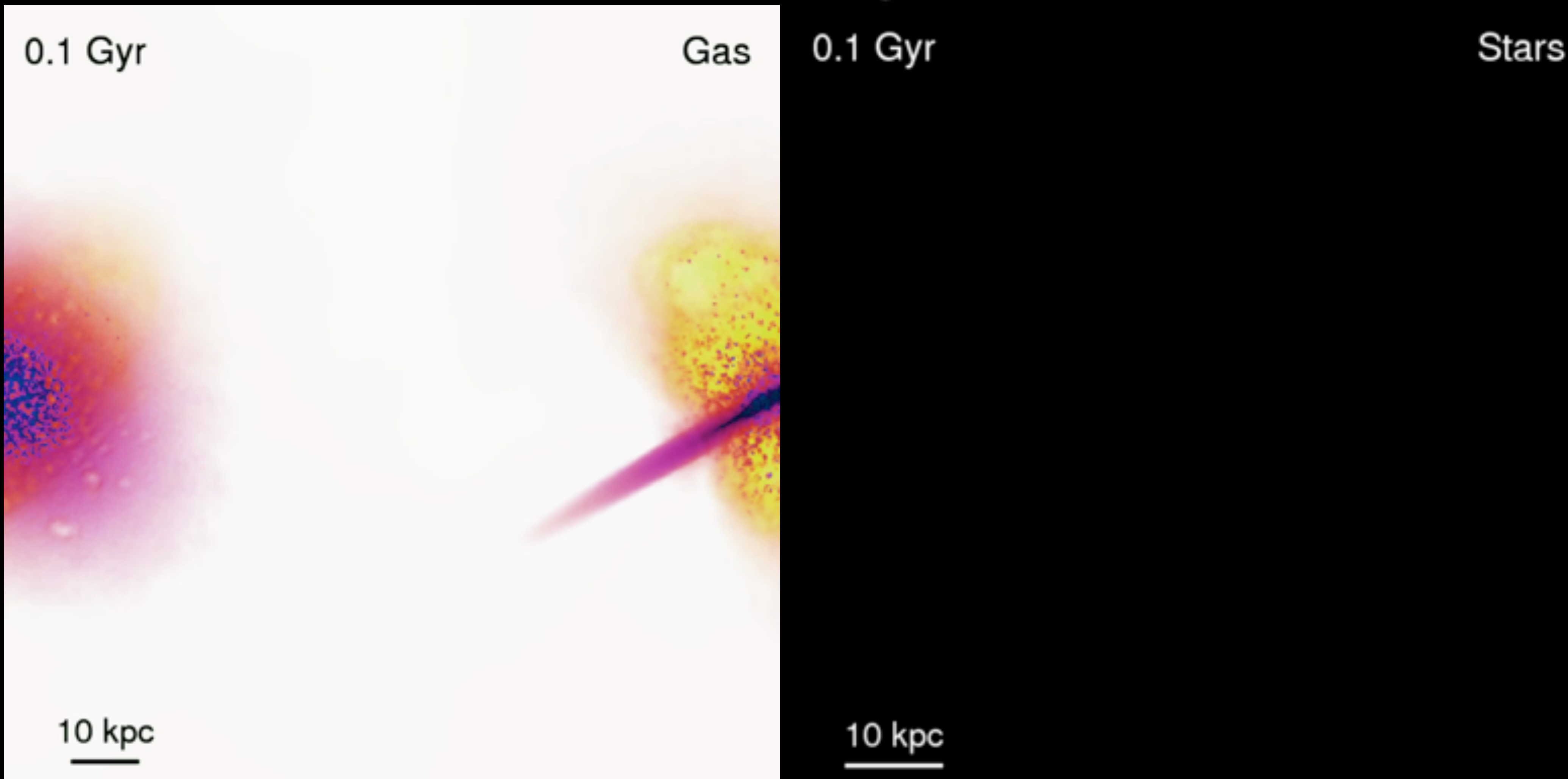
Milky Way

Starburst Disks

The Structure of the Interstellar Medium: Turbulence, Gravity, & Feedback



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

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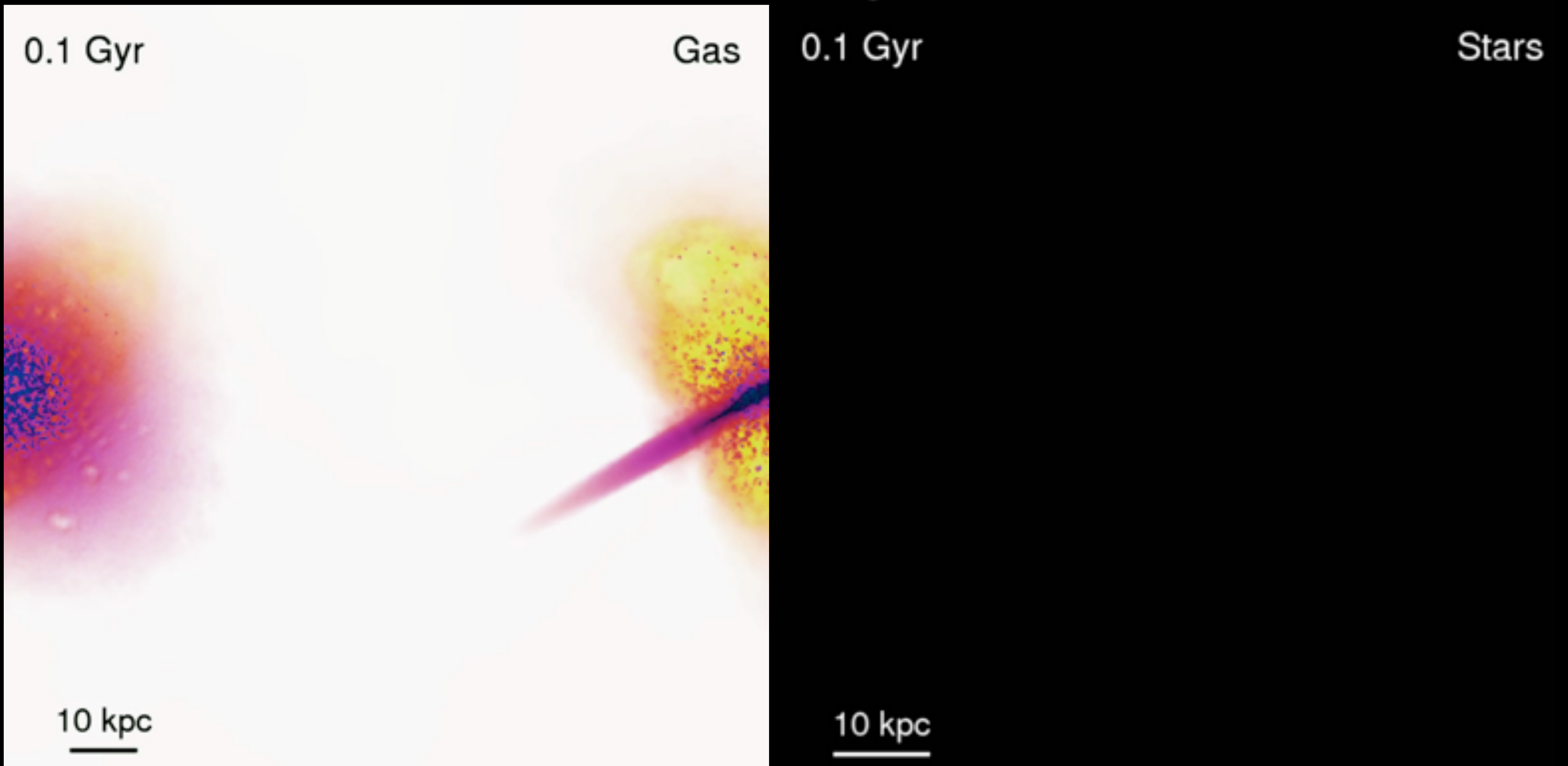


Philip Hopkins

PFH 2011, 2012 (arXiv:1111.2863, 1201.4387)
PFH, Quataert, & Murray 2011a,b,c
(arXiv: 1101.4940, 1110.4636, 1110.4638)


PINNACLES

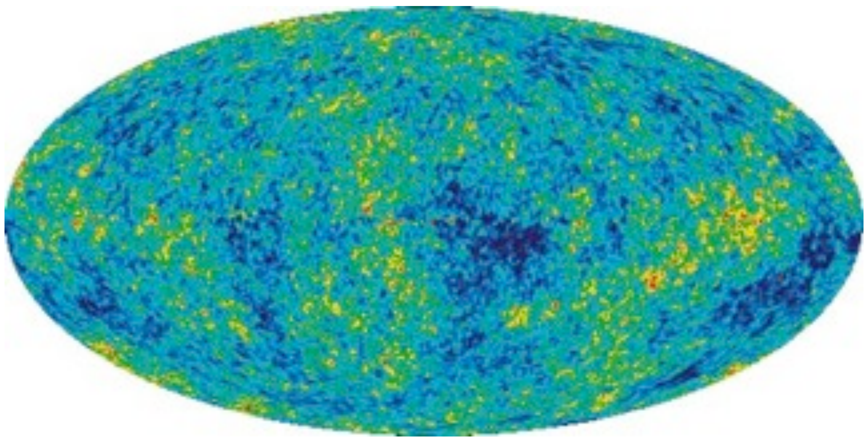
Overview

- **(1) The Problem**

- **(2) The ISM as a Random Process:**
  - **Supersonic Turbulence + Gravity: Regularity from Chaos**
  - **Applications of the "Excursion Set" Formalism**

- **(3) What Role Does "Feedback" Physics Play?**
  - **"Microphysics" of the ISM**

KEEP?



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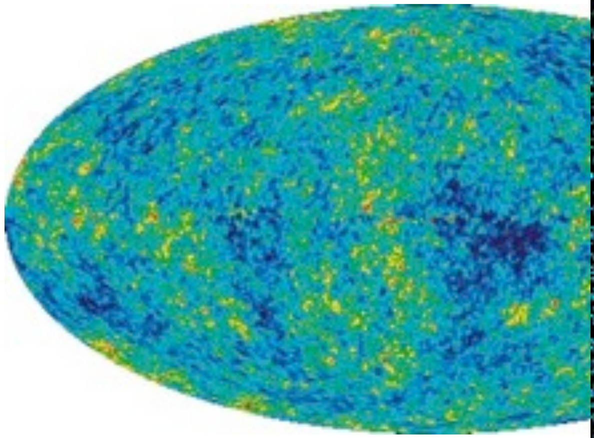
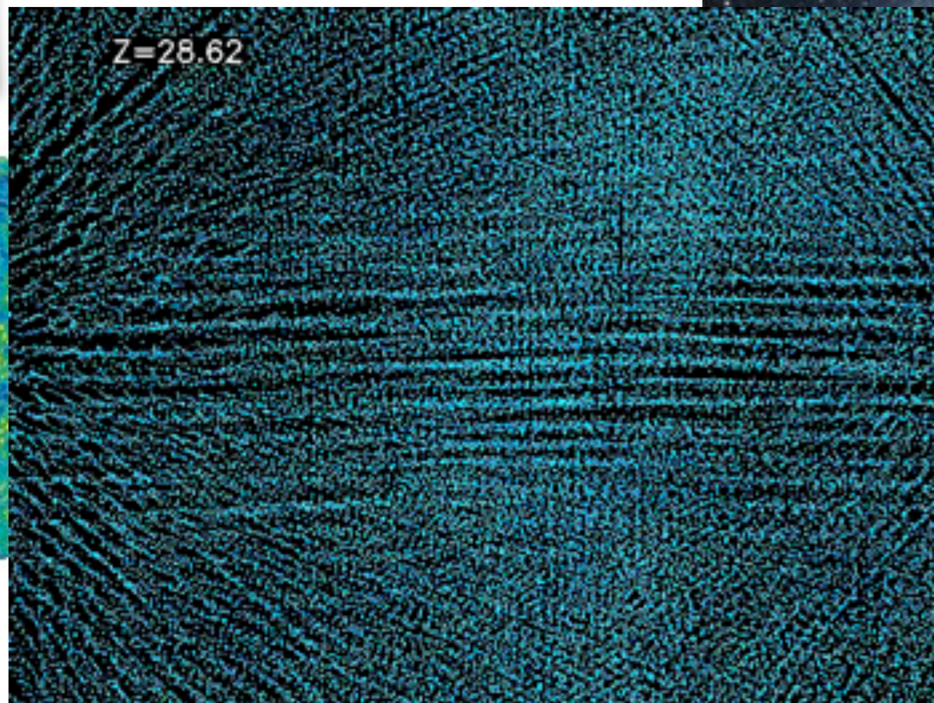
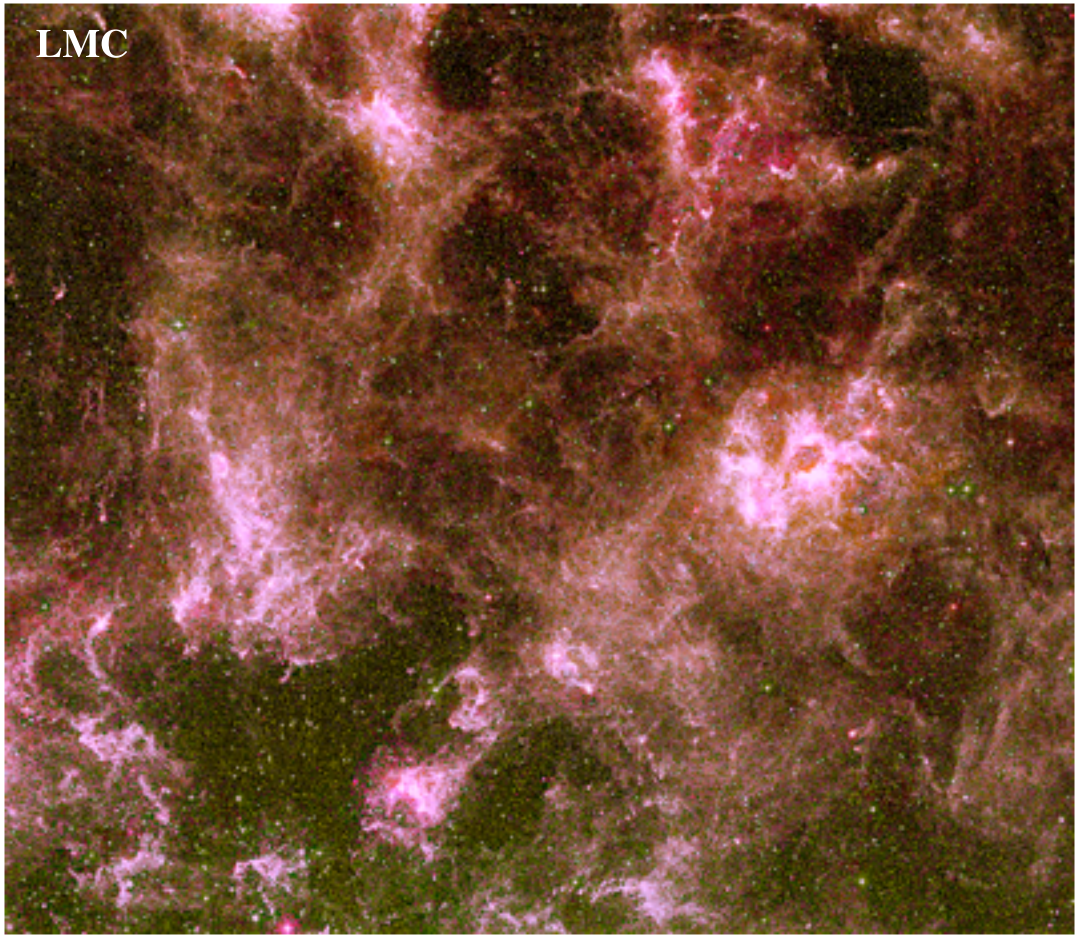
KEEP?

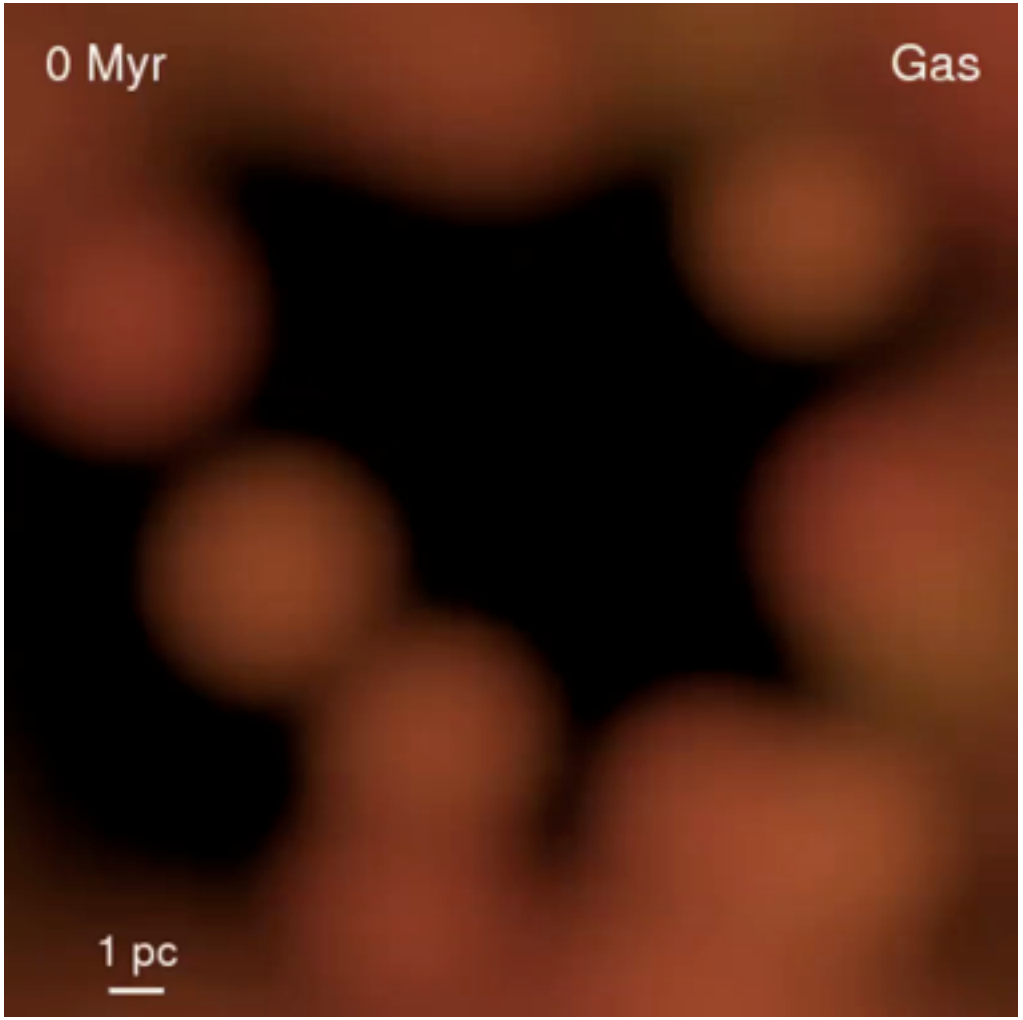




The ISM

SUPER-SONIC TURBULENCE DOMINATES (ALMOST) ALL SCALES



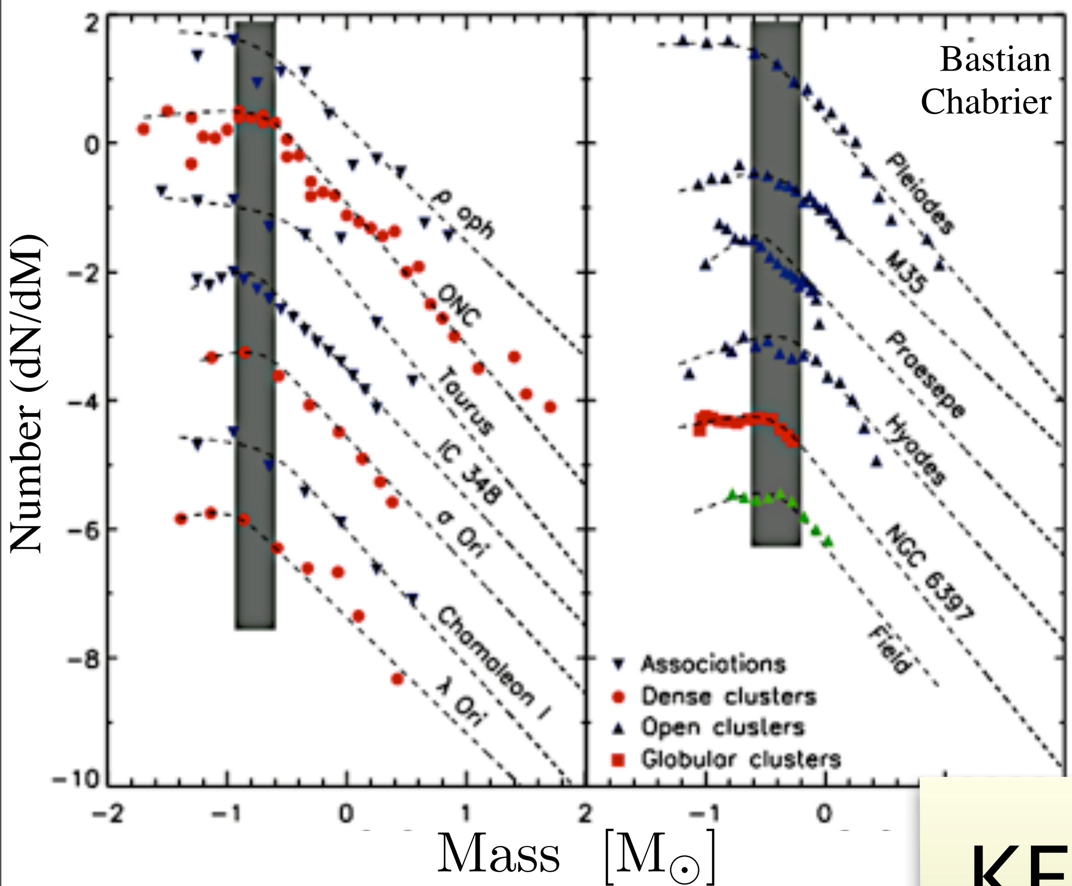


- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs, external galaxies, etc.

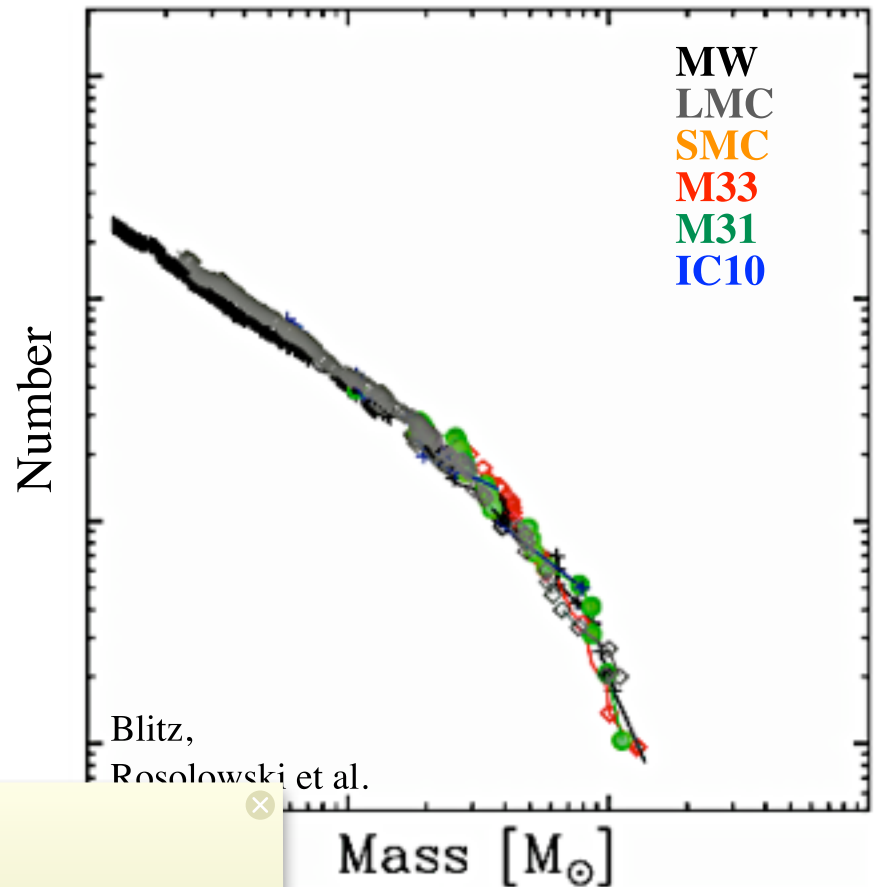
The ISM

YET THERE IS SURPRISING REGULARITY

Stars & Pre-Stellar Gas Cores:



Giant Molecular Clouds:



KEEP PWRLAW LABELS?

The ISM

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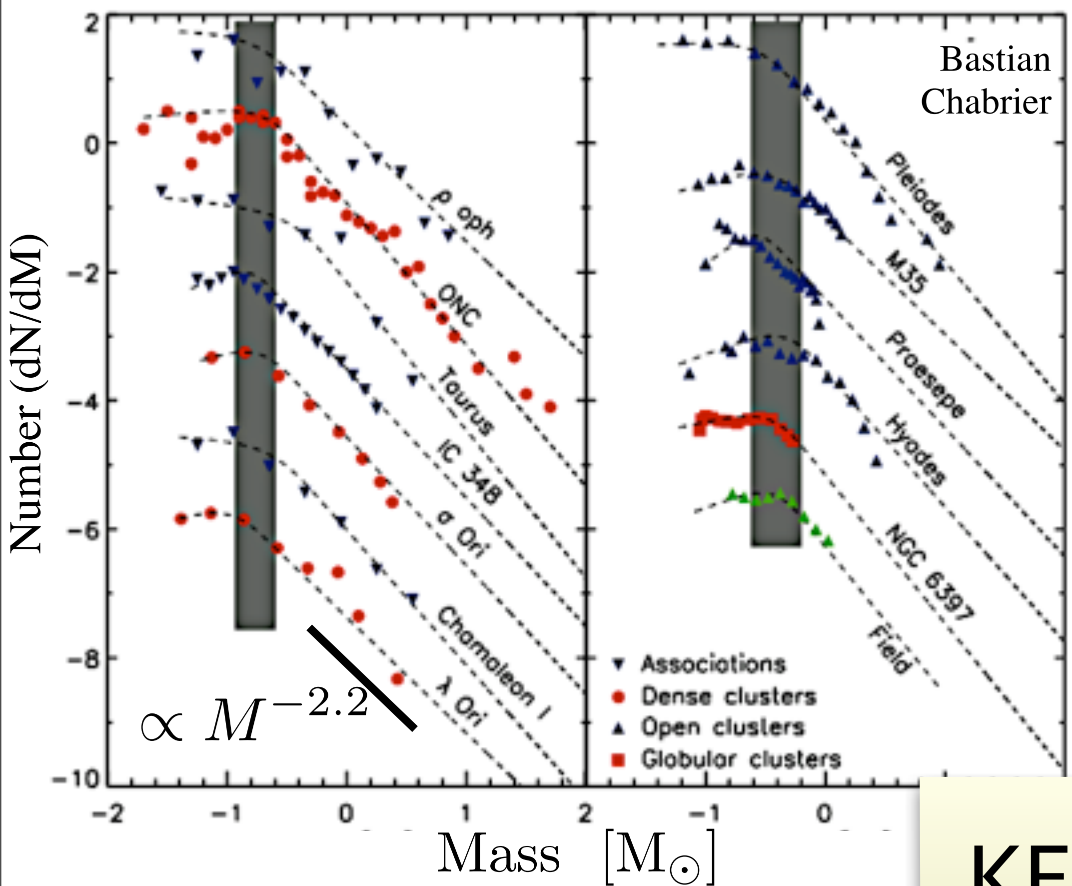

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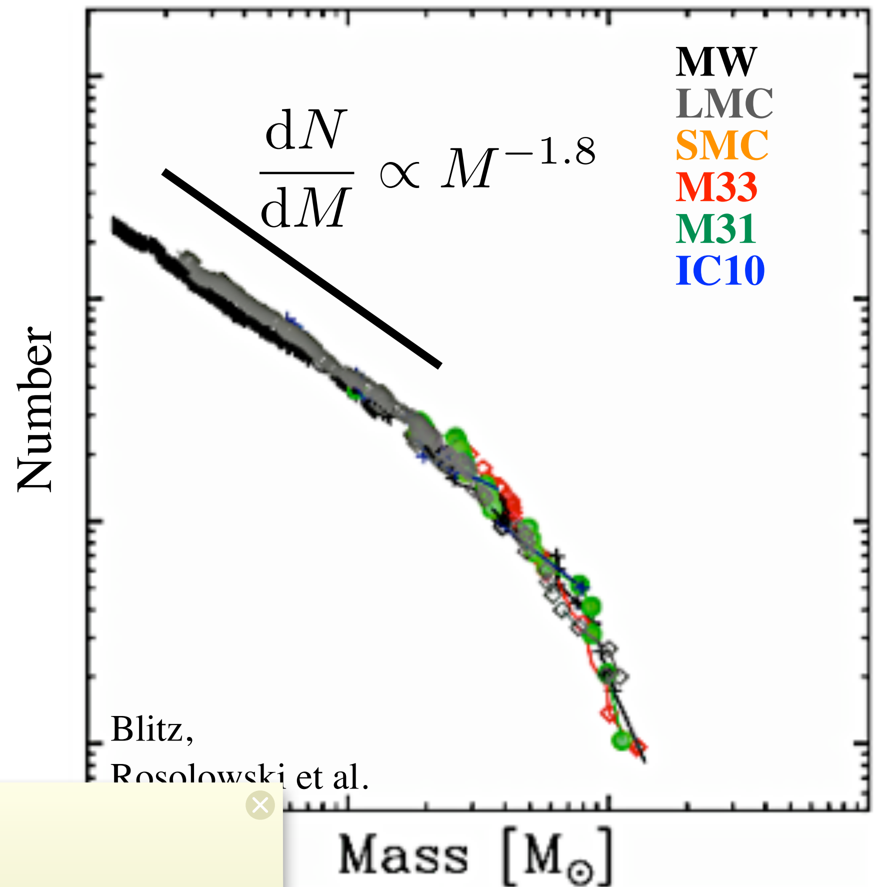

KEEP PWRLAW LABELS?

