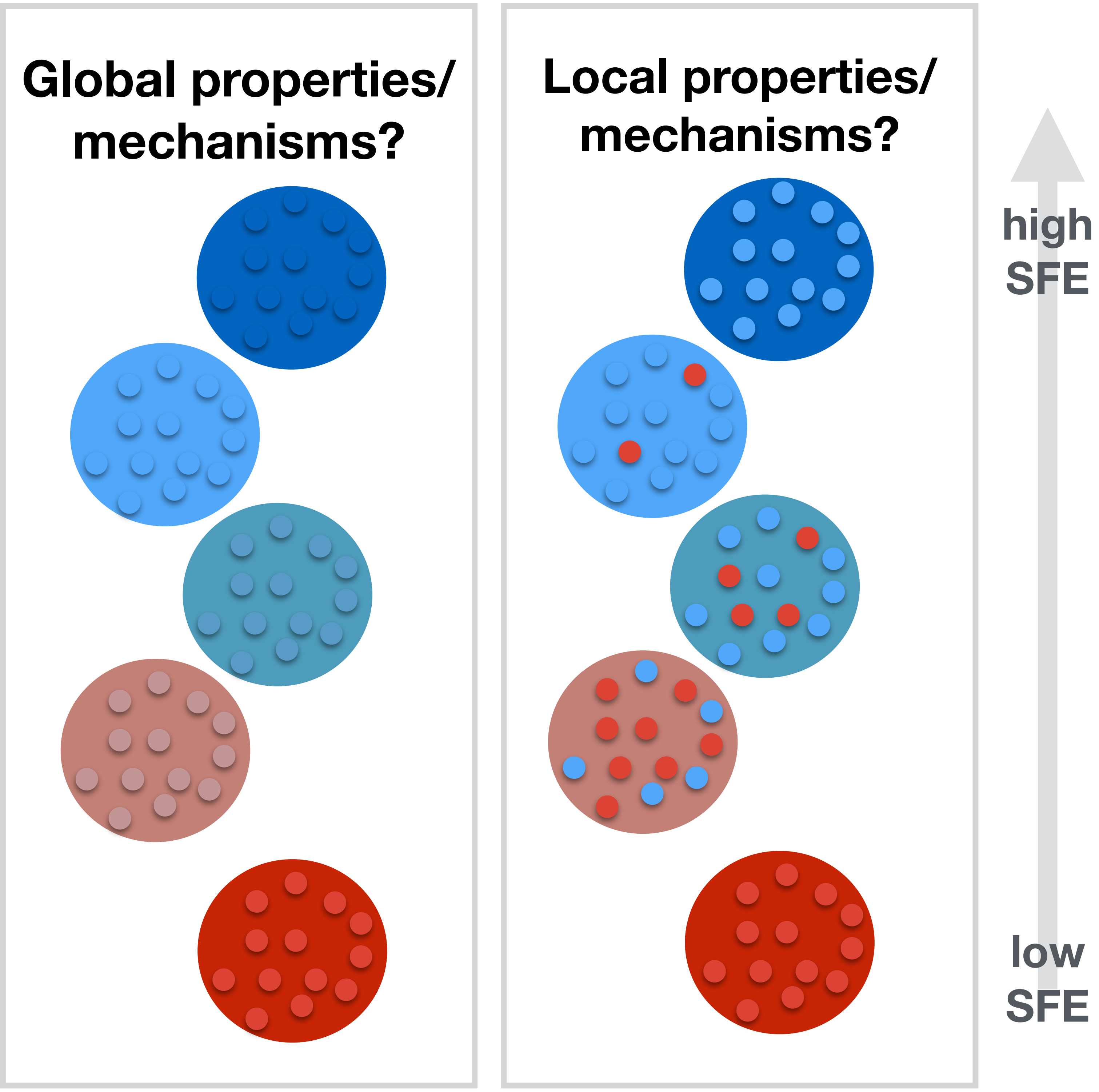
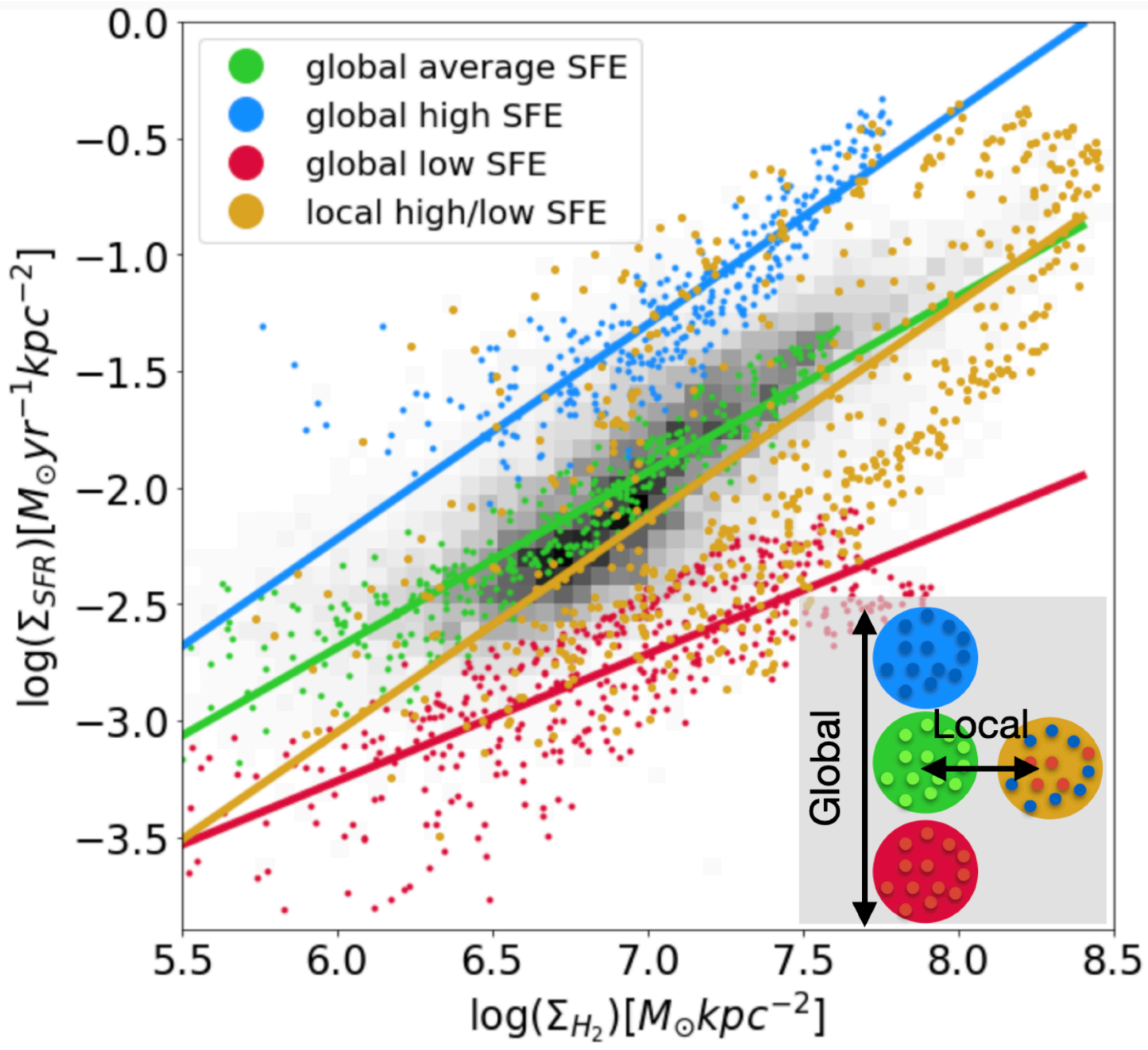


