Title: Exploring the bottom of the CDM hierarchy using scale-free simulations

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Abstract: Many numerical studies show that dark matter halos have a plethora of substructure, down to the smallest resolved scales. However, the very bottom of the Cold Dark Matter (CDM) hierarchy at a few earth masses, where the spectral index n approaches -3 and structure begins to form simultaneously on a variety of scales, remains relatively unexplored. It is possible that the subhalo mass distribution, which appears to be described by a simple power-law down to mass scales 10^6 solar masses, remains unchanged and independent of scale and n. A few studies have indicated that this appears to be the case, which is surprising considering all other statistical indicators, such as the halo mass function, as well as the internal properties of halos, such as concentration, show a dependence on n. To explore the effect of the spectral index on the subhalo mass function we ran two large, scale-free simulations, P(k)=Ak^n with n=-1 and -2.5. We find that the subhalo mass function does depend on the spectral index, with the power-law becoming shallower as n->-3.

Subhalo Mass Function in Scale-Free Cosmologies at Steep Spectral Indices

Pascal Elahi

PASCOS 2008

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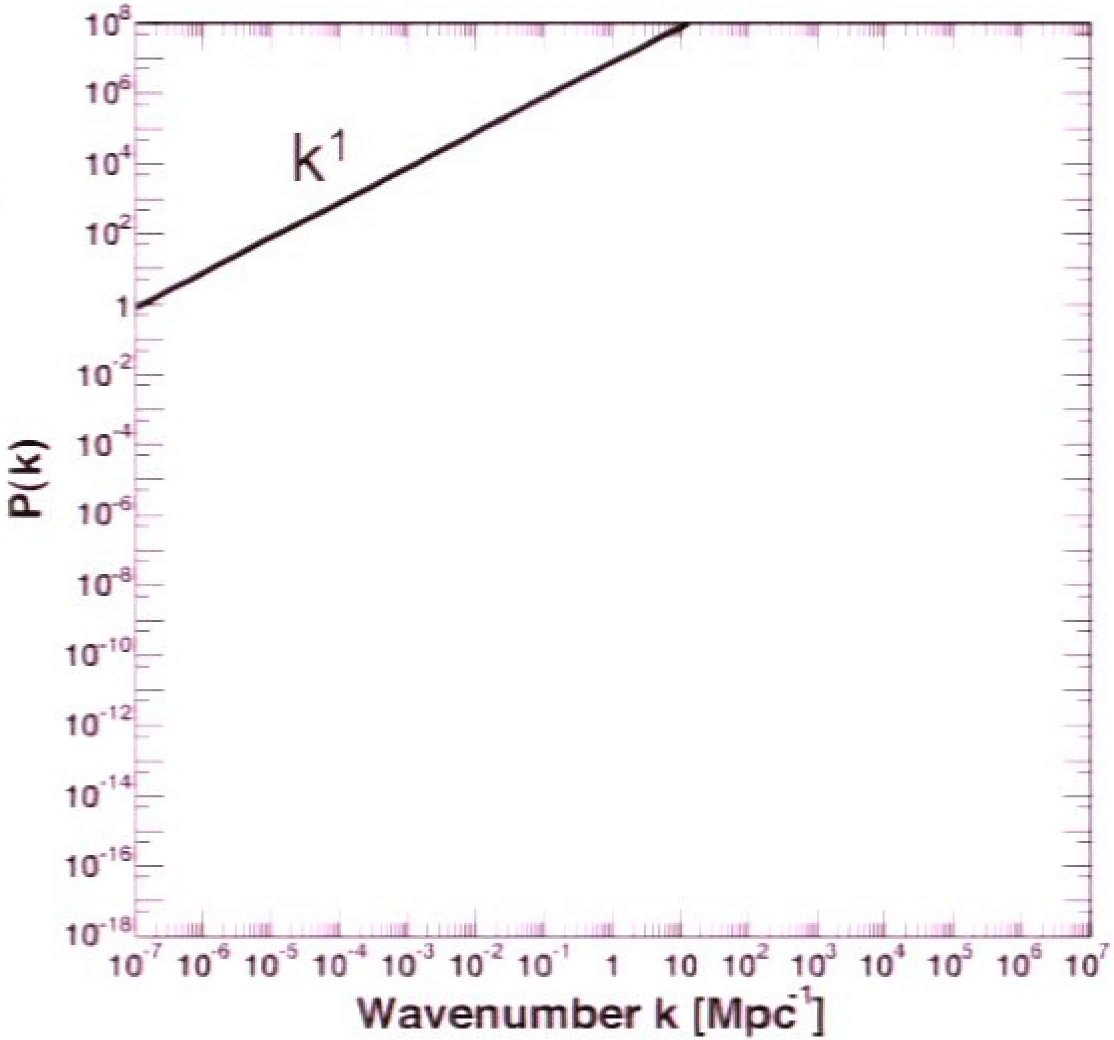
Outline

1. Structure Formation, ΛCDM & SUSY
2. Numerical Experiments: Why Scale-Free?
3. Results: Subhalo Mass Function & Self-Similarity

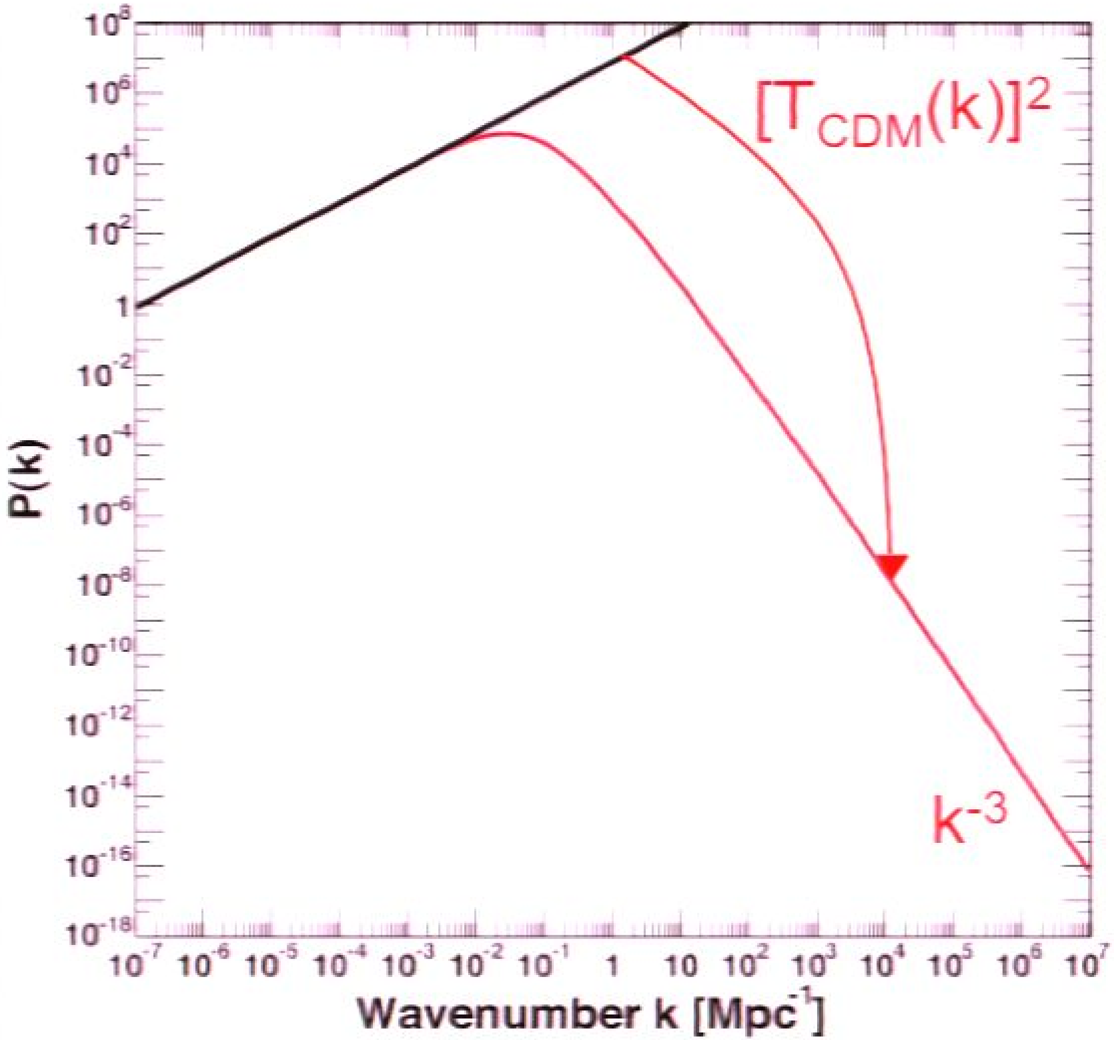
Density Perturbations



- Inflation gives scale-free Gaussian density perturbations. Various models.
  - e.g. Guth (1998)

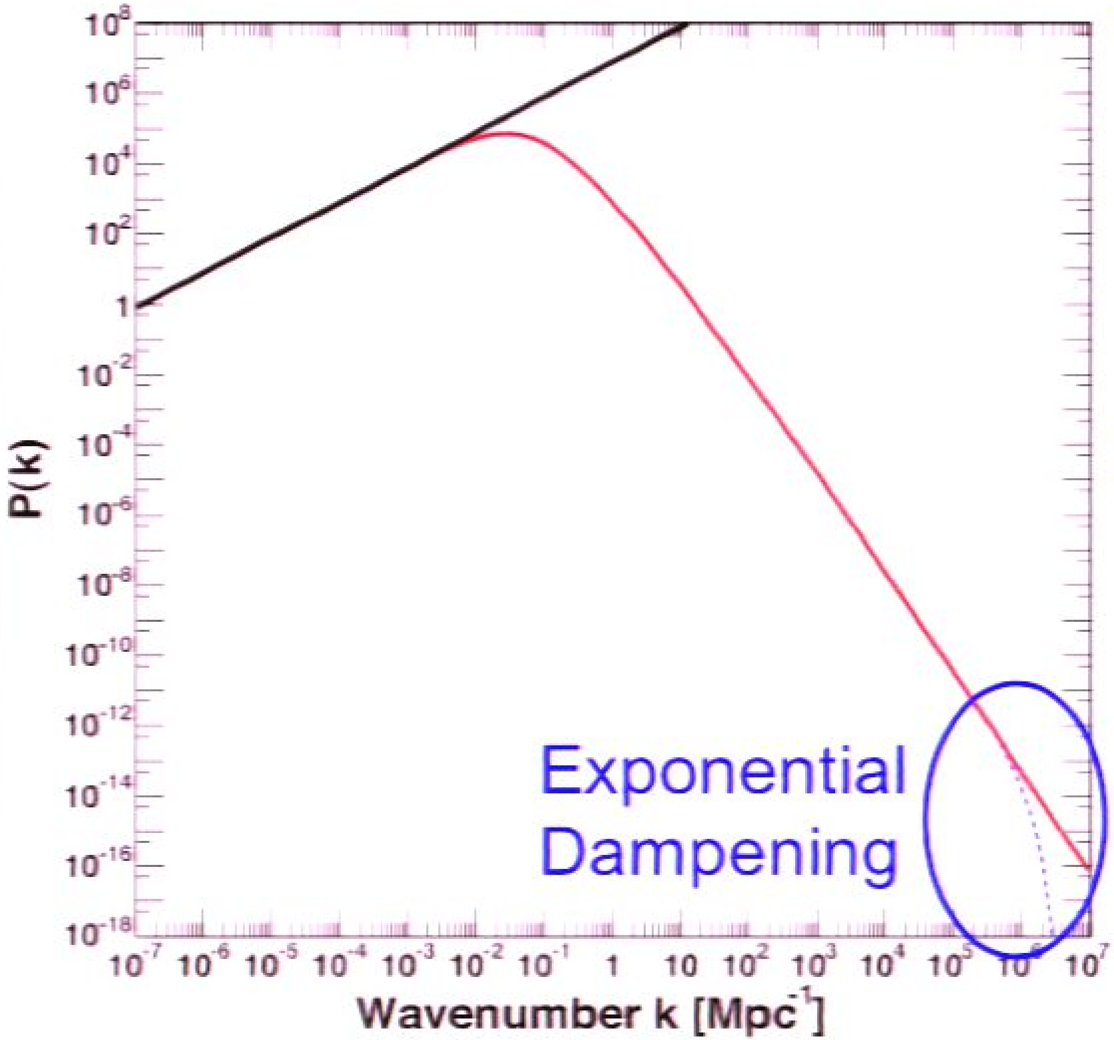
$P(k) \propto \langle |\delta(k)|^2 \rangle$

Density Perturbations



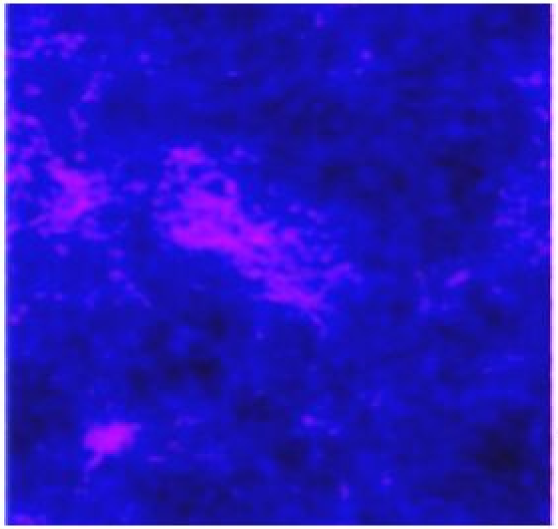
- Modes evolve upon entering horizon, dependent on density make up of universe. CDM dominated mode evolution given by transfer function $T_{cdm}(k)$.
  - e.g. Eisenstien & Hu (1998), (1999)

Density Perturbations

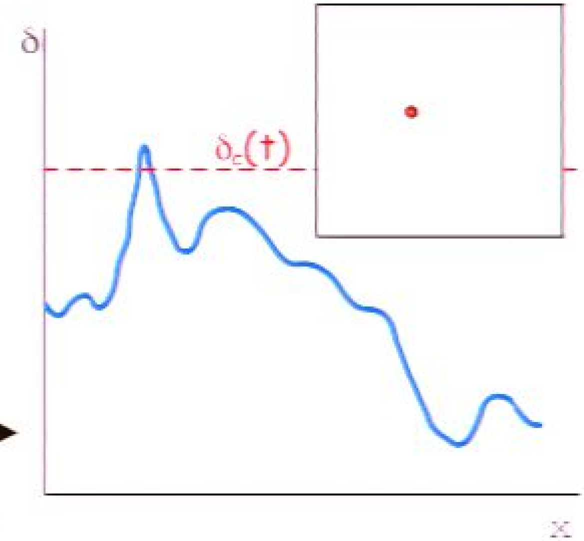


- CDM: σ_{cross} & m_{WIMP} govern scale of free-streaming/collisional-dampening, below which δ washed out.
- **Bottom of CDM hierarchy.**
  - SUSY Neutralino m~100 GeV → parsec (k~10^6 h/Mpc), earth mass (~10^{-6} $M_\odot$). **So galaxy is 10^{18} times more massive!**

