Controversies of LCDM on small scales

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Cosmology on the Beach 2014, Los Cabos

Contents

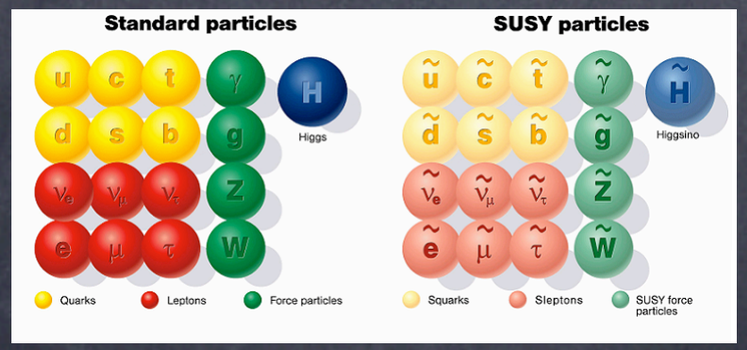
- LCDM, the simplest cosmological scenario
- What are the LCDM controversies on small scales?
- Is baryon physics behind the controversies?
- Relax assumptions: dark matter alternatives
- Key challenges
- Concluding remarks

...To take home

- A better understanding of the gastrophysics and the baryon-dark matter interaction is necessary to acquire before claiming for issues at small scales

- Key tests for LCDM: discovery of the predicted abundant substructure and the halo triaxiality

- The dark sector is likely much more complex than our simple models, with its own (self)interactions and particle zoo. SIDM is promising.



The emergence of the CDM scenario

Critical issues in Astronomy/Cosmology during decades

1. Dynamical inferences from observations (under GR and Newton dynamics) in conflict with *luminous mass* distributions → ***lack of gravitational forces***

- *kinematics of galaxies and clusters* ($V_{rot}(r)$, $\sigma(r)$, etc.) **+**
- *cosmological determinations of baryonic and dynamical mass densities:* $\Omega_b << \Omega_{dyn}$ **+**
- *gravitational lensing.*

2. Galaxy ***disks are dynamically unstable,*** but today ~80% of galaxies are of disk type

3. Silk damping of baryonic fluctuations in the hot universe erases perturbations of scales $<10^{13}$ M_{sun} --> ***no seeds for galaxy formation!***

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- *gravitational lensing.*

Dominant fraction of non-baryonic DARK MATTER.

DM should be COLD to avoid free-streaming (WARM DM could work well too).

Besides in Particle Physics the dark sector is required

Lacking forces in galaxies/clusters + dynamical stability of disks + issues of $\Omega_b << \Omega_{dyn}$ & Silk damping + necessity of a dark sector in the SM of particles (best candidates: WIMPs)

Cold Dark matter and Λ

- If Ω_{tot}=1 and h=0.7, T<12 Gyr
- Observations: Ω_{dyn}~0.3 but first peak in the CMBR anisotropies Ω_{tot}=1
- ***Accelerated expansion (SN Ia, GRBs, BAOs)***

(Λ)CDM: *A cosmological and cosmogonical scenario developed iteratively on the basis of astronomical observations and within the context of the standard physical theories and models.*

Fundaments and predictions

Homogeneous universe ⟷ Inhomogeneities

Cosmology

- **Big Bang Theory** *(GR + cosmological principle + SM of particle physics)*
- **Inflationary model** *(GR +quantum field theory + supersymmetry?)*

Consistent with the BBT and Inflation predictions:

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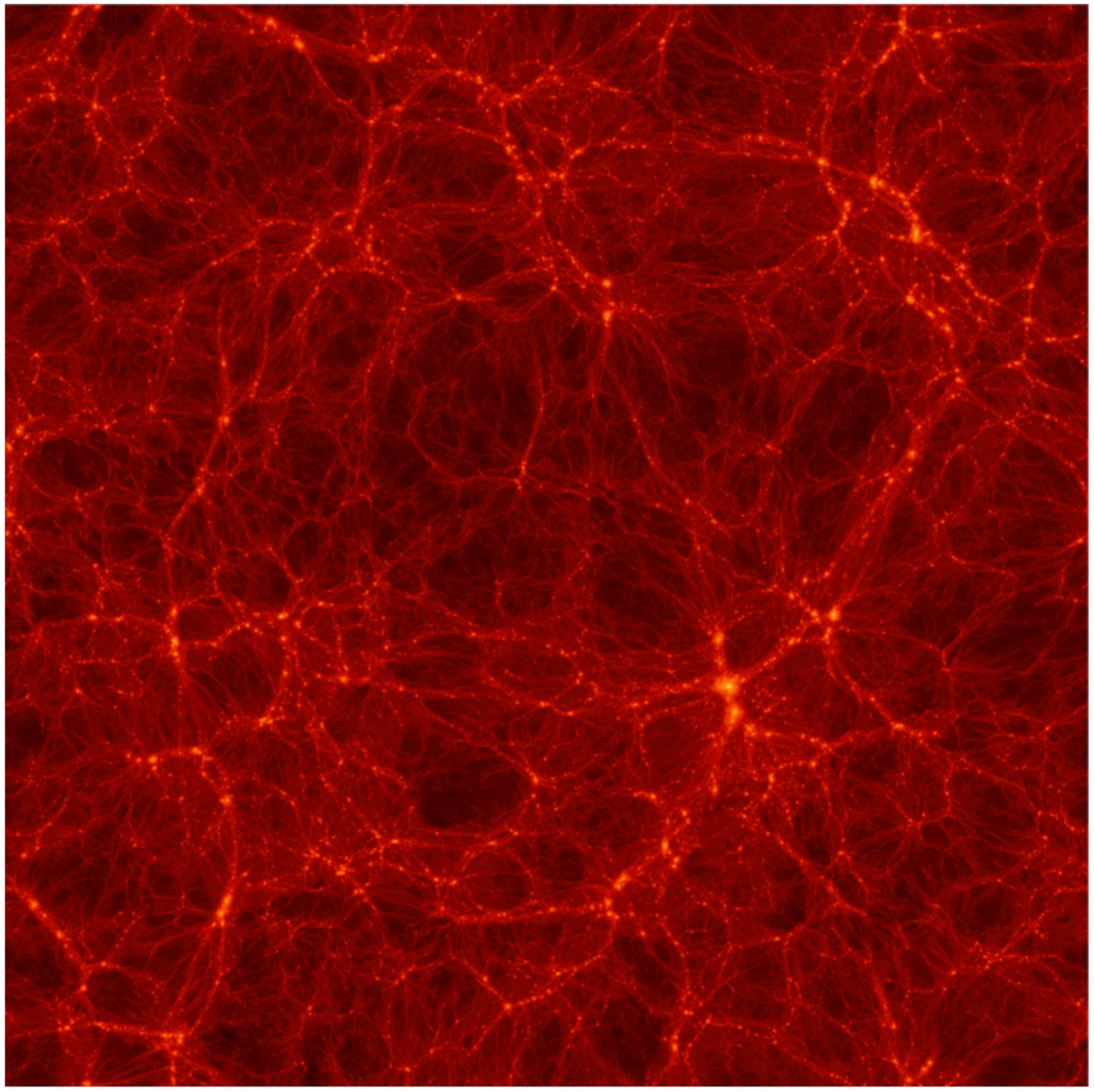
Cosmogony

- **Gravitational paradigm + relativistic hot plasma thermo-hydro-dynamics** *(Silk damping!)*
- **Gravitational collapse and Galaxy Formation** *(non-linear and complex gastrophysics, yet in diapers)*

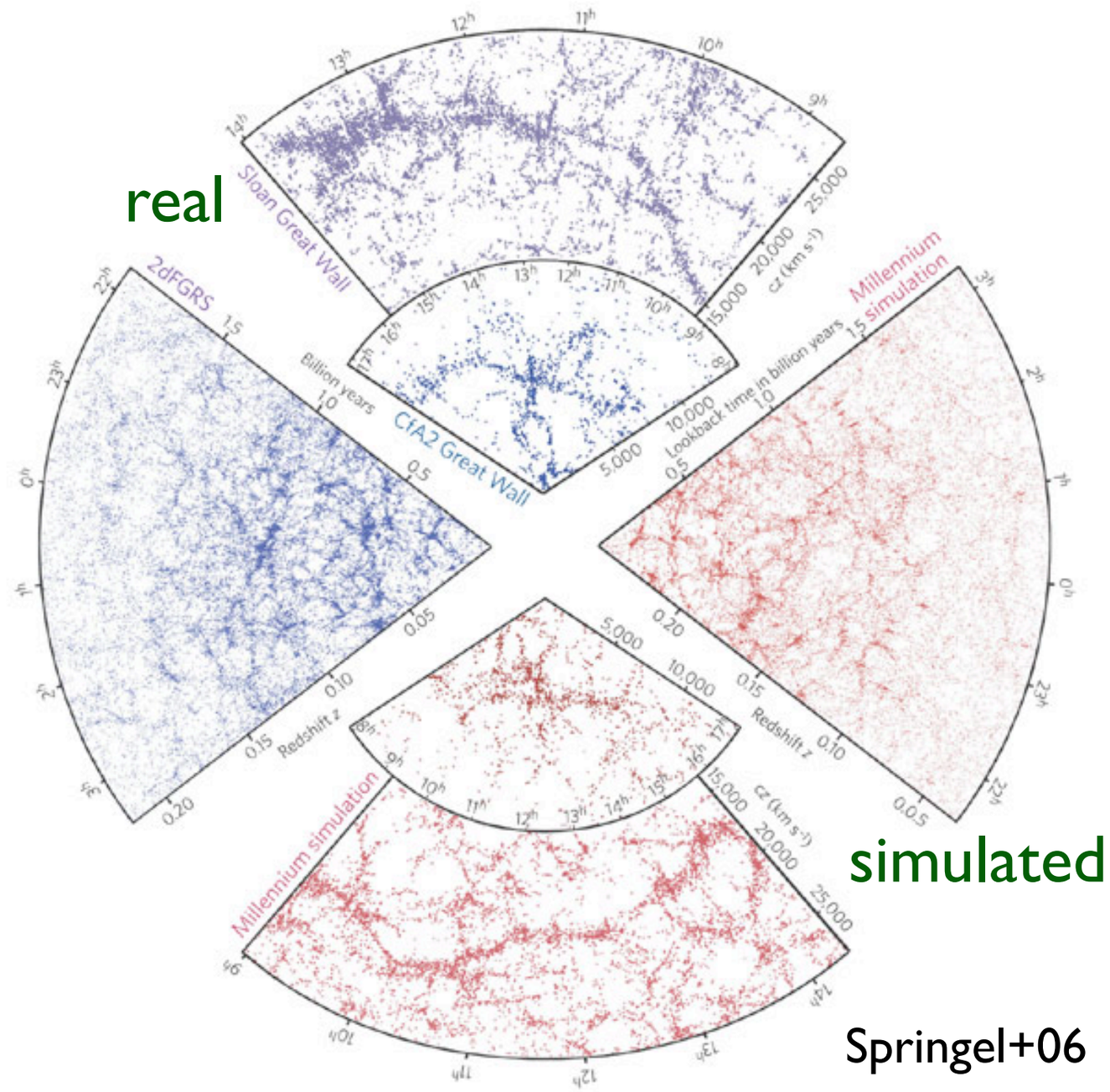
Amazing consistency with:

Large scale structure (local and at high z)

LSS from N-body pure DM simulations



Using galaxies as tracers of halos



Springel+06

The gravitational (collisionless) non-linear evolution produces the cosmic web of walls, filaments and voids as observed

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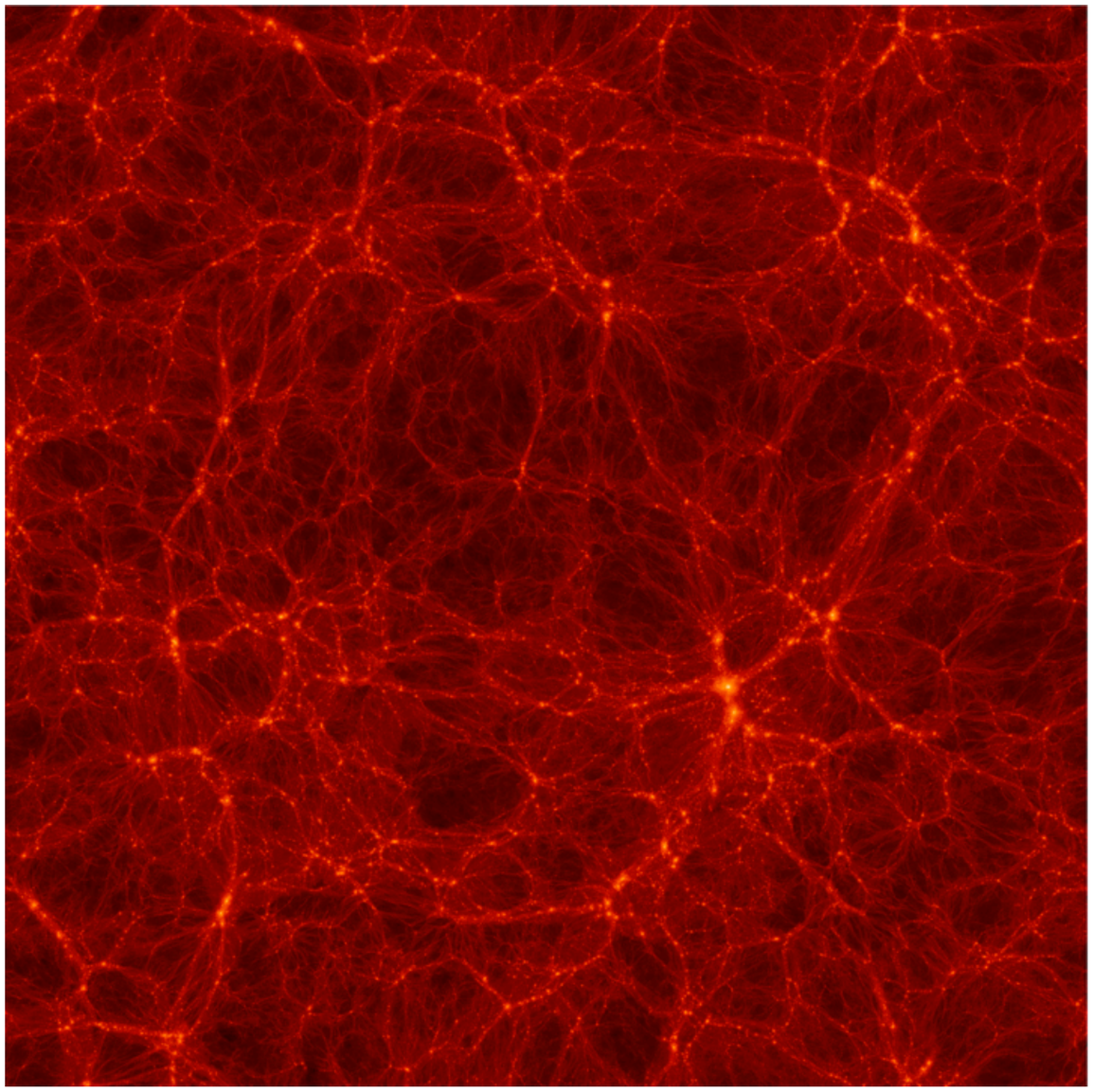
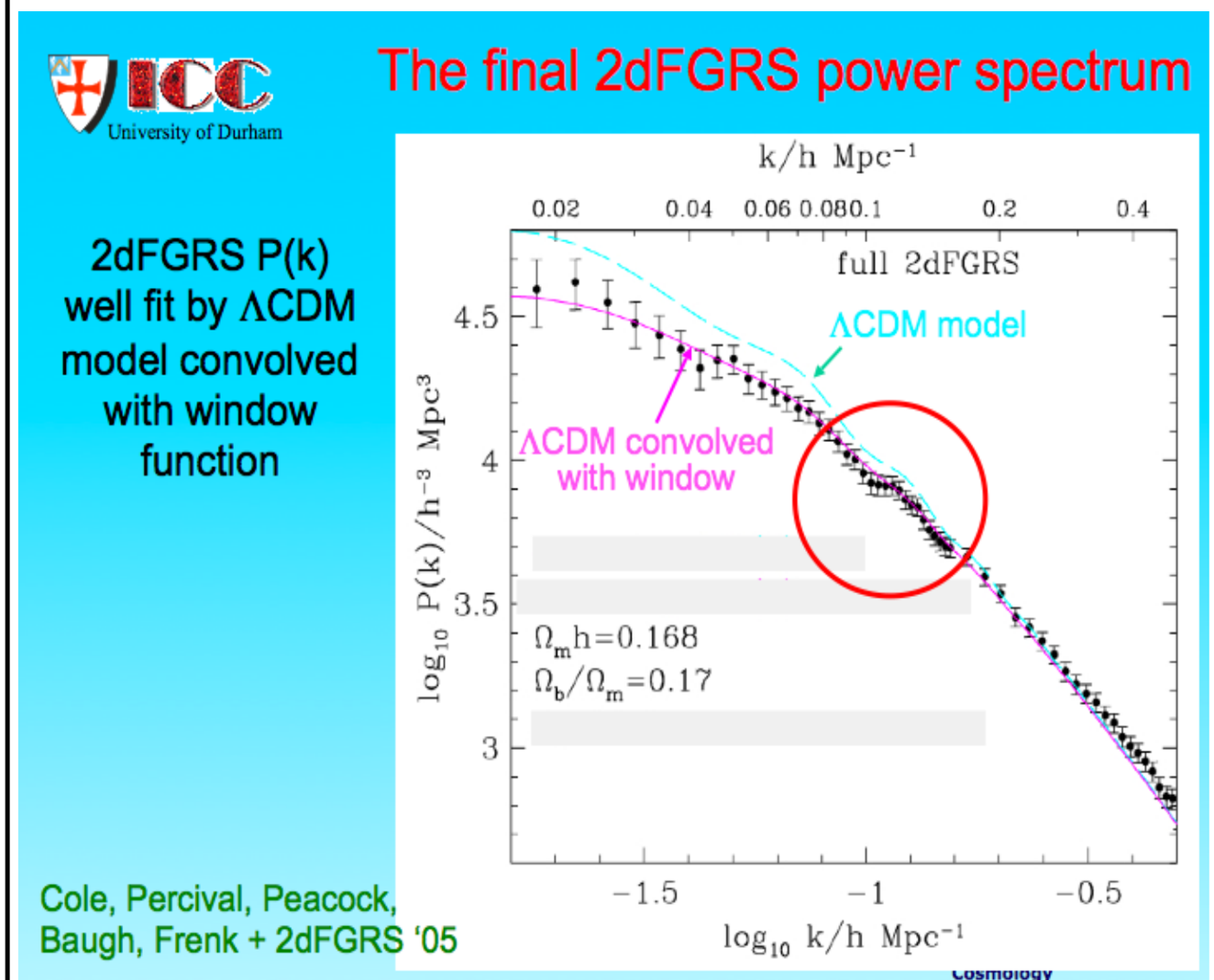


Excellent agreement w/observations of LSS at a quantitative level (*correlation functions, power spectrum, etc.*)



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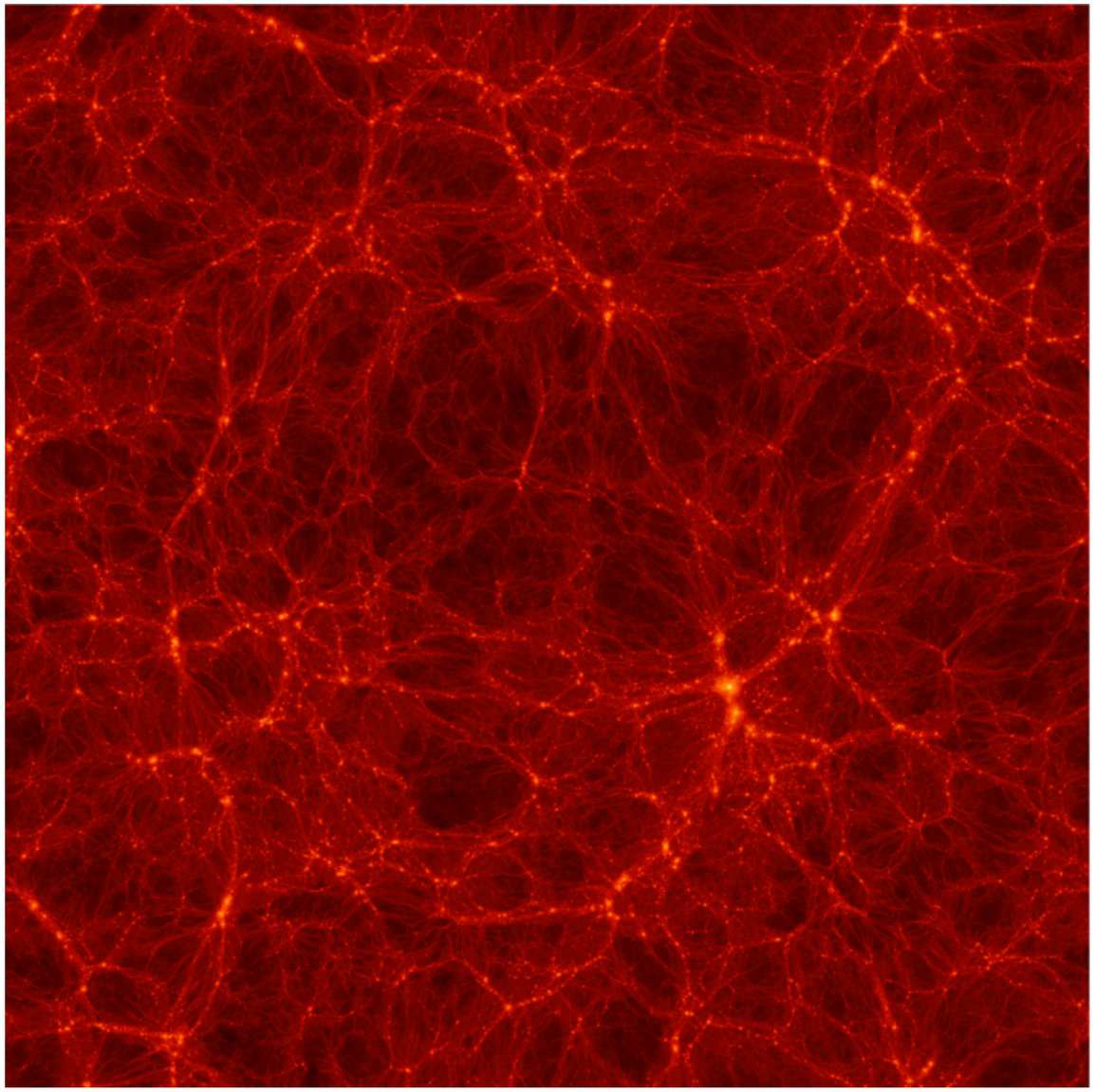

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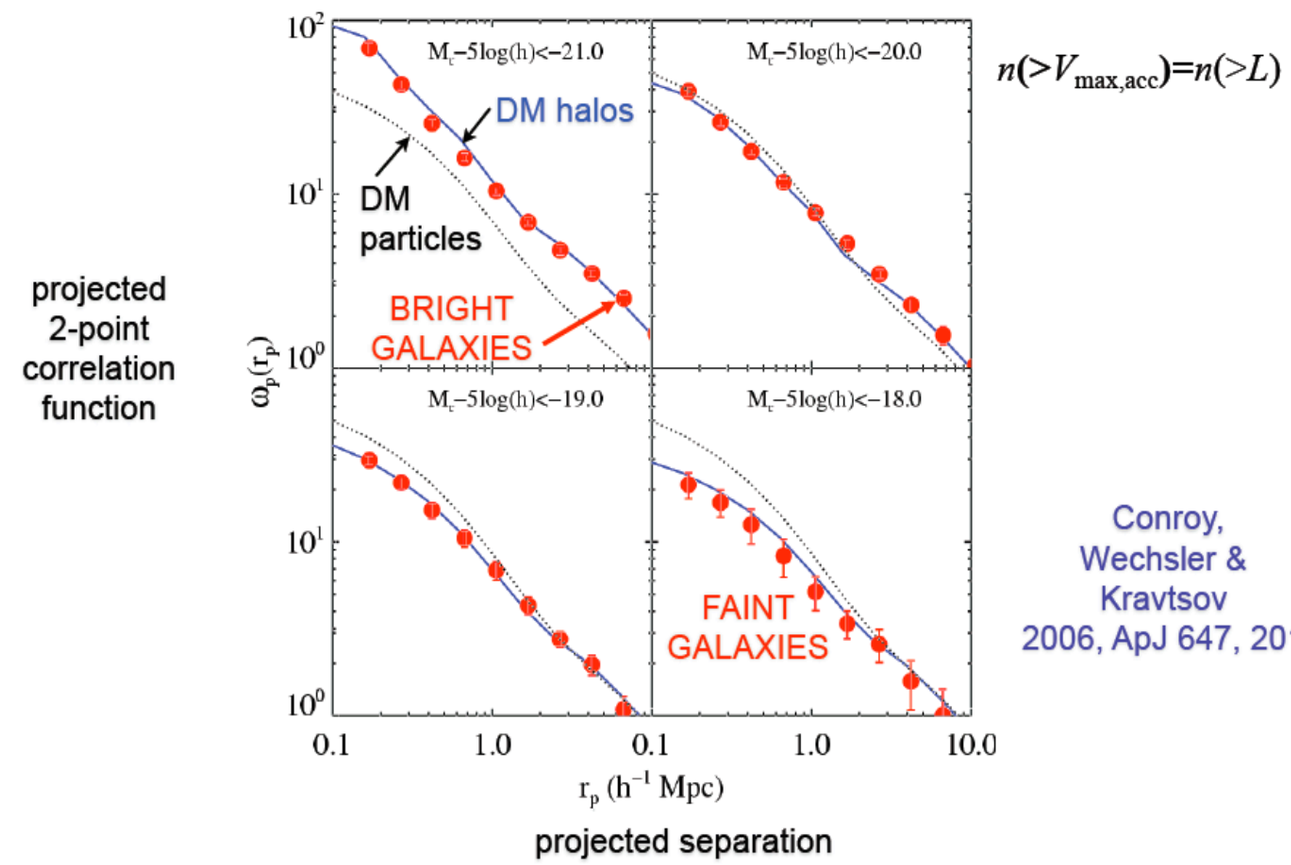
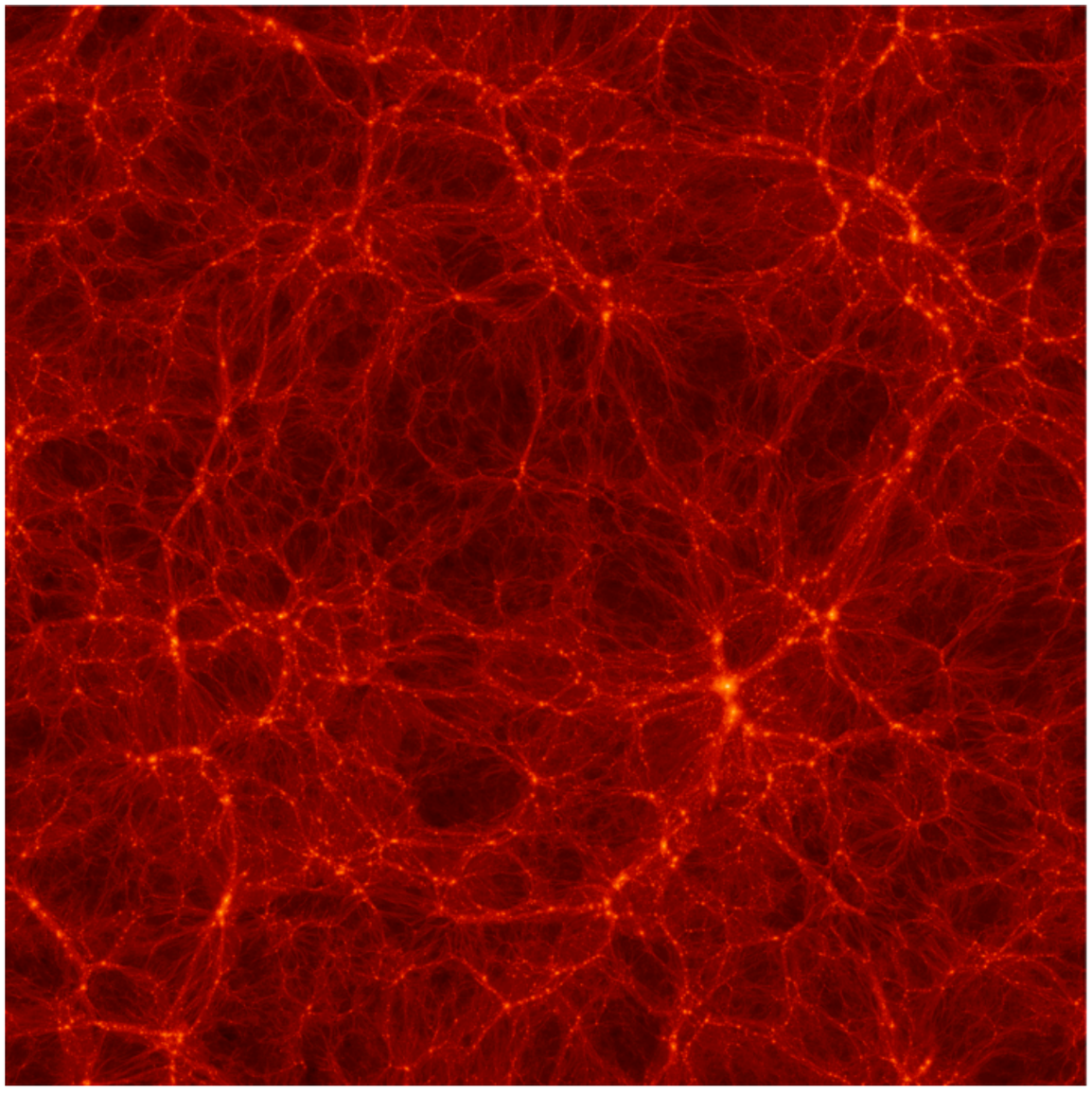
Galaxy clustering in SDSS at z~0 agrees with ΛCDM simulations



Conroy, Wechsler & Kravtsov 2006, ApJ 647, 201

Large scale structure (local and at high z)

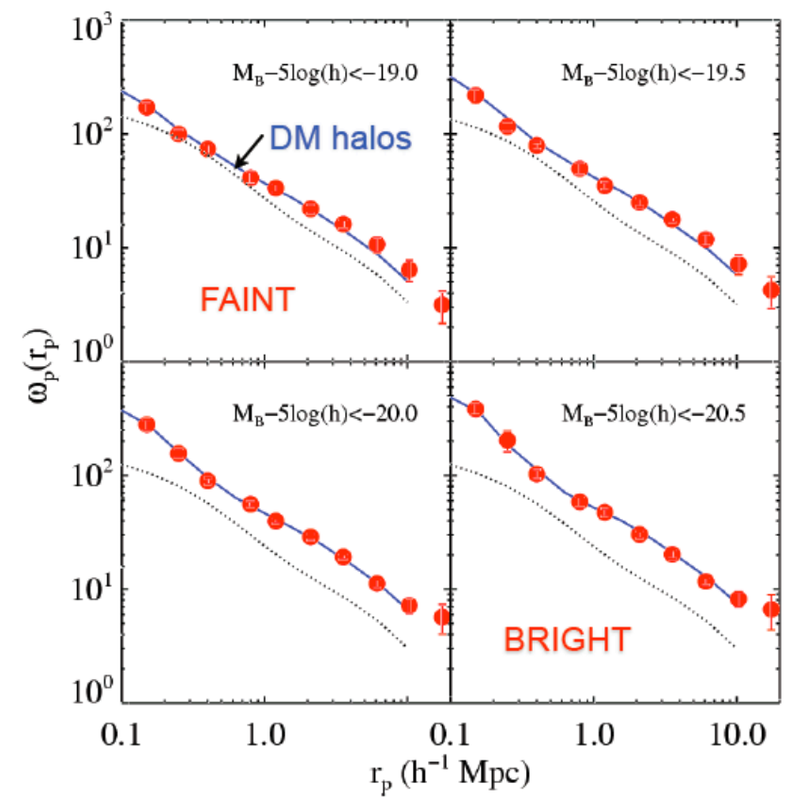
LSS from N-body pure DM simulations



Excellent agreement w/observations of LSS at a quantitative level (*correlation functions, power spectrum, etc.*)

and at redshift z~1 (DEEP2)!

