Dark Matter and its Detection - I

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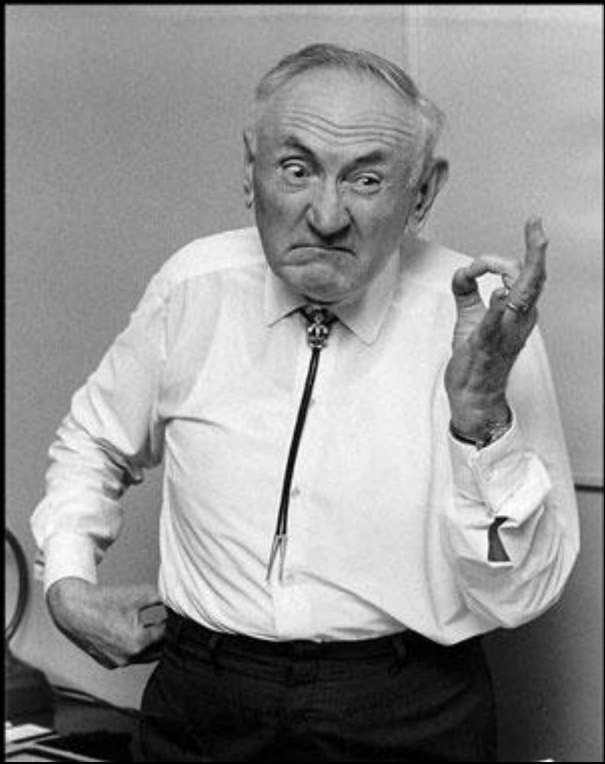
UniverseNet

The second network school and meeting

Oxford, UK

22 to 26 September 2008



Fritz Zwicky, 1933: Velocity dispersion of galaxies in Coma cluster indicates presence of Dark Matter , $\sigma \sim 1000$ km/s $\Rightarrow$ $M/L \sim 50$

"If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter."

"It is, of course, possible that luminous plus dark (cold) matter together yield a significantly higher density…" - Zwicky 1933

Smith (1936) confirmed Zwicky's results using Virgo cluster.

Zwicky (1937) notes that gravitational lensing may be used as a tool to estimate the total mass of galaxies.

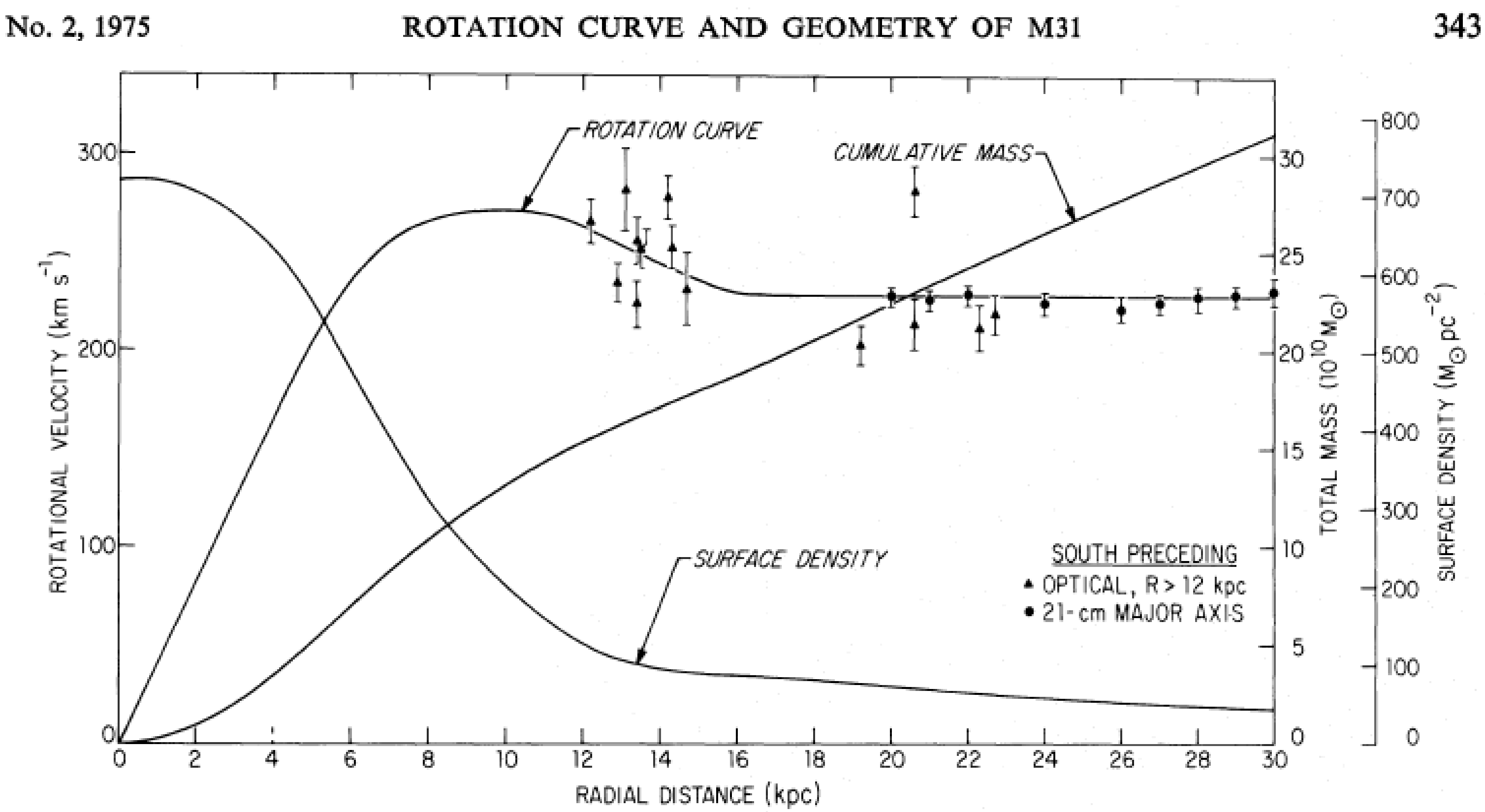
Babcock (1939) measured rotation curve of M31 (Andromeda).

From Babcock's paper, 1939:

age mass per cubic parsec is 0.98☉. The total luminosity of M31 is found to be 2.1×10^9 times the luminosity of the sun, and the ratio of mass to luminosity, in solar units, is about 50. This last coefficient is much greater than that for the same relation in the vicinity of the sun. The difference can be attributed mainly to the very great mass calculated in the preceding section for the outer parts of the spiral on the basis of the unexpectedly large circular velocities of these parts.

Then essentially nothing happened for 30 years….

Then Rubin & Ford (1970), and Roberts & Whitehurst (1975) measured a flat rotation curve of M31 far outside the optical radius.



Einasto, Kaasik & Saar;
Ostriker, Peebles & Yahil
(1974):

Dark halos surround all galaxies and have masses ~ 10 times larger than luminous populations, thus dark matter is the dominant population in the universe: Ω_{DM} =0.2.

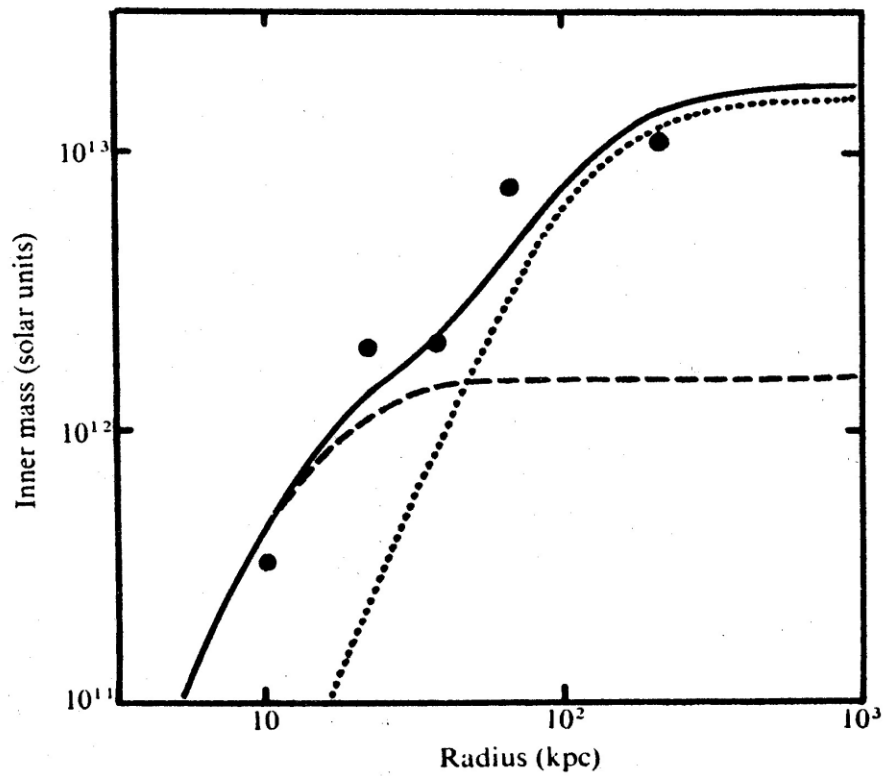
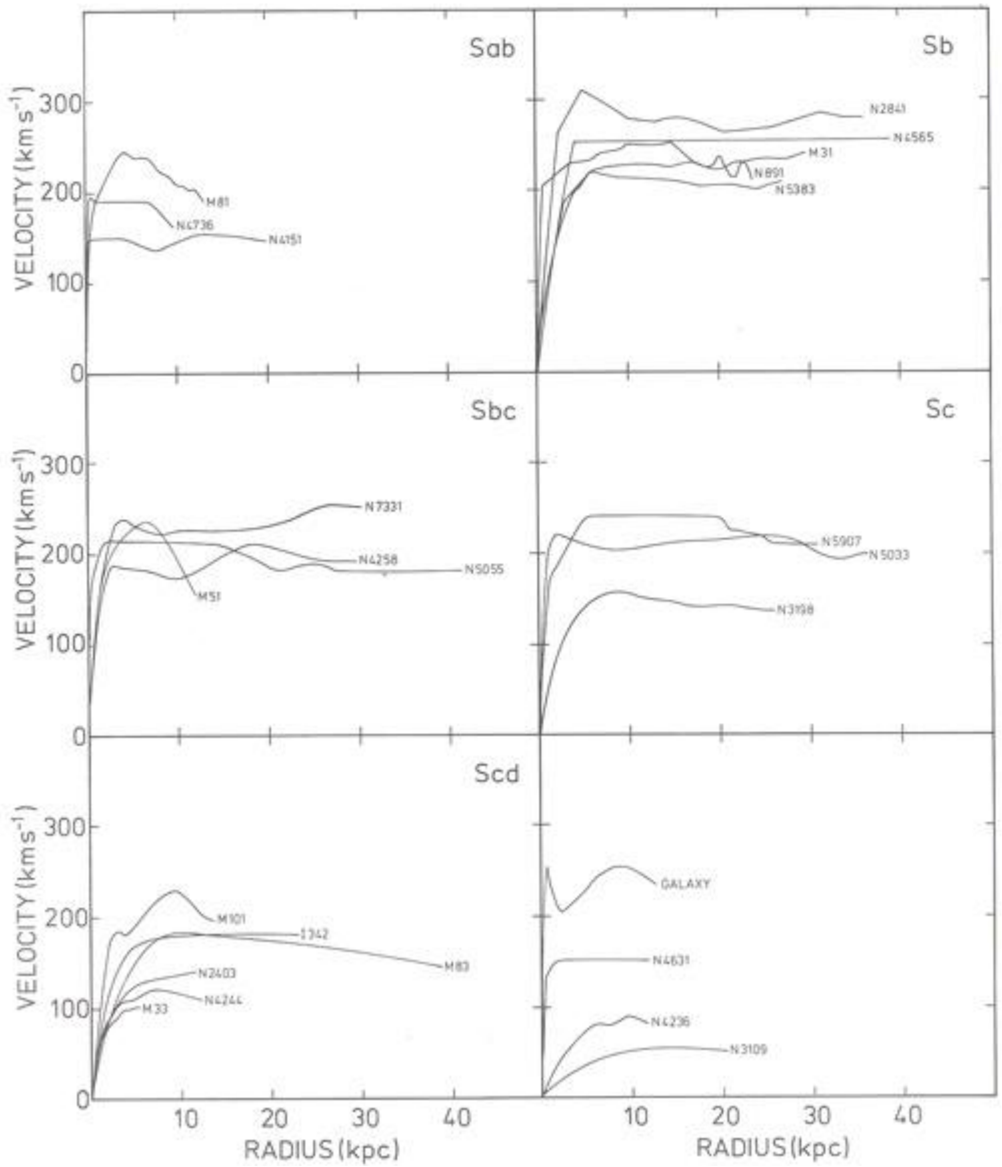


Fig. 2 The distribution of the mean inner mass, $\langle M(R) \rangle$, obtained from 105 pairs of galaxies. Symbols as in Fig. 1.

Flat rotation curves are the rule:

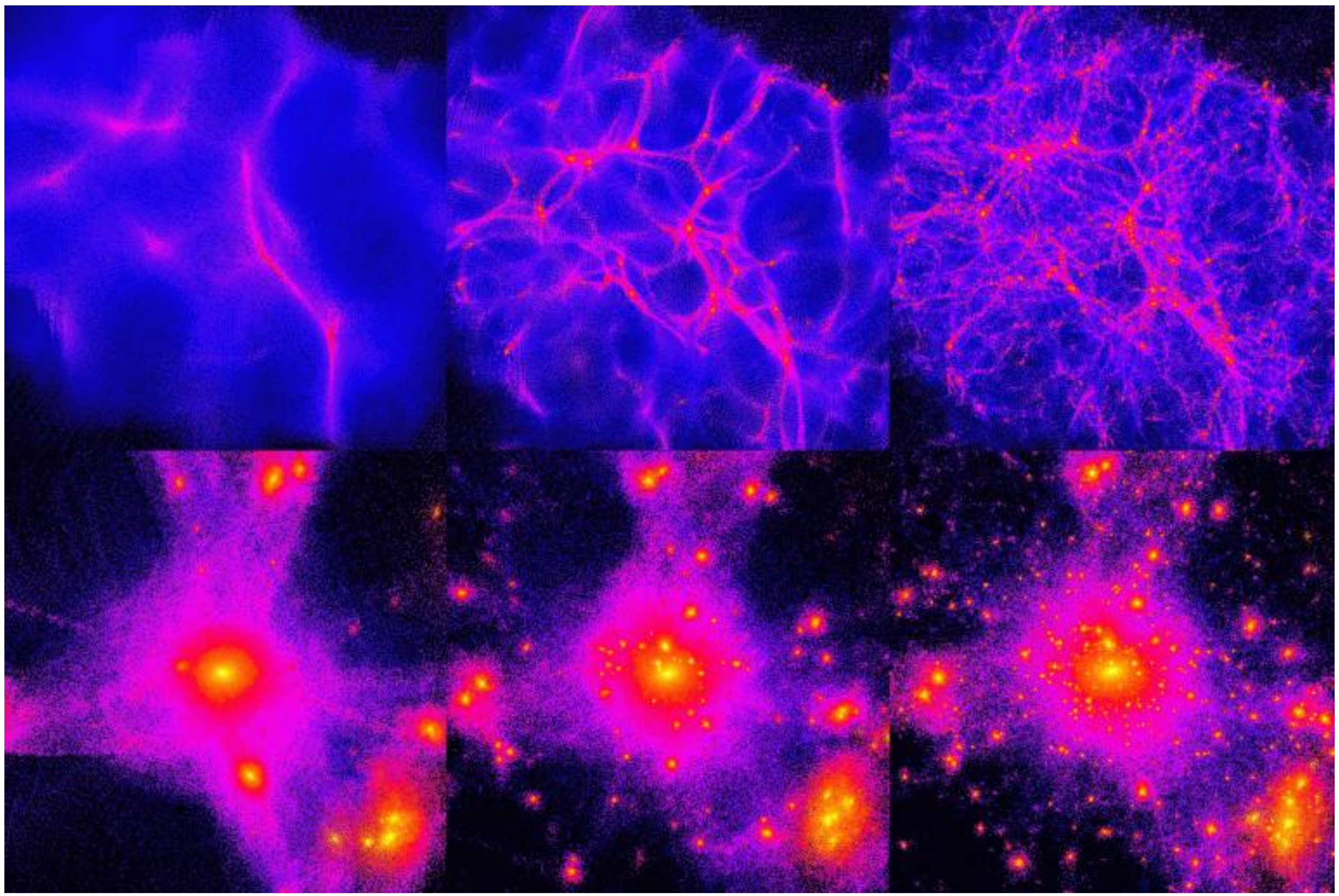
From 21 cm results in thesis of A. Bosma, 1978 (cf also Rubin, Thonnard & Ford, 1978):



Around 1982 (Peebles; Bond, Szalay, Turner; Sciama) came the Cold Dark Matter paradigm: Structure formation scenarios (investigated through N-body simulations) favours hierarchical structure formation. Hot Dark Matter (like neutrinos) would first form structure at large scales (Zel'dovich pancakes) which then fragments to smaller scales – does not agree with observations. The theoretical belief, based on inflation, was that $\Omega_M = 1$

Melott et al 1983; Blumenthal, Faber, Primack & Rees 1984,...

Hot Dark Matter →



← Cold Dark Matter

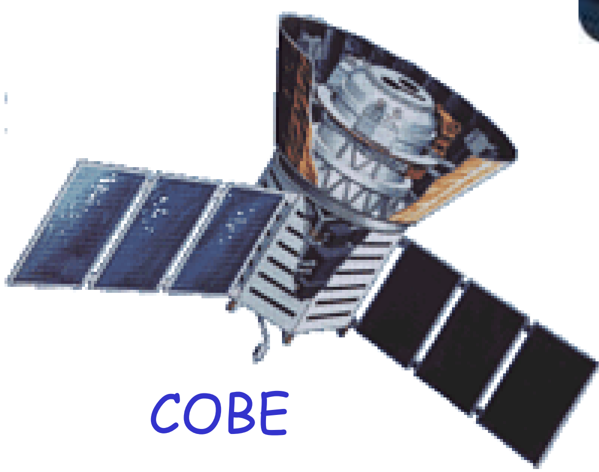
B. Moore

1990's: Opening of a new era, which has turned the tide in favour of cold dark matter: Precision Cosmology

Nobel Prize in Physics 2006

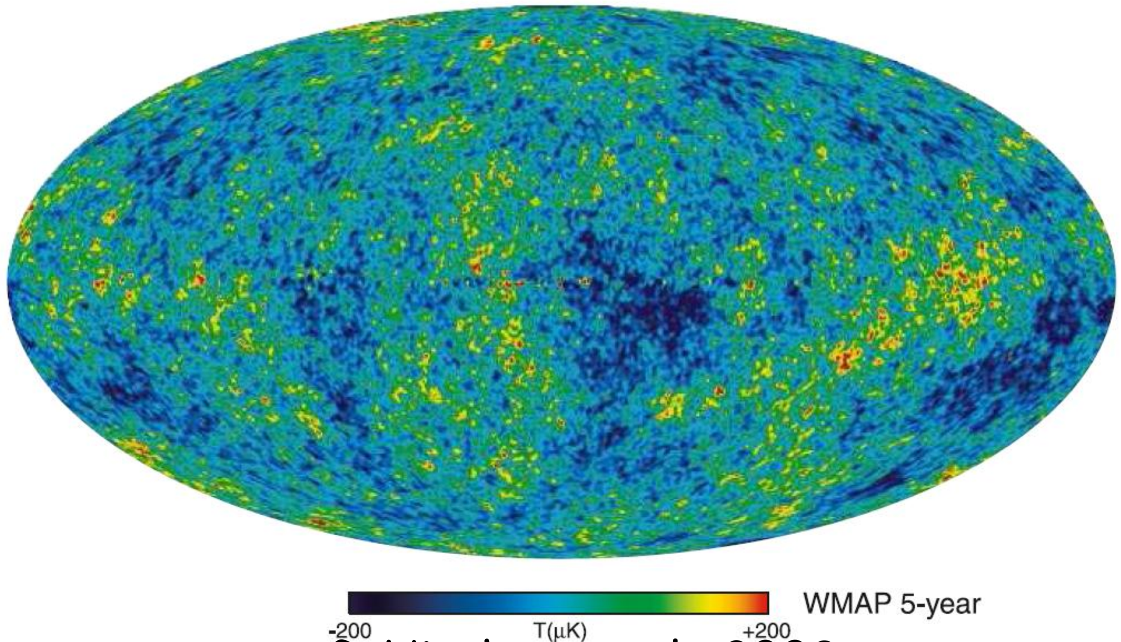
John Mather

George Smoot

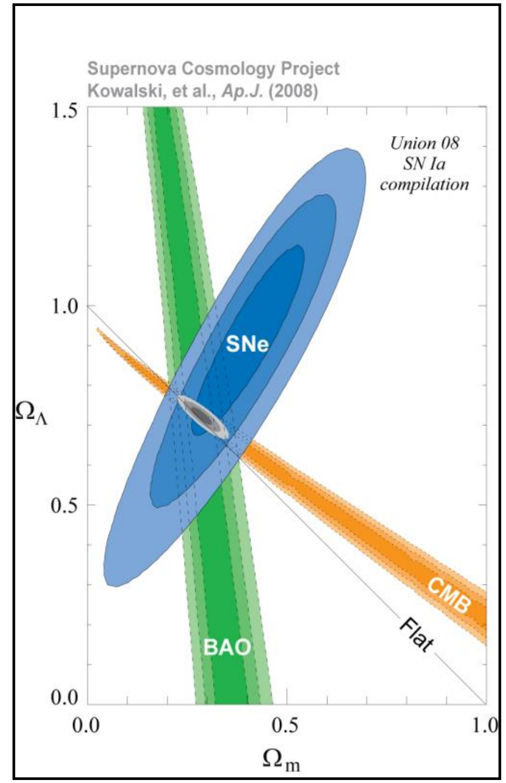


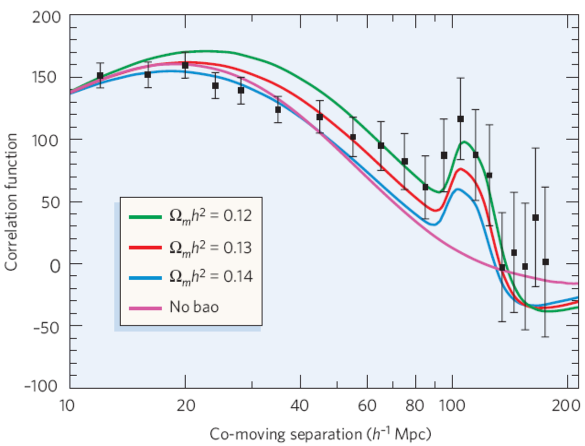
COBE

"... for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."

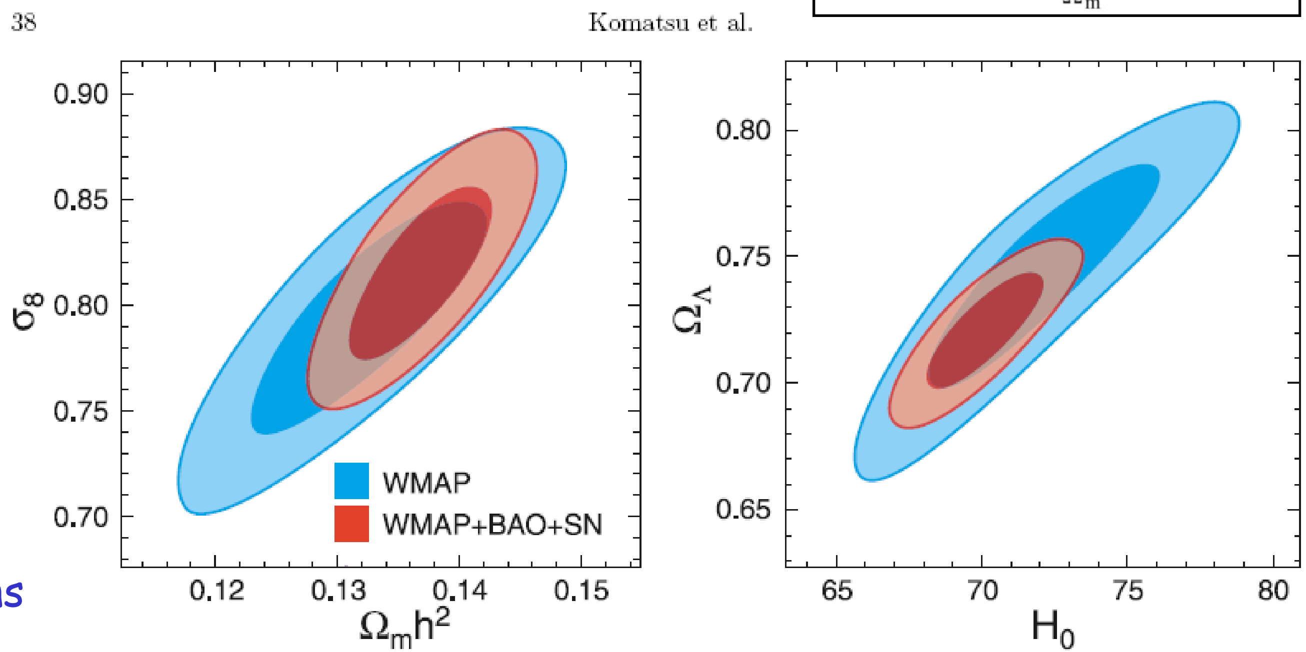


G. Hinshaw et al., 2008

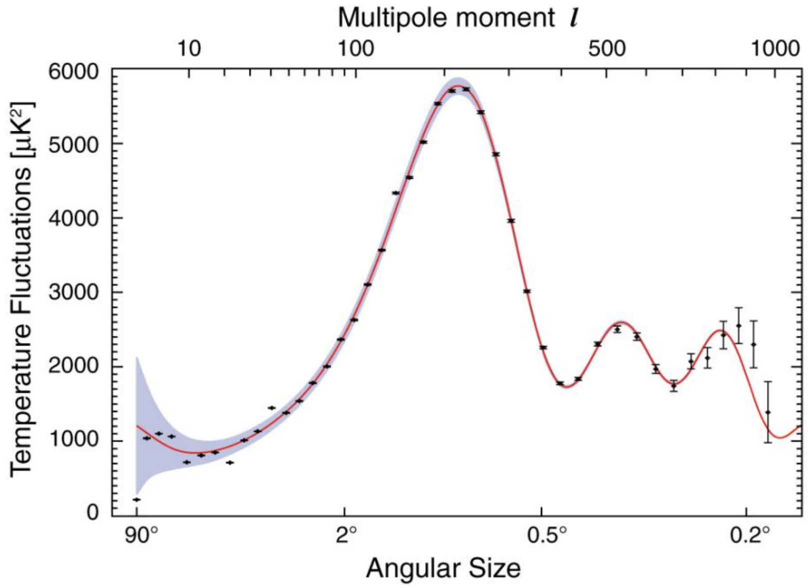


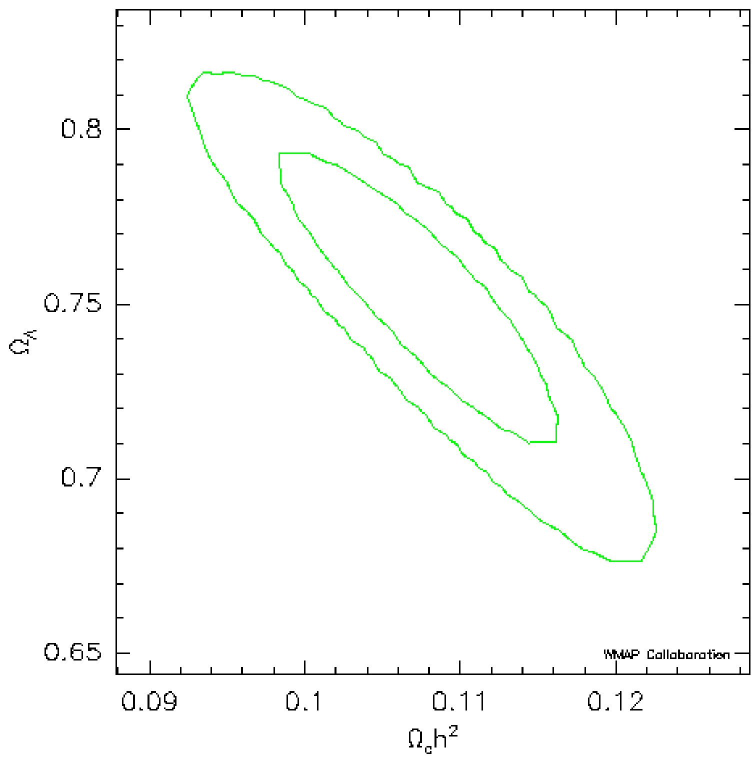


Baryon Acoustic Oscillations
(BAO)SDSS, 2005



WMAP 5-year, Komatsu & al., 2008





Result from best-fit model from WMAP5, Concordance ΛCDM Model (for flat Universe):

- Only 4.4 % baryonic matter, $\Omega_b h^2 = 0.0227 \quad 0.0006$
- Around 22 % Cold Dark matter, $\Omega_{CDM} h^2 = 0.110 \quad 0.006$
- Around 74 % "Dark energy", $\Omega_\Lambda = 0.74 \quad 0.03$
- Age of Universe: 13.69±0.13 Gyr

WMAP Collaboration (Spergel & al), 2006:

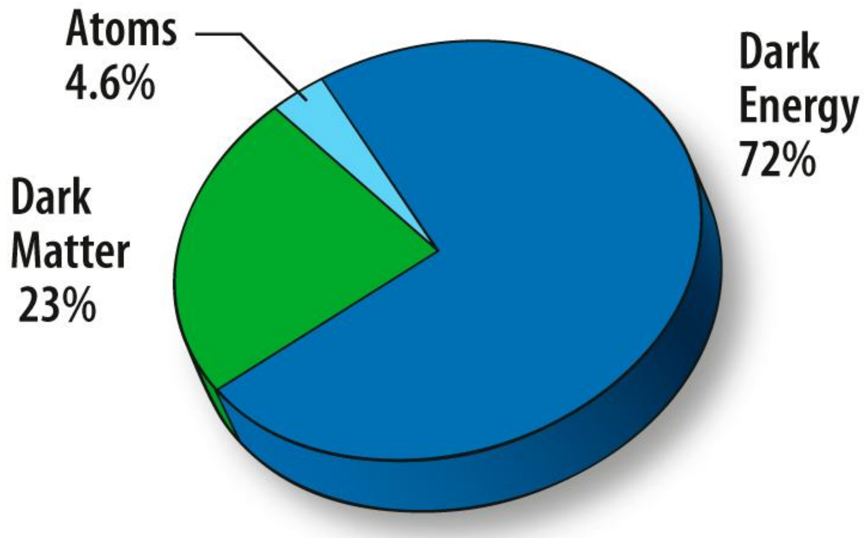
Nonbaryonic Dark Matter exists!

	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	**Power Law ΛCDM**	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	-3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	-6	7
M11	Running Spectral Index & Tensor Modes	-3	8
M12	Sharp cutoff	-1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	-22	20

At the time the CMBR was emitted, the redshift was $z \sim 1100$. Since $\rho_{CDM} \sim mc^2 \times (1+z)^3$ due to dilution of the number density of particles, and $\rho_\Lambda \sim (1+z)^0$ = const (cosmological constant), the ratio of energy densities, which is now $\rho_{CDM}/\rho_\Lambda \sim 1/3$, was then

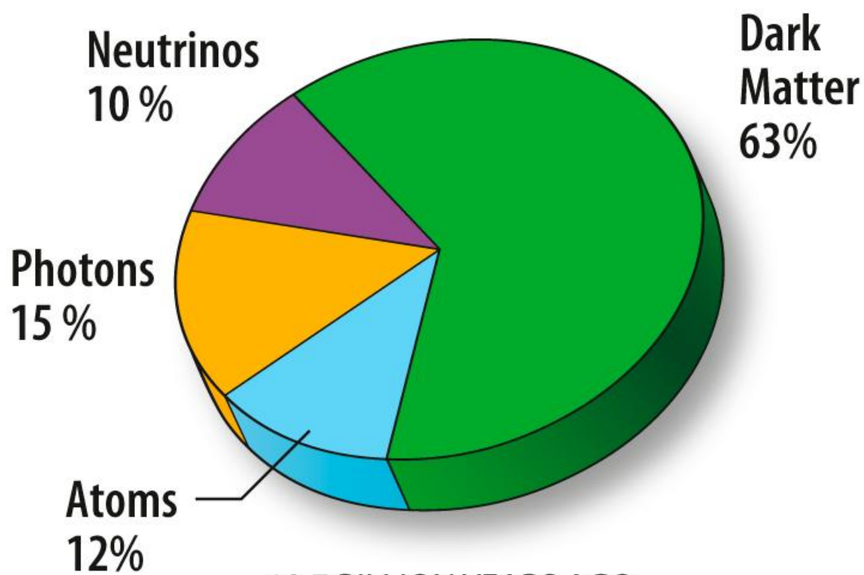
$$\rho_{CDM}/\rho_\Lambda \sim 4\times10^8$$

Cold dark matter ruled the universe! (And it still dominates over baryons)



TODAY

Now



13.7 BILLION YEARS AGO

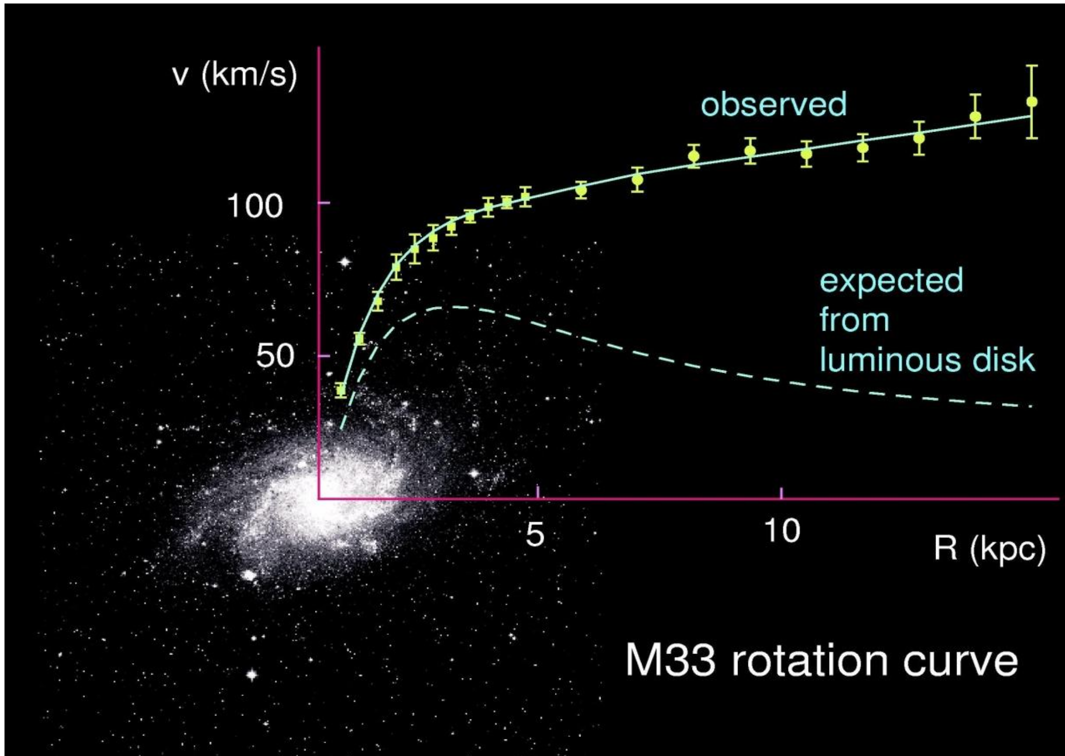
(Universe 380,000 years old)