& Structures

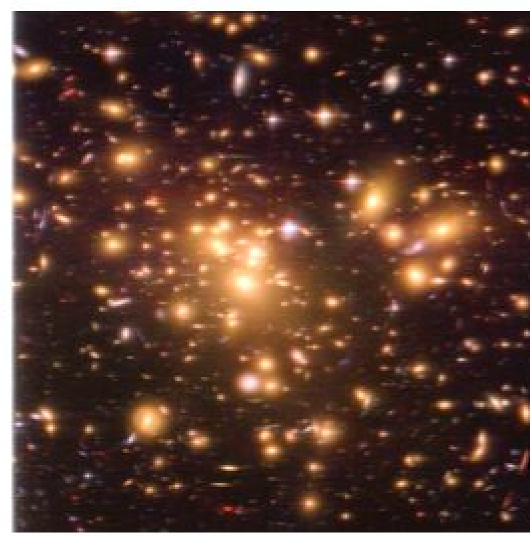


Density perturbations grow and collapse



Form hierarchy of objects

Add baryonic physics



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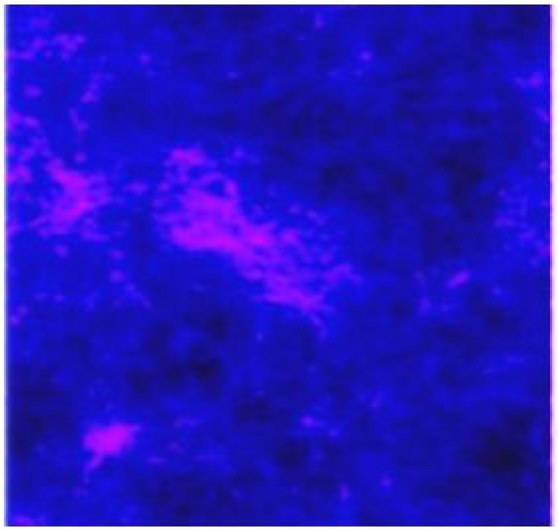

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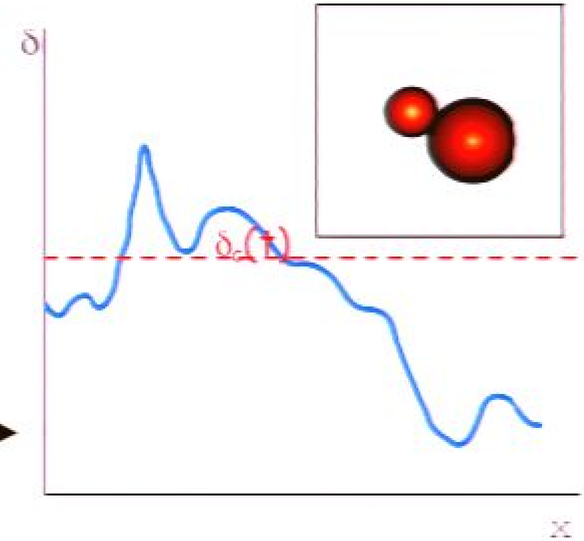

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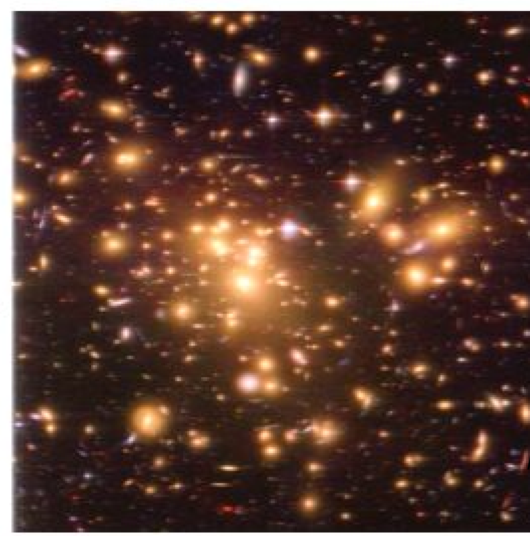

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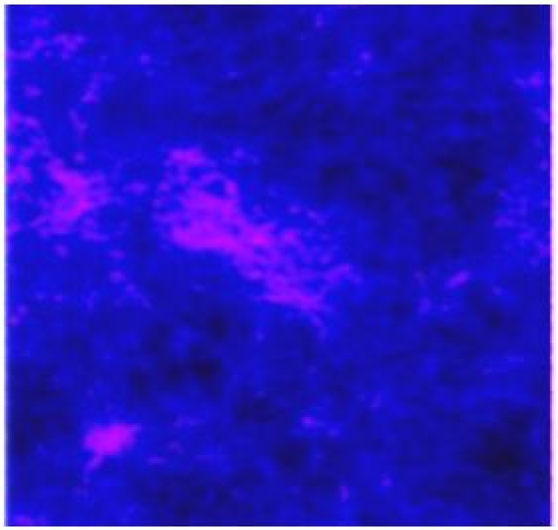

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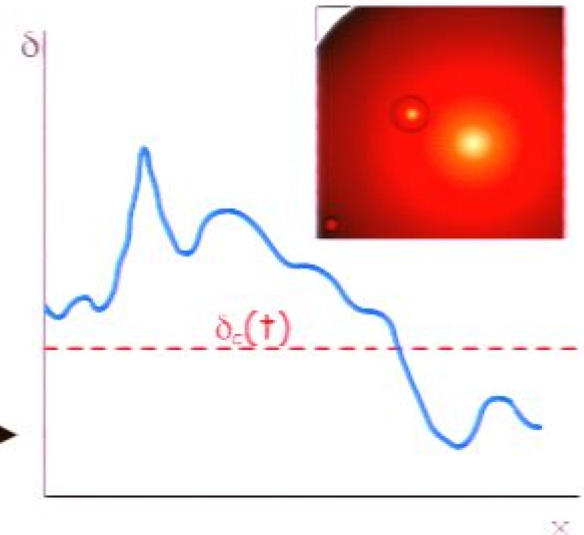

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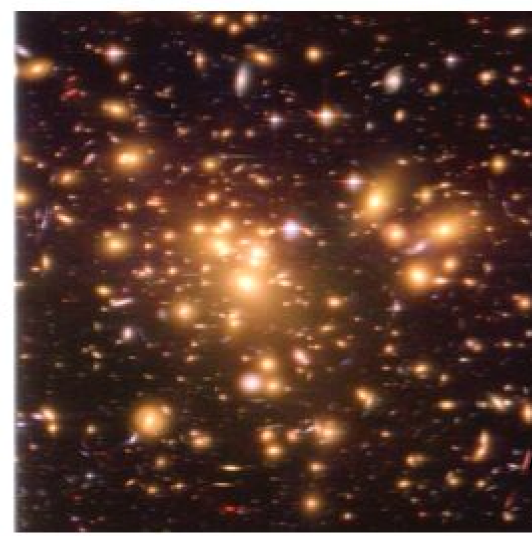

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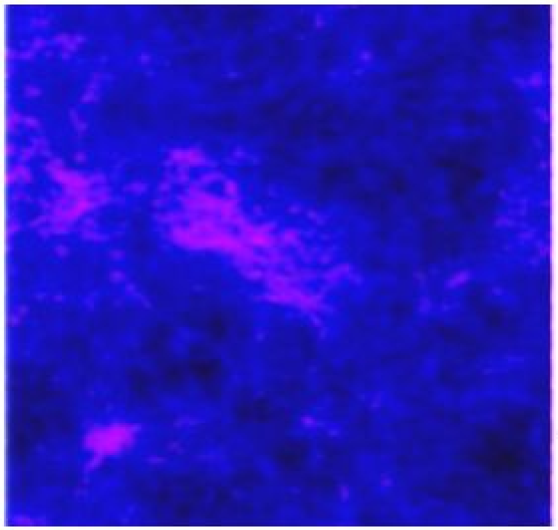

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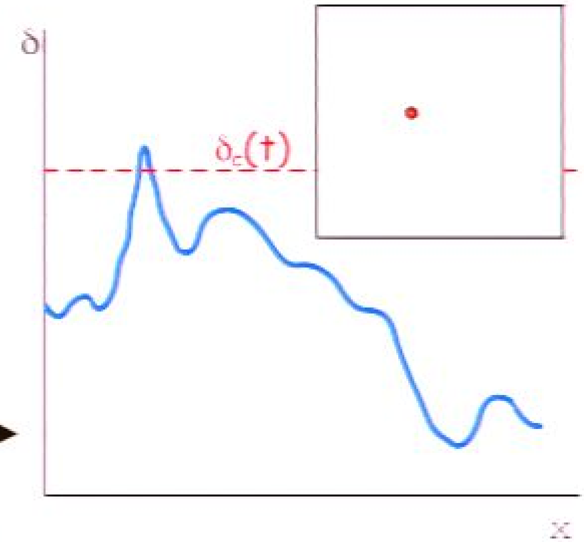

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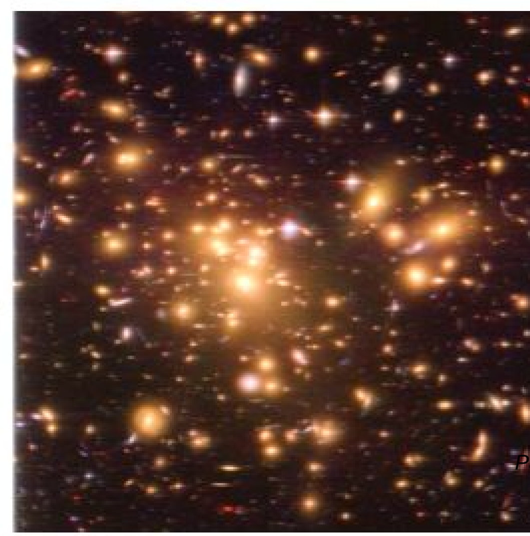

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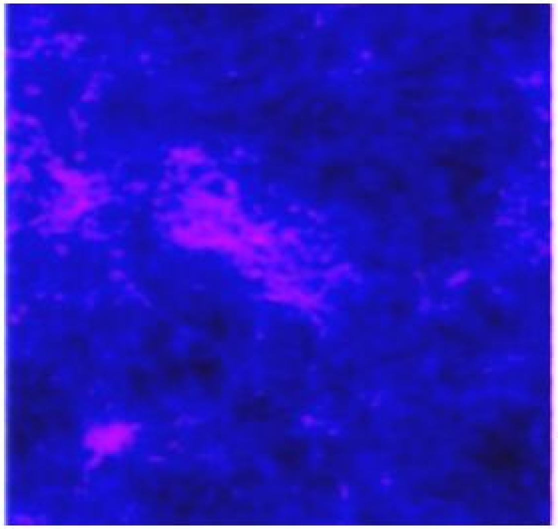

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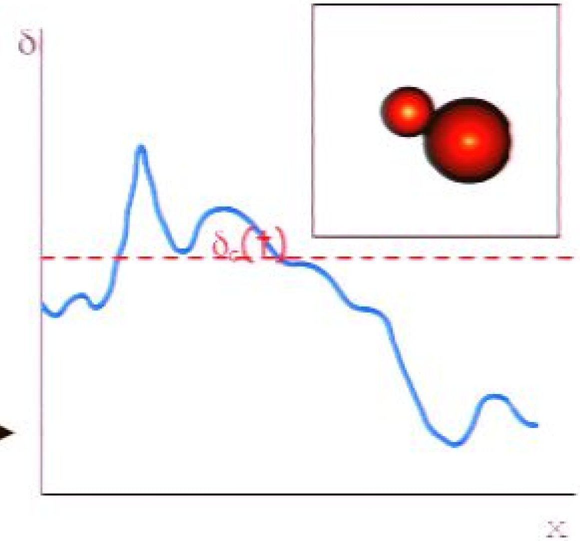

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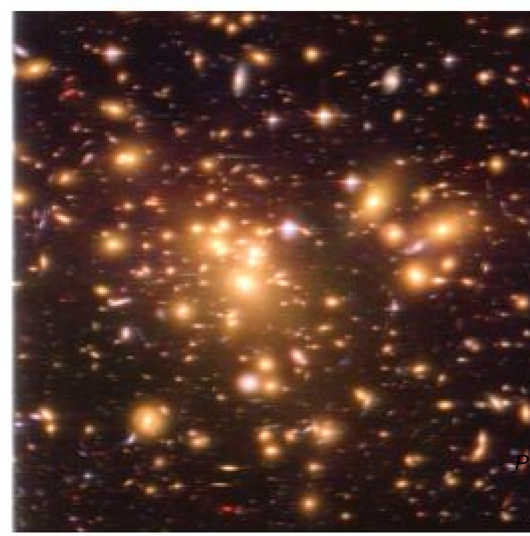

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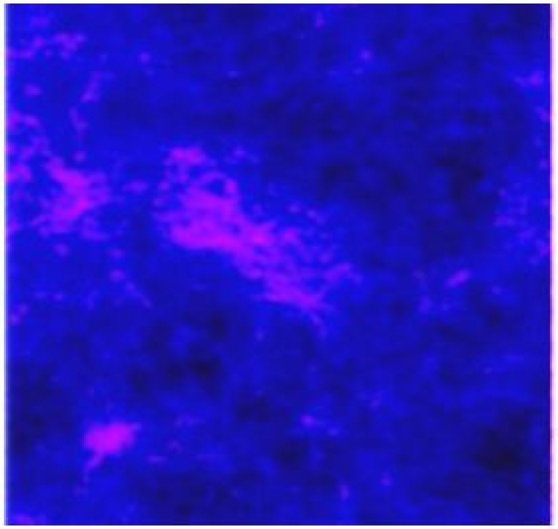

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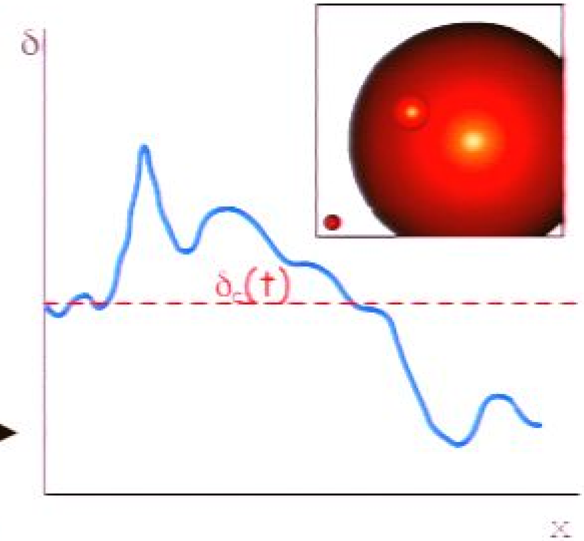

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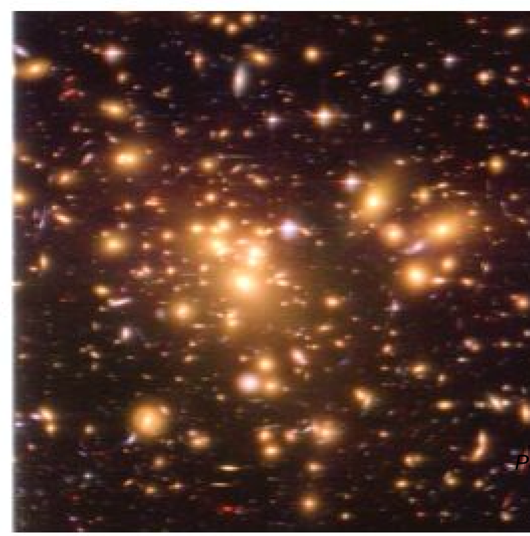

