New Physics with Large Gamma-Ray Telescopes

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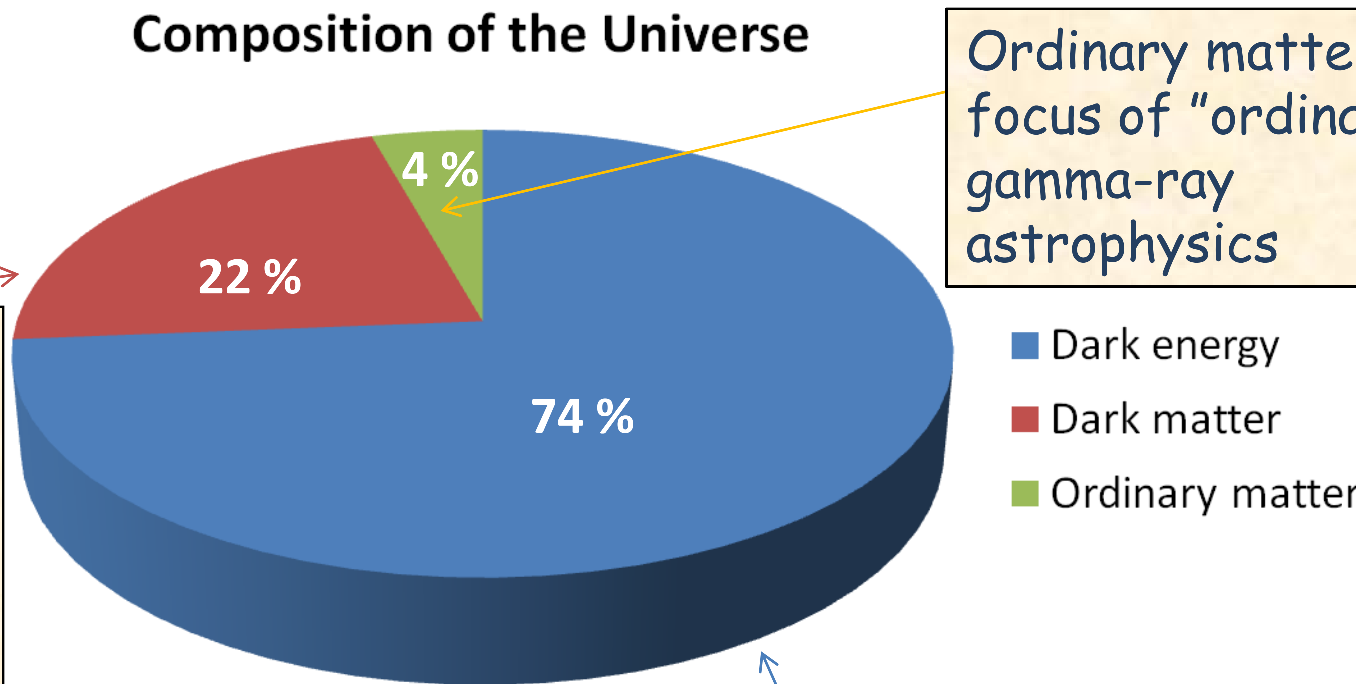
New Physics **needed** in cosmology: Dark Matter and Dark Energy

New Physics **needed** in particle physics: Neutrino Masses, Baryon Asymmetry, Higgs(es), Hierarchy $m_W \ll m_{Pl}$

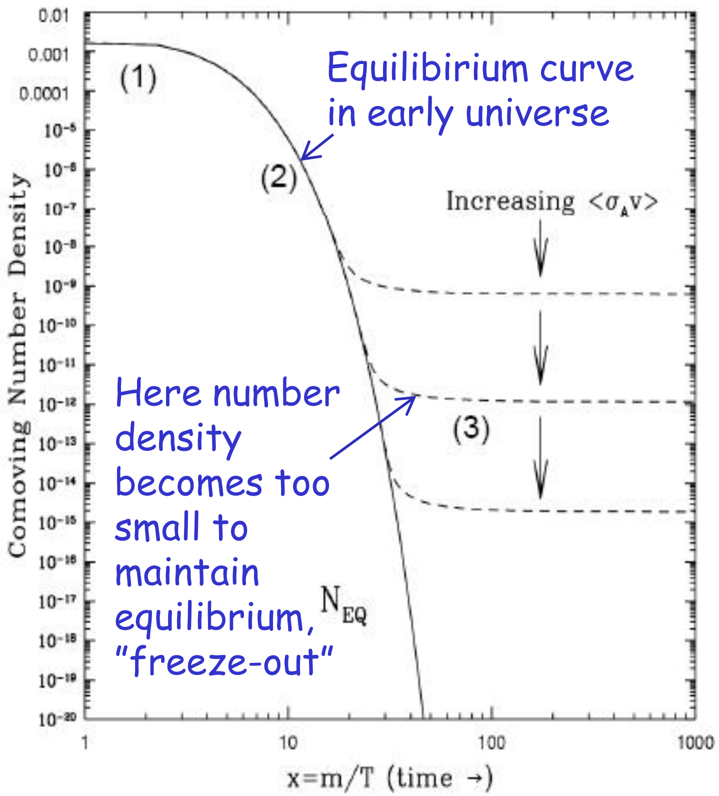


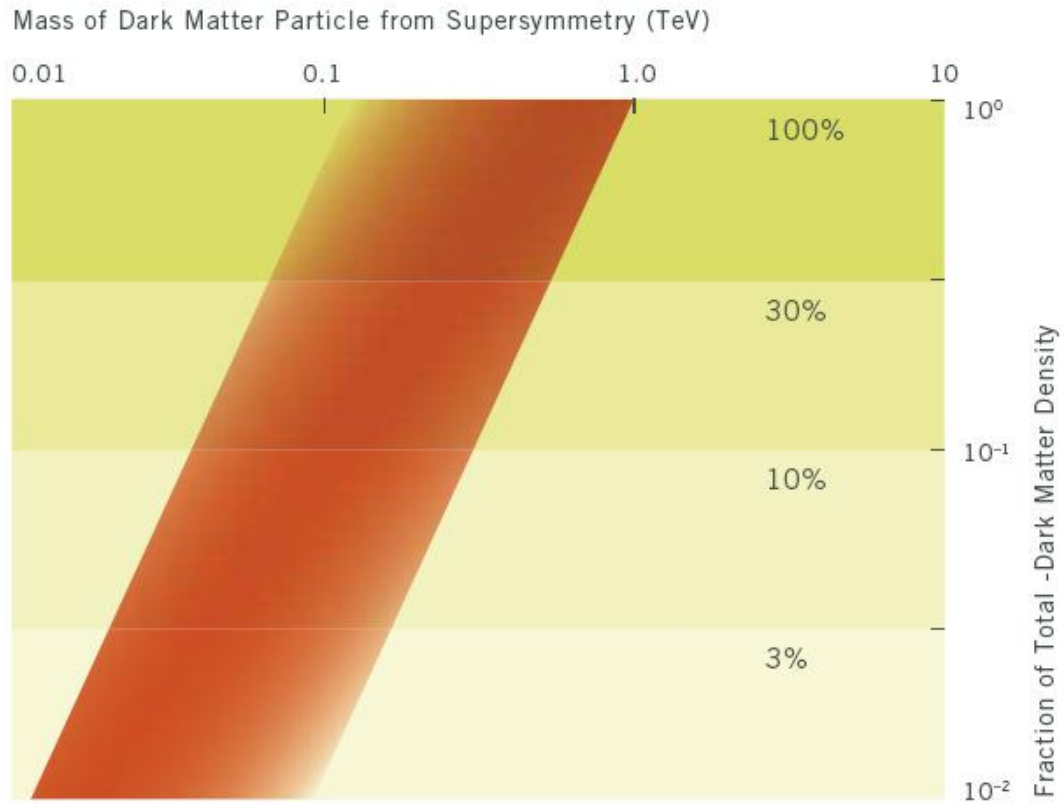
Ordinary matter: focus of "ordinary" gamma-ray astrophysics

Dark Matter: What is it? Is it related to new particle physics? Does it have a signature in gamma-rays?

Dark energy: cosmological constant or time-evolving field? Probably no connection to gamma-ray astrophysics?

The "WIMP miracle"

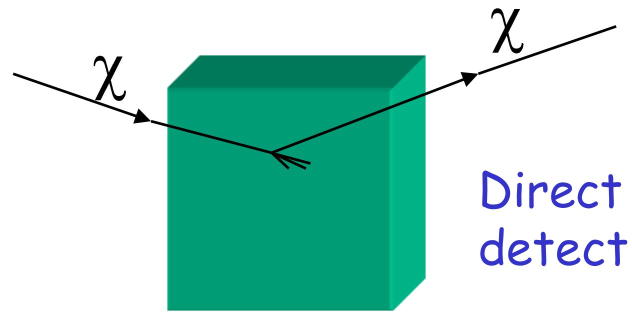




J. Feng & al, ILC report 2005

Methods of WIMP Dark Matter detection:

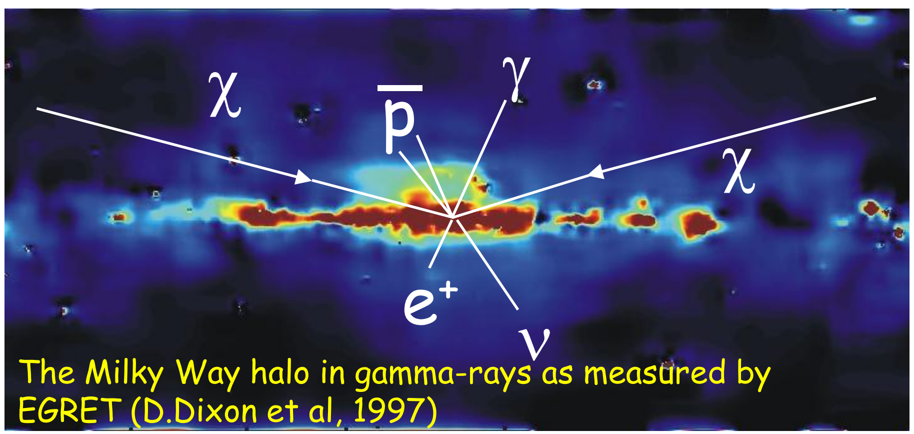
- Discovery at accelerators (Fermilab, LHC, ILC...).
- Direct detection of halo particles in terrestrial detectors.
- Indirect detection of neutrinos, gamma rays, antiprotons, positrons in ground- or space-based experiments.
- For a convincing determination of the identity of dark matter, plausibly need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



