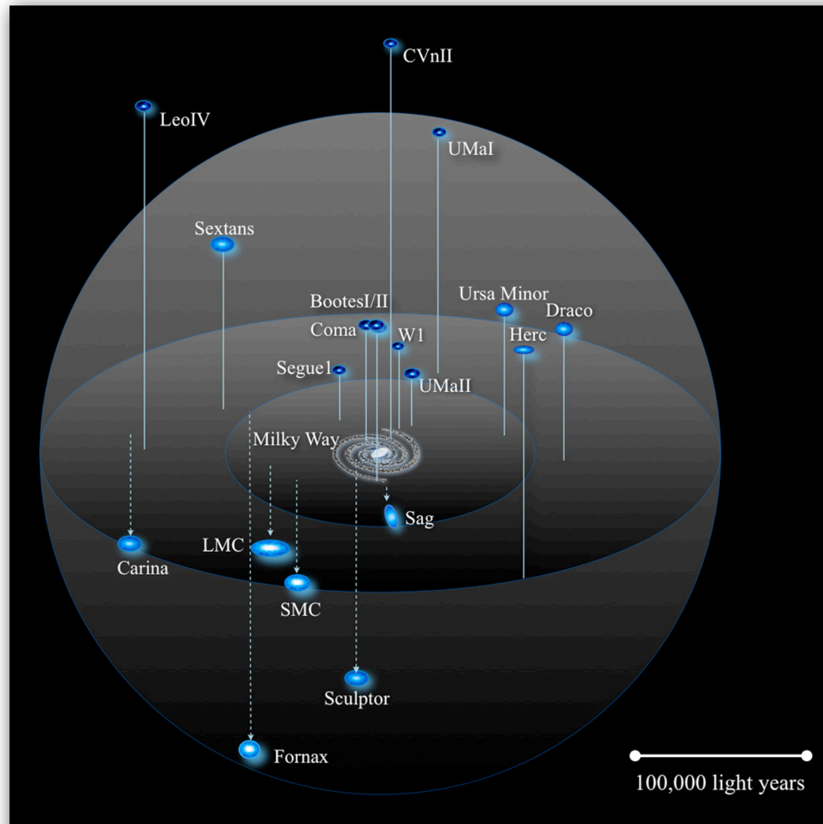
CDM and the Substructure Crisis

J. S. Bullock
XX Canary Islands Winter School, LG Cosmology

Theory: $N>10^{10}$



Observation: N~20

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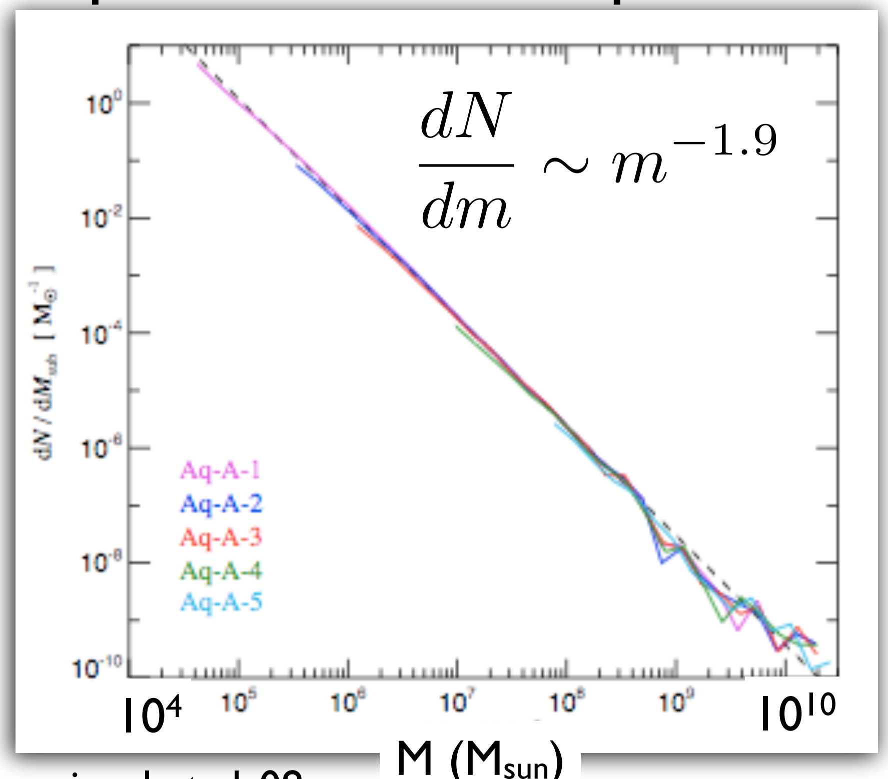
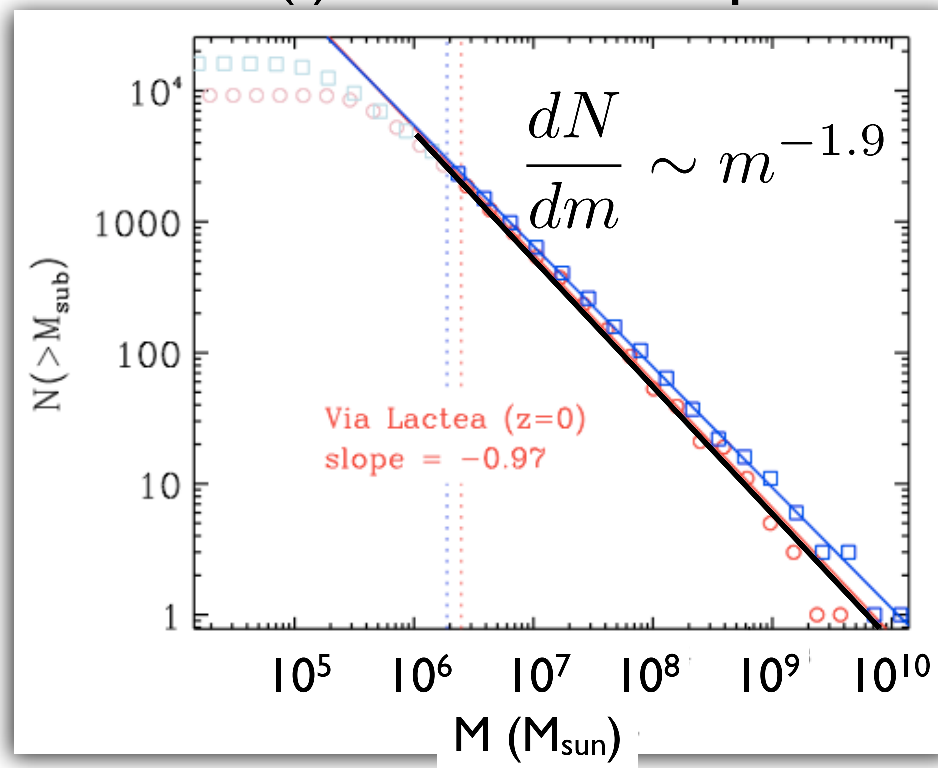
Lecture 2: Subhalo Redux

aquarius: 1.5 billion particles



springel et al. 08

via lactea(I) : 250 million particles



diemand et al. 07; madau et al. 08

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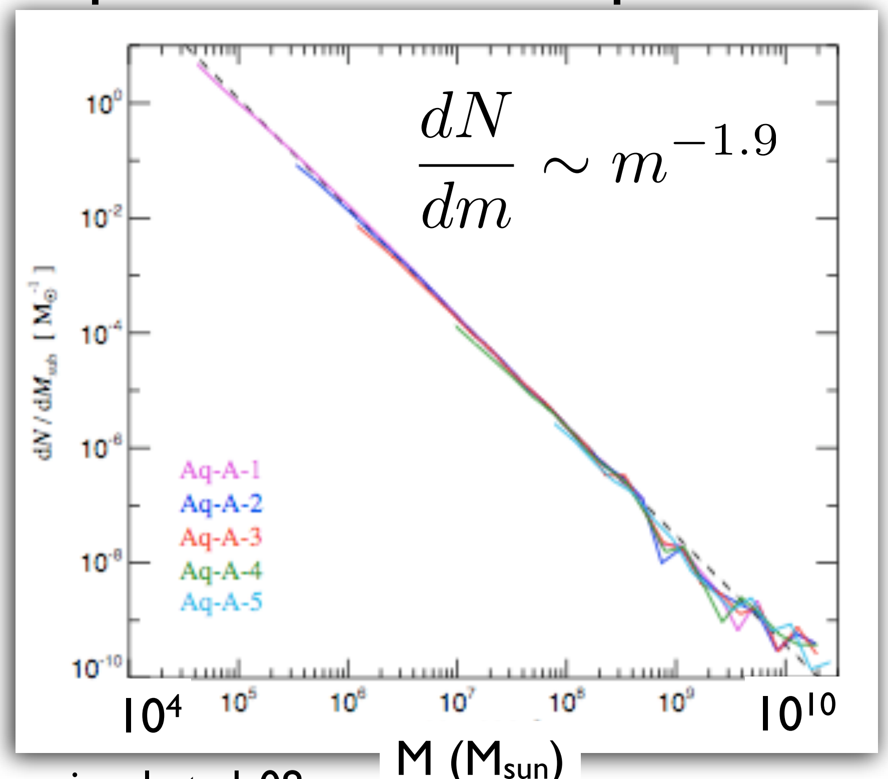

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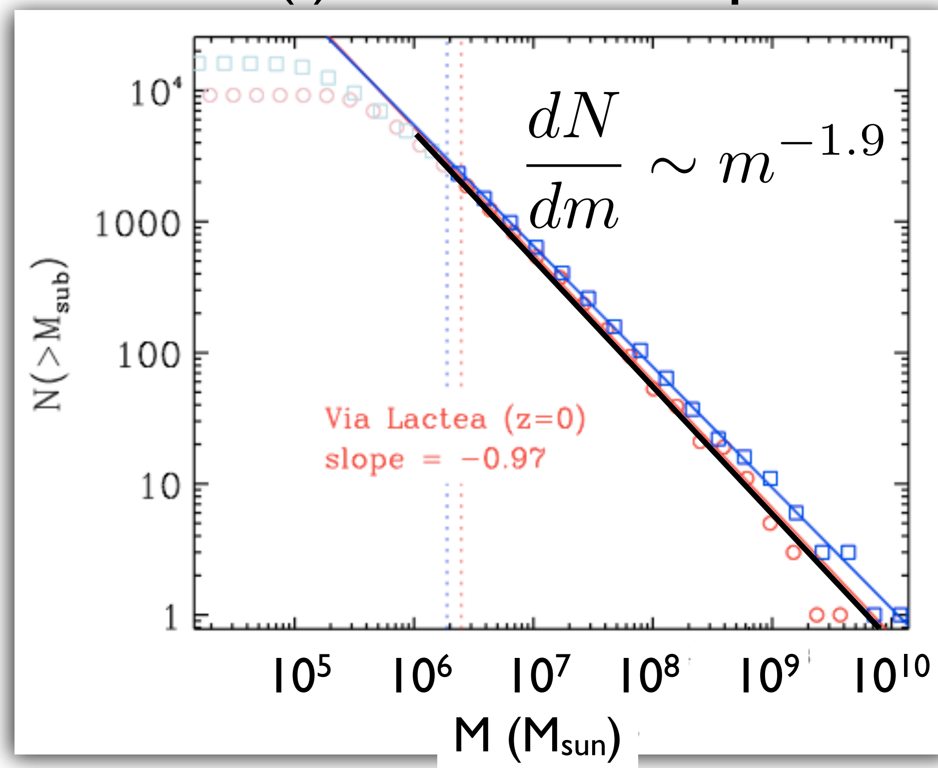

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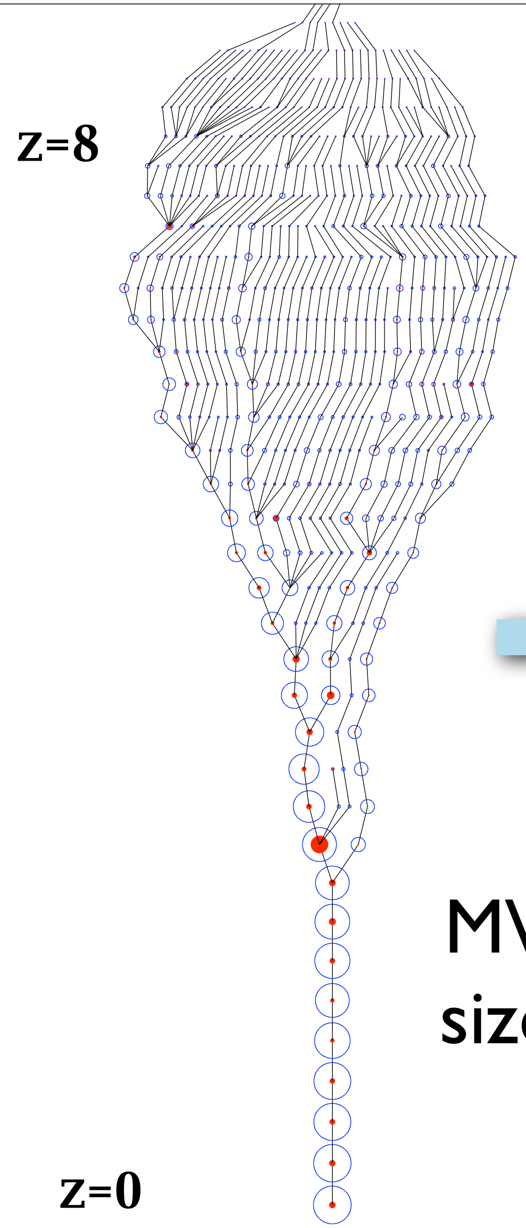
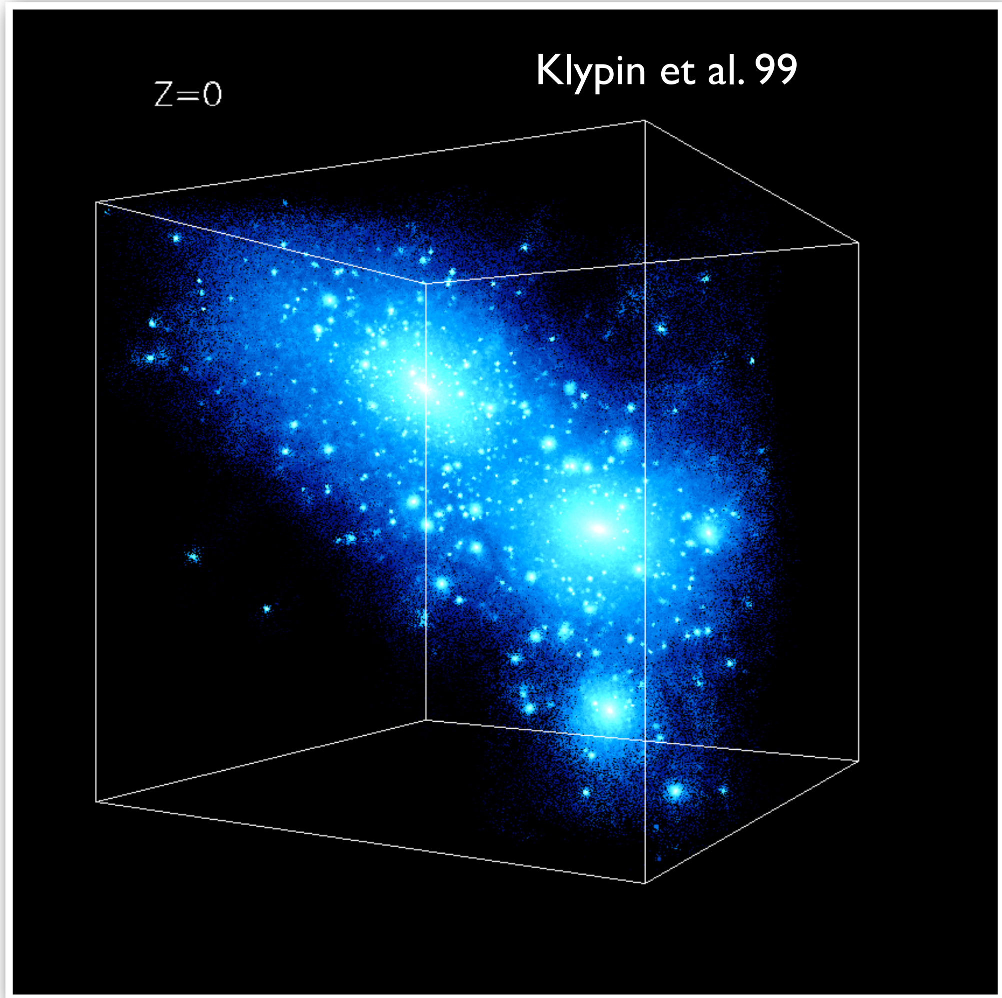
Surviving Substructure is abundant



MW / M31
size system



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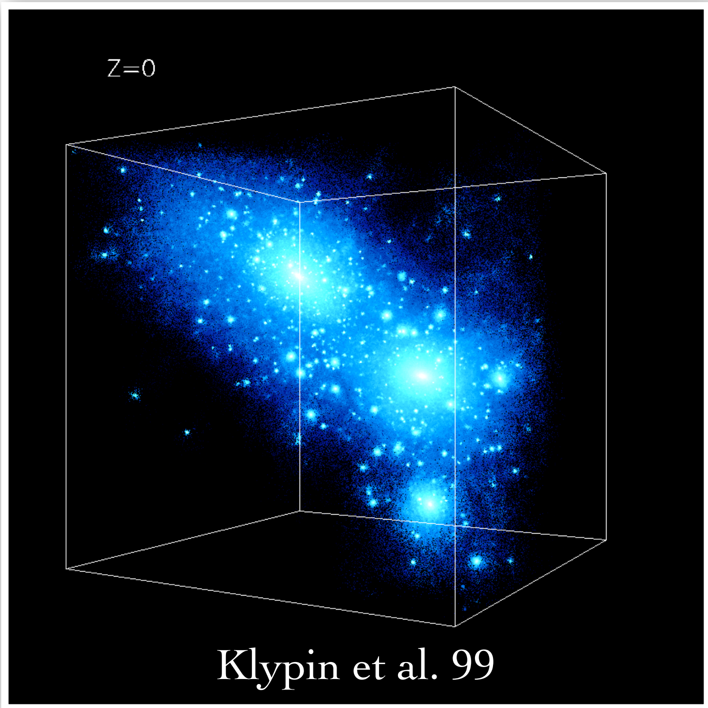

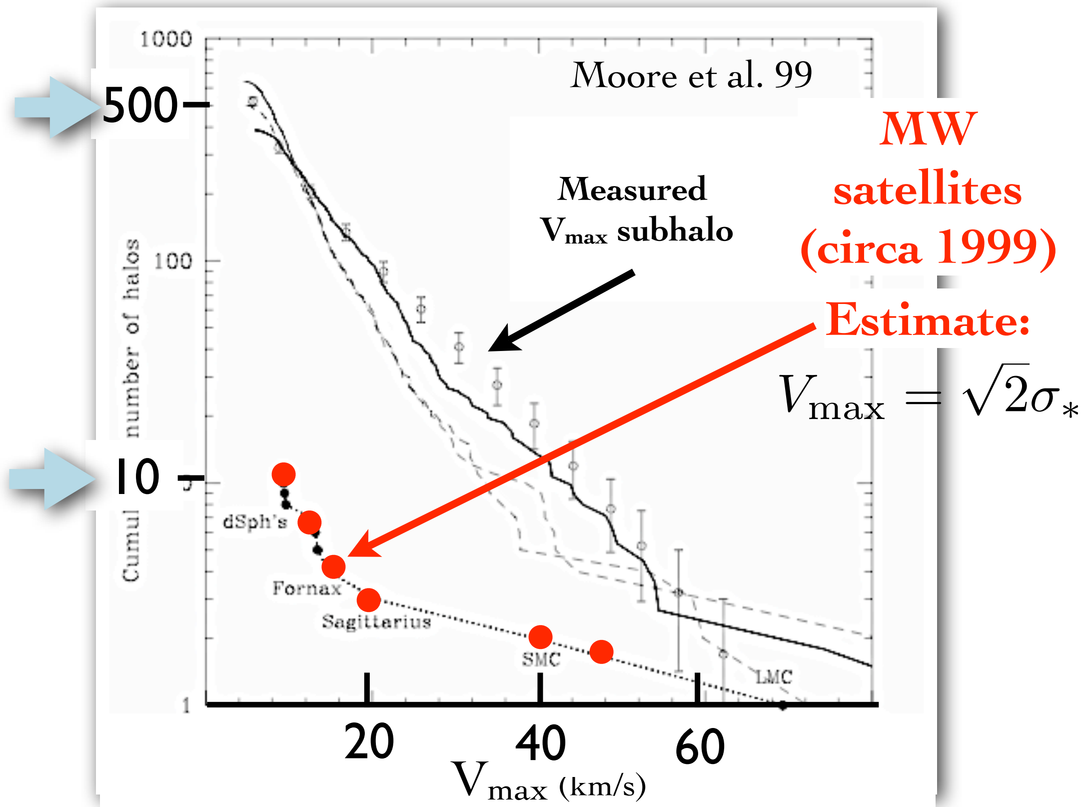

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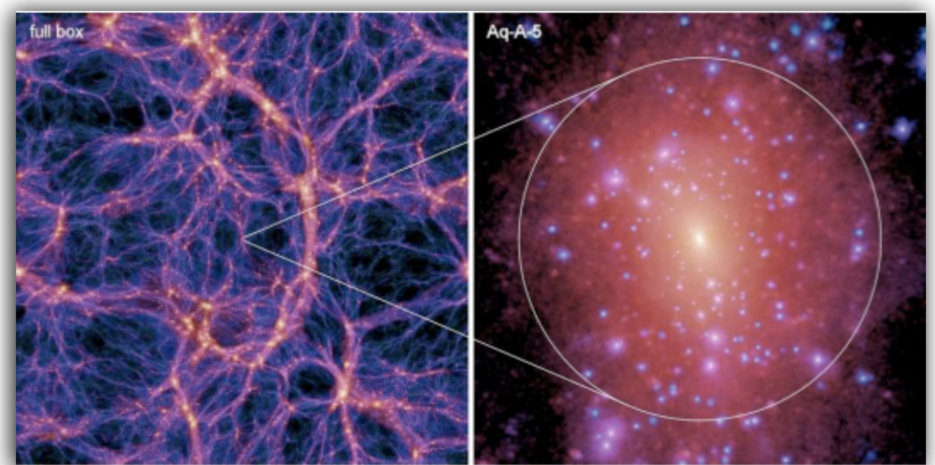
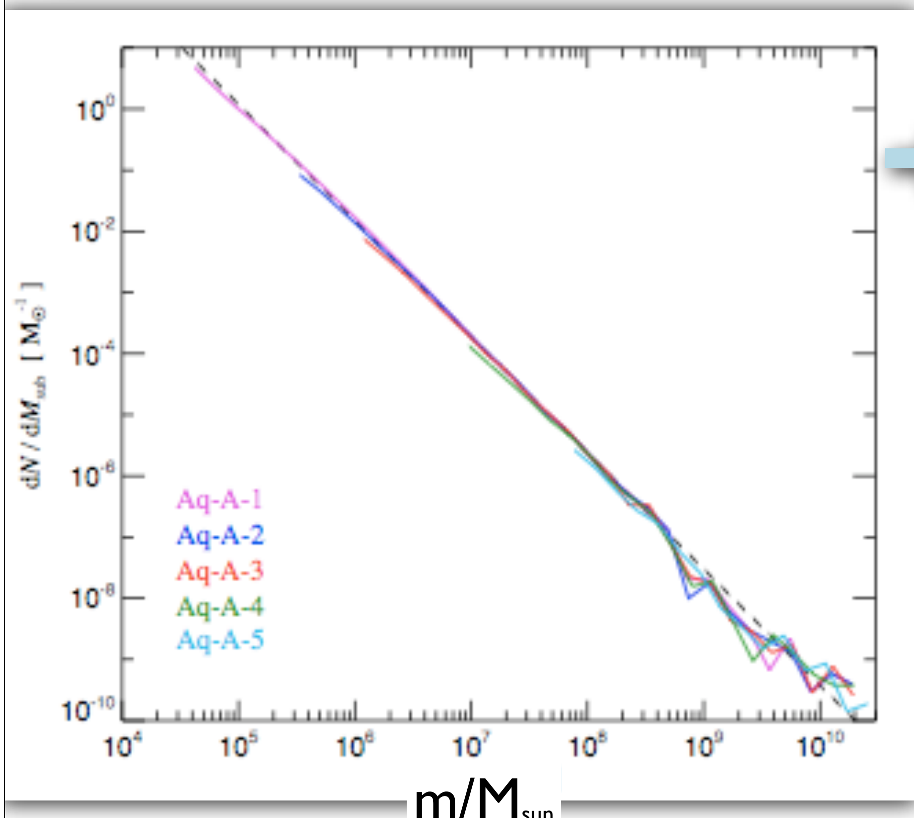
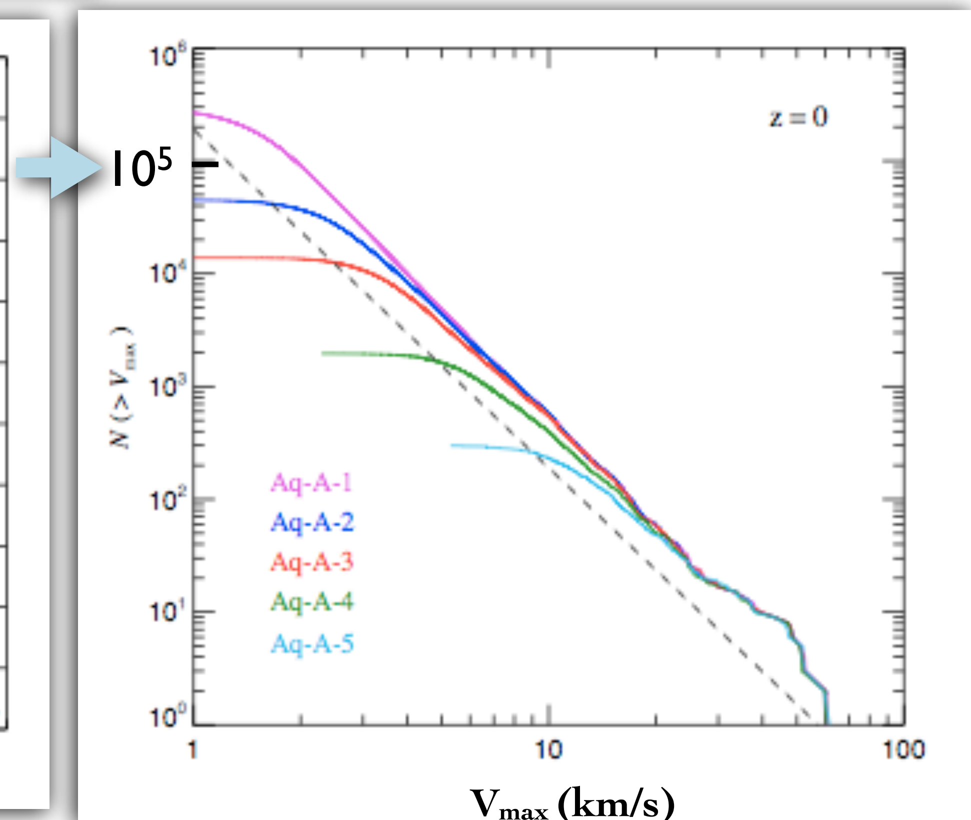


Aquarius MW simulation
Springel et al. 08
1.5 billion particles w/in 430kpc
m_p~1000 M_{sun}





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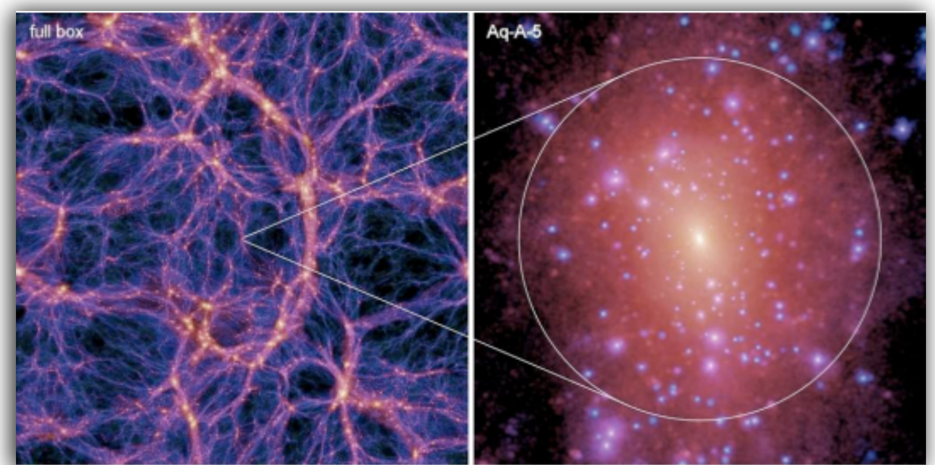