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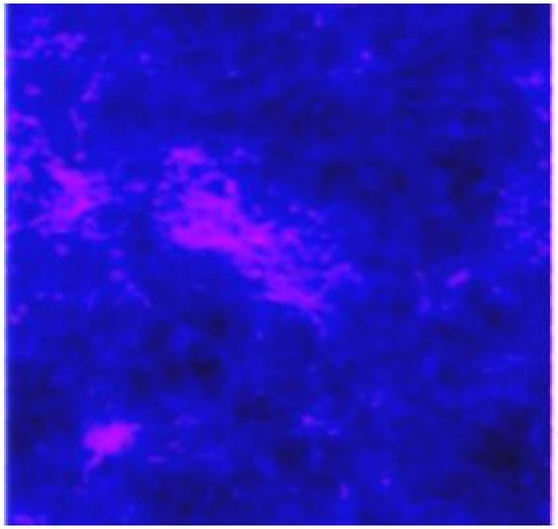

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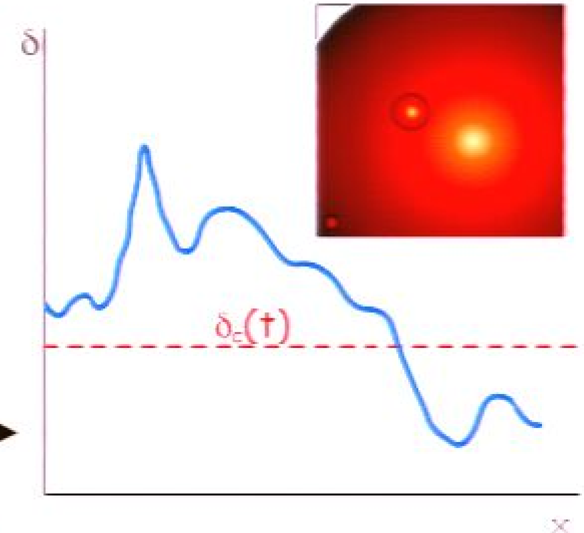

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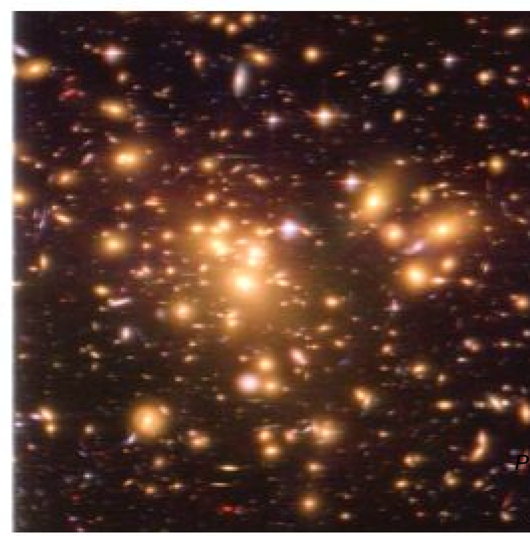

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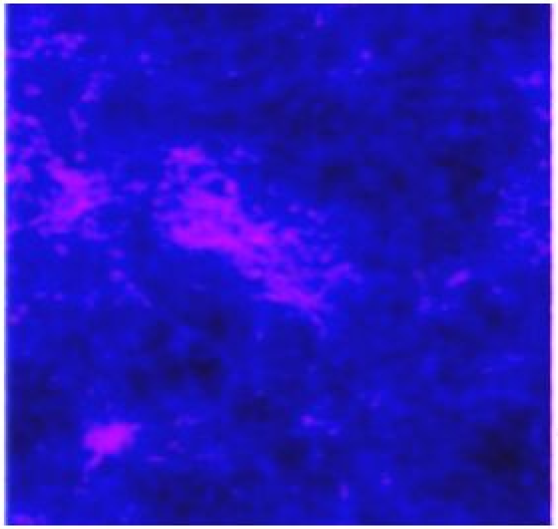

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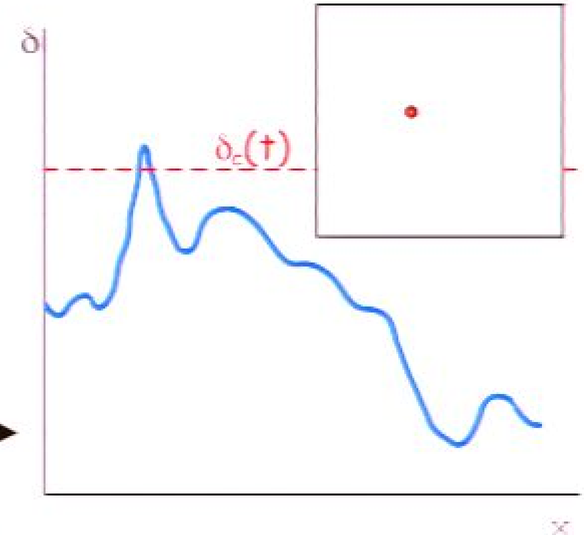

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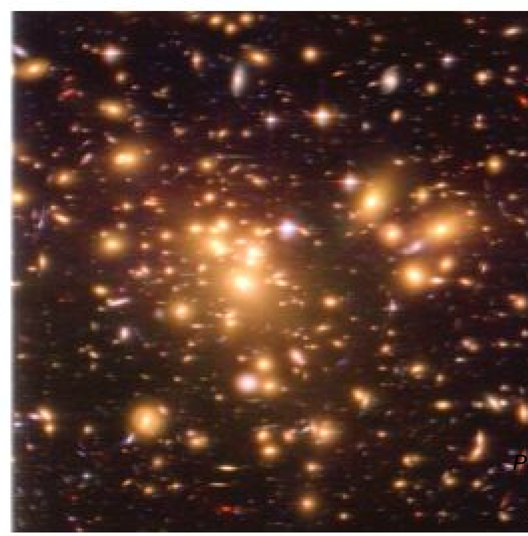

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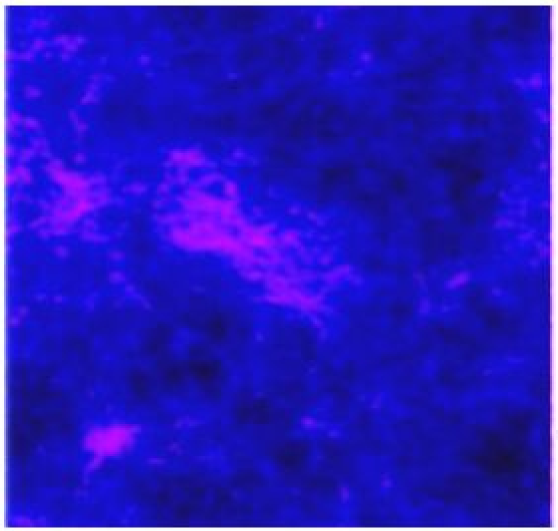

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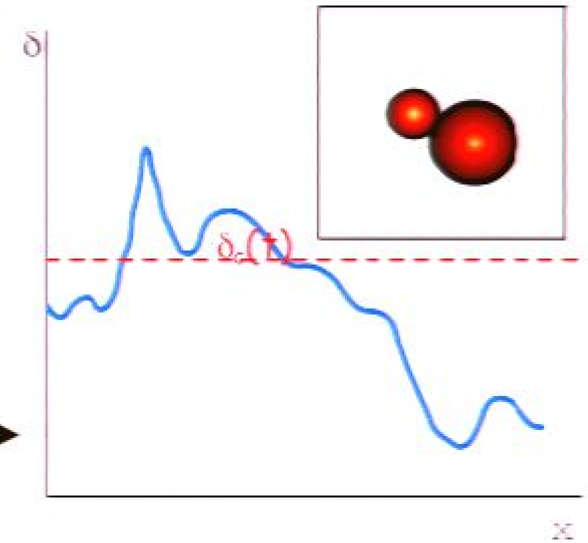

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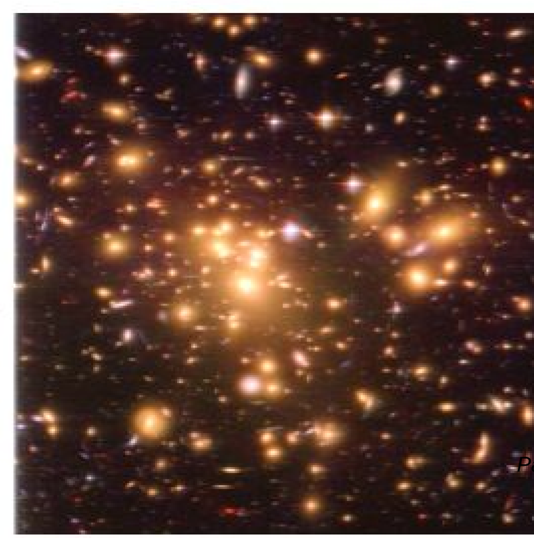

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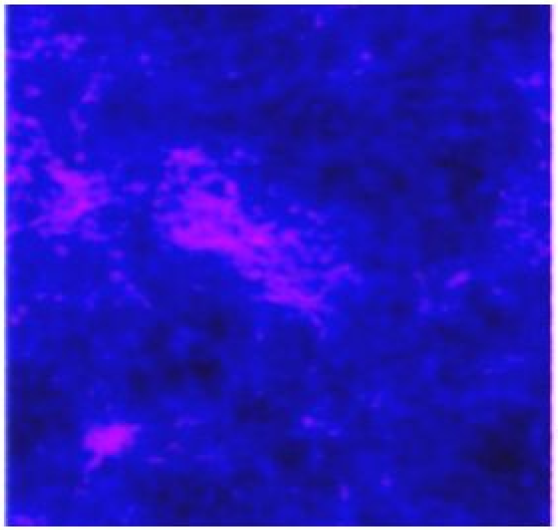

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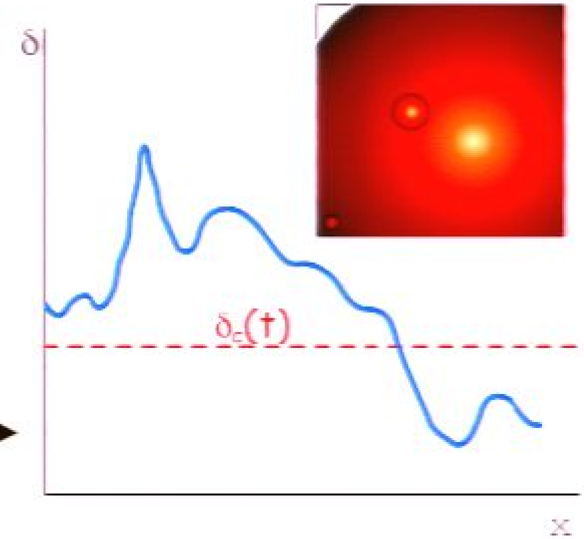

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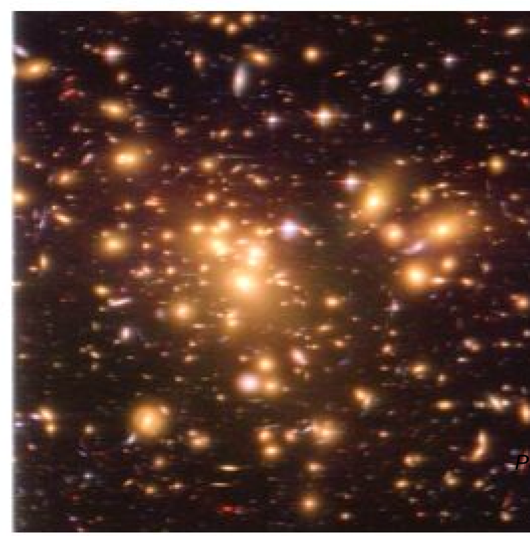

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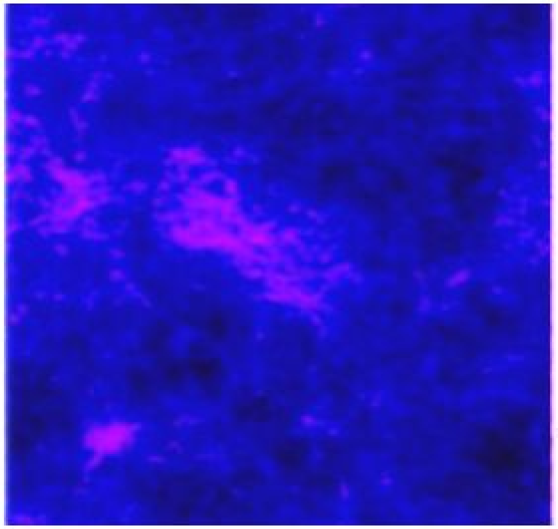

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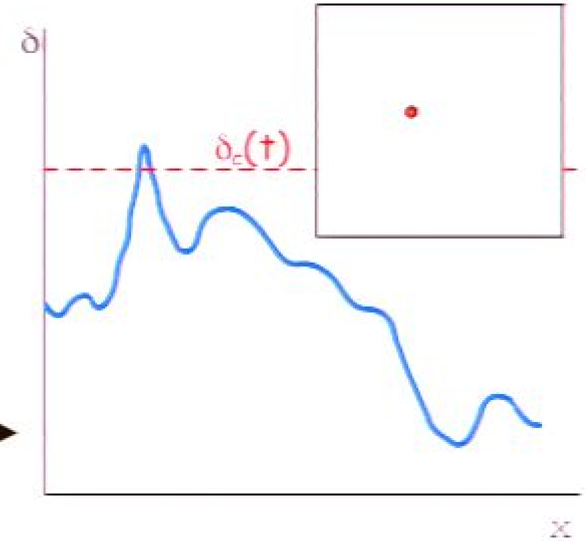

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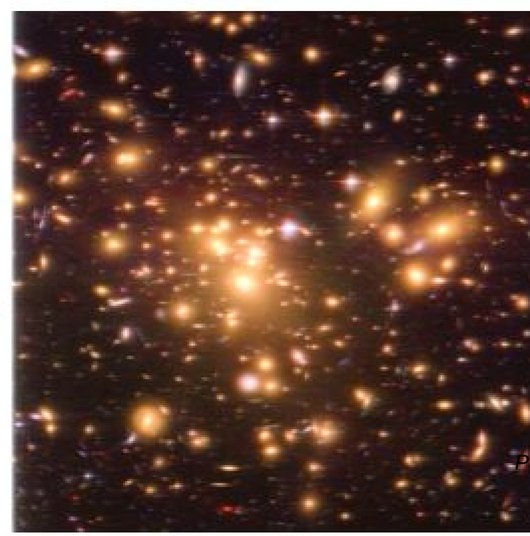
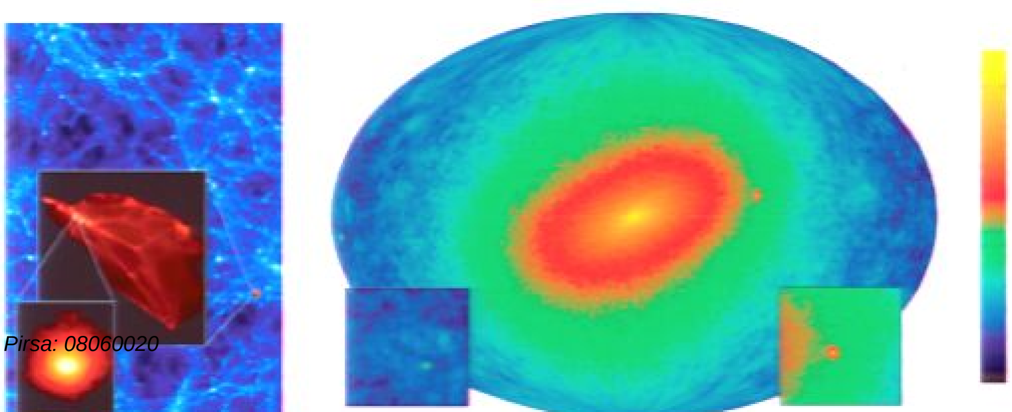
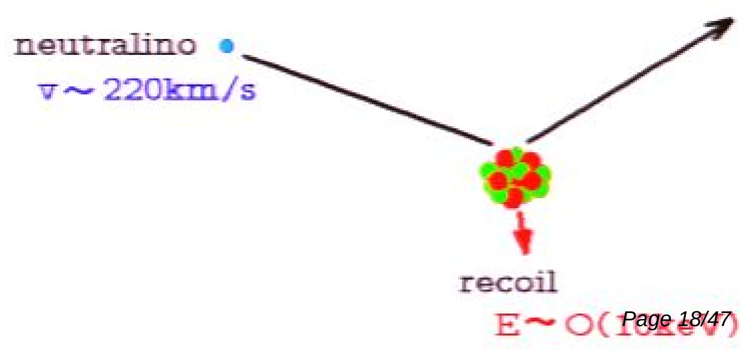


Why do we care about the bottom of the CDM hierarchy?

