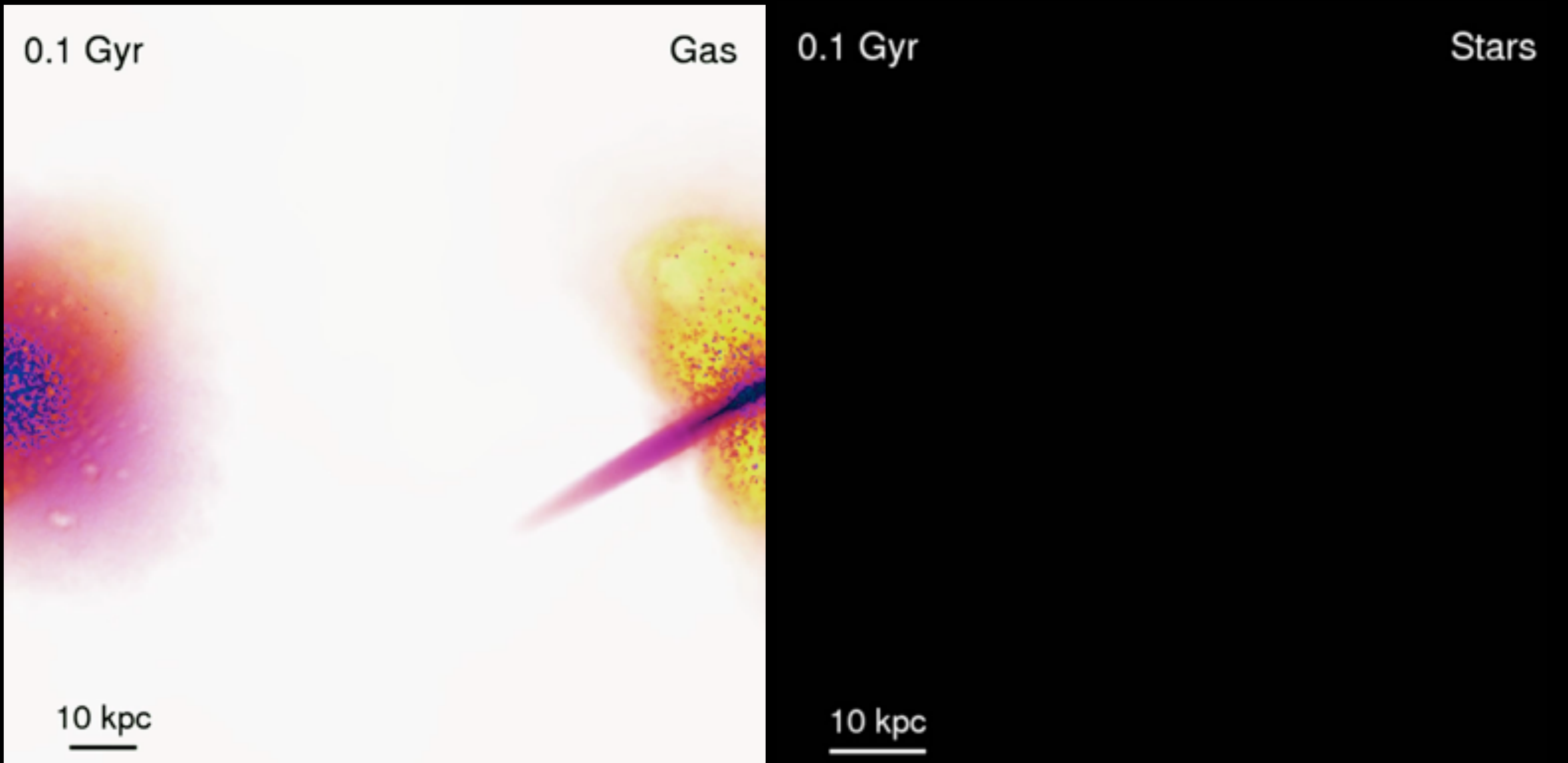
Theory of the IMF at the Galaxy-Scale

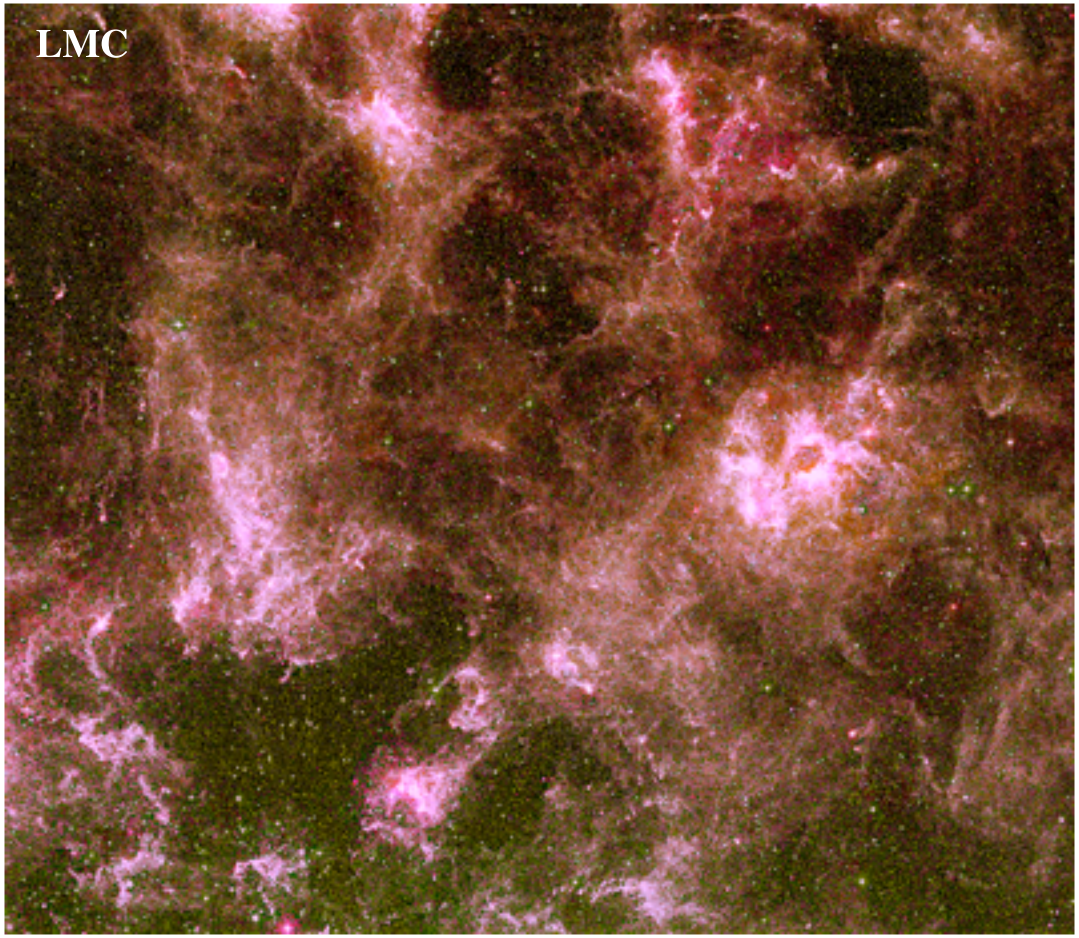


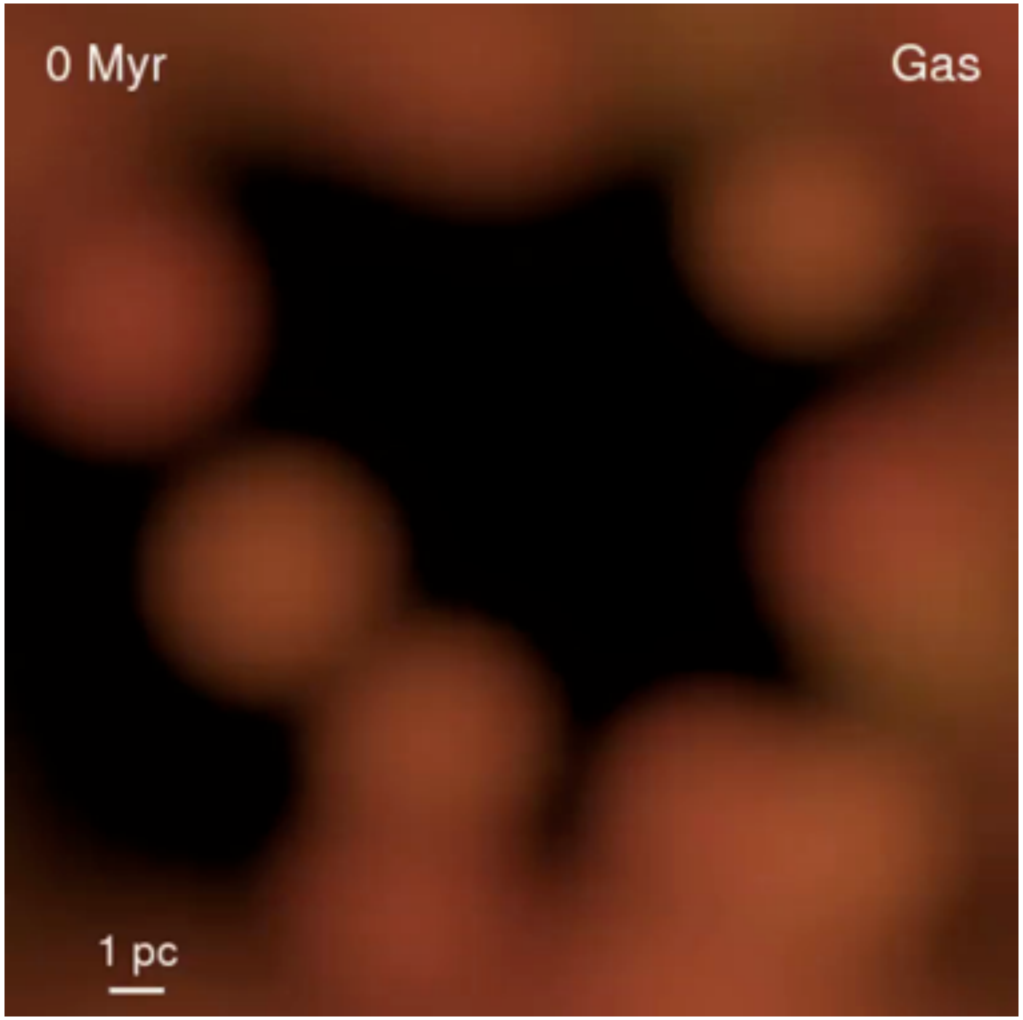
Philip Hopkins

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



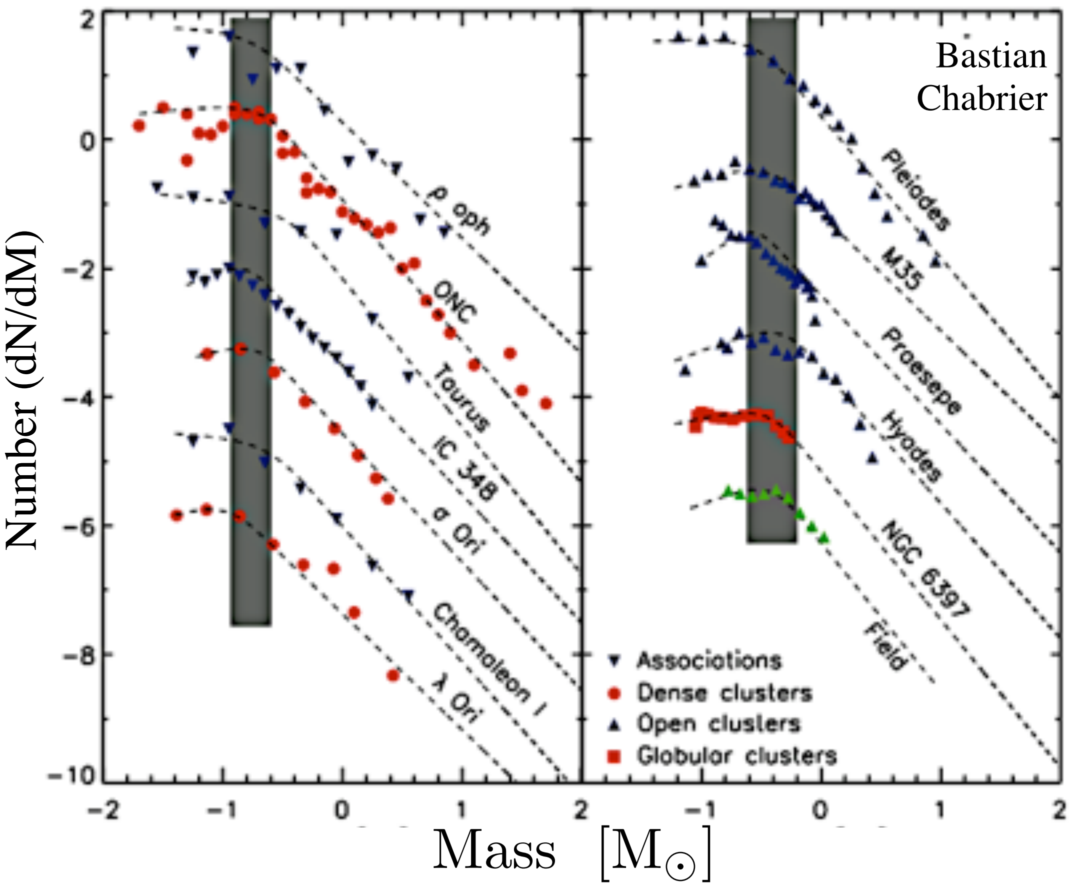


- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs,
  external galaxies, etc.

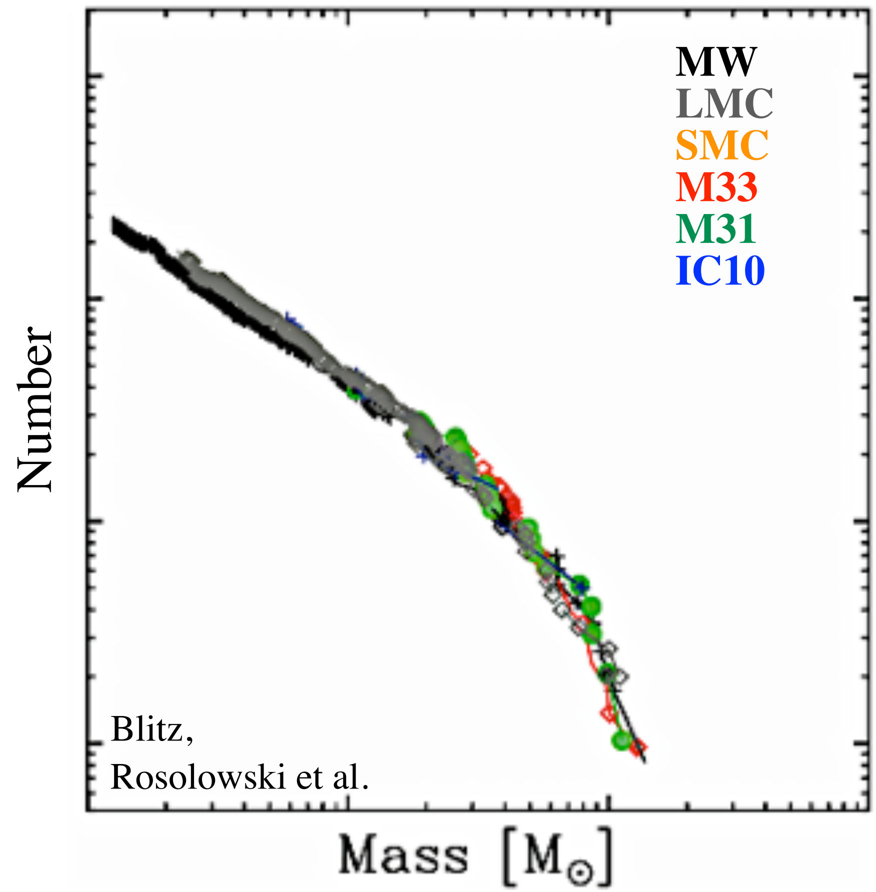
The ISM

YET THERE IS SURPRISING REGULARITY

Stars & Pre-Stellar Gas Cores:



Giant Molecular Clouds:



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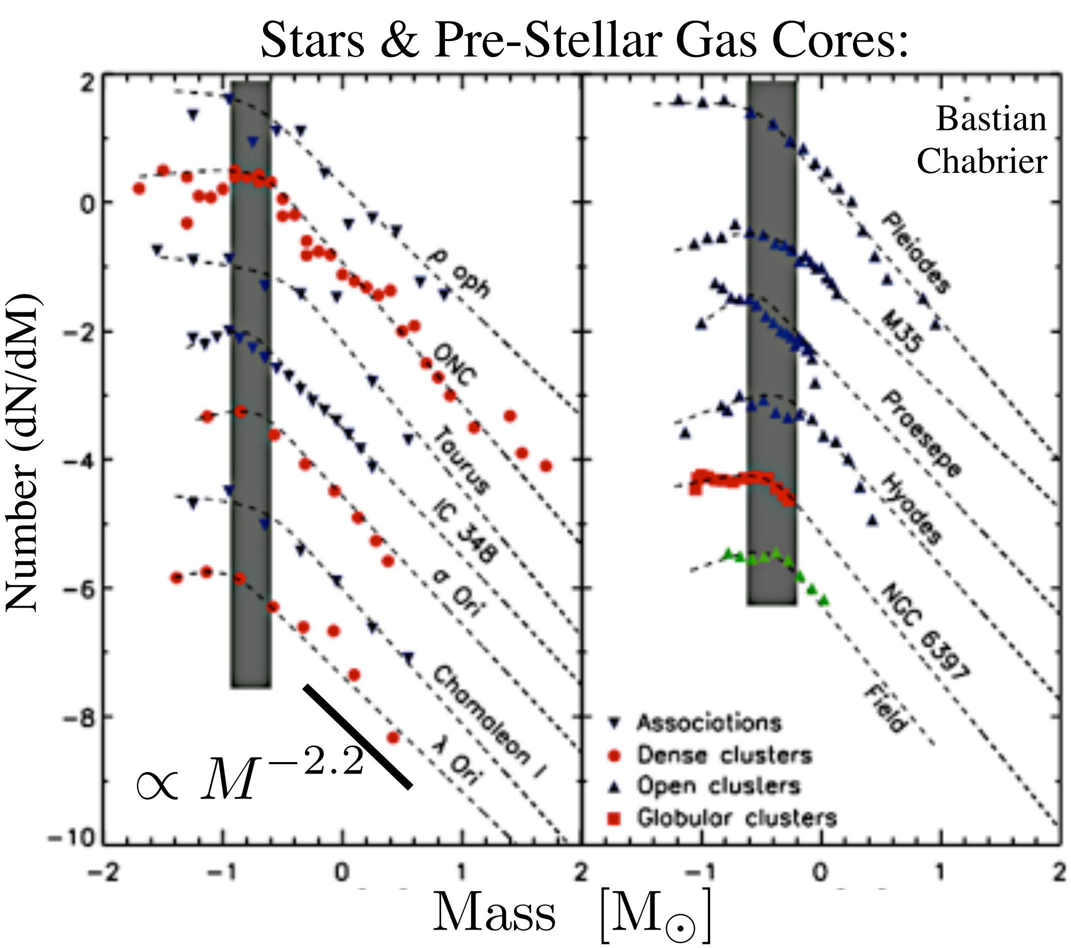

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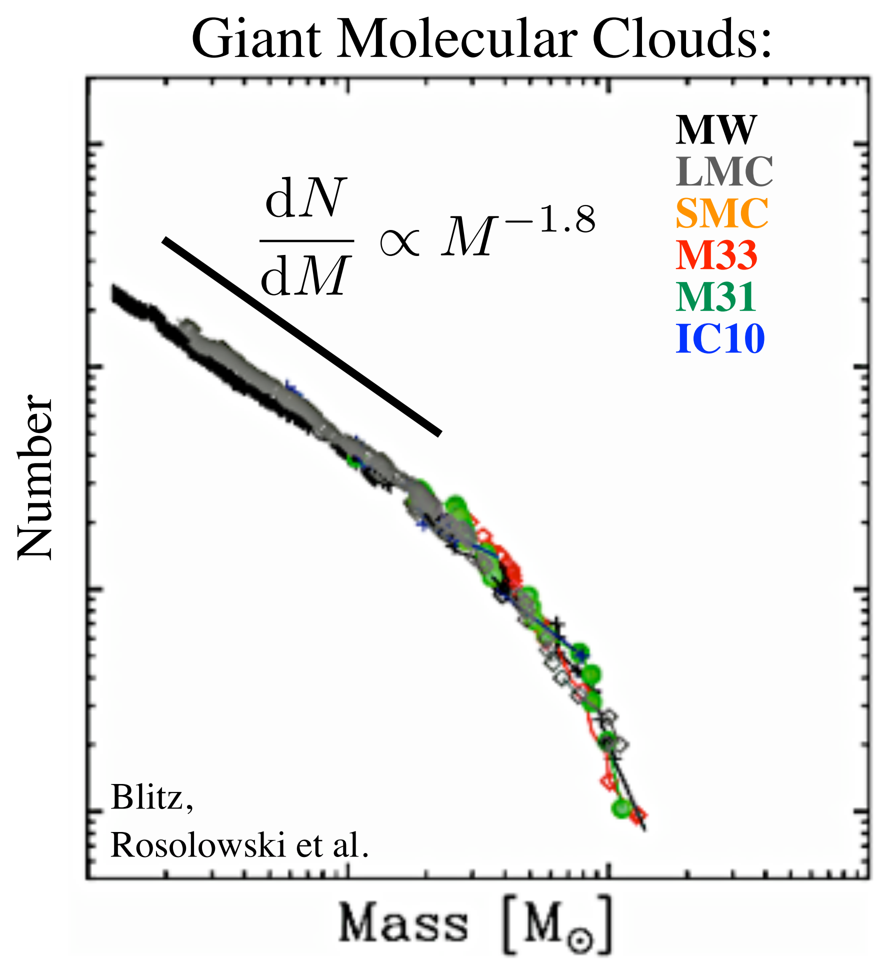

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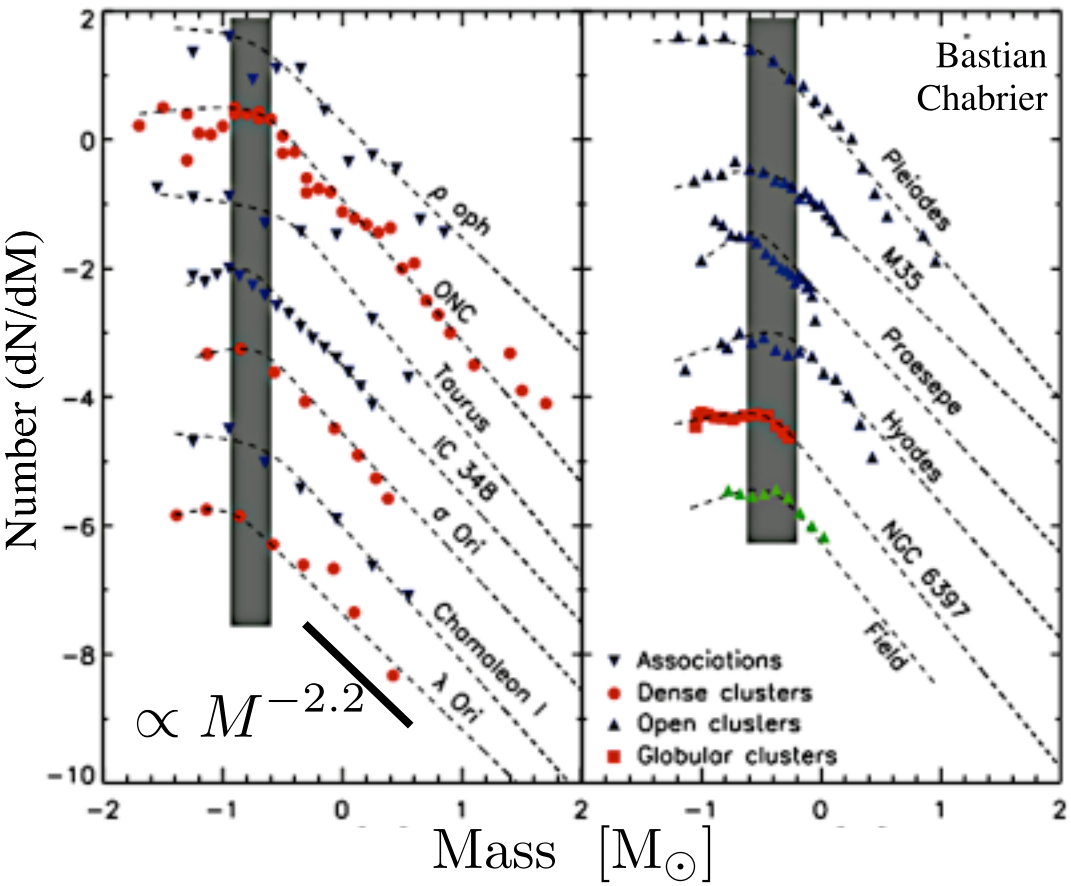

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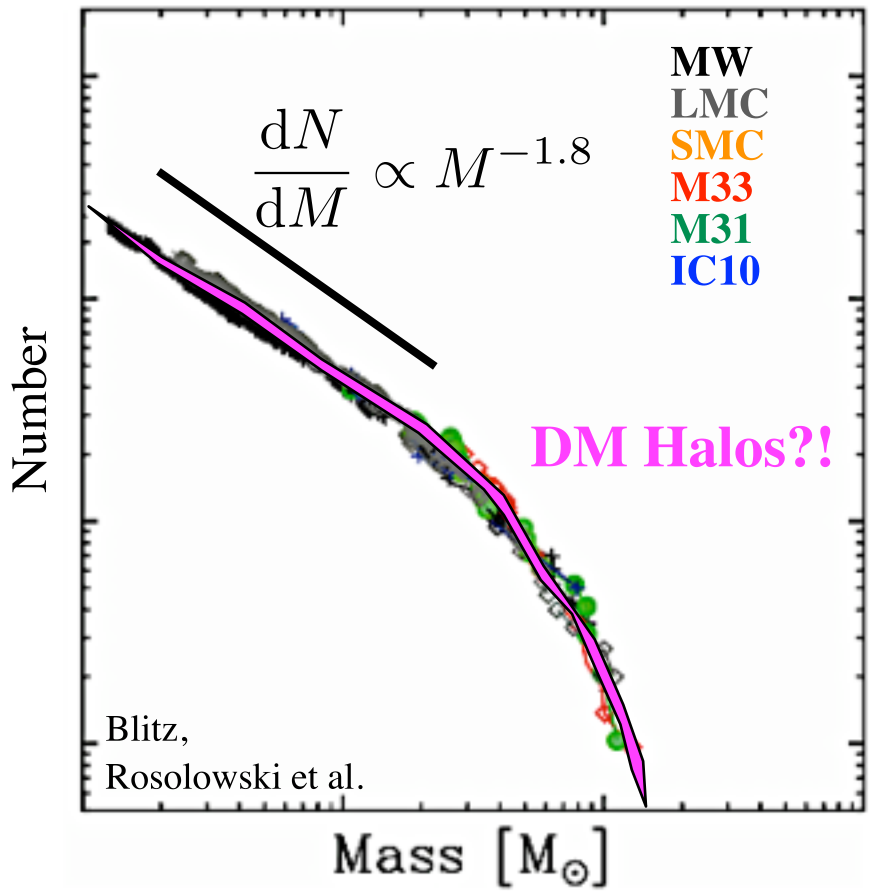
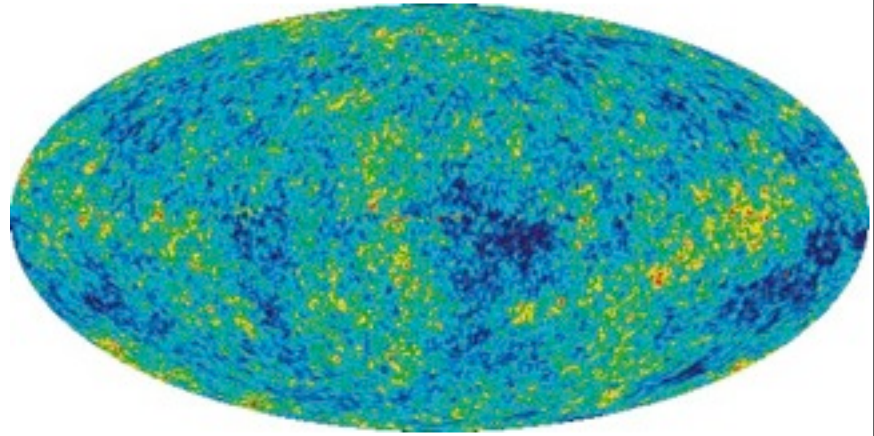
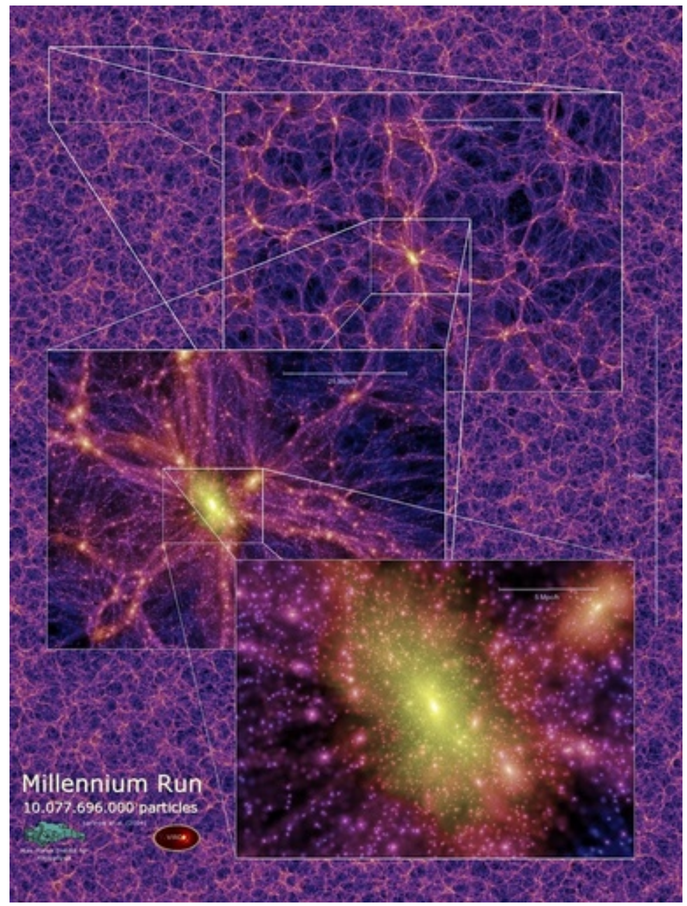


Extended Press-Schechter / Excursion-Set Formalism



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



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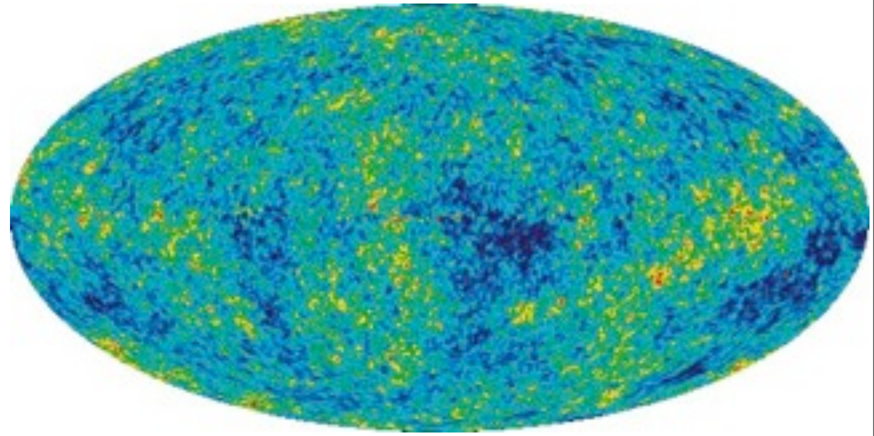

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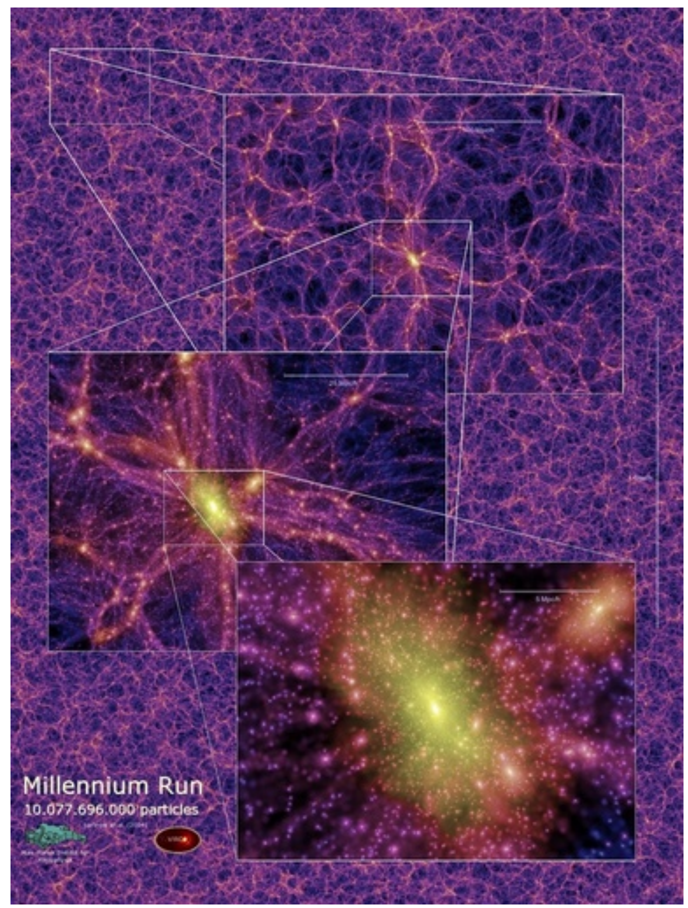

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$$\bar{\rho}(< R \sim 1/k) > \rho_{\rm crit}$$

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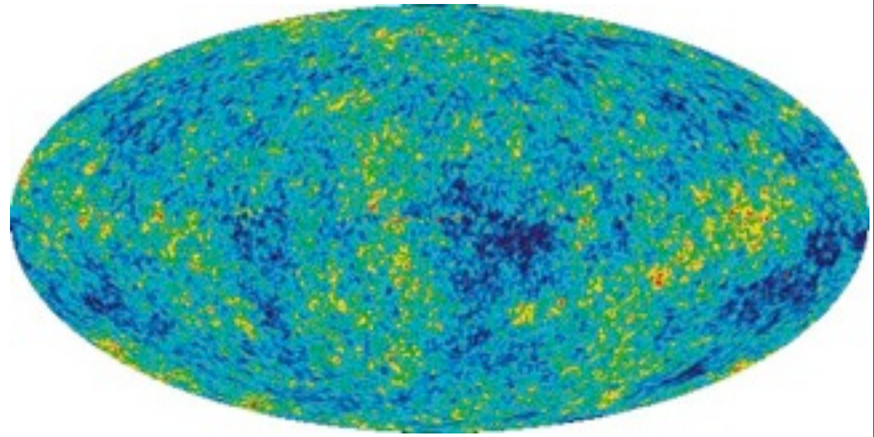

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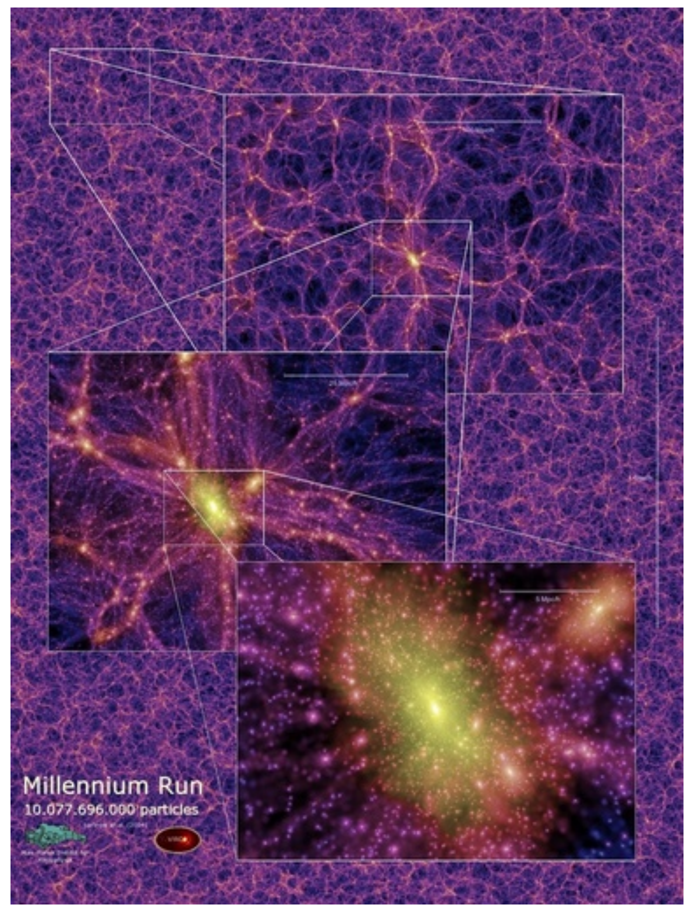

