ダークマター･エネルギー研究の最近の話題
ー宇宙物理学的側面からー

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(京大理)

高エネルギー宇宙の総合的理解
東大　宇宙線研究所　平成１６年3月8〜9日

Outline

- Indirect searches for dark matter neutralinos
  - Astrophysical uncertainties
  - Prospects for detection
  - Possible physical effects on astrophysical systems
    - Implications for the cooling flow problem of galaxy clusters
  - Comparison to direct/accelerator searches
- Searches for DM MACHOs
  - Constraint from binary destruction
  - M87 in the Vigro cluster: MACHO candidates
  - Cluster-cluster microlensing search for MACHOs
- Dark energy study by distant supernovae
  - A note on the systematic effect from dust extinction

Indirect detection of DM neutralinos by gamma-rays

SUSY Dark Matter (WIMPs, Neutralinos)

- The most popular theoretical candidate for the dark matter
  - SUSY: theoretically well motivated.
  - Lightest SUSY partners (LSPs) are stable by R-parity
  - Neutralinos (l.c. of SUSY partners of photon, Z, and neutral Higgs): the most likely LSP
  - Predicted relic abundance is close to the critical density of the universe

$$\langle \sigma \upsilon \rangle = 3\times 10^{-27} /(\Omega_{\chi} h^{2}) \ \mathrm{cm}^{3}\ \mathrm{s}^{-1}$$

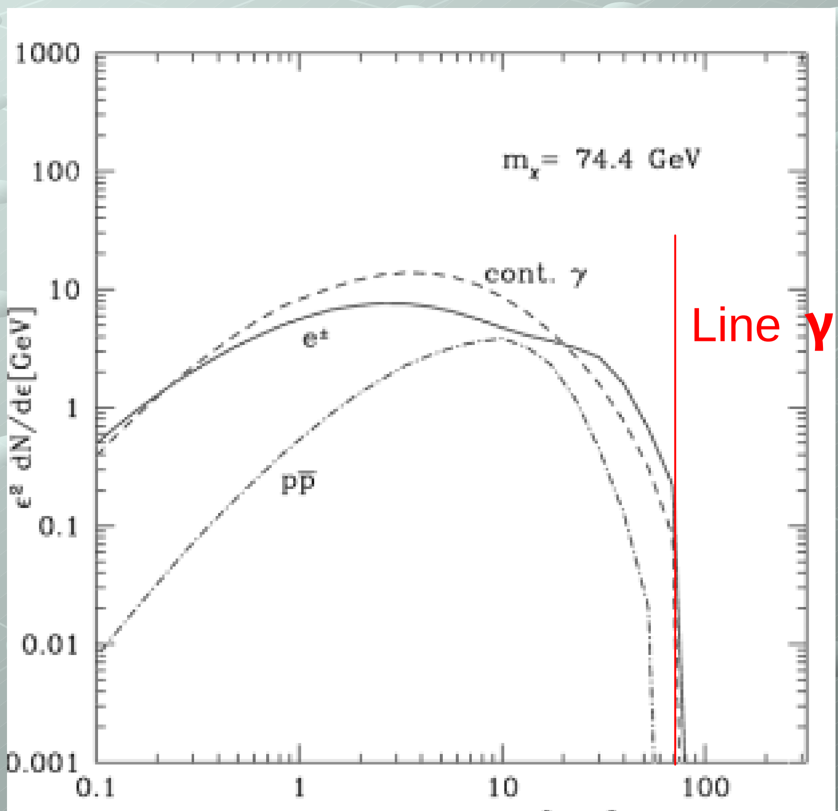
- Constraint on the neutralino mass
  - 50 GeV ~< m_{χ} <~ 10 TeV
  - Lower bound from accelerator experiments
  - Upper bound from cosmic overabundance

Search for Neutralino Annihilation Signals

- Line gamma-rays:
  - $\chi\ \chi \rightarrow 2\gamma$
  - $\chi\ \chi \rightarrow Z\gamma$
  - $\sigma v_{line} \sim 10^{-29}\ cm^3s^{-1} << \sigma v \sim 10^{-26}\ cm^3s^{-1}$
- Continuum gamma-rays, $e^{\pm}$, p, p-bar, ν's
- Search:
  - Line/continuum gamma-rays from GC, nearby galaxies
  - Positron/antiproton excess in cosmic-rays

Annihilation yields by hadron jets

- Annihilation energy goes to gammas, $e^{\pm}$,p, p-bars, neutrinos as: ~1/4, 1/6, 1/15, 1/2
- Particle energy peaks at: 0.05, 0.05, 0.1, 0.05 $m_\chi c^2$.
  - (From DarkSUSY package, Gondolo et al. 2001)
  - Most energy is carried by ~GeV particles for m_χ<100GeV



An example for yield Spectra from DarkSUSY

Gamma-ray search

- Search regions:
  - The Galactic Center
  - Nearby dwarf galaxies, MW substructure (Sgr, Draco,…)
  - M31
  - M87
- Uncertainties:
  - Density profile of DM in the center
    - Core? Cusp?
    - NFW? Moore? …

$$\mathrm{NFW}: \rho \propto \frac{1}{x\ (1+x\ )^2}$$

$$\mathrm{Moore}: \rho \propto \frac{1}{x^{1.5}(1+x^{1.5})}$$

$$\mathrm{Burkert}: \rho \propto \frac{1}{(1+x)(1+x^2)}$$

$$(x = r/r_c)$$

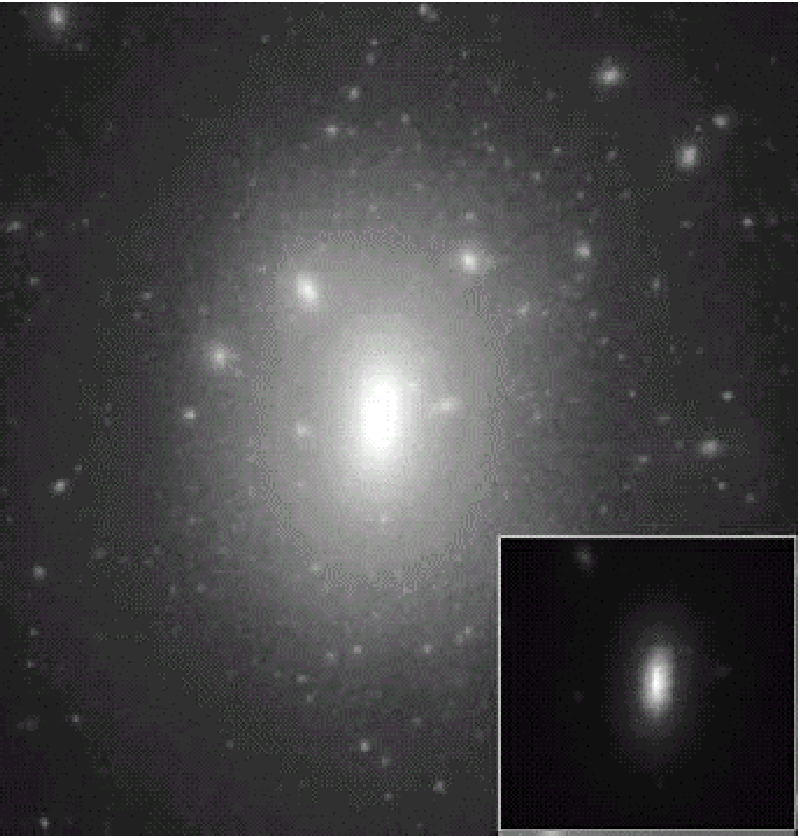
Peirani et al. 2004

Table 1. Reduced intensity in the direction of the galactic centre

Profile	$\int \rho^2 ds$ (GeV^{2}cm^{-5})	Reference
Moore	3.3×10^{26}	[33]
NFW	2.8×10^{25}	[45]
core	3.0×10^{22}	[45]
cusp	2.4×10^{22}	[46]
NFW	5.2×10^{25}	[34]
SWTS	1.8×10^{24}	[34]

Annihilation from a simulated halo

Stoehr et al. 2004



ure 1. The distribution of DM in our highest-resolution simulation
.3n. The region displayed is a cube of side 270 kpc, i.e. 1 times r_{200}.
ch particle is weighted by its local density so that the picture represents
image in annihilation radiation. The main image has a logarithmic inten-
scale, whereas the small image reproduces the centre on a linear intensity
le. This figure is available in colour in the online version of the journal
Synergy.

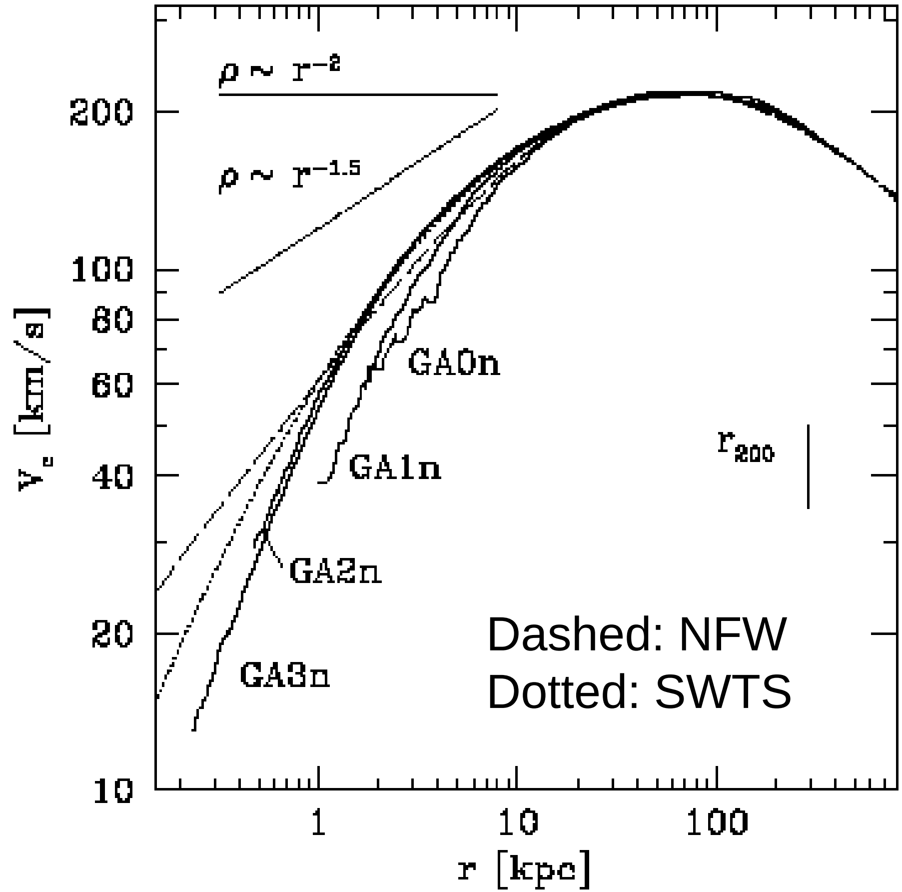
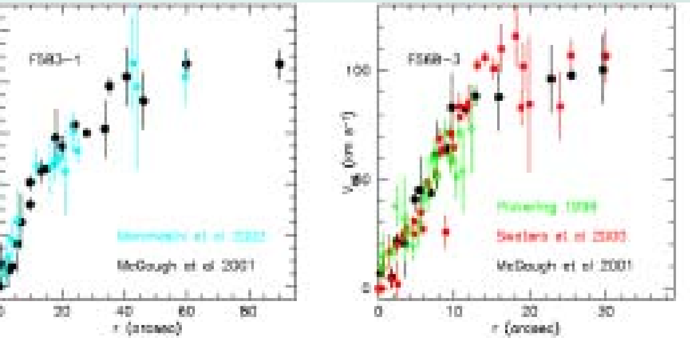


Figure 2. Circular velocity curves for the simulations GA0n, GA1n, GA
and GA3n. The vertical line indicates the location of the virial radius r_2
The best-fitting NFW profile with concentration $c_{NFW} = 10$ is plotted
long dashes. A fit of the form proposed by SWTS with $a = 0.17$ is show
in dots. At small radii, the slope for GA3n is considerably below that corr
sponding to a density profile with $\rho \propto r^{-1.5}$.

Image for **ρ** ^{2}

The core/cusp problem of LSB galaxies



igure 1. Comparison of raw Hα rotation curves observed by independent groups. *Left panel:* F583-1. Circles: data from McGaugh, ubin & de Blok (2001). Squares: data from Marchesini et al. (2003). *ight panel:* Circles: data from McGaugh et al. (2001). Squares: data om Swaters, Madore & Trewhella (2000). Asterisks: data from Pickring (1998).

