Dark Matter

-Models and Indirect Detection Methods

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NEUTRINO 2002 MUNICH

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Basic facts:

$$\Omega_i \equiv \frac{\rho_i}{\rho_{crit}}$$

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

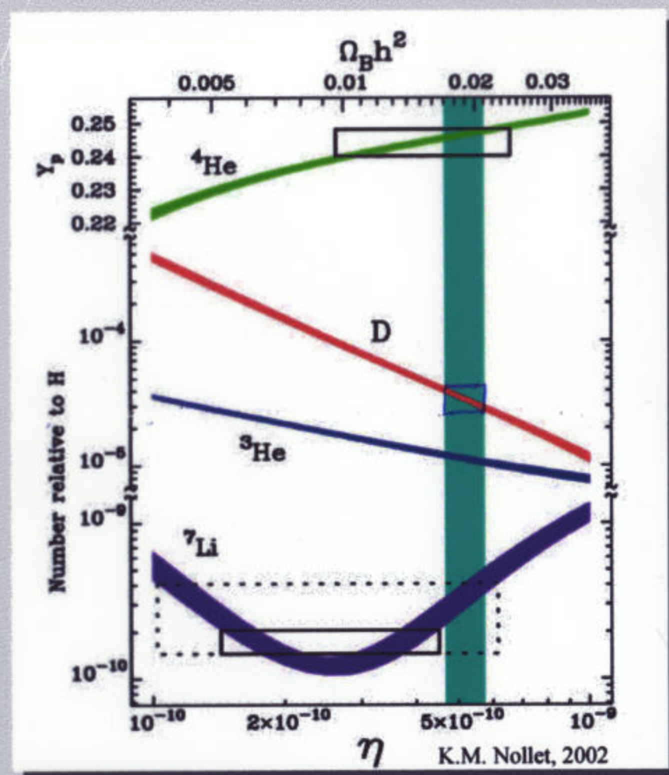
$$h \equiv \frac{H_0}{100\ kms^{-1}\ Mpc^{-1}}$$

Observations give $0.6 < h < 0.8$

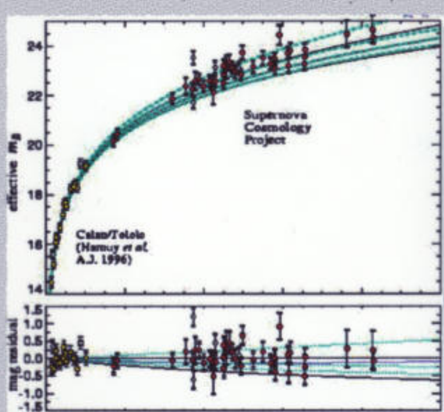
Big Bang nucleosynthesis and cosmic microwave background determine baryon contribution $\Omega_B h^2 \approx 0.02$.

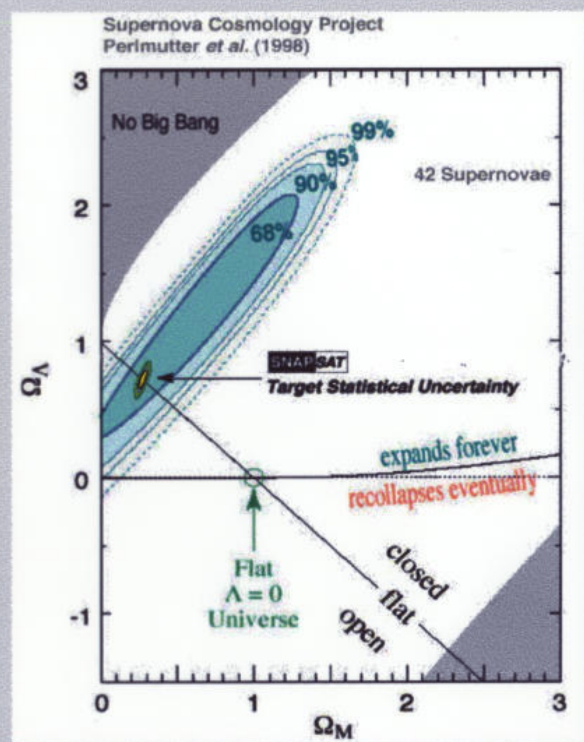
$\Omega_{lum} \approx (4 \pm 2) \cdot 10^{-3}$ (stars, gas, dust) => baryonic dark matter has to exist (maybe as warm intergalactic gas?)

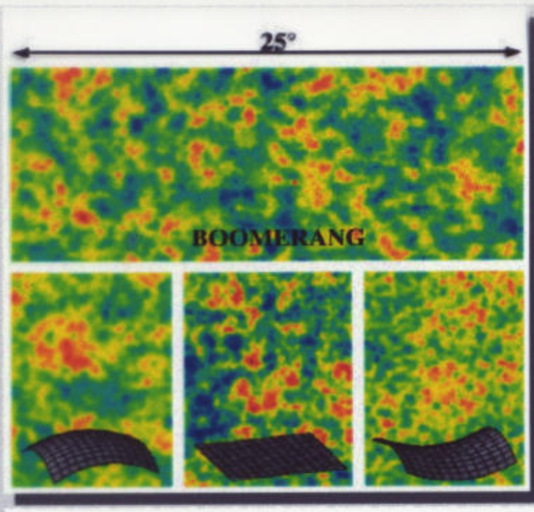
But, if $\Omega_M > 0.06$, there has to exist non-baryonic dark matter!



SNAP - supernova/acceleration probe

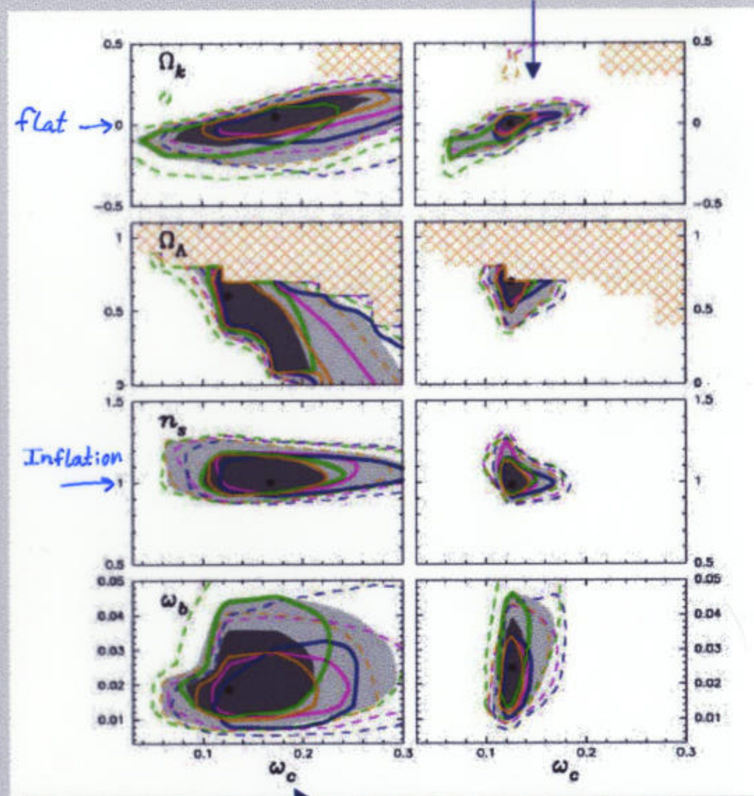


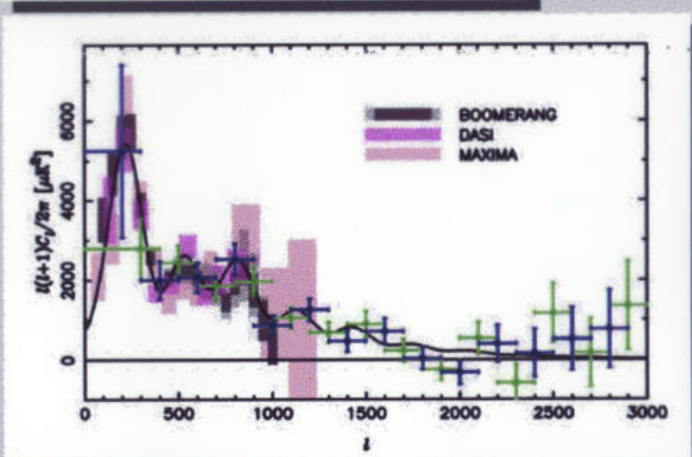




New combined fit using CBI data (J.L. Sievers et al., astro-ph/0205387, May 24, 2002)

Using LSS





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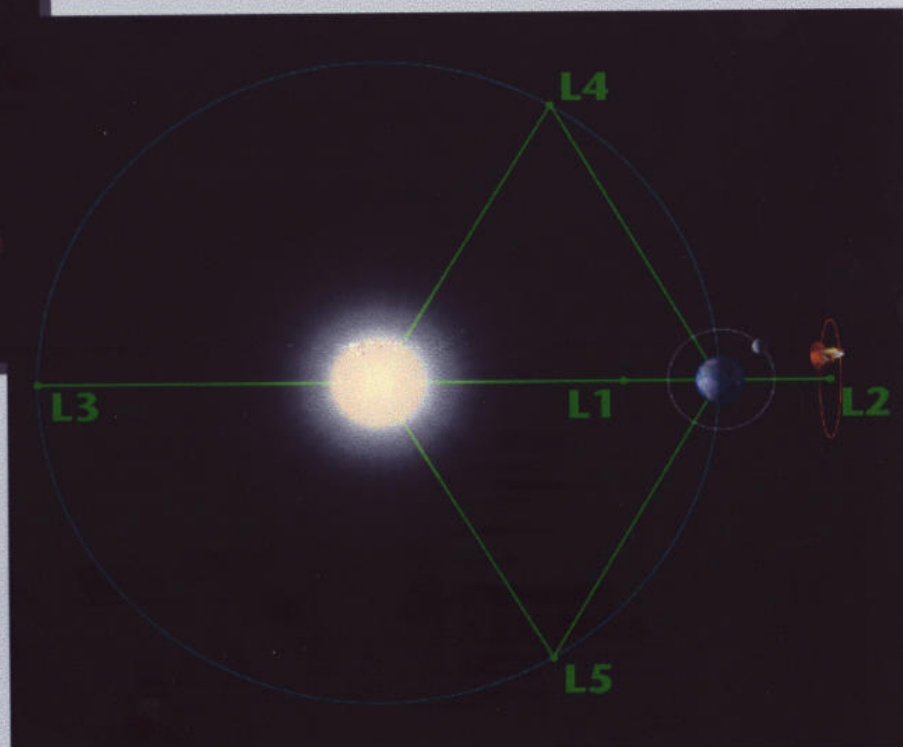
$$\omega_c \equiv \Omega_{CDM} h^2$$

$h \in [0.6, 0.8] \Rightarrow \Omega_{CDM} \sim 0.2 - 0.5$

Since January 2002: Taking data!