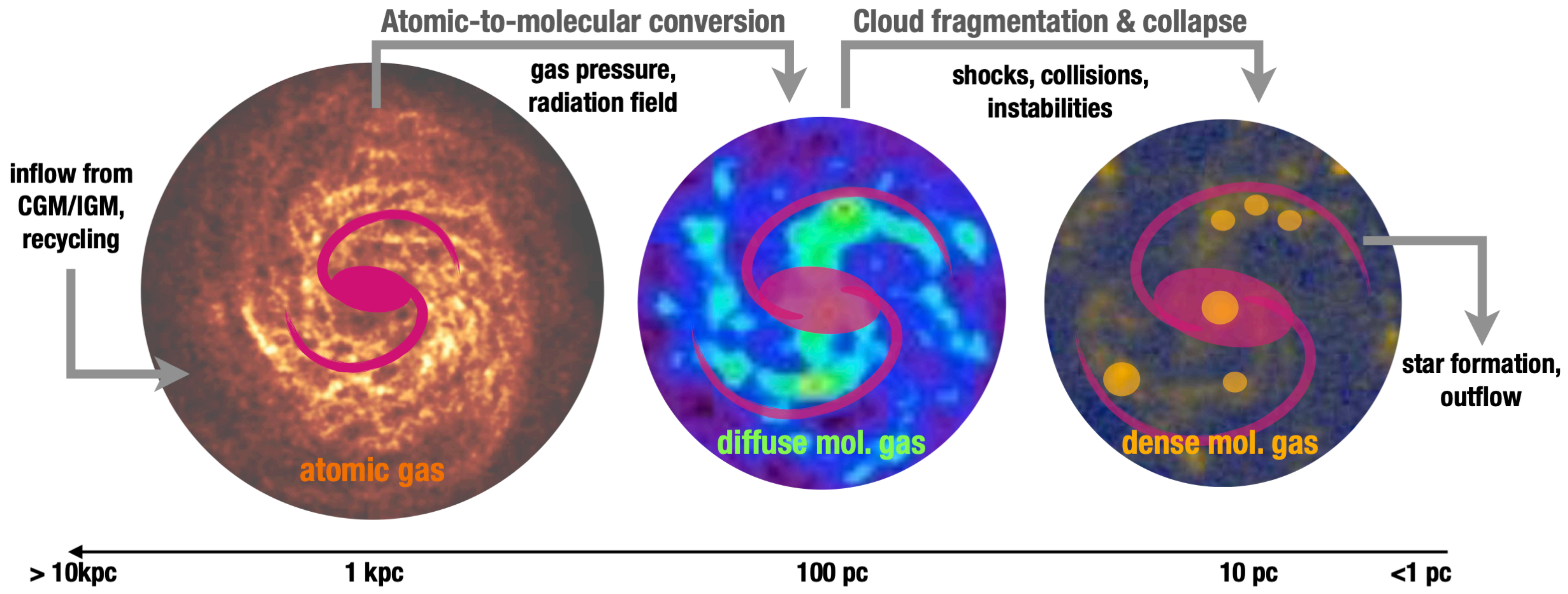


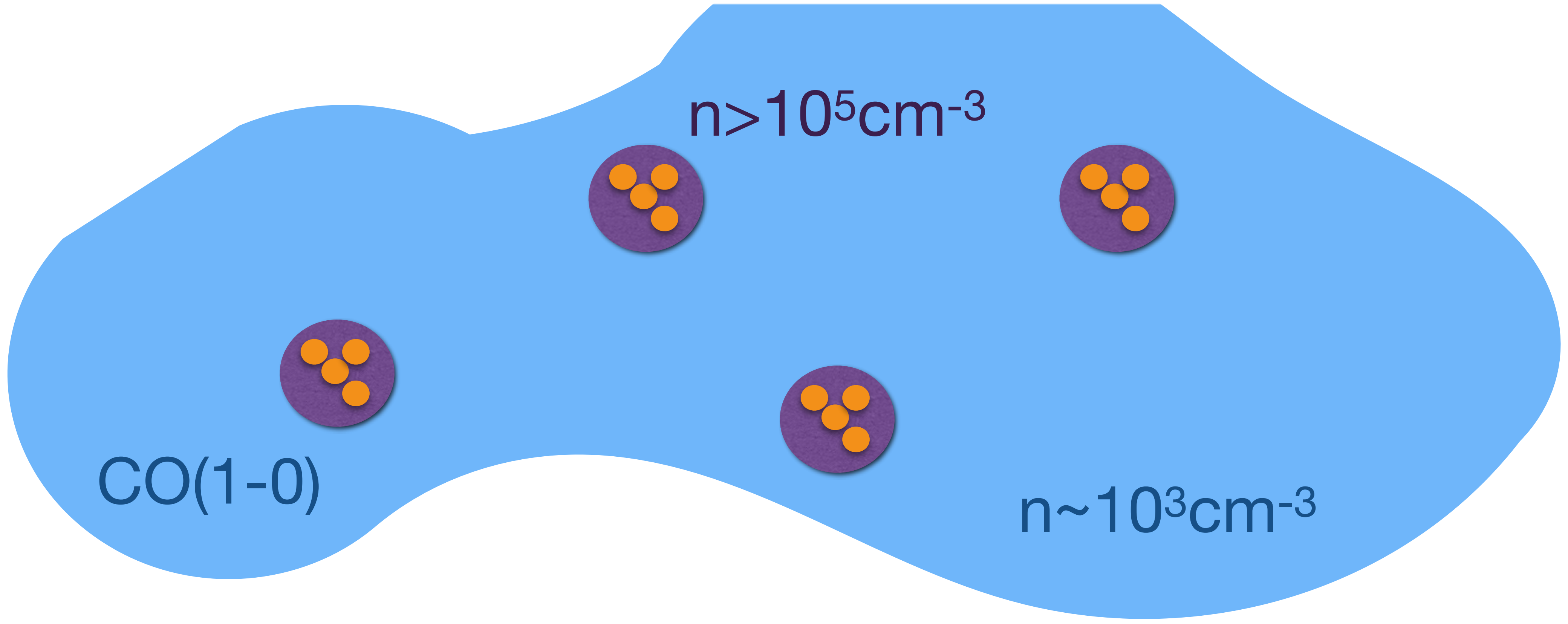


Linking small and large scales with resolved observations of both gas and star formation (e.g. combining MaNGA/SAMI/CALIFA and ALMA/CARMA)

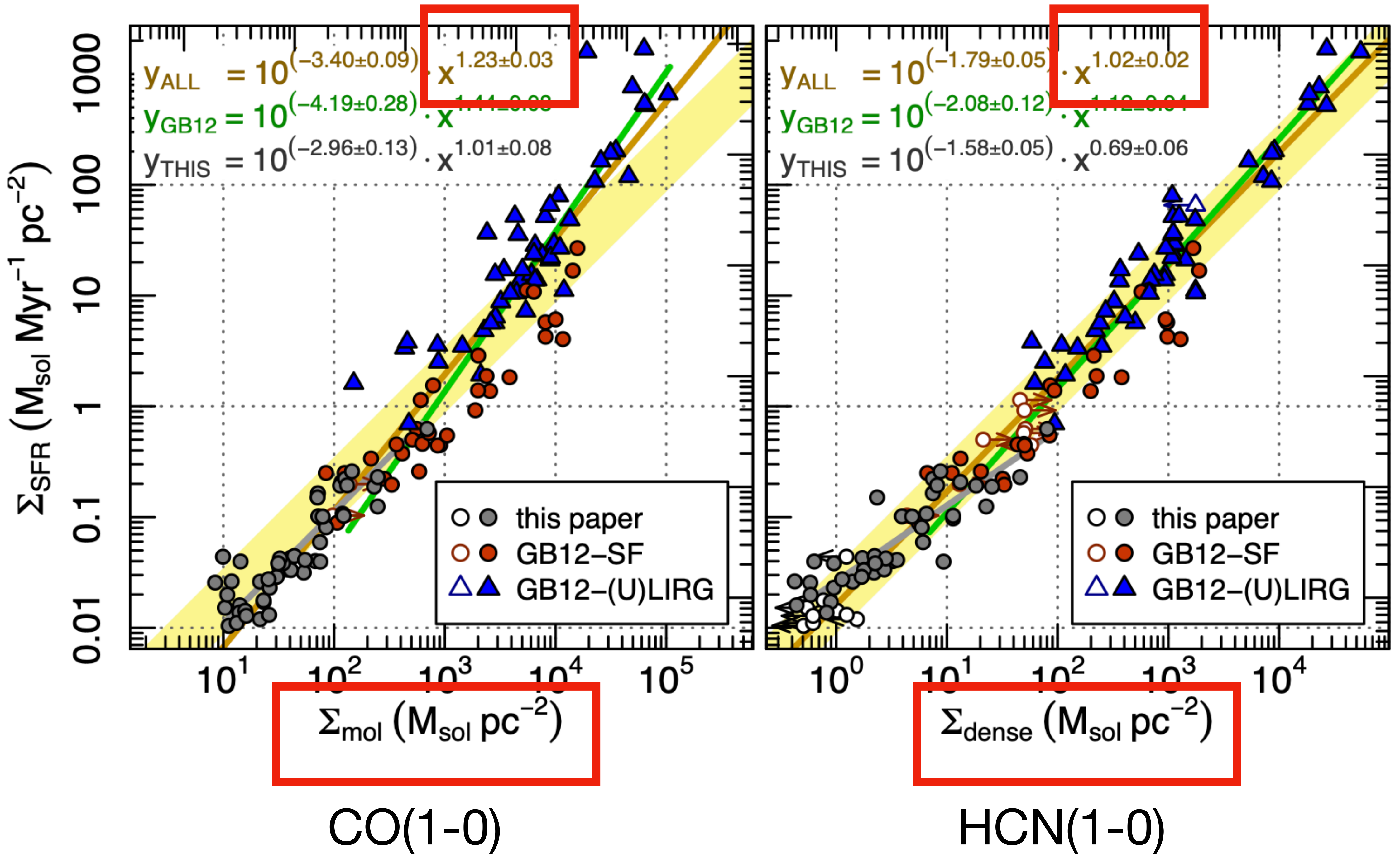
importance of both spatial resolution and statistics over large samples / broad parameter space

