What FIREs Up Star Formation? The Emergence of Kennicutt-Schmidt from Feedback

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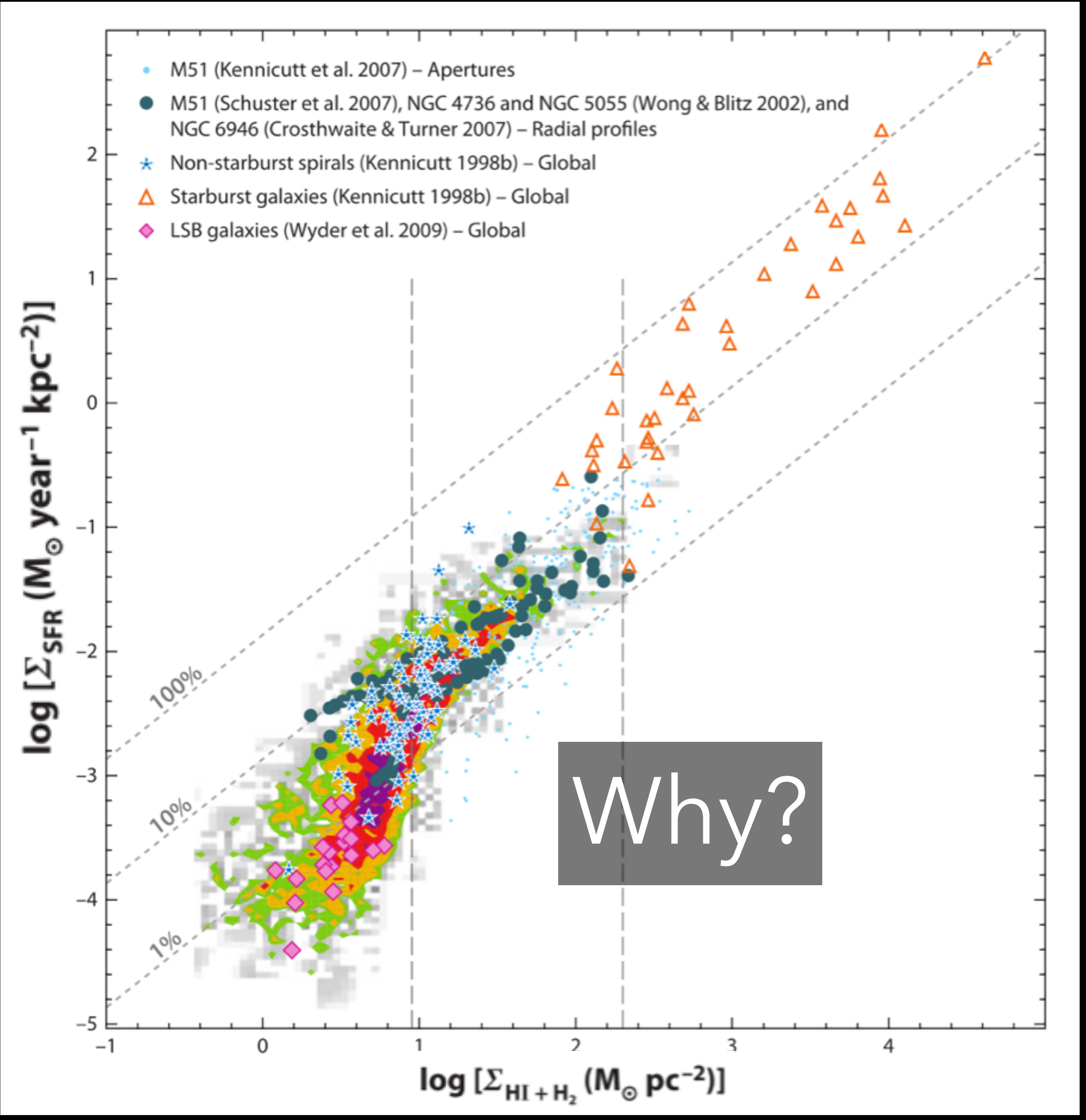
(arXiv:1701.01788)

Why the scatter and slope of the KS law?

Linear to quadratic slope & ~1-2 dex scatter, dependent on Σ_{gas}



Bigiel et al. 2008

Kennicutt & Evans 2012

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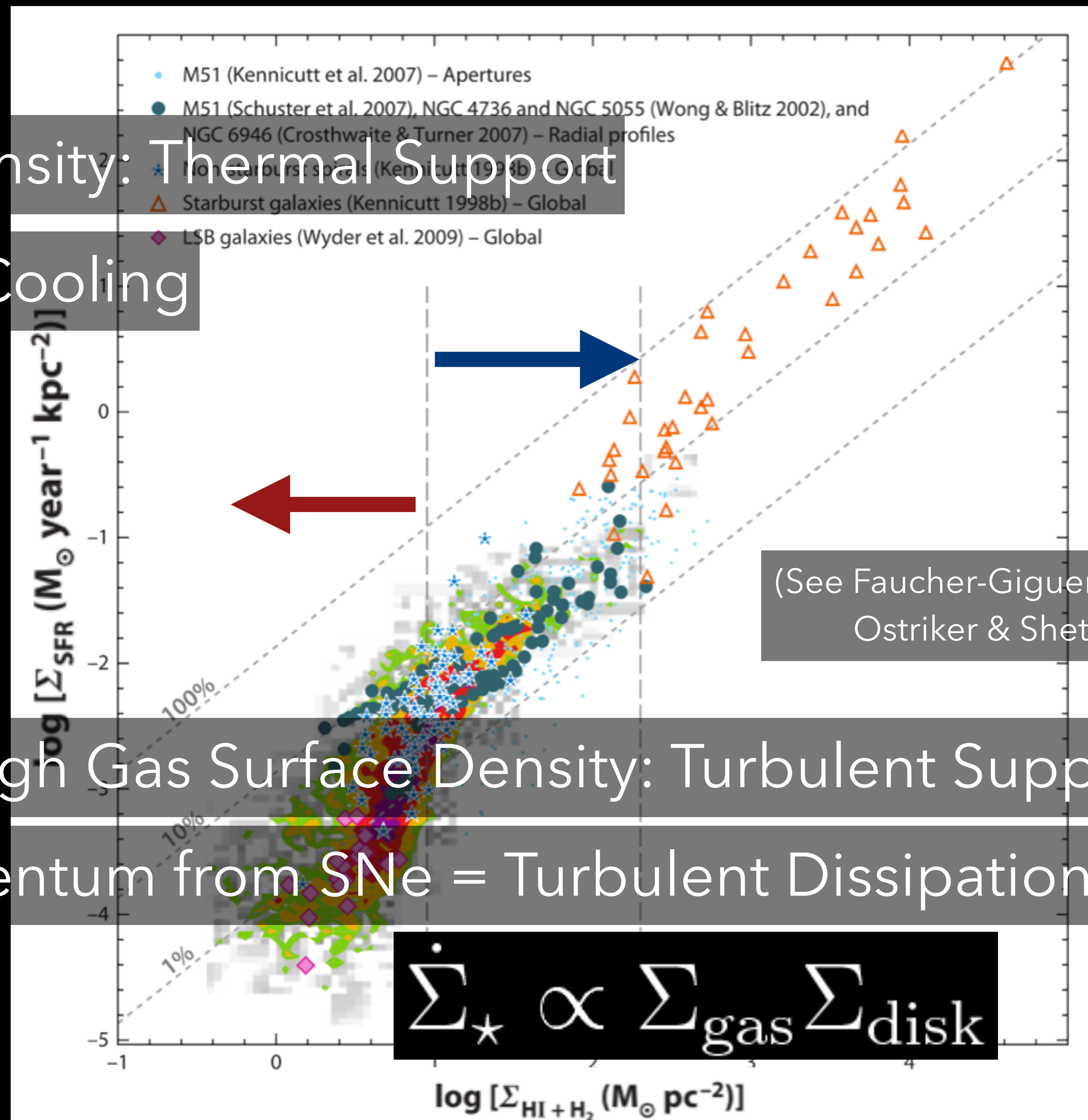
What do we expect from feedback in equilibrium?

Low Gas Surface Density: Thermal Support

Heating = Cooling

$$\dot{\Sigma}_\star \propto Z\Omega\Sigma_{\rm gas}^2/f_{\rm abs}$$

(See Hayward & Hopkins 2015, Ostriker et al. 2010)



(See Faucher-Giguere et al. 2013, Ostriker & Shetty 2011)

High Gas Surface Density: Turbulent Support

Momentum from SNe = Turbulent Dissipation in ISM

$$\dot{\Sigma}_\star \propto \Sigma_{\rm gas}\Sigma_{\rm disk}$$

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Where we come in: Simulations
FIRE: Feedback In Realistic Environments

GIZMO/Gadget 2 SPH Code
Includes all the feedback we need!

Cosmological, 10^9-10^{12} $M_\odot$ halos

Mass resolution ~10^2-10^4 $M_\odot$

Multiphase ISM –>
Consequential Feedback Physics

Collaboration Site: http://fire.northwestern.edu/

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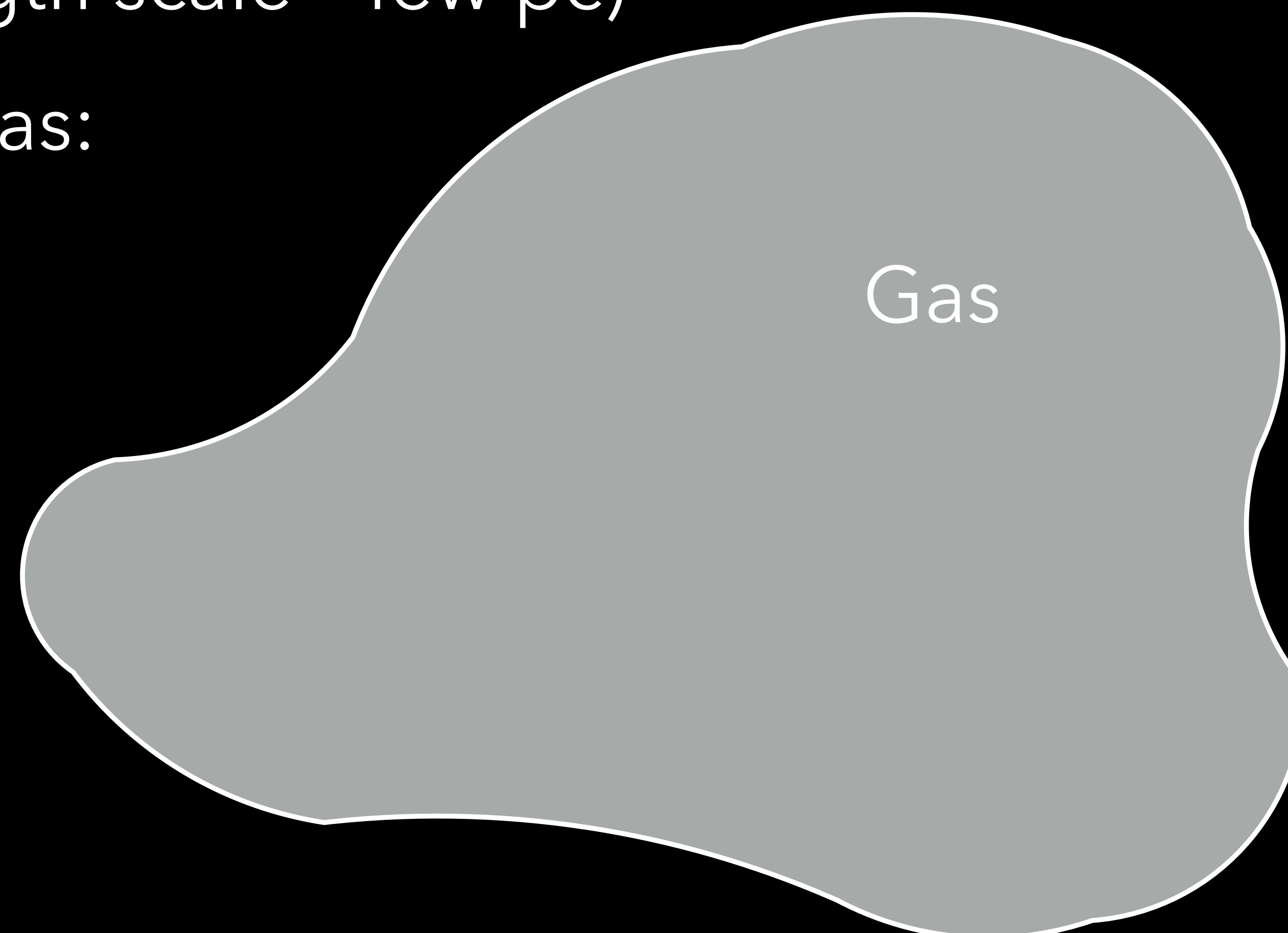
Star Formation on FIRE