MAP – Microwave Anisotropy Probe

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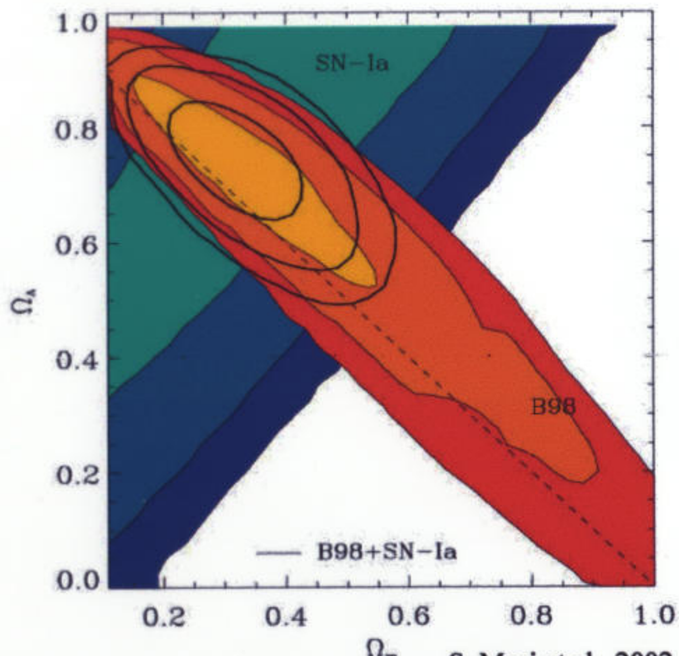
Combination of supernovae and cosmic microwave background gives "Concordance Model":

$\Omega_M \approx 0.3, \Omega_\Lambda \approx 0.7$



S. Masi et al., 2002

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Terminology:

• **Hot Dark Matter (HDM).** Particles which are relativistic when they decouple from the early Universe. Example ν (neutrino), mass few eV. Free-streaming with relativistic velocities, thus can only cluster on large scales (which may then fragment to smaller scales) – disfavoured by observations.

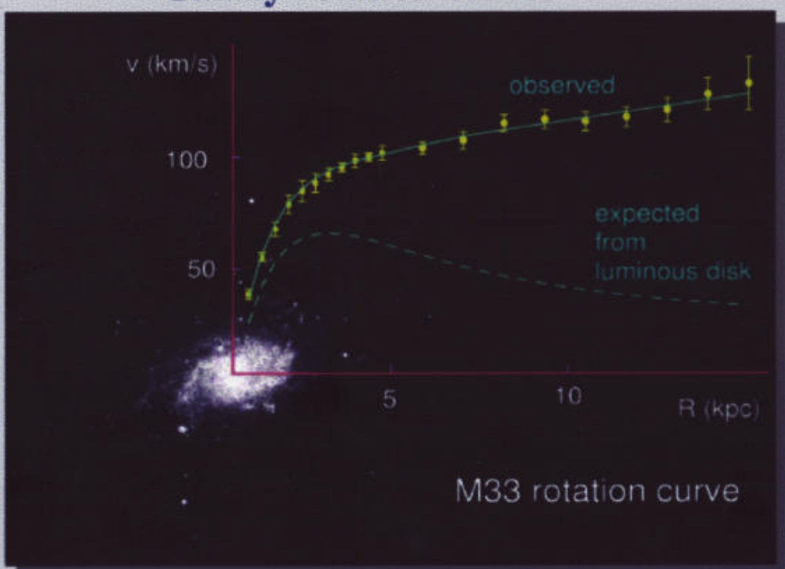
• **Cold Dark Matter (CDM).** Particles which are non-relativistic at decoupling. Example: χ (neutralino of MSSM) or more generally, Weakly Interacting Massive Particle (WIMP). Mass of a few GeV up to the TeV range. Forms structure on all scales, through successive mergers. (Axions also behave as CDM – see Juan Collar's talk)

•**Warm Dark Matter (WDM).** Intermediate case, typical mass in the keV range. Examples: gravitino, keV sterile neutrino.

•**Non-clustering Dark Energy (Λ).** Gives repulsive contribution to gravity. Causes the Universe to accelerate. Examples: cosmological constant, quintessence.

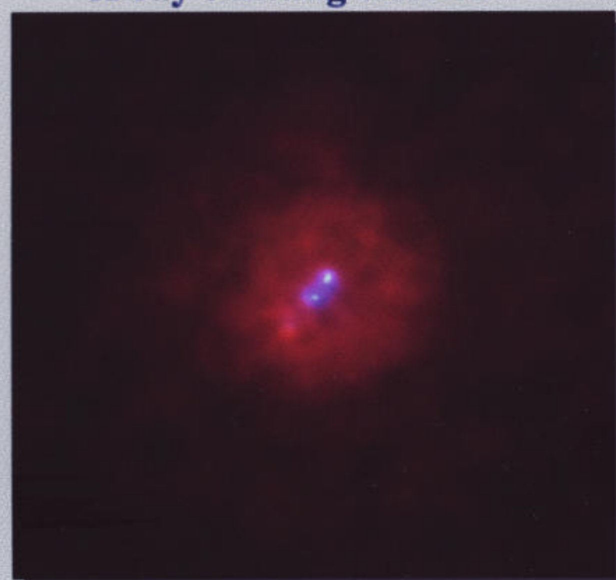
Dark matter needed on all scales!
(⇒ MOND and other *ad hoc* attemps to modify Einstein or Newton gravity appear very unnatural & unlikely)

Galaxy rotation curves



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

X-ray emitting clusters



Cluster 3C295 (Chandra)

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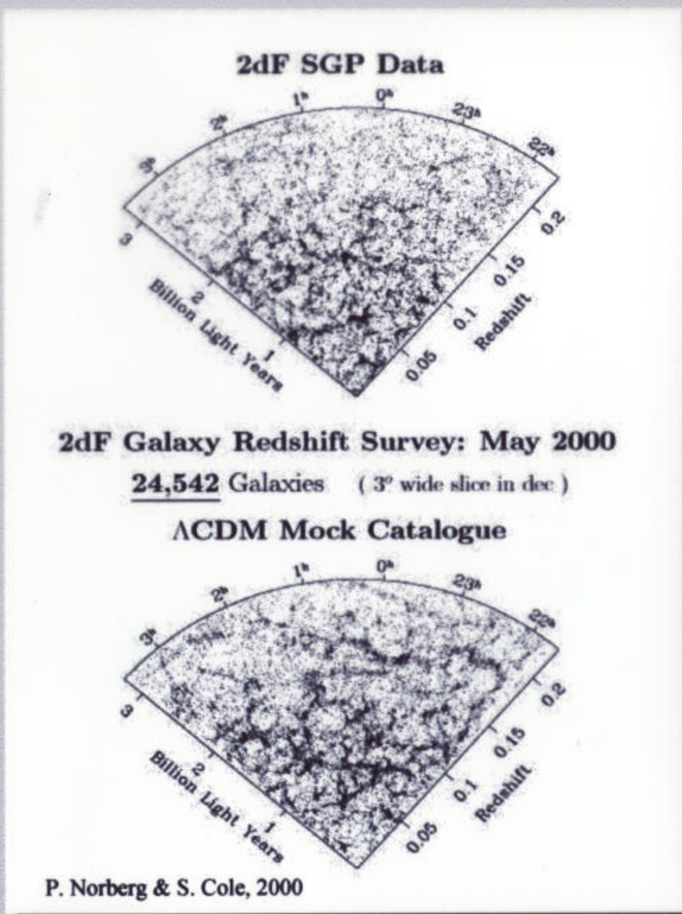

Large-scale structure is in striking agreement with the Concordance Model,

ΛCDM ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

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New era:

Since 1998 (Super-Kamiokande) we know that non-baryonic dark matter actually does exists! If $m_\nu \approx \Delta m_\nu \approx 10^{-2} - 10^{-1}$ eV

then $$\Omega_\nu h^2 \approx \frac{m_\nu}{94 \text{ eV}} \approx 10^{-4} - 10^{-3}$$

Thus, neutrinos contribute at least as much to the mass density of the Universe as do all the visible stars!