projected 2-point correlation function



$n(>V_{max,acc})=n(>L)$

Conroy, Wechsler & Kravtsov

projected separation

projected separation

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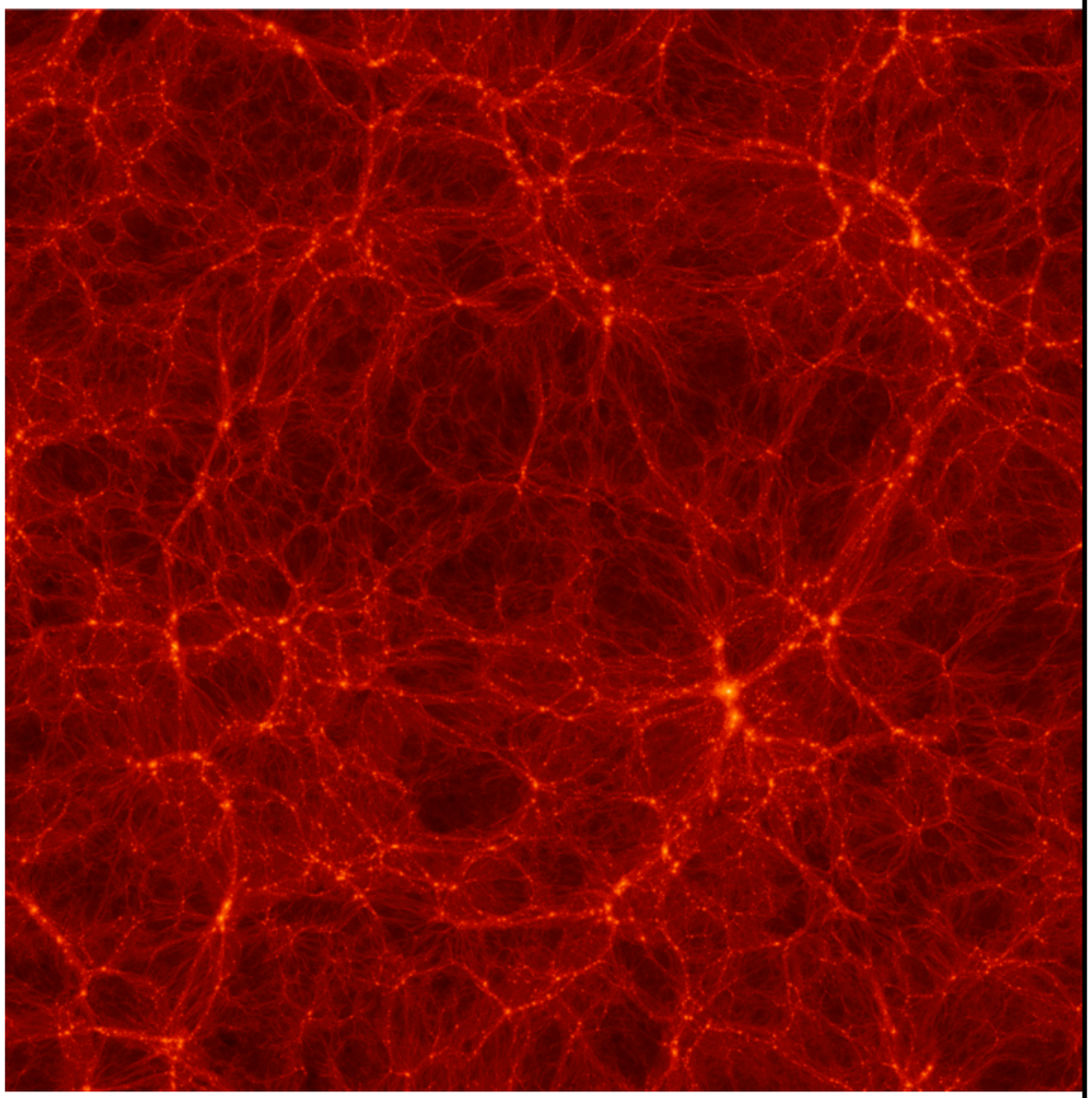
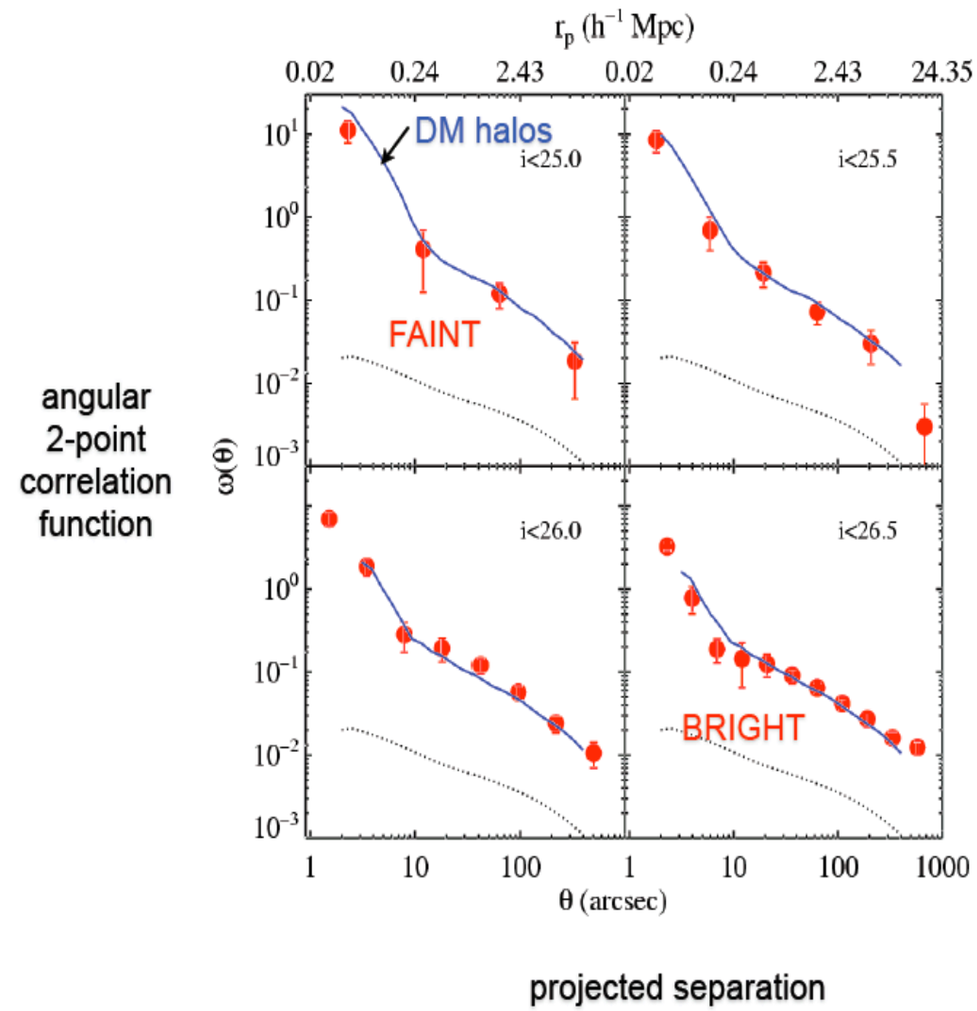


and at z~4-5 (LBGs, Subaru)!!



$n(>V_{max,acc})=n(>L)$

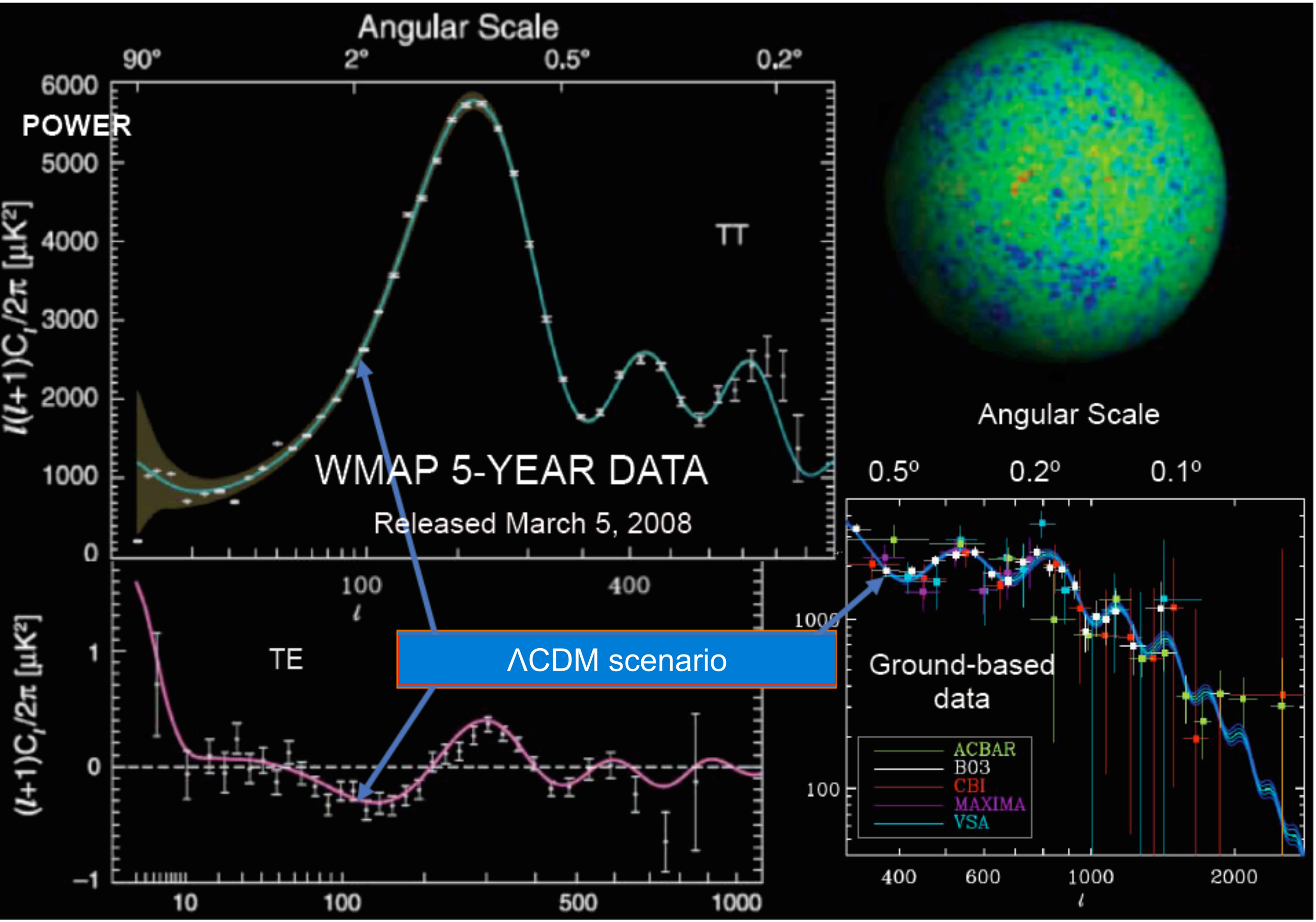
angular 2-point correlation function

projected separation

Conroy, Wechsler & Kravtsov

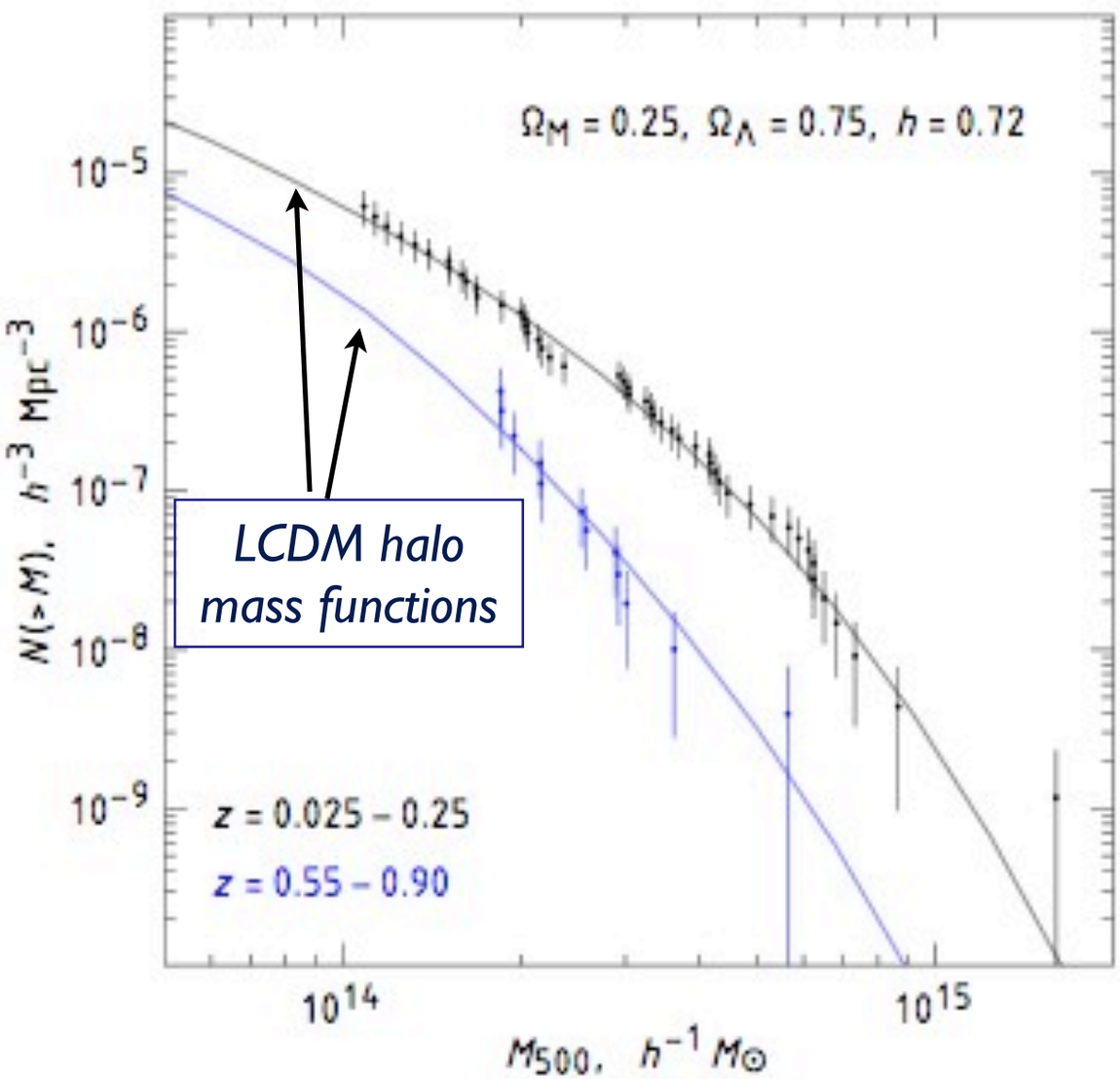
The gravitational (collisionless) non-linear evolution produces the cosmic web of walls, filaments and voids as observed

Fully consistent with the observed CMBR anisotropies

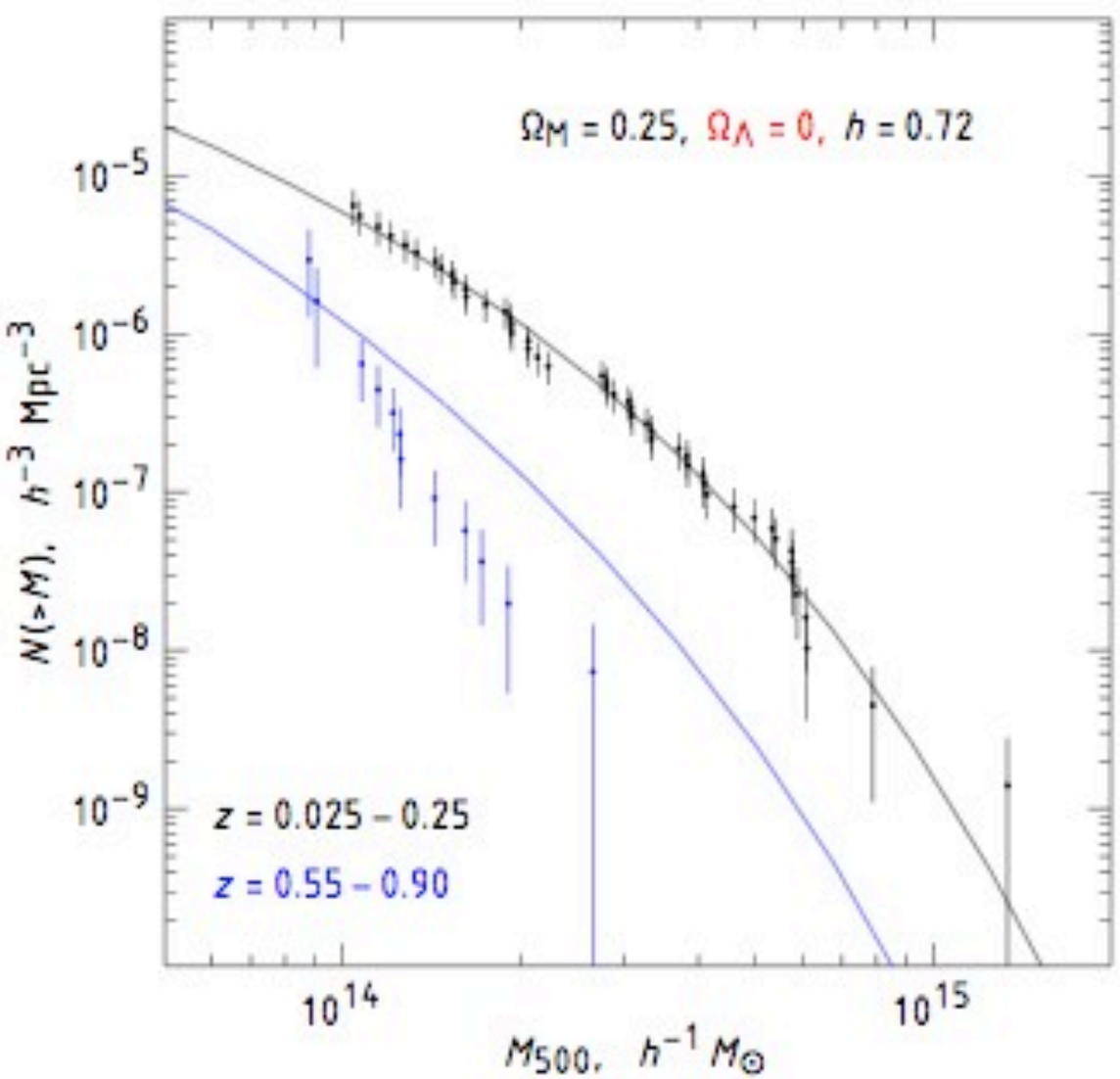


CDM halo mass function = observed cluster/group mass function

At difference of galaxies, the halo masses of clusters can be measured directly (velocity dispersions, hot gas dynamics, lensing)



Vikhlinin+09

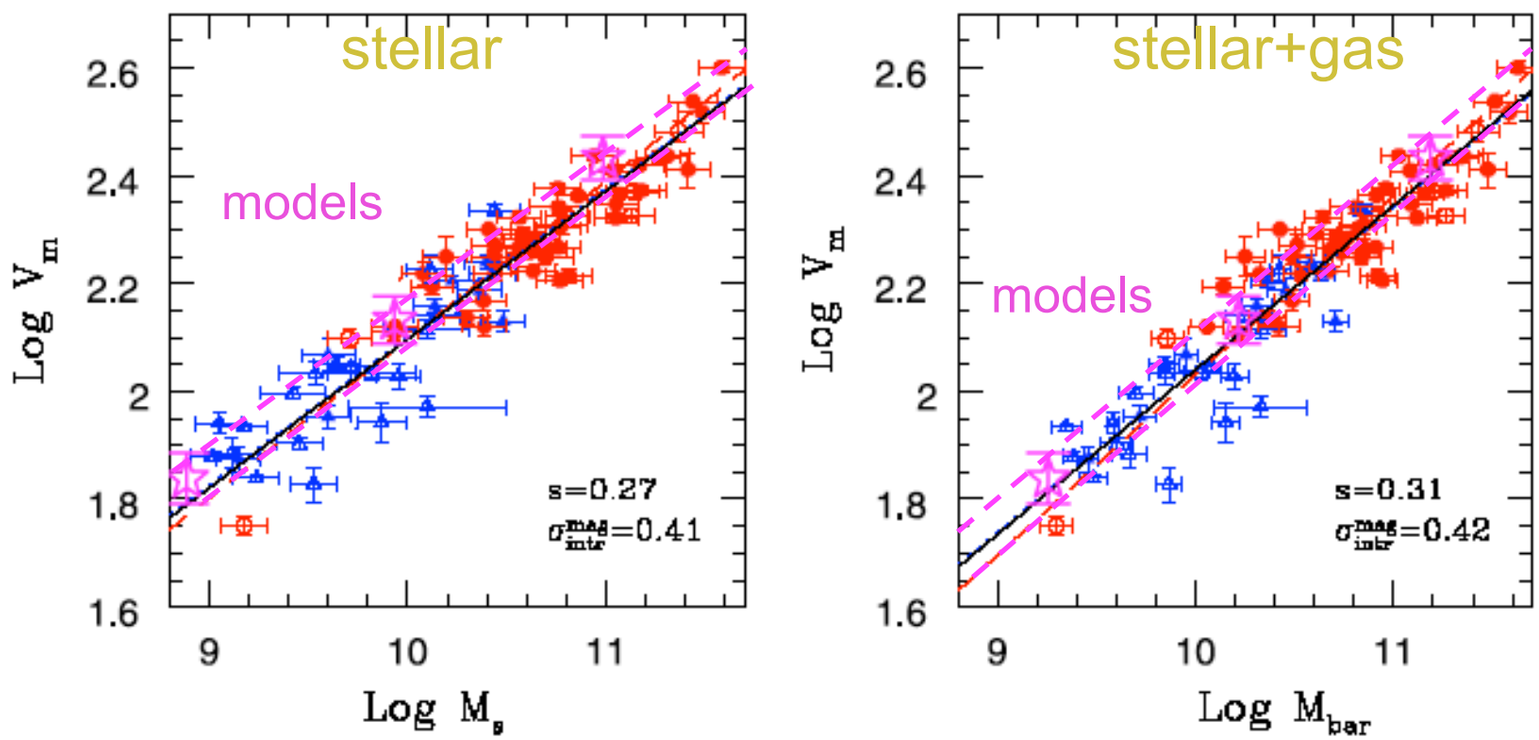


Lambda is necessary!

The Tully-Fisher relation: V_m vs M

an imprint of the ~flat region of the power spectrum of density perturbations

Firmani & Avila-Reese 00; Avila-Reese+ 08



$M_s \propto V^m$, m≈3.3, is a consequence of the **$M_h \propto V^{3.2}$** cosmological relation **(Avila-Reese+ 99), and this is due to the PS flattening:**

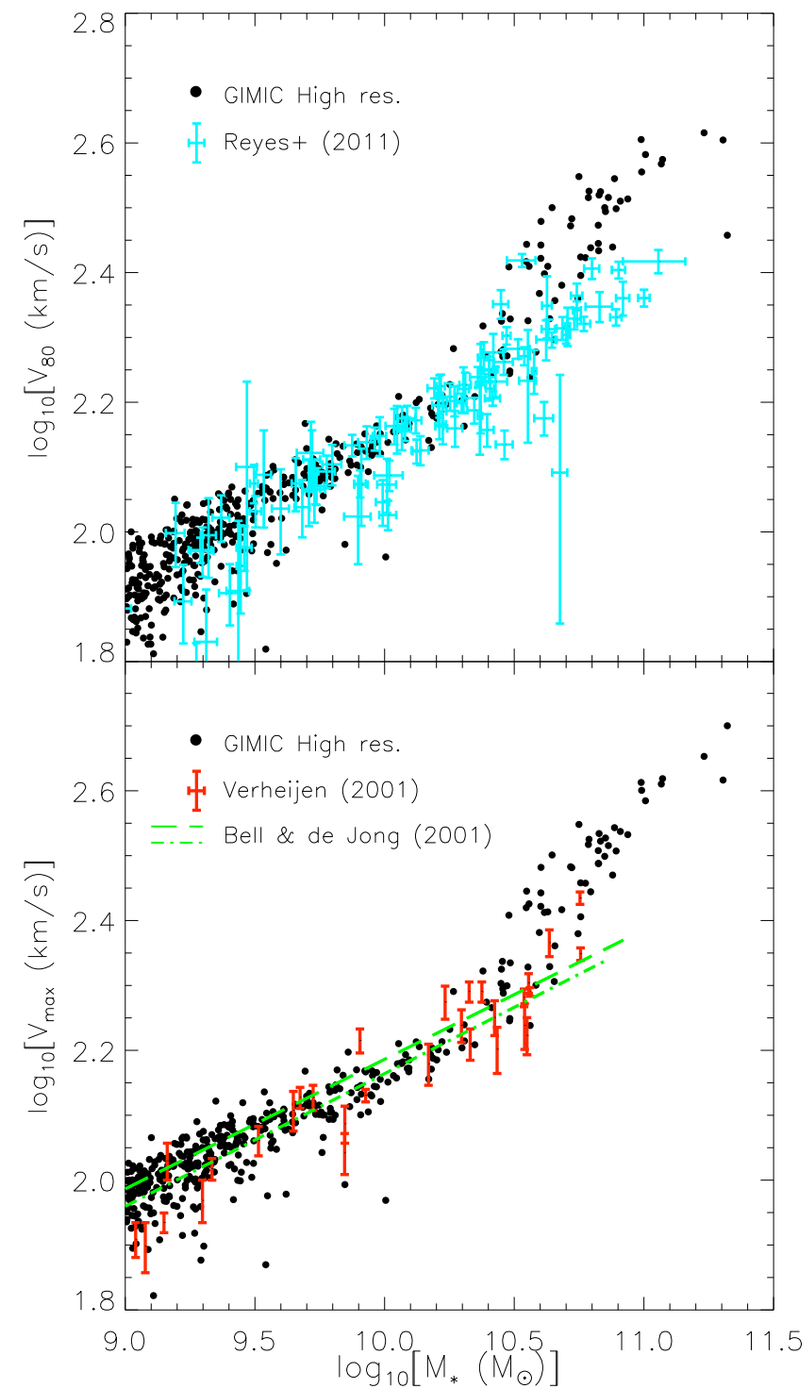
$\sigma \approx$ **const** $\rightarrow$ **$\langle\rho_h\rangle \approx$ const**

$\langle\rho_h\rangle \propto M_h/r^3 \propto$ const

$V \propto (GM/r)^{1/2}$

$$M_h \propto V^3$$

The TFR is an imprint of the primordial power spectrum of density fluctuations



From cosmological simulations

(Λ)CDM, the simplest case: *A cosmological and cosmogonical scenario built up iteratively on the basis of astronomical observations and within the context of the standard physical theories and models.*

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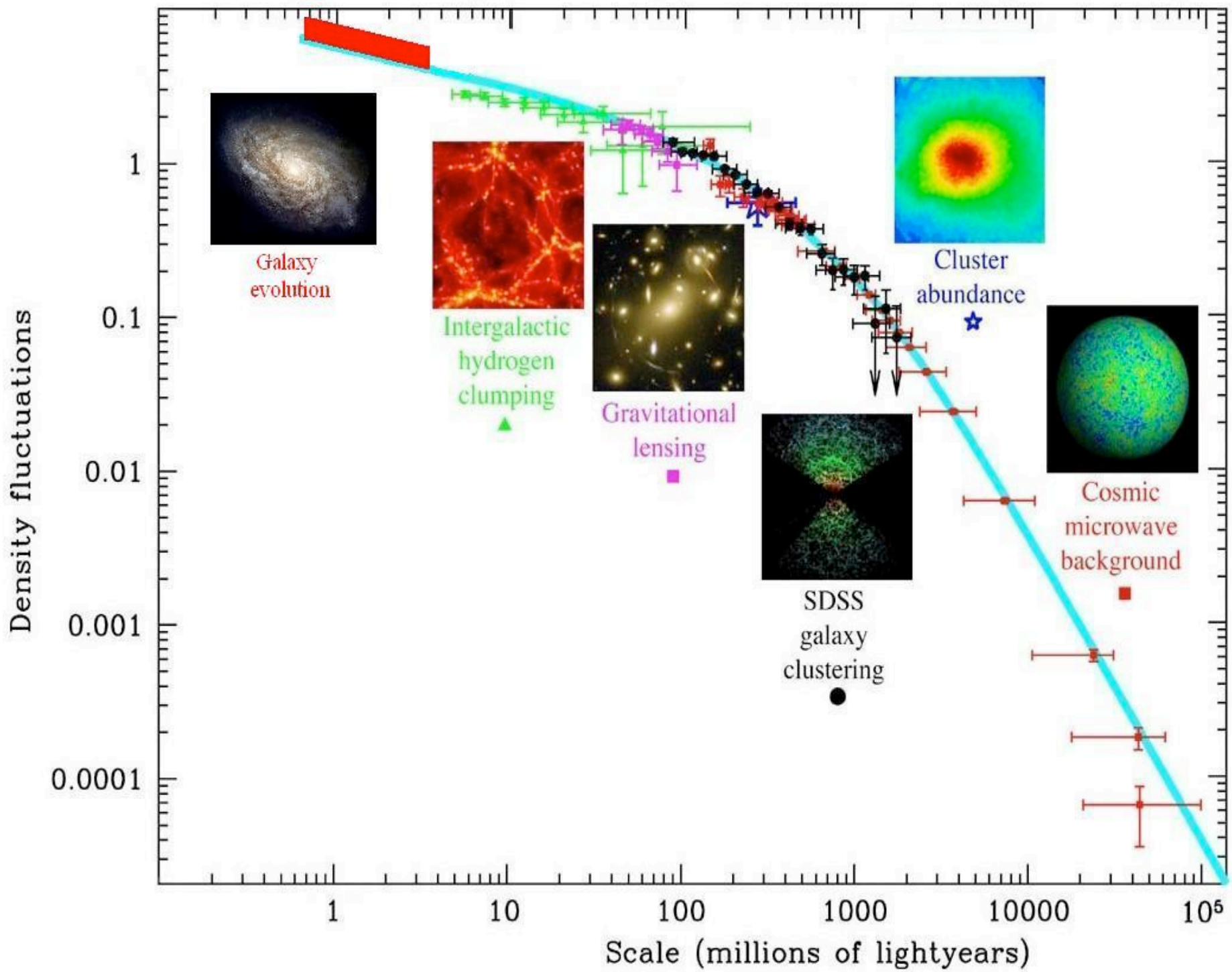
Amazing consistency with: *1) Observed LSS, 2) CMBR anisotropies, 3) Cluster mass function, 4) Tully-Fisher relation, 5) Galaxy properties and correlations?, satellite distributions?, inner structure and dynamics of galaxies?* <-- POTENTIAL SMALL SCALE ISSUES!

