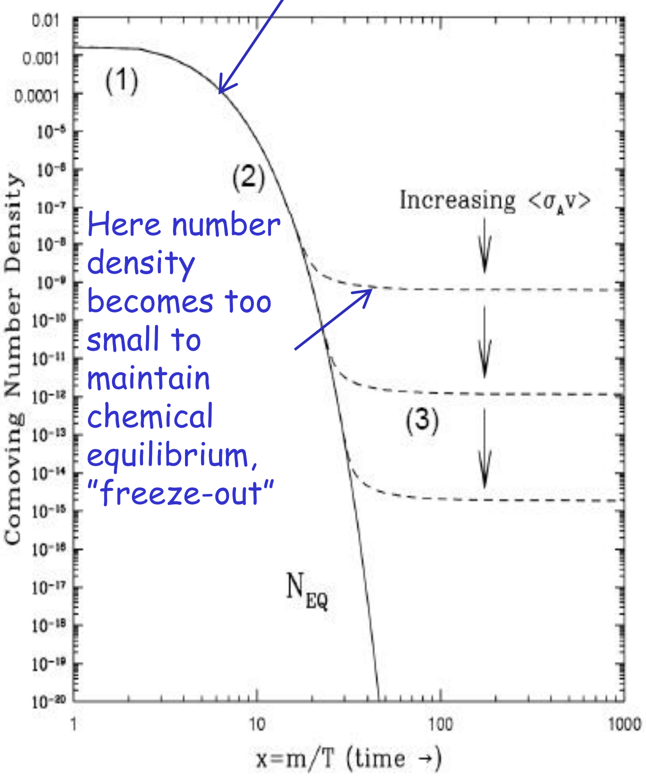
Preliminary lecture programme:

1. The particle universe: introduction, cosmological parameters
2. Basic cross sections for neutrinos and gamma-rays; IceCube
3. Density of relic particles from the early Universe
4. Dark matter: Direct and indirect detection methods; the galactic centre & other promising DM sources
5. Neutrinos and antimatter from dark matter, Sommerfeld enhancement
6. Particular dark matter candidates (WIMPS, Kaluza-Klein particles, sterile neutrinos,…)
7. Supersymmetric dark matter, DarkSUSY.
8. Diffuse extragalactic gamma-rays, Primordial black holes, Hawking radiation
9. Gravitational waves

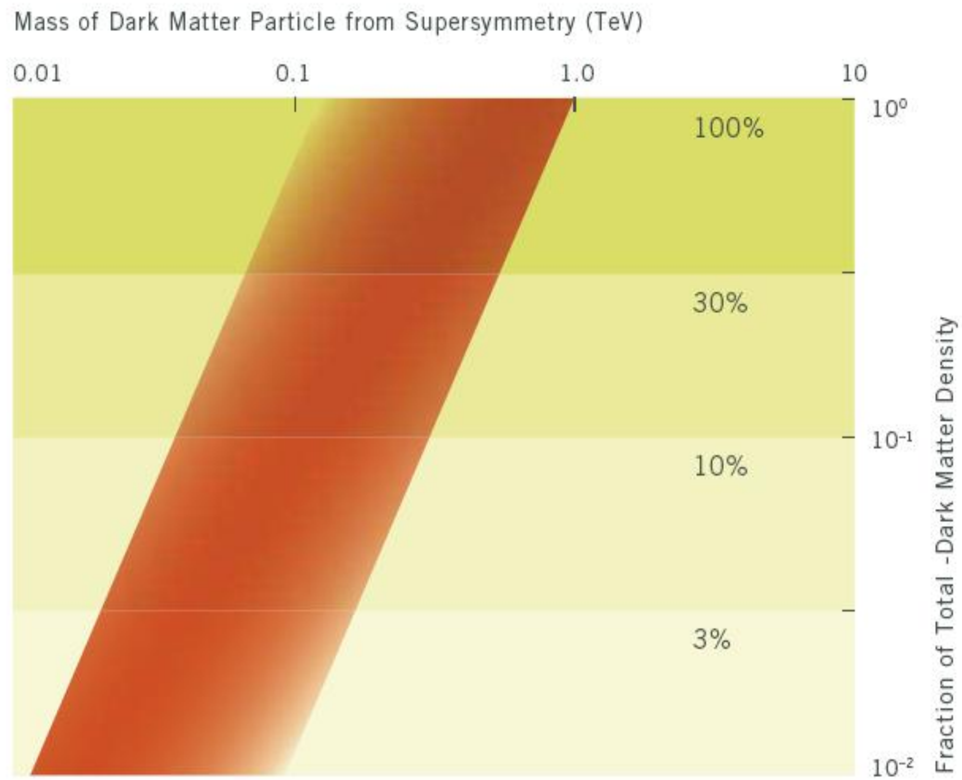
One more time - remember the "WIMP miracle": If new physics appears related to the electroweak mass scale, and that new physics contains a stable, neutral particle - we may have a solution to the dark matter problem.

Equilibirium curve in early universe

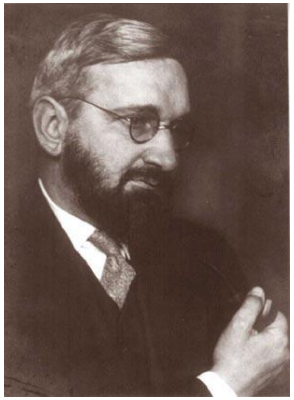


Here number density becomes too small to maintain chemical equilibrium, "freeze-out"

Example: The mass range for SUSY WIMPs is roughly 10 GeV to a few TeV



J. Feng & al, ILC report 2005

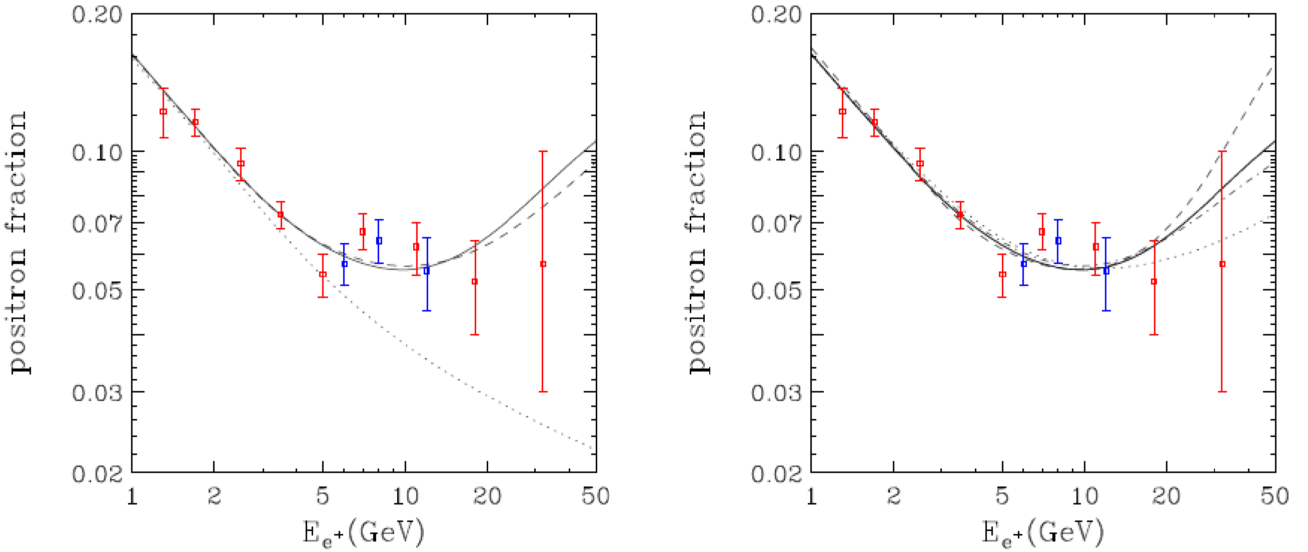


The Kaluza-Klein theory of extra dimensions:
The lightest KK boson may be a dark matter spin-1 WIMP

Oskar Klein, Stockholm, 1894-1977. Professor at Stockholm University 1930 – 1962. Inventor of theory with extra dimensions.
(Also Klein paradox, Klein-Nishina formula, Klein-Gordon equation, Klein-Jordan quantization, pre-gauge theory of SU(2), Alfvén-Klein cosmology)

Theodor Kaluza, 1885-1954. Inventor of theory with extra dimensions.

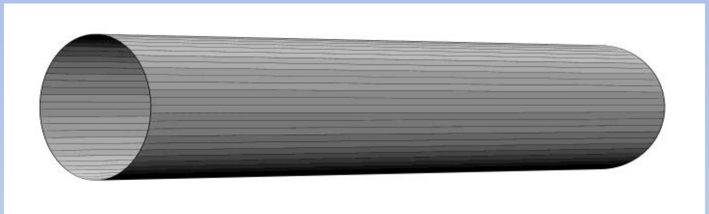
Pre-PAMELA prediction of positron fraction:



D. Hooper and S. Profumo, Phys.Rept.453:29-115,2007

Extra dimensions: the basic idea

Compactify extra dimensions on some small scale R:

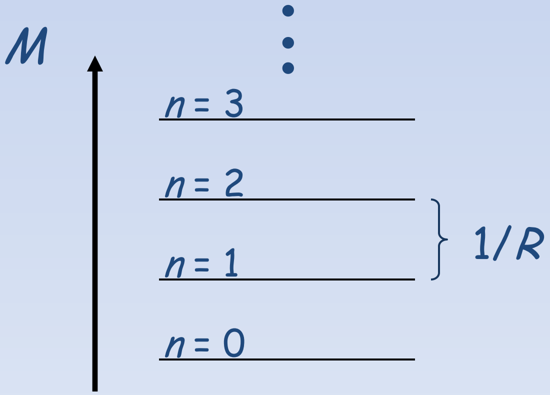


2 R

line $\times$ circle = cylinder
R small $\Rightarrow$ hidden dimension

For large distances (low energies), ordinary 4D physics is recovered.

In the effective 4D theory, there appears a Kaluza-Klein "tower" of new, very massive states.

