DM Workshop@UT Austin
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Constraints on dark matter annihilation cross section with the Fornax cluster

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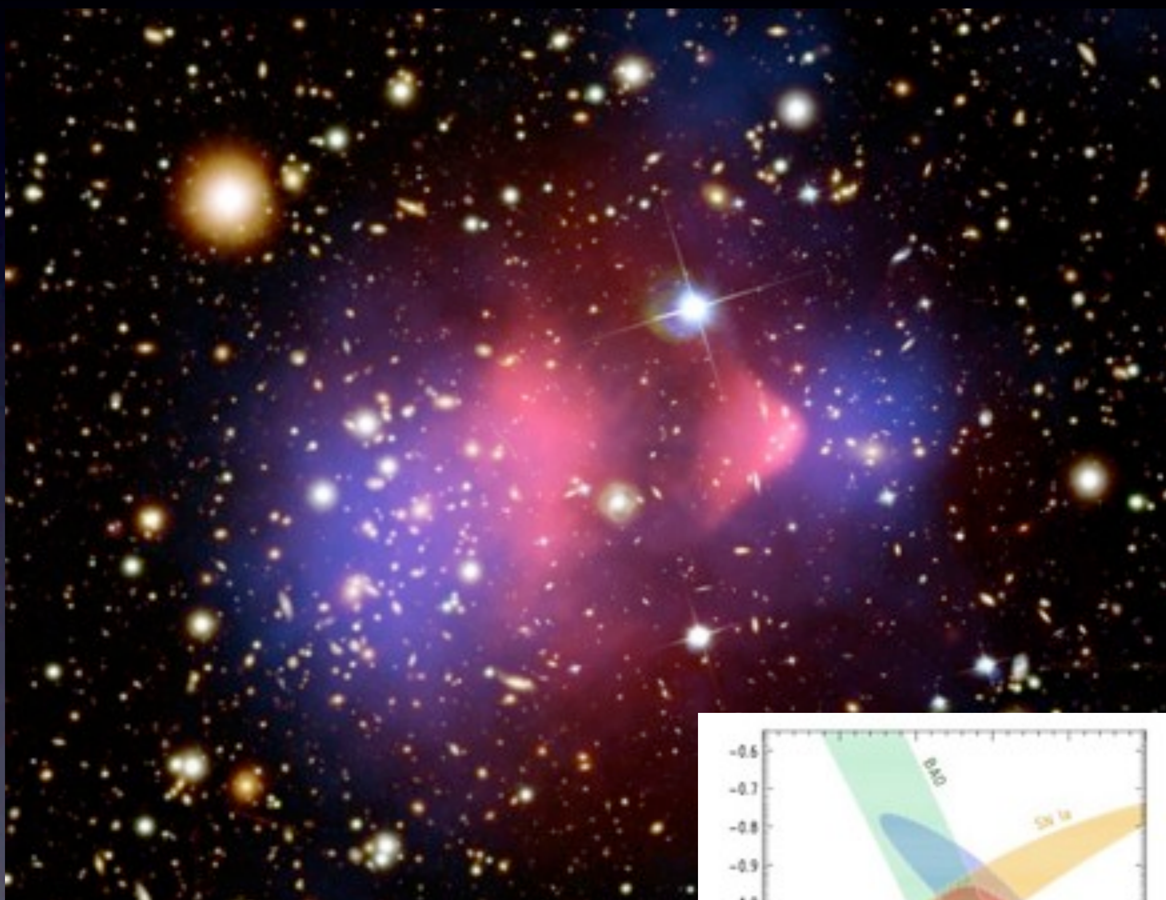
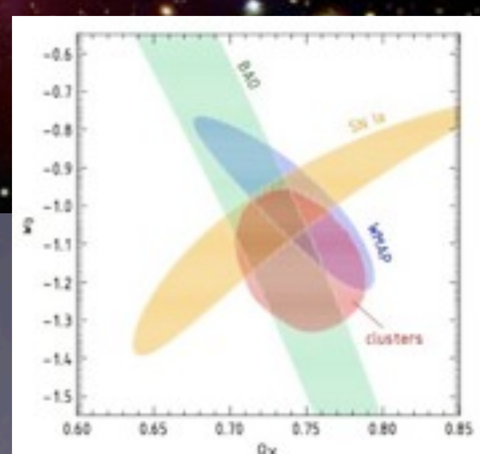
Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]

Galaxy clusters: Why interesting?

Bullet cluster (1E0657-56)

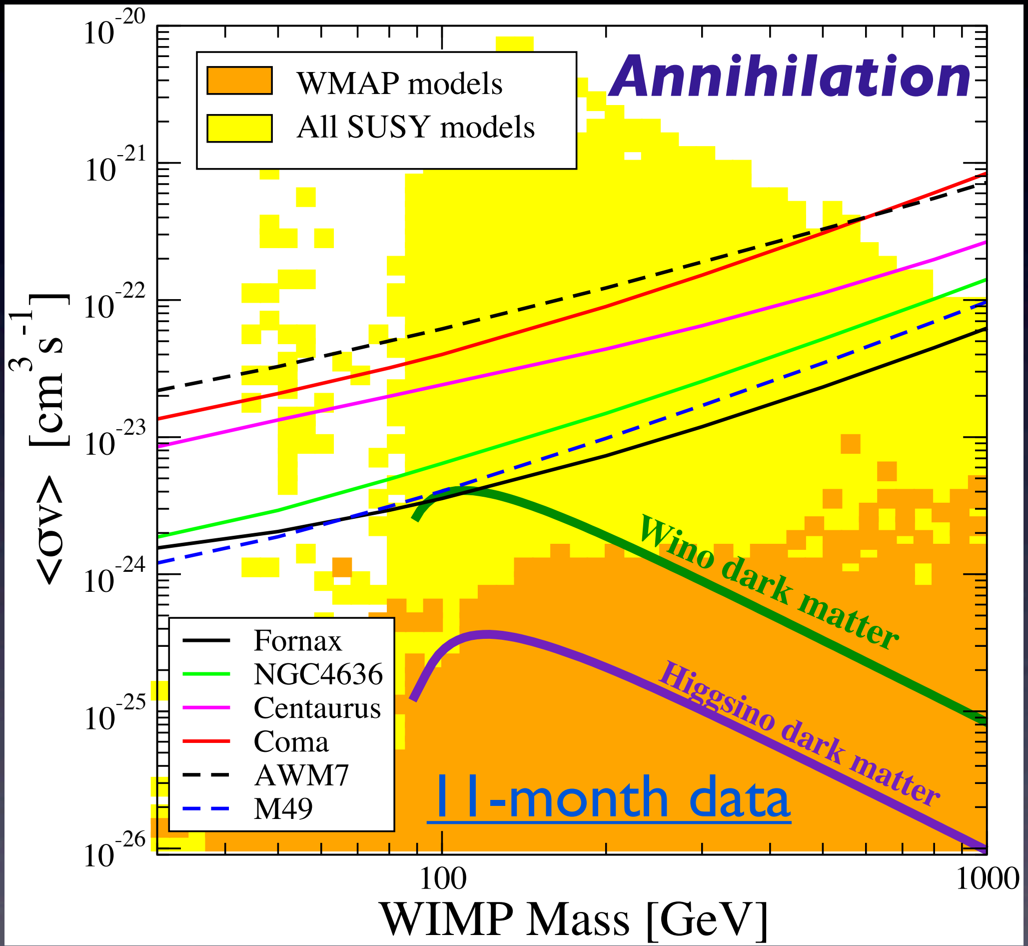




- The largest virialized dark-matter structure
- The largest number of dark matter particles
- Presence of *collisionless* dark matter clearly seen in bullet cluster
- Good probe of cosmological parameters

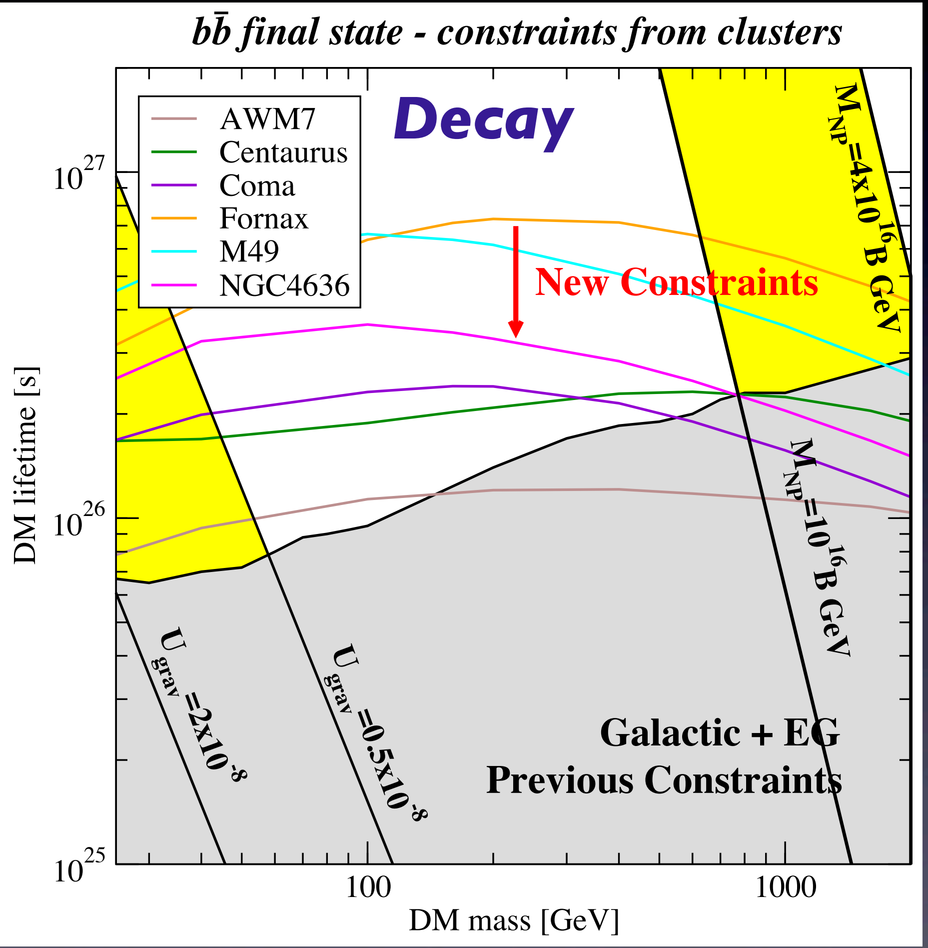
Cluster constraints on DM properties

Ackermann et al., *JCAP* **1005**, 025 (2010)



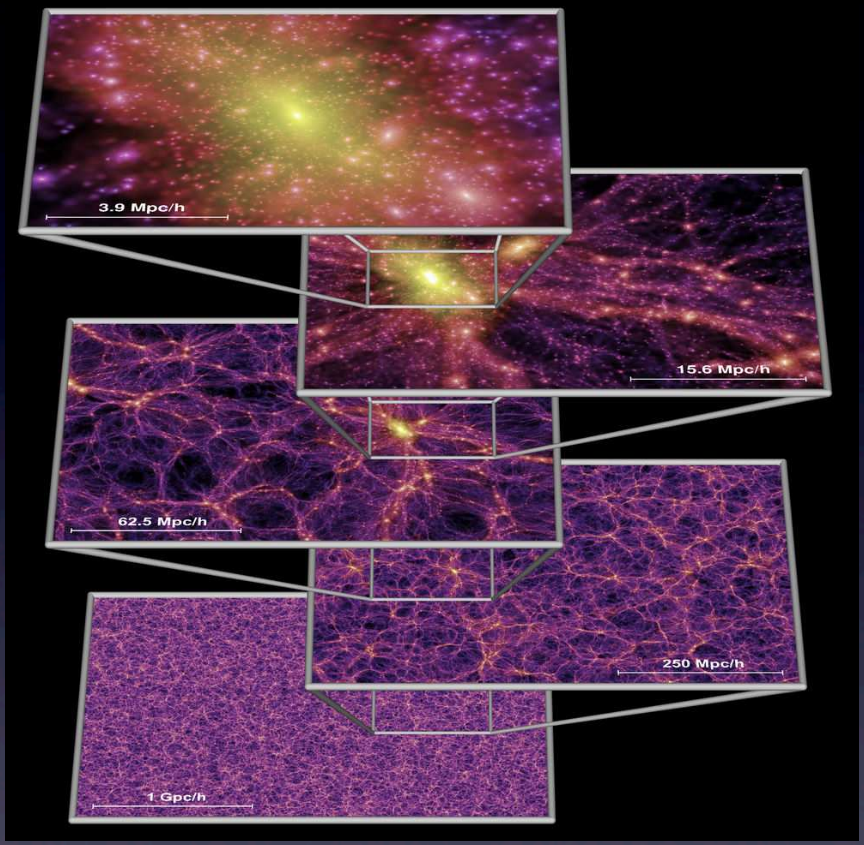
Factor >30 gap from canonical cross section