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- Generalize to conditional probabilities,
  N-point statistics, resolve “cloud in cloud” problem
  (e.g. Bond et al. 1991)

Turbulence

BASIC EXPECTATIONS

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

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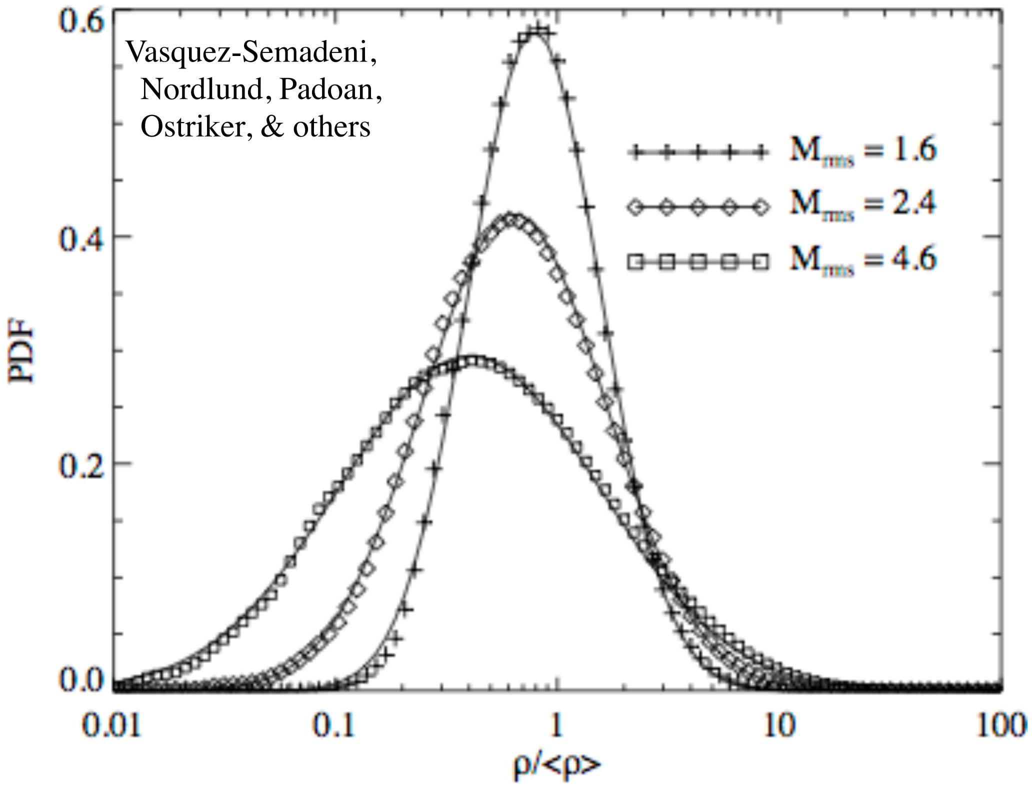

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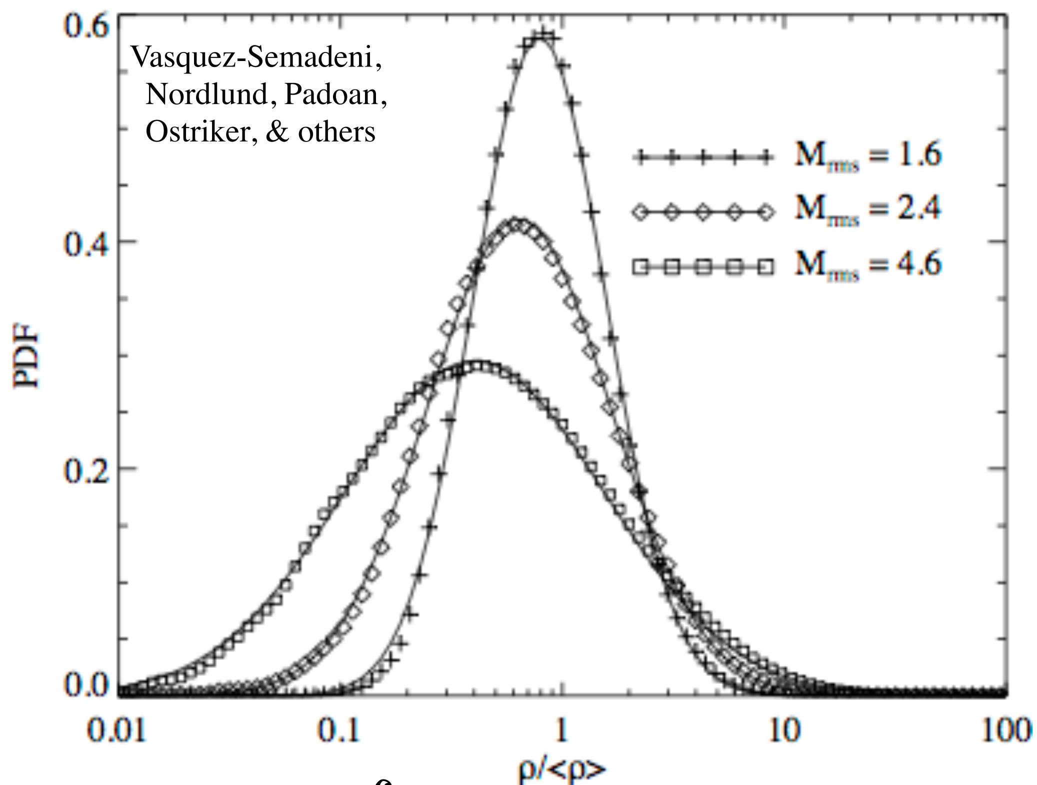

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Super-Sonic Turbulence

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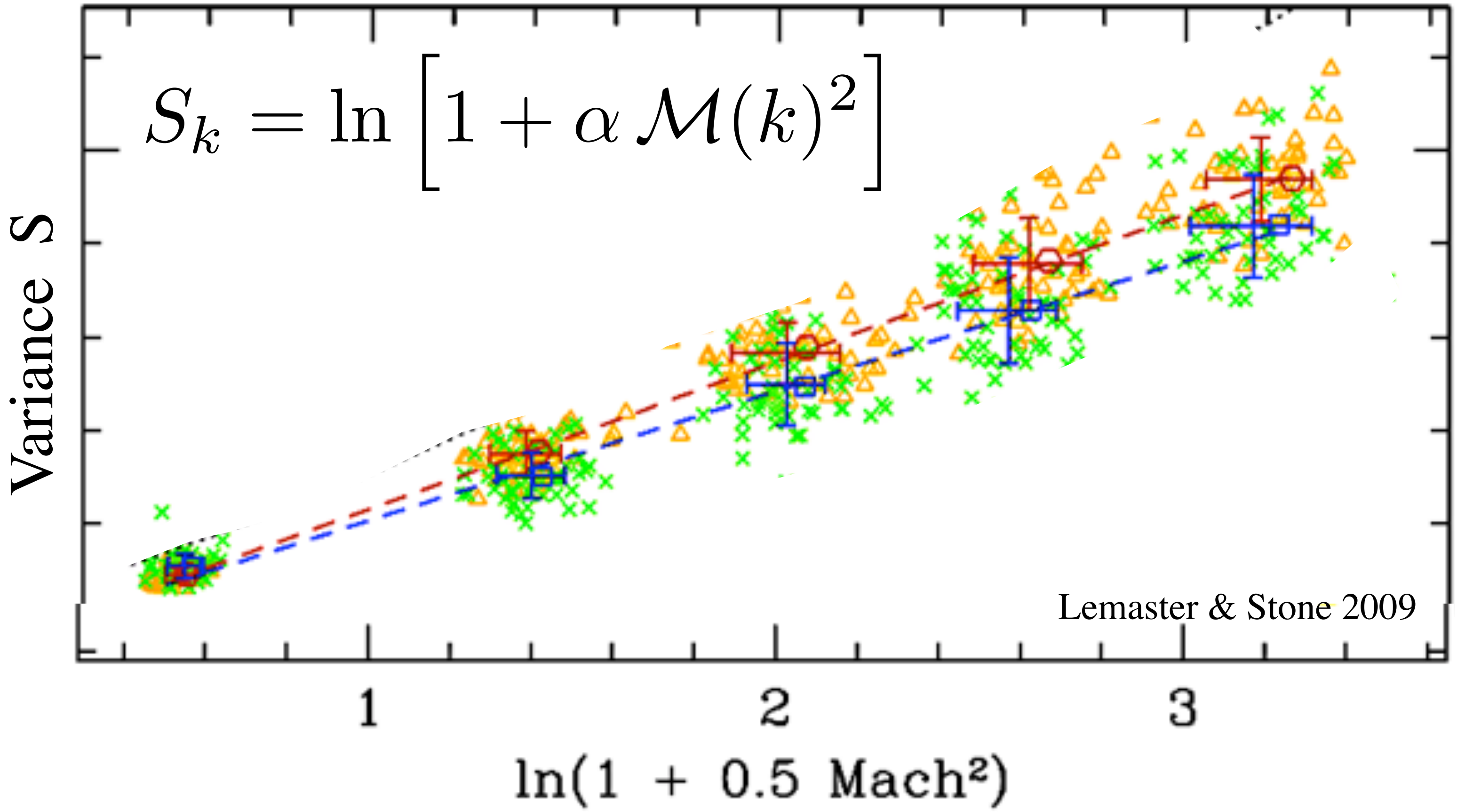

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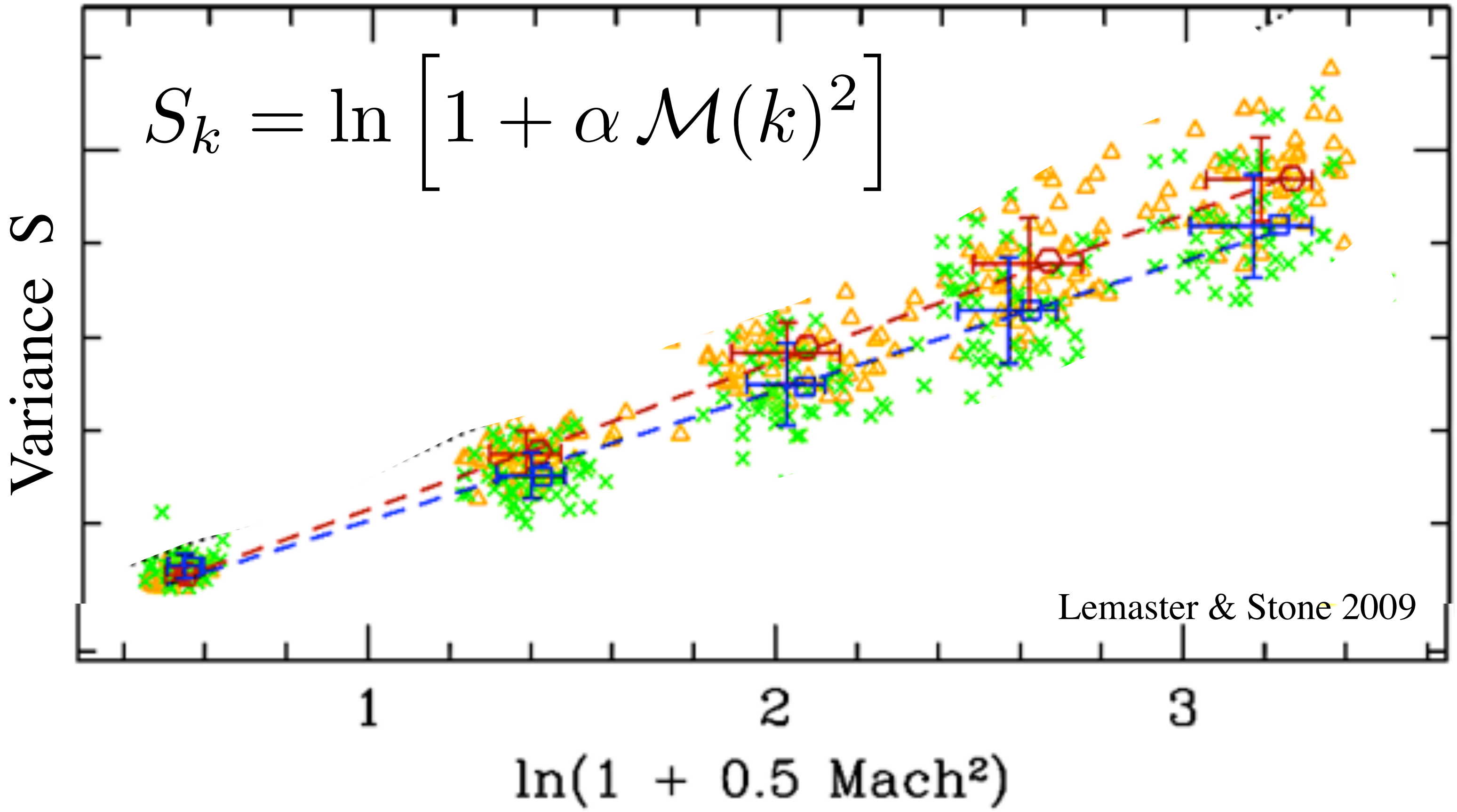

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What Defines a Fluctuation of Interest?

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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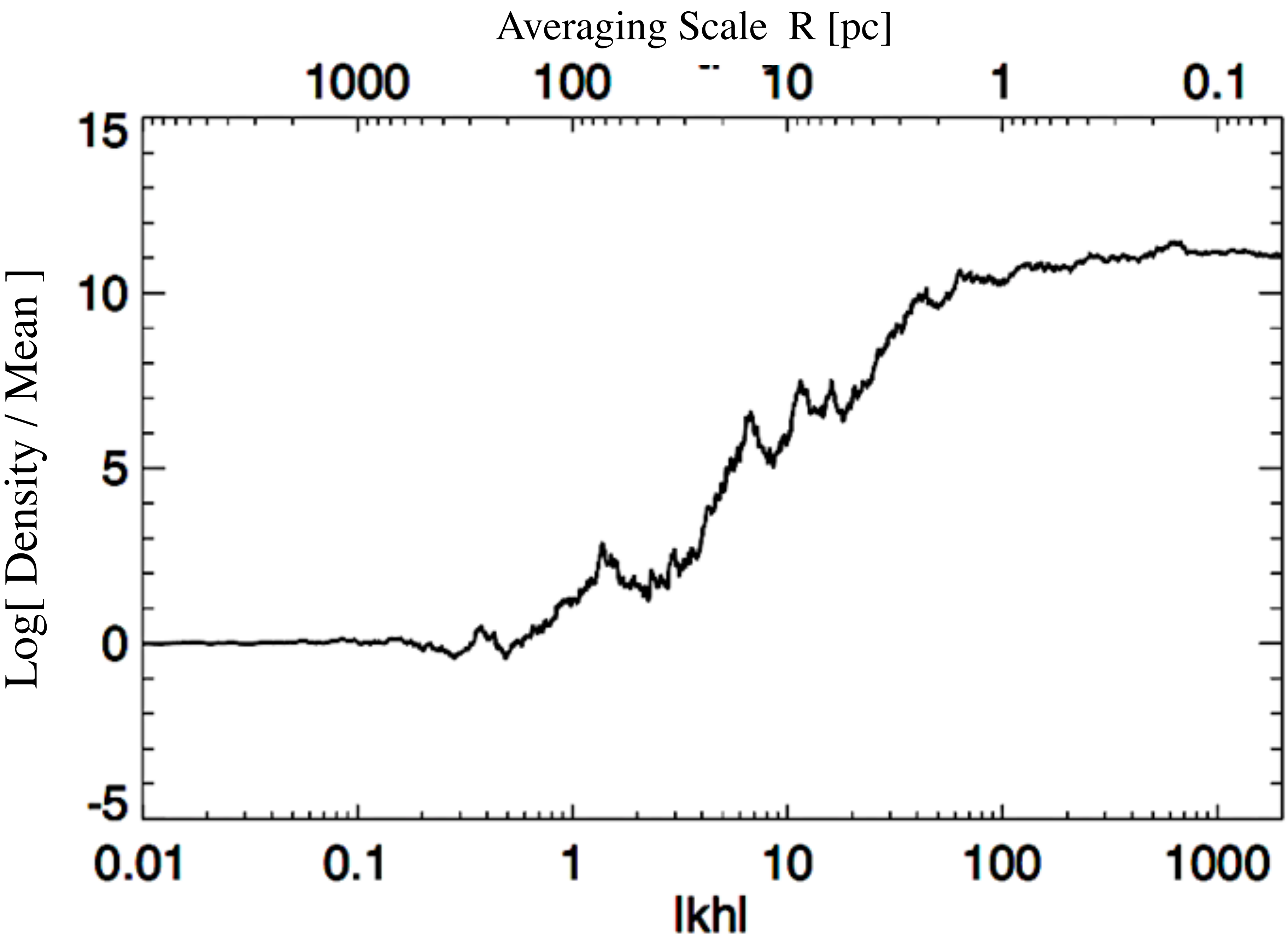
Mode Grows (Collapses) when w<0:

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

Chandrasekhar ‘51, Vandervoort ‘70, Toomre ‘77

"Counting" Collapsing Objects

EVALUATE DENSITY FIELD vs. "BARRIER"



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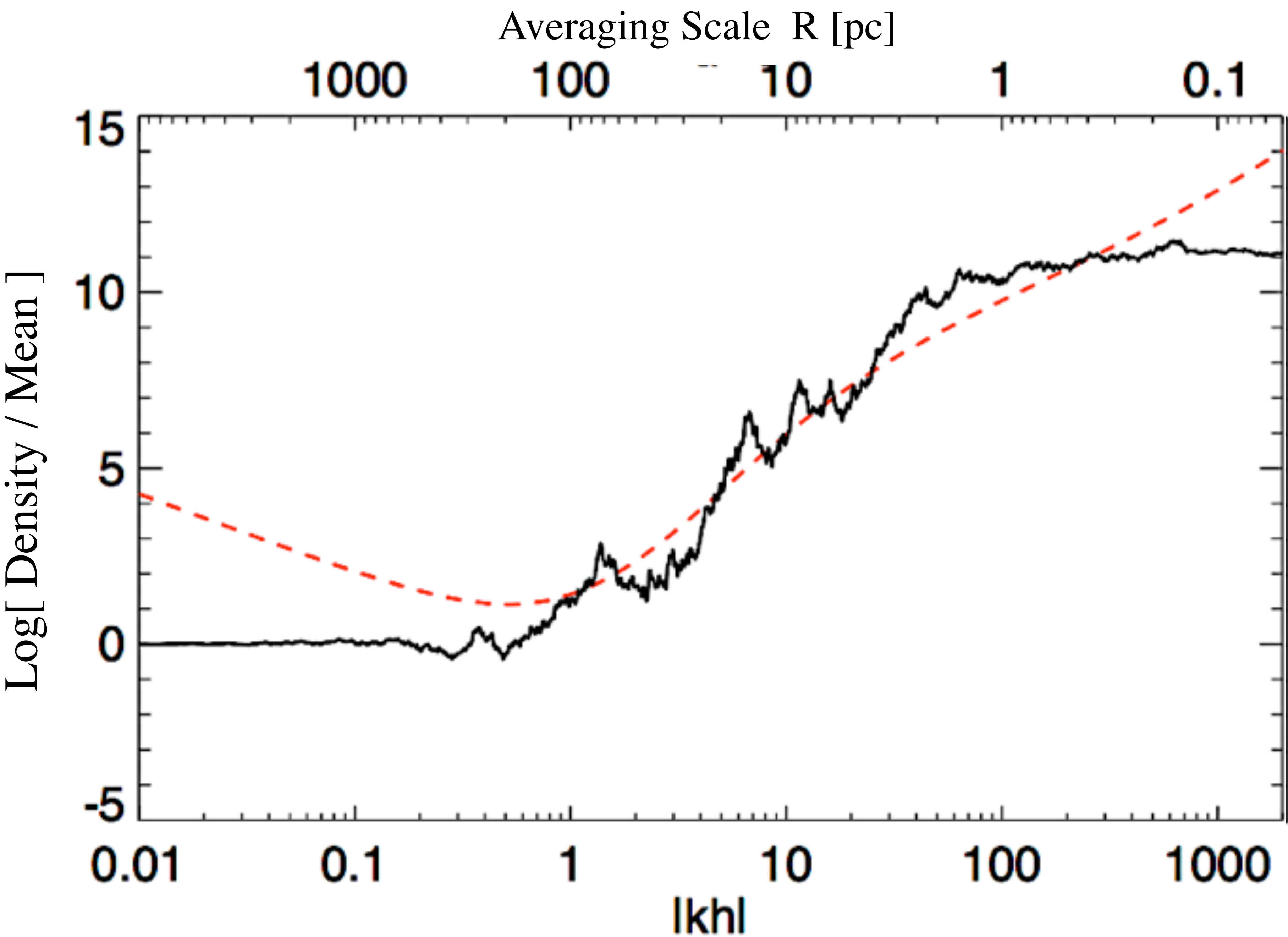

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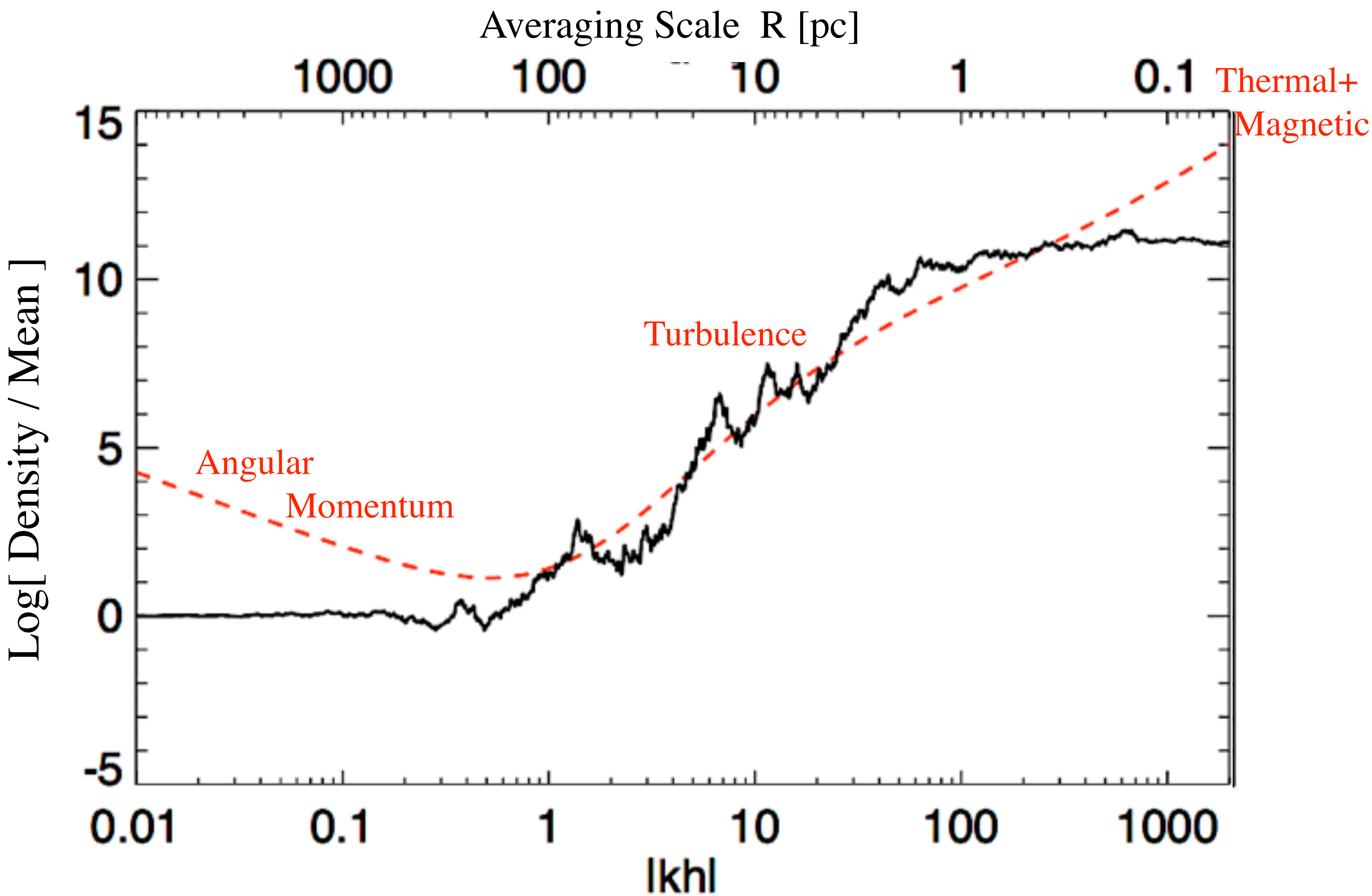

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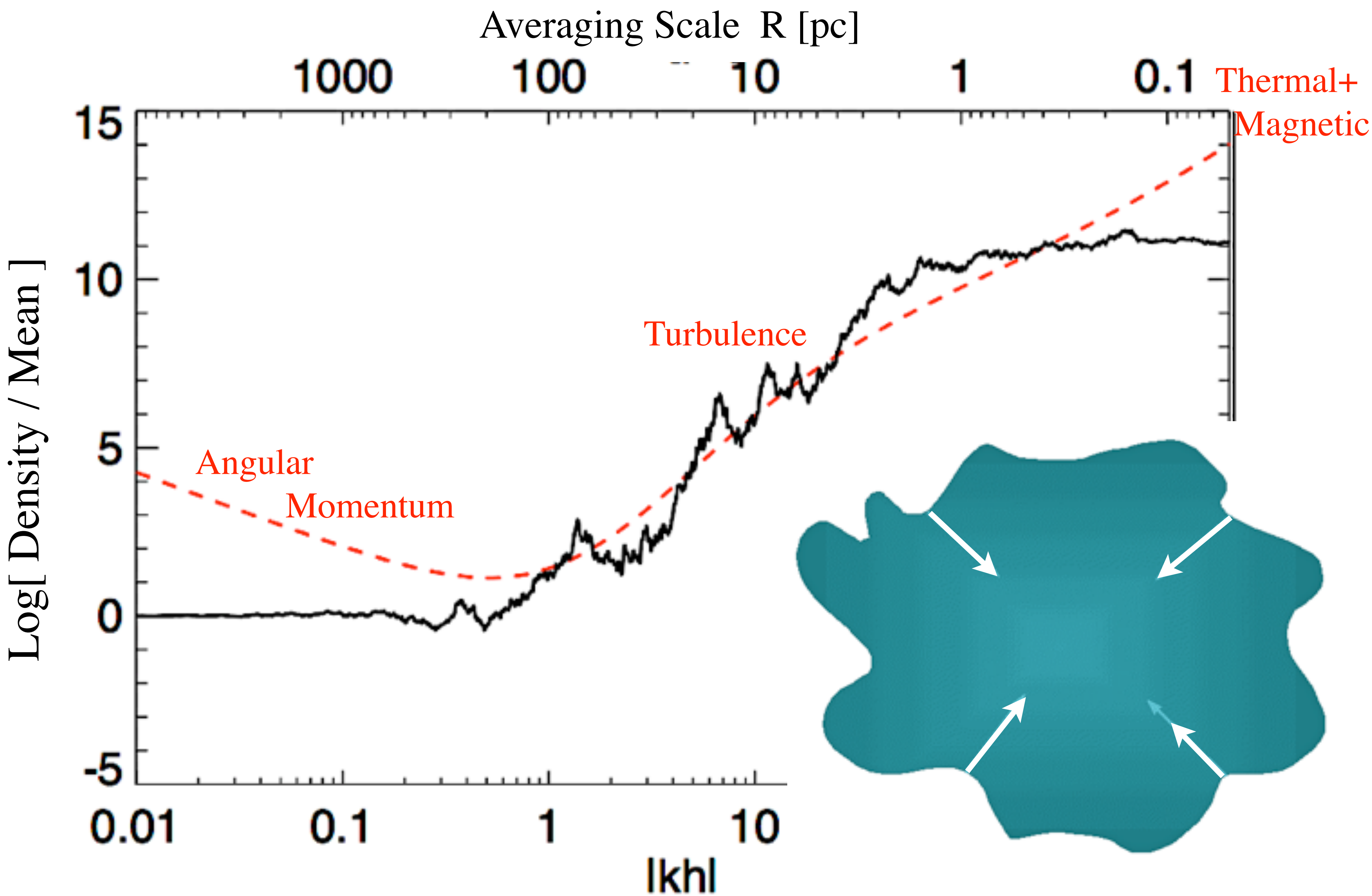

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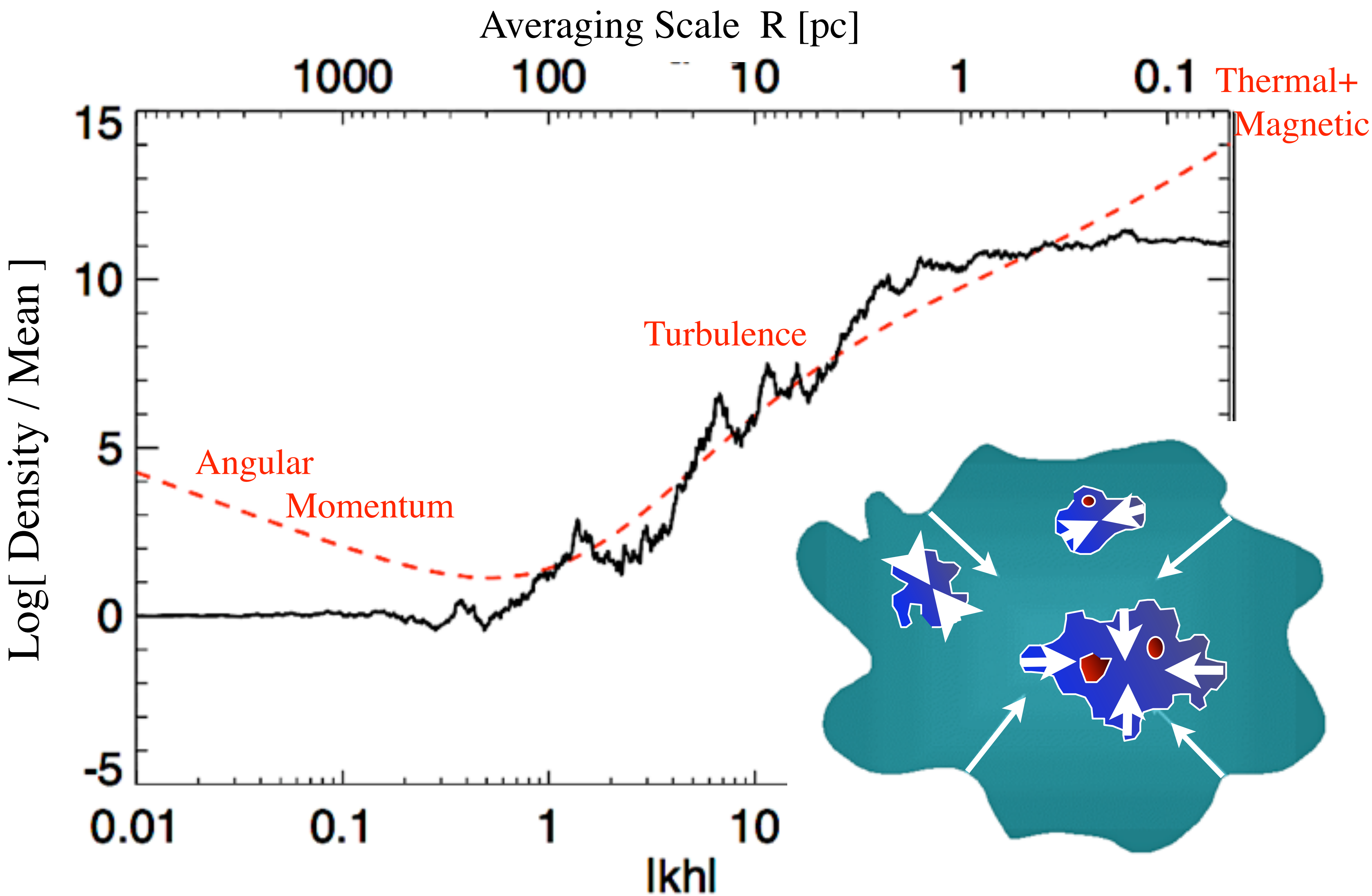

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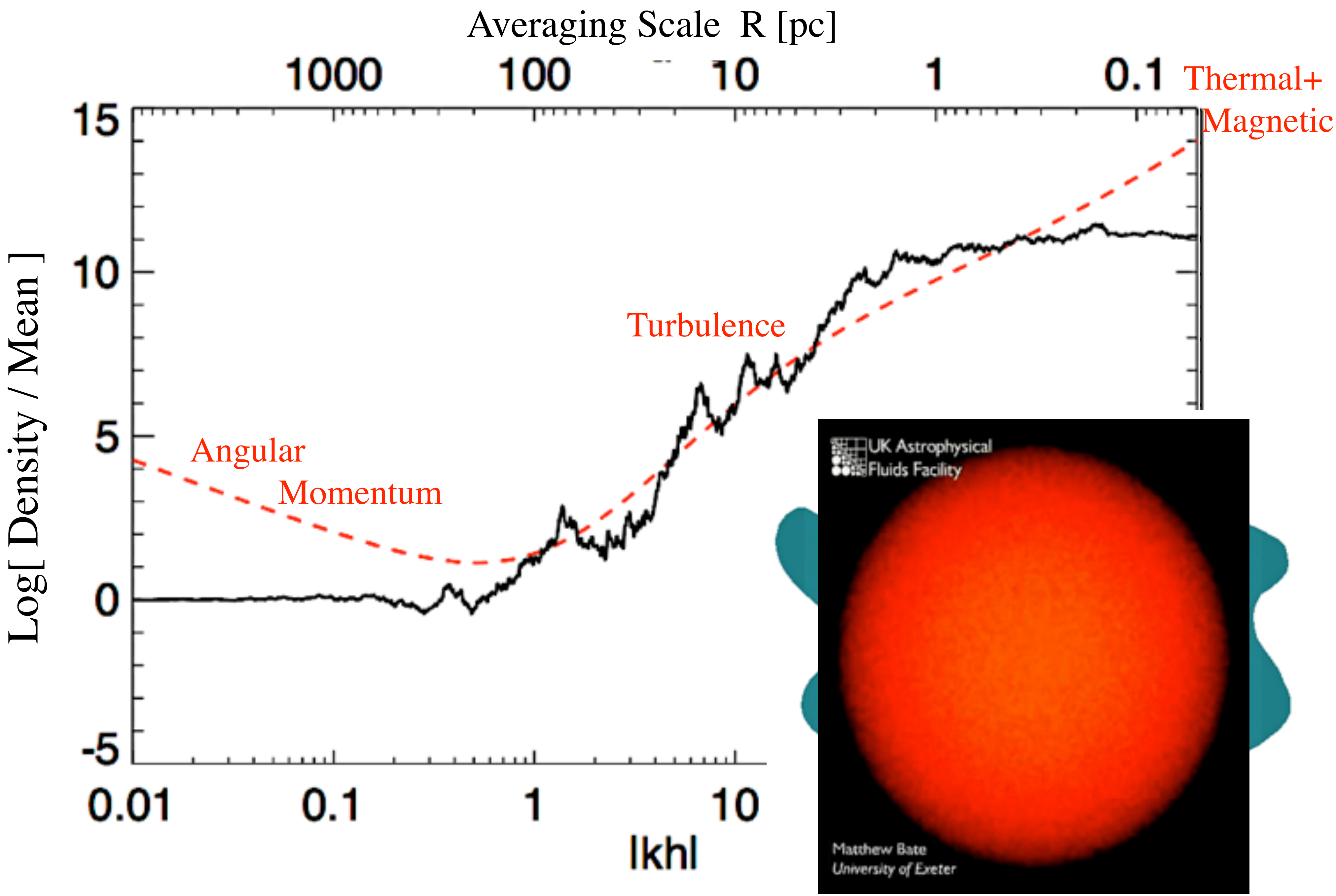