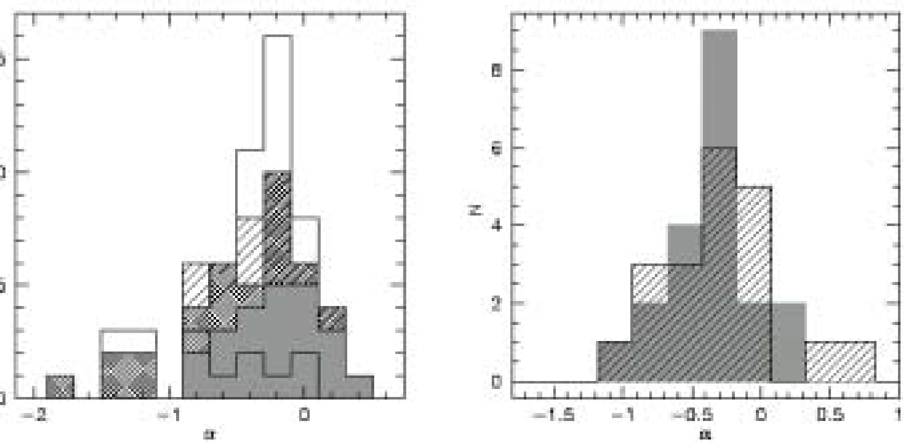
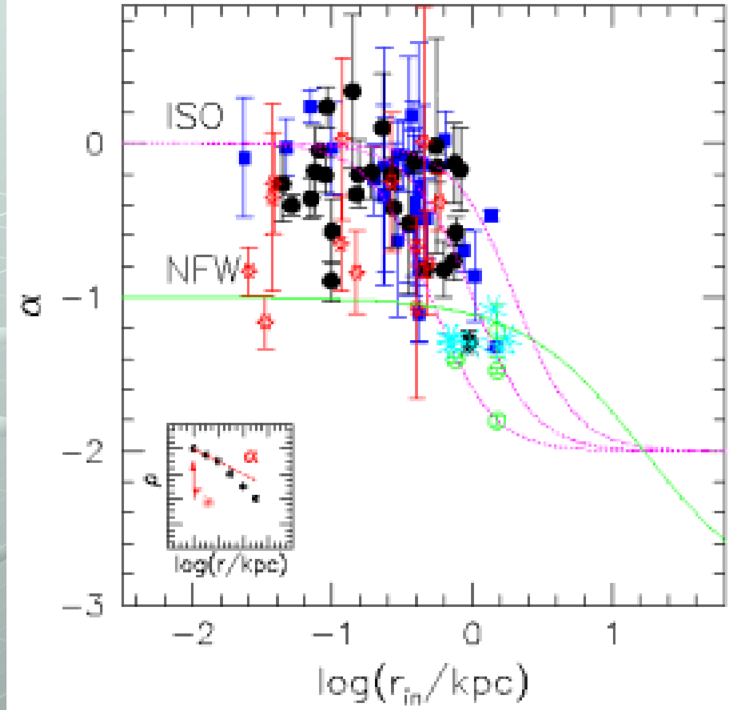


Figure 2. *Left:* Histogram of inner mass-density slopes. See text for explanation. *Right:* Distribution of the mass-density slopes of galaxies rom de Blok et al. (2001a) for which photometry and HI are available. Full grey histogram: minimum disc. Open, hatched histogram: nonminimum disc, $M/L_*(R) = 1.4$.



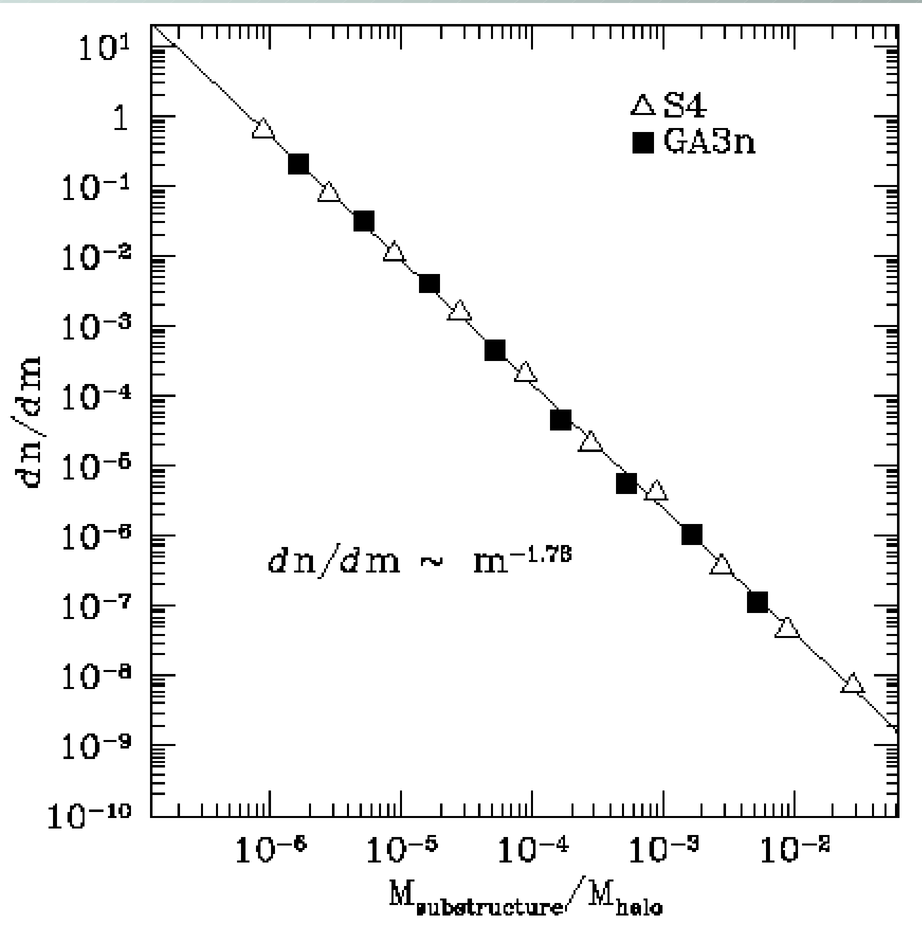
- Low surface brightness galaxies: DM dominated
- Alpha=1.5 (Moore) rejected, alpha=1(NFW) marginally rejected

De Block ‘03, astro-ph/0311117
Swaters ’03, astro-ph/0311480

Halo substructure (1)

- 5-10% of halo mass in substructure/subhalos
- Power-law mass function for subhaloes
- Substructure could enhance the annihilation signal
  - Calcaneo-Roldan & Moore '00; Tasitsiomi & Olinto '02; Taylor & Silk '03)

Stoehr et al. '04



ure 3. Subhalo mass functions for the GA3n (Milky Way) and S4 (cl

Halo substructure (2)

- Subhalos are less cuspy and less dense, and enhancement is at most a factor of a few (Stoehr et al. ’04)

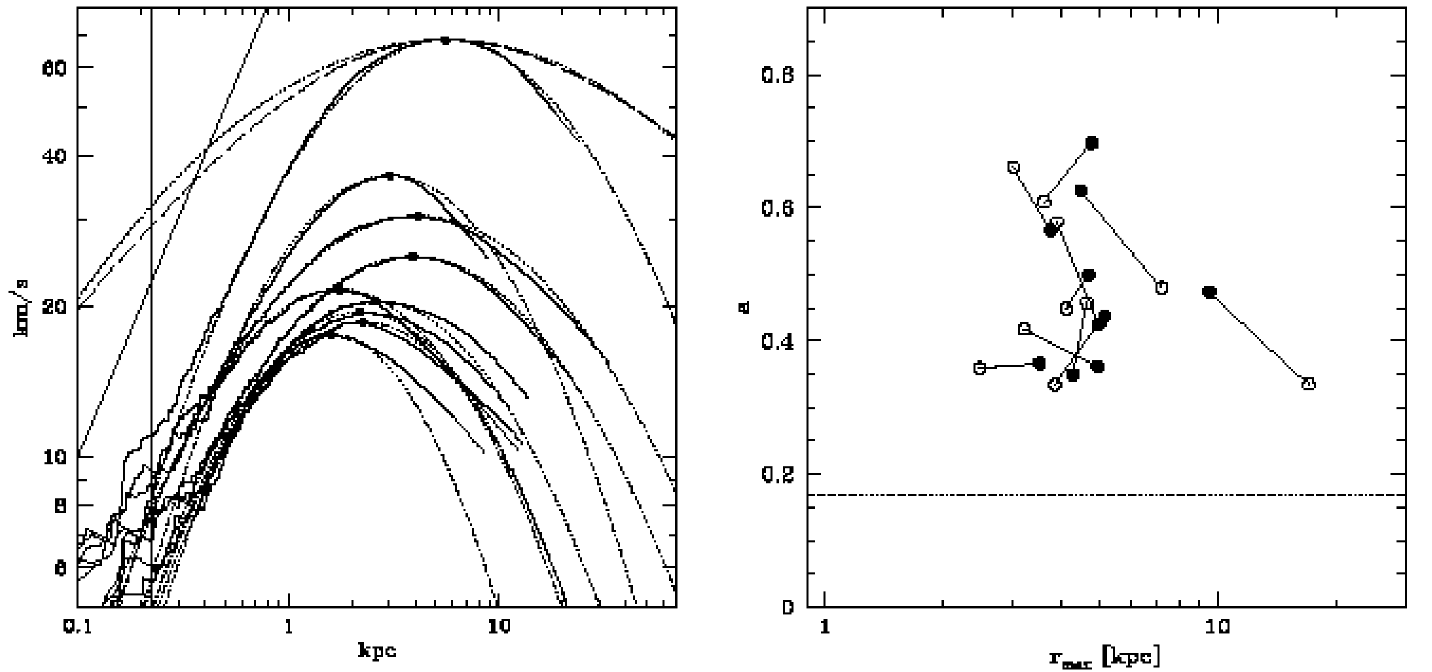
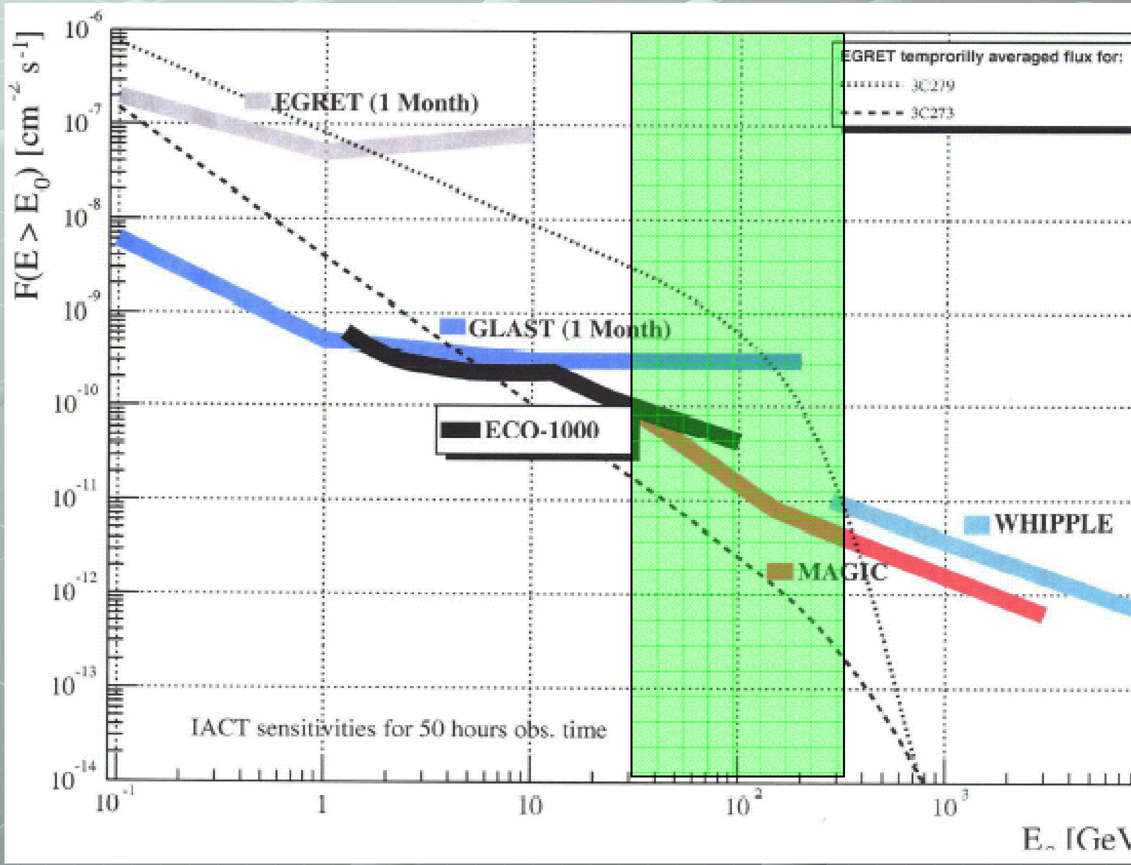


Figure 4. Left-hand panel: Circular velocity curves for the GA3n subhaloes ranked 1, 5, 10, … 40 in mass (solid) together with corresponding SW (dotted). For comparison, an NFW profile (dashed) and an SWTS profile with $a = 0.17$ (the value for the main halo) are overplotted on the most r subhalo. The vertical solid line shows the softening length; the diagonal line shows the profile slope corresponding to a constant density. Right-hand Values of a and r_{max} (the radius of maximum circular velocity) for matching subhaloes in GA2n (open) and GA3n (filled). The horizontal line is $a = 0.$ value for the main halo.

