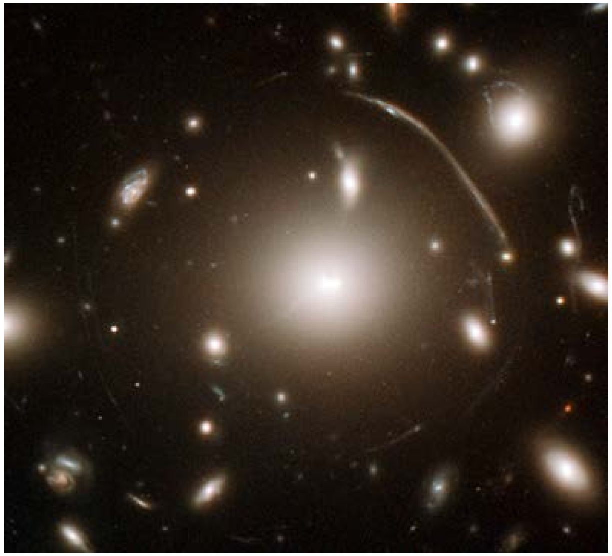
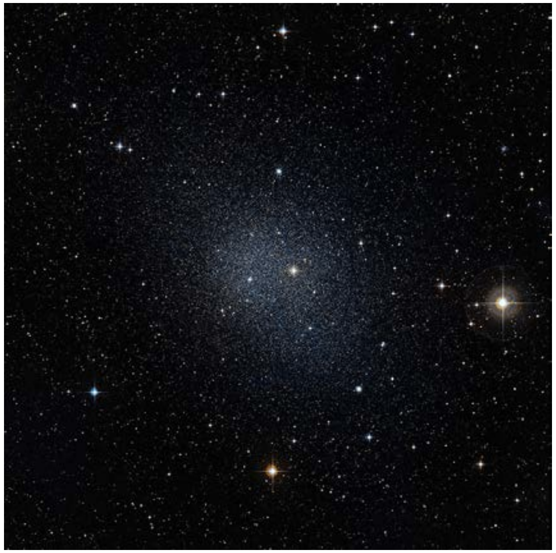


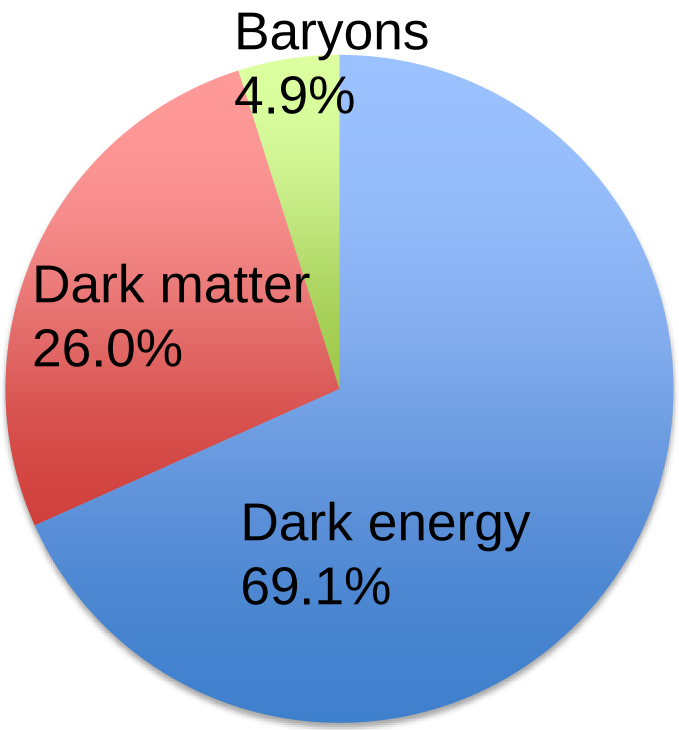


Astrophysical Constraints on Dark Matter

Drew Newman

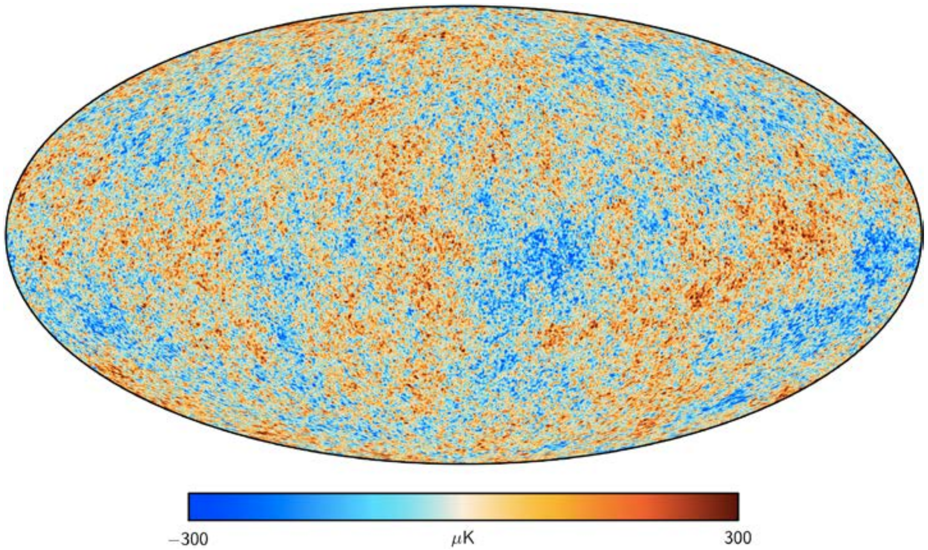
August 30, 2017
DaMaSC

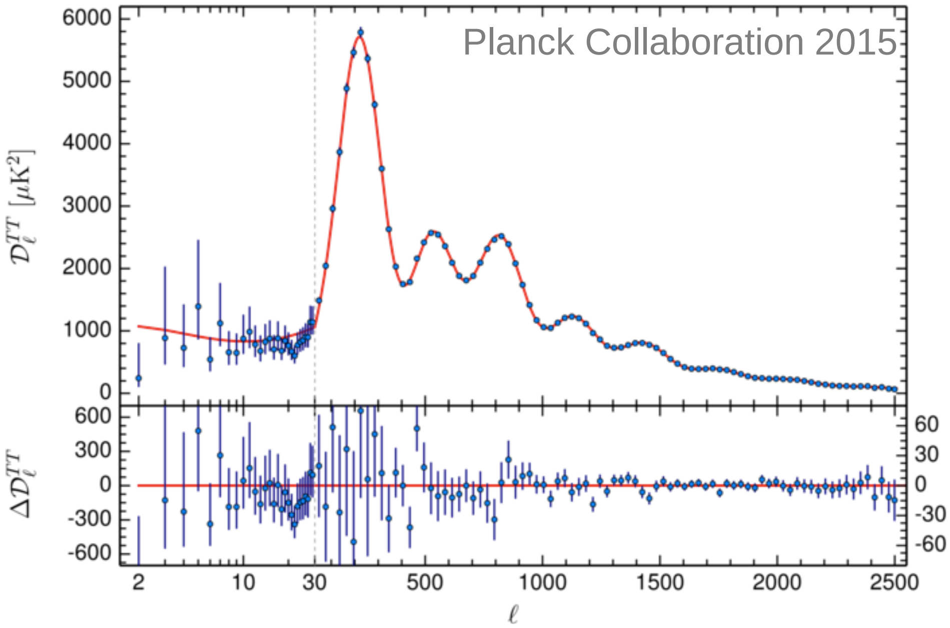
“Vanilla” CDM model from astronomers’ POV



- Dark matter is “cold”
  - Non-relativistic at decoupling
  - Negligible velocities
- It interacts only gravitationally
  - Collisionless
  - No decays