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

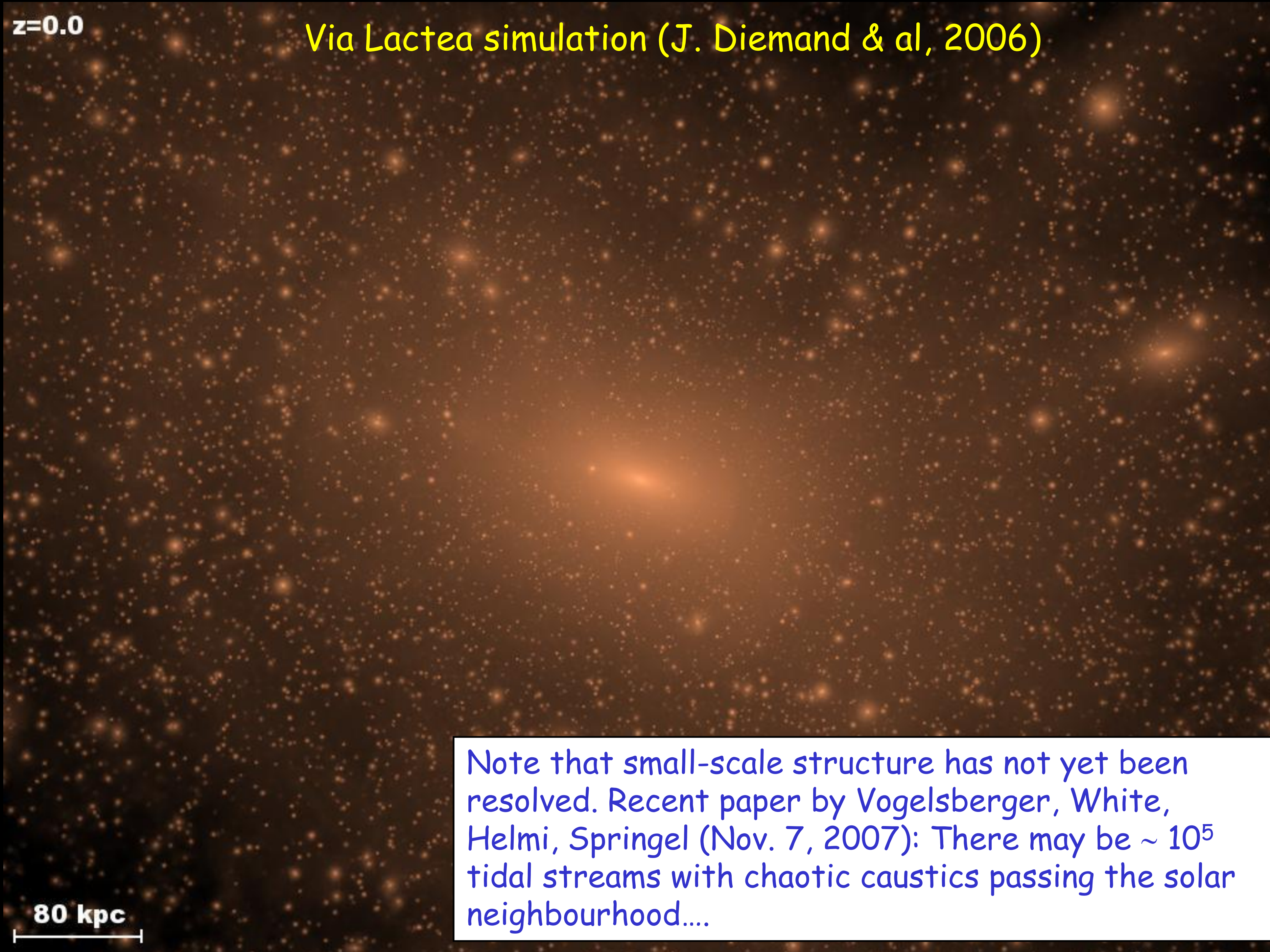


The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

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

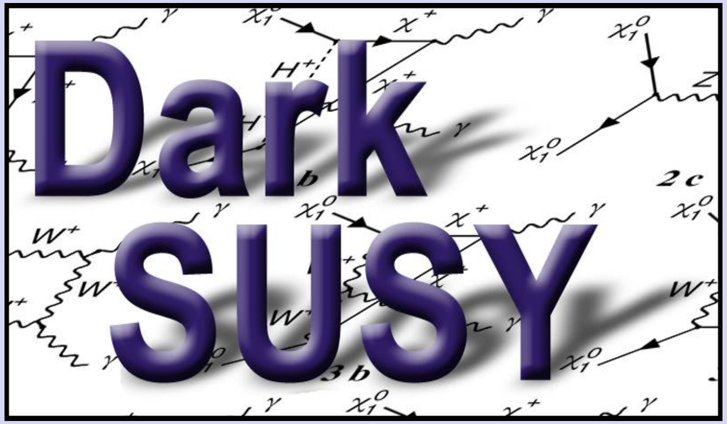
Annihilation rate enhanced for clumpy halo; near galactic centre and in subhalos

Via Lactea simulation (J. Diemand & al, 2006)



Note that small-scale structure has not yet been resolved. Recent paper by Vogelsberger, White, Helmi, Springel (Nov. 7, 2007): There may be ~ 10^5 tidal streams with chaotic caustics passing the solar neighbourhood….

Template for WIMP: the lightest supersymmetric particle – prime candidate for Dark Matter (solves the hierarchy problem)



P. Gondolo, J. Edsjö, L.B., P. Ullio, Mia Schelke and E. A. Baltz, JCAP 0407:008, 2004 [astro-ph/0406204]

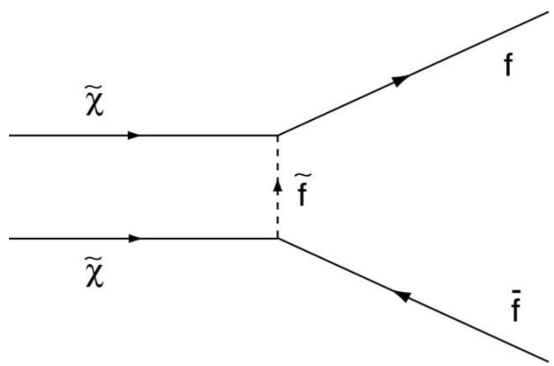
"Neutralino dark matter made easy" – public code. Can be freely dowloaded from http://www.physto.se/~edsjo/ds

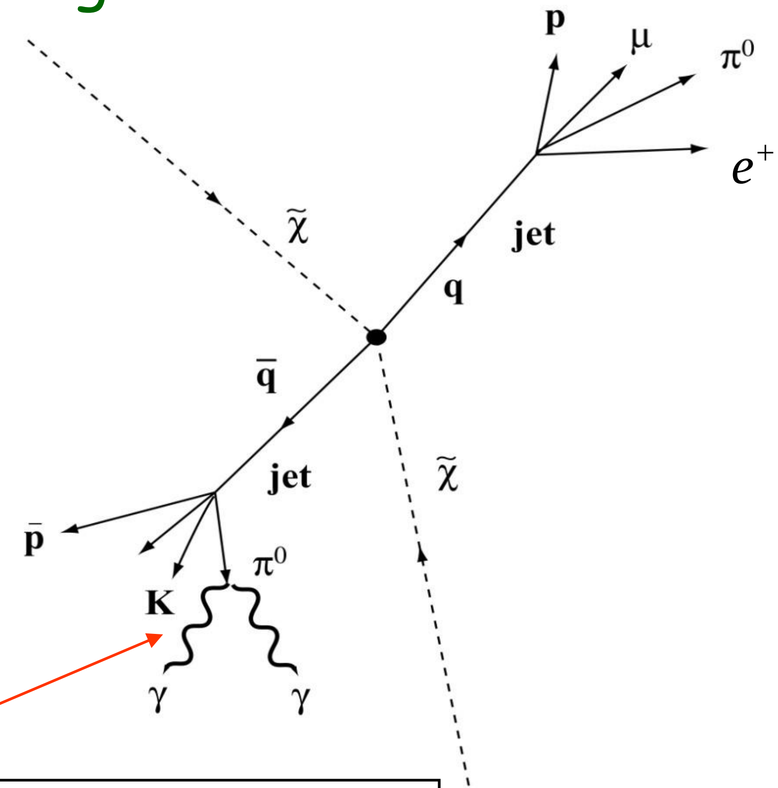
Other codes: micrOMEGAs (Bélanger & al. - public); Baer & al.; Bottino & al.; Falk & al.; Roszkowski & al…

Release 4.1: includes coannihilations & interface to Isasugra

New release 4.2 soon, interface to Galprop, important QED corrections. Already available from edsjo@physto.se

Example of indirect detection: annihilation of neutralinos in the galactic halo



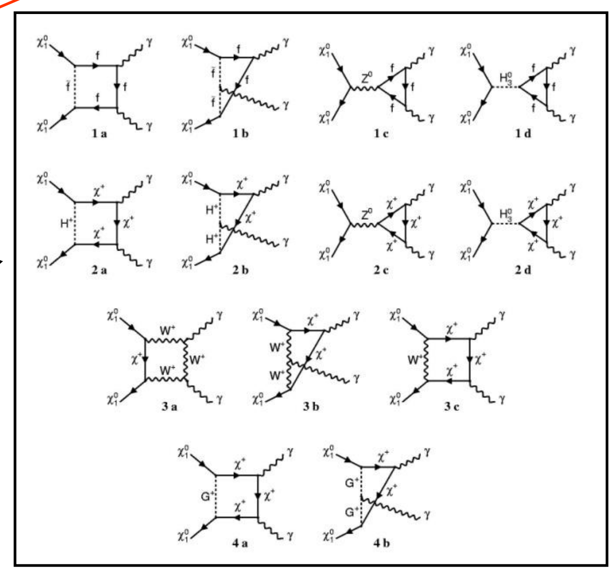


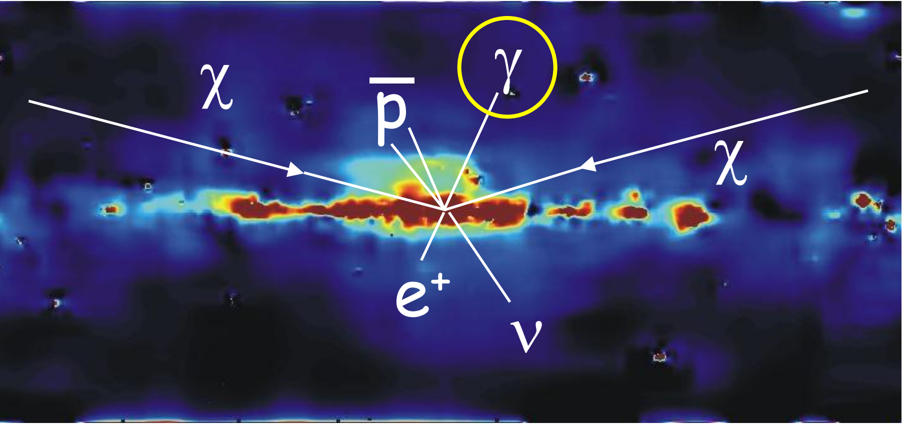
Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

