Lecture 5
how galaxies form stars

the physical origin of long gas depletion time

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based on:

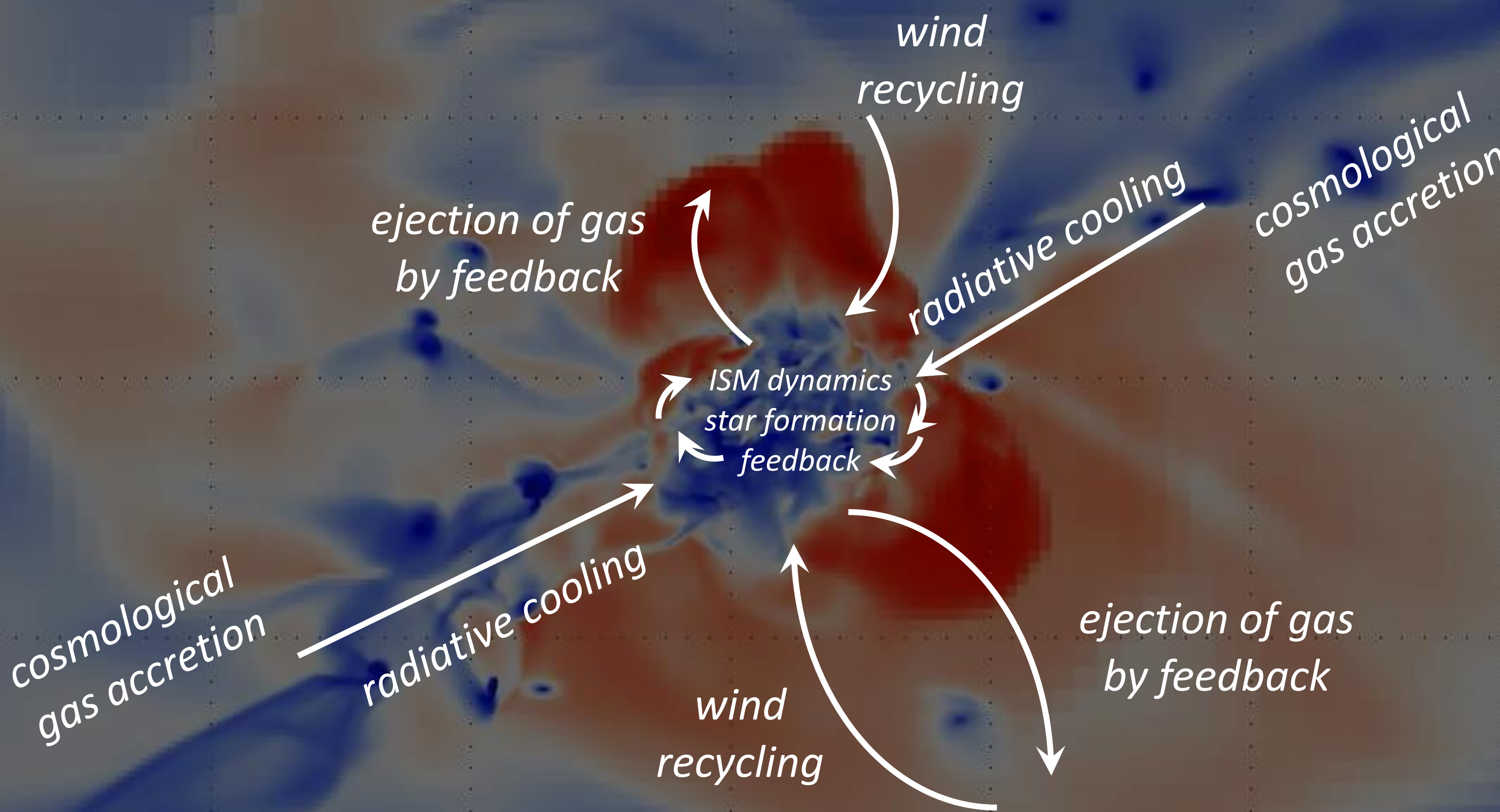
Semenov, Kravtsov & Gnedin 2017, ApJ 845, 133
2018, ApJ 861, 4
2019, ApJ 870, 79

Nick Gnedin
(Fermilab/U.Chicago)

Credit: NASA/ESA/Hubble Heritage (W. Blair and R. O'Connell)

https://apod.nasa.gov/apod/ap140128.html

How does depletion time affects galaxy evolution?



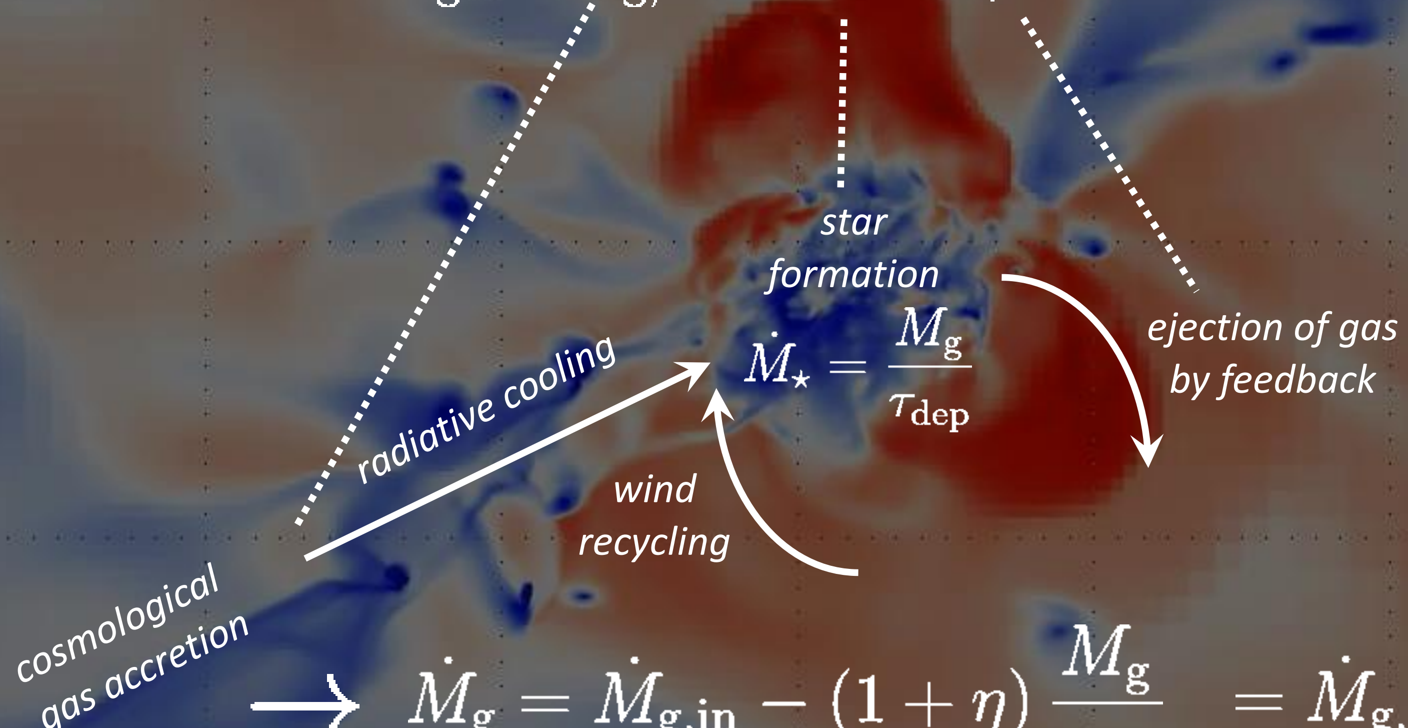
important cycles of gas during galaxy formation

background image: temperature distribution in a simulation of galaxy formation at z=4

a simplified mass accounting of gas cycling

Bouché et al. 10; Davé et al. 12; Krumholz & Dekel 12; Lilly et al. 13; Forbes et al. 14; Peng & Maiolino 14; Dekel & Mandelker 14; Feldmann 13, 15

$$\dot{M}_{\rm g} = \dot{M}_{\rm g,in} - \dot{M}_{\star} - \eta \dot{M}_{\star}$$



$$\dot{M}_{\star} = \frac{M_{\rm g}}{\tau_{\rm dep}}$$

$$\longrightarrow \quad \dot{M}_{\rm g} = \dot{M}_{\rm g,in} - (1+\eta)\frac{M_{\rm g}}{\tau_{\rm dep}} = \dot{M}_{\rm g,in} - \frac{M_{\rm g}}{\tilde{\tau}}$$