However, neutrinos (ν_e, ν_μ, ν_τ) can only be a small fraction of the dark matter (less than around 20%), because:

- **Structure formation incompatible with Hot Dark Matter (see Steen Hannestad's talk).**

- **Pauli priciple forbids clumping of massive neutrinos in, e.g., dwarf galaxies**

Hot dark matter: Zeldovich pancakes

keV sterile neutrino: warm dark matter

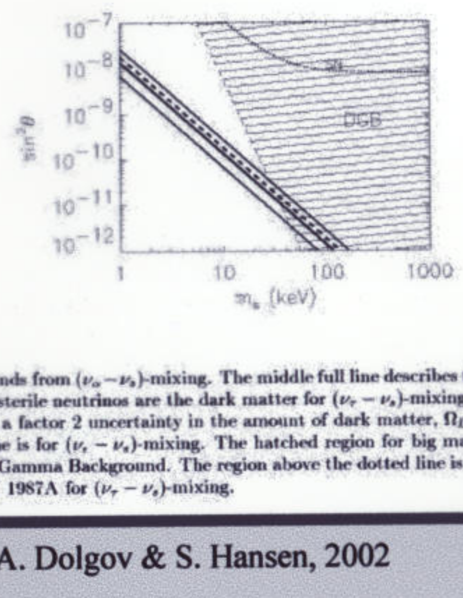
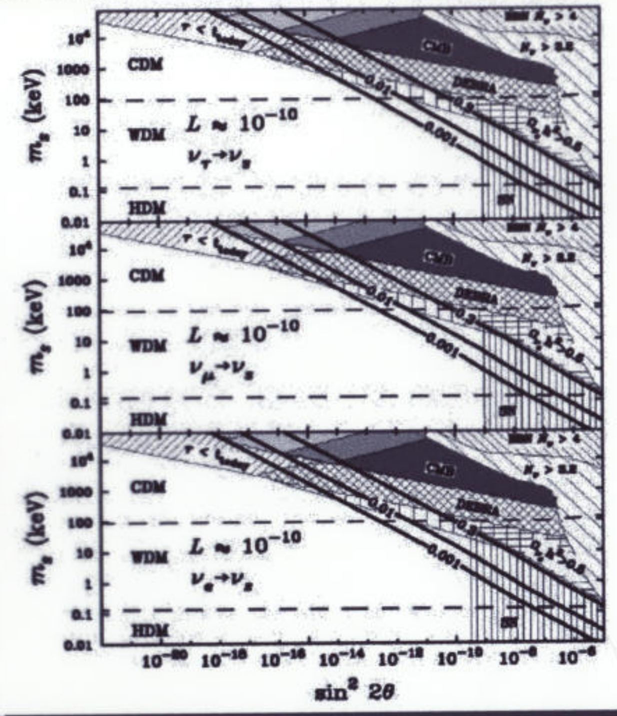


Figure 1: Bounds from $(\nu_e - \nu_s)$-mixing. The middle full line describes the mass-mixing relationship if sterile neutrinos are the dark matter for $(\nu_\tau - \nu_s)$-mixing. The two other full lines allow a factor 2 uncertainty in the amount of dark matter, $\Omega_{DM} = 0.15 - 0.6$. The dashed line is for $(\nu_\tau - \nu_s)$-mixing. The hatched region for big masses is excluded by the Diffuse Gamma Background. The region above the dotted line is excluded by the duration of SN 1987A for $(\nu_\tau - \nu_s)$-mixing.

A. Dolgov & S. Hansen, 2002



Abazajian, Fuller & Patel, 2001

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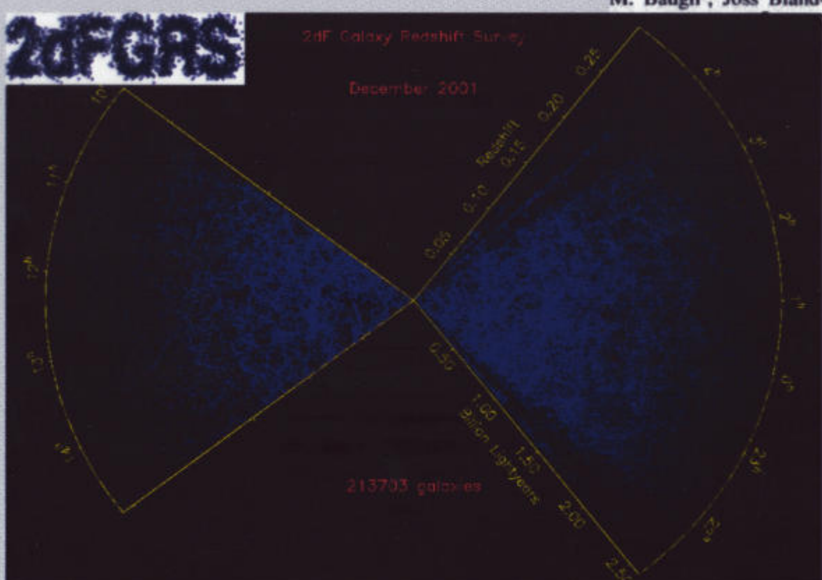
The 2-degree Field Galaxy Redshift Survey (cf. SDDS)

@ New York Times, Jan 8, 2002

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

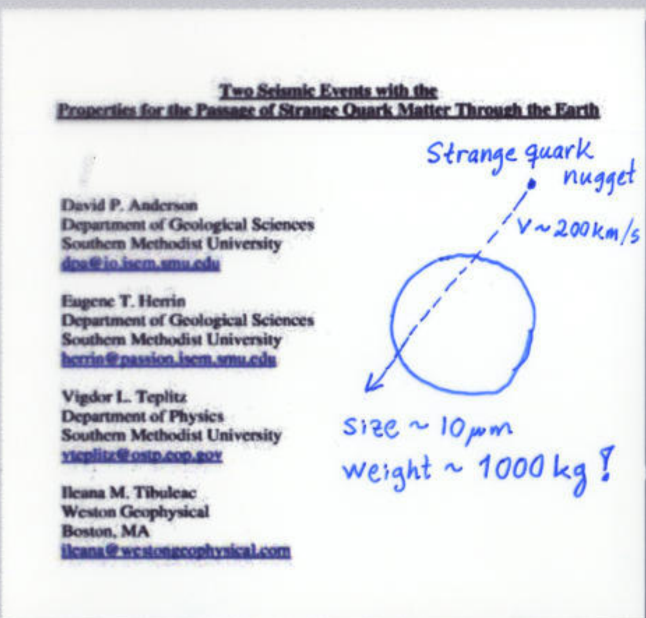
Licia Verde[1,2], Alan F. Heavens[3], Will J. Percival[3], Sabino Matarrese[4], Carlton M. Baugh[5], Joss Bland-Hawthorn[6], Terry Bridges[6], Russell Cannon[6], Shaun Cole[5], … Collins[8], Warrick Couch[9], Gavin Dalton[10], Roberto De …[11], George Efstathiou[12], Richard S. Ellis[13], Carlos S. Frenk[5],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



Result:

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

astro-ph/0205089: Strange Quark Matter as Dark Matter?



Two Seismic Events with the Properties for the Passage of Strange Quark Matter Through the Earth

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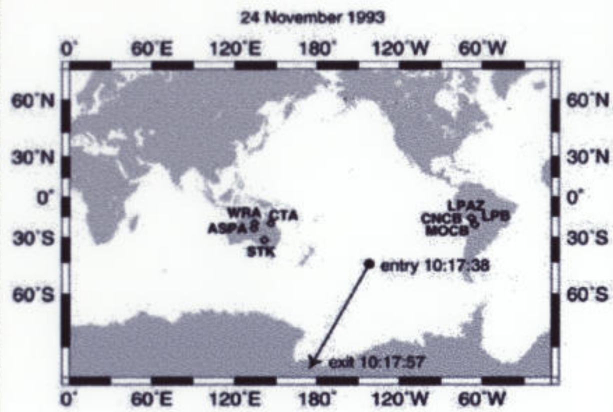
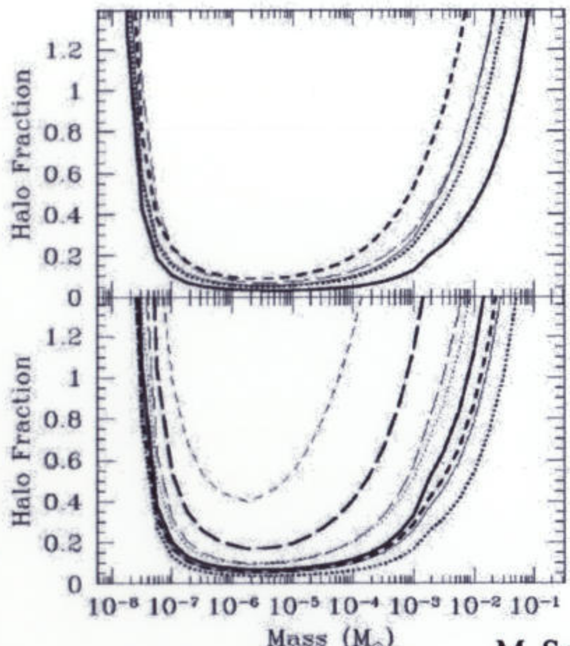


Figure 6. Surface trace for second event.

Results from EROS and MACHO collaborations: Light 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.

J. Madsen, astro-ph/9809032

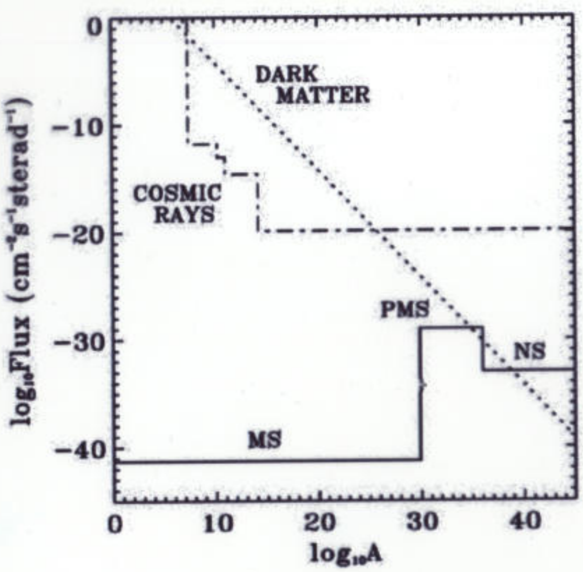
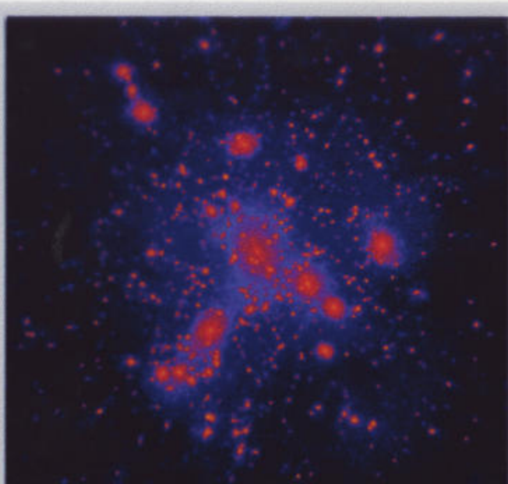


Figure 7: Astrophysical flux-limits [121] compared to the flux expected for a galactic halo of nuggets being the dark matter [118], and to the experimental results for cosmic rays [119, 120]. The three horizontal parts of the solid curve correspond to capture in main sequence supernova progenitors, post main sequence stars, and neutron stars younger than the Vela pulsar (10^4 years).