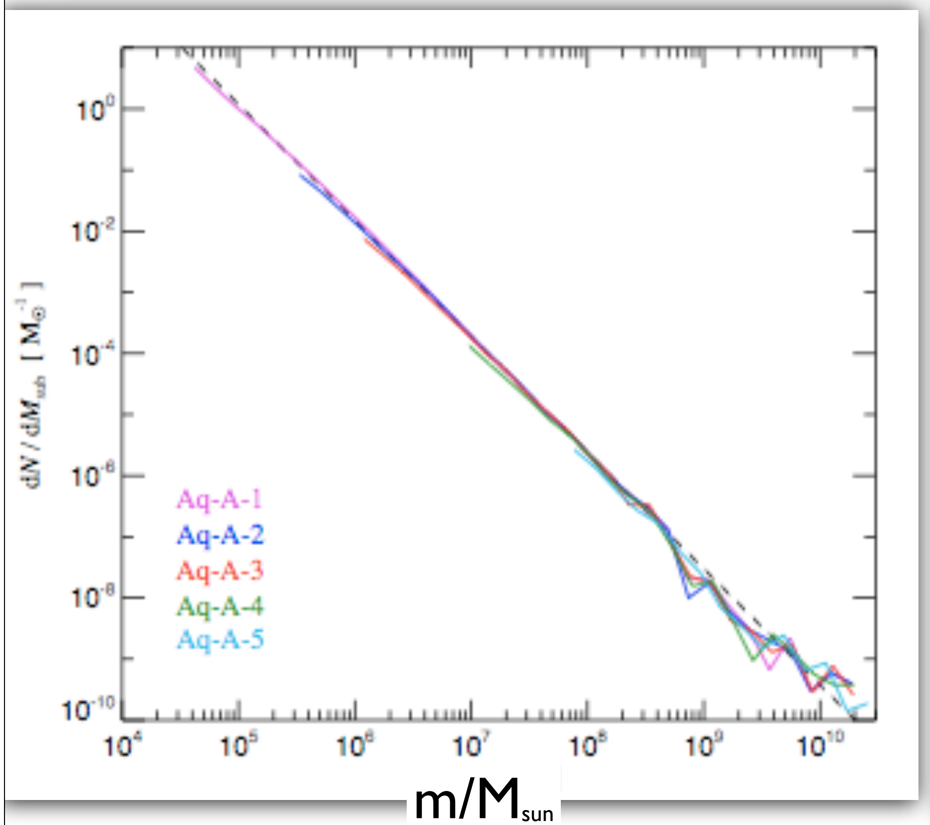

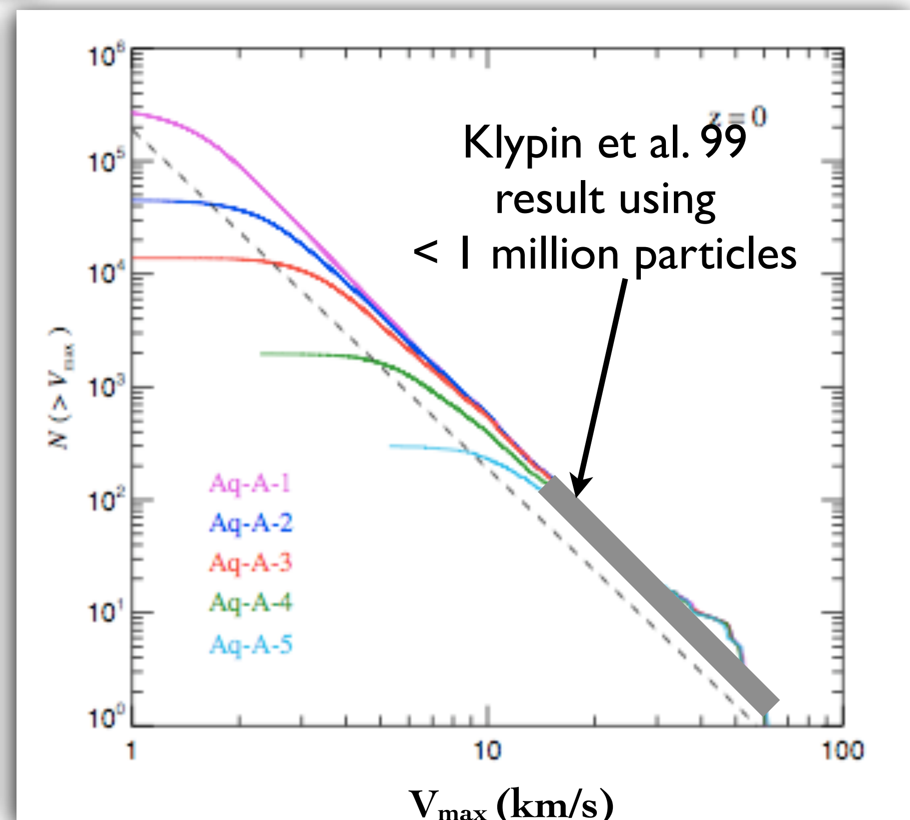

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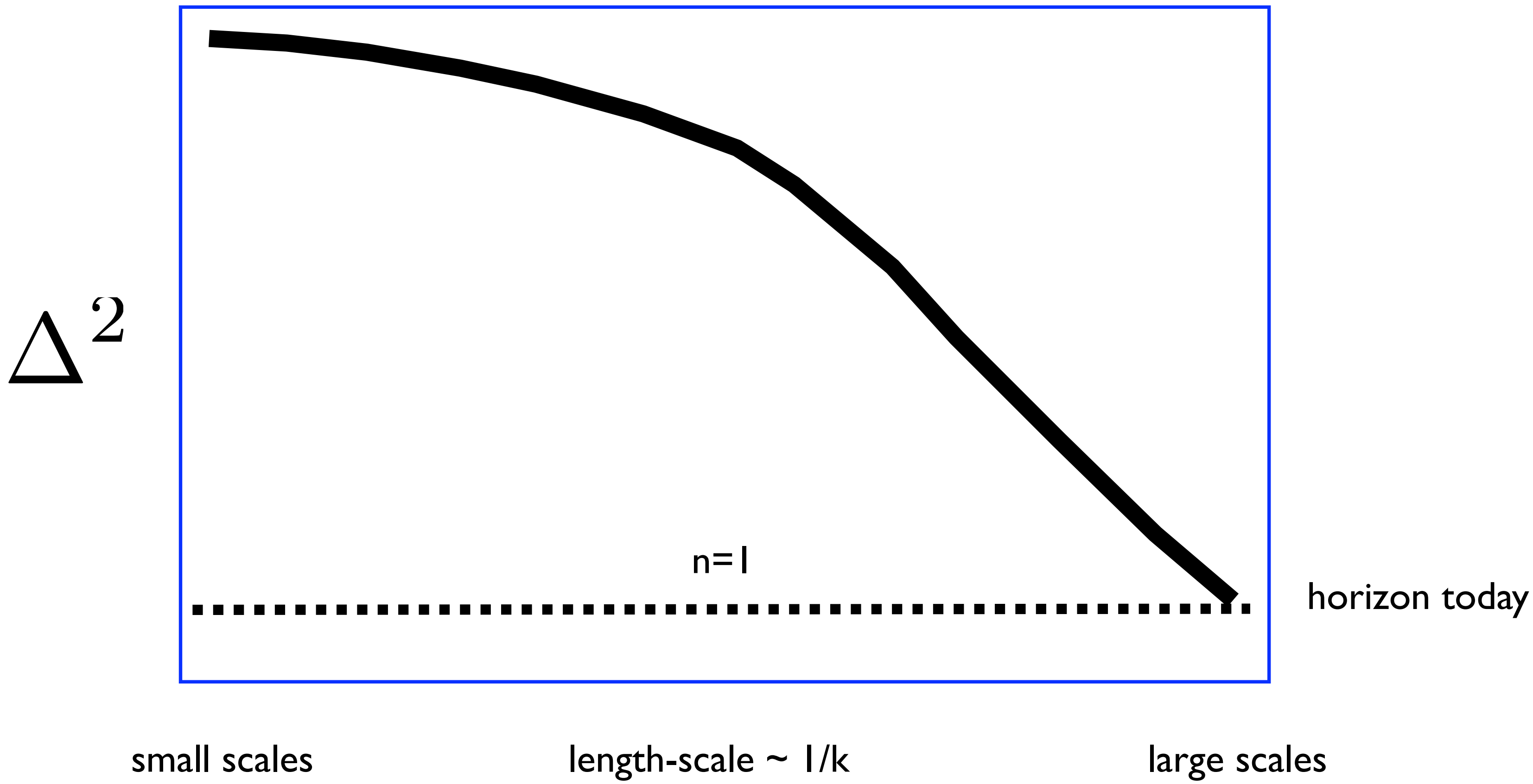
How might we change this story?



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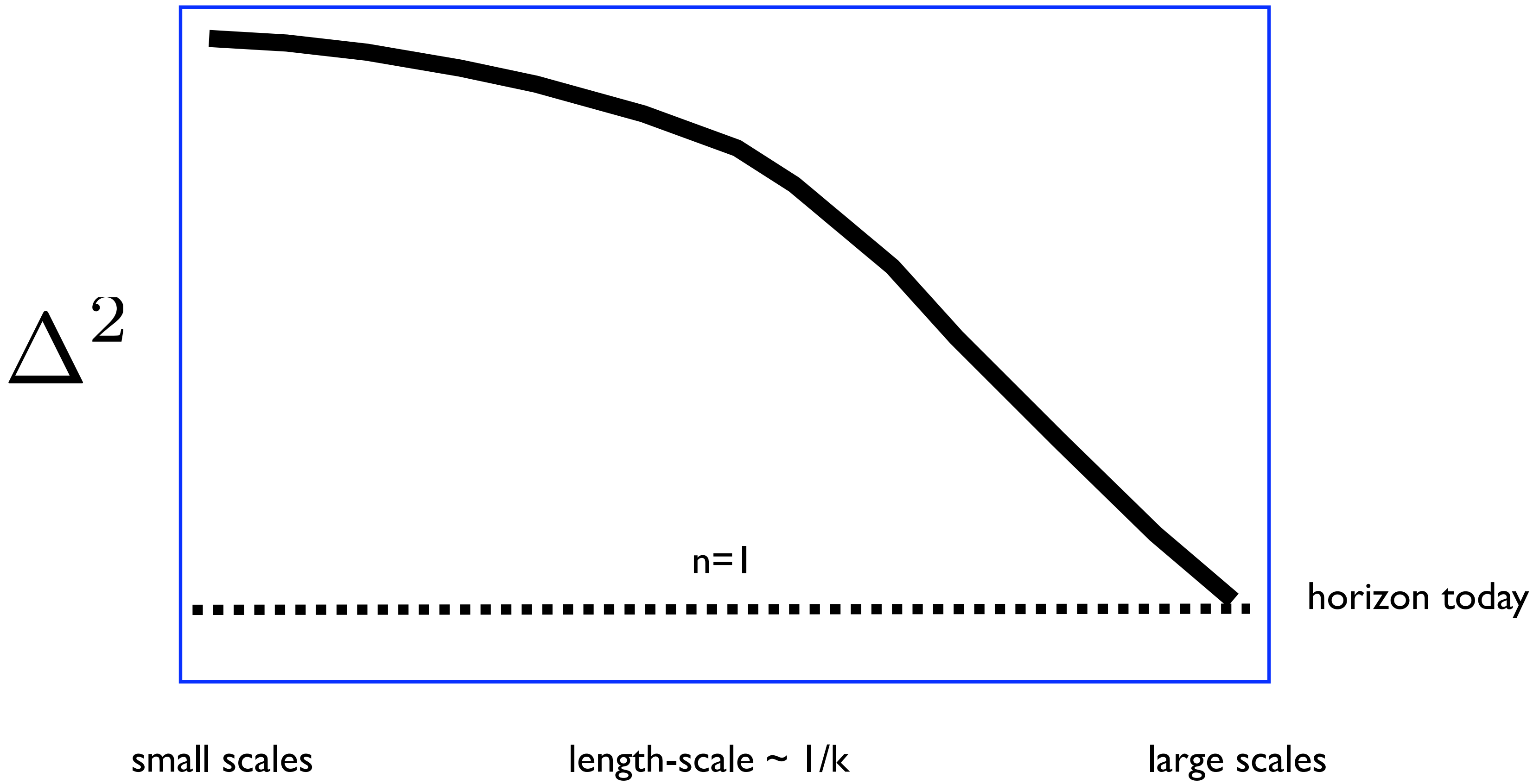
How might we change this story?

Change inflationary power spectrum



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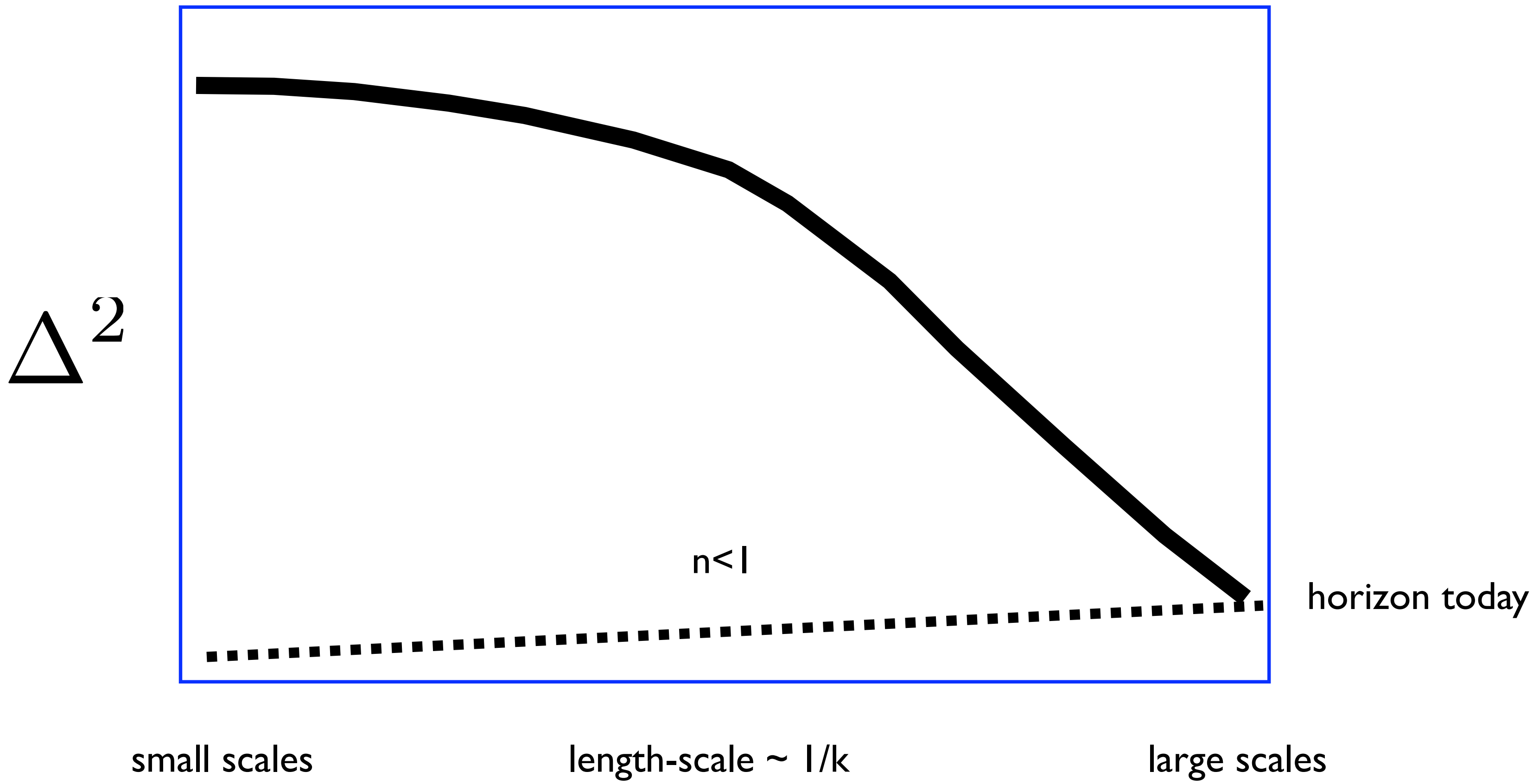
tilt n<1: less power on small scales



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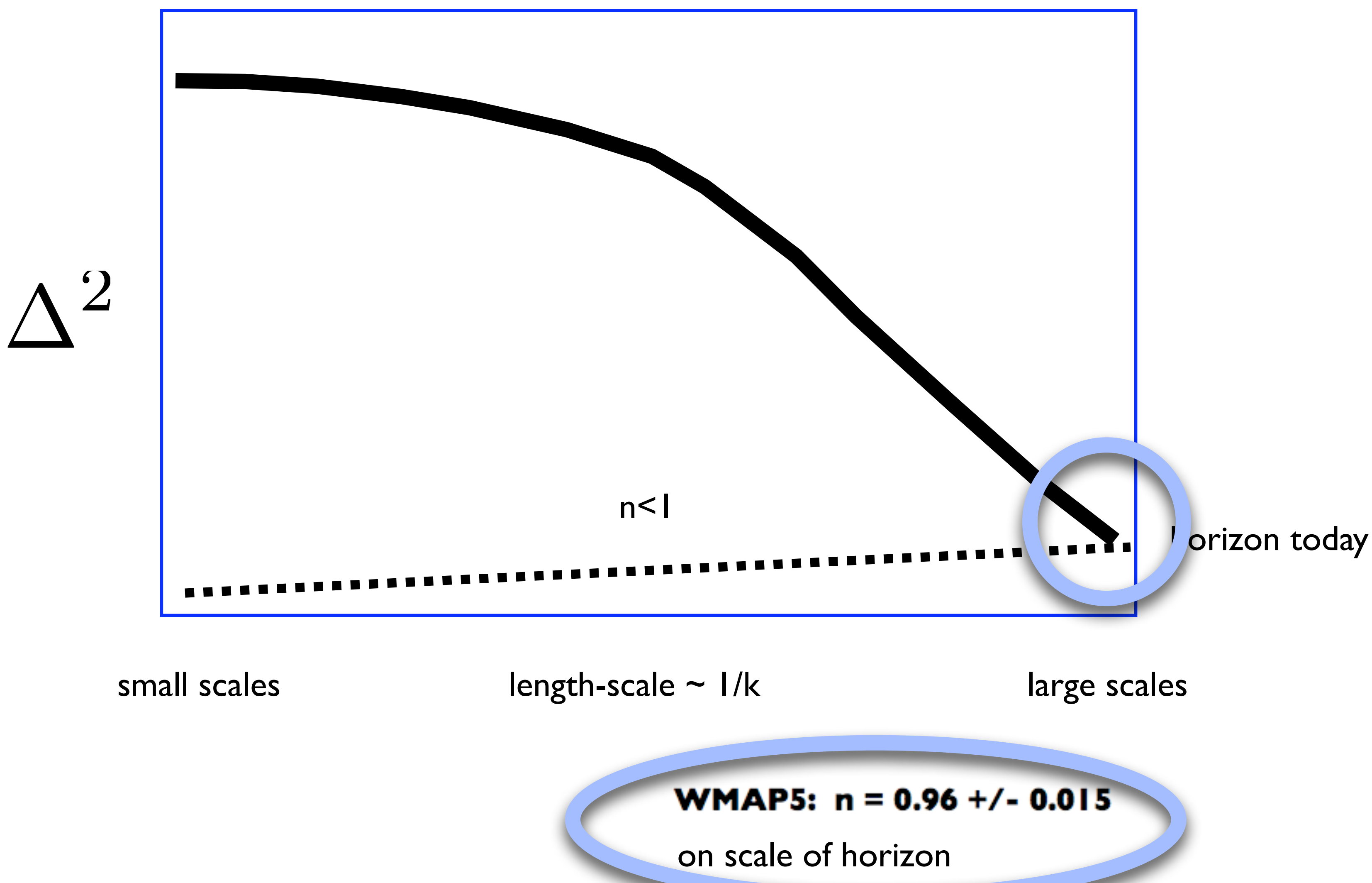

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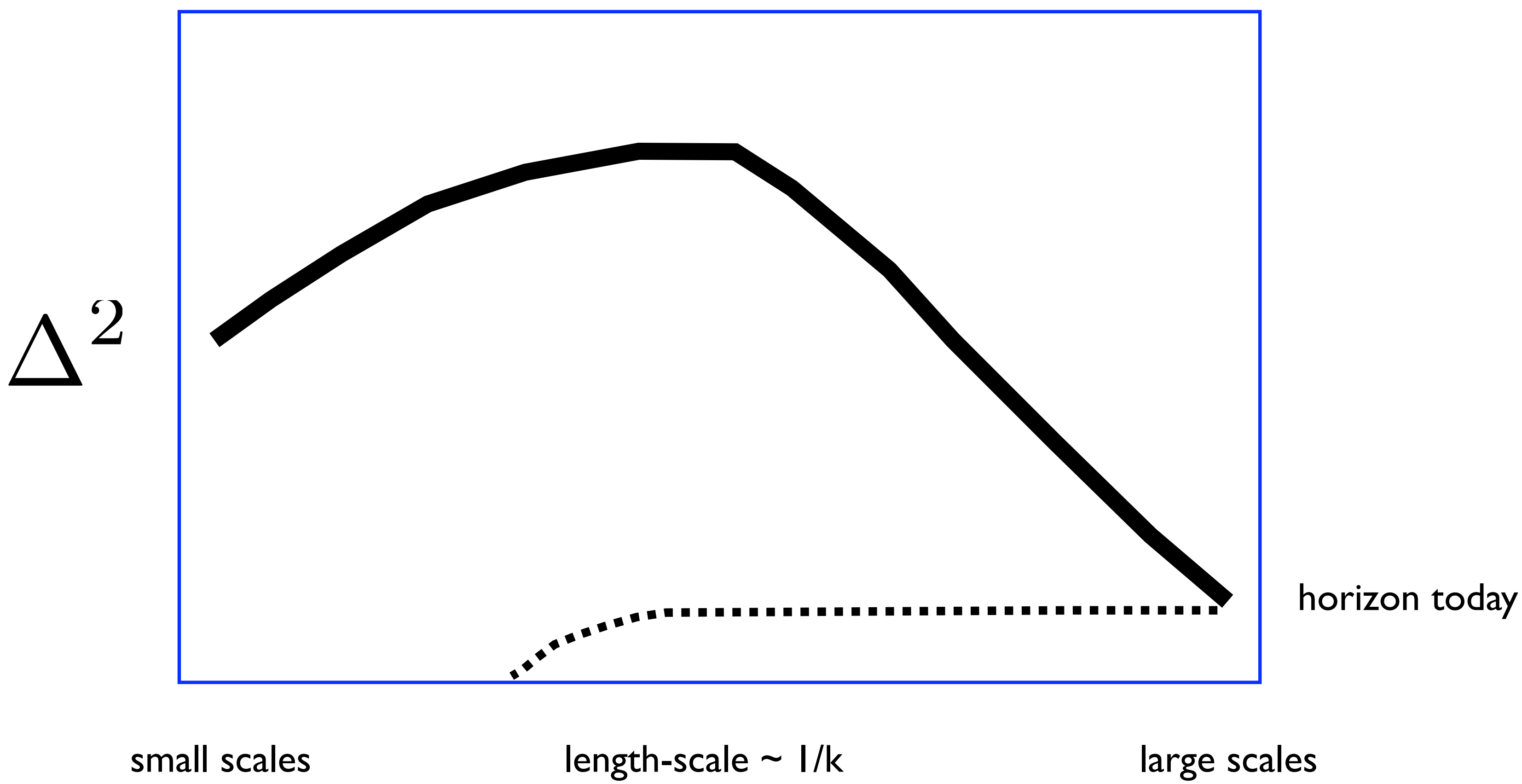
running tilt - curved primordial P(k)



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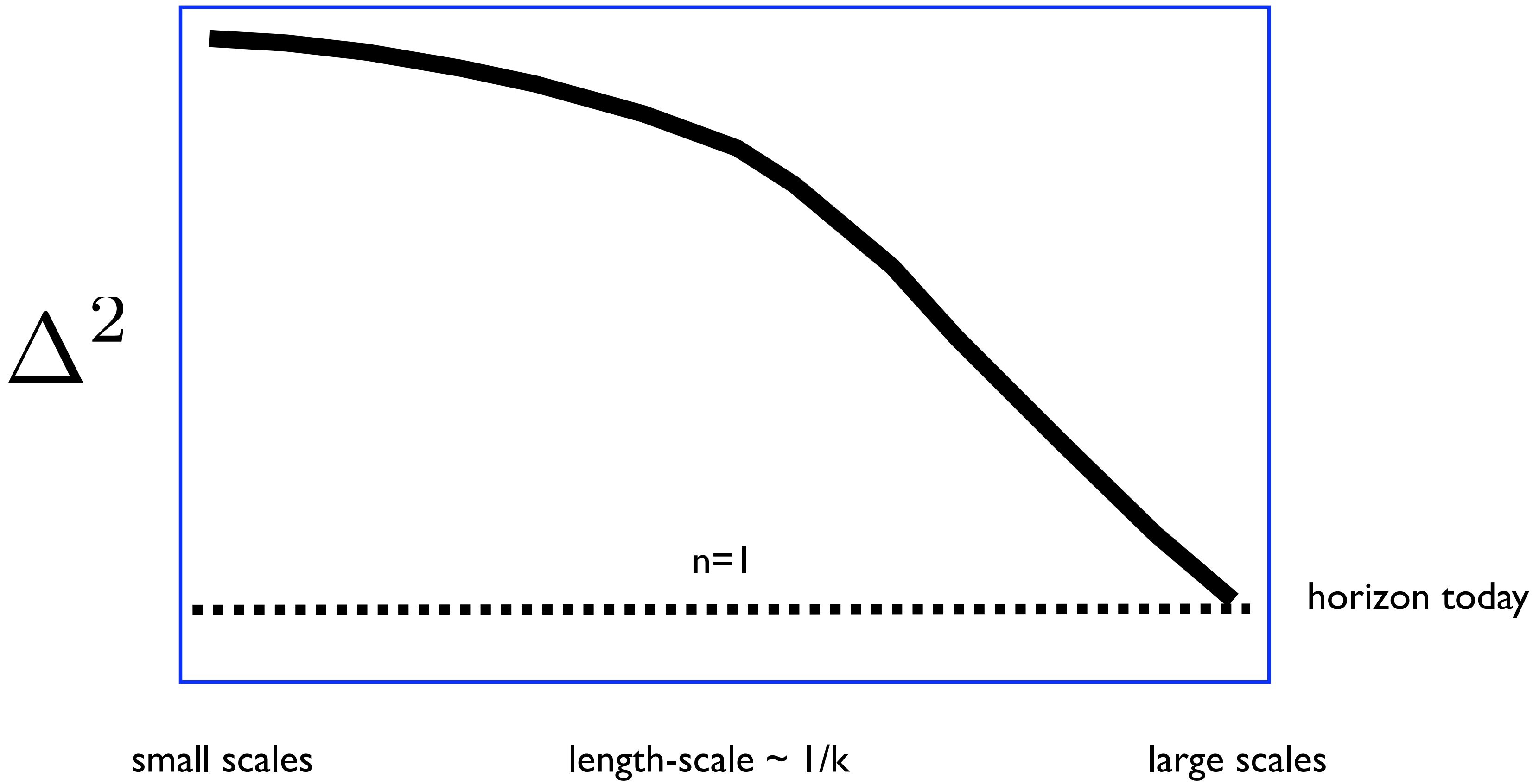
How else could clustering be different?

or... put a scale in the dark matter clustering



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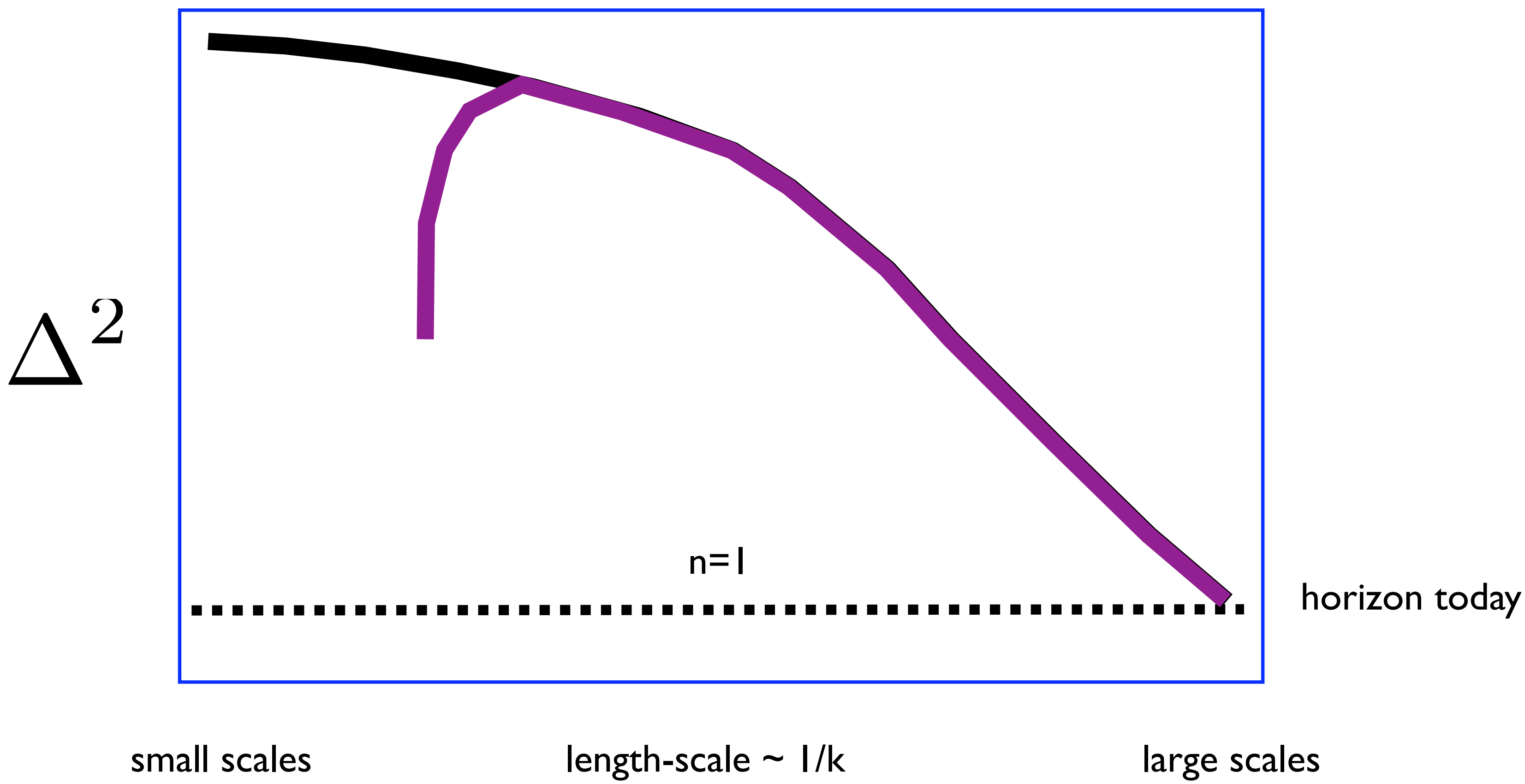
A scale in DM clustering

