Seminar
IPMU, U. Tokyo
October 11, 2011

Gamma-ray probes of dark matter annihilation

Shin'ichiro Ando
GRAPPA, University of Amsterdam

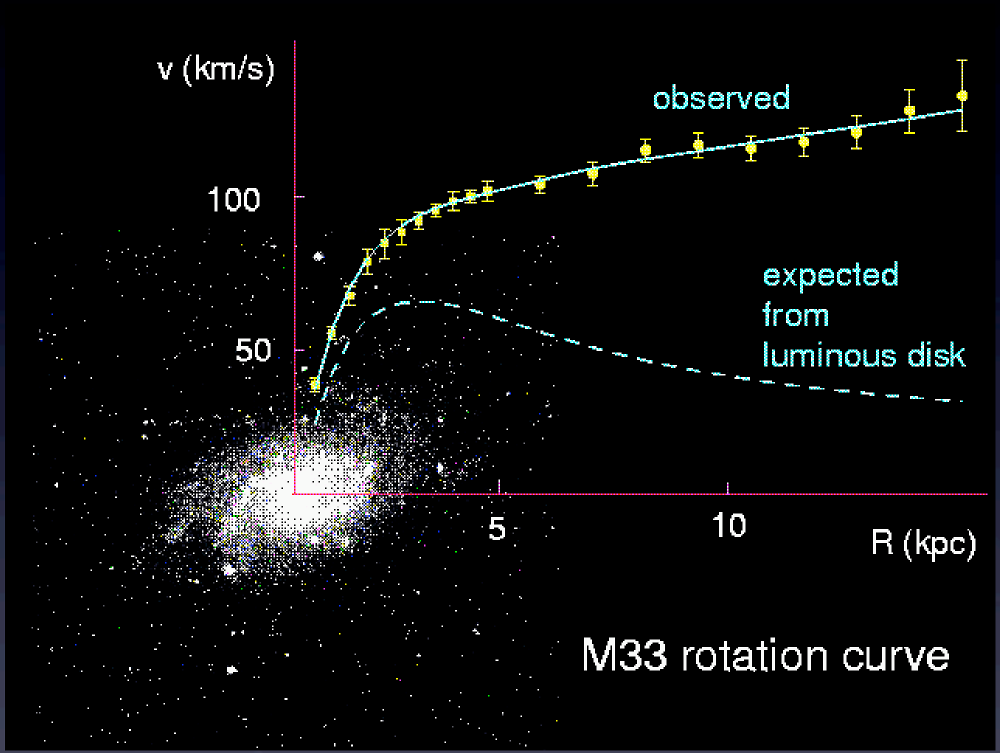
Self-introduction

- 2001–2006: Graduate student and JSPS Fellow, University of Tokyo
- 2006–2009: Sherman Fairchild Postdoctoral Scholar, Caltech
- 2009–2011: Senior Postdoctoral Scholar (JSPS Fellowship for Research Abroad), Caltech
- 2011 onward: Assistant Professor, University of Amsterdam

Introduction

Nonbaryonic dark matter

Bergstrom, *Rep. Prog. Phys.* **63**, 793 (2000)



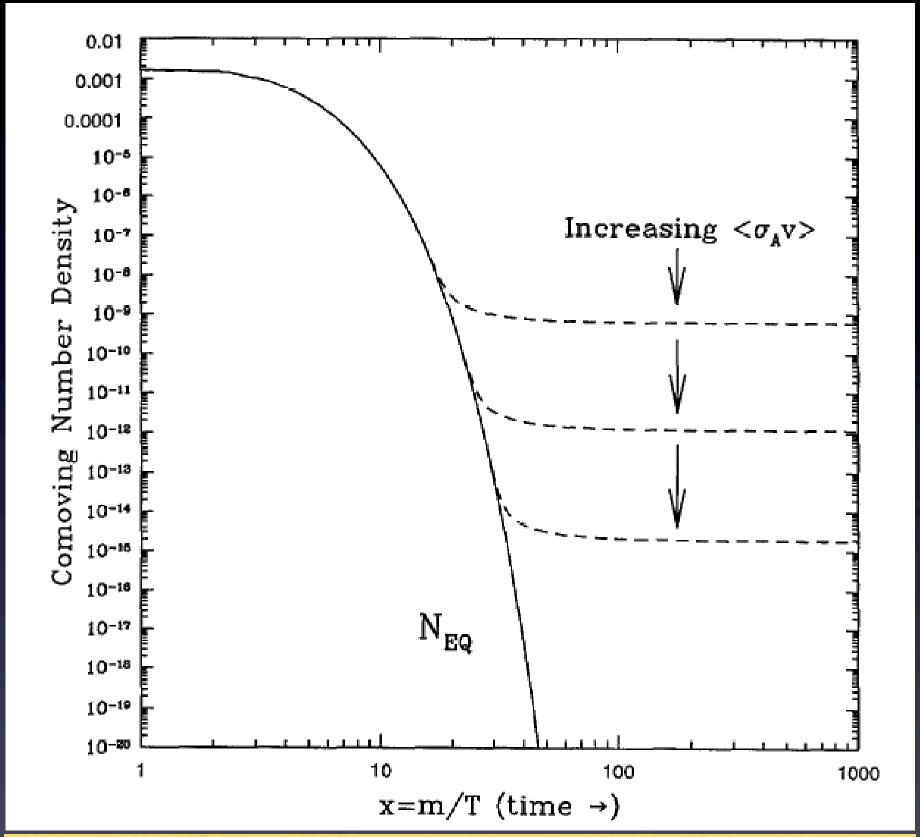
Bullet cluster (1E0657-56)

- Many observations indicate presence of *nonbaryonic dark matter*
  - Galaxy rotation curves, galaxy clusters, gravitational lensing, CMB anisotropy, etc.
- ~80% of total matter in the Universe

Identity: WIMP?

- Weakly Interacting Massive Particle (WIMP)
- WIMP with weak-scale interactions naturally explains the relic density
- E.g., supersymmetric neutralino

Jungman, Kamionkowski, Griest, *Phys. Rep.* **267**, 195 (1996); Bertone, Hooper, Silk, *Phys. Rep.* **405**, 279 (2005)



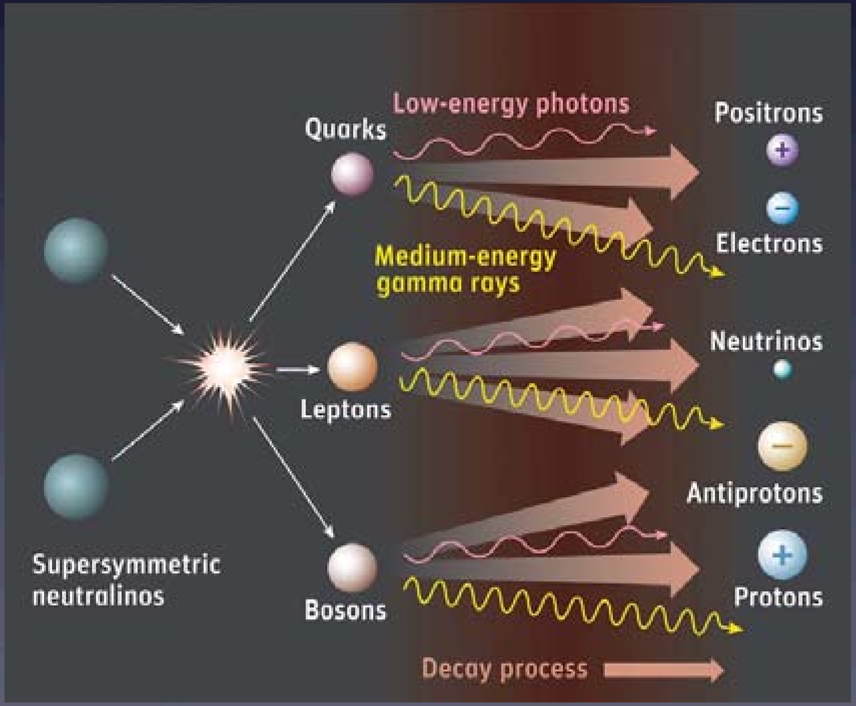
$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v\rangle}$$

$$\langle \sigma_{\mathrm{ann}} v\rangle \sim \alpha^2 (100\ \mathrm{GeV})^{-2}$$

$$\sim 3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

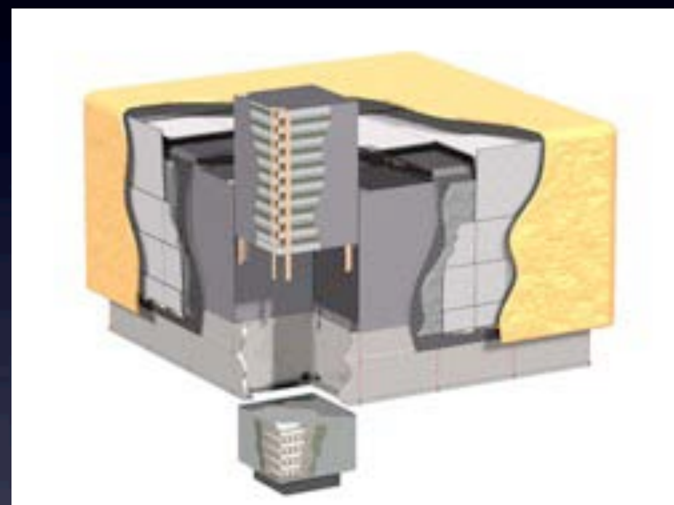
Dark matter annihilation

- WIMPs may annihilate into standard model particles (photons, positrons, neutrinos, etc.)
- Energy of product particles is fractions of WIMP mass (E ~ GeV–TeV)
  - High-energy detectors are necessary
- Ongoing projects
  - Fermi, ACTs (γ, $e^{\pm}$)
  - PAMELA, ATIC ($e^{\pm}$)
  - IceCube, ANTARES (ν)

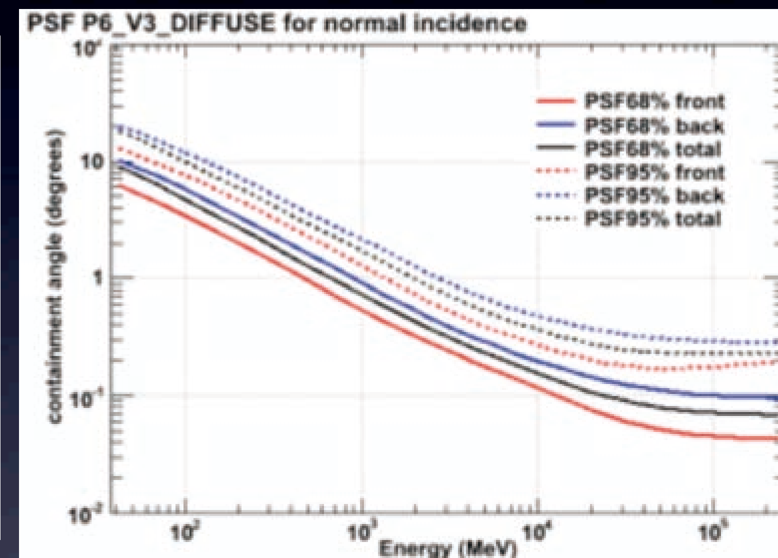


Fermi Gamma-Ray Space Telescope

Large Area Telescope (LAT)



Pre-launch PSF (P6_v3)



- Launched in summer 2008
- Collect photons from all sources in the entire sky
- Sensitive to photons between ~20 MeV and 300 GeV
- Angular resolution gets sub-degree for > 1 GeV

Where to look for annihilation signature

- Galactic center
- Galactic smooth halo component
- Nearby dwarf galaxies (substructure)
- Galaxy clusters
- Diffuse gamma-ray background

Contributions from both Galactic subhalos and large-scale structure

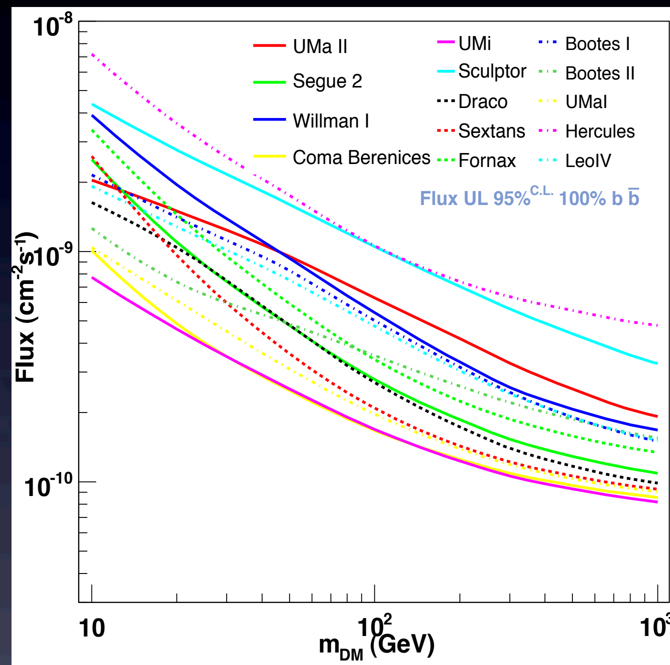
Dark matter substructure seen by simulations

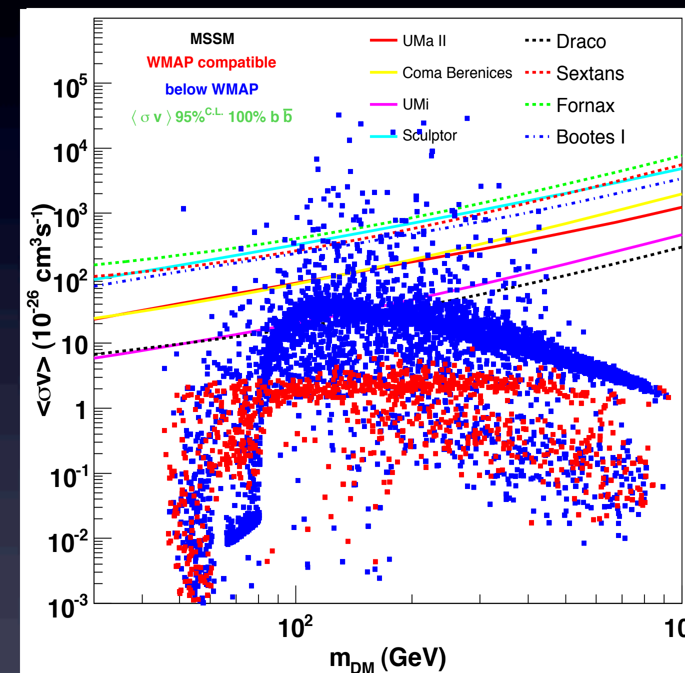
e.g., Diemand, Kuhlen, Madau, *Astrophys. J.* **657**, 262 (2007)

Search for dark matter in dwarf galaxies

Fermi-LAT, Abdo et al., *Astrophys. J.* **712**, 147 (2010)

Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8
Ursa Major II	30± 5	2006	4000^{+3700}_{-2100}
Segue 2	35	2009	650
Willman 1	38± 7	2004	770^{+930}_{-440}
Coma Berenices	44± 4	2006	1100^{+800}_{-500}
Bootes II	46	2007	18000??
Bootes I	62±3	2006	1700^{+1400}_{-700}
Ursa Minor	66± 3	1954	290^{+140}_{-90}
Sculptor	79± 4	1937	18^{+6}_{-5}
Draco	76± 5	1954	200^{+80}_{-60}
Sextans	86± 4	1990	120^{+40}_{-35}
Ursa Major I	97±4	2005	1800^{+1300}_{-700}
Hercules	132±12	2006	1400^{+1200}_{-700}
Fornax	138± 8	1938	$8.7^{+2.8}_{-2.3}$
Leo IV	160±15	2006	260^{+1000}_{-200}





- No detection so far, constraining <σv> < 10^{-25} cm^3 s^{-1}, but starting to constrain some SUSY parameters