Strange quark matter nuggets could in principle be the dark matter. However, formation and survival in sufficient quantities from the quark-hadron transition not very likely.

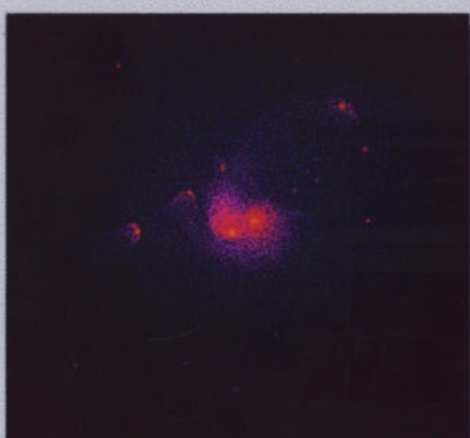
Cold Dark Matter

- 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. 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.



Too many subhalos in CDM? Maybe dark!
Gravitational lensing may need subhalos (Dalal & Kochanek, 2002)

Radial profile too singular? Observations unclear; baryonic feedback not included in simulations



Simulations by Ben Moore, http://www.nbody.net

Simulation of self-interacting dark matter halo

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Elliptical galaxy NGC 4636, Chandra X-ray image

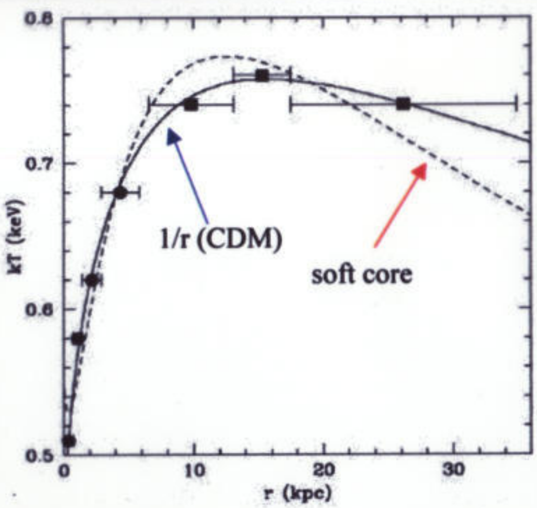

Figure 1. *Chandra* (filled circles) and *XMM-Newton* (filled squares) temperatures, and profiles for overall best-fit model (which has an r^{-1} dark matter density cusp; solid curve), and best-fit model with dark matter density core (broken curve).

CHANDRA LIMITS ON NATURE OF DARK MATTER

Dark matter distribution seems highly concentrated, in agreement with CDM.

Self-interacting dark matter ruled out?

(Loewenstein and Mushotzky, astro-ph/0205359)

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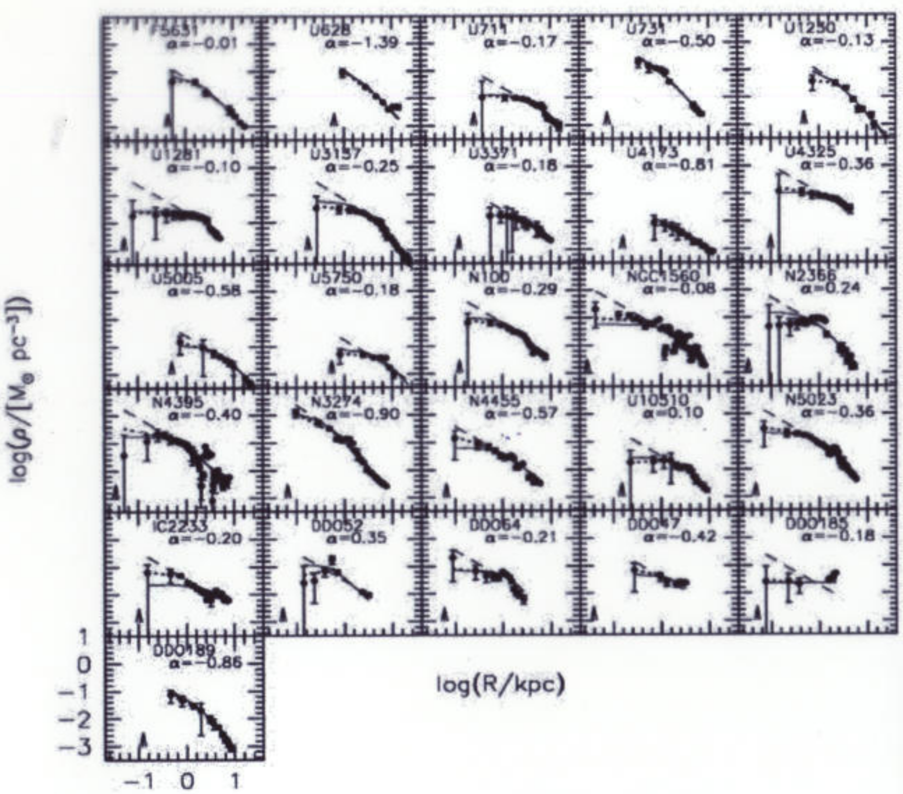
de Blok & Bosma: LSB galaxy rotation curves



de Blok and Bosma 2002:

Rotation curves of low surface brightness galaxies not well fit by CDM?

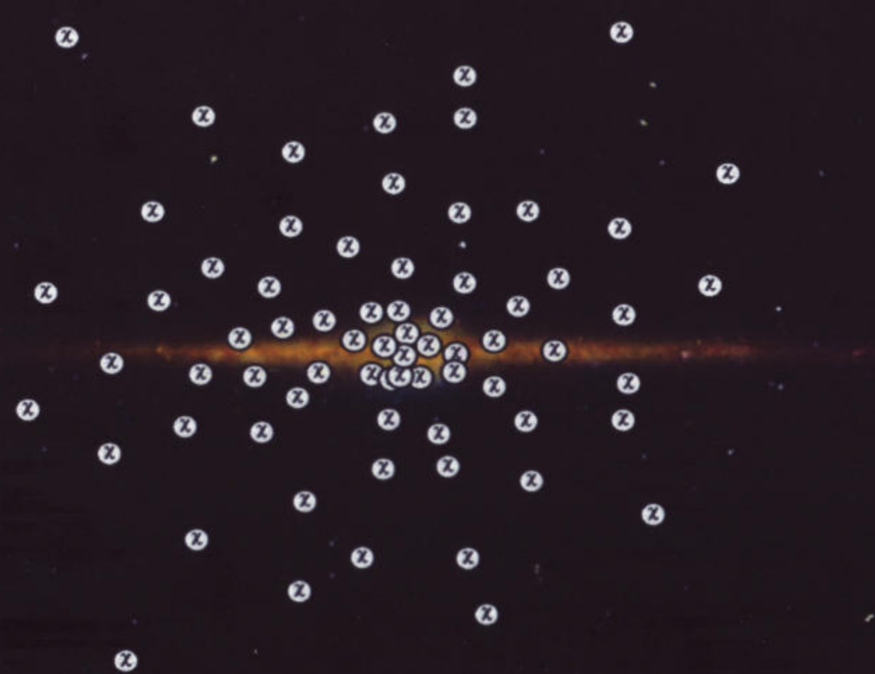
Prime candidate: MSSM χ, thermally produced in the early Universe
However, there are other possibilities for Dark Matter related to supersymmetry:

- $\tilde{\nu}$, sneutrinos (Hall & Murayama, …)
- ã, axinos (Kim & Roszkowski, …)
- Wimpzillas (Kolb & al) – superheavy relics
- Cryptons (J. Ellis & al) – superheavy relics
- Q-balls (Kusenko & al,..), $Q \rightarrow \chi$ (non-thermal)
- Self-interacting DM (Spergel& Steinhardt)?

WIMPZILLA

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

Model for Neutralino Galactic Halo:

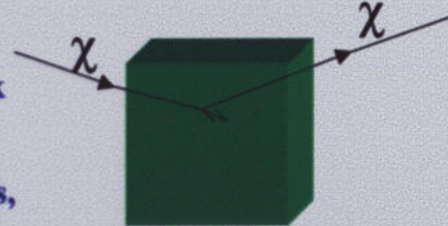


$\rho_{local} \sim 0.3$ GeV/cm^3, $v/c \sim 10^{-3}$, $m_\chi \sim 100$ GeV

$\Rightarrow$ flux 10^{3} cm^{-2} s^{-1} sr^{-1} !