(At the smoothing length scale ~few pc)

Rules for star formation in gas:



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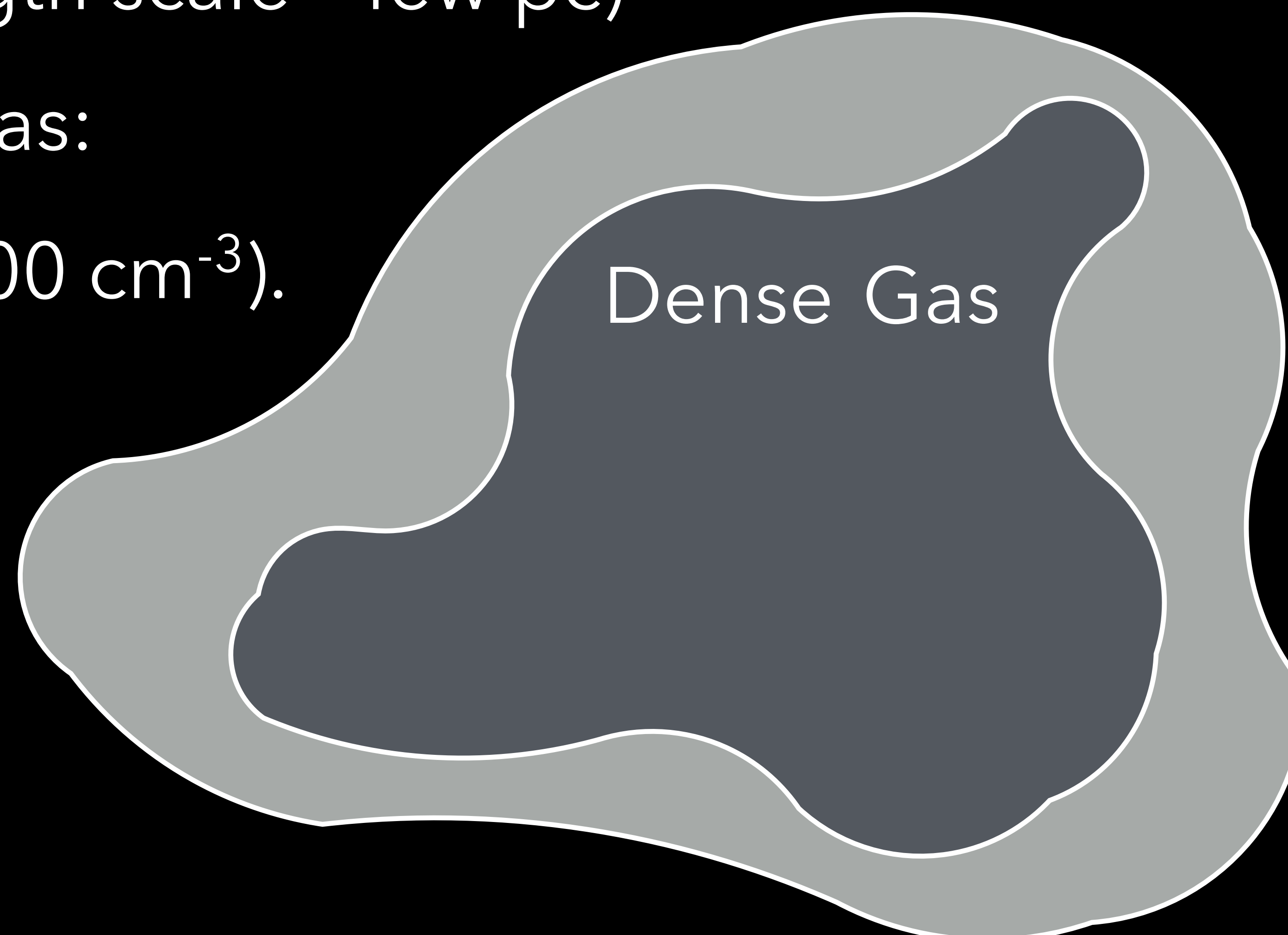

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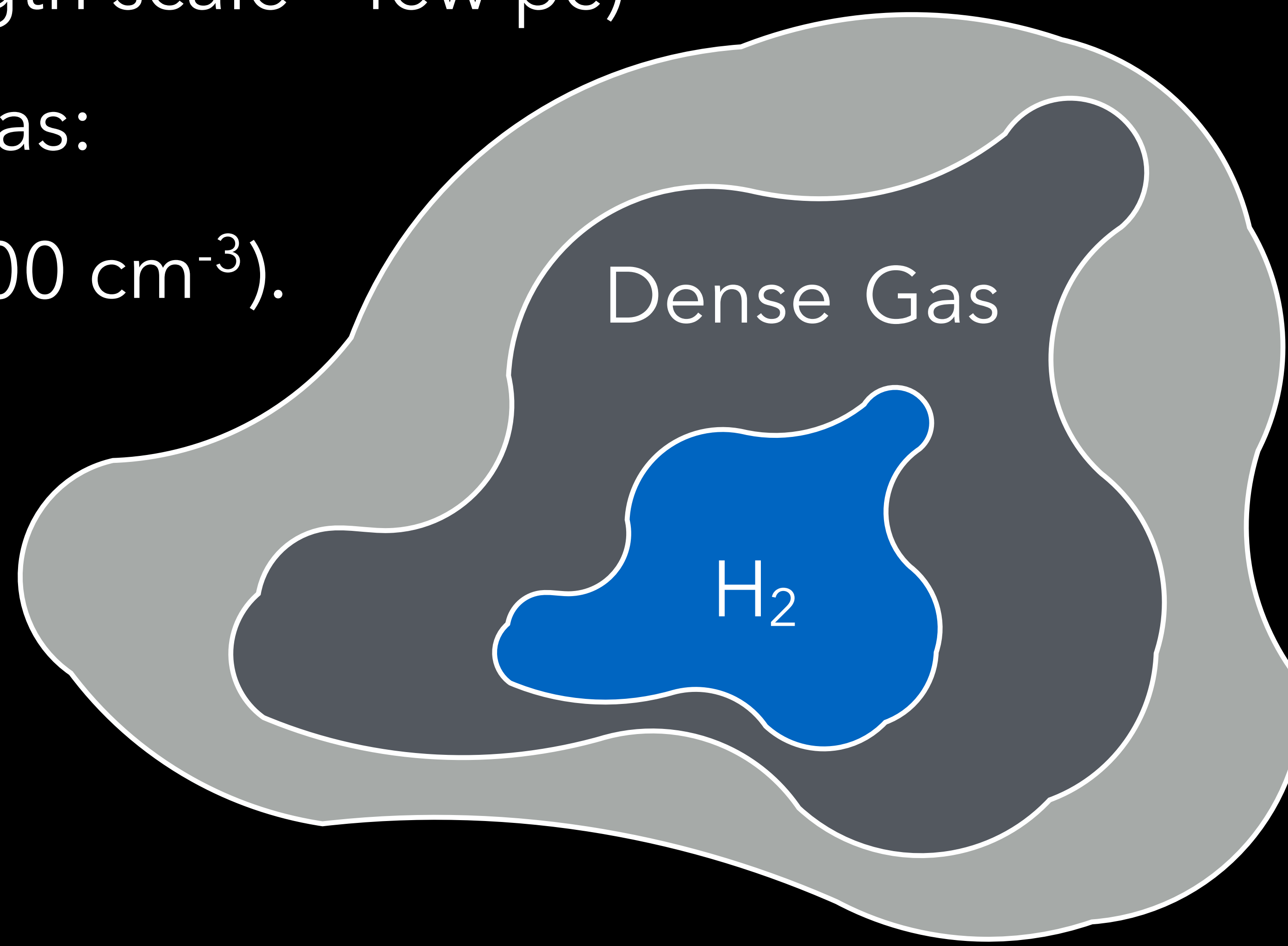
Predominantly molecular in nature, i.e. $f_{H_2} > 1/2$.