Dugger et al., *JCAP* **1012**, 015 (2010)



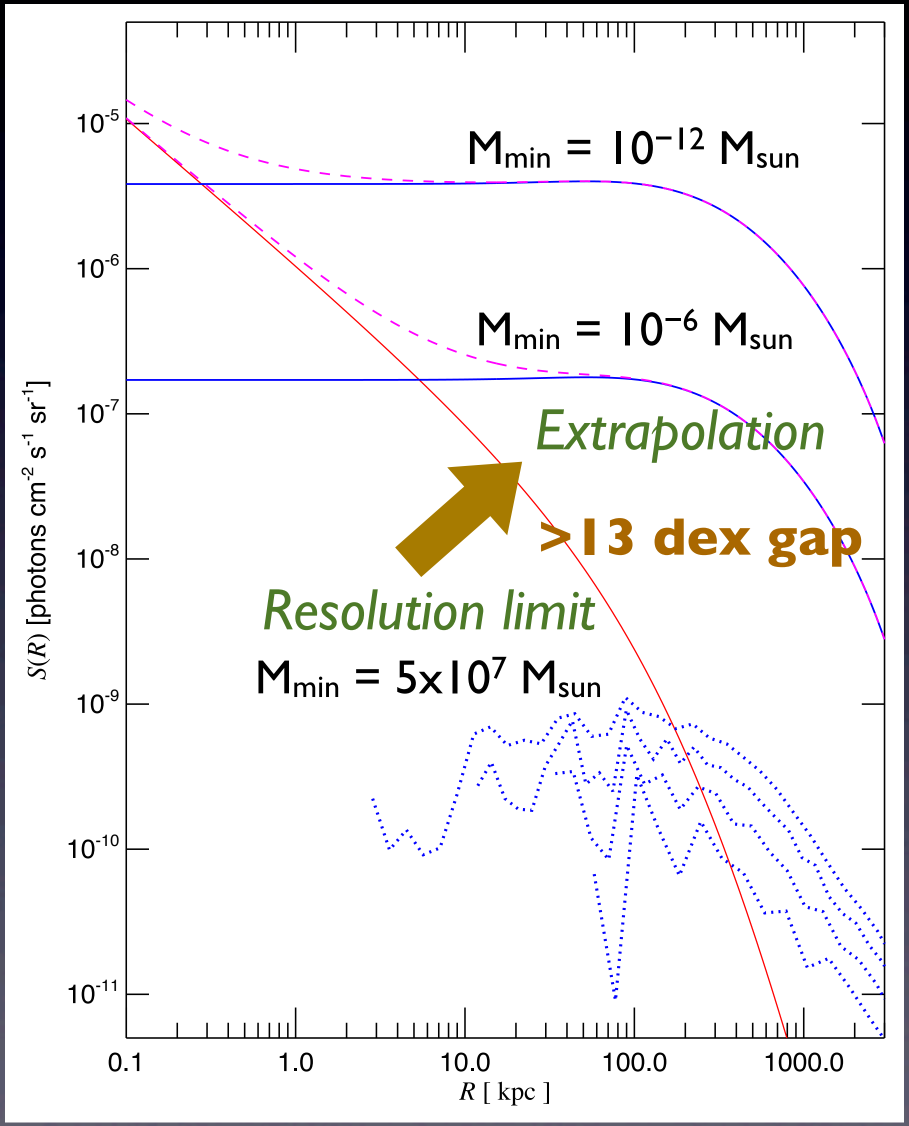
Most stringent constraint on decay lifetime

Annihilation boost in substructure



Millennium Simulation

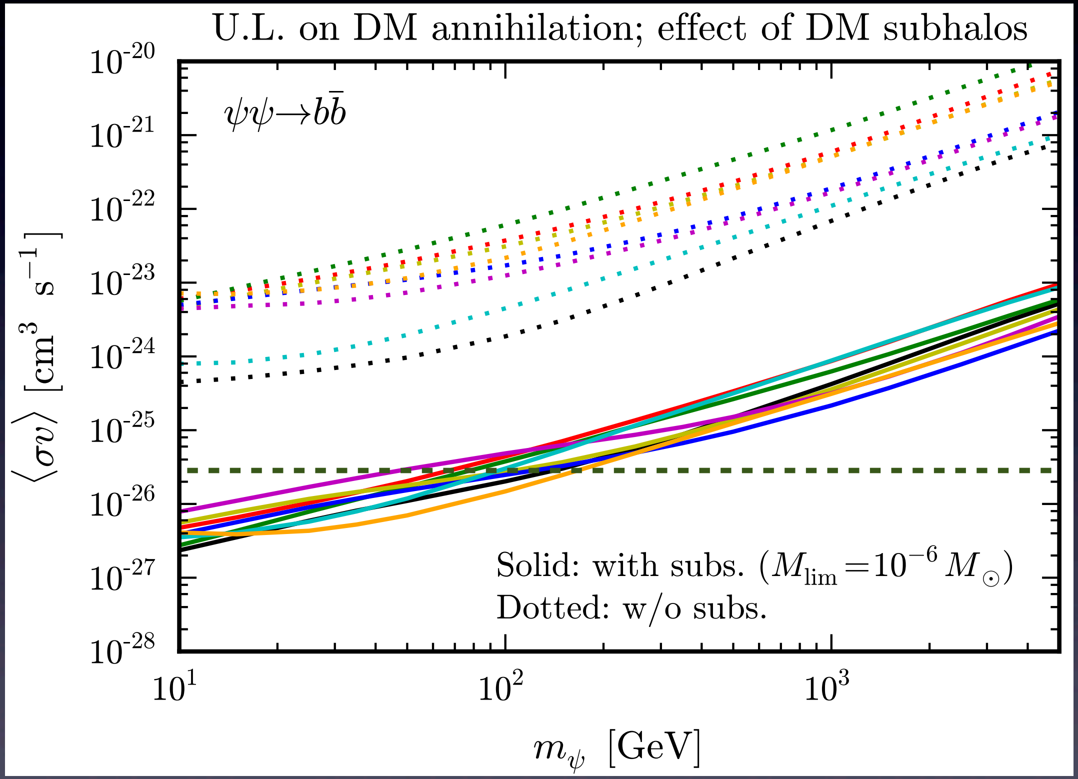
Gao et al., arXiv:1107.1916



Flux boosted by
a factor of ~1000

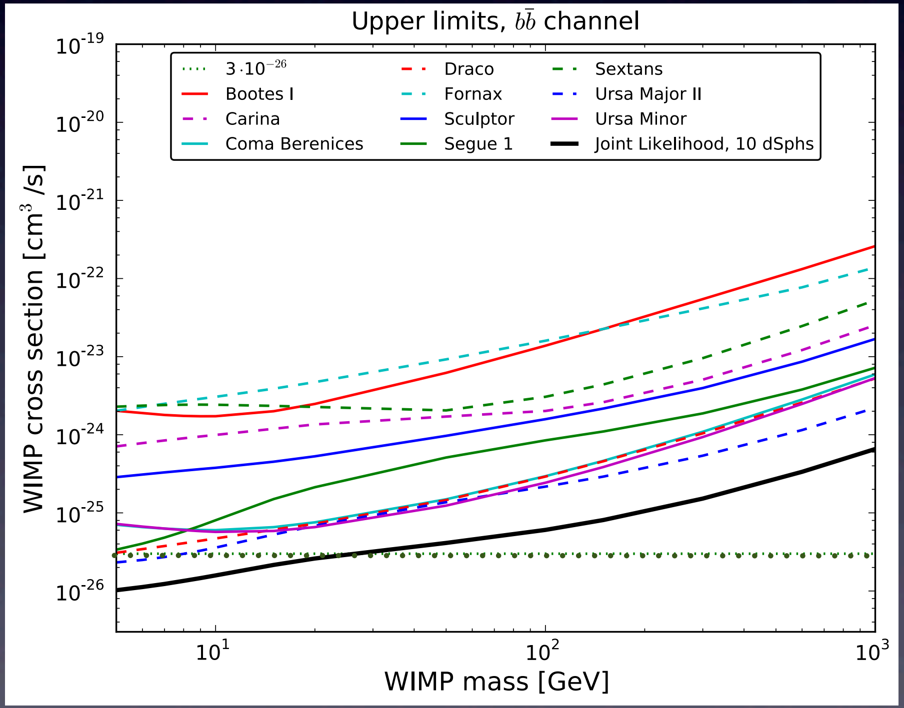
Annihilation boost in substructure

Huang et al., arXiv:1110.1529



Cluster limits with subhalos

Dwarf limits (no subhalos)



Ackermann et al., arXiv:1108.3546
Geringer-Sameth & Koushiappas, arXiv:1108.2914

Motivation

- Does *stacking* help? If so, how much?
  - There are many more clusters than dwarfs!!

→ ***No! It doesn't help***

- What is the effect of baryons (stars+gas)?
  - Baryons dominate gravitational potential at central regions
  - This should modify dark matter profile (adiabatic contraction)