Example: **Free Streaming**
light DM particles stay relativistic a long time ->
'free stream' out of small primordial fluctuations.

$$\lambda_{FS} \simeq \int \frac{v(a)}{a}\, dt$$



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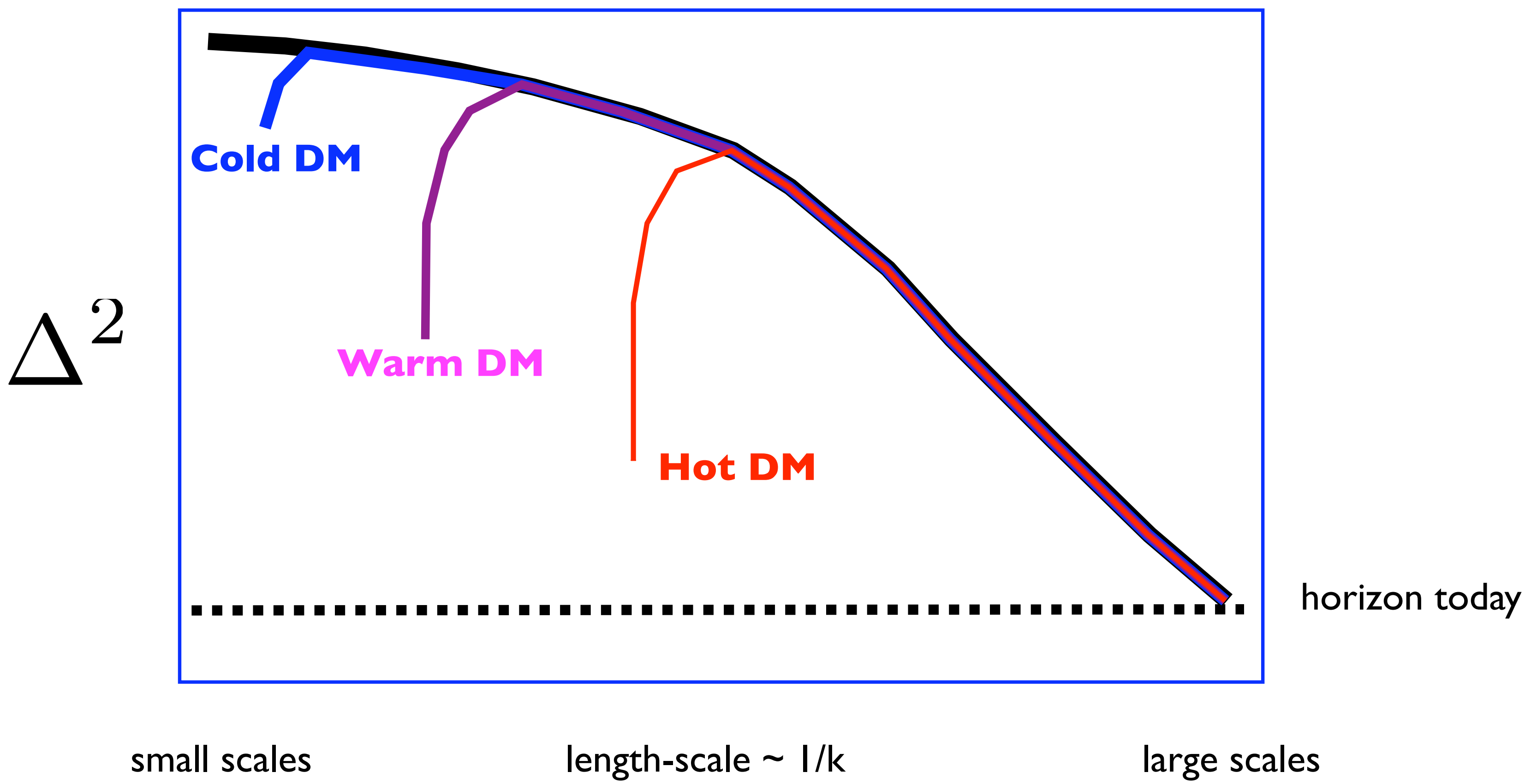

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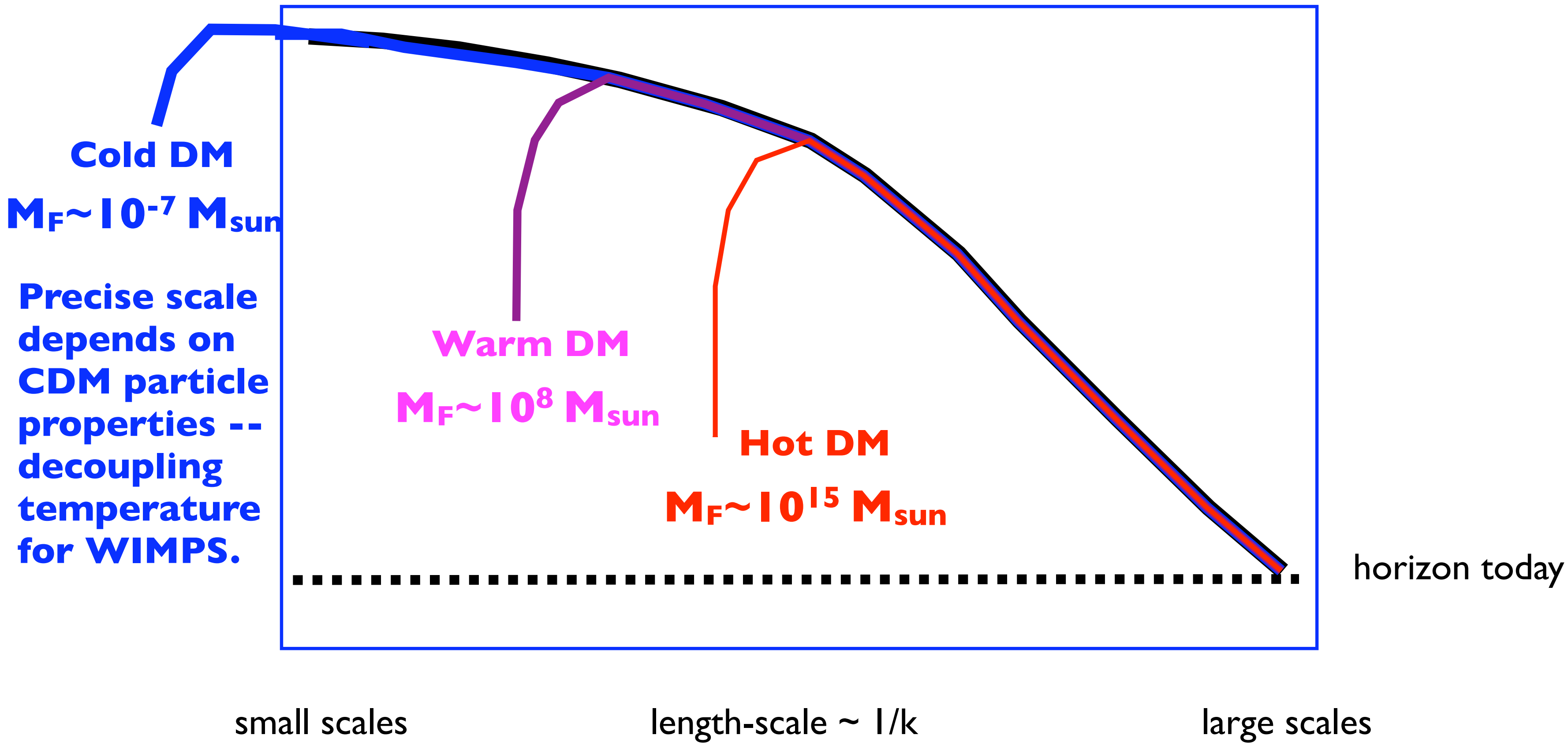
A scale in DM clustering

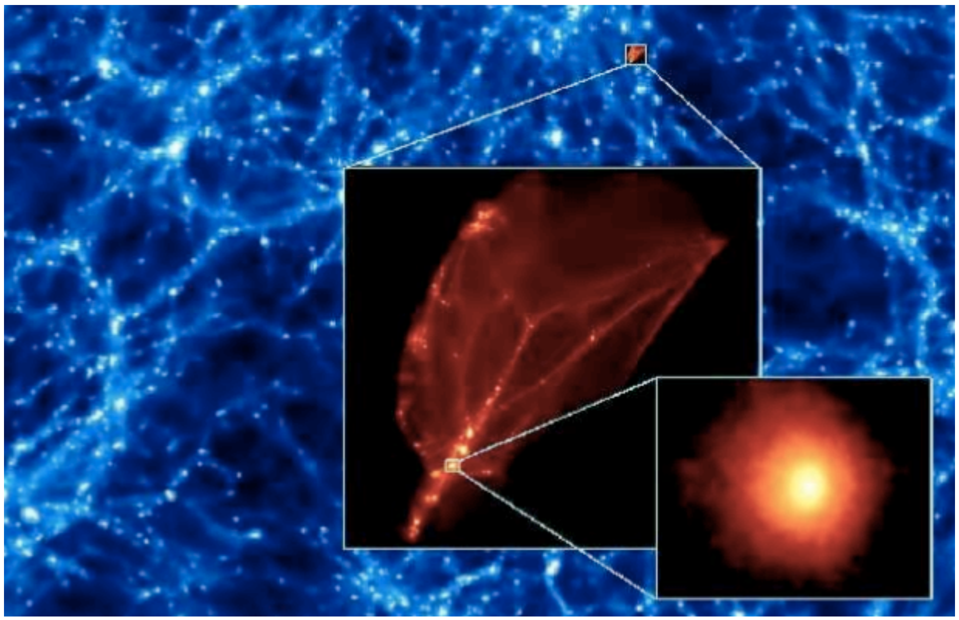
Filtering Mass: $M_F \simeq \lambda_F^3 \rho$

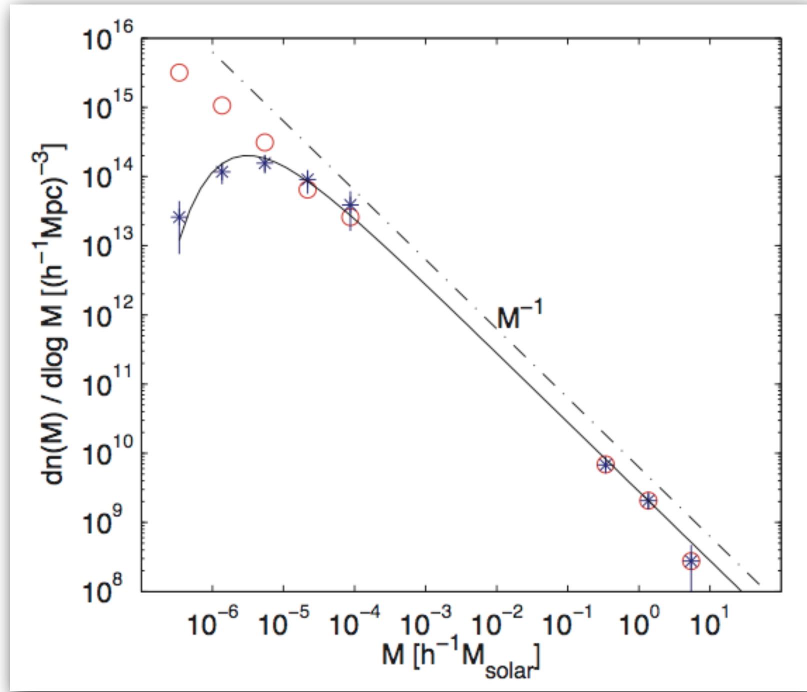


NOTE: for popular CDM models, filtering is driven by early accoustic oscillations not free streaming, but it scales in a similar way as FS (Loeb & Zaldarriaga 06)

https://webfiles.uci.edu/bullock/Public/Canary2008/

Diemand et al. 05 Recovered a break the DM halo mass spectrum in CDM corresponding the Filtering mass for one particular model P(k)





use multiscale technique to resolve
a tiny volume at very high redshift
z~30, box ~ 60pc

https://webfiles.uci.edu/bullock/Public/Canary2008/

Minimum Mass Halo for CMSSM ~ 10^{-6}-10^{-7} M_{sun}

'constrained' Minimal Supersymmetric Standard Model *

$$M_F \simeq 10^{-6} M_\odot \left(\frac{T_{kd}}{10 MeV} \right)^{-3}$$

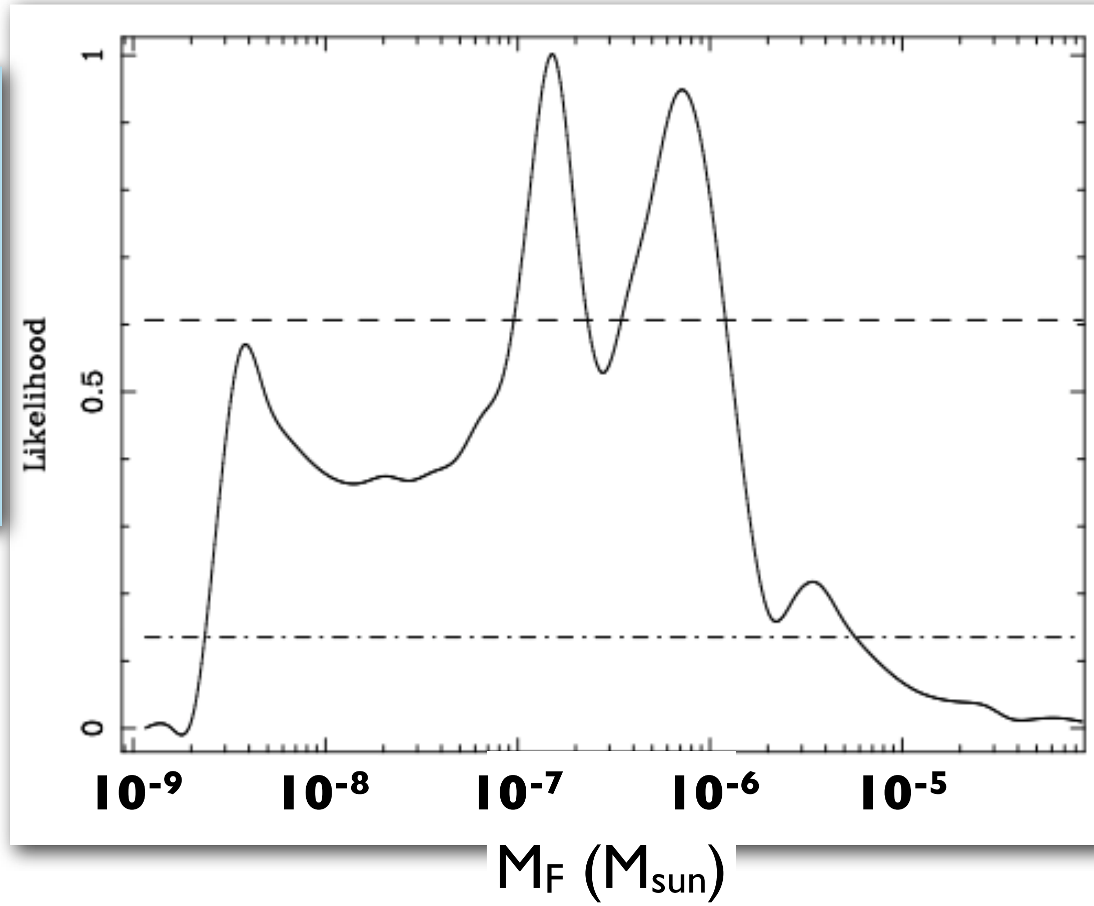
Greg Martinez et al. 2008

Filtering mass is set by T_{kd}:
-later dm decouples, the larger the filtering mass.

Kinetic decoupling temperature. Depends on

- **DM particle mass**
- **DM coupling to leptons (e's, neutrinos, taus, mu's)**

See: Loeb & Zaldarriaga 06; Bertschinger 2006

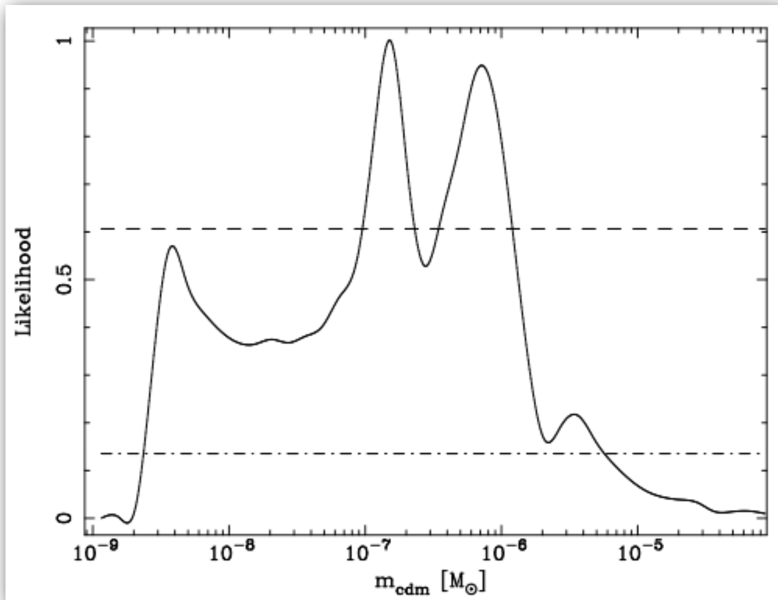


Note: some non-constrained SUSY models produce M_F ~ 1000 M_{sun}
e.g. Profumo et al. 07

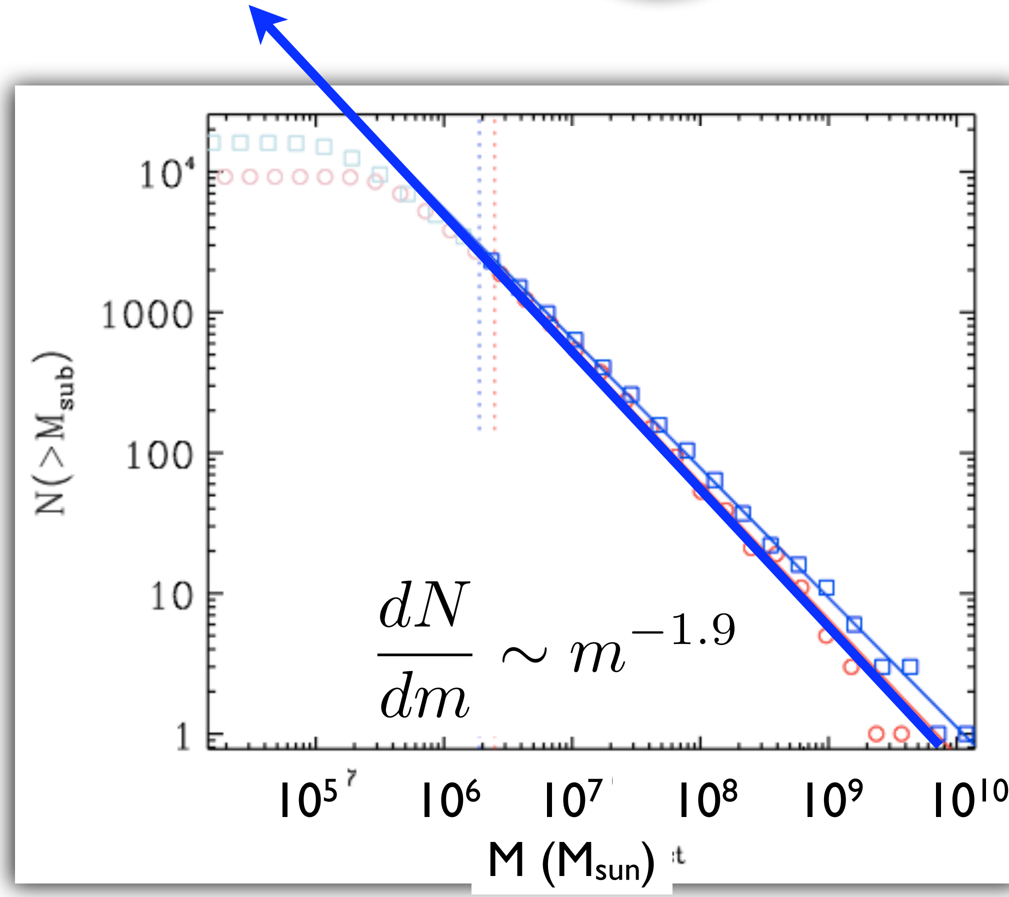
* Generic SUSY (MSSM) introduces over a hundred new parameters. Constained MSSM (CMSSM) requires SUSY parameters to unify at a high energy (GUT-scale), and has only 5 parameters.

