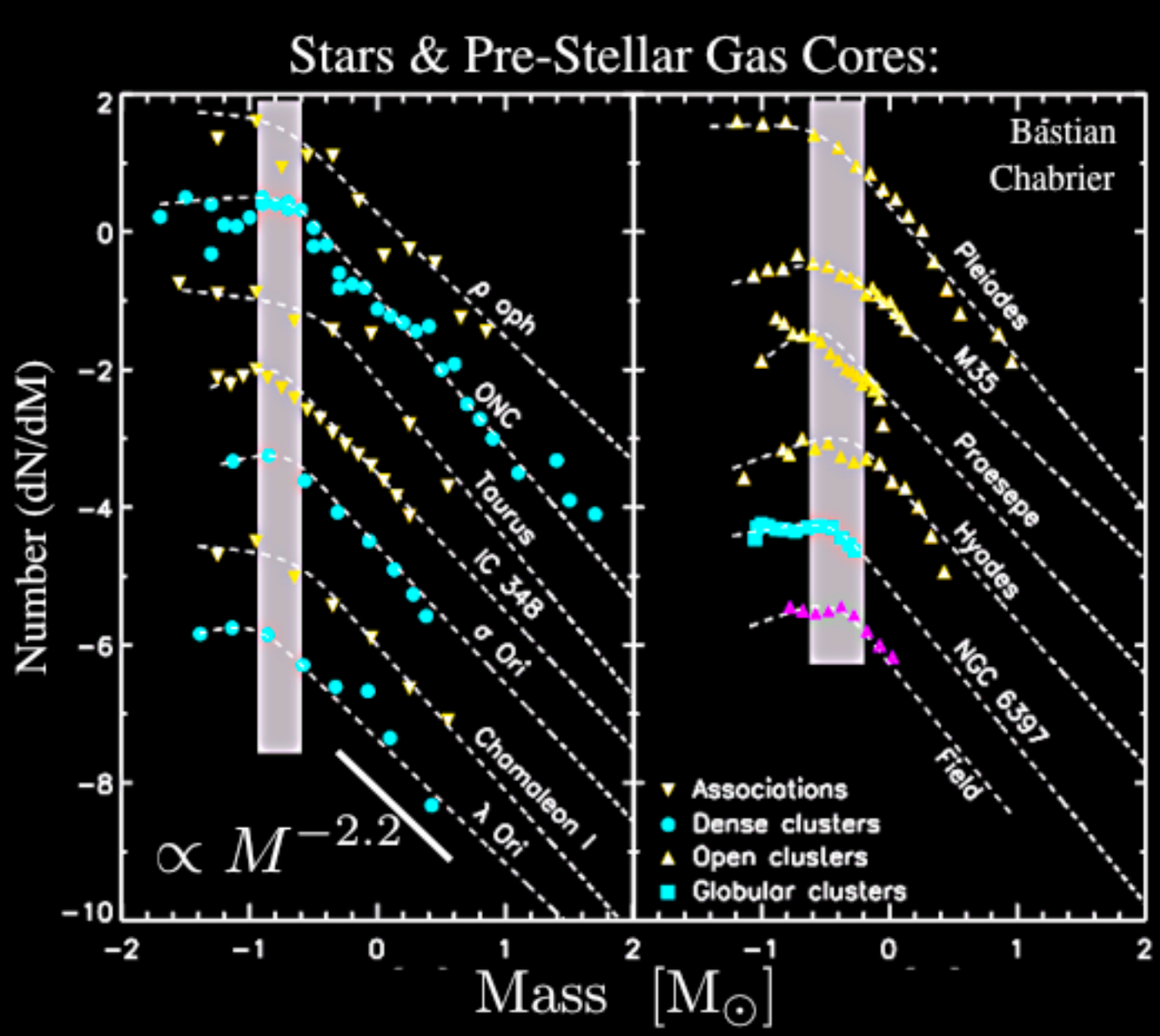
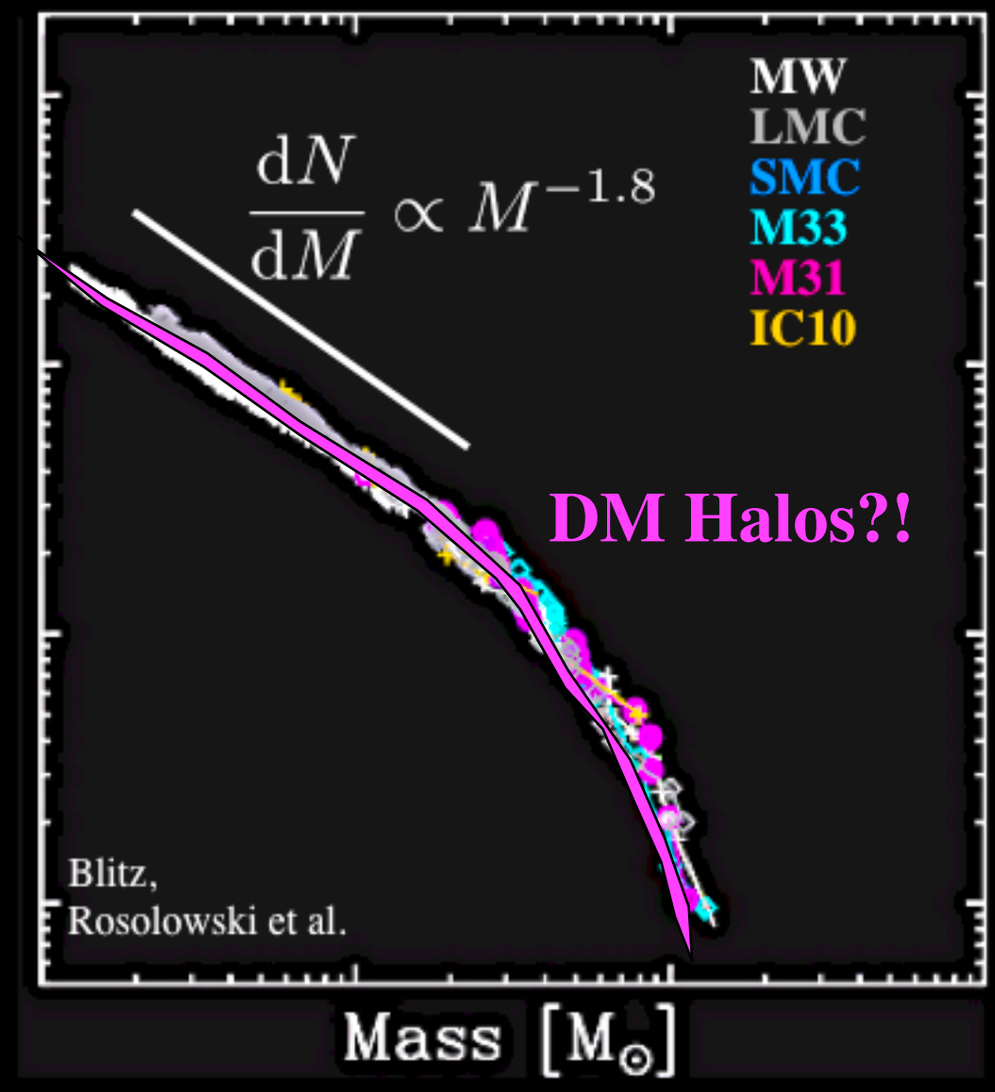
The ISM Is Messy….

YET THERE IS SHOCKING REGULARITY

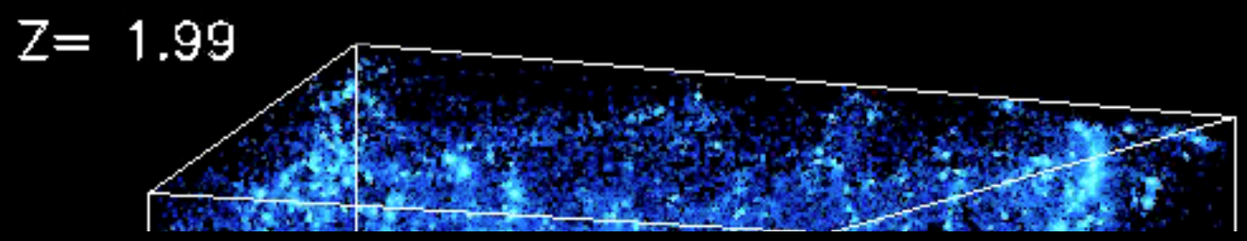




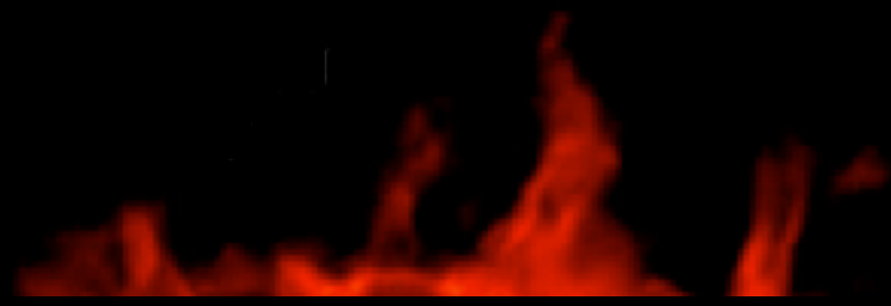
Also: correlation functions, scaling laws (size-mass)

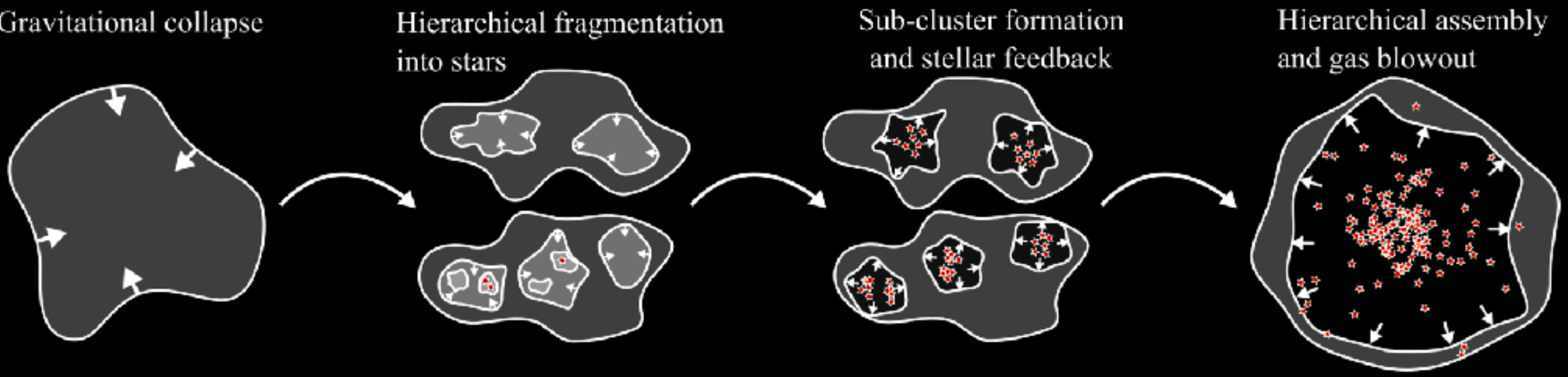
Is this an accident?

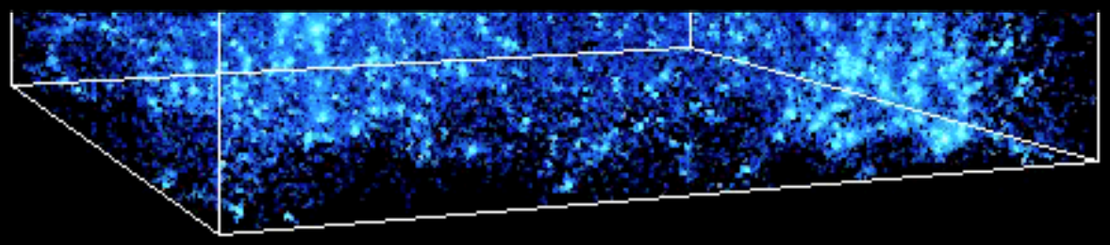
STRUCTURE FORMATION

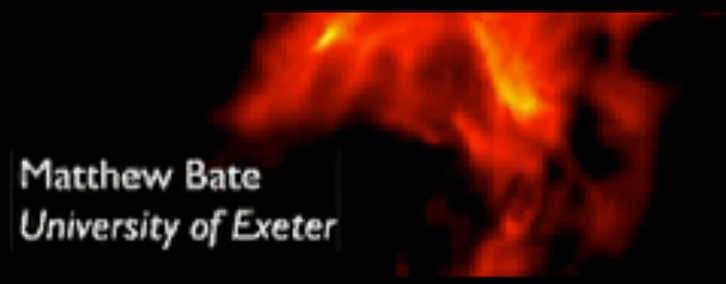


STAR FORMATION









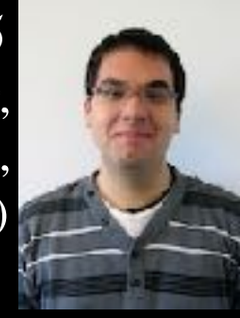
Guszejnov 15,16, 17
Grudic 16, 17 (prep)

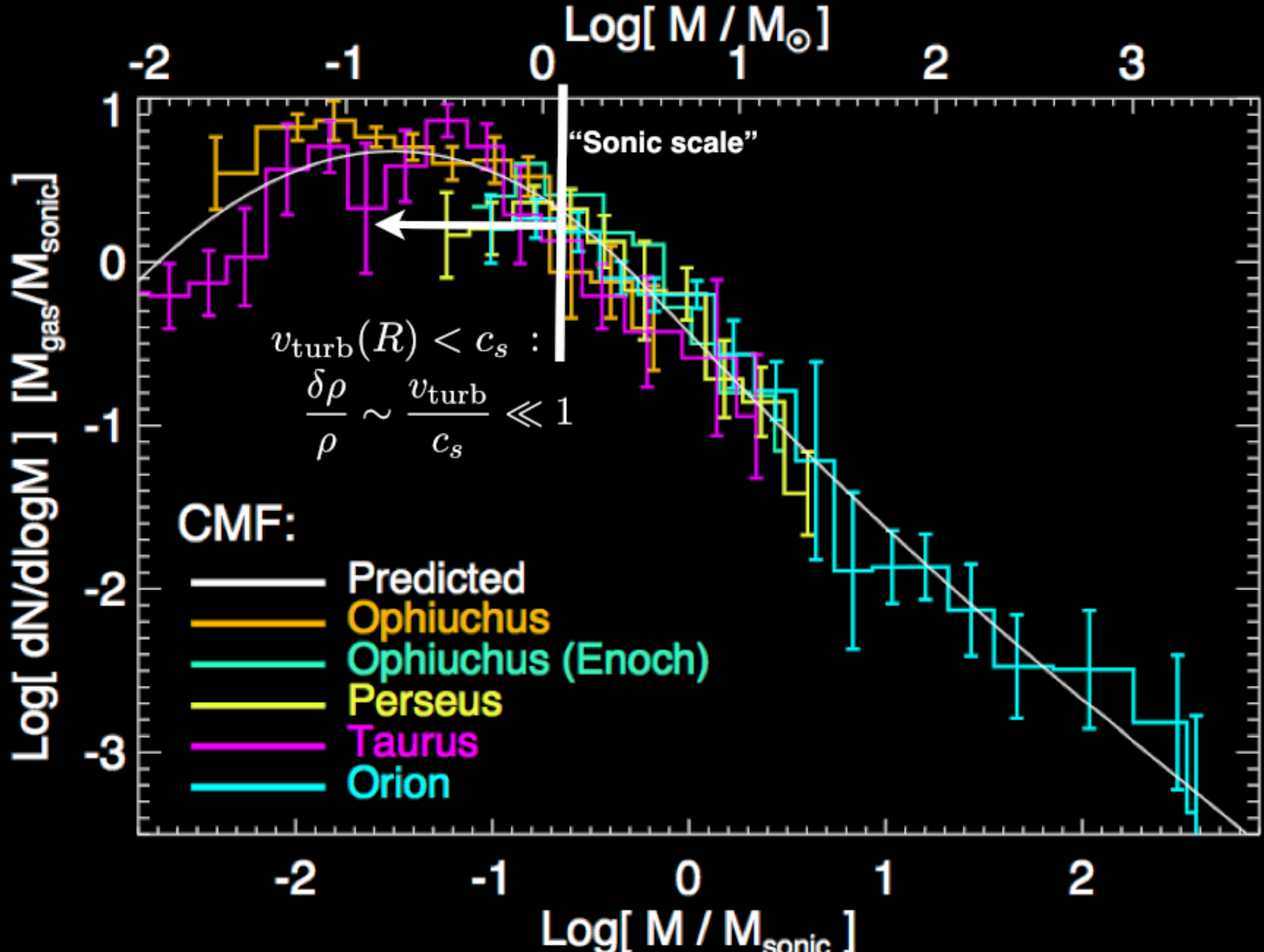
The IMF & Sub-Cloud Scales

Cores: "Smallest Structures" (Before IMF)

SALPETER SLOPE UNTIL NON-SCALE-FREE

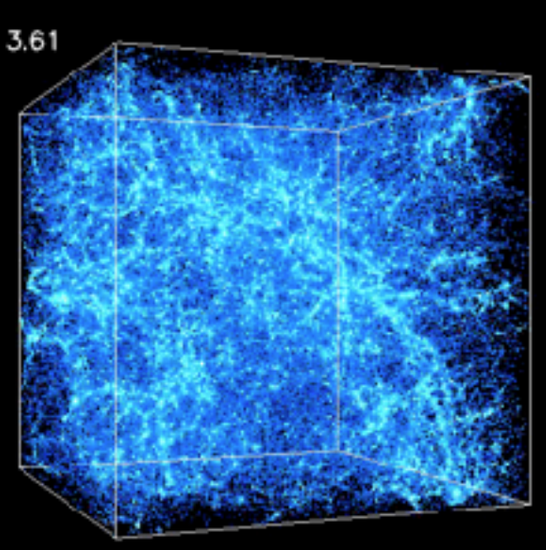
Guszejnov '15
(Hennebelle & Chabrier, Padoan & Nordlund, PFH)



