Dark Matter

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Basic facts

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

$$\rho_c = \frac{3H_0^2 m_{Pl}^2}{8\pi} = 1.88h^2 \cdot 10^{-29} g/cm^3$$

$$h \equiv \frac{H_0}{100\, km\, s^{-1} Mpc^{-1}}$$

Observations $\Rightarrow h \in [0.4, 0.8]$ $h = 0.65 \pm 0.15$

$\Omega_{lum} \propto (4 \pm 2) \cdot 10^{-3}$ stars, gas, dust, ...

BBN (low D/H) $\Rightarrow \Omega_b \propto 0.02/h^2$

$\Rightarrow$ **There is plenty of dark baryons!**
(neutral gas, molecular clouds, MACHOS...)

If Ω_M is greater than around 0.1 there has to exist also Nonbaryonic Dark Matter

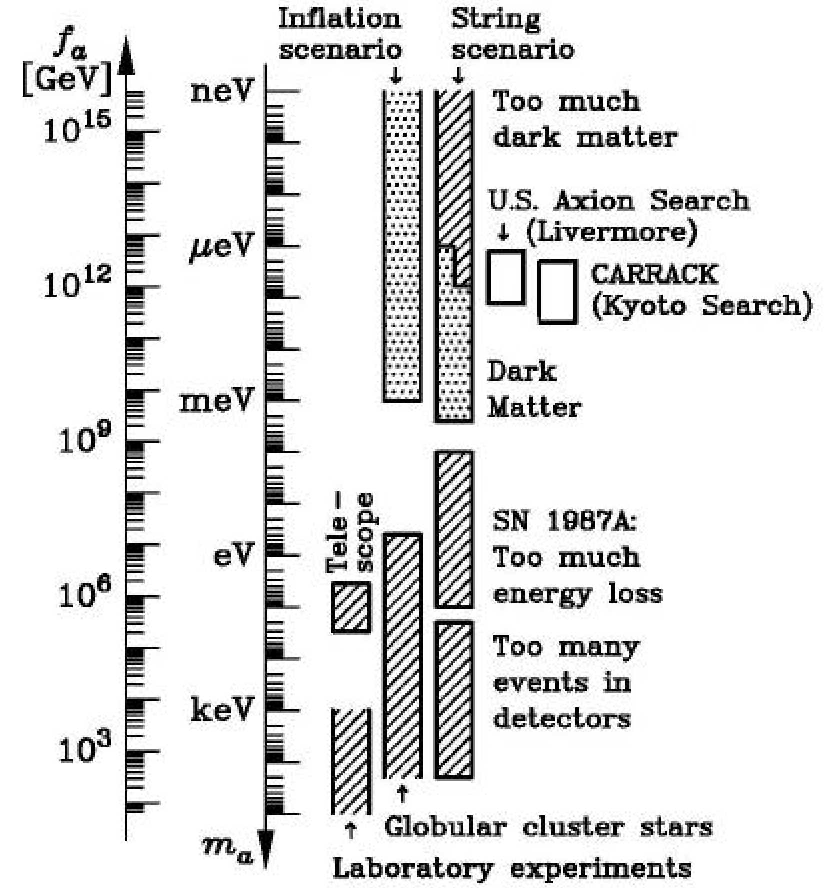
$\Omega_\nu h^2 = \left(\frac{\sum_i m_{\nu_i}}{93 eV} \right)$

Particle dark matter:

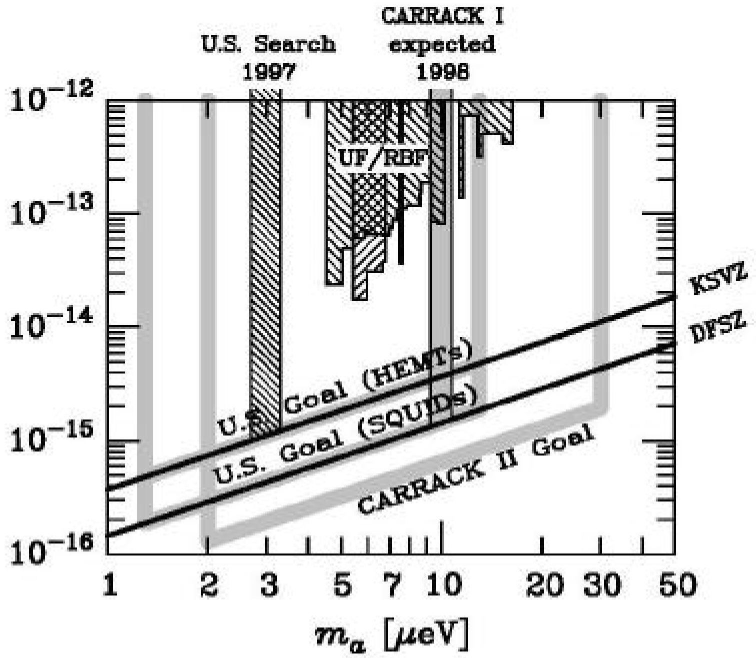
Hot Dark Matter (HDM) - light (eV) ν
Cold Dark Matter (CDM) - heavy (GeV-TeV) χ WIMP
Warm Dark Matter (WDM) -intermediate (keV) $\tilde{G}$, ν_s
Cosmological Constant (ΛDM) - vacuum energy Λ quintessence

axion, $m_a \sim 10^{-6} - 10^{-3}$ eV acts as CDM

The axion – strong CP & dark matter solver?



Courtesy of G. Raffelt



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New era:

Since 1998 (Super-Kamiokande)
We know that

NON-BARYONIC DARK MATTER EXISTS!

If $m_\nu \approx \Delta m_\nu \approx 10^{-2} - 10^{-1}$ **eV, as the Super-K results suggest, then**
$\Omega_\nu \approx 10^{-4} - 10^{-3}$
(i.e. contributes as much as all stars!)

However, neutrinos cannot explain all dark matter (at most 10%):

- *Structure formation wrong*
- *Pauli principle forbids clumping in dwarf galaxies*

W. Hu

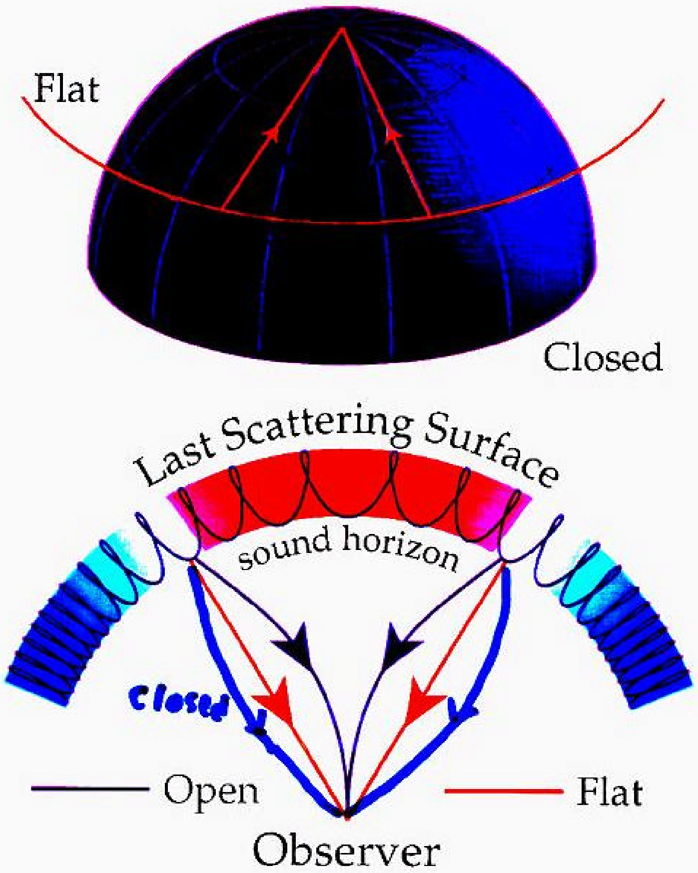
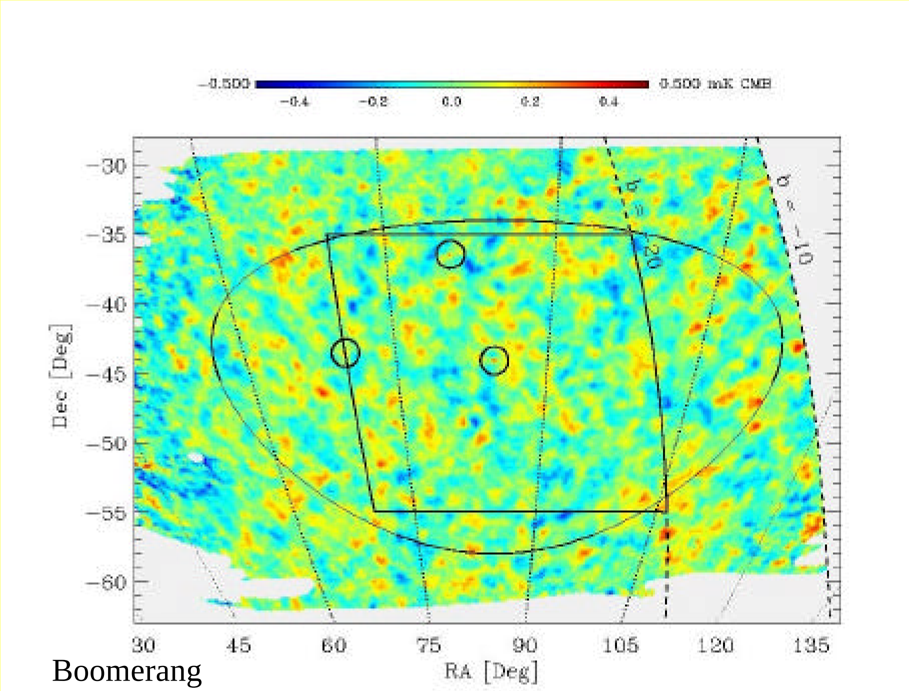


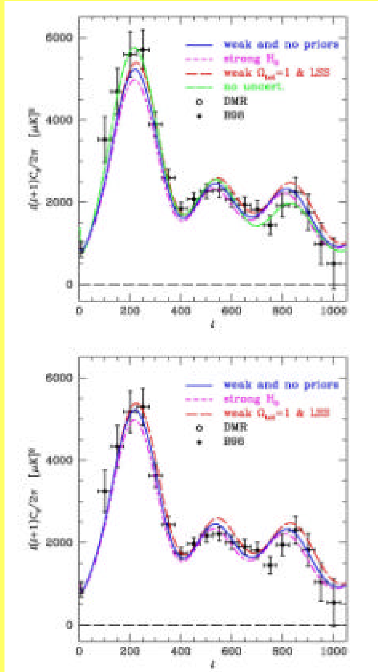
FIG. 3. Projection effects. Temperature fluctuations the last scattering surface appear as anisotropies on the sky. The angular size depends on the geometry of the universe and the distance to this surface. At a fixed distance, a smaller physical scale is required to subtend the same angle in a closed universe and larger in an open universe (schematically flattened for clarity). Physical scales such as the sound horizon at last scattering can be used to measure the curvature.

The Universe is flat! (W_{tot} = 1)

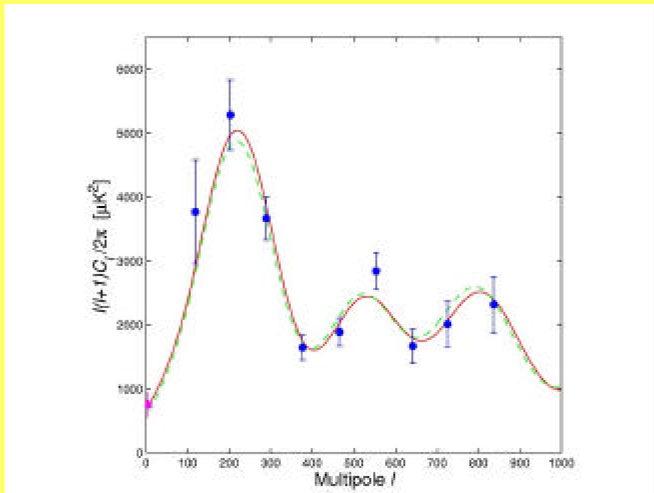
Boomerang, Maxima, DASI,.. – and soon MAP



Boomerang



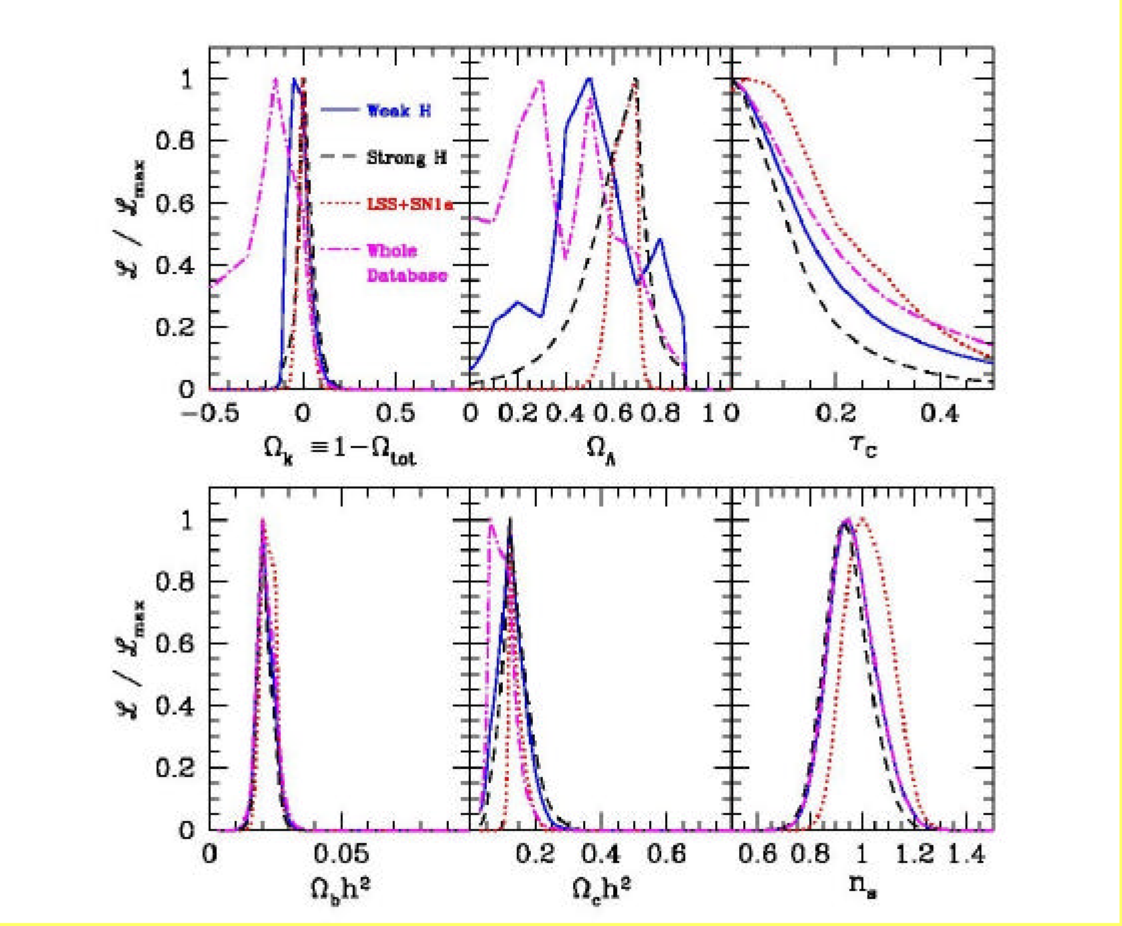
Boomerang



DASI

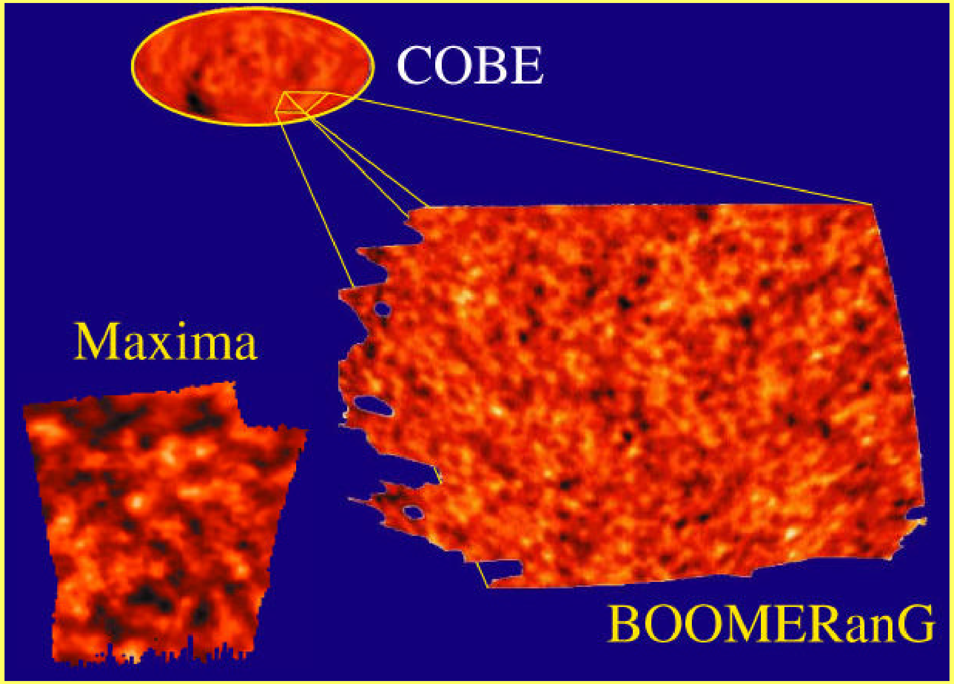
Lars Bergstrom, lbe@physto.se

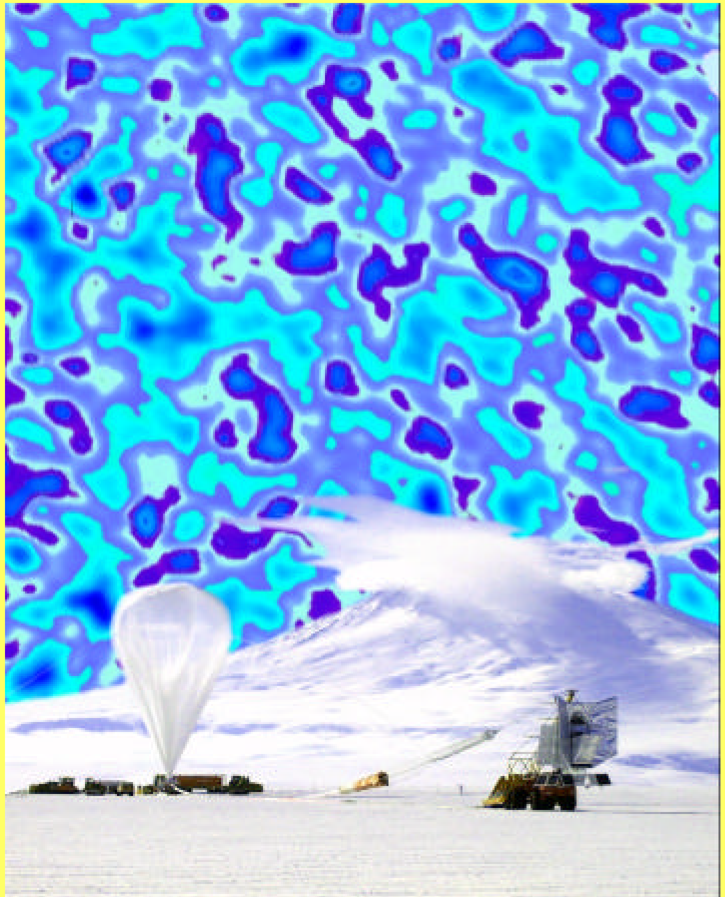
Cosmological parameters from Boomerang data