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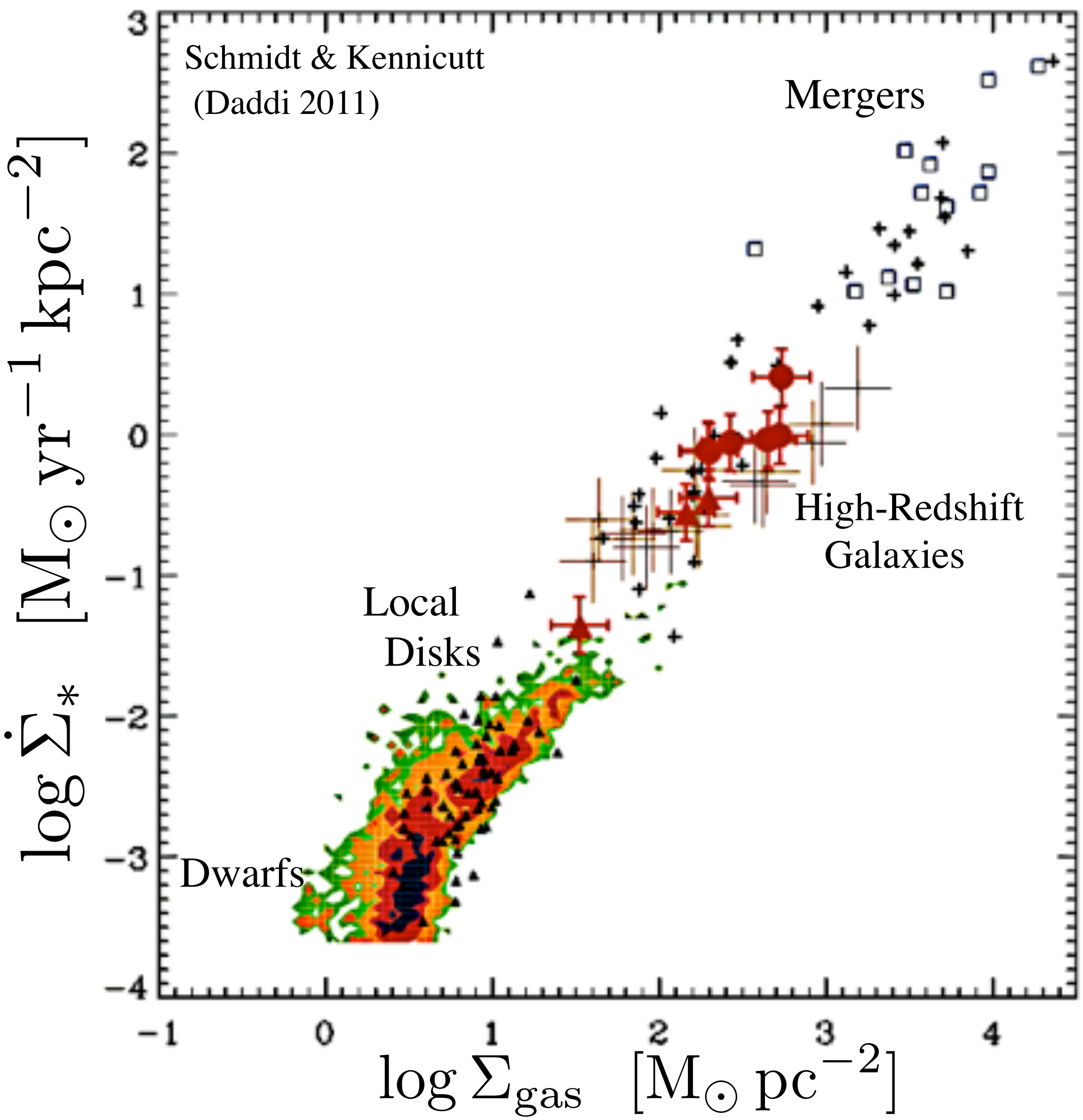
Star Formation Rates:



BASIC EXPECTATIONS

$$E(k) \propto k^{-p} \qquad \mathrm{d}E \equiv E(k)\,\mathrm{d}k$$

$$(k\,E(k) \sim u_t(k)^2)$$

Super-Sonic Turbulence

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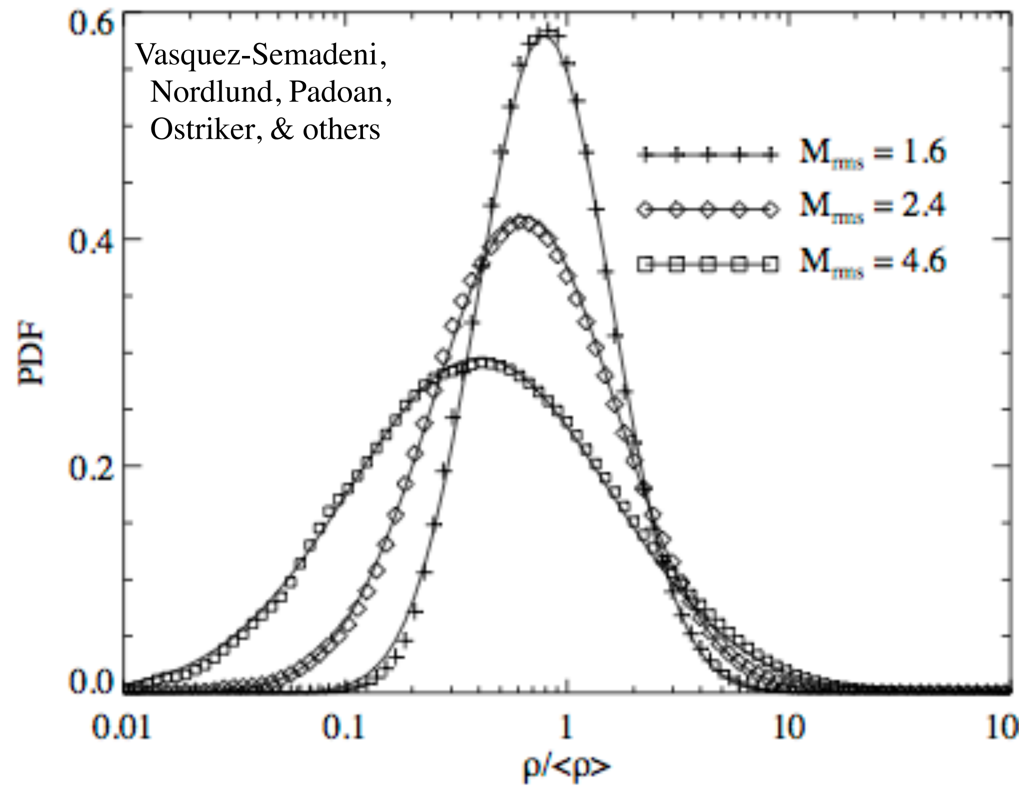

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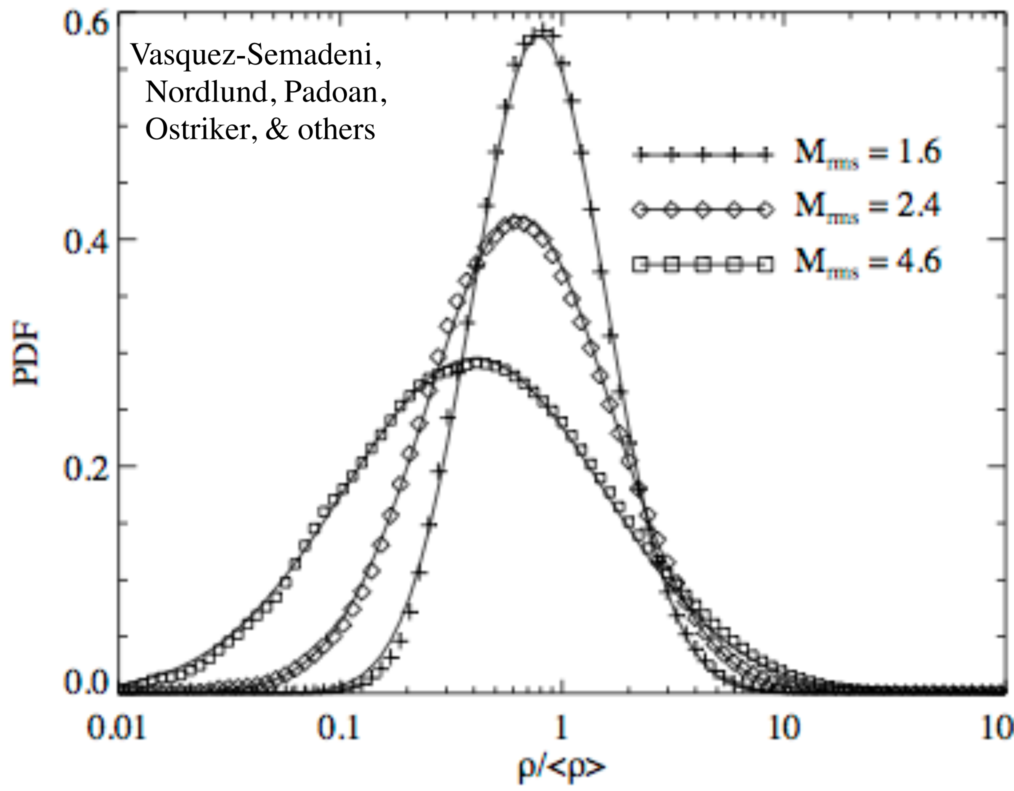
$$\frac{\partial \ln\rho}{\partial t} = -\mathbf{u}\cdot\nabla\ln\rho - \nabla\cdot\mathbf{u}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u}\cdot\nabla)\,\mathbf{u} - c_s^2\,\nabla\ln\rho$$



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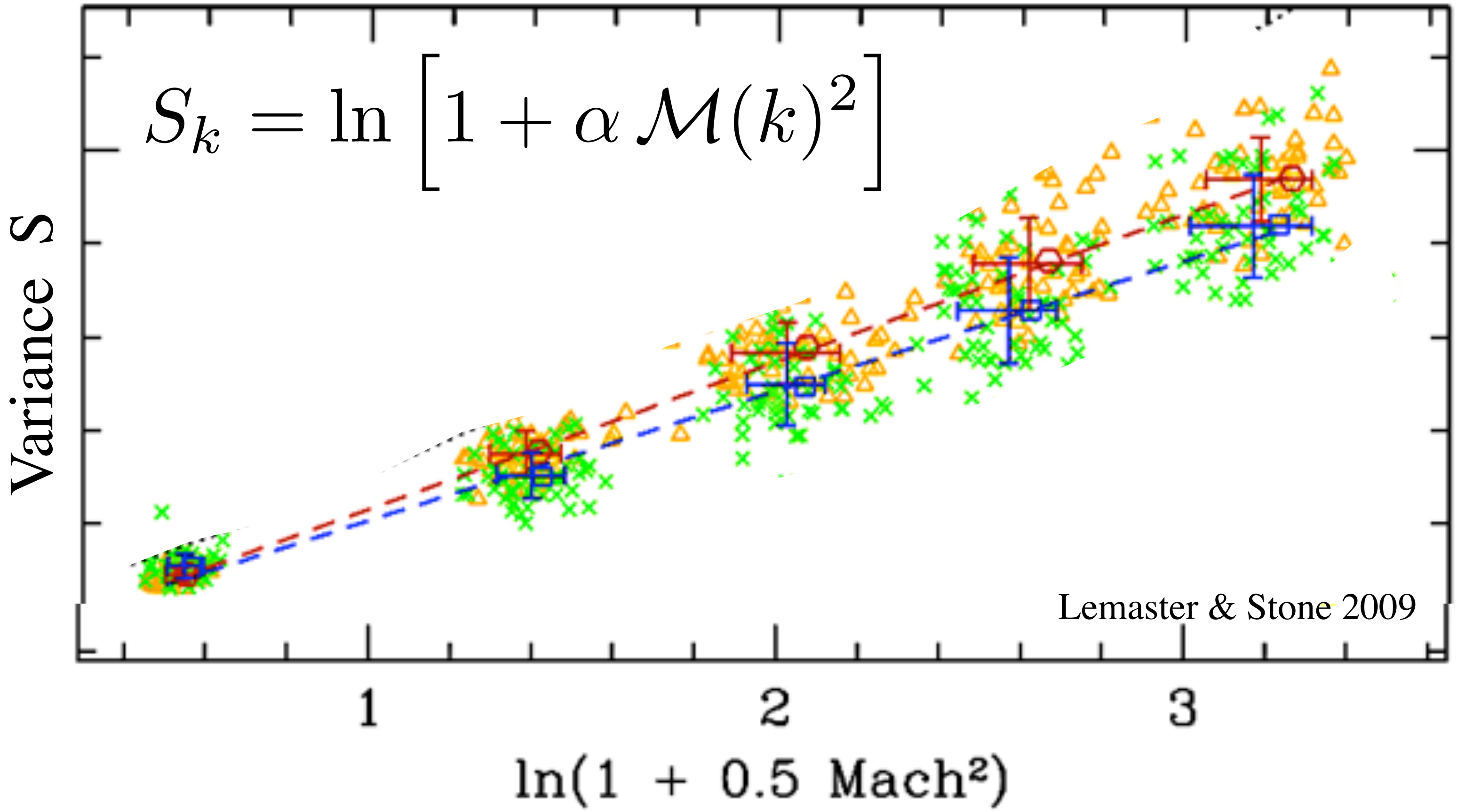

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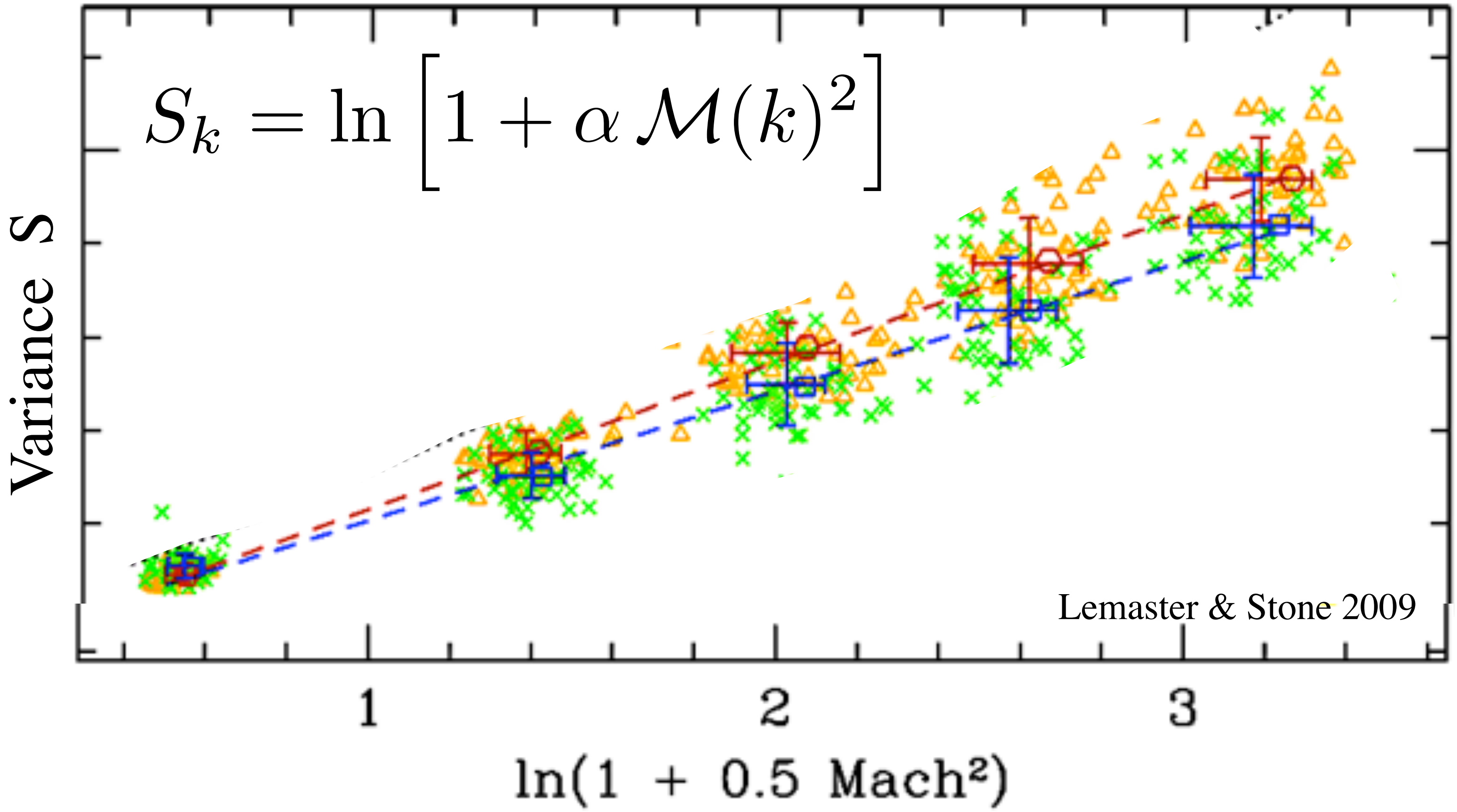
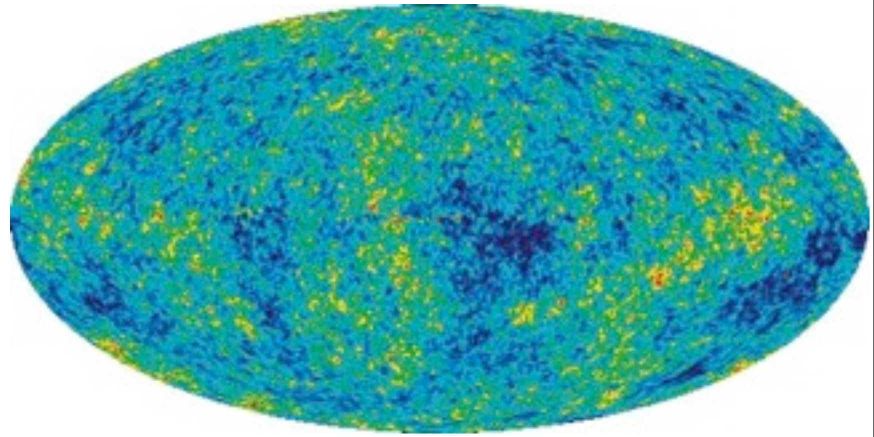
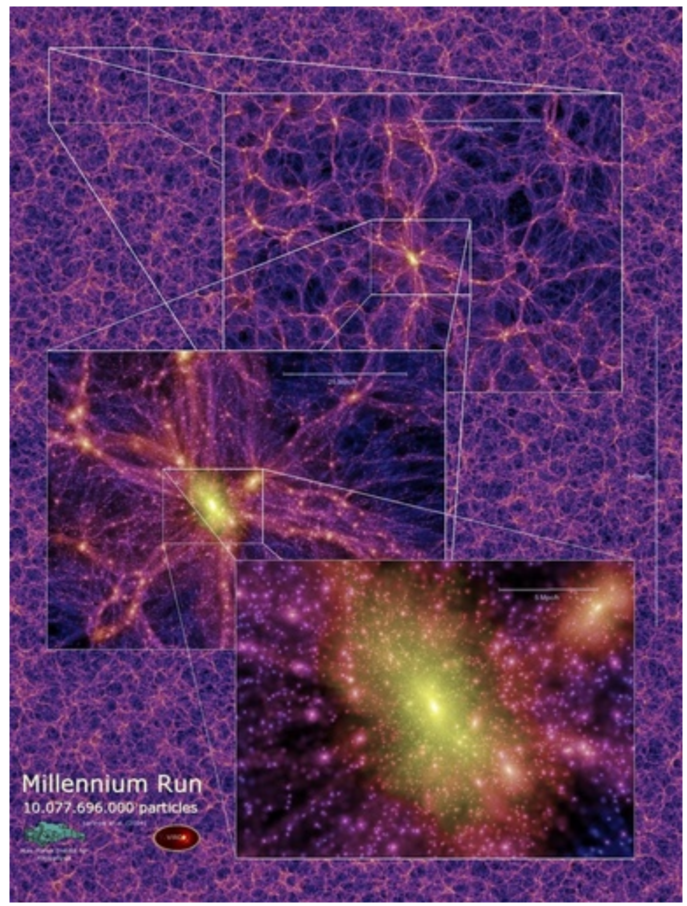


$$S(R) = \int \mathrm{d}\ln k\, S_k\, |W(k,\, R)|^2$$

Extended Press-Schechter / Excursion-Set Formalism

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





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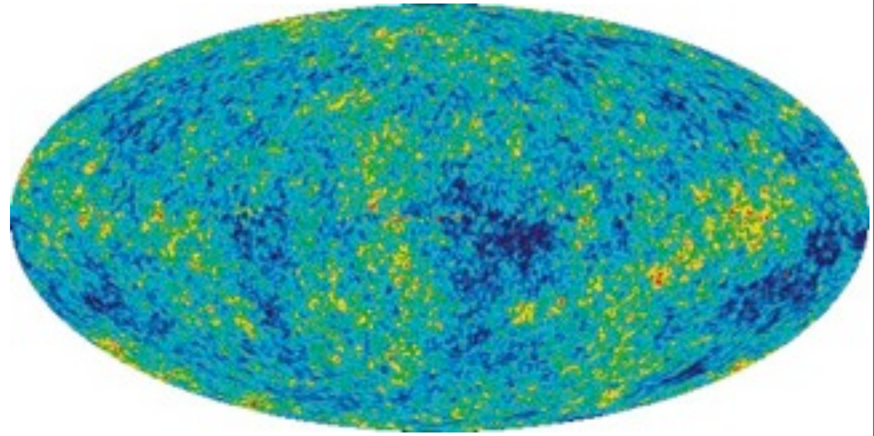

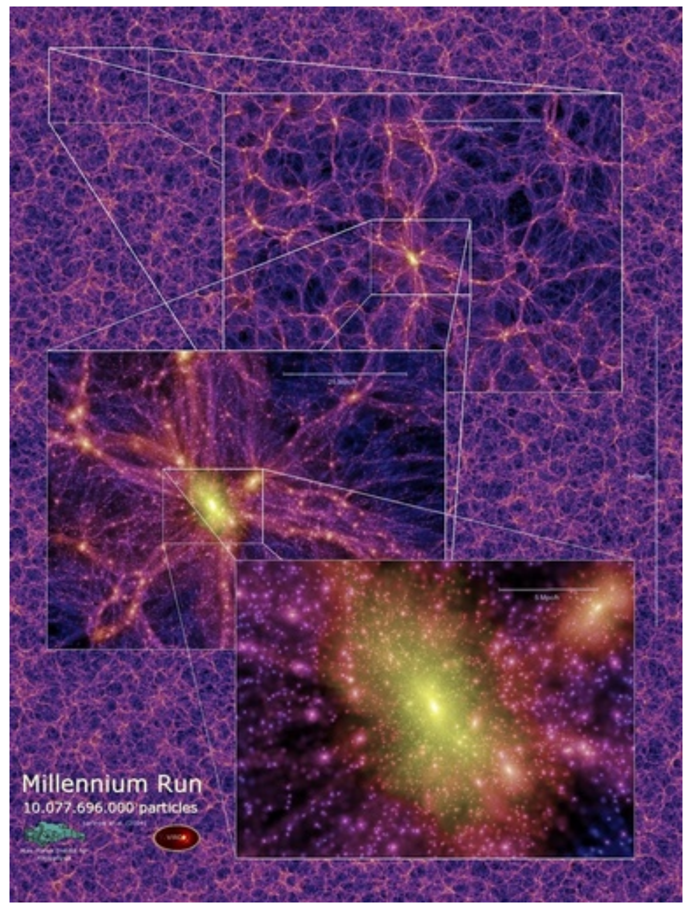

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$$\bar{\rho}(< R \sim 1/k) > \rho_{\rm crit}$$

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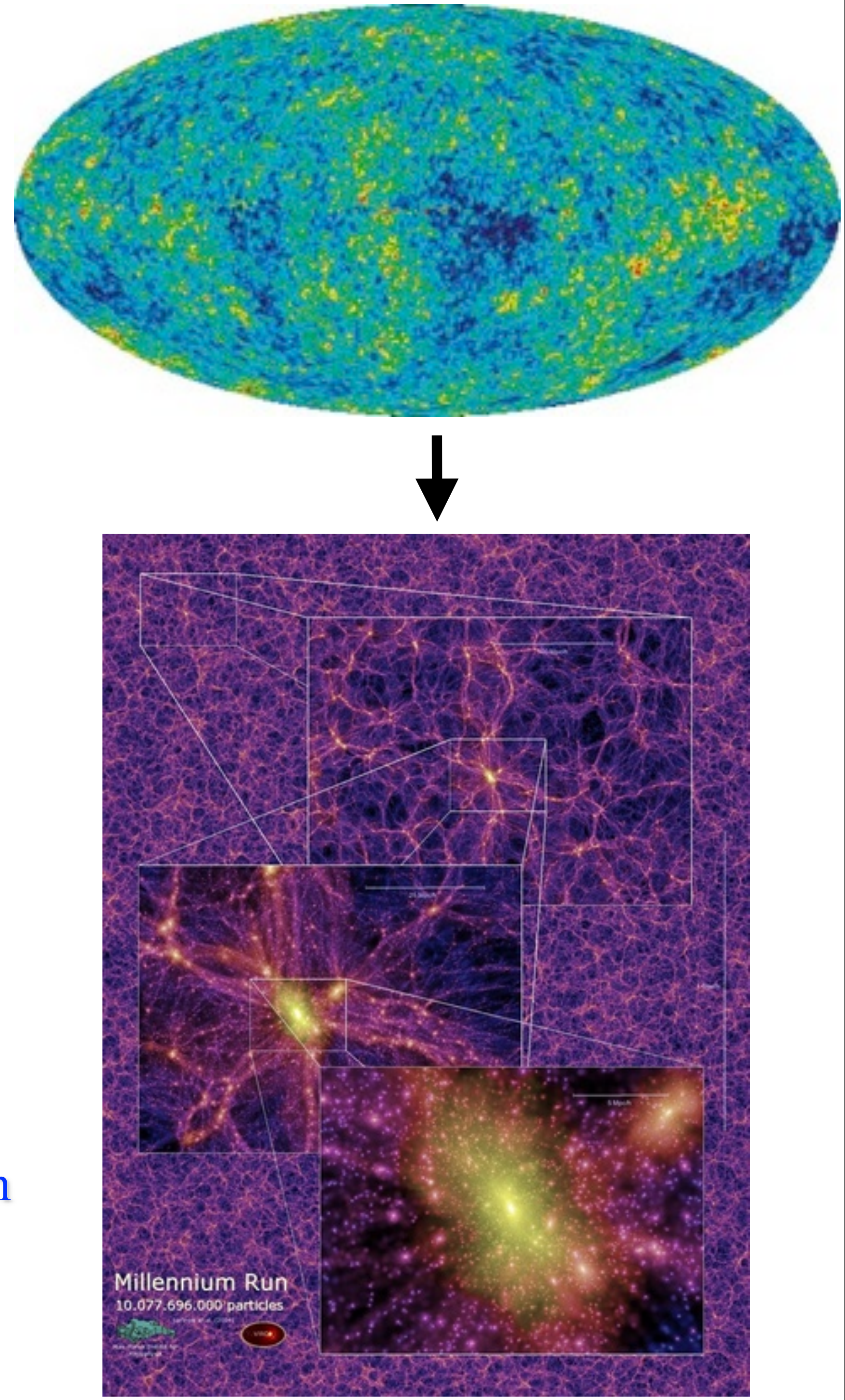

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- Generalize to conditional probabilities,
  N-point statistics, resolve “cloud in cloud” problem
  (e.g. Bond et al. 1991)

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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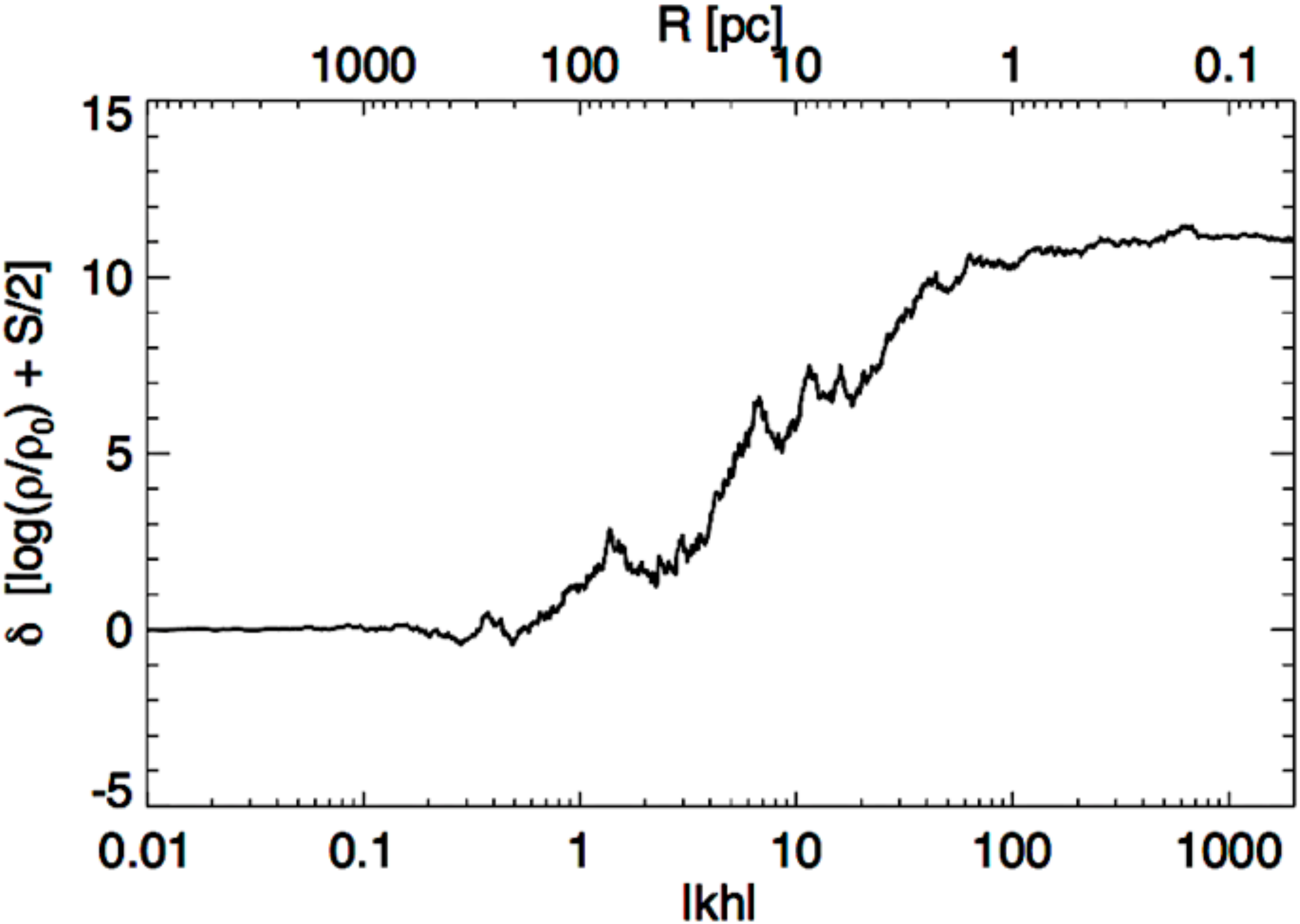
Mode Grows (Collapses) when w<0:

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

Chandrasekhar ‘51, Vandervoort ‘70, Toomre ‘77

"Counting" Collapsing Objects

EVALUATE DENSITY FIELD vs. "BARRIER"



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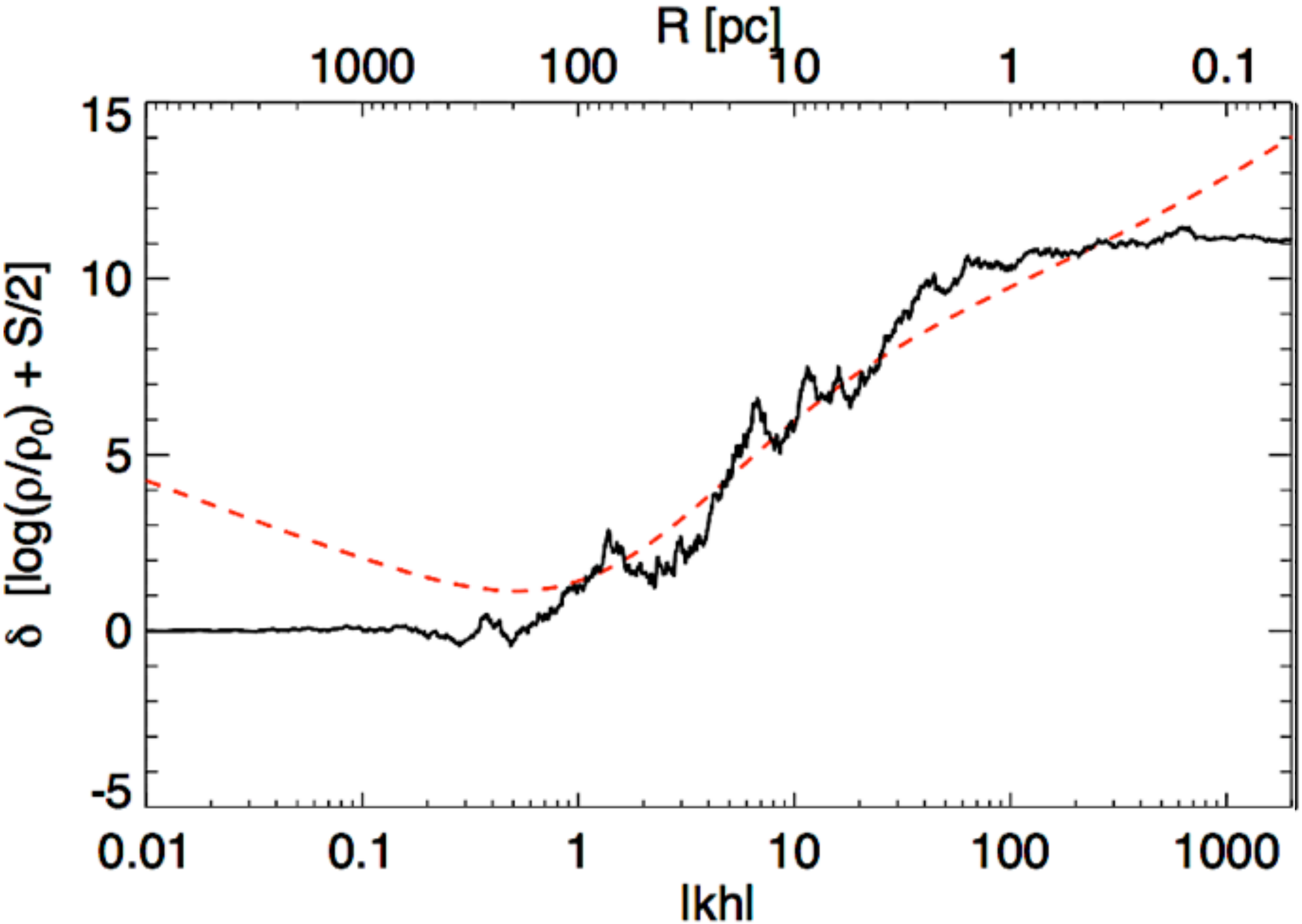