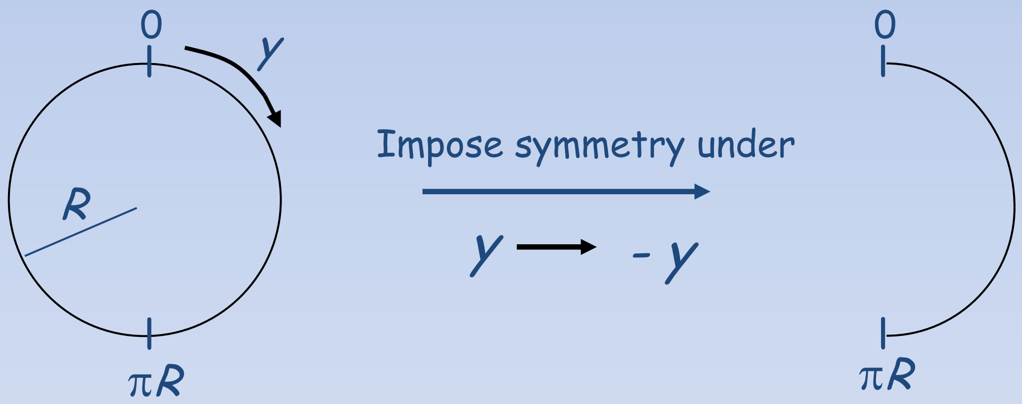


Universal Extra dimensions (UED)

Appelquist, Cheng & Dobrescu, PRD '01, T. Bringmann, 2004

All standard model fields are allowed to propagate in the extra dimensions.

Compactification on an orbifold:



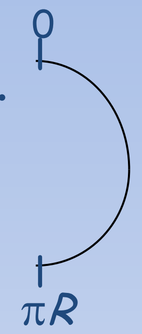
This is needed in order to get rid of unwanted degrees of freedom at the zero mode level.

(Fields can transform *even,* $\Phi(x^\mu, y) \rightarrow \Phi(x^\mu, -y)$, or *odd,* $\Phi(x^\mu, y) \rightarrow -\Phi(x^\mu, -y)$, under orbifold transformations. The latter have no zero modes.)

The lightest Kaluza-Klein particle

Compactification on an orbifold

- allows chiral fermions for one extra dim.
- translational invariance broken
- 5D momentum (and thus KK number) no longer conserved



... but KK parity $(-1)^n$ is still conserved

$\Rightarrow$ The lightest KK particle (LKP) is stable and cannot decay into standard model particles. This is one very important condition for a dark matter candidate.

But, does this give viable dark matter candidate?

What is the LKP?

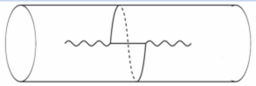
Cheng, Matchev & Schmaltz, PRD '02

At tree level, the mass of the KK modes is given by: $m^2 = \frac{n^2}{R^2} + m_{\mathrm{EW}}^2$

Including radiative corrections,

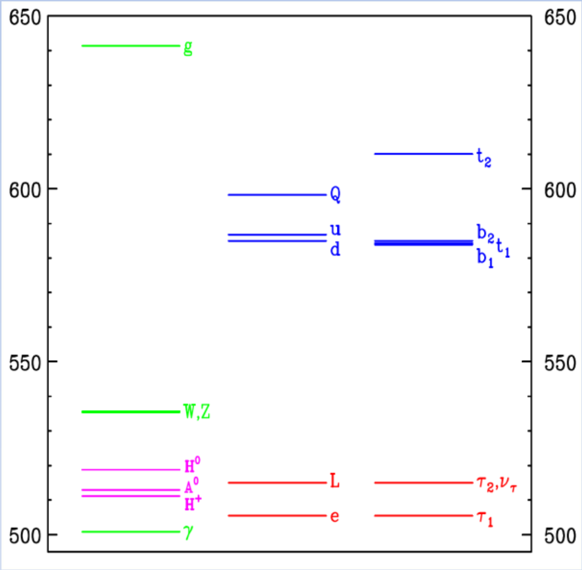
$$m_{B^1}^2 \simeq \frac{1}{R^2}\left[1 + \frac{g'^2}{16\pi^2}\left(-\frac{39\zeta(3)}{2\pi^2} - \frac{1}{3}\ln \Lambda R + (2\pi R v)^2\right)\right]$$

bulk contribution



Contribution from orbifold fixpoints (depends on cutoff Λ)

electroweak contribution



Mass spectrum at first KK level

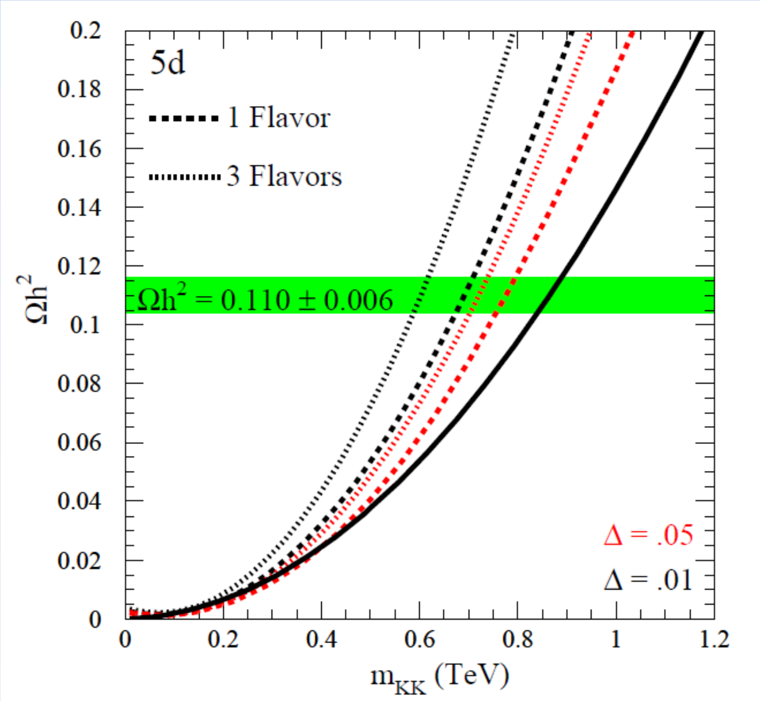
The LKP is in most KK models given by the neutral $B^{(1)}$

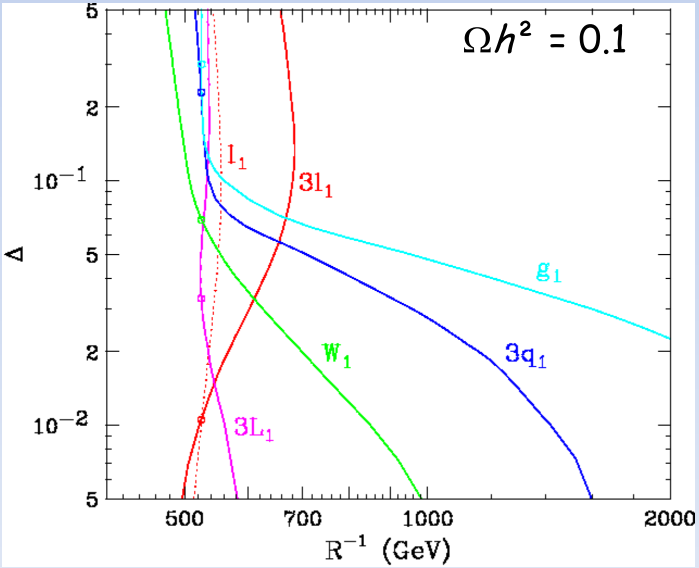
The LKP WIMP Dark Matter

The thermal relic density of the $B^{(1)}$ can be computed, as for any standard WIMP.

(Including coannihilations,
second KK level resonances,...)

Servant & Tait, 2003





KM

Collider bounds

Current bounds

- Direct non-detection: $R^{-1} > 300$ GeV — Appelquist, Cheng & Dobrescu, PRD '01; Agashe, Deshpande & Wu, PL B '01

- Electroweak precision tests: $R^{-1} > 350$ GeV — Appelquist, Cheng & Dobrescu, PRD '01; Appelquist & Yee, PRD '03

LHC reach: $R^{-1} > 3$ TeV — Rizzo, PRD '01; Macesanu, McMullen & Nandi, PRD '02

Indirect detection

$B^{(1)}\,B^{(1)}$ annihilation ratios at tree level:

- 59% into leptons
- 35% into quarks
- 4% into neutrinos
- 2% into gauge and Higgs bosons

Quite different from SUSY, where we have helicity suppression!

Indirect detection methods making use of the high branching ratio into leptons are very promising.

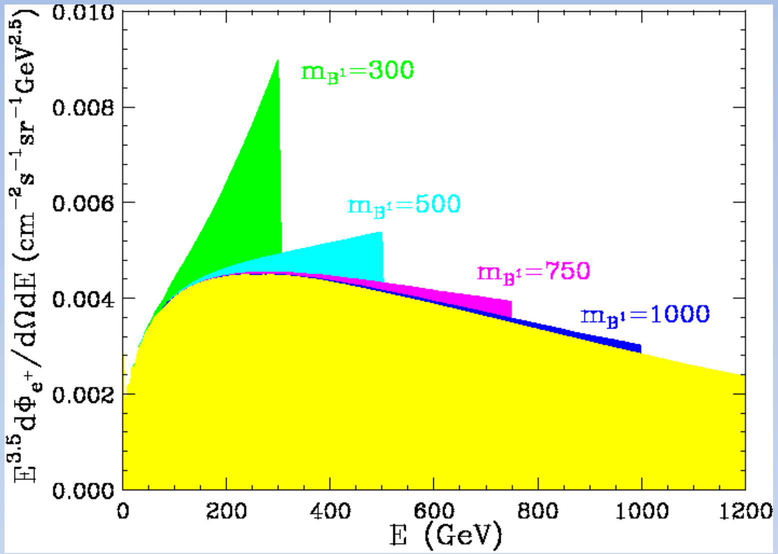
Can even be used to discriminate between the LKP and a Majorana dark matter candidate!

The positron peak prediction (many years before PAMELA & ATIC)

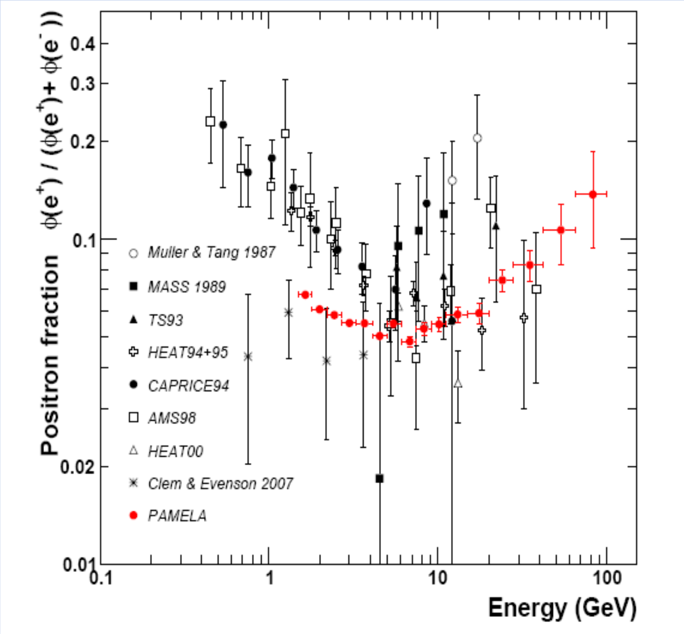
Cheng, Feng & Matchev, PRL '02
Hooper & Kribs, PRD '04
Hooper & Silk, PRD '05

Appearance of a "smoking gun" signature in the spectrum.