Stoehr et al. ‘04

Detectability: GLAST vs. ACTs

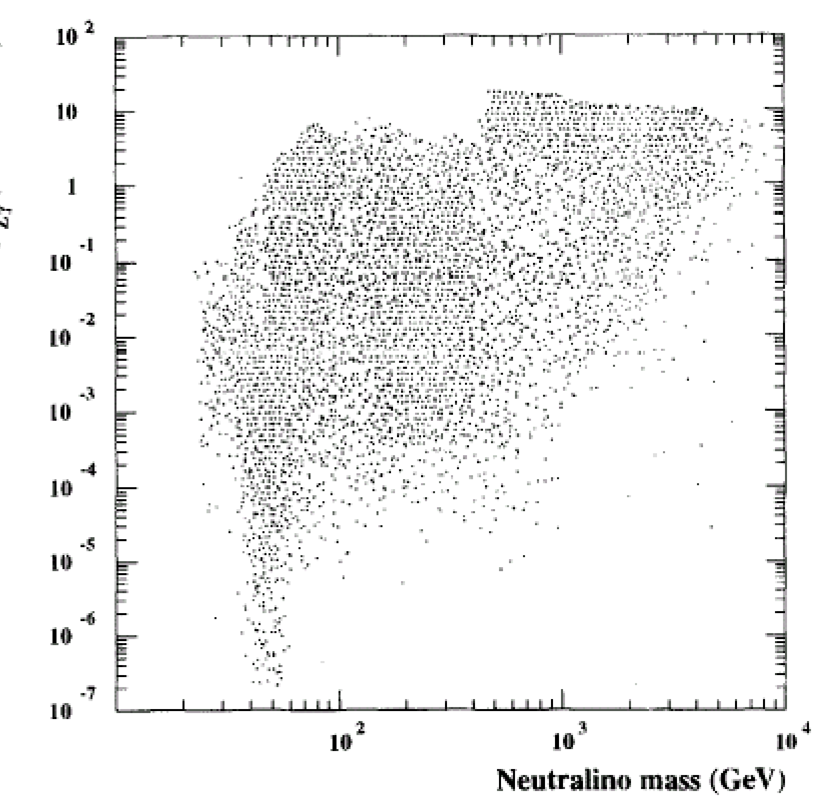
- Neutralino mass
  - Massive → ACT
  - Small → GLAST
- Line/Continuum
  - Line → ACT
  - Continuum → GLAST



Elsaesser @DM 2004

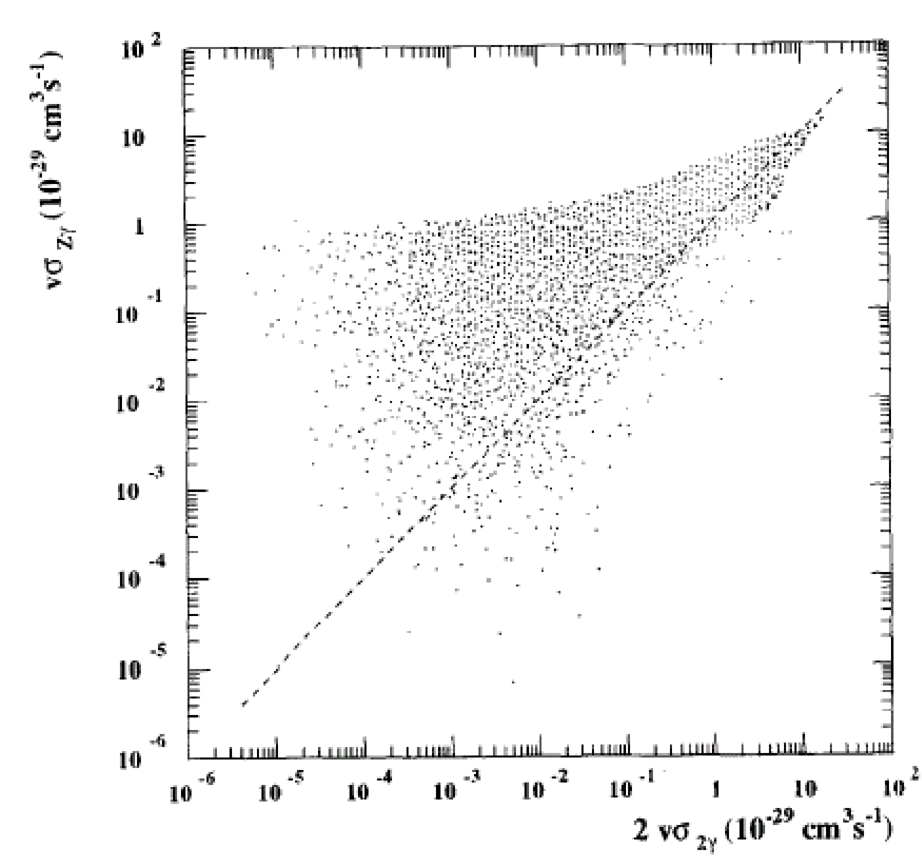
Detectability: 1. line (i)

Cross section for **2 γ** mode



rate of neutralinos into the 2γ final state for the sample of supersymmetric models describ

ratio of Z **γ** to 2 **γ**



for SUSY parameters satisfying 0.025 < **Ω**<1
Bergstrom et al. '98

Detectability 1. line (ii)
ACT prospects

2 **γ** Z **γ**

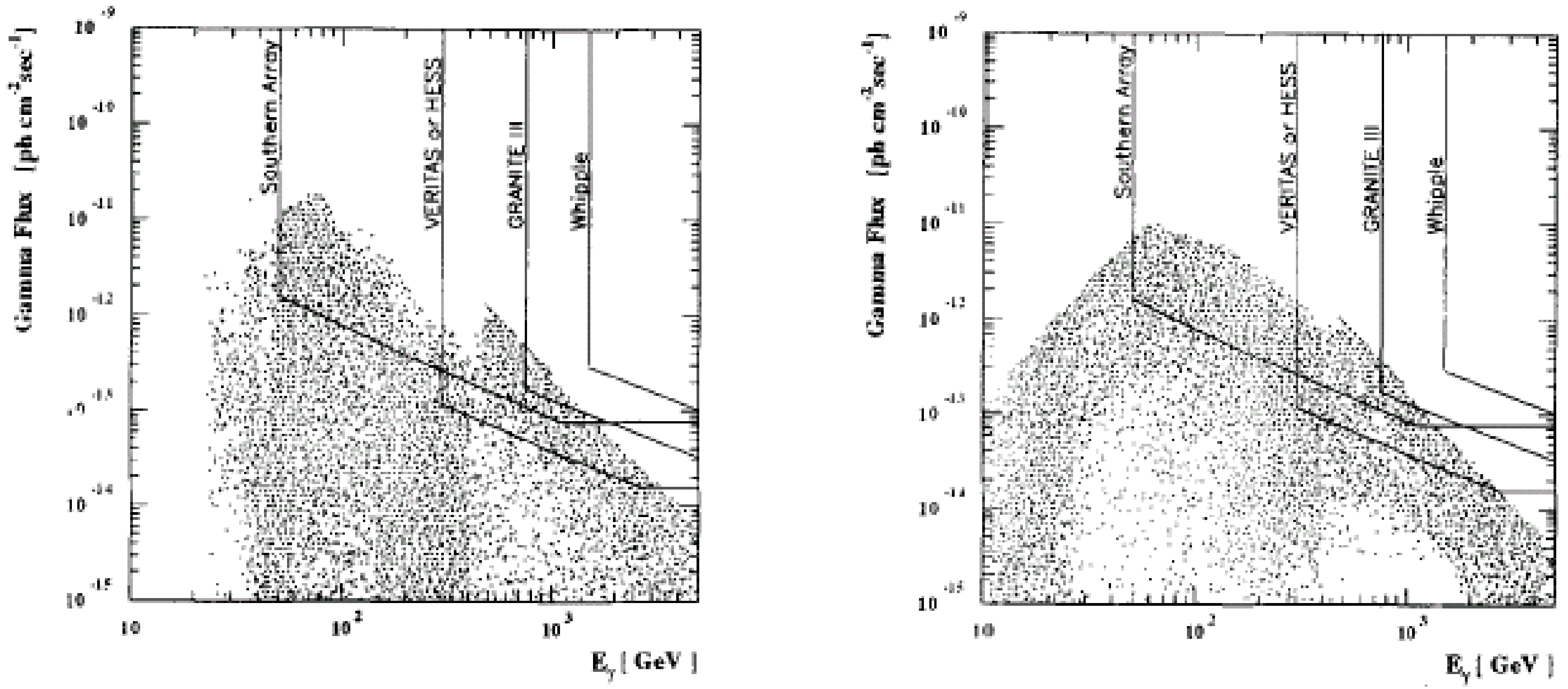


Fig. 9. Gamma-ray flux from a 10^{-5} sr cone encompassing the galactic center for the 2γ (on the left) and the $Z\gamma$ annihilation line (on the right). The NFW halo profile giving the maximal flux has been assumed. The solid lines show the 5σ sensitivity curves of the ACT detectors described in the text.

NFW profile for the G.C.
Bergstrom et al. '98

Detectability 1. line (iii)
GLAST prospects

2 γ   Z γ

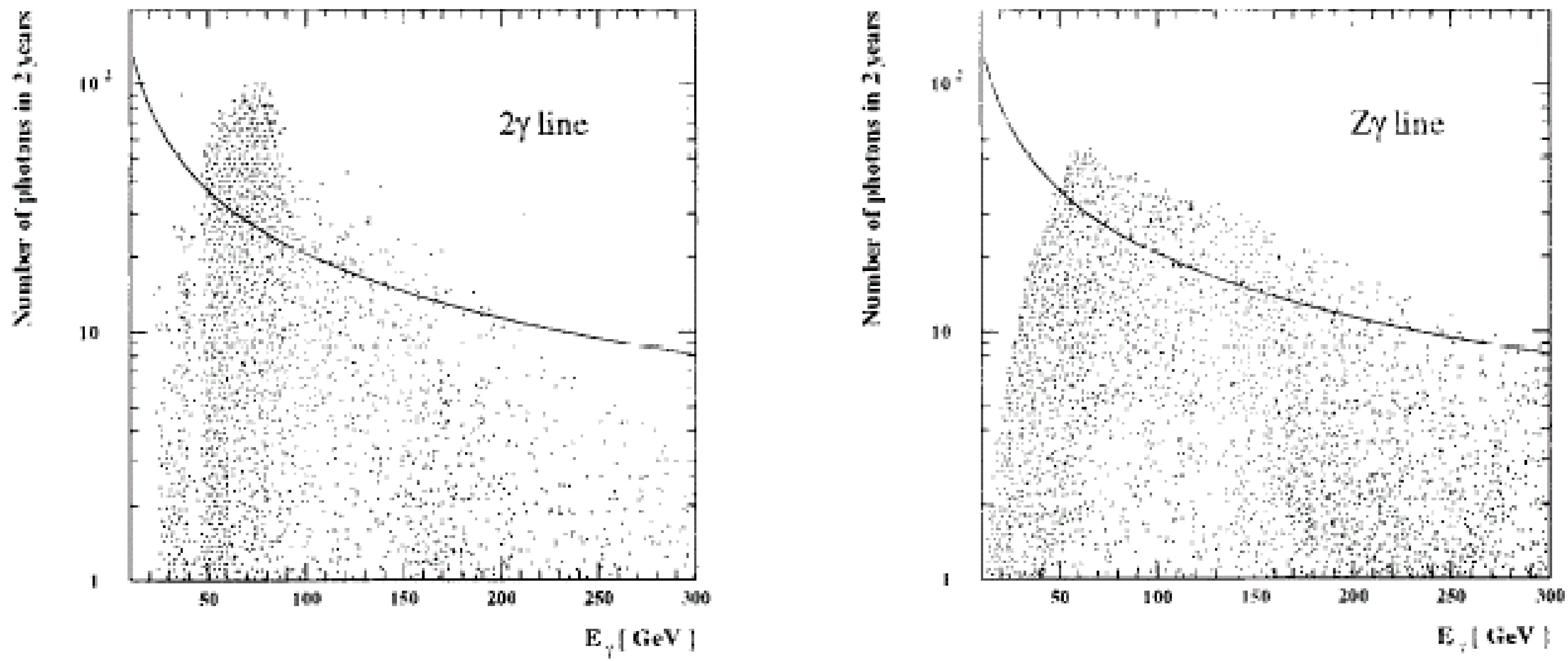
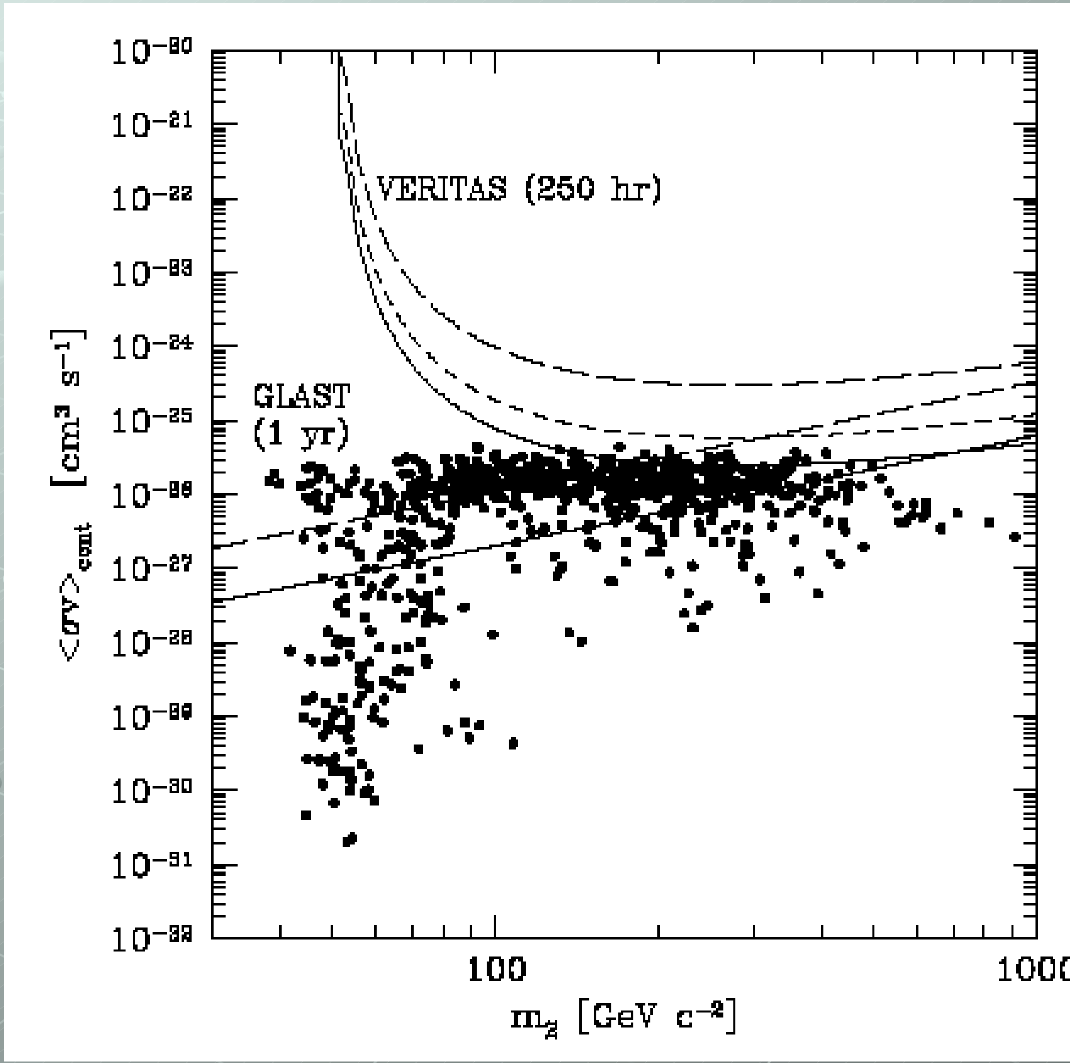