Minimum Mass Halo for CMSSM ~ 10^{-7} M_{sun}

$N(>10^{-7}\ M_{sun}) \sim 10^{17}$



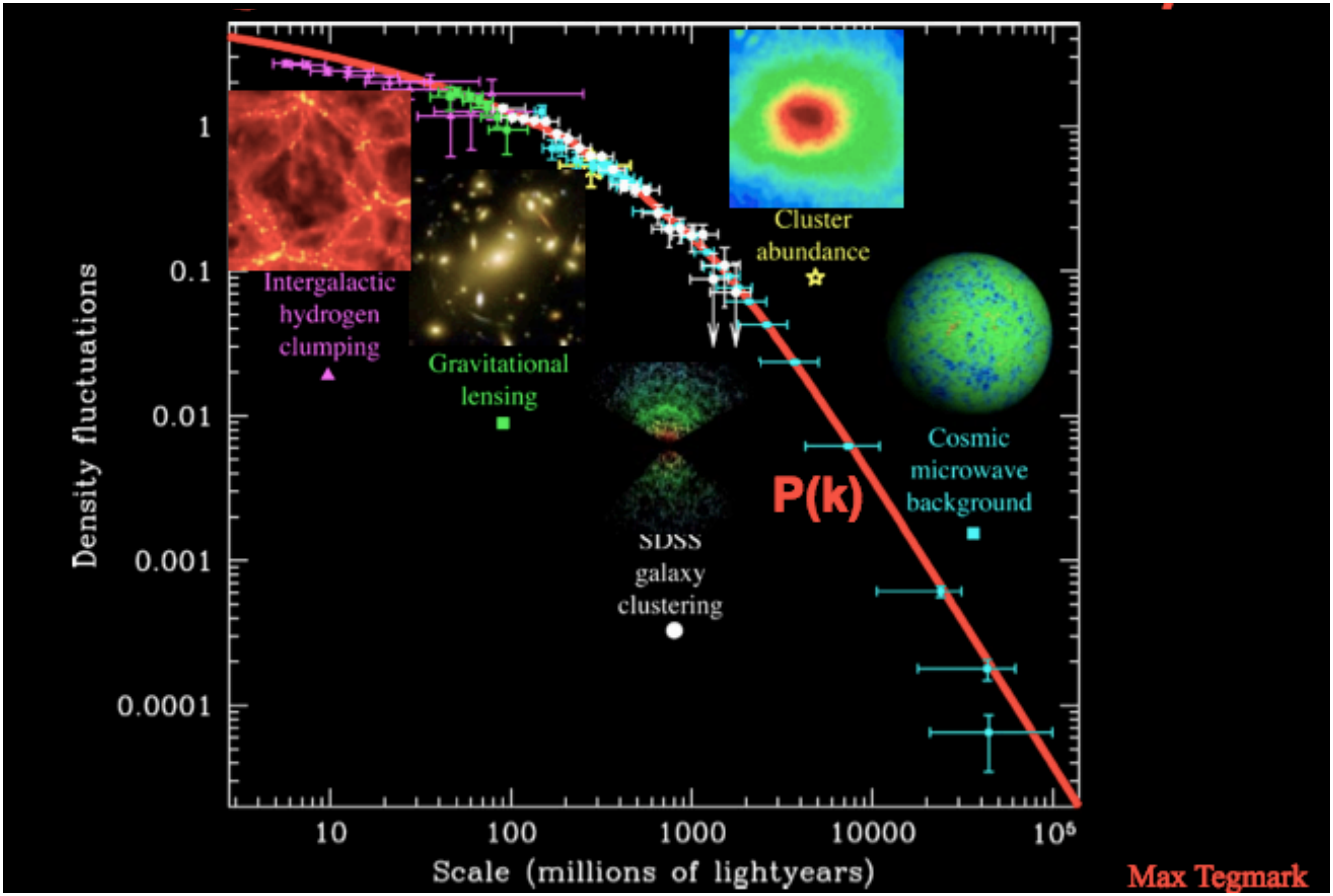
Martinez et al. 2008



Madau, Diemand, Kuhlen 08

https://webfiles.uci.edu/bullock/Public/Canary2008/

Large Scales: looks like CDM + Dark Energy



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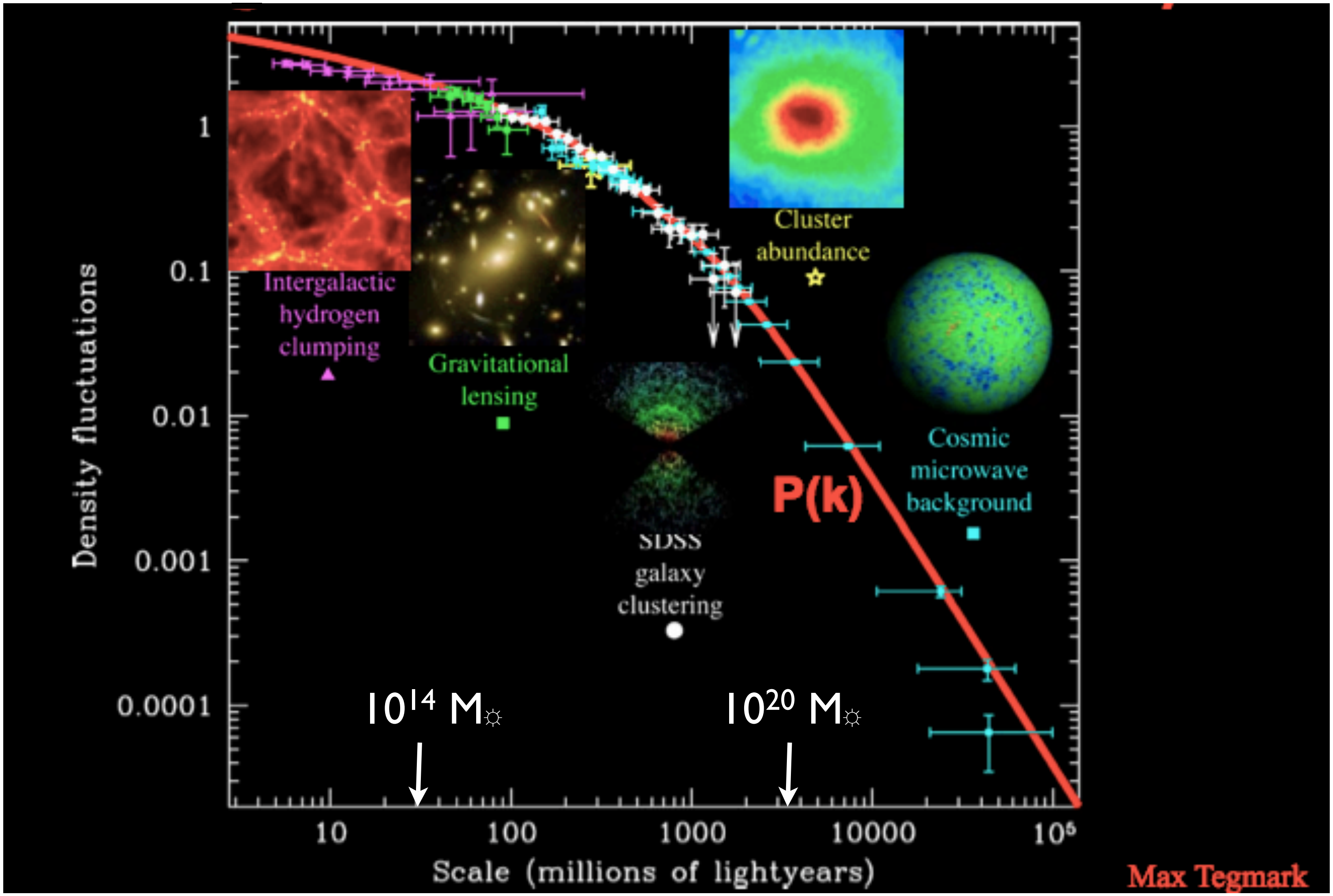
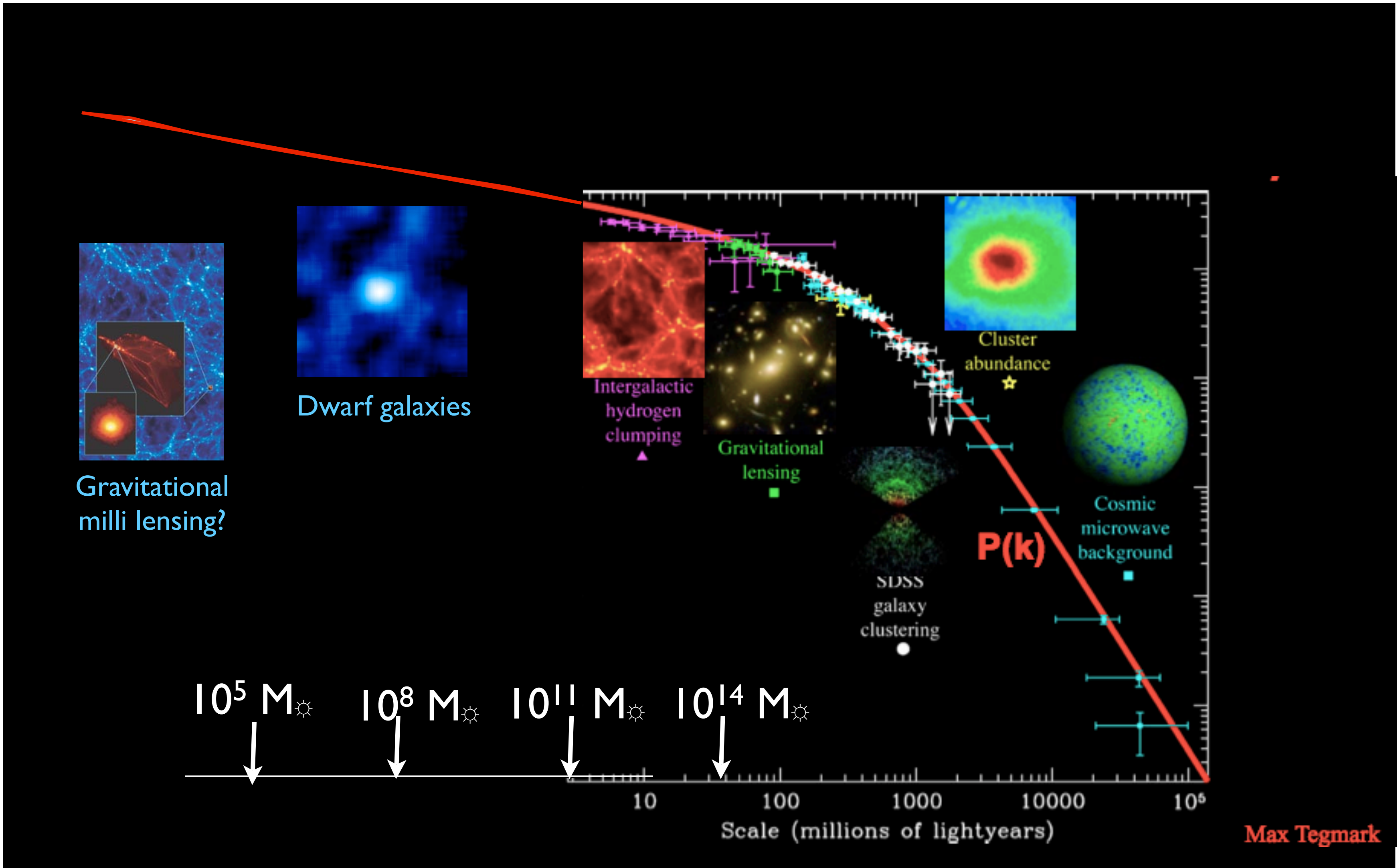


What about smaller scales?



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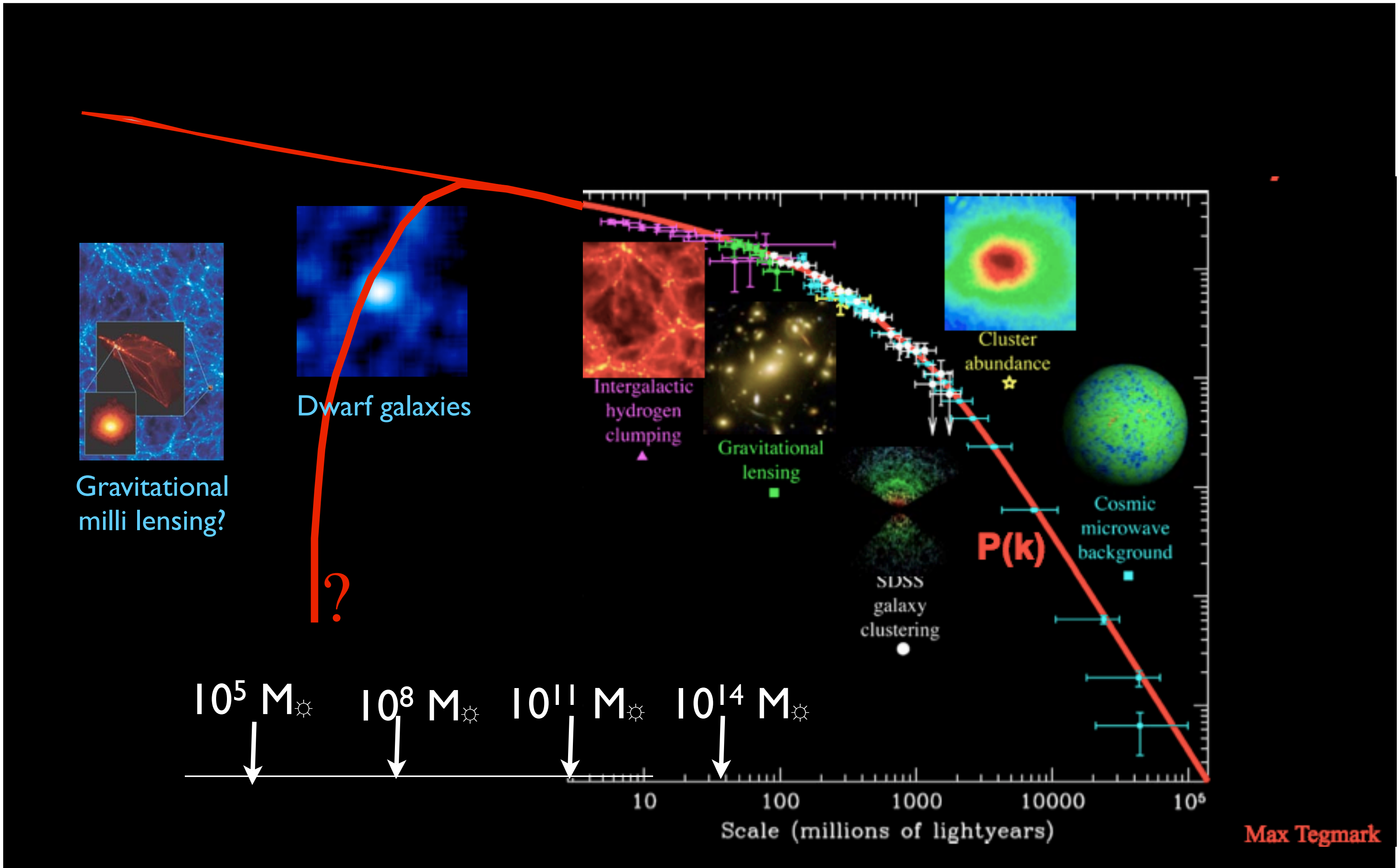
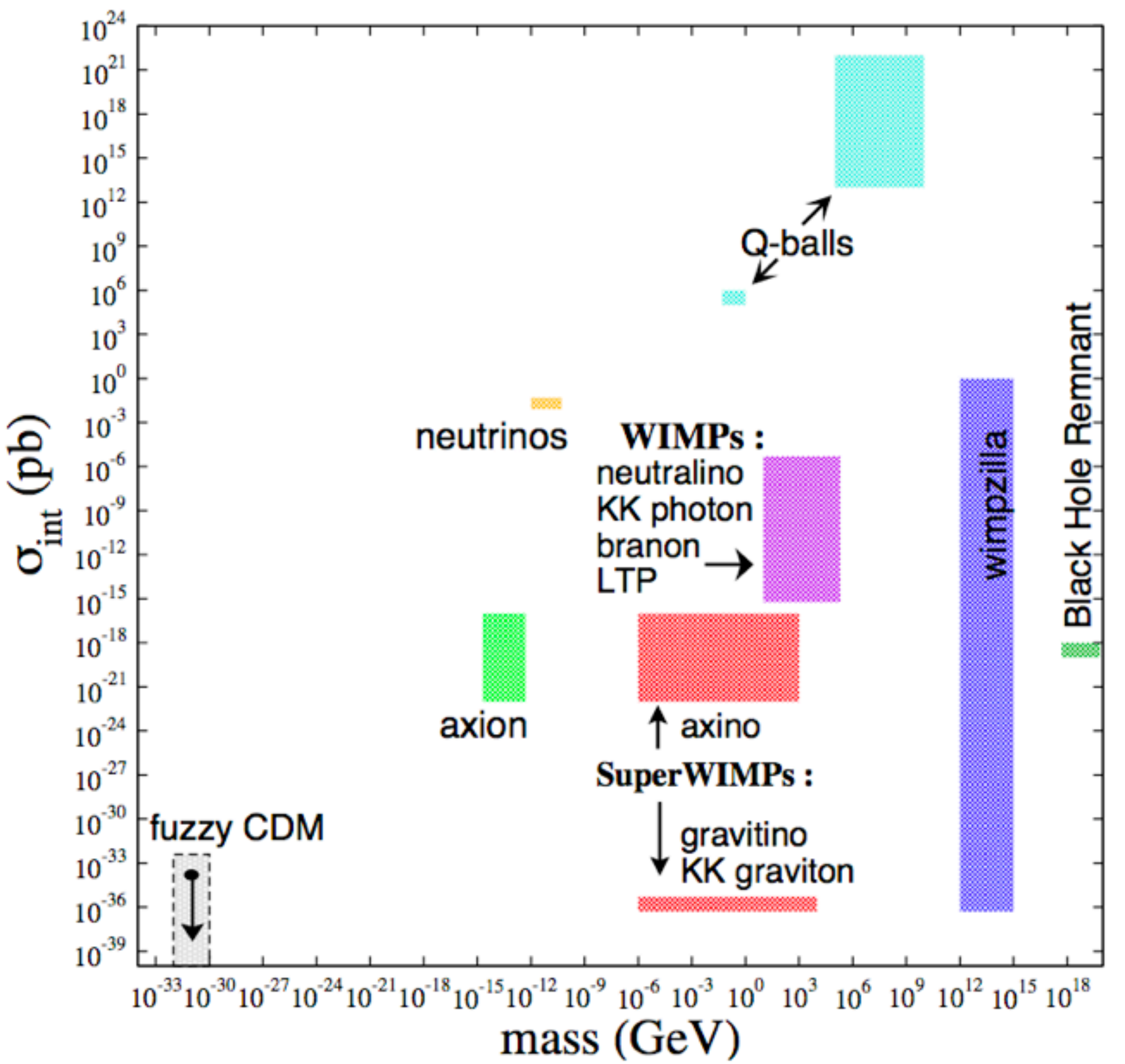


Sobel et al. 07 *Dark Matter Scientific Assessment Group* (DMSAG)



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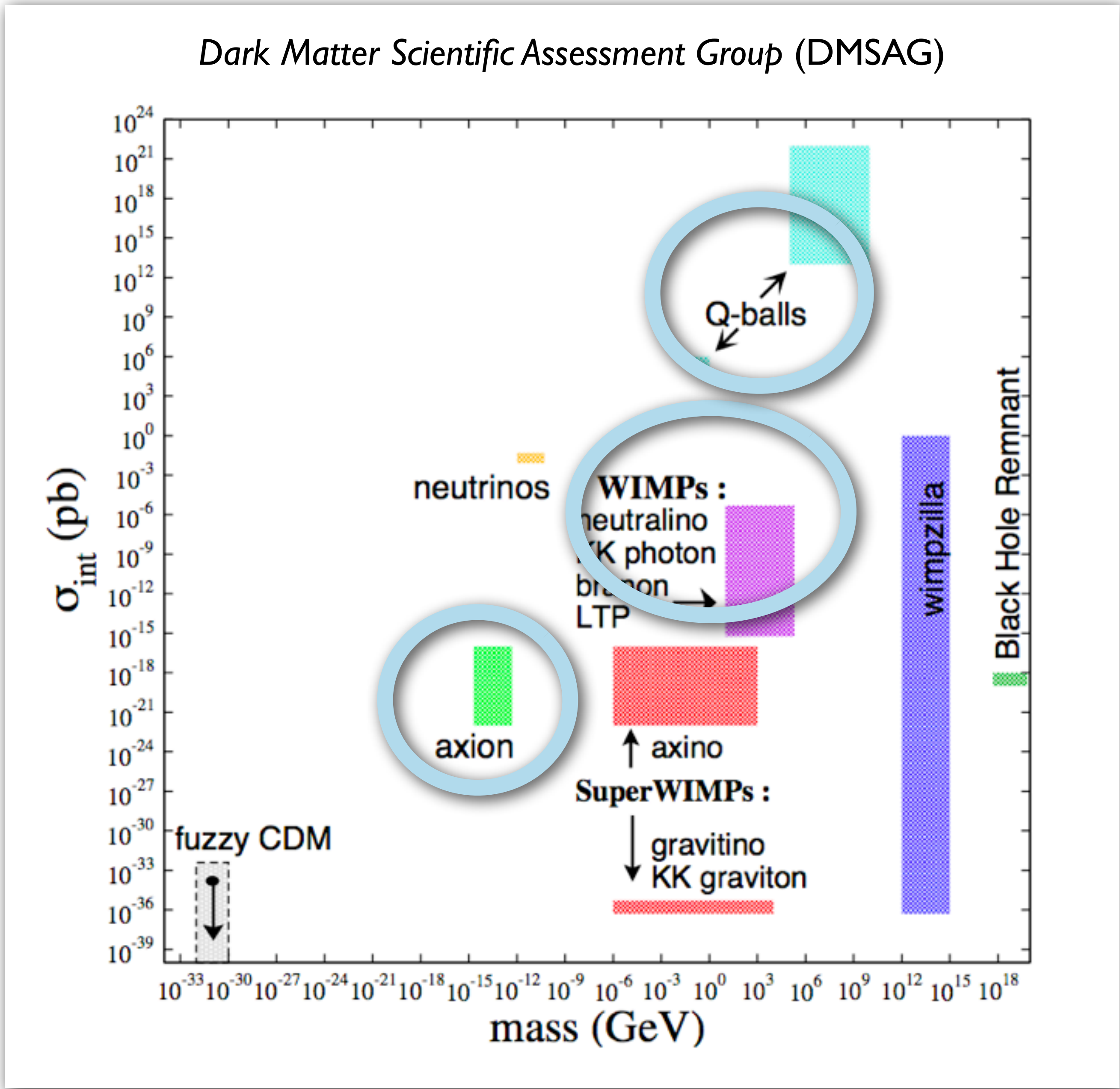

Cold Dark Matter

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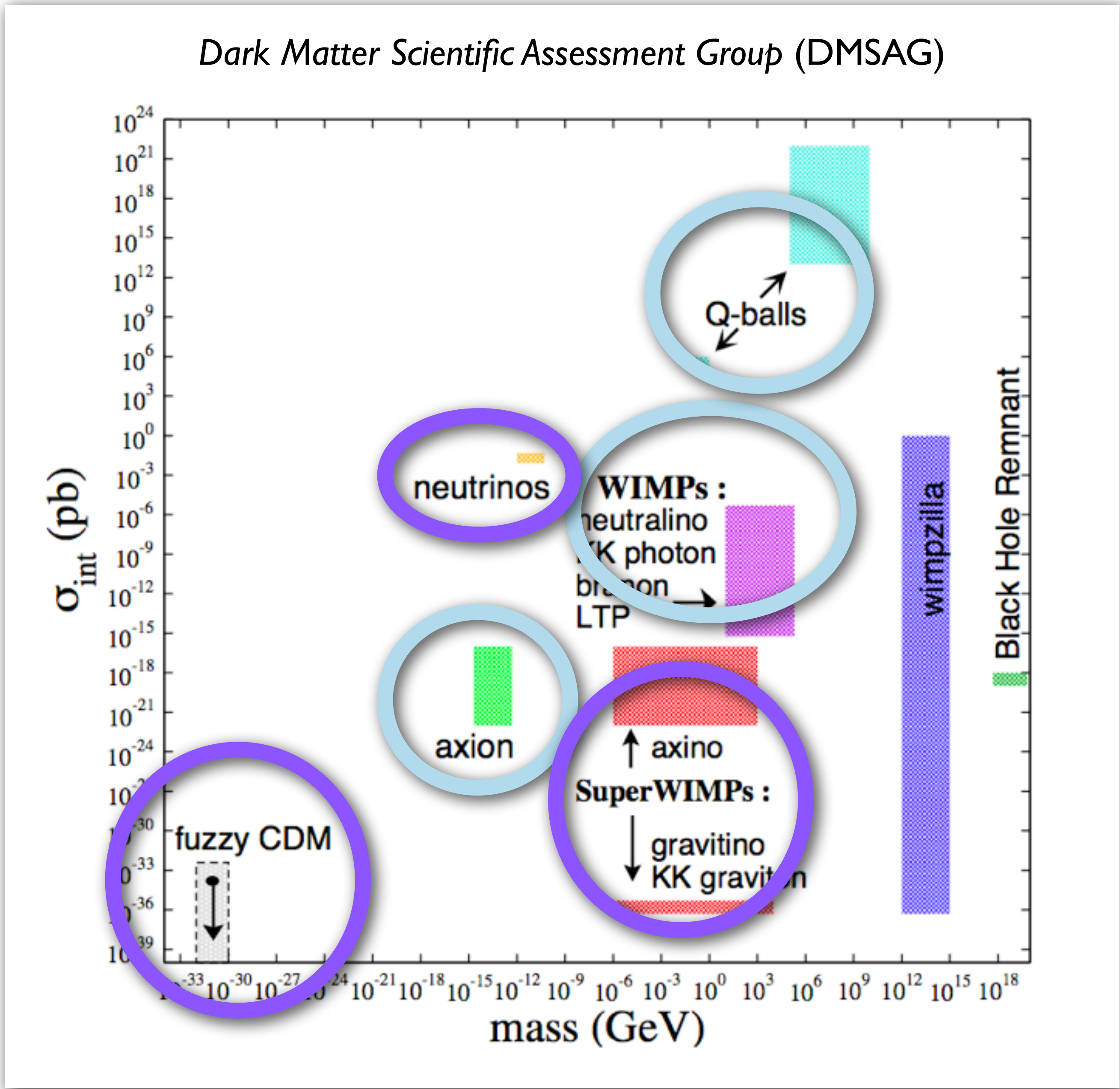

Cold Dark Matter

Warm Dark Matter

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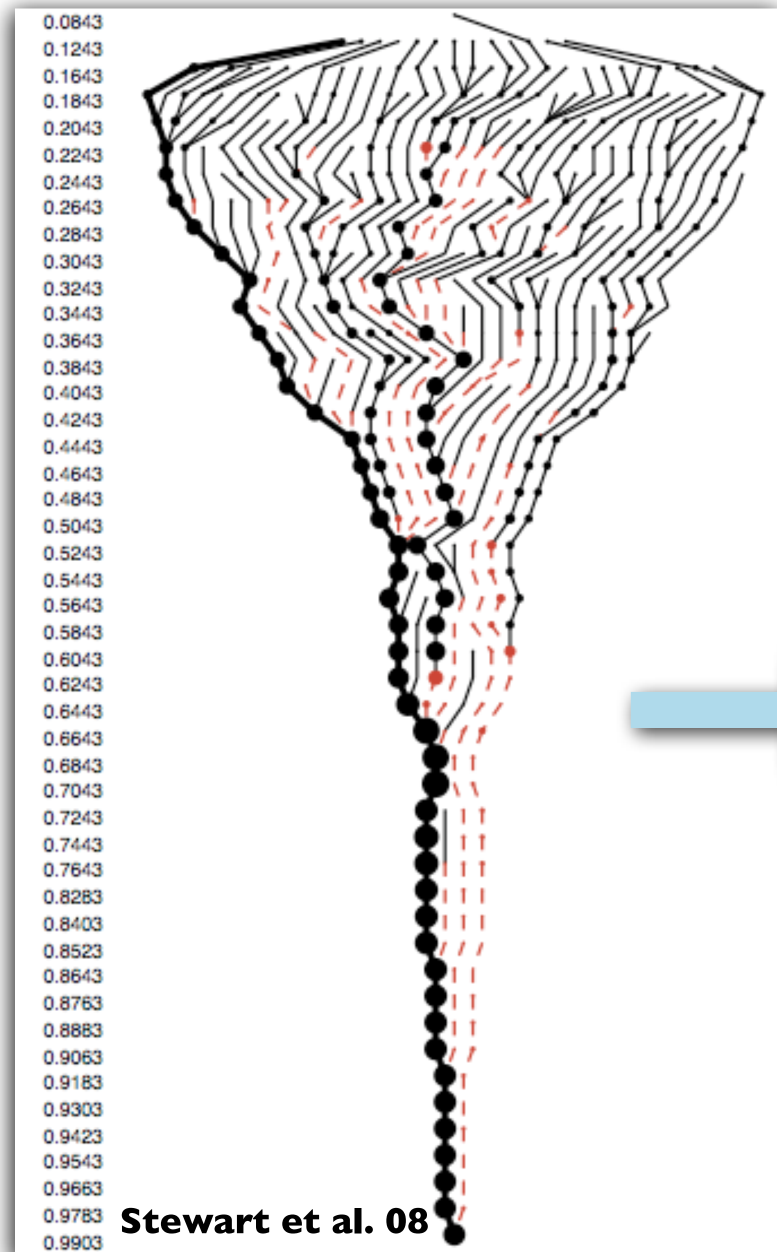
What processes determine the substructure count?

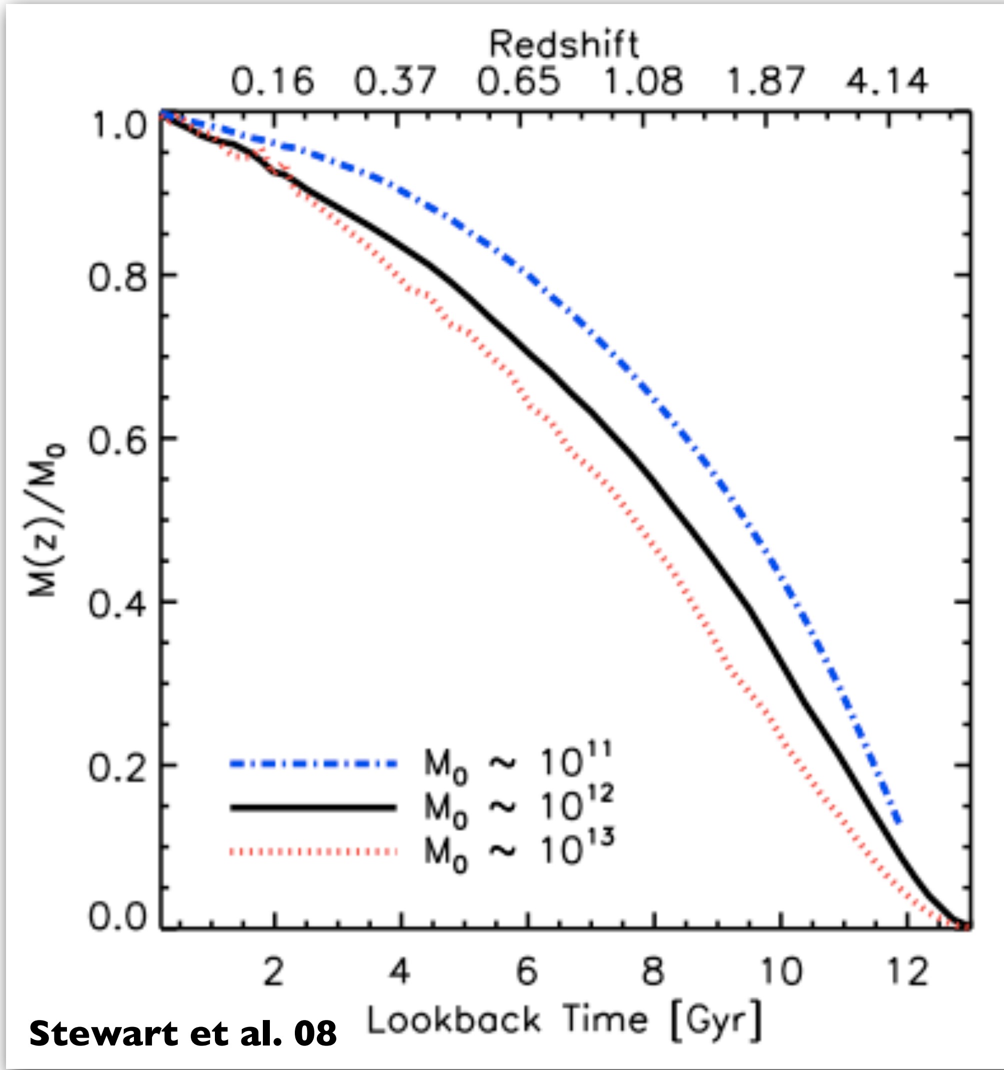


Stewart et al. 08

Diemand et al. 08

How do DM halos grow?

1. Rapid, early accretion phase   2. late time, slower accretion



Massive halos end their rapid accretion phase later

Wechsler et al. 02

van den Bosch et al. 03

...

