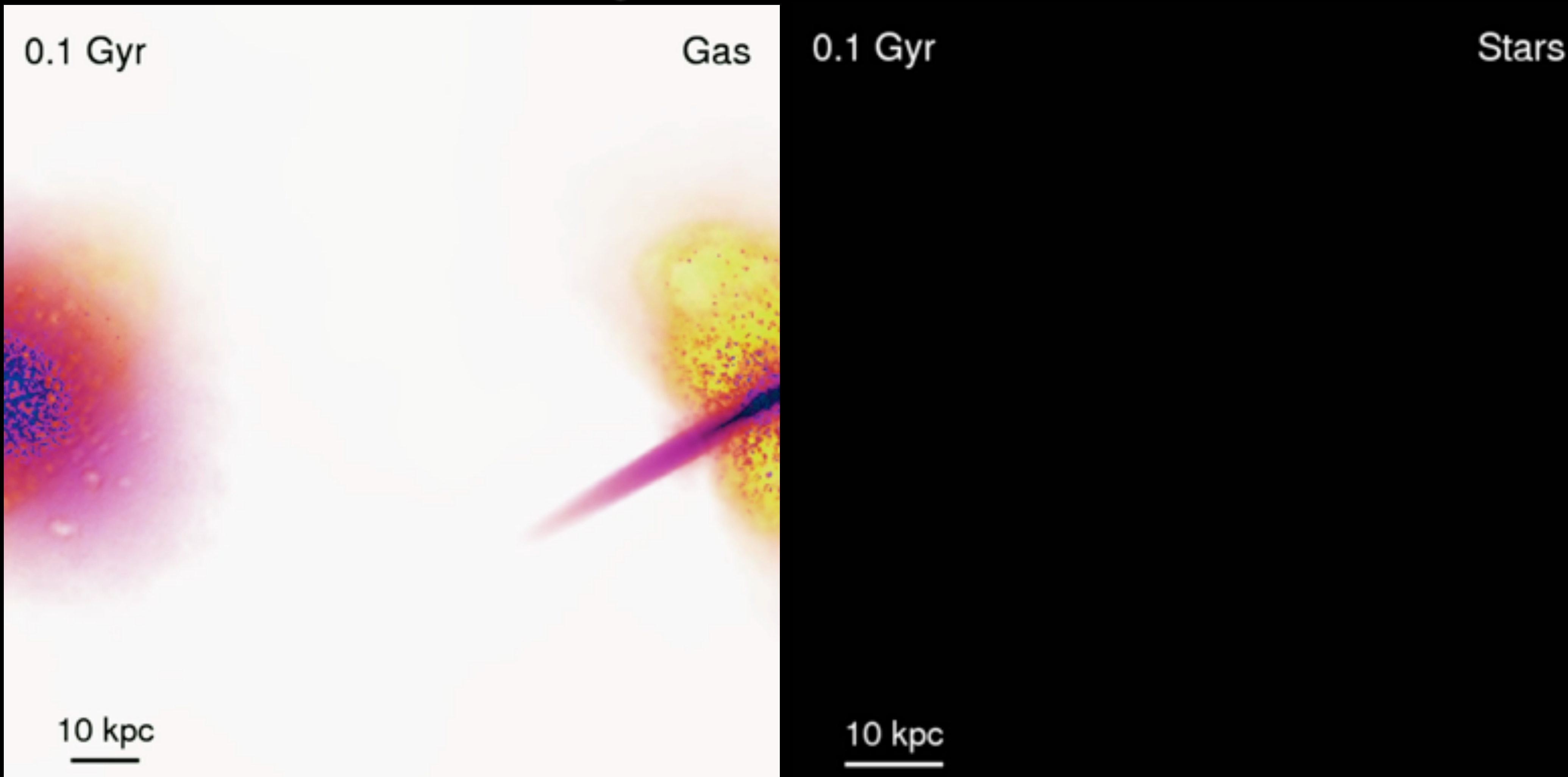
# ISM Structure, Stellar Clustering, & a (Nearly) Universal IMF

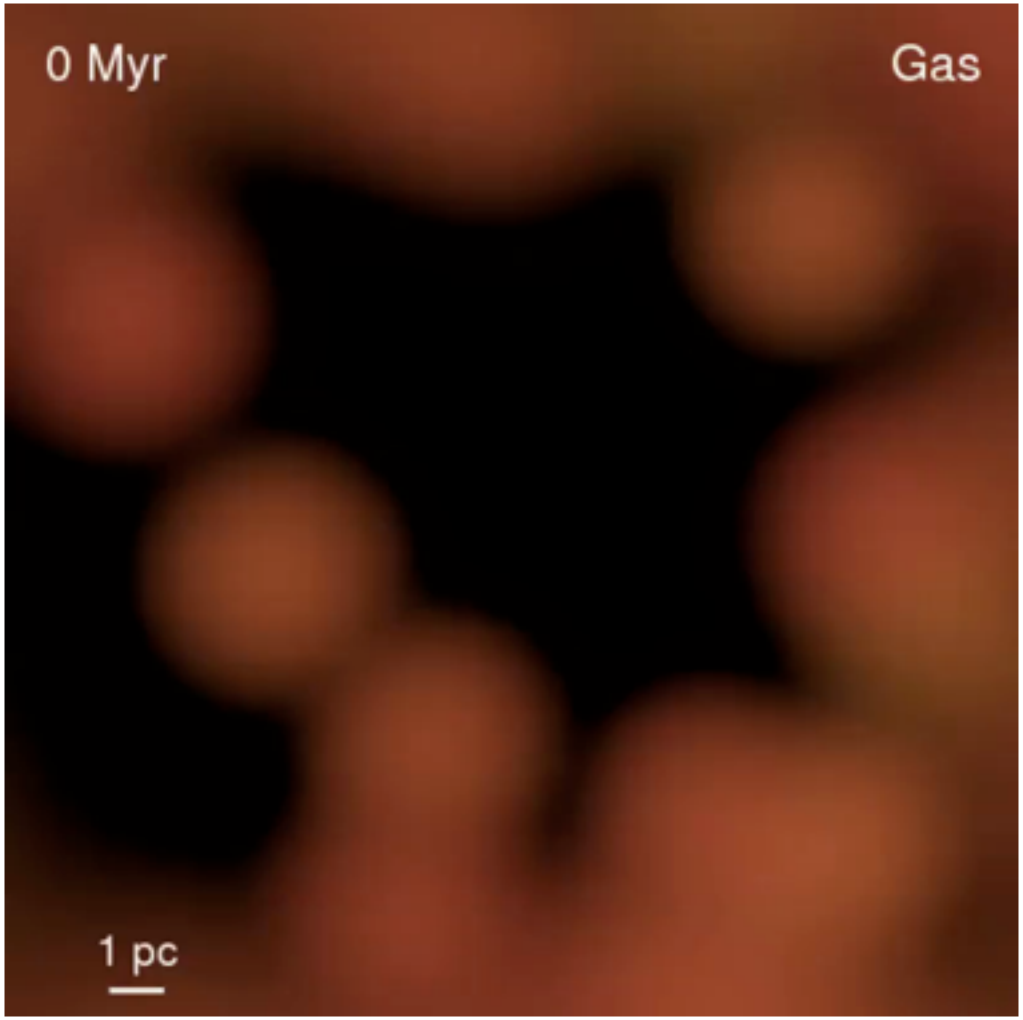


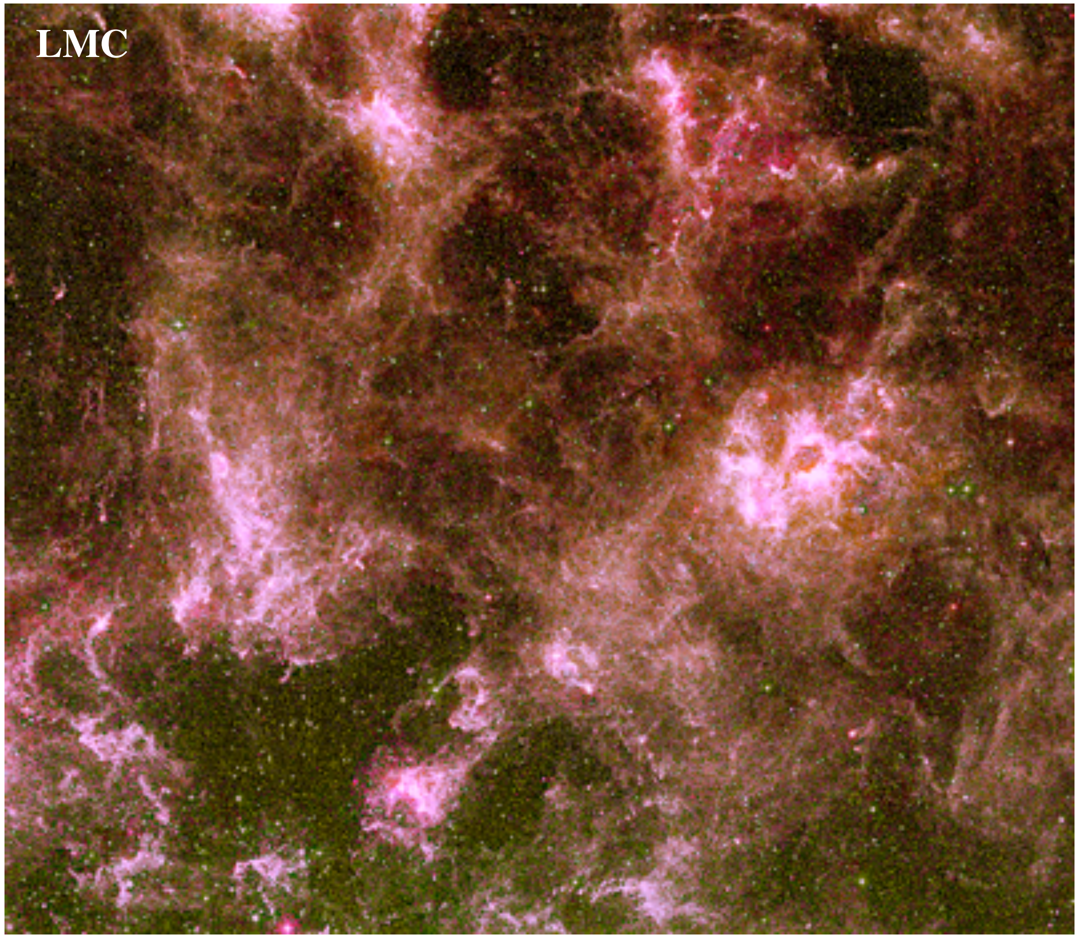

Philip Hopkins

with Eliot Quataert, Norm Murray,
Lars Hernquist, Dusan Keres, Todd Thompson, Desika Narayanan,
Dan Kasen, T. J. Cox, Chris Hayward, Kevin Bundy, & more

# The Turbulent ISM

## IMPORTANT ON (ALMOST) ALL SCALES



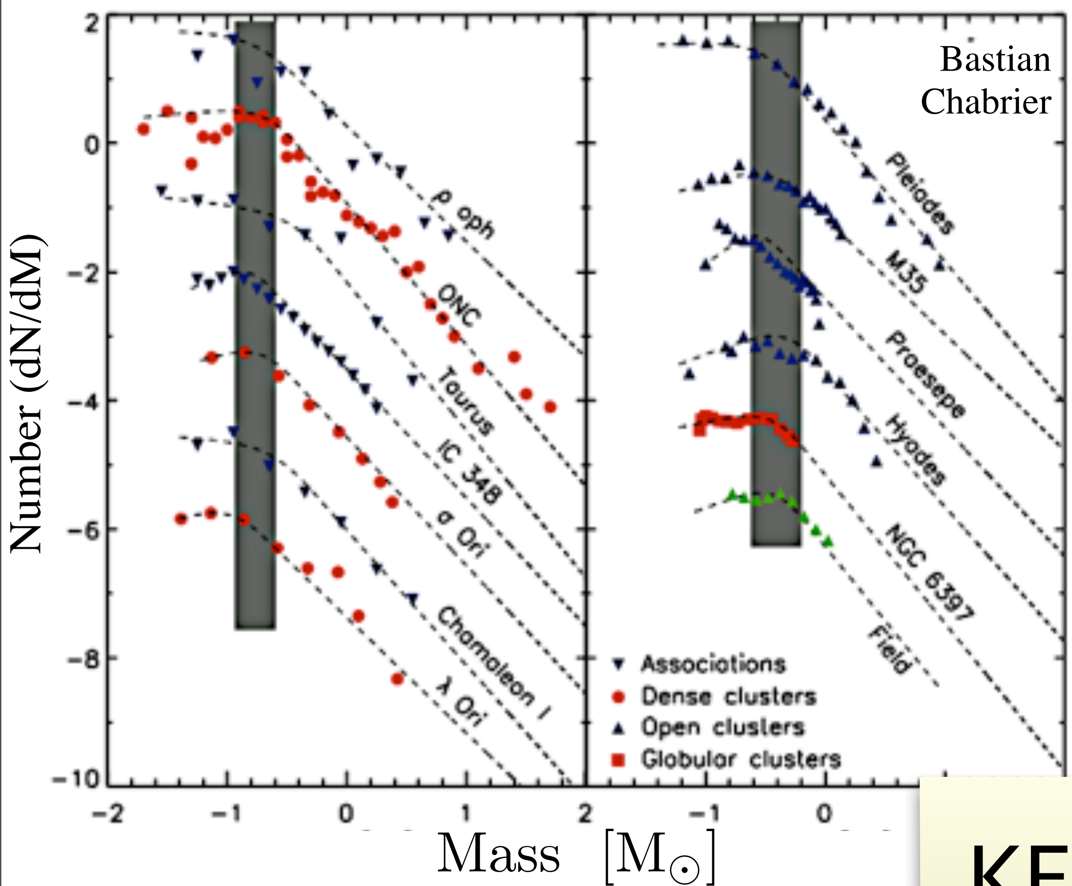




- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs, external galaxies, etc.

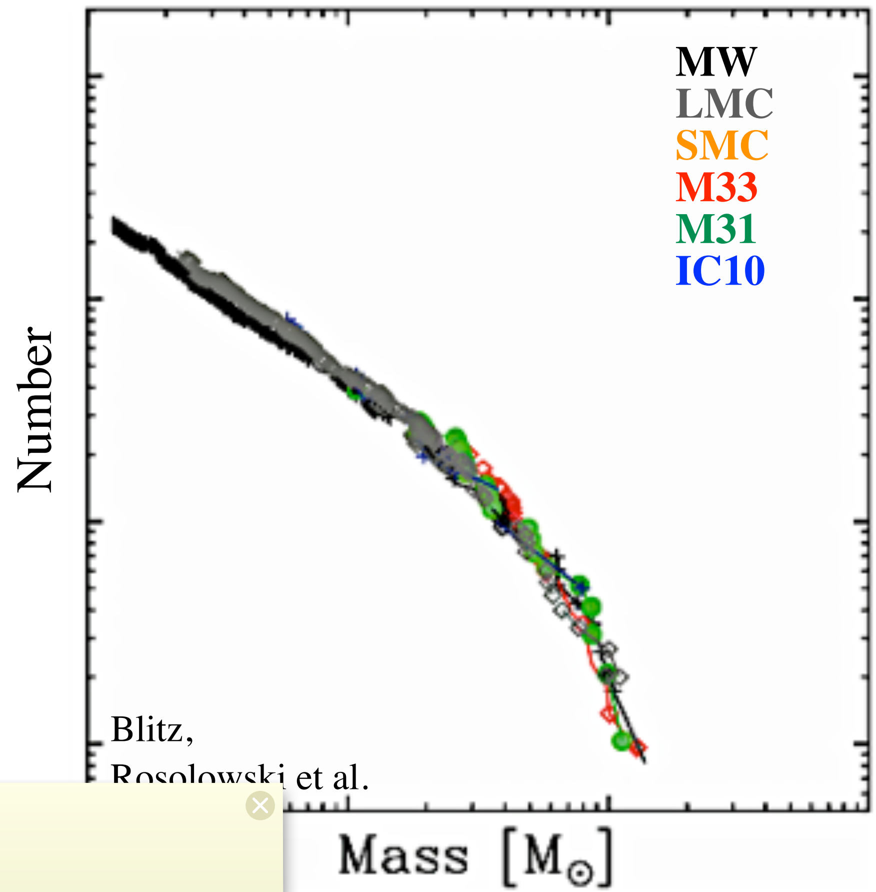
# The ISM

## YET THERE IS SURPRISING REGULARITY

Stars & Pre-Stellar Gas Cores:




Giant Molecular Clouds:




KEEP PWRLAW LABELS?

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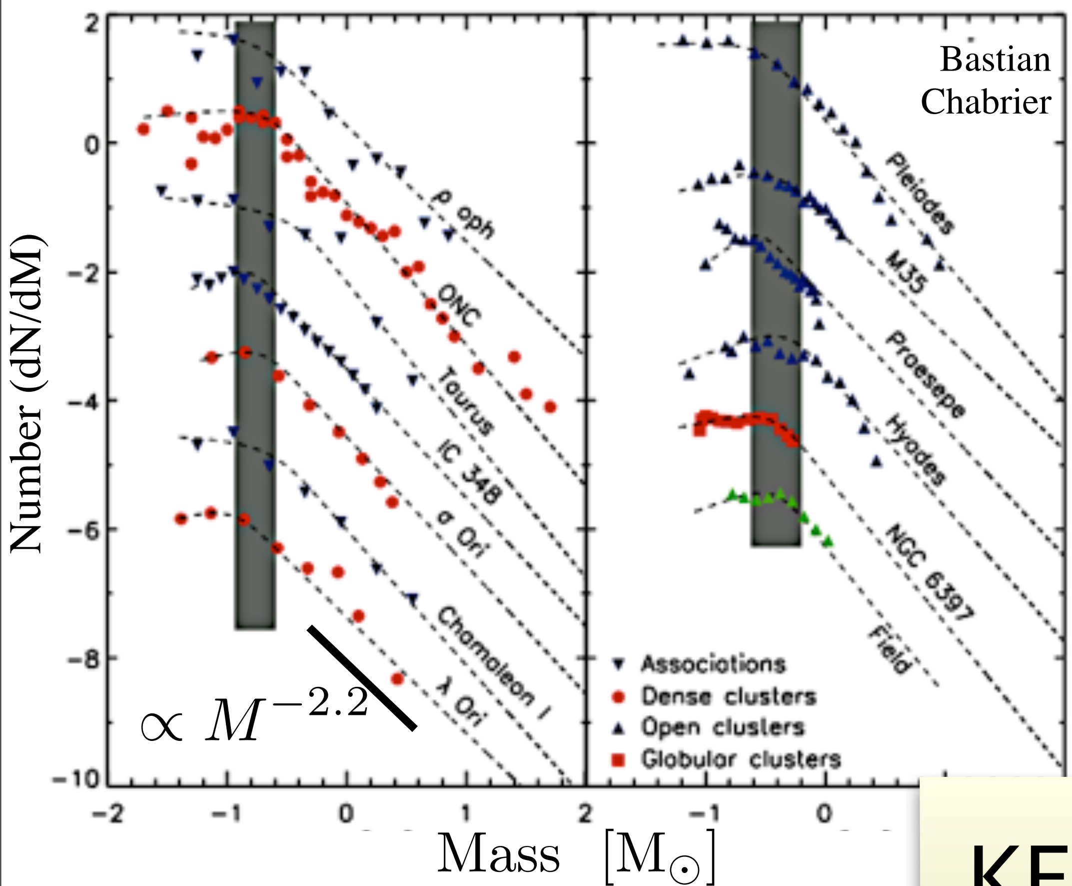


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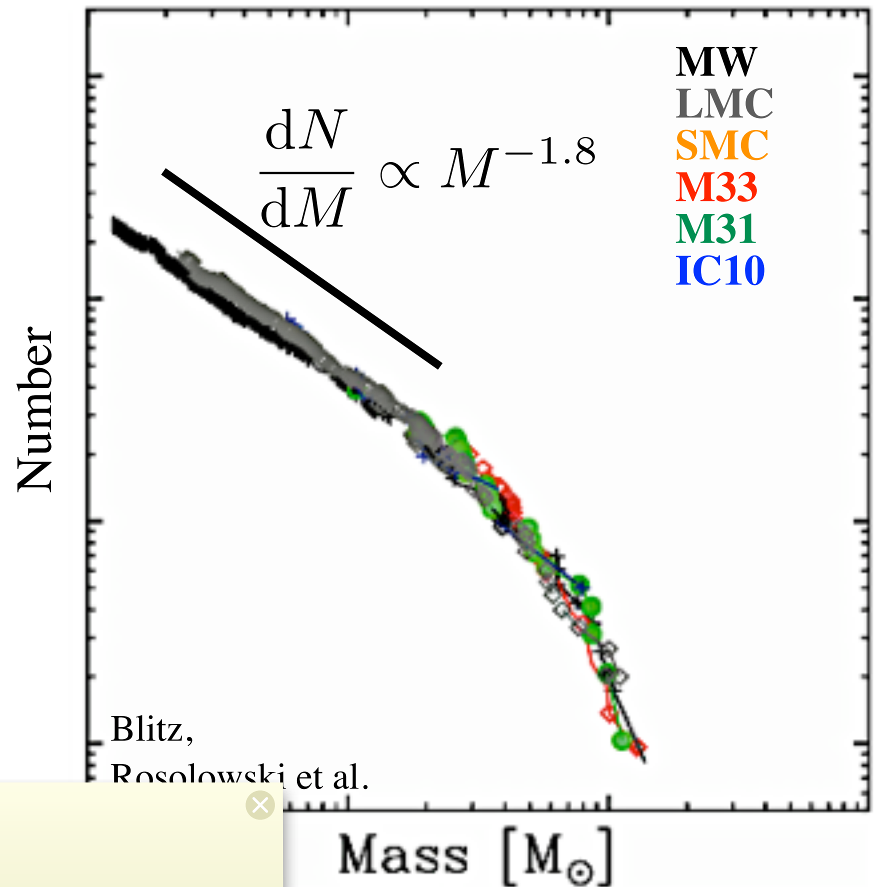


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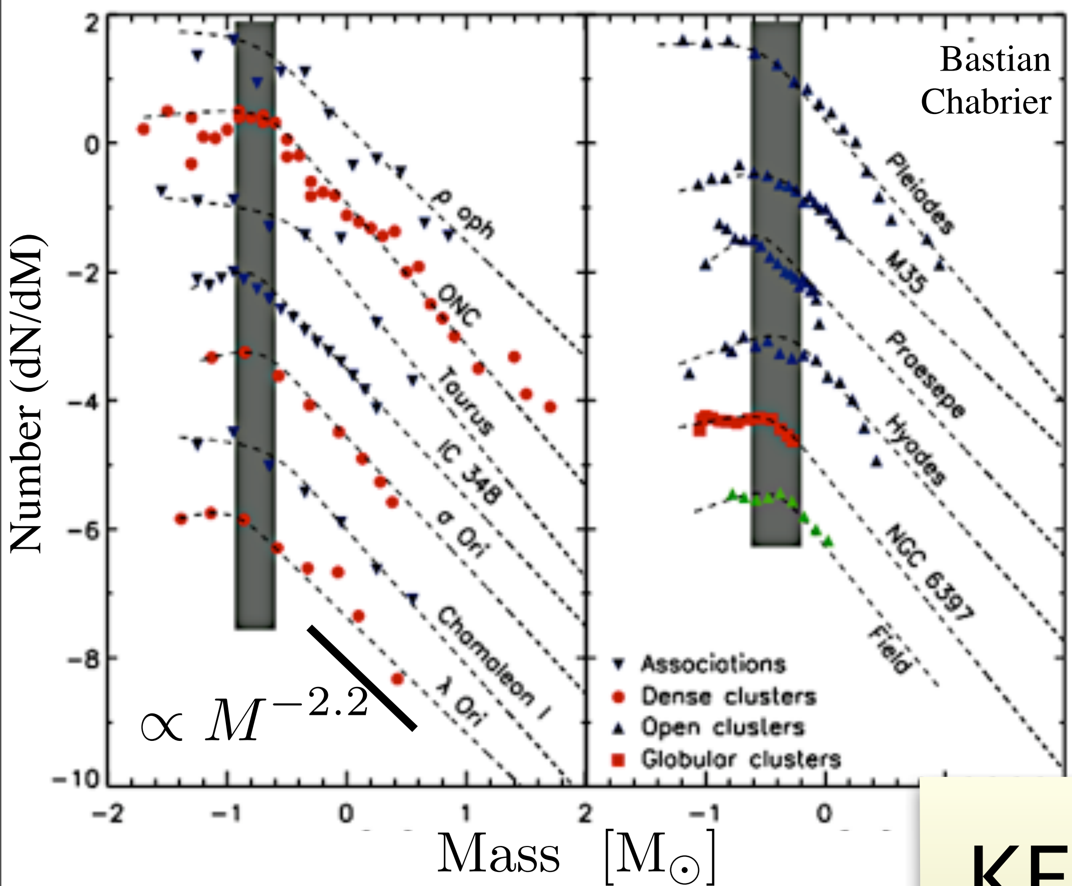


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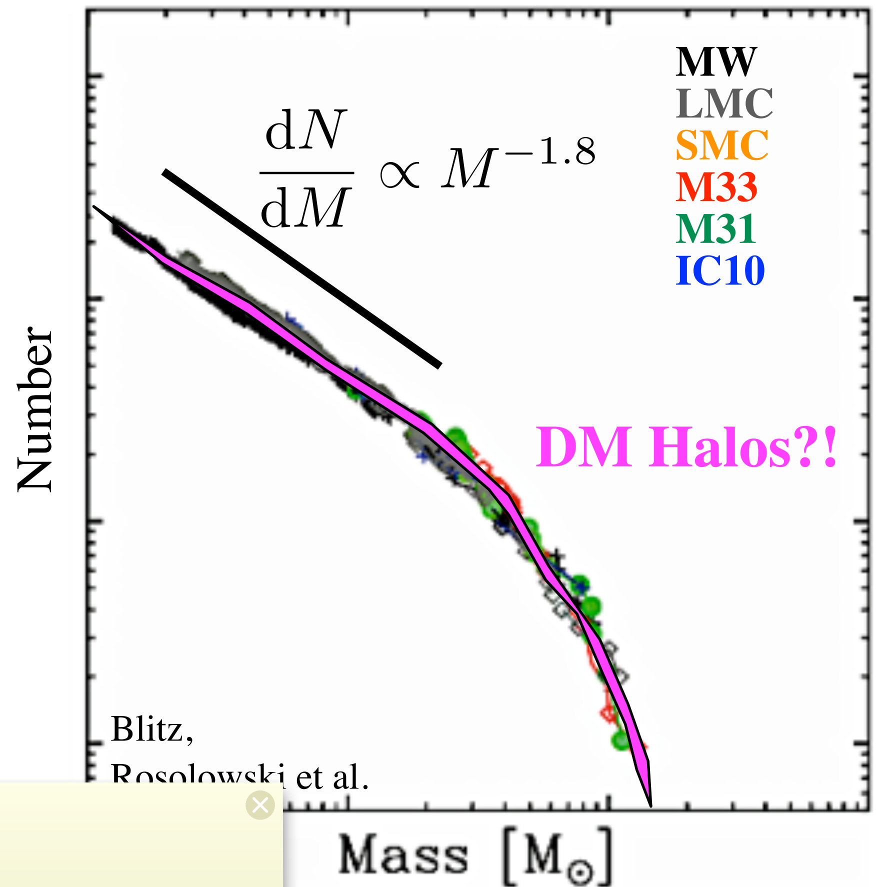


KEEP PWRLAW LABELS?

