Dark Matter Lecture 1: Evidence and Gravitational Probes

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ICTP Summer School on Cosmology
Trieste
6 June 2016

Goals (Lecture I)

- Explain the arguments for particle dark matter.
- Outline current observations of the dark matter distribution in the cosmos, and their implications.
- Discuss the imprints of possible novel dark-matter physics on small and large scales, independent of any coupling to the known particles.

Historical review

The missing mass

- Zwicky, 1933: estimated the mass in a galaxy cluster in two ways.

<u>Method 1</u>

Estimate mass from mass-to-light ratio, calibrated to local system.

- Count galaxies
- Add up total luminosity
- Convert to mass using mass-to-light ratio of ~3, calibrated from local Kapteyn stellar system.

Mass estimate 1

<u>Method 2</u>

Use virial theorem + measurements of galaxy velocities to estimate gravitational potential, and hence infer mass.

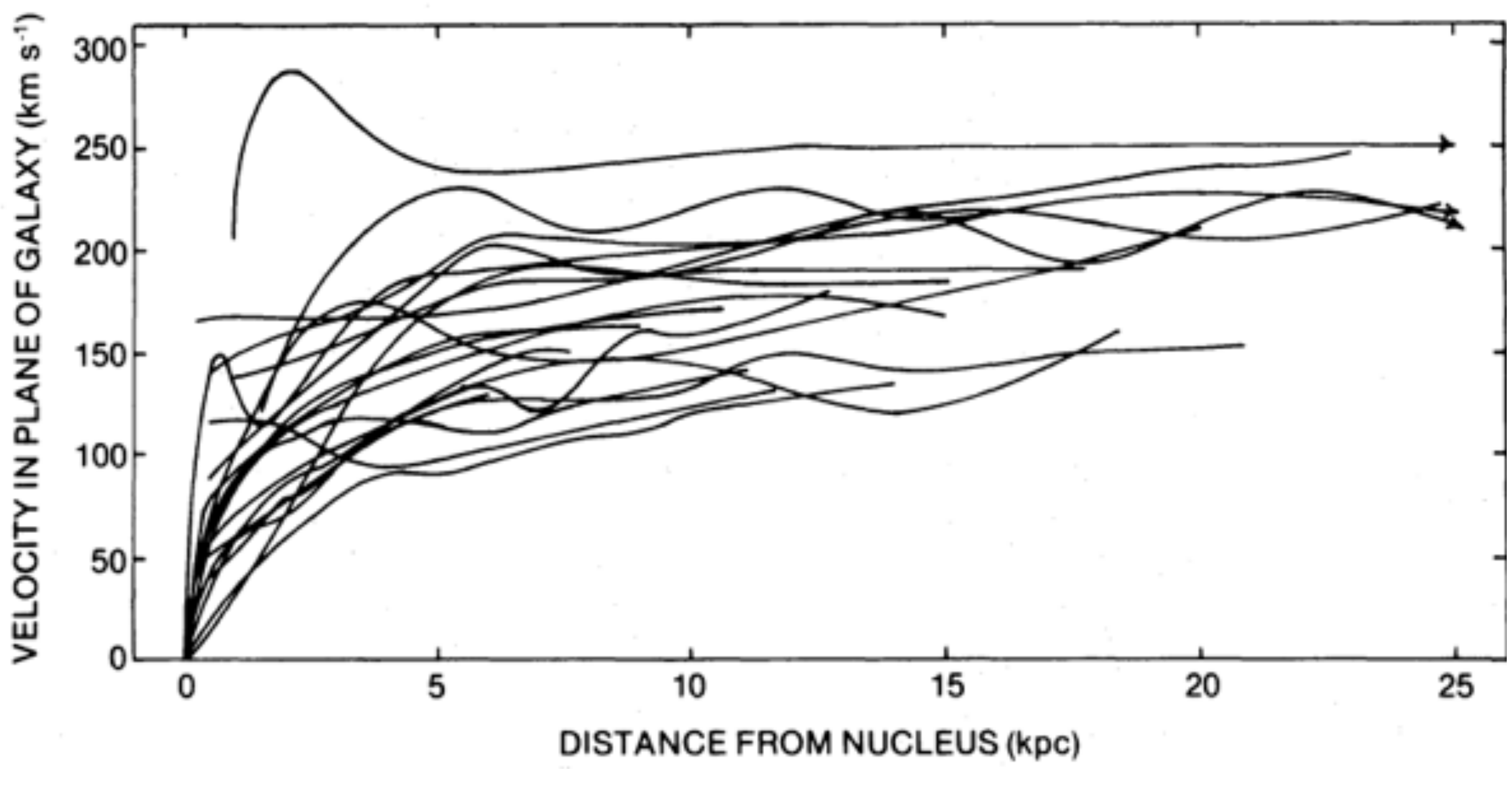
Galactic velocities measured by Doppler shifts

$$\mathrm{KE} = -\frac{1}{2}\mathrm{PE} \quad \text{in equilibrium}$$

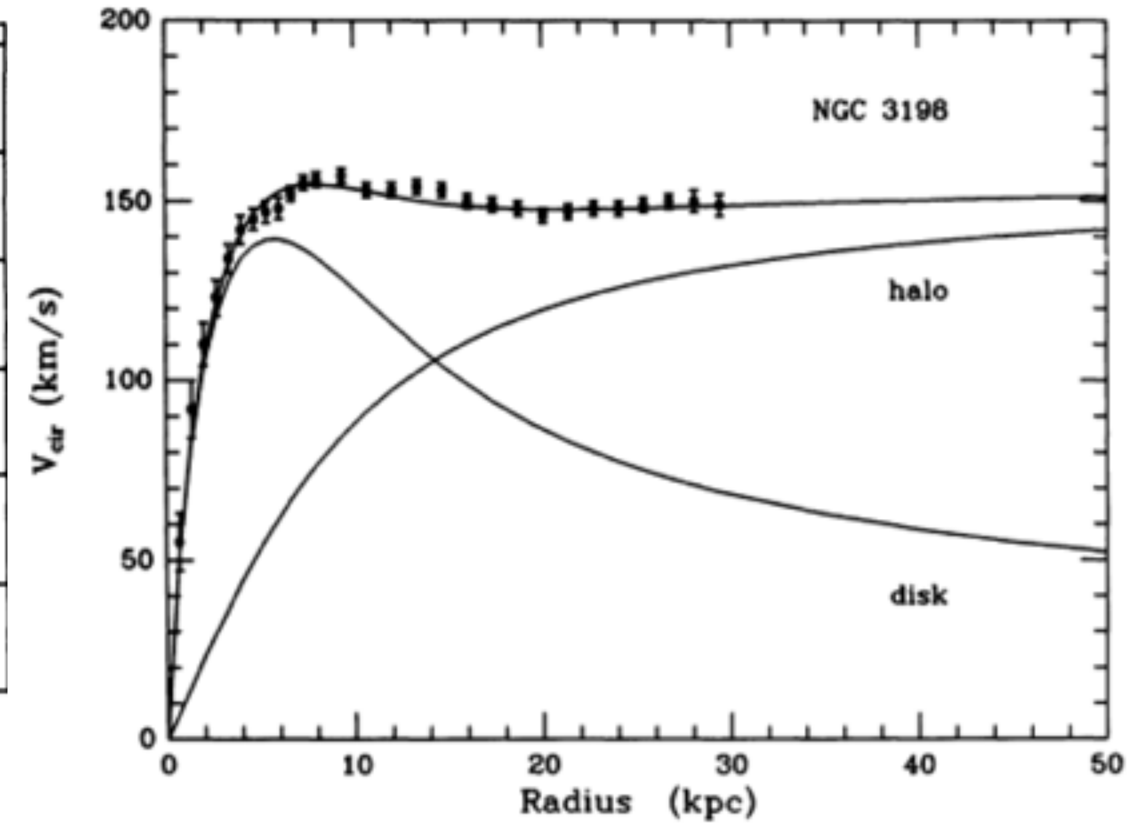
Mass estimate 2

- These numbers are different by 2+ orders of magnitude (second one is larger).
- One possibility: there is (lots of) gravitating non-luminous matter.

Rotation curves



Rubin, Ford & Thonnard, 1980



van Albada, T. S., Bahcall, J. N., Begeman, K., & Sancisi, R., 1985

- Rubin, Ford & Thonnard 1980 (following work in the 1970s): galactic rotation curves are flat, not falling as one would expect if mass was concentrated in the bulge at the Galactic center.
- Modified gravity? Or some "dark" unseen matter? If the latter, needs to extend to much larger radii than the observed Galactic disk - "dark halo".

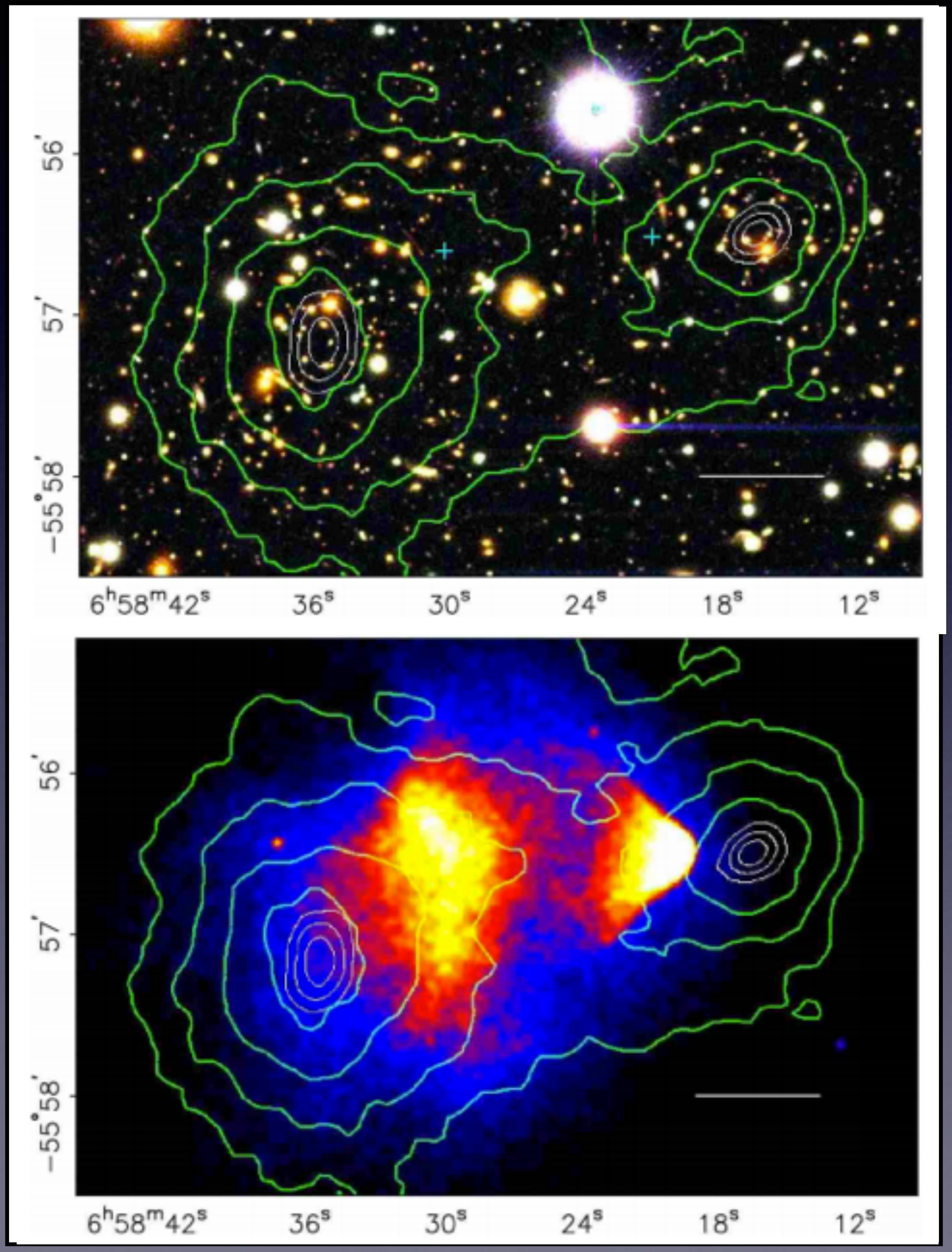
$$\frac{v^2}{r} = \frac{GM(r)}{r^2}$$

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

$$M(r) \propto r \Rightarrow v \, \mathrm{constant}$$

New matter or modified gravity?

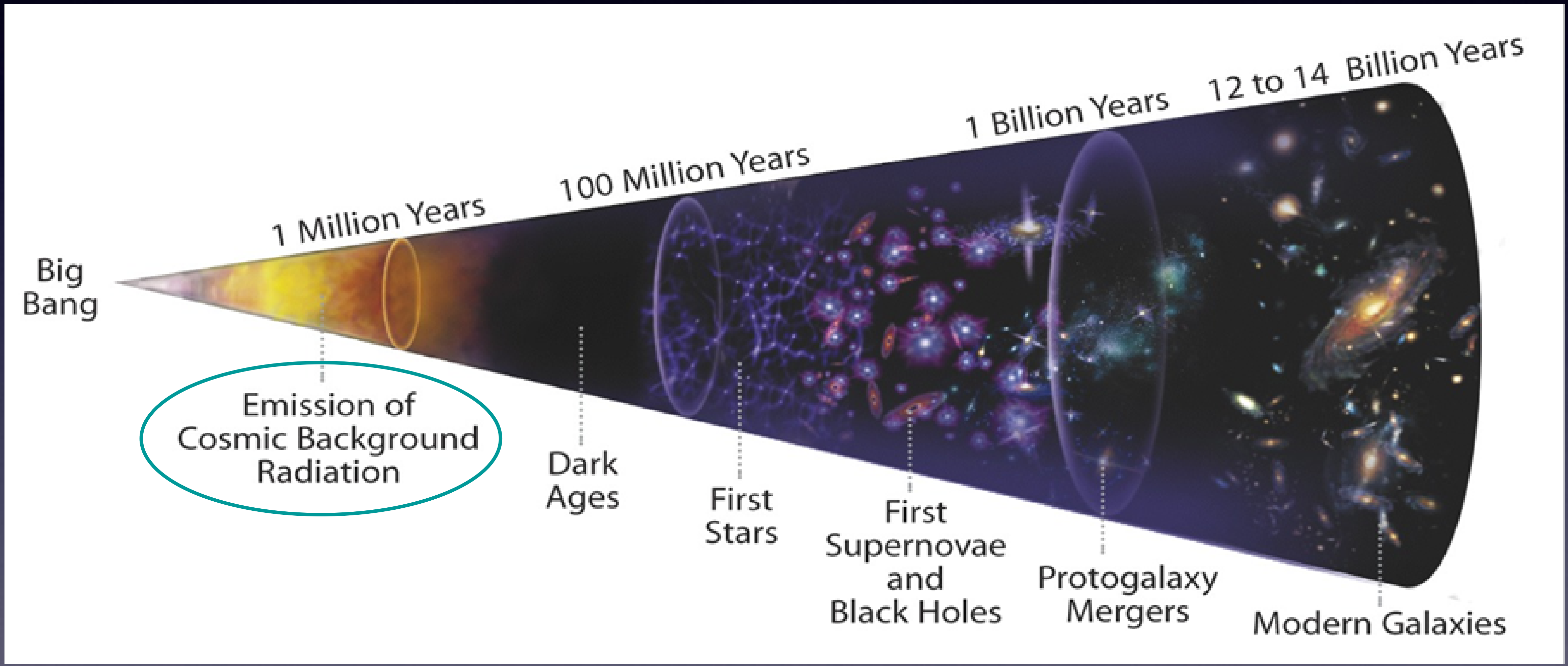
- Clowe et al 2006: studied the Bullet Cluster, system of two colliding clusters.
    - X-ray maps from CHANDRA to study distribution of hot plasma (main baryonic component).
    - Weak gravitational lensing to study mass distribution.
- Result: a substantial displacement between the two.
- Attributed to a collisionless cold dark matter component. When the clusters collided, the dark matter halos passed through each other without slowing down - unlike the gas.



Particle DM or MACHOs?

- MACHOs = Massive Compact Halo Objects, e.g. brown dwarfs, primordial black holes. Effectively collisionless, and probably exist to some degree: can they be most of the dark matter?
- Tisserand et al, 2006: search for microlensing events due to MACHOs passing near the line of sight between Earth and stars in the Magellanic clouds, temporarily amplifying star's flux. (Related study by Wyrzykowski et al '09.)
  - Found 1 candidate event, ~40 would have been expected if the dark matter in the halo was entirely ~0.4 solar-mass objects.
  - Ruled out MACHOs of mass between 0.6×10^{-7} and 15 solar masses, as the primary constituents of the Milky Way halo.
- Can also look for disruption of binary systems by massive objects passing through (e.g. Monroy-Rodriguez and Allen '14), which appears to rule out MACHOs above ~5 (optimistic) or ~100 (conservative) solar masses comprising 100% of the halo.

The cosmic microwave background



- When the universe was ~400 000 years old (redshift ~ 1000), H gas became largely neutral, universe transparent to microwave photons.
- Cosmic microwave background (CMB) radiation was last scattered at that time. We can measure that light now.
- Gives us a snapshot of the universe very early in its history.

CMB anisotropies

- Universe at z~1000 was a hot, nearly perfectly homogeneous soup of light and atoms.
- Oscillations in temperature/density from competing radiation pressure and gravity.
- Photon temperature anisotropies today provide a “snapshot” of temperature/density inhomogeneities at recombination.
- Peaks occur at angular scales corresponding to a harmonic series based on the sound horizon at recombination.