Fig. 11. The number of events expected in GLAST from a 1 sr cone encompassing the galactic center, assuming a 2 year exposure and calorimetry as described in the text, for the 2γ (on the left) and the $Z\gamma$ annihilation line (on the right). The NFW halo profile giving the maximal flux has been assumed. The solid line shows the number of events needed to obtain a 5σ detection over the background as estimated from EGRET data.

NFW profile for the G.C.
Bergstrom et al. '98

Detectability 2. continuum (i) G.C. and subhalos

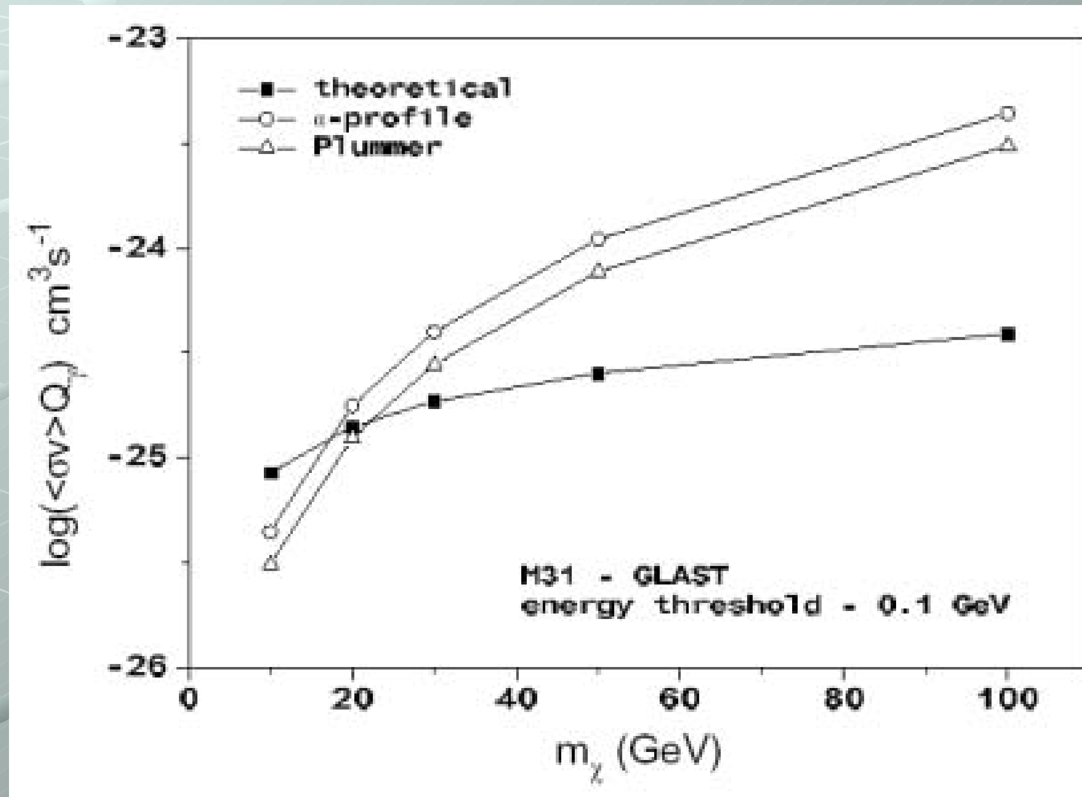
- ACT
  - Galactic Center
  - NFW(solid), SWTS(short-dashed)
- GLAST
  - 30 deg away from G.C.
  - Background = extragalactic GBR
- Brightest subhalo (long-dashed)
- SUSY parameters for
  - 0.17 < Ω<0.43



Stoehr et al. '03

Detectability 2. continuum (ii) M31, M87, Sgr, Draco

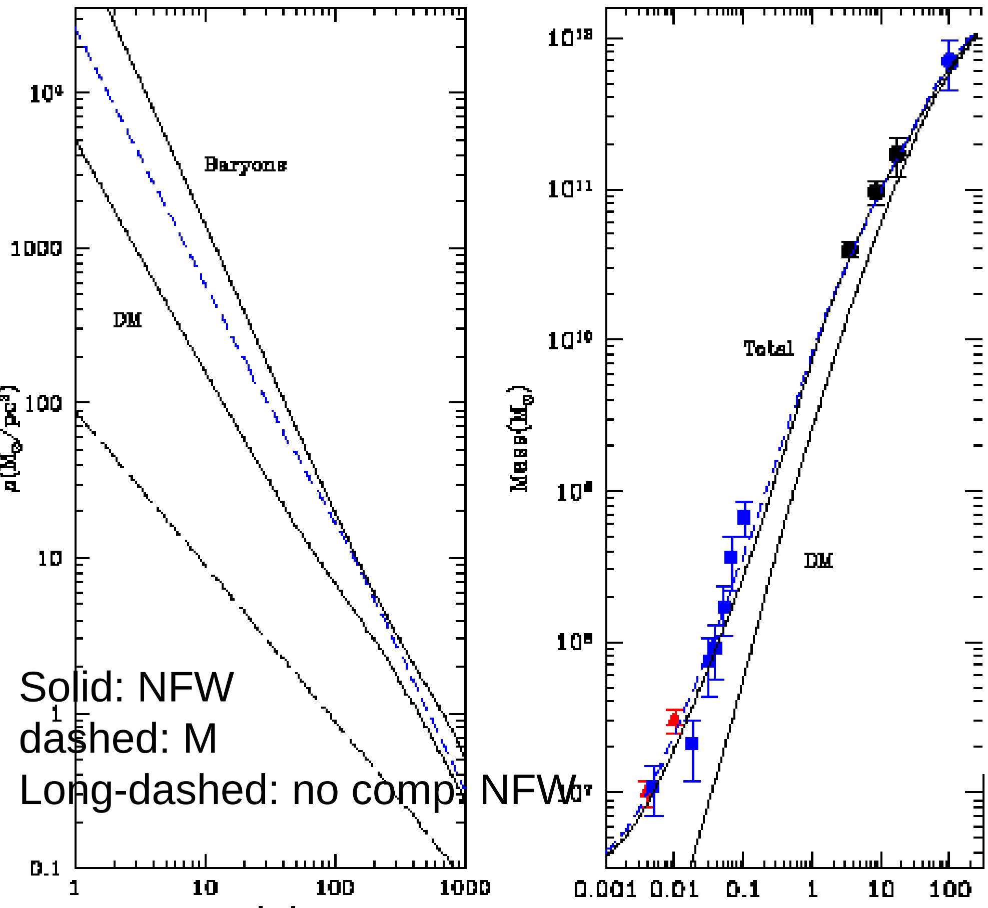
- M31: yes, if m_χ<20GeV
- Sgr: yes, if m_χ<50GeV
- M87, Draco: no, unless adiabatic growth of SMBH
- MW halo at b=90 deg:
  - Explain EGRET residual if m_χ<50GeV
- Also depends on density profile
- SUSY parameters for
  - 0.17 < Ω<0.43



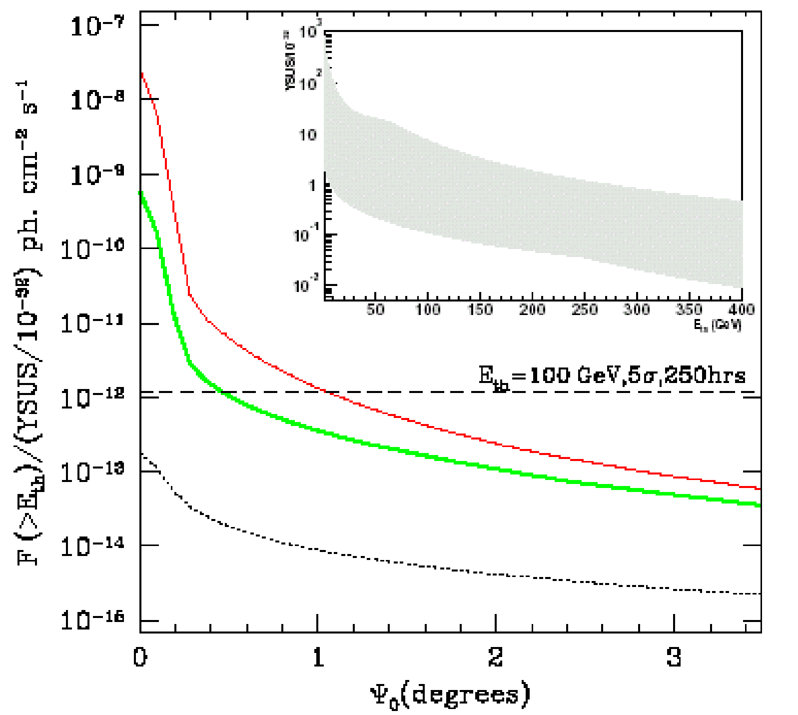
Peirani et al. ‘03

Baryonic infall and adiabatic compression of dark matter

- Prada et al. astro-ph/0401512
- Baryonic infall vs. angular momentum transfer?



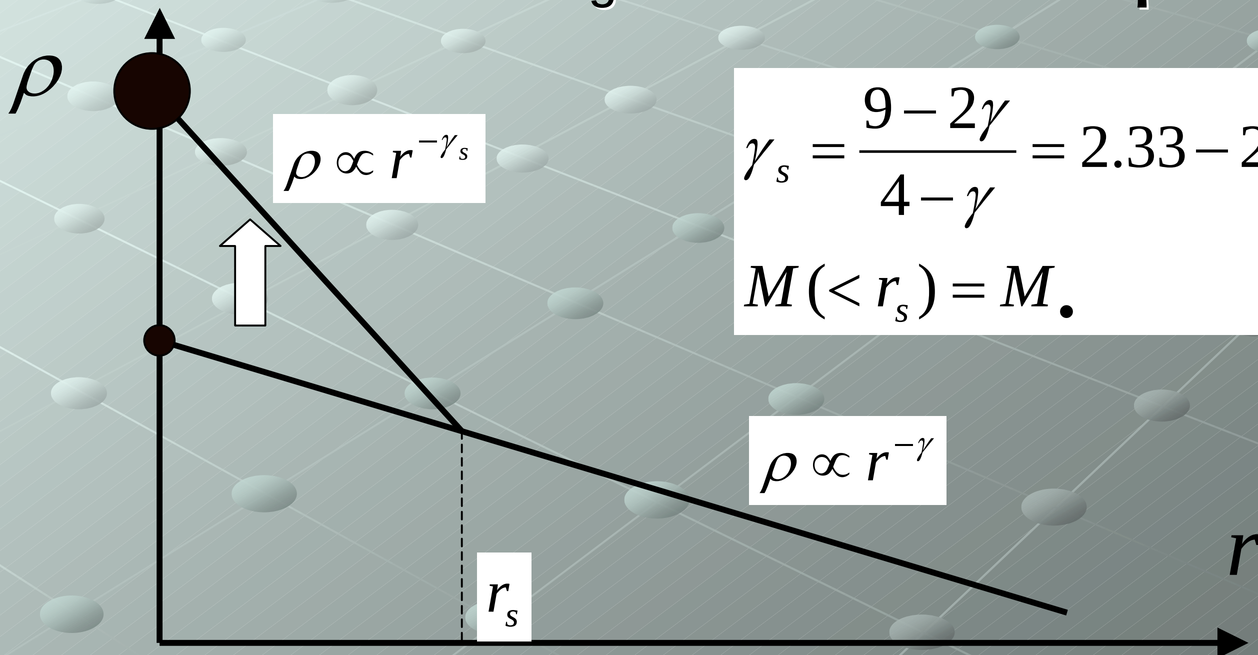
Solid: NFW
dashed: M
Long-dashed: no comp. NFW



Green: NFW
Red: M
Dotted: no comp. NFW

Adiabatic growth by SMBH

- Density "spike" can be formed by the growth of supermassive black hole (SMBH) mass at the center.
  - Young (1980); for stellar density cusps in elliptical galaxies
  - Gondolo & Silk (1999); for DM cusps
  - "Adiabatic" = growth time scale > orbital period at r_s
  - Annihilation rate divergent with $r \rightarrow 0$ since $\gamma > 1.5$



$$\gamma_s = \frac{9-2\gamma}{4-\gamma} = 2.33 - 2.4$$

$$M(<r_s) = M_\bullet$$

Does adiabatic growth happen?