When CMBR was emitted

WMAP 2008

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

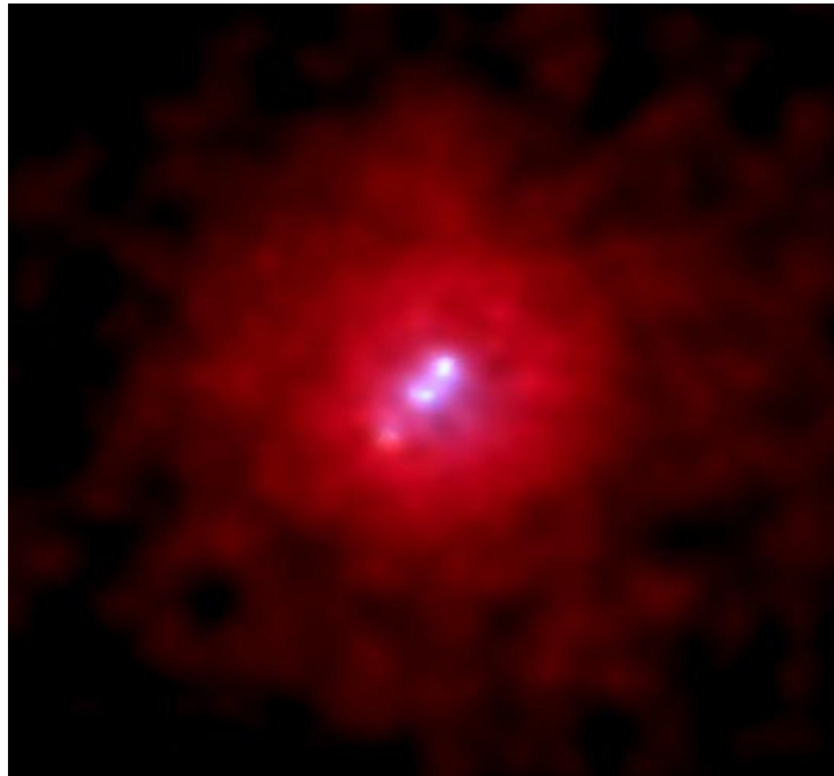
Galaxy rotation curves



L.B., Rep. Prog. Phys. 2000

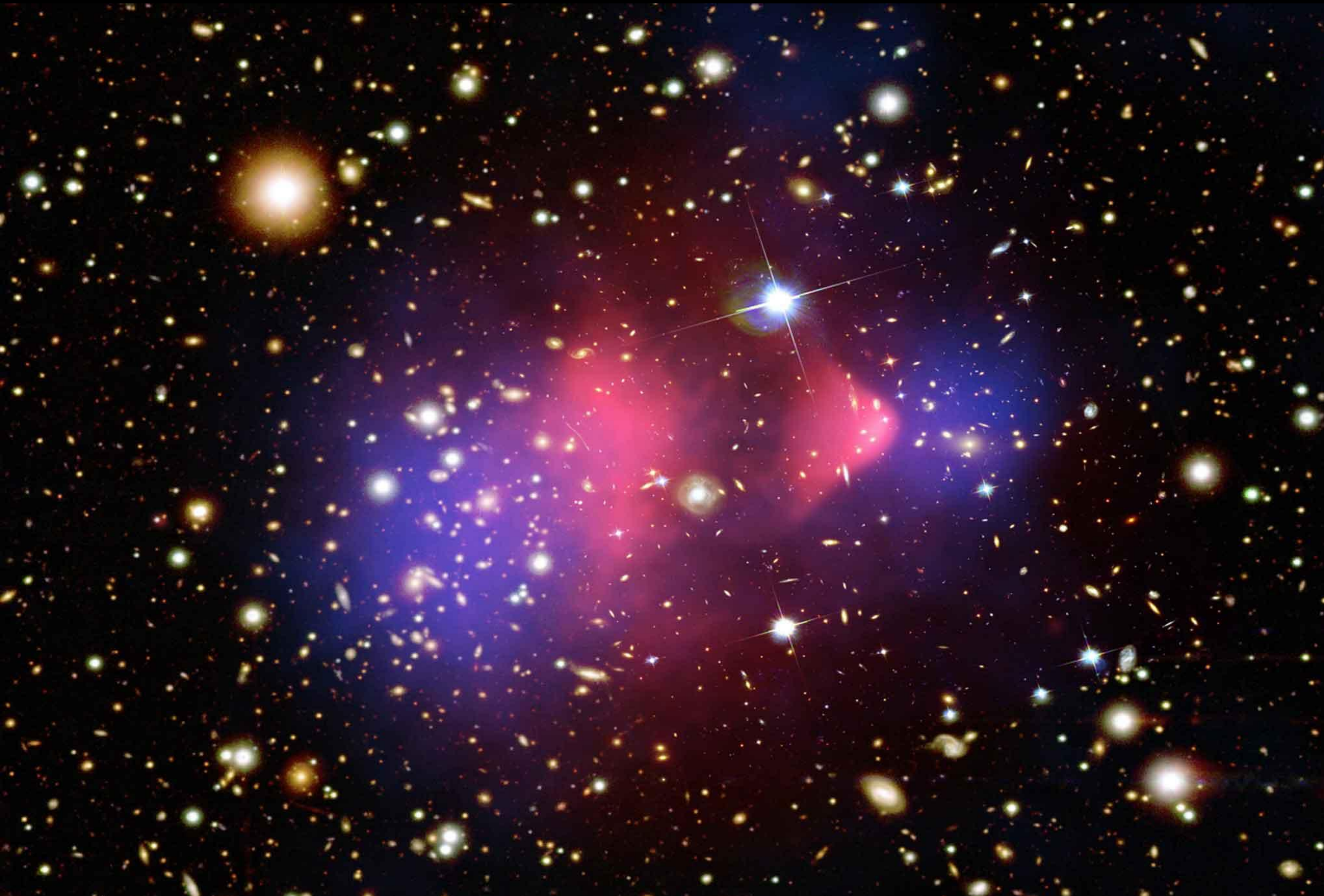
cf. Babcock, 1939

X-ray emitting clusters



Cluster 3C295 (Chandra)

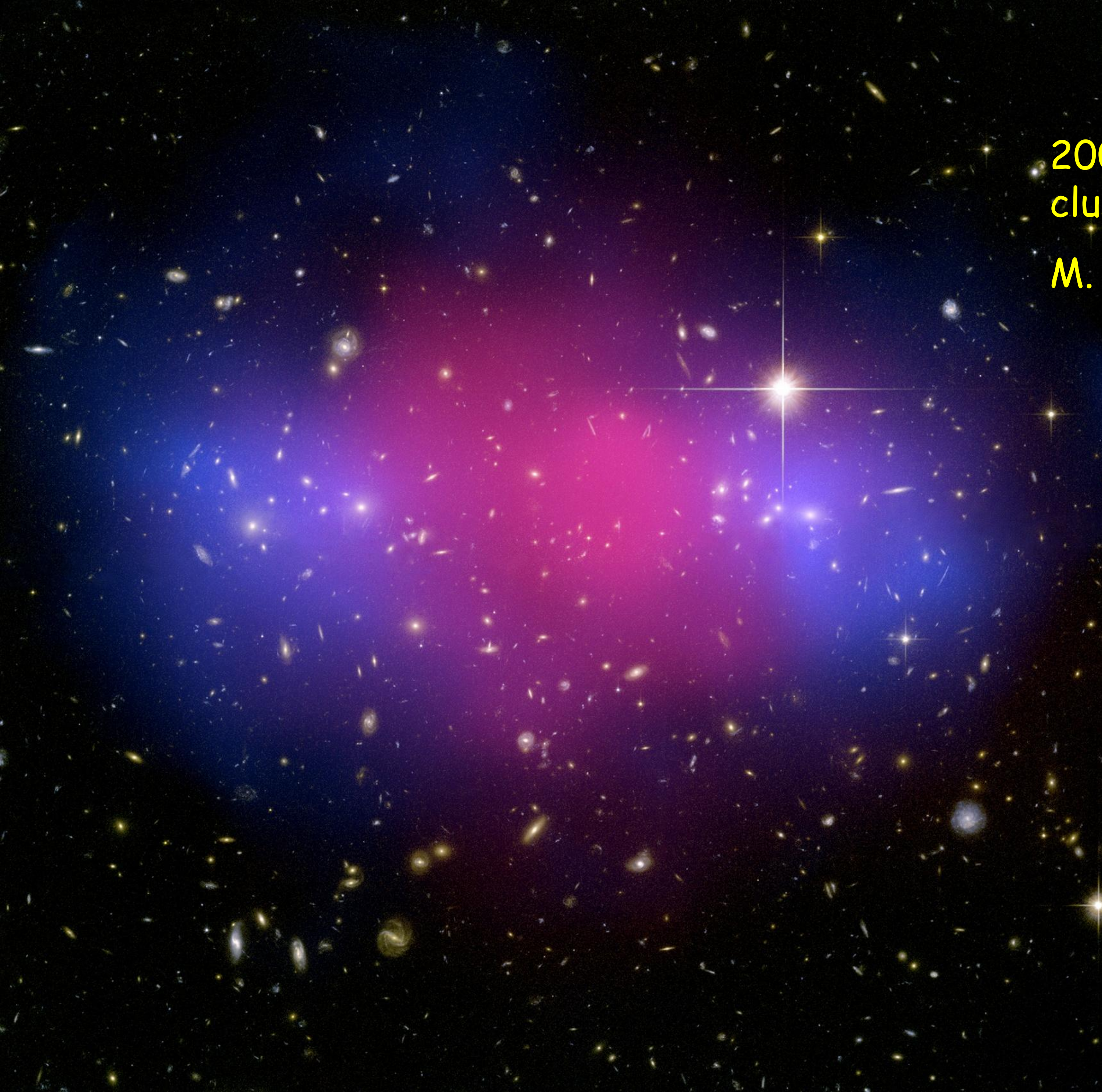
cf. Zwicky, 1933



2006: Strong new evidence for nonbaryonic dark matter

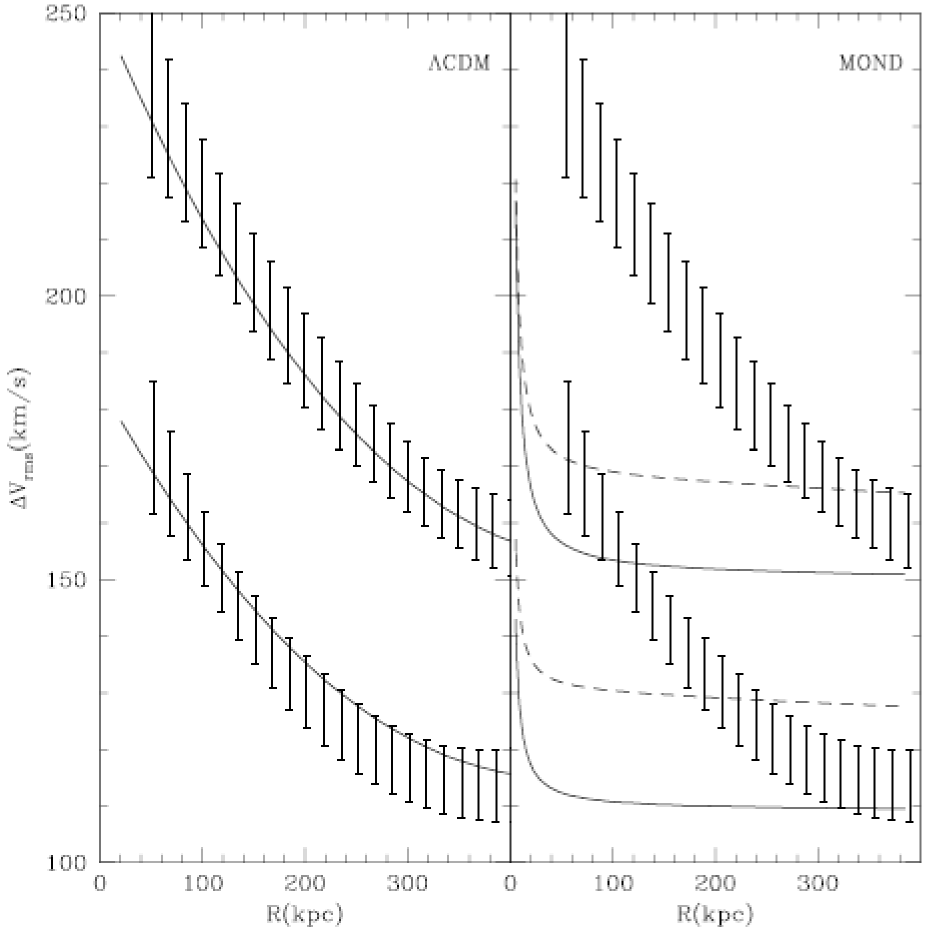
"Bullet cluster"

MOND seems to be ruled out, or at least has to have dark matter also (and more exotic dark matter than neutrinos: Natarajan & Zhao, 2008)



2008: New pair of colliding clusters, MACSJ0025

M. Bradac, S. Allen & al.



Klypin & Prada, ApJ 2008:

Comparison between CDM and MOND for line-of-sight velocity distribution of 5000 satellites orbiting isolated red galaxies, from Sloan data

The situation today:

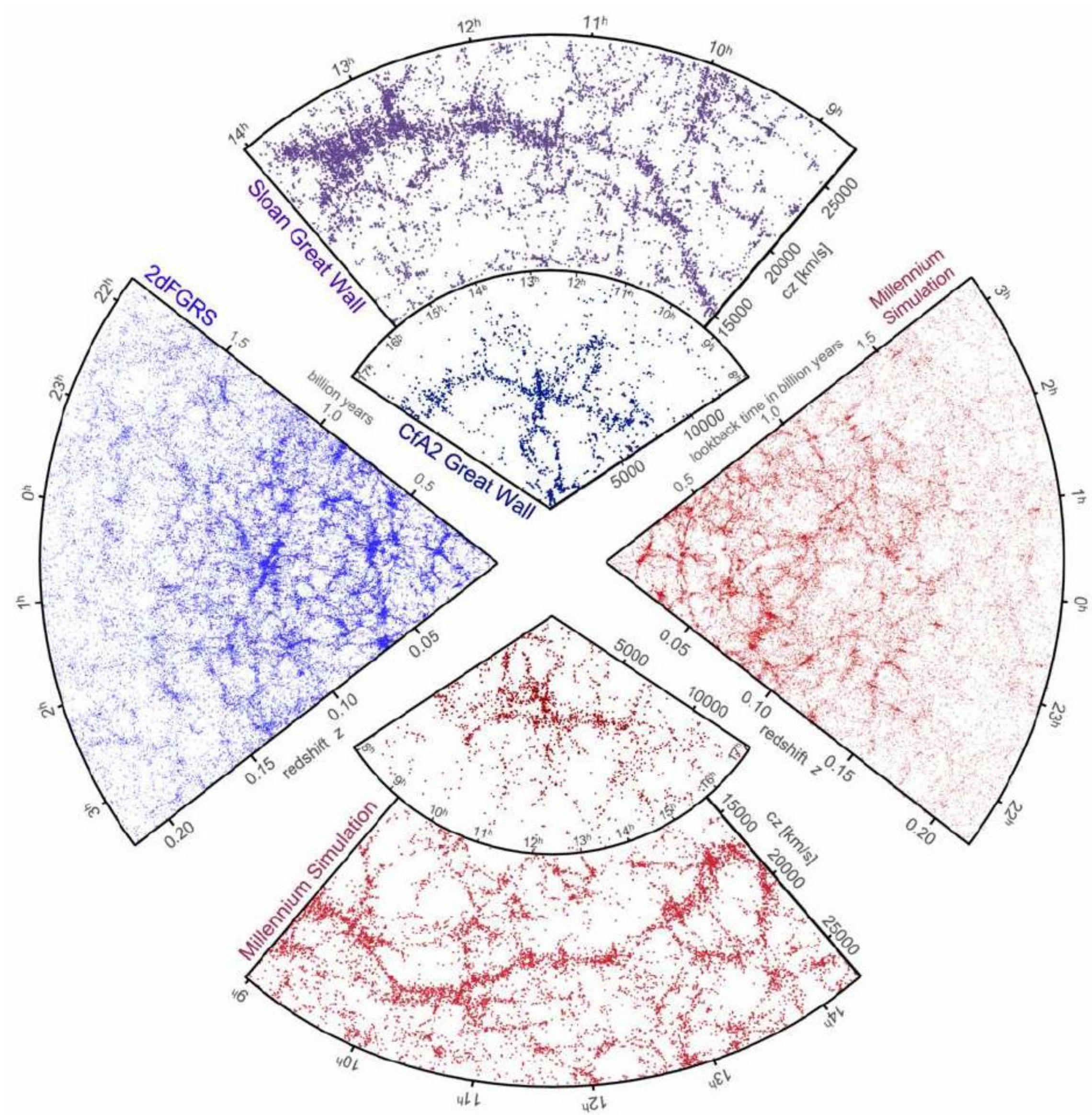
The existence of Dark Matter, especially Cold DM on cosmological scales, has been established by a host of different methods…

…but, the question remains:

what is it?

Cold Dark Matter (CDM)

- Part of the "Concordance ΛCDM Model" of cosmology, $\Omega_{DM} \sim 0.22$, $\Omega_\Lambda \sim 0.74$
- Gives excellent description of CMB, large scale structure, Ly-α forest, gravitational lensing, supernova distances …
- If consisting of particles, may be related to electroweak mass scale: weak cross section, non-dissipative Weakly Interacting Massive Particles (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 less successful. Probably non-linear astrophysical feedback processes are acting (bar formation, tidal effects, mergers, supernova winds,…). This is a crucial problem of great importance for dark matter detection rates.
- Another potential problem may be the exact form of rotation curves: CDM predicts centrally concentrated (cuspy) halos, some observed ones may be better fit by a central core instead. This may however be related to the approximation methods when fitting an observed rotation curve to a triaxial real halo. Again: more work is needed!



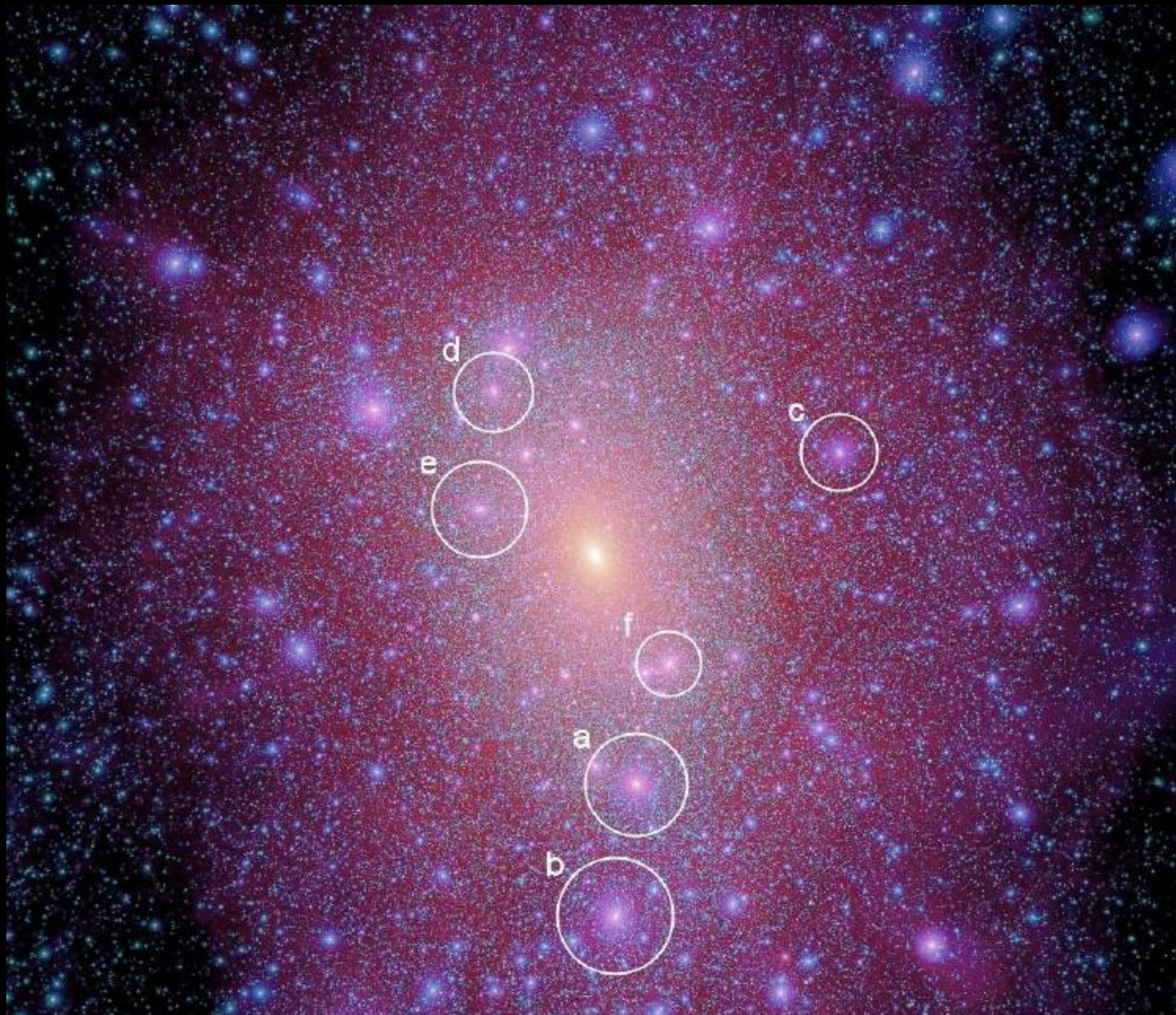
Comparing the distribution of mass on the largest scales (CfA, Sloan and 2dF data), with simulations in a ΛCDM model (millennium simulation)

Springel, Frenk & White, 2006

Via Lactea II simulation (J. Diemand & al, 2008)

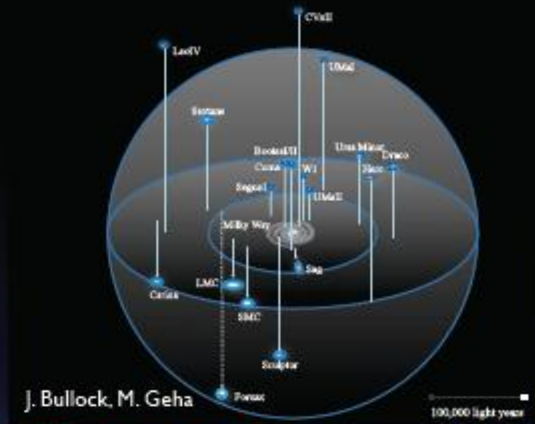
Lots of clumps of dark matter in the halo – but where are they, observationally? "Missing satellite" problem!

Aquarius project, V. Springel et al, 2008



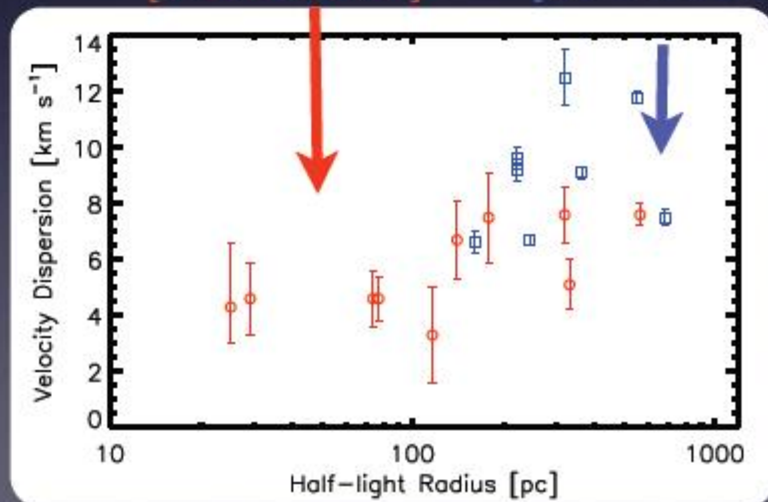
Milky Way Circa 2008

Satellite	Year Discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	2005
Willman I	2005
Ursa Major II	2006
Bootes	2006
Canes Venatici I	2006
Canes Venatici II	2006
Coma Bereniices	2006
Segue I	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Bootes II	2007
Leo V	2008



Ultra-faint satellites
[Simon & Geha 2007]

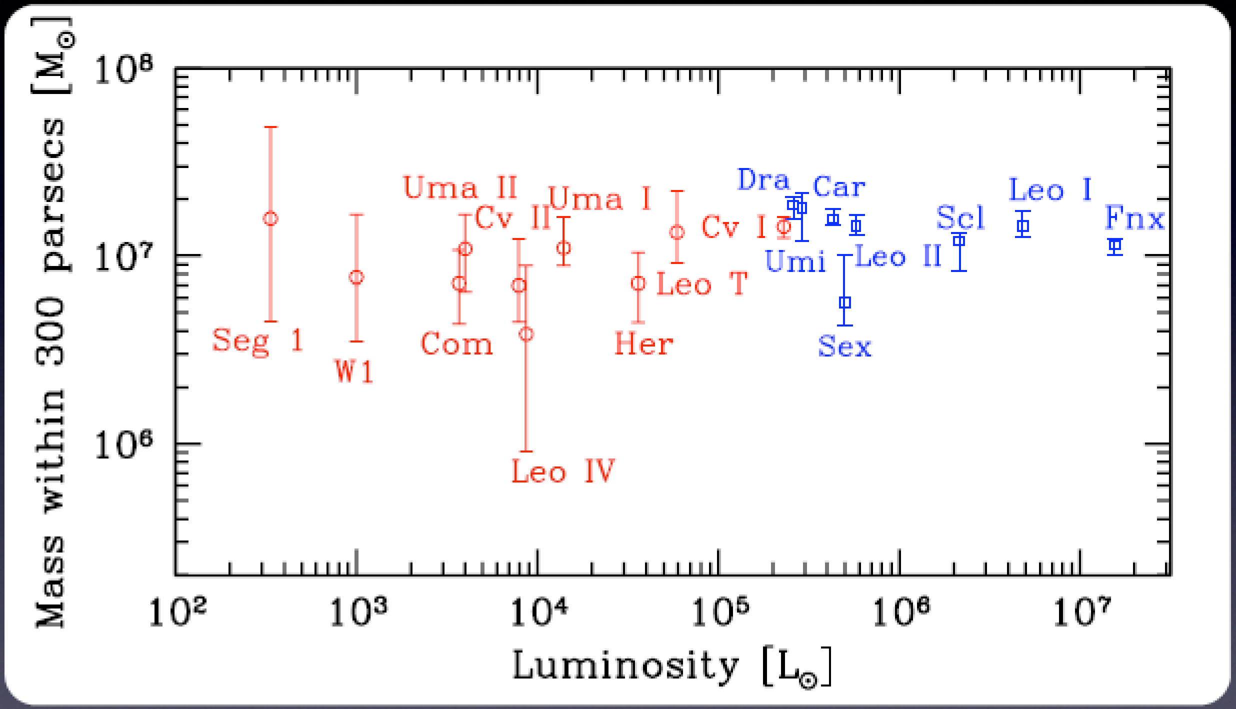
Classical satellites
[Walker et al 2007]



L. Strigari, idm Stockholm talk, 2008

Mystery:

Common Mass Scale for Milky Way Satellites



$\rho \sim 4$ GeV/cm^3 Is this universal mass within 300 pc due to properties of the dark matter, or of details of how these dwarfs formed?

Apart from these (interesting) problems, CDM seems in good shape. But, what is making up CDM? Baryons are only 4 %, so it has to be non-baryonic matter.

Since 1998 (Super-K), we know that non-baryonic dark matter exists!
$\Delta m_\nu \neq 0 \Rightarrow m_\nu \neq 0$
However, neutrinos are hot dark matter and cannot be the main component of dark matter (10% at most) :

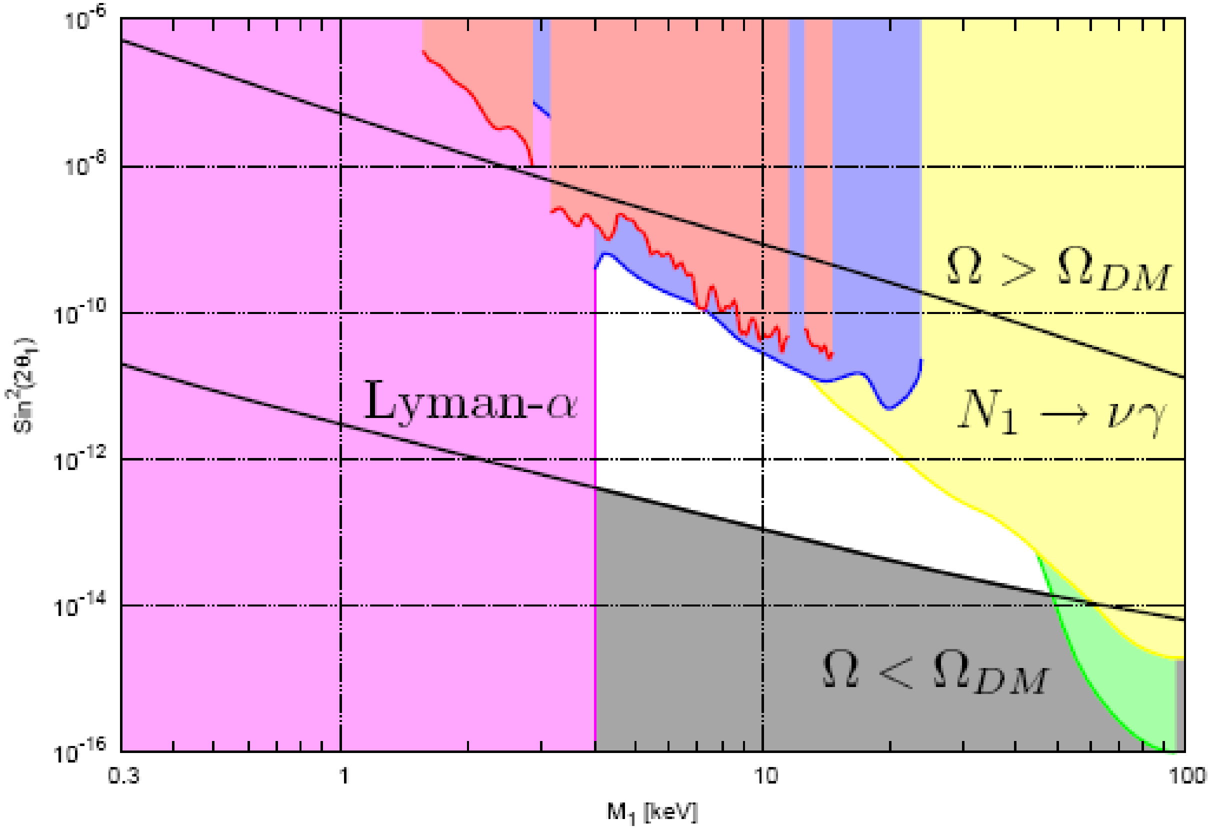
- $\Omega_\nu = \dfrac{\sum_\nu m_\nu}{50 \text{ eV}} = \Omega_{DM} \approx 0.2 \Rightarrow \sum_\nu m_\nu \approx 10 \text{ eV}$ Too small for dwarf halos

because Pauli principle $\Rightarrow$ ν's cannot clump in dwarf halos unless $\sum_\nu m_\nu > 120$ eV (Tremaine & Gunn), increased to around 1 keV by the new dwarf satellite data (L. Strigari et al., 2008)

- 10 eV is too large for structure formation distribution $\Rightarrow$ limit on sum of ν masses:

WMAP5, BAO, SN data: $\Sigma\, m_\nu < 0.61$ eV (Komatsu et al., 2008)

The Planck satellite and future galaxy surveys will put further constraints on hot dark matter (and perhaps reach the sensitivity to detect a finite mass). These limits do not apply for sterile neutrinos.



Sterile neutrinos: the allowed window is shrinking…

(M. Shaposhnikov, 2008)

Good particle physics candidates for Cold Dark Matter:

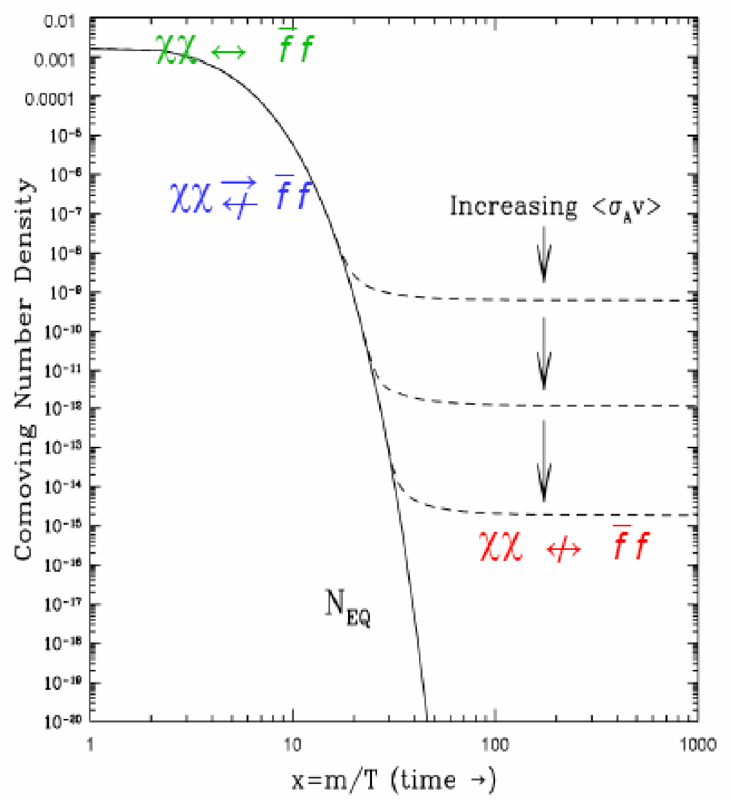
Independent motivation from particle physics

- Weakly Interacting Massive Particles (WIMPs, 3 GeV < m_X < 50 TeV), thermal relics from Big Bang:
  - Supersymmetric neutralino
  - Kaluza-Klein states
  - Extended Higgs sector
  - Axino, gravitino – SuperWIMPS
  - Heavy neutrino-like particles
  - Mirror particles
  - plus hundreds more in literature…
- Axions (introduced to solve strong CP problem)
- Non-thermal (maybe superheavy) relics: wimpzillas, cryptons, …

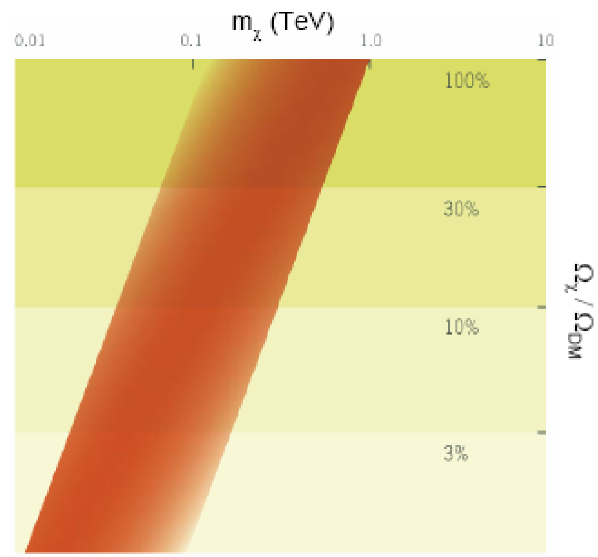
"The WIMP miracle": for typical gauge couplings and masses of order the electroweak scale, $\Omega_{wimp}h^2 \approx 0.1$ (within factor of 10 or so)

J. Feng:

The WIMP "Miracle"



$$\Omega_\chi \sim <\sigma_A v>^{-1} \sim m_\chi^2/(k\alpha^2)$$



HEPAP LHC/ILC Subpanel (2005)

[k = 0.5 – 2, S- and P-wave]

Note 1: There may exist also non-thermal production mechanisms.

Note 2: The produced particles may also decay with long lifetime, "decaying dark matter".

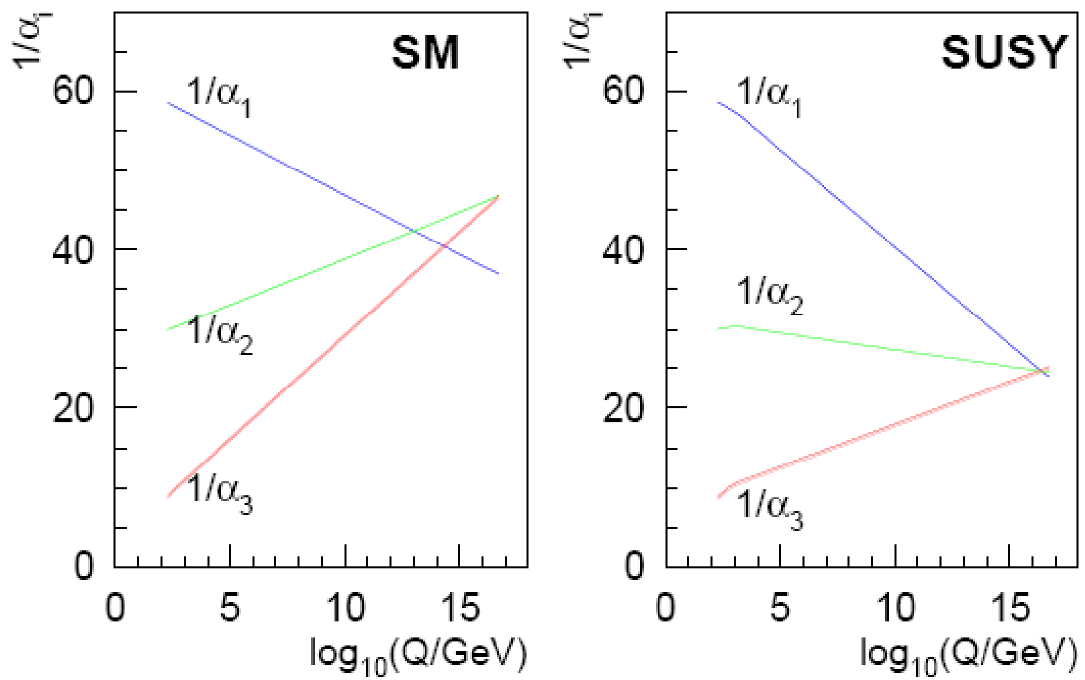
Note 3: The thermally produced particles may decay (rapidly?) to, e.g., gravitons, "Super-WIMPS"

R parity conservation ⇒ Lightest SUSY particle stable ⇒ relic density can be computed from thermal freeze-out in early Universe

Note that a larger annihilation cross section means a smaller relic density.

Supersymmetry

- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Can solve the hierarchy problem
- Gives right scale for neutrino masses
- Predicts light Higgs (< 130 GeV)
- May be detected at LHC
- Gives an excellent dark matter candidate (If R-parity is conserved $\Rightarrow$ stable on cosmological timescales)
- May generate EW symmetry breaking radiatively
- Useful as a template for generic WIMP - Weakly Interacting Massive Particle



The lightest neutralino: probably the most natural WIMP dark matter candidate (H. Goldberg 1983; J. Ellis & al., 1984).

$$\tilde{\chi}^0 = a_1\tilde{\gamma} + a_2\tilde{Z}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

DarkSUSY

P. Gondolo, J. Edsjö, P. Ullio,
L. Bergström, M. Schelke
and E.A. Baltz

Version 5.0 available now
Contributions also from T. Bringmann and G. Duda

- MSSM or mSUGRA
- Masses and couplings
- Relic density
- Lab constraints
- Rates: neutrino telescopes
- Rates: gamma rays
- Rates: antiprotons, positrons, antideuterons
- Rates: direct detection

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

JCAP 06 (2004) 004 [astro-ph/0406204]

DarkSUSY: computing supersymmetric dark-matter properties numerically

P Gondolo[1], J Edsjö[2], P Ullio[3], L Bergström[2], M Schelke[2] and E A Baltz[4]

www.physto.se/~edsjo/darksusy

Uses FeynHiggs, HDecay and Isasugra.
v4.2 will also use galprop and include final state radiation and neutrino oscillations.