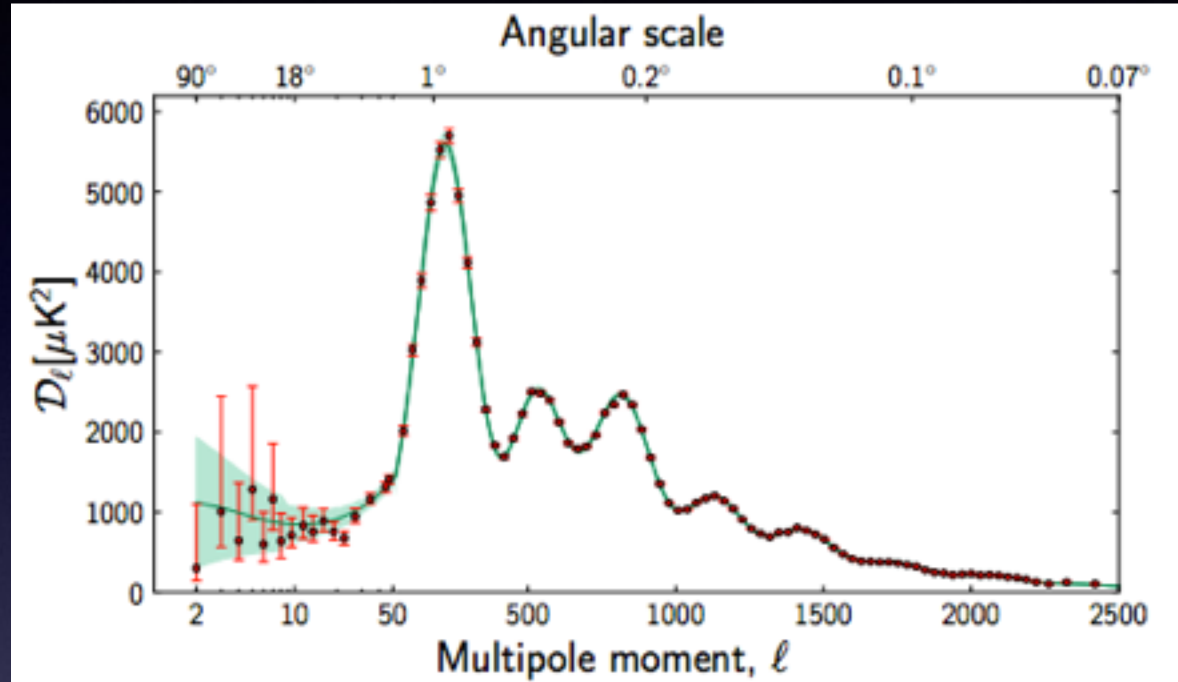


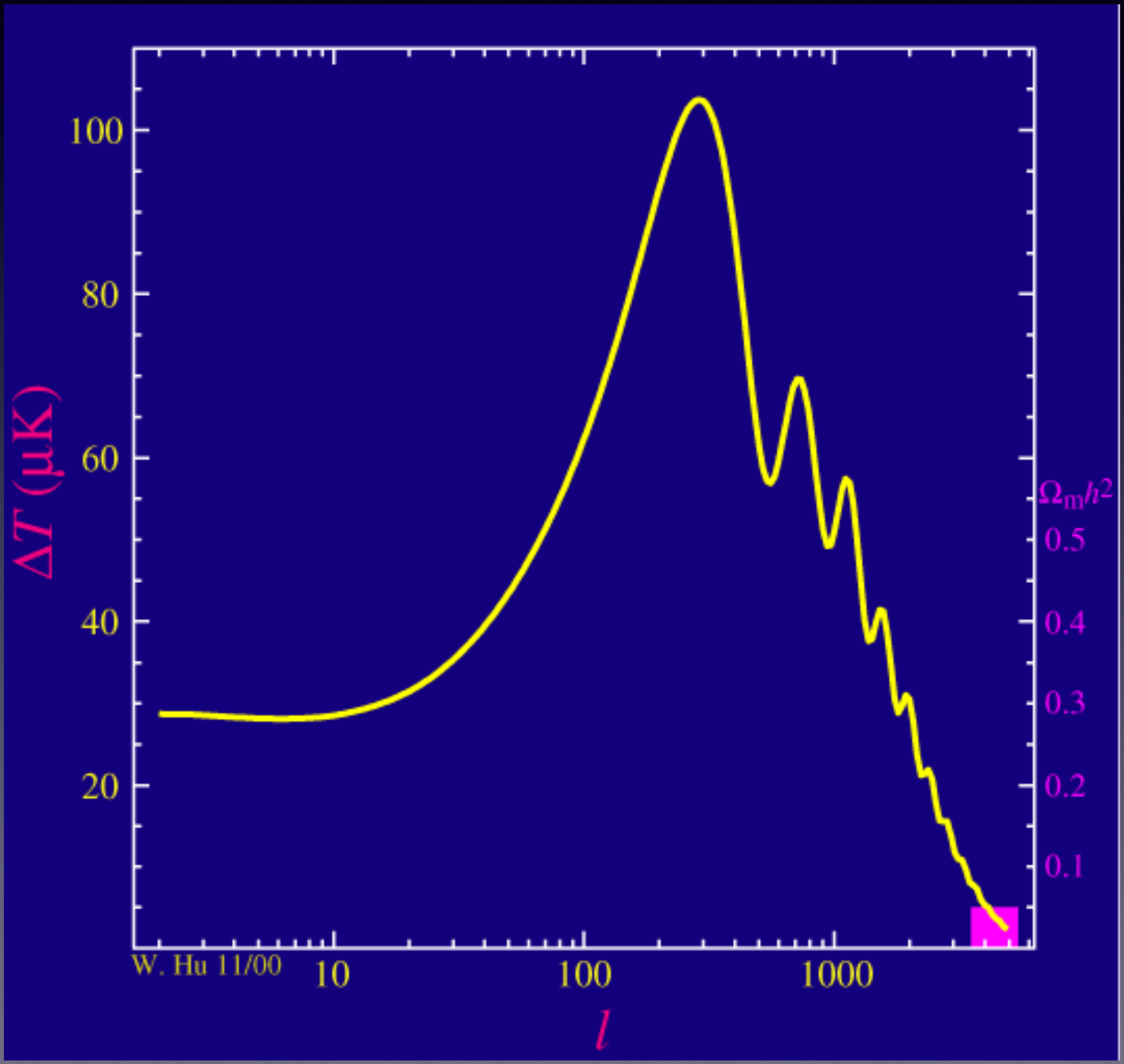
Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

Table 8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the six primary parameters included directly in the estimation process, and the bottom section contains constraints on derived parameters.

	Planck		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14305	0.1426 ± 0.0025
Age/Gyr	13.819	13.813 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.48	1090.43 ± 0.54
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{eq}	3402	3386 ± 69	3403	3391 ± 60

Measuring dark matter from the CMB

- Model universe as photon bath + coupled baryonic matter fluid + decoupled “dark” matter component (+ “dark” radiation, i.e. neutrinos).
- Dark component: does not experience radiation pressure, effects on oscillation can be separated from that of baryons.
- Result: this simple model fits the data well with a dark matter component about 5x more abundant than baryonic matter (total matter content is ~0.3 x critical density).



Wayne Hu, http://background.uchicago.edu/~whu/

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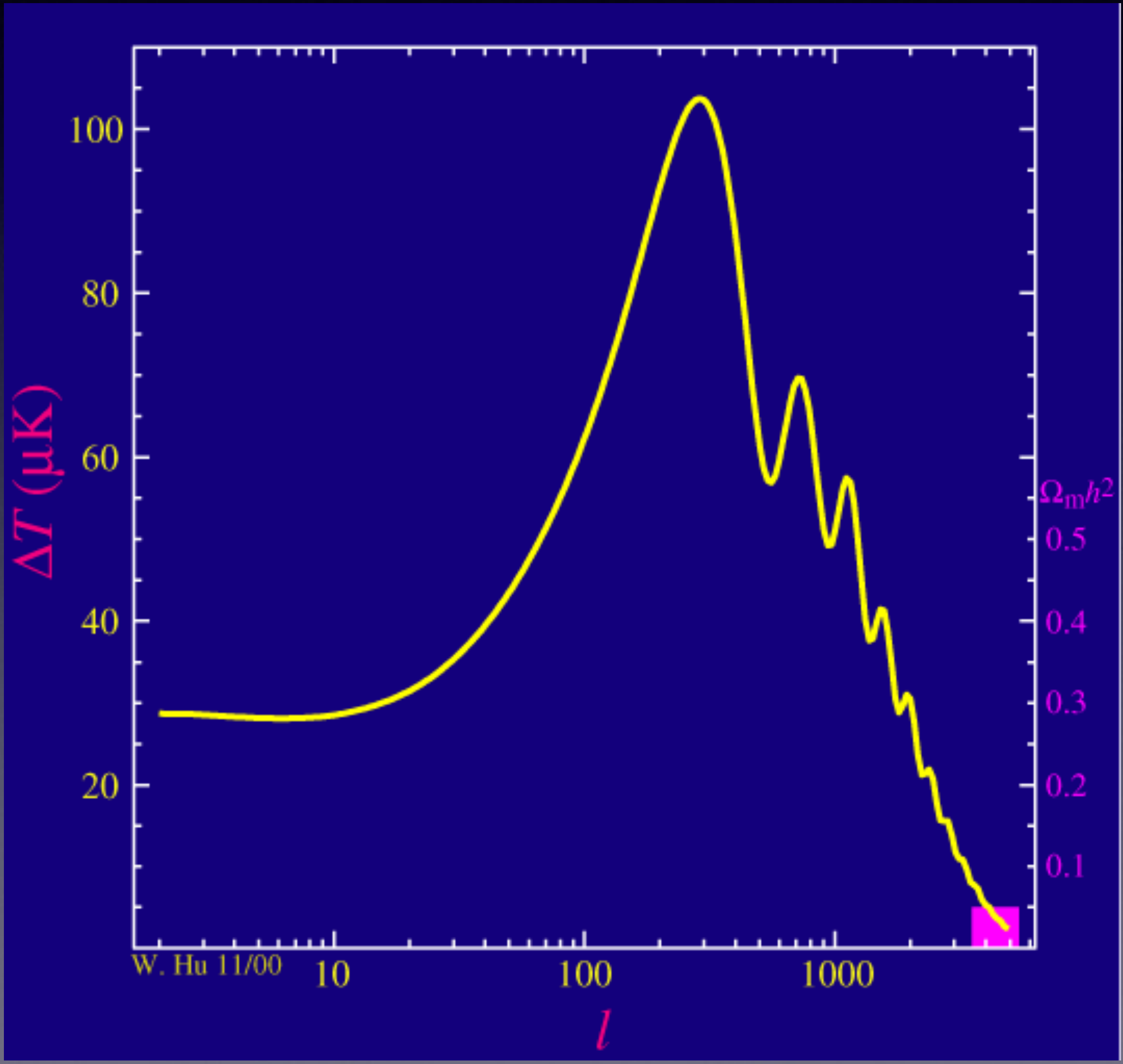

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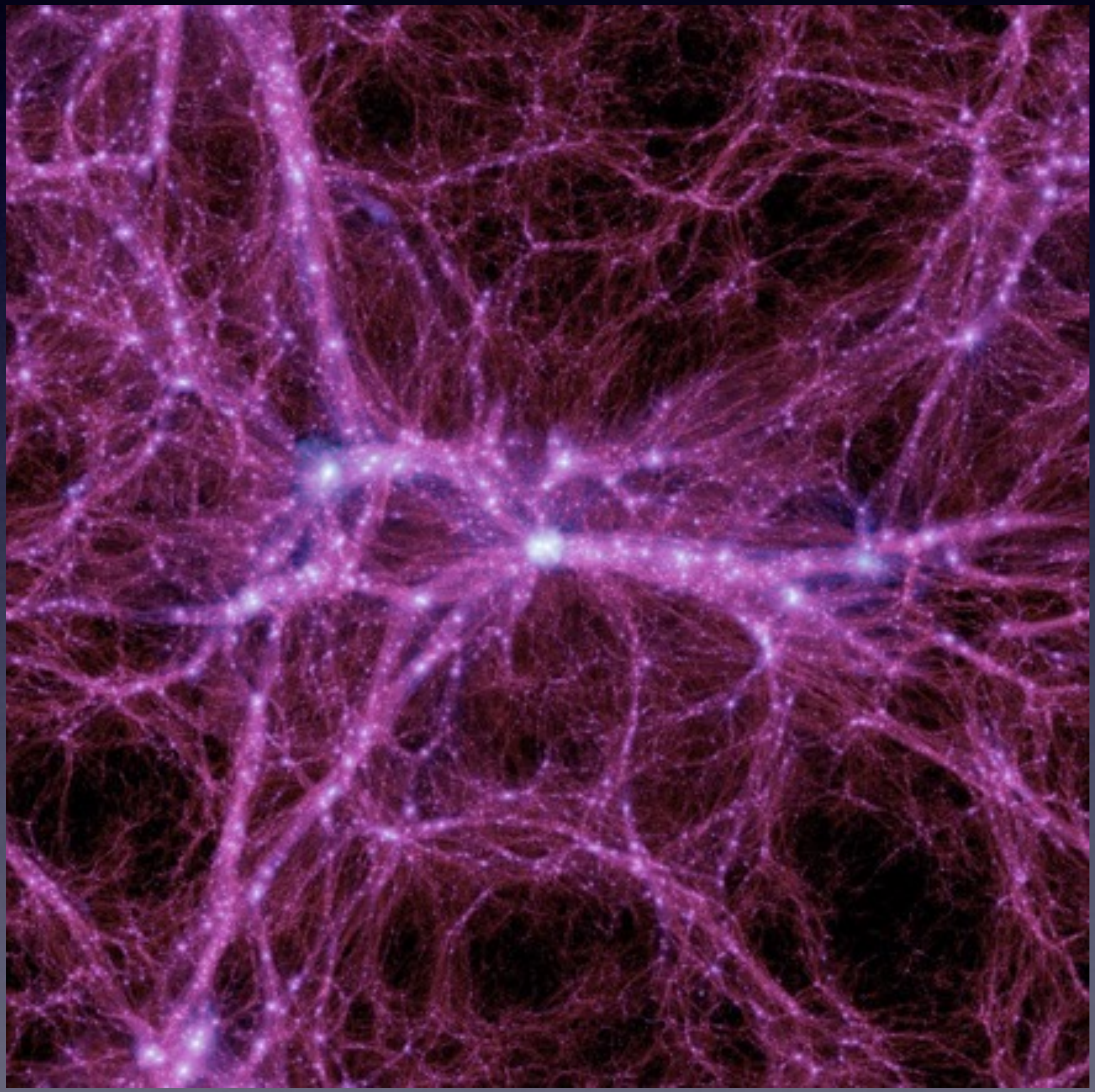
Structure formation

- CMB also maps out initial conditions for cosmic structure formation.
- After the photons decouple from the baryons, overdensities continue to grow under gravity, eventually collapsing into virialized structures.



Hot or cold? (or warm)

- Structure formation varies markedly according to the kinematics of the dark matter, in particular whether it can free-stream during the growth of perturbations.
- If most DM is "hot" (relativistic during the early phases of structure formation), free-streaming erases structures on small scales. Large structures form first, then fragment.
- If most DM is "cold" (non-relativistic throughout this epoch), small clumps of DM form first, then accrete together to form larger structures.
- The relative ages of galaxies and clusters tell us that the bulk of DM must be cold - if dark matter was hot, galaxies would not have formed by the present day.
- Equivalently, hot dark matter predicts a low-mass cutoff in the matter power spectrum, that is not observed.
- Neutrinos <u>are</u> hot dark matter - but cannot be all the DM.

DM as new physics

- Standard Model (SM) of particle physics has been spectacularly successful - but no dark matter candidate. We need something:
  - Stable on cosmological timescales
  - Near-collisionless, i.e. electrically neutral
  - "Cold" or "warm" rather than "hot" - not highly relativistic when the modes corresponding to the size of Galactic dark matter halos first enter the horizon (around $z \sim 10^6$, temperature of the universe around 300 eV).
- Only stable uncharged particles are neutrinos, and they would be hot dark matter.

- DM is one of the most powerful pieces of evidence for physics beyond the SM.
- Everything we have learned so far has come from studying the gravitational effects of dark matter, or from its inferred distribution.

What more can we say from observations of dark matter?

Gravitational probes

- Abundance of dark matter at the epoch of last scattering:

  $$\Omega_c h^2 = 0.1186 \pm 0.0020$$

  $$h = H_0/(100\mathrm{km/s/Mpc}) = 0.6781 \pm 0.0092$$

- The power spectrum of matter fluctuations, measured from the CMB and direct observation.
- The distribution of dark matter today, in objects close enough that we can probe their dark matter content directly, via:
  - Gravitational lensing
  - Observations of stellar motions
- Our cosmic neighborhood provides us with many examples of dark matter structures at a range of mass scales, and including non-equilibrium configurations - can be quite sensitive to dark matter microphysics.

Cold dark matter structure formation

- Full treatment requires numerical simulations, but we can get an estimate using Press-Schechter formalism.
- Modeling DM halo as spherically symmetric, isolated system (in curved spacetime), overdensities grow initially and then collapse on themselves.
- Collapse criterion: overdensity $\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}} \approx 1.686$
- Real collapse isn't perfectly spherical, no collapse to a point - final states are virialized halos.

Press-Schechter formalism

- Assume density perturbations are a Gaussian random field (sourced by same fluctuations that source CMB anisotropies).
- For a given mass scale M, smooth this field (in real space) by a top-hat function with $R = (3M/4\pi\rho)^{1/3}$. Gives a Gaussian random field with variance $\sigma^2(M)$.
- Fluctuations above collapse threshold δ_c yield collapsed regions. Fraction of mass in halos > M given by:

$$\frac{1}{\sqrt{2\pi}\sigma(M)}\int_{\delta_c}^{\infty} d\delta e^{-\delta^2/2\sigma^2(M)} = \frac{1}{2}\mathrm{erfc}\left(\delta_c/\sqrt{2}\sigma(M)\right)$$

- Asymptotes to 1/2 as $\sigma(M)$ becomes large as only overdensities participate in collapse - add fudge factor of 2. (Justified better in extended Press-Schechter formalism.)
- Differentiating with respect to M gives fraction in range M to M+dM, multiplying by overall number density gives PS mass function:

$$\frac{dn}{d\ln M} = \sqrt{\frac{2}{\pi}}\frac{\rho_m}{M}\frac{d\ln\sigma^{-1}}{d\ln M}\nu e^{-\nu^2/2} \qquad \nu = \delta_c/\sigma(M)$$

The mass function

- Features of the PS mass function:
  - exponential suppression when M >> M*, defined such that $\sigma(M^*) = \delta_c$.
  - At low masses dn/dlnM ~ 1/M - many small halos
- Other empirical mass functions often used instead, inspired by PS:
  - Sheth-Torman 1999:

$$\frac{dn}{d\ln M} \propto \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M} \frac{d\ln\sigma^{-1}}{d\ln M} \left(1 + (a\nu^2)^{-p}\right) \nu e^{-a\nu^2/2} \qquad a = 0.75,\ p = 0.3$$

  - Jenkins et al 2001:

$$\frac{dn}{d\ln M} = 0.301 \frac{\rho_m}{M} \frac{d\ln\sigma^{-1}}{d\ln M} e^{-|\ln\sigma^{-1} + 0.64|^{3.82}}$$

Decoupling from the Standard Model

- IF dark matter has non-negligible interactions with the Standard Model (not guaranteed) then DM may be kinetically coupled to SM in early universe.
- i.e. even "cold" non-relativistic DM is maintained at the temperature of the SM, by its coupling to the Standard Model thermal bath.
- Such a tight coupling damps DM density fluctuations - specifically, fluctuations that have "entered the horizon" (have characteristic length smaller than the horizon scale) at the time of kinetic decoupling are suppressed (review by Bringmann 0903.0189). Cuts off power on small scales.

$$M_{\rm ao} \approx \frac{4\pi}{3} \frac{\rho_\chi}{H^3}\Big|_{T=T_{\rm kd}} = 3.4 \times 10^{-6} \left(\frac{T_{\rm kd} g_{\rm eff}^{1/4}}{50\,{\rm MeV}} \right)^{-3} M_\odot$$

T_{kd} typically ~1 MeV or higher - can be much higher

- Furthermore, even non-relativistic dark matter can free-stream after it is decoupled - it just doesn't go very far, so suppresses power only on very small scales.

