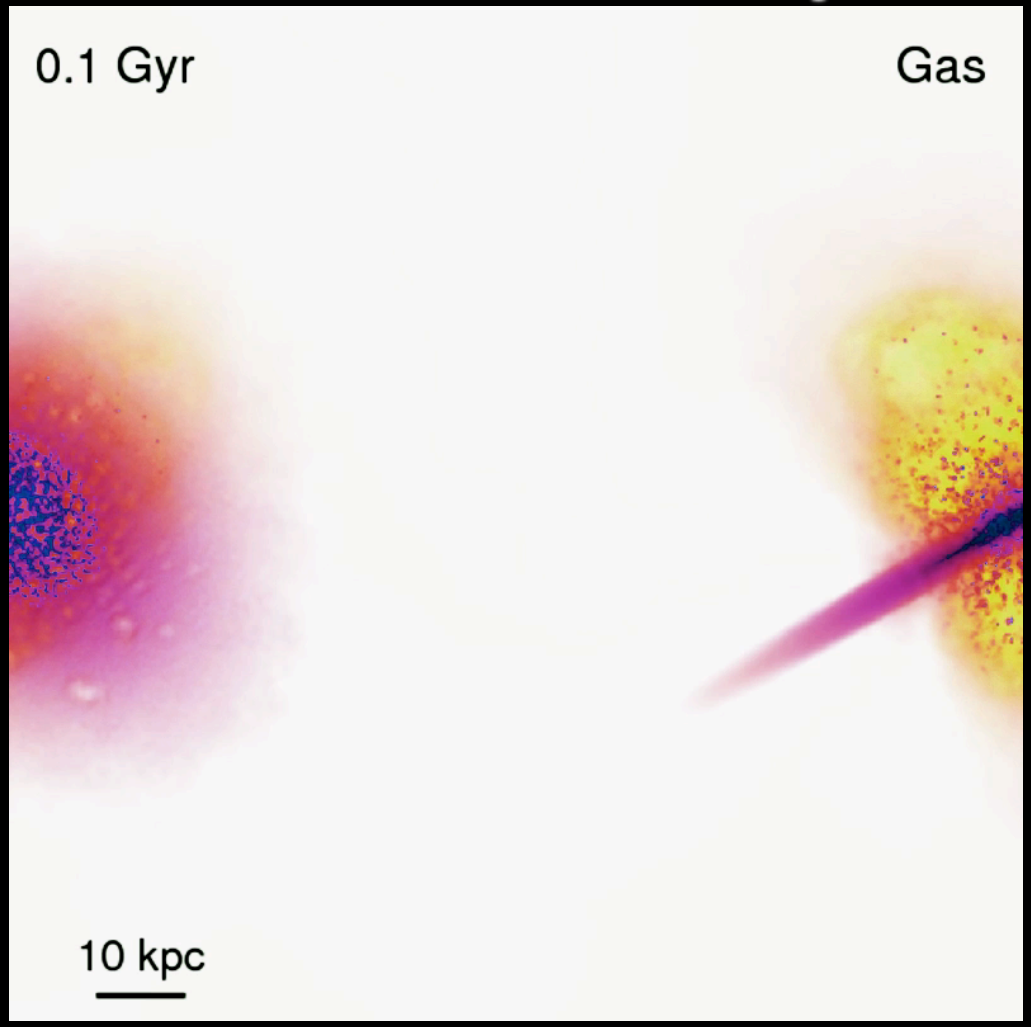
ISM Structure, Stellar Clustering, & a (Nearly) Universal IMF

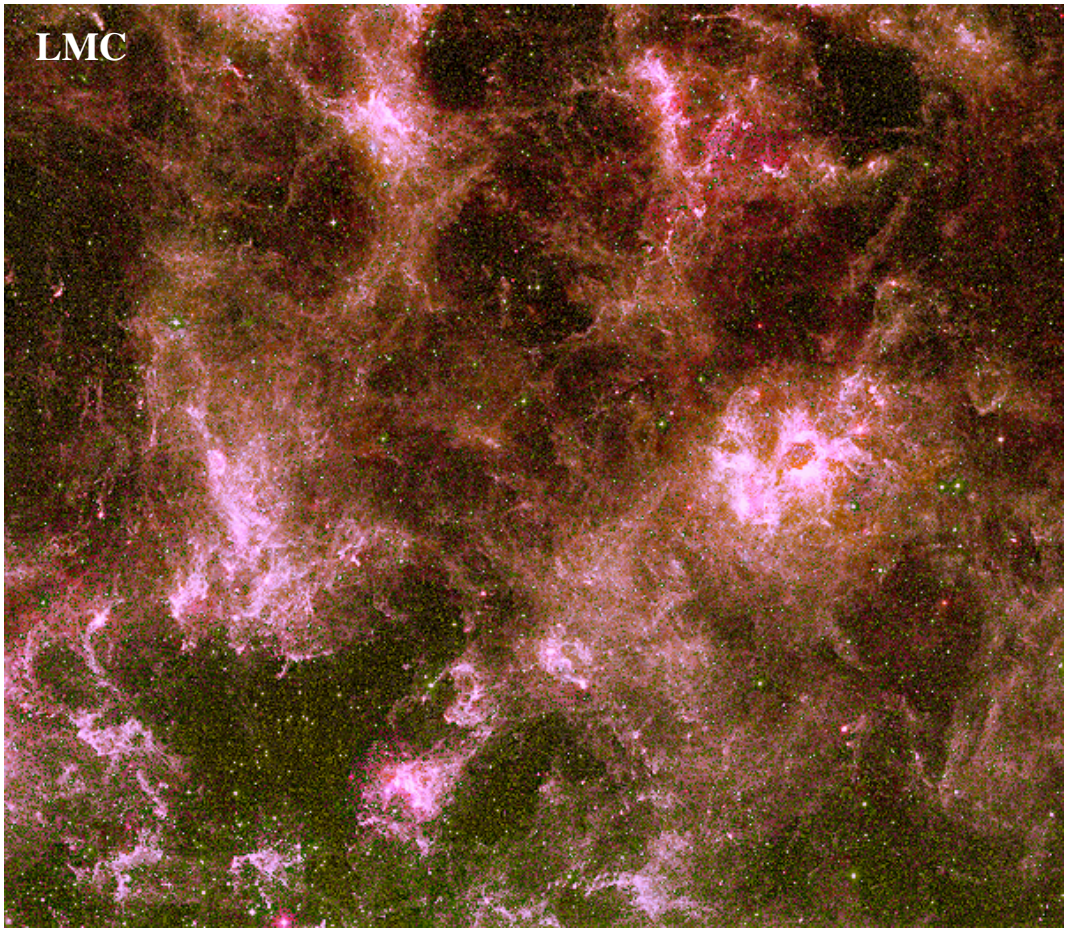


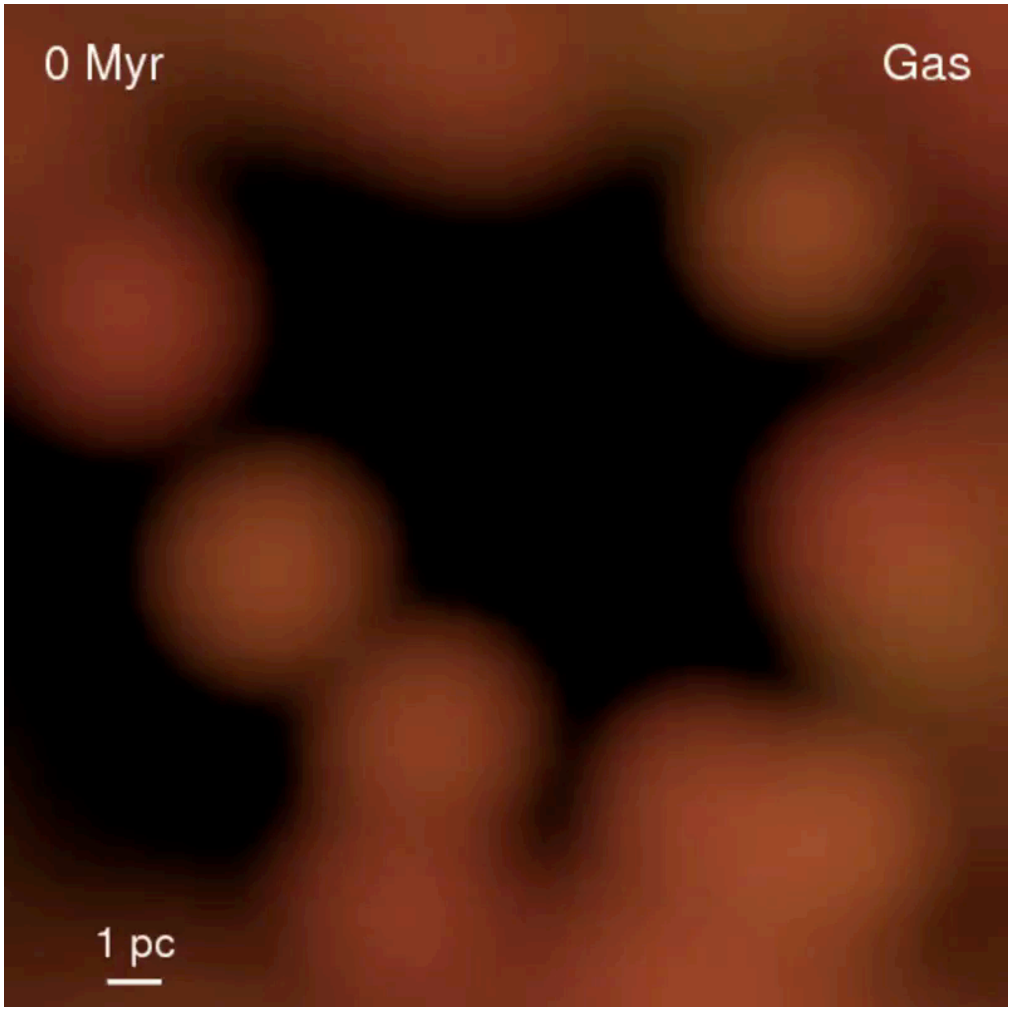
Philip Hopkins

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



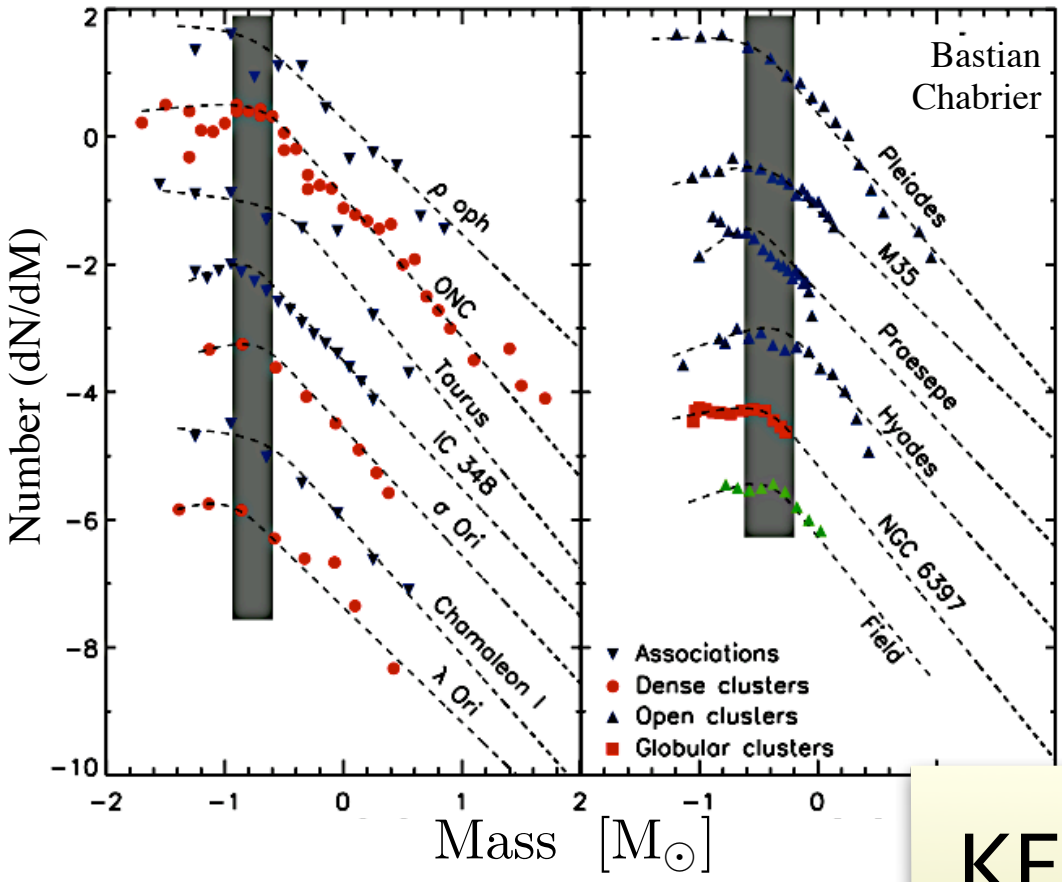


- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs, external galaxies, etc.

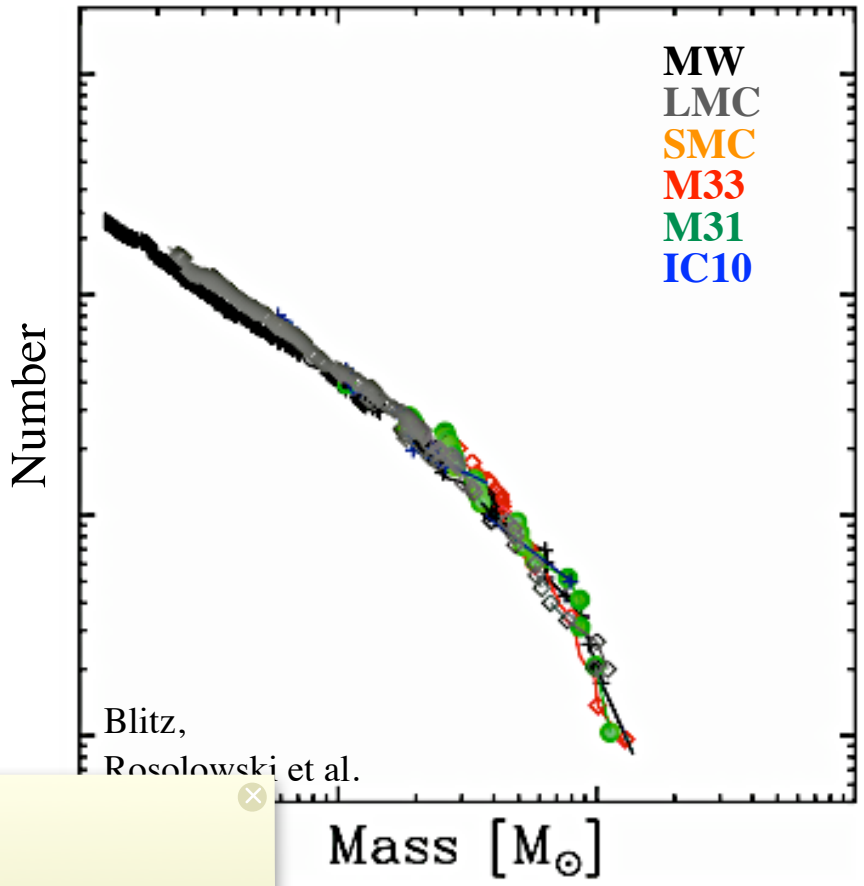
The ISM

YET THERE IS SURPRISING REGULARITY

Stars & Pre-Stellar Gas Cores:



Giant Molecular Clouds:



KEEP PWRLAW LABELS?

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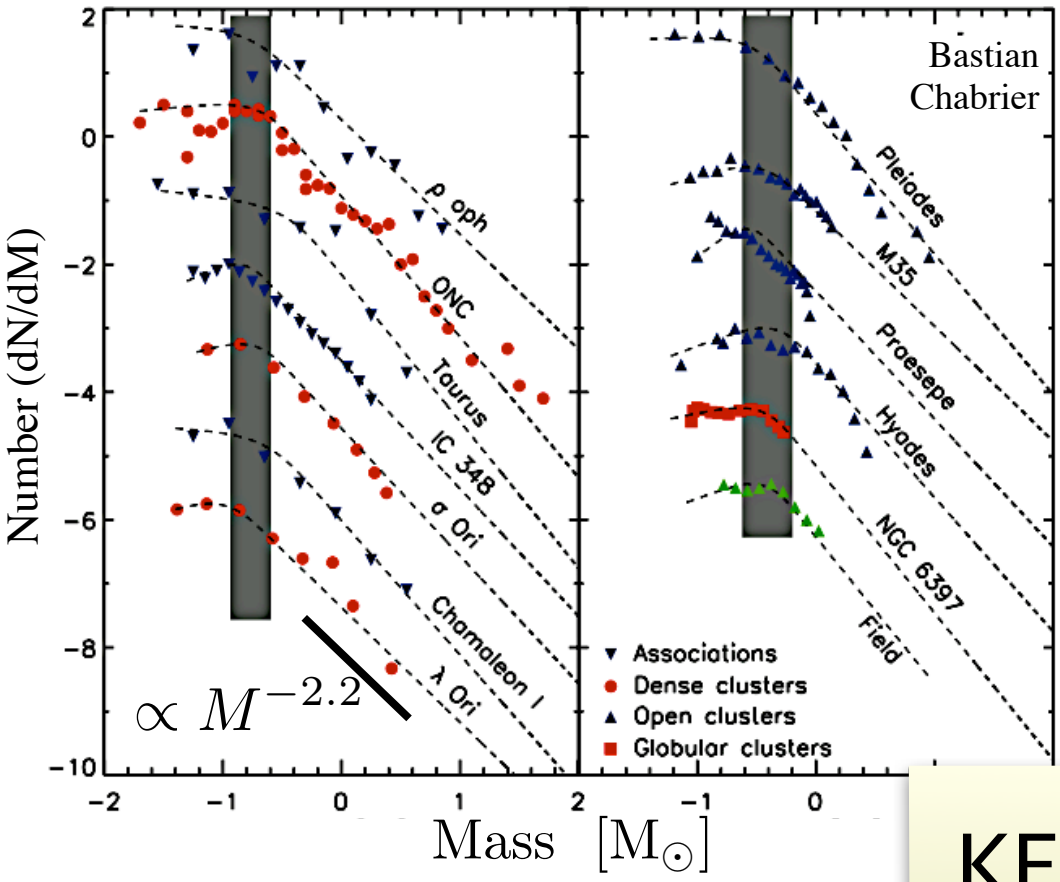

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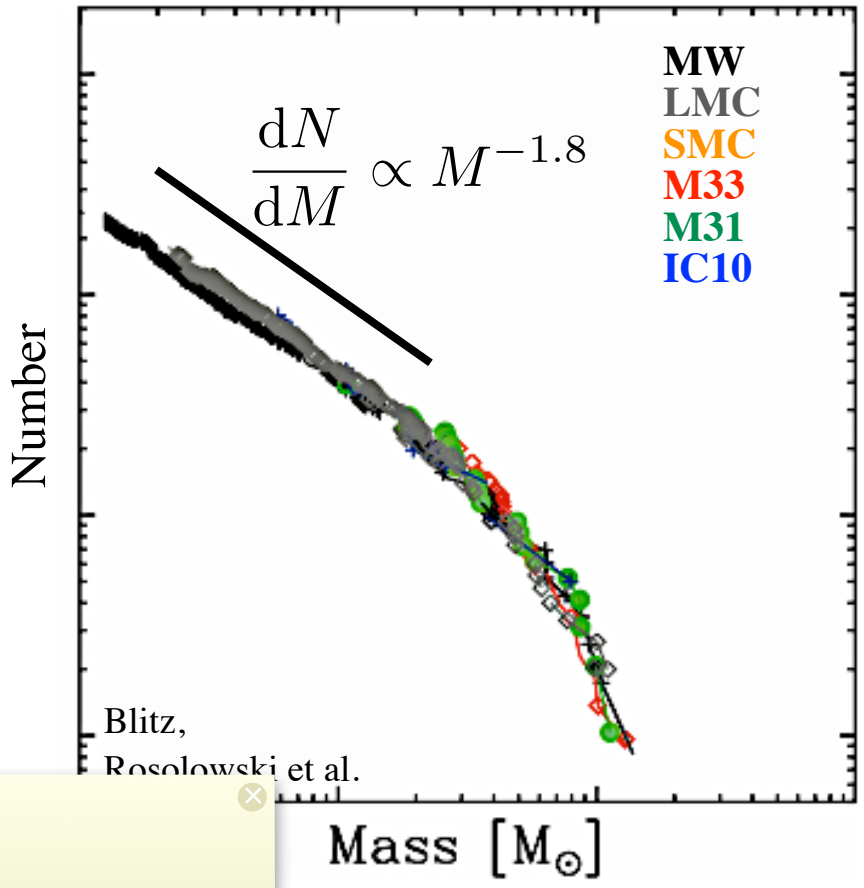

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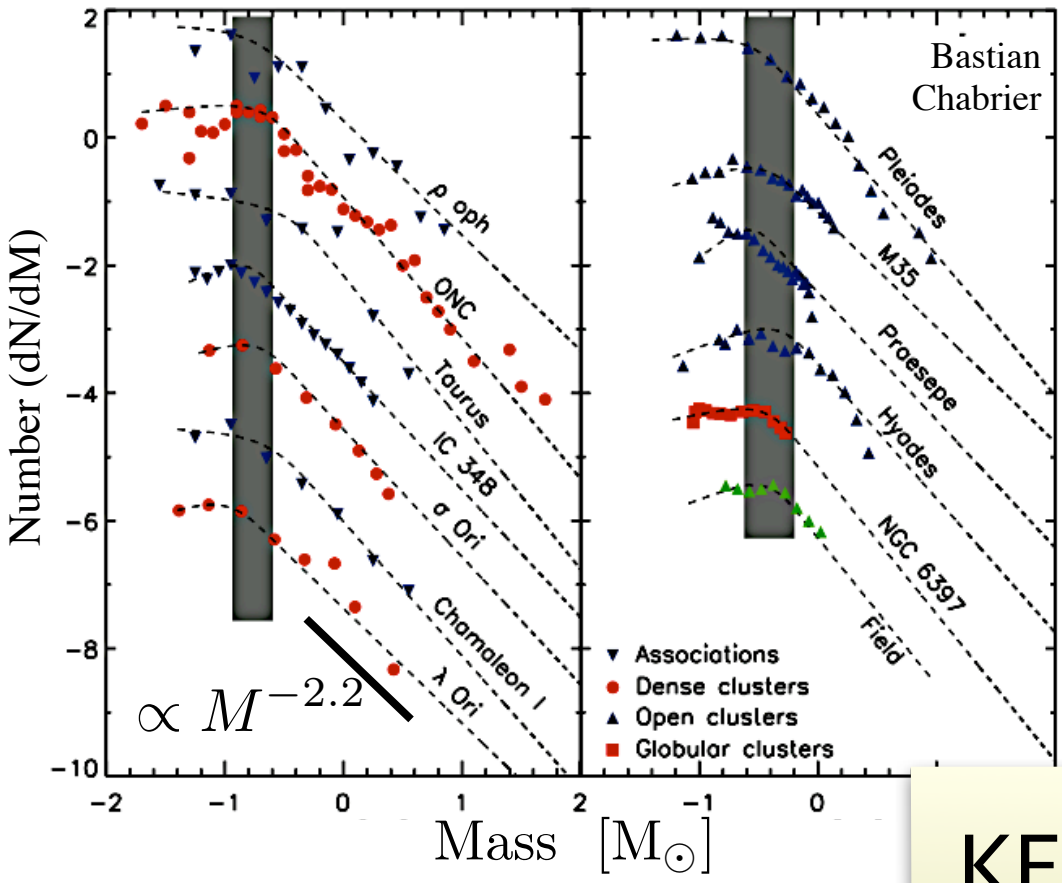

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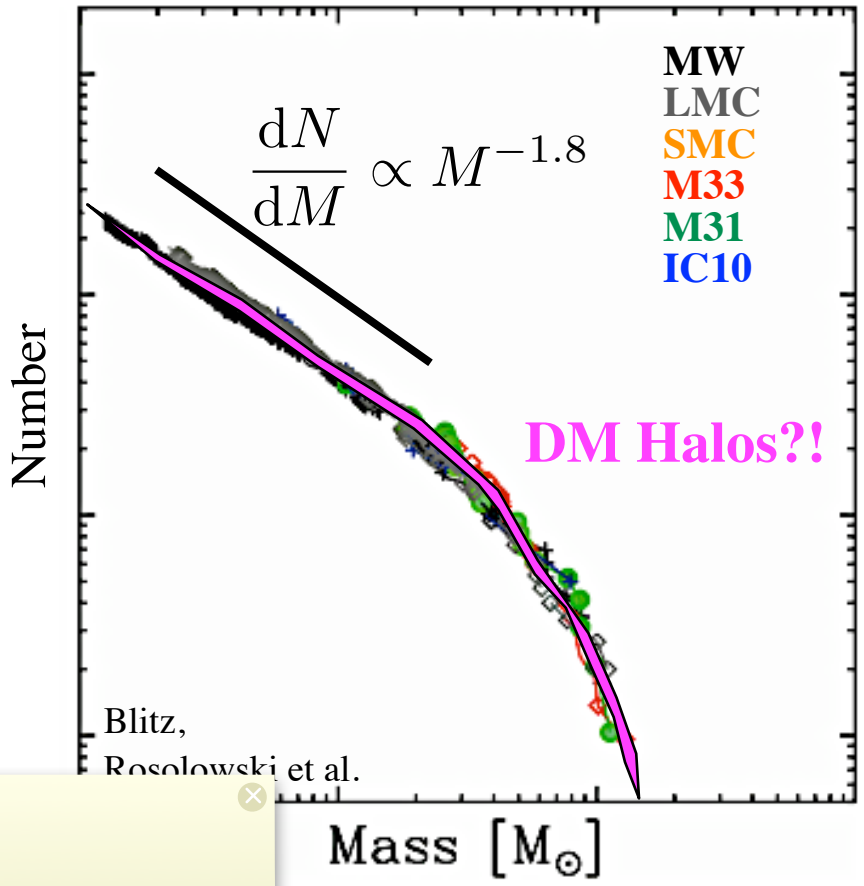
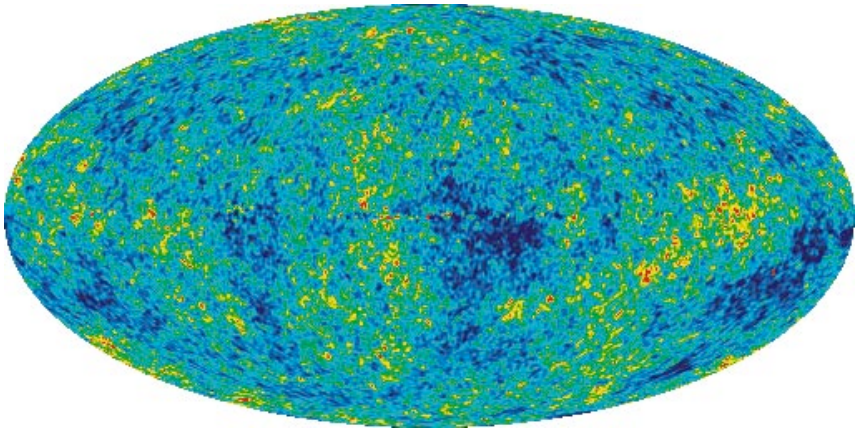
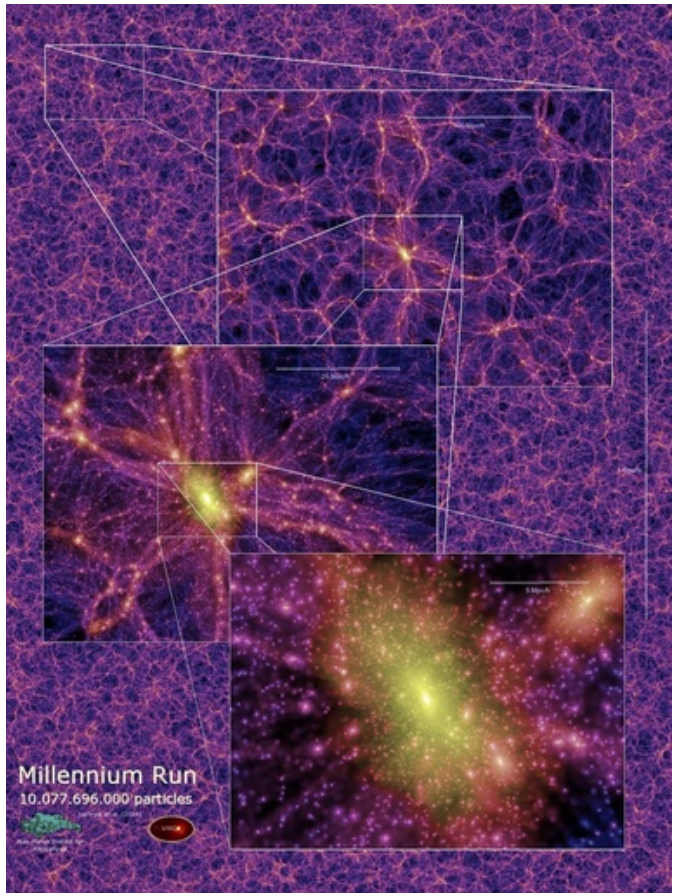


KEEP PWRLAW LABELS?