Exploiting molecular gas tracers



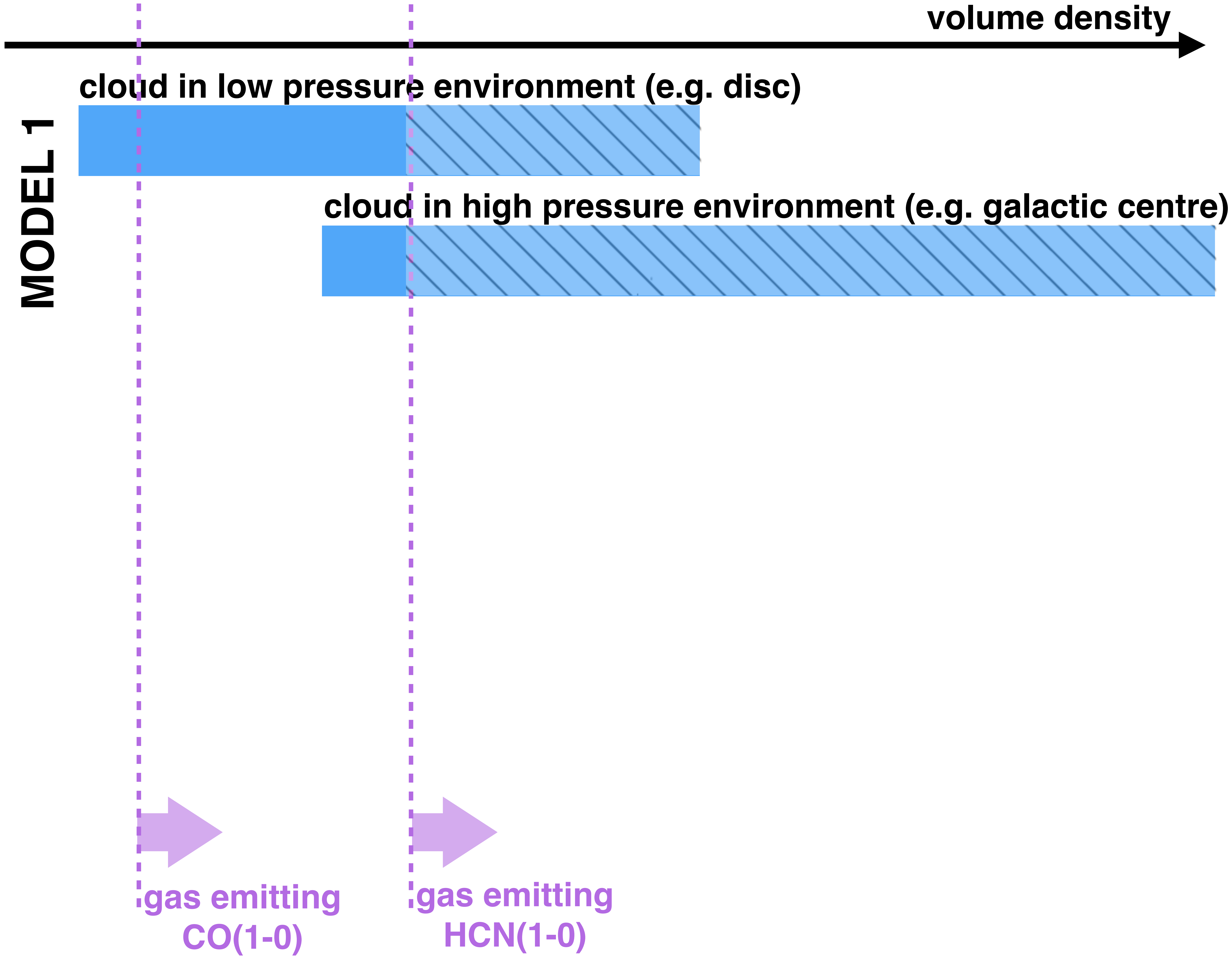


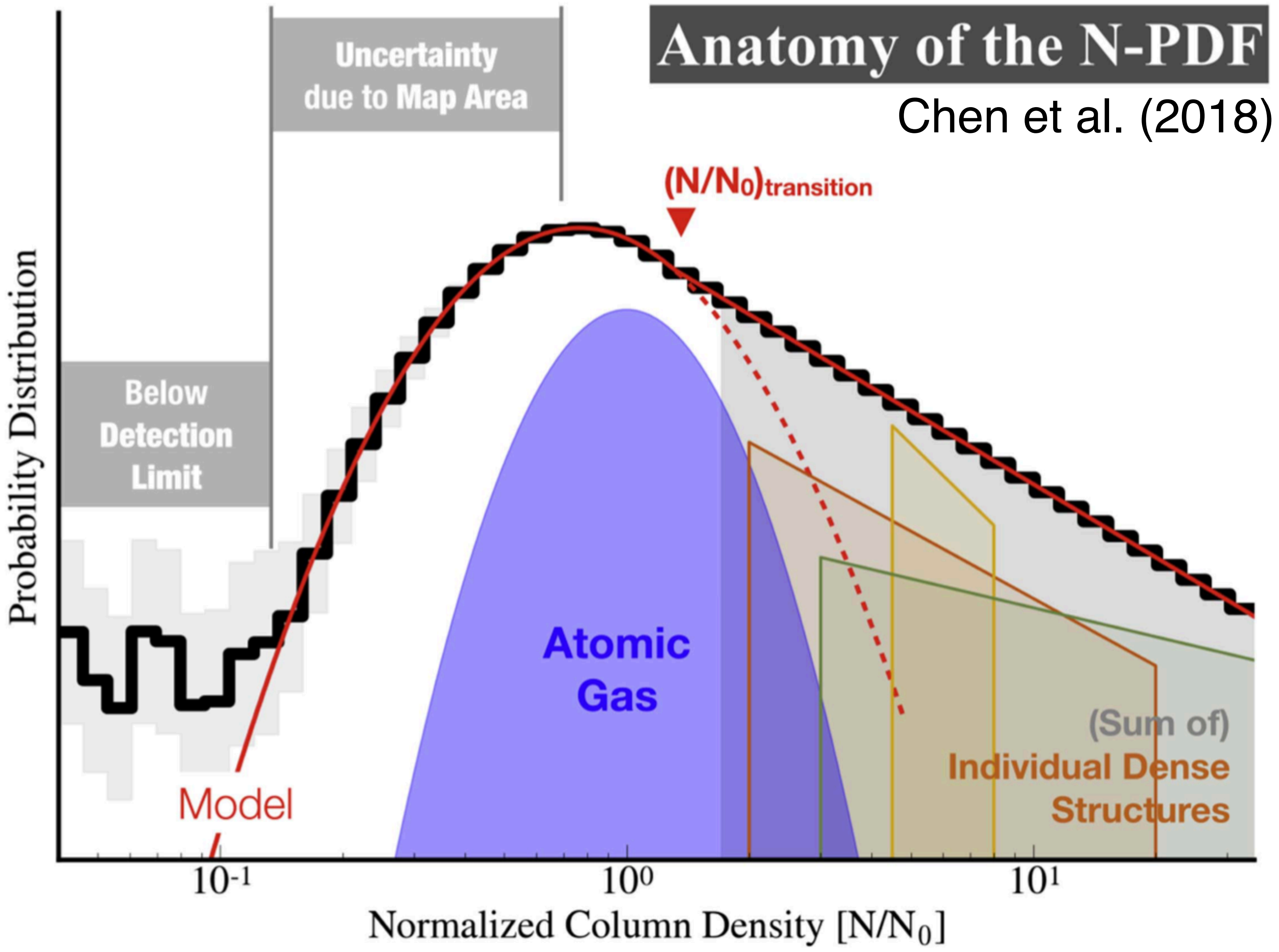
The relation between gas surface density and SFR is both tighter and more linear when using a dense gas tracer:



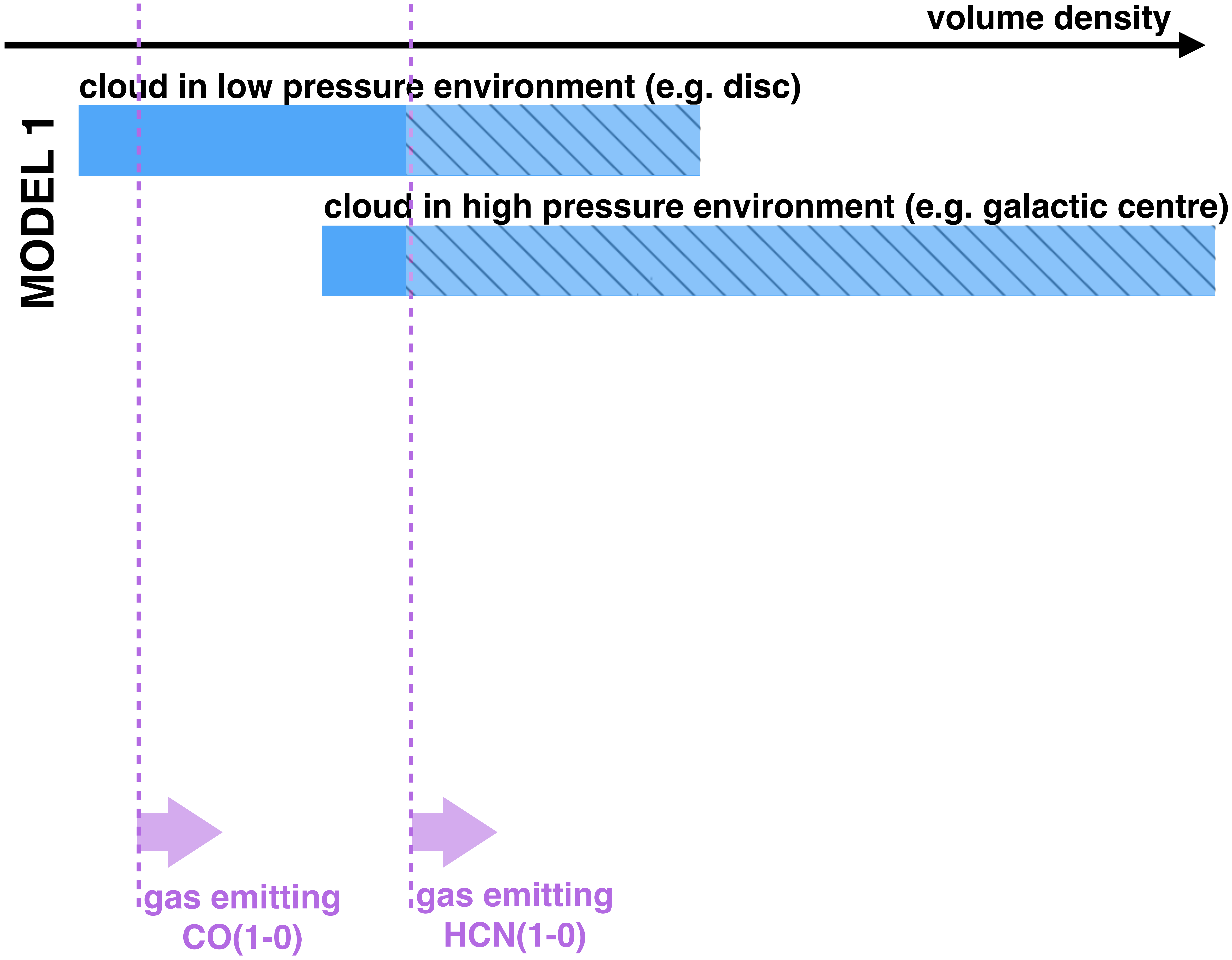
Usero et al. (2015)