Characteristic scale

$$k_{\rm fs} \approx \left(\frac{m_\chi}{T_{\rm kd}} \right)^{1/2} \frac{a_{\rm eq}/a_{\rm kd}}{\ln(4a_{\rm eq}/a_{\rm kd})} \frac{a_{\rm eq}}{a_0} H_{\rm eq}$$

Resulting mass cutoff

$$M_{\rm fs} \approx \frac{4\pi}{3}\rho_\chi \left(\frac{\pi}{k_{\rm fs}}\right)^3 = 2.9 \times 10^{-6} \left(\frac{1 + \ln\left(g_{\rm eff}^{1/4} T_{\rm kd}/50\,{\rm MeV}\right)/19.1}{(m_\chi/100\,{\rm GeV})^{1/2}\, g_{\rm eff}^{1/4}\, (T_{\rm kd}/50\,{\rm MeV})^{1/2}} \right)^3 M_\odot$$

The matter power spectrum

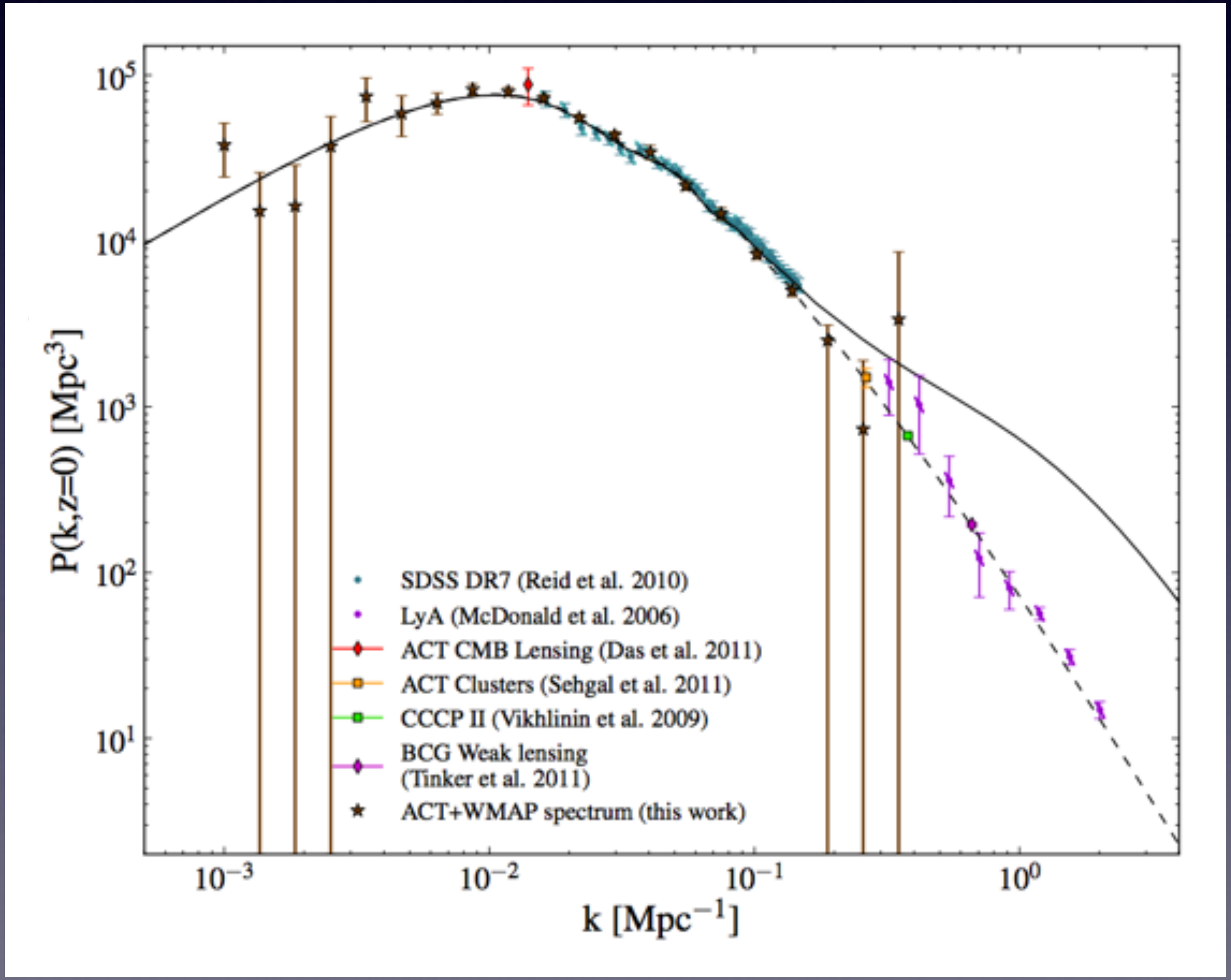
$$\delta(\mathbf{r}) = \frac{\rho(\mathbf{r}) - \bar{\rho}}{\bar{\rho}} \qquad \delta(\mathbf{k}) = \frac{1}{(2\pi)^3} \int \delta(\mathbf{x}) e^{-i\mathbf{kx}} d\mathbf{x} \qquad P(k) = \langle |\delta(\mathbf{k})|^2 \rangle$$

- At large scales (k up to ~0.2 Mpc^{-1}), can be predicted directly from CMB anisotropy measurements.

$$P(k, z=0) = 2\pi^2 k \mathcal{P}(k) G^2(z) T^2(k)$$

↑ Primordial power spectrum

- Measurements of galaxies and clusters (esp. at higher redshift), and the Lyman-alpha forest, allow the matter power spectrum to be filled in to down to ~10^{12} solar masses, k~2 Mpc^{-1}).



Hlozek et al '12

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Growth of matter perturbations

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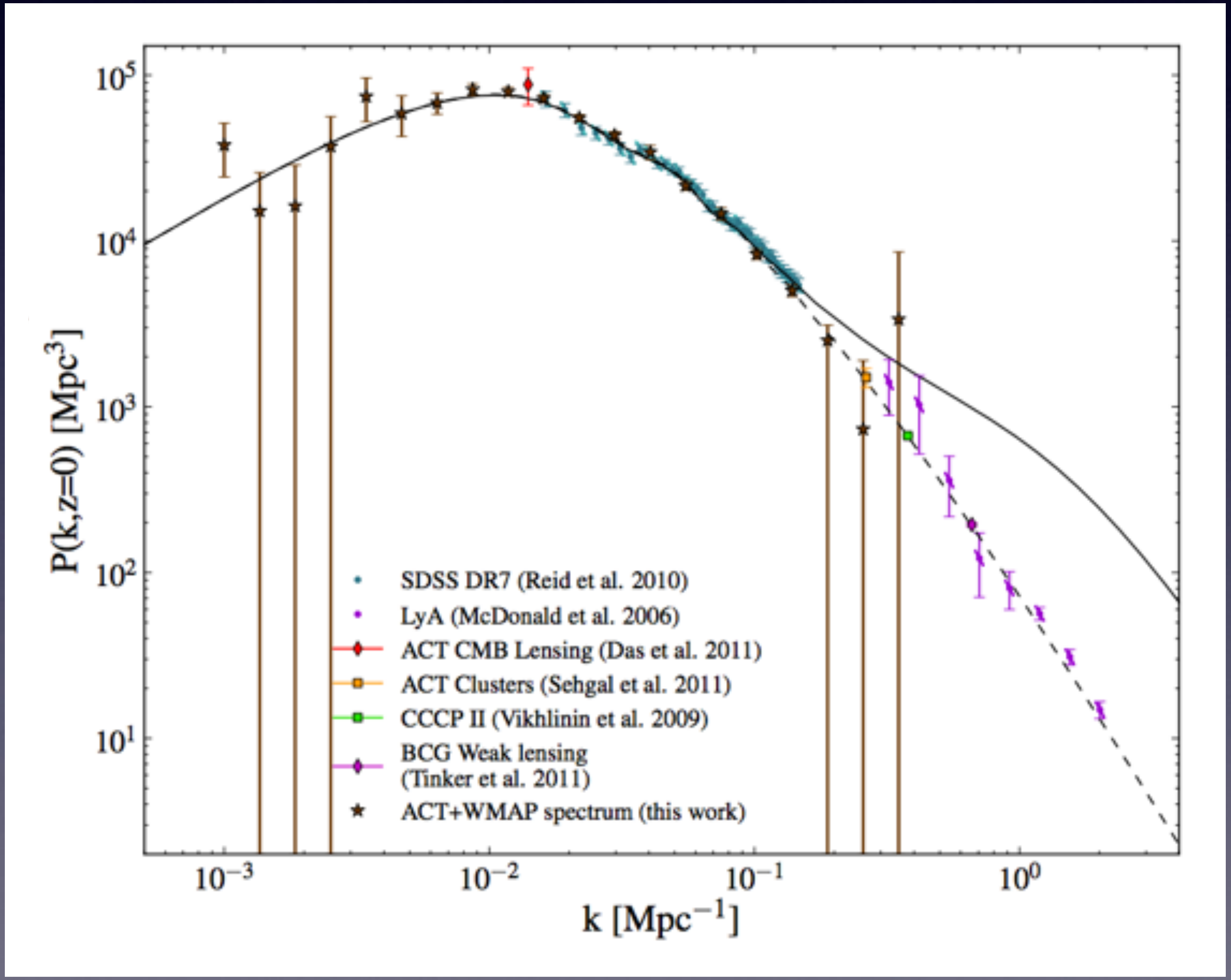

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Matter transfer function

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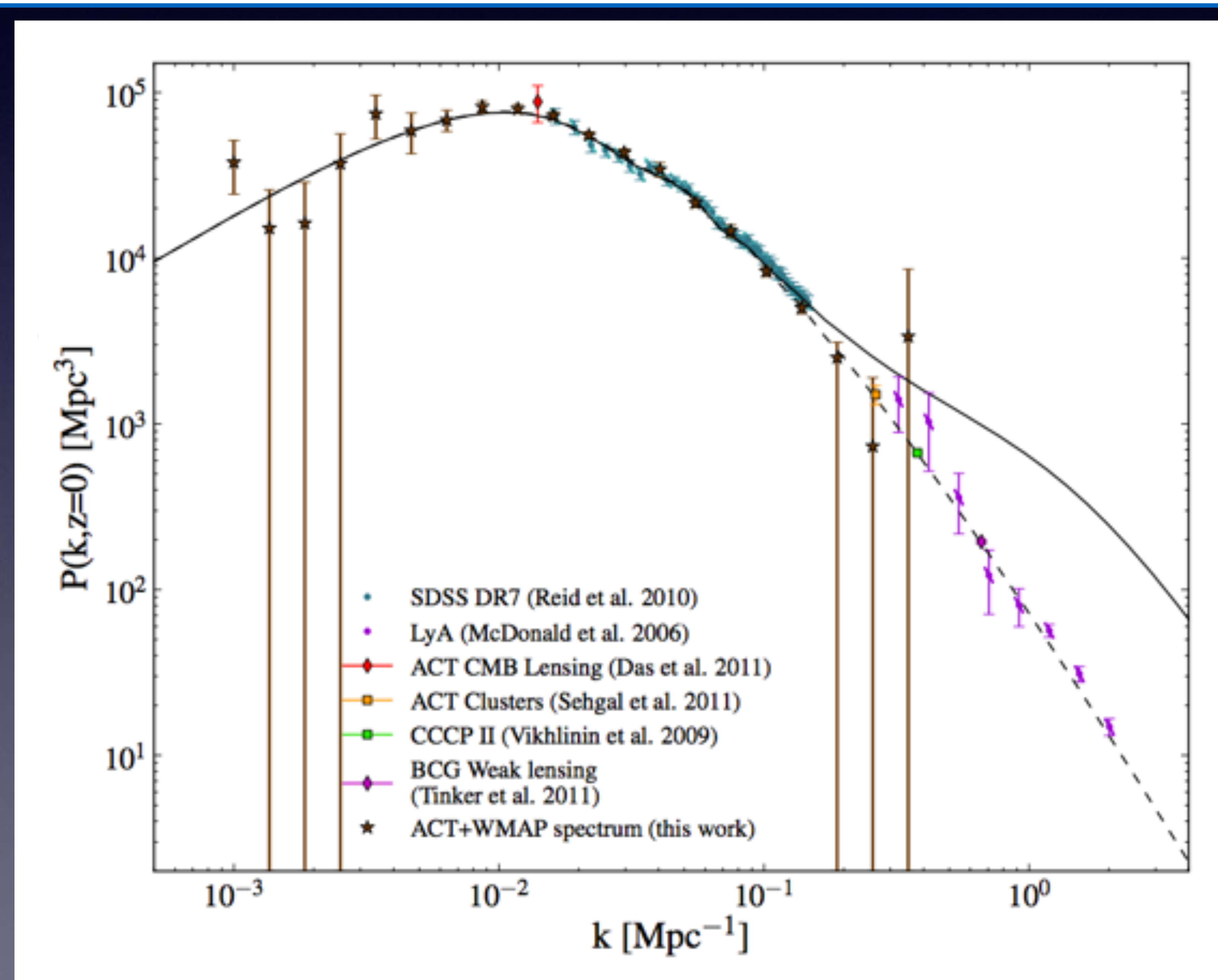

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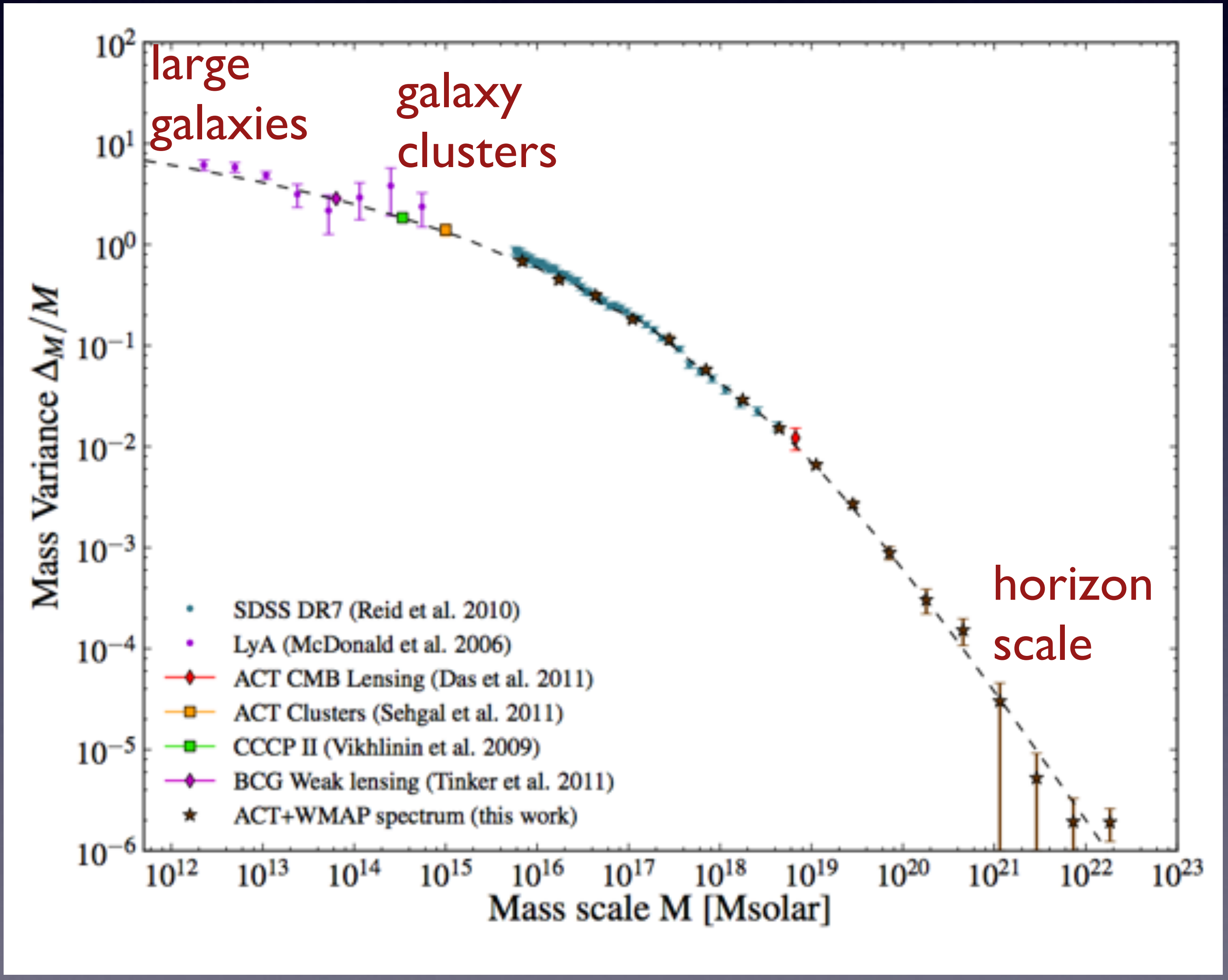


Hlozek et al '12

Limits on hot dark matter (HDM)

- HDM free-streaming suppresses the growth of matter perturbations at early times, damps the matter power spectrum on small scales.
- Model-dependent limits depending on HDM mass:
  - If HDM is still relativistic at surface of last scattering (z~1000, T~0.3 eV), then it can also affect the CMB, behaving as (dark) radiation rather than matter (see e.g. Hannestad et al '10 for discussion).
  - Likewise, subdominant HDM can affect cosmological evolution, altering matter power spectrum + CMB fluctuations.
- Combined limits for axion and neutrino HDM (Archidiacono et al '13):

Neutrinos (3 fermion species)

$$\sum m_\nu < 0.27\mathrm{eV}$$

$$\Omega_\nu \approx 0.02 (\sum m_\nu)/\mathrm{eV}$$

Axion (1 scalar species)

$$m_a < 0.67\mathrm{eV}$$

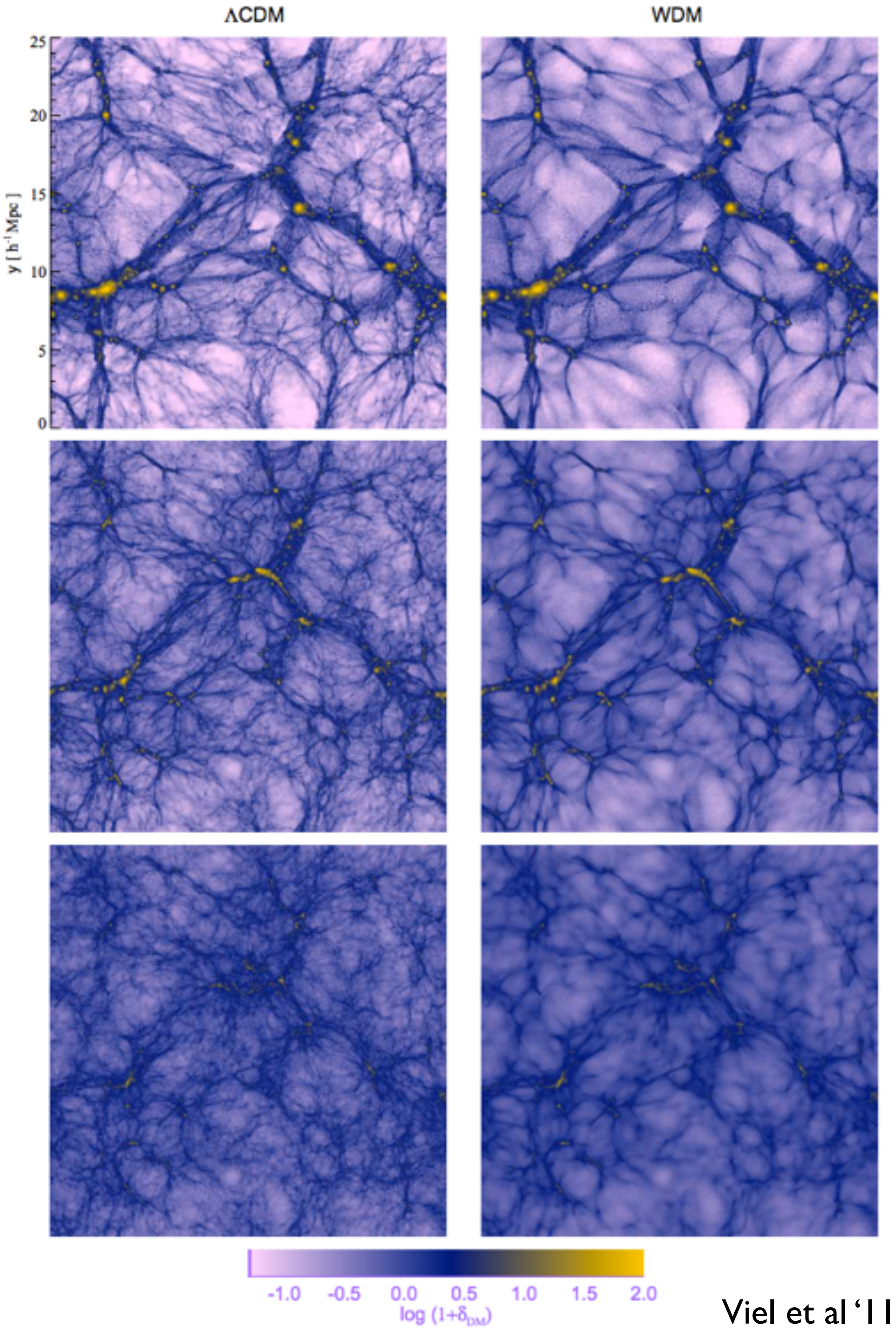
$$\Omega_a \approx 0.01 m_a/\mathrm{eV}$$