$\longrightarrow$ *overall timescale of "galactic metabolism" is the ratio of the star formation depletion time and wind mass loading factor +1 :*

$$\tilde{\tau} = \frac{\tau_{\rm dep}}{1+\eta}$$

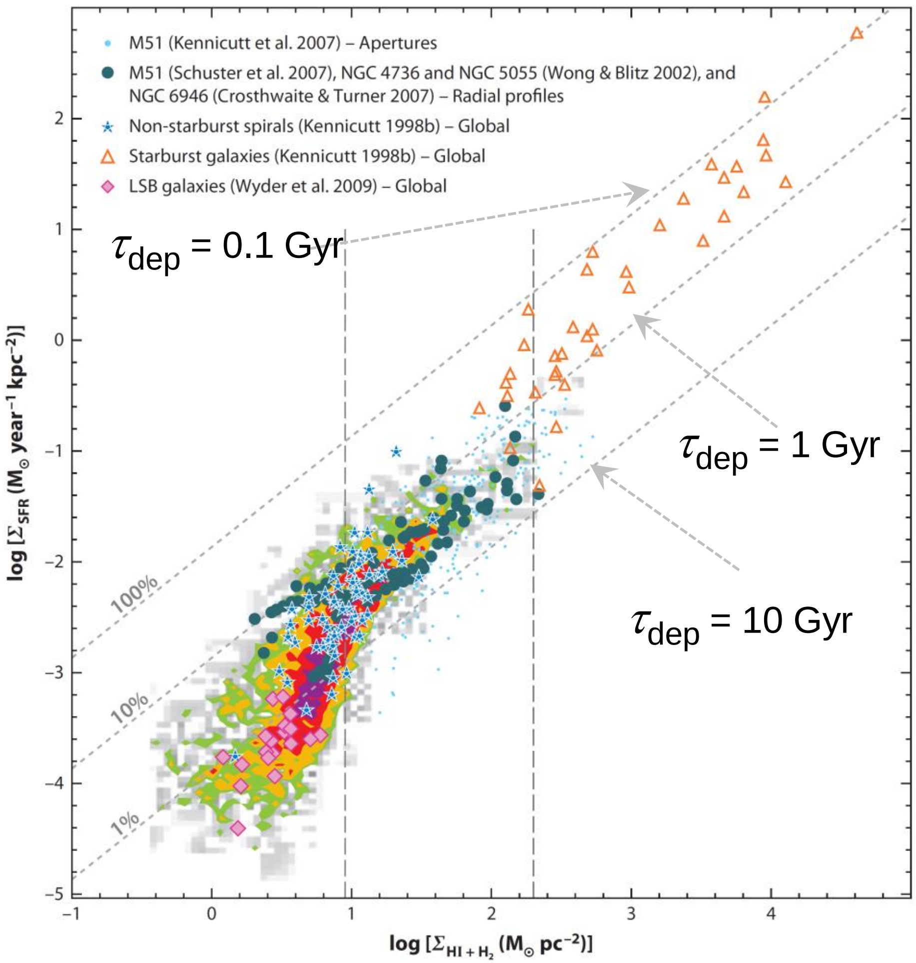
the Kennicutt-Schmidt (KS) relation: relation between $\dot{\Sigma}_\star$ and $\Sigma_{\rm gas}$ measured on >~kpc scales

M. Schmidt (1959, 1963); R. Kennicutt (1989, 1998)

+ Sanduleak (1969), Madore et al (1974), Martin & Kennicutt 2001, Biegel et al. (2008, 2011), Leroy et al. 2013 ...

for a review see Kennicutt & Evans 2012, ARAA 50, 531

$\log_{10}$ surface density of star formation rate $\dot{\Sigma}_\star$ Msun/yr/kpc^2



$\log_{10}$ surface density of HI+H$_2$ ($\Sigma_{\rm gas}$) in Msun/pc^2

Inverse of normalization of this relation has units of time and gives gas depletion time

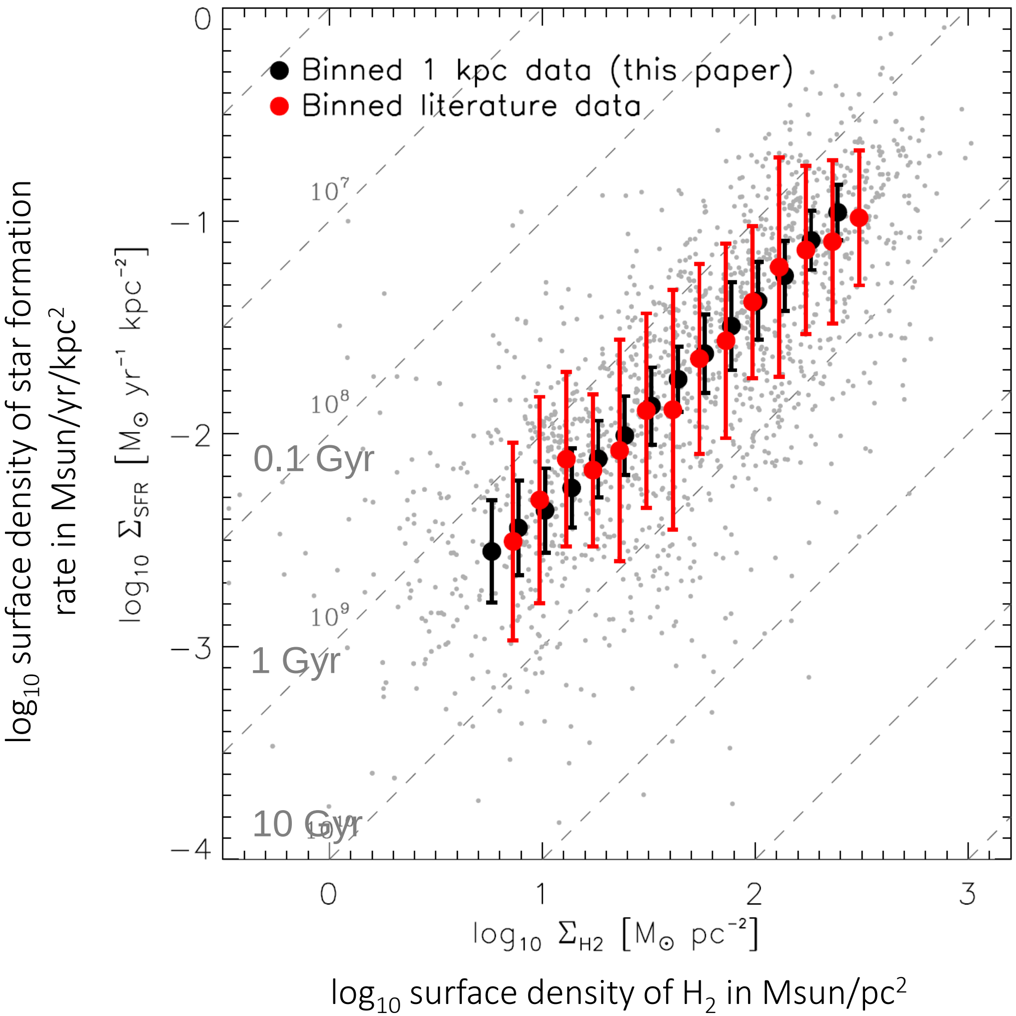
$$\tau_{\rm dep} = \frac{\Sigma_{\rm gas}}{\dot{\Sigma}_\star} \sim \frac{M_{\rm gas}}{\dot{M}_\star}$$

Maarten Schmidt and Rob Kennicutt

at the 2009 conference celebrating 50th anniversary of Maarten Schmidt's 1959 paper

molecular Kennicutt-Scmidt relation: correlation of star formation surface density with surface density of molecular gas

e.g., Wong & Blitz 2002; Biegel et al. 2008, 2011; Leroy et al. 2008, 2013; Genzel et al. 2010, 2015; Bolatto et al. 2011, 2017; Utomo et al. 2017; Tacconi et al. 2018; Colombo et al. 2018 at z~0



inverse of normalization of this relation has units of time and gives ***molecular gas depletion time,*** which is also rather long

$$\tau_{\rm dep,H_2} \equiv \frac{\Sigma_{\rm H_2}}{\dot{\Sigma}_\star} = \frac{M_{\rm H_2}}{\dot{M}_\star} \approx 2.3 \pm 1 \ {\rm Gyr}$$

but is nearly constant across different patches within regular galaxies – i.e. *molecular KS relation is close to linear*. *

This implies that the non-linear form of the HI+H2 KS relation is simply due to variation of molecular fraction.