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





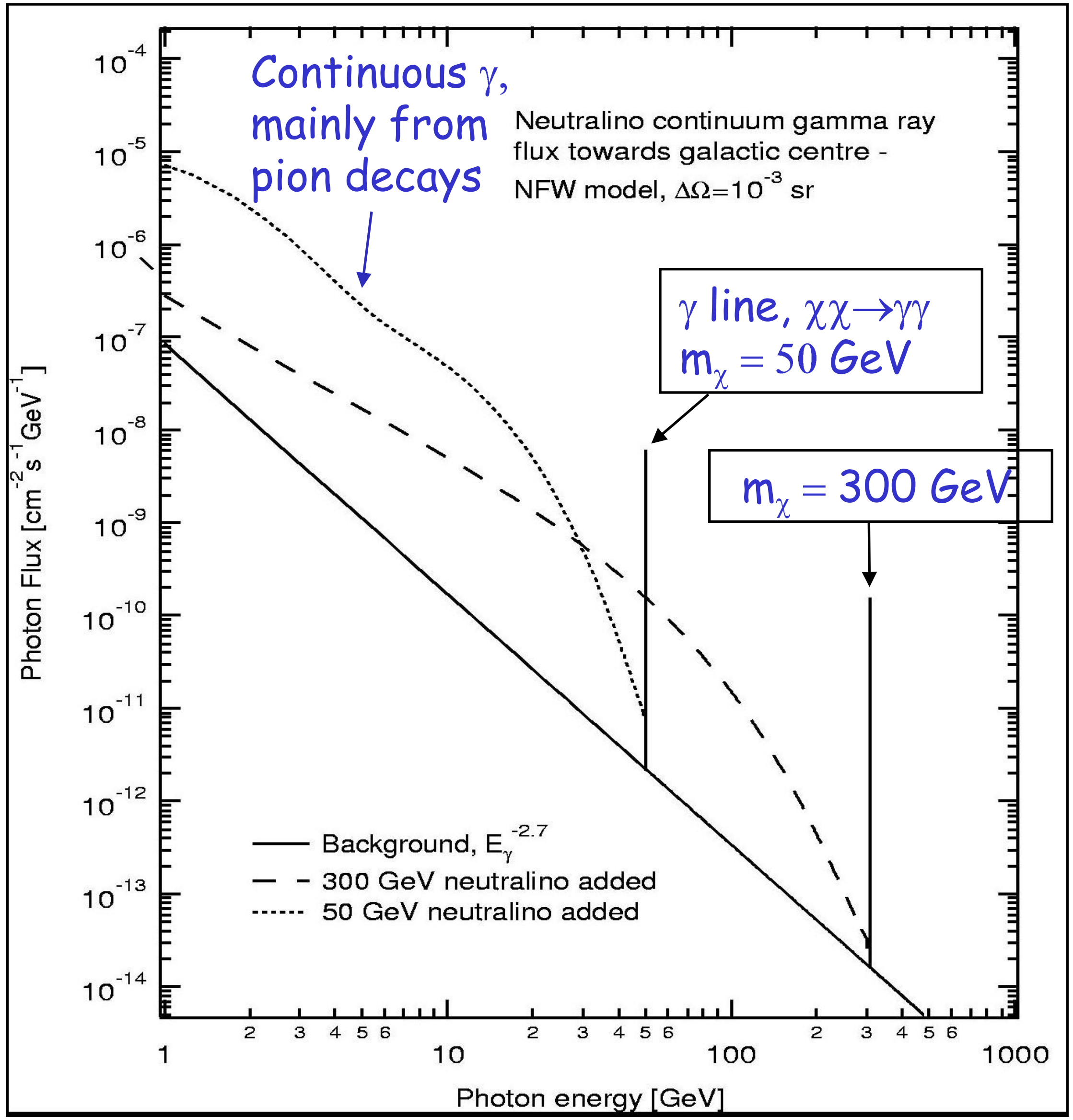
Gamma-rays from DM annihilation

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

- Continuous
  and
- Monoenergetic line

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

Unfortunately, large uncertainties in the predictions of absolute rates

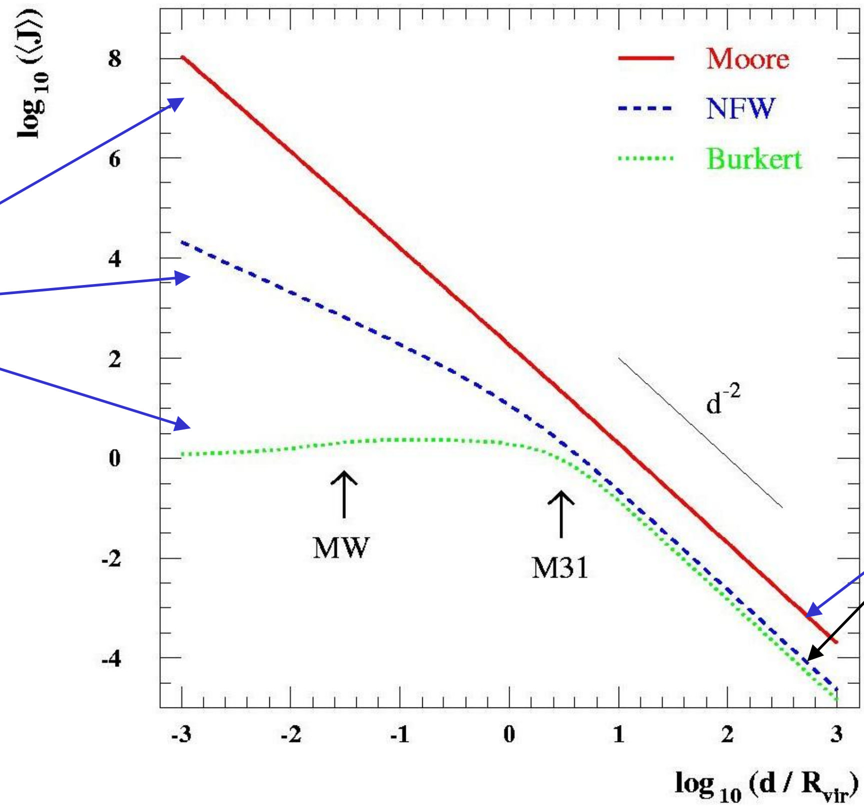


L.B., P.Ullio & J. Buckley 1998

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

~ <σv> ~ J

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



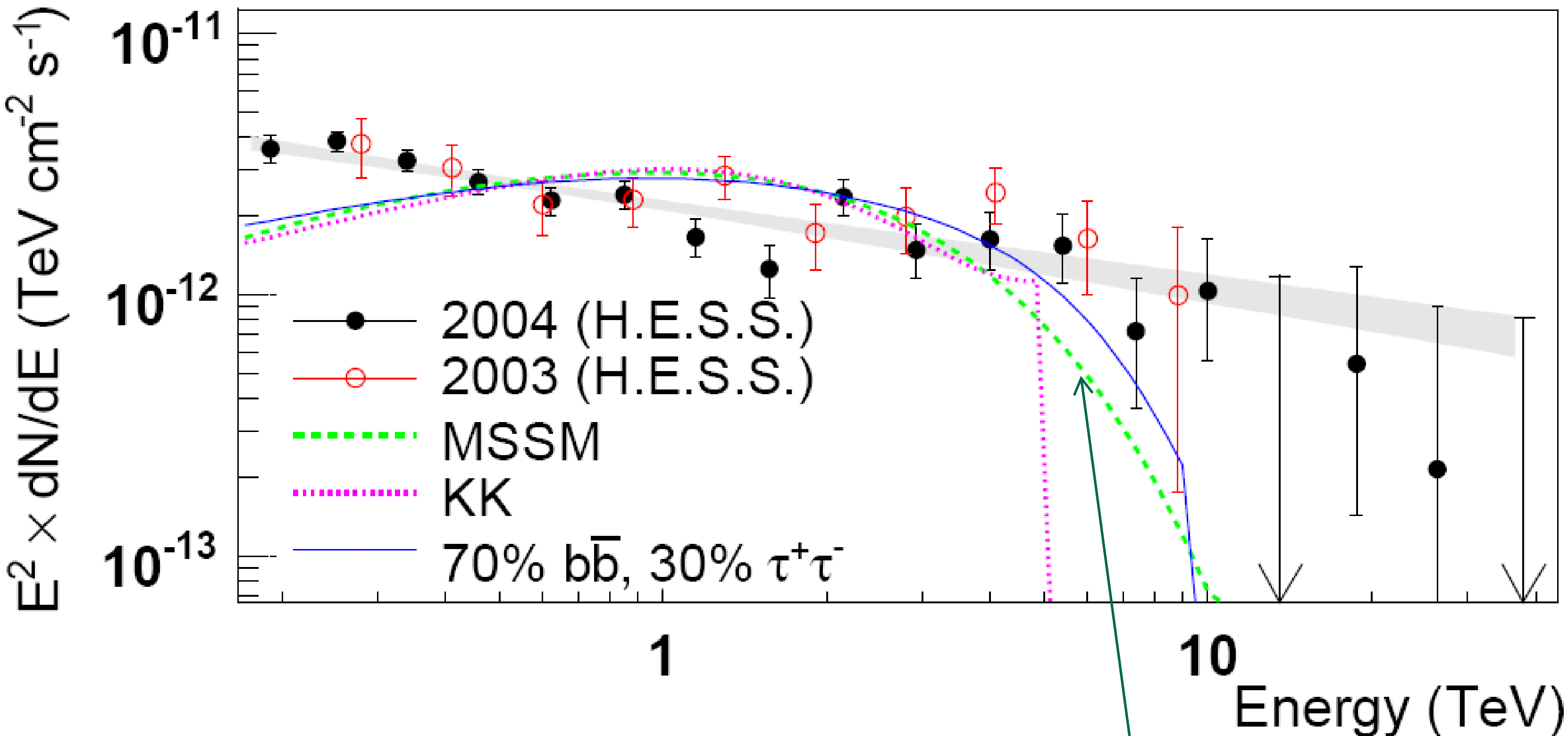
In this region (for small clumps or cosmological distances), the uncertainty is much smaller

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.

2006: H.E.S.S. data towards galactic centre

MAGIC (2006) data agree with HESS

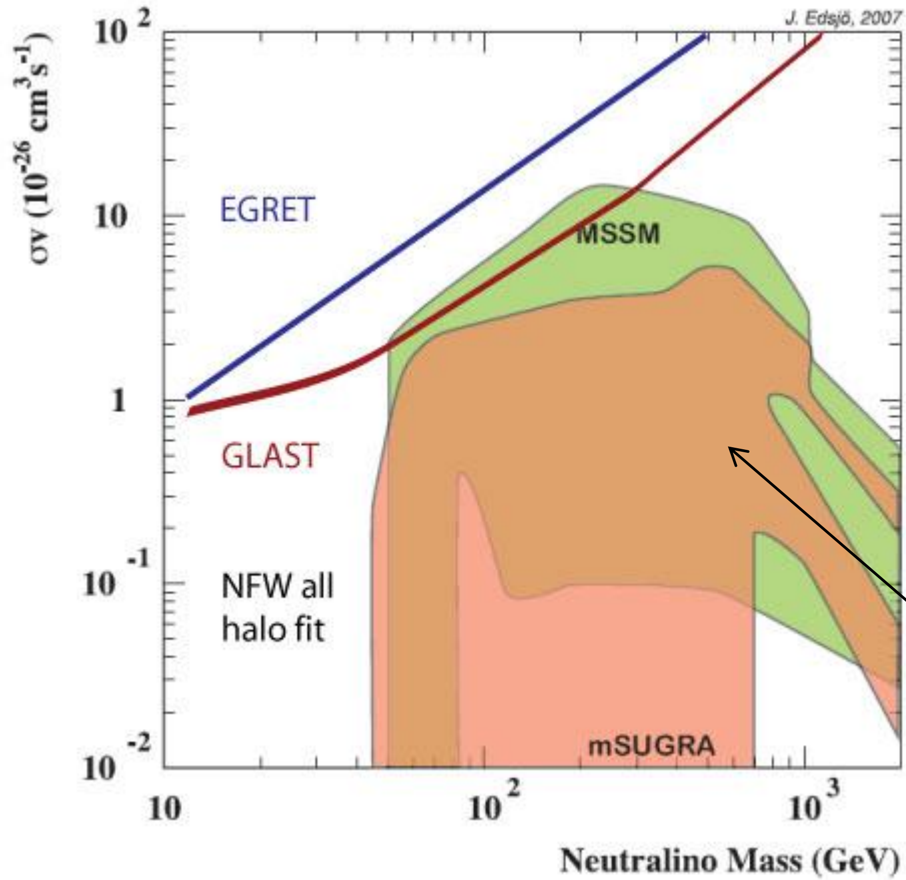


Steady (time-independent) spectrum, pointlike within HESS angular resolution, could be Moore cusp instead of NFW?

But: Probably too high energy (and wrong shape of spectrum) for WIMP annihilation explanation

Shape of these curves uncertain, depends on QED corrections and fragmentation of 5-10 TeV jets. LHC should give important input here.

3σ exclusion limit, 1 year of GLAST data

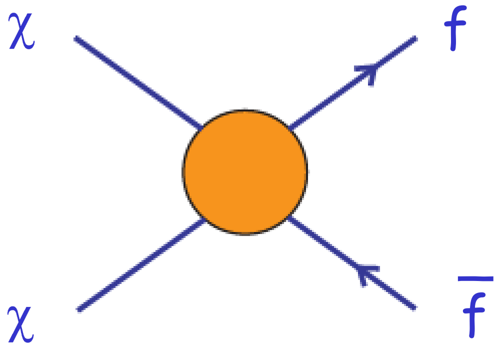


"Conservative" approach, NFW halo profile assumed, no substructure.
Moore halo + substructure would improve the limits and detection potential by 1-2 orders of magnitude.

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

GLAST working group on Dark Matter and New Physics, E.A. Baltz & al., in preparation (2007).

How to avoid helicity suppression for Majorana particles

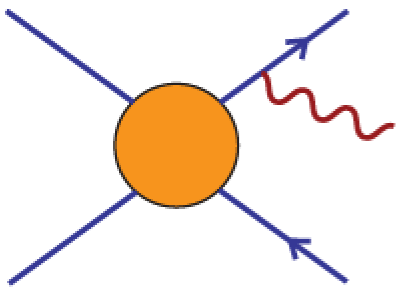


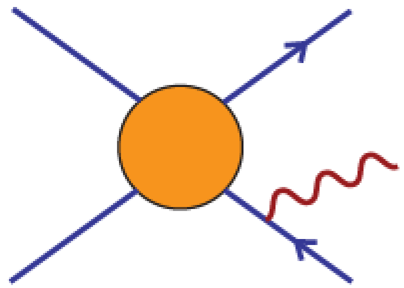
$\sim m_f$

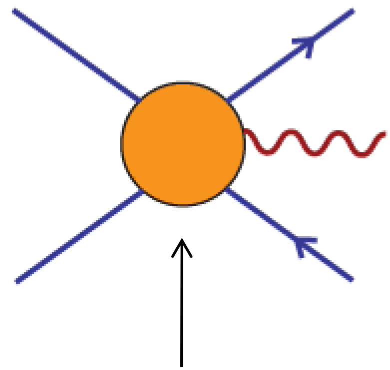
for Majorana particles in limit $v/c \to 0$

"Final state radiation"

"Internal bremsstrahlung", IB

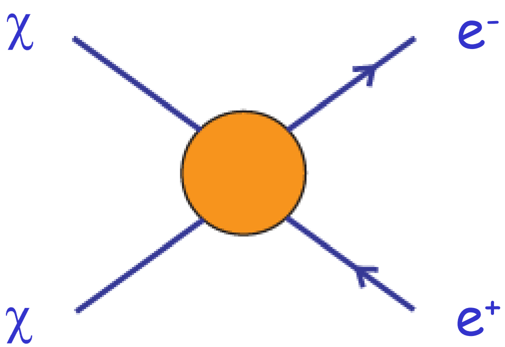






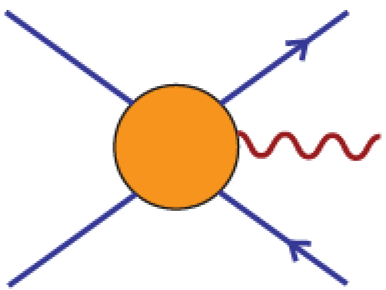
$\sim m_f$ $\sim m_f$ No m_f suppression!