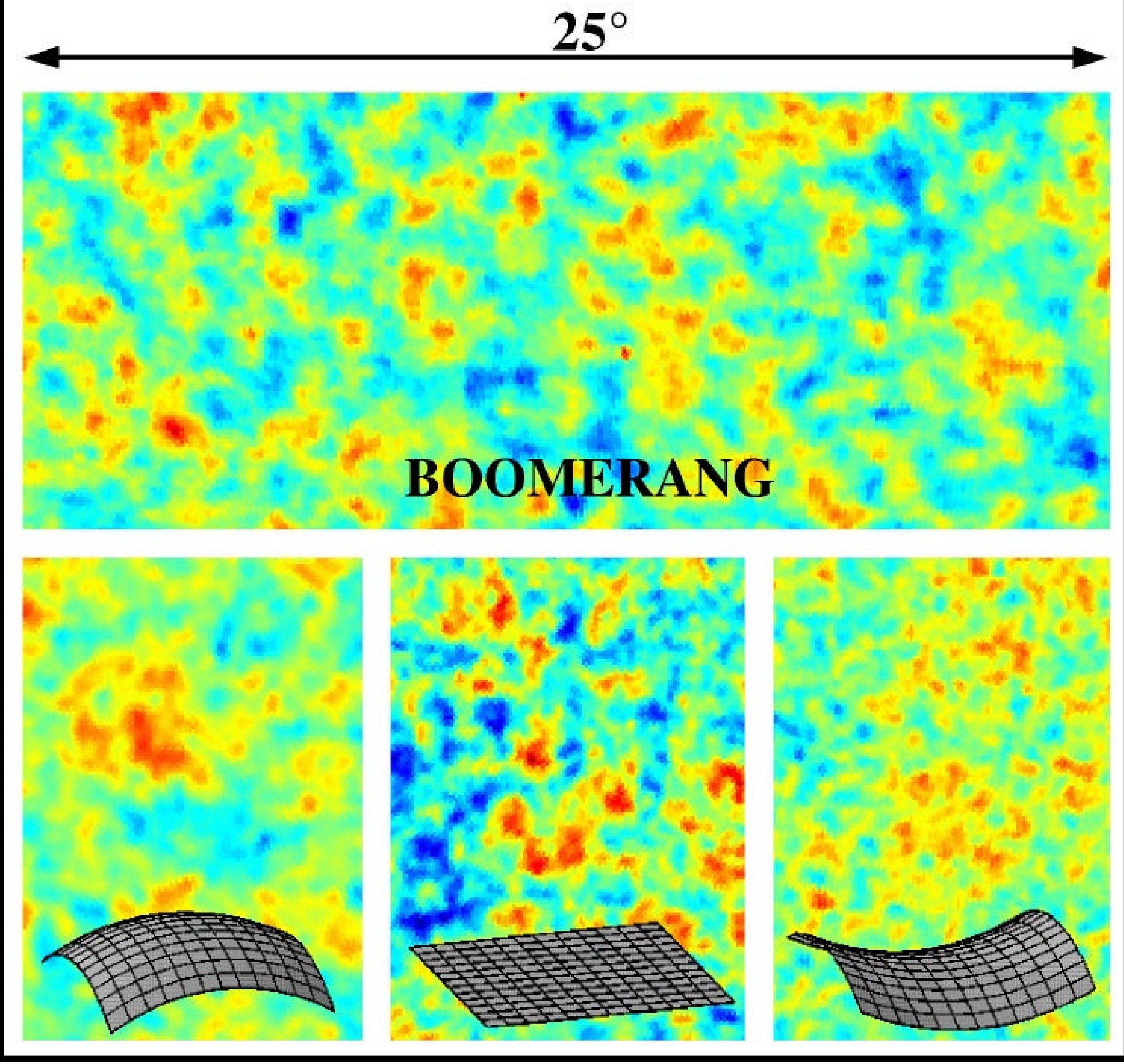
Boomerang collaboration

Lars Bergstrom, lbe@physto.se

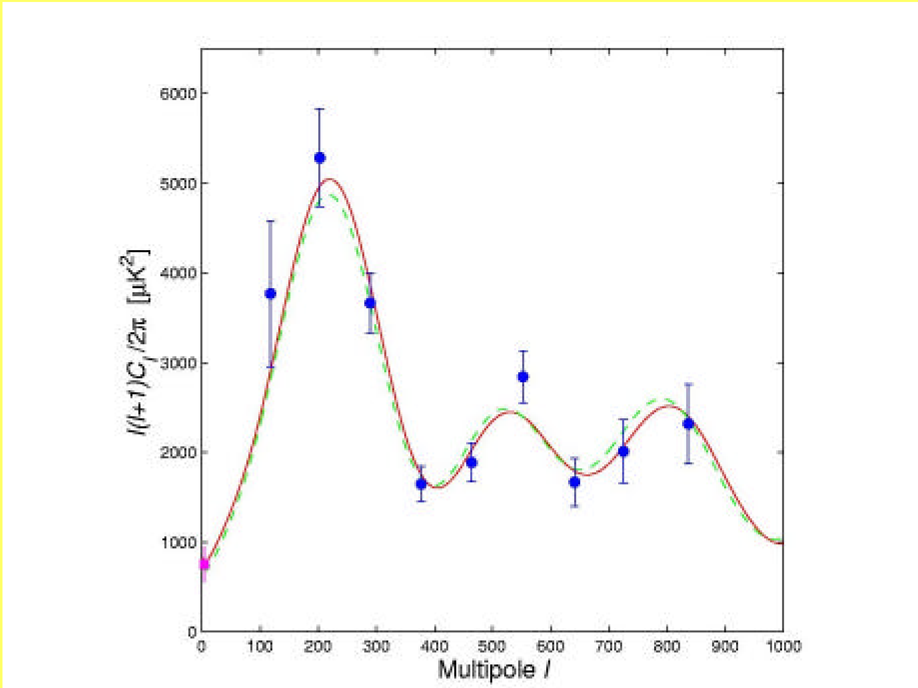




Pictures by Boomerang collaboration



25°
BOOMERANG



DASI

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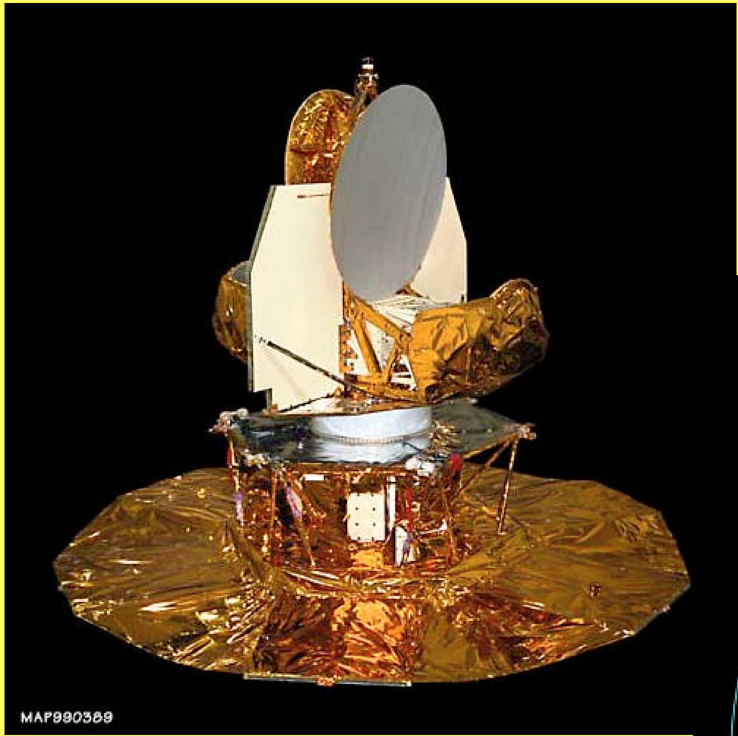
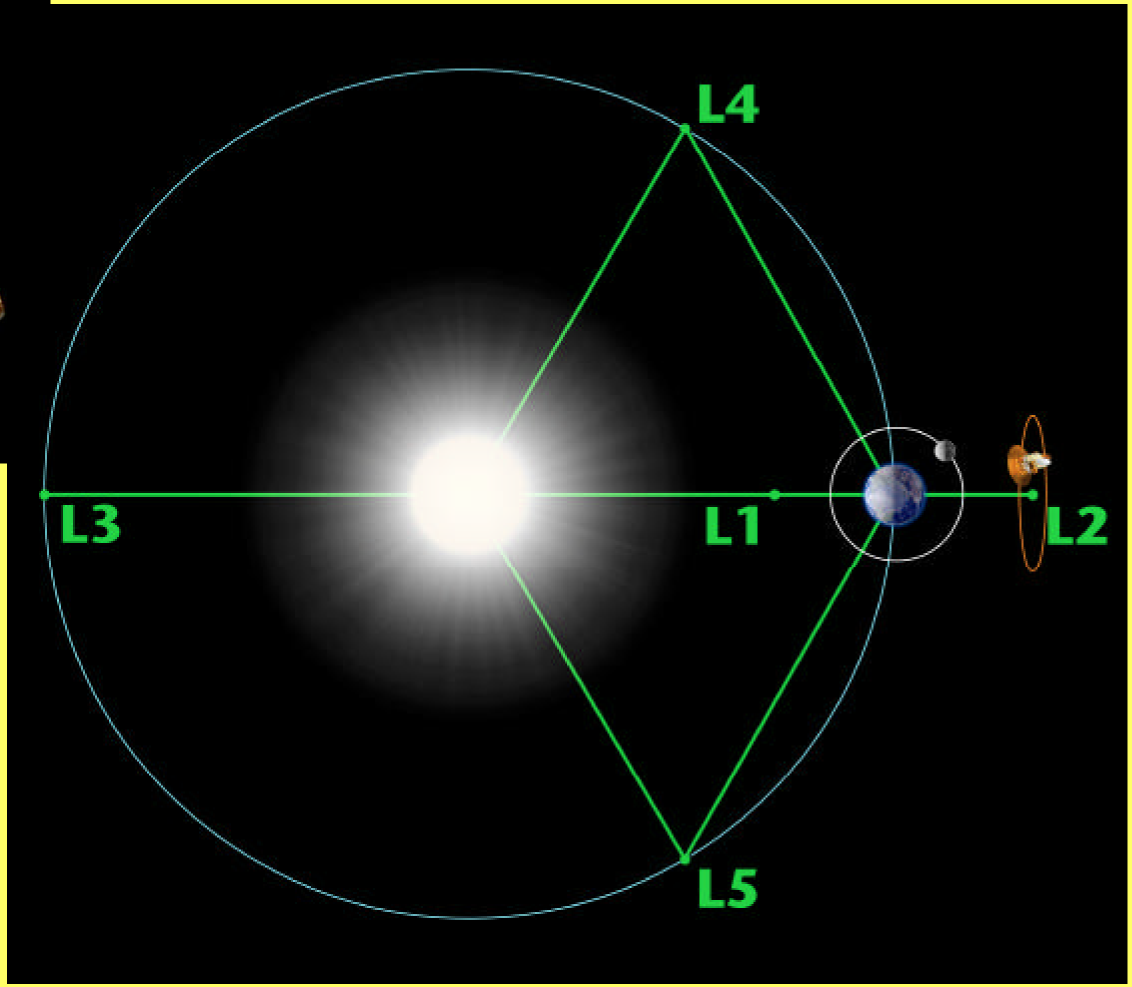
Pictures by DASI collaboration, J. Carlstrom et al.



January 2002: Taking data!



MAP – Microwave Anisotropy Probe

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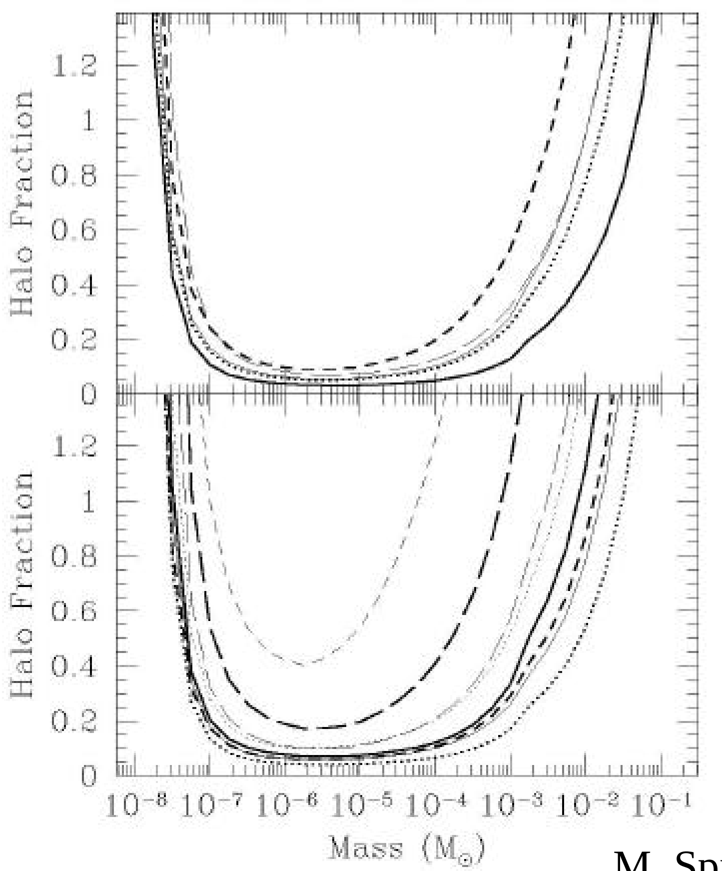
Stars and planets ("Jupiters") cannot be a large fraction of Milky Way halo dark matter!

(Stellar-mass objects excluded from chemical evolution & detection of extragalactic TeV gamma-rays)

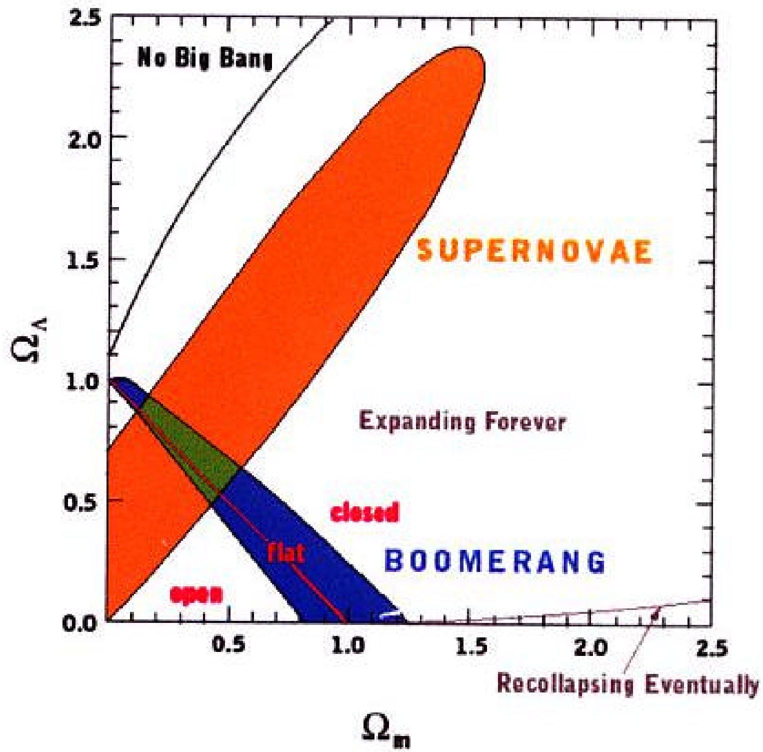


M. Spiro

Fig. 3.— Halo fraction upper limit (95% c.l.) versus lens mass for the five EROS models (top) and the eight MACHO models (bottom). The line coding is the same as in Figure 2.