Stewart et al. 08

Zhao et al. 08

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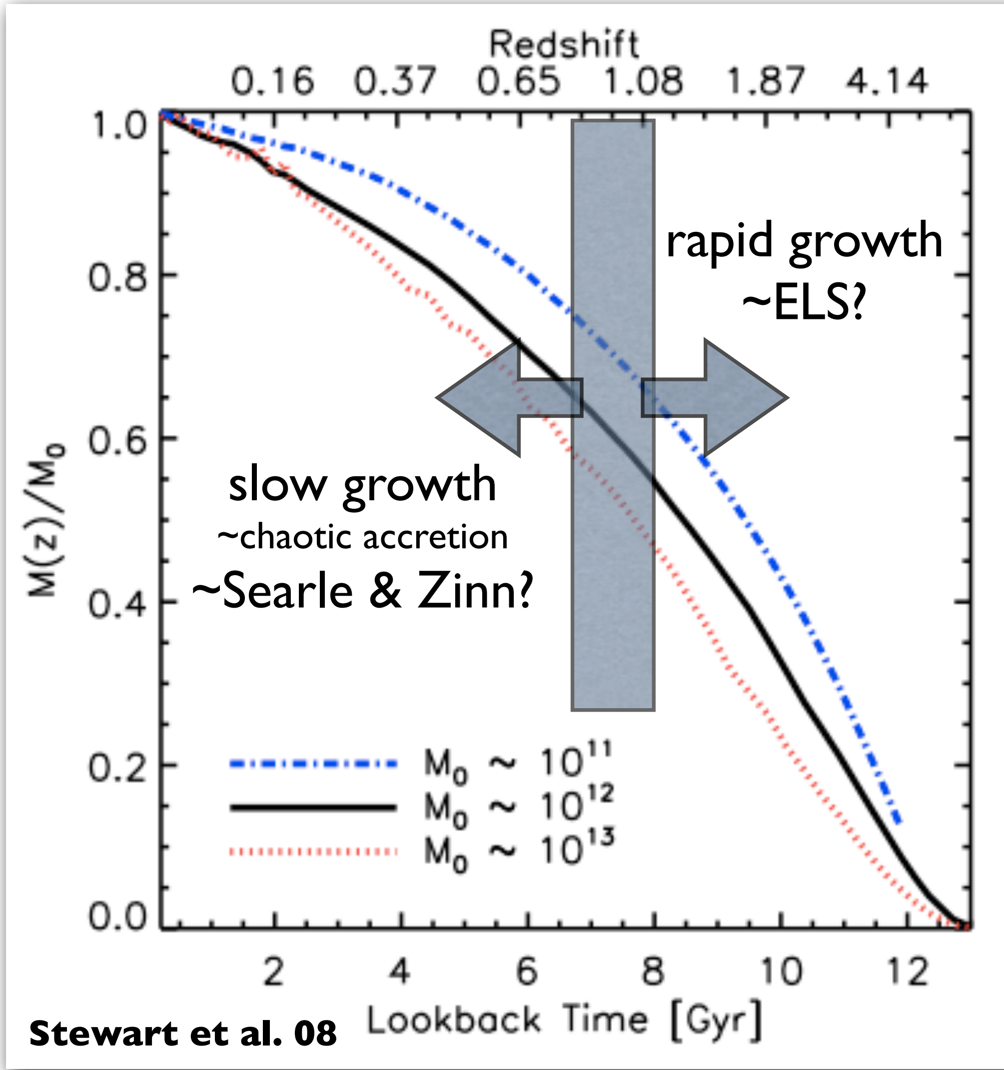

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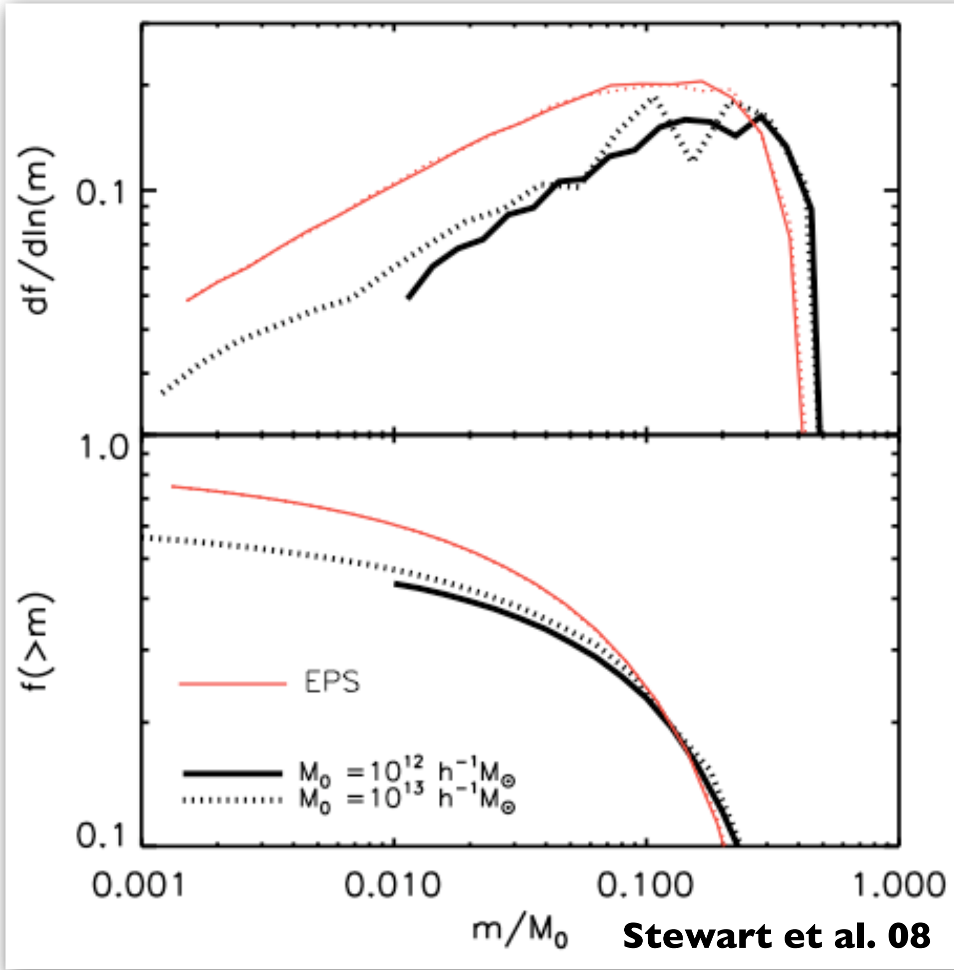
How is mass accreted?



Mergers that are ~1/10 of the final halo mass dominate its mass growth.

For typical 10^{12} M_{sun} halo:

- M ~10^{11} mergers dominate mass buildup.

Lacey & Cole 93; Zentner & JSB 03; Purcell et al. 07

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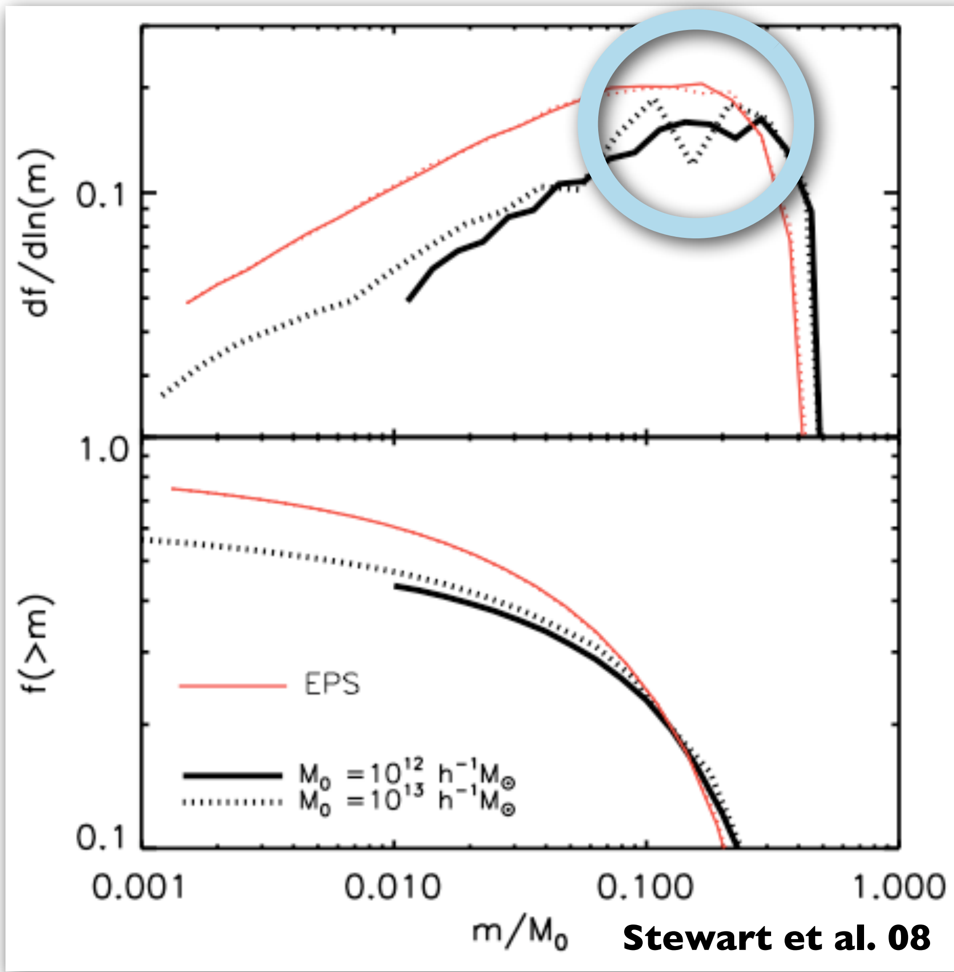

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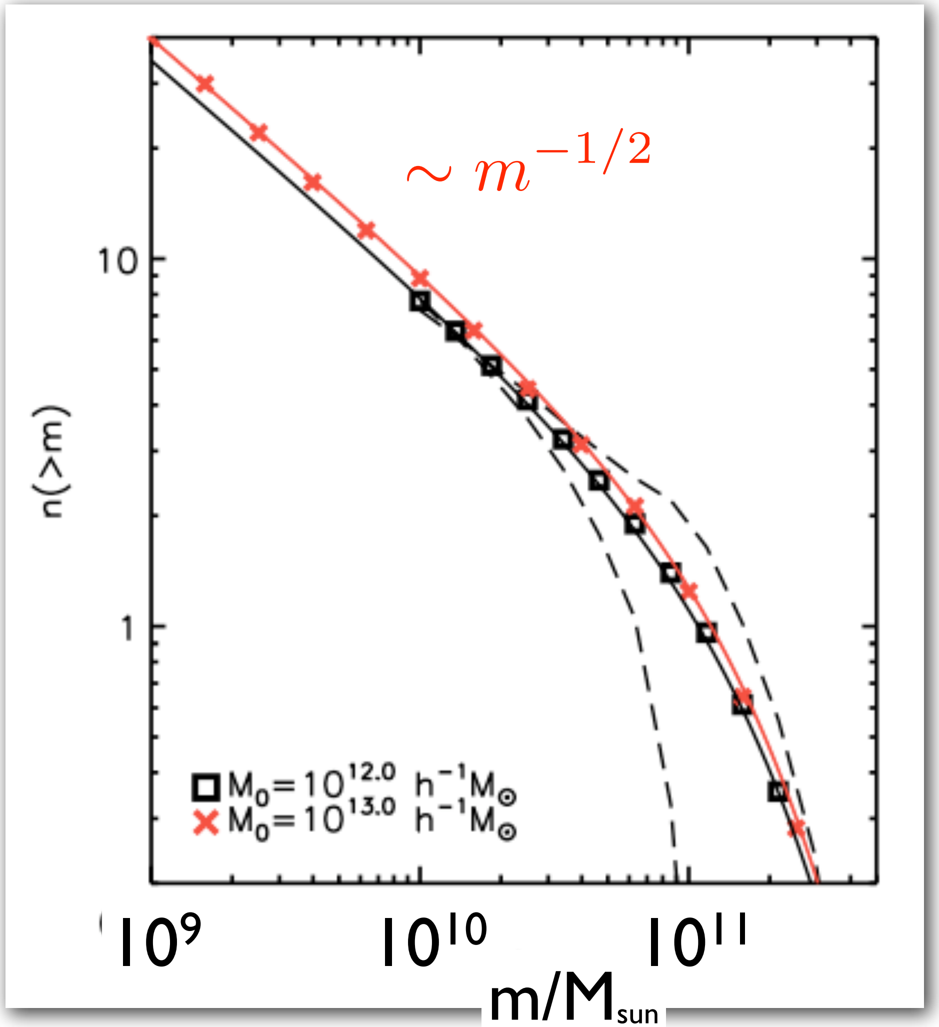
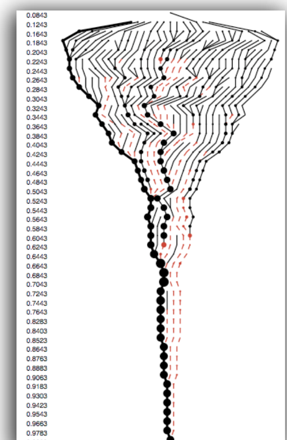
Cumulative # of accretions over a halo's history



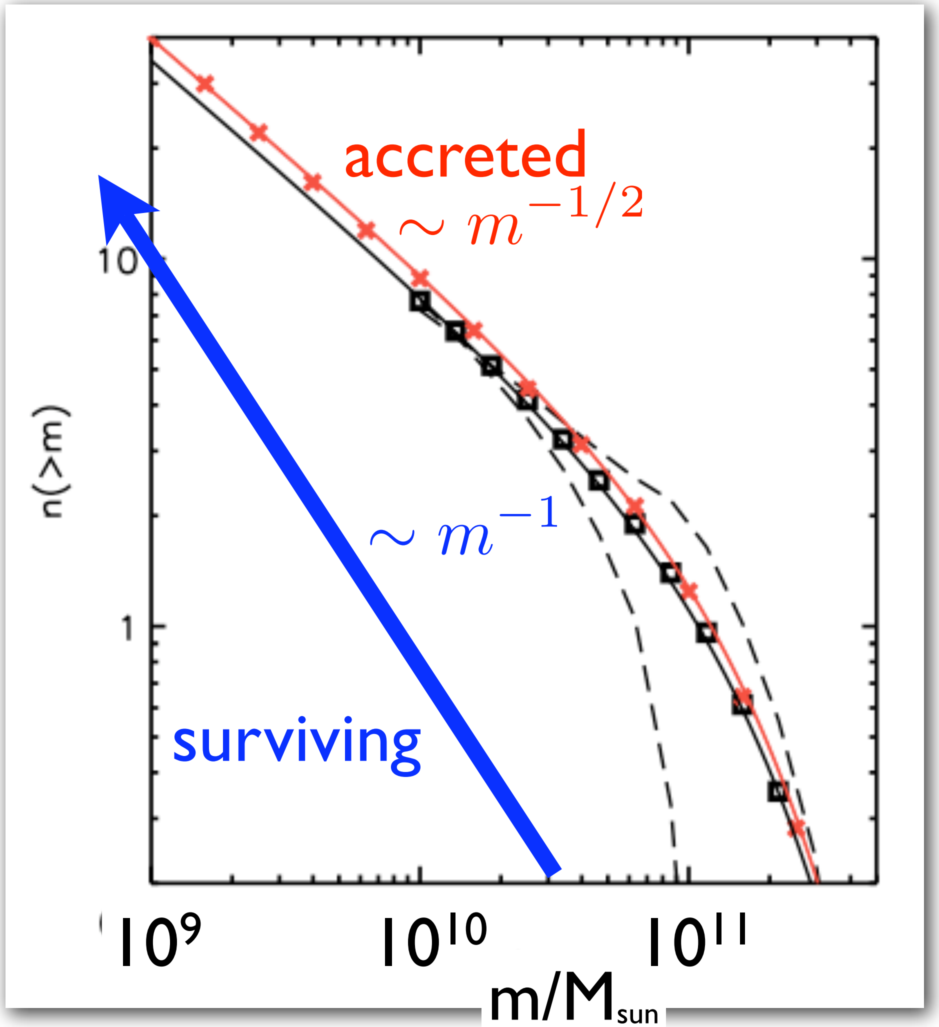
Stewart et al. 08

For typical $10^{12}\ M_{sun}$ halo:

- ~1 10^{11} merger
- ~7 10^{10} mergers
- increasing #'s of smaller mergers



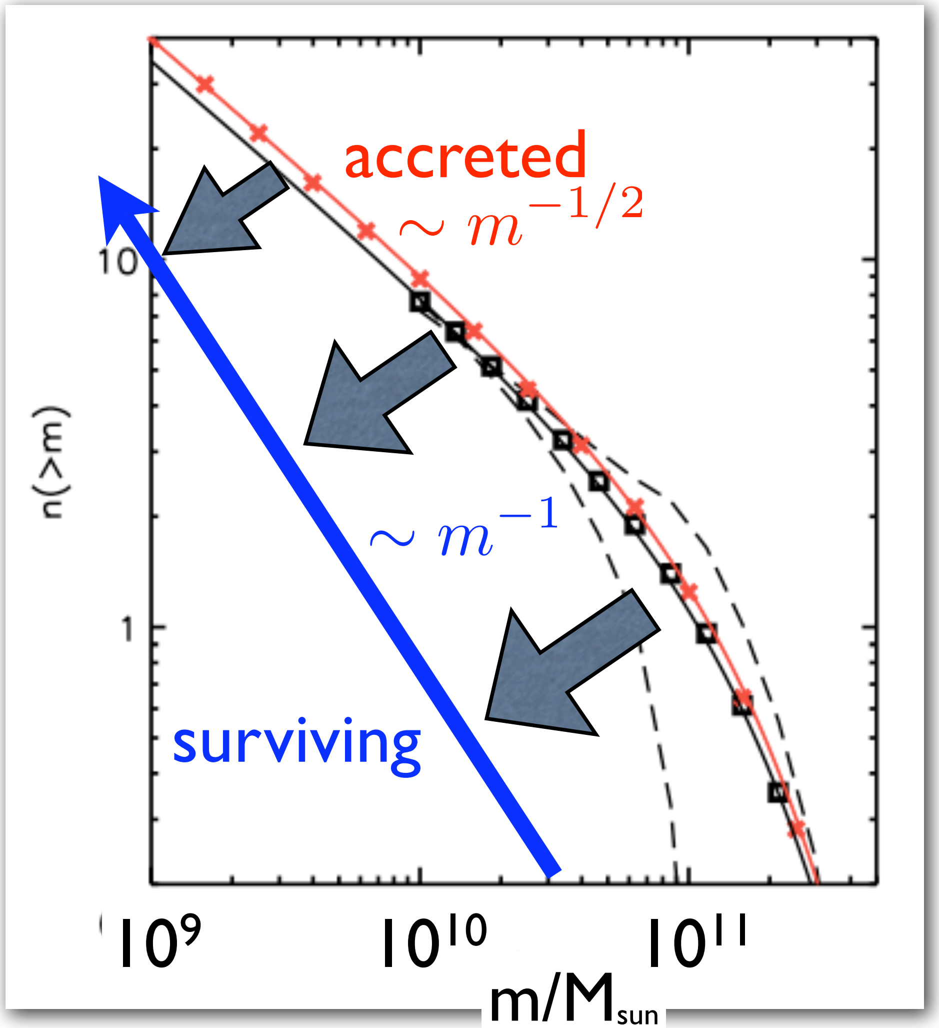
Merged vs. Surviving?



Surviving for typical 10^{12} M_{sun} halo:

- ~0 10^{11} M_{sun} subhalos
- ~1 10^{10} M_{sun} subhalos
- ~10 10^{9} M_{sun} subhalos

Majority of accreted objects in MW-size halos get destroyed

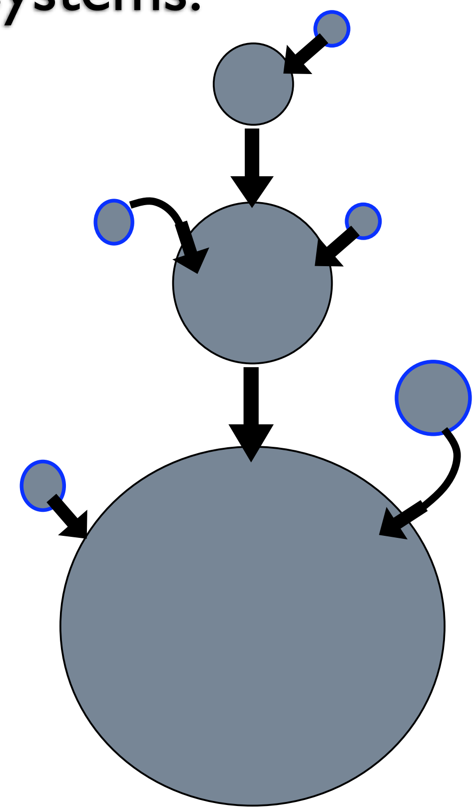


destroyed = lose most of their mass (90-99%)

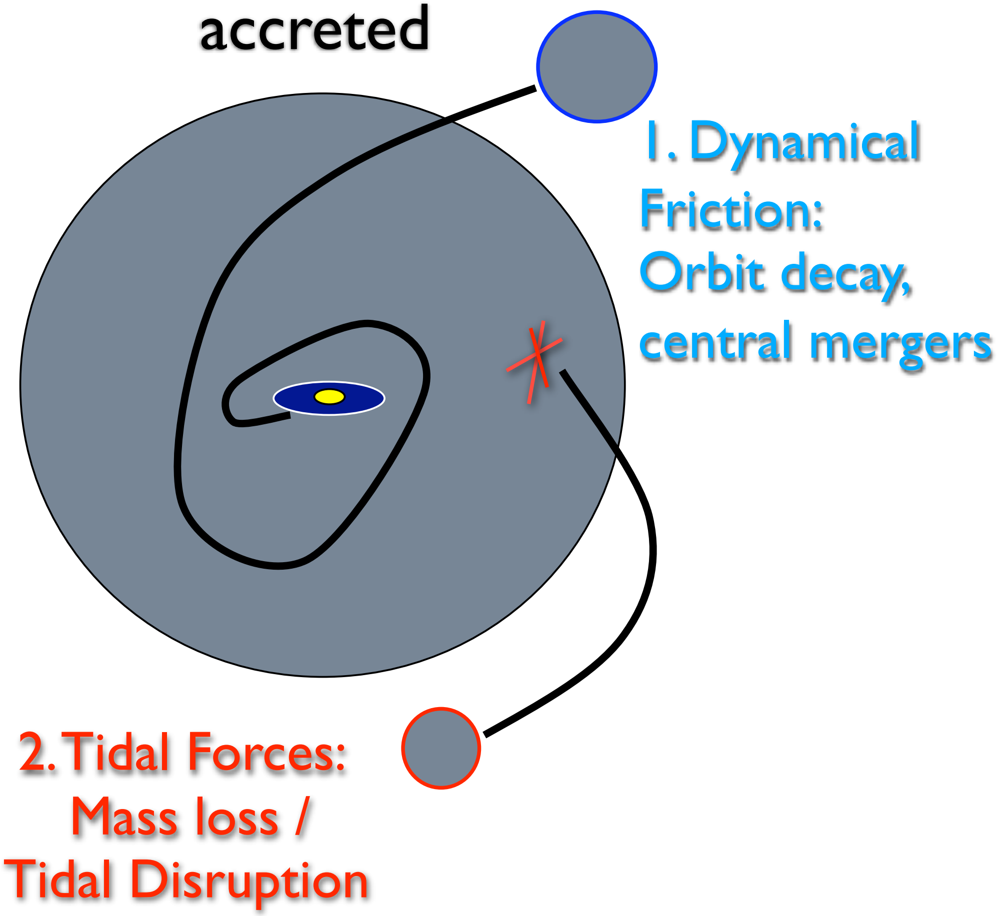
What determines halo substructure?

Competition between destructive mass loss and fresh accretion

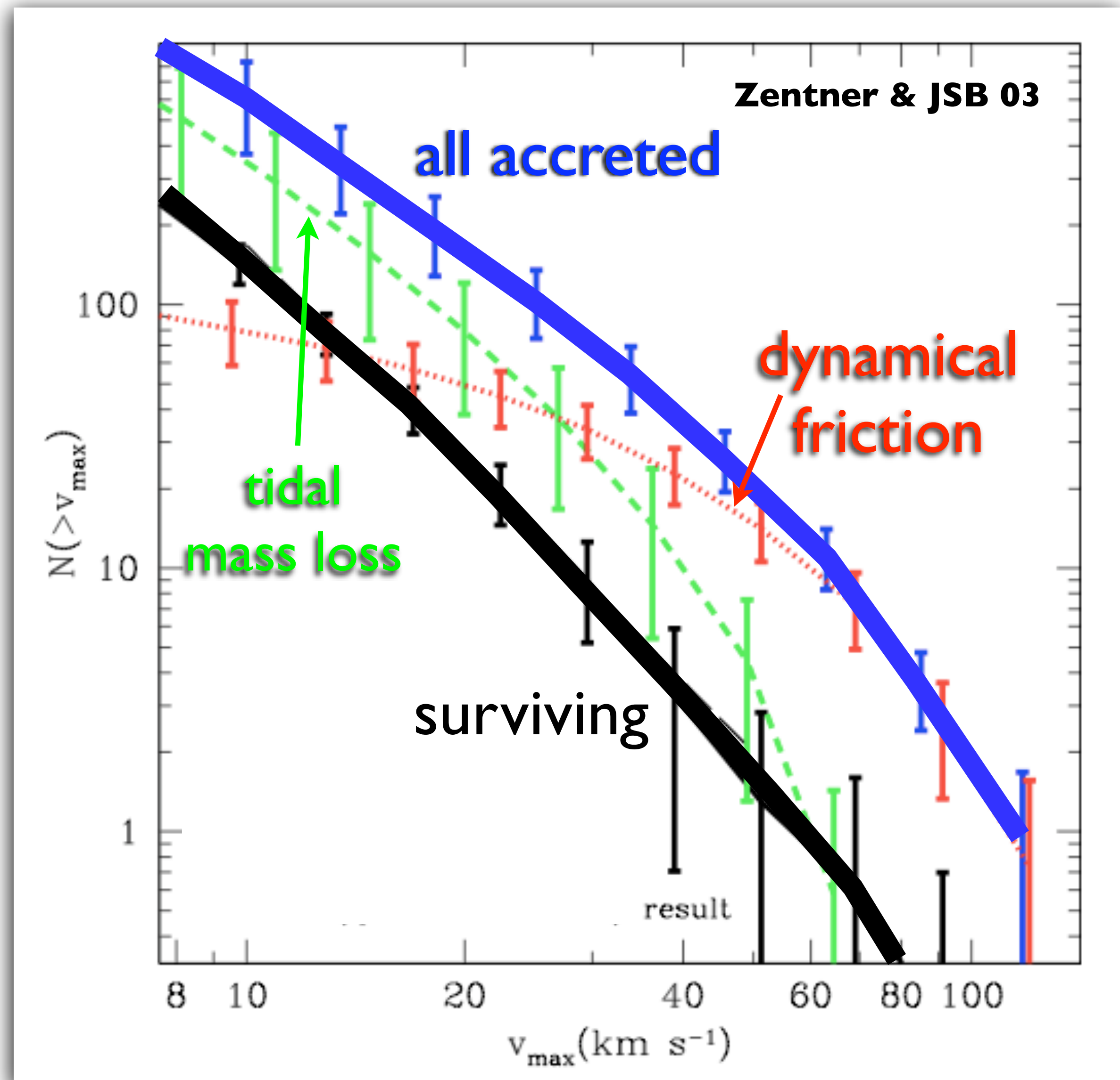
1. Halo growth via accretion of low-mass systems.



2. Destruction of substructure once accreted



semi-analytic: merger trees + orbit integration



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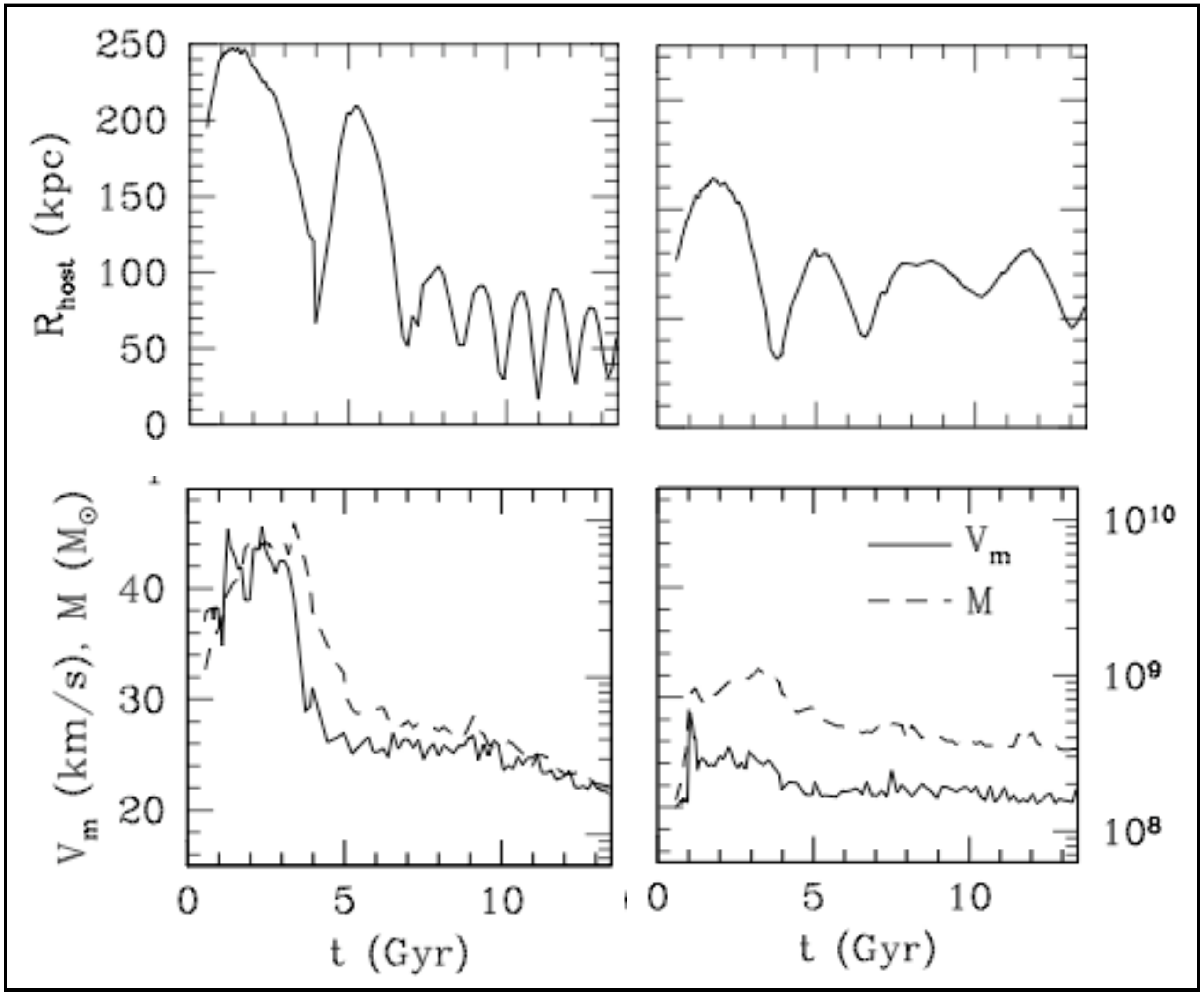
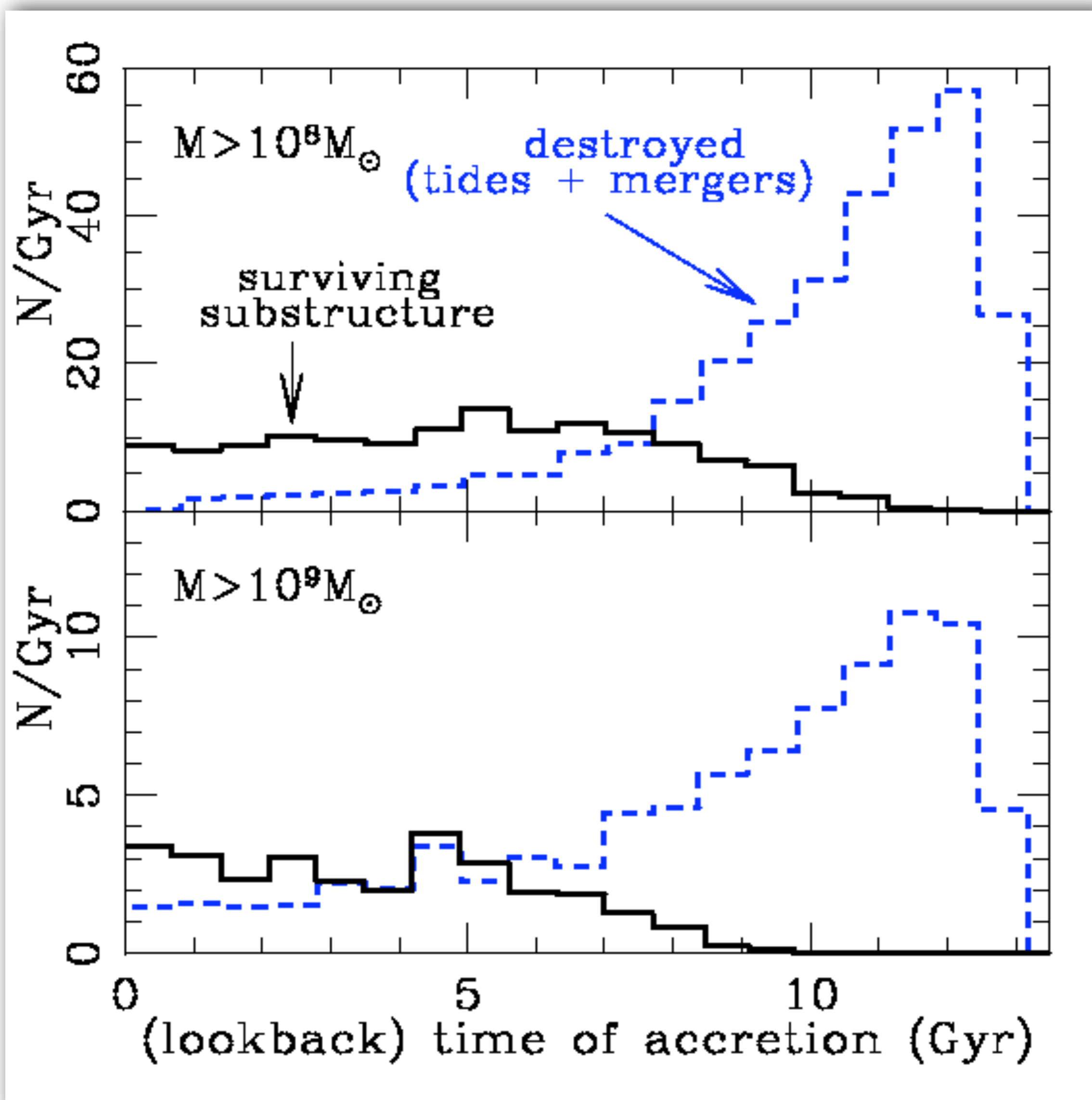
Kravtsov et al. 2004 -
track infalling substructure evolution in simulations

note: mass loss especially fast in massive accretions



Early accretions get destroyed. Late accretions survive.