LCDM cosmogony: *Gaussian density perturbations, *scale invariant PS without a cut-off, *dominate collisionless, non-interacting, v_{rms}=0 particles.

It's the simplest case from the point of view of cosmic structure formation



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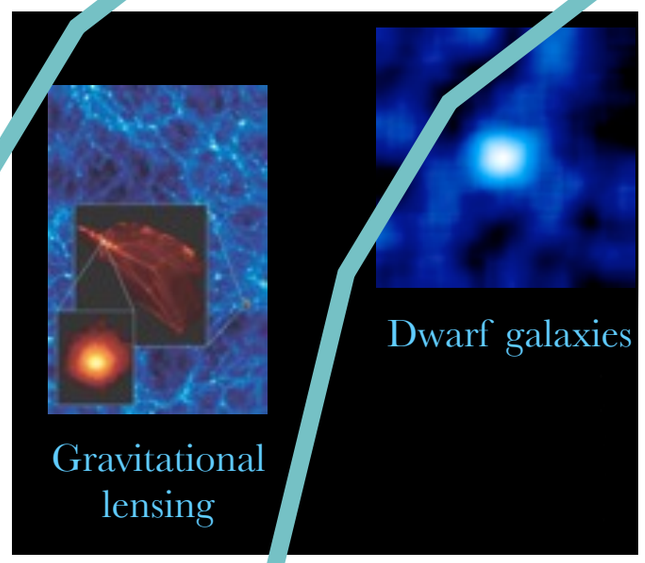

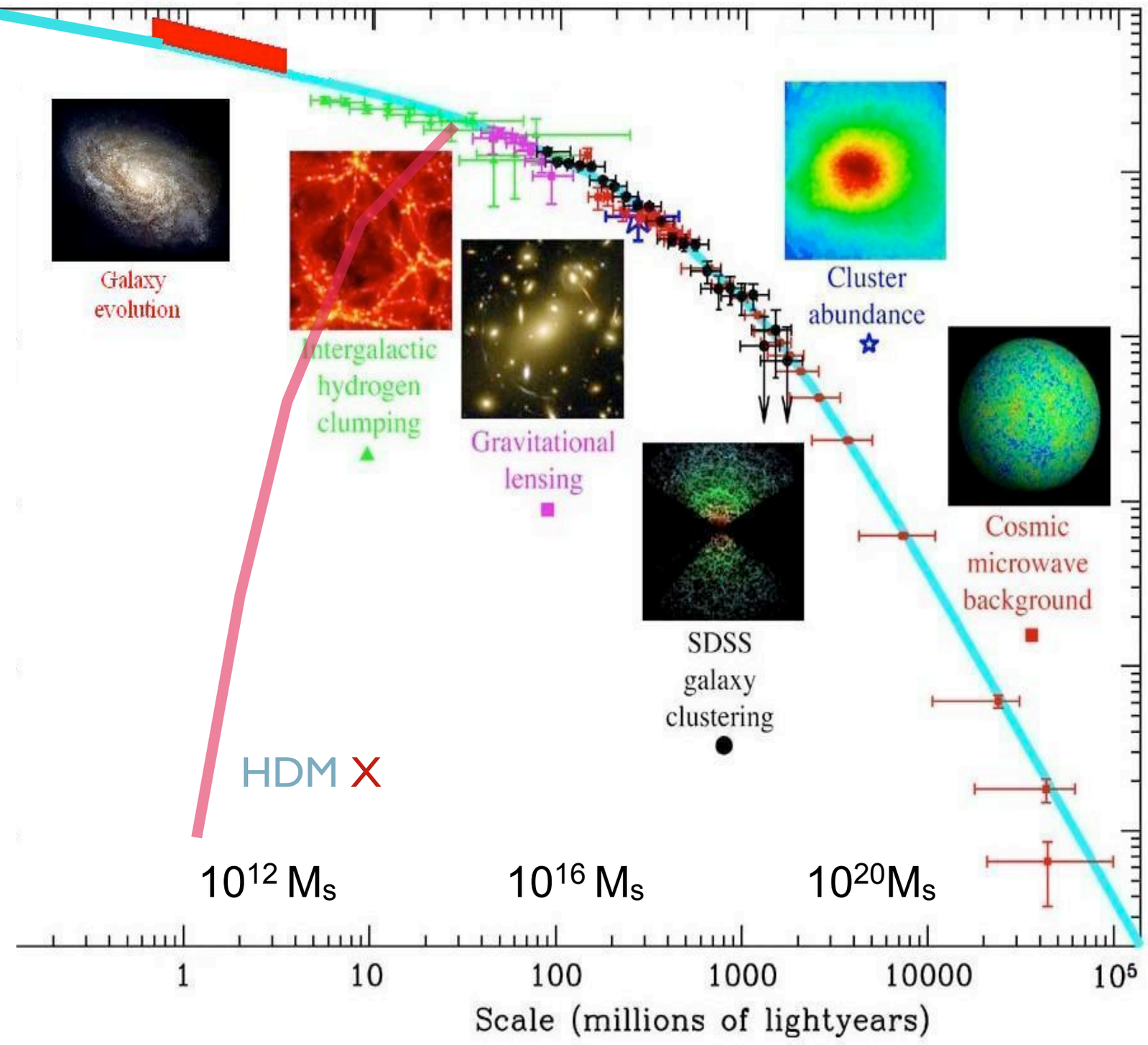

WDM ?

HDM X

$1M_s$ $10^5 M_s$ $10^8 M_s$ $10^{12} M_s$ $10^{16} M_s$ $10^{20} M_s$

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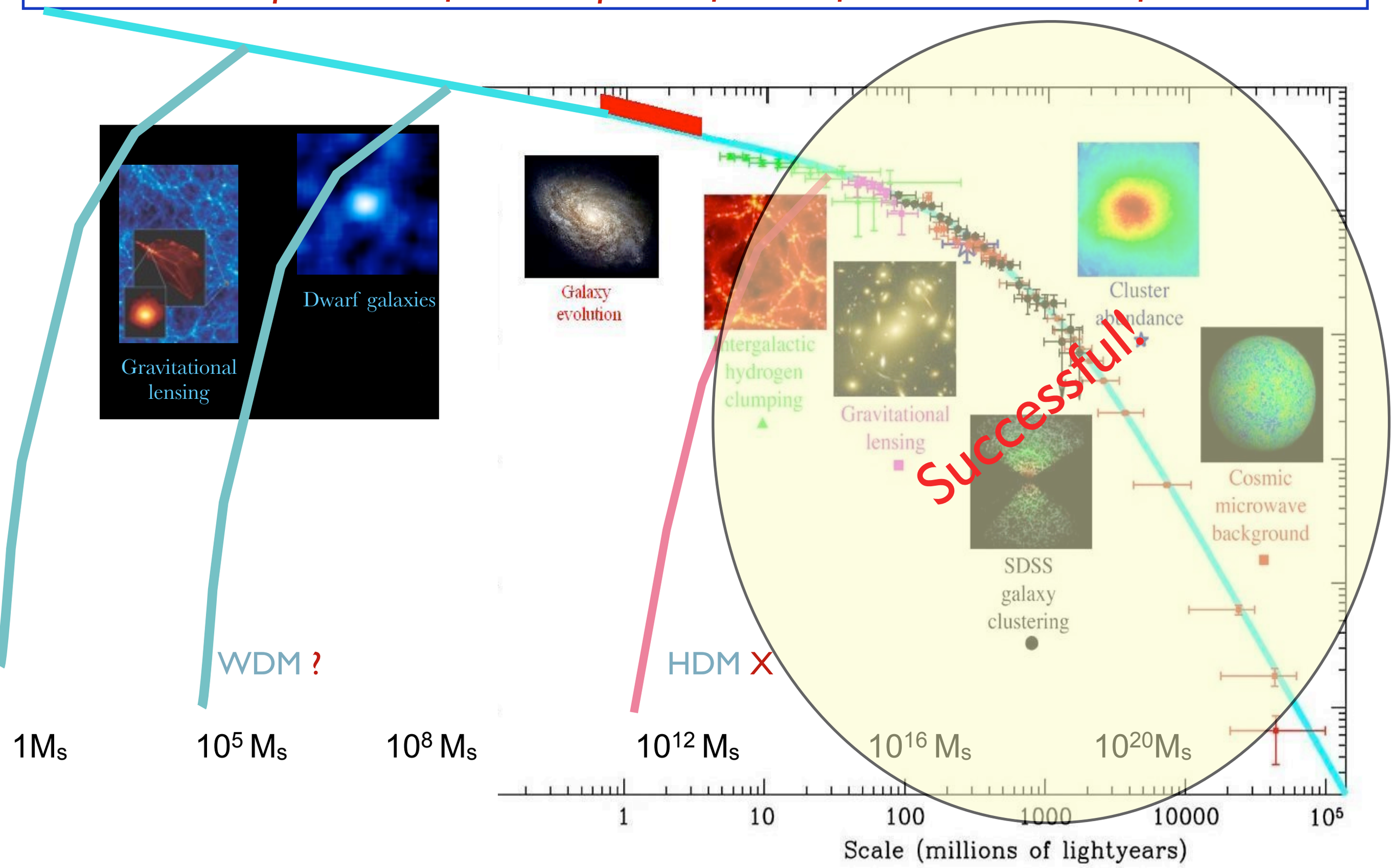

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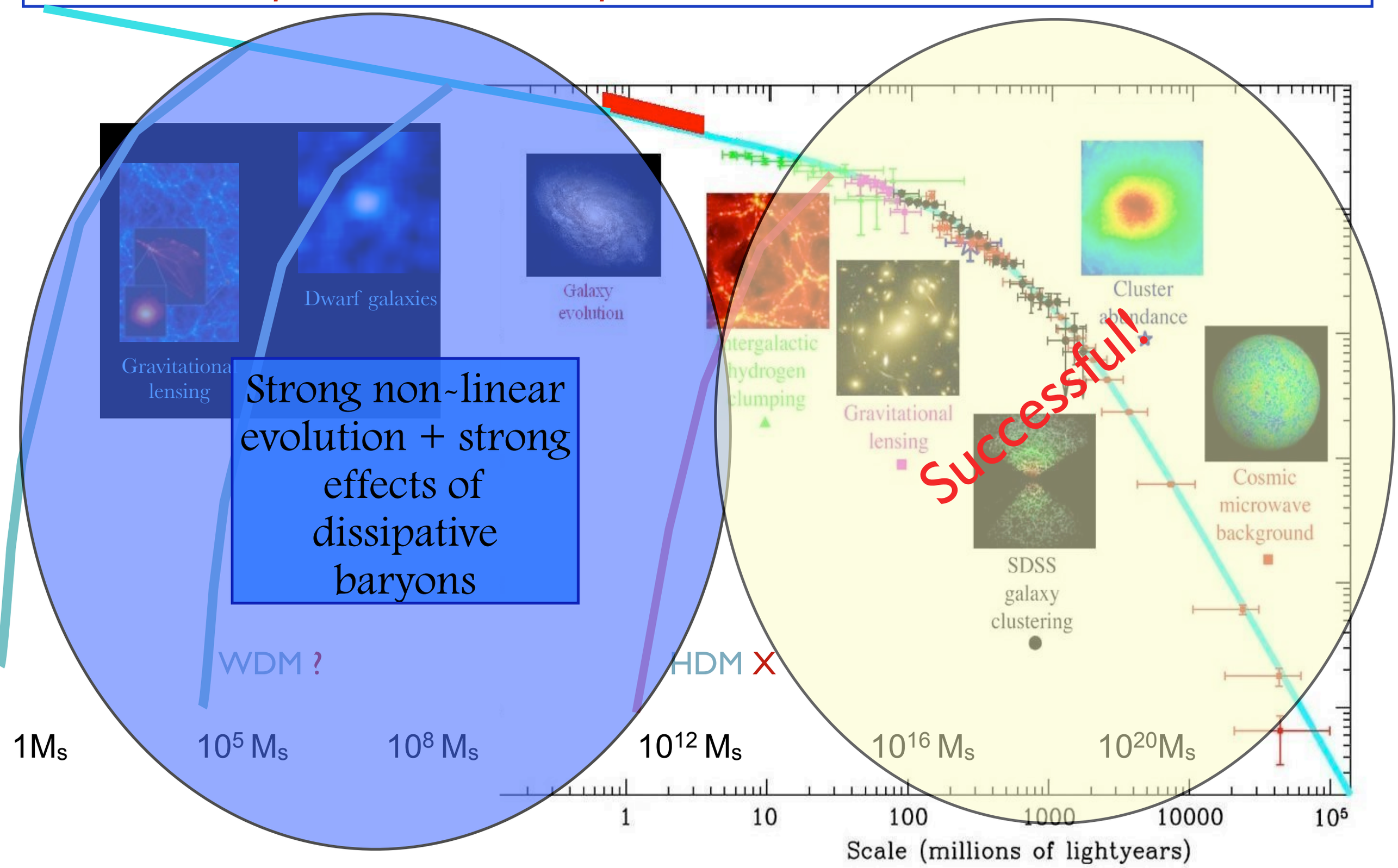
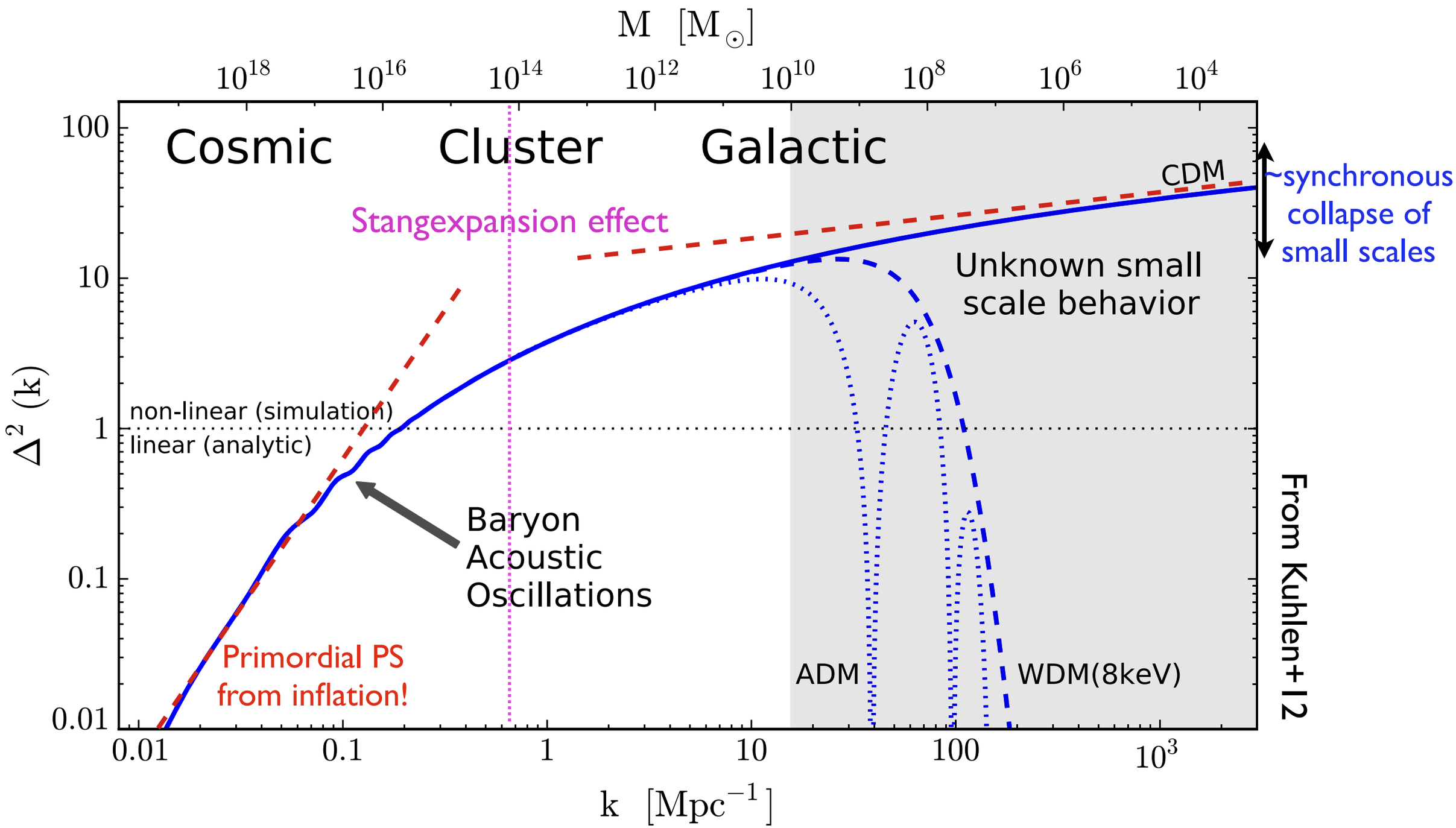


Genetic code for cosmic structure formation: scales



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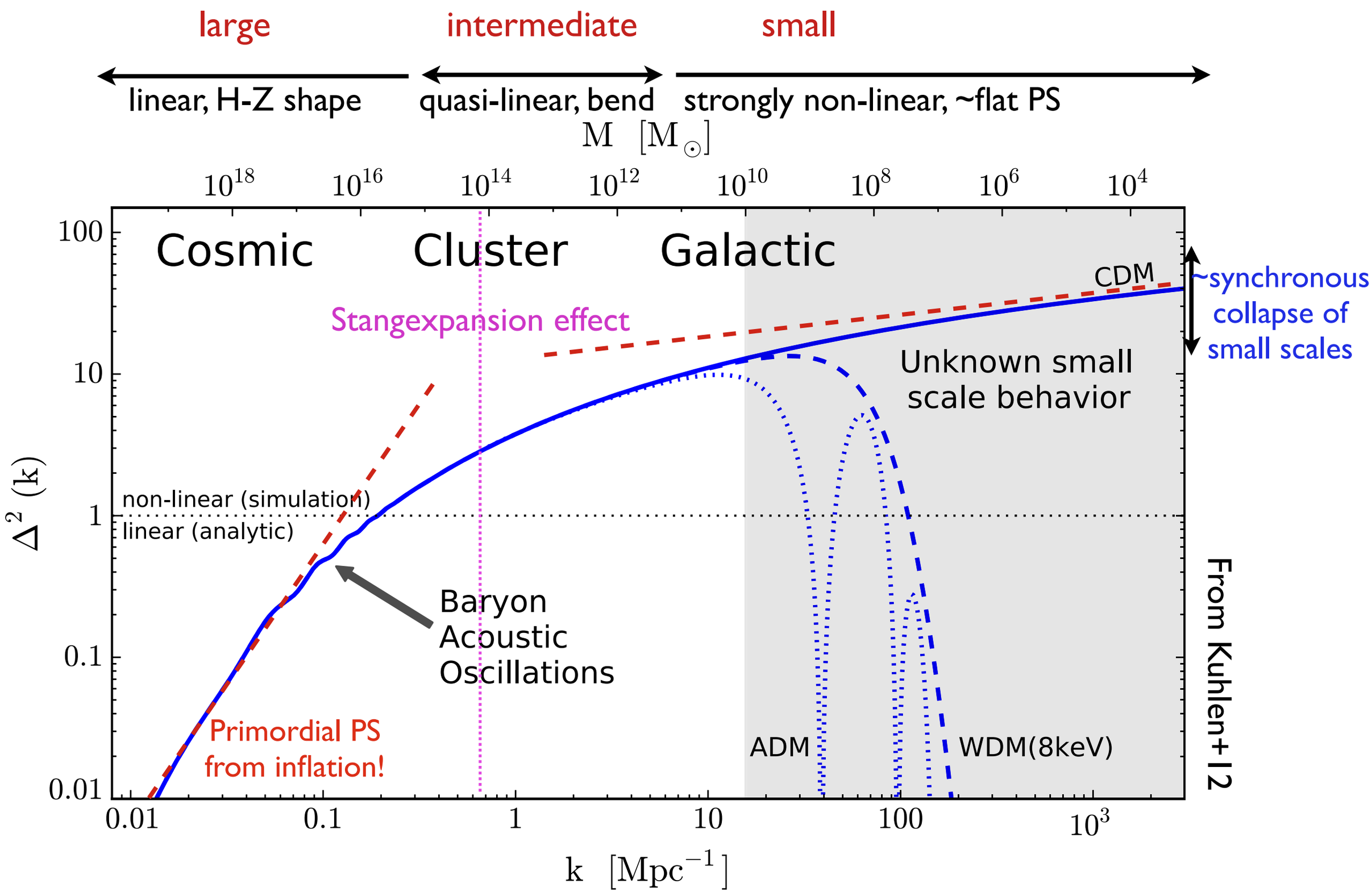

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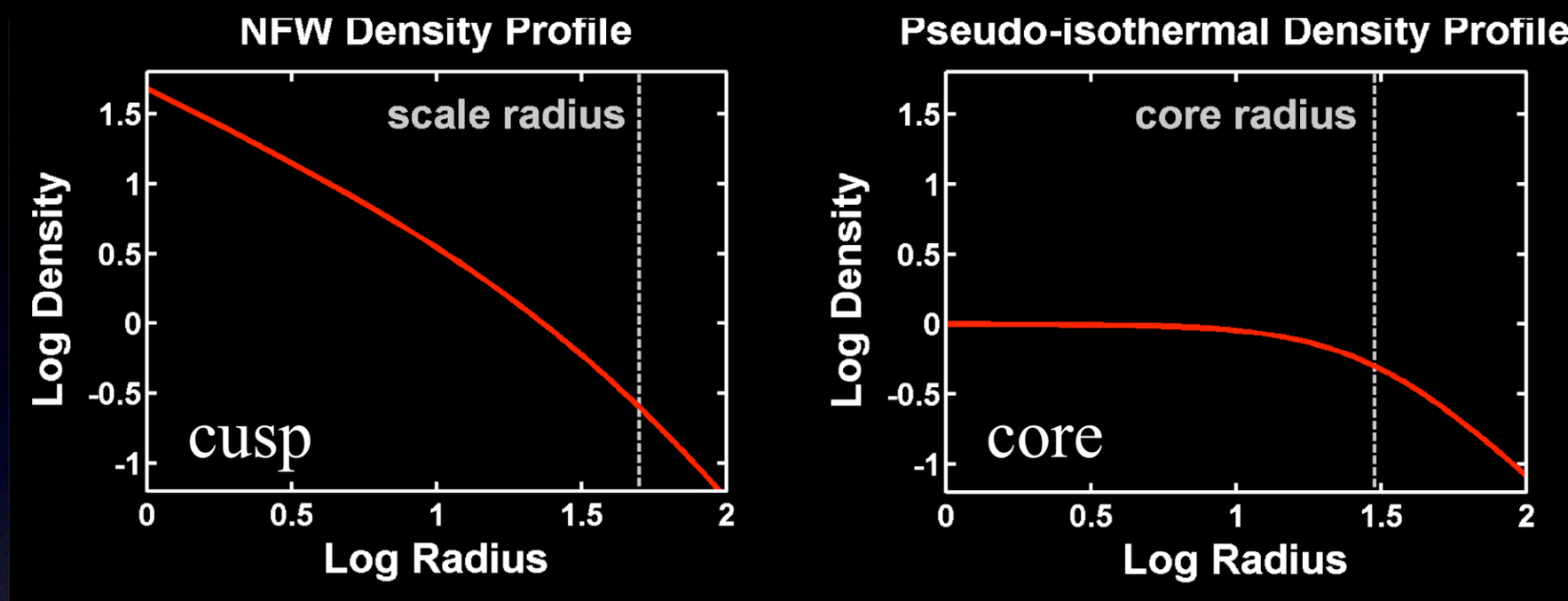
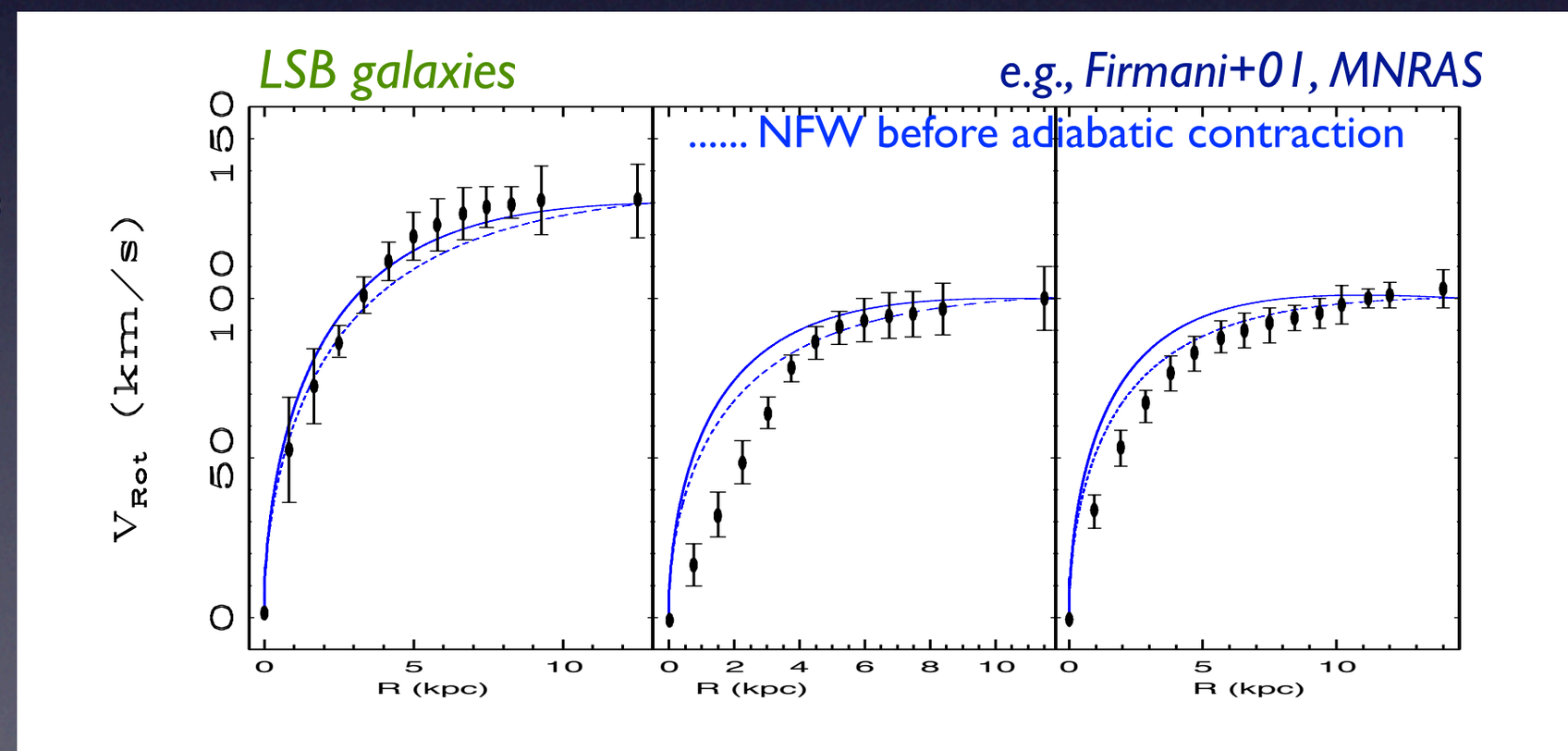
1. The cusp-core problem



Controversy since late 90's. Observations improved, the problem remains but less stringent *(e.g., de Blok+05,08; Strigari +08; Kuzio de Naray+08,11; Oh+11; Salucci+12)*

RCs of DM-dominated galaxies (LSBs & dwarfs) are supposed to trace the halo gravitational potential

$$\frac{GM(<r)}{r^2} = \frac{v^2}{r}$$

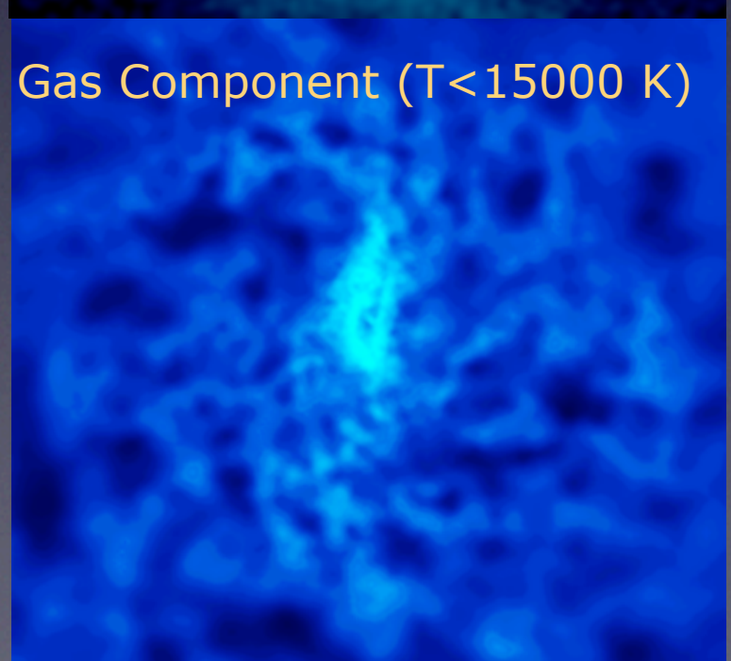


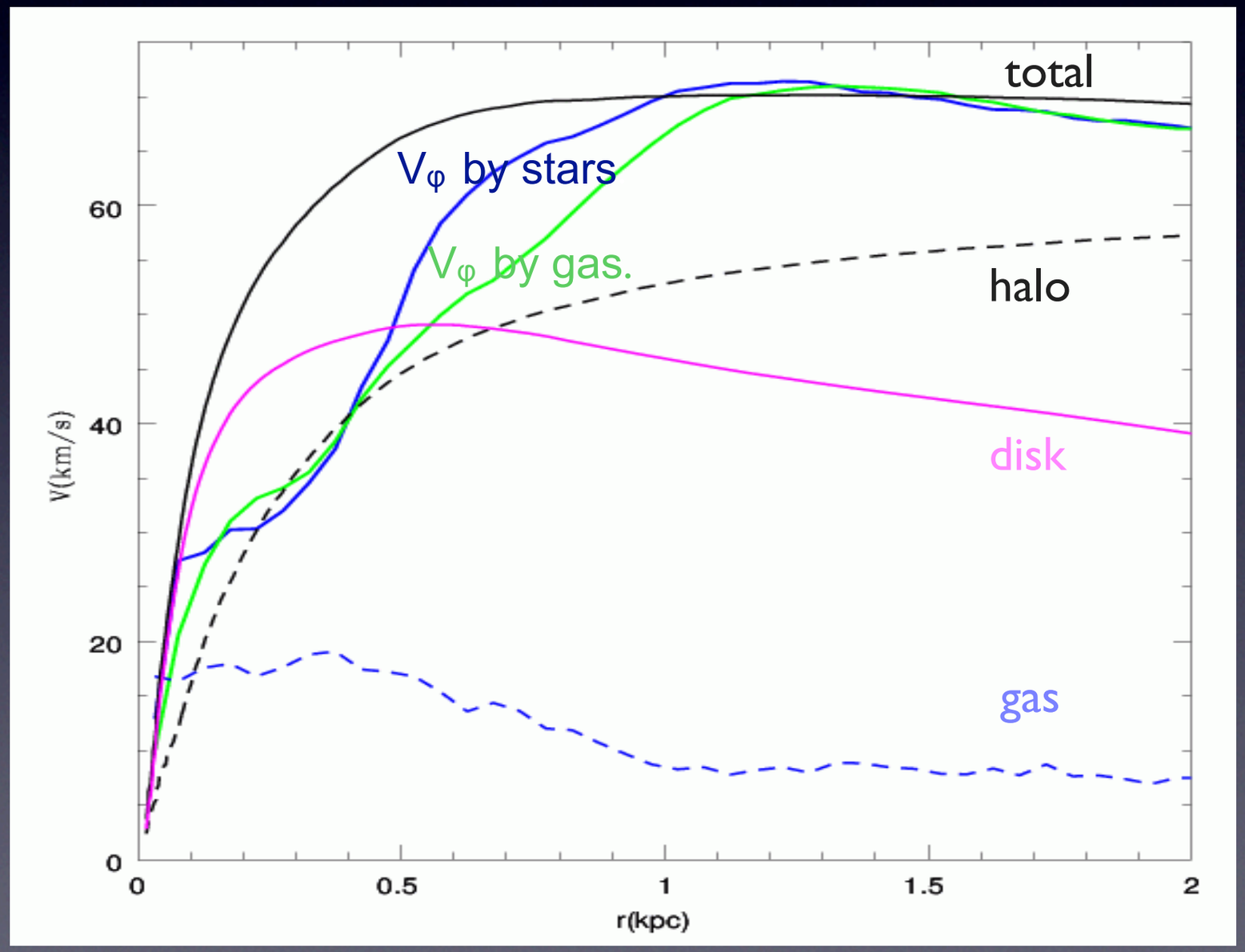
However: 1) If the disk is not axisymmetric/non-circular motions (e.g., bar) and there are pressure gradients: $V_c \neq V_\varphi$ (V_φ accounts for other contributions!)