For high masses, however, this cannot be discriminated against the background unless one invokes a large boost factor.



CFM



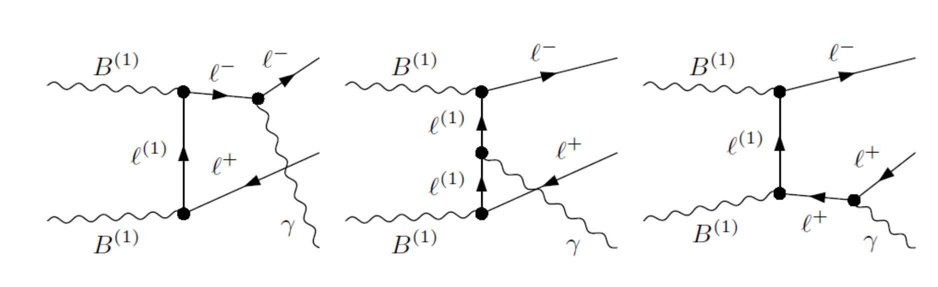
A clumpy halo distribution can boost the positron flux by a factor around 2-10. Sommerfeld enhancement should not be operative here.

With a boost factor of only 5, AMS would be able to see a peak up to $m_B \sim$ 1 TeV. However, for PAMELA/ATIC data, a factor of 600 is needed…

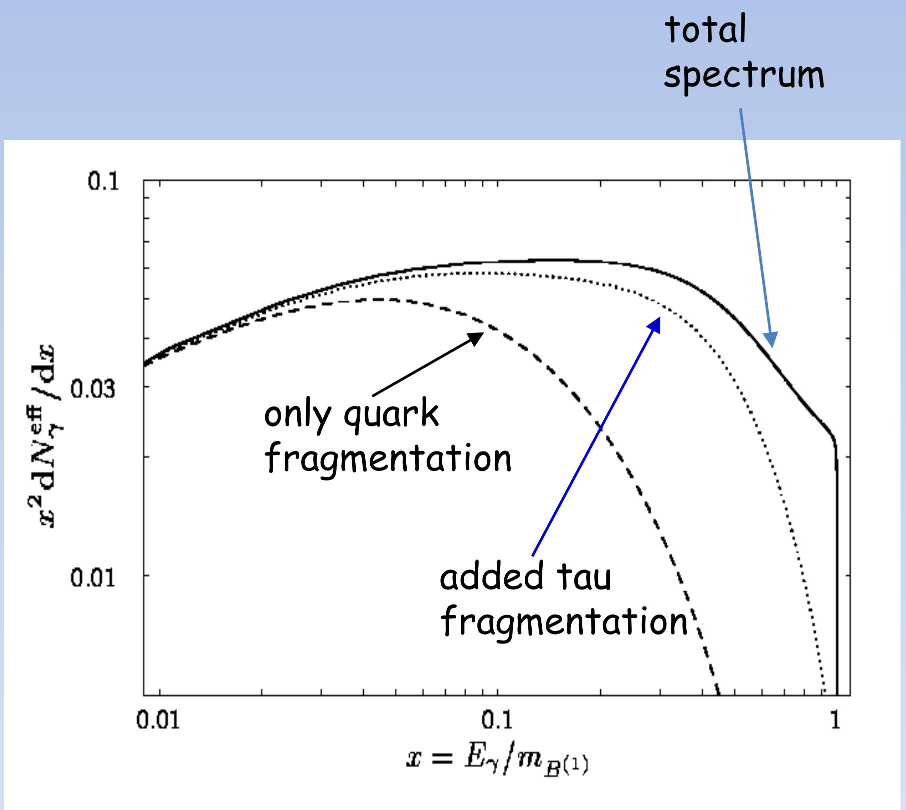
The gamma-ray spectrum

L.B., T. Bringmann, M. Eriksson & M. Gustafsson, PRD '05

At high energies, the gamma-ray spectrum is dominated by internal bremsstrahlung from final state leptons:



$$\frac{dN_\gamma^\ell}{dx} \equiv \frac{d(\sigma_{\ell^+\ell^-\gamma}v)/dx}{\sigma_{\ell^+\ell^-}v} \simeq \frac{\alpha}{\pi}\frac{(x^2-2x+2)}{x}\ln\left[\frac{m_{B^{(1)}}^2}{m_\ell^2}(1-x)\right],$$

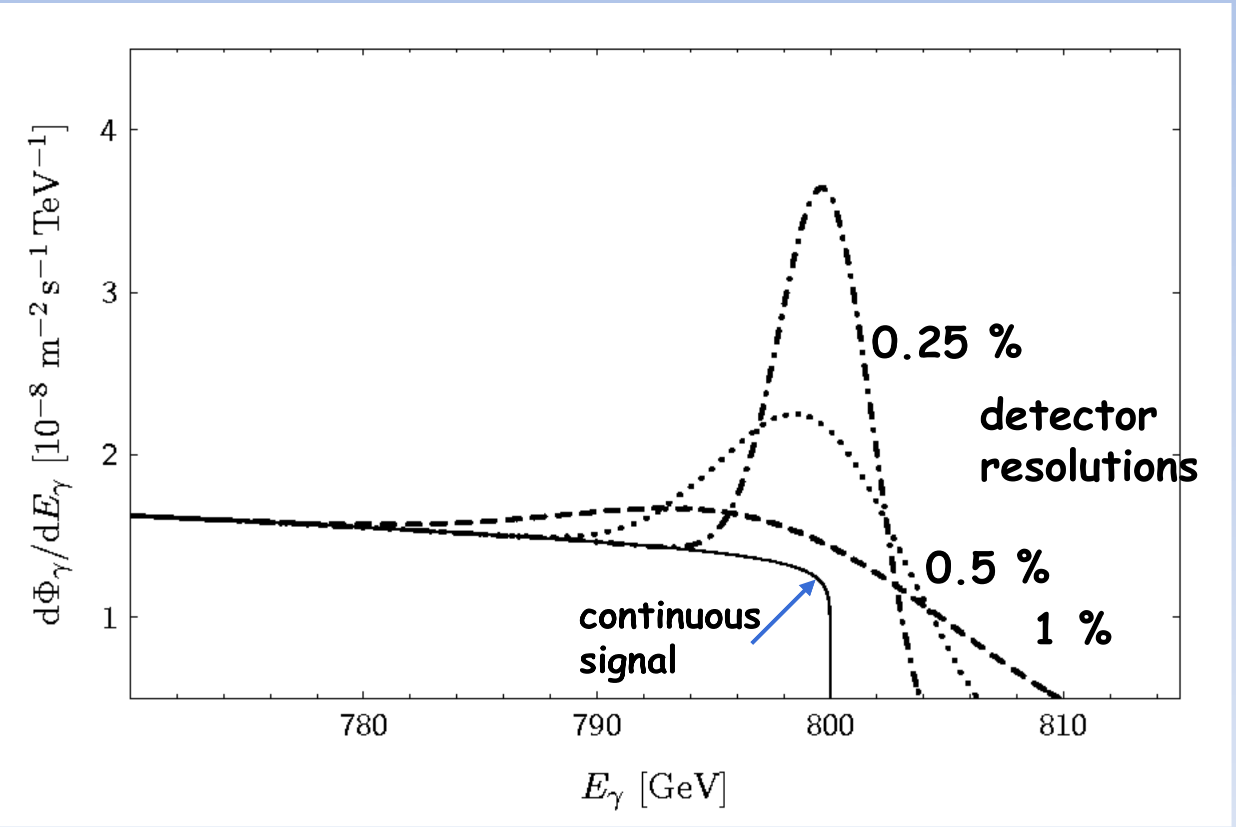


This gives a nice signature to look for.

Can one see the photon peak?

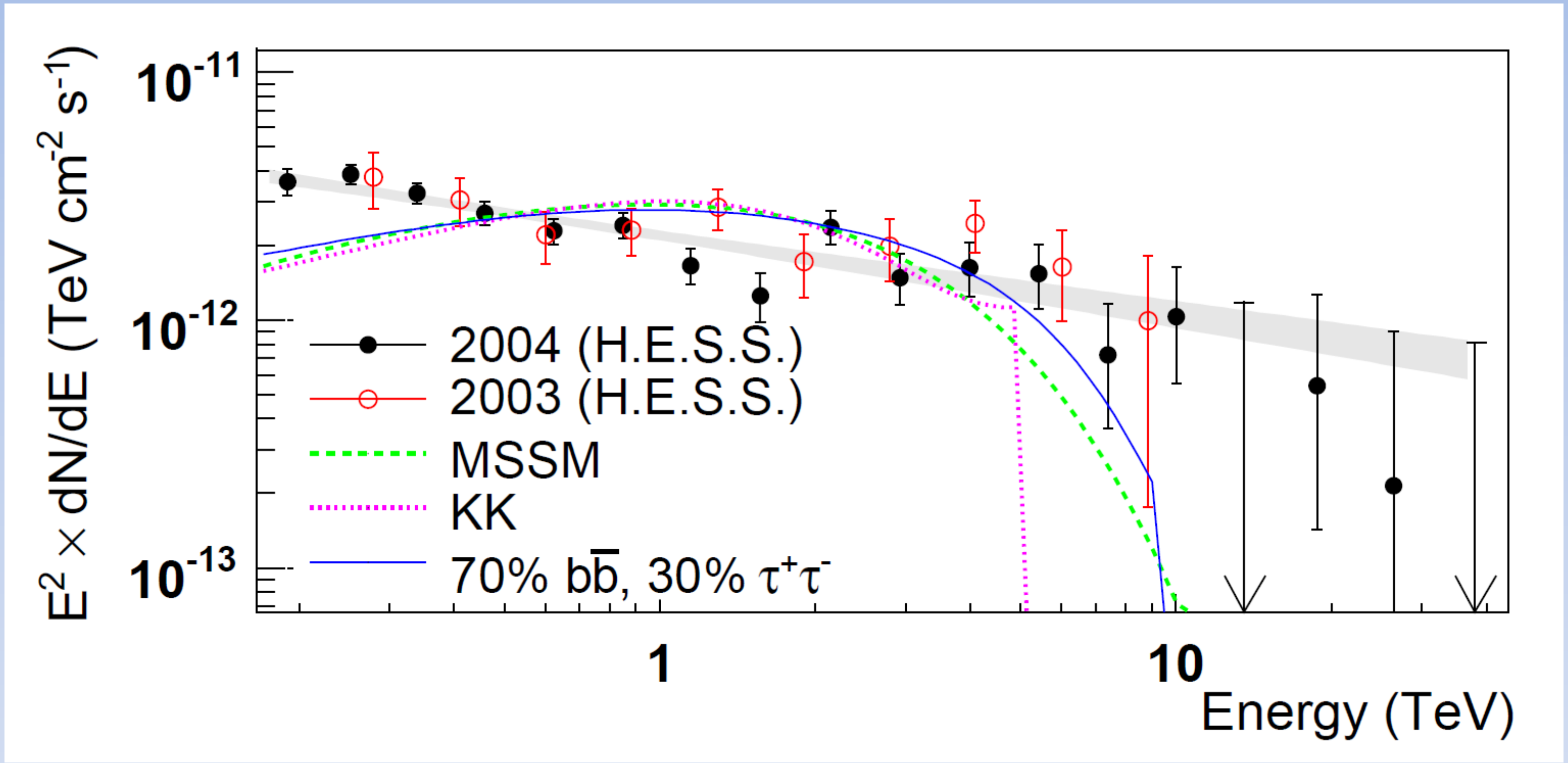
L.B., T.Bringmann, M. Eriksson & M. Gustafsson, JCAP '05