Extended Press-Schechter / Excursion-Set Formalism

- Press & Schechter ‘74:
  - ρ Fluctuations a Gaussian random field
  - Know linear power spectrum P(k~1/r): variance $\sim k^3 P(k)$





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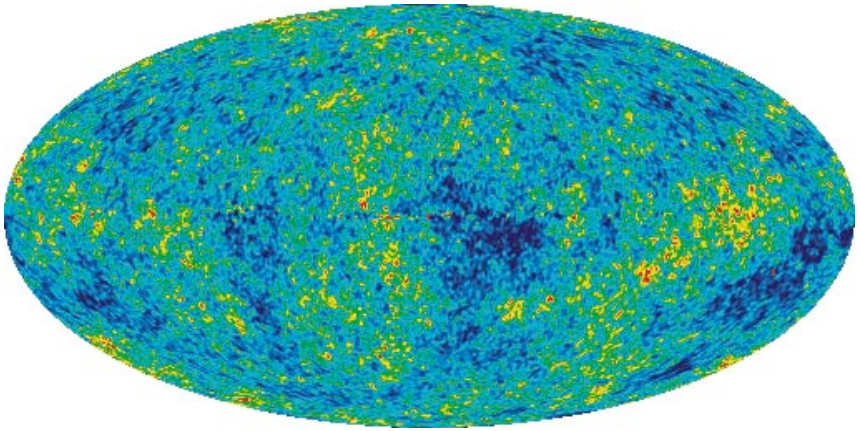

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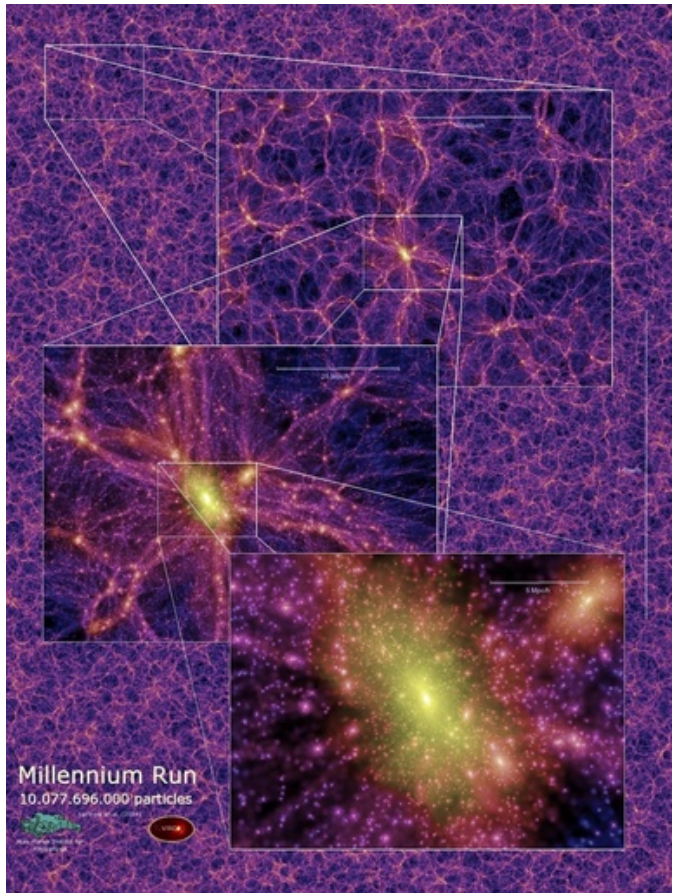

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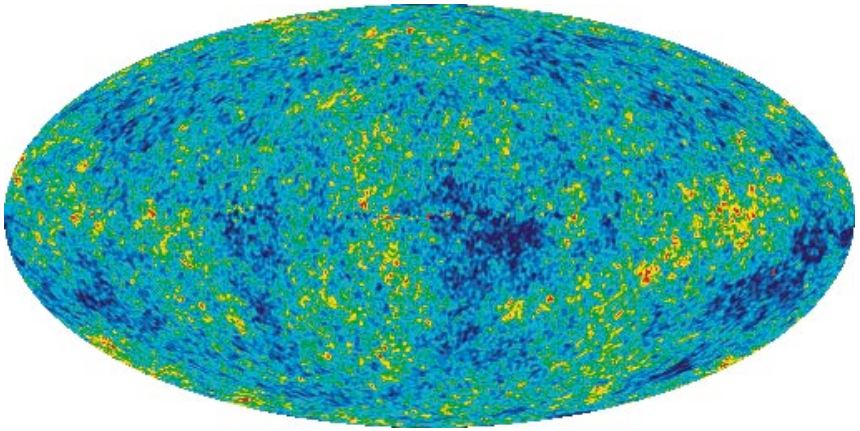

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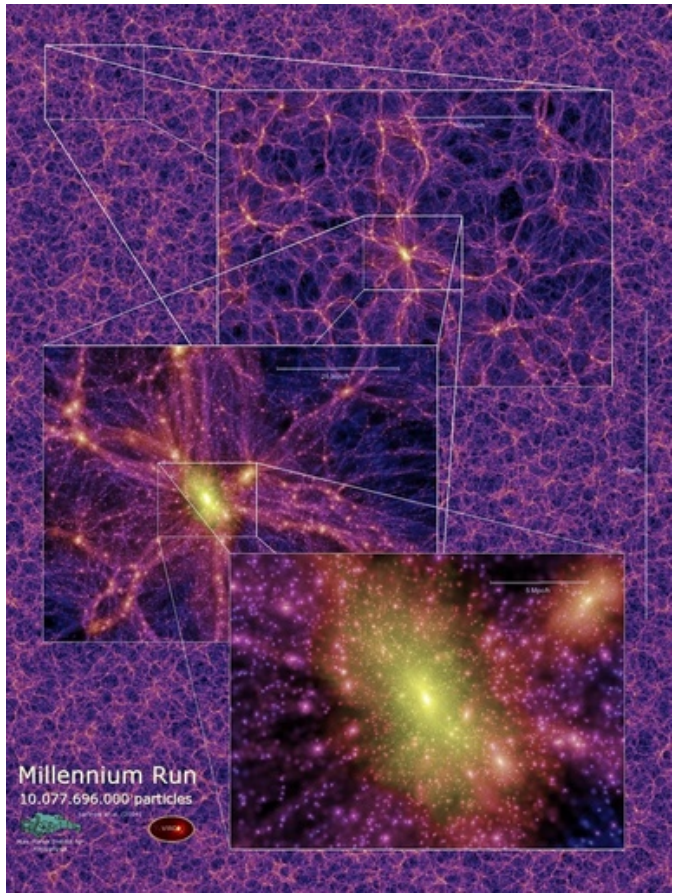

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- Generalize to conditional probabilities,
  N-point statistics, resolve "cloud in cloud" problem
  (e.g. Bond et al. 1991)

Turbulence

BASIC EXPECTATIONS

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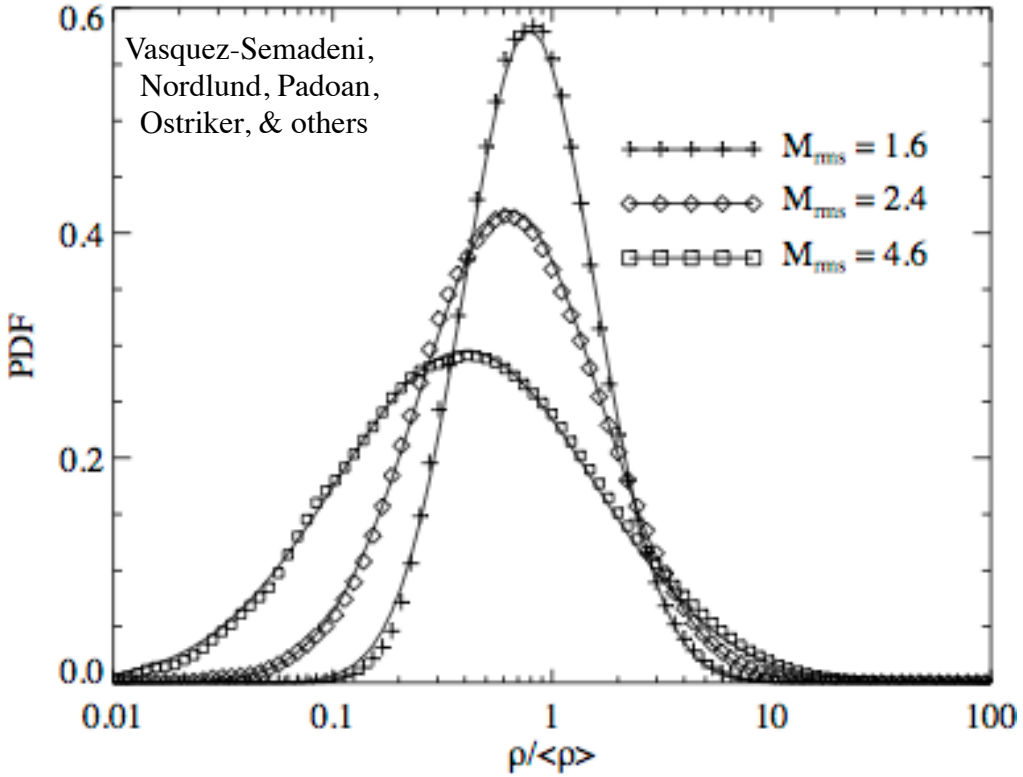

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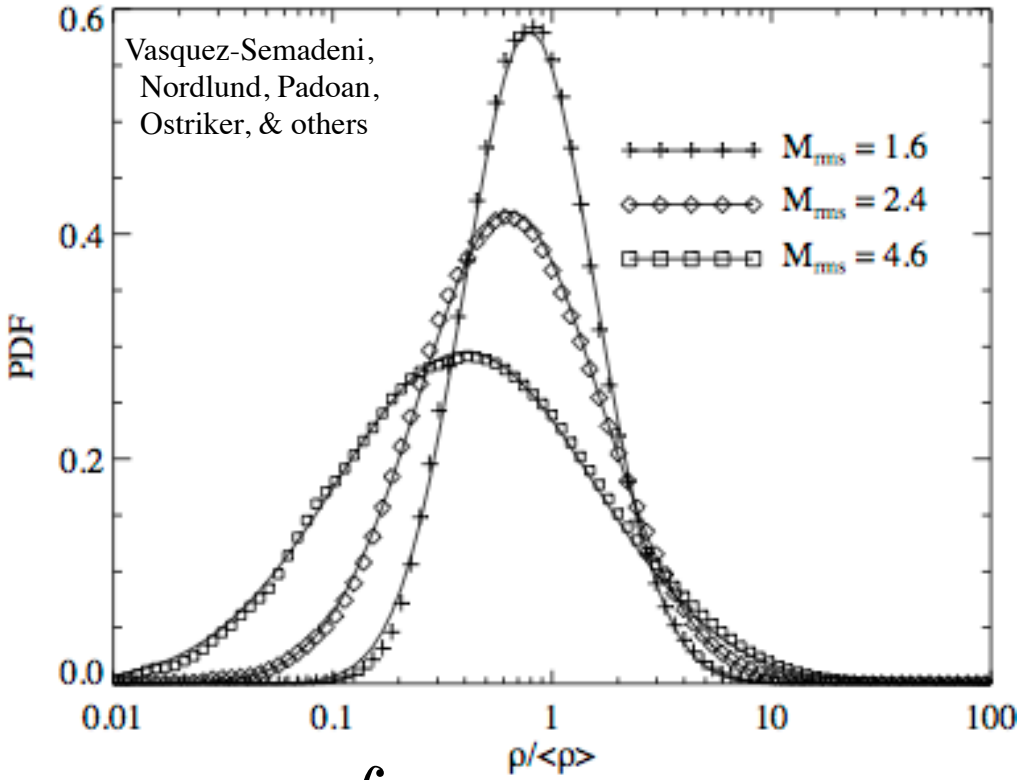

$$S(R) = \int \mathrm{d}\ln k\, S_k\, |W(k,\, R)|^2$$

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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Gravity

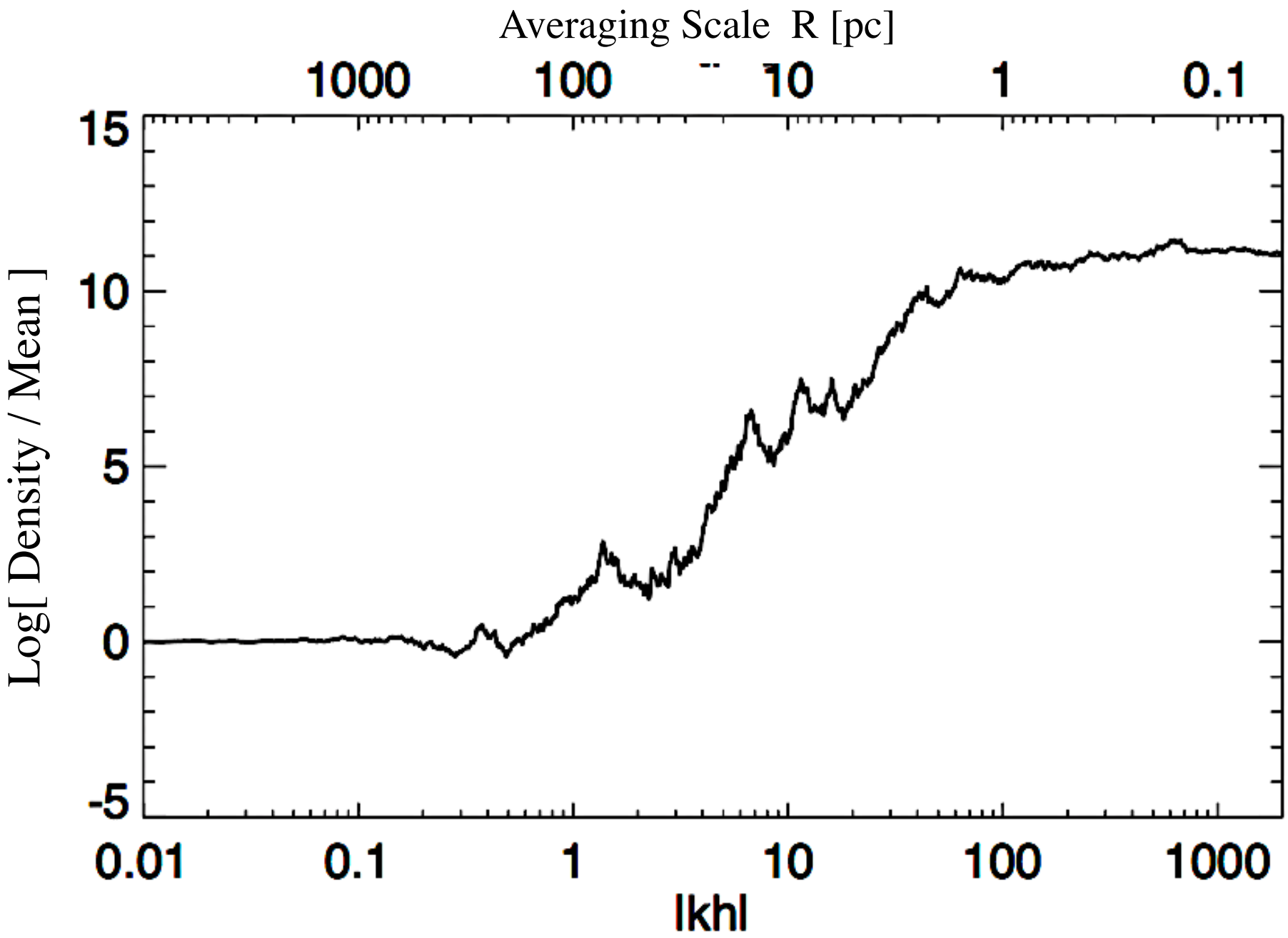
Mode Grows (Collapses) when $\omega < 0$:

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

Chandrasekhar '51, Vandervoort '70, Toomre '77

"Counting" Collapsing Objects

EVALUATE DENSITY FIELD vs. "BARRIER"



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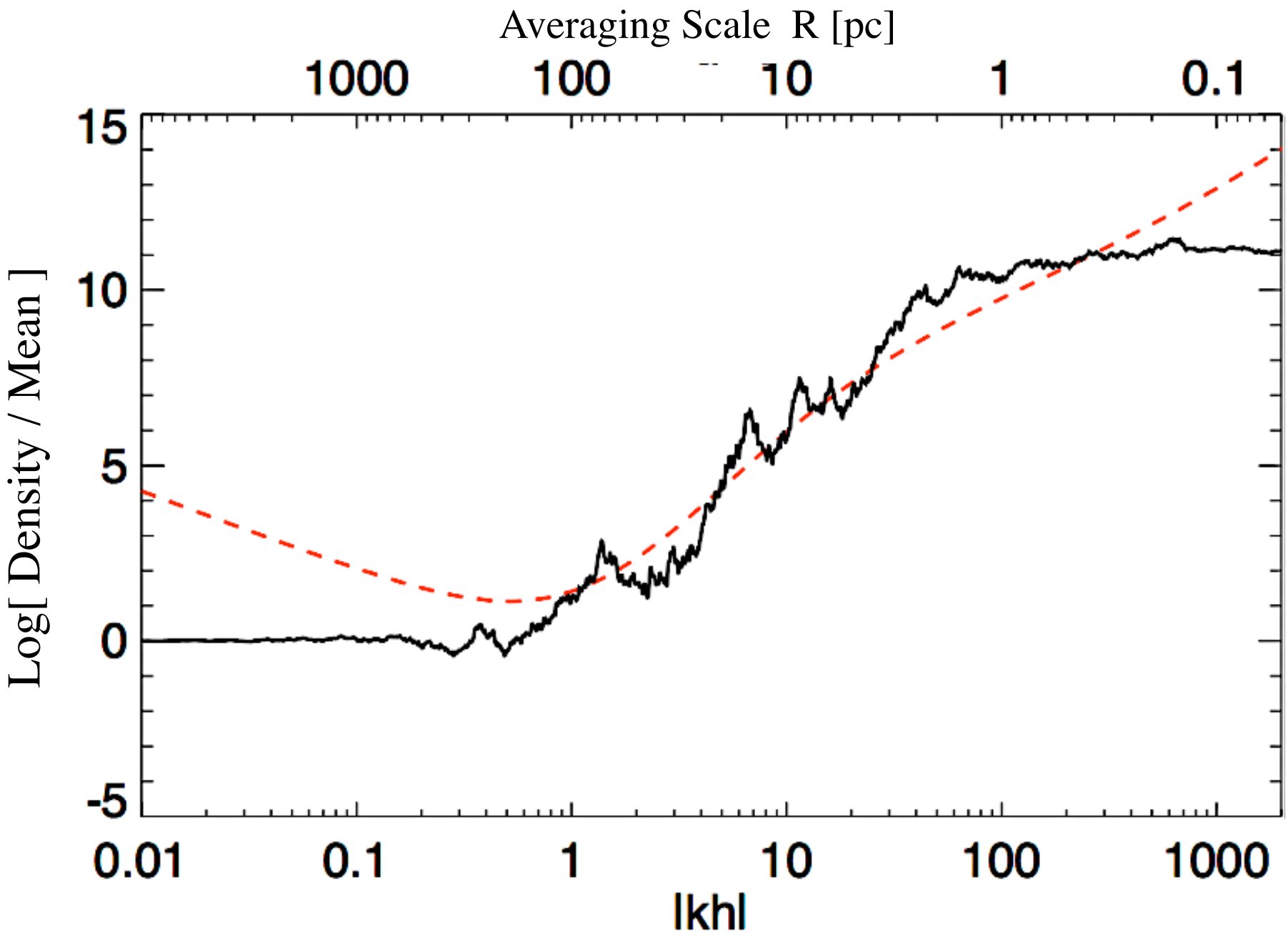

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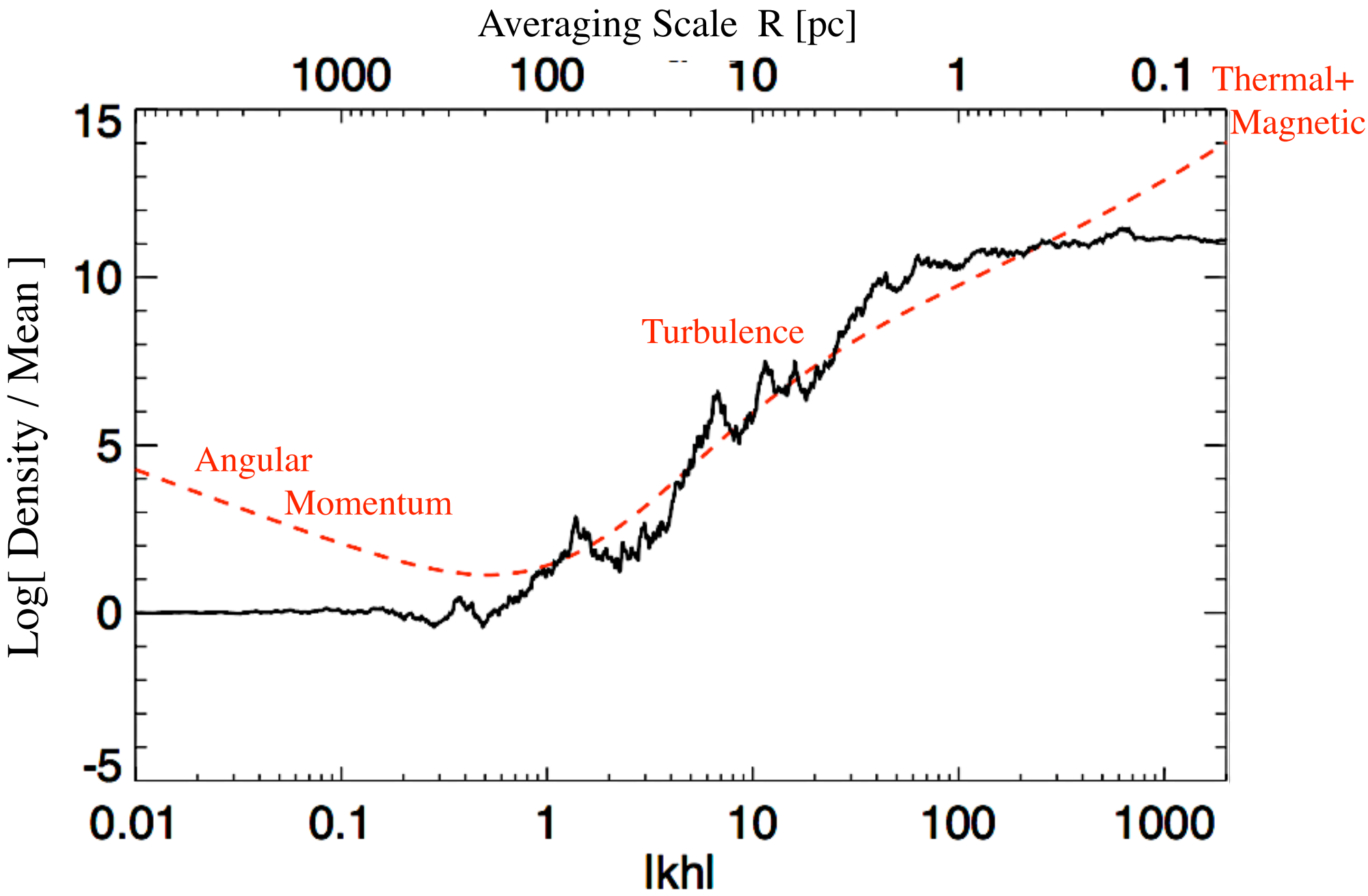

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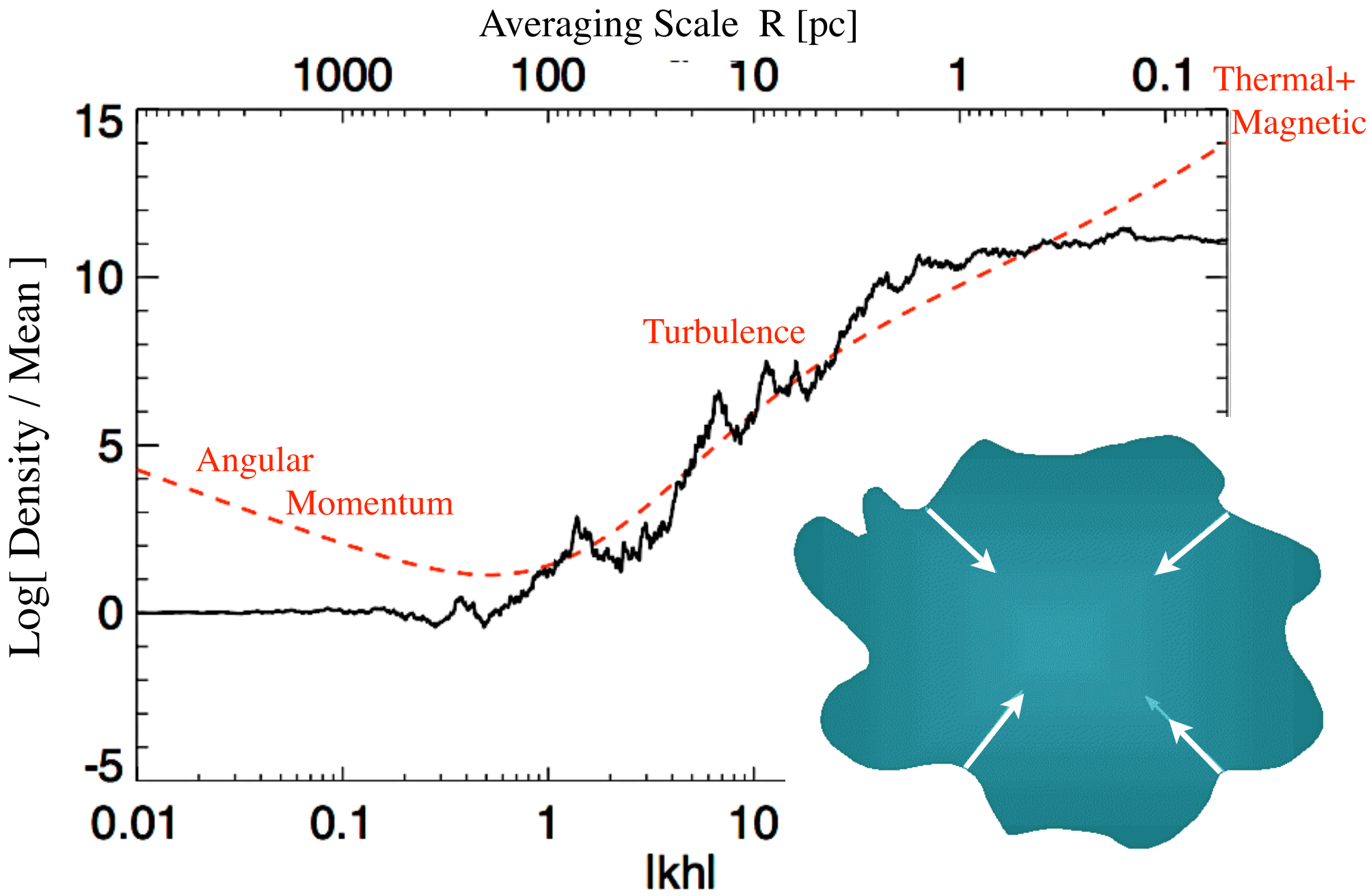

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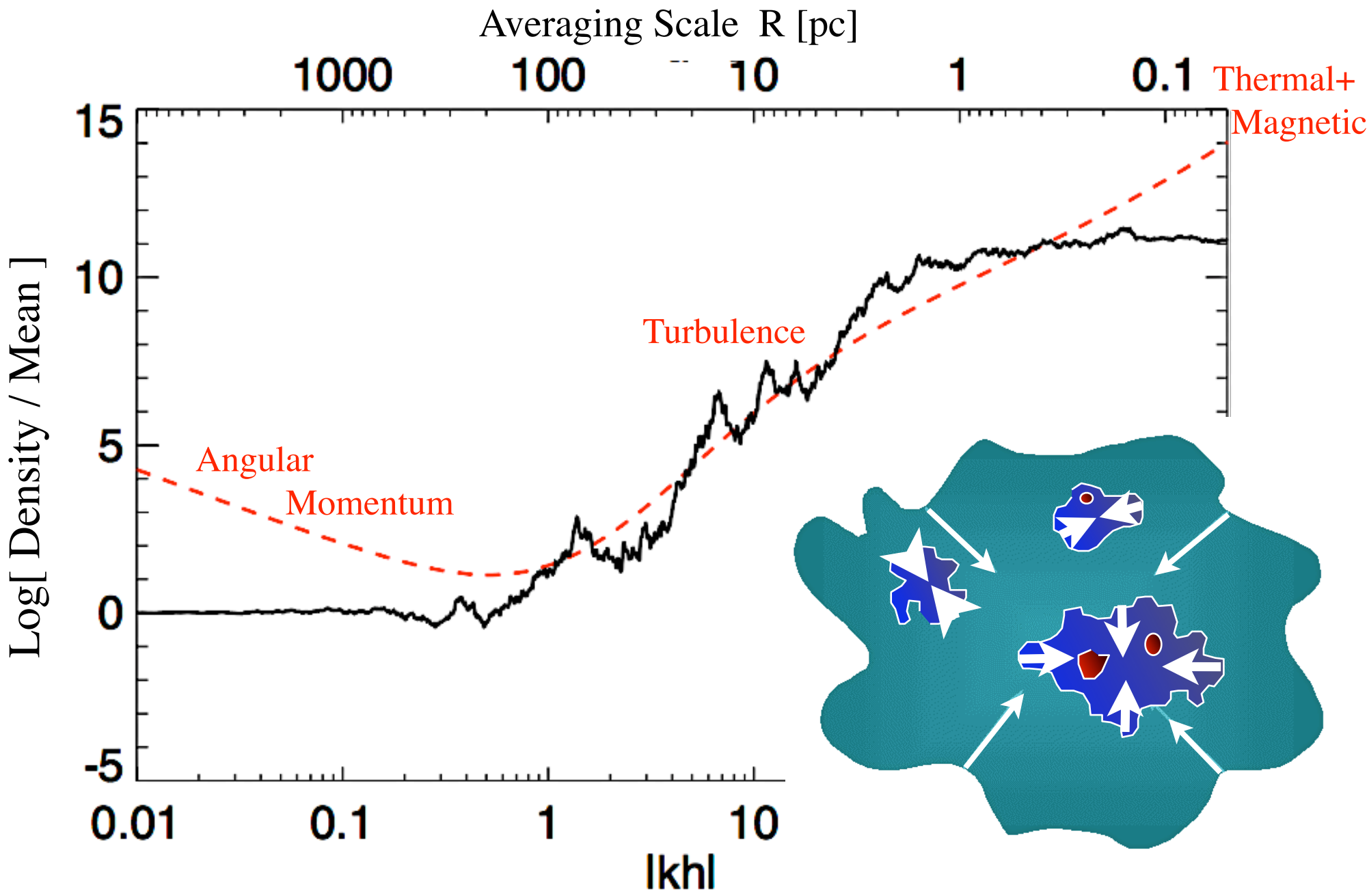

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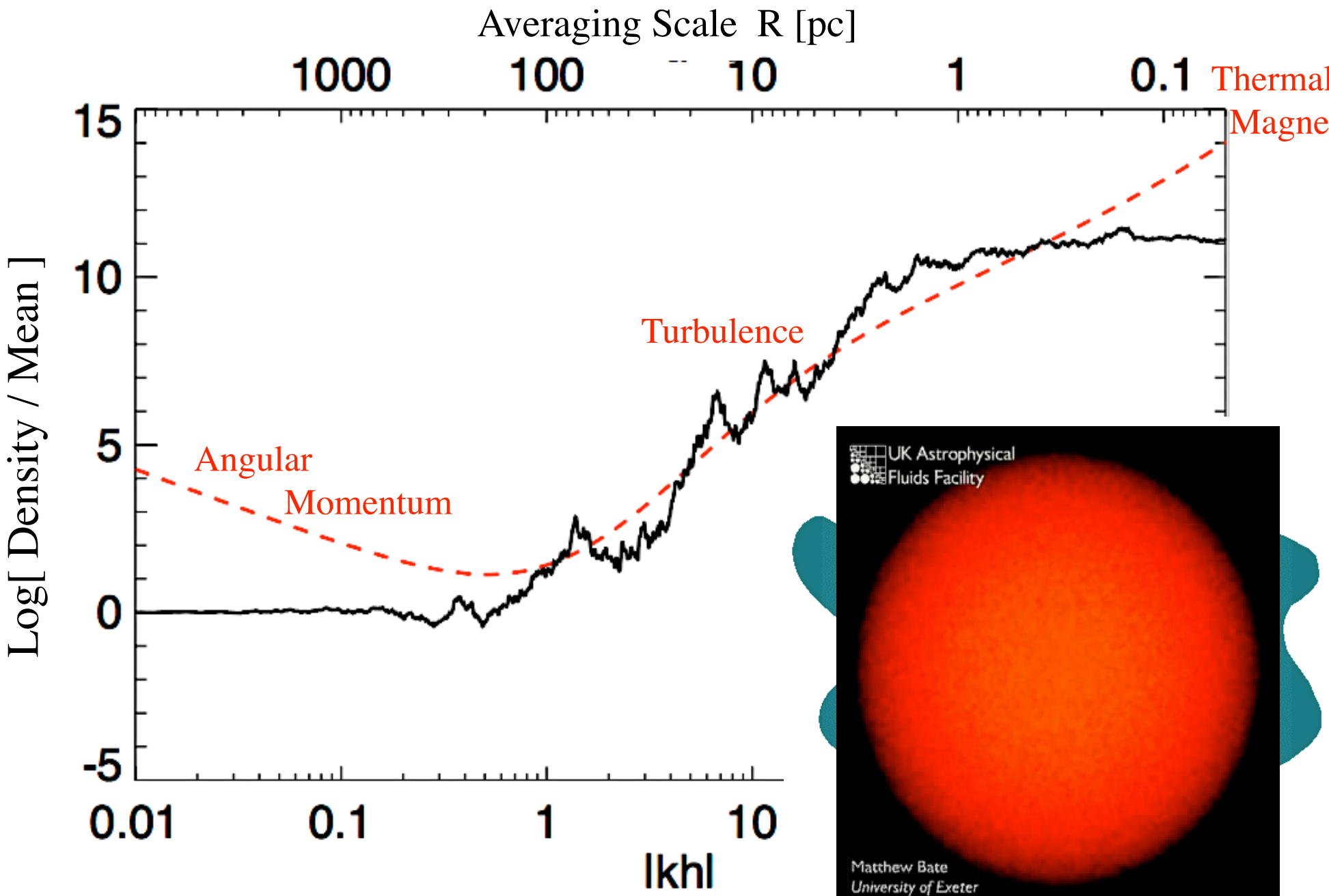