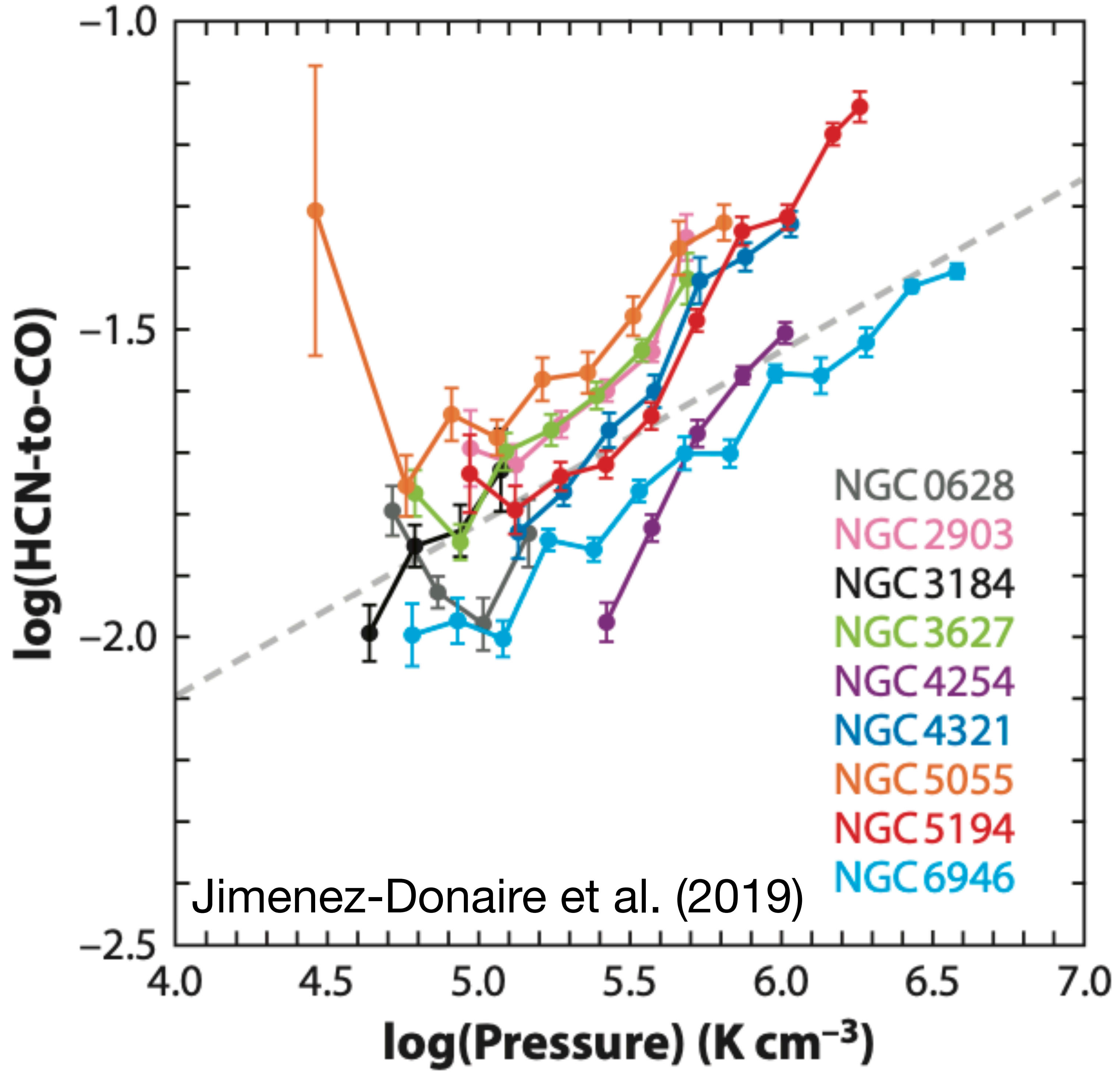
Testing star formation models





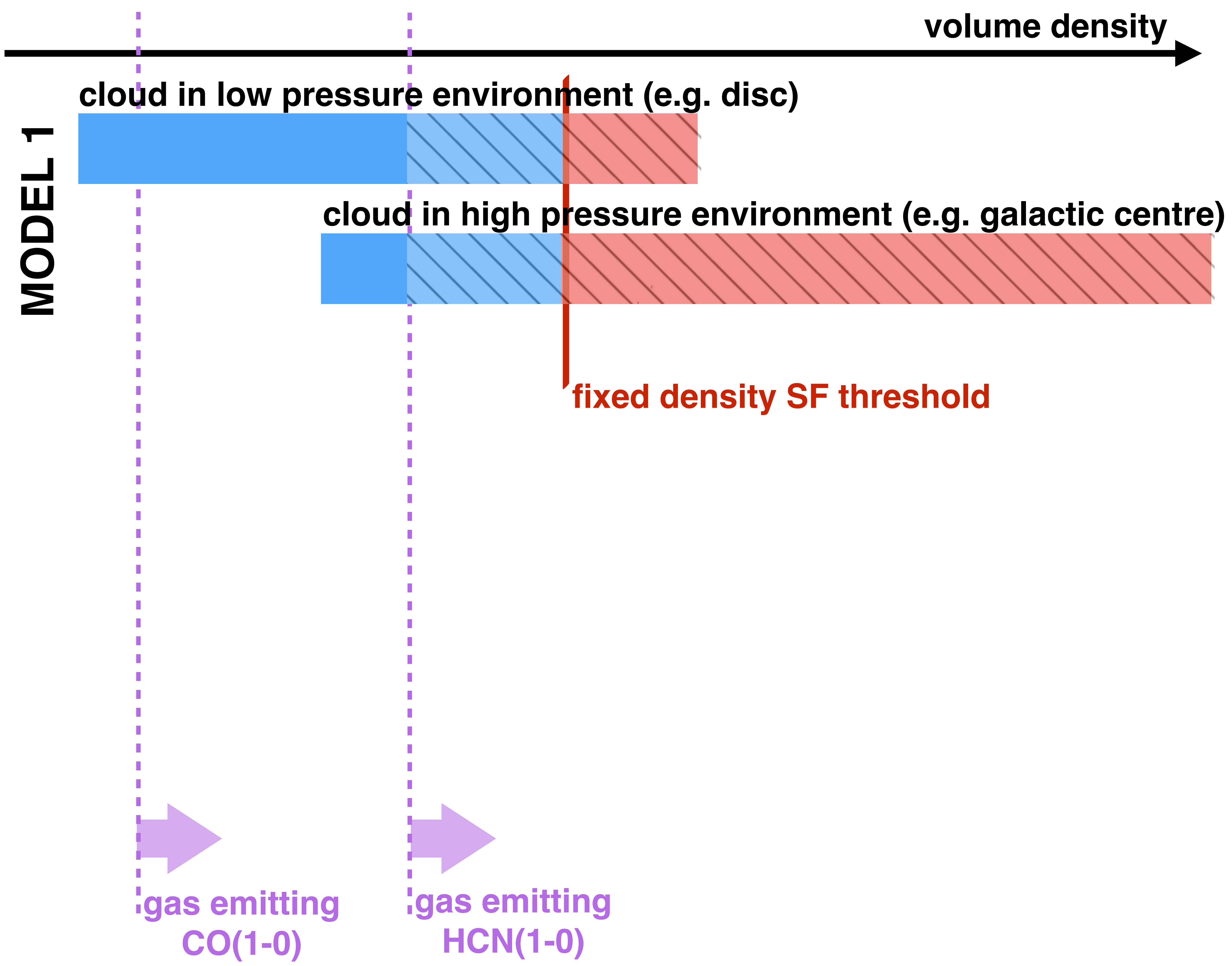
Testing star formation models



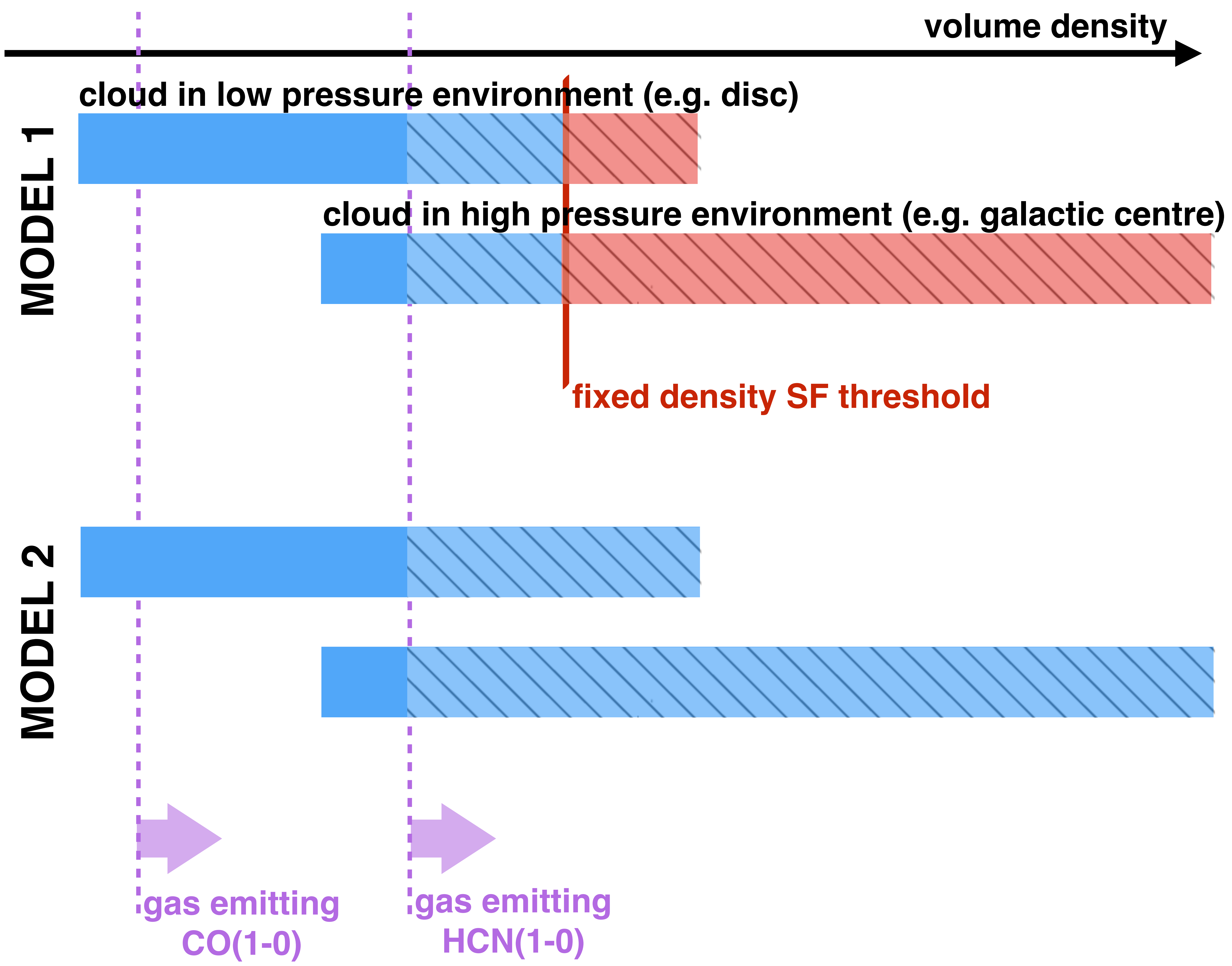


dense gas fraction scales with pressure, as expected

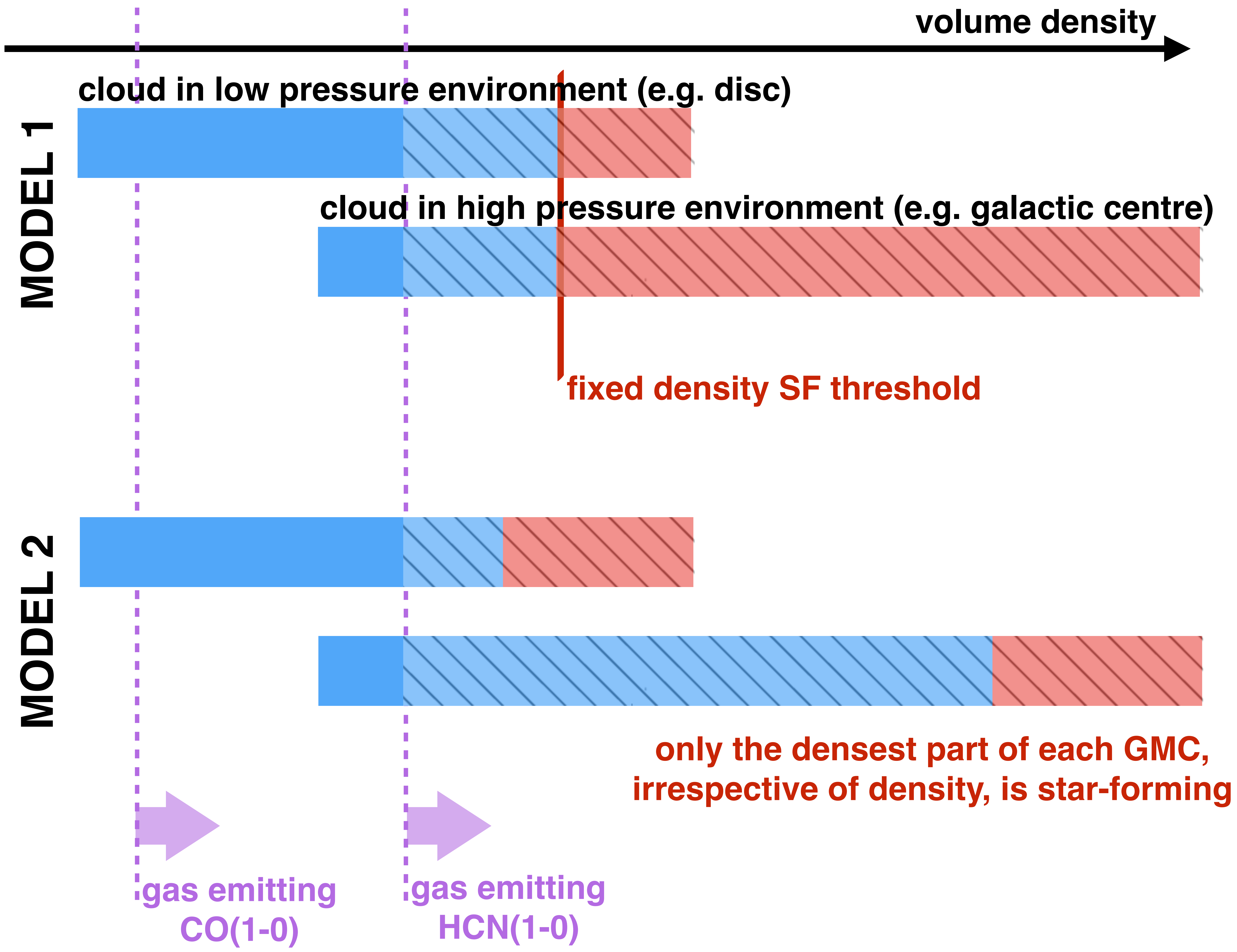