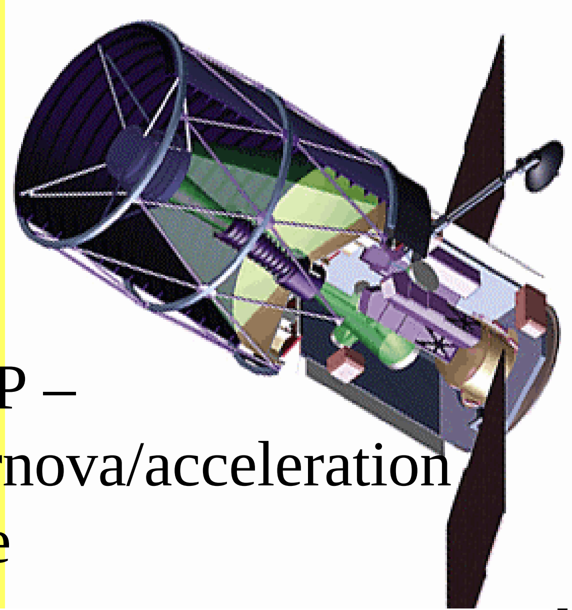
Determination of cosmological parameters

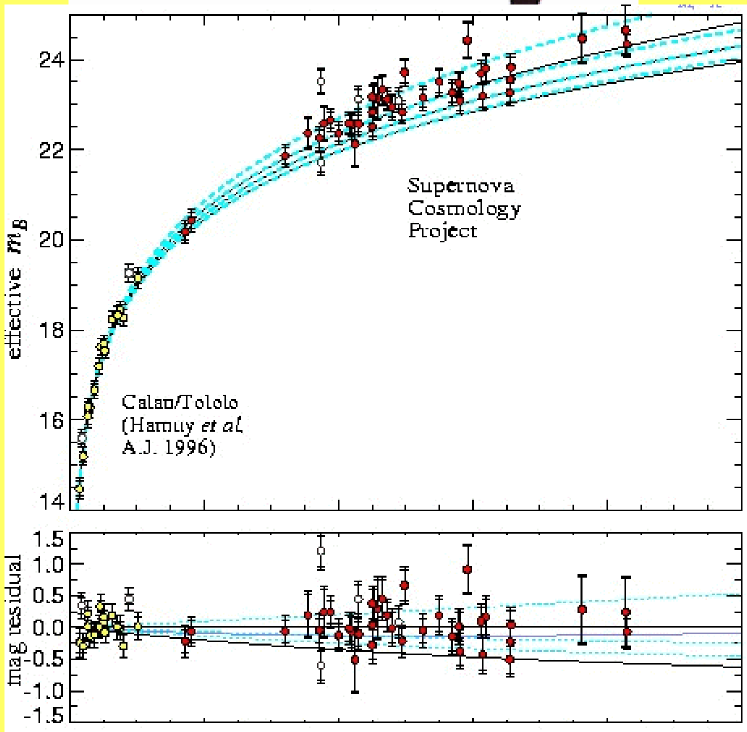
H_0, Ω_m, $\Omega_\Lambda \ldots$

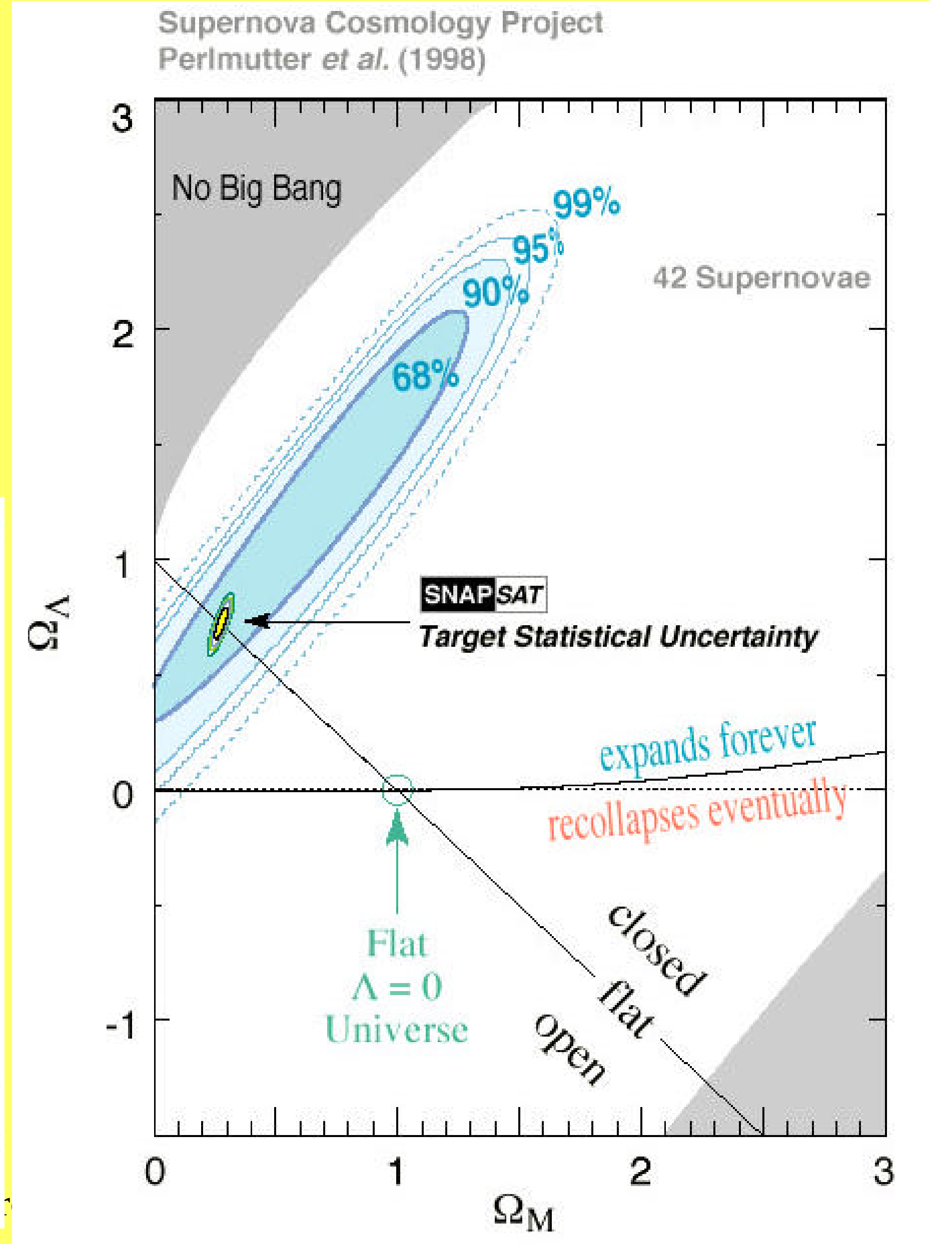


Current data are in agreement with:
$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

SNAP – supernova/acceleration probe

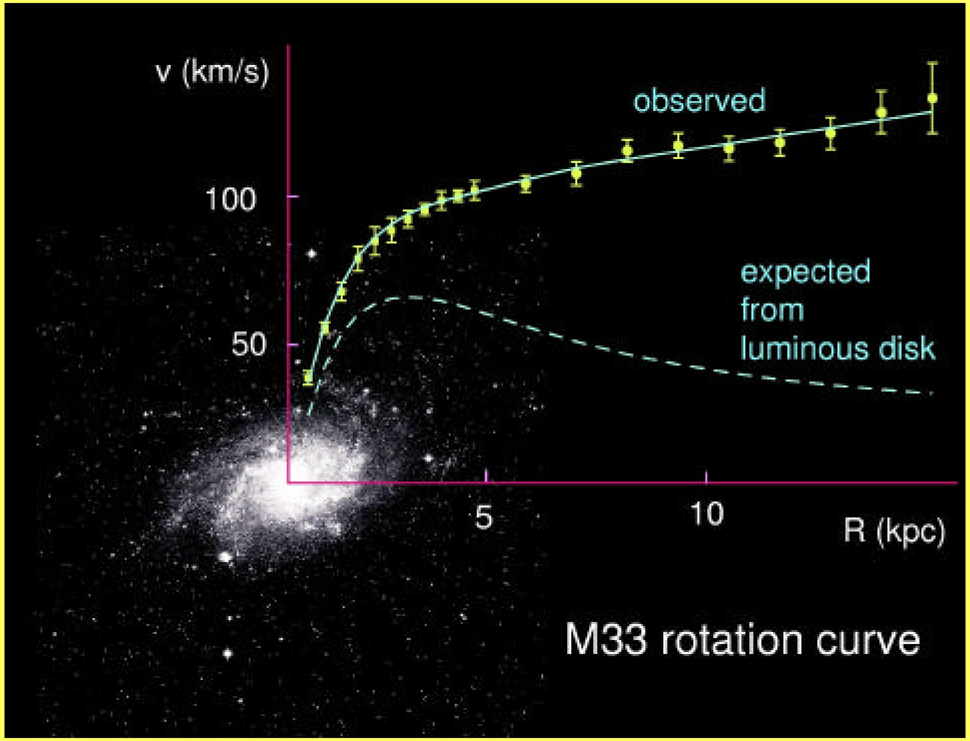






Dark matter needed on all scales!
(Þ MOND and other attemps to modify gravity very unlikely)

Galaxy rotation curves



NED/STScI; E. Corbelli & P. Salucci (1999)

X-ray emitting clusters

Cluster 3C295 (Chandra)

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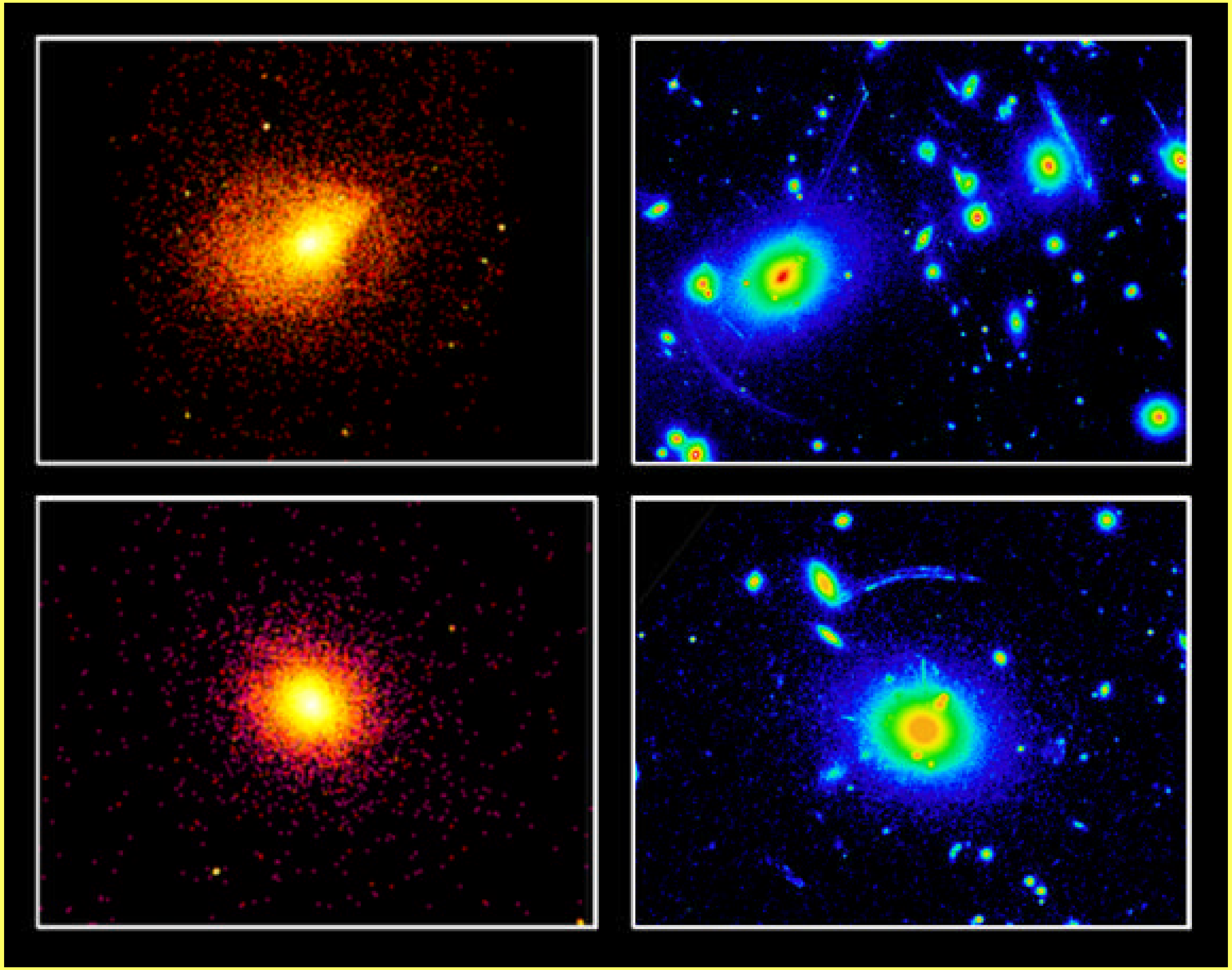
Mass estimates from X-ray & gravitational lensing agree



Abell 2390

MS2137.3-2353

Chandra

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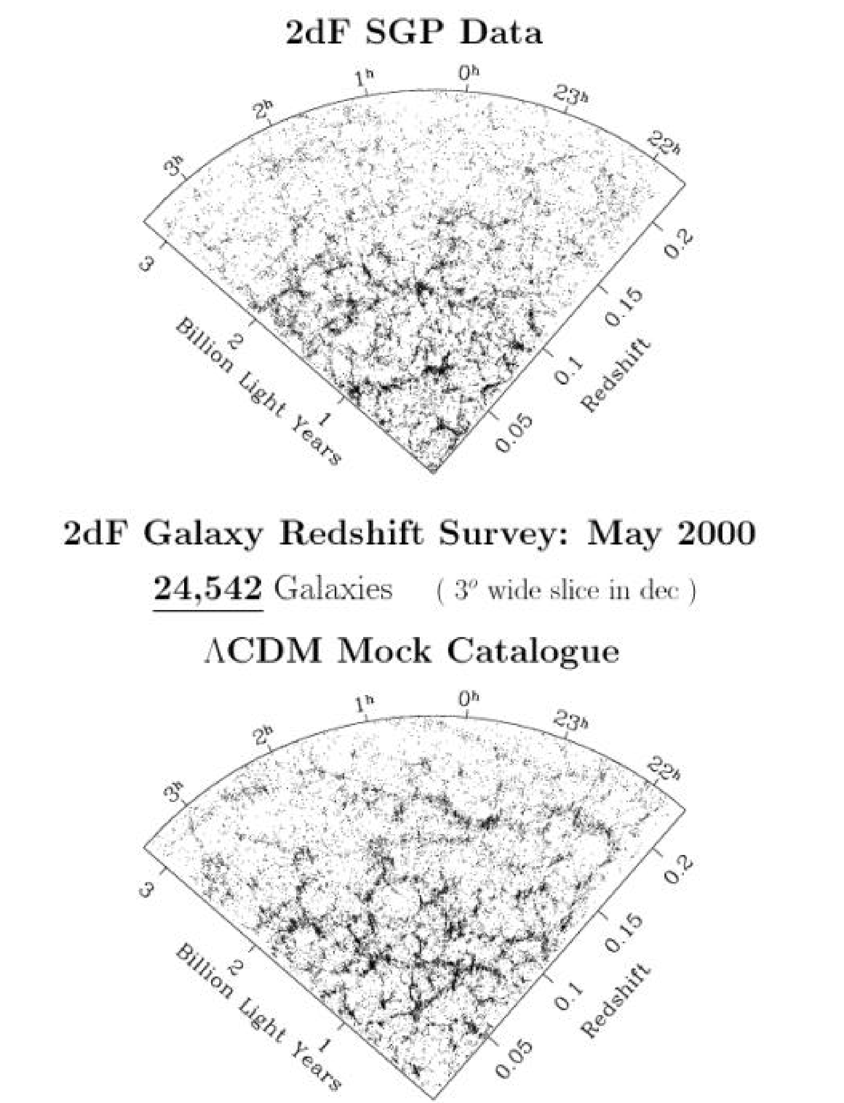
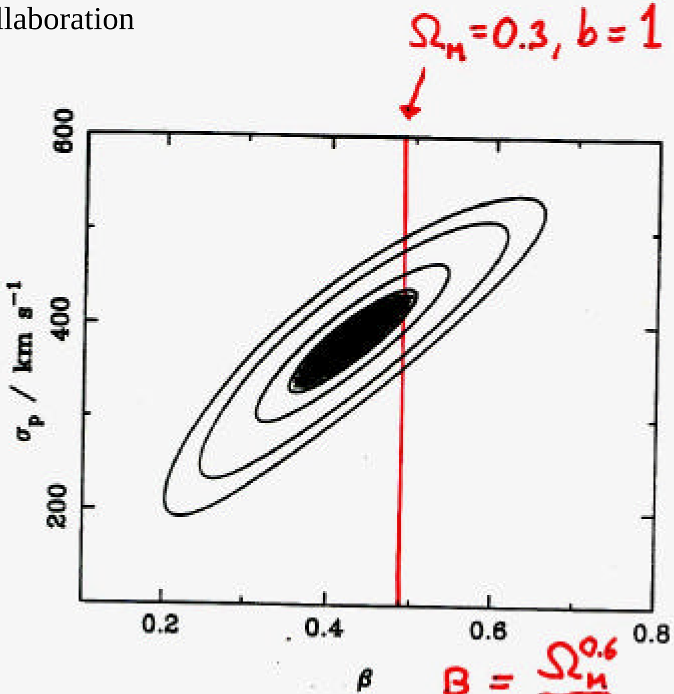


P. Norberg & S. Cole, 2000

Large-scale structure in striking agreement with the ”standard cosmology”, ΛCDM ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)



$\beta = \frac{\Omega_M^{0.6}}{b}$ b: "bias factor"

$\left(\frac{\delta\rho}{\rho}\right)_{gal} = b \cdot \left(\frac{\delta\rho}{\rho}\right)_{mass}$

Figure 4 Likelihood contours for β and the fingers-of-God smearing parameter σ_p, based on the data in Fig. 3 (considering $8\,h^{-1}$ Mpc $< r < 25\,h^{-1}$ Mpc). These are plotted at the usual positions for one-parameter confidence of 68% (shaded region), and two-parameter confidence of 68%, 95% and 99% (i.e. $\Delta\chi^2 = 1, 2.3, 6.0, 9.2$). The maximum-likelihood solution is $\beta = 0.43$ and $\sigma_p = 385\,\mathrm{km\,s^{-1}}$. The value for the large-scale pairwise dispersion is in reasonable agreement with previously suggested values[30]; however, for the present analysis σ_p is an uninteresting parameter. If we marginalize over σ_p (i.e. integrate over σ_p, treating the likelihood as a probability distribution), the final estimate of β and its rms uncertainty is $\beta = 0.43 \pm 0.07$.