Example, annihilation into electrons and positrons:



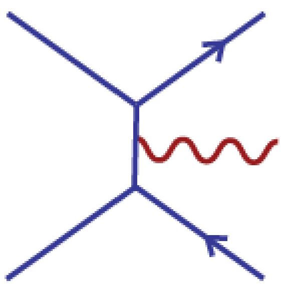
Annihilation rate $\sigma v \sim 3{\cdot}10^{-26}$ $cm^{-3}s^{-1}$ at freeze-out, due to non-suppressed p-wave in early universe, $(v/c)^2 \sim 0.3 \Rightarrow$ WMAP relic density constraint fulfilled, $\Omega_{CDM}h^2 = 0.1$

Annihilation rate in the halo today $\sigma v \sim 10^{-25}\,(m_e/m_\chi)^2\ cm^3s^{-1} \sim 10^{-37}\ cm^3s^{-1}$ for slow-moving χ of mass 500 GeV. Impossible to detect!



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

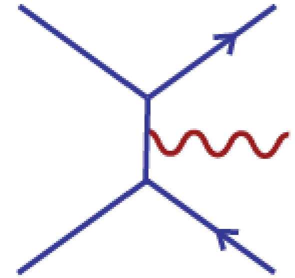
t-channel selectron exchange



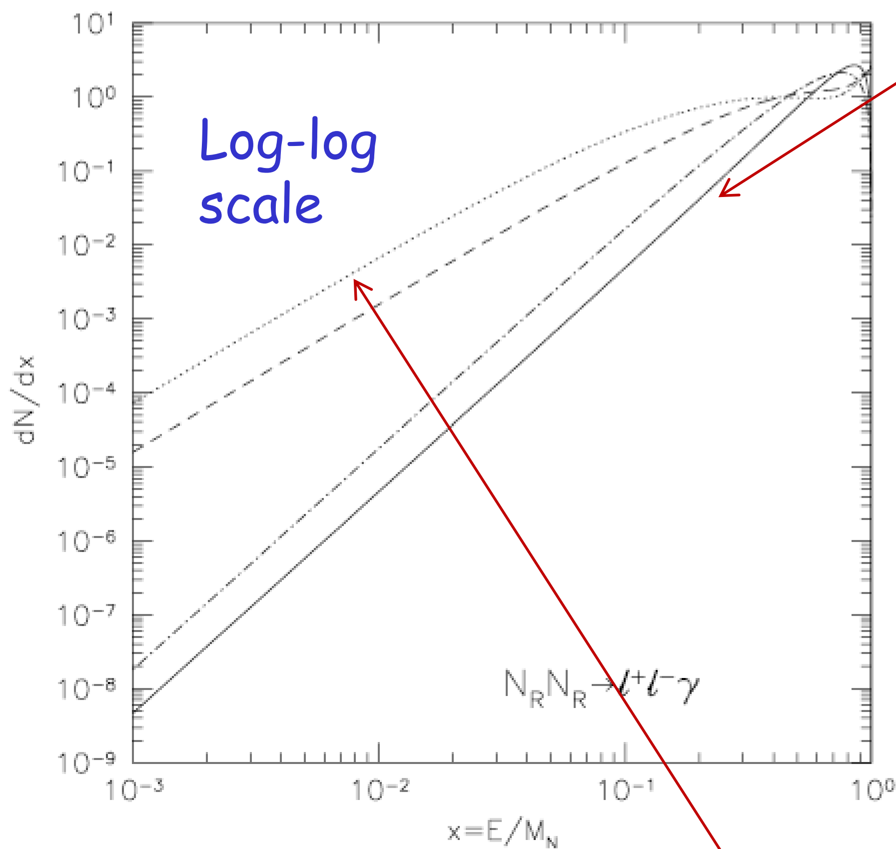
The "typical" QED correction of a per cent is here a factor of a billion instead! May give detectable rates!

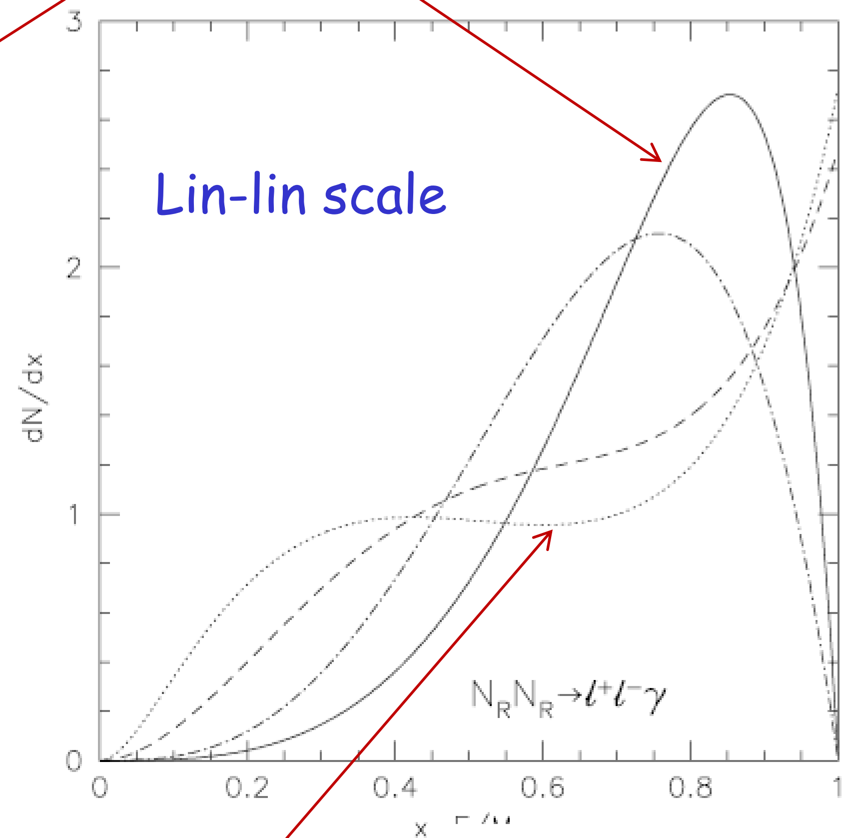
(L.B. 1989)

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 model of see-saw)



Gamma-ray spectrum

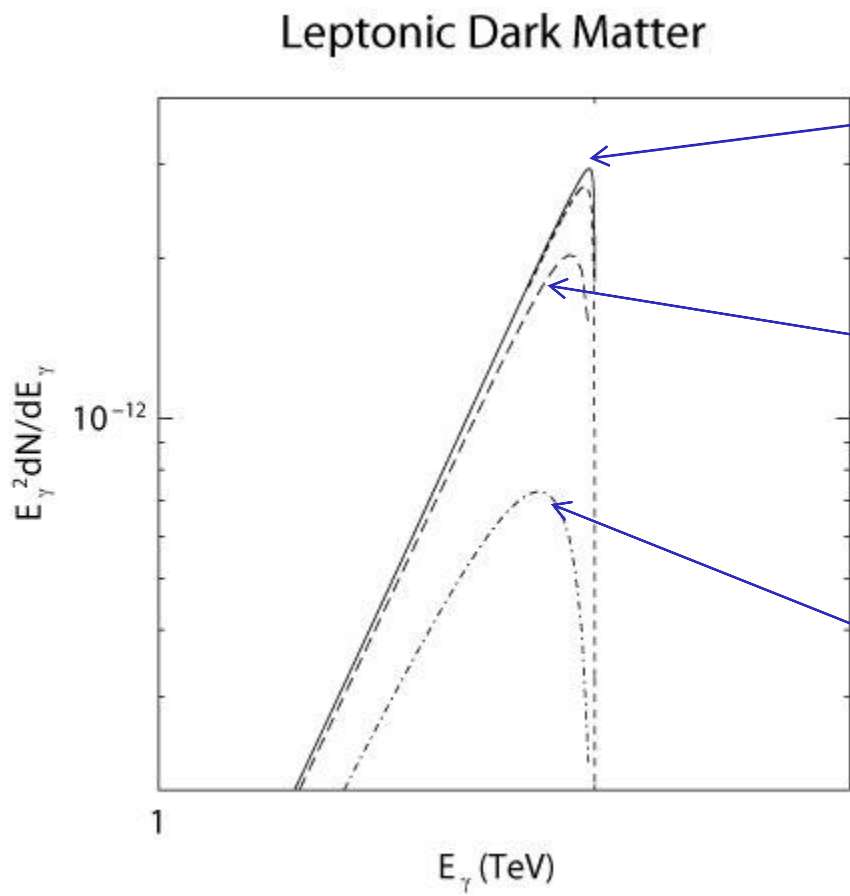




Electron spectrum

Almost like a delta function at highest gamma-ray energy!

Dependence on mass degeneracy between dark matter particle and particle in the t-channel

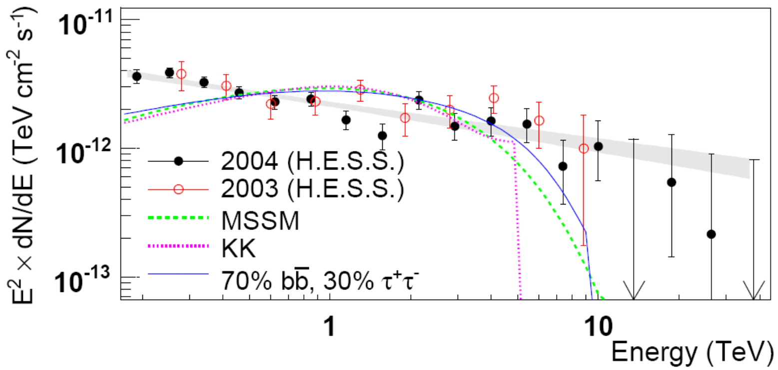


$\Delta m/m$ = 0 limit

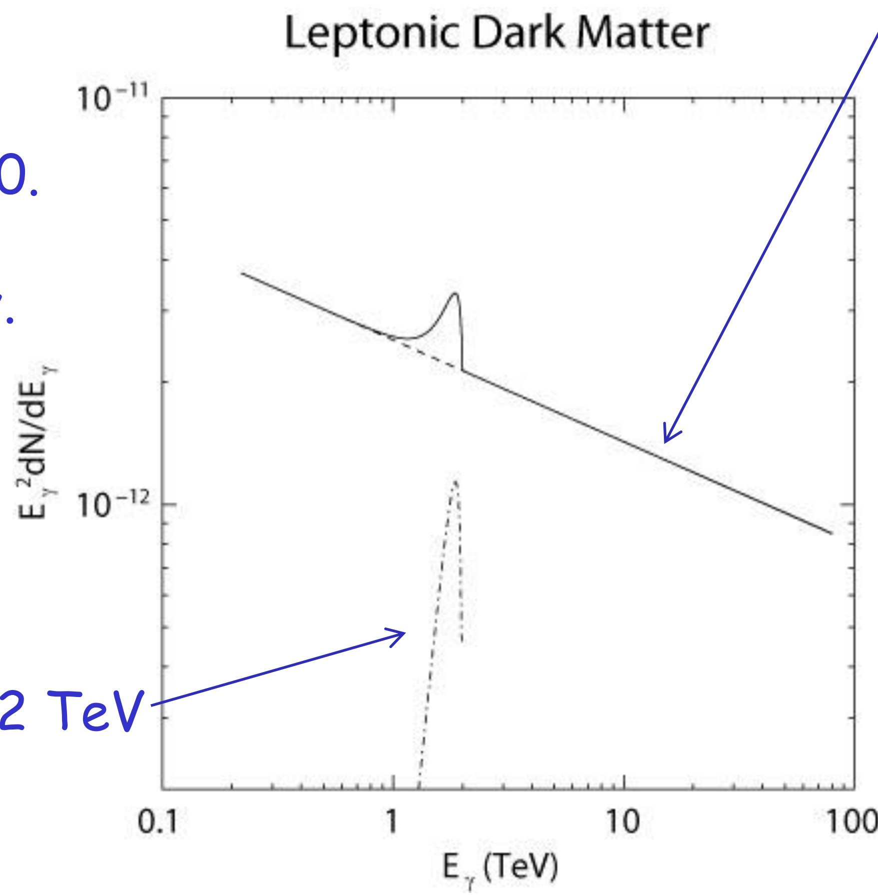
$\Delta m/m$ = 0.01

$\Delta m/m$ = 0.1

m_N = 2 TeV



HESS measurements towards g.c. (Probably not related to dark matter?)



NFW halo, $J\Delta\Omega$ =100.
Rate determined by WMAP relic density.
$\Delta m/m = 0.1$

$N_R N_R \rightarrow l^+ l^- \gamma$, $m_N = 2$ TeV

This type of dark matter candidate, which may also explain neutrino masses, can only be seen in gamma-rays in ACT.
Not at LHC, not in GLAST, not in direct detection,...