# Extended Press-Schechter / Excursion-Set Formalism

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  - r Fluctuations a Gaussian random field
  - Know linear power spectrum P(k~1/r):
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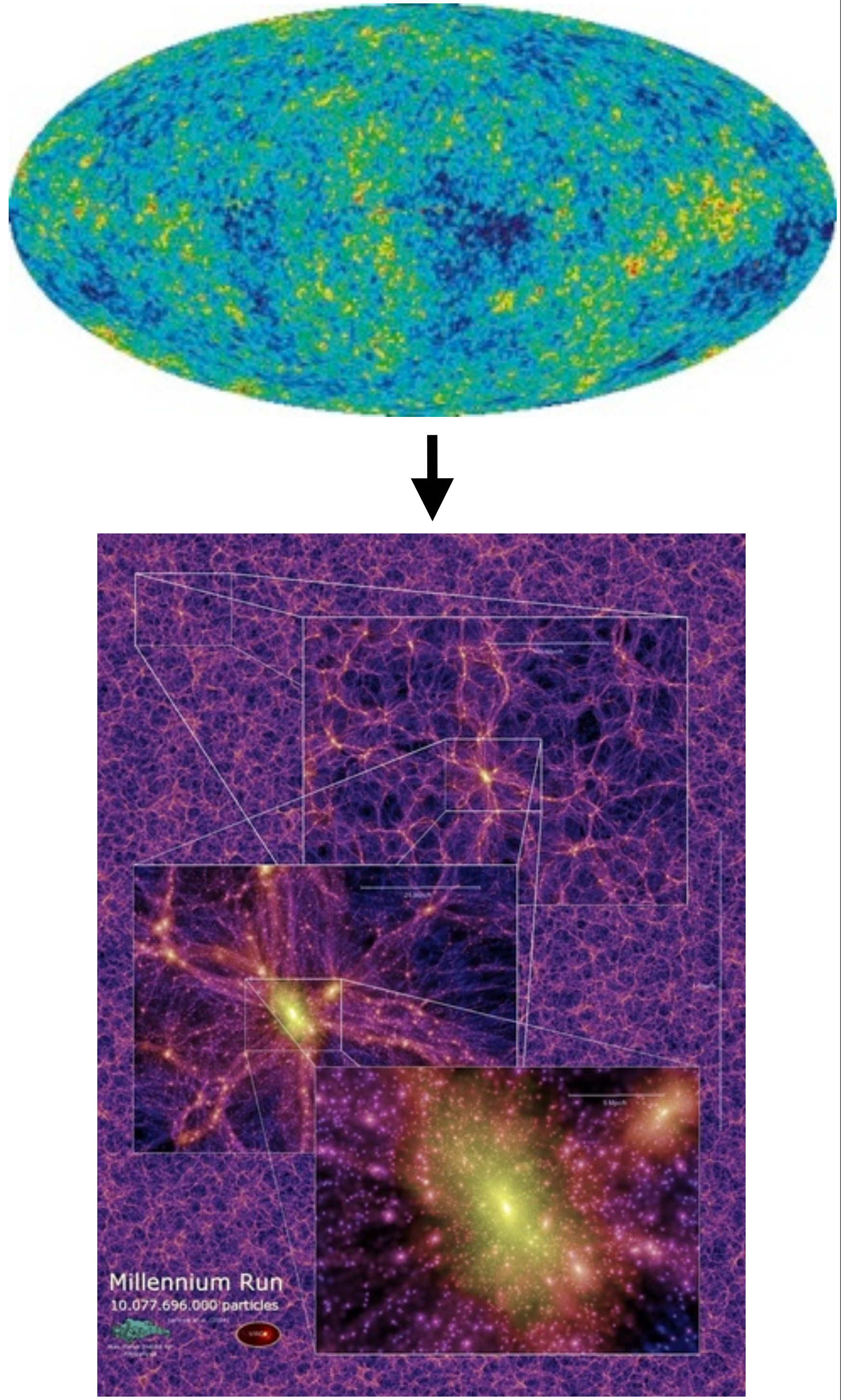

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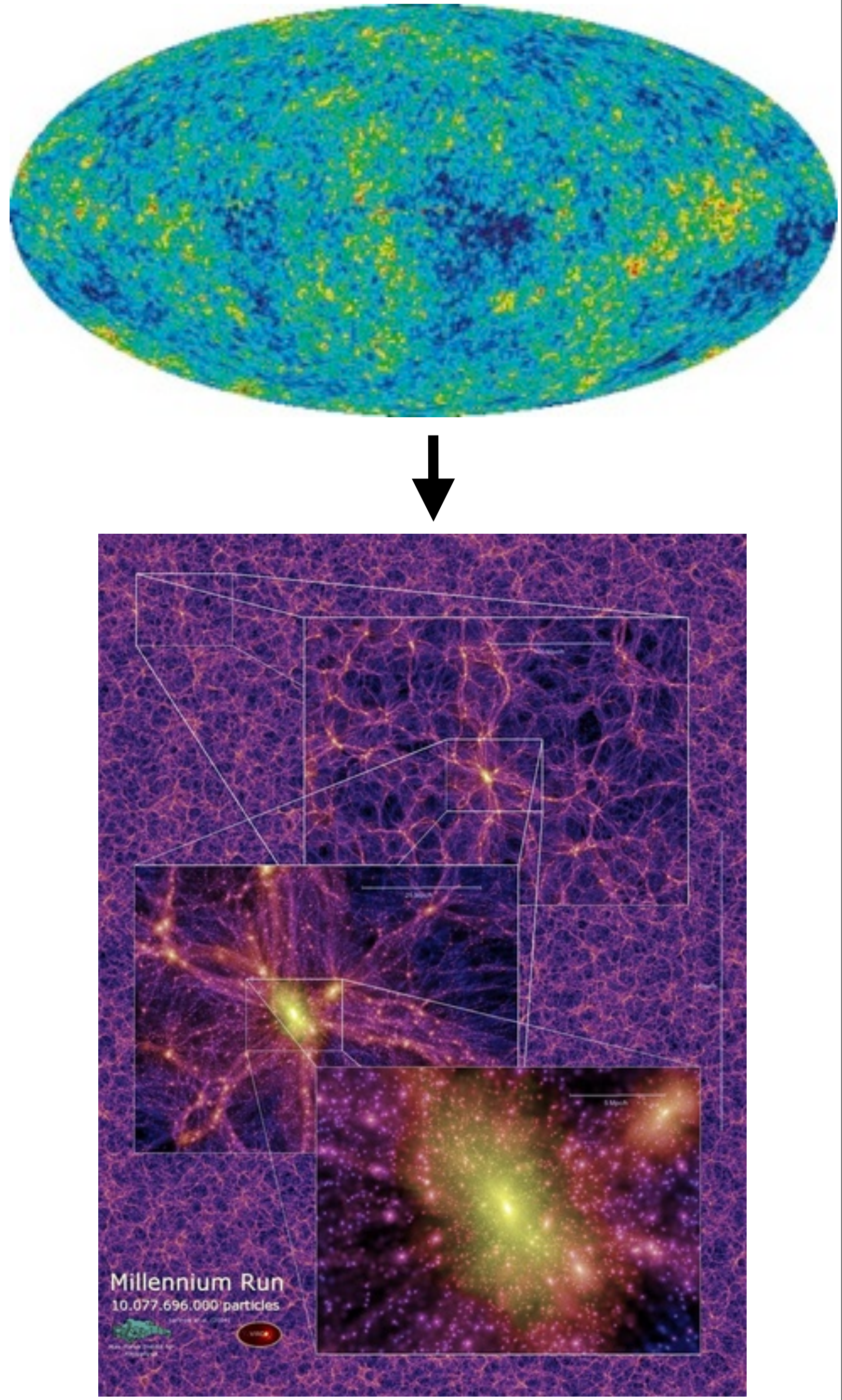
  - Turnaround & gravitational collapse

$$\bar{\rho}(< R \sim 1/k) > \rho_{\rm crit}$$



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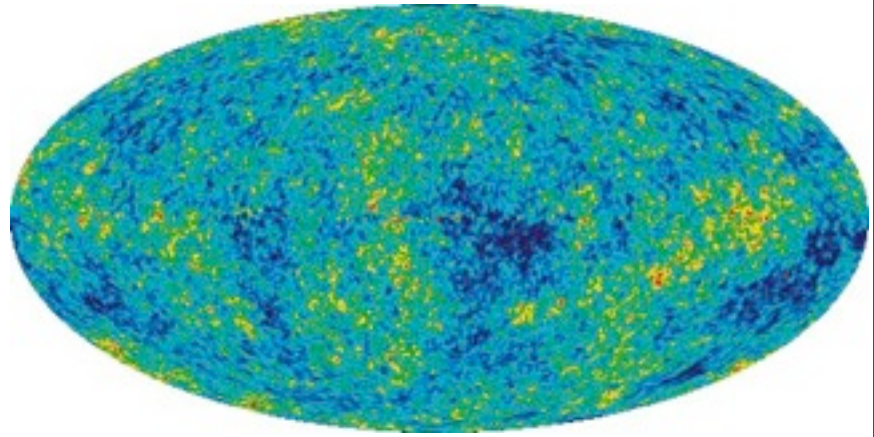

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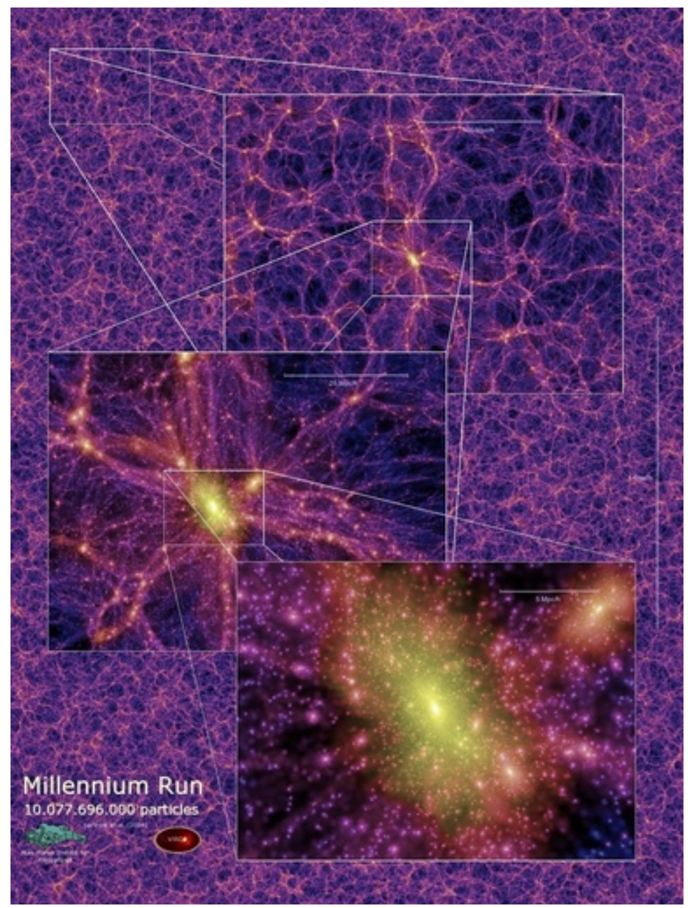


- Generalize to conditional probabilities, N-point statistics, resolve "cloud in cloud" problem (e.g. Bond et al. 1991)

## BASIC EXPECTATIONS

Velocity: $E(k) \propto k^{-p}$ $\quad (k\,E(k) \sim u_t(k)^2)$

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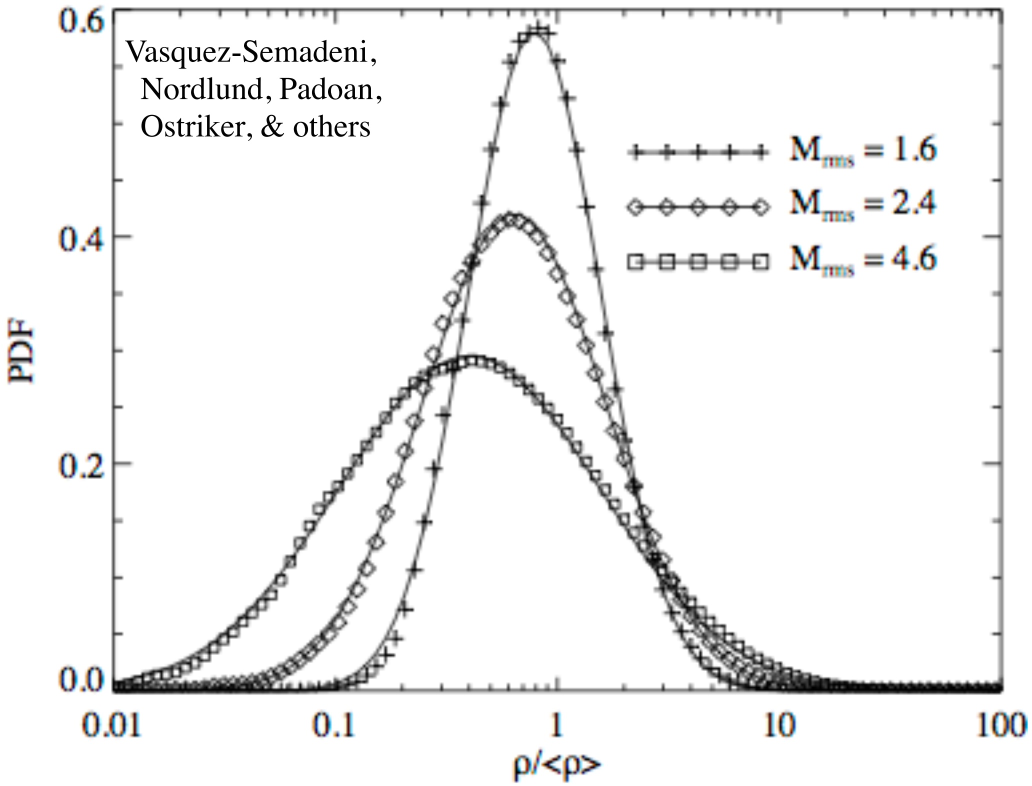

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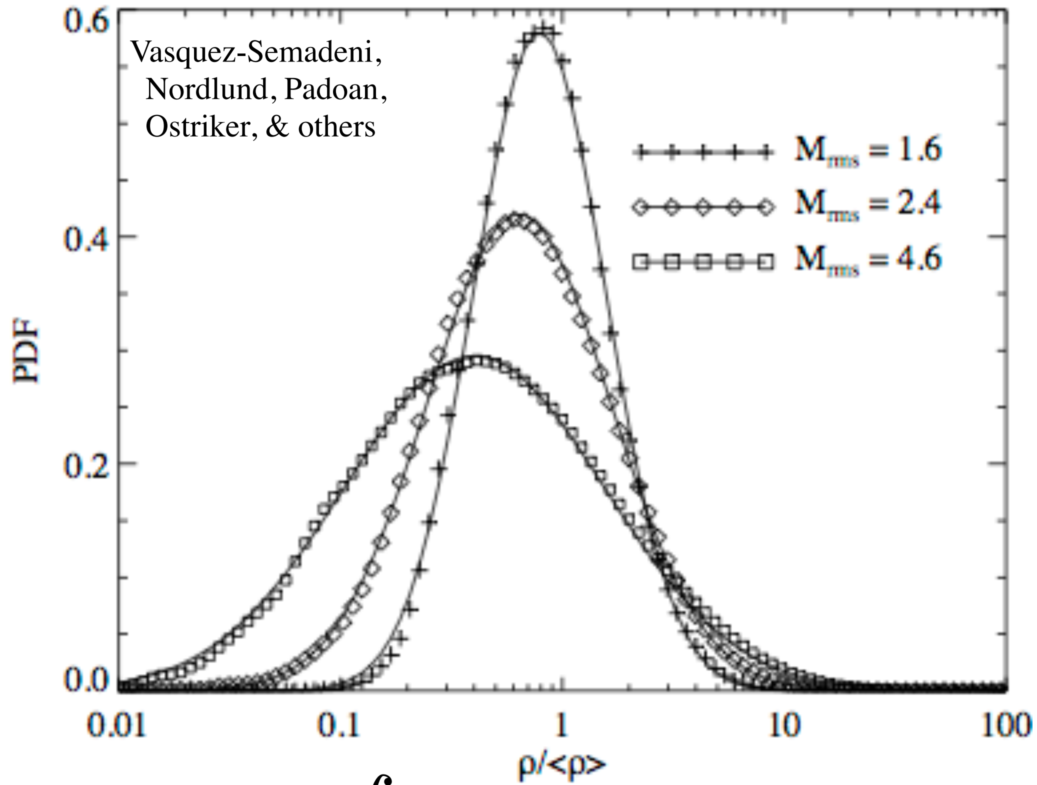


$$S(R) = \int \mathrm{d}\ln k\, S_k\, |W(k,\, R)|^2$$

# What Defines a Fluctuation of Interest?

## DISPERSION RELATION:

$$\omega^2 = \kappa^2 + c_s^2\, k^2 + u_t(k)^2\, k^2 - \frac{4\pi\, G\, \rho\, |k| h}{1 + |k| h}$$

Chandrasekhar '51, Vandervoort '70, Toomre '77

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### Mode Grows (Collapses) when w<0:

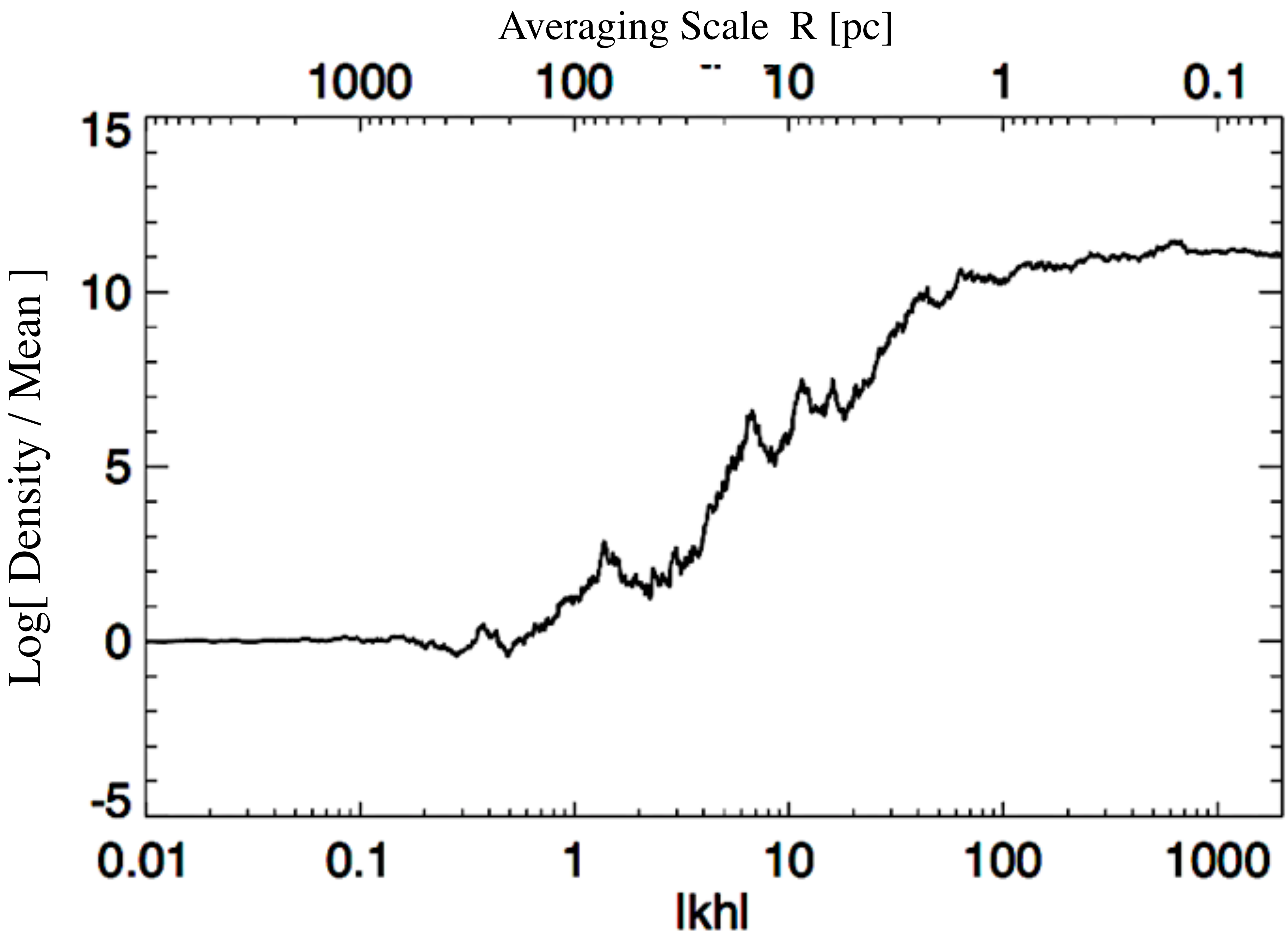
$$\rho > \rho_c(k) = \rho_0\, (1 + |kh|) \left[ (\mathcal{M}_h^{-2} + |kh|^{1-p})\, kh + \frac{2}{|kh|} \right]$$

Chandrasekhar ‘51, Vandervoort ‘70, Toomre ‘77

# “Counting” Collapsing Objects



## EVALUATE DENSITY FIELD vs. “BARRIER”



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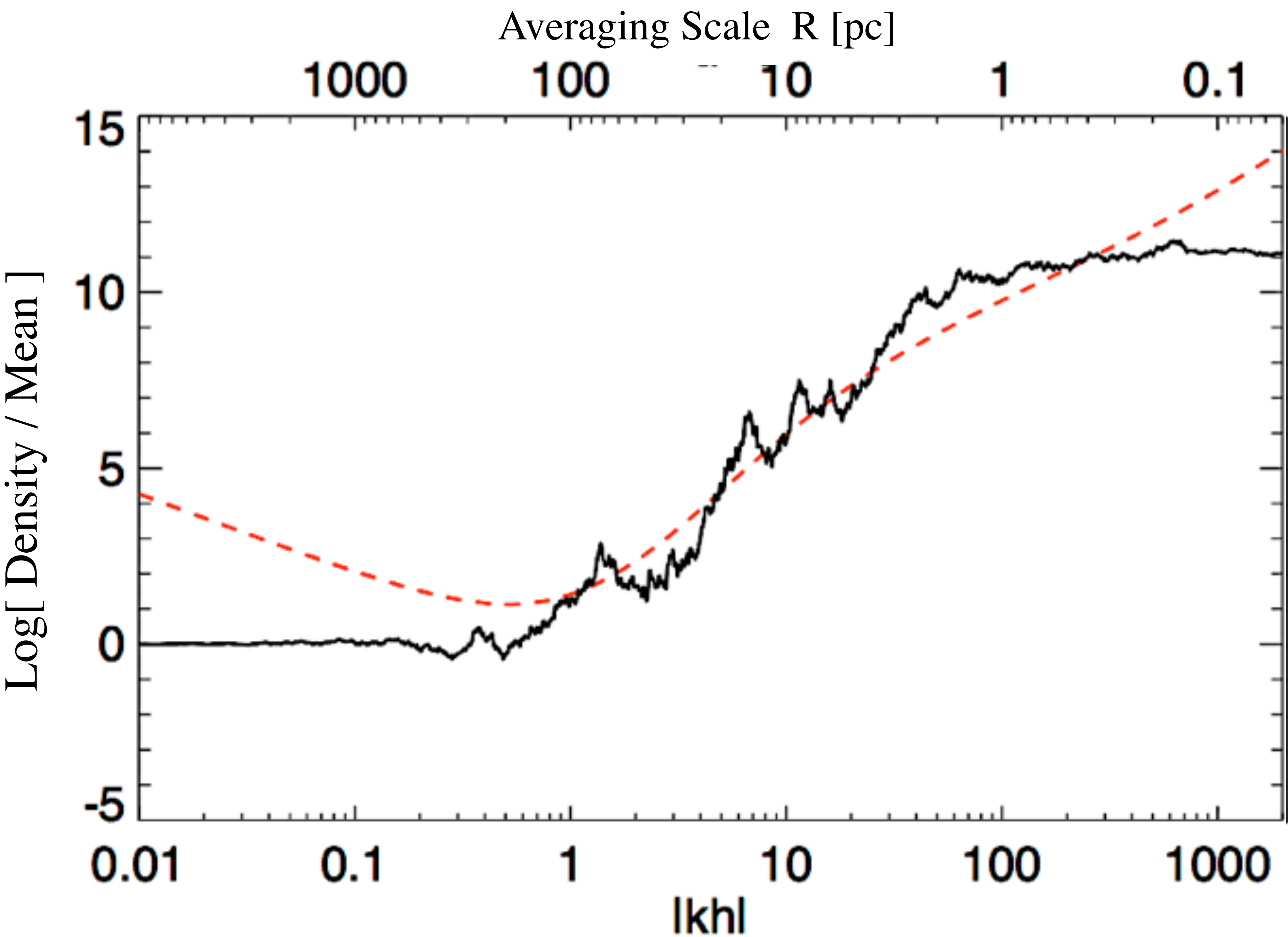

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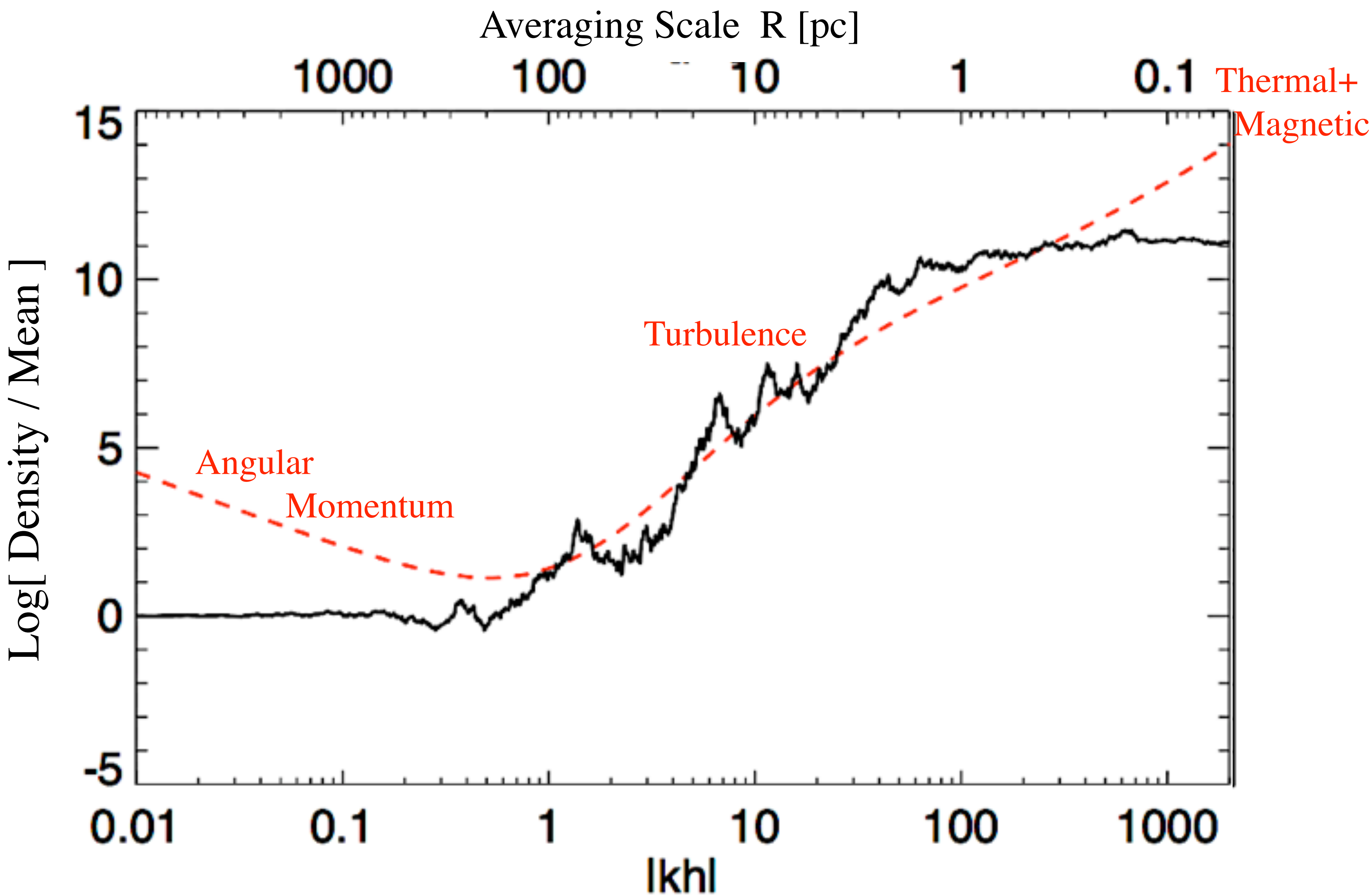

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PFH 2011

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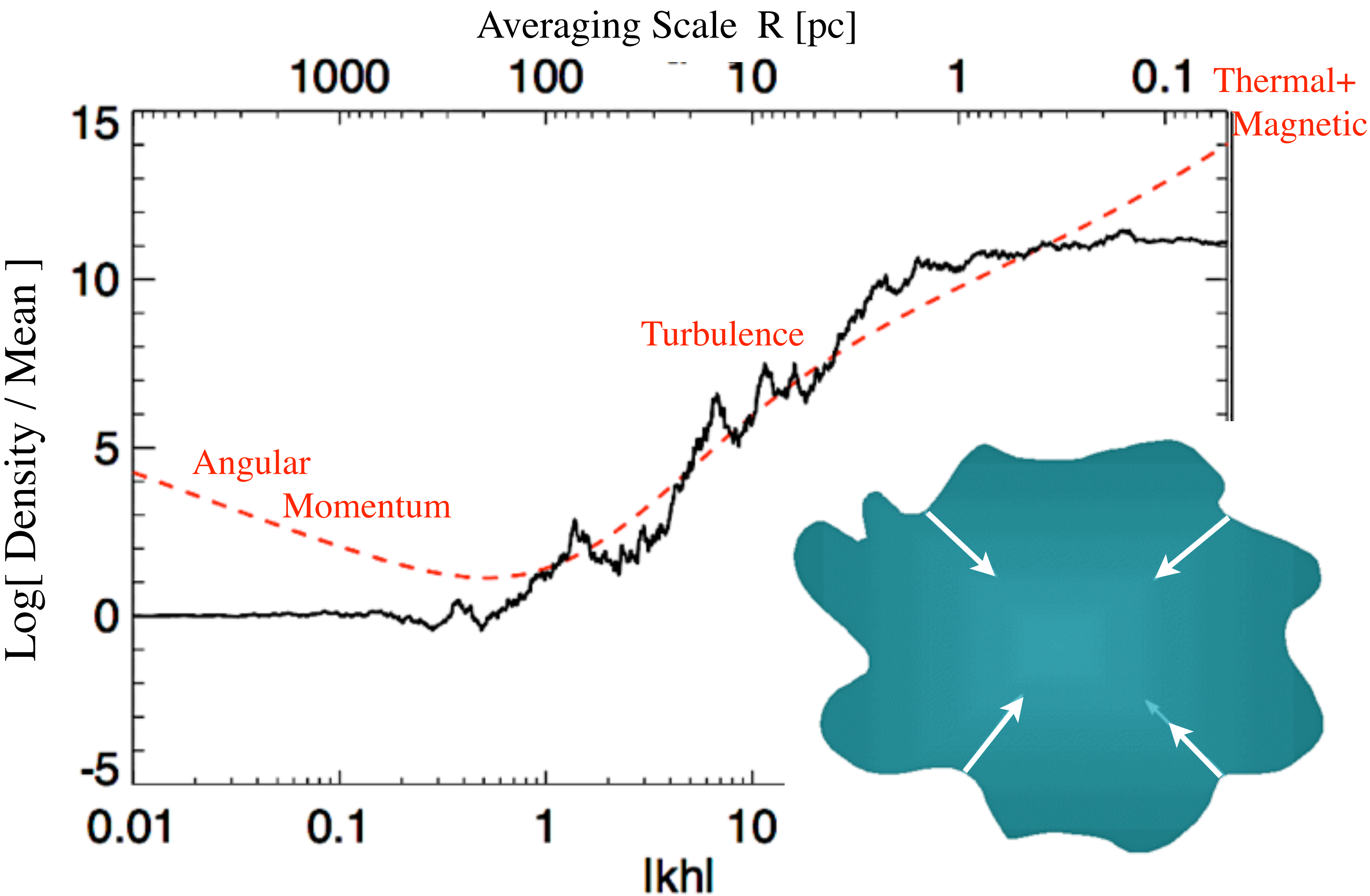

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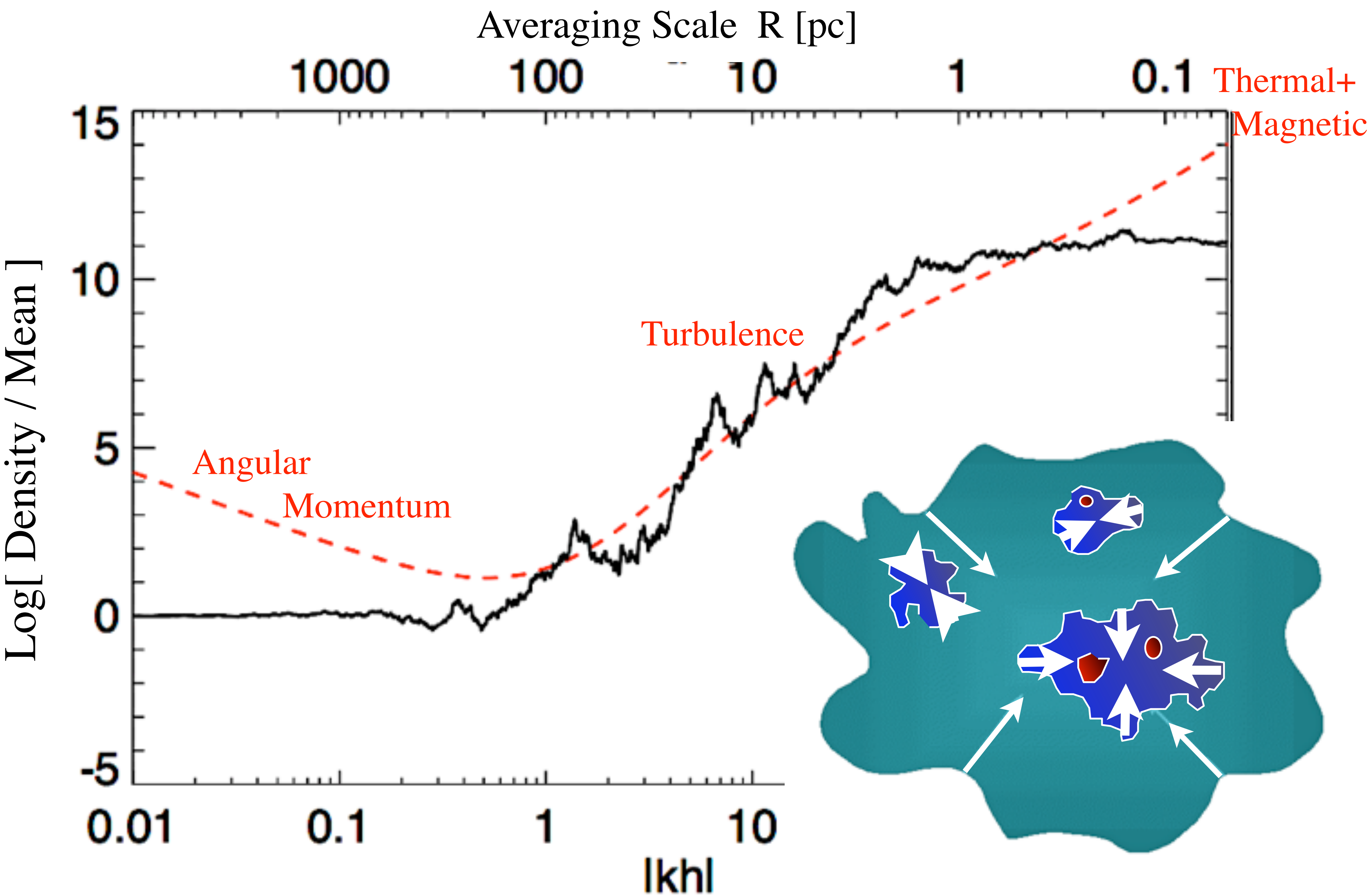