*In higher surface density environments of starbursts and high-z galaxies molecular depletion time seems to decrease somewhat (*Genzel et al. 2010, 2015; Saintonge+ 2011; Tacconi+ 18*)

WHY depletion times are so long?

relevant time scales governing evolution of gas in the interstellar medium are much shorter than gas depletion time

orbital period, free-fall time, turbulent crossing time of diffuse ISM gas, etc.

$$t_{\rm orb} = \frac{2\pi R}{V_{\rm rot}} \approx 200\ {\rm Myr}|_{R=R_\odot}$$

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}} \approx 10 - 50\ {\rm Myr}$$

$$t_{\rm turb} = \frac{h}{\sigma_{\rm turb}} \approx 10 - 30\ {\rm Myr}$$

this makes depletion time of a few ~Gyrs a puzzle
(and it was discussed as a puzzle since 1970s)

Goldreich & Kwan 1974; Zuckerman & Evans 1974

one factor is inefficiency of star formation in star-forming molecular ~10-100 pc scale "clouds" where stars actually form

but by itself inefficiency in star forming regions does not explain the long global depletion time, because observational estimates show that depletion time in star-forming regions is only:

$$\tau_{\rm dep,sf} \equiv \frac{M_{\rm sf}}{\dot{M}_{\star,\rm sf}} \qquad \tau_{\rm dep,sf} \sim 50 - 500\ \rm Myrs$$

i.e., a factor of ~10-200 shorter than the global depletion time and a factor of ~5-50 shorter than depletion of molecular gas

(Evans+'09, 14; Heiderman+ '10; Murray '11; Lada+ '10, 12
Heyer et al '16; Lee+ '16; Vutisalchavakul et al. 2016; Miville-Deschênes et al. 2017)

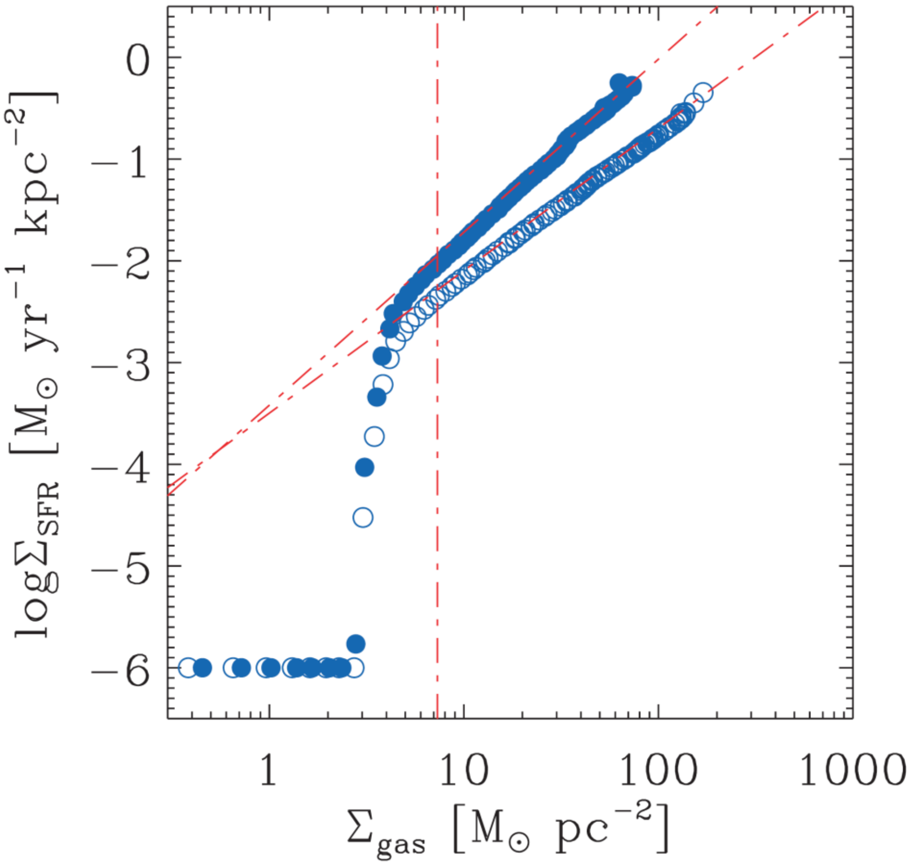
questions:

- What is the physical origin of long gas depletion time scales in galaxies?
- How is star formation in individual star forming regions related to star formation on global galactic scales?
- What sets the slope of the molecular Kennicutt-Schmidt relation?

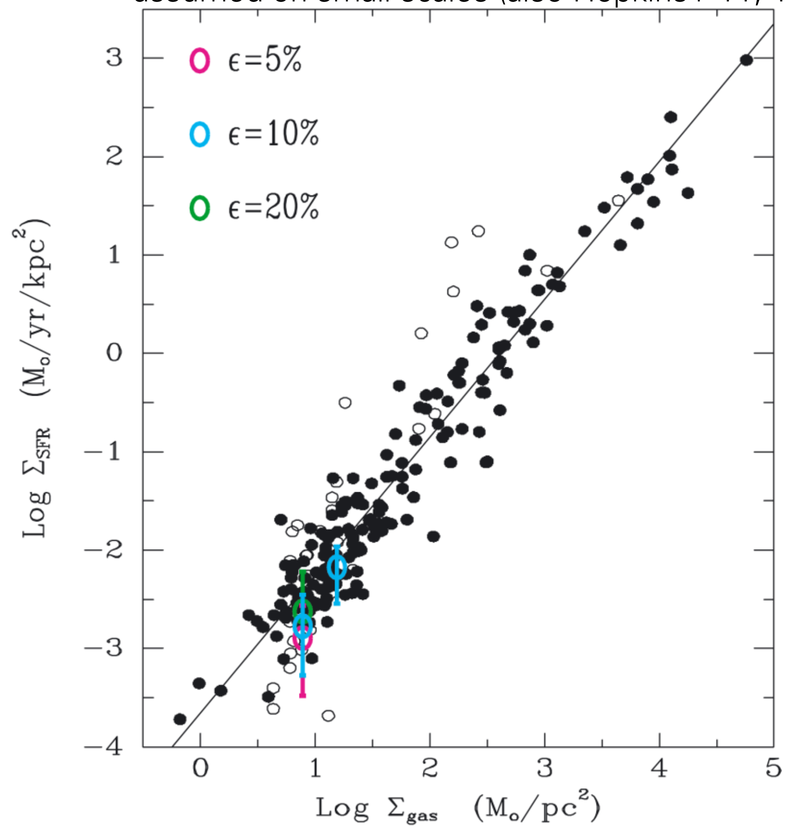
Numerical simulations of galaxies generally can reproduce the observed normalization and slope of KS relation

However, there was no agreement and clarity about the mechanism setting the long depletion time and how simulation assumptions about star formation on small-scales are reflected in the KS relation on ~kpc scales

Schaye & Dalla Vecchia 2008 (also Gnedin 2014) argued that slope of the KS relation simply reflects the slope of star formation "law" in star forming regions



Dobbs, Burkert & Pringle 2011, intriguingly, found that normalization of KS relation is insensitive to star formation efficiency ε assumed on small scales (also Hopkins+ 11, 13)



to understand what's going on
we used a suite of controlled galaxy simulations

- Simulations of an ~L_* *sized isolated disk galaxy* (non-cosmological) with a small bulge embedded in 10^{12} Msun NFW halo (AGORA initial conditions)
  $M_{\rm disk} \sim 4.3\times10^{10}\, M_{\rm sun},\ R_{\rm disk} = 3.5$ kpc, $f_{\rm gas} = 0.2$; $\Delta = 40$ pc
  (also checked $\Delta = 20$, 10 pc)