Cosmic microwave background



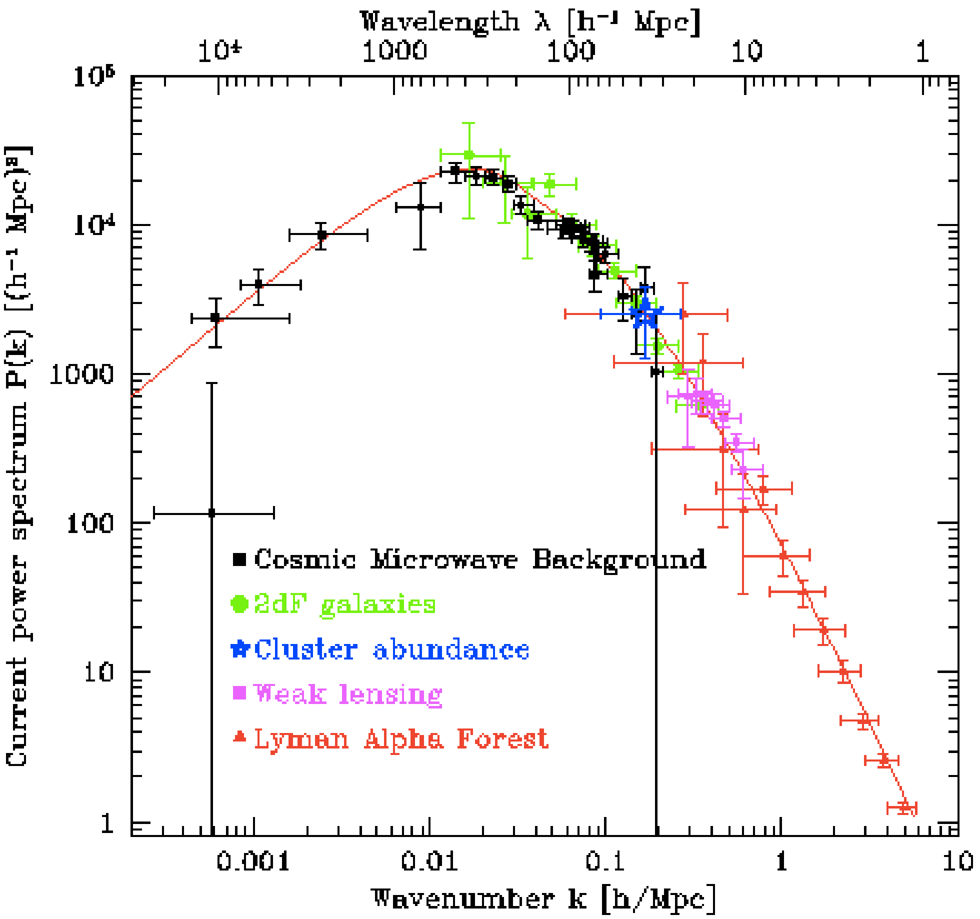


"Vanilla" LCDM cosmology adequate to fit exquisite *Planck* data

No extensions clearly demanded by CMB data

Ω_m = 0.309 with 2% uncertainty

Matter power spectrum

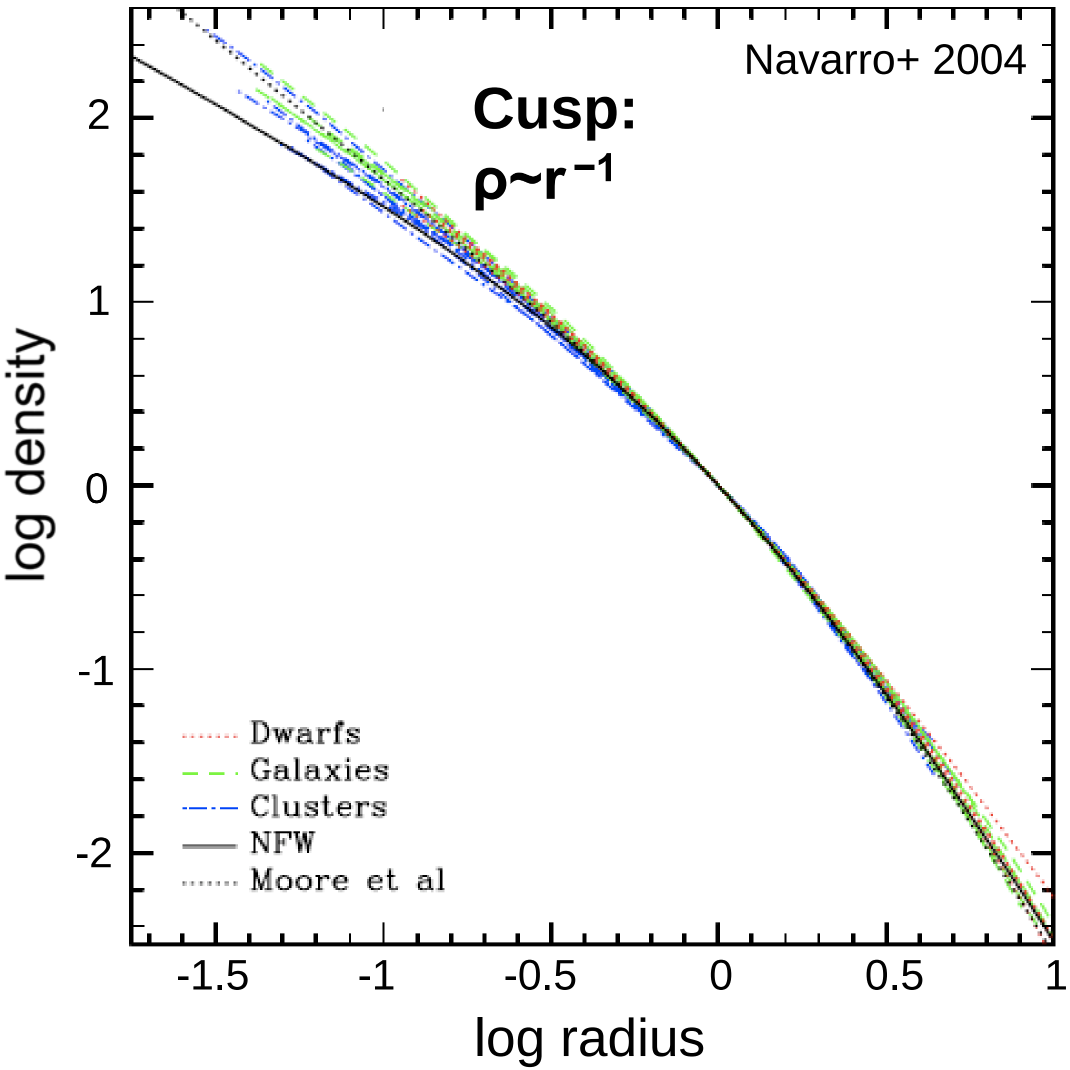


Tegmark 2003

Matter power spectrum agrees excellently with diverse observations spanning scales ~10 Gpc – 1 Mpc

→ Dark matter must look a lot like vanilla LCDM on > 1 Mpc scales

Structure of collapsed objects ("halos")



Collisionless CDM predicts a self-similar ("universal") density structure for collapsed halos

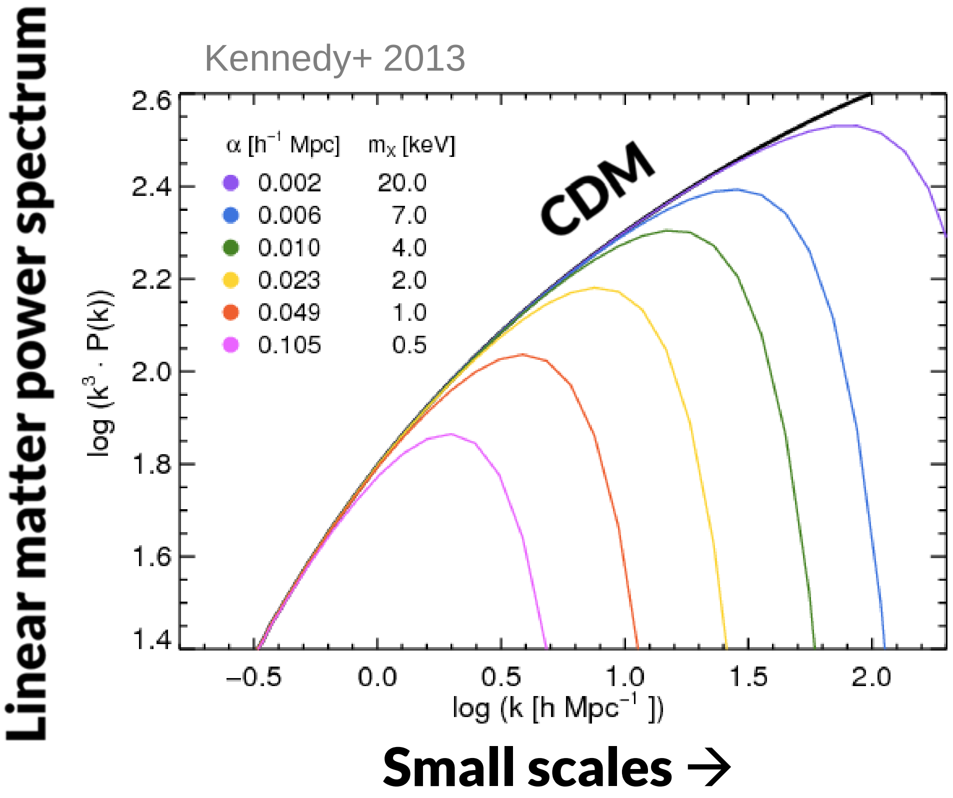
Navarro, Frenk & White 1996

Key feature:
Cold center with density cusp $\rho_{DM} \sim 1 / r$

Outline

- What observations of the *small-scale distribution* of DM can constrain its properties?
- Where/how can effects of galaxy formation (“baryonic physics”) mimic non-standard DM signatures
- What parameter spaces are allowed, specifically for warm or self-interacting models

Warm dark matter



Structures below free-streaming mass cannot form

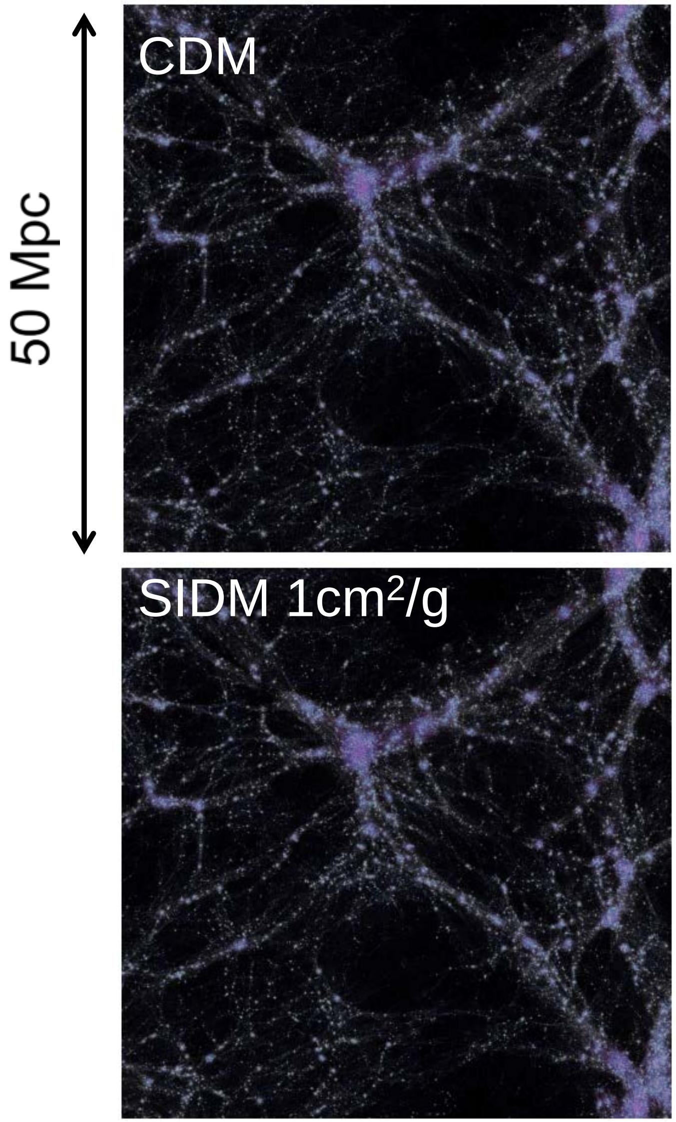
Structures that do form collapse later and have lower density

Typical to quote constraints on m_{WDM} for a *thermal relic* for which relevant masses are ~keV

Same observations → different mass constraints for non-thermal production

Self-interacting dark matter

Carlson 1992; Spergel & Steinhardt 2000



Rocha+ 2013

Introduce DM-DM elastic scattering

Cross-sections of interest have
$\sigma / m \sim 1\ \mathrm{cm^2/g} \sim 1$ barn/GeV