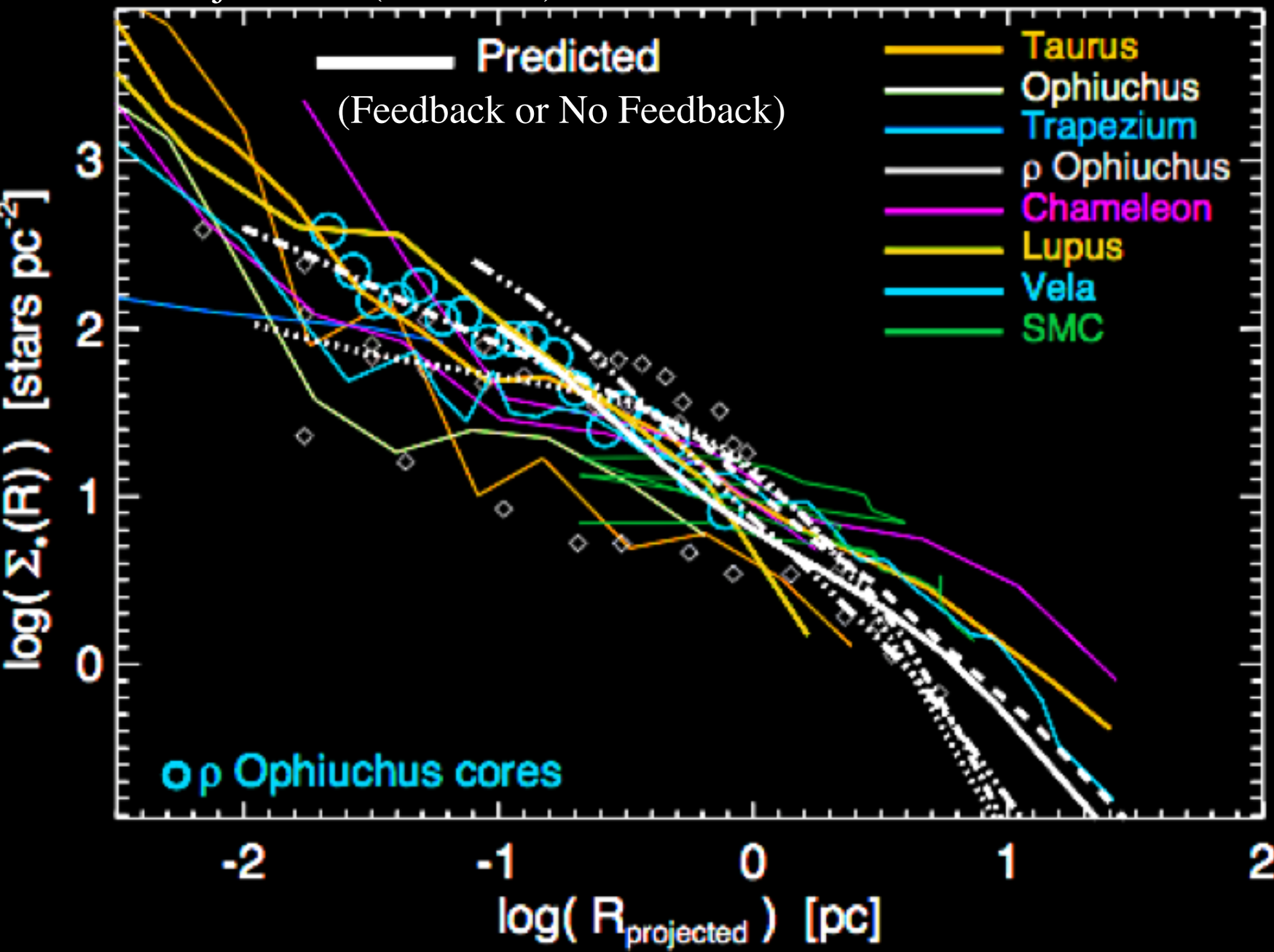


Why Is Star Formation Clustered?

INEVITABLE IN GRAVITATIONAL COLLAPSE



Guszejnov+ 16 (+PFH '12)



Guszejnov+ 17,
+ Grudic+ 17:

Stars
Cores
Clumps
GMCs
Star clusters
Galaxies

$$\xi_{3d} \propto r^{-2}$$

$$(\omega(\theta) \propto \theta^{-1})$$

(fractal D~1-1.5)

(compare Grasha+17)

GMC & Star Cluster Scales

GMCs: Just the "First Crossing"

"TOP SCALE" OF FRAGMENTATION CASCADE

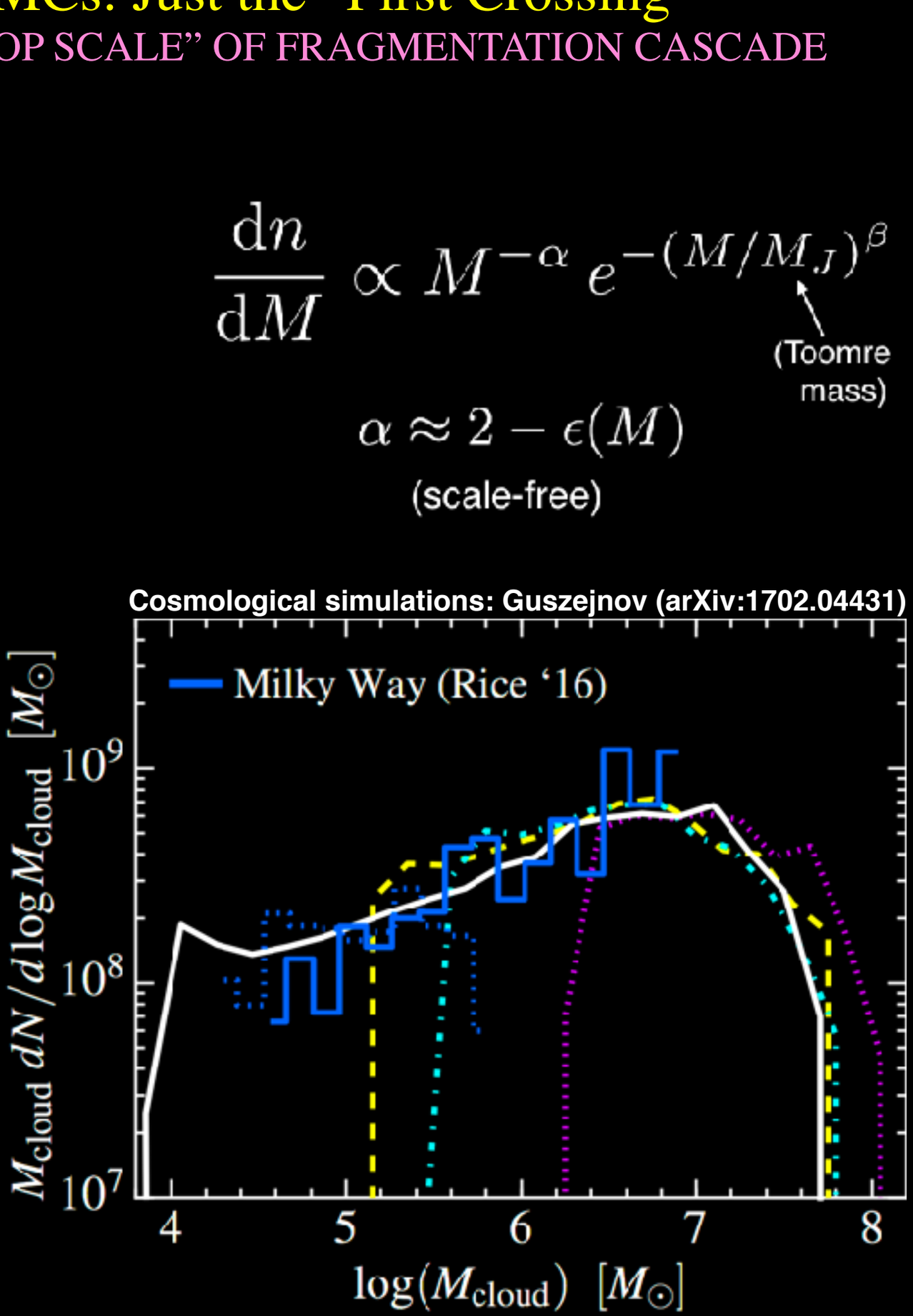
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha}\, e^{-(M/M_J)^{\beta}}$$

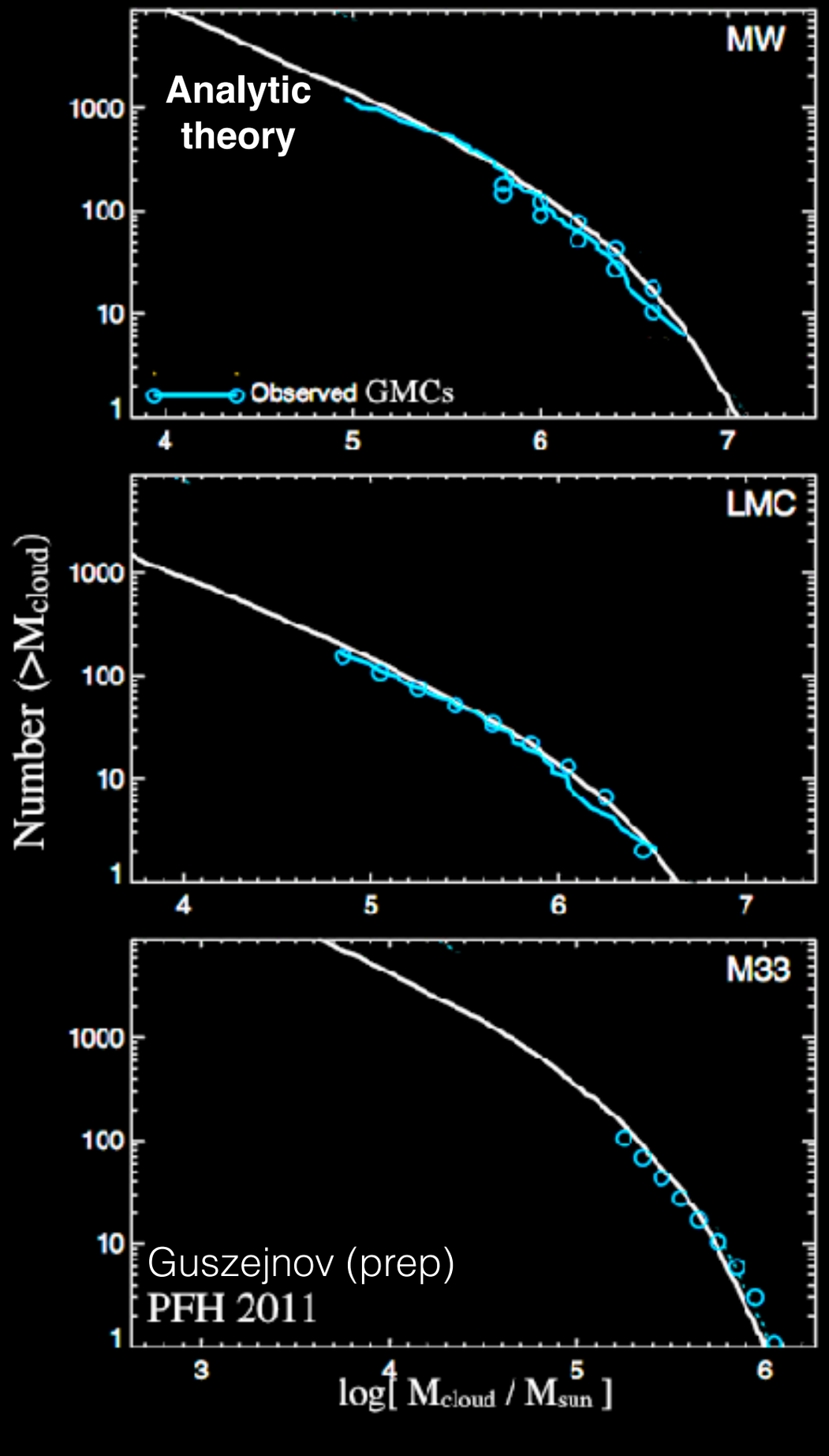
(Toomre mass)

$$\alpha \approx 2 - \epsilon(M)$$

(scale-free)

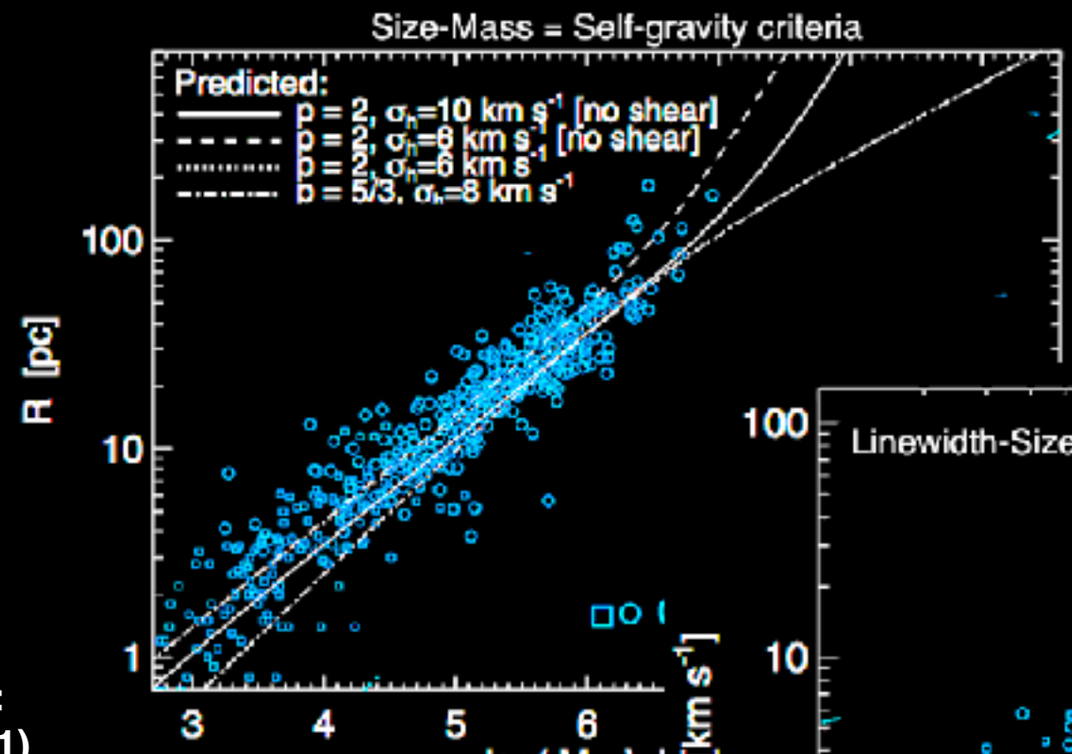
Cosmological simulations: Guszejnov (arXiv:1702.04431)



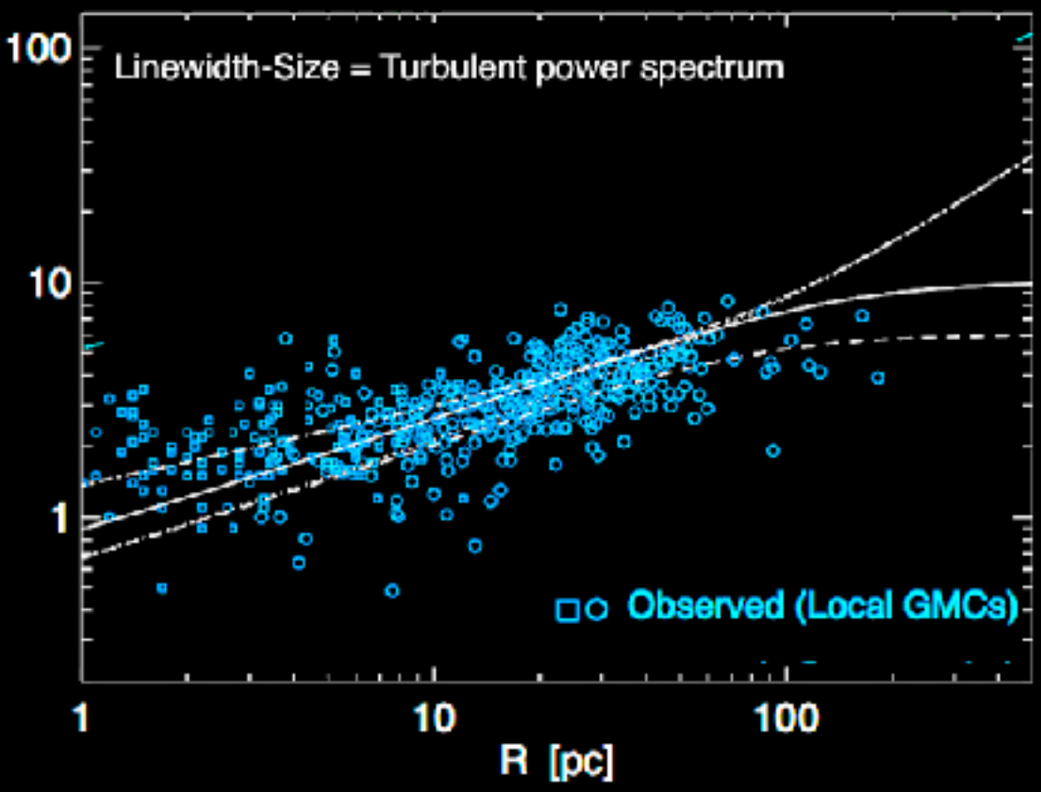


GMCs: Structural Properties

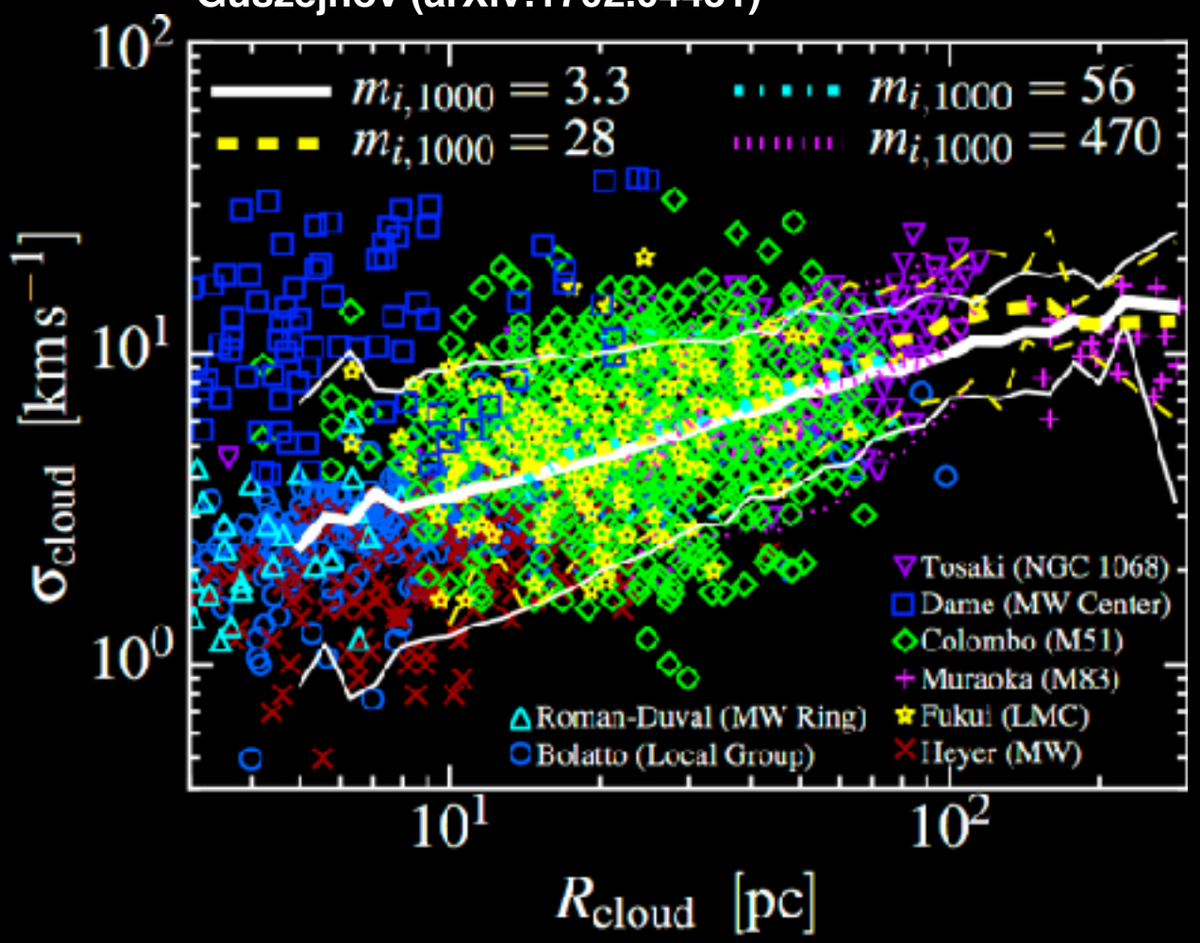
LARSON'S LAWS EMERGE = GRAVITY+TURBULENCE