QED corrections in supersymmetry. Further good news for gamma-ray searches for dark matter:

New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation

arxiv:0710.3169

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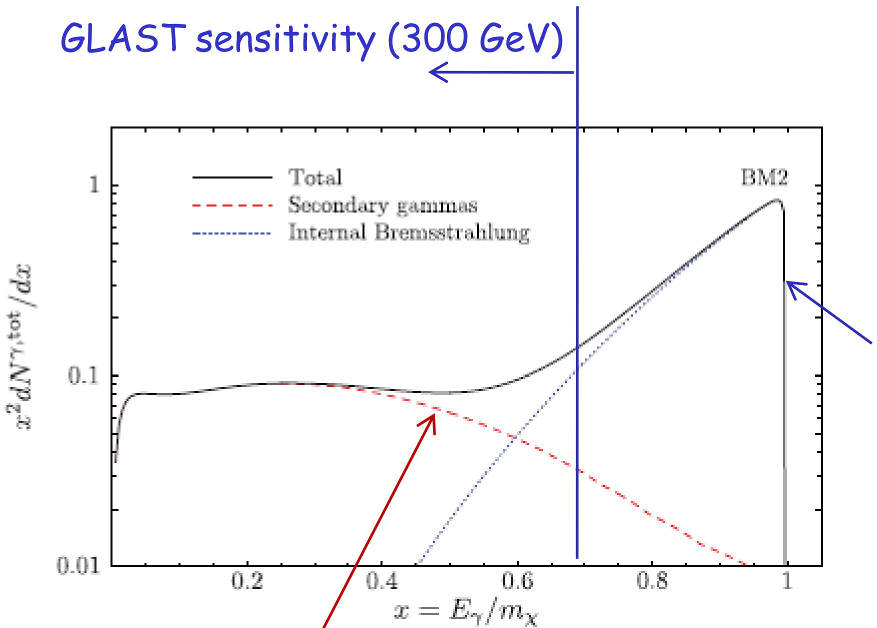
Department of Physics, Stockholm University, AlbaNova University Center, SE - 106 91 Stockholm, Sweden

(Dated: October 16, 2007)

GLAST sensitivity (300 GeV)



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

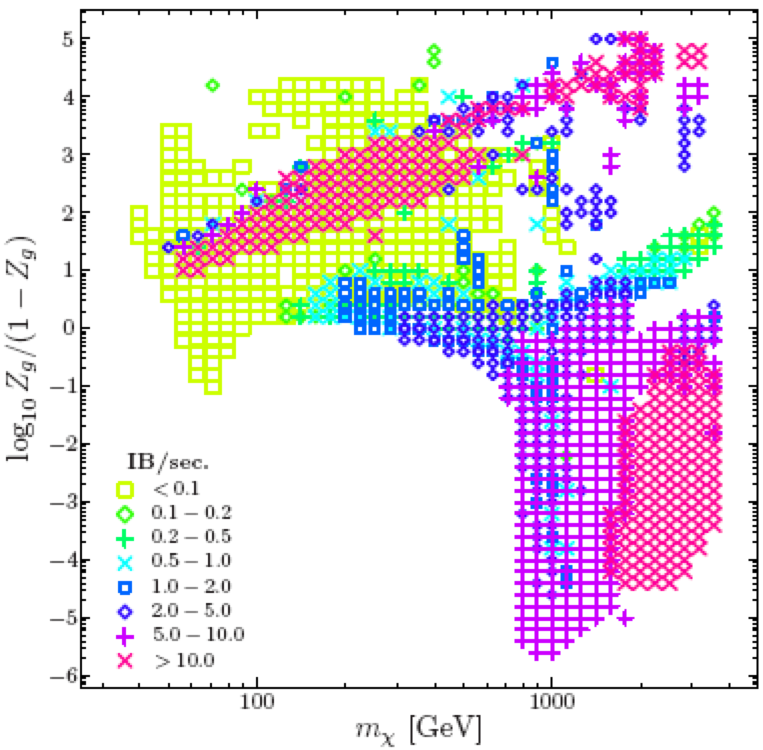
New calculation including inner bremsstrahlung (DarkSUSY 4.2). Energy falls just outside the GLAST range…

Previous estimate of gamma-ray spectrum (DarkSUSY 4.1)

Model	m_0 [GeV]	$m_{1/2}$ [GeV]	$\tan\beta$	A_0 [GeV]	$\text{sgn}(\mu)$	m_χ [GeV]	$Z_g/(1-Z_g)$	Ωh^2	t-channel	$\mathcal{S}$	IB/sec.	IB/$(\gamma\gamma + Z\gamma)$
BM1	3700	3060	5.65	$-1.39 \cdot 10^4$	-1	1396	$3.0 \cdot 10^4$	0.082	$\tilde{t}(1406)$	$8.1 \cdot 10^{-5}$	19.2	4.5
BM2	801	1046	30.2	$-3.04 \cdot 10^3$	-1	446.9	1611	0.110	$\tilde{\tau}(447.5)$	0.044	10.6	8.5
BM3	107.5	576.4	3.90	28.3	$+1$	233.3	220	0.084	$\tilde{\tau}(238.9)$	1.19	$2.3 \cdot 10^3$	5.0
BM4	$2.21 \cdot 10^4$	7792	24.1	17.7	$+1$	1926	$1.2 \cdot 10^{-4}$	0.11	$\tilde{\chi}_1^+(1996)$	0.012	10.8	2.1

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

Number of gamma-ray events above $0.6 m_\chi$ compared to old continuum calculations.

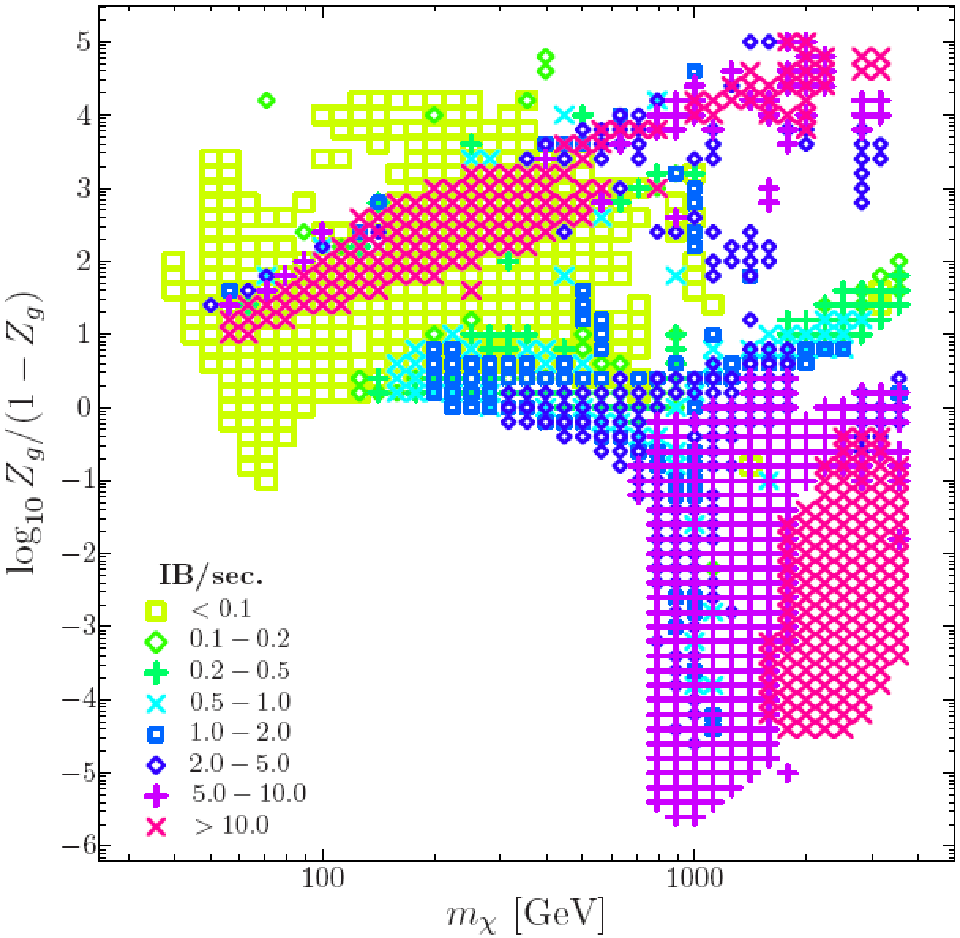


All SUSY models

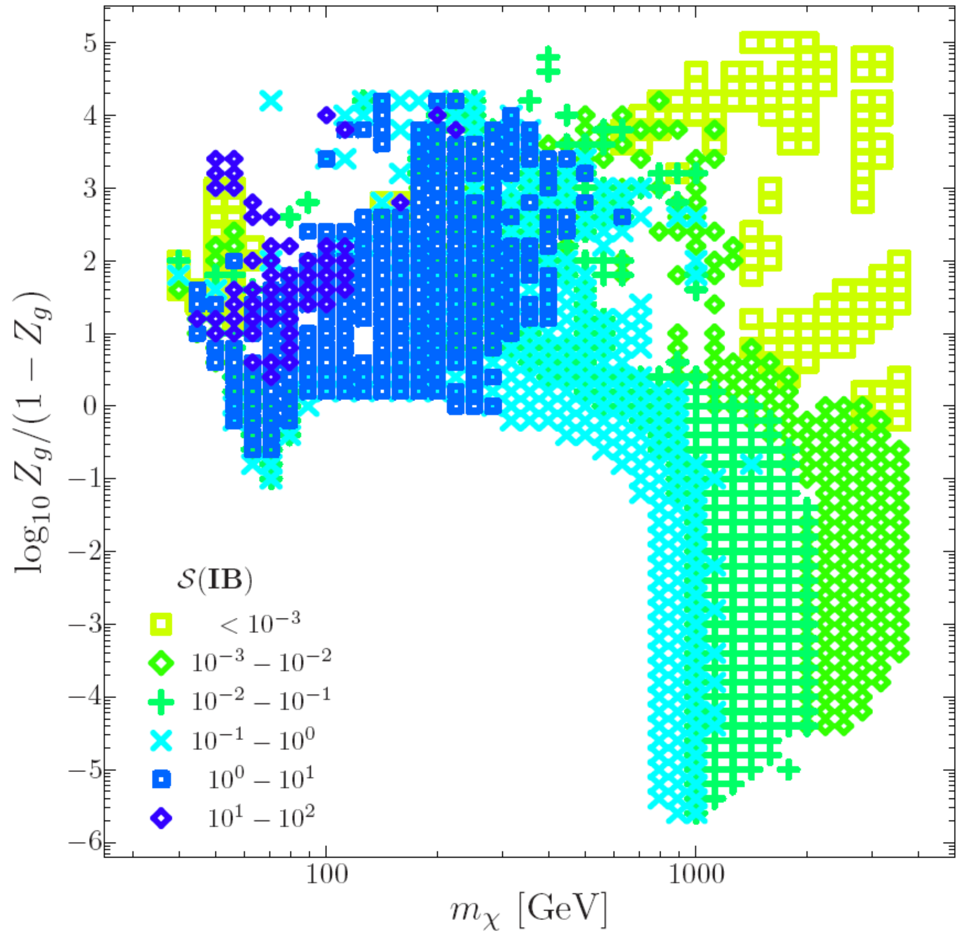
Compared to gamma lines

T. Bringmann, L.B., J.Edsjö, Oct. 2007

T. Bringmann, L.B., J.Edsjö, Oct. 2007



Ratio IB/(Old results)