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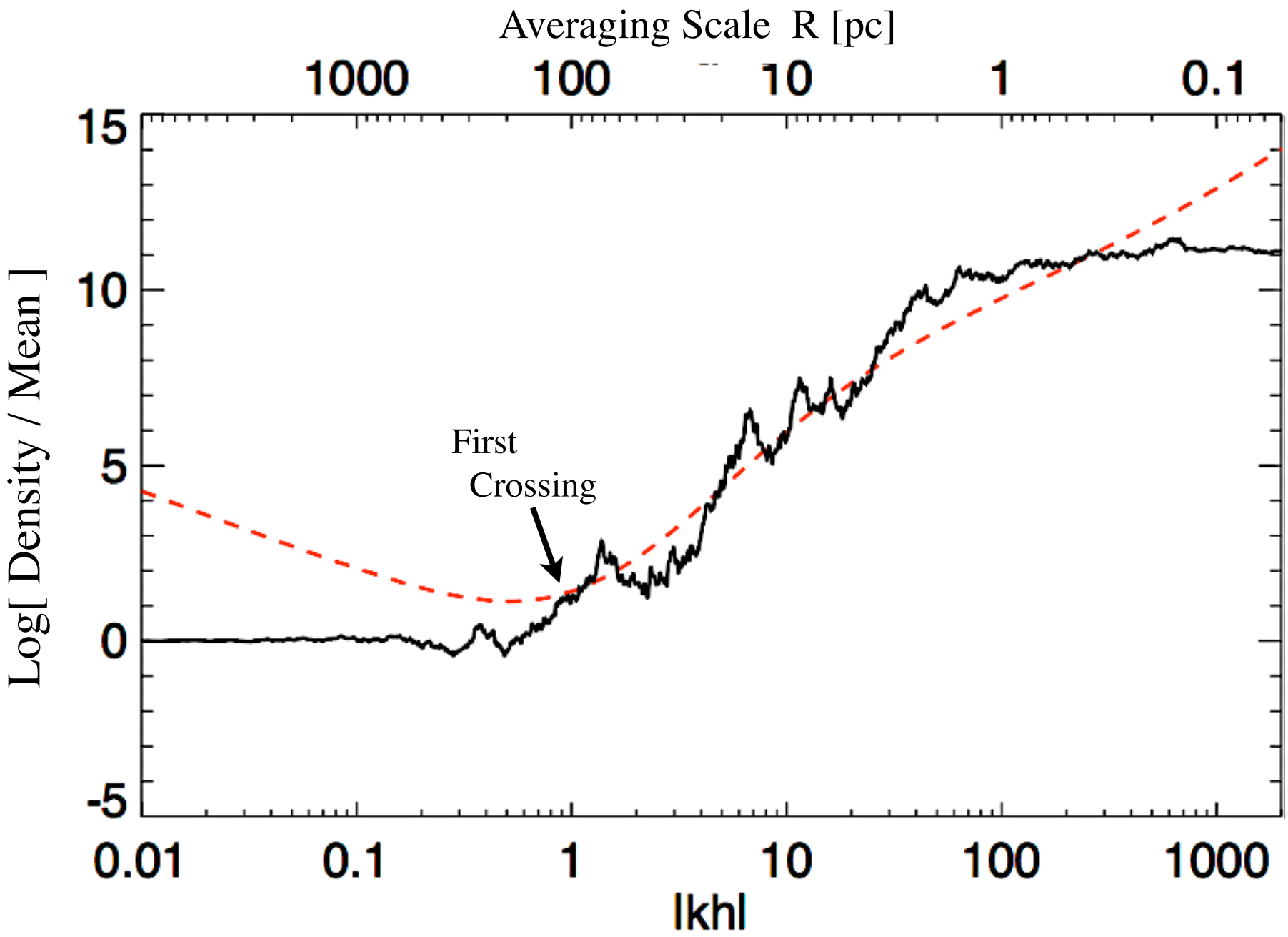

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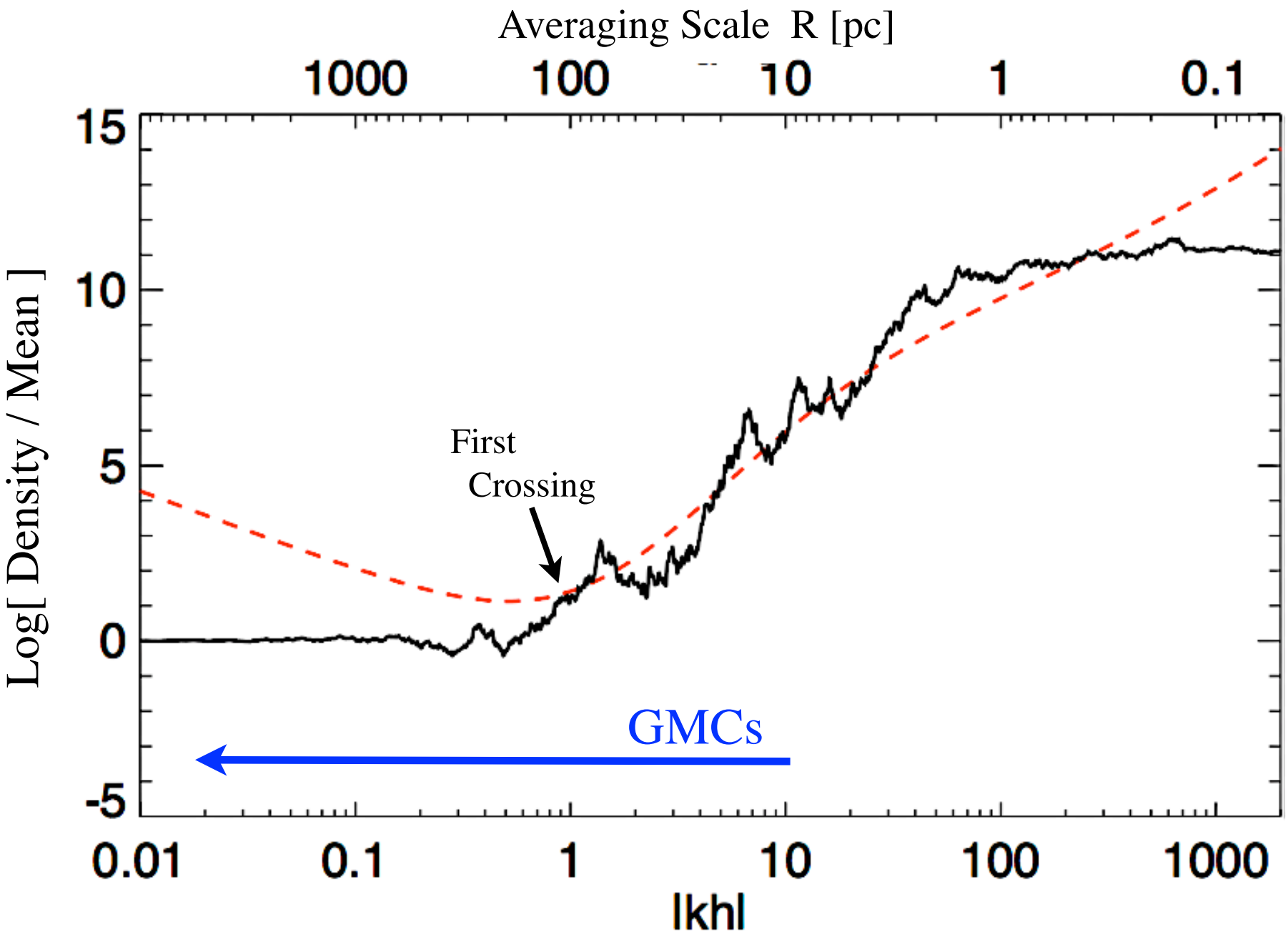

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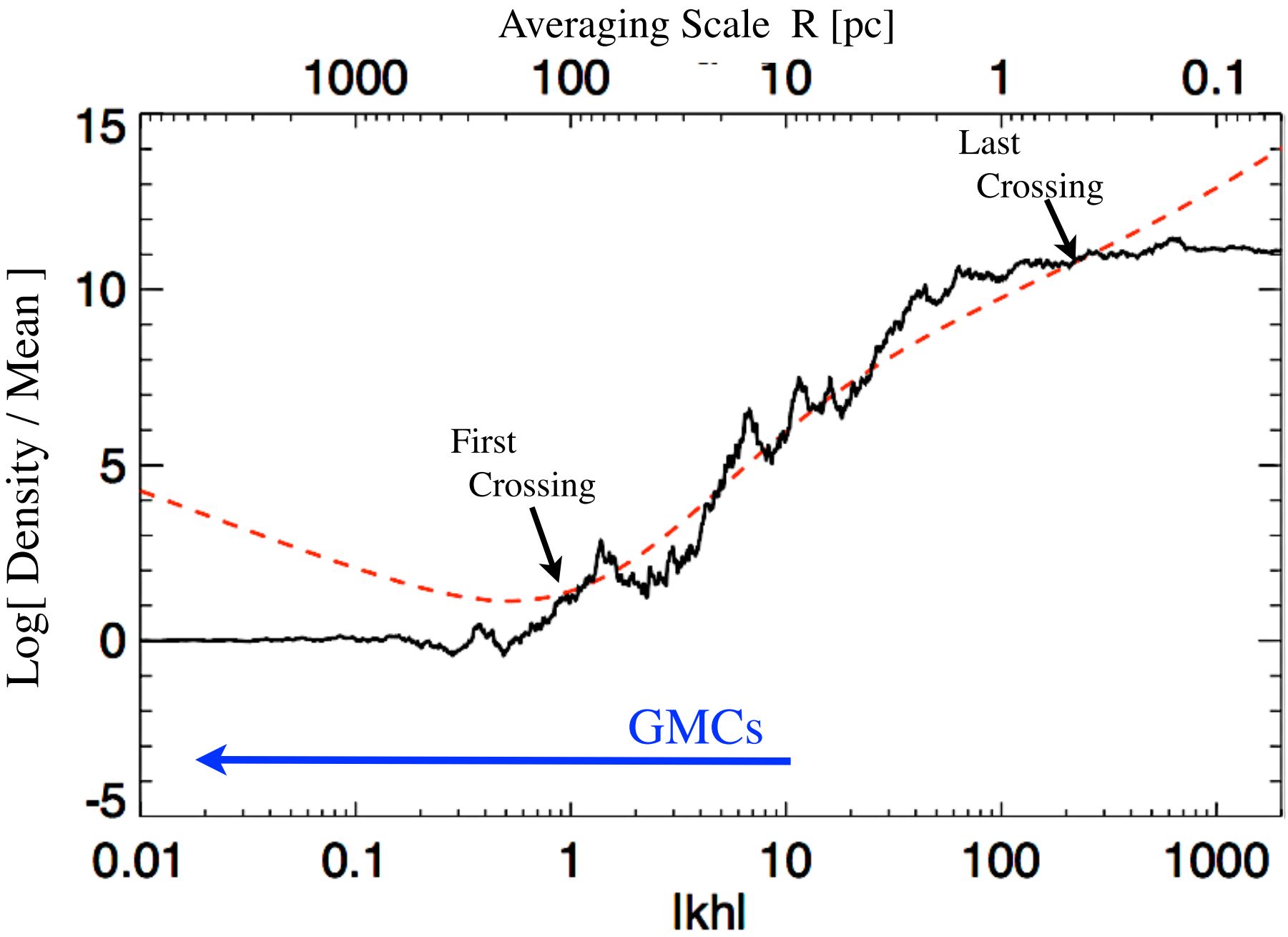

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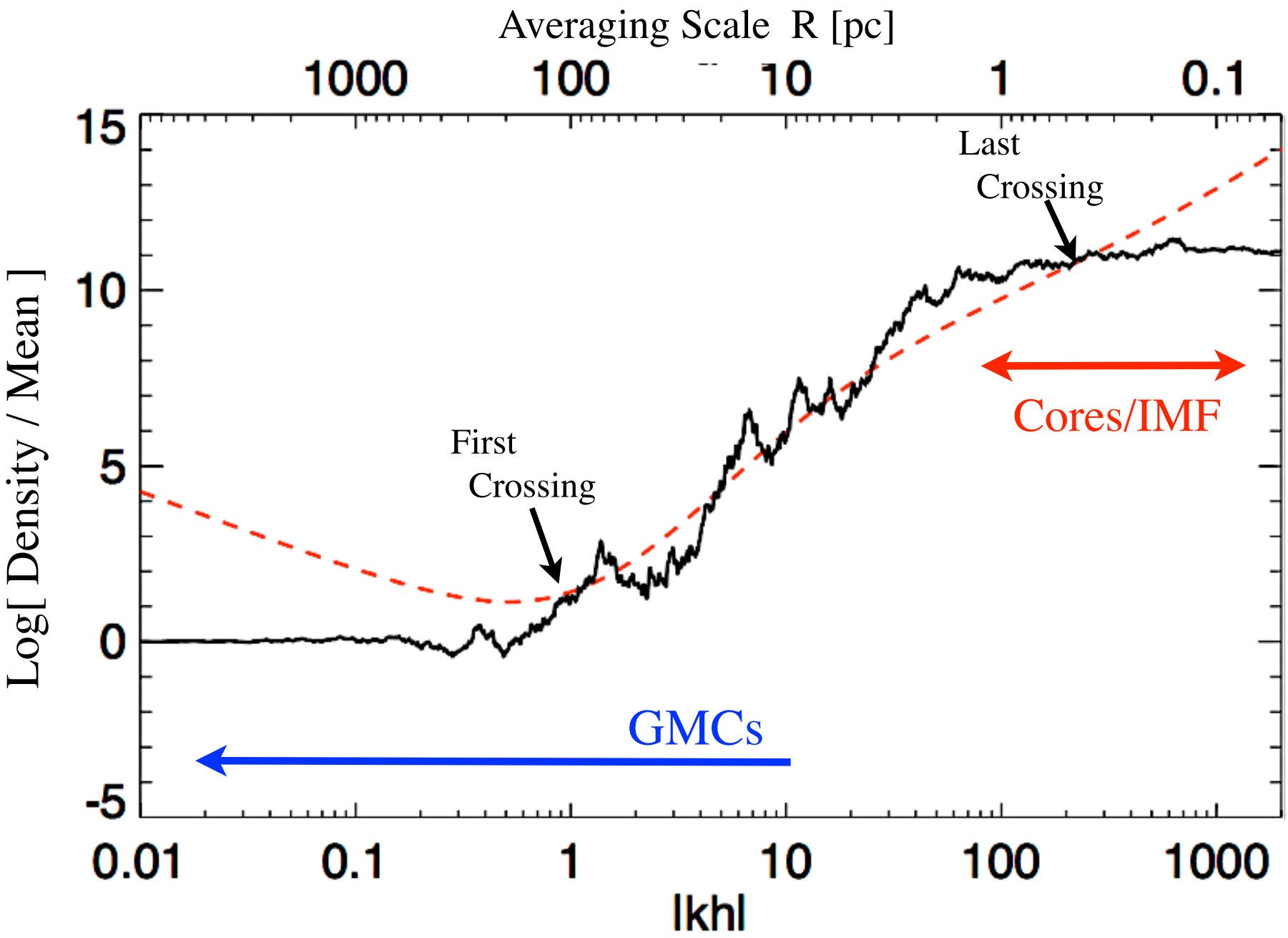
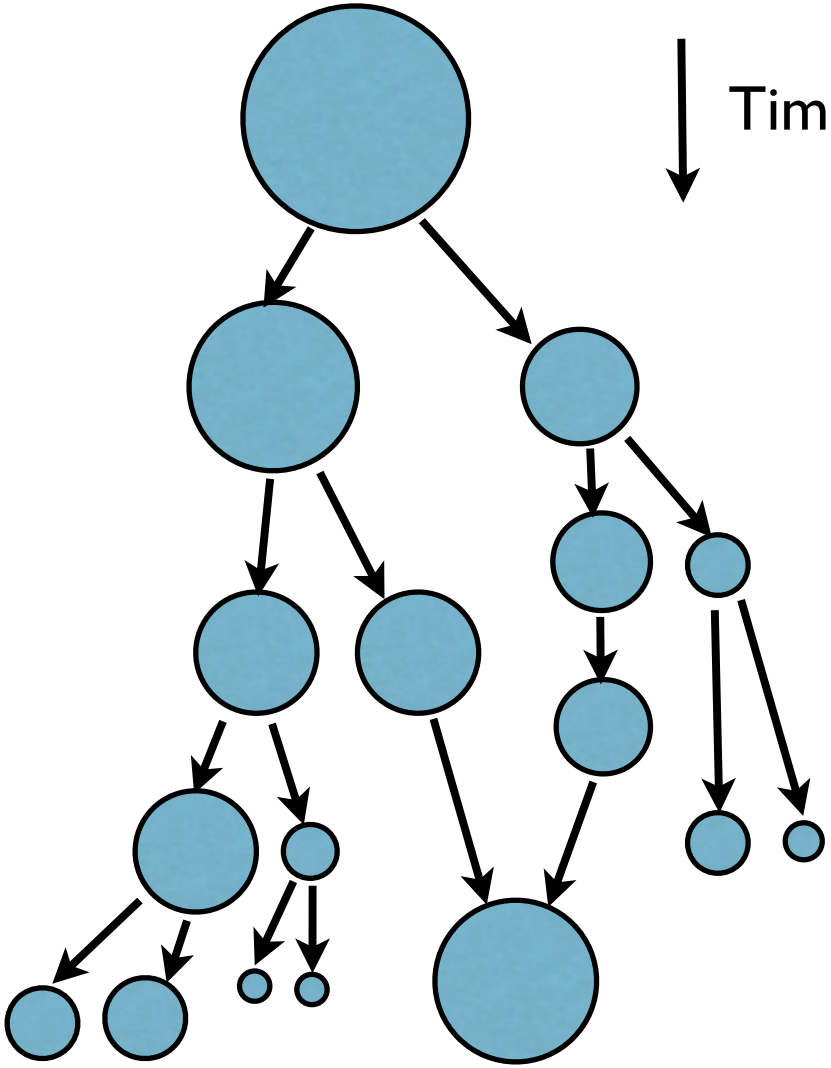


Evolve the Fluctuations in Time

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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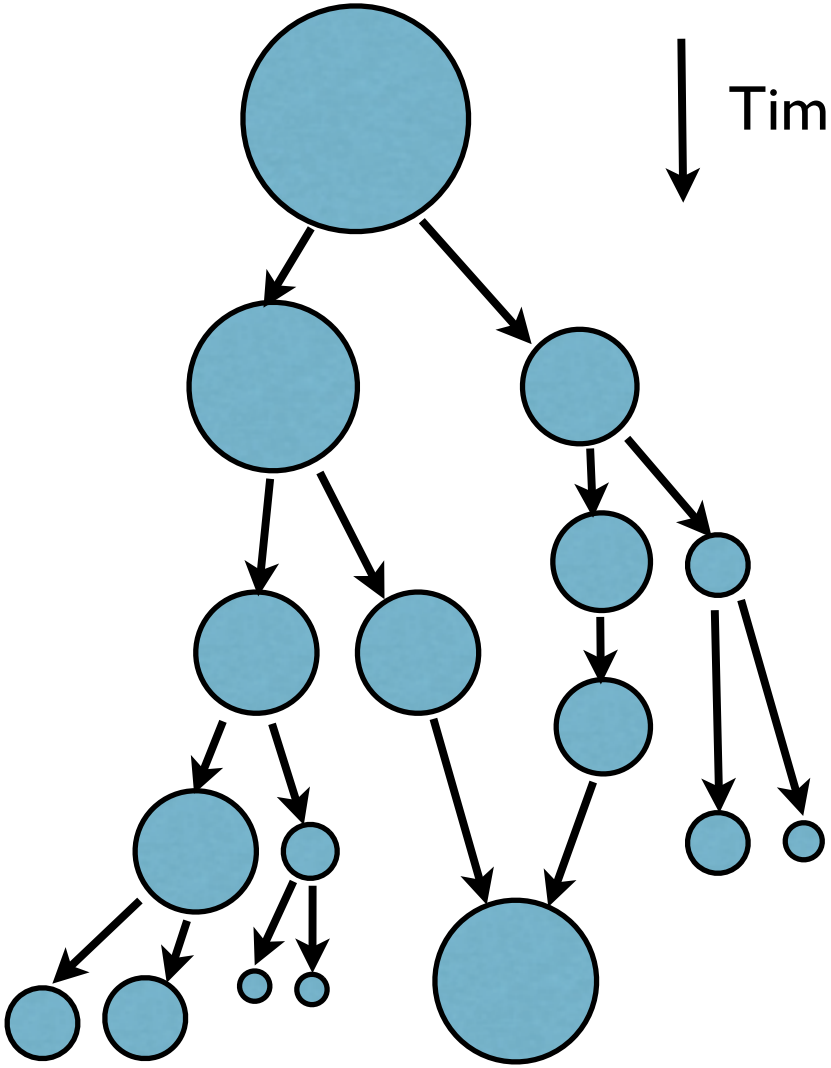
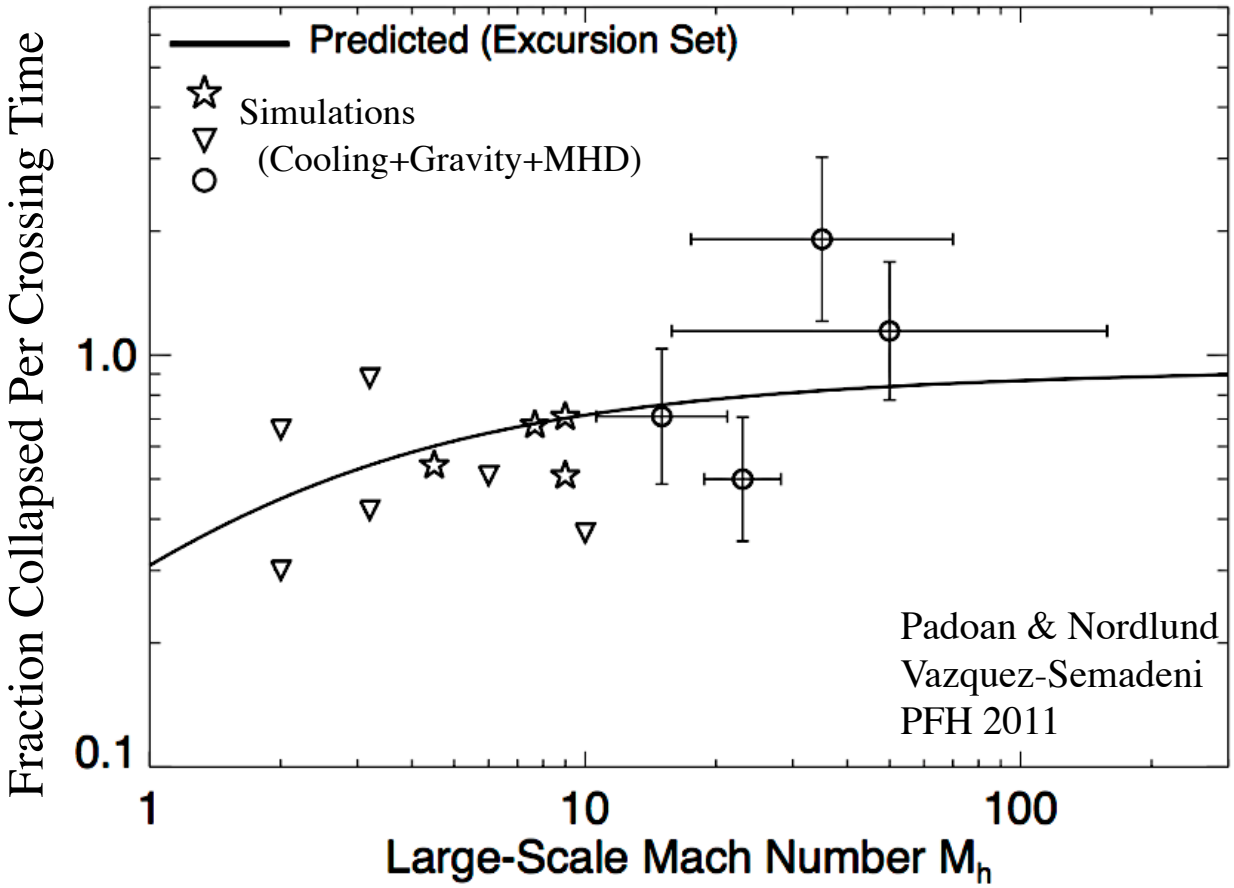
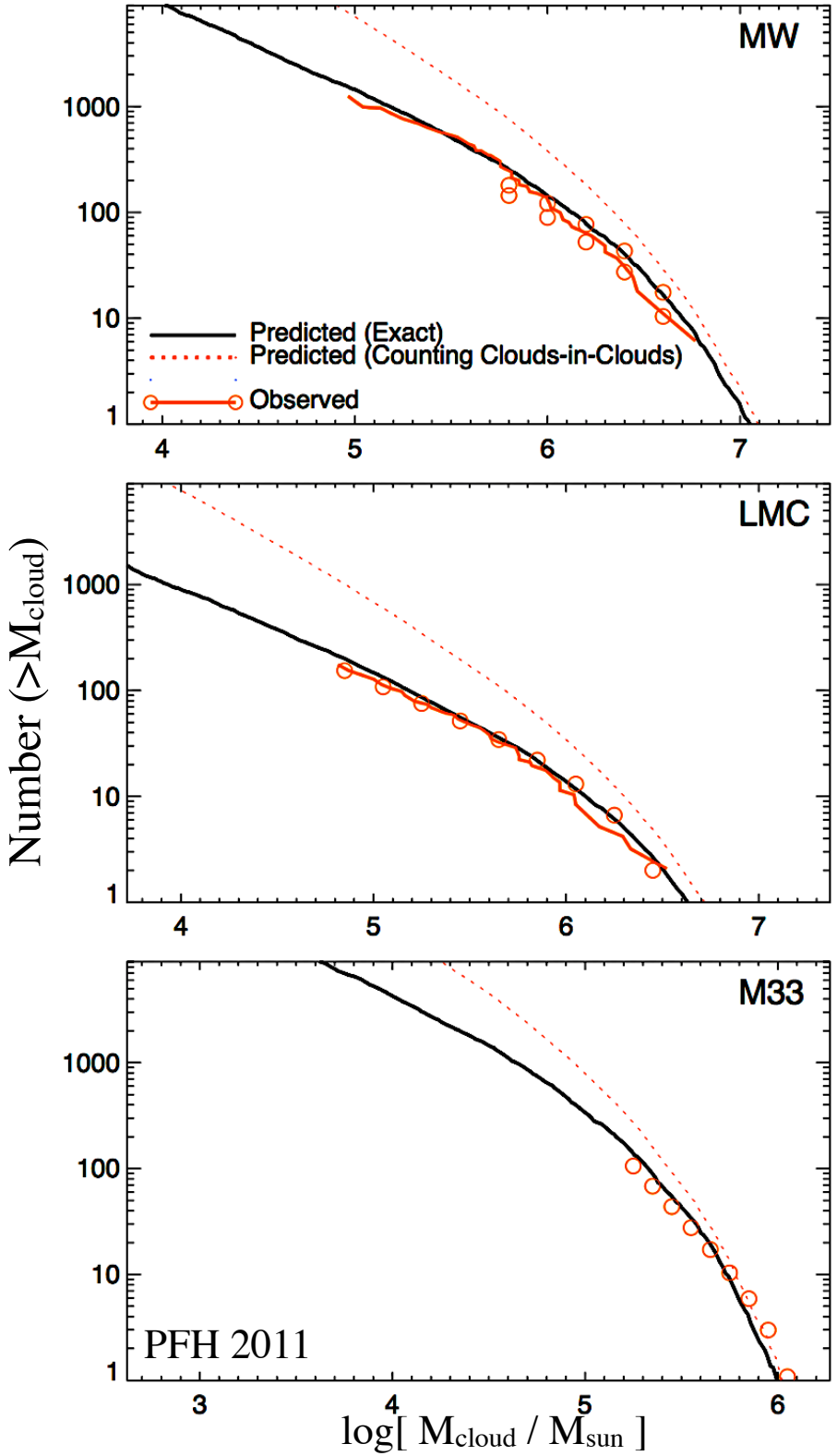




The “First Crossing” Mass Function

VS GIANT MOLECULAR CLOUDS



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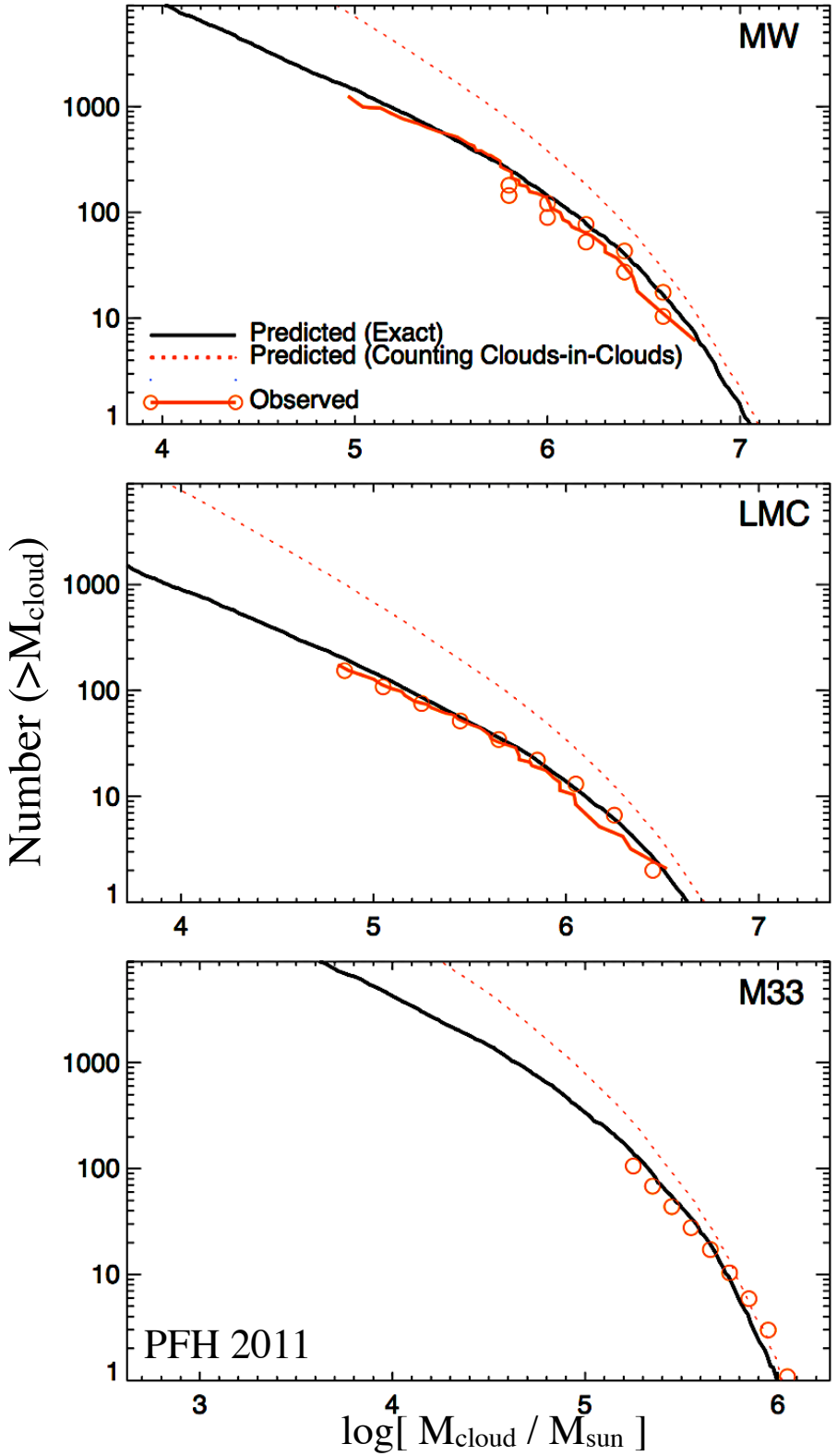