Analytic Theory
PFH '11



Cosmological simulations:
Guszejnov (arXiv:1702.04431)



What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

Supernovae
+ Winds
+ Radiation Pressure
(+ Jets + Photo-heating
+ Cosmic-rays)

$$\text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (...)\, M_*$$

$$\text{Gravity} \sim \frac{G\, M_{\rm tot}\, M_{\rm gas}}{R^2} \propto M_{\rm tot}\, \Sigma_{\rm gas}$$

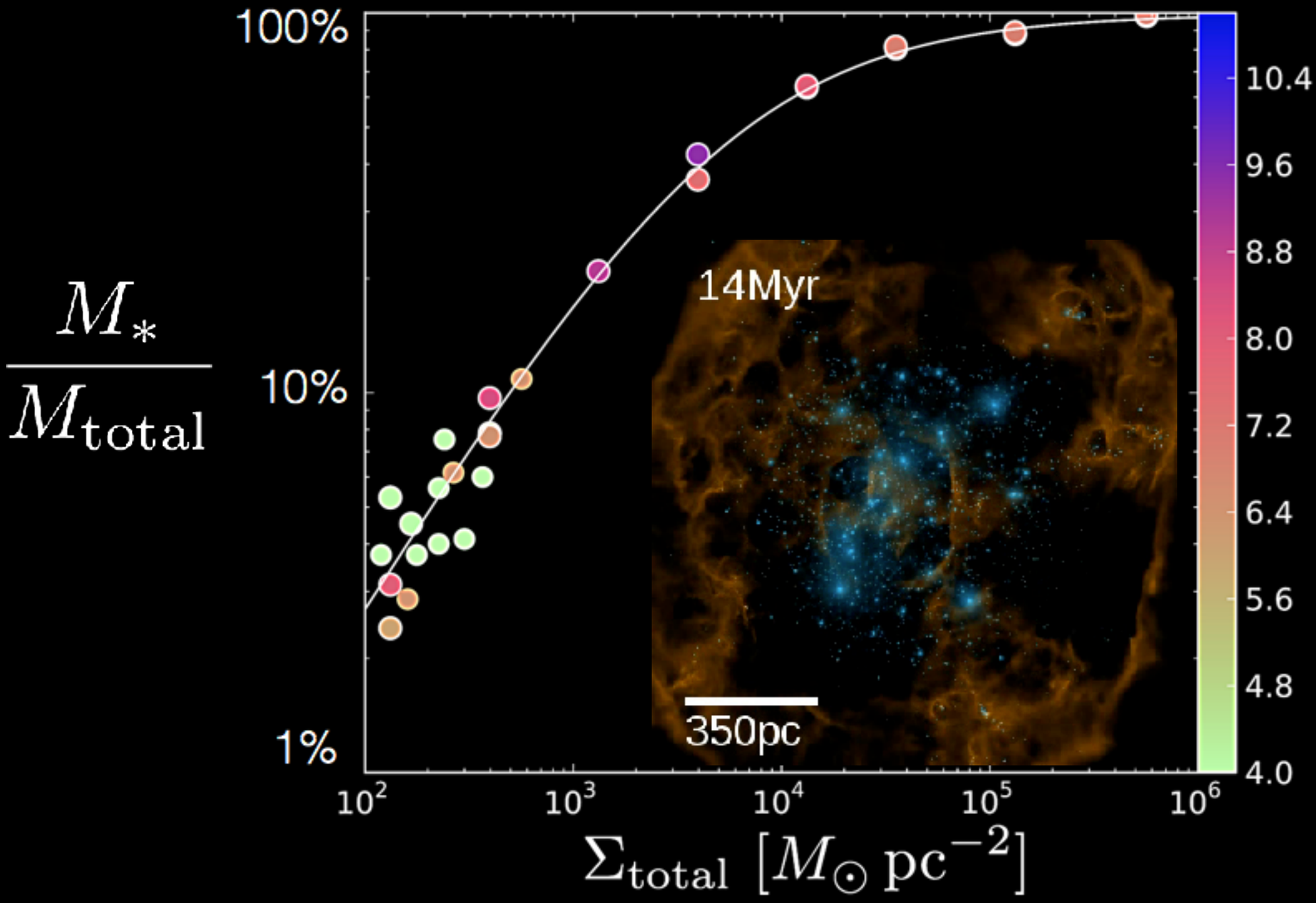
$$\rightarrow \frac{M_*}{M_{\rm tot}} \sim \frac{\Sigma}{(\text{few})\, 10^4\, M_\odot\, \text{pc}^{-2}}$$

see Matzner ’08,10

What Determines Cloud Star Formation Efficiencies?

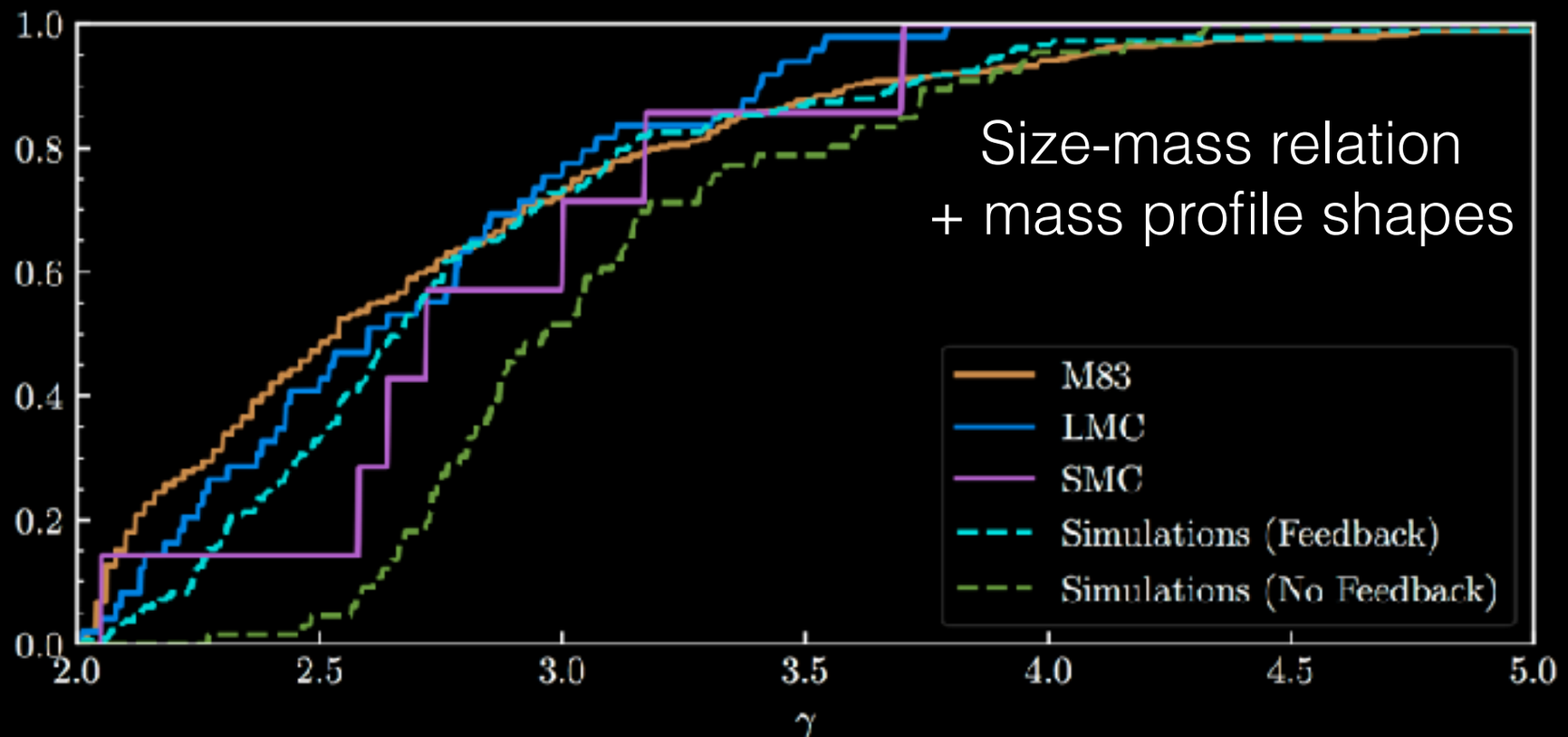
FEEDBACK VS. GRAVITY

Mike Grudic
(arXiv:
1612.05635)

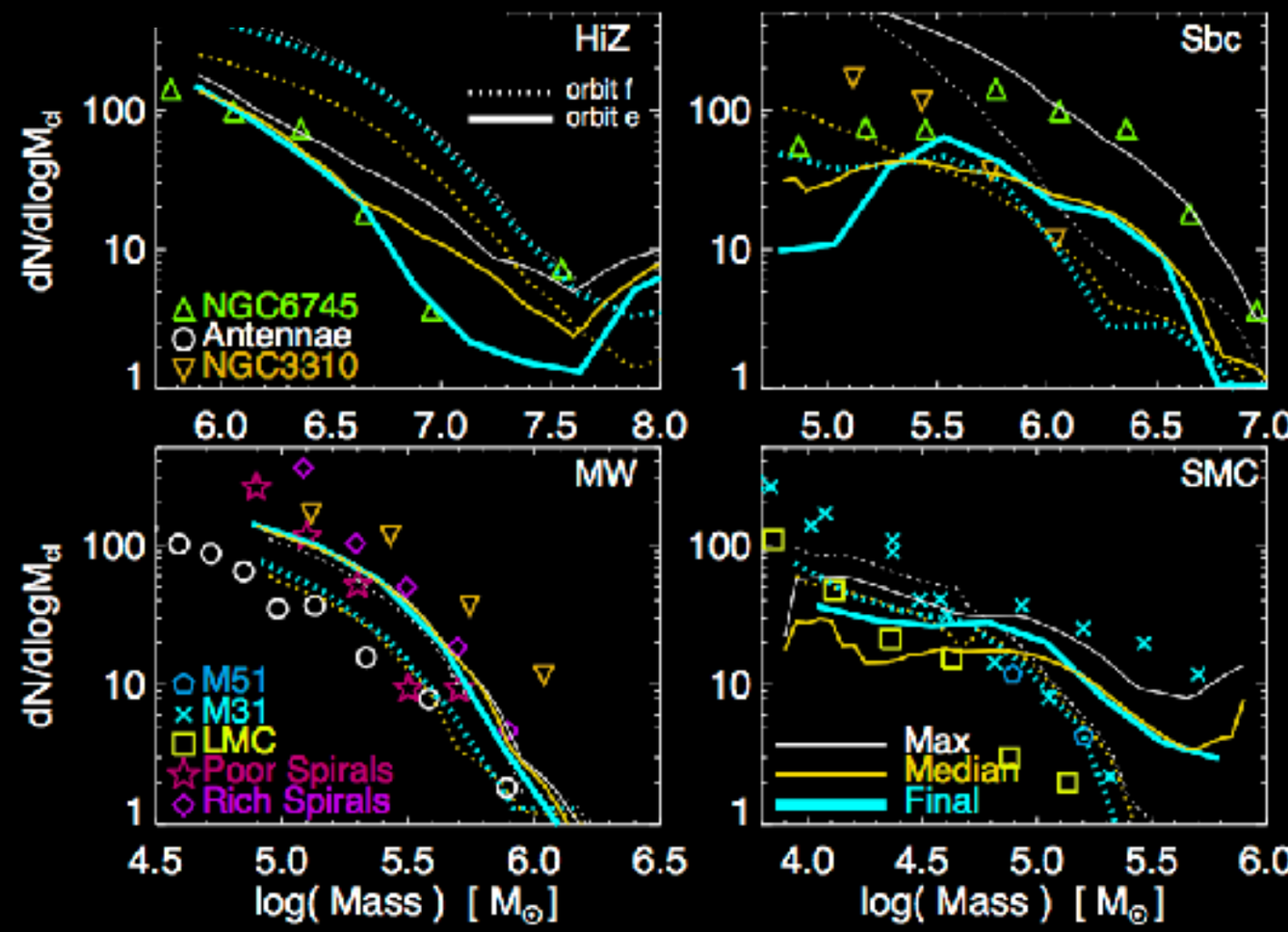


Mike Grudic
(in prep)

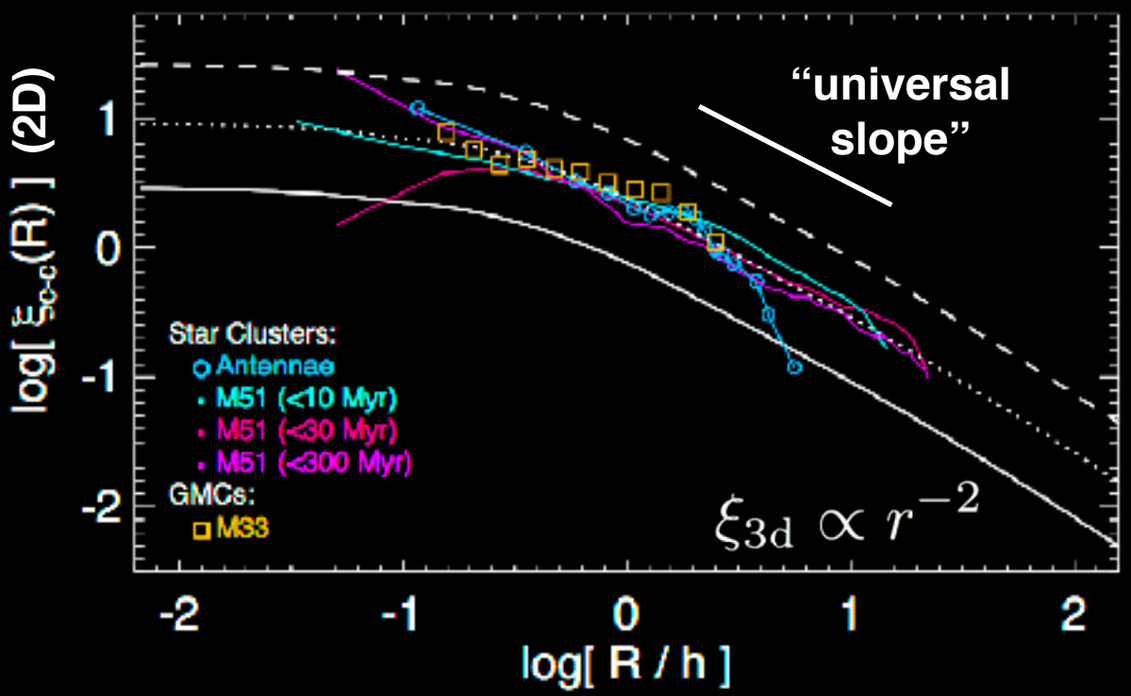
Size-mass relation + mass profile shapes