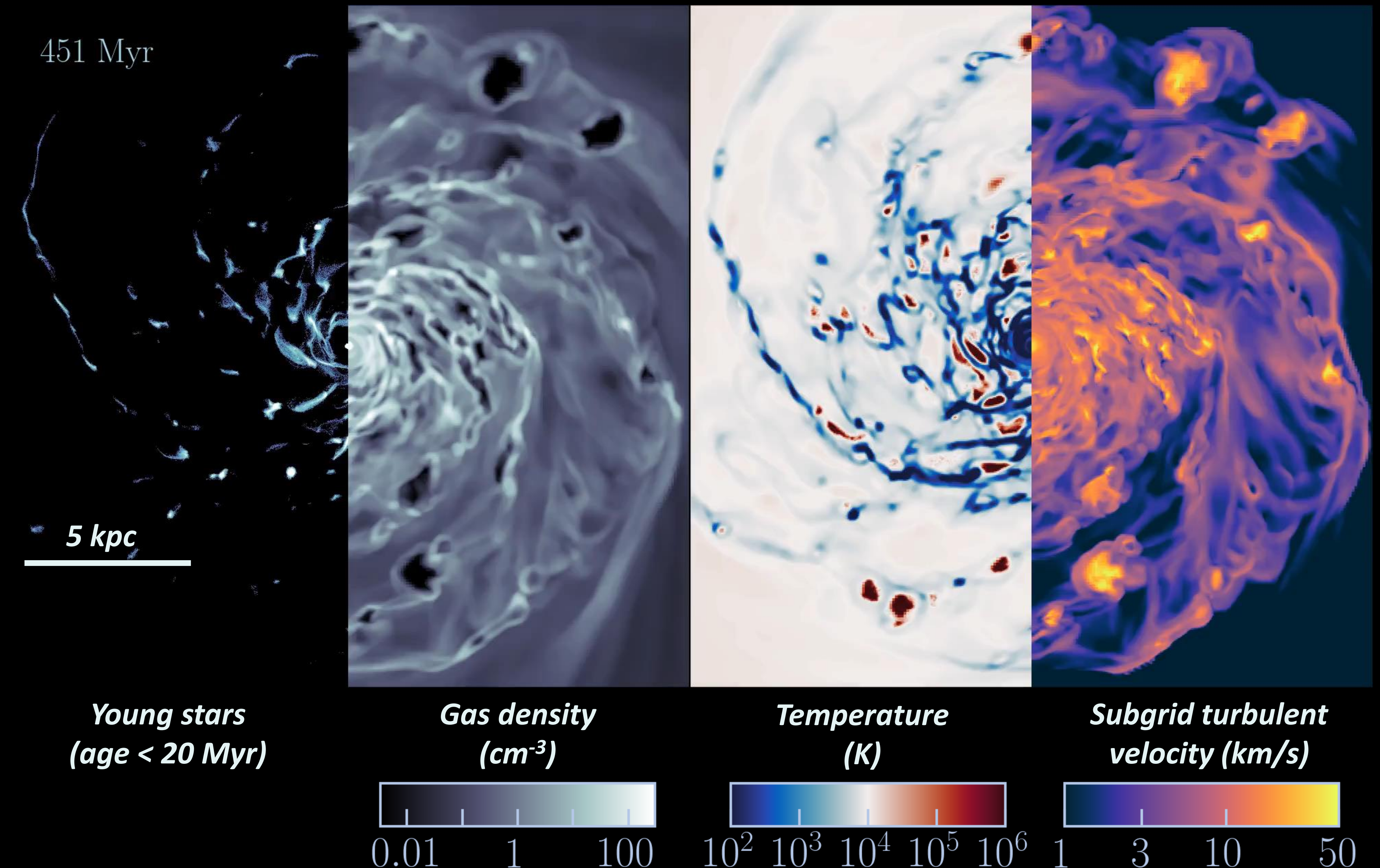
- N-body+hydrodynamics of gas, stellar particles, and dark matter with *Adaptive Mesh Refinement ART code* (Kravtsov+ '2002)

- Z-dependent heating + cooling and self-shielding calibrated on RT simulations. Efficient SN energy+momentum feedback calibrated on SN remnant simulations and accounting for boost of momentum due to multiple SNe and cosmic rays. Vary feedback strength with the multiplicative boost factor b relative to fiducial.

- *+ shear-improved subgrid turbulence model* (Schmidt+ '14; Semenov+ '16) allows us to follow turbulent velocity dispersion on a subrid level and compute local effective temperature and "virial parameter"

$$\sigma_{\rm tot} = \sqrt{c_s^2 + \sigma_{\rm turb}^2} \qquad\qquad \alpha_{\rm vir} = \frac{5}{3}\frac{\sigma_{\rm tot}^2 R}{GM}$$

Semenov, Kravtsov & Gnedin 2016, ApJ 826, 200


451 Myr
5 kpc
Young stars
(age < 20 Myr)
Gas density
(cm-3)
0.01
1
100
Temperature
(K)
10^2
10^3
10^4
10^5
10^6
Subgrid turbulent
velocity (km/s)
1
3
10
50

prescription for star formation in eligible computational cells (i.e. on ~10-40 pc scale)

- Stars form in cells in which virial parameter is smaller than a threshold value $\alpha_{vir} < \alpha_{vir,sf} = 10$, as indicated by simulations of star formation in molecular clouds

$$\alpha_{\rm vir} \equiv \frac{5\sigma_{\rm tot}^2 R}{3GM} \approx 9.4\,\frac{(\sigma_{\rm tot}/10\,{\rm km s^{-1}})^2}{(n/100\,{\rm cm^{-3}})(R/40\,{\rm pc})^2} \qquad \sigma_{\rm tot} = \sqrt{c_s^2 + \sigma_{\rm turb}^2}$$

- use standard Poisson method for spawning stellar particles with the average rate of:

$$\dot{\rho}_\star = \varepsilon_{\rm ff}\,\frac{\rho_0}{t_{\rm ff,0}}\left(\frac{\rho}{\rho_0}\right)^\beta \propto \rho^\beta$$

with a *constant* ε_{ff} or varying $\varepsilon_{ff}(\alpha_{vir})$

$t_{ff,0}$ is a free-fall time at ρ_0;
β is density dependence slope (β=1.5 is the most common choice in simulations)

we explored star formation, KS relation, and depletion time in a suite of simulations, in which ε_{ff}, β, feedback strength were varied within a wide range of values

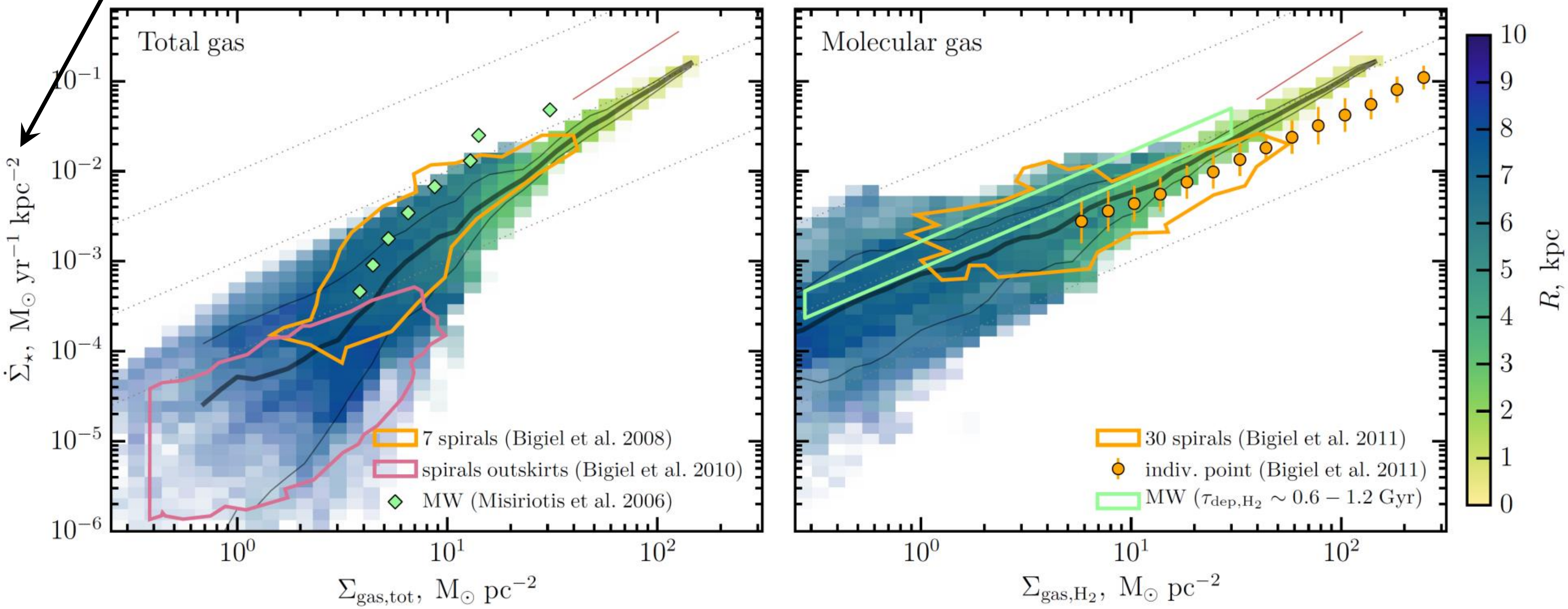
simulation with fiducial parameters (β=1.5, ε_{ff}=1%, α_{vir}<10) reproduces observed Kennicutt-Schmidt relation