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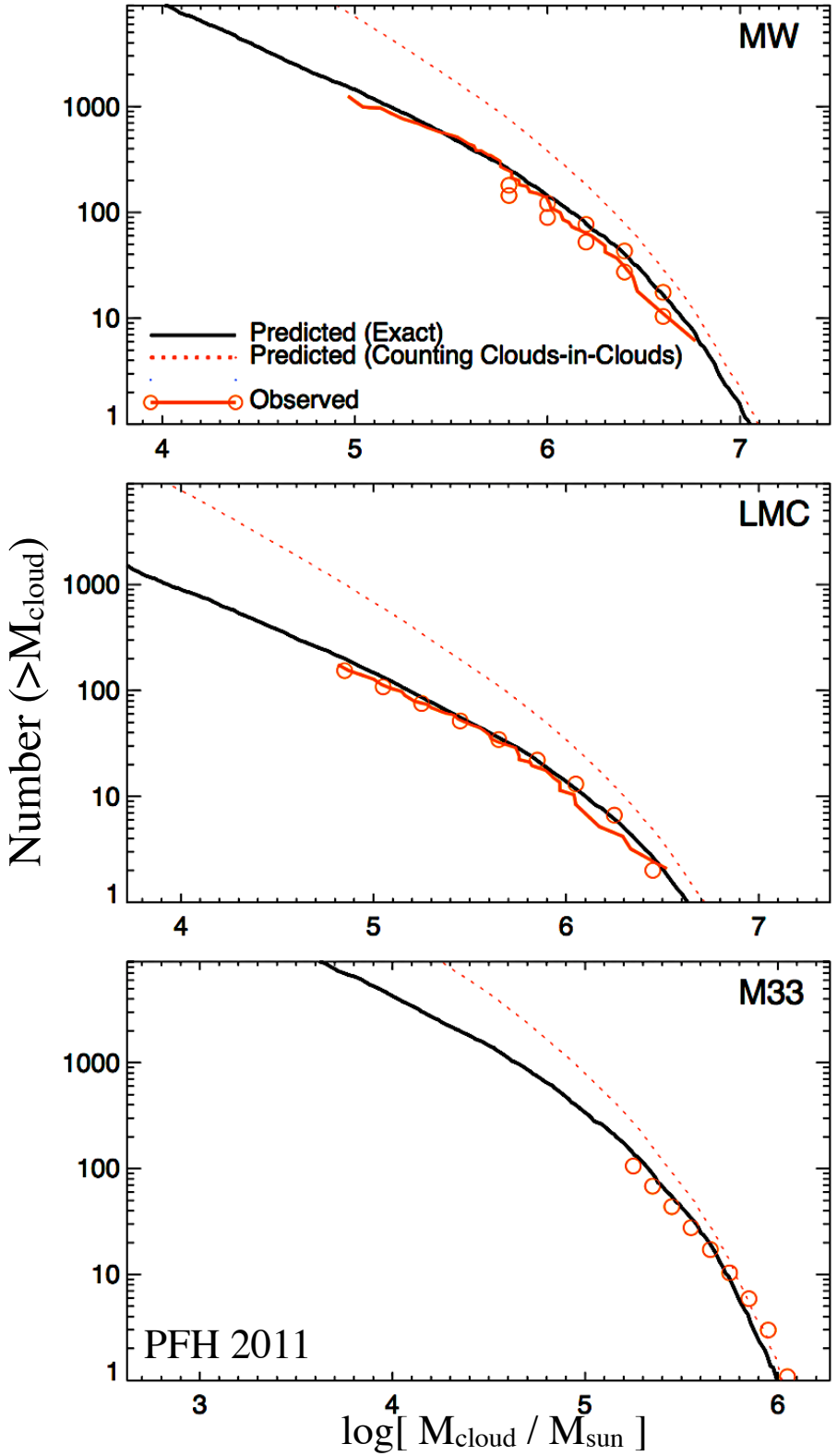

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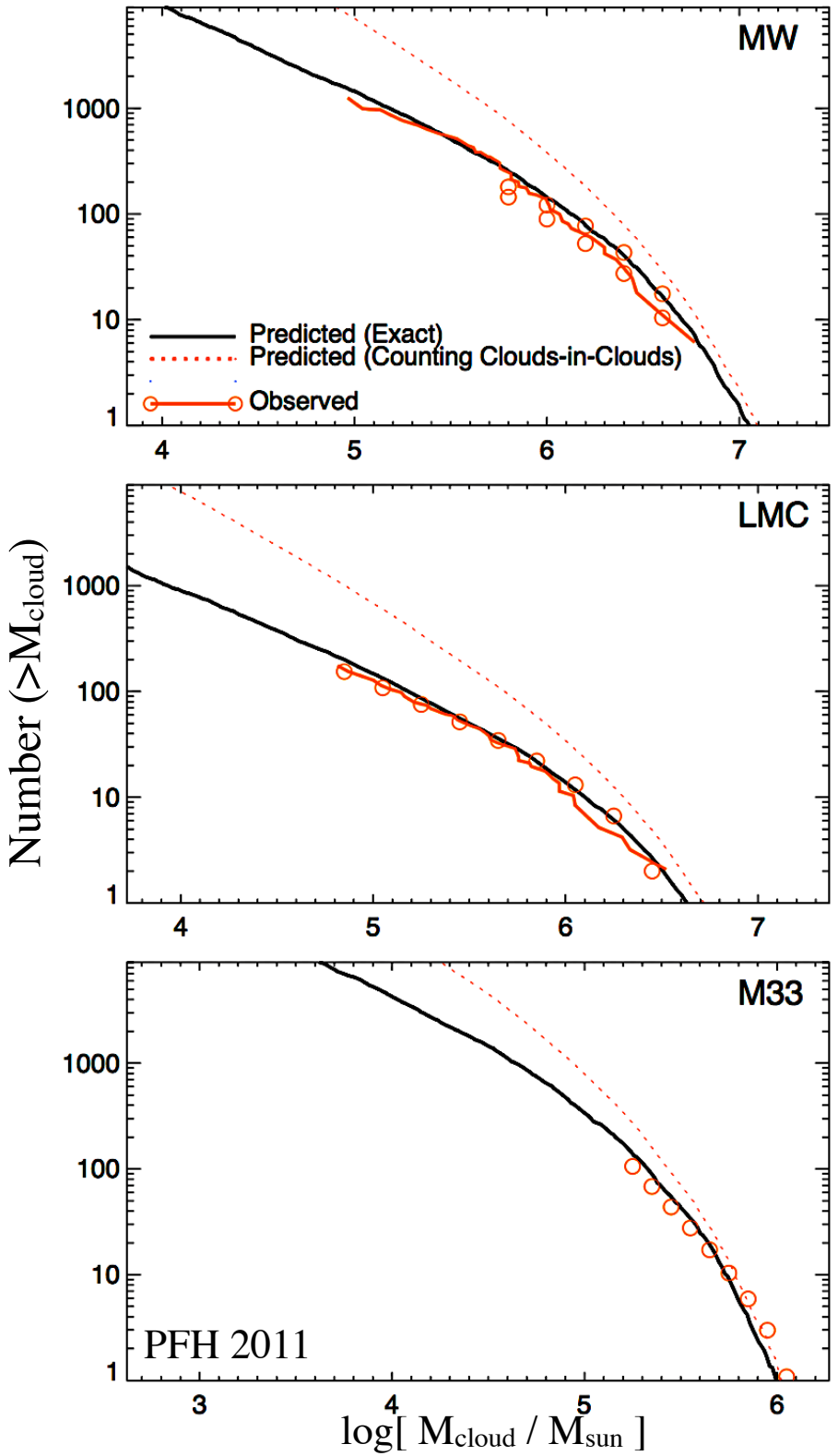
$$\alpha \approx -2 + \frac{(3-p)^2}{2\,S\,p^2} \ln\left(\frac{M_J}{M}\right)$$

$$\approx -2 + 0.1\,\log\left(\frac{M_J}{M}\right)$$



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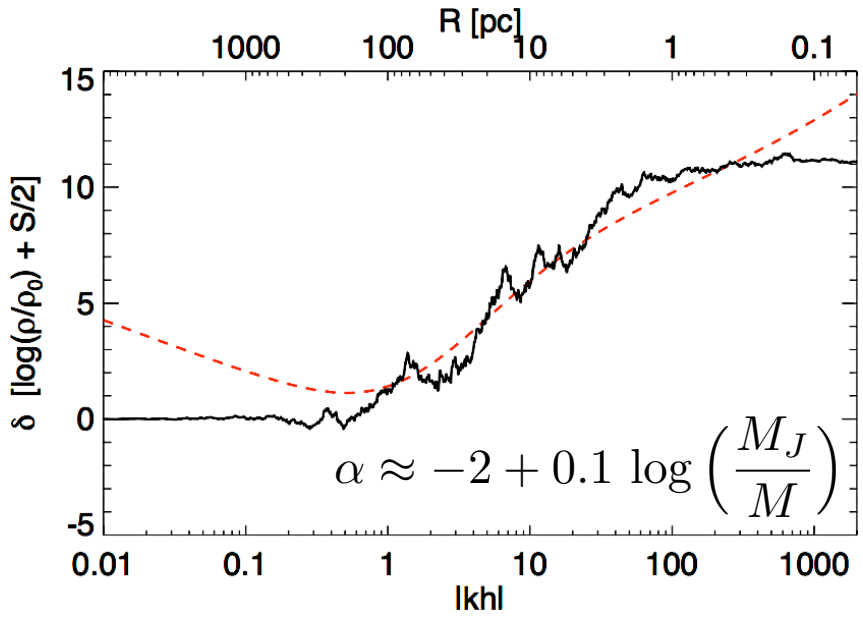

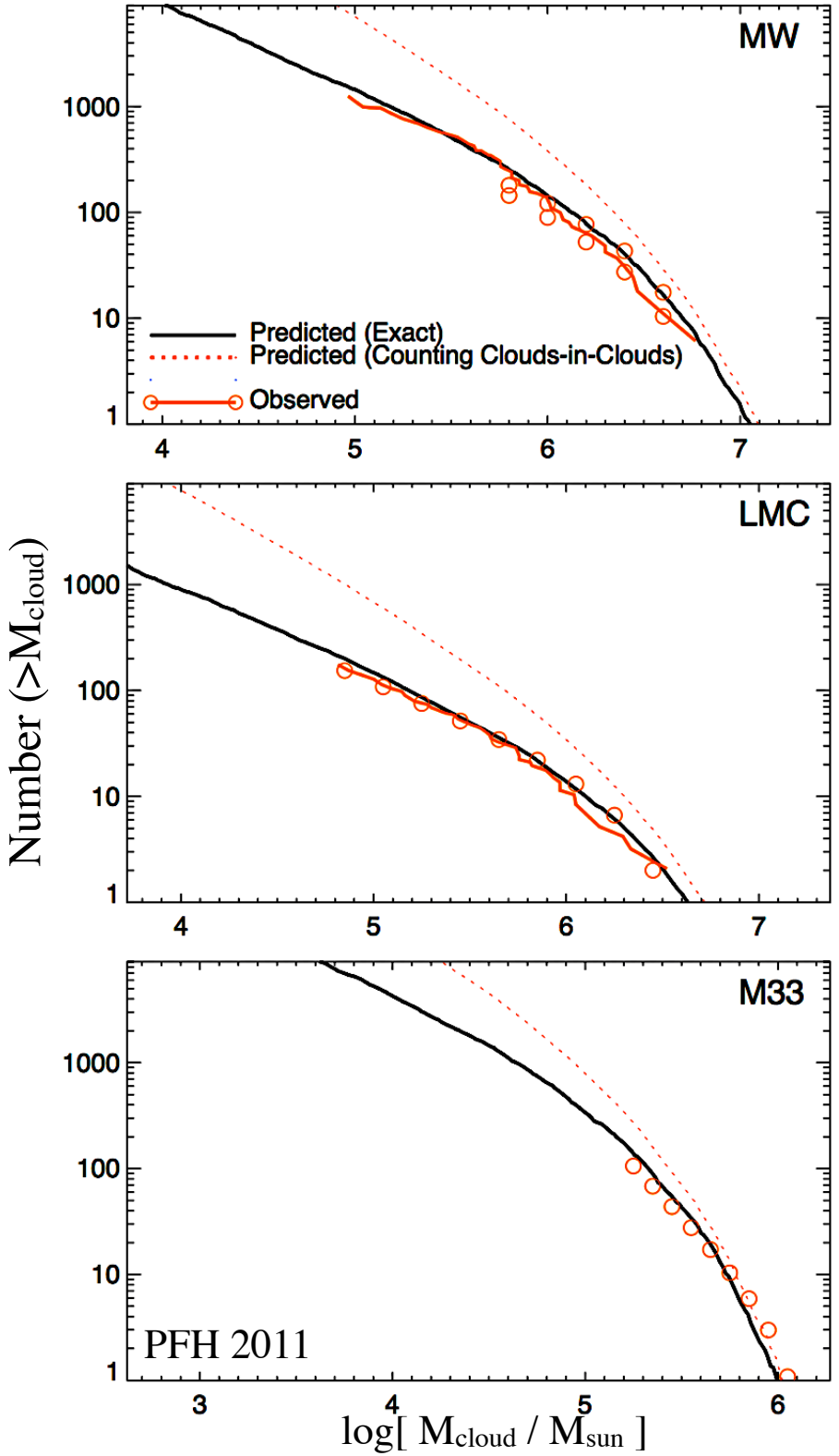

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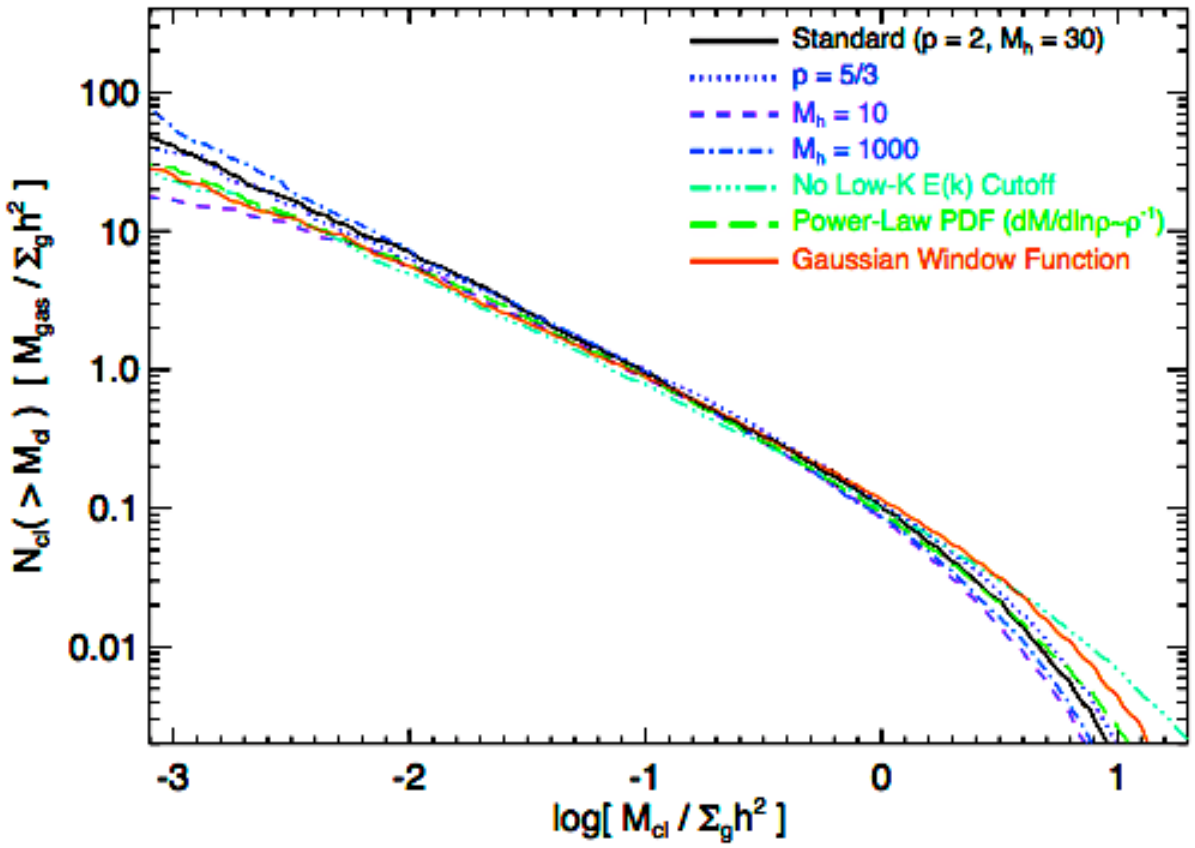
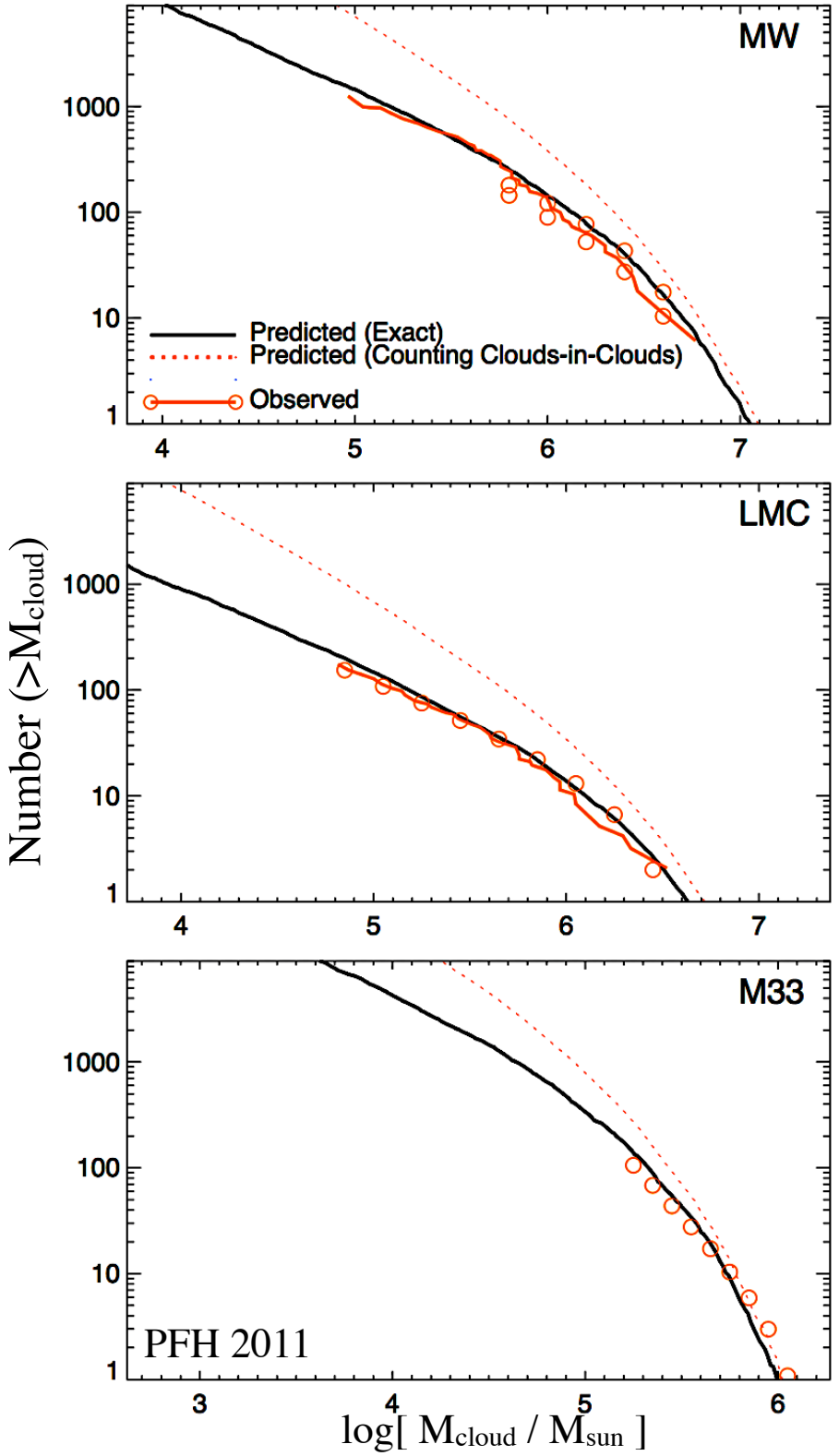
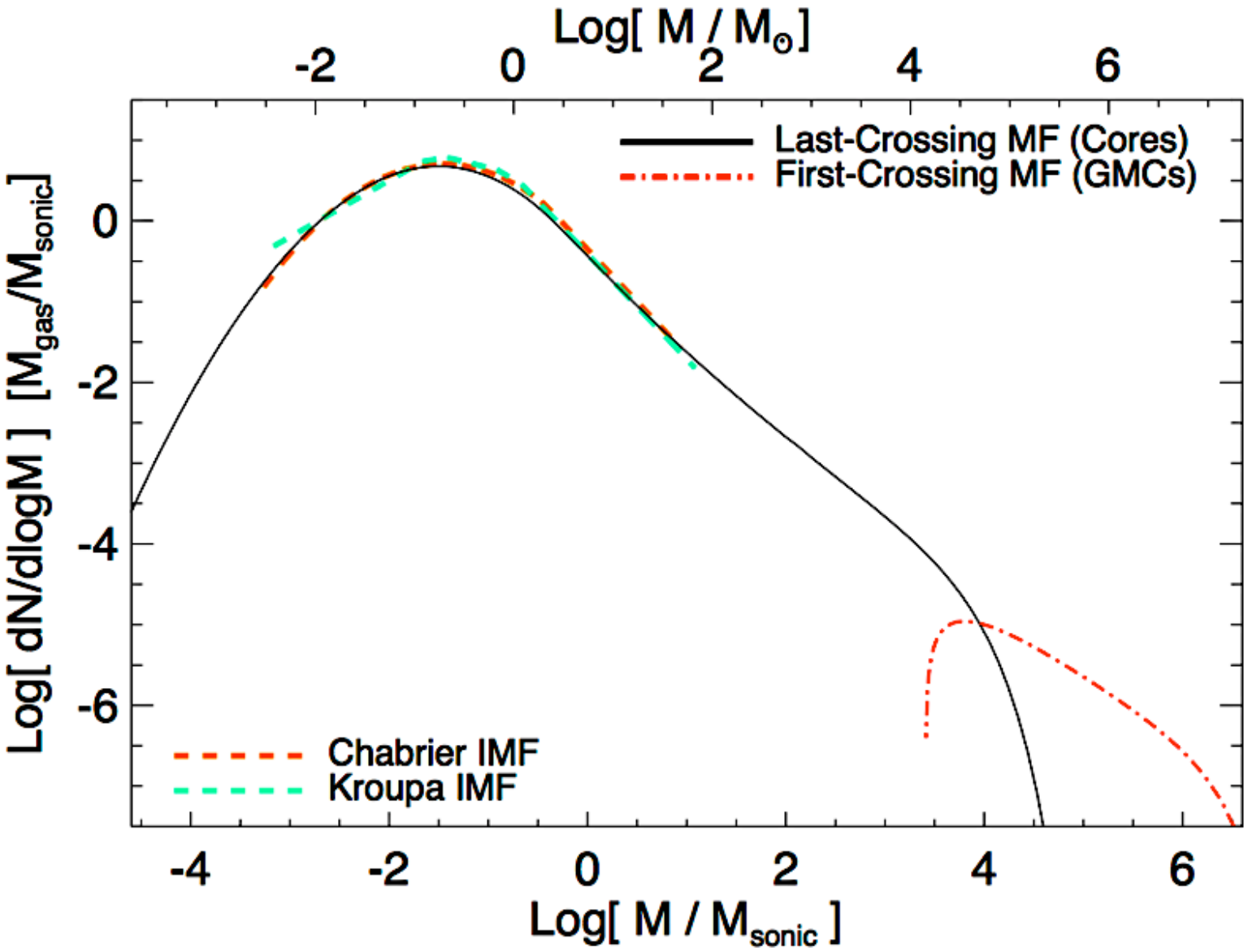




The “Last Crossing” Mass Function

VS PROTOSTELLAR CORES & THE STELLAR IMF



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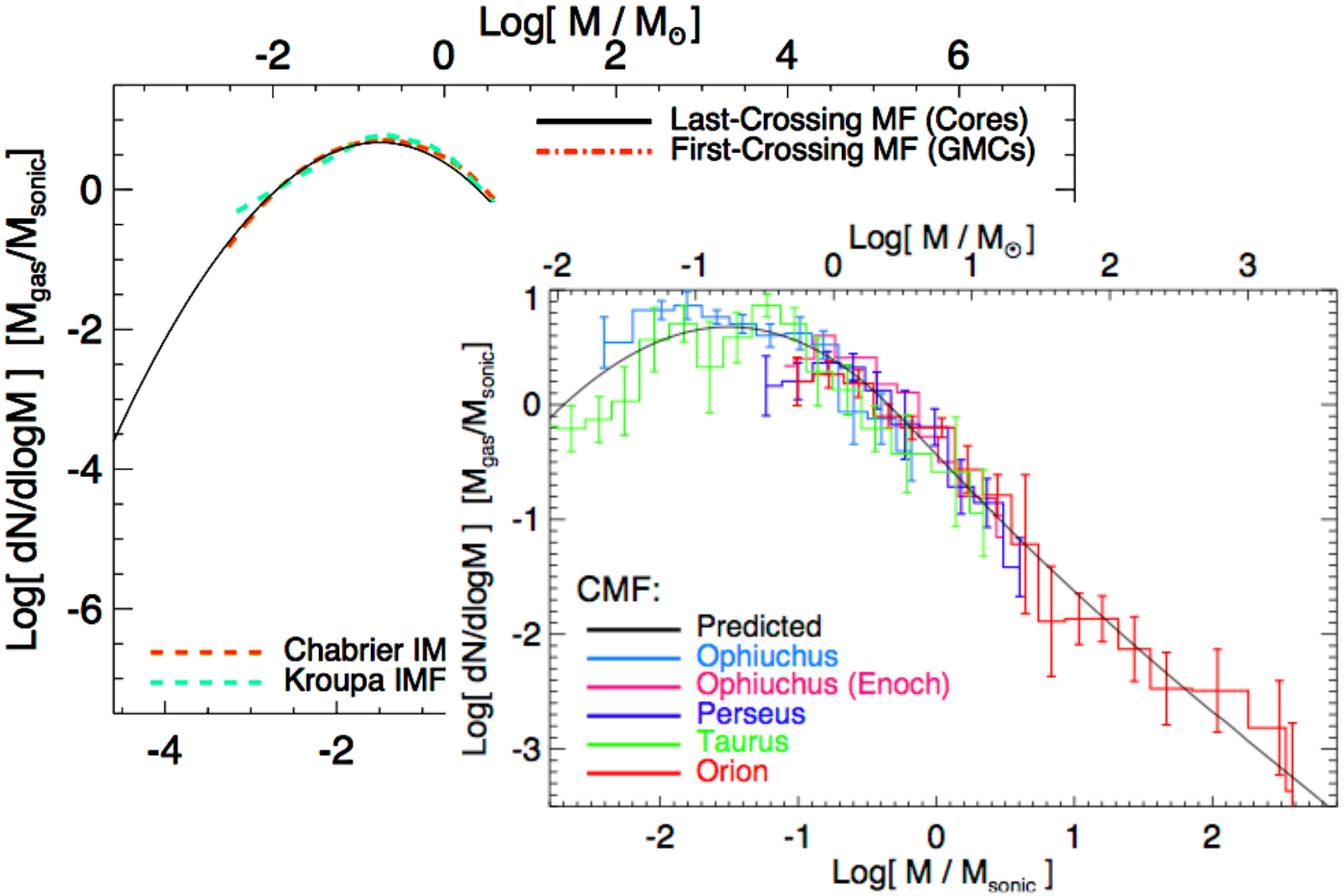
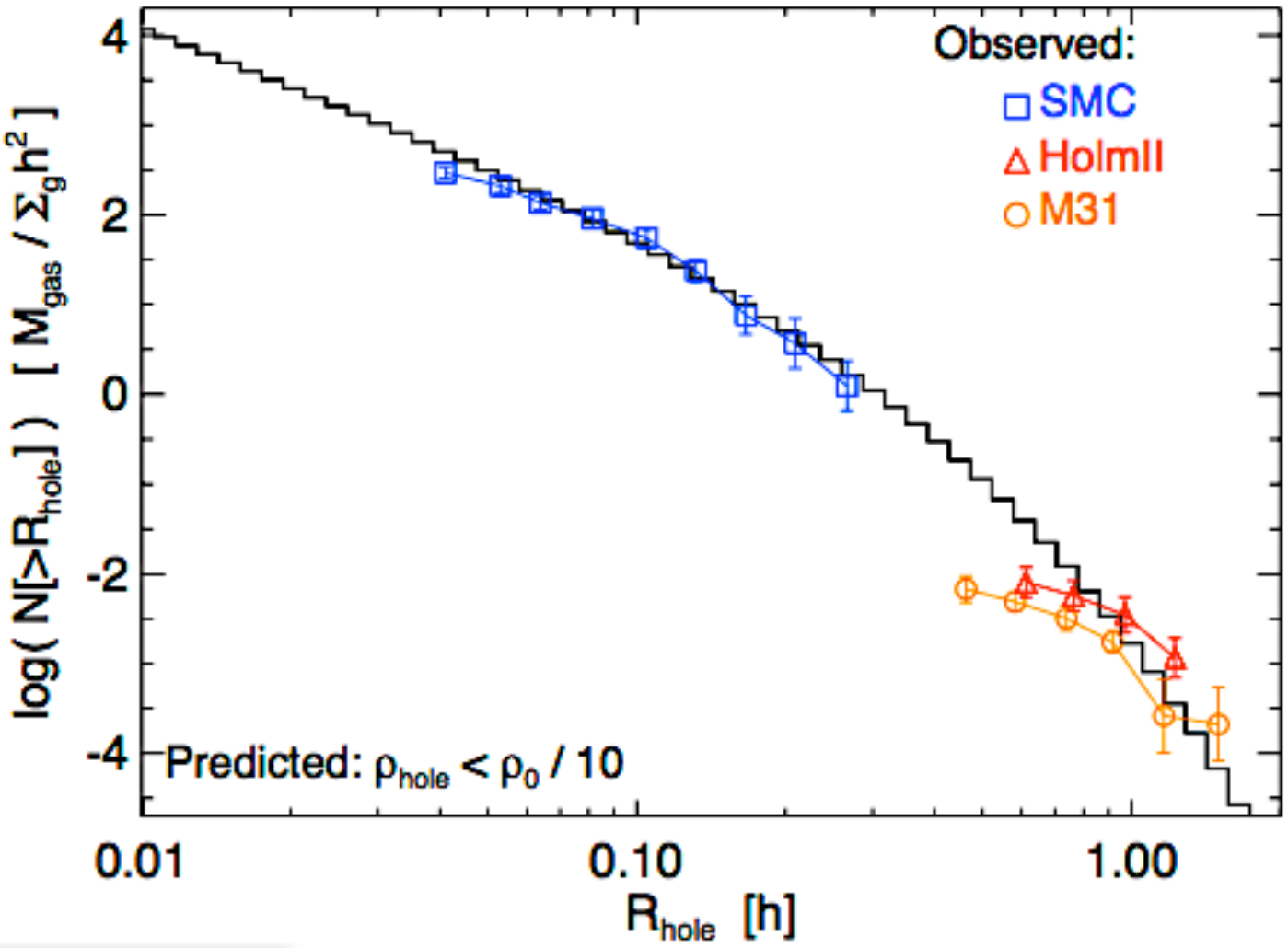


"Void" Abundance

VS HI "HOLES" IN THE ISM

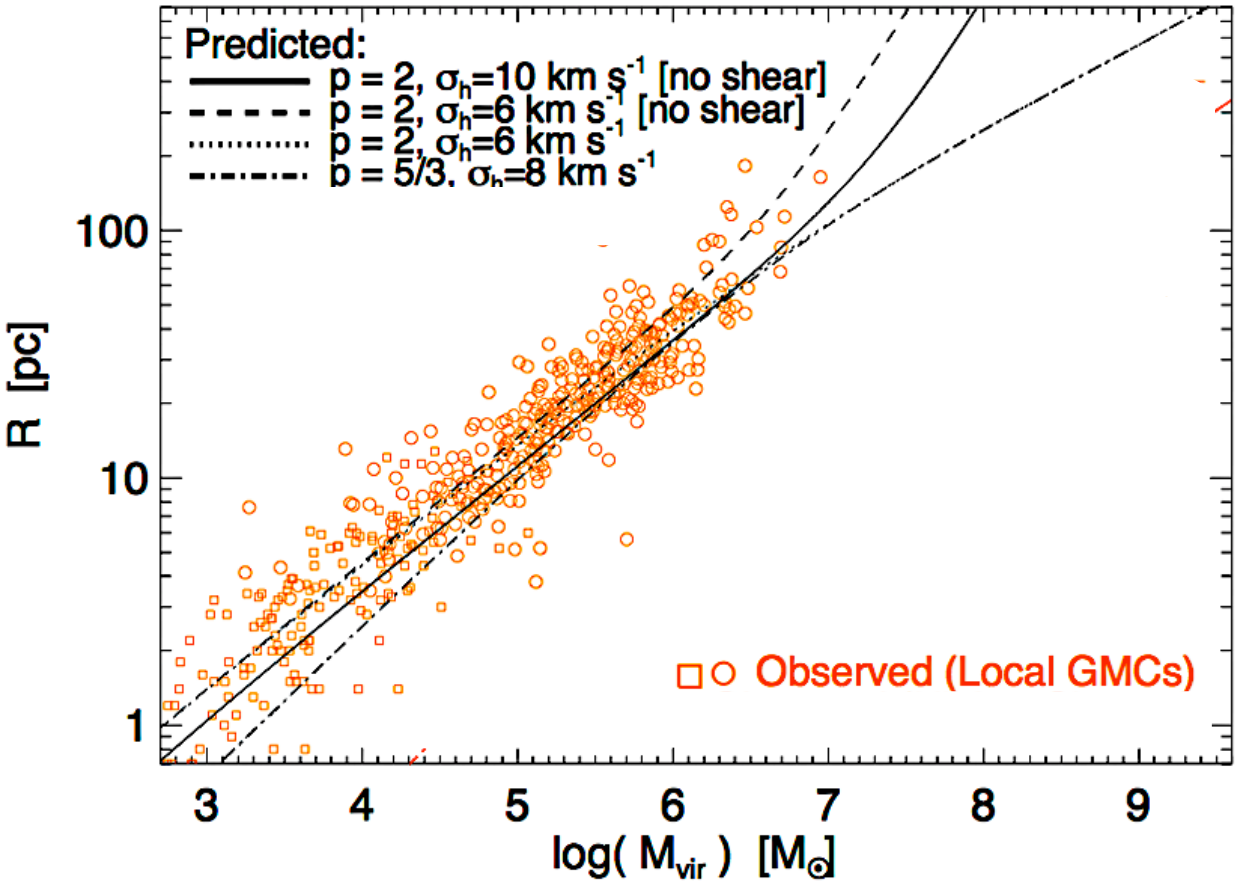


KEEP?