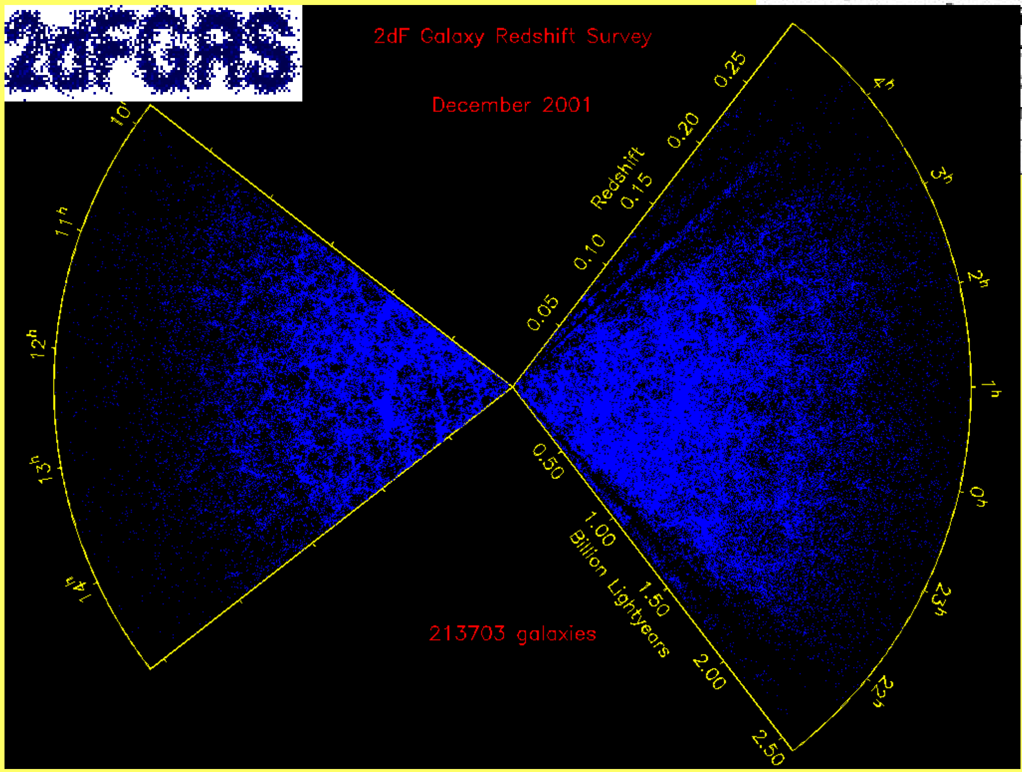
We believe that this result is robust, in the sense that systematic errors in the modelling are smaller than the random errors. We have tried assuming that the power spectrum for $k < 0.1\,h\,\mathrm{Mpc}^{-1}$ has the shape of a $\Omega = 0.3$ ΛCDM model, rather than the APM measurement; this has a very small effect. A more serious issue is whether the pairwise velocity dispersion of galaxies may depend strongly on separation, as is found for mass particles in numerical simulations[31]. Assuming that the pairwise velocity dispersion σ_p rises to twice its large-scale value below $1\,h^{-1}$ Mpc reduces the best-fit β by 0.04. This correction is small because our analysis excludes the nonlinear data at $r < 8\,h^{-1}$ Mpc.

The 2-degree Field Galaxy Redshift Survey (cf. SDDS)

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 6 December 2001 (MN LaTeX style file v1.4)

The 2dF Galaxy Redshift Survey: The bias of galaxies and the density of the Universe

Licia Verde[1,2], Alan F. Heavens[3], Will J. Percival[3], Sabino Matarrese[4], Carlton M. Baugh[5], Joss Bland-Hawthorn[6], Terry Bridges[6], Russell Cannon[6], Shaun Cole[5],
…s Collins[8], Warrick Couch[9], Gavin Dalton[10], Roberto De
…r[11], George Efstathiou[12], Richard S. Ellis[13], Carlos S. Frenk[5],
…ole Jackson[7], Ofer Lahav[12], Ian Lewis[10], Stuart Lumsden[15],
… Madgwick[12], Peder Norberg[5], John A. Peacock[3], Bruce A.
…nd[3], Keith Taylor[6]



Result:

$$\Omega_m = 0.27 \pm 0.06.$$

$$\Omega_M \approx 0.3$$

instead of

$$\Omega_M \approx 1$$

→ Good news for Dark Matter searches!

???

$$\rho_{DM}(r) \leftrightarrow \Omega_M$$

~ 0.3 GeV/cm³ in solar neighbourhood

N-body simulations

$$\Omega_{DM} \sim 1/(\sigma_{ann} v)$$

Crossing symmetry

$$\Rightarrow \sigma_{ann} \sim \sigma_{scatt}$$

So, low Ω_{DM} (if enough to make up galaxy halos) means higher annihilation & scattering rates

⇒ good news for detection!

Cold Dark Matter

- **Part of the "Concordance Model"**
- **Gives excellent description of large scale structure, Ly-**a **forest, gravitational lensing**
- **If consisting of particles, may be related to electroweak mass scale: weak cross section, non-dissipative "WIMPs" (Weakly Interacting Massive Particles)**
- **Potentially detectable directly or indirectly**
- **May or may not describe small-scale structure in galaxies: Controversial issue, but alternatives (self-interacting DM, warm DM, self-annihilating DM) seem worse**

Supersymmetry

- **Invented in the 1970's**
- **Necessary in most string theories**
- **Restores unification of couplings**
- **Solves hierarchy problem**
- **Gives right scale for neutrino masses**
- **Predicts light Higgs (< 130 GeV)**
- **May be detected at Fermilab/LHC**
- **Gives an excellent dark matter candidate (If R-parity is conserved)**
- **Useful as a template for generic "WIMP" (Weakly Interacting Massive Particle)**

Work done in collaboration with

- **P. Gondolo (Munich/Case Western)**
- **J. Edsjö (Stockholm)**
- **P. Ullio (Caltech/SISSA)**

and also

- **E. Baltz (UC Berkeley/Columbia)**
- **T. Damour (Paris)**
- **L. Krauss (Case Western)**

For a review, see L. Bergström, Rep. Prog. Phys. 63 (2000) 793 [hep-ph/0002126].

MSSM

It is the simplest supersymmetric extension to the SM:

- one supersymmetry generator ⇒ one superpartner to each SM particle
- 2 Higgs doublets ⇒ 5 physical Higgs bosons
- most general soft SUSY-breaking terms

The most general R-parity conserving MSSM is defined by 124 free parameters

"phenomenological" MSSM

We reduce to 7 real parameters:

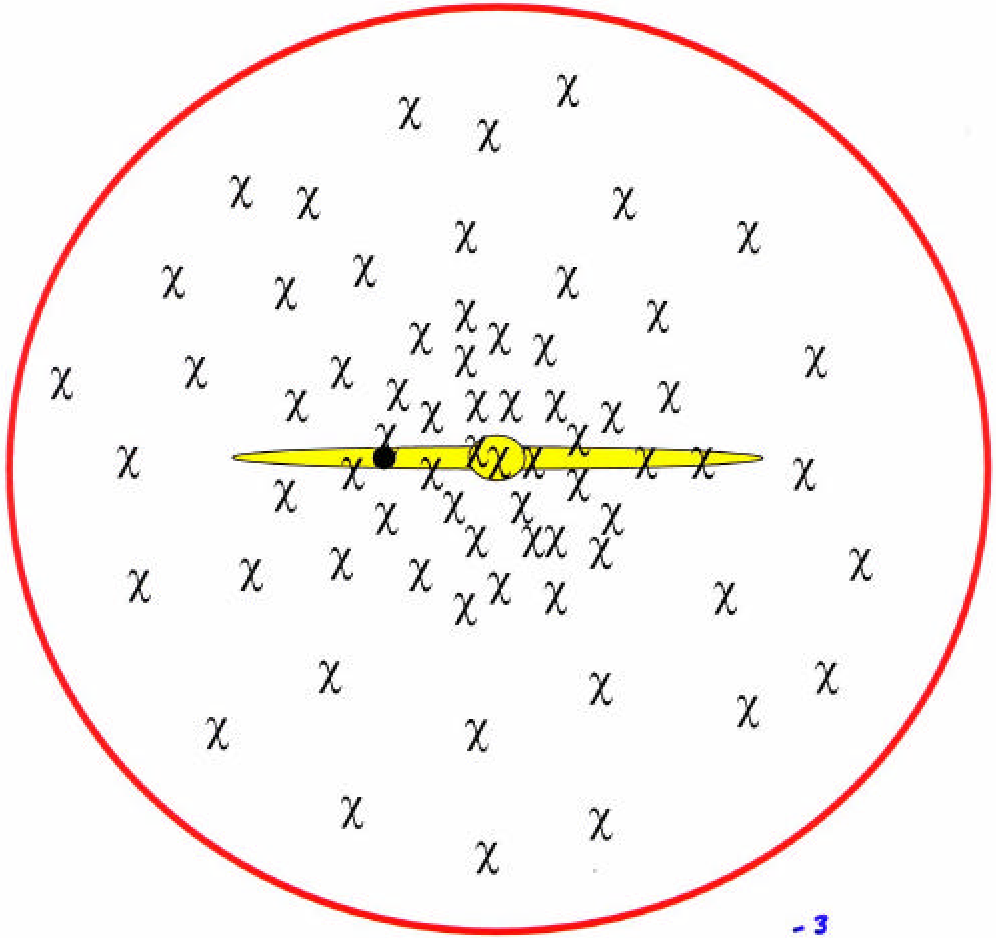
- μ - Higgsino mass parameter
- M_2 - Gaugino mass parameter ($M_1 \cong 0.5 M_2 \cong 0.15 M_3$)
- $\tan\beta$ - ratio of Higgs vacuum expectation values
- $m_{H_3^0}$ - mass of CP-odd Higgs boson
- m_0 - scalar mass parameter
- A_b , A_t - 2 soft trilinear parameters

No CP violation - No FCNCs

Assume lightest susy particle is χ_1^0

R-parity conservation → stable

Neutralino galactic halo



$\rho_{local} \sim 0.3\ GeV/cm^3 \quad v/c \sim 10^{-3}$

$m_\chi \sim 100\ GeV \Rightarrow Flux \sim 10^4\ cm^{-2} s^{-1} sr^{-1}$!

Will only consider MSSM χ, thermally produced in the early Universe

There are other possibilities for Dark Matter related to supersymmetry:

- ν, sneutrinos (Hall & Murayama)
- a, axinos (Kim & Roszkowski)
- Wimpzillas (Kolb & al)
- Cryptons (J. Ellis & al)
- Q-balls (Kusenko & al)
- Self-interacting DM (Farrar & al)

χ DM useful template for generic Weakly Interacting Massive Particle (WIMP) – also non-supersymmetric ones

Dark SUSY

Paolo Gondolo, Joakim Edsjö, Lars Bergström,

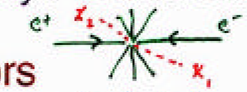
Piero Ullio and Edward A. Baltz

Release / download

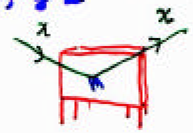
- Major code reorganization to make it user-friendly.
- Tested on RedHat Linux 7.2, LinuxPPC and Alphas.
- Released now as a fully working *beta-version*.
- Full release later 2002 with manual and long paper.
- Download at
  http://www.physto.se/~edsjo/darksusy/
- If you use it, please sign up on the DarkSUSY mailing list on that page!

Supersymmetric Dark Matter

If the Lightest Supersymmetric Particle (LSP) is Dark Matter, there are several ways to find out:



- Discovery of SUSY at accelerators
  (LEP II, Tevatron, LHC,...) (+ constraints)
  $b \to s + \gamma$; $g-2$



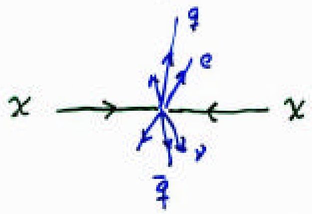
- Direct detection of halo particles
  (Si, NaI, Ge, Sapphire, Mica, ...)

- Indirect detection of:

neutrinos	gammas	antiprotons	positrons
Super-Kam	GLAST	BESS	HEAT
AMANDA	Air Cher.	Caprice	.....
Antares	.....	Pamela	
Nestor		AMS	
Baksan		......	
Baikal			
MACRO			

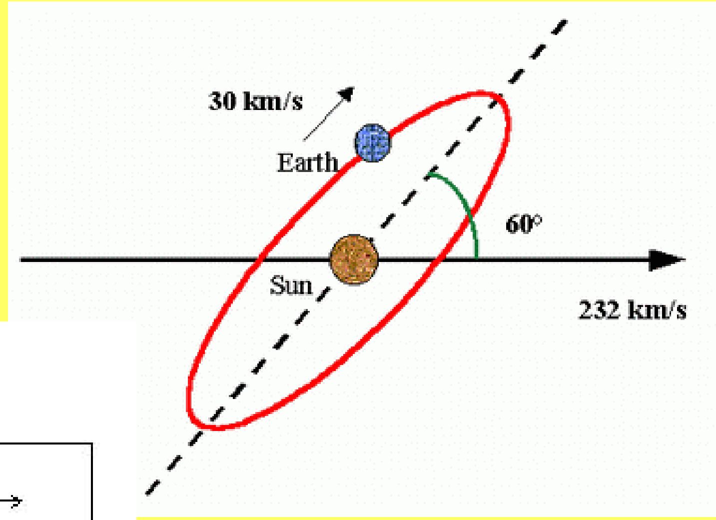
The basic process for indirect detection is annihilation:

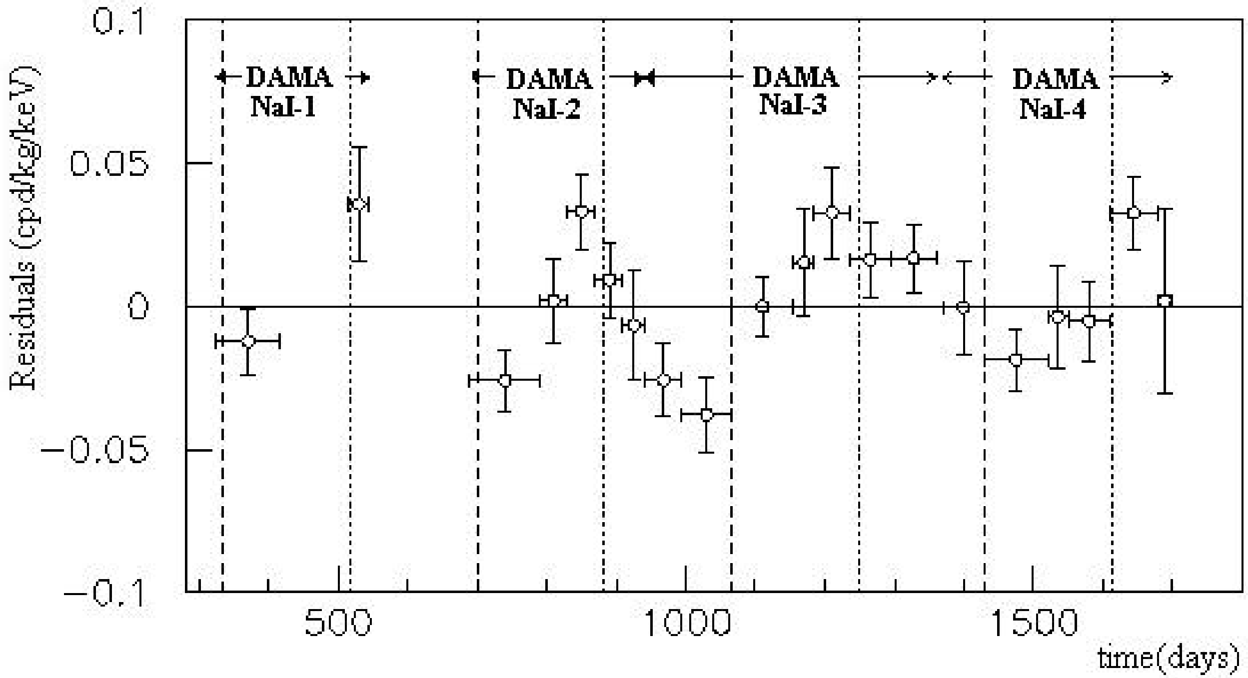
$$\chi + \chi \to \gamma, \nu, e^{+}, \bar{p}, \ldots$$

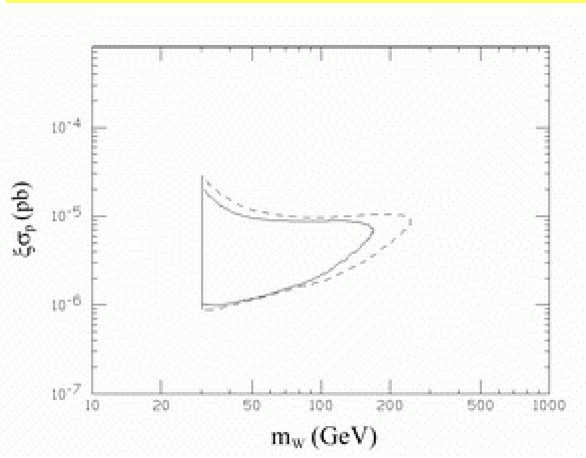


(χ are Majorana particles)