Zentner & JSB 03

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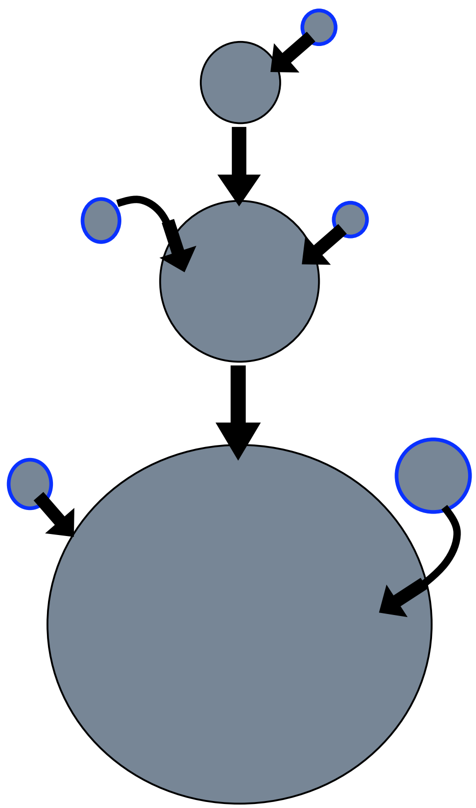


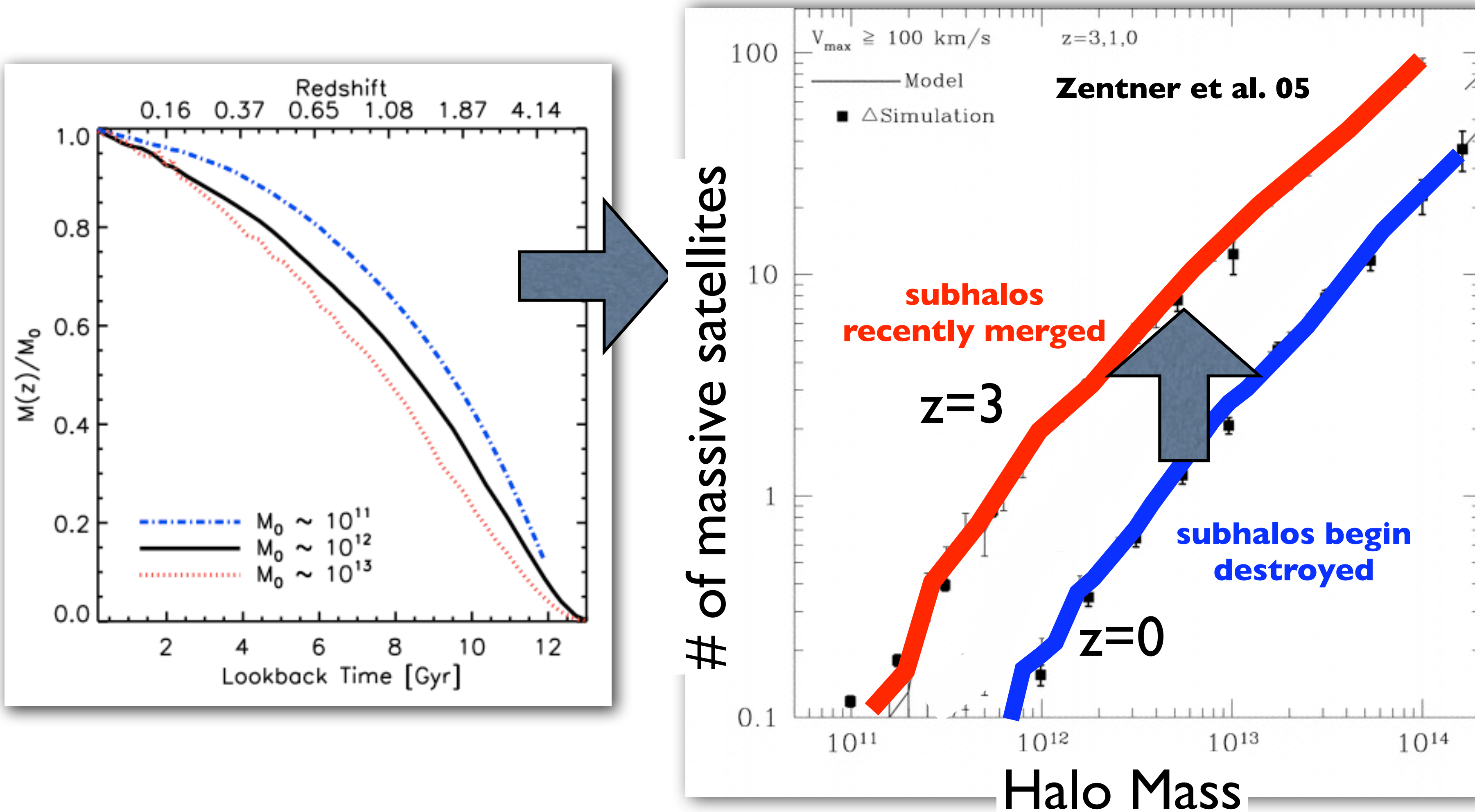
if $t_{acc} < t_{dynamical}$

→ substructure builds up

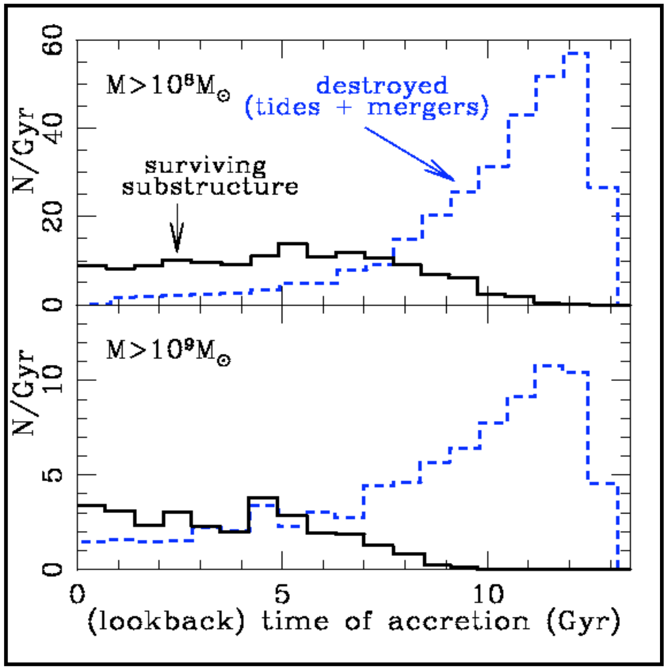
if $t_{acc} > t_{dynamical}$

→ substructure washes away

Halos at high redshift should have more substructure



Early accretions do not survive

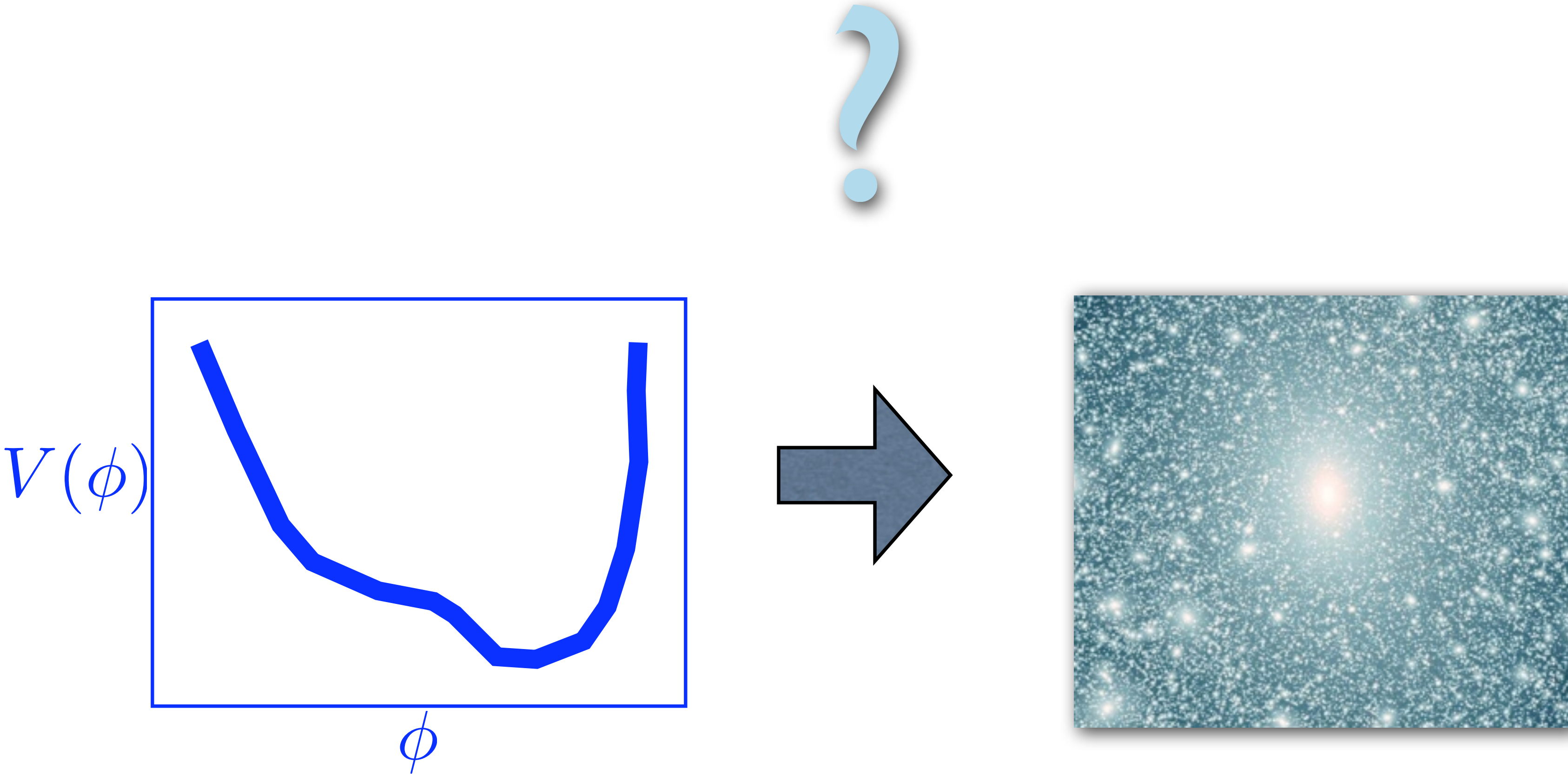


Zentner & JSB 03

Massive halos (which form later) will have more substructure than low-mass halos [normalized to a fixed fraction of the host mass, m/M.](see Gao et al. 04)

Halos form earlier will have fewer subhalos. (see Zentner et al. 05)

Remnant material from accreted, disrupted subhalos will be a biased (older/metal poor) compared to surviving population. (See Robertson et al. 05; Helmi et al. 07)



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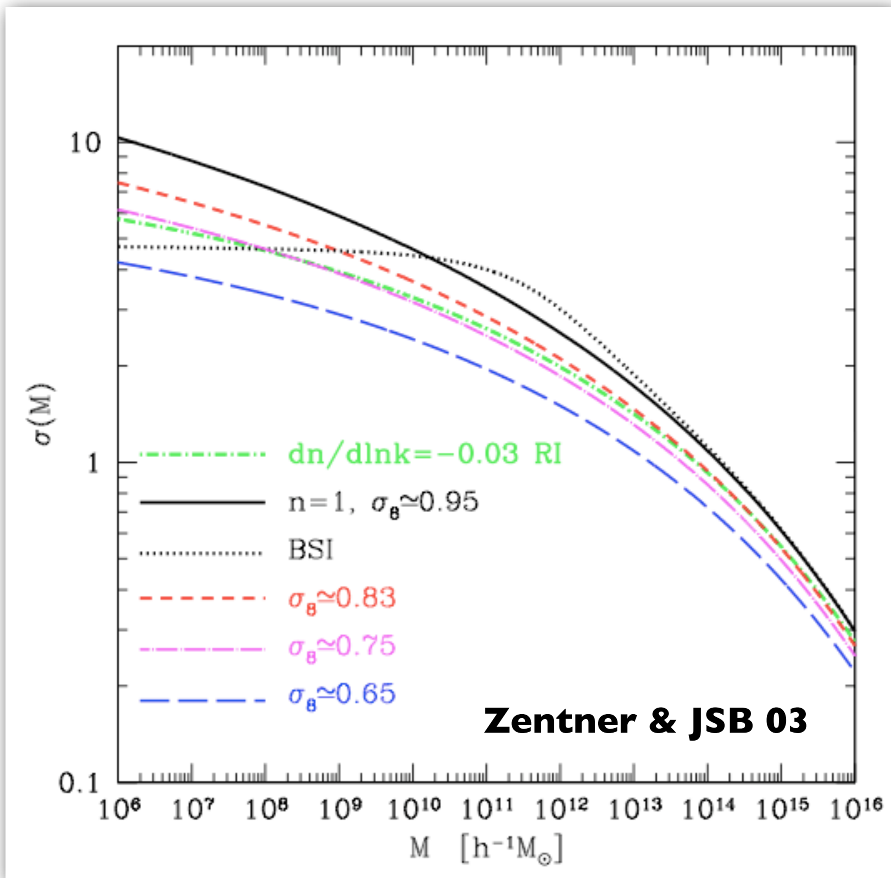
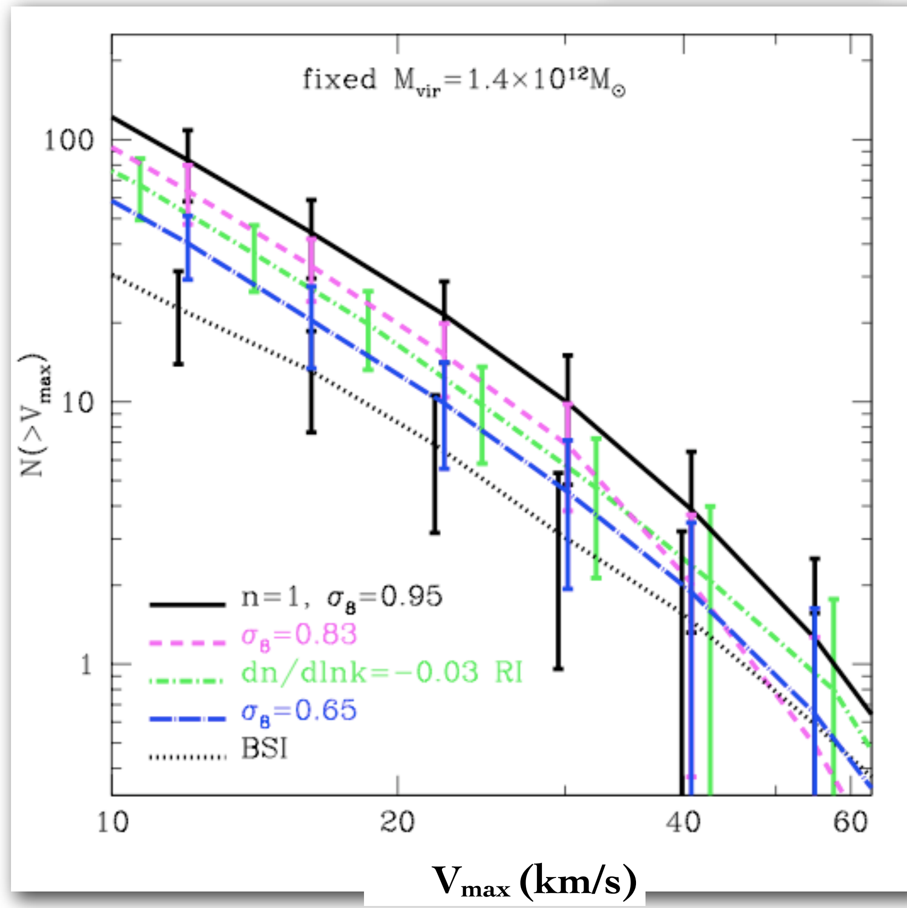


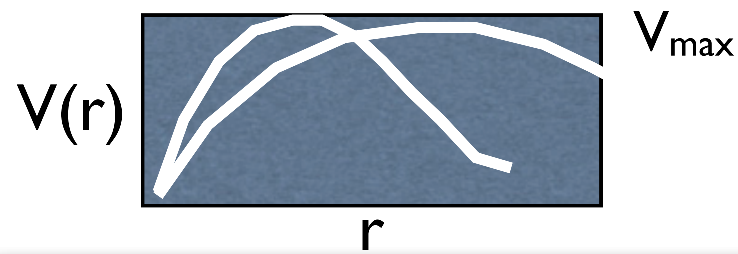


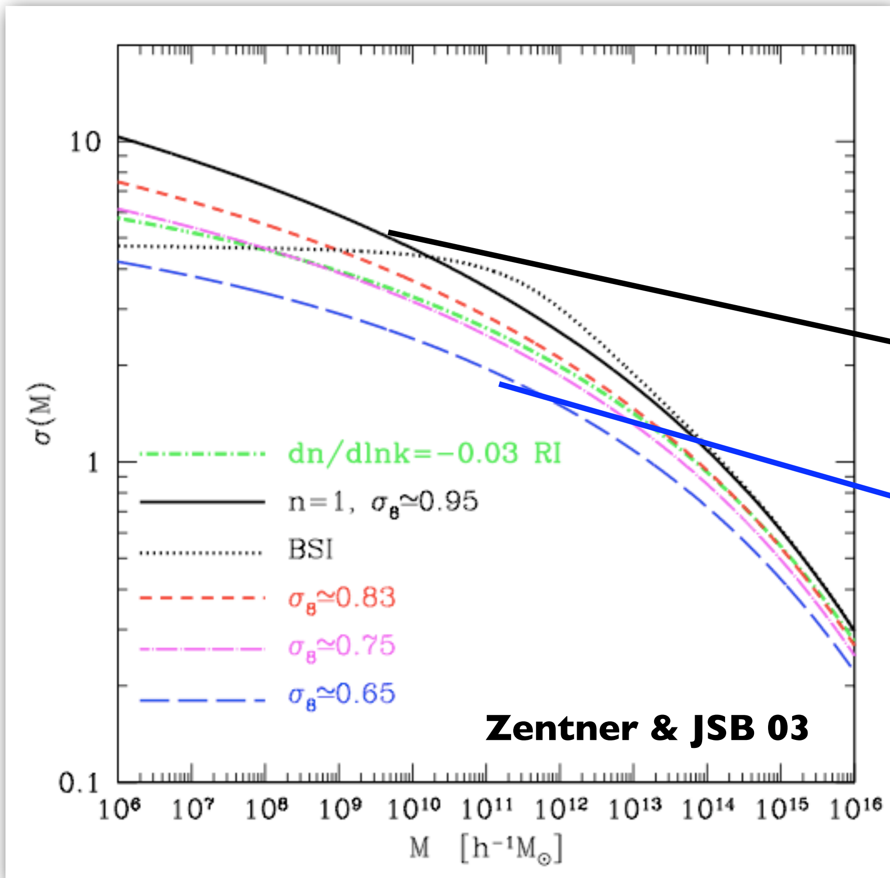
https://webfiles.uci.edu/bullock/Public/Canary2008/

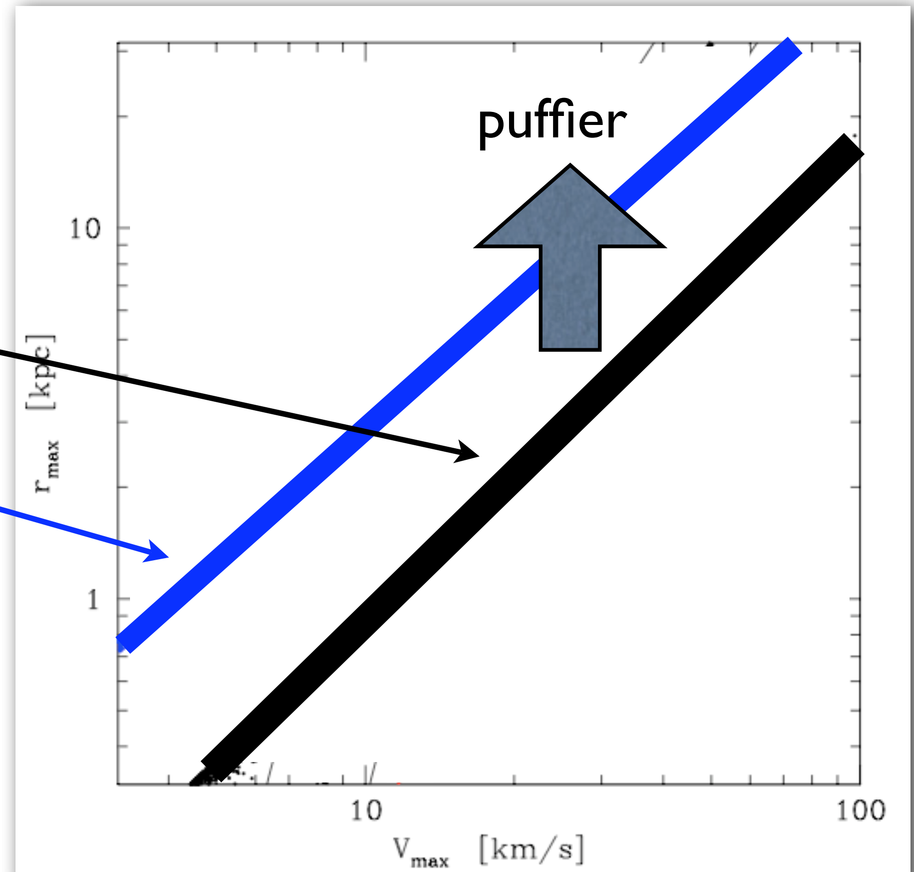
2 competing effects

1. Reduce small scale power & small halos get puffier (form later)

⟶ more easily destroyd







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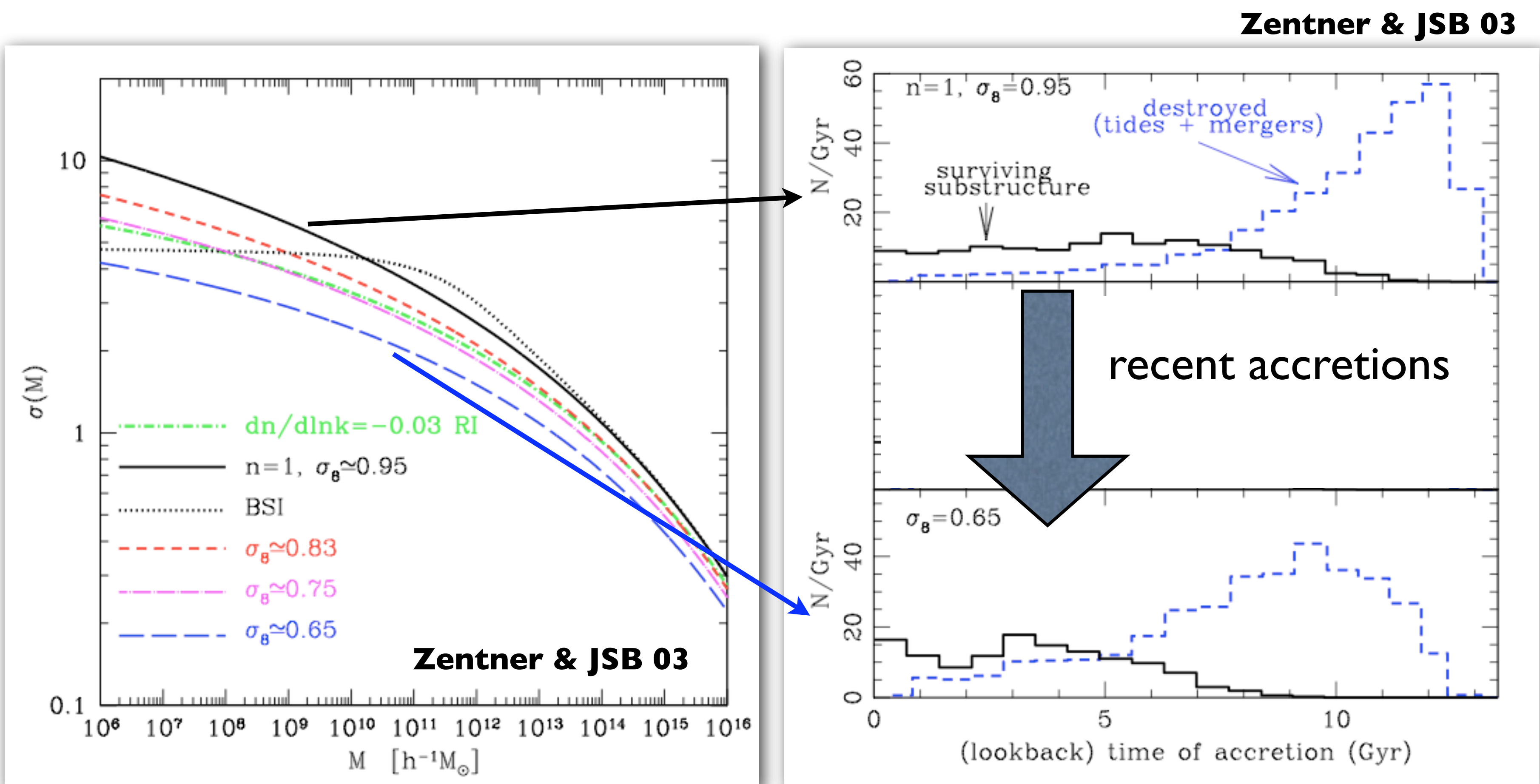
2 competing effects

2. Reduce small scale power & host halos form more recently

→ Subhalos have less time to be destroyed.