and thus the observed long depletion times of both total and molecular gas
(we can use simulations to understand why depletion time is long!)

note that KS relation for molecular gas is linear, even though local star formation rate depends on density nonlinearly

star formation rate per area in Msun/yr/kpc^2

Semenov, Kravtsov & Gnedin 2017

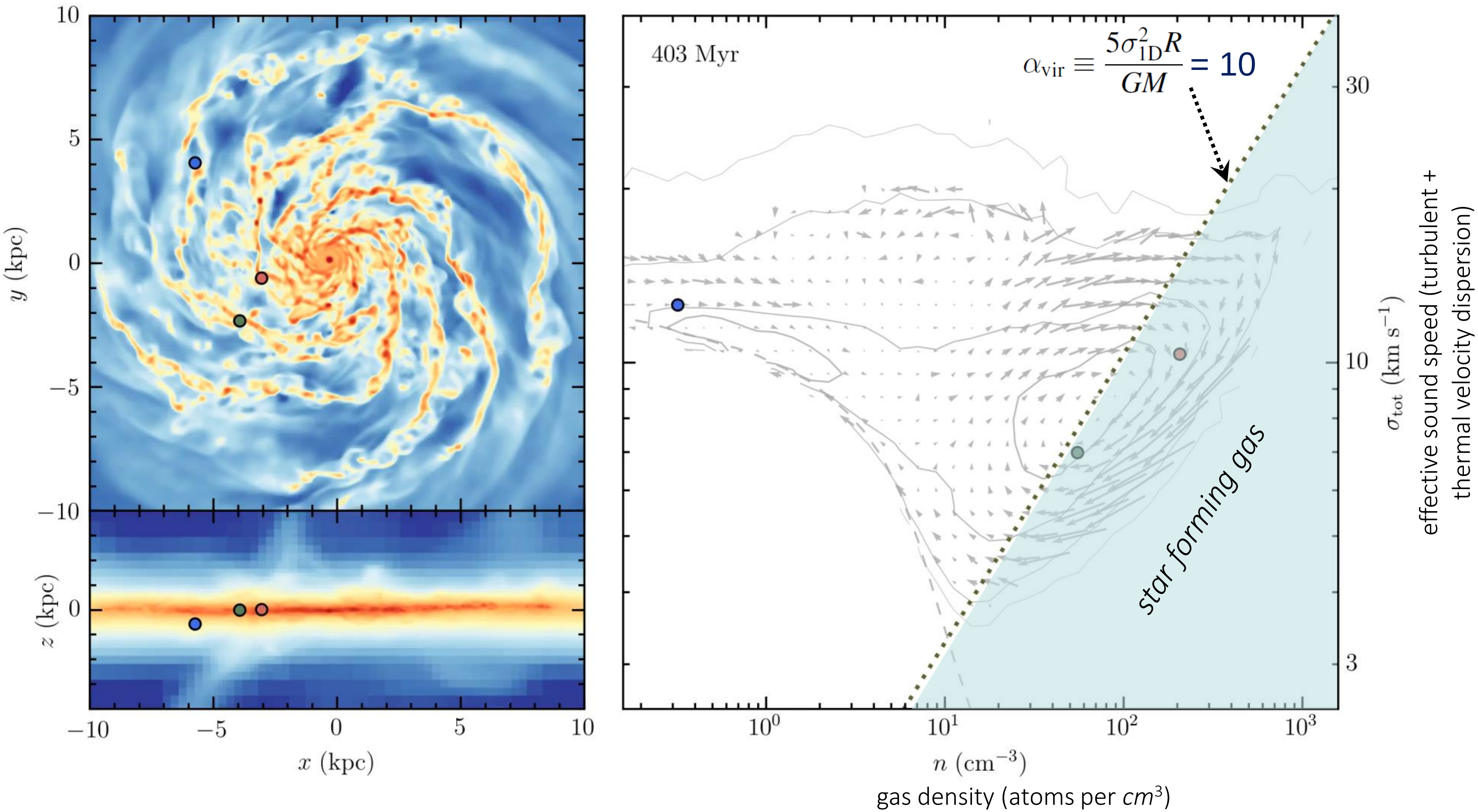


surface density of HI+H_2 in Msun/pc^2

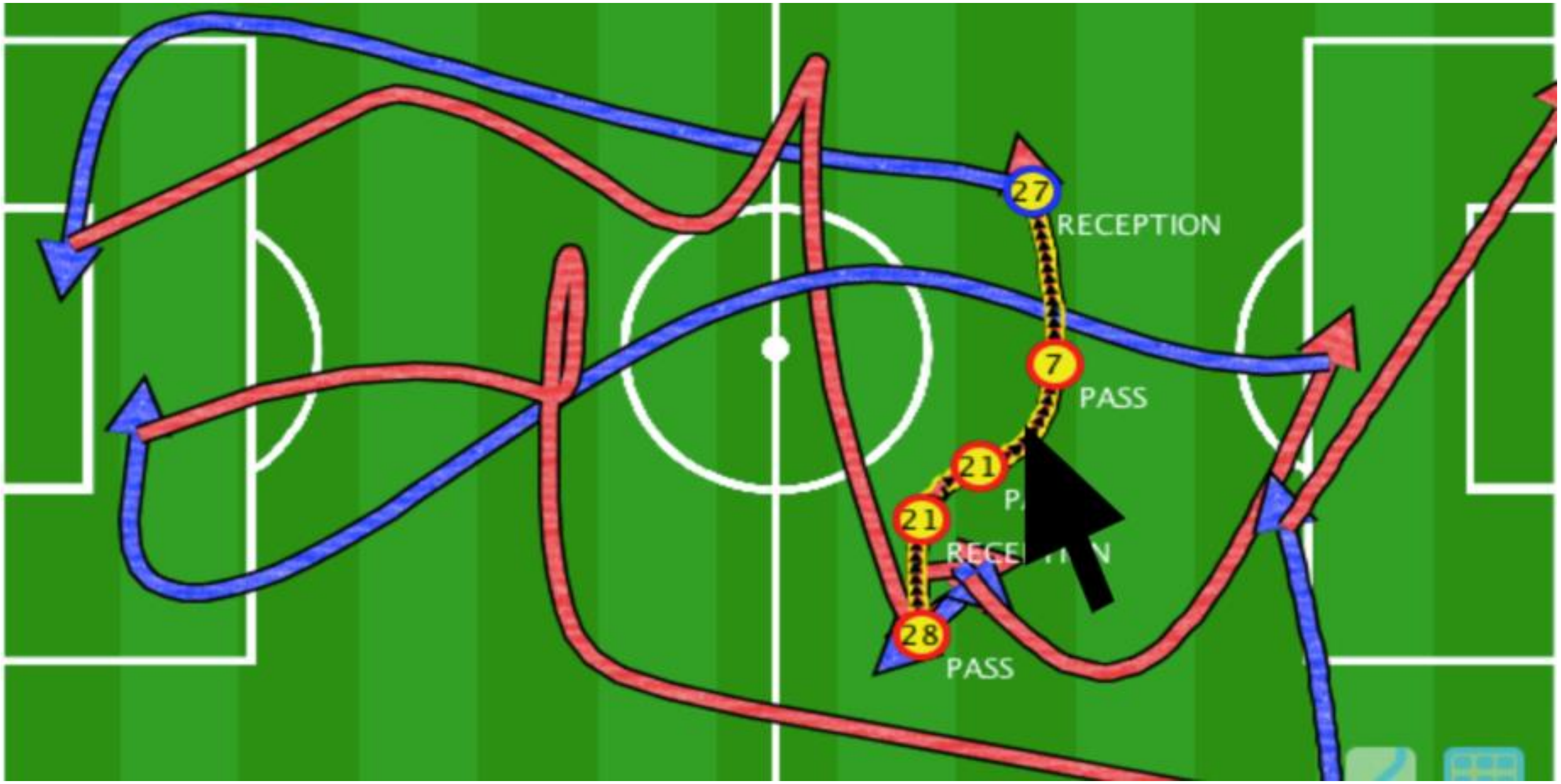
surface density of H_2 in Msun/pc^2

evolution of three representative ISM gas tracers

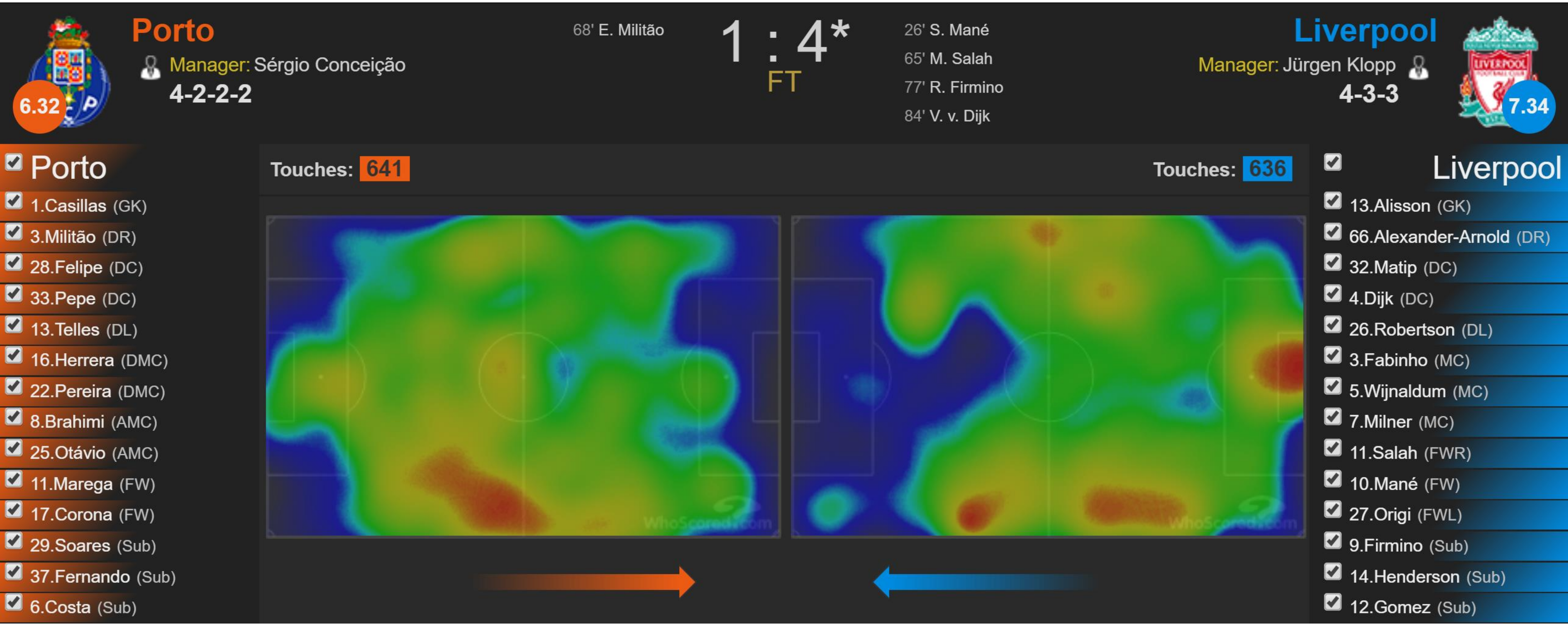
- tracers cycle between non-star forming and star forming regions on ~10-50 Myr time scales
- stellar feedback disrupts star forming regions and limits time in star forming stage
- tracers spend a significant fraction of time in non-star forming, diffuse gas



an analogy…



trajectories of individual tracers can be converted into density distribution of tracers over some Δt...



Strong feedback = good defense -> little time in the penalty area for the opposite team, which thus needs many attacks and a long time in order to score