The lightest neutralino: the most natural SUSY dark matter candidate

$$\tilde{\chi}^0 = a_1\tilde{\gamma} + a_2\tilde{Z}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

$$\sum_{i=1}^{4} |a_i|^2 = 1;$$

$|a_1|^2 + |a_2|^2 \equiv Z_g$ gaugino fraction

$|a_3|^2 + |a_4|^2 \equiv Z_h \; (= 1 - Z_g)$ higgsino fraction

Neutralinos are Majorana particles (their own antiparticles)

Tree-level annihilation: $\tilde{\chi}^0 + \tilde{\chi}^0 \to f\,\bar{f}, W^+W^-, Z^0Z^0, H_{1,2}^0 H_3^0, \ldots$

$\frac{v}{c} \approx 10^{-3} << 1$ in galactic halos $\Rightarrow$ S-wave should dominate.

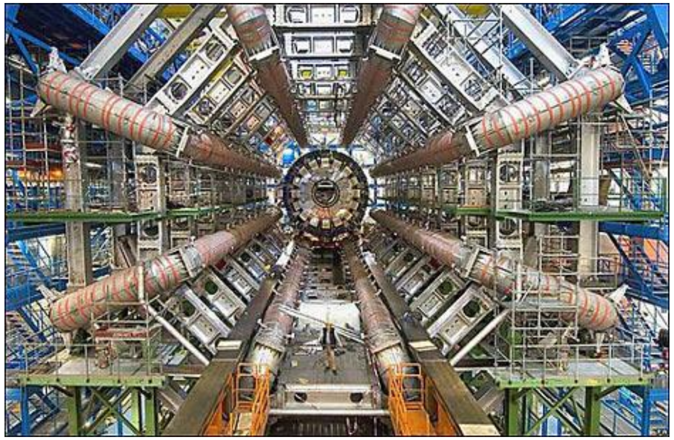
However, due to Majorana property,

$\left(\tilde{\chi}^0\tilde{\chi}^0\right)_{{}^3S}$ is forbidden, and due to helicity

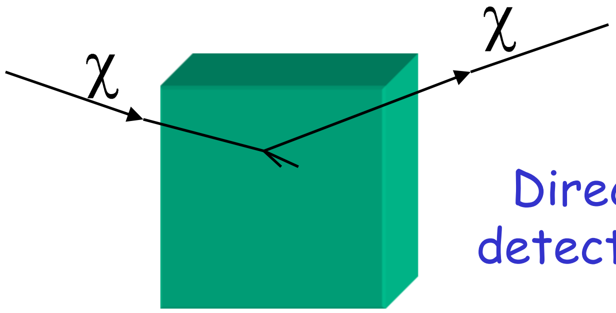
$\left(\tilde{\chi}^0\tilde{\chi}^0\right)_{{}^0S} \to f\bar{f} \propto m_f^2$

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…).
- Direct detection of halo particles in terrestrial detectors.
- Indirect detection of neutrinos, gamma rays & other e.m. waves, antiprotons, positrons in ground- or space-based experiments.
- For a convincing determination of the identity of dark matter, plausibly need detection by at least two different methods.



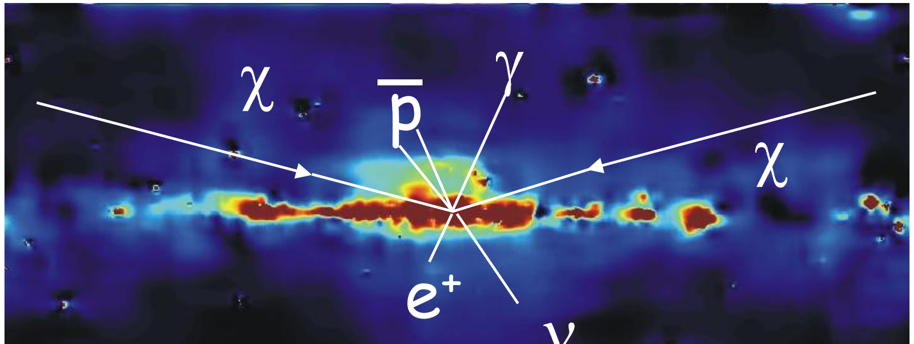
CERN/Atlas



Direct detection

$$\frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 F_A(q) \propto A^2$$

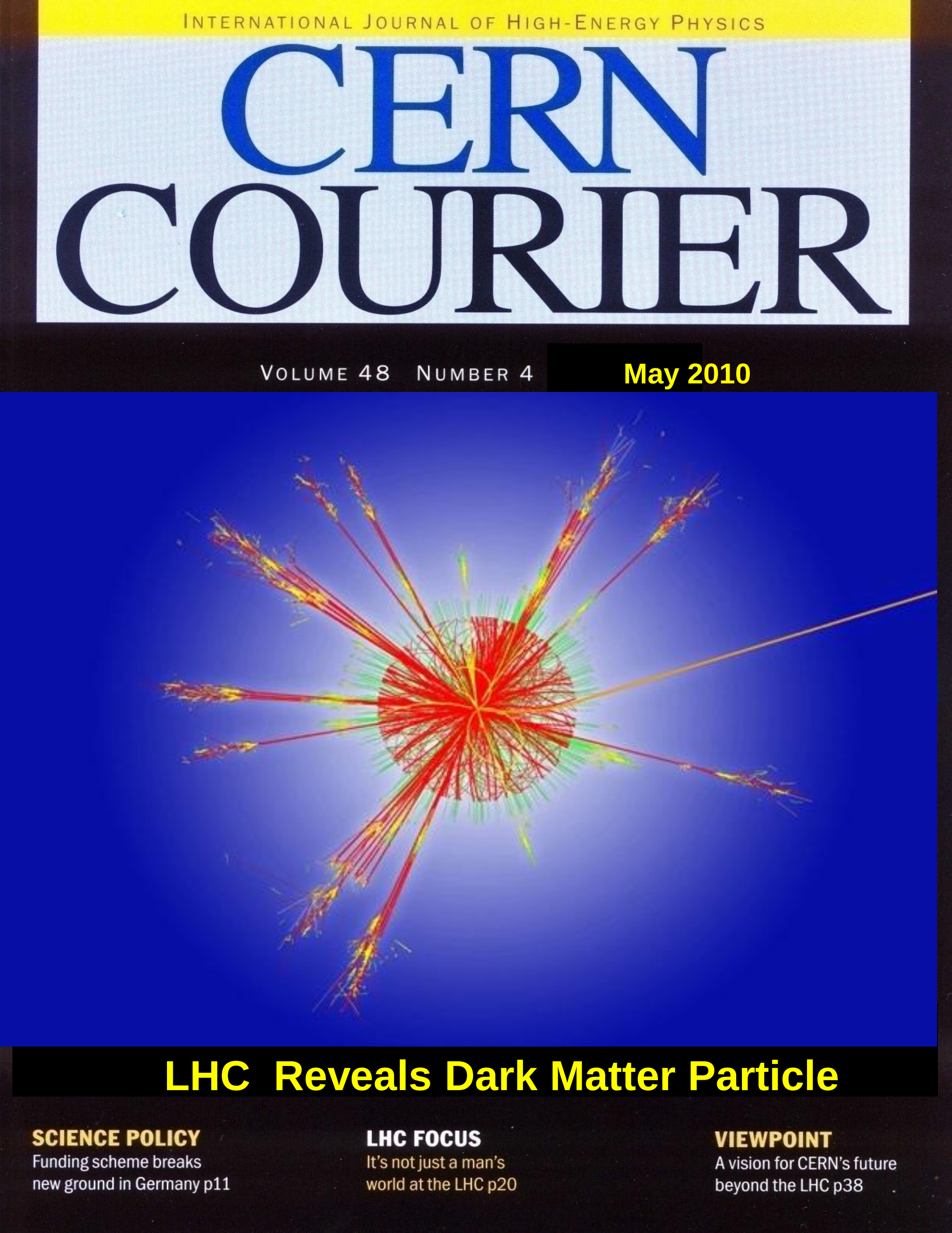
Indirect detection



The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

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

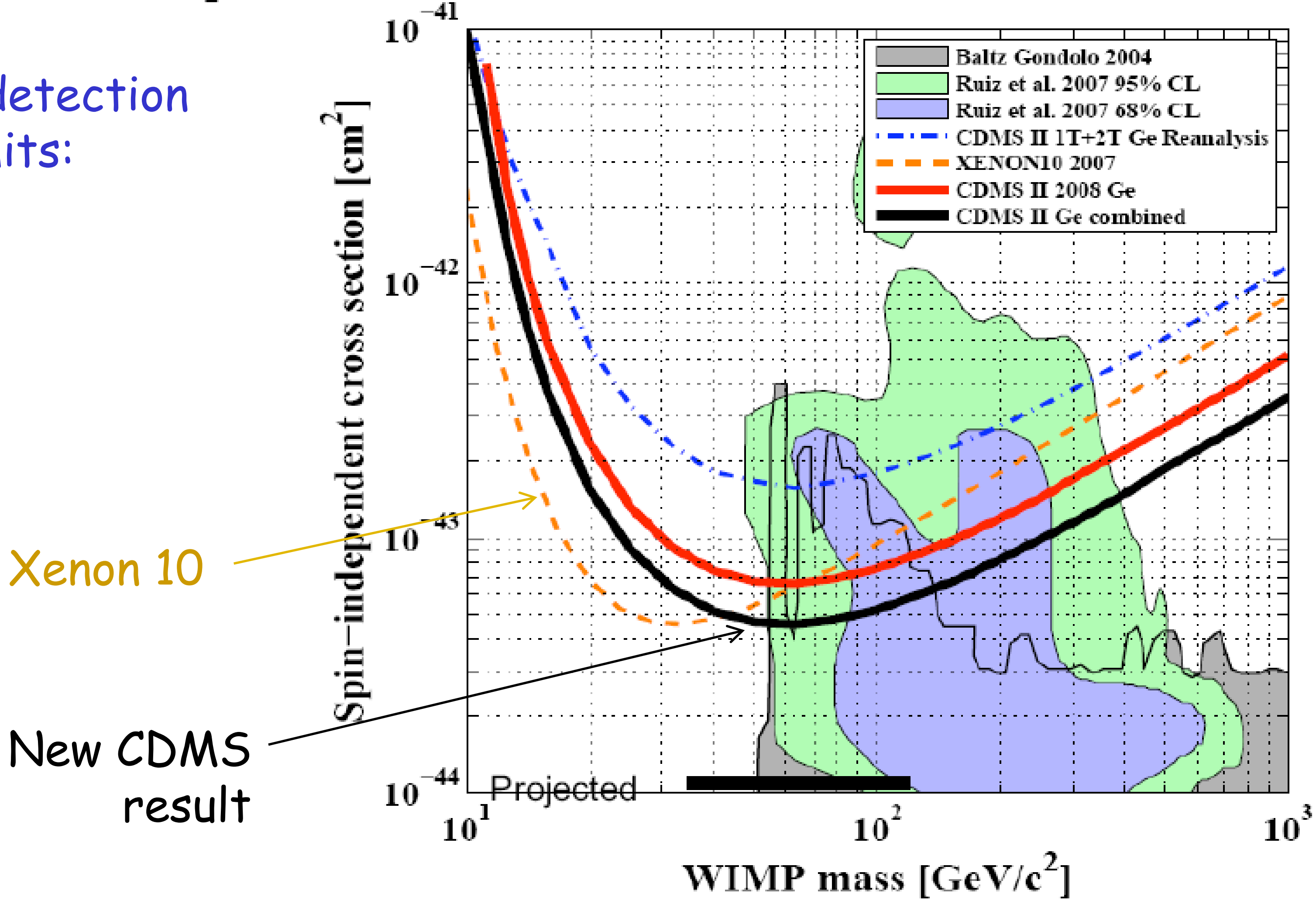
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos



The dream we all hope will come true…

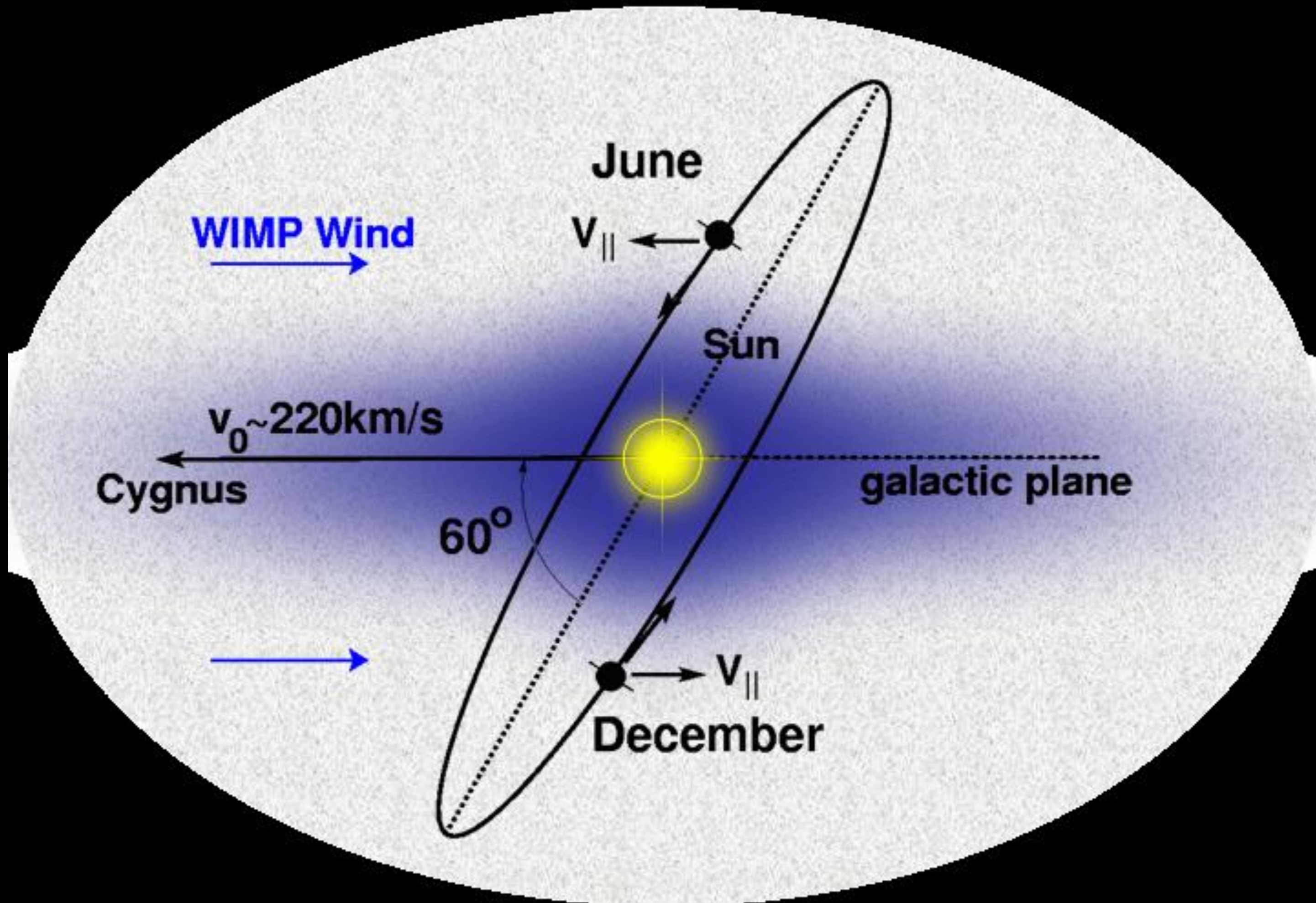
Spin-Independent Exclusion Limit

Direct detection limits:

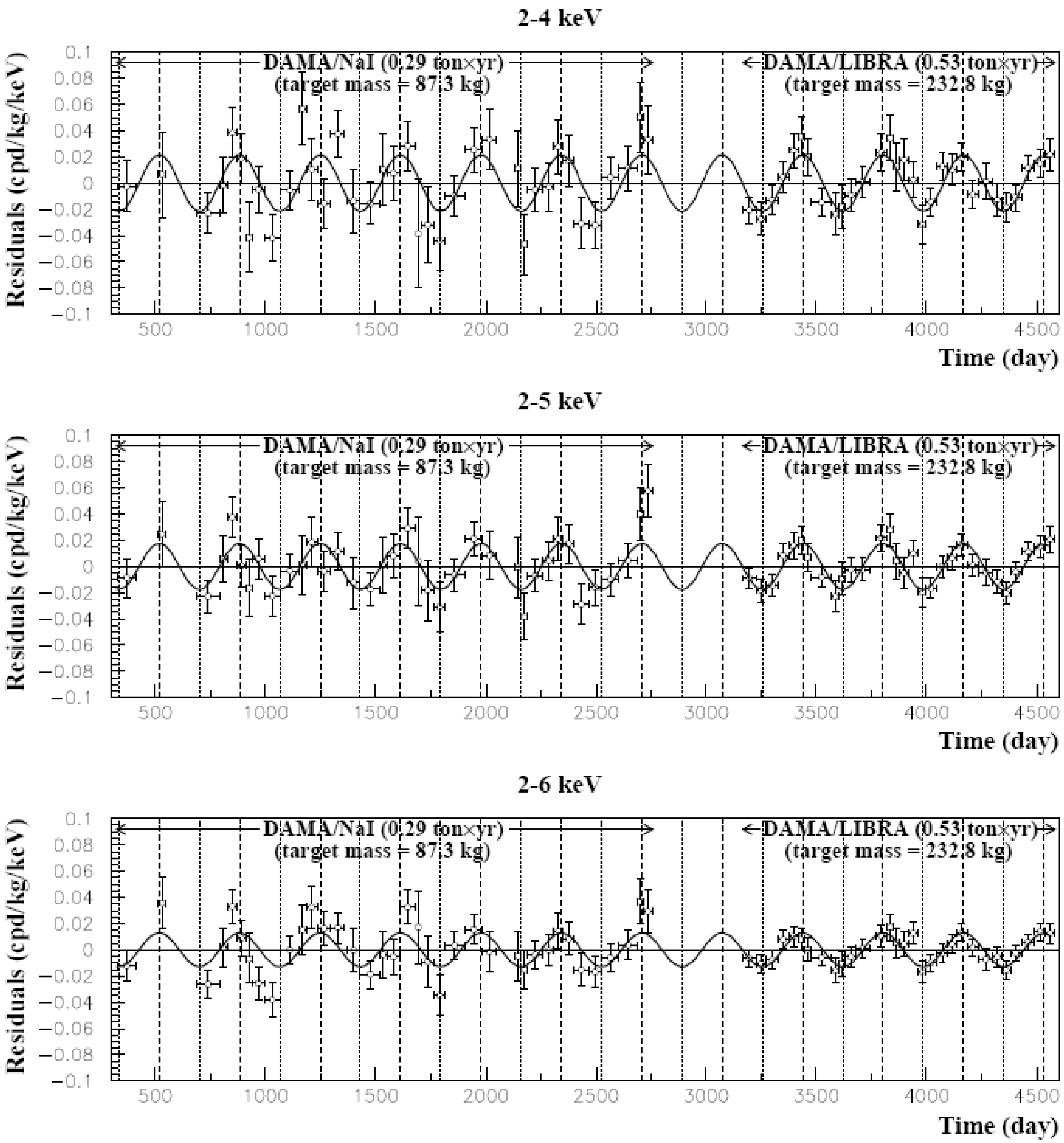


Reanalysis result from 1T+2T Data available in W. Ogburn's (Stanford) Thesis

Caution: Where does DAMA fit in?



Drukier, Freese, Spergel, 1986

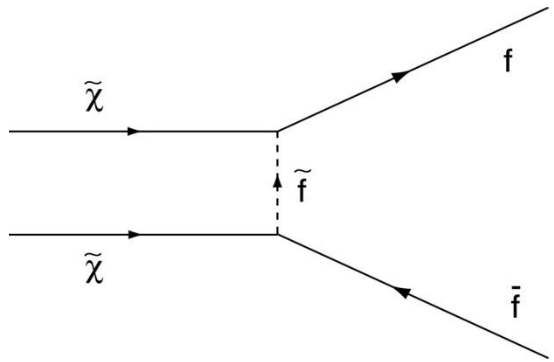


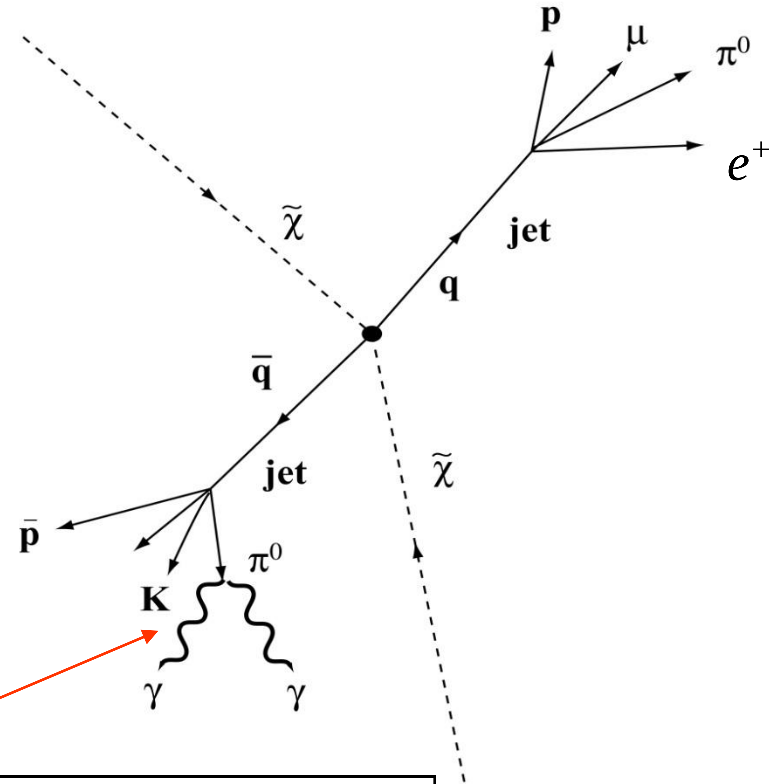
DAMA/LIBRA: Annual modulation of unknown cause. Consistent with dark matter signal (but not confirmed by any other experiment).

Claimed significance: More than 8σ !

What is it? Does not fit in in standard WIMP scenario...

Indirect detection: annihilation of neutralinos in the galactic halo



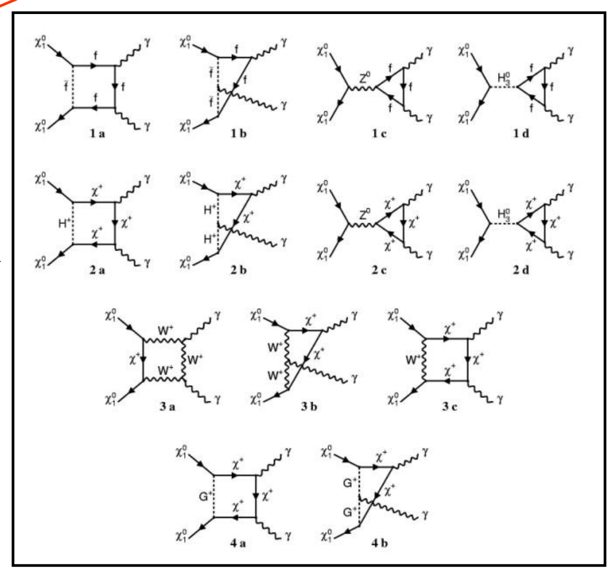


Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

Note: equal amounts of matter and antimatter in annihilations

Decays from neutral pions, kaons etc:
DarkSUSY uses PYTHIA.

One-loop effect: 2γ or $Z\gamma$ final state gives narrow lines



Indirect detection rate = (particle physics part) $\times$ (astrophysical part)

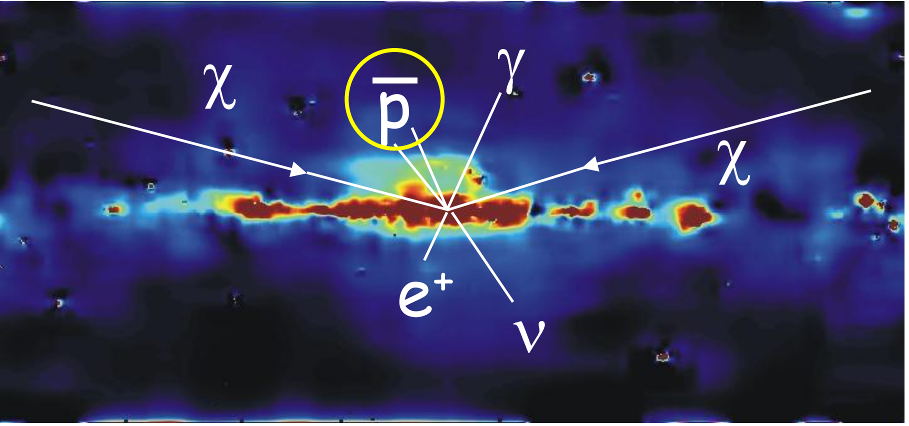
PPP APP

PPP: Model for DM particle (spin, mass); $\langle\sigma v\rangle$ at $v/c \sim 10^{-3}$; branching ratio and energy distribution for a given final state particle. Even for relic abundance fixed by cosmology (e.g., $\Omega h^2 = 0.11$), the yield of a specific final state particle at a specific energy can vary by orders of magnitude.

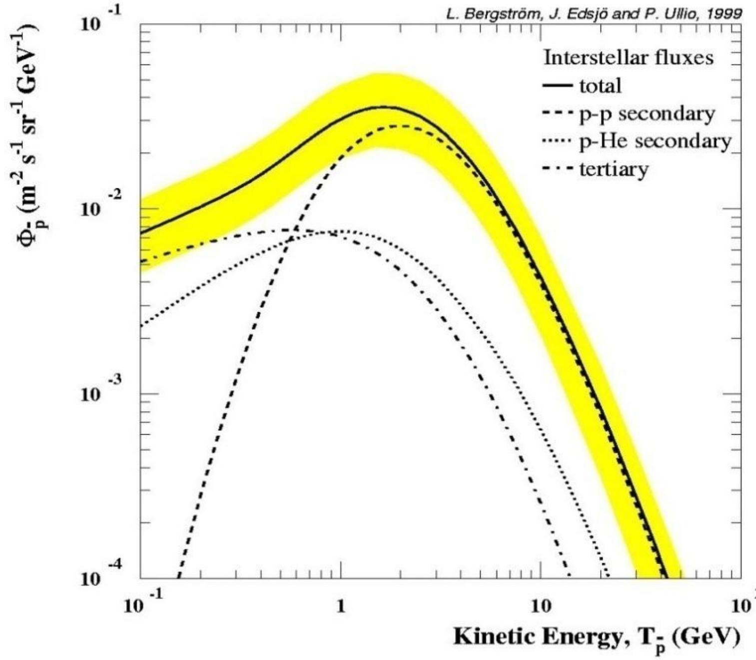
APP: Density of DM particle at production site (halo model and model for subhalos); eventual effects of diffusion and absorption, etc. May give rise to model-dependent predictions which differs by orders of magnitude.

Disclaimer: Unfortunately, no really solid predictions for detection rates can be made; in particular, the absence of a signal cannot directly be converted to a useful limit of particle physics parameters.

If a signal is claimed to be found, one will probably need some distinctive feature, e.g. energy or angular distribution, to be convinced. Also, cross-correlations between different detection methods (direct, indirect, accelerator) will be crucial.



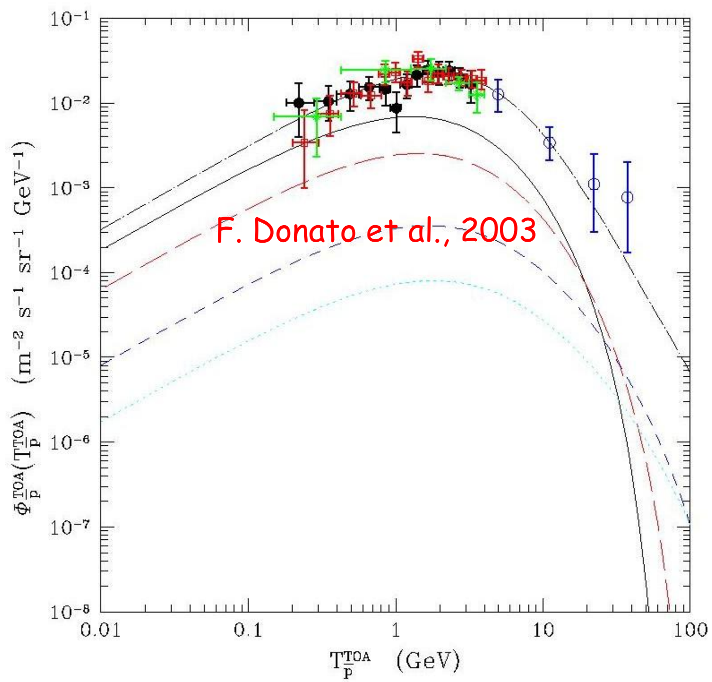
Antiprotons



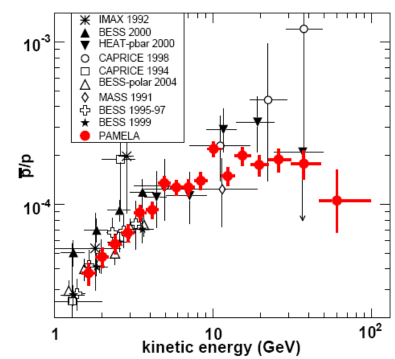
L.B., J. Edsjö and P. Ullio, 2000;
Bieber & Gaisser, 2000

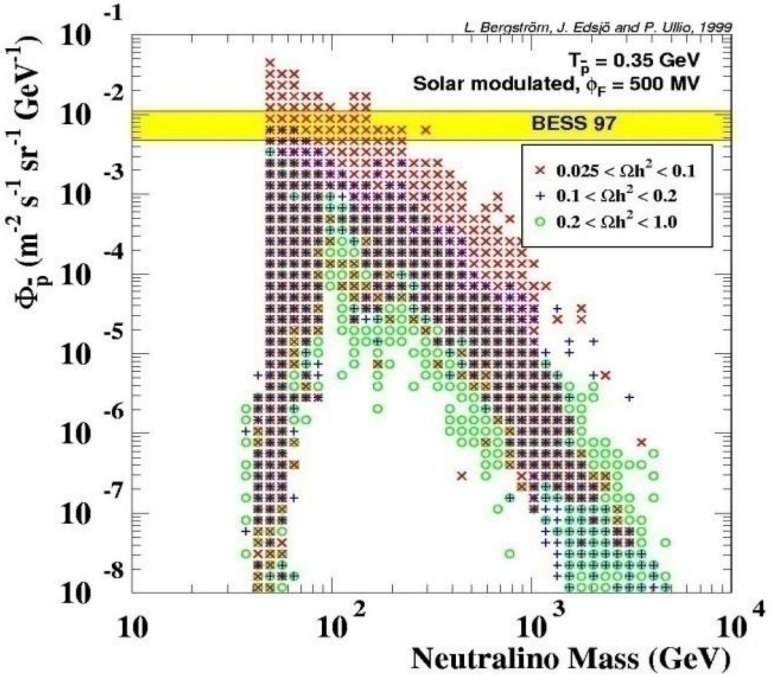
Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

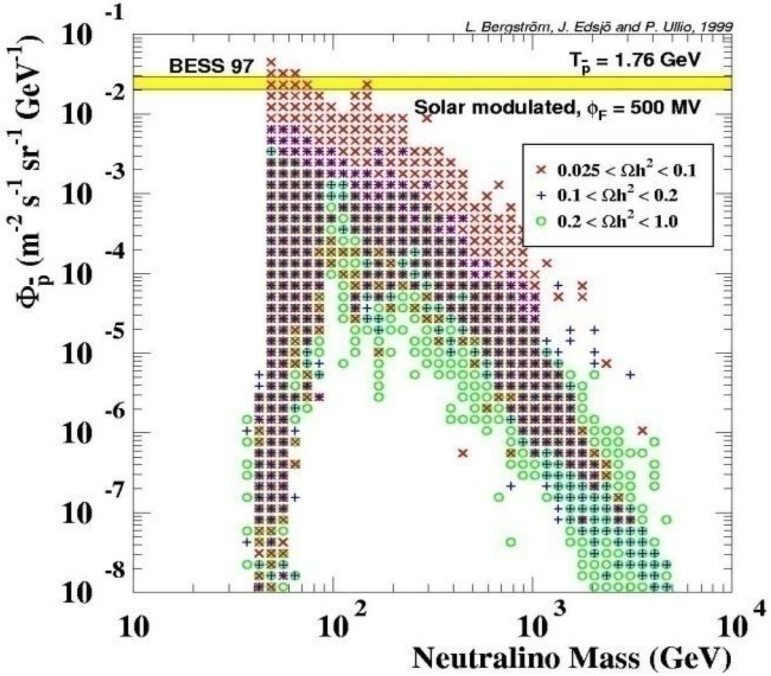
However, p-He reactions and energy losses due to scattering of antiprotons $\Rightarrow$ low-energy gap is filled in. BESS data are compatible with conventional production by cosmic rays.
Antideuterons may be a better signal – but rare? (Donato et al., 2000)



PAMELA 2008

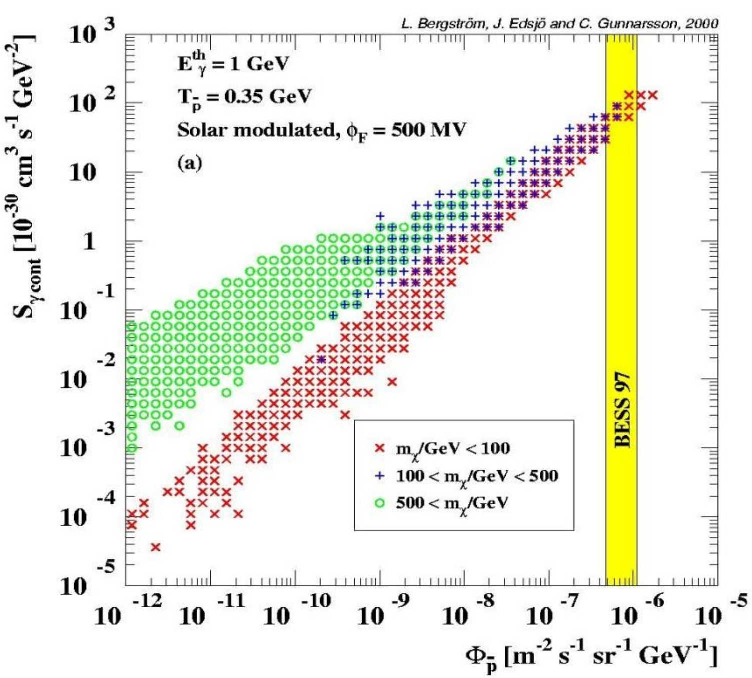


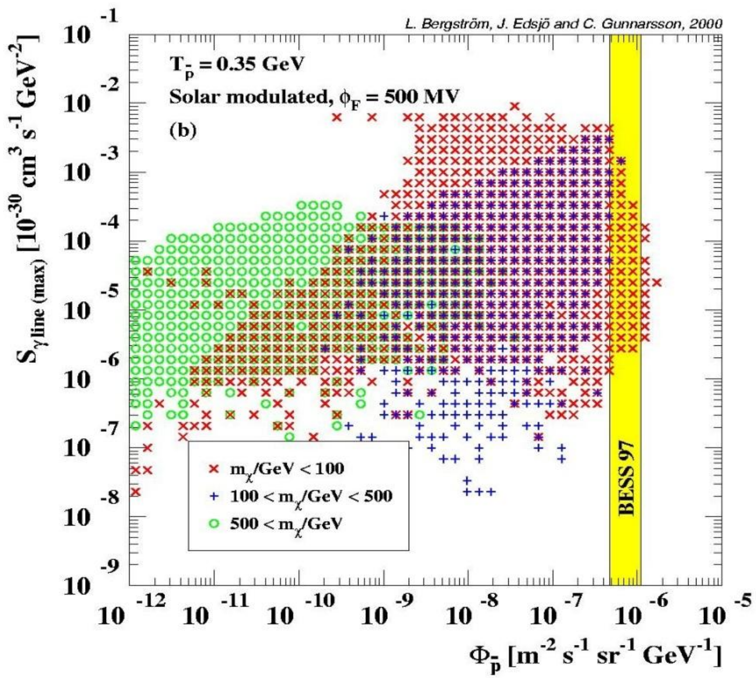




Existing data cuts into MSSM parameter space.

PAMELA will soon publish more data





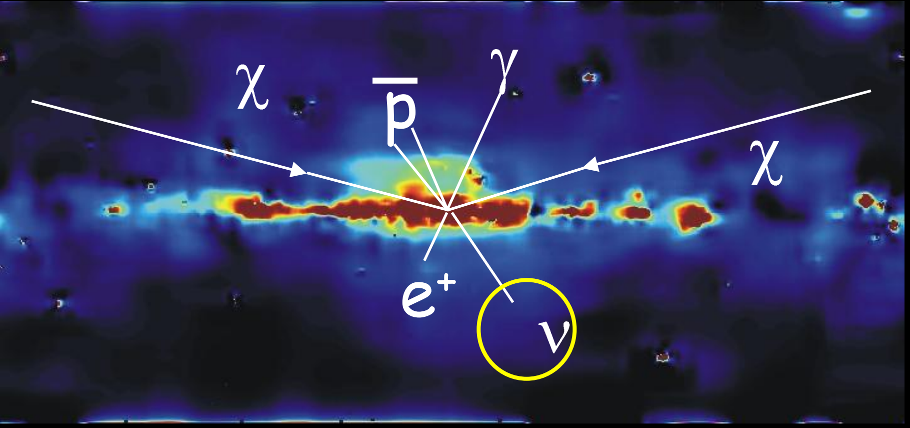
Antiprotons and continuum gamma rays are strongly correlated (through fragmentation of quark jets).