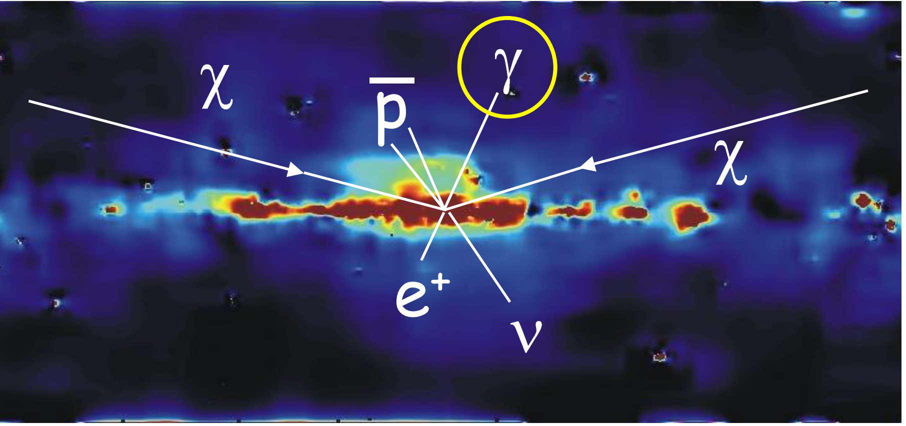


Absolute flux factor S

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

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

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



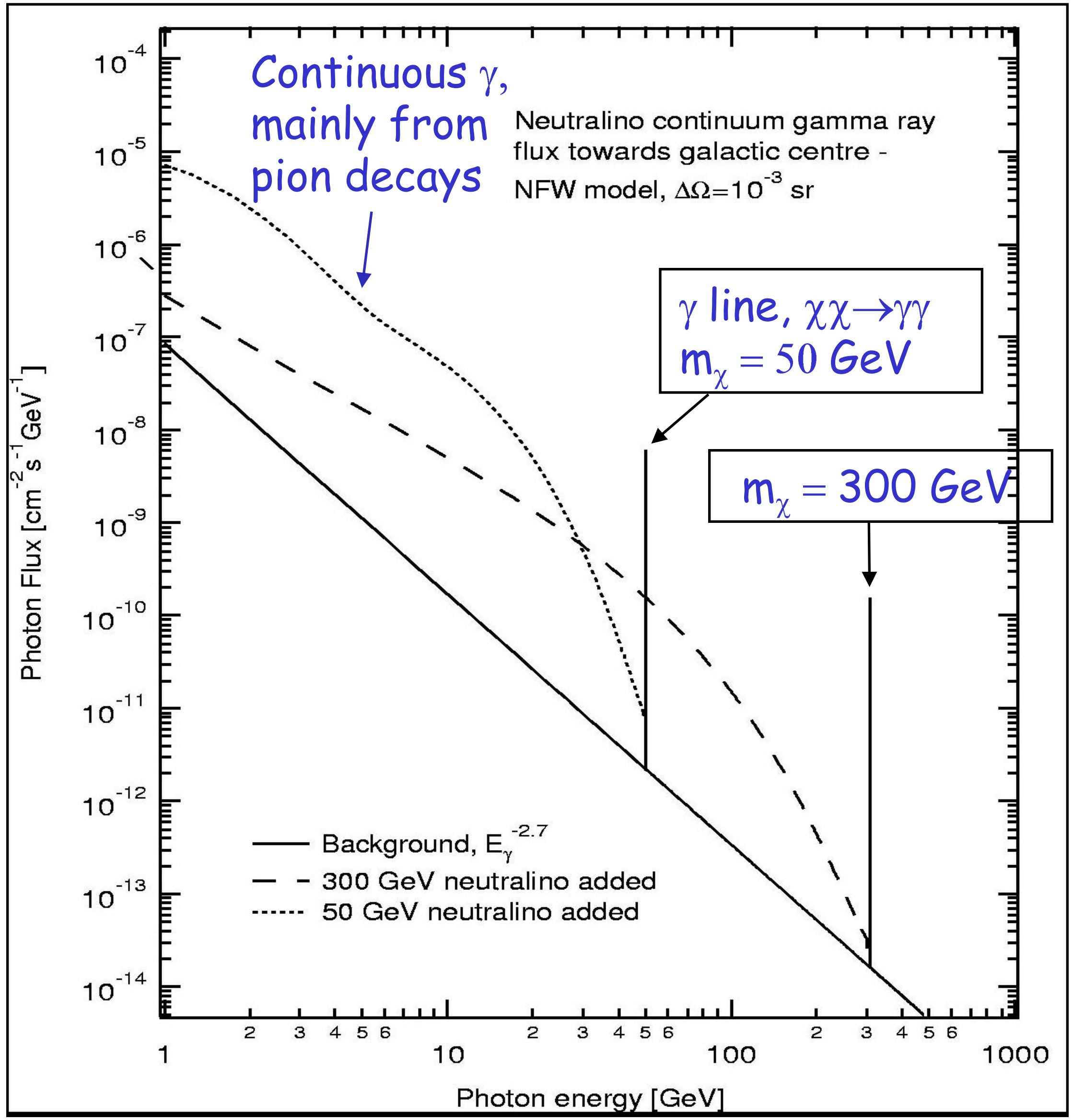
Gamma-rays from DM annihilation

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

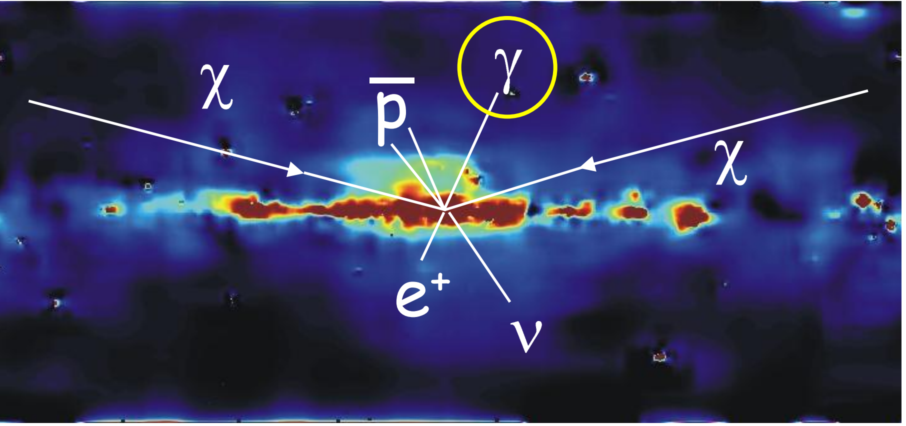
- Continuous
  and
- Monoenergetic line

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

Unfortunately, large uncertainties in the predictions of absolute rates



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



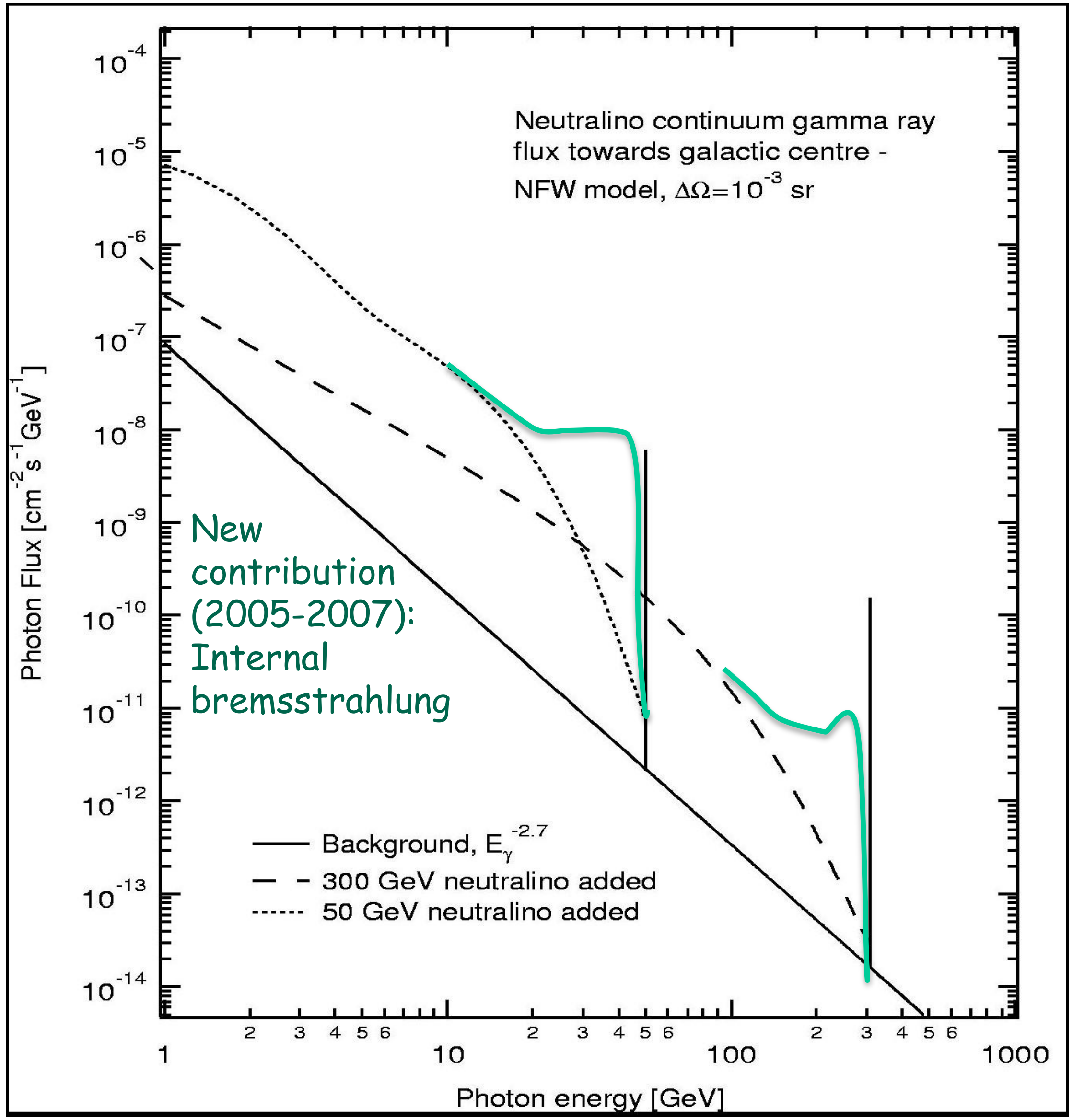
Gamma-rays

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

- Continuous
  and
- Monoenergetic line
  and
- Internal bremsstrahlung

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

Unfortunately, large uncertainties in the predictions of absolute rates



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

T. Bringmann, L.B., J. Edsjö, 2007

Other model II.

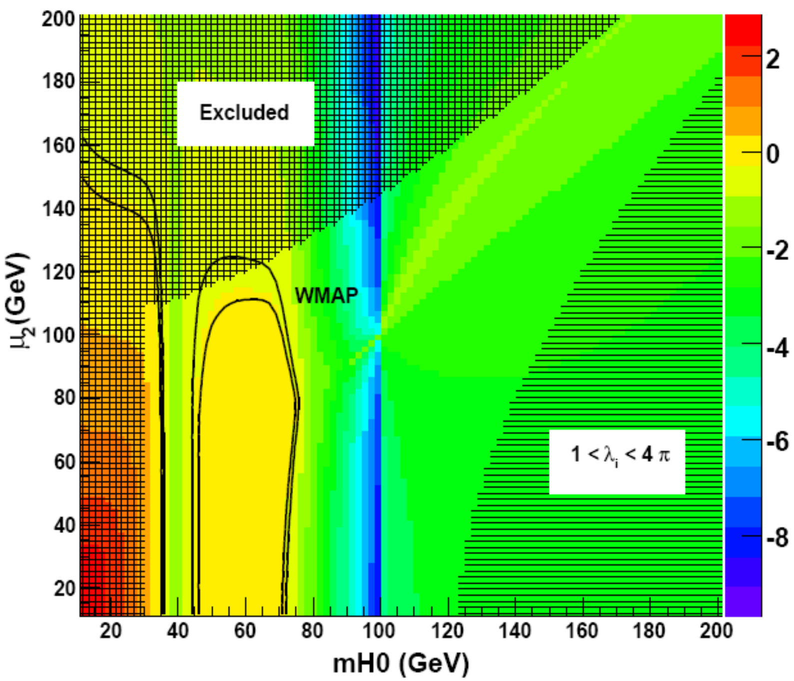
Inert Higgs model

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) .

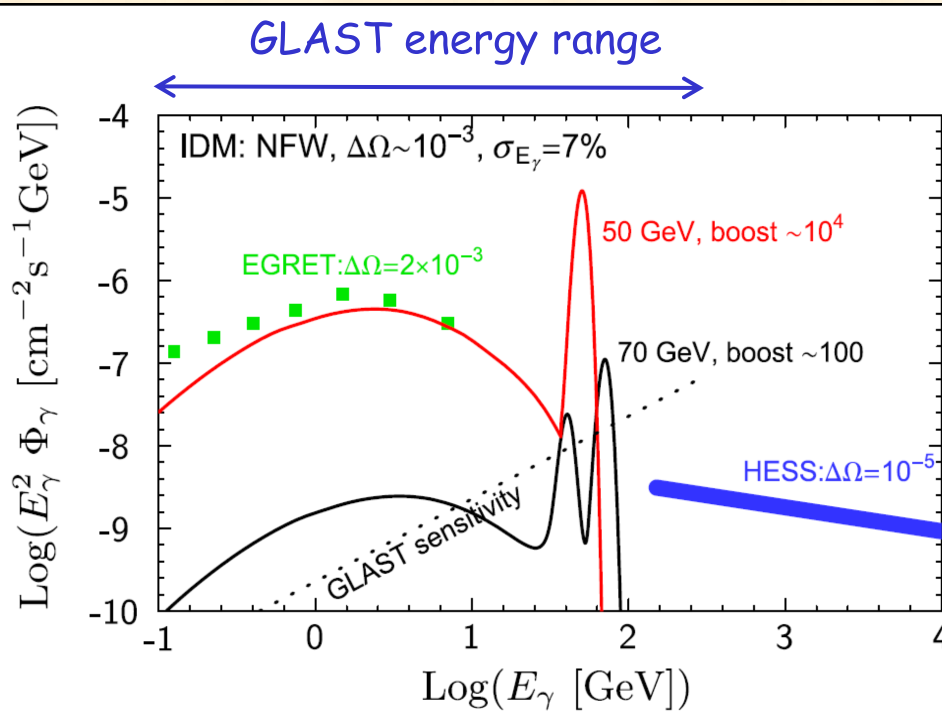
This model may also break EW symmetry radiatively, the Coleman-Weinberg Mechanism (Hambye & Tytgat, 2007).