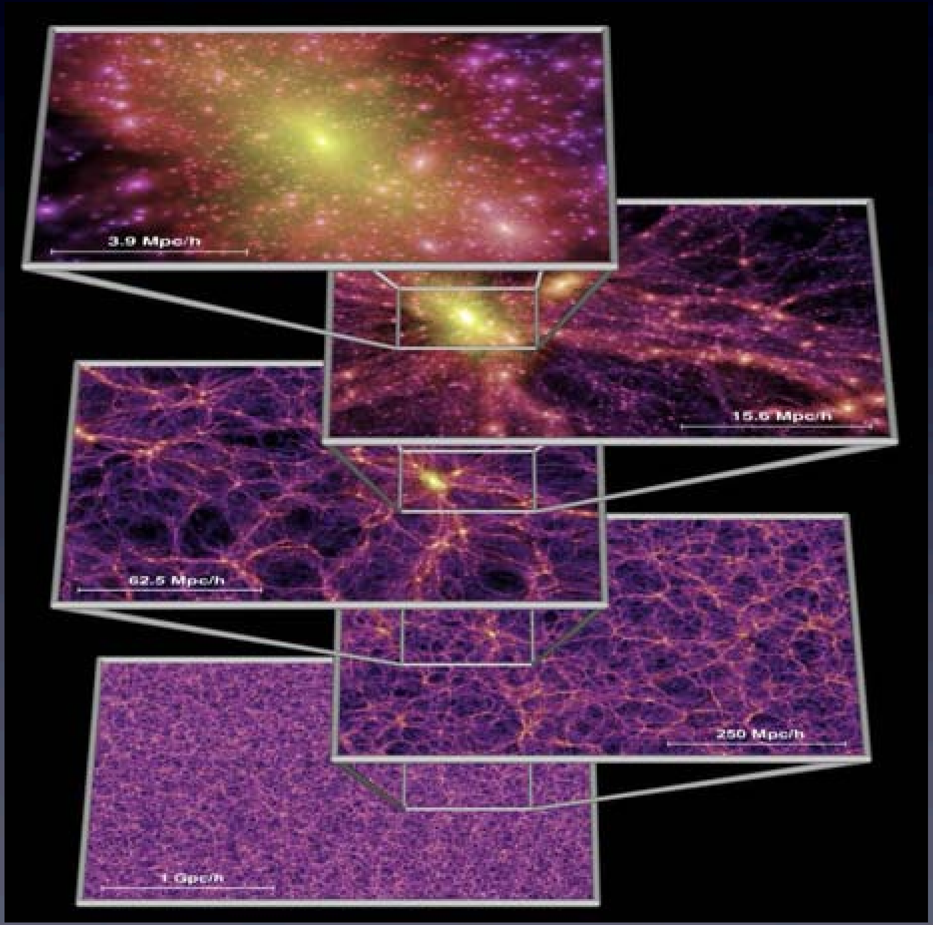
Plan of this talk

- Gamma rays from dark-matter annihilation from galaxy clusters

- Angular power spectrum of the gamma-ray background from dark matter annihilation

Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)
Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)
Ando, *Phys. Rev. D* **80**, 023520 (2009)

Gamma rays from dark matter annihilation in galaxy clusters



Work in progress with
E. Komatsu & D. Nagai

Galaxy clusters

- The largest virialized dark-matter structure
- The largest number of dark-matter particles
- The largest rate of annihilation

- Density profile well represented by NFW
- Abundance of subhalos not well known yet

What we do

- Theory
  - Estimate of gamma-ray flux for 49 large nearby clusters
  - Using the latest models of clusters and halos (e.g., mass-concentration relation)
- Analysis
  - 2.8 years of Fermi-LAT data (cf., 11-month data in previous LAT paper)
  - Use updated models of diffuse backgrounds and sources
  - Analyze 49 clusters (cf., 7 clusters analyzed so far)
  - Improve upper limits on cross section with stacking analysis

Dark matter annihilation in galaxy clusters

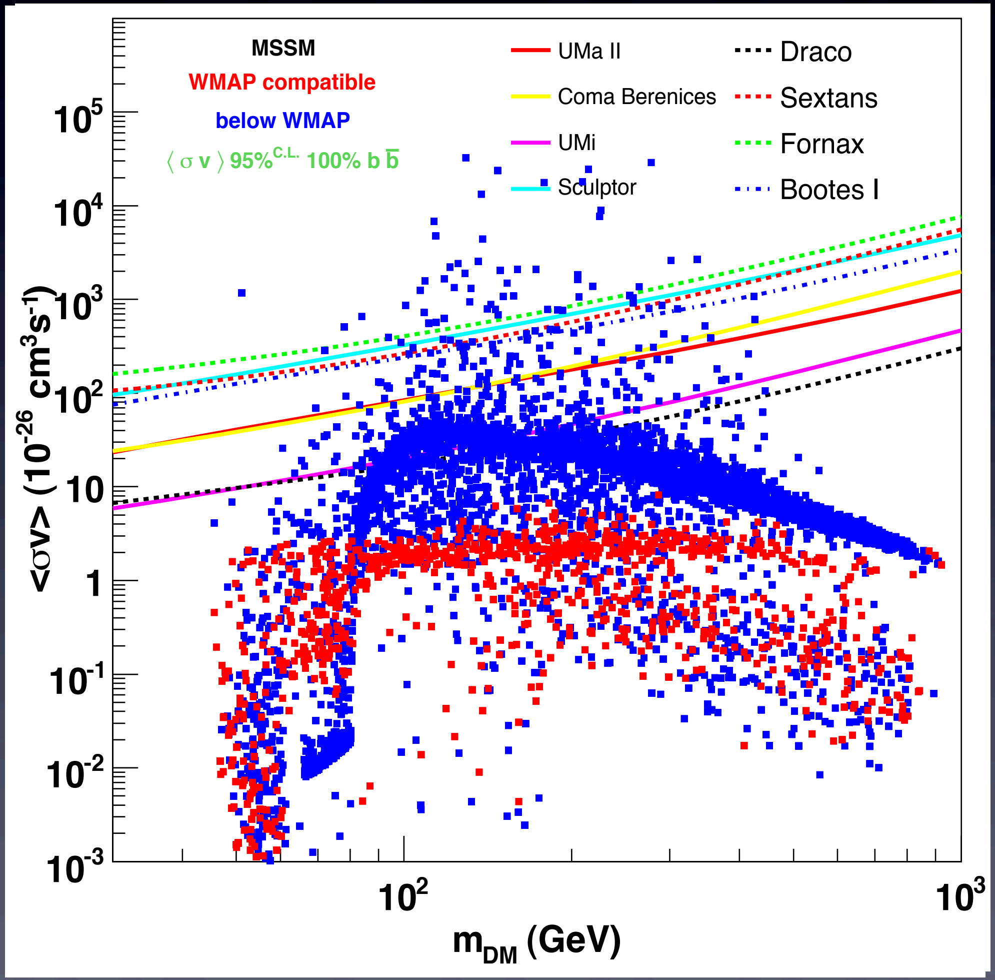
Gamma-ray intensity from annihilation

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

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

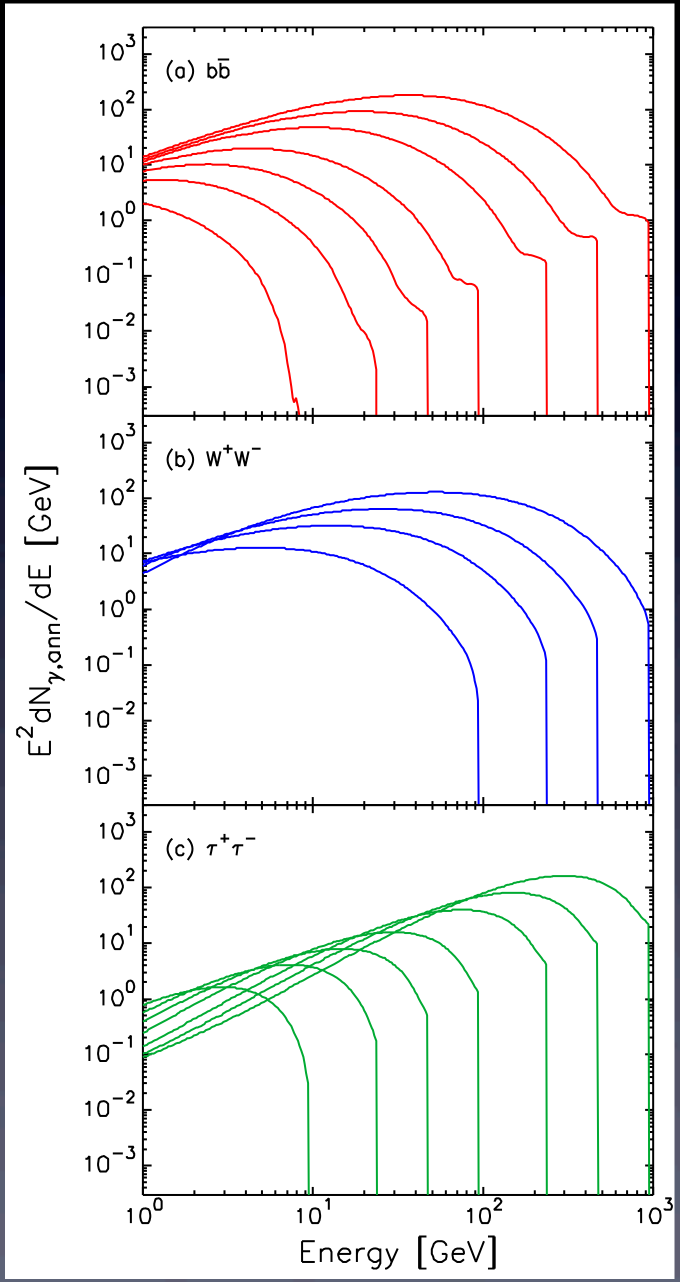
- Depends on three factors
  - Particle physics: annihilation cross section and dark-matter mass; depends on SUSY models, etc.
  - Astrophysics: density profile and subhalos
  - Cosmological redshift: straightforward if redshift is measured

Mass and annihilation cross section



- Mass of WIMP (neutralino) is typically tens of GeV to TeV
- To thermally produce dark matter with correct abundance, the cross section will be $<\sigma v> \sim 3\times10^{-26}\ cm^3/s$

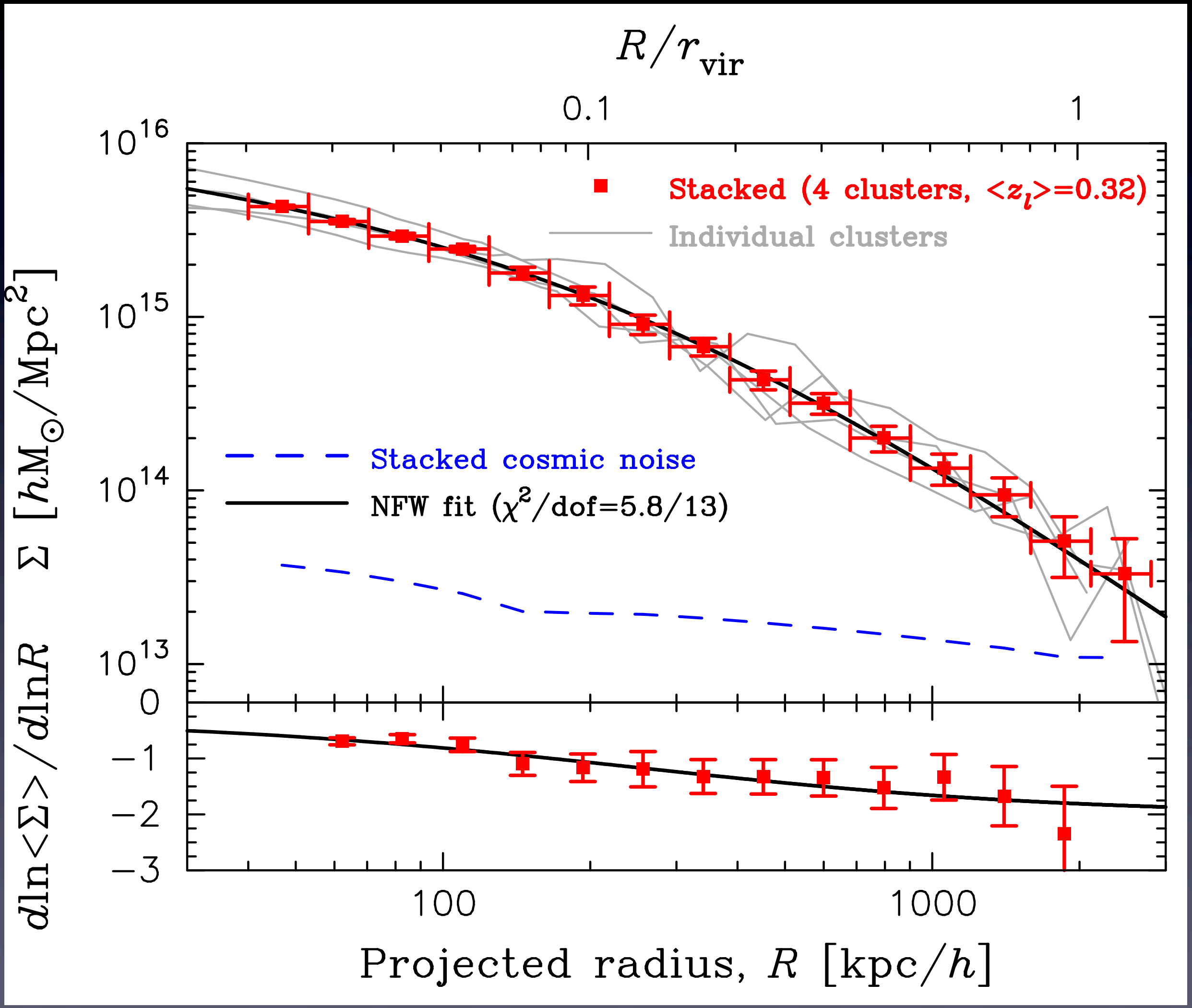
Annihilation channel and gamma-ray yields



- Annihilation channel depends on what the neutralino is (i.e., mainly gaugino or higgsino)
- Here, we treat three annihilation channels phenomenologically
- Gamma rays from both hadronic decays and internal bremsstrahlung are included

Astrophysical factor: density profile

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



- Numerical simulations imply universal form of density profile: NFW

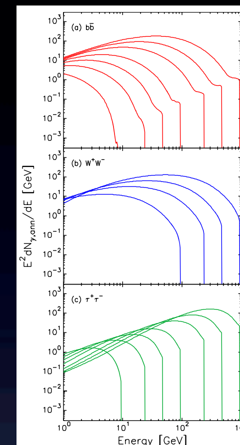
$$\rho = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2}$$