Don't need SNe to "clear out" voids

Structural Properties of “Clouds”

LARSON’S LAWS EMERGE NATURALLY



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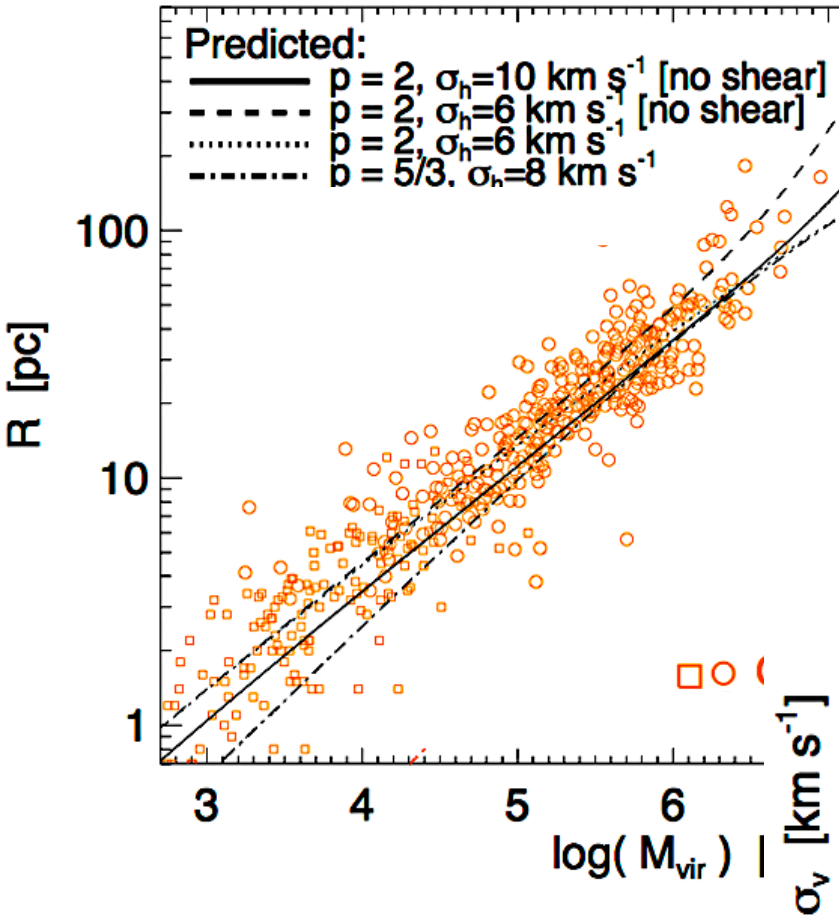
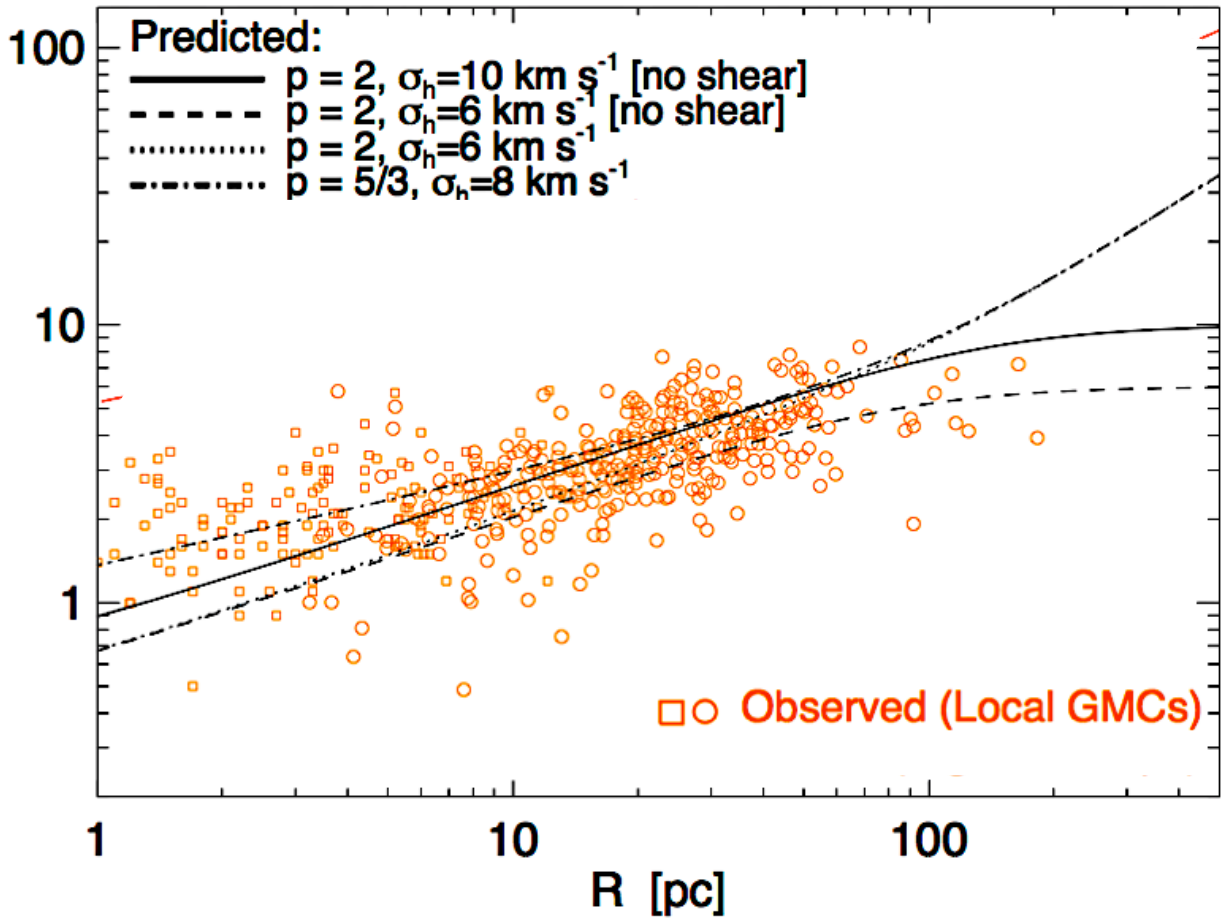


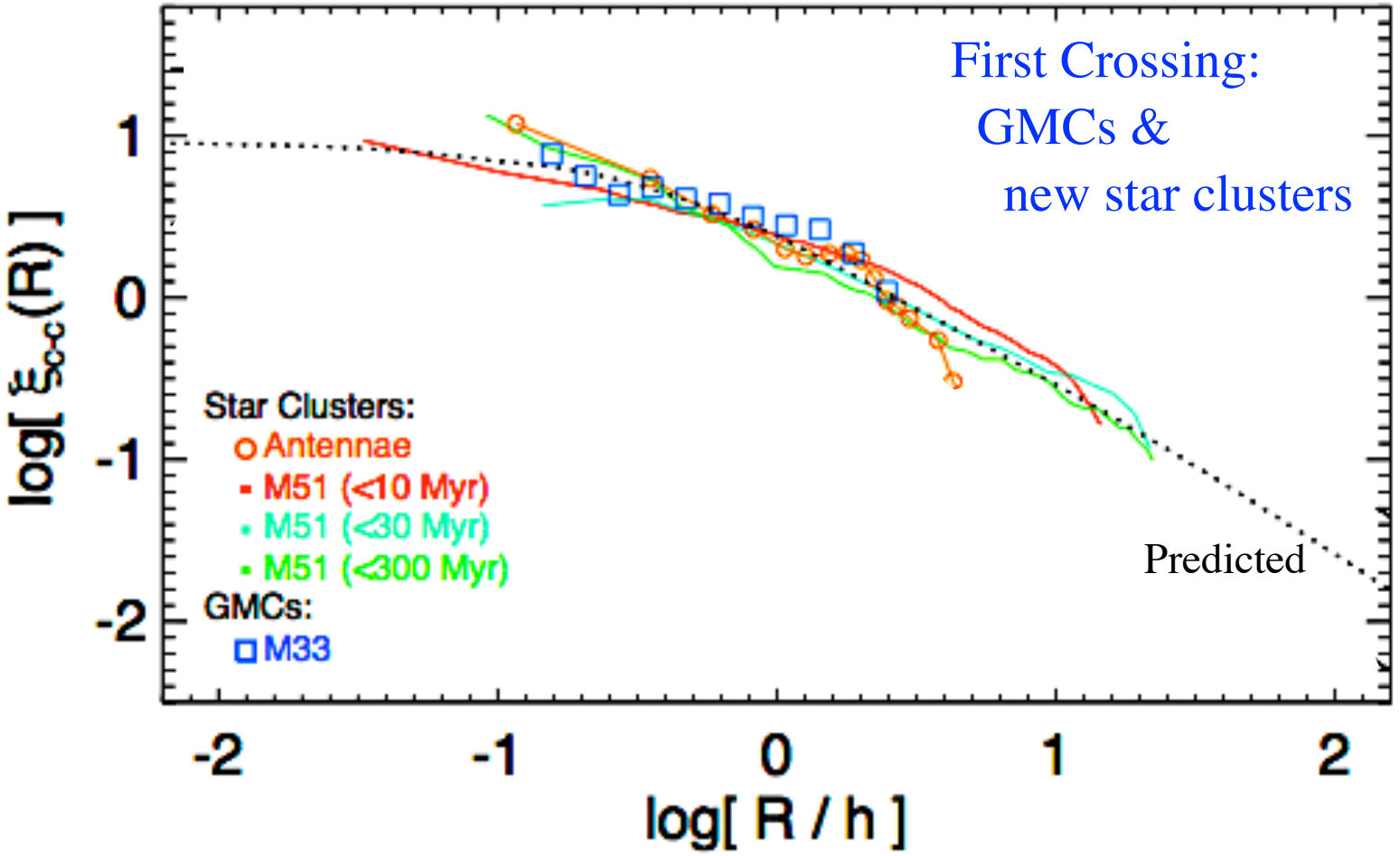


KEEP?

Clustering

PREDICT N-POINT CORRELATION FUNCTIONS

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



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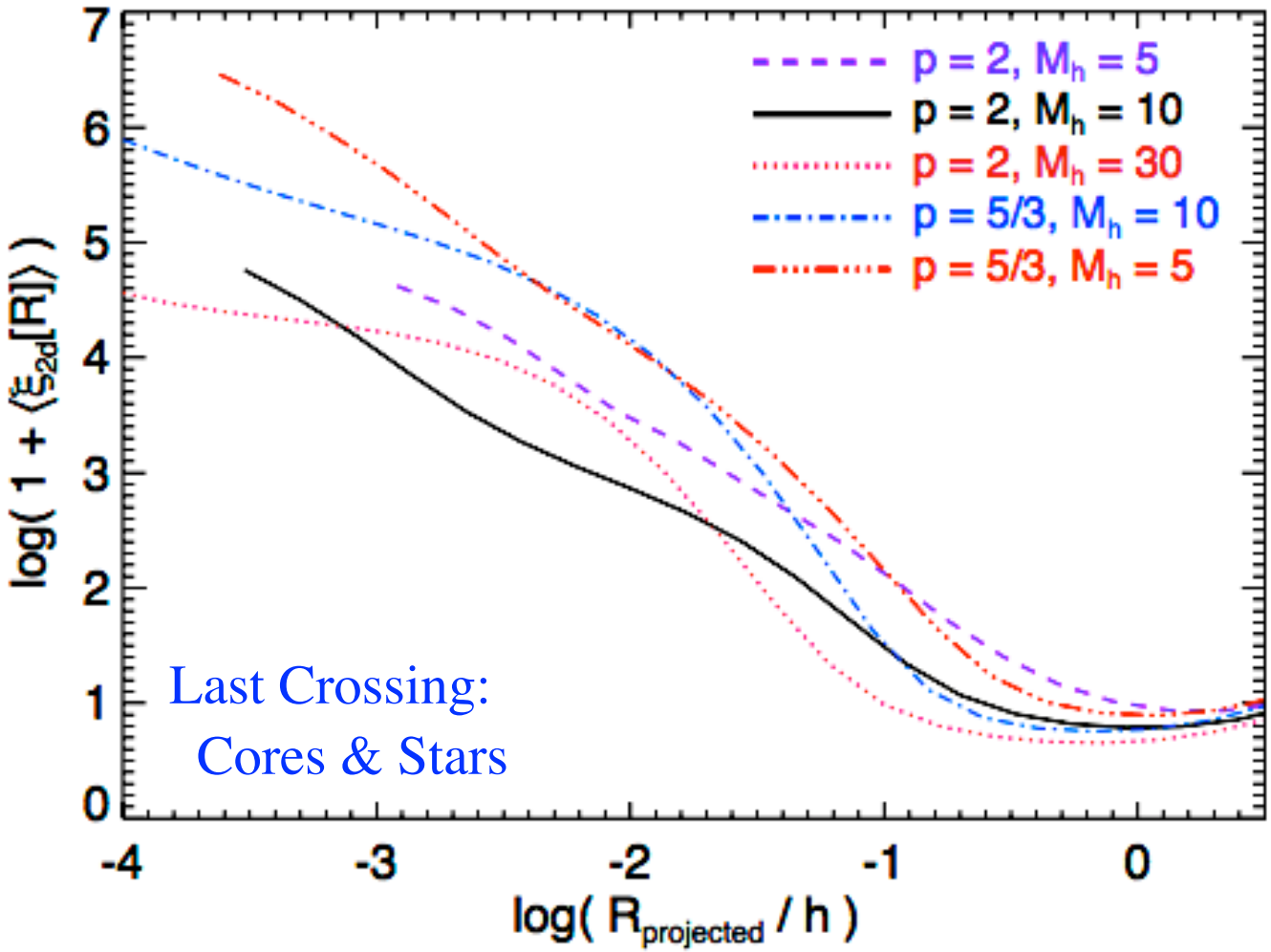
PFH 2012b



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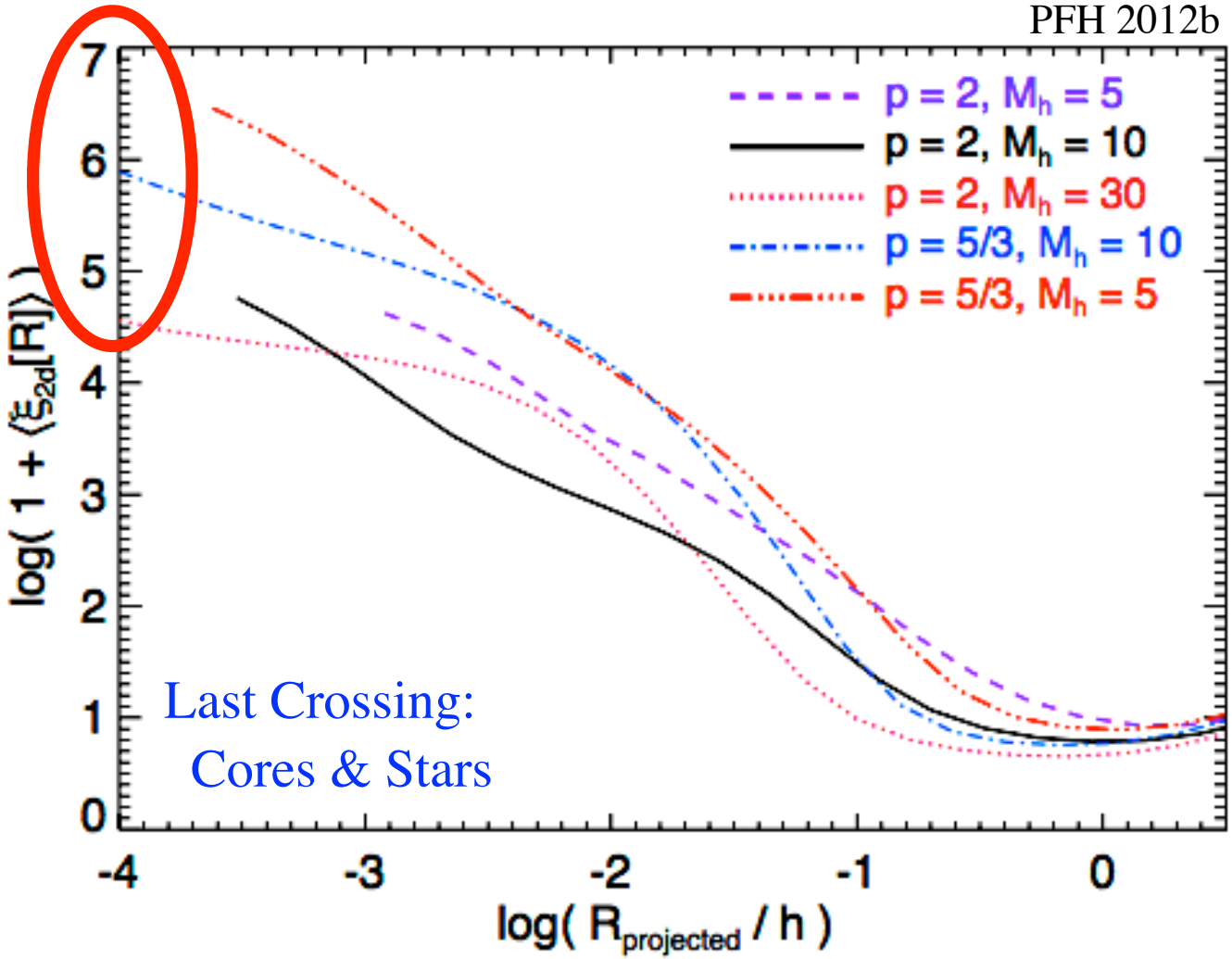

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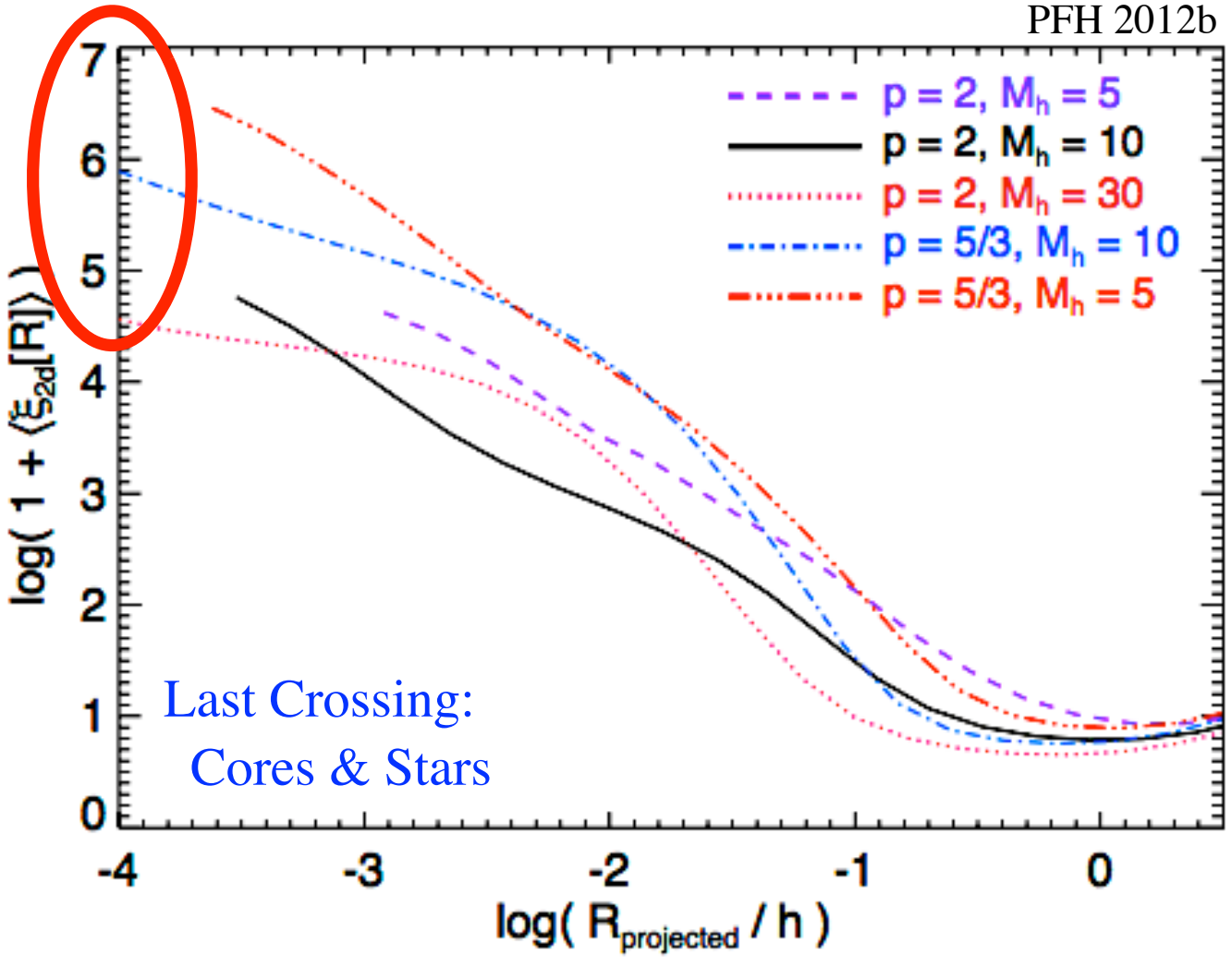


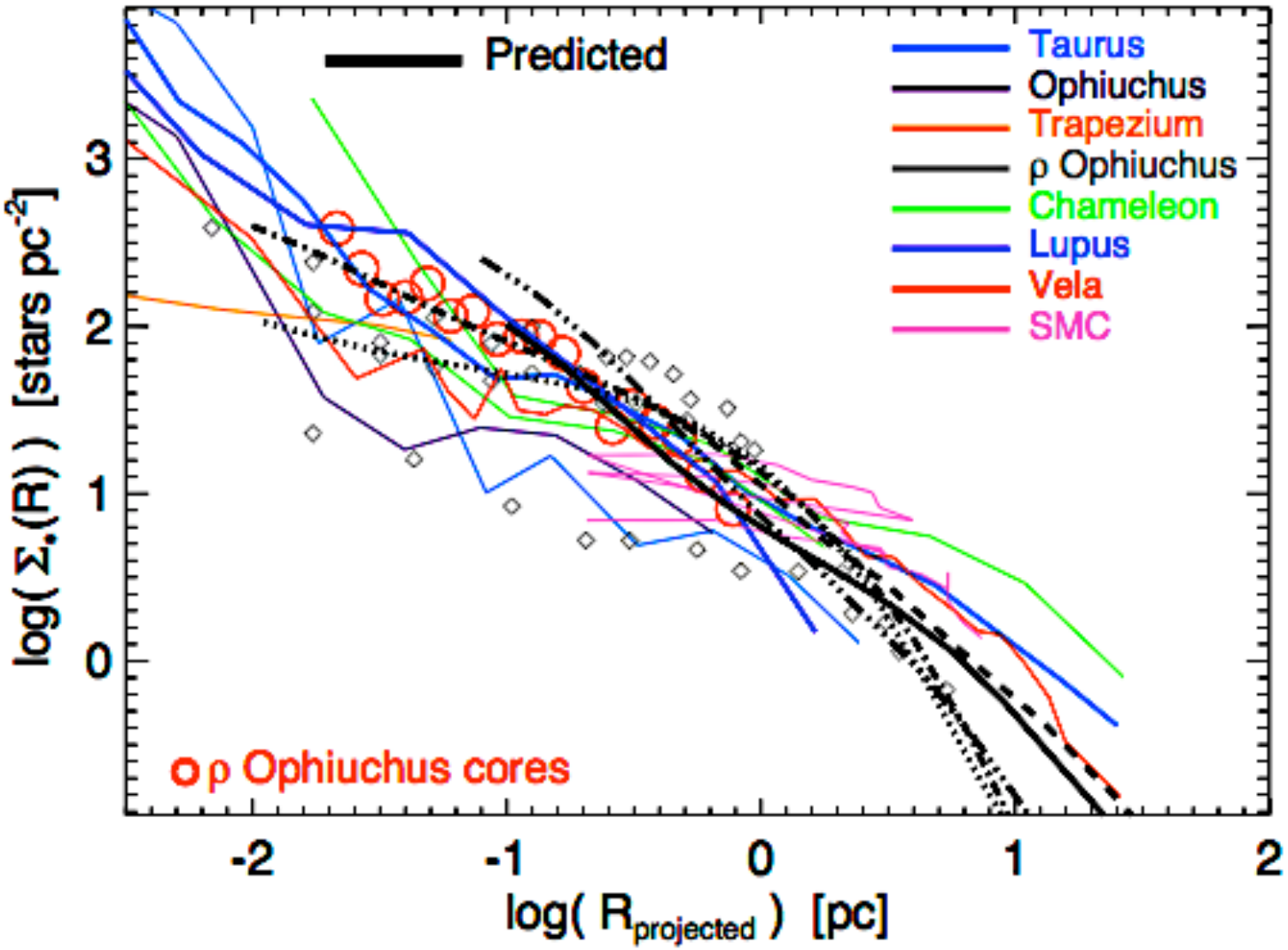
Why is Star Formation Clustered?

$$S \sim \ln \mathcal{M}(k)^2$$

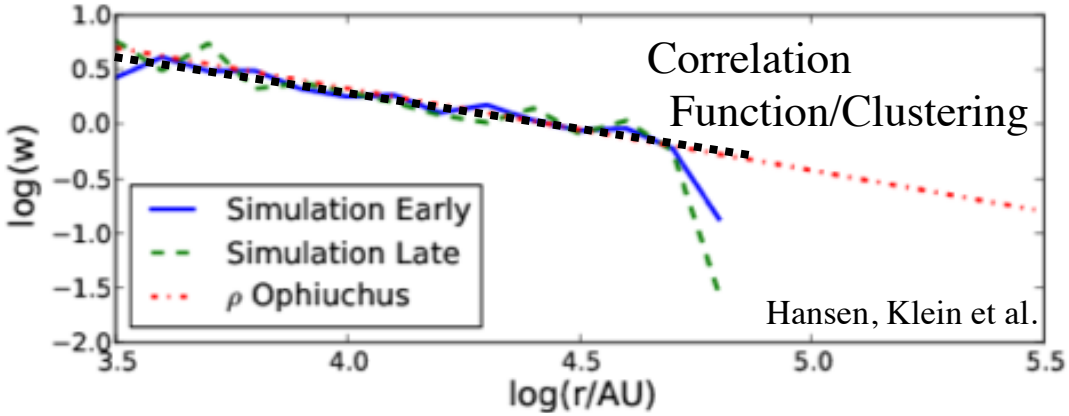
$$\sim \ln r^{3-p}$$

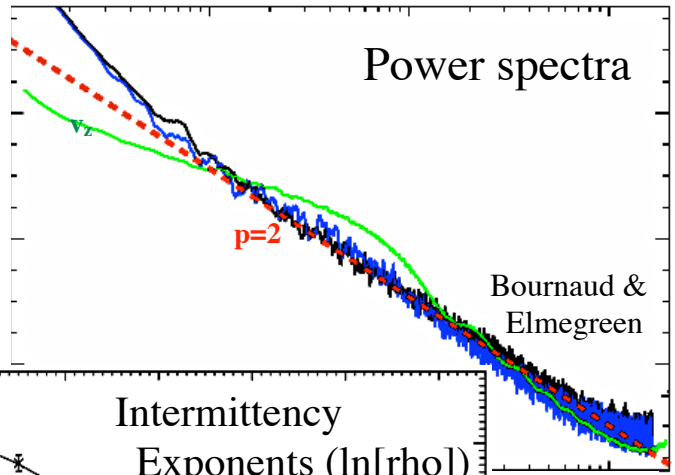
Clustering of Stars: Predicted vs. Observations

