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

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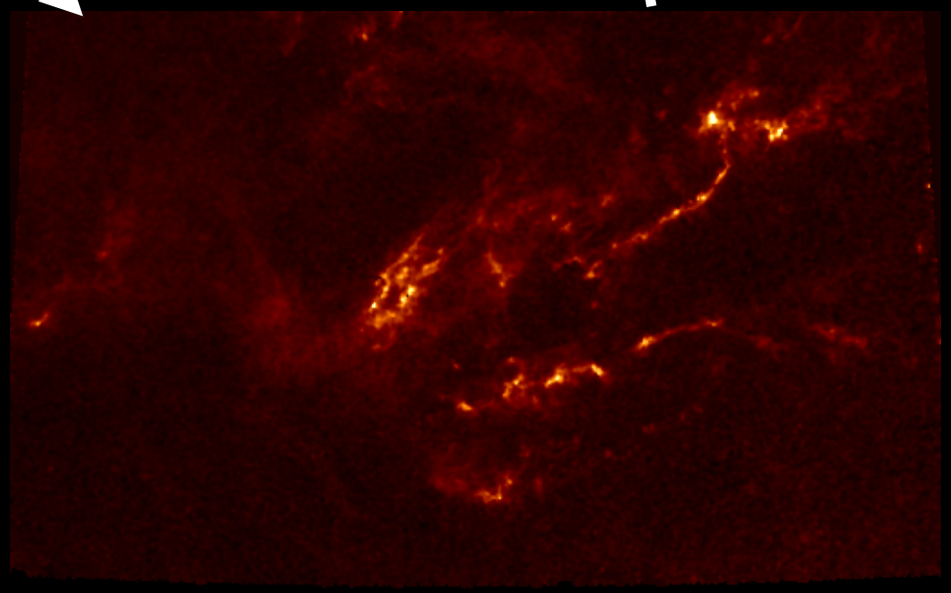
Star Formation



Stars form in galaxies from dust & gas, understanding what governs this is integral to understanding galaxy evolution.

Hubble Archive (http://hubblesite.org/), Goldsmith et. al 2008

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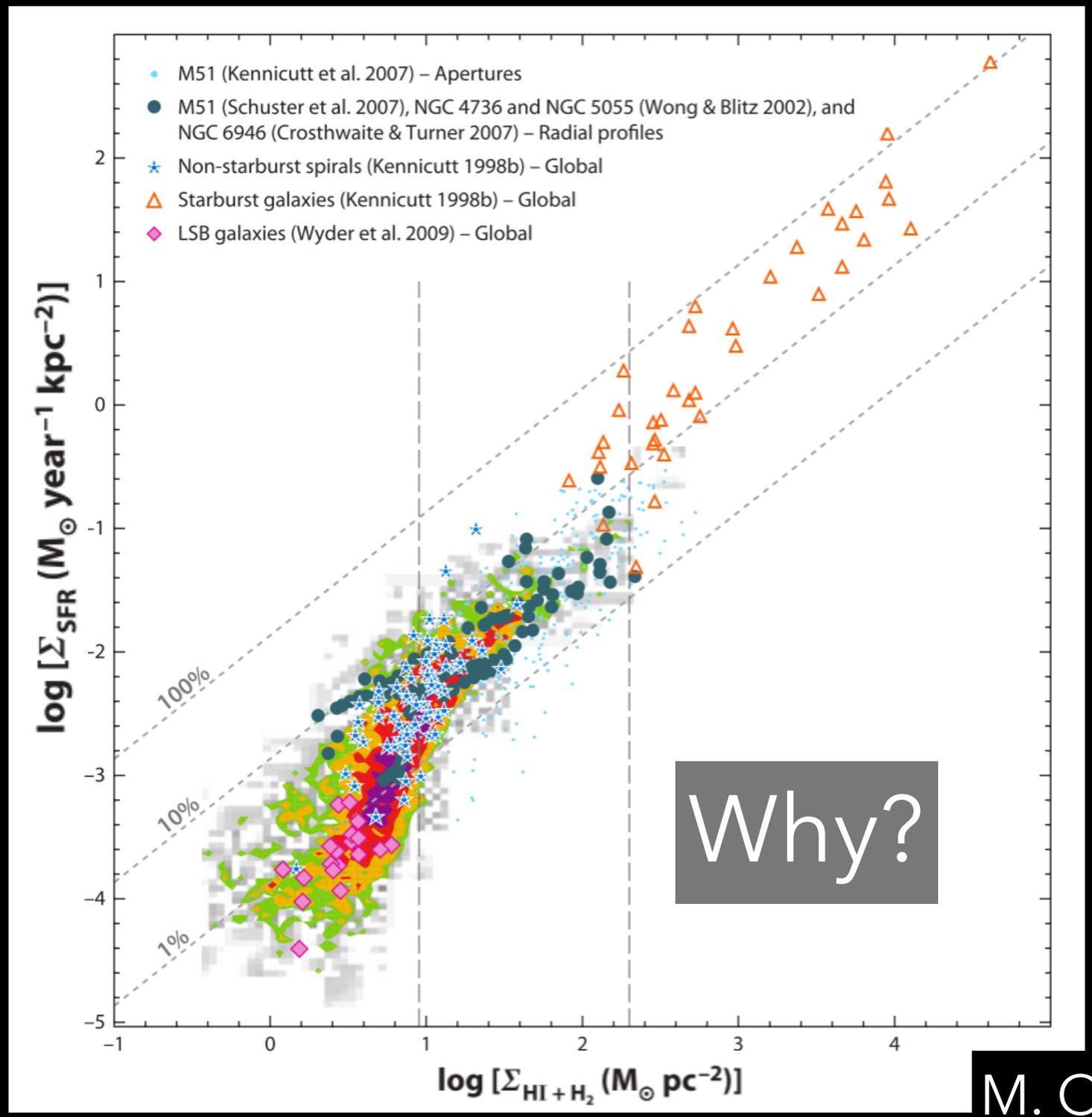
Kennicutt-Schmidt Relation

Observational relation between surface density of gas and star formation

Star formation is slow, 50x slower than the free fall time of the gas



Bigiel et al. 2008
Kennicutt & Evans 2012

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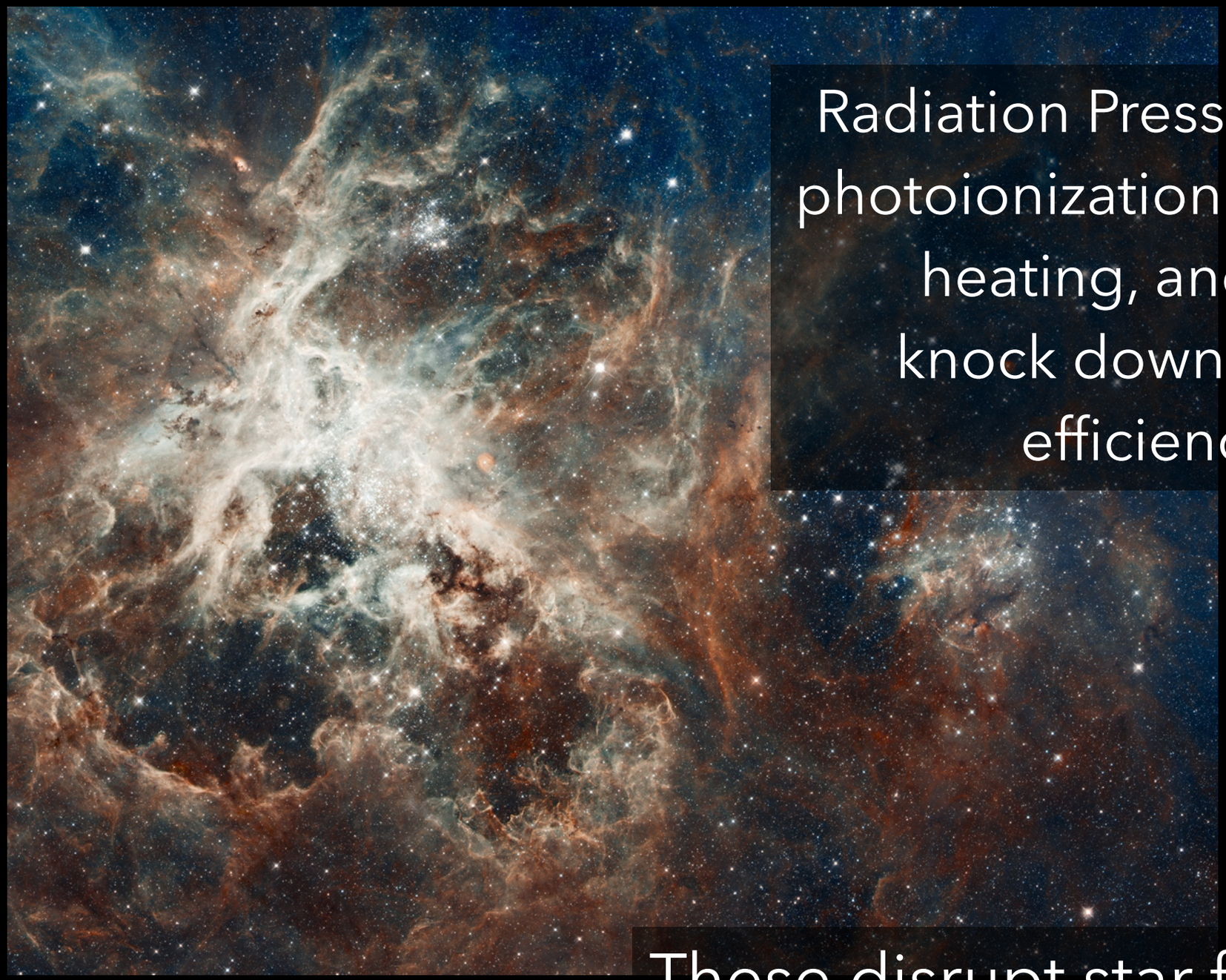
Feedback!