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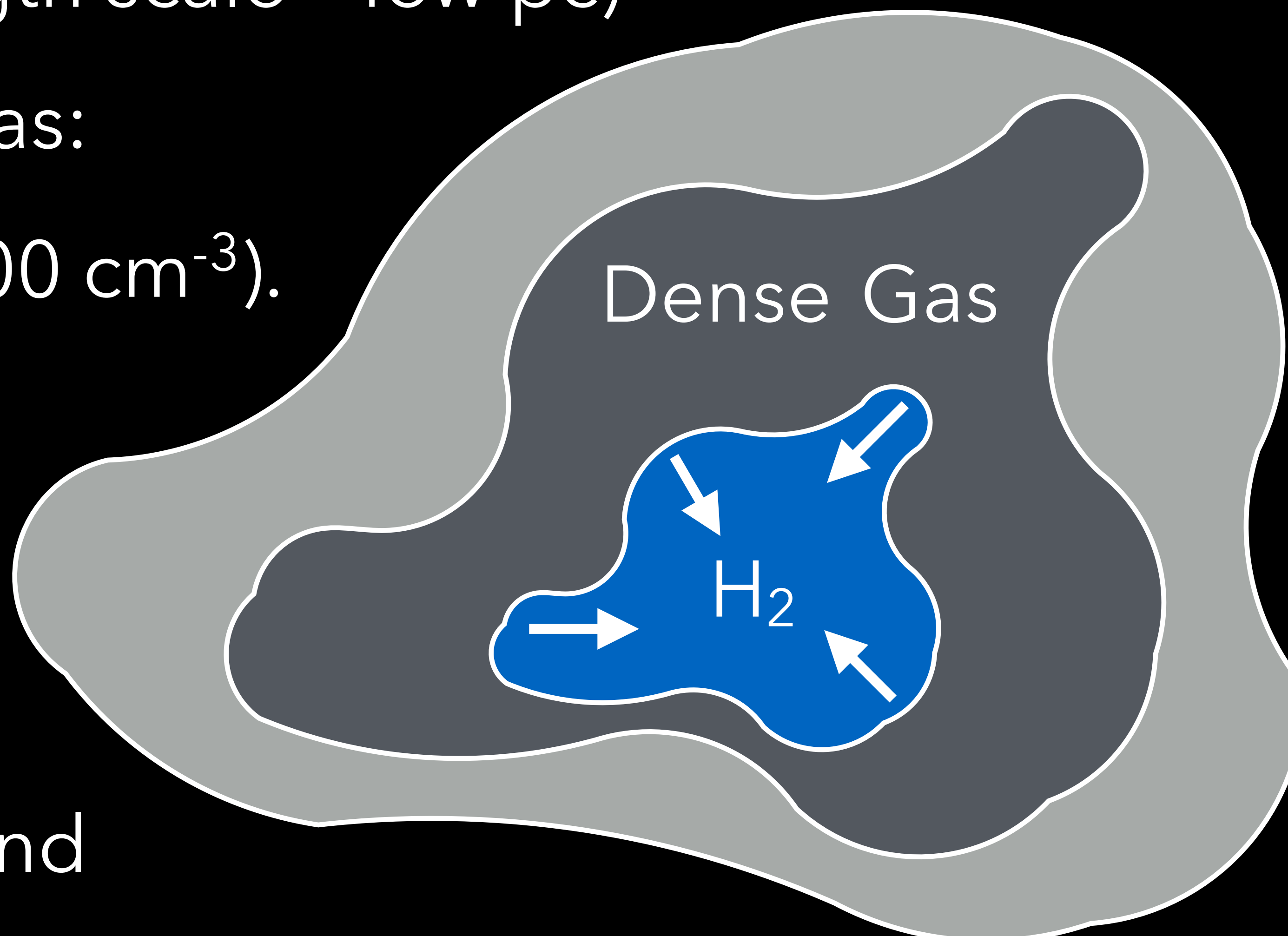
Is locally gravitationally bound



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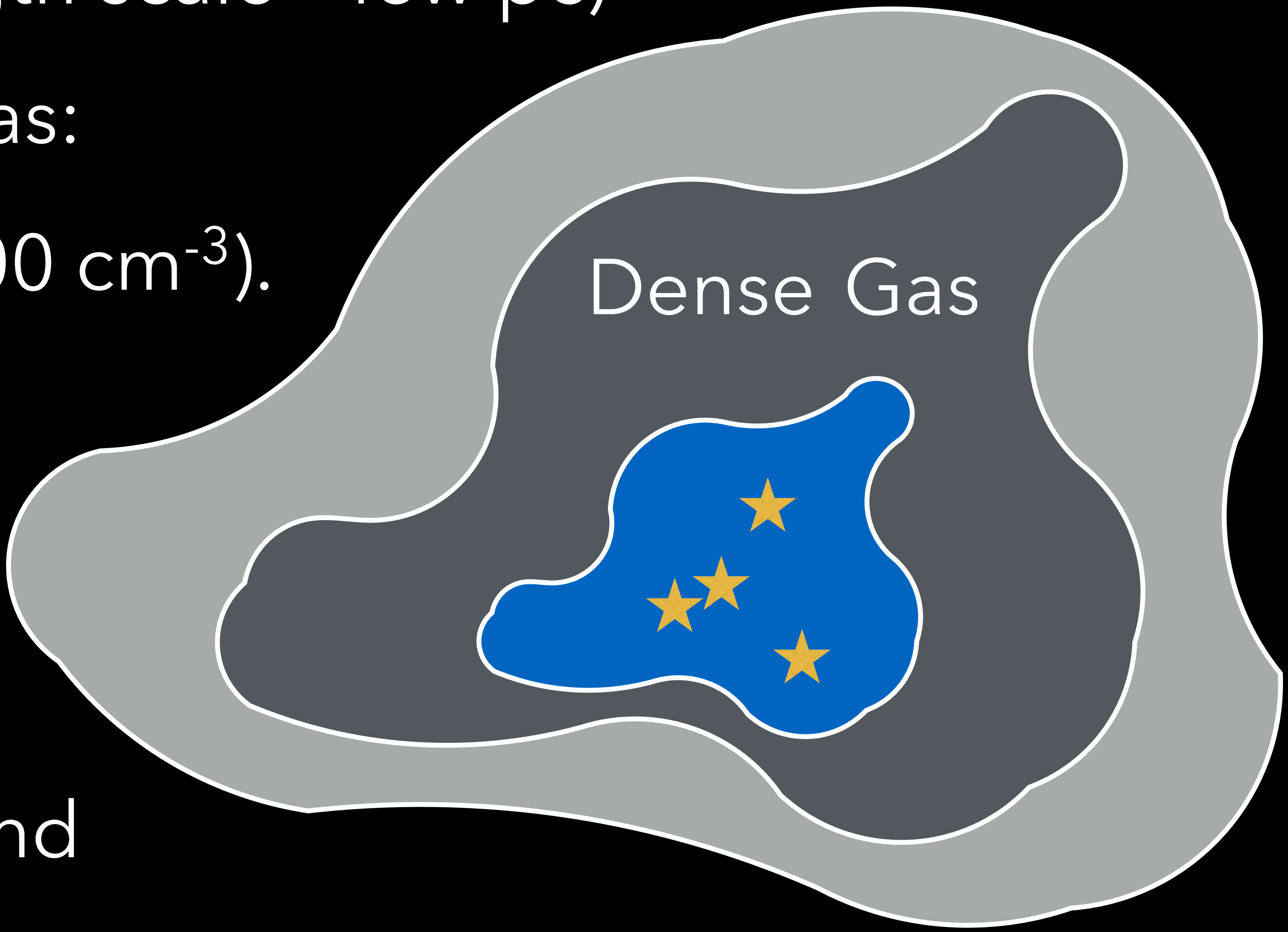

Then: $$\dot{\rho}_\star = \epsilon_{\rm sf}\rho_{\rm mol}/t_{\rm ff}$$

where: $\epsilon_{\rm sf} = 1$

locally 100% efficient star formation

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(At the smoothing length scale ~few pc)

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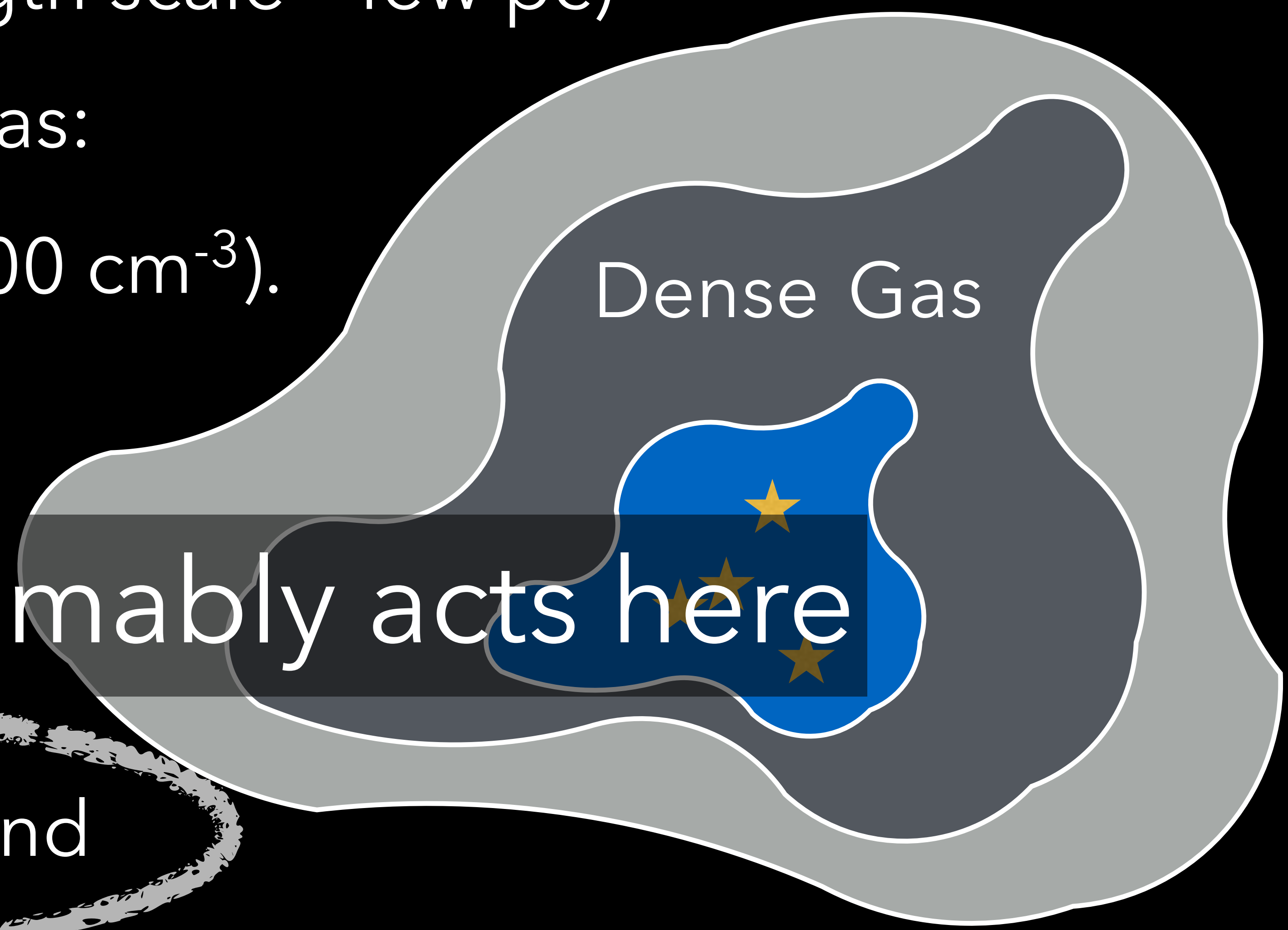
Feedback presumably acts here

Is locally gravitationally bound



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Back to KS: Galaxy Maps

Face-on projection

Halos from:
Hopkins et al. 2014,
Chan et al. 2015,
Feldmann et al. 2016

(Not FIRE.. NCG 1232)