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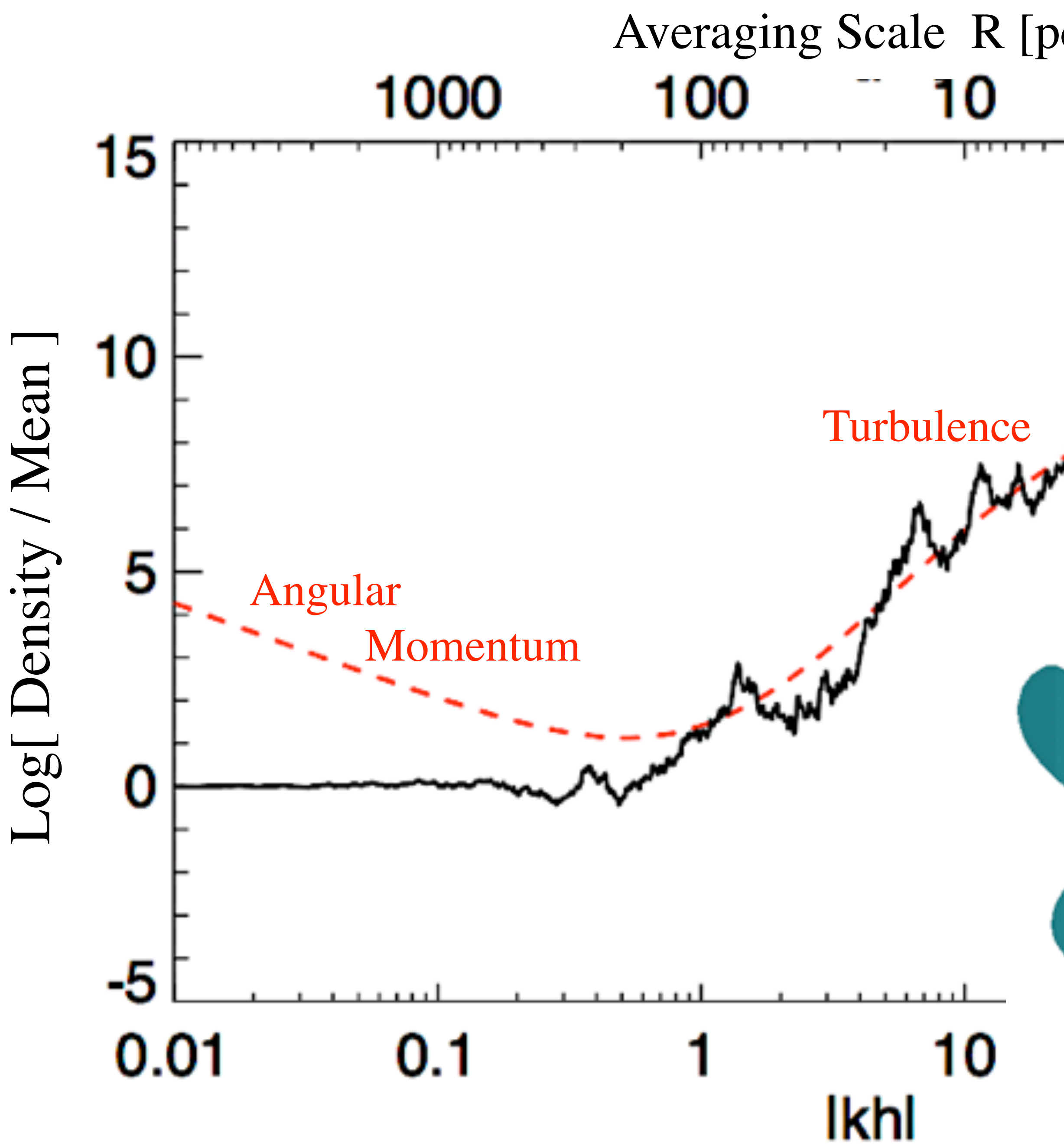


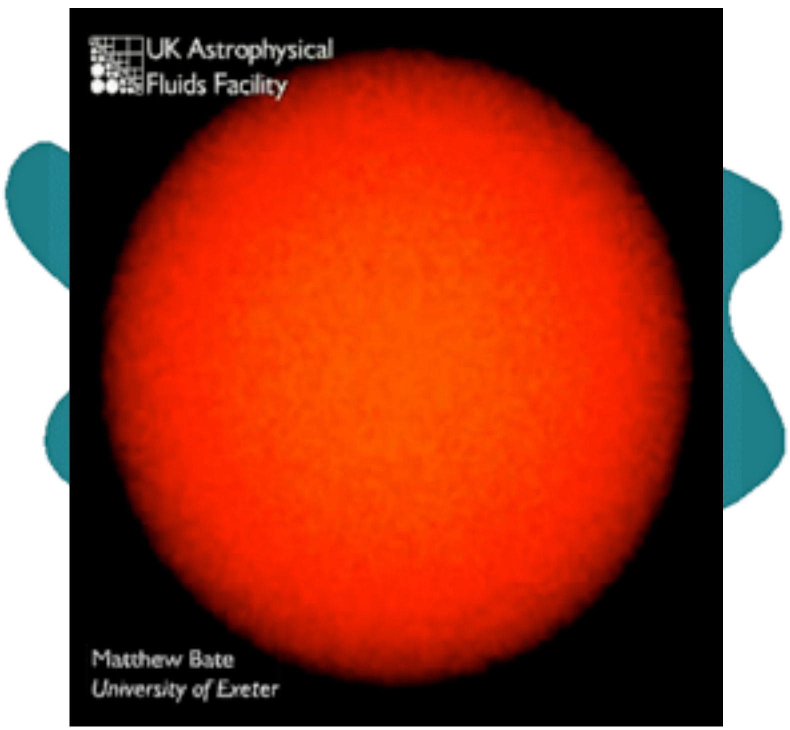

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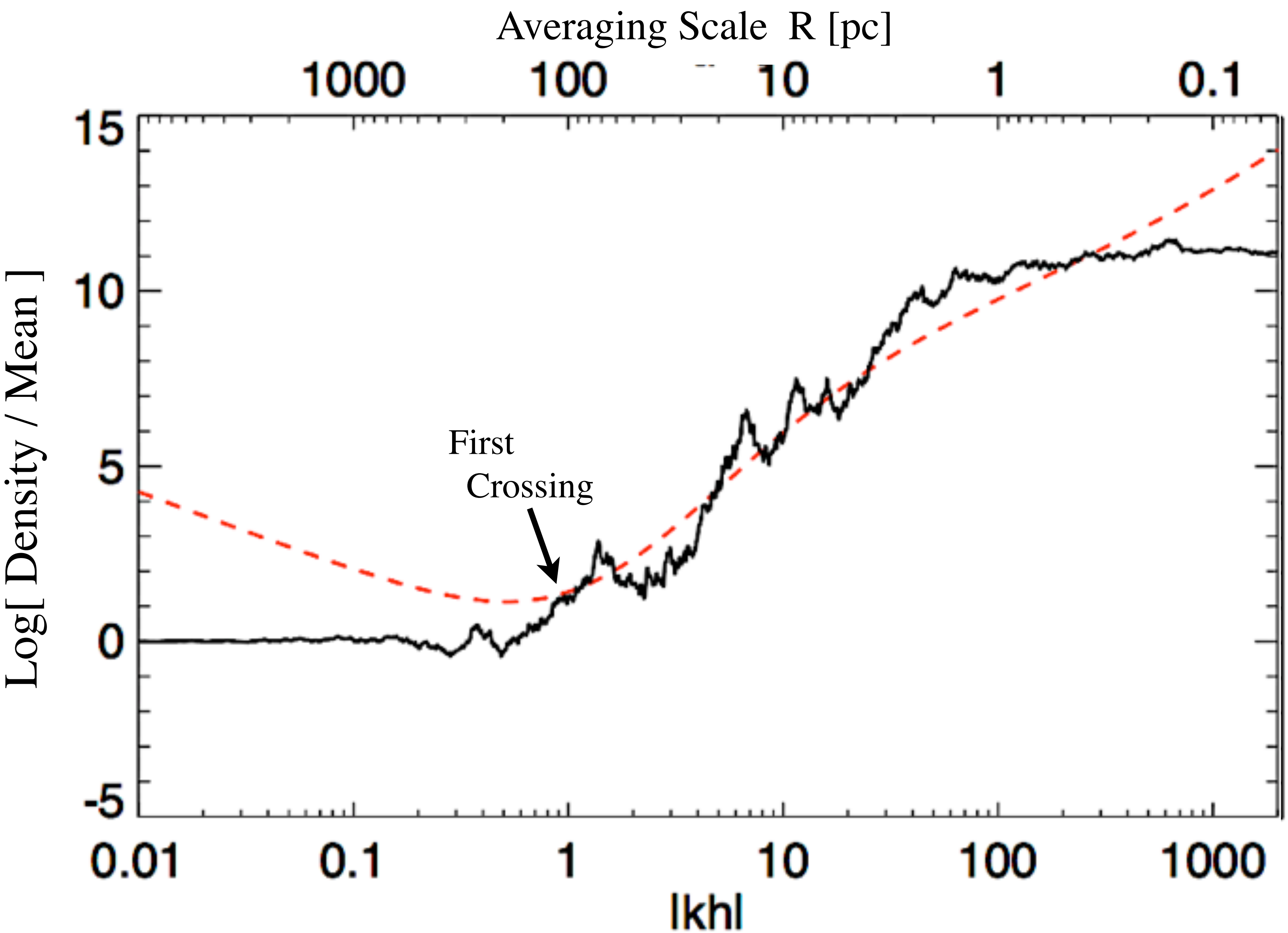

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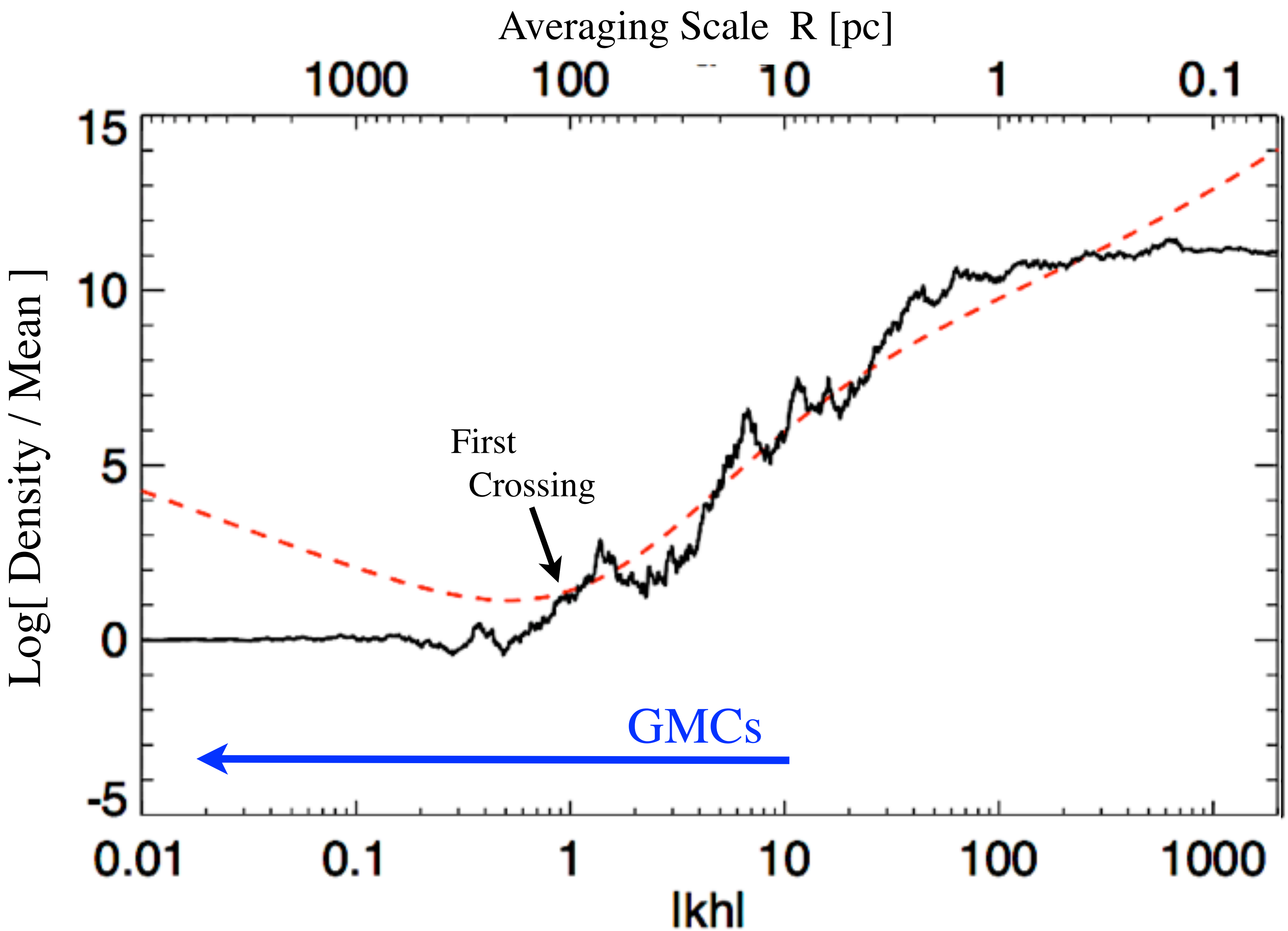

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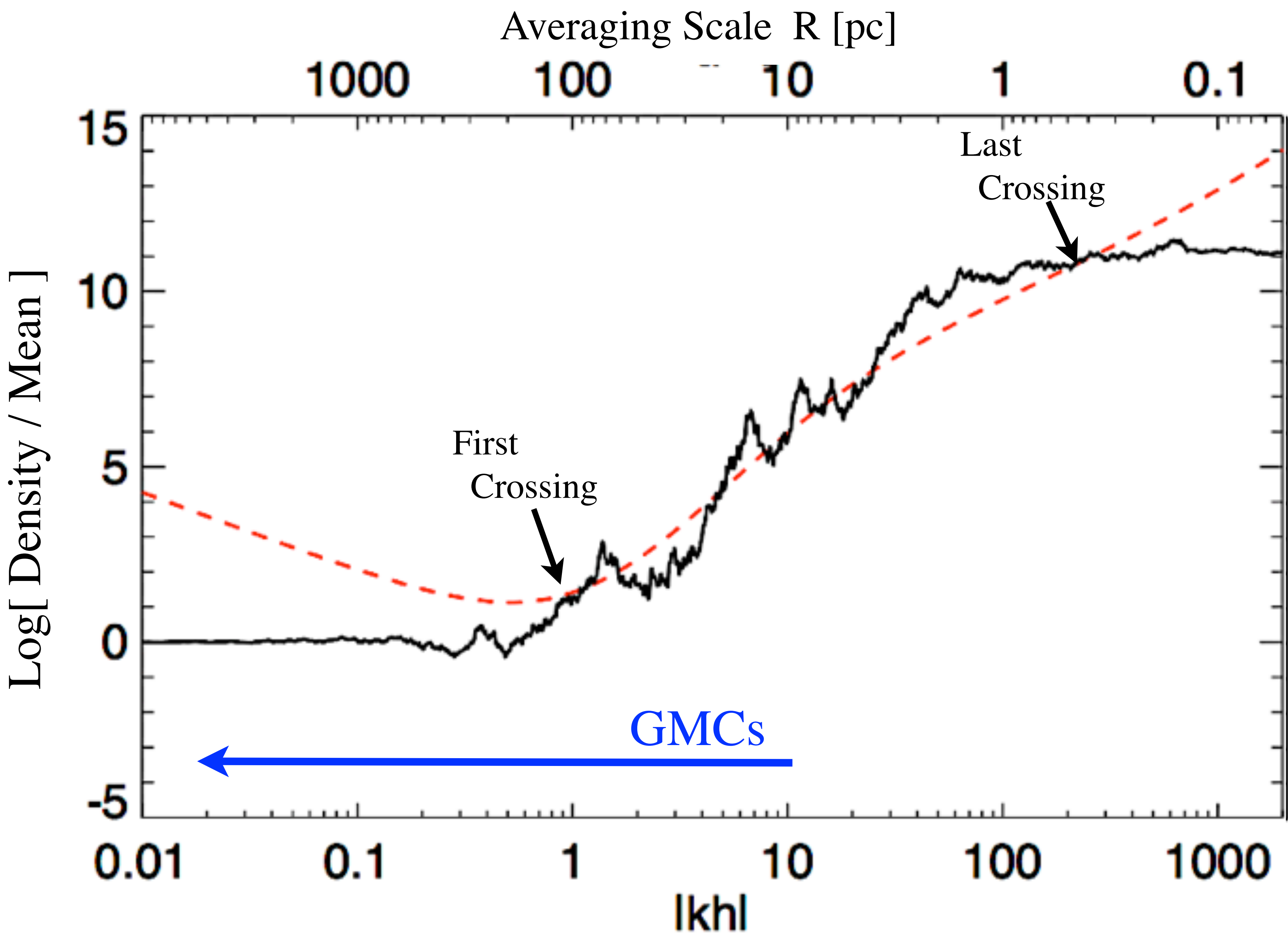

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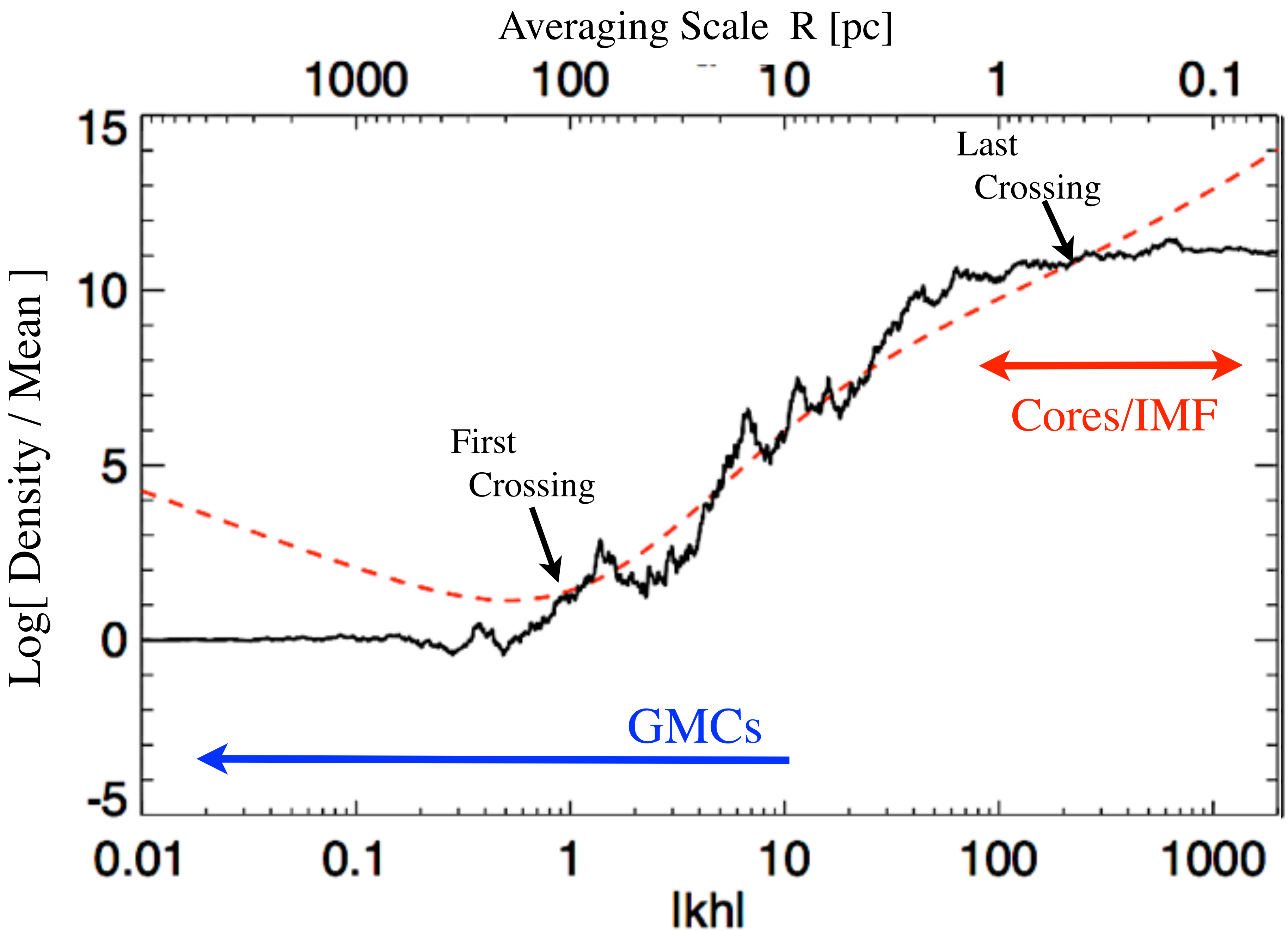
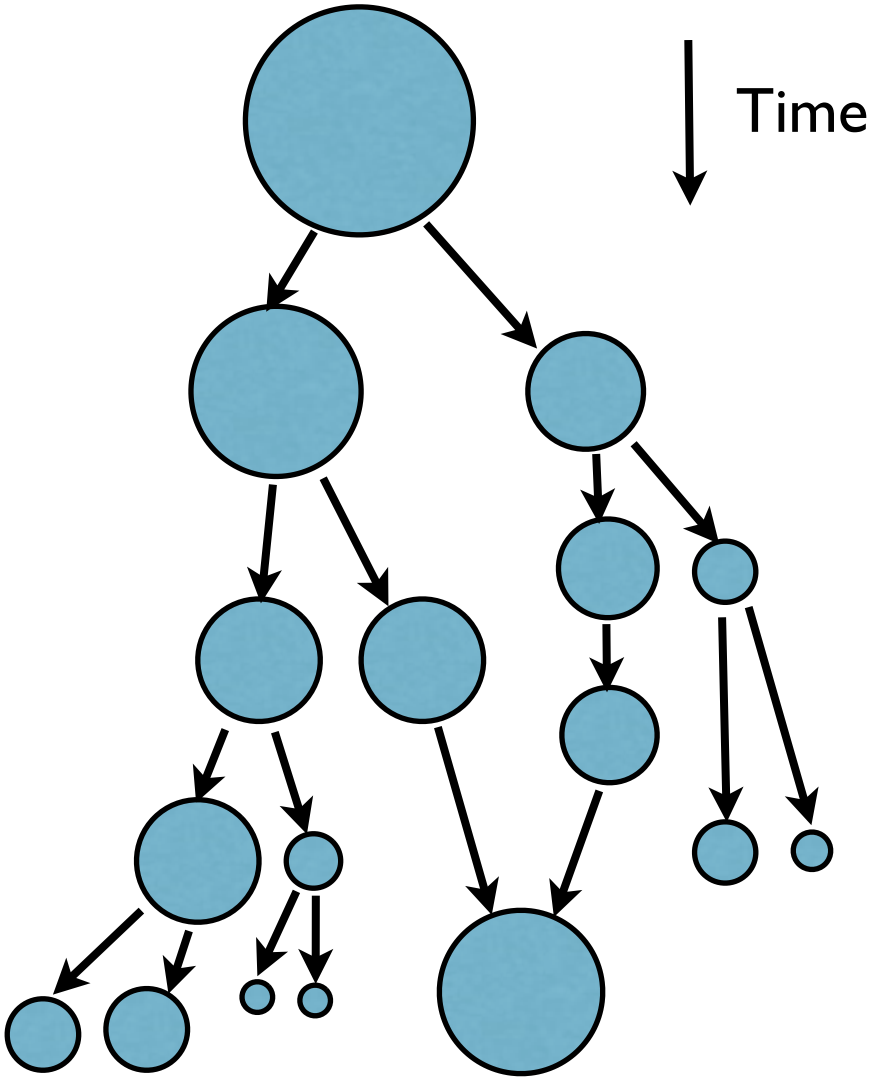


# Evolve the Fluctuations in Time

## CONSTRUCT "MERGER/FRAGMENTATION" TREES

$$p(\delta\,|\,\tau) = \frac{1}{\sqrt{2\pi\, S\,(1-\exp{[-2\tau]})}}\,\exp\left[-\frac{(\delta-\delta(t=0)\,\exp{[-\tau]})^2}{2\,S\,(1-\exp{[-2\tau]})}\right]$$



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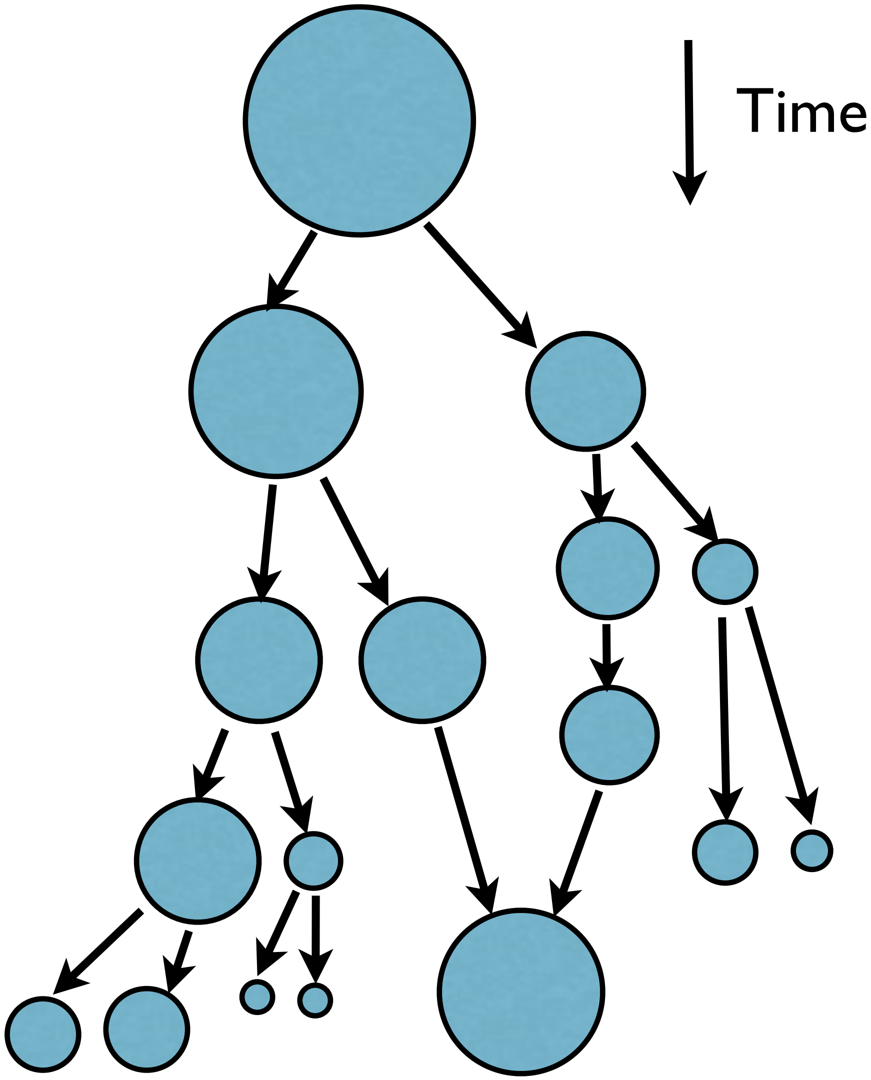
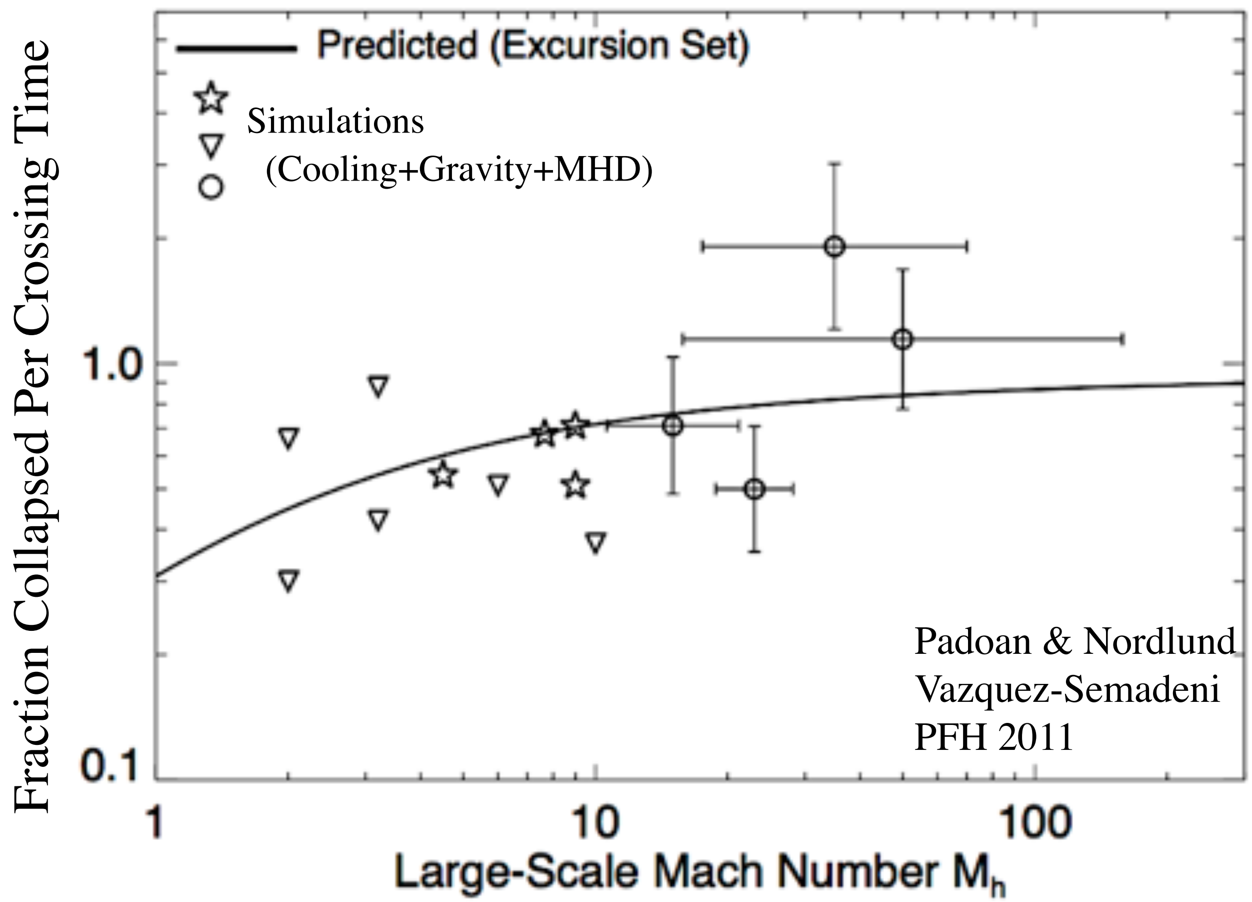
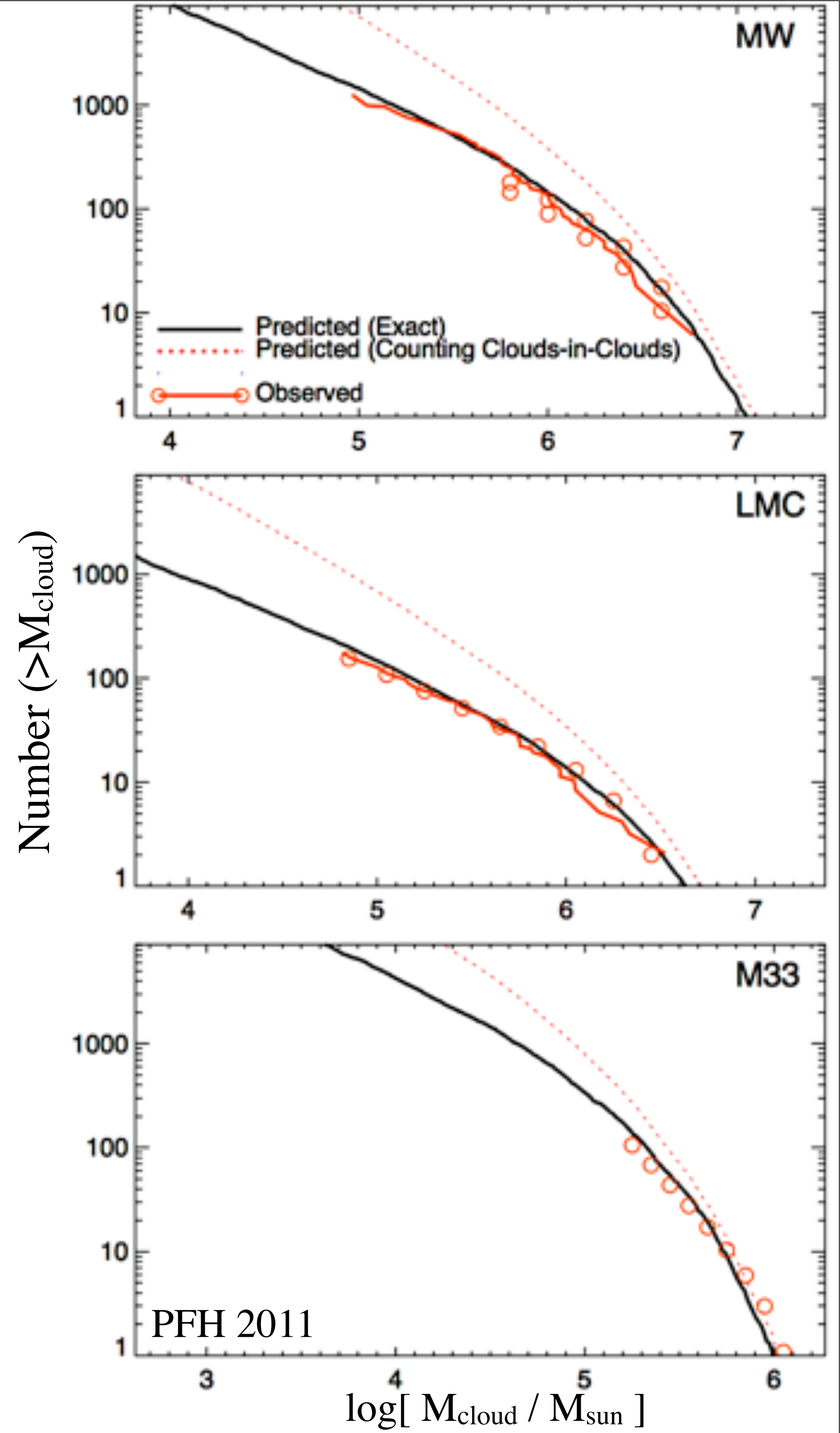