DETECTION

- Clumpy → Indirect
  - IF CDM self-annihilate, detect γ-rays or other decay products. Signal $\propto \rho^2$. More subhaloes, better signal. Density/energy distribution at small scales?
- GLAST, HESS, Icecube
  - [e.g. Diemand, Khulen & Madau (2007); Bertone, Hooper & Silk (2005)]
- Smooth → Direct
  - IF SUSY WIMPS, nuclear recoil experiments could detect it. Remnants/tidal streams leave energy signature.
- DAMA, PICASO, etc
  - [e.g. Stiff, Widrow & Frieman (2001 Green (2007), Kamionkowski & Koushiappas (2008)]



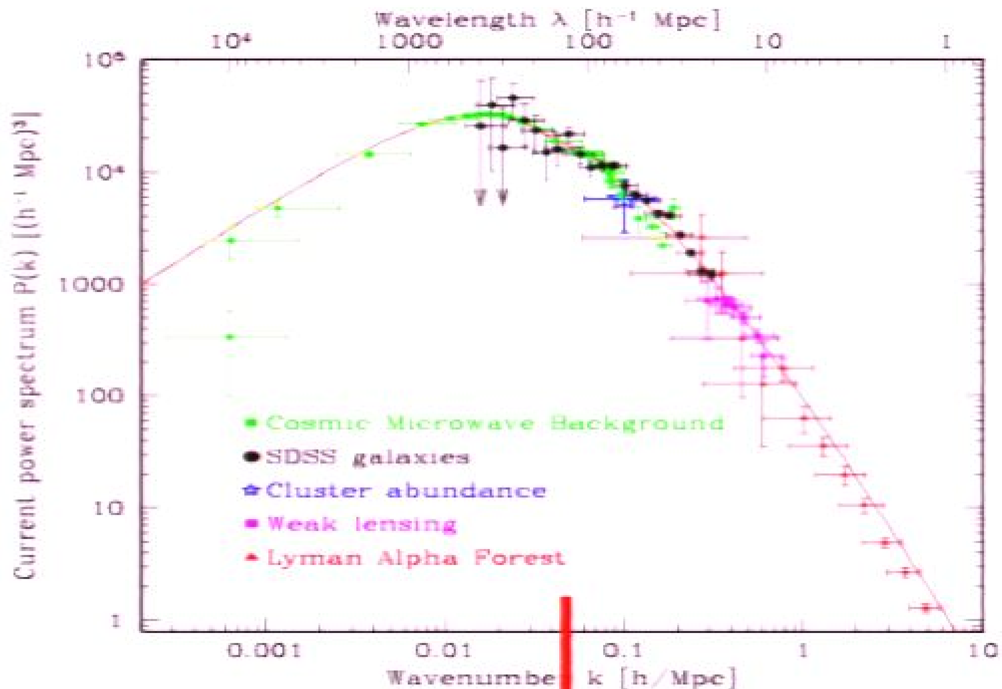


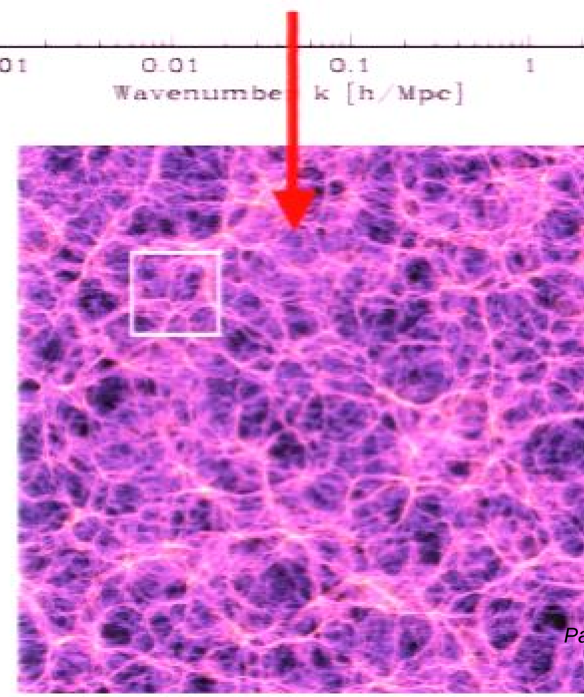
Exploring Structure Formation

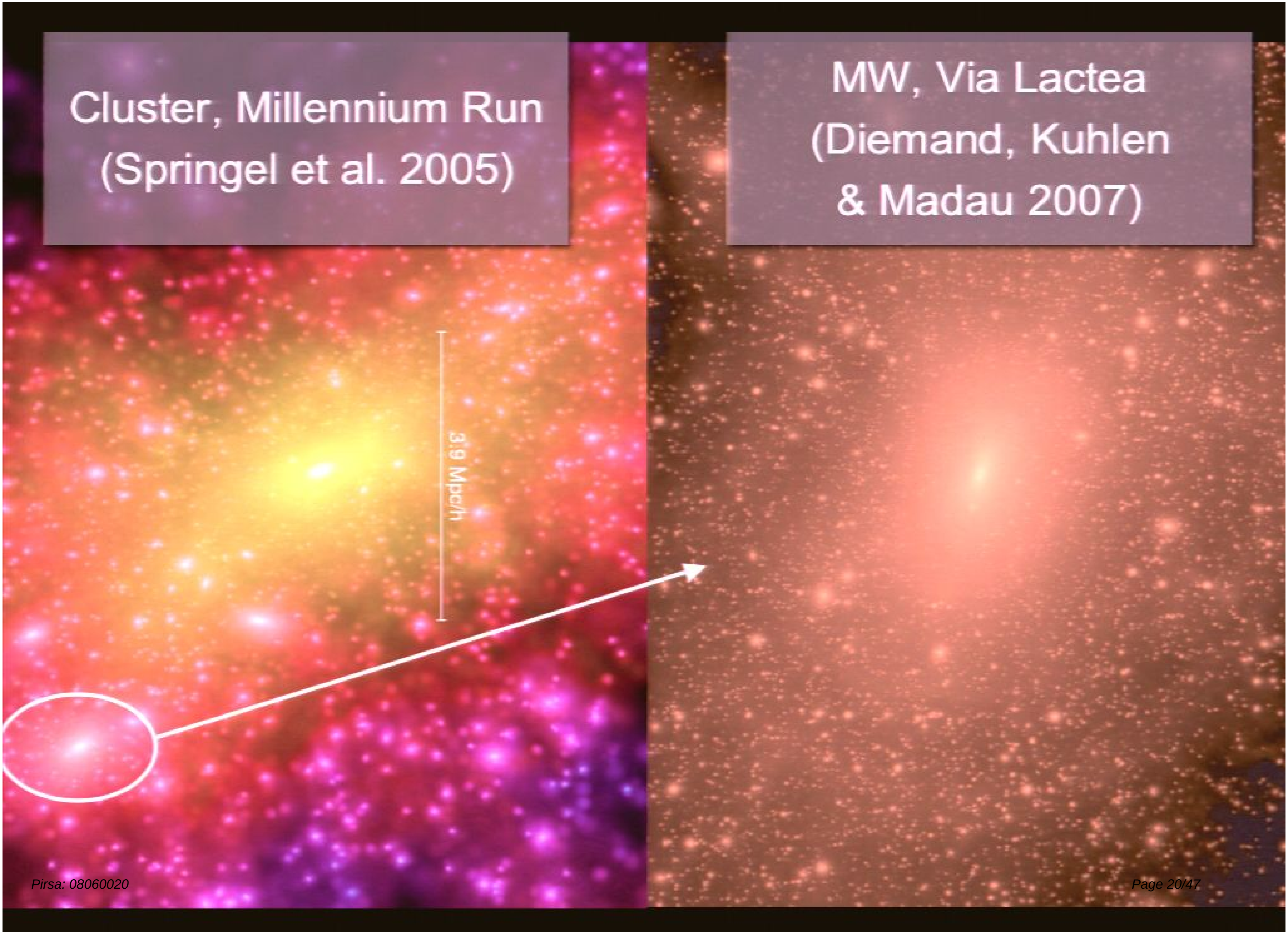
1. Inflation (or some IC), along with CDM physics gives **P(k)**

2. "Quasilinear" regime: Zeldovich (ZA), second order perturbation theory (2LPT). Use to start simulation.

3. Nonlinear gravitational clustering: **Simulations**. BUT dynamic range issue. How to model **10^8** factors of scale, **10^{24}** factors of mass? What can save us? **Self-similarity**.

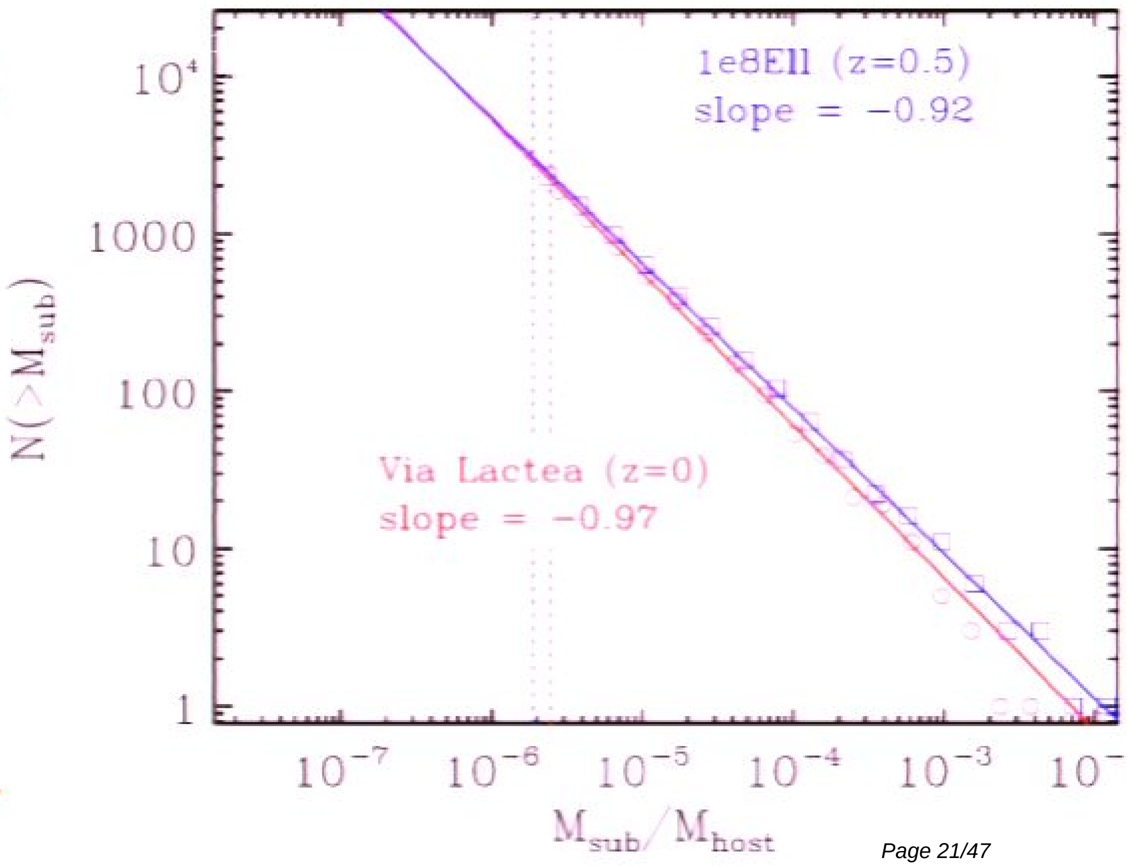


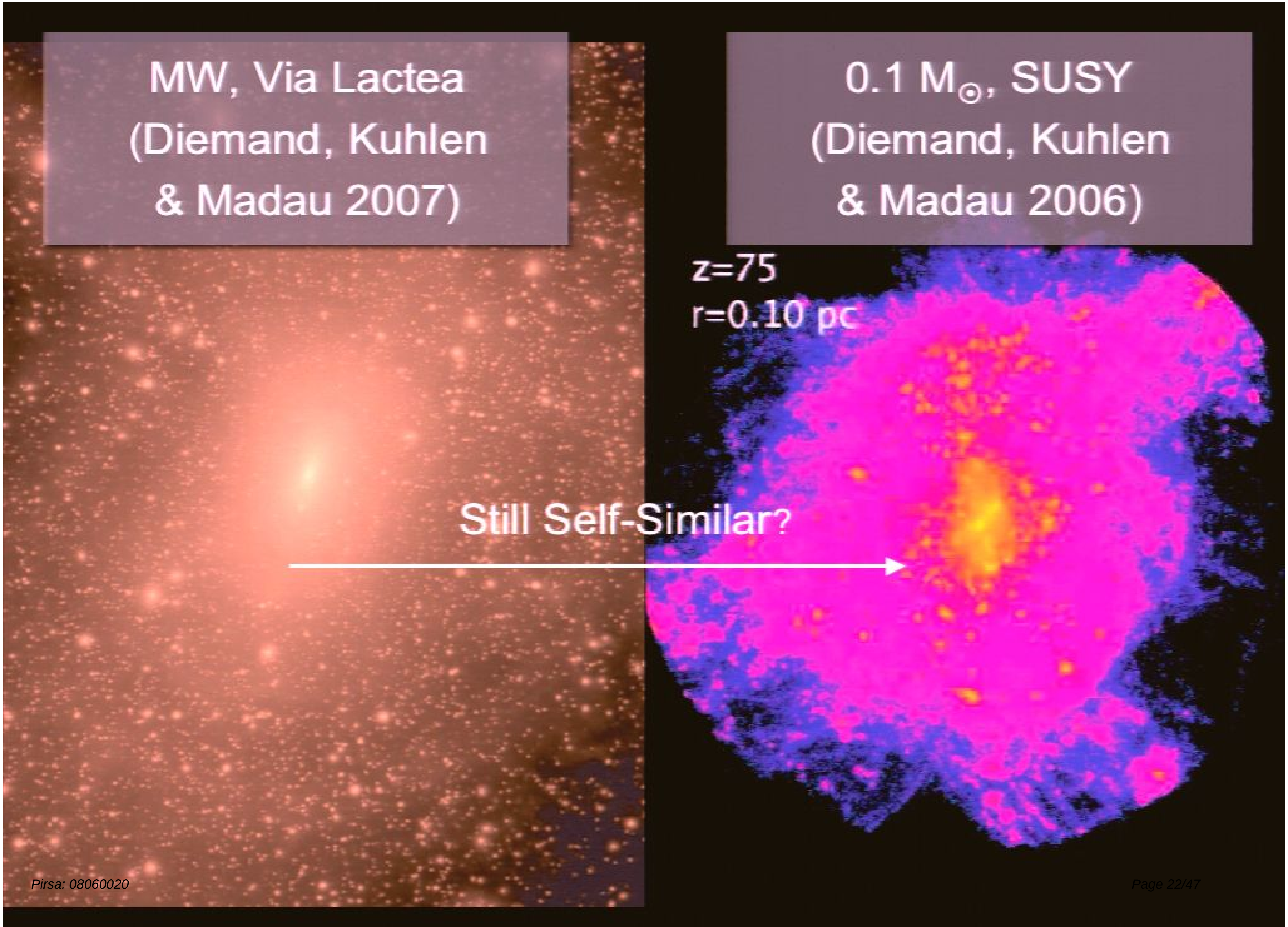



Cluster, Millennium Run
(Springel et al. 2005)
MW, Via Lactea
(Diemand, Kuhlen
& Madau 2007)
3.9 Mpc/h

Substructure: Self-Similar?