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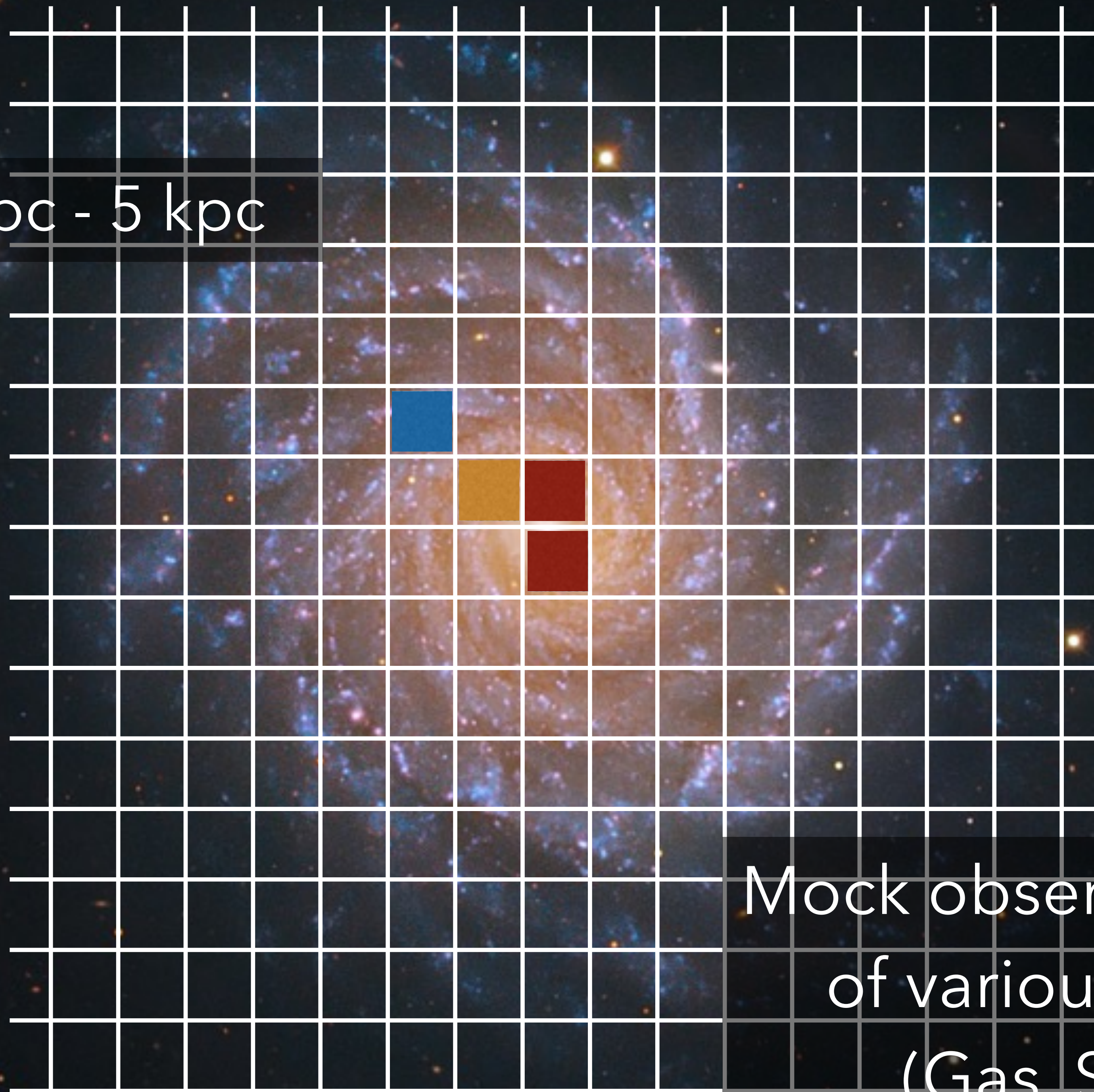
Back to KS: Galaxy Maps

Pixel sizes 100 pc - 5 kpc



Mock observational maps of various quantities (Gas, SFR, Ω_{dyn})

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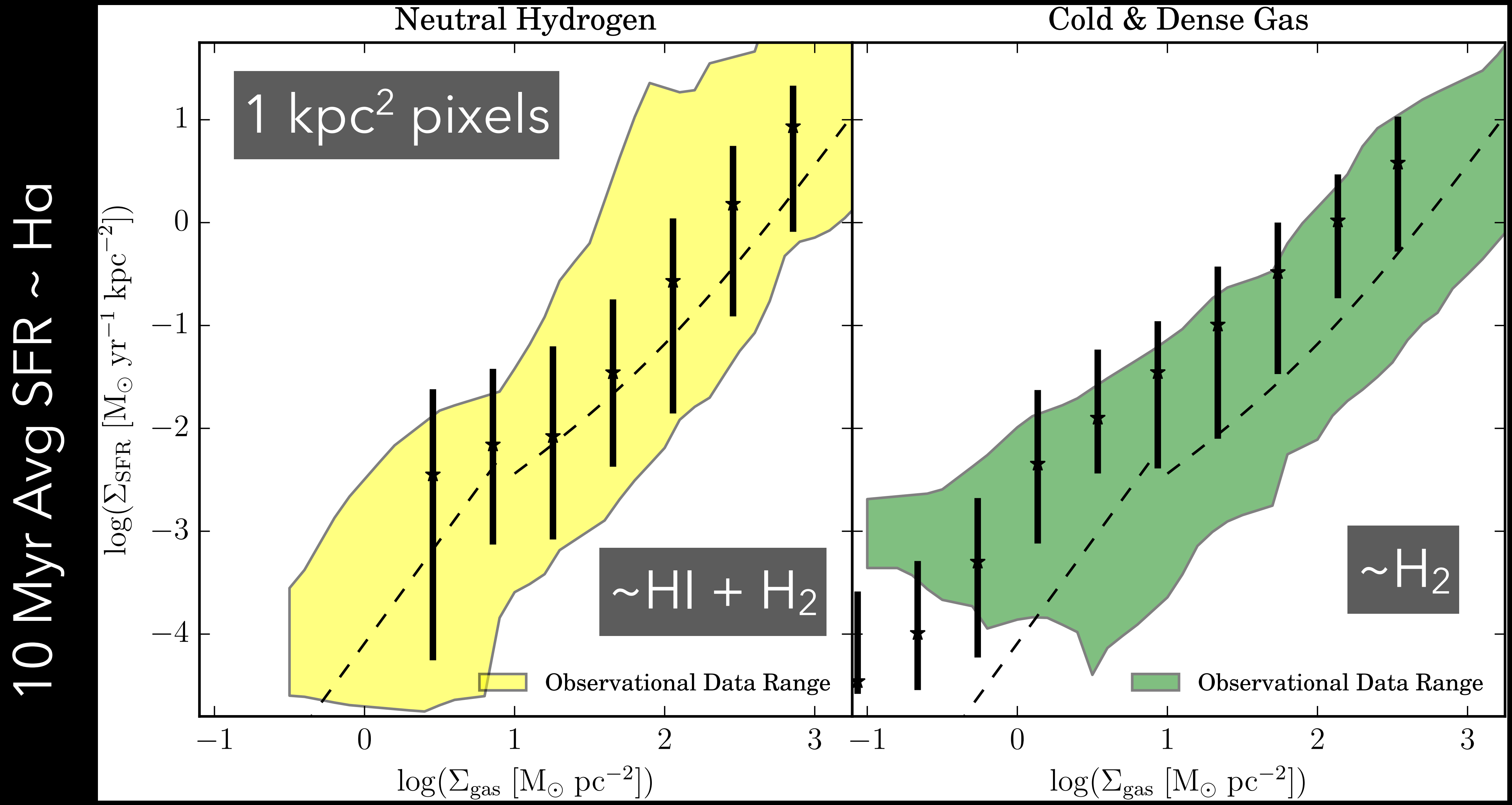
Kennicutt-Schmidt is there!



Cold & Dense ~ <300 K, >10/cc

Likely an underestimate by ~1/2 dex

Observations from Kennicutt (1998), Kennicutt, Jr. et al. (2007), Bigiel et al. (2008), Bothwell et al. (2010), Boquien et al. (2011), Daddi et al. (2010), Verley et al. (2010), and Lisenfeld et al. (2011), Genzel et al. (2010), Onodera et al. (2010), and Shi et al. (2011).

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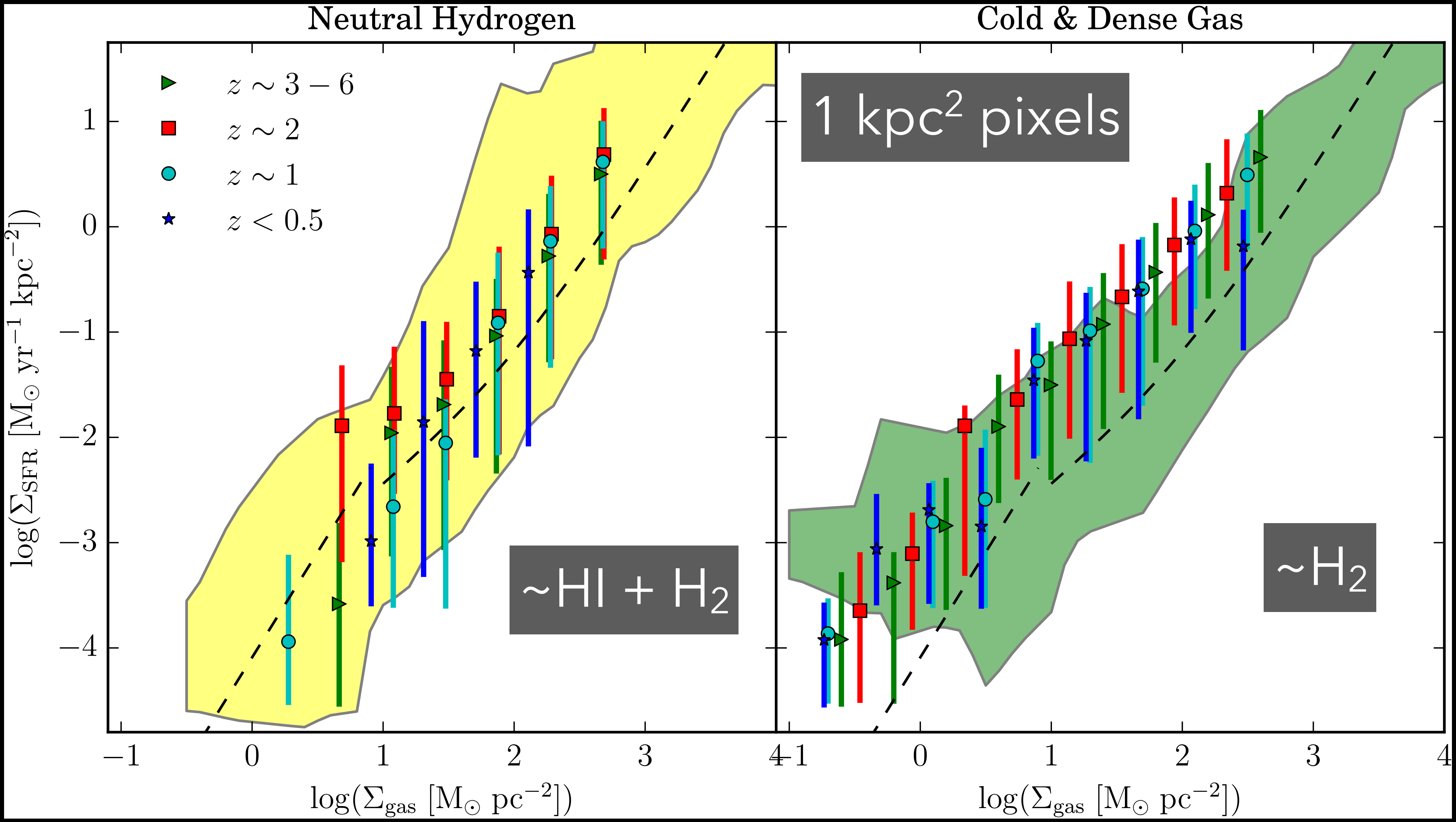
No apparent redshift dependence