# The "First Crossing" Mass Function

## VS GIANT MOLECULAR CLOUDS



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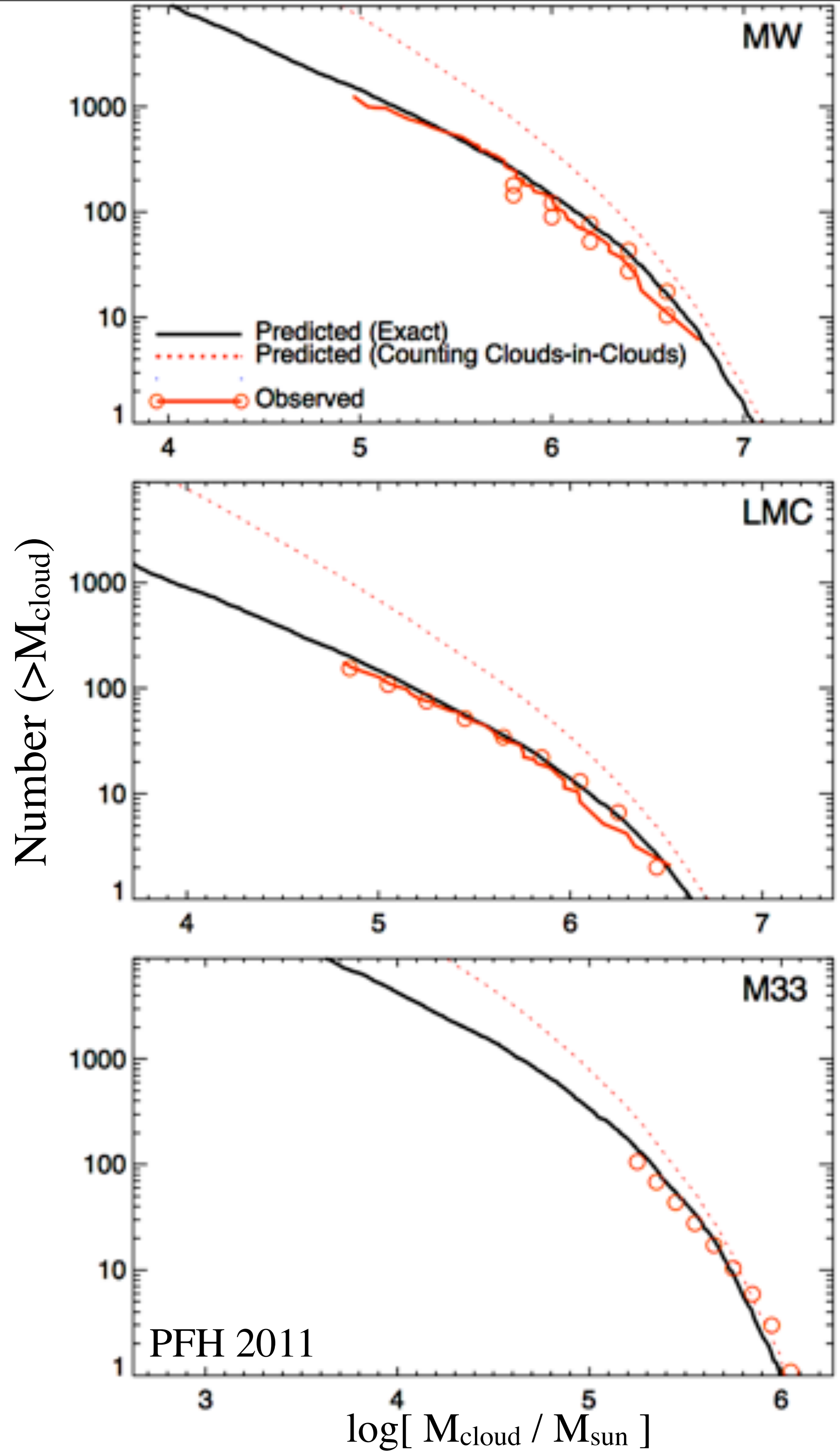

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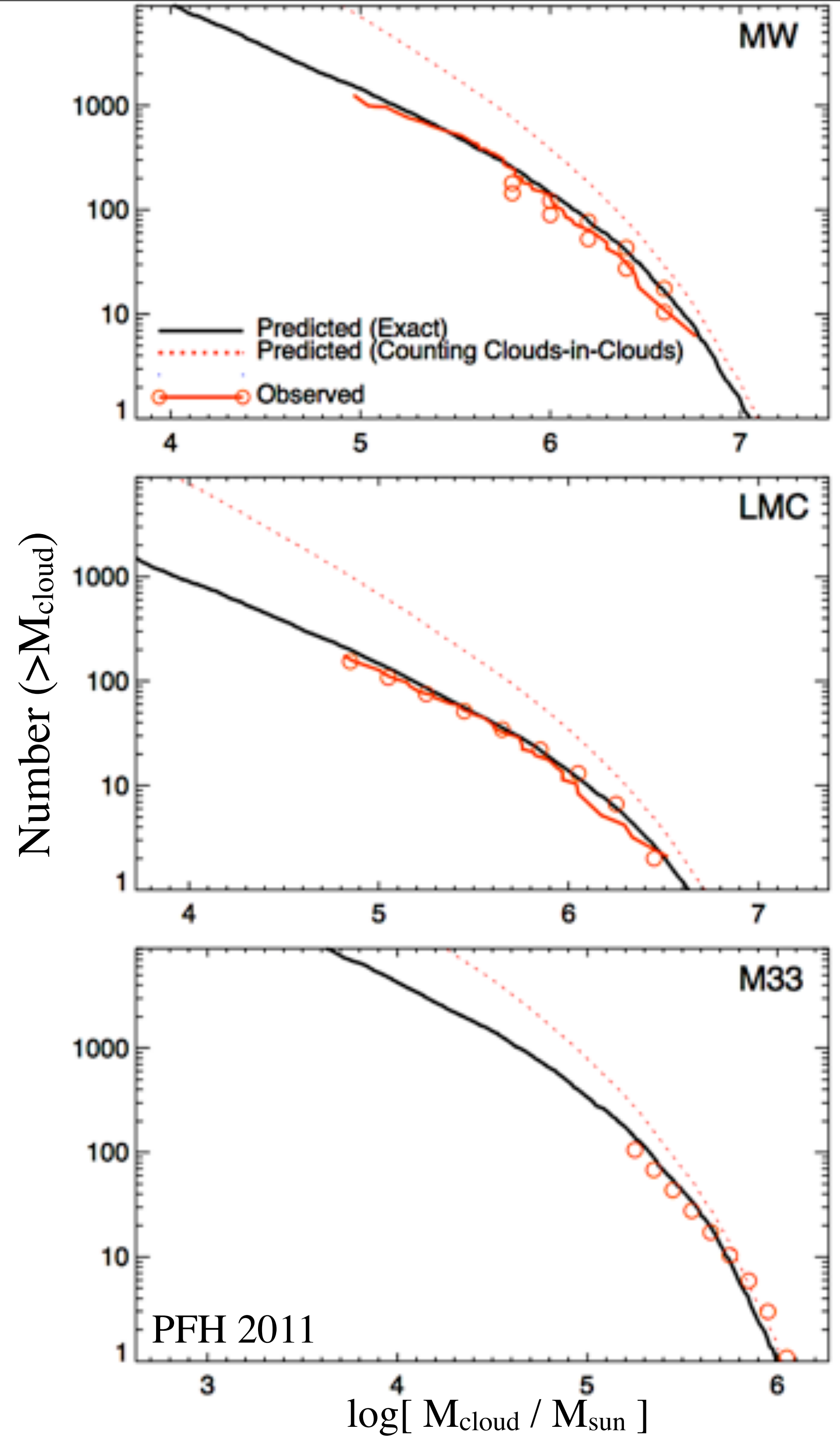

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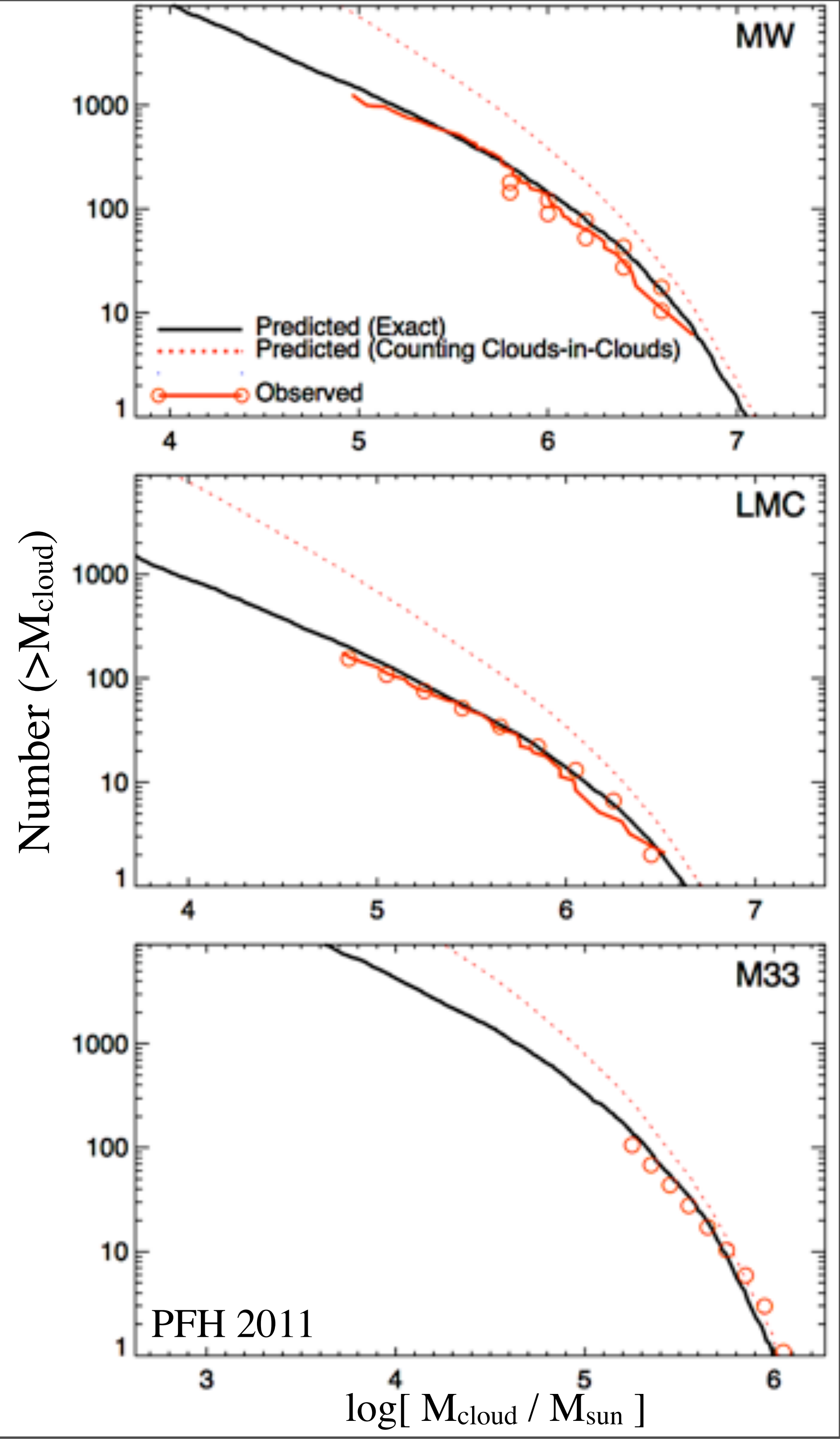

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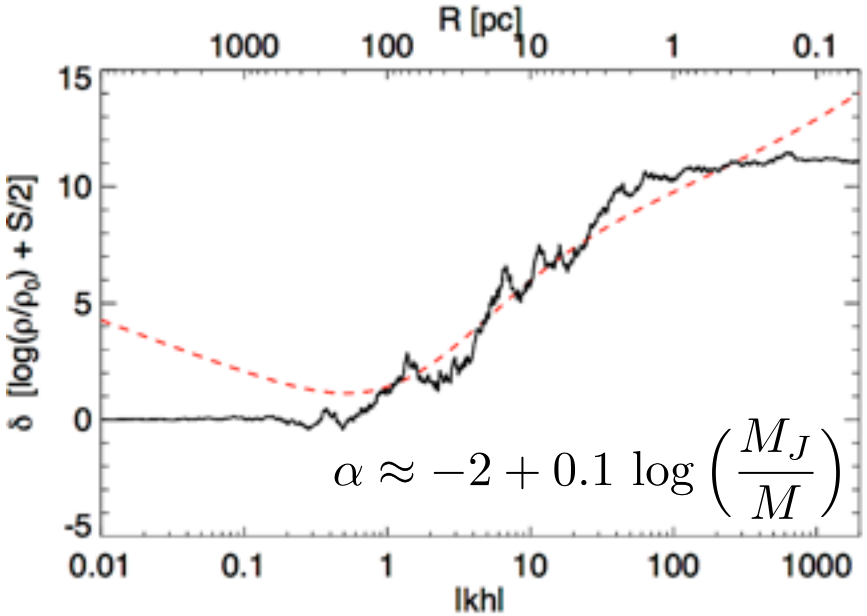


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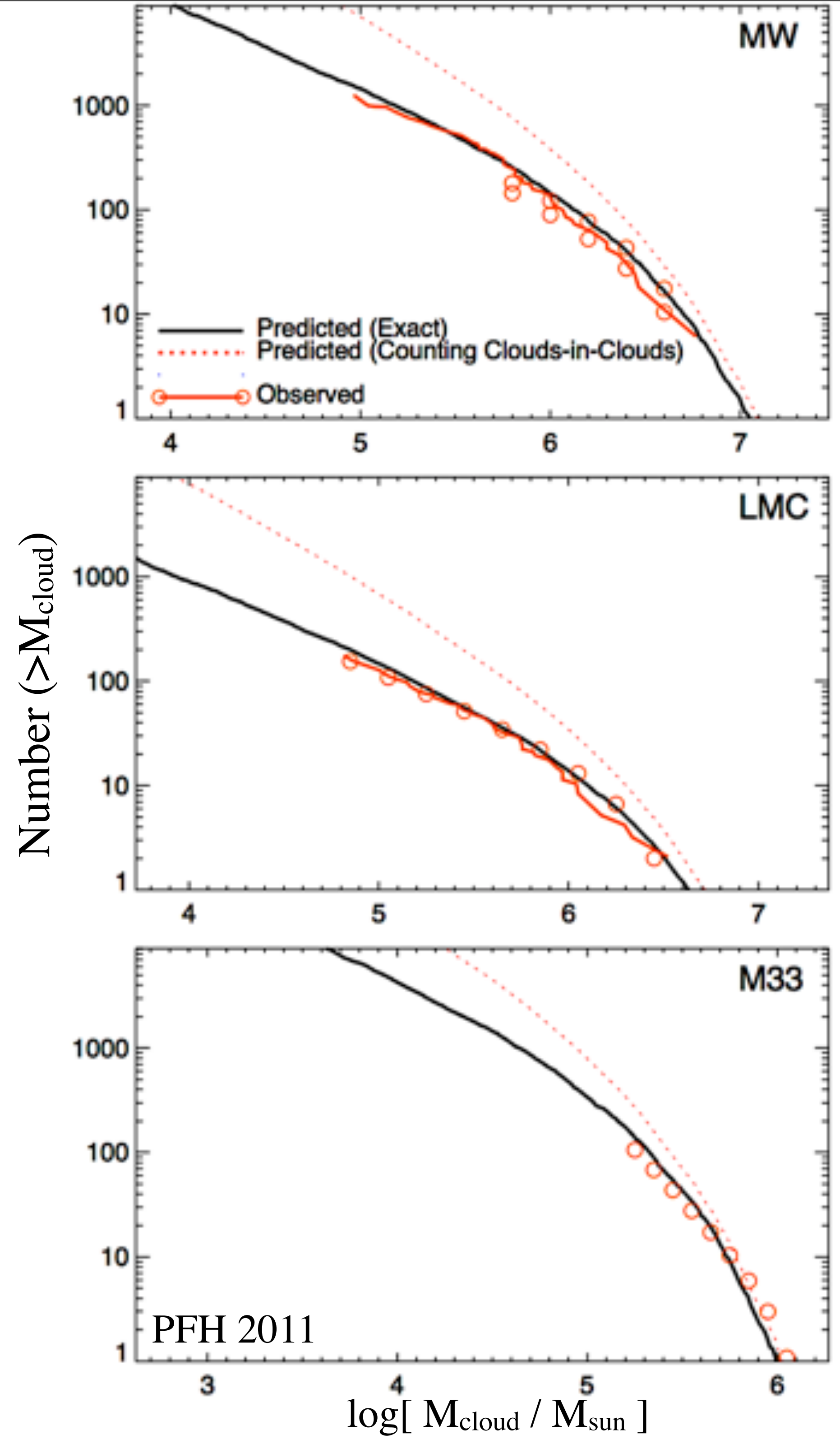

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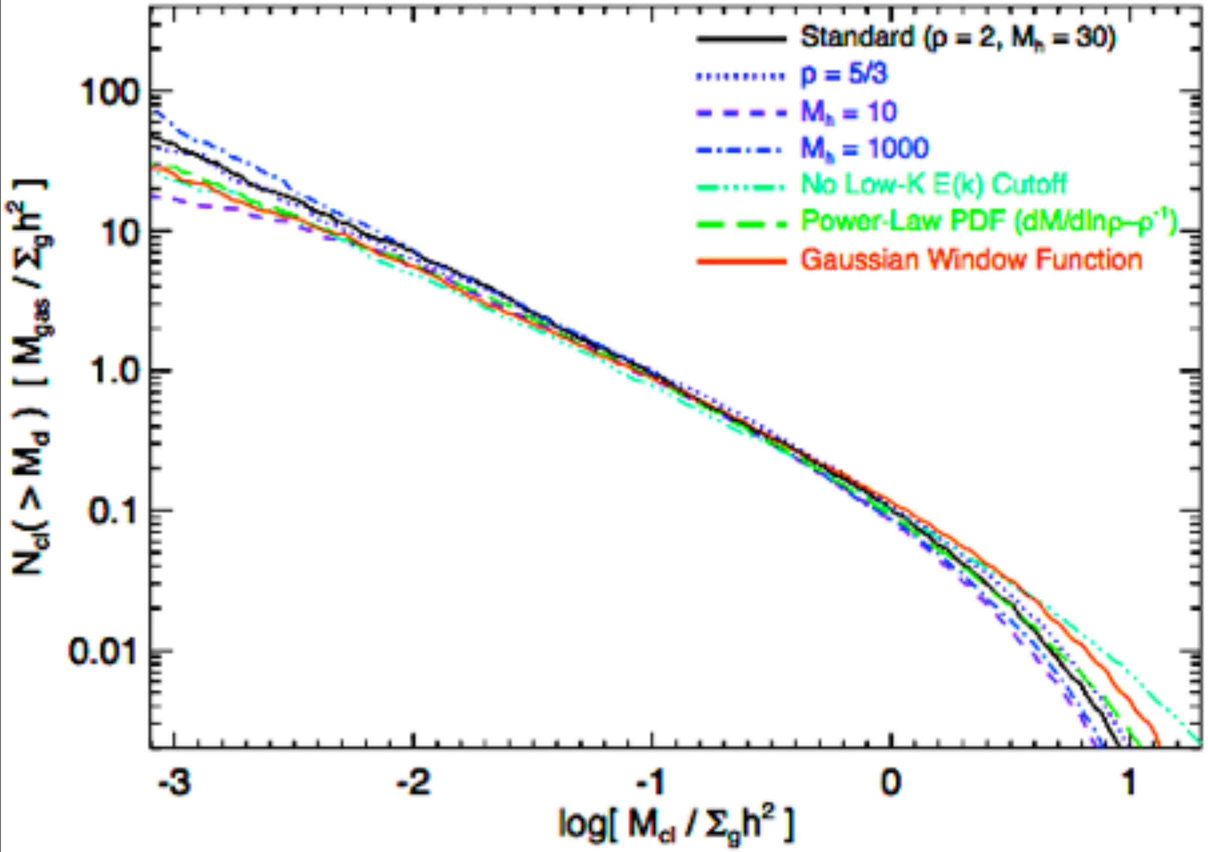
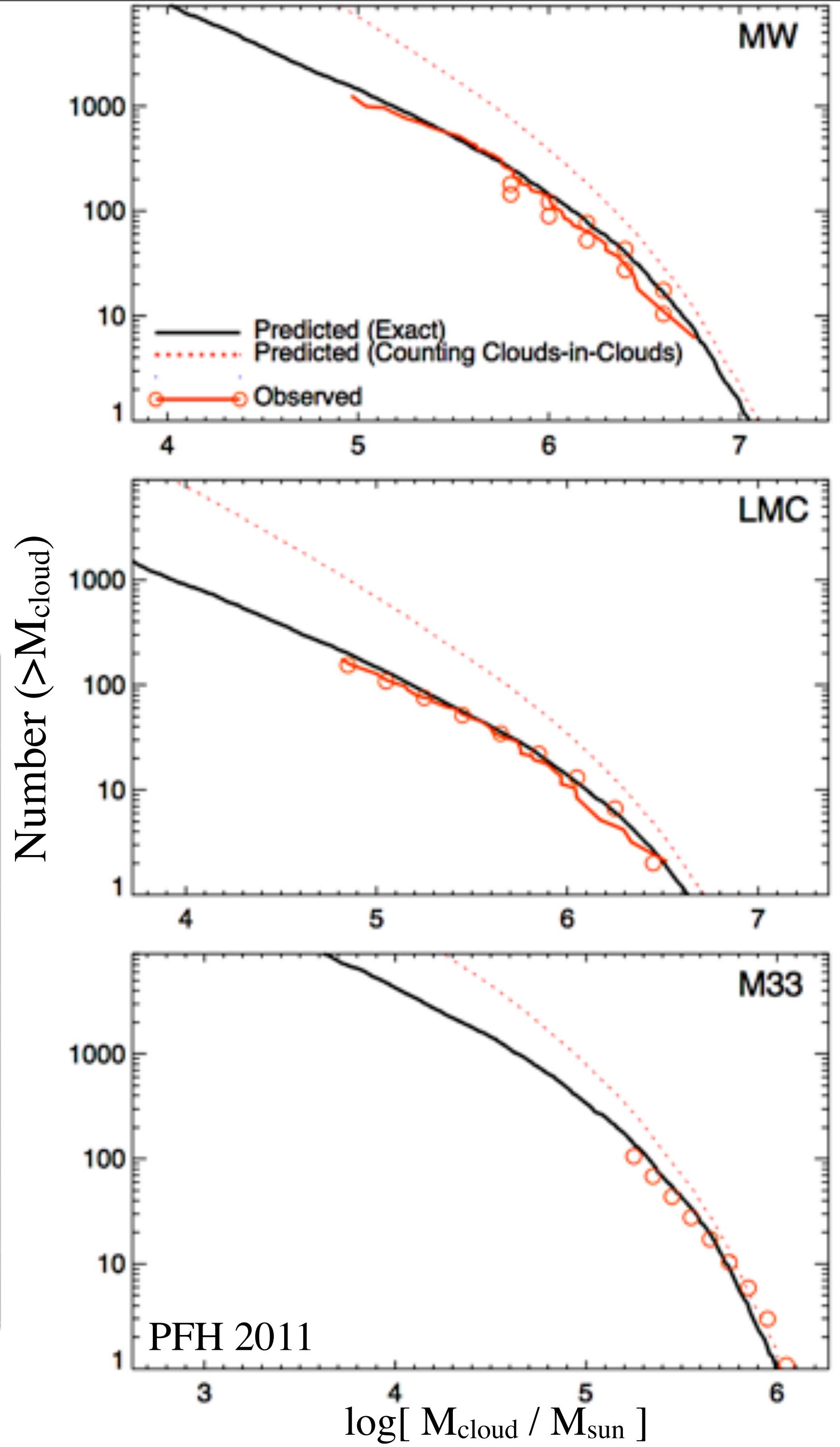
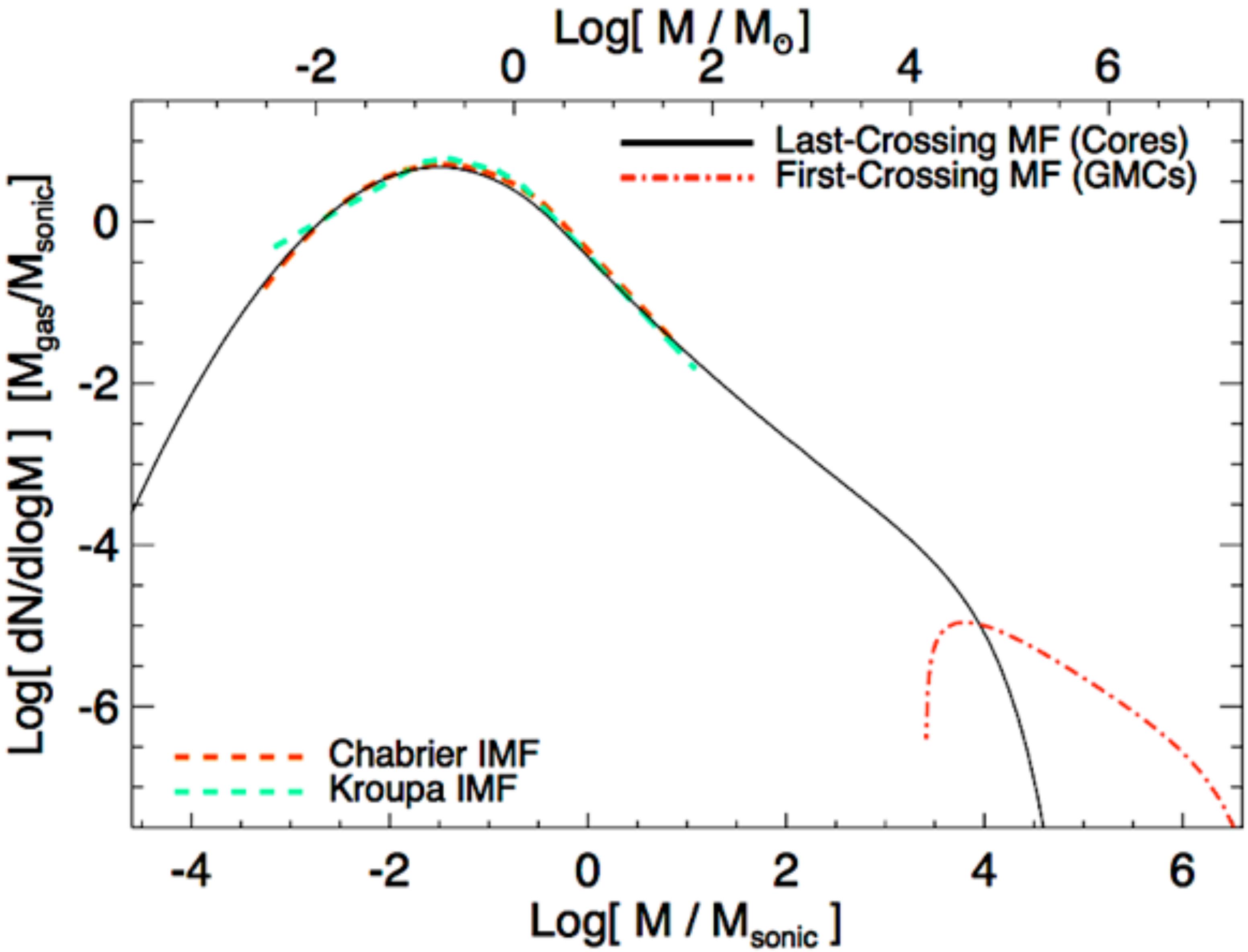