Limits on warm dark matter (WDM)

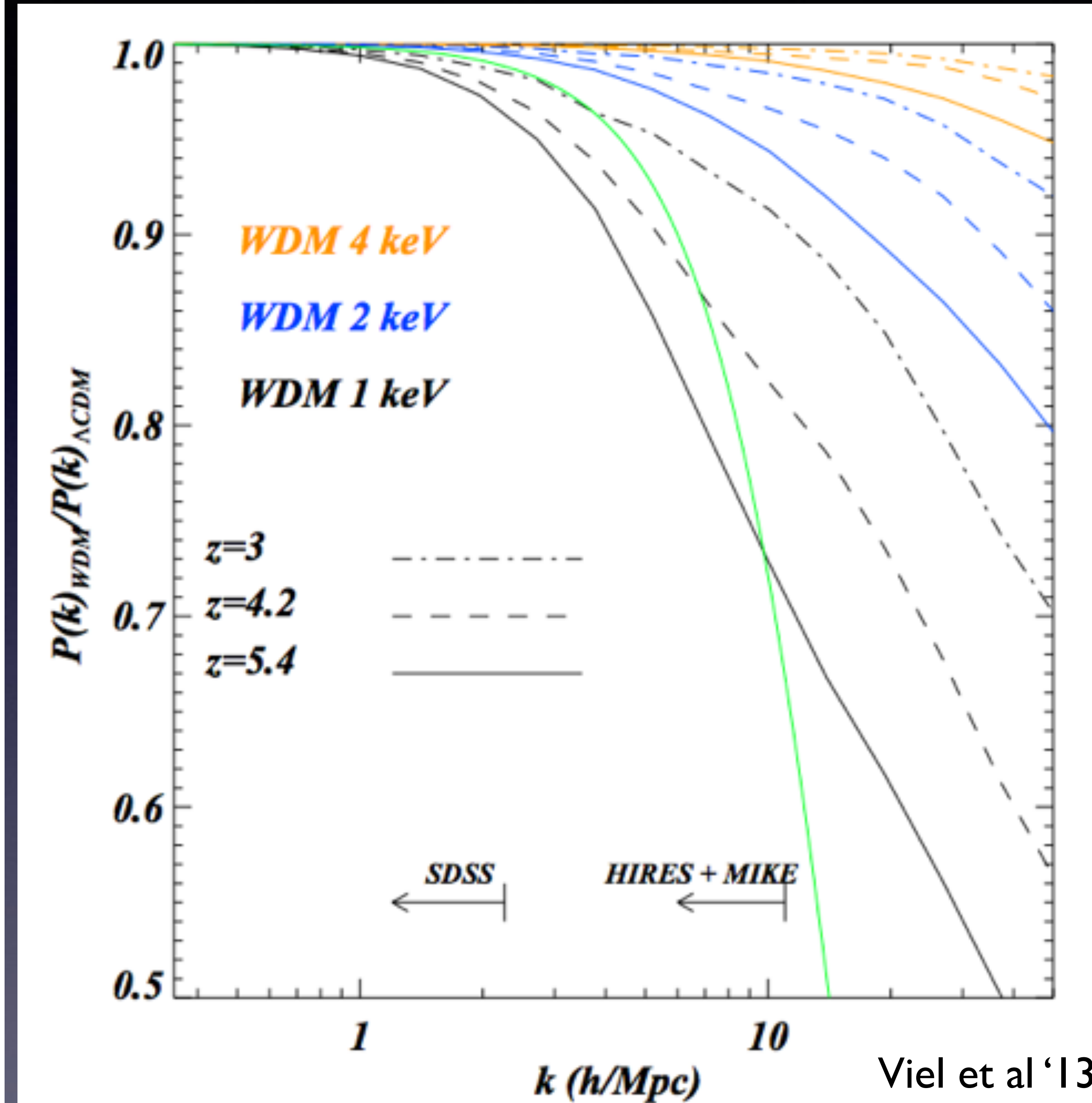
- “Lyman-alpha forest”: distant quasars emit radiation which is absorbed by extragalactic neutral hydrogen. The resulting spectral lines measure the redshifts of these clouds.
- Probe of the matter power spectrum at z~2-6, at scales from ~1-100 Mpc^{-1}.
- Warm dark matter, like HDM, suppresses density fluctuations below a (WDM-mass-dependent) comoving wavenumber.
- Viel et al ‘13: if all dark matter is WDM, m_{WDM} > 3.3 keV (95%). Corresponds to cutoff scale of ~$3x10^8$ solar masses.

(Incidentally, Vegetti et al ’12 claim detection of a $2x10^8$ solar mass dark satellite at z=0.881 via gravitational lensing.)

- A subdominant component of WDM is hard to constrain; Boyarsky et al ’09 found any mass was allowed if <35% of the DM was warm.



Viel et al ‘11

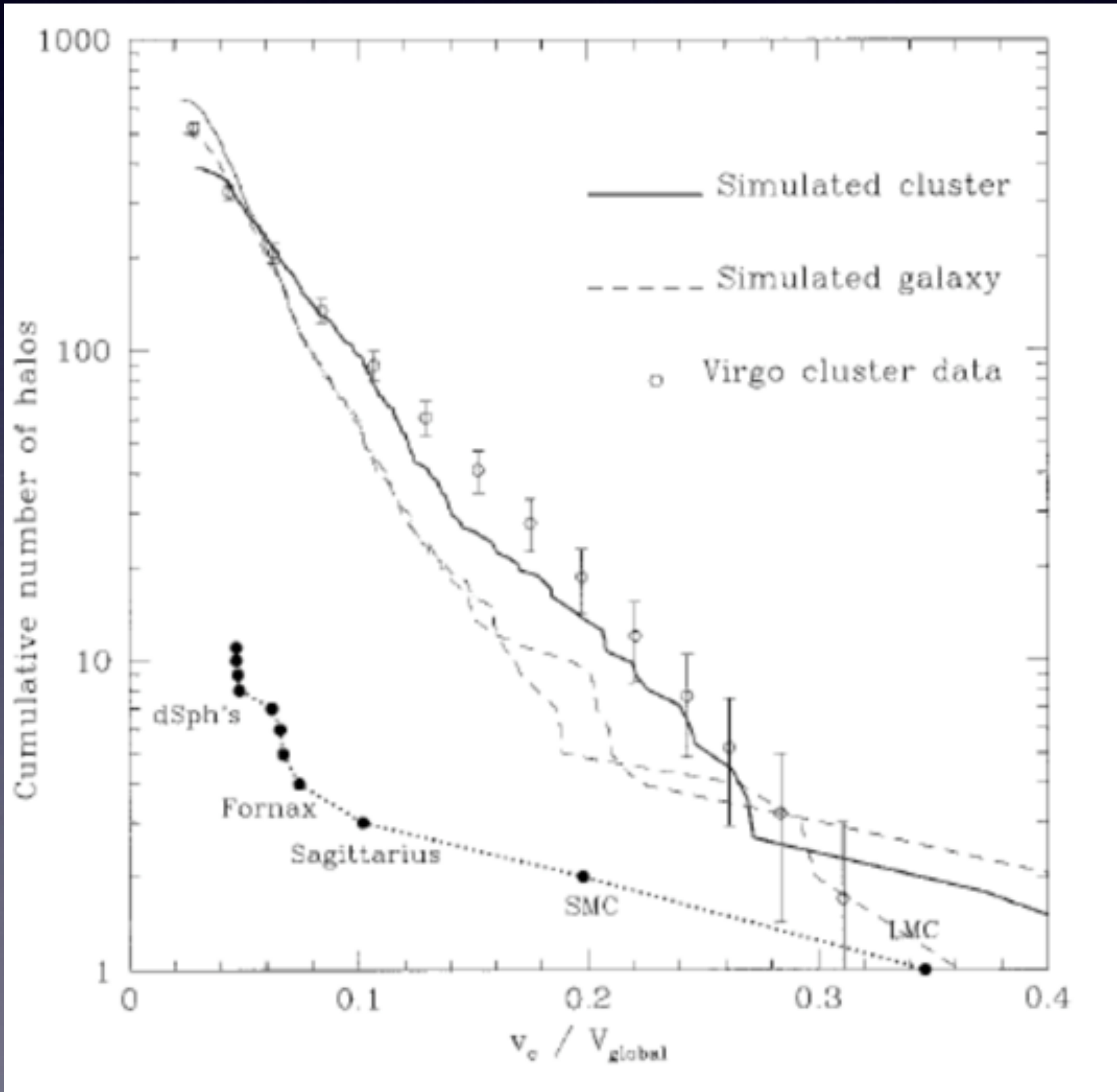


Viel et al ‘13

Does CDM have problems on small scales?

The “missing satellite problem”

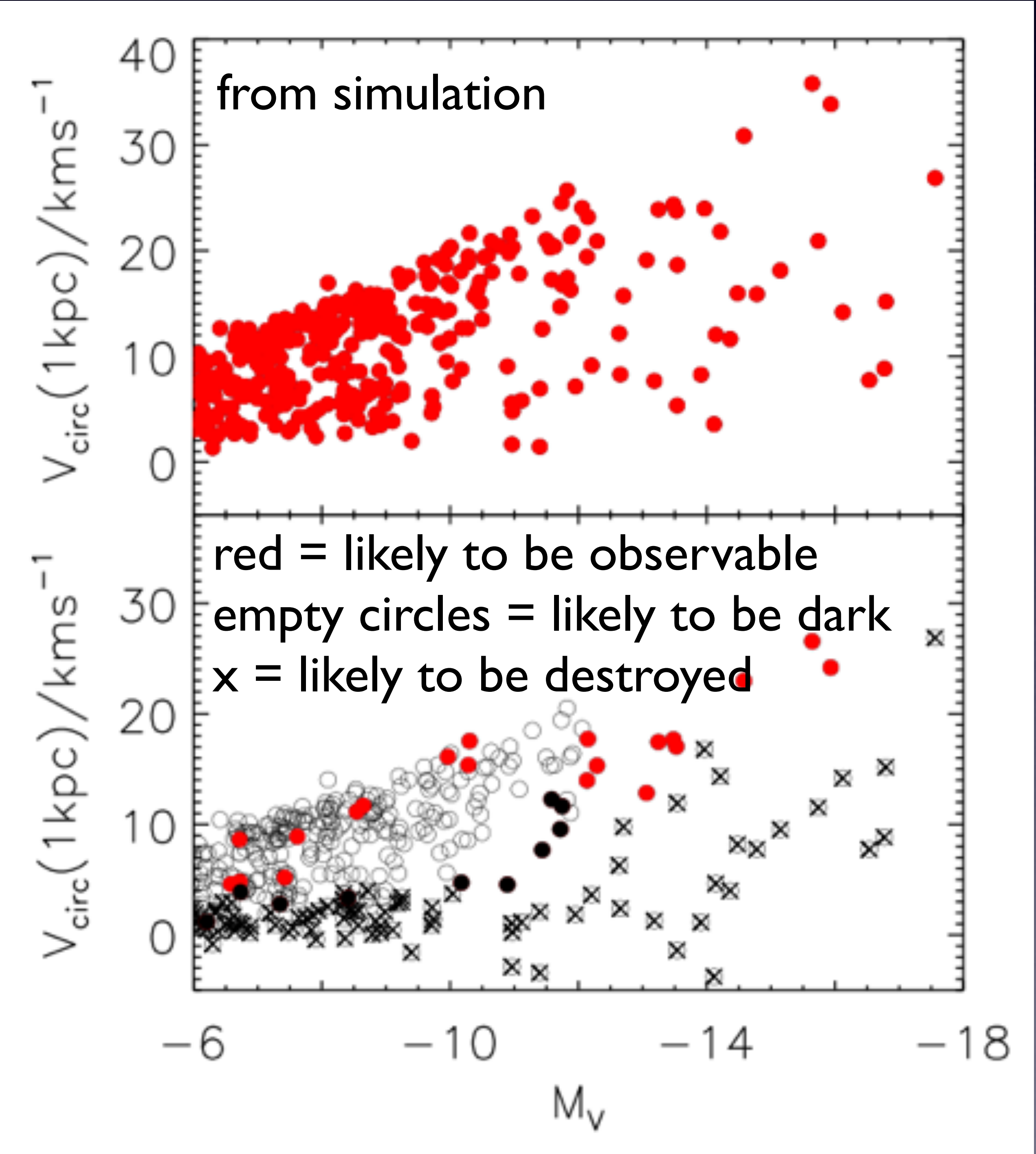
- Traditional N-body simulations model the formation of halos assuming cold, collisionless dark matter (interacting only by gravity).
- Evolve assuming initial random fluctuations + cosmology determined by CMB.
- The predicted number of high-mass subhalos of the Milky Way exceeds the observed number of luminous satellites by ~1 order of magnitude (Klypin et al 1999, Moore et al 1999).



Is it still a problem?

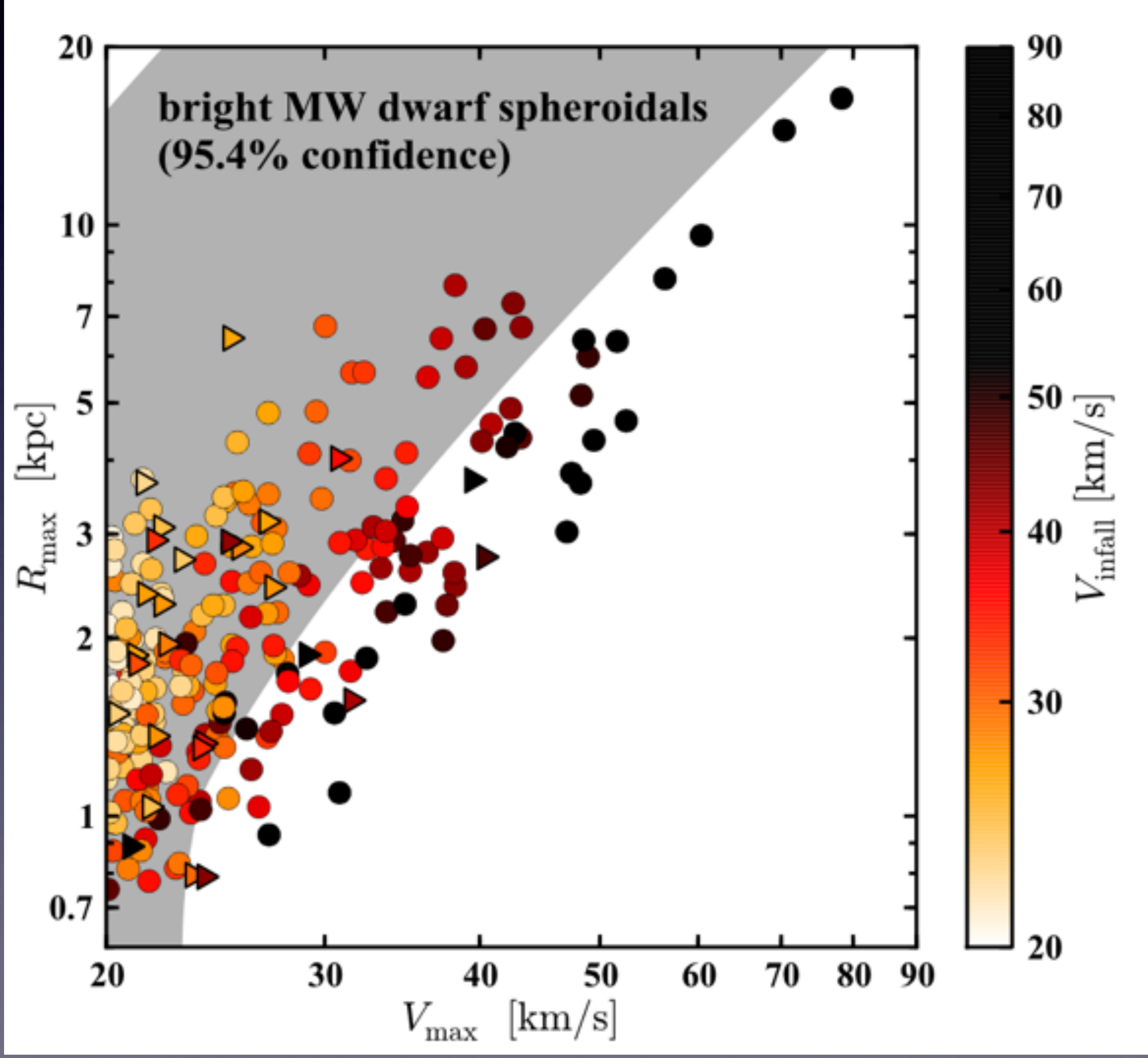
Brooks et al '12

- Not all halos may form stars. In particular, in small halos:
  - Significant mass may be evaporated during reionization (e.g. Okamoto & Frenk '09).
  - Satellites may be tidally stripped as they move through the host halo's disk.
  - Supernovae may expel material from the halo.
- Furthermore, faint galaxies may be present but not observed.