No correlation for lines

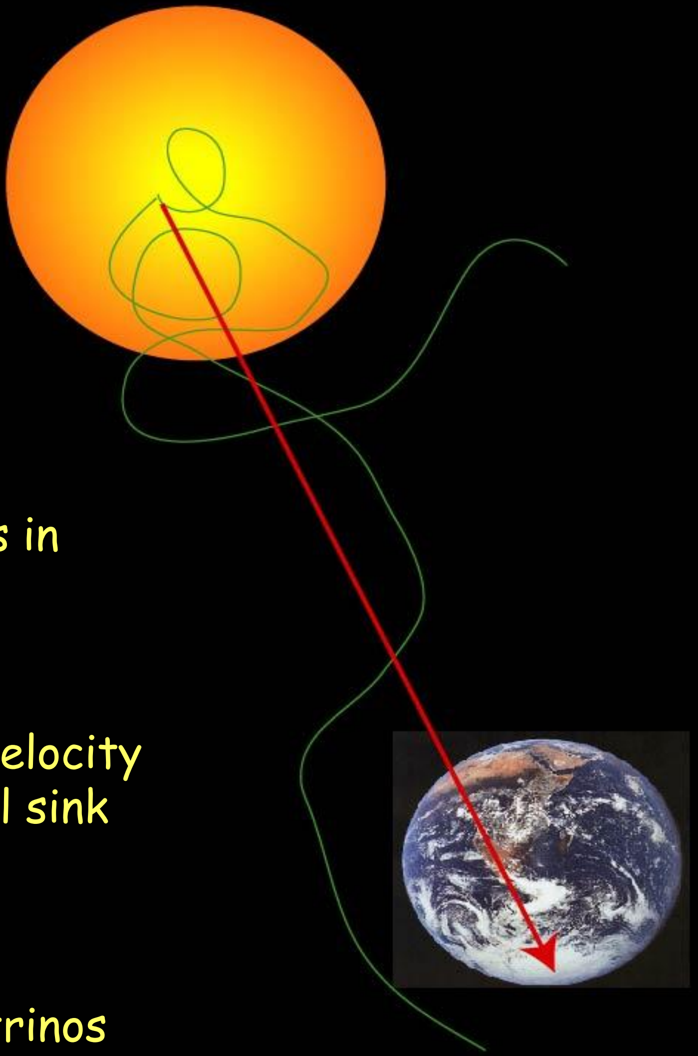
Summary for antiprotons

Measured rate agrees well with standard background estimate (secondary production from cosmic rays interacting with gas and dust in the galaxy). This can be used to set limits on the yield of antiprotons from "exotic" sources like dark matter annihilation.

The production rate for antiprotons in DM annihilation is strongly correlated to the continuum gamma rate.



Neutrinos

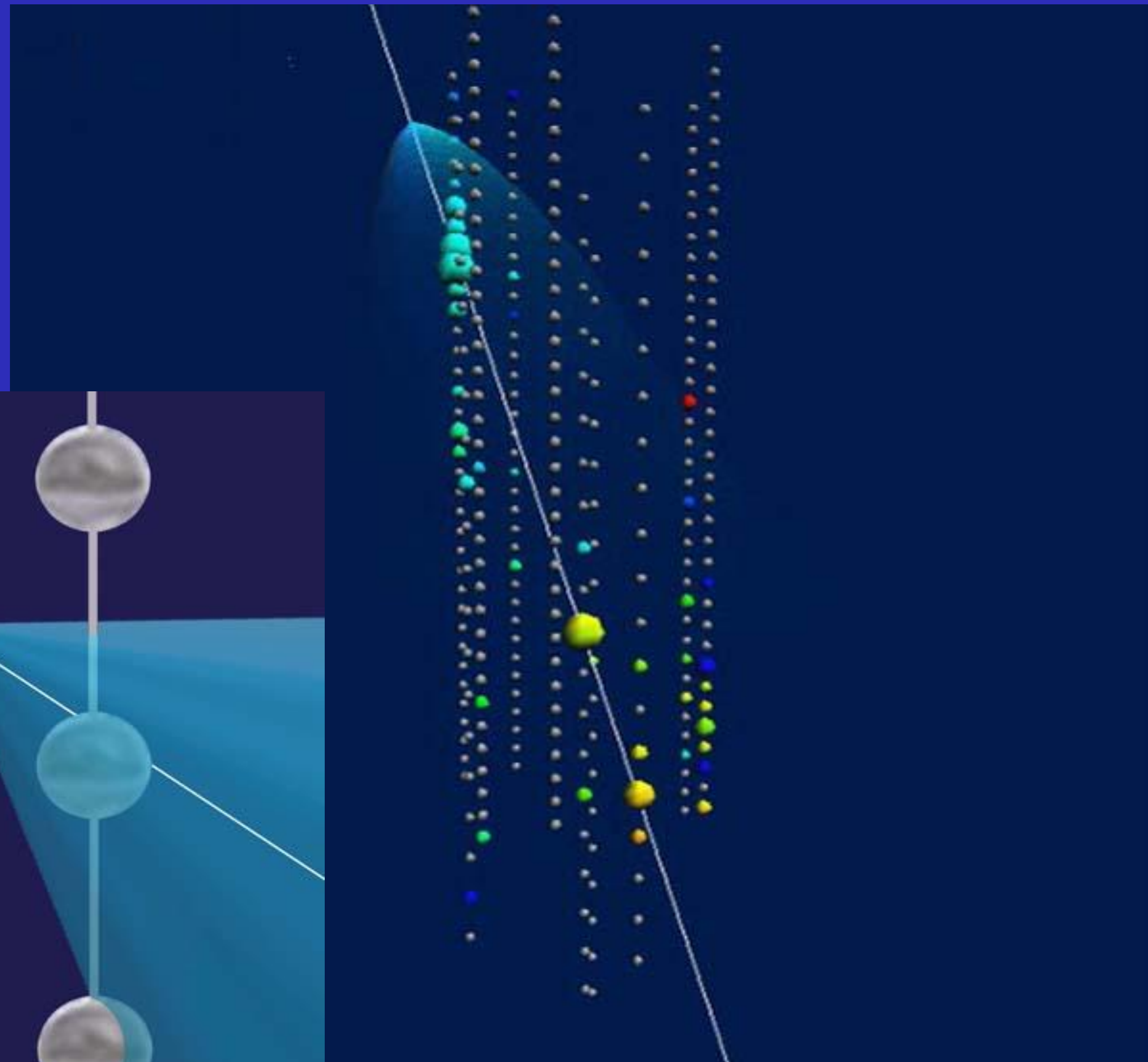


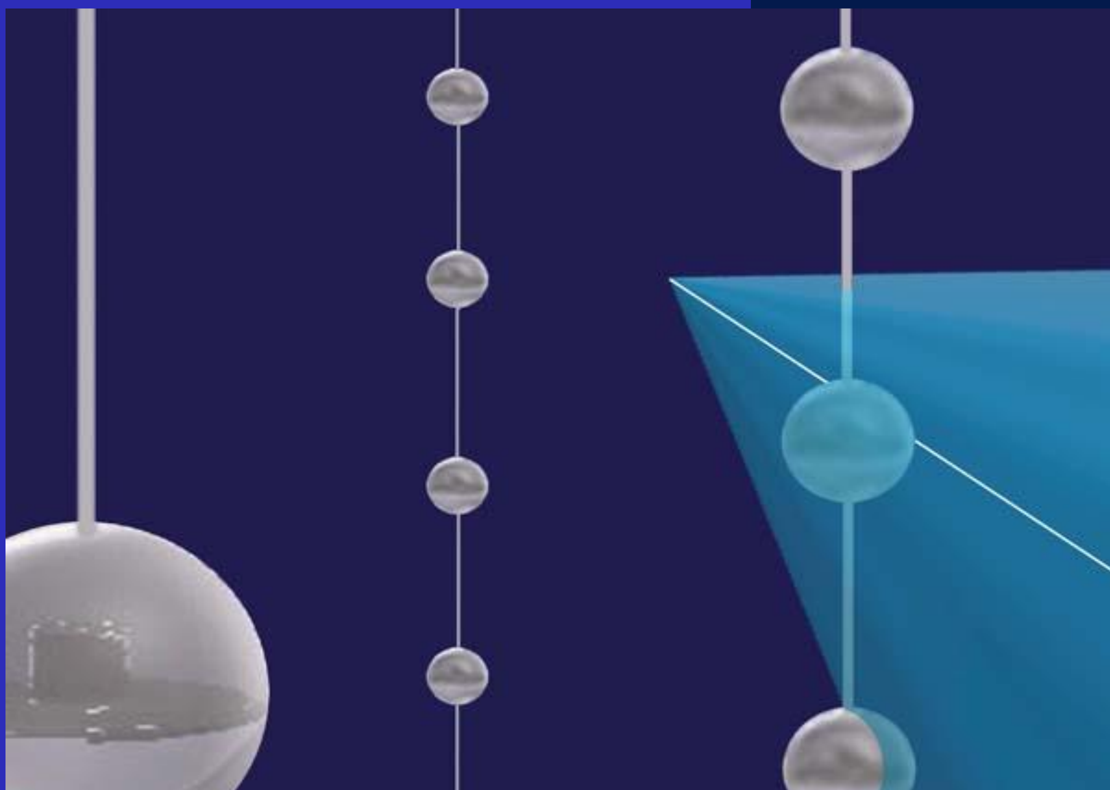
Neutrinos from the center of the Earth or Sun in large neutrino telescopes: IceCUBE at the South Pole, Antares in Mediterranean, KM3…

WIMPs are trapped gravitationally by scattering; when velocity after scattering is below escape velocity, the WIMPs will sink down to the center

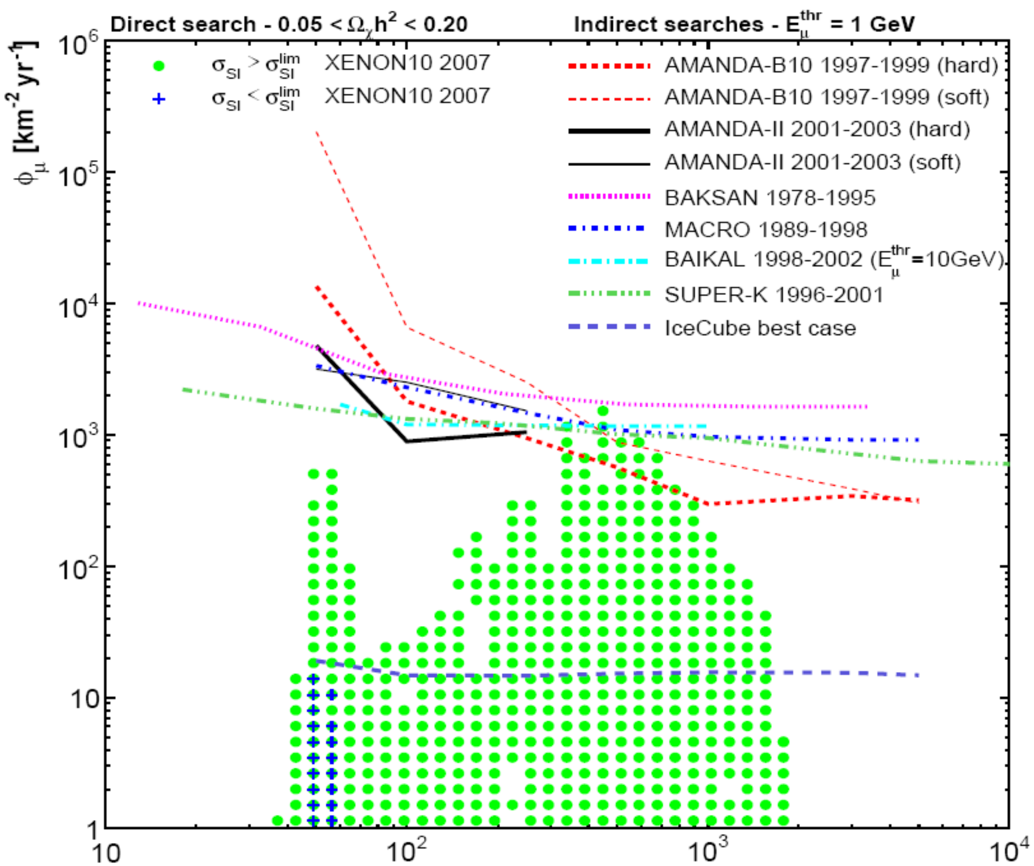
Annihilation rate $\sim\rho^2 \Rightarrow$ Good signature: high energy neutrinos pointing back to the center of the Earth or Sun

IceCube

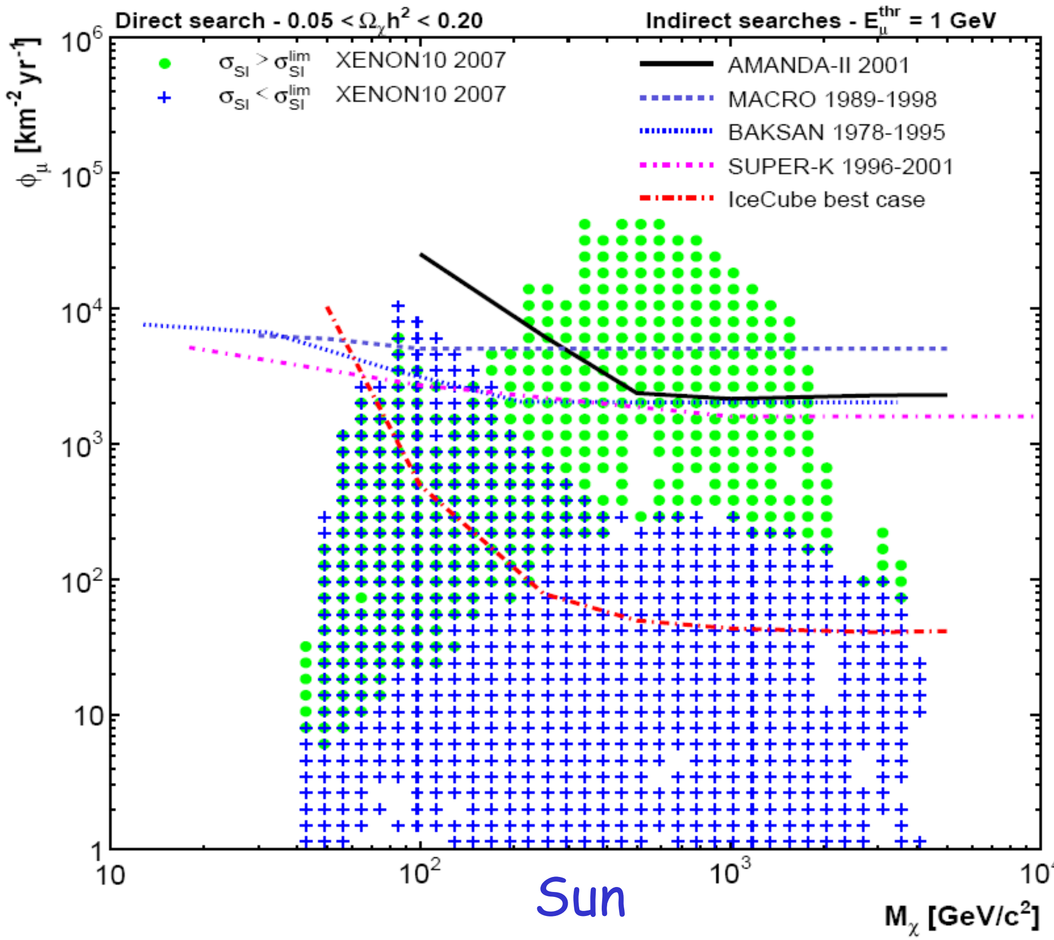




Neutrinos from annihilation in the Earth are probably not detectable, due to stringent bounds on spin-independent direct detection (all heavy elements in the Earth have spin-0). The Sun, however, consists of 70 % protons, which have spin-dependent interactions



Earth



Sun

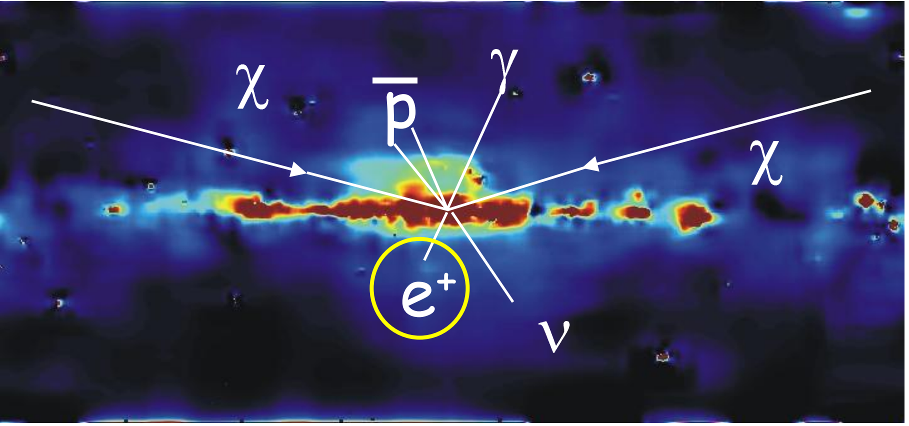
J. Edsjö, 2007

Rates computed with DarkSUSY

Summary for neutrinos

Can not be detected from annihilation in the halo (the interaction rate of neutrinos are too small), except perhaps in the case of an extreme concentration of DM (a "spike") near the black hole at the galactic center.

However, gravitational trapping of DM in the Sun may give a signal with a striking signature. The Earth seems less promising due to the strong limits now coming from direct detection.



Positrons

The Astrophysical part for positrons has some uncertainty (faster energy loss than antiprotons): Diffusion equation (see, e.g., Baltz and Edsjö, 1999):

$$\frac{\partial}{\partial t} f_{e^+}(E,\vec{r}) = K(E)\nabla^2 f_{e^+}(E,\vec{r}) + \frac{\partial}{\partial E}\left[b(E) f_{e^+}(E,\vec{r})\right] + Q(E,\vec{r})$$

Energy-dependent diffusion coefficient

Energy loss (mostly synchrotron and Inverse Compton)

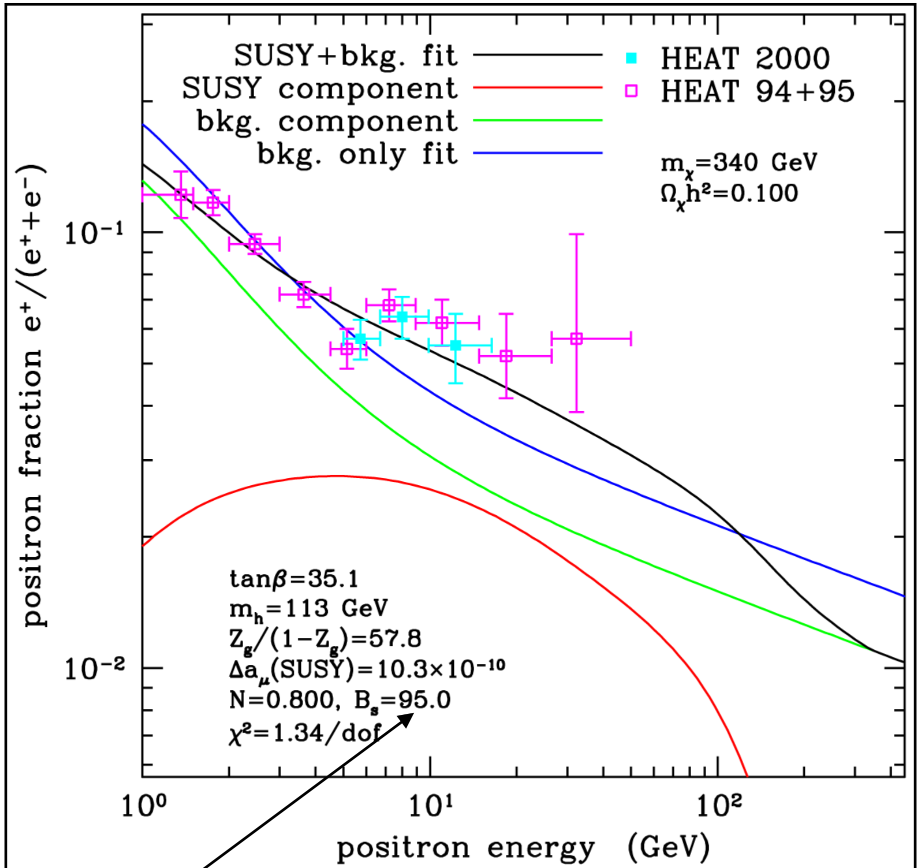
Source term (from annihilation)

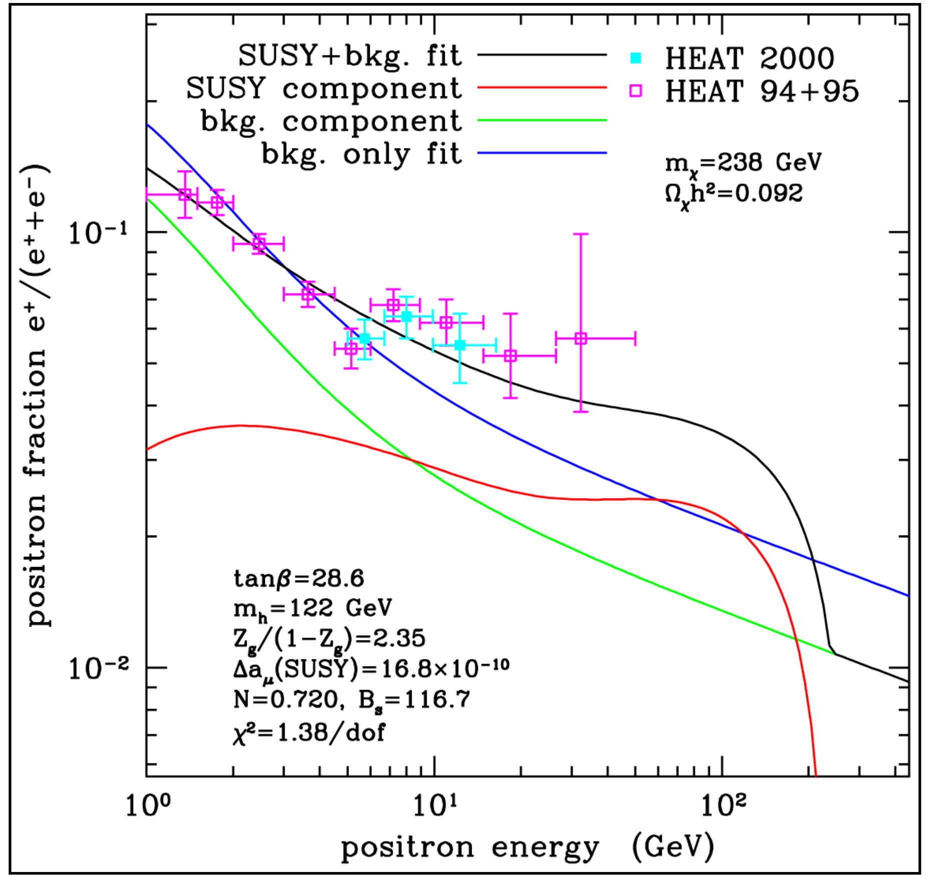
$$b(E) \;=\; 10^{-16}(E/1\ \mathrm{GeV})^2 \quad (\mathrm{GeV s^{-1}})$$

$$K(E) \;=\; 3.3\times 10^{27}\left[3^{0.6} + (E/1\ \mathrm{GeV})^{0.6}\right] \quad (\mathrm{cm^2 s^{-1}})$$

Positrons from neutralino annihilations – explanation of feature, "HEAT bump", at 10 – 30 GeV?

New experiments are coming: PAMELA (launched 2006, preliminary data 2008), AMS (?)





Need high "boost factor"

Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002; Hooper & Kribs, 2004; Hooper & Silk, 2004,...

Positrons from neutralino annihilations – explanation of feature, "HEAT bump", at 10 – 30 GeV?

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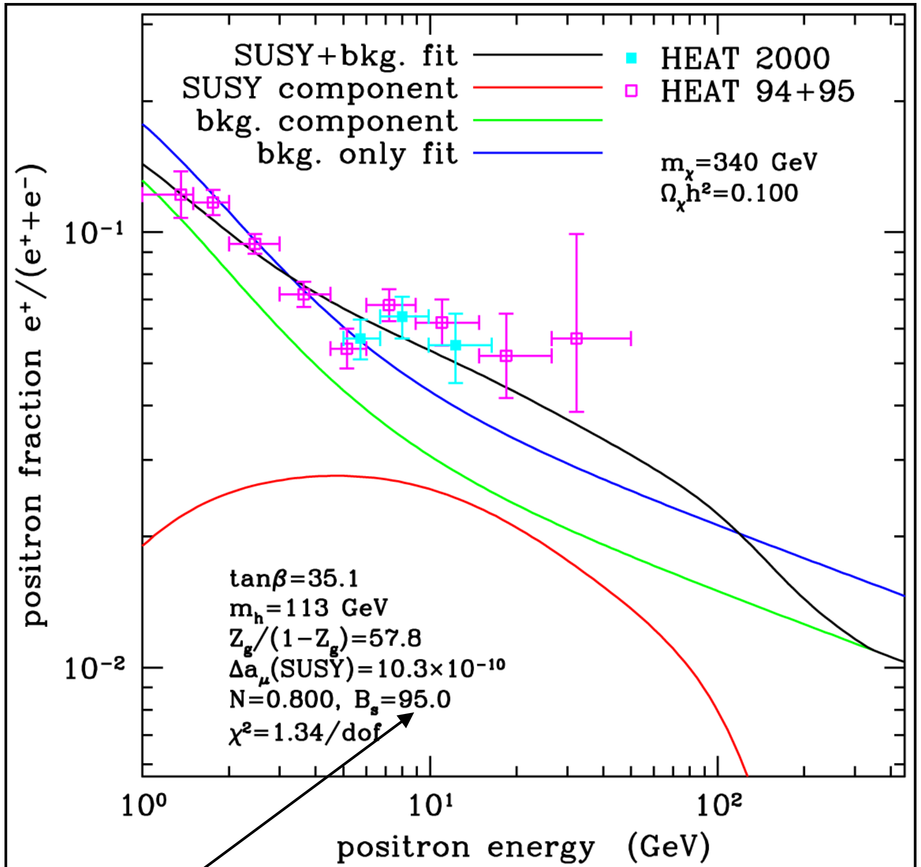

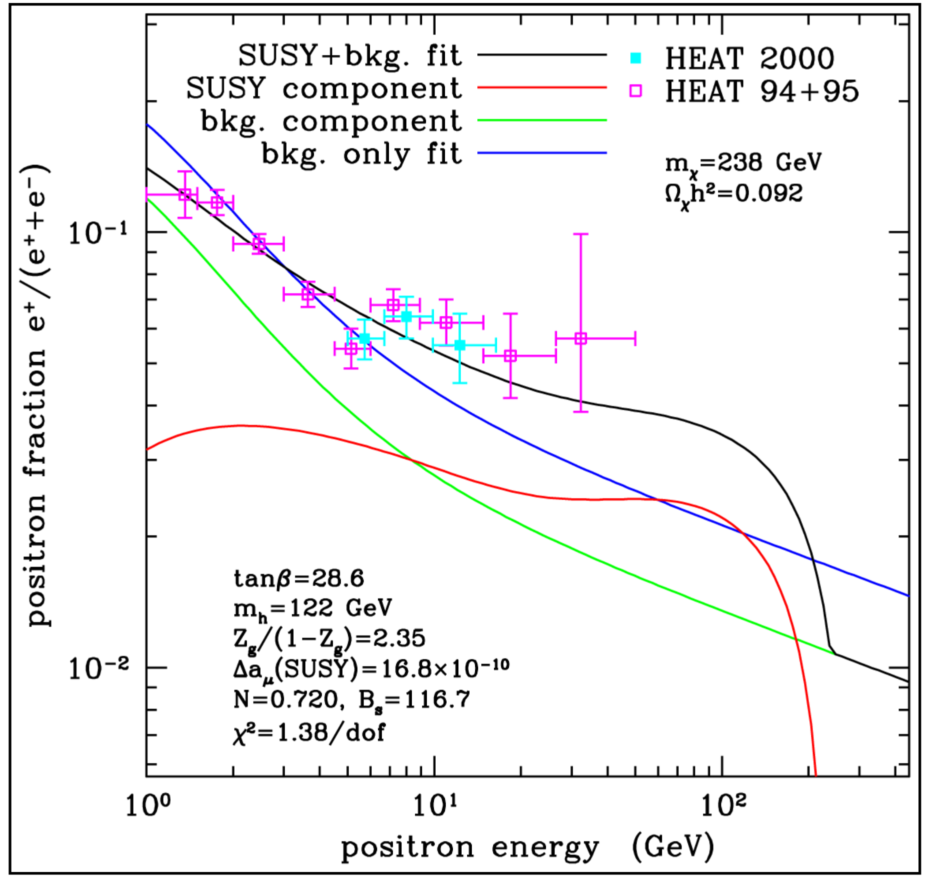

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Dark Matter and its Detection - II

Lars Bergström
Department of Physics
Stockholm University
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UniverseNet

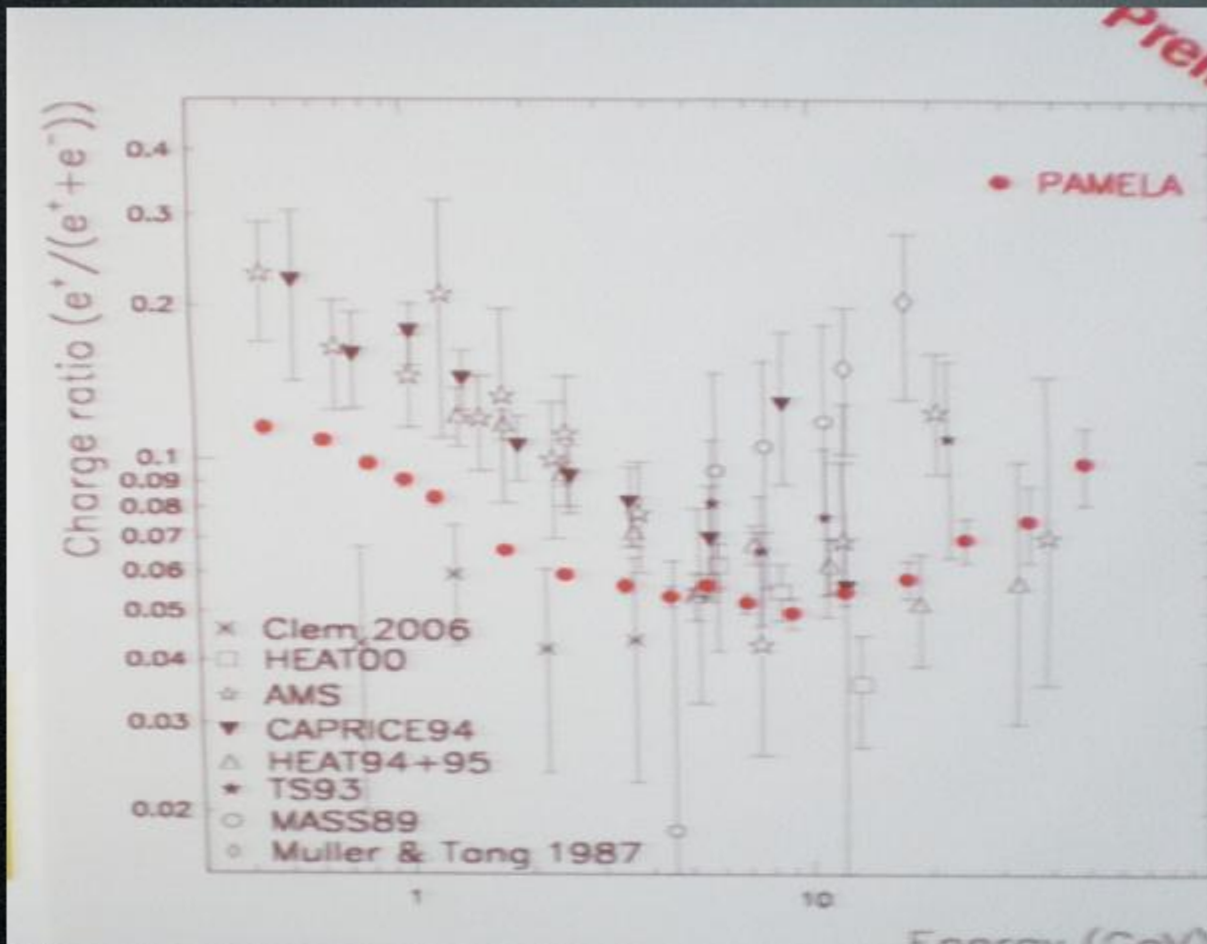
The second network school and meeting

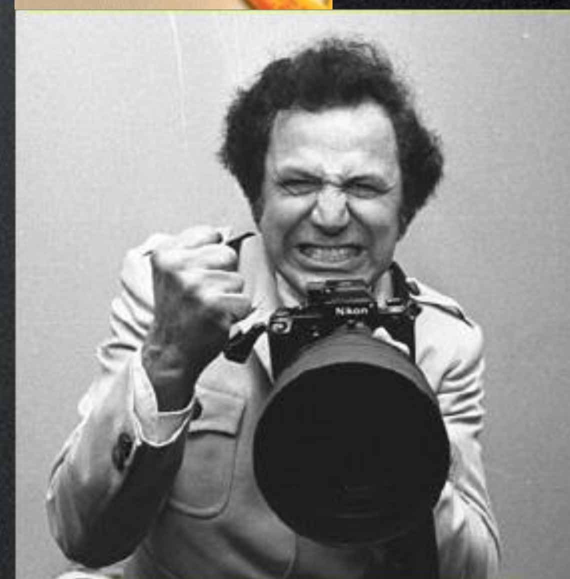
Oxford, UK

22 to 26 September 2008

From M. Cirelli, idm2008
Stockholm talk

Need to catch PAMELA when she is exposed.





Physicists aflutter about data photographed at conference

Nature, August 28, 2008

When is data public?

An Italian-led research group's closely held data have been outed by paparazzi physicists, who photographed conference slides and then used the data in their own publications.

For weeks, the physics community has been buzzing with the latest results on 'dark matter' from a European satellite mission known as PAMELA (Payload for Antimatter Matter Exploration and Light-

Matter conference in Stockholm, Sweden.

"We had our digital cameras ready," says Marco Cirelli, a theorist at the Institute of Theoretical Physics in Gif-sur-Yvette, France, and one of those who took pictures. The preprints fully acknowledge the source of the data and reference the presentation photographed.

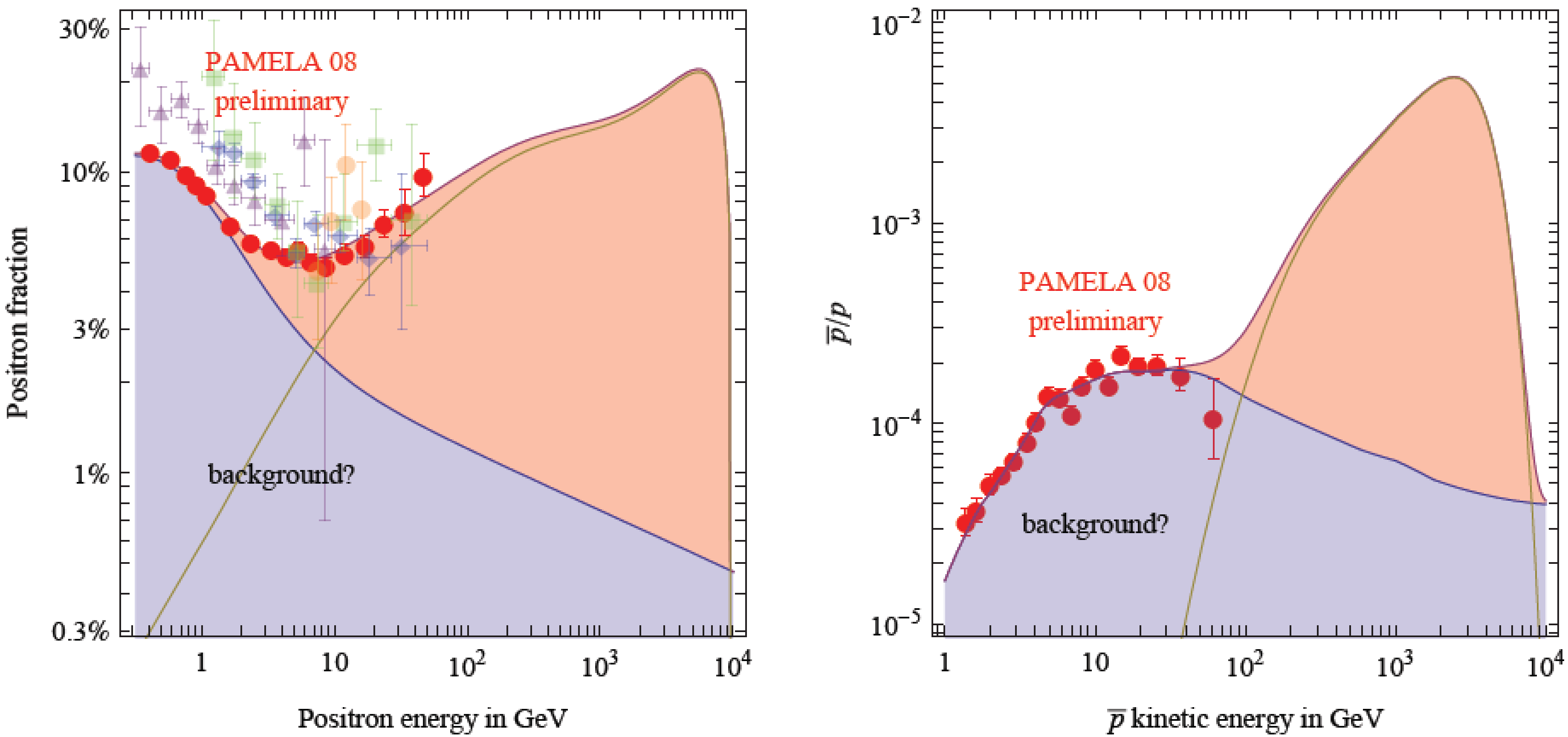
PAMELA has been attracting such interest because it has reportedly seen an excess of high-energy positrons in space. Those positrons could stem from the collision and annihilation of dark-matter particles, which could make up most of the mass of the Universe. If the data hold up, they would be the most direct clue yet to

conference presentations is common in some fields, such as biology, but is relatively rare in physics. Falkowski says he can't recall another case. Still, he says, "I personally don't find anything wrong with it." ■

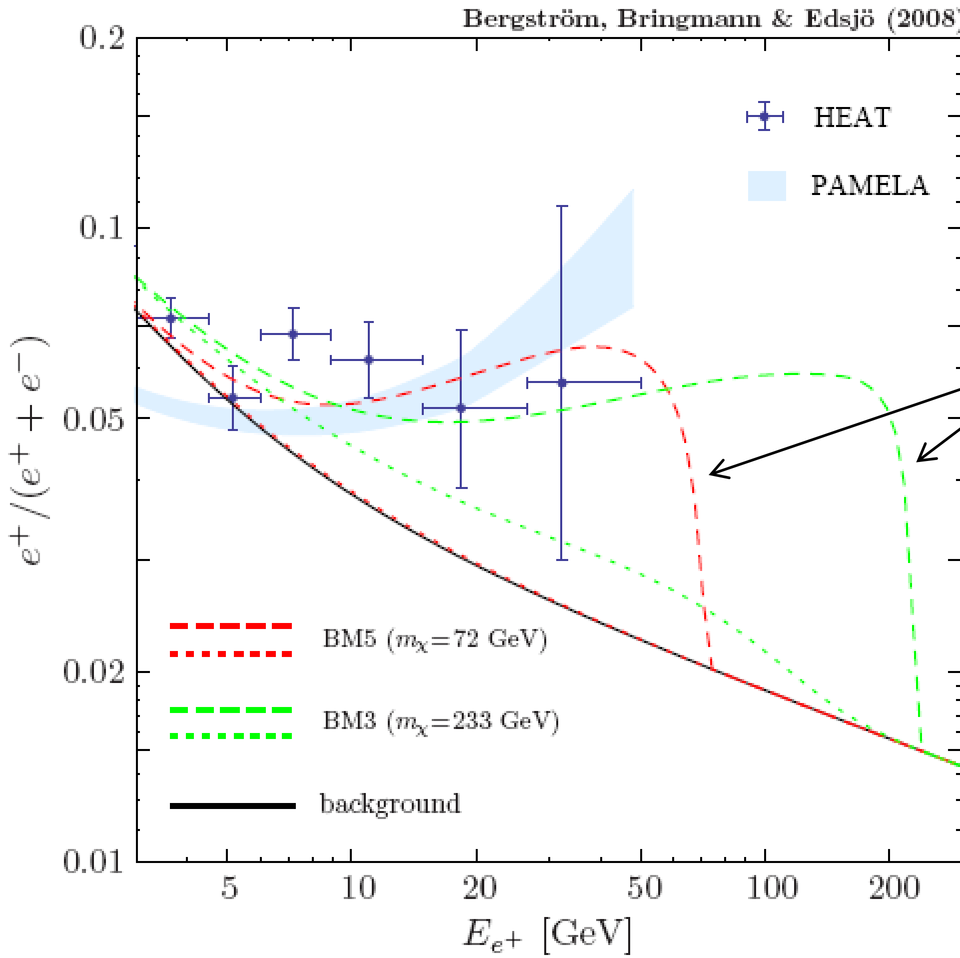
Geoff Brumfiel

Is this the right place for digital cameras?