$$v_c^2 = v_\phi^2 - \sigma^2 \left(\frac{\partial \ln \rho}{\partial \ln R} + \frac{\partial \ln \sigma^2}{\partial \ln R} \right)$$

2) If the halos is triaxial, V_φ is larger and the central mass is underestimated

Valenzuela+2007: **Simulated Barred Dwarf Irregular Galaxy: Realistically Including all the kinematis and pressure effects. Cuspy Halo. 2% M_{disk}/M_{halo} . 60 pc resolution.**





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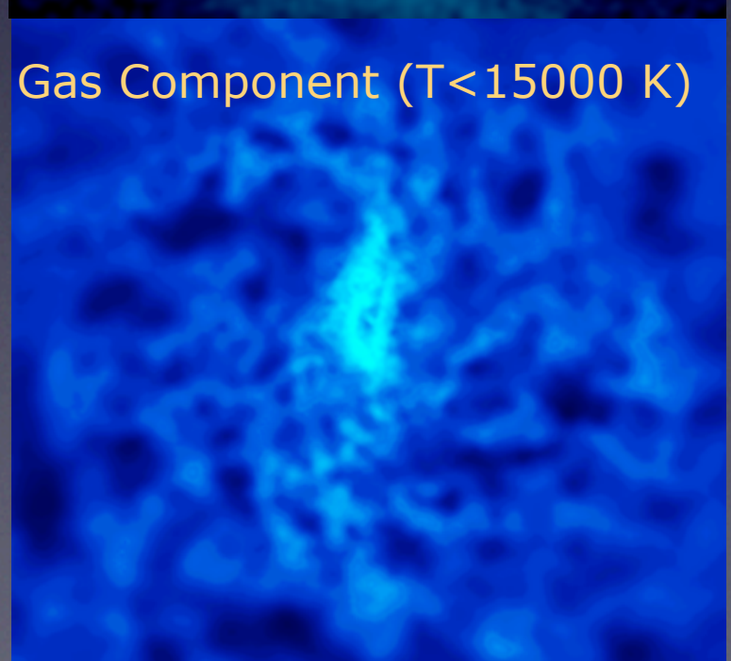
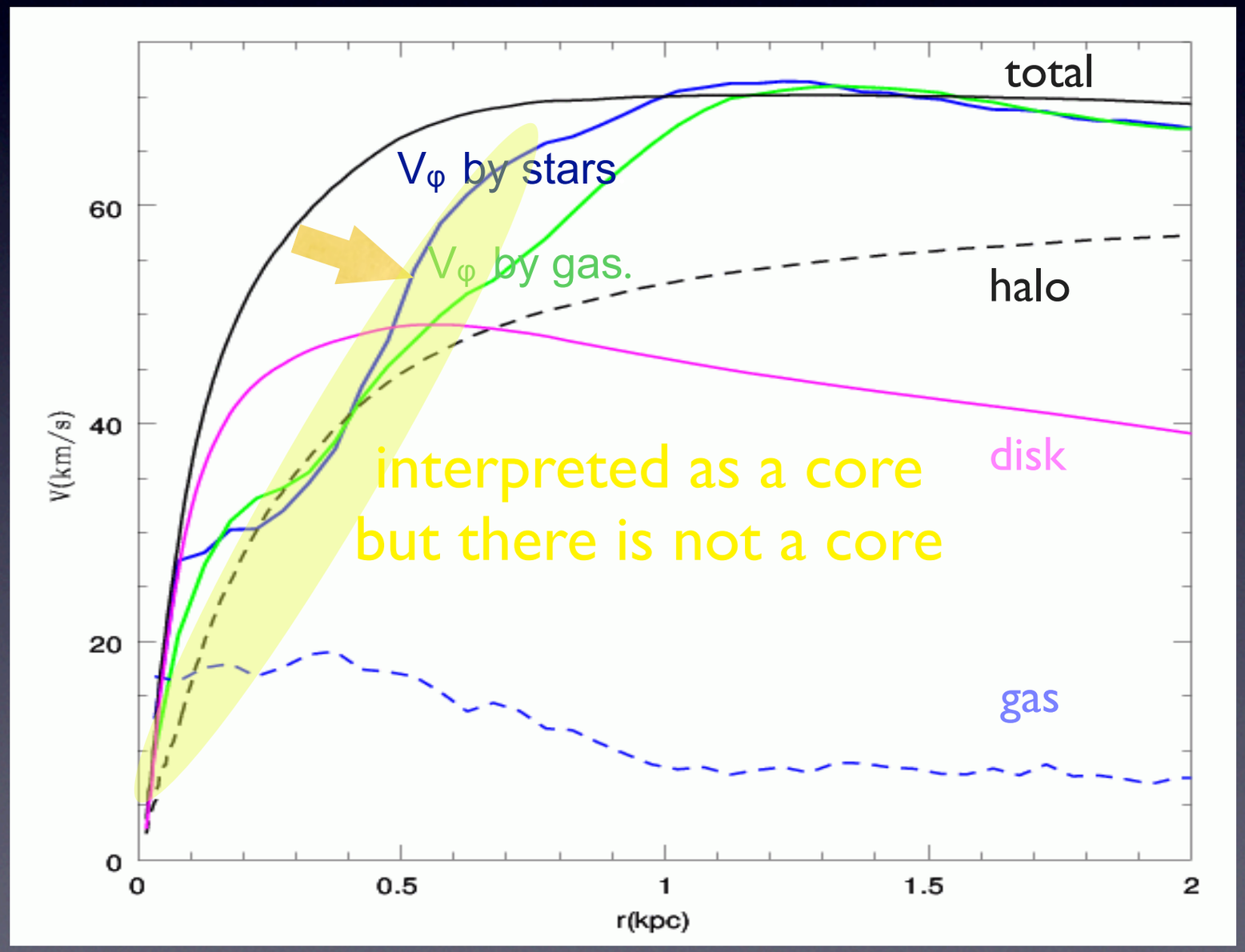




Besides deviations from axisymmetry and circular motions,

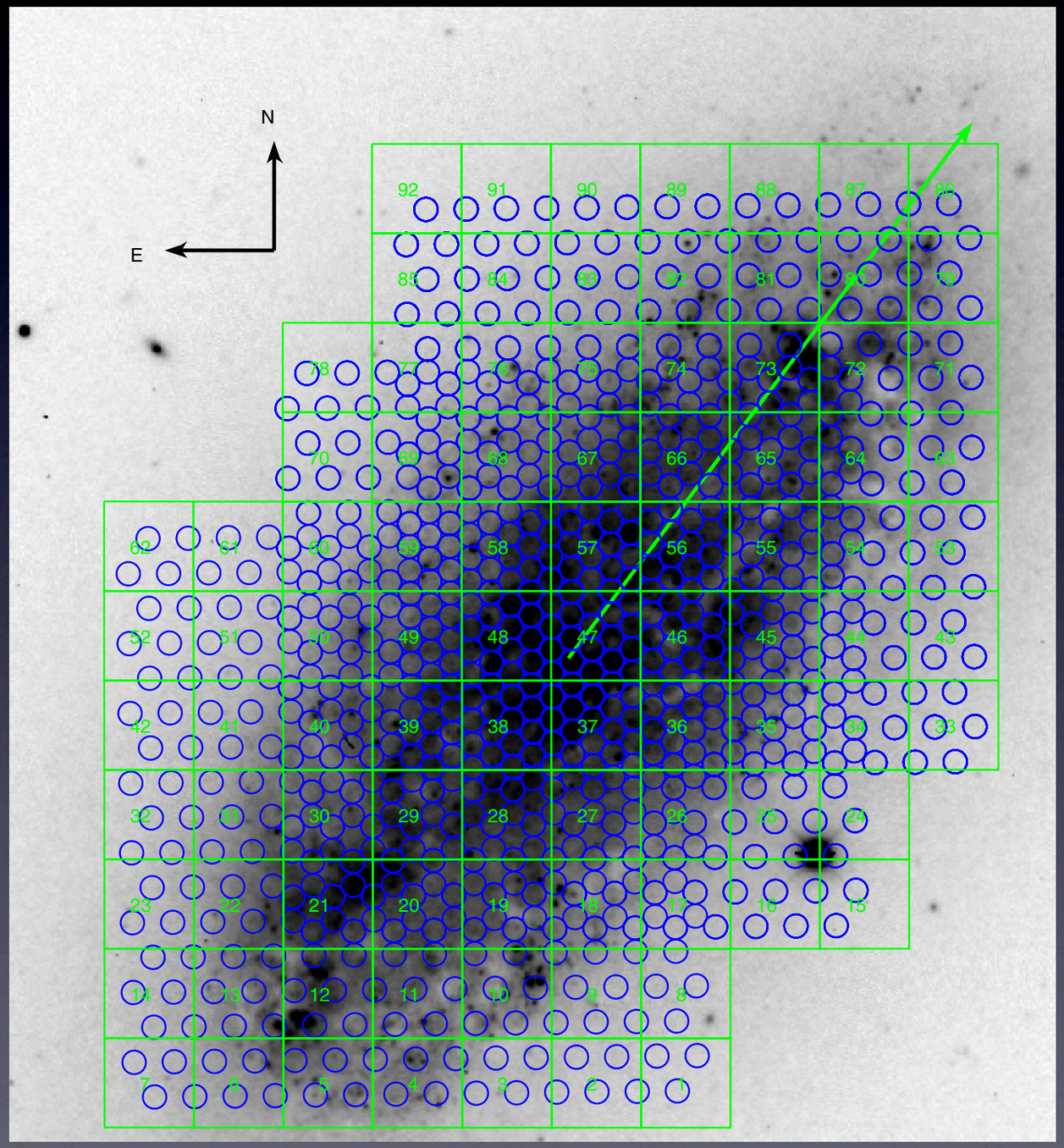
- the degeneracies (e.g., between M/L ratio and core slope) are too strong to make a constraint by the kinematics alone: **stellar pop. synthesis helps.**
- gaseous and stellar kinematics are often different, giving different constraints

Integral field spectroscopy (2D stellar/gaseous maps)

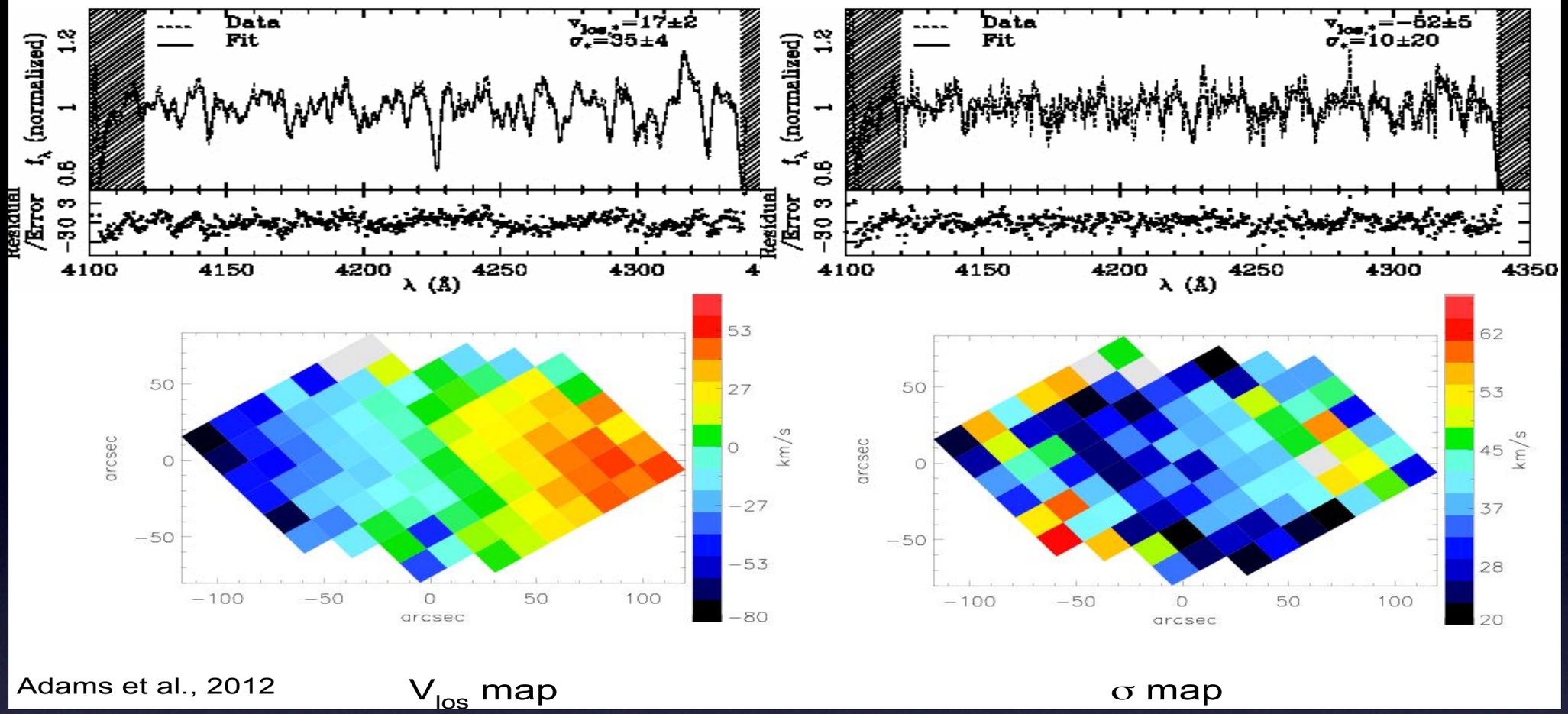
Example:

NGC2974 -the prototype of cored dwarf galaxy *(Simons+03, Ha kinematics)*

VIRUS-P data + Jeans Anisotropic Model + Stellar Pop Synthesis *(Adams+12, ApJ)*



Data on NGC 2976

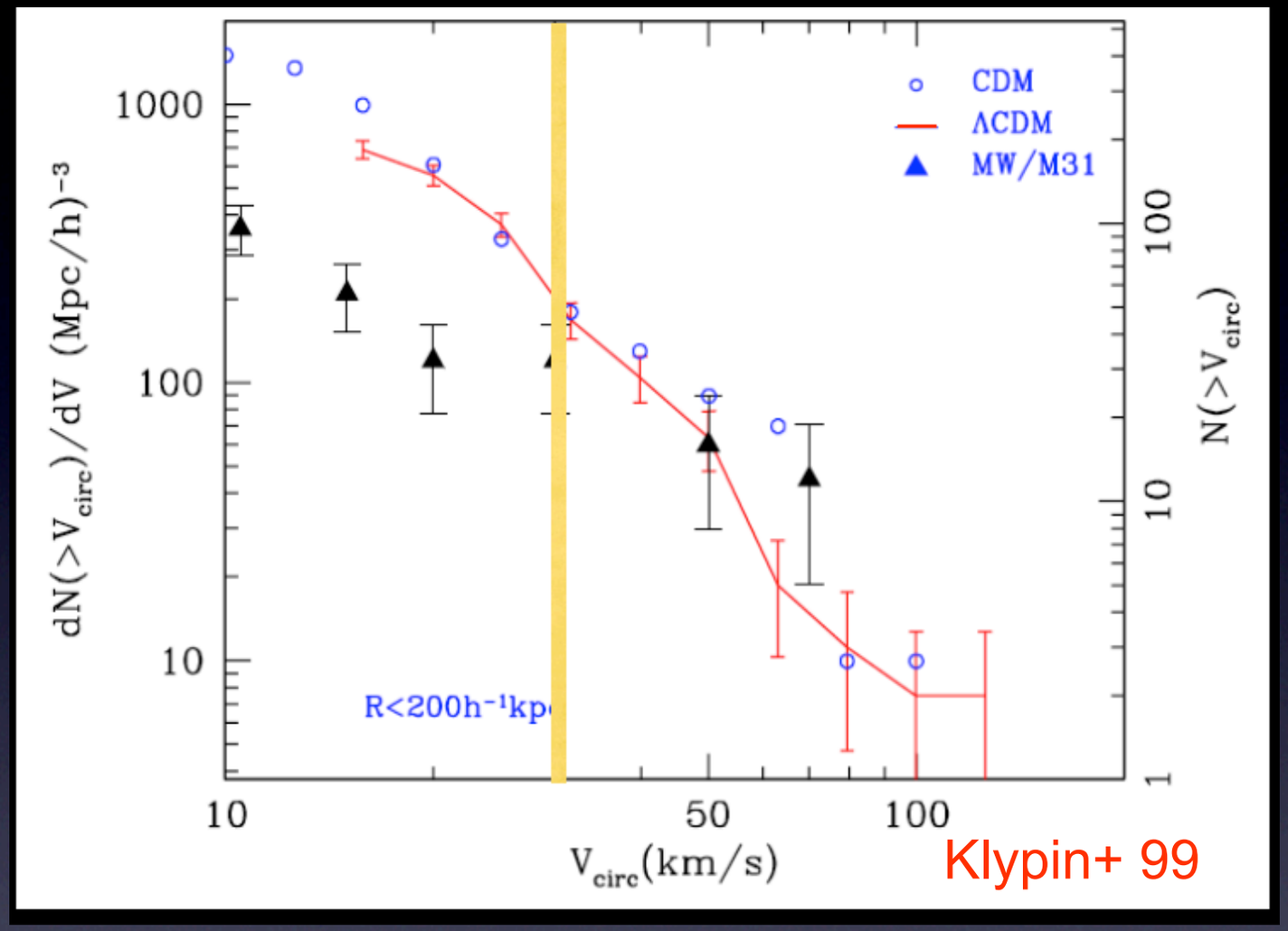


Adams et al., 2012 V_{los} map σ map

- Stellar kinematics + stellar pop. synthesis: slope=0.9 ±0.15 *(core ruled out at 2σ!!!)*
- Gaseous kinematics (slope~0) can be made compatible with stellar one after taking into account gas motions
- 10 more dwarfs in study: *a cusp seems to be favored in most of the cases (Adams+14, in prep)*, but some cores are also present.

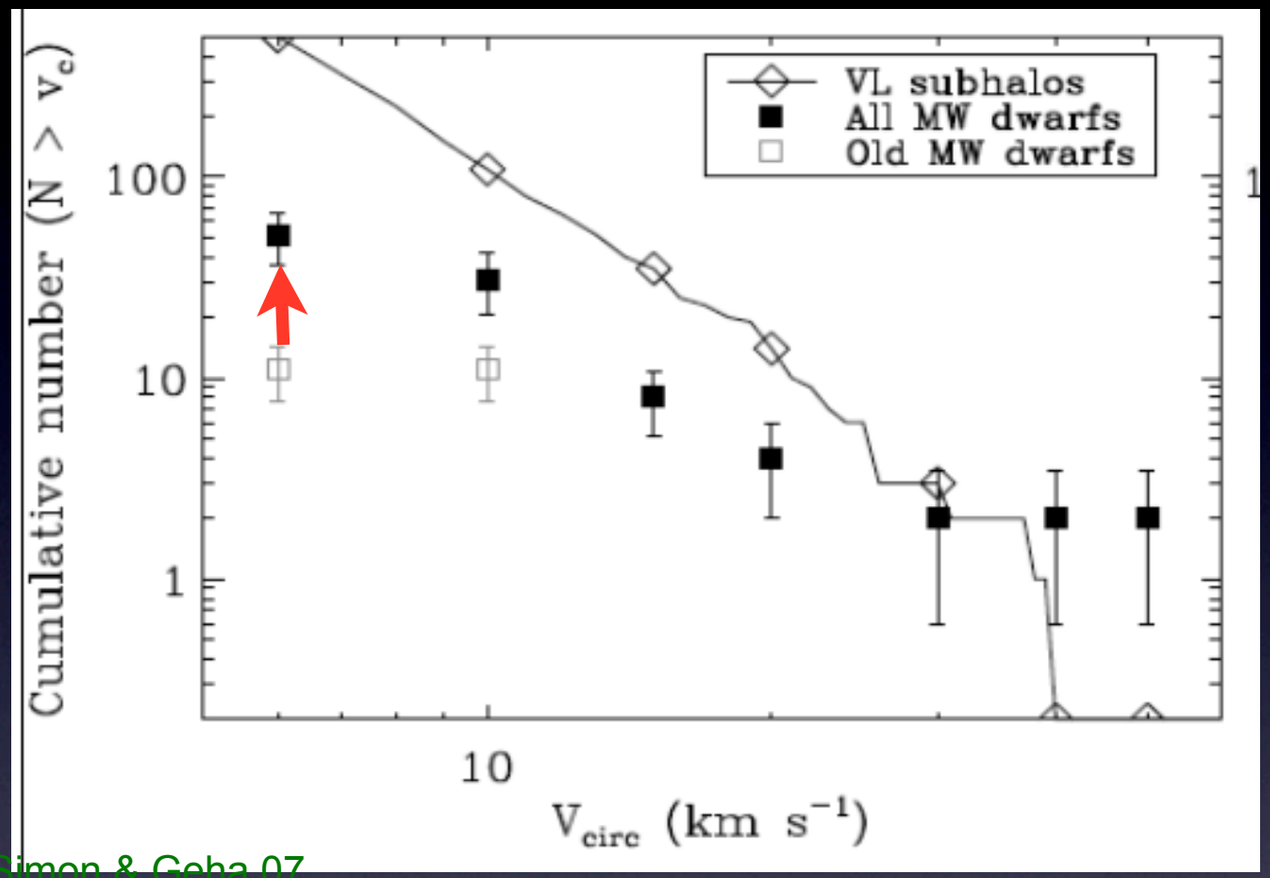
MaNGA/SDSS-IV survey in the next years!

2a. The missing satellite problem

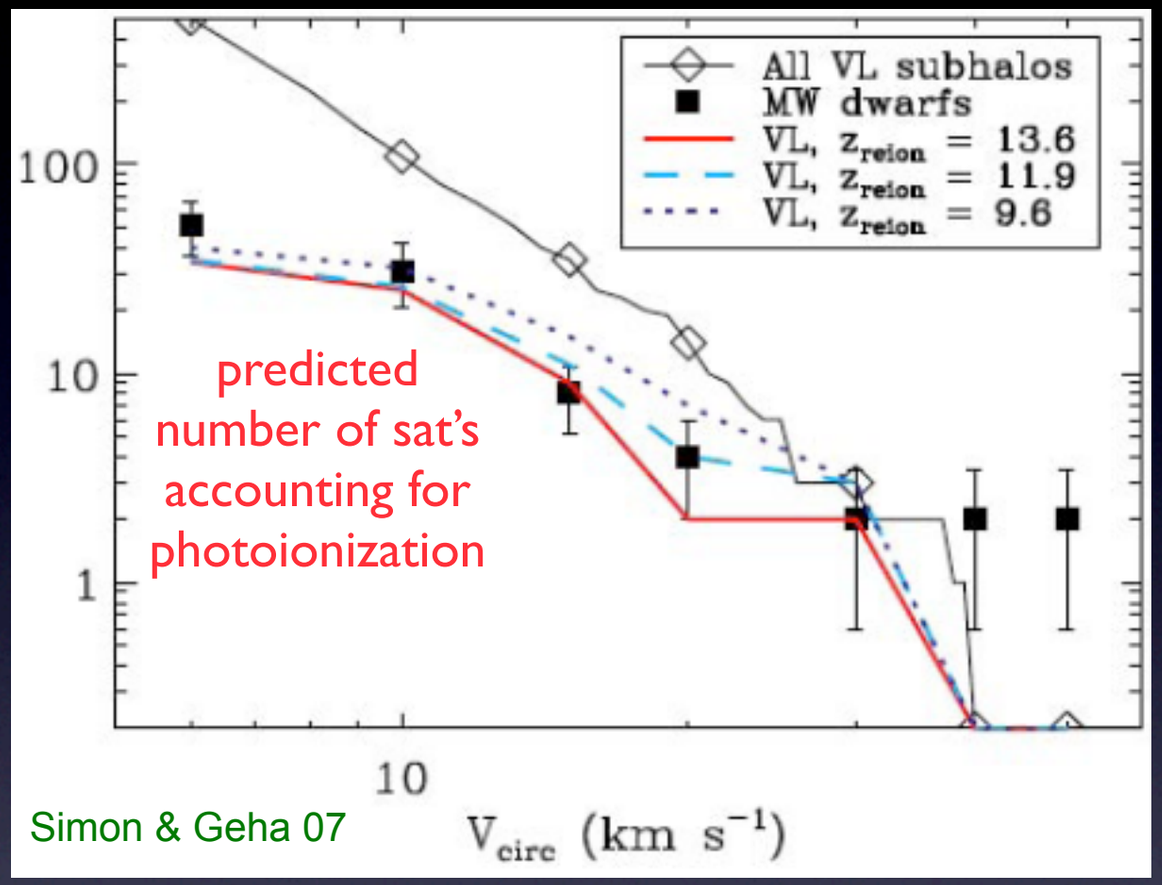


LCDM: Smaller structures collapse earlier and some of them survive as sub-halos within larger halos. A numerous population of subhalos is predicted *(e.g., ~1000 with V_c>10 km/s in the MW, or $2x10^6$ with $M>10^4 M_\odot$)*

However, it seems not to be a problem



Simon & Geha 07



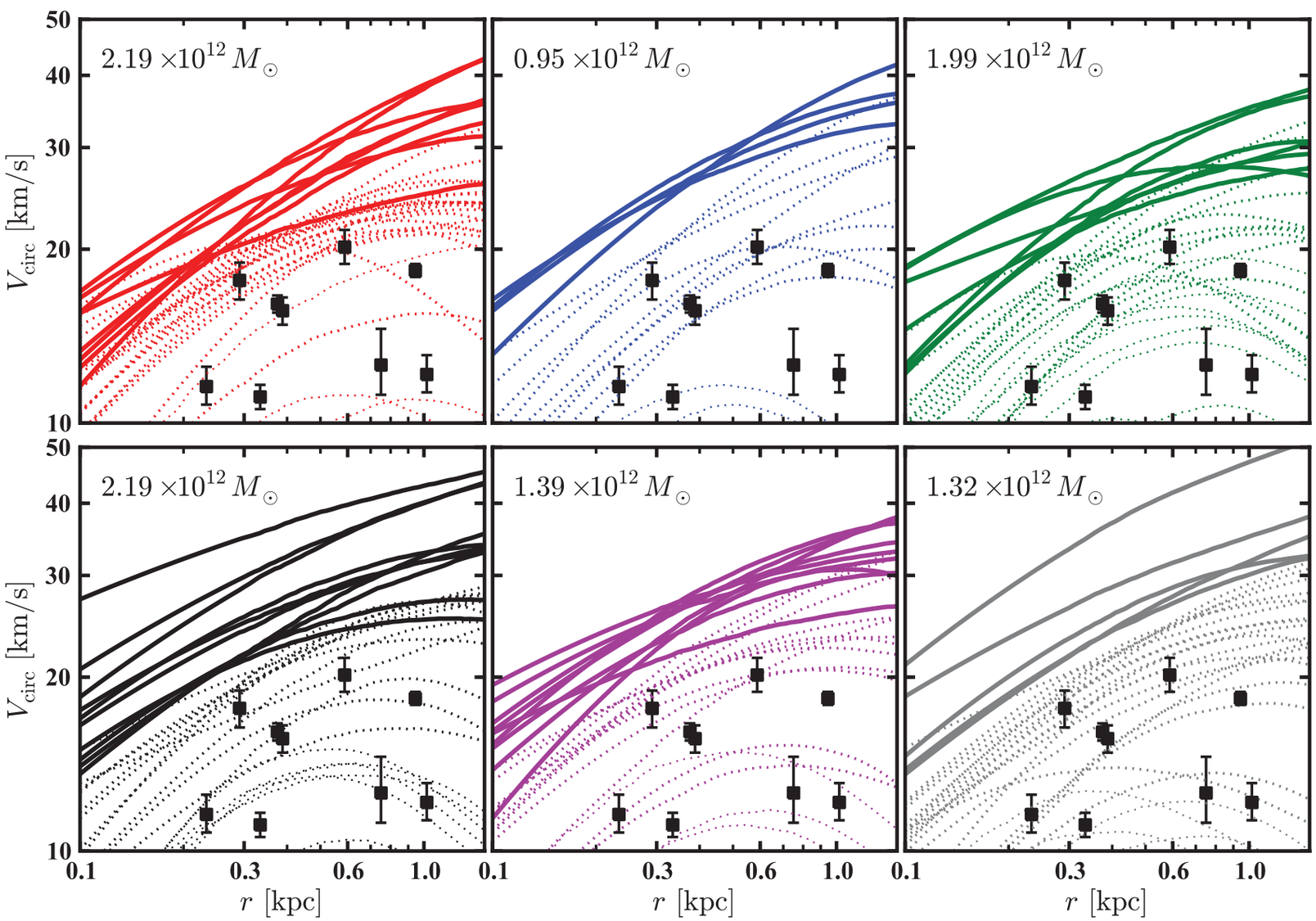
Simon & Geha 07

SDSS discovered ~15 ultrafaint dwarfs. LSST and GAIA may discover more.

Galaxies in subhalos of Vc<30 km/s are naturally suppressed by UV radiation from reionization!