Radiation Pressure, Stellar winds, photoionization and photoelectric heating, and supernovae knock down star formation efficiency globally

These disrupt star forming regions

Hubble Archive (http://hubblesite.org/)

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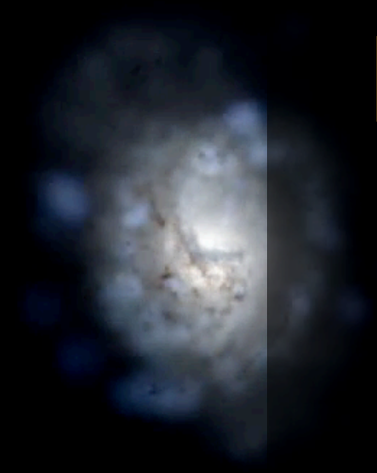
Where we come in: Simulations

FIRE: Feedback In Realistic Environments

z=0.50



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

Locally 100% Efficient Star Formation

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/

See Hopkins et al. 2014

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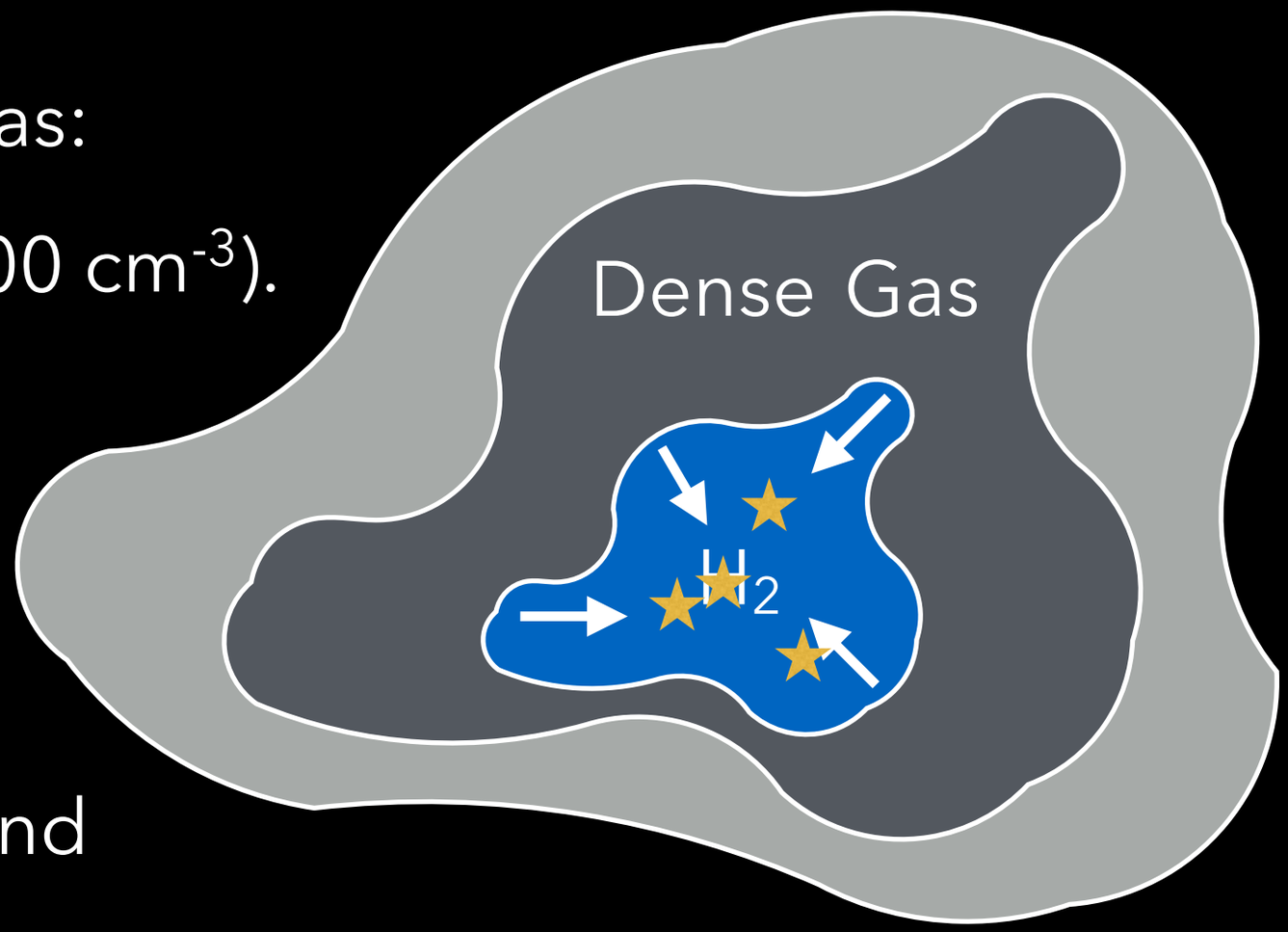
Star Formation on FIRE

Rules for star formation in gas:

Gas is dense, n_{crit} (~100 cm^{-3}).

Predominantly molecular in nature, i.e. $f_{H2} > 1/2$.



Is locally gravitationally bound

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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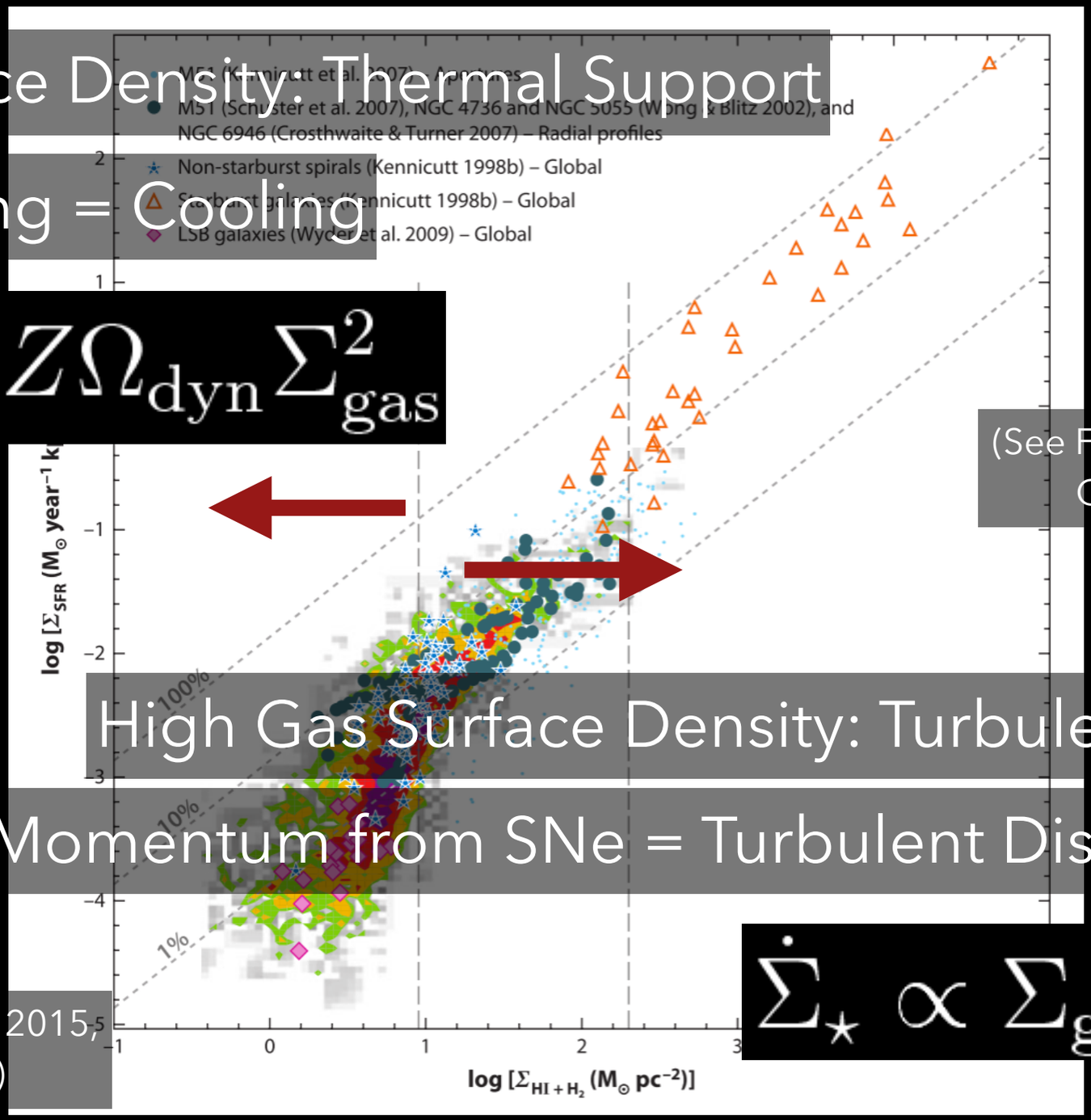
What do we expect from Feedback?

Low Gas Surface Density: Thermal Support

Heating = Cooling

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



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

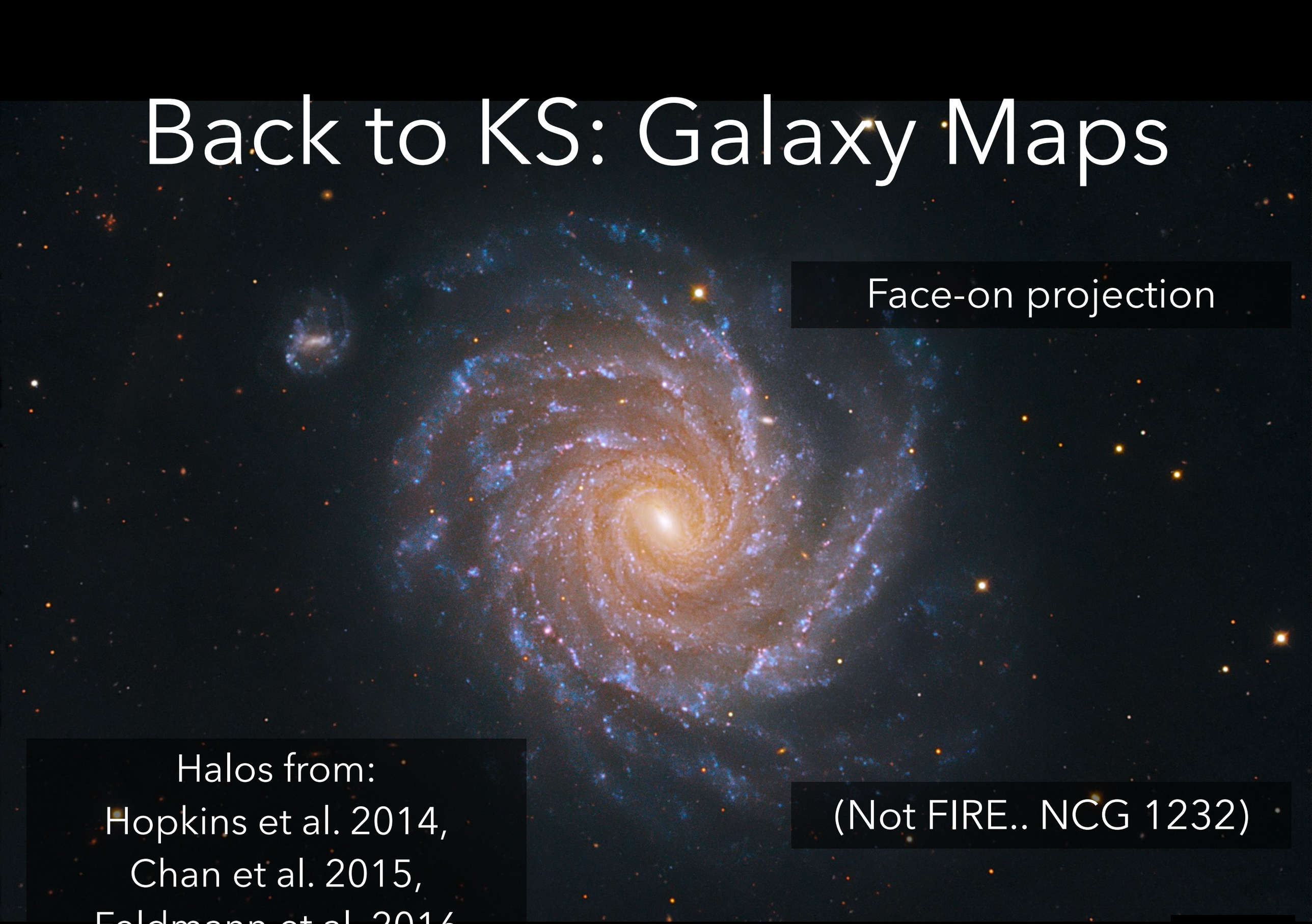
High Gas Surface Density: Turbulent Support

Momentum from SNe = Turbulent Dissipation in ISM

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

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

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 quantaties
(Gas, SFR, Ω_{dyn})