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

- NFW profile is confirmed with lensing observations

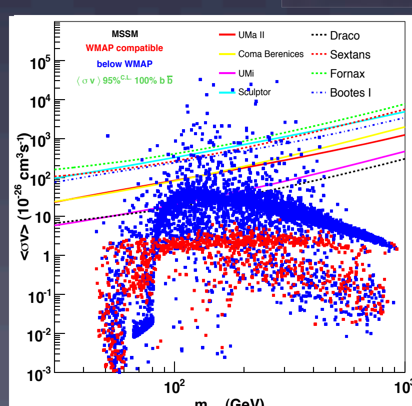
Recap: gamma-ray intensity

Gamma-ray intensity from annihilation

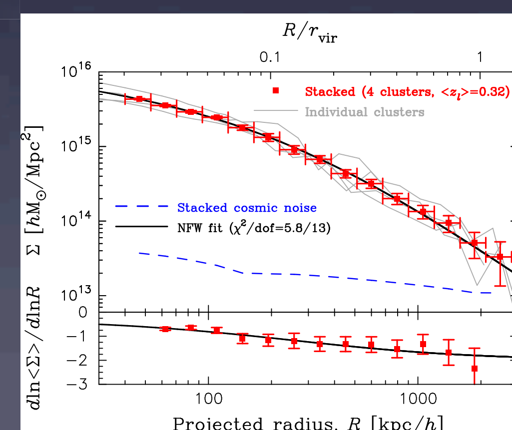


Gamma-ray spectra per annihilation

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

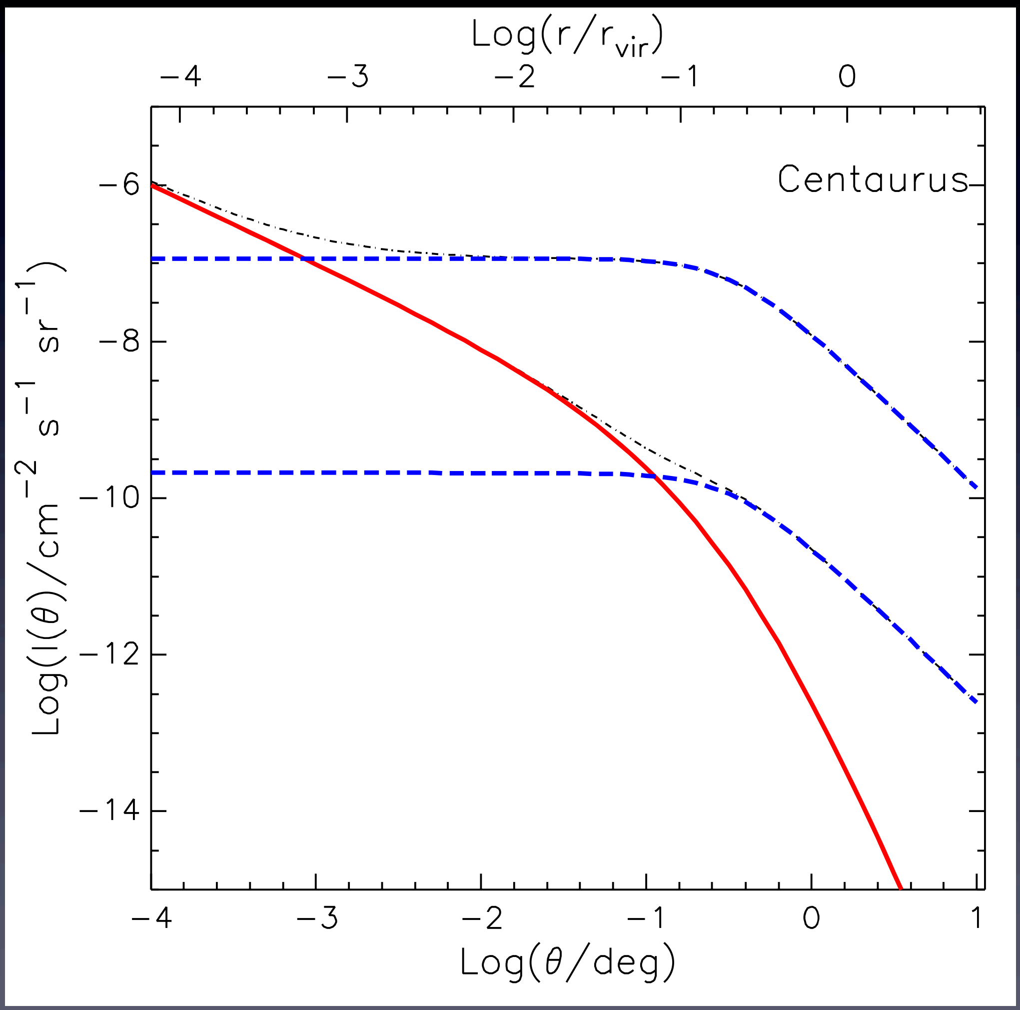


Mass and annihilation cross section



Density profile: NFW

Intensity profile

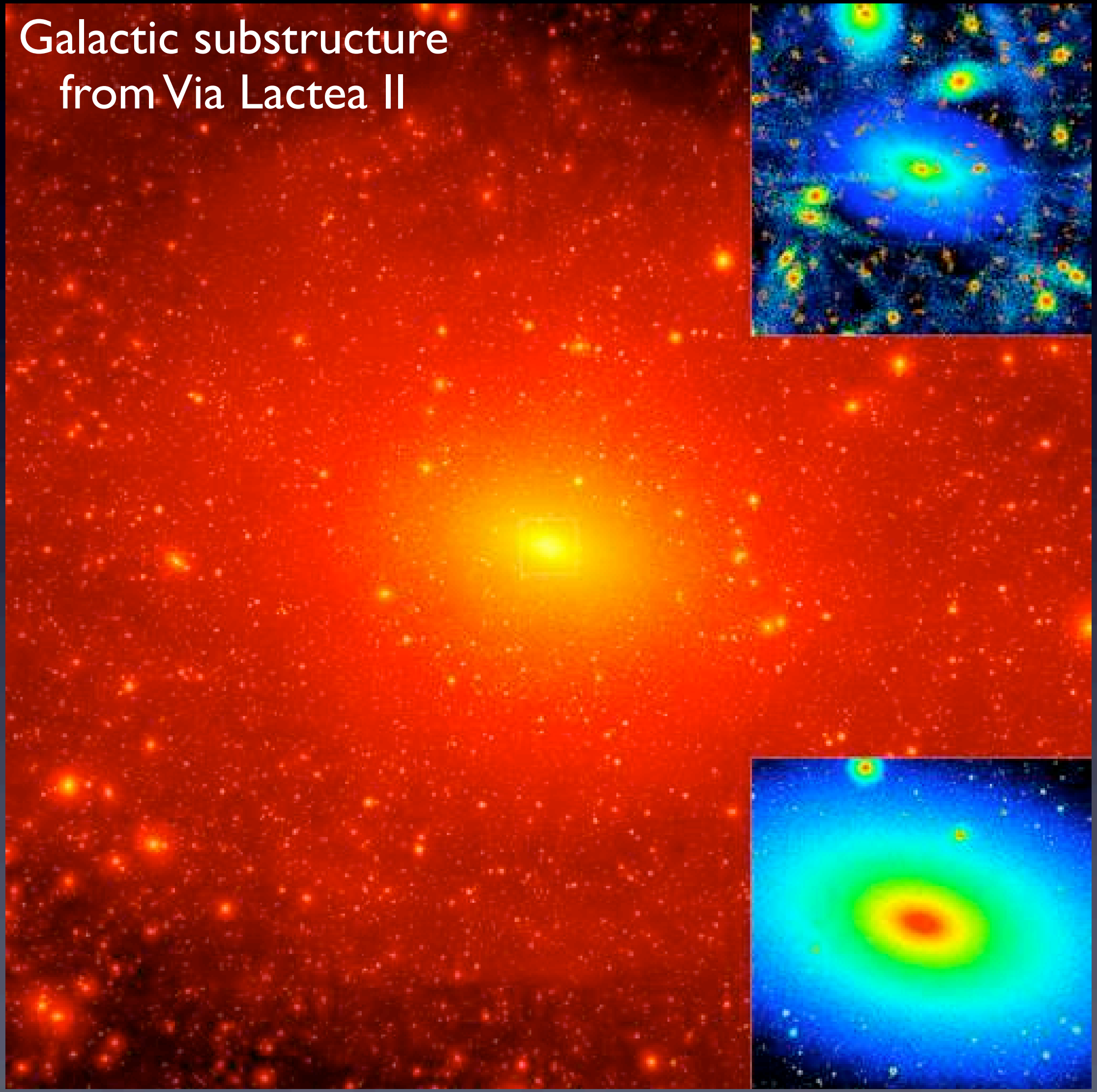


- DM mass: 100 GeV
- Cross section assumed: $<\sigma v> = 3\times10^{-26}$ cm^3/s
- Photon per annihilation: $N_\gamma = 1$

Three representative clusters:

	z	M_{vir} (10^{14} h^{-1} M_{sun})	r_{vir} (h^{-1} Mpc)
Fornax	0.005	0.8	0.9
Coma	0.023	6.8	1.8
Centaurus	0.05	62	3.7

Uncertainty: substructure

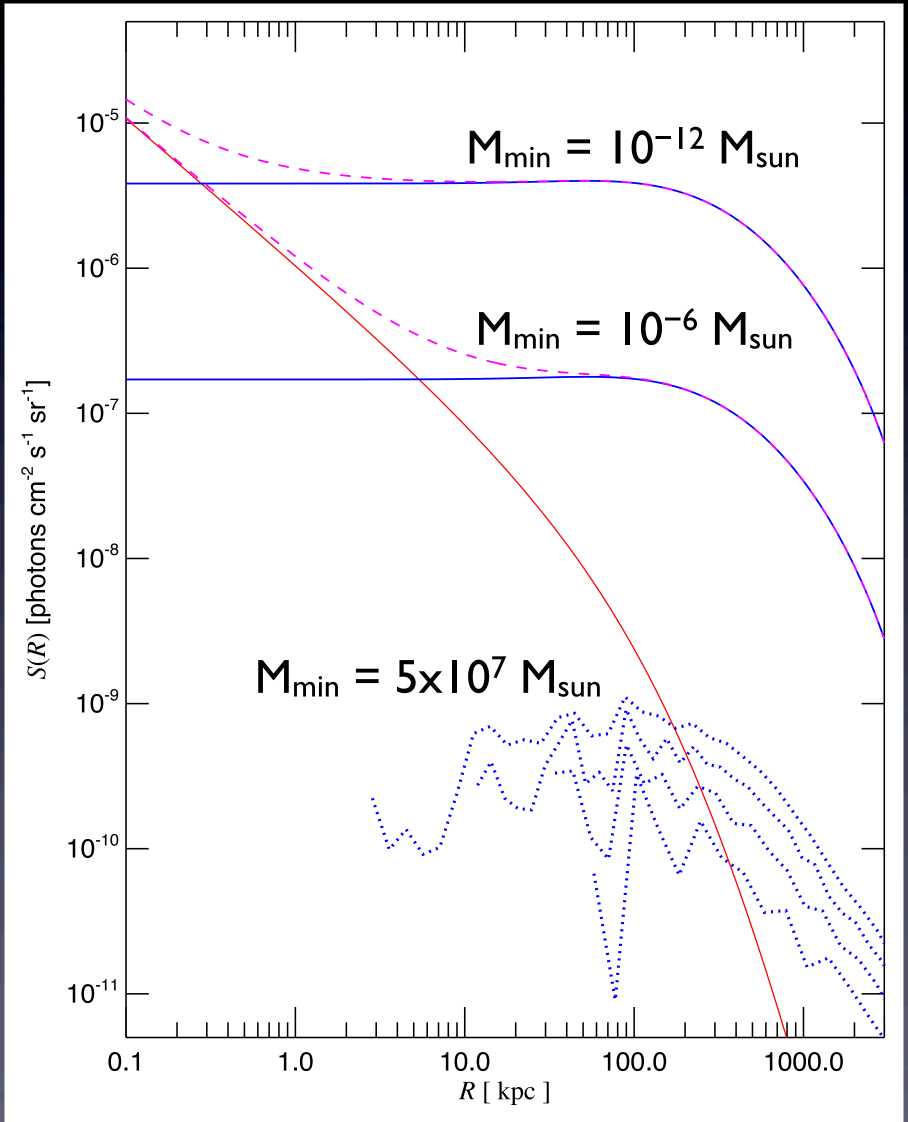


Diemand et al., *Nature* **454**, 735 (2008)

- Numerical simulations find lots of substructure
- This will boost annihilation signals
- Current resolution limits for cluster-like halos are ~5×10^7 M_{sun}

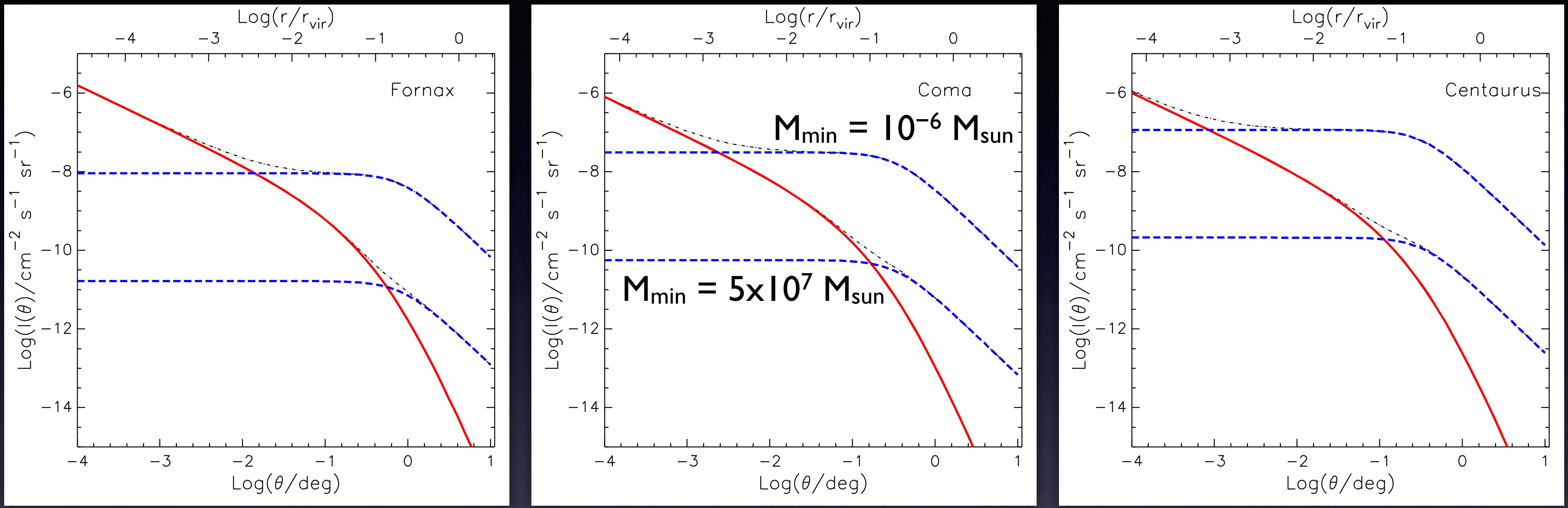
Uncertainty: subhalos

Gao et al., arXiv:1107.1916 [astro-ph.CO]



- Minimum subhalo mass may be as small as Earth mass (10^{-6} M_{sun}) for the neutralino dark matter
- Currently no simulations can resolve such fine structure
- Simple extrapolation shows that the boost highly depends on the minimum subhalo mass