→ ***It improves limits by a factor ~4***

Dark matter annihilation in galaxy clusters

Gamma-ray intensity from annihilation

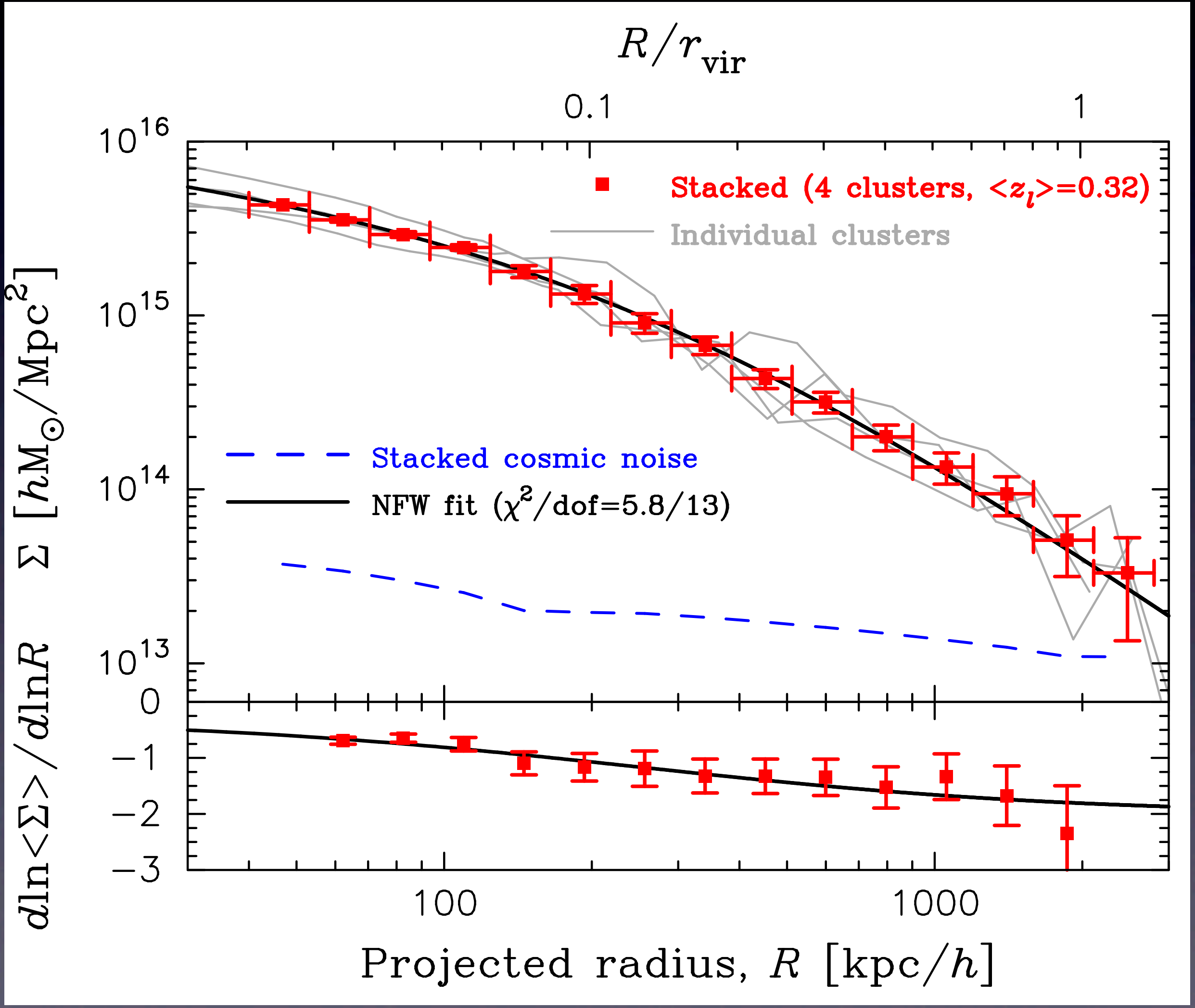
$$I_\gamma(\theta, E) = \frac{1}{4\pi} \frac{1}{(1+z)^2} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN_\gamma((1+z)E)}{dE} \int dl\ \rho^2(r(l,\theta))$$

Cosmological redshift *Particle-physics factor* *Astrophysical factor*

- Depends on three factors
  - Particle physics: annihilation cross section and dark-matter mass; depends on SUSY models, etc.
  - Astrophysics: density profile and subhalos
  - Cosmological redshift: straightforward if redshift is measured

Astrophysical factor: density profile

Umetsu et al., *Astrophys. J.* **738**, 41 (2011)



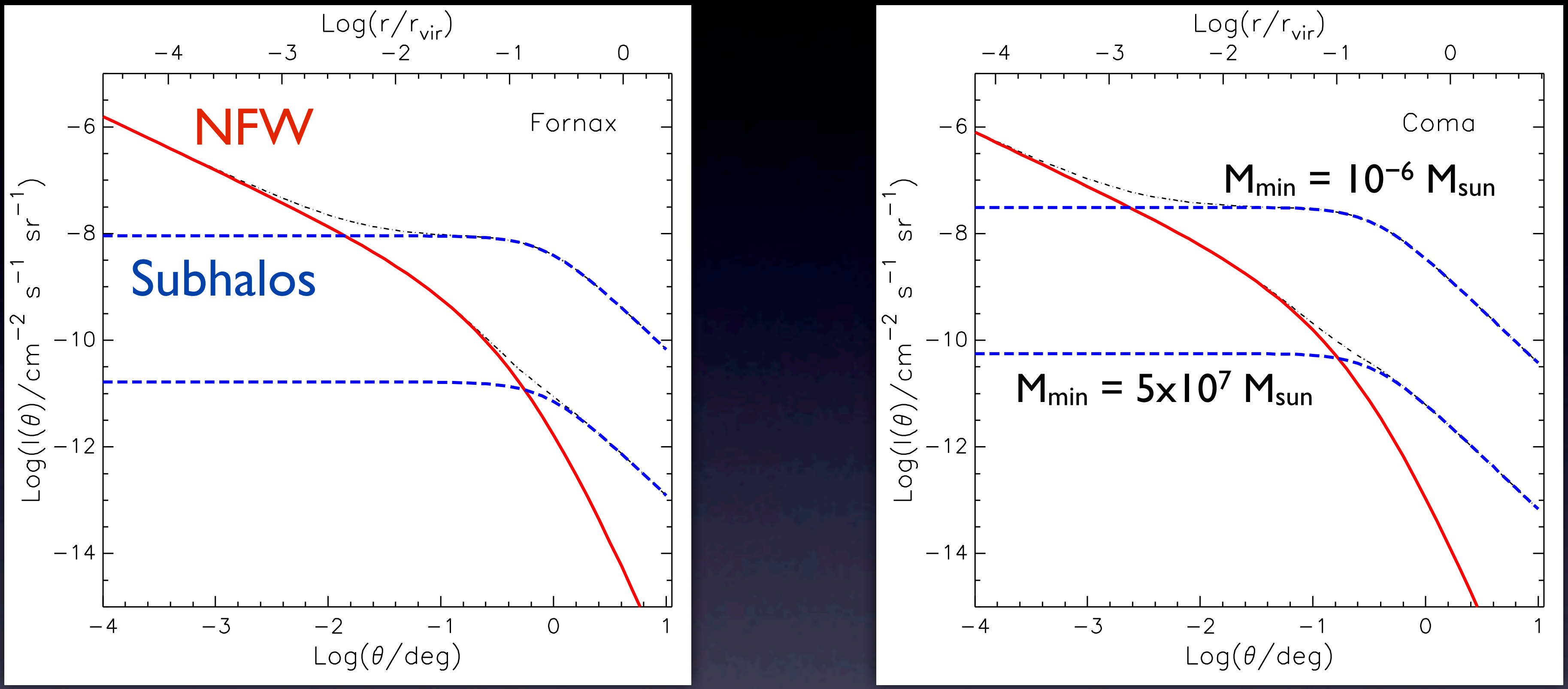
- Numerical simulations imply universal form of density profile: NFW

$$\rho = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2}$$

- $\rho \sim r^{-1}$ for small radii, and $\rho \sim r^{-3}$ for large radii

- NFW profile is confirmed with lensing observations

Gamma-ray intensity



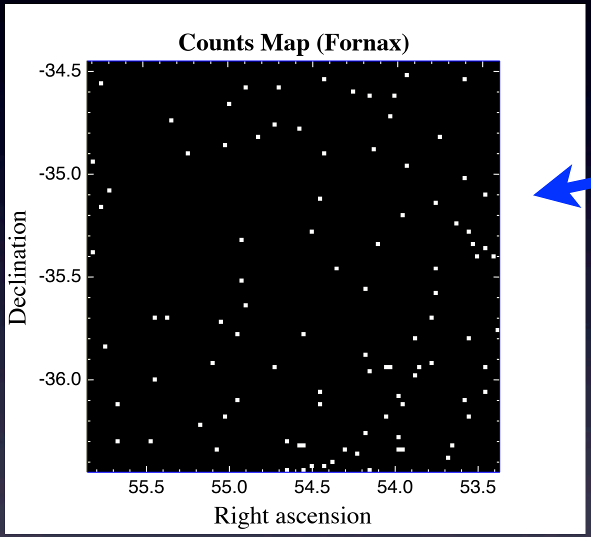
	z	M_{vir} $(10^{14}\, h^{-1}\, M_{sun})$
Fornax	0.005	1.2
Coma	0.023	9.6

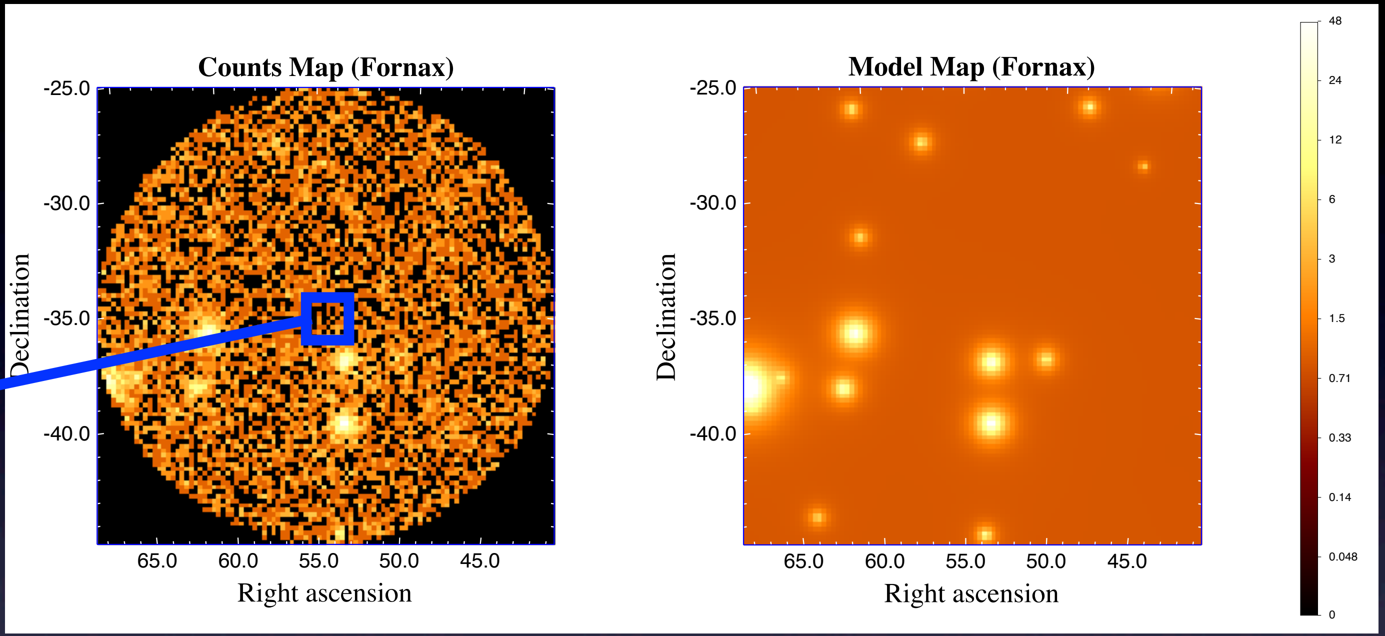
- Intensity due to subhalos is much more extended than the smooth component
- Subhalo boost factor is ~1000 for cluster-size halos, if minimum subhalos are of Earth size

Analysis of Fermi-LAT data

- We analyze data of Fermi-LAT for 2.8 years around 49 relatively large galaxy clusters
  - DIFFUSE and DATACLEAN class of photon data between MET = 239557417 s and 329159098 s
  - 23 clusters from X-ray (Reiprich & Boehringer 2002) and 34 from cosmology catalogs (Vikhlinin et al. 2009); 3 are found in both and 5 are at low Galactic latitudes
- We first perform likelihood analysis of the data using the *known* sources (from 2FGL catalog) as well as both Galactic and extragalactic backgrounds
  - Use photons between 1 GeV and 100 GeV, and divide them into 20 energy bins equally spaced logarithmically
  - Models are convolved with P6_V11 instrumental response functions