Testing star formation models



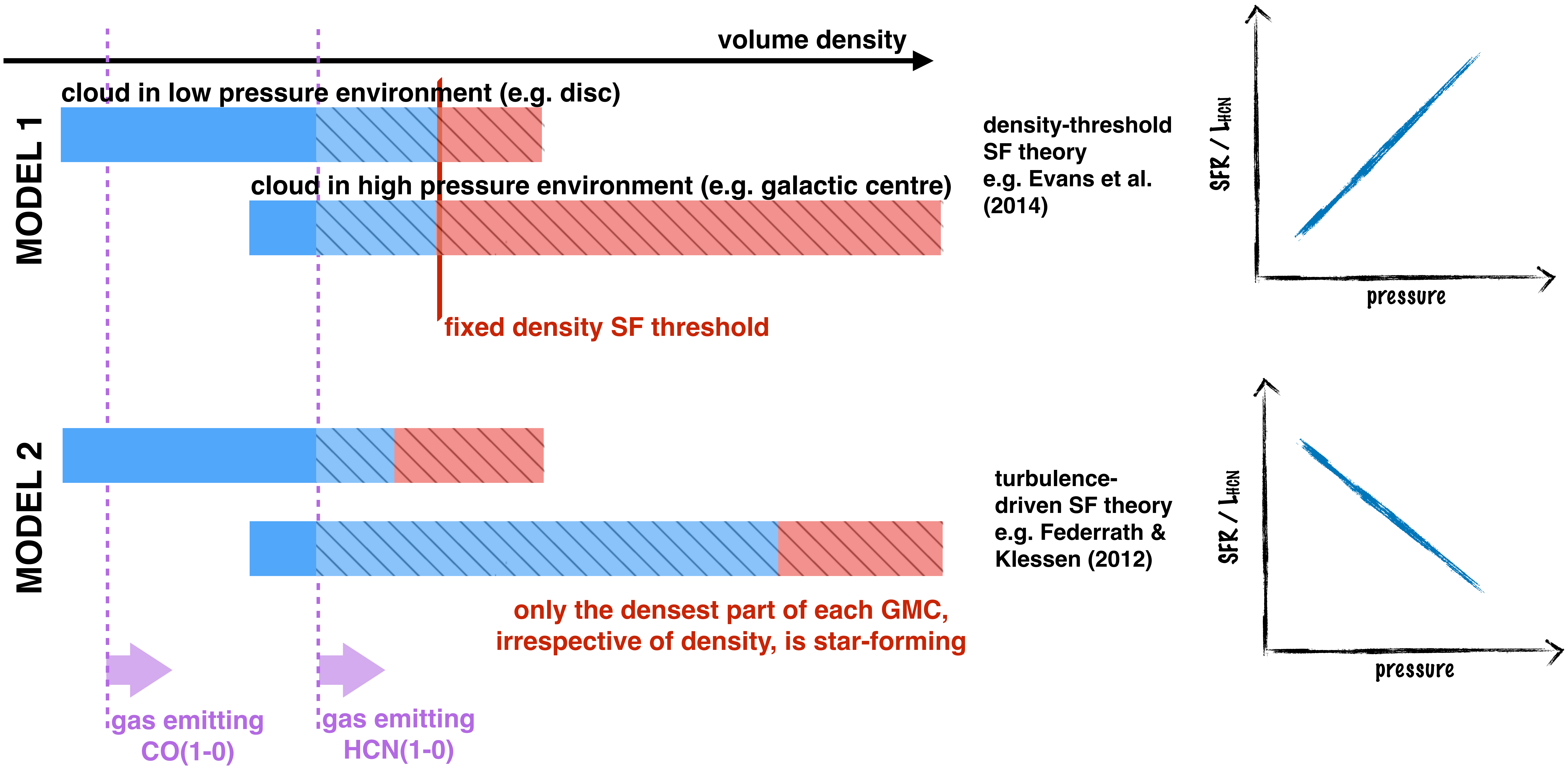
Testing star formation models



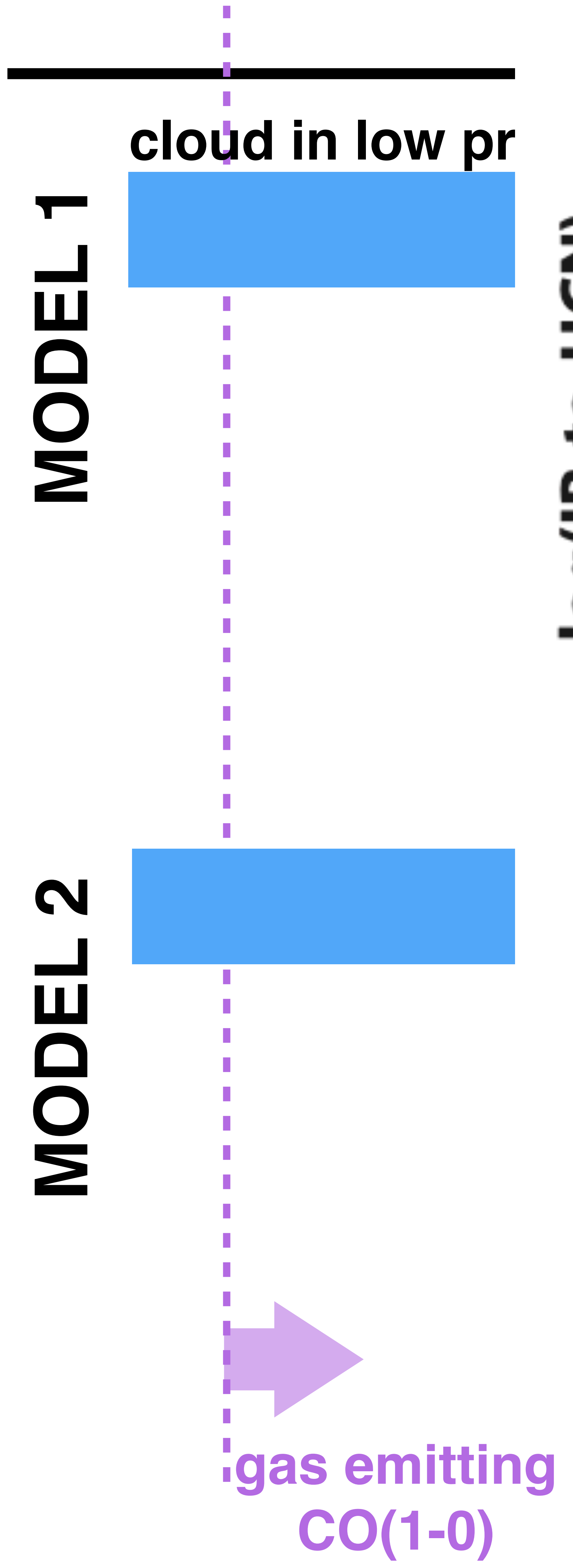
Testing star formation models

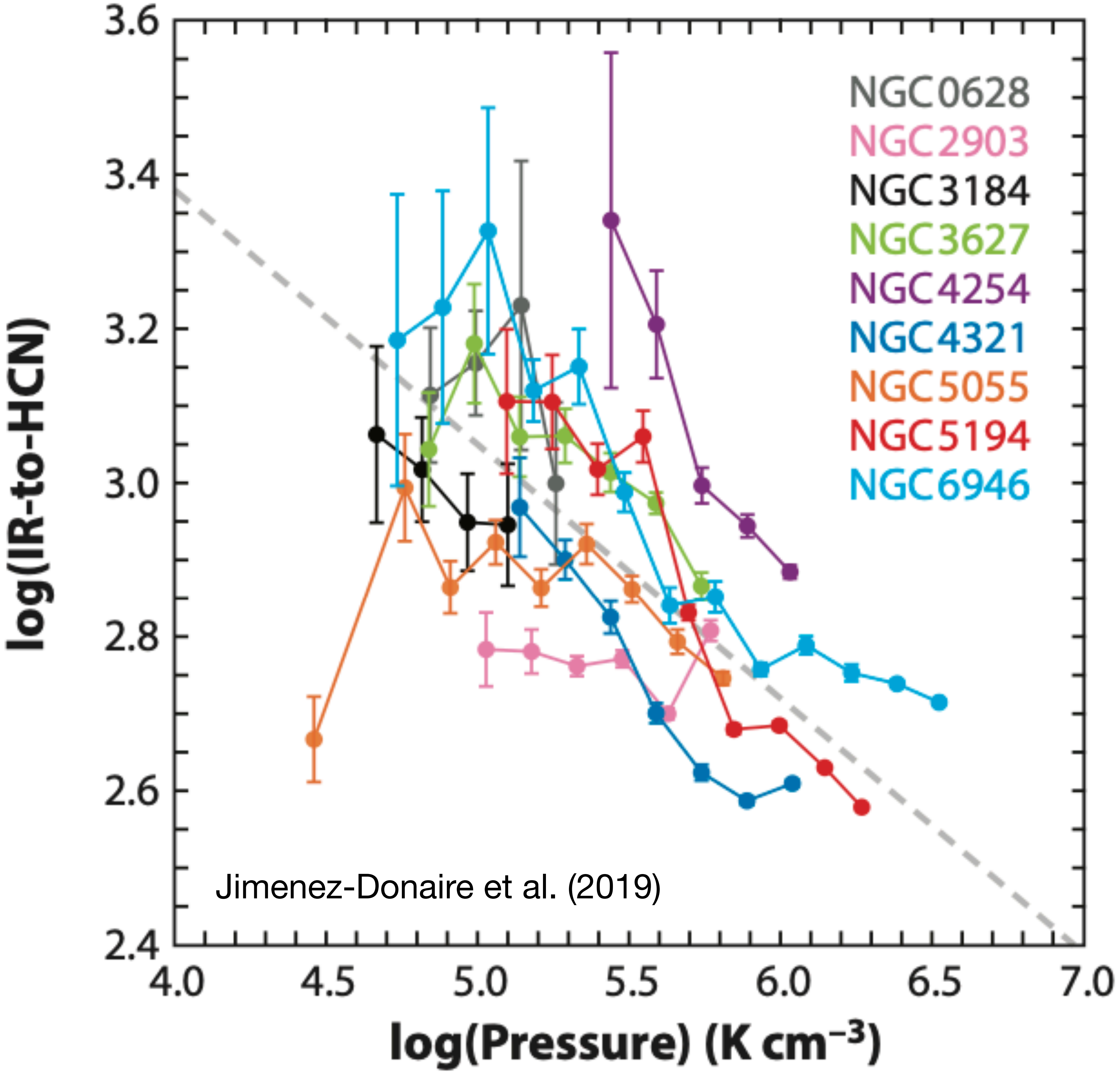


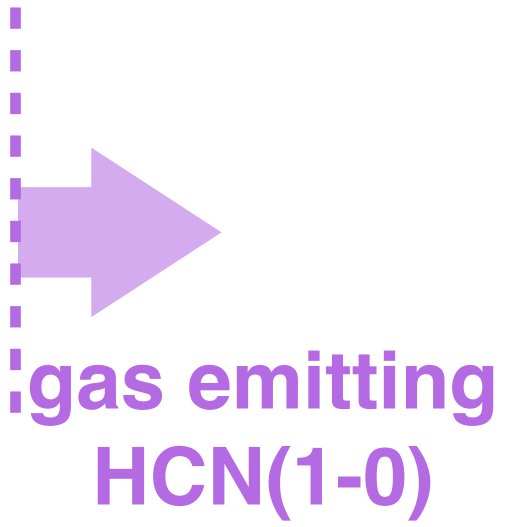
Testing star formation models