- Simulations show clusters like galaxies, subhaloes smaller versions of haloes
- cumulative subhalo mass function $n(>M) \propto M^{\alpha}$, ($\alpha \approx -1$)
  - (e.g. Moore *et al* 1999, Gao *et al* 2004, Diemand *et al* 2007, Madau *et al* 2008)
- Amplitude known to vary with peak height, so is mass function truly scale-free?



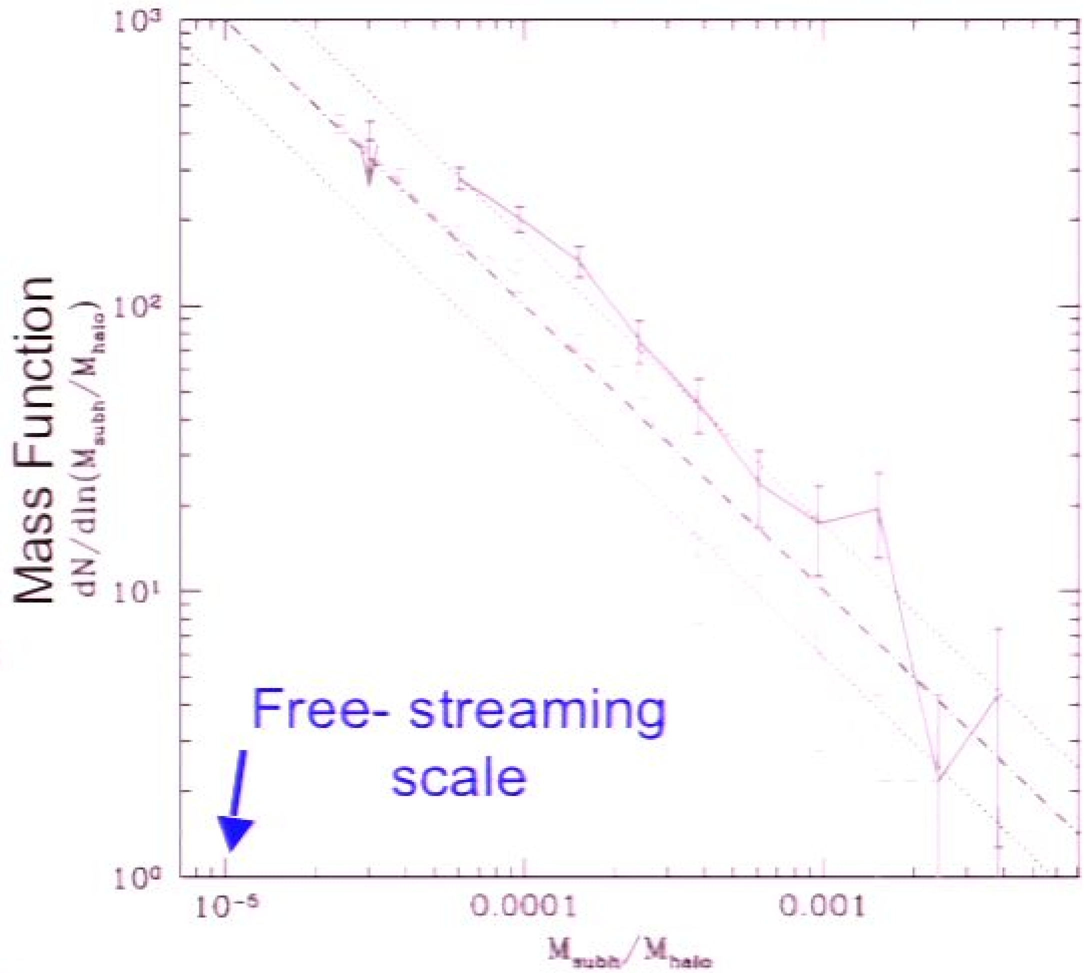


MW, Via Lactea (Diemand, Kuhlen & Madau 2007)
0.1 $M_\odot$, SUSY (Diemand, Kuhlen & Madau 2006)
z=75
r=0.10 pc
Still Self-Similar?

High Redshift SUSY Sims

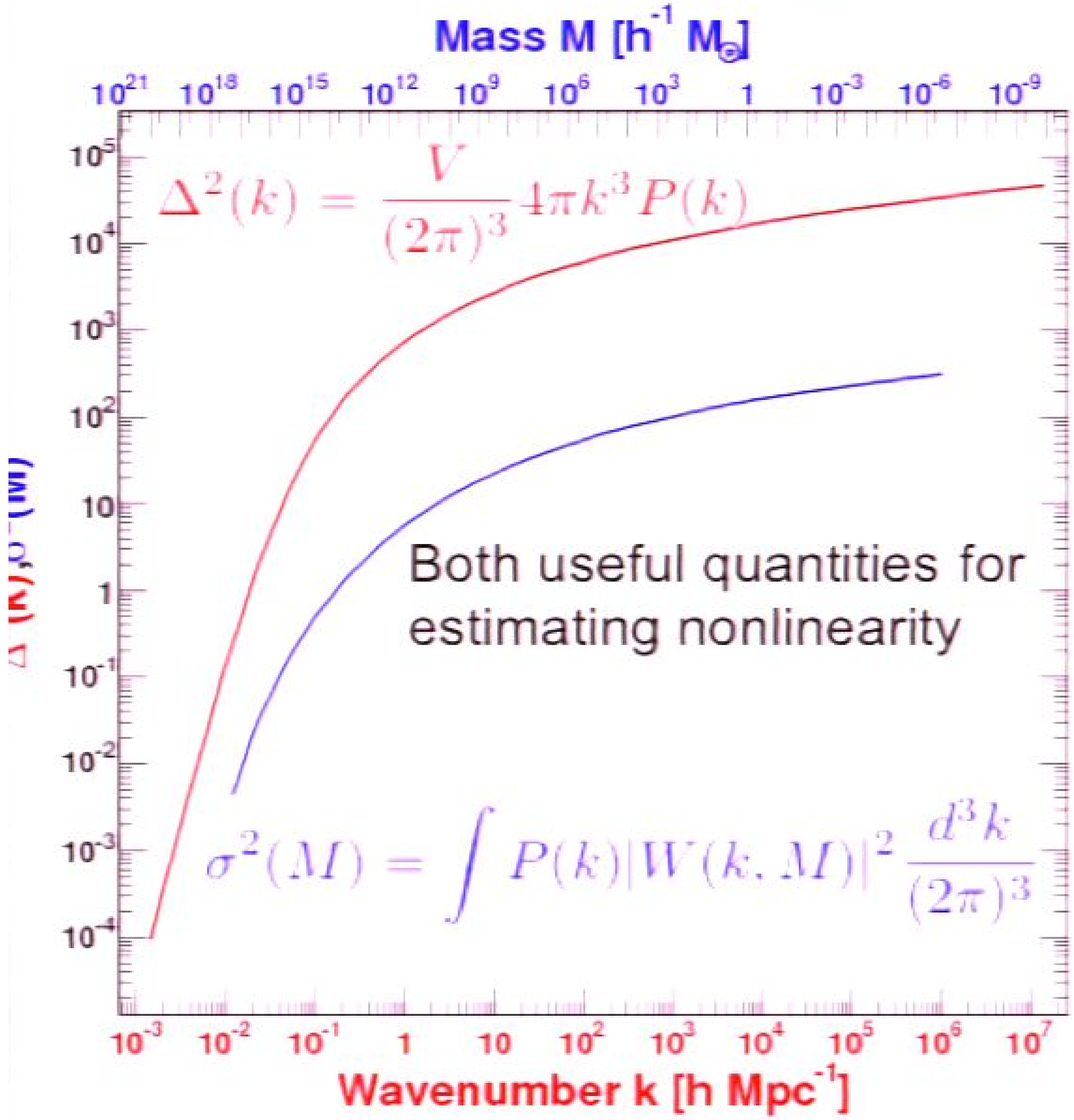
- Pure DM simulations, ΛCDM cosmology, high z, 3 kpc box size.
- Shows similar distribution, normalization uncertain. BUT sims look different and small volume so can we trust it?
- Can get estimates of ~10^{15} SUSY objects.

Side note: SUSY subhaloes susceptible to disruption by stars (?) e.g. Zhao et al (2007)

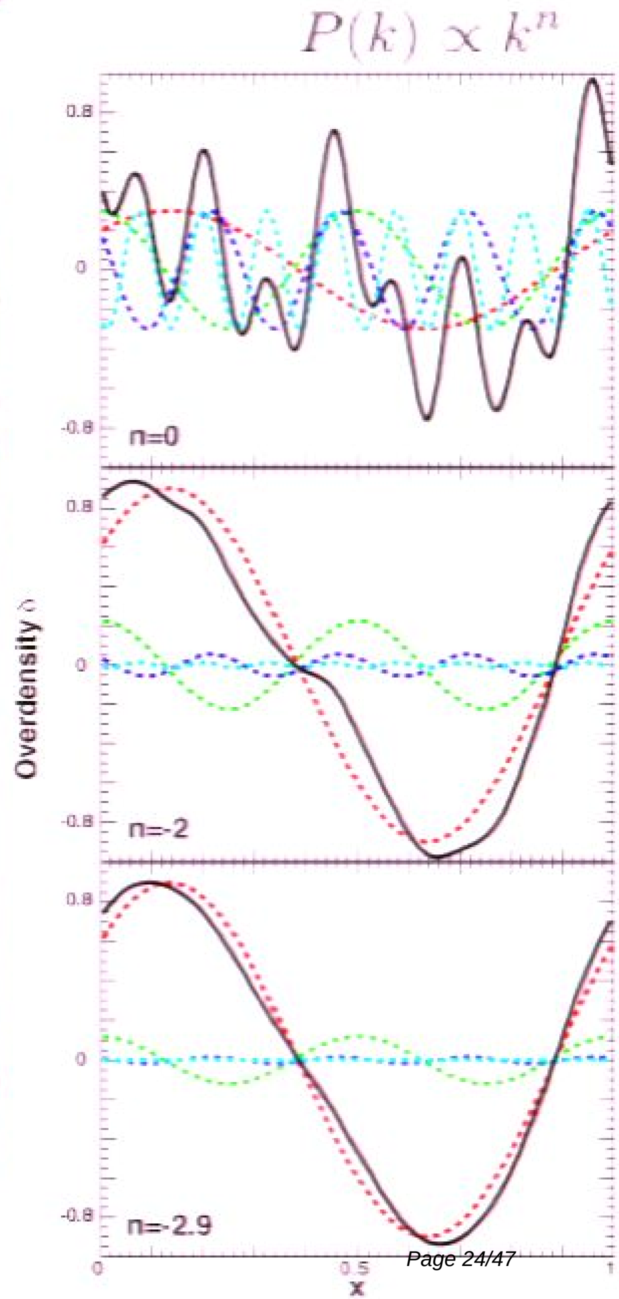


Diemand, Moore & Stadel (2005), Diemand, Khulen & Madau (2006)

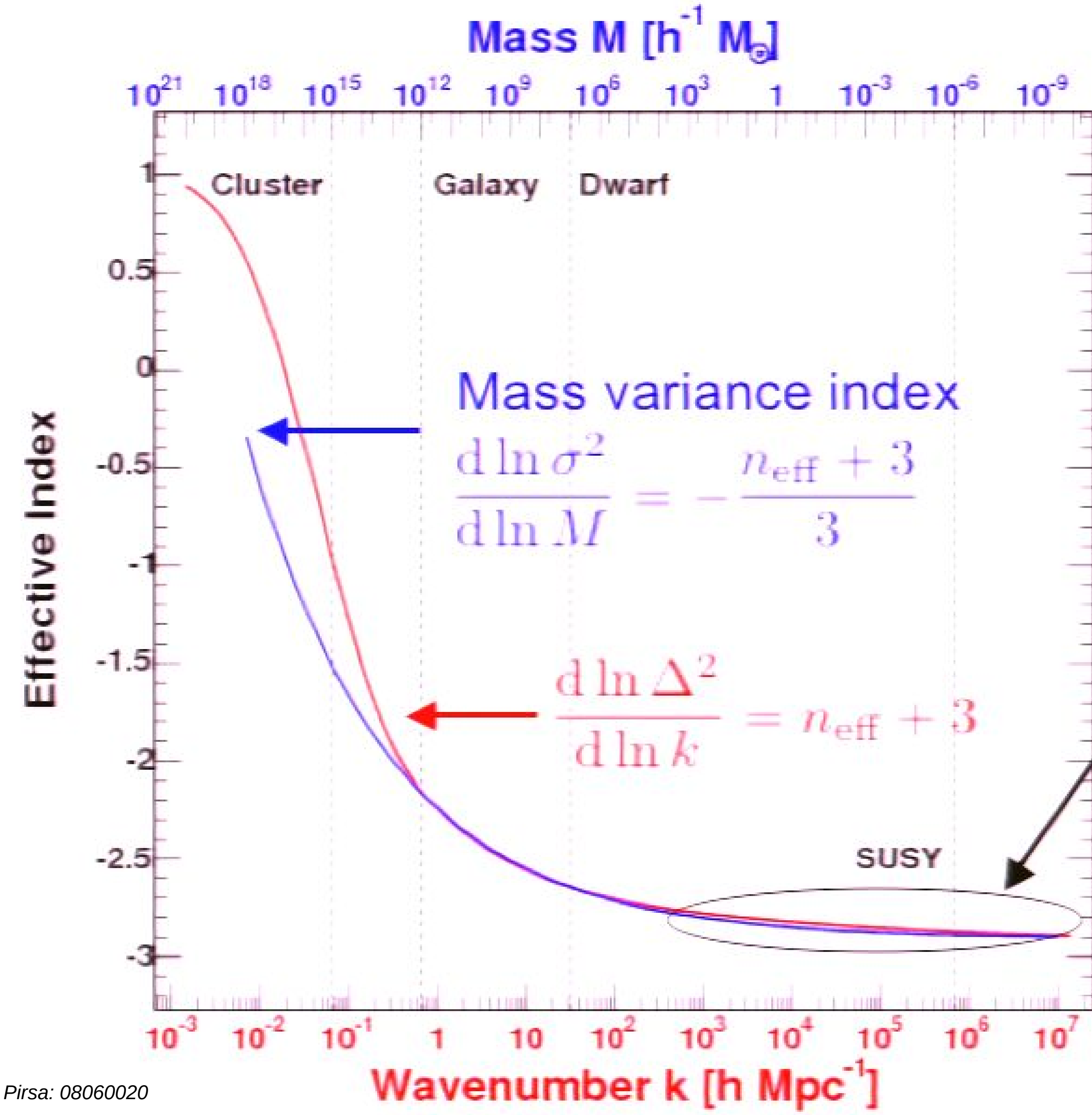
P(k) Revisited



Large-scale modes increasingly important.