# The “Last Crossing” Mass Function



## VS PROTOSTELLAR CORES & THE STELLAR IMF



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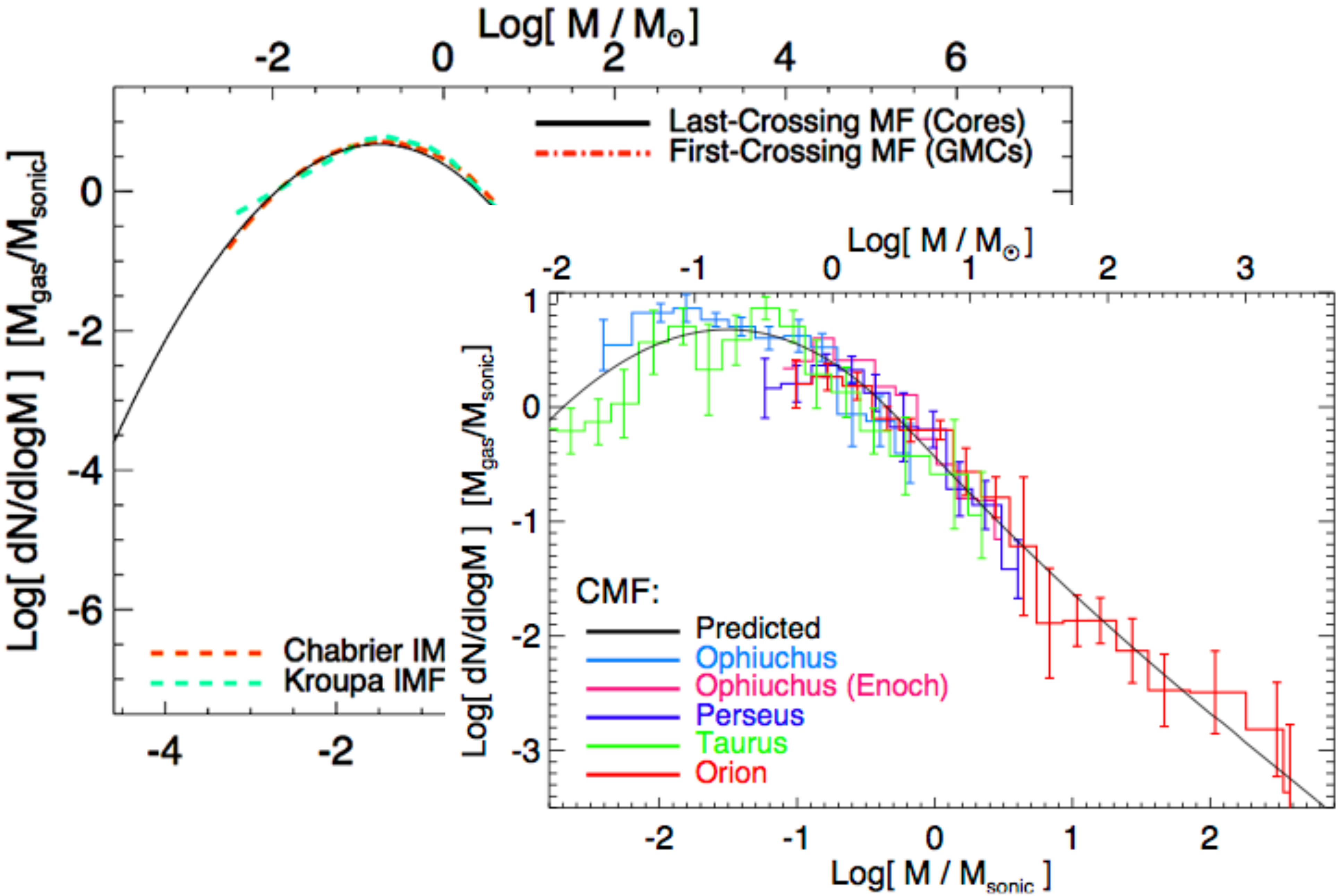
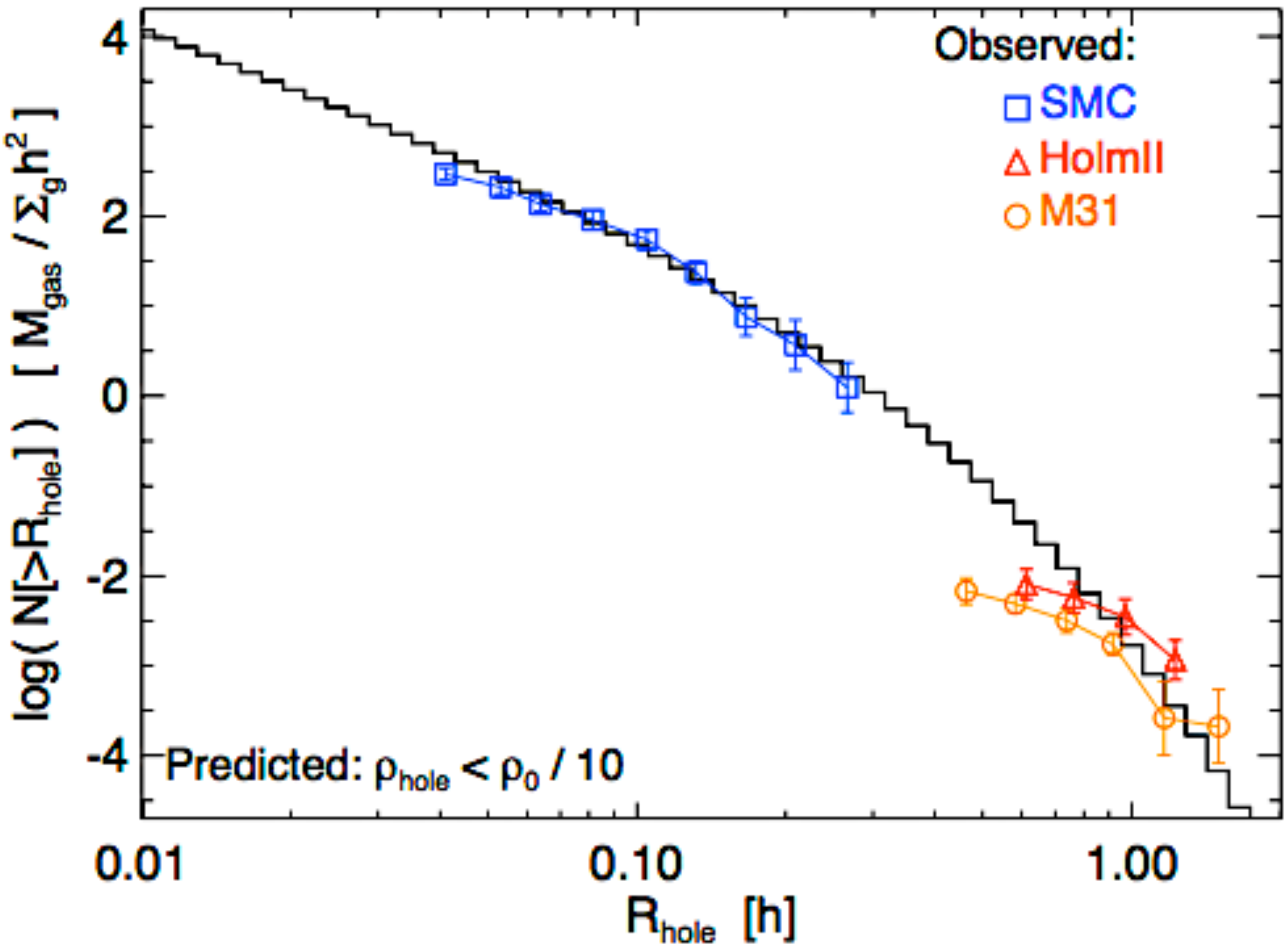


# "Void" Abundance

## VS HI "HOLES" IN THE ISM

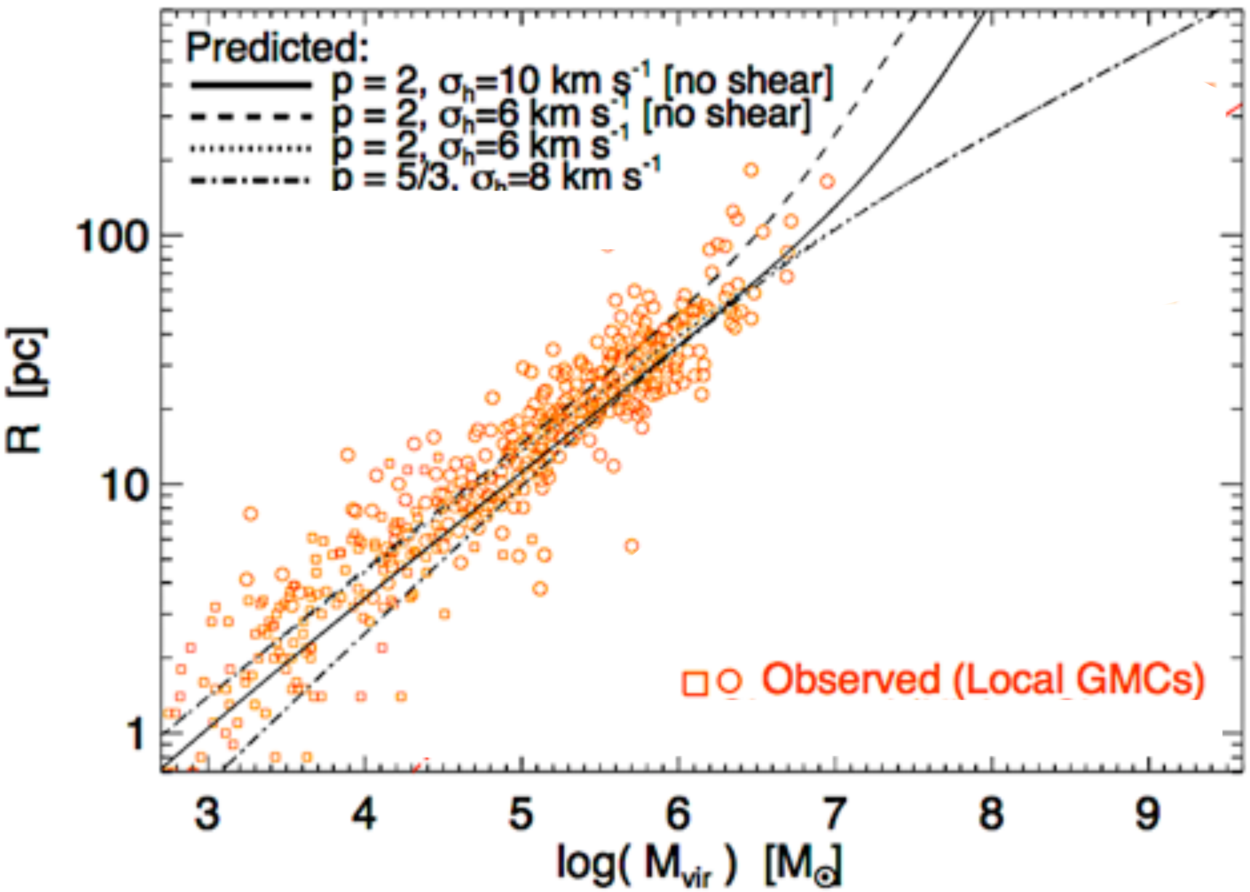



KEEP?

Don't need SNe to "clear out" voids

# Structural Properties of "Clouds"

## LARSON'S LAWS EMERGE NATURALLY




KEEP?

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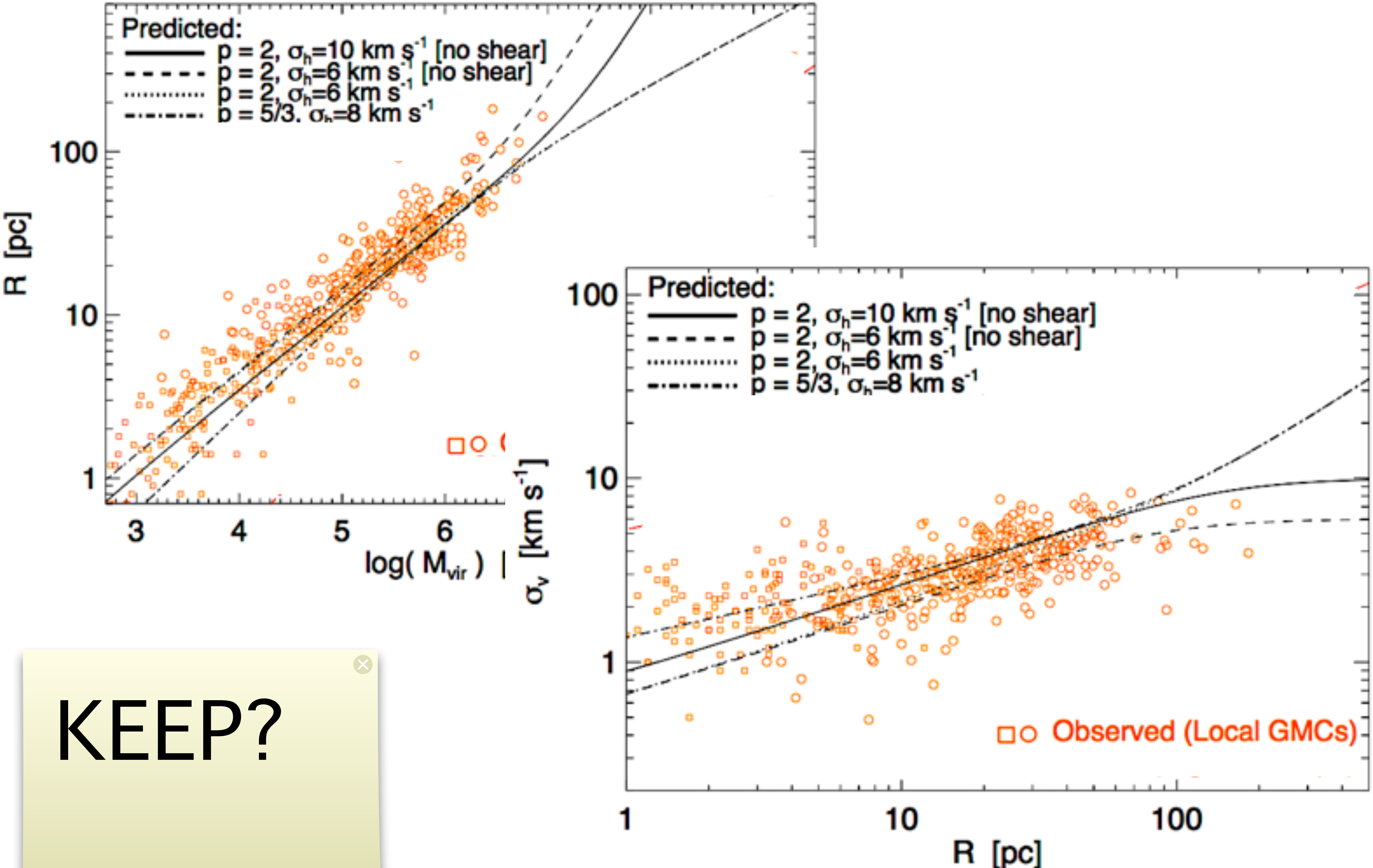
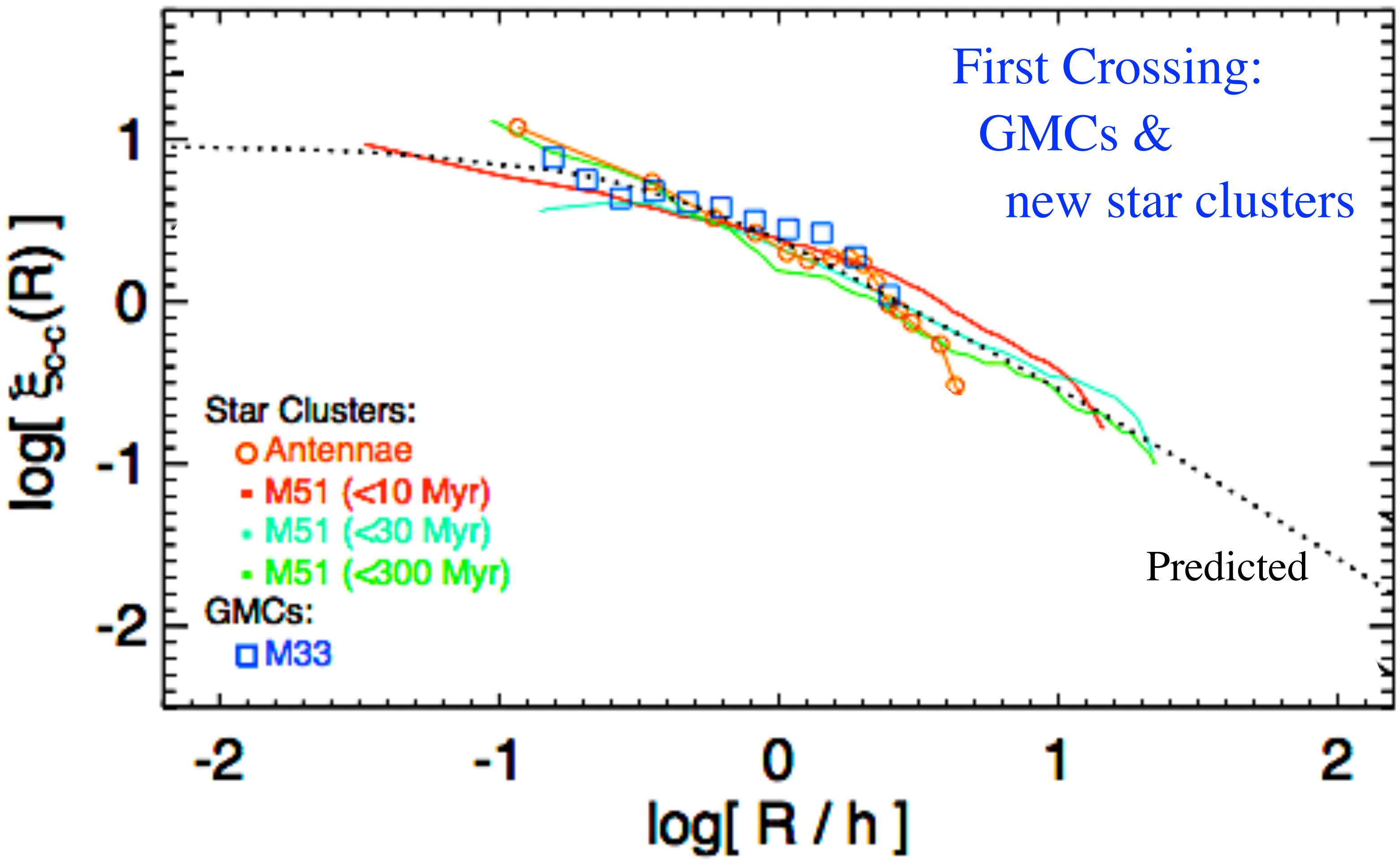



KEEP?

# Clustering

## PREDICT N-POINT CORRELATION FUNCTIONS

$$1 + \xi(r \,|\, M) \equiv \frac{\langle n[M \,|\, r' < r] \rangle}{\langle n[M] \rangle}$$



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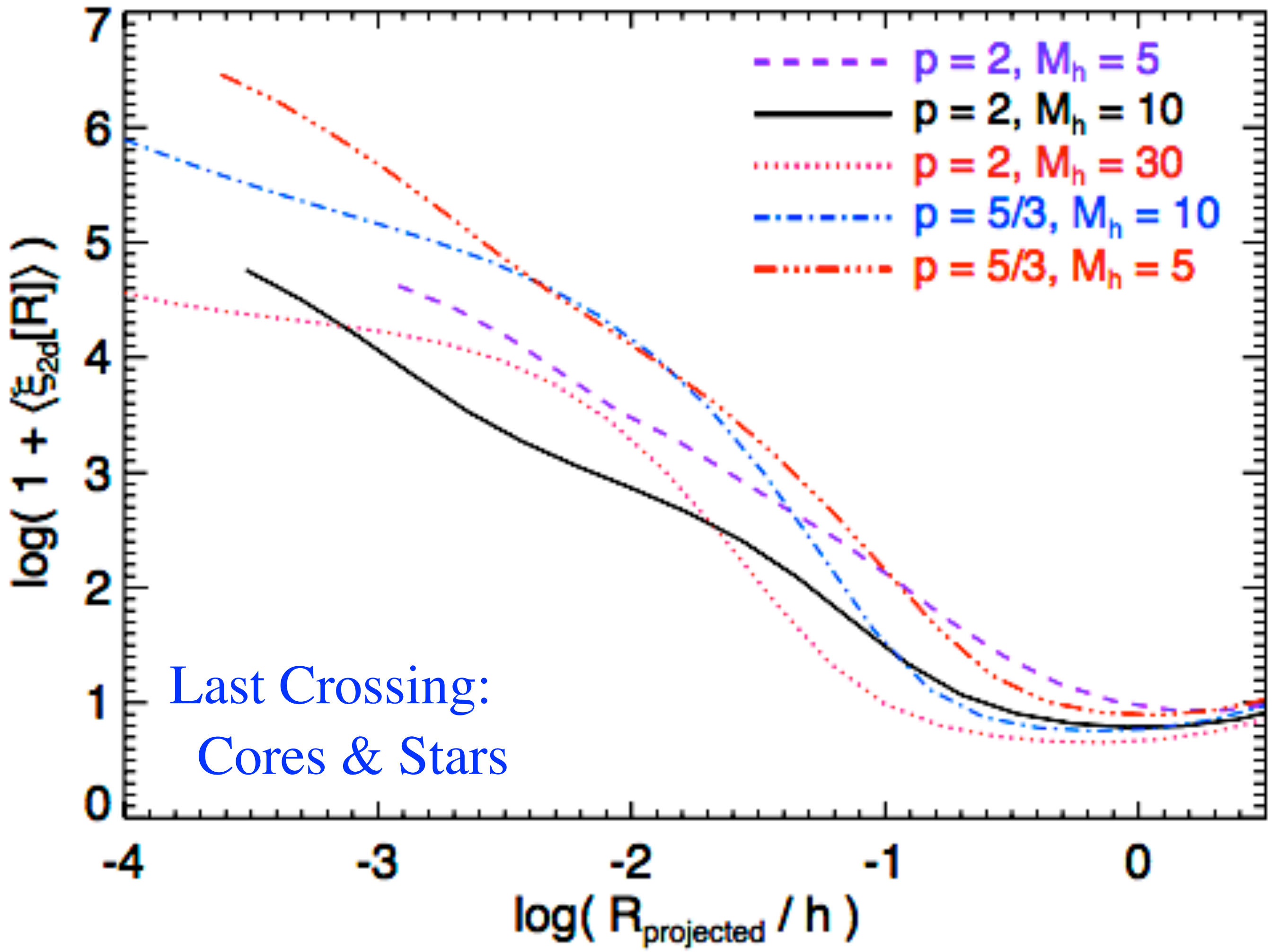

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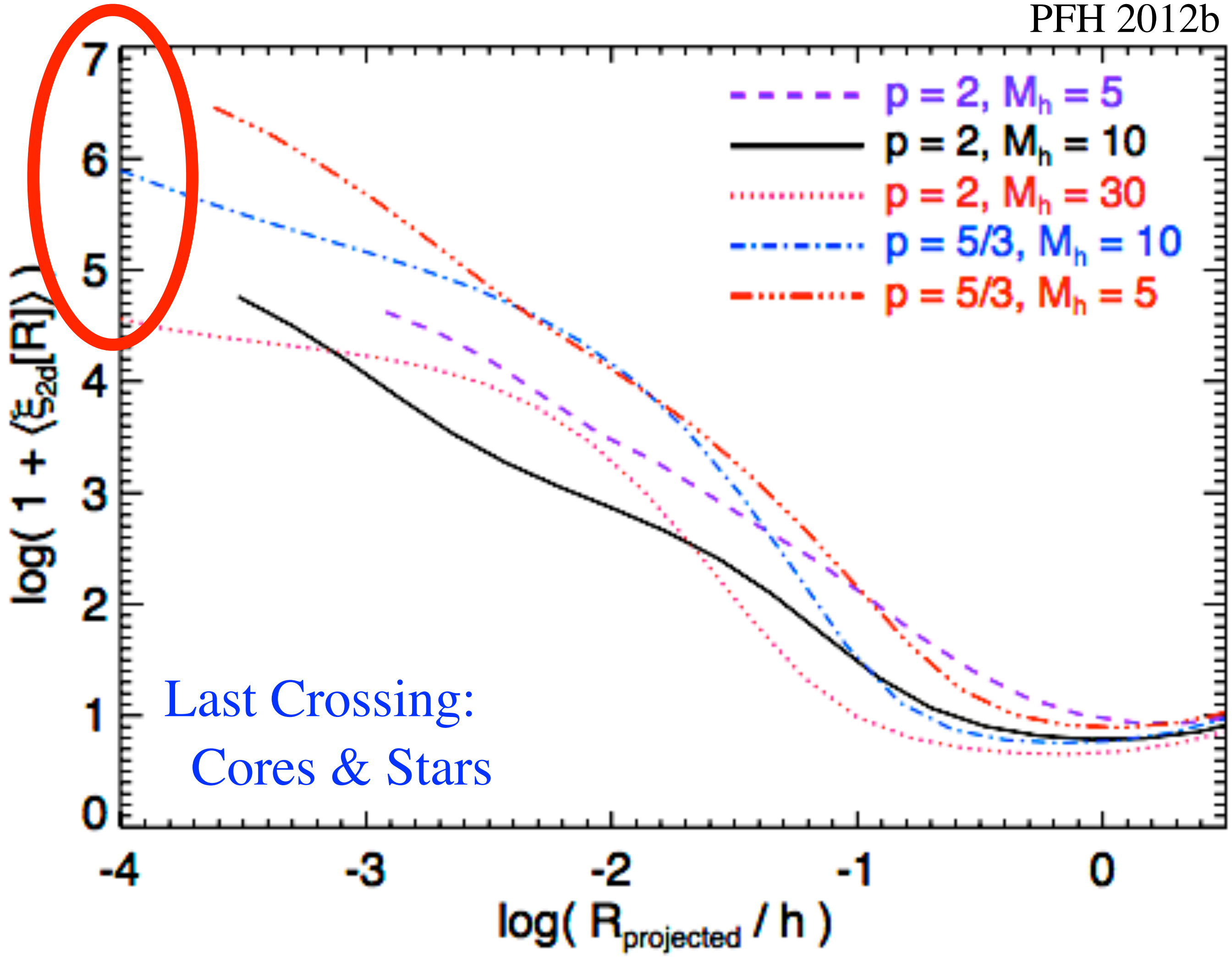

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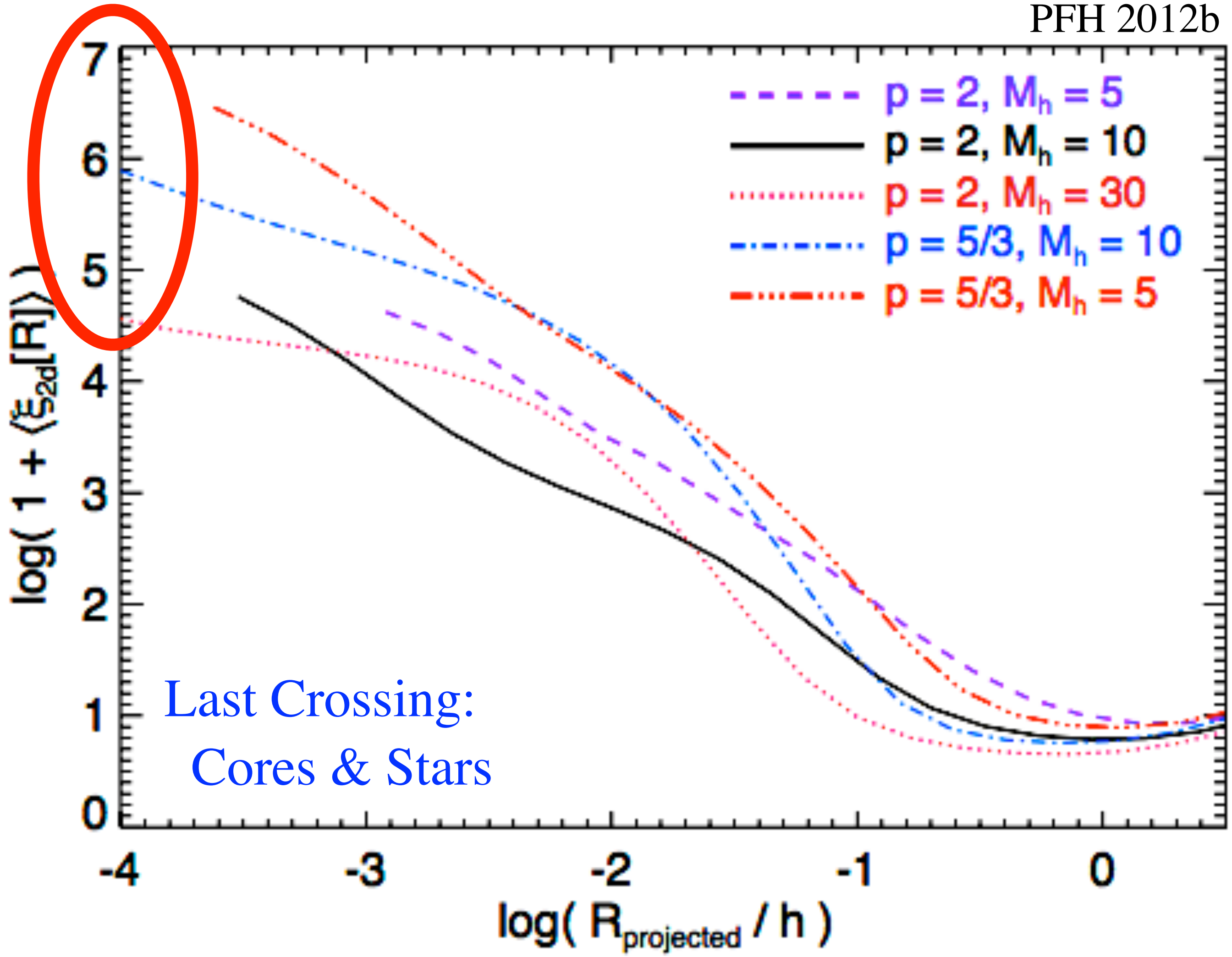
PFH 2012b

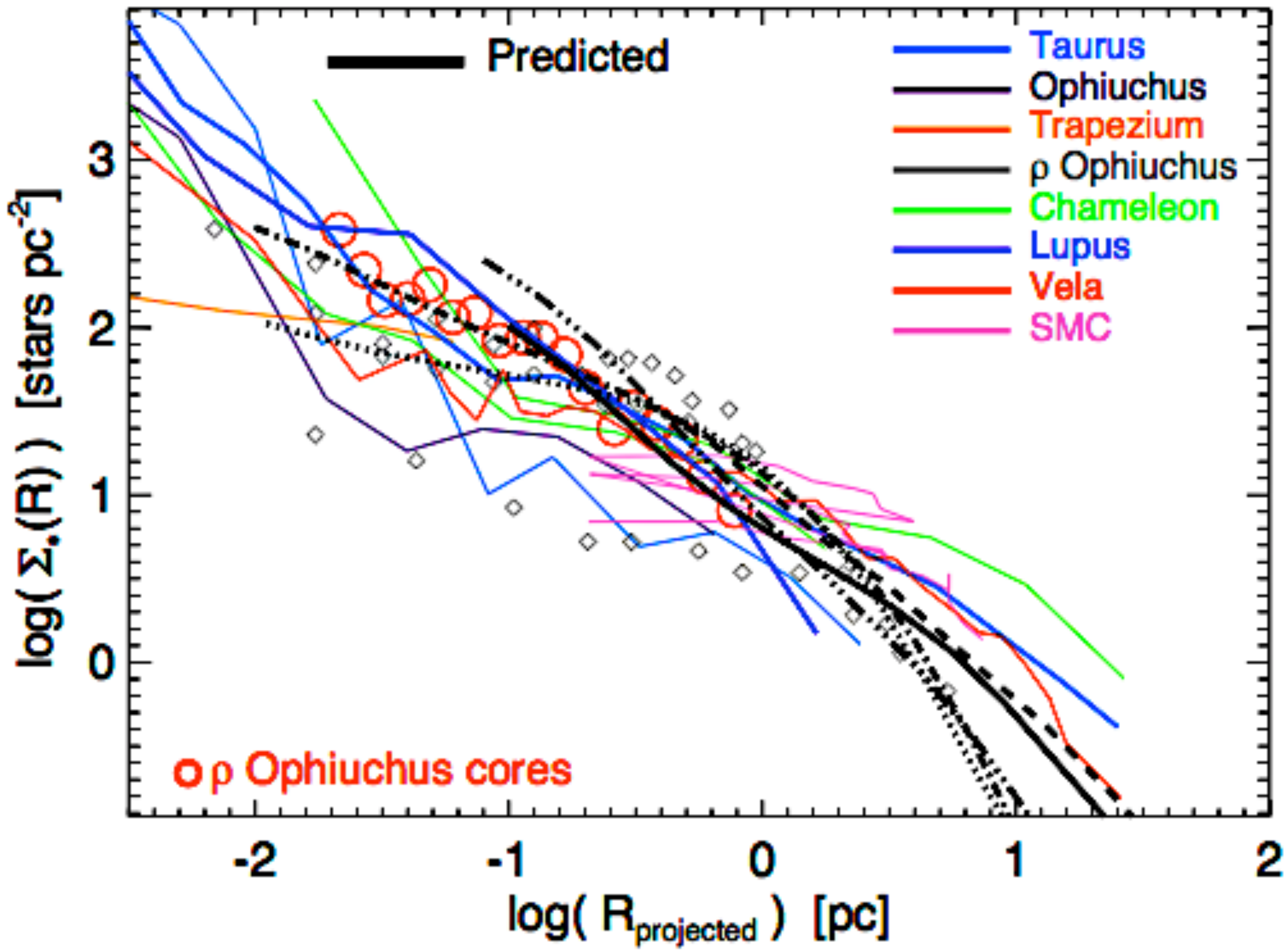
Why is Star Formation Clustered?

$$S \sim \ln \mathcal{M}(k)^2$$
$$\sim \ln r^{3-p}$$



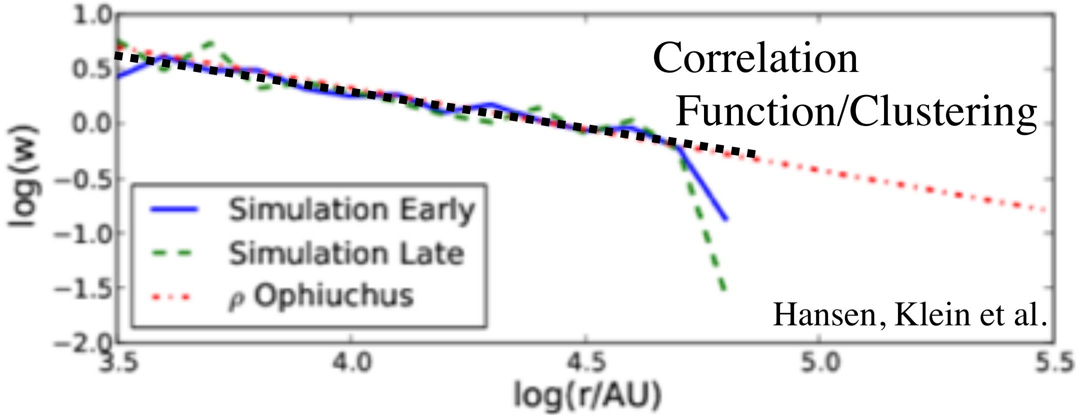
# Clustering of Stars: Predicted vs. Observations