Testing star formation models

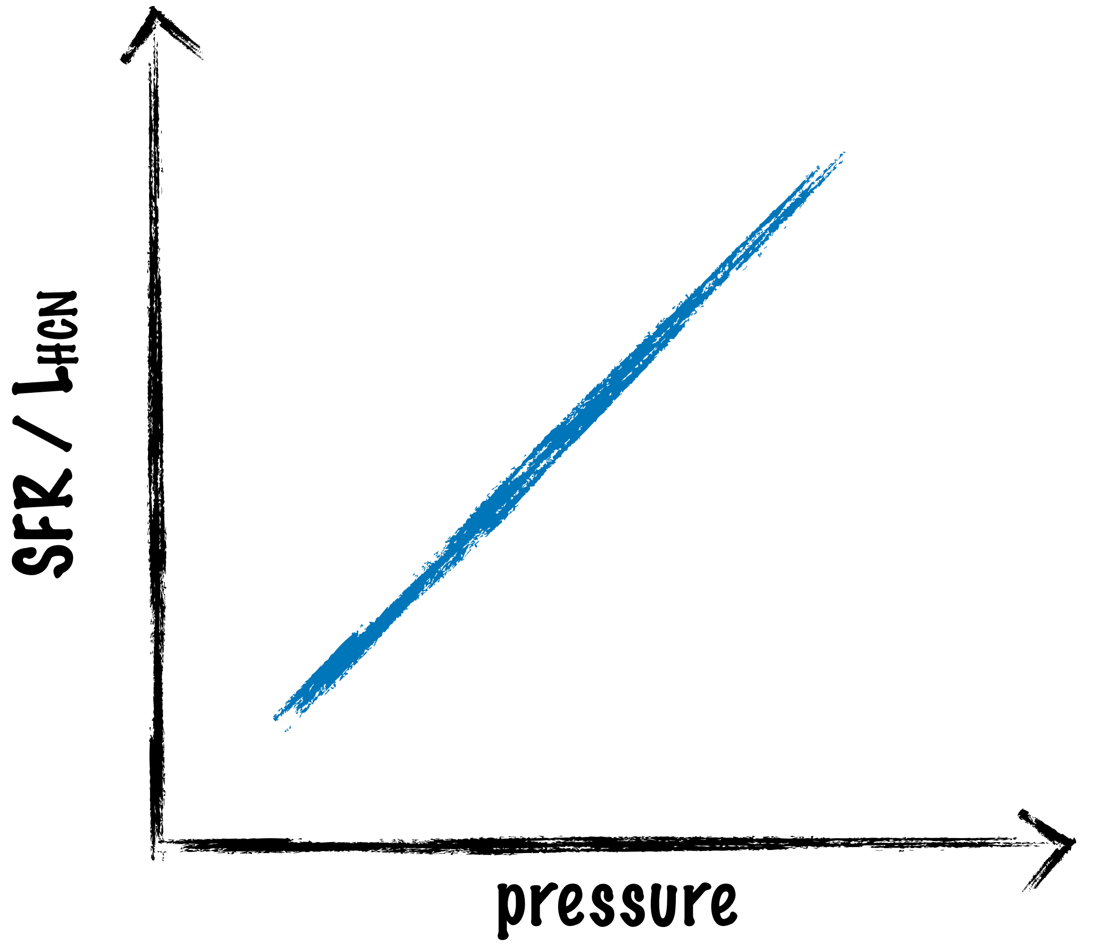




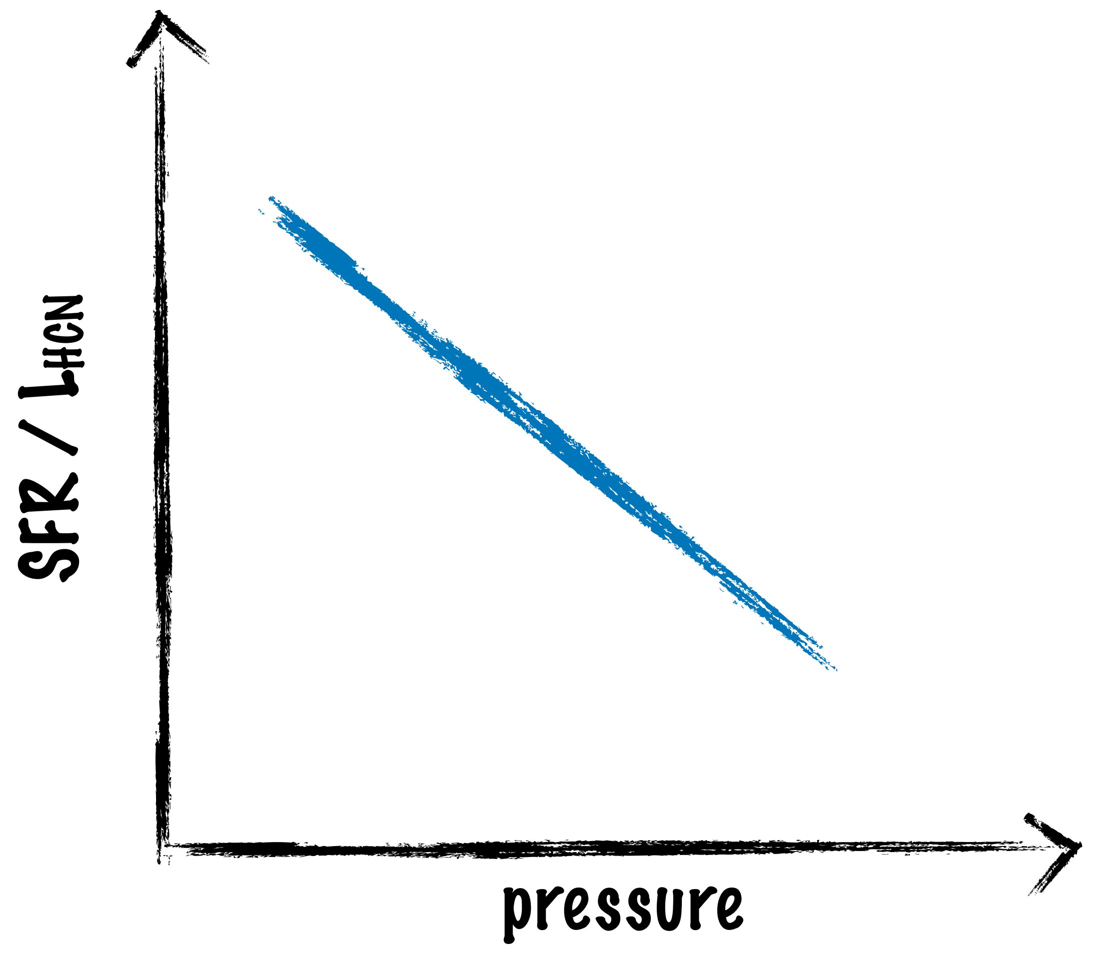


only the densest part of each GMC,
irrespective of density, is star-forming

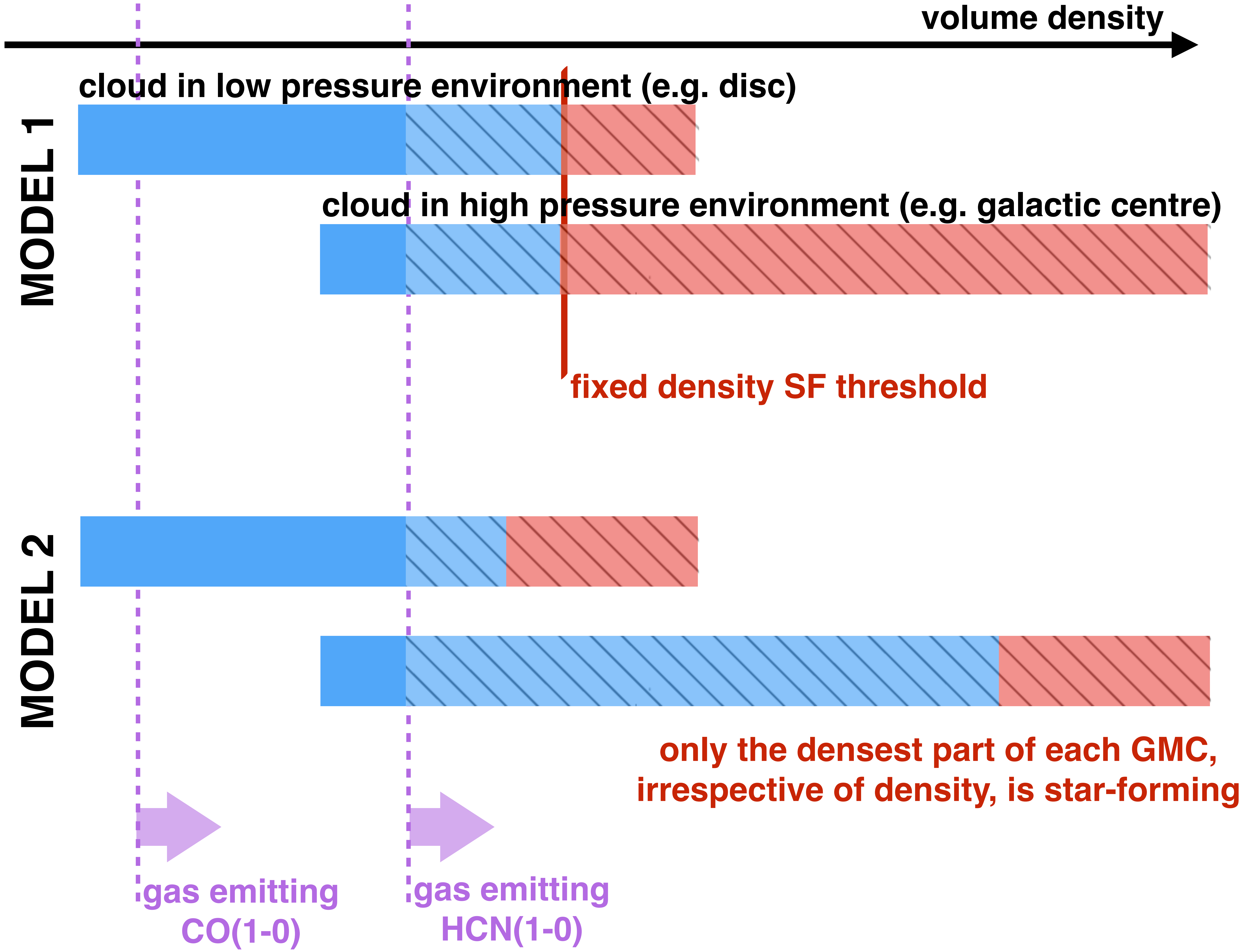
density-threshold SF theory
e.g. Evans et al. (2014)