Mass functions (~M^{-2}) vs. environment



Correlation functions

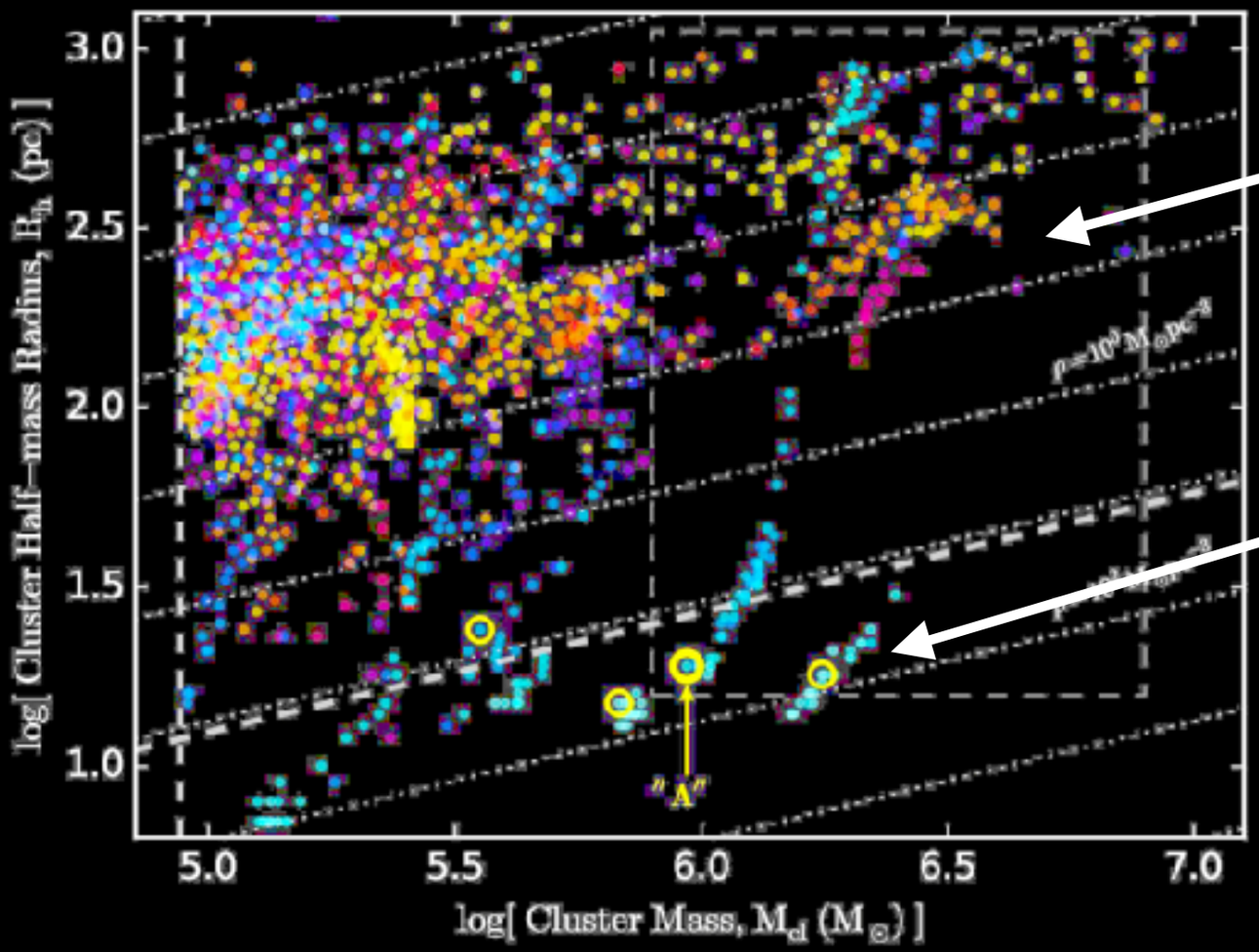


"Latte" (A. Wetzel): Cosmological MW with ~800 M_{sun} , sub-pc resolution

Resolving Bound Clusters in Fully-Cosmological Simulations

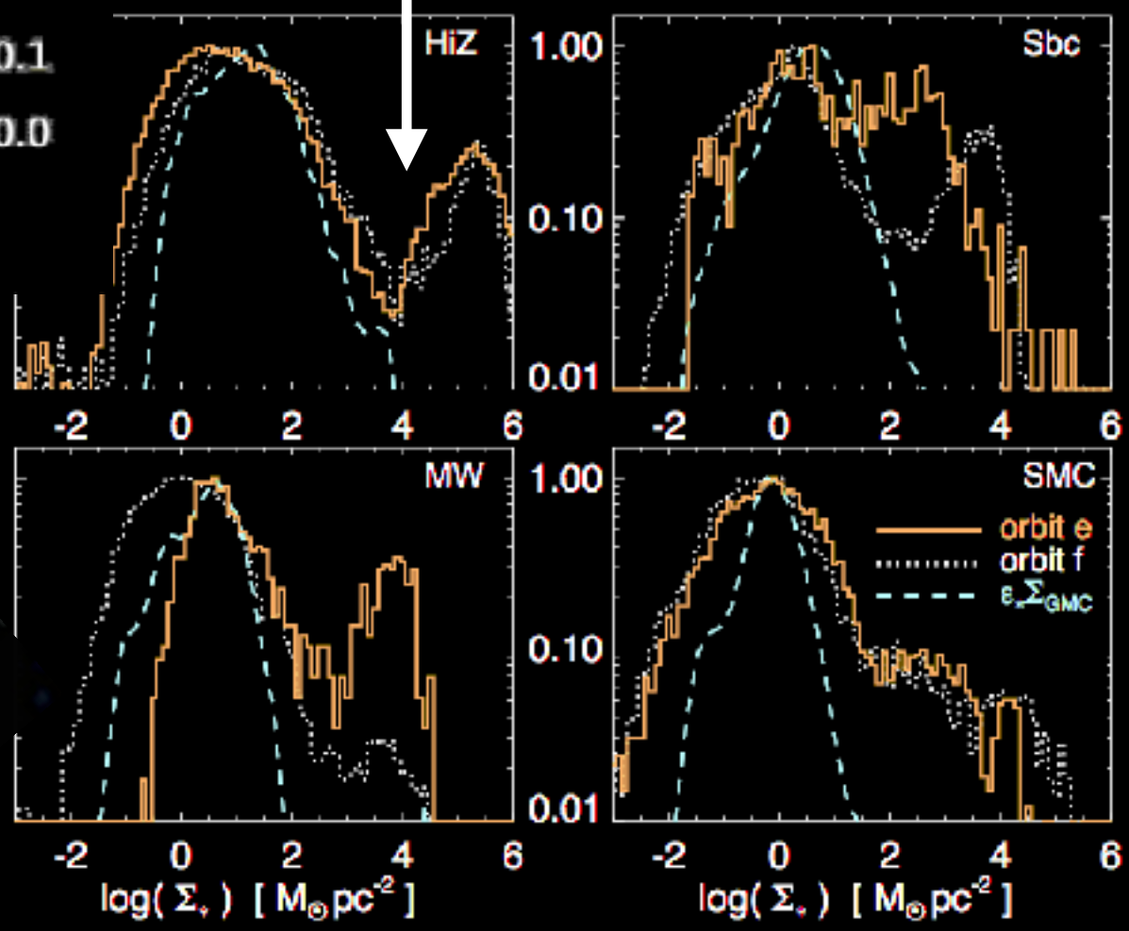
KIM '17 + GRUDIC '17: MW-MASS WITH <1000 M_{sun} RESOLUTION

Ji-Hoon Kim
(arXiv:
1704.02988)



Most form
open clusters

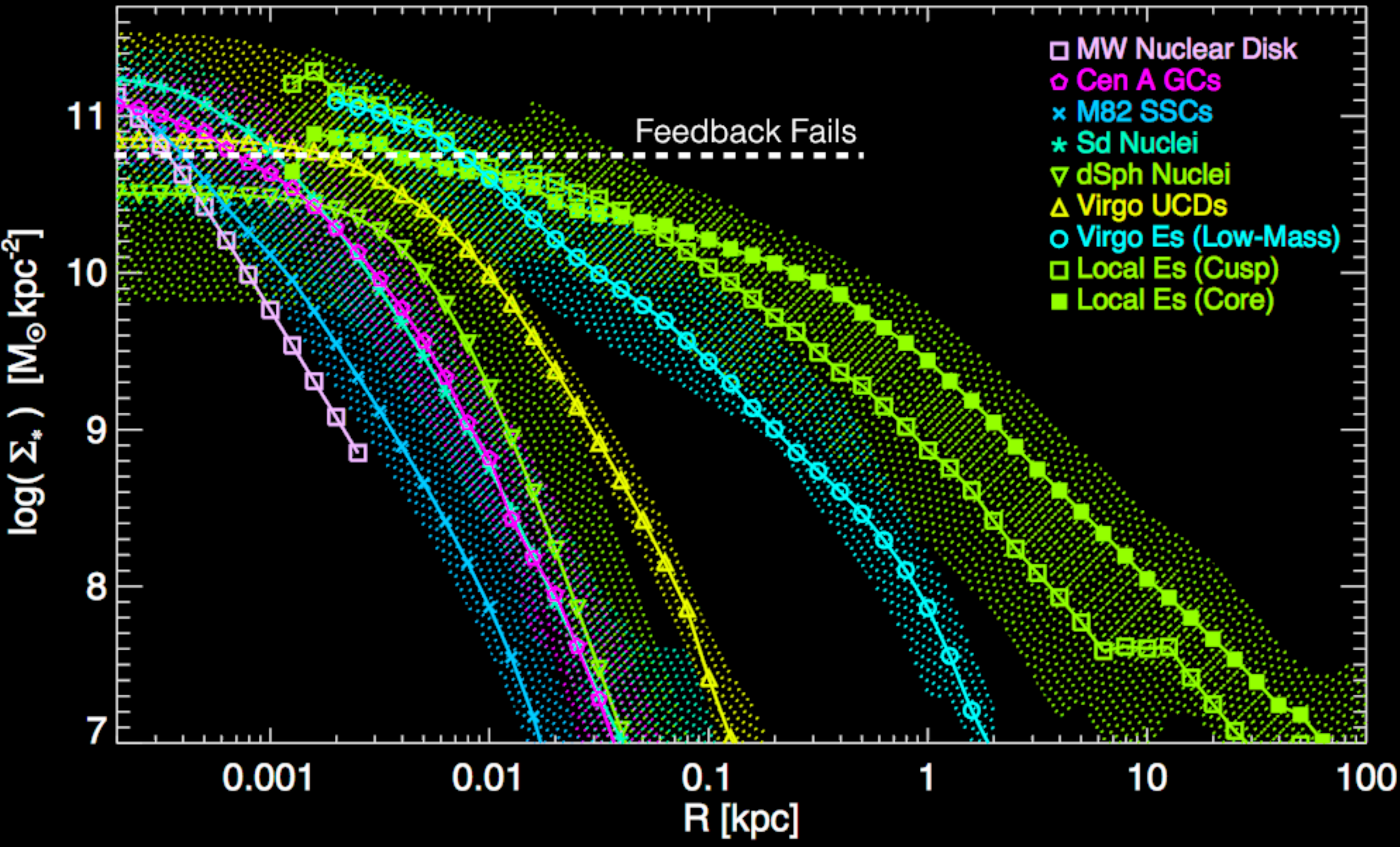
Except long-lived
population, around critical $\Sigma_{\rm cloud}$



Where Does Feedback Fail?

GRUDIC ’17: PREDICT AN “UPPER LIMIT”

Hopkins, Murray, Quataert, & Thompson 2010



Where Does Feedback Fail?

GRUDIC ’17: PREDICT AN “UPPER LIMIT”

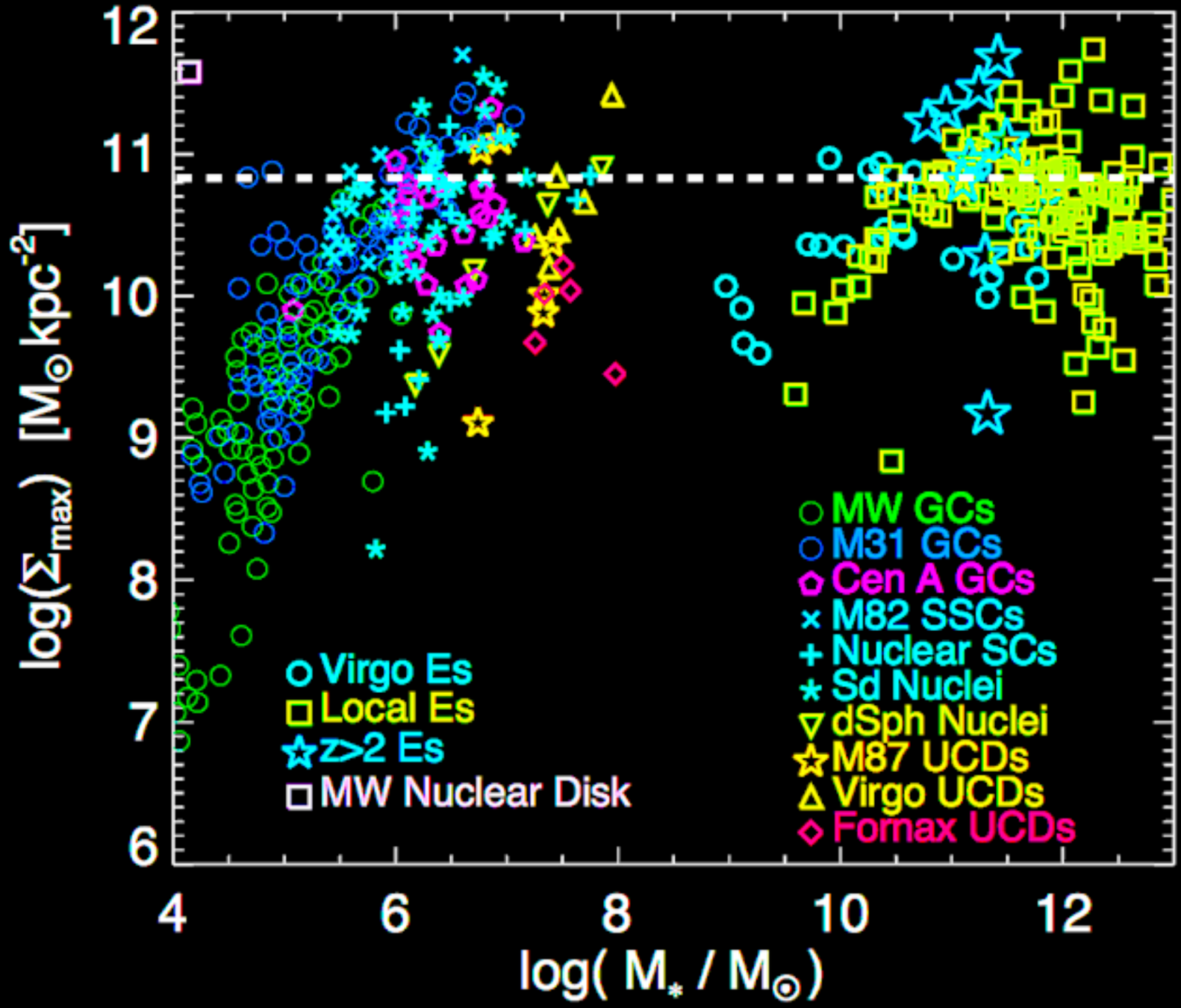
$$R_{\rm eff} \sim 0.1 - 10^4\,{\rm pc}$$

$$M_* \sim 10^4 - 10^{12}\,M_\odot$$

$$\rho \sim 1 - 10^5\,\frac{M_\odot}{{\rm pc}^3}$$

$$Z \sim 0.01 - 5\,Z_\odot$$

$$\mathrm{Redshift}_{\rm form} \sim 0 - 6$$

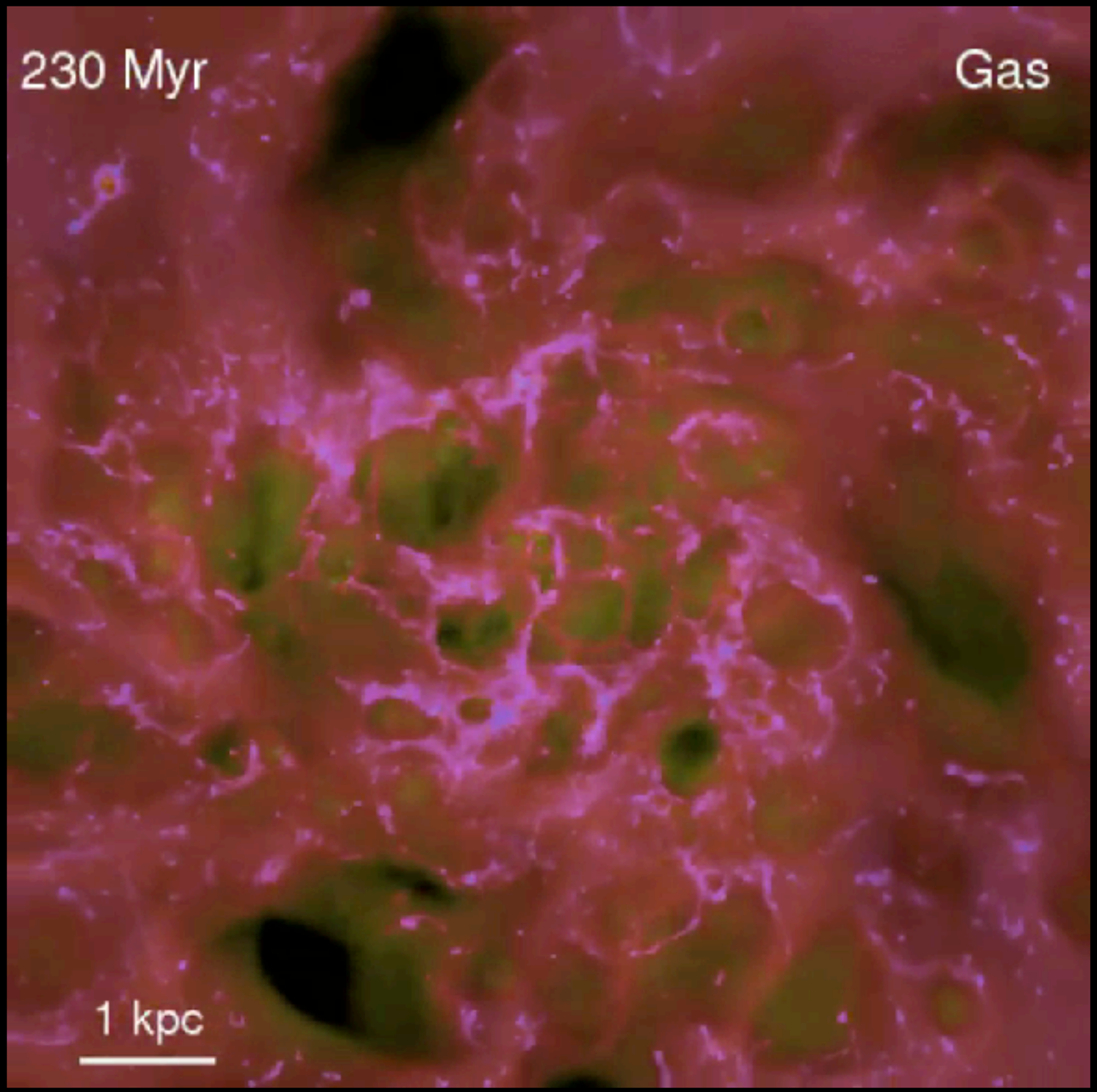


Hopkins, Murray, Quataert, & Thompson 2010

~kpc Scales: Kennicutt-Schmidt

The FIRE Project

Feedback In Realistic Environments



Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K

- **<u>Feedback:</u>**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)

- now with…
  - Magnetic fields
  - Anisotropic
    conduction & viscosity
  - Cosmic rays

KS Law Emerges Naturally

FEEDBACK VS. GRAVITY

Matt Orr (1701.01788)
Agertz+14 , PFH+ 11,12,14
Shetty & Ostriker ’08.11, Kim & Ostriker ’11,13

No Feedback

Observed

$$\frac{\text{Feedback}}{\text{Area}} \propto (...)\,\dot{\Sigma}_*$$

$$\frac{\text{Gravity}}{\text{Area}} \propto G\,\Sigma_{\rm tot}\,\Sigma_{\rm gas} \propto \Sigma_{\rm gas}^{1-2}$$

$\log(\,\Sigma_{\rm SFR}\,)$ $[\mathrm{M_\odot\ yr^{-1}\ kpc^{-2}}]$

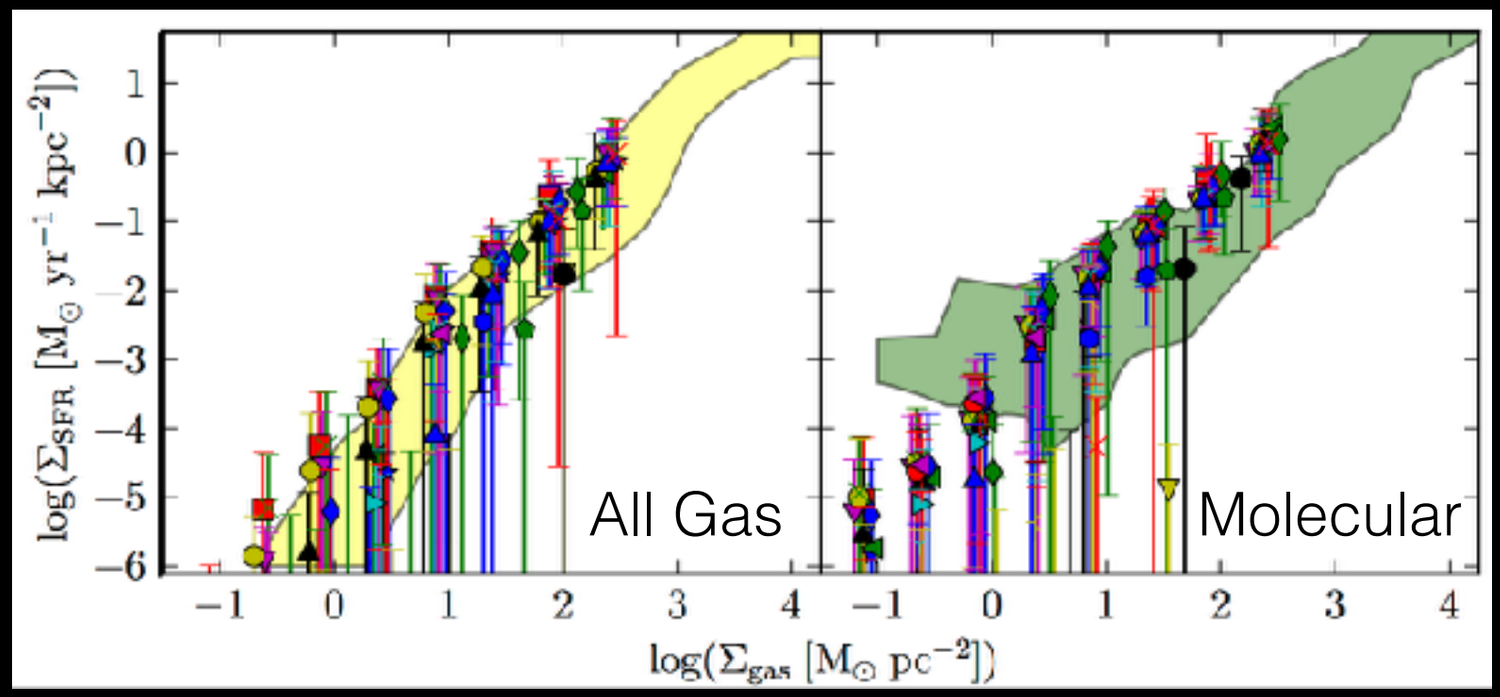
$\log(\,\Sigma_{\rm gas}\,)$ $[\mathrm{M_\odot\ pc^{-2}}]$