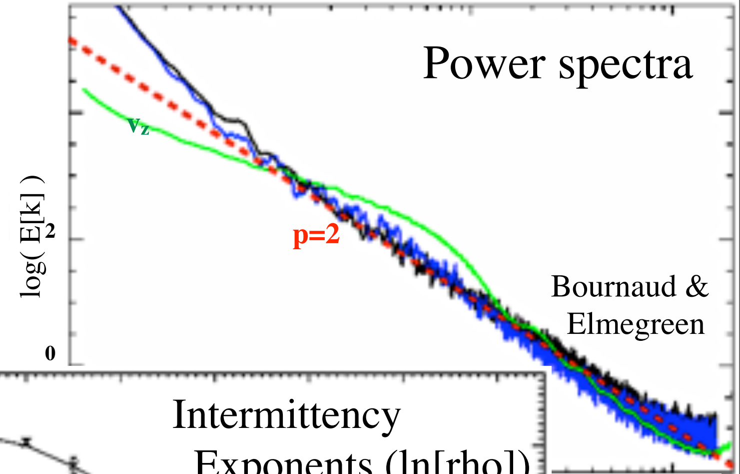
## PREDICT N-POINT CORRELATION FUNCTIONS

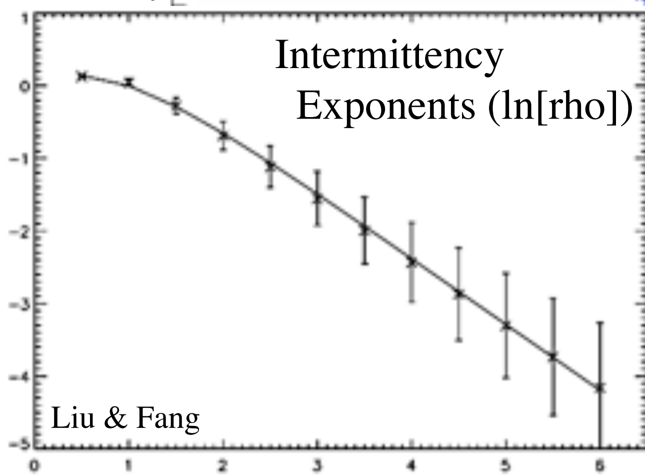


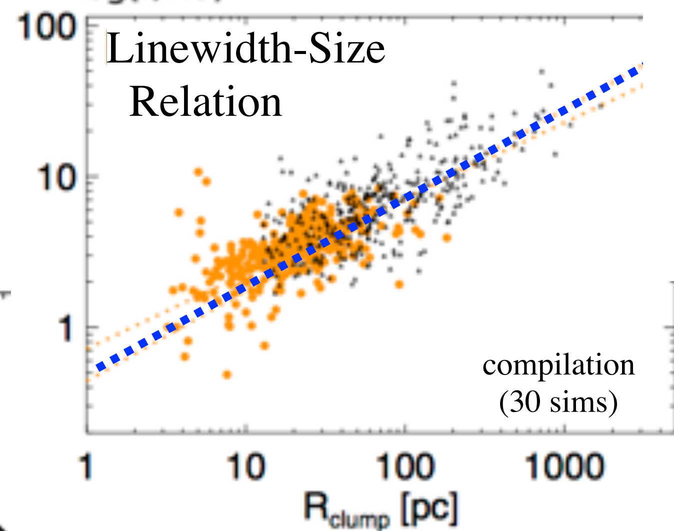
# Testing the Analytics

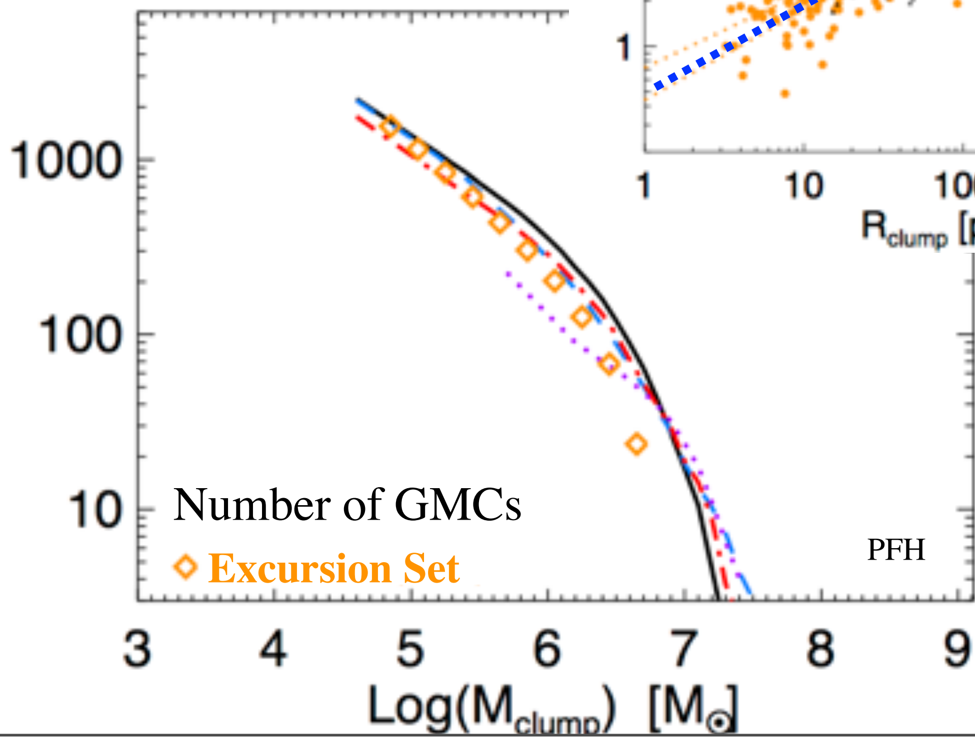
## vs. NUMERICAL SIMULATIONS

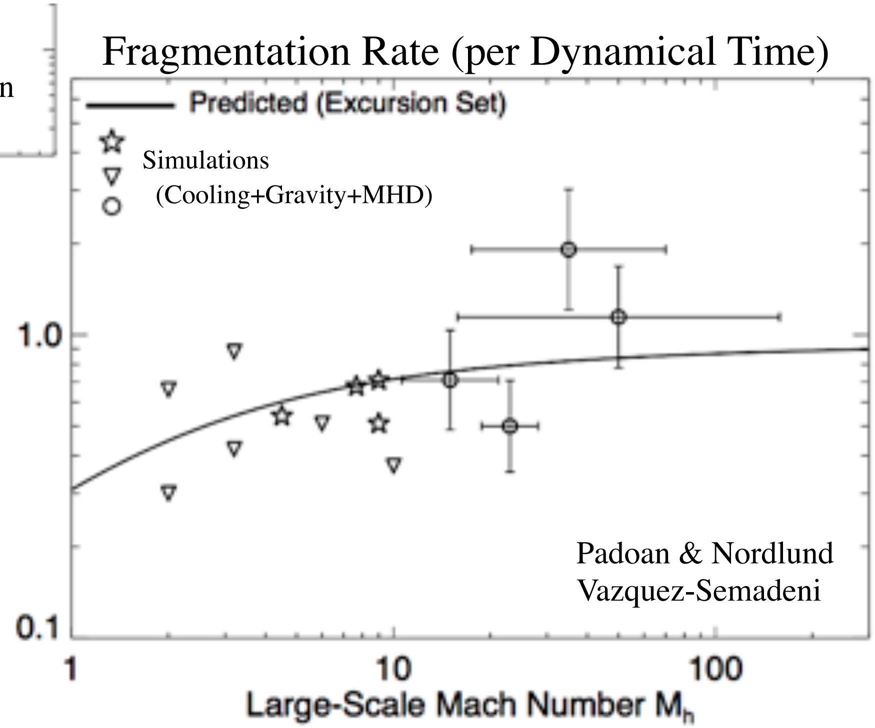


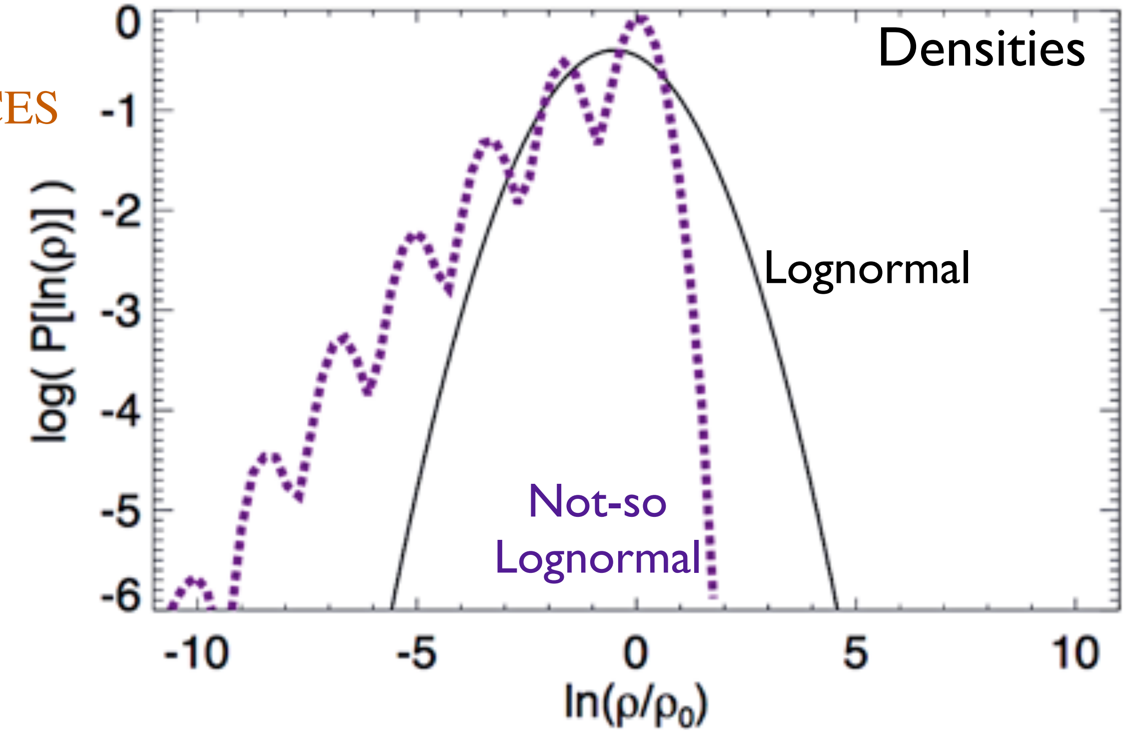



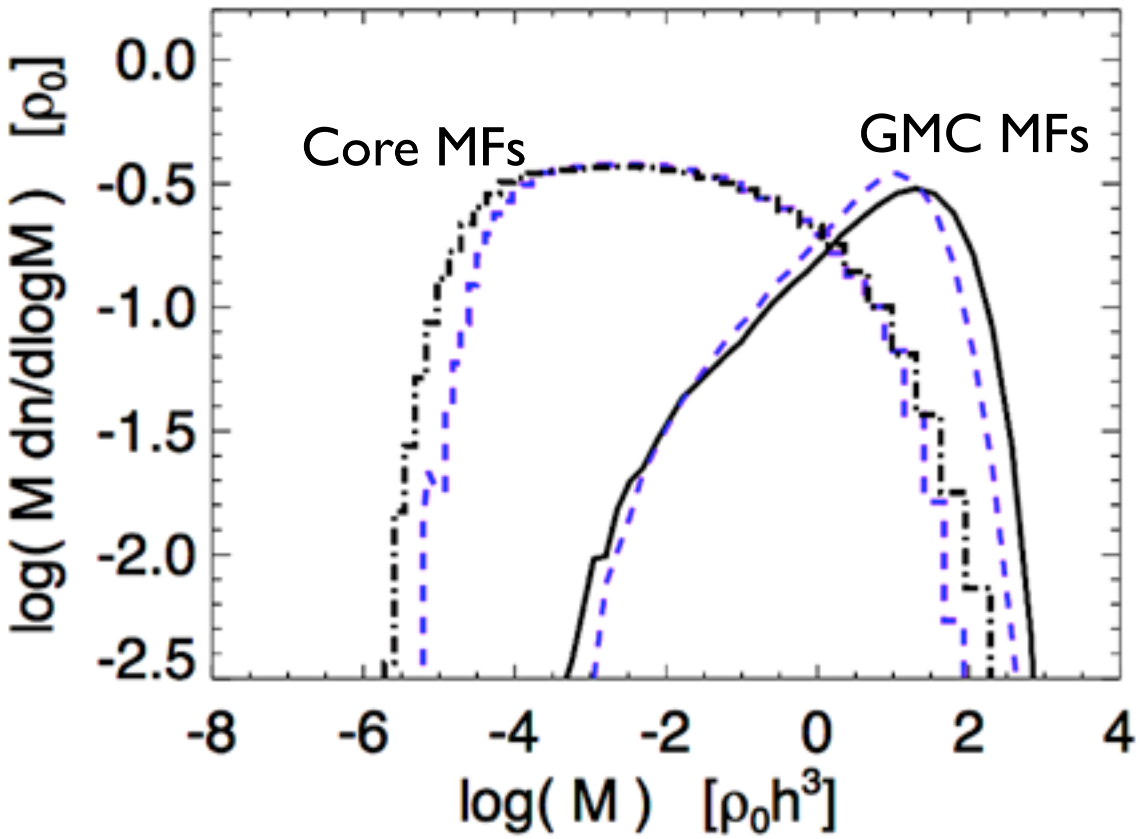



# General, Flexible Theory:
EXTREMELY ADAPTABLE TO MOST CHOICES

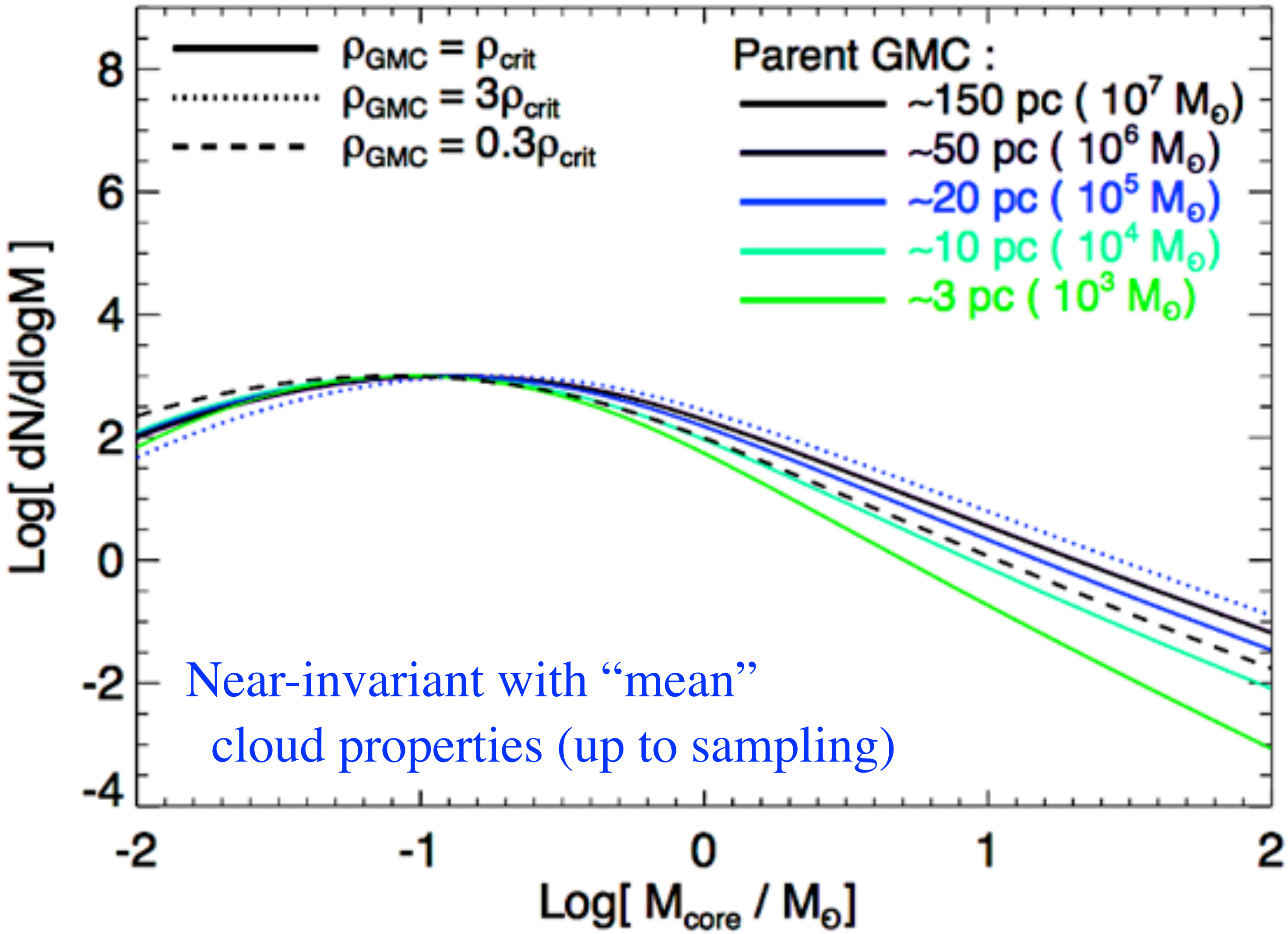
- Complicated, multivariable gas equations of state
- Accretion
- Magnetic Fields
- Time-Dependent Background Evolution/Collapse
- Intermittency
- Correlated, multi-scale driving



# Variation in the Core Mass Function

## VS "NORMAL" IMF VARIATIONS




Near-invariant with "mean" cloud properties (up to sampling)

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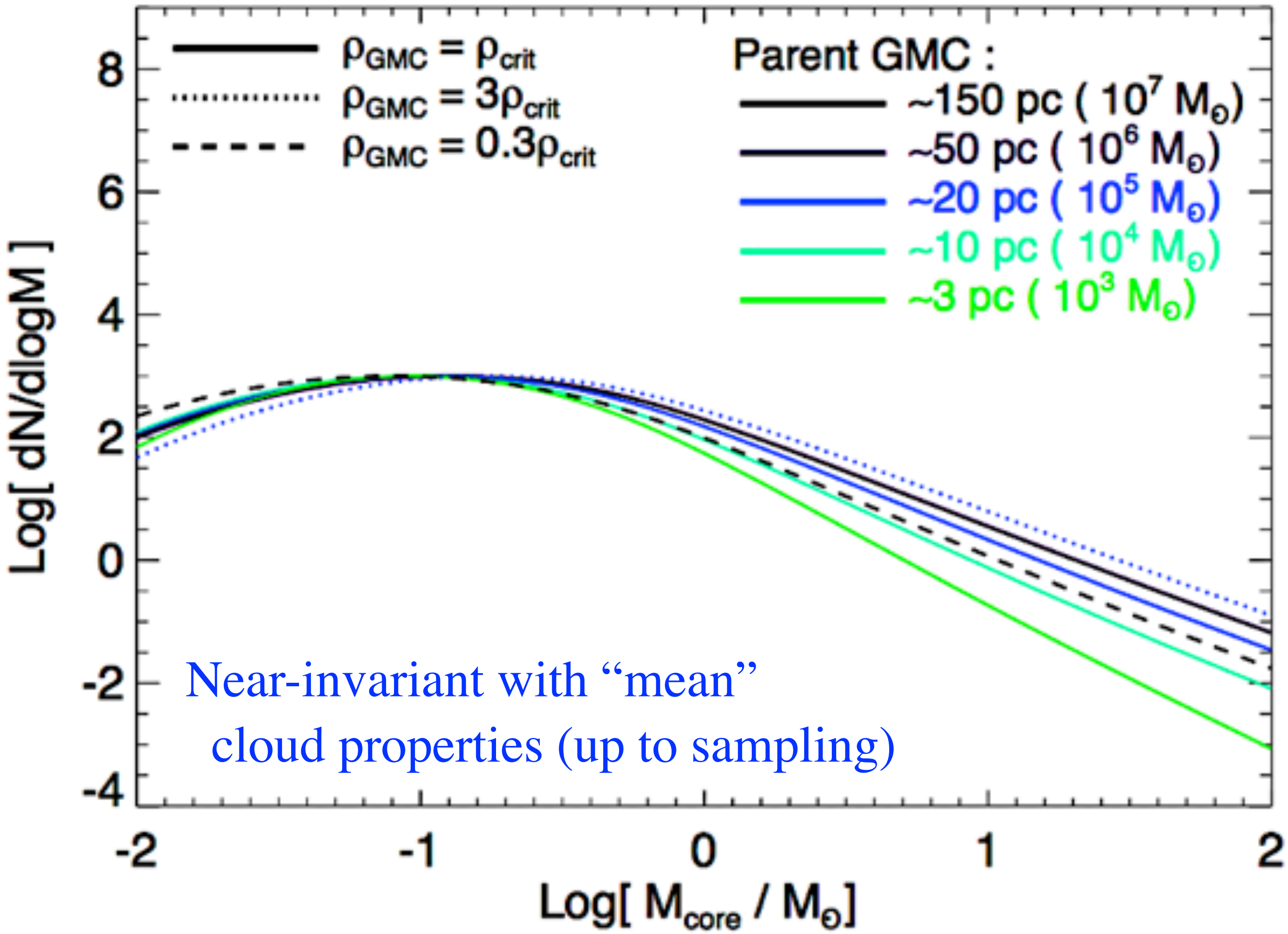


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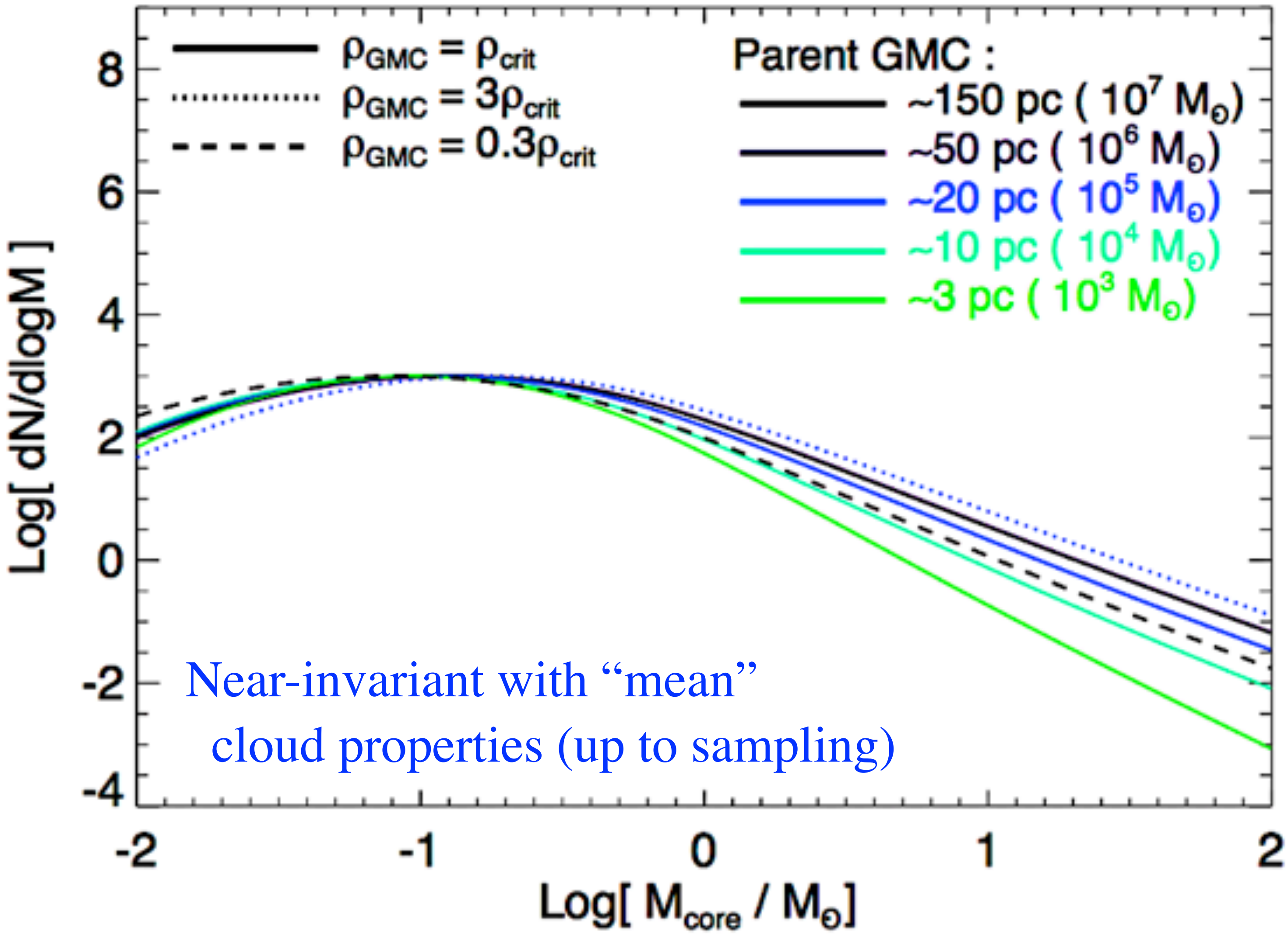


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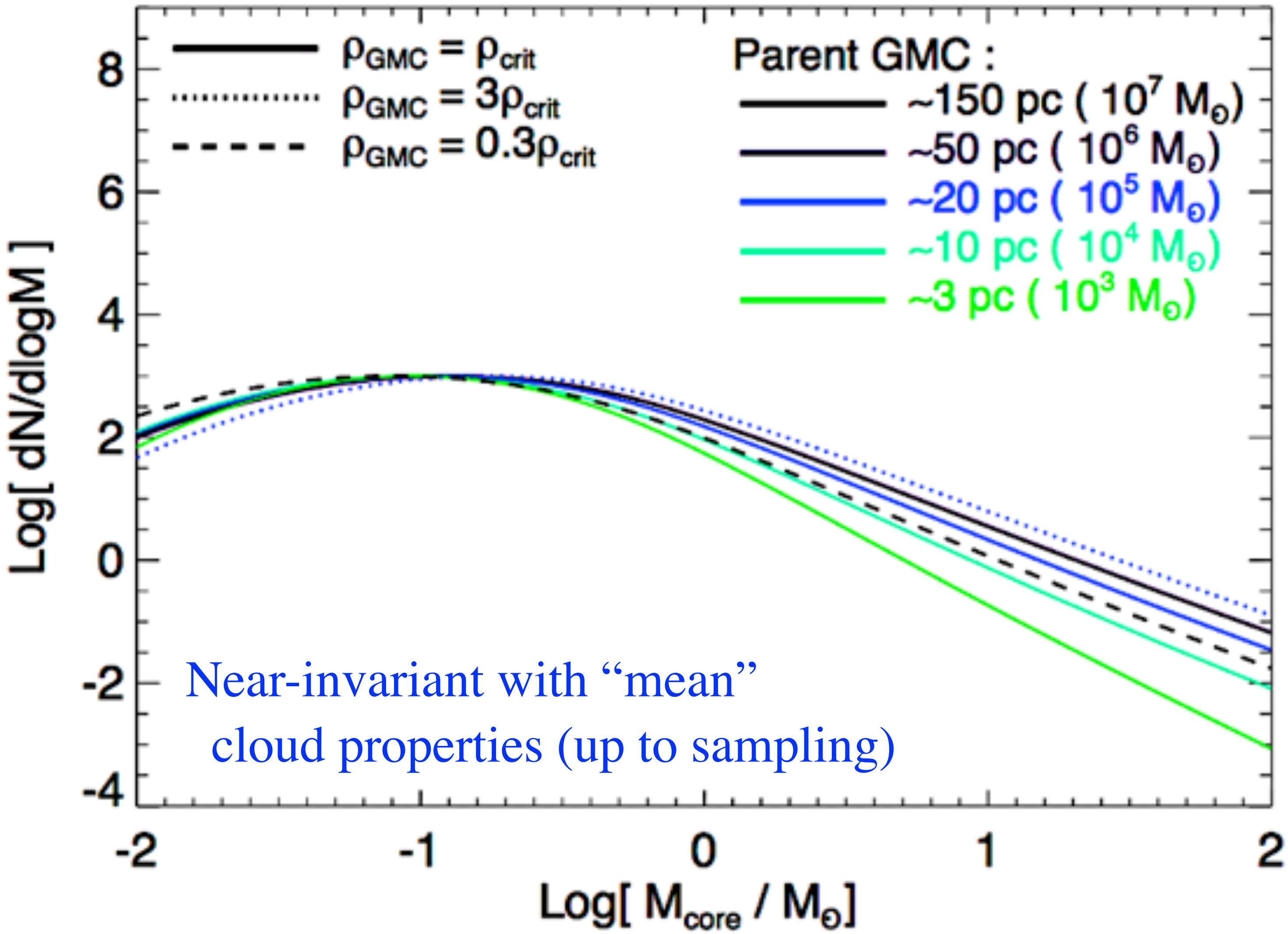


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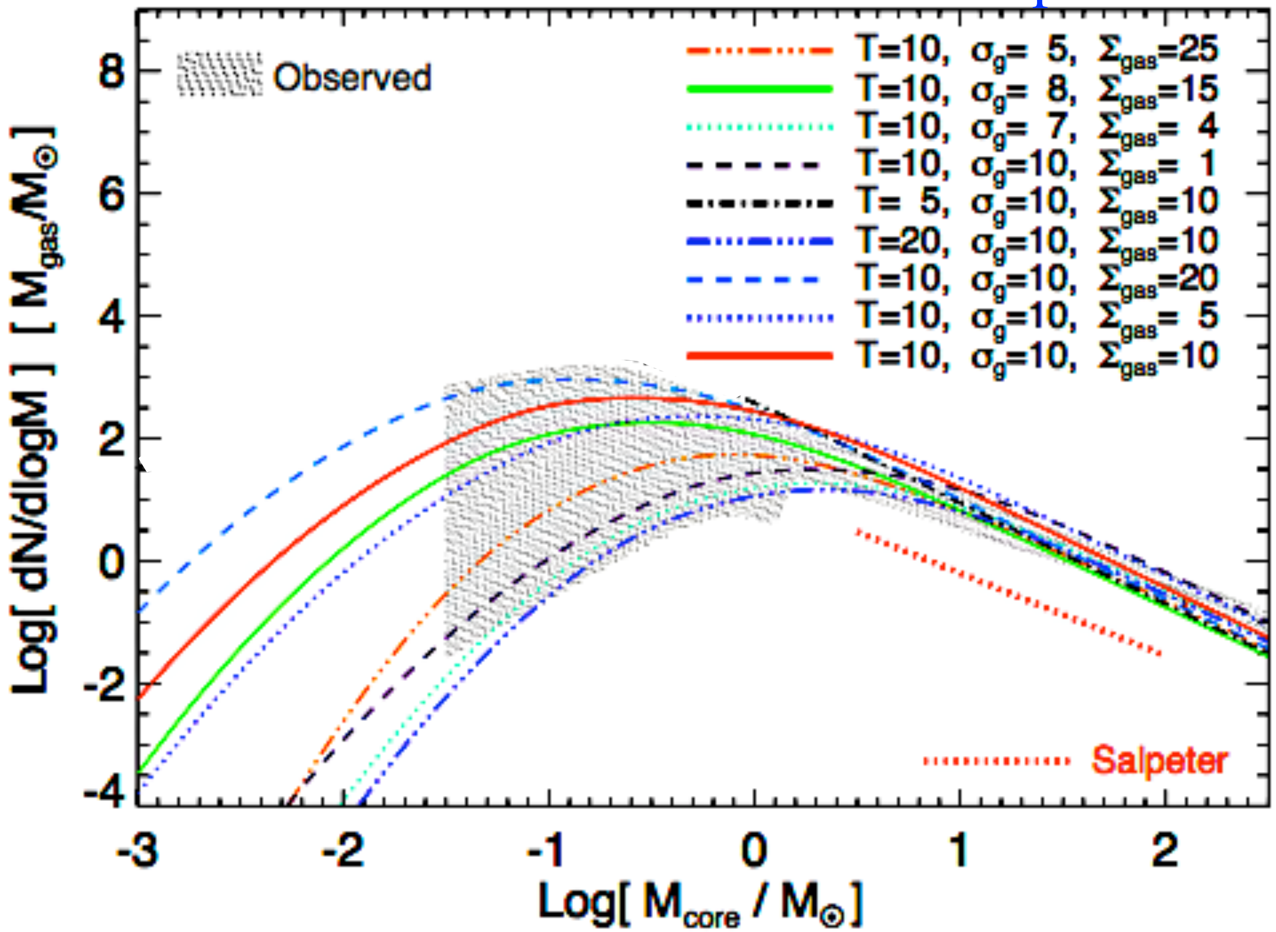
*Weak* variation with Galactic Properties

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# BUT, What About Starbursts?