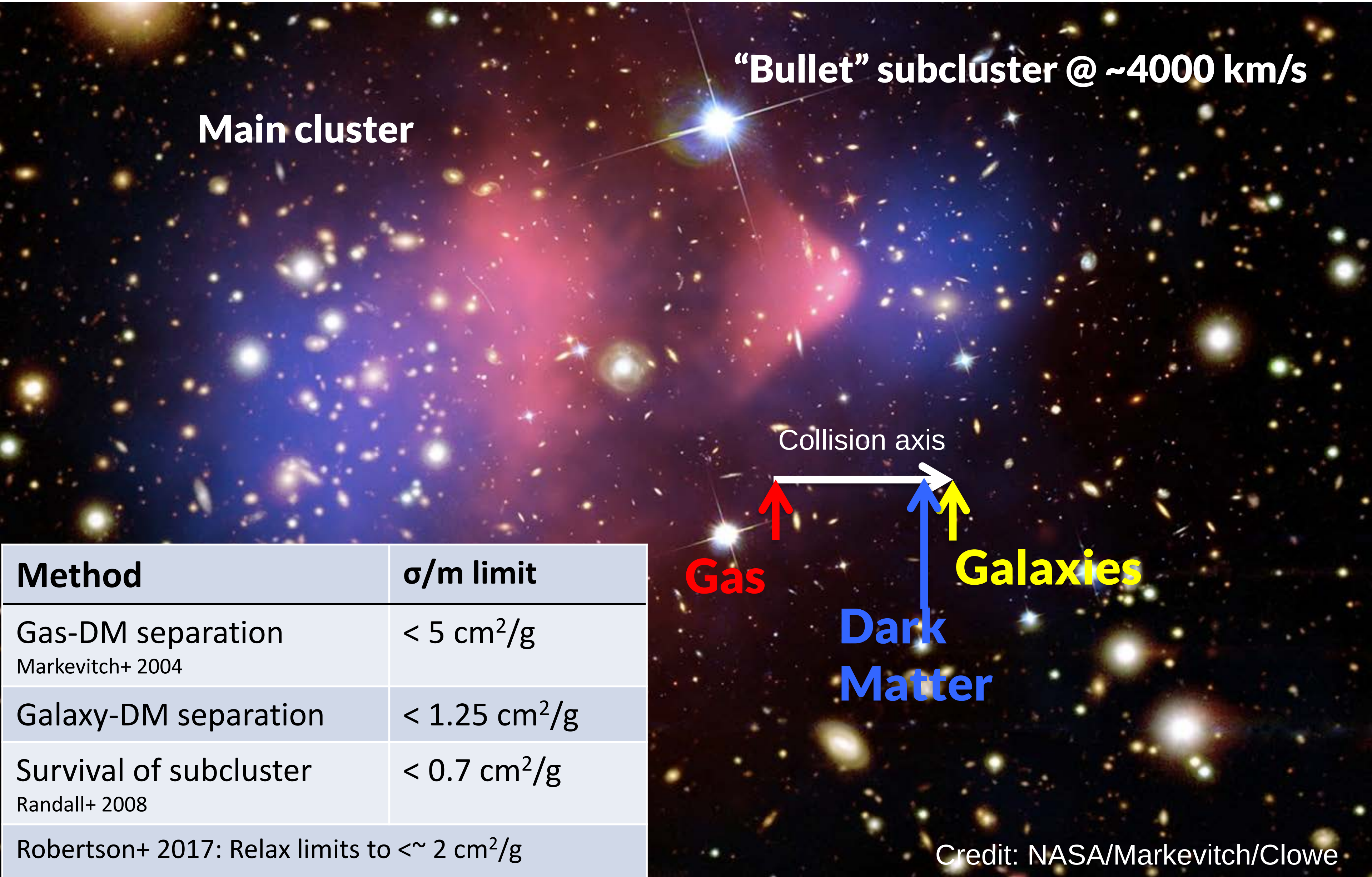
May or may not be velocity- (scale-) dependent

Looks just like collisionless CDM on large scales → preserve successes

Differences appear in centers of halos where scattering occurs

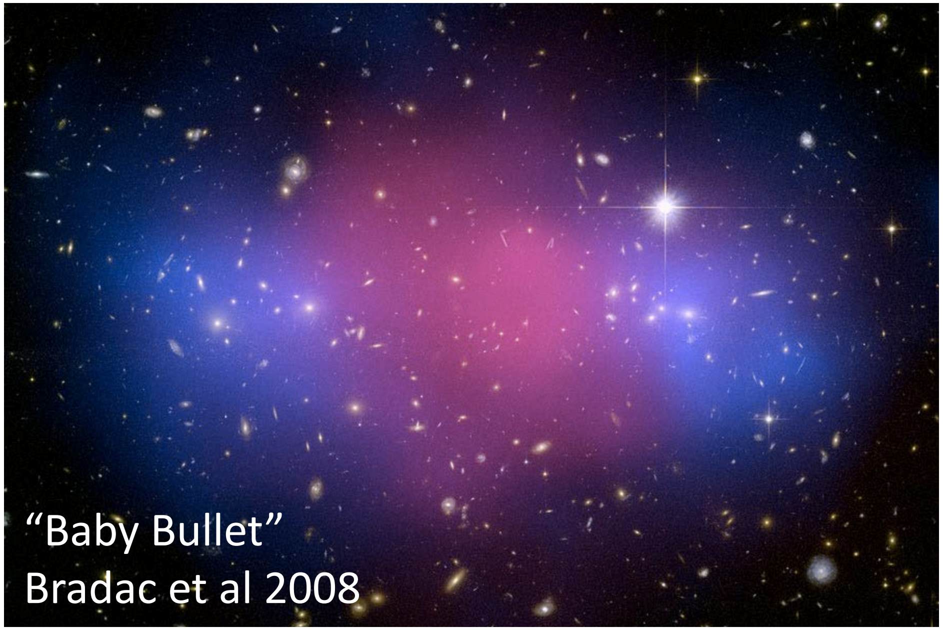
Galaxy Clusters

Probing DM-DM Interactions with Colliding Clusters



Method	**σ/m limit**
Gas-DM separation Markevitch+ 2004	< 5 cm^2/g
Galaxy-DM separation	< 1.25 cm^2/g
Survival of subcluster Randall+ 2008	< 0.7 cm^2/g
Robertson+ 2017: Relax limits to <~ 2 cm^2/g	

Constraints from Galaxy-DM Separation in Merging Clusters



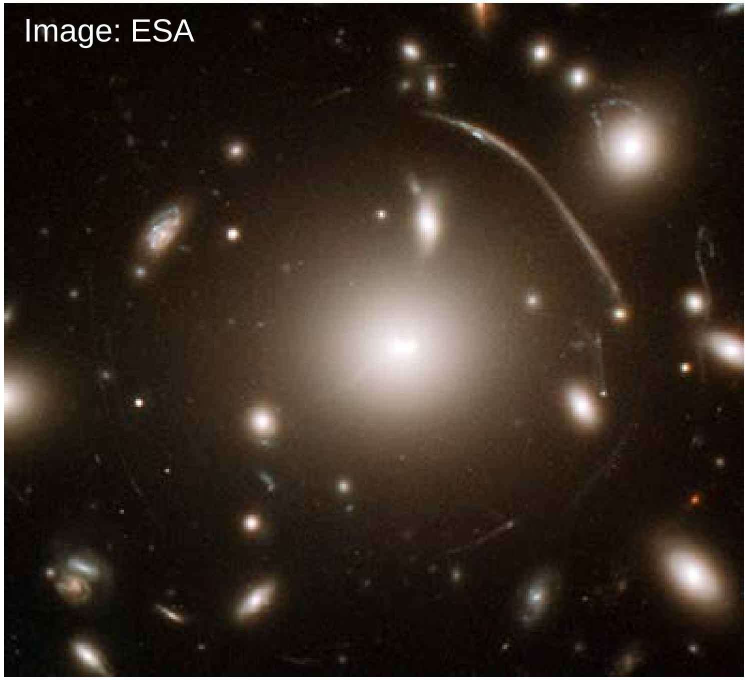
- Expect ~50-150 kpc stochastic offsets between galaxies and *collisionless* DM

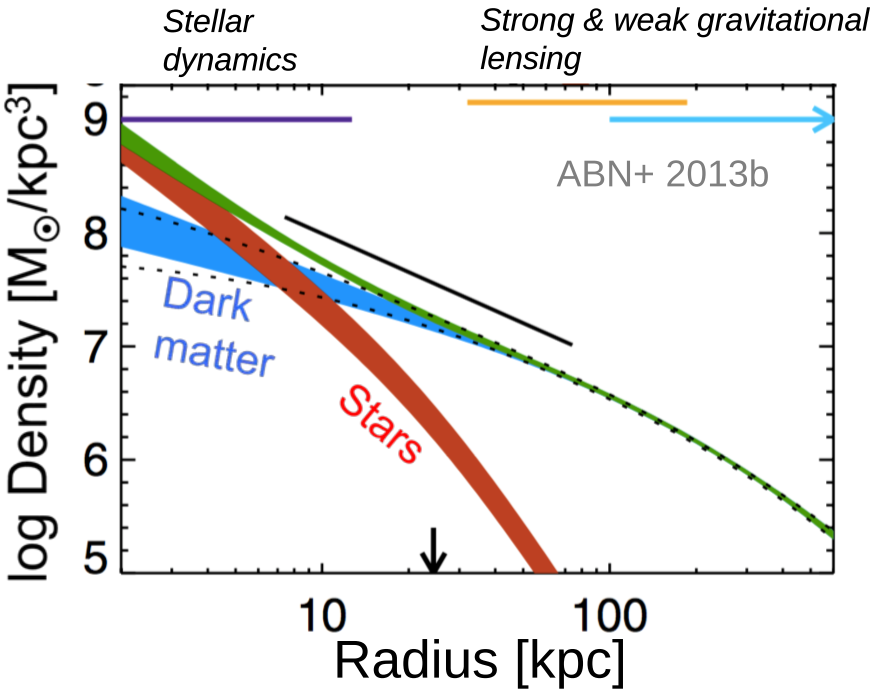
- This is similar to or larger than expected SIDM signals
  (Kim et al 2017)

- ~7 systems analyzed so far
  (Randall et al 2008; Bradac et al 2008; Dawson 2013; Clowe et al 2012; Williams & Saha 2011; Jee et al 2014, 2015, Massey+ 2017)

- Some tantalizing hints, but overall galaxy-DM offset distribution consistent with collisionless CDM (Ng et al 2017)