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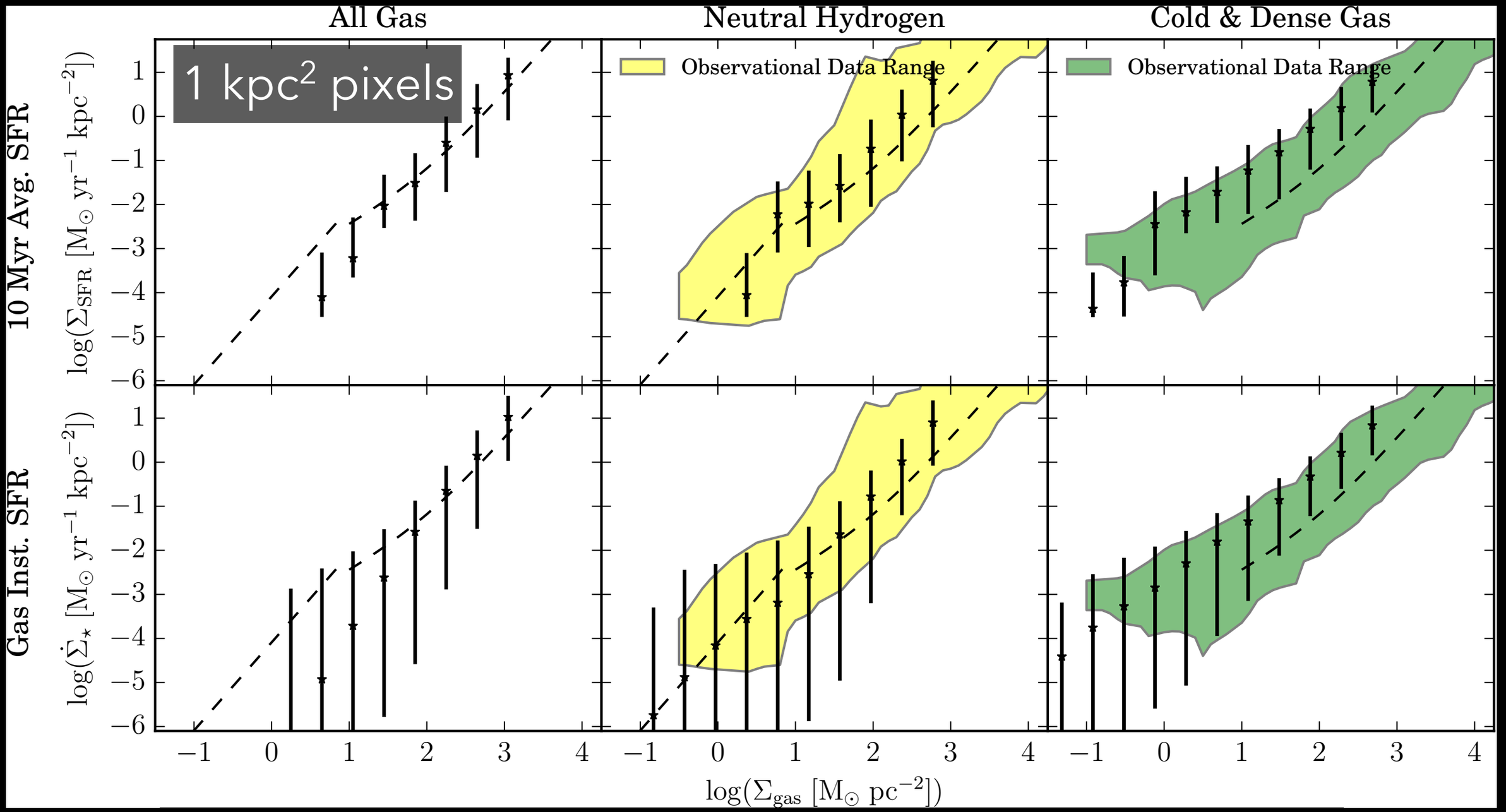
Kennicutt-Schmidt is there!



For just about every tracer, Kennicutt-Schmidt is there!

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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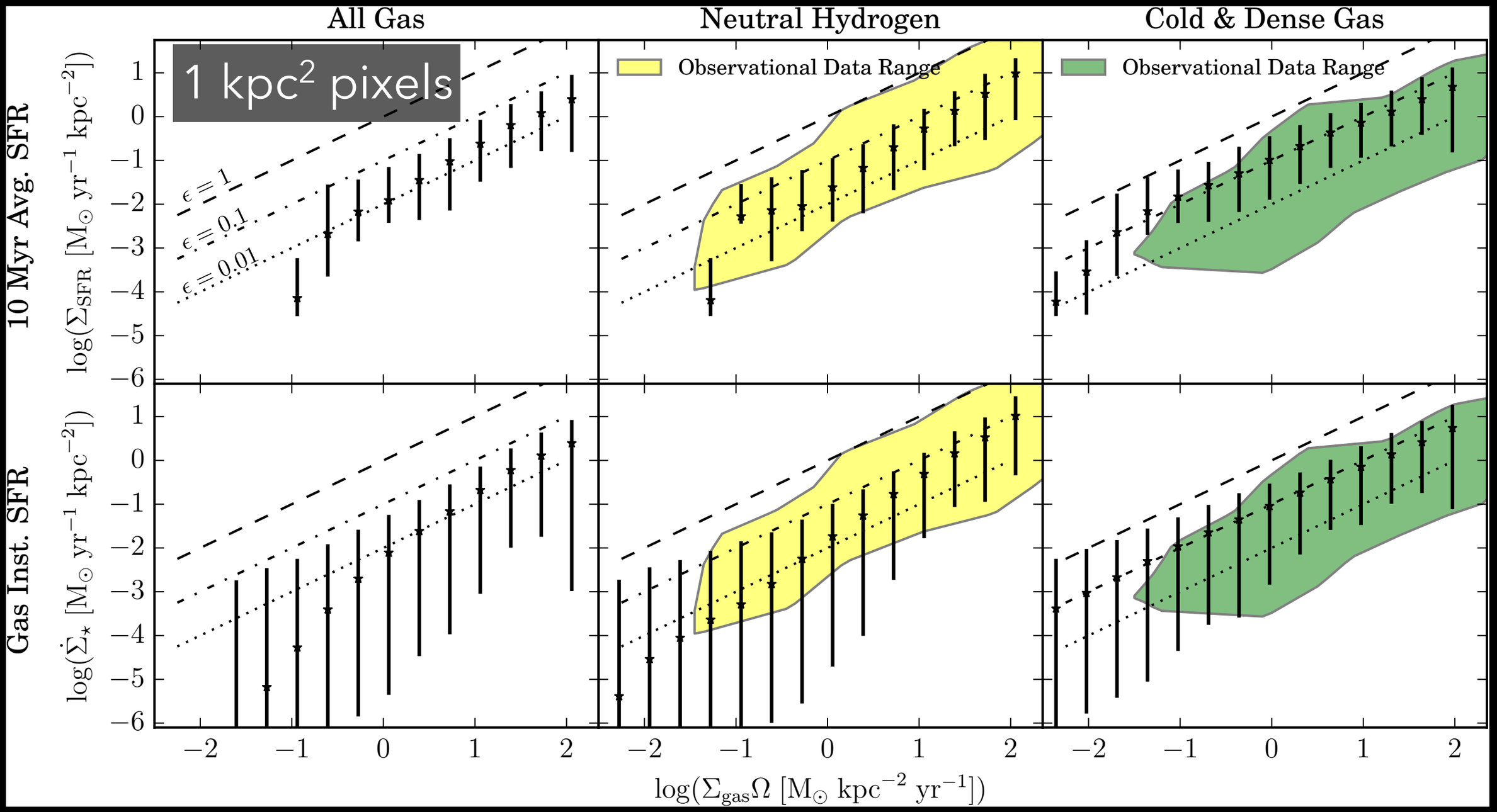
Elmegreen-Silk too!



Effective efficiency is less than ~10%

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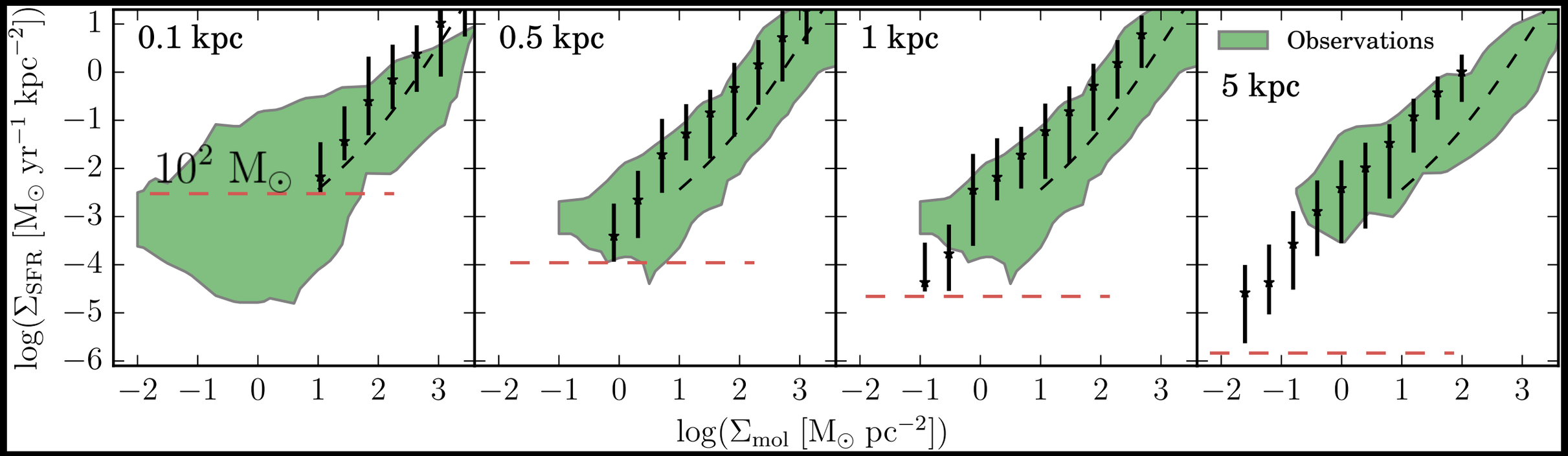
Observations from Kennicutt (1998), Daddi et al. (2010), Kennicutt, Jr. et al. (2007) & Genzel et al. (2010)

Pixel Size Dependence



10 Myr averaged SFR

Cold & Dense Gas (T < 300 K n>10)
("Molecular" Gas)

Observations from Kennicutt 1998 Kennicutt, Jr. et al. 2007 Bigiel et al. 2008 Genzel et al. 2010 Bothwell et al. 2010 Onodera et al. 2010 Verley et al. 2010 Shapiro et al. 2010 Wei et al. 2010 Daddi et al. 2010 Shi et al. 2011 Lisenfeld et al. 2011 Boquien et al. 2011 Tacconi et al. 2013 Freundlich et al. 2013