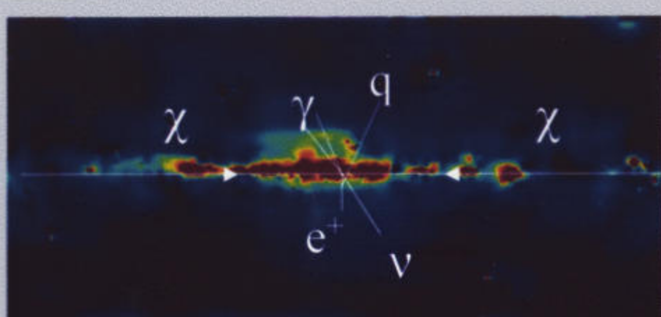
Methods of SUSY Dark Matter detection:

- **Discovery at accelerators (Tevatron II, LHC,..)**
- **Direct detection of halo particles (see Yorck Ramacher's talk)**
- **Indirect detection of neutrinos, gamma rays, radio waves, antiprotons, positrons**



The basic process for indirect detection is annihilation:

(Neutralinos are Majorana particles)



$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

Enhanced for clumpy halo; near galactic centre and in Sun & Earth

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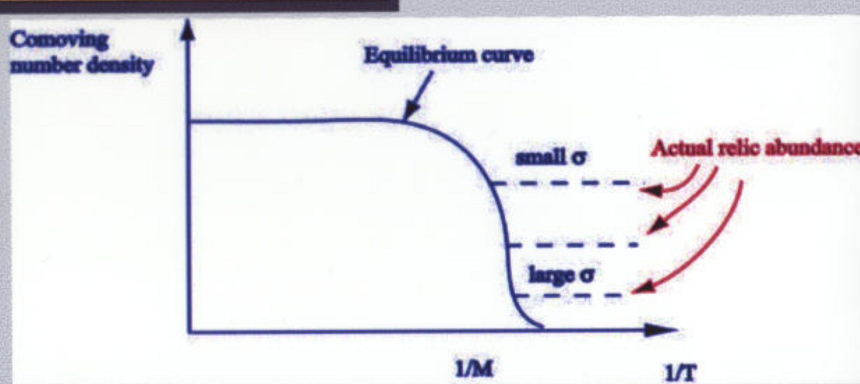
$\Omega_M \sim 0.3$ in **Concordance Model** instead of $\Omega_M \sim 1$ in the **"Standard CDM"** of the 1980's

→ Good news for dark matter searches!

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

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

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



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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 in autumn of 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!

Alternative approach: use small number of "well-motivated" points in SUSY parameter space (Snowmass 2001)

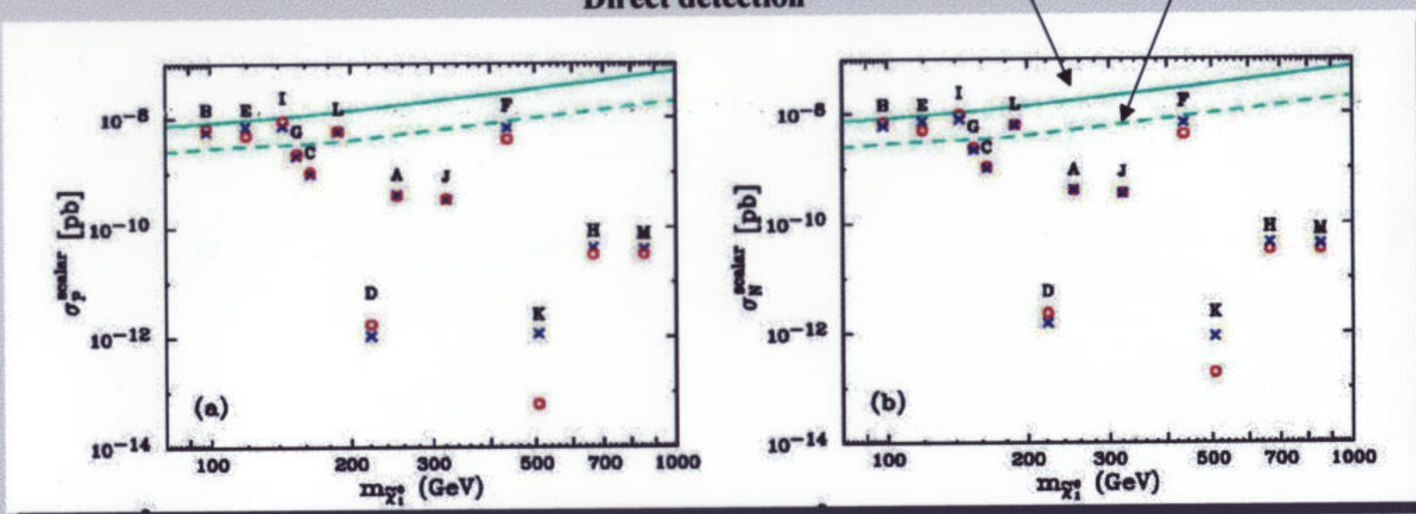
Prospects for Detecting Supersymmetric Dark Matter at Post-LEP Benchmark Points

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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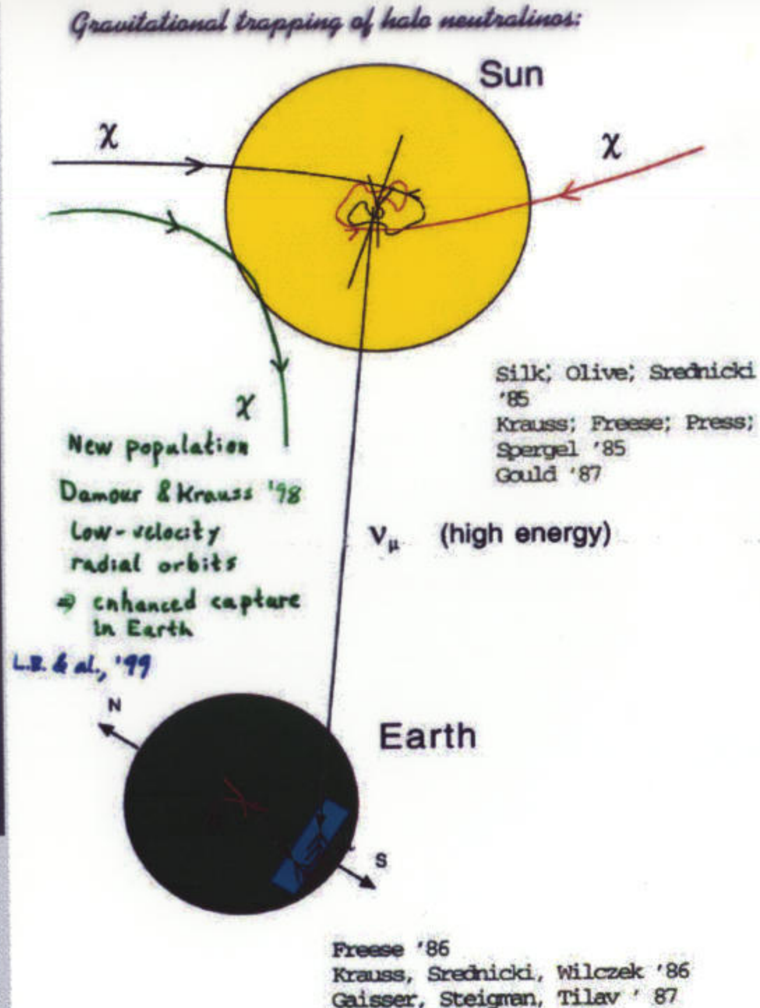
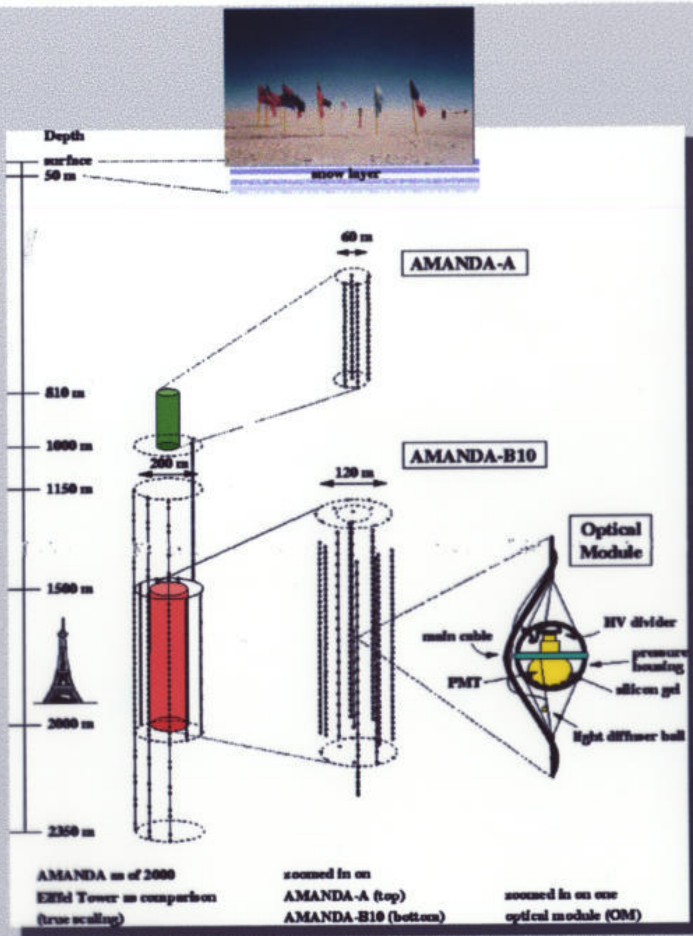
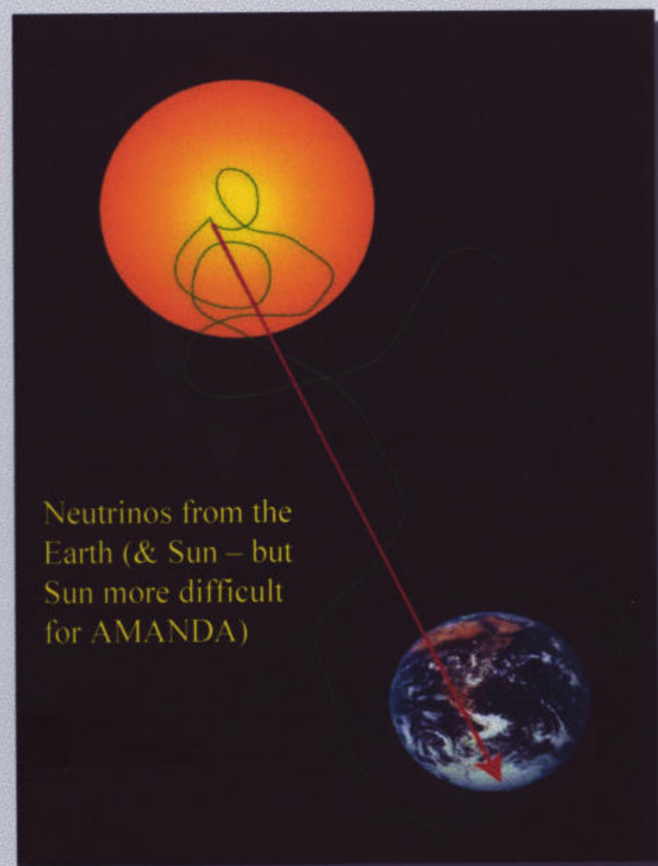
Indirect detection through neutralino capture and annihilation at the centre of the Earth or the Sun – one of the most promising methods for the detection of WIMPs.