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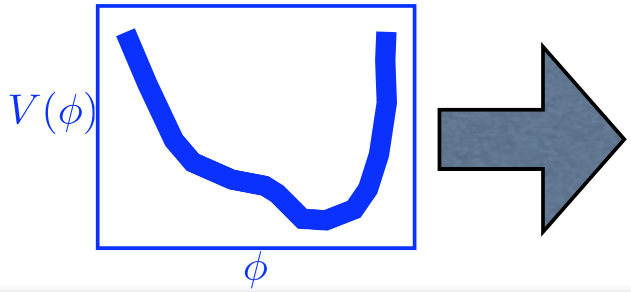
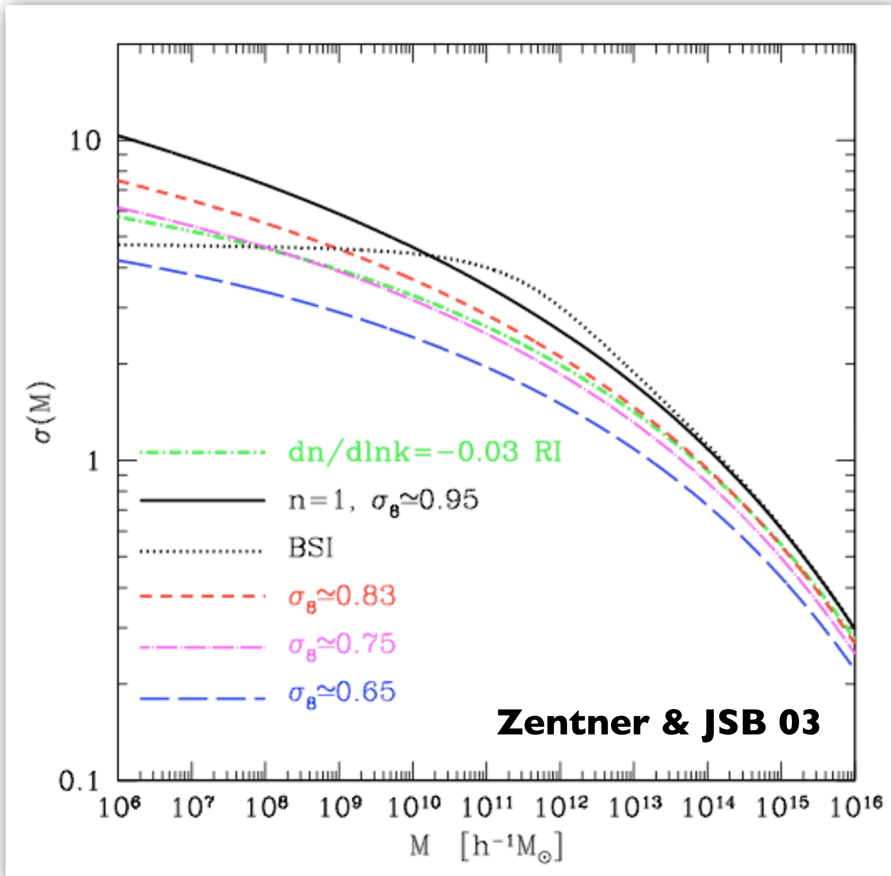
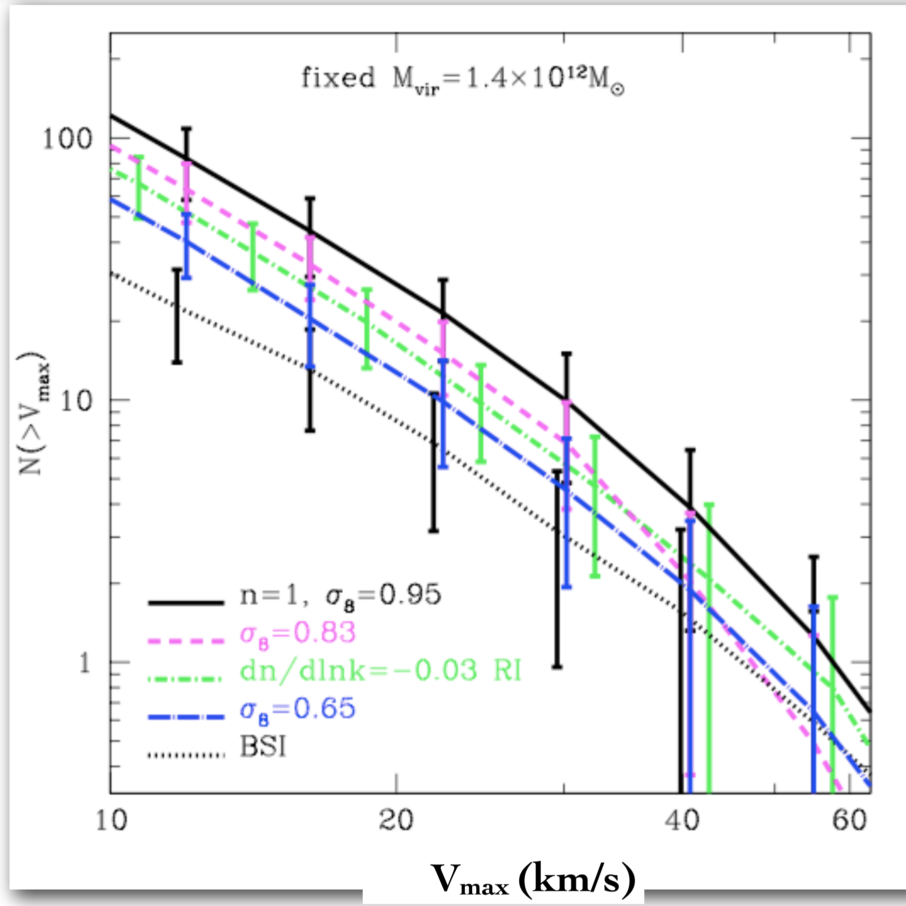


Tilted/running P(k) have much bigger effect than just lowering power uniformly .





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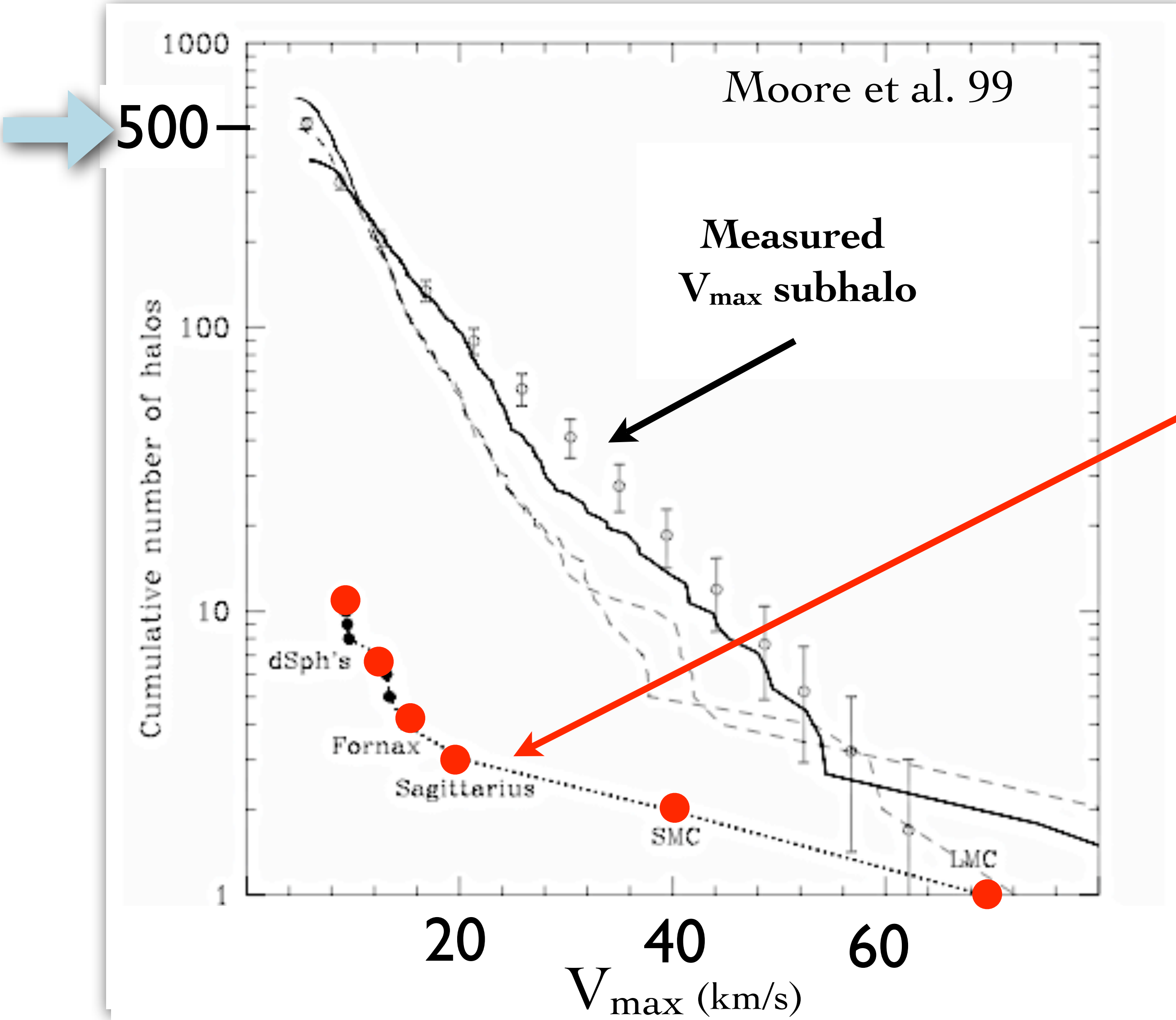
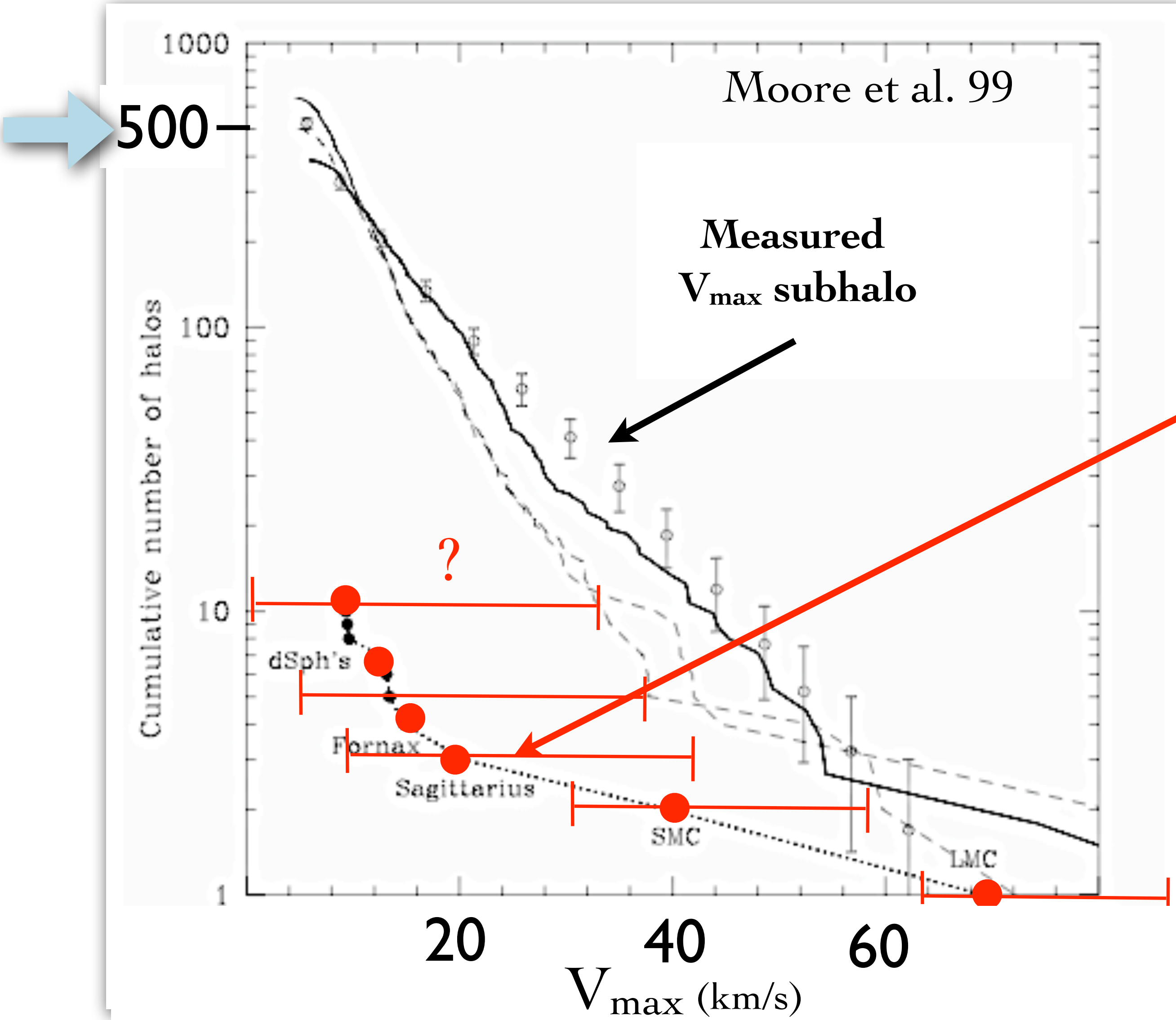
Missing Galactic Satellites?



Estimate:

$$V_{\max} = \sqrt{2}\sigma_*$$

What kind of subhalos host these satellites?



Estimate:

$$V_{\rm max} = \sqrt{2}\sigma_*$$

SDM White 00

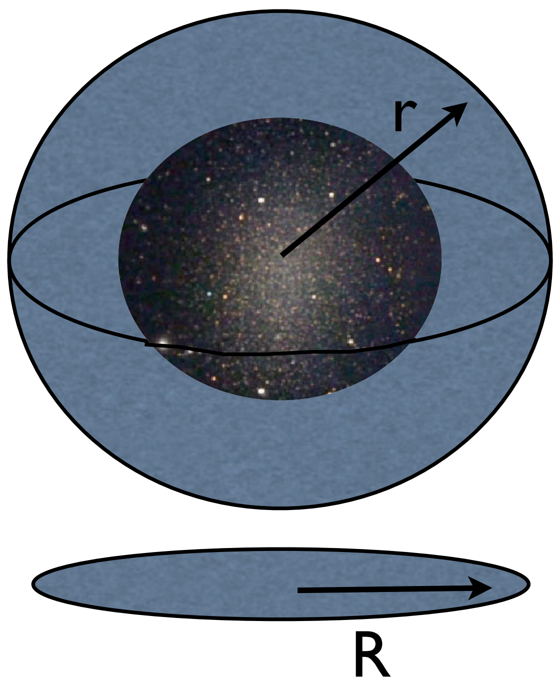
Stoehr et al. 03

Hayashi et al. 04

Kazantzidis et al. 04

Penarrubia et al. 08

Interpreting Kinematics: Jeans Equation



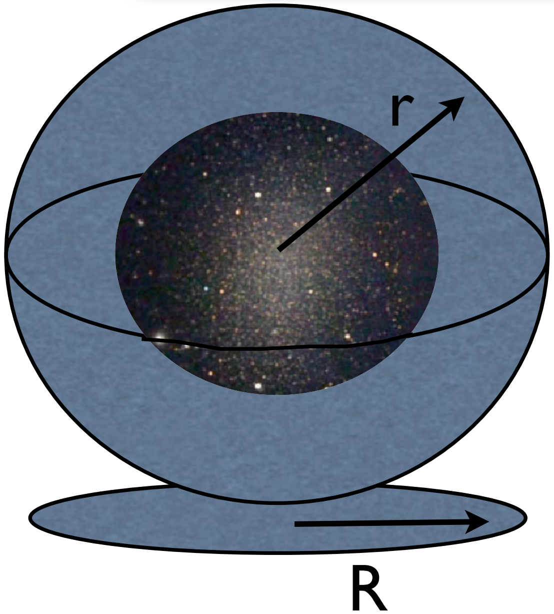
Observables:

1. Line of sight velocity dispersion: $\sigma_{los}(R)$
2. Stellar distribution: $I_*(R) \longrightarrow \rho_*(r)$

$$\sigma^2_{los}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\rho_* \sigma_r^2 r \mathrm{d}r}{\sqrt{r^2 - R^2}}$$

https://webfiles.uci.edu/bullock/Public/Canary2008/

Interpreting Kinematics: Jeans Equation



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Infer 3d radial velocity dispersion of the stars: σ_r

unknown function

Jeans Equation: $$\rho_* \frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\frac{\mathrm{d}(\rho_* \sigma_r^2)}{\mathrm{d}r} - 2\frac{\beta}{r}\rho_* \sigma_r^2$$

Global Potential - what we want to know

Spherical Jeans Equation:

$$\rho_* \frac{\mathrm{d}\Phi}{\mathrm{dr}} = -\frac{\mathrm{d}(\rho_* \sigma_r^2)}{\mathrm{d}r} - 2\frac{\beta}{r}\rho_* \sigma_r^2$$

Rewrite:

$$M(< r) = \frac{r\sigma_r^2}{G}\left[-\frac{\mathrm{d}\ln \sigma_r^2}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln \rho_*}{\mathrm{d}\ln r} - 2\beta\right]$$

Example: $\beta = 0, \quad \sigma_r = \mathrm{const}$

$$M(< r) = \frac{r\sigma_r^2}{G}\left|\frac{\mathrm{d}\ln \rho_*}{\mathrm{d}\ln r}\right|$$

$$V^2(r) = \sigma_r^2\left|\frac{\mathrm{d}\ln \rho_*}{\mathrm{d}\ln r}\right|$$

more concentrated stellar distribution gives a higher mass at fixed observed velocity dispersion

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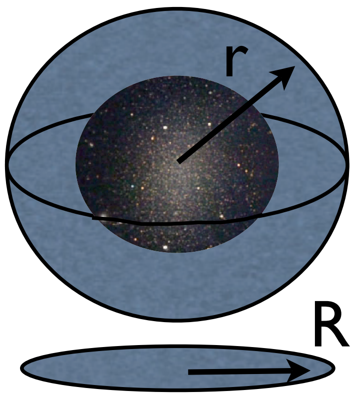
Simple Estimate: Only look at central (R=0) los velocity dispersion



$$\sigma^2_{los}(R) = \frac{2}{I_*(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2}\right) \frac{\rho_* \sigma_r^2 r \mathrm{d}r}{\sqrt{r^2 - R^2}}$$

Assume β = 0

$$\sigma_0^2 = \frac{2}{I_*^0} \int_0^{R_t} \rho_* \sigma_r^2 \mathrm{d}r \simeq \frac{2}{I_*^0} \int_0^{R_t} \alpha \rho_* V^2(r) \mathrm{d}r$$

one constraint

At least 2 unknowns

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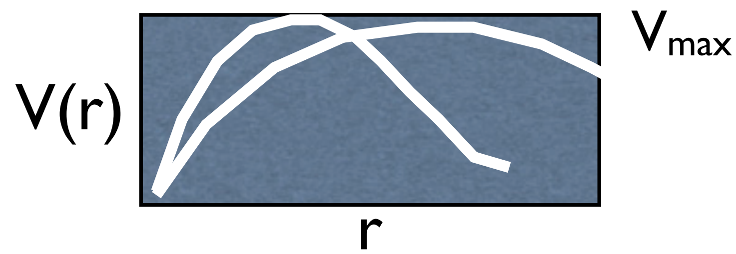

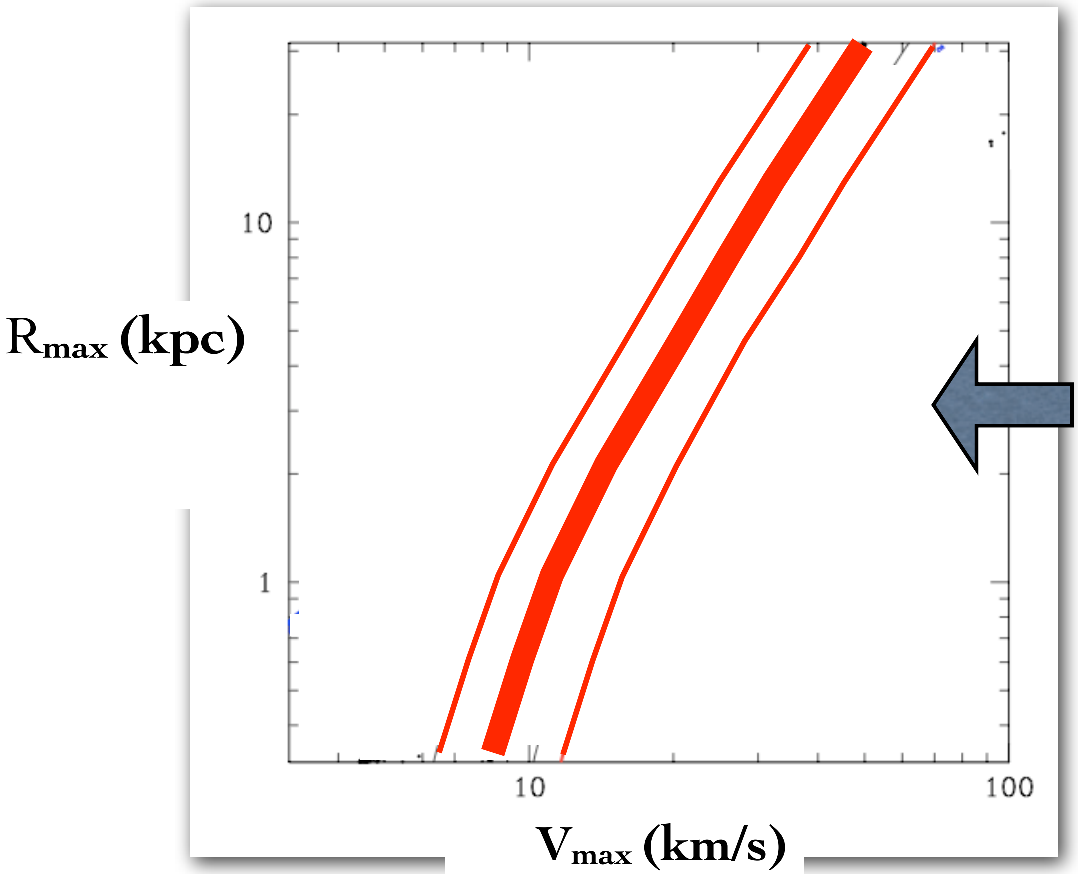

This region matches central velocity dispersion of Carina.(width is central velocity dispersion error)

Zentner & JSB 03

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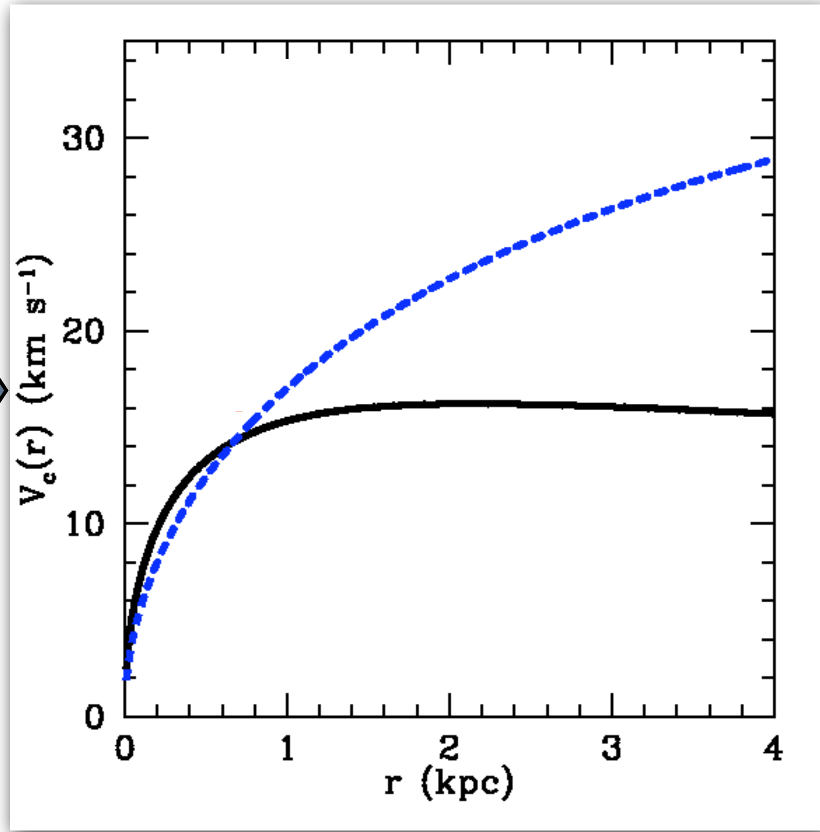
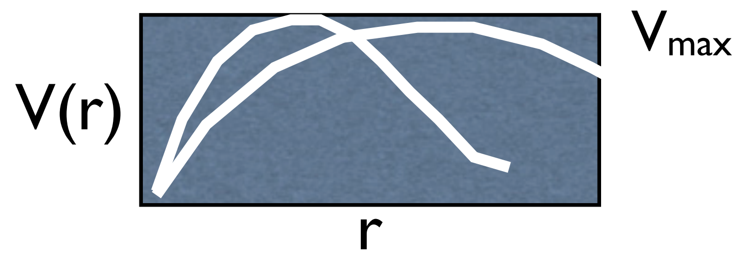
Dwarf V_{max} is hard/impossible to measure directly

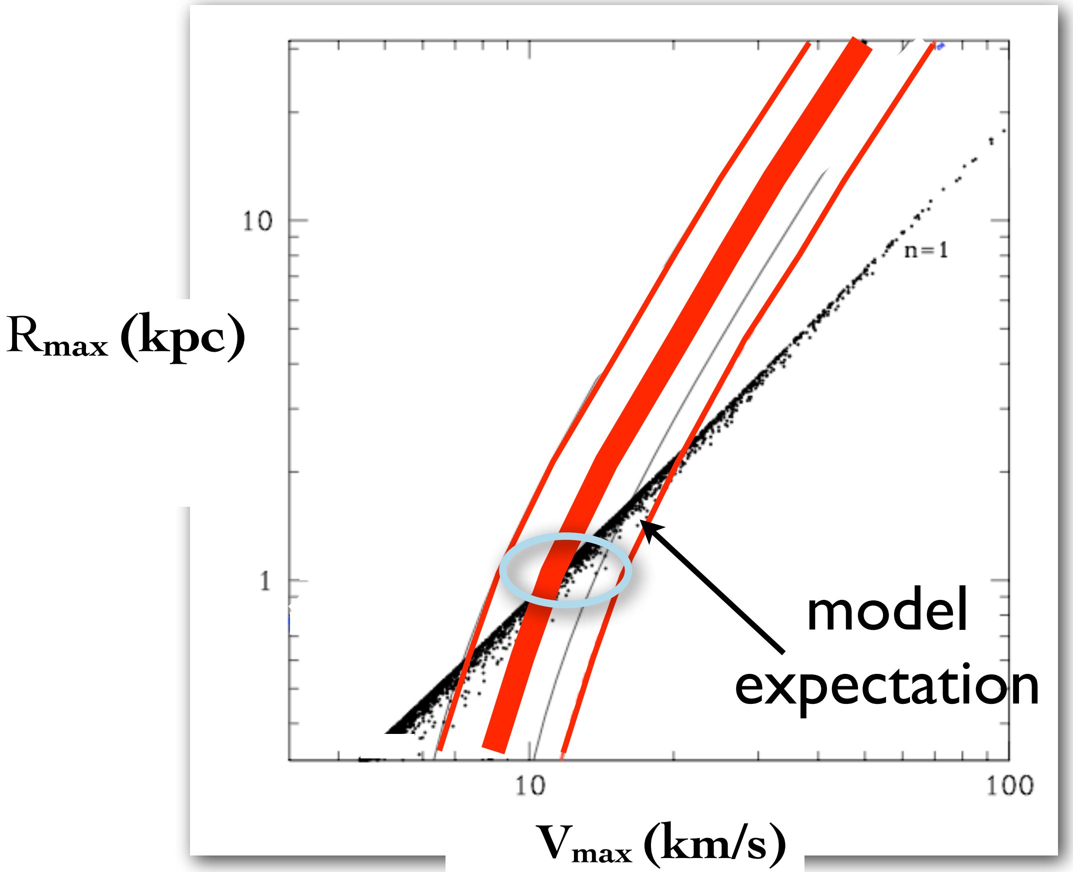
Both of these rotation curves reproduce observed velocity dispersion of Carina