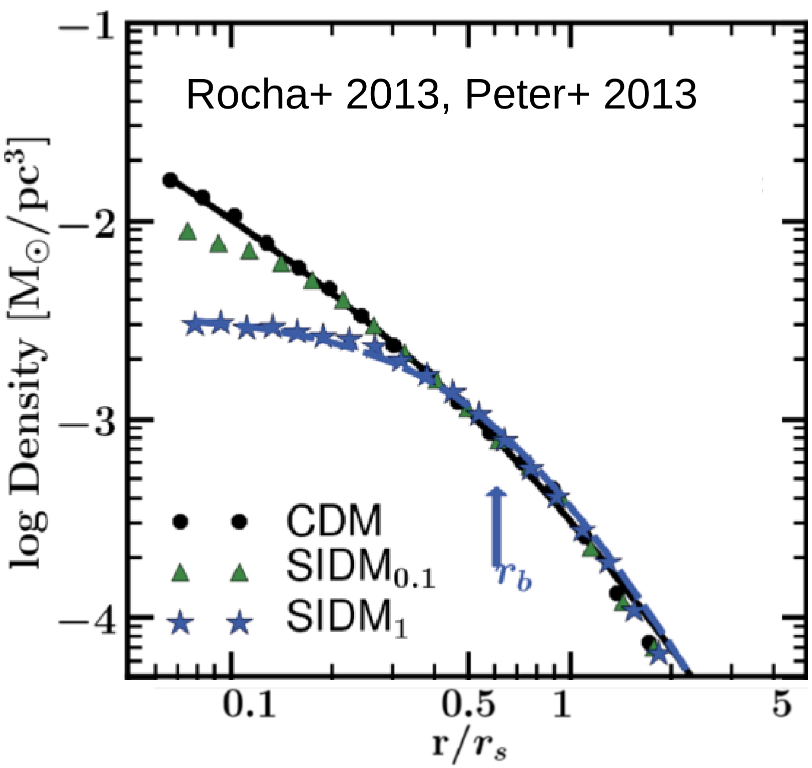
Galaxy cluster density profiles





- Remarkable agreement with CDM over 98% of radial range (e.g. Umetsu+ 2011)
- But evidence for *shallower* density profile in inner tens of kpc (Sand+ 2004, 2008, Zappacosta+ 2006, ABN+ 2011, 2013a,b)
- $<\Upsilon> = 0.50 \pm 0.17$ (ABN+ 2013b) [where $\rho_{DM} \sim r^{-\Upsilon}$] c.f. Υ=1 for collisionless CDM

Galaxy cluster density profiles



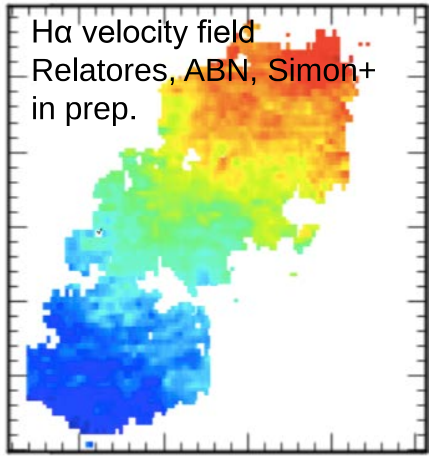
- Main uncertainty: precise separation of baryons/dark matter
- SIDM with σ/m~0.1 cm^2/g would produce appropriate cores (Rocha+ 2013)
- Or, CDM heated via baryonic effects:
  - Dynamical friction from infalling galaxies (Laporte+ 2012)
  - Gas outflows driven by supermassive black hole (Martizzi+ 2012)

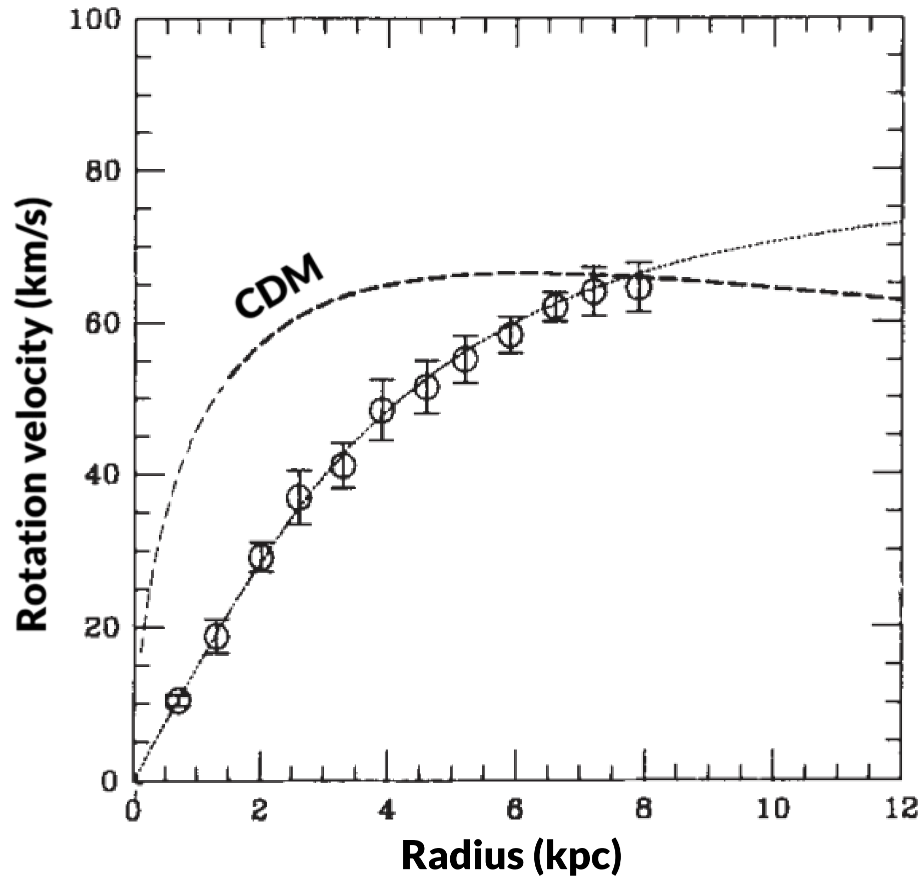
Low-mass disk galaxies

10^{-2} – 10^{-1} x stellar mass of Milky Way

More dark matter dominated

Low-mass disk galaxies: “Cores” vs “Cusps”

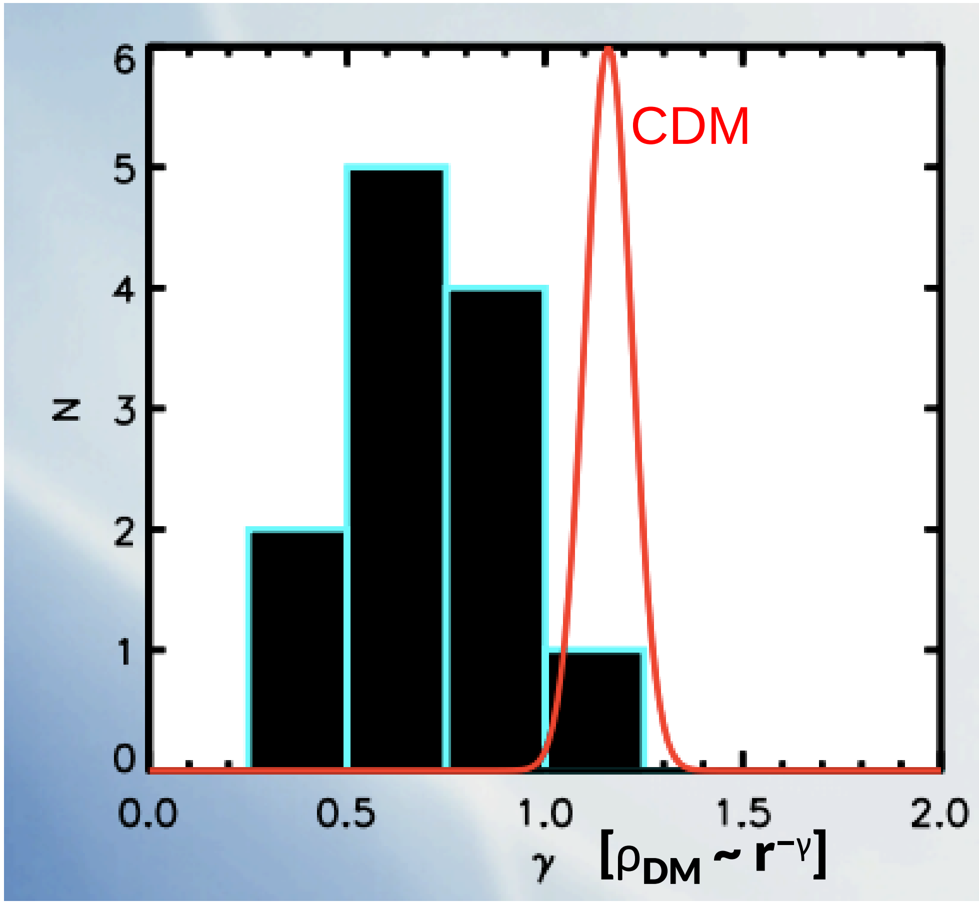




Moore 1994

- Low-mass disk galaxies are increasingly DM-dominated
- Their mass distribution can be inferred from gas (or stellar) rotation curve
- Many are slowly rising, more consistent with a constant-density “core” than the “cusp” ($\rho \sim r^{-1}$) expected for CDM

Better data – still shallow DM profiles



Compilation of galaxies from Adams+ 2014, Oh+ 2011, Simon+ 2005 (figure J. Simon)

History of gradually improving observations

de Blok+ 2001, 2008, Swaters+ 2003, Simon+ 2003, 2005, Oh+ 2008, 2011, Kuzio de Naray + 2006, 2008, …

Uncertainties in interpretation:

Non-circular motion

Subtraction of baryon mass

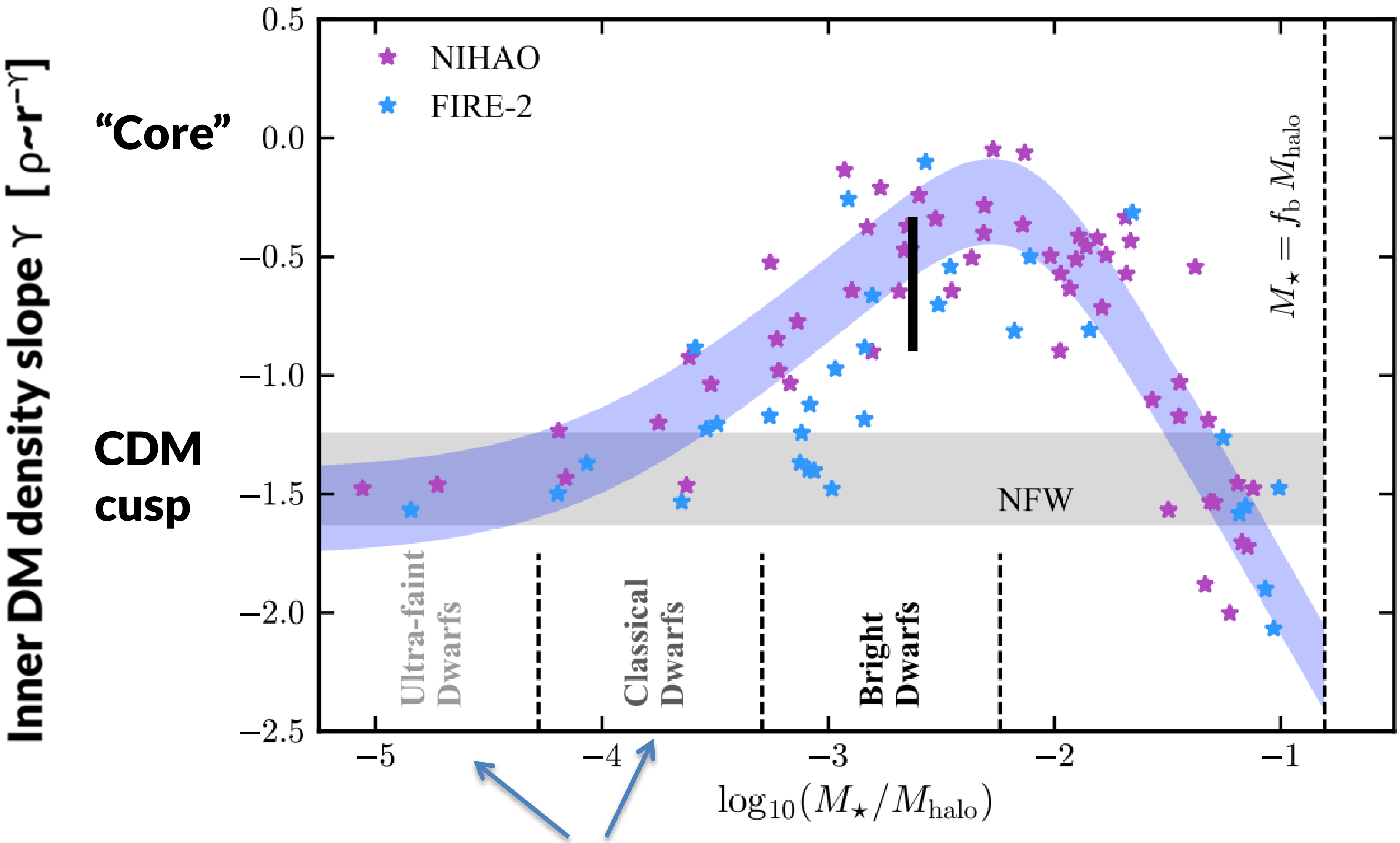
…

Cleanest cases with best data cases DM profiles normally shallower then CDM:

$\langle\gamma\rangle$ = 0.63 ± 0.28 (left panel)

Dark matter cores from supernova feedback

Dark matter cores from supernova feedback



Lower-mass galaxies should retain cusps!

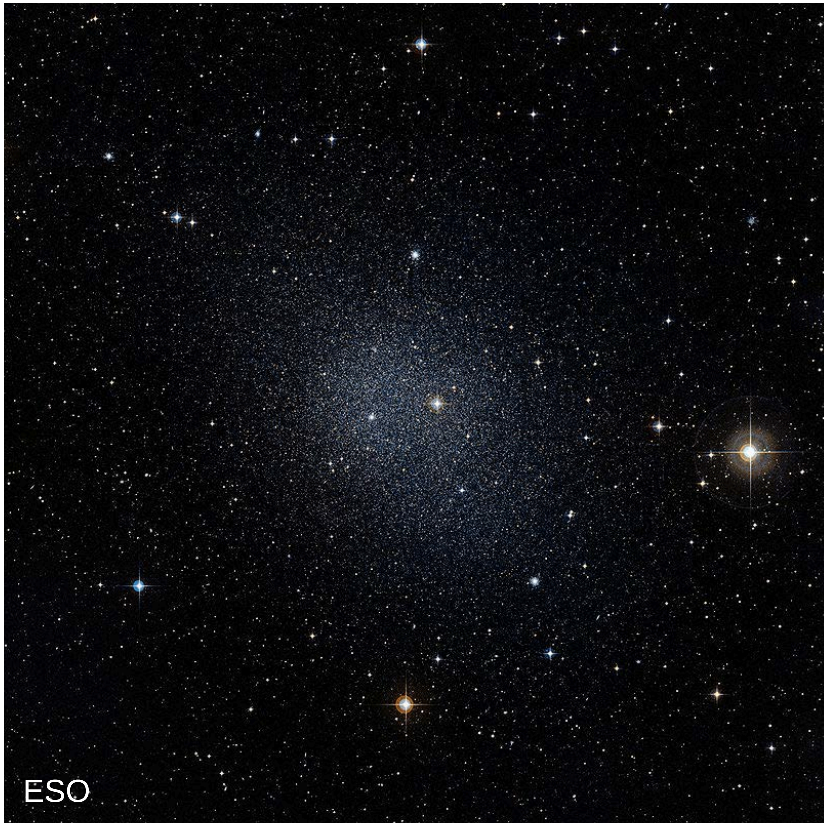
Compilation figure from Bullock & Boylan-Kolchin 2017

Non-LCDM solutions

- Warm dark matter
  - Lower densities, but still cuspy on observationally relevant scales (e.g. Macciò+ 2012)

- SIDM
  - Creates cores
  - Coupling with baryons in SIDM might explain diversity of rotation curves shapes observed
    (Kamada+2016, talk by Hai-Bo Yu)

Dwarf Spheroidals around Milky Way & Local Group



10^{-3} – 10^{-8} x stellar mass of Milky Way

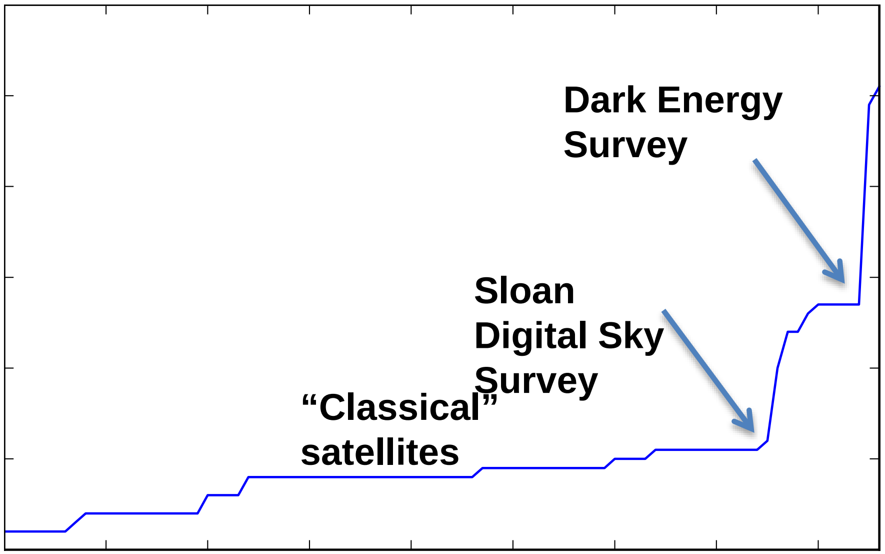
Most dark matter dominated galaxies

Missing satellites / Excess substructure?

CDM predicts 1000s of subhalos around Milky Way-mass galaxies
Before 2005 only 9 “classical” satellite galaxies known (excluding MCs)

Are the subhalos not there?
Or do they contain very dim galaxies—or remain dark?

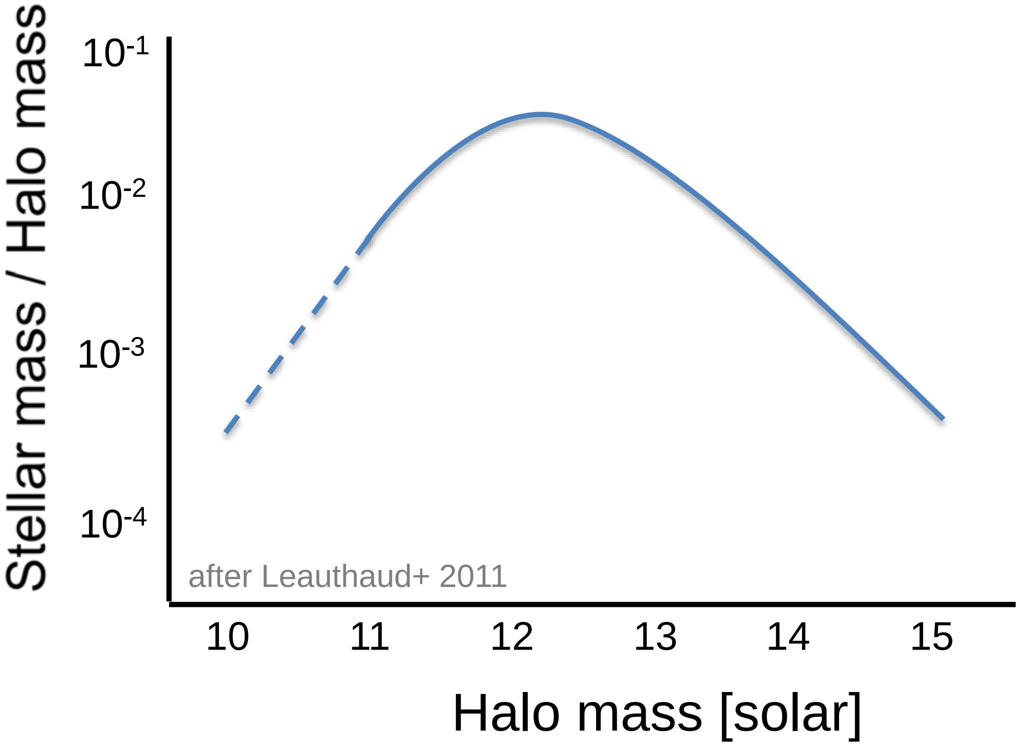
A plethora of new dwarfs



- Explosion in number of Milky Way satellites
  - ~Doubled since 2015
  - Koposov+ 2015, Bechtol+ 2015, Drlica-Wagner+ 2015, Laevens+ 2015, Simon+ 2015, 2017, Kirby+ 2014, 2015, 2017, Walker+ 2015, 2016, Martin+ 2016, Li+ 2017, …
- "Ultrafaint" galaxies extending to luminosities ~10^4x smaller than classical dwarfs (~100s of stellar masses)
- ~100-1000 dwarfs expected all-sky
  (R <~ 400 kpc, $M_V < 0$)

  (Tollerud+ 2008, Newton+ 2017)