Effective Index



Relative formation time:

$$a_1(t)/a_2(t) = (M_1/M_2)^{(n_{\rm eff}+3)/}$$

Small scales, n→-3, simultaneous collapse. Haloes: no time to virialize before accreted.

Would this leave imprint on subhalo mass distribution?

(P(k) from Eisenstien & Hu 1998)

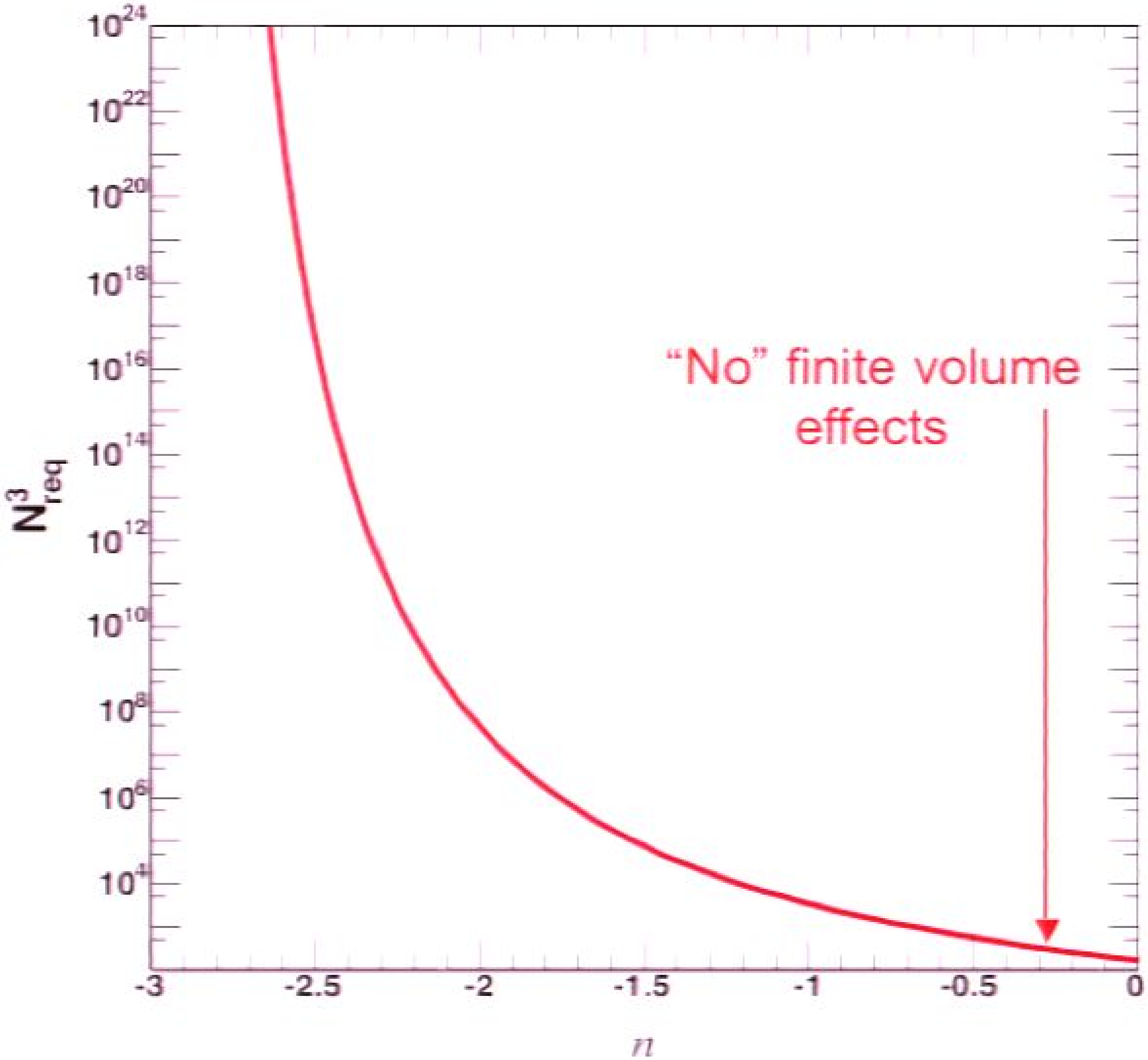
Slippery Slope to n→-3

Finite volume effects play an important role at steep indices.

$$\sigma^2_{\rm miss} \approx \frac{\Delta^2(k_{\rm b})}{n+3} = 0.04$$

Minimizing ***finite volume*** effects gives

$$N^3_{\rm req} \geq 2^3 \left[\frac{\Delta^2(k_{\rm Ny})}{0.04(n+3)}\right]^{3/(n+3)}$$



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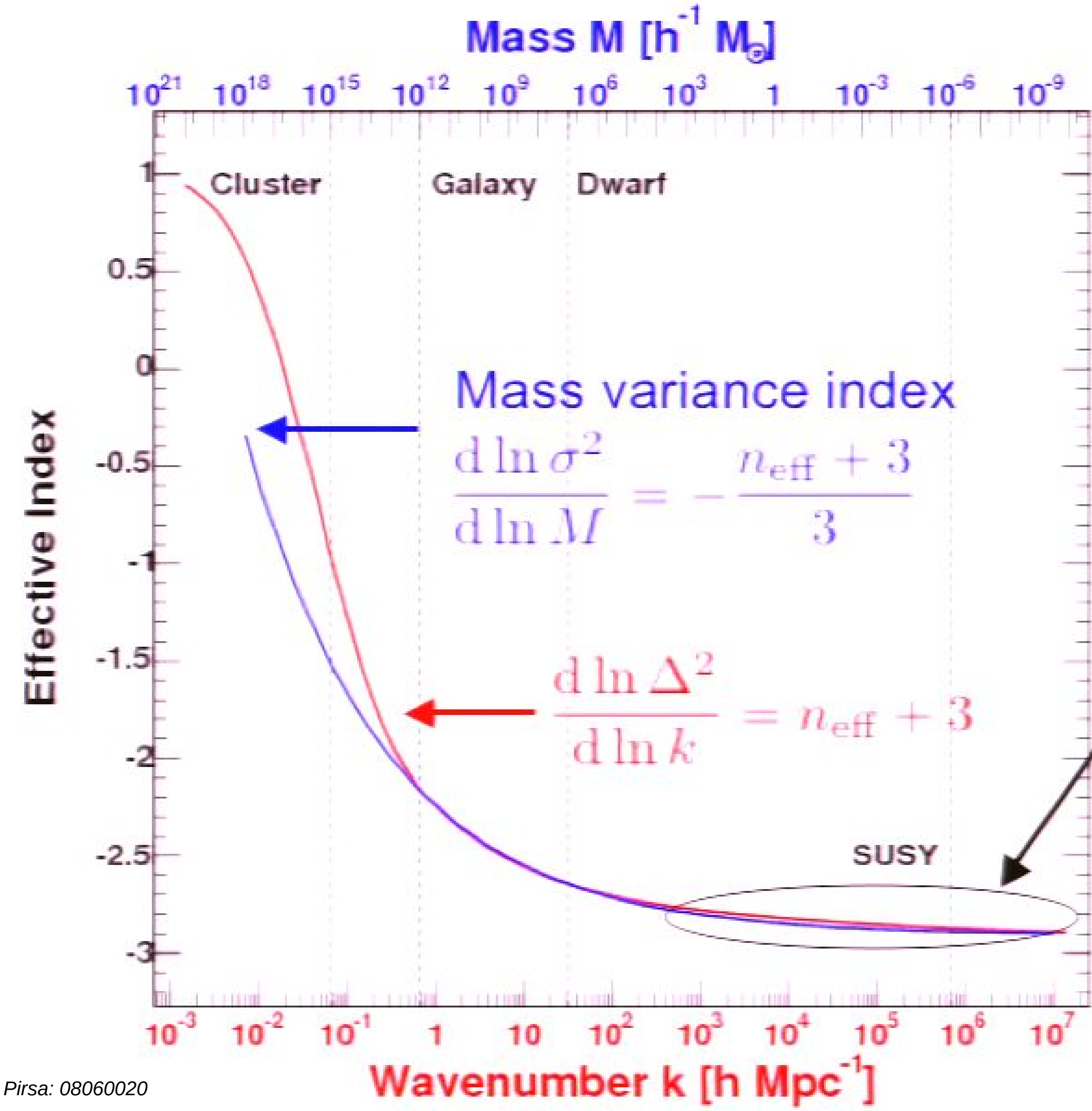

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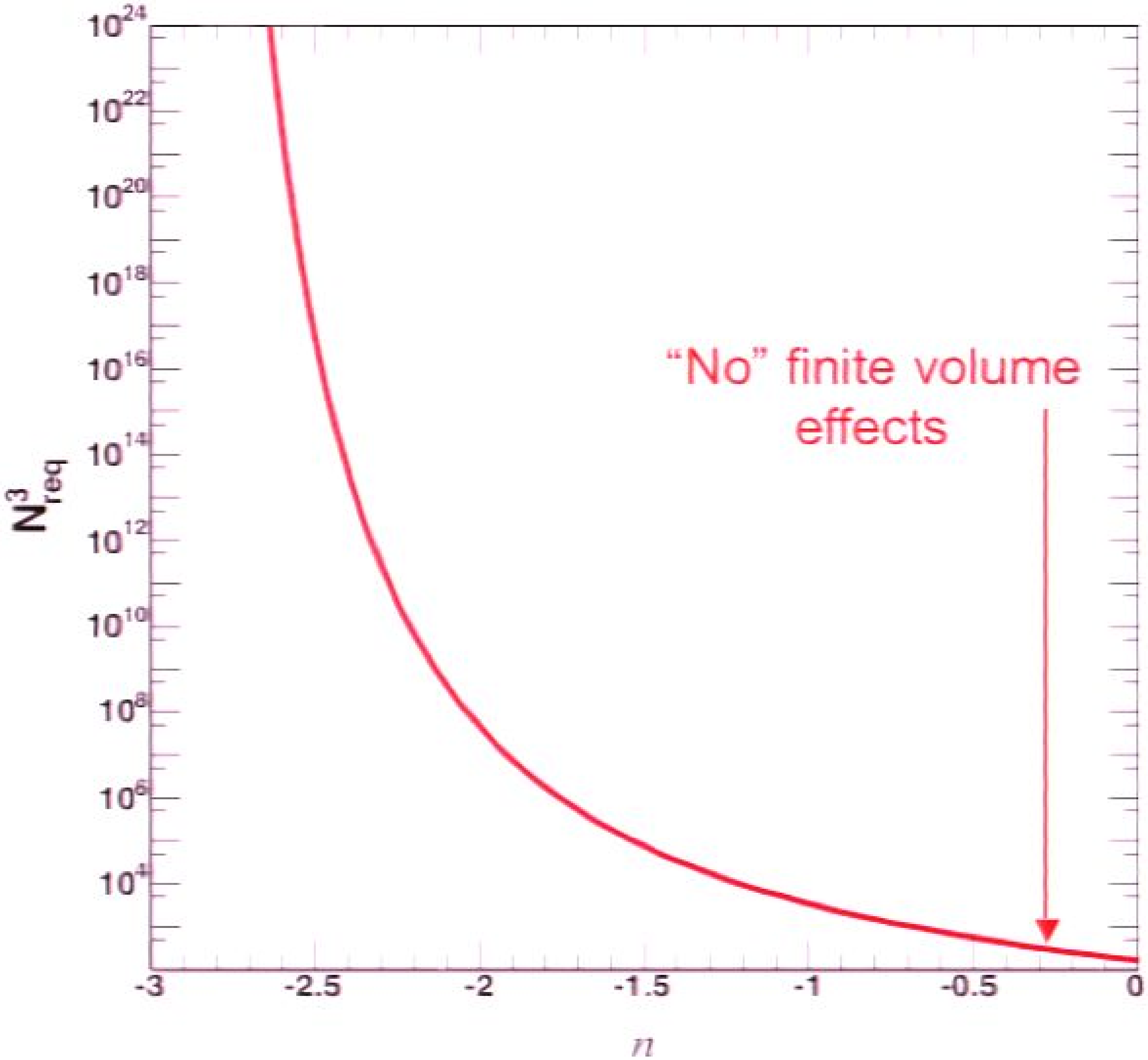