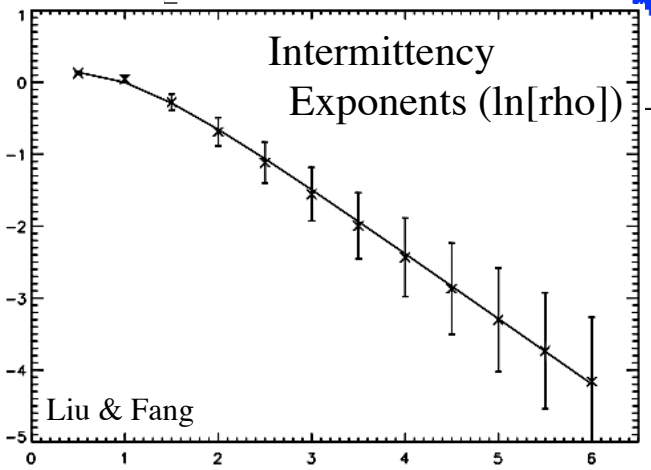
PREDICT N-POINT CORRELATION FUNCTIONS

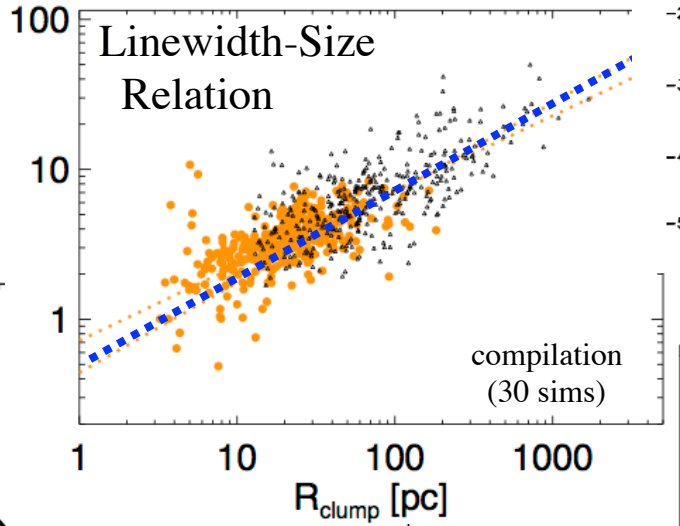


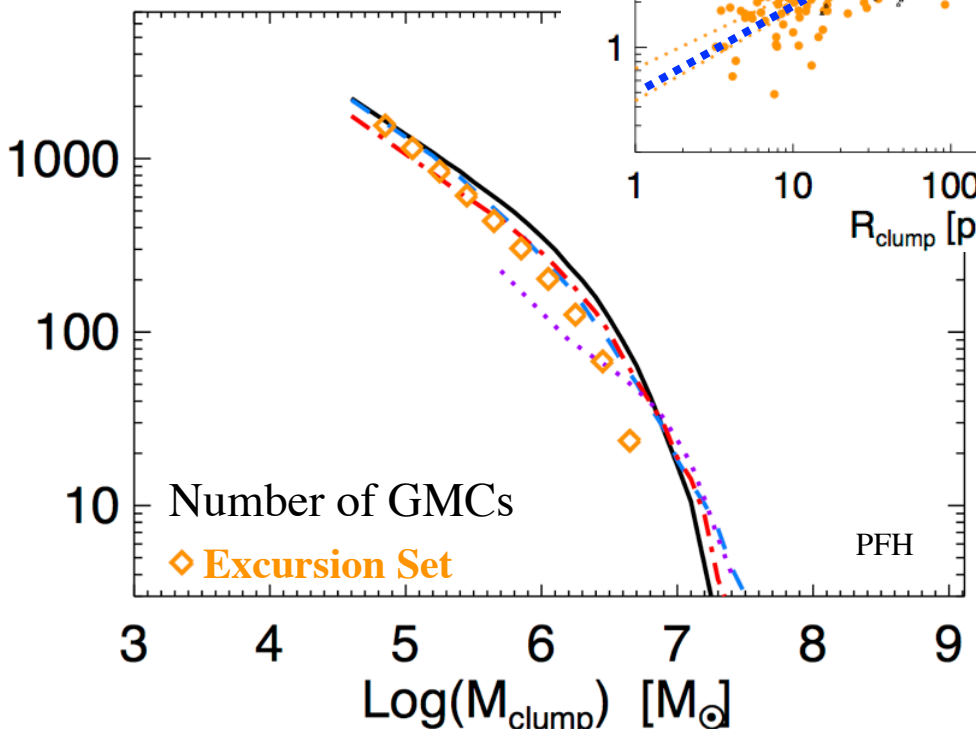
Testing the Analytics
vs. NUMERICAL SIMULATIONS

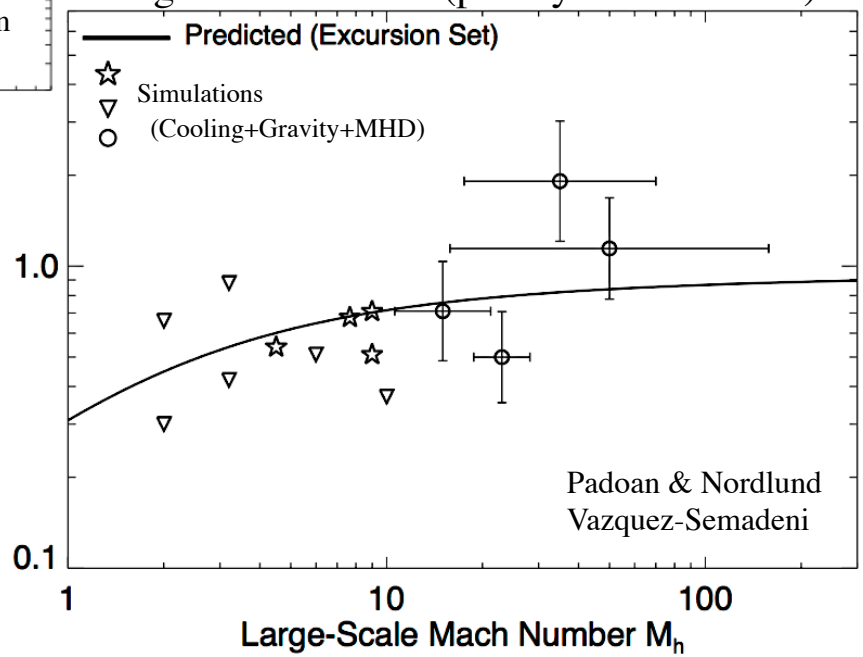






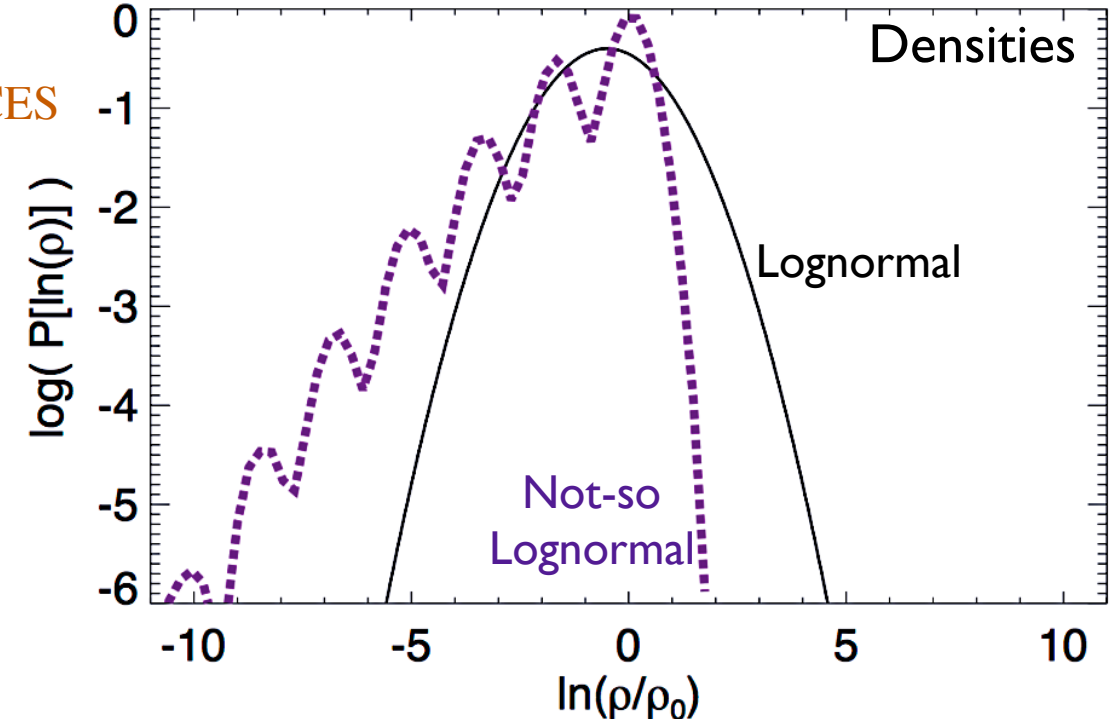


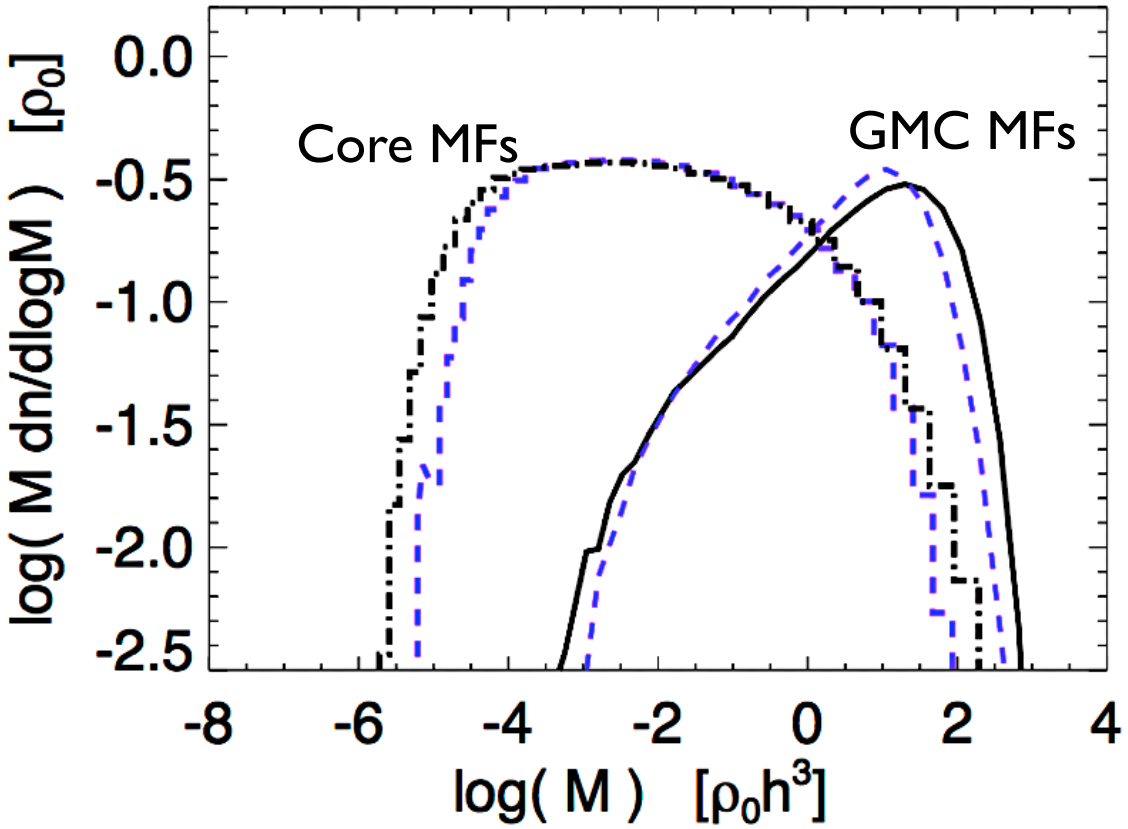




General, Flexible Theory:
EXTREMELY ADAPTABLE TO MOST CHOICES

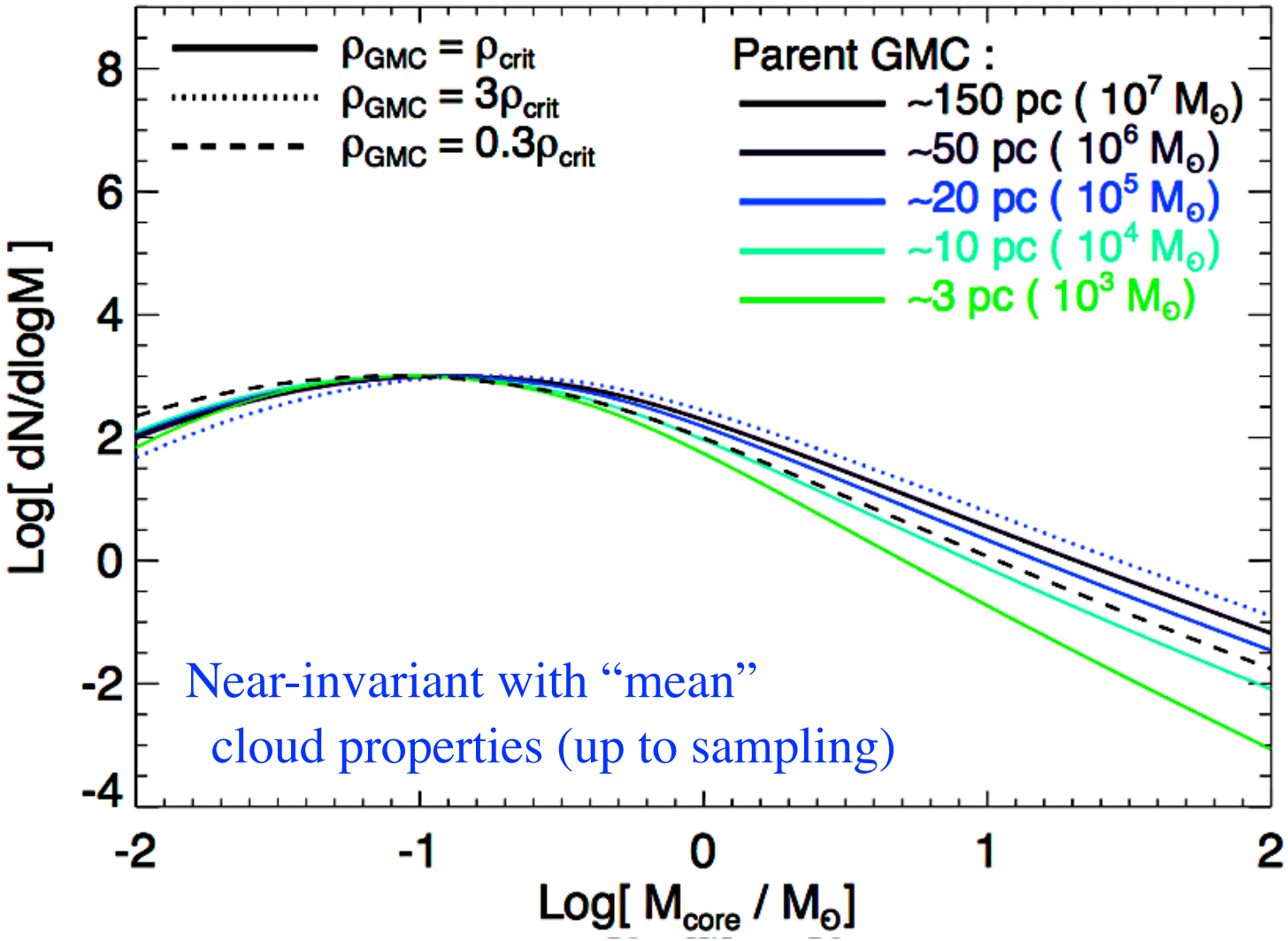
- Complicated, multivariable gas equations of state
- Accretion
- Magnetic Fields
- Time-Dependent Background Evolution/Collapse
- Intermittency
- Correlated, multi-scale driving





Variation in the Core Mass Function

VS "NORMAL" IMF VARIATIONS



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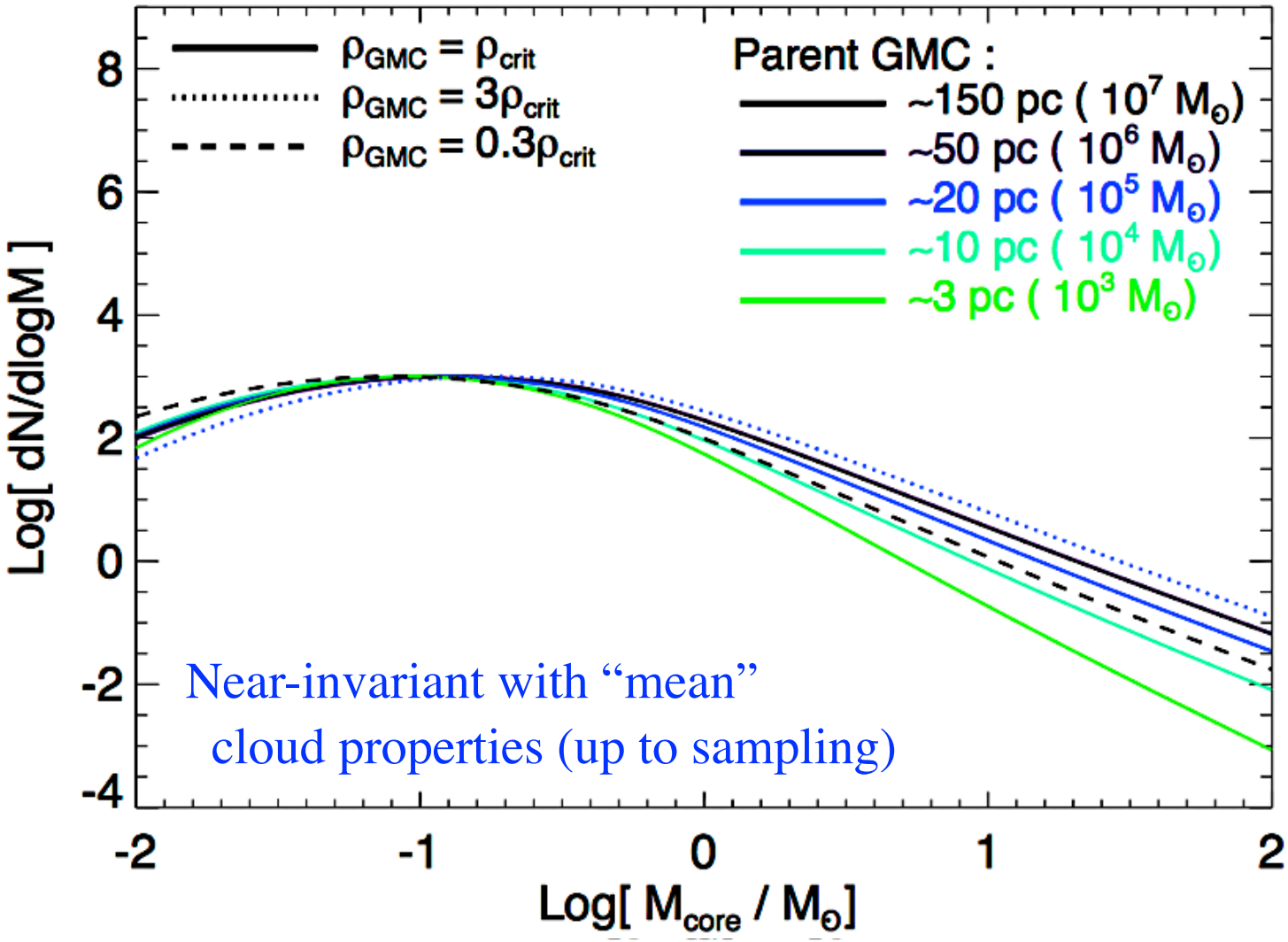

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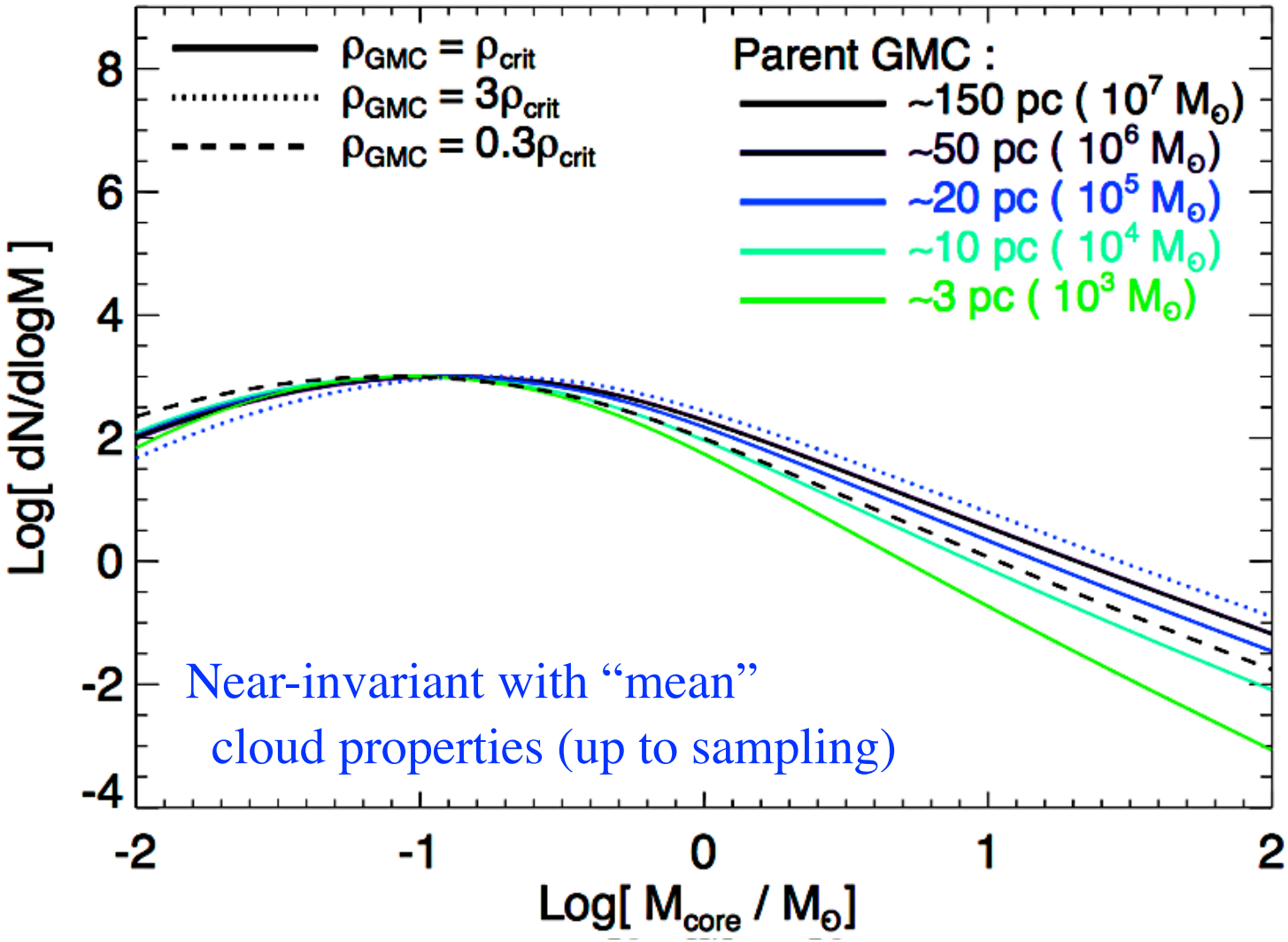

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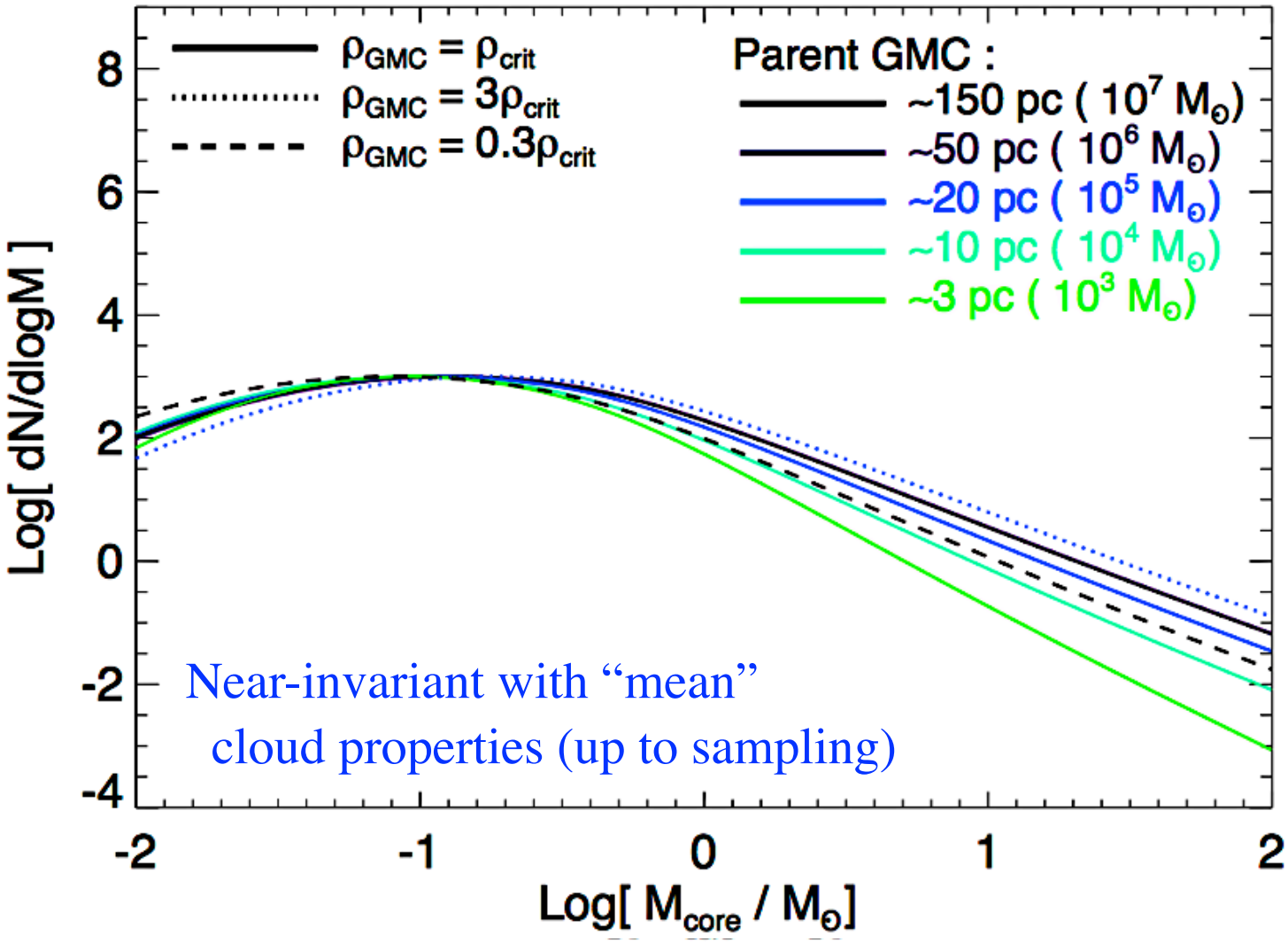

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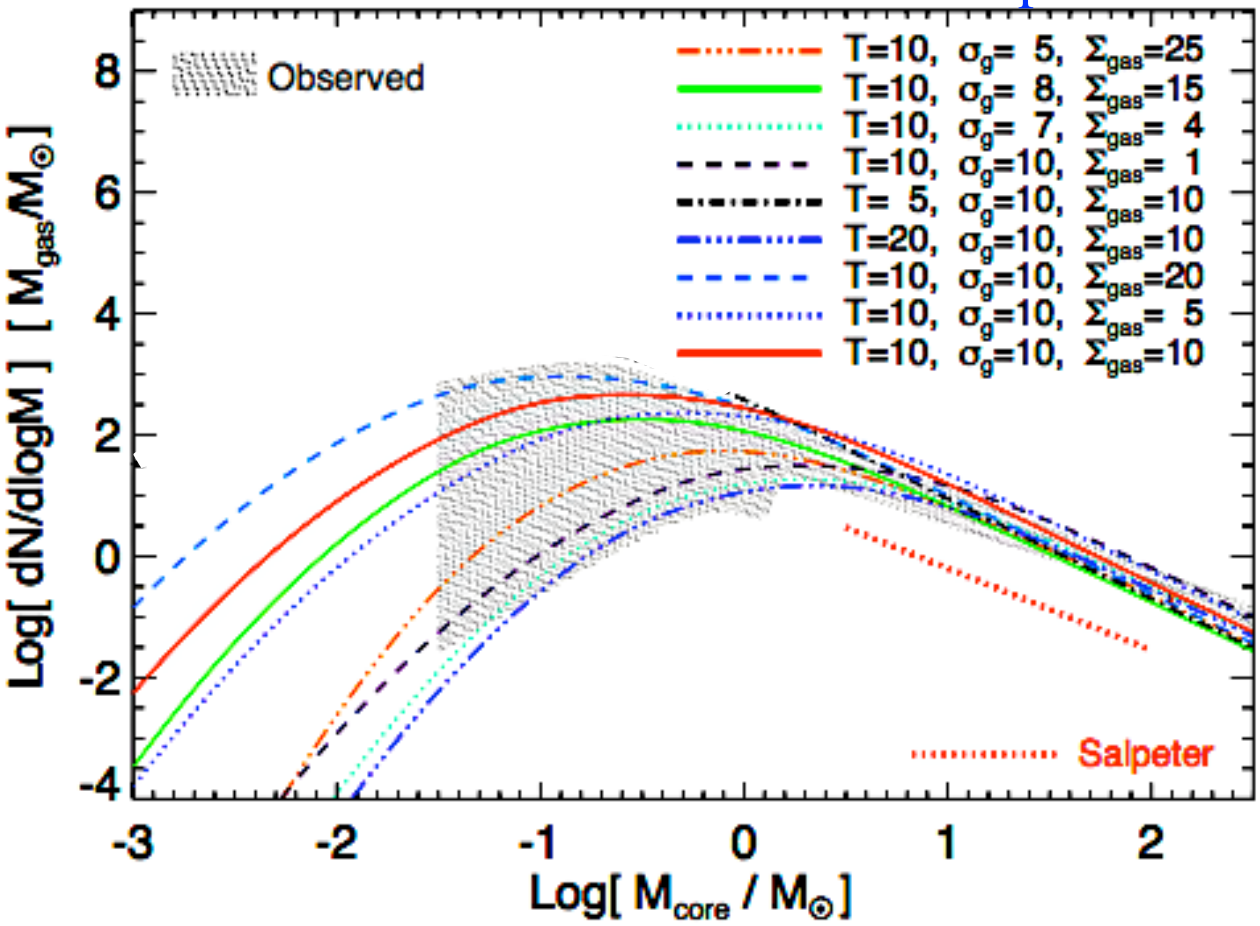
Weak variation with Galactic Properties



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BUT, What About Starbursts?