As for SUSY, direct annihilation into $\gamma\gamma$ or $Z\gamma$ is loop-suppressed.



For comparison: HESS has an energy resolution of only 15 % ...

Galactic Center, HESS data (F.Aharonian & al., 2006)



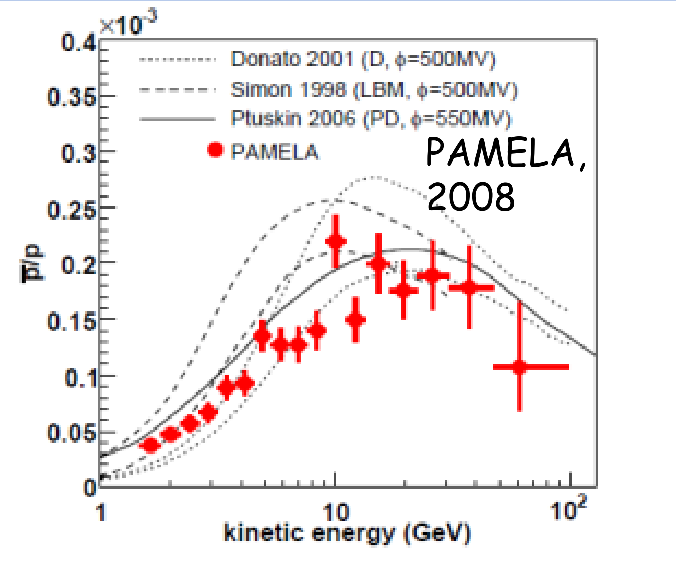
Dark matter fit seems to have wrong shape. Also, the source is consistent with being point-like, not expected from DM.

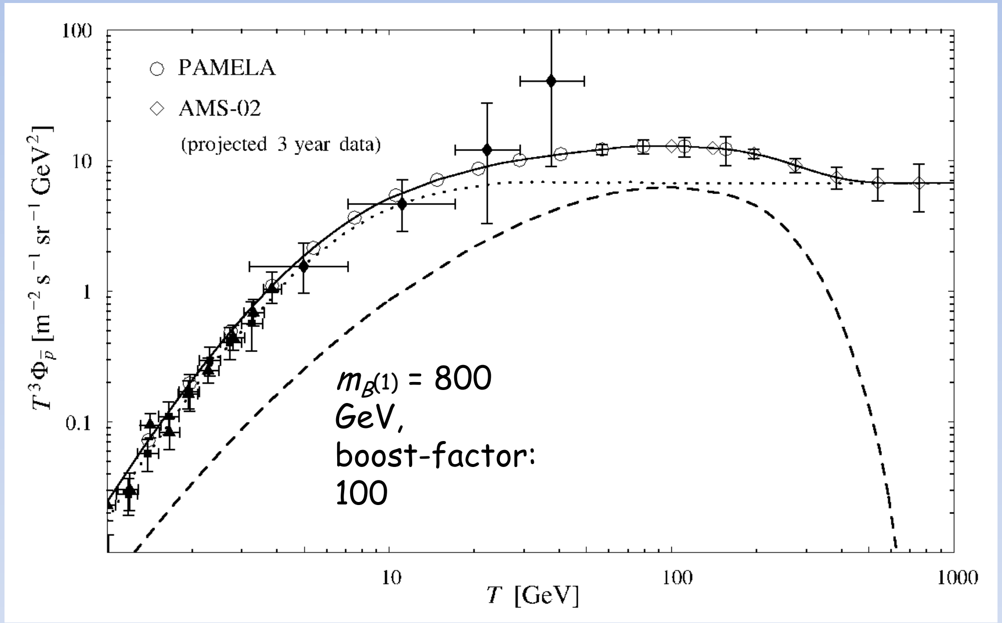
Antiprotons from KK dark matter

Expected fluxes are in general too low to be seen

Allowing for some boost factor, however, PAMELA and AMS will be able to see a characteristic distortion in the spectrum.

T. Bringmann., JCAP '05
Barrau *et al.*, PRD '05





T.Bringmann '05

In that case, there must appear a positron peak as well (like the ATIC peak – seems now disfavoured, FERMI, 2009).

Upcoming direct-detection experiments

Hooper & Profumo, '07

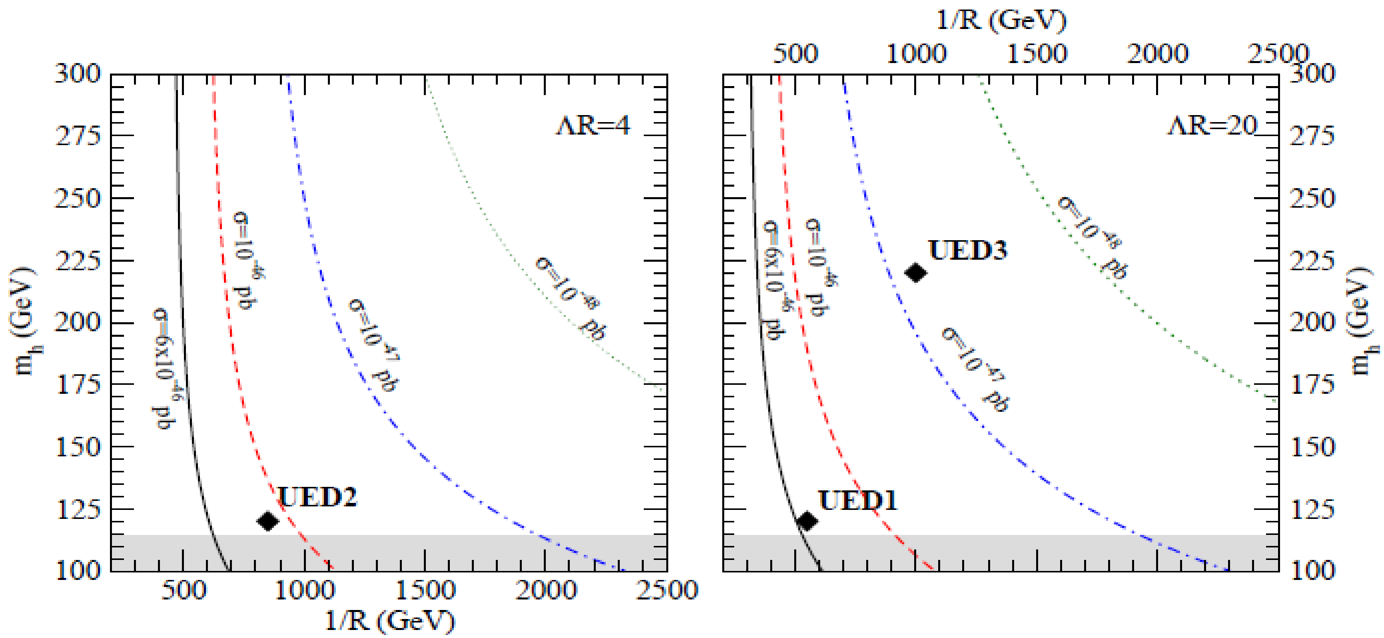


Figure 14: Contours of constant spin-independent $B^{(1)}$-proton scattering cross sections in the $(1/R, m_h)$ plane, for two choices of $\Lambda R = 4$ and 20. The reach of the future direct detection experiments "Xenon-1 ton" and "Super-CDMS C" approximately correspond to the black solid line and to the red dashed line. We also indicate the location of three of the benchmark models of Appendix A.

Promising prospects for direct detection in the future…

Two extra dimensions: the chiral square, (Dobrescu & Ponton 2004) . Analog of the orbifold construction: Identify opposite sides of the square which represents the extra dimensions: "Fold the square along the diagonal and then smoothly glue the sides together."