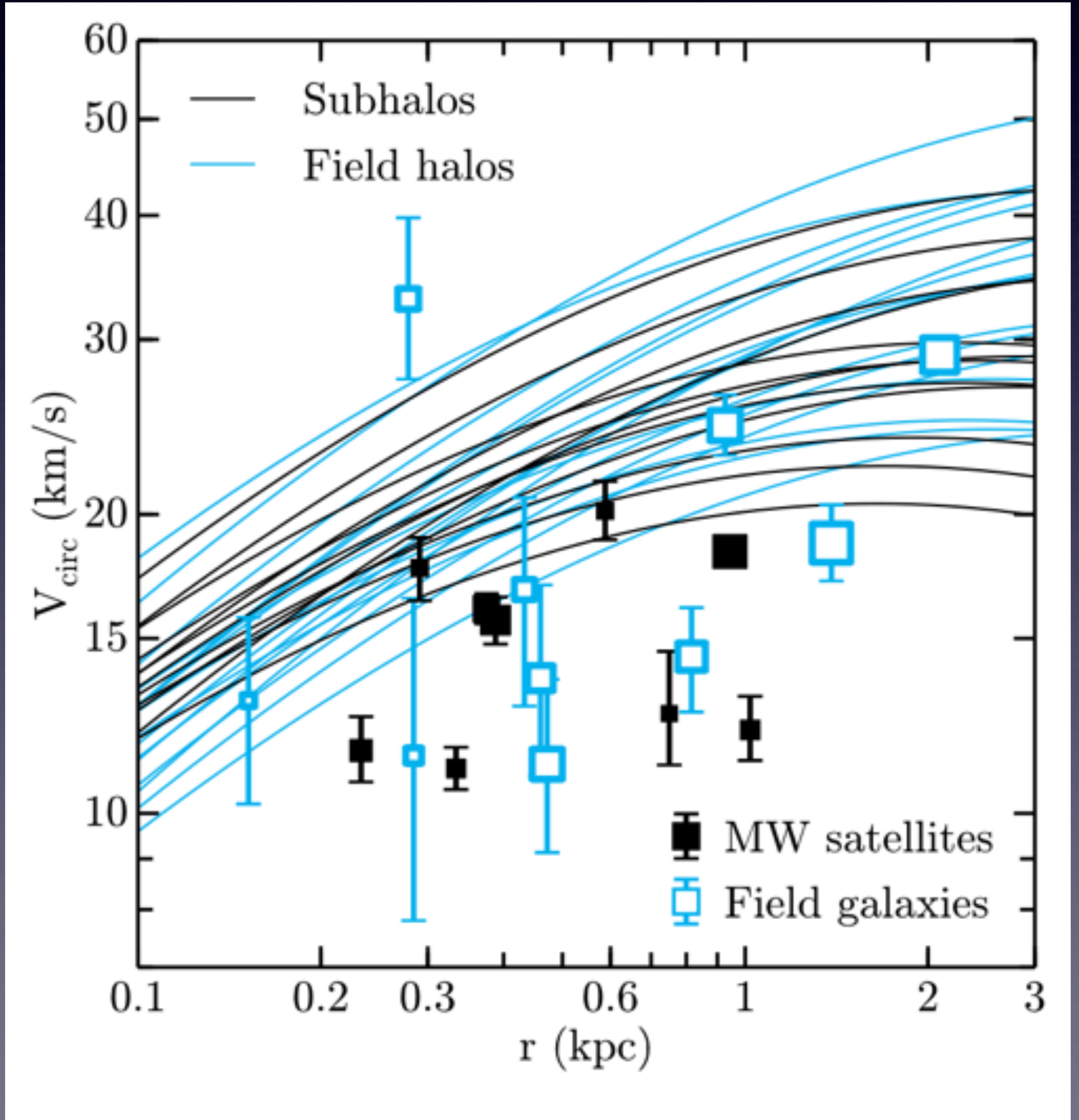
"Too big to fail"

- As well as the general deficit in satellites, simulations predict many more <u>massive</u> and <u>dense</u> satellites than are seen (Boylan-Kolchin et al '12).
- Original argument: star formation should not be suppressed in such massive halos, nor should they go unobserved. (They are "too big to fail" at forming stars.)



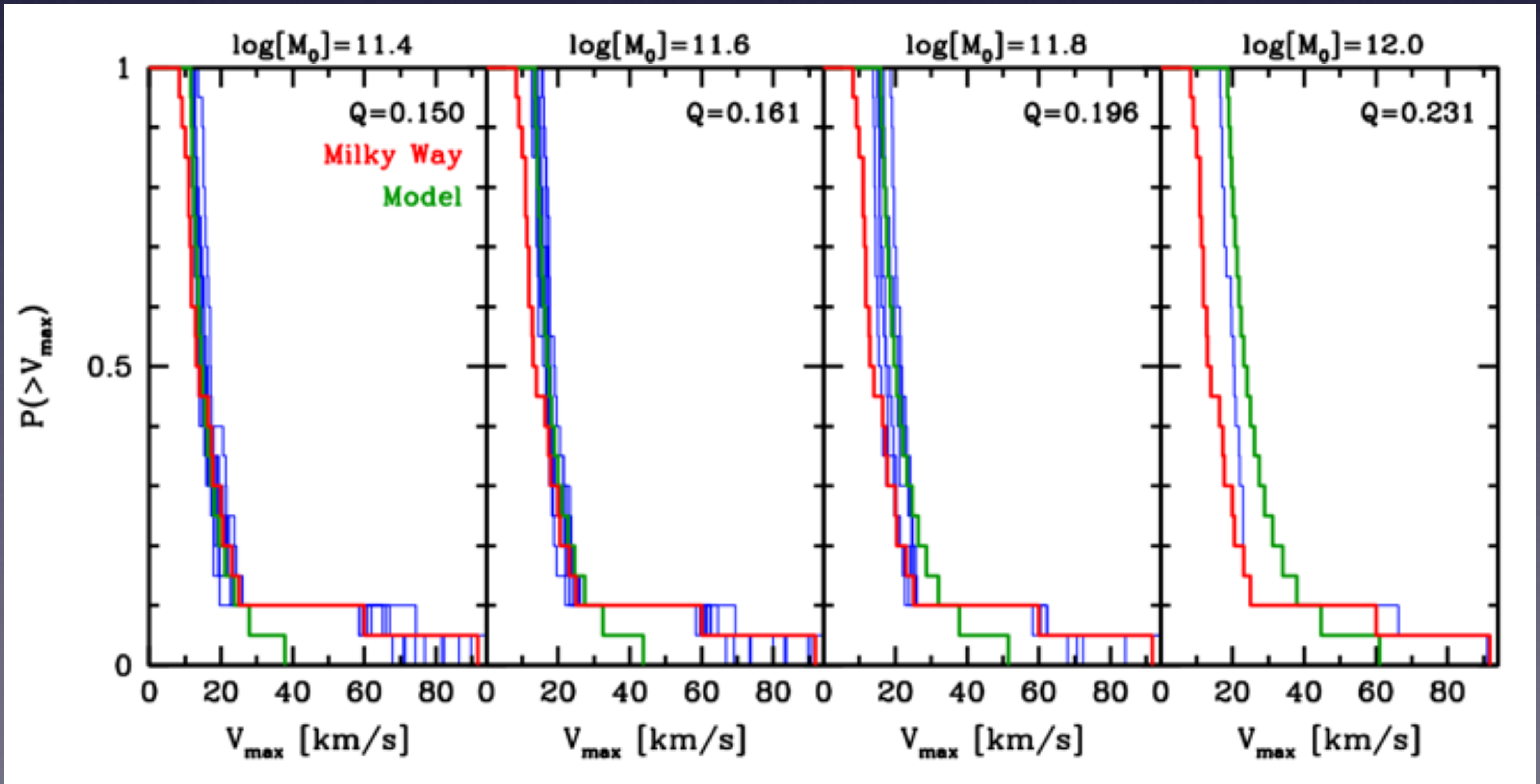
"Too big to fail in the Local Group"

- Similar results from studies of dwarf galaxies in the Local Group, but away from the Milky Way and Andromeda Galaxies (Garrison-Kimmel et al '14).
- Simulations again over-predict dense massive halos that should host substantial star formation - issue not isolated to the Milky Way.



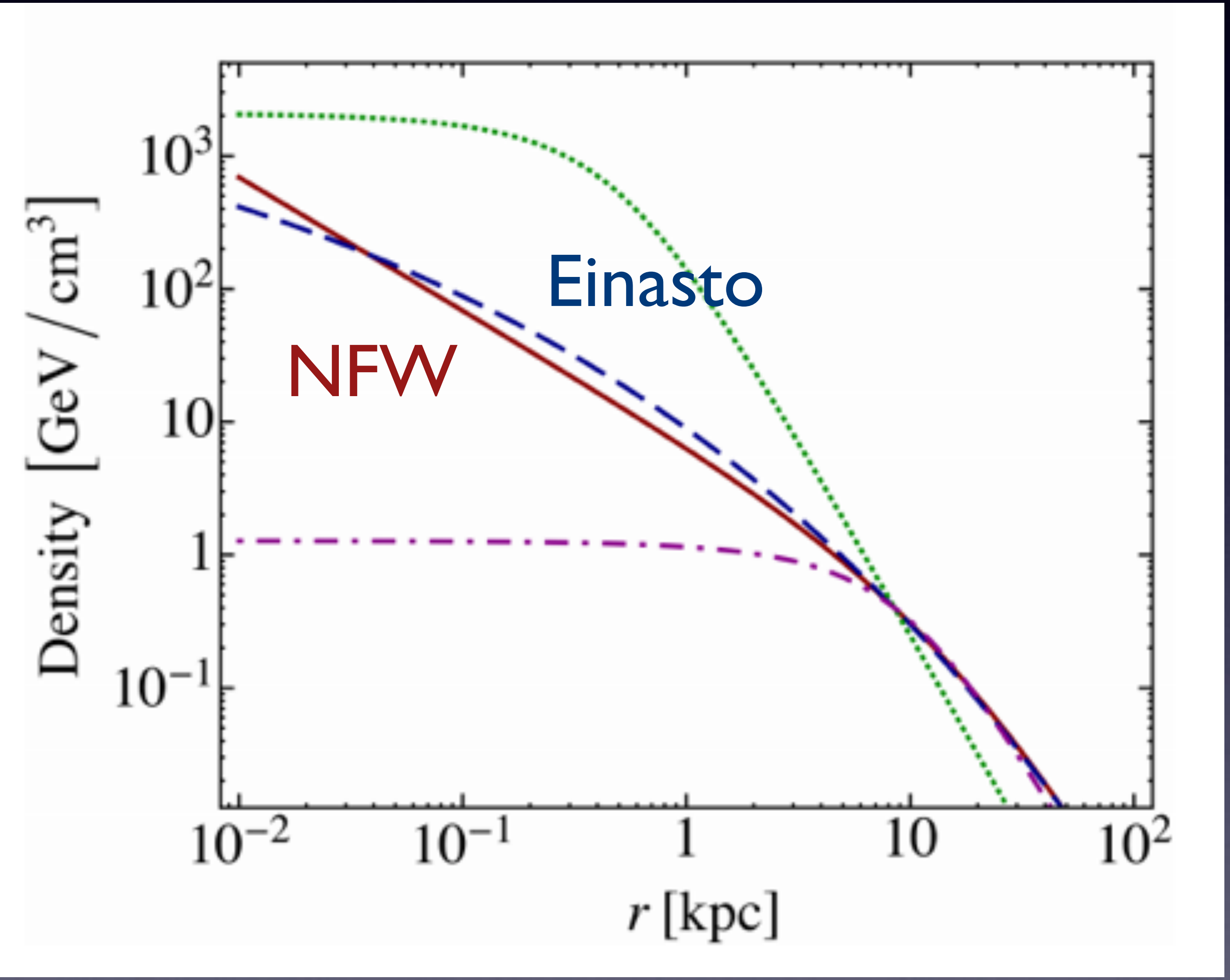
Could it be a fluke?

- Chance of consistency is ~1.4% according to Jiang and van den Bosch '15 (using semi-analytic prescription for subhalos), considering only the largest known MW satellite galaxies.
- Consistency probability drops to < 5×10^{-4} when lower-mass satellites are considered.
- Explore consistency between distribution of subhalo masses, in simulations vs observations.



The density profile of dark matter halos

- Dark matter N-body simulations typically predict a ~universal density profile for halos.
- Common parameterizations include:



Einasto

$$\rho(r) \propto e^{-(r/r_0)^\alpha}$$

$$\frac{d\ln\rho}{d\ln r} = -\alpha\left(\frac{r}{r_0}\right)^{-\alpha}$$

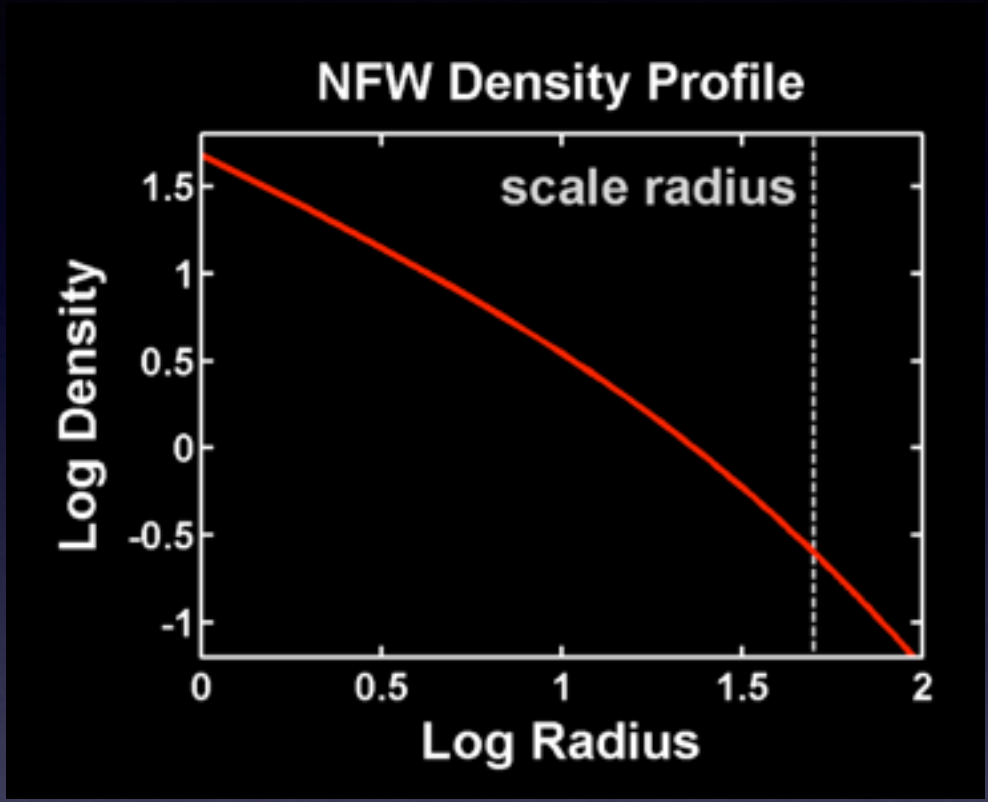
Navarro-Frenk-White

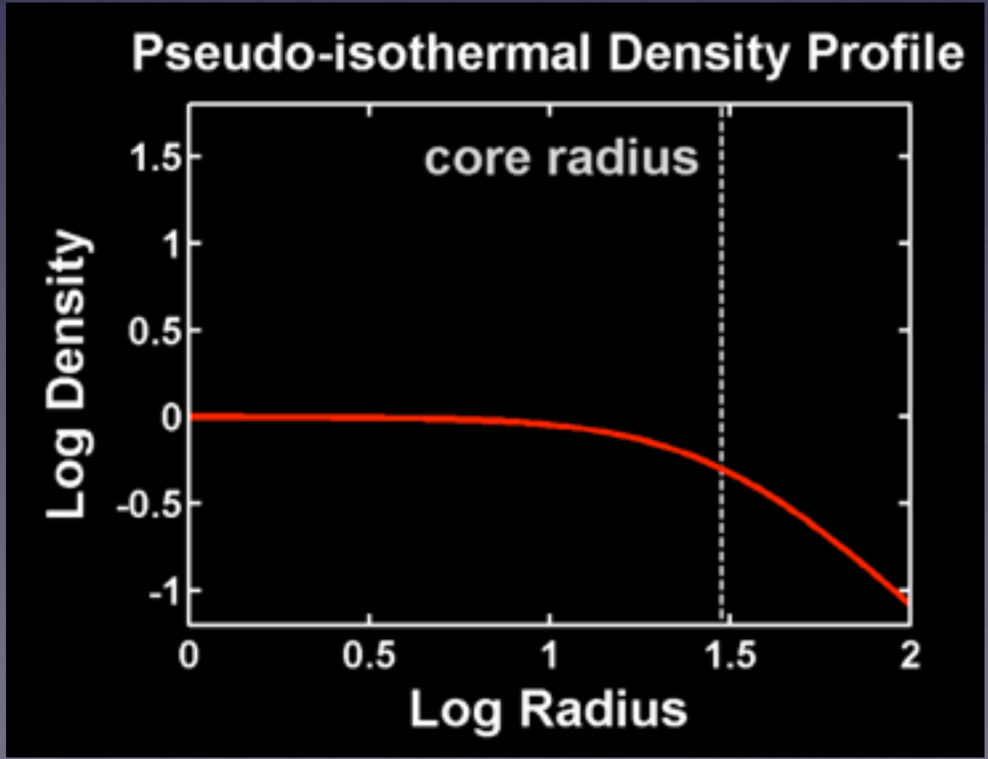
$$\rho(r) \propto \frac{(r/r_s)^{-1}}{(1+r/r_s)^2}$$

$$\frac{d\ln\rho}{d\ln r} = -1 - 2\frac{r}{r+r_s}$$

The cusp-core problem

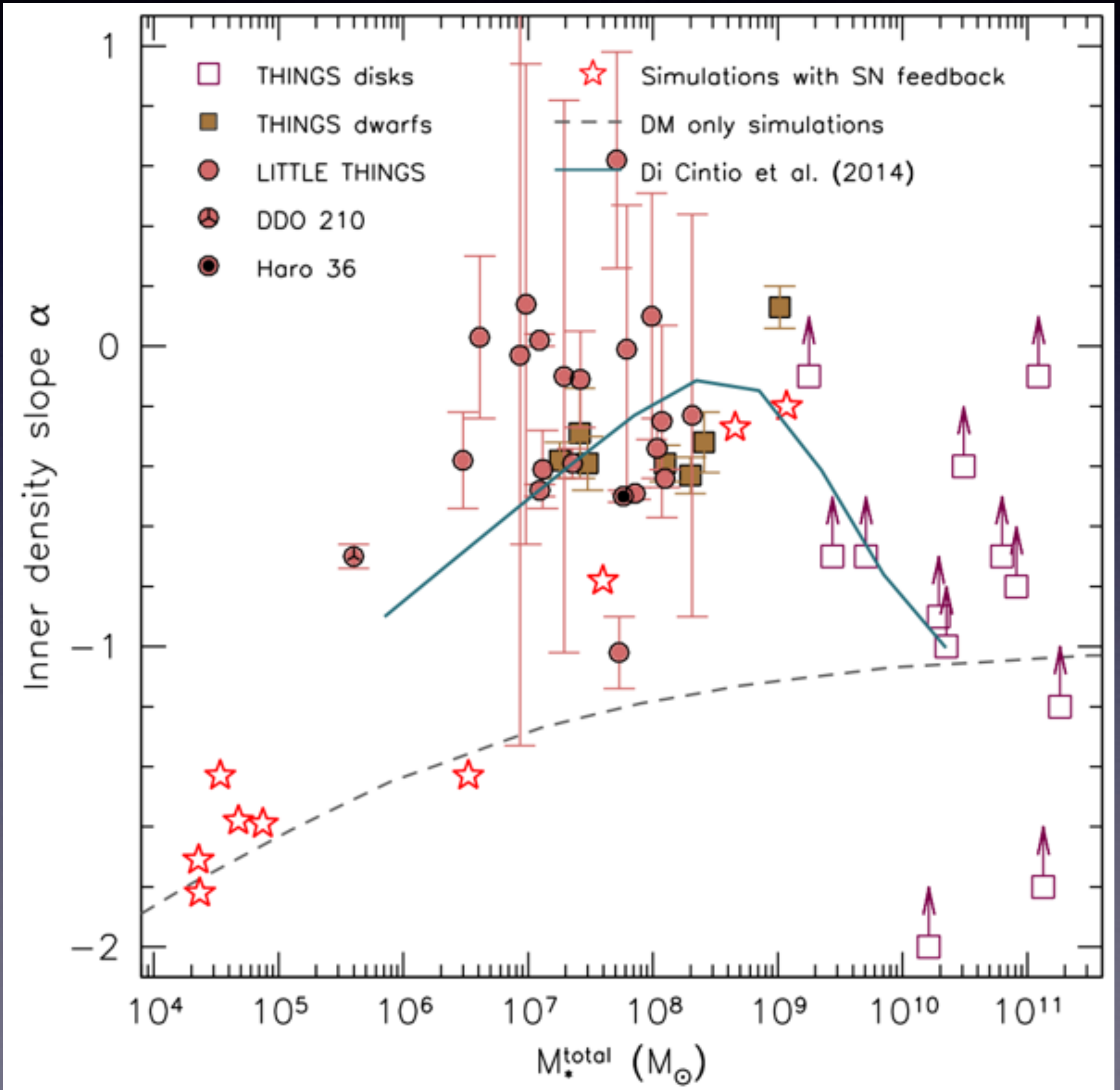
- DM-only simulations typically predict DM density continuing to grow toward the center of halos, down to the resolution of the simulation - a "cusp".
- However, observations find evidence for flatter "cored" profiles in several regimes (going back to 1994, see e.g. review by de Blok '09):
  - Dwarf spheroidal galaxies
    - Satellites of the Milky Way
    - Field dwarfs
  - Galaxy clusters
  - Low surface brightness spiral galaxies (de Blok et al '01, '02; Simon et al 05)
  - High surface brightness spirals (Gentile et al '04)
- Long-standing debates over whether systematics could account for apparent cores (e.g. resolution issues, assumptions of sphericity biasing reconstructed profile, etc).