Fermi-LAT data and best-fit model for Fornax



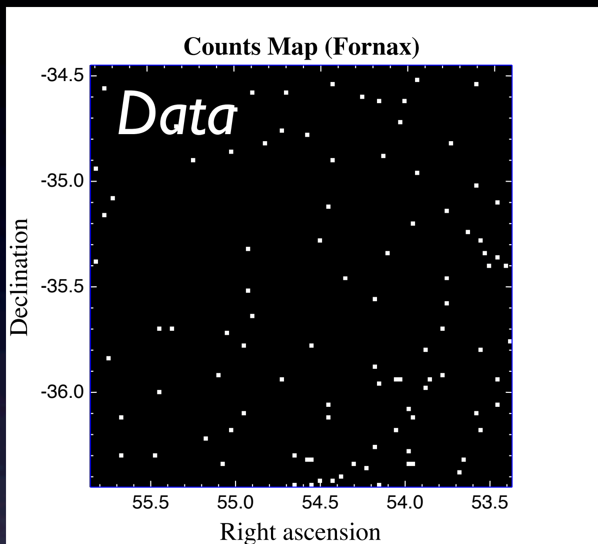


Integrated maps for 1–100 GeV

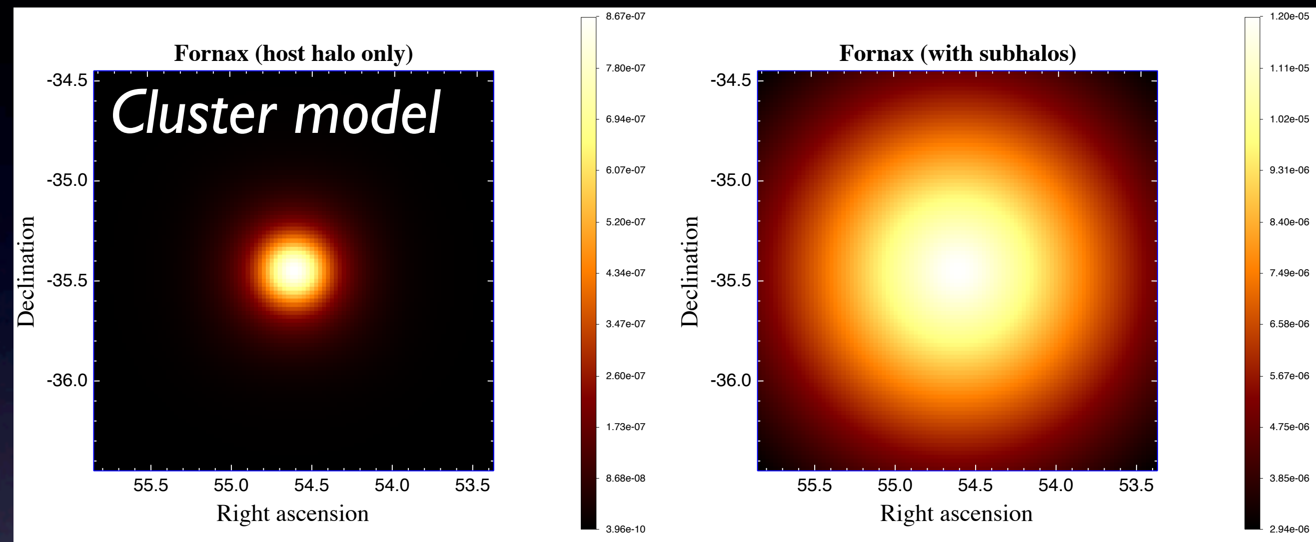
- There is no gamma-ray source at cluster location
- We then add cluster component at the center of the best-fit model map, to put upper limit on that component

Upper limits on cluster component

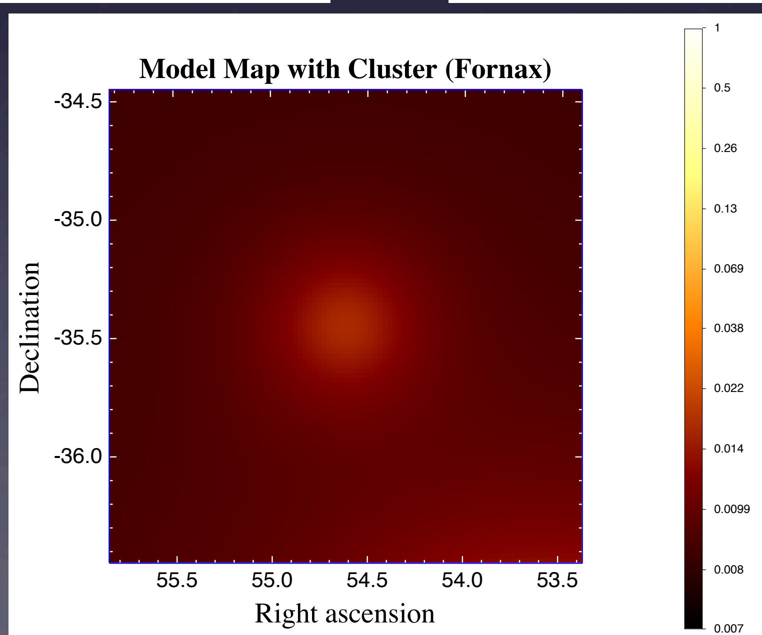
Analyze



With



Outcome

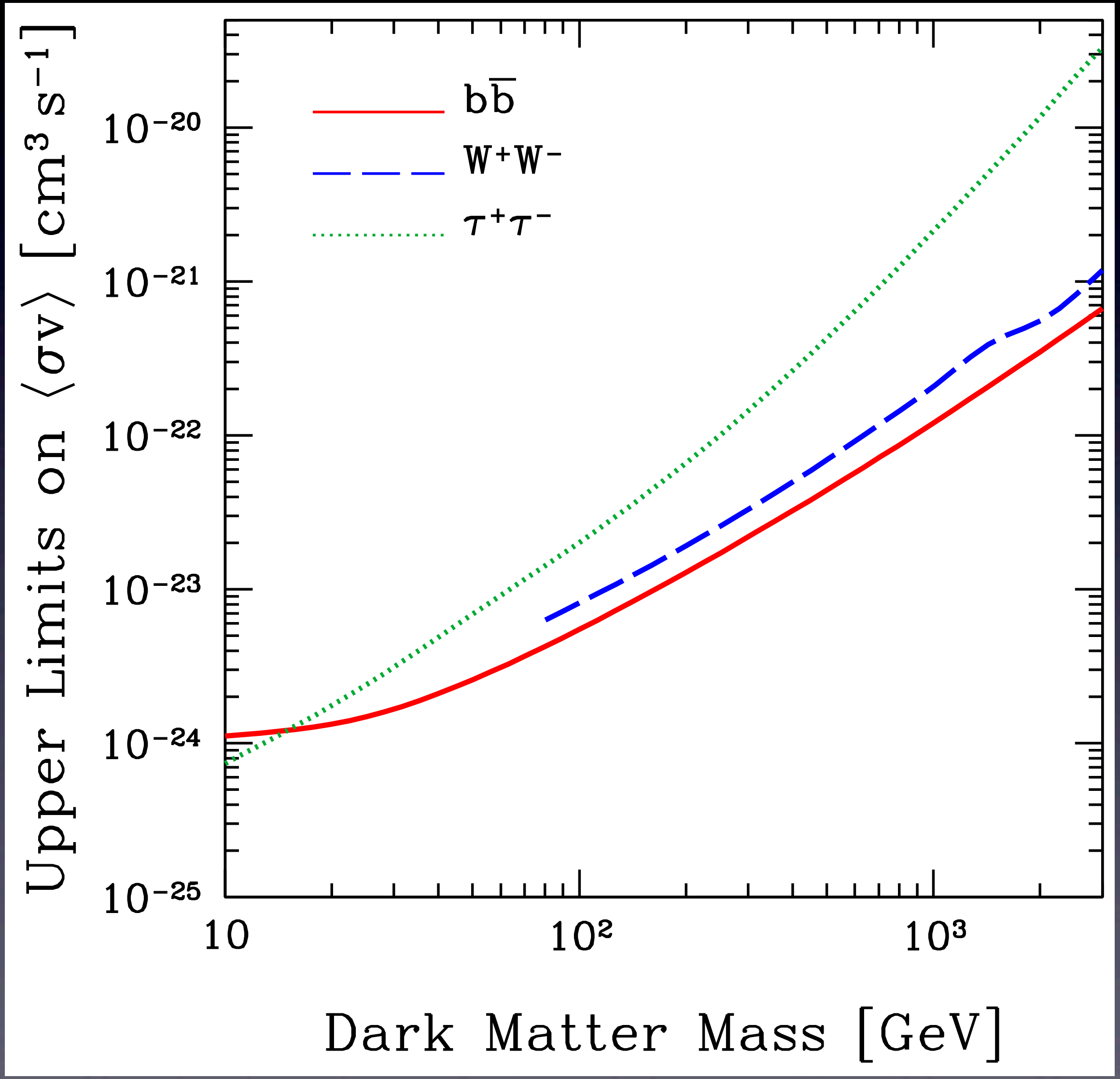


Best-fit model (almost isotropic background) and cluster component (no subhalos) allowed by 5%

95% CL upper limits on annihilation cross section

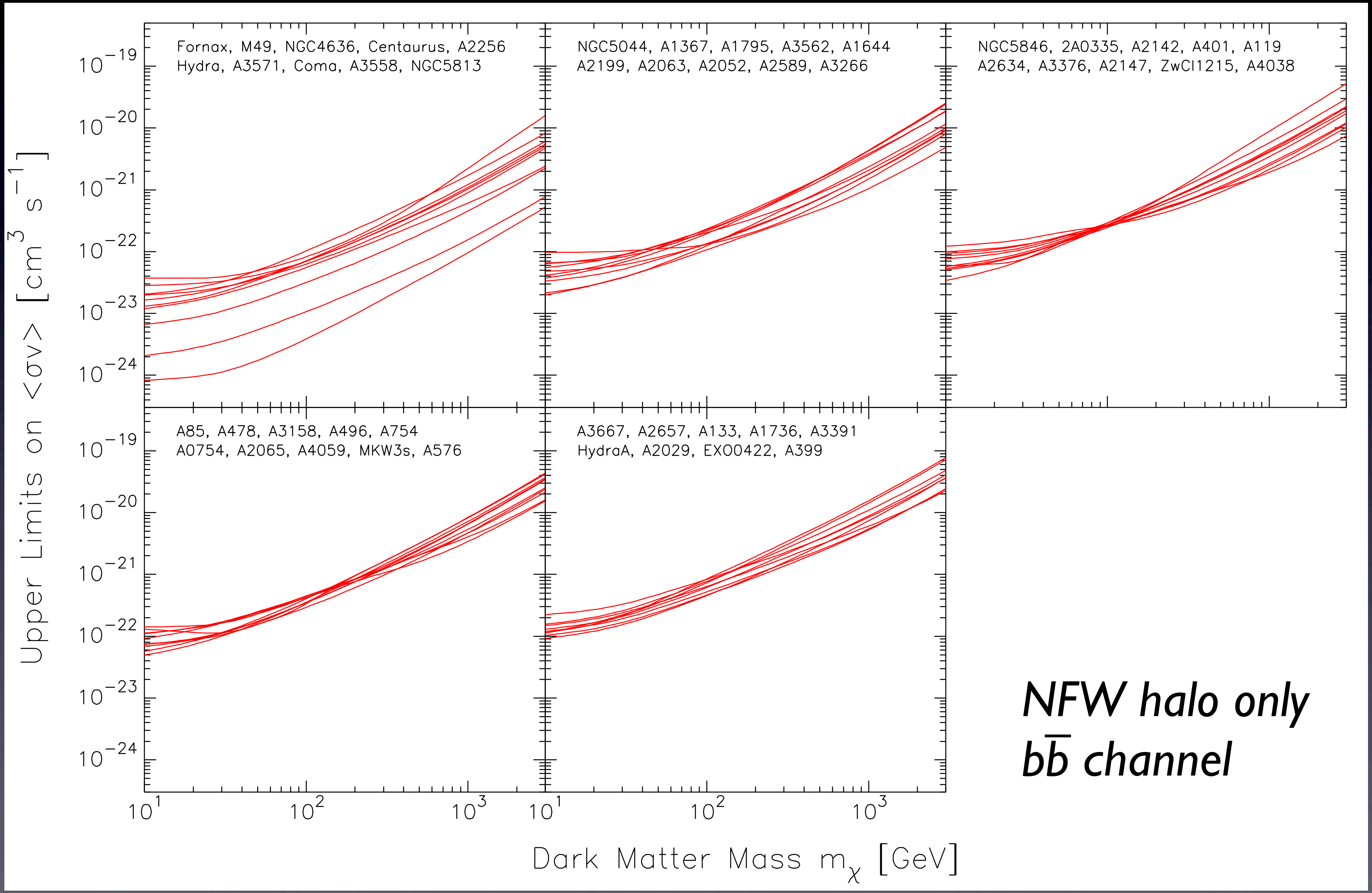
Limits on annihilation cross section from Fornax