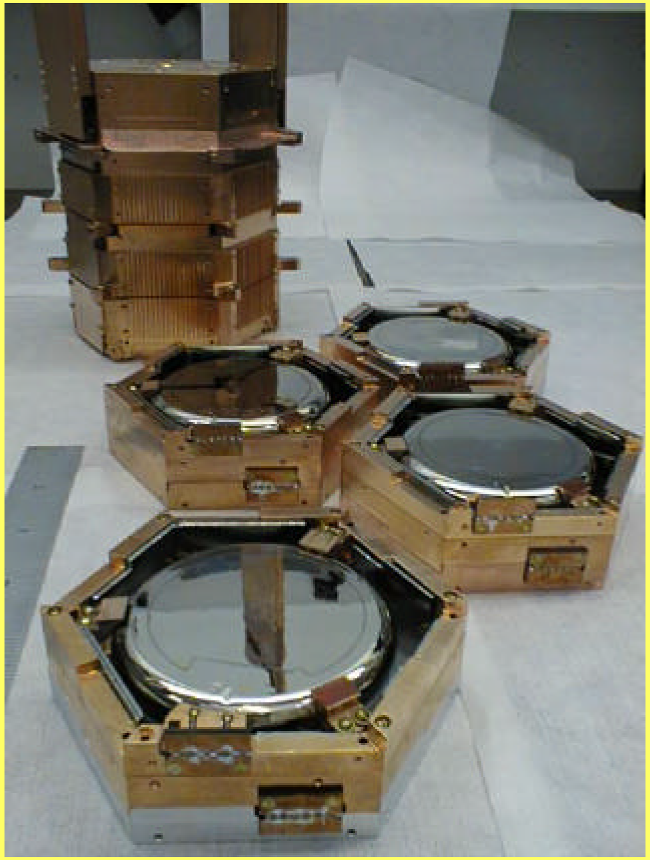
$\Gamma_{ann} \sim n_\chi^2 \Rightarrow$ enhanced for clumpy halo & near g.c. & in Sun & Earth

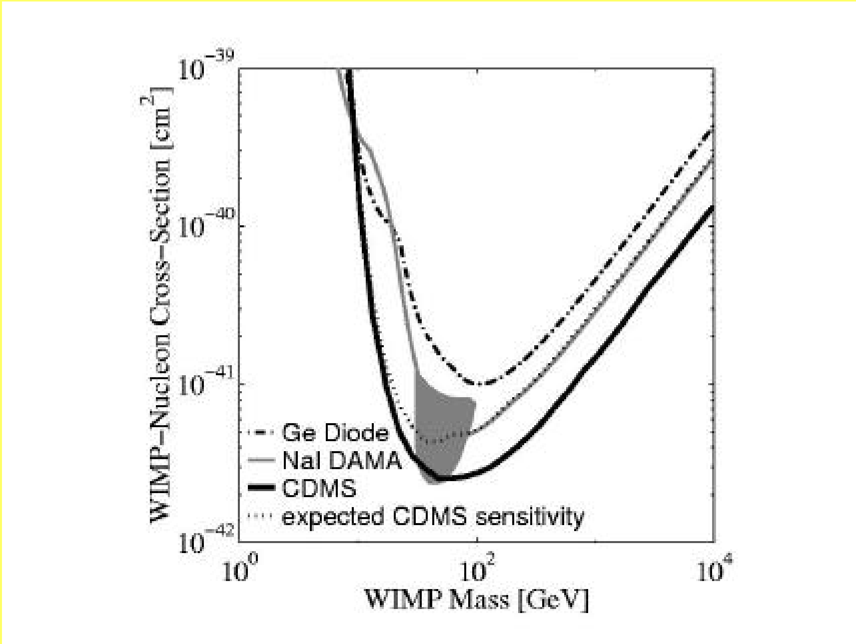

30 km/s
Earth
60°
Sun
232 km/s


DAMA NaI-1
DAMA NaI-2
DAMA NaI-3
DAMA NaI-4
Residuals (cpd/kg/keV)
0.1
0.05
0
−0.05
−0.1
500
1000
1500
time(days)


ξσ_p (pb)
m_W (GeV)

CDMS Collaboration

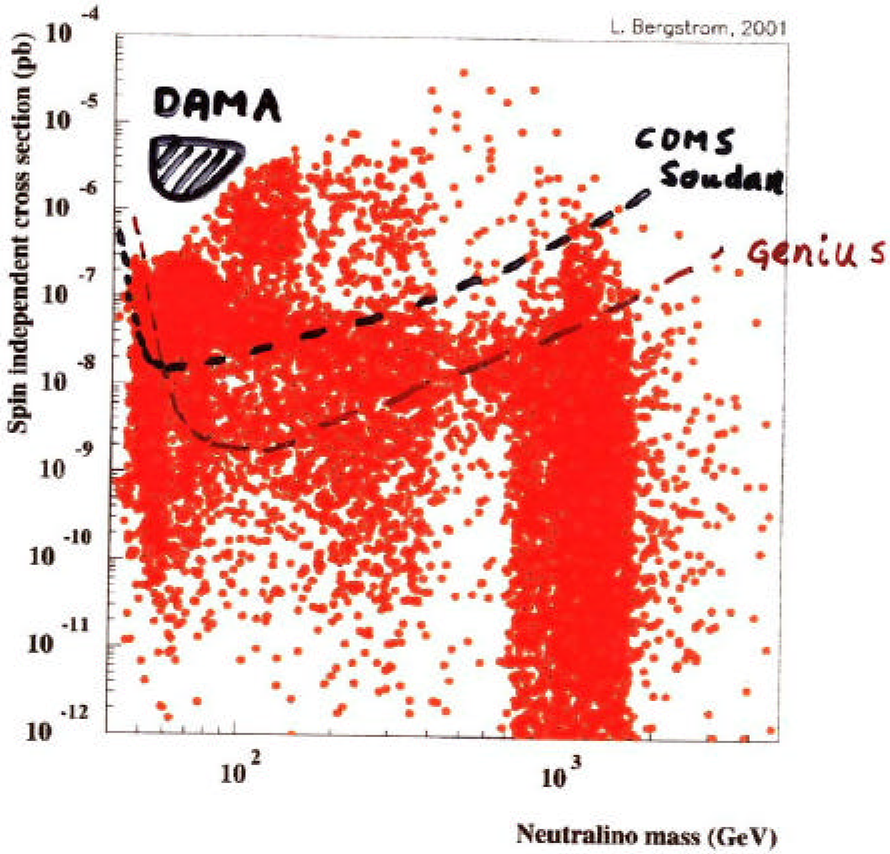




DarkSUSY scan

DAMA signal seems somewhat too high.

However, halo phase space distribution uncertain (and to some extent also nuclear physics part)



$\rho_0 = 0.3\ \mathrm{GeV/cm^3}$

$0.05 < \Omega_\chi h^2 < 0.25$

New generation of detectors (both nuclear recoil and ionization detection) – CDMS, Edelweiss, ZEPLIN, GENIUS, …

LYCEN 2001-38
December 11, 2001

First Results of the EDELWEISS WIMP Search using a 320 g Heat-and-Ionization Ge Detector

The EDELWEISS Collaboration:
A. Benoit[1], L. Bergé[2], A. Broniatowski[2], B. Chambon[3], M. Chapellier[4], G. Chardin[5], P. Charvin[5,6], M. De Jésus[3], P. Di Stefano[5], D. Drain[3], L. Dumoulin[2], J. Gascon[3], G. Gerbier[5], C. Goldbach[7], M. Goyot[3], M. Gros[5], J.P. Hadjout[3], A. Juillard[2,5], A. de Lesquen[5], M. Loidl[5], J. Mallet[5], S. Marnieros[2], O. Martineau[3], N. Mirabolfathi[2], L. Mosca[5], L. Miramonti[5], X.-F. Navick[5], G. Nollez[7], P. Pari[4], M. Stern[3], L. Vagneron[3]

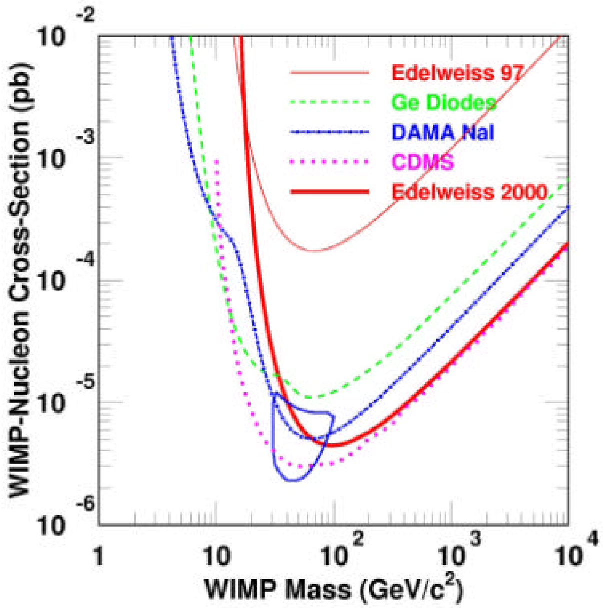


Figure 4: Spin-independent exclusion limit (dark solid curve) obtained in this work. Thin solid curve: previous EDELWEISS results [10]. Dashed curve: combined Ge diode limit [4]. Dash-dotted curve: DAMA NaI limit using pulse-shape discrimination [5]. Dotted curve: CDMS limit with statistical subtraction of the neutron background [7]. Closed contour: allowed region at 3σ CL for a WIMP r.m.s. velocity of 270 km/s from the DAMA annual modulation data [6].

Note sensitivity aquired with a 320 g detector – cf. DAMA 100 kg

Spin-dependent limits:

M. Altmann et al., astro-ph/0106314

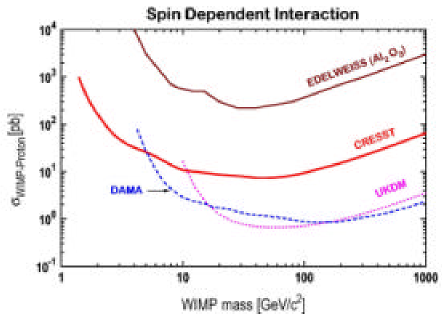
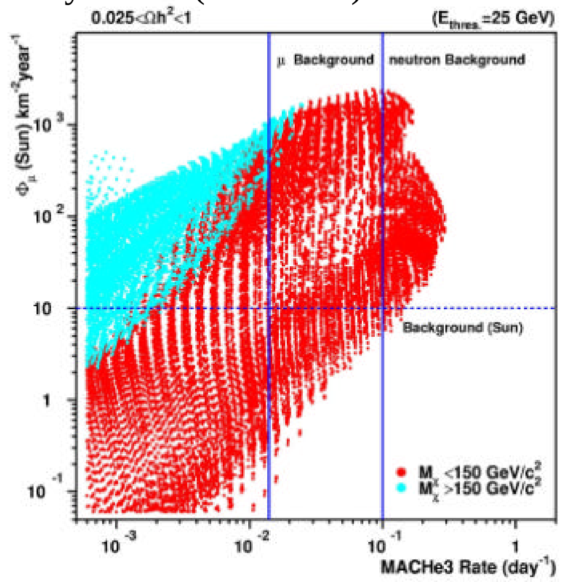


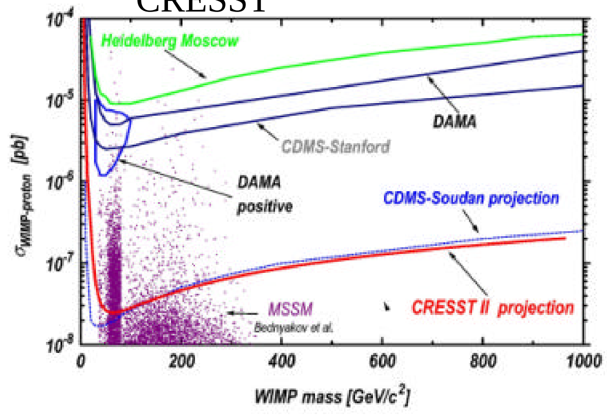
Figure 13: Equivalent WIMP-proton cross section limits (90 % CL) for spin-dependent interaction as a function of the WIMP mass from 1.51 kg days exposure of a 262 g sapphire detector. For comparison we show limits from the EDELWEISS dark matter search with cryogenic sapphire detectors [16], from DAMA with NaI detectors using pulse-shape discrimination [17], and from the UK dark matter search with NaI detectors [18].

F. Mayet et al (MACHe3)

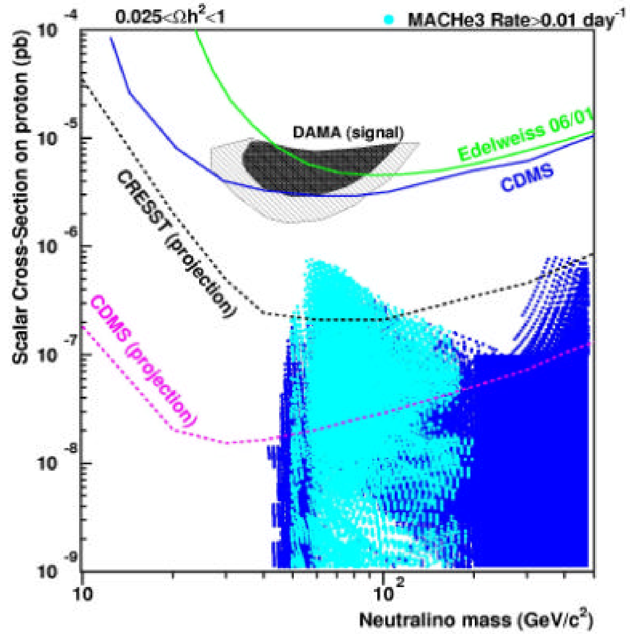


Future projects:

CRESST



MACHe3 vs CDMS-II



Lars Bergstrom, lbe@physto.se

New approach: use small number of ”well-motivated” points in SUSY parameter space

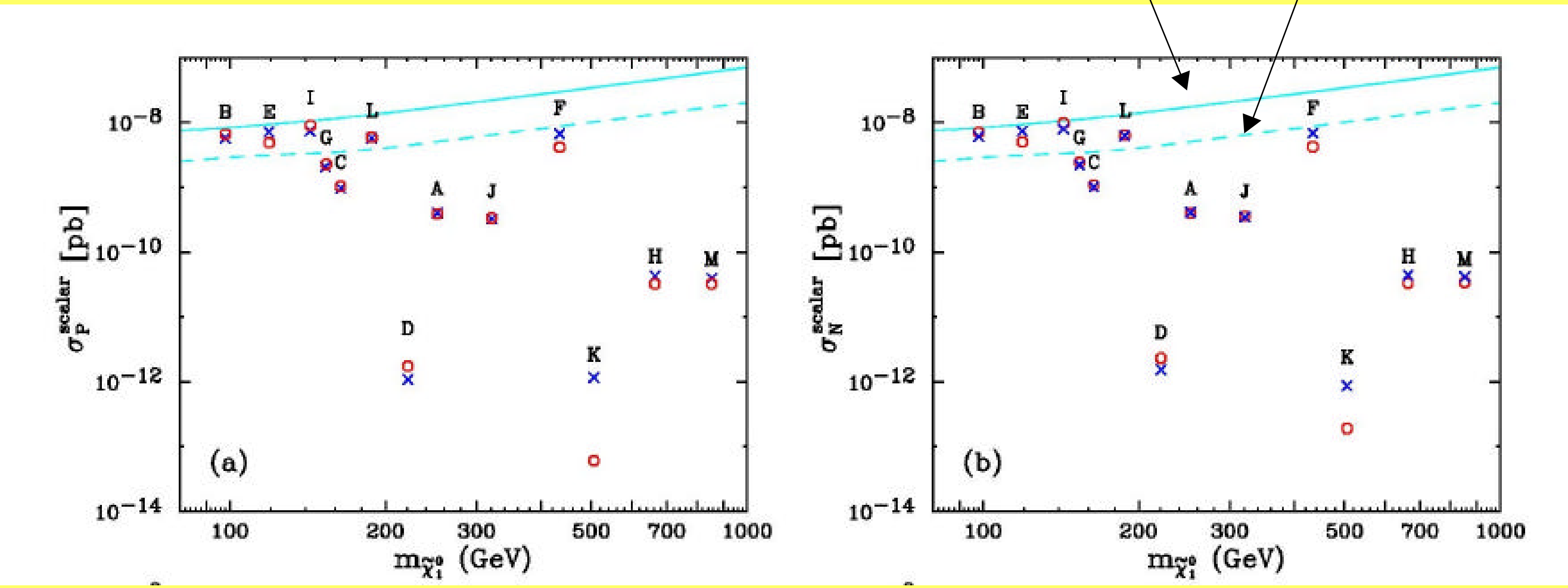
Prospects for Detecting Supersymmetric Dark Matter at Post-LEP Benchmark Points

John Ellis[1], Jonathan L. Feng[2,3], Andrew Ferstl[4],
Konstantin T. Matchev[1] and Keith A. Olive[5]