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

The perfect candidate for detection in GLAST or ACT with low energy threshold!



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 (cf. Berezinsky, Dokuchaev & Ereshenko, 2003). Maybe the effects of caustic streams discussed by Vogelsberger et al., 2007, will give larger boost factors (will soon be computed).

- In specific locations, however, like the region around the galactic center, factors up to 10^5 are easily possible from cusps or spikes (large variation between different halos).

- Also, the existence of intermediate mass black holes may give very large local boost factors (Bertone, Zentner & Silk, 2005).

- Baryon contraction of the dark matter may give another few orders of magnitude near the g.c (Gnedin & Primack, 2004).

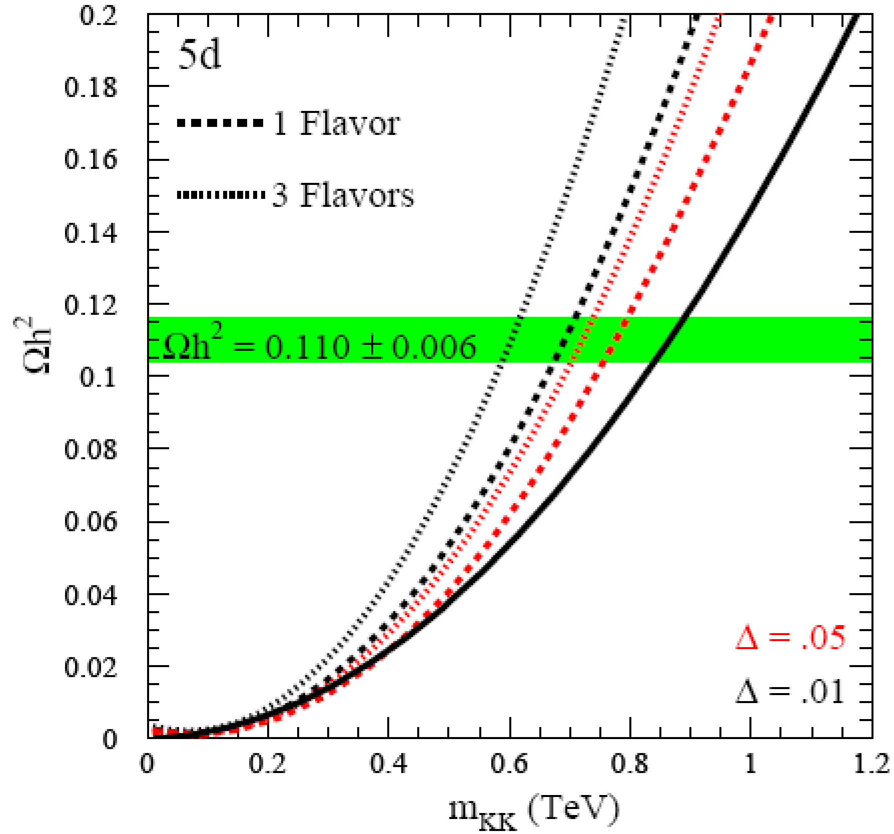
- It seems thus that we could expect many good surprises as computations improve.

- The downside of this is a lack of predictability of absolute counting rates for indirect detection. If a signal is found, however, important information about a combination of particle physics (mass of particle, spin, branching ratios etc) and astrophysics (structure of DM halos) will be obtained.

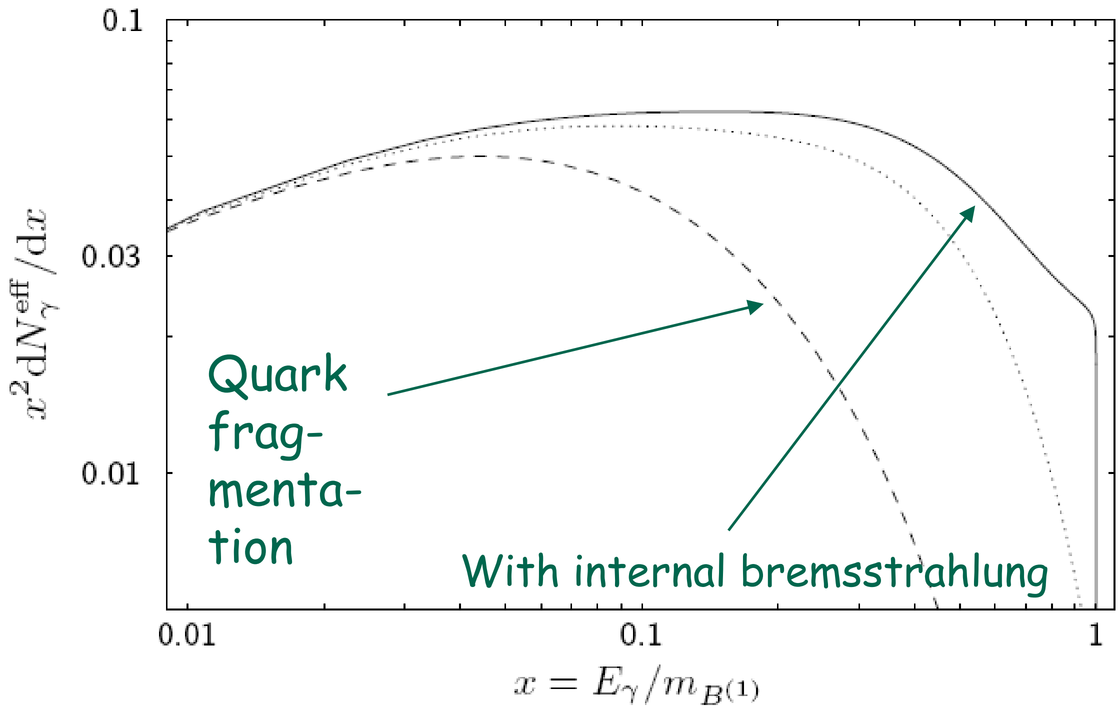
Other model III: Kaluza-Klein (KK) dark matter in Universal Extra Dimensions

Universal Extra Dimensions, UED (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
- Variation (Agashe & Servant, 2004): Randall-Sundrum warped GUT with Z_3 symmetry, LZP stable

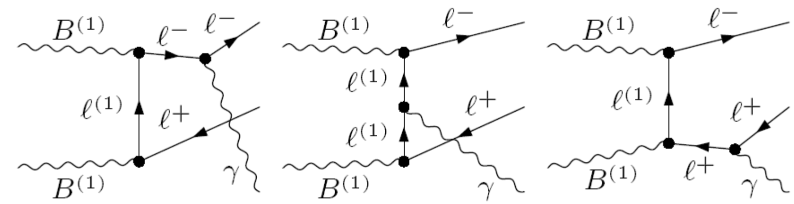


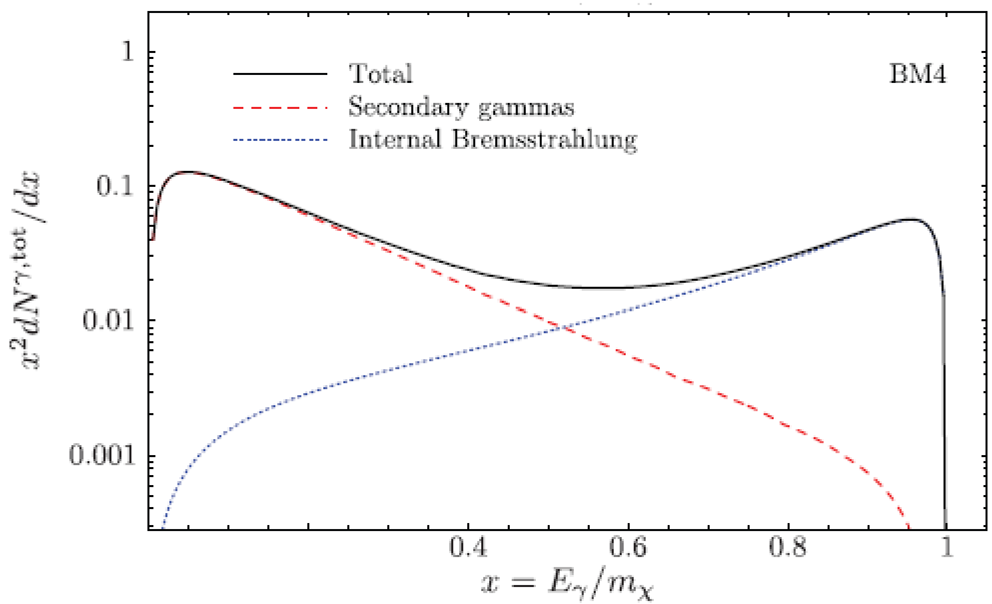
Servant & Tait, 2003



Internal bremsstrahlung is important in Kaluza-Klein models, M ~ 1 TeV

L.B., T. Bringmann, M.Eriksson & M. Gustafsson, PRL 2005



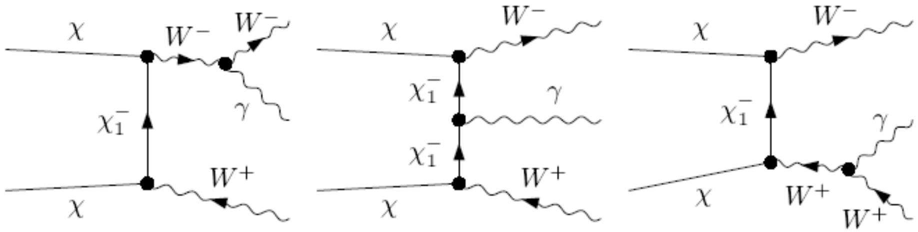


MSSM benchmark model, M = 1.9 TeV

New result for supersymmetry: these processes are even more important for SUSY!

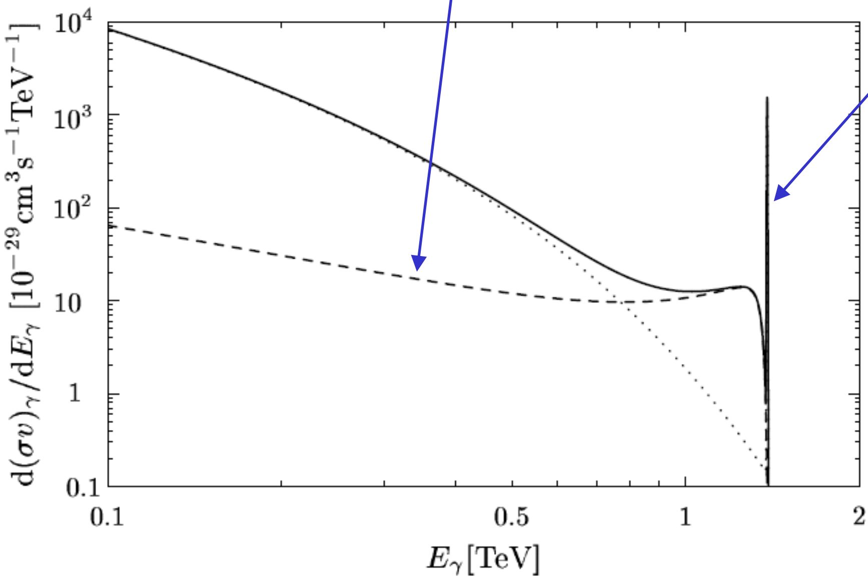
(T. Bringmann, L.B., J. Edsjö, 2007)