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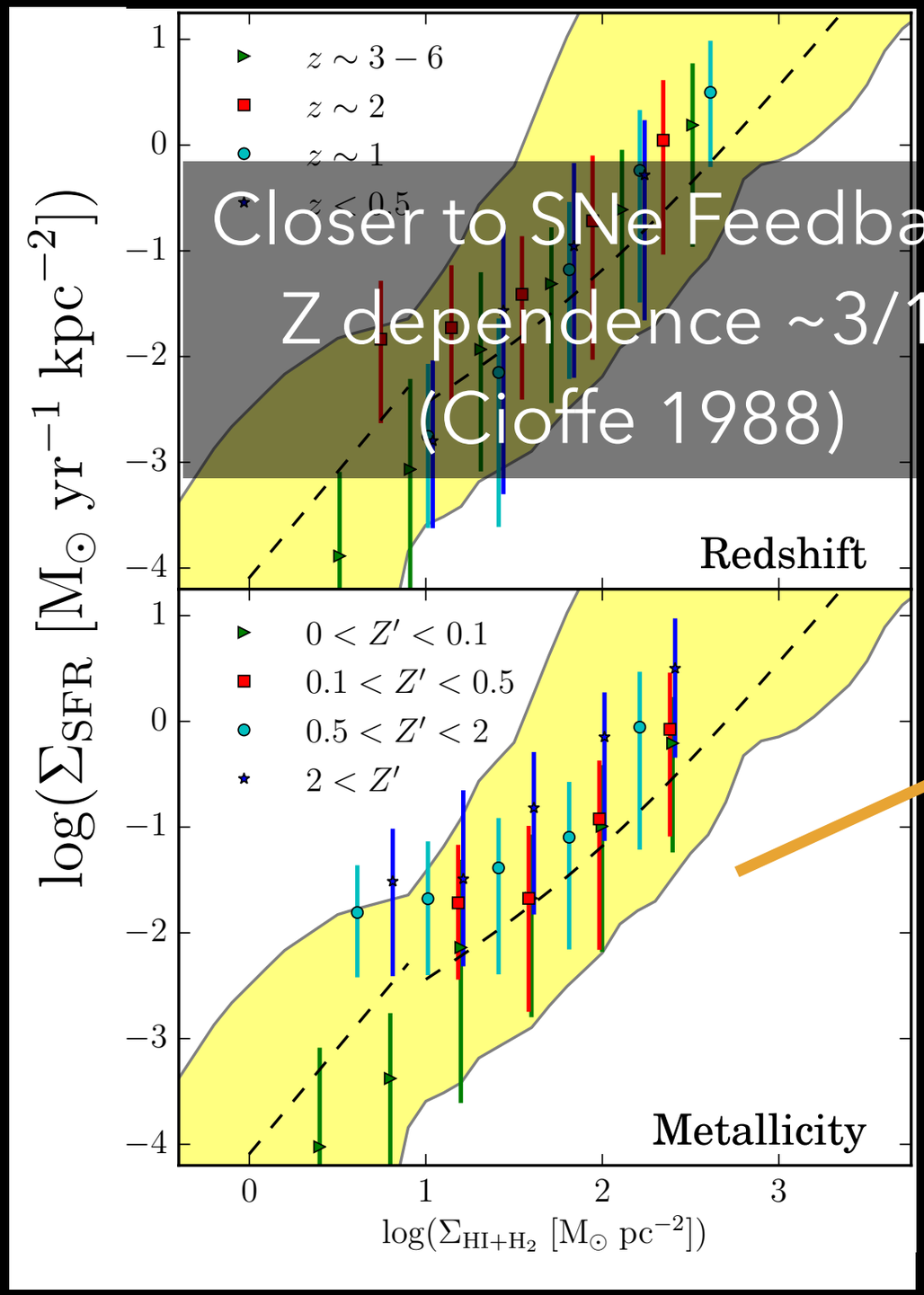
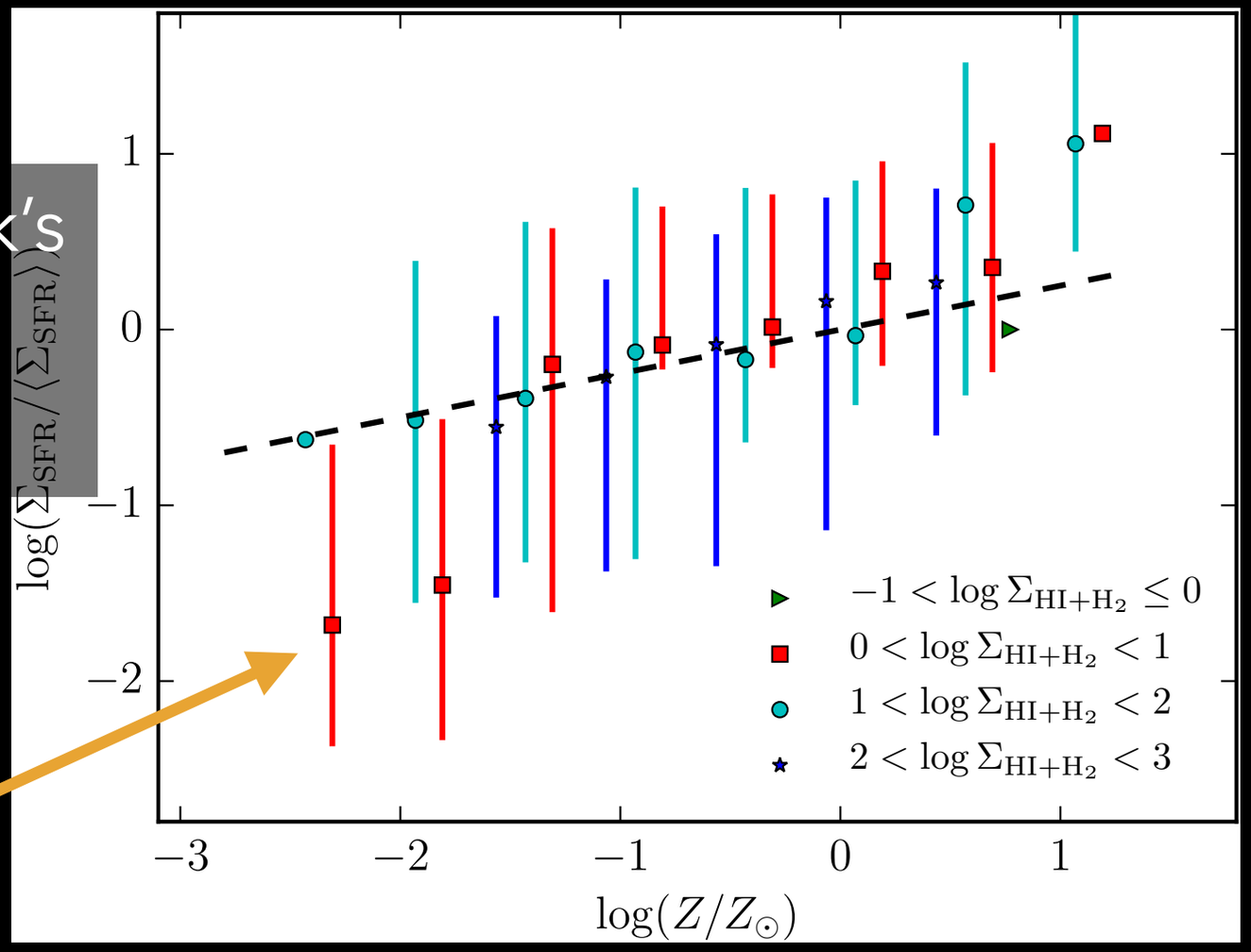
Redshift Independent & Metallicity Dependent



Closer to SNe Feedback's Z dependence ~3/14 (Cioffe 1988)



Weak ~1/4 slope Z dependence.

No apparent z dependence.

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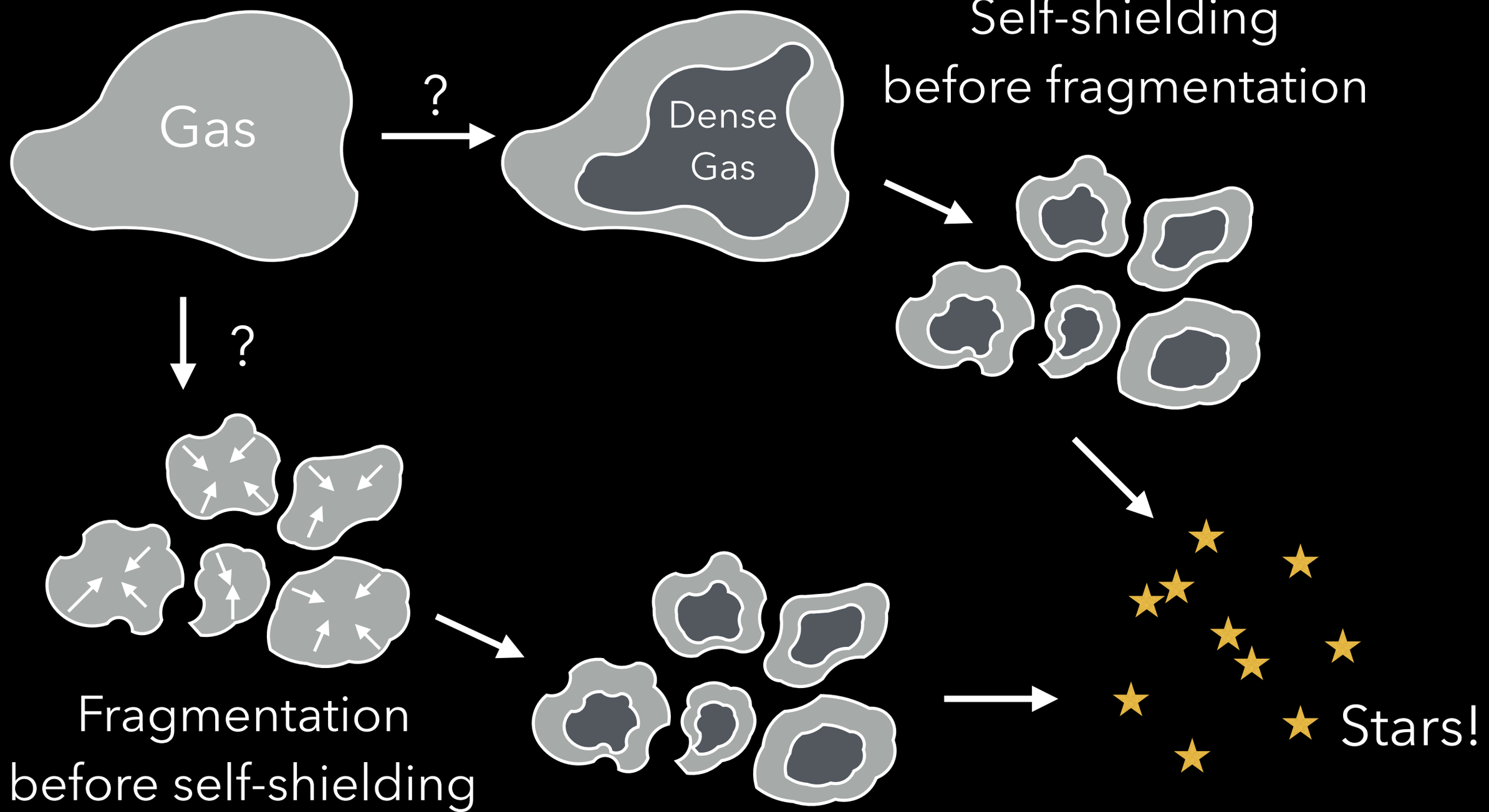
So what *FIREs up star formation?*

Star Formation: Order of Operations



How Does It Relate to Galaxies?