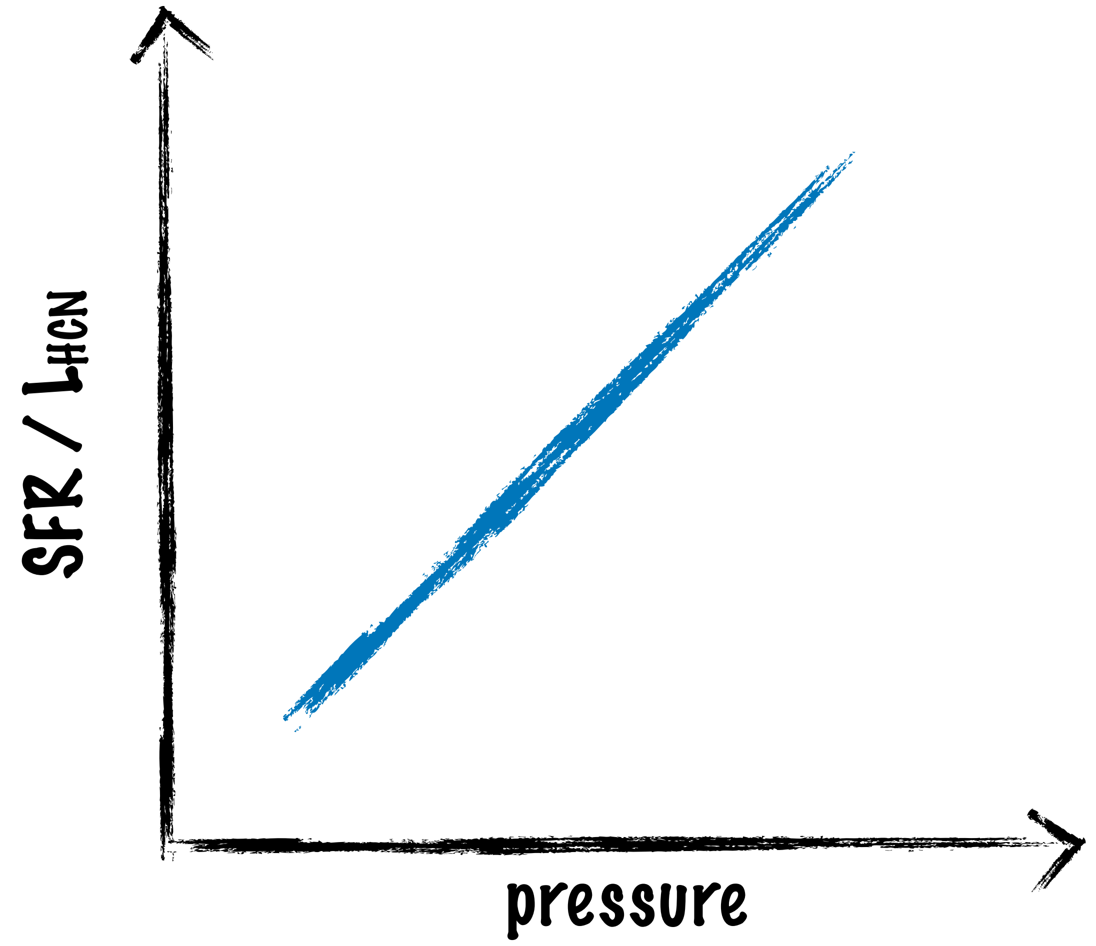
turbulence-driven SF theory
e.g. Federrath & Klessen (2012)



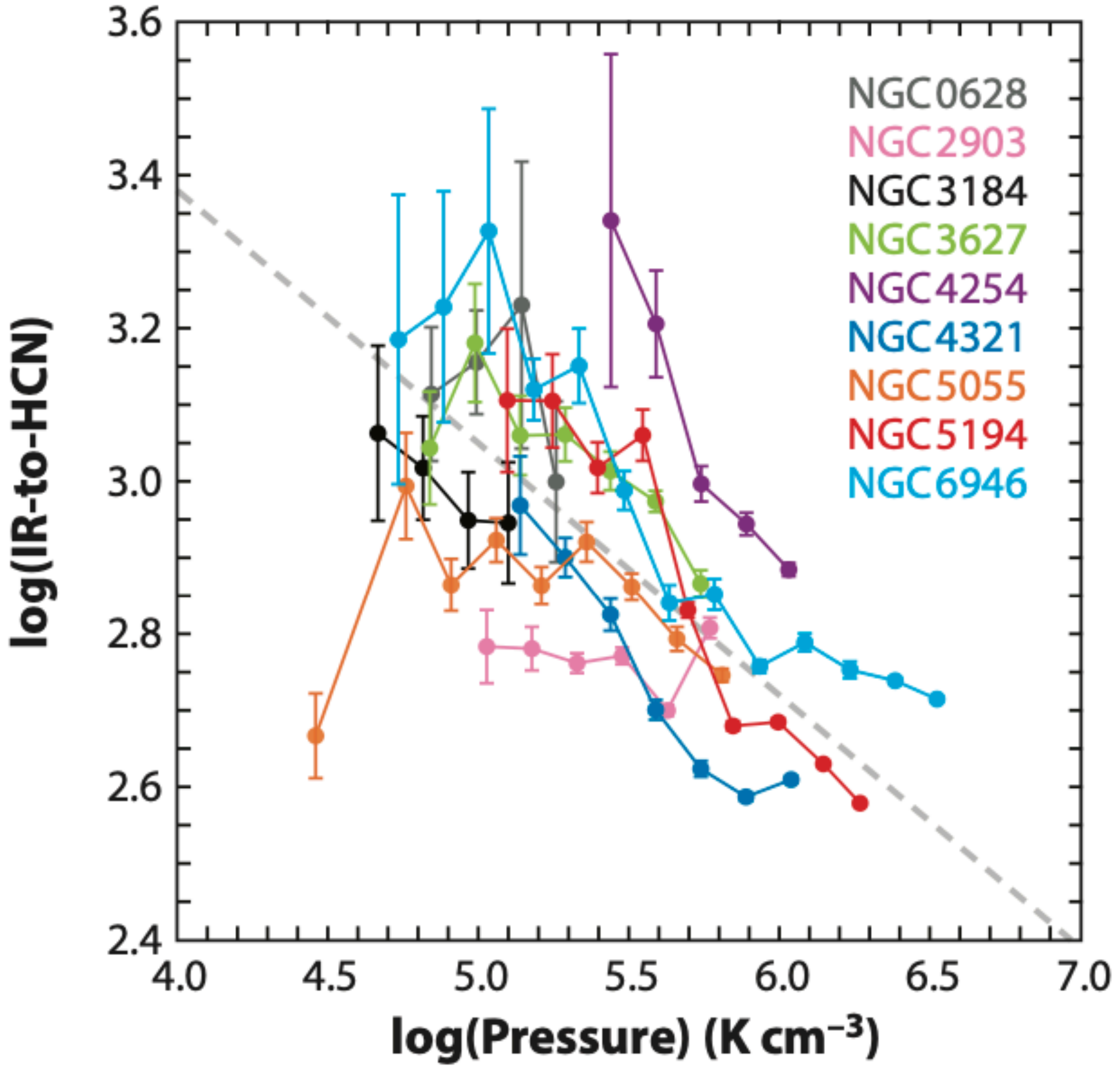
Testing star formation models



density-threshold SF theory e.g. Evans et al. (2014)



turbulence-driven SF theory e.g. Federrath & Klessen (2012)



Jimenez-Donaire et al. (2019), Tan et al. (2018), Heyer et al. (2022)

Open questions and active areas of research

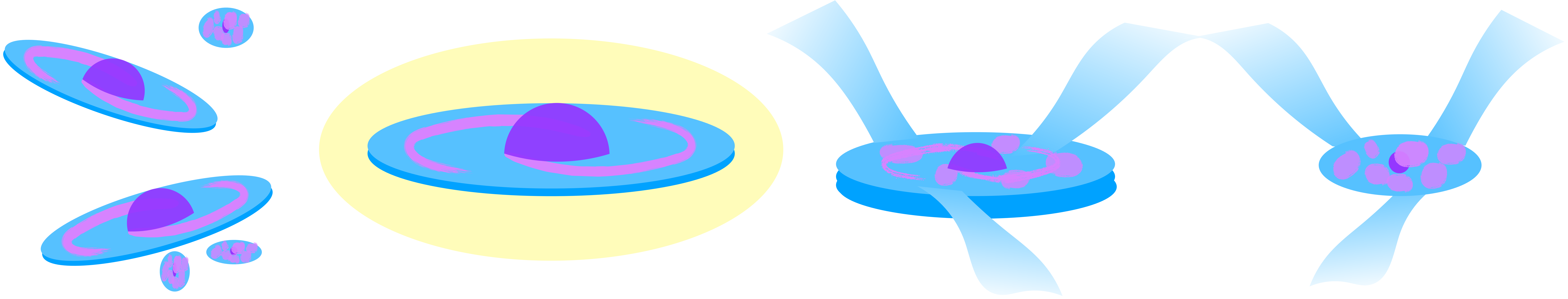
Gas supply (from cosmological accretion to molecular clouds)

- Why do galaxies of a given mass have such varied gas reservoir masses?
- What is the role of the large scale environment? (clusters/groups/isolated, filaments/nodes/voids, halo mass, close neighbours…)
- How does gas get into galaxies? (Different modes of accretion? Radial flows? Galactic fountains?) How does this change with redshift and galaxy mass?
- What shuts down accretion? (AGN heating? Change from cold- to hot-mode?)
- How is gas transported from the outer disc, all the way to the circumnuclear regions? What is the role of magnetic fields?
- How does AGN feeding proceed? How do their feedback affect gas reservoirs?