- The Galactic Center
  - If happens, constraints on SUSY and/or density profile (Gondolo & Silk 1999)
  - It seems unlikely (Ullio et al. 2001; Merritt et al.2002)
    - The GC is baryon dominated.
      - Is SMBH at the DM center?
      - Disturbed by baryonic processes, e.g., starbursts and supernovae
    - Merger of SMBHs destroys the spike and cusps

- The cooling-flow clusters:
  - A giant cD galaxiy always at the dynamical center
  - DM dominates baryons to the center (Lewis et al. 2003)
  - Adiabatic growth happens as a feed back to the cooling flow

$$\left.\begin{array}{l} \text{cooling flow} \sim 10^{2\text{-}3} M_{sun}/\text{yr} \\ M_\bullet \sim 10^{9-10} M_{sun} \end{array}\right\} \Rightarrow t_{growth} >\sim 10^8 \, \text{yr} > t_{orb}$$

$$r \sim 1.5 M^{1/2} \, \text{kpc}, \quad t \sim 6\times10^7 M^{1/4} \, \text{yr}$$

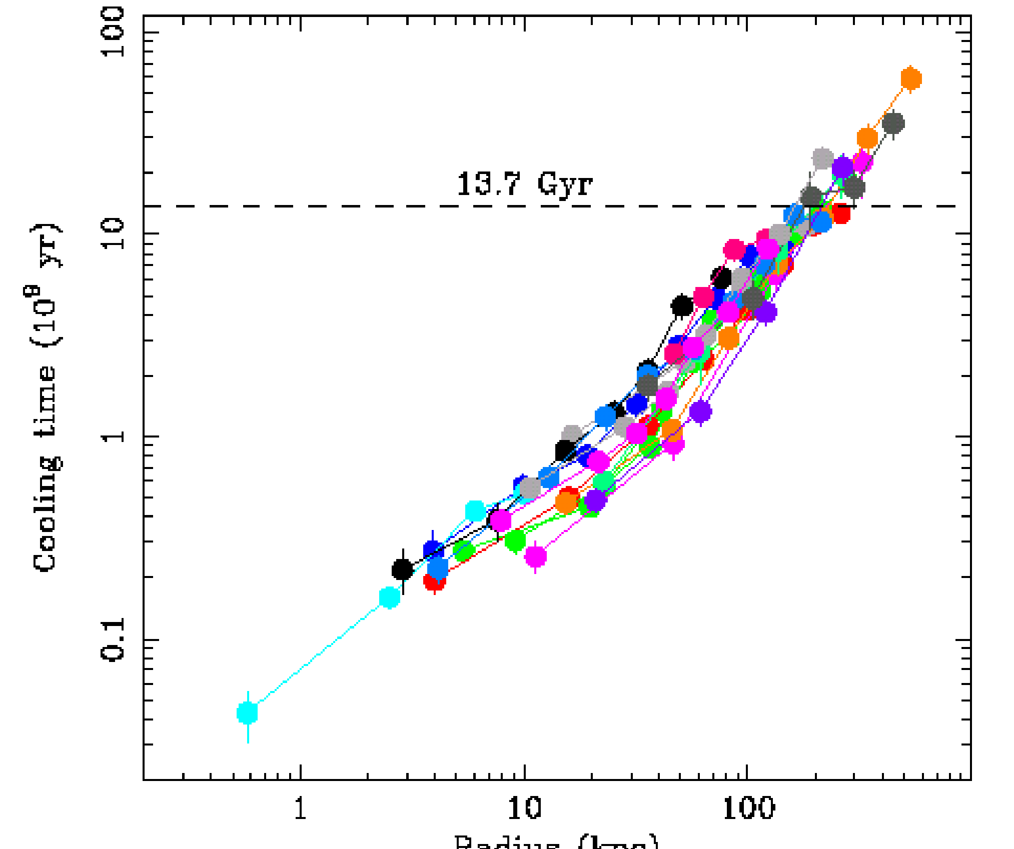
Solving the cooling flow problem of galaxy clusters by dark matter neutralino annihilation

T. Totani astro-ph/0401140

To appear in PRL

Introduction: the Cooling Flow Problem of Galaxy Clusters

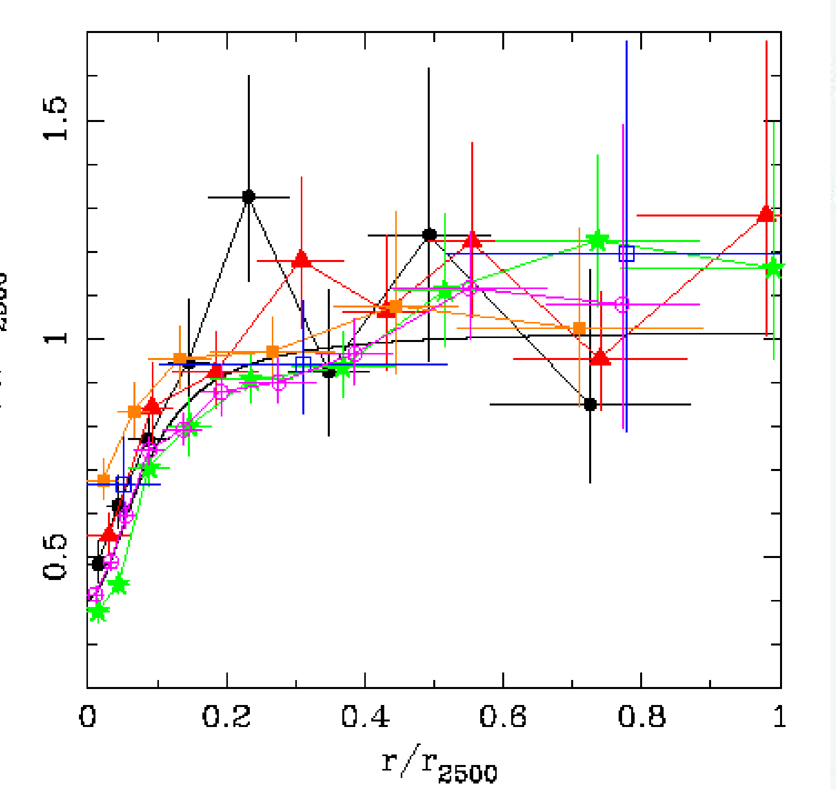
- "Cooling flow clusters"
  - Central gas cooling time < the Hubble Time (~10^{10}yr)
  - Theory predicts cooling flow: ~100-1000 M_{sun} / yr



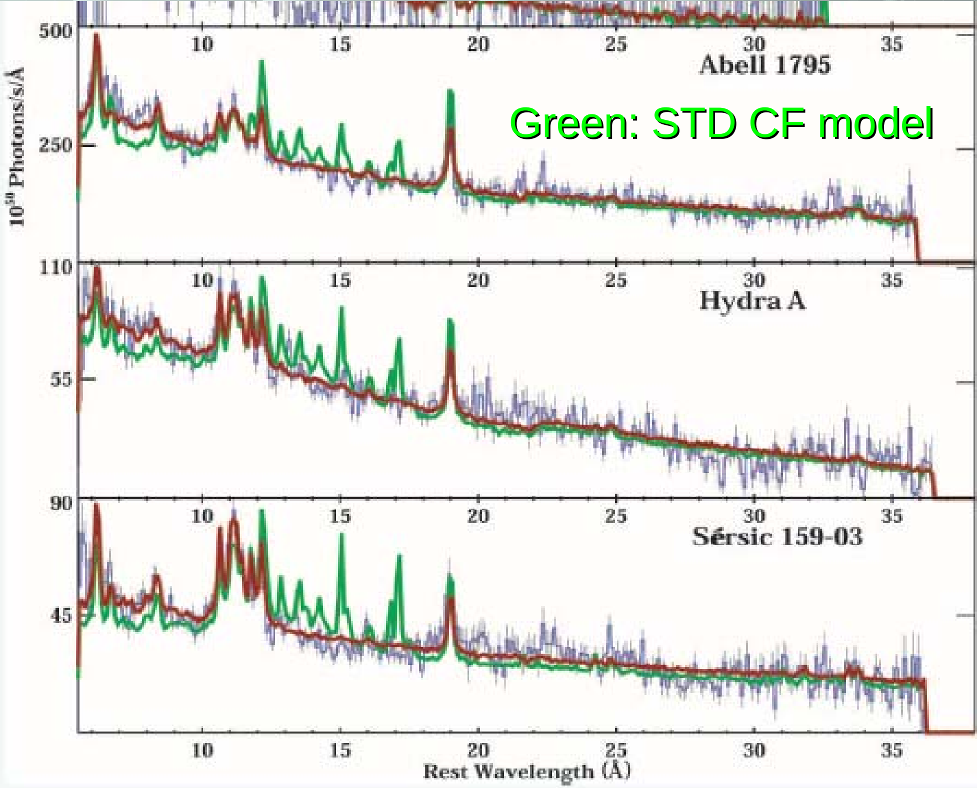
Voigt & Fabian 03

Introduction: the Cooling Flow Problem of Galaxy Clusters

- No evidence for strong cooling flows from latest X-ray observations
  - A heating source required.
  - Required heating rate: $\sim 10^{45}$ erg/s during 10^{10}yr for a rich cluster



Fabian '02



Peterson et al. '03

Introduction: the Cooling Flow Problem of Galaxy Clusters

- Heat conduction
  - Effective if κ ~0.3 Spitzer value
  - Useful for stabilizing intracluster gas
  - A fine tuning necessary, and not all clusters can be explained (e.g. Bregman & David 98; Zakamska & Narayan '03)

- AGNs
  - Efficiency must be high (>~10% of BH rest mass to heat)
  - Stability?
    - AGNs generally episodic, intermittent
    - t_E~10^7 yr, L_E >> 10^{45} erg/s
  - Actual heat process unclear (jet? buoyant bubbles?)

Does adiabatic growth happen?

- The Galactic Center
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  - It seems unlikely (Ullio et al. 2001; Merritt et al.2002)
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$$r \sim 1.5 M^{1/2}\ \text{kpc},\quad t \sim 6\times10^{7} M^{1/4}\ \text{yr}$$