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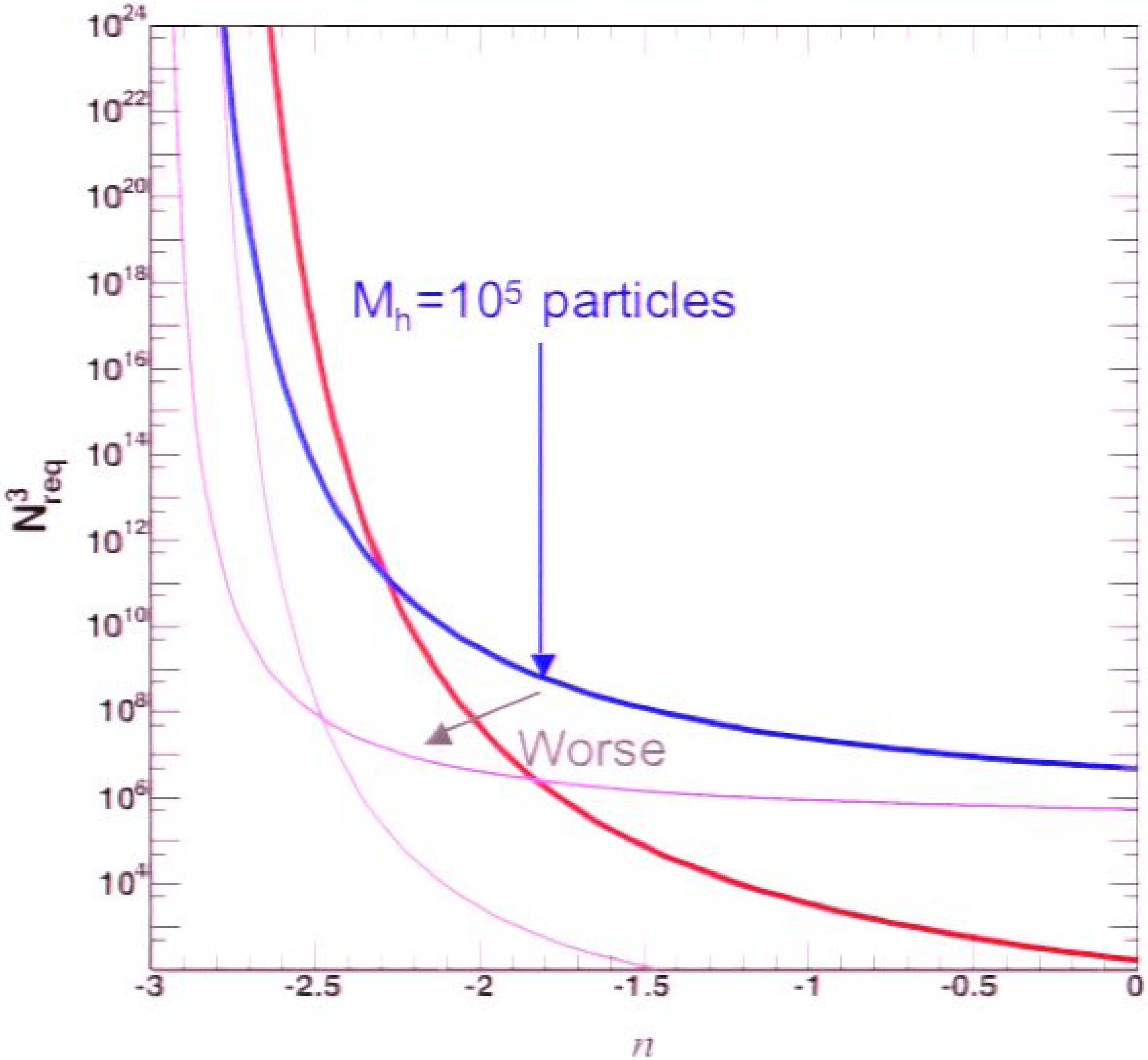
Minimum resolution requirements for haloes

$$N^3_{\rm req} \geq \frac{6M_{\rm h}}{\pi m_{\rm p}} \left[\frac{\sigma^2(M_{\rm h})}{\sigma^2(M_{\rm b})}\right]^{3/(n+3)}$$



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Ensuring haloes with enough particles not too big

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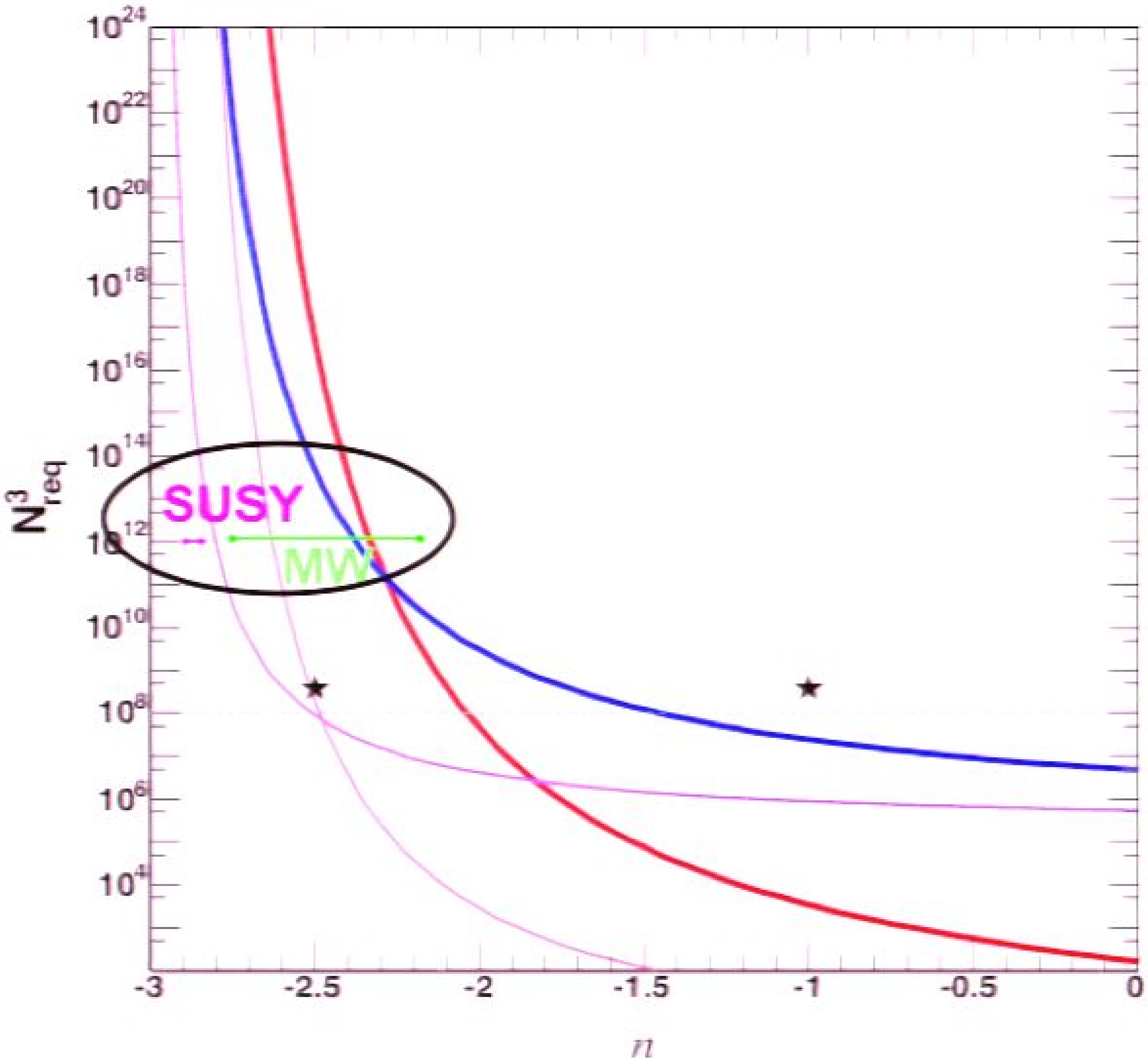
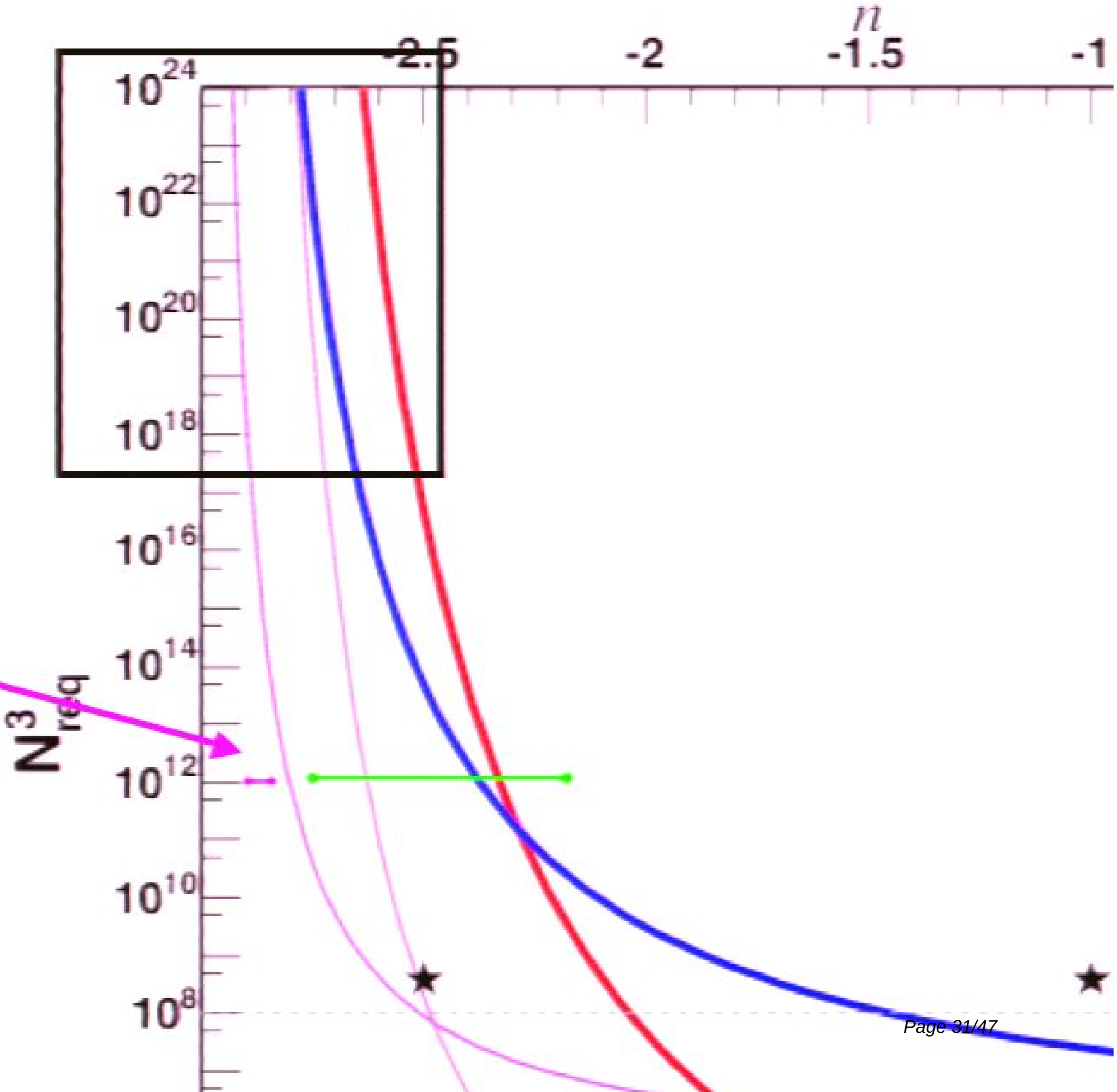


Slippery Slope to n→-3

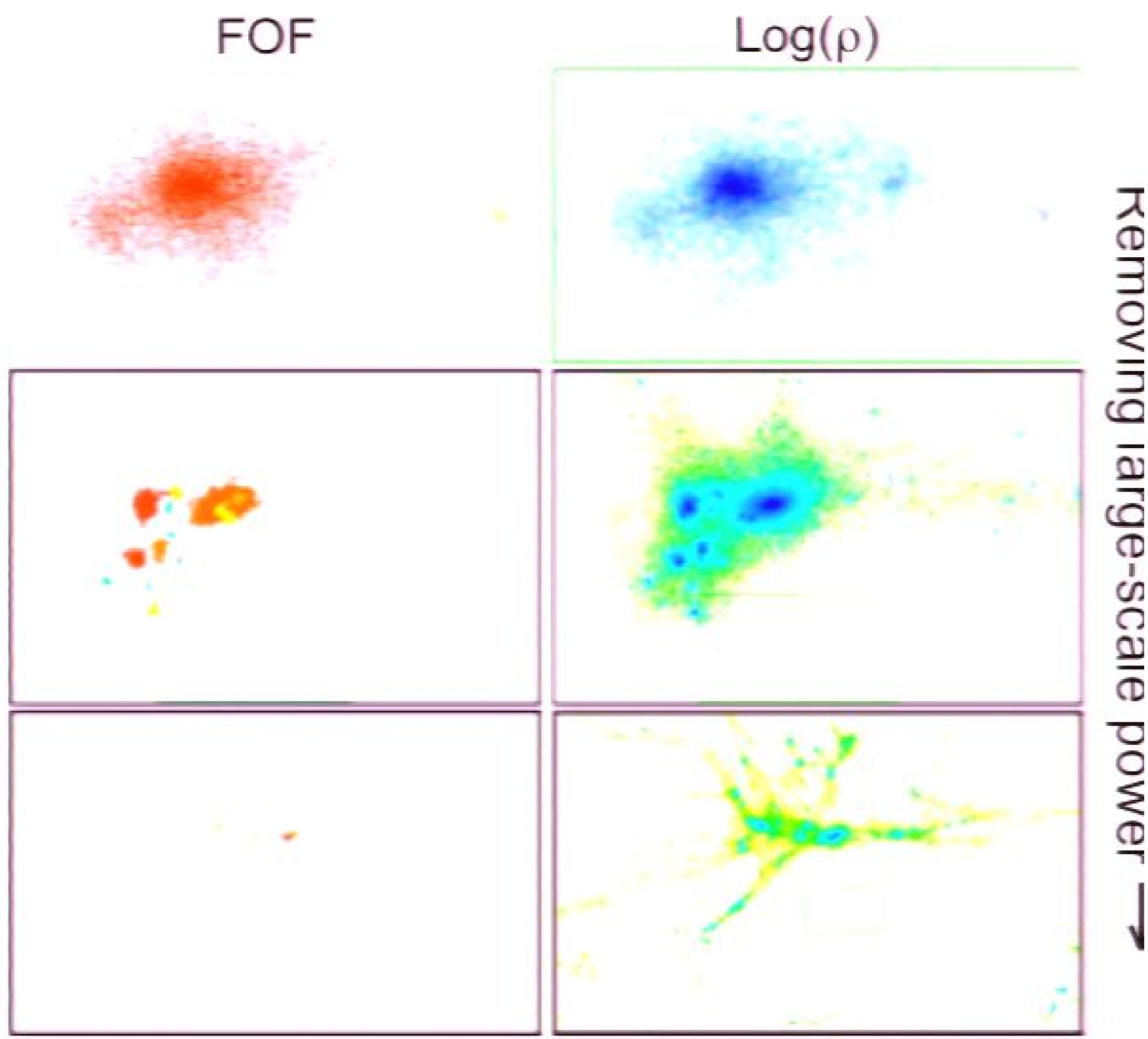
Very Tricky to do small steep simulations