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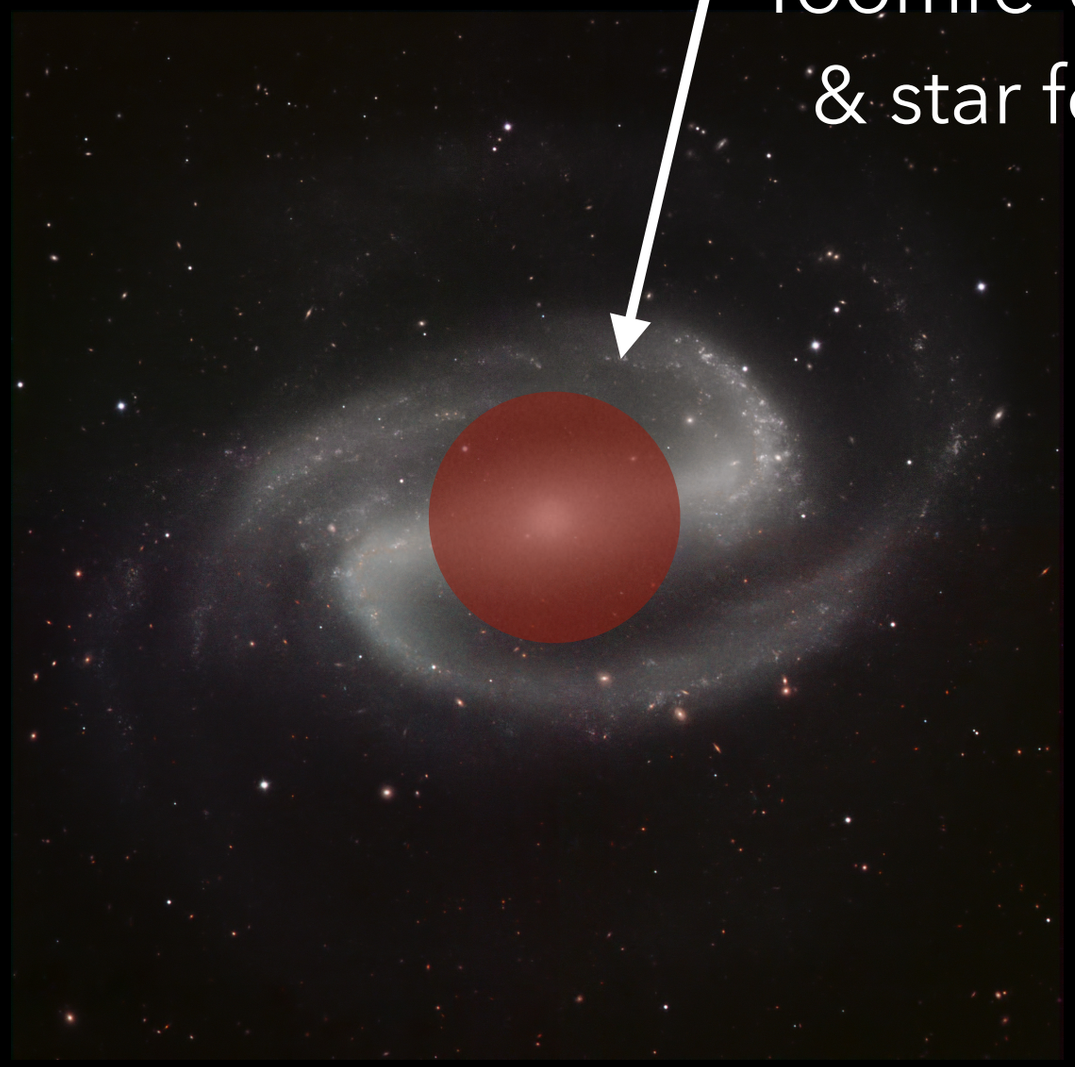
How Does It Relate to Galaxies?

Self-shielded,
Toomre-Unstable,
& star forming.



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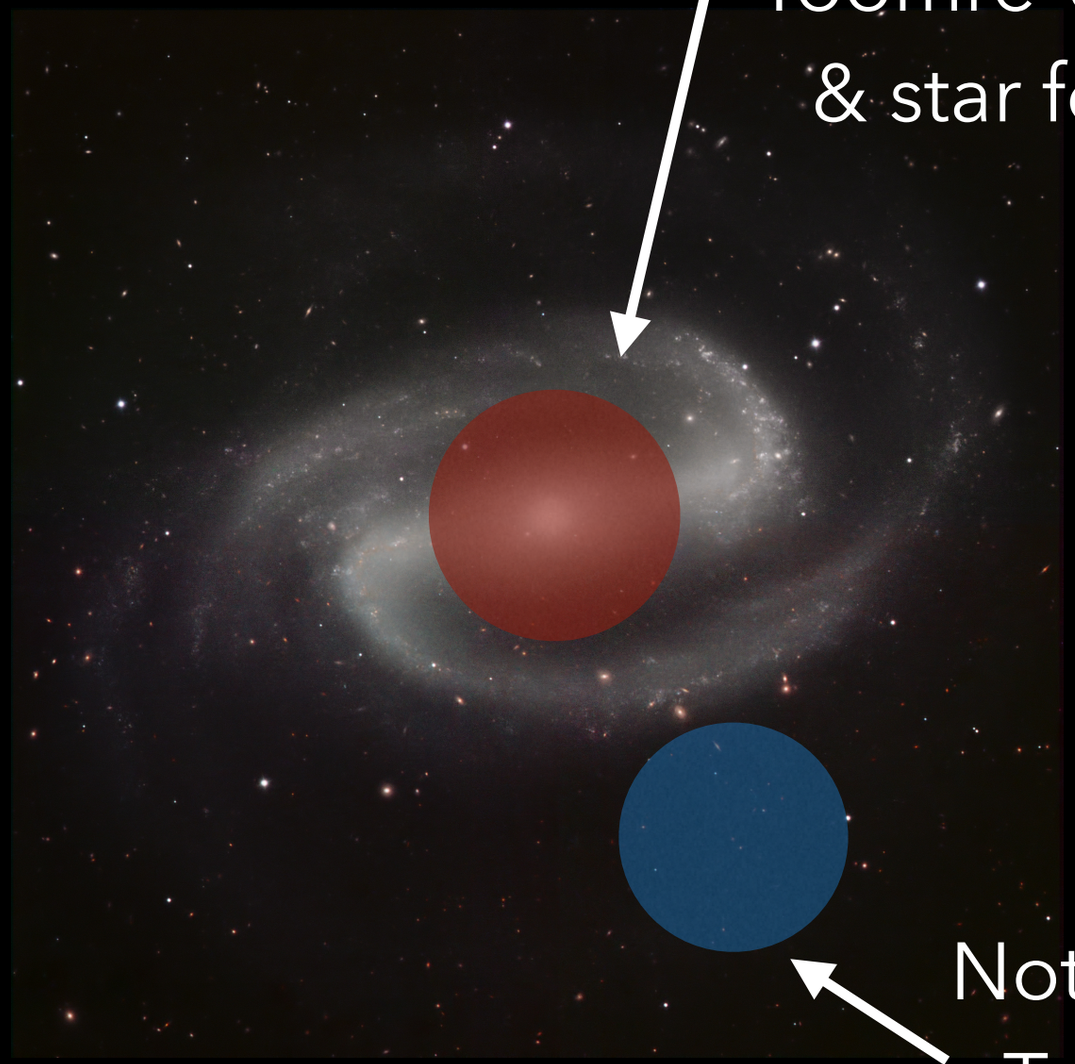

Not Self-shielded,
Toomre-stable,
& not star forming.

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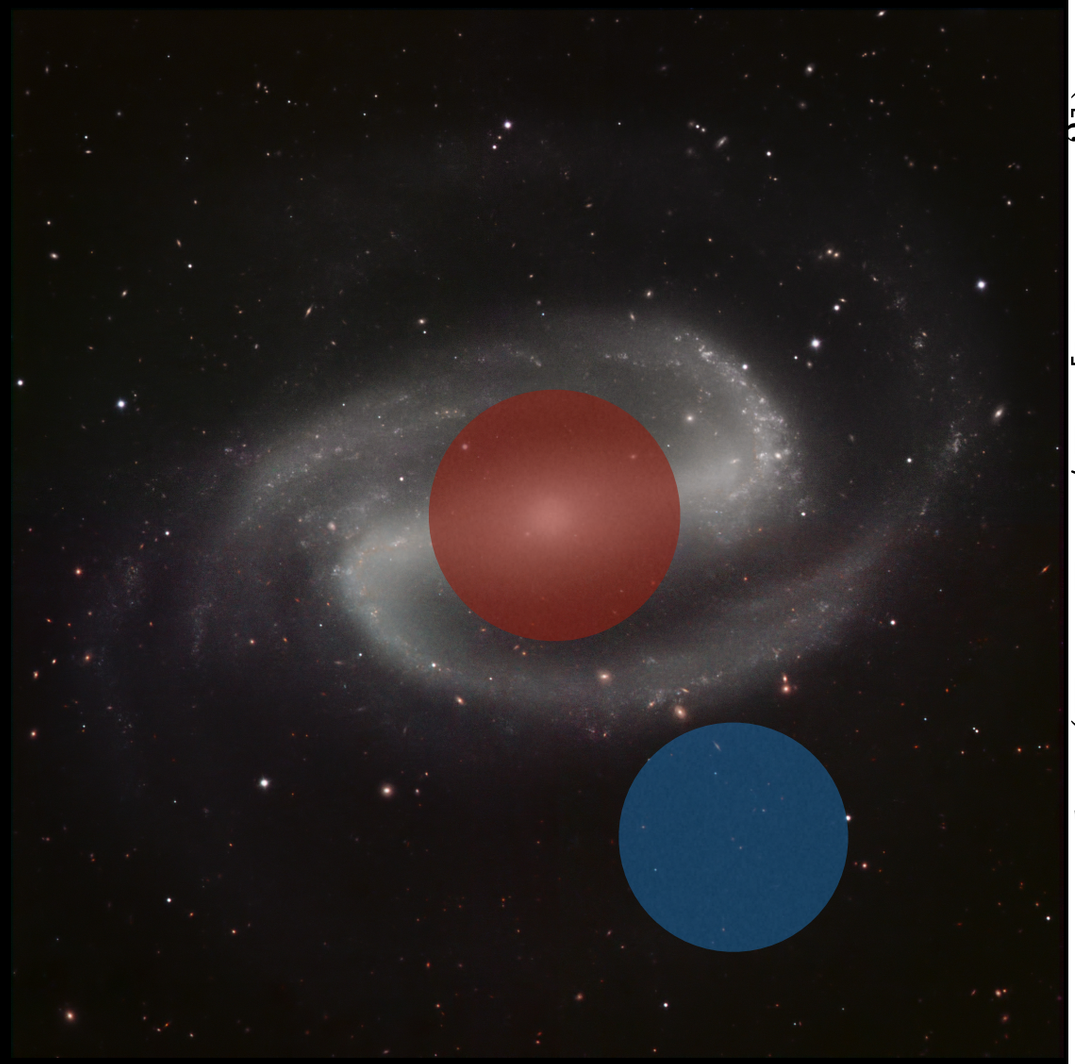
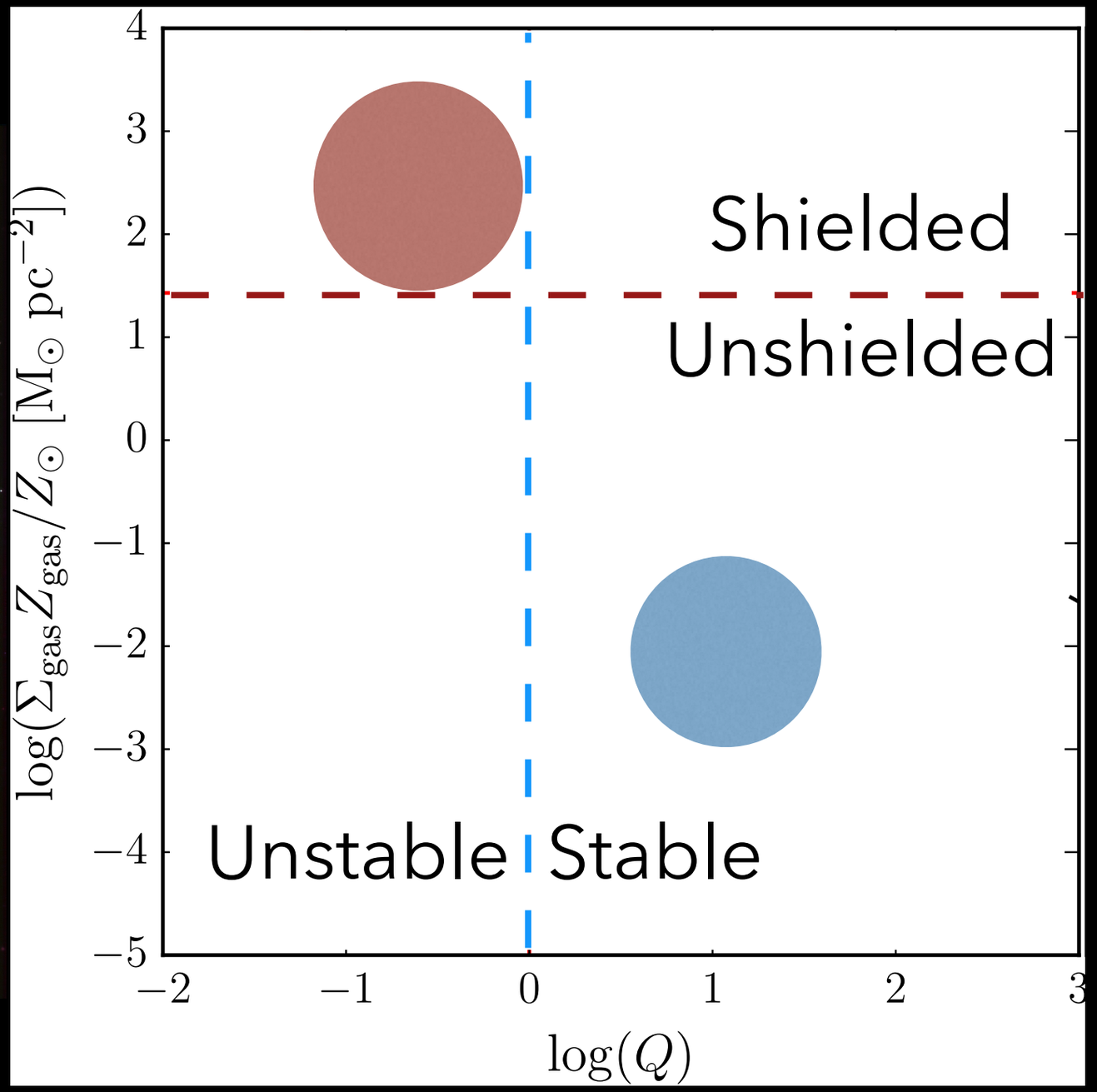
How Does It Relate to Galaxies?