Subhalo boost of intensity

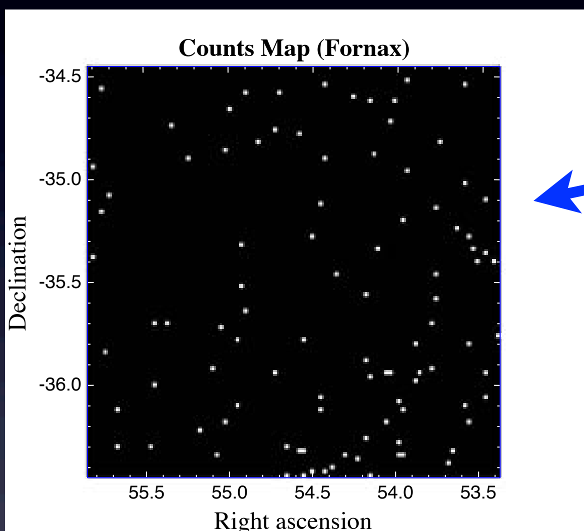


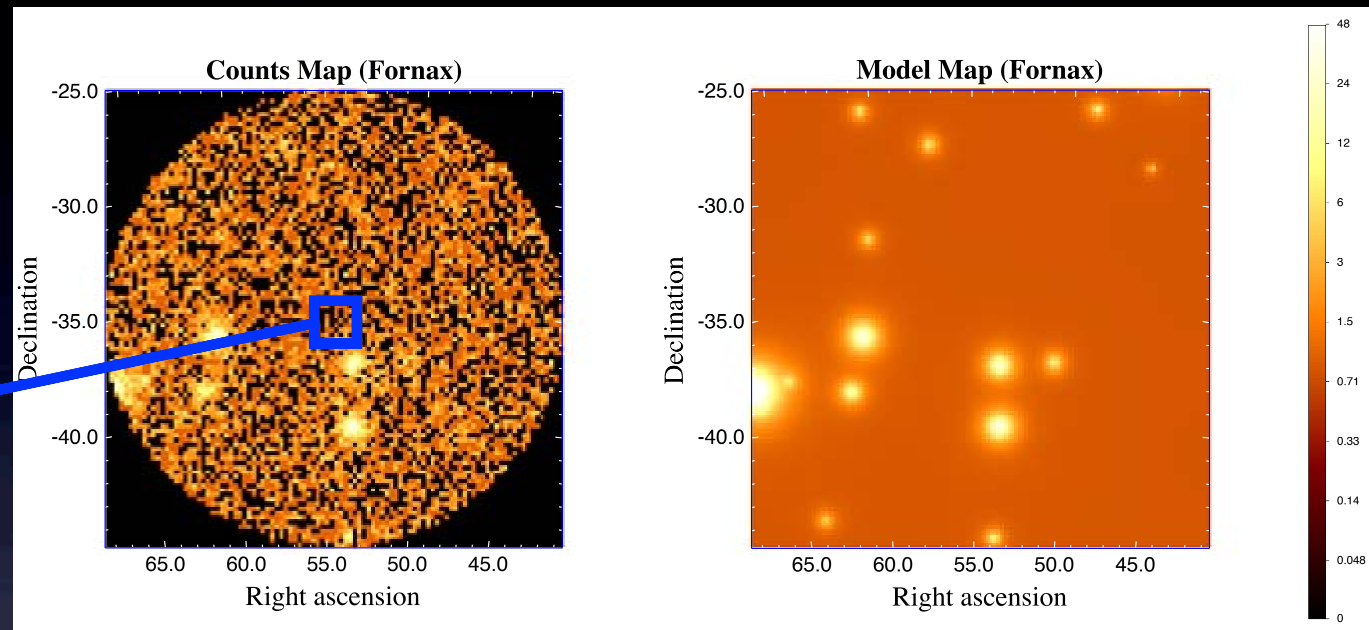
- Intensity due to subhalos is much more extended than the smooth component
- Subhalo boost factor is ~1000 for cluster-size halos, if minimum subhalos are of Earth size

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 & H. 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



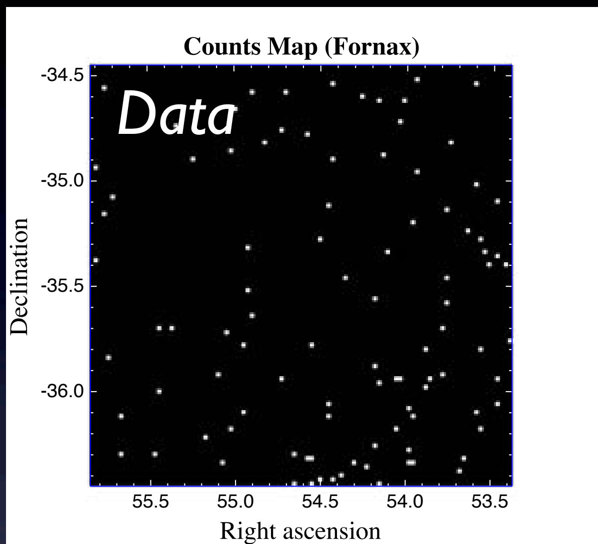


Integrated maps for 1–100 GeV

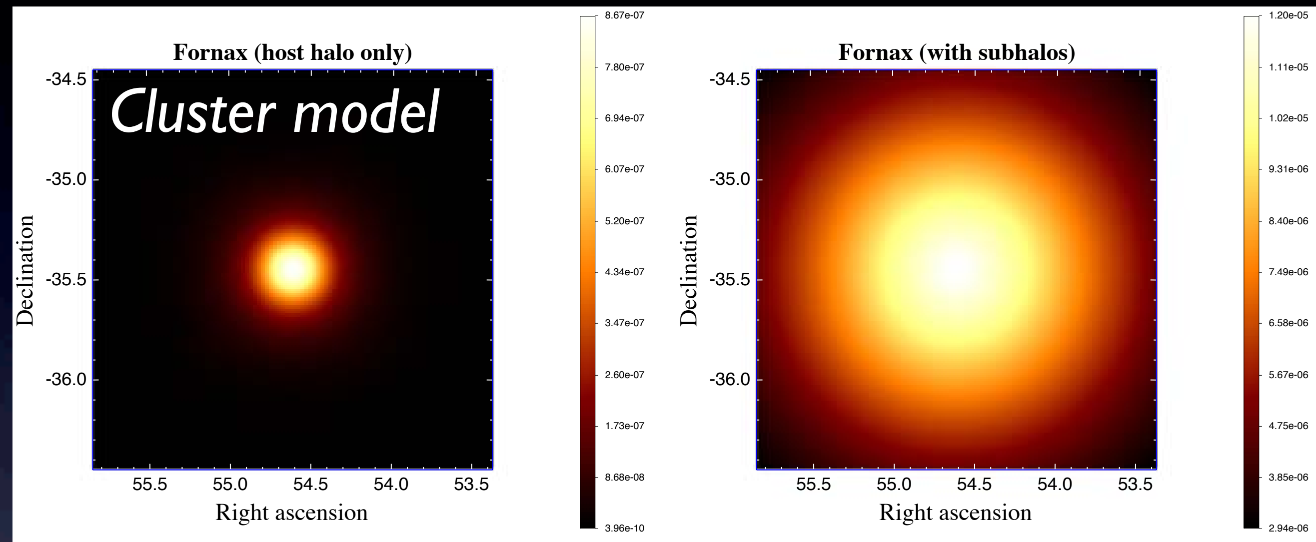
- There is no gamma-ray source at cluster location
- We then add cluster component at the center of the best-fit model map, to put upper limit on that component

Upper limits on cluster component

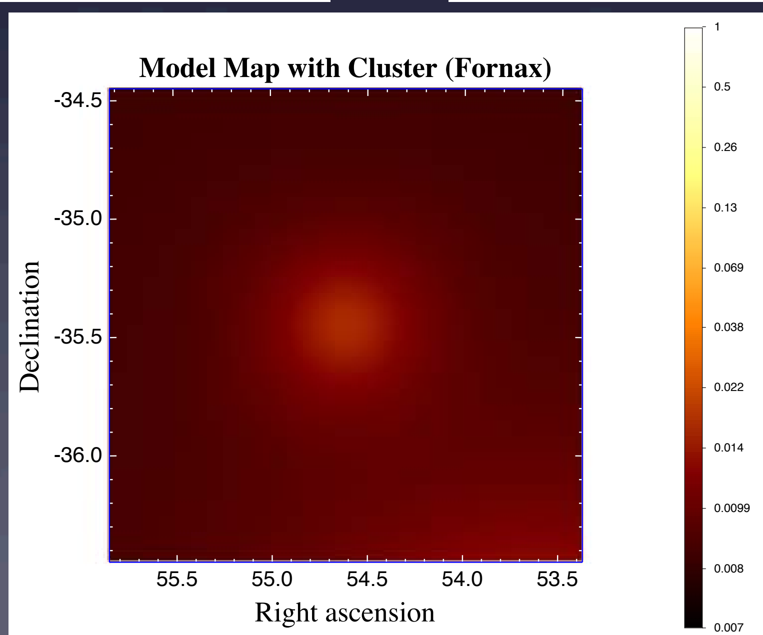
Analyze



With



Outcome

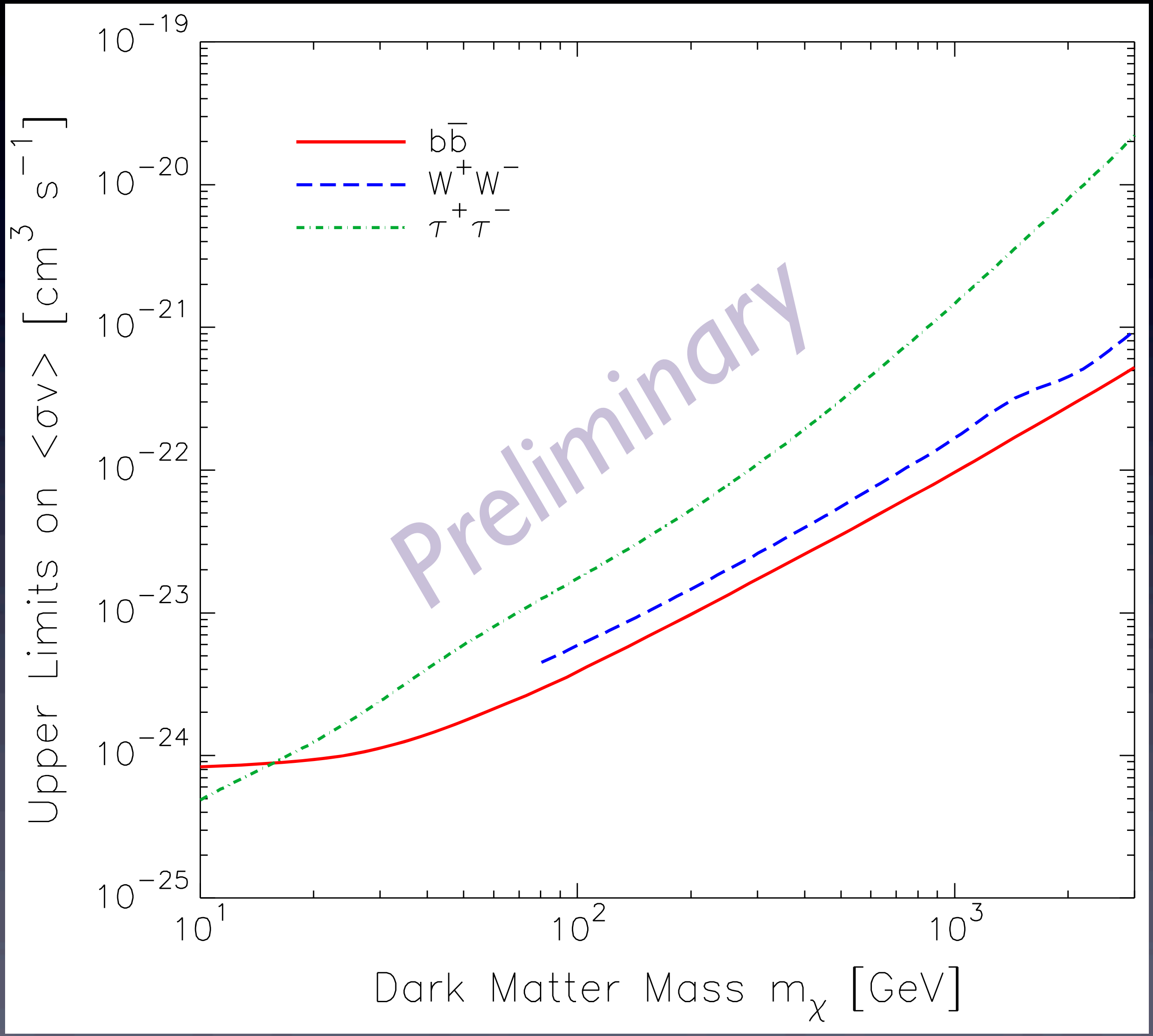


Best-fit model (almost isotropic background) and cluster component (no subhalos) allowed by 5%

95% CL upper limits on annihilation cross section

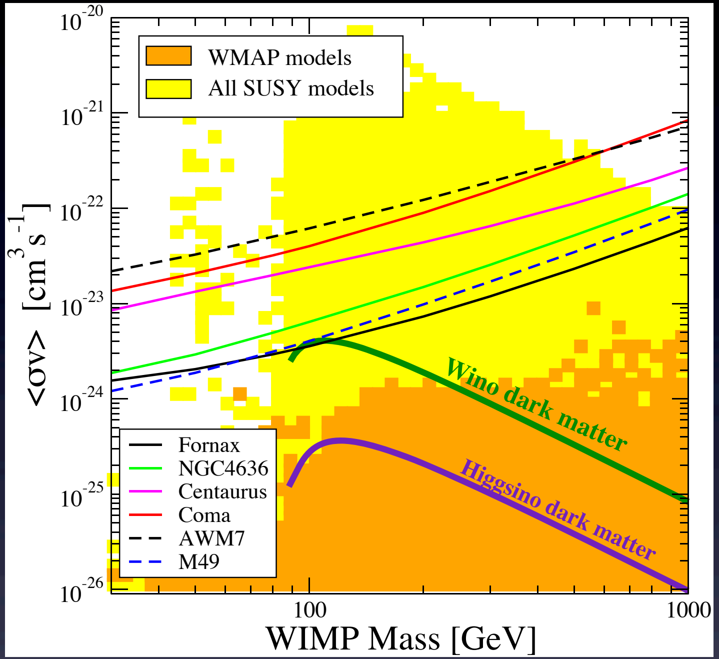
Limits on annihilation cross section from Fornax

Host halo only



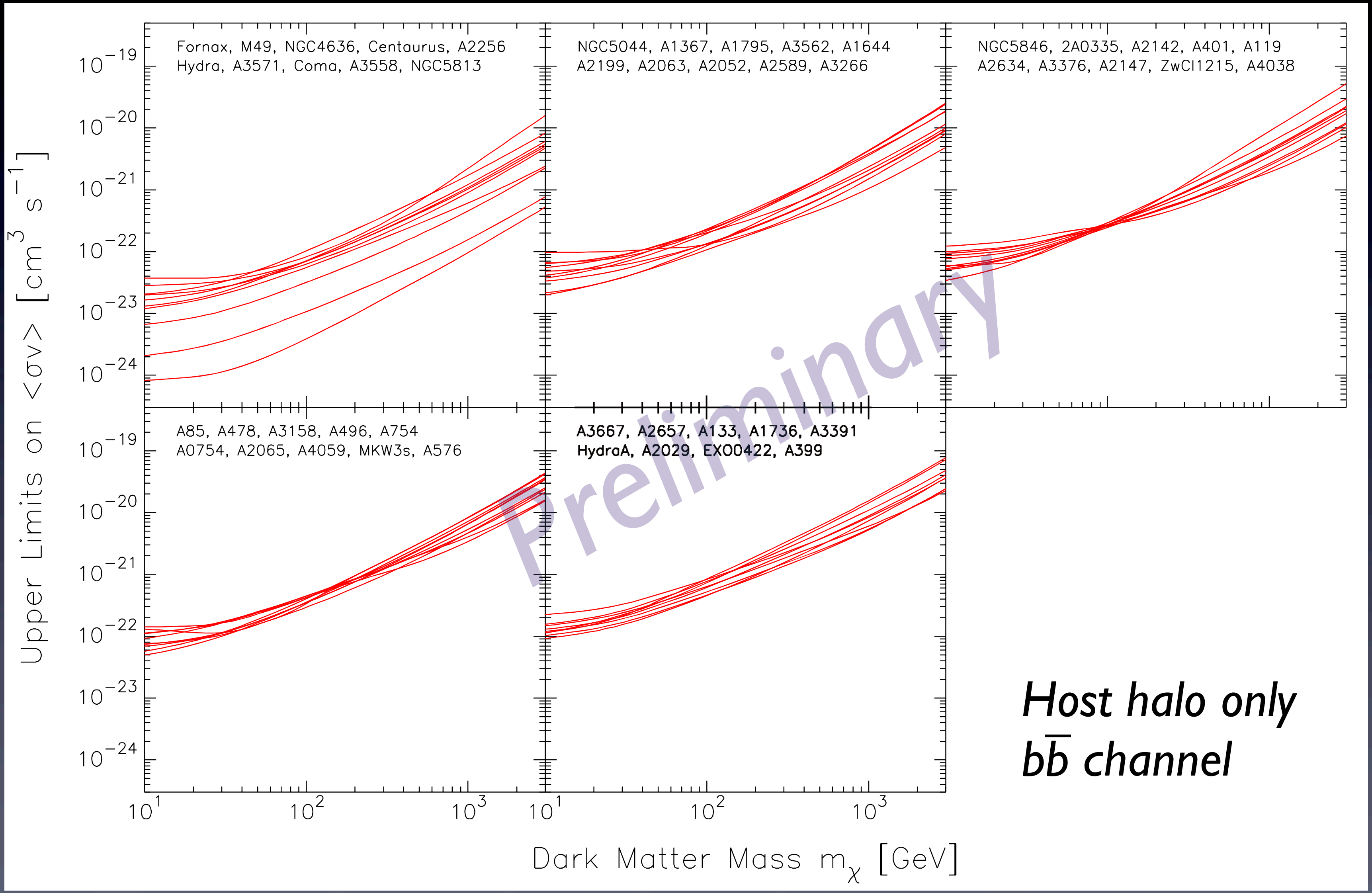
34-month data

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

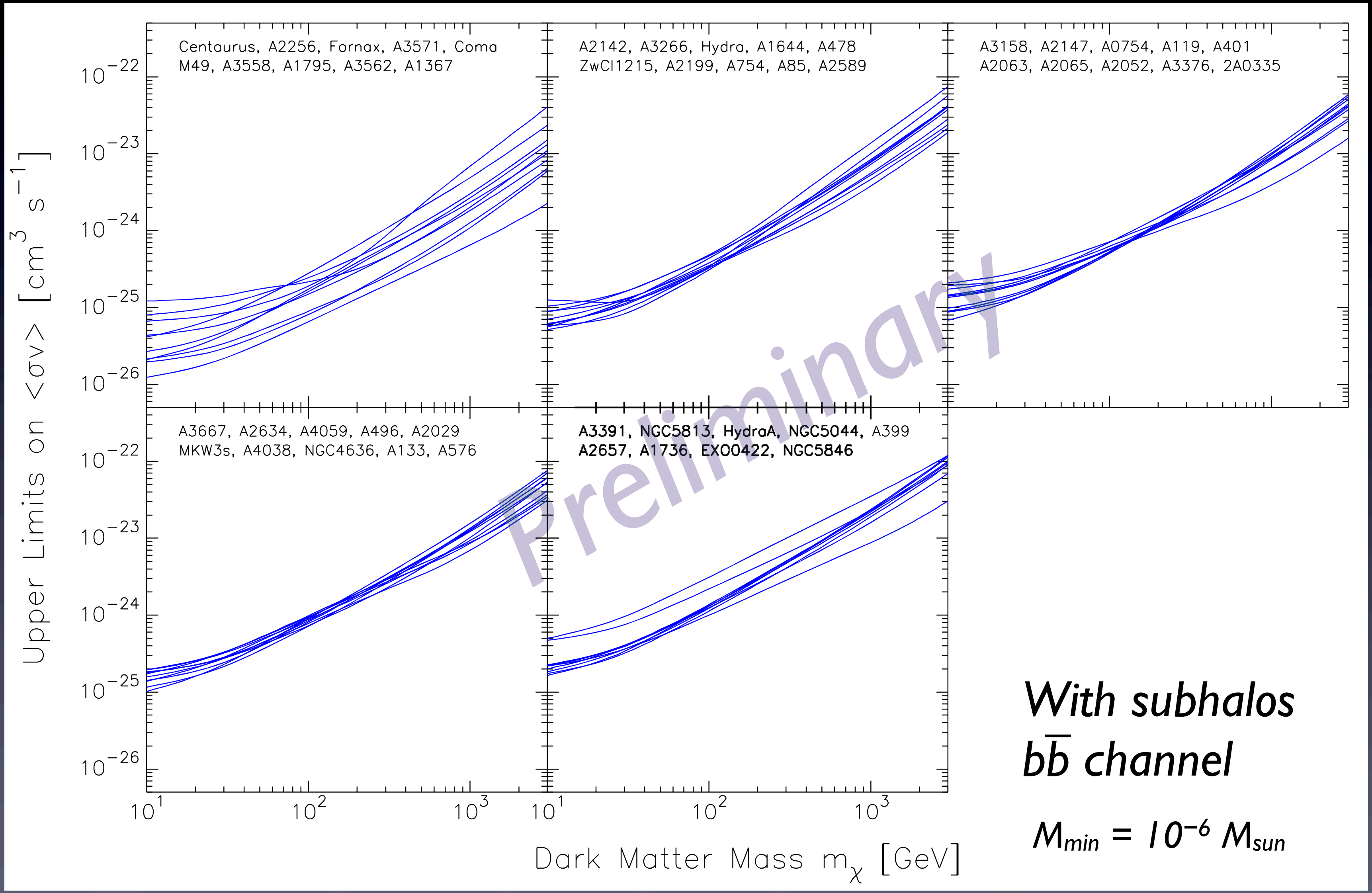


11-month data

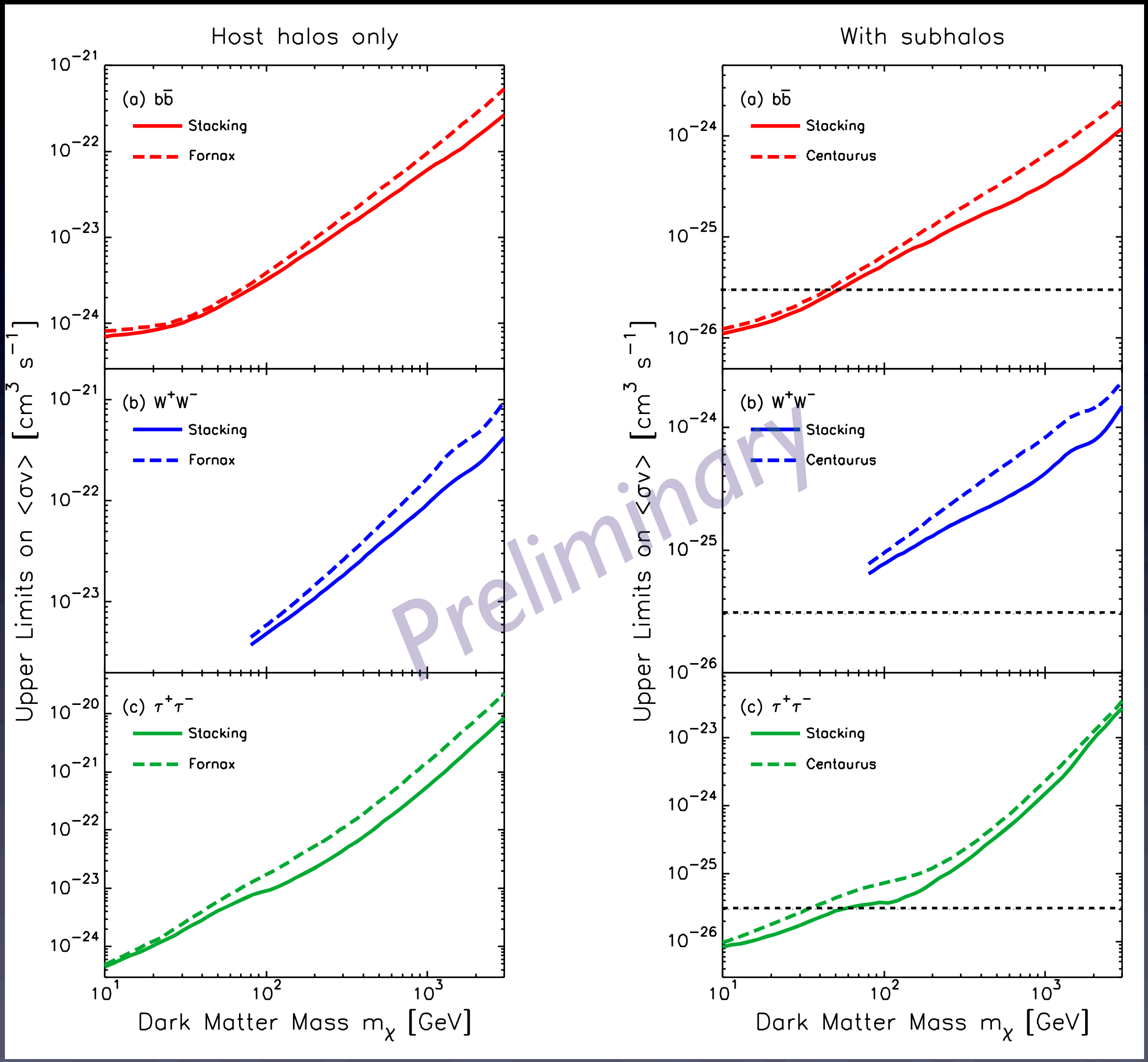
Cross section limits for all clusters



Cross section limits for all clusters

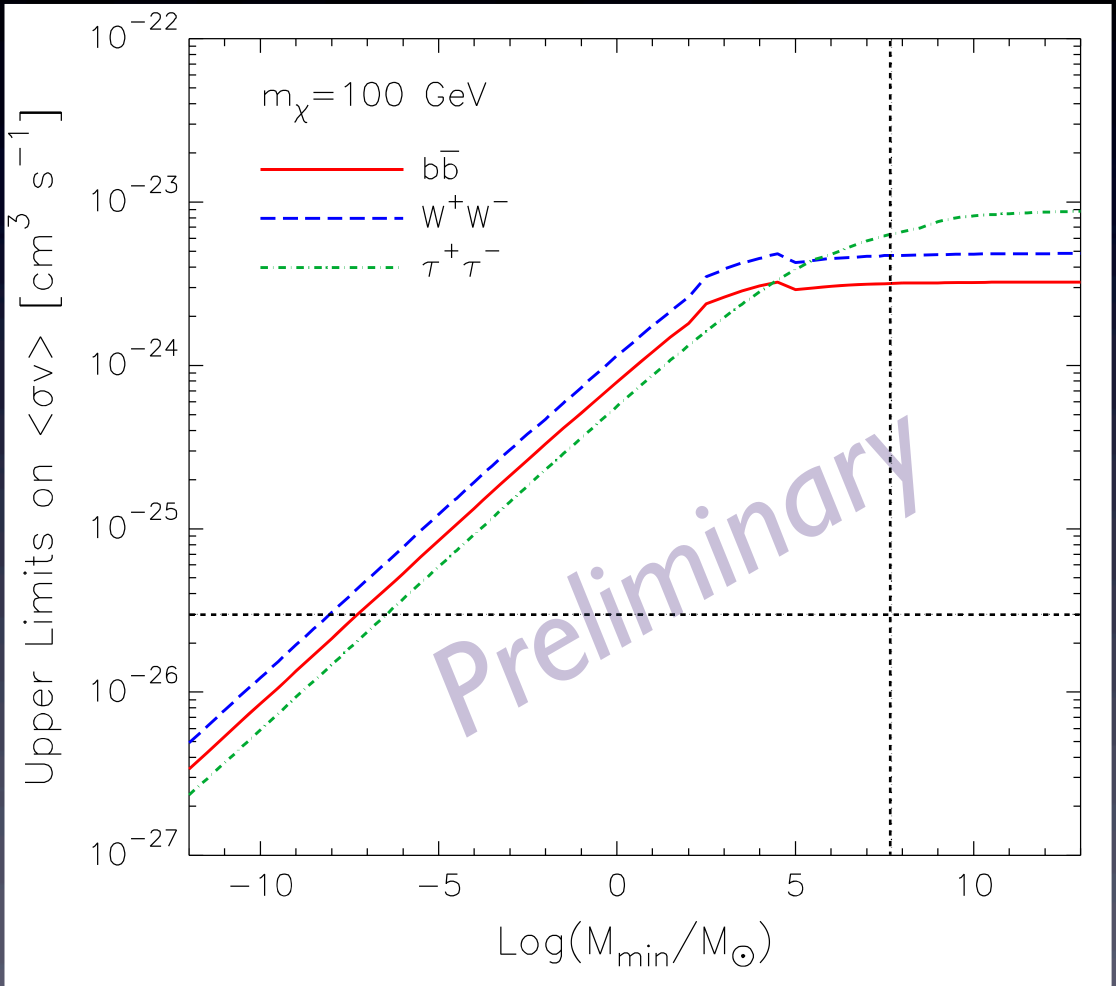


Cross section limits from stacking analysis



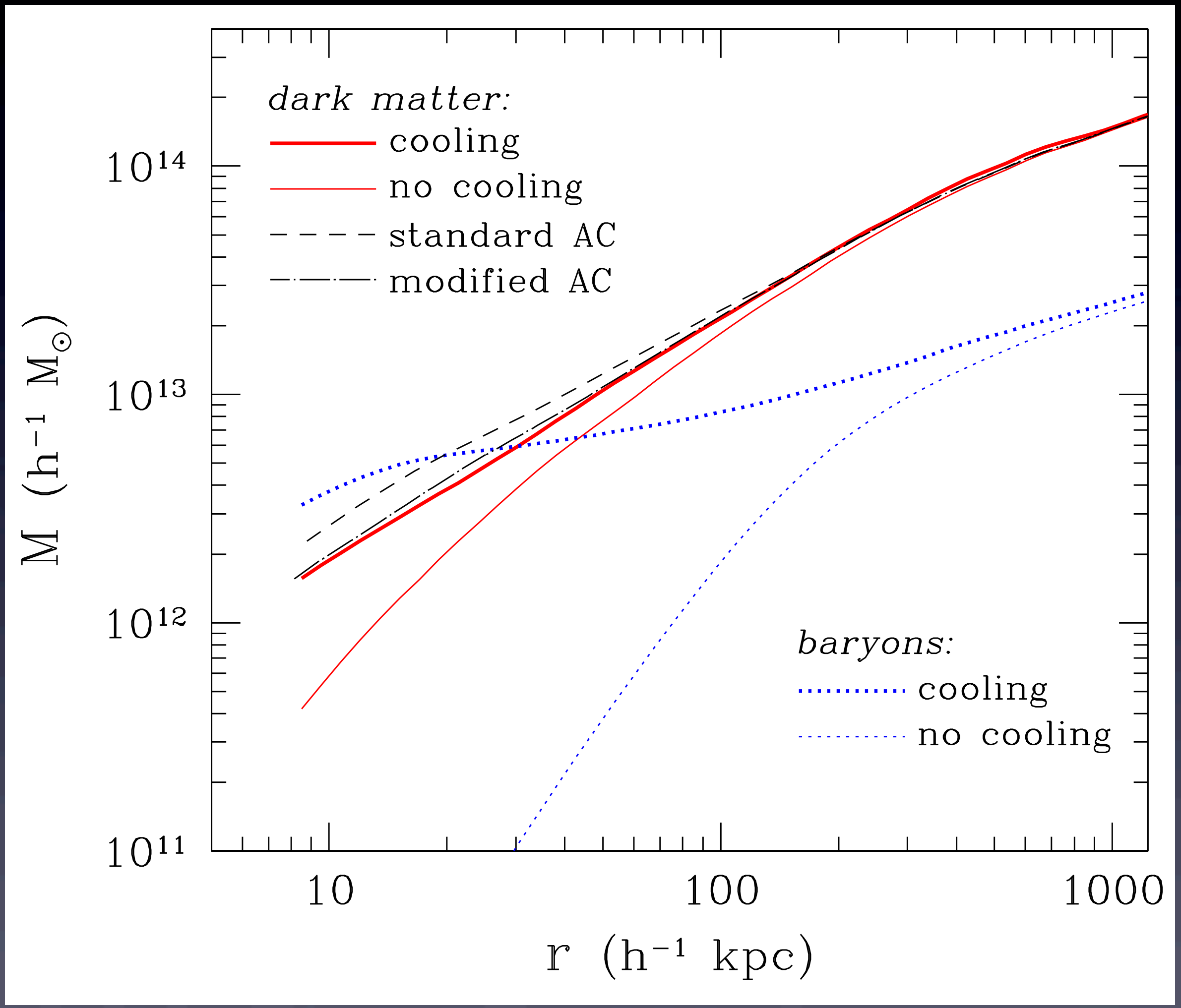
Limits improve by 10–20% (low masses) to a factor of 2 (high masses)

Dependence on minimum suhalo mass



- If the minimum subhalo mass is around Earth size, then the canonical value of annihilation cross section is excluded
- This does not depend on annihilation channel that much
- If the minimum mass is around the current resolution limit, then the host-halo component dominates the signal

Another effect: baryon contraction



Gnedin et al., *Astrophys. J.* **616**, 16 (2004); arXiv:1108.5736 [astro-ph.CO]

- Baryons lose energy and angular momentum due to radiation
- This will *increase* the gravitational potential toward the center
- Dark matter is also dragged toward the center as a result of this
- This affects annihilation flux by a factor of ~2–200 (preliminary)

Summary: galaxy clusters

- We analyzed 2.8-yr Fermi-LAT data for 49 galaxy clusters
  - Comparison made with the latest source models, diffuse backgrounds, and cluster models
  - Obtain upper limits on annihilation cross section
- Strongest limits are obtained with Fornax for smooth host-halo model, and with Centaurus for clumpy subhalo model
- Stacking clusters will improve limits by ~10–20% (low masses) to a factor of 2 (high masses)
- Astrophysical implications will be discussed (future)

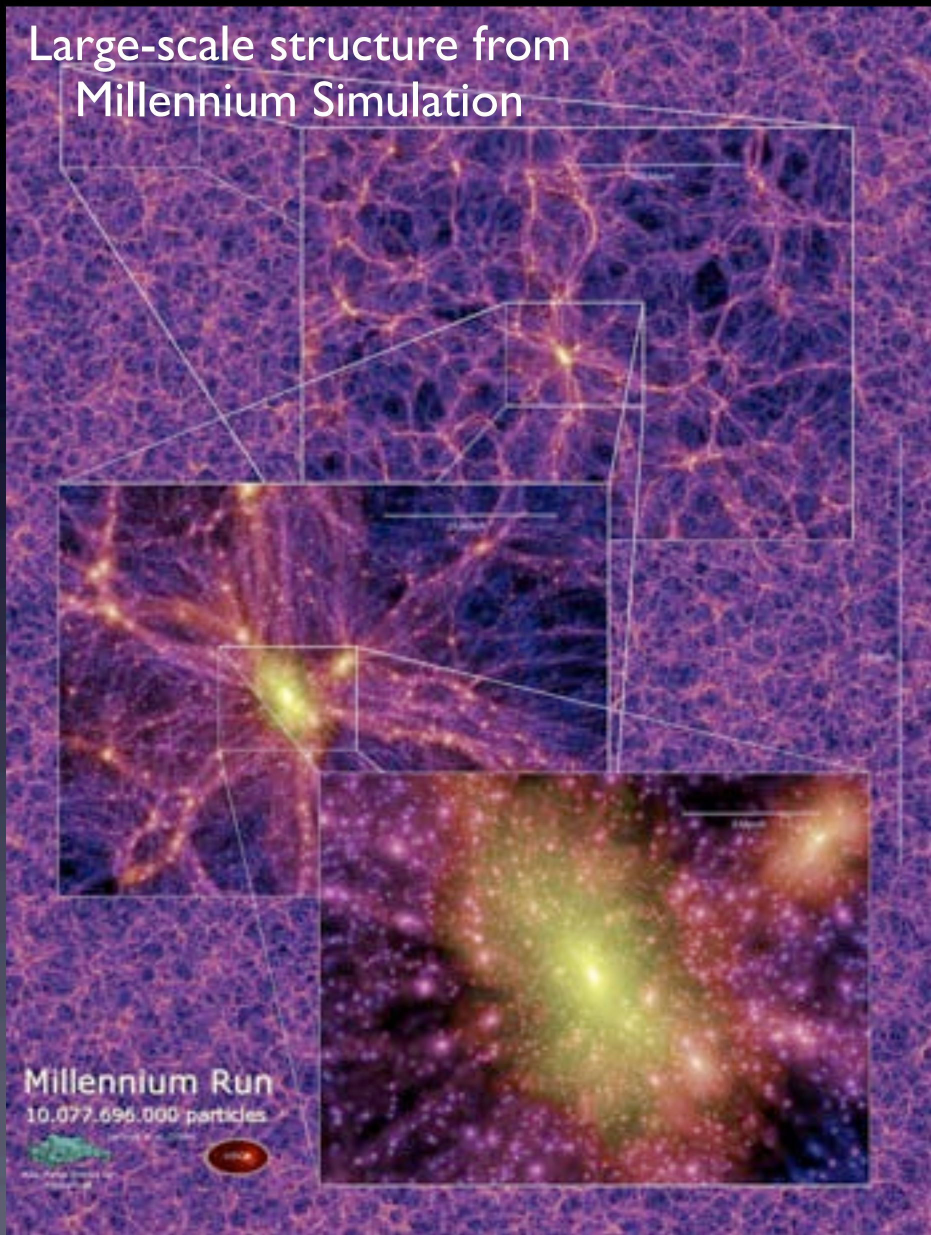
Plan of this talk

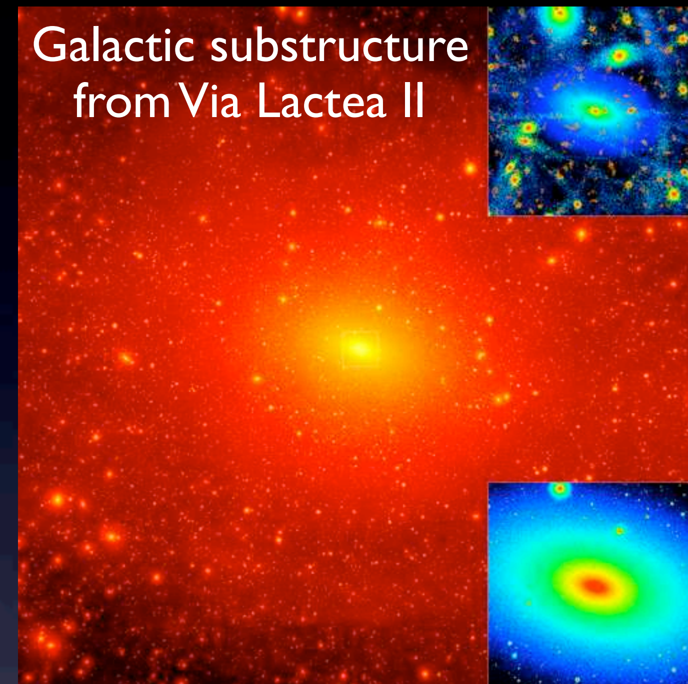
- Gamma rays from dark-matter annihilation from galaxy clusters

- Angular power spectrum of the gamma-ray background from dark matter annihilation

Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)
Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)
Ando, *Phys. Rev. D* **80**, 023520 (2009)

Gamma-ray background from dark matter

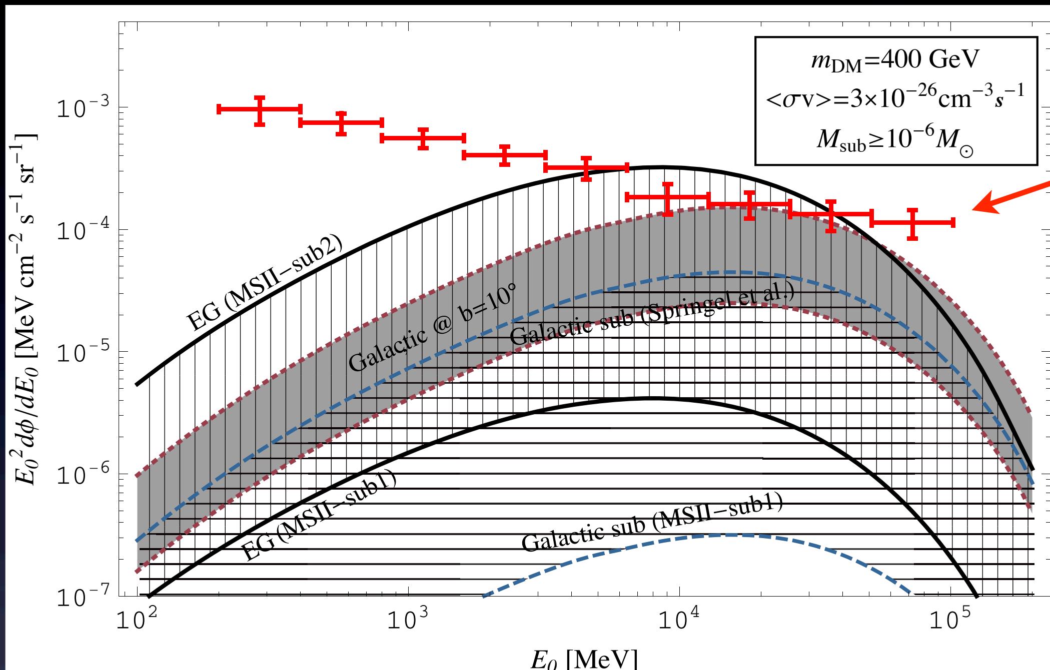




Diemand et al., *Nature* **454**, 735 (2008)

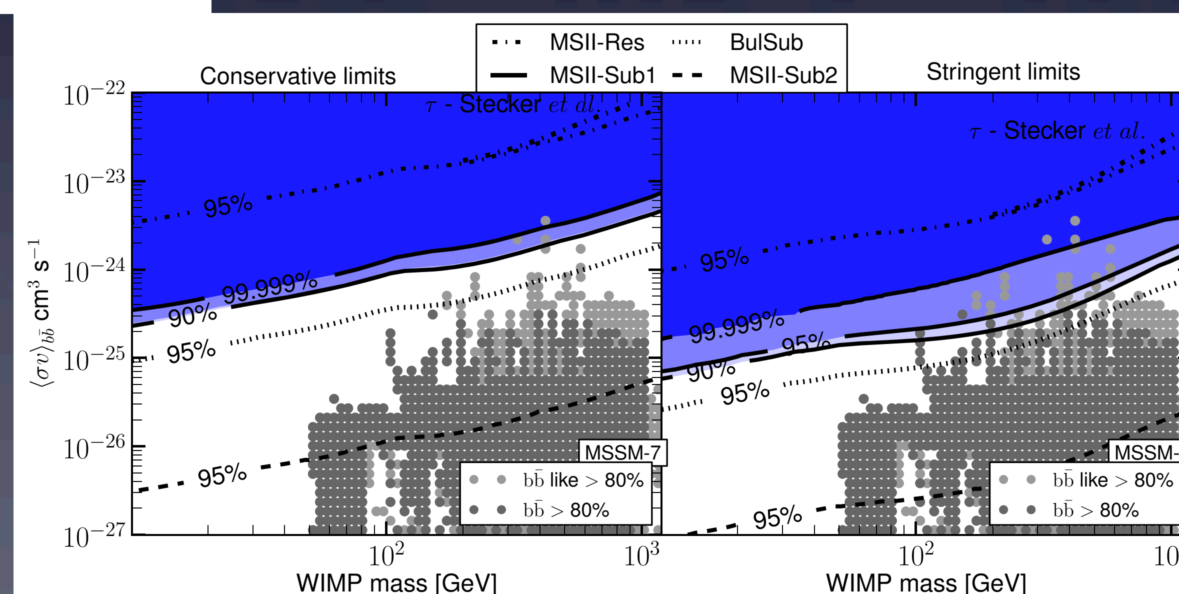
- Dark matter is annihilating everywhere!
- It gives contribution to the gamma-ray background

Fermi 1st year result on cosmological annihilation

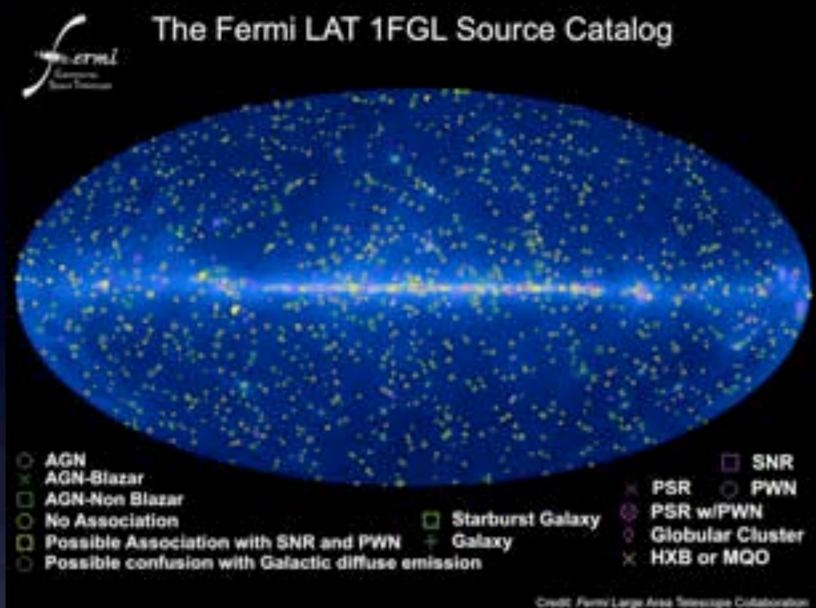


Spectrum of "isotropic" gamma-ray background

Fermi-LAT, Abdo et al., *JCAP* **04**, 014 (2010)

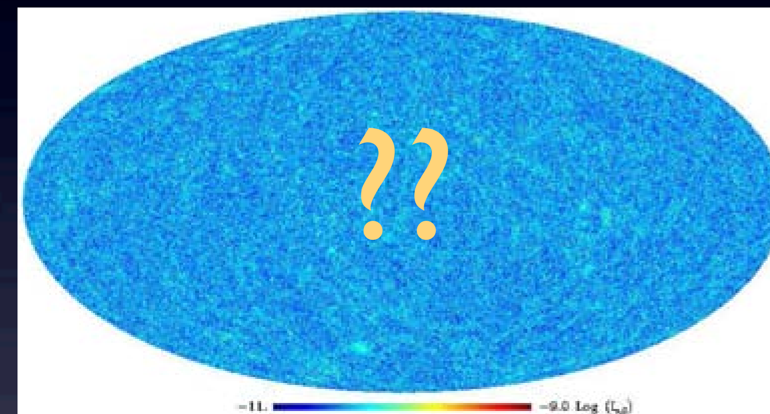


Diffuse gamma-ray background



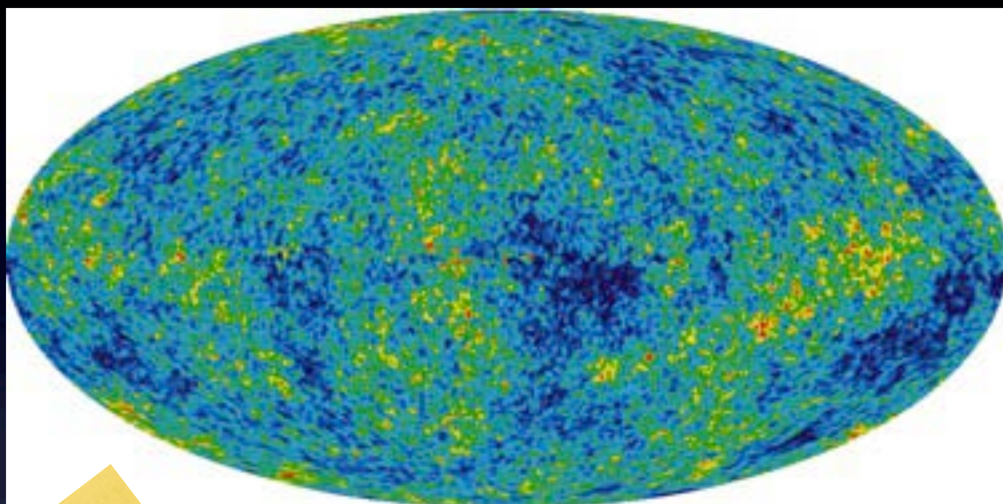
Remove all the identified sources

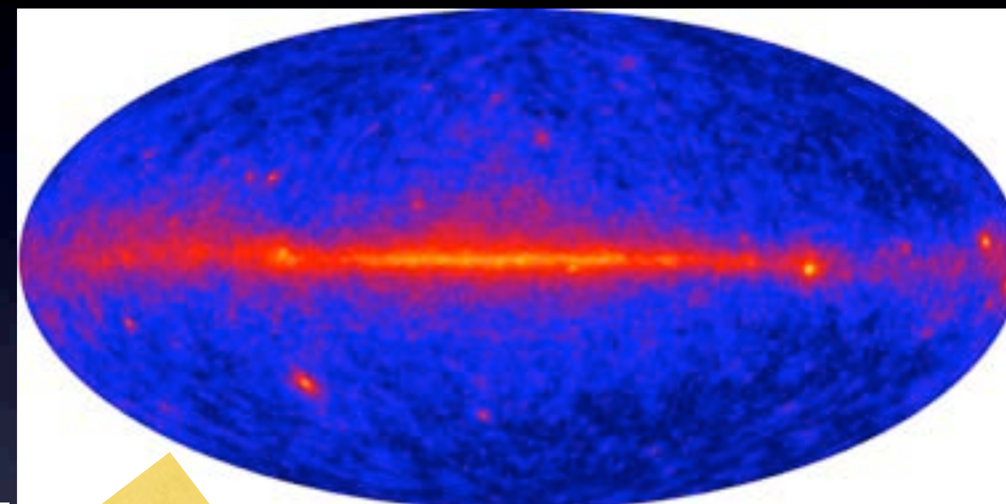
Zavala, Springel, Boylan-Kolchin, *MNRAS* **405**, 593 (2010)

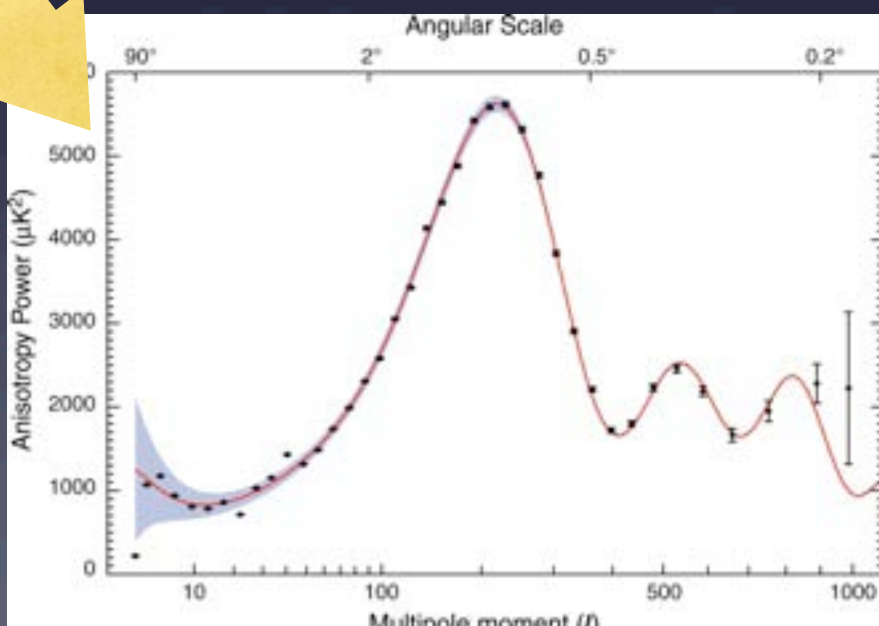


- What would the gamma-ray background map look like?
- What information on dark matter can we extract from the gamma-ray map, and how?

2-point statistics: Angular correlation



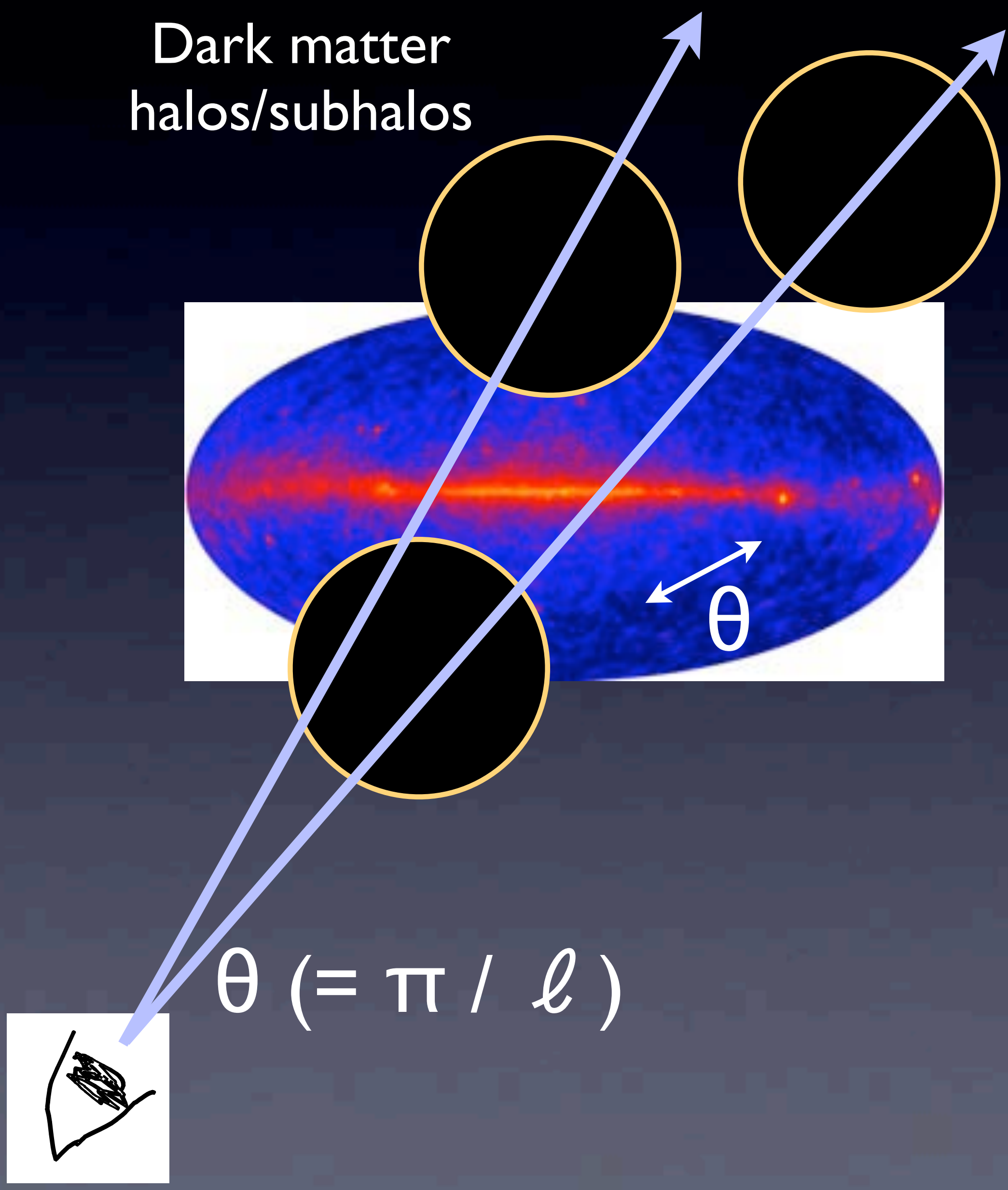




?

- Can Fermi do the same as WMAP in gamma-ray sky?

Angular power spectrum

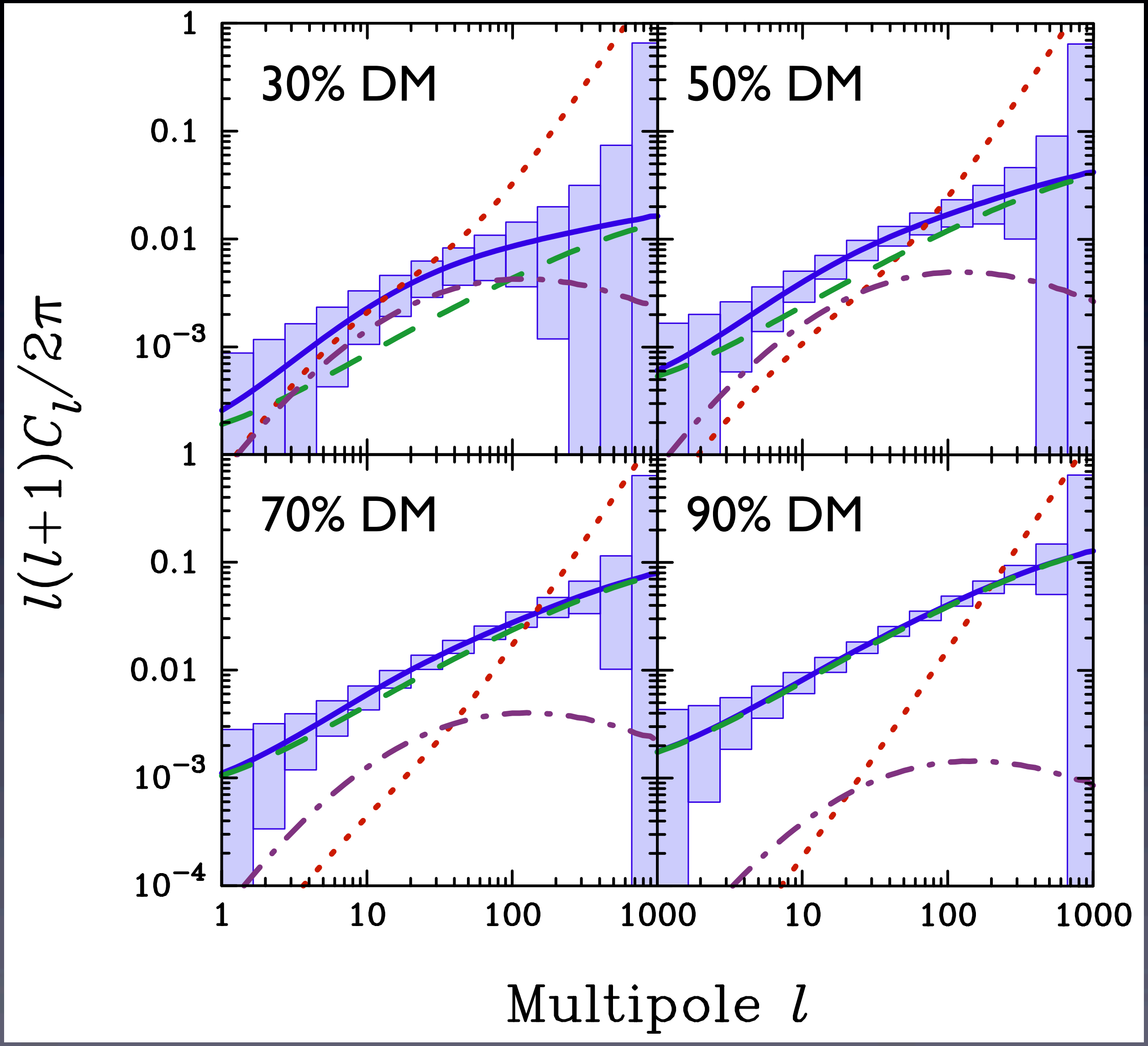


- Take spherical harmonic expansion → square of coefficient: power spectrum
- Multipole ℓ is related to θ through $\theta = \pi / \ell$
- We need to know how the halos are distributed, mass function, and density profiles
- We apply "halo model" to compute the power spectrum

Ando, Komatsu, *Phys. Rev. D* **73**, 023521 (2006)

Detectability of the angular power spectrum

Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)



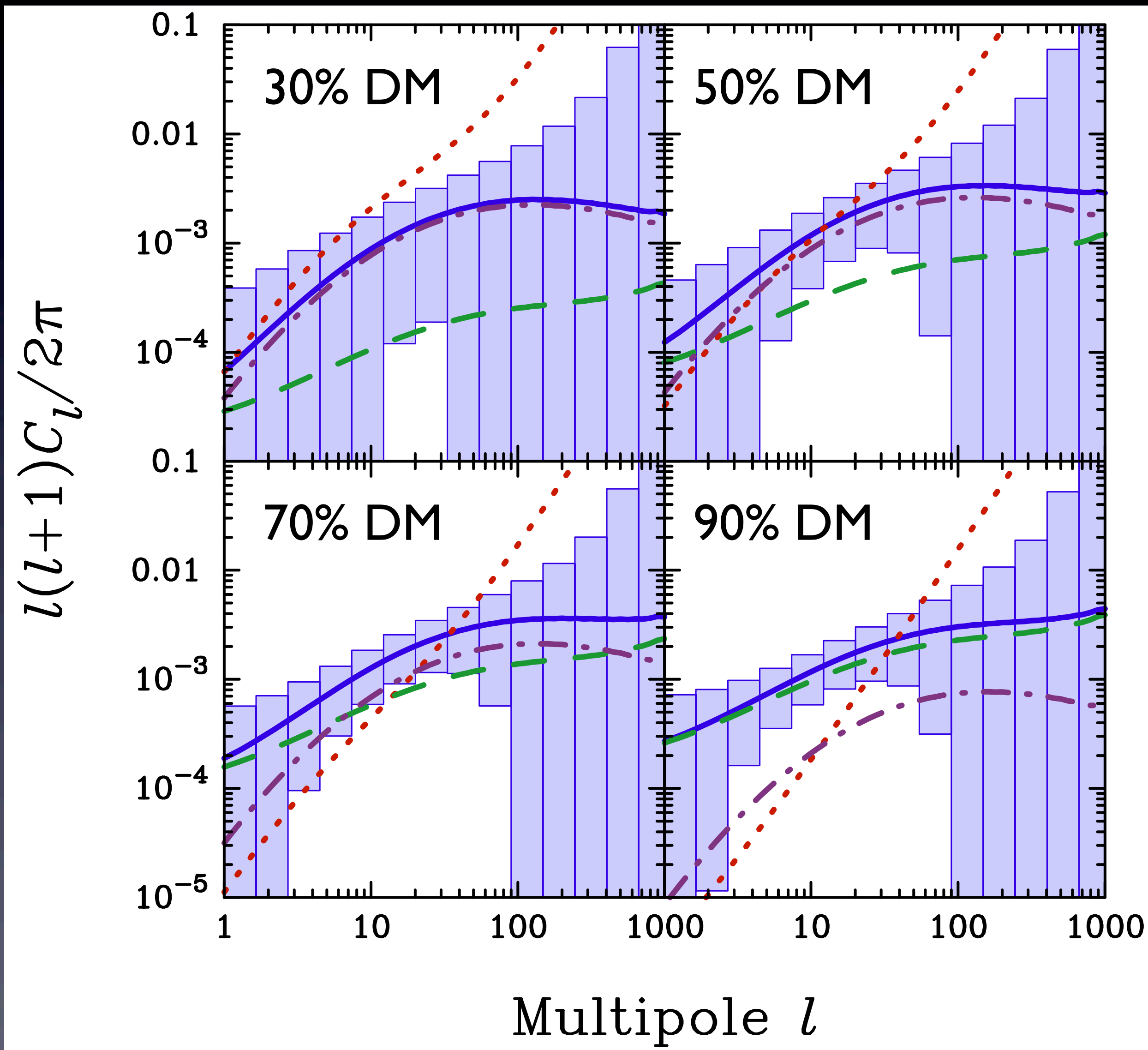
"Subhalo-dominated"

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross correlation

- Dark matter mass: 100 GeV
- At 10 GeV for 2-yr exposure
- Blazar component is easily discriminated
  - Blazar power spectrum is nearly independent of energy

“No substructure” or “smooth halo” limit

Ando, Komatsu, Narumoto, Totani, *Phys. Rev. D* **75**, 063519 (2007)



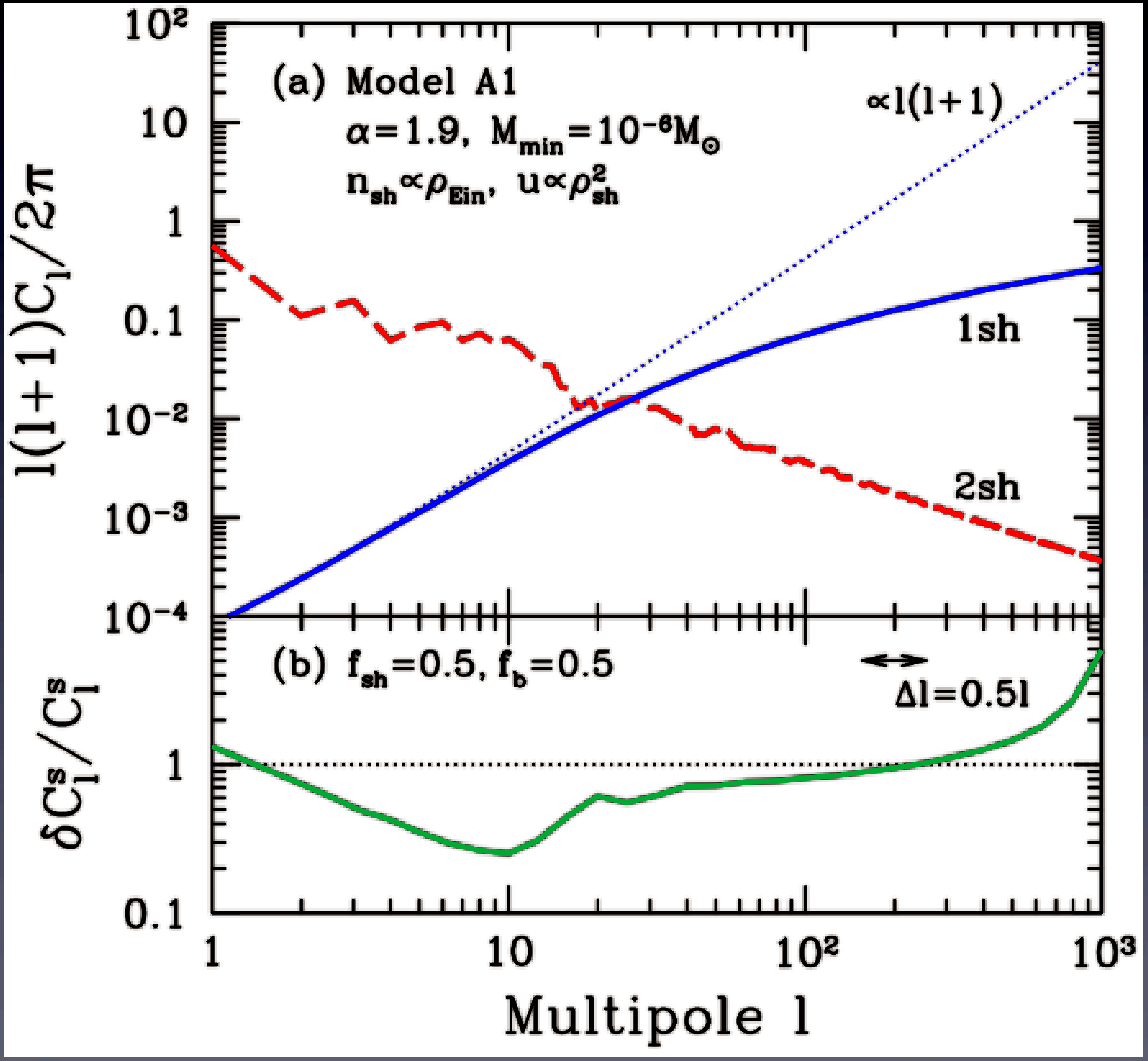
“Host-halo-dominated”

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross correlation

- $M_{min} = 10^{-6} M_{sun}$
- Our best estimate: “If DM annihilation contributes > 30% of the mean intensity, Fermi should be able to detect DM anisotropy”

Anisotropy due to Galactic subhalos

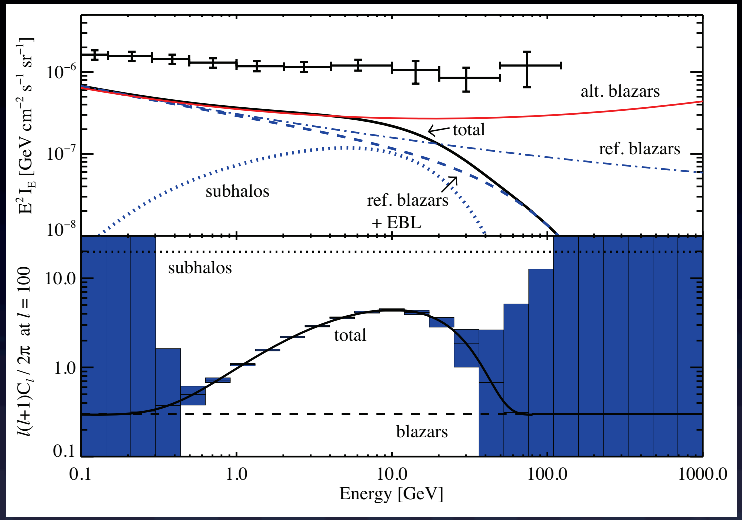
Ando, *Phys. Rev. D* **80**, 023520 (2009)

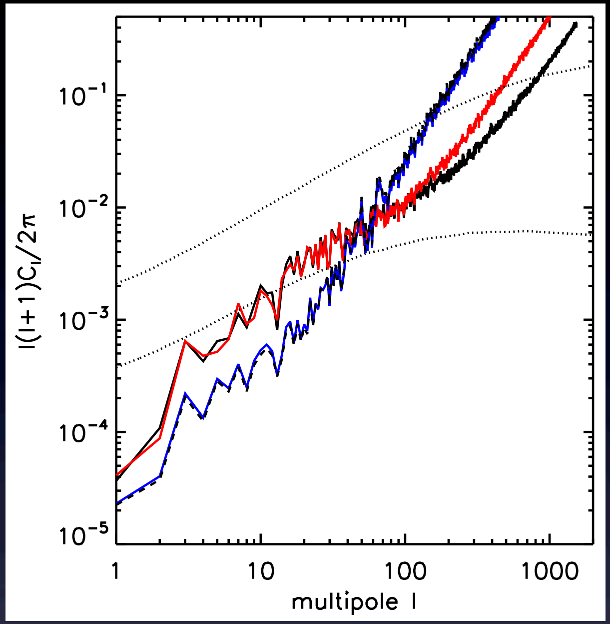


- $M_{min} = 10^{-6}\, M_{sun}$
- 1sh term dominates at smaller scales
- Deviation from shot noise is due to spatial extention of subhalos
- Good chance of detection if 50:50 mixture with blazars

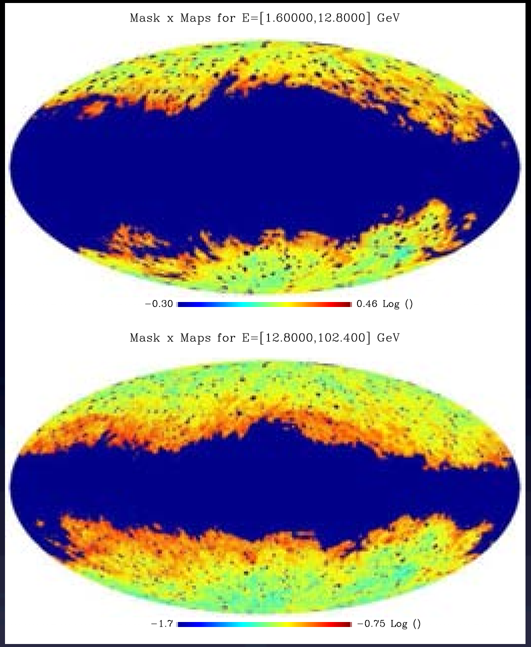
Followup studies

Siegal-Gaskins, Pavlidou (2009)





Zavala, Springel, Boylan-Kolchin (2010)



Cuocco et al. (2010)

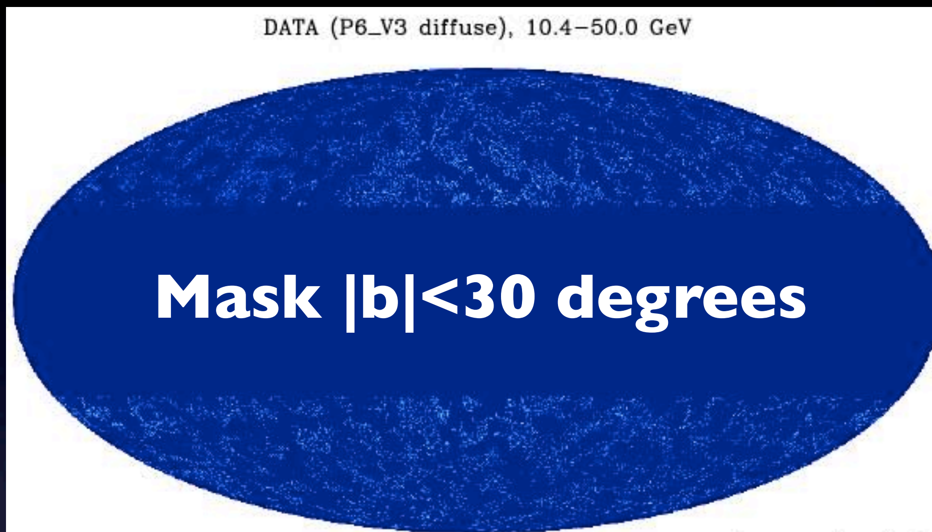
- Dark matter annihilation

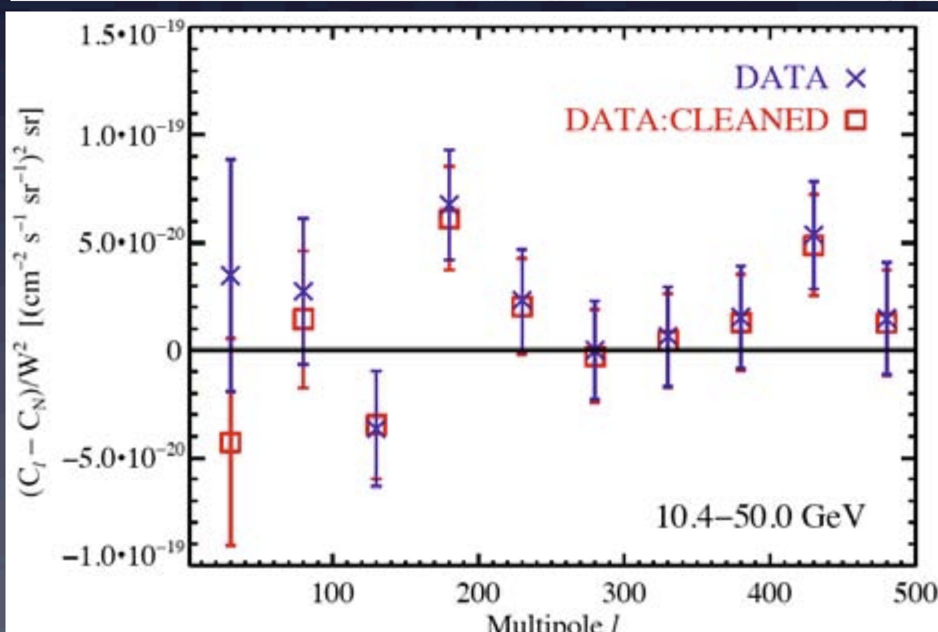
  Cuocco et al. 2007, 2008; Siegal-Gaskins 2008; Zhang, Sigl 2008; Taoso et al. 2008; Fornasa et al. 2009; Siegal-Gaskins, Pavlidou 2009; Zavala et al. 2010; Hensley et al. 2010; Ibarra et al. 2010; Cuocco et al. 2010; Zhang et al. 2010

- Astrophysical sources

  Miniati et al. 2007; Ando, Pavlidou 2009; Siegal-Gaskins et al. 2010

Analysis ongoing...





From Komatsu's talk at IPMU, 2011

Fermi-LAT Collaboration + Komatsu

- So far the angular power spectrum is consistent with shot noise due to finiteness of the photon counts
- The real difficulty, though, is to remove astrophysical contribution (mainly from blazars)

Summary: gamma-ray background anisotropy

- Fermi will provide information on the origin of the gamma-ray background through anisotropy
  - This isn't just for dark matter, but *anything* contributing considerably
- From angular power spectrum, we see that if extragalactic DM component is > 30%, Fermi should discriminate it from blazars' in anisotropy
- Galactic subhalos might give larger power spectrum, and so detection would be more promising
- This series of research is now expanding farther, including energy dependence of power spectrum, 1-point PDF (Lee, Ando, Kamionkowski 2009), etc.

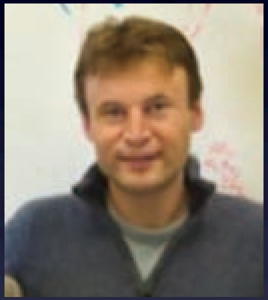
GRAPPA

- GRavitation and AstroParticle Physics Amsterdam

Kick-off members

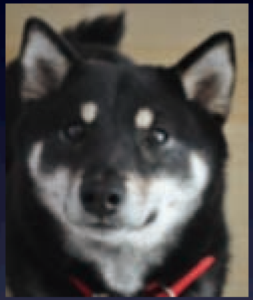
G. Bertone

P. Decowski

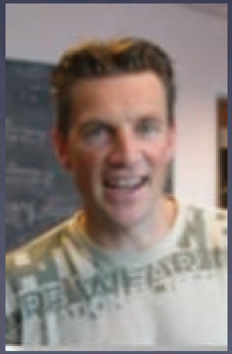


B. Freivogel

S. Ando



Existing members



J. de Boer

S. Bentvelsen

R. Wijers

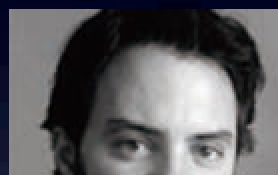
I amsterdam

GRAPPA

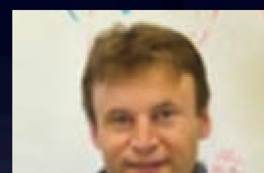
- GRavitation and AstroParticle Physics Amsterdam

Kick-off members

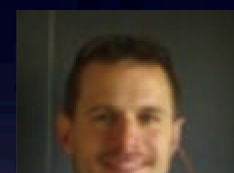
G. Bertone



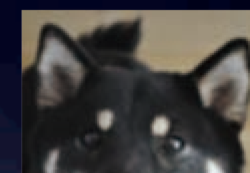
P. Decowski



B. Freivogel

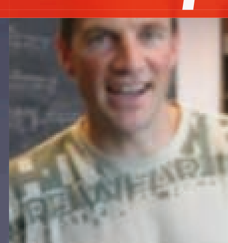


S. Ando

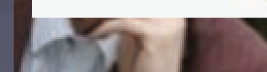


We welcome visits of enthusiastic students and postdocs (of course senior people, too)!

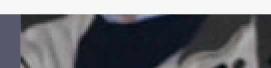
Existing members



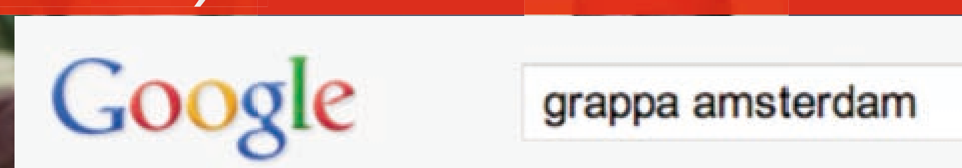
J. de Boer



S. Bentvelsen



R. Wijers



I amsterdam