NFW halo with no subhalos

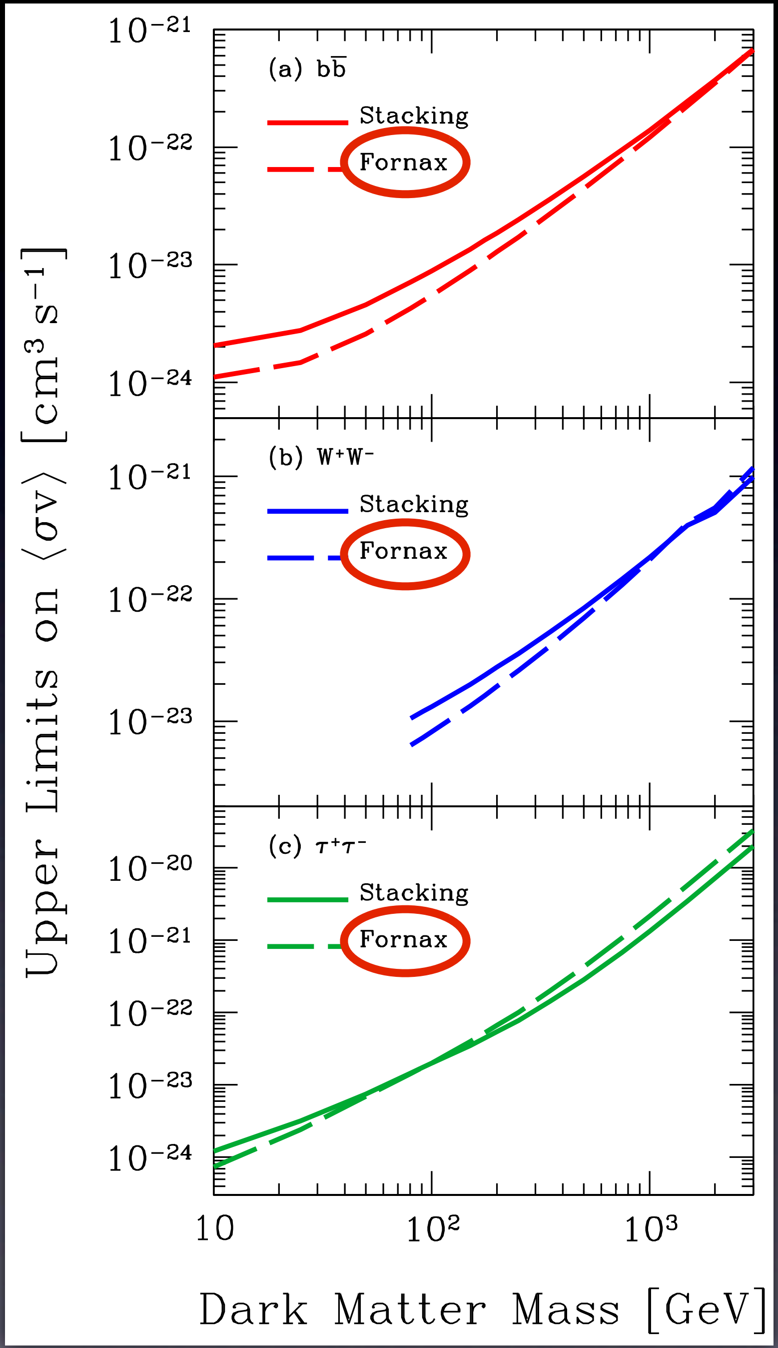


Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]

Cross section limits for all clusters



Cross section limits from stacking analysis

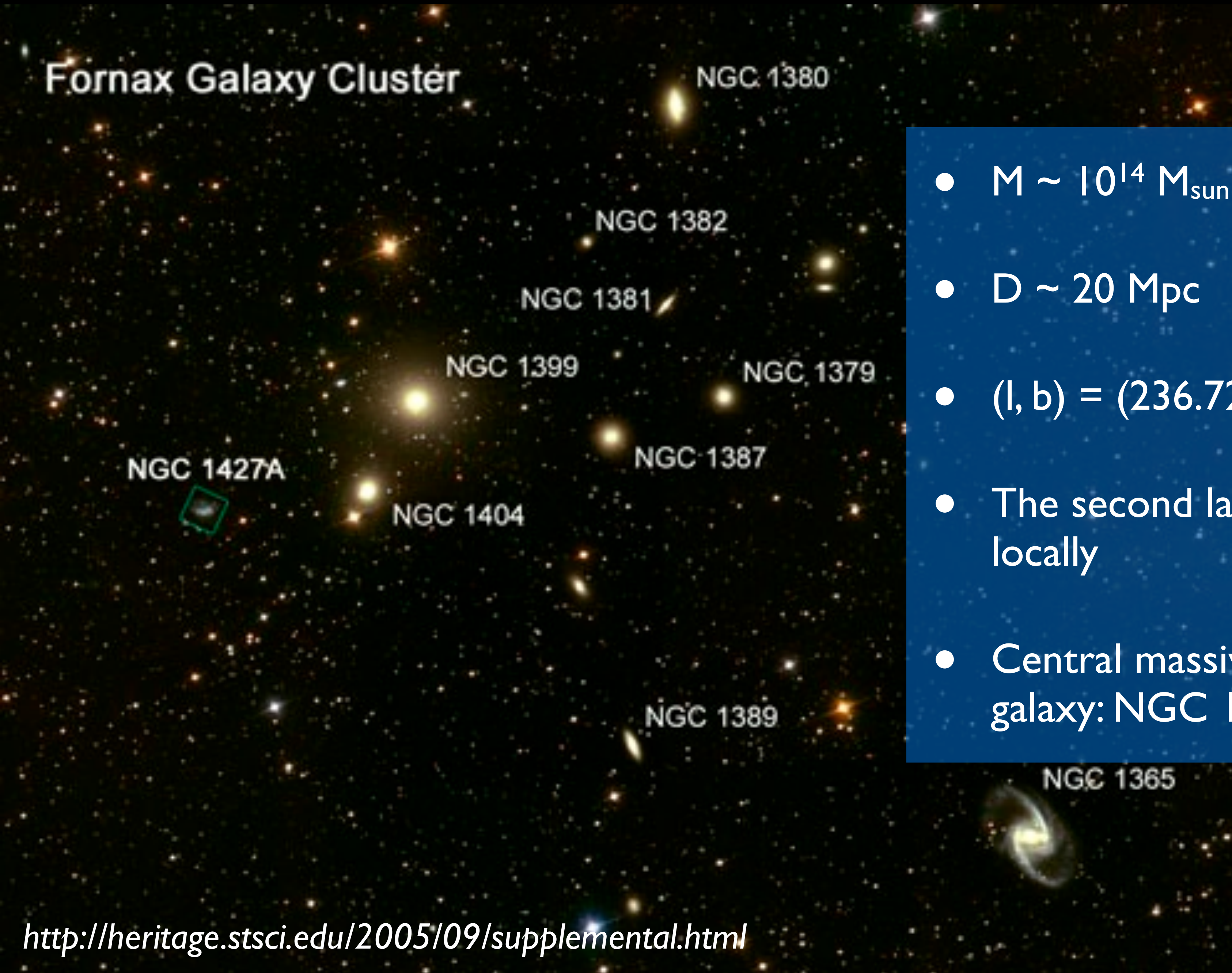


- Procedure
  - Remove clusters with >3σ excess compared with (fixed) background
  - This reduces to 38 clusters to be analyzed
- Result
  - Stacking does not help
  - ***Better to model Fornax more precisely***

Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]

The Fornax cluster

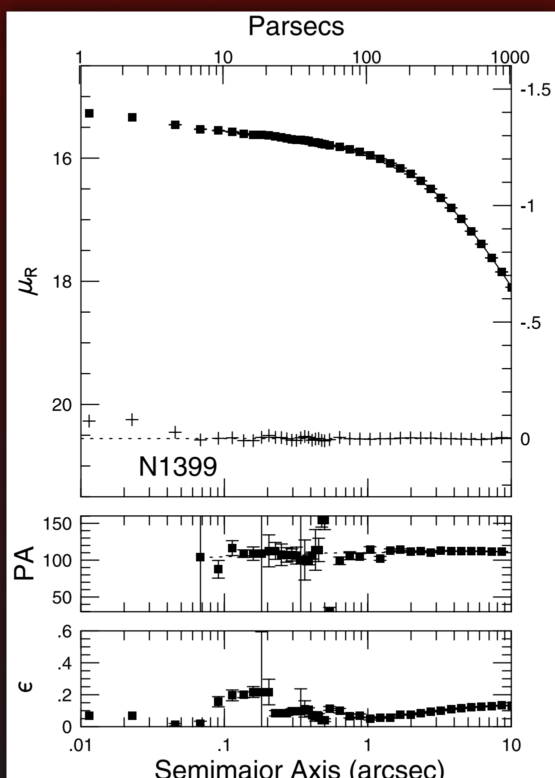
- $M \sim 10^{14}\ M_{sun}$
- D ~ 20 Mpc
- (l, b) = (236.72 deg, −53.64 deg)
- The second largest cluster locally
- Central massive elliptical (cD) galaxy: NGC 1399



http://heritage.stsci.edu/2005/09/supplemental.html

Baryons in Fornax

HST photometry (4"x4" region)

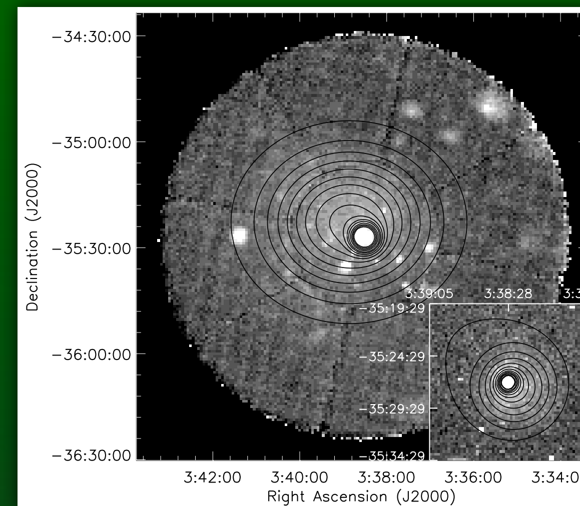


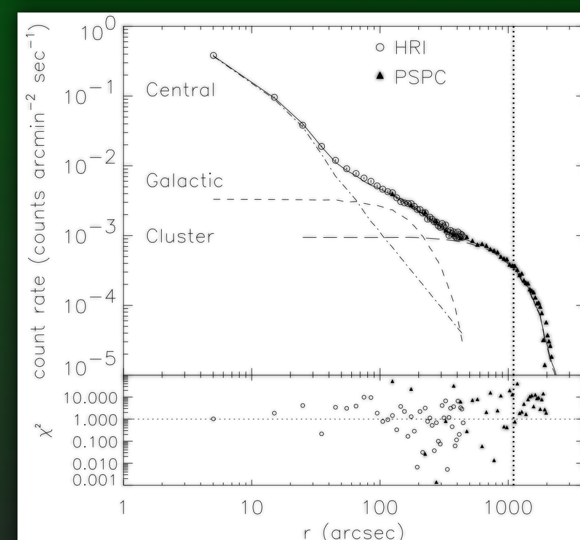
Stars

Precision measurement down to 1 pc!