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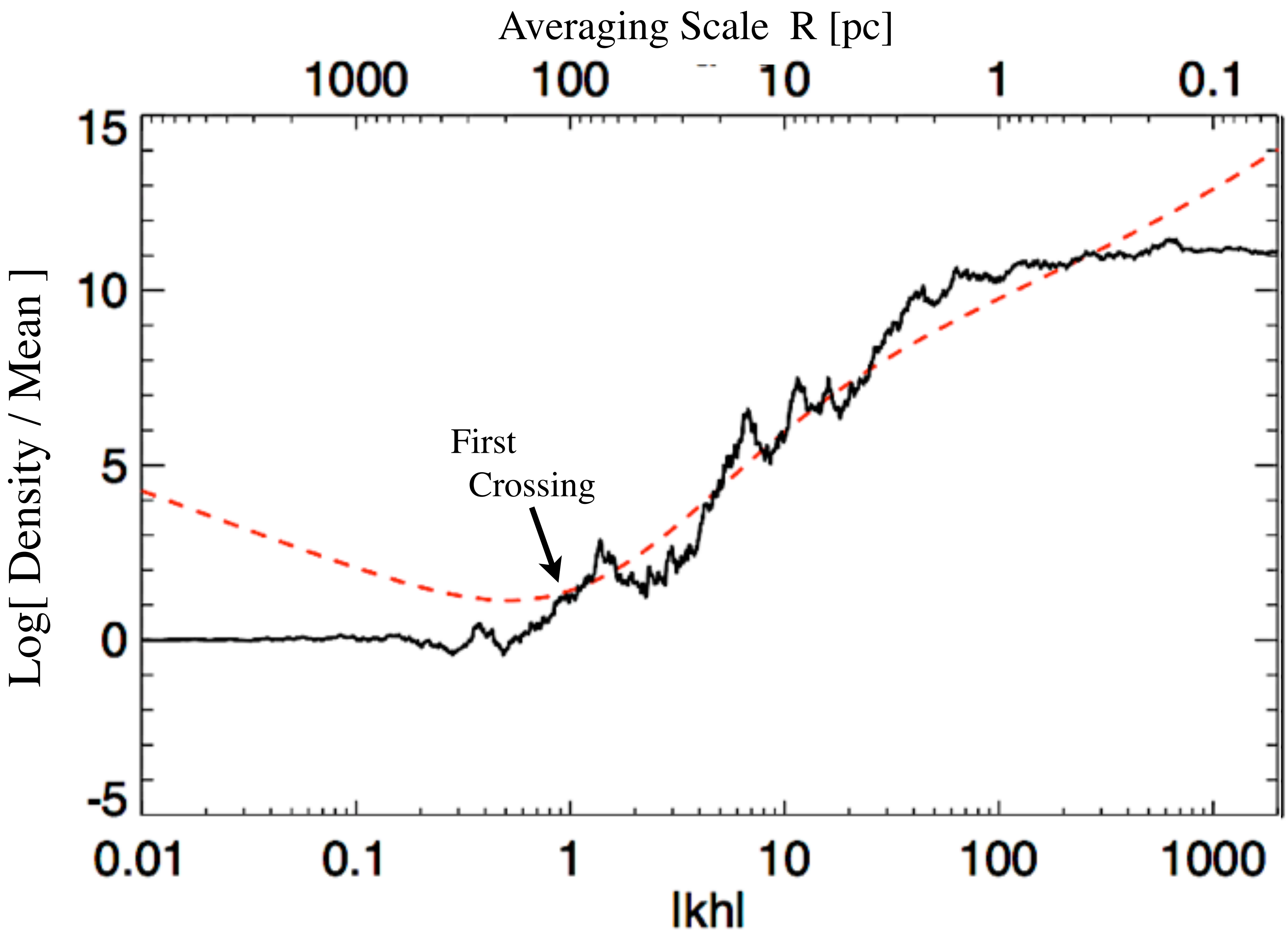

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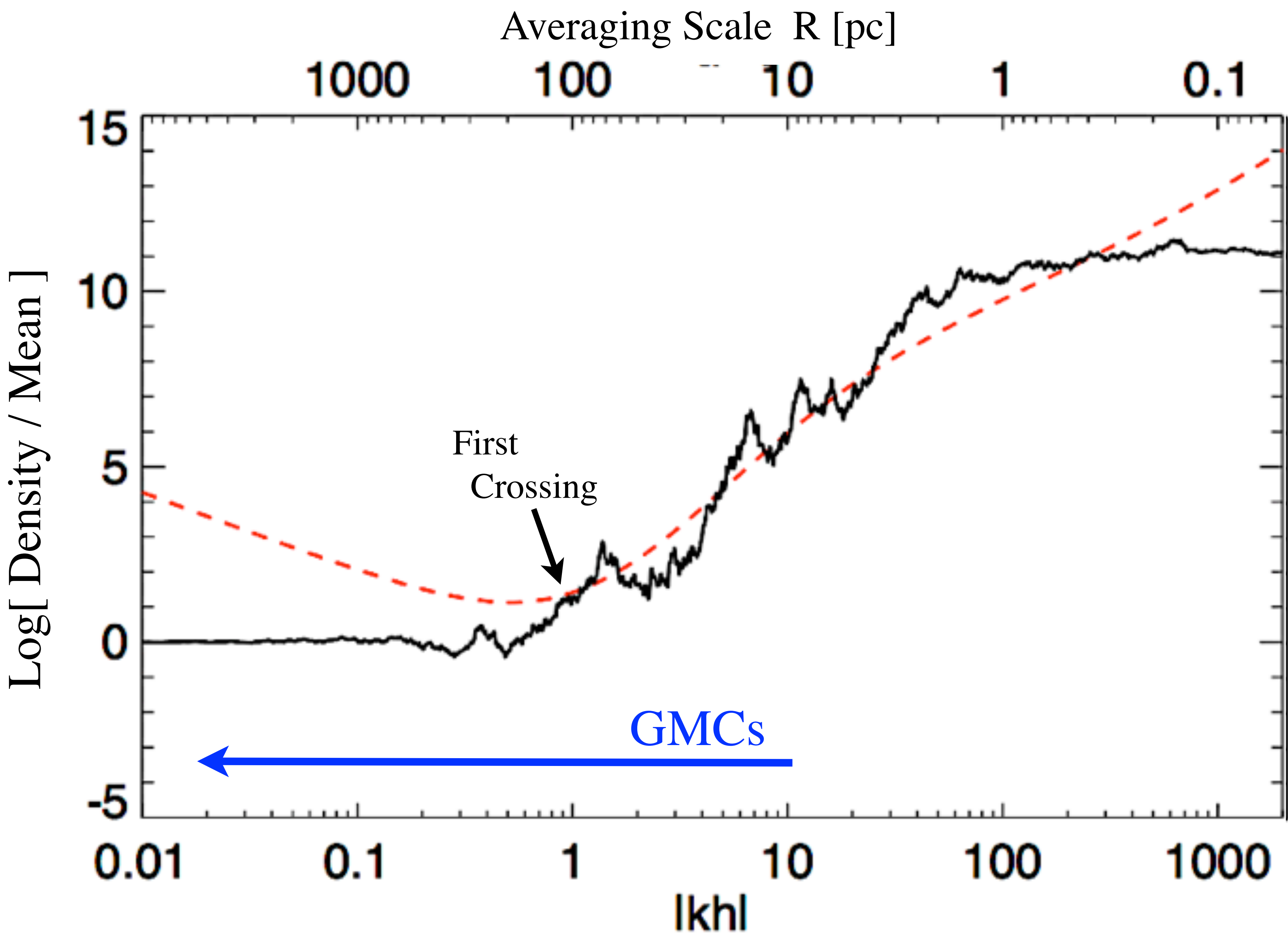

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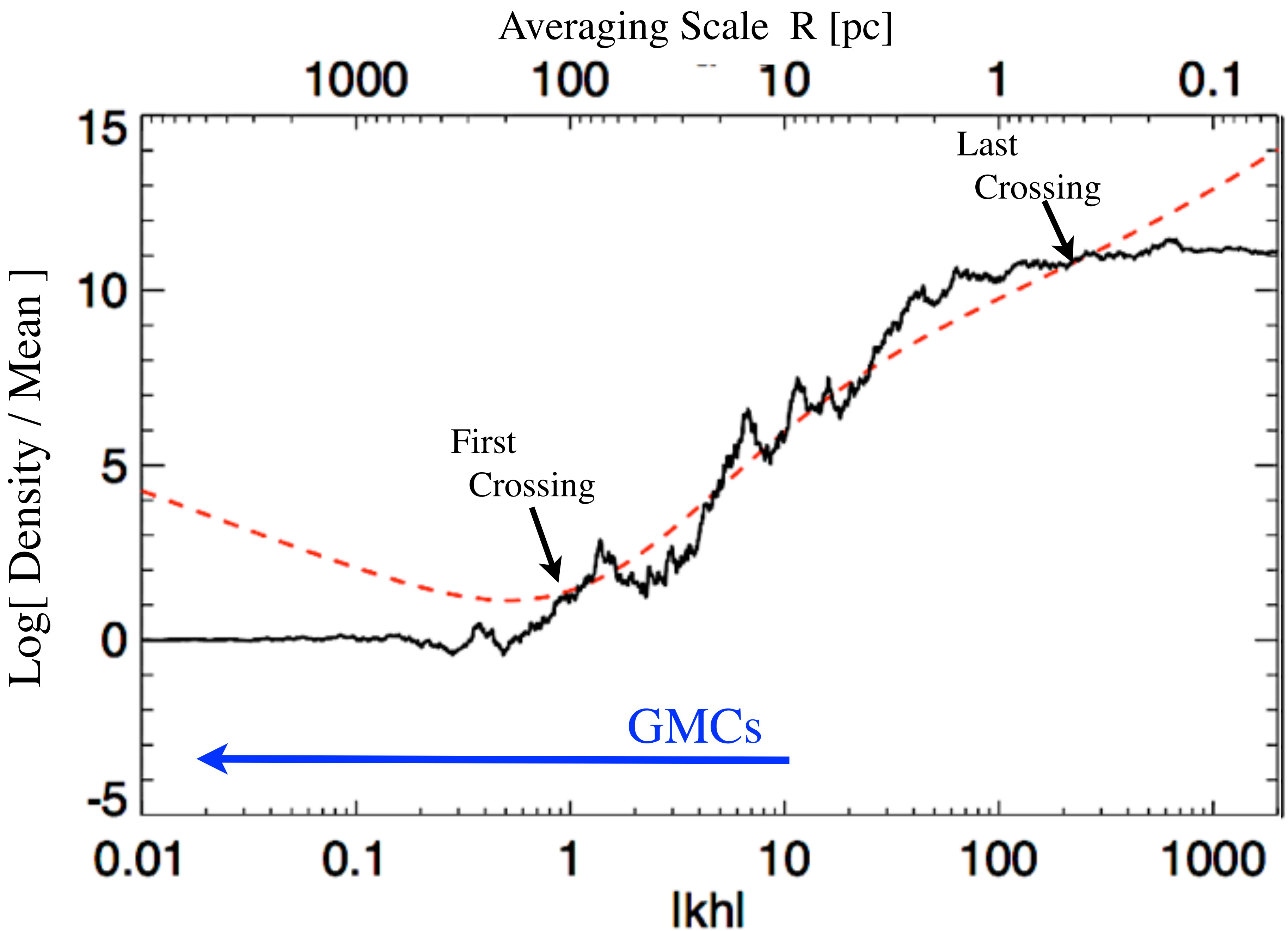

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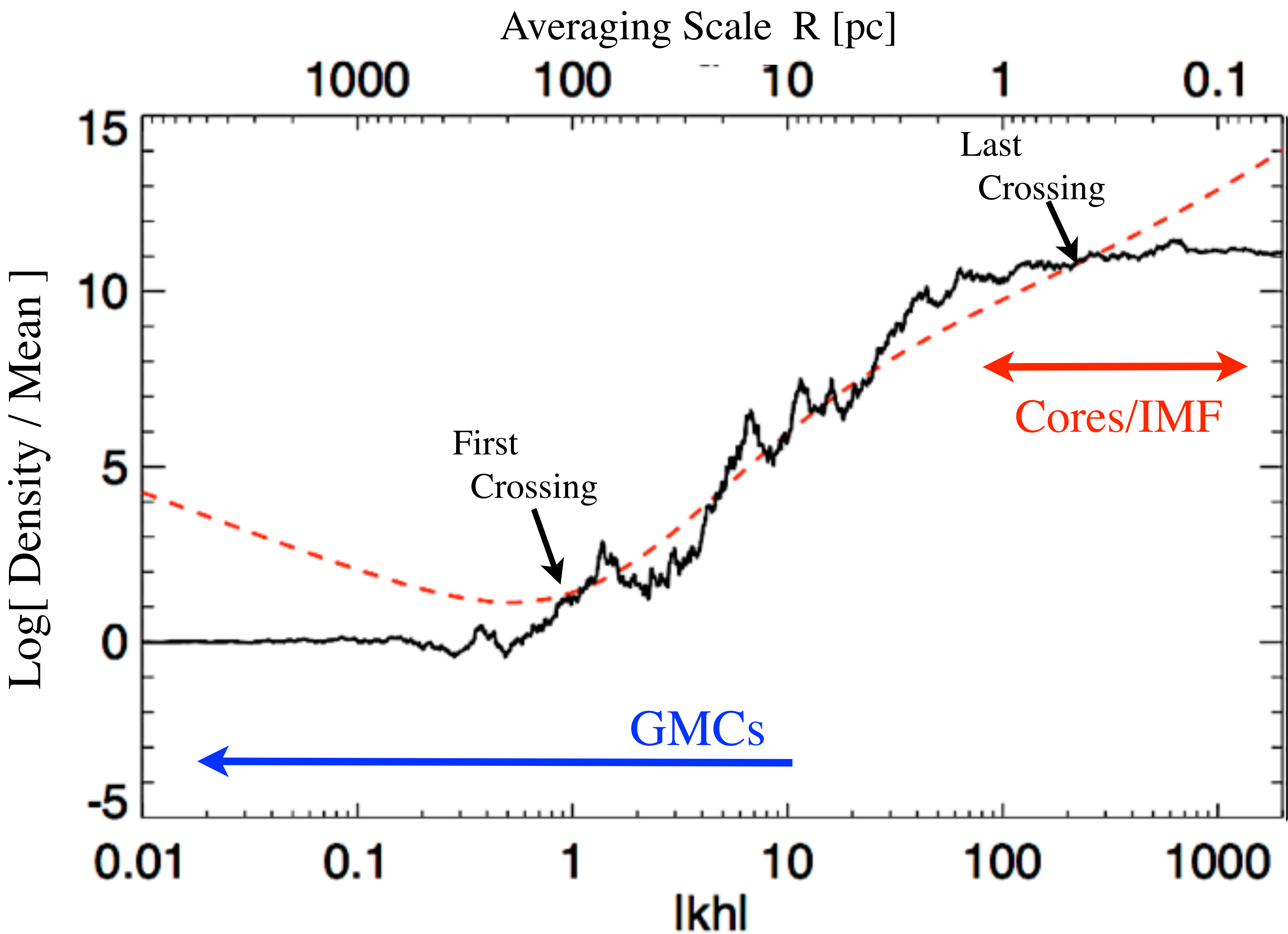
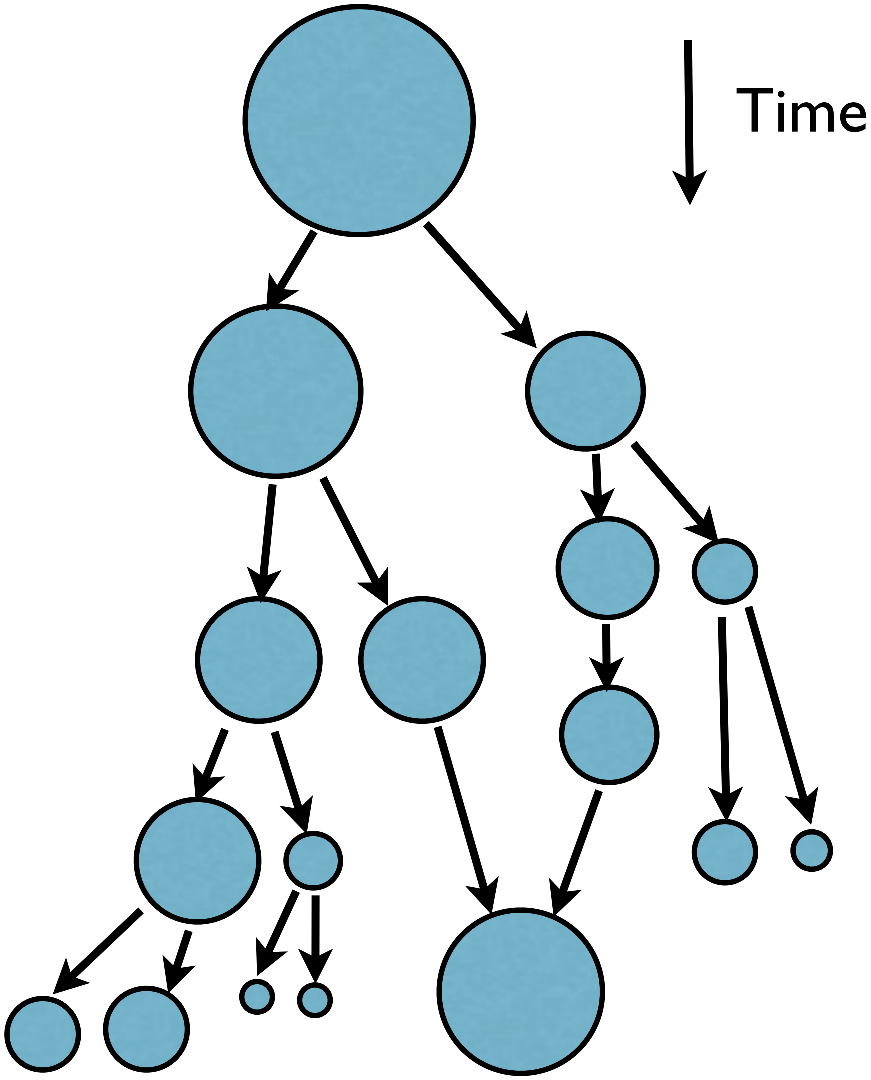


Evolve the Fluctuations in Time

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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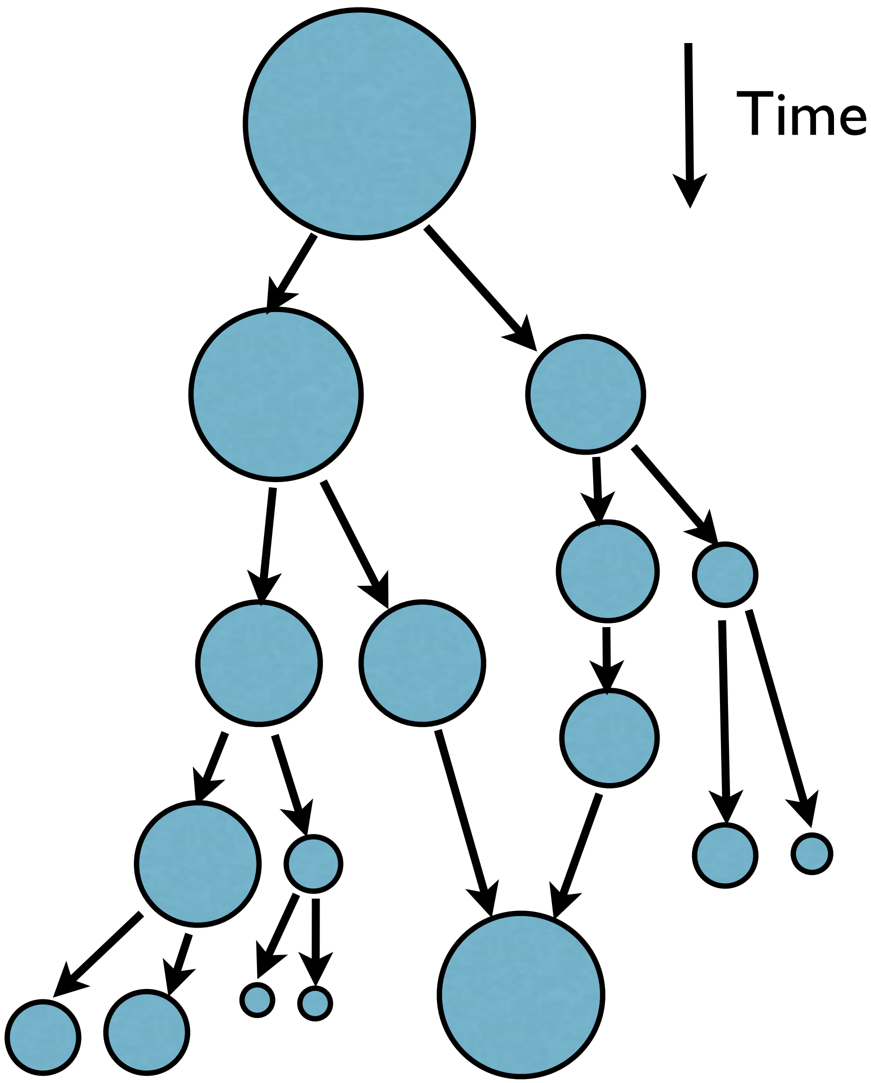
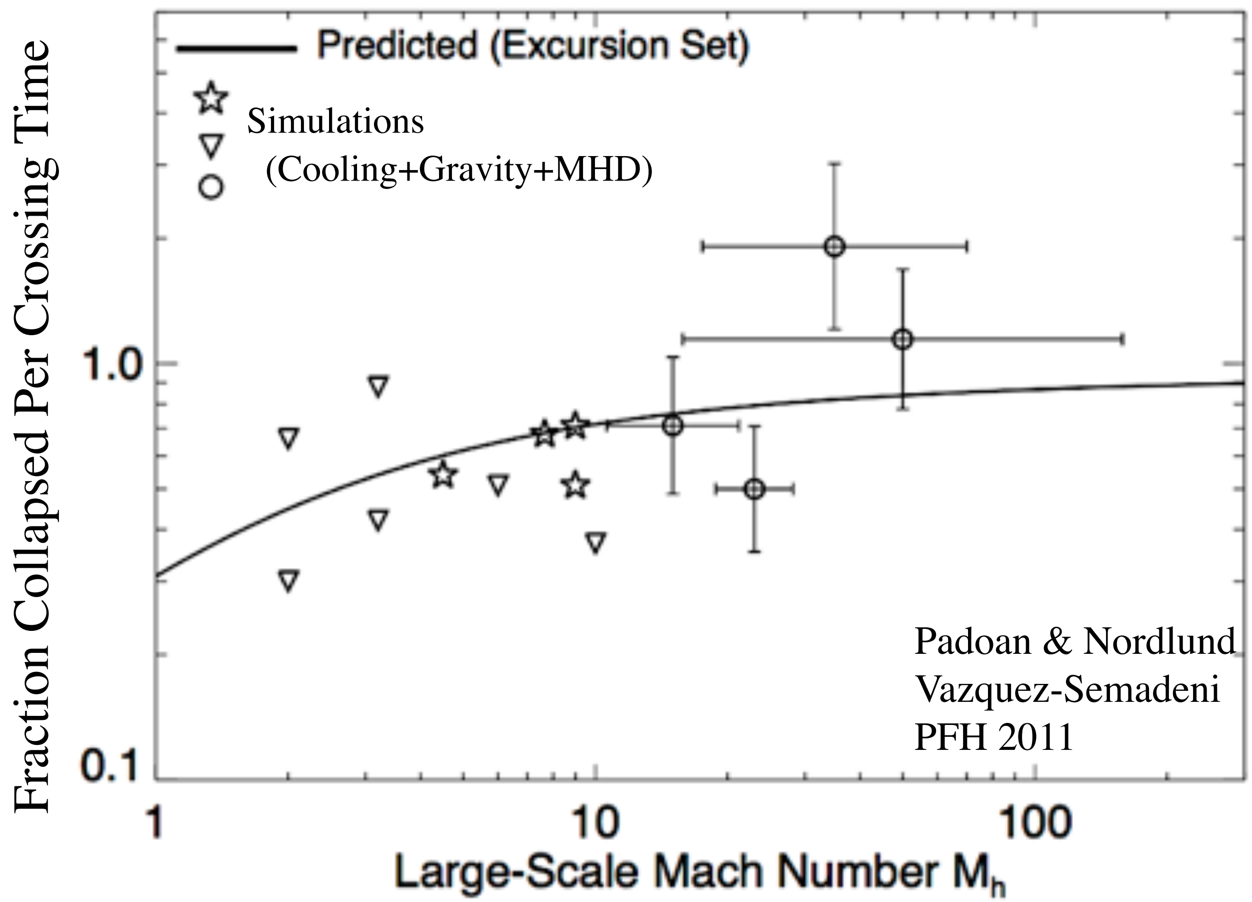
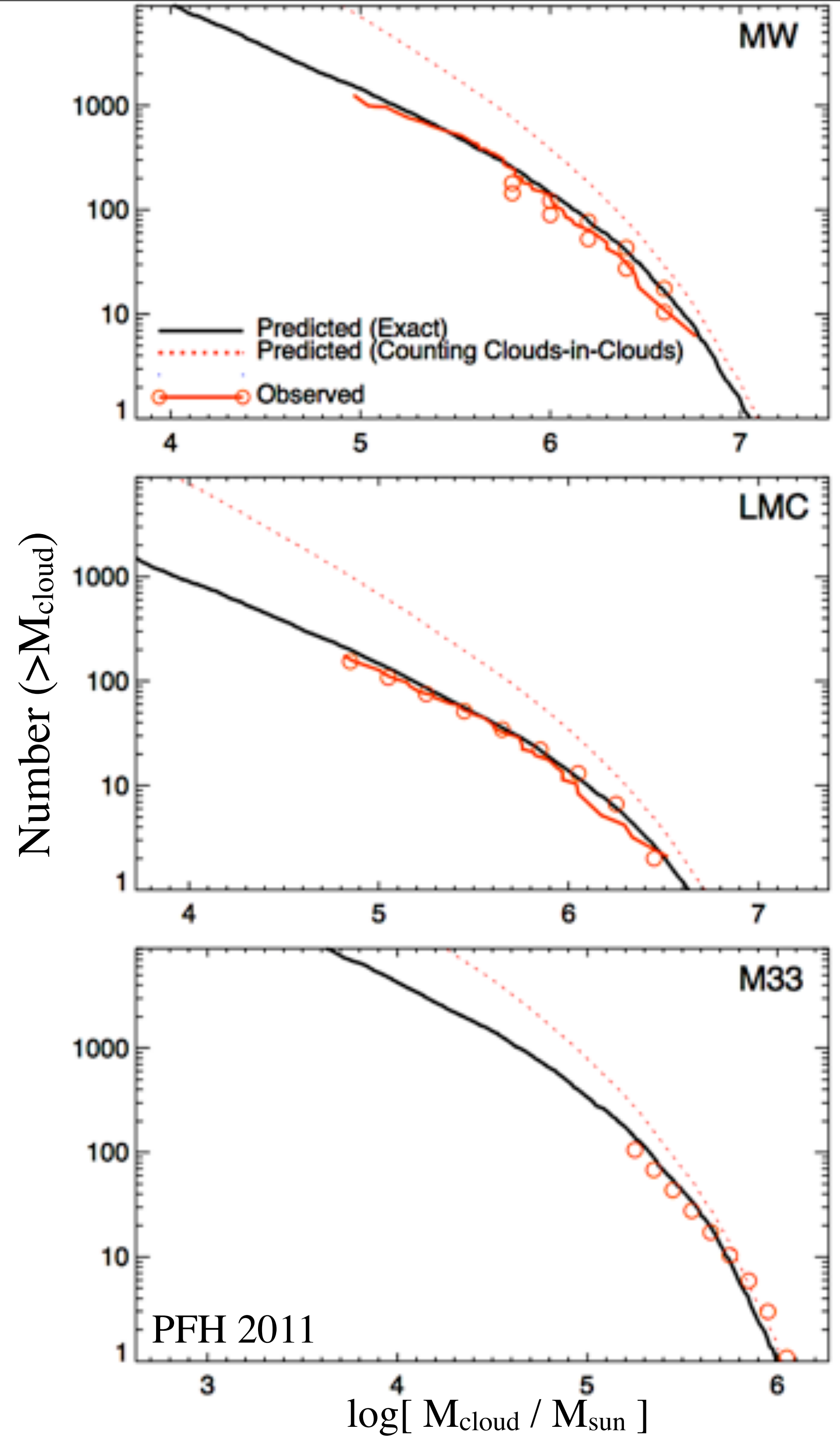




The "First Crossing" Mass Function

VS GIANT MOLECULAR CLOUDS



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$$r_{\mathrm{sonic}} \ll r \ll h$$

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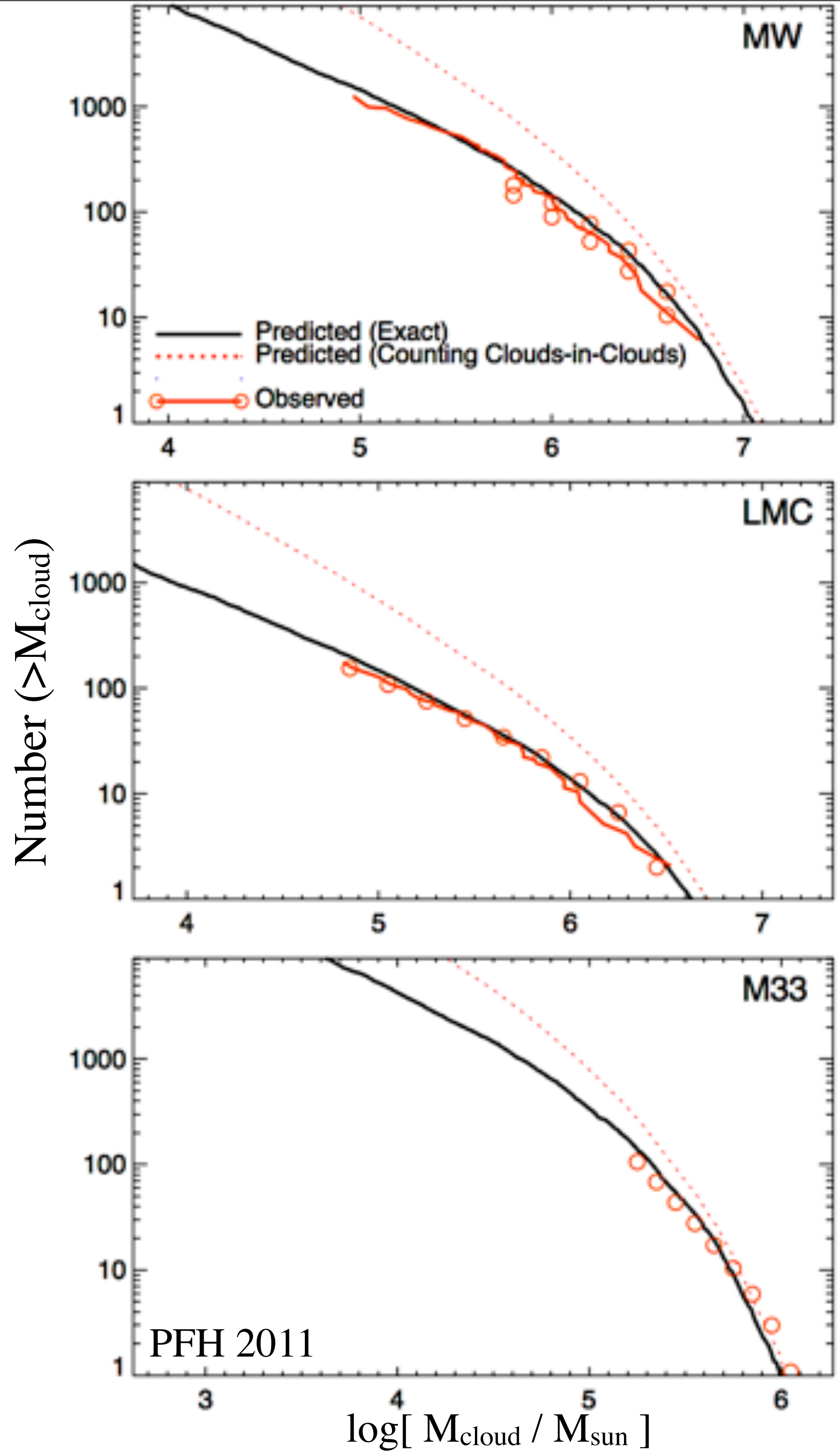

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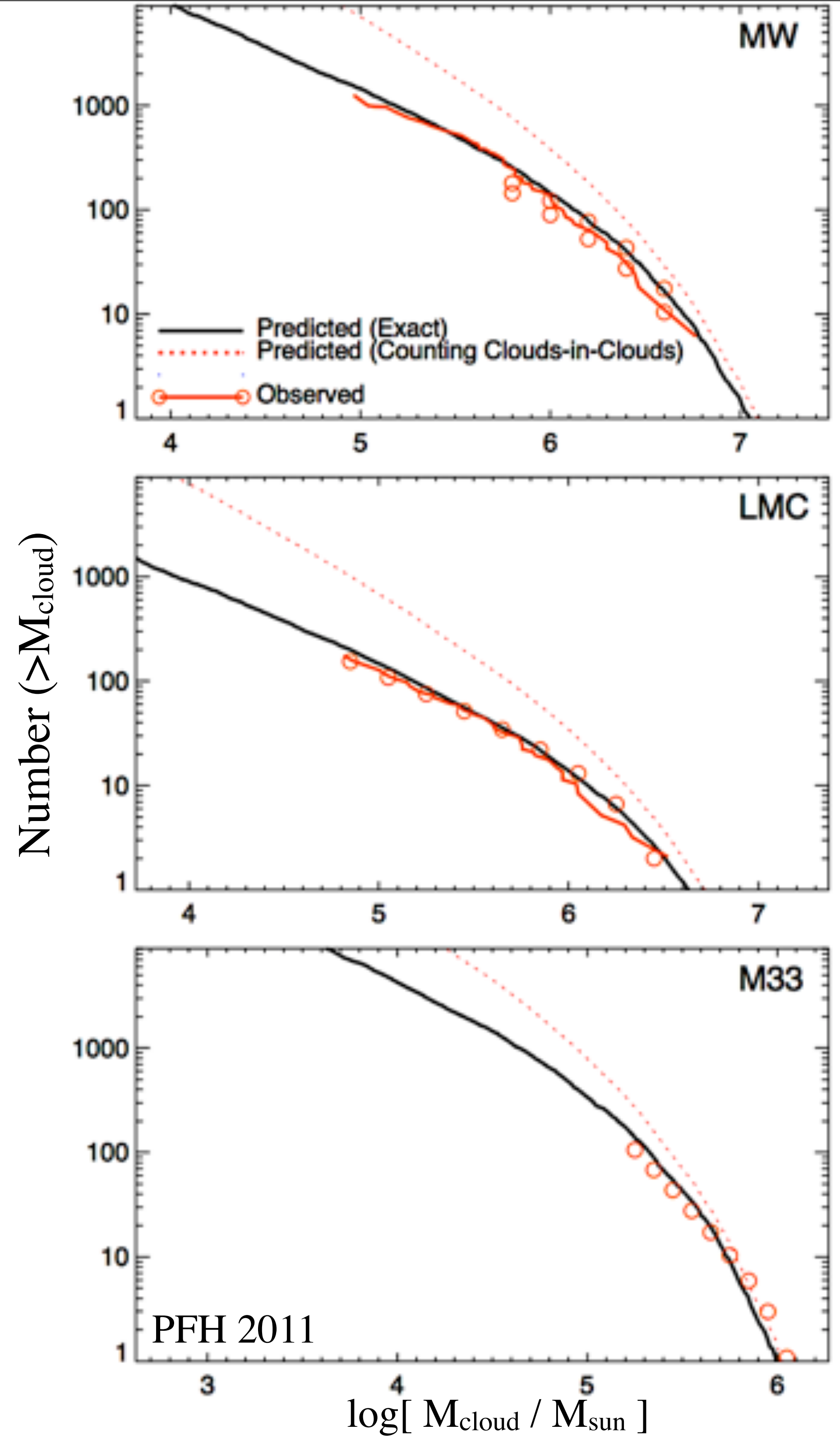