2b. The too-big-to-fail problem

Six Aquarius MW-sized simulations: there are many subhalos with V>30 km/s that are not seen in the MW: they are too big to not forming galaxies *(Boylan-Kolchin+11,12)*



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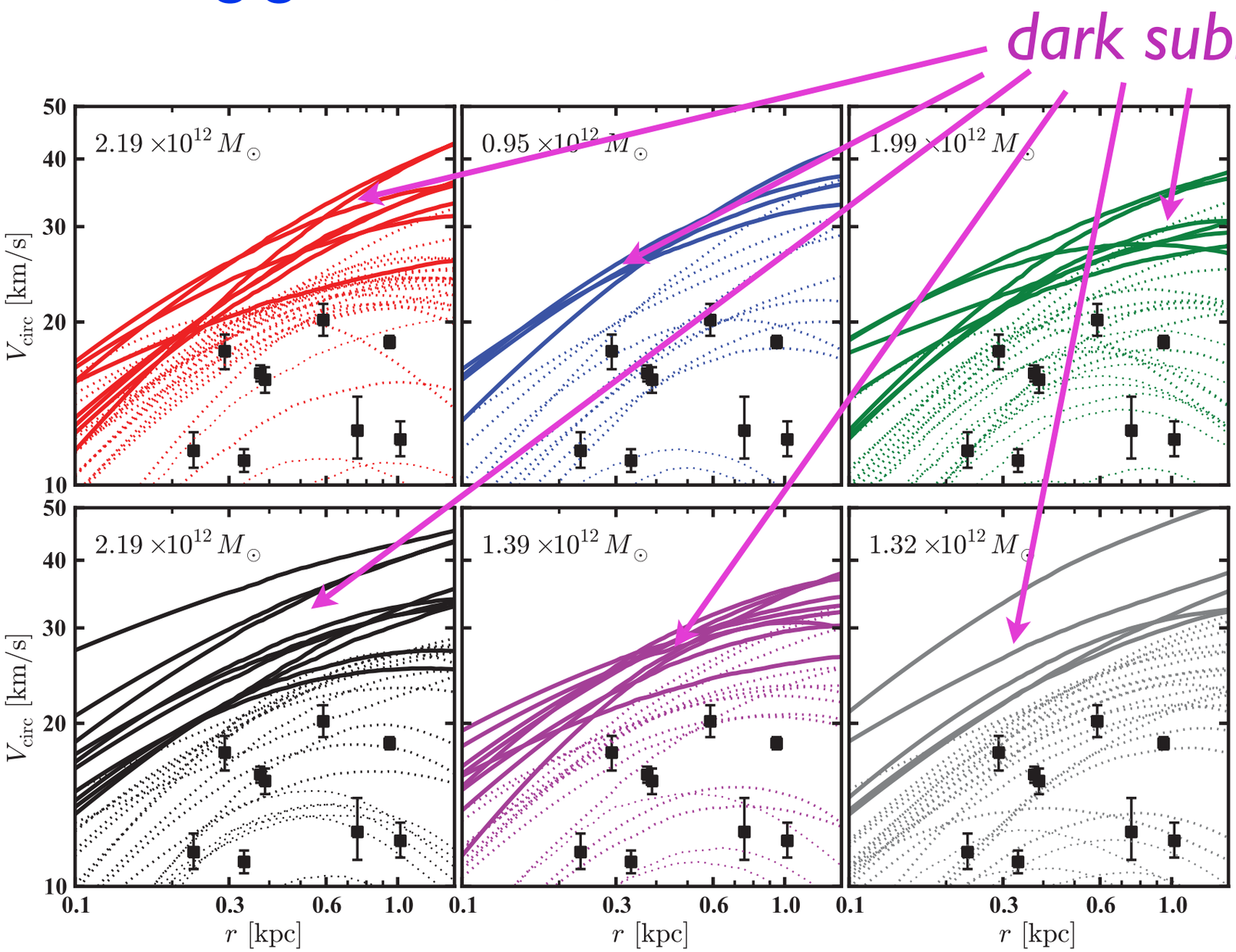


Caveats

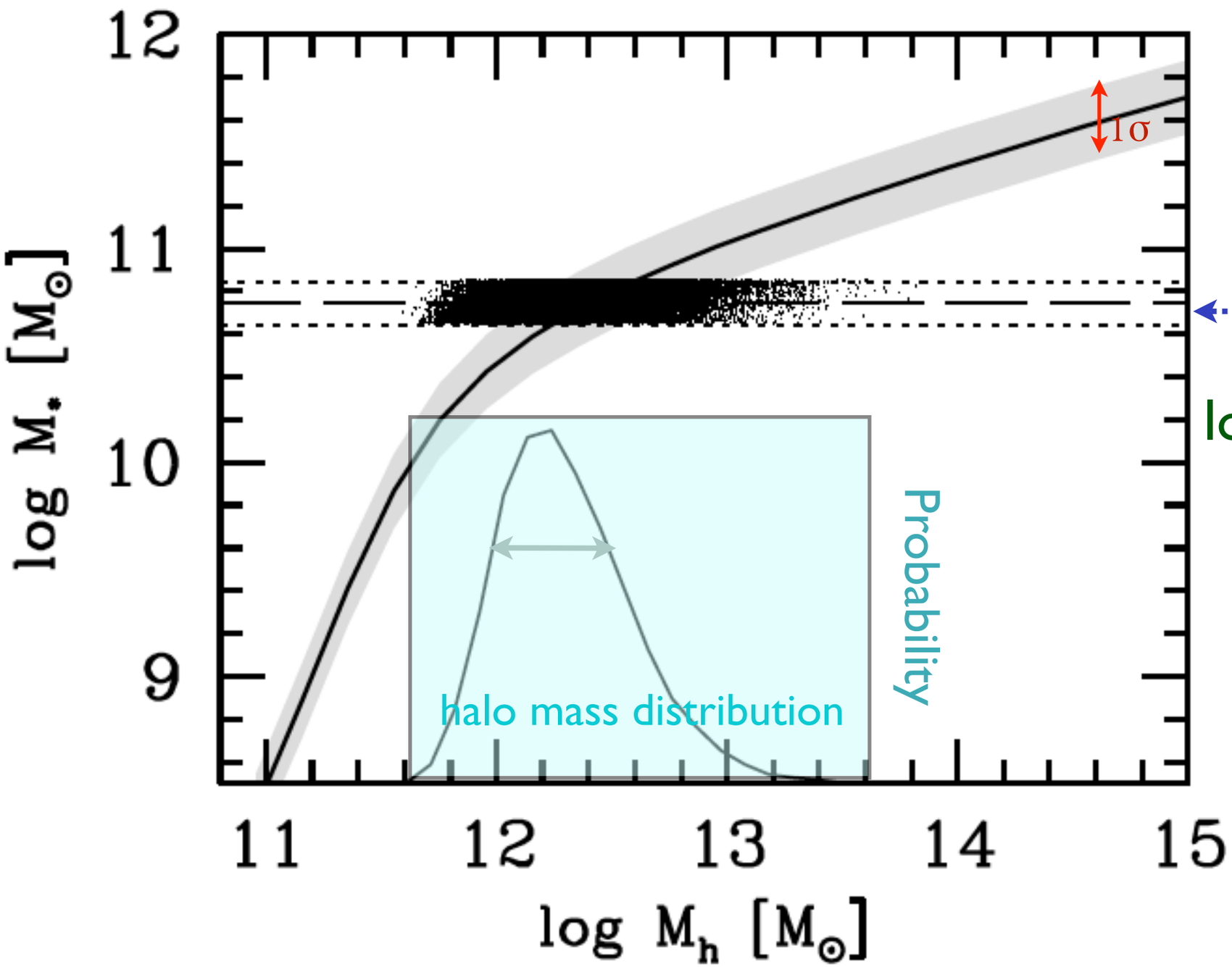
- Is the MW + sat's an exceptional system? (Purcell & Zentner12)
- Is the MW halo mass $<10^{12}\ M_\odot$? *(Wang+12)*

Can we have statistics for many galaxies?

Rodriguez-Puebla+2012, 2013a, ApJ: Semi-empirical model of galaxy-(sub)halo connection and halo occupation -->

A mock catalog of 2 10^6 central galaxies, each one with their satellites *(by construction it reproduces the observed cen/sat GSMFs & 2-point corr. functions)*.
Select those centrals with MW mass ($\log M_s = 10.74 \pm 0.1$): ~41000 gal's

It's an extension of observations



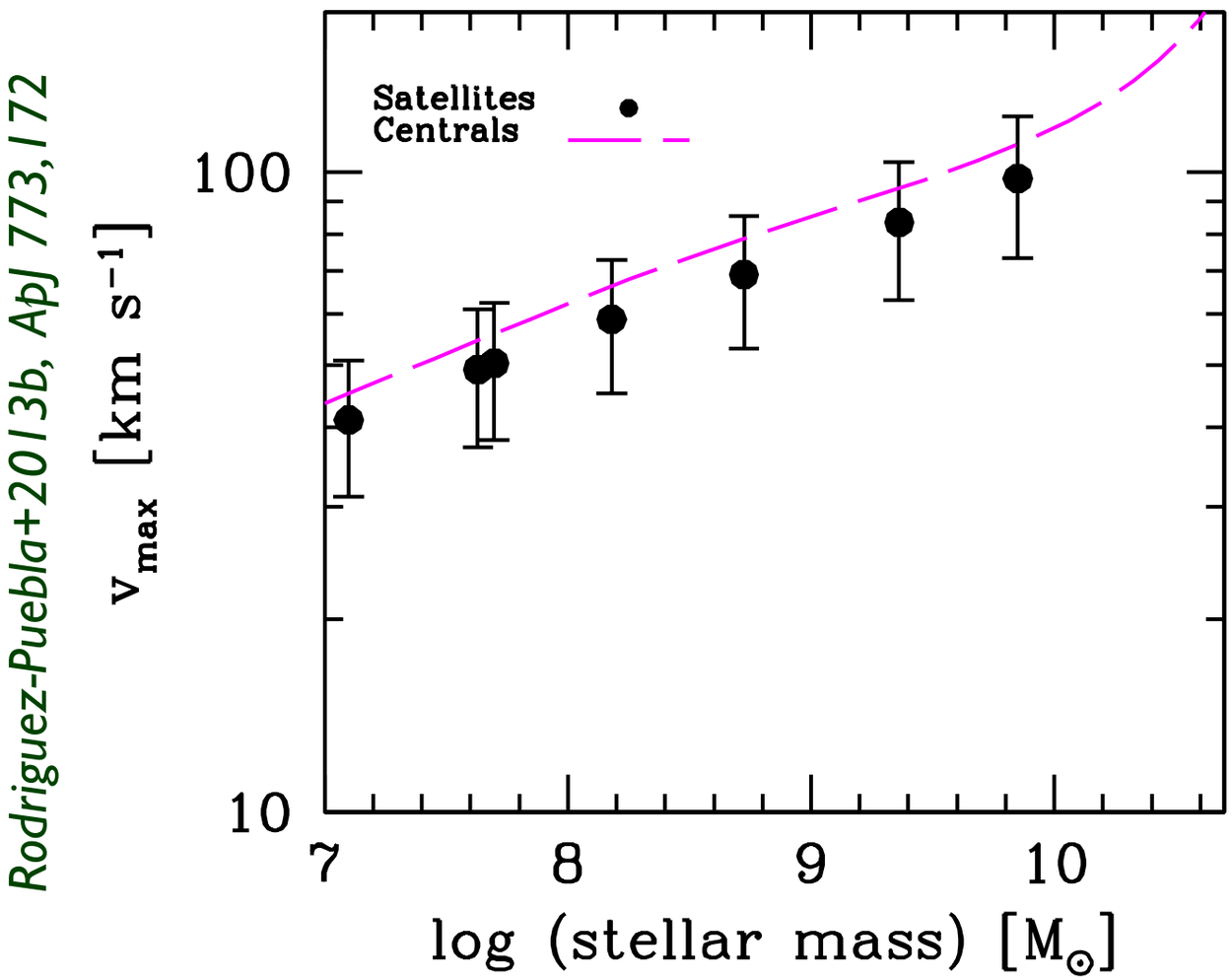
Rodriguez-Puebla+2013b, ApJ 773,172

$\log M_h = 12.31 \pm 0.27$

satellite masses:
$m_s > 2.5 \times 10^7 M_\odot$

The inner dynamics of the satellites

We have 41K 'quasi-observed' MW systems. By construction, there is not a subhalo-satellite abundance problem for the LCDM, BUT...



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Halo/subhalo max. circular velocity vs central/satellite stellar mass

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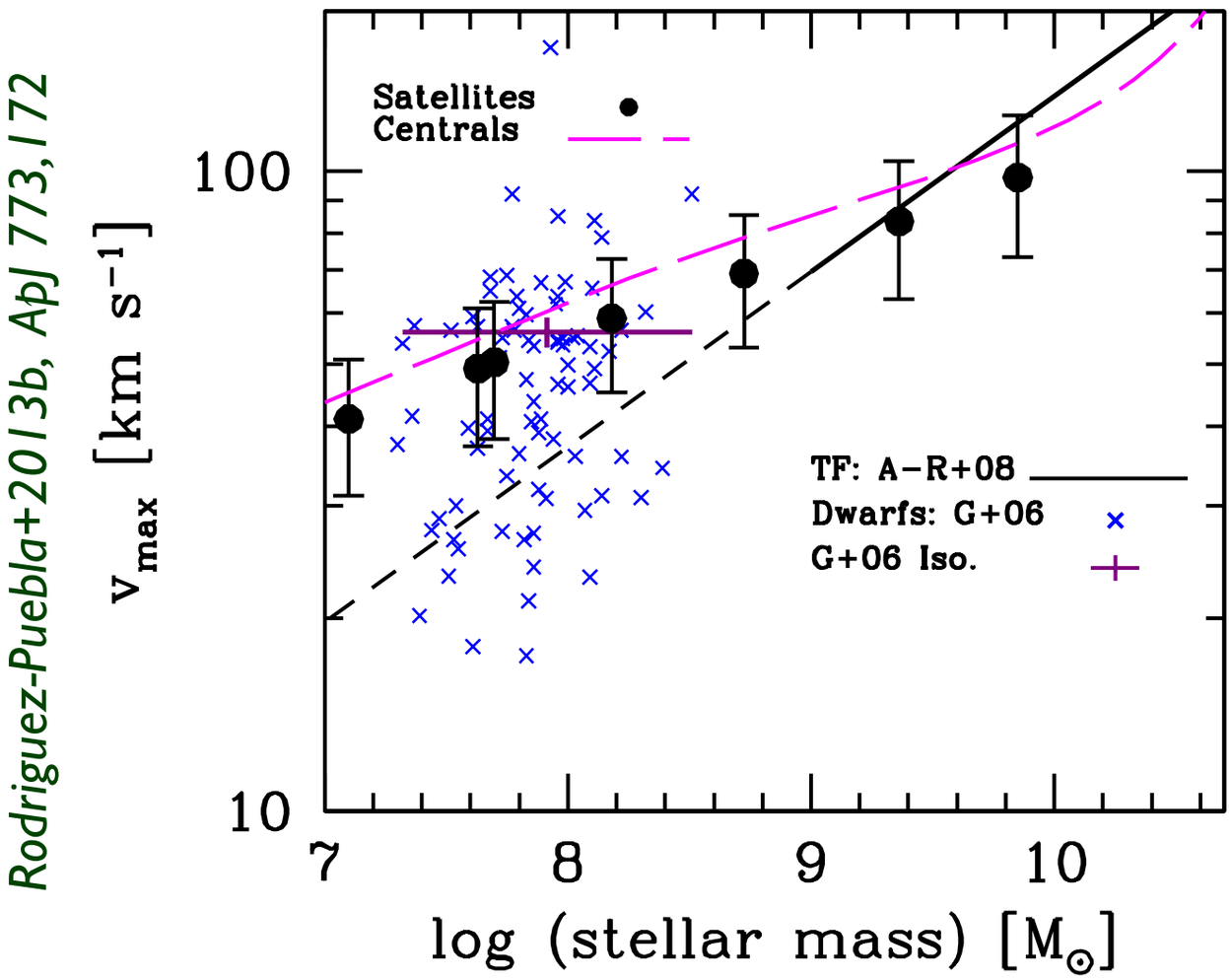

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Halo/subhalo max. circular velocity vs central/satellite stellar mass

x Observations: isolated and satellite dwarf galaxies (Geha +2006)

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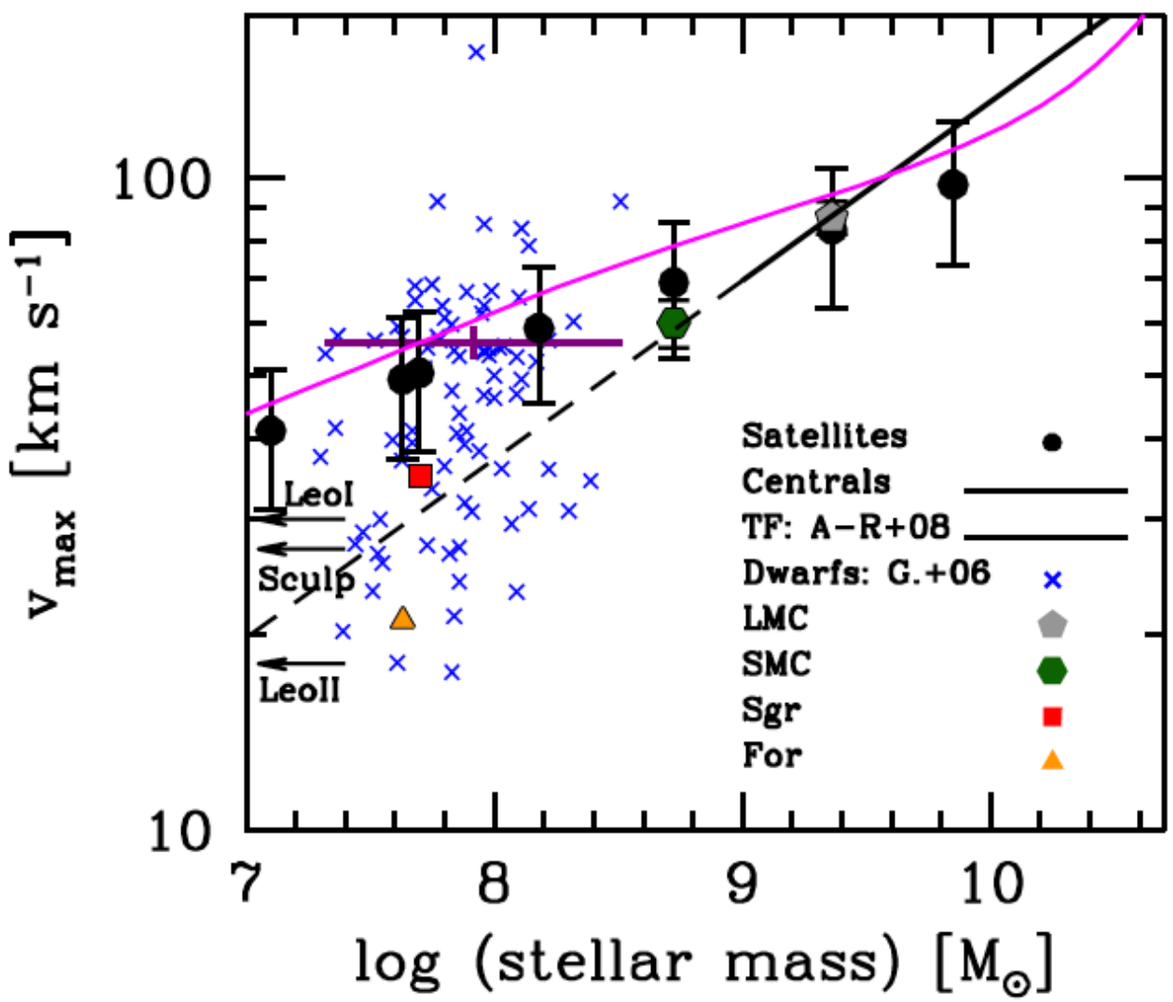
Rodriguez-Puebla+2013b, ApJ 773,172



Halo/subhalo max. circular velocity vs central/satellite stellar mass

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symbols = MW (massive) satellites

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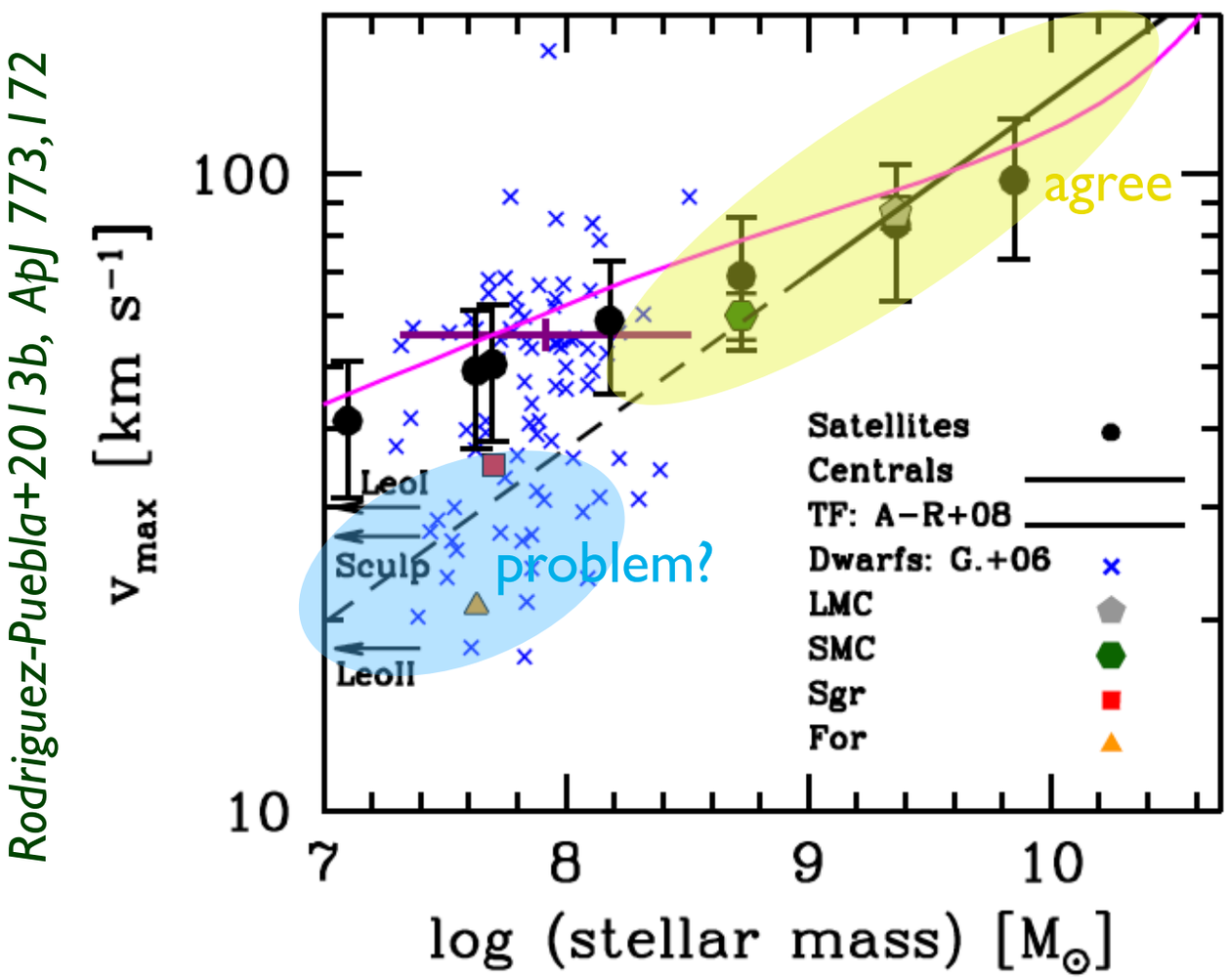


Halo/subhalo max. circular velocity vs central/satellite stellar mass

x Observations: isolated and satellite dwarf galaxies (Geha +2006)

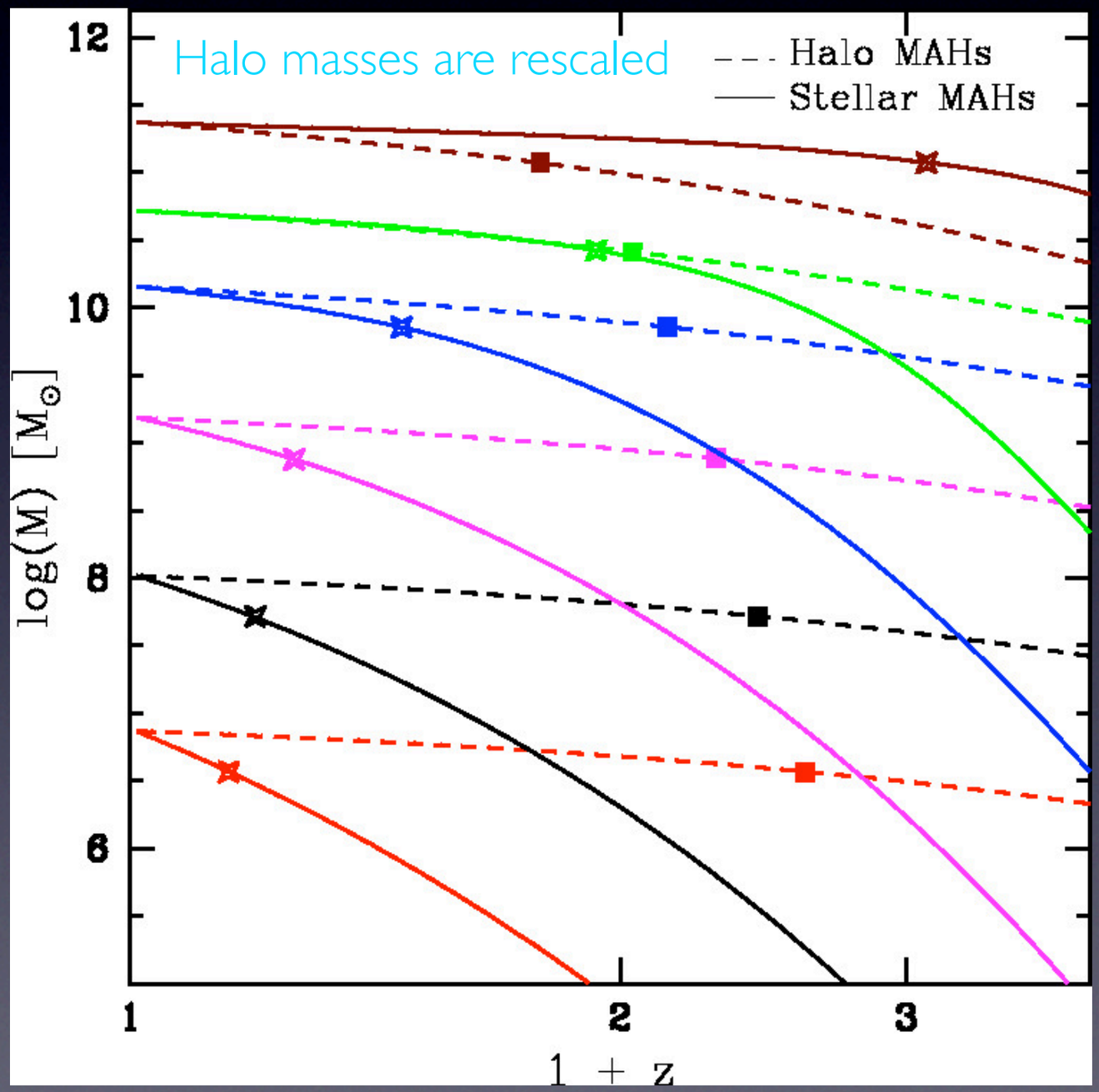
symbols = MW (massive) satellites

The subhalos of dwarf sat's ($M_s<10^8$) are too concentrated w.r.t. (few) observations. Does remain this issue for isolated halos?

being satellite could make the difference

3. The Downsizing problem

From empirical inferences: the smaller the galaxies, the latter they assemble on average their stellar masses, opposite to the CDM halo trend *(Firmani & Avila-Reese 10; Behroozi+13; Leitner 12; Moster+13)*



Halo and stellar mass growth histories

(See Gonzalez-Samaniego's poster)

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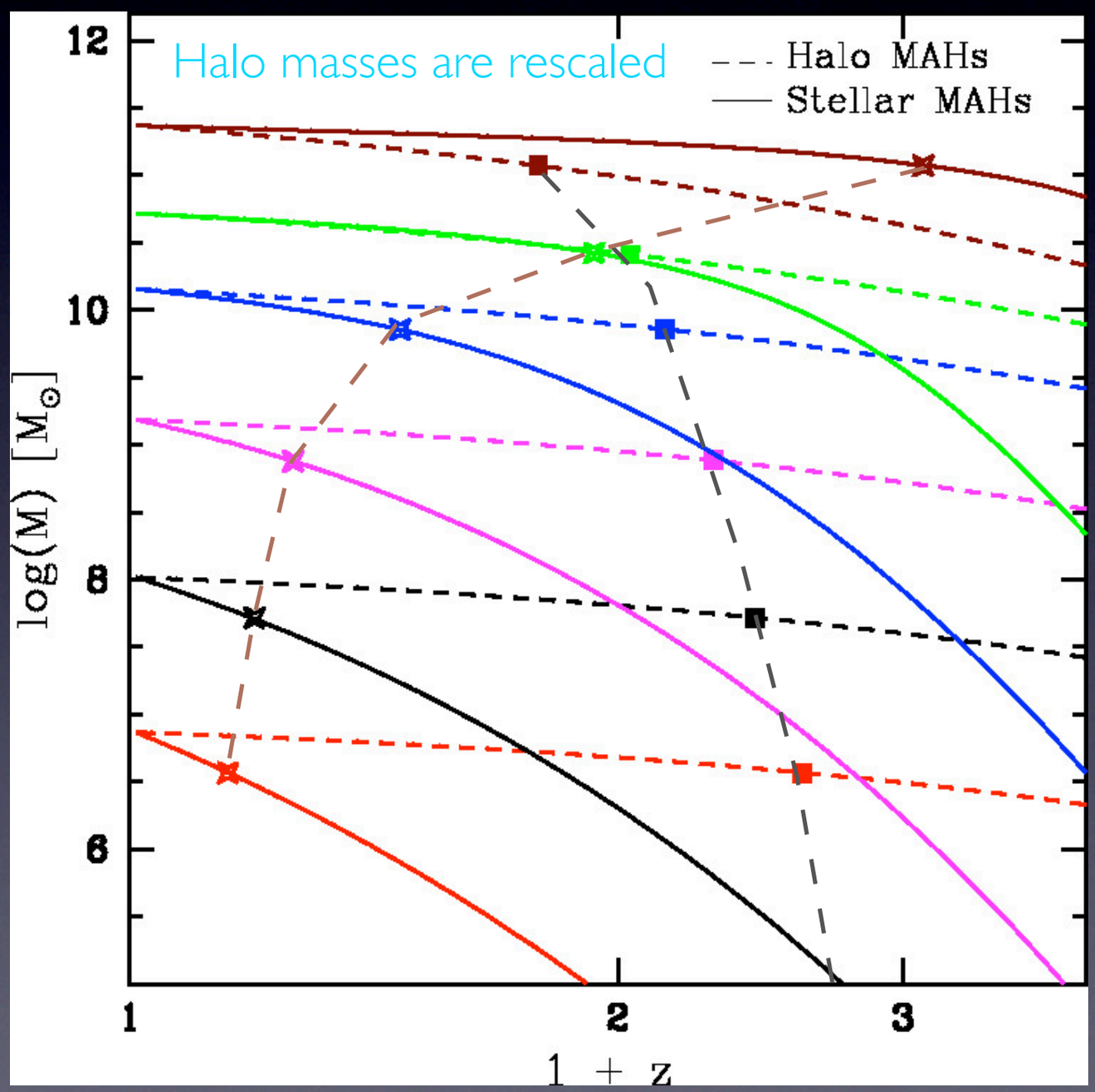