Lauer et al. *Astron. J.* **129**, 2138 (2005)

ROSAT observations

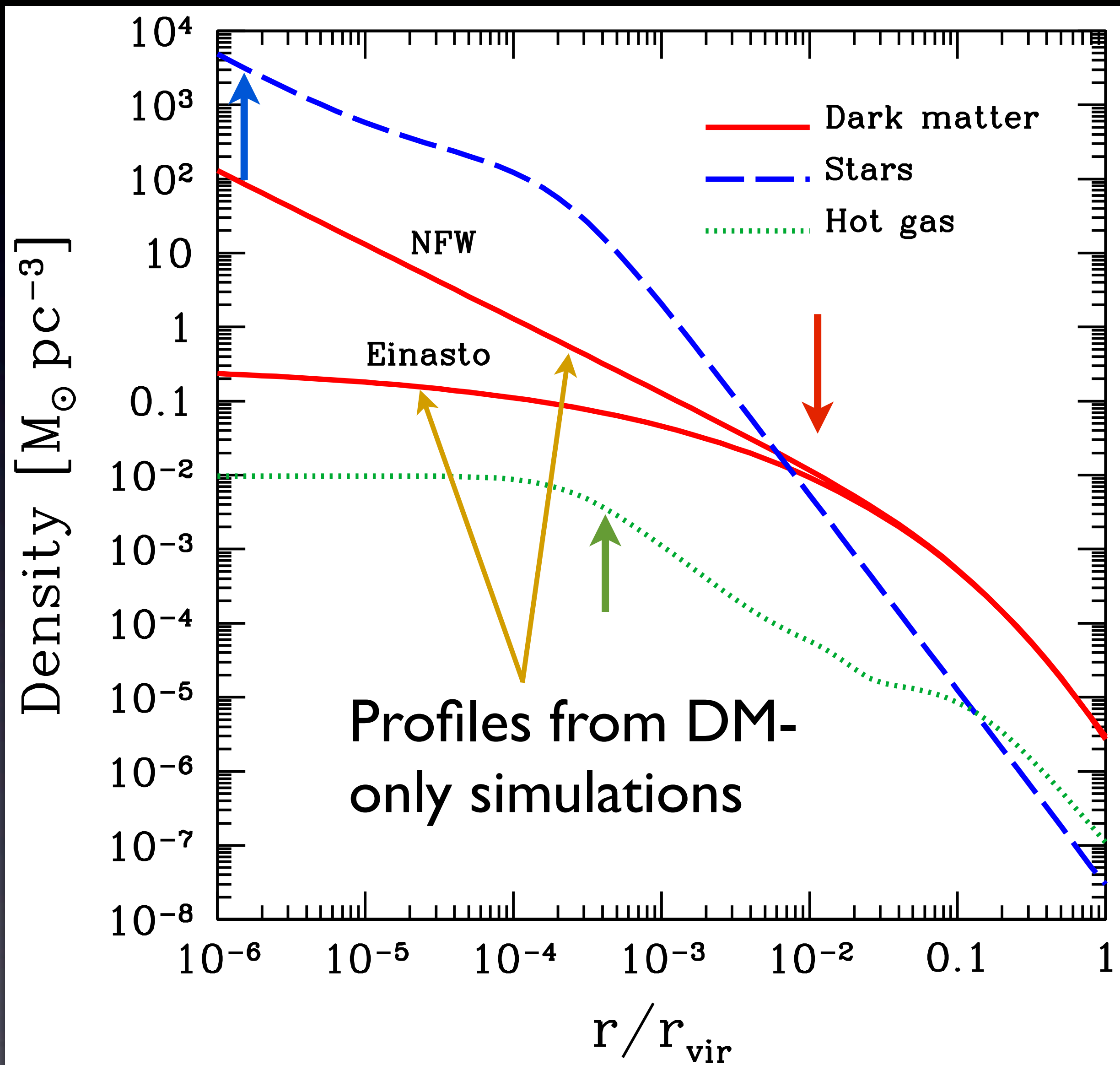




Gas

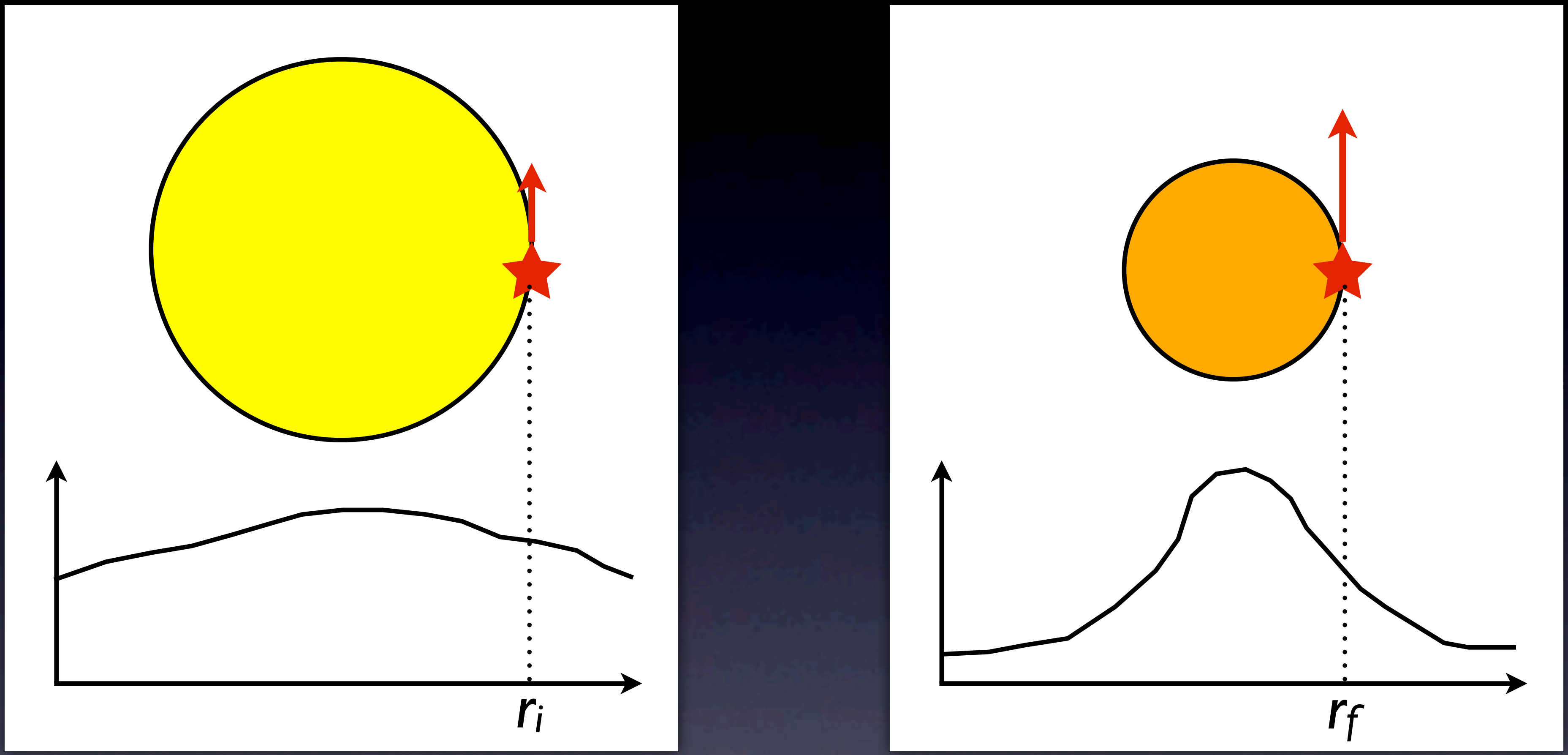
Paolillo et al. *Astrophys. J.* **565**, 883 (2002)

Density profiles of Fornax



- Surface brightness → luminosity profile → density profile
- Stars dominate the gravitational potential at the central region
- *What is the feedback effect of this deepened potential?*

Adiabatic contraction



Blumenthal et al. *Astrophys. J.* **301**, 27 (1986)

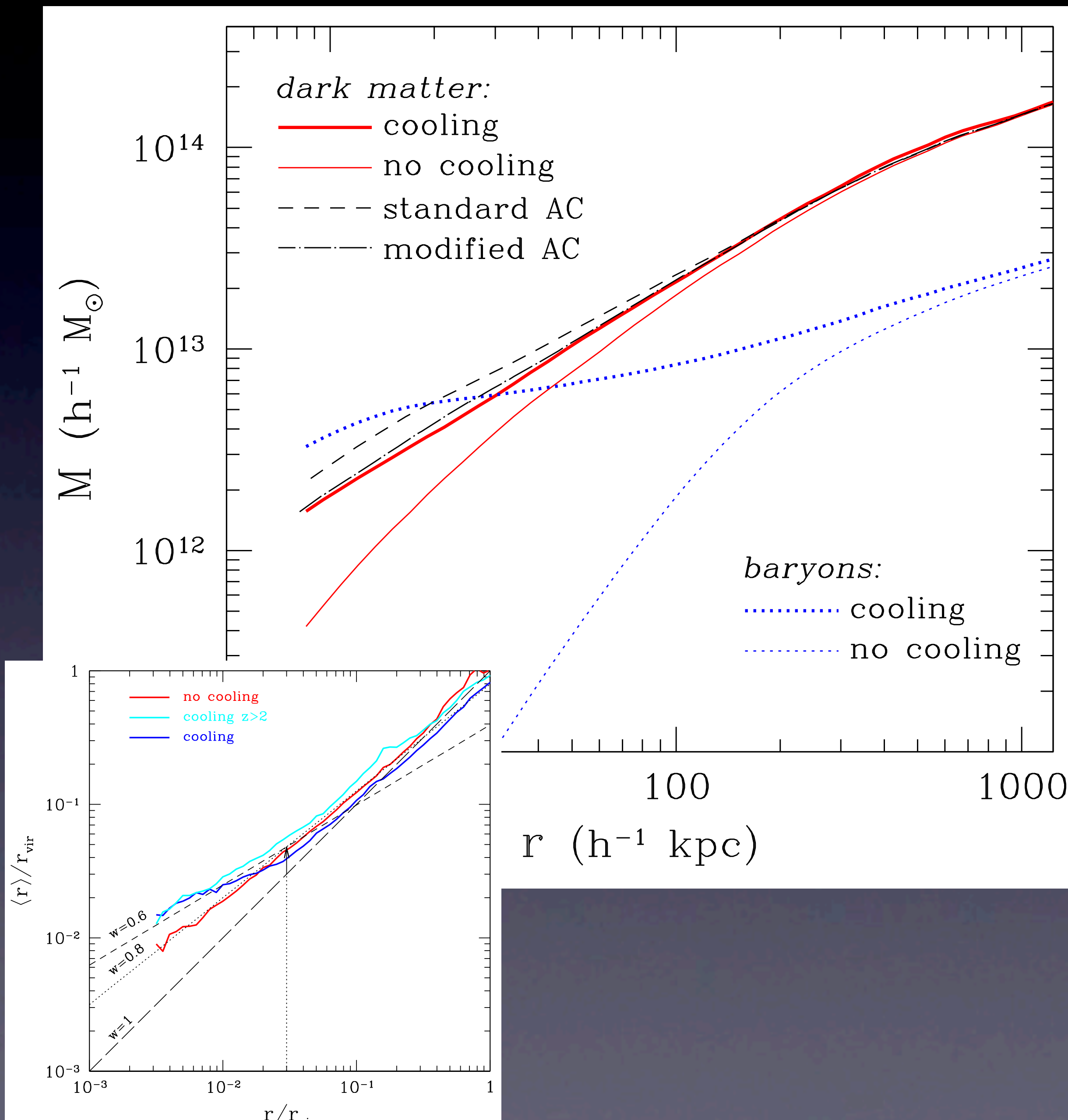
Angular momentum conservation:

$$M_i(r_i)r_i = M_f(r_f)r_f$$

$$M_f(r_f) = [M_{\mathrm{dm},f}(r_f) + M_{\mathrm{b},f}(r_f)]r_f = [M_{\mathrm{dm},i}(r_i) + M_{\mathrm{b},f}(r_f)]r_f$$