CRESST & CDMS II projected limits

GENIUS

Direct detection



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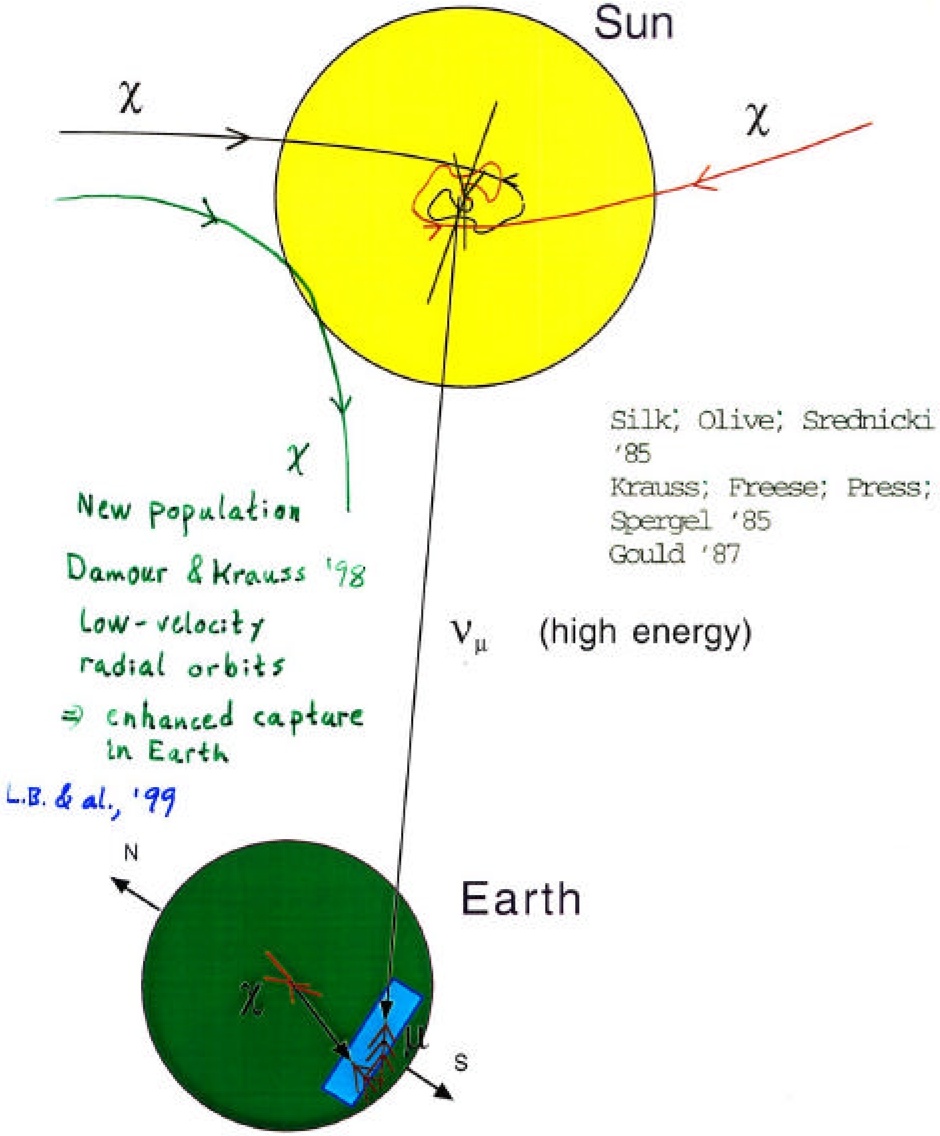
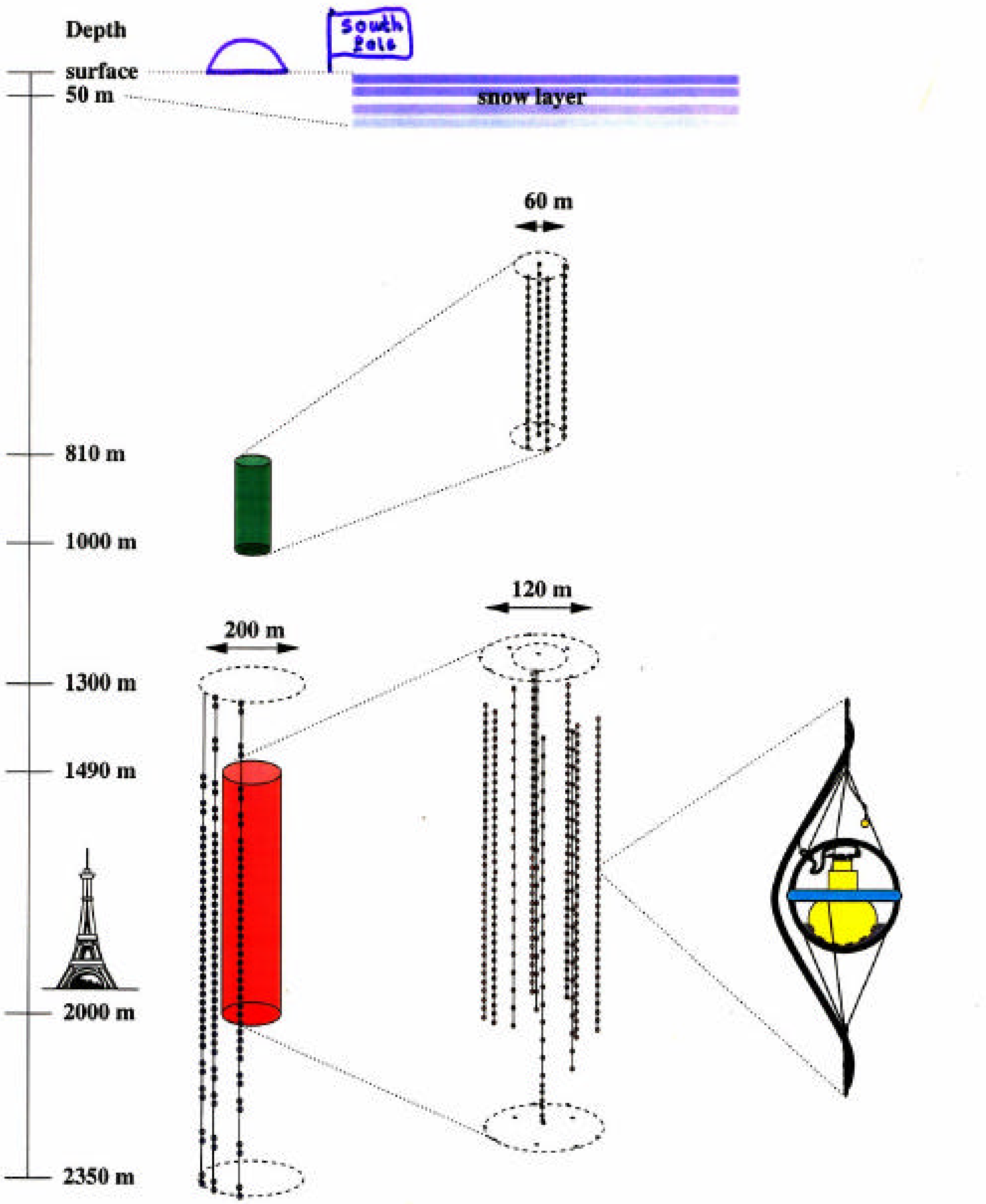
Gravitational trapping of halo neutralinos:



Freese '86
Krauss, Srednicki, Wilczek '86
Gaisser, Steigman, Tilav ' 87



AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

First AMANDA (B-10) limits on WIMPs

(X. Bai *et al.* IDM2000, York, England, 18-22 Sep 2000, astro-ph/0012285)

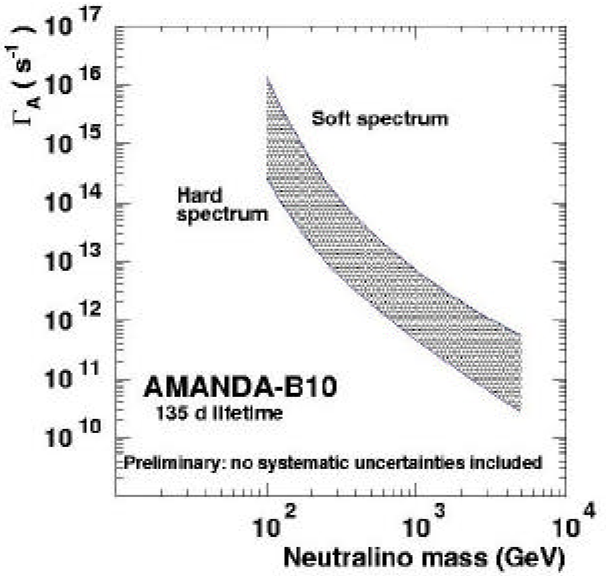
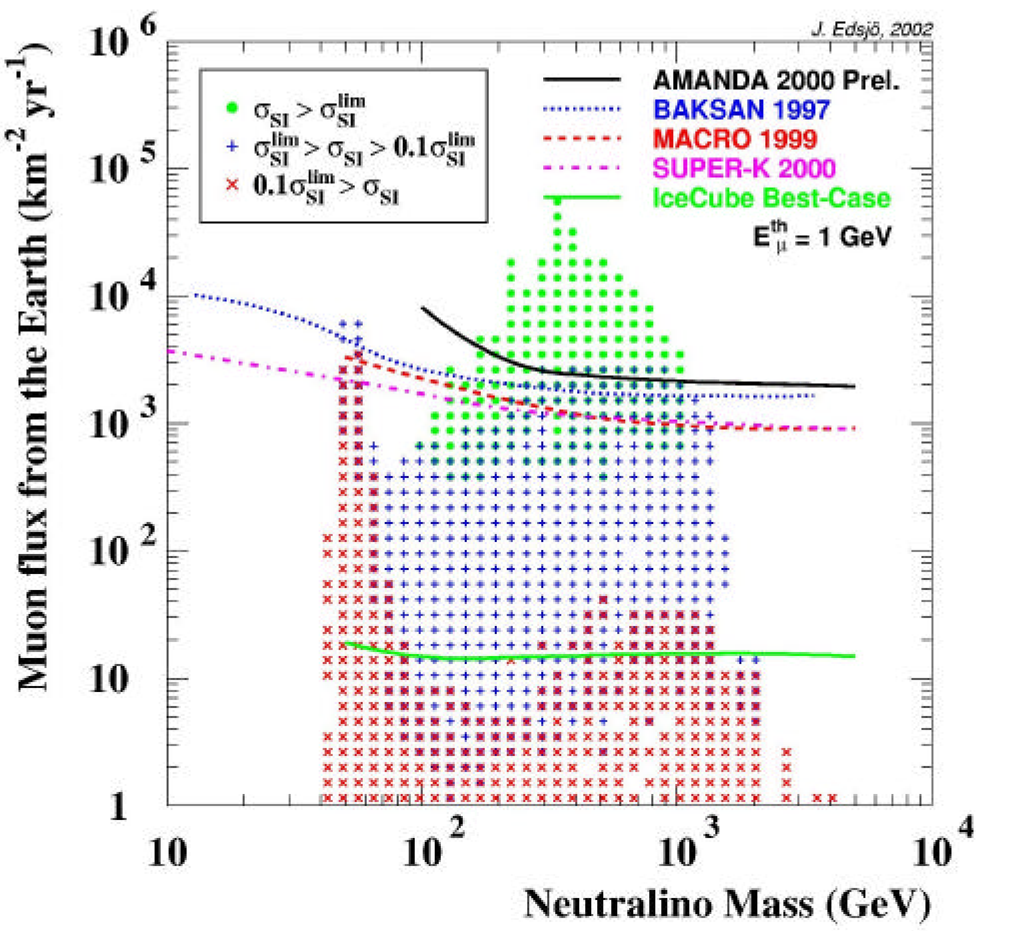
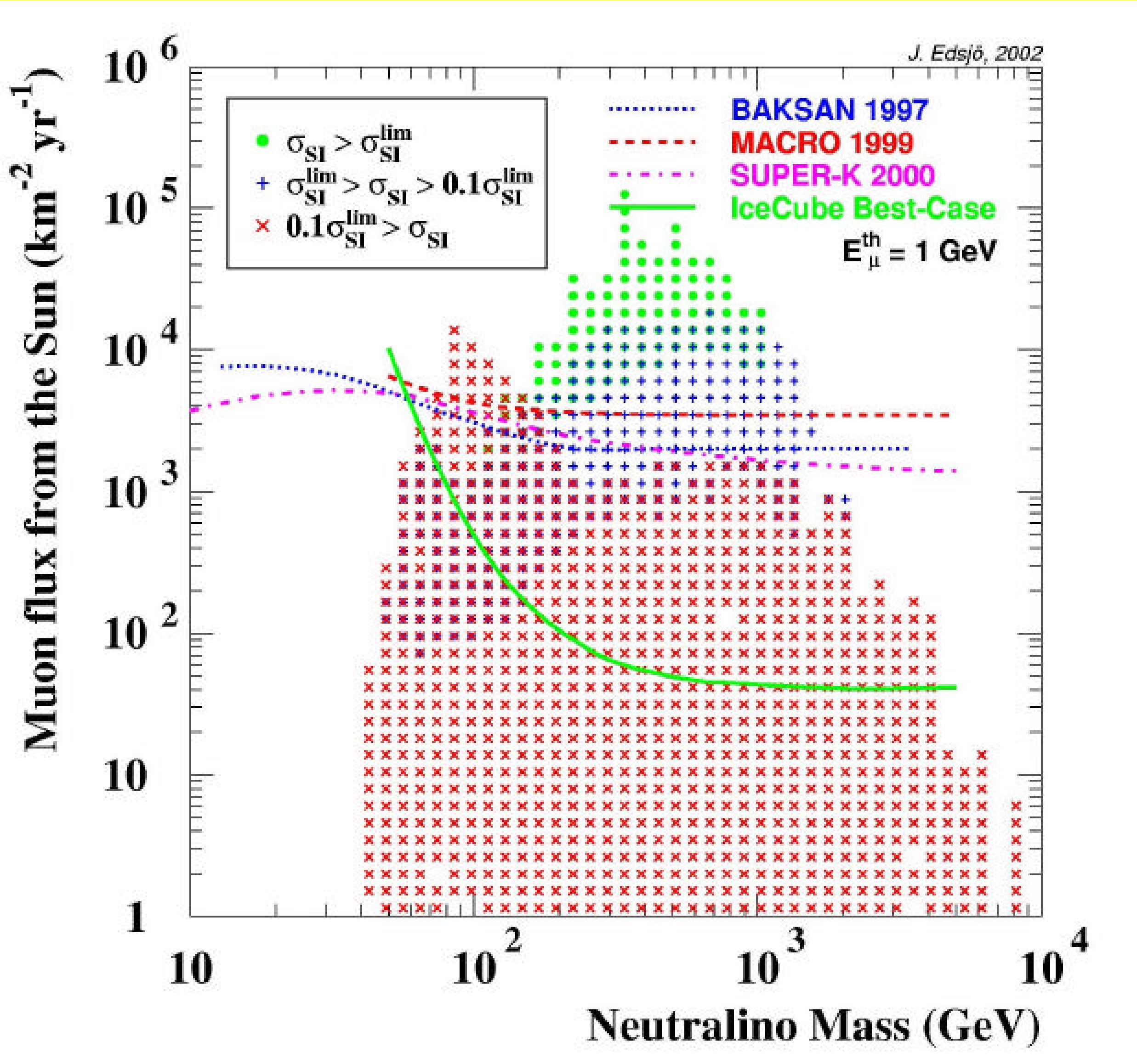


Figure 2. 90% confidence level upper limits on the WIMP annihilation rate in the center of the Earth, as a function of the WIMP mass and for the two extreme annihilation channels considered in the analysis.



Neutrinos from the Sun more difficult to detect with IceCube at low masses. (Antares may have better sensitivity.)



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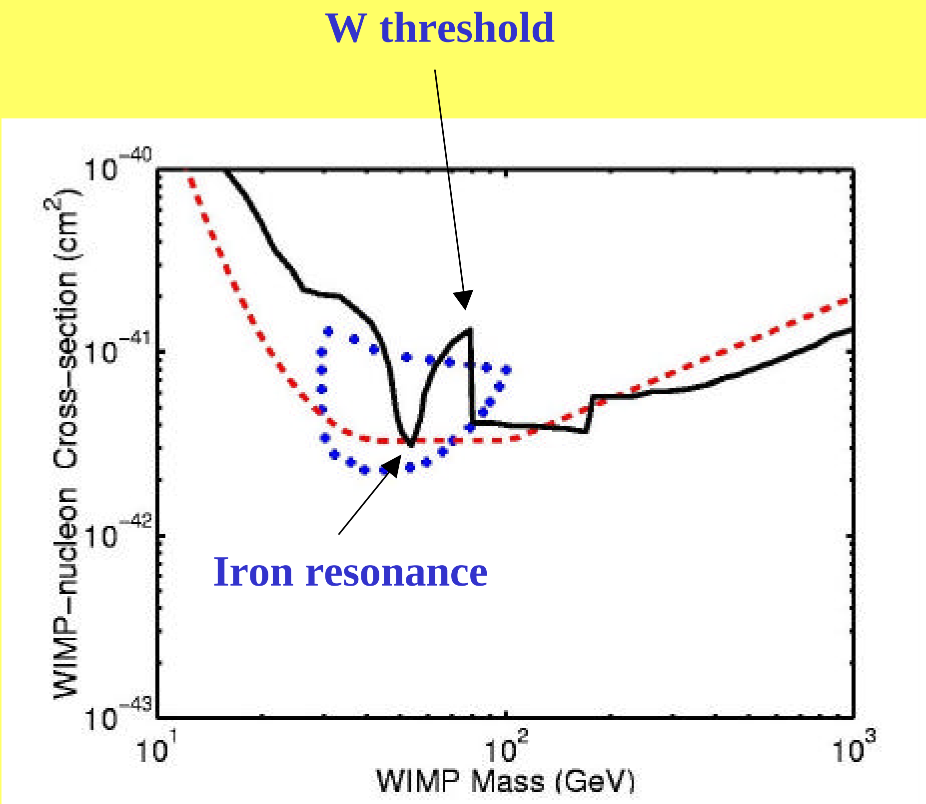
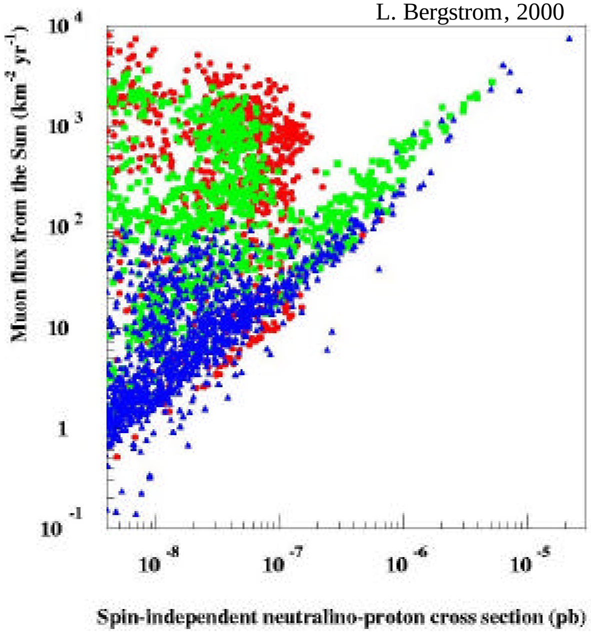


Fig. 3. Super-K 90% c.l. exclusion region in WIMP cross section vs. WIMP mass parameter space (above solid line), compared to the DAMA 3σ allowed region (inside crosses) and the CDMS 90% c.l. excluded region (above dashed line).