SUSY simulation does not meet even poor criteria



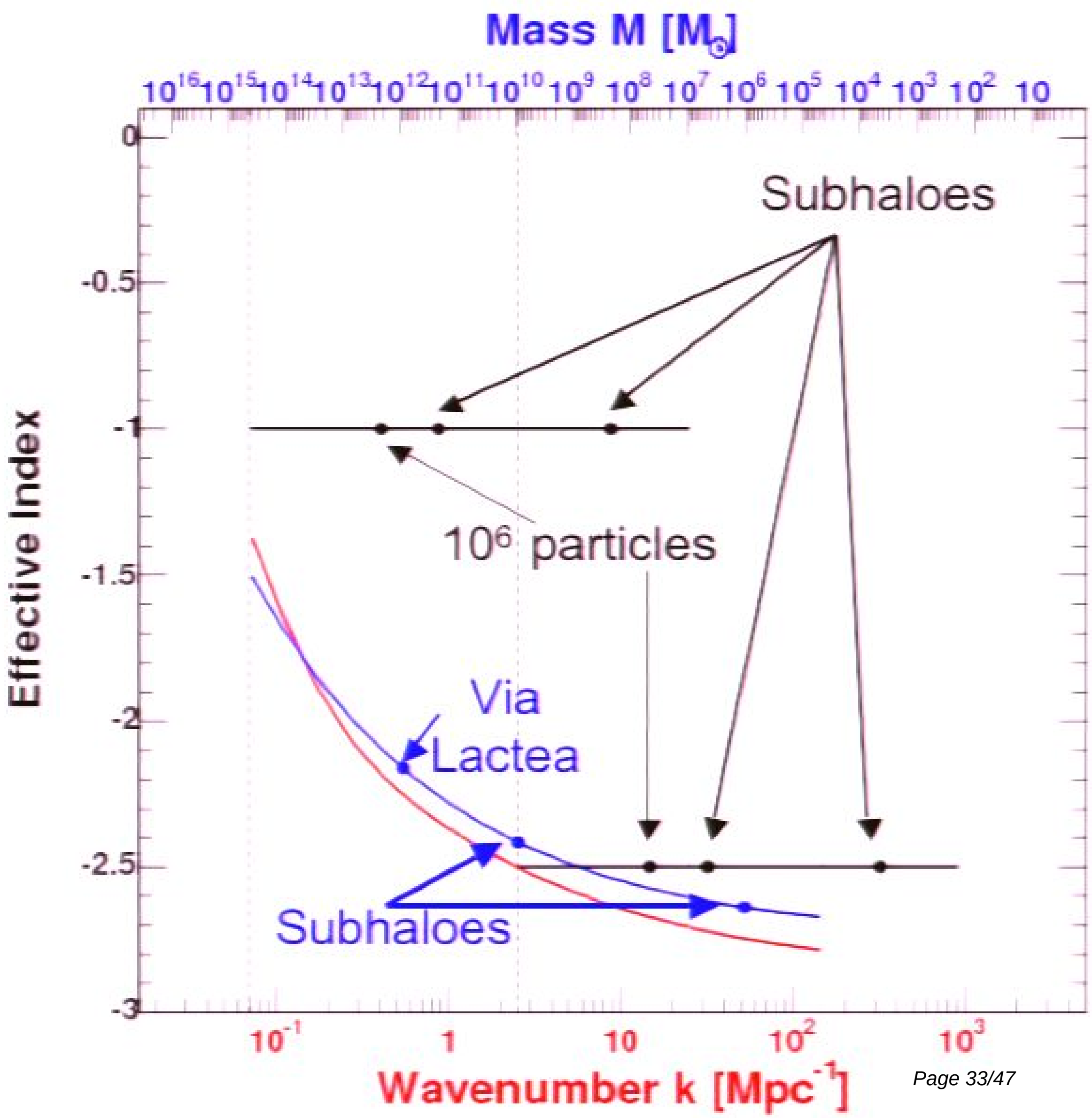
How wrong can it be? Case of n=-2.9

- n=-2.9, $N^3=512^3$, 3 sims with cutoff in P(k) at L_b, $L_b/2$, $L_b/4$
  - Note sims already "wrong", too much missing variance (N_{req} enormous)
- Increasing missing variance
  1. Pushes formation time forward
  2. More haloes → more subhaloes(?)

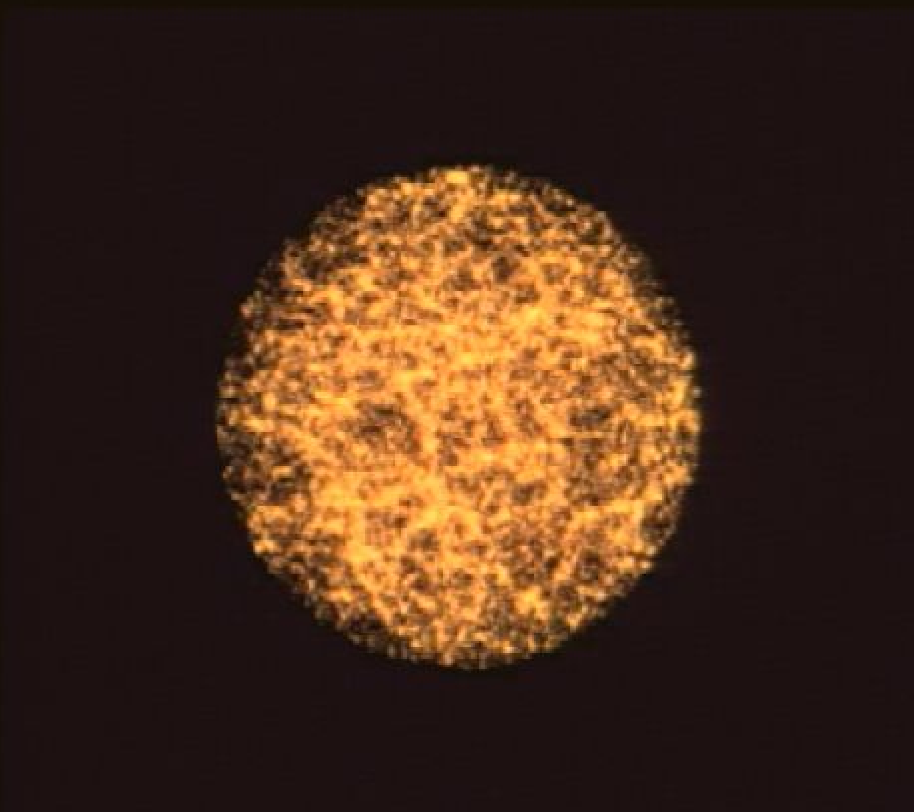


Numerical Experiments

- Scale-Free, Einstein-de Sitter ($P(k)=Ak^n$), n=[-1, -2.5], $N^3=720^3$
- Why Scale-Free?
  1. Simple, "know" form of answer ahead of time (self-similar scaling).
  2. Separate merger/accretion physics from IC.
  3. Model specific scales in CDM hierarchy. (e.g. Knollmann, Power & Knebe 2008)



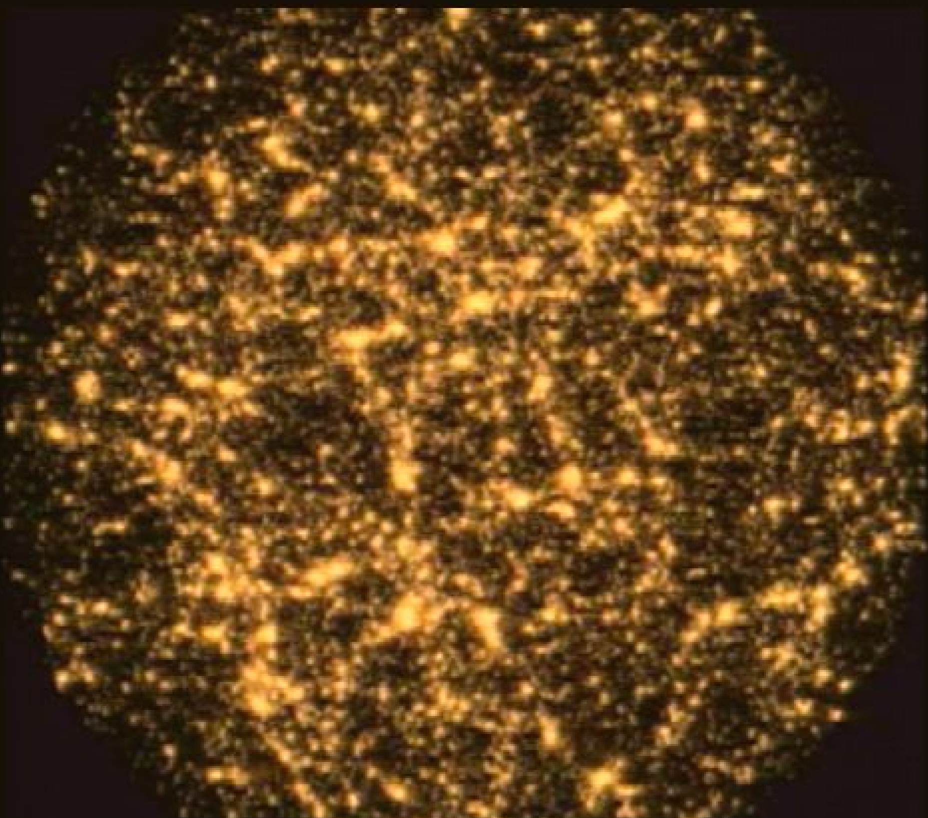
Scale-Free Simulations



n=-1: index corresponds
> galaxy cluster masses

n=-2.5: corresponds to dwarf
galaxy or smaller

Scale-Free Simulations



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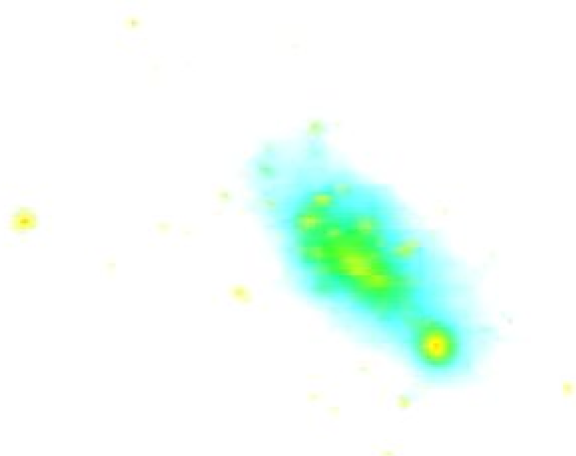
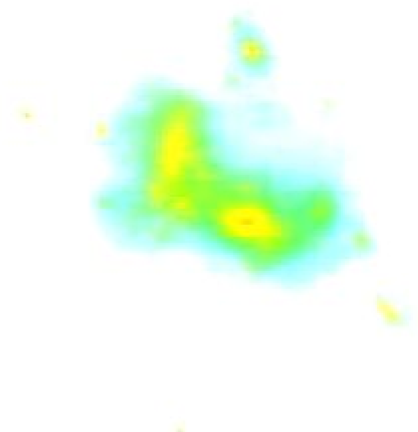
Searching for (Sub)Haloes

- Search for candidate (sub)haloes using Friends-of-Friends (3DFOF) and 6DFOF.
  - 3DFOF: $\frac{(\mathbf{x}_1 - \mathbf{x}_2)^2}{l_{\mathrm{h}}^2 (L_{\mathrm{b}}/N)^2} < 1$
  - 6DFOF: $\frac{(\mathbf{x}_1 - \mathbf{x}_2)^2}{l_{\mathrm{s}}^2 (L_{\mathrm{b}}/N)^2} + \frac{(\mathbf{v}_1 - \mathbf{v}_2)^2}{b_{\mathrm{v}}^2 v_{\mathrm{h}}^2} < 1, \; v_{\mathrm{h}}^2 = \frac{GM}{R}$
- Halo: l_h=0.2
- Subhalo: 3DFOF l_s<0.2.
  6DFOF uses halos to calculate v_h, l_s=0.1 & b_v=[0.05,0.10,0.20].
- ***UNBIND***

Halos & Subhalos

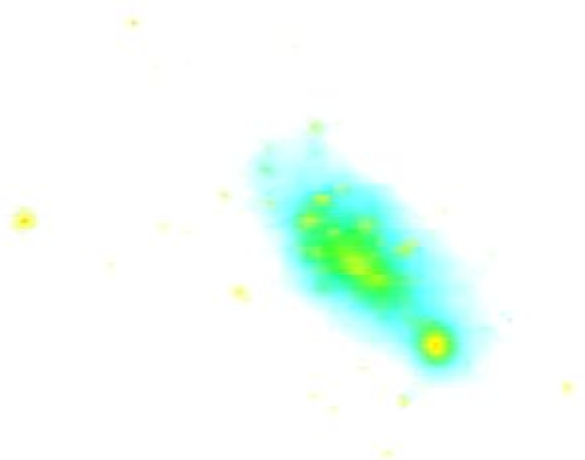


n=-1



n=-2.5

Halos & Subhalos



n=-1

n=-2.5

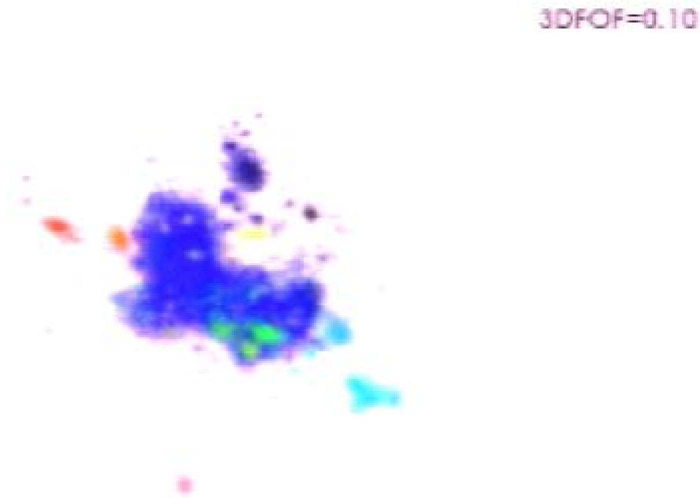
3DFOF vs 6DFOF

n=-1: 3DFOF/density info ok.

n=-2.5: Substructure not as noticeable from density, need full phase-space.

3DFOF vs 6DFOF

n=-1: 3DFOF/density info ok.



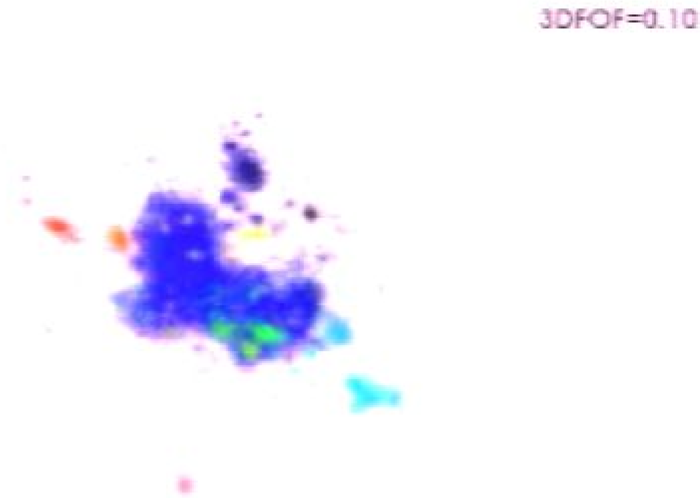
n=-2.5: Substructure not as noticeable from density, need full phase-space.

3DFOF vs 6DFOF

n=-1: 3DFOF/density info ok.

n=-2.5: Substructure not as noticeable from density, need full phase-space.

3DFOF vs 6DFOF



n=-1: 3DFOF/density info ok.

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3DFOF vs 6DFOF

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Summary

Very Tricky to get the simulations right at steep indices (high redshifts).

- Worry about missing power
- Must unbind.

Sims suggest **self-similarity cannot naively save us**, as ***n*→-3**:

- Less substructure
- Morphologically different, poorly defined boundary. Loosely bound streams, better for direct detection.
- Subhalo mass function logarithmic slope shallower, α ~-0.8 compared to -0.9. How sensitive is it?