Modified halo contraction

Gnedin et al., *Astrophys. J.* **616**, 16 (2004); arXiv:1108.5736



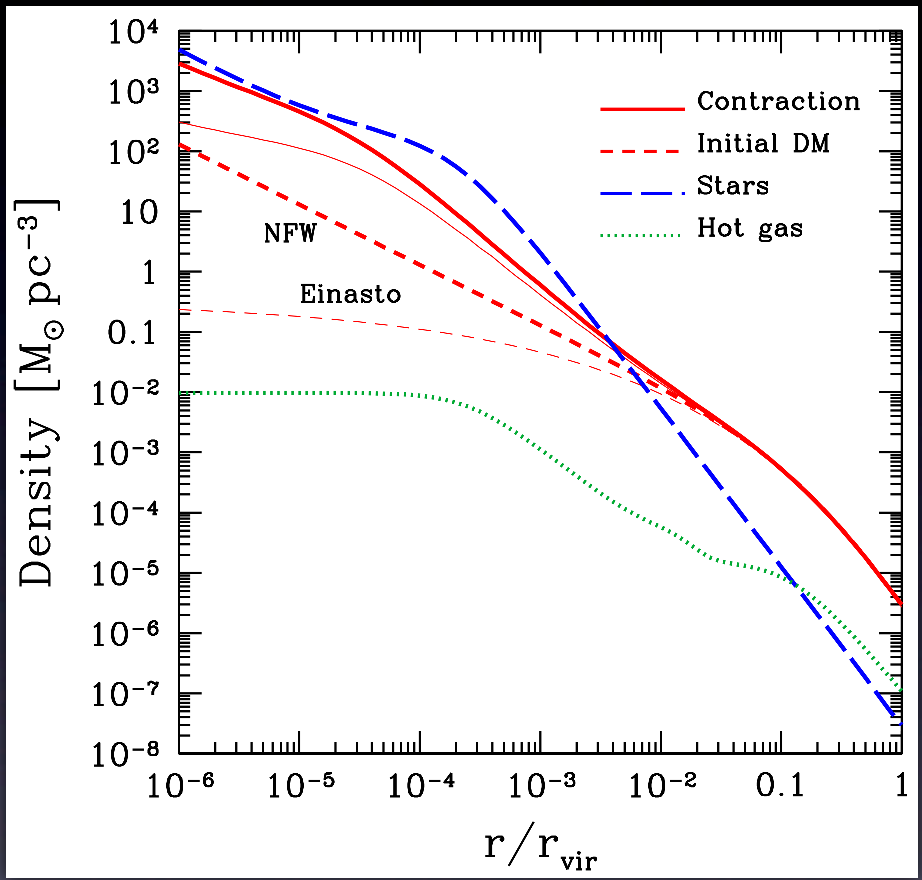
$$M_i(\bar{r}_i)r_i = [M_{\mathrm{dm},i}(\bar{r}_i) + M_{\mathrm{b},f}(\bar{r}_f)]r_f$$

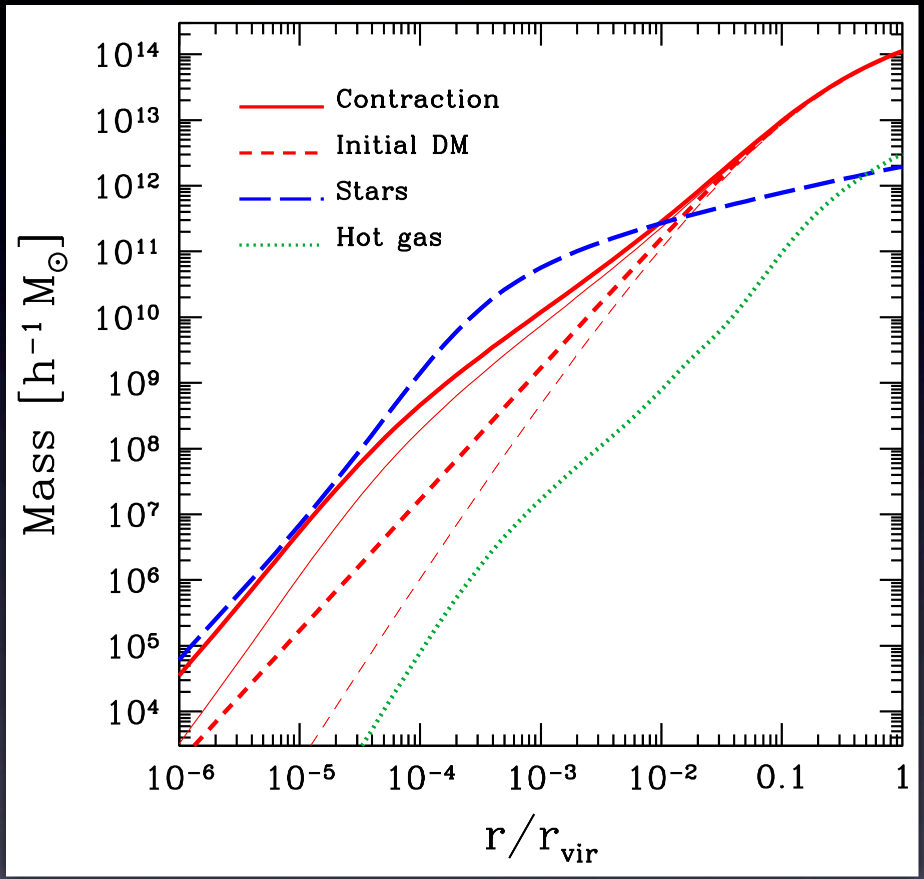
$$\frac{\bar{r}}{0.03r_{\mathrm{vir}}} = A_0\left(\frac{r}{0.03r_{\mathrm{vir}}}\right)^w$$

- $A_0 = 1.6$, $w = 0.8$ well explain simulation results
- Uncertainty range: $w = 0.6–1$
- There is no firm observational evidence for/against this effect yet

Effect of halo contraction

Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]

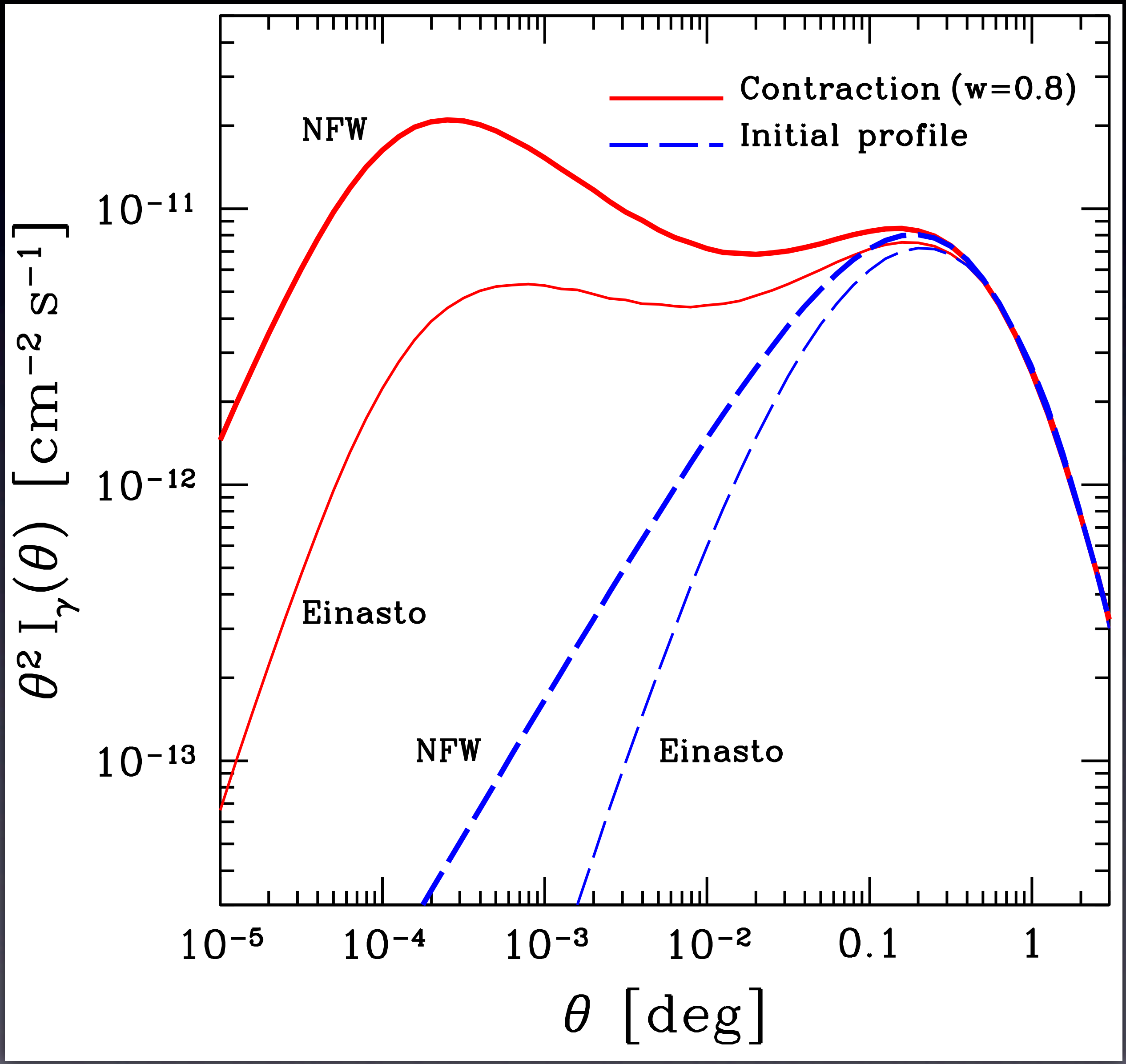




- Canonical contraction model (A_0=1.6, w=0.8)
- Density is enhanced at the center for both NFW and Einasto profiles