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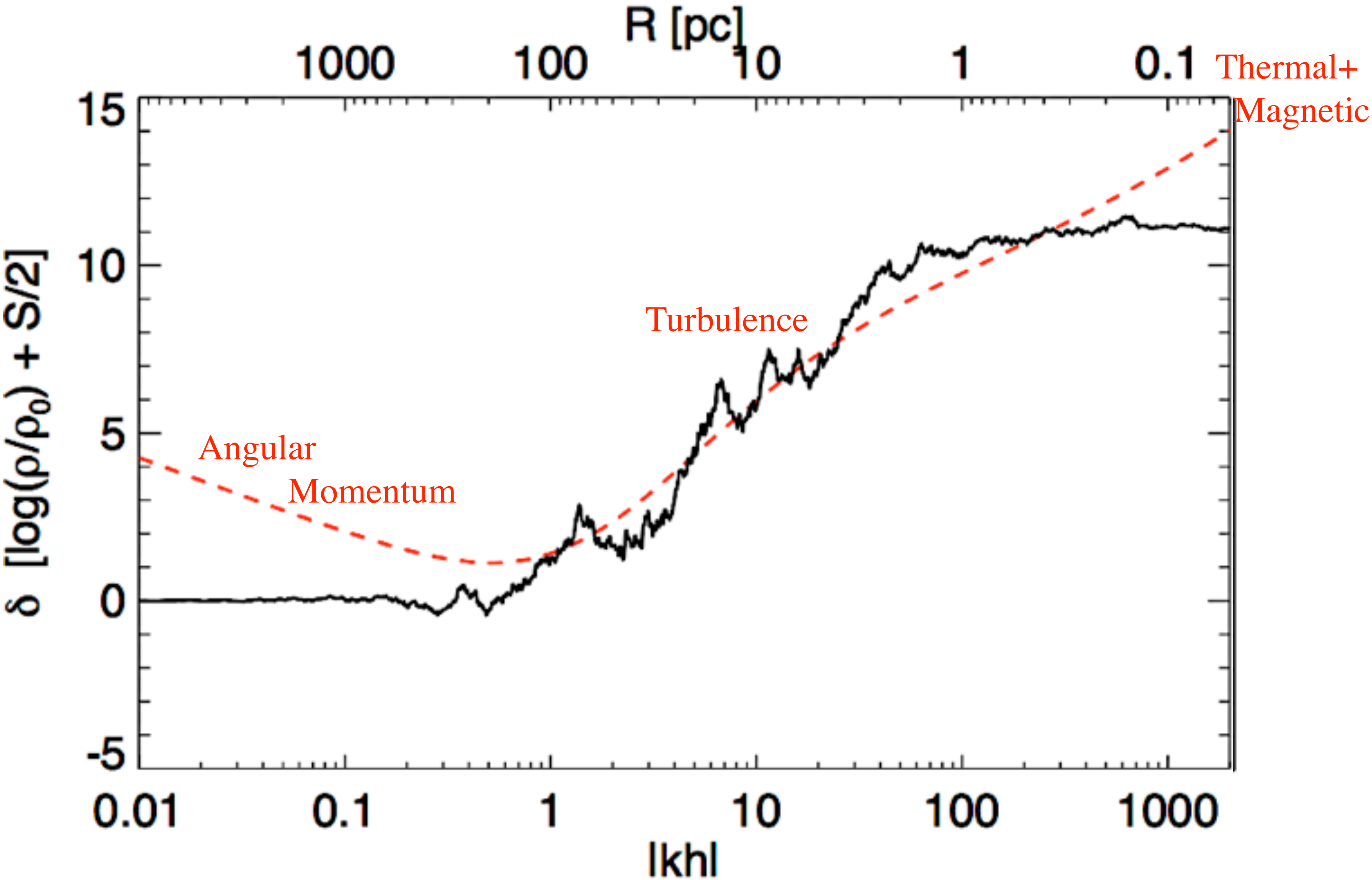

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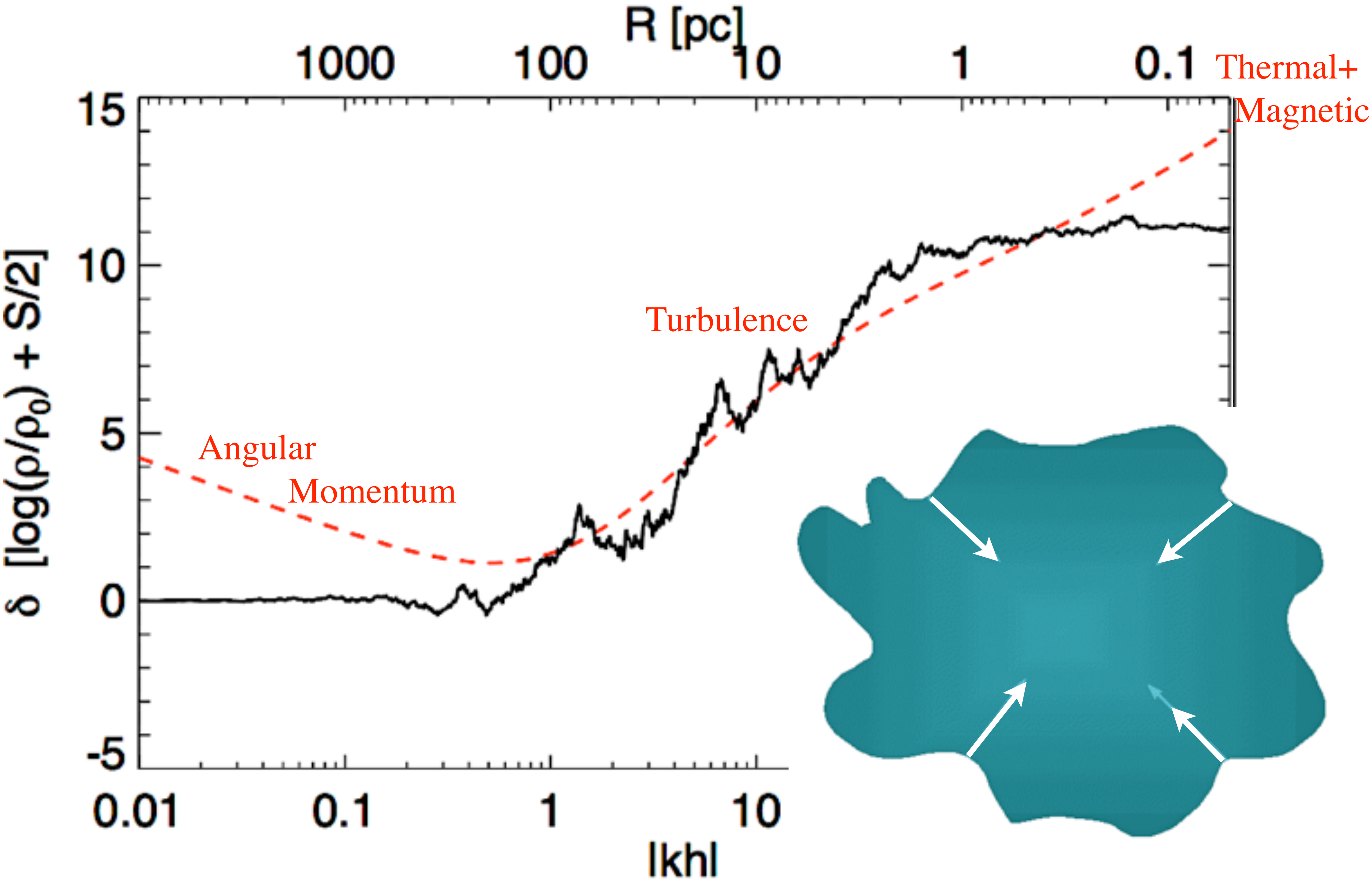

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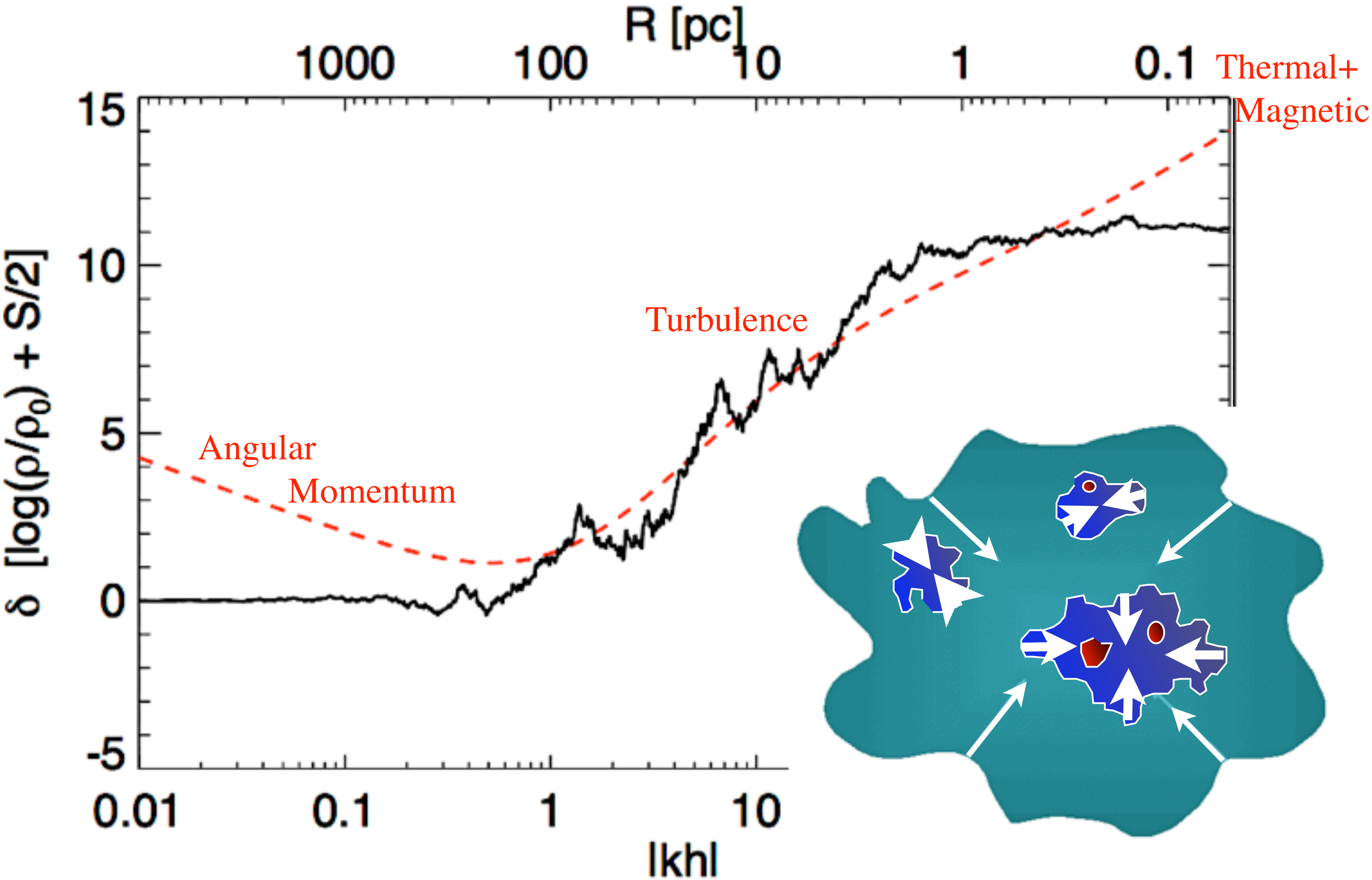

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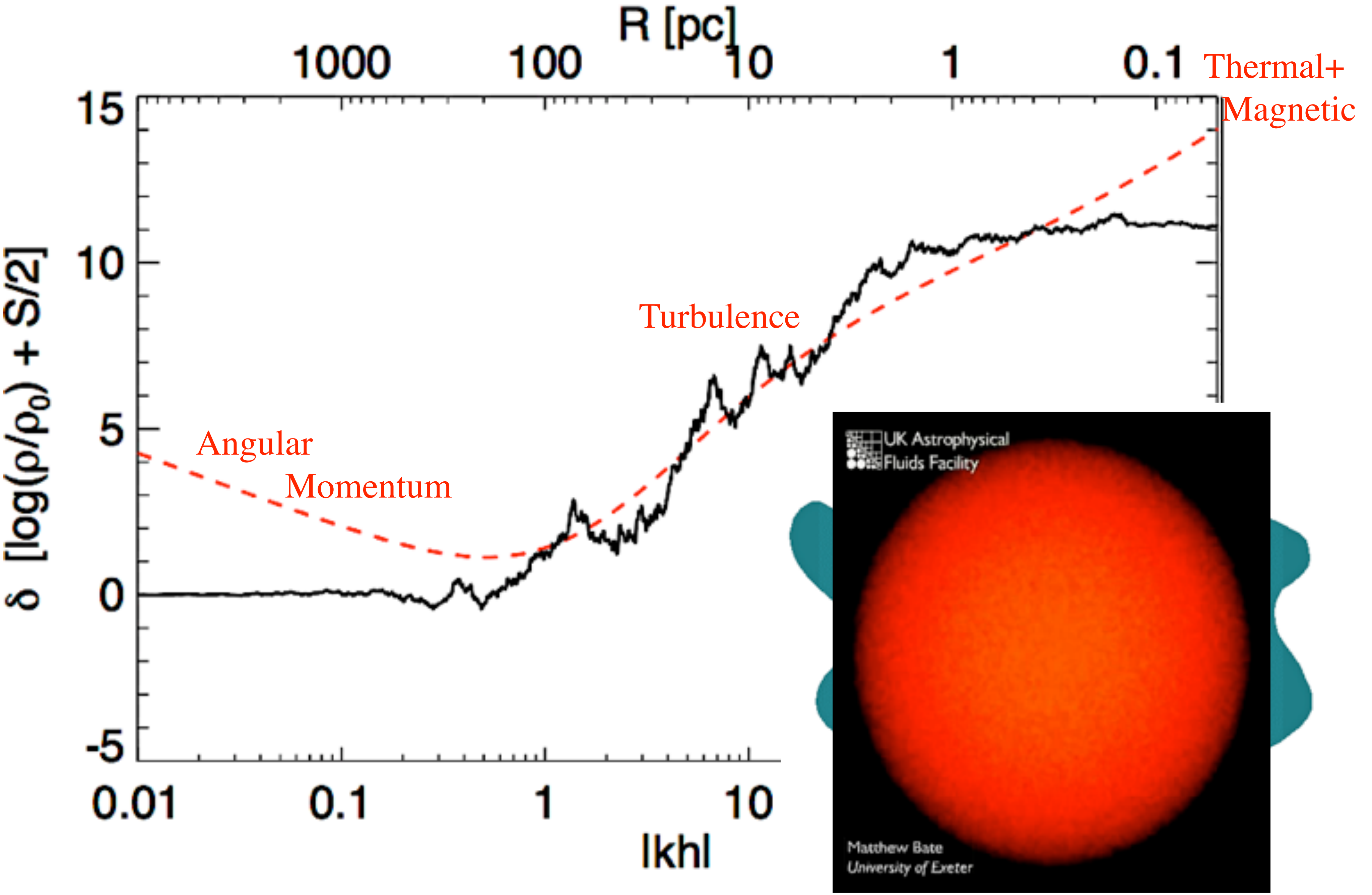

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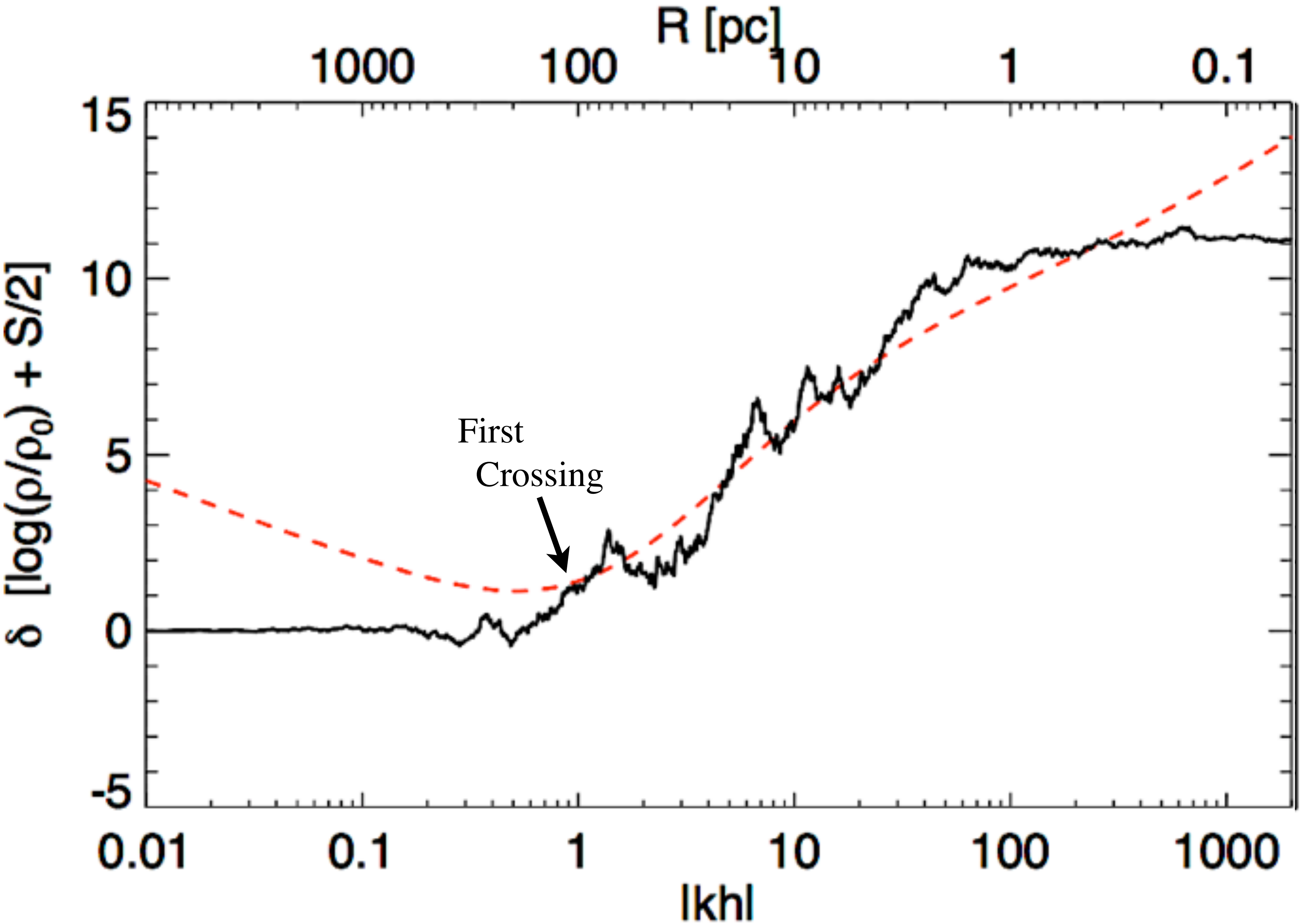

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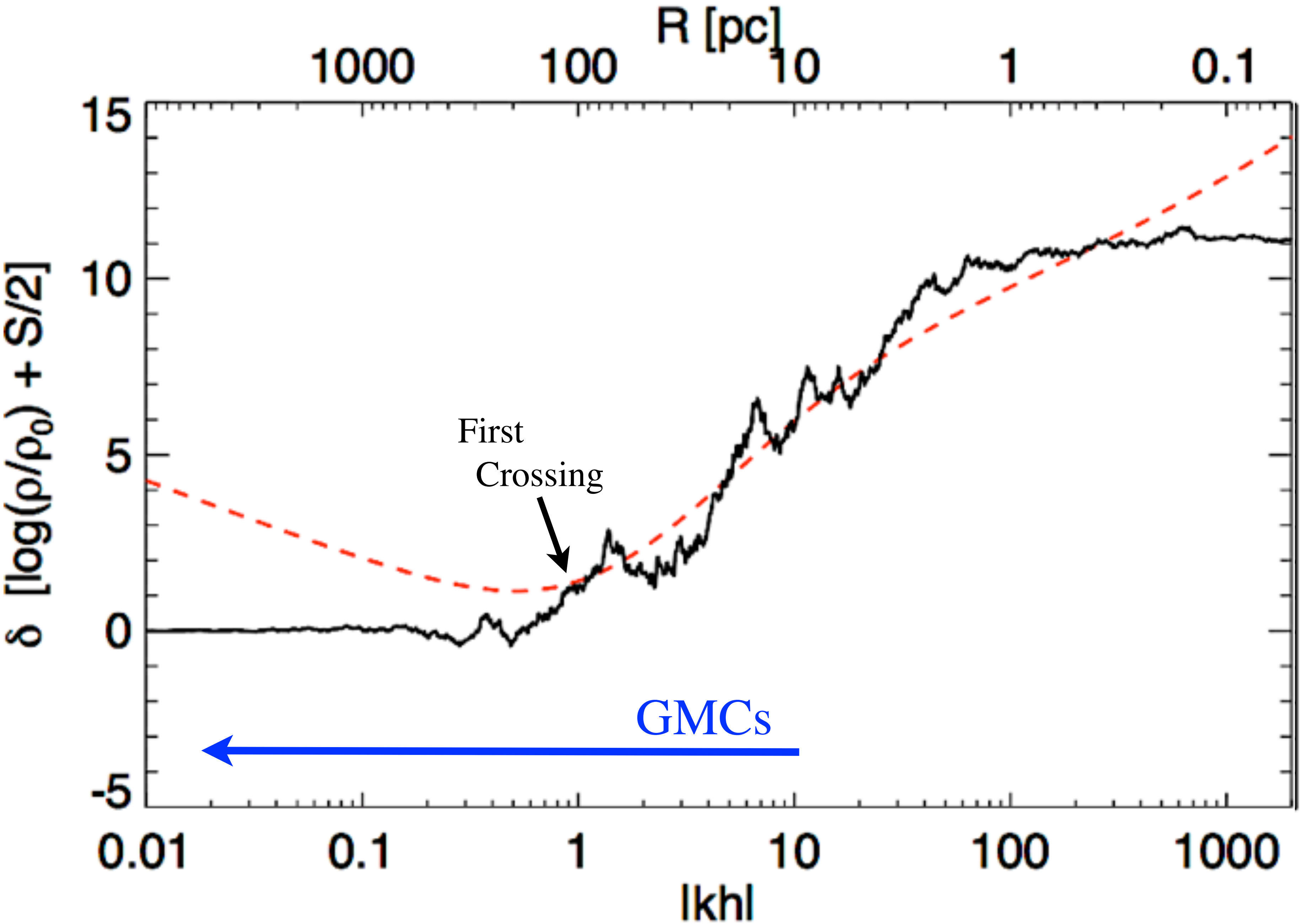

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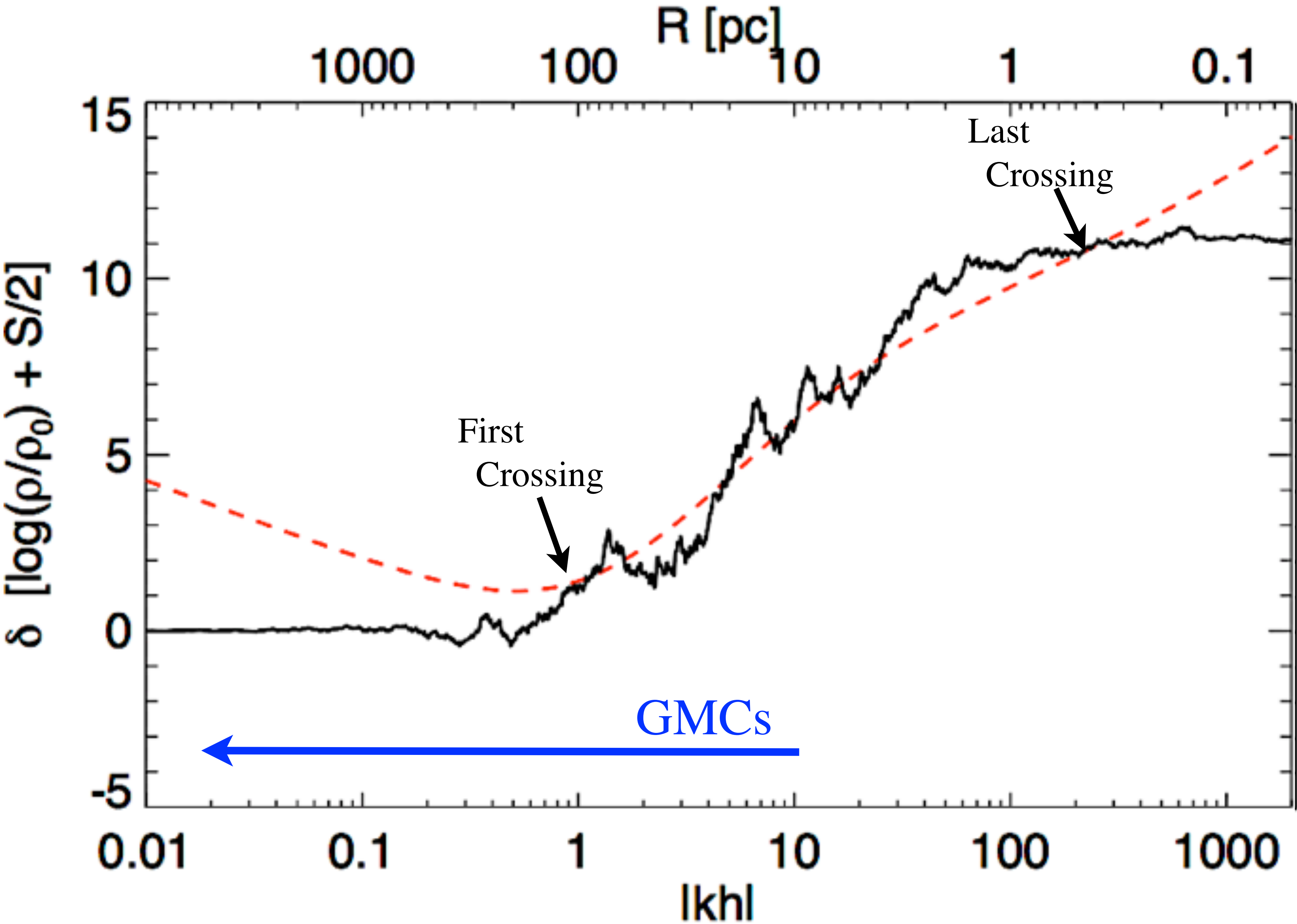

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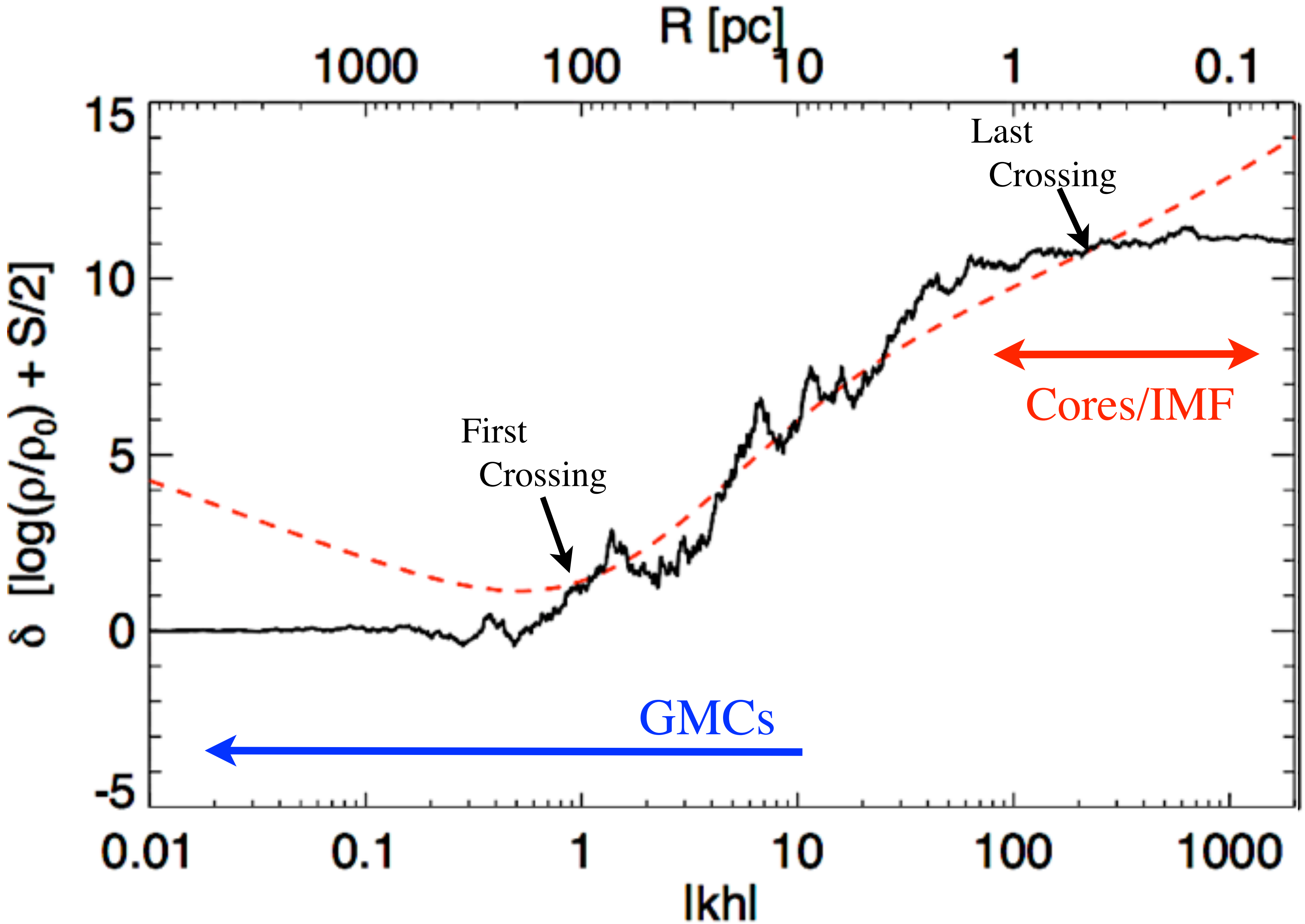
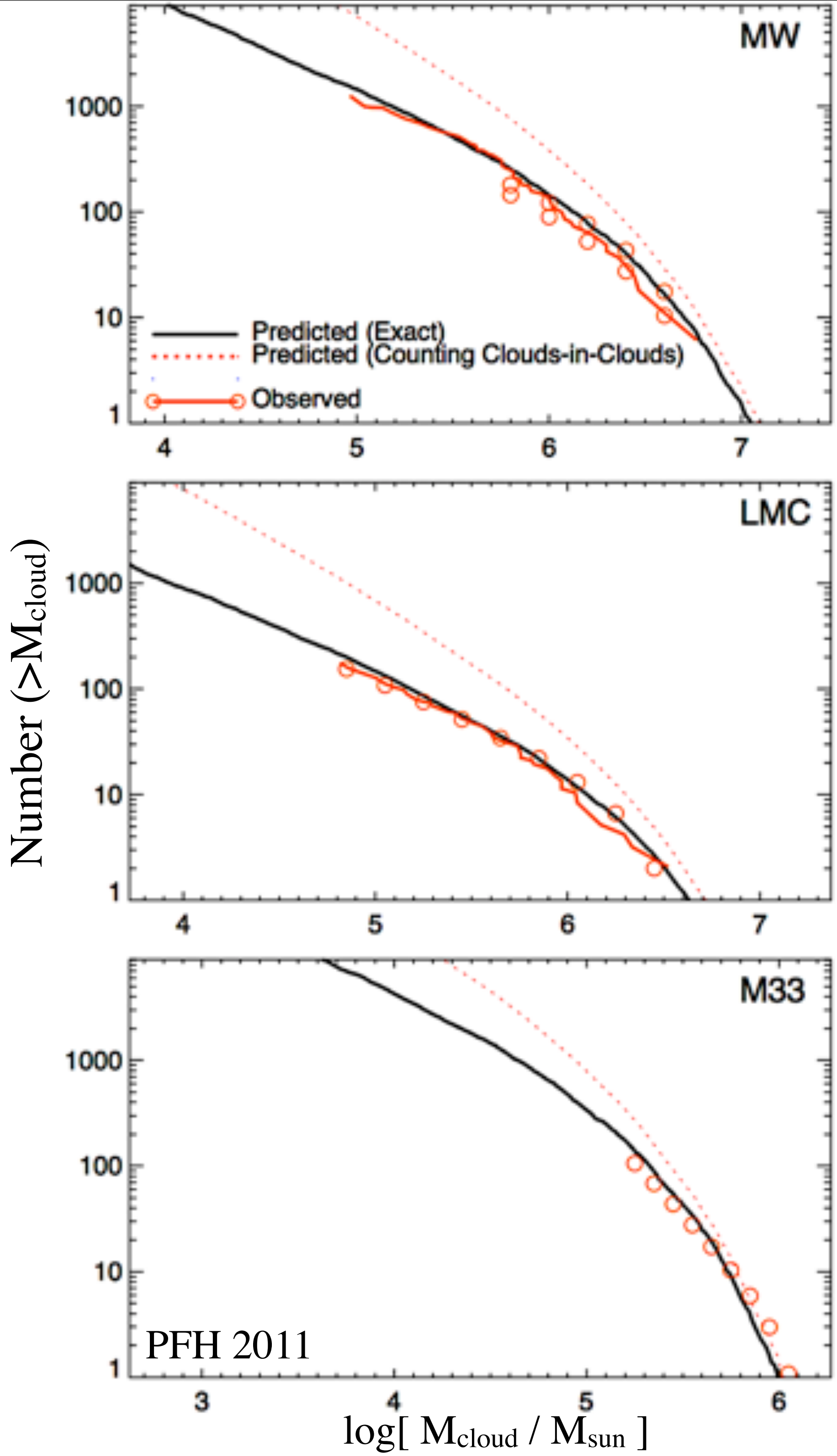