2 1 0 −1 −2 −3 −4 −5

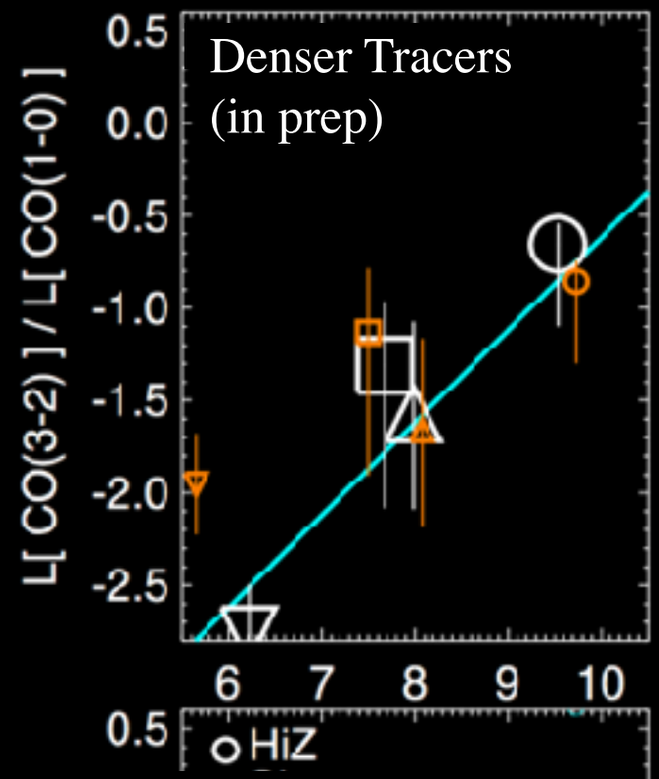
0 1 2 3 4

The KS Law: It's Feedback.

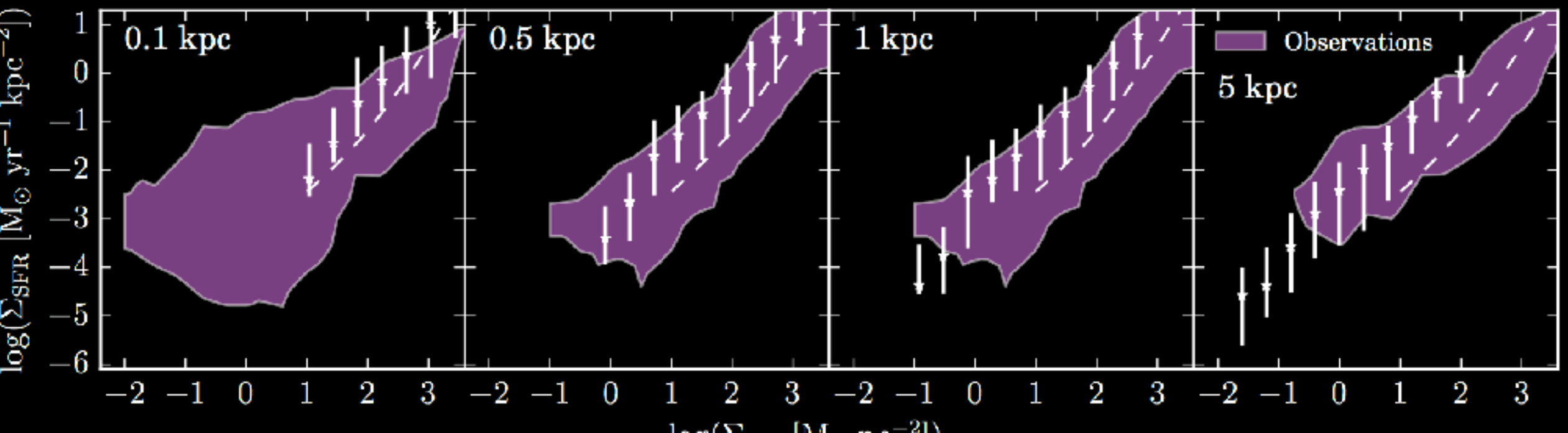
Matt Orr (1701.01788)
Agertz+14 , PFH+ 11,12,14
Shetty & Ostriker '08.11
Kim & Ostriker '11,13



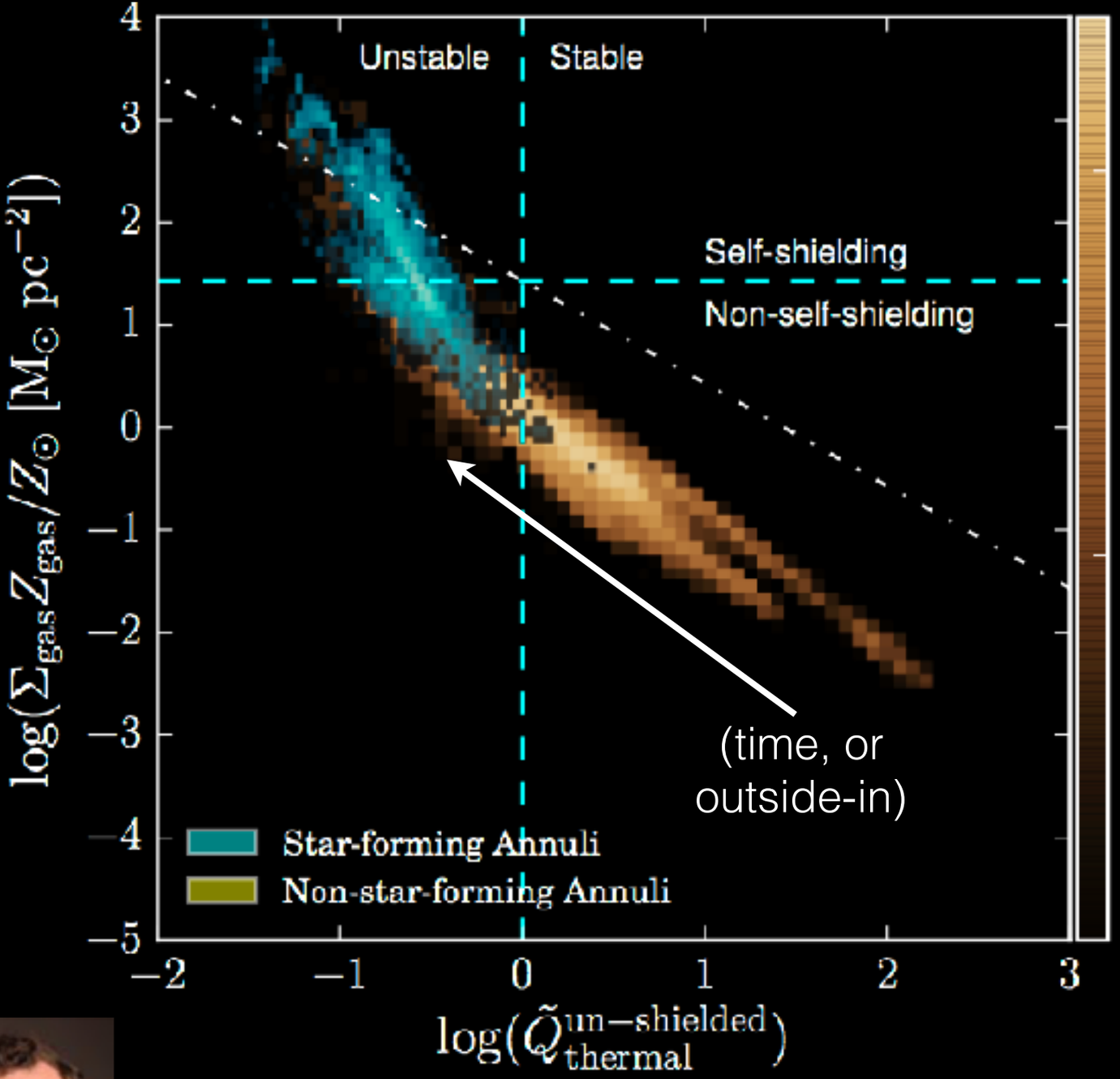
Redshift-independent, weakly metallicity-dependent



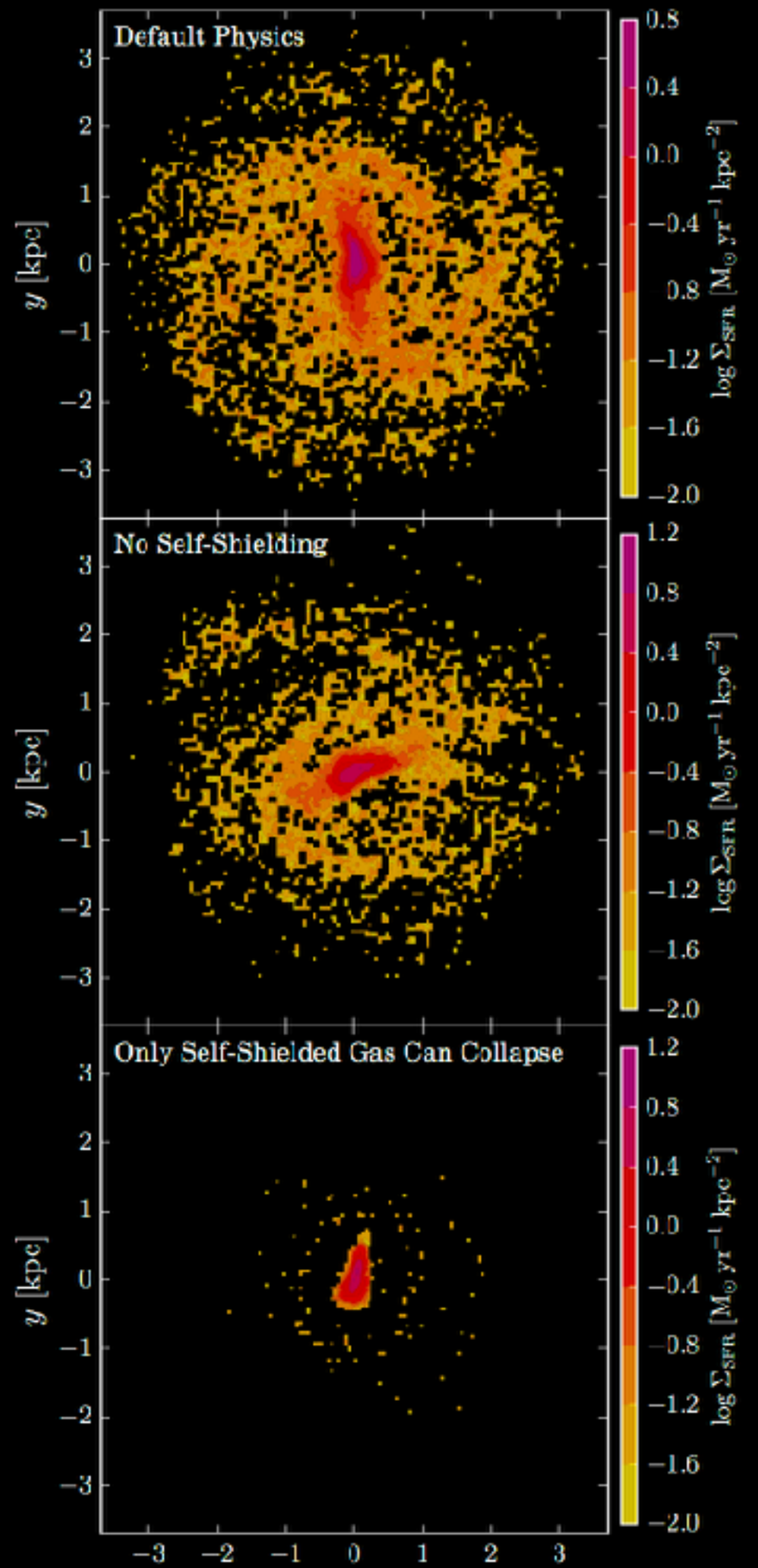
Weak size-scale dependence:



The KS Law: It's Feedback + Gravity

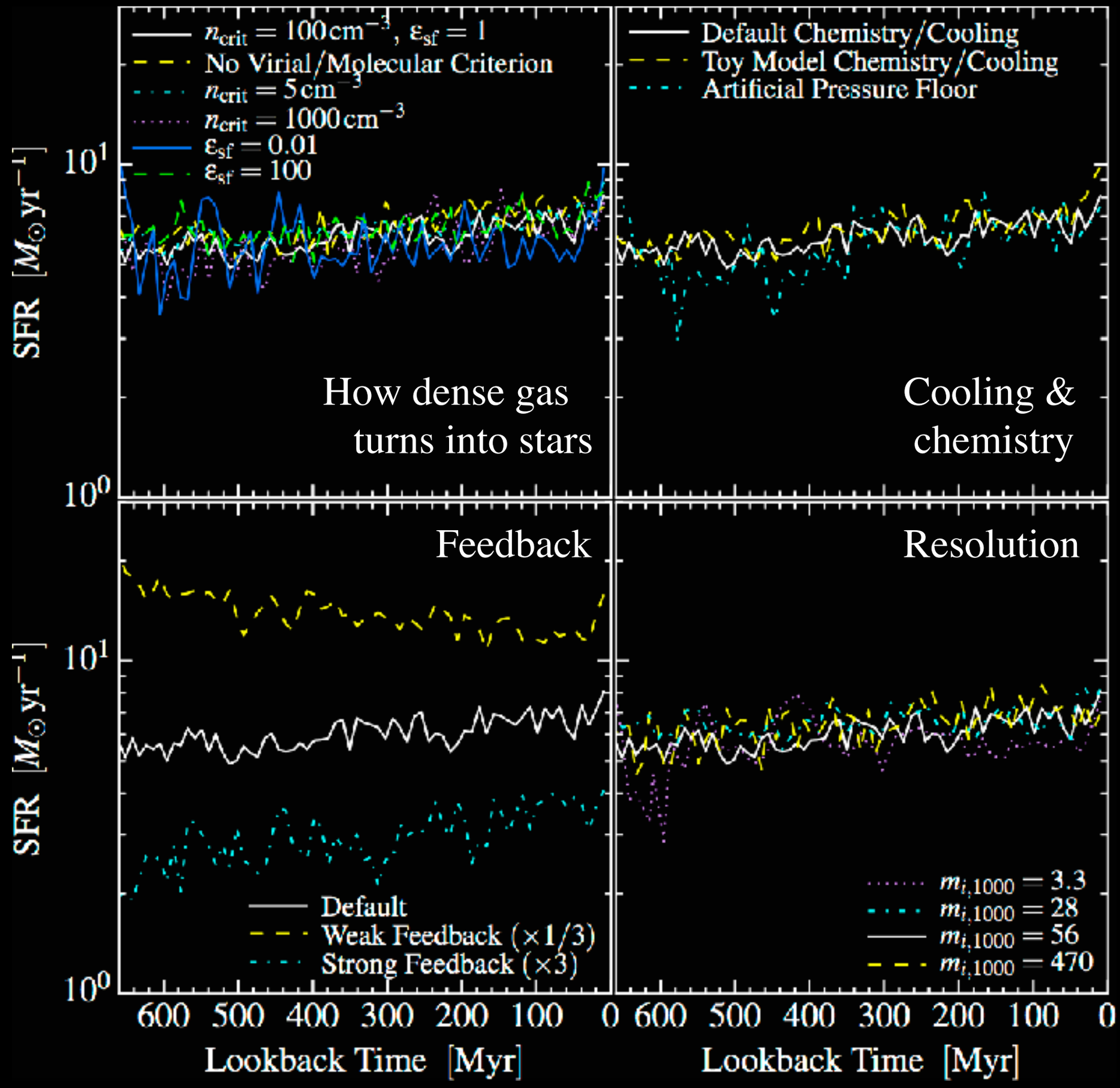


Matt Orr (arXiv:1701.01788)



(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!