Dwarf galaxies

- Dwarf galaxies are generally small (10^{7-9} solar masses) and have high mass-to-light ratios.
- Recent years have seen great improvements in data.
- Example: THINGS and LITTLE THINGS surveys of the Local Group (Oh et al '12, '15) measured inner slopes for 7 and 26 dwarf galaxies respectively, finding power-law indices of -0.29 ± 0.07 and -0.34 ± 0.24.
- Typical "core" size is 0.1-1 kpc.
- Measurements span ~2+ orders of magnitude in mass.
- Also other studies of Local Group and Milky Way dwarfs find cores (Adams et al '14, Kirby et al '14, Tollerud et al '14, Walker & Penarrubia '11, Boylan-Kolchin et al '11).

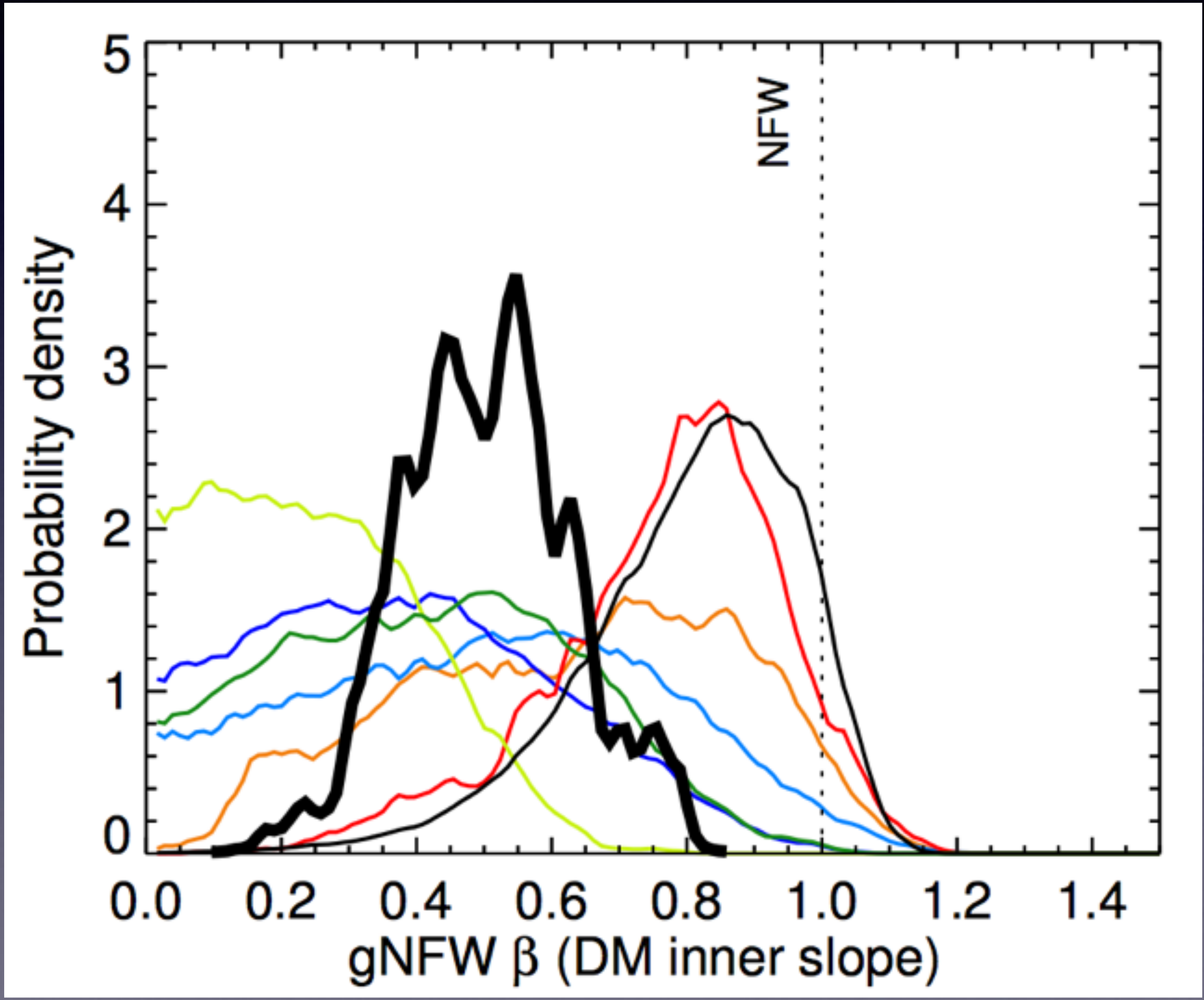


Clusters

- Newman et al '12 claimed evidence for shallow profiles in the cores of seven massive galaxy clusters, power-law slope

-0.5 ± 0.1 (stat) ±0.14 (sys).

- Equally well fit by flat core with 10 kpc radius.
- Note: Schaller et al '14 note this study assumed isotropic stellar orbits, not fully consistent with simulations.



Summary of small-scale discrepancies

- Predictions from CDM-only simulations seem to systematically over-predict the density of dark matter on small (~10 kpc and less) scales. Can be framed as a general "mass deficit" problem.
  - Dwarf galaxies with stellar mass ~$10^{7\text{-}9}$ solar masses appear less concentrated than predicted.
    - Flattened cores, ~0.1-1 kpc in size.
    - Fewer massive+dense dark matter subhalos than expected, both among satellites and in the field.
  - Cluster halos may also possess ~10 kpc cores.

What can this teach us?

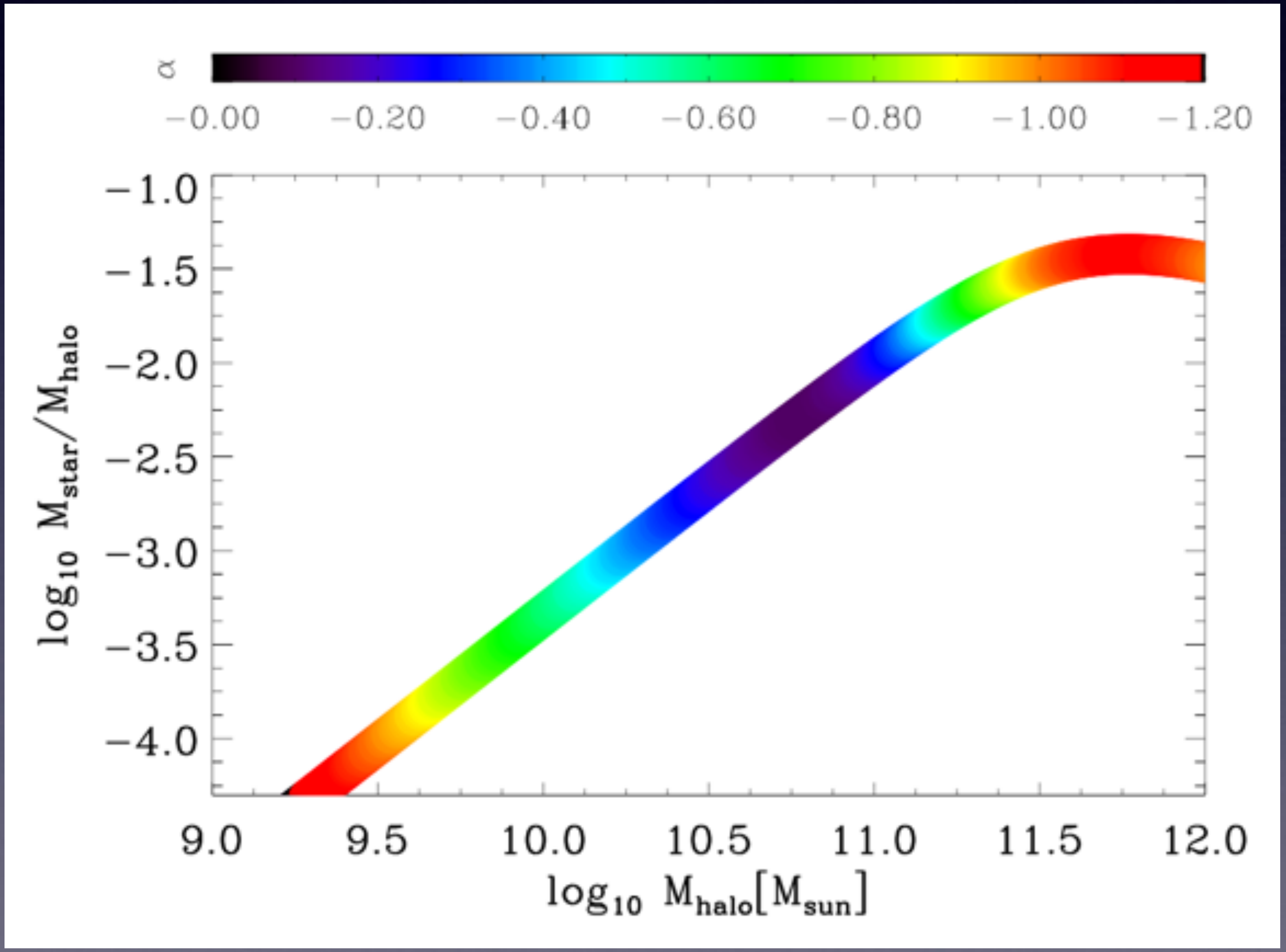
Baryonic possibilities

(see review by Alyson Brooks 1407.7544 and references therein)

- Outflows of baryonic matter can remove low-angular-momentum material from the centers of halos, disrupting cusps.
- Can also potentially solve other problems in galaxy formation, e.g. bulgeless disk galaxies.
- Trickle-down solutions: if large host halos are cored and/or less massive, can also reduce predicted abundance of massive subhalos (see also Brook & di Cintio '14).
- Effect can depend strongly on whether star formation history is "bursty" or smooth - bursts of star formation create fluctuations in the gravitational potential, disrupting cusps and spurring outflows.

Baryonic possibilities: future tests

- At high mass, simulations including baryons do not seem to predict cluster cores (but may be partly due to oversimplified modeling of stellar orbits).
- At low mass, kpc-scale cores require significant star formation, estimated requirement of $M_* \sim 10^7$ solar masses.
- It is possible to push this scale lower ($M_* \sim 10^6$ solar masses), but strongly dependent on star formation history - Onorbe et al '15.
- Cores in lower-mass dwarfs would thus be challenging to explain.



di Cintio et al '13

Dark matter physics

- Alternatively, predictions so far assume collisionless cold dark matter. What if instead some novel DM physics is responsible?
- Possibilities include:
  - Warm dark matter.
  - Collisional/self-interacting dark matter.
  - Inelastic/metastable dark matter.
  - In all cases, this component can either be all the DM, or only a small fraction of the DM.

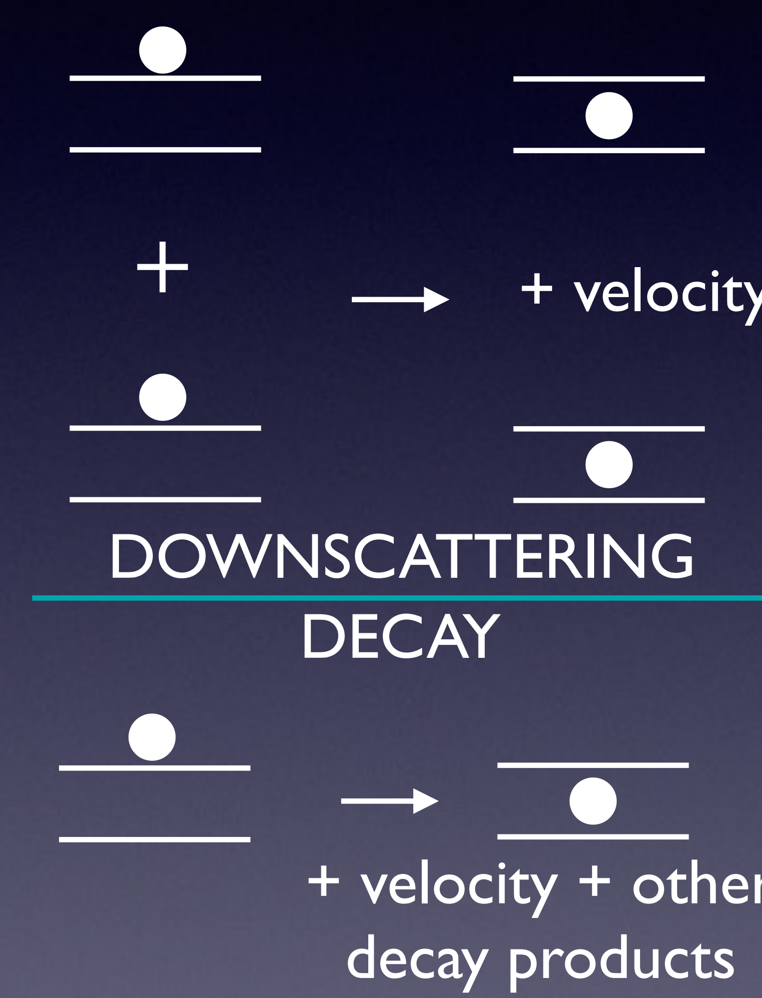
Warm dark matter

- As discussed previously, suppresses structure at small scales - free-streaming can disrupt formation of dense early halos, reduce number of small halos.
- However, to directly create a 1 kpc core, warm dark matter would need to be ~0.1 keV or lighter (Maccio et al '12) - in conflict with bounds from the Lyman-alpha forest.
- The maximum suppression scale of $\sim 10^8$ solar masses is also too low to significantly affect the missing satellite problem.
- Structure formation is delayed in WDM models as the smallest structures are wiped out; halos that form at later times are less concentrated, which alleviates the Too Big To Fail problem (Lovell et al '12).
- However, full solution to TBTF requires mass ~2 keV or lighter (Schneider et al '14), in tension with Lyman-alpha forest bounds.
- In general, 2+ keV WDM is difficult to distinguish from CDM.

Decaying/inelastic DM

(see e.g. Wang et al 1406.0527 and references therein)

- If dark matter possesses a slightly heavier excited state, populated in the early universe, then decays from that state can give the DM a velocity "kick" at late times.
- Collisions between DM particles could also stimulate de-excitation, with similar effects.
- Decays can reduce the internal density and number of DM halos, alleviating the "too big to fail" and "missing satellite" problems.
- Velocity kick must be ~ few tens of km/s.

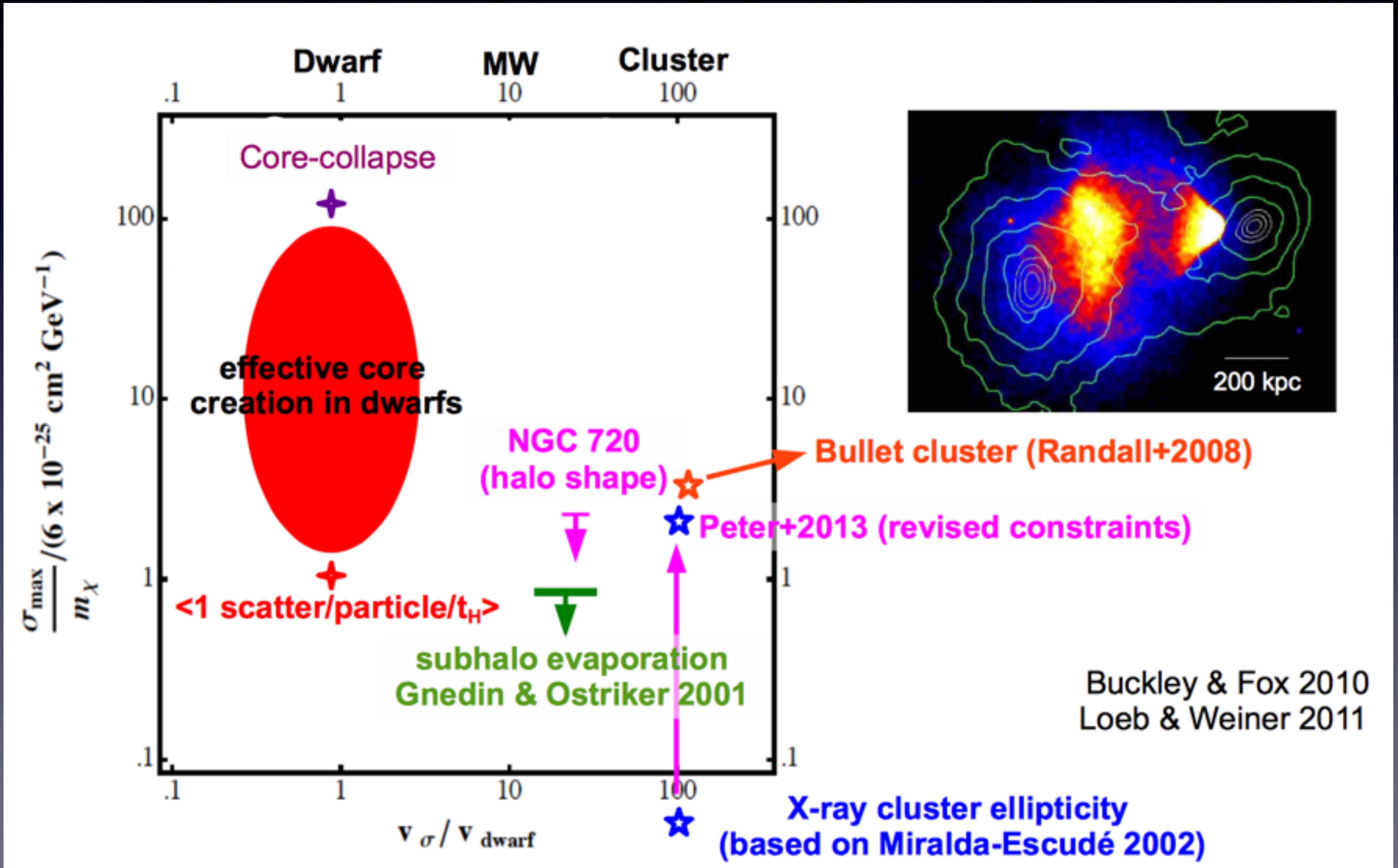


Such small splittings can be natural in the presence of a symmetry that is broken by radiative effects or a higher-dimension operator (e.g. Arkani-Hamed et al '08).