F.CHMURA/ALAMY



M. Cirelli and A. Strumia, 2008



Curves for radiatively corrected neutralino annihilation (more about that later)

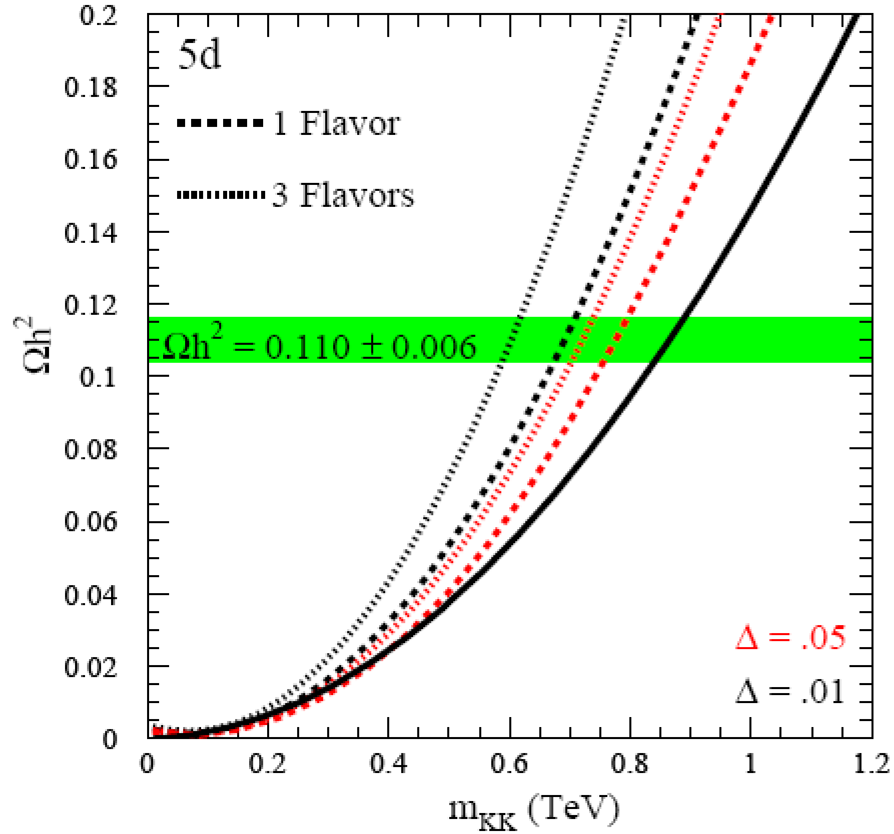
Huge "boost factor" needed: DM interpretation not very likely (?)

L.B., T. Bringmann and J. Edsjö, 2008

Other model: Kaluza-Klein (KK) dark matter in Universal Extra Dimensions

Universal Extra Dimensions (Appelquist & al, 2002):

- All Standard Model fields propagate in the bulk → in effective 4D theory, each field has a KK tower of massive states
- Unwanted d.o.f. at zero level disappear due to orbifold compactification, e.g., S^1/Z_2 , $y \leftrightarrow -y$
- KK parity $(-1)^n$ conservation → lightest KK particle (LKP) is stable → possible dark matter candidate
- One loop calculation (Cheng & al, 2002): LKP is $B^{(1)}$.
- Difference from SUSY: spin 1 WIMP → no helicity suppression of fermions



Servant & Tait, 2003

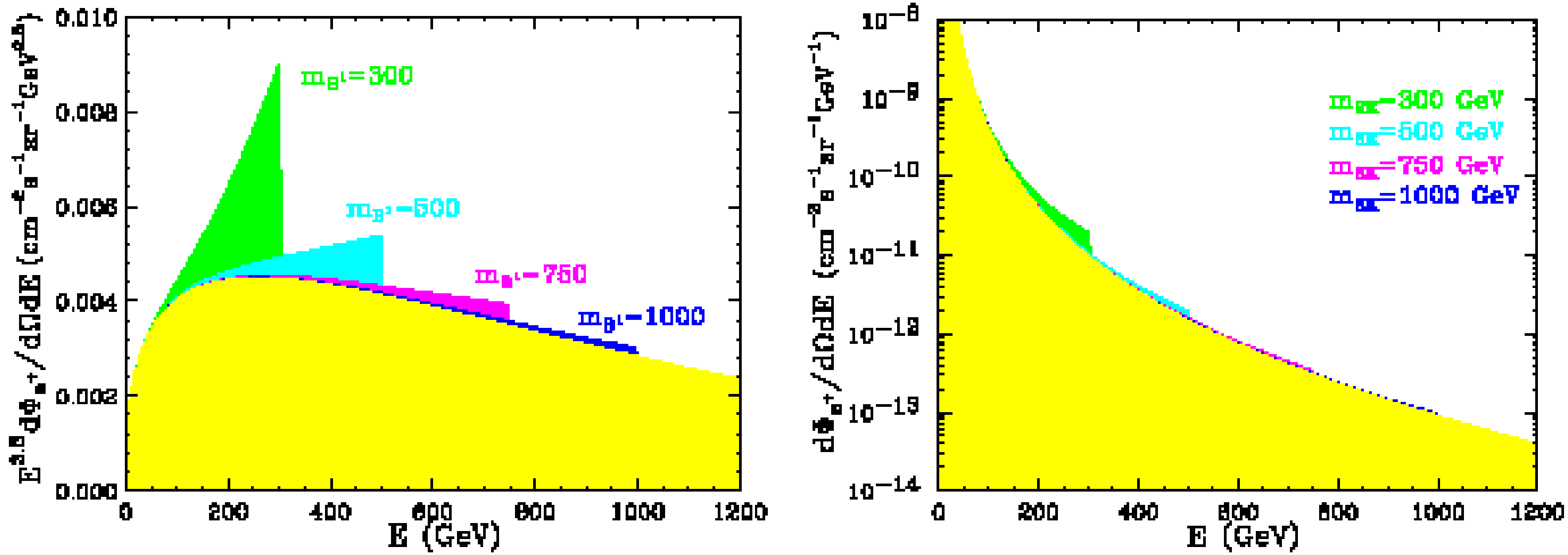
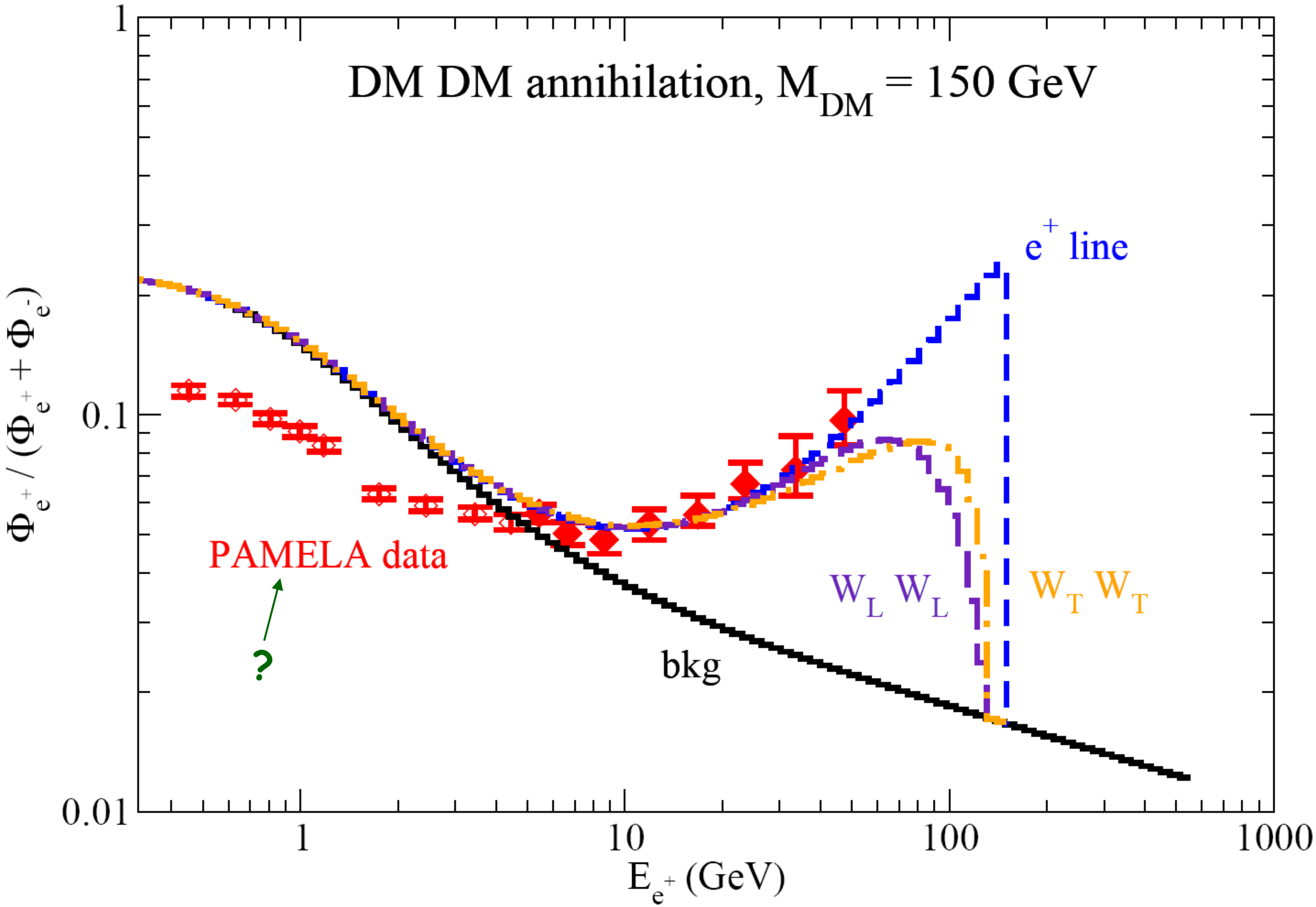


Figure 3. Positron spectra from B^1 dark matter annihilation for various B^1 masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor E^3 in the left panel.

Positrons (Cheng, Feng & Matchev, 2003)



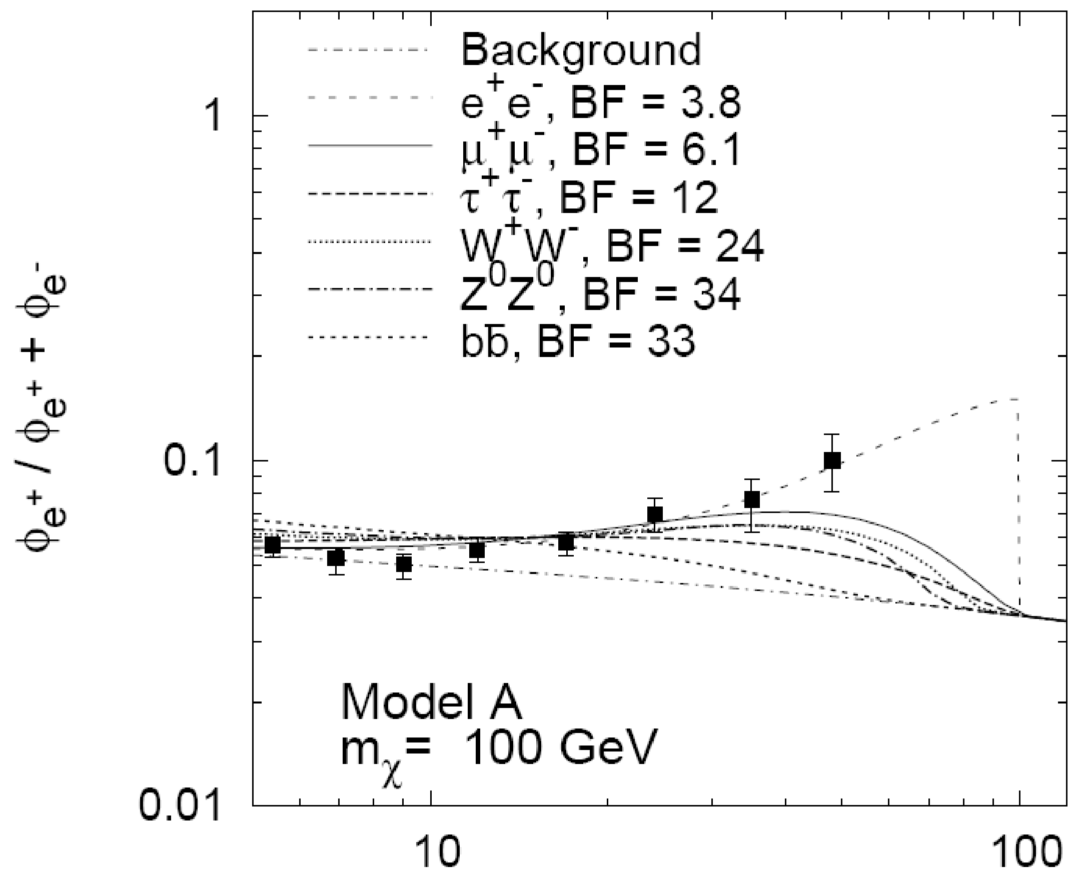
Barger, Keung, Marfatia, Shaughnessy, 2008

High Energy Positrons From Annihilating Dark Matter

Ilias Cholis,[1] Lisa Goodenough,[1] Dan Hooper,[2,3] Melanie Simet,[3,2] and Neal Weiner[1]

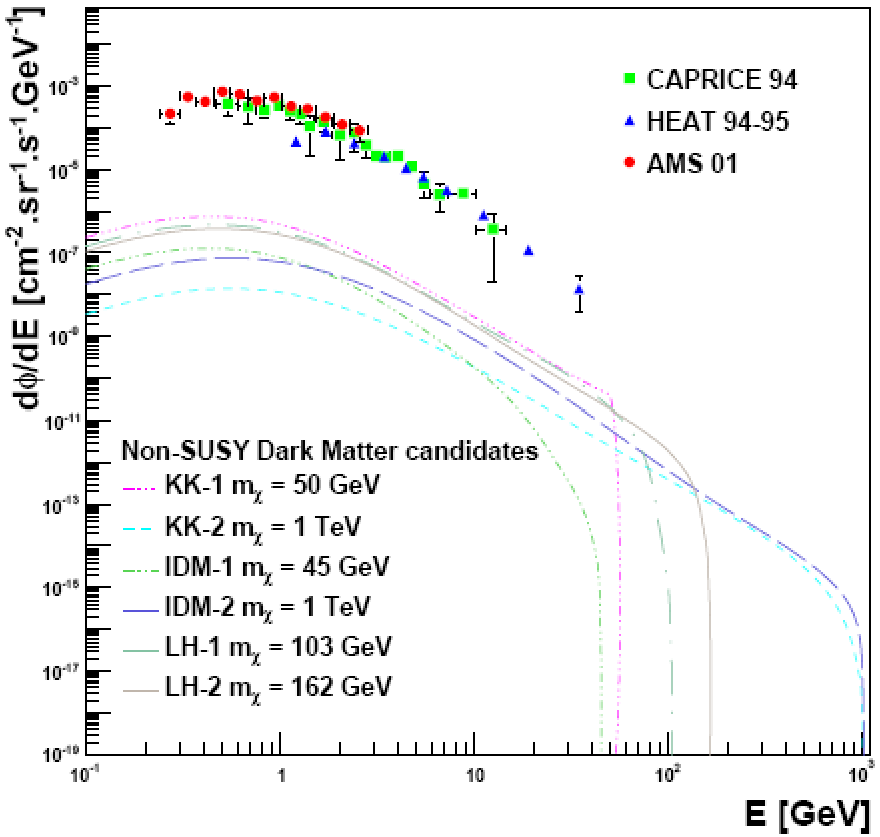
Large boost factors needed:

		Model A		Model B		Model C	
Mass	Mode	χ^2/df	BF	χ^2/df	BF	χ^2/df	BF
100	e^+e^-	0.152	3.8	1.459	23	0.555	2.4
100	$\mu^+\mu^-$	1.028	6.1	0.175	25	1.577	4.3
100	$\tau^+\tau^-$	2.893	12	2.019	45	3.224	9.0
100	W^+W^-	1.758	24	0.728	91	2.259	17
100	ZZ	1.921	34	1.139	100	2.413	24
100	$b\bar{b}$	5.154	33	4.692	100	5.107	24
300	e^+e^-	0.182	32	1.132	430	0.439	18
300	$\mu^+\mu^-$	0.186	44	0.475	250	0.532	29
300	$\tau^+\tau^-$	1.131	57	0.387	240	1.586	39
300	W^+W^-	2.598	66	2.483	240	2.781	47
300	ZZ	3.126	74	2.993	250	3.256	53
300	$b\bar{b}$	4.133	57	3.735	180	4.216	42
1000	e^+e^-	0.106	310	1.533	6300	0.210	170
1000	$\mu^+\mu^-$	0.128	450	0.902	4200	0.339	270
1000	$\tau^+\tau^-$	0.333	430	0.118	2400	0.693	280
1000	W^+W^-	2.243	210	1.757	820	2.515	150
1000	ZZ	2.552	210	2.055	770	2.809	150
1000	$b\bar{b}$	2.877	160	2.270	570	3.141	110



arXiv:0809.1683

cf. Lavalle & al., arXiv:0808.0332



It is *very* difficult to get a detectable signal in realistic halo models

Summary for positrons:

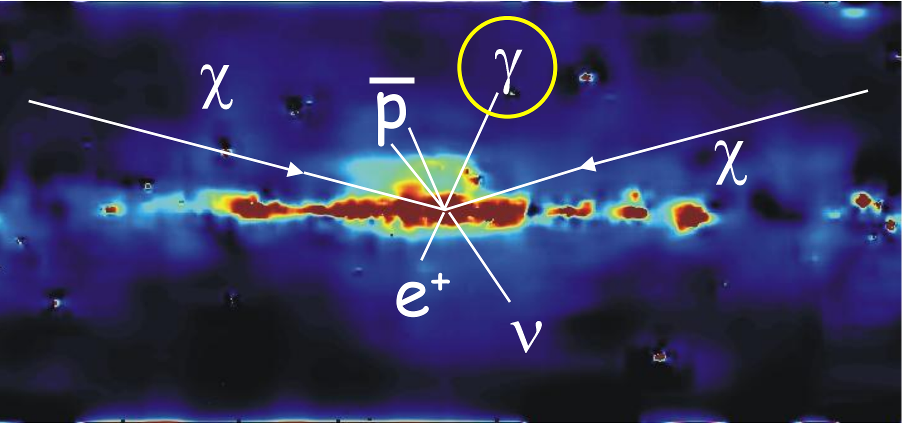
The advantage compared to gamma-rays is that generated positrons are stored in the galaxy for millions of years. However, the diffusion also erases all spatial and much of the spectral information.

Some non-SUSY models of dark matter give a strong primary source of positrons.

The present indication of an anomaly in the positron/electron by the PAMELA satellite needs really exotic DM models.

Most DM models need very large "boost factors": 10 – 1000 times enhancement of rates

Caution: Nearby SN remnants (e.g. d = 100 pc, Age = 10^5 yr) may easily explain both strength and slope of positron ratio (Aharonian, Atoyan and Völk, 1995)

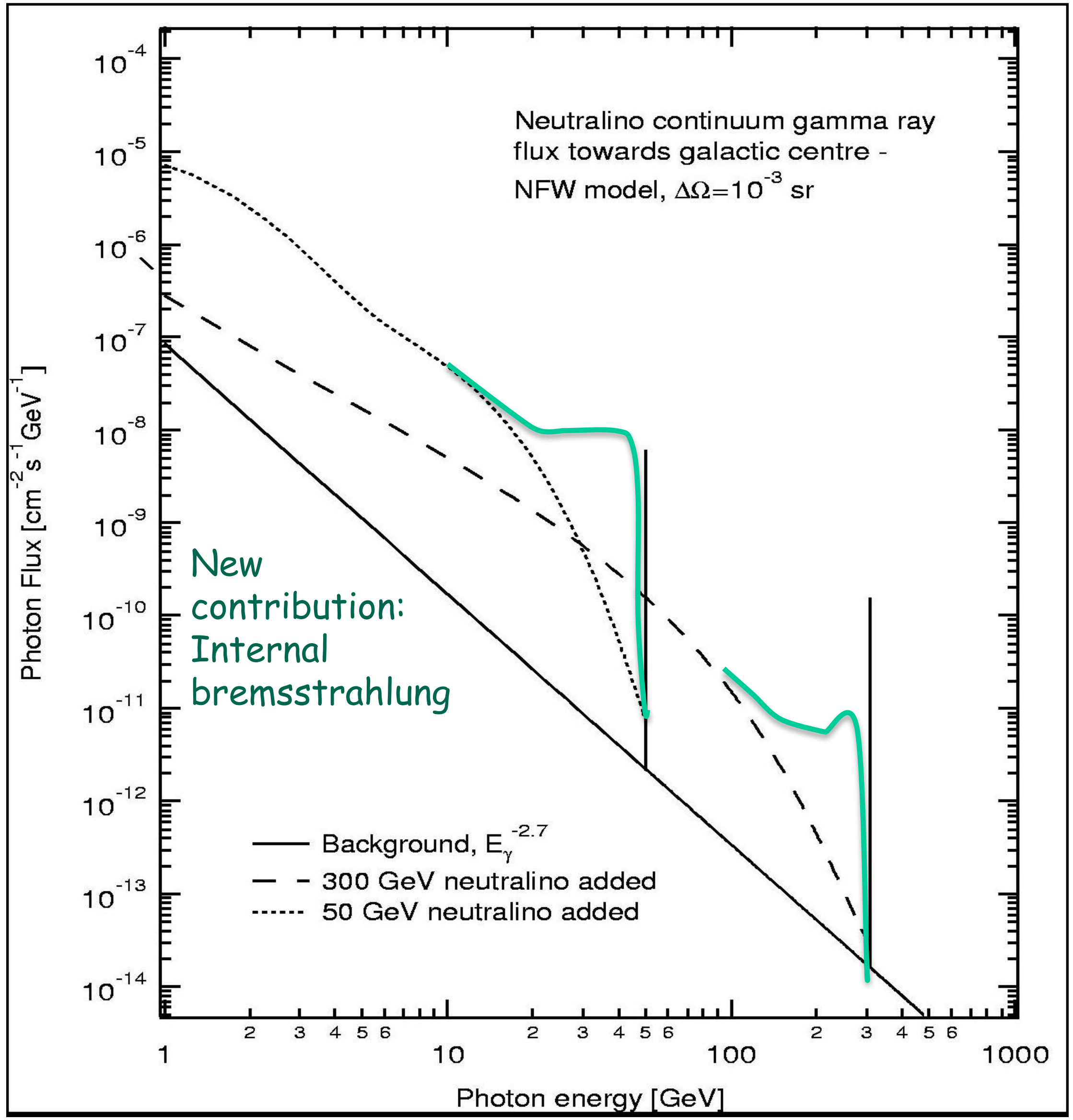


Gamma-rays

Indirect detection through γ-rays.
Three types of signal:

- Continuous from π^0, K^0, … decays
  and
- Monoenergetic line
  and
- Internal bremsstrahlung from QED process.

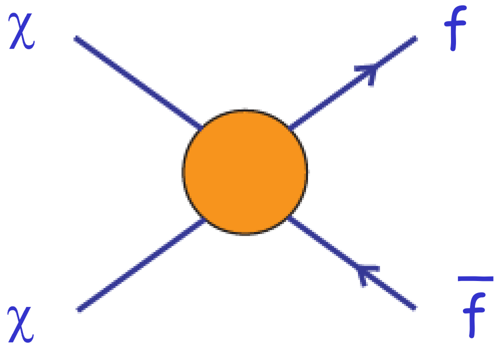
Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)
Good spectral signatures!
Unfortunately, large uncertainties in the predictions of absolute rates



L.B., P.Ullio & J. Buckley 1998

T. Bringmann, L.B., J. Edsjö, 2007

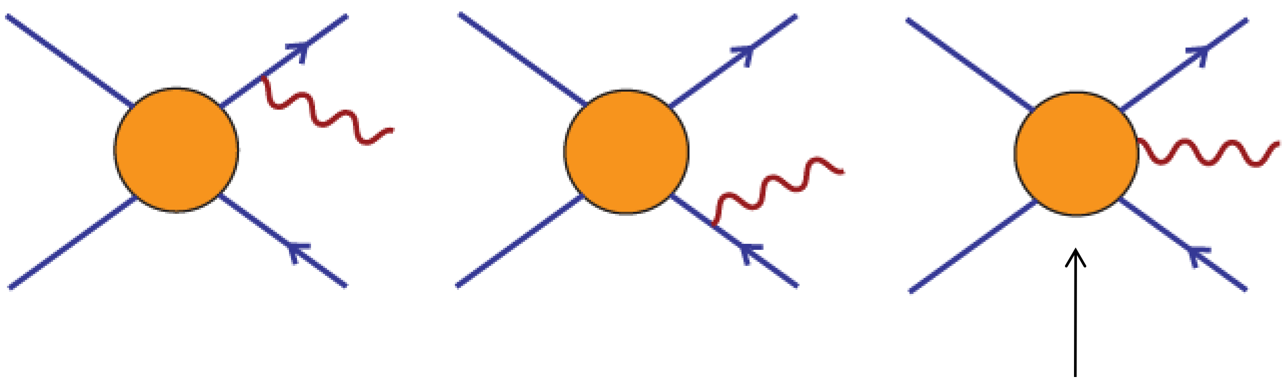
Recent development: New observational signature for Majorana particles



$\sim m_f$ for Majorana particles in limit $v/c \to 0$

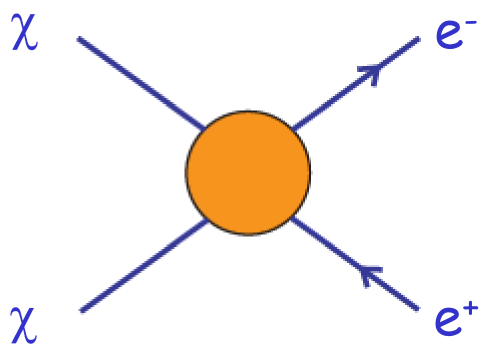
"Final state radiation"

"Internal bremsstrahlung", IB



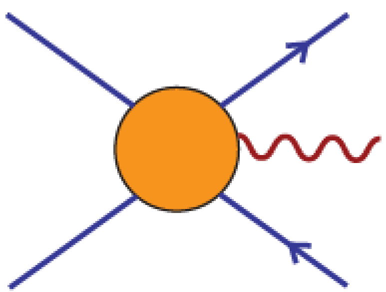
$\sim m_f$ $\sim m_f$ No m_f suppression!

Example, SUSY particle annihilating only into electrons and positrons (if selectron much lighter than other sfermions):



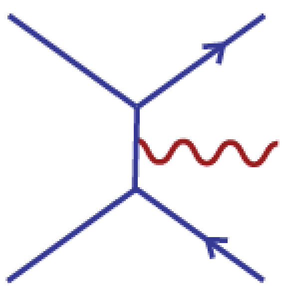
Annihilation rate $(\sigma v)_0 \sim 3{\cdot}10^{-26}$ cm^{-3}s^{-1} at freeze-out, due to p-wave at $(v/c)^2 \sim 0.3$. $\Omega_{CDM}h^2 = 0.1$ for mass ~ 500 GeV.

Annihilation rate today (S-wave)
$\sigma v \sim 10^{-25}\,(m_e/m_\chi)^2$ cm^{3}s^{-1} $\sim 10^{-37}$ cm^{3}s^{-1} for $v/c \sim 10^{-3}$.
Impossible to detect! Even adding P-wave, it is too small.



First order QED "correction" (Internal Bremsstrahlung):
$(\sigma v)_{QED}/\,(\sigma v)_0 \sim (\alpha/\pi)\,(m_\chi/m_e)^2 \sim 10^9 \Rightarrow 10^{-28}$ cm^{3}s^{-1}

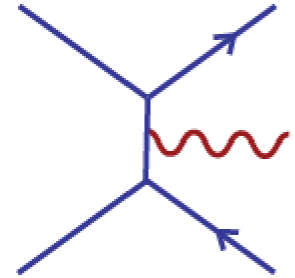
t-channel selectron exchange



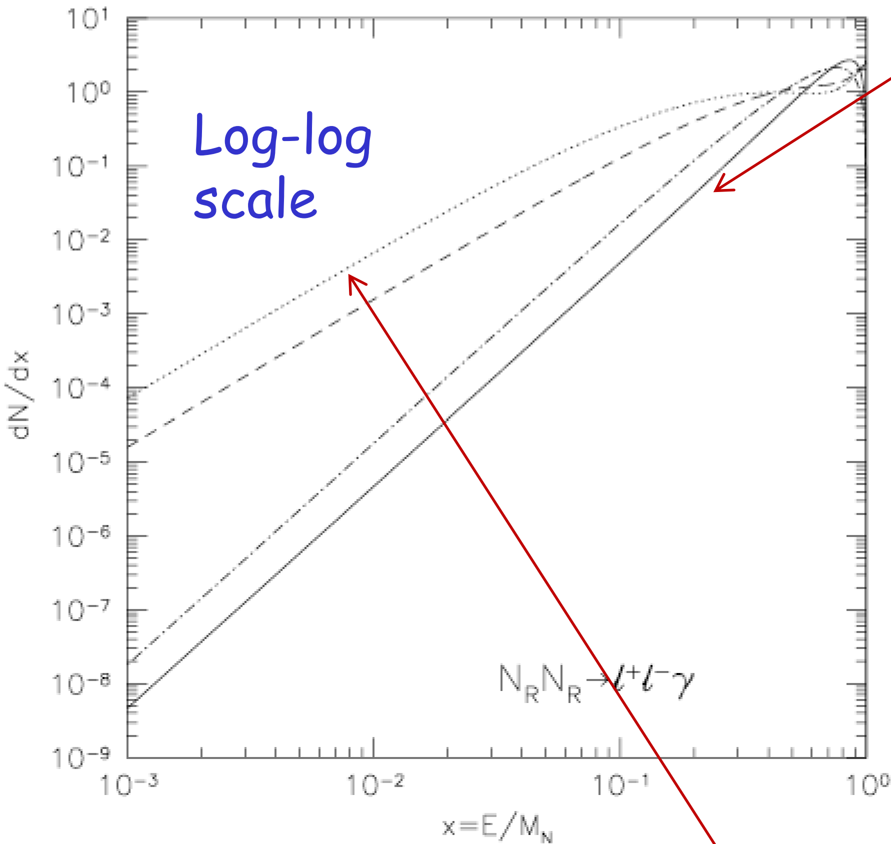
The "expected" QED correction of a few per cent is here a factor of 10^9 instead! May give detectable gamma-ray rates – and with good signature!

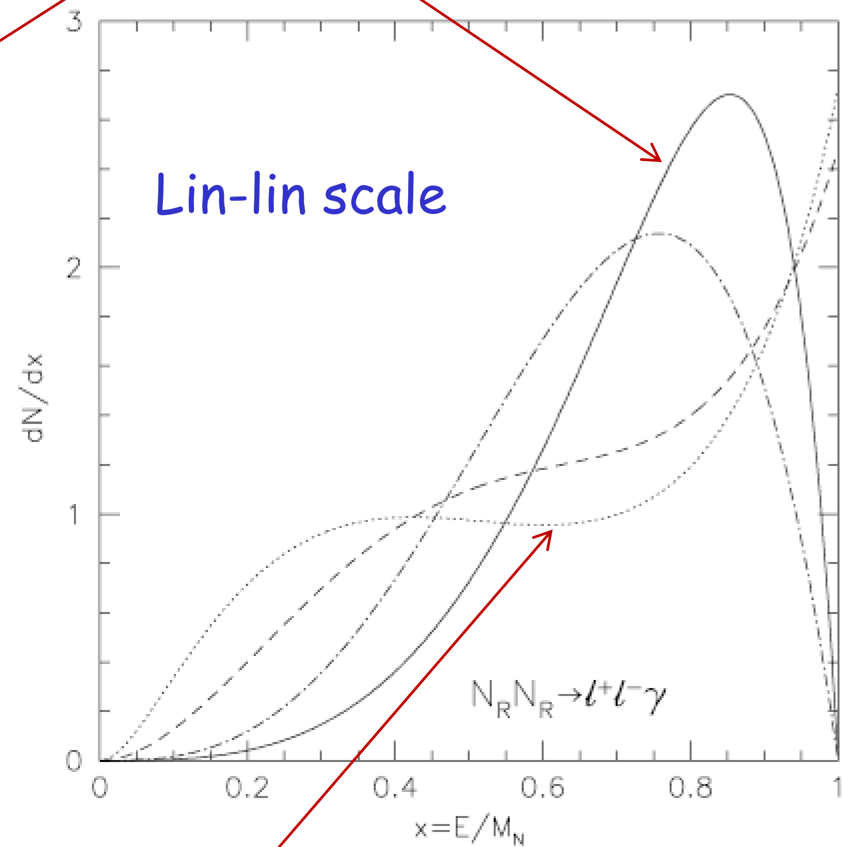
(L.B. 1989, E.A. Baltz & L.B. 2003, T. Bringmann, L.B. & J. Edsjö, 2008)

E.A. Baltz & L.B., PRD 2003: Leptonic dark matter (right-handed Majorana neutrinos of mass around 1 TeV, to explain neutrino masses in Zee version of see-saw mechanism)



Gamma-ray spectrum





Positron spectrum

Almost like a delta function at highest gamma-ray energy. Very good signature

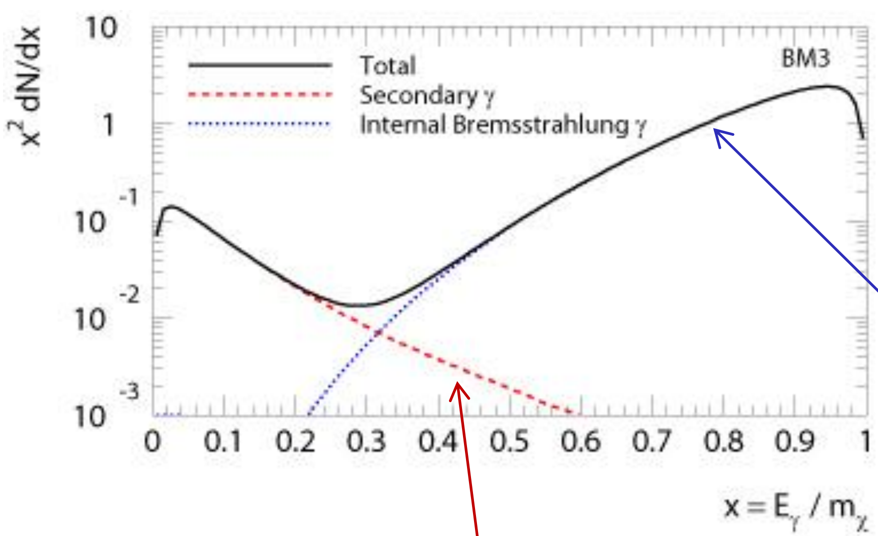
QED corrections (Internal Bremsstrahlung) in the MSSM: good news for detection probability in gamma-rays:

New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation

JHEP, 2008

Torsten Bringmann*
SISSA/ISAS and INFN, via Beirut 2 - 4, I - 34013 Trieste, Italy

Lars Bergström† and Joakim Edsjö‡
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden
(Dated: October 16, 2007)



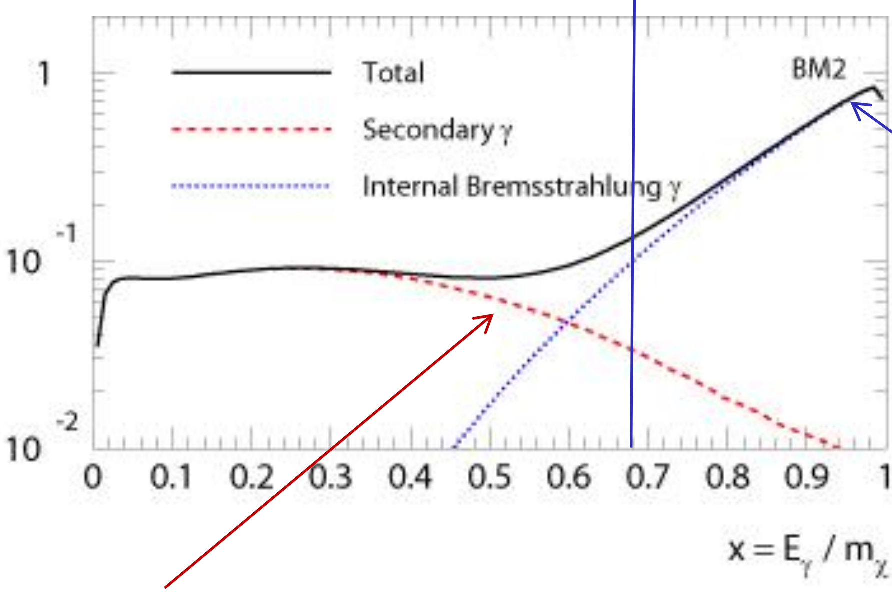
Example: benchmark point BM3, mass = 233 GeV, fulfils all accelerator constraints, has WMAP-compatible relic density (stau coannihilation region).