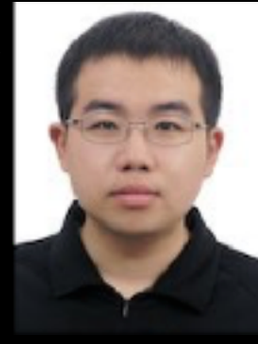
Orr (1701.01788)
Saitoh+ 11
Hopkins+ 11,12,14
Agertz+14

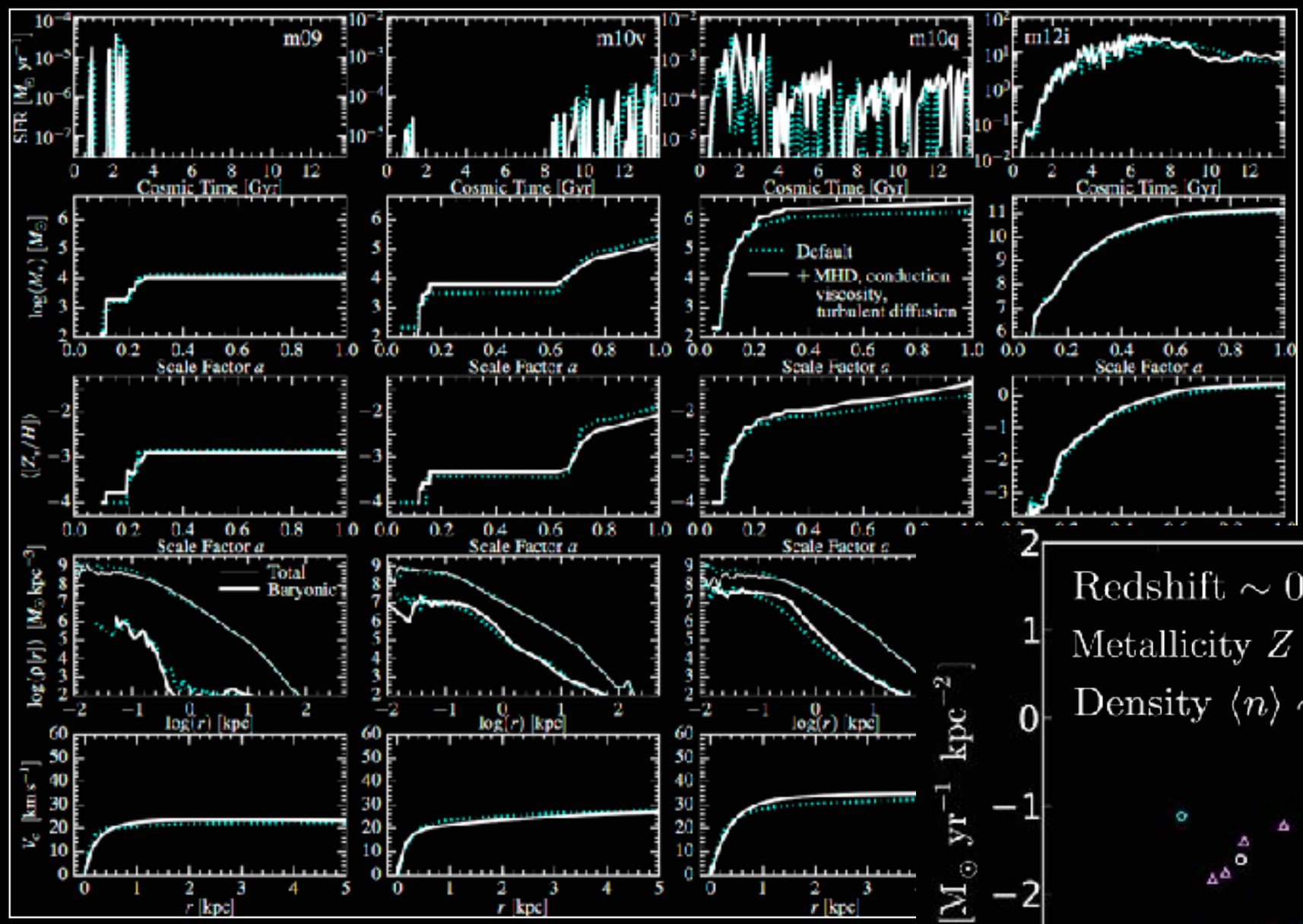


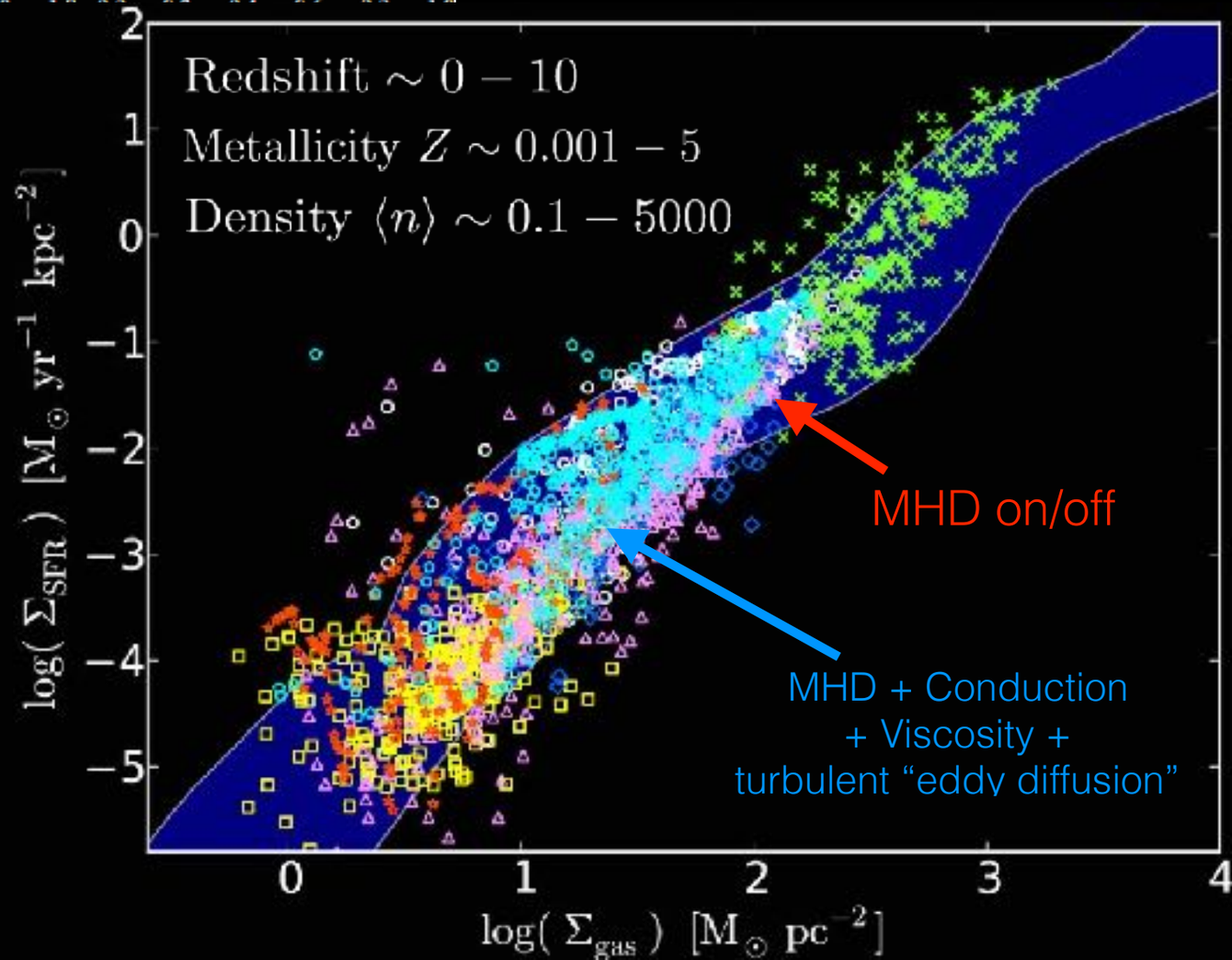
No dependence on MHD, conduction, viscosity, etc.

ONLY SEE IF FEEDBACK IS ARTIFICIALLY WEAK

Kung-Yi Su
(arXiv:
1607.05274)



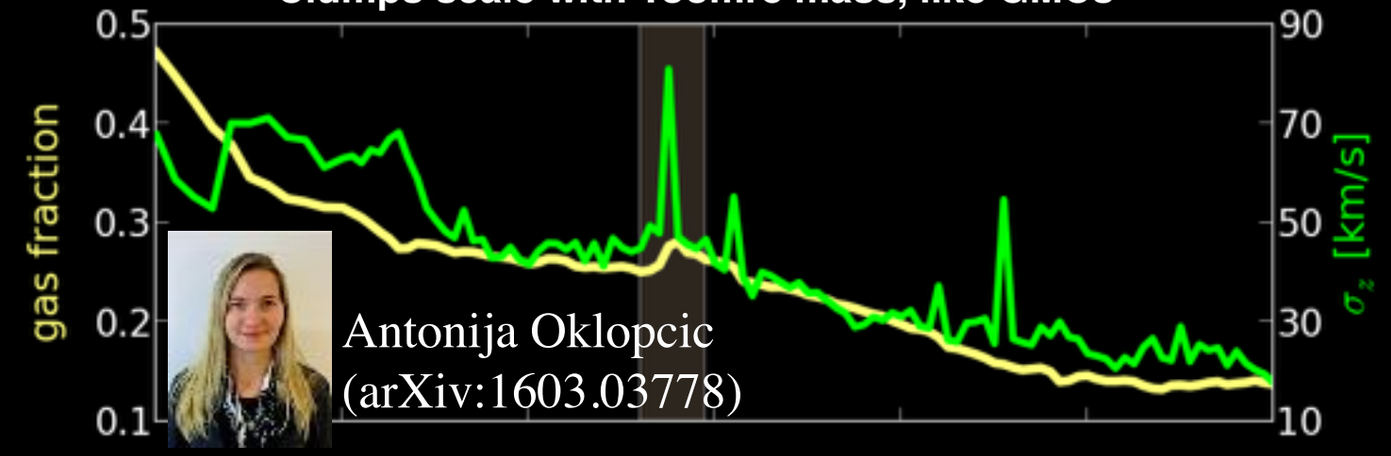




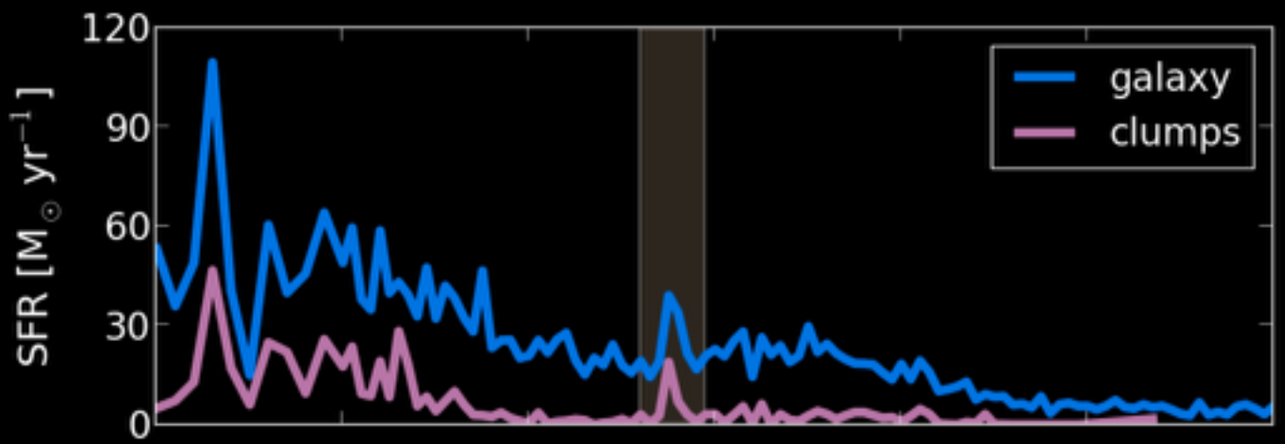
Giant "Clumps"

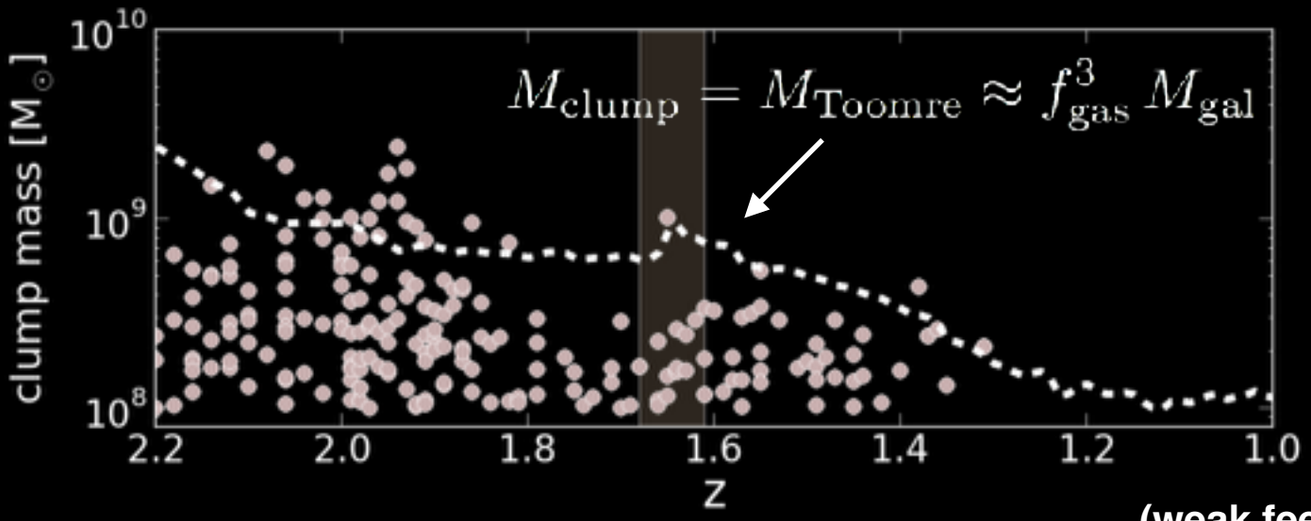
JUST AN EXTENSION OF GMCs

Clumps scale with Toomre mass, like GMCs

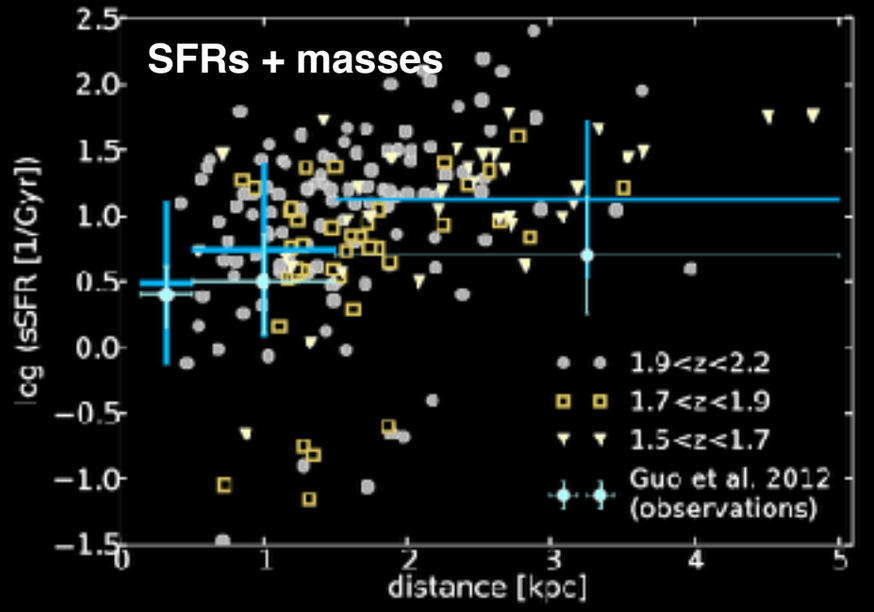


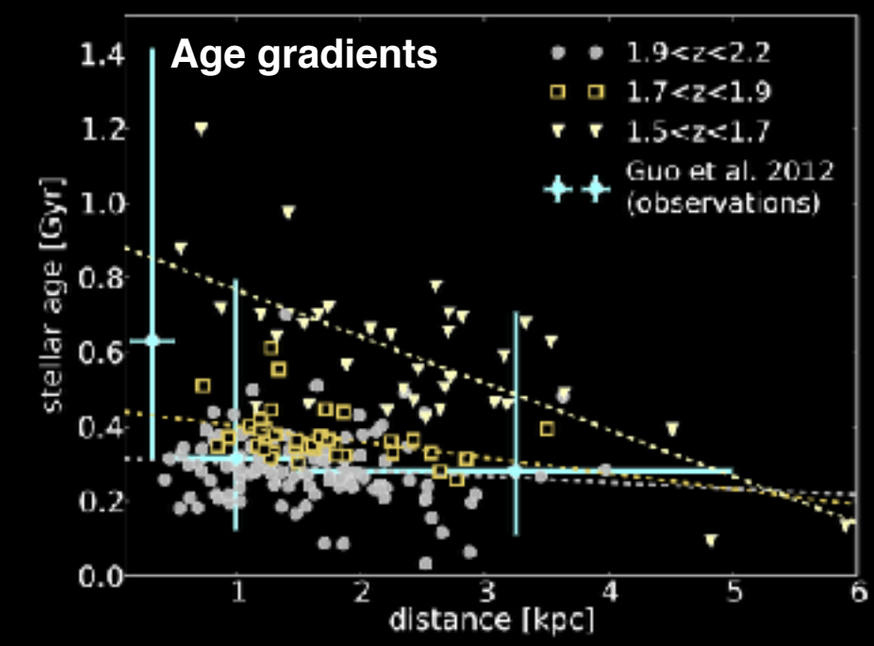
Antonija Oklopcic
(arXiv:1603.03778)



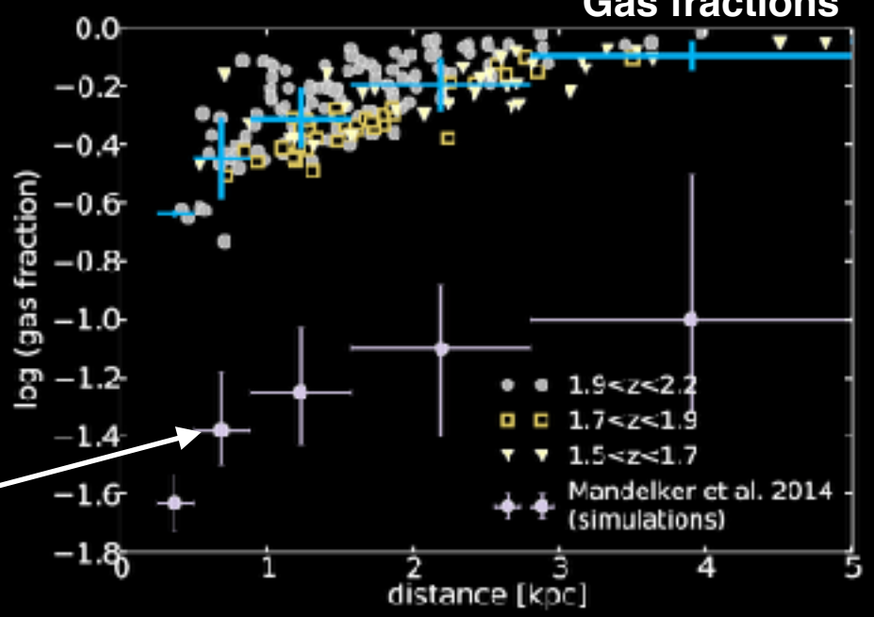


(weak feedback, long-lived clump model)