Self-interacting dark matter

- In general, interesting to consider the observable implications of more-complex dark sectors - what if DM has its own interactions?
- Dark matter must be approximately collisionless (from Bullet Cluster), but cross section limits are quite large.
- Dark matter self-scatterings can transfer energy + momentum + angular momentum - at low cross sections, cause particles to move outward from localized dense regions where scattering is common (Spergel & Steinhart 2000).
- At sufficiently high scattering rates, can cause collapse of cores, formation of "dark disk", etc (e.g. Fan et al '13).

Constraints on SIDM



Taken from talk by Jesus Zavala at UCLA Physics & Astronomy, August 2013

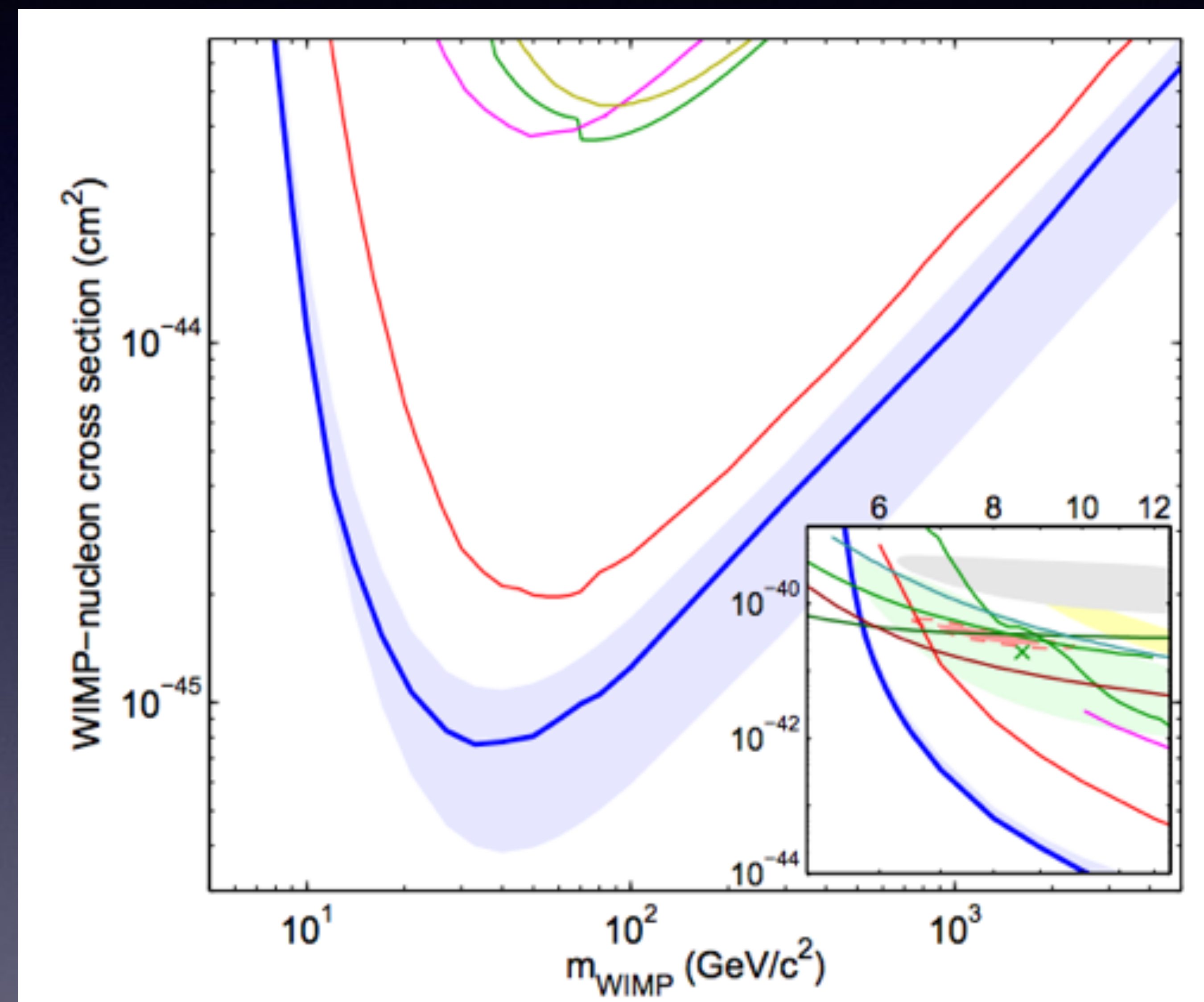
A note on cross sections

- 1 $cm^2/g \sim 2 \times 10^{-24}$ cm^2/GeV.
- So for GeV+ DM, self-interaction strong enough to affect dwarfs requires

$$\sigma > 10^{-24}\ cm^2 = 1\ \text{barn}.$$

- For comparison, current bounds on DM-nucleus scattering cross section for ~30 GeV DM reach cross sections of

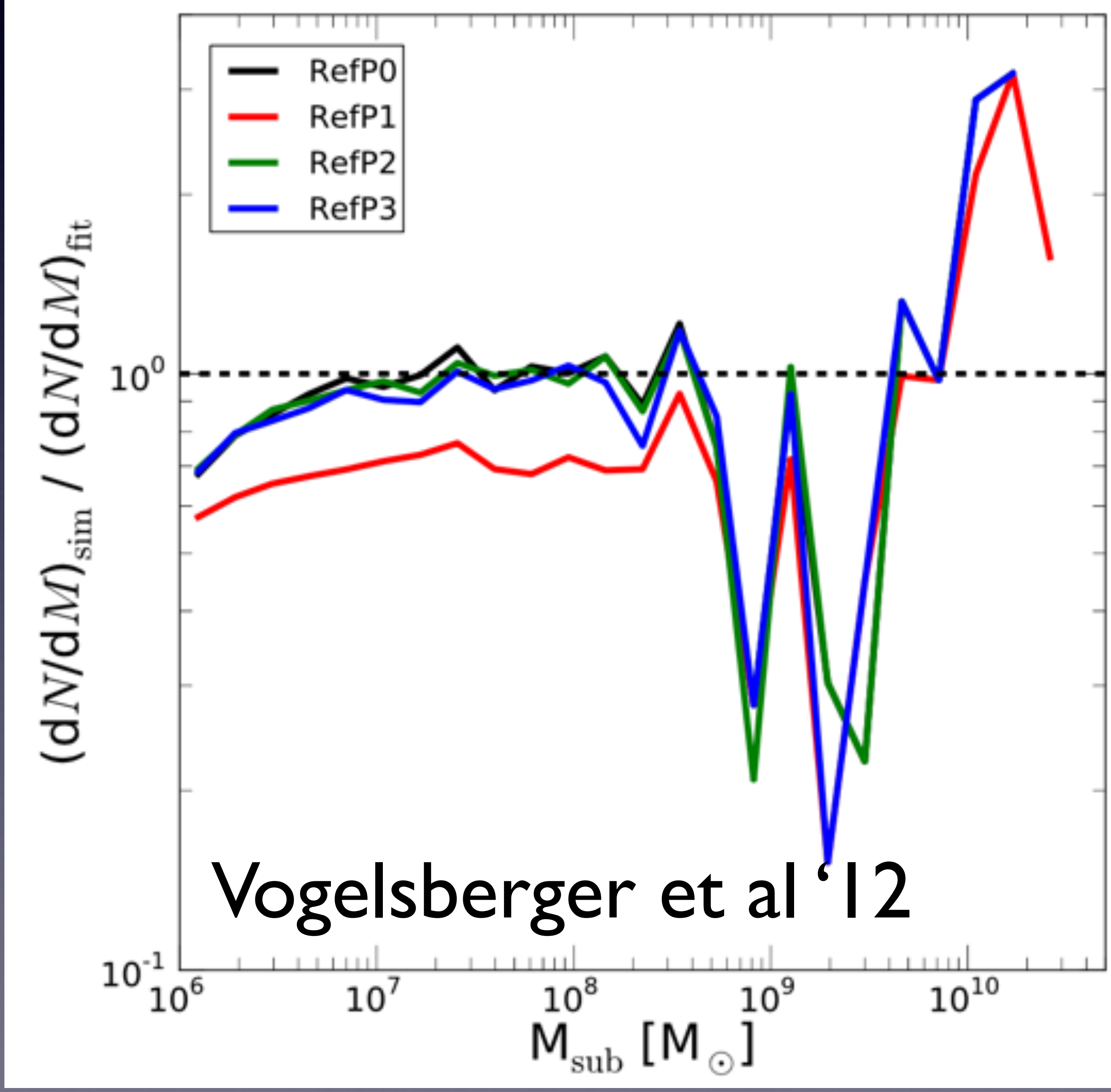
$$\sigma \sim 10^{-45}\ cm^2$$



LUX Collaboration '13

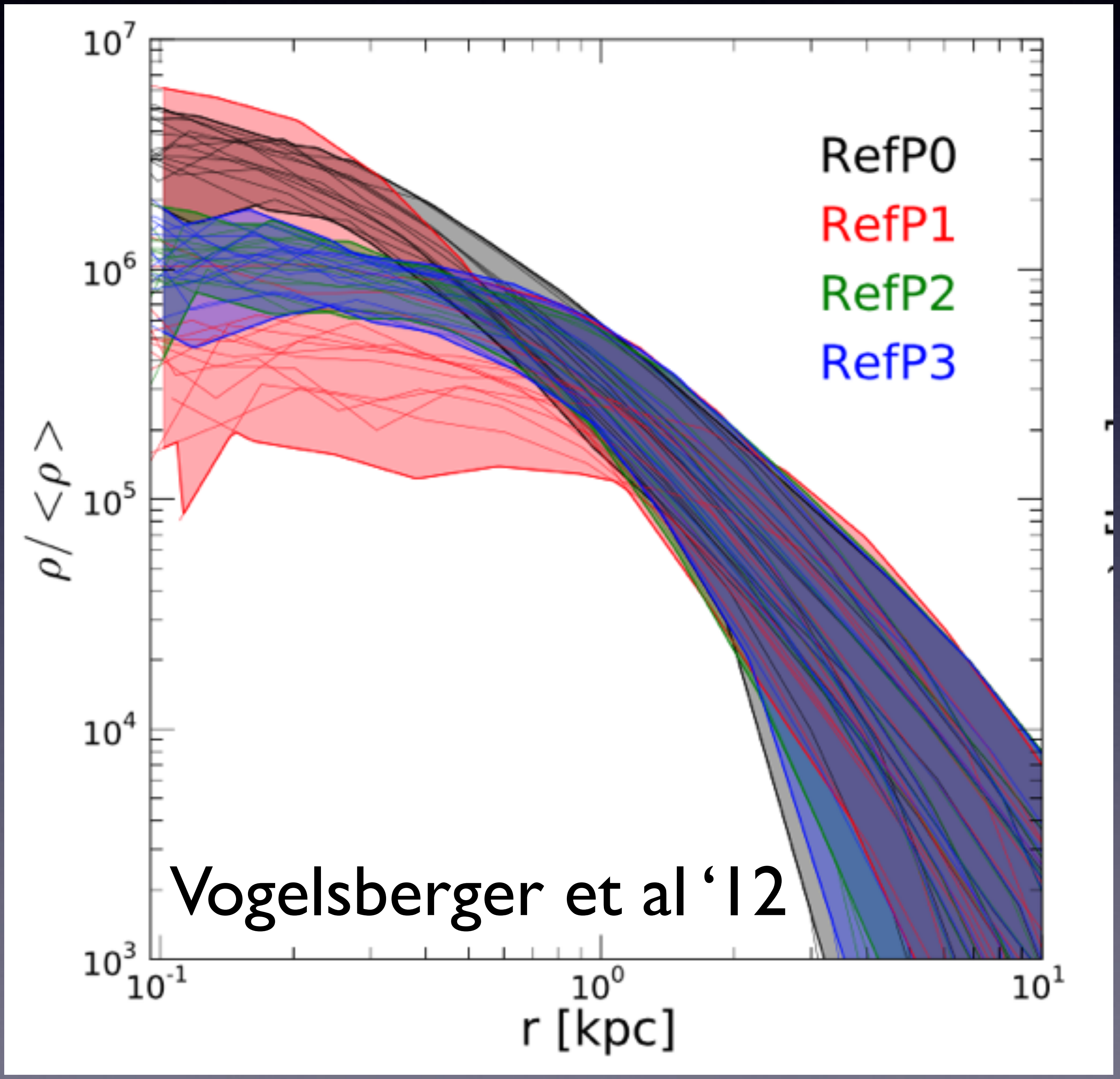
The effect of SIDM: the halo mass function

- Impact on the number of subhalos, or the subhalo mass function, is fairly small (except for models ruled out for other reasons, as is the case for the red line here).
- Black line = CDM model, green/blue lines = SIDM models (not ruled out).
- Consequently, does not affect missing satellite problem.



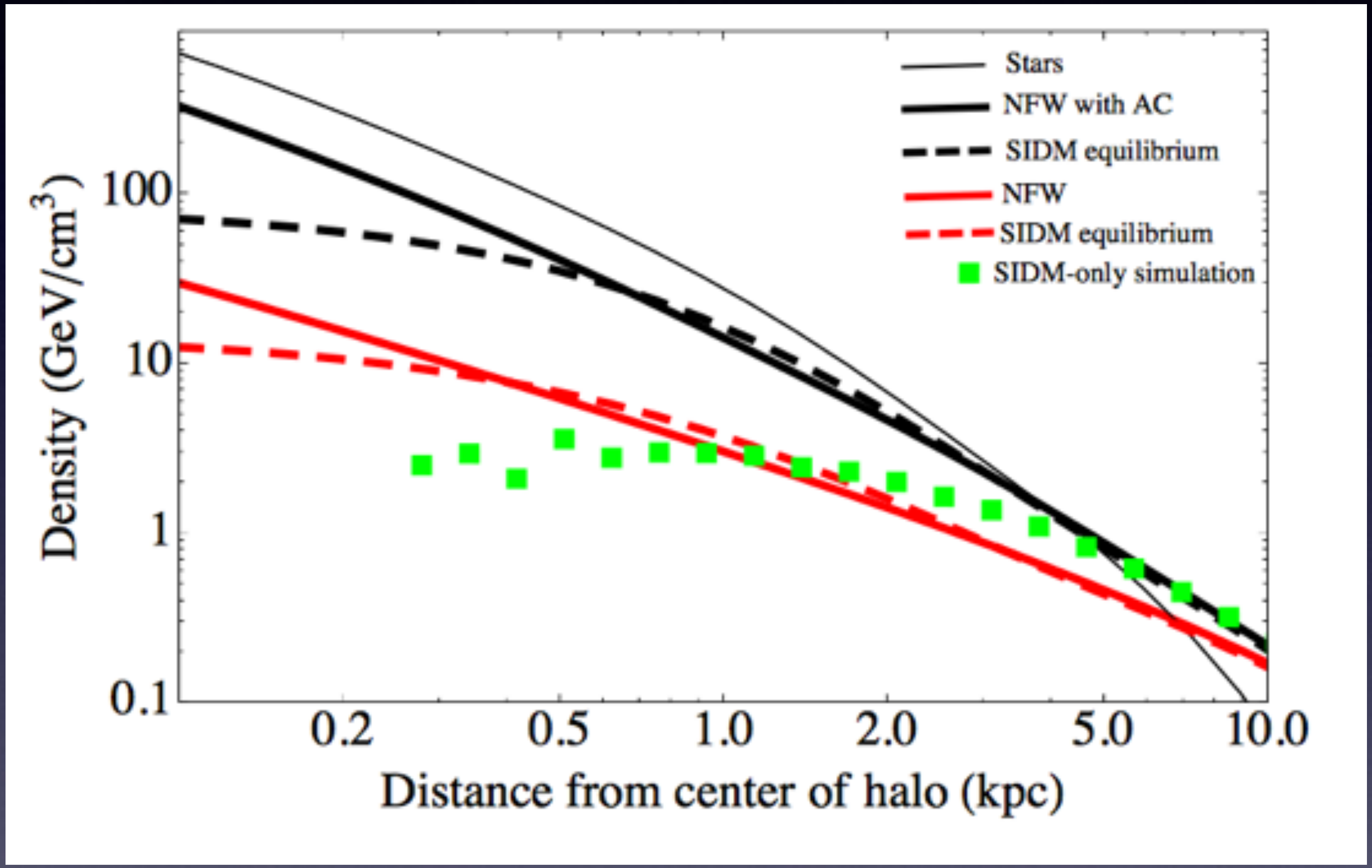
SIDM and Cores

- Early studies found that with a cross section $\sigma/m \sim 0.1\text{-}1$ cm^2/g, self-interaction could create ~kpc cores in dwarf galaxies.
- In MW-scale galaxies, O(10) kpc cores can be produced.



However -

- Cannot ignore the existence of baryons in SIDM predictions for large galaxies (Kaplinghat et al '14, Vogelsberger et al '14).
- Including baryons <u>reduces</u> the core size relative to pure SIDM, with the effect largest in baryon-dominated systems.
- For MW-size halo, core size drops to ~0.3 kpc.
- Can also render halo non-spherical where baryons dominate the potential.

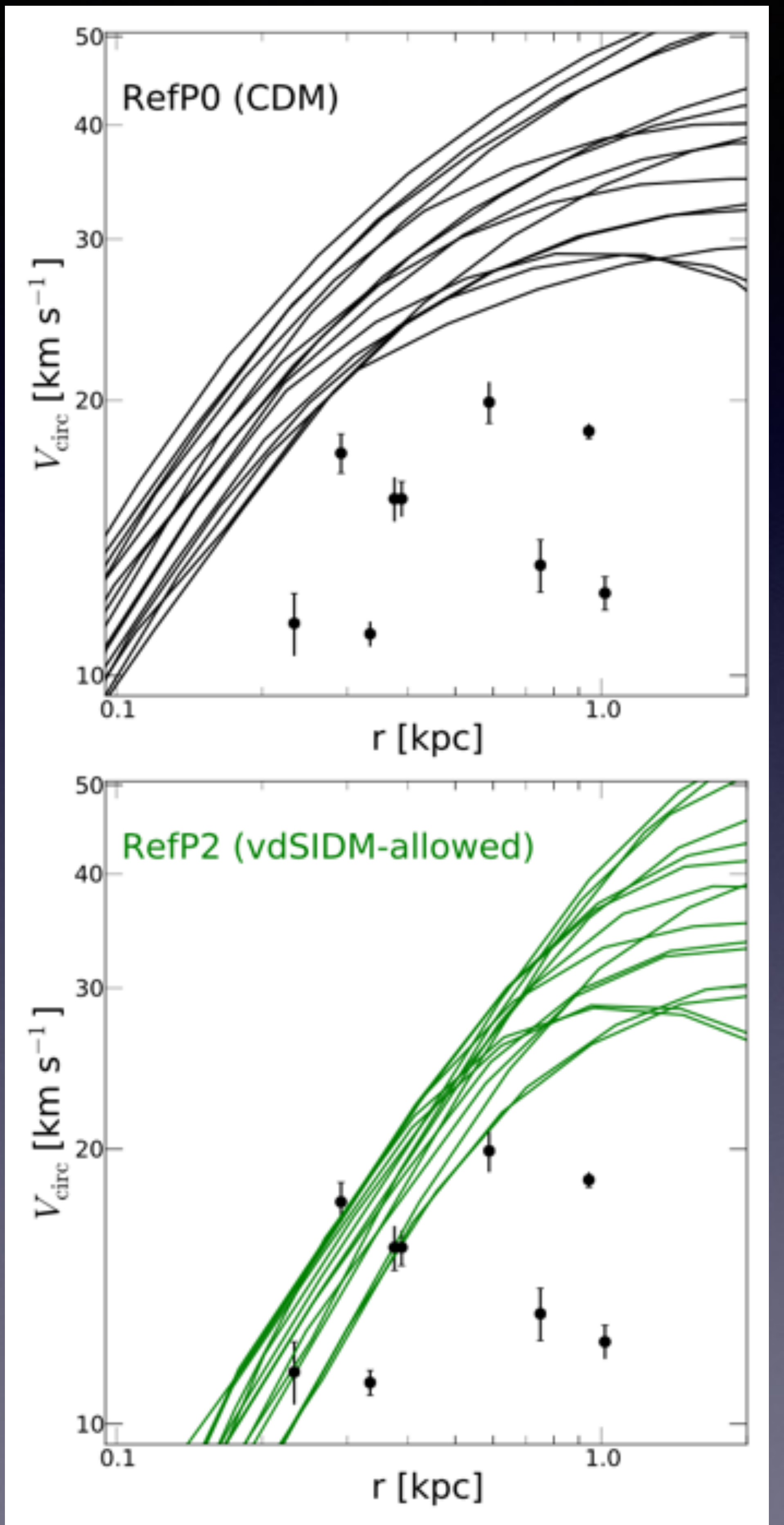


- Fry et al '15 study SIDM case where baryonic effects are sufficient to create cores, find it is difficult to distinguish CDM/SIDM in that case.
- Argue that a large cross section $\sigma/m > 10$ cm^2/g would be needed to generate cores in small dwarfs.