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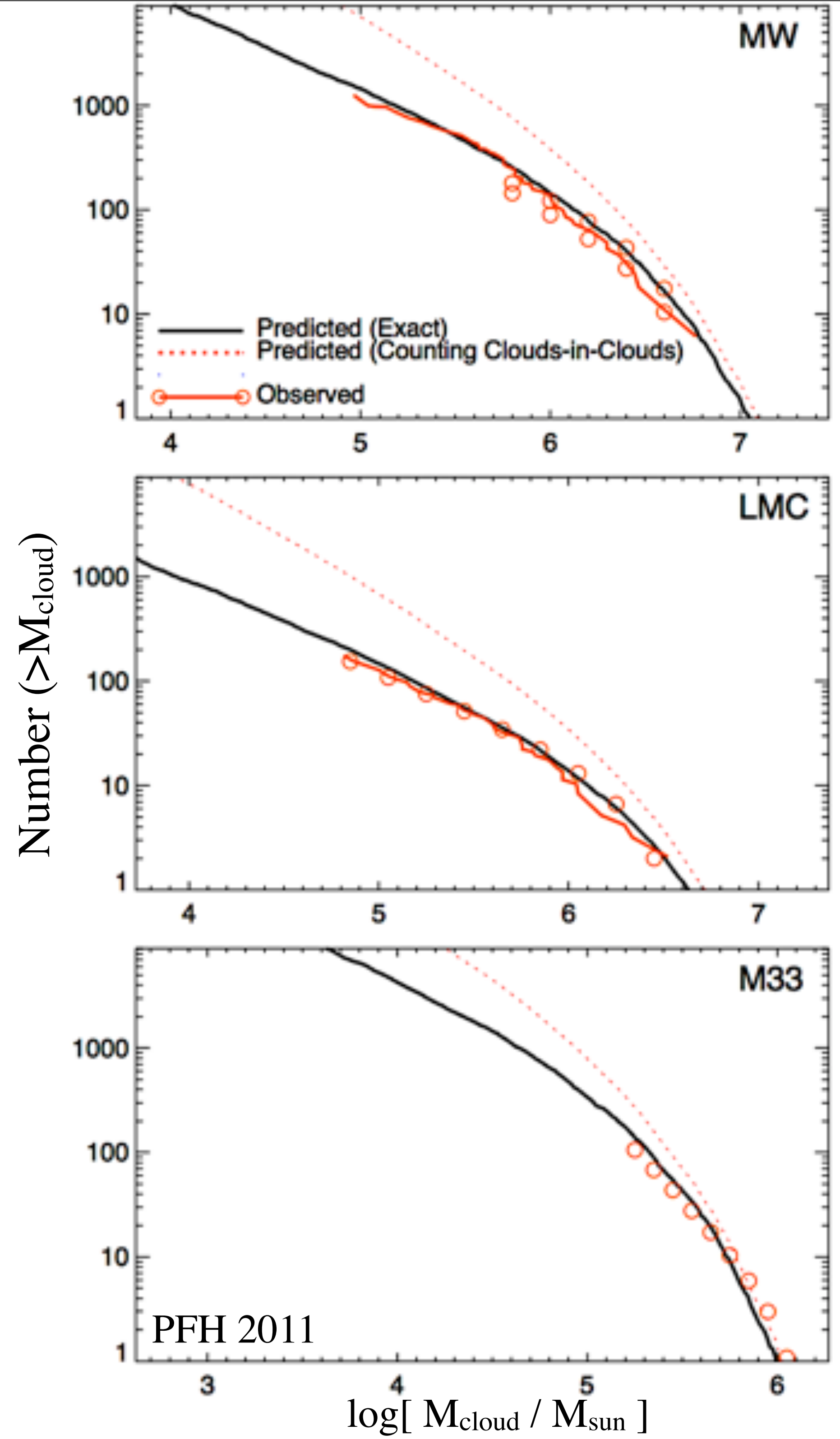
$$\alpha \approx -2 + \frac{(3-p)^2}{2\,S\,p^2}\,\ln\left(\frac{M_J}{M}\right)$$

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



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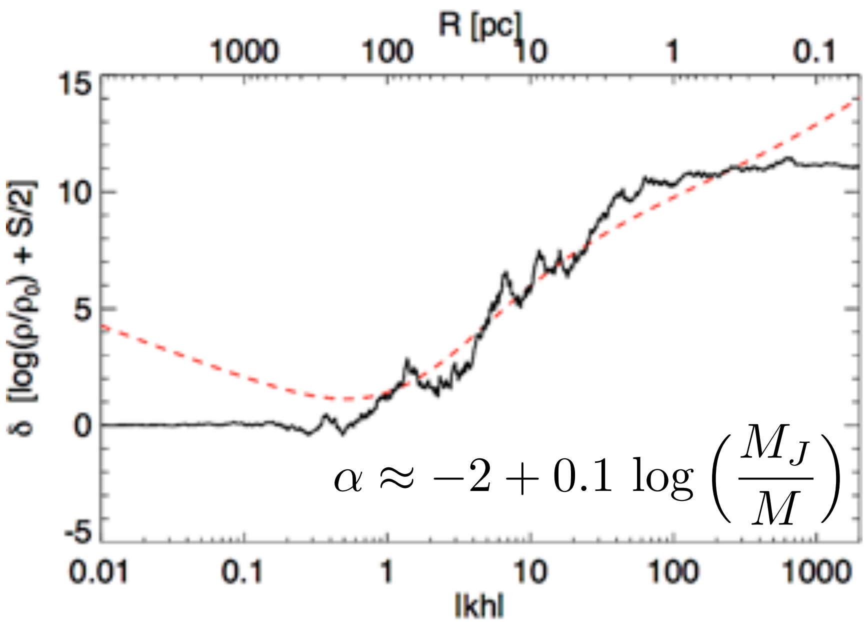

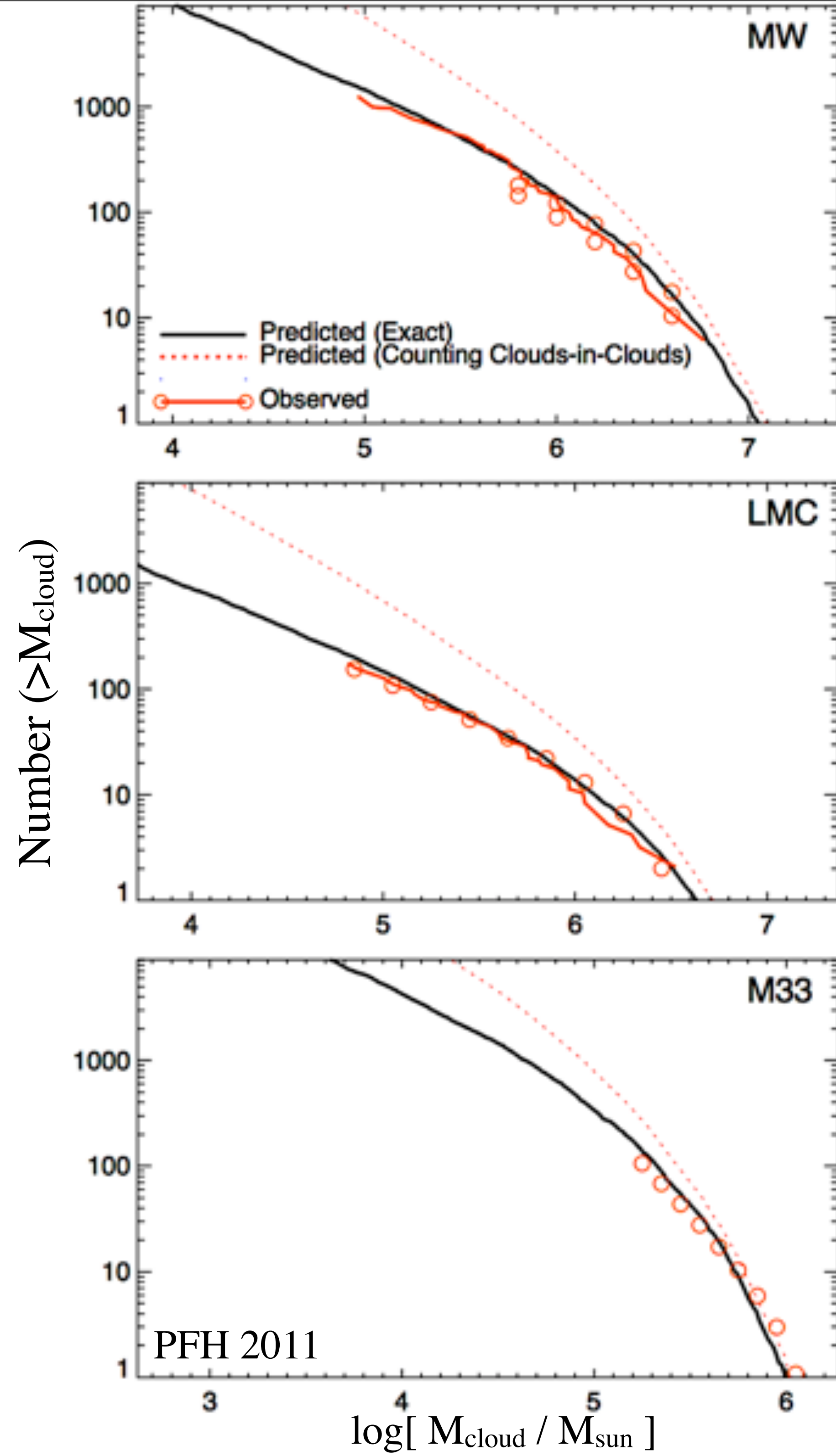

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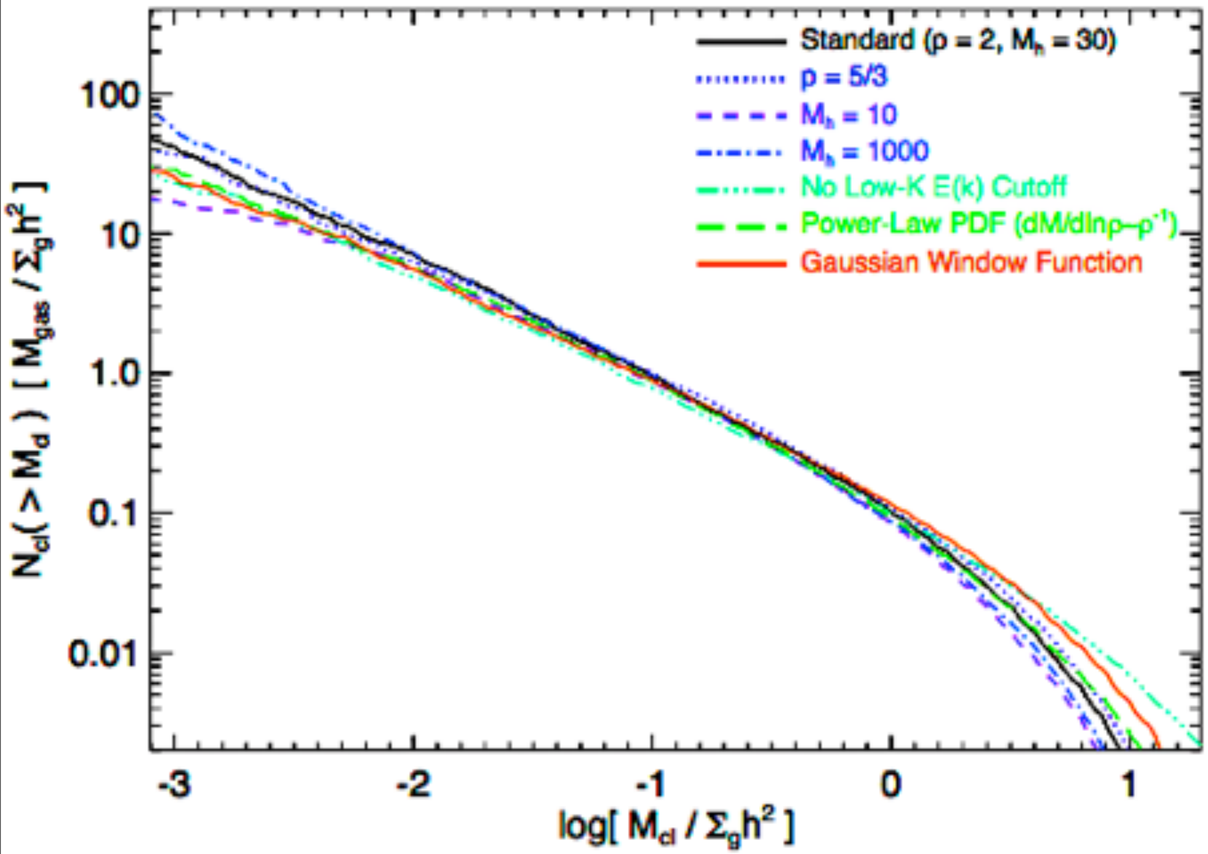
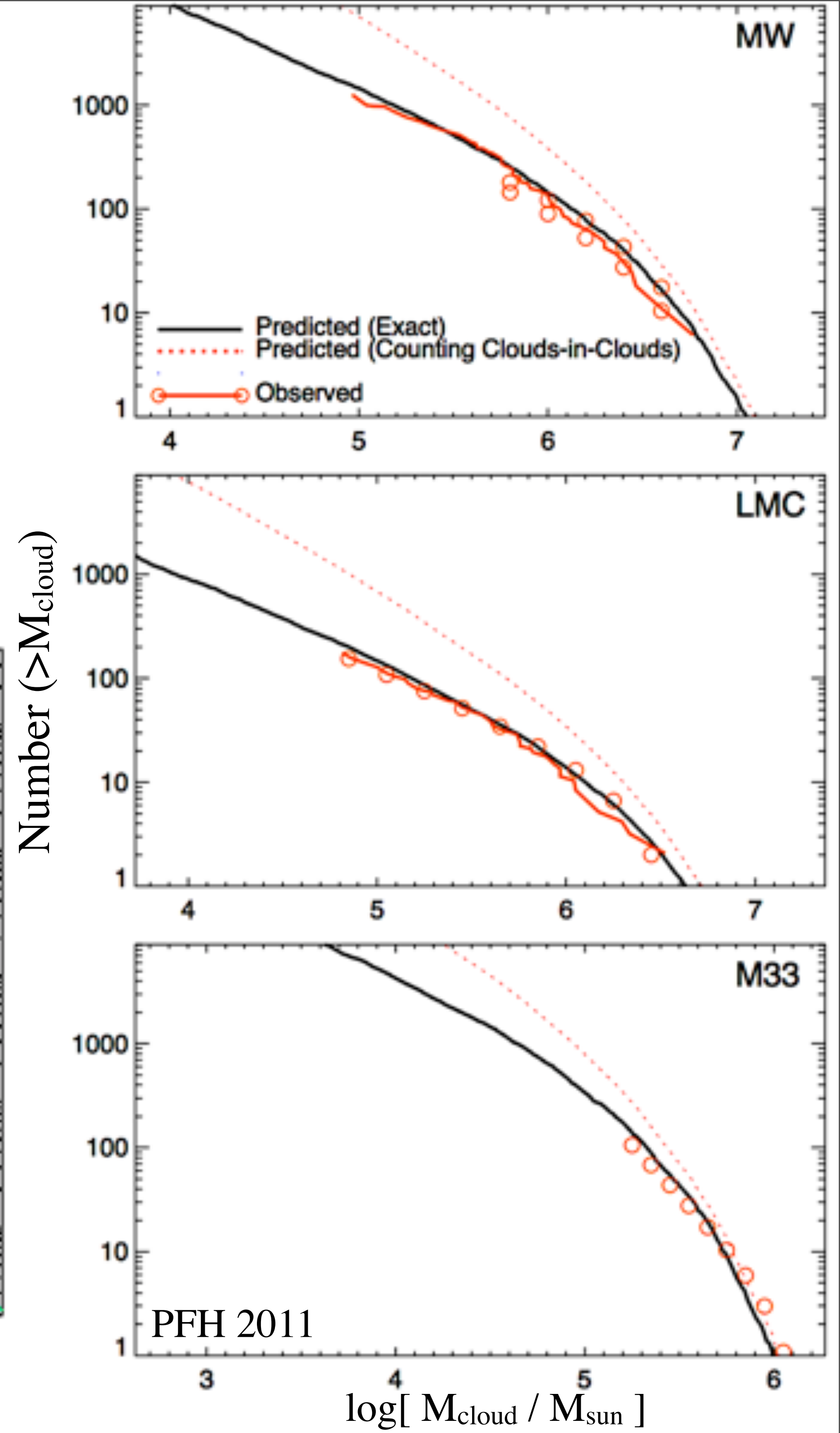
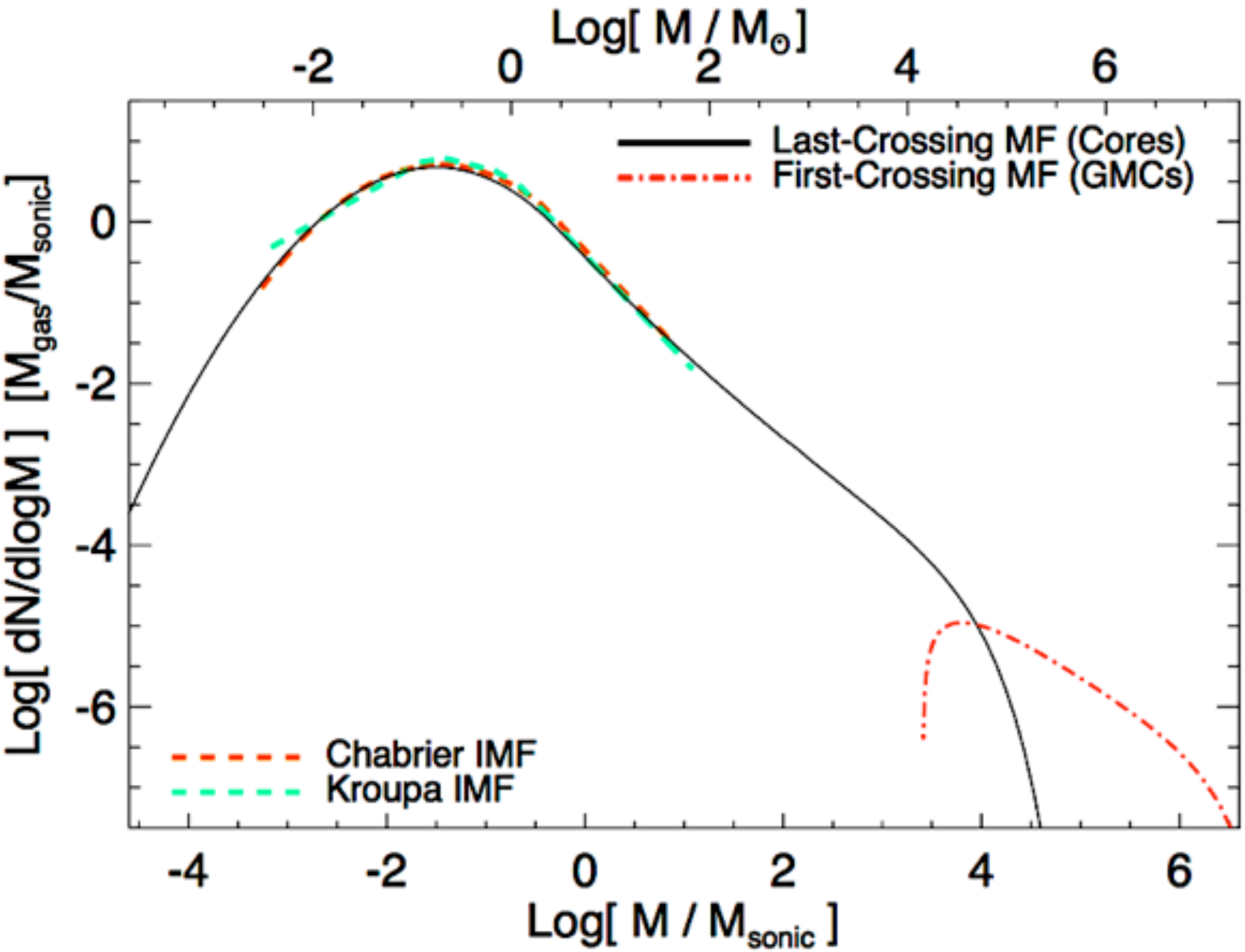




The "Last Crossing" Mass Function

VS PROTOSTELLAR CORES & THE STELLAR IMF



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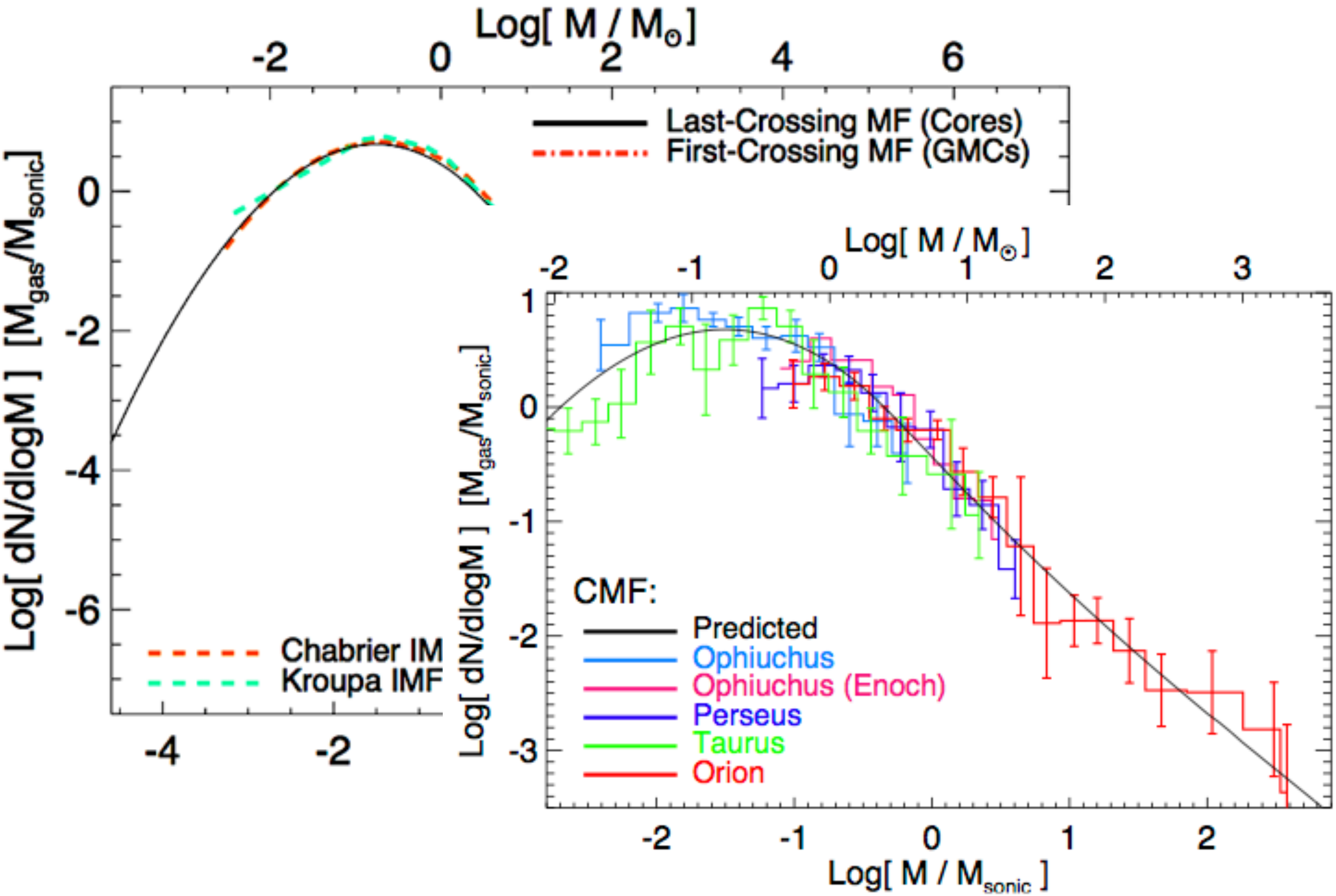

The “Last Crossing” Mass Function

VS PROTOSTELLAR CORES & THE STELLAR IMF

For $r \ll \ell_{\rm GMC} \ll h$ this becomes Hennebelle-Chabrier theory:

$$\mathcal{N}(\tilde{M}) = 2\mathcal{N}_0 \frac{1}{\tilde{R}^3} \frac{1}{1+(2\eta+1)\mathcal{M}_*^2\tilde{R}^{2\eta}} \frac{1+(1-\eta)\mathcal{M}_*^2\tilde{R}^{2\eta}}{\left(1+\mathcal{M}_*^2\tilde{R}^{2\eta}\right)^{3/2}} \times \exp\left\{-\frac{\left[\ln\left(\tilde{M}/\tilde{R}^3\right)\right]^2}{2\sigma^2}\right\} \frac{\exp(-\sigma^2/8)}{\sqrt{2\pi}\sigma},$$

The "Last Crossing" Mass Function

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$$\times \exp\left\{-\frac{\left[\ln\left(\tilde{M}/\tilde{R}^3\right)\right]^2}{2\sigma^2}\right\} \frac{\exp(-\sigma^2/8)}{\sqrt{2\pi}\sigma},$$

... ***BUT***,

The "Last Crossing" Mass Function

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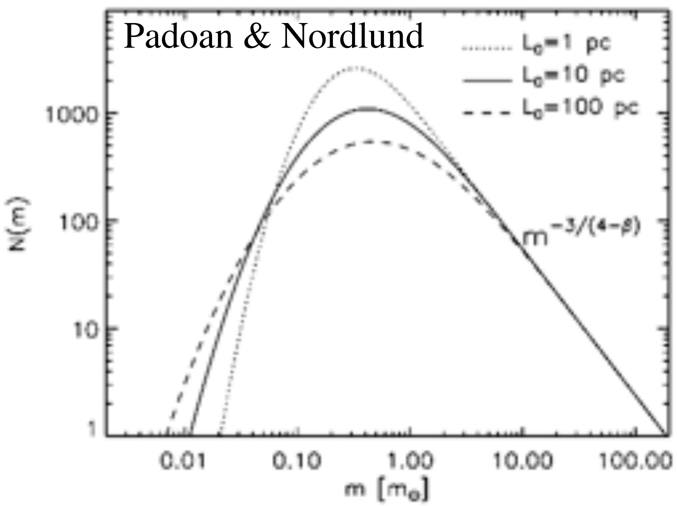
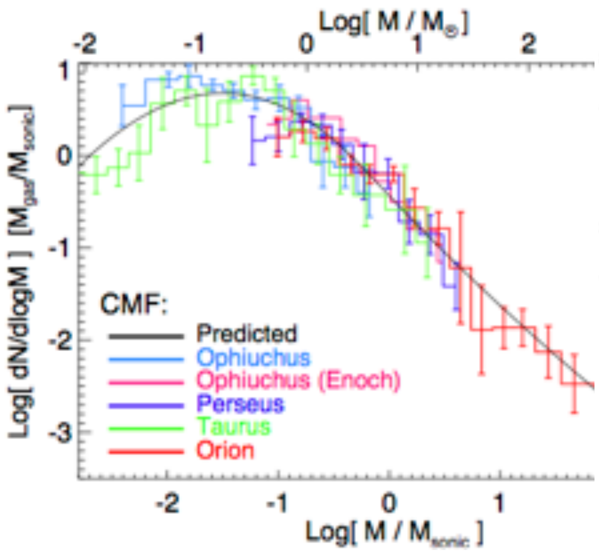
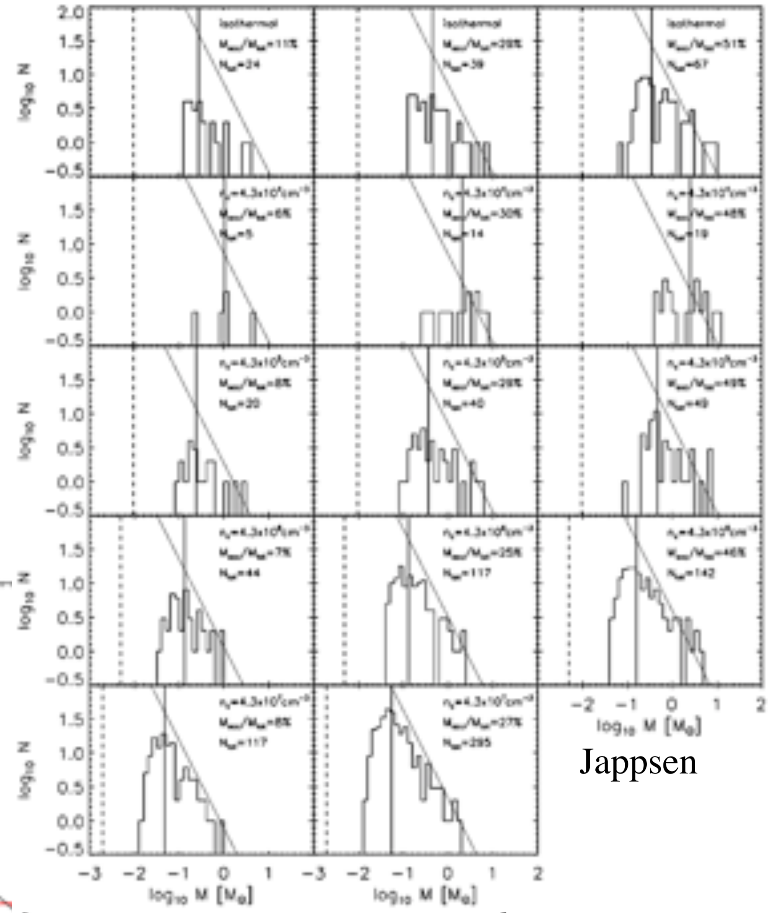
For $r \ll \ell_{\rm GMC} \ll h$ this becomes Hennebelle-Chabrier theory:

$$\mathcal{N}(\tilde{M}) = 2\mathcal{N}_0 \frac{1}{\tilde{R}^3} \frac{1}{1+(2\eta+1)\mathcal{M}_*^2\tilde{R}^{2\eta}} \frac{1+(1-\eta)\mathcal{M}_*^2\tilde{R}^{2\eta}}{\left(1+\mathcal{M}_*^2\tilde{R}^{2\eta}\right)^{3/2}}$$
$$\times \exp\left\{-\frac{\left[\ln\left(\tilde{M}/\tilde{R}^3\right)\right]^2}{2\sigma^2}\right\} \frac{\exp(-\sigma^2/8)}{\sqrt{2\pi}\sigma},$$

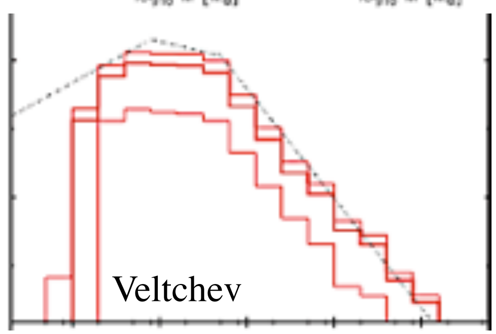
... ***BUT***,







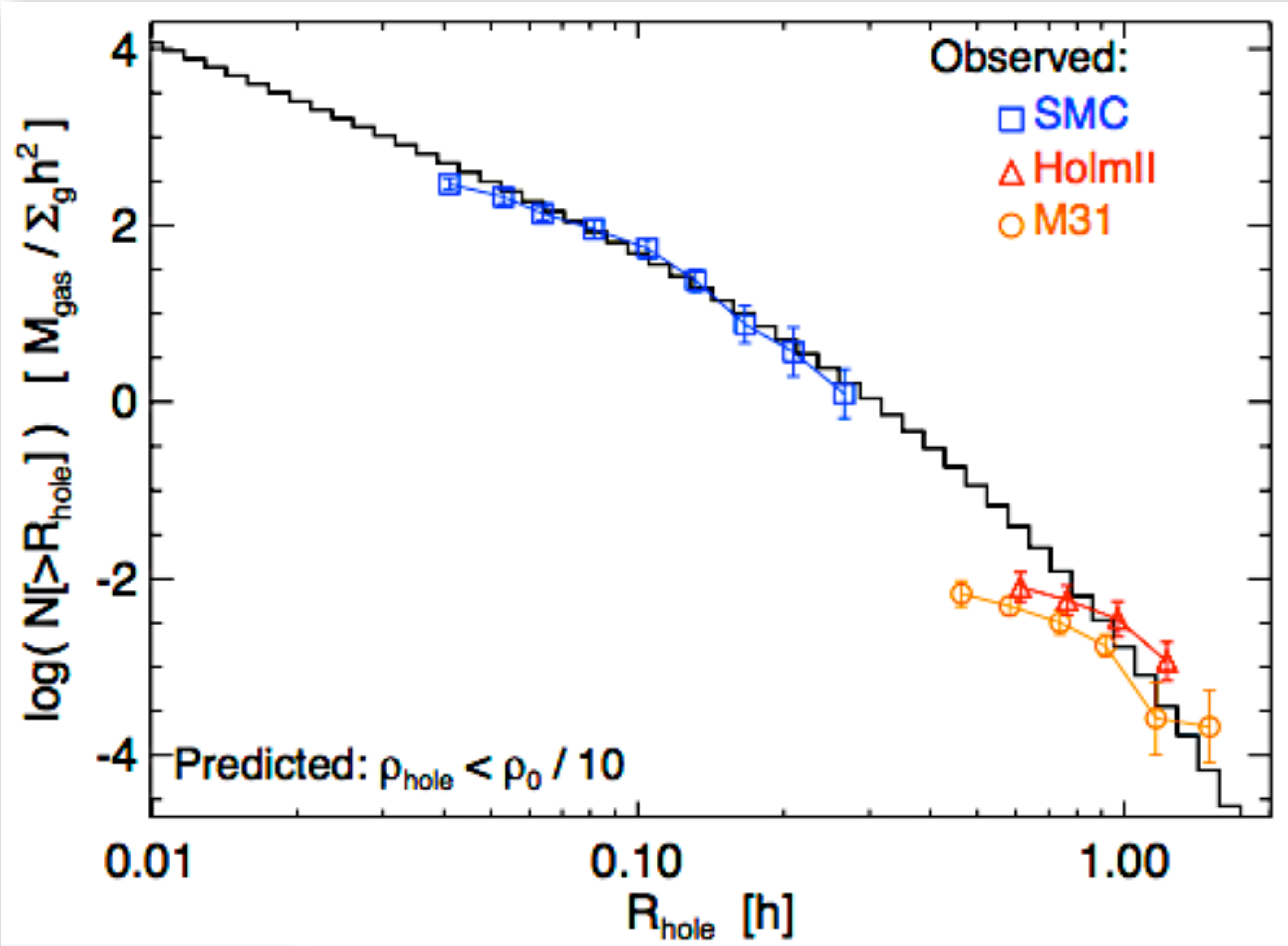
Jappsen



Bate & Bonnell 2005 (Accretion-Ejection)
Larson 1992 (Fractal collapse)
Elmegreen 1997 (Fractal GMCs)
Padoan & Nordlund (Turb. Frag.)
Hennebelle & Chabrier (Press-Schechter)
Veltchev+ 2011 (Clump mass-density + turb + accretion)

“Void” Abundance

VS HI “HOLES” IN THE ISM

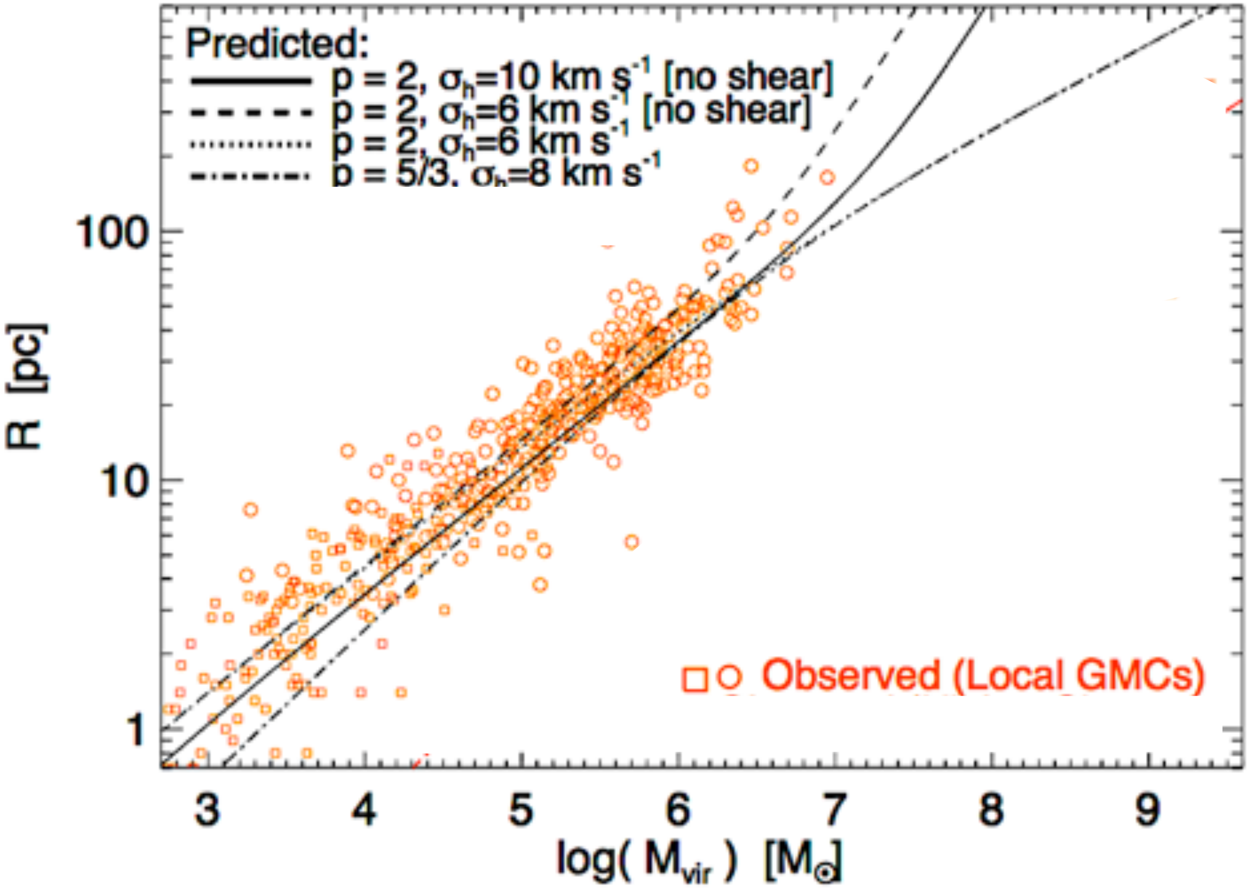


KEEP?