Peculiar feature: Has very strong gamma-ray lines (G. Bertone & al., 2009), so a line search like that of Fermi should also be performed at ACTs:

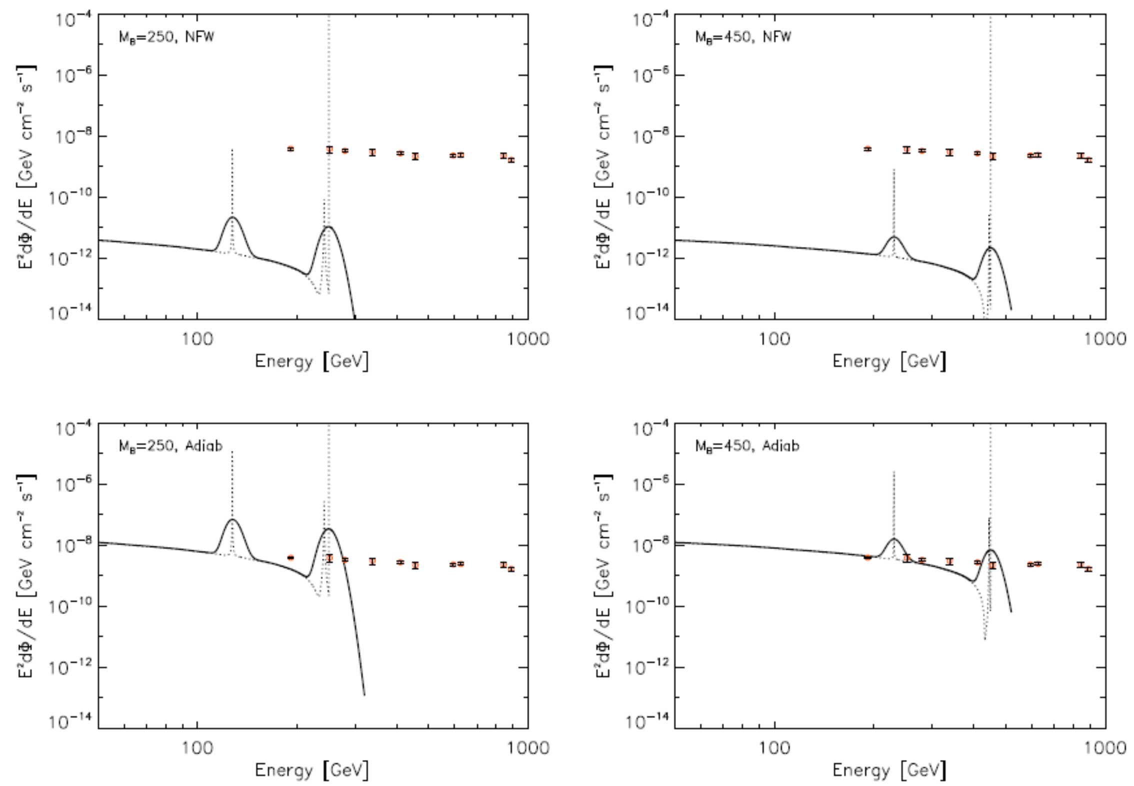


FIG. 4: Predicted fluxes, from a solid angle $\Delta\Omega = 10^{-5}$ towards the GC, for the chiral square model with $M_{B_H} = 250$ GeV (left column) and $M_{B_H} = 450$ GeV (right). We show both the actual spectrum (dotted lines) and the spectrum as it would be observed by an experiment with a 10% energy resolution (solid) like Fermi LAT. An NFW (adiabatically compressed) profile has been adopted for the lower (upper) panels. We show for reference the HESS data relative to the gamma-ray source detected at the Galactic center.

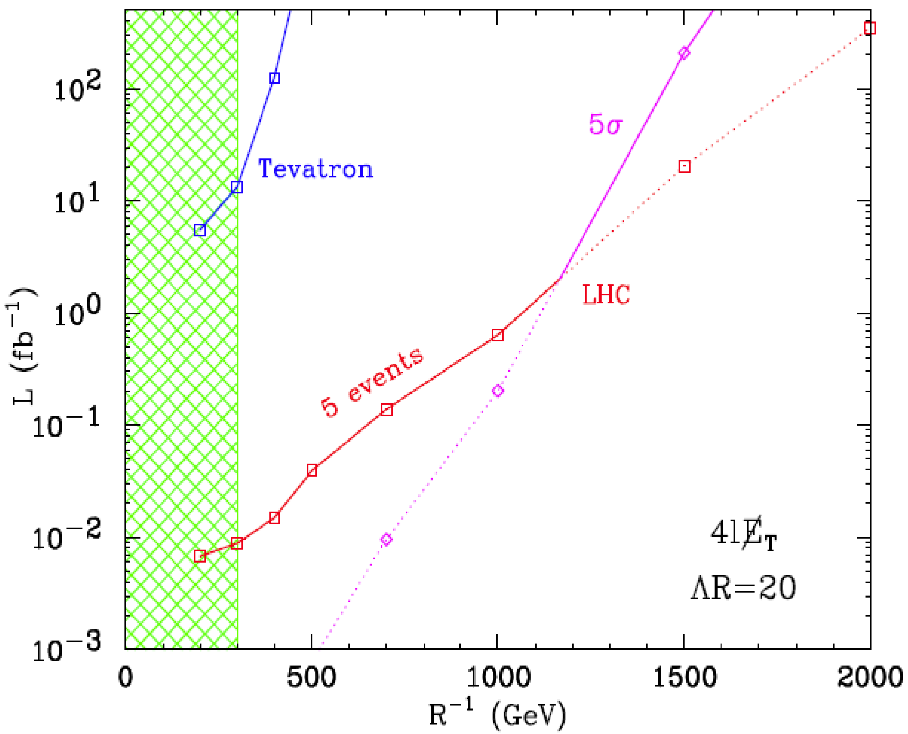
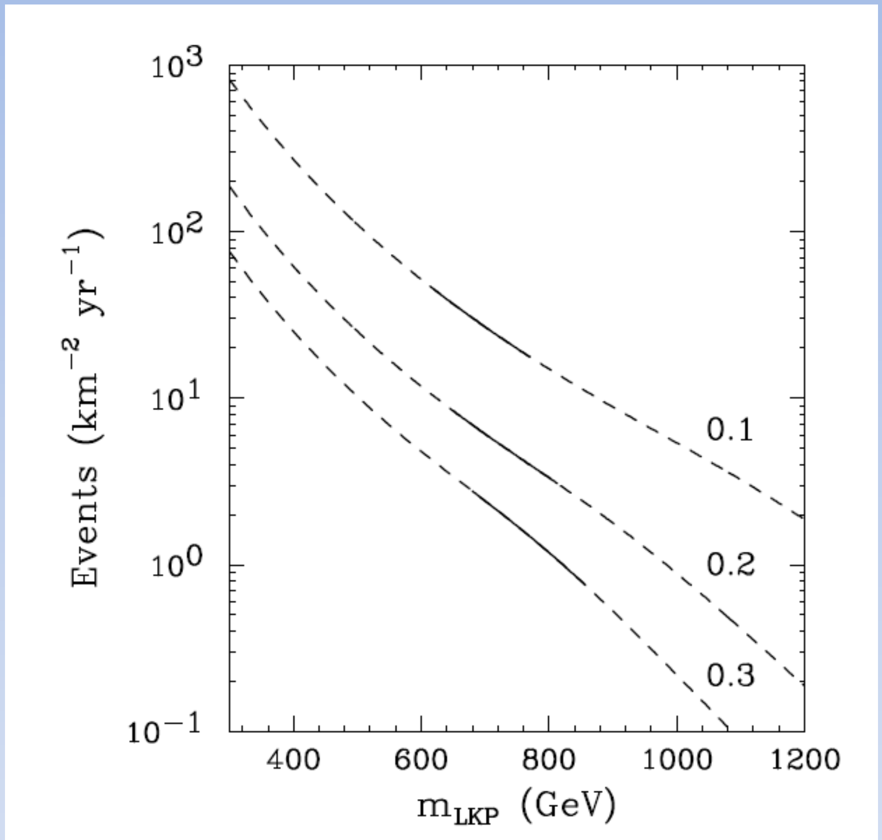


Figure 4. Luminosity required at LHC for a 5σ signal in the $4l+E_T^{\rm miss}$ channel in the UED model,

Cheng, Matchev, Schmaltz, 2002

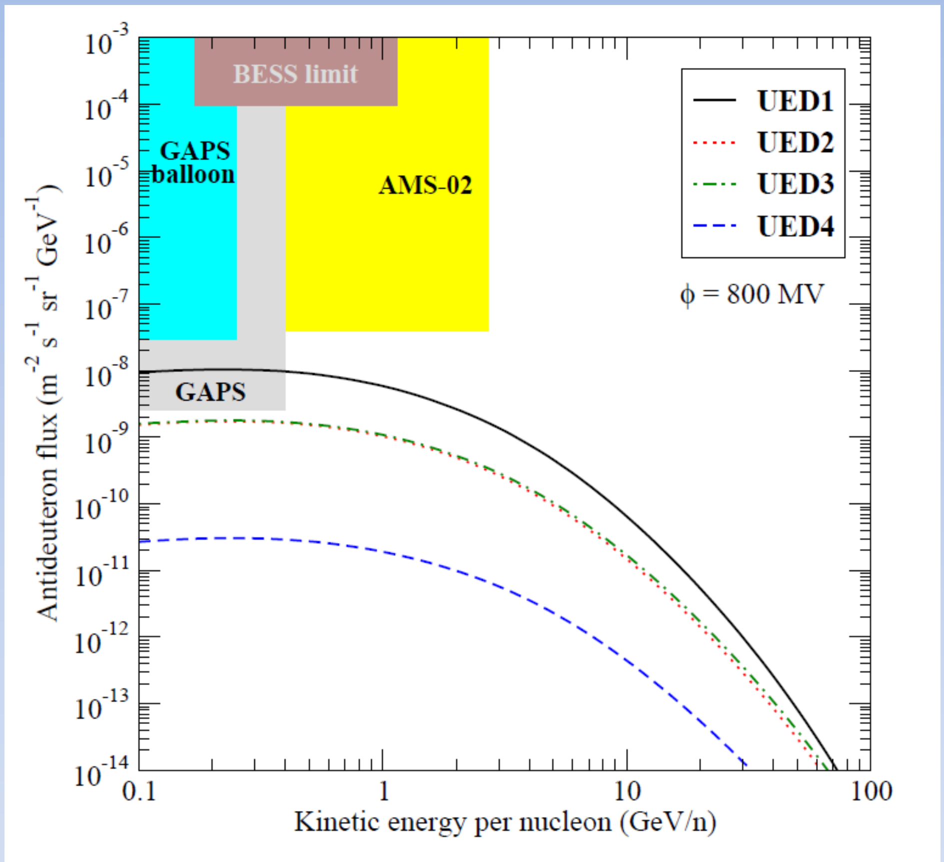
LHC may open up the extra dimensions…

Neutrinos:



Hooper & Kribs, 2003

Antideuterons:

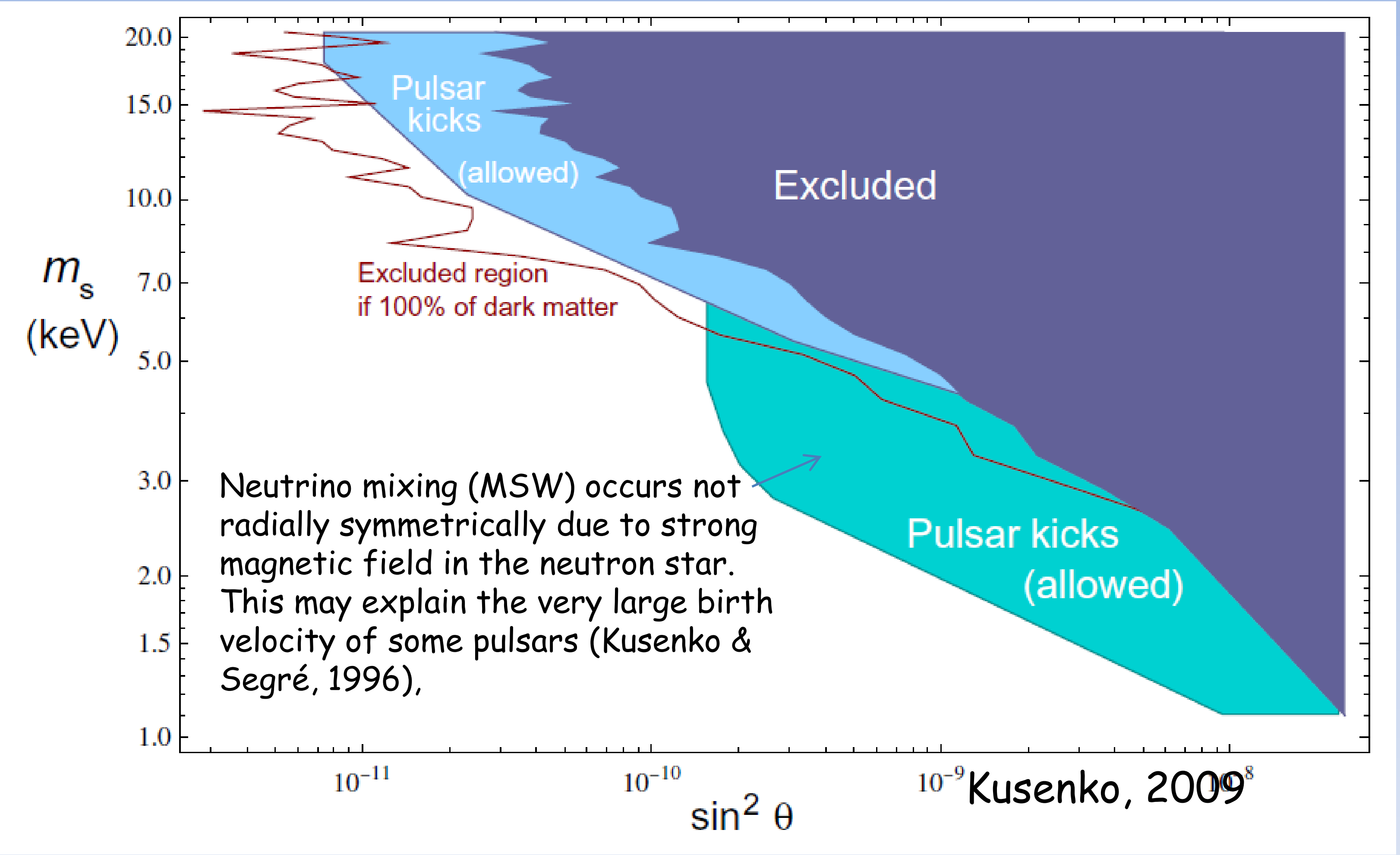


Donato, Fornengo, Salati, 2000; Hooper & Profumo, 2007

Summary:

KK Dark Matter is an interesting spin-1 candidate for dark matter, with promising prospects for detection at LHC, IceCube, antideuterons, TeV gamma-rays, direct detection…

Sterile neutrinos: They have to exist, since neutrinos have mass. Interesting phenomenology if they are light (but in most models they are extremely heavy…).



Neutrino mixing (MSW) occurs not radially symmetrically due to strong magnetic field in the neutron star. This may explain the very large birth velocity of some pulsars (Kusenko & Segré, 1996),

Kusenko, 2009

Evidence for X-ray line from 5 keV neutrino decay?

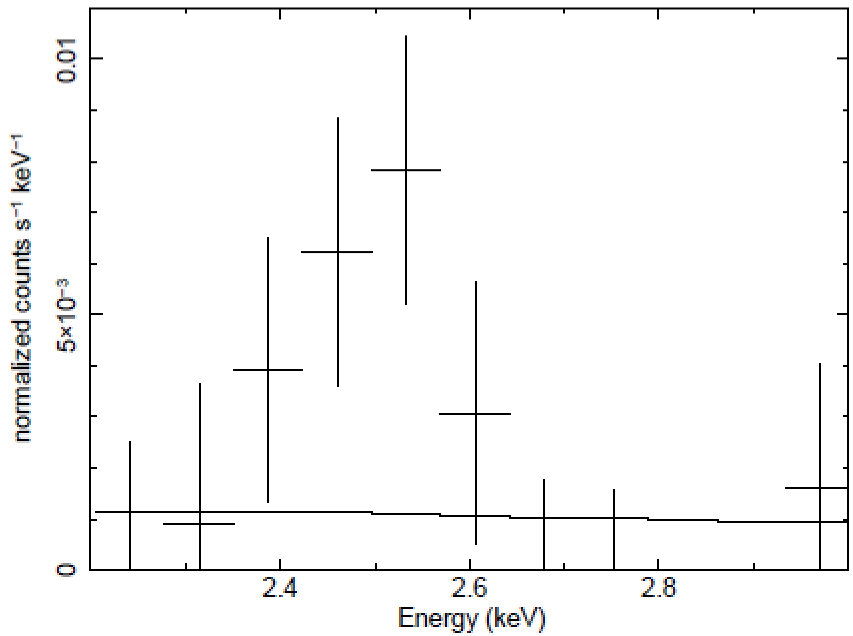
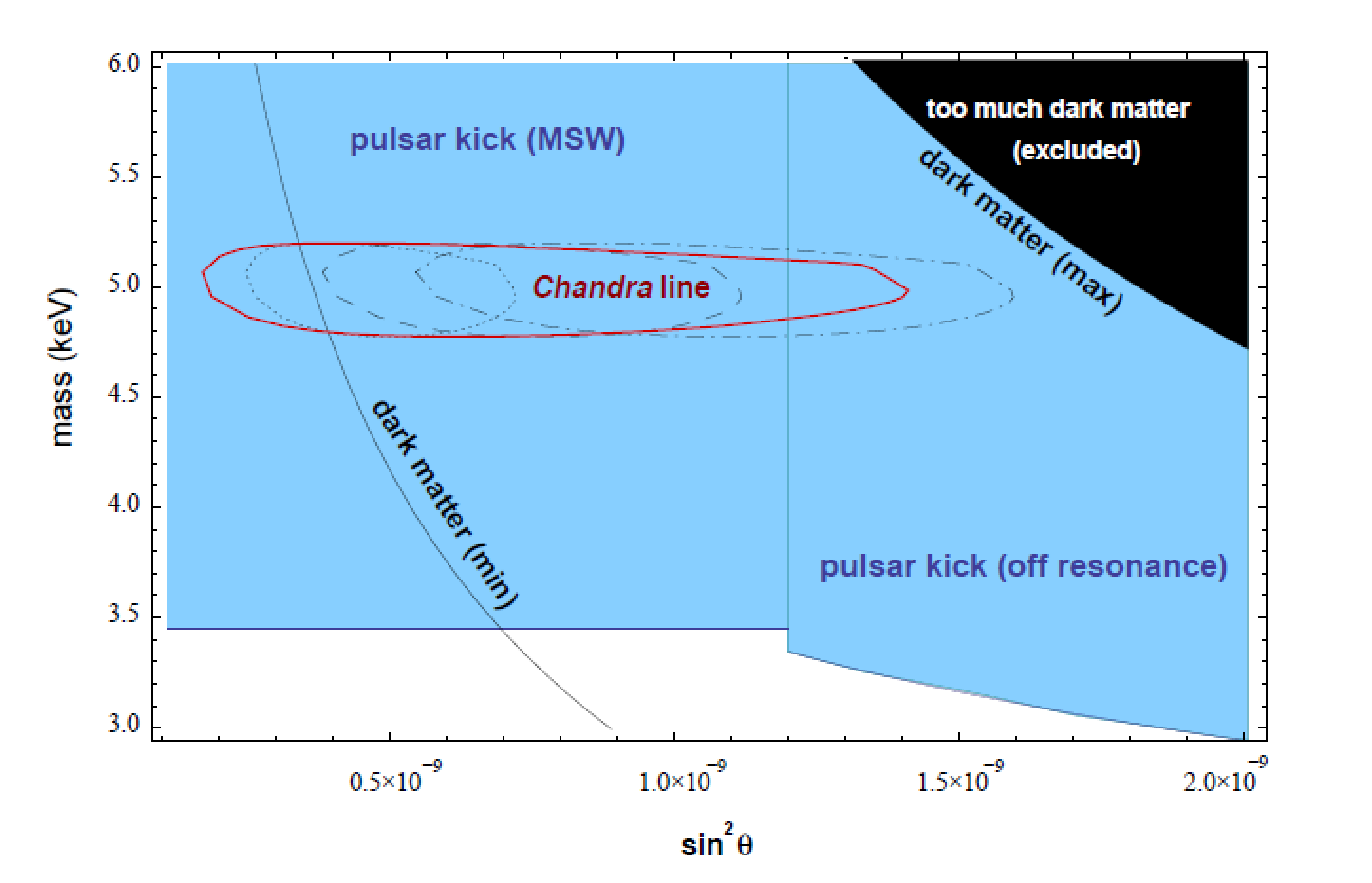


Fig. 5.— (a) Data and best-fit power-law model to the 2.2-5 keV spectrum, in the 2.2-3 keV energy region (**top**), and (**b**) contributions to χ^2 over 2.2-5 keV(**bottom**).