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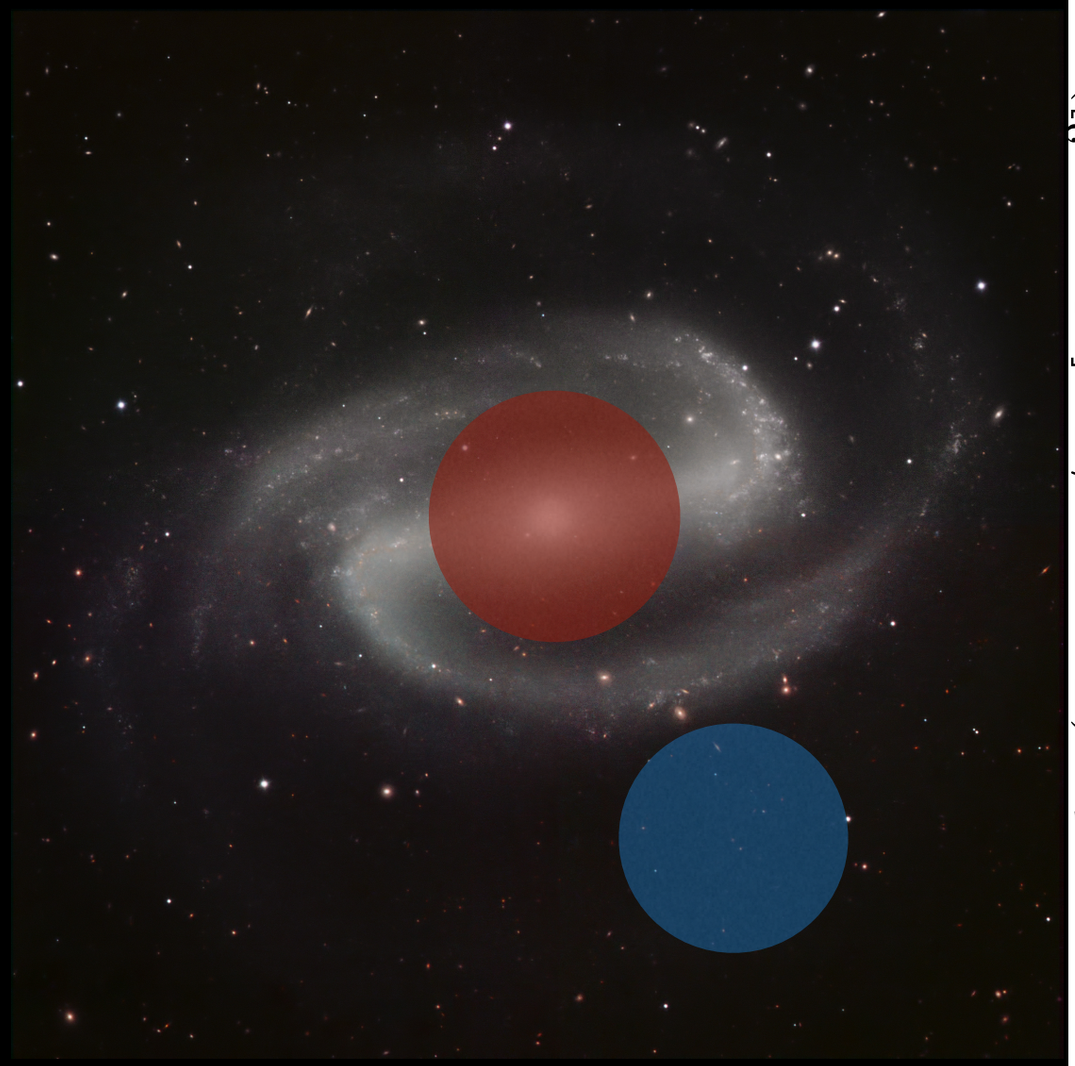
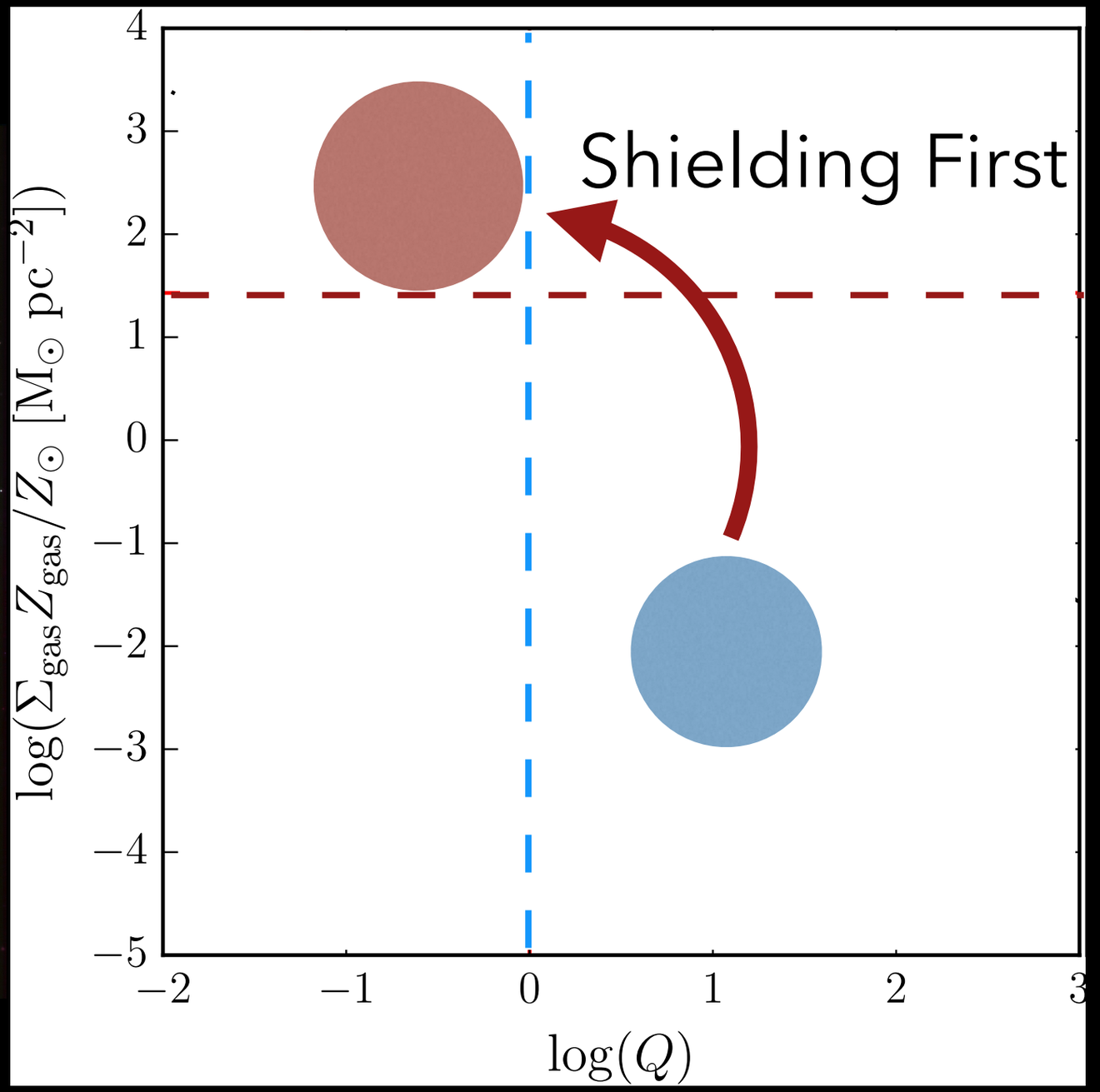
Which Radius First?