The "First Crossing" Mass Function

VS GIANT MOLECULAR CLOUDS



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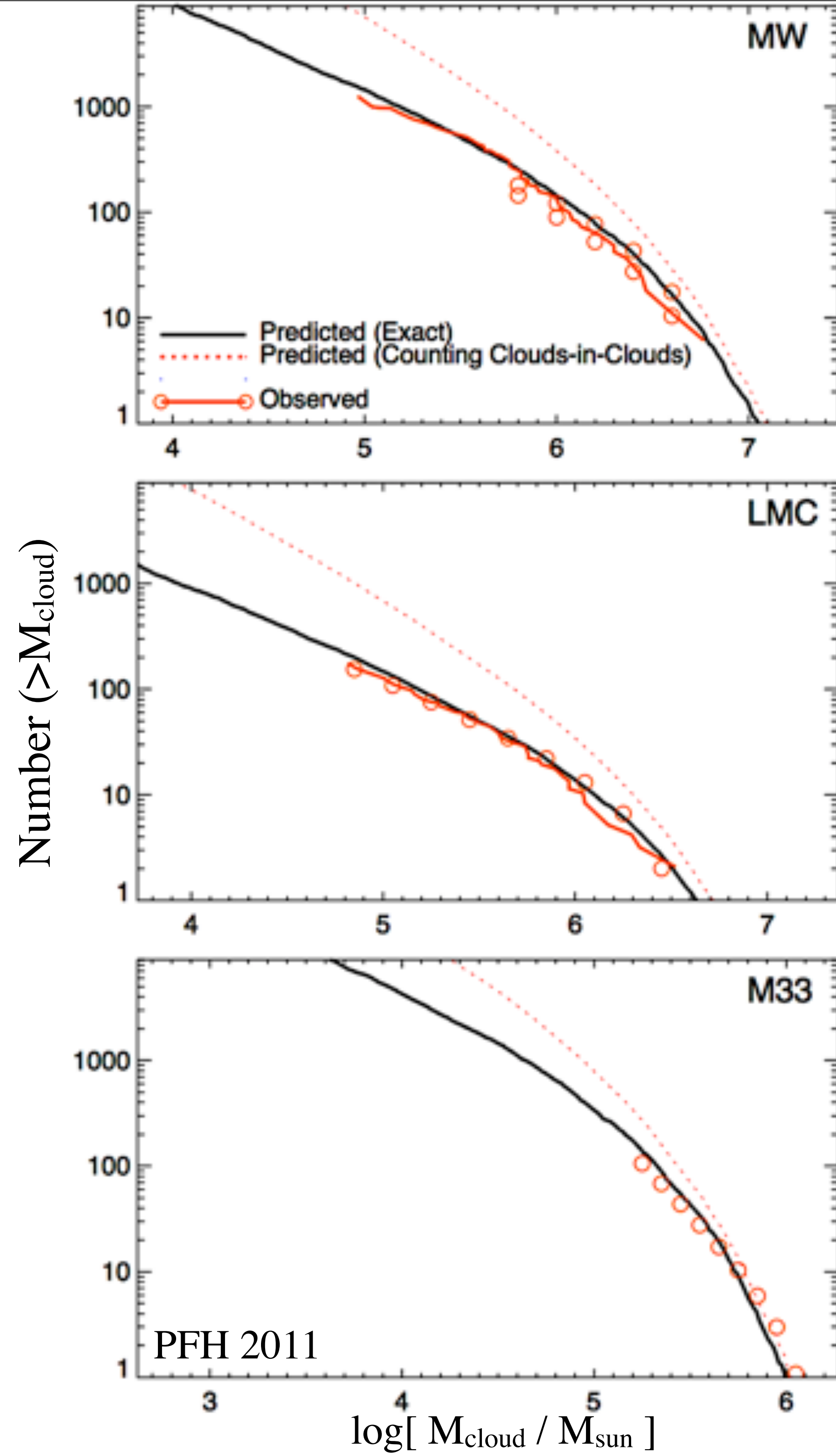
$$r_{\rm sonic} \ll r \ll h$$

$$S(r) \sim S_0$$



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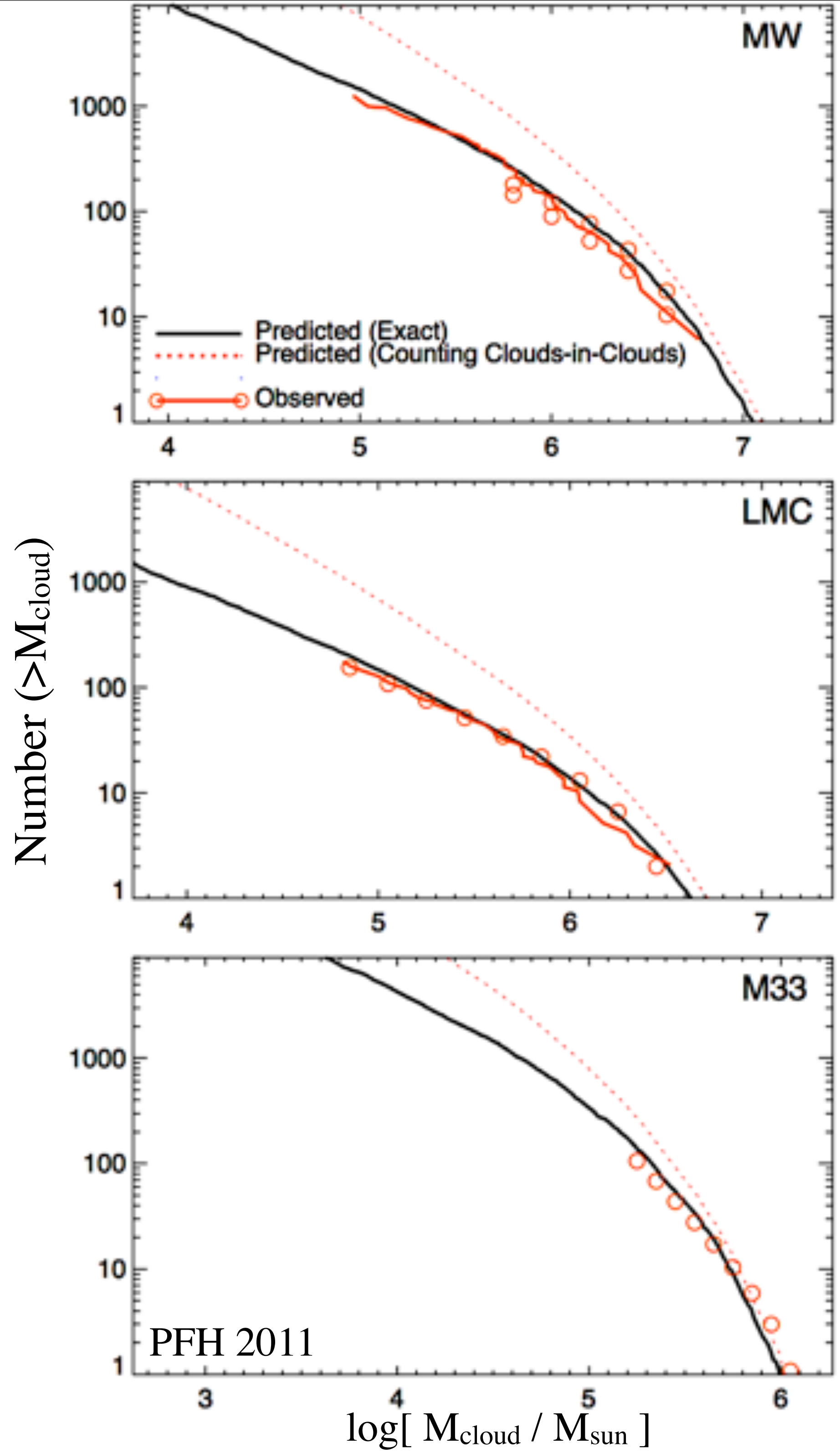

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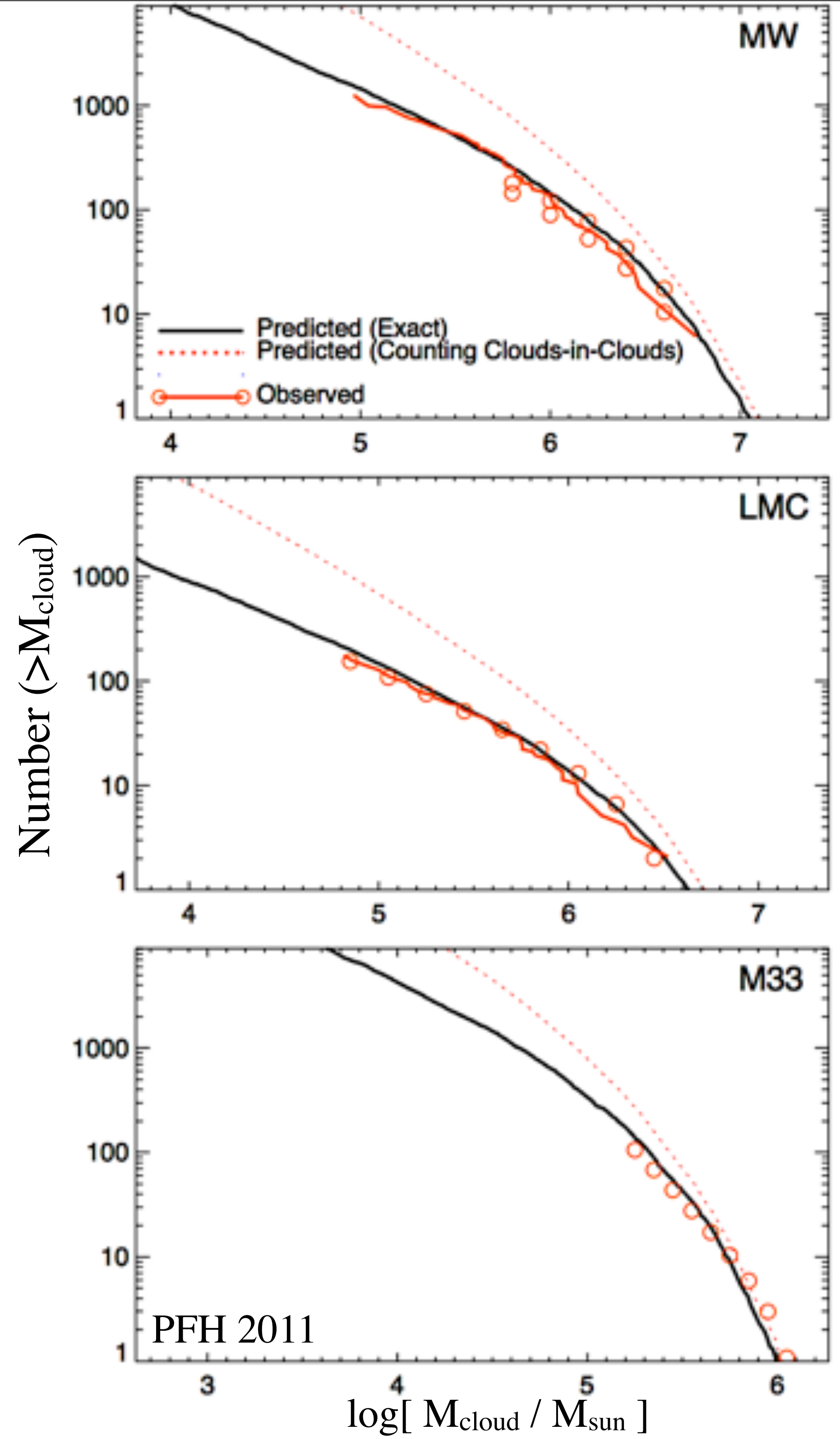
$$\alpha \approx -2 + \frac{(3-p)^2}{2\,S\,p^2}\ln\left(\frac{M_J}{M}\right)$$

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



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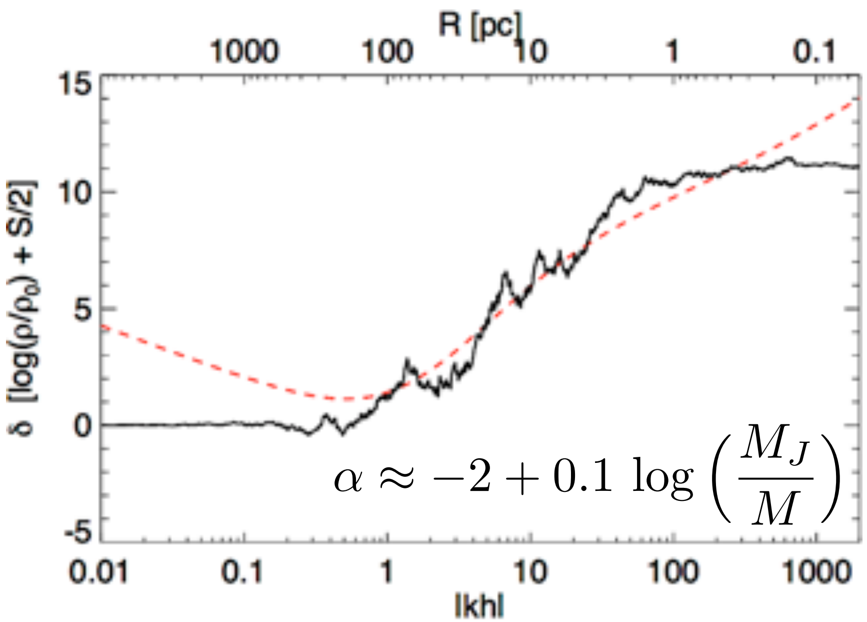

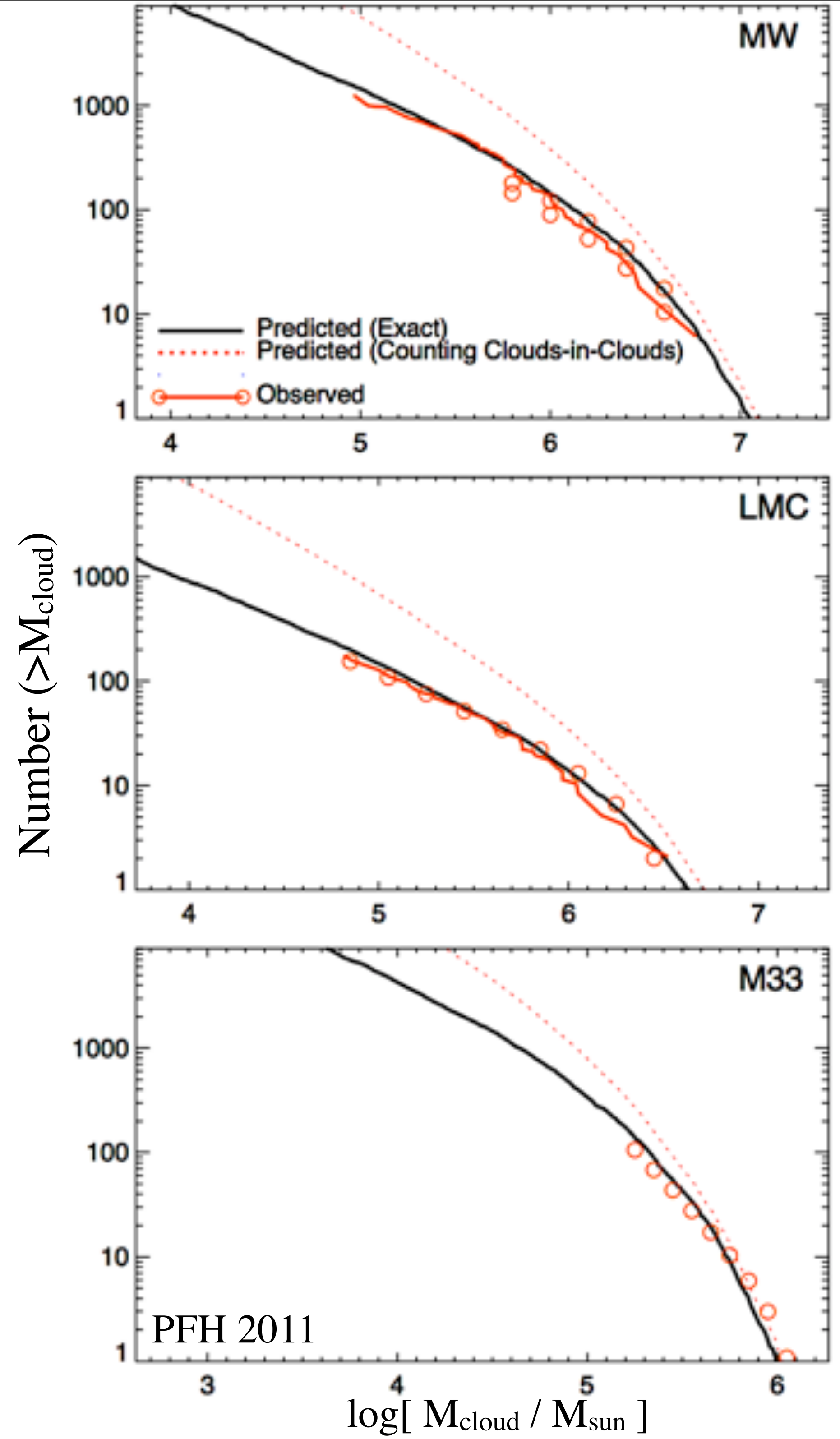

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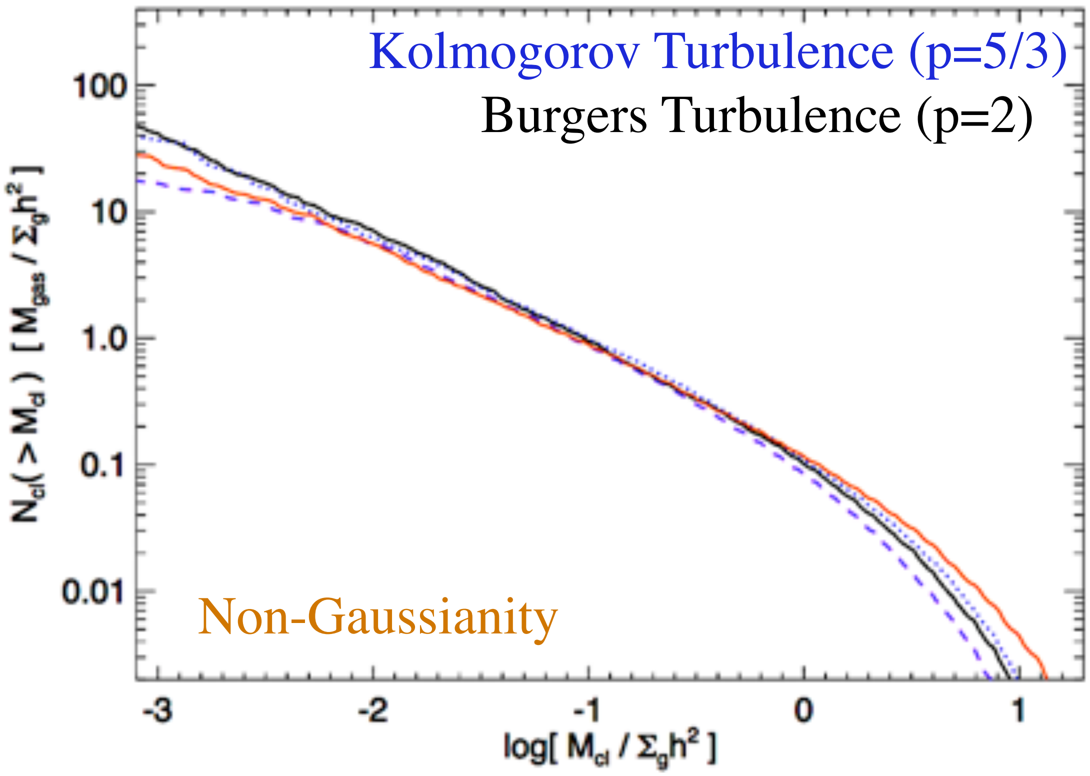
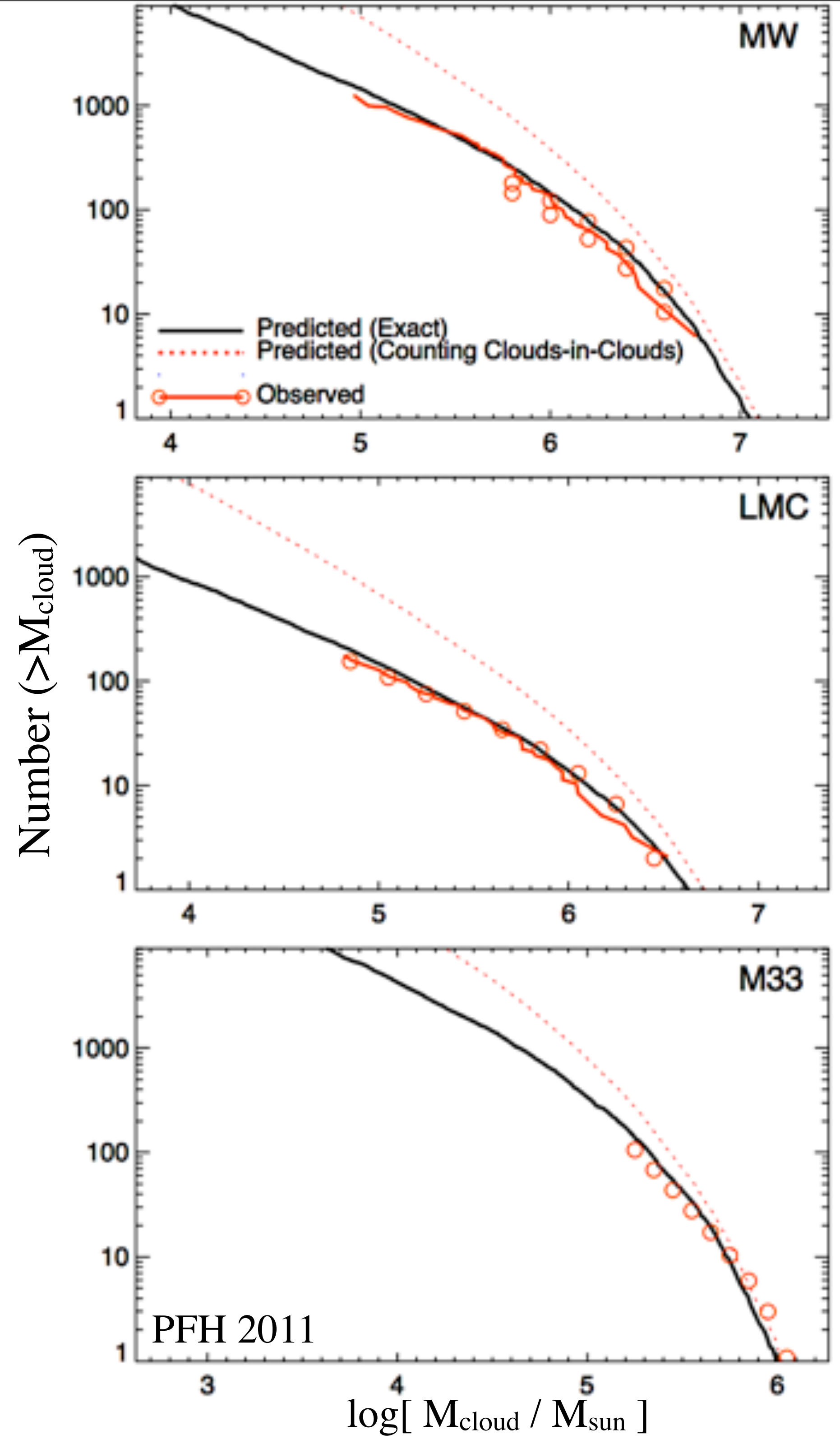
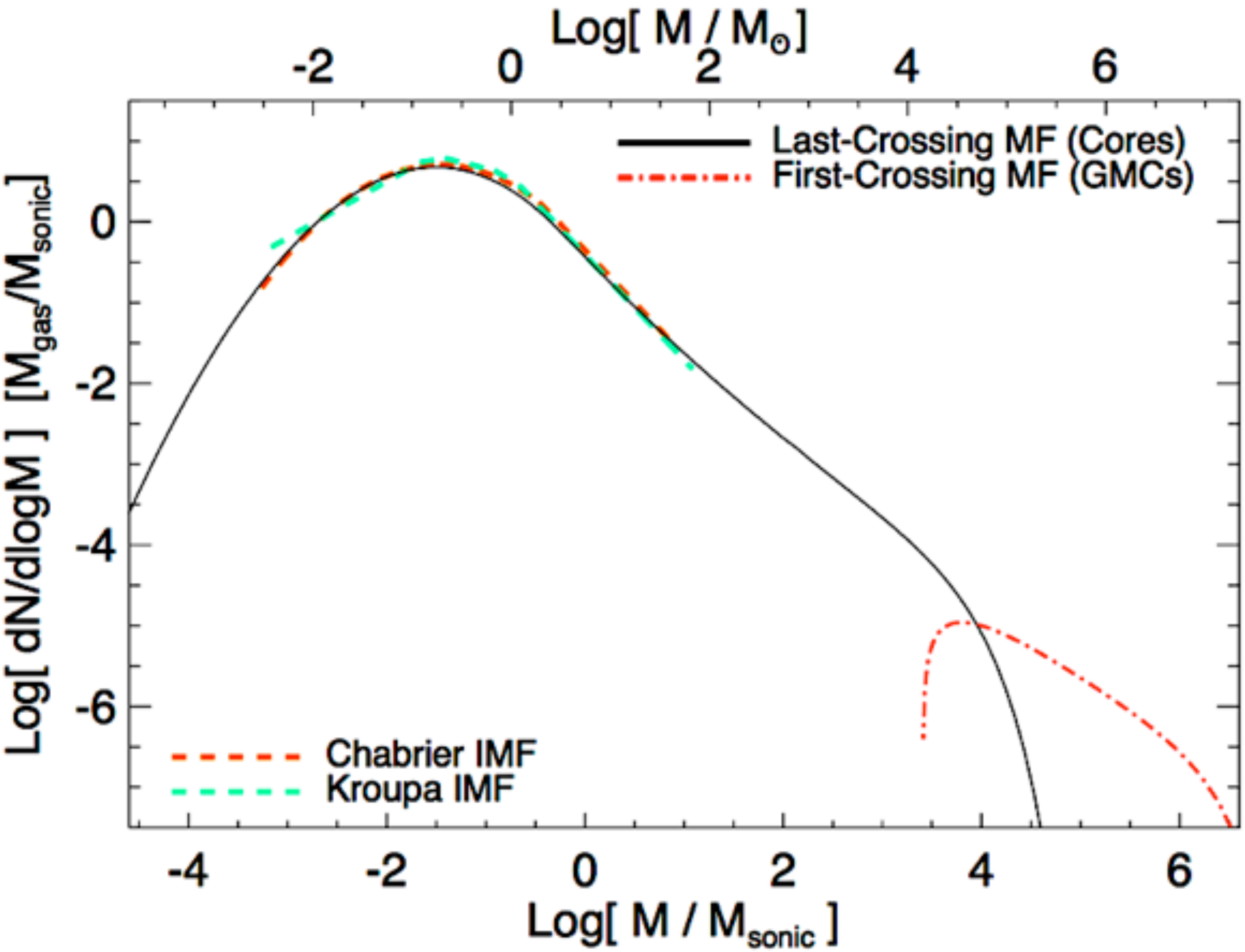




The “Last Crossing” Mass Function

VS PROTOSTELLAR CORES & THE STELLAR IMF



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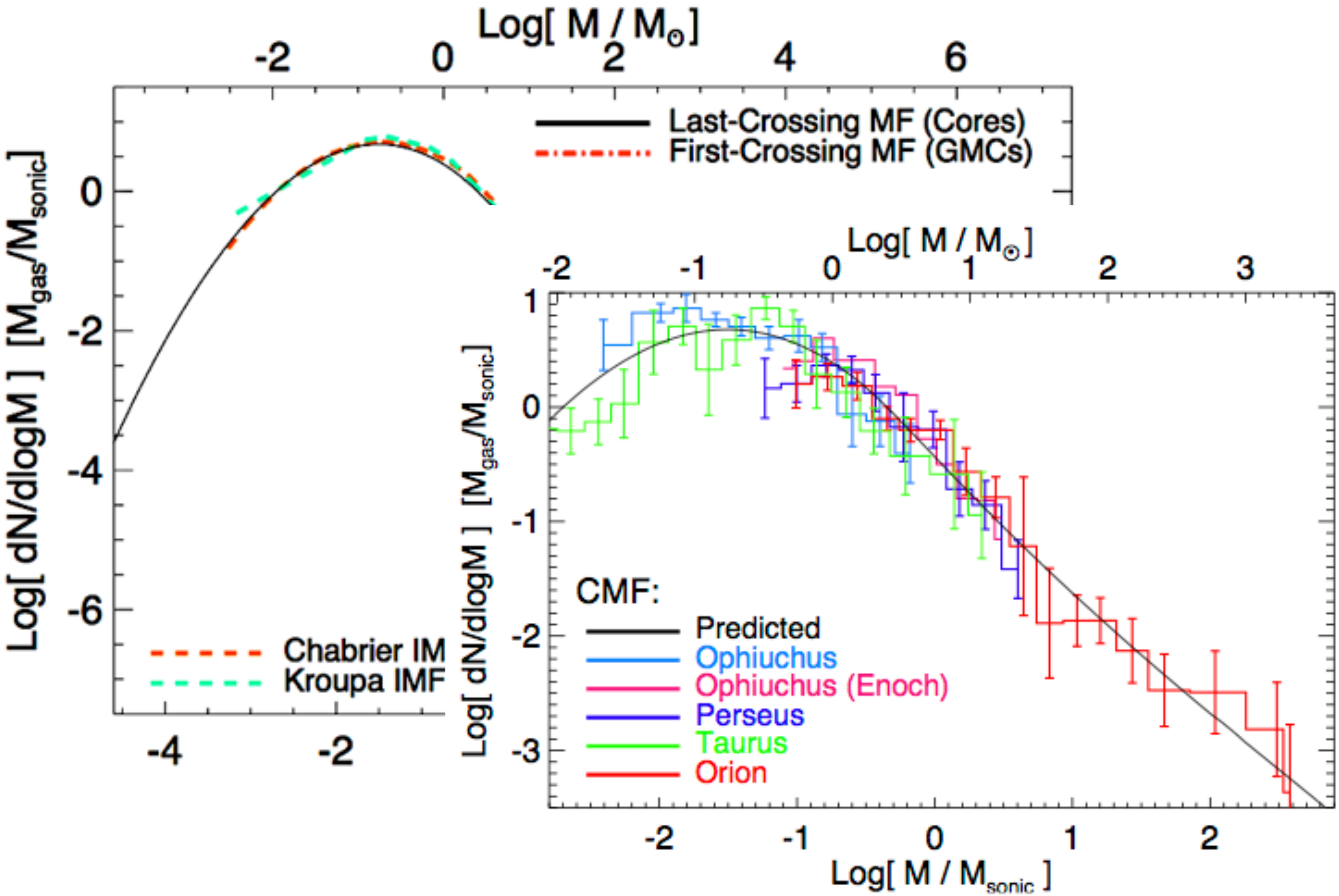
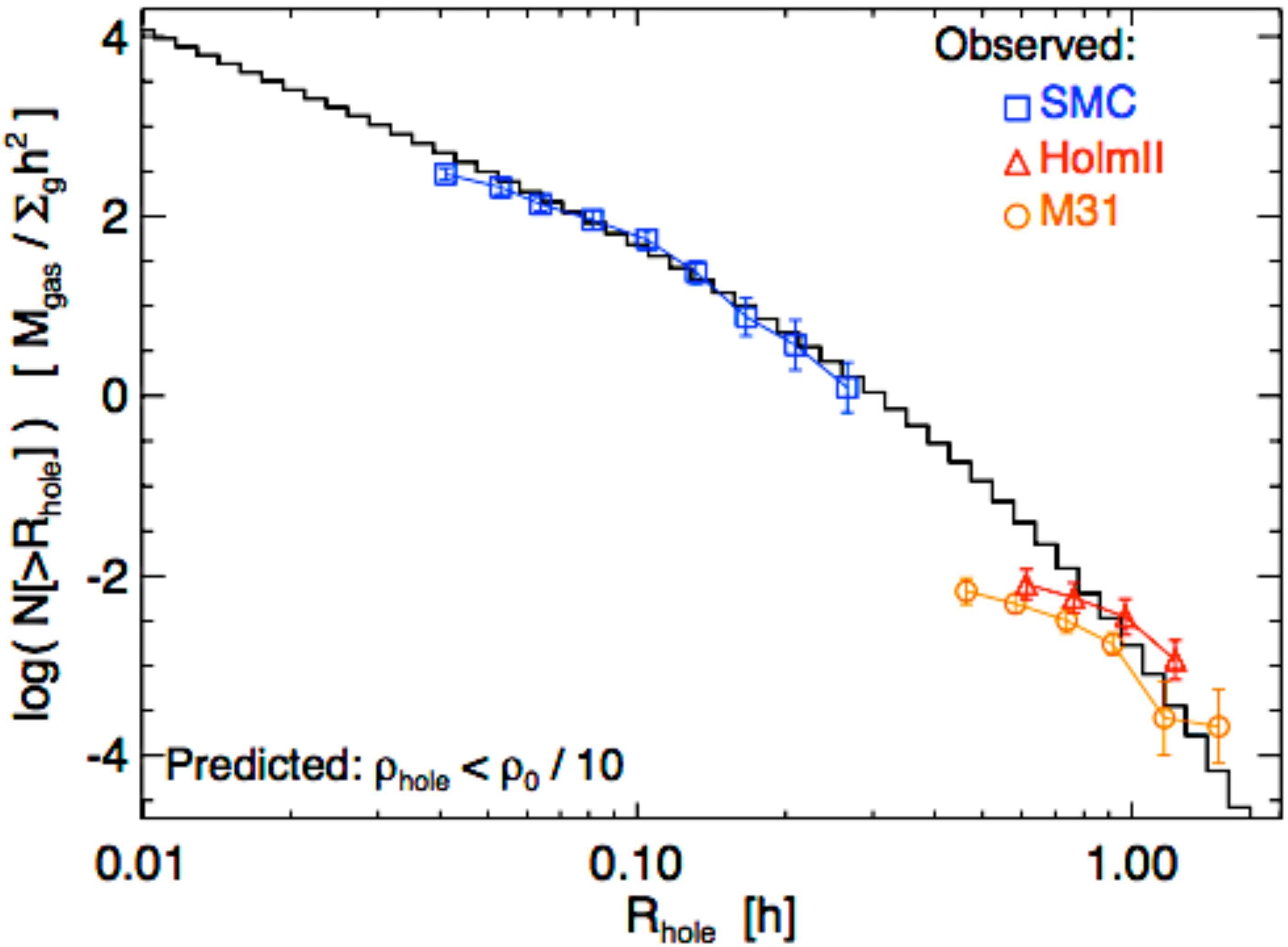


“Void” Abundance

VS HI “HOLES” IN THE ISM

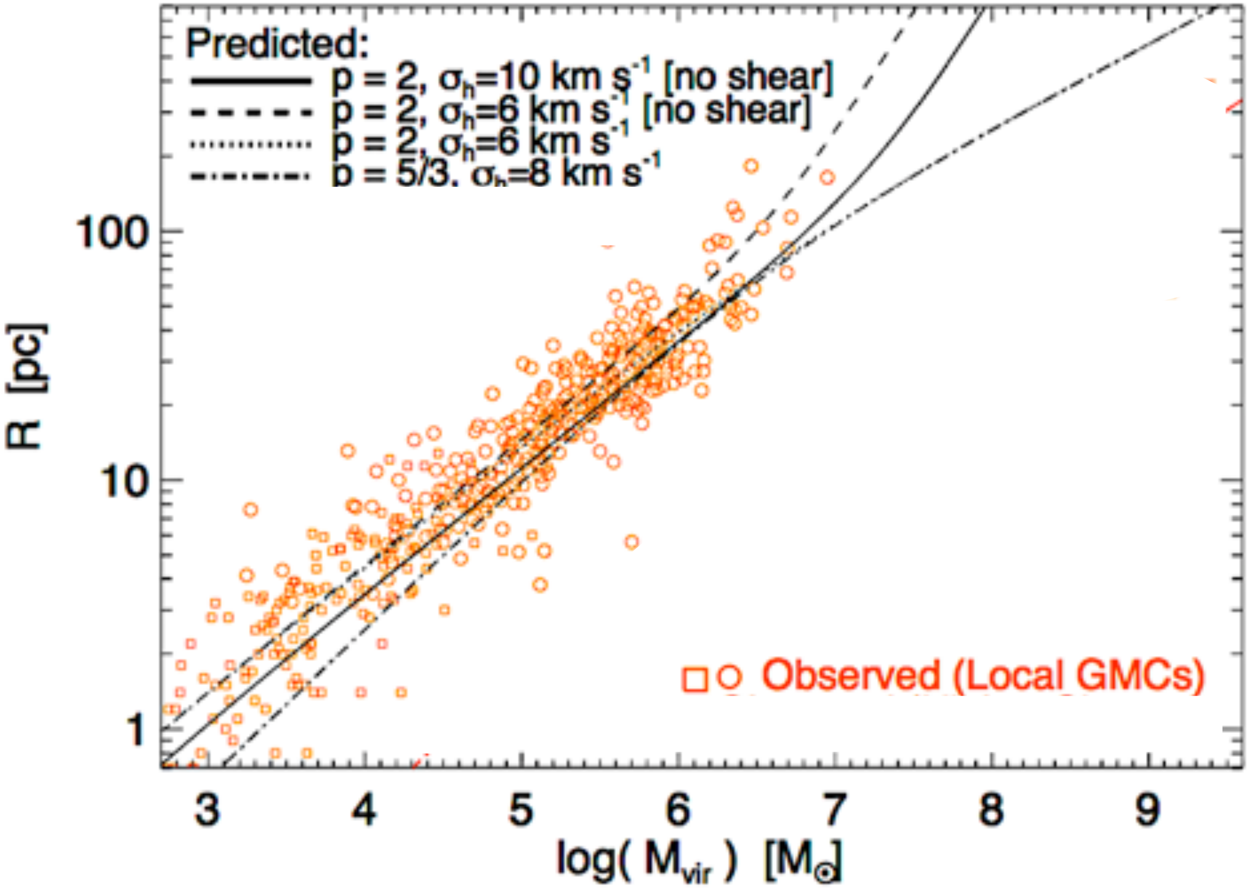


KEEP?