Voids follow same GMC/IMF slope!

Structural Properties of “Clouds”

LARSON’S LAWS EMERGE NATURALLY



KEEP?

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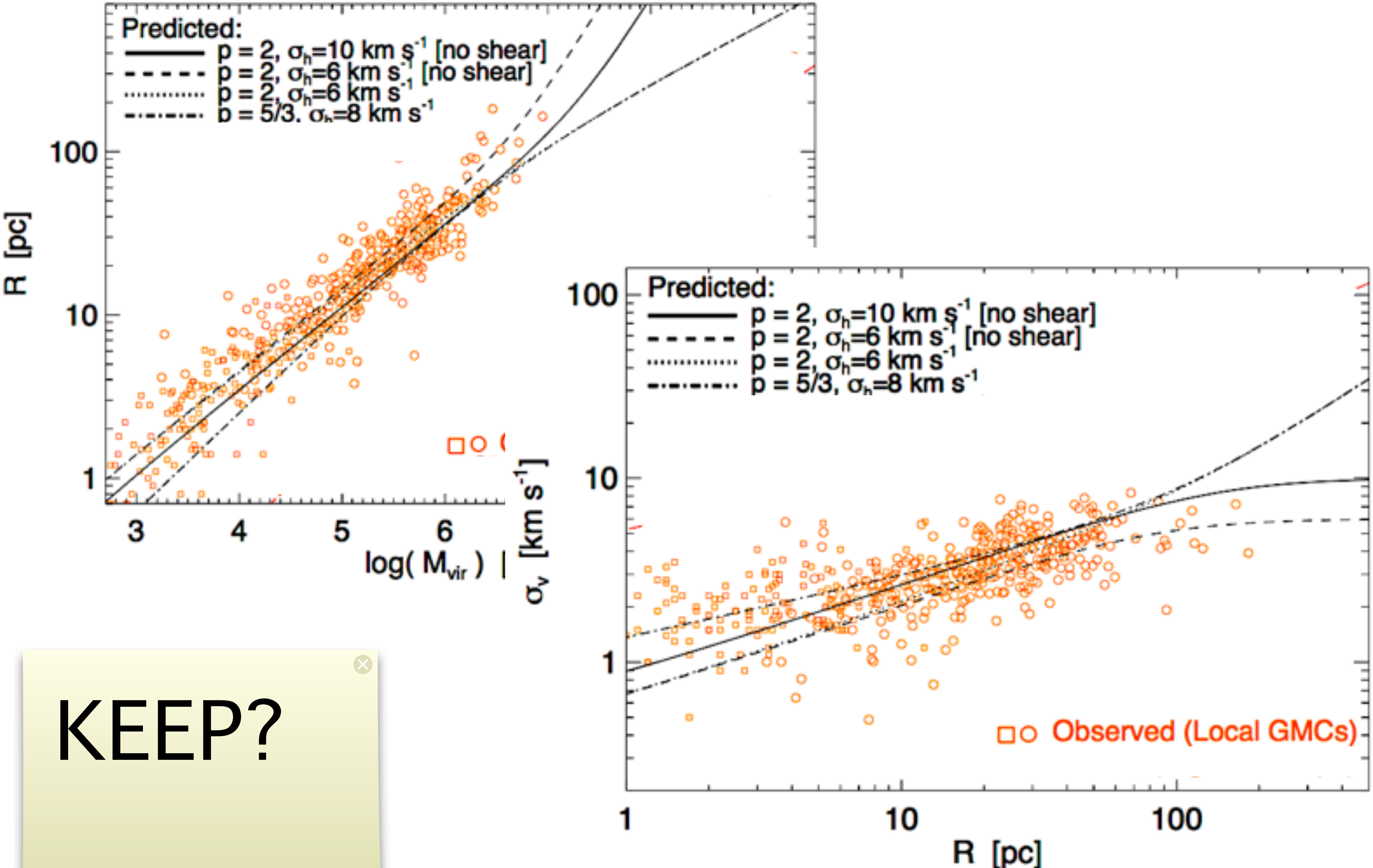


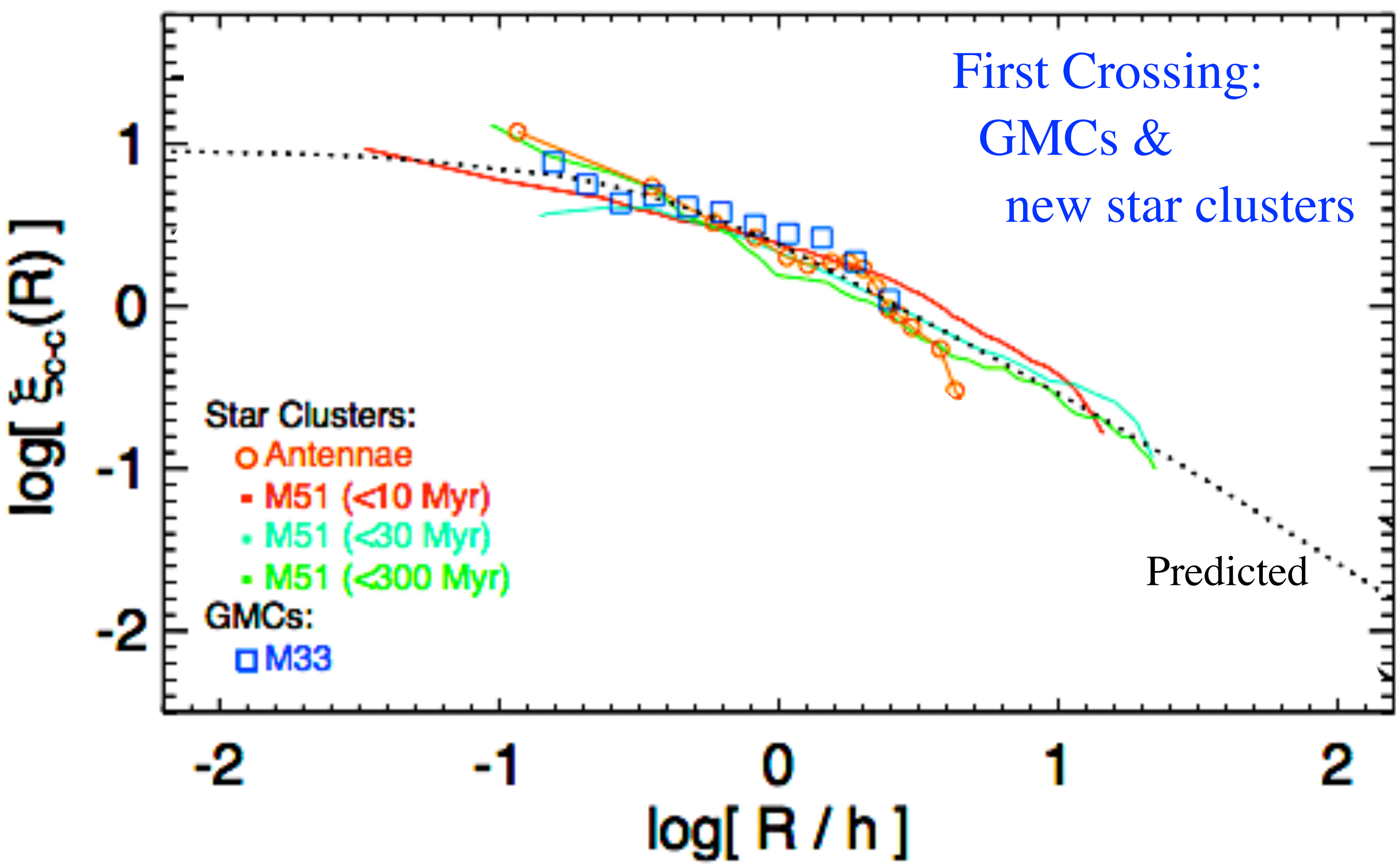
KEEP?

PFH 2011

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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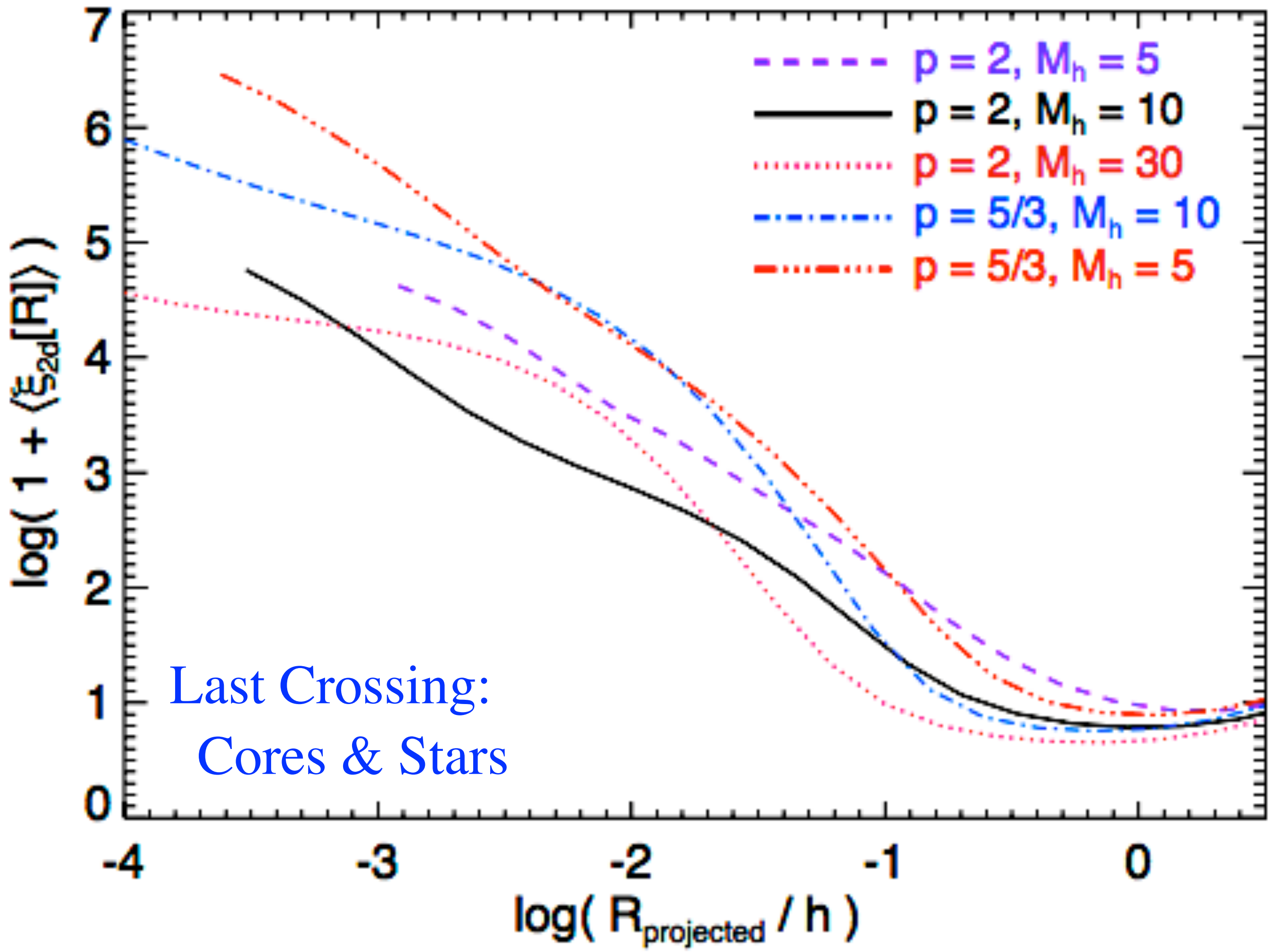
PFH 2012b



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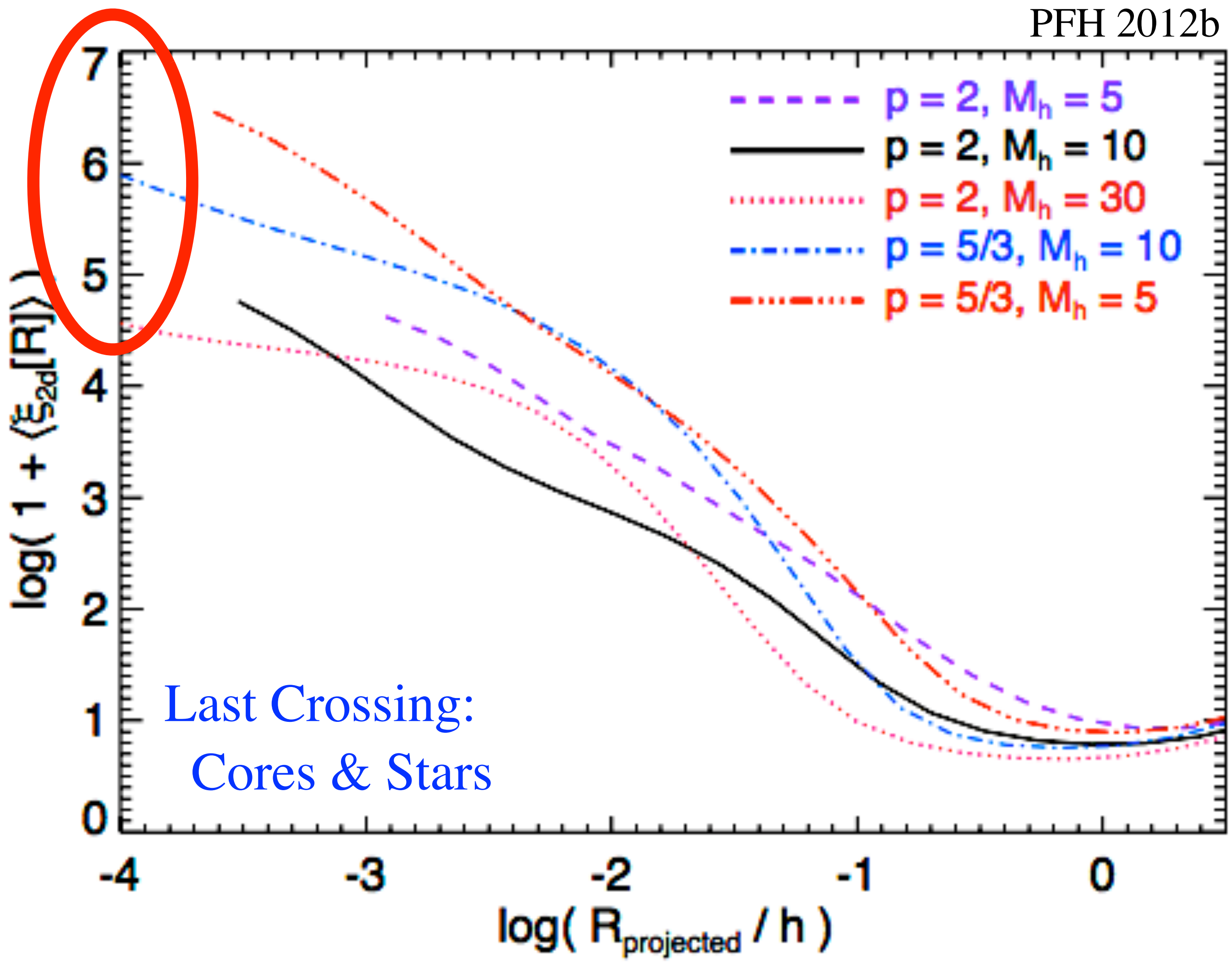

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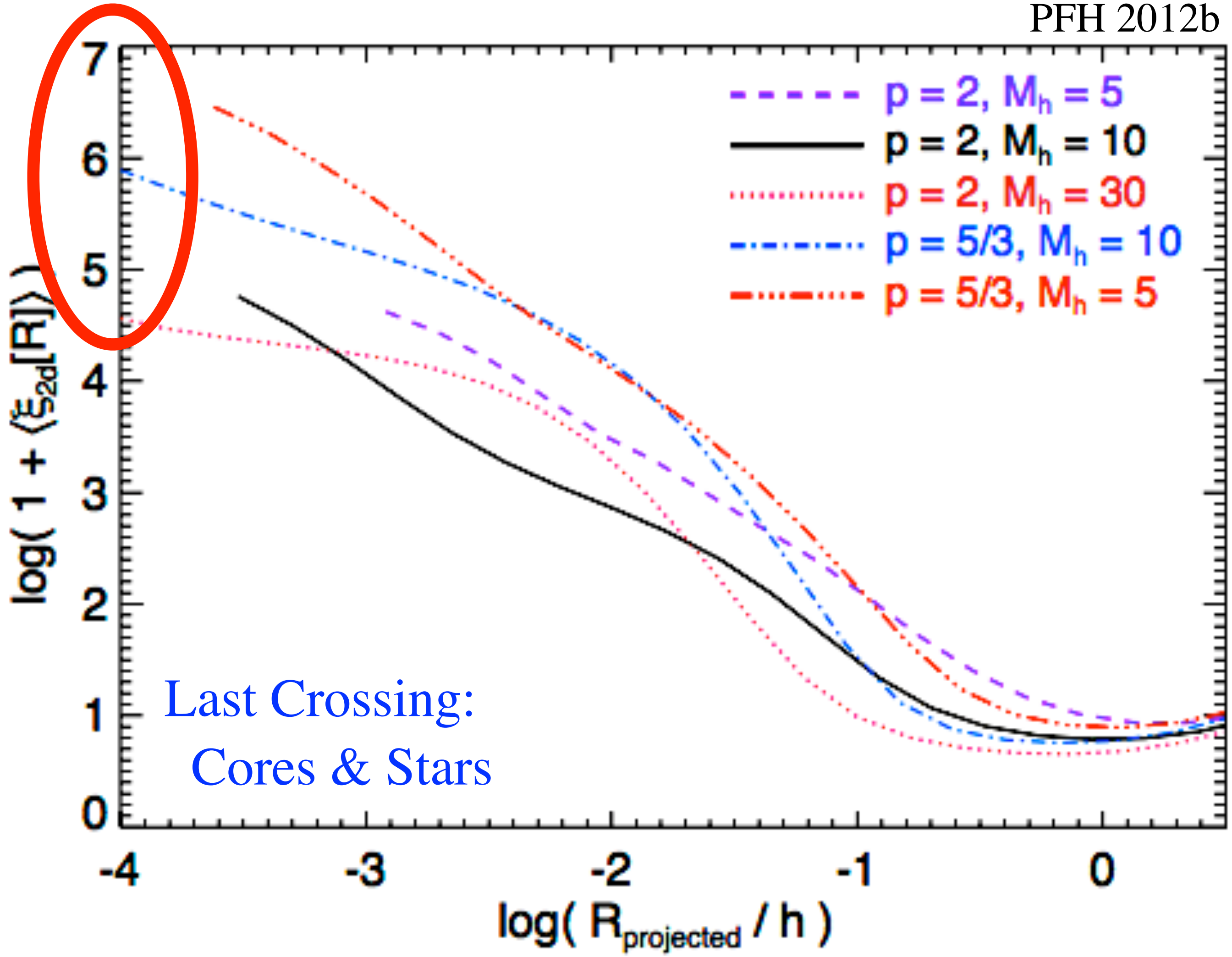
PFH 2012b

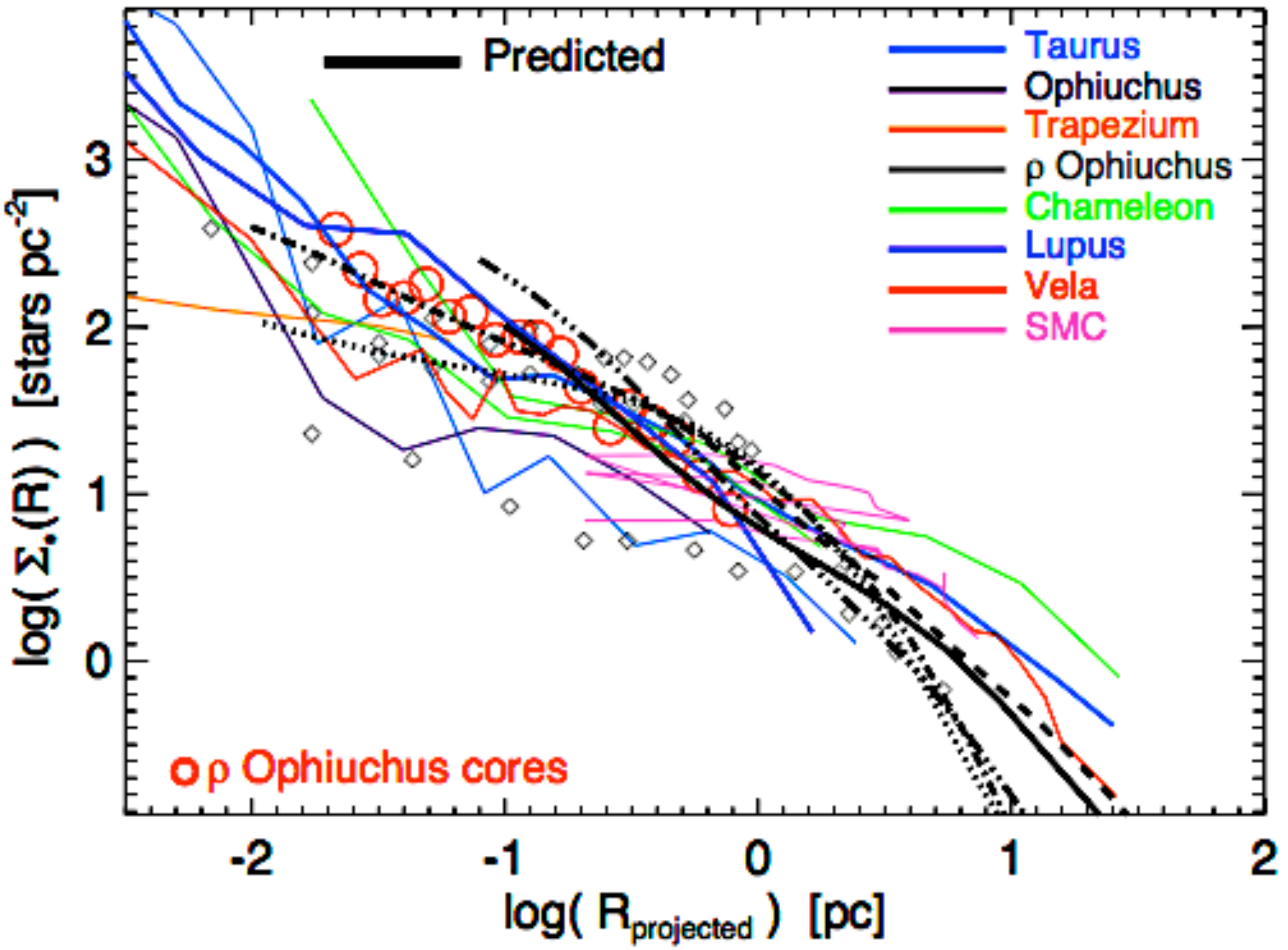
Why is Star Formation Clustered?

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

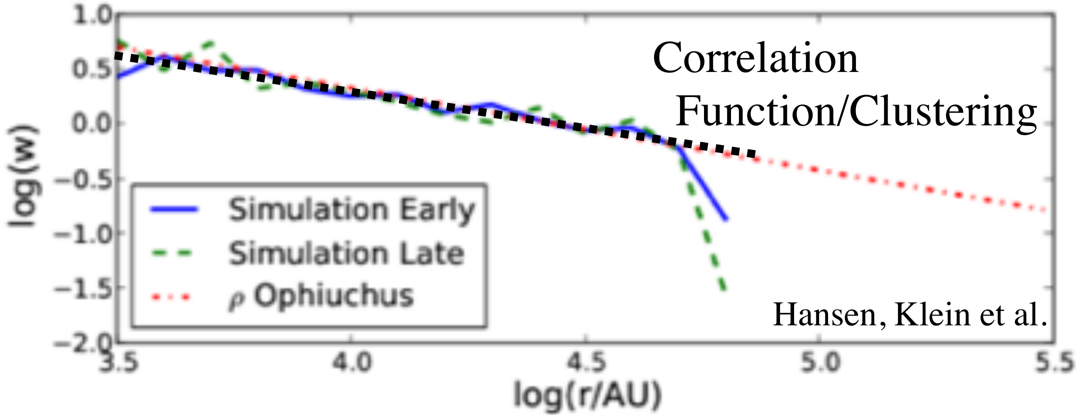


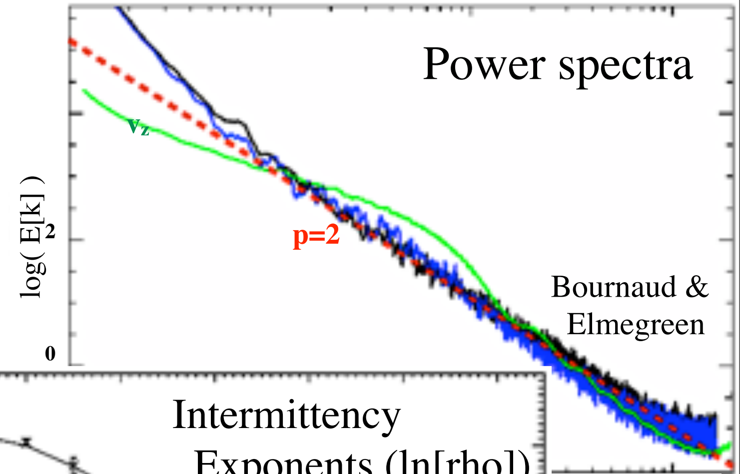
Clustering of Stars: Predicted vs. Observations

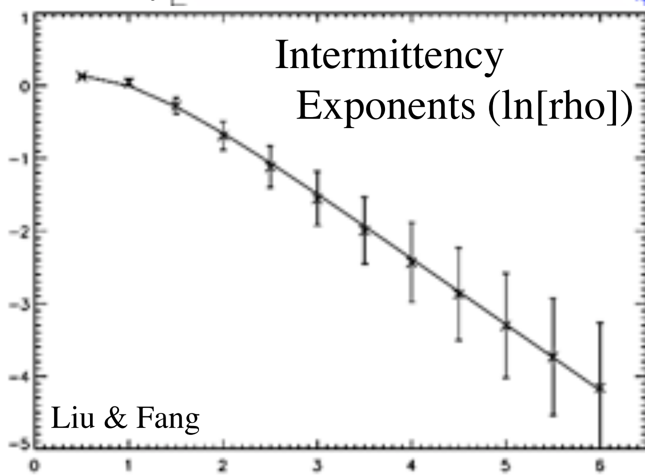
PREDICT N-POINT CORRELATION FUNCTIONS

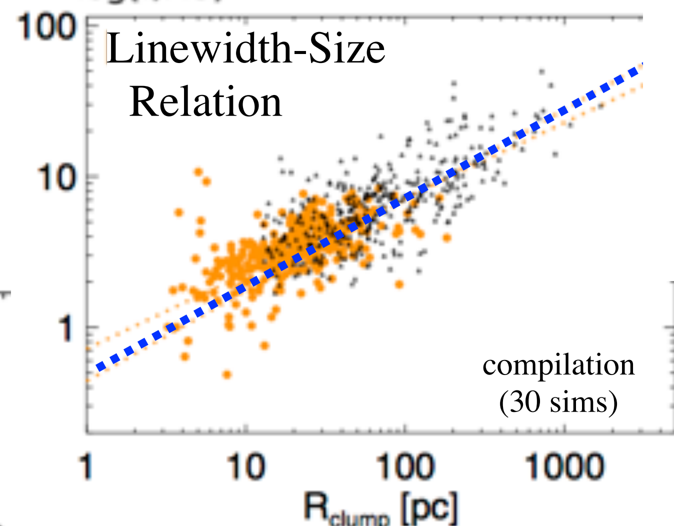


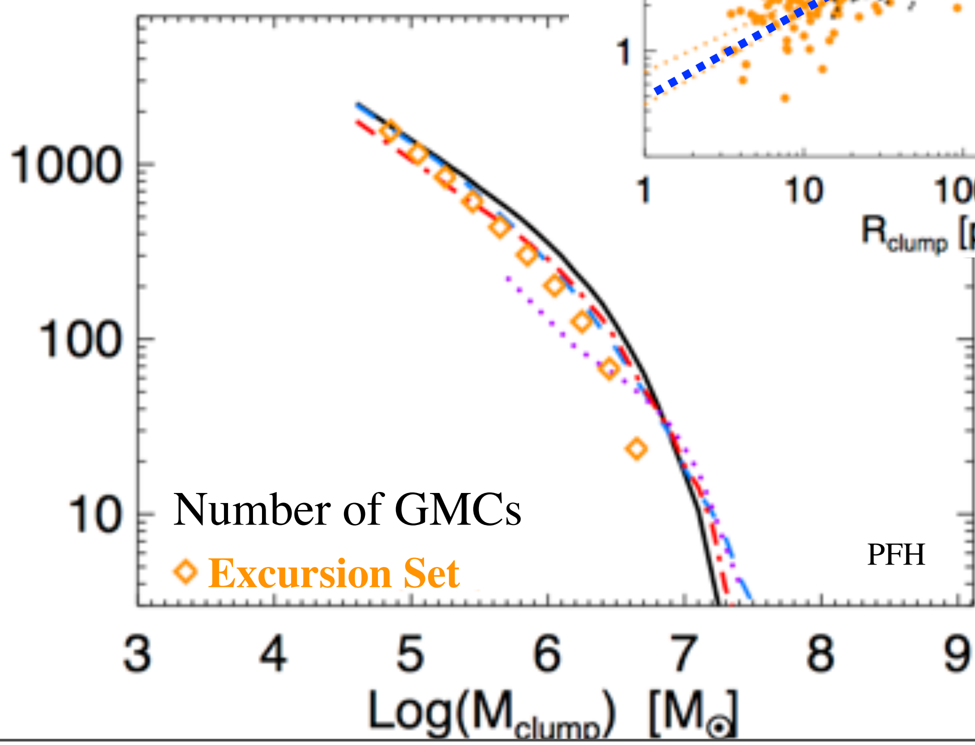
Testing the Analytics
vs. NUMERICAL SIMULATIONS

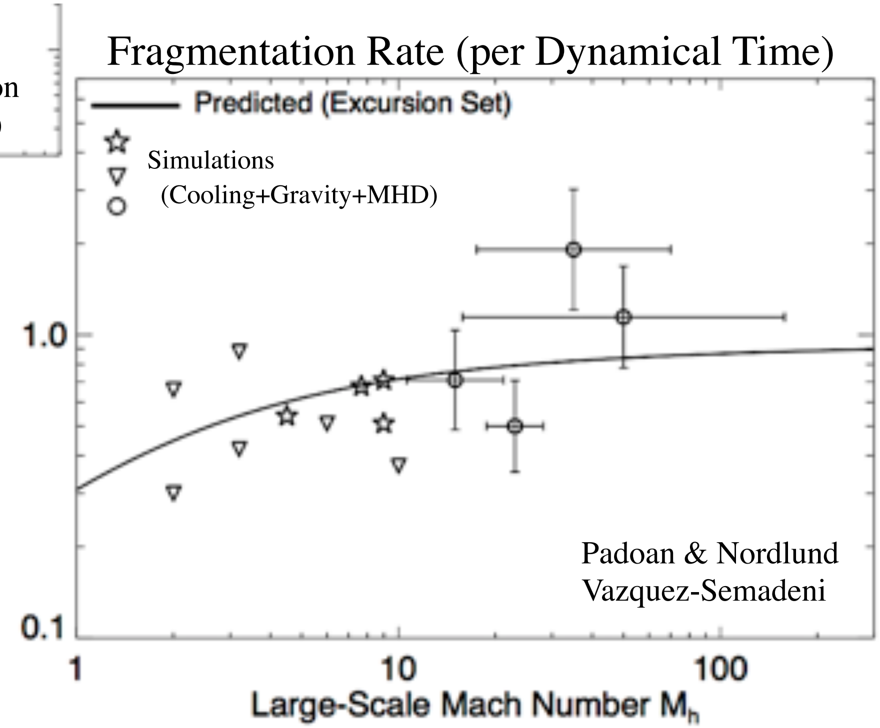








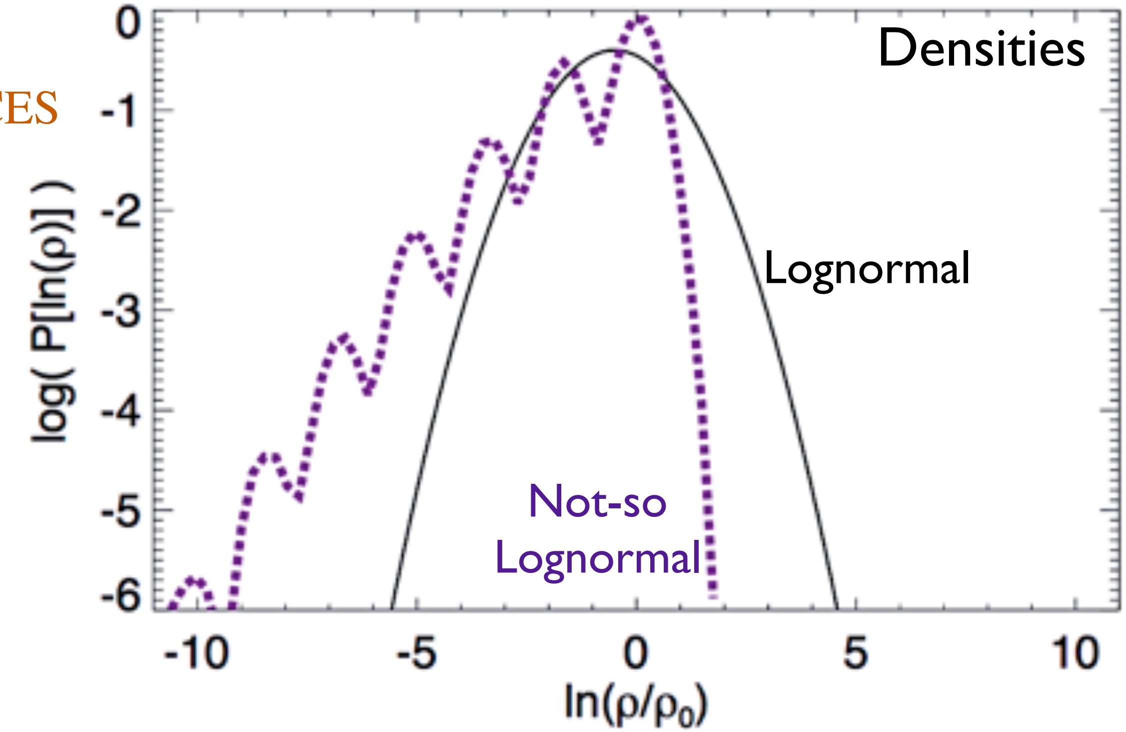


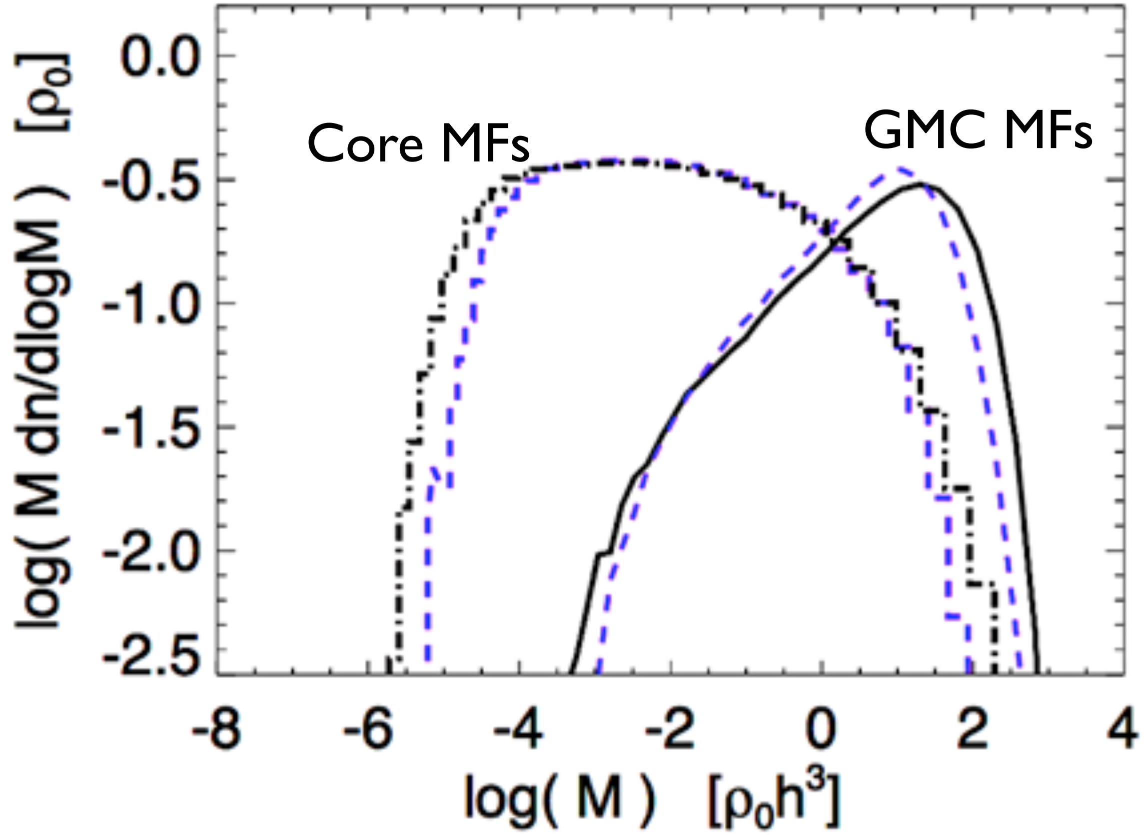


General, Flexible Theory:

EXTREMELY ADAPTABLE TO MOST CHOICES

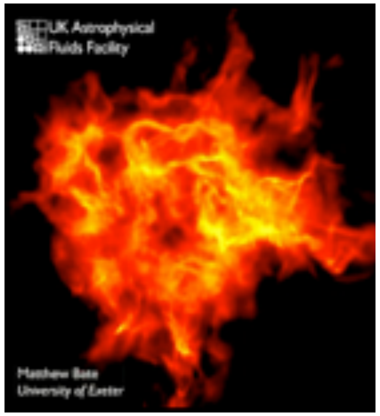
- Complicated, multivariable gas equations of state
- Accretion
- Magnetic Fields
- Time-Dependent Background Evolution/Collapse
- Intermittency
- Correlated, multi-scale driving





What Can We Say About Galactic-Scale IMF Variation?