The cluster density profiles from X-ray observations

Abell 2029
Lewis et al. 2003

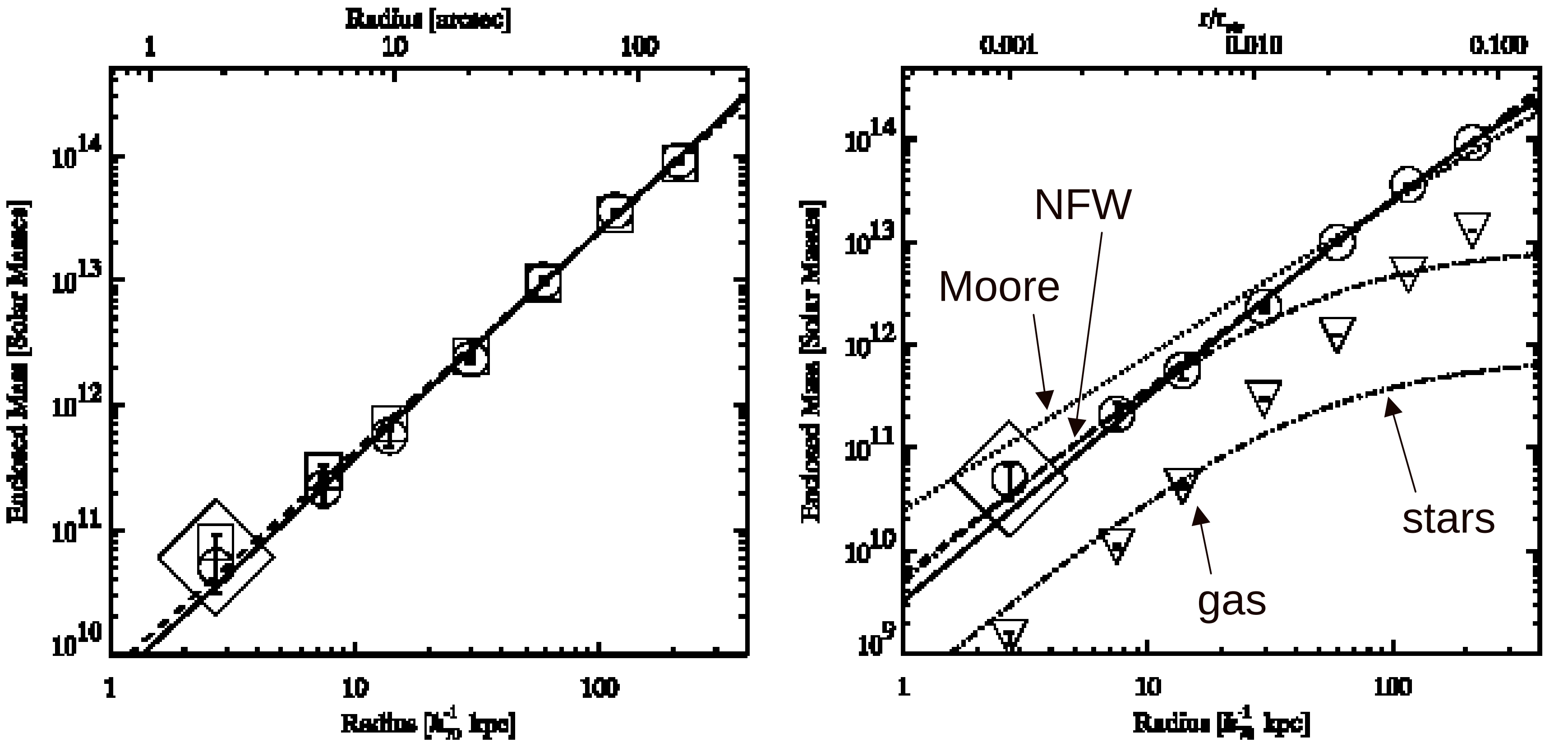


FIG. 2.—*Left*: Total enclosed cluster mass, obtained from the BM86 fit (*open circles*) and the power-law fit (*open squares*) to the temperature data. The cusp model for ρ_g was used in both cases. Power-law fits to the mass points are overlaid on both data sets (*solid line*: BM86 T_g model; *dashed line*: power-law T_g model). We have used large open symbols to identify the data points, as some of the error bars are barely visible in this logarithmic plot. The first data points are also enclosed with a large open diamond to emphasize the large additional systematic uncertainty at this radius (see §§ 3.2 and 3.4). *Right*: Total enclosed cluster mass (data points enclosed with open circles), overlaid with three different mass models: NFW97 (*solid curve*), power-law (*dashed line*), and M99 (*dotted curve*). The total enclosed gas mass is plotted as data points enclosed with open triangles. We have also overlaid an estimate of the stellar mass (*dot-dashed curves*; see § 5.1). The bottom curve assumes a M_*/L_V of 1; the top curve assumes a M_*/L_V of 12. [*See the electronic edition of the Journal for a color version of this figure.*]

Annihilation energy from the density spike at the cluster center

- Density maximum determined by annihilation itself:

$$\rho_c \langle \sigma \upsilon \rangle / m_\chi = t_{cl} \equiv 10^{10} t_{10} \text{ yr}$$

$$r_c = 0.17 M_{\bullet,10}^{2/7} m_2^{-3/7} \langle \sigma \upsilon \rangle_{-26}^{3/7} t_{10}^{3/7} \text{ pc}$$

- The annihilation luminosity from $r<r_c$:

$$L_{\chi\bar{\chi}} = 2 m_\chi c^2 \langle \sigma \upsilon \rangle \left(\frac{\rho_c}{m_\chi} \right)^2 \left(\frac{4\pi r_c^3}{3} \right)$$

$$= 2 \times 10^{44} M_{\bullet,10}^{6/7} m_2^{-2/7} \langle \sigma \upsilon \rangle_{-26}^{2/7} t_{10}^{-5/7} \text{ erg/s}$$

- A factor of about 10 enhancement by $r>r_c$ and time average
- Steady energy production after turned on!

Electron/positron energy loss

- Electron/positrons lose their energy mainly by heating rather than radiation

Coulomb interaction: $t_{ci} = 5\times10^{8} n_{-1}^{-1}\varepsilon_0$ yr

two stream instability (Scott et al. 1980; Rosner & Tucker 1983)

$$t_{tsi} = 8\times10^{6} P_{-9}^{-2} n_{-1}^{1.5}\varepsilon_0^{4} \text{ yr}$$

CMB Inverse Compton: $t_{ic} = 1.2\times10^{9}\varepsilon_0^{-1}$ yr

Synchrotron: $t_{sy} = t_{ic}(B/3.3\mu G)^{-2}$

where,

$\varepsilon_0 = \varepsilon_{\pm}/1\text{GeV}$

$n_{-1} = n_{ICgas}/(0.1\text{cm}^{-3})$

$P_{-9} = P_{ICgas}/(10^{-9}\text{erg cm}^{-3})$ (equal to relativistic $e^{\pm}$ pressure)

- Proton/antiprotons lose their energy by Coulomb and pp inelastic scattering

$$t_{pp} = 3.3\times10^{8} n_{-1}^{-1} \text{ yr}$$

The Neutralino Mass Prediction

- m_χ <~ 100 GeV favored.
  - Annihilation rate $\propto m_\chi^{-2/7}$
  - Heating loss should be more efficient than radiative loss

Observability of annihilation signal: gamma-rays

- Continuum gamma-rays at ~1-10 GeV (for m_χ<100GeV)
  - ~30 gamma-rays per annihilation
  - Very close to the EGRET upper limit for a cluster @ 100Mpc

$$F_\gamma \sim 7\times10^{-8} L_{45} m_2^{-1} (d/100\mathrm{Mpc})^{-2}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

  - Many positional coincidence between clusters and un-ID EGRET sources (e.g. Reimer et al. 2003)
  - GLAST will likely detect

- Line gamma-rays
  - A few photons for a cluster with $\langle \sigma v \rangle_{line} = 10^{-29}\ \mathrm{cm}^3\mathrm{s}^{-1}$ for GLAST in ~5 yr operation.
  - Negligible background rate (~10^{-3}) within the energy and angular resolution
  - Air Cerenkov telescopes should have low energy threshold, since the prediction m_χ<100 GeV is correct

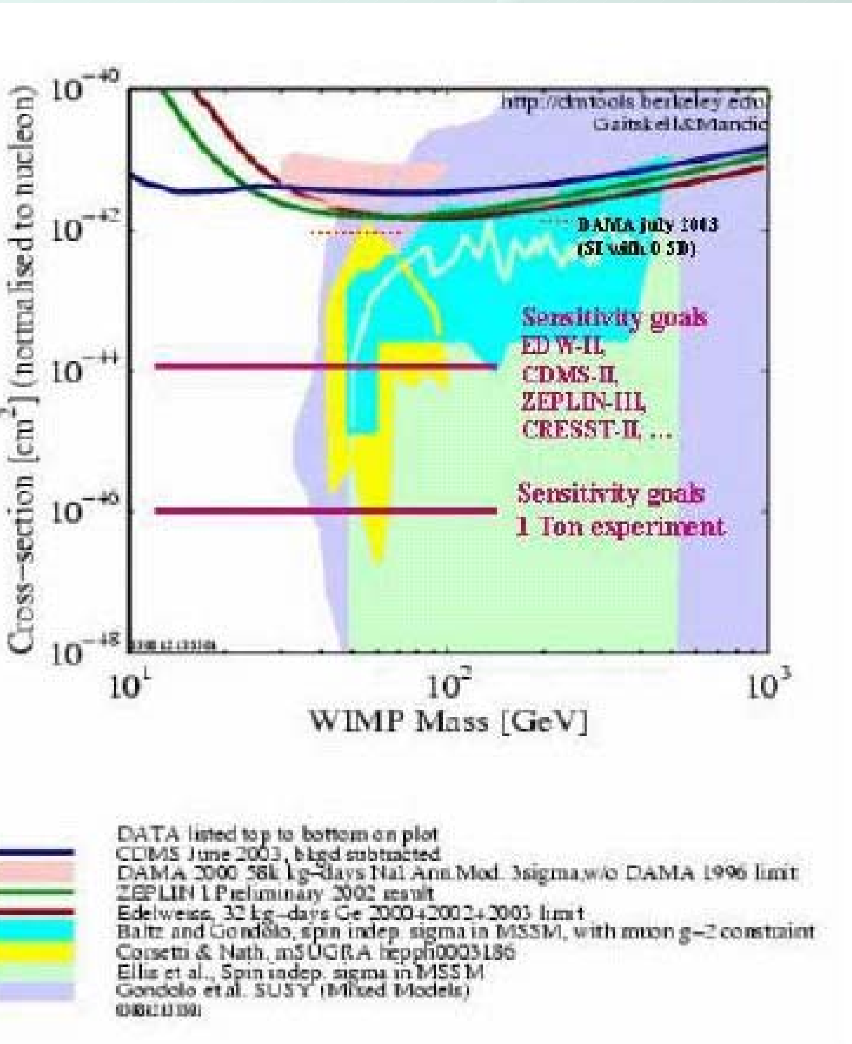
Annihilation gamma-ray detectability: summary

- ACTs:
  - May detect line gamma-rays from the G.C.
  - Continuum may be detected, especially if baryonic infall has significant effect
- GLAST:
  - may detect continuum from the Galactic halo, if $\mathbf{m_\chi}$<~50
- Continuum detection from G.C. or halo: how to prove?
- Clusters of galaxies
  - Promising target, if cooling flow is suppressed by annihilation.
  - Continuum: can be separated from CRs or AGNs, by
    - Steady or variable
    - Point or extended

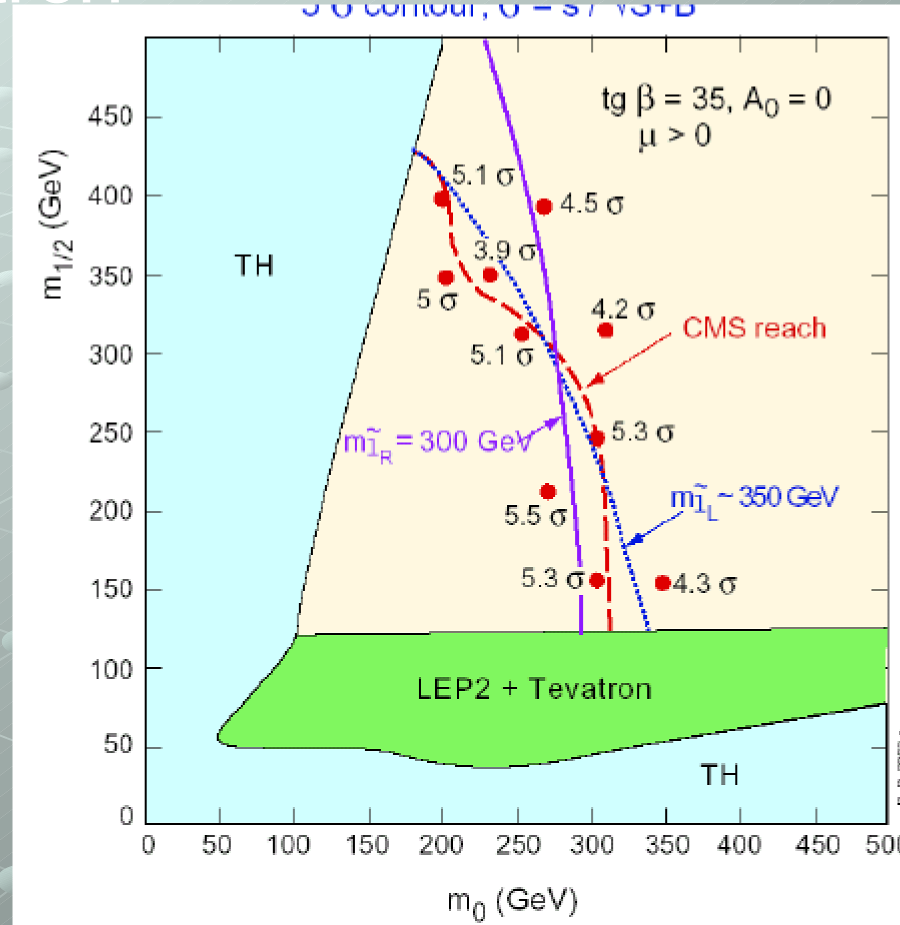
Galactic center vs. Galaxy Clusters

- M/D^2:
  - Center/cluster ~ 10^4
- Enhancement by SMBH adiabatic growth:
  - ~10^{4-5} for clusters
- Galactic center: extended
- Clusters: practically point source
- Many clusters: superposition would increase S/N