The effect of SIDM: Too Big To Fail

Vogelsberger et al '12

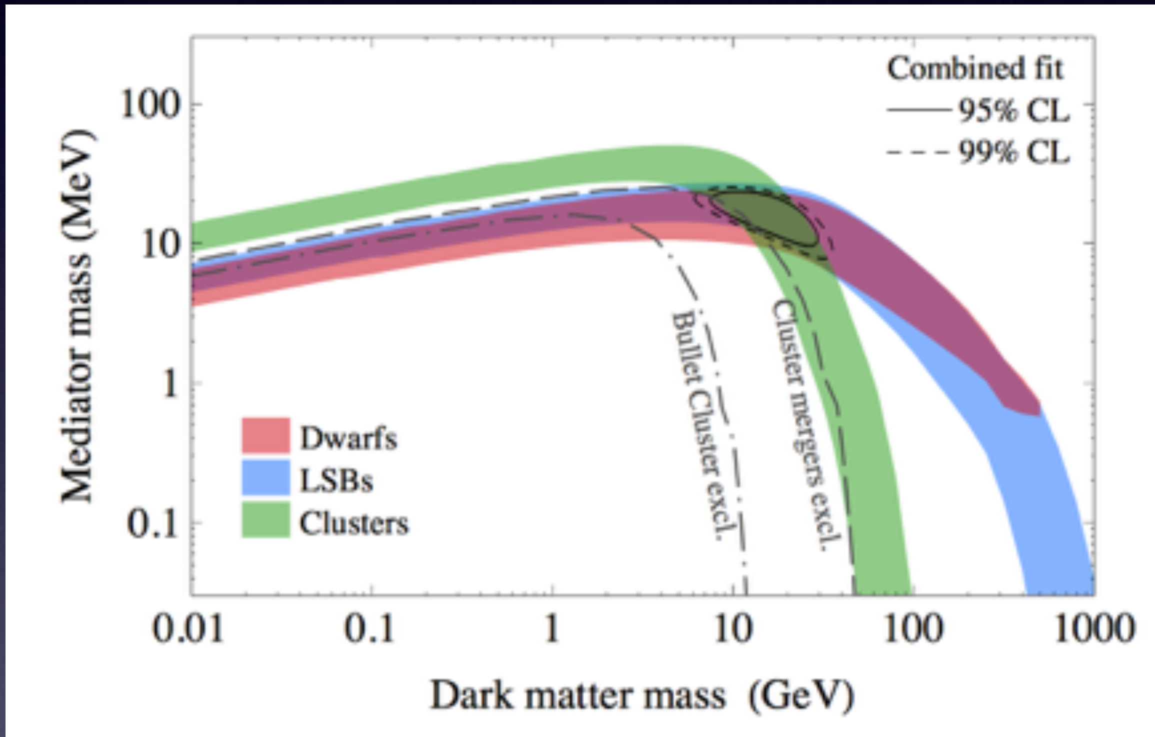
- Subhalo concentrations and accordingly circular velocities are generally reduced.
- Helps to alleviate Too Big To Fail problem.
- Cross sections required are similar to those needed to produce cores (since both require reducing central density of subhalos).
- Elbert et al '14 find that SIDM cross sections $\sigma/m \sim 0.5\text{-}50\ cm^2/g$ at dwarf scales produce cores and alleviate TBTF.



Models for SIDM

- Interaction cross sections needed to solve small-scale problems are typically large by particle physics standards, implying fairly light force carriers.
- Simple model that has been studied in depth is "dark photon" - MeV-GeV scale U(1) vector boson.
- Generates Yukawa potential if DM is charged under dark U(1) - naturally yields velocity-dependent interaction cross section.
- This mass scale can be generated naturally in the context of SUSY if the dark photon mixes kinetically with the photon, inherited from the weak scale (Cheung et al '09).

Kaplinghat et al '15



$$\mathcal{L} \supset -\frac{\epsilon}{2} F_d^{\mu\nu} F_{\mu\nu}$$

$$\mathcal{L} \supset -\frac{\epsilon}{2} \int d^2\theta W_Y W_d$$

$$V_{\mathrm{D-term}} = \epsilon D_Y D_d$$

$$m_d^2 = g_d \epsilon \langle D_Y \rangle$$

SIDM and mergers

- Bullet cluster sets constraints on SIDM close to relevant cross sections - suggests cluster/galaxy collisions may have sensitivity for detection.
- Simple picture: gas is collisional, stars ~collisionless. Does DM trace gas, stars or something in between? Offset from stars = diagnostic of self-interaction.
- Difficulties:
  - Requires non-equilibrium systems, so the various components have not relaxed into the common gravitational potential. These are rare.
  - Mapping the DM density in detail in colliding systems can be highly non-trivial.
  - What are the systematics and backgrounds? Not yet well explored (some work by Schaller et al '15, Harvey et al '16, Robertson et al '16). For example,
    - it is not always easy to correctly associate the lensed images with the underlying objects
    - mismodeling of DM/gas distributions can lead to biases - on one hand constraints from Bullet Cluster are probably too strong, but asymmetric gas/DM distributions could lead to the false appearance of an offset

Nonetheless…

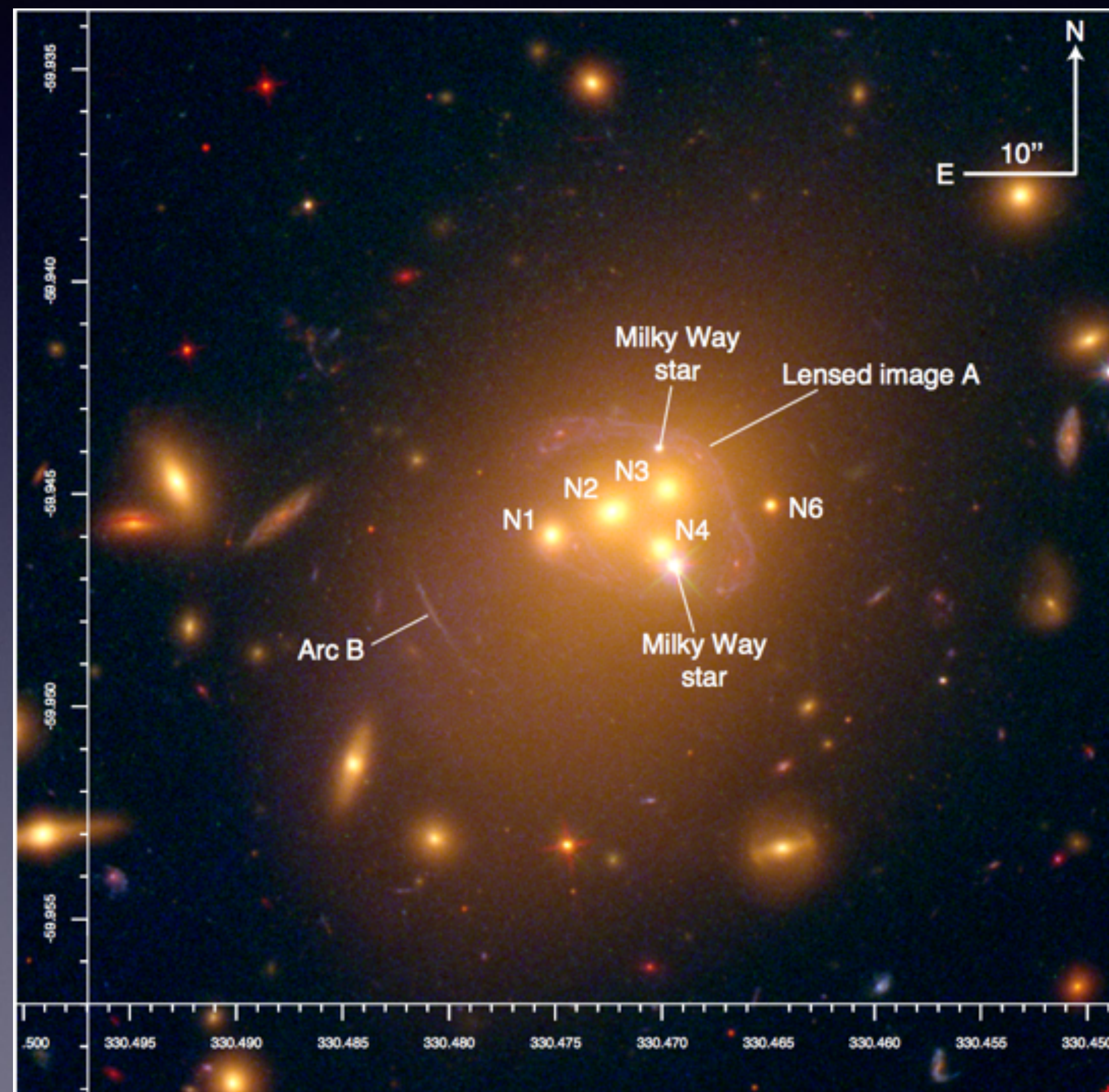
The behaviour of dark matter associated with 4 bright cluster galaxies in the 10 kpc core of Abell 3827

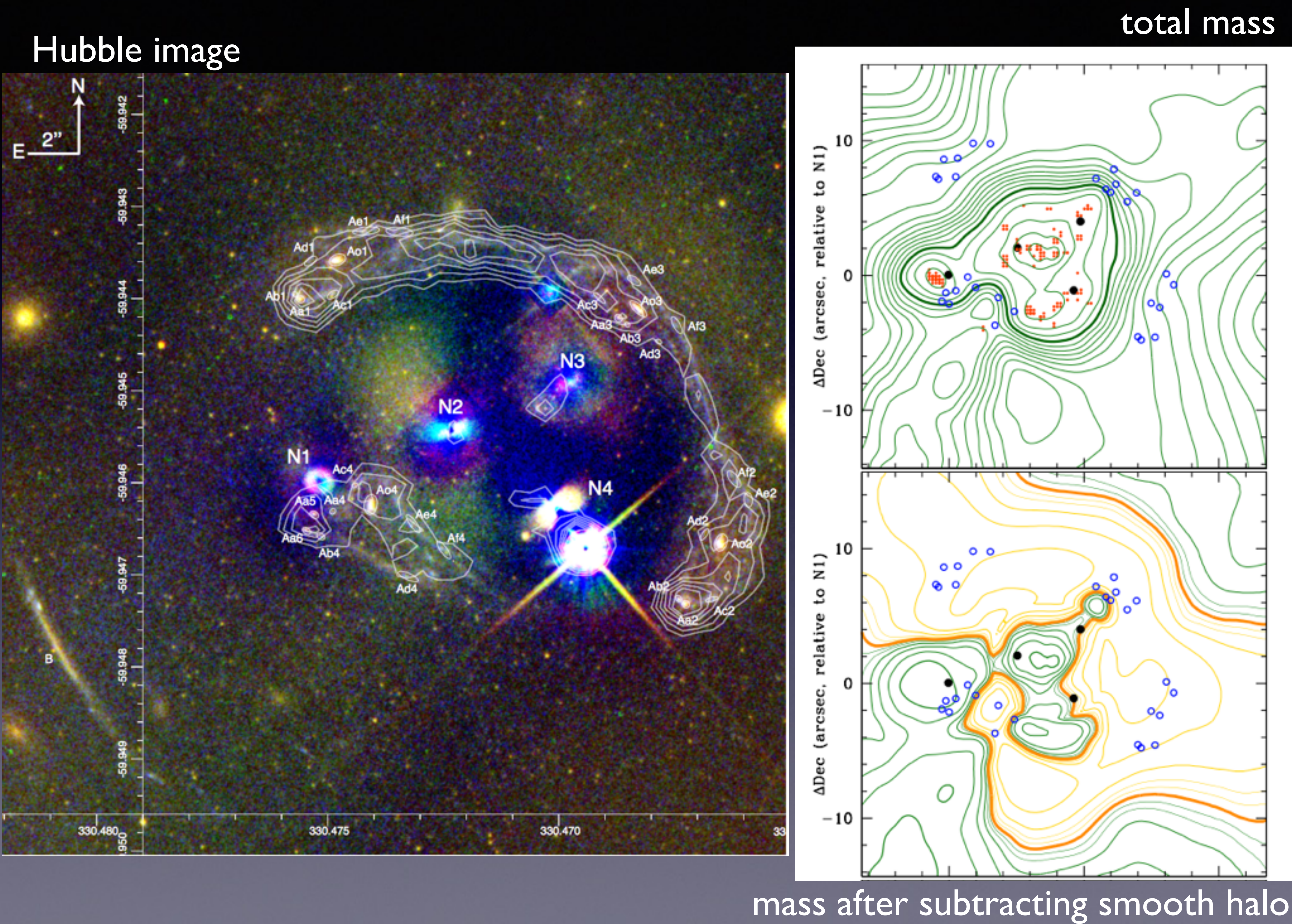
Richard Massey[1,2⋆], Liliya Williams[3], Renske Smit[2], Mark Swinbank[2], Thomas D. Kitching[4], David Harvey[5], Mathilde Jauzac[1,6], Holger Israel[1], Douglas Clowe[7], Alastair Edge[2], Matt Hilton[6], Eric Jullo[8], Adrienne Leonard[9], Jori Liesenborgs[10], Julian Merten[11,12], Irshad Mohammed[13], Daisuke Nagai[14], Johan Richard[15], Andrew Robertson[2], Prasenjit Saha[13], Rebecca Santana[7], John Stott[2] & Eric Tittley[16]

Galaxy cluster Abell 3827 hosts the stellar remnants of four almost equally bright elliptical galaxies within a core of radius 10 kpc. Such corrugation of the stellar distribution is very rare, and suggests recent formation by several simultaneous mergers. We map the distribution of associated dark matter, using new *Hubble Space Telescope* imaging and *VLT/MUSE* integral field spectroscopy of a gravitationally lensed system threaded through the cluster core. We find that each of the central galaxies retains a dark matter halo, but that (at least) one of these is spatially offset from its stars. The best-constrained offset is $1.62^{+0.47}_{-0.49}$ kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. Such offsets are not seen in field galaxies, but are predicted during the long infall to a cluster, if dark matter self-interactions generate an extra drag force. With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section $\sigma_{\rm DM}/m \sim (1.7 \pm 0.7) \times 10^{-4}\,{\rm cm}^2/{\rm g}$ $\times (t_{\rm infall}/10^9\,{\rm yrs})^{-2}$, where $t_{\rm infall}$ is the infall duration.

The case of Abell 3827

- System of four elliptical galaxies in a cluster, presumably formed recently by several simultaneous mergers.
- Map the mass distribution using gravitational lensing. (Used two independent methods to reconstruct the distribution, with good agreement.)
- Find evidence for an offset of 1.6±0.5 kpc between one DM halo and the associated stellar halo.
- See Sepp et al '16 for a simulated theoretical model.





Hubble image
total mass
mass after subtracting smooth halo
N
E
2"
N1
N2
N3
N4
330.480
330.475
330.470
ΔDec (arcsec, relative to N1)
10
0
−10

Converting an offset to a cross section

- Original paper: estimate drag force on DM from self-interactions, slows the subhalo's infall.
- Look at difference in accelerations, assuming same starting point; infer difference in distance traveled after a time t_{infall}.
- Kahlhoefer et al '15 argue one must include the gravitational pull on the stars from the subhalo - drag force must outweigh this restoring force in order for there to be a separation.
- Resulting cross section is much higher, in mild tension with other cluster bounds (but these bounds may be overly strong, see Robertson et al '16).

$$F_{st} \sim \frac{G M_{co} M_{st}}{r^2}$$

$$F_{dm} \sim \frac{G M_{co} M_{dm}}{r^2} \times \left[1 - \frac{M_{dm}\,\sigma/m}{\pi s^2}\right]$$

$$d \sim \left(\frac{F_{st}}{M_{st}} - \frac{F_{dm}}{M_{dm}}\right) t^2 = \frac{G M_{co} M_{dm}\,\sigma/m}{\pi r^2 s^2}\, t^2$$

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\rm infall}}{10^9\ \rm yrs}\right)^{-2} \rm cm^2/g.$$

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{1}{4}\frac{\tilde{\sigma}}{m_{\rm DM}} v^2 \rho \qquad \frac{F_{\rm sh}}{m_{\rm star}} = \frac{G_{\rm N}\, M_{\rm sh}(\Delta)}{\Delta^2}$$

$$F_{\rm sh}/m_{\rm star} < F_{\rm drag}/m_{\rm DM}$$

$$\frac{\tilde{\sigma}}{m_{\rm DM}} > \frac{4}{v^2 \rho}\frac{G_{\rm N}\, M_{\rm sh}\, \Delta}{a_{\rm sh}^3} \gtrsim 2\ {\rm cm^2\, g^{-1}}$$

Summary (Lecture 1)

- The distribution and gravitational effects of dark matter can be a powerful probe of dark-matter properties and interactions, independent of any interaction with the known particles. We have direct observational tests of:
  - Any dark matter physics that modifies the low end of the matter power spectrum (e.g. warm dark matter below the ~keV scale, subdominant hot dark matter, very low decoupling temperatures).
  - Any dark matter physics that produces a "drag force" or similar effect on dark matter in merging clusters.
  - Any dark matter physics that modifies ~galactic-scale halos, in regions where stellar orbits can be used to probe the DM distribution (from dwarfs to the central regions of clusters). Generally constrains DM-DM interactions with rates > 1/Hubble time.
  - Also the overall cosmological abundance of dark matter (at least at redshift 1000) - to be discussed in more depth next time.
- Understanding systematic uncertainties (and guaranteed effects) due to ordinary / baryonic matter is important, and a major research direction. Needed to understand possible hints that dark matter may not be perfectly collisionless and cold.
- At opposite ends of the mass scale, small field dwarfs and galaxy clusters should furnish new probes of dark sector physics, as the data continue to improve.