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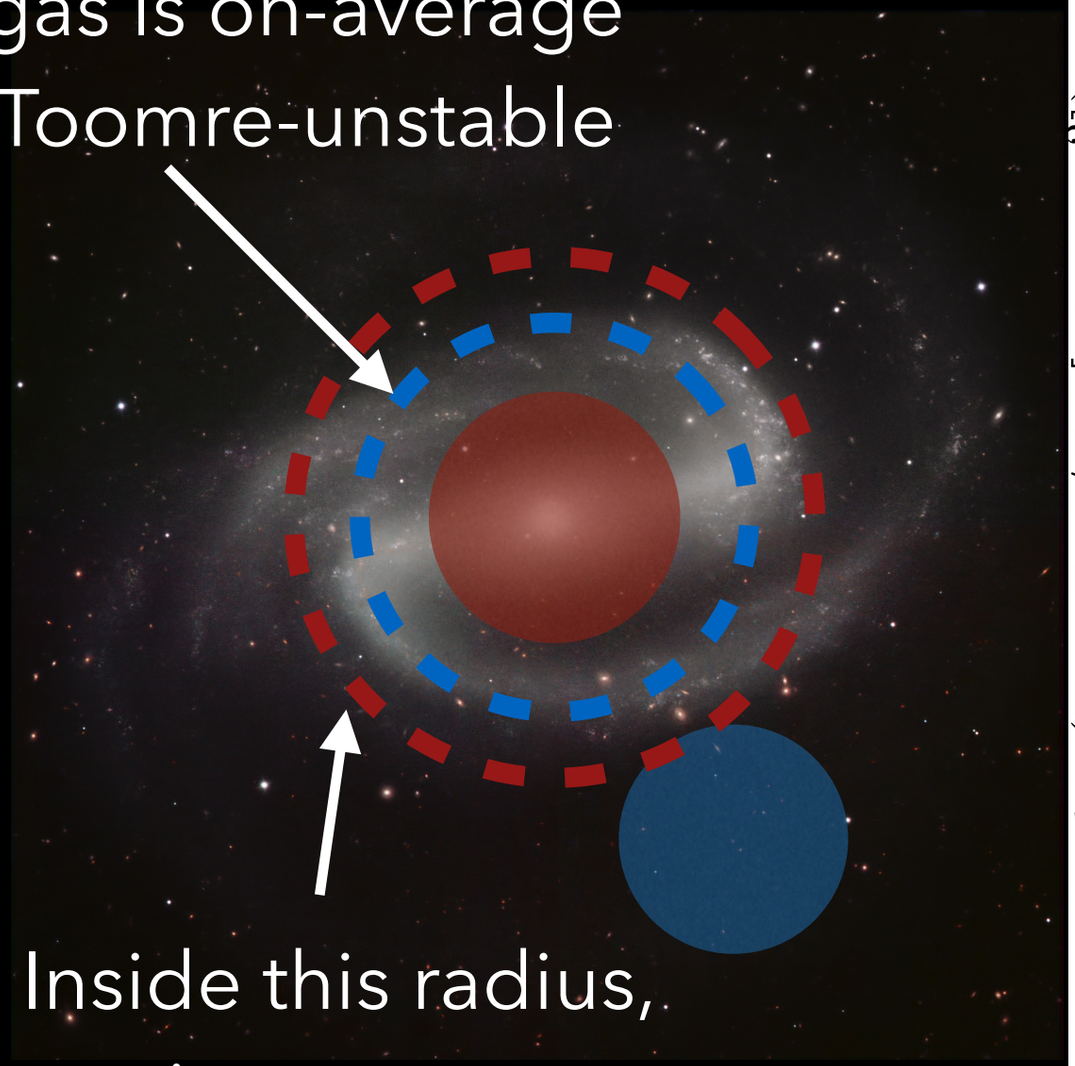
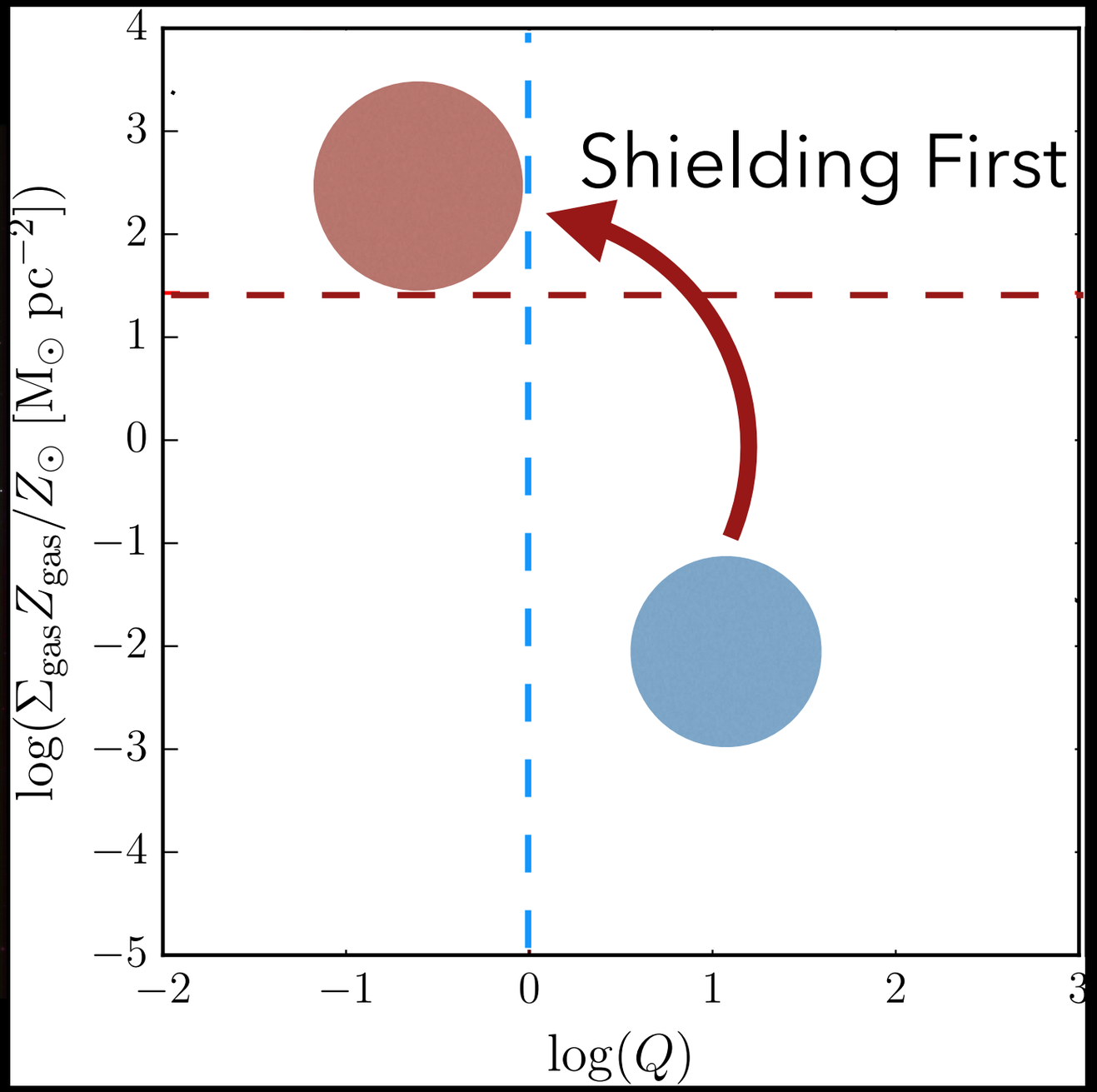
Which Radius First?

Inside this radius,
gas is on-average
Toomre-unstable



Inside this radius,
gas is on-average
self-shielded



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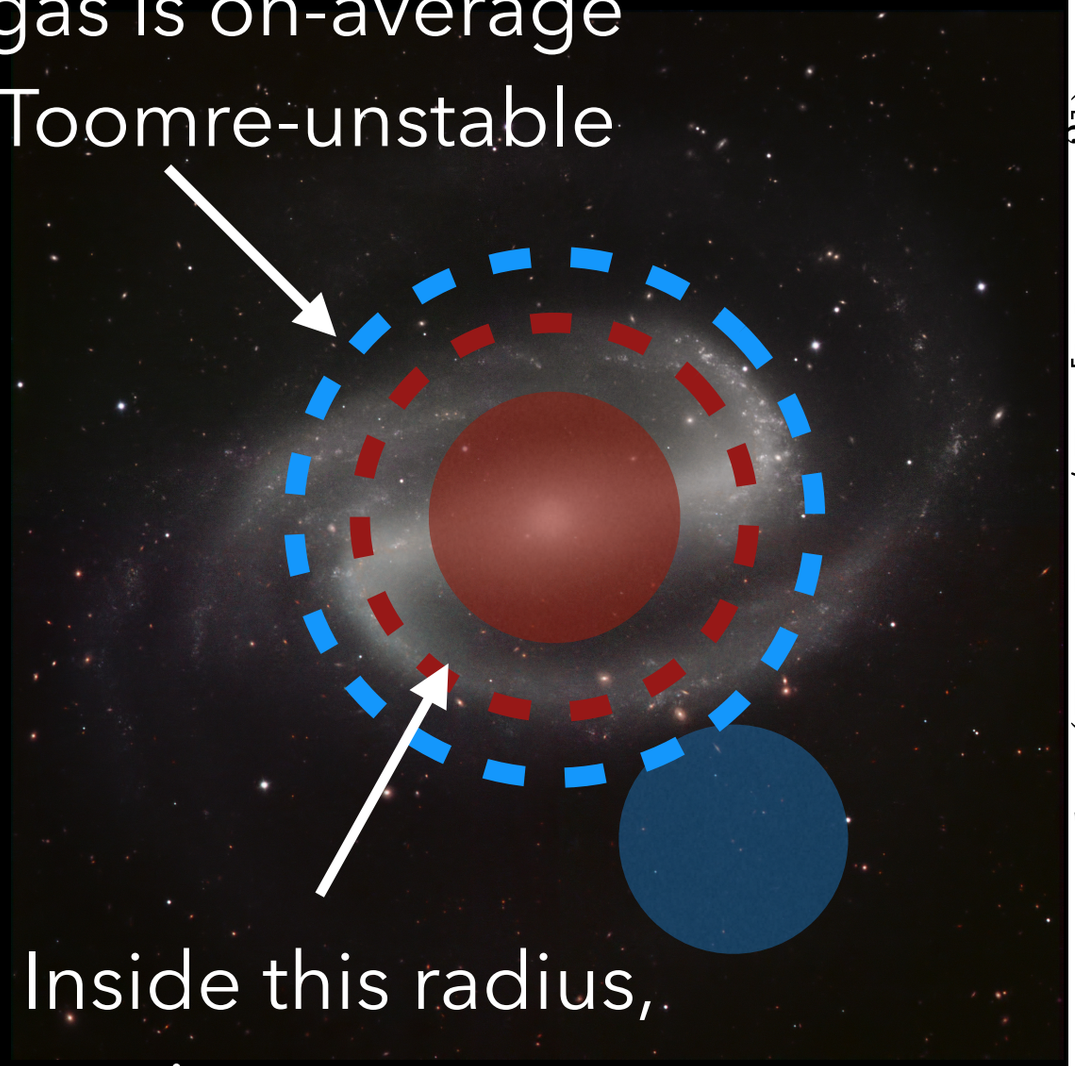
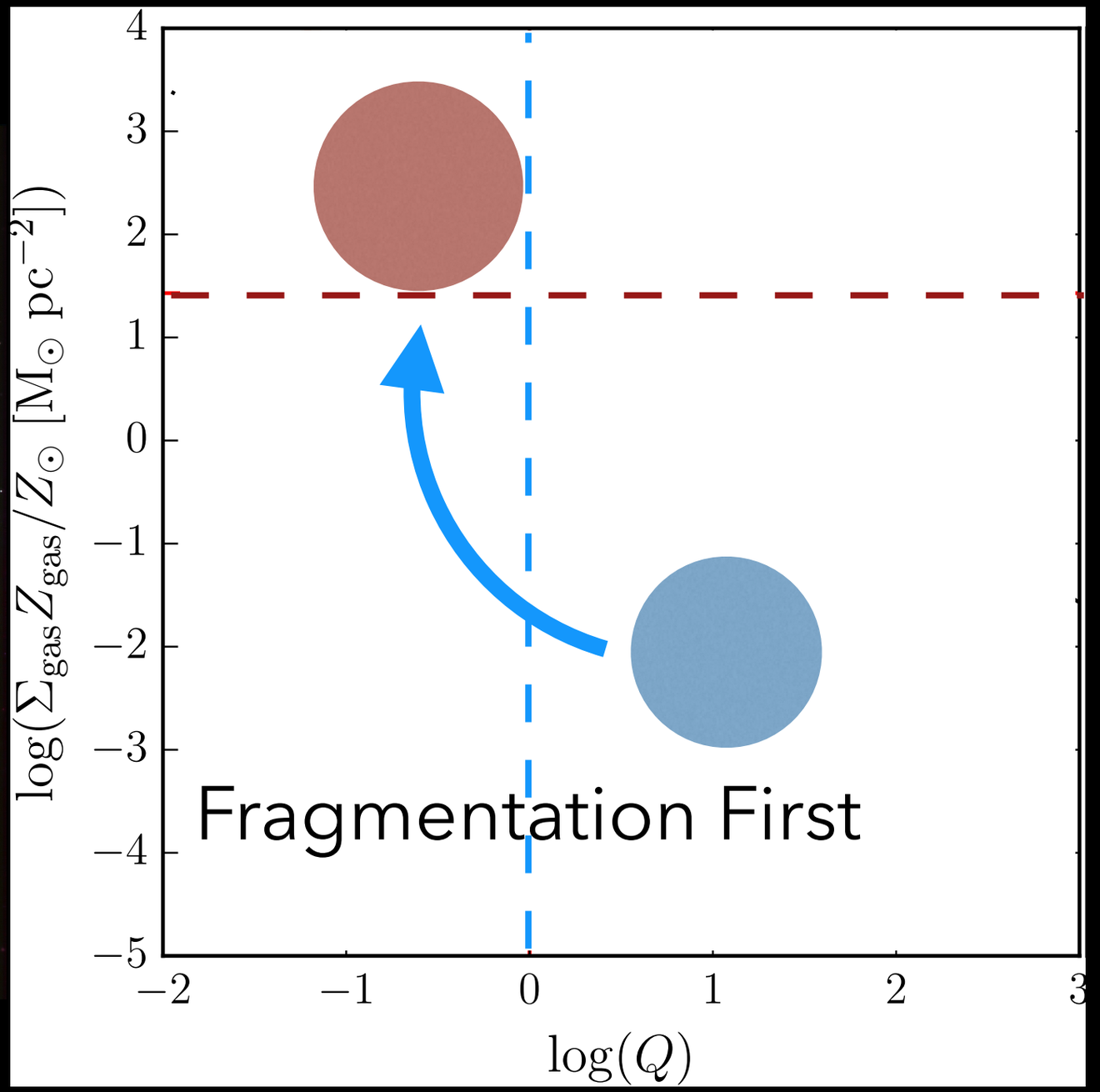
Fragmentation First?