New calculation including Internal Bremsstrahlung (DarkSUSY 4.2). Spectral drop att 233 GeV is nicely inside the GLAST range…

Previous estimate of gamma-ray spectrum (DarkSUSY 4.1)

Effect generally increases with mass:

GLAST sensitivity (300 GeV)

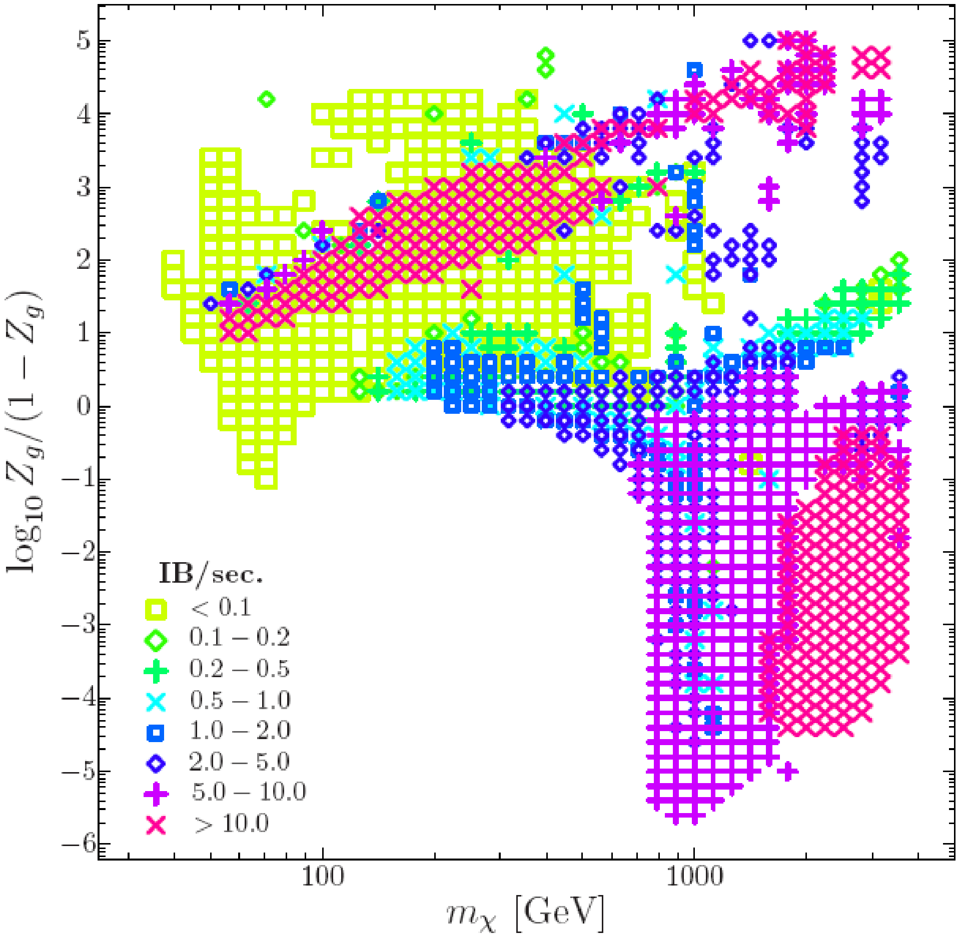


Previous estimate of gamma-ray spectrum (DarkSUSY 4.1)

Example: benchmark point BM2, mass = 447 GeV, fulfills all accelerator constraints, has WMAP relic density

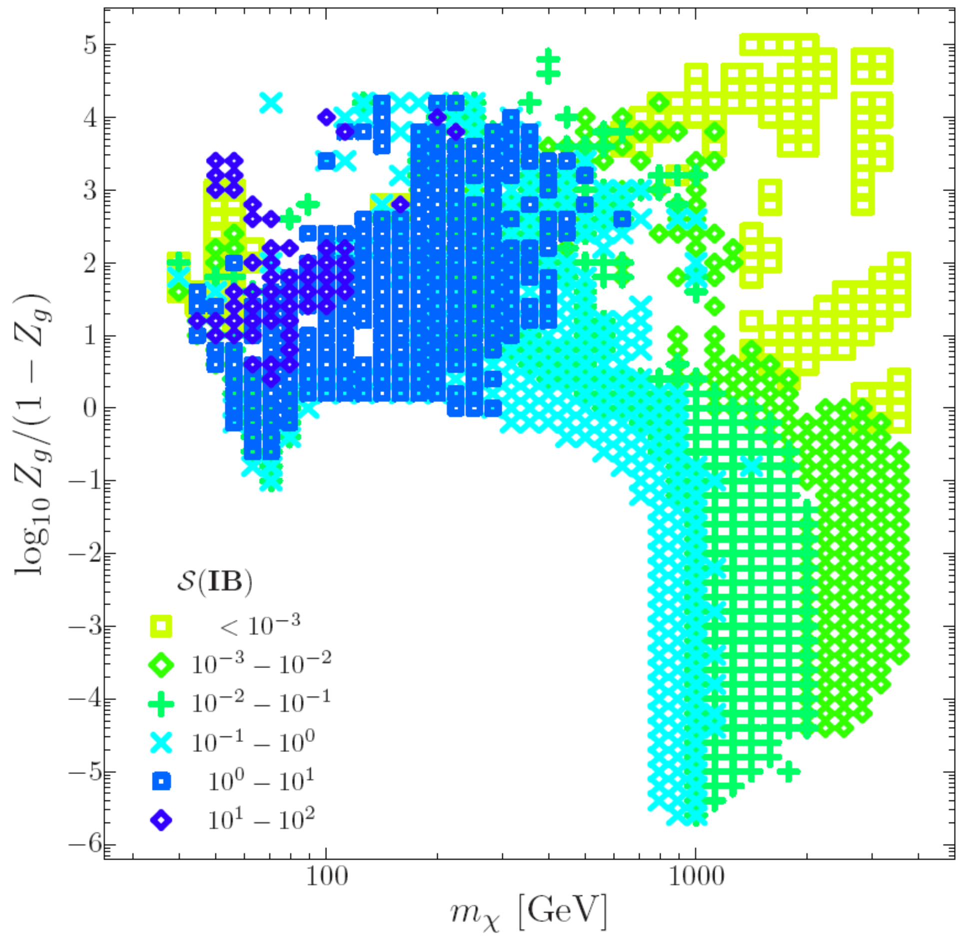
New calculation including Internal Bremsstrahlung (DarkSUSY 4.2).
Energy falls just outside the GLAST range...
Something for new imaging ACT arrays to hunt for!

T. Bringmann, L.B., J.Edsjö, JHEP 2008



Ratio IB/(Old results)

(The IB rates are usually larger than the gamma lines also)

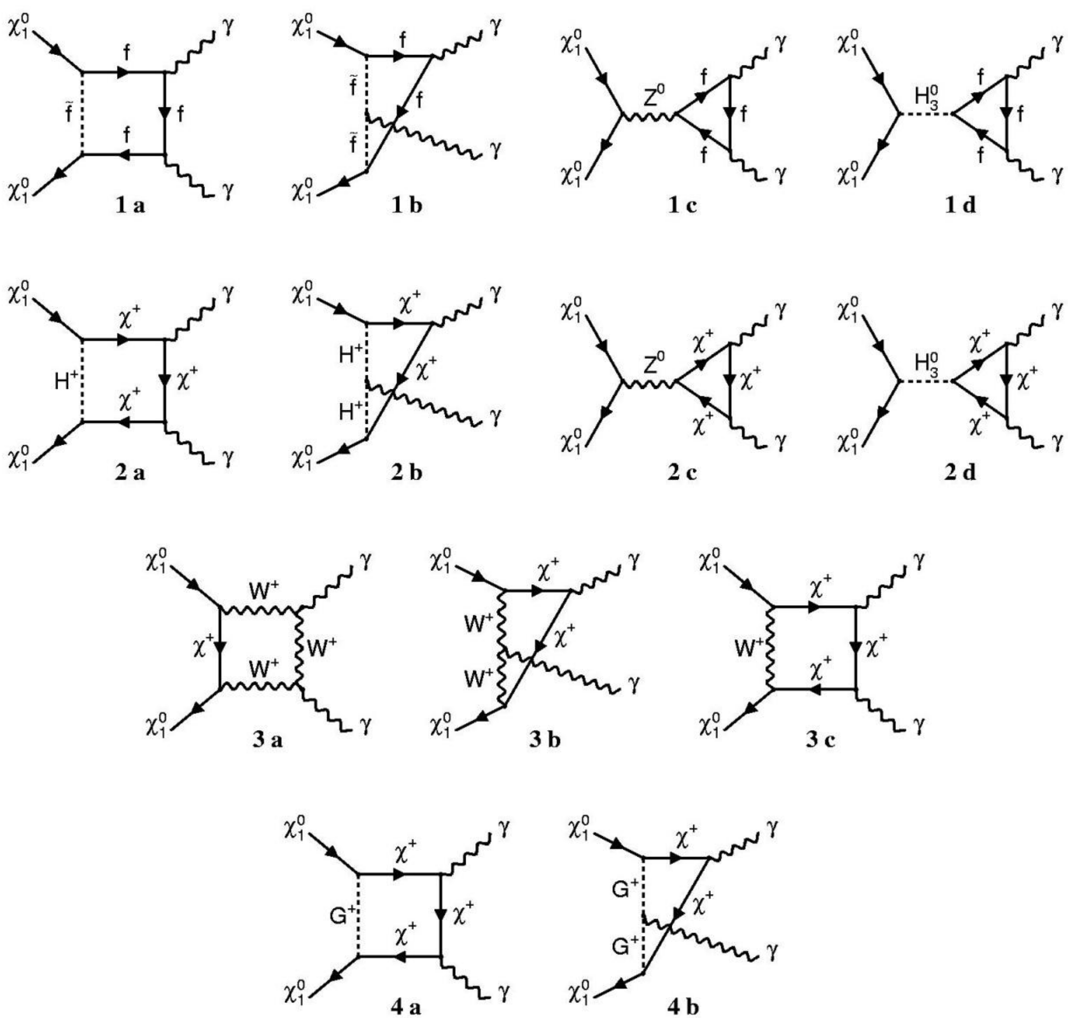


Absolute flux factor S

$$\mathcal{S} \equiv N_\gamma \frac{\langle \sigma v \rangle}{10^{-29}\mathrm{cm}^3\mathrm{s}} \left(\frac{m_\chi}{100\mathrm{GeV}}\right)^{-2}$$

All SUSY models with accelerator constraints included, WMAP-compatible relic density. Detailed predictions for gamma-ray experiments are in preparation (T. Bringmann et al., 2008).

Loop-induced 2γ (or Z γ) final state: source of nearly monoenergetic photons



L.B. & P. Ullio, 1998

v/c ≈ 10^-3^ $\Rightarrow \; E_\gamma \approx m_\chi$

(for γγ) or $E_\gamma \approx m_\gamma \left(1 - \dfrac{m_Z^2}{4m_\chi^2}\right)$

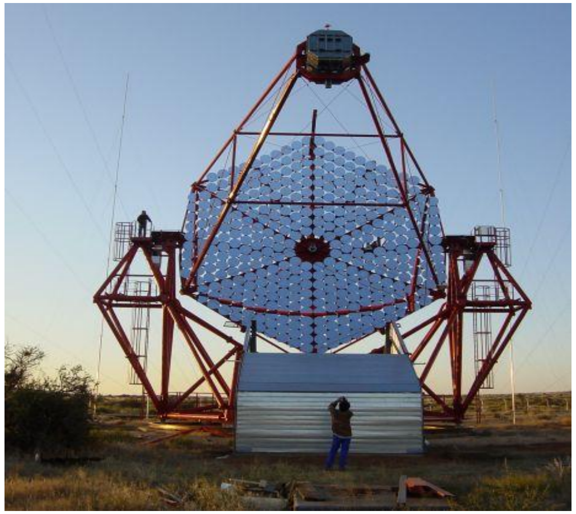
(for Zγ)

Rates in SUSY are generally small but can be large (B.R. $\propto 10^{-3}$ - 10^{-2}) for higgsino-like neutralinos (in particular, also for TeV-scale higgsinos).

Detectors in Gamma-Ray Astrophysics

High Sensitivity

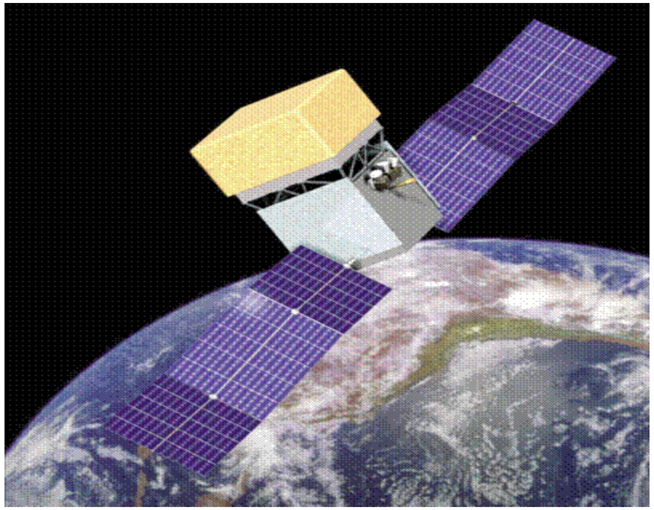
HESS, MAGIC, CANGAROO, VERITAS, (CTA, AGIS,…)



Energy Range 0.1-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution 0.05°
Aperture 0.003 sr
Duty Cycle 10%

Low Energy Threshold

EGRET (1991-2000)/Fermi (2008-)

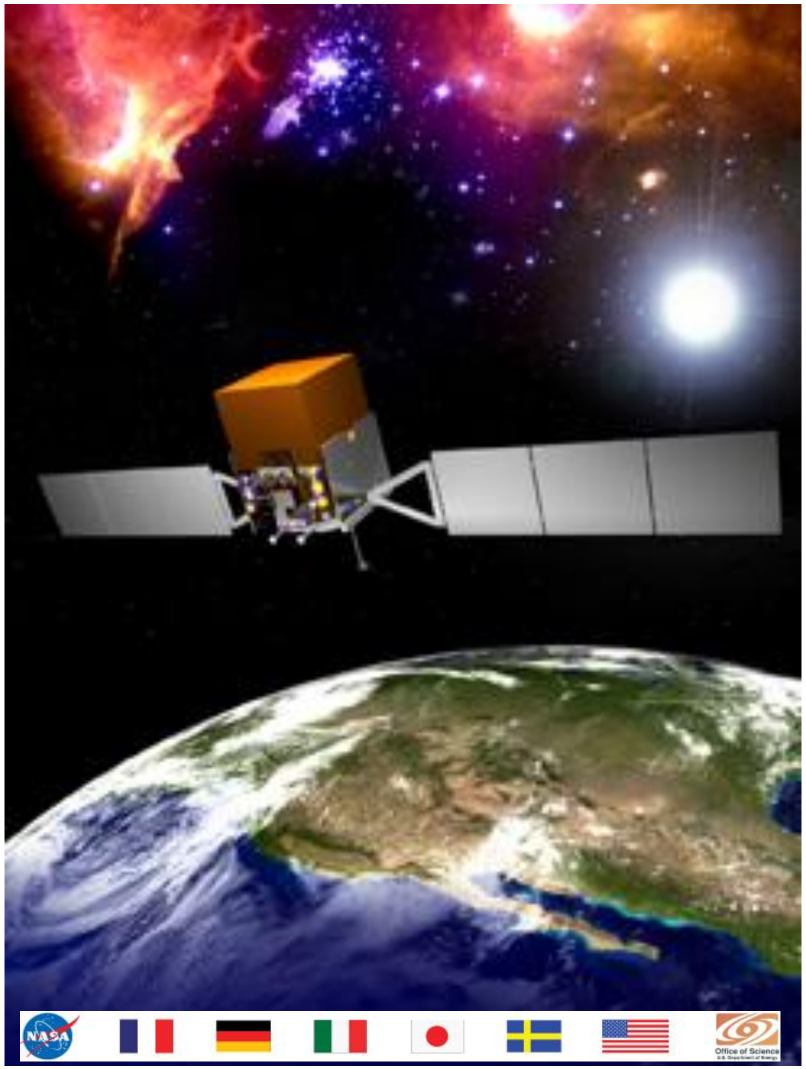


Energy Range 0.1-300 GeV
Area: 1 m^2
Background Free
Angular Resolution 0.1° - 0.3°
Aperture 2.4 sr
Duty Cycle > 90%

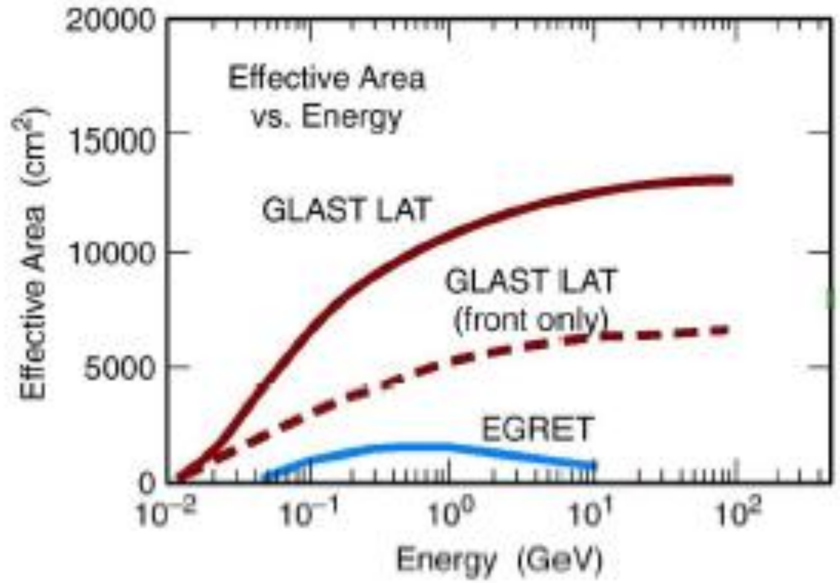
Large Aperture/High Duty Cycle

Milagro, Tibet, ARGO, HAWC

Energy Range 0.1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Aperture > 2 sr
Duty Cycle > 90%



USA-France-Italy-Sweden-Japan – Germany collaboration, launched June 2008

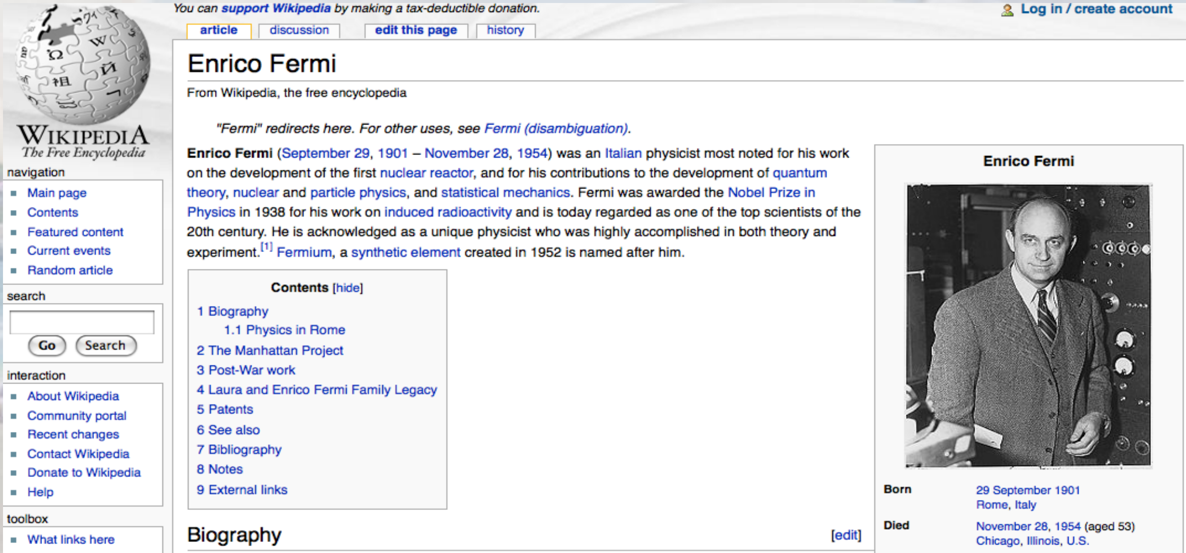


Fermi/GLAST can search for dark matter signals up to 300 GeV. It is also likely to detect a few thousand new AGNs (GeV blazars)...

What's in a Name?

GLAST renamed to Fermi on Aug 26

Fermi
Gamma-ray
Space Telescope



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Enrico Fermi

From Wikipedia, the free encyclopedia

"Fermi" redirects here. For other uses, see Fermi (disambiguation).

Enrico Fermi (September 29, 1901 – November 28, 1954) was an Italian physicist most noted for his work on the development of the first nuclear reactor, and for his contributions to the development of quantum theory, nuclear and particle physics, and statistical mechanics. Fermi was awarded the Nobel Prize in Physics in 1938 for his work on induced radioactivity and is today regarded as one of the top scientists of the 20th century. He is acknowledged as a unique physicist who was highly accomplished in both theory and experiment.[1] Fermium, a synthetic element created in 1952 is named after him.

Contents [hide]

Enrico Fermi

Born	29 September 1901 Rome, Italy
Died	November 28, 1954 (aged 53) Chicago, Illinois, U.S.

Biography
[edit]

Fermi Schedule

- June 11, 2008: Launch successful , Fermi in orbit
- *Day 1 - 14:*
Satellite testing and configuration
- *Day 15 - 60:*
Calibration of detectors and first science runs
- *Day 61 (mid Aug.) -*
Full science data taking

GLAST LAT Collaboration

United States

- California State University at Sonoma
- University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
- Goddard Space Flight Center – Laboratory for High Energy Astrophysics
- Naval Research Laboratory
- Ohio State University
- Stanford University (SLAC and HEPL/Physics)
- University of Washington
- Washington University, St. Louis

France

- IN2P3, CEA/Saclay

Italy

- INFN, ASI

Japanese GLAST Collaboration

- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Inst of Technology

Spain

- ICREA and Inst de Ciencies de l'Espi

Swedish GLAST Collaboration

- Kalmar University
- Royal Institute of Technology (KTH)
- Stockholm University

PI: Peter Michelson (Stanford & SLAC)

~270 Members (including ~90 Affiliated Scientists, plus 37 Postdocs, and 48 Graduate Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

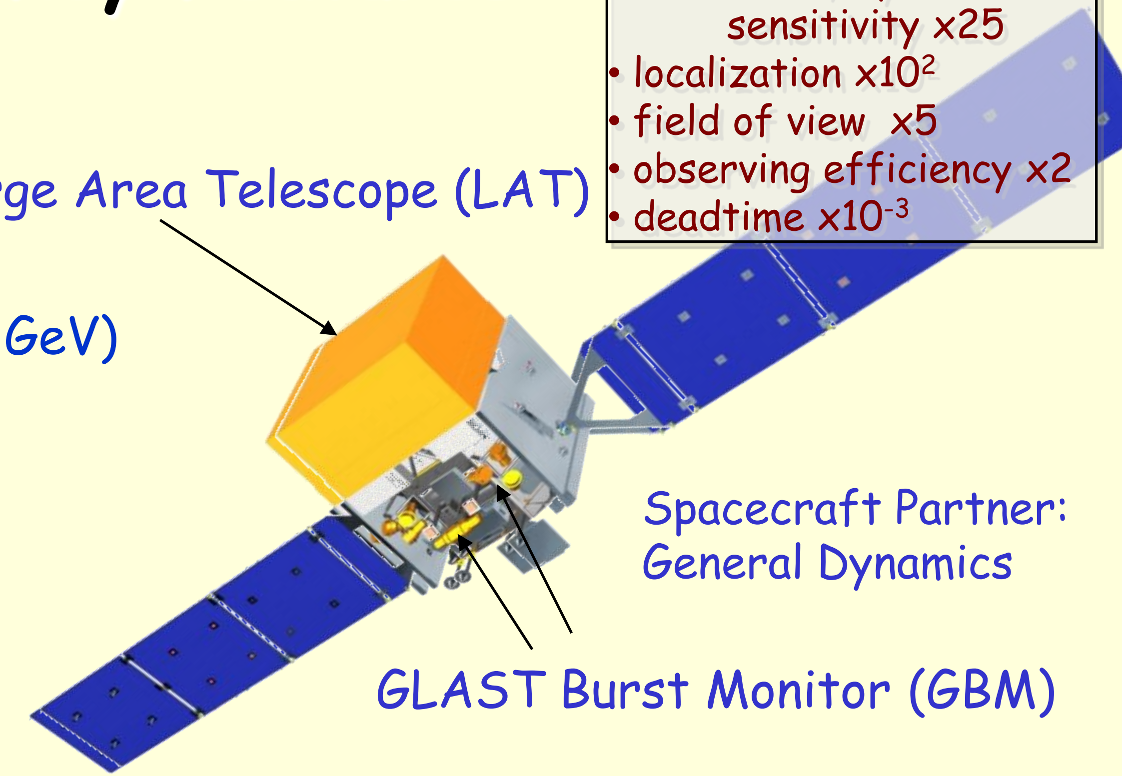
Managed at Stanford Linear Accelerator Center (SLAC).

Fermi
Gamma-ray Space Telescope

GLAST Key Features

Compared to EGRET:
- > 100 MeV, 1 yr sensitivity x25
- localization $\times 10^2$
- field of view x5
- observing efficiency x2
- deadtime $\times 10^{-3}$

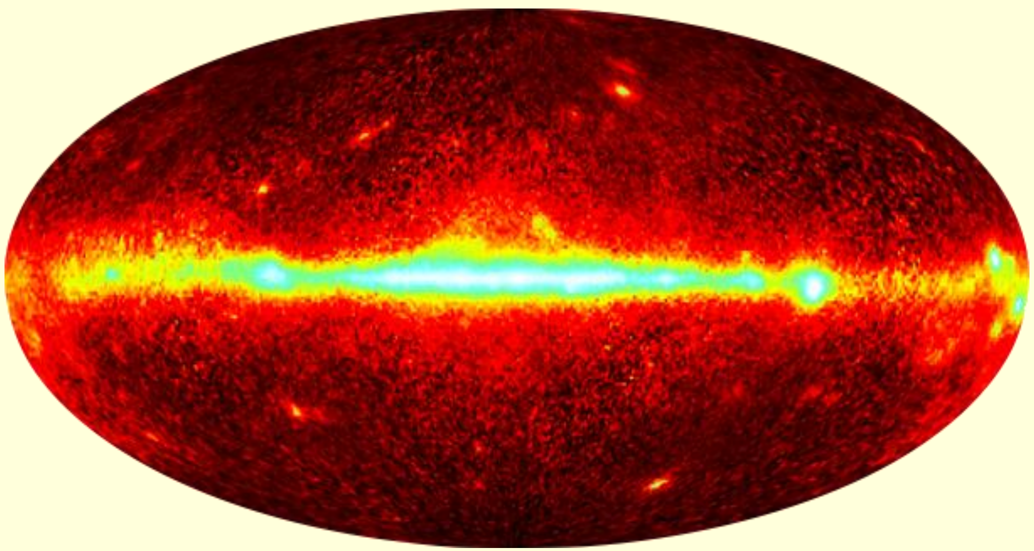
- Two GLAST instruments:
  - LAT:
    - high energy (20 MeV – >300 GeV)
  - GBM:
    - low energy (8 keV – 30 MeV)



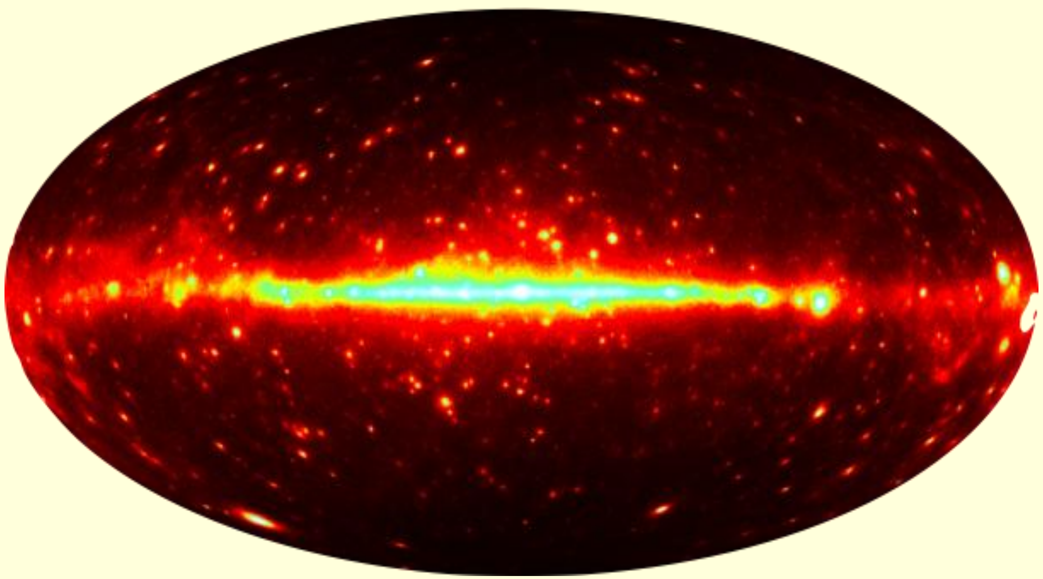
- Huge field of view
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV
- Large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.

Some Questions GLAST Will Address

- How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?
- What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?
- What is the origin of the cosmic rays that pervade the galaxy?
- How does the Sun generate high-energy gamma-rays in flares?
- How has the amount of starlight in the Universe changed over cosmic time?
- What are the unidentified gamma-ray sources found by EGRET?
- What is dark matter?



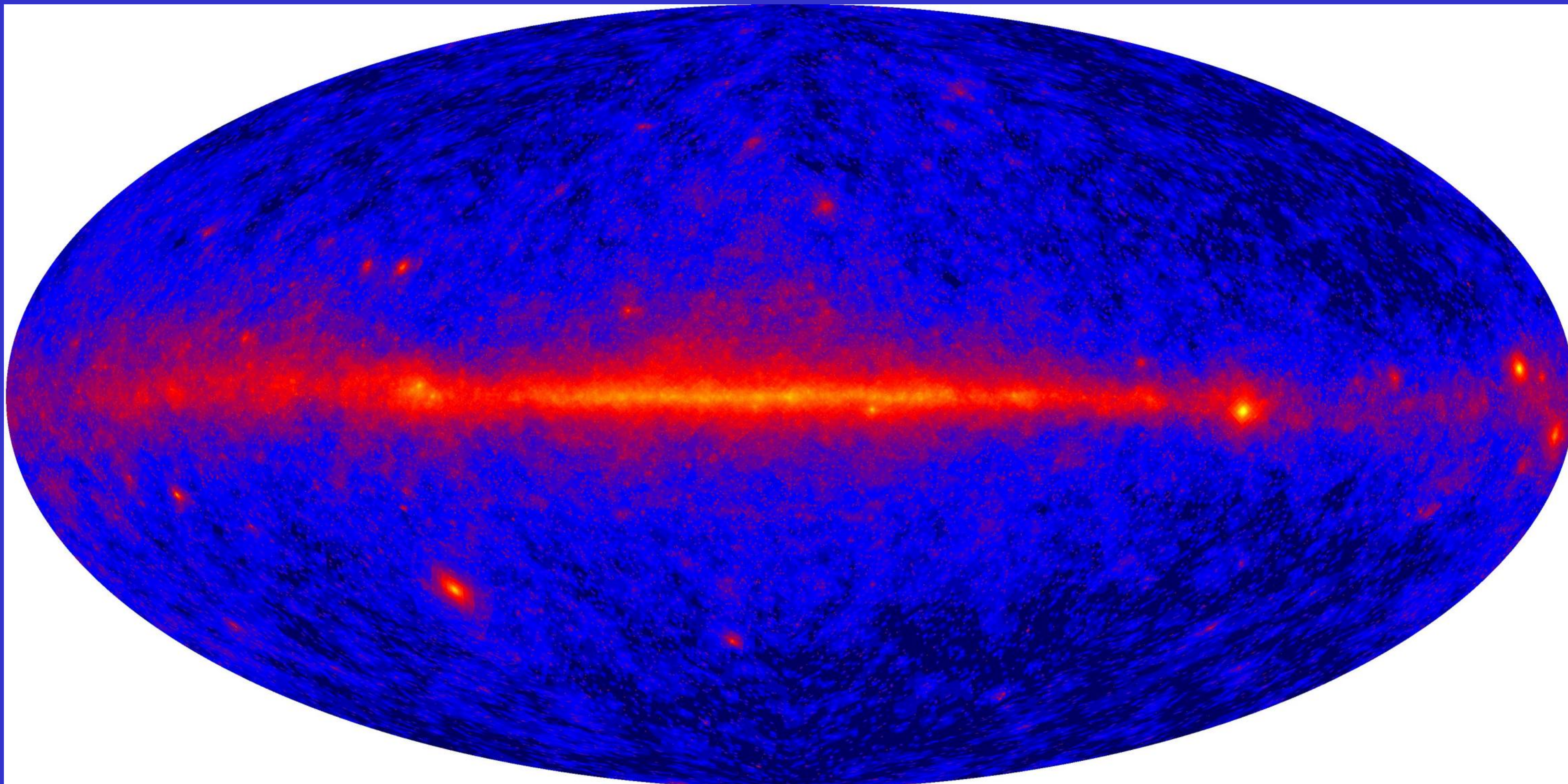
5 yrs EGRET



1 yr (sim) GLAST

R. Dubois

After a few days, the Fermi sky map is superior to that of EGRET after several years!



Fermi "fist light" map

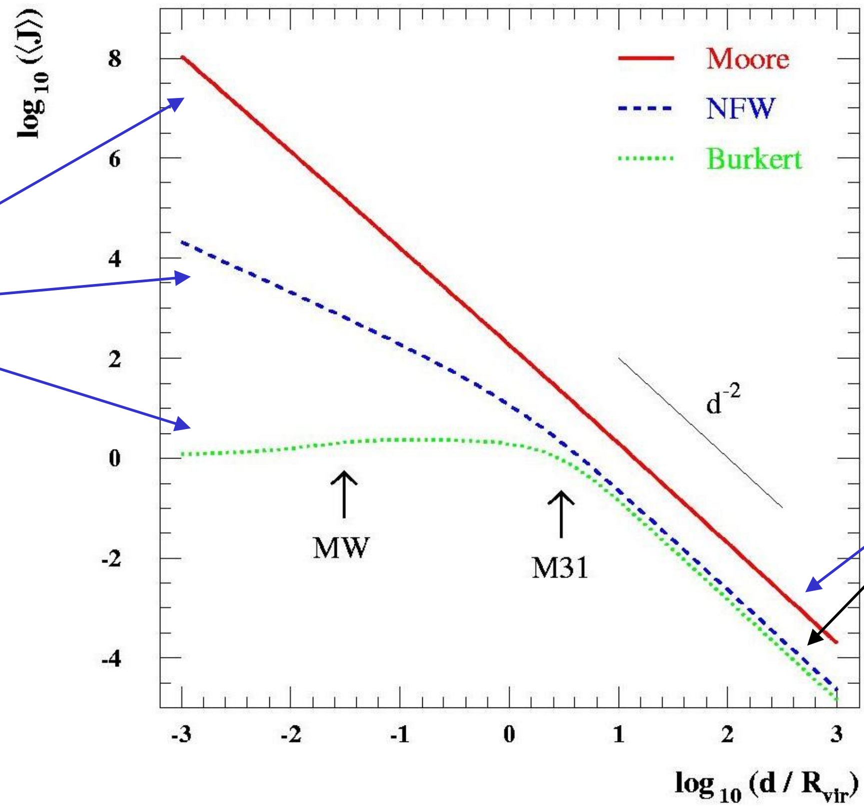
Dark Matter

Detection rate = (PPP)×(APP)

~ ⟨σv⟩ ~ J

$$\bar{J}(\hat{n};\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int d\Omega \int \frac{dl}{(8.5\,kpc)}\left(\frac{\rho(\vec{r})}{0.3\,GeV/cm^3}\right)^2$$

Note large uncertainty of flux for nearby objects (Milky Way center, LMC, Draco,...)