Variation in the Mass Function & the Jeans Mass



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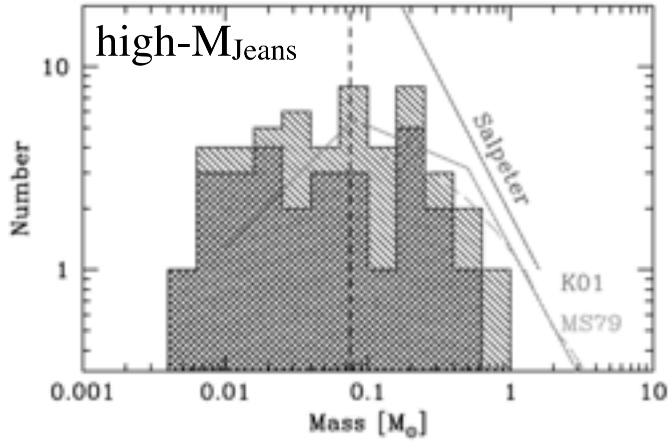

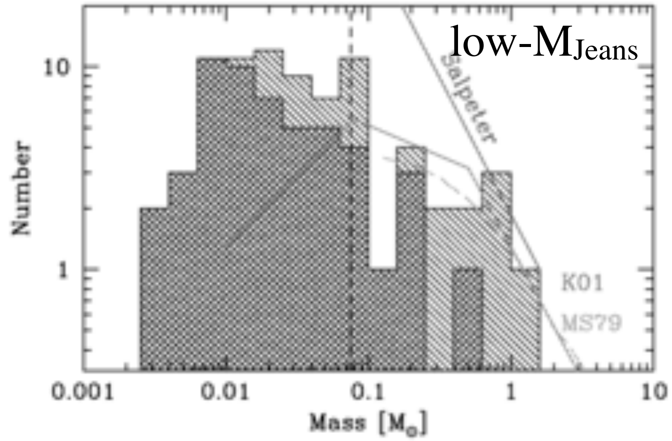

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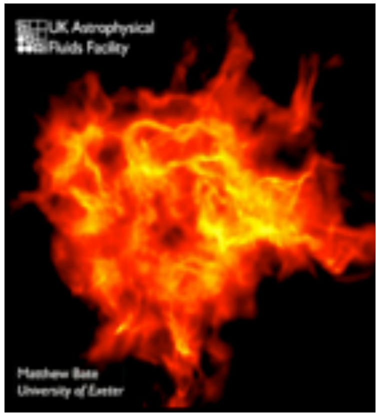

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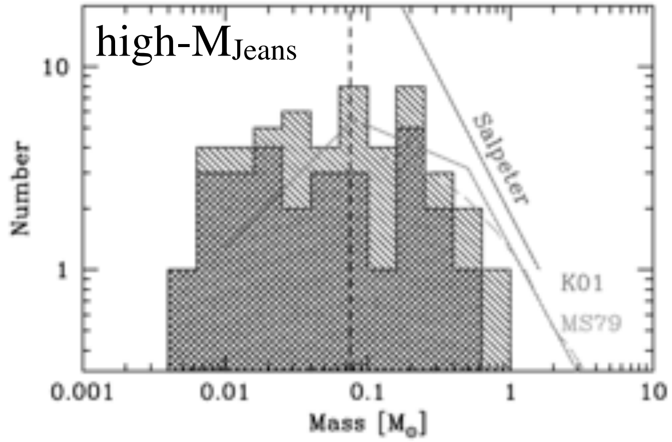

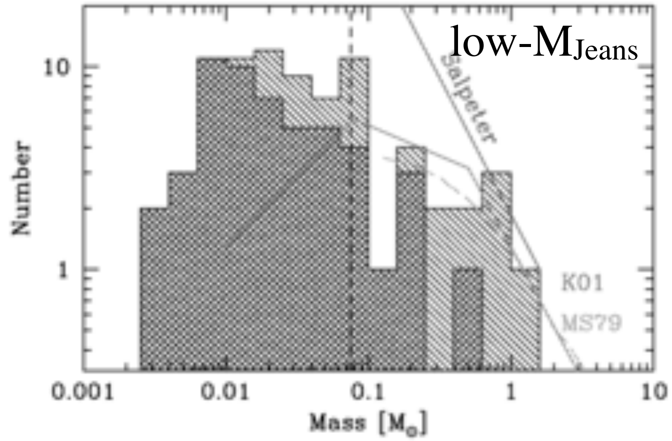

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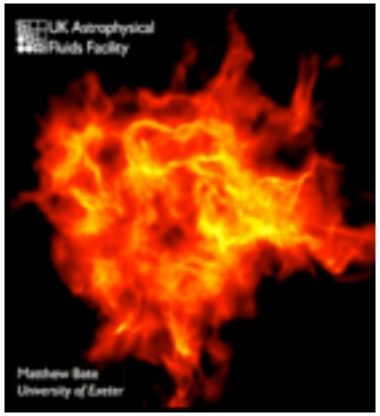

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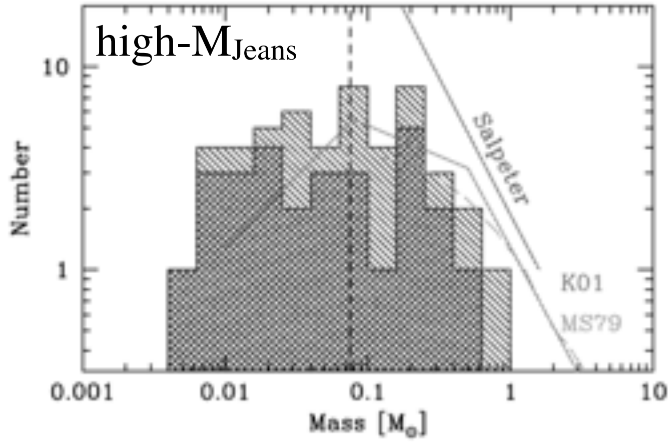

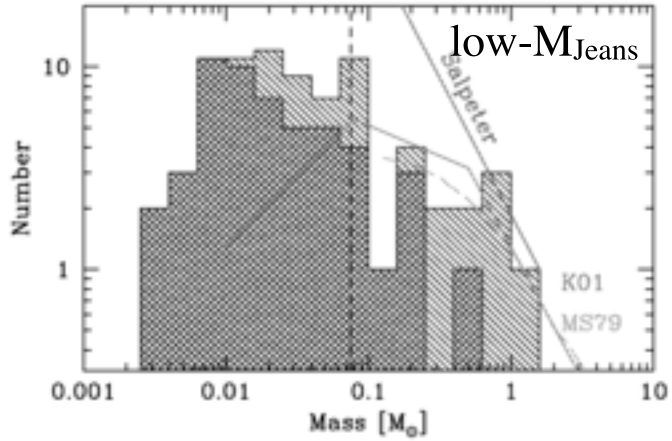

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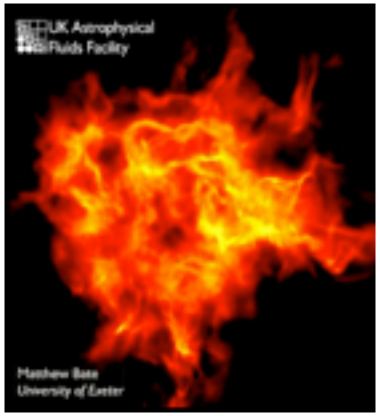

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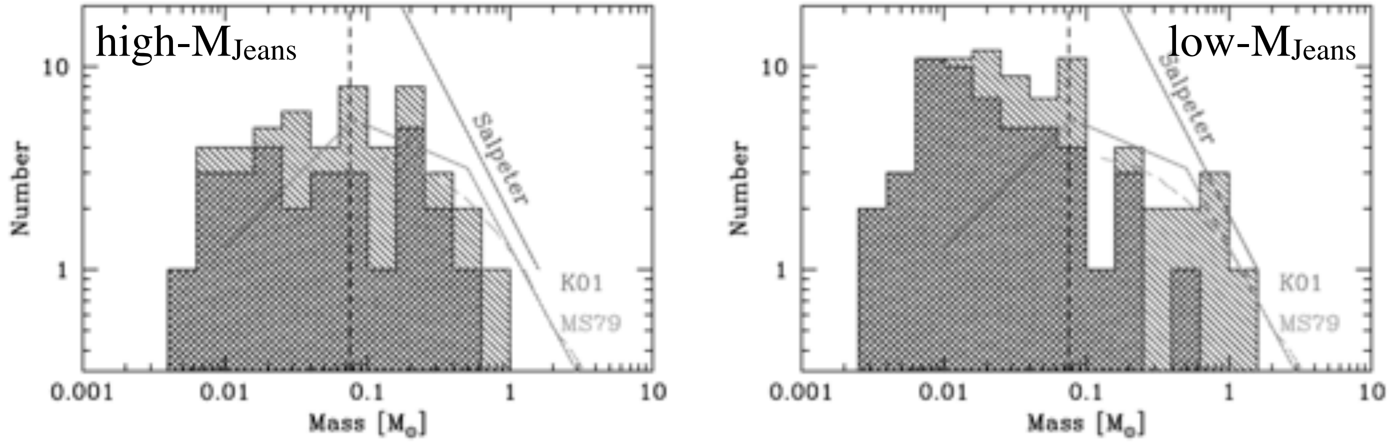

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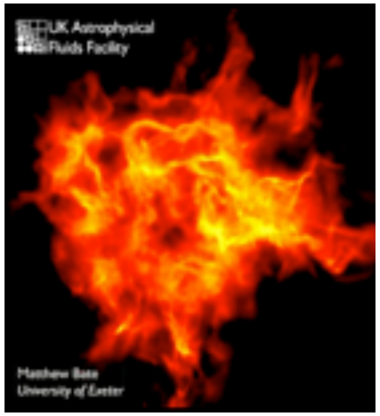

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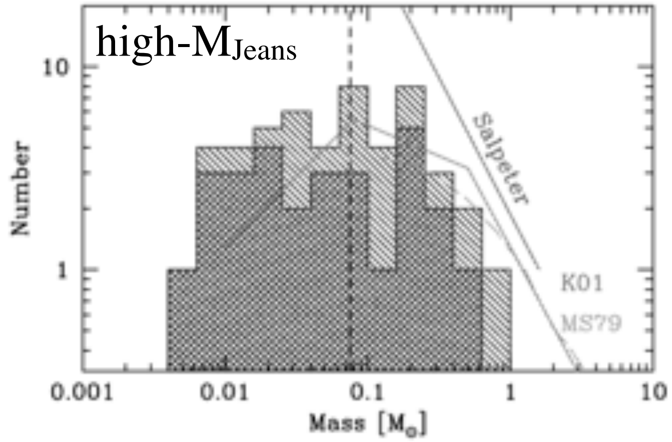

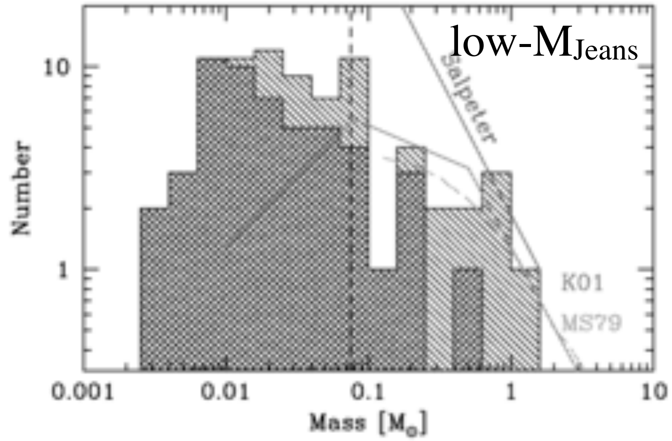

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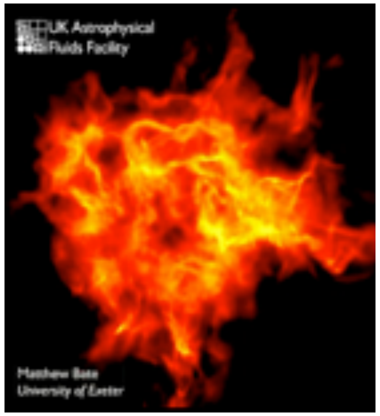

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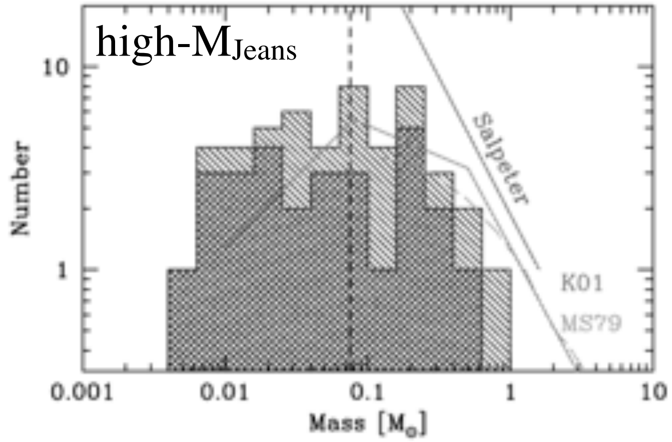

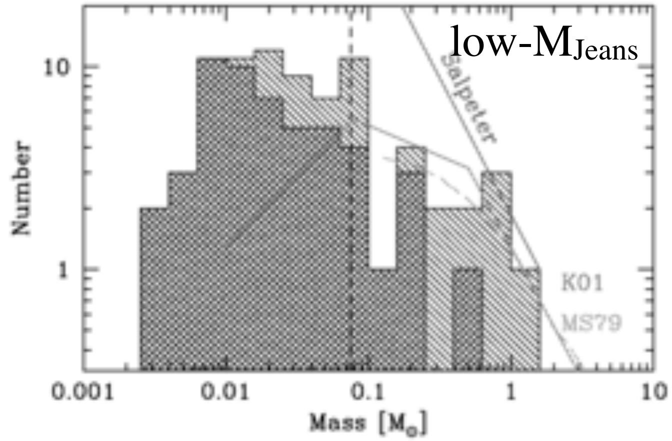

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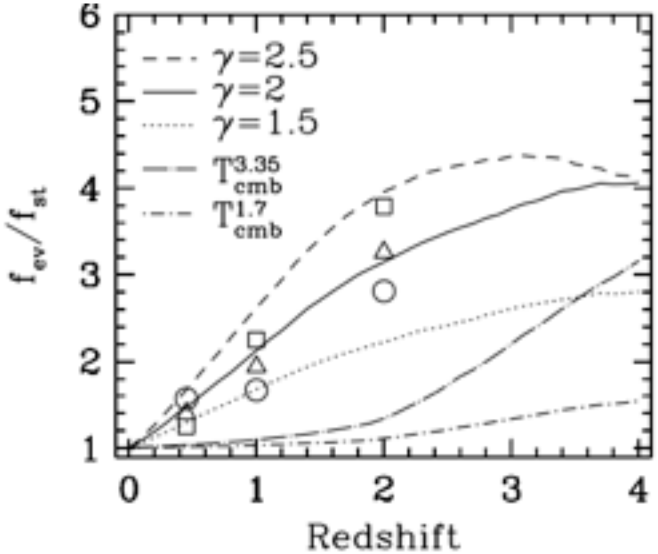

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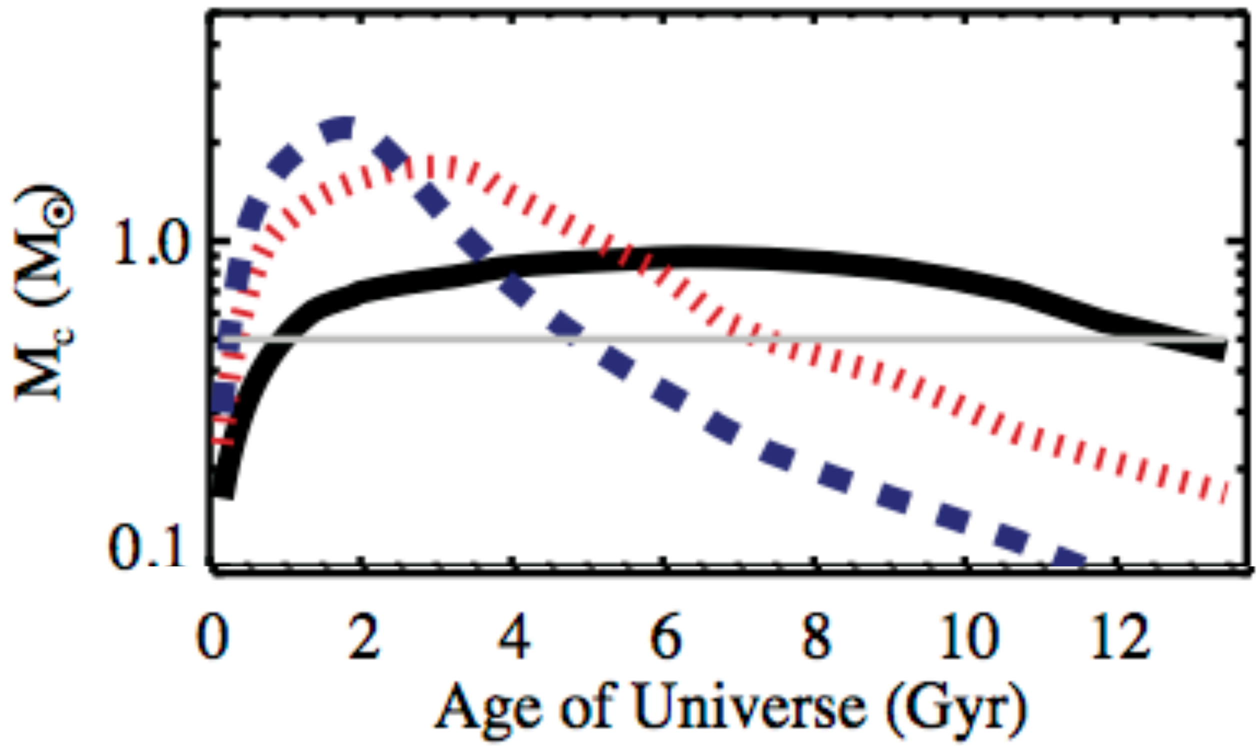
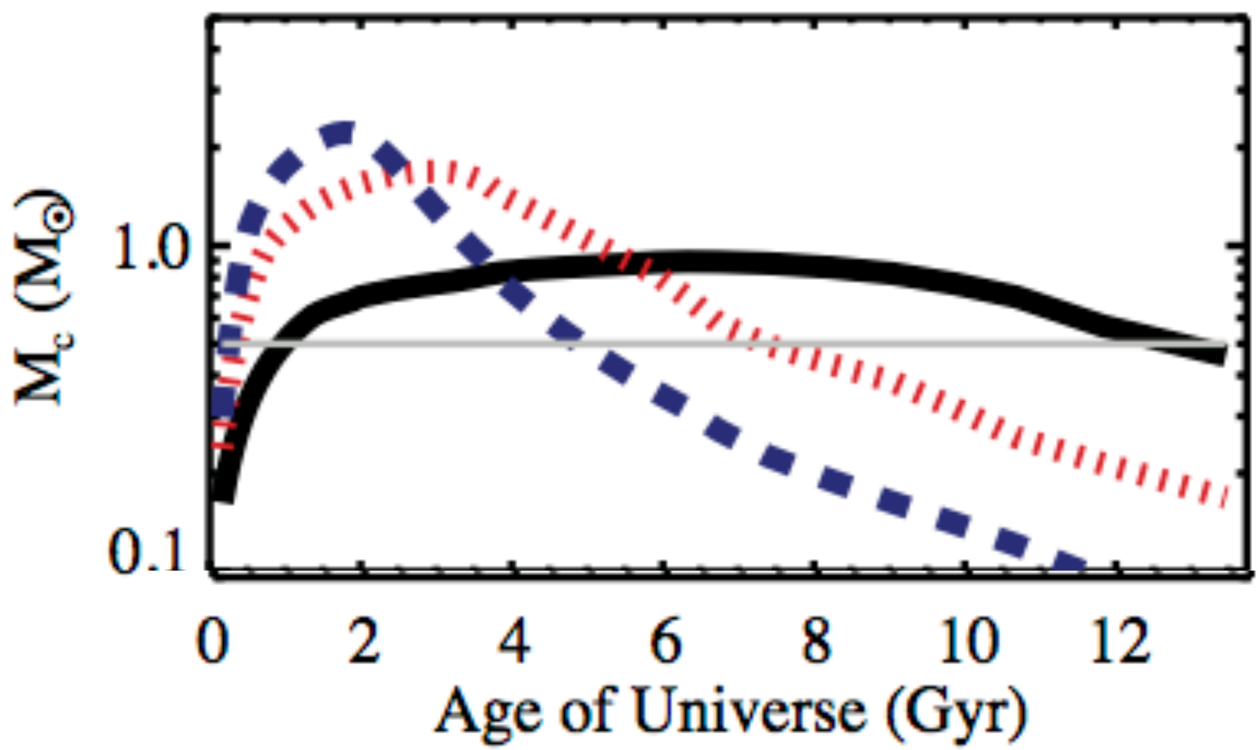


Variation in the Mass Function & the Jeans Mass

Narayanan 2012: estimate “mean” thermal state of clouds



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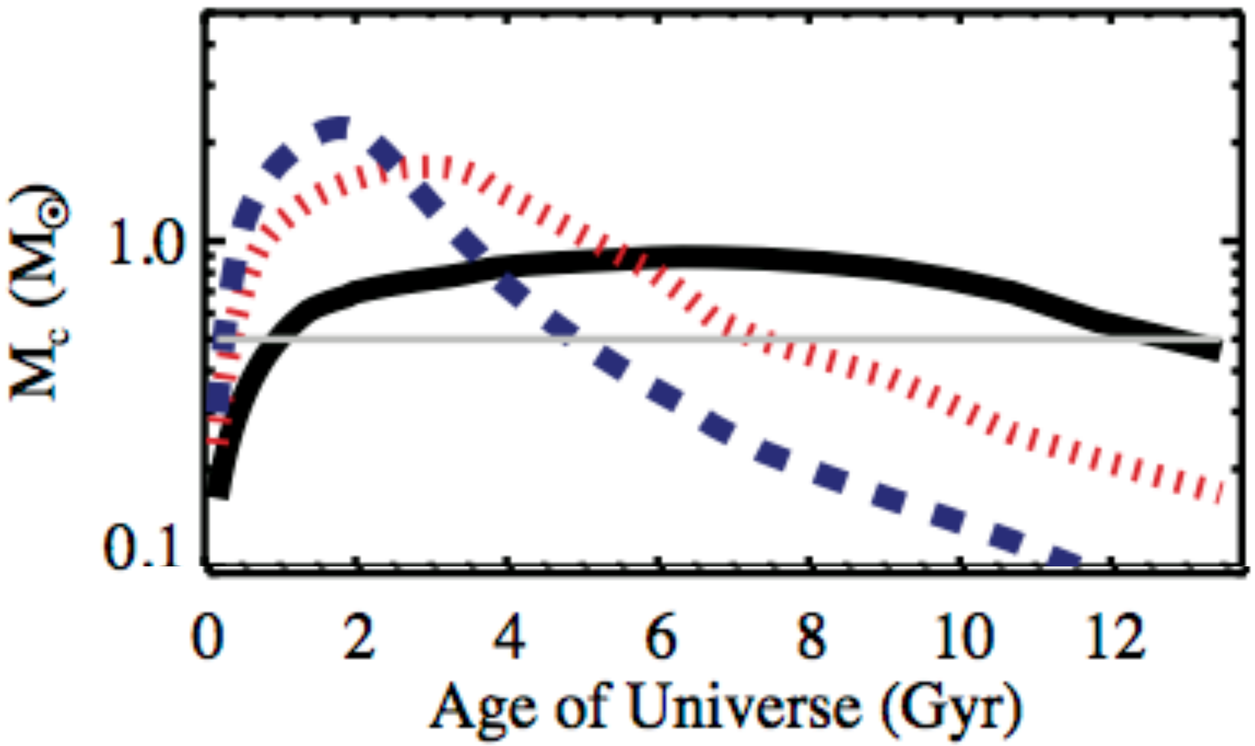

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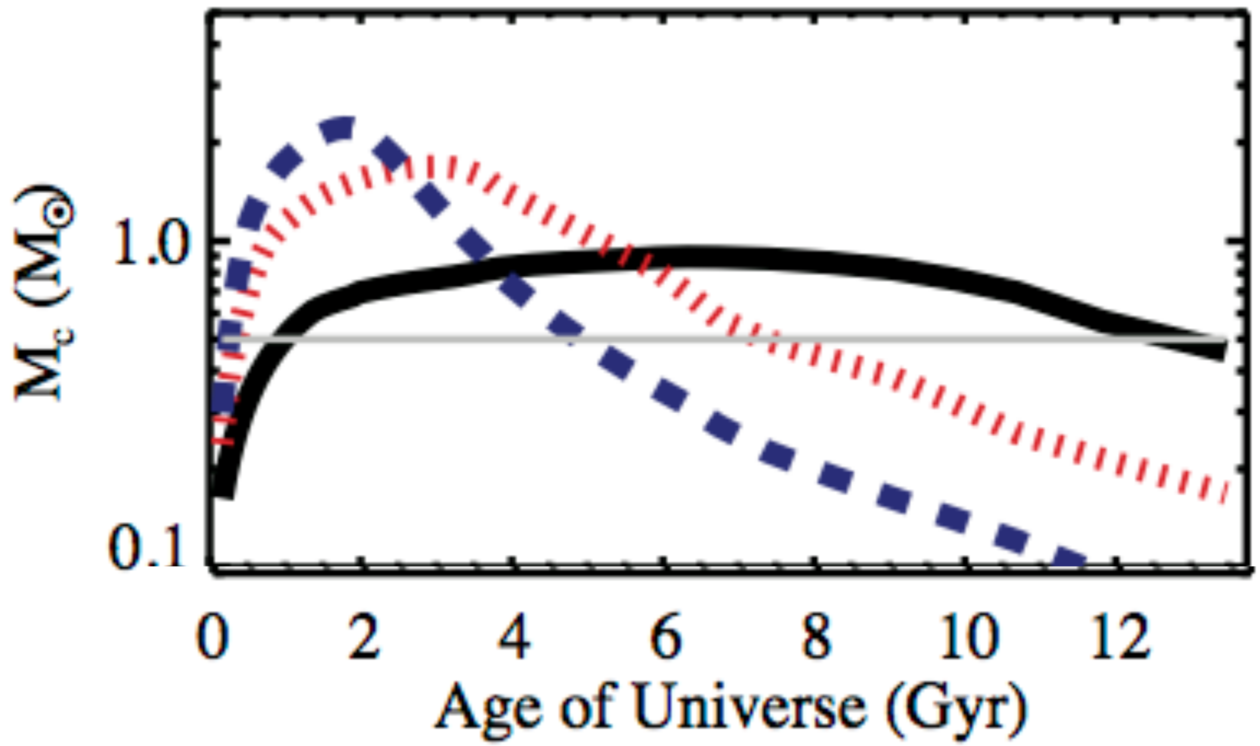

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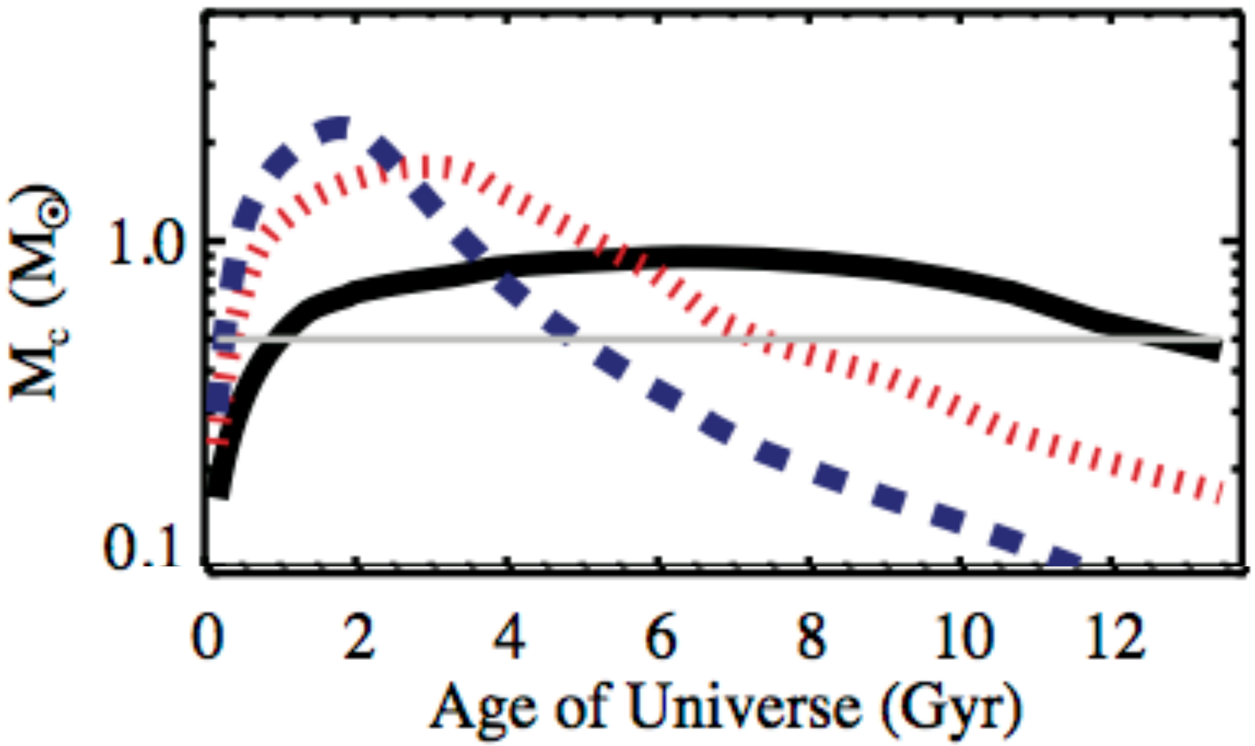

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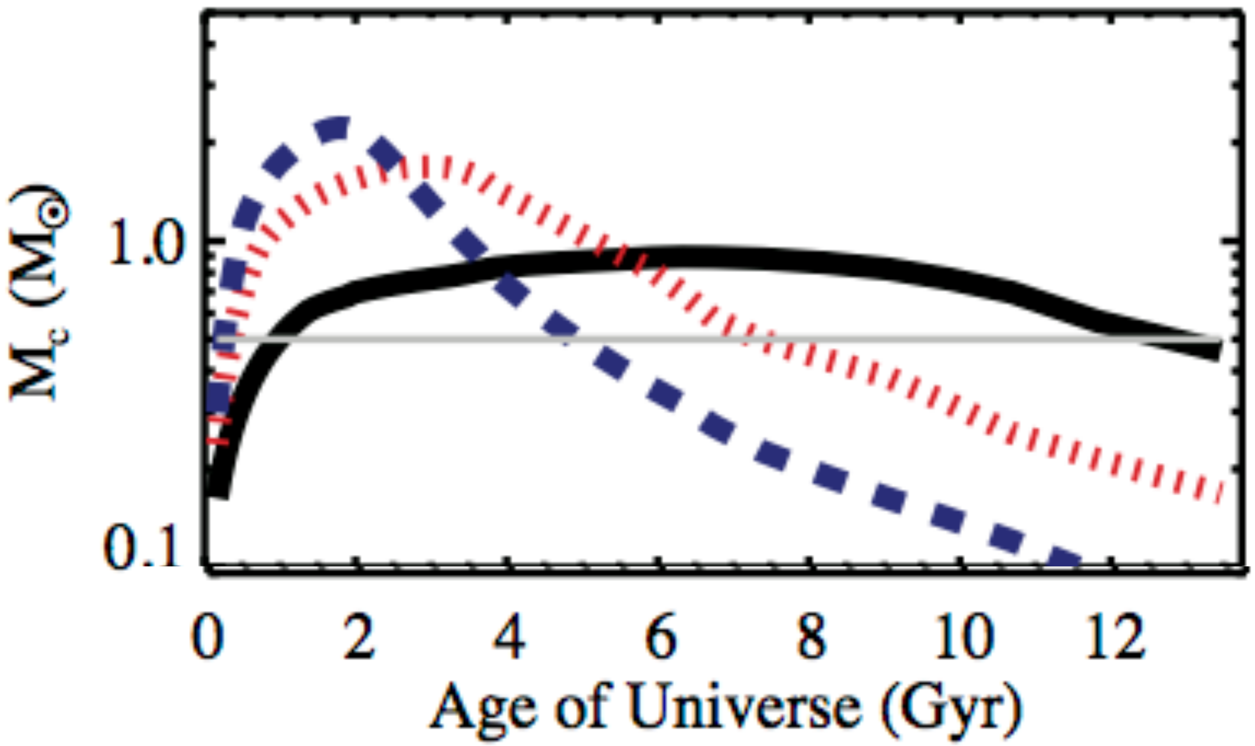
  - Observed (Downes & Solomon, Bryant & Scoville)