Inside this radius,
gas is on-average
Toomre-unstable



Inside this radius,
gas is on-average
self-shielded



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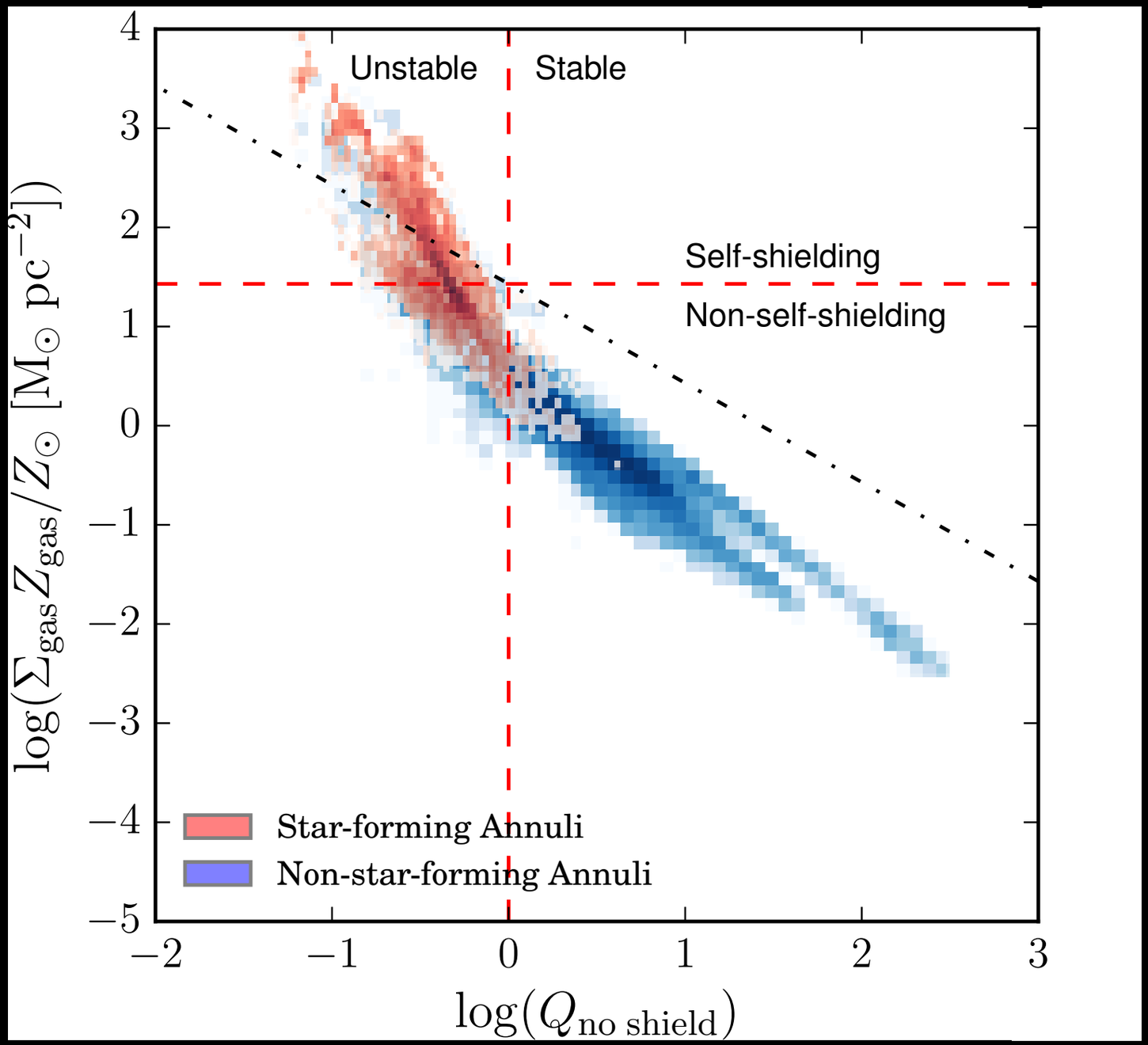
Fragmentation First

Q is a measure of stability against fragmentation

Q < 1 is unstable

$\Sigma_{\rm gas} Z/Z_\odot$ proportional to opacity



$$Q_{\rm no\ shield} \equiv \frac{\sqrt{2} c_s (T = 10^4 {\rm K}) \Omega_{\rm dyn}}{\pi G \Sigma_{\rm disk}}$$

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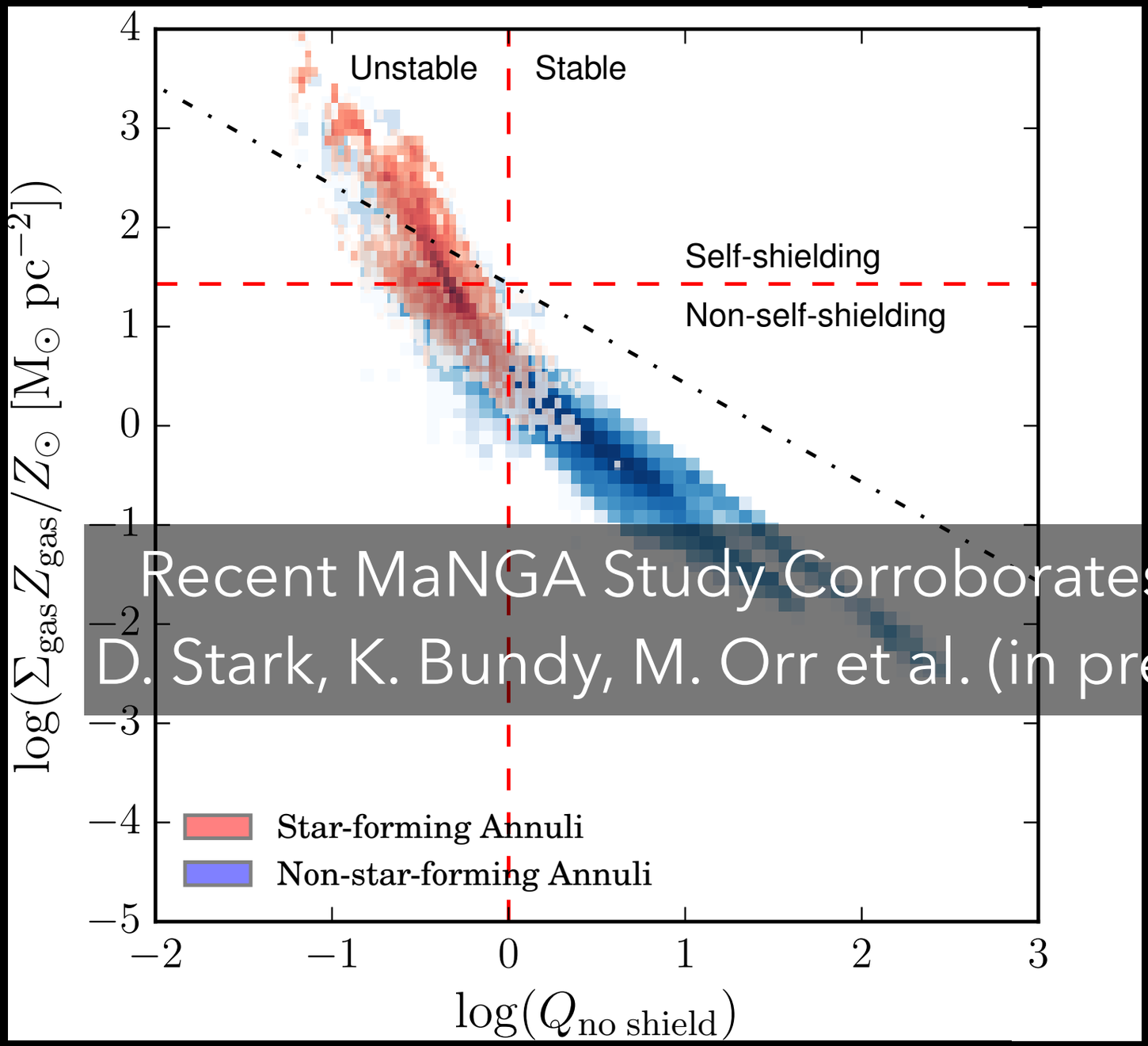

Recent MaNGA Study Corroborates!

D. Stark, K. Bundy, M. Orr et al. (in prep)

$$Q_{\rm no\ shield} \equiv \frac{\sqrt{2} c_s (T = 10^4 {\rm K}) \Omega_{\rm dyn}}{\pi G \Sigma_{\rm disk}}$$

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Conclusions

- Kennicutt-Schmidt emerges as a time and spatially averaged equilibrium between star formation and feedback processes in the FIRE simulations.

- Weak metallicity dependence.

- Star formation is triggered by gas fragmenting and then subsequently becoming self-shielding, rather than vice versa.

THANKS FOR LISTENING

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