Why low-mass halos should be dim



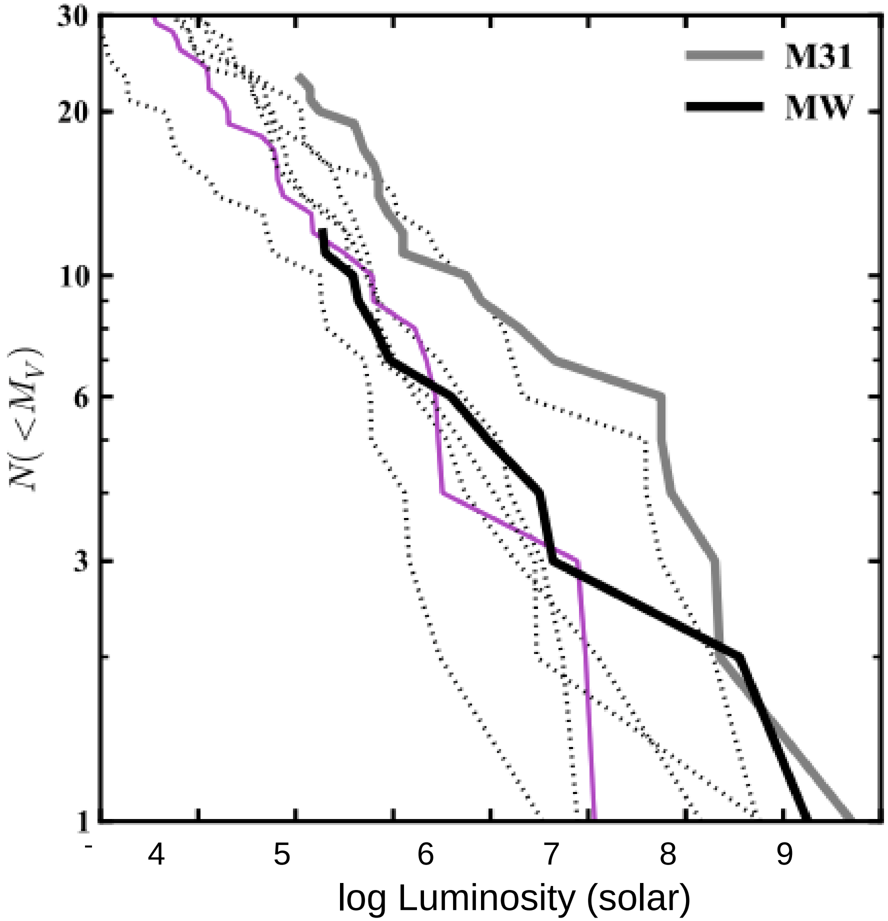
- **Reionization**

  Suppresses galaxy formation in subhalos smaller than $\sim 10^{10}\ M_\odot$
  Benson+ 2002, Okamoto+ 2008

- **Supernova feedback**

  <2% of gas ultimately forms stars; increasingly effective at lower masses

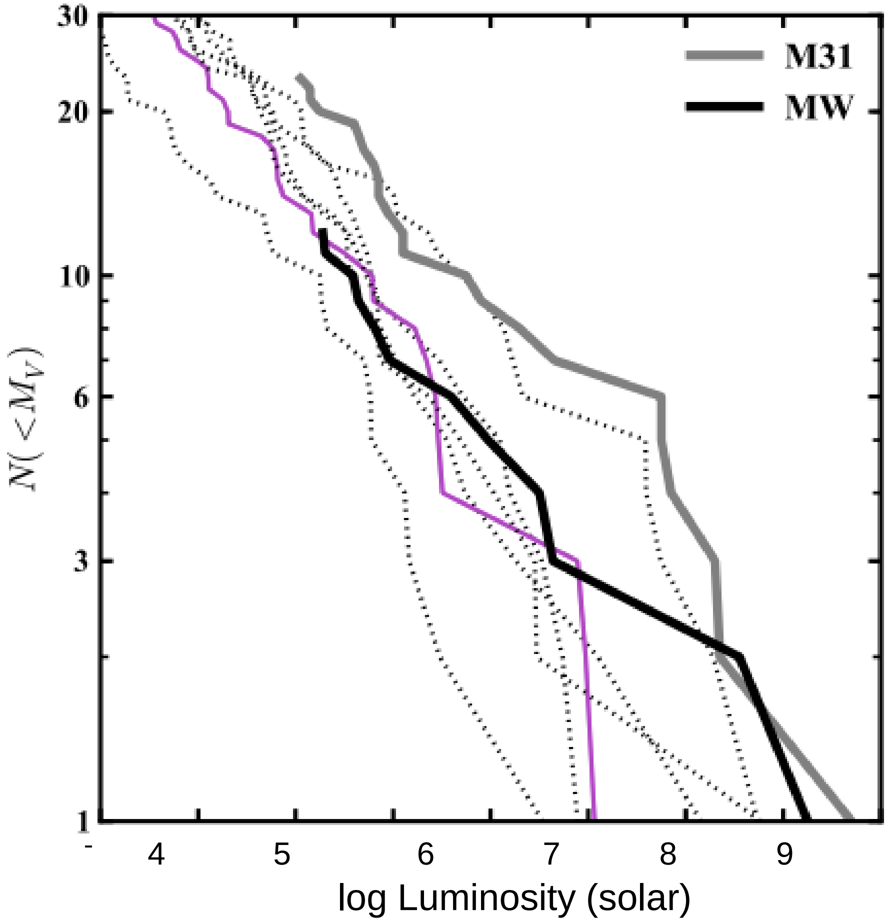
Right number of satellites…



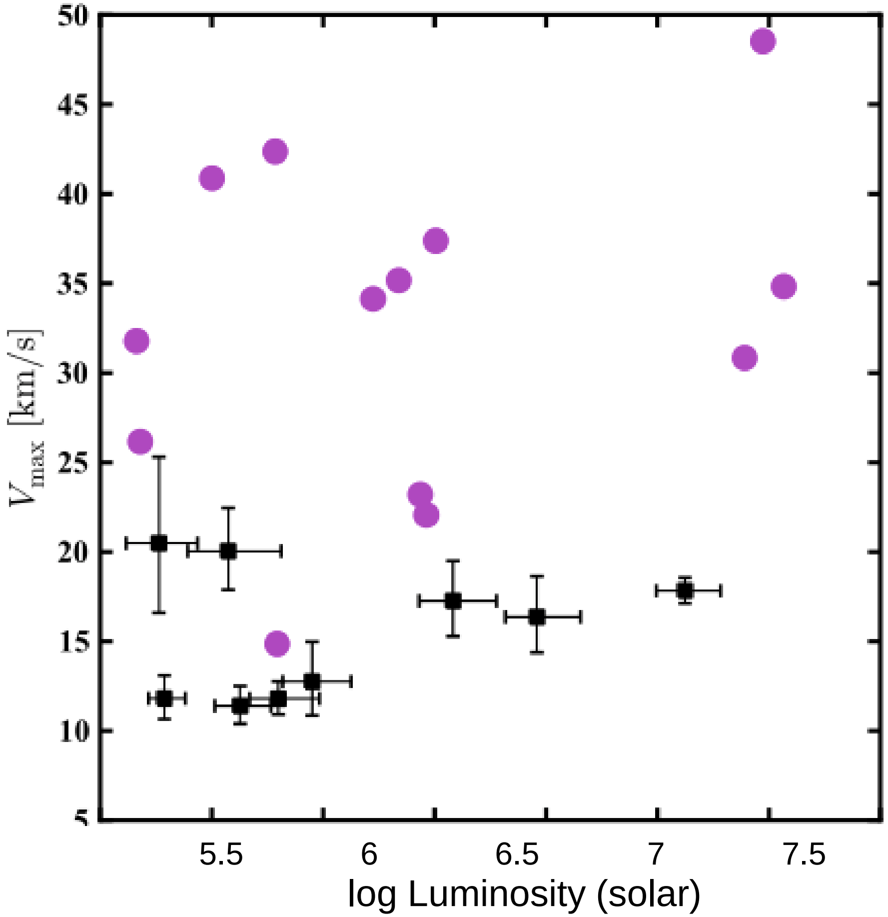
Luminosities assigned to subhalos then agree with classical dwarfs (no “missing satellites”)…

Boylan-Kolchin, Bullock & Kaplinghat 2011, 2012

… but wrong densities (“Too big to fail” problem)



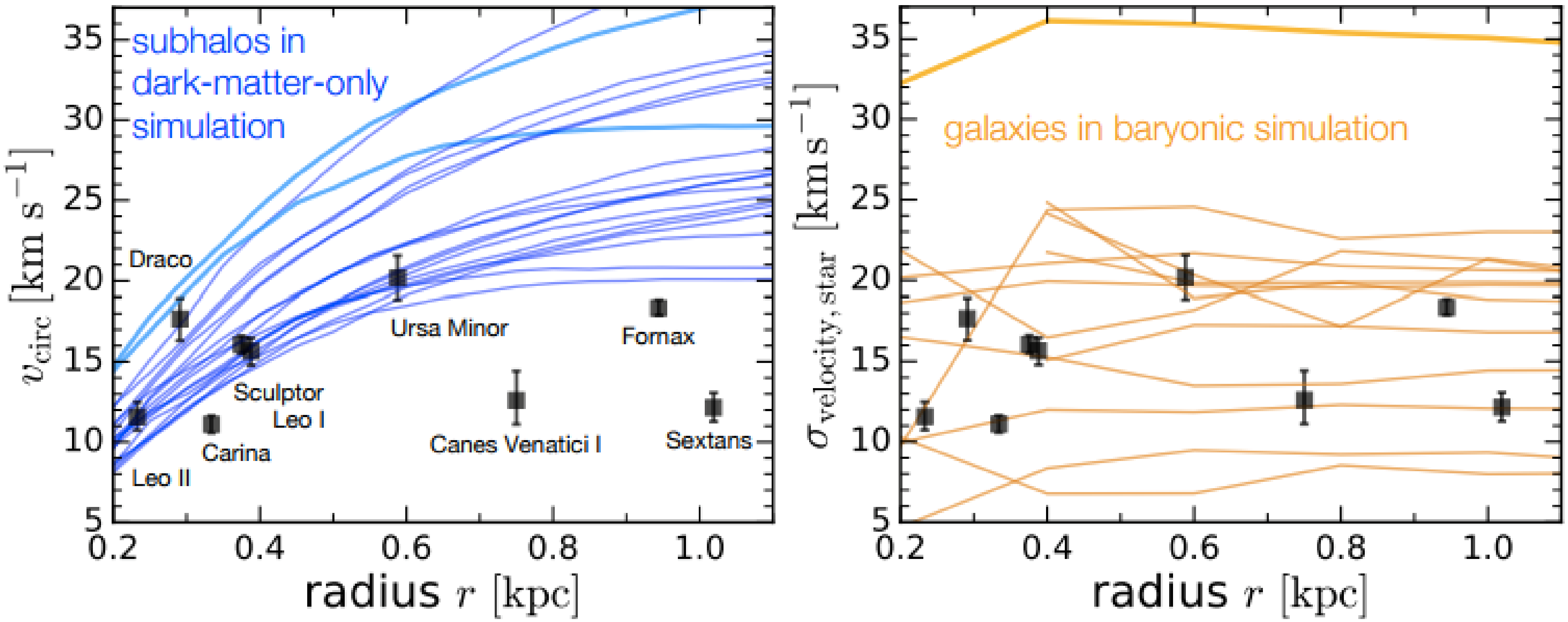
Luminosities assigned to subhalos then agree with classical dwarfs (no “missing satellites”)…



but the classical dwarfs have much lower central densities than the most massive subhalos (“too big to fail” problem).