Don’t need SNe to “clear out” voids

Structural Properties of "Clouds"

LARSON'S LAWS EMERGE NATURALLY



KEEP?

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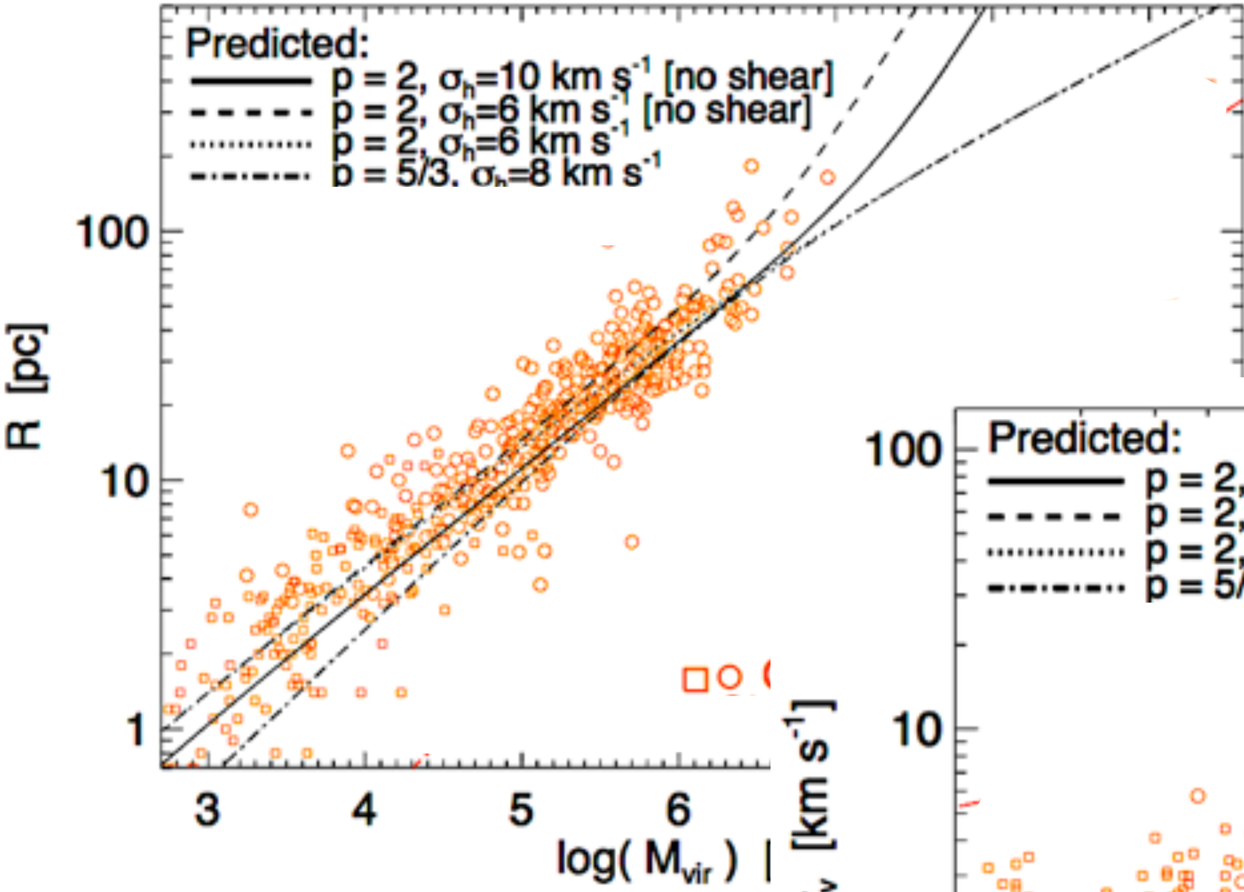
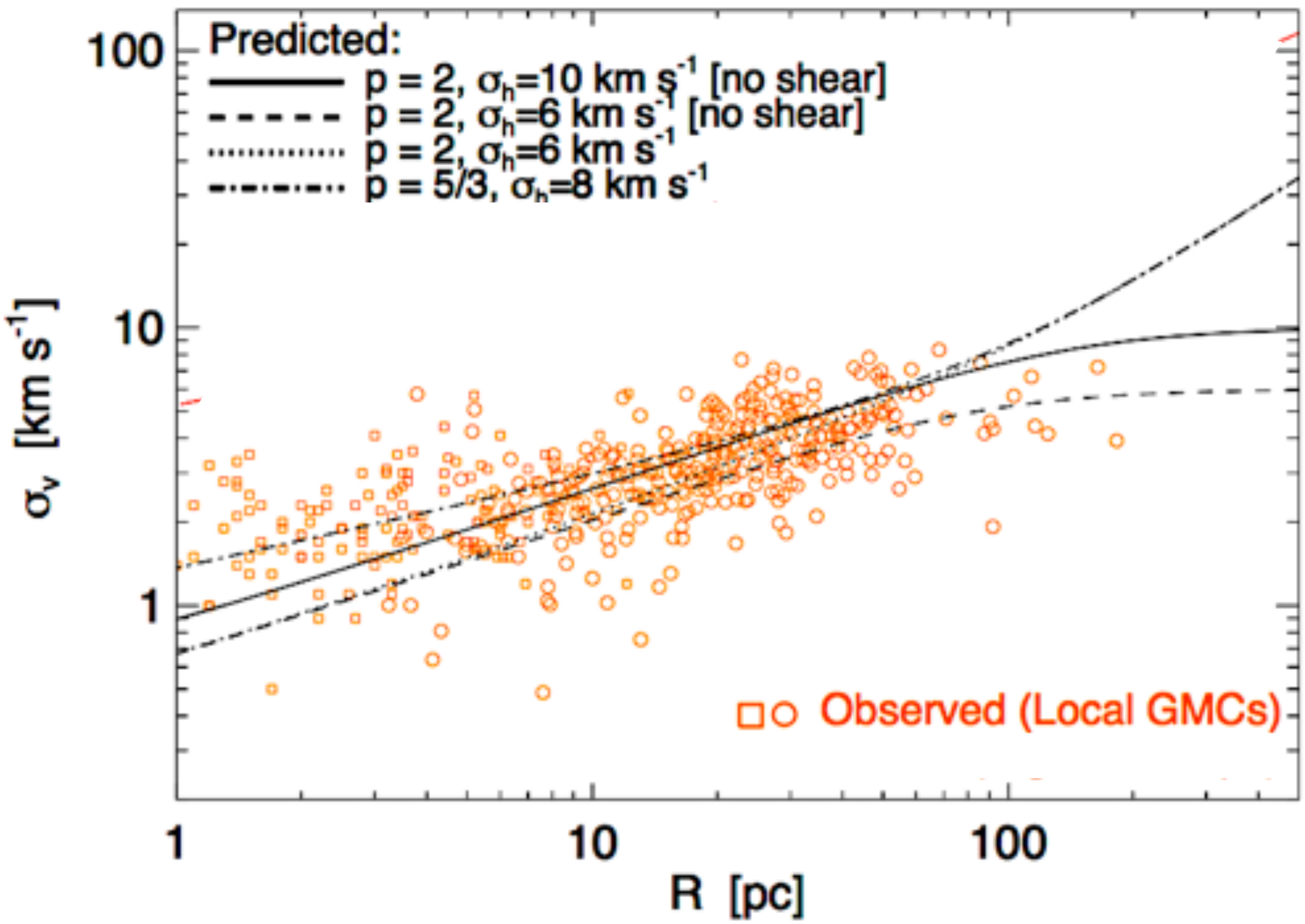


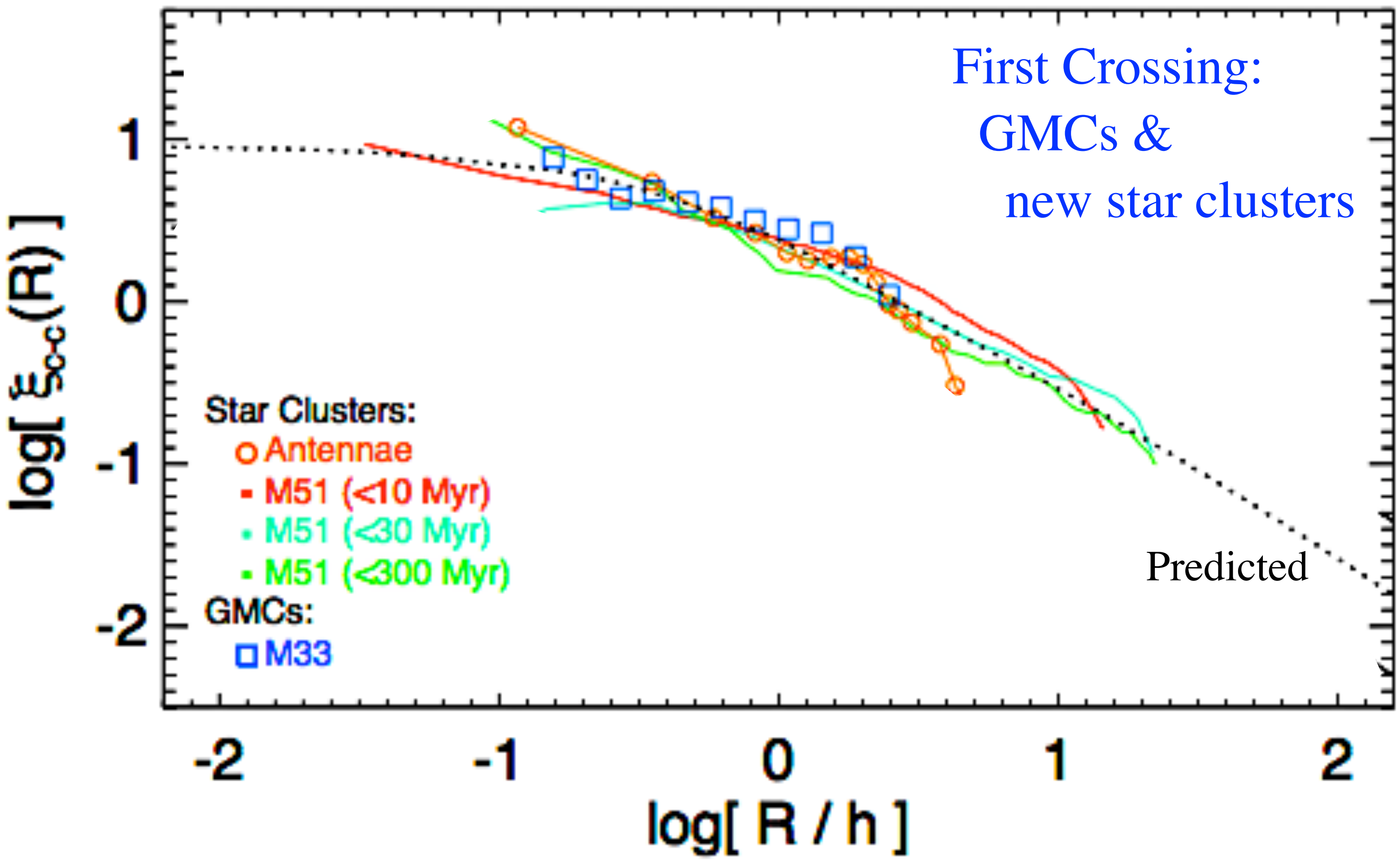


KEEP?

Clustering

PREDICT N-POINT CORRELATION FUNCTIONS

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



Clustering

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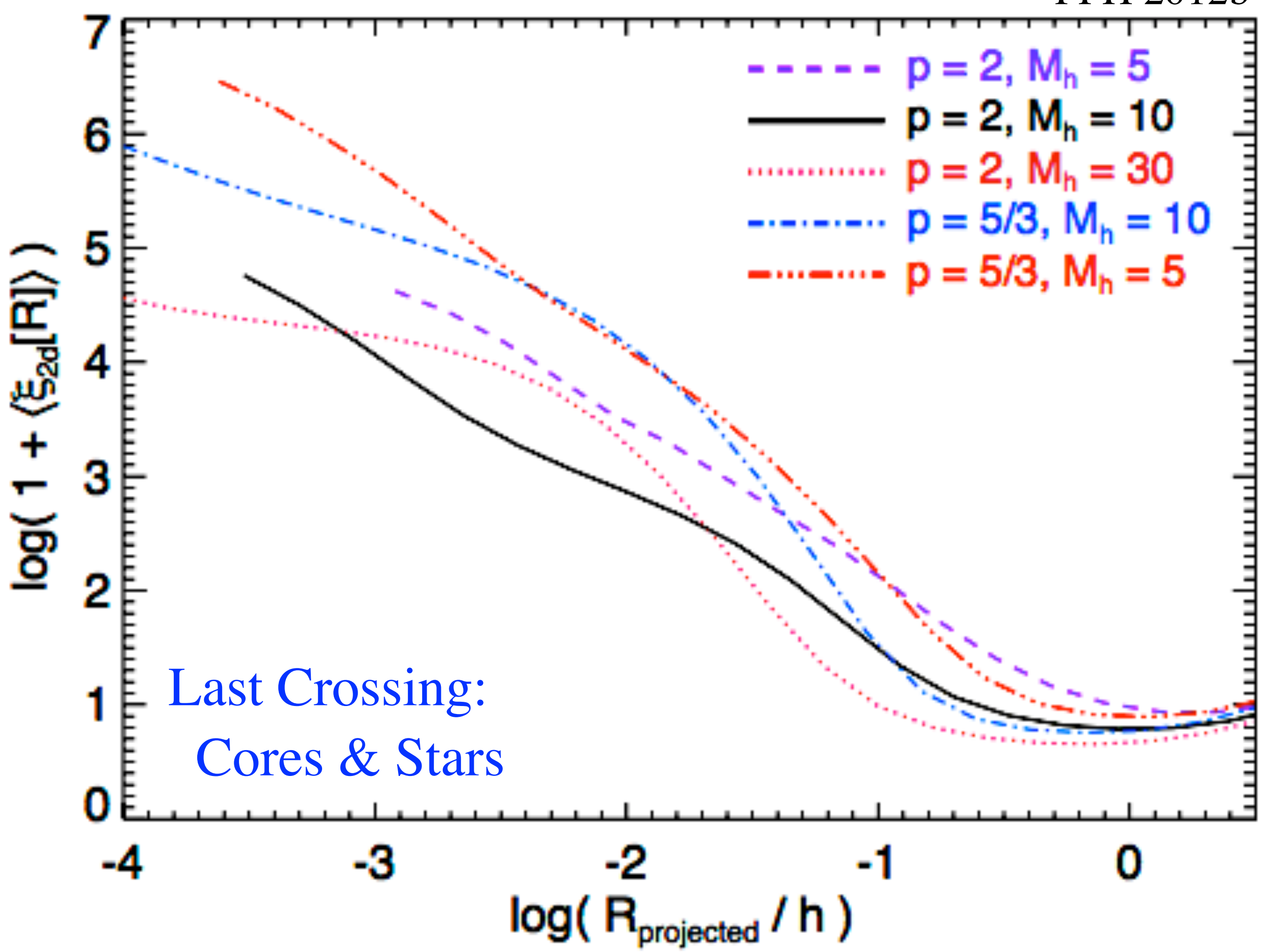
PFH 2012b



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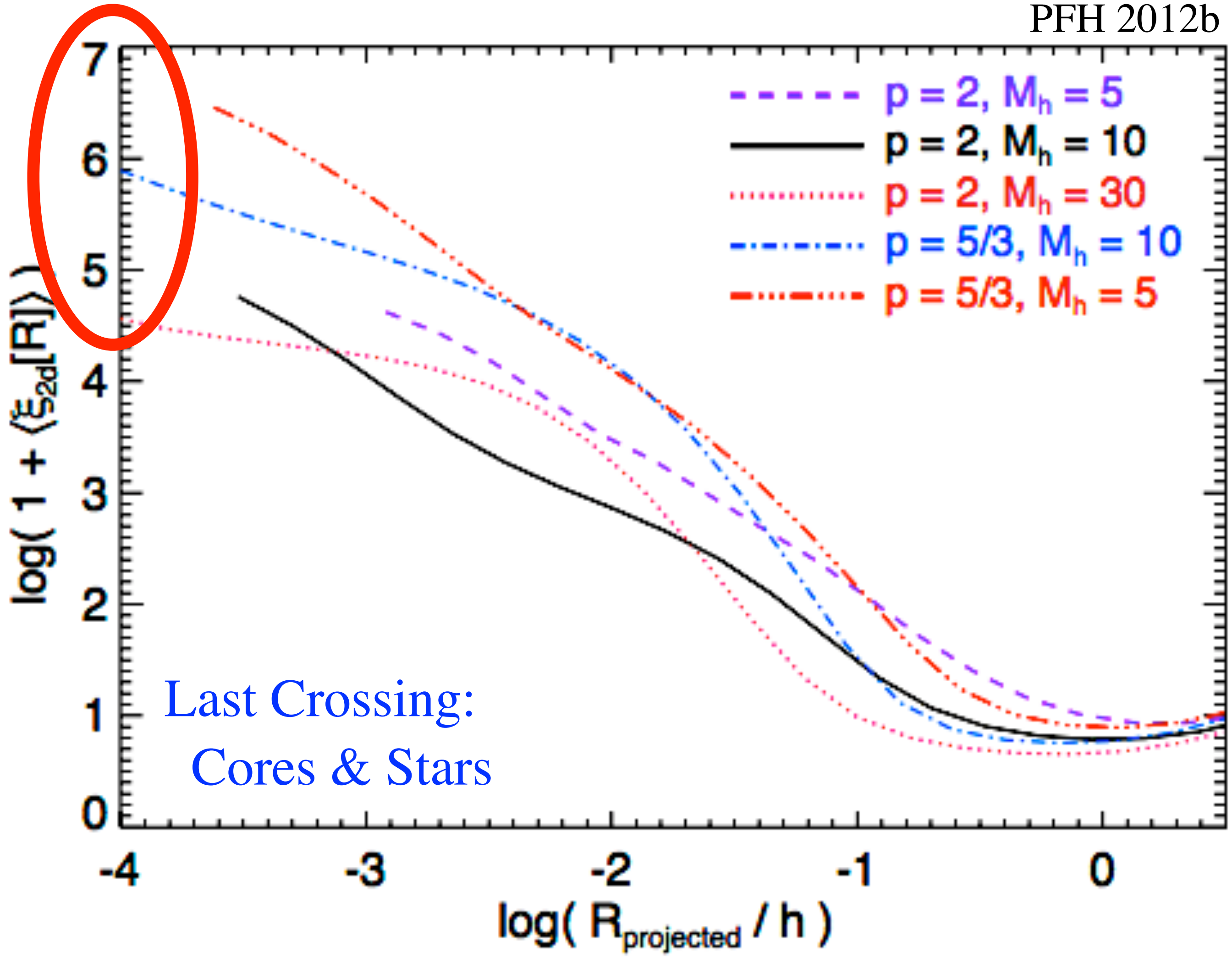
PFH 2012b



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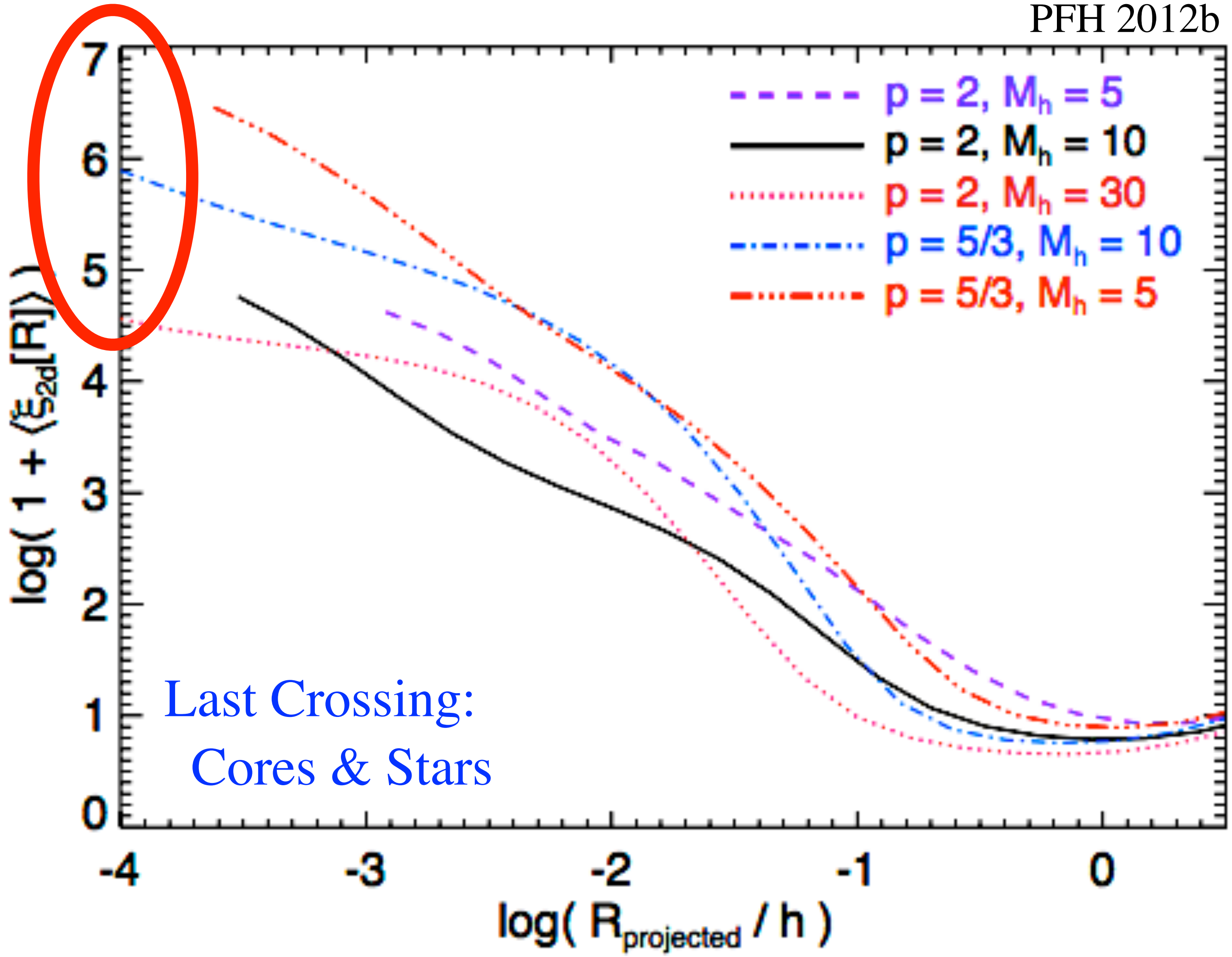
Why Do Stars Form in Clusters?

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

PFH 2012b



Evolve the Fluctuations in Time

CONSTRUCT "MERGER/FRAGMENTATION" TREES

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

$$\tau \equiv u_t(k)\,k\,t \sim \frac{t}{t_{\rm cross}}$$

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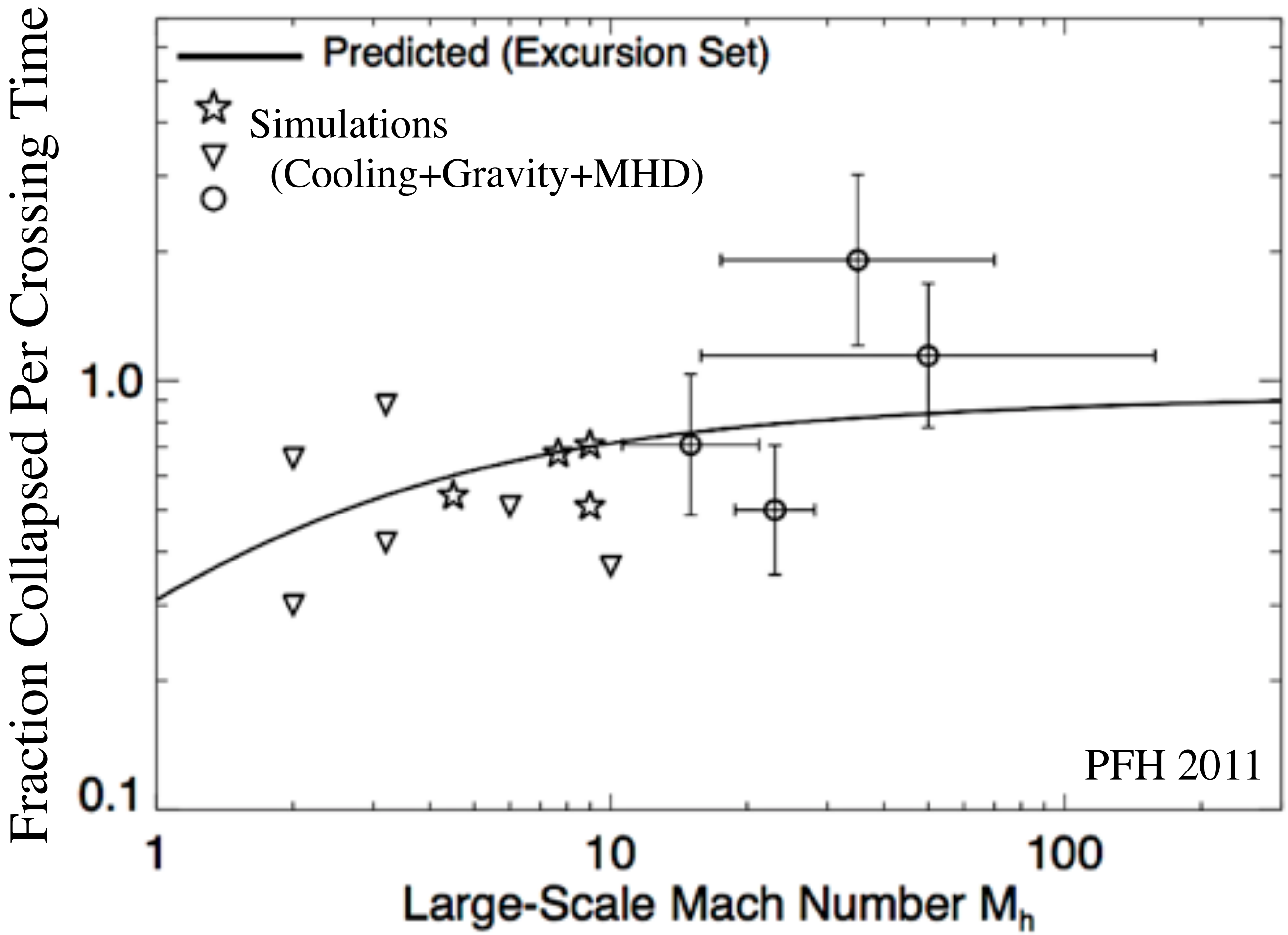

Open Questions:

1. What Maintains the Turbulence?

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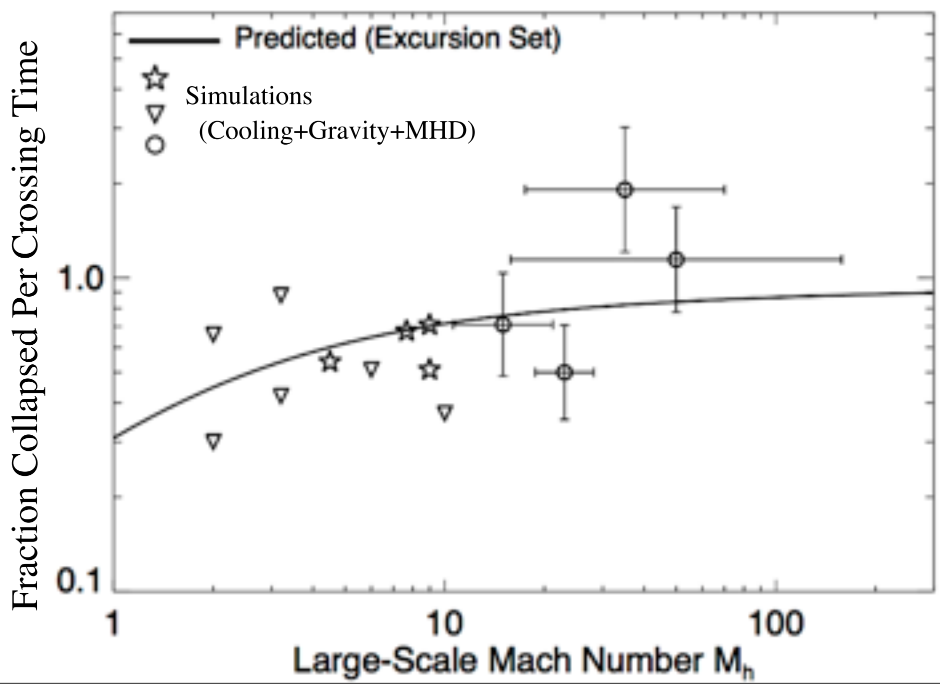
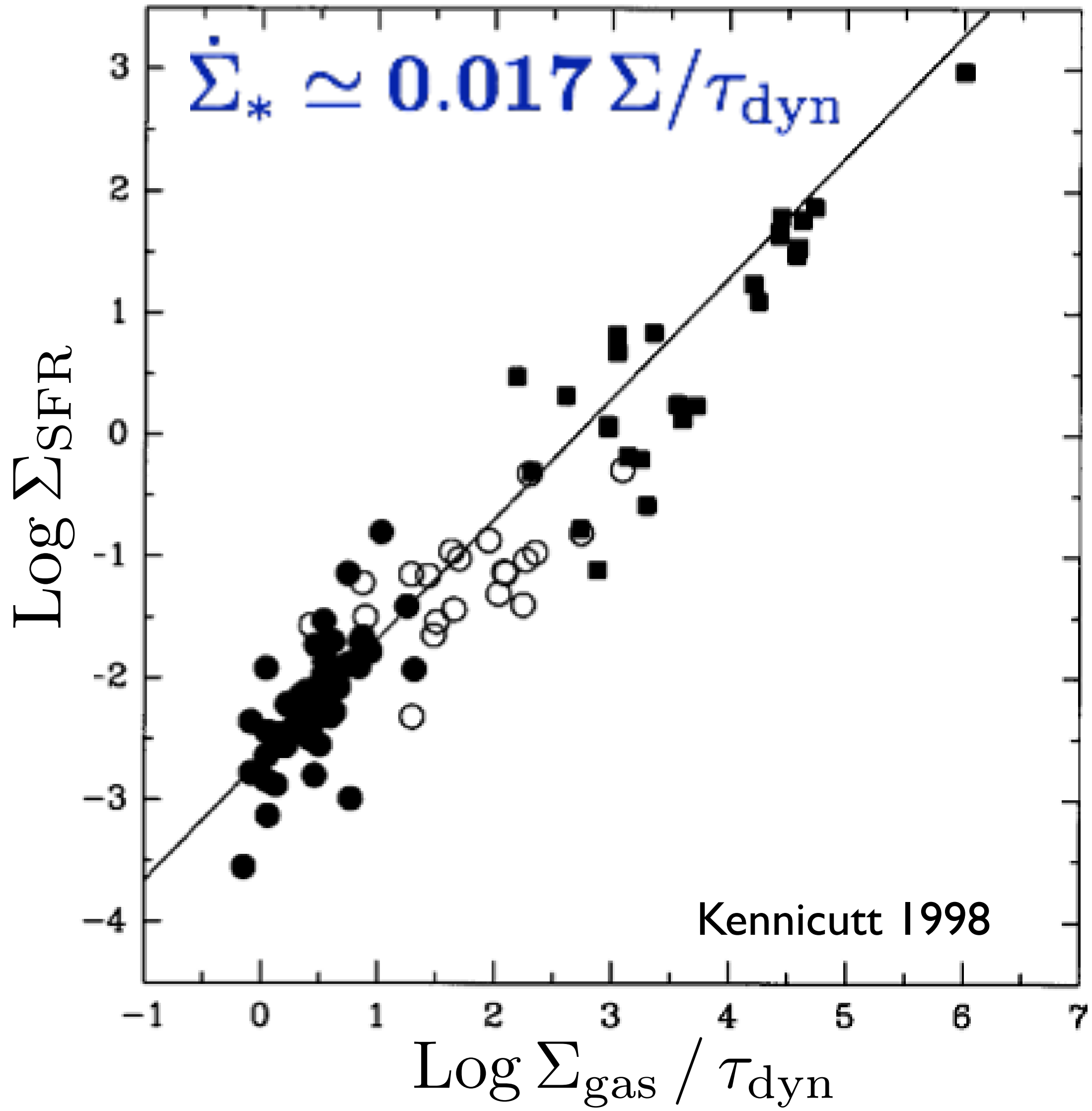


Why Doesn't Everything Collapse?