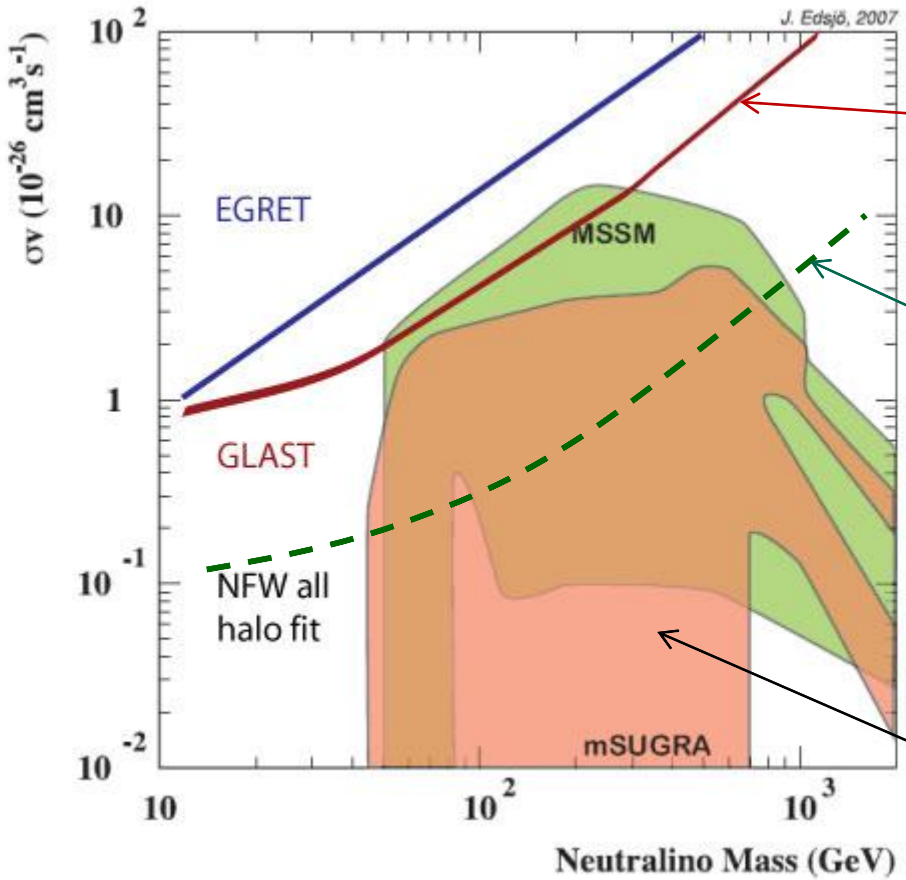
In this region (at cosmological distances), the uncertainty is much smaller

P. Ullio, L. B., J. Edsjö, 2002

FIG. 4: Scaling of the collected γ-ray flux with the distance d between the detector and the center of a halo, for three different halo profiles. The angular acceptance of the detector is assumed to be $\Delta\Omega = 10^{-3}$sr. The plot is for a $10^{12}\,M_\odot$ halo, the arrows indicate the position on the horizontal axis for the Milky Way and Andromeda; the case for other masses is analogous.

3σ exclusion limit, 1 year of GLAST data

Note: the regions with high gamma rates are very weakly correlated with models of high direct detection rates ⇒ complementarity



"Conservative" approach, g.c.,

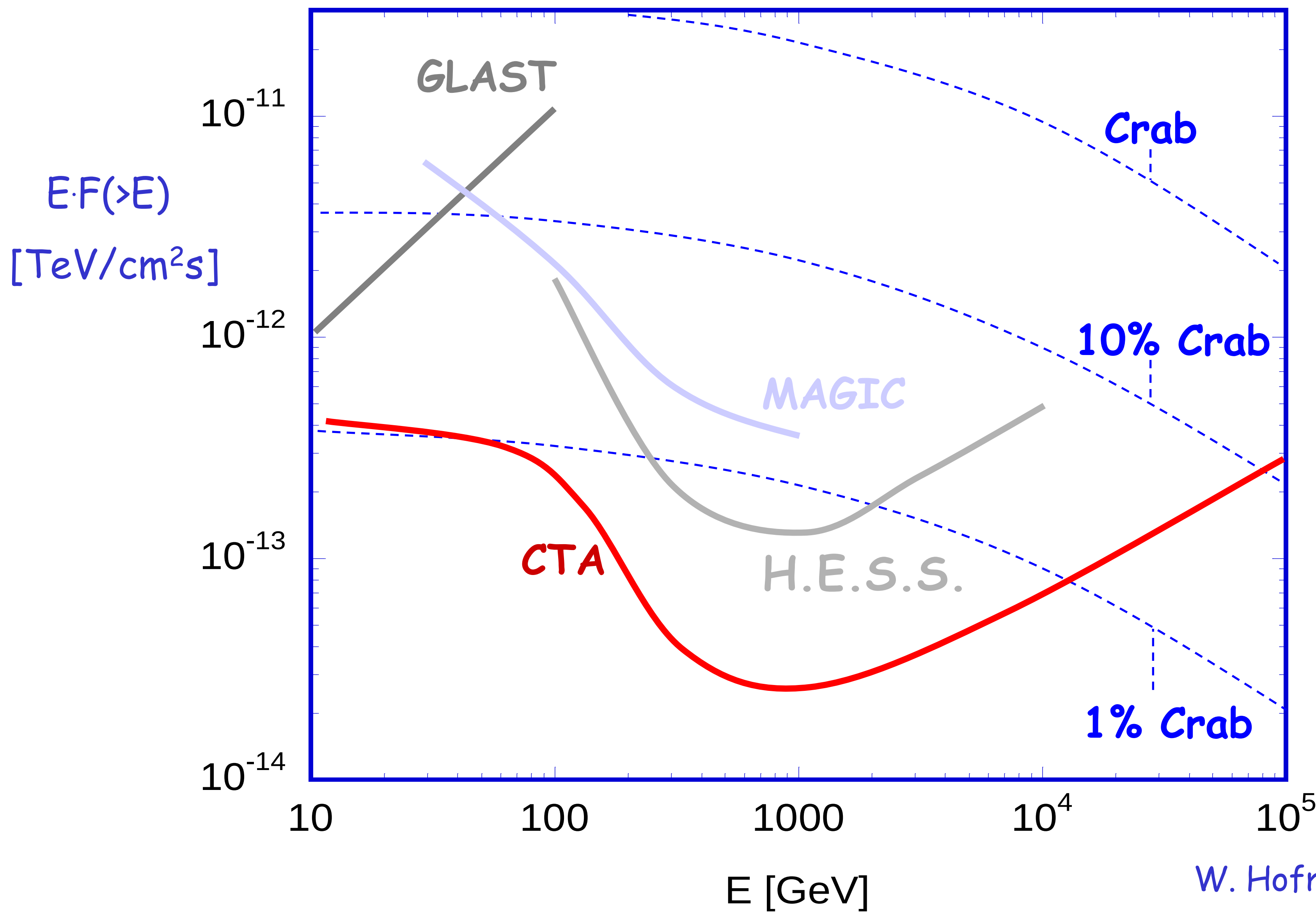
NFW halo profile assumed, no substructure.

Including all halo, with substructure (my guesstimate)

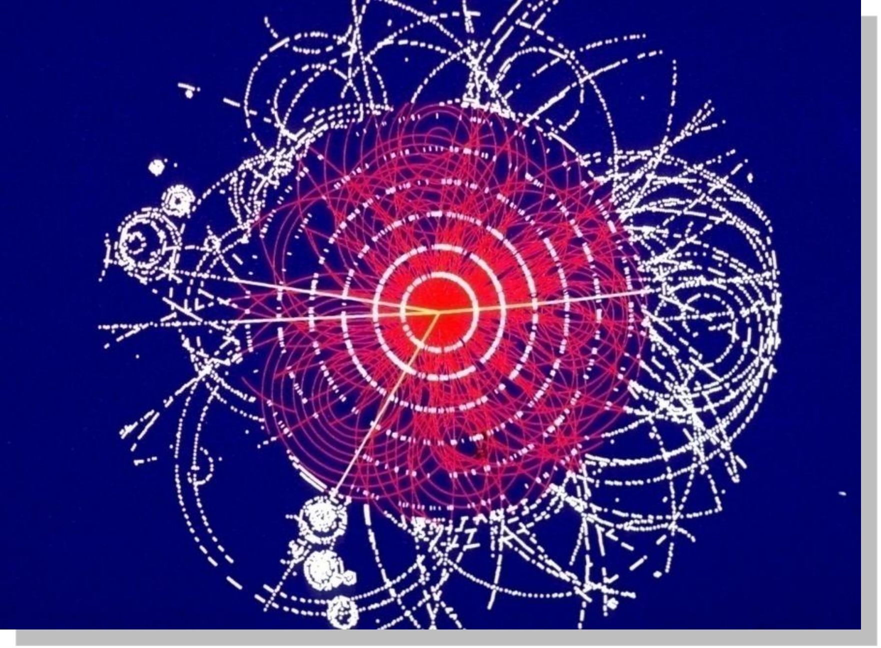
Vast region of opportunity for next generation of gamma-ray instruments!

GLAST working group on Dark Matter and New Physics, E.A. Baltz & al., JCAP, 2008.

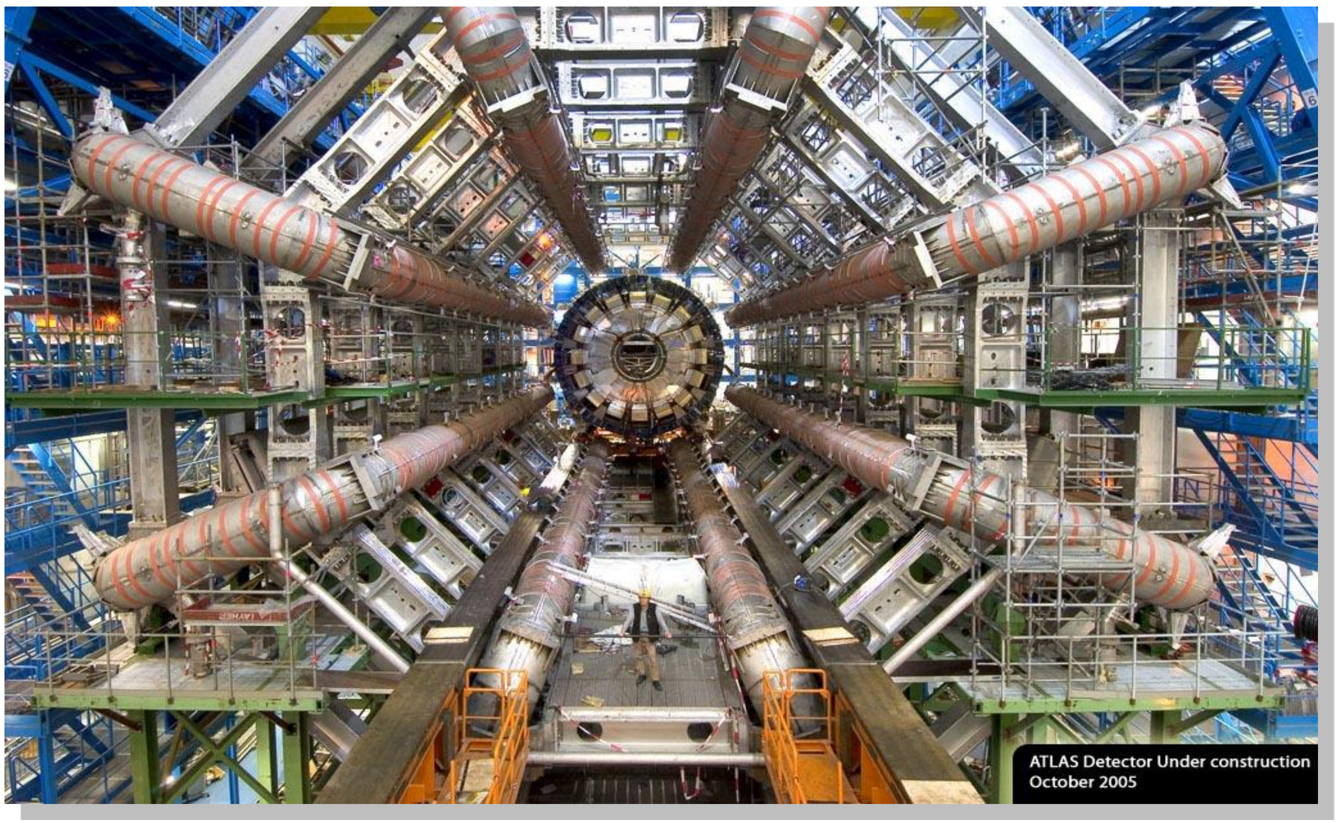
The future? Possible Cherenkov Telescope Array (CTA) sensitivity



W. Hofmann



LHC will also start taking data, 2009!



The ATLAS-detector

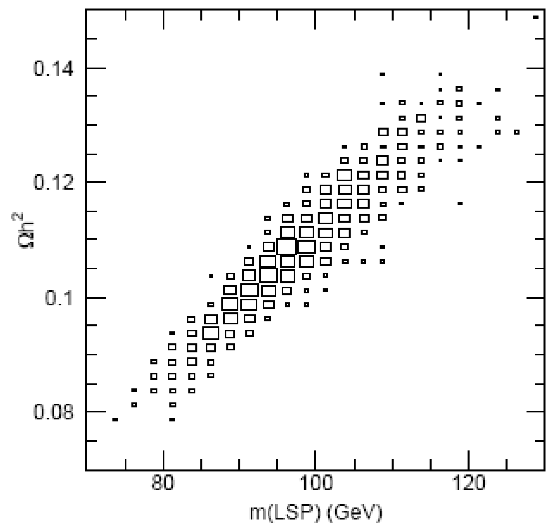
Will LHC discover dark matter first?

To claim discovery of Dark Matter particles at an accelerator, need to show:

• Particle is neutral, with long (infinite) lifetime

• Has couplings consistent with giving the right $\Omega h^2 \sim 1/\langle\sigma v\rangle \sim 0.1$

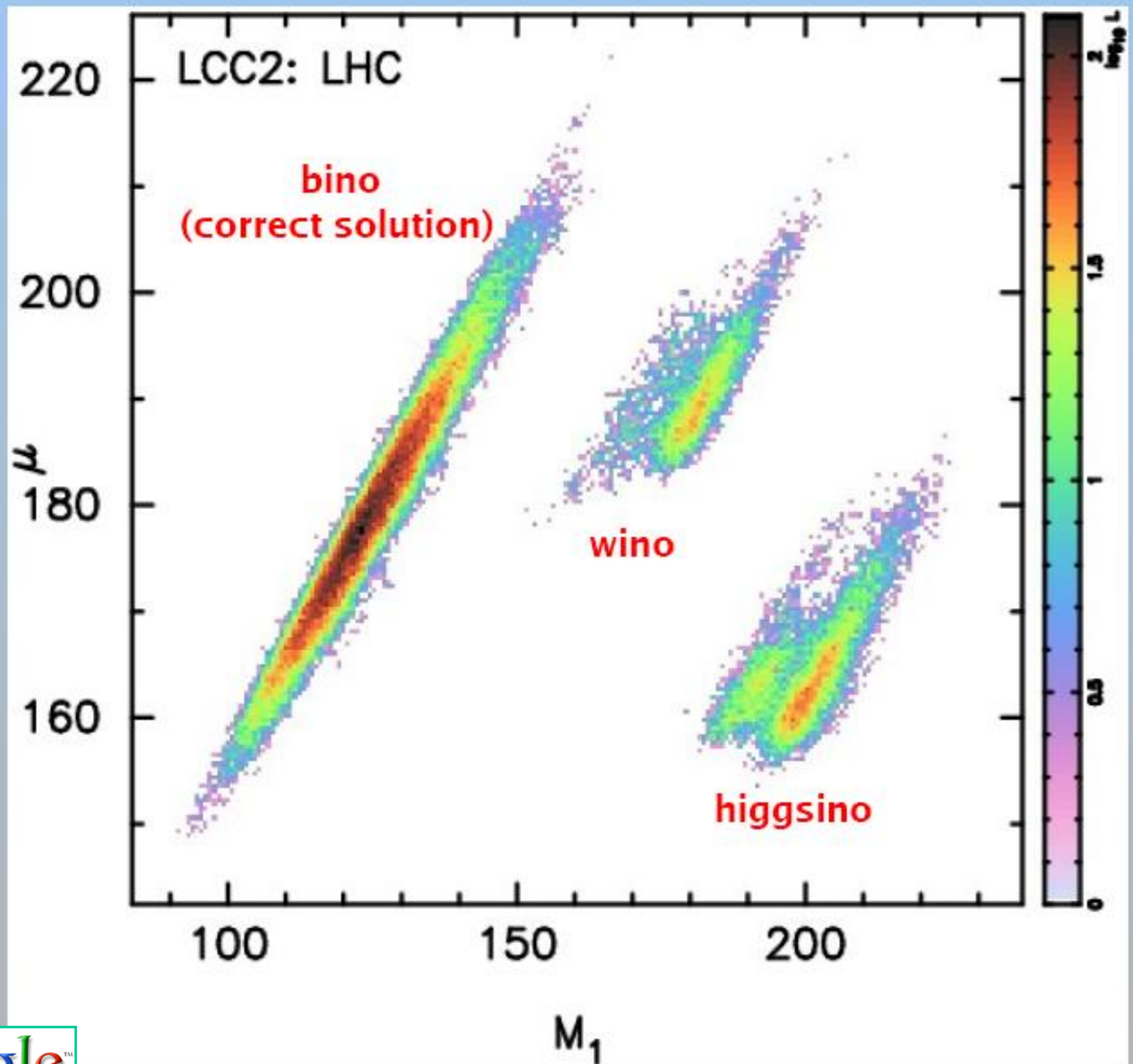
• Compatible with direct and indirect detection rates (or limits)



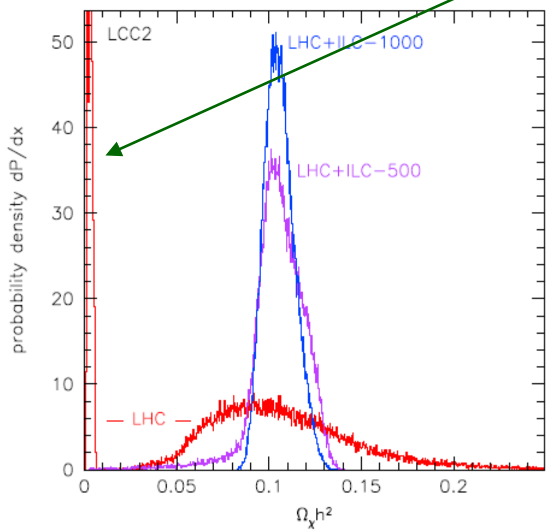
Value of the predicted relic density $\Omega_\chi h^2$ as a function of the measured $\tilde{\chi}_1^0$ mass.

Nojiri, Polesello & Tovey, 2005

LCC2: Probability Islands for Neutralinos @ LHC



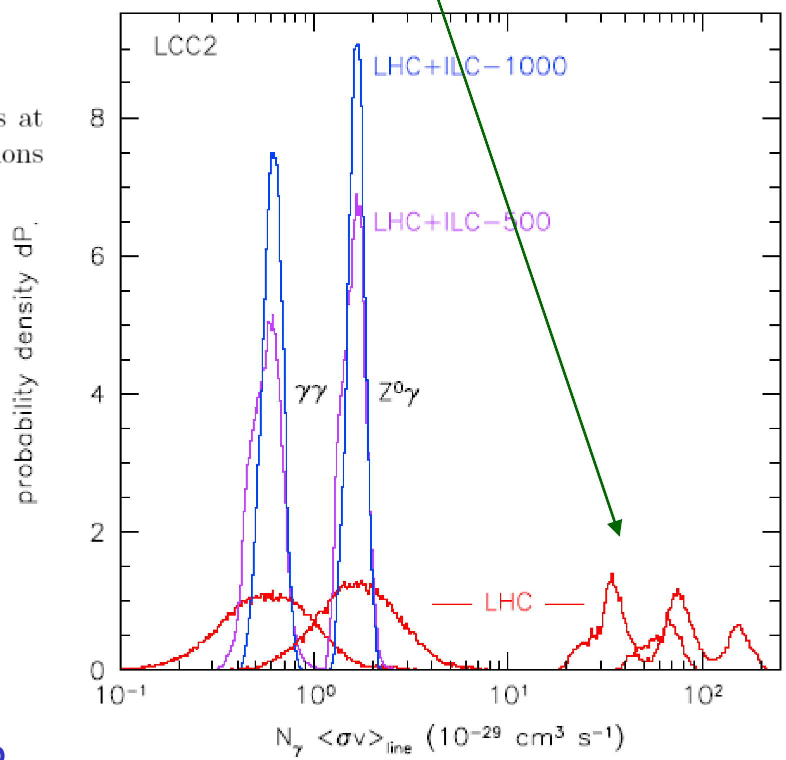
LCC2



Extra probability peaks with low Ω, due to wino or higgsino solution to LHC constraints

Figure 24: Relic density for point LCC2. There are two overlapping very high peaks at $\Omega_\chi h^2 < 0.01$, with maxima at $dP/dx = 122$ and 165, due to the wino and Higgsino solutions to the LHC constraints. See Fig. 8 for description of histograms.

Large gamma line rates for wino and higgsino solutions



E.A. Baltz, M. Battaglia, M.E. Peskin & T. Wizansky, 2006

Must Nature be supersymmetric?

Other model: A more "conventional" dark matter model with a spin-0 dark matter candidate: Inert Higgs Doublet Model

Introduce extra Higgs doublet H_2, impose discrete symmetry $H_2 \rightarrow -H_2$ similar to R-parity in SUSY (Deshpande & Ma, 1978, Barbieri, Hall, Rychkov 2006)

$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \lambda_5 Re\left[(H_1^\dagger H_2)^2\right]$$

$\Rightarrow$ Ordinary Higgs h can be as heavy as 300 GeV without violation of electroweak precision tests

$\Rightarrow$ 40 - 70 GeV inert Higgs H^0 gives correct dark matter density

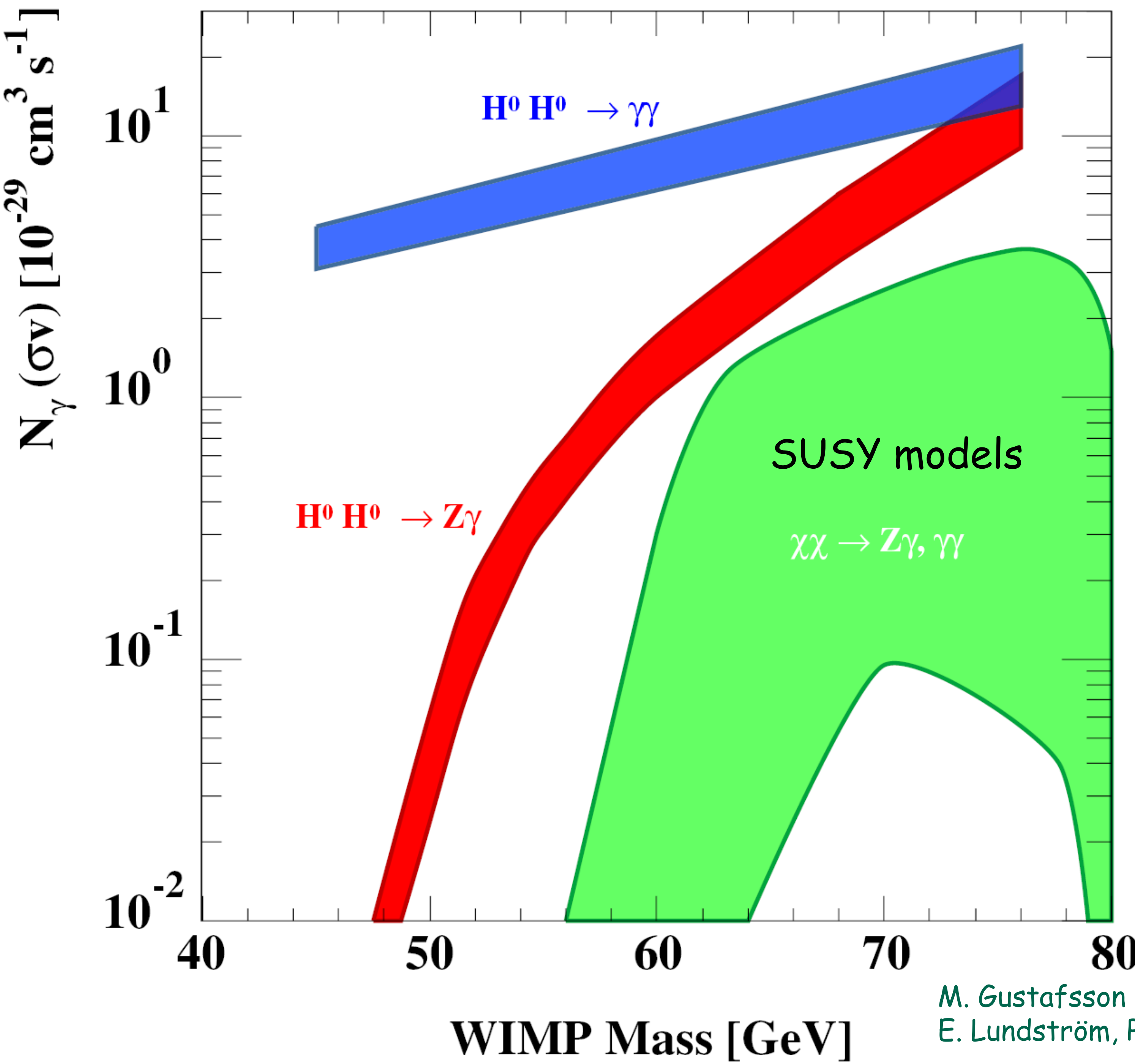
$\Rightarrow$ Coannihilations with pseudoscalar *A* are important

$\Rightarrow$ Can be searched for at LHC

$\Rightarrow$ Interesting phenomenology: Tree-level annihilations are very weak in the halo; loop-induced $\gamma\gamma$ and $Z\gamma$ processes dominate!

$\Rightarrow$ The perfect candidate for detection in Fermi!

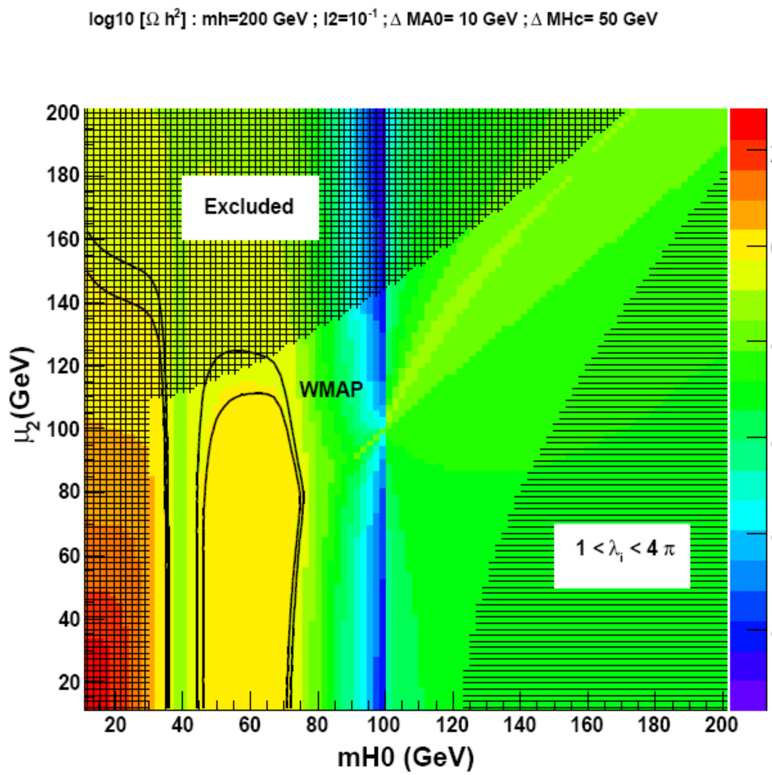
M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL, 2007.



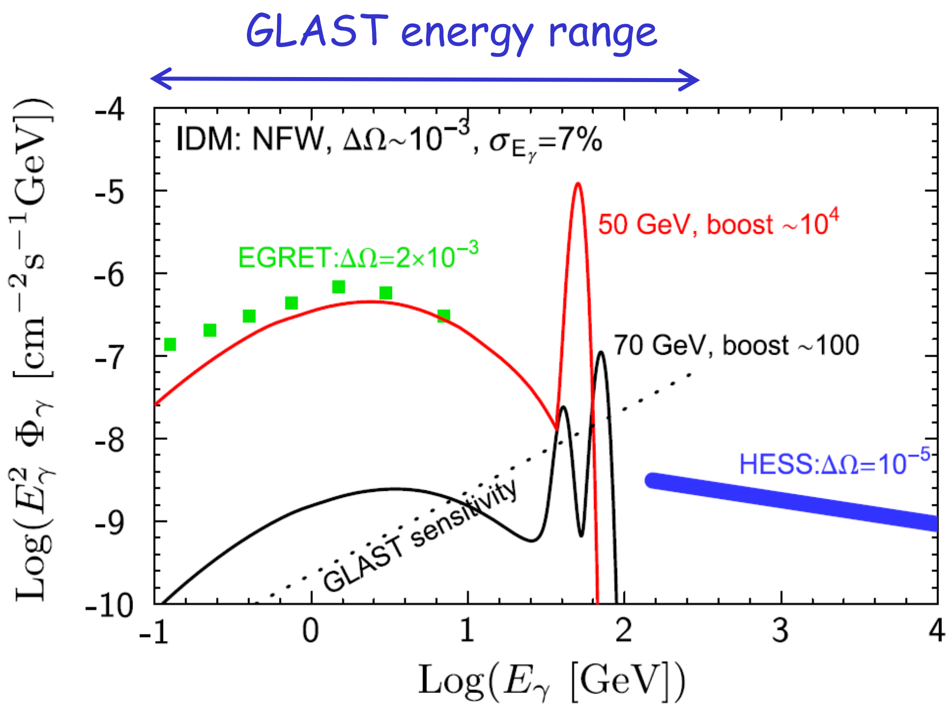
See talk by
M. Gustafsson

M. Gustafsson , L.B., J. Edsjö,
E. Lundström, PRL, 2007

Hambye & Tytgat, July, 2007: This model may also break EW symmetry radiatively (the Coleman-Weinberg Mechanism)



Lopez Honorez et al, 2007

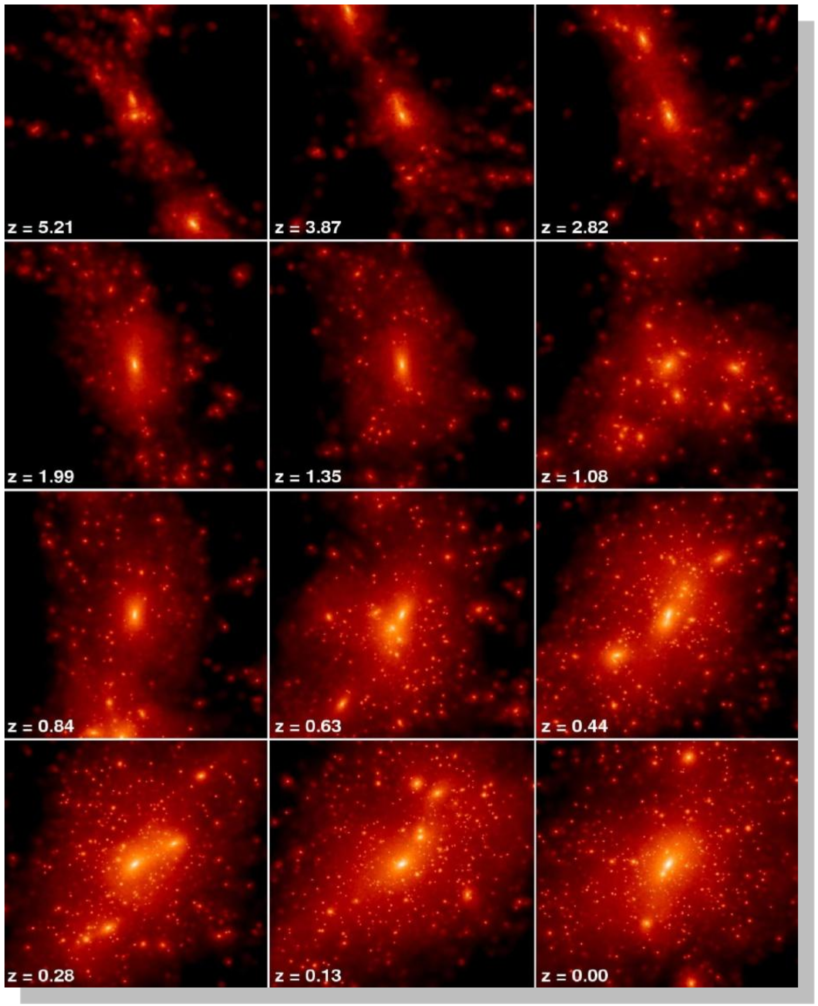


M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL, July 27, 2007

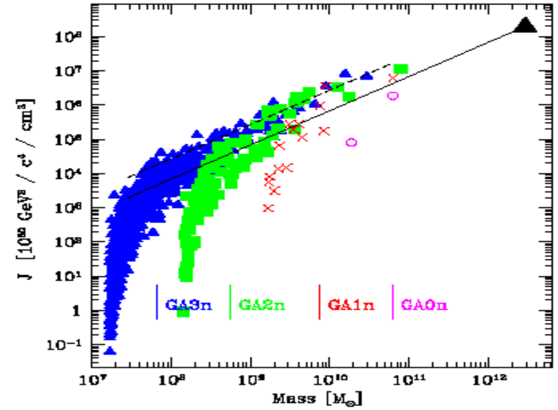
Note on boost factors: the overall average enhancement over a smooth halo, from DM substructure etc, is hardly greater than 2 – 10. In one specific location, however, like the region around the galactic center, factors up to 10^5 are easily possible.