MW: $T_{\text{cold}} \sim 10\,K$

$\sigma_{\text{gas}} \sim 10\,\text{km}\,\text{s}^{-1}$

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ULIRG: $T_{\rm cold} \sim 70\,K$
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$(Q \sim 1 \text{ for } \Sigma_{\rm gas} \sim 1000\,M_{\odot}\,{\rm pc^{-2}})$

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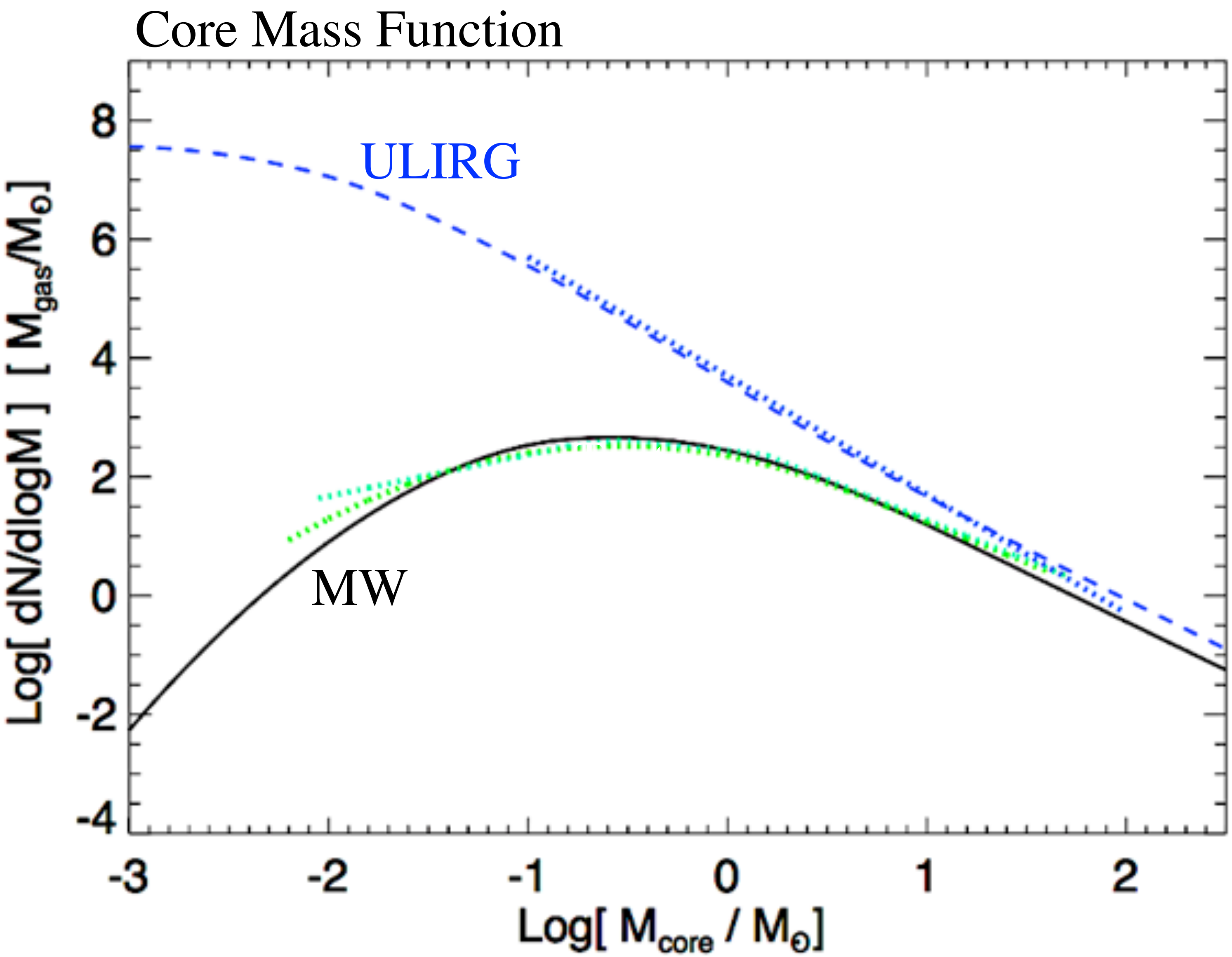

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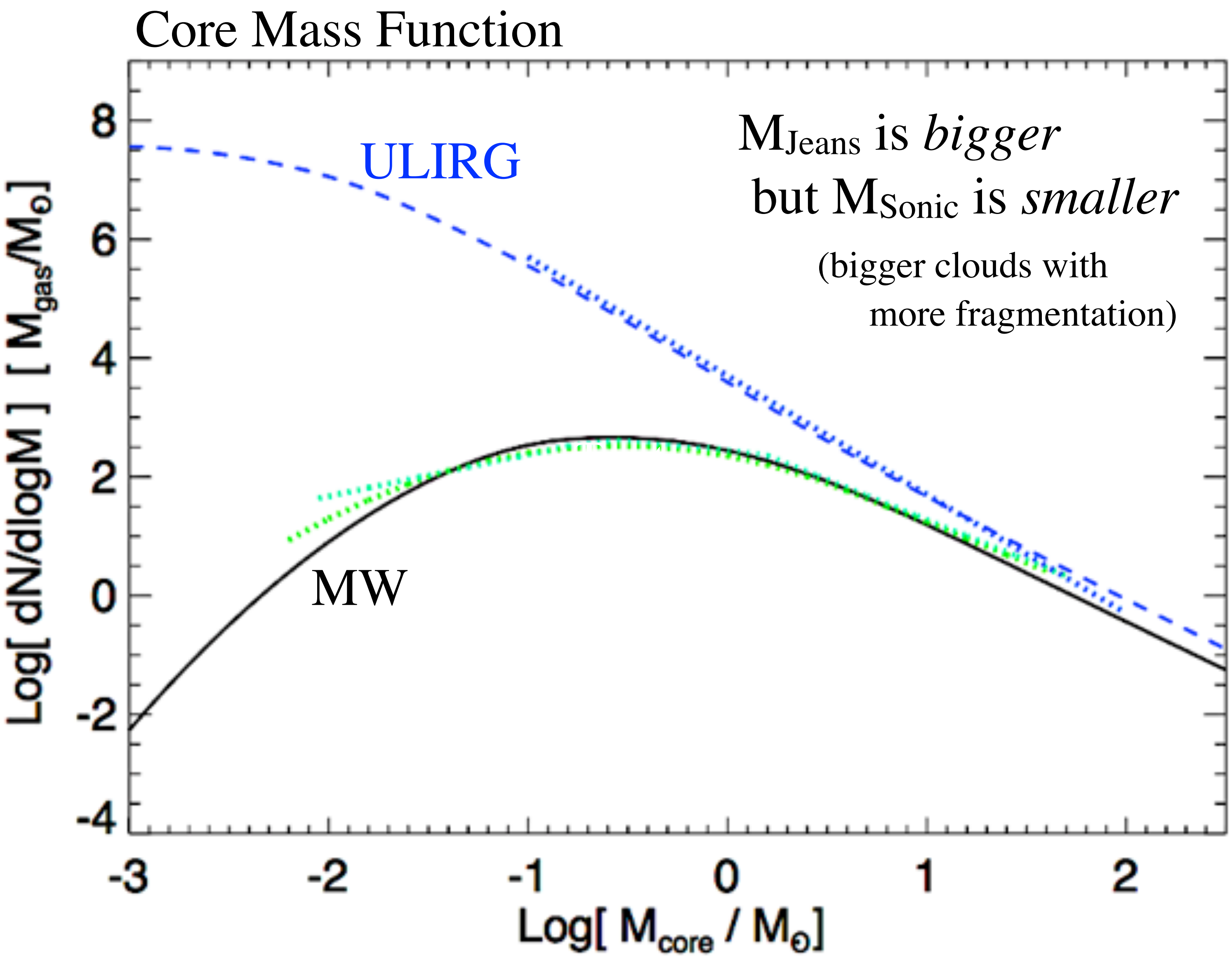
## BOTTOM-HEAVY: TURBULENCE WINS!




Mach number in ULIRGs: $\mathcal{M} \gtrsim 100$

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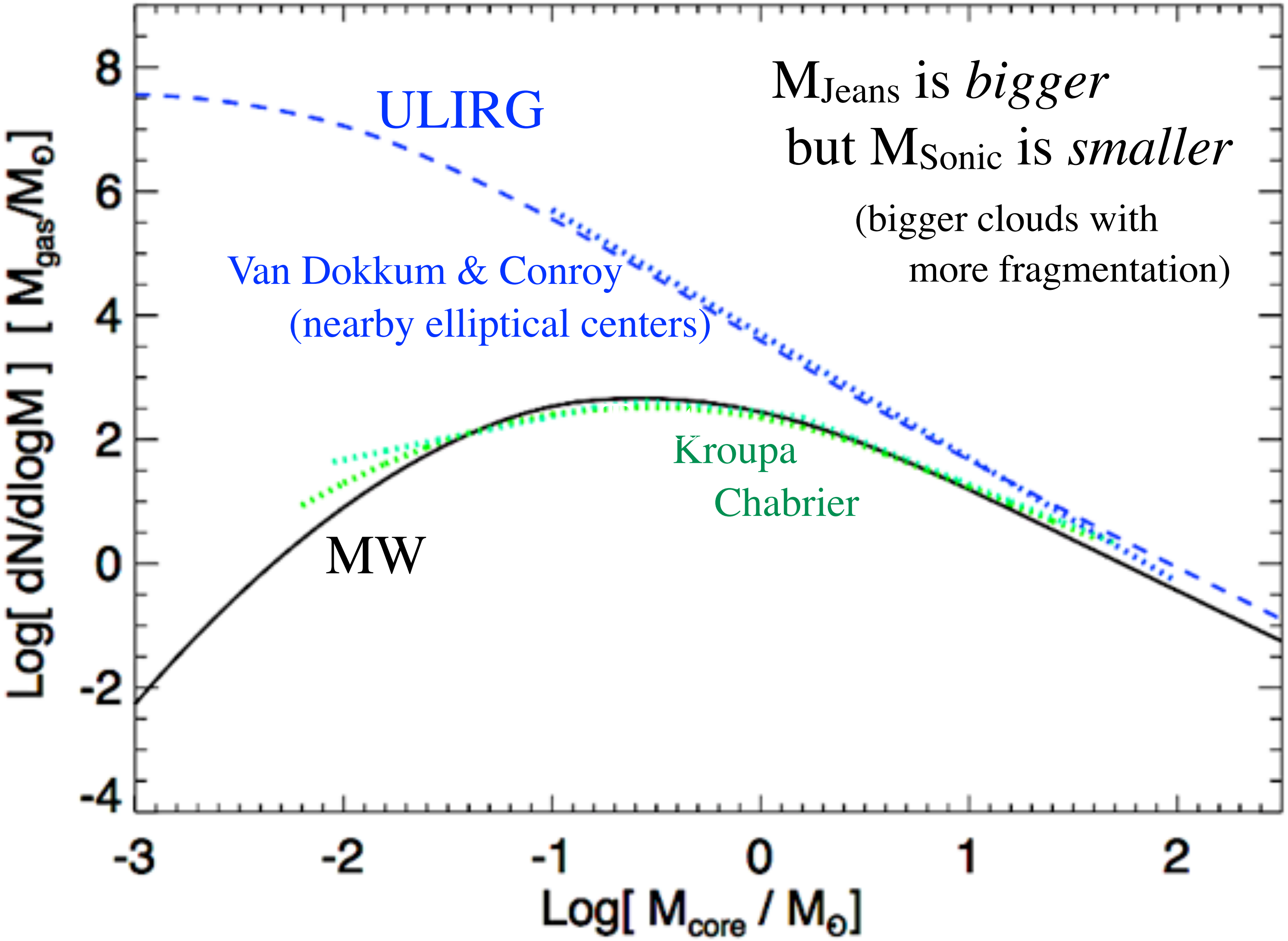


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## 2. Why Doesn't Everything Collapse?

"Top-down" turbulence can't stop collapse once self-gravitating

Fast Cooling: $\dot{M}_* \sim \frac{M_{\rm gas}}{t_{\rm freefall}}$

# Summary:

*** ISM *statistics* are far more fundamental than we typically assume ***

- **Turbulence + Gravity:** ISM structure follows
  - Lognormal density PDF is ***not*** critical
  - *ANALYTICALLY* understand:
    - **GMC Mass Function & Structure** ("first crossing")
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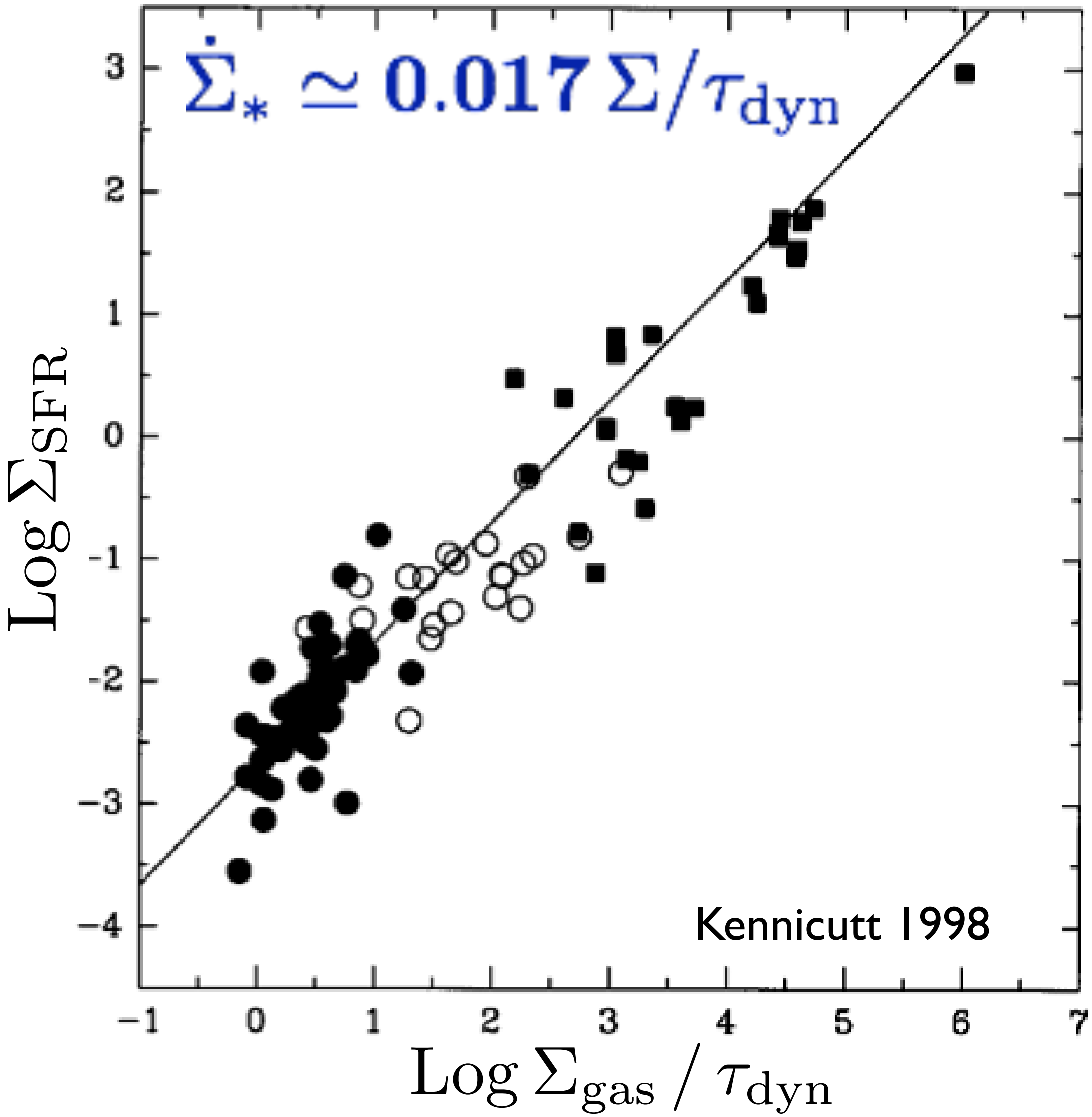
    - **Clustering** of Stars (correlation functions)

- **Feedback Regulates & Sets Efficiencies of Star Formation**
  - K-S Law: 'enough' stars to offset dissipation (set by gravity)
    - ***Independent*** of small-scale star formation physics (how stars form)

# Why Doesn't Everything Collapse?

## Q: WHY IS STAR FORMATION SO INEFFICIENT?



# Stellar Feedback is Key to Galaxy Formation!

## SO WHAT'S THE PROBLEM?

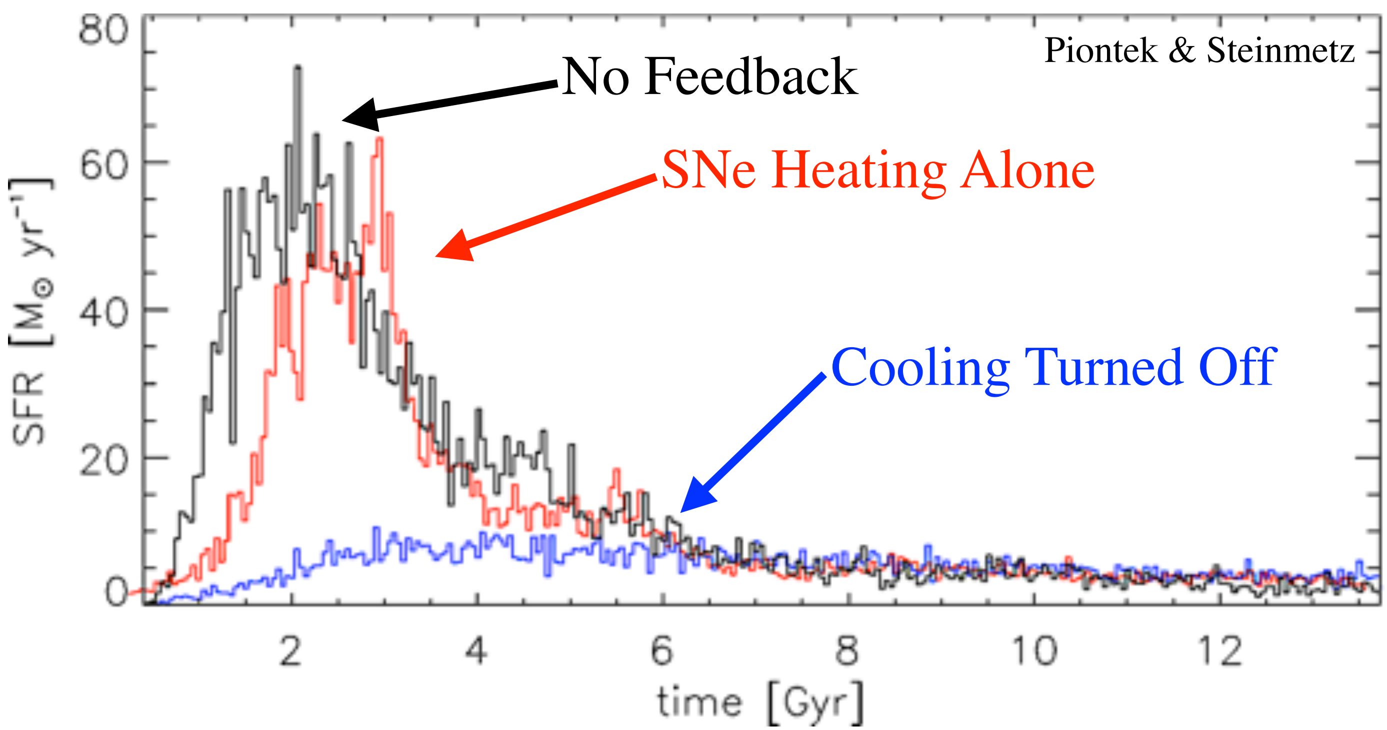
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- FAILS:

$$t_{\rm cool} \sim 4000\,{\rm yr}\left(\frac{n}{{\rm cm}^{-3}}\right)^{-1}$$

$$t_{\rm dyn} \sim 10^{8}\,{\rm yr}\left(\frac{n}{{\rm cm}^{-3}}\right)^{-1/2}$$

- "Cheat":
  - Turn off cooling
  - Force wind by hand
    ('kick' out of galaxy)



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- *Explicit* Momentum Flux:
  - Radiation Pressure

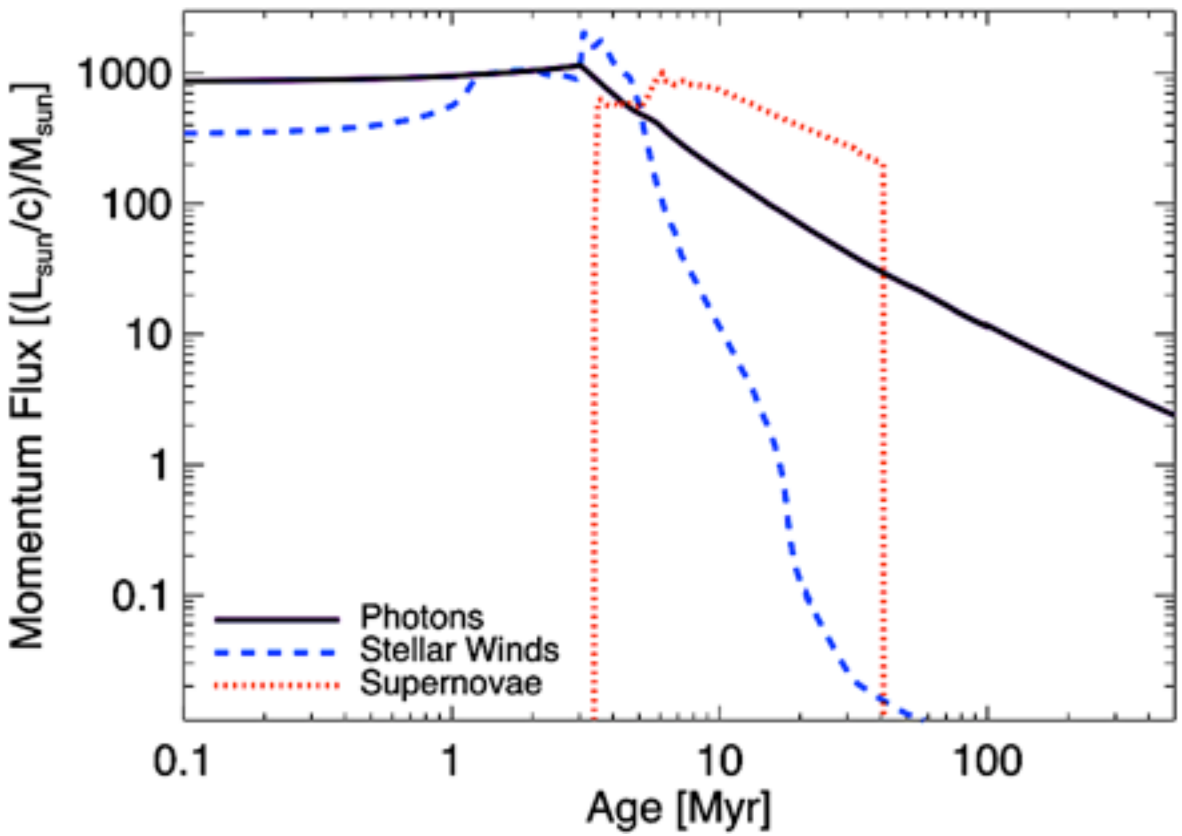
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

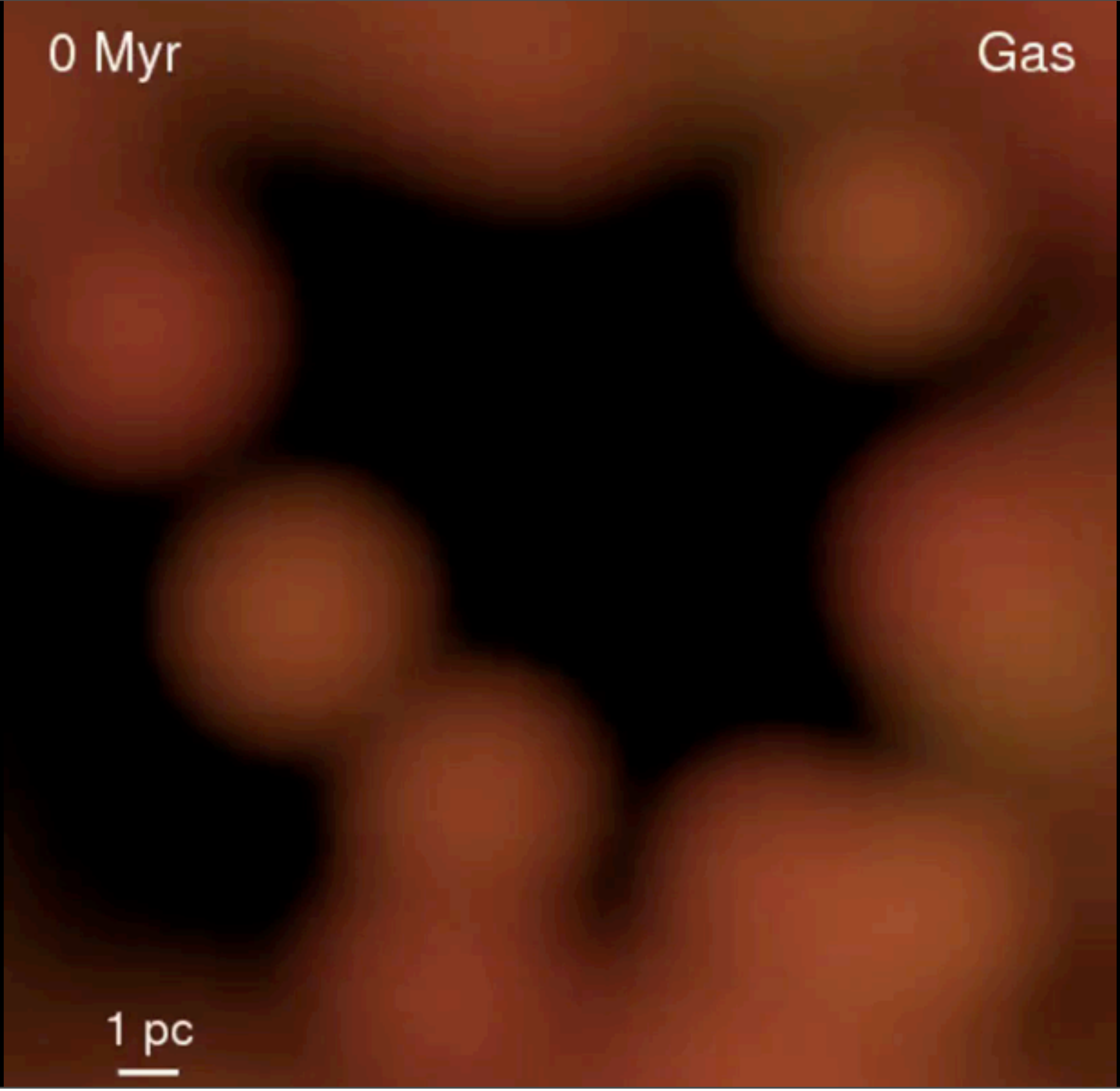
  - SNe

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

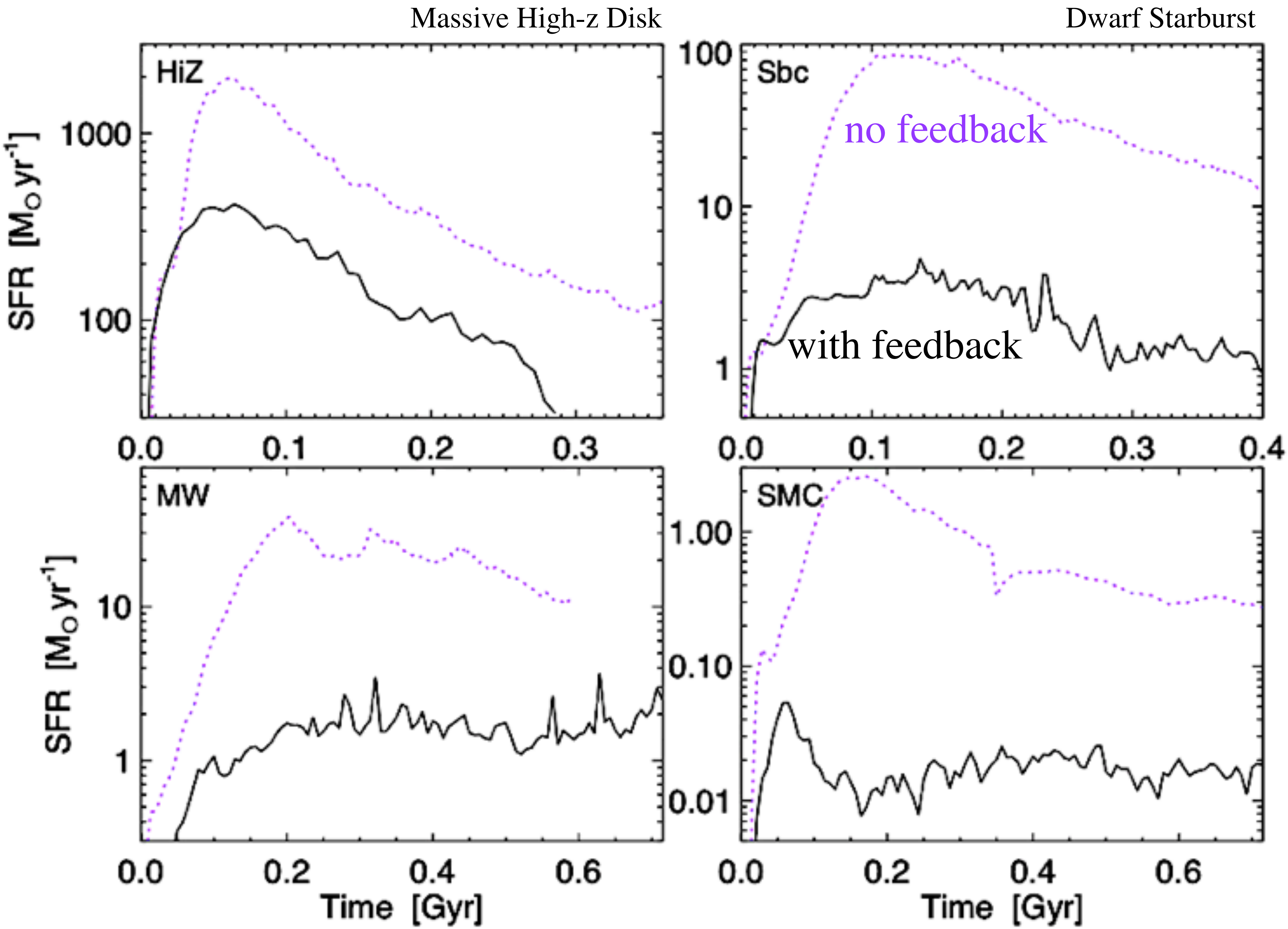
  - Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