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Stellar Feedback is Key to Galaxy Formation!

SO WHAT'S THE PROBLEM?

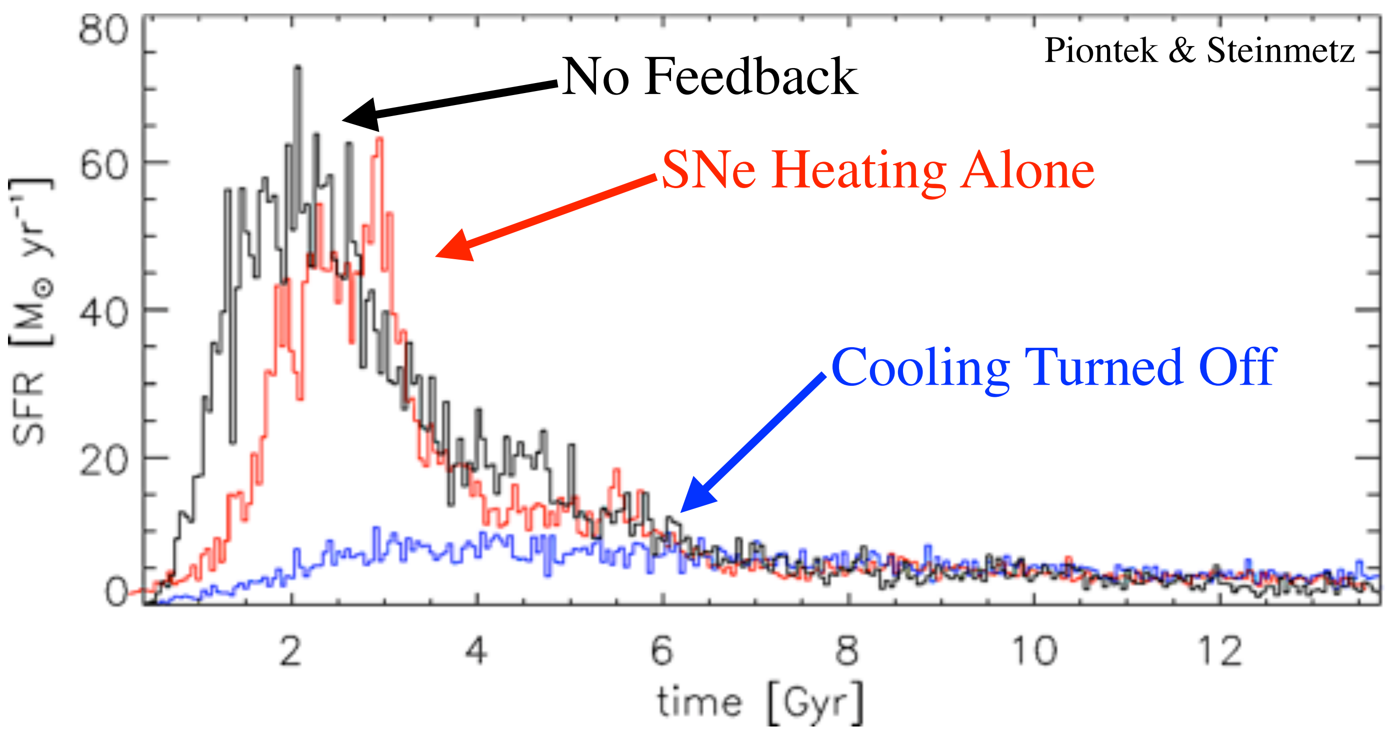
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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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- "Energy Injection":
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)
- *Explicit* Momentum Flux:
  - Radiation Pressure

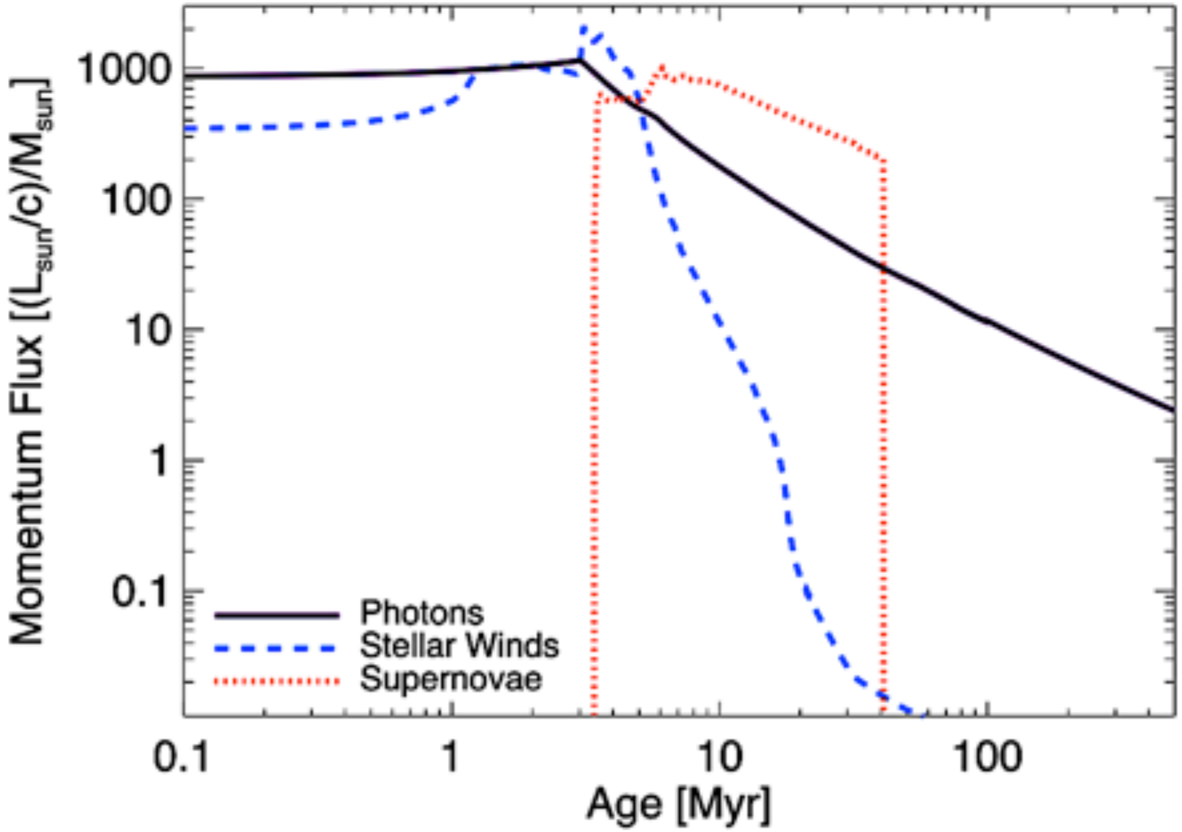
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

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



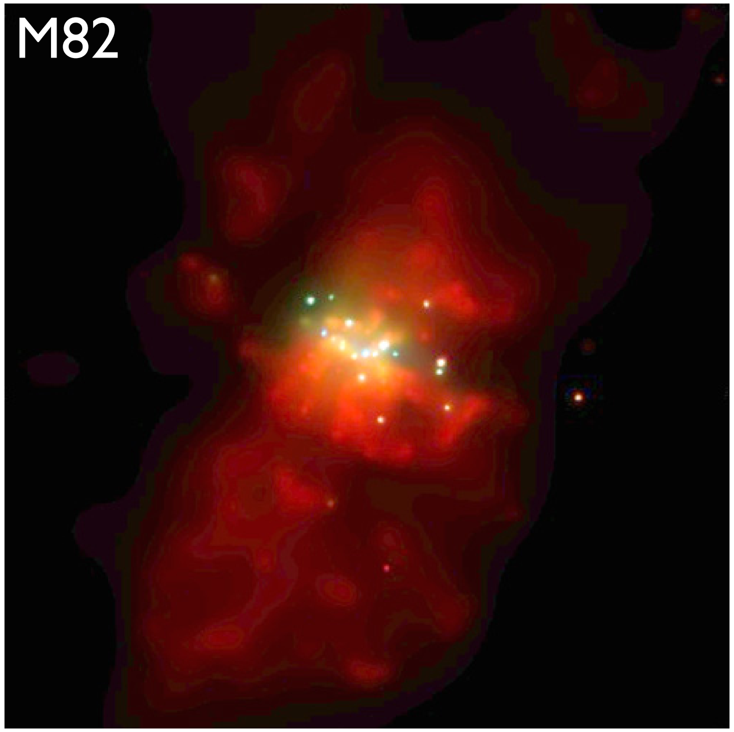
Feedback 101:

Energy

(dilute gas)

Heat to $C_s > V_{esc}$: unbound

eg: solar wind
SN-heated galactic wind



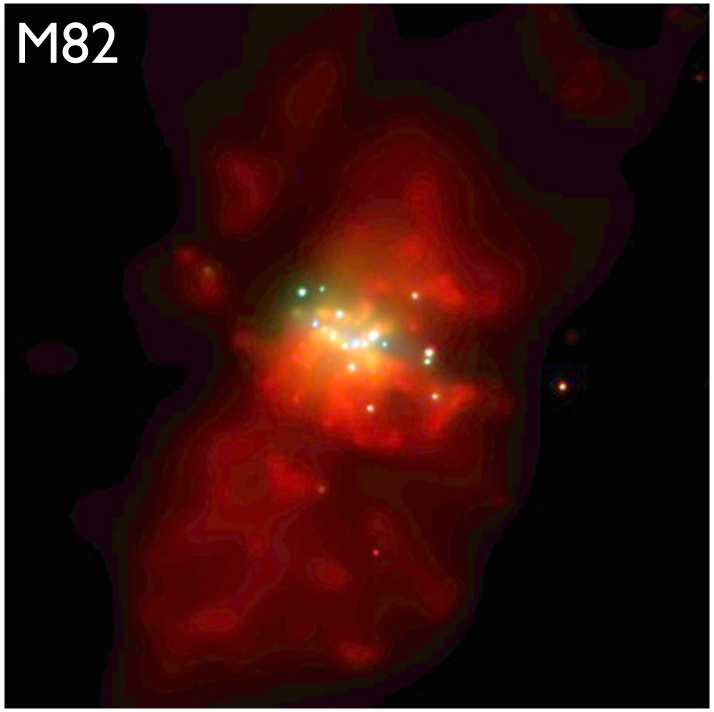
Momentum

(dense gas; energy radiated)

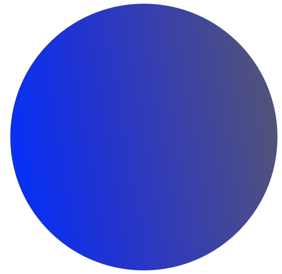
Force induces δV :
if $\sim V_{esc}$ drive wind

eg: O-star winds
molecular gas δV's

Feedback 101:



$$\Sigma_g\,(\text{cold gas}) \sim 0.1 - 100\,\mathrm{g\,cm^{-2}}$$



Equilibrium:

Pressure = $\pi G \Sigma_g^2$

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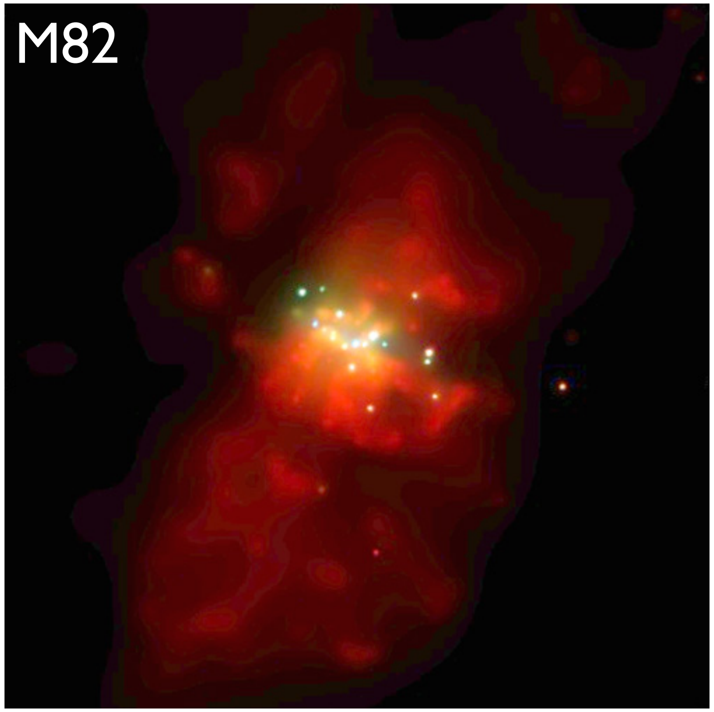

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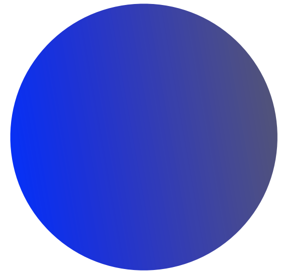

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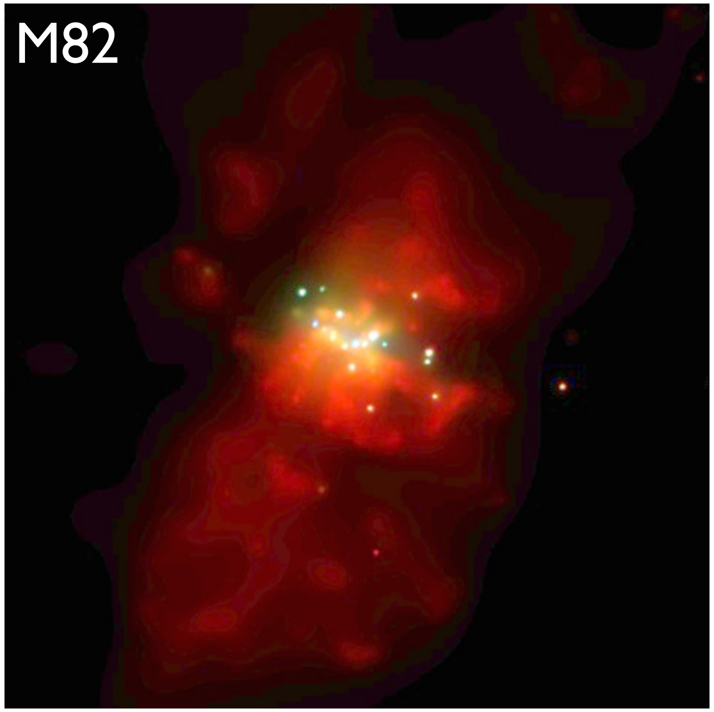

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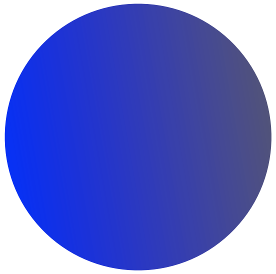

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$$p_{\rm hot} \gtrsim \pi G \Sigma_g^2 \rightarrow \dot{E}_{\rm cool} \gg \dot{E}_{\rm SNe} \text{ for } \Sigma_g \gtrsim 0.02\,\mathrm{g\,cm^{-2}}$$

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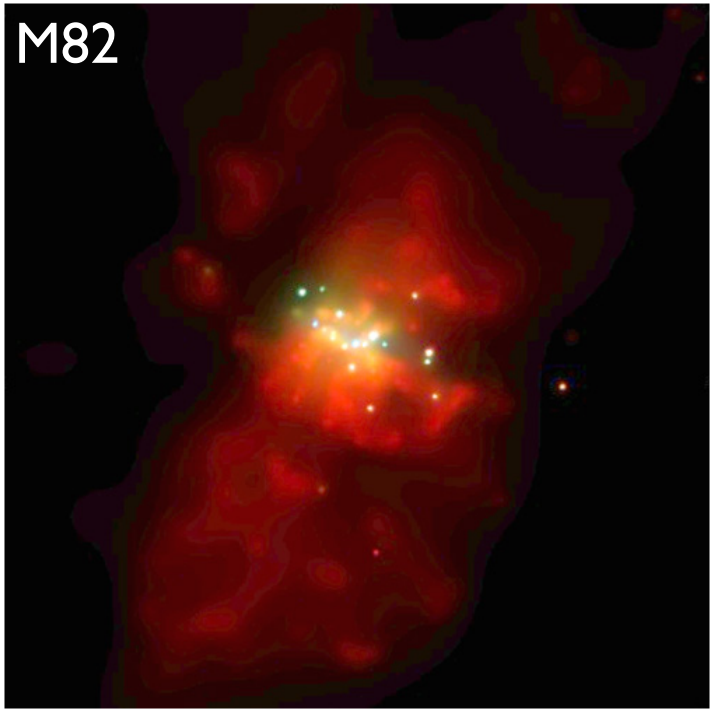

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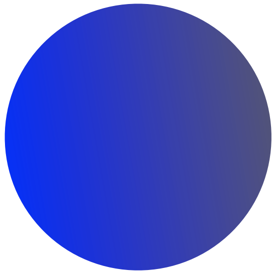

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- Hot gas can *vent*: cannot affect bulk of gas mass

Kennicutt-Schmidt relation *should* emerge naturally

(*IF* IT'S REALLY FEEDBACK-REGULATED)

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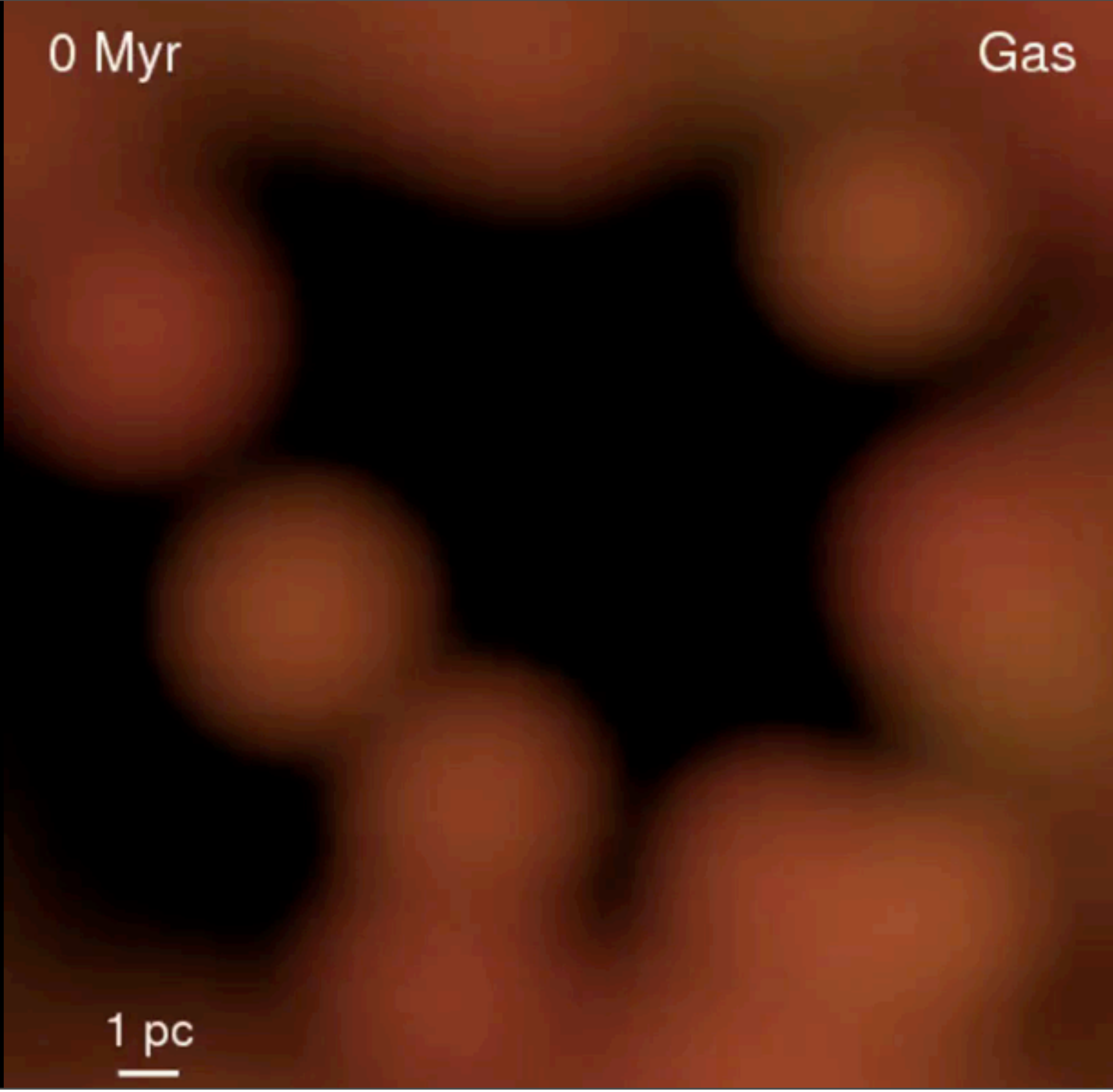
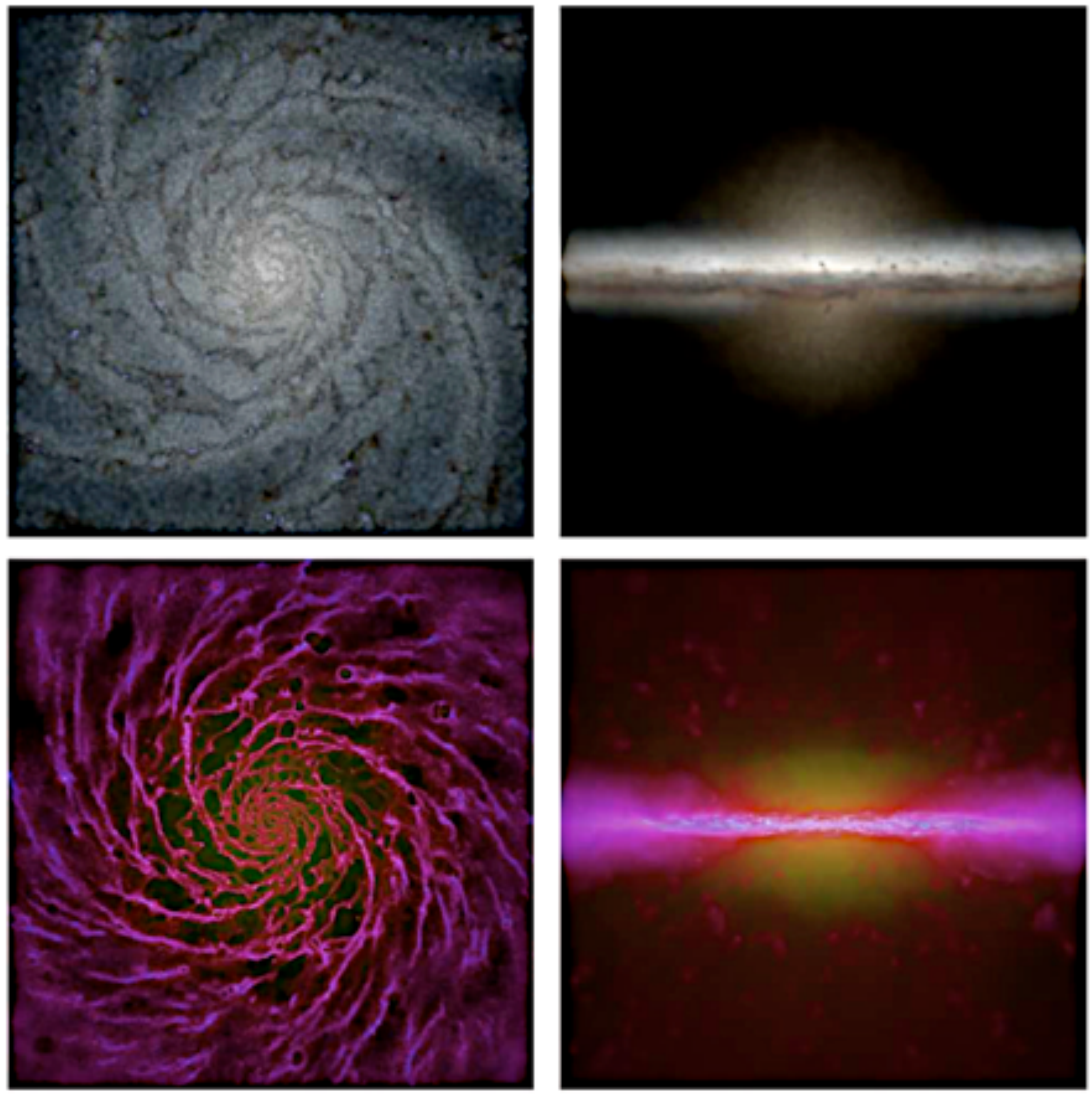
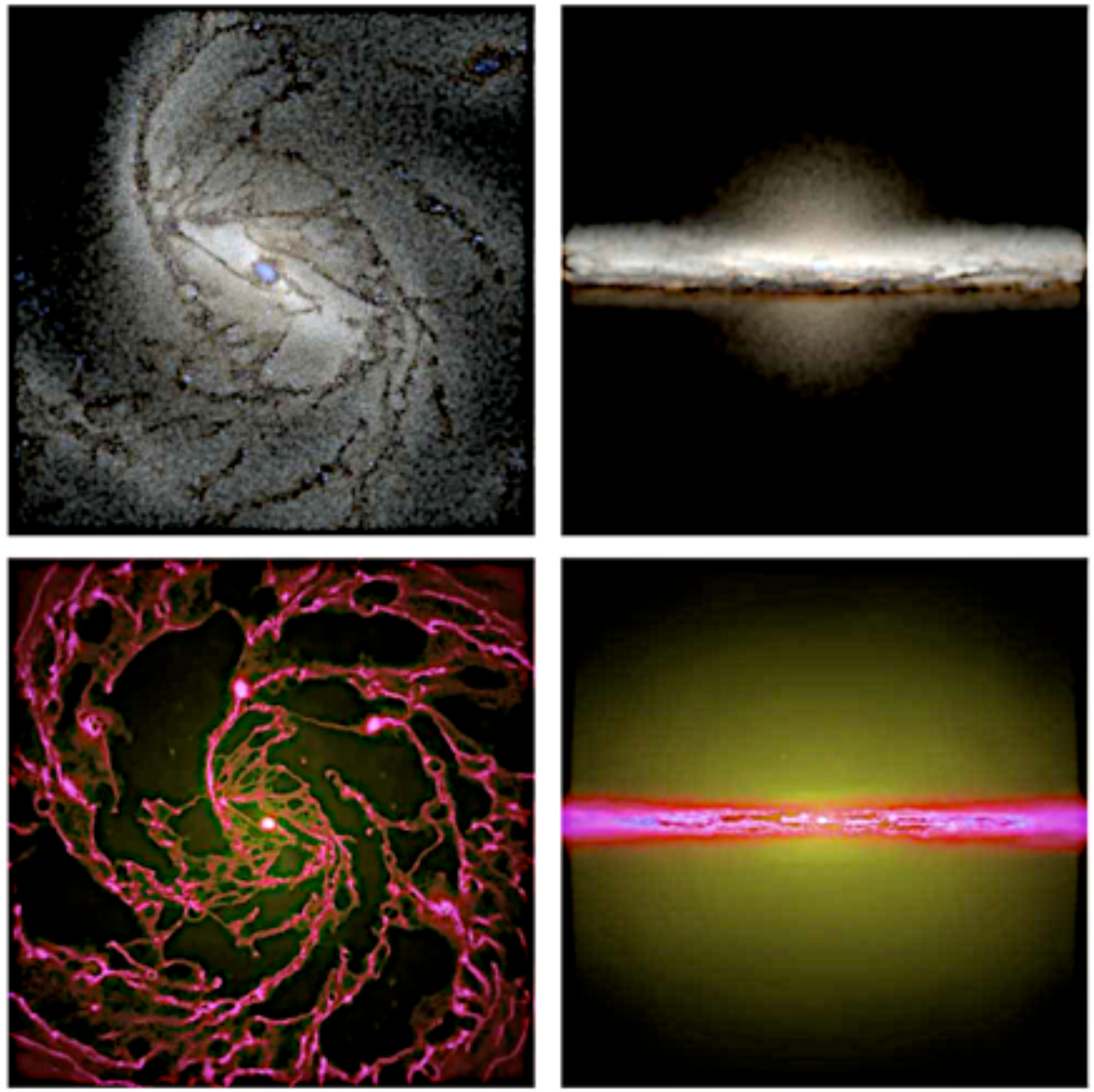
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$


0 Myr
Gas
1 pc



KEEP?