10 Myr Avg SFR ~ Hα



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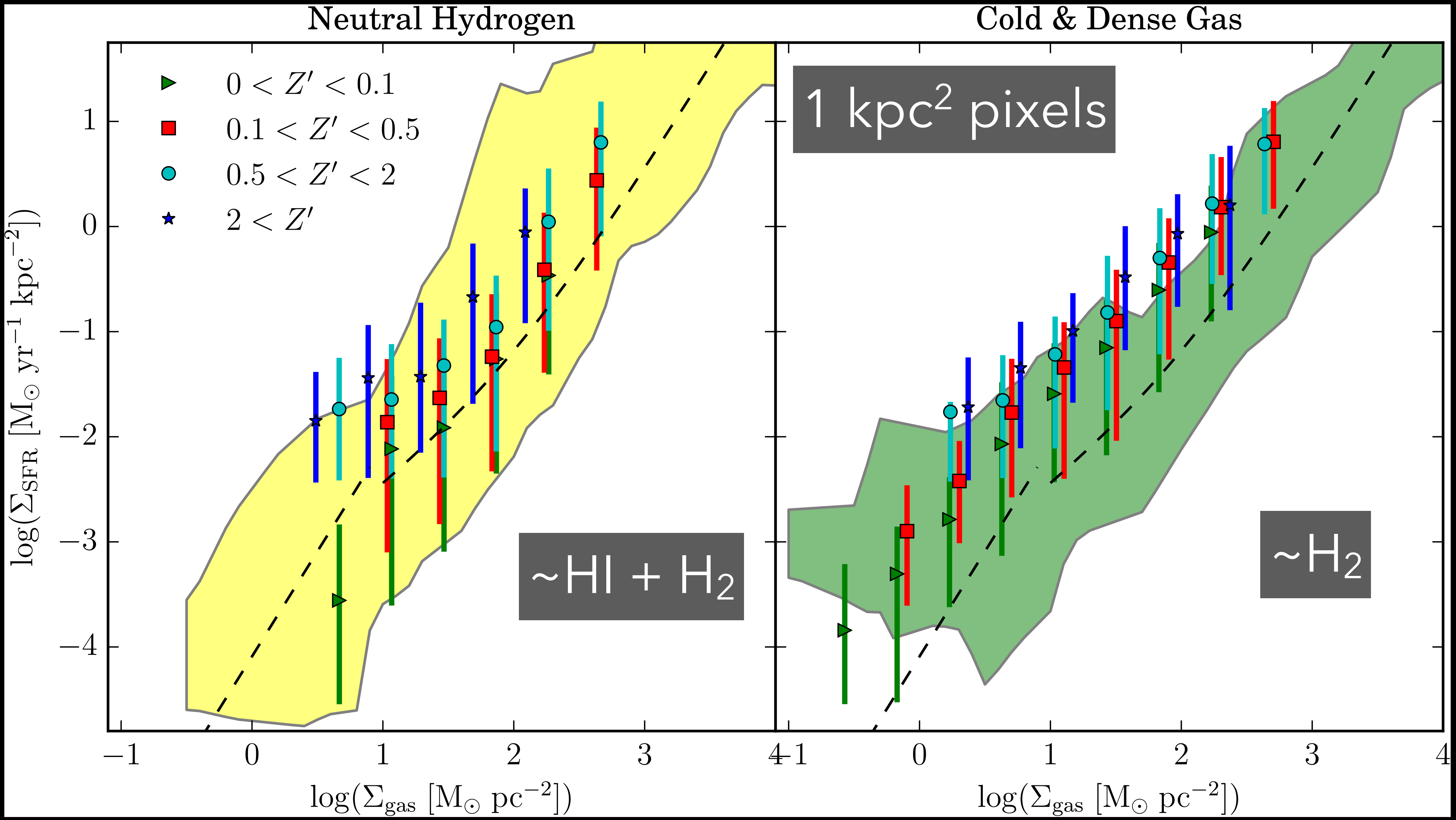
There is a weak metallicity dependence

10 Myr Avg SFR ~ Hα



Large overlap, but systematic average dependence

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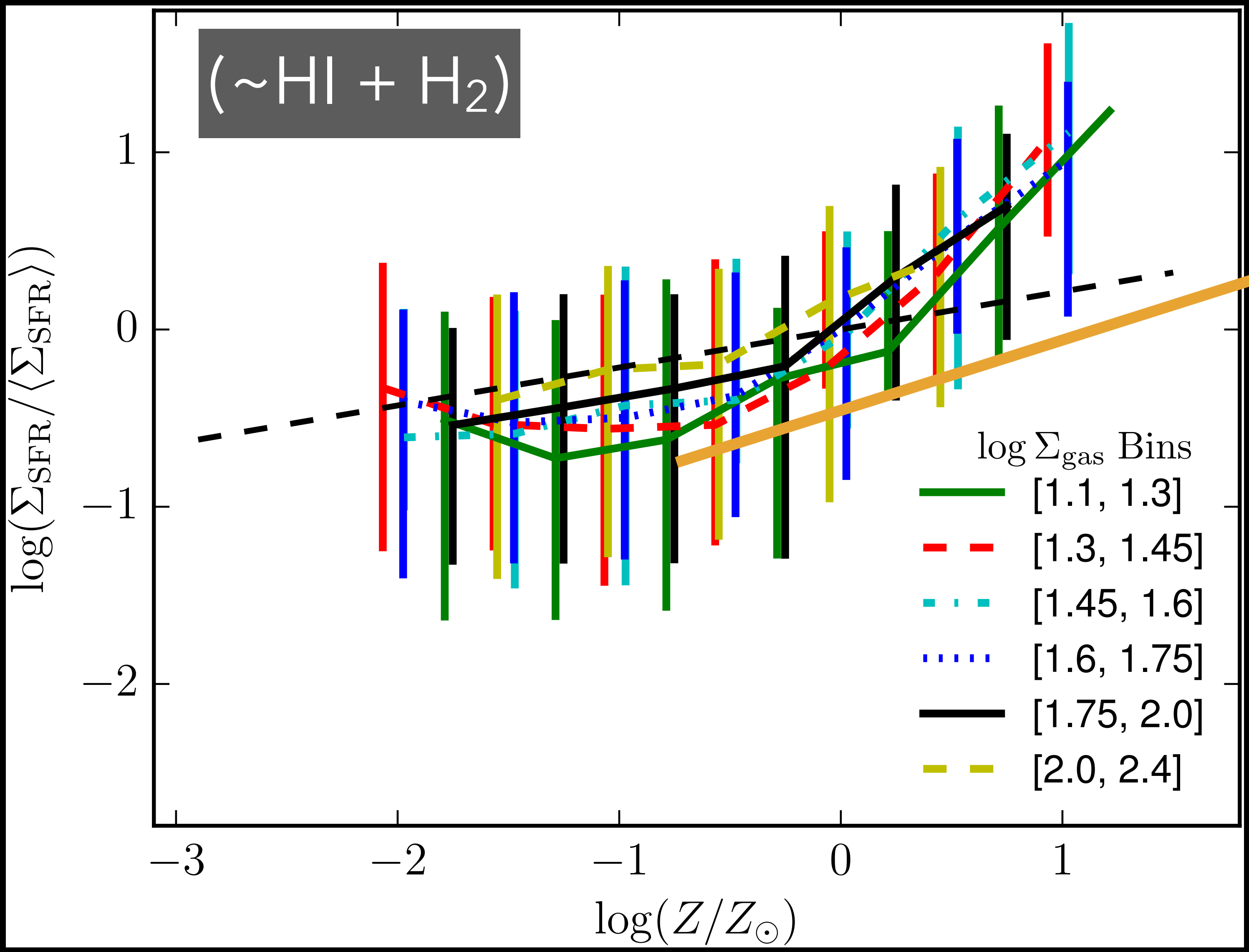
Z Dependence is Consistent with Expectation from SNe Feedback



Close-ish to SNe Feedback's Z dependence ~3/14 (Cioffe 1988)

Upturn at high metallicity

Weak SFR~ $Z^{1/4ish}$ dependence.

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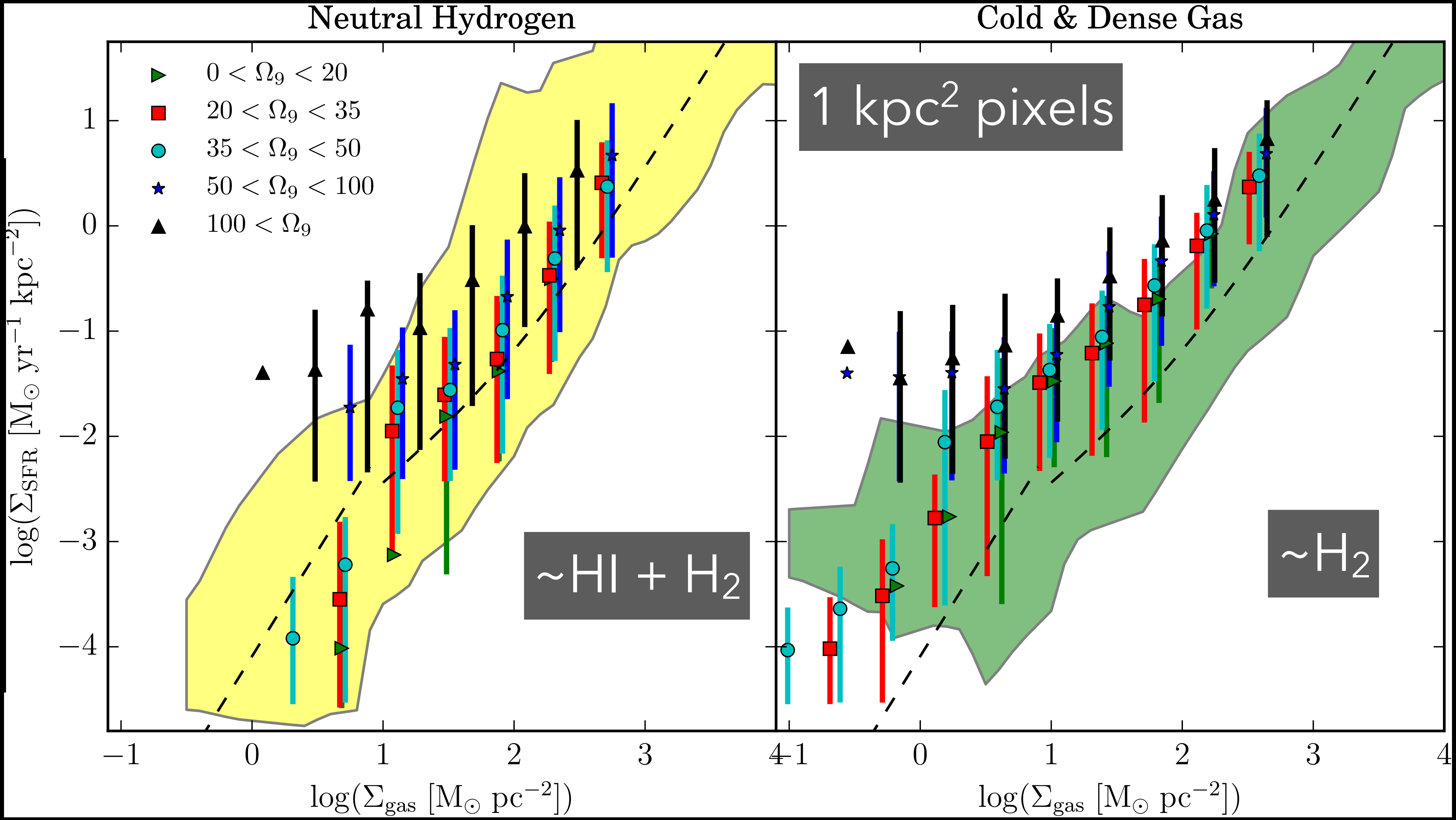
Dynamical Times correlate more strongly than metallicity

10 Myr Avg SFR ~ Hα



Much more strongly, when dynamical timescale ~ feedback timescale

Observations from Kennicutt (1998), Kennicutt, Jr. et al. (2007), Bigiel et al. (2008), Bothwell et al. (2010), Boquien et al. (2011), Daddi et al. (2010), Verley et al. (2010), and Lisenfeld et al. (2011), Genzel et al. (2010), Onodera et al. (2010), and Shi et al. (2011).