0 Myr
Gas
1 pc

# Stellar Feedback gives Self-Regulated Star Formation



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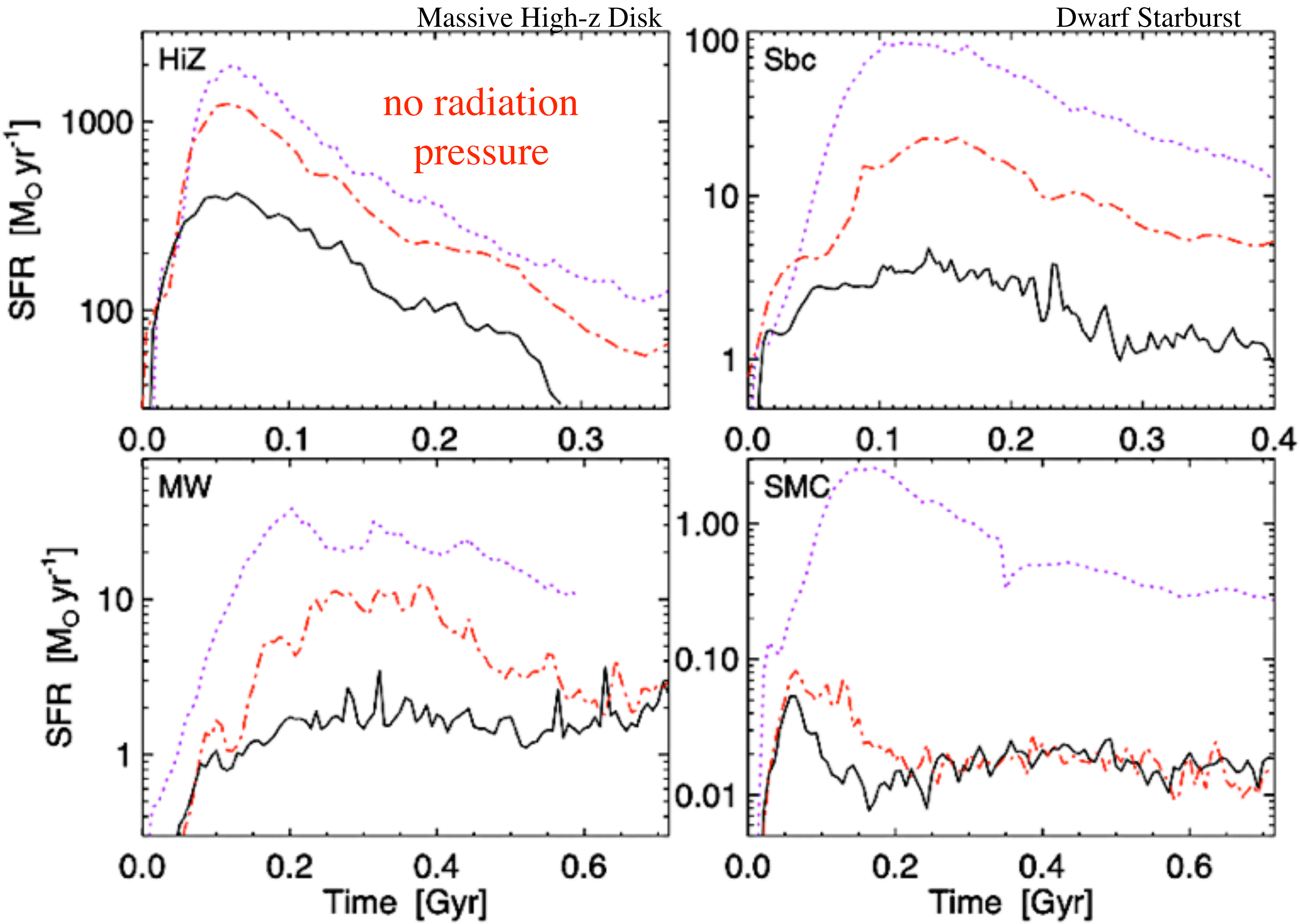

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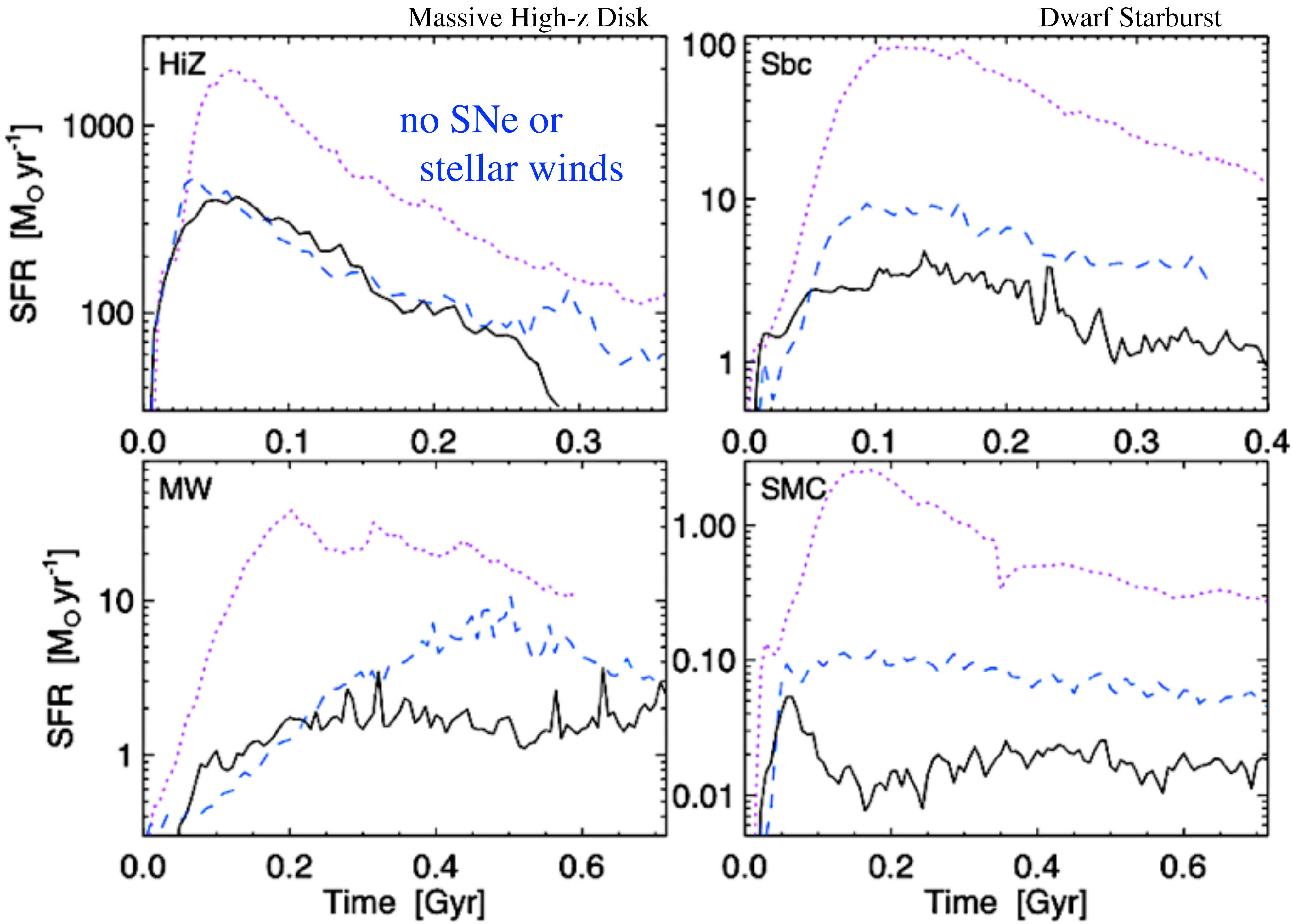
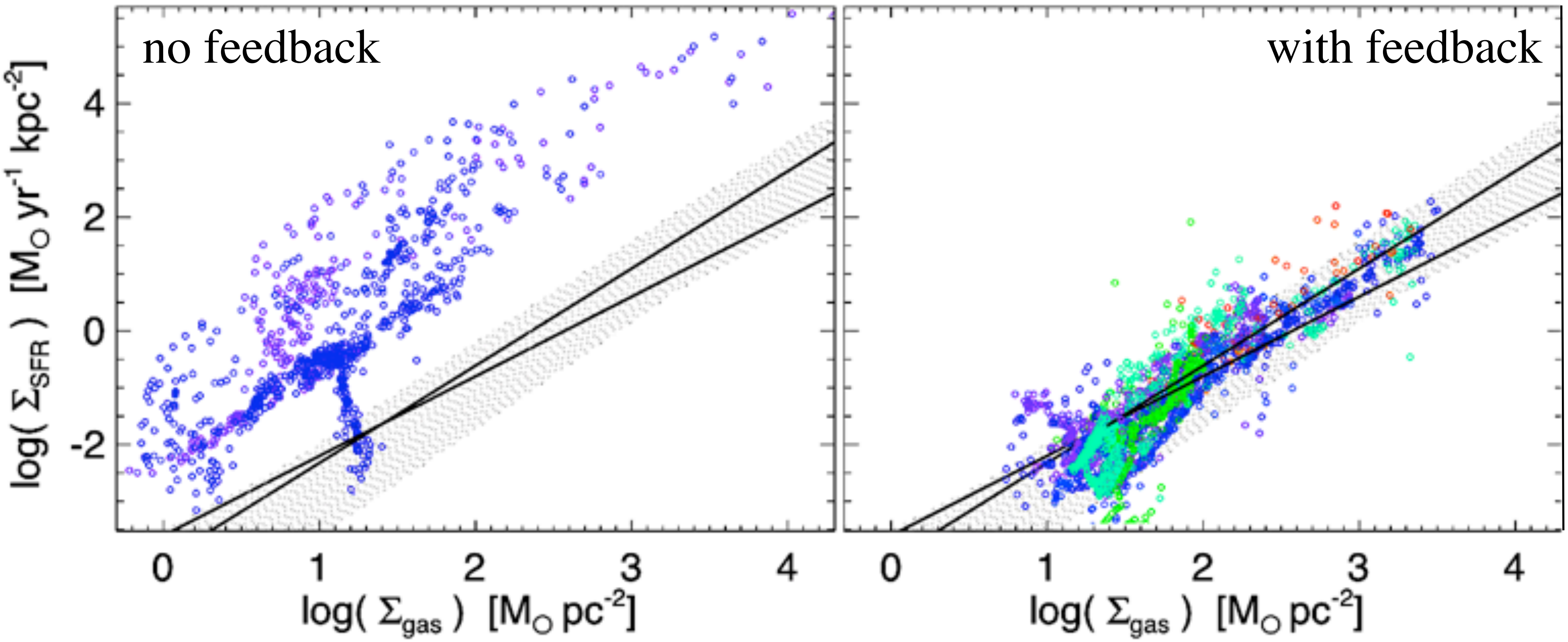


# Kennicutt-Schmidt relation emerges naturally




PFH, Quataert, & Murray, 2011a

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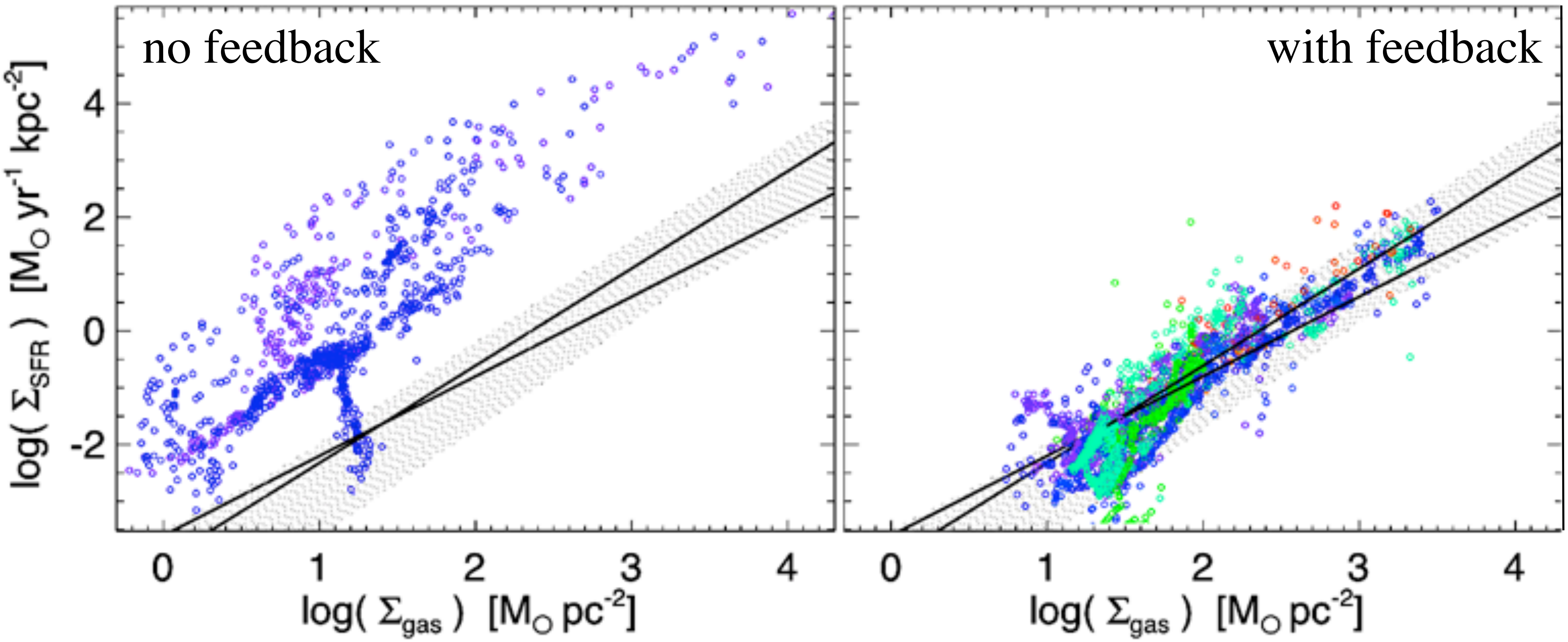
$$\dot{\Sigma}_* \sim \Sigma_{\rm gas}/\tau_{\rm dyn}$$

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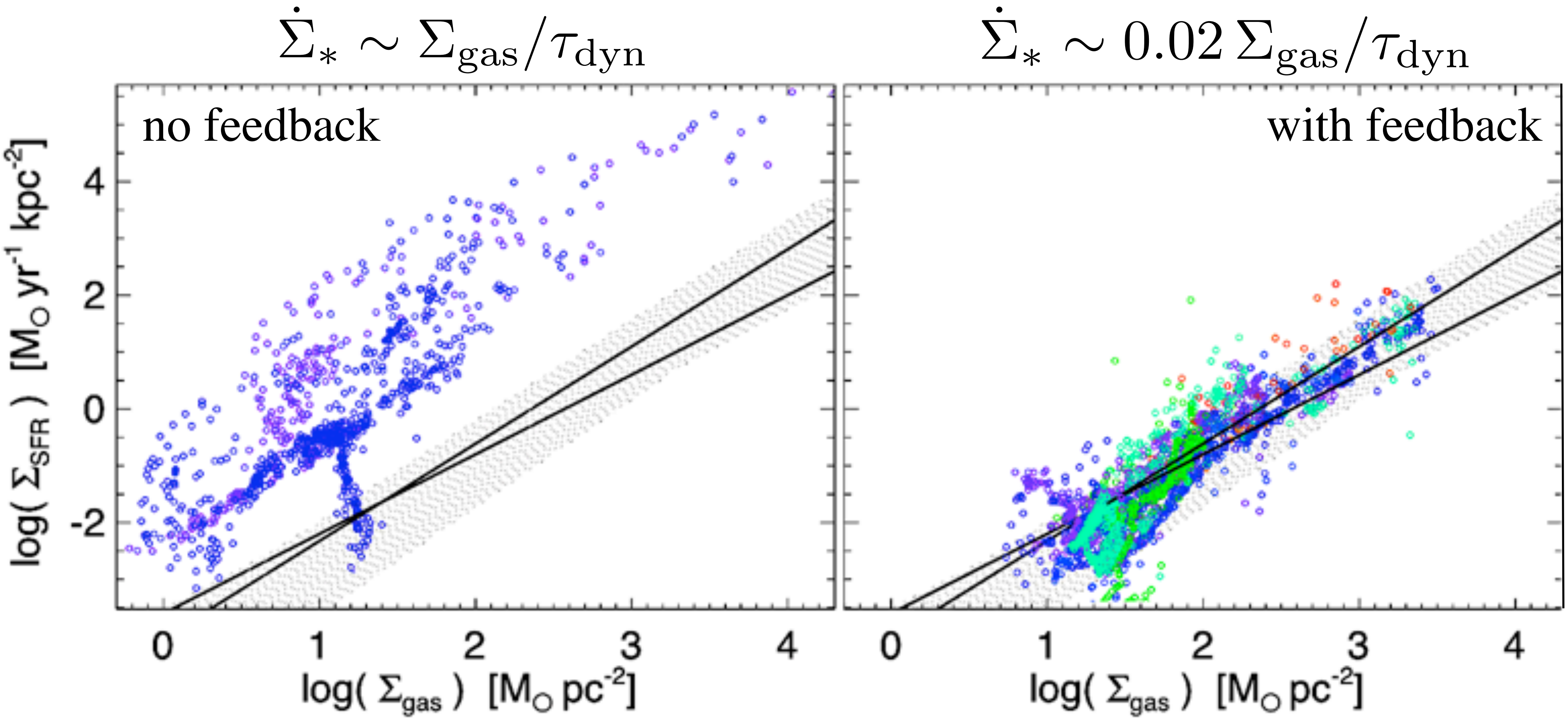


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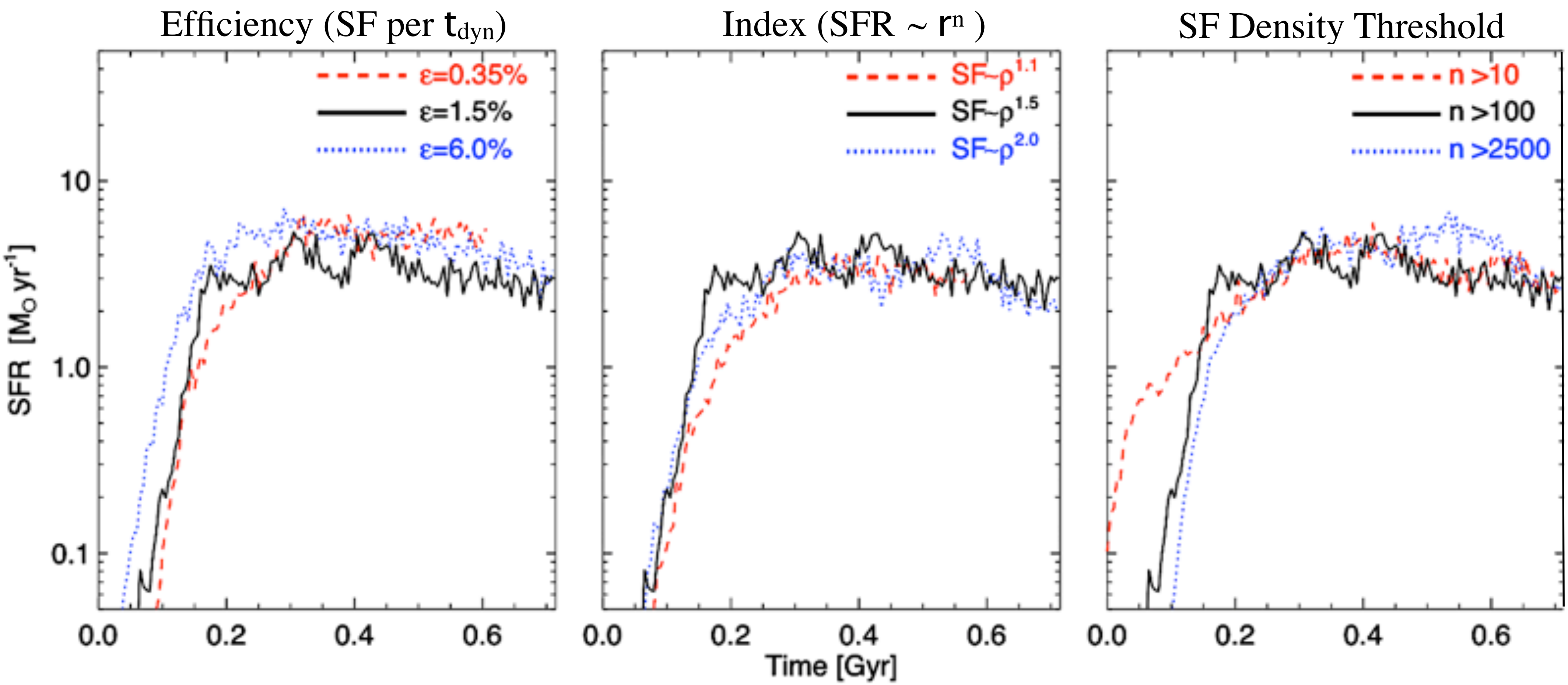
$$\longrightarrow \dot{\Sigma}_{*} \sim \left(\frac{\sigma}{\epsilon_{*} c}\right) \Sigma_{\rm gas} \Omega \sim 0.02\, \Sigma_{\rm gas} \Omega$$

# Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law




Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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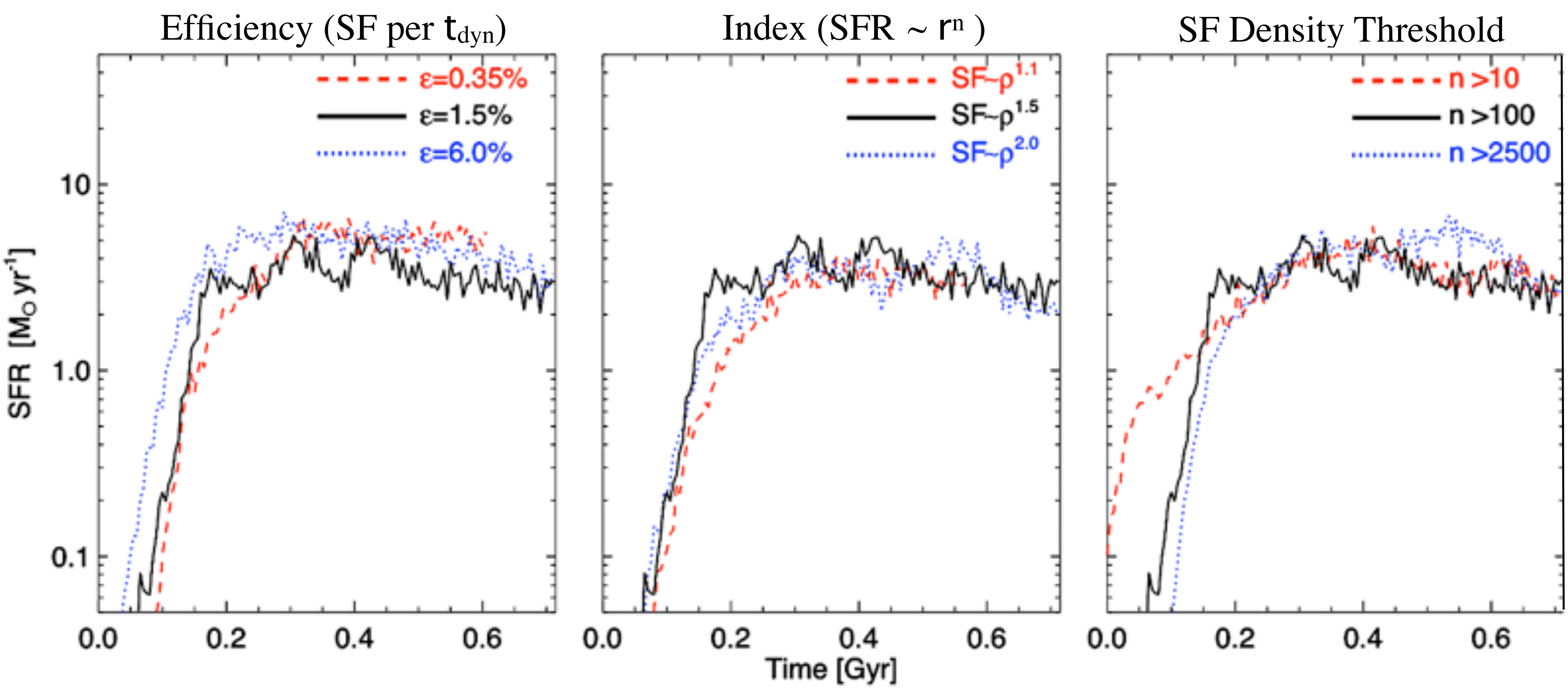


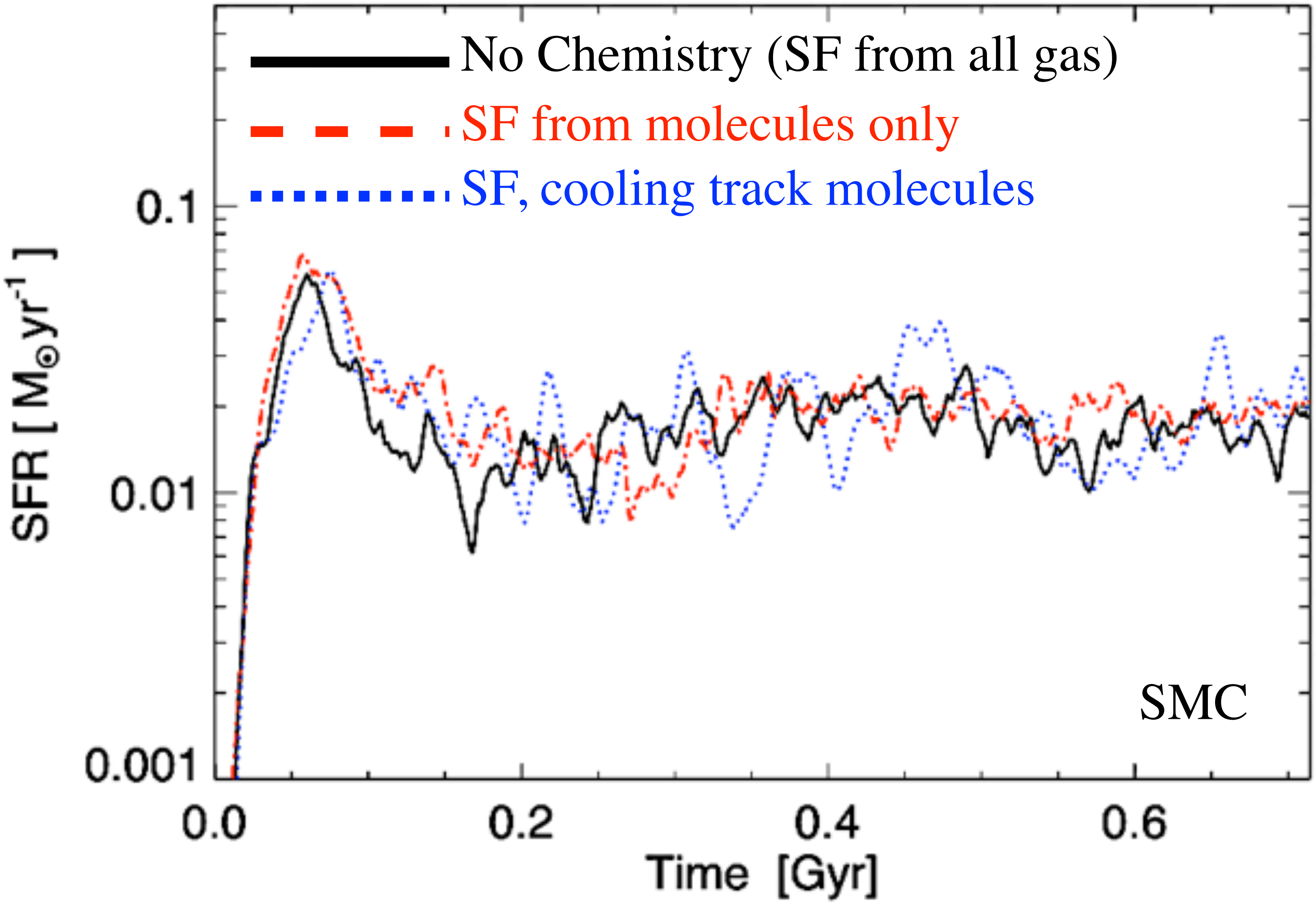

- Set by feedback (i.e. SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

## Molecules Don’t Matter!

THEY ARE A *TRACER*

see also Glover 2011



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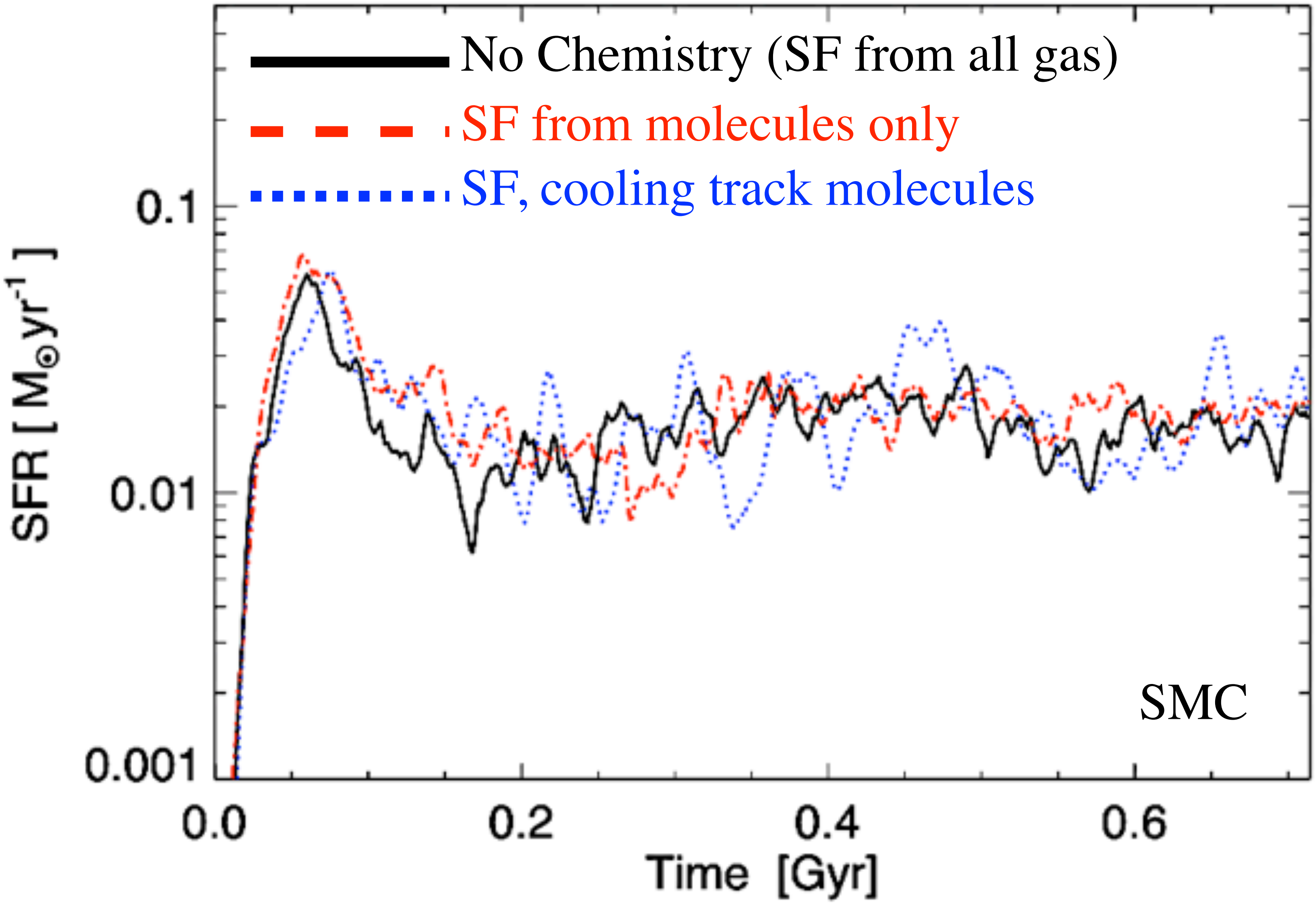


- Just need *some* cooling channel: changes at $M_{gal} < 10^6\ M_{sun}$, $Z<0.01\ Z_{sun}$

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