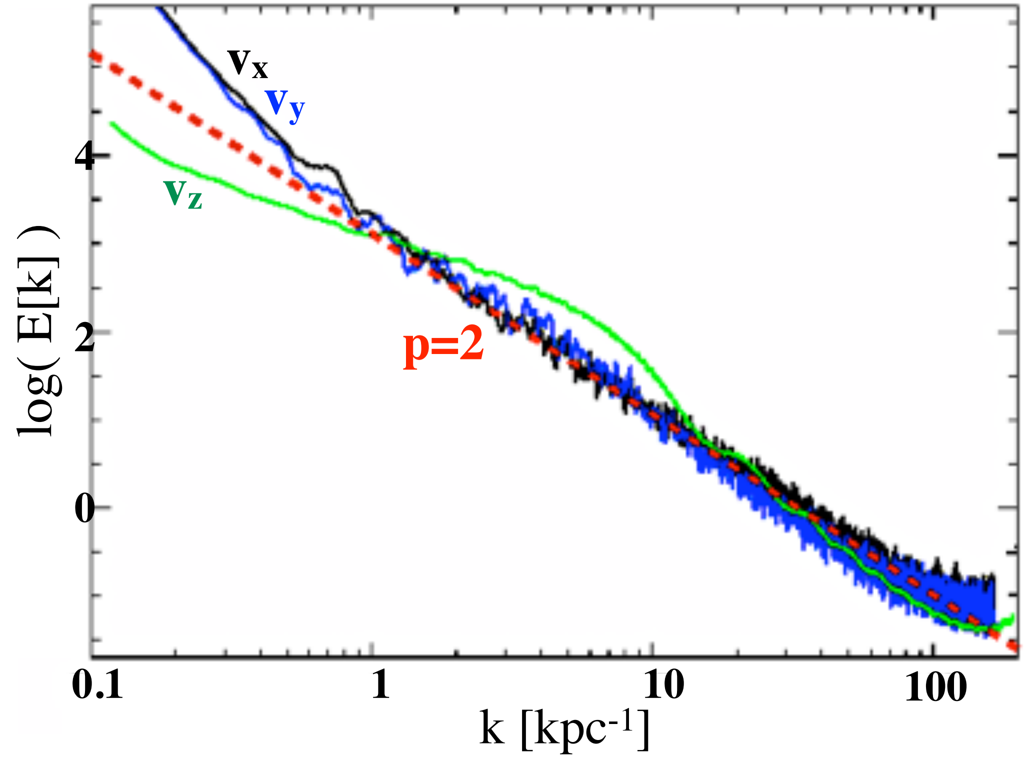
Hopkins, Quataert, & Murray, 2011b

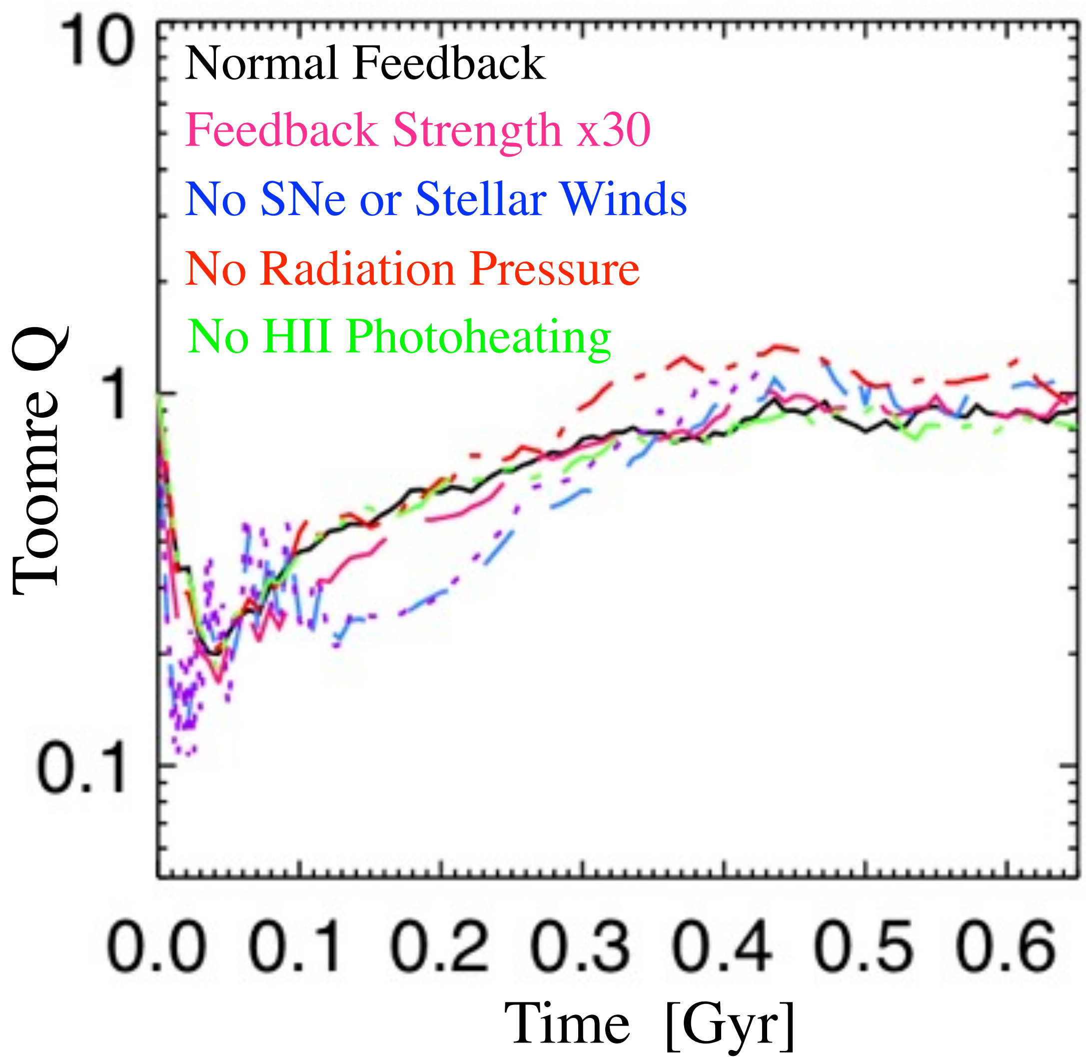


Hopkins, Quataert, & Murray, 2011b

Feedback Maintains Turbulence

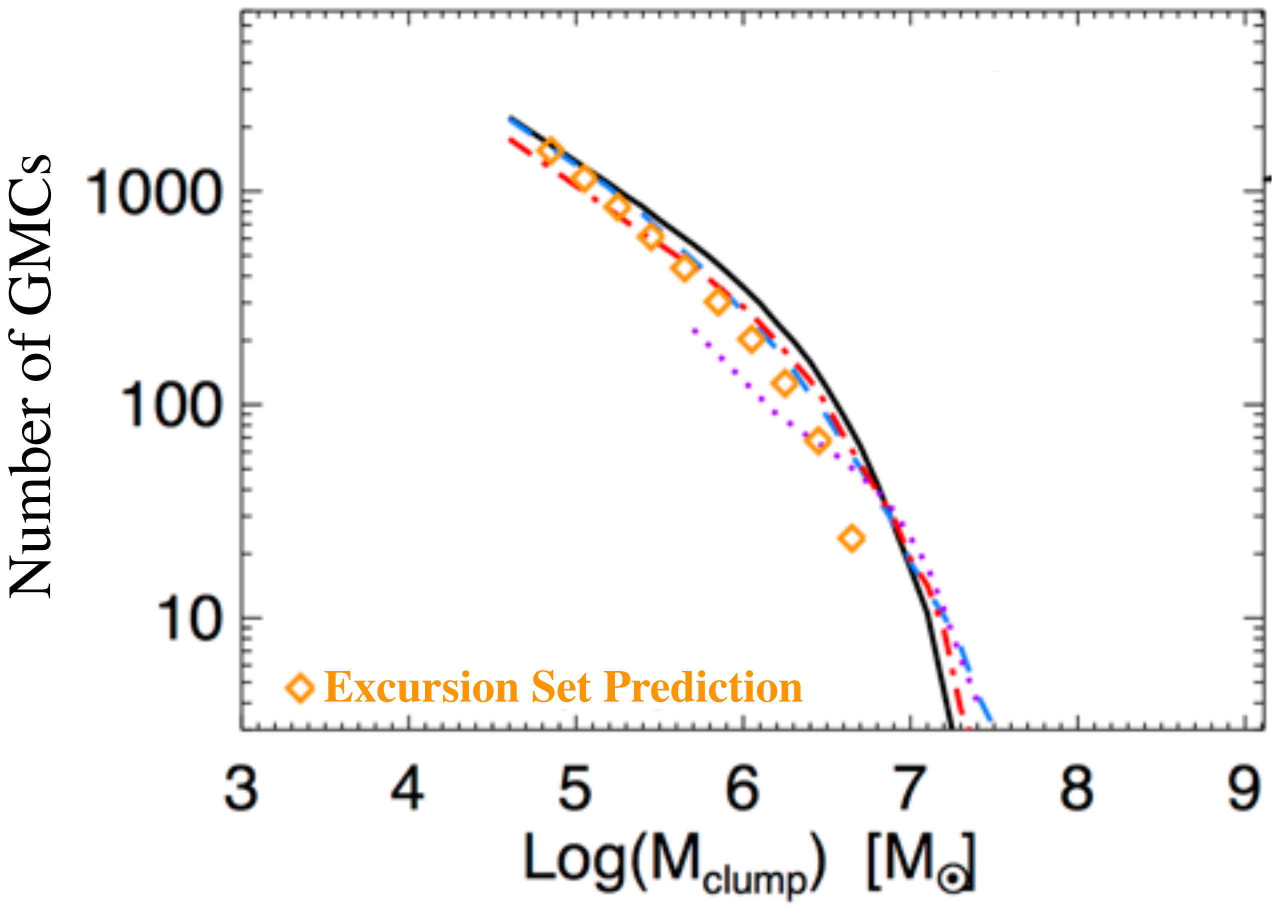
CASCADE INVARIANT TO MICROPHYSICS

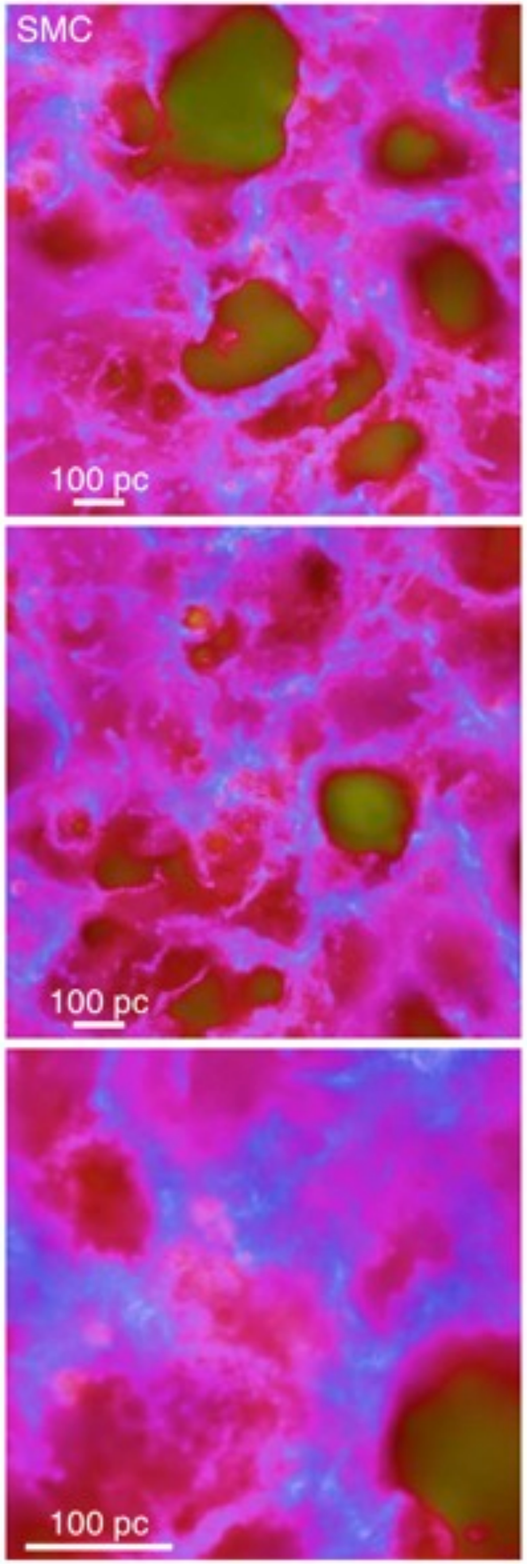




Compare GMC Mass Function

INDEPENDENT OF FEEDBACK, ONCE TURBULENCE MAINTAINED

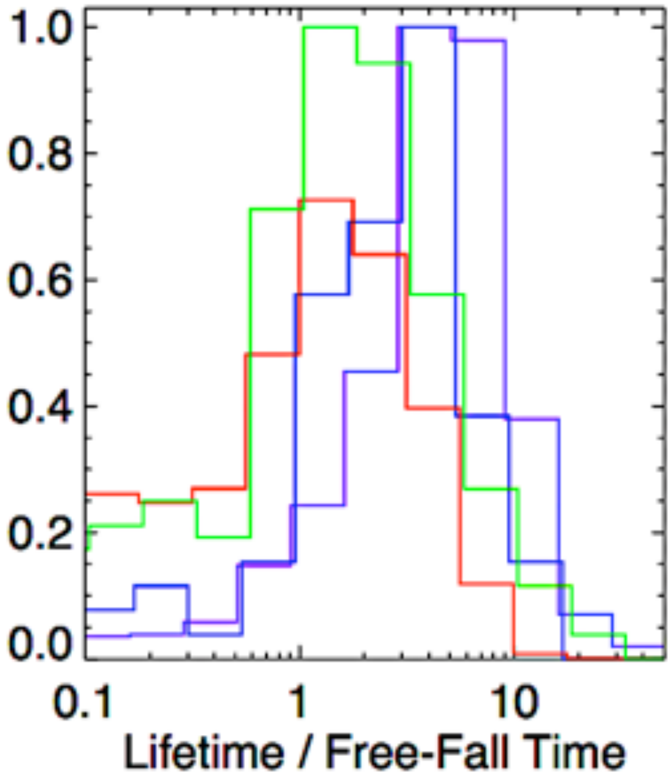


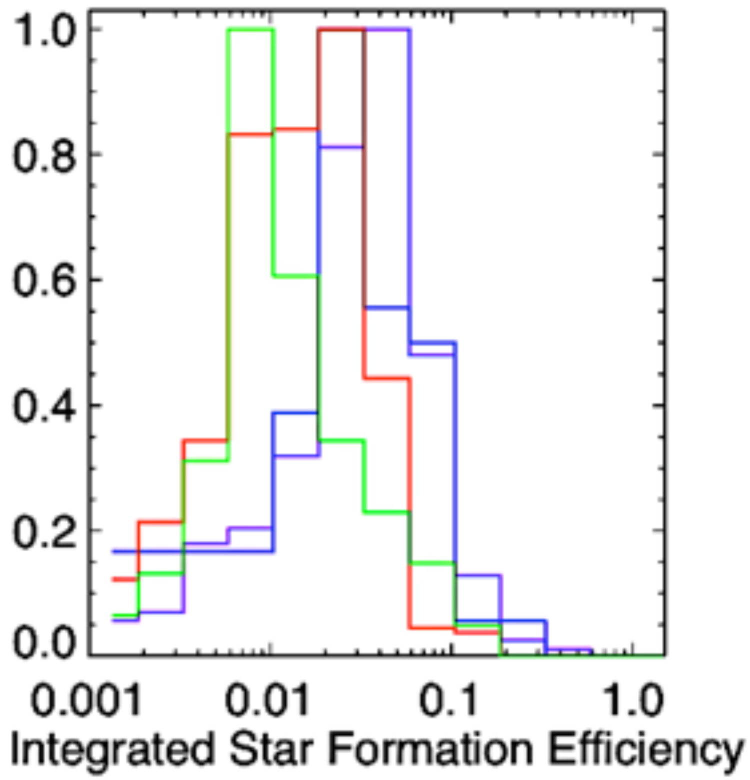


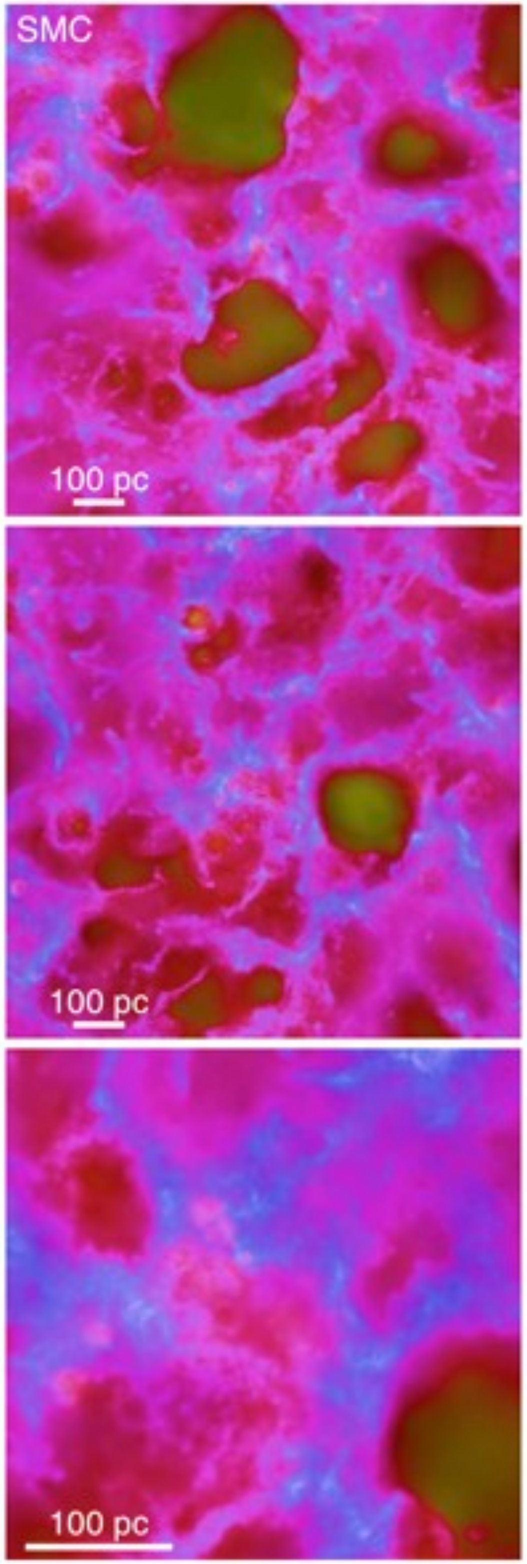
PFH, Quataert, & Murray, 2011b

BUT, GMCs are Short-Lived

FEEDBACK "RECYCLES" MASS: STEADY-STATE MASS FUNCTION



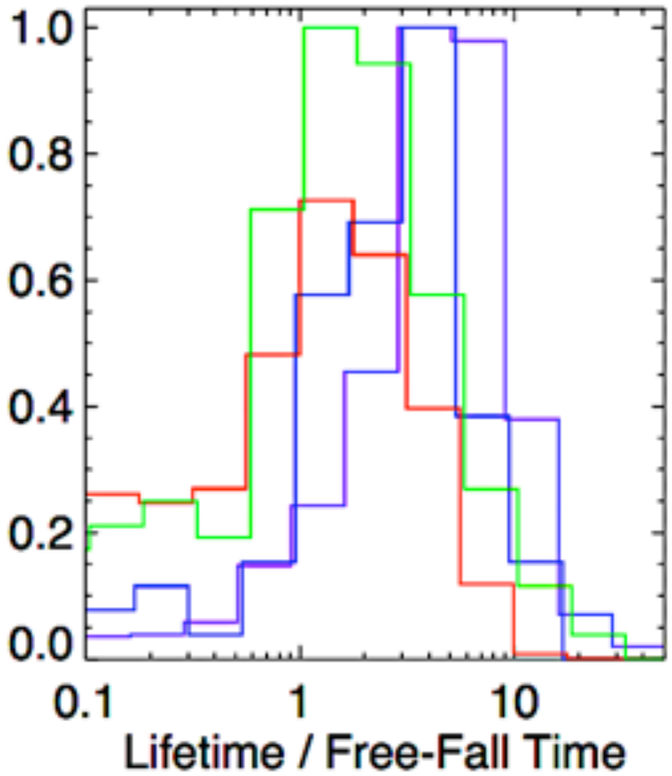


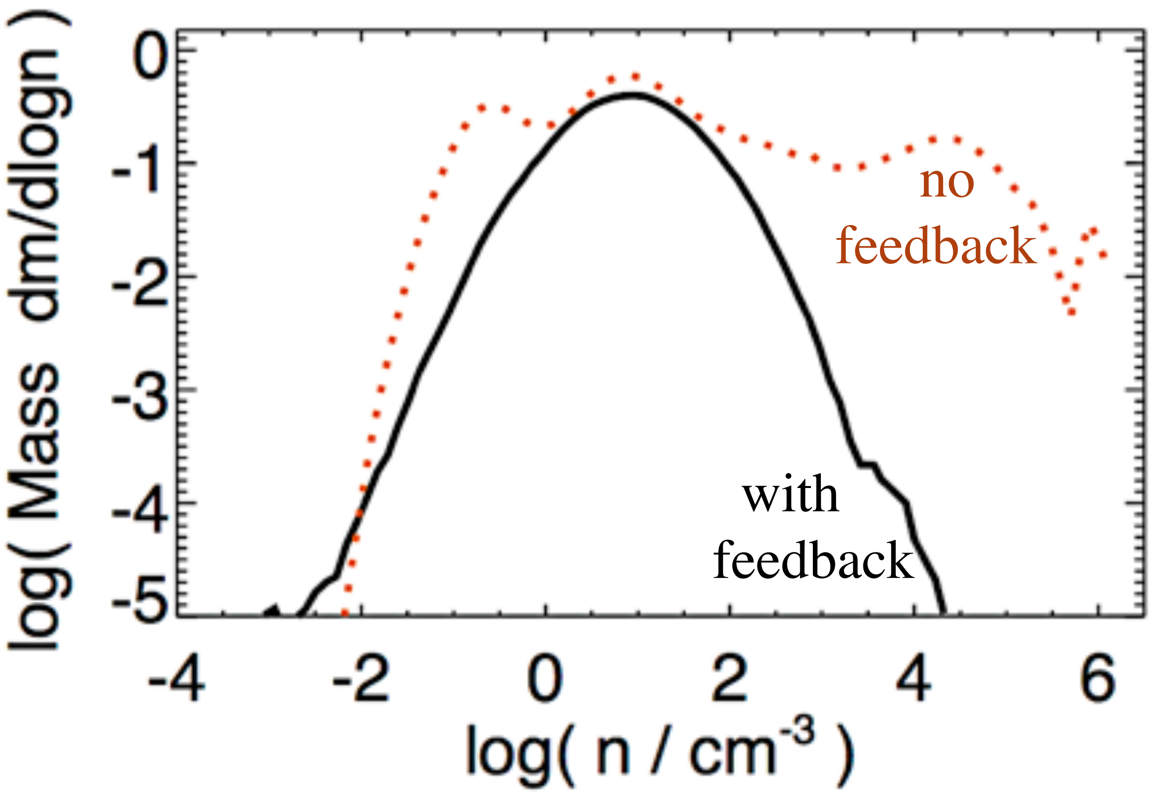


$$\dot{P}_* = \dot{\epsilon}_*\, M_*\, c > F_{\rm grav} \sim \frac{G\, M_{\rm cl}^2}{R_{cl}^2}$$

PFH, Quataert, & Murray, 2011b

BUT, GMCs are Short-Lived
PREVENTS RUNAWAY COLLAPSE

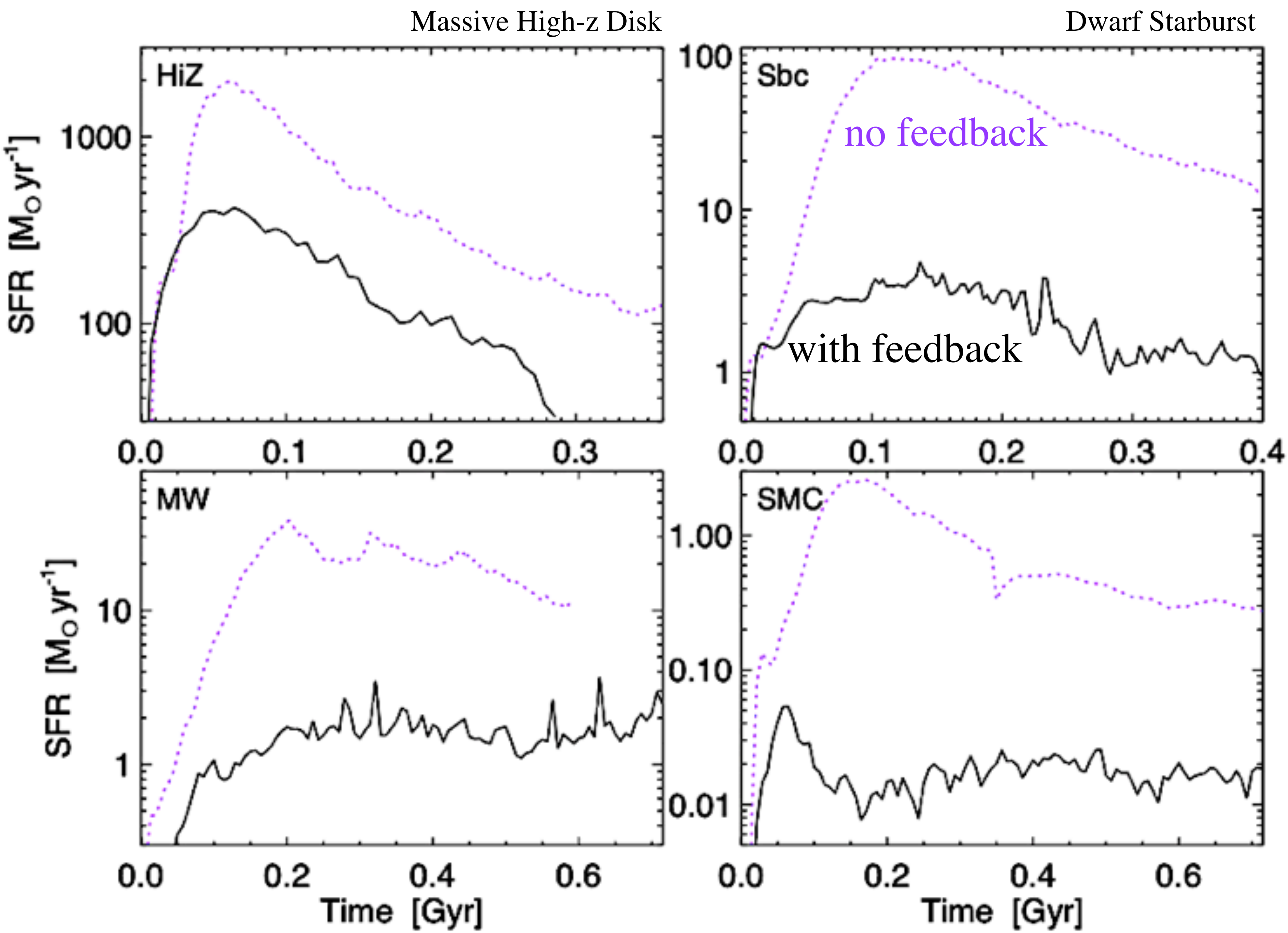




KEEP?

PFH, Quataert, & Murray, 2011b

Stellar Feedback gives Self-Regulated Star Formation



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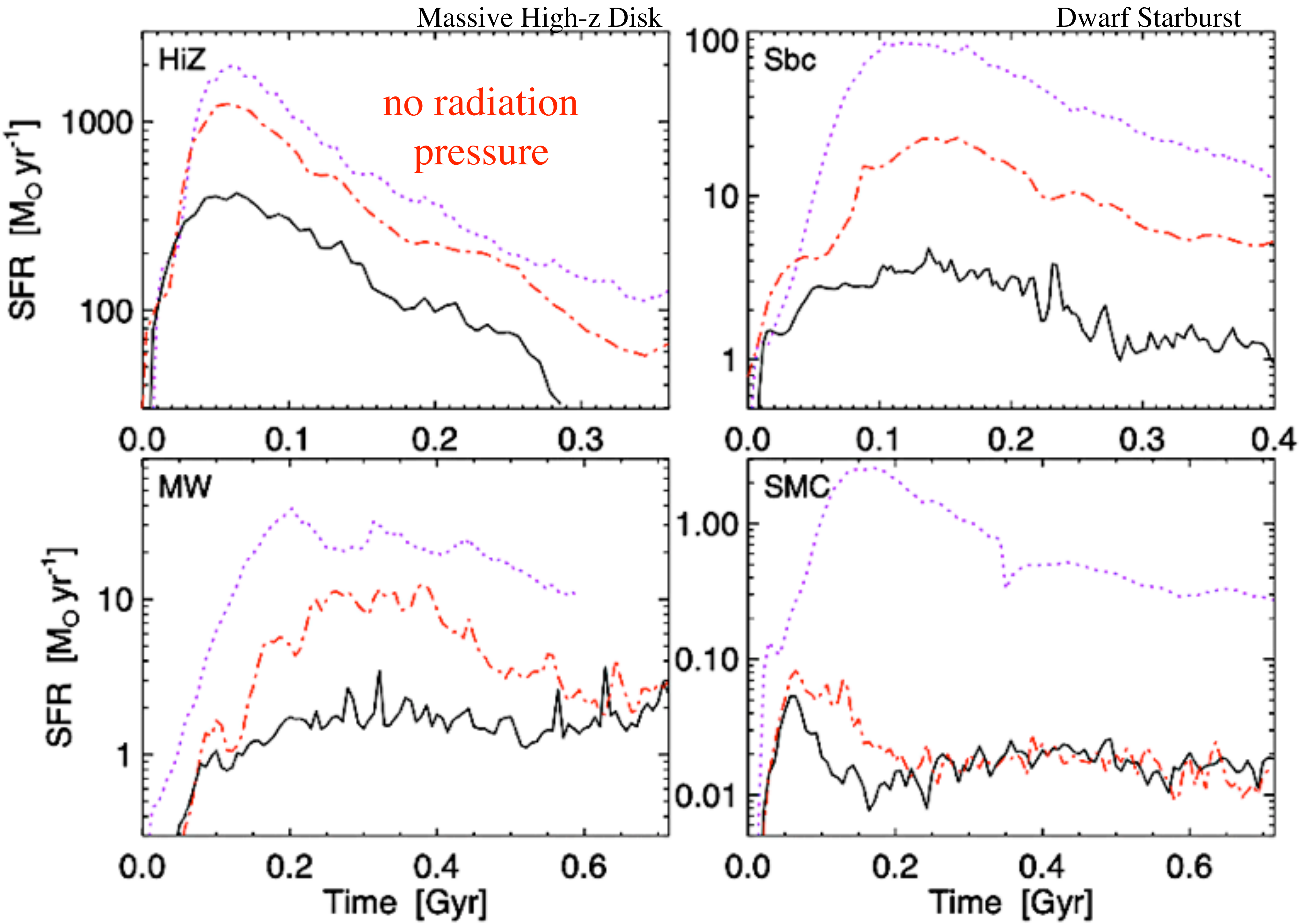

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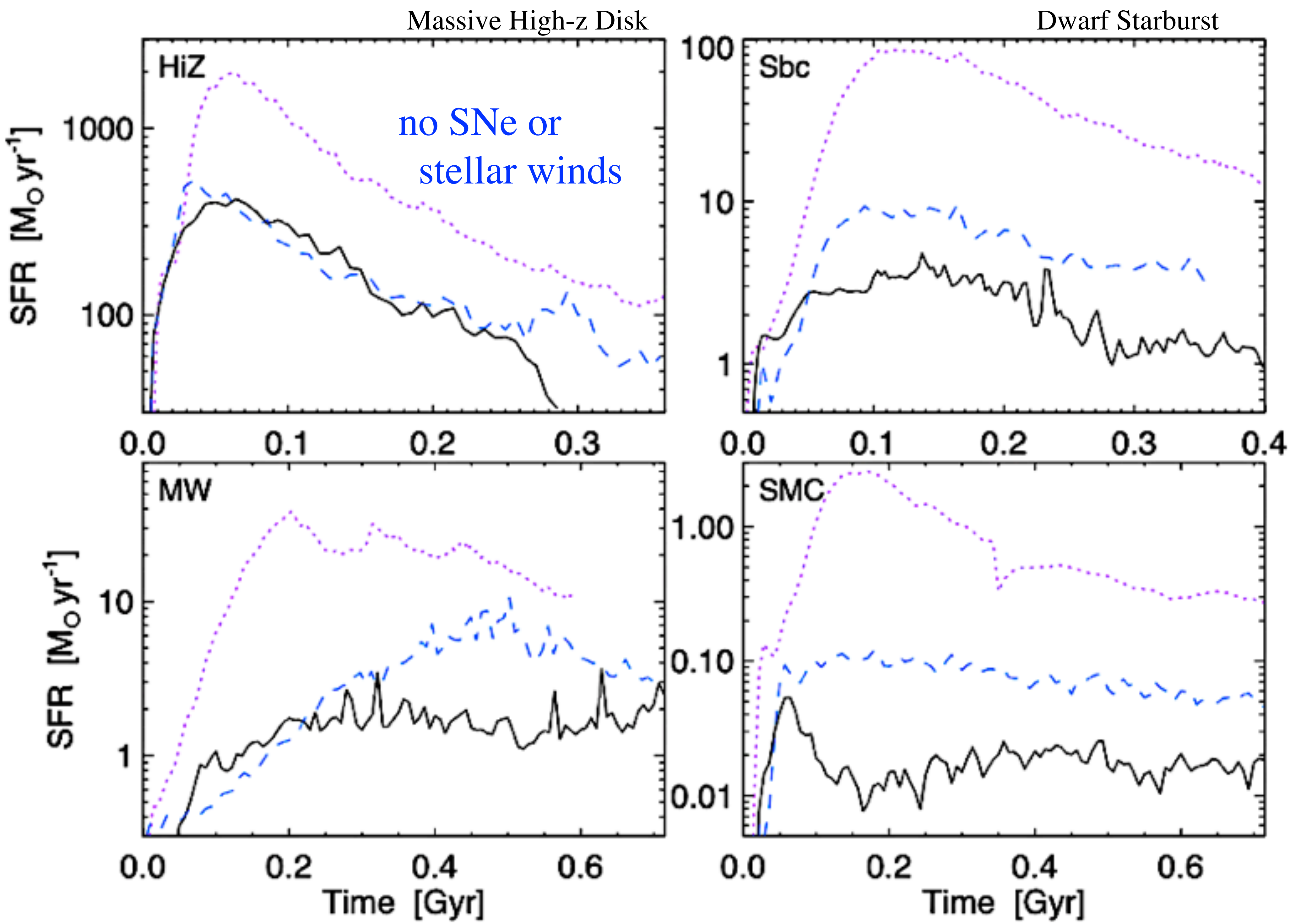
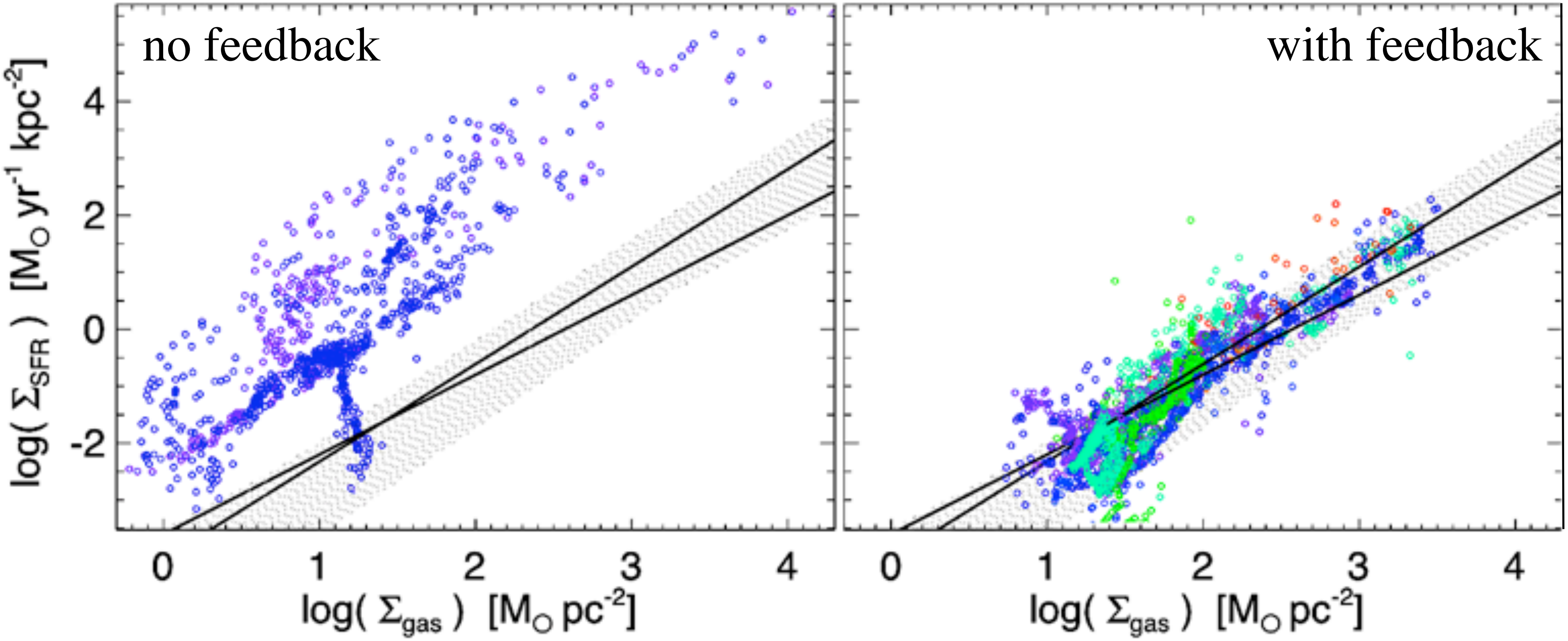


Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

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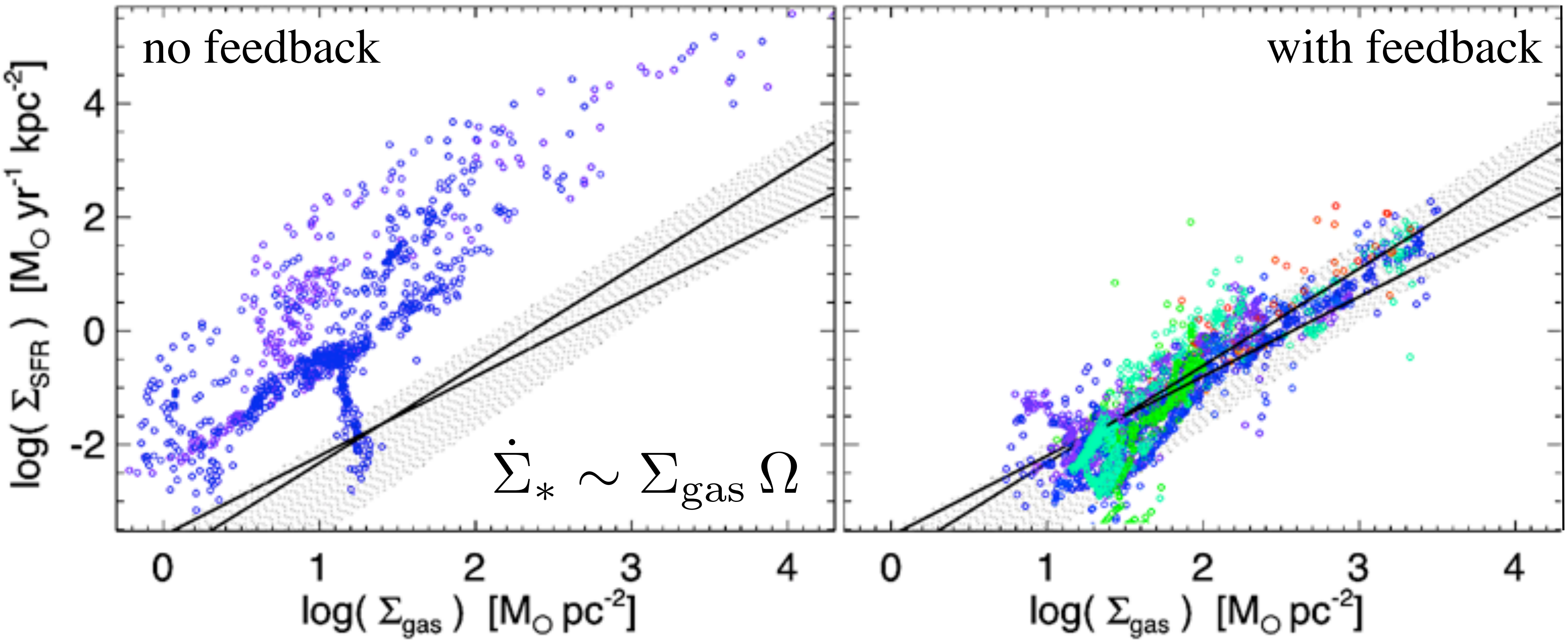

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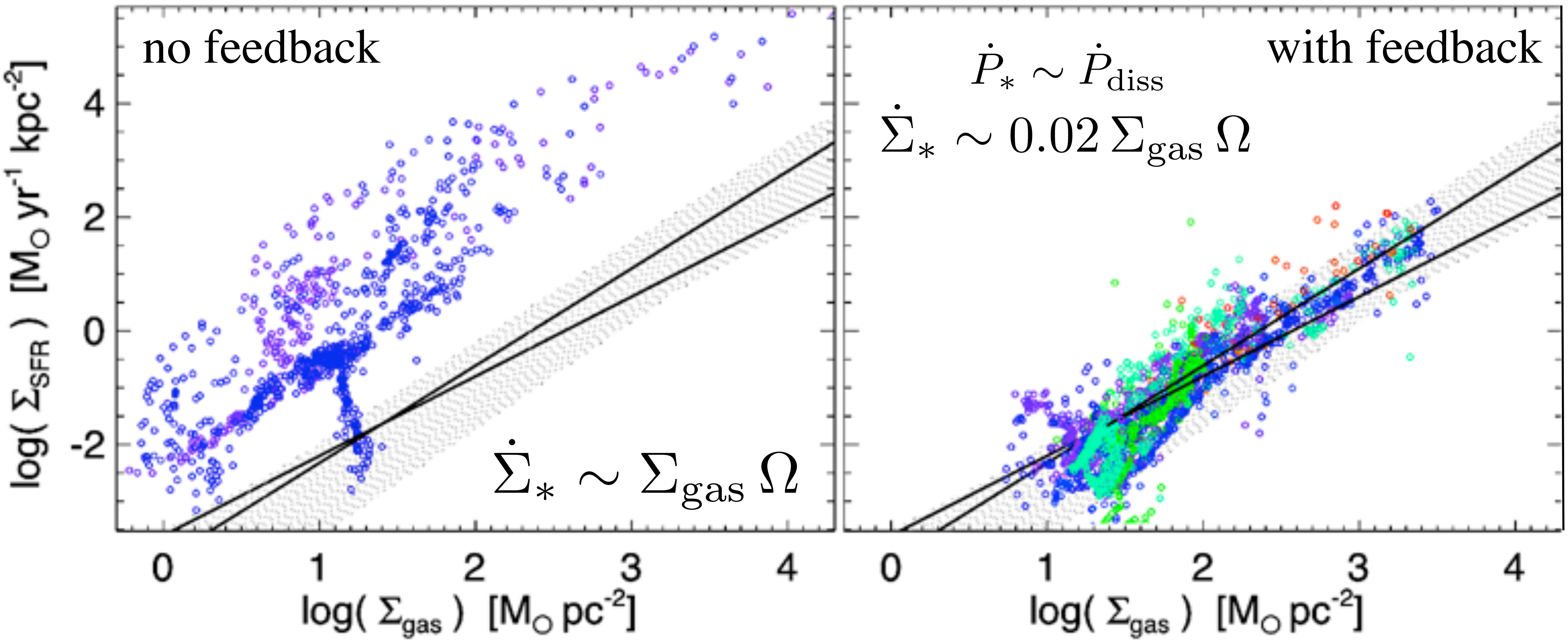
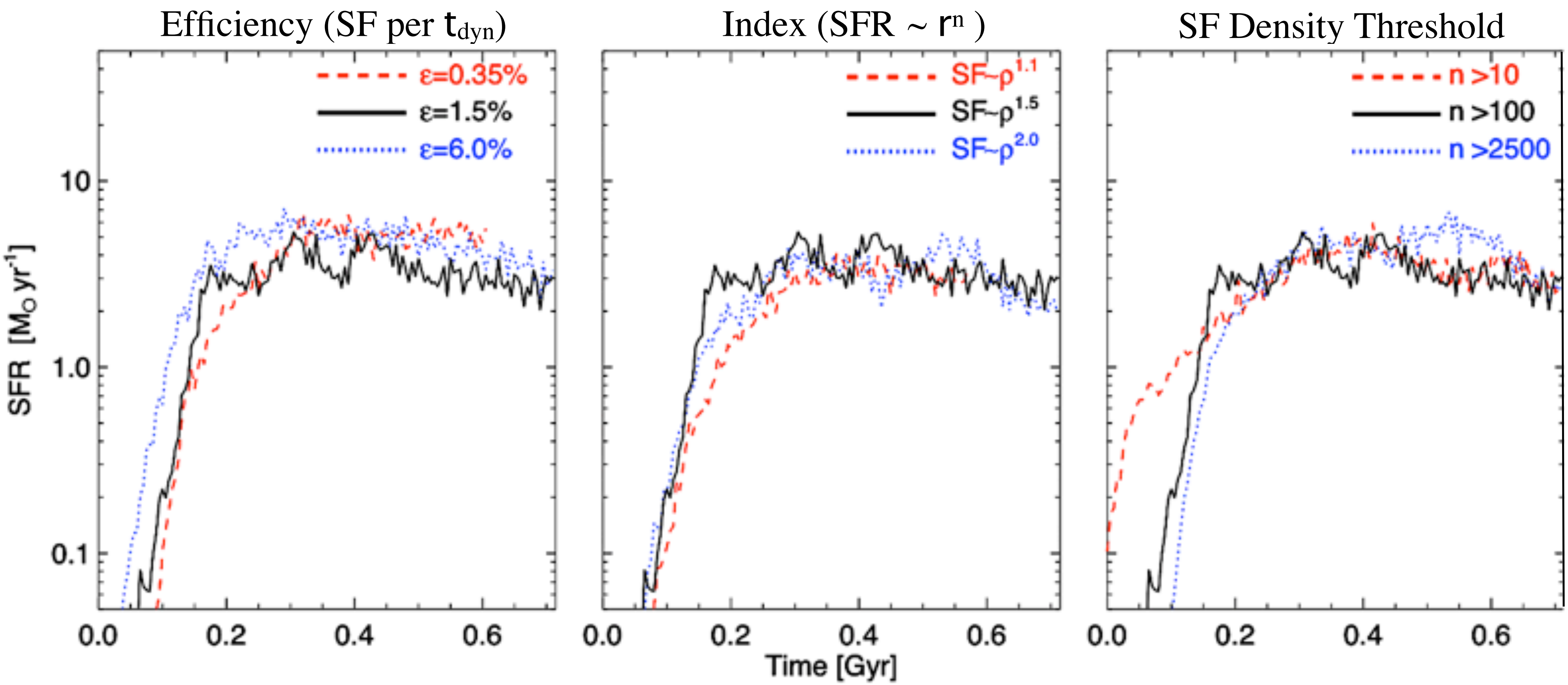


PFH, Quataert, & Murray, 2011a

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



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

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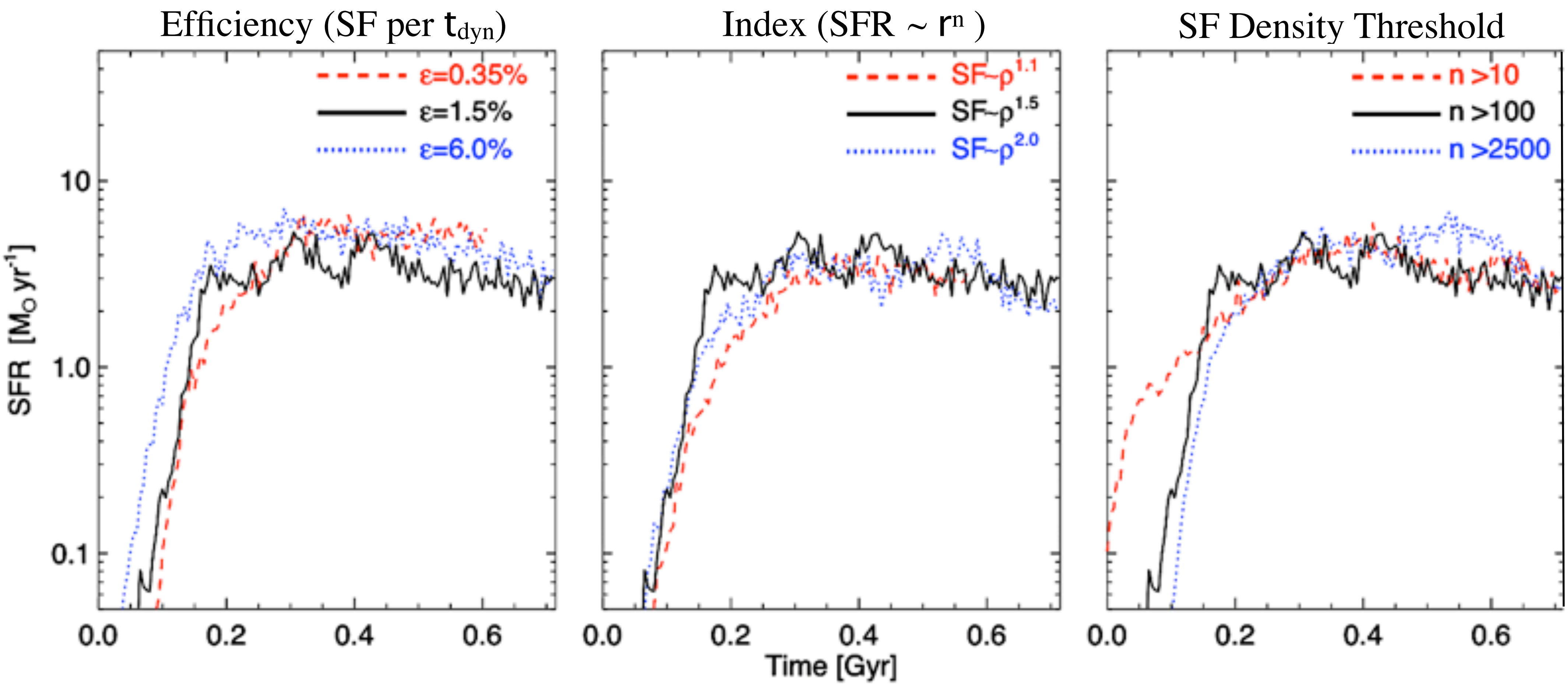
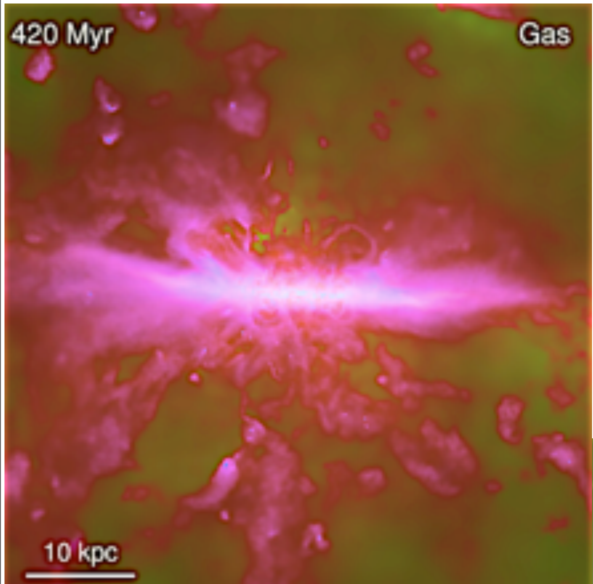
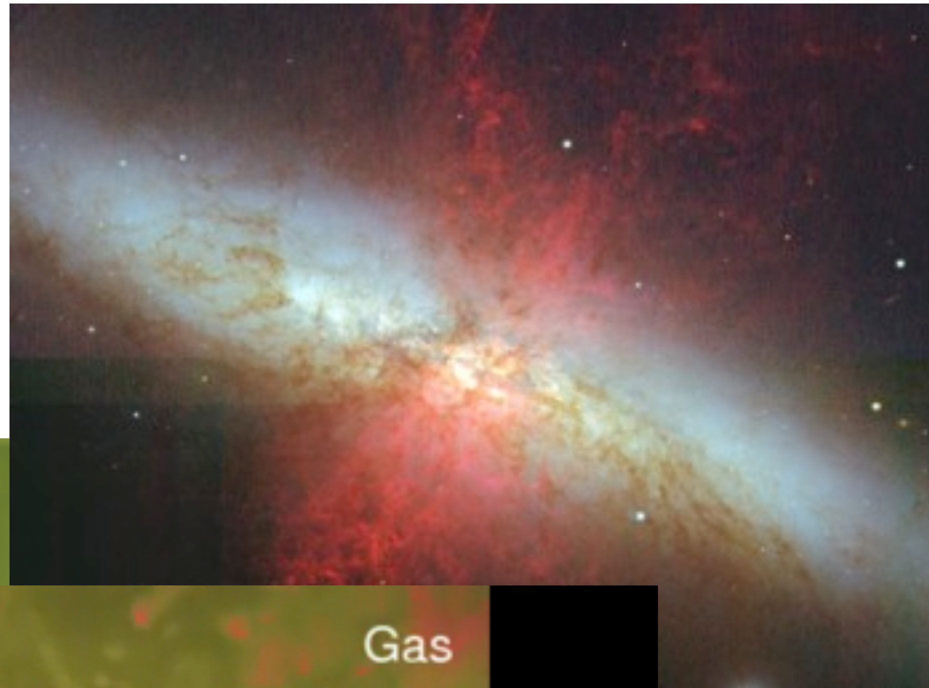


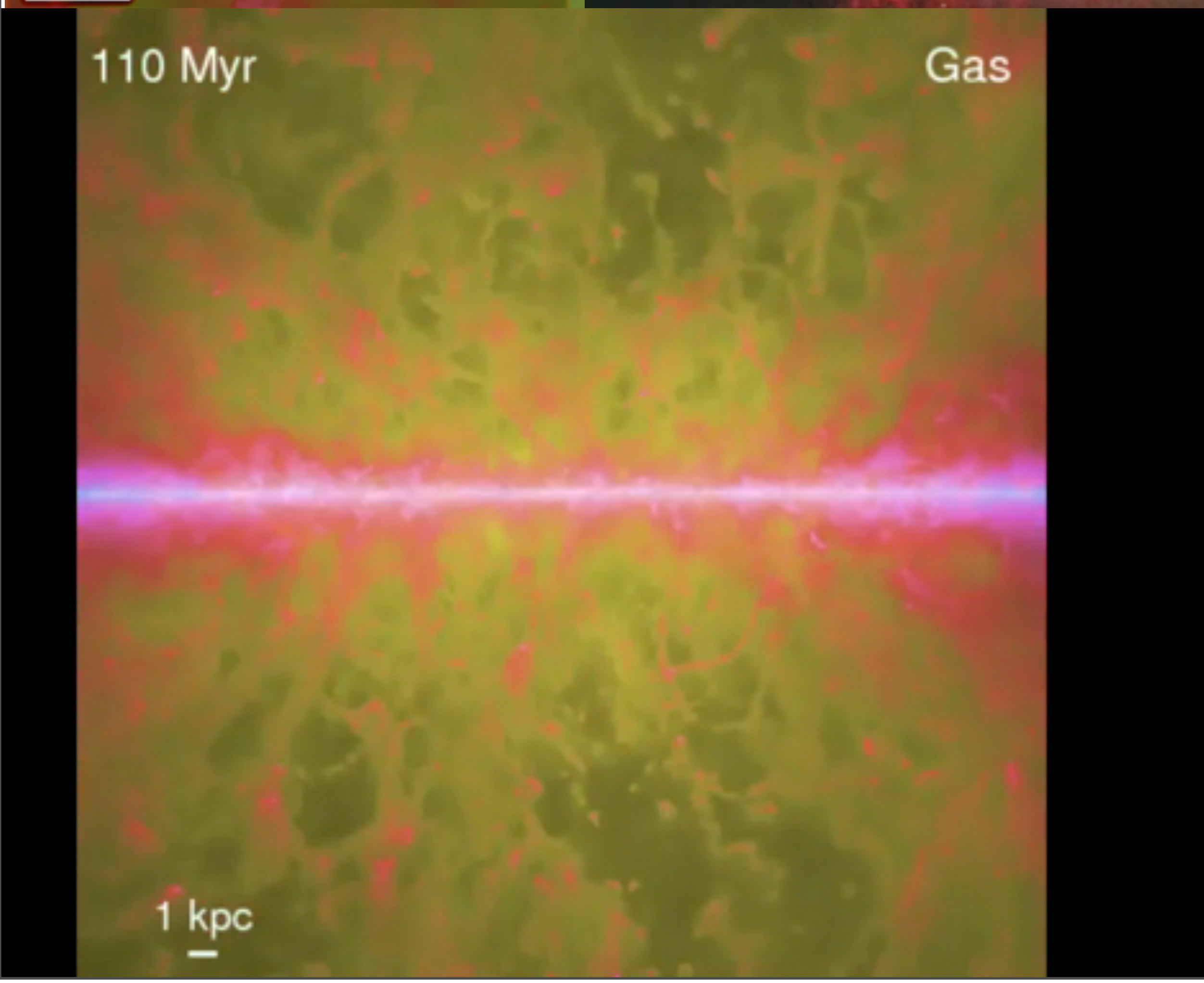
- Set by feedback (i.e. SFR) needed to maintain marginal stability

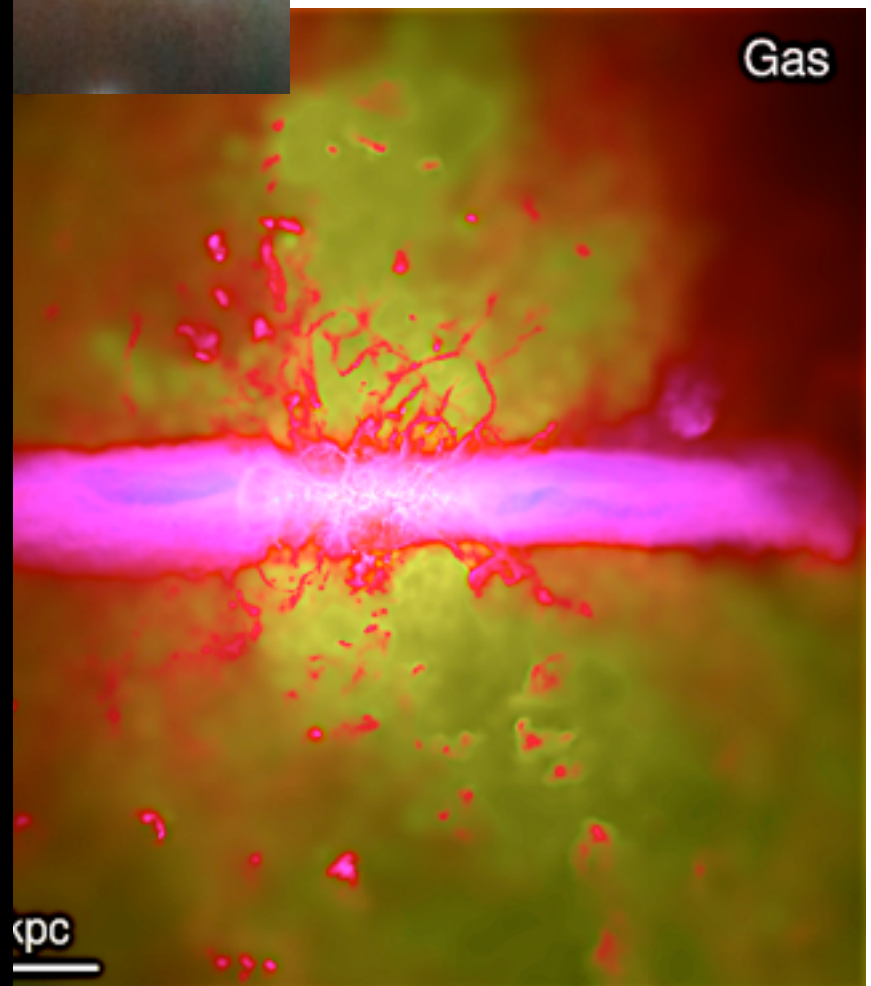
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

Galactic Super-Winds





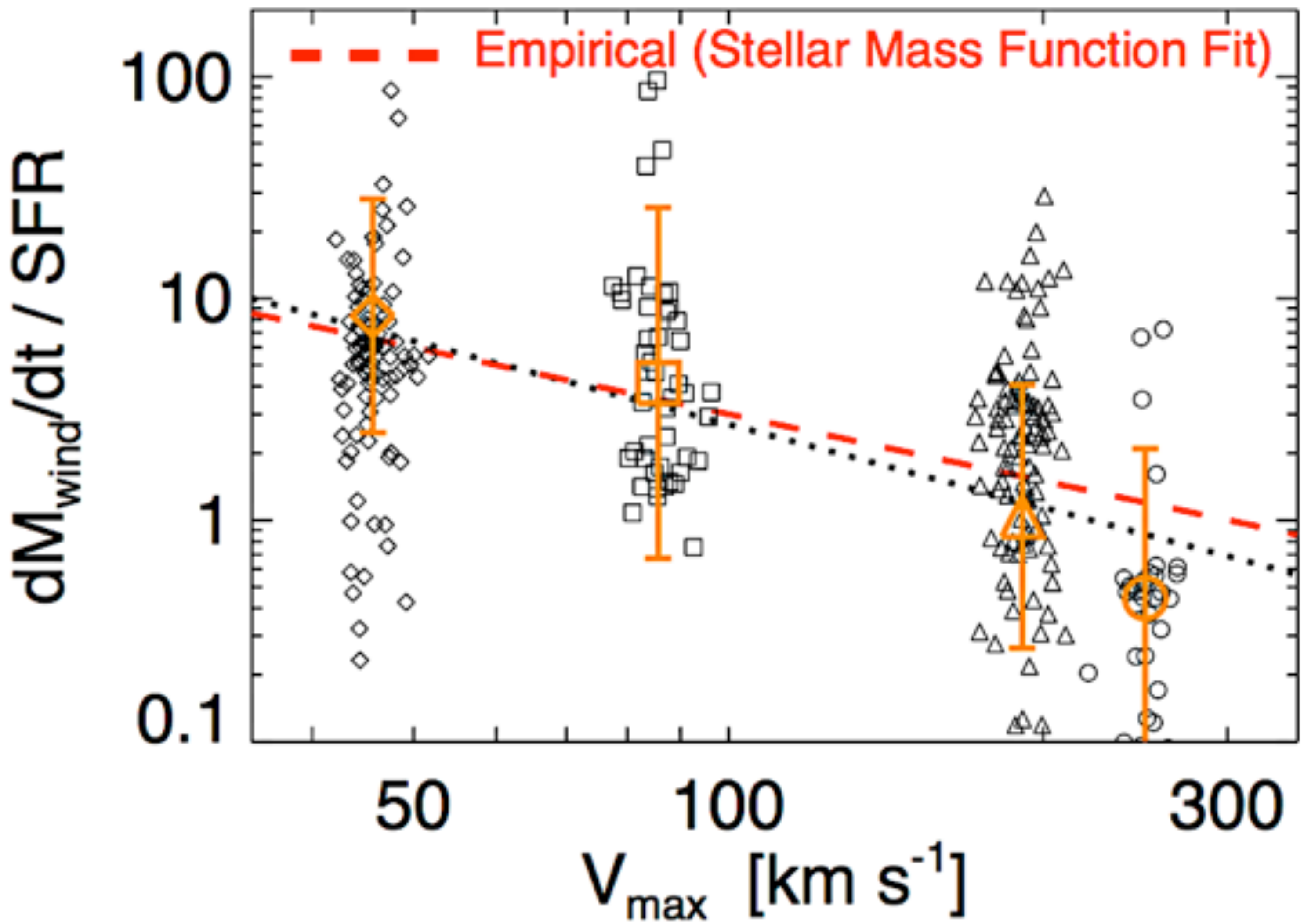




How Efficient Are Galactic Super-Winds?

DOES IT RESOLVE THE GALAXY MASS FUNCTION PROBLEM?

PFH, Quataert, & Murray, 2011c

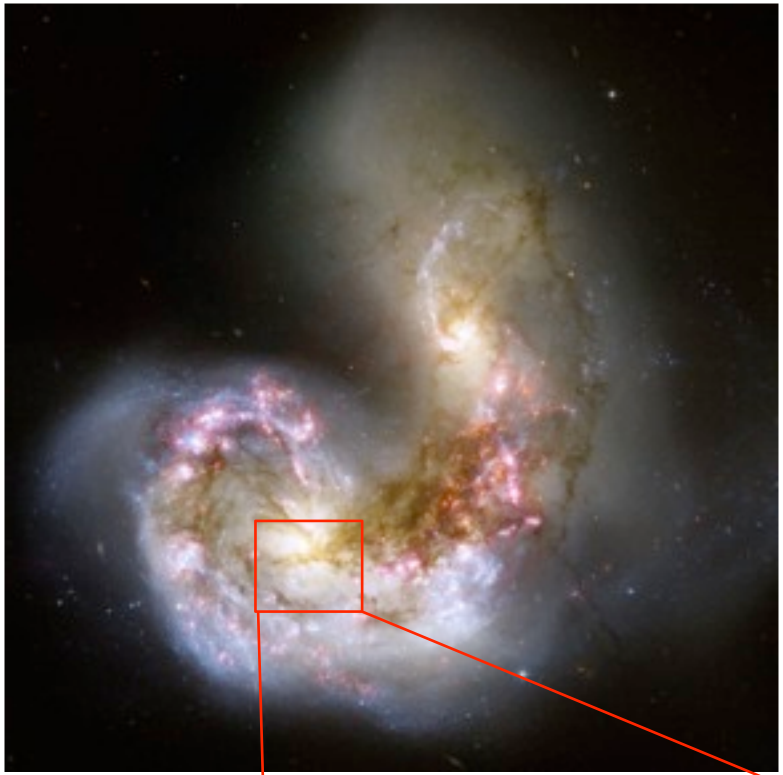


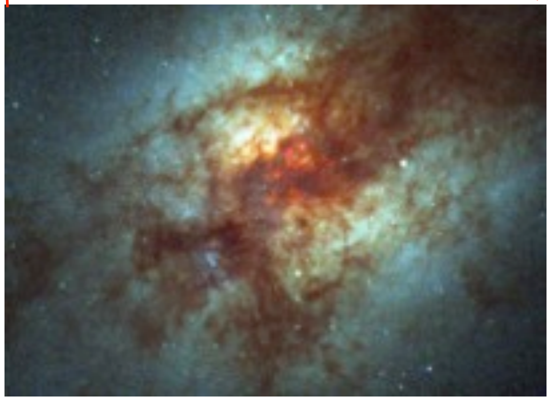
$$\dot{M}_{\rm wind} \approx 10\,\dot{M}_{*}\left(\frac{V_{\rm max}}{100\,{\rm km\,s^{-1}}}\right)^{-1}\left(\frac{\Sigma_{\rm gas}}{10\,M_{\odot}\,{\rm pc}^{2}}\right)^{-0.6}$$

Future Directions

WHAT CAN WE EXPLORE WITH MORE REALISTIC ISM/FEEDBACK PHYSICS?

- Galactic “Super-Winds”
- Star & Globular Cluster Formation
- Mergers & Starbursts: ~1000x “normal” densities
  (D. Narayanan, T.J. Cox)
- Cosmological:
  - Galaxy disk formation (D. Keres)
  - Dwarf populations: CDM “crisis”? (M. Kuhlen)
- AGN Feedback: Physics & Coupling:
  - Radiation Pressure, Relativistic Jets, Accretion Disk Winds
    (D. Kasen, J. DeBuhr, N. Roth)





Summary:

- ISM structure derives from **supersonic turbulence + gravity**:
  - Lognormal density PDF: Gaussian random field
  - Predict & understand:
    - **GMC Mass Function & Structure** ("first crossing")
    - **Stellar IMF** ("last crossing")
      - (Nearly) scale-free collapse in turbulent field
    - **Clustering** of Stars
    - General **Turbulent Collapse** (e.g. "turbulent box" simulations)

- **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
  - Need 'enough' stars to offset dissipation (set by gravity)
  - Leads to Kennicutt relation & super-winds

- Different mechanisms dominate different regimes:
  - High densities: radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low densities: SNe & stellar wind shock-heating
    - **No *one* mechanism works**