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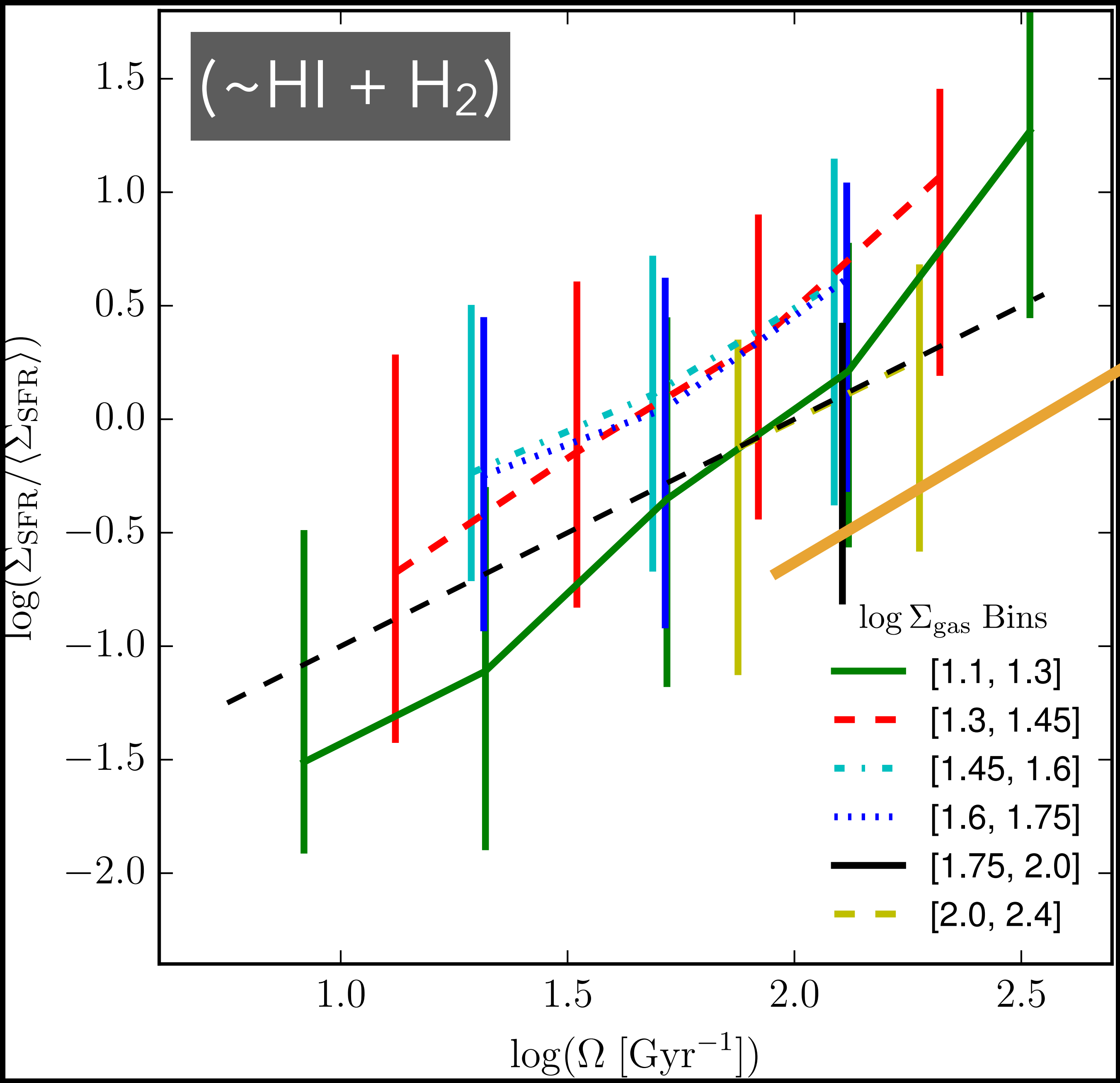
$1/t_{dyn}$ Dependence is nearly linear



~Linear dependence
Close to expectation value of turbulent equilibrium

$$\dot{\Sigma}_\star \propto \sigma \Omega \Sigma_{\rm gas}$$

Momentum injection from young stars ~turbulent momentum injection

Strong SFR~ 1/Dynamical Time dependence.

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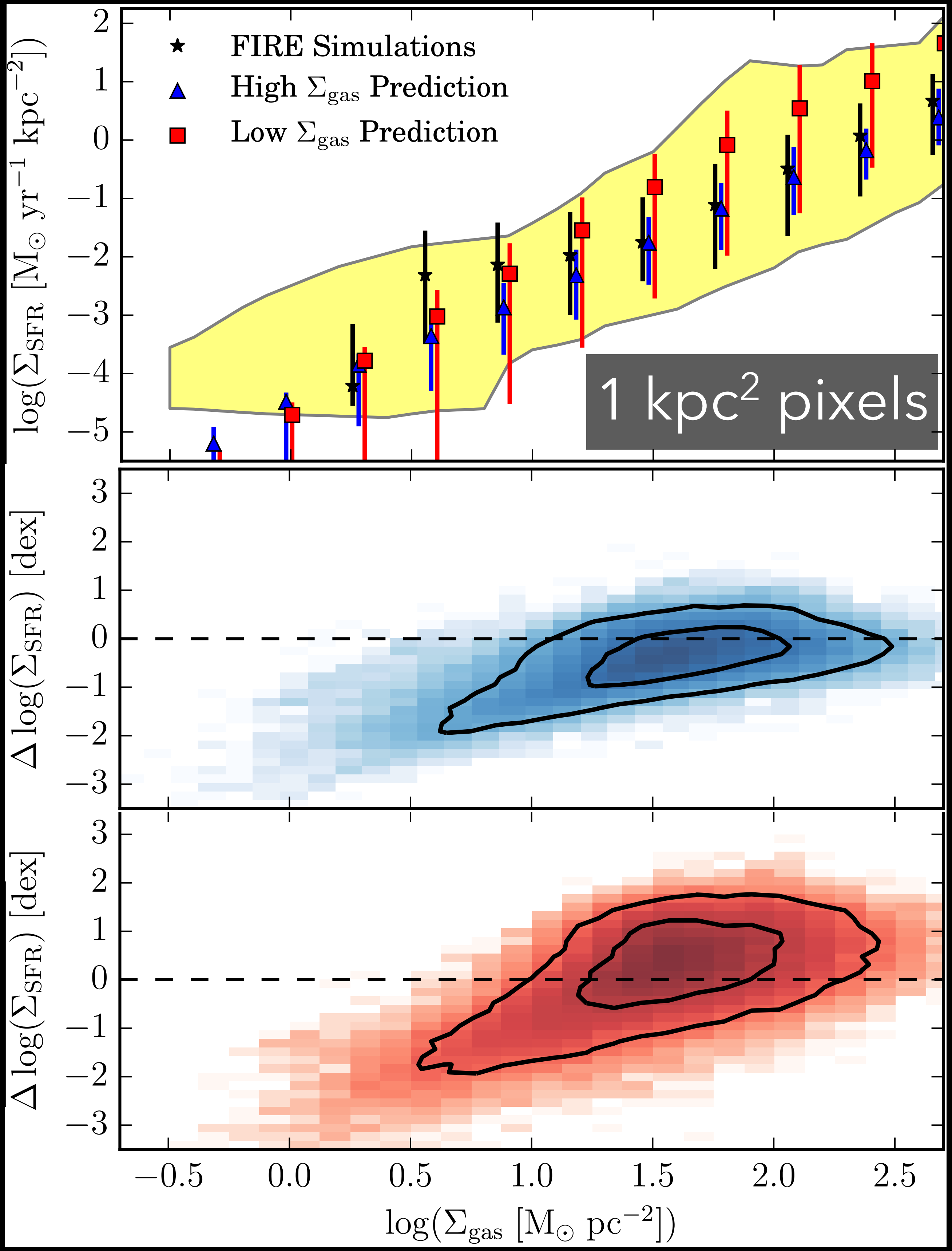
Not far from predicted equilibrium SFRs