Zentner & JSB 03

Need to add theoretical Prior to determine V_{max}



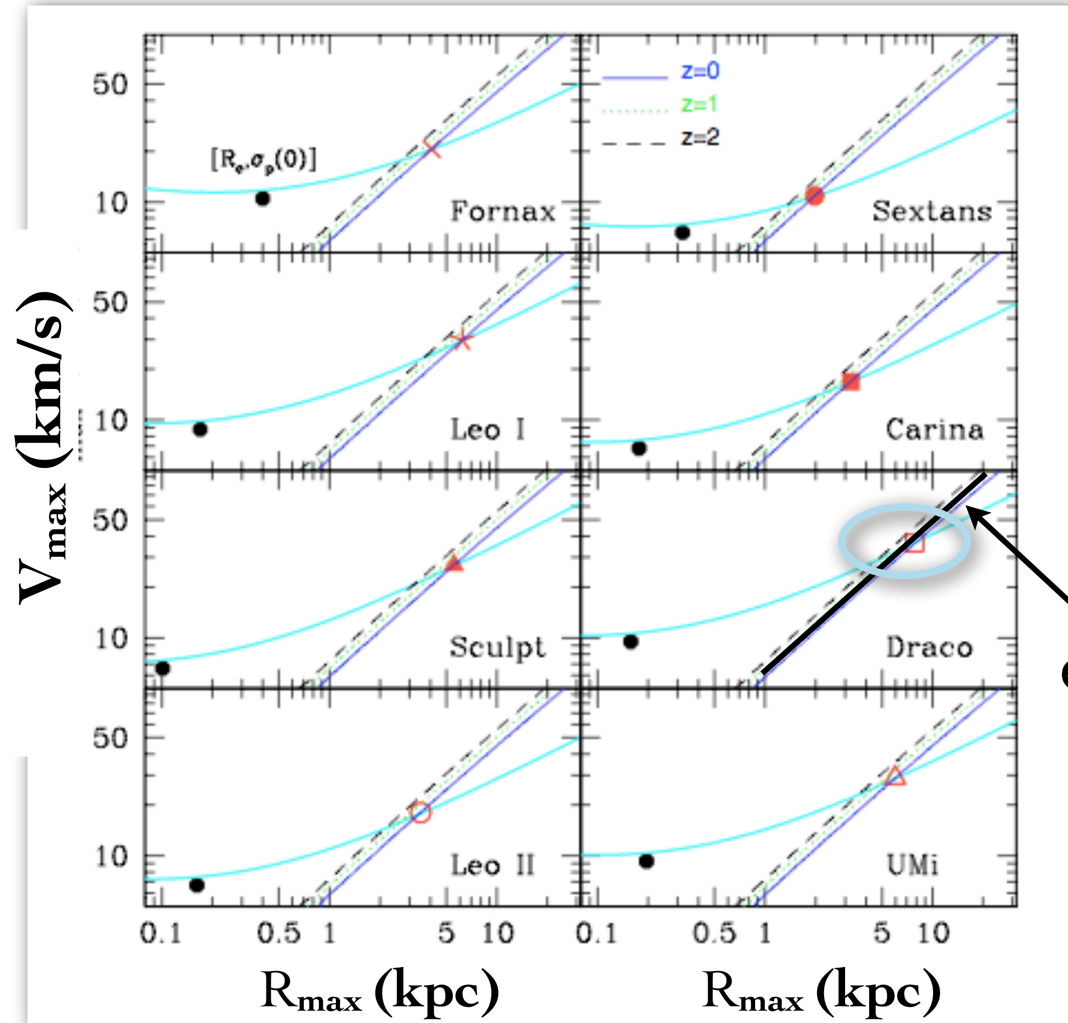


Zentner & JSB 03

https://webfiles.uci.edu/bullock/Public/Canary2008/

Need to add theoretical Prior to determine V_{max}

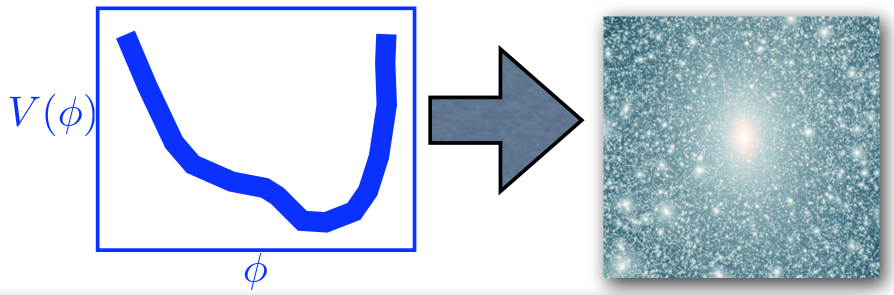
Here: LCDM-motaved V_{max}/R_{max} relation + $\beta = 0$

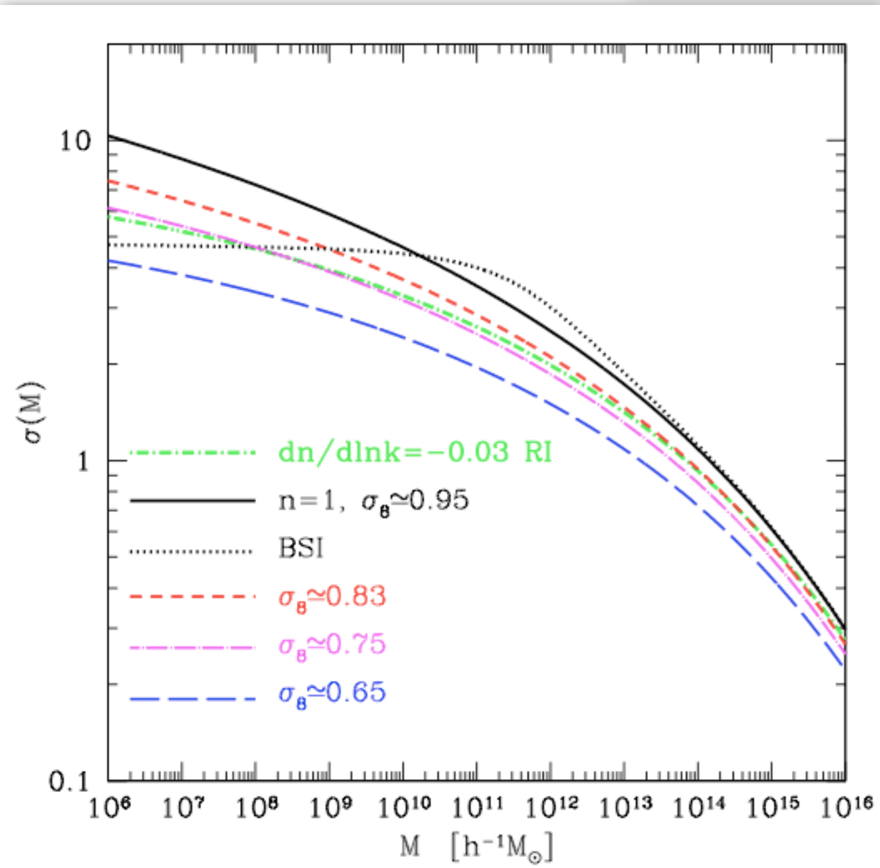


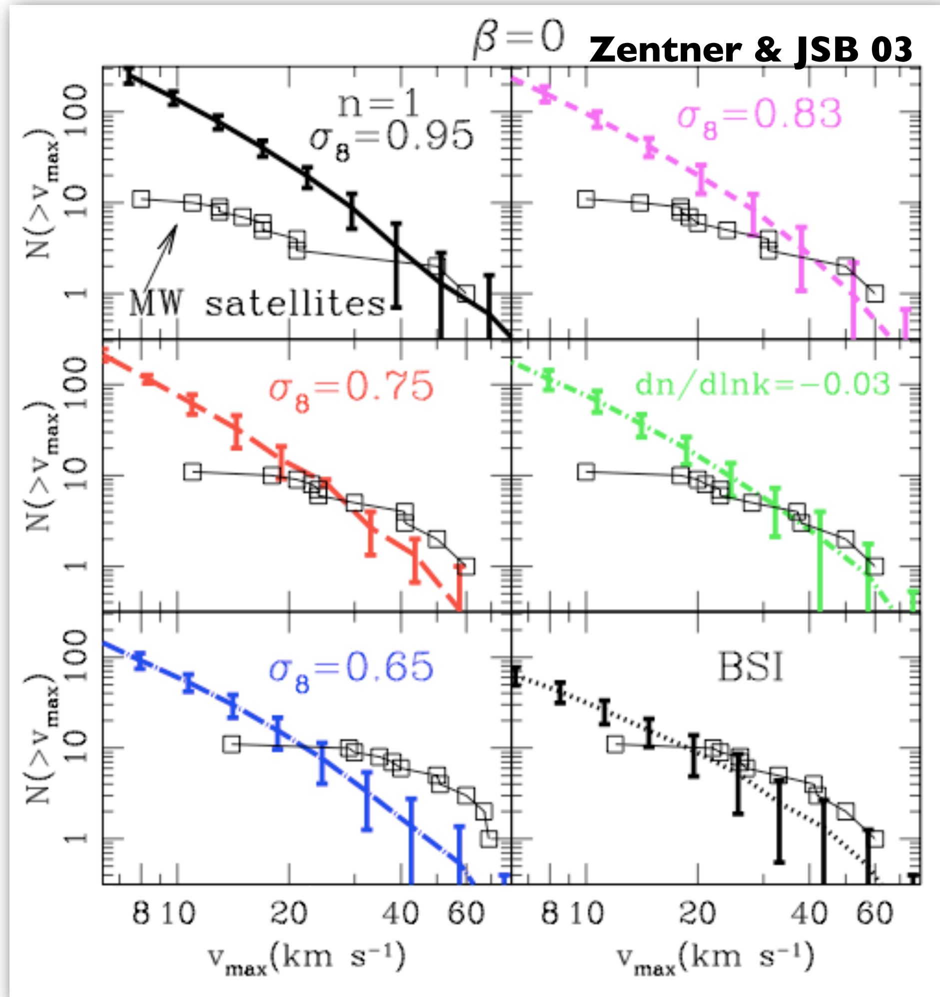
Penarrubia et al. 2008

model expectation

https://webfiles.uci.edu/bullock/Public/Canary2008/







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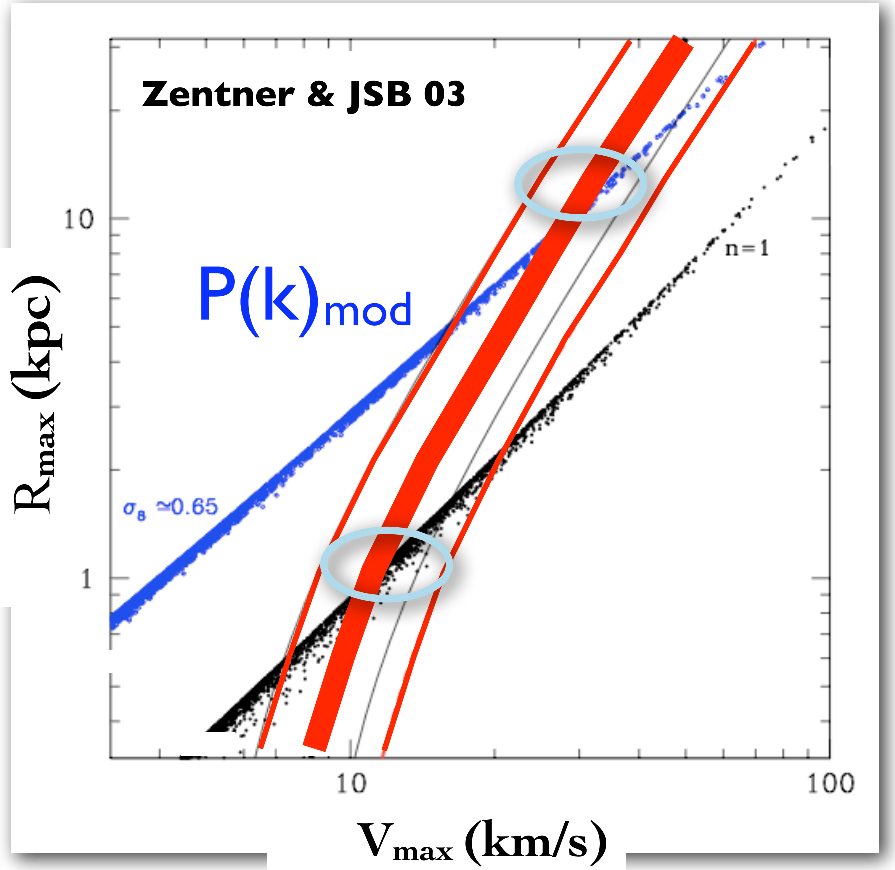

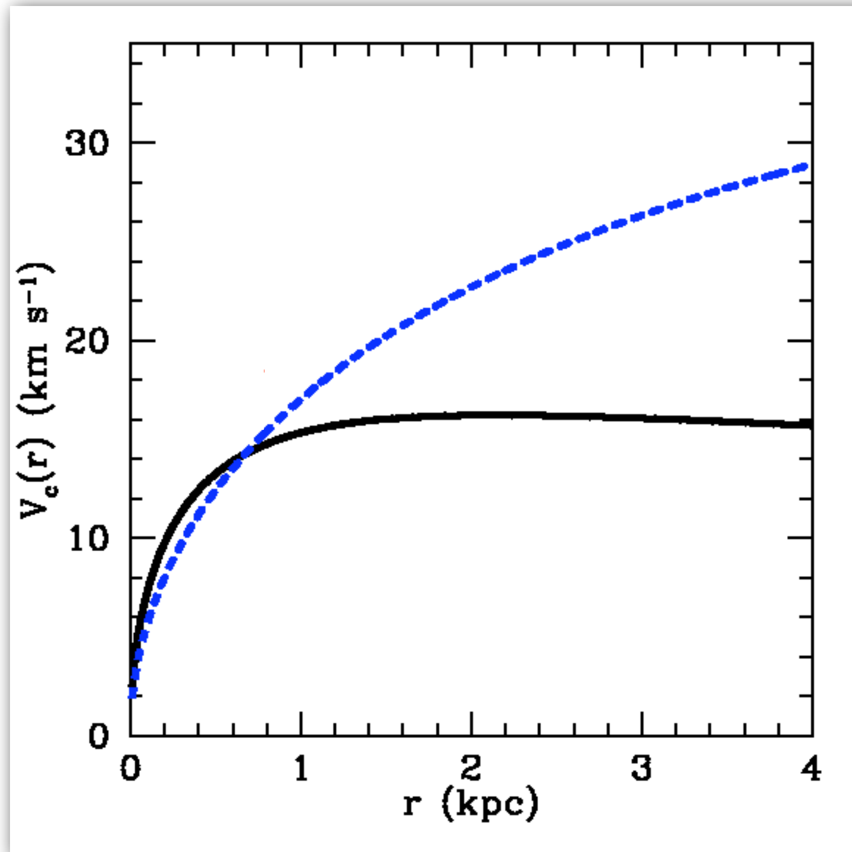

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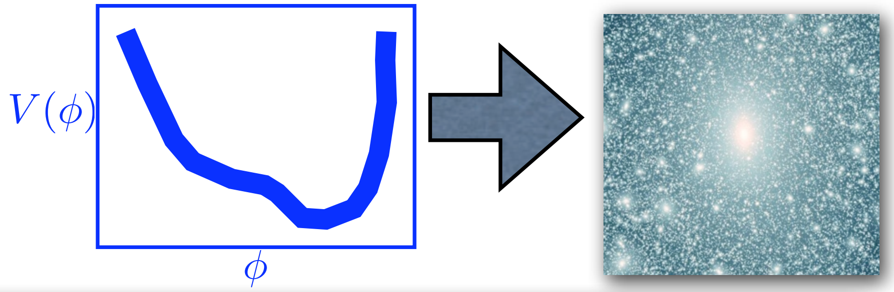

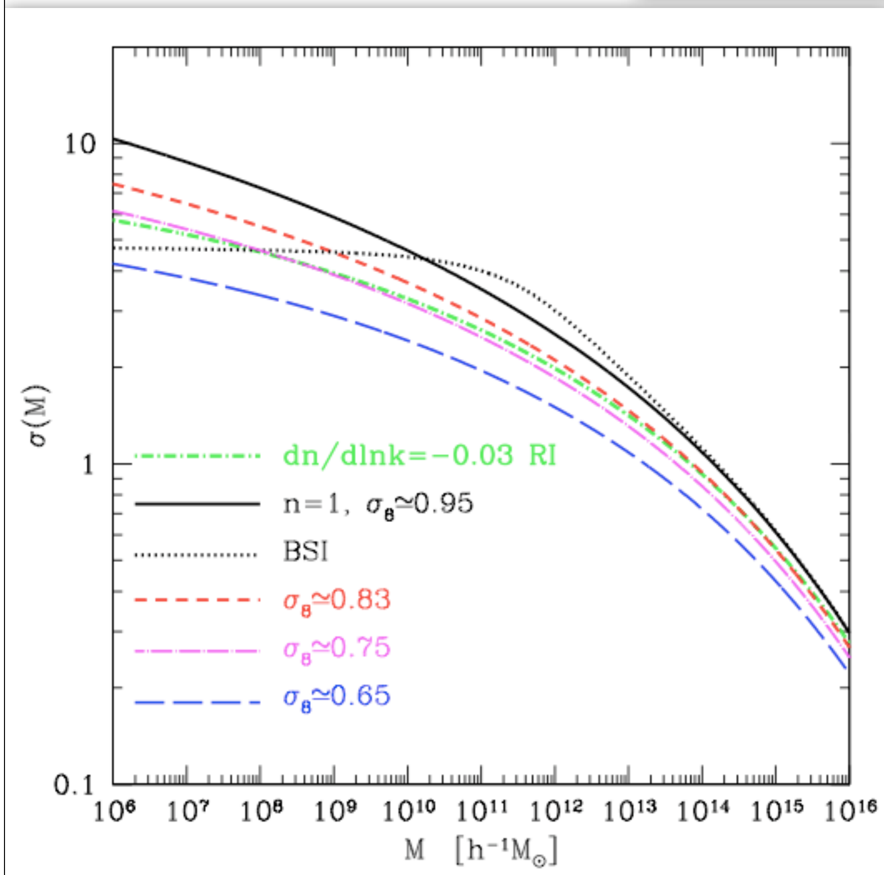

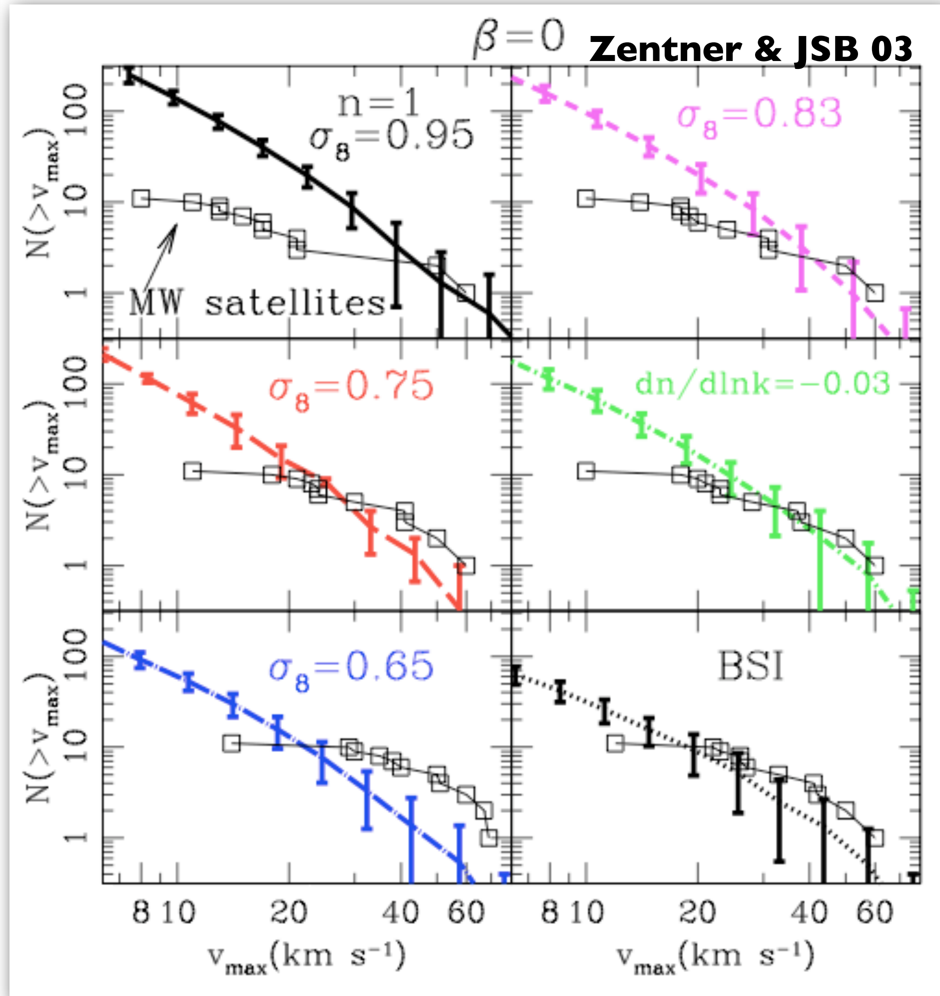

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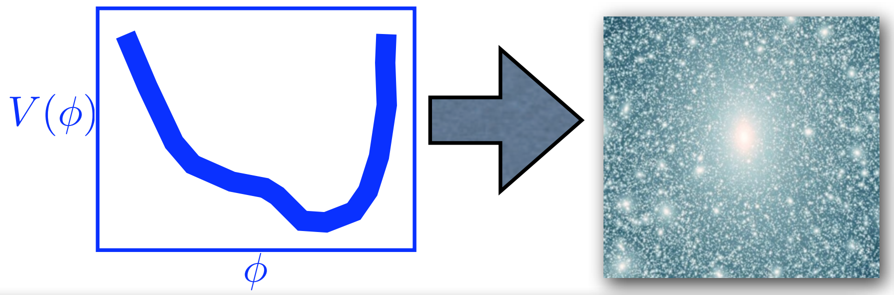

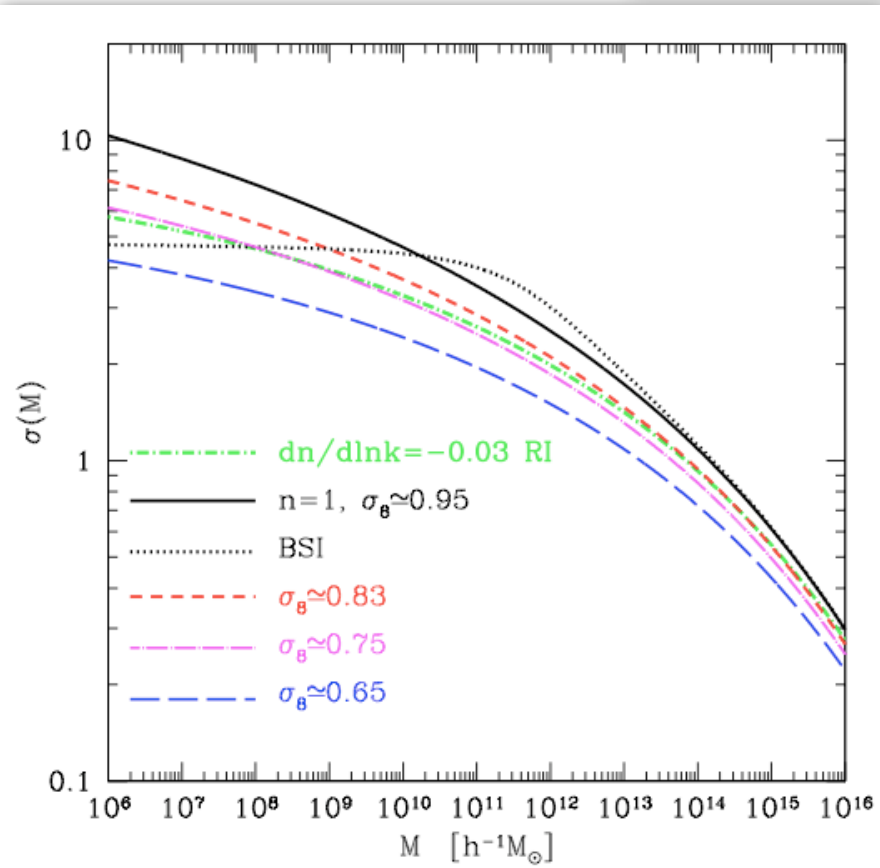

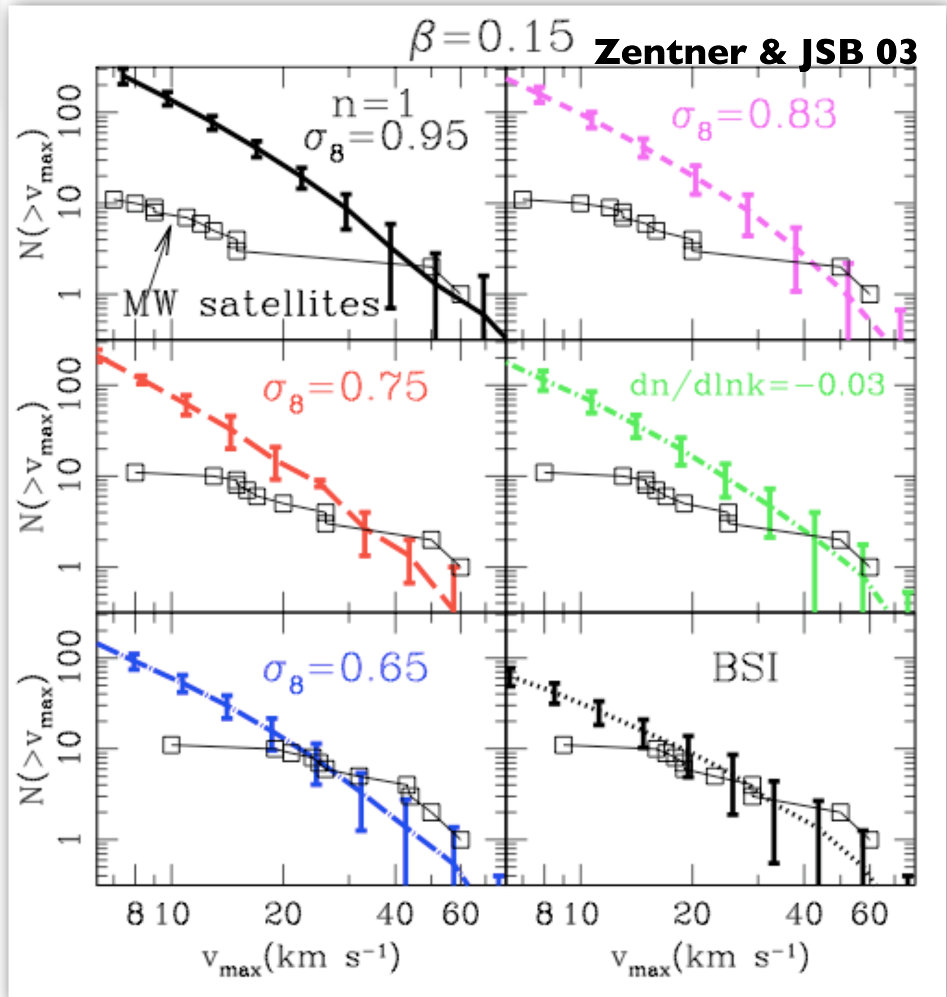

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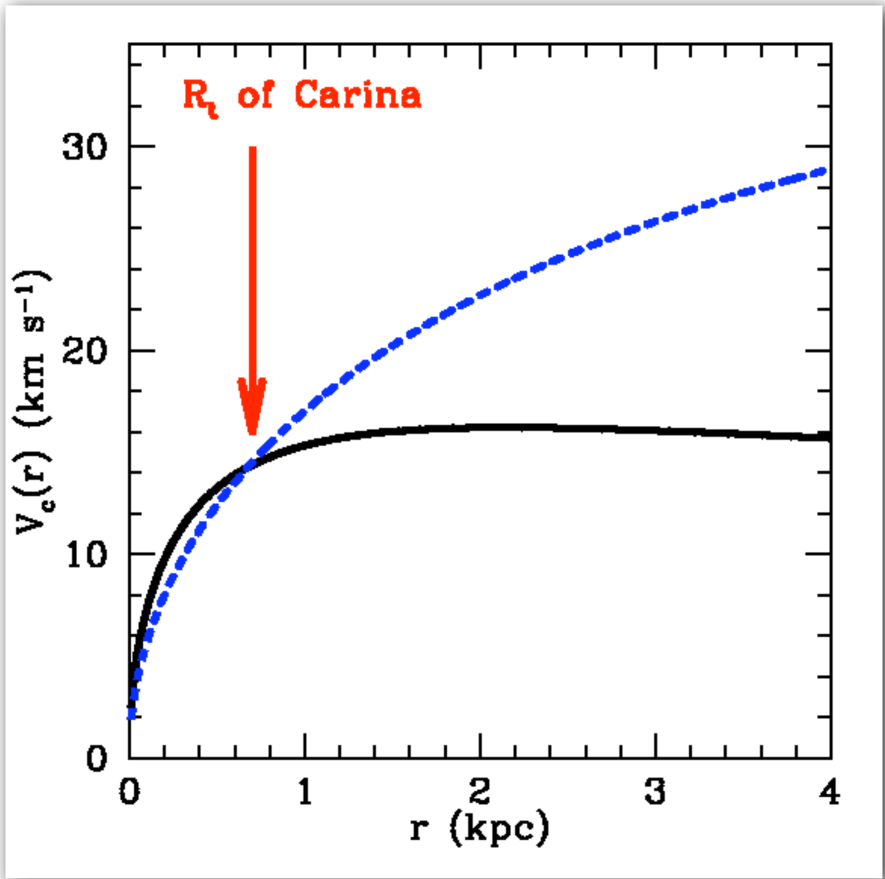
What can we determine?

Mass within the stellar radius



Strigari et al. 07

End Lecture 2

https://webfiles.uci.edu/bullock/Public/Canary2008/