Halo and stellar mass growth histories

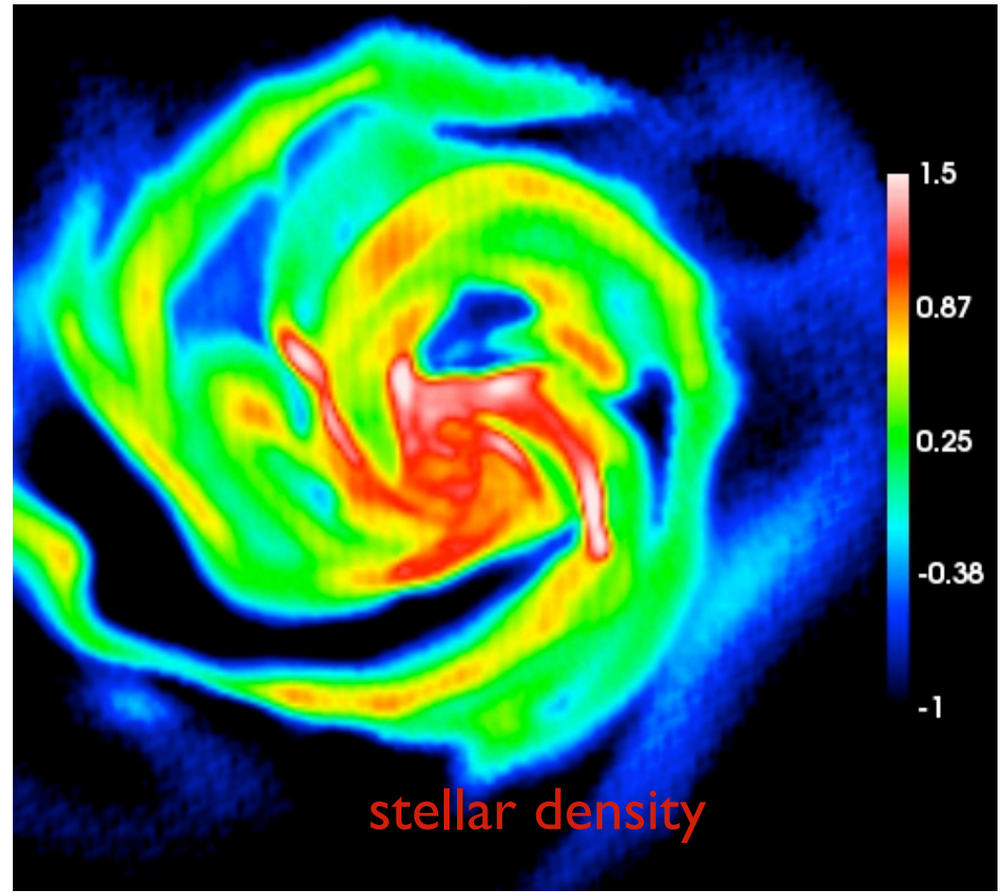
----- Small halos assembled half their masses earlier on average than large halos (hierarchy)

_____ The corresponding small galaxies assembled their M_s later than large galaxies (downsizing)

(See Gonzalez-Samaniego's poster)

High-resolution hydro/N-body simulations of low-mass galaxies:

H-ART code: Colin+10; Avila-Reese+11; Gonzalez-Samaniego+14
GADGET code: de Rossi, Avila-Reese+13



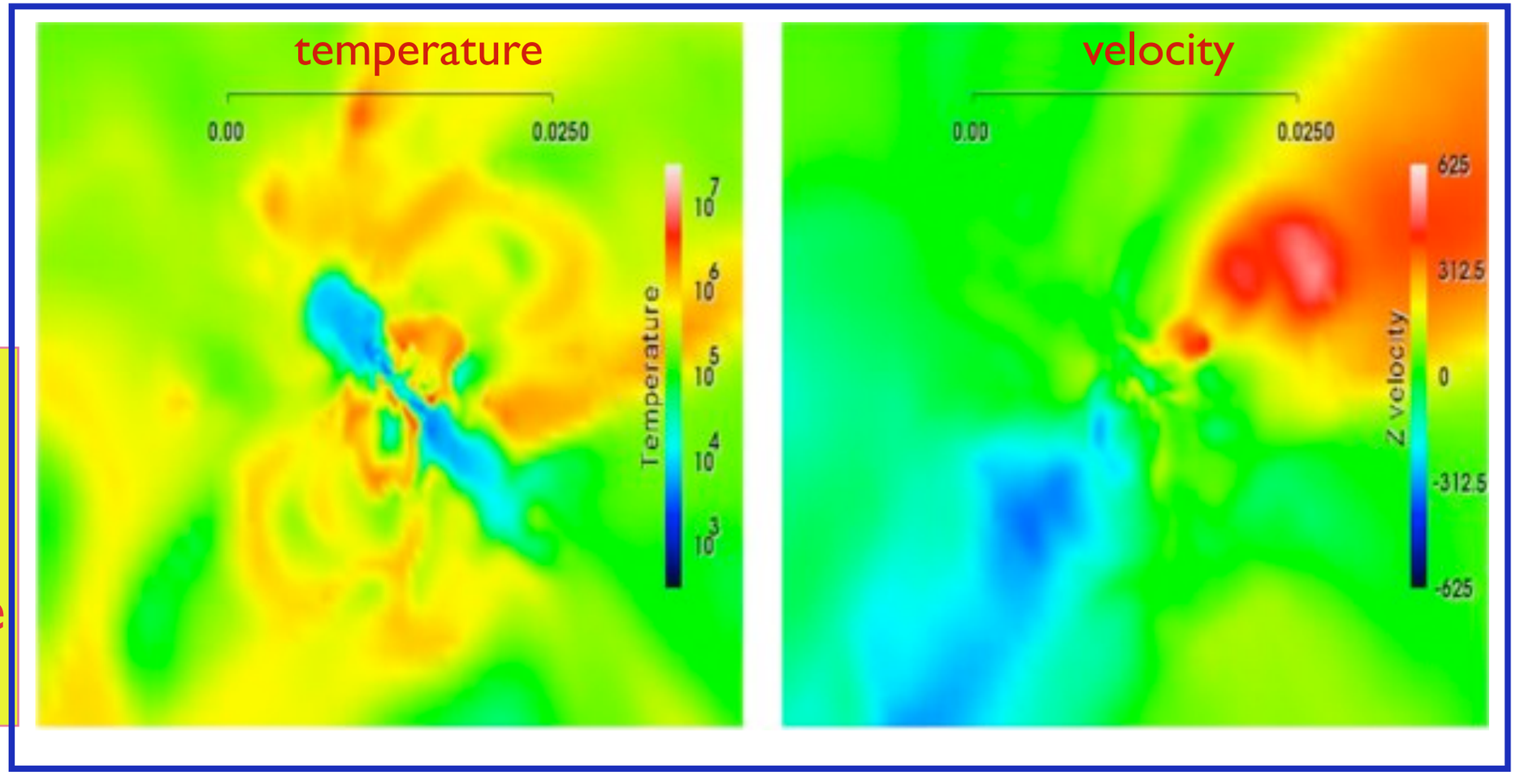
Rotating disks with nearly flat rotation curves, realistic structures and ISM properties!

Follow the observed scaling relations

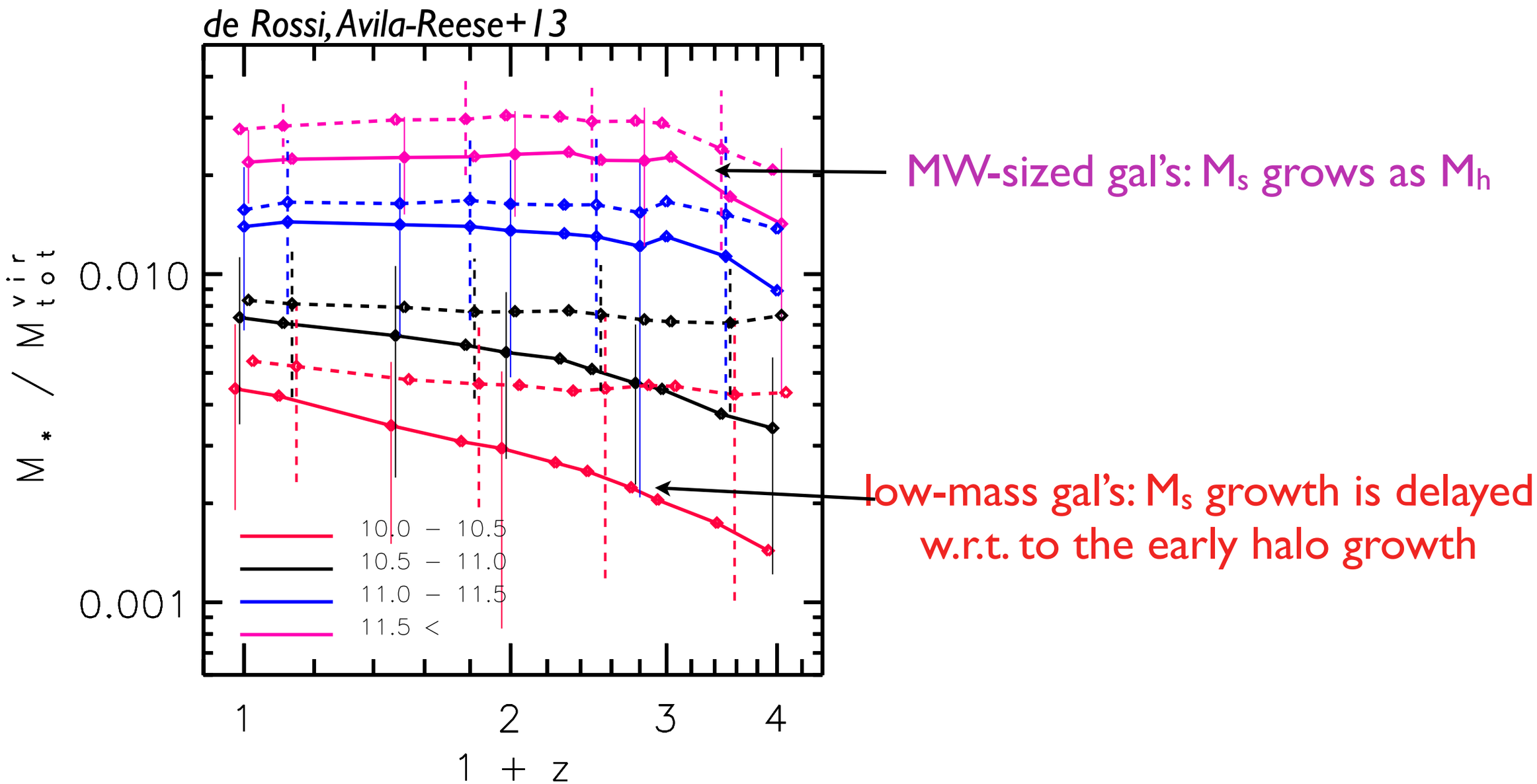
Strong SN-driven outflows.

IGM: infalling and outflowing gas

SN-feedback and SF processes delay slightly SF as less massive the halos are (downsizing)...



Evolution of the stellar-to-halo mass ratio



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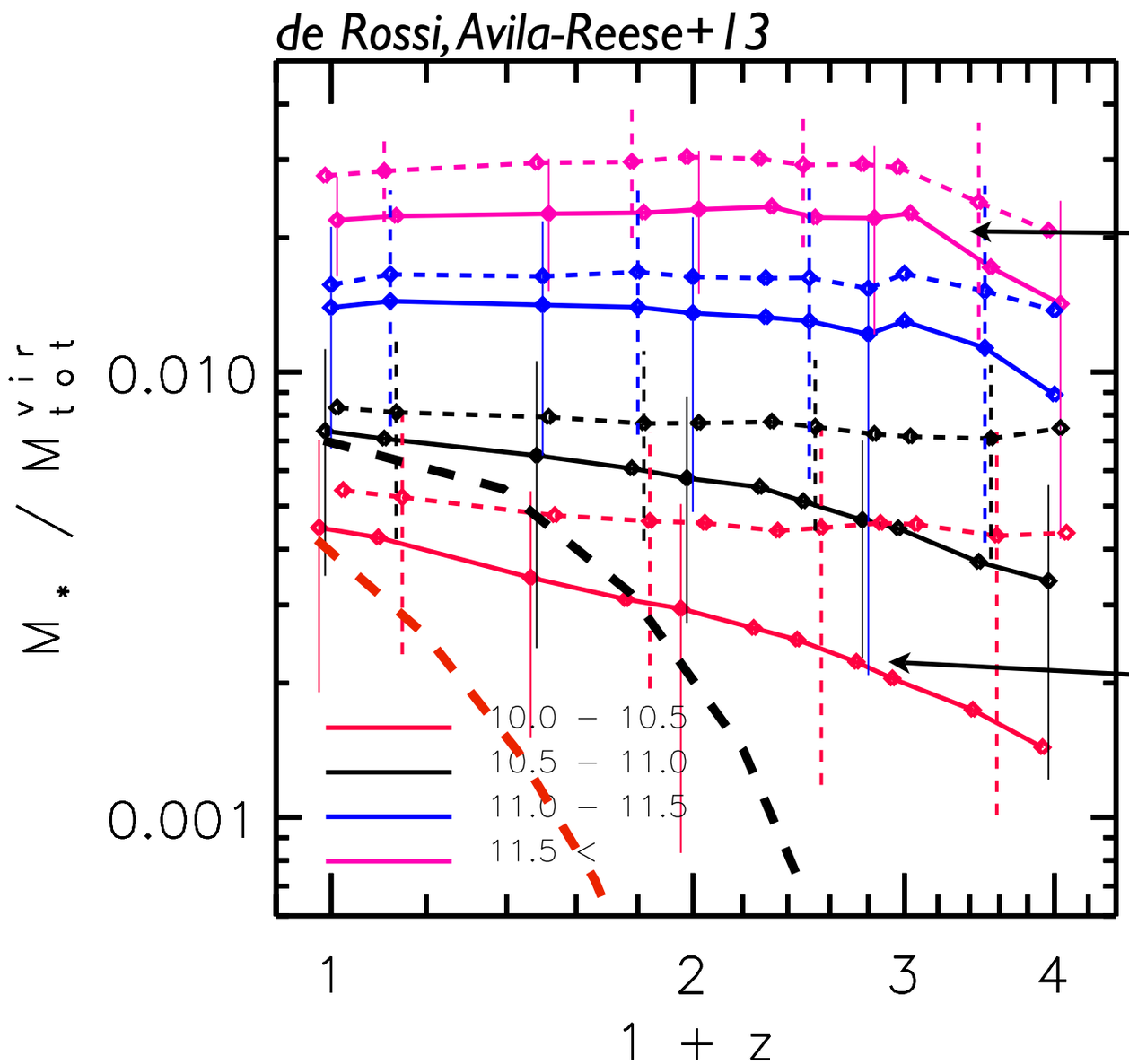

MW-sized gal's: M_s grows as M_h

low-mass gal's: M_s growth is delayed w.r.t. to the early halo growth

Empirical inferences

...BUT not enough as observations suggest; *M_s growth does not detach significantly from M_h growth for low mass galaxies!*

but see Brooks+12; Munch+13 (extreme ejective SN feedback)

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To have in mind

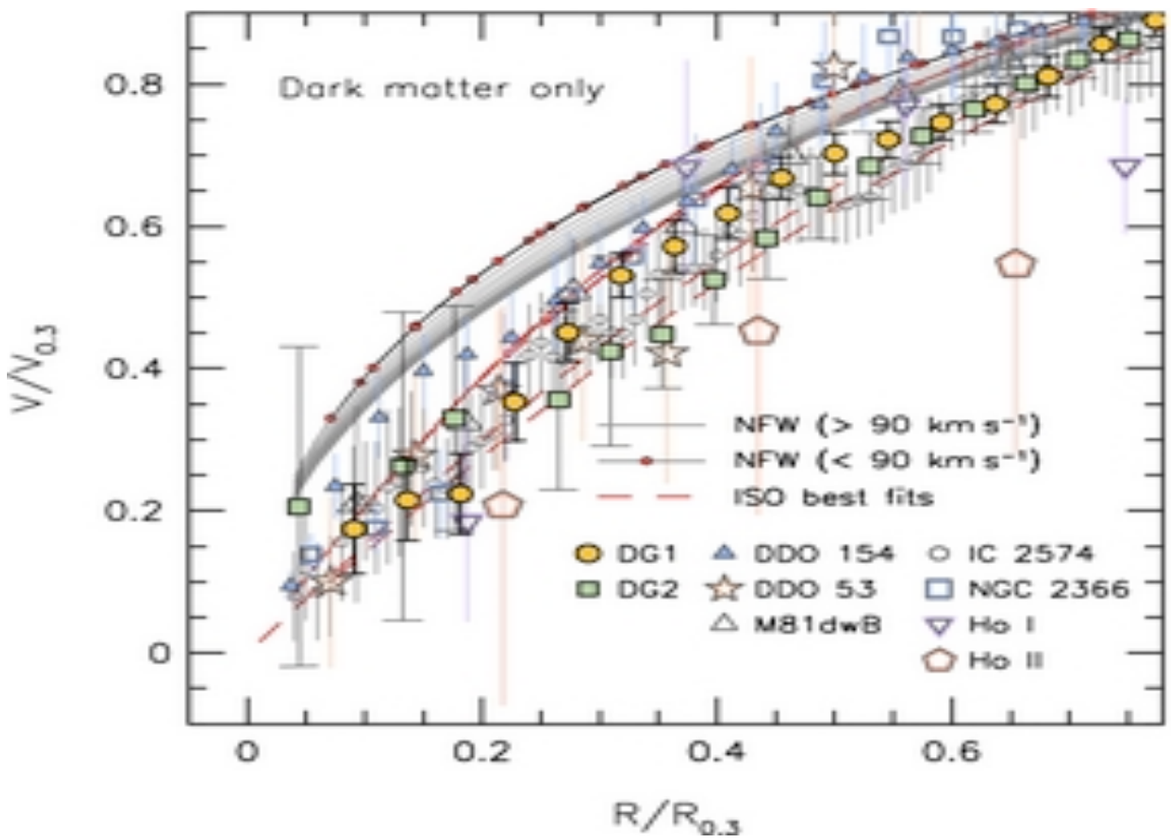
- The strongly dissipative baryonic physics affects the dynamics of dark matter in low-mass halos.

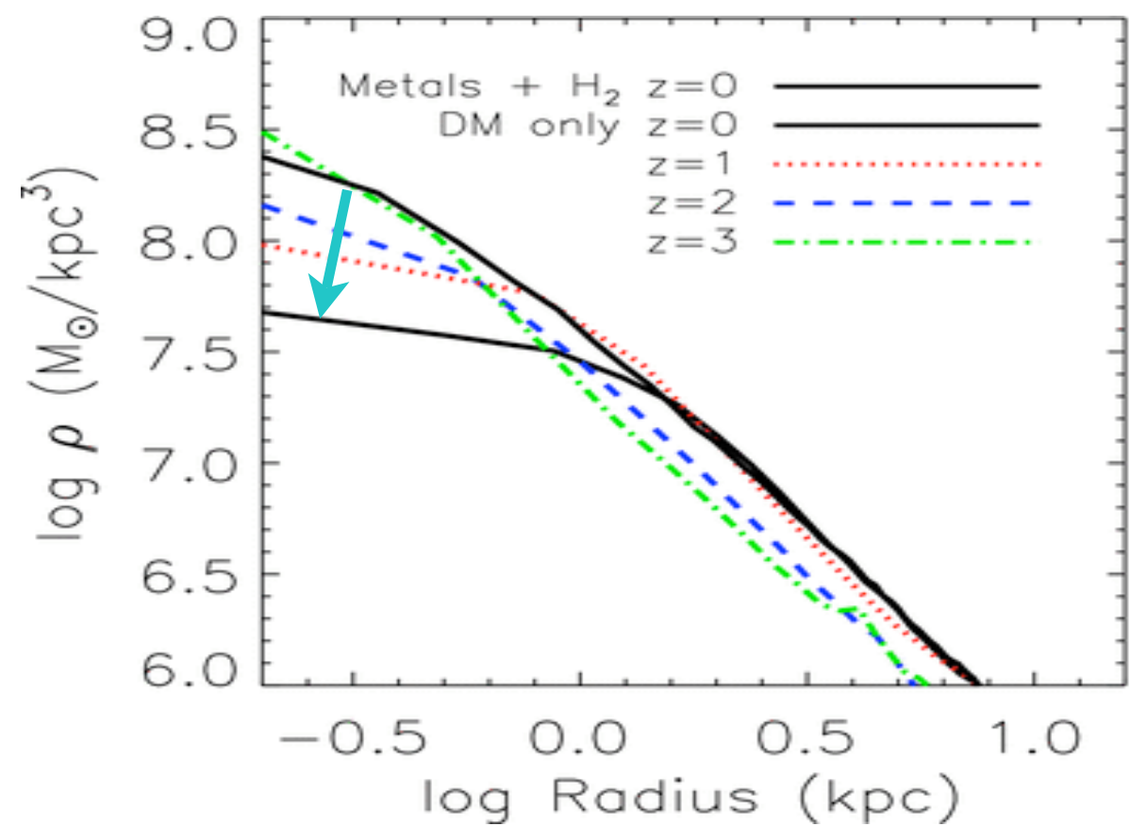
- The 'gastrophysics' and DM-baryon coupling should be understood in order to constrain LCDM at small scales from observations (this applies to any other alternative scenario!)

- Current controversies at small scales: cuspy, too concentrated (sub)halos, missing satellites and downsizing could be all related to baryon effects in low mass halos.

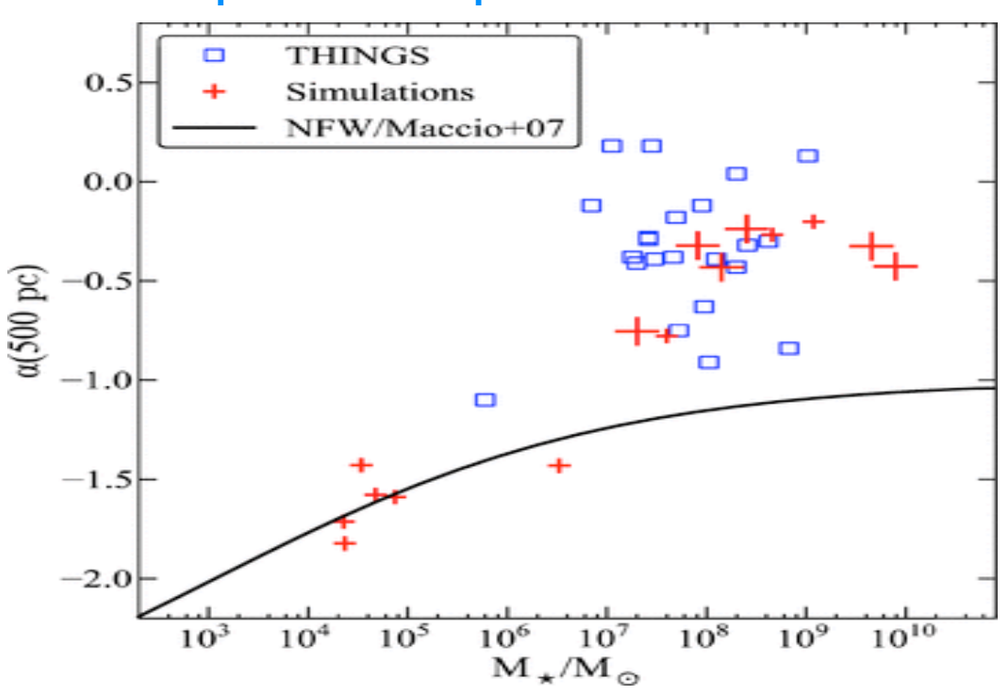
Early SN-driven ejective feedback produces shallow cores and it lowers V_{max} in halos $<10^{11}$ $M_\odot$

Oh+11; Governato+12; Teyssier+12





Inner slope at 0.5 kpc vs M_s: observations vs simulations



Do the SFR histories of dwarfs imply as much SNe in the past as in the simulations?

No: Boylan-Kolchin+12; Garrison-Kimmel+13.

Yes: Amorisco+13 (Fornax & Sculptor sat's).

For satellite galaxies: early feedback + ram pressure + tidal heating from the host --> shallow core *(Arraki+12; Zolotov+12)*.

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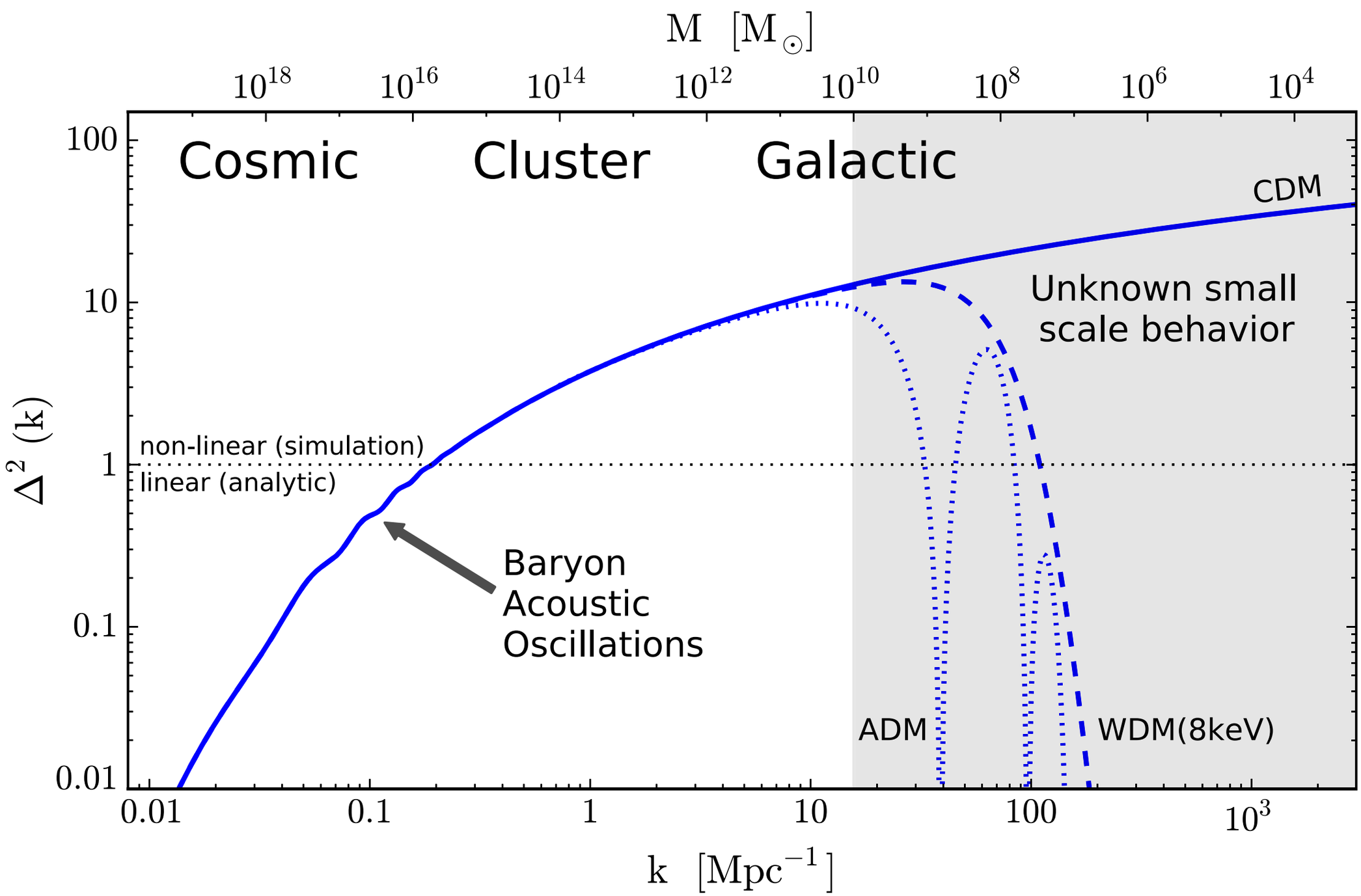
In case the small-scale issues are real: relax assumptions

LCDM cosmogony: *Gaussian density perturbations, *scale invariant PS without a cut-off, *dominate collisionless, non-interacting, v_{rms}=0 particles.