Boylan-Kolchin, Bullock & Kaplinghat 2011, 2012

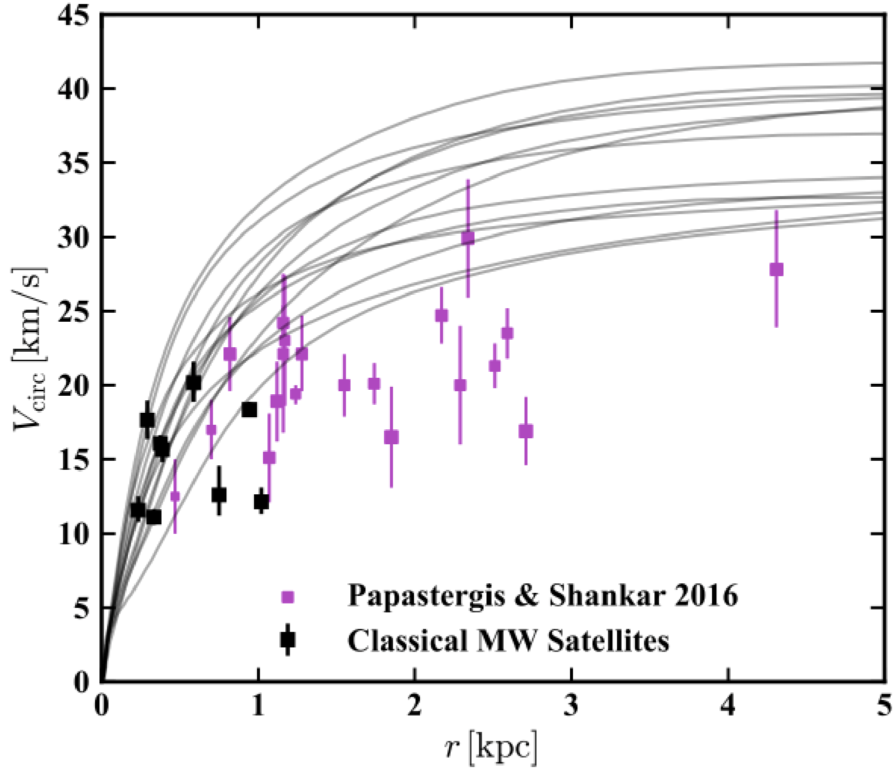
“Too big to fail”: Solutions within LCDM?



Wetzel+ 2016 and see Madau+ 2014, Sawala+ 2015, Dutton+ 2015

Central densities of massive subhalos are reduced due to supernova feedback

“Too big to fail”: Still a problem in the field?



Bullock & Boylan-Kolchin 2017; Papastergis & Ponomareva 2017

Simulations (curves) from Fitts+ 2017

But simulations that solve TBTF in Milky Way satellites do *not* necessarily agree with kinematics of similar field galaxies measured at larger radii (via HI interferometry).

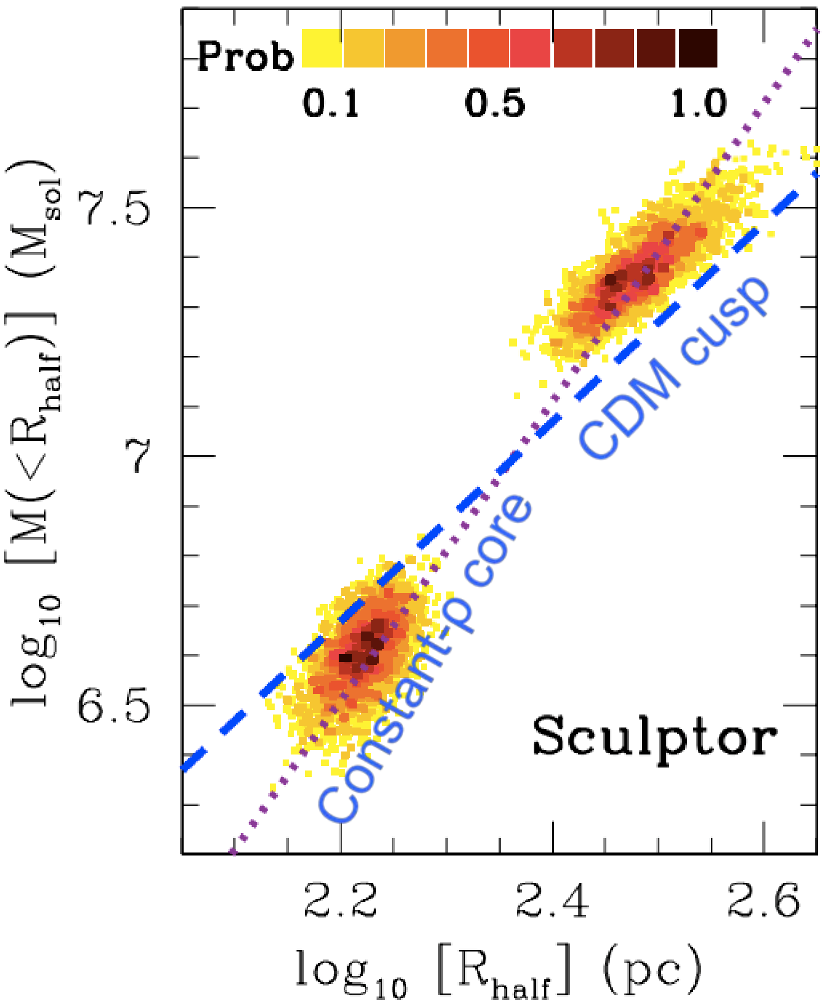
Klypin+ 2015, Papastergis+ 2015, Papastergis & Shankar 2016

“Too big to fail”: Non-LCDM solutions

- Warm DM
  - Need m~1-2 keV for a thermal particle
    Papastergis+ 2015, Lovell+ 2012, Schneider+ 2014
  - Inconsistent with Lyα forest (later) and possibly with # of satellites of Galaxy & M31
    Kennedy+ 2014, Polisensky & Ricotti 2010, Lovell+ 2014, Horiuchi+ 2014
  - More room for “mixed” WDM or more gradual cutoff to power spectrum

- Self-interacting DM
  - $\sigma / m \sim 0.5 - 50\ cm^2/g$ on dwarf galaxy scales
    Vogelsberger+ 2012, Zavala+ 2013, Elbert+ 2015

Density profiles in classical MW satellites



Walker & Peñarrubia 2011

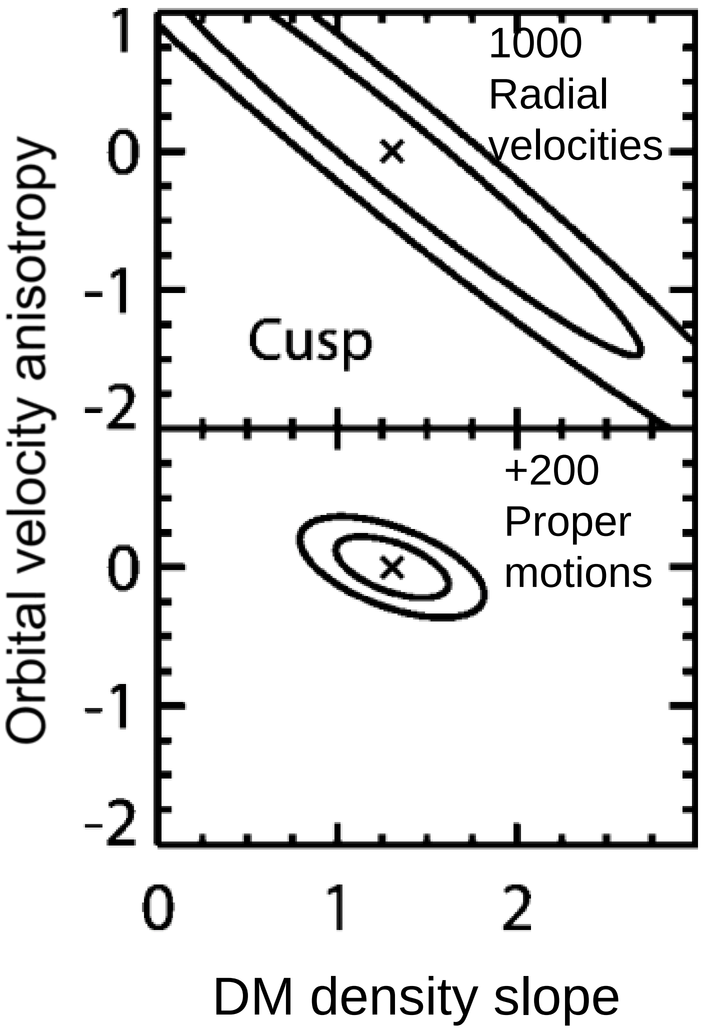
- Two chemically distinguishable sub-population of stars exist in Fornax & Sculptor
- Robustly determine mass at two radii, hence slope
  Walker & Peñarrubia 2011
- Find shallow density profiles, getting close to masses where supernovae should be ineffective:

$\gamma = 0.39^{+0.43}_{-0.37}$ Fornax

$\gamma = 0.05^{+0.51}_{-0.39}$ Sculptor

$[\rho \propto r^{-\gamma}]$

Future constraints from MW satellites

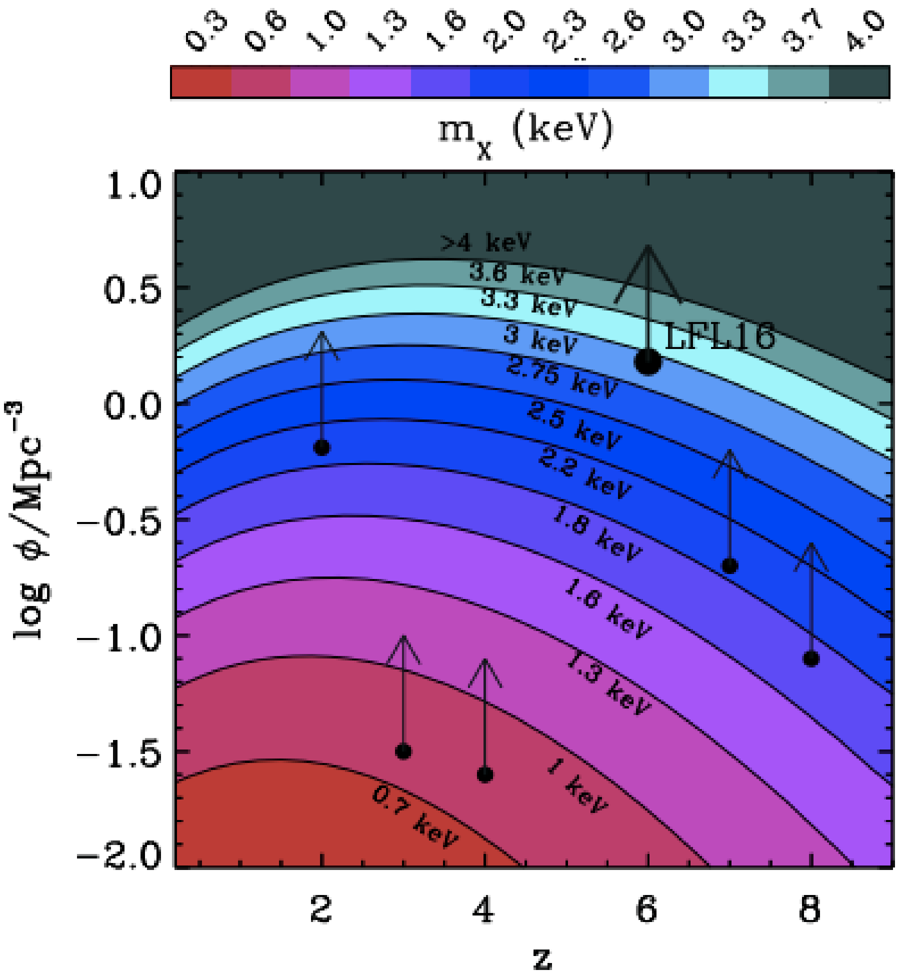


Strigari+ 2007

- 30m-class telescopes will enable observations of 3D velocity vectors
  - 10^4 radial velocities
  - Proper motions via ~30μas astrometry
- Expect precision of 0.2 on log slope of density profile
  Strigari+ 2007, Evslin+ 2015
- For $M_\star$<~10^6 $M_\odot$ cusps should survive feedback
  Fitts+ 2017

Low-Mass Structures
Beyond the Local Volume

Constraints on WDM from early galaxies



Menci et al 2016; Livermore et al 2017

WDM models erase small halos and delay growth of larger ones.