Star formation

- What sets the star formation efficiency (SFE), at all scales (from galaxy-integrated to cloud scales)?
- Are variations in SFE larger within galaxies, or from galaxy-to-galaxy? Do local and global mechanisms both contribute?
- Does star formation proceed differently in starbursts? What Galactic environments are most similar?
- How does the global stability of the disc impact the details of star formation?
- What are the main bottlenecks in converting the large gas reservoirs of low mass galaxies into stars?
- How do gas kinematics impact on star formation?

The many physical- and time-scales of star formation and galaxy evolution



z=0

MW and Local Group

accretion from galactic fountain and satellites

galaxies in equilibrium (gas reservoir drying up)

z<0.5

stable, rotation-dominated discs

accretion from galactic fountain and extended HI reservoirs

galaxies in equilibrium (gas reservoir drying up)

SF limited by gas reservoir

0.5<z<3

turbulent, Toomre-unstable discs

cold accretion from the cosmic web

galaxies in equilibrium (accretion balanced by SF + outflows)

SF limited by accretion rate

z>3

non-equilibrium galaxies

cold accretion from the cosmic web and minor mergers

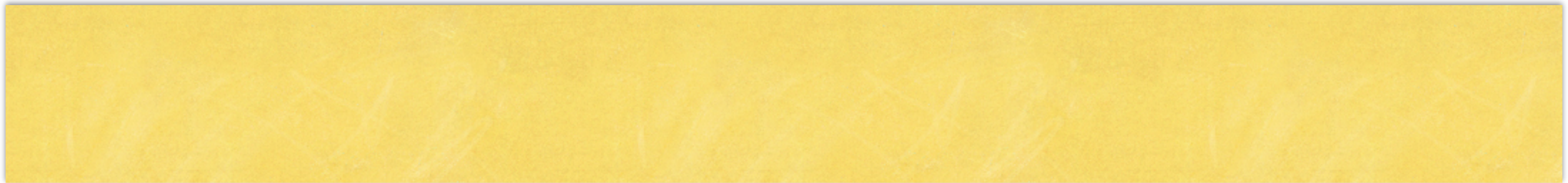
galaxies not yet in equilibrium (gas reservoir filling up)

SF at maximum efficiency (t_{dep})

Davé et al. (2012), Lilly et al. (2013), Saintonge et al. (2013), Tacconi et al. (2020), Saintonge & Catinella (2022)

Large spectroscopic surveys: stars, atomic gas, and molecular gas

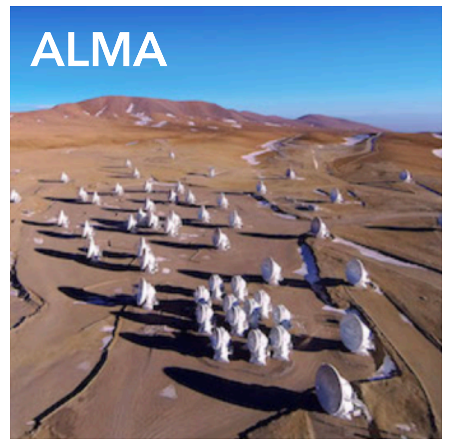
SDSS

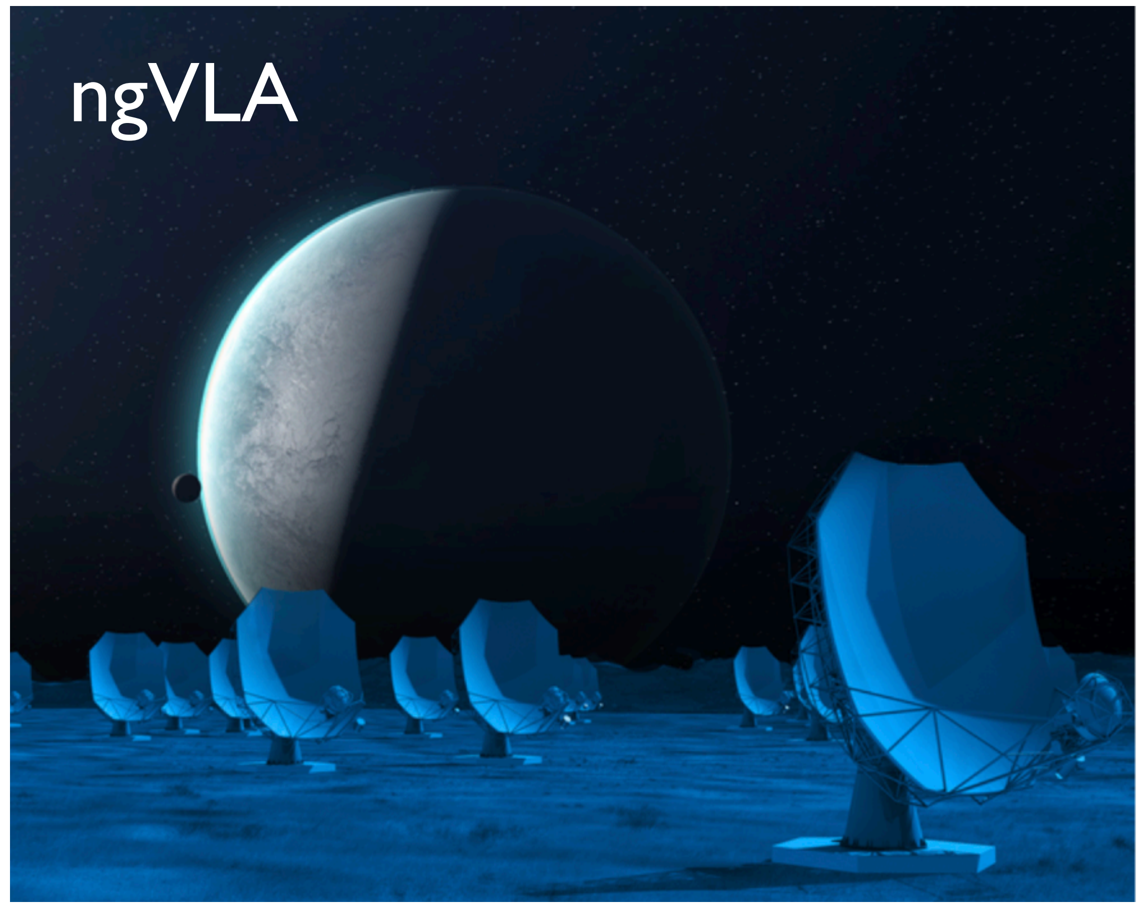


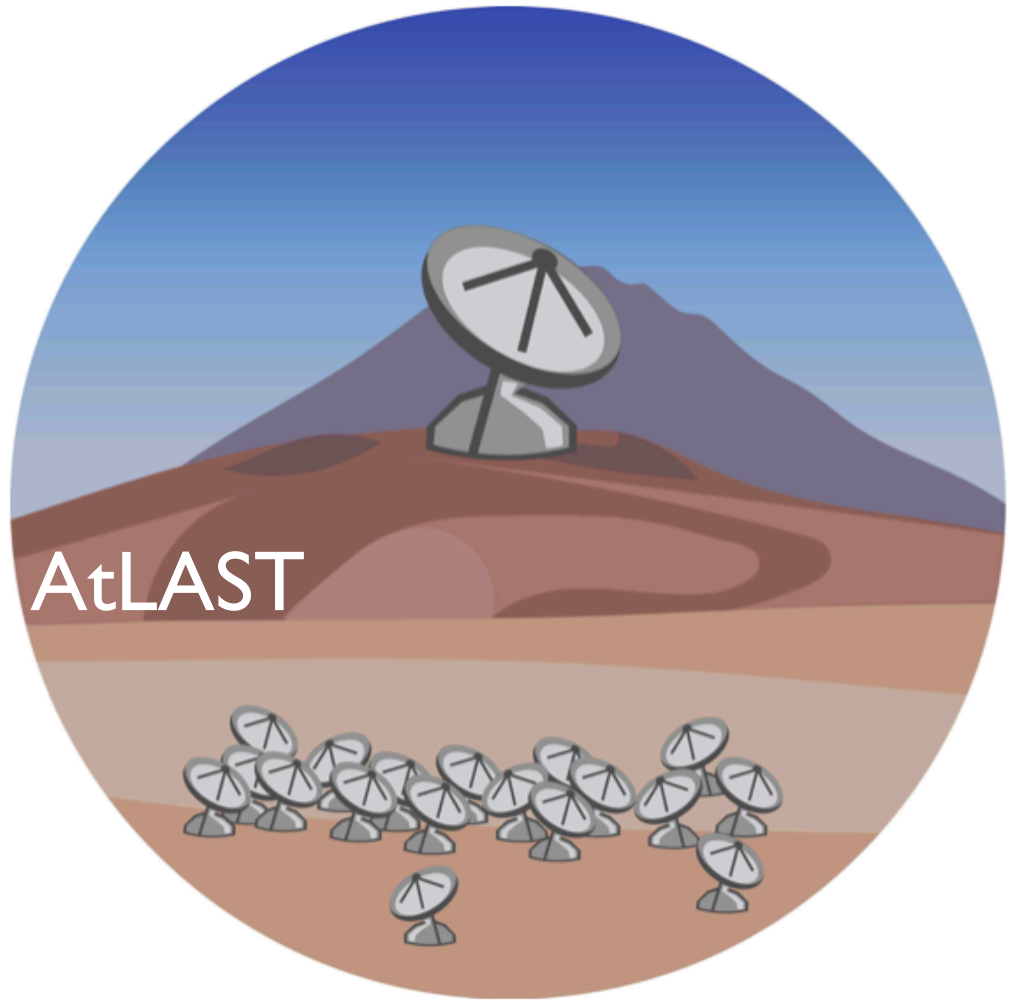
Large spectroscopic surveys: stars, atomic gas, and molecular gas

Large spectroscopic surveys: stars, atomic gas, and molecular gas

Large spectroscopic surveys: the future







Conclusions and outlook

- Information about the cold ISM is central to our understanding of galaxy evolution. Since the ISM is multi-phase and multi-scale, ***the more tracers the better***
- ***Large statistical samples are crucial to disentangle competing effects*** (even if at the cost of spatial resolution). Broad coverage of parameter space is key.
- Galaxy evolution and star formation is a complex multi-scale process; we need combination of large systematic surveys and high resolution follow-up
- Physical and chemical properties of the ISM are highly constraining for simulations but an underused tool
- Good progress connecting galaxy evolution with SF physics, but significant ground to break in connecting with CGM/IGM and cosmic web