Depth
surface
50 m
snow layer
60 m
AMANDA-A
810 m
1000 m
200 m
AMANDA-B10
120 m
1150 m
Optical Module
1500 m
HV divider
main cable
PMT
silicon gel
2000 m
light diffuser ball
2350 m
AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)
zoomed in on one
optical module (OM)


Neutrinos from the Earth (& Sun – but Sun more difficult for AMANDA)

New AMANDA limits on WIMPs from the Earth (see Doug Cowen's talk)

Limits to the muon flux from WIMP annihilation in the center of the Earth with the AMANDA detector

J. Ahrens,[1] E. Andrés,[2] X. Bai,[3] G. Barouch,[4] S.W. Barwick,[5] R.C. Bay,[6] T. Becka,[1] K.-H. Becker,[1] D. Bertrand,[7] A. Biron,[8] O. Botner,[9] A. Bouchta,[8,*] S. Carius,[10] A. Chen,[4] D. Chirkin,[6,11] J. Conrad,[9] J. Cooley,[4] C.G.S. Costa,[7] D.F. Cowen,[12] E. Dalberg,[2,†] C. De Clercq,[13] T. DeYoung,[4,‡] P. Desiati,[8] J.-P. Dewulf,[7] P. Doksus,[4] J. Edsjö,[2] P. Ekström,[2] T. Feser,[1] T.K. Gaisser,[3] M. Gaug,[8,§] L. Gerhardt,[5] A. Goldschmidt,[14] A. Goobar,[2] A. Hallgren,[9] F. Halzen,[4] K. Hanson,[12] R. Hardtke,[4] T. Hauschildt,[8] M. Hellwig,[1] G.C. Hill,[4] P.O. Hulth,[2] S. Hundertmark,[5] J. Jacobsen,[14] A. Karle,[4] J. Kim,[5] B. Koci,[4] L. Köpke,[1] M. Kowalski,[8] J.I. Lamoureux,[14] H. Leich,[8] M. Leuthold,[8] P. Lindahl,[10] P. Loaiza,[9] D.M. Lowder,[6,¶] J. Ludvig,[14] J. Madsen,[4] P. Marciniewski,[9,**] H.S. Matis,[14] C.P. McParland,[8] T.C. Miller,[3,††] Y. Minaeva,[2] P. Miočinović,[6] P.C. Mock,[5,‡‡] R. Morse,[4] T. Neunhöffer,[1] P. Niessen,[13] D.R. Nygren,[14] H. Ogelman,[4] Ph. Olbrechts,[13] C. Pérez de los Heros,[9,§§] A. Pohl,[10] R. Porrata,[5,¶¶] P.B. Price,[6] G.T. Przybylski,[14] K. Rawlins,[4] W. Rhode,[11] M. Ribordy,[8] S. Richter,[4] J. Rodríguez Martino,[2] P. Romenesko,[4] D. Ross,[5] H.-G. Sander,[1] T. Schmidt,[8] D. Schneider,[4] E. Schneider,[5] R. Schwarz,[4] A. Silvestri,[11,8] M. Solarz,[6] G.M. Spiczak,[15] C. Spiering,[8] D. Steele,[4] P. Steffen,[8] R.G. Stokstad,[14] O. Streicher,[8] P. Sudhoff,[8] K.H. Sulanke,[8] I. Taboada,[12] L. Thollander,[2] T. Thon,[8] S. Tilav,[3] M. Vander Donckt,[7] C. Walck,[2] C. Weinheimer,[1] C.H. Wiebusch,[8,***] R. Wischnewski,[8] H. Wissing,[8] K. Woschnagg,[6] W. Wu,[5] G. Yodh,[5] and S. Young[5]

(The AMANDA collaboration)

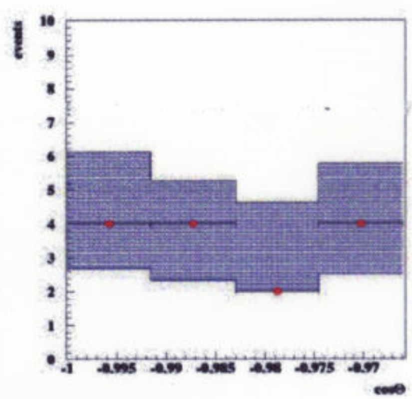


FIG. 5: Angular distribution of the remaining data events (dots) and simulated atmospheric neutrino events (shaded area) at filter level 5. The angular range shown is between 165° and 180°. The shaded area represents the total uncertainty in the expected number of events.

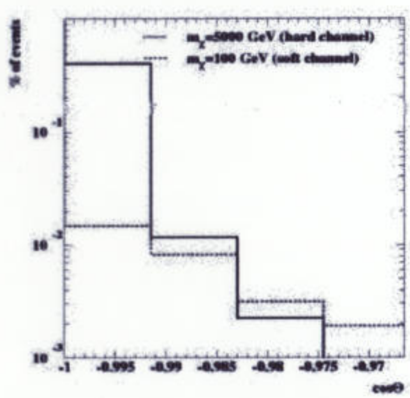


FIG. 6: Angular distribution of the remaining fraction of neutralinos at filter level5 with respect to trigger level from the two extreme neutralino masses studied in this paper. The angular range shown is between 165° and 180°.

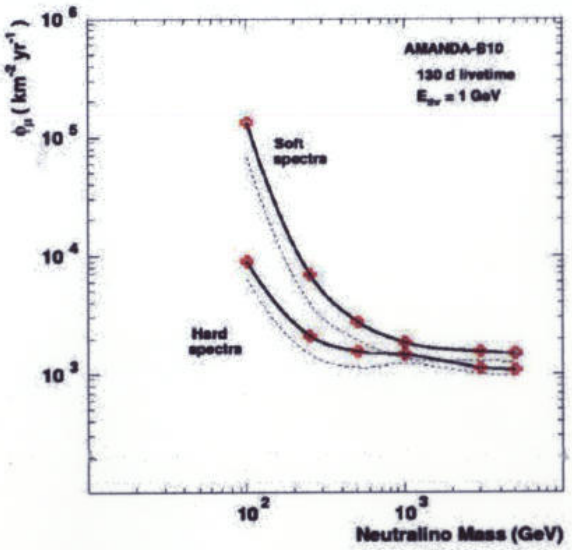


FIG. 10: 90% confidence level upper limits on the muon flux at the surface of the Earth, ϕ_μ, as a function of the neutralino mass and for the two extreme annihilation channels considered in the analysis. The dashed lines indicate the limits obtained without including systematic uncertainties and correspond to the numbers in parentheses in table III. The symbols indicate the masses used in the analysis. Lines are to guide the eye.

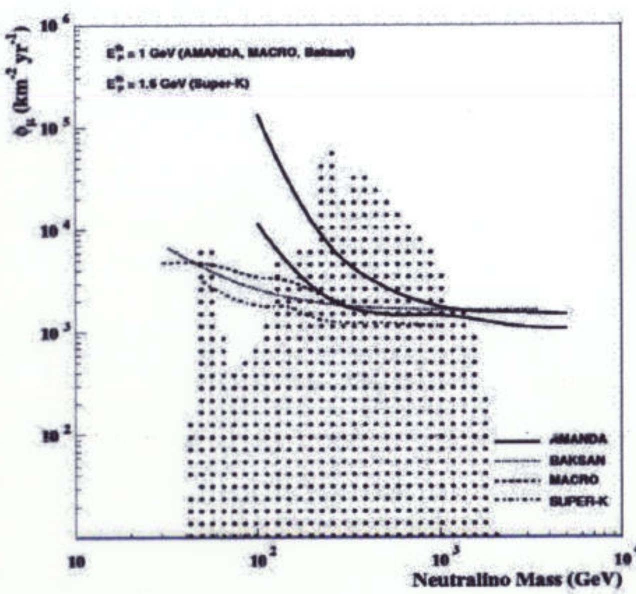
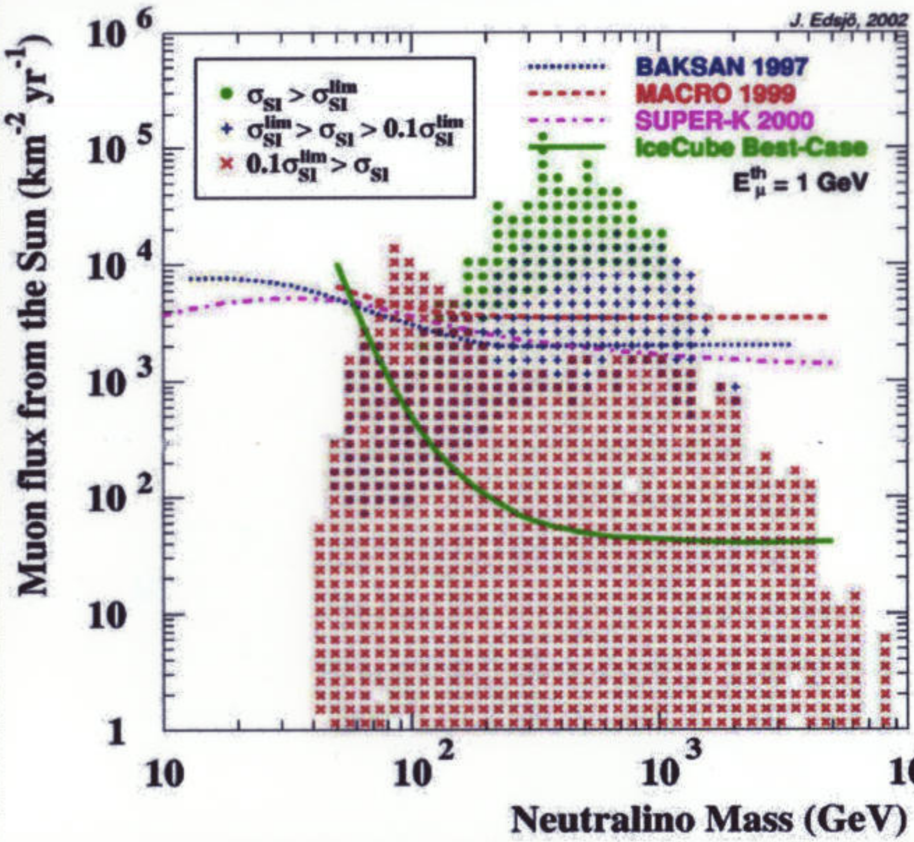


FIG. 11: The AMANDA limits on the muon flux from neutralino annihilations from figure 10 compared with published limits from MACRO, Baksan and Super-Kamiokande. The dots represent model predictions from the MSSM, calculated with the DarkSUSY package[39].