Loewenstein & Kusenko, 2009. Not very significant (2-3 σ; controversial)


6.0
5.5
5.0
4.5
4.0
3.5
3.0
mass (keV)
pulsar kick (MSW)
too much dark matter
(excluded)
dark matter (max)
Chandra line
dark matter (min)
pulsar kick (off resonance)
0.5×10^-9
1.0×10^-9
1.5×10^-9
2.0×10^-9
sin^2 θ

Spin-0 Dark Matter

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

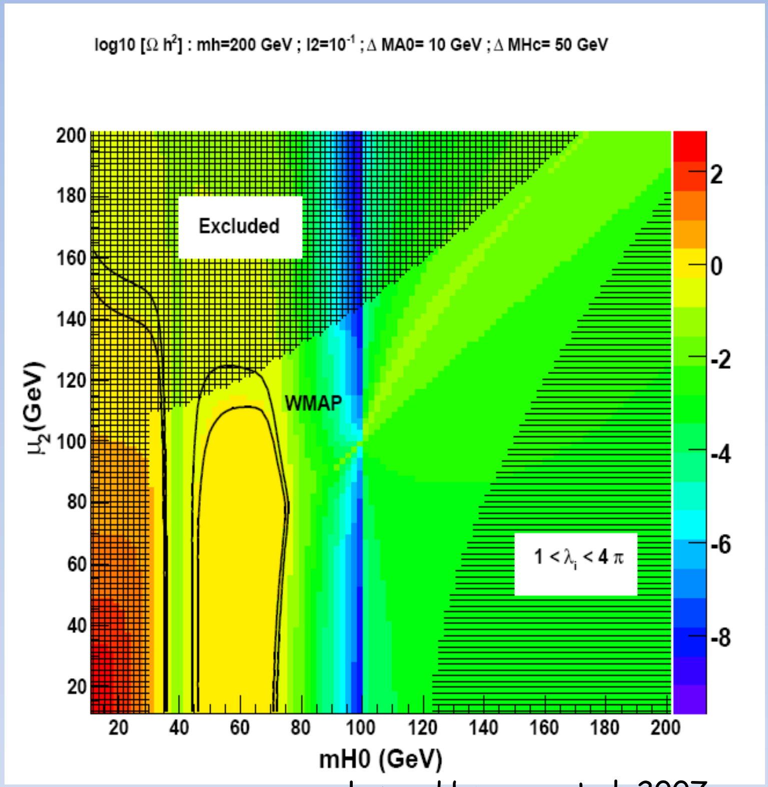
Introduce extra Higgs doublet H_2, impose discrete symmetry $H_2 \to -H_2$ similar to R-parity in SUSY (Deshpande & Ma, 1978, Barbieri, Hall, Rychkov 2006)

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

$\Rightarrow$ Ordinary Higgs h can be as heavy as 400 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!

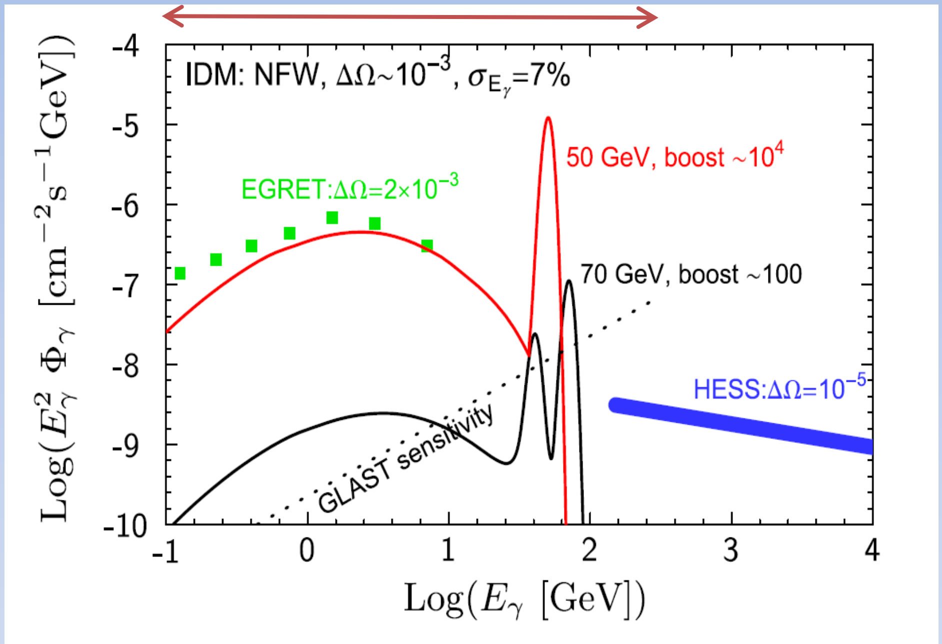
M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL 2007.

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



Lopez Honorez et al, 2007

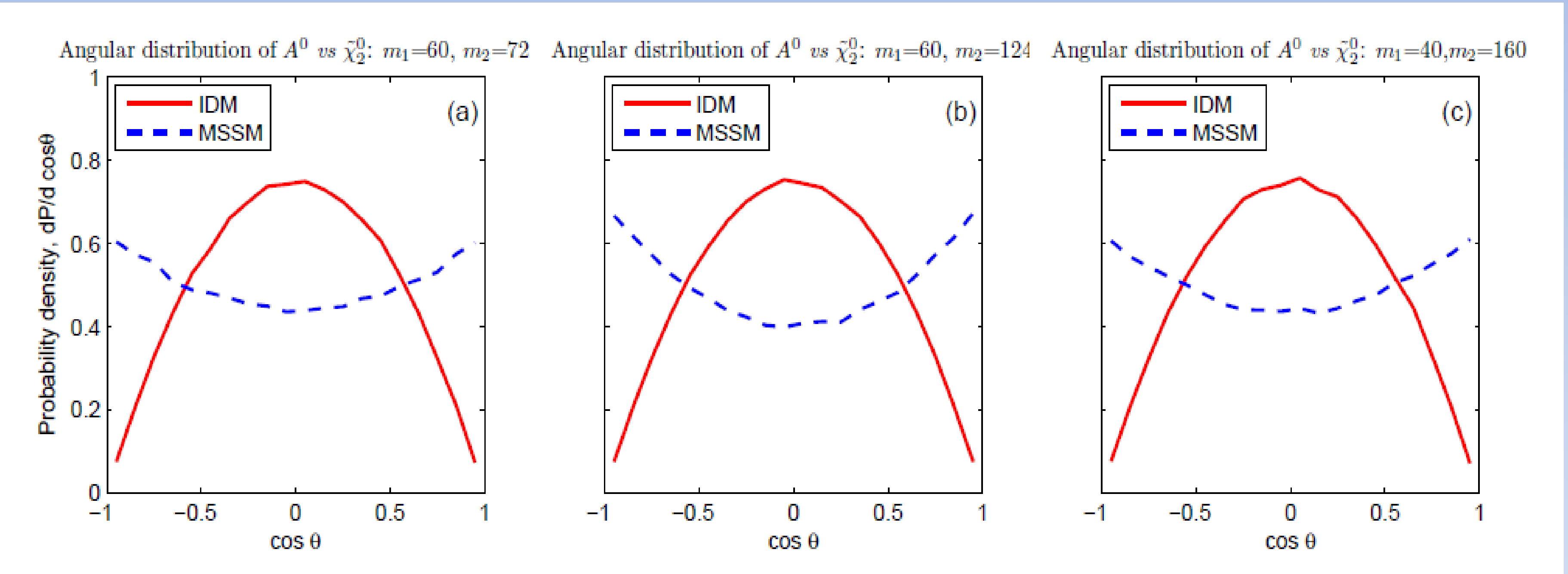
FERMI energy range



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

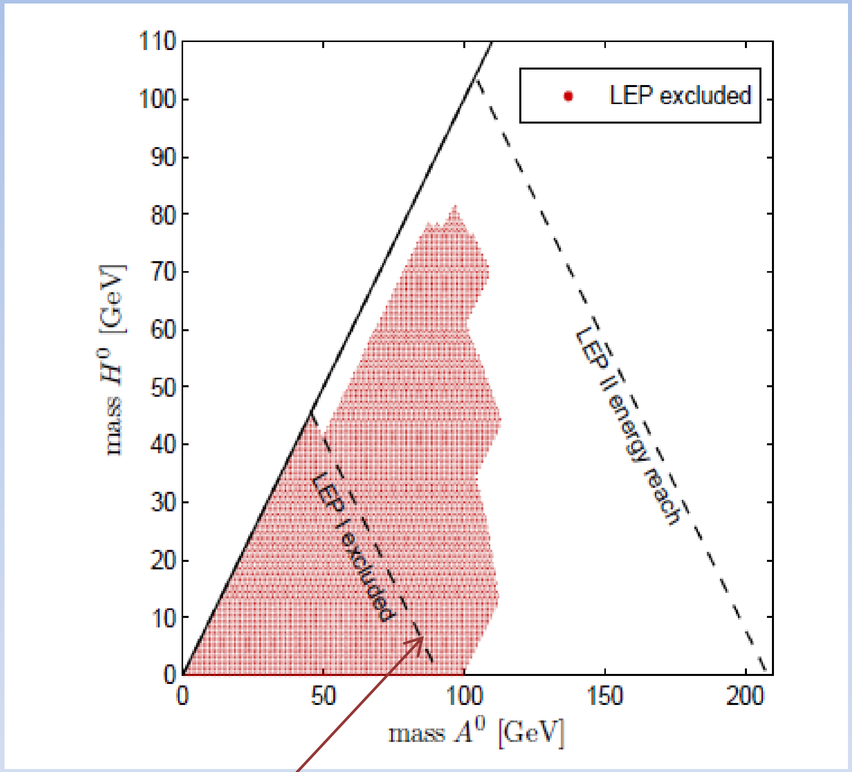
Note on boost factors: the overall average enhancement over a smooth halo, from DM substructure etc, is hardly greater than 2 – 10. In one specific location, however, like the region around the galactic center, factors up to 10^4 are easily possible.