$\dot{\Sigma}_\star \propto \Sigma_{\rm gas}\Sigma_{\rm disk}$

Log difference between High Surf. Dense Predict and actual 10 Myr SFR

Log difference between Low Surf. Dense Predict and actual 10 Myr SFR

$\dot{\Sigma}_\star \propto Z\Omega\Sigma_{\rm gas}^2$



Pixel-to-pixel comparison

Only ~1/2 dex out of turbulent equilibrium

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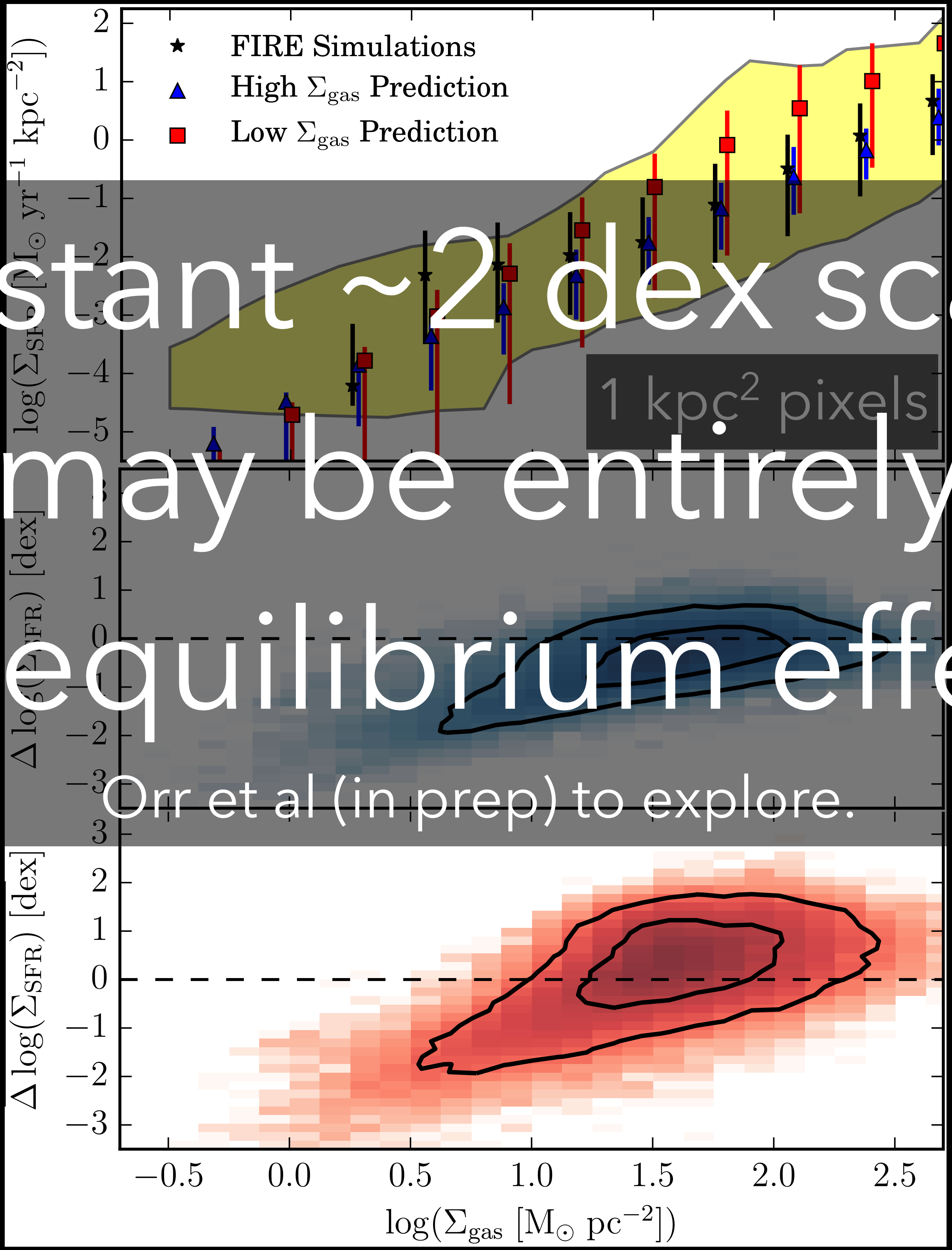

Pixel-to-pixel comparison

$\dot{\Sigma}_\star \propto \Sigma_{gas}\Sigma_{disk}$

Log difference between High Surf. Dense Predict and actual 10 Myr SFR

Only ~1/2 dex out of turbulent equilibrium

Log difference between Low Surf. Dense Predict and actual 10 Myr SFR

$\dot{\Sigma}_\star \propto Z\Omega\Sigma_{gas}^2$

Constant ~2 dex scatter may be entirely non-equilibrium effects?

Orr et al (in prep) to explore.

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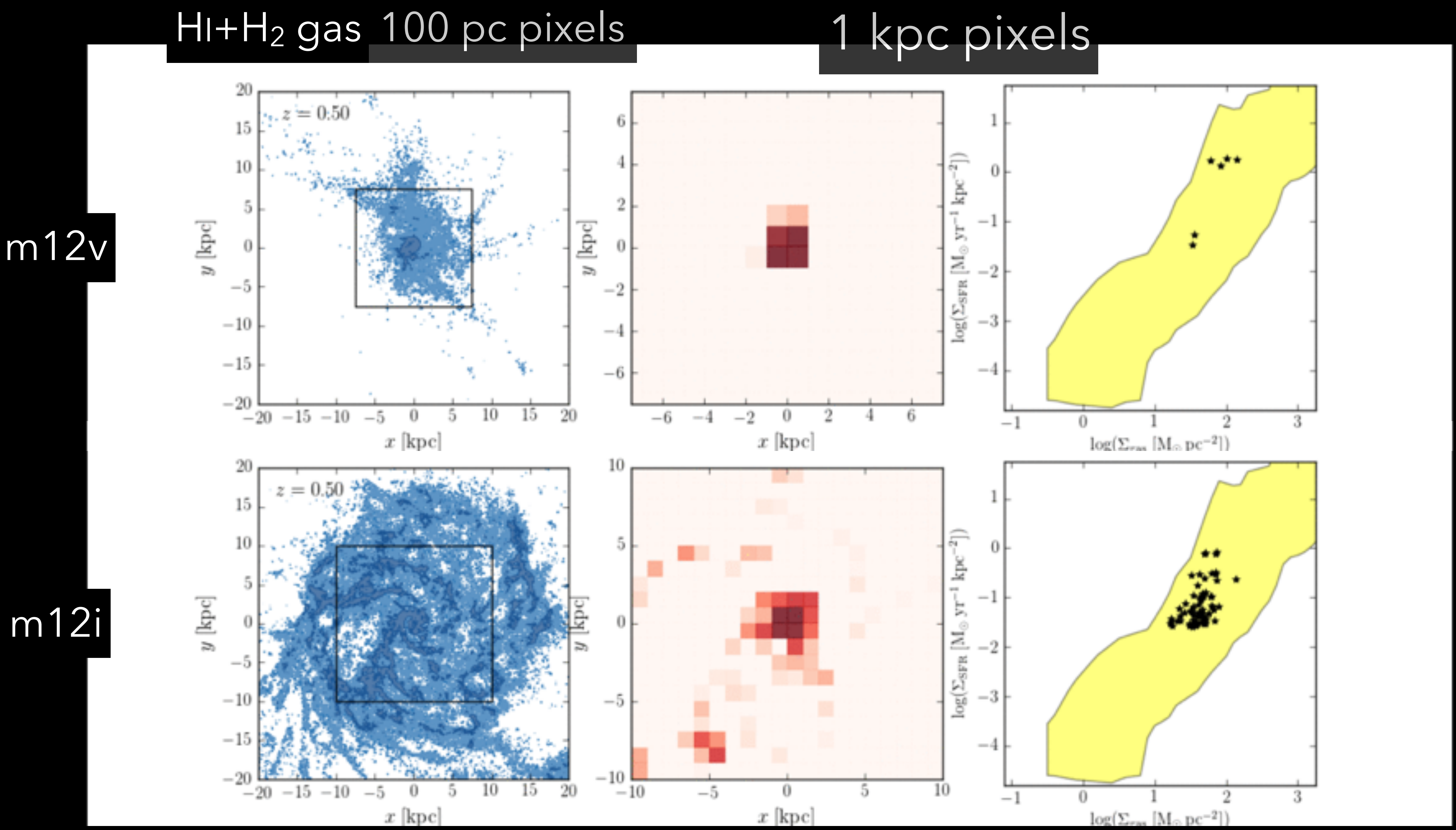
KS is not smooth in time.



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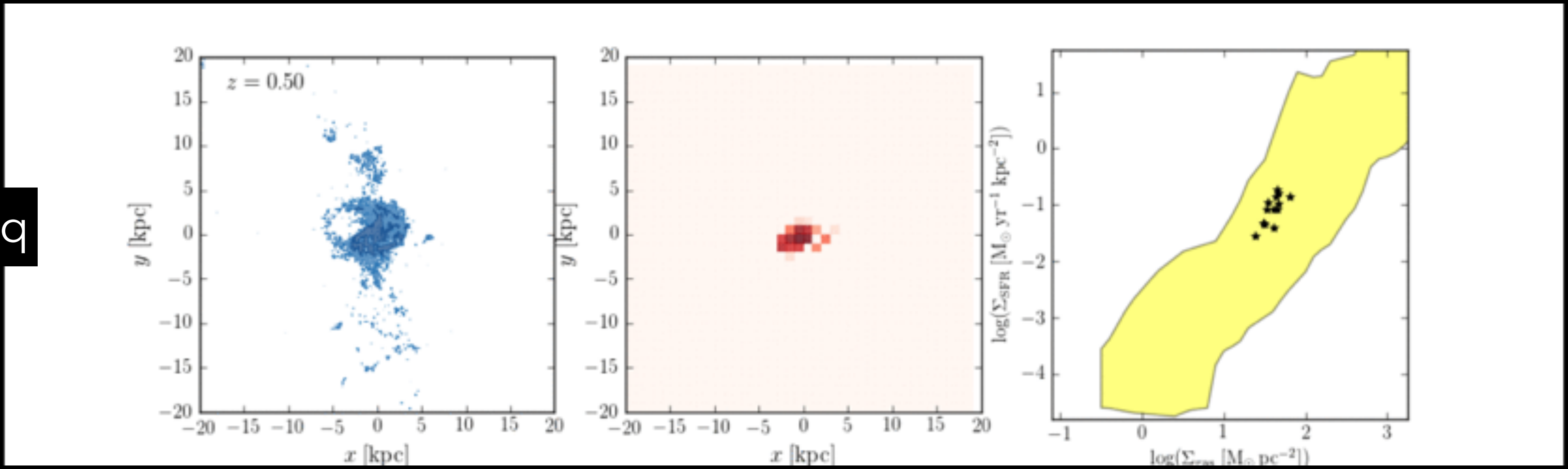
KS is not smooth in time.

HI+H_2 gas 100 pc pixels 1 kpc pixels

m12q



A weird one.. small gas disk, aligned with stellar disk face-on,
and a large ~10 kpc radius gas stream.
Has a particularly largely varying KS relation

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Efficiencies?

How many dynamical times in a depletion time?

Low Gas Surface Density

$$\dot{\Sigma}_\star \propto Z\Omega\Sigma_{\rm gas}^2/f_{\rm abs}$$

$$\epsilon = \frac{\dot{\Sigma}_\star}{\Sigma_{\rm gas}\Omega} \propto \frac{Z\Sigma_{\rm gas}}{f_{\rm abs}}$$

Very low gas surface densities

$$\epsilon \propto \text{Constant}$$

High Gas Surface Density

$$\dot{\Sigma}_\star \propto \Sigma_{\rm gas}\Sigma_{\rm disk}$$

$$\epsilon = \frac{\dot{\Sigma}_\star}{\Sigma_{\rm gas}\Omega} \propto \Sigma_{\rm disk}/\Omega \propto 1/Q$$