evolution of gas tracers elucidates the physics of depletion time

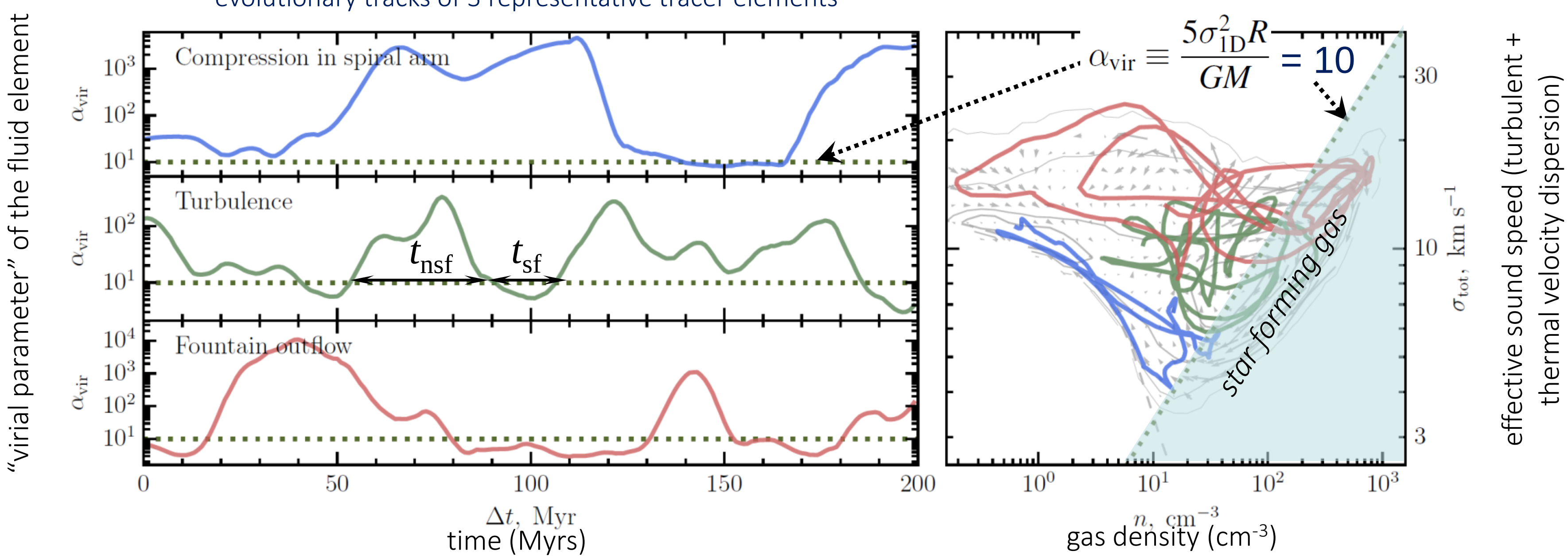
Depletion time is $$\tau_{\rm dep} \equiv \frac{M_{\rm g}}{\dot{M}_\star} \equiv \frac{M_{\rm sf}}{f_{\rm sf}}\frac{1}{\dot{M}_\star} \equiv \frac{\tau_{\rm dep,sf}}{f_{\rm sf}}$$ where $M_{\rm sf}$ is mass of gas in star forming regions

Statistically, mass fraction of gas in star forming regions is $$f_{\rm sf} = \frac{M_{\rm sf}}{M_{\rm g}} \sim \frac{t_{\rm sf}}{t_{\rm sf}+t_{\rm nsf}} = \frac{1}{1+t_{\rm nsf}/t_{\rm sf}}$$

combining the two: $$\tau_{\rm dep} \sim \tau_{\rm dep,sf}\left(1+\frac{t_{\rm nsf}}{t_{\rm sf}}\right) = \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}}\,t_{\rm nsf}$$

depletion time = depletion time of gas in star forming regions
+ time spent in non-star forming state over $N_{\rm dep}$ cycles $\left(N_{\rm dep} = \frac{\tau_{\rm dep,sf}}{t_{\rm sf}}\right)$

evolutionary tracks of 3 representative tracer elements



- What is the physical origin of long gas depletion time scales in galaxies?