Neutrinos from the Sun more difficult to detect from Antarctica at low masses (the Sun is too close to the horizon during winter. Antares may have better sensitivity.)



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Positrons from neutralino annihilations – explanation of feature at 10 – 30 GeV?

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Cosmic ray positron excess and neutralino dark matter

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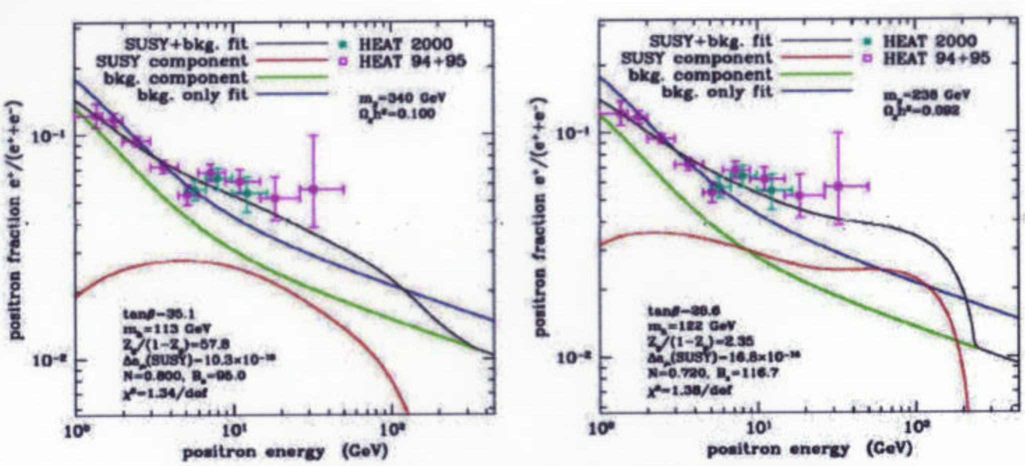
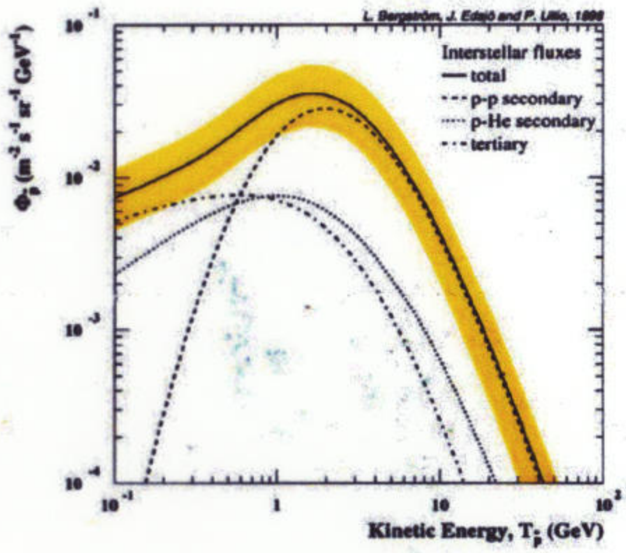


FIG. 1. Positron fraction data and fits. We illustrate positron data from HEAT 94+95 and HEAT 2000, a background only fit, and a SUSY+background fit from two interesting models from the MSSM database. Two additional curves separately display the SUSY and background components of the combined SUSY+background 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.

Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

However, p-He reactions and energy losses due to scattering of antiprotons ⇒ low – energy gap is filled in



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Antiprotons from neutralino annihilation

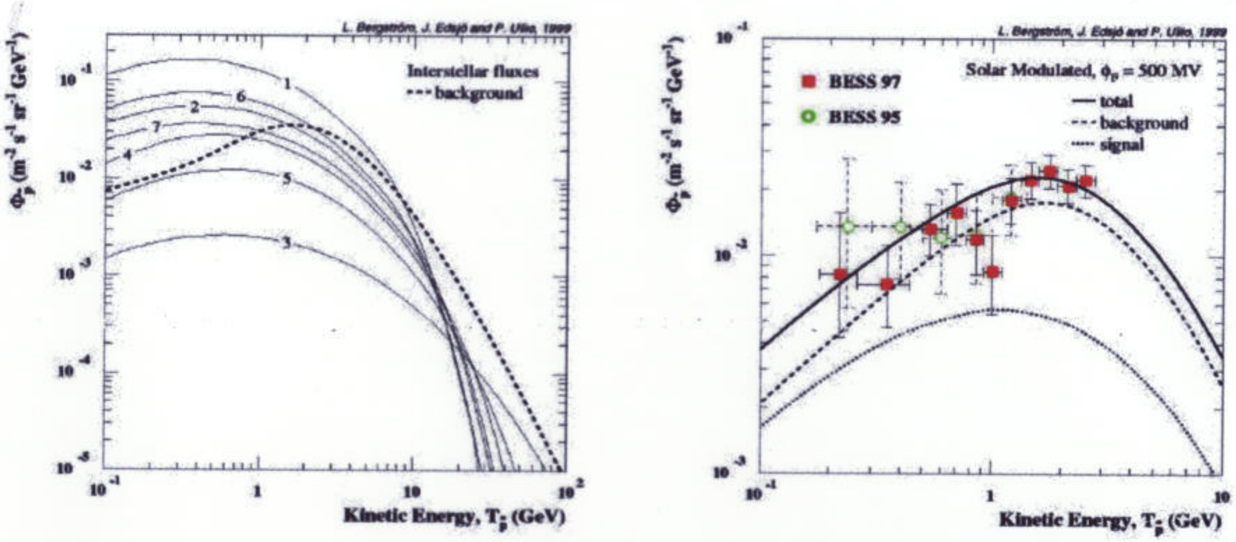
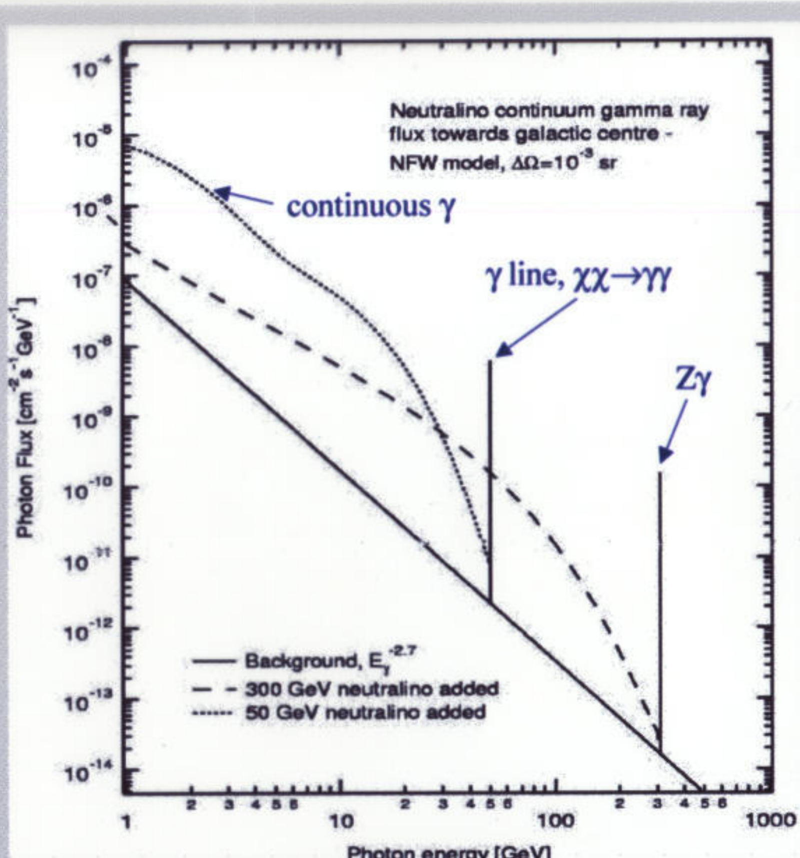


FIG. 11.— (a) Antiproton spectra for all 7 models appearing in Table 3. (b) Example of a composite spectrum consisting of our reference background $\bar{p}$ flux (Fig. 1) reduced by 24 % with the addition of the predicted flux from annihilating dark matter neutralinos of MSSM model number 5 in Table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

Advantage of gamma rays: point back to the source. Enhanced flux possible thanks to substructure (as predicted by CDM)



L.B. & H. Snellman 1986;L.B., P.Ullio & J. Buckley 1998

Spectral Gamma-ray Signatures of Cosmological Dark Matter Annihilations

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(PRL 87 (2001) 251301.)