Super-K limits on WIMP cross section (A. Habig et al., hep-ex/0106024)

Simplified analysis based on correlation between capture rate in Earth and scattering rate in NaI through spin-independent interaction.



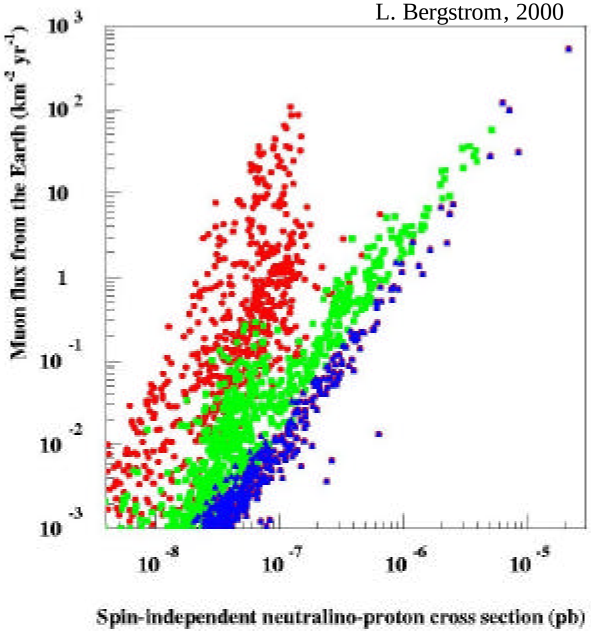
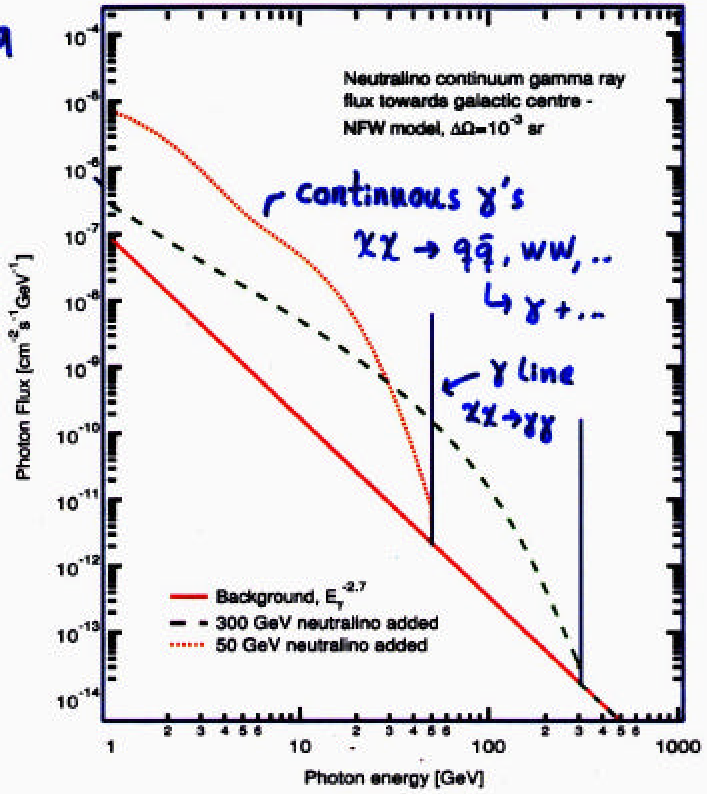


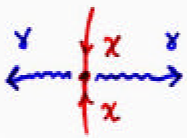
Figure 11. The predicted muon rates from neutralino annihilations in the Sun (left-hand figure) and in the Earth (right-hand figure) versus the neutralino-proton scattering cross section. A muon detection threshold of 1 GeV has been assumed. The requirements $m_{\chi^\pm} > 95$ GeV, $m_{H_2} > 100$ GeV, $0.1 < \Omega_\chi h^2 < 0.2$ have been imposed. For details on the computational procedure, see [134, 196]. The filled circles denote higgsino-like models with gaugino fraction $Z_g < 0.01$, squares are mixed models with $0.01 < Z_g < 0.99$ and triangles are gaugino models with $Z_g > 0.99$.

Gamma rays



L.B., P. Ullio & J. Buckley
Astropart. Phys. 9 (1998) 137.

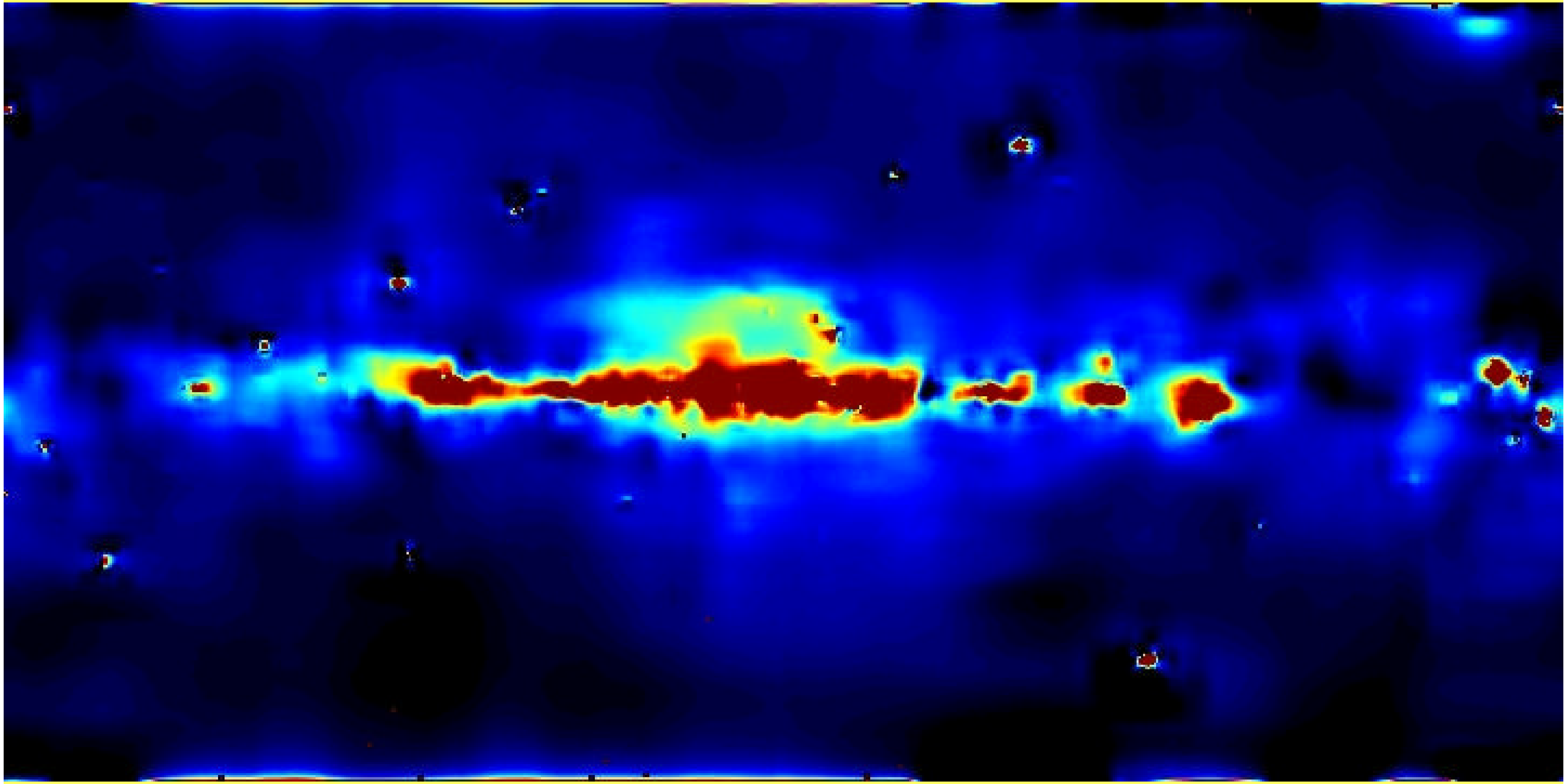
$\chi\chi \to \gamma\gamma$ line (L.B. & H. Snellman '86)



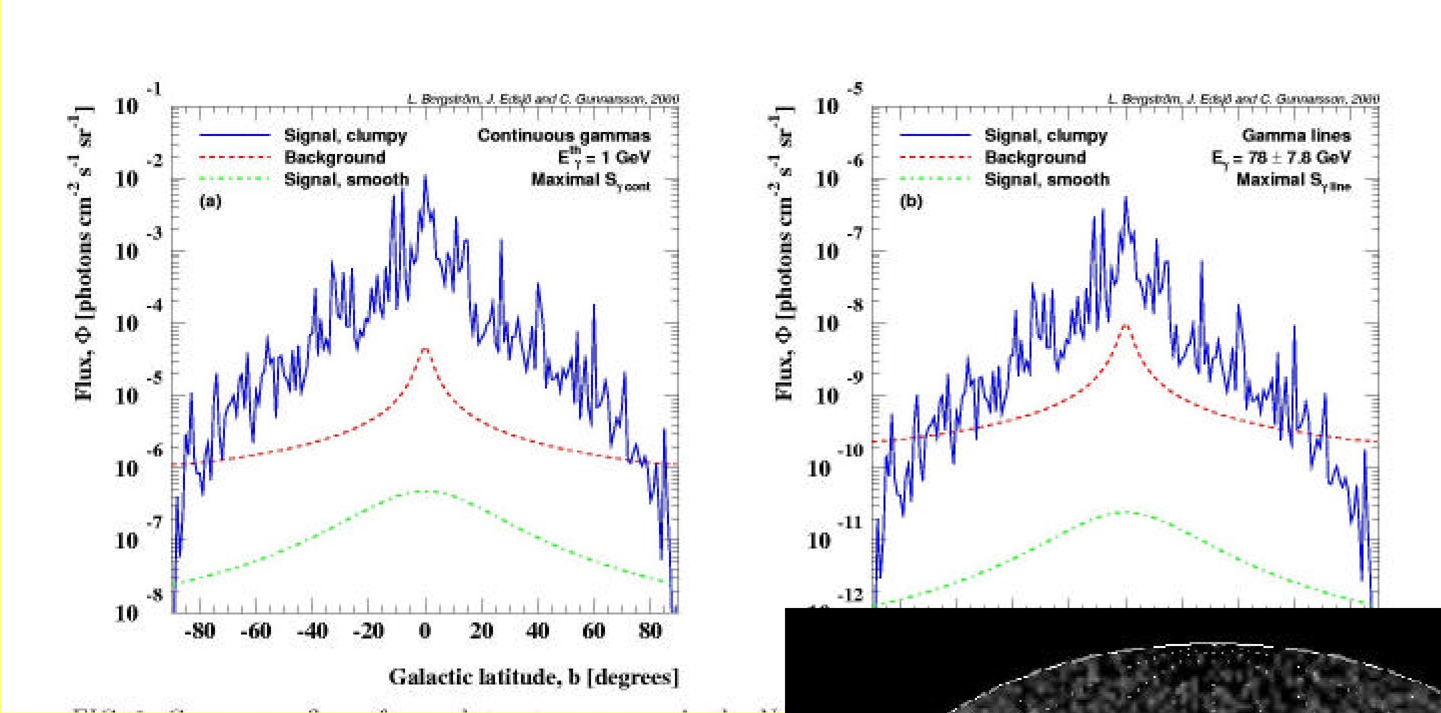
$E_\gamma = (1 \pm 10^{-3})\, m_\chi$

(or $\chi\chi \to Z\gamma$)
P. Ullio & L.B.

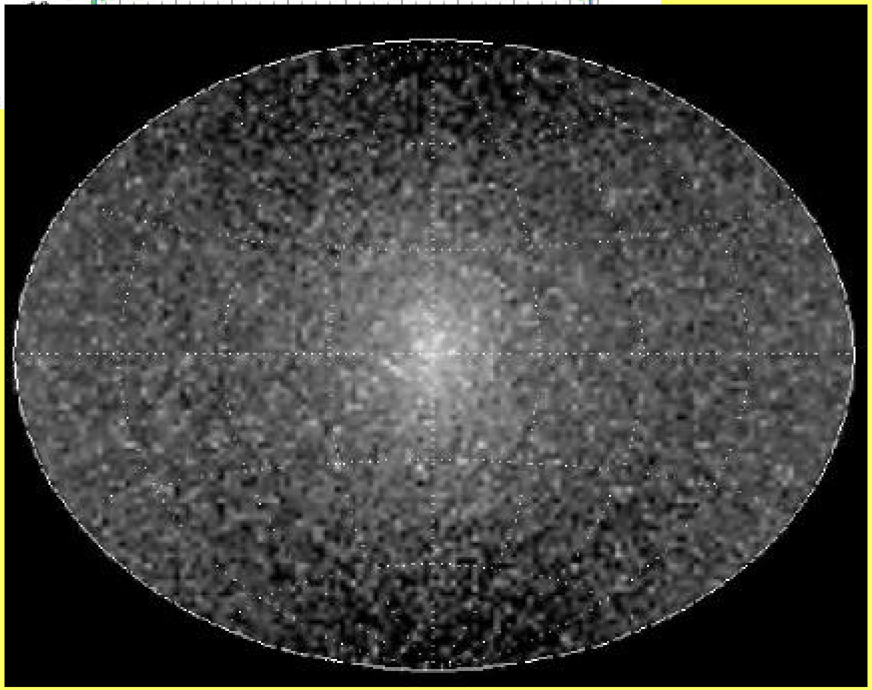
(Srednicki, Theisen & Silk, 1986 : $\chi\chi \to (c\bar{c})_{bound} + \gamma_{line}$
Too small rate to be detectable.)



EGRET discovery of gamma-ray halo of Milky Way (D. Dixon et al., 1997)



L. Bergström, J. Edsjö & C. Gunnarsson, PRD 2000



CDM simulation of SUSY gamma-ray sky

(Calcaneo-Roldan & Moore, 2000)

Spectral Gamma-ray Signatures of Cosmological Dark Matter Annihilations

Lars Bergström, Joakim Edsjö
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Piero Ullio
SISSA, via Beirut 4, 34014 Trieste, Italy

PRL, Dec. 2001

Idea: Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type cuspy halos and substructure

$$\phi_\gamma = \frac{c}{4\pi}\frac{dn_\gamma}{dE_0} = 8.3 \cdot 10^{-14}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1} \times \frac{\Gamma_{26}\Omega_M^2 h^3}{m_{100}^2}\int_0^{z_{up}} dz\, \frac{\Delta^2(z) e^{-z/z_{\max}}}{h(z)}\frac{dN_\gamma(E_0(1+z))}{dE}$$

Redshift factor

Enhancement factor due to substructure

Cosmology

Absorption on IR and optical background radiation

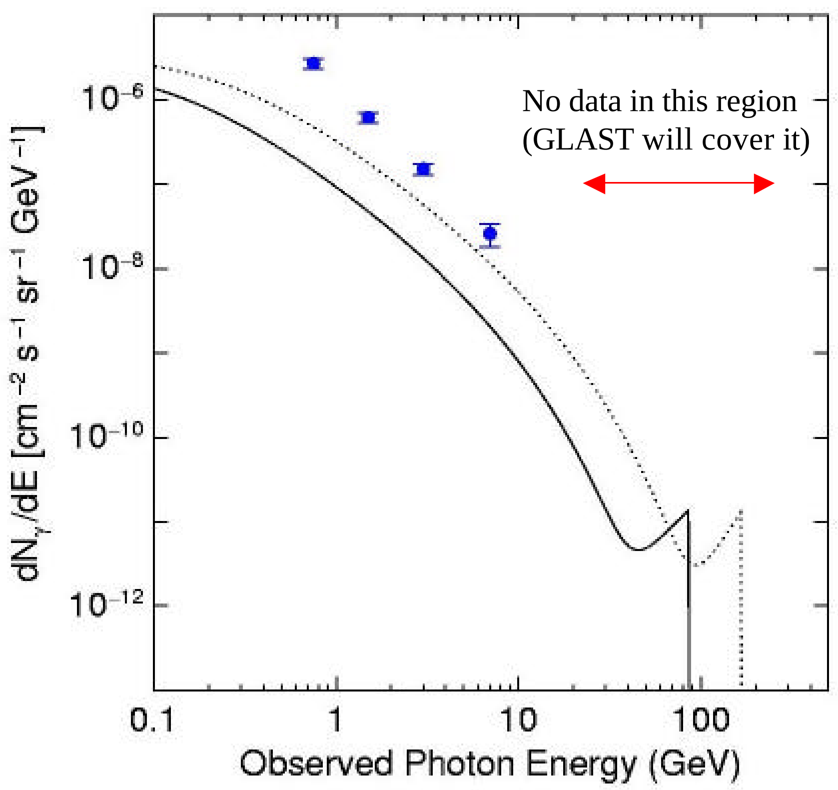
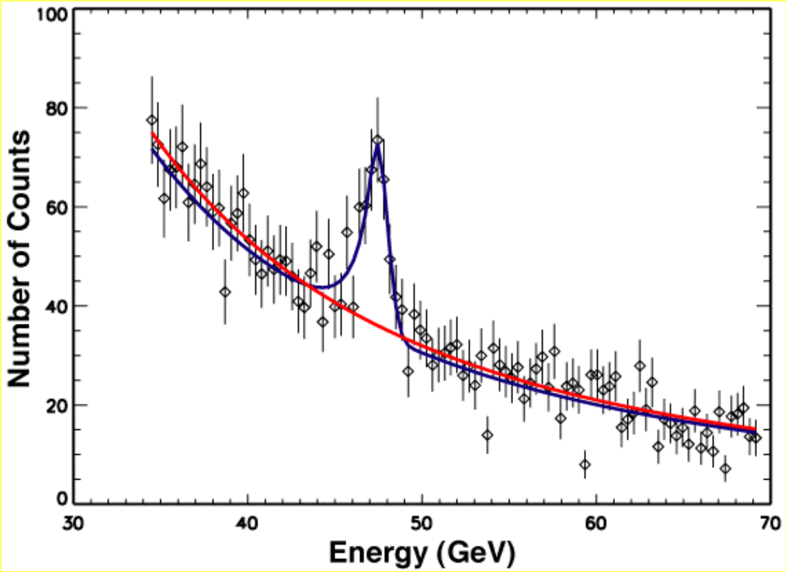


FIG. 1. The predicted diffuse γ-ray flux, from cosmic annihilations into continuum gamma-rays, and a gamma-ray line. The redshifted line gives the conspicuous feature at the highest energies. Shown are cosmic annihilation of 86 GeV (solid line) and 166 GeV (dotted line) neutralinos. A Moore density profile for the halo substructure has been assumed. The EGRET data [26] on the extragalactic flux are the data points with error bars shown.