- How is star formation in individual star forming regions related to star formation on global galactic scales?

Depletion time in galaxies is long because only a small fraction of star-forming gas is converted into stars before star-forming regions are dispersed by feedback and dynamical processes.

Thus, gas cycles into and out of star-forming state multiple times, which results in a long time scale on which galaxies convert gas into stars.

$$\tau_{\rm dep} = \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}}\, t_{\rm nsf}$$

When feedback is efficient, t_{sf} is short and this framework explains the long-standing puzzles of why $\tau_{\rm dep} \gg \tau_{\rm dep,sf}$ and why $\tau_{\rm dep} \gg t_{\rm nsf}$

Semenov, Kravtsov & Gnedin 2017, ApJ 845, 133
2018, ApJ 861, 4

LETTER

Krujssen et al. 2019, Nature Letters

Fast and inefficient star formation due to short-lived molecular clouds and rapid feedback

J. M. Diederik Kruijssen[1,2], Andreas Schruba[3], Mélanie Chevance[1], Steven N. Longmore[4], Alexander P. S. Hygate[2,1], Daniel T. Haydon[1], Anna F. McLeod[5,6], Julianne J. Dalcanton[7], Linda J. Tacconi[3] & Ewine F. van Dishoeck[8,3]

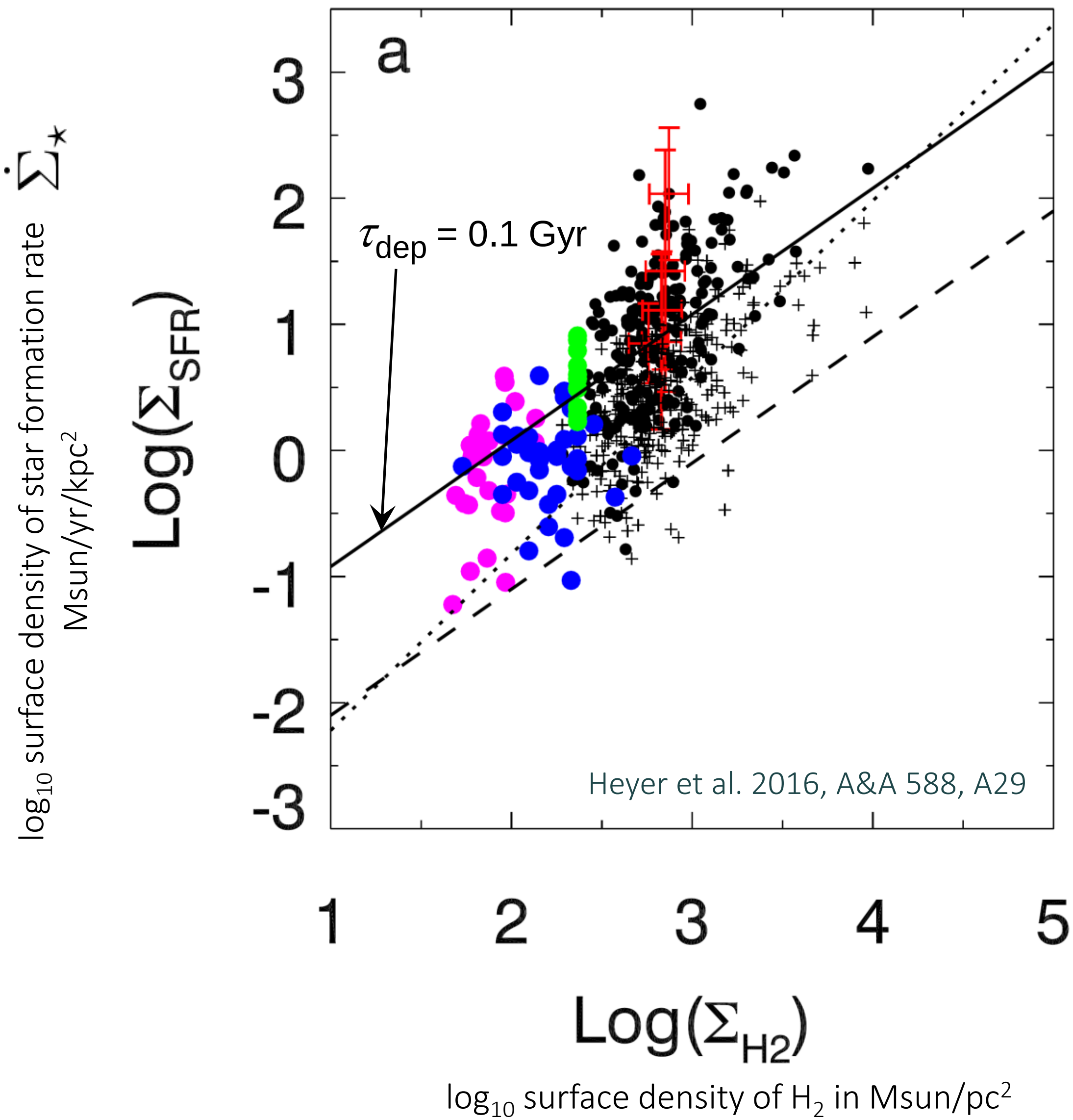
The physics of star formation and the deposition of mass, momentum, and energy into the interstellar medium by massive stars ('feedback') are the main uncertainties in modern cosmological simulations of galaxy formation and evolution[1,2]. These processes determine the properties of galaxies[3,4], but are poorly understood on the $\lesssim$100 pc scale of individual giant molecular clouds (GMCs)[5,6] resolved in modern galaxy formation simulations[7,8]. The key question is why the timescale for depleting molecular gas through star formation in galaxies ($t_{\rm dep} \approx 2$ Gyr)[9,10] exceeds the dynamical timescale of GMCs by two orders of magnitude[11]. Either most of a GMC's mass is converted into stars over many dynamical times[12], or only a small fraction turns into stars before the GMC is dispersed on a dynamical timescale[13,14]. Here we report our observation that molecular gas and star formation are spatially de-correlated on GMC scales in the nearby flocculent spiral galaxy NGC300, contrary to their tight correlation on galactic scales[5]. We demonstrate that this de-correlation implies rapid evolutionary cycling between GMCs, star formation, and feedback. We apply a novel statistical method[15,16] to quantify the evo-

We characterise the lifecycle of GMCs and star-forming regions by applying a new statistical method[16] to maps of the molecular gas and emission from young massive stars in NGC300. This method requires observational data at high sensitivity and resolution over a large field-of-view, now available with the Atacama Large Millimeter/submillimeter Array (ALMA). NGC300 is the perfect target for the first application of this method, as it is the closest ($D = 2$ Mpc), face-on, star-forming disc galaxy accessible from the southern hemisphere. Figure 1 (left) shows the molecular gas traced by our high-resolution ($2'' = 20$ pc) ALMA map of CO(1-0). We combine this with a matched-resolution map of Hα-emitting HII regions from the MPG/ESO 2.2-m telescope to trace recent star formation. The use of Hα means that we define 'star formation' to refer to an unembedded stellar population, with a mass of at least 200 $M_\odot$ and a normal stellar initial mass function (see Methods).