Direct DM search and accelerator SUSY search



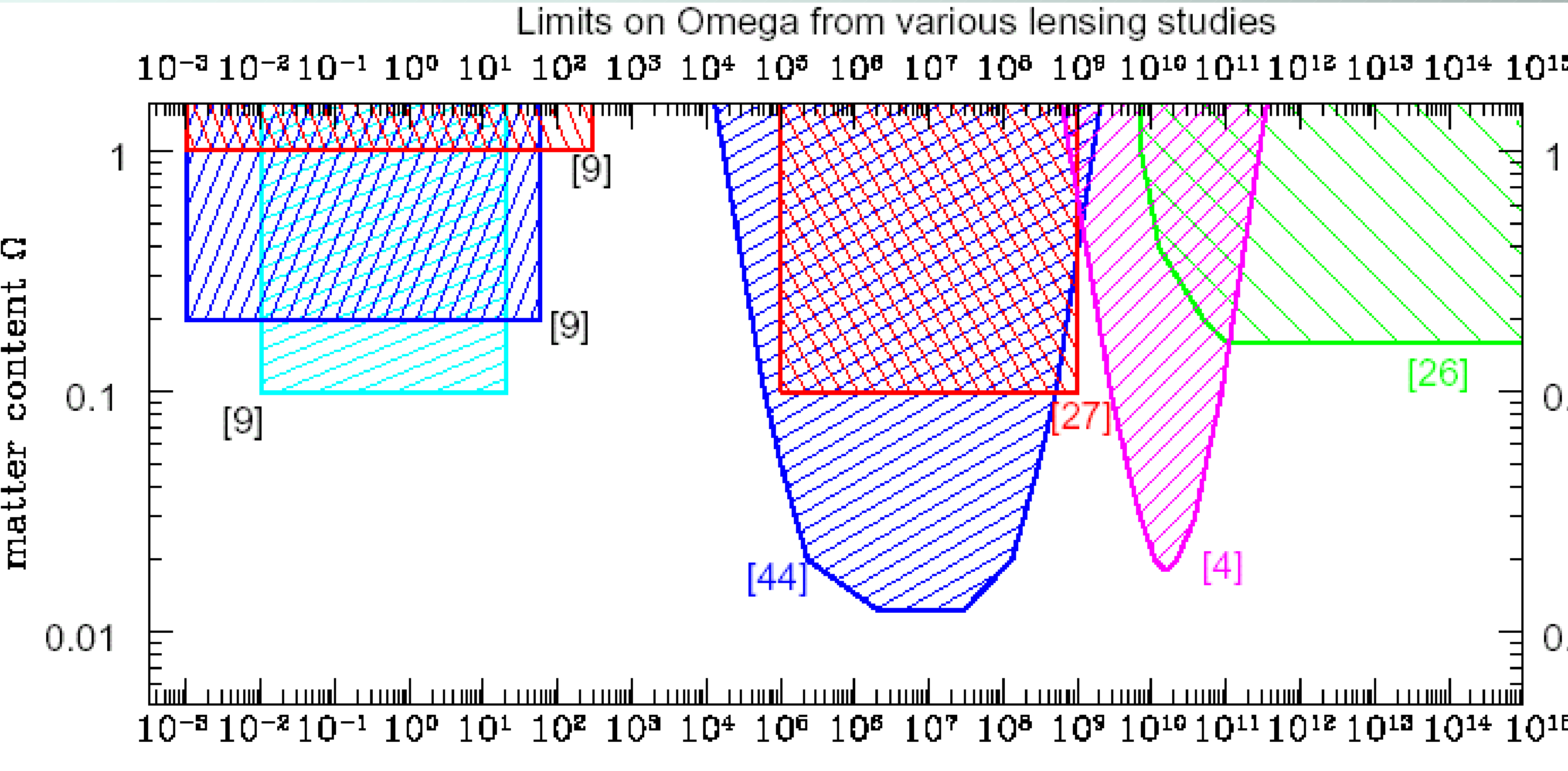
WIMP direct detection status
De Jesus '04



LHC reach (2007)
Andreev @ DM2004

MACHOs 探索の最近の話題

Constraint on MACHO DM



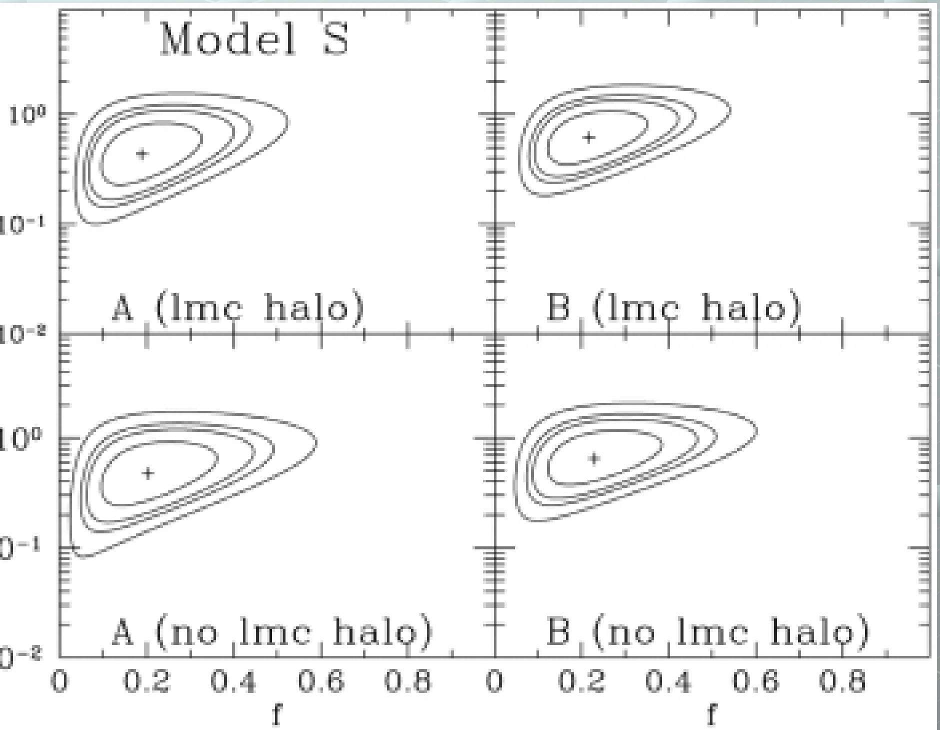
Wambsganss 2002

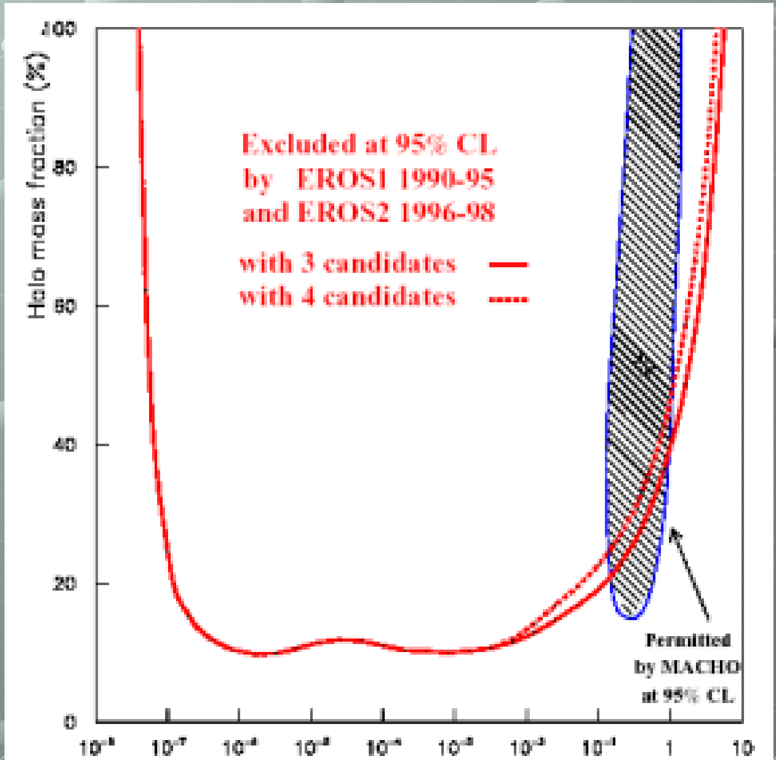
igure 4: Limits on the matter content of the universe in form of cosmologically distributed compa
ojects: the shaded regions are excluded. This diagram combines various studies (as listed in brackets
ased on different techniques: statistical microlensing of quasars [9], VLBI investigation for multip
omponents of compact radio sources [4, 44], frequency of multiply imaged quasars [26], or search fo
ultiple gamma-ray bursts [27].

$\sim M_{sun}$ MACHO searches

- Controversy in MACHO seaches to LMC:
  - MACHO collab. Has claimed ~20% MACHO contribution to MW halo
    - Theoretical challenge!
  - Self lensing is alternative explanation

EROS result (Lasserre et al. '00

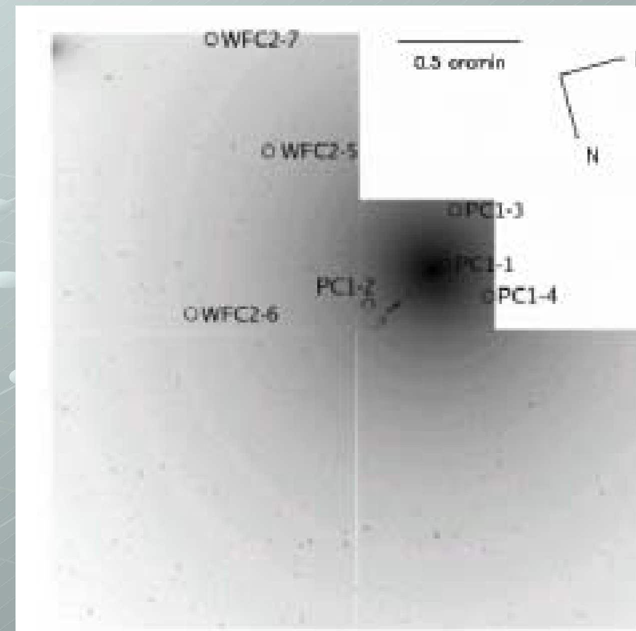


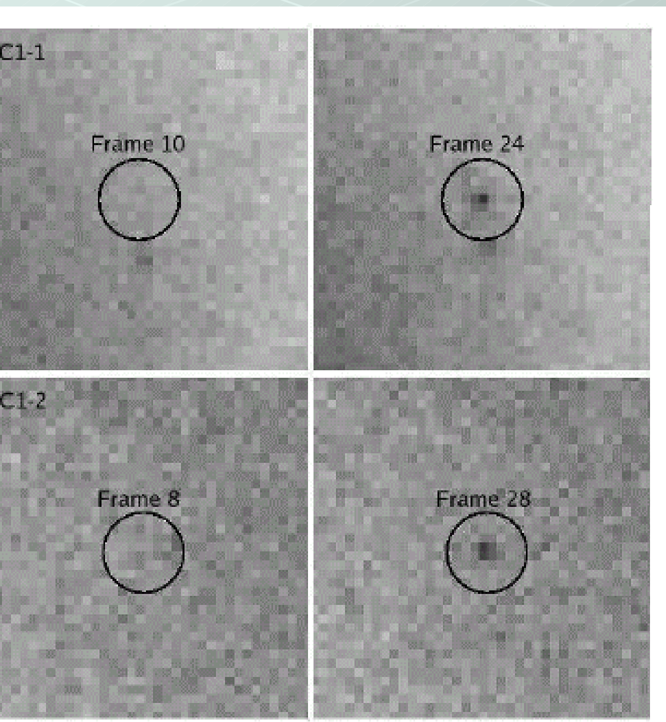


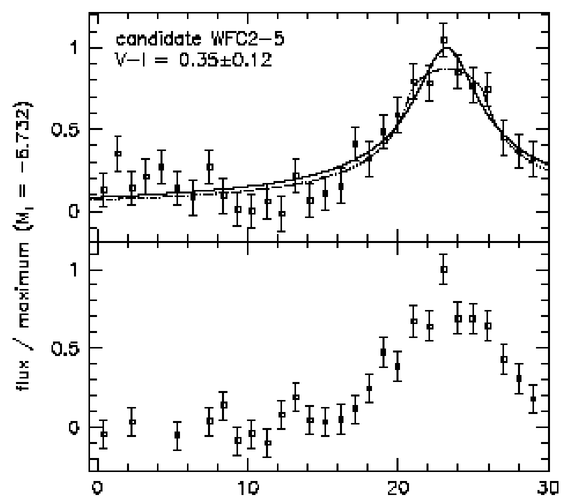
MACHO result (Alcock et al. 2000)

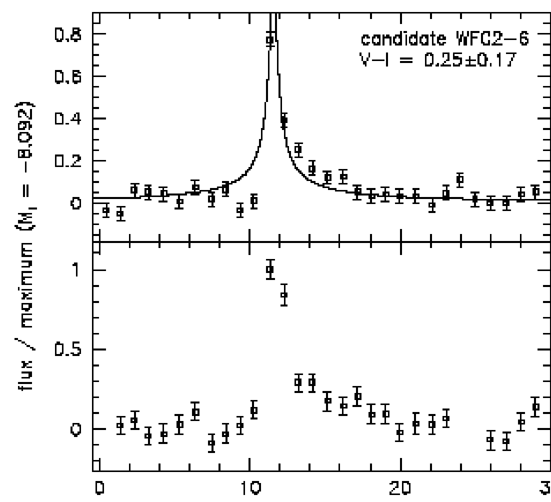
MACHO candidate in M87/Virgo cluster?