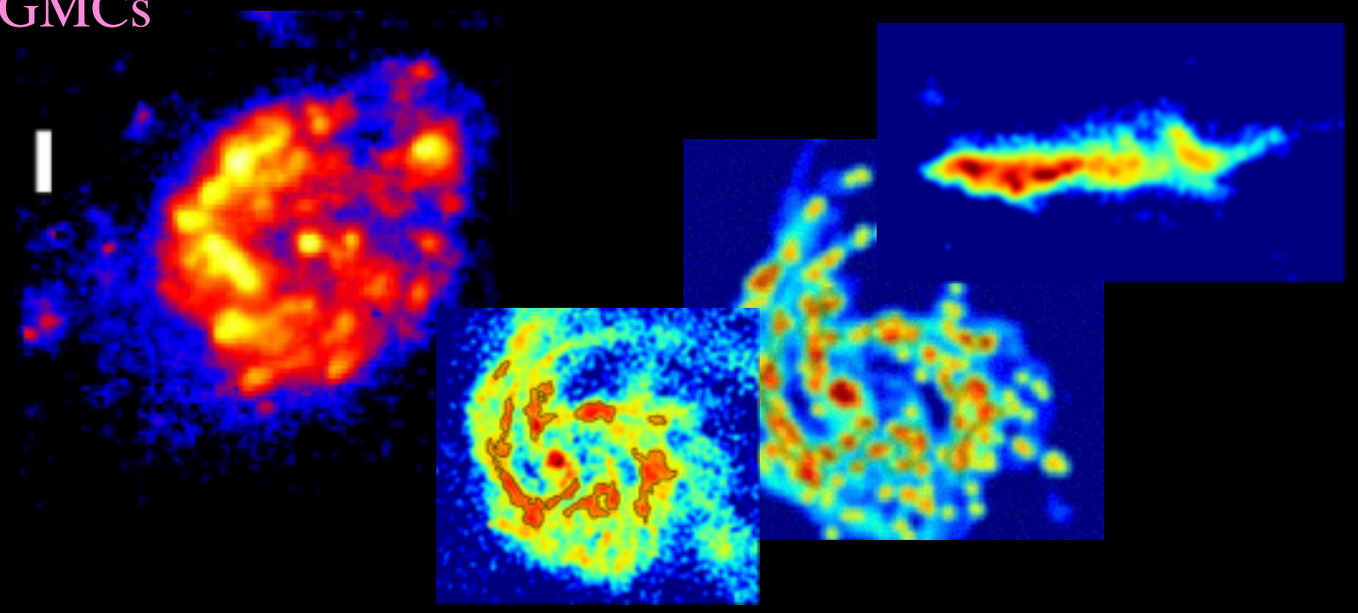


Gas fractions

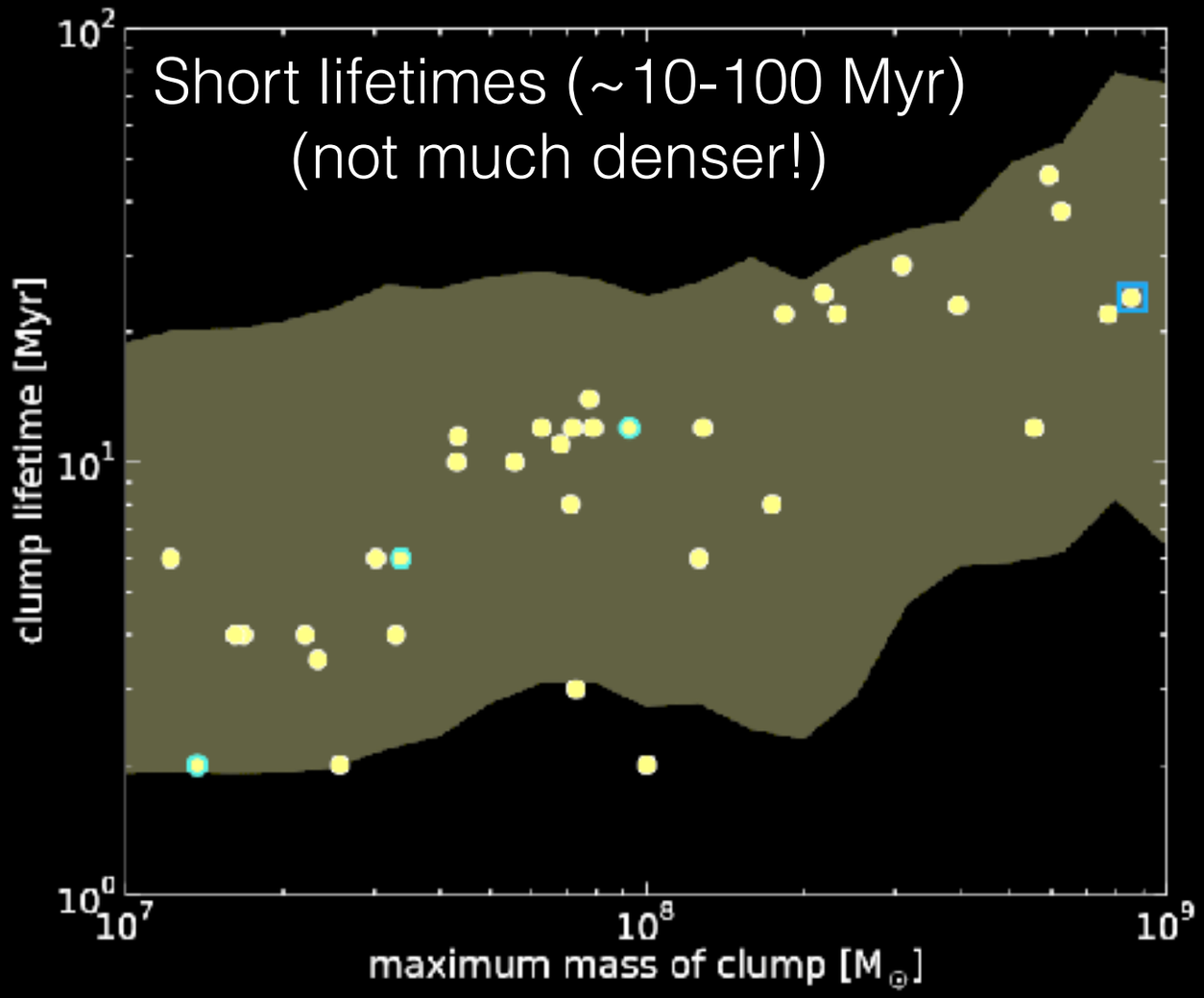


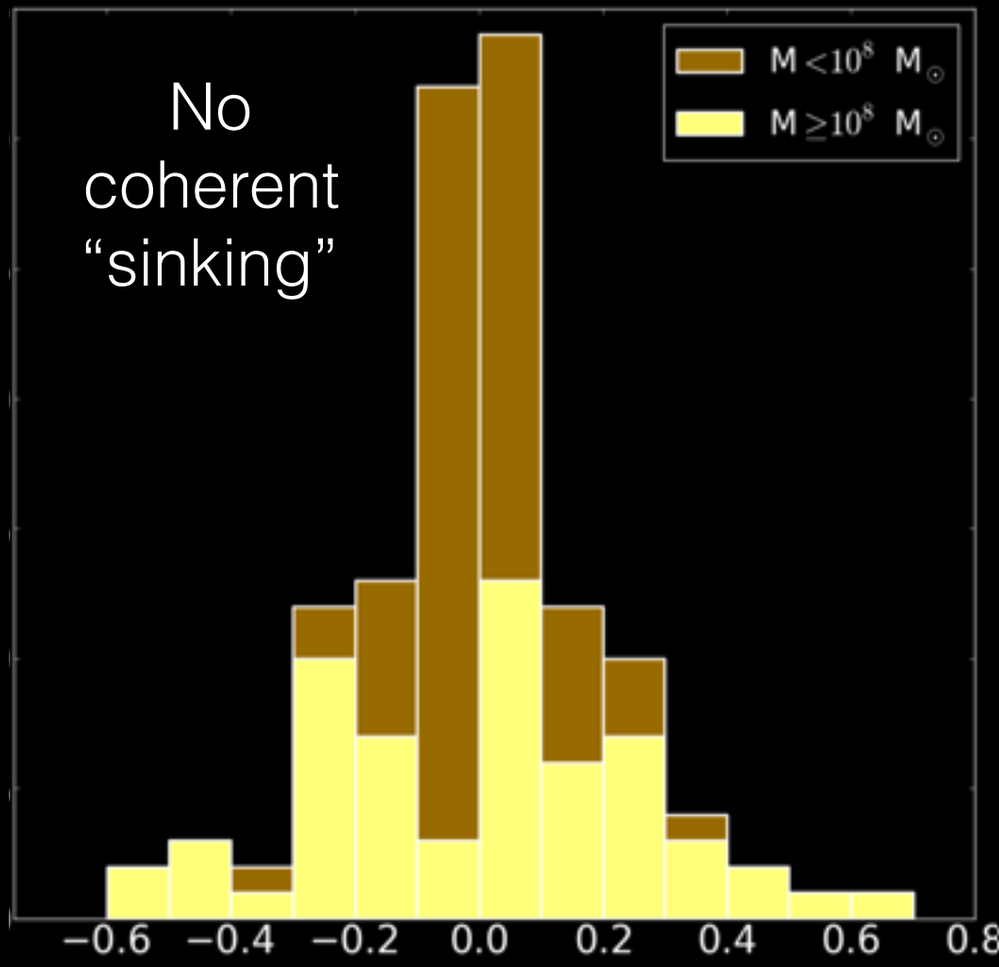
Giant "Clumps" Blow Up, Don't Sink

JUST AN EXTENSION OF GMCs



Antonija Oklopcic
(arXiv:1603.03778)





Fractional Change in Clump Orbital Angular Momentum

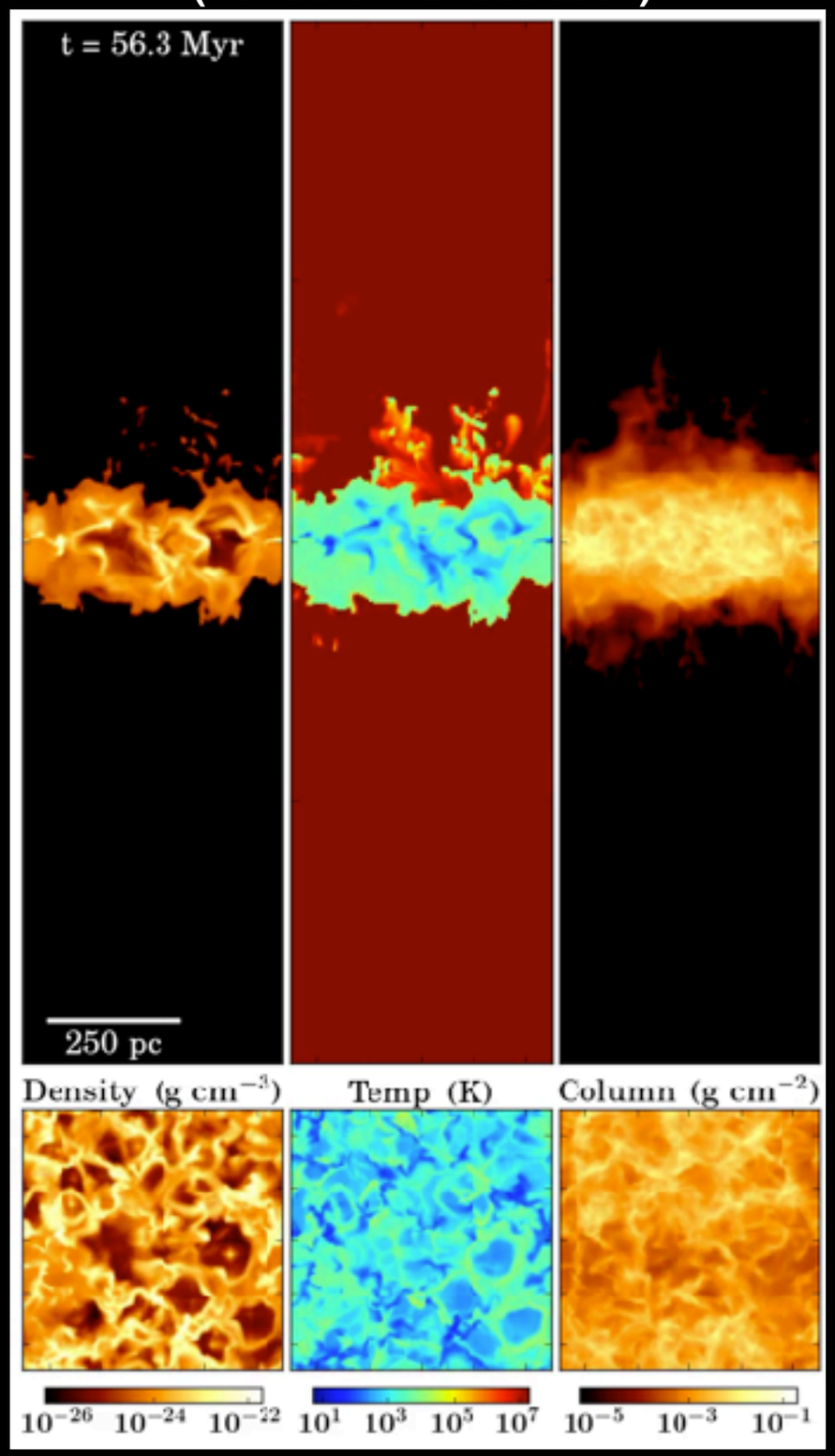
Galactic/Cosmological SFRs:
Driving Winds

Remember Stellar Clustering?

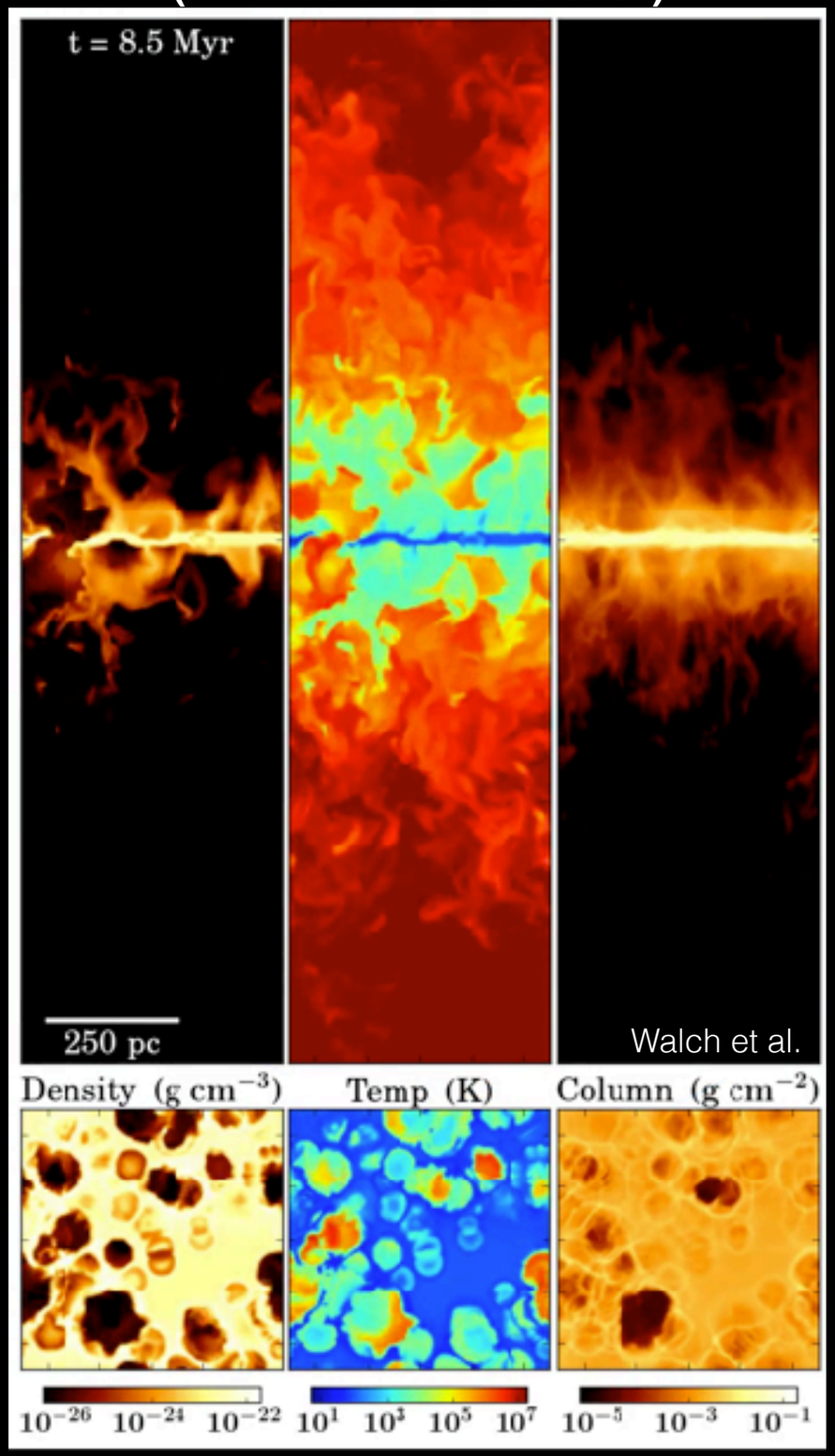
THIS MATTERS, A LOT!

Murray+, Martizzi+,
Walch+, Barnes+
Hopkins+, Hayward+,
Shetty+, Hennebelle+

SNe Explode in Density Peaks
(no radiative feedback)

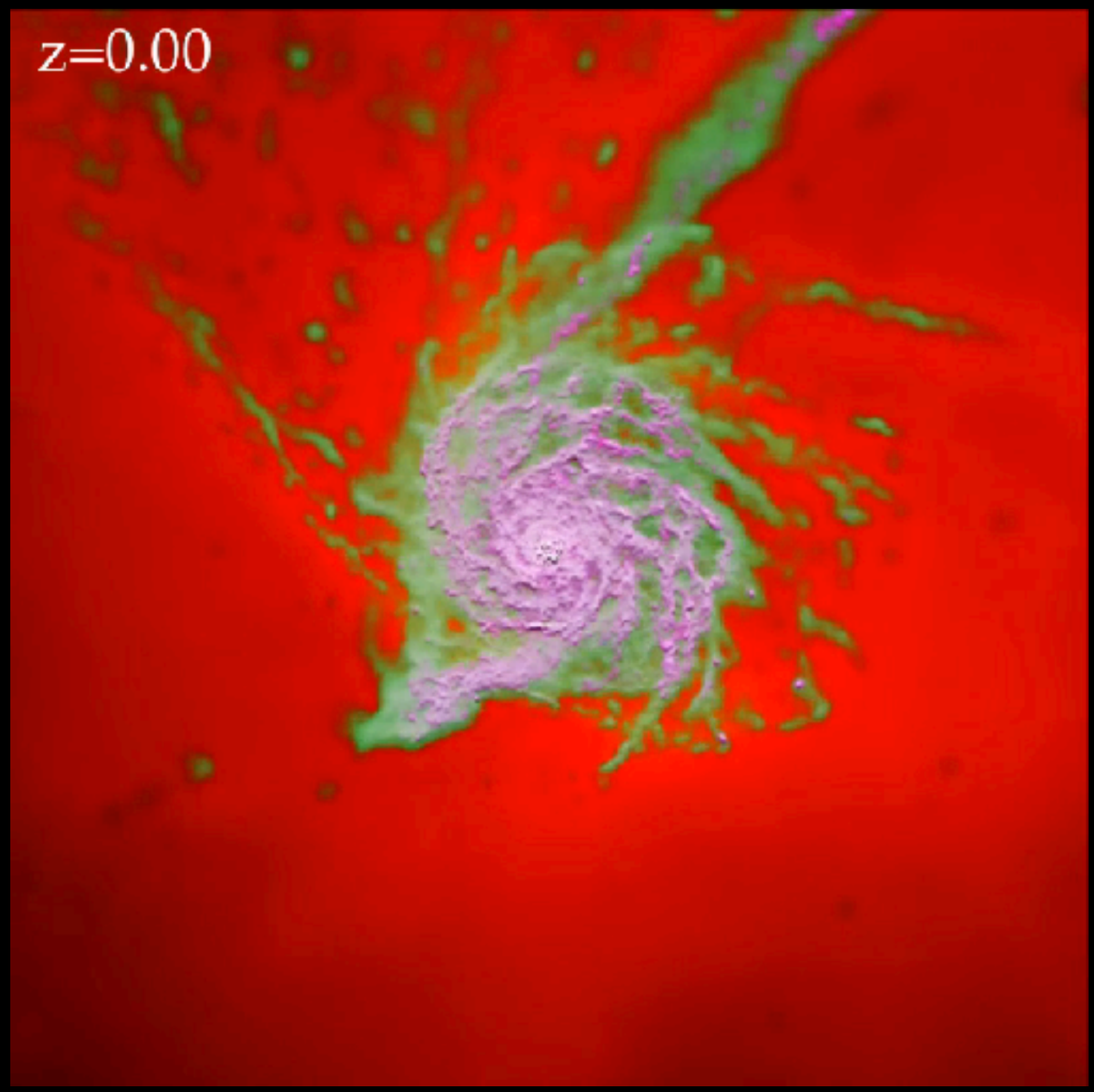


SNe Clustered & Off-Peak
(with radiative feedback)



Walch et al.