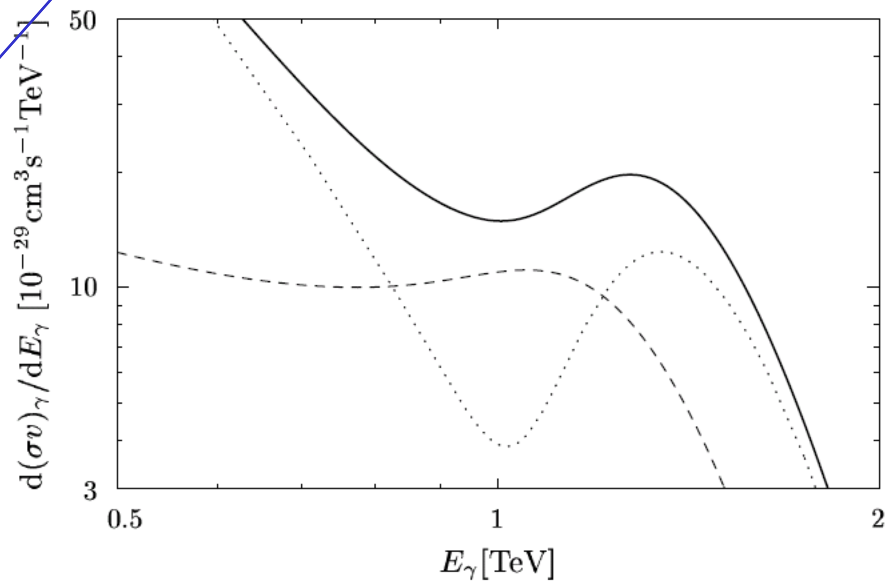
Interesting candidate for ACT: 1.4 TeV Higgsino with WMAP relic density, like in split SUSY (L.B., T.Bringmann, M.Eriksson and M.Gustafsson, PRL 2005)



New contribution (internal bremsstrahlung)

Intrinsic line width $\Delta E/E \sim 10^{-3}$





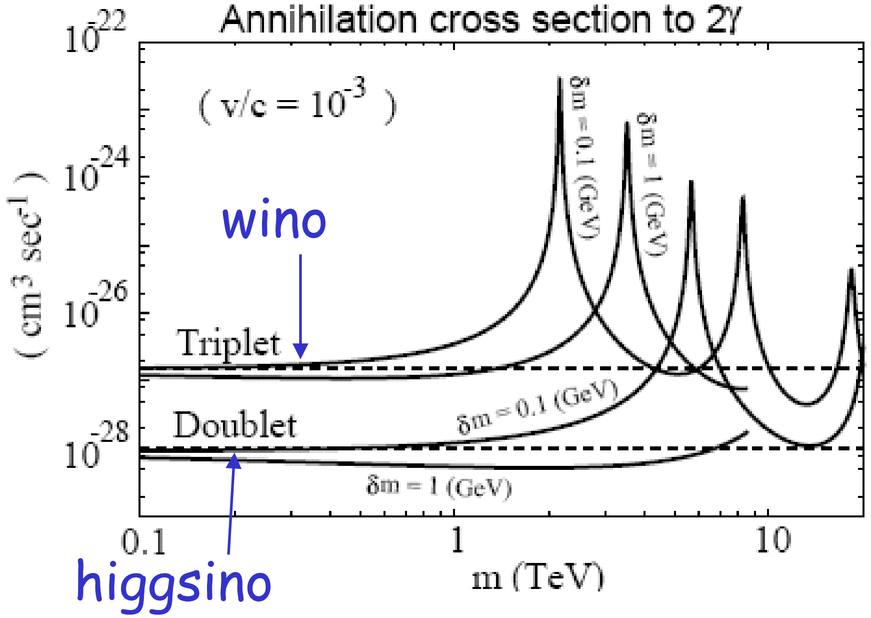
Gamma-ray spectrum seen by an ideal detector

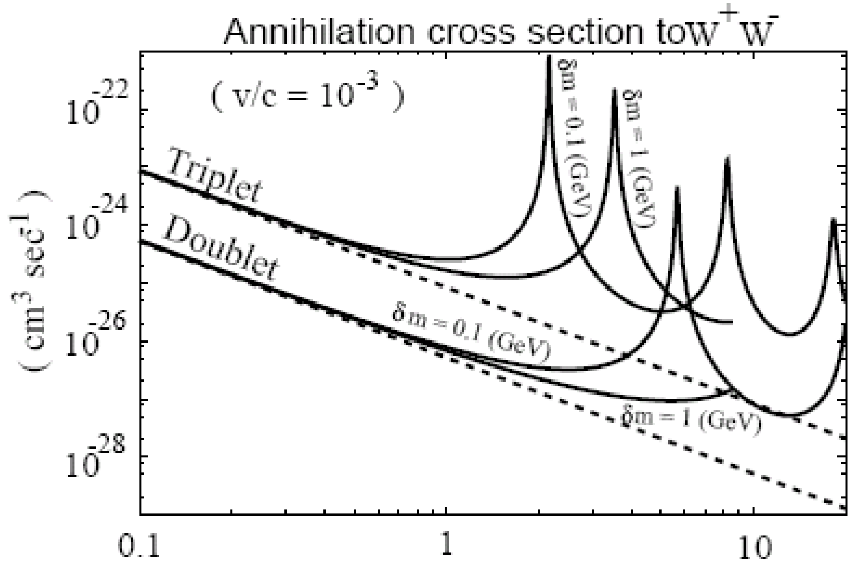
Same spectrum seen with 15% energy resolution (typical of ACT). Is there a way to improve energy resolution?

"Miracles" in gamma-rays for heavy (> 1 TeV) neutralinos:

- Heavy MSSM neutralinos are almost pure higgsinos (in standard scenario) or pure winos (in AMSB & split SUSY models)
- Just for these cases, the gamma line signal is particularly large (L.B. & P.Ullio, 1998)
- In contrast to all other detection scenarios (accelerator, direct detection, positrons, antiprotons, neutrinos,..) the expected signal/background increases with mass $\Rightarrow$ unique possibility, even if LHC finds nothing.
- Rates may be further enhanced by non-perturbative binding effects in the initial state (Hisano, Matsumoto & Nojiri, 2003)
- There are many large Air Cherenkov Telescopes (ACT) either being built or already operational (CANGAROO, HESS, MAGIC, VERITAS) that cover the interesting energy range, $1\ \mathrm{TeV} \leq E_\gamma \leq 20\ \mathrm{TeV}$.
- A new generation of ACT arrays is presently being planned: AGIS, HAWC, CTA

"Explosive annihilation", Hisano & al, 2003, 2004

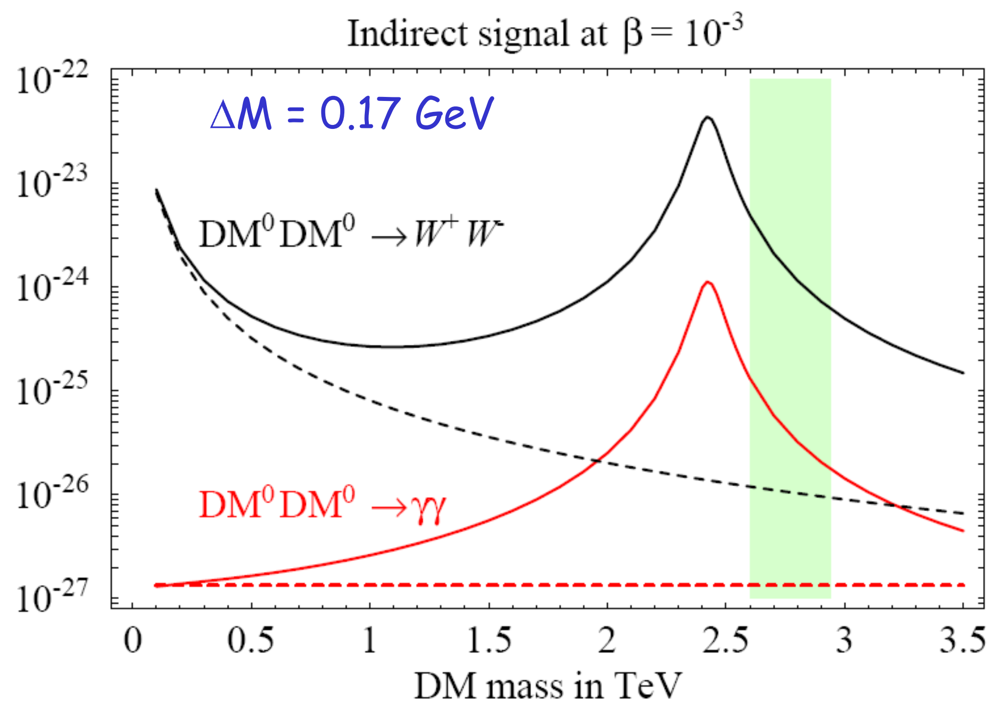




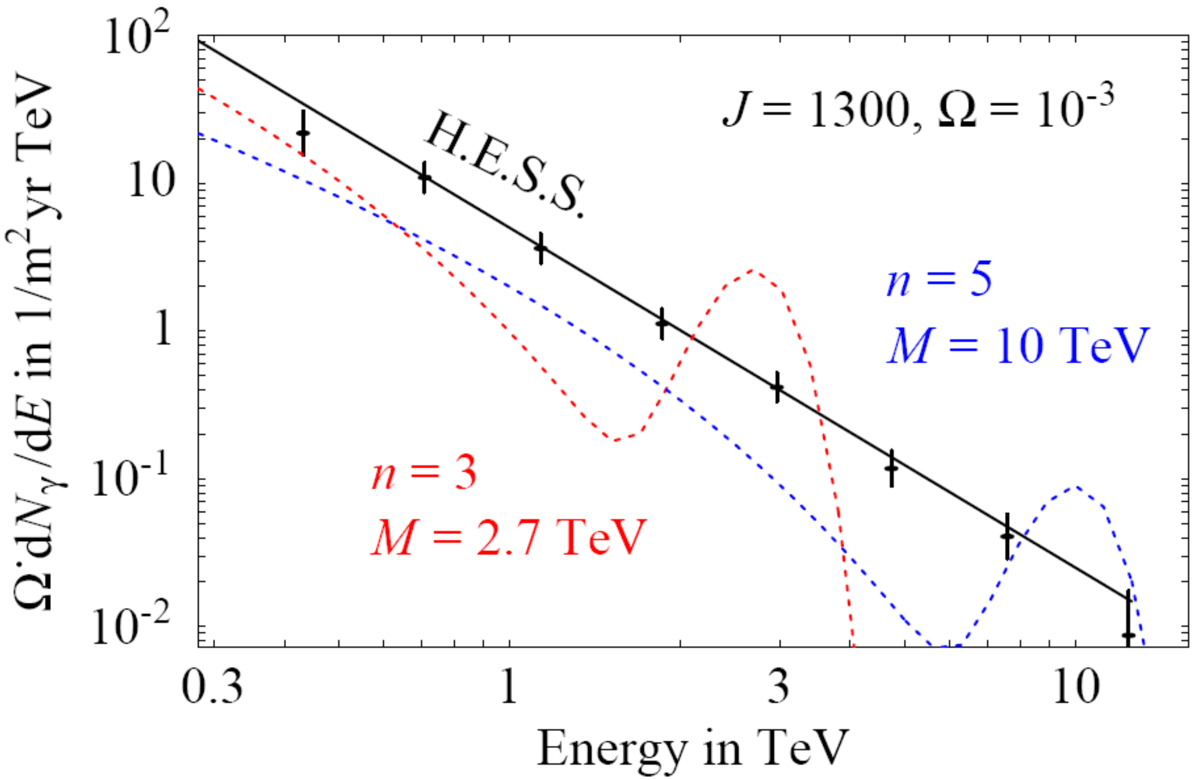
In MSSM without standard GUT condition (AMSB; split SUSY) m_{wino} ~ 2 – 3 TeV; δm ~ 0.2 GeV.

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 .



M. Cirelli, A. Strumia & M. Tamburini, 2007



M. Cirelli, A. Strumia & M. Tamburini, 2007

Striking gamma-line signature possible for ACT arrays. But, internal bremsstrahlung should also be computed.
G.C. probably not optimal because of power law background process.
Dwarf galaxies may be more suitable? Or, since the energy signatures should be the same wherever one looks, maybe even "blank fields" used for subtraction of bkg to point source signals already contains exciting information? (Diffuse extragalactic emission should show the same energy features.)

Conclusions

- The various indirect and direct detection methods are complementary to each other and to LHC.
- Supersymmetry is still the (my) favorite, but several other interesting candidates exist: Extra dimensions, extended Higgs sector, right-handed neutrinos.
- There is an unexplained gamma-ray excess from Galactic Center. But the featureless power-law up to very high energies does not have the characteristics of dark matter annihilation.
- However, g.c. is a very promising place to search for superimposed features – the gamma line or the structure near $E_\gamma = m_\chi$ caused by internal bremsstrahlung would be a "smoking gun".
- GLAST will open a new window: Will search for "hot spots" in the sky up to 300 GeV. These may be investigated by ACTs. For higher energies, or for smaller signal rates, new ACTs may have unique possibilites for detection of dark matter annihilation.
- The dark matter problem may be near its solution – and gamma-rays may be a crucial part of that.
- Dream instrument: Large area, low energy threshold, excellent energy resolution, large field of view. Point not only towards the g.c., but also in regions where galactic foregrounds are smallest. A dedicated Dark Matter Telescope?