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

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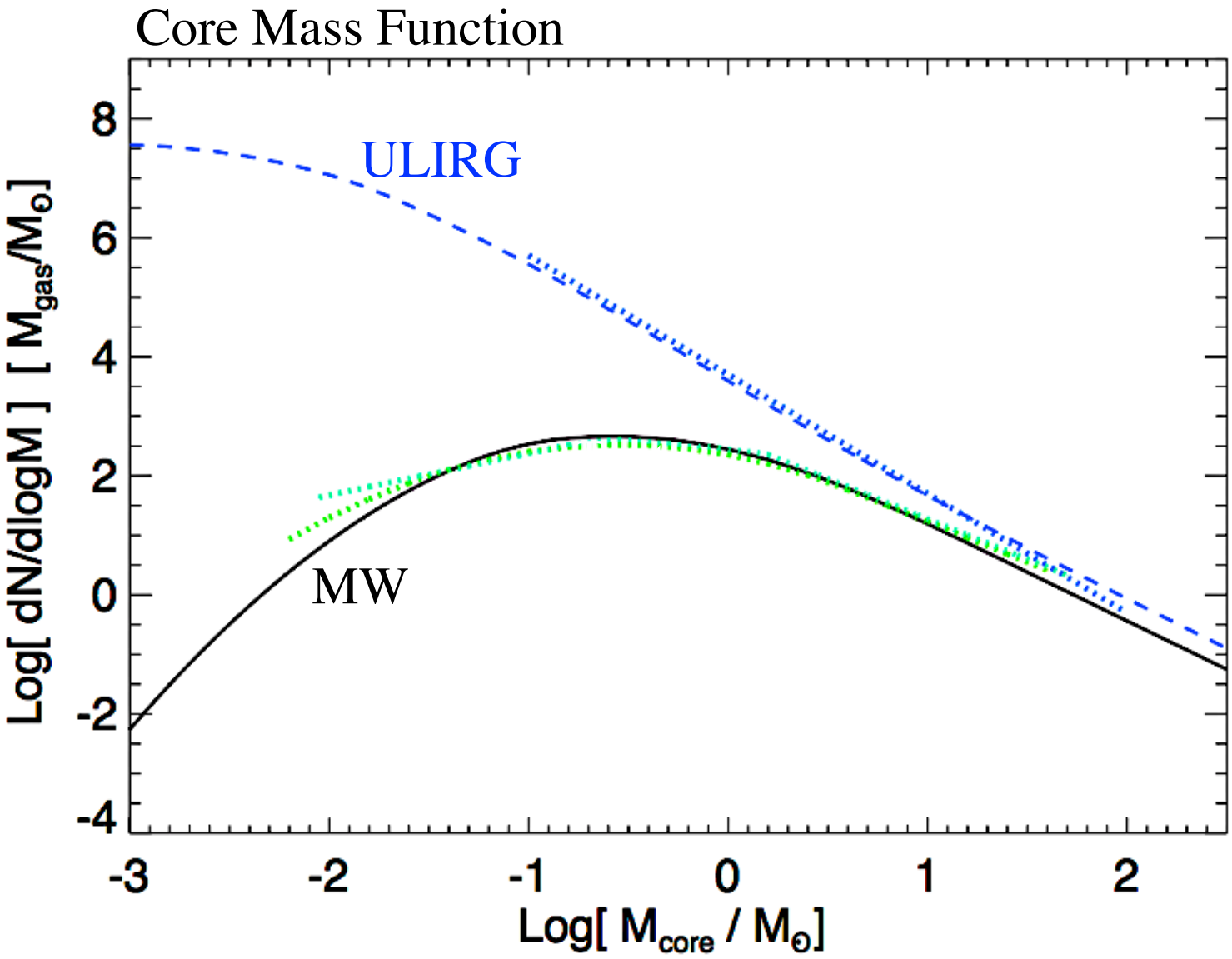

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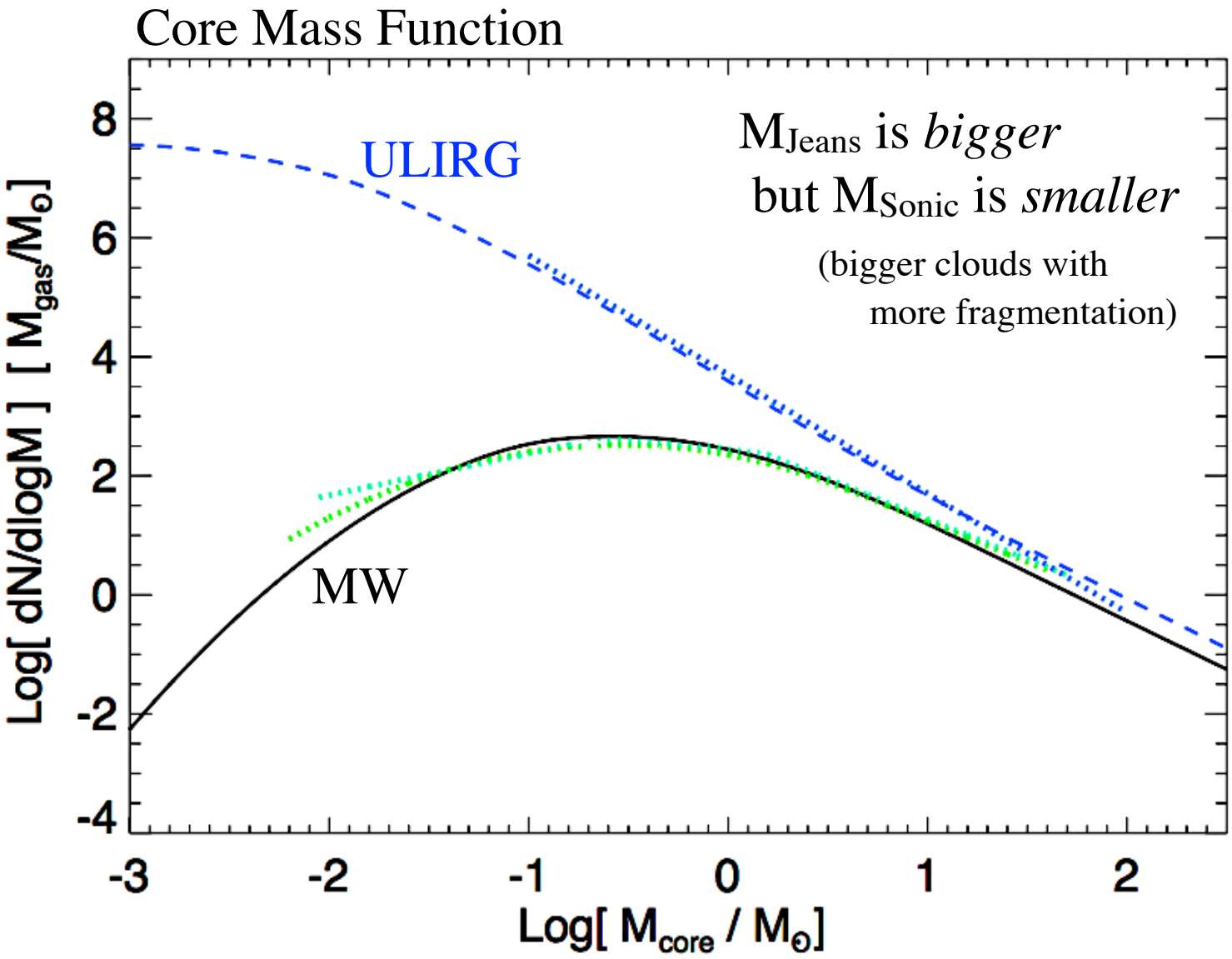
BOTTOM-HEAVY: TURBULENCE WINS!



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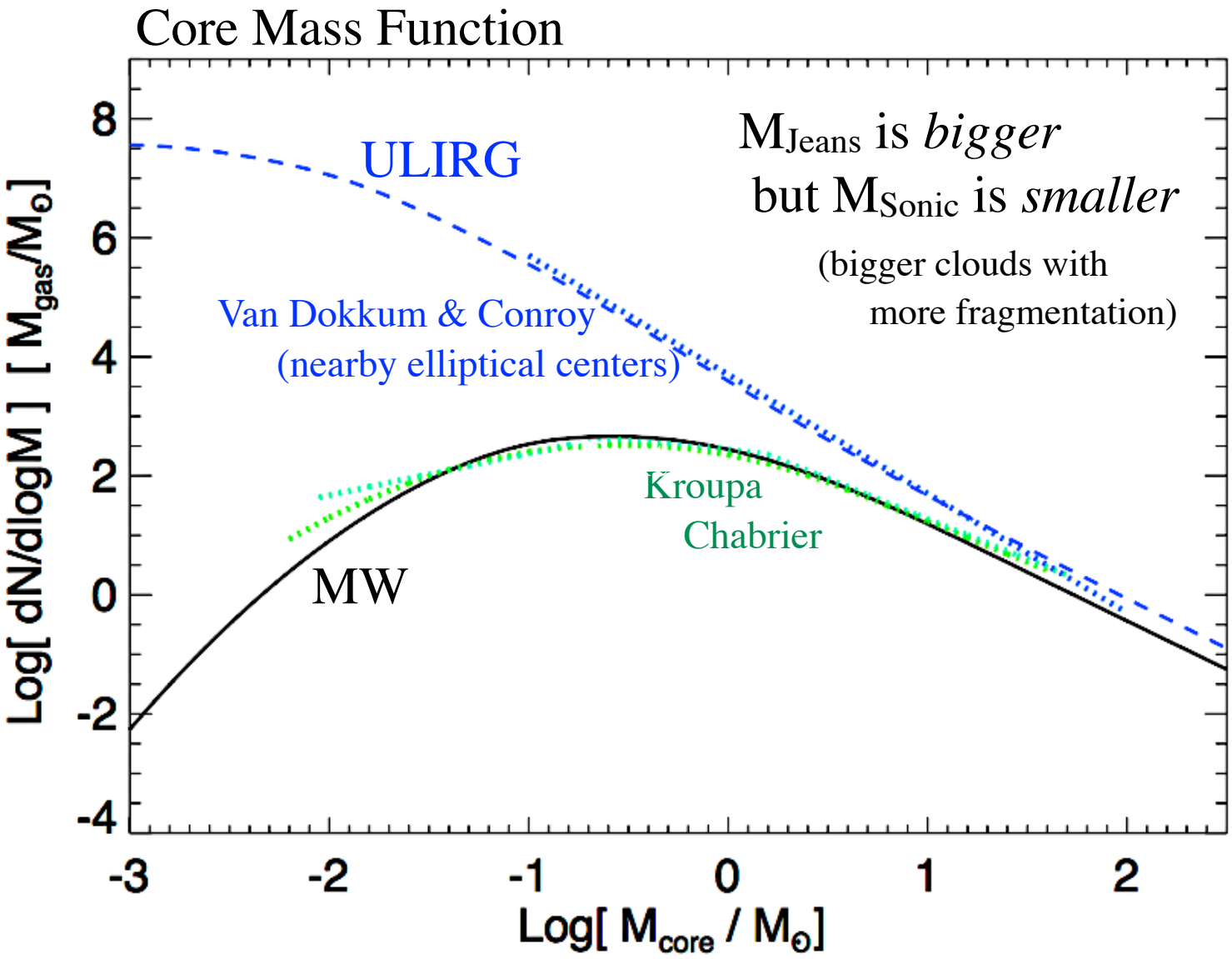

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2. Why Doesn't Everything Collapse?

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

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

Summary:

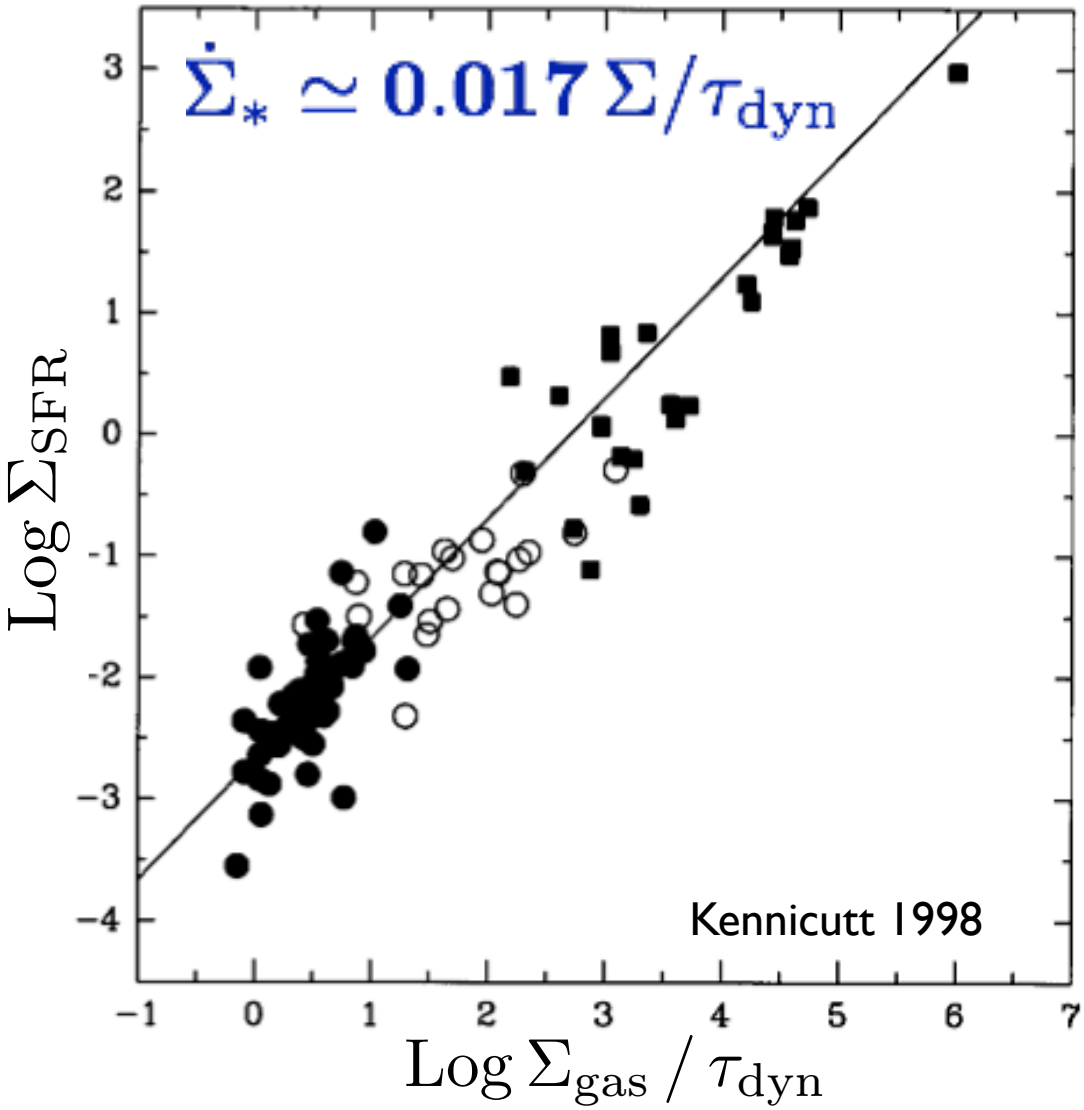
*** ISM *statistics* are far more fundamental than we typically assume ***

- **Turbulence + Gravity:** ISM structure follows
  - Lognormal density PDF is ***not*** critical
  - *ANALYTICALLY* understand:
    - **GMC Mass Function & Structure** ("first crossing")
    - **Core MF** ("last crossing") & **Linewidth-Size-Mass**
    - **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?

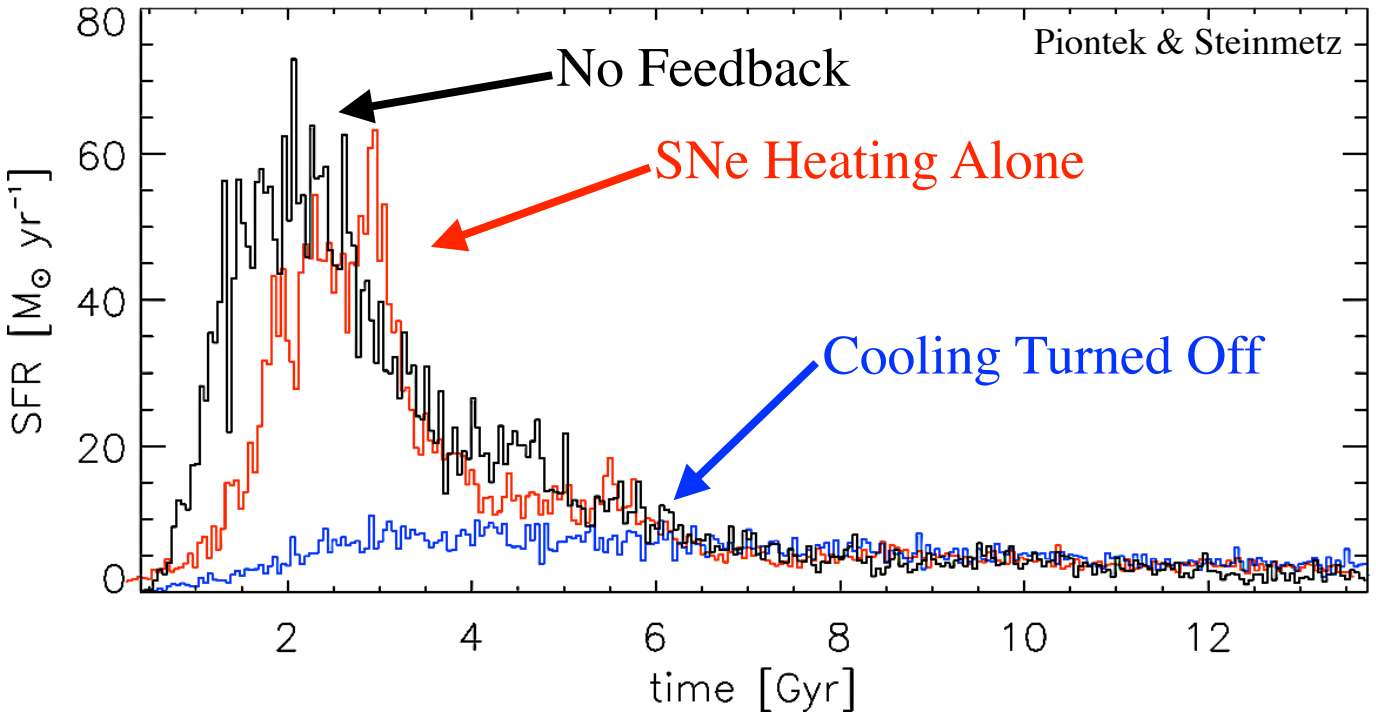
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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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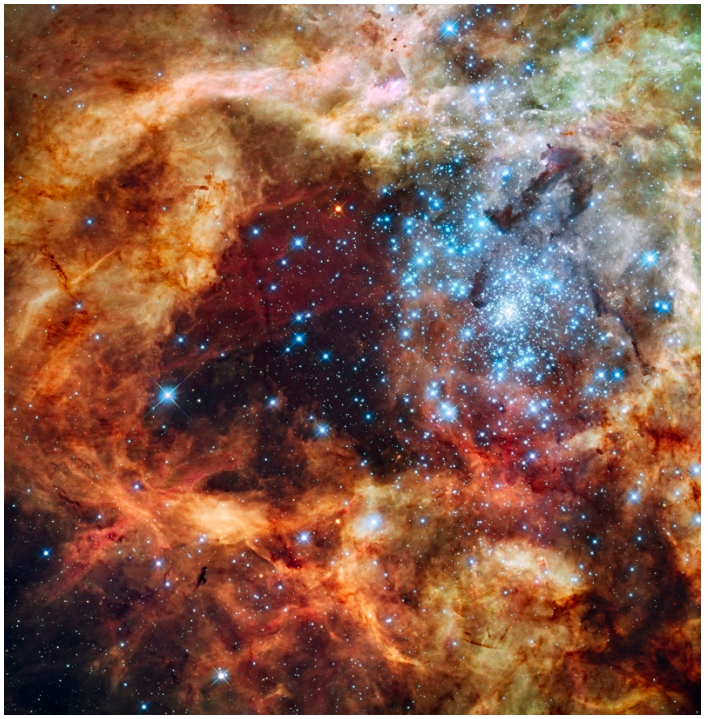

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  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

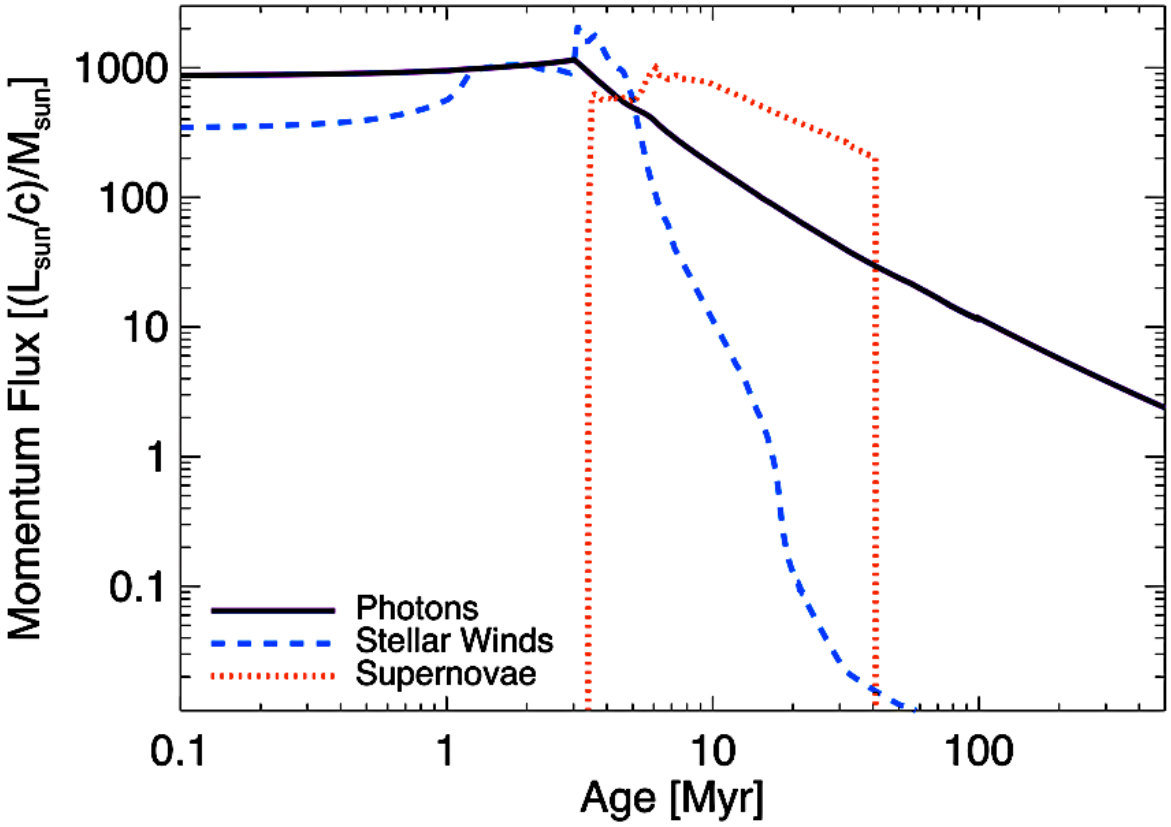
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

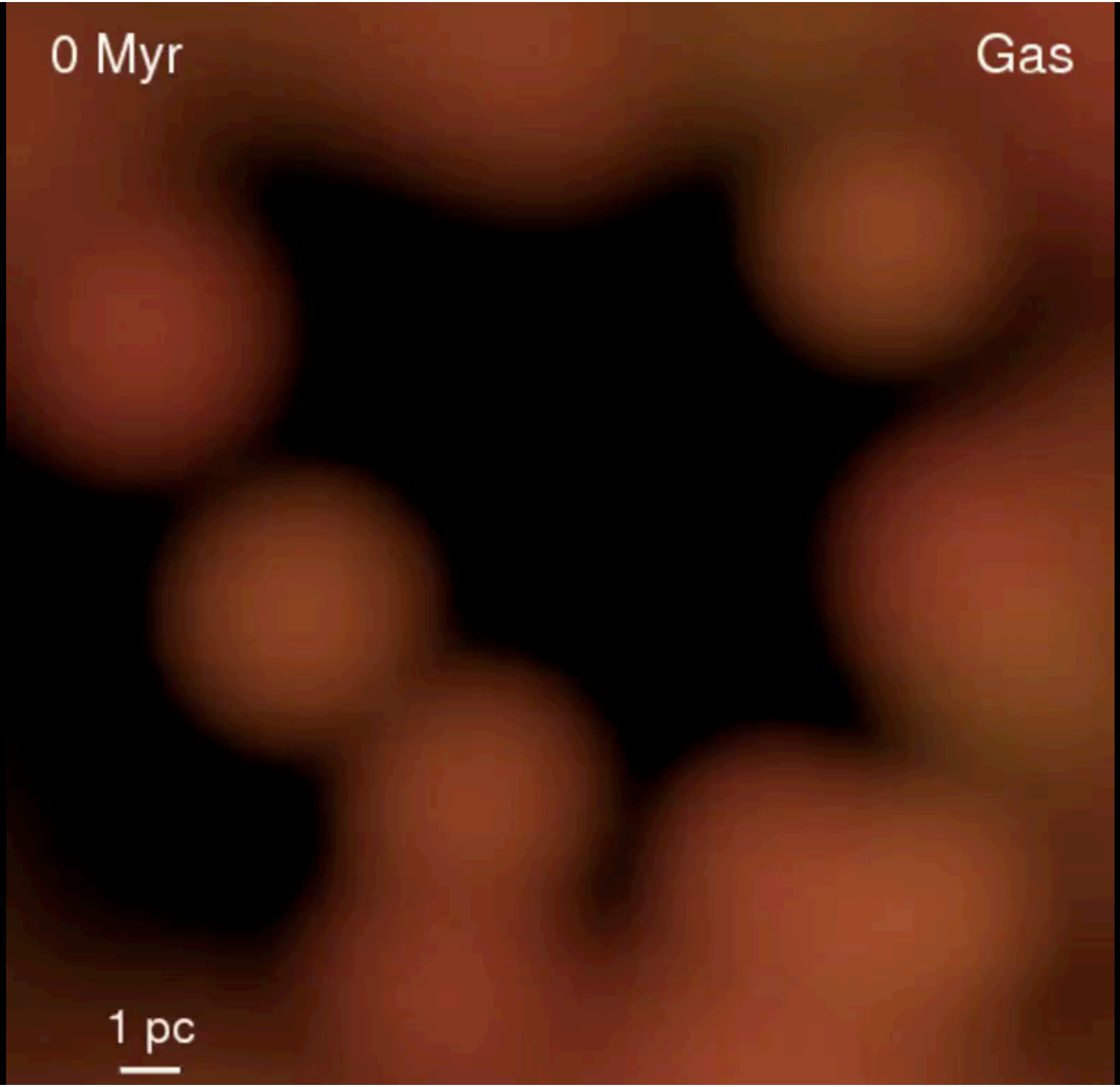
  - SNe

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

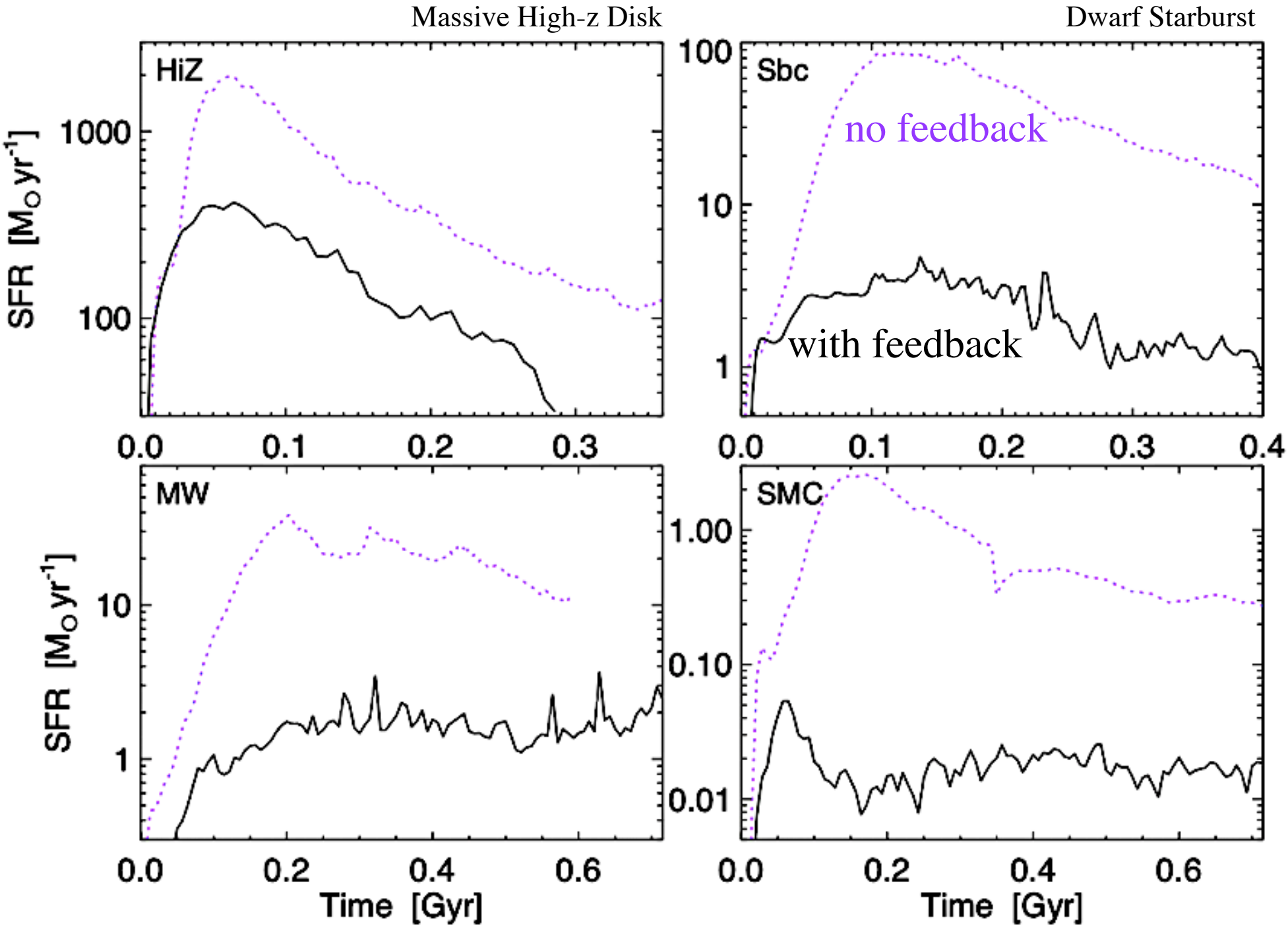
  - Stellar Winds

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




0 Myr
Gas
1 pc

Stellar Feedback gives Self-Regulated Star Formation



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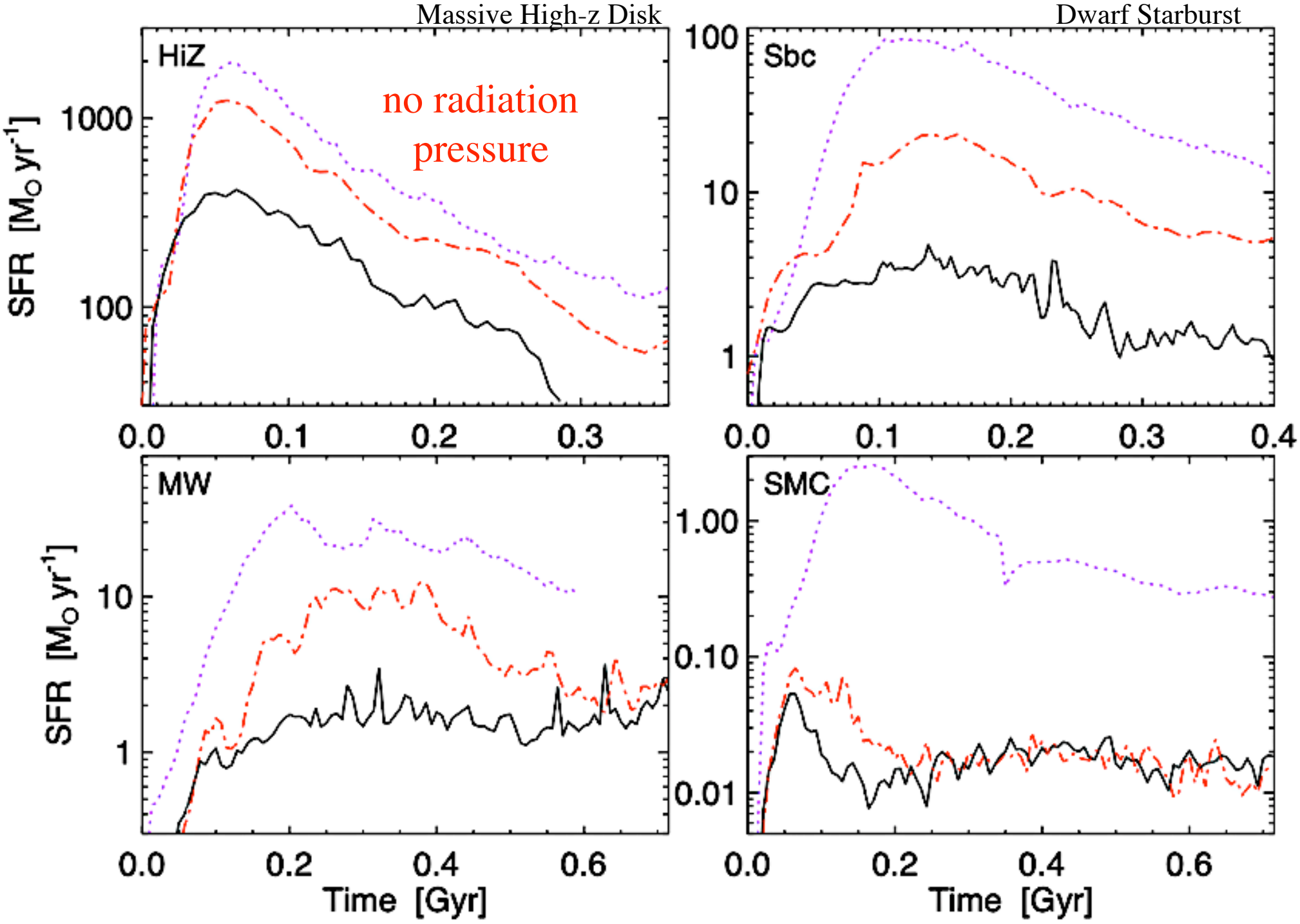