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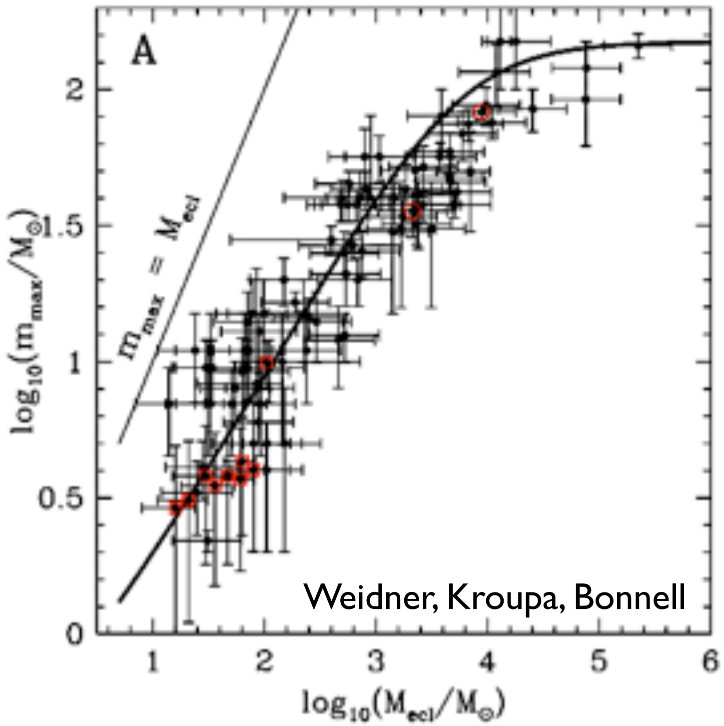
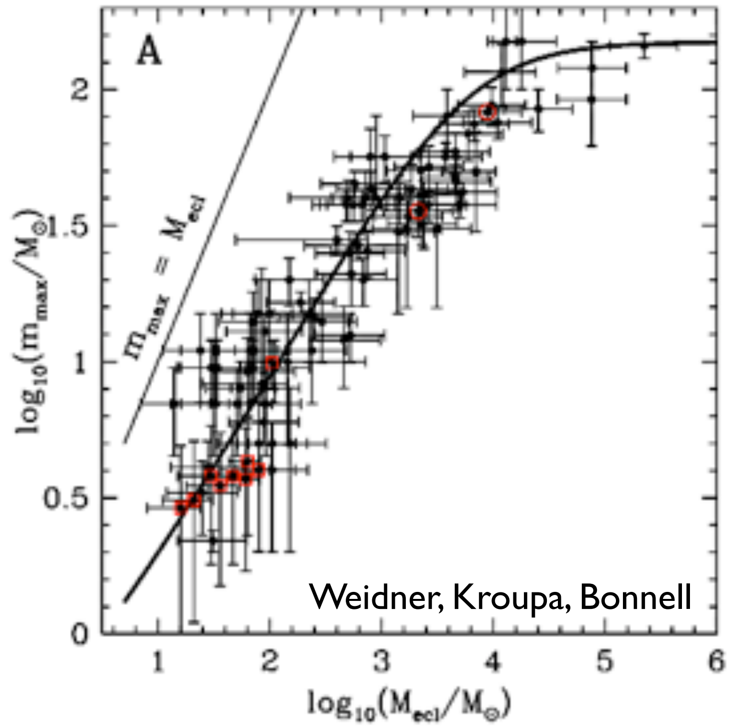


Variation in the Mass Function & the Jeans Mass

Kroupa, Weidner & Kroupa, et al. :



Variation in the Mass Function & the Jeans Mass

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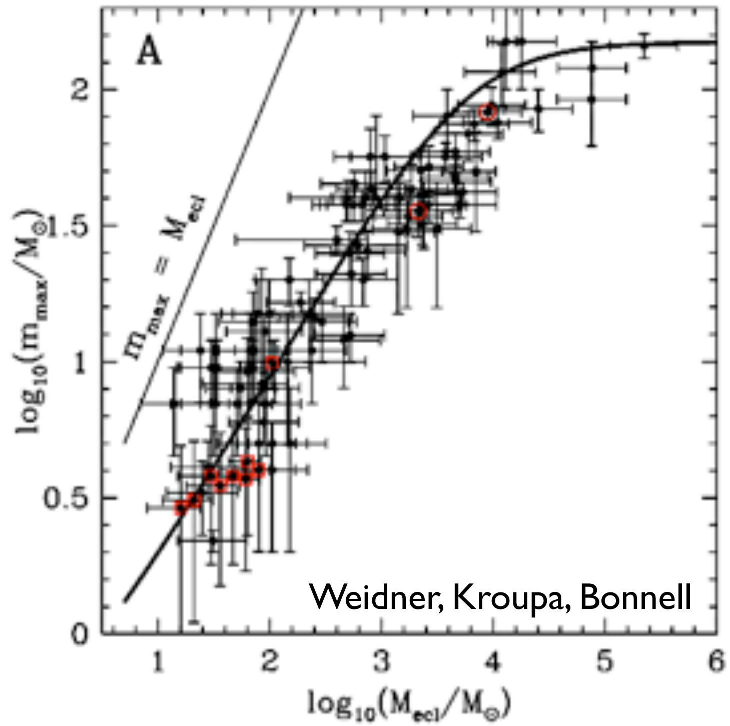
- Maximum M_{star} in cluster scales with $M_{cluster}$



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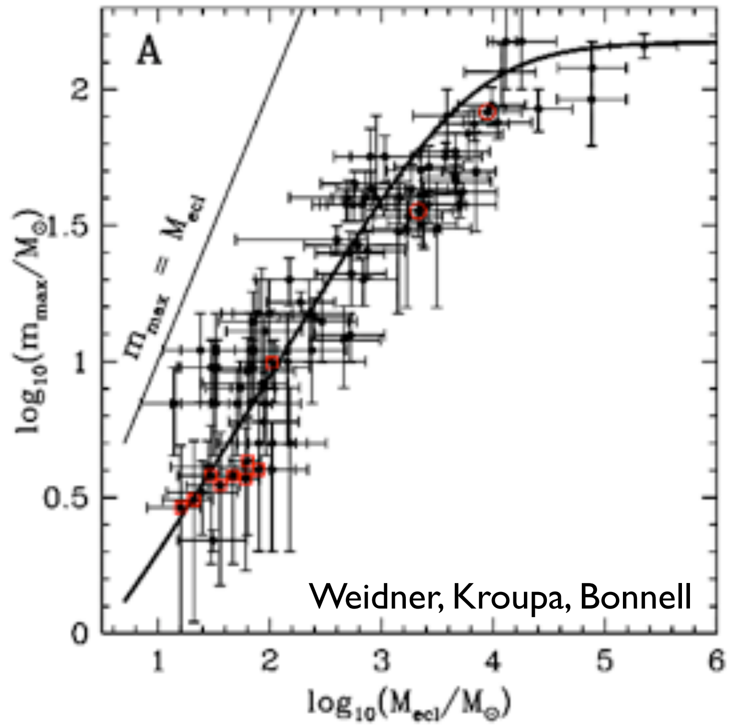

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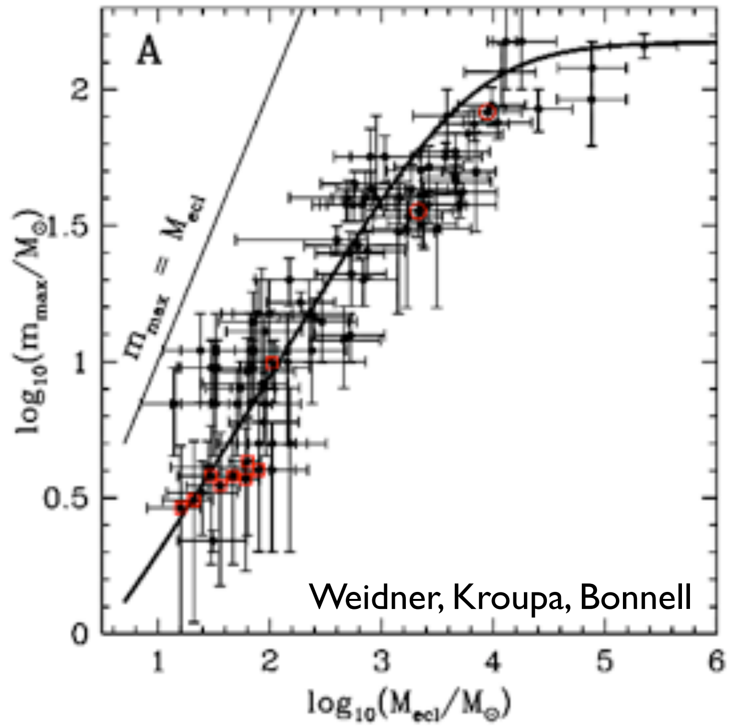

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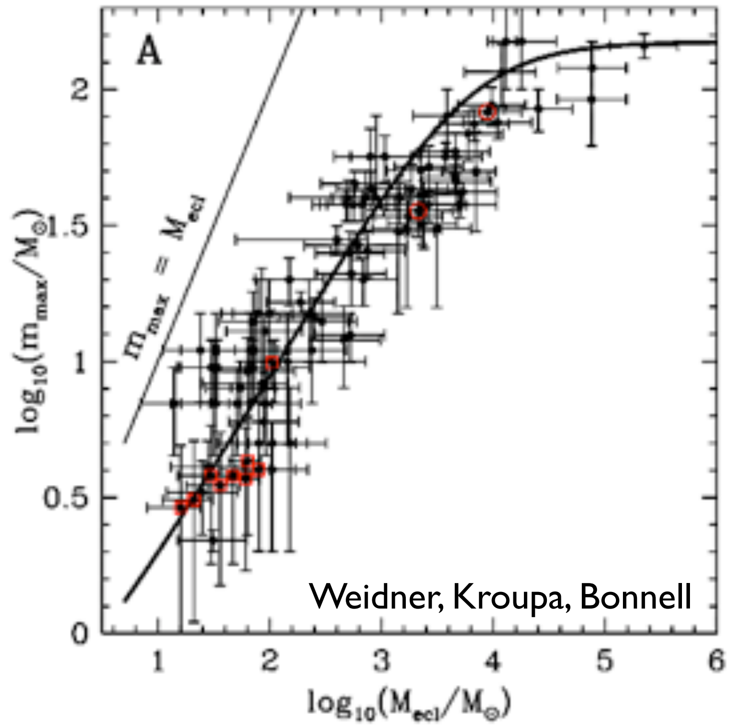

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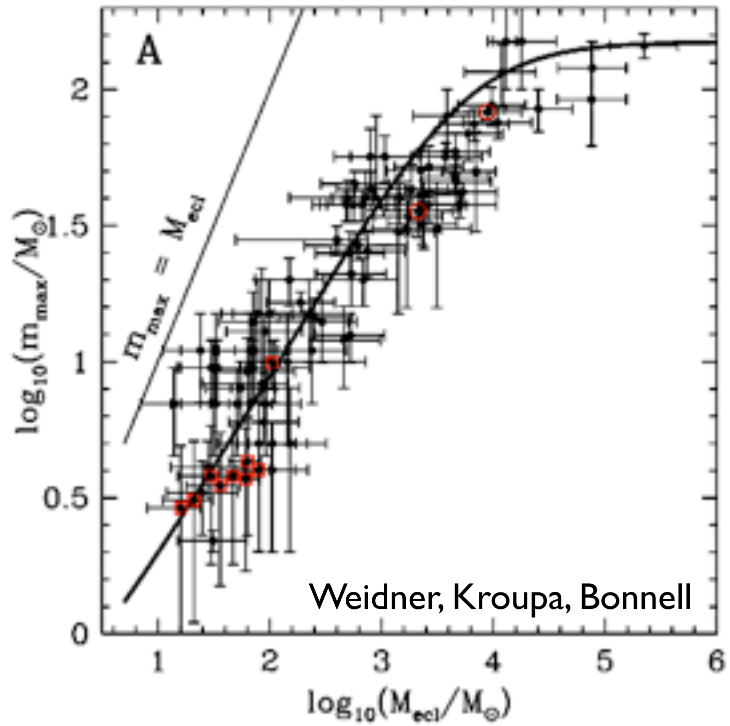

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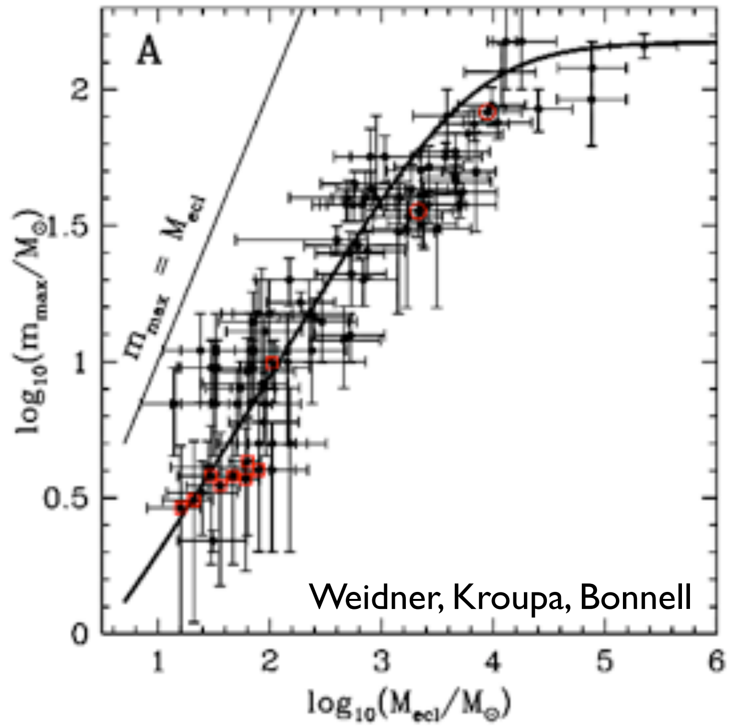

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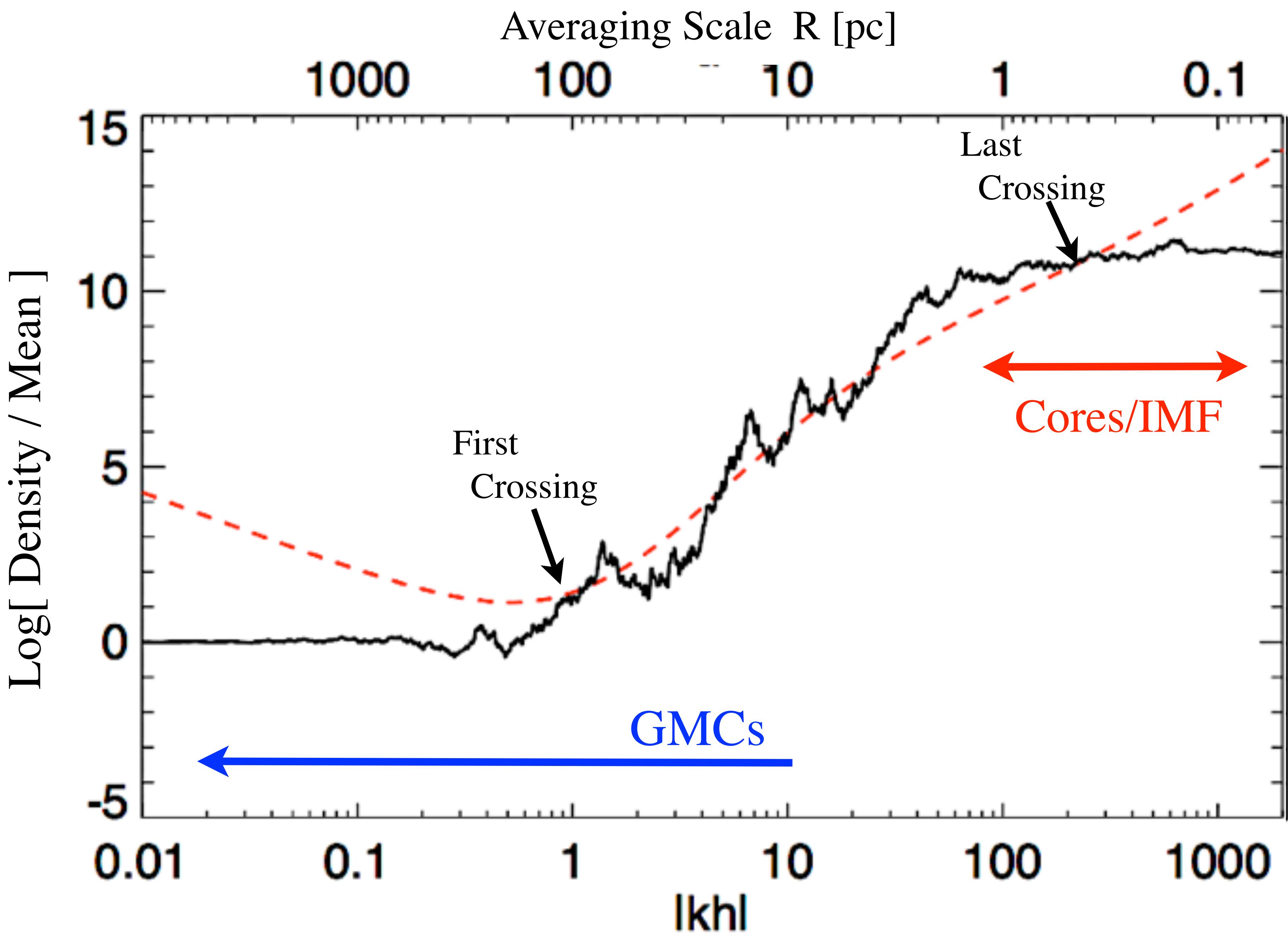
    - Lower metallicity? (less clear)
      - Similar to "mean galaxy Jeans mass" case

Variation in the Core Mass Function



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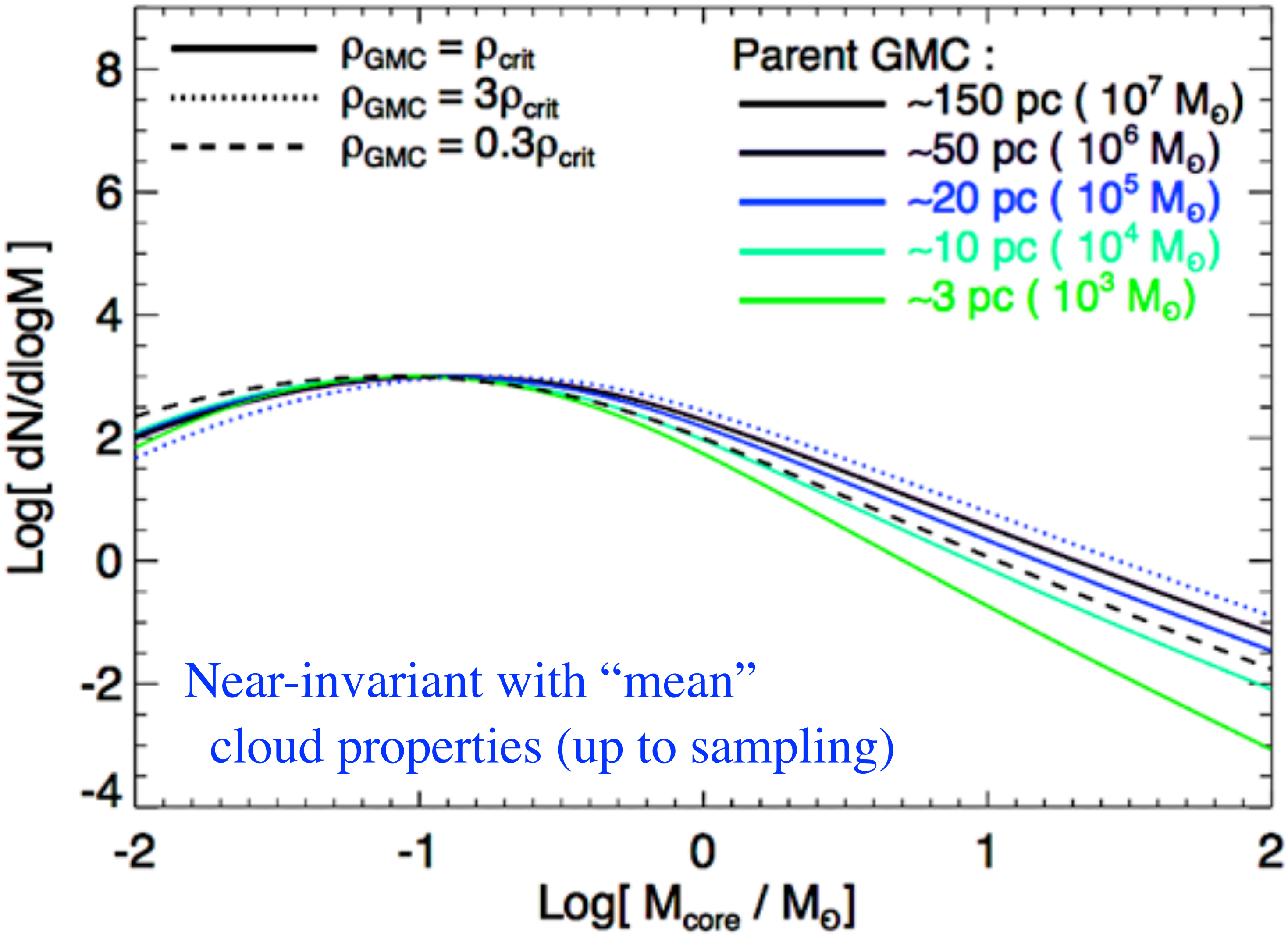
VS "NORMAL" IMF VARIATIONS



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Sonic Length & Mass: $R_{\rm Sonic} \sim R(\mathcal{M}=1) \sim h_{\rm disk}\,\mathcal{M}(h_{\rm disk})^{-2}$

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VS "NORMAL" IMF VARIATIONS

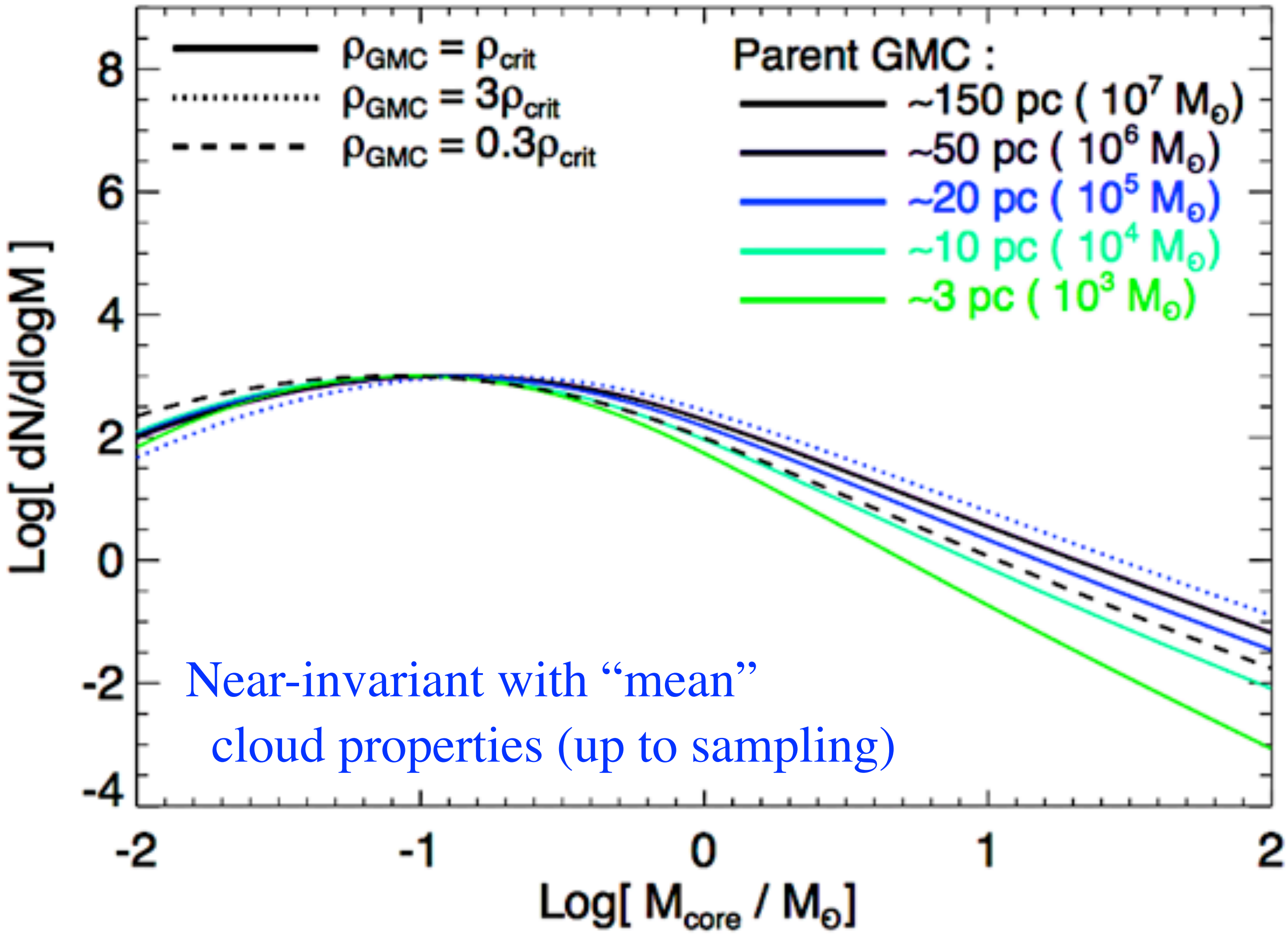
Jeans Length & Mass: $\ell_{\rm Jeans} \sim \dfrac{c_s}{\sqrt{G\,\rho}}$ $\quad M_{\rm Jeans} \sim \dfrac{c_s^3}{G^{3/2}\,\rho^{1/2}}$

Sonic Length & Mass: $R_{\rm Sonic} \sim R(\mathcal{M}=1) \sim h_{\rm disk}\,\mathcal{M}(h_{\rm disk})^{-2}$

$$M_{\rm sonic} \sim \frac{c_s^2\,R_{\rm sonic}}{G} \sim \frac{c_s^4}{G^2\,Q_{\rm disk}\,\Sigma_{\rm disk}}$$

Variation in the Core Mass Function

VS "NORMAL" IMF VARIATIONS



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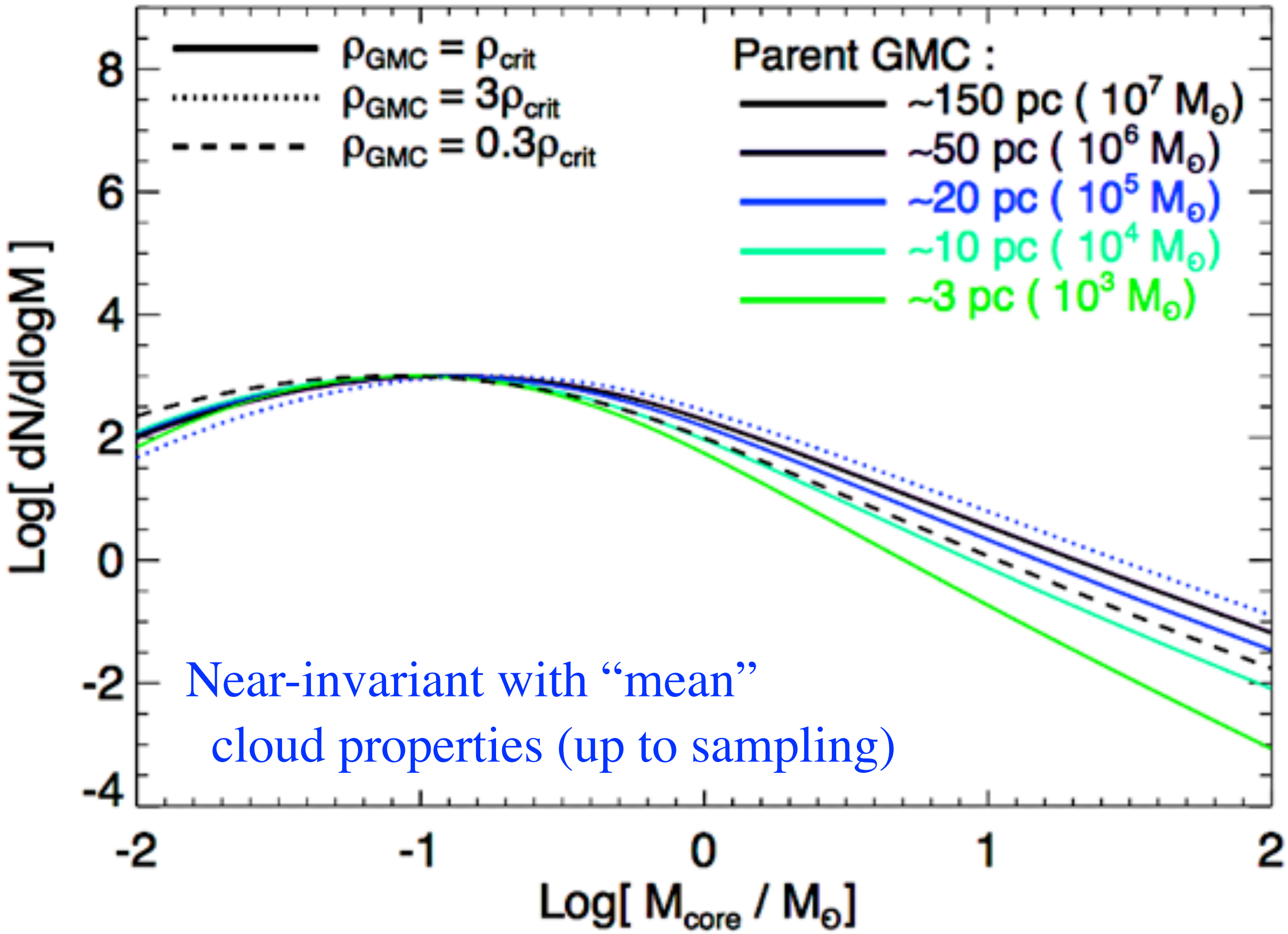

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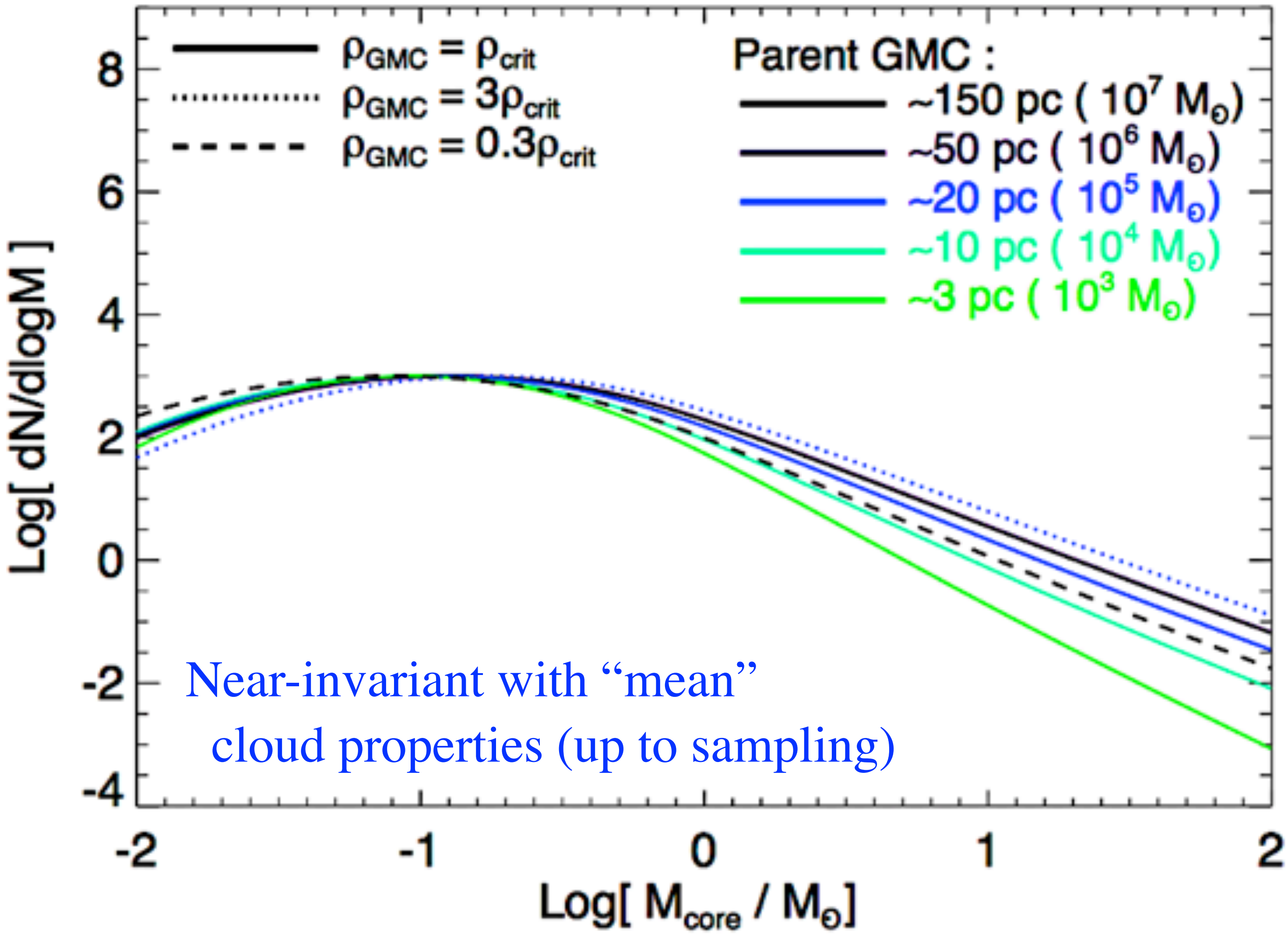