It's the simplest case from the point of view of cosmic structure formation



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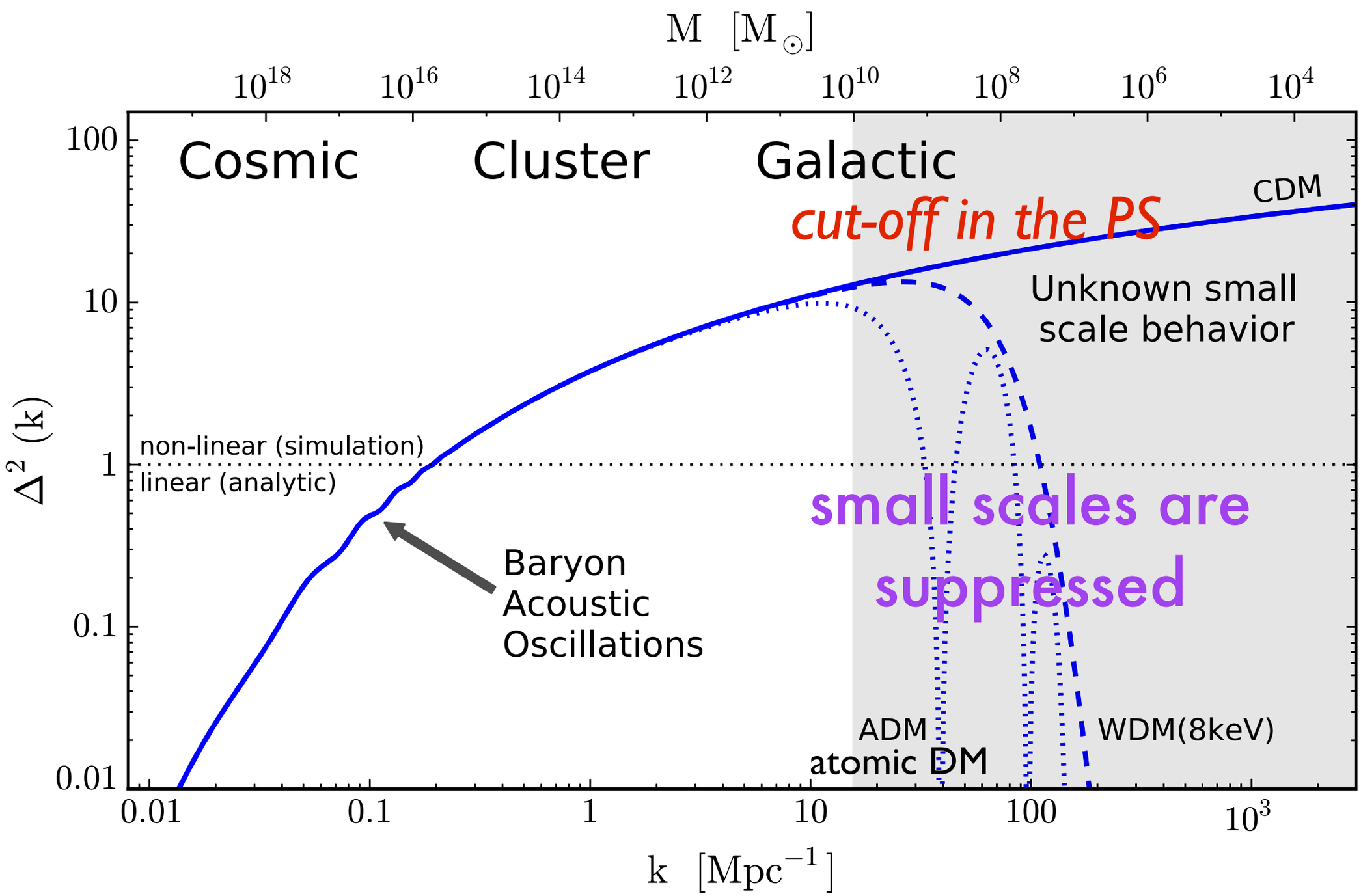
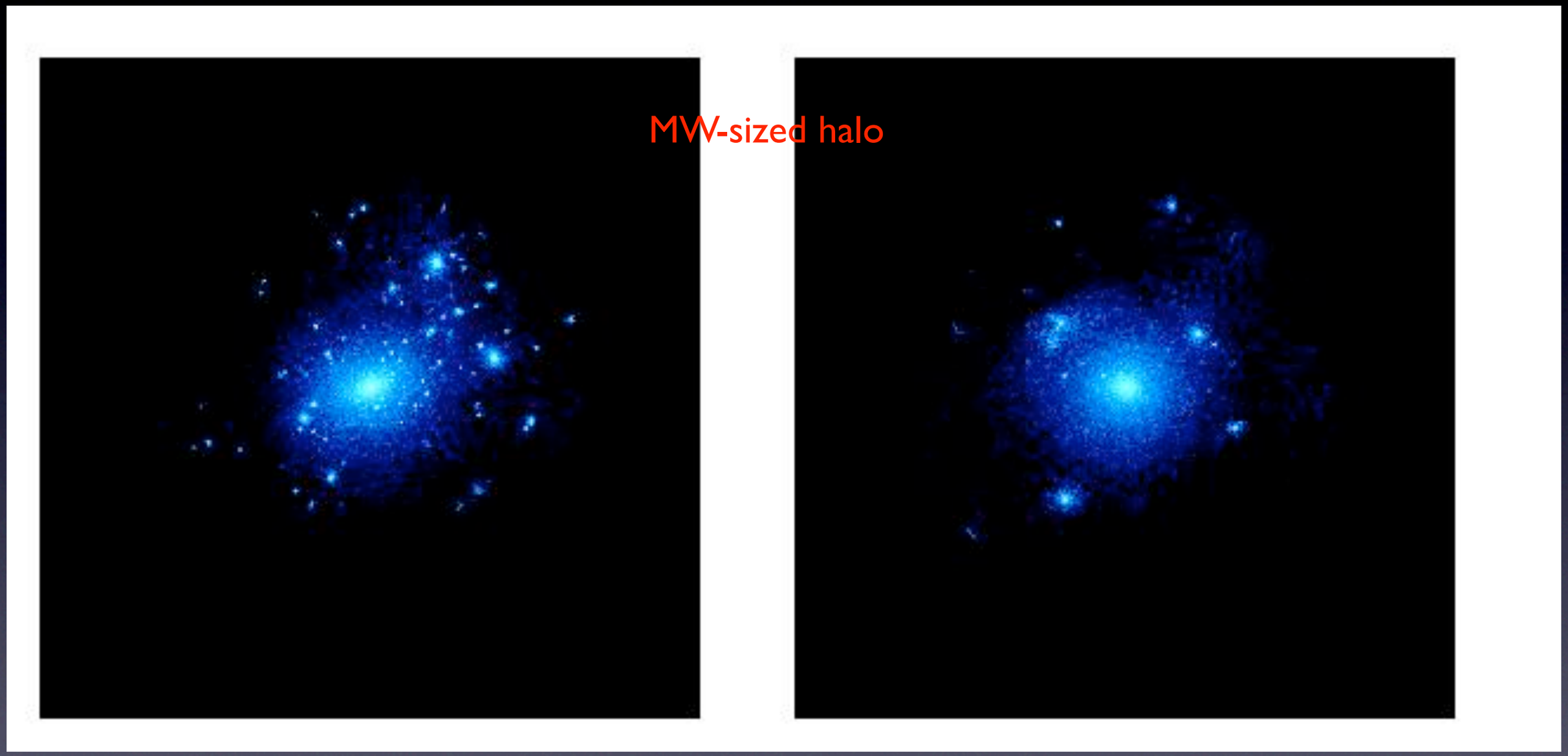


WDM candidates: ***sterile neutrinos*** (νMSM model, resonantly produced) ***and thermal ~keV particles (e.g., gravitinos)***

CDM Colín+ 00, 08; Avila-Reese+01 WDM



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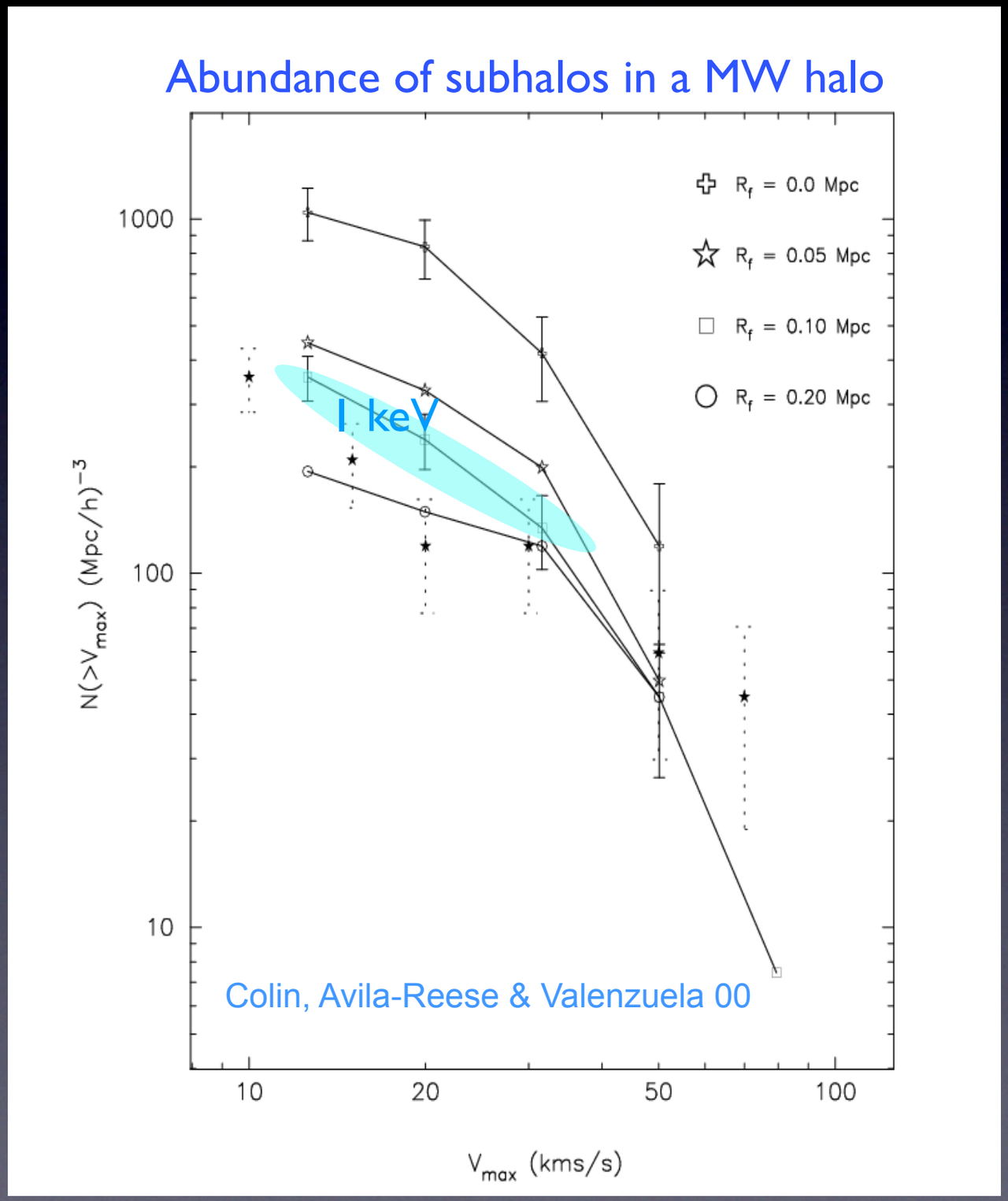

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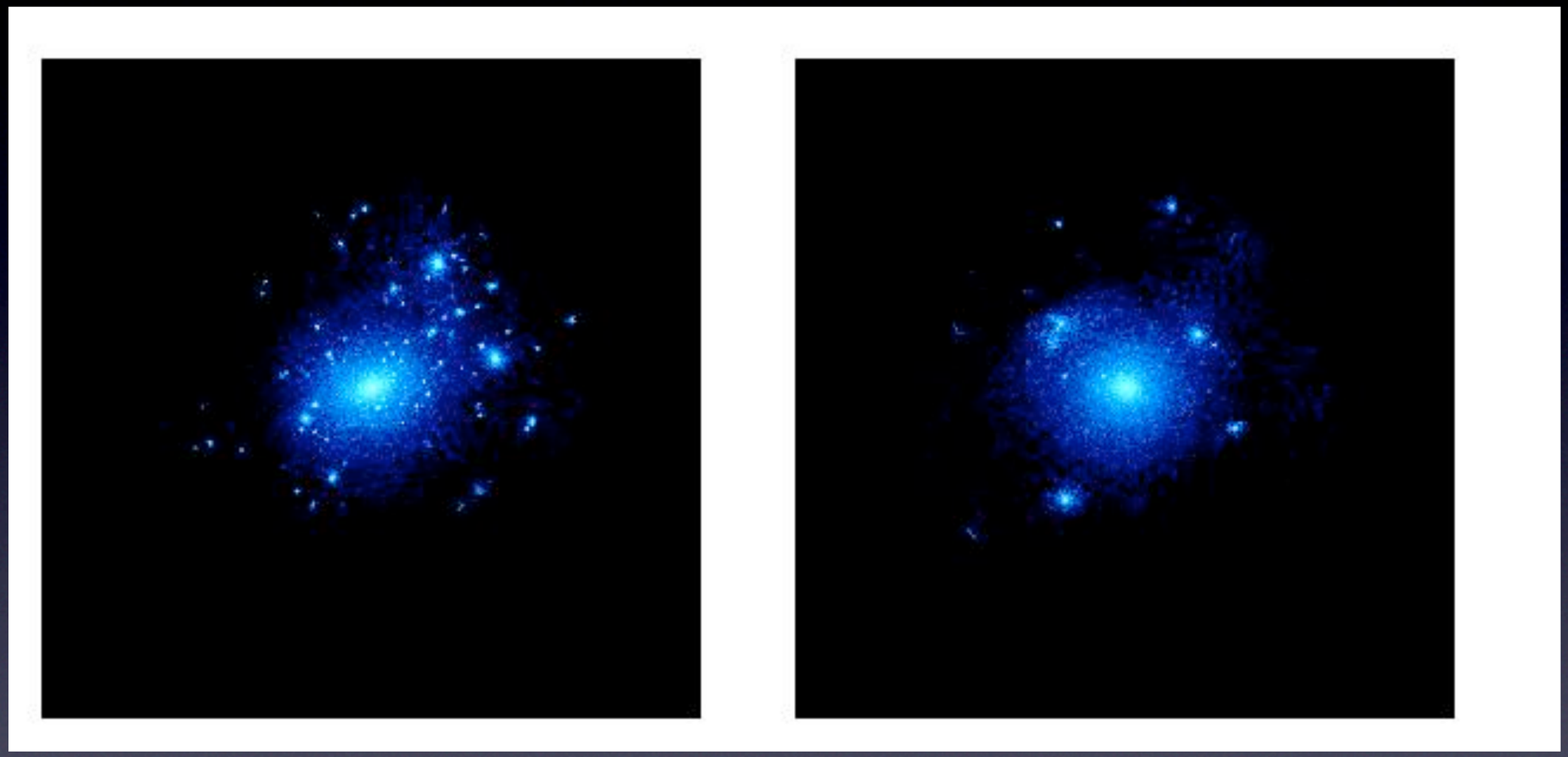
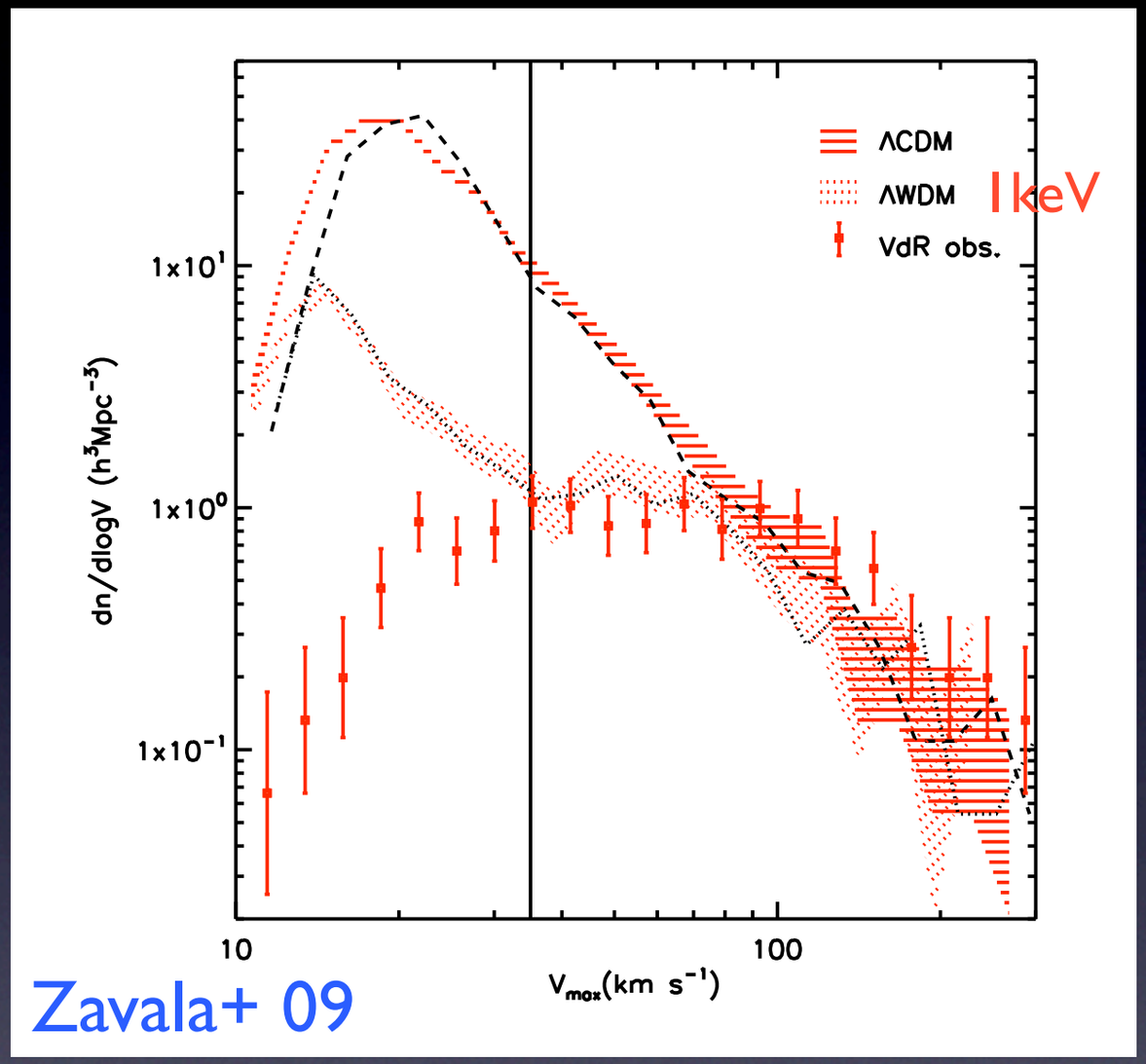


-WDM produces also: less concentrated halos with less angular momentum *(Avila-Reese+ 01; Bode+01)*, subhalos with smaller Vc (Lowell+11), delays SF in halos close to the cut-off (Colin+)

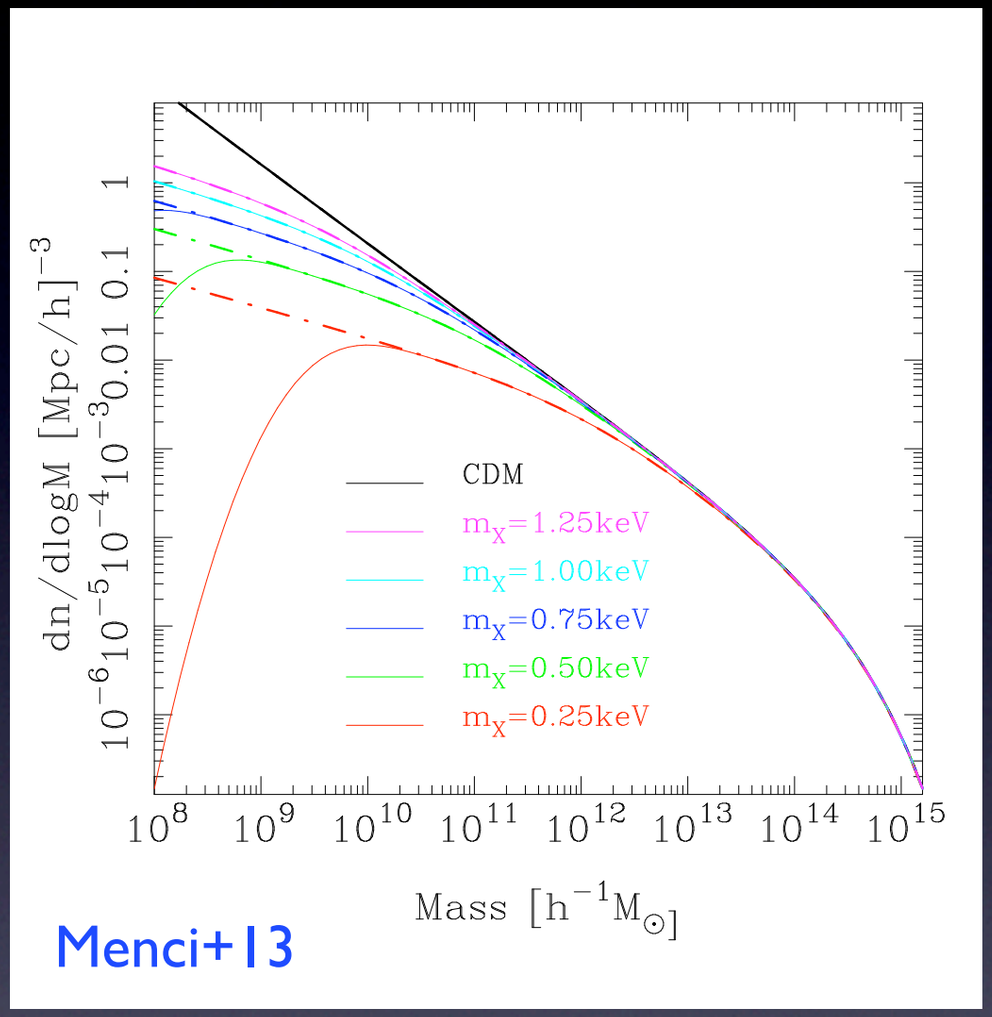
-But it doesn't produce soft cores, unless 'unrealistic' amounts of thermal relict velocities are introduced *(Colín+ 08;Padirou+ 09; Shao+ 12)*, as in meta-DM models: neutrinos decay lately into gravitinos. See also BDM model (De la Macorra 11, PRD)

The HI velocity (or mass) function of galaxies

Velocity function from HI observations vs simulations of the local universe



Halo mass function



<u>Challenges for WDM:</u> The good results are for m~1-2 keV, but

- (a) the linear PS of fluctuations at z>2 from the Ly-α forest observations can't be reproduced with a cut-off corresponding to these masses (>3.3 keV, *Viel+13*);
- (b) too few subhalos to host the observed ultrafaint dwarfs (*Polisiensky & Ricotti 11*)

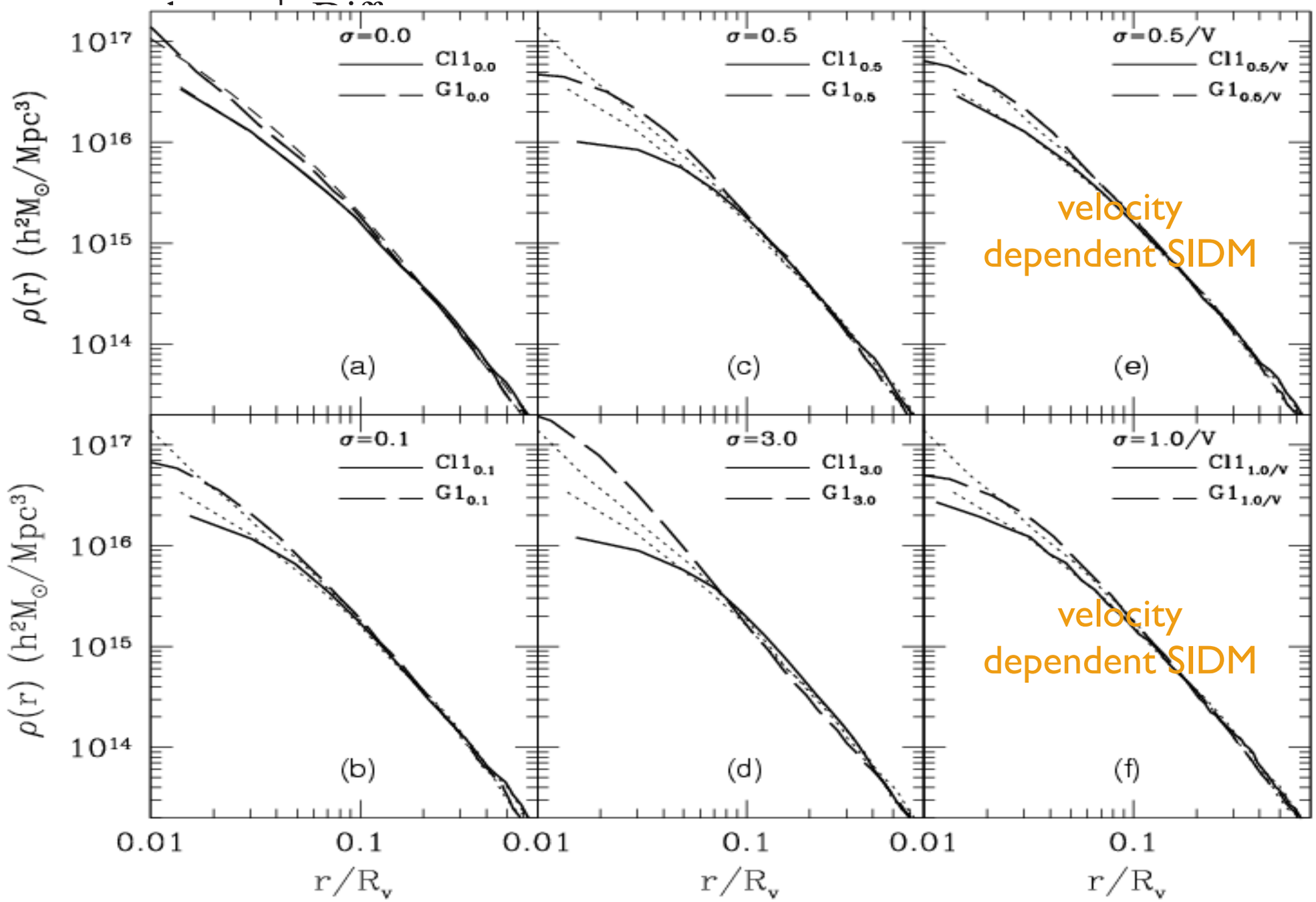
LCDM cosmogony: *Gaussian density perturbations, *scale invariant PS without a cut-off, *dominate ~~collisionless, non-interacting~~, v_{rms}=0 particles.

Self-interacting Dark Matter *(Spergel & Steinhardt 00; Firmani+00, 01, MNRAS)*

Colín+02: Cluster & galaxy-sized halc N-body simulations

Self-interaction--> gravothermal processes: core expansion (but also core collapse)

$$\sigma_{DM} = \sigma_0 (1/v_{100})^{\alpha} \, cm^2 \, g^{-1}$$ (~ nuclear-scale cross-section)



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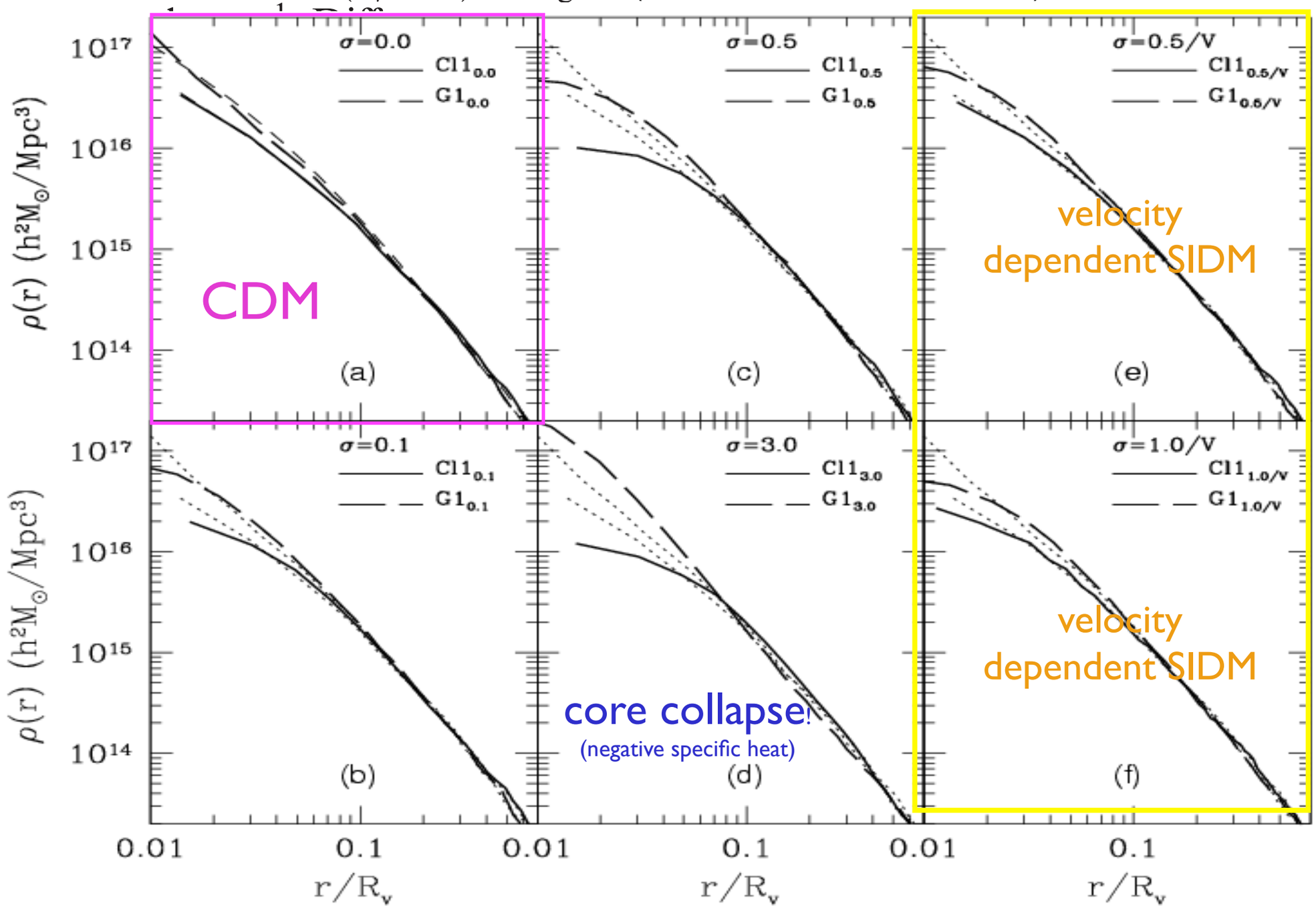
Self-interacting Dark Matter *(Spergel & Steinhardt 00; Firmani+00, 01, MNRAS)*

Colín+02: Cluster & galaxy-sized halo N-body simulations

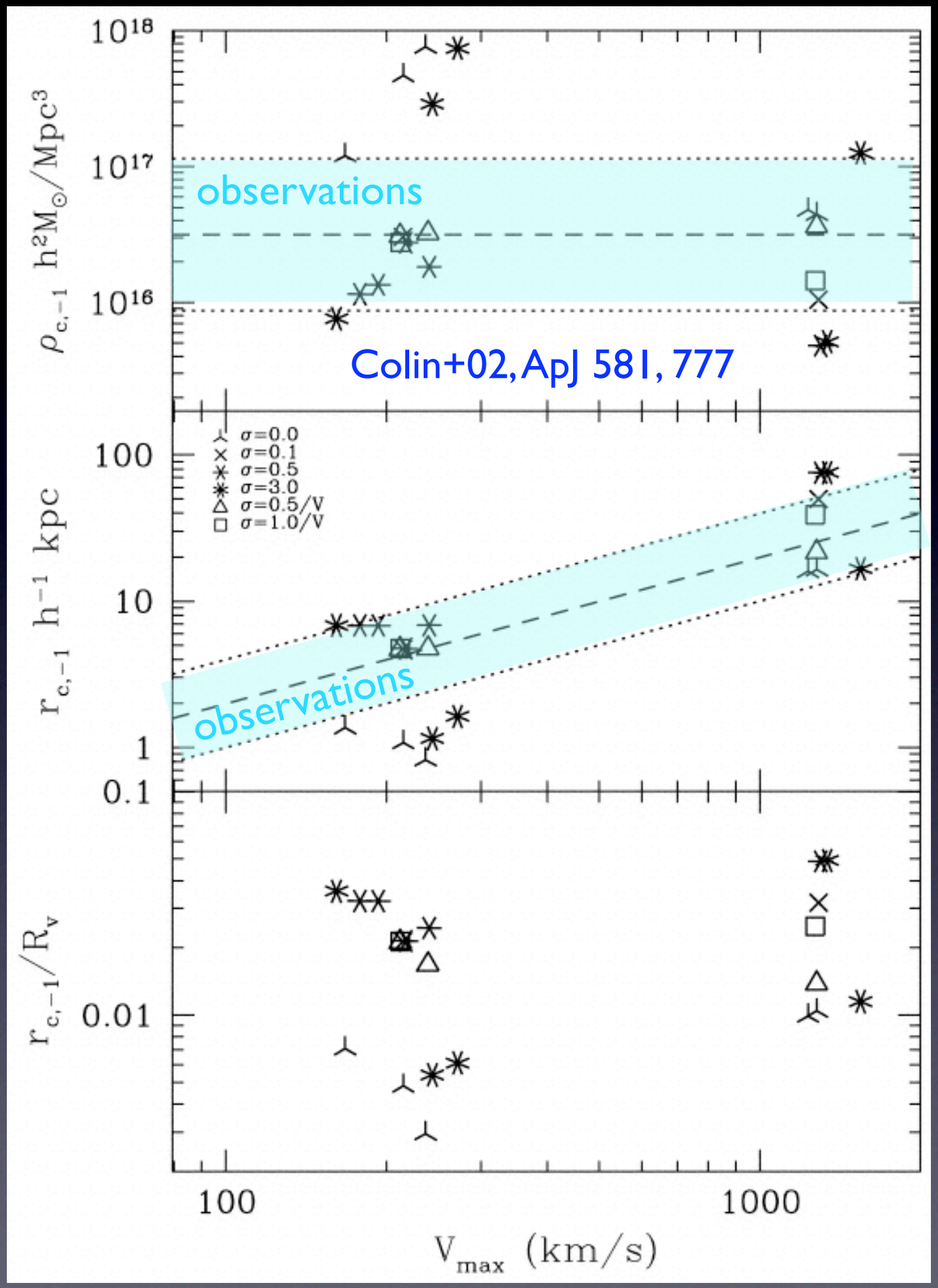
Soft cores are formed (but cuspy also due to core collapse!), but when σ=const, the range of values for producing viable solutions is small (fine-tuning)