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

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

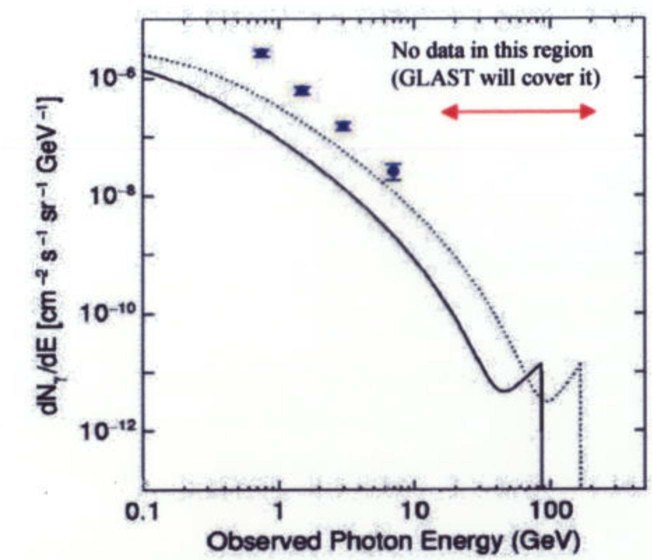

FIG. 1. The predicted diffuse γ-ray flux, from cosmic annihilations into continuum gamma-rays, and a gamma-ray line. The redshifted line gives the conspicuous feature at the highest energies. Shown are cosmic annihilation of 86 GeV (solid line) and 166 GeV (dotted line) neutralinos. A Moore density profile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

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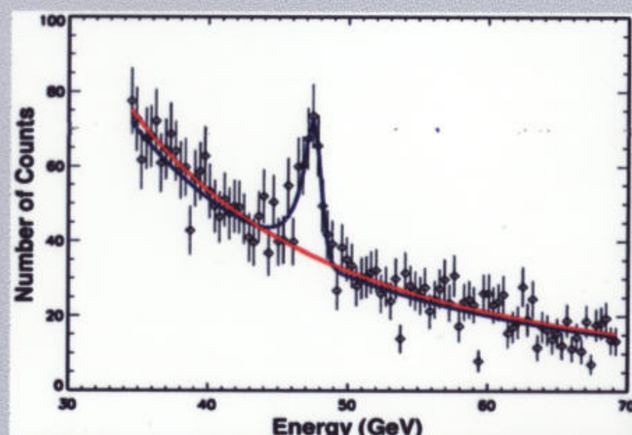
GAMMA-RAY LARGE AREA SPACE TELESCOPE

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



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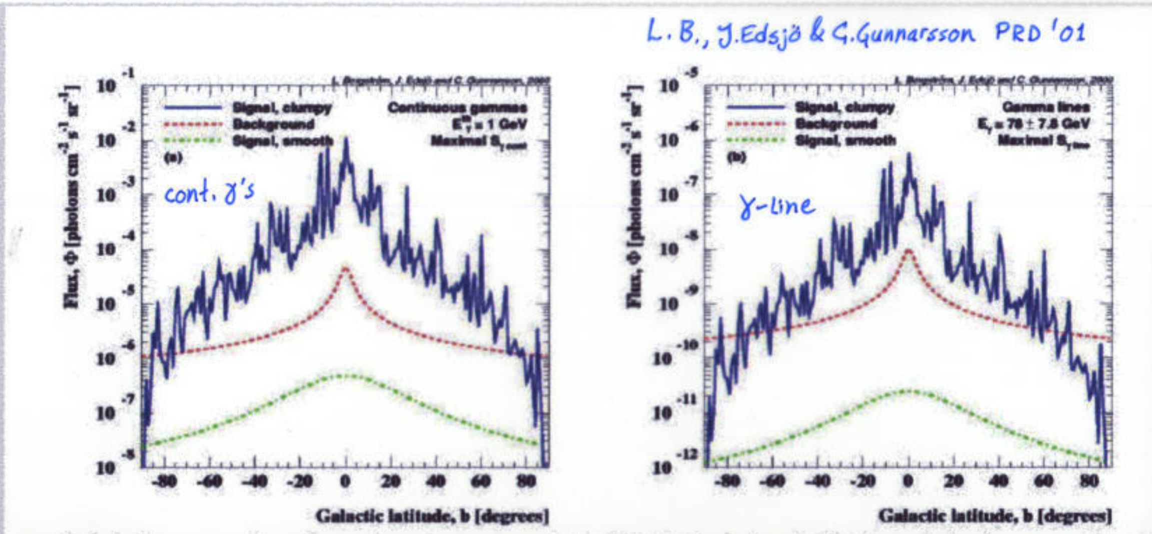
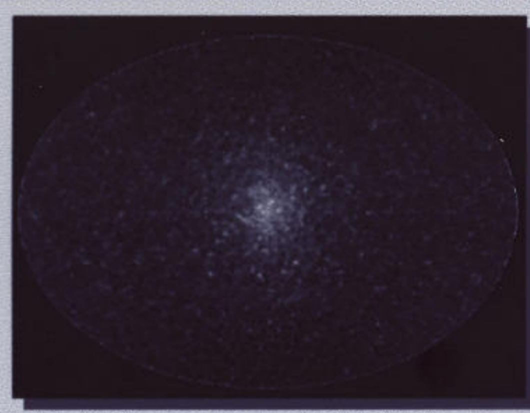


CDM simulation of SUSY gamma-ray sky

(Calcaneo-Roldan & Moore, 2000)



Possible signature in CMBR and radio background? (Blasi, Olinto & Tyler, astro-ph/0202049)

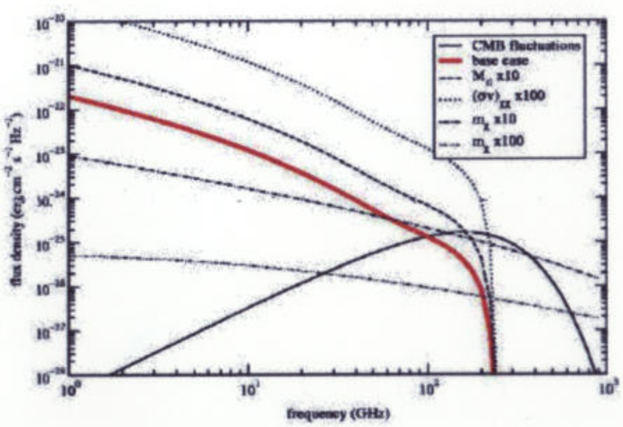


Fig. 2. Spectrum of synchrotron emission from an example NFW clump, compared with the CMB anisotropies (thin line) in the same solid angle as the clump. This clump is chosen to lie at Galactocentric coordinates [-4,0,0] kpc, 4.5 kpc away from us. The heavy solid line is the base case, where $M_{cl} = 10^8\ M_{\odot}$, $\langle\sigma v\rangle_{\chi\bar{\chi}}$ =

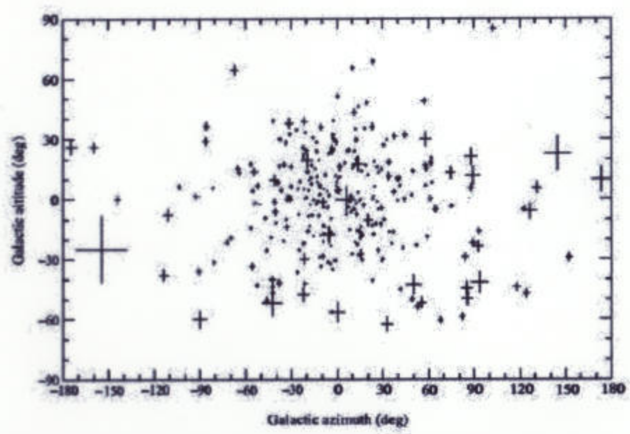


Fig. 3. A simulated sky of observable NFW dark matter clumps. Each cross indicates a clump, observable by the criteria laid out in section 2.3. The size of the cross indicates the angular size of the clump such that half its light originates inside the area shown. Angular sizes are exaggerated by a factor of 10.

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Neutrinos

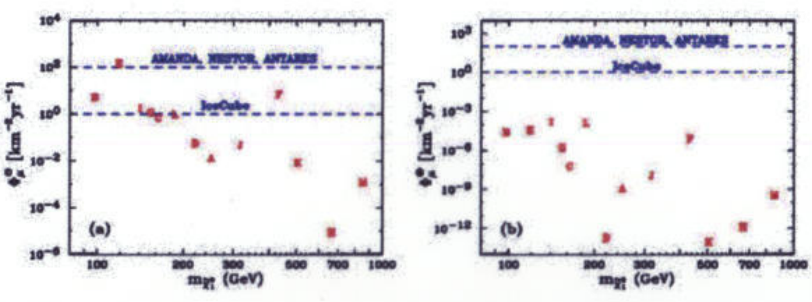

Figure 3: *Muon fluxes from neutrinos originating from relic annihilations inside (a) the Sun and (b) the Earth. Approximate sensitivities of near future neutrino telescopes ($\Phi_\mu = 10^2$ km^{-2} yr^{-1} for AMANDA II [45], NESTOR [46], and ANTARES [47], and $\Phi_\mu = 1$ km^{-2} yr^{-1} for IceCube [48]) are also indicated.*

Gamma-rays

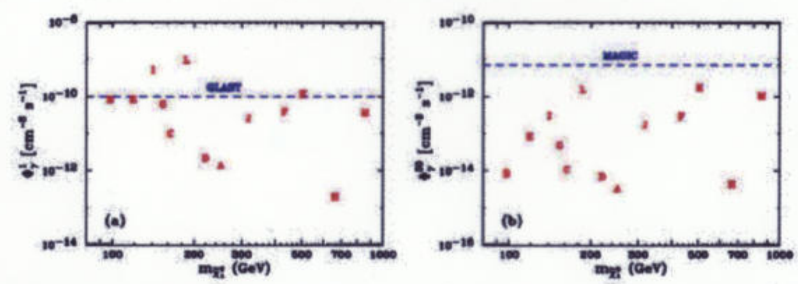

Figure 5: *Comparisons between predicted integrated fluxes and prospective experimental sensitivities for photons with (a) a 1 GeV threshold, and (b) a 50 GeV threshold, following [15]. Estimated sensitivities for (a) GLAST [53] and (b) MAGIC [54] are also shown. A moderate halo parameter $\bar{J} = 500$ is assumed.*

Conclusions

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

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