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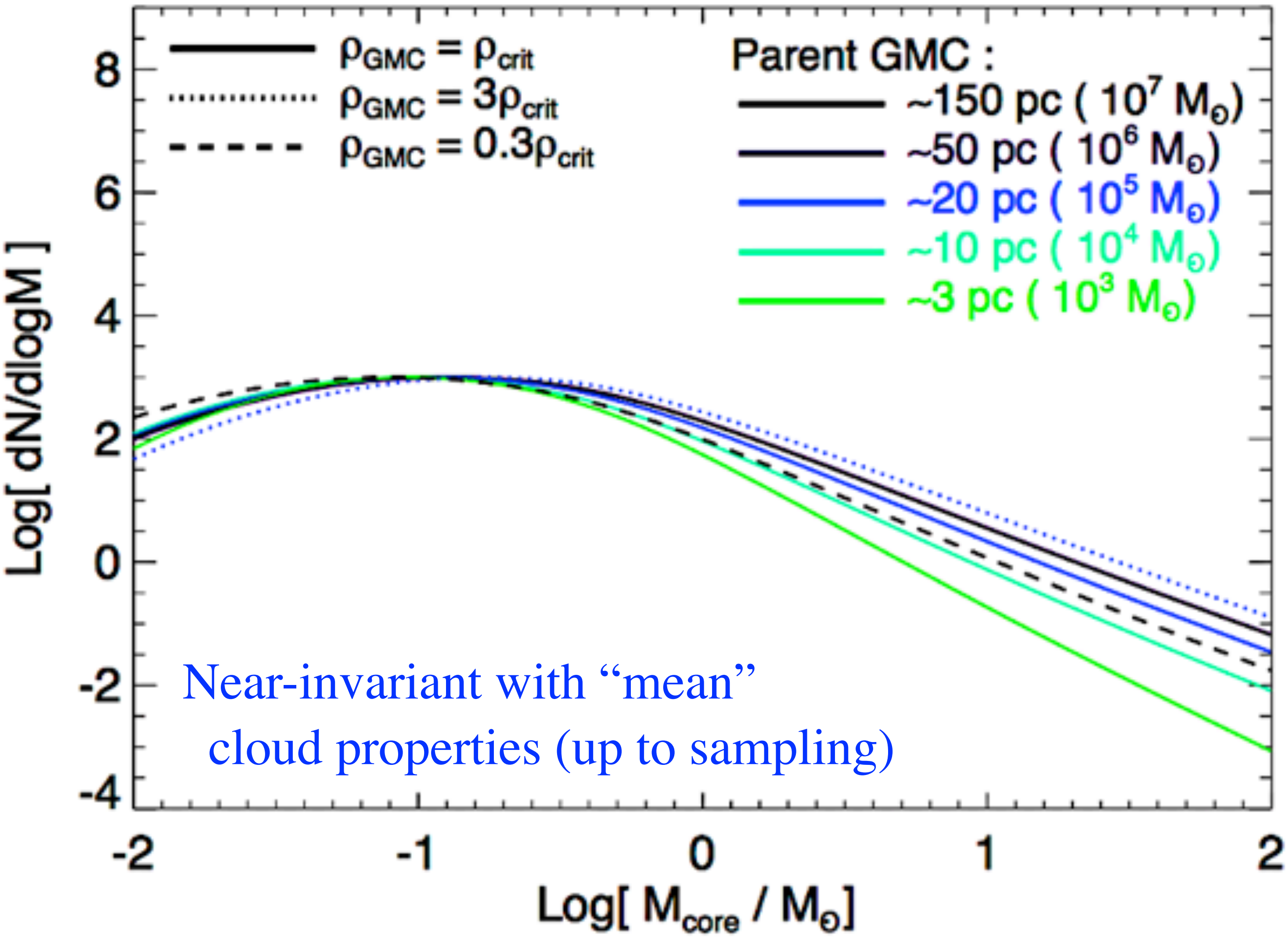

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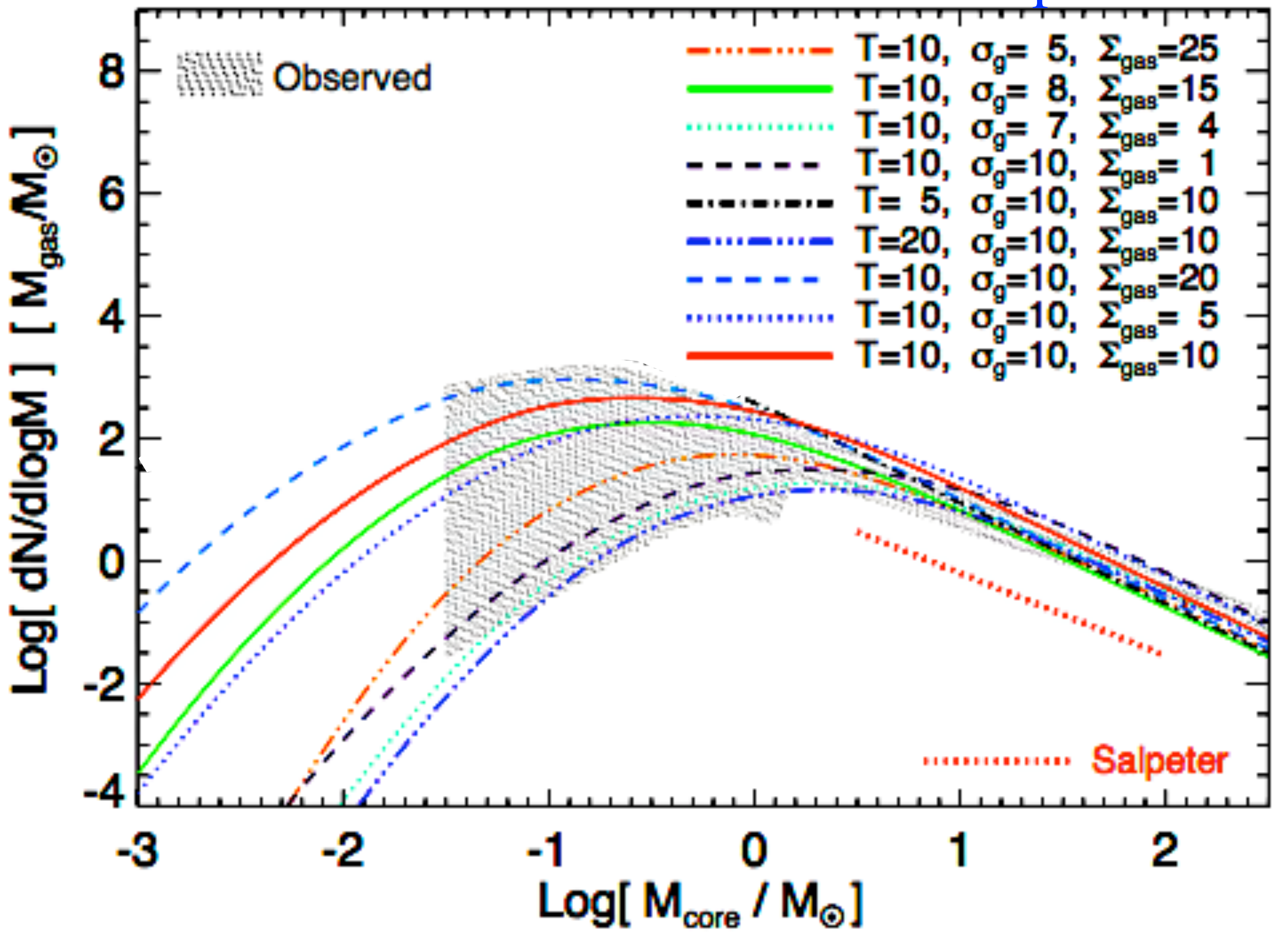
VS "NORMAL" IMF VARIATIONS

Weak variation with Galactic Properties



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BUT, What About Starbursts?

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

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ULIRG: $T_{\rm cold} \sim 70\,K$

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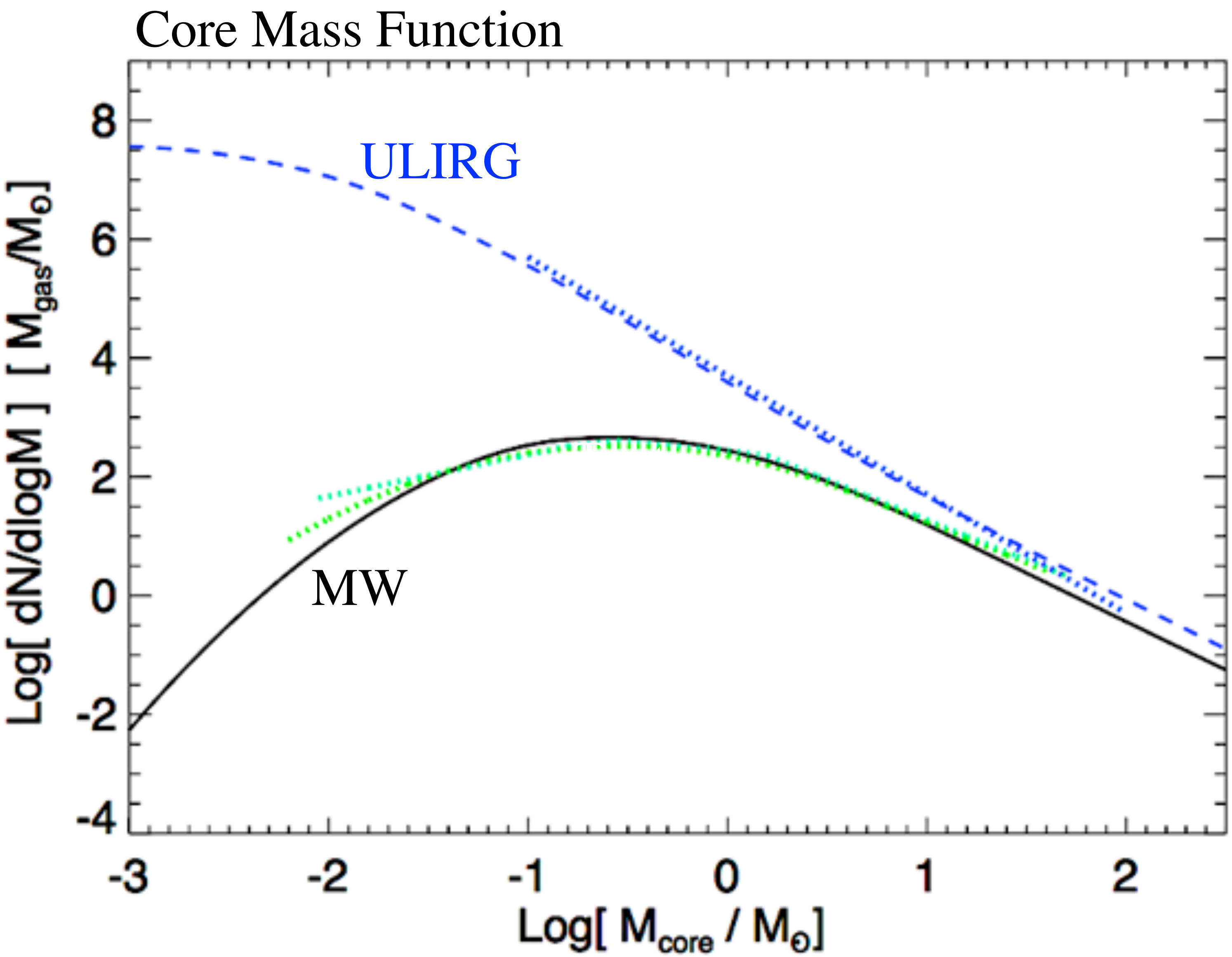

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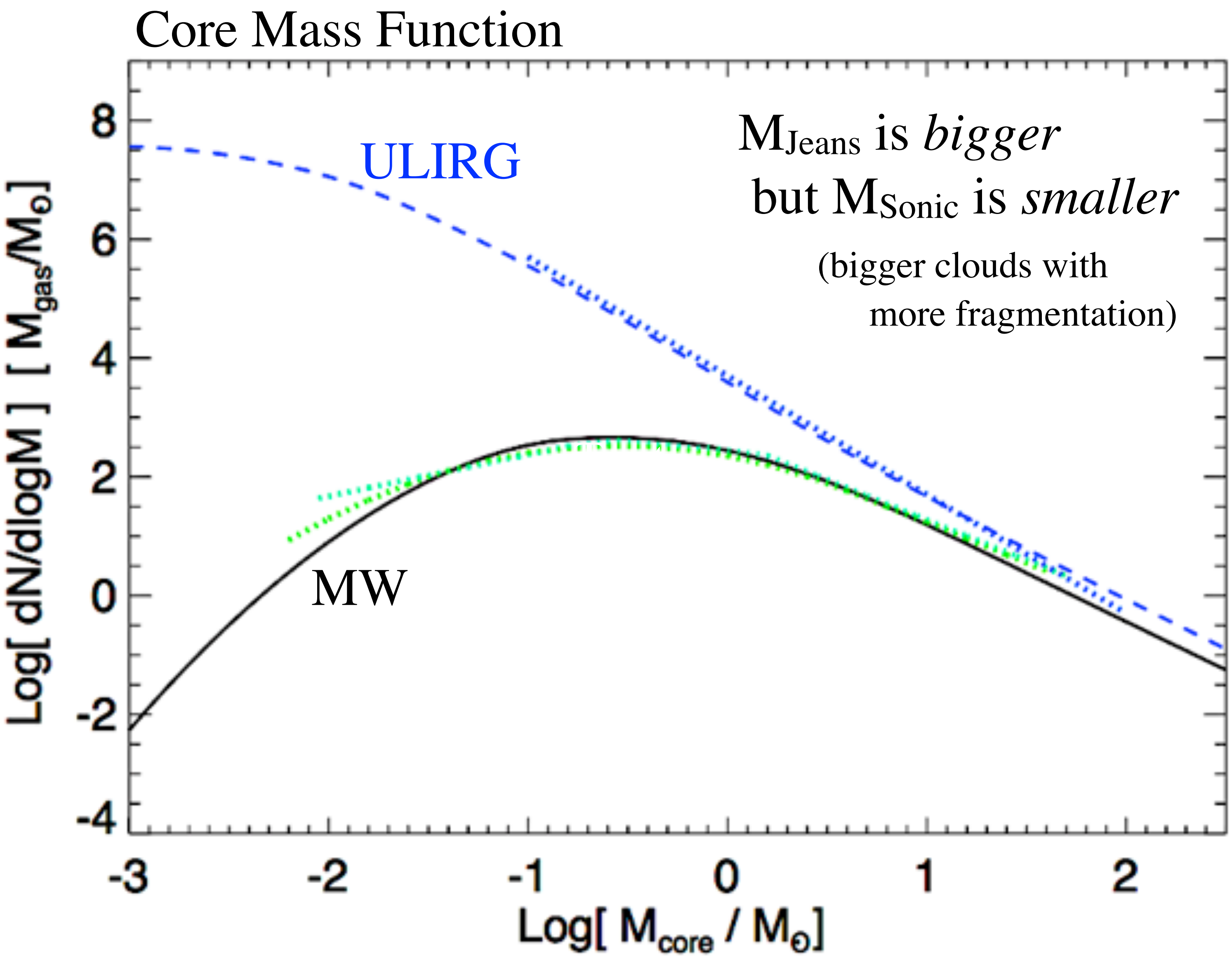

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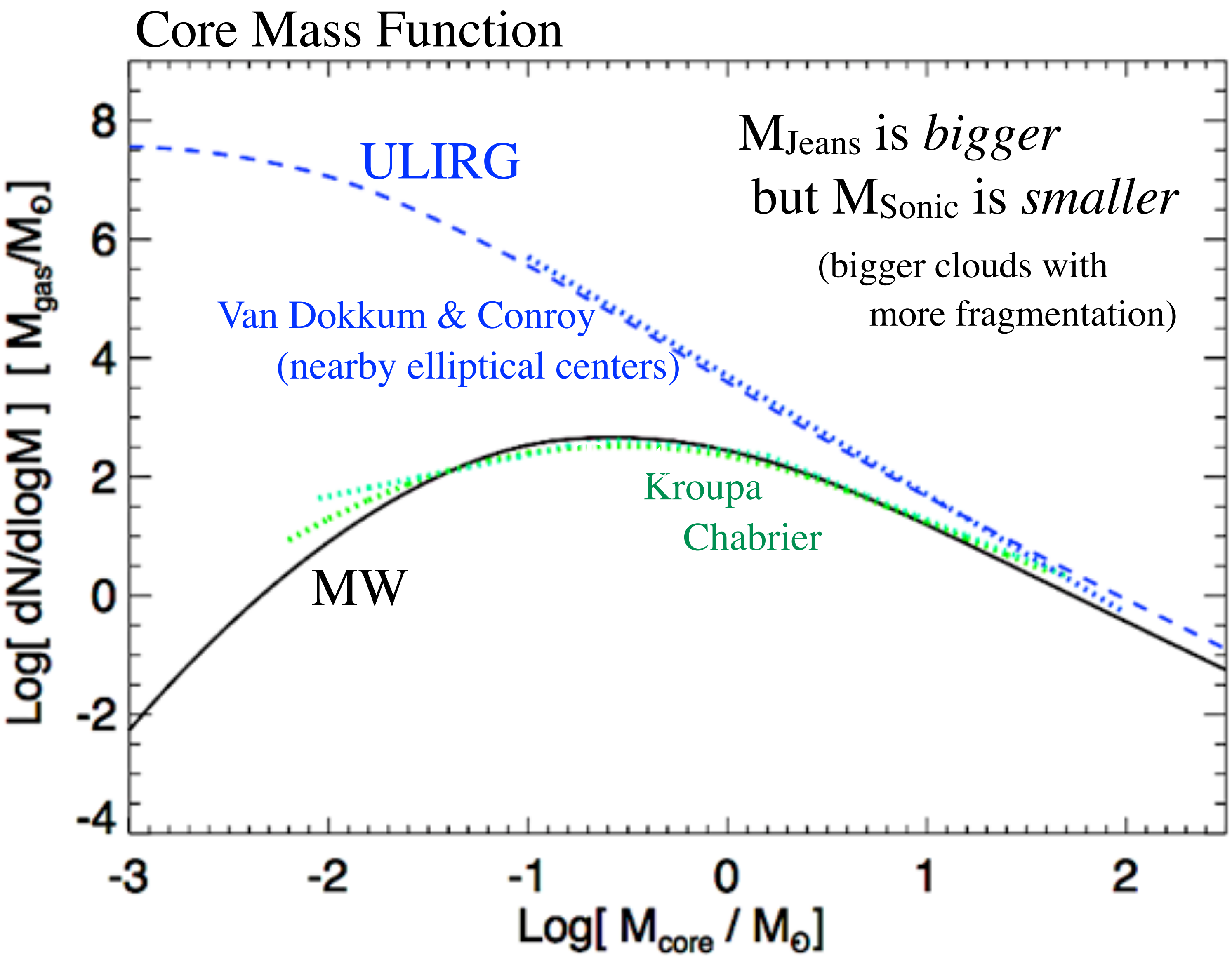

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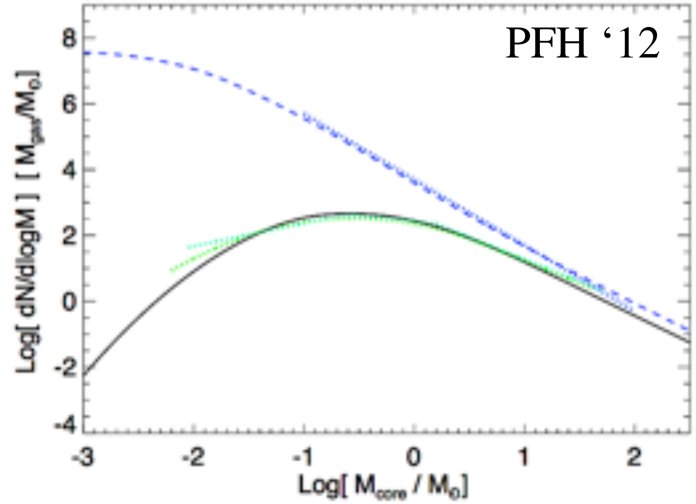
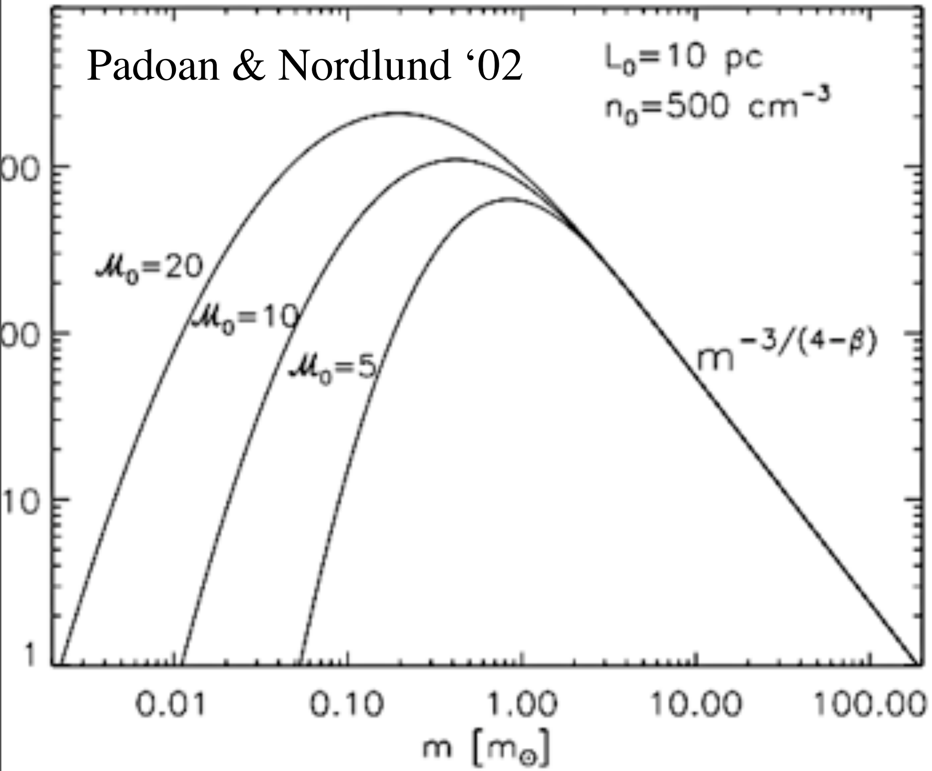
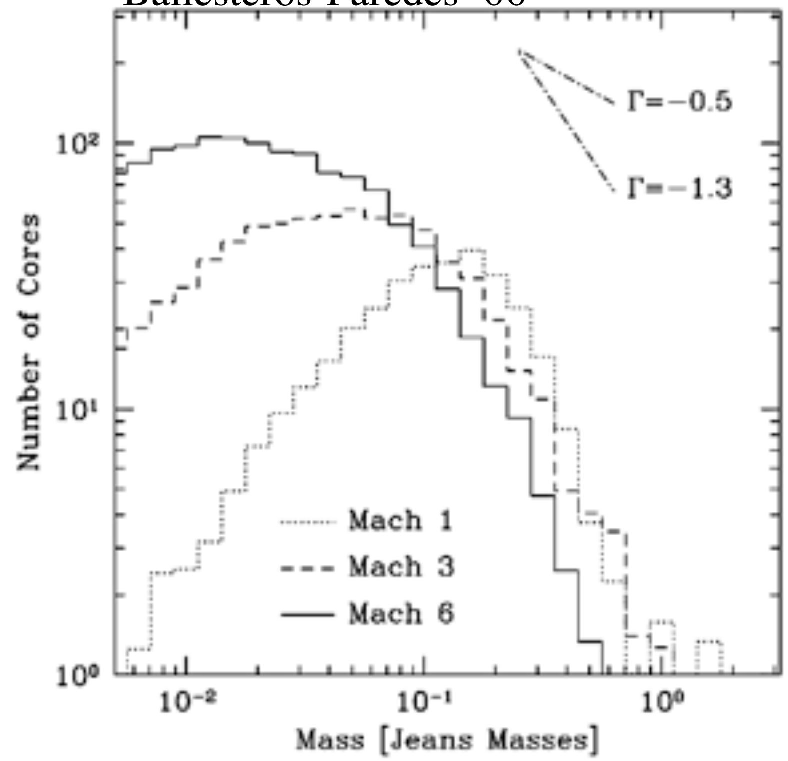
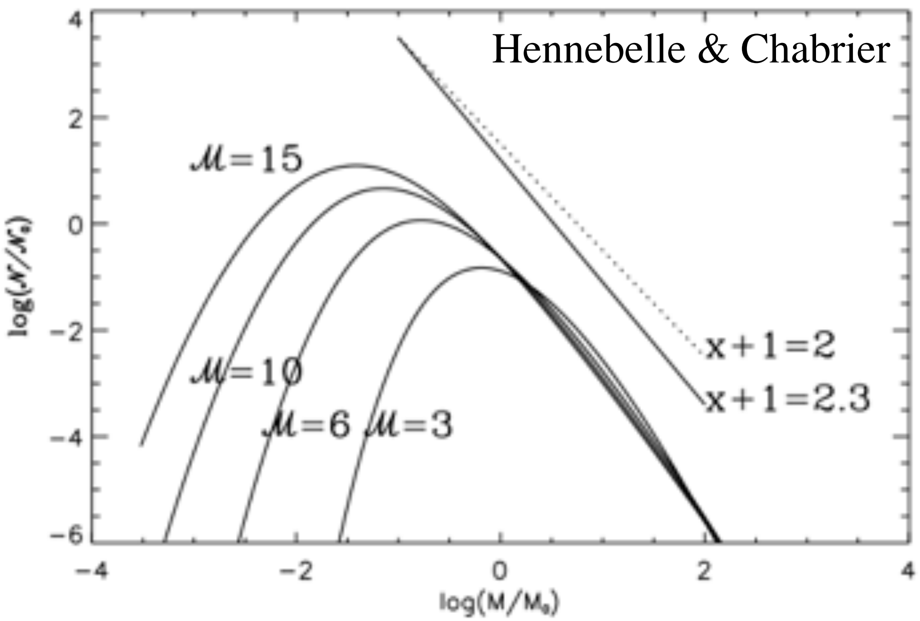




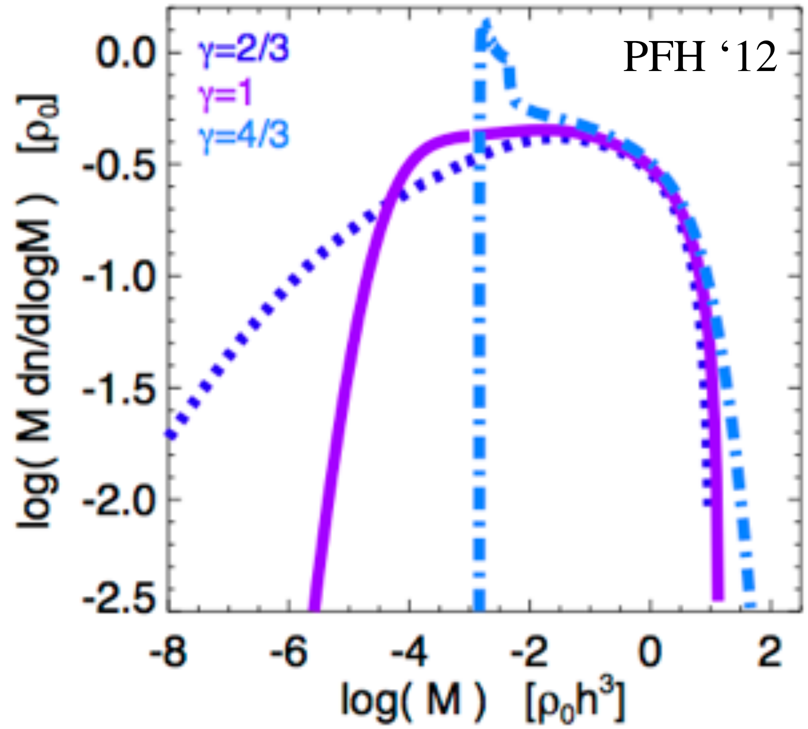
Ballesteros-Paredes '06

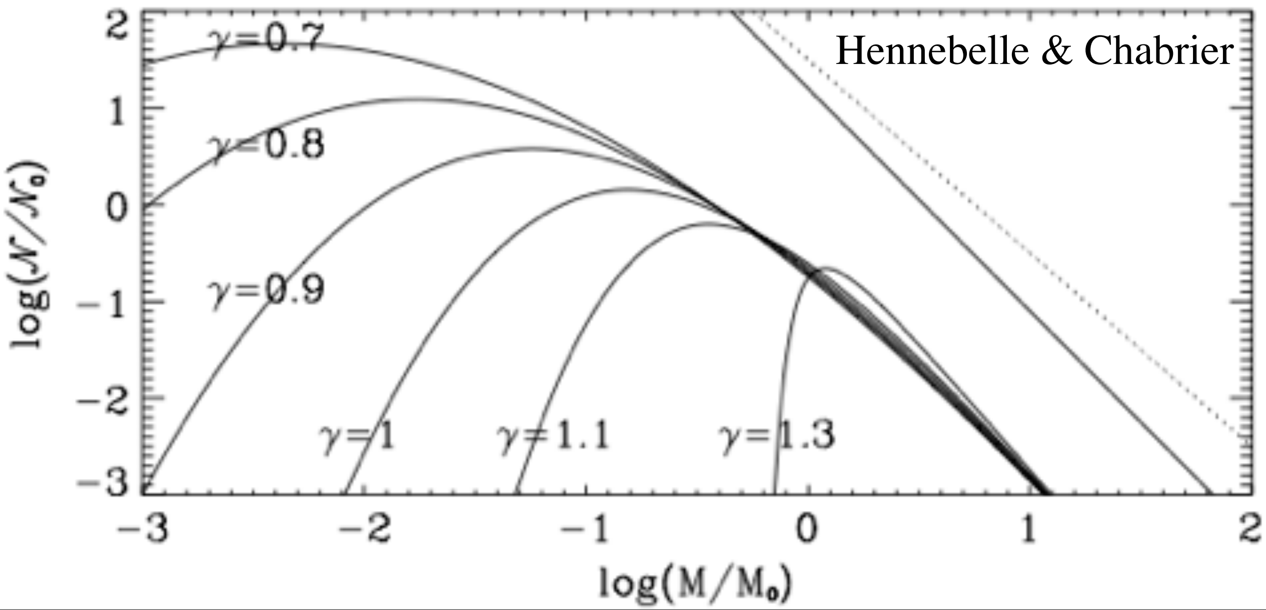




We can make some guesses for other galaxies...

HOWEVER, CAUTION IS NEEDED!





also
Li, Klessen, & Mac-Low '03

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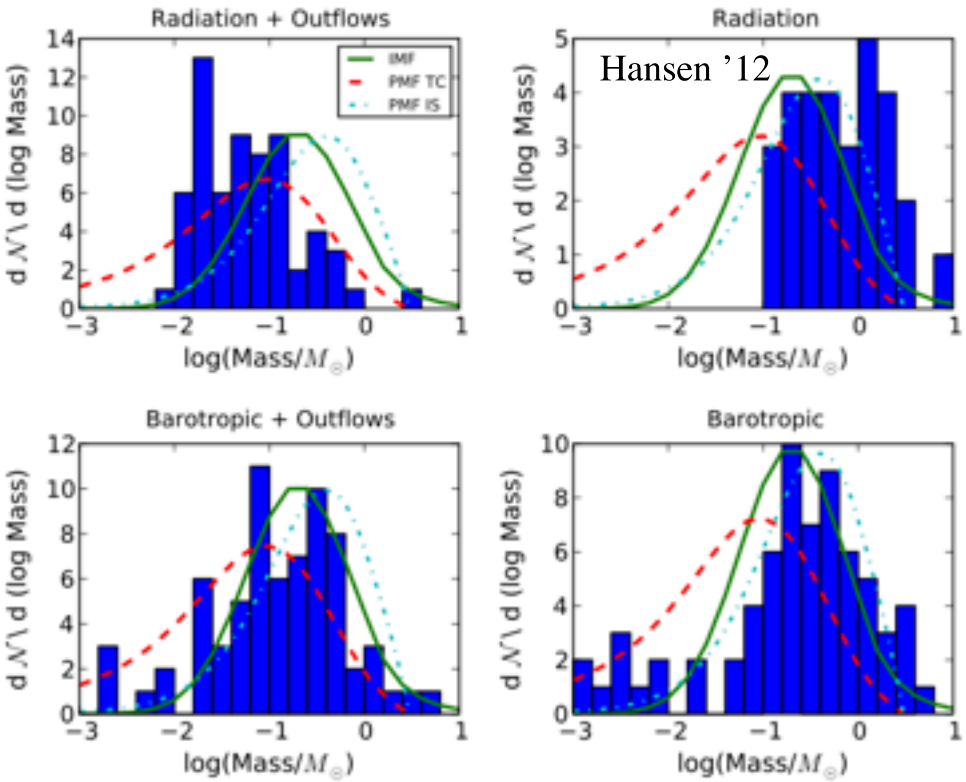

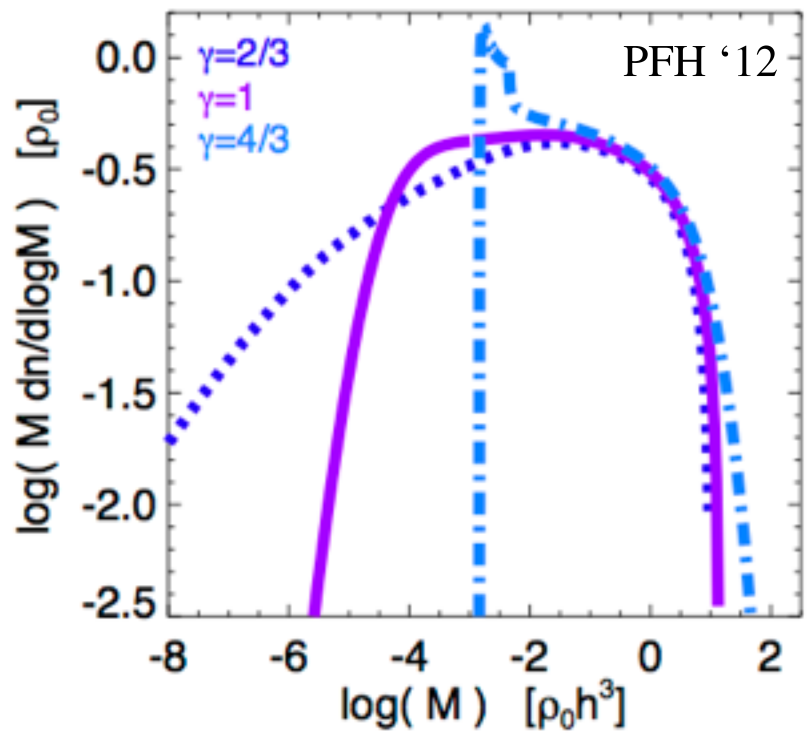

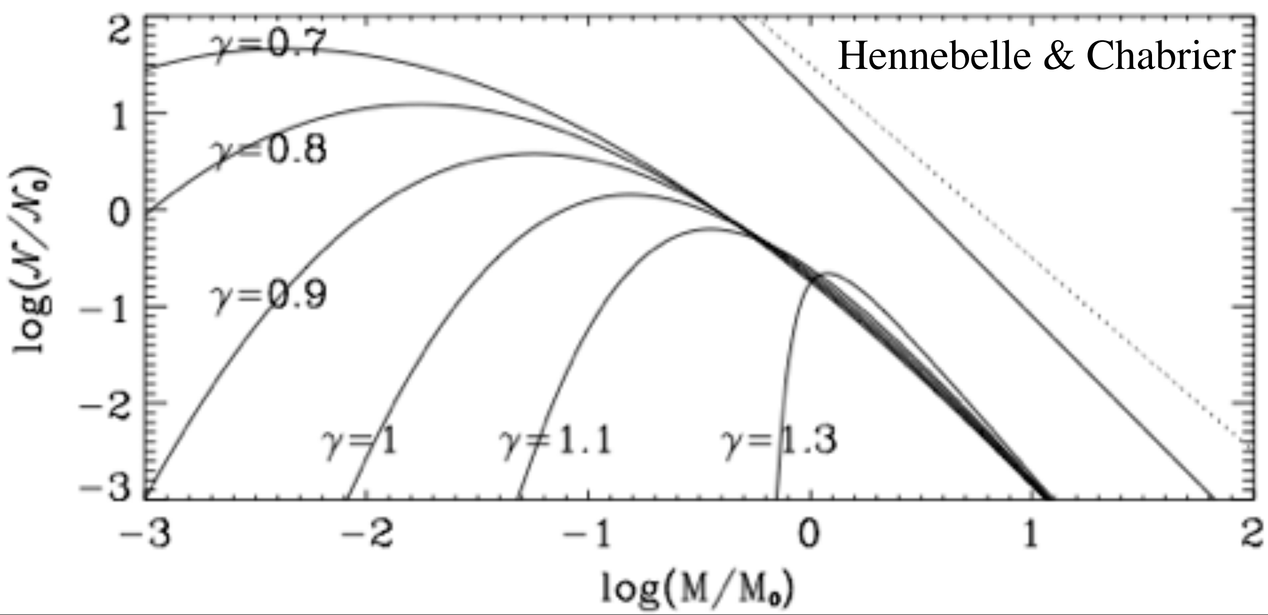

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Open Questions:

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1. What Maintains the Turbulence?

Efficient Cooling: $$\dot{P}_{\mathrm{diss}} \sim \frac{M_{\mathrm{gas}}\, v_{\mathrm{turb}}}{t_{\mathrm{crossing}}}$$

2. Why Doesn't Everything Collapse?

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

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

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)