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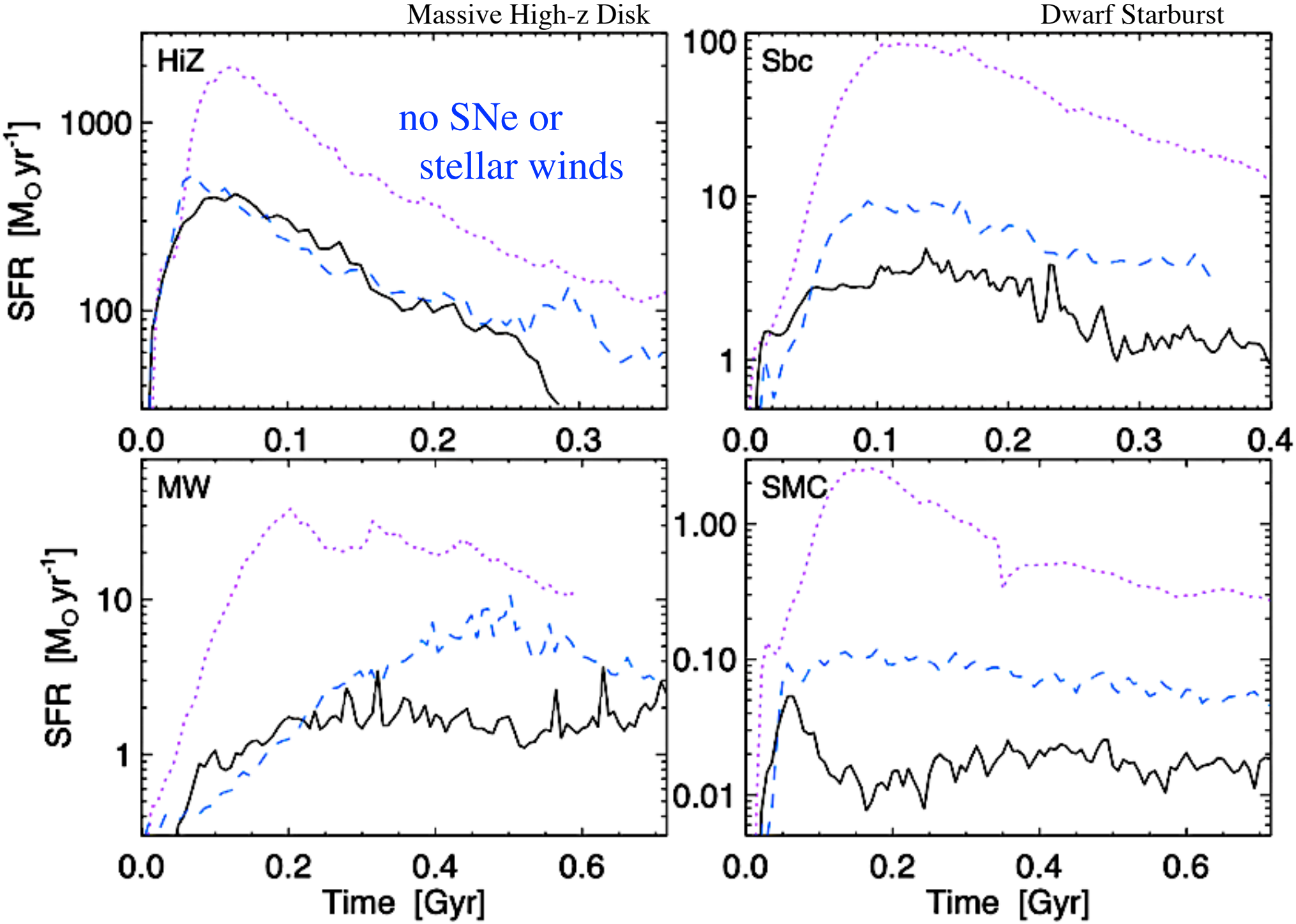
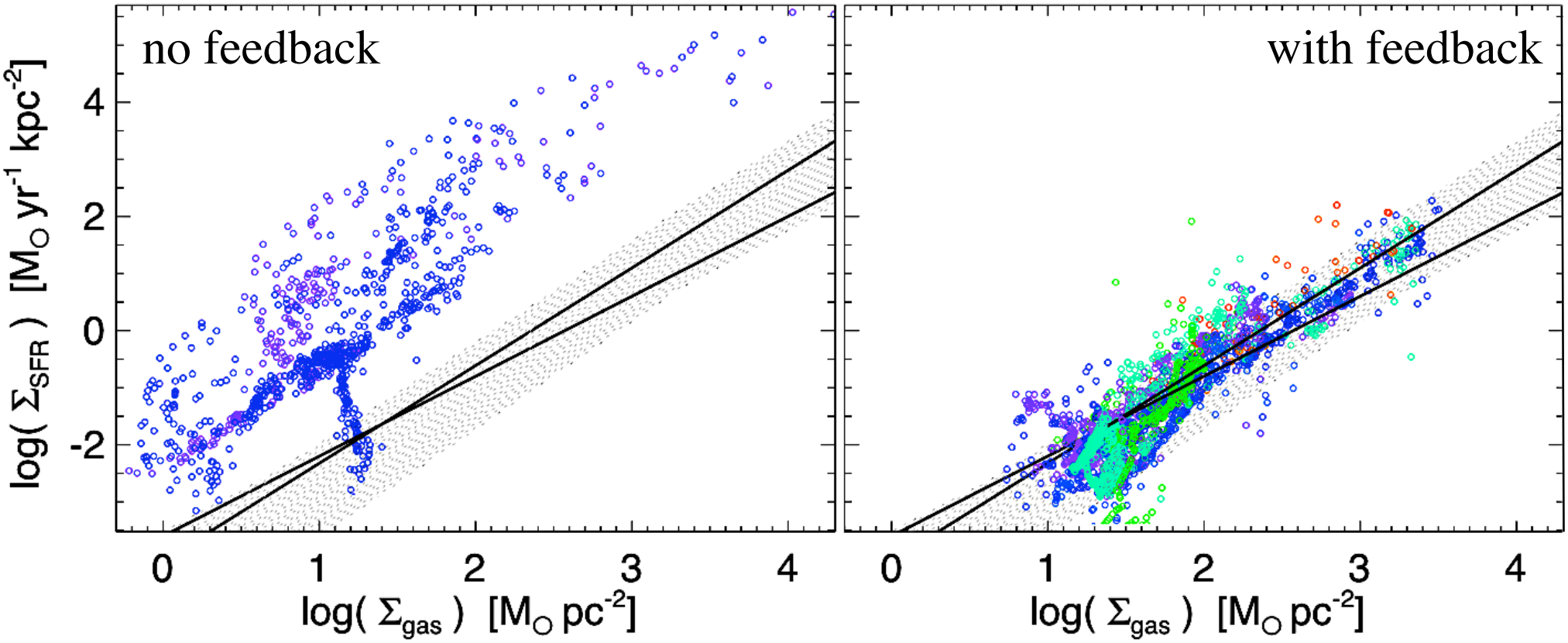


Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

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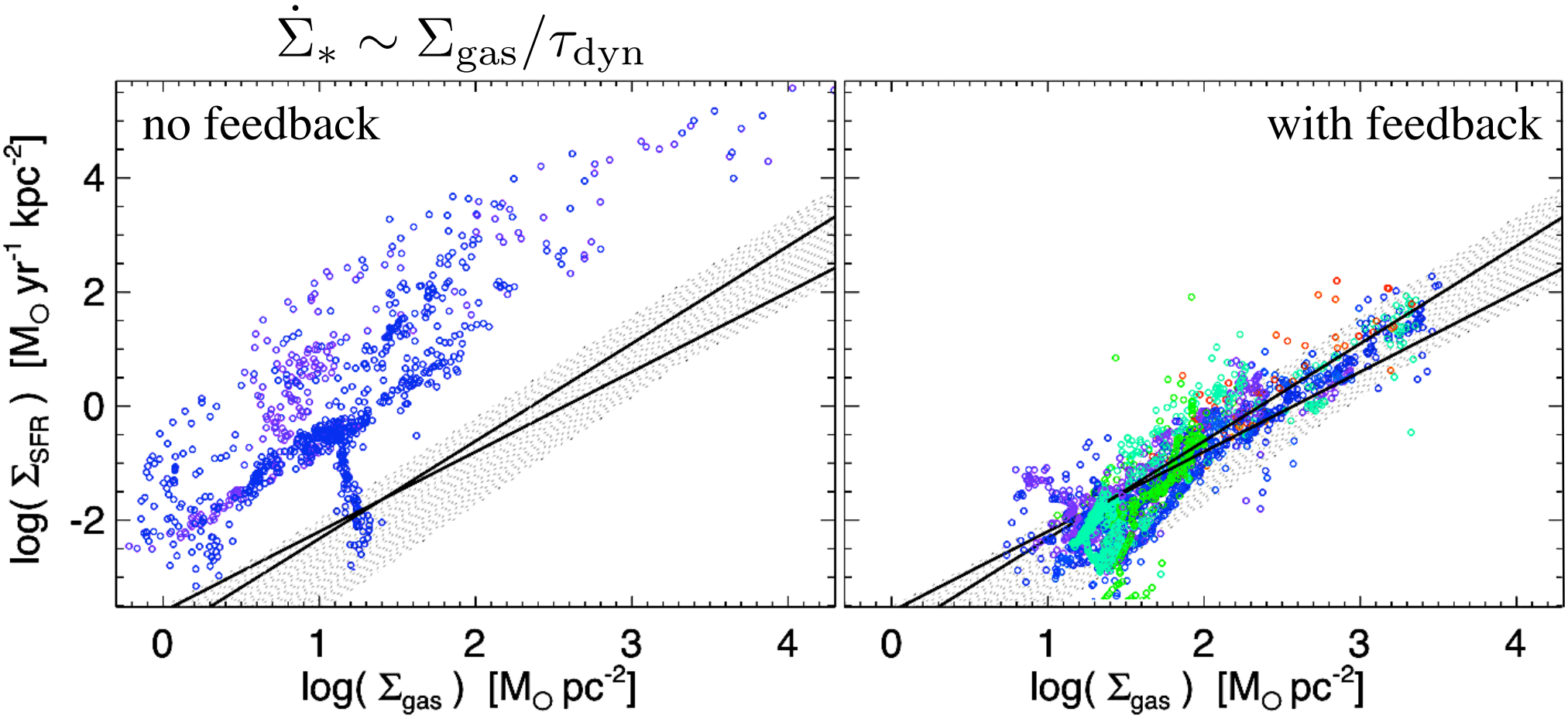

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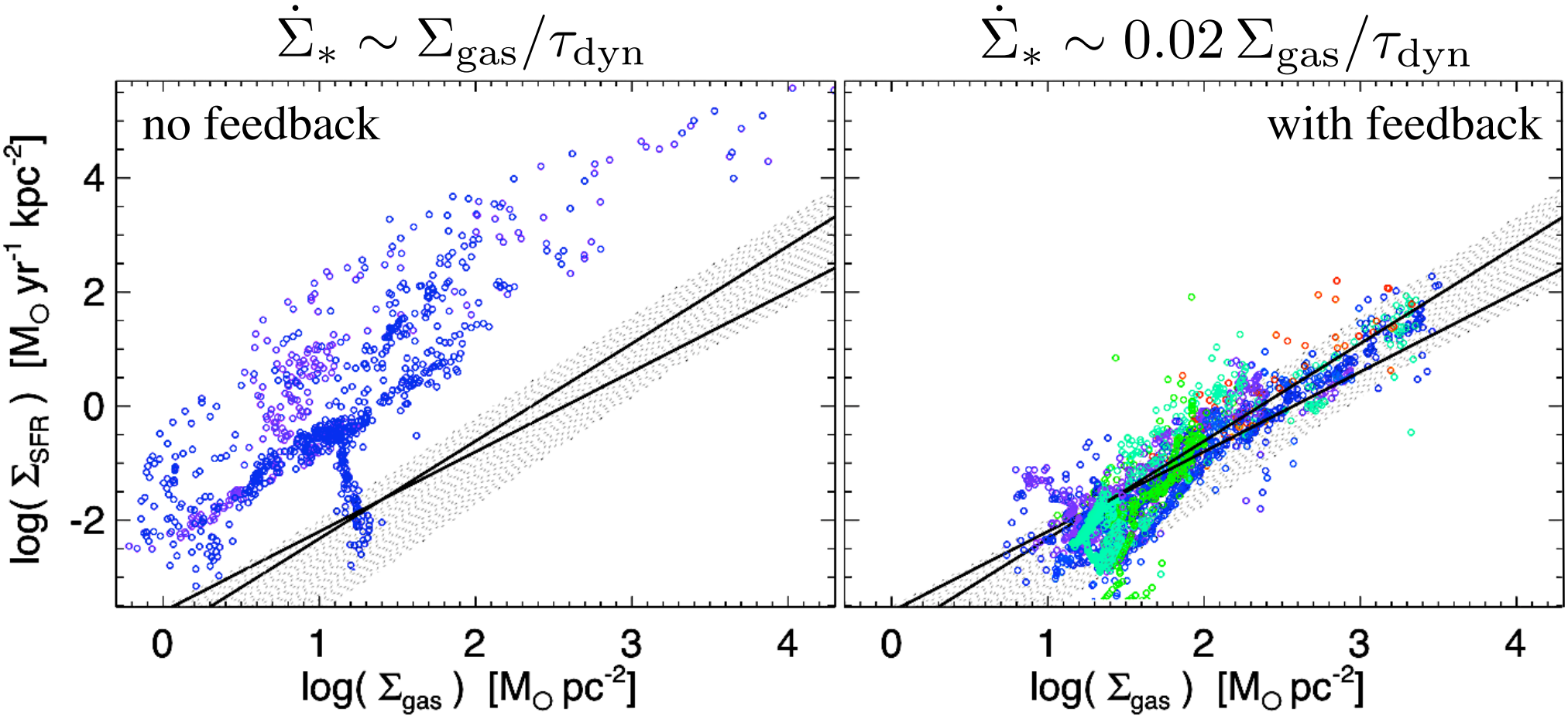

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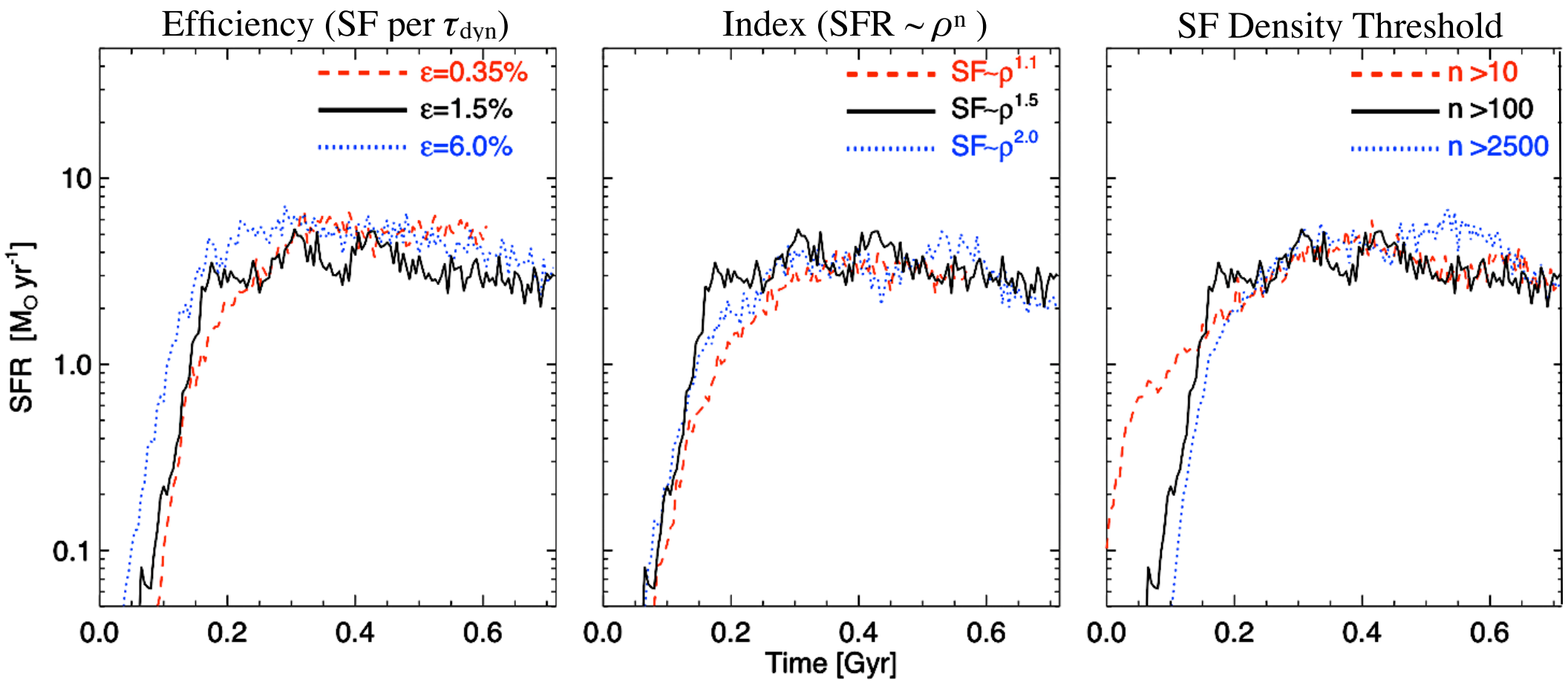
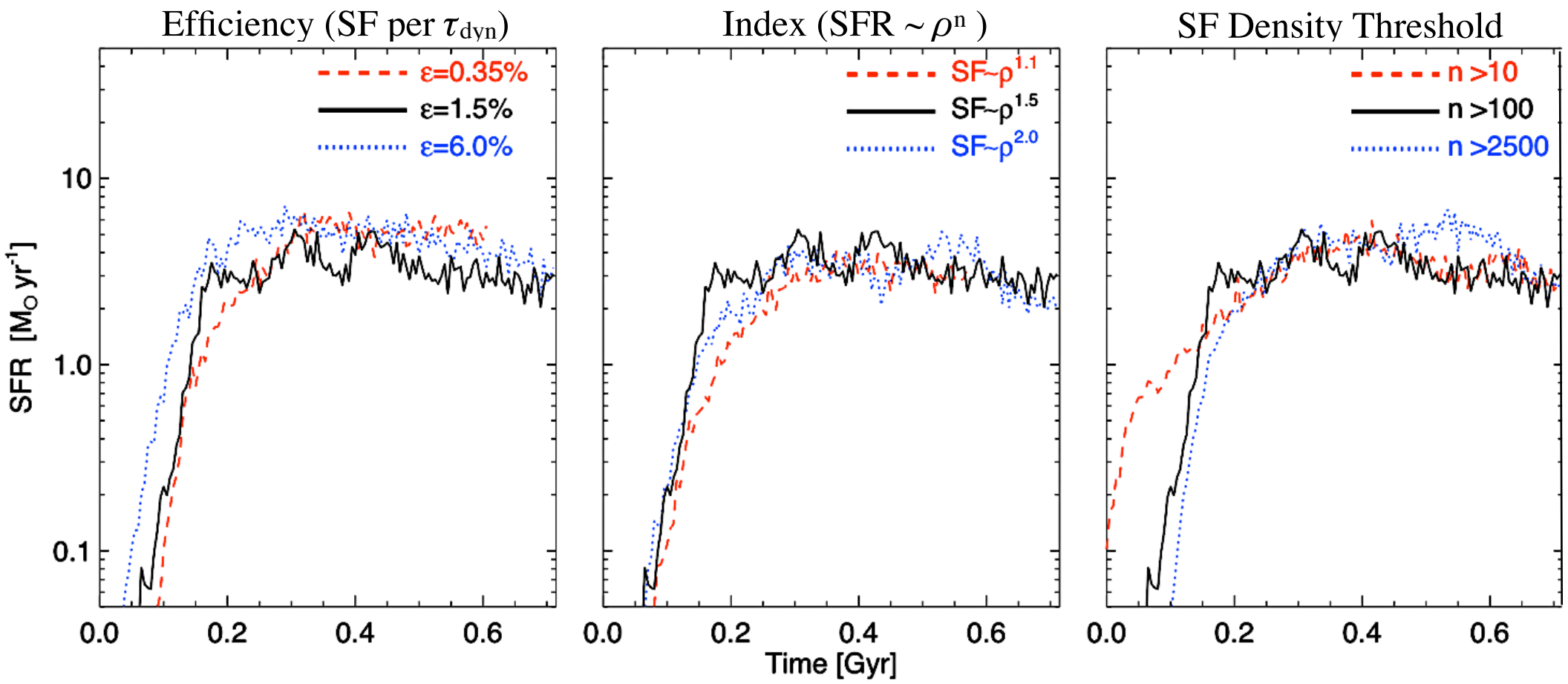
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas} \Omega \sim 0.02\, \Sigma_{\rm gas} \Omega$$

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



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

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



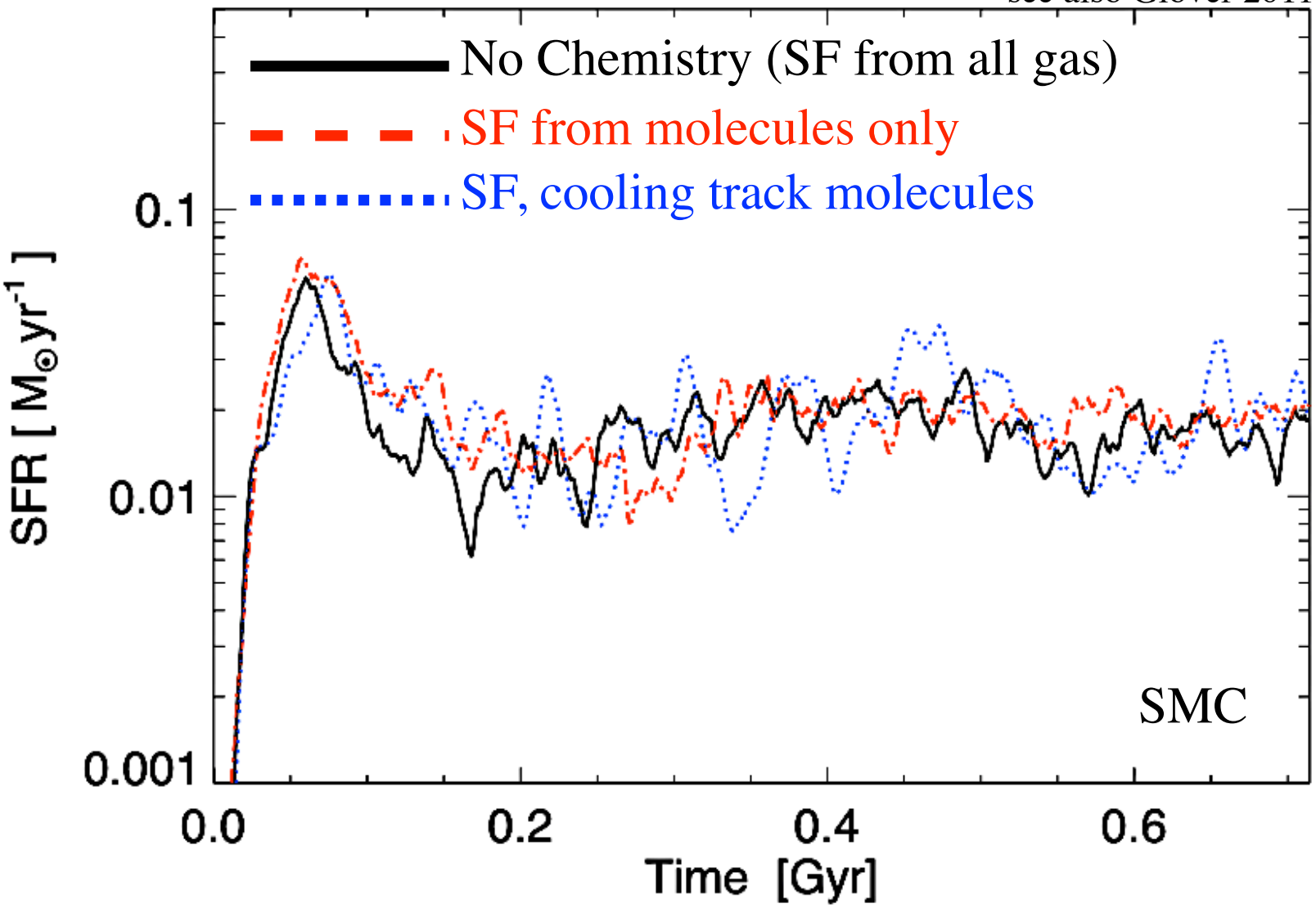
- Set by feedback (i.e. SFR) needed to maintain marginal stability

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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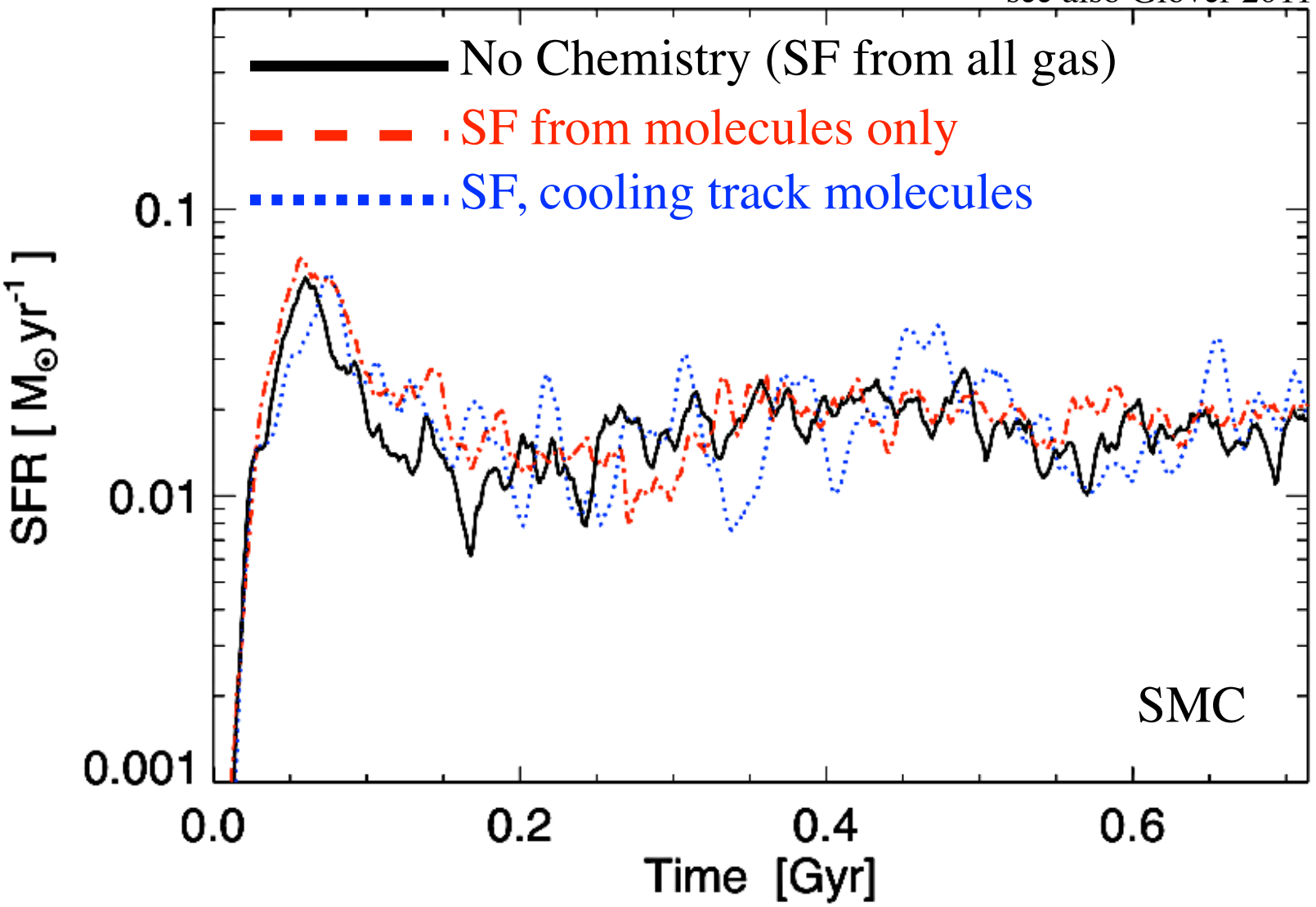

- Just need *some* cooling channel: changes at $M_{gal} < 10^6 M_{sun}$, $Z<0.01 Z_{sun}$

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")
    - **Core MF** ("last crossing") & **Linewidth-Size-Mass**
    - **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)