E. Lundström, M. Gustafsson, J. Edsjö, 2008

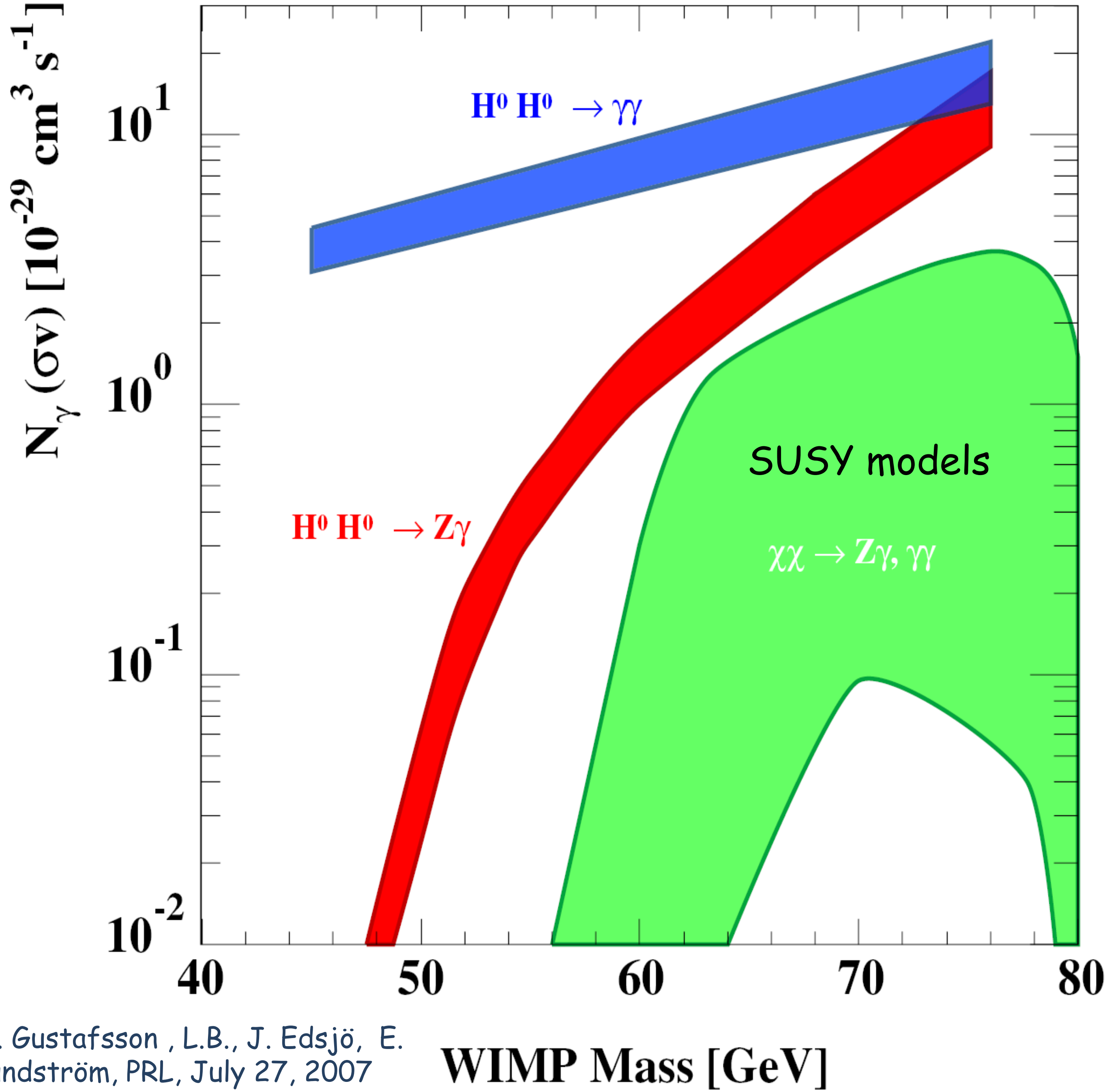


Spin-0 vs. Spin-1/2 Dark Matter

E. Lundström, M. Gustafsson, J. Edsjö, 2008

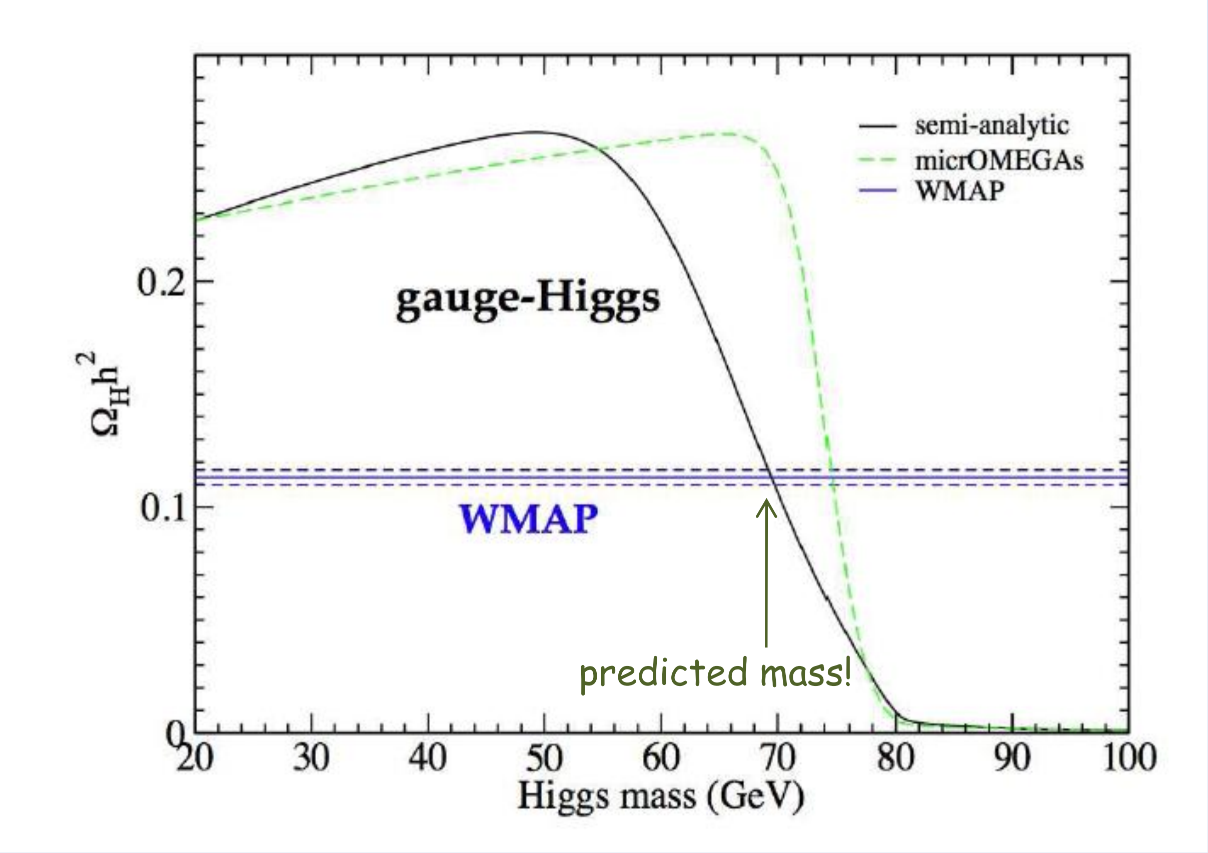


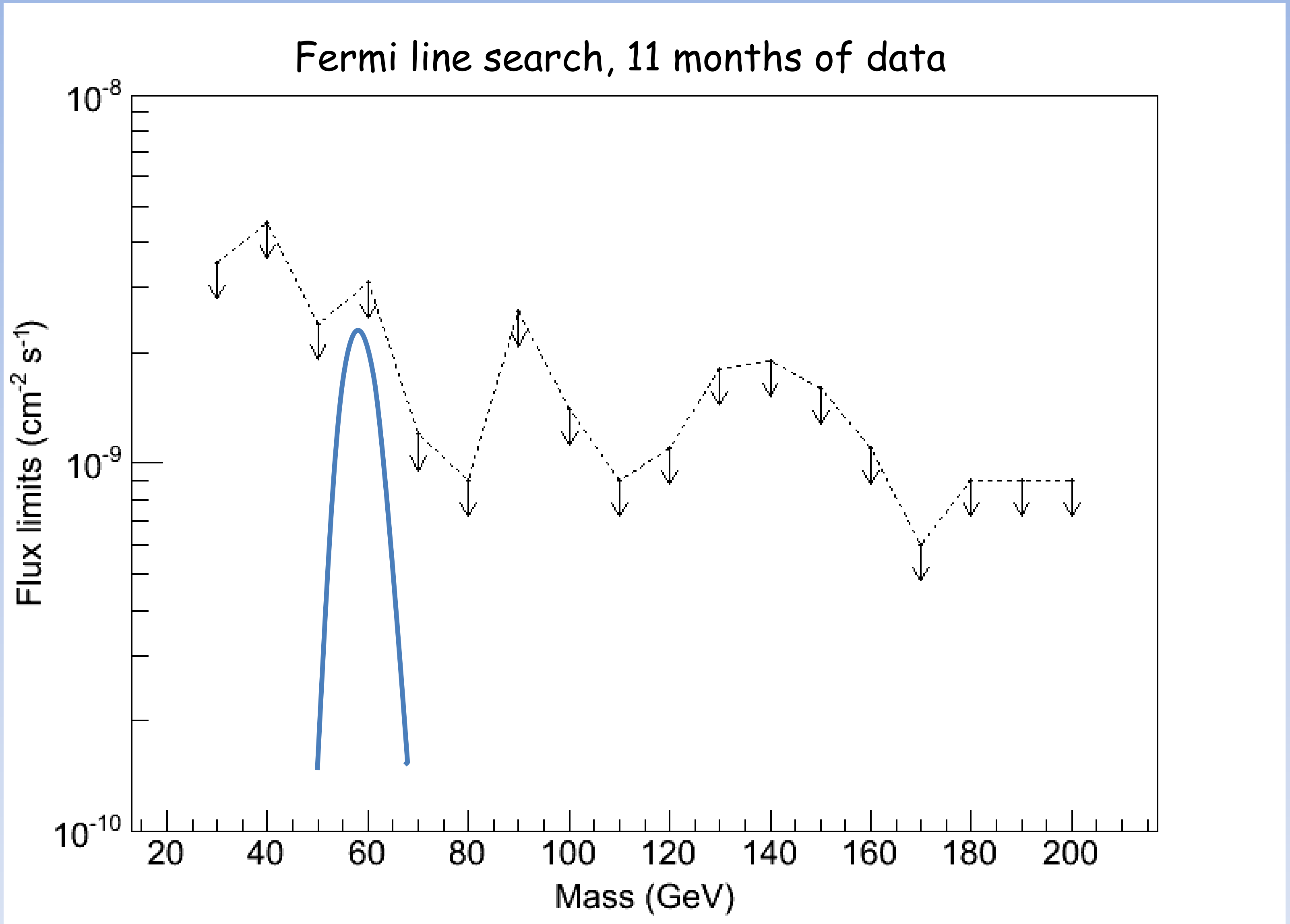
From Z
width



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

Extradimensional Higgs model (Hositani, 2010), gives gauge - Higgs unification, and predicts dark amtter in the form of a stable 70 GeV Higgs, which does not couple to Z, and thus avoids LEP Higgs bounds. It should give a large gamma-ray line branching fraction through loops of to quarks and virtual Ws. It would have rather small cross section for direct detection, but could be found in a gamma-ray line search around 60-70 GeV.





Fermi Collaboration, T. Ylinen & al. 2010