(movies at fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

Gas: Magenta: cold $(< 10^4\,K)$

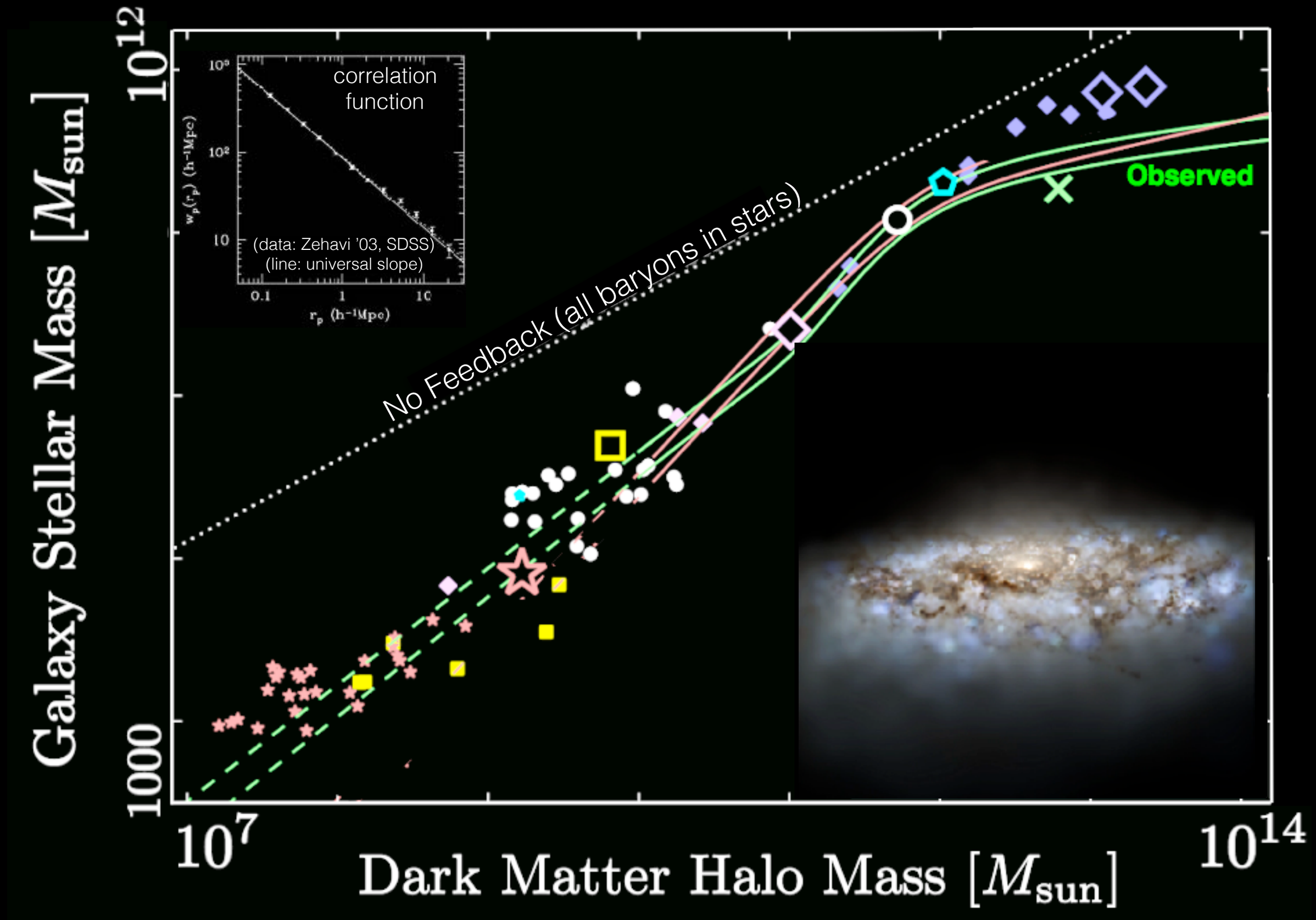
Green: warm (ionized)

Red: hot $(> 10^6\,K)$

This Works (More or Less) if You Resolve Key Scales

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)



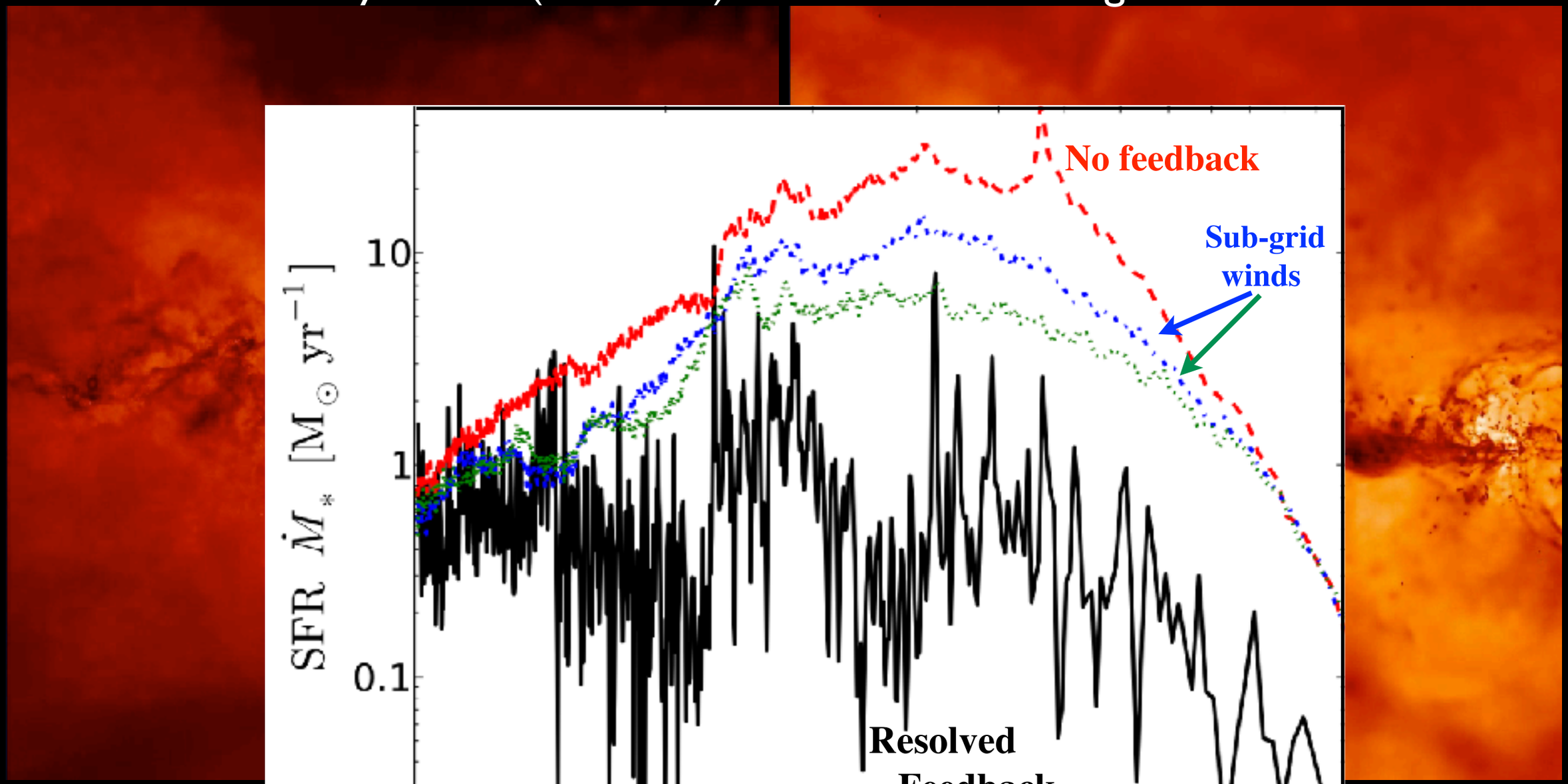
Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

PFH '14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

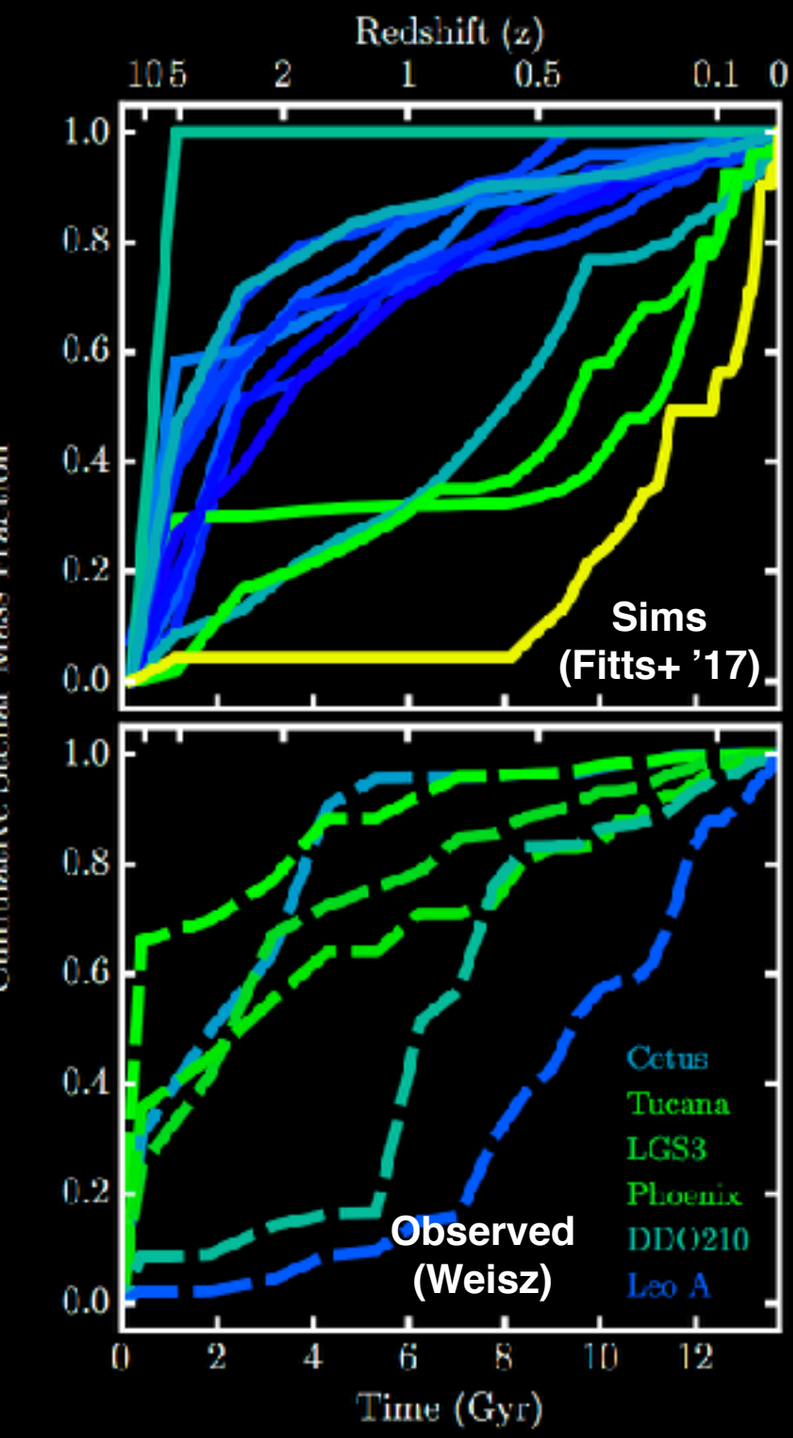
Following Full Feedback



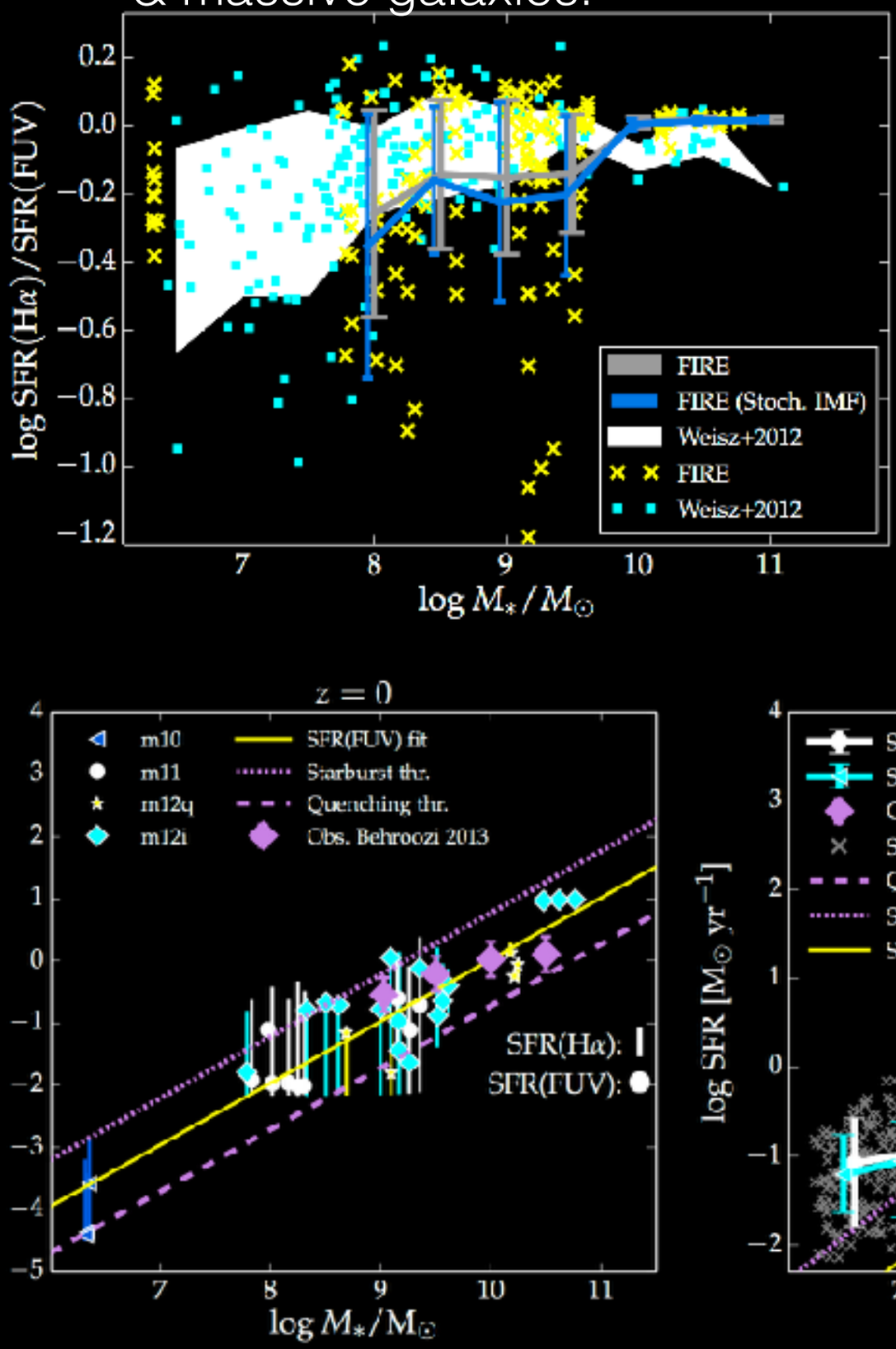
Bursti-ness & the SFR-M_{stars} relation

M. Sparre
arxiv:1510.03869

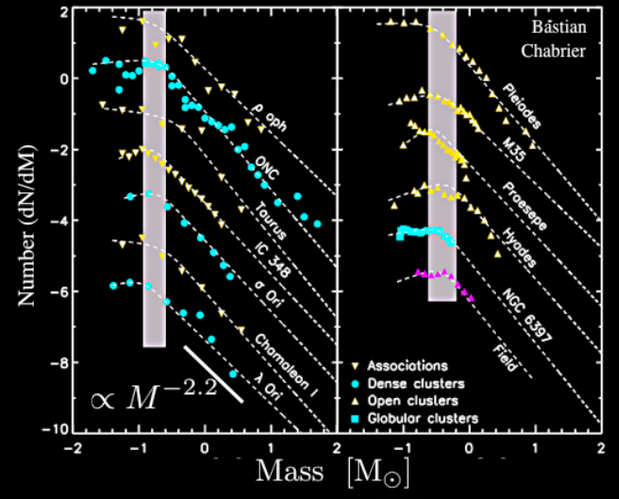
Bursti-ness in Dwarfs:

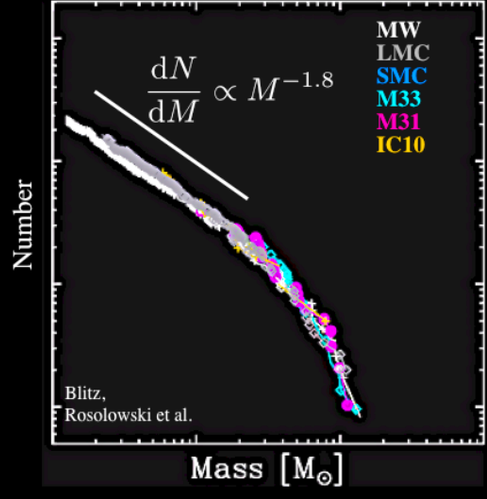


& massive galaxies:



Thank You!





- **SF is "coherent" (statistically clustered in space & time) on *all scales***
- **Largely scale-free: turbulence, gravity, feedback**
- **Scales:**
  - **time:** $\mathrm{cluster/cloud\ SF} \lesssim \Delta t \sim 30\,\mathrm{Myr} \lesssim \mathrm{steady-state\ SF}$
  - **space/mass:** $H_{\rm disk},\ \sim \int^3_{\rm gas} M_{\rm gal}\ (\mathrm{Toomre/clump/GMC\ scale})$, $[\mathrm{also}\ M_\odot (\sim 0.1\,\mathrm{pc})]$