We characterise the correlation between GMCs and star formation by placing apertures on peaks of CO(1-0) or Hα emission, and measuring how the enclosed CO-to-Hα flux ratios are elevated or suppressed, respectively, relative to the galactic average as the aperture size

depletion time in observed star forming regions

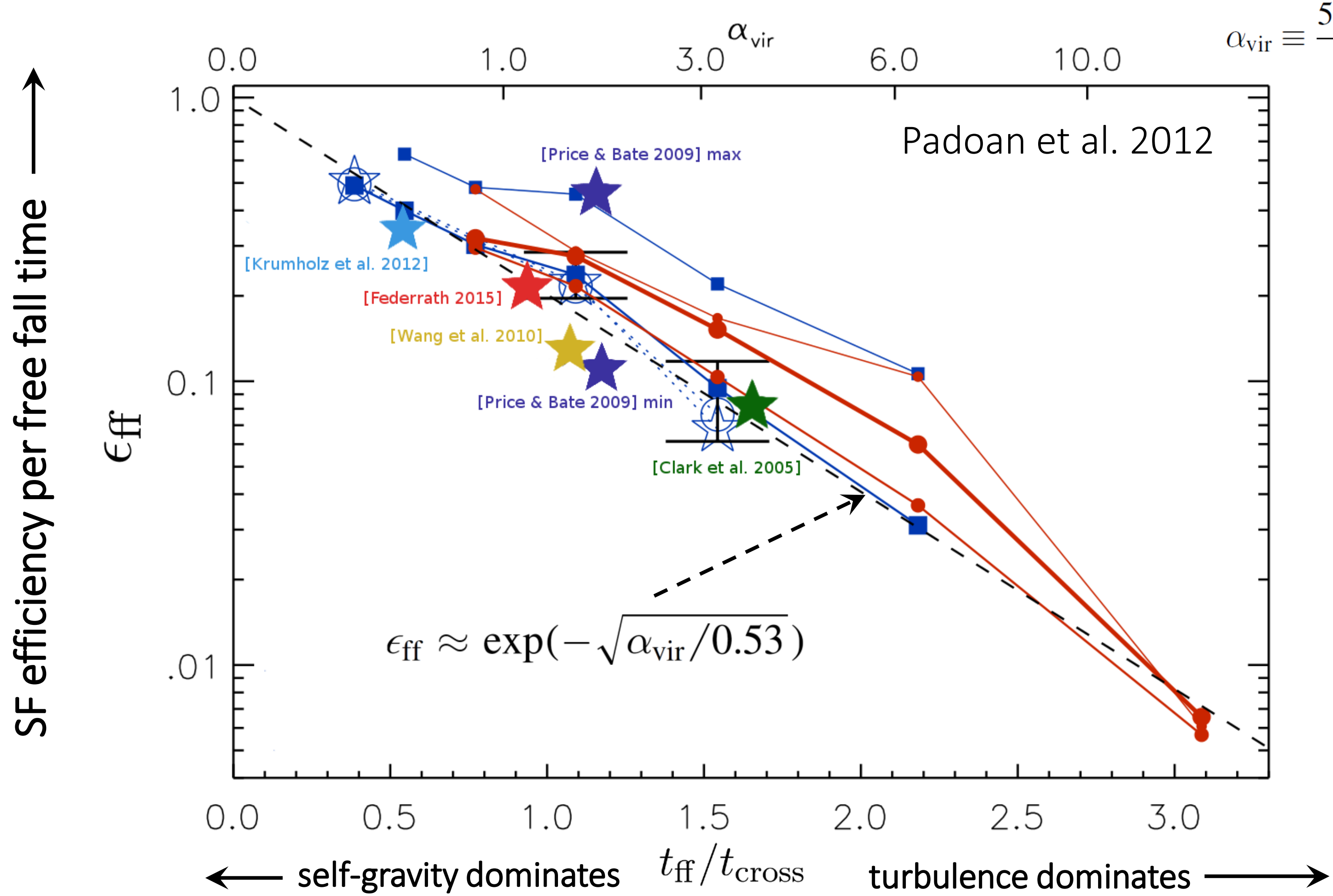
Evans+'09, 14; Heiderman+ '10; Murray '11; Lada+ '10, 12
Heyer et al '16; Lee+ '16; Vutisalchavakul et al. 2016; Miville-Deschênes et al. 2017)



Results of simulations of turbulent molecular clouds

show that virial parameter α_{vir} is the main factor controlling efficiency of star formation in star forming regions

$$\alpha_{vir} \equiv \frac{5\sigma_{1D}^2 R}{GM}$$



$$t_{ff} = \sqrt{3\pi/32G\rho}$$

$$t_{cross} = \Delta/2\sigma$$

the model also explains behavior of depletion time as a function of ε_{ff} and "self-regulation" in numerical simulations

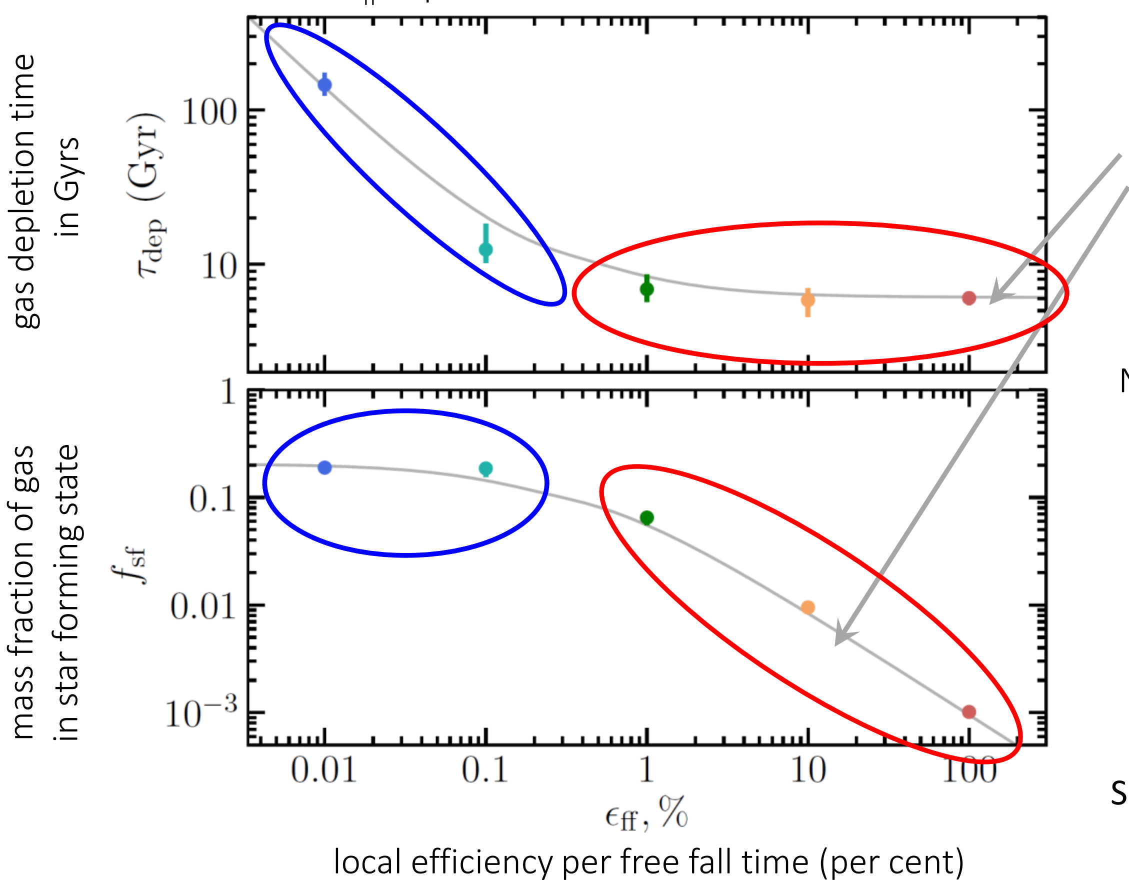
i.e. weak sensitivity of depletion time to local star formation efficiency ε_{ff}
(Dobbs, Burkert & Pringle '11; Agertz & Kravtsov '14; Benincasa+ '15; Hopkins+ '17; Orr+ '17)

$$\tau_{\rm dep} = \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}} t_{\rm nsf}$$

$$\tau_{\rm dep,sf} \sim \frac{t_{\rm ff}}{\epsilon_{\rm ff}} \propto \epsilon_{\rm ff}^{-1};$$

when feedback is efficient: $t_{\rm sf} \propto \epsilon_{\rm ff}^{-1}$

so ε_{ff} dependence in the 2nd term cancels out



Note the opposite behavior for the star forming gas mass fraction

$$f_{\rm sf} = \frac{1}{1 + t_{\rm nsf}/t_{\rm sf}}$$

Semenov, Kravtsov, Gnedin 2018, ApJ 861, 4