A velocity (energy) dependent cross-section is viable for galaxy and cluster scales: vdSIDM

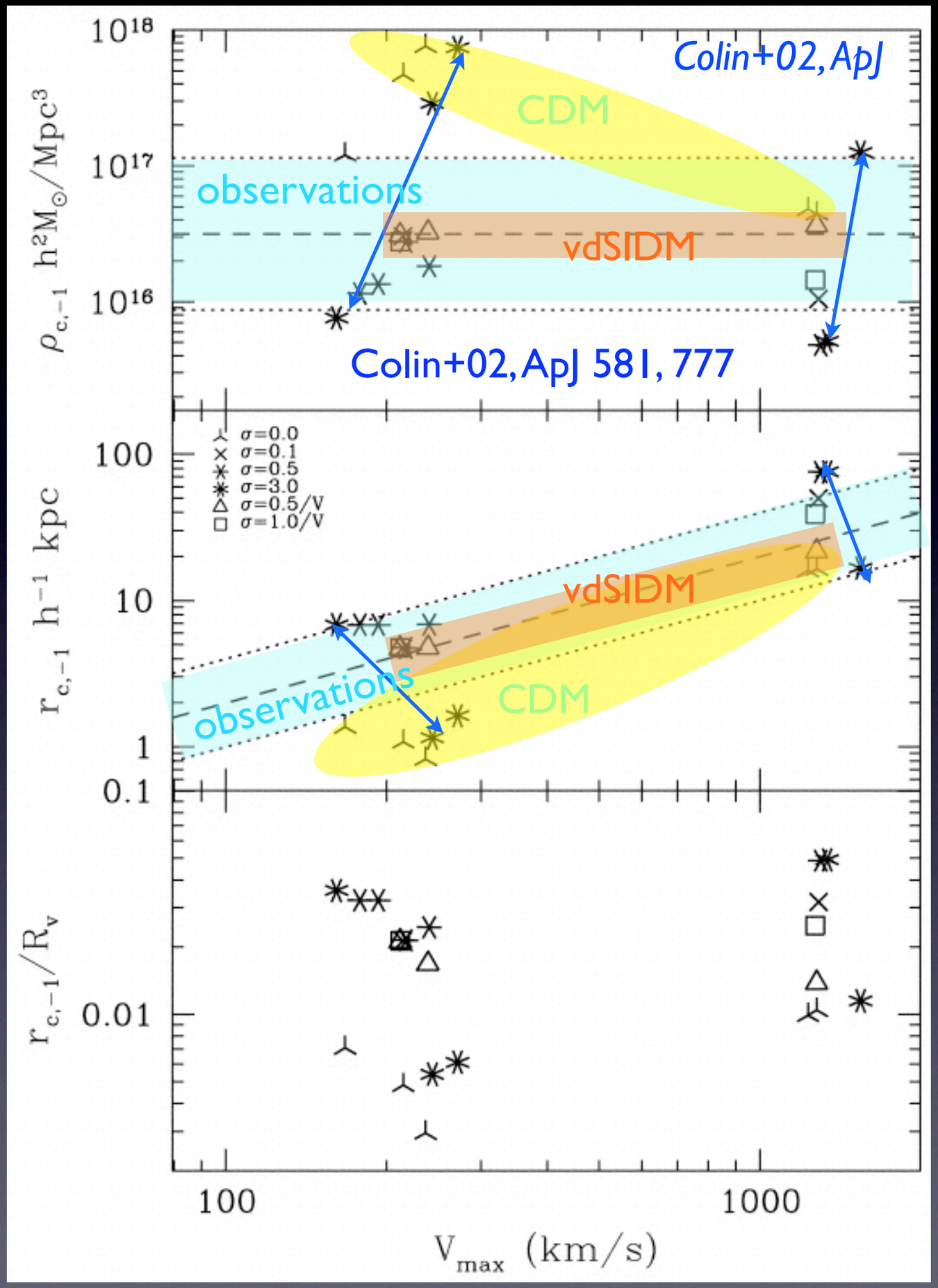
$\sigma_{DM} = \sigma_0 (1/v_{100})^{\alpha}$ cm^2 g^{-1} (~ nuclear-scale cross-section)



Halo Scaling Laws



- The vdSIDM case is the best one (soft cores in small halos, almost no cores in clusters)



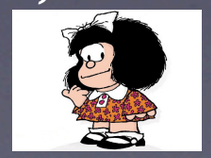
Halo Scaling Laws

- The vdSIDM case is the best one (soft cores in small halos, almost no cores in clusters)
- The SIDM halos are rounder than the CDM ones.
- The subhalo population of the vdSDM is similar to the CDM one

Renaissance of SIDM:

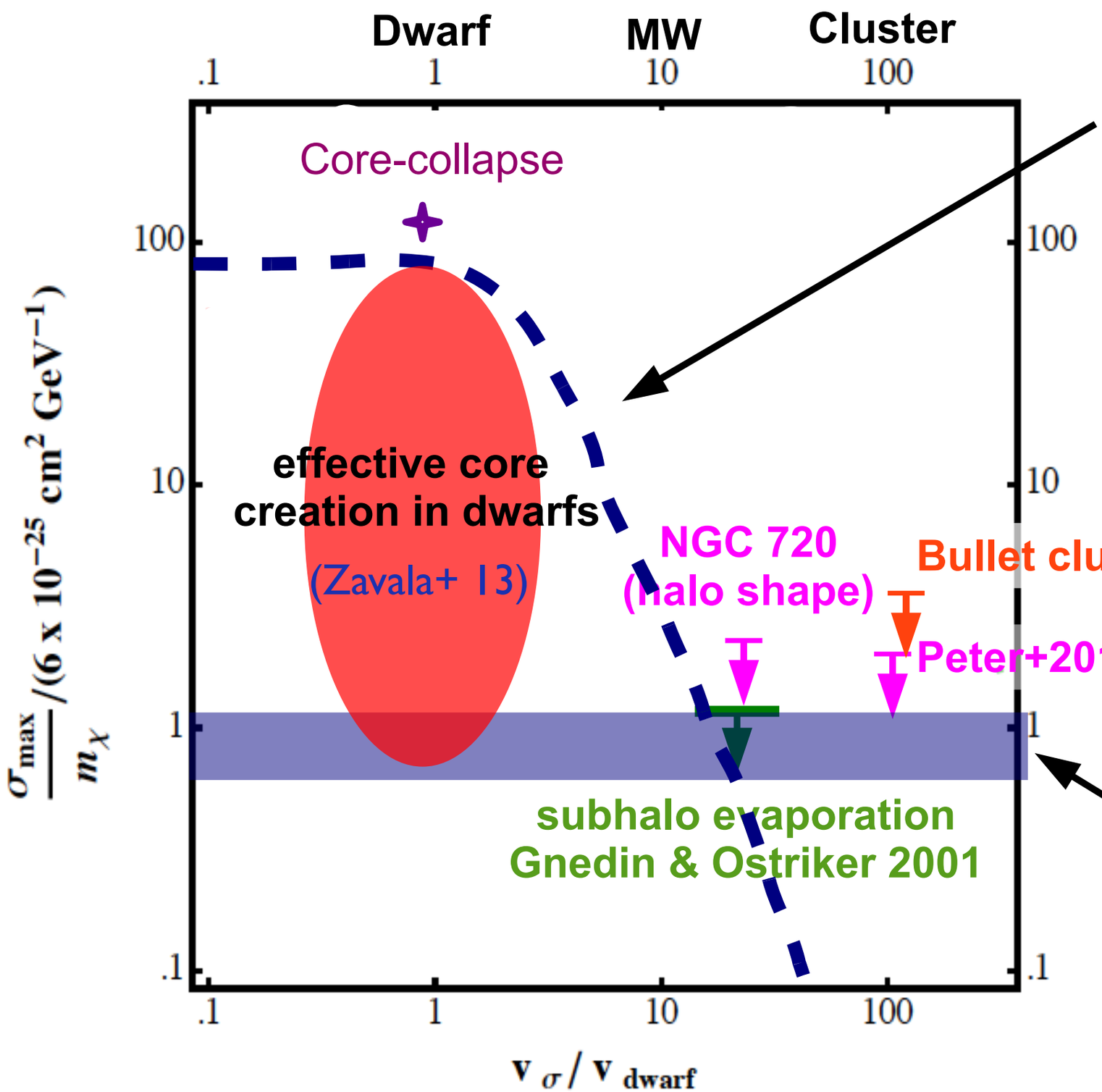
'Hidden dark sectors' in particle models: velocity-dependent cross sections *(Ackerman+09; Buckely+10; Feng +10;Tulin 13)*

New simulations: *Vogelsberger+12; Zavala +13; Rocha+13; Peter+13*



Constraints on collisional DM

DM cores, central spherical halo shapes, near-Maxwellian velocity distributions, are generic predictions of "astrophysically interesting" SIDM models



vdSIDM models motivated by a new force in the "dark sector", e.g. Yukawa-like, (e.g. Feng+09, Feng+10, Loeb & Weiner 2011)

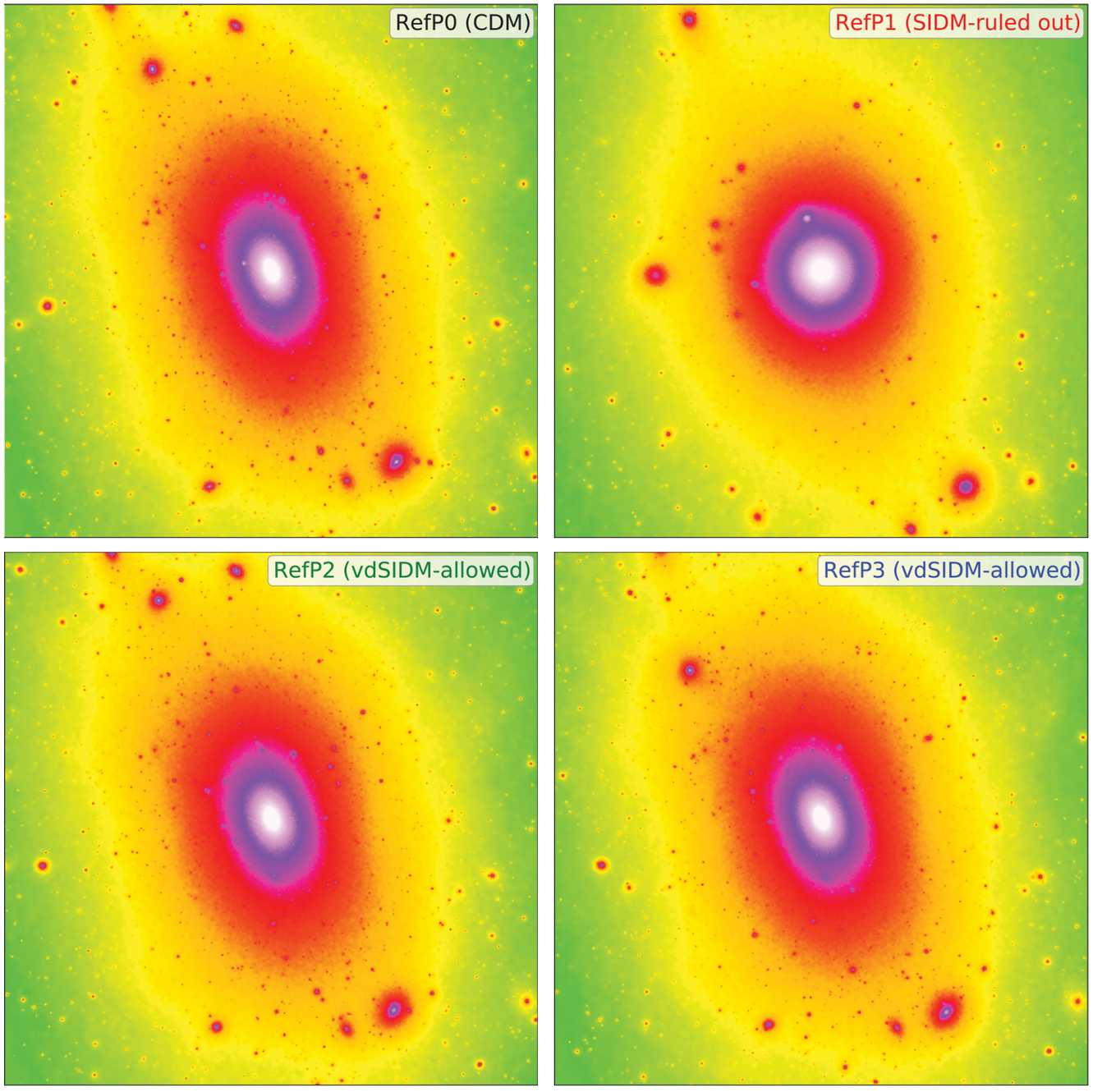
"hard-sphere" original idea introduced by Spergel & Steinhardt 2000

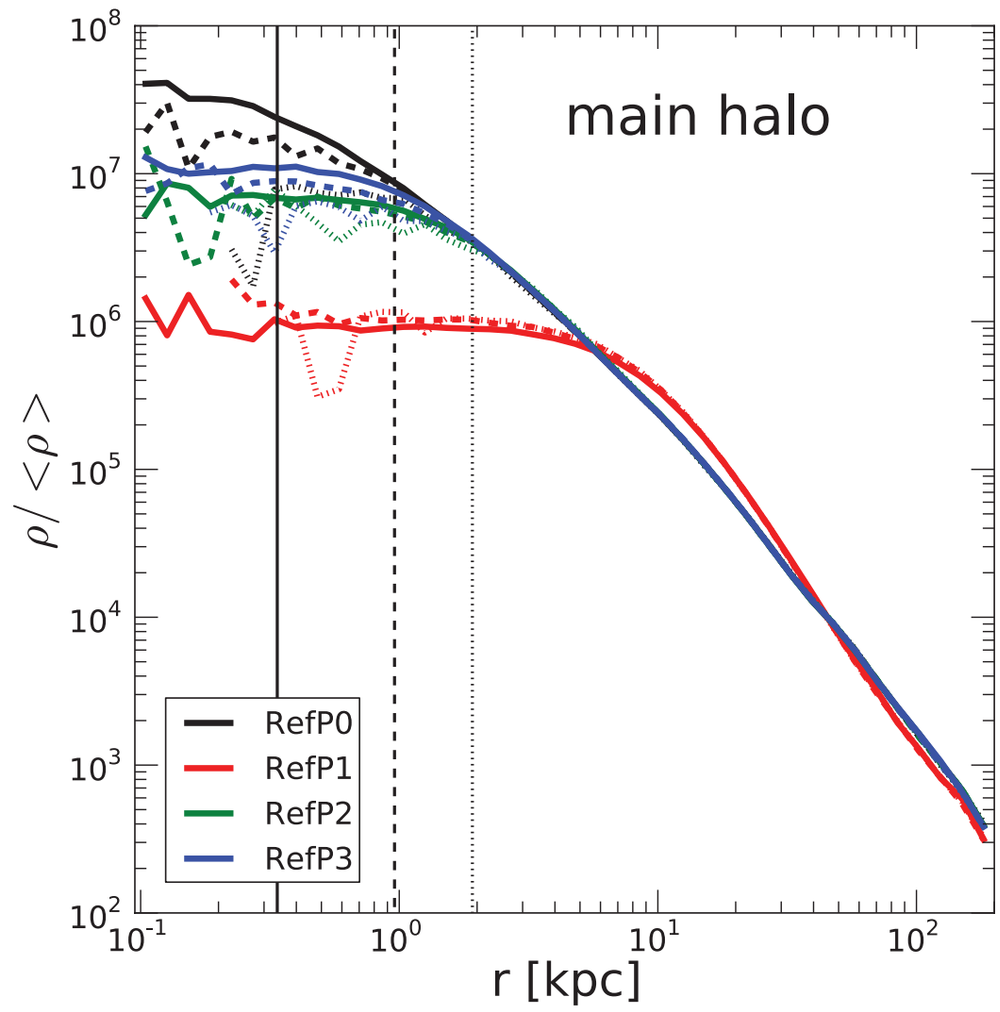
Vobelsberg, Zavala, Loeb 11

We use a simplified particle physics model where the self-scattering between DM particles of mass m_χ is set by an attractive Yukawa potential with coupling strength α_c mediated by a new gauge boson of mass m_ϕ (either scalar or vector) in the dark sector. We refer

$$\frac{\sigma_T}{\sigma_T^{max}} \approx \begin{cases} \frac{4\pi}{22.7}\beta^2 \ln(1+\beta^{-1}), & \beta < 0.1, \\ \frac{8\pi}{22.7}\beta^2(1+1.5\beta^{1.65})^{-1}, & 0.1 < \beta < 10^3, \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3, \end{cases} \quad (1)$$

where $\beta = \pi v_{max}^2/v^2 = 2\alpha_c m_\phi/(m_\chi v^2)$ and $\sigma_T^{max} = 22.7/m_\phi^2$,





The subhalos are less concentrated than in LCDM

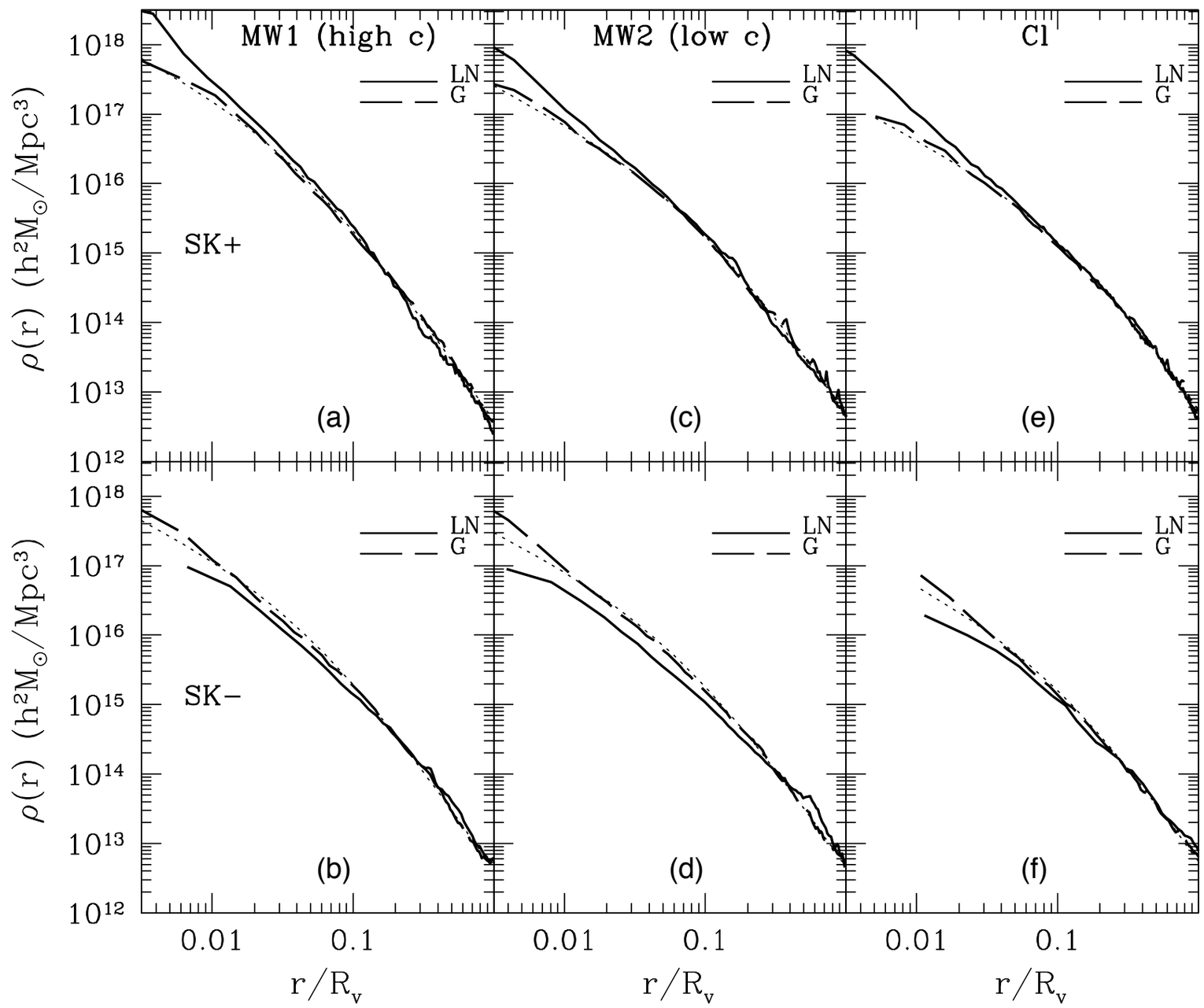
LCDM cosmogony: *~~Gaussian density perturbations~~, *scale invariant PS without a cut-off, *dominate collisionless, non-interacting, v_{rms}=0 particles.

Avila-Reese, Colín, Piccinelli 03, ApJ

Positive and negative skewed statistics

Positive: more cuspy and concentrated halos, less ang, momentum

Negative: shallower and less concentrated halos, more ang. momentum



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LCDM makes a strong prediction: large population of dark subhalos around galaxies (absent in WDM).
How to detect them?

-Flux anomalies *(Dalal & Kochanek 02; Metcalf & Amara 12)* or astrometric deviations *(Vegetti+12)* in QSO gravitational lenses produced by subhalos.

Current detections (e.g., CLASS survey) are marginal and, if any, imply *more substructure than CDM!* Other sources (e.g., globular clusters, distant galaxies) should be taken into account *(Xu+10)*.

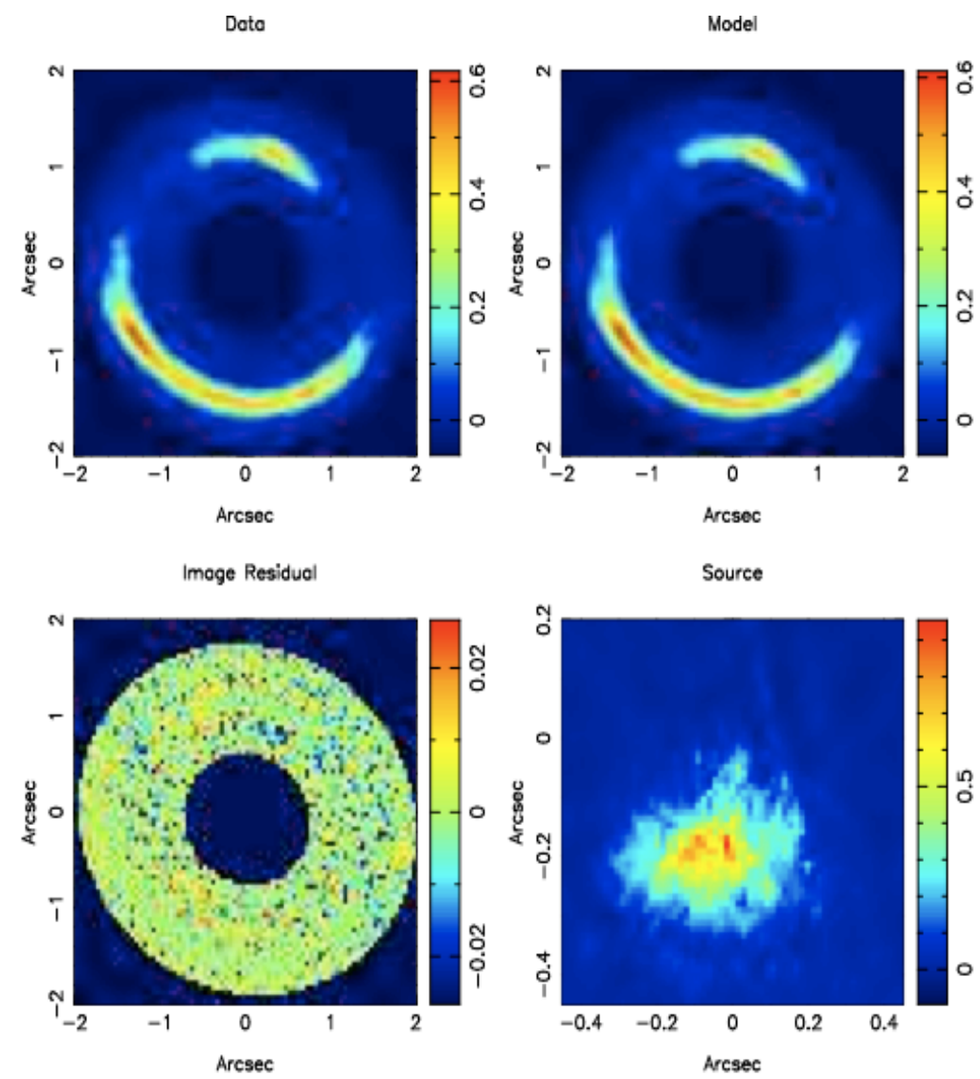
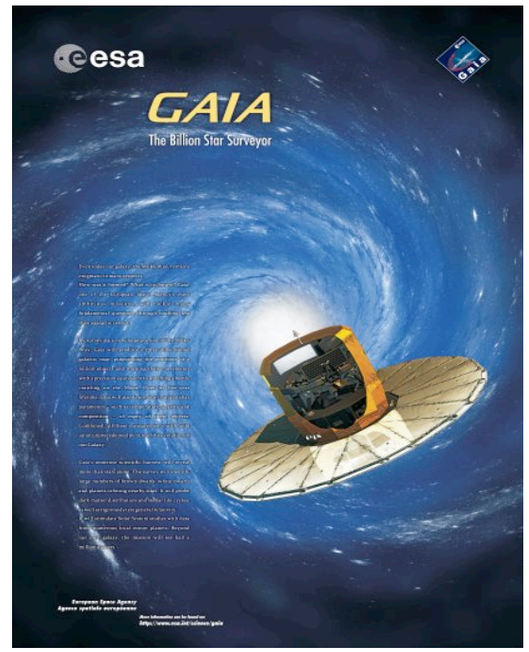


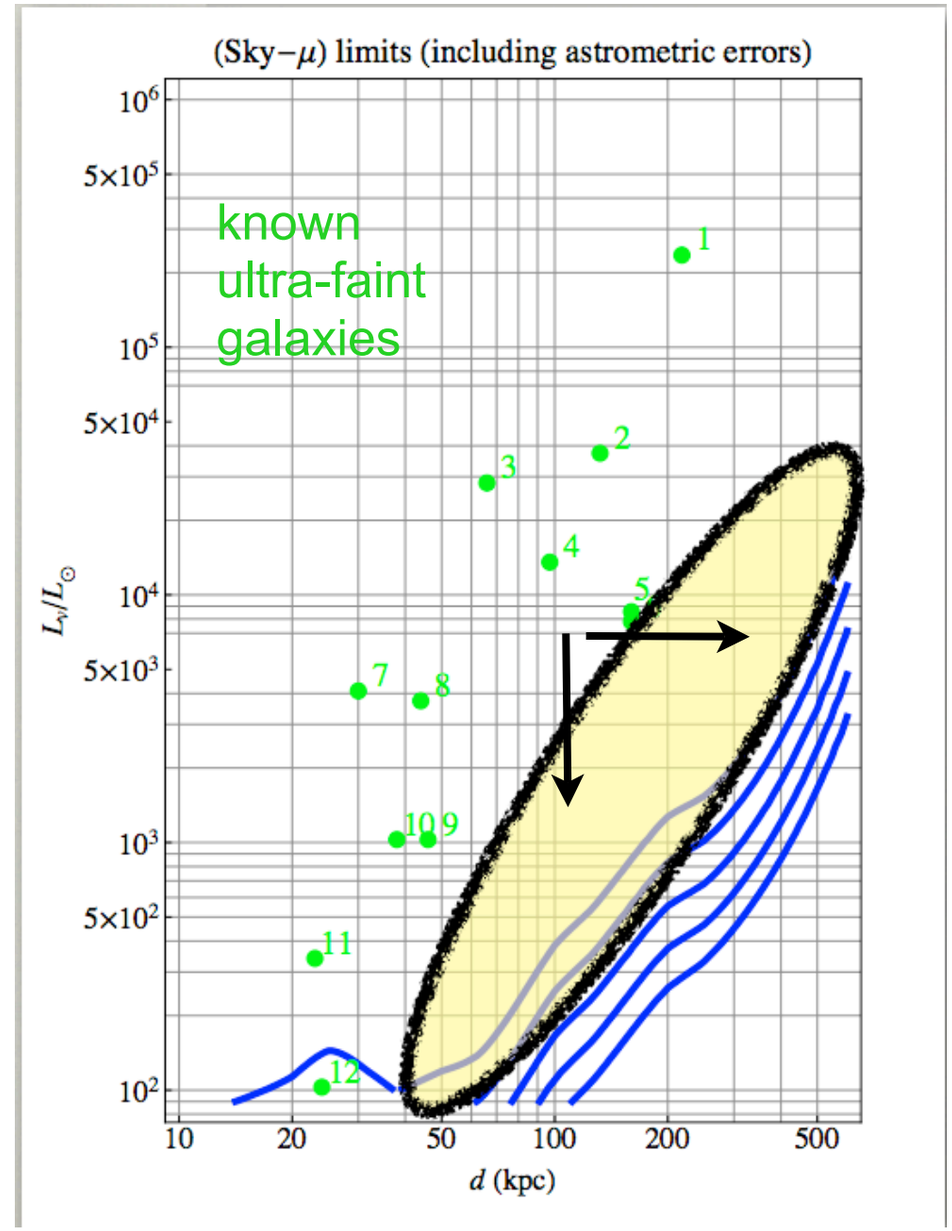
Figure 2. Results of the lens and source reconstruction under the hypothesis of a smooth potential. The top-right panel shows the original lens data, while the top-left one shows the final reconstruction. On the second row the image residuals (left) and the source reconstruction (right) are shown.

- Perturbations of the tidal streams in the MW by the subhalos (Carlberg & Grillmaiur 13)... preliminary evidence. GAIA.

-Ultra-faint galaxies in the MW, a proof of small-scale structure

GAIA: Potential to find them in the multi-space of stellar coordinates, velocities and metallicities



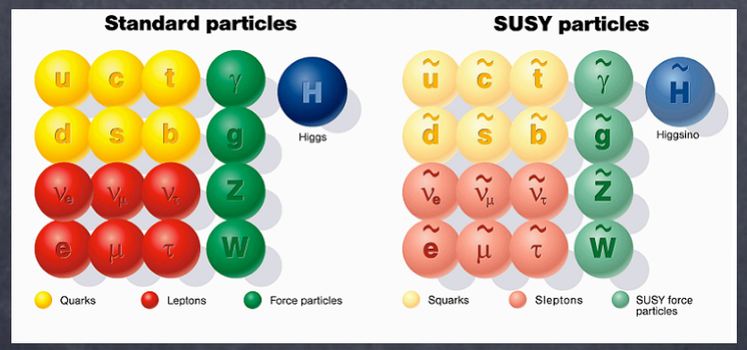


-Triaxiality of the galaxy dark halos from stellar and gaseous kinematics (Integral Field Spectroscopy -MaNGA)

-Power spectrum of gas clouds in H21 cm line at z>10 (proto-structures at all scales)

To take home

- A better understanding of the gastrophysics and the baryon-dark matter interaction is necessary to acquire before claiming for issues at small scales

- Key tests for LCDM: discovery of the predicted abundant substructure and the halo triaxiality

- The dark sector is likely much more complex than our simple models, with its own (self)interactions and particle zoo. SIDM is promising.