Shultz et al 2014:

m > 1.3 keV (2σ) from redshift z=6-8 galaxies in Hubble Ultradeep Field

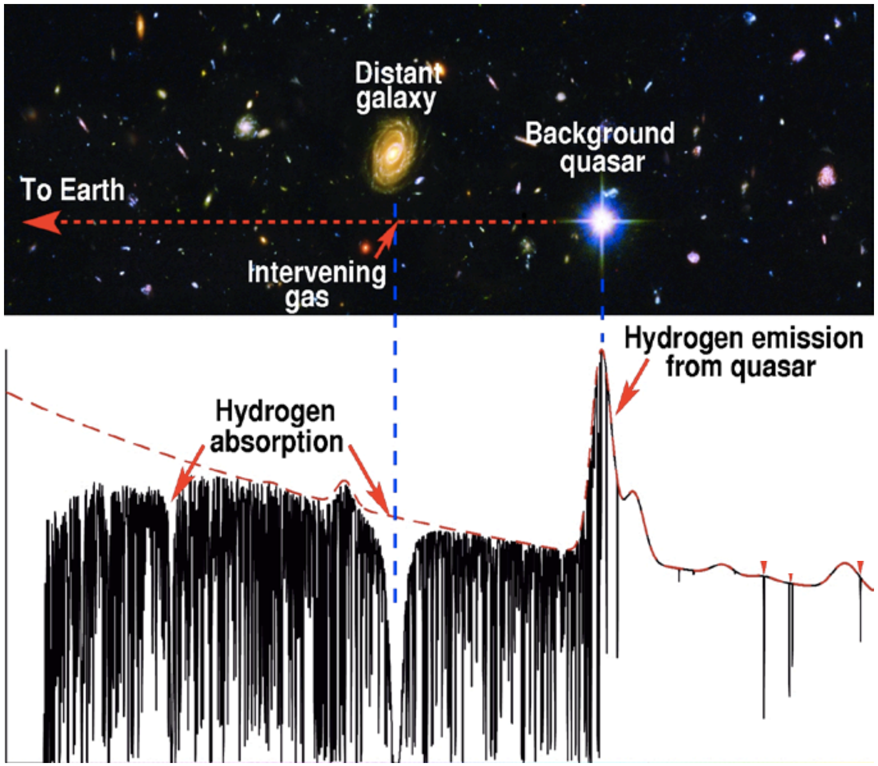
Menci et al 2016:

From faintest lensed galaxies (M = -12.5) at z=6, find **m > 2.4 keV (2σ)**

James Webb Space Telescope launches next year!

Lyα Forest

Image J. Liske



Observed wavelength

- Statistics of spectrum can be related to matter power spectrum

- Strongest claimed constraints on WDM:

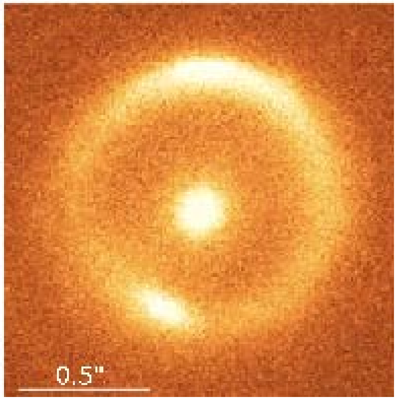
  Viel et al (2013):
  $\mathbf{m_{WDM} > 3.3\ keV}$ (2σ, thermal)

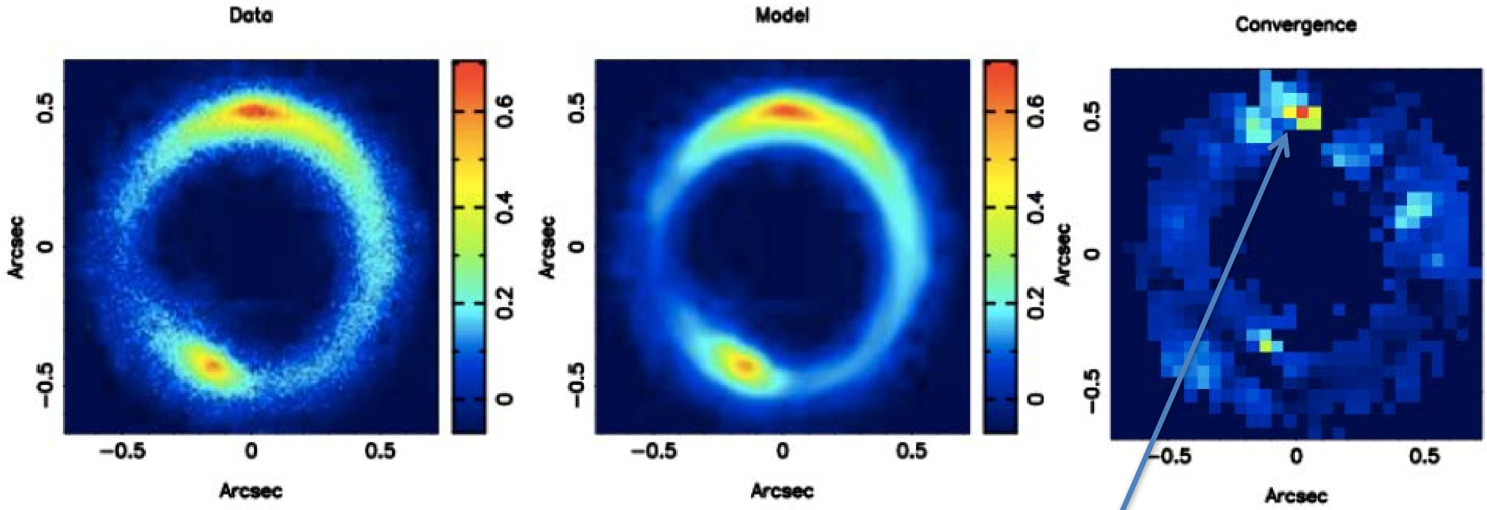
  Iršič et al (2017):
  $\mathbf{m_{WDM} > 5.3\ keV}$ (2σ, thermal)

- Uncertainties: equation of state of intergalactic gas, effect of galactic winds on gas distribution & thermal state

Substructure “Imaging” with Strong Lensing

SHARP collaboration





Vegetti+ 2012

Mass $2\times10^{8}\ M_{\odot}$
within 600 pc

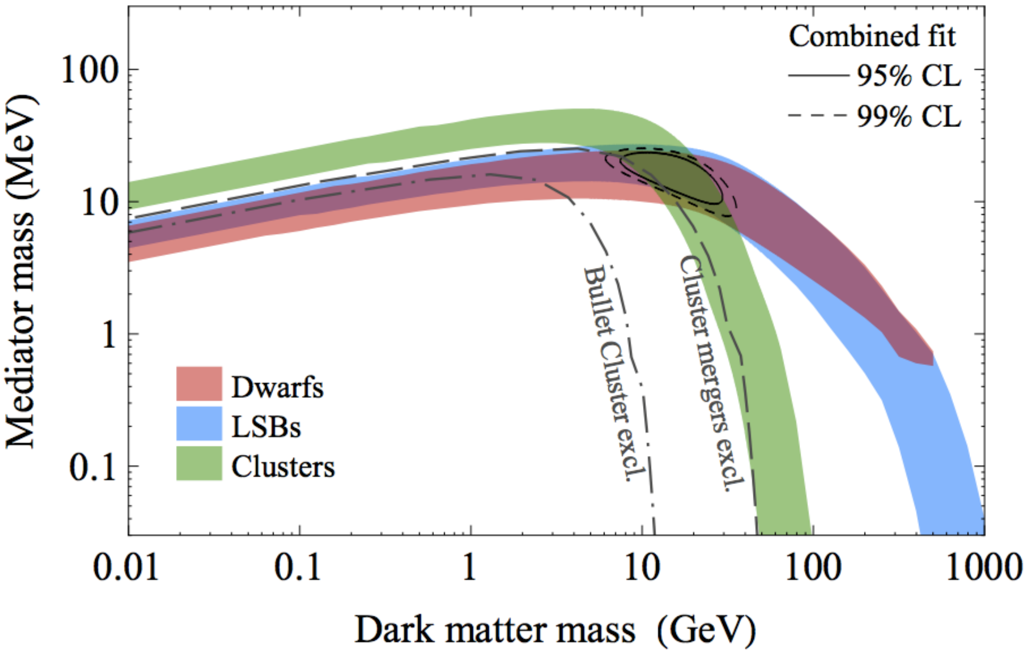
- Images of gravitationally lensed sources are very sensitive to foreground mass ‘clumps’ near the images
- *Possible to detect dark substructures!*
- See S. Birrer talk

The current state

Observations from dwarf galaxy to clusters scales are suggestive of DM physics beyond “vanilla CDM”

Unified modeling can constrain specific particle models (right panel)

(Multiple) baryonic/galaxy formation effects within “vanilla CDM” are also a viable explanation



Kaplinghat, Tulin & Yu 2016
Constrains on SIDM dark photon model

Some exciting future directions

- Density profiles of low-mass disk galaxies
  - Testing supernova feedback scenarios

- Density profiles of dwarf spheroidals
  - 30 m-class telescopes

- Detection and characterization of dark low-mass substructures
  - Must be present if DM is cold
  - Gravitational lensing very promising; see S. Birrer talk