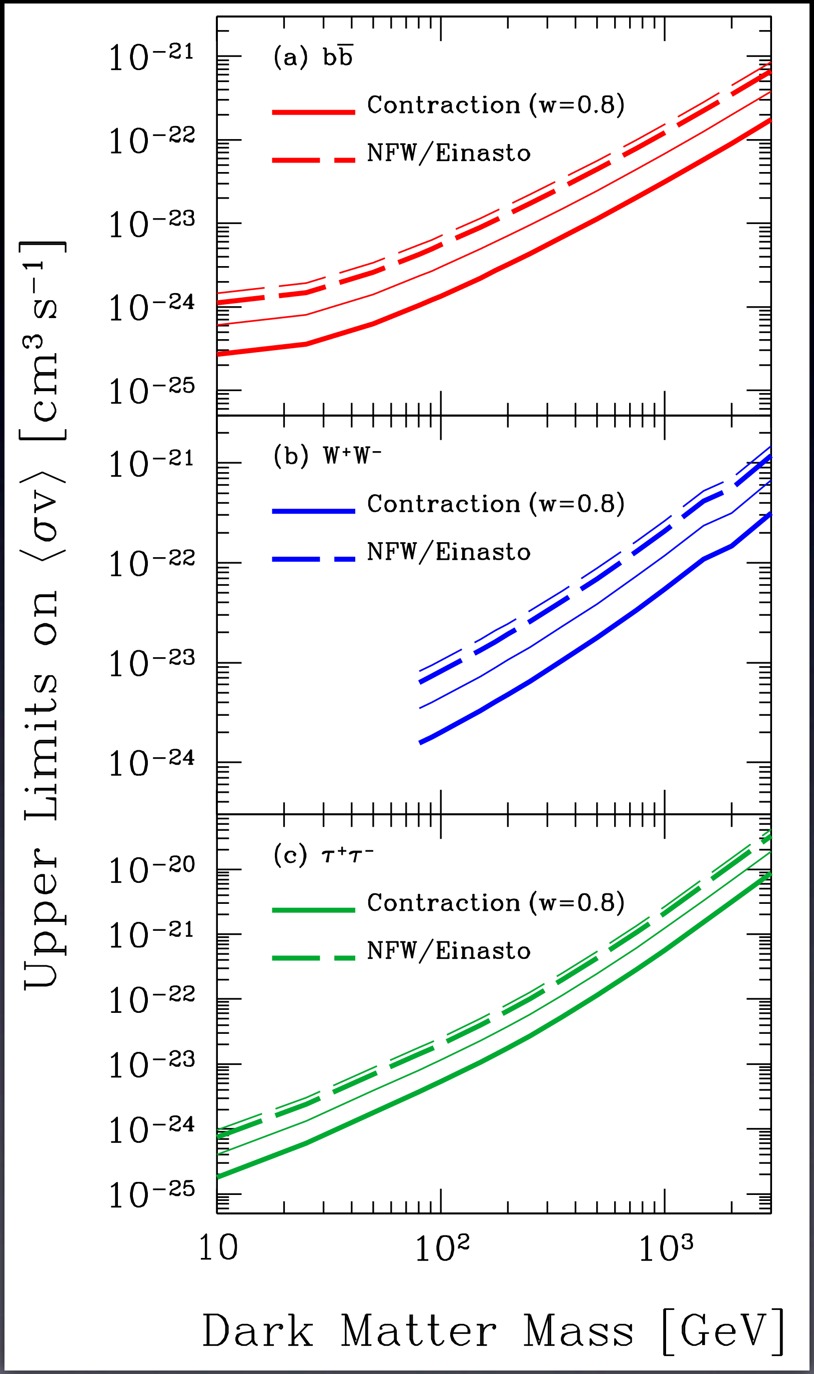
Gamma-ray intensity enhanced

Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]



- Contraction produces sub-PSF structure at 10^{-4}–10^{-3} deg (30–300 pc)
- Gamma-ray flux is boosted by a factor of
    - ~4 (NFW)
    - ~2 (Einasto)

Cross section upper limits

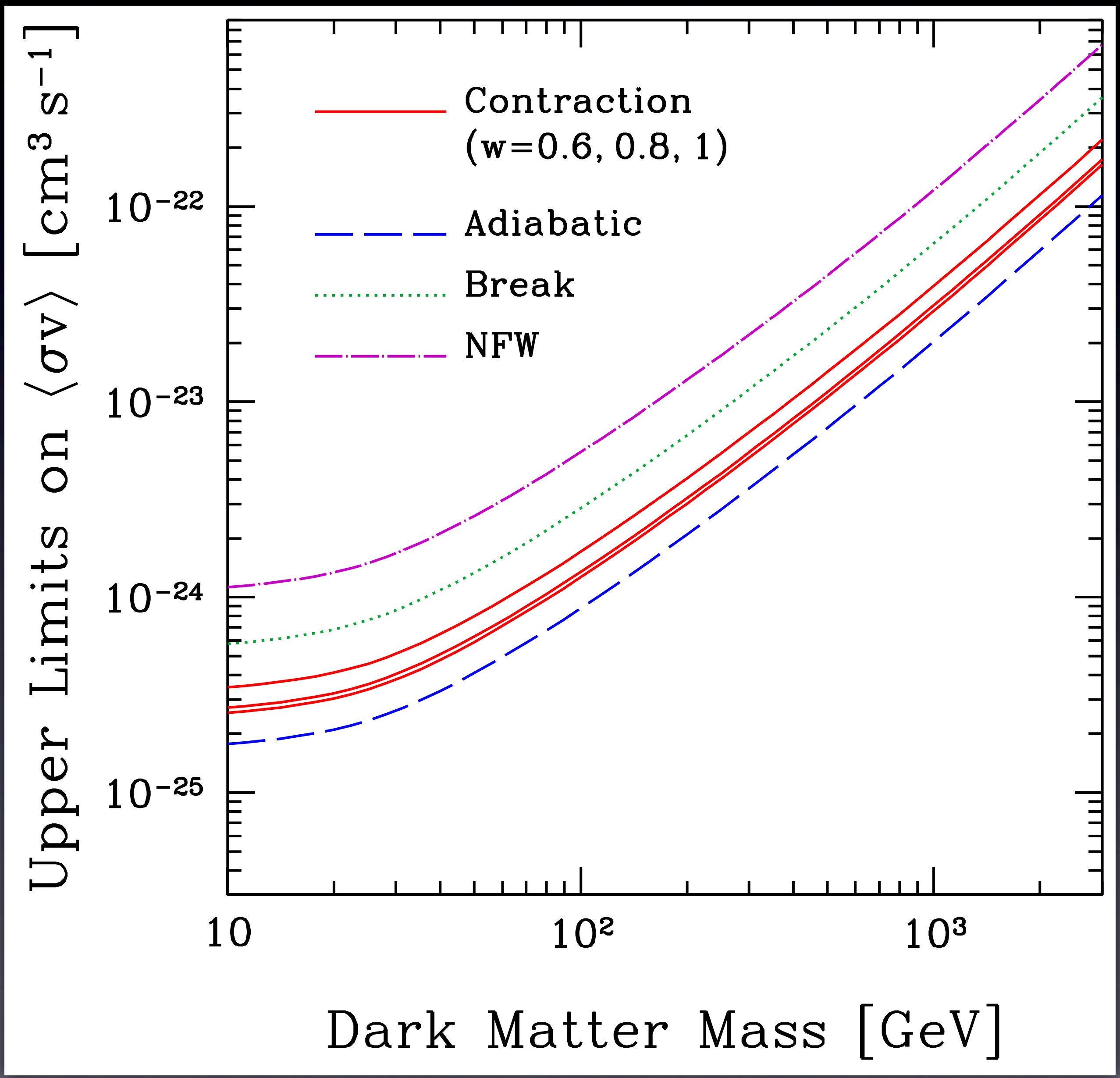


- Limits improve by a factor of
  - 4.1 (NFW)
  - 2.4 (Einasto)
- This is almost independent of mass and annihilation channel
- $\langle\sigma v\rangle < (2\text{–}3)\times10^{-25}$ cm^3/s for low-mass WIMPs

Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]

Other model parameters

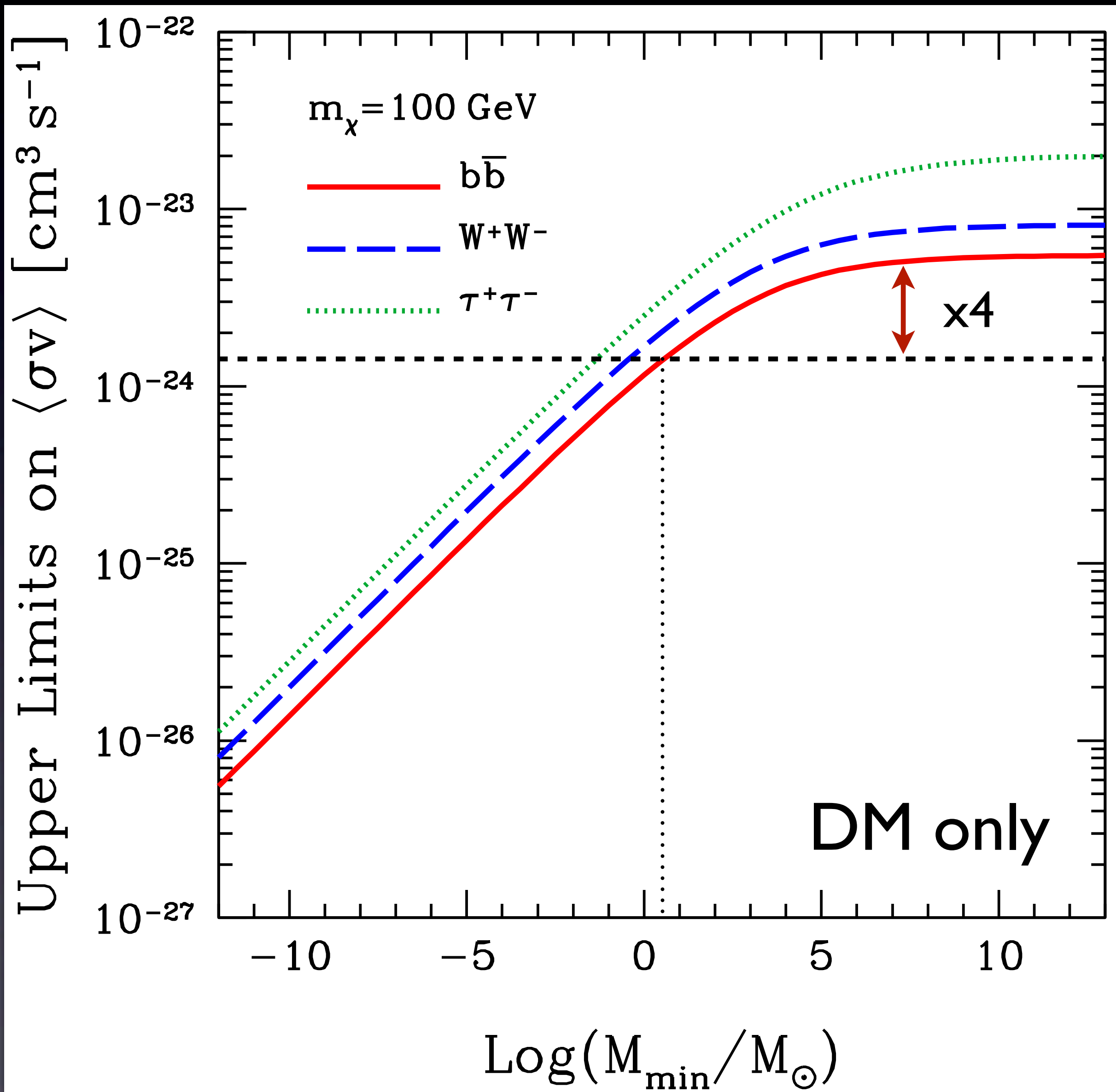
Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]



- "Adiabatic": A_0=1, w=1
- "Break": no contraction within 1 kpc (~ current resolution limit)
- Uncertainty range of the boost: 2–6

How important is this?: Compare with subhalos

Ando & Nagai, arXiv:1201.0753 [astro-ph.HE]



- To boost the limit by a factor of 4, the minimum subhalo mass has to be smaller than 1 M_{sun}
- Otherwise, one cannot ignore the effect of halo contraction

Conclusions

- Galaxy clusters are potentially strong source of gamma rays from dark matter annihilation
- We showed that stacking ~50 clusters does not improve the limits obtained with Fornax
- The detailed mass modeling of Fornax is therefore important
- We computed the halo contraction of Fornax and showed that the cross section limits improved by a factor of ~4
- The limits for low-mass WIMPs are within a factor of 10 from the canonical annihilation cross section after ~3 years