Which should roughly be a constant too…

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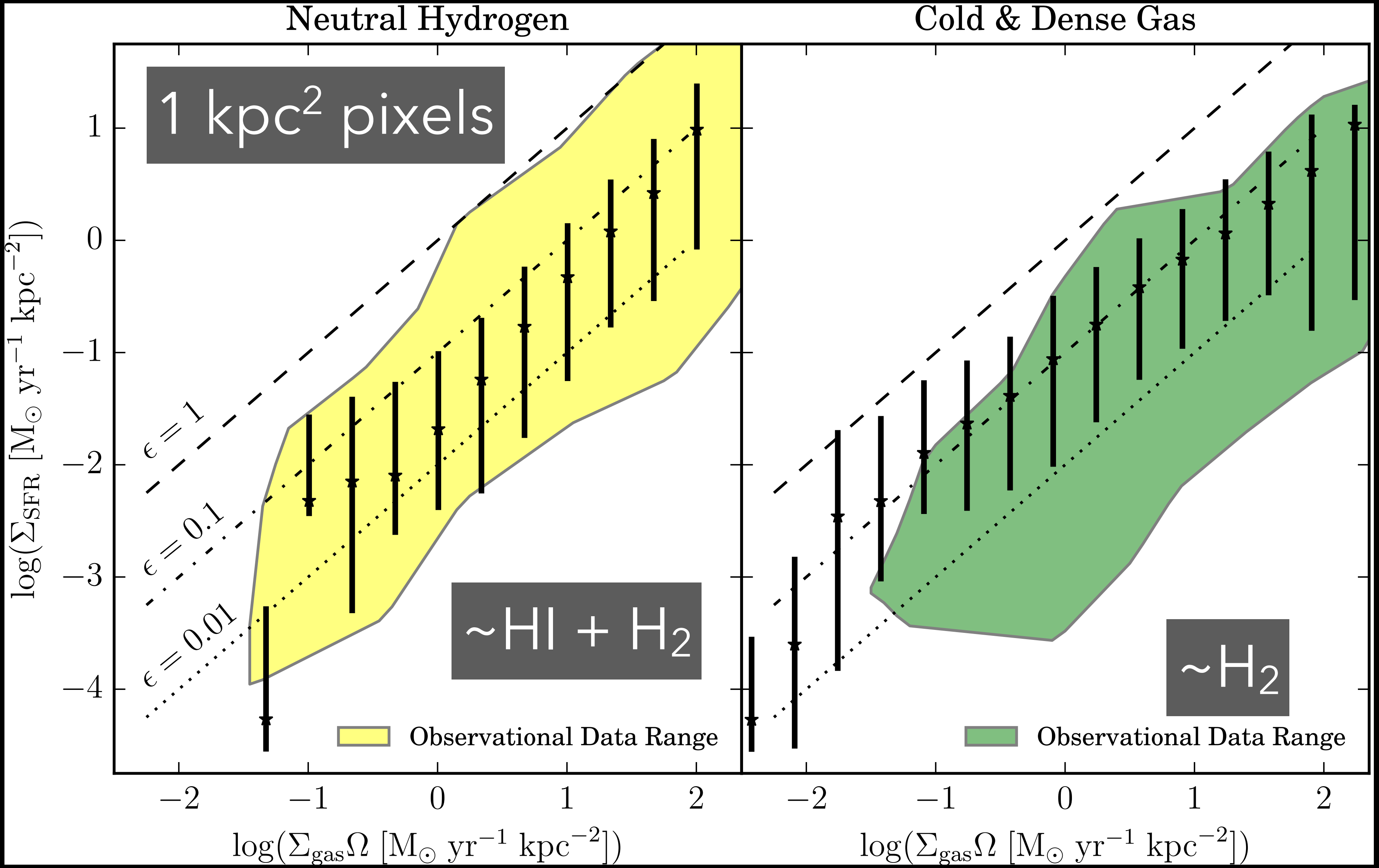
Roughly constant efficiencies

10 Myr Avg SFR ~ Hα



Effective efficiency per dynamical time is less than ~10%

Observations from Kennicutt (1998), Daddi et al. (2010), Kennicutt, Jr. et al. (2007) & Genzel et al. (2010)

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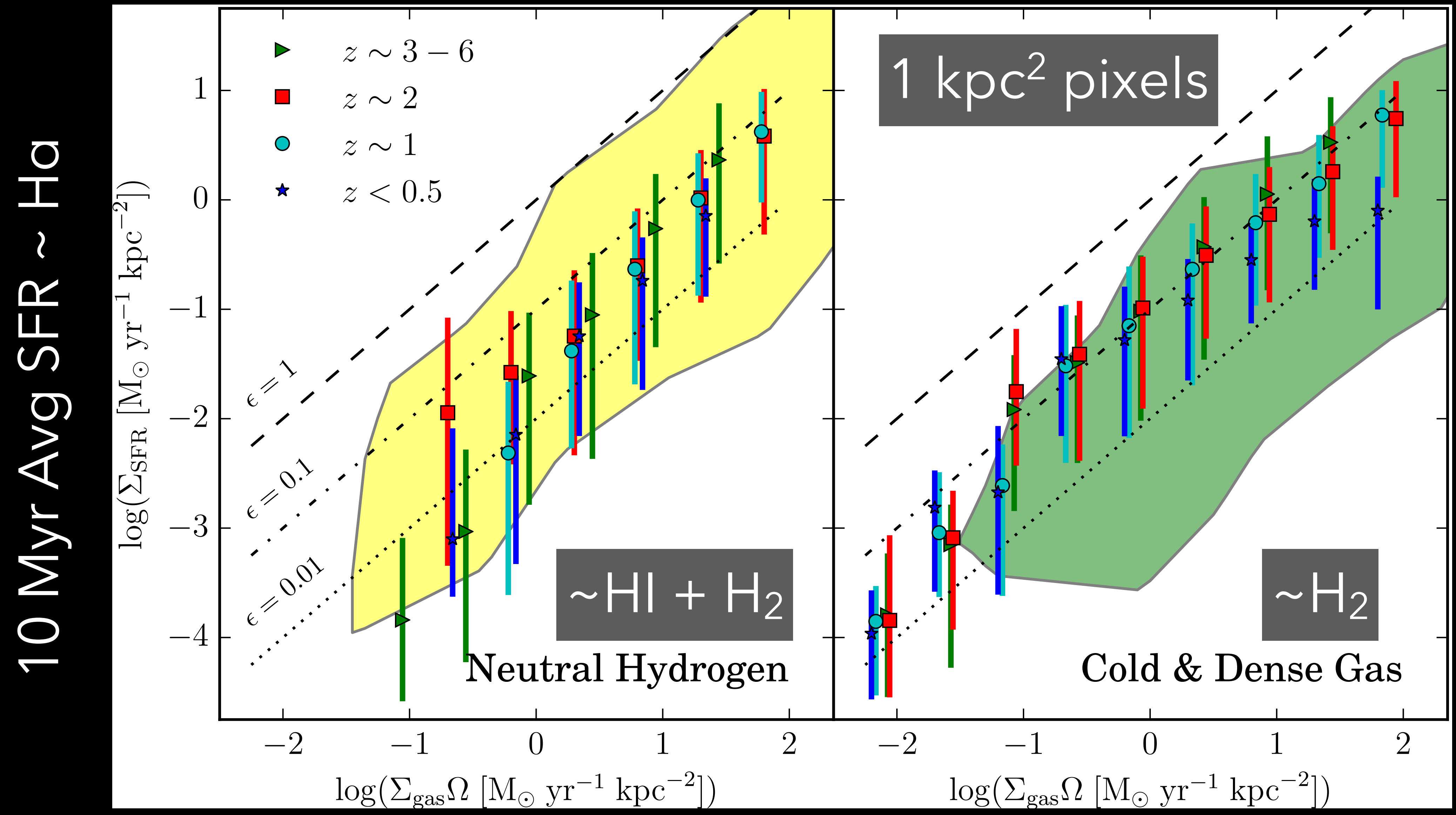
No redshift dependence



Lots of scatter, but no separation.

Observations from Kennicutt (1998), Daddi et al. (2010), Kennicutt, Jr. et al. (2007) & Genzel et al. (2010)

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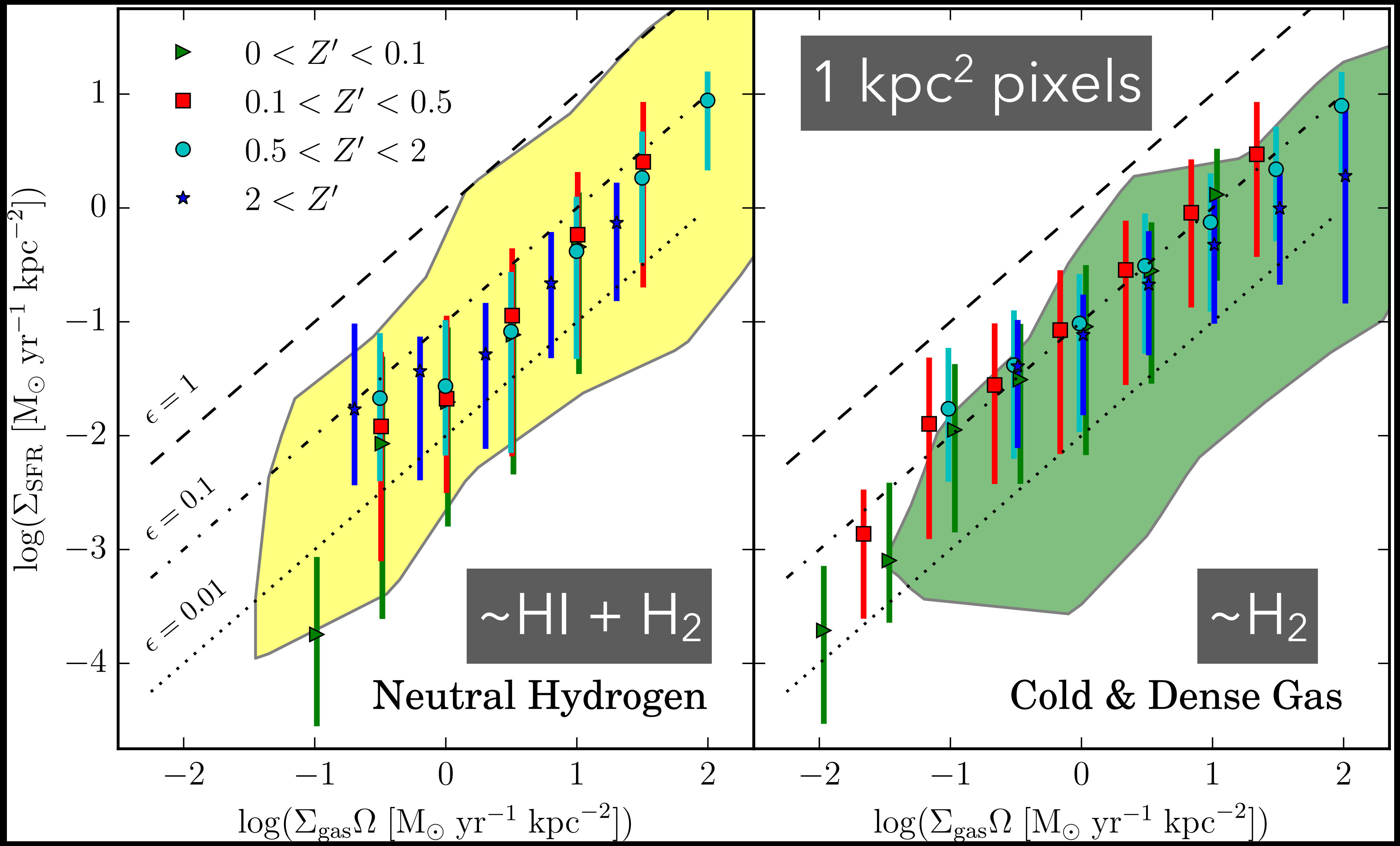
No metallicity dependence here!

10 Myr Avg SFR ~ Hα



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Summary

- Kennicutt-Schmidt emerges as a time and spatially averaged equilibrium between star formation and feedback processes in the FIRE simulations.
- Weak metallicity dependence, linear $1/t_{dyn}$ dependence
- ~1-2 dex ±2 sigma scatter appears intrinsic, non-equilbium?
- .Efficiencies in the 1-10% range, no apparent metallicity/dynamical time dependencies.

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THANKS FOR LISTENING

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