USA-France-Italy-Sweden-Japan collaboration, launch 2006



Lars Bergstrom, lbe@physto.se

Positrons from neutralino annihilations

E. Baltz, J. Edsjö, K. Freese and P. Gondolo, 2001 (cf Kane, Wang & Wells, 2001)

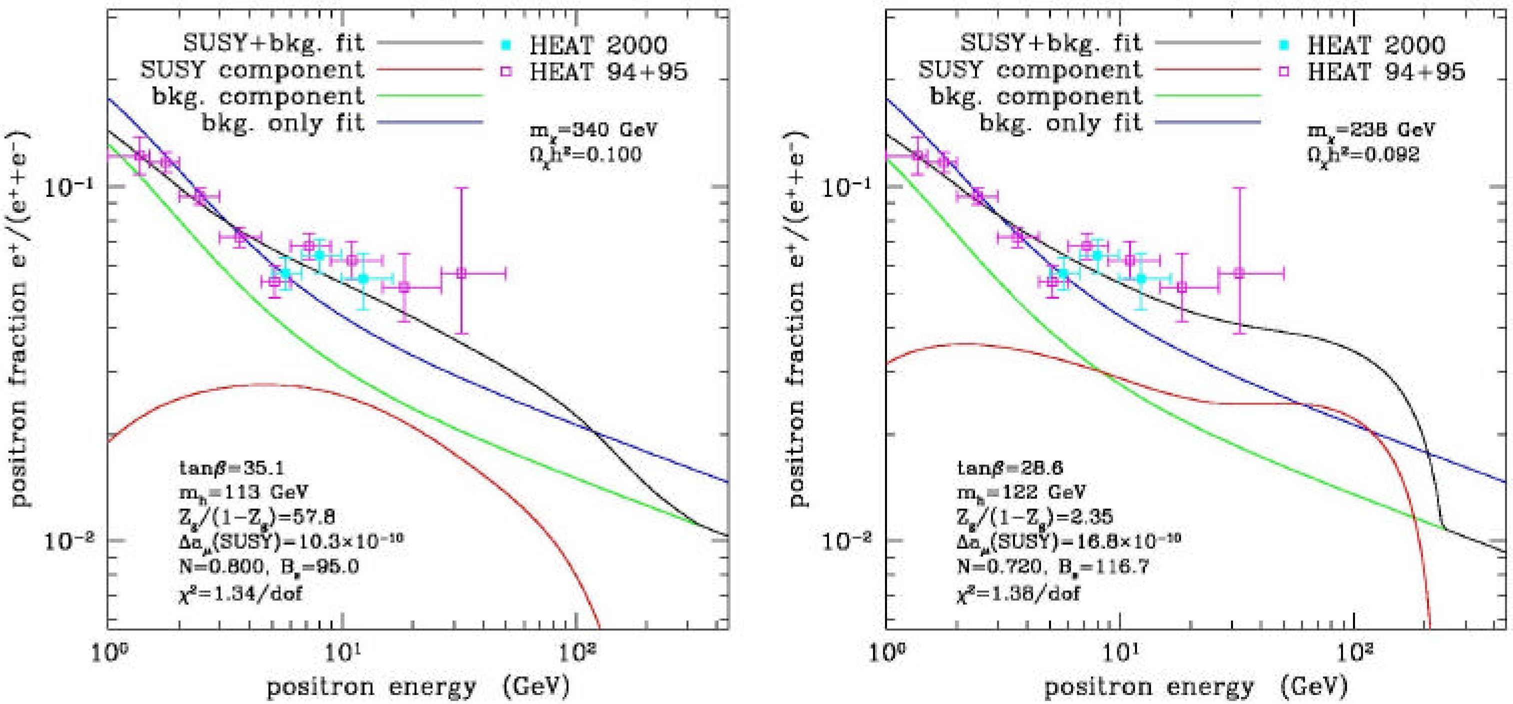
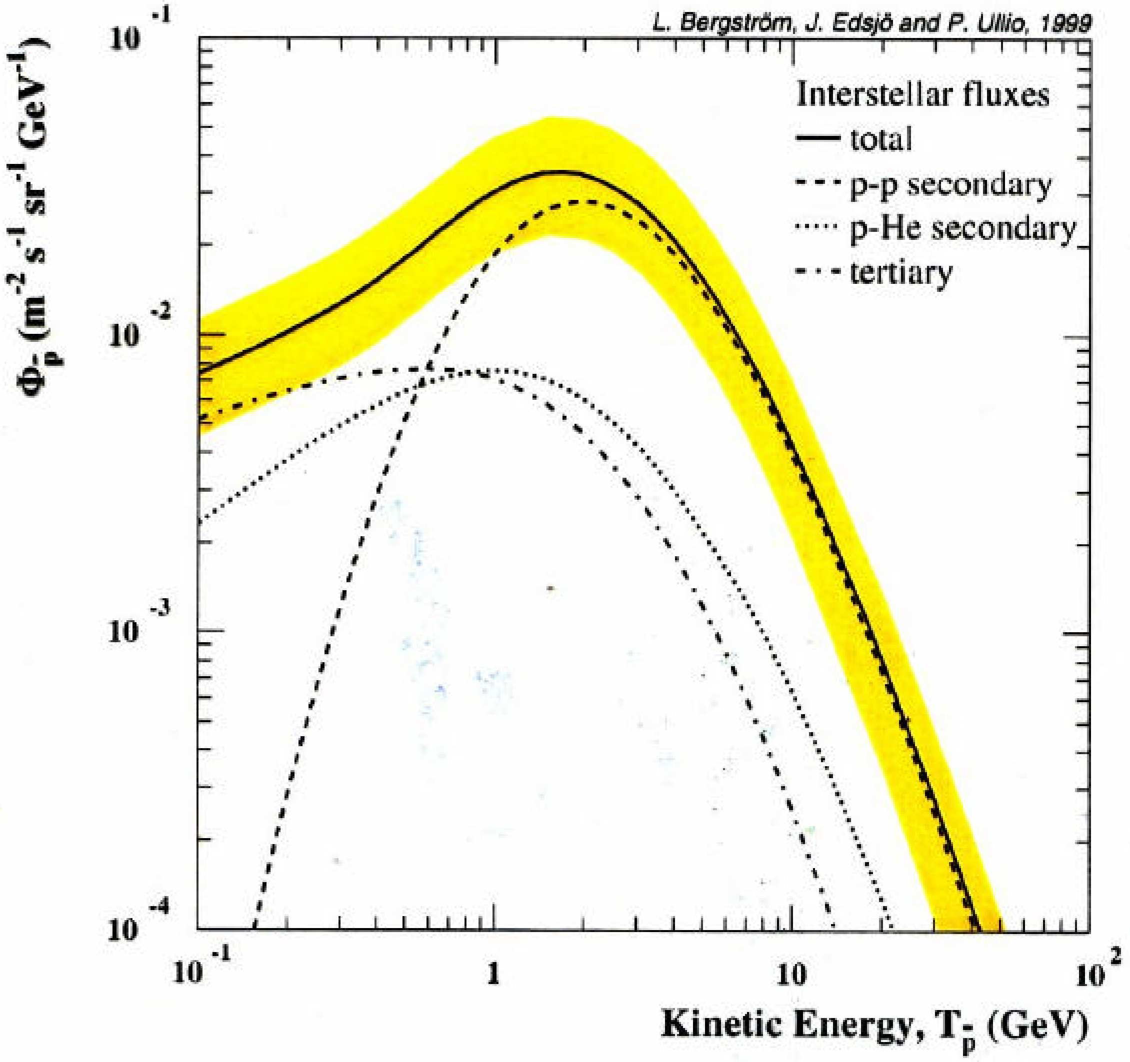


FIG. 1. Positron fraction data and fits. We illustrate positron data from HEAT 94+95 and HEAT 2000, a background only fit, and a SUSY+background fit from two interesting models from the MSSM database. Two additional curves separately display the SUSY and background components of the combined SUSY+background fit. These models are gaugino dominated and have contributions to a_μ in line with the experimental discrepancy. The model in Fig. 1a has positrons primarily from hadronization, while the model in Fig. 1b has hard positrons from direct gauge boson decays.



L. Bergström, J. Edsjö and P. Ullio, 1999
Interstellar fluxes
total
p-p secondary
p-He secondary
tertiary
$\Phi_{\bar{p}}$ (m^{-2} s^{-1} sr^{-1} GeV^{-1})
Kinetic Energy, $T_{\bar{p}}$ (GeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^{2}

Antiprotons from neutralino annihilation

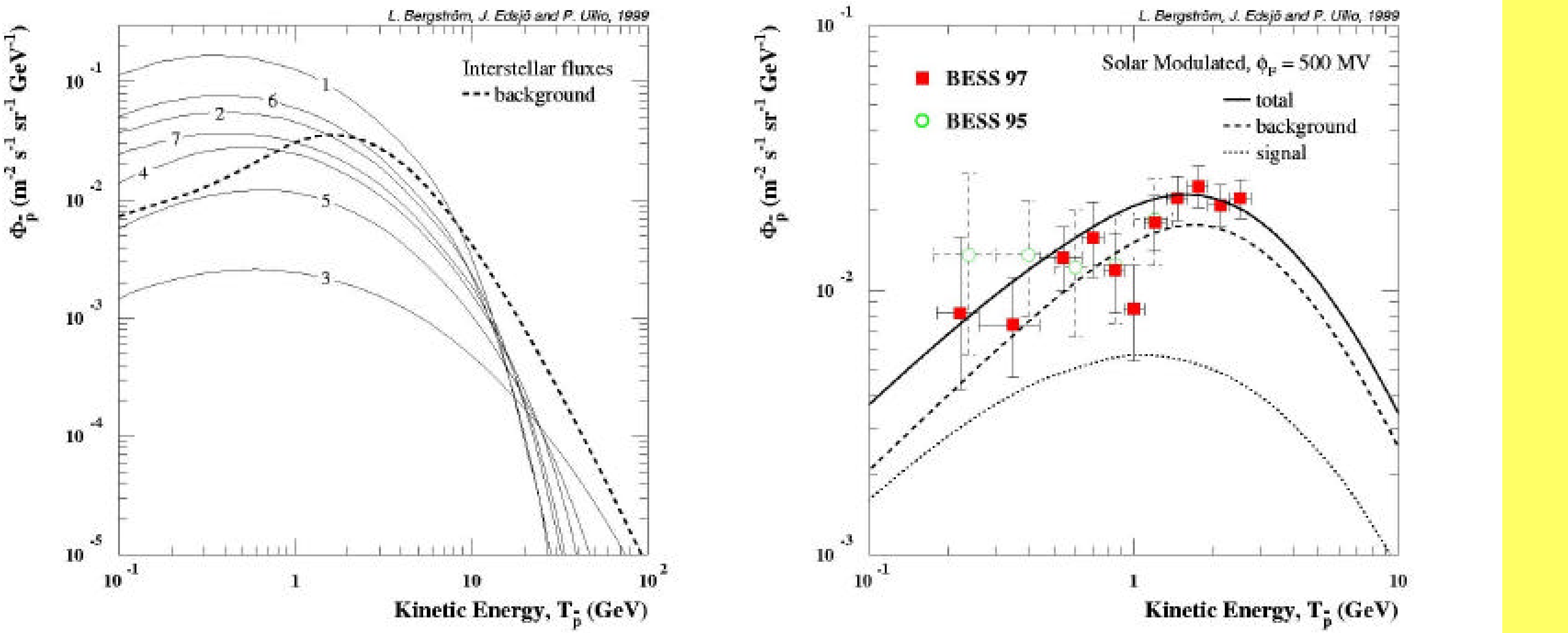
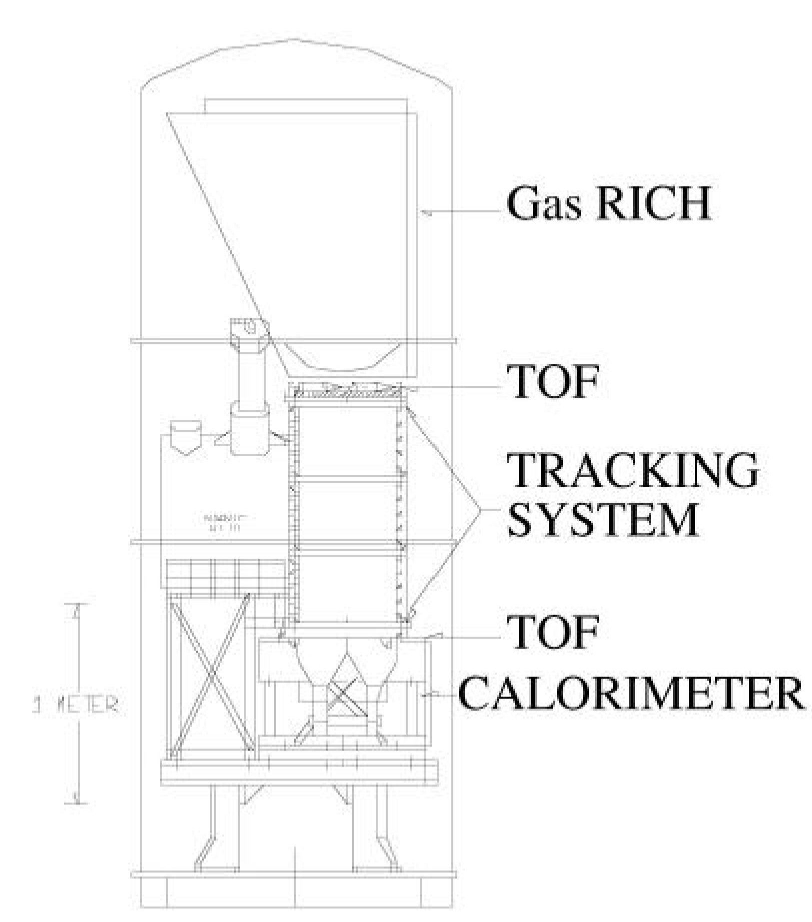


FIG. 11.— (a) Antiproton spectra for all 7 models appearing in Table 3. (b) Example of a composite spectrum consisting of our reference background $\bar{p}$ flux (Fig. 1) reduced by 24 % with the addition of the predicted flux from annihilating dark matter neutralinos of MSSM model number 5 in Table 3.

CAPRICE



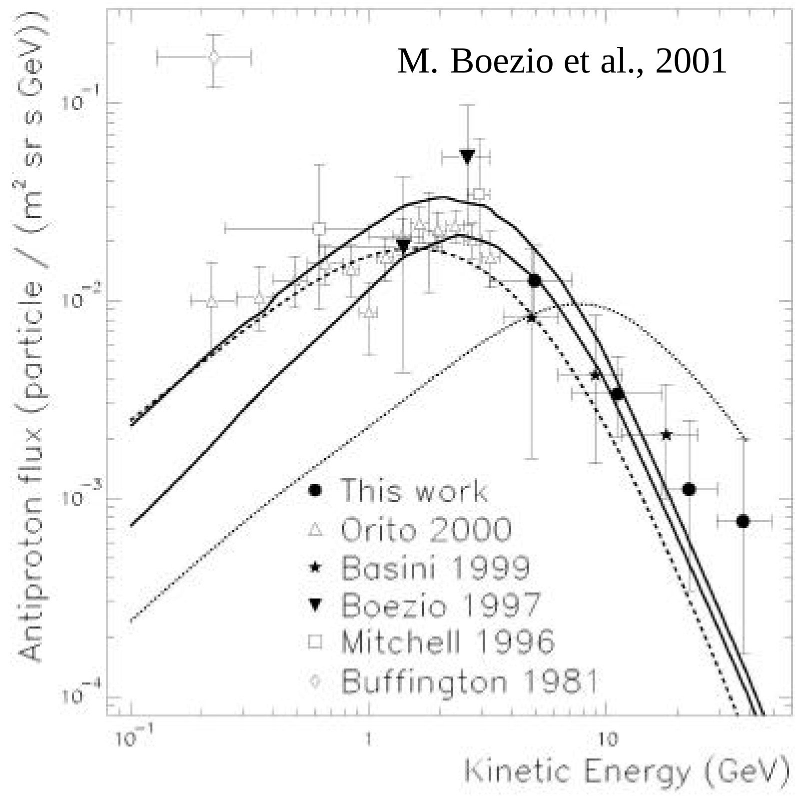


Fig. 9.— The antiproton flux at the top of the atmosphere obtained in this work and compared to other experiments that have published results on the antiproton flux (Buffington, Schindler, & Pennypacker 1981; Mitchell et al. 1996; Boezio et al. 1997; Basini et al. 1999; Orito et al. 2000). The two solid lines shows the upper and lower limit of a calculated flux of interstellar secondary antiprotons by Simon, Molnar, & Roesler (1998). The dashed line shows the interstellar secondary antiproton flux calculated by L. Bergström & P. Ullio (1999, private communication). The dotted line shows the primary antiproton flux given by annihilation of neutralino from MSSM with a mass of 964 GeV (Ullio 1999).

Conclusions

- **Existence of dark matter more certain than ever**
- **CDM seems favoured**
- **Maybe only gravitational interactions – horror scenario**
- **If related to electroweak scale (WIMPs) then prospects for detection are good!**