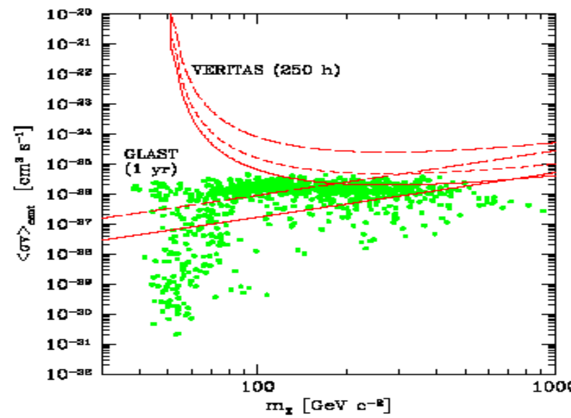
See talk of M. Gustafsson

Boost factor from Dark Matter clumps in the halo



'Milky Way' simulation, Helmi, White & Springel, PRD, 2002

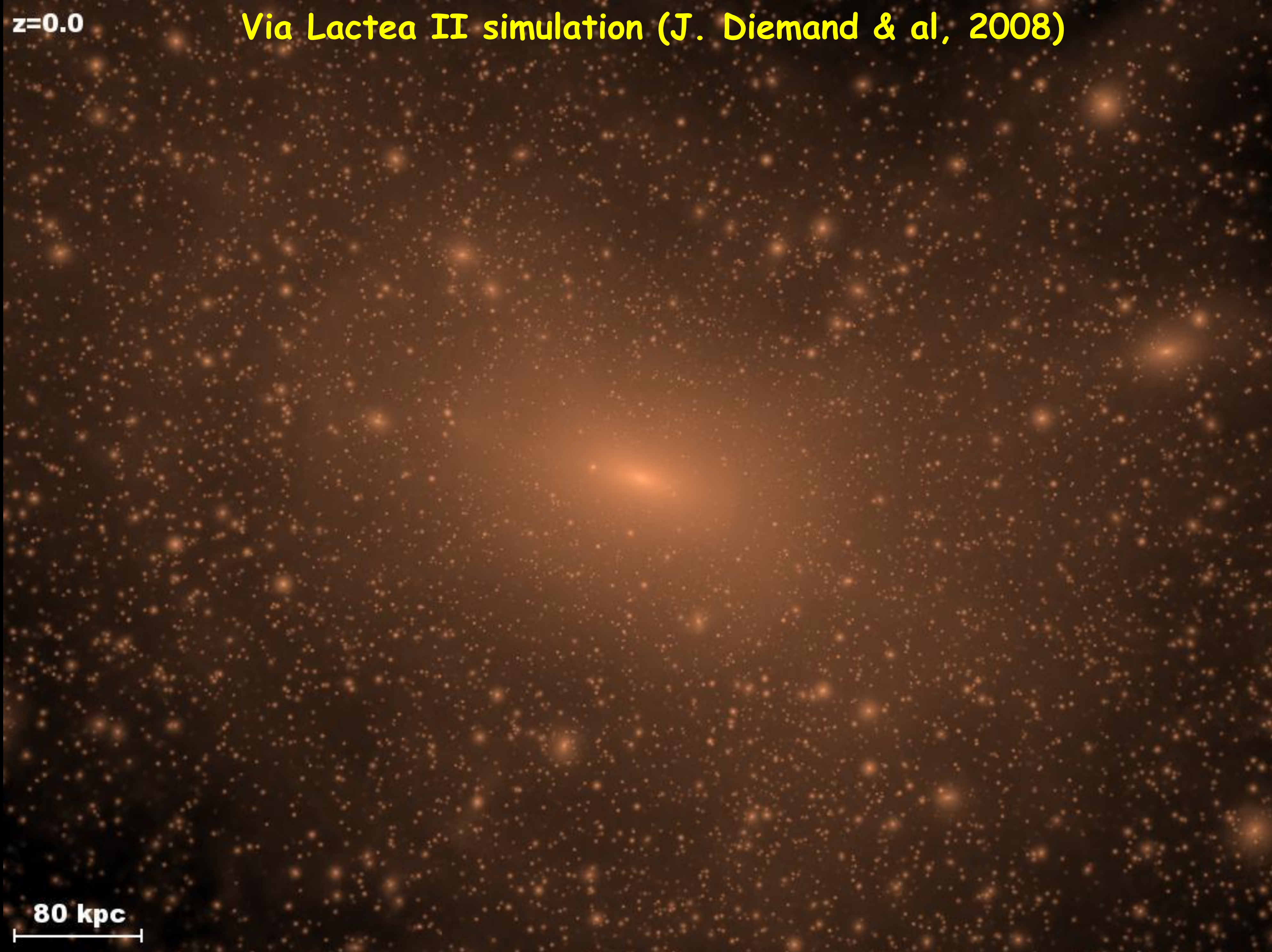




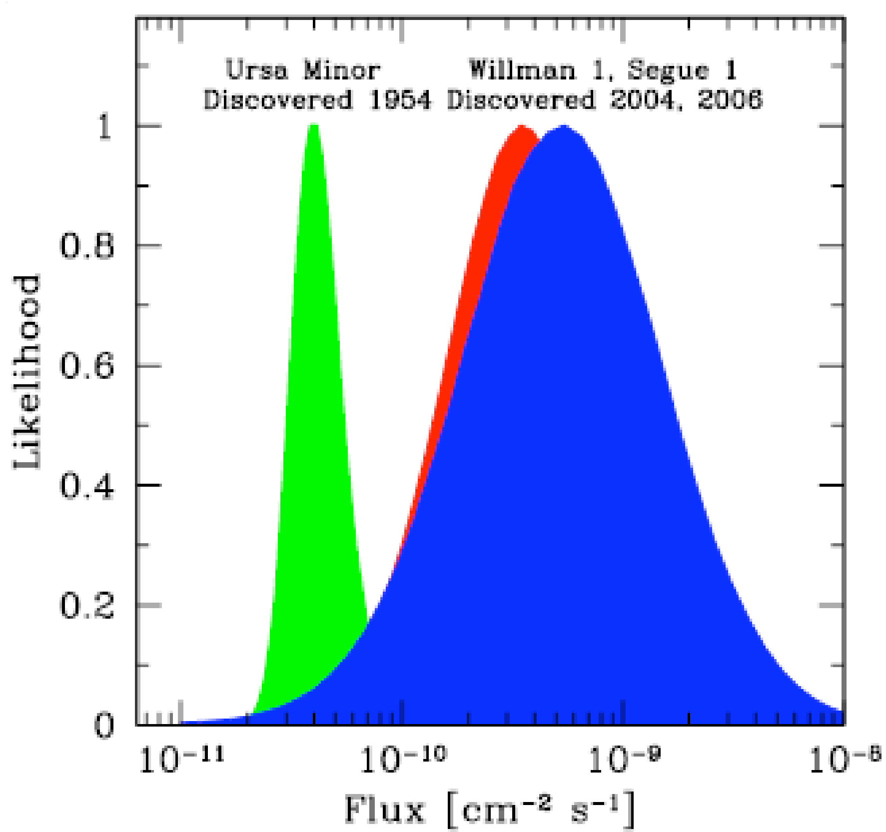
Rates computed with DarkSUSY

Stoehr, White, Springel,Tormen, Yoshida, MNRAS 2003. (Cf Calcaneo-Roldan & Moore, PRD, 2000.)

Important problem: What is the fate of the smallest substructures? Berezinsky, Dokuchaev & Eroshenko, 2003 & 2005; Green, Hofmann & Schwarz, 2003; Diemand, Moore & Stadel, 2005; Ando, 2005; Diemand, Kuhlen, Madau, 2007, V. Springel & al., 2008,...


z=0.0
Via Lactea II simulation (J. Diemand & al, 2008)
80 kpc

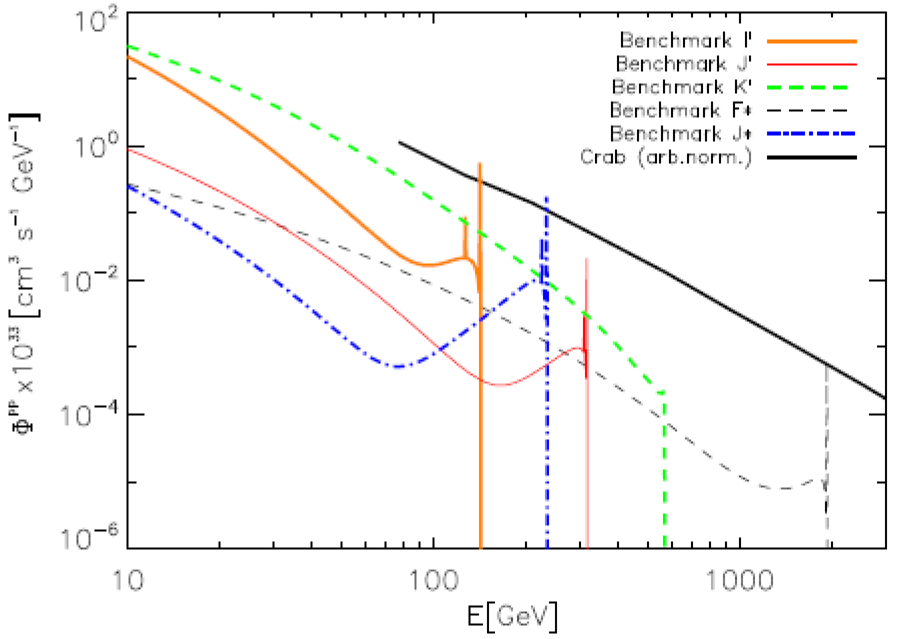
Some of the newly found dwarf galaxies
may give favourable rates:

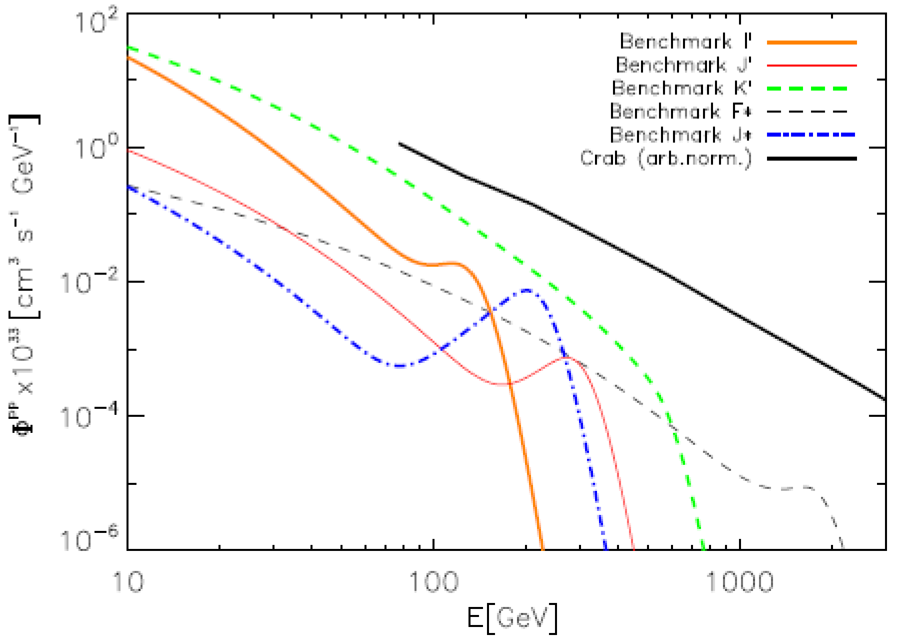


L. Strigari & al, 2008

Bringmann, Doro, Fornasa, arXiv:0809.2269

Draco observations: Importance of radiative corrections





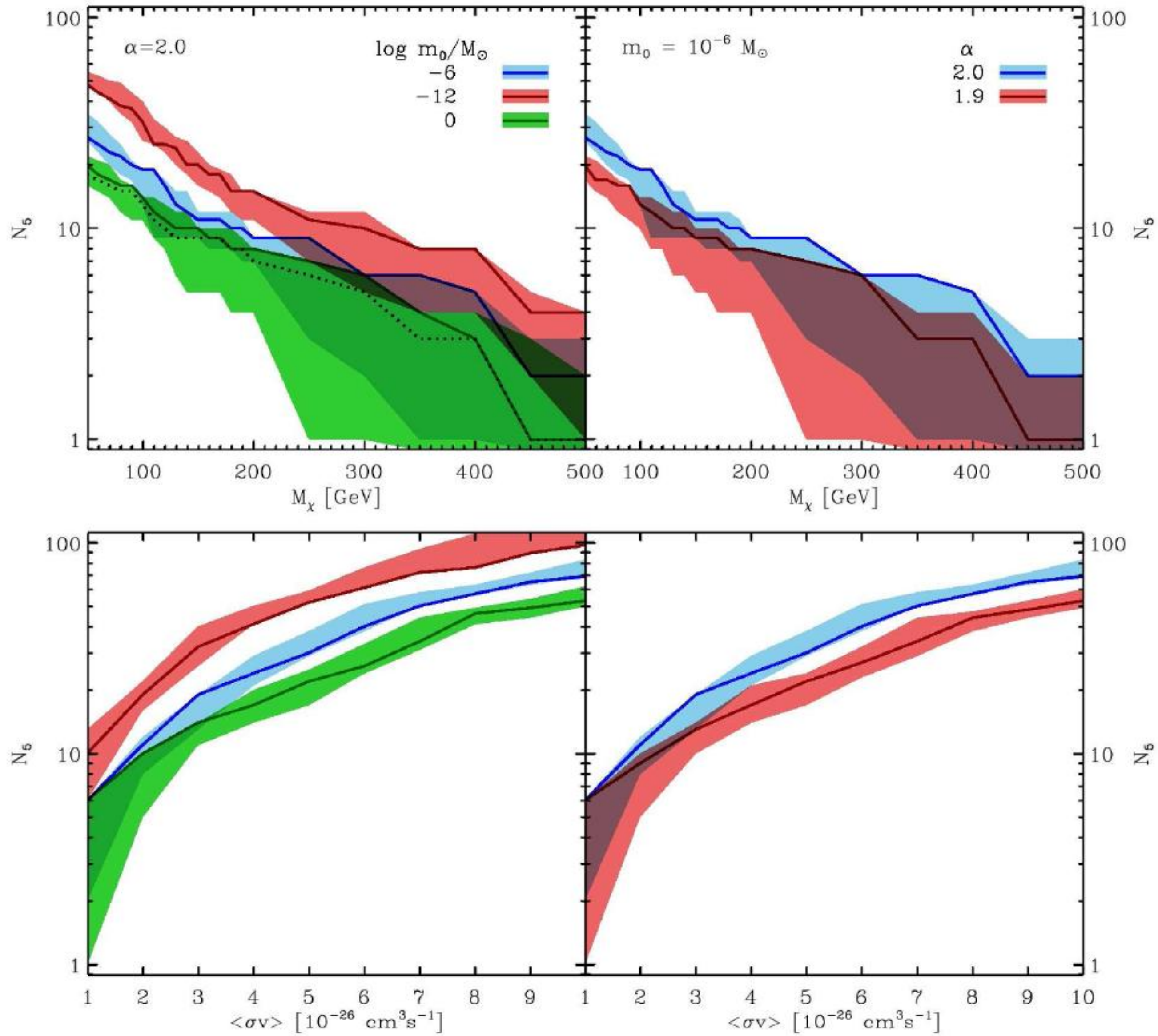
Kuhlen, Diemand & Madau, 2008:

For WIMPs below ~ 300 GeV, GLAST will have a very good chance of gamma-ray detection

(Based on Via Lactea II simulation)

The other large simulation, Aquarius (V. Springel & al.), finds less optimistic results.

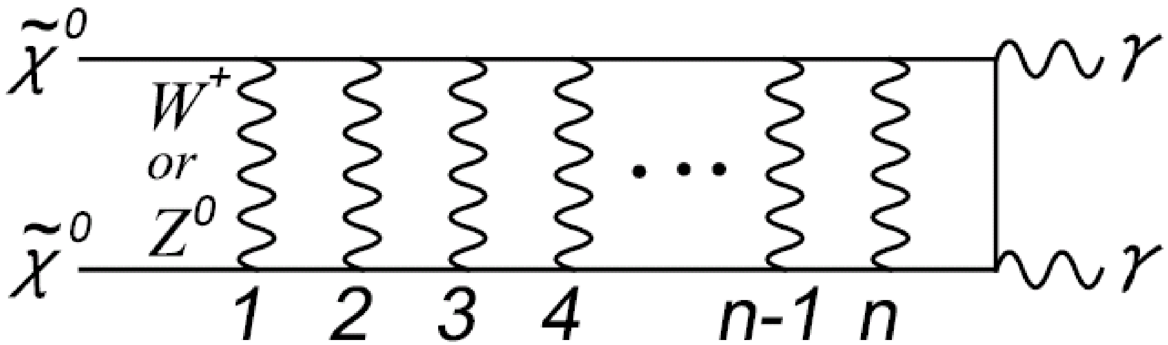
The dust has to settle before making solid predictions…



IG. 7.— N_5, the number of simulated subhalos exceeding $\mathcal{S} = 5$, as a function of the DM particle mass M_χ for $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 ^{1} (*top*) and the cross section $\langle\sigma v\rangle$ for M_χ = 100 GeV (*bottom*). Dependence on the subhalo mass function cutoff mass m_0 for slope = 2.0 (*left*) and on α for $m_0 = 10^{-6}\,M_\odot$ (*right*). The $\alpha = 1.8$ case is almost identical to $\alpha = 1.9$ and has been omitted from this plot. The shaded regions indicate the range of N_5 for ten randomly chosen observer locations and the solid lines refer to an observer placed along the intermediate axis of the host halo ellipsoid. The dotted line is the case without a boost factor.

Interesting possibility for high-mass WIMPs:

Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004



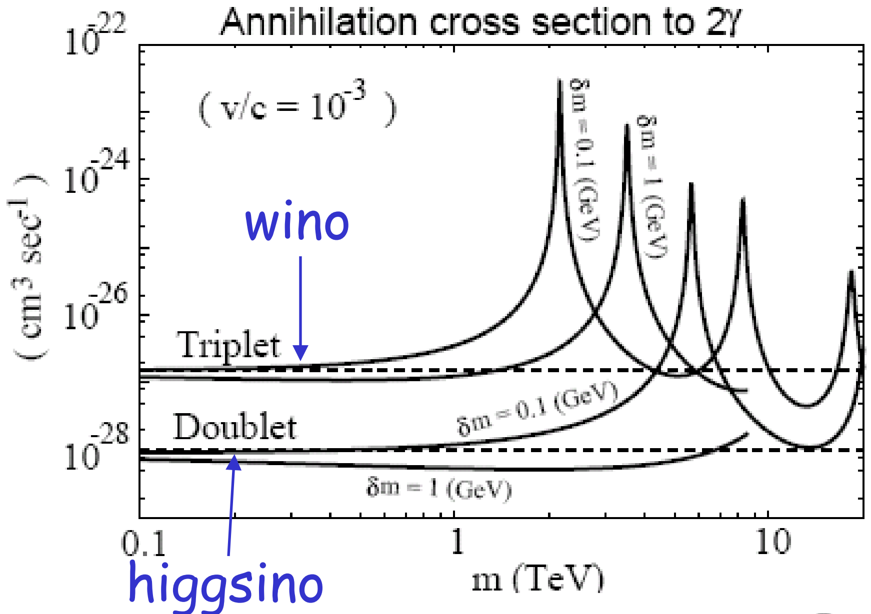
$$\mathcal{S}^{(II)} = \int d^4x d^3r\ \Phi^\dagger(x,\vec{r}) \left\{ \left(i\partial_{x^0} + \frac{\nabla_x^2}{4m} + \frac{\nabla_r^2}{m} \right) - \mathbf{V}(\vec{r}) + 2i\mathbf{\Gamma}\delta(\vec{r}) \right\} \Phi(x,\vec{r})$$

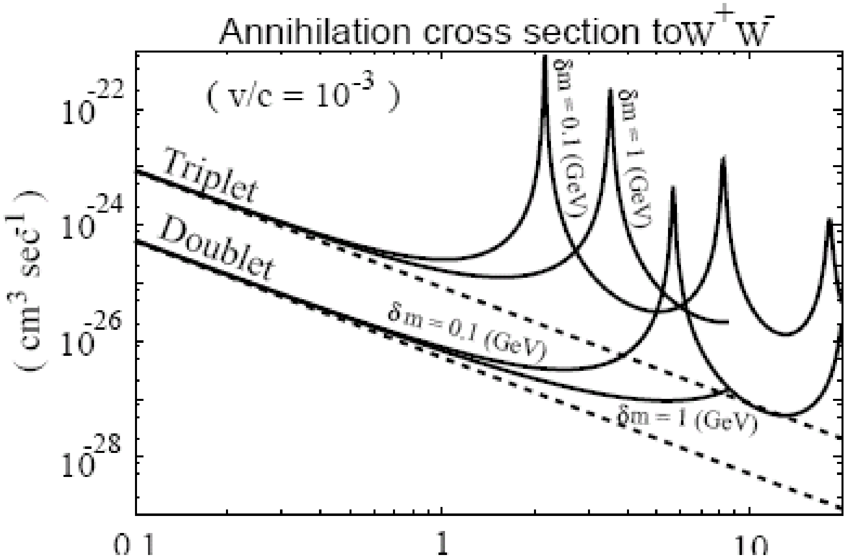
$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

$$\mathbf{\Gamma}_{W^+W^-} = \frac{\pi\alpha_2^2}{4m^2} \begin{pmatrix} 2 & \sqrt{2} \\ \sqrt{2} & 4 \end{pmatrix}, \qquad \mathbf{\Gamma}_{Z^0Z^0} = \frac{\pi\alpha_2^2}{m^2} \begin{pmatrix} c_W^4 & 0 \\ 0 & 0 \end{pmatrix},$$

$$\mathbf{\Gamma}_{\gamma Z^0} = \frac{\pi\alpha\alpha_2}{m^2} \begin{pmatrix} 2c_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \qquad \mathbf{\Gamma}_{\gamma\gamma} = \frac{\pi\alpha^2}{m^2} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}.$$

Neutralino and chargino nearly degenerate; attractive Yukawa force from W and Z exchange $\Rightarrow$ bound states near zero velocity $\Rightarrow$ enhancement of annihilation rate for small (Galactic) velocities. Little effect on relic density (higher v). "Explosive annihilation"!

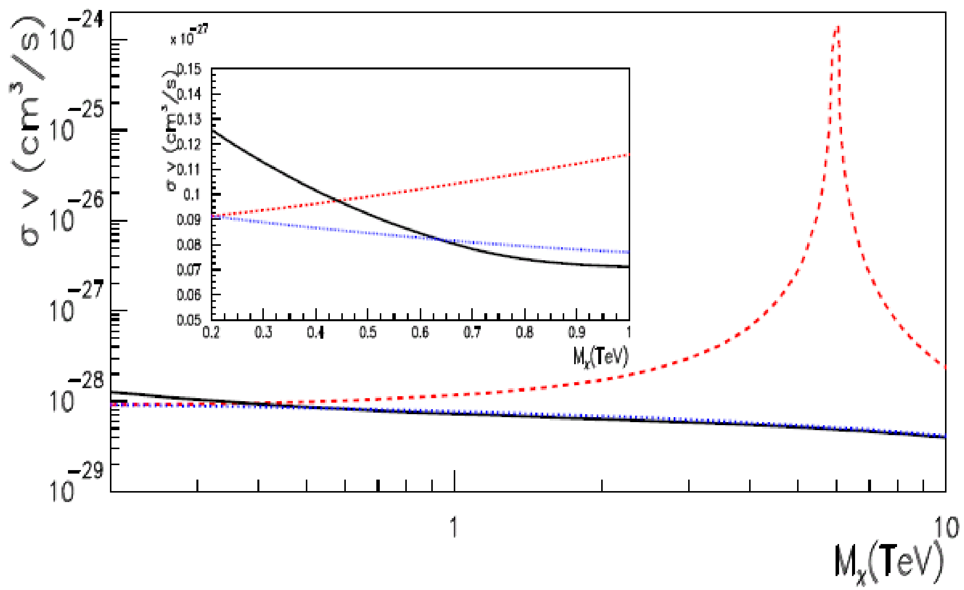




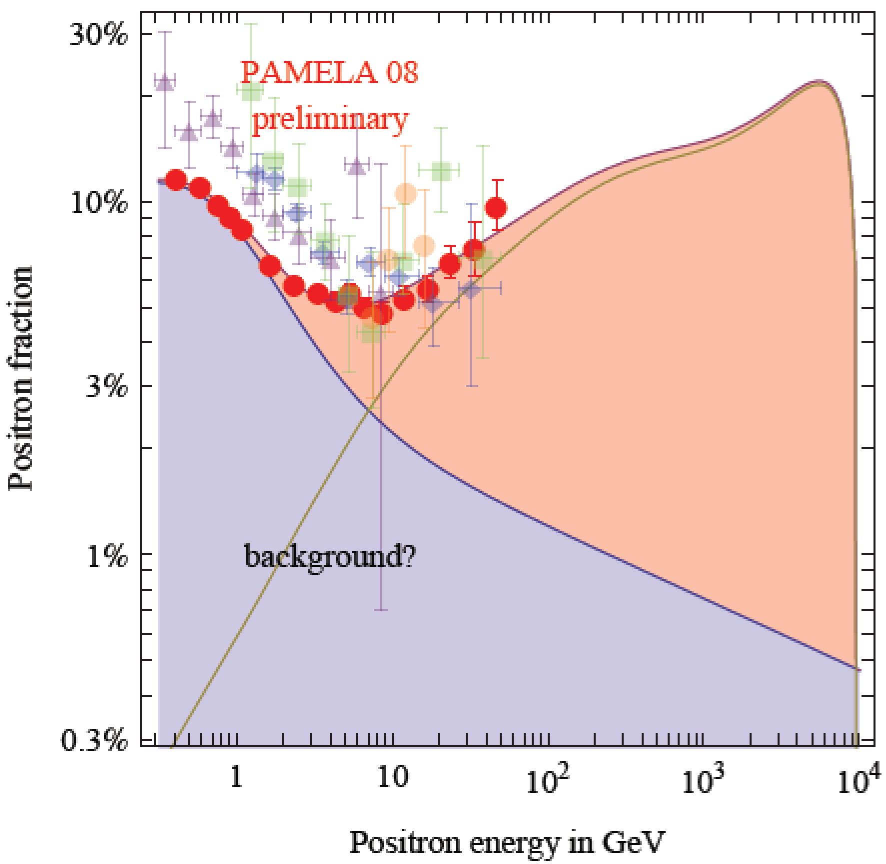
In MSSM without standard GUT condition (AMSB; split SUSY) m_{wino} ~ 2 – 3 TeV; δm ~ 0.2 GeV

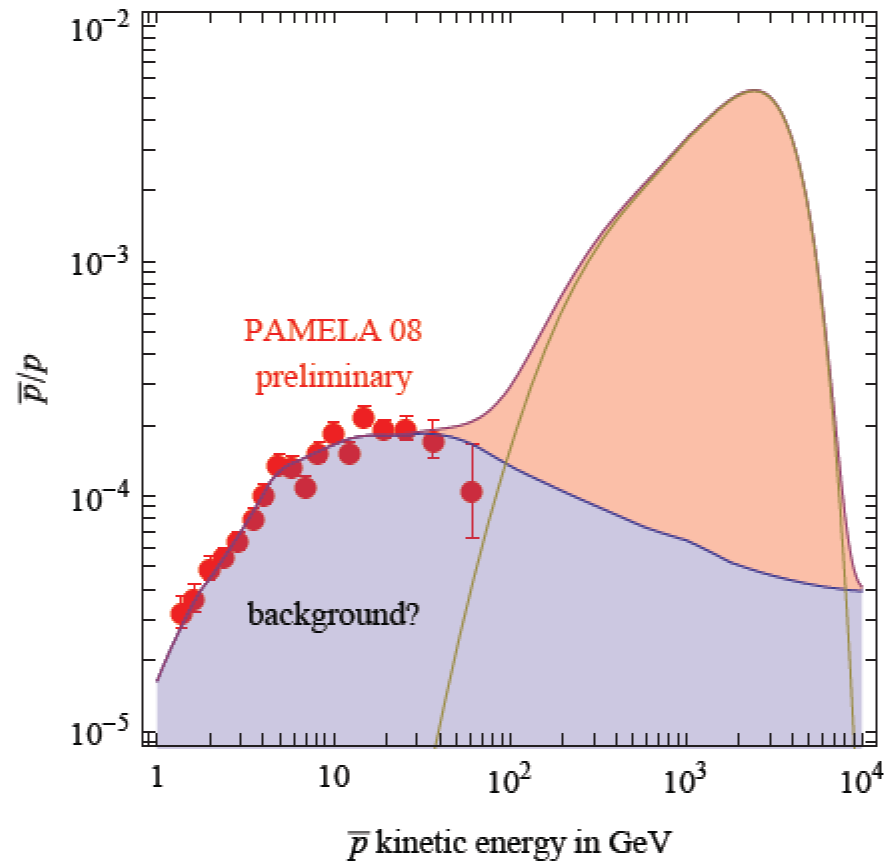
Factor of 100 – 1000 enhancement of annihilation rate possible. B.R. to γγ and Zγ is of order 0.2 – 0.8!

Non-perturbative resummation explains large lowest-order rates to γγ and Zγ. It also restores unitarity at largest masses



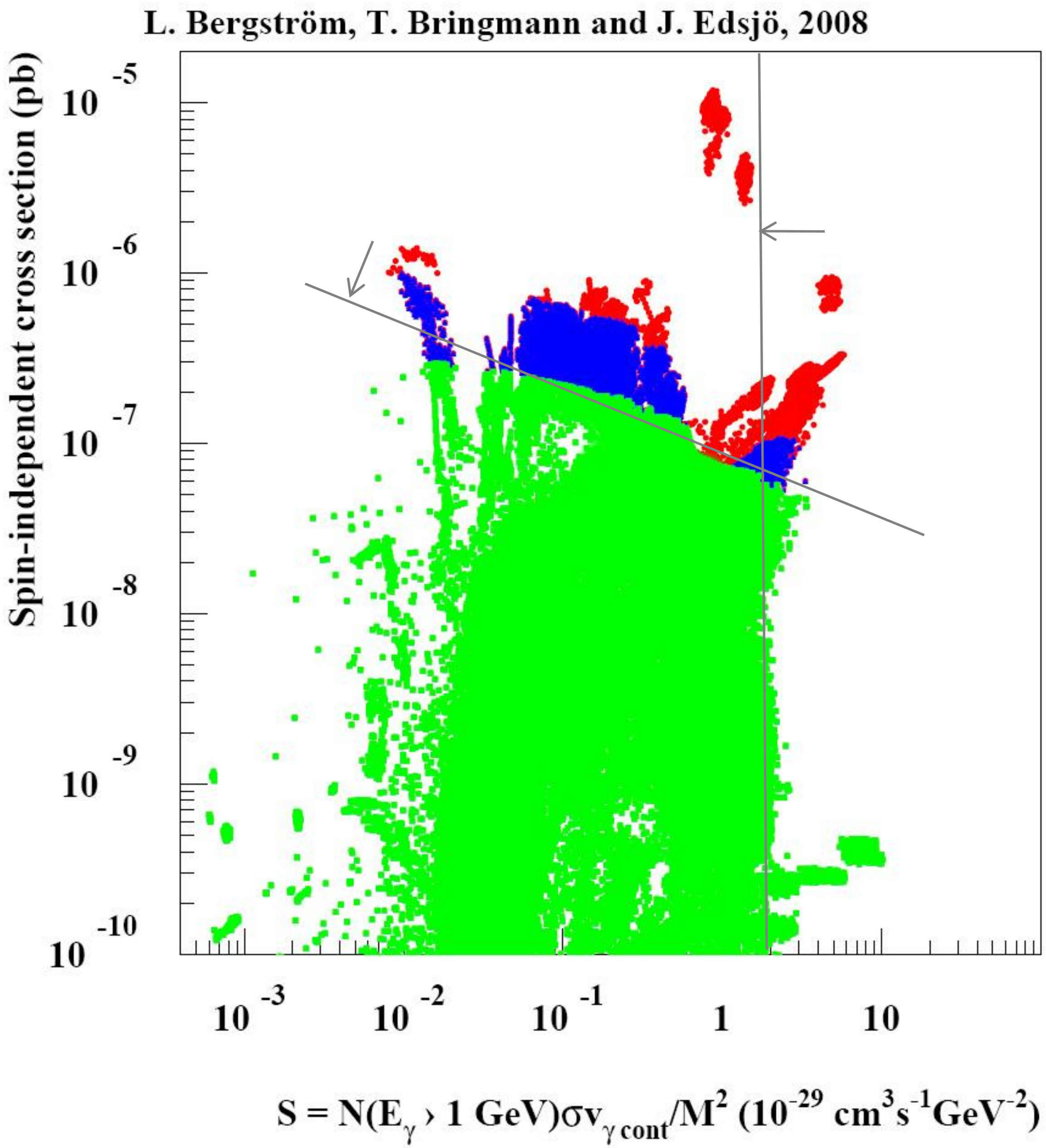
F. Boudjema, A. Semenov, D. Temes, 2005





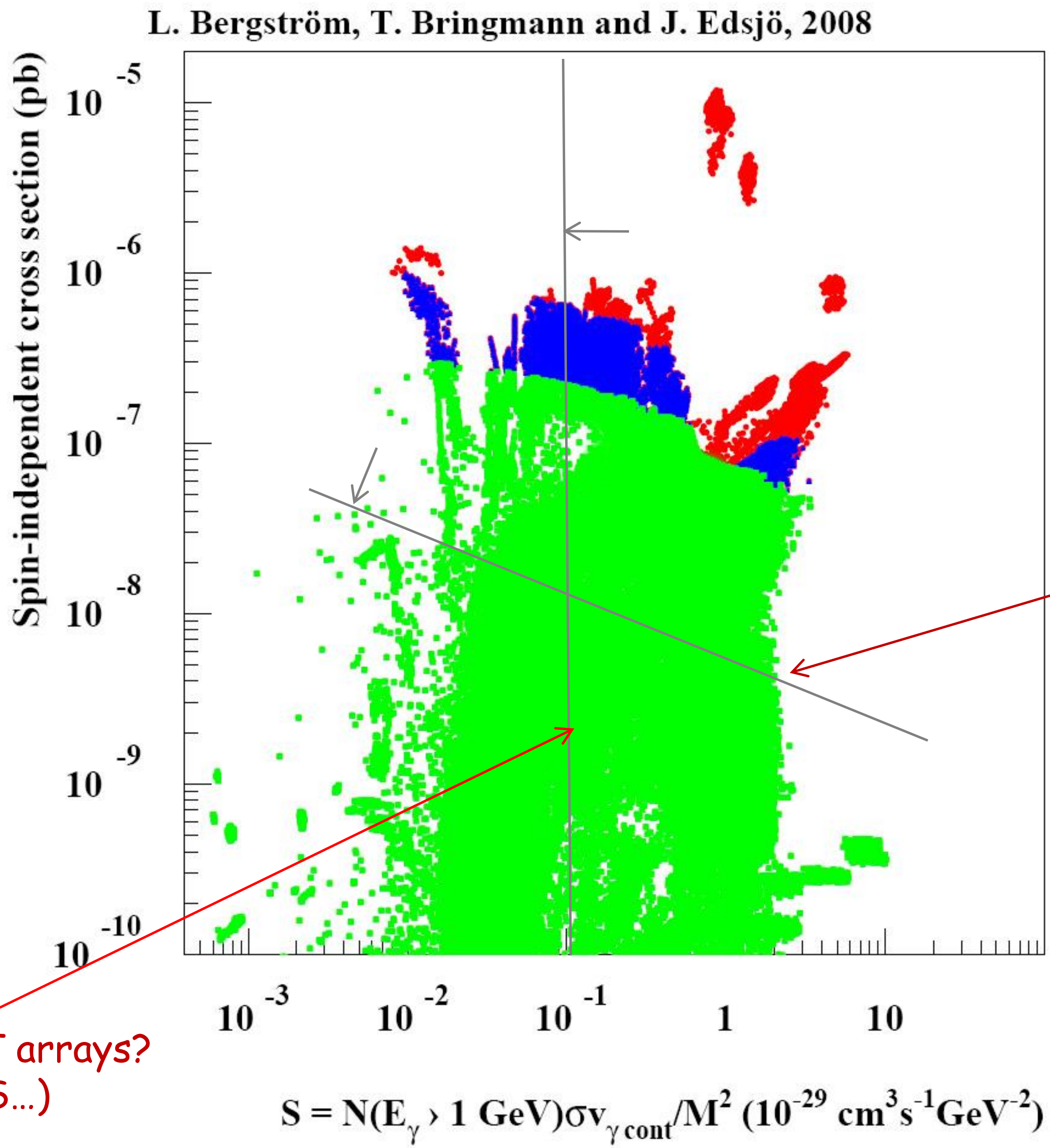
M. Cirelli and A. Strumia, 2008

Complementarity between direct and indirect detection



Present situation

Complementarity between direct and indirect detection



Future direct detection experiments? (Xenon-1 tonne, Super-CDMS)

Future ACT arrays? (CTA, AGIS…)

Summary for gamma rays:

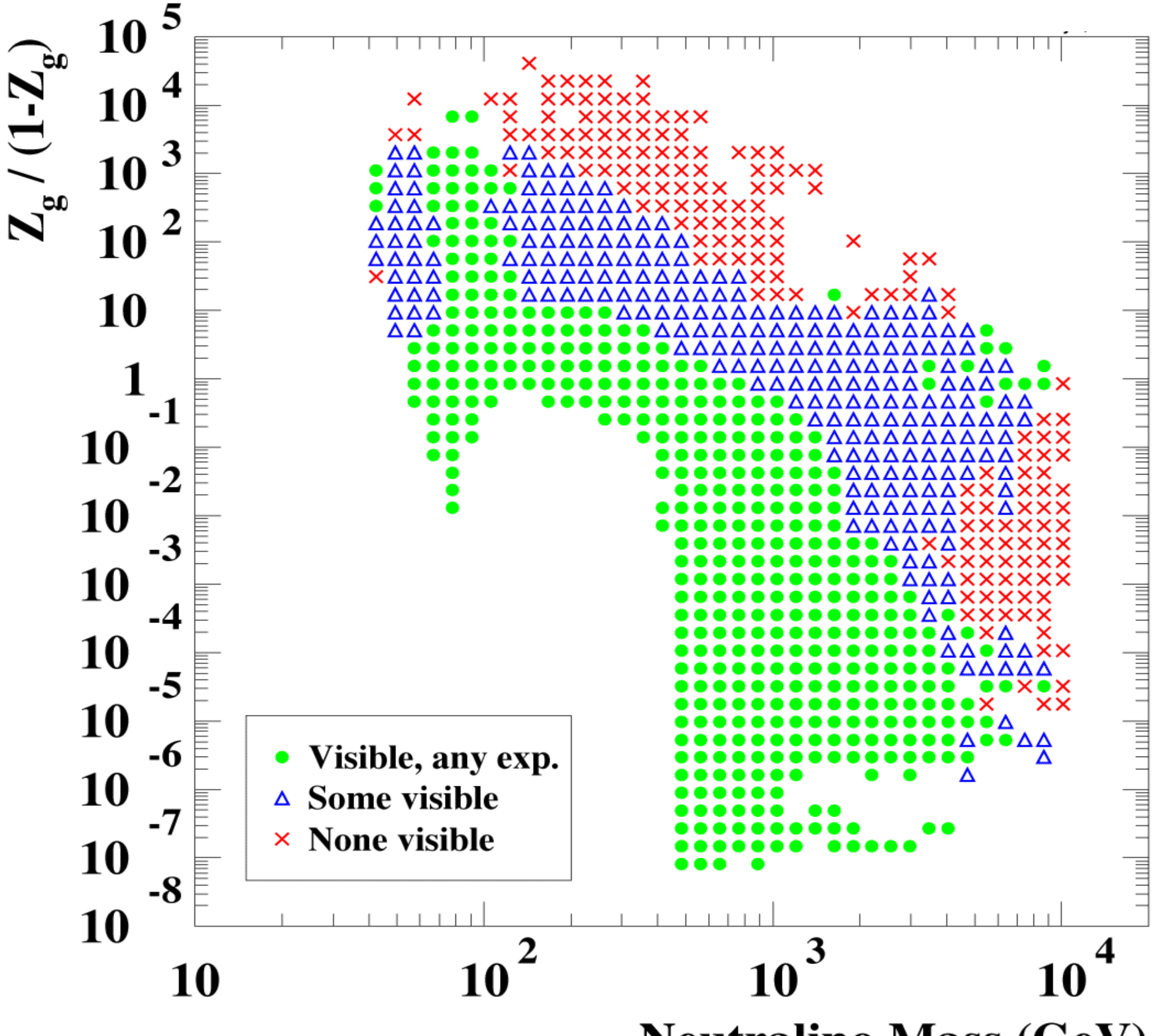
Detection will be challenging. Rates may be too small to stand out against background. However, one set of the most recent N-body simulations give ground for optimism.

A signal may be discriminated by angular or energy spectrum signature. There are other effects that may help detection. Fermi/GLAST will open an important new window for WIMP search. Large Air Cherenkov arrays will be the next step.

Indirect detection through gamma-rays is complemetary to, e.g., direct detection.

Summary of detection methods: MSSM parameter space
All next generation dark matter searches combined

(courtesy J. Edsjö)



Large parts of SUSY parameter space can be probed by future searches – combining direct and indirect (gamma, antiproton, positron, neutrino) detection methods

In most (but not all) of parameter space, LHC will have an impact

Rates computed with DarkSUSY