- HST search by Baltz et al. ’04
- Several candidates, most of them could be nova
- Consistent with ~20% mass fraction of MACHOs in DM

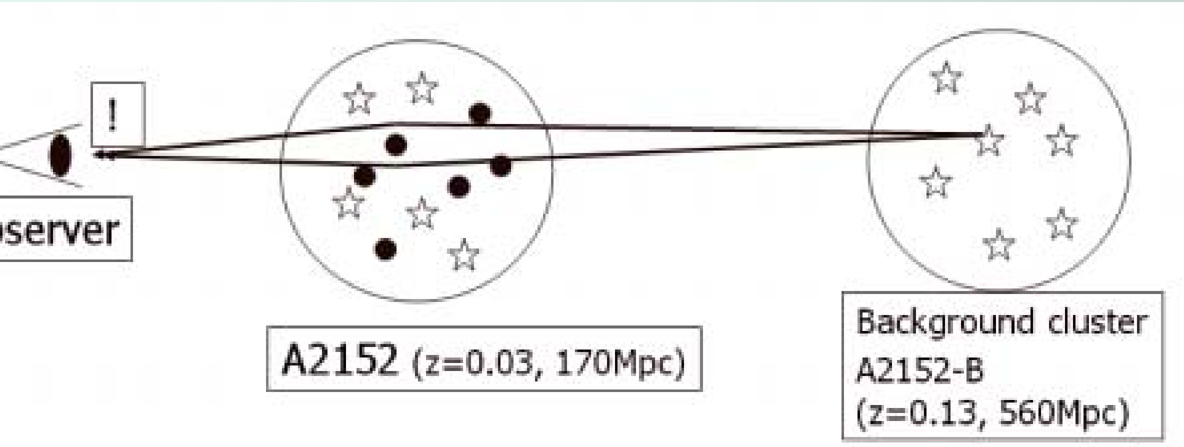




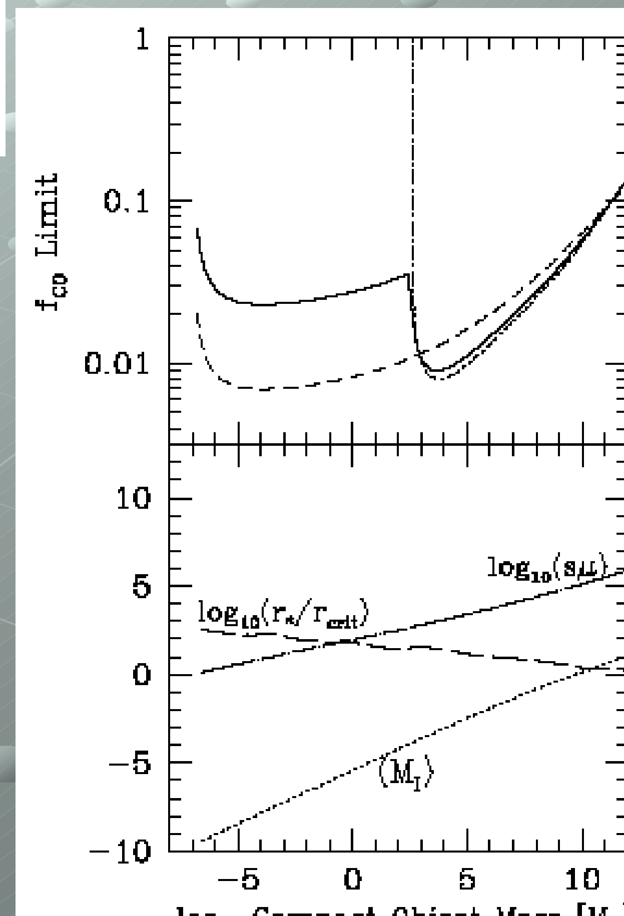




Cluster-Cluster Microlensing

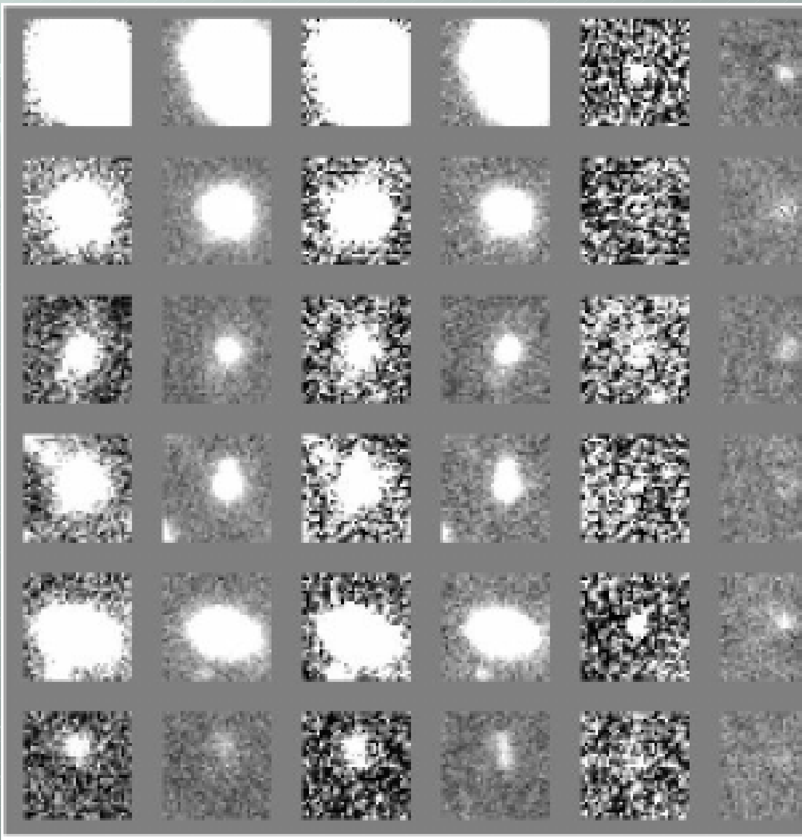


- Search intracluster MACHOs in A2152 by ultra-magnified microlensing event of a star in A2152-B
- A new probe of MACHOs in the open mass window (10-10^5 M_{sun}) (Totani 2003)
- First observation made in 2003 May/June by Subaru/Suprime-Cam, analysis now underway



Cluster-Cluster Microlensing (2)

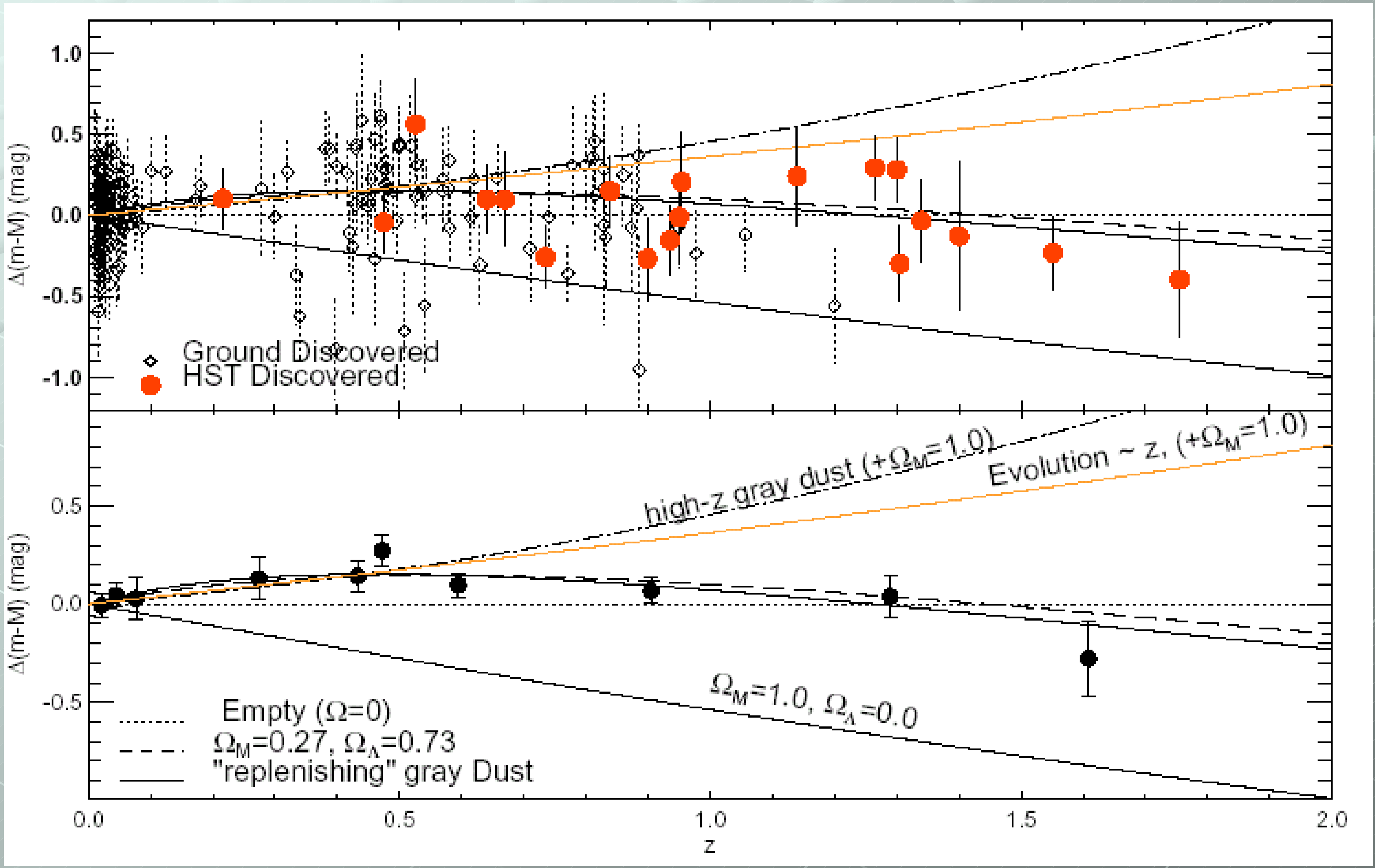
A2152 field (approx. 30’x30’)



Dark Energy Study by Distant Supernovae

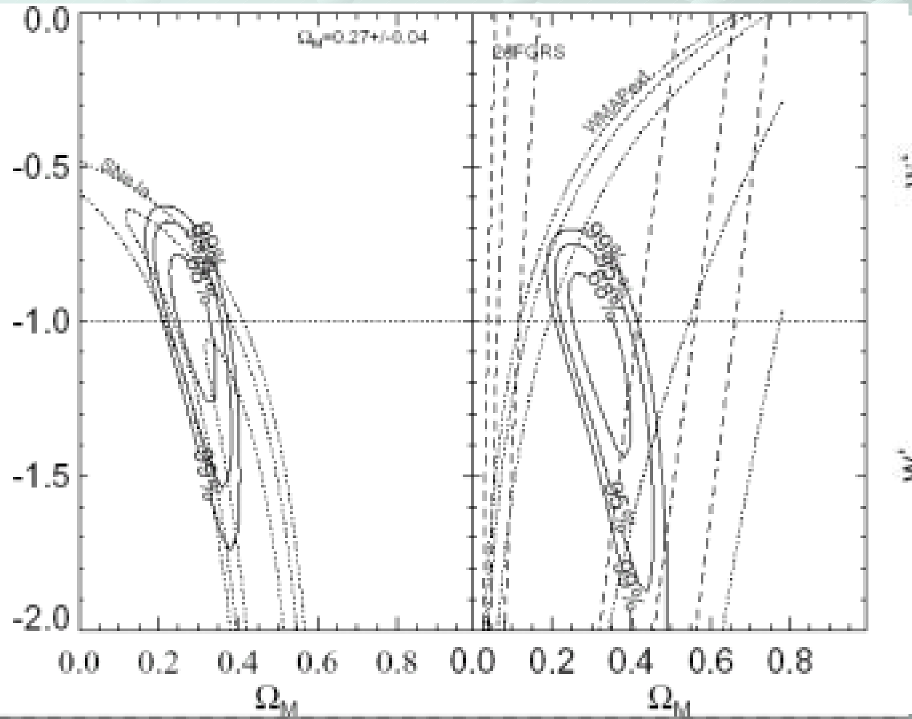
Latest Hubble diagram of high-z supernovae

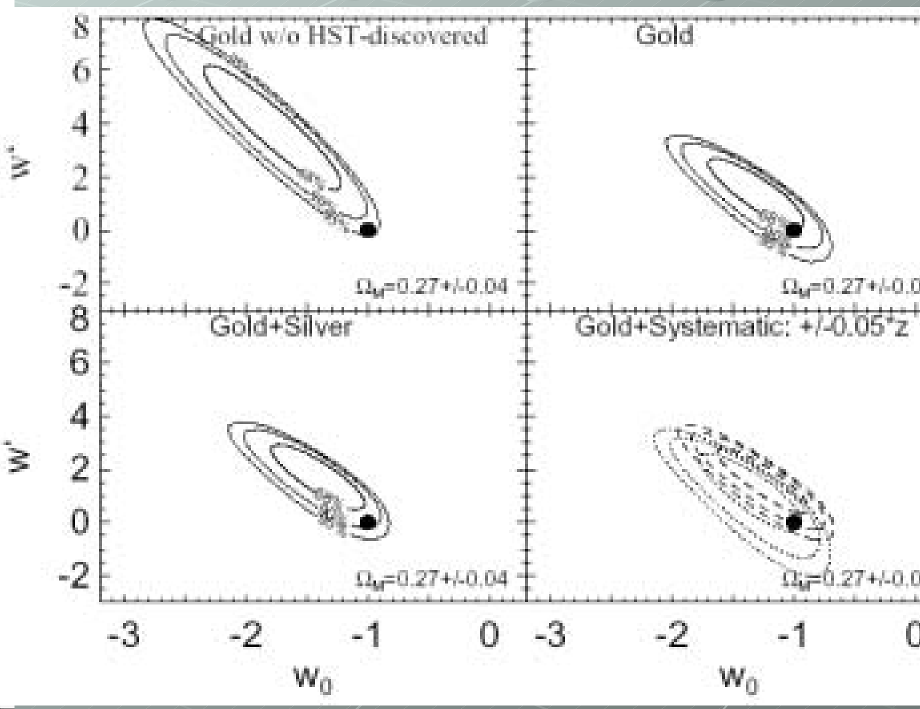
- Riess et al. astro-ph/0402512
- 8 z>1 SNe from GOODS survey



Constraint on Dark Energy

- The cosmological constant (w_0=1, dw/dz=0) consistent with the data





Systematic effect from extinction by dust

- Systematic evolution of extinction by host galaxy evolution
- Reddening is not large enough to be reliably removed
- Trend of evolution is similar to the effect of **Λ**
  - Interstellar gas increase, metal decrease, to high-z

- How